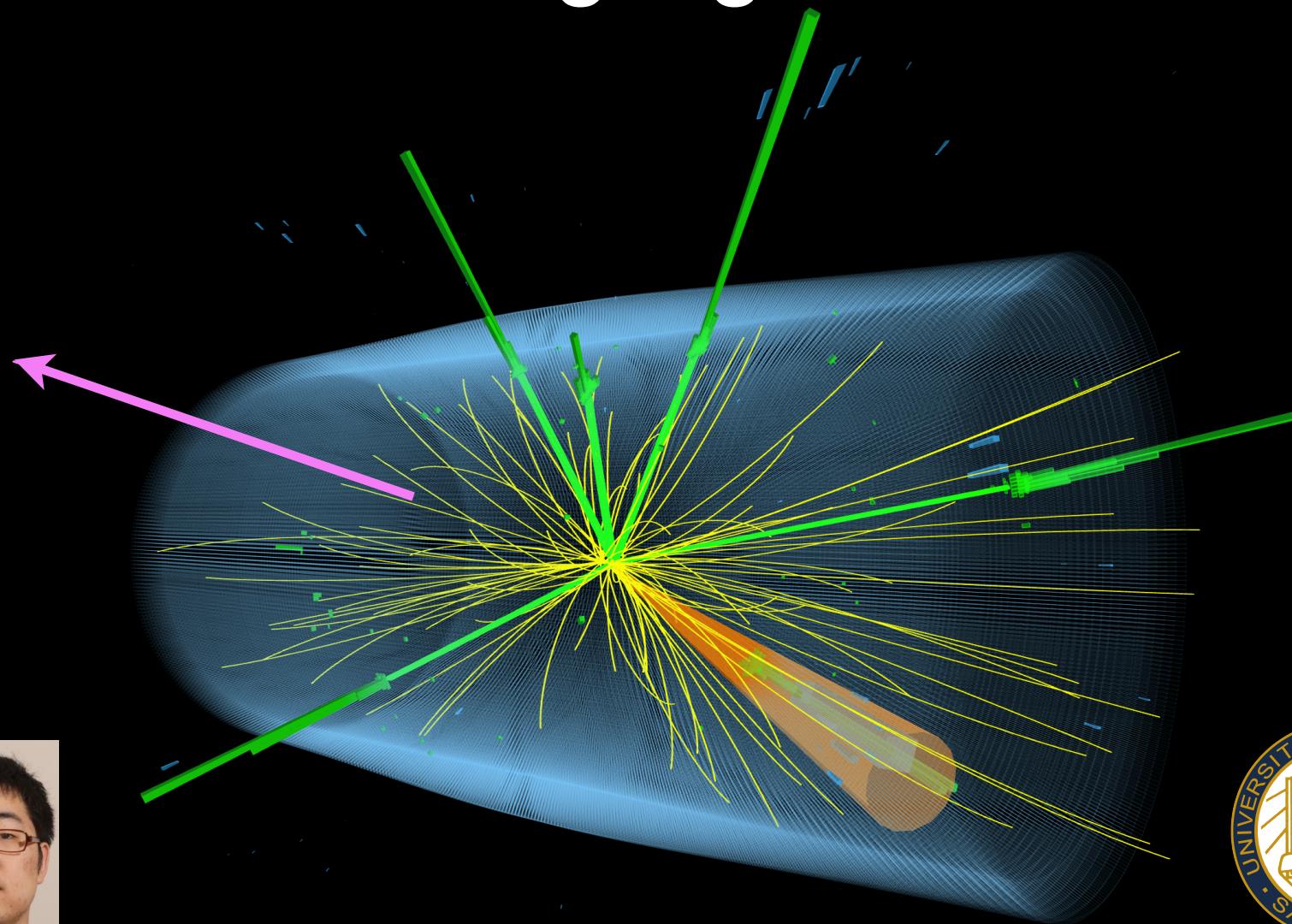


# First observation of production of three massive gauge bosons

$V = W, Z$



Philip  
Chang

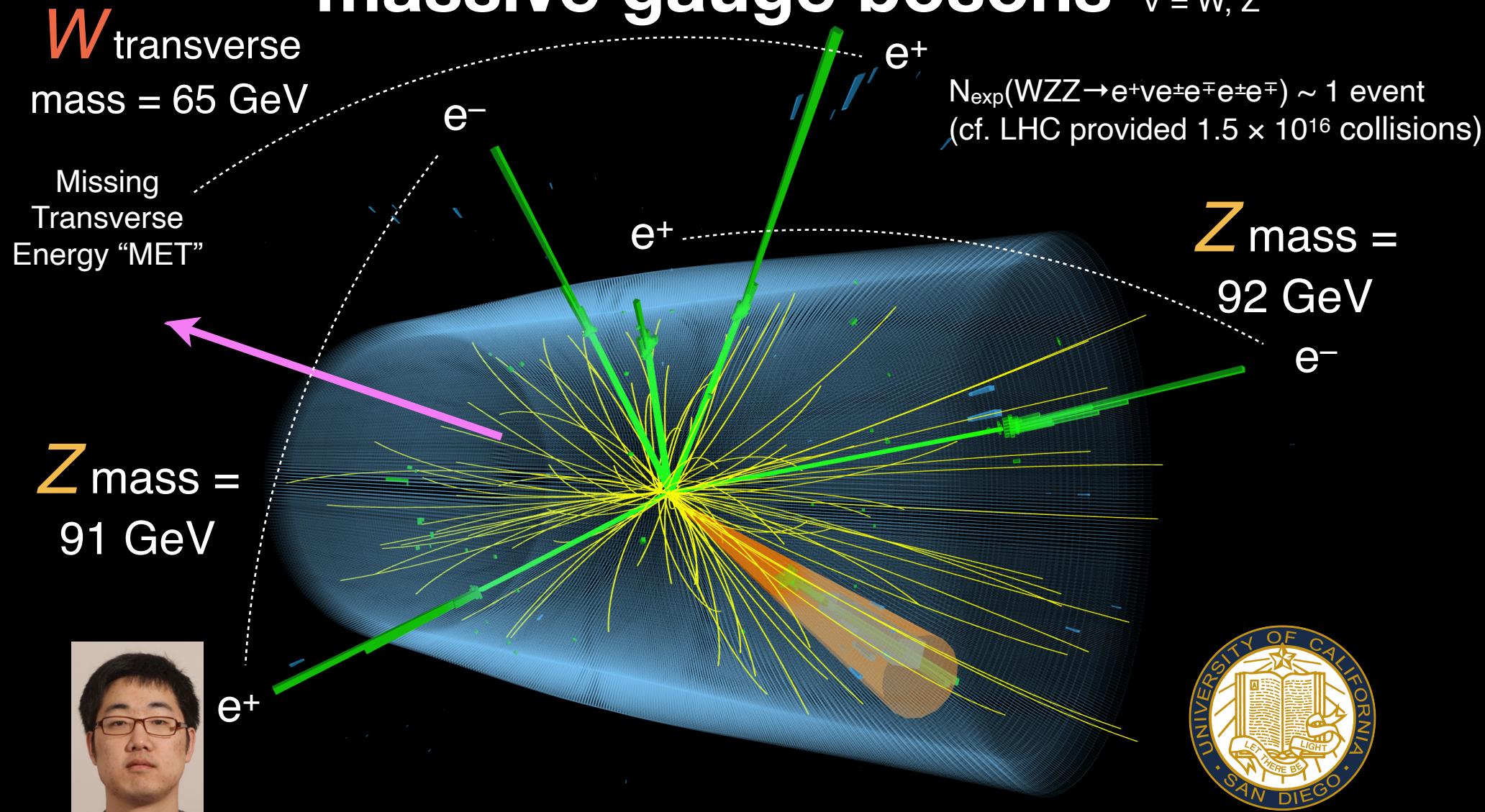
Hanyang Univ. HEP Seminar  
July 23, 2020



Univ. of California  
San Diego

# First observation of production of three massive gauge bosons

$V = W, Z$



Philip  
Chang

Hanyang Univ. HEP Seminar  
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Univ. of California  
San Diego



- Why study multi-*boson* interactions?
- How do we study multi-boson productions at LHC?
- First observation of production of three massive gauge bosons
- Where do we go in the next 15 years?

# Discovery of Higgs boson

**Chang**  
UCSD

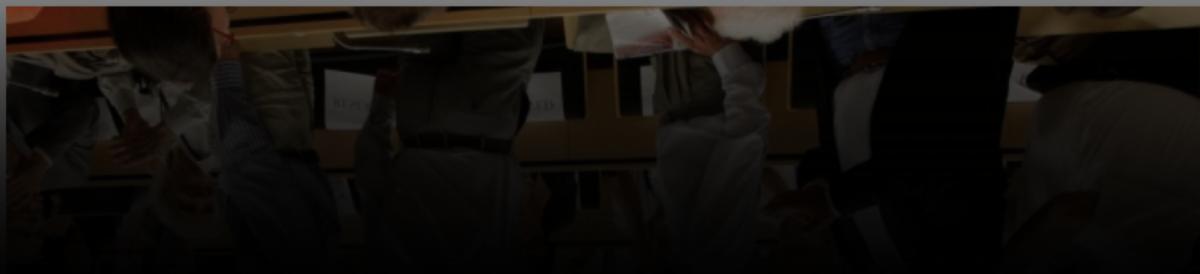


July 4, 2012

Oct 8, 2013

# The New York Times

# *Physicists Find Elusive Particle Seen as Key to Universe*



10

## The Nobel Prize in Physics 2013

# The Nobel Prize in Physics 2013

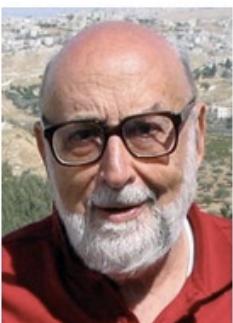


Photo: Pnicolet via  
Wikimedia Commons  
**François Englert**

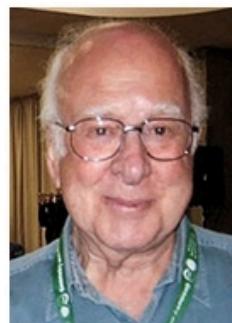


Photo: G-M Greuel via  
Wikimedia Commons

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

# Why was Higgs boson important?



Building blocks of nature (fermions)

## Quarks

<i>u</i>	<i>c</i>	<i>t</i>
up	charm	top

<i>d</i>	<i>s</i>	<i>b</i>
down	strange	bottom

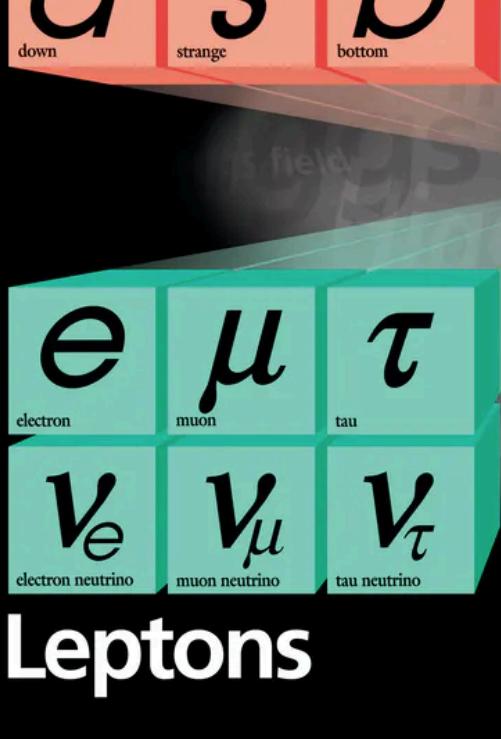
<i>e</i>	<i><math>\mu</math></i>	<i><math>\tau</math></i>
electron	muon	tau

$\nu_e$	$\nu_\mu$	$\nu_\tau$
electron neutrino	muon neutrino	tau neutrino

## Leptons

Binding forces  
(bosons)

## Forces



- (Was) Last missing piece of the puzzle in the Standard Model
- Higgs field is responsible for giving masses to other particles
- Only fundamental spin-0 particle we know
- Couples to multitude of particles that have mass

Advanced our knowledge of the origin of mass in major way

# Importance of Higgs

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Lee, Quigg, Thacker (1977)

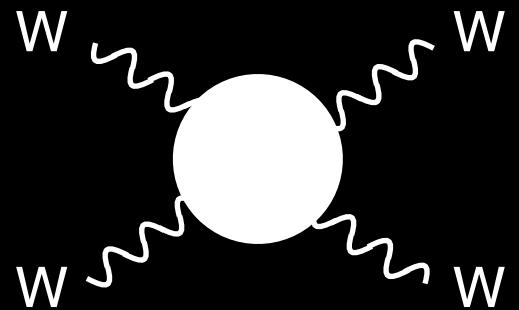
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WW scattering



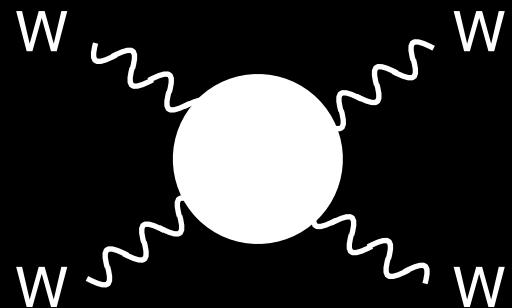
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UCSD



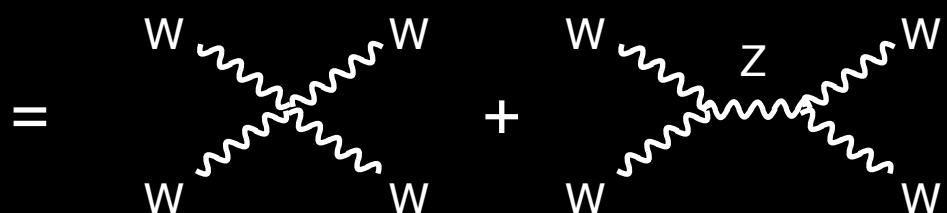
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WW scattering



$$P(WW \rightarrow WW) \sim E^2$$

(i.e. at high E, P > 1)

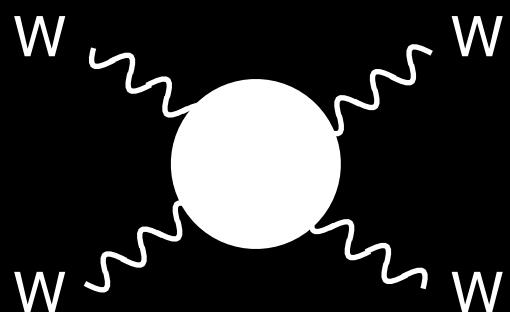


Bad high energy behavior

# Importance of Higgs

Lee, Quigg, Thacker (1977)

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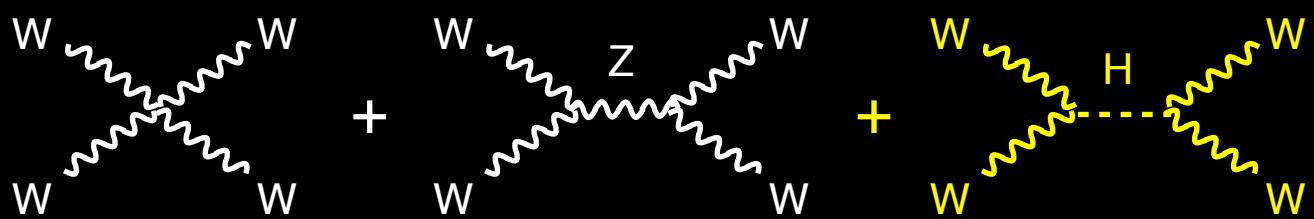


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With Higgs P < 1

=



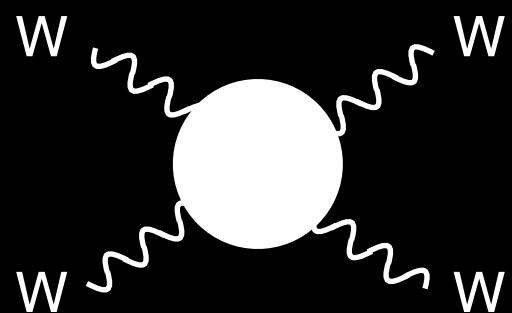
Bad high energy behavior

Cancel bad  
high E behavior

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Lee, Quigg, Thacker (1977)

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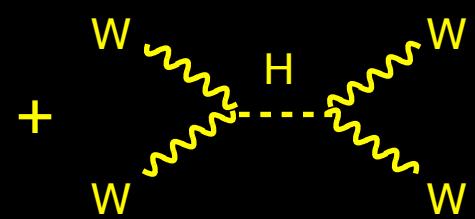
=

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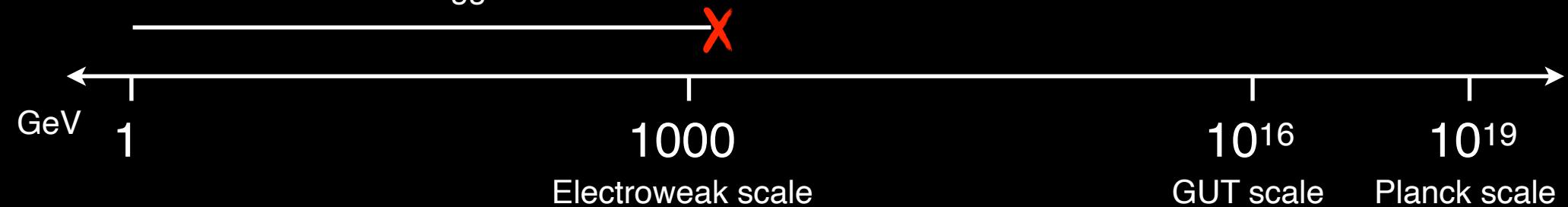
Bad high energy behavior

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Cancel bad  
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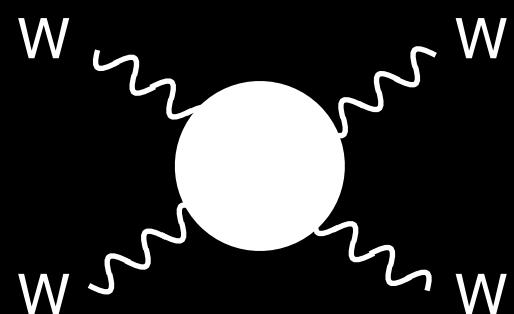
SM Before Higgs boson



# Importance of Higgs

Lee, Quigg, Thacker (1977)

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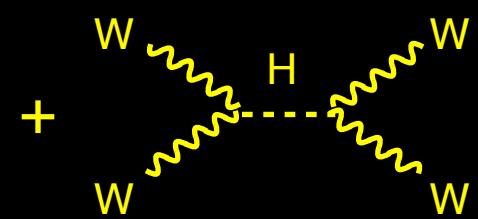
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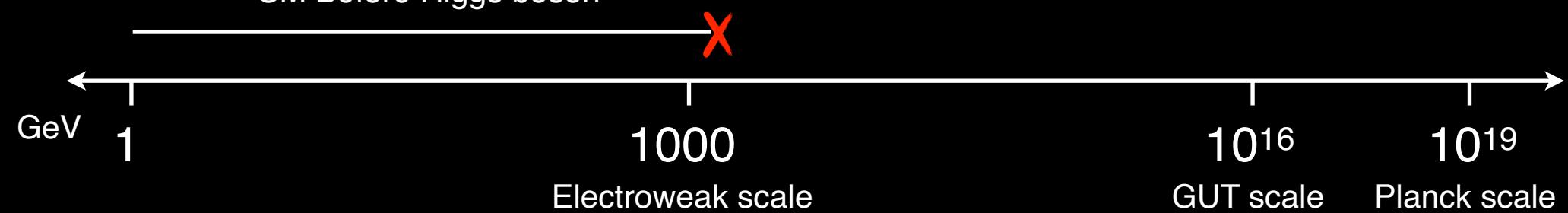
Bad high energy behavior

With Higgs P < 1



Cancel bad  
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SM Before Higgs boson



Previous experiments

LHC

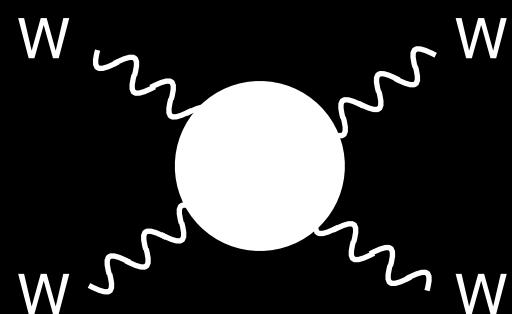
# Importance of Higgs

Chang  
UCSD



Lee, Quigg, Thacker (1977)

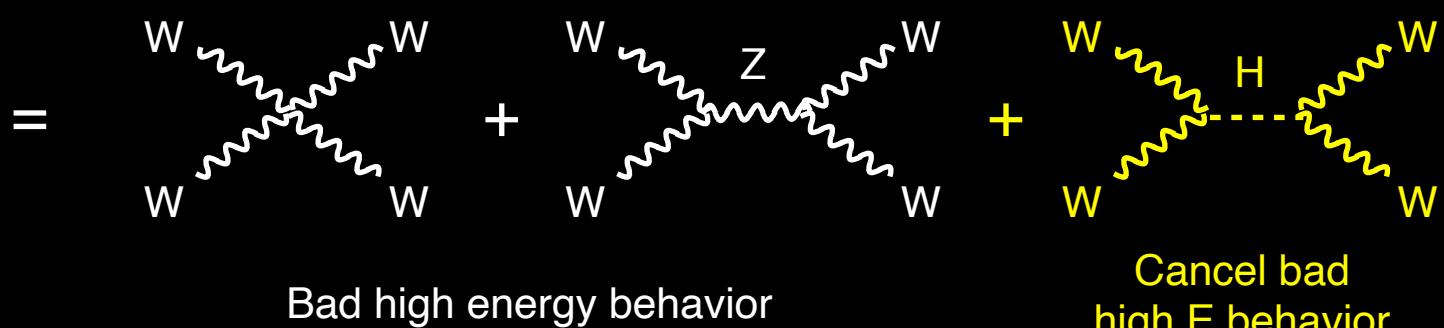
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With Higgs  $P < 1$



Cancel bad  
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SM Before Higgs boson

SM After Higgs boson (in principle)



1000  
Electroweak scale

$10^{16}$   
GUT scale  
 $10^{19}$   
Planck scale

Previous experiments

LHC

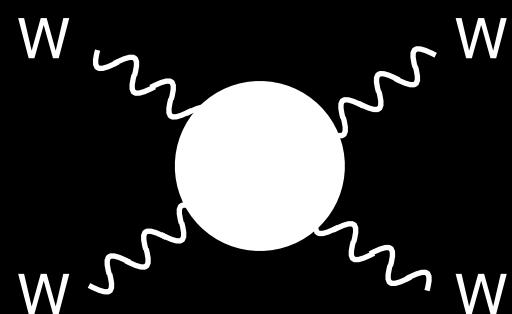
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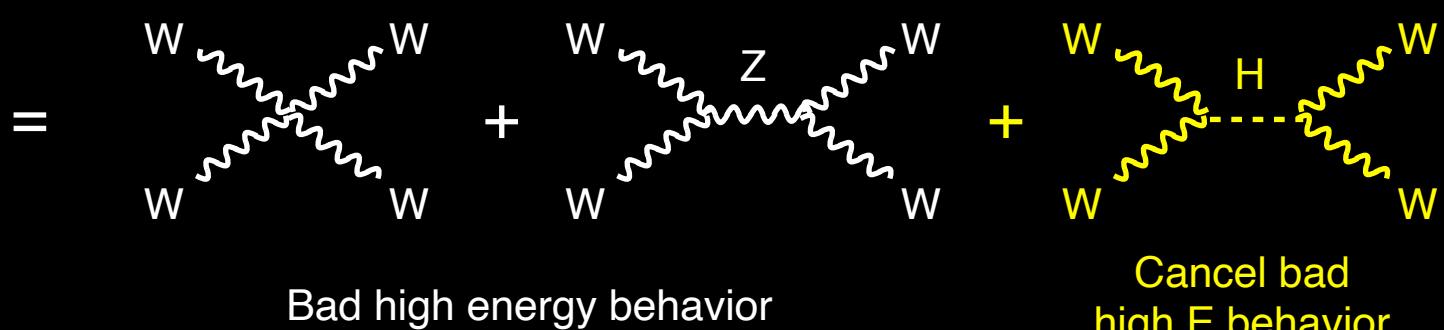
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GeV

Previous experiments

LHC

Is this picture all true?

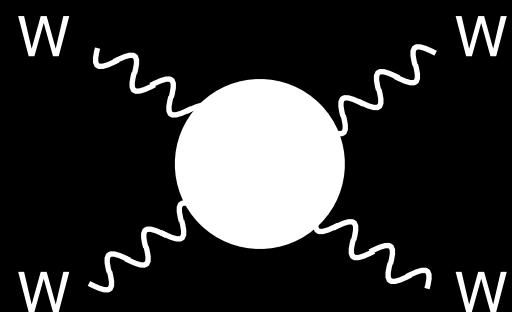
# Importance of Higgs

Chang  
UCSD



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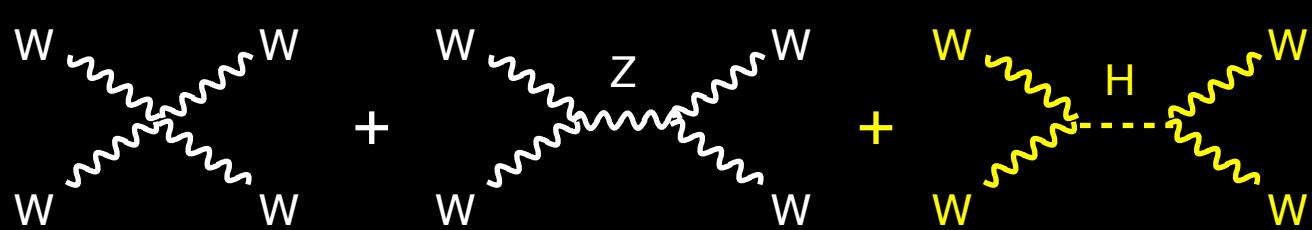
WW scattering



=

$$P(WW \rightarrow WW) \sim E^2 \\ (\text{i.e. at high } E, P > 1)$$

With Higgs  $P < 1$



Bad high energy behavior

Cancel bad  
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SM Before Higgs boson

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LHC

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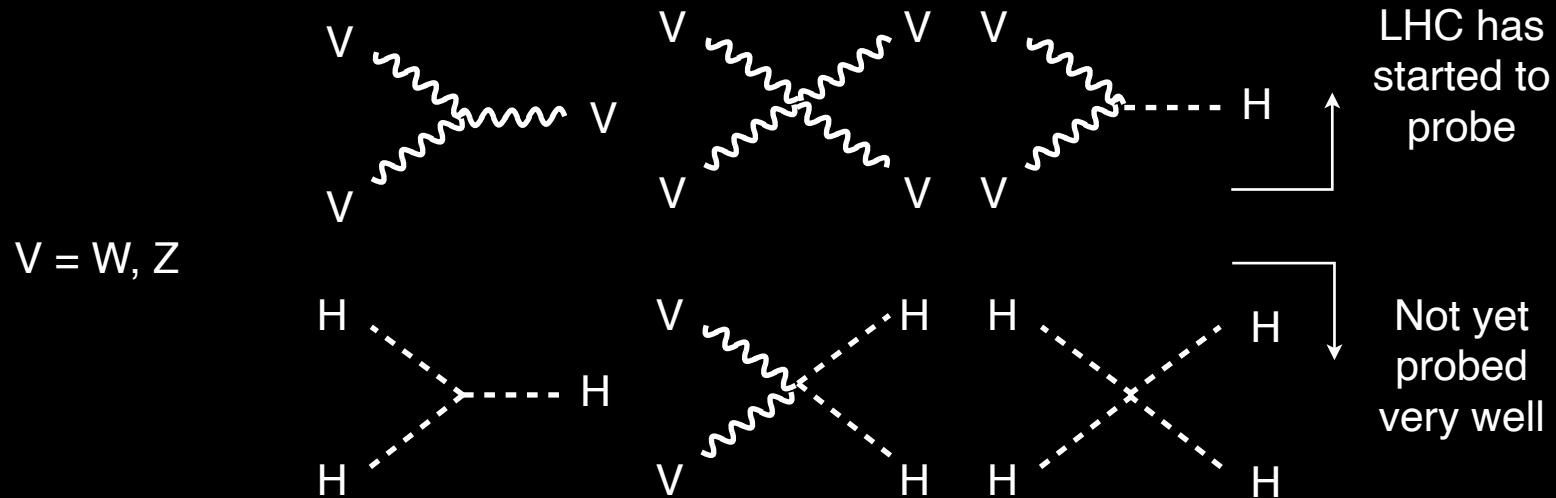
Higgs boson is integral to the multi-boson interactions

# Remaining questions in electroweak sector

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## List of multi-boson interactions



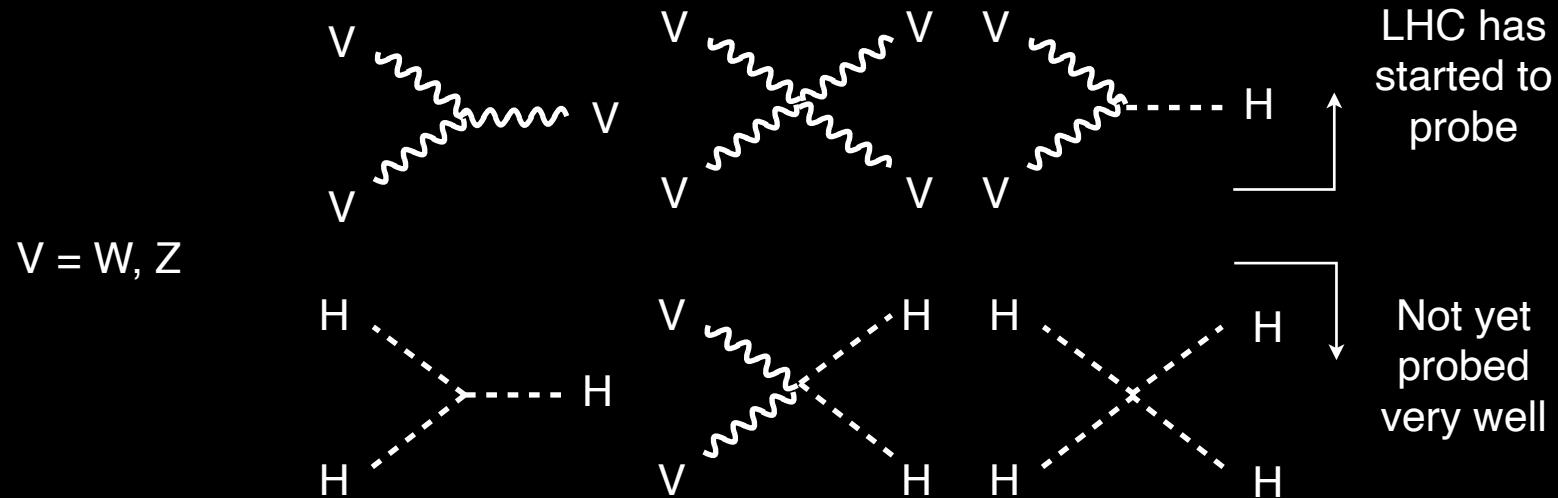
- Are multi-*bosons* interactions SM? (including Higgs self-coupling)
  - (Deep implications, e.g. baryogenesis, stability of the universe.)
- Is it the only Higgs boson? (or are there more?  $H_1, H_2, \dots ??$ )
- If so, what are their role in the electroweak symmetry breaking?

# Remaining questions in electroweak sector

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## List of multi-boson interactions

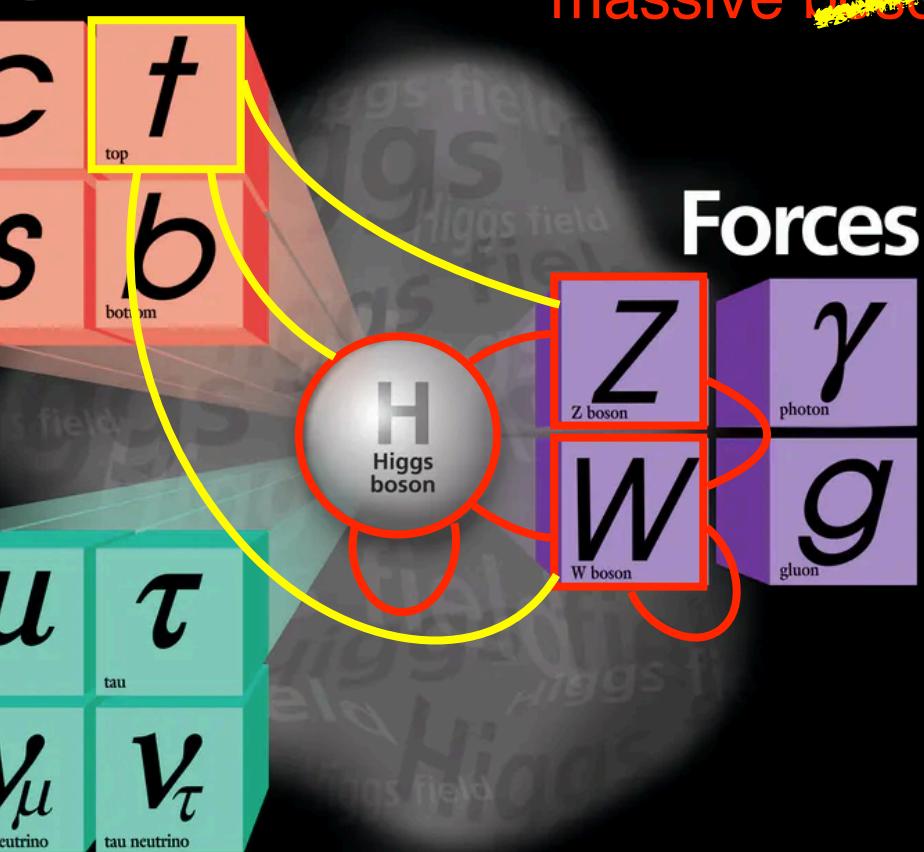


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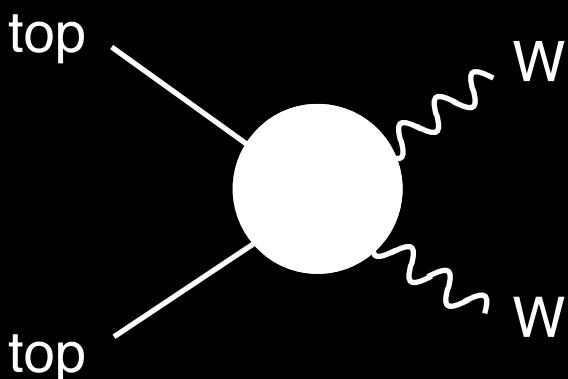
***Studying multi-boson interactions can answer these questions***

# Multi- $X$ electroweak interactions

Top is also connected



## Forces



also  
bad high E  
behavior  
w/o Higgs

1978 (way) before top/W/Z/Higgs discovery  
Chanowitz, Furman, Hinchliffe

F,  $W^\pm$ , Z and H become “sthenons” in the sense of Appelquist and Bjorken [4] : they couple strongly to one another <sup>\*1</sup> but weakly to non-sthenons (i.e., the light particles in the theory).

Multi- $X$  ( $X = t, W, Z, H$ ) electroweak interactions must be studied in detail

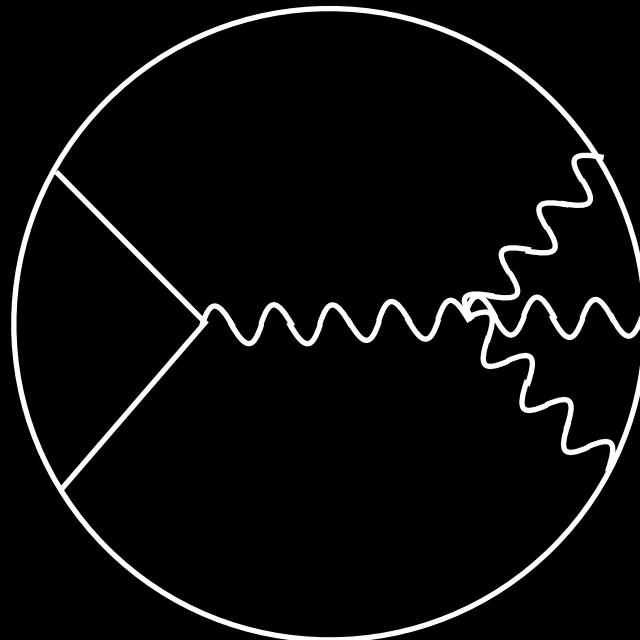
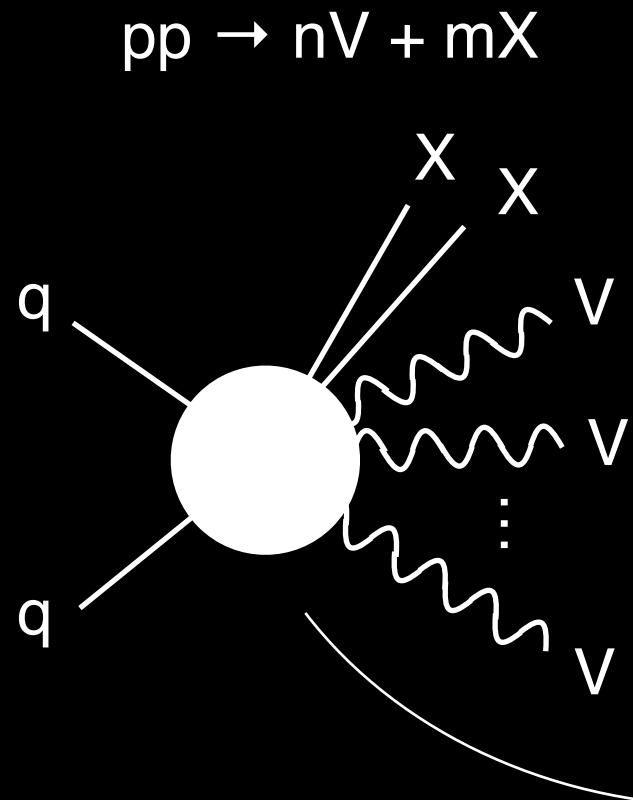
# Probing multi-boson physics in hadron collider

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UCSD



Consider multi-object production process

Can probe quartic gauge coupling



For example

Study multi-boson production process to study multi-boson interactions

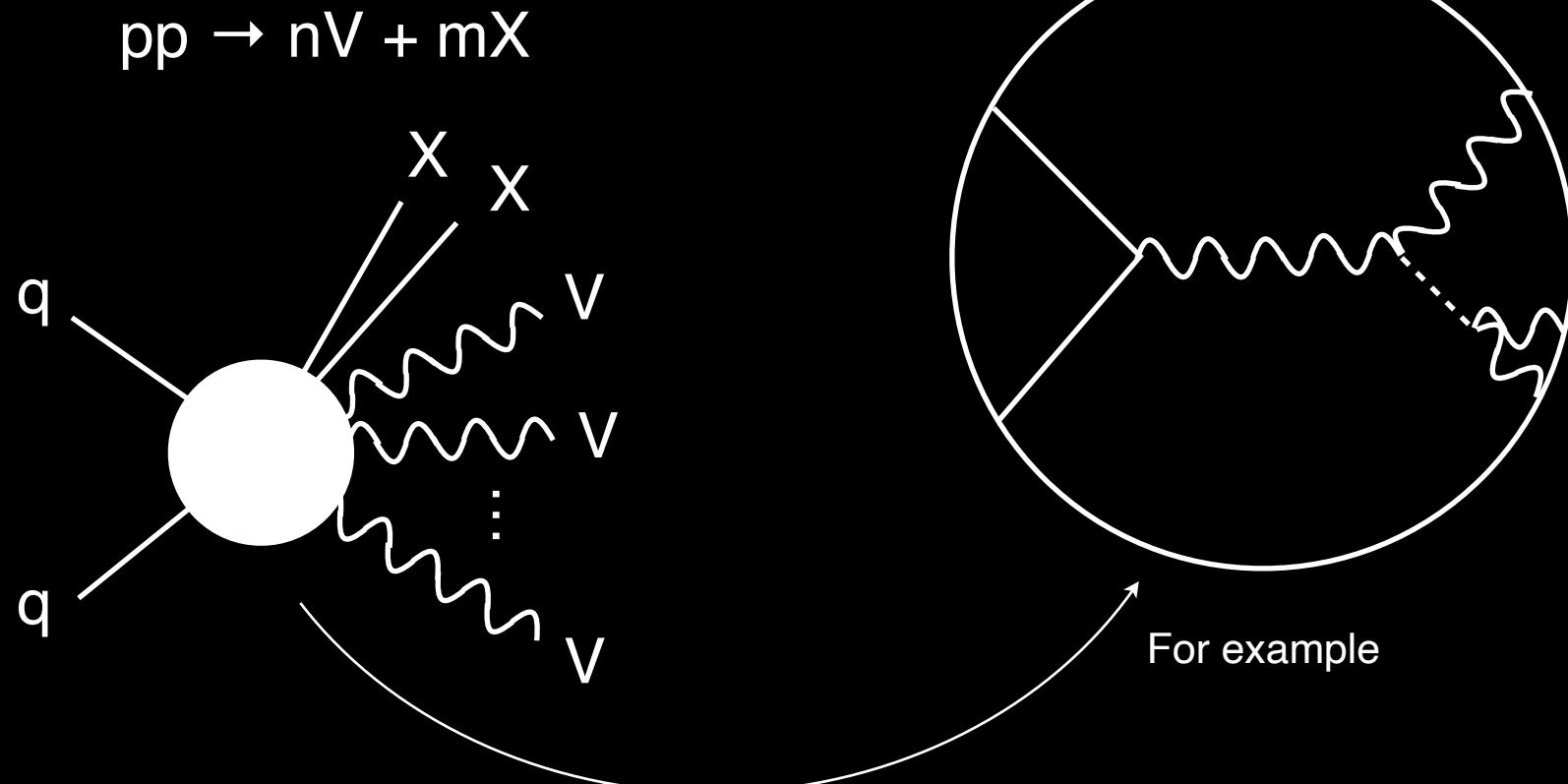
# Probing multi-boson physics in hadron collider

Chang  
UCSD



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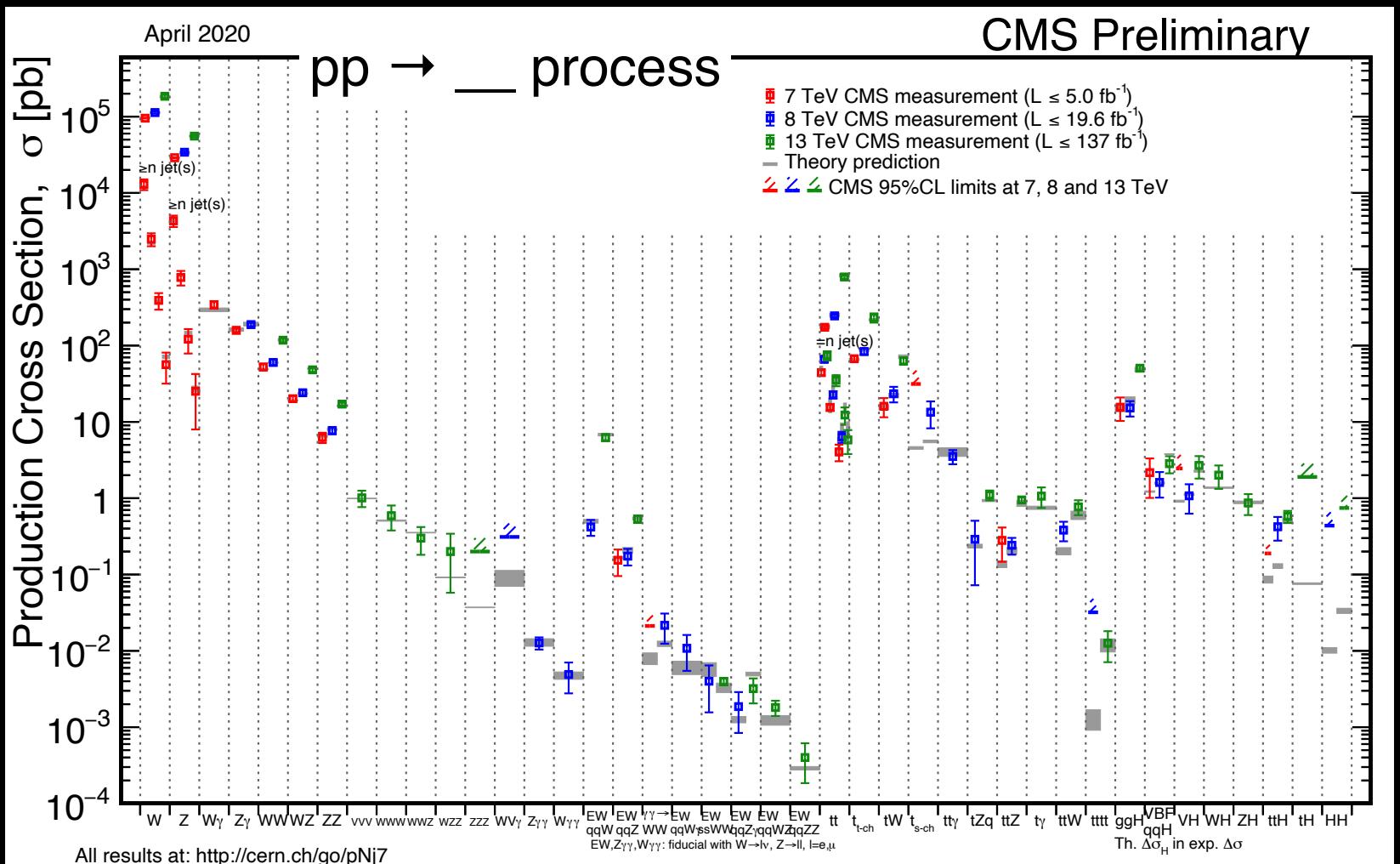
Can also probe  
Higgs-gauge  
coupling



Study multi-boson production process to study multi-boson interactions

# Multi-X processes are rare and “heavy”

Chang  
UCSD



N.B. xsec  $\times$  decay BR can be even smaller

# Multi-X processes are rare and “heavy”

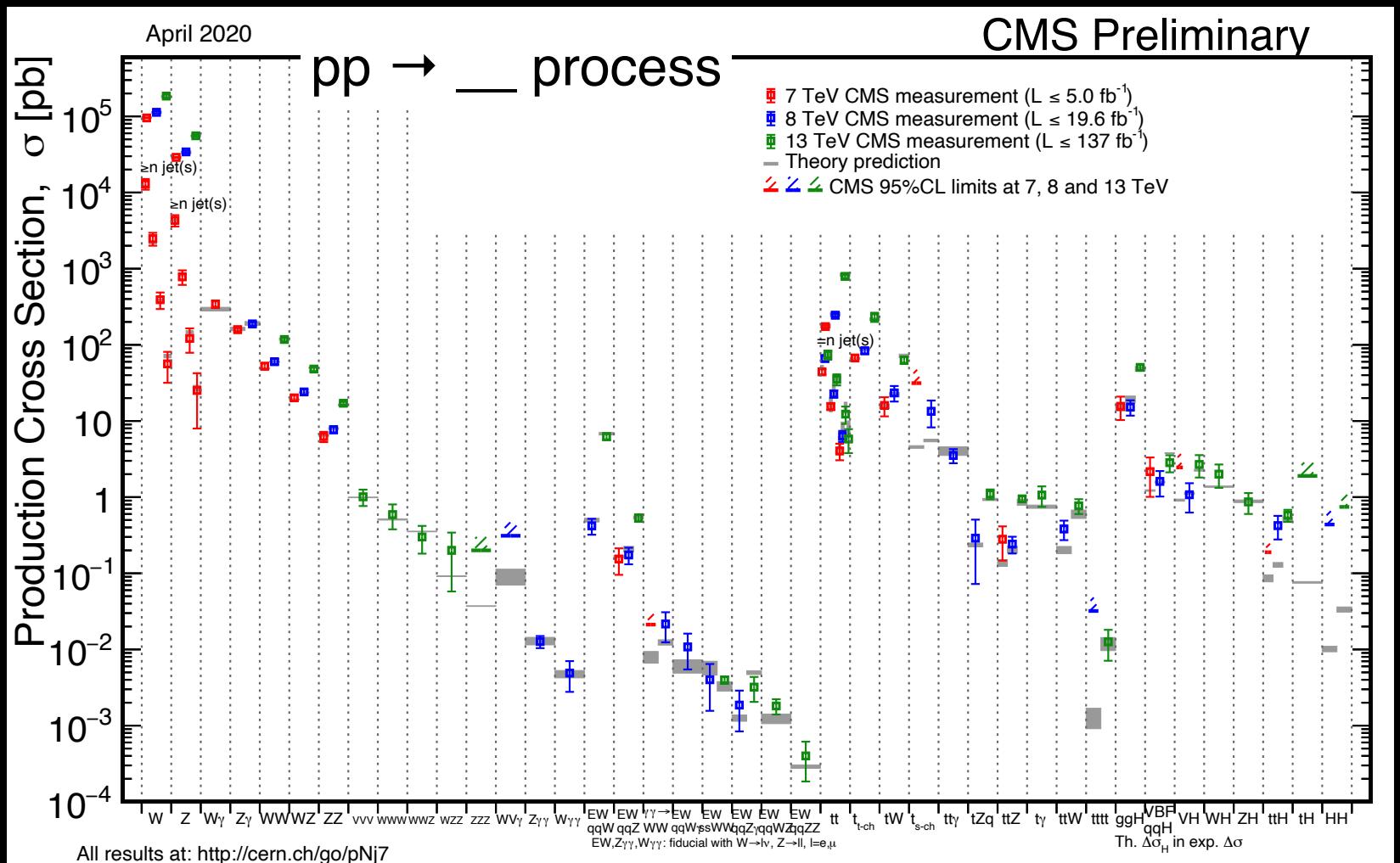
Chang  
UCSD



More frequent



Less frequent



N.B.  $xsec \times \text{decay BR}$  can be even smaller

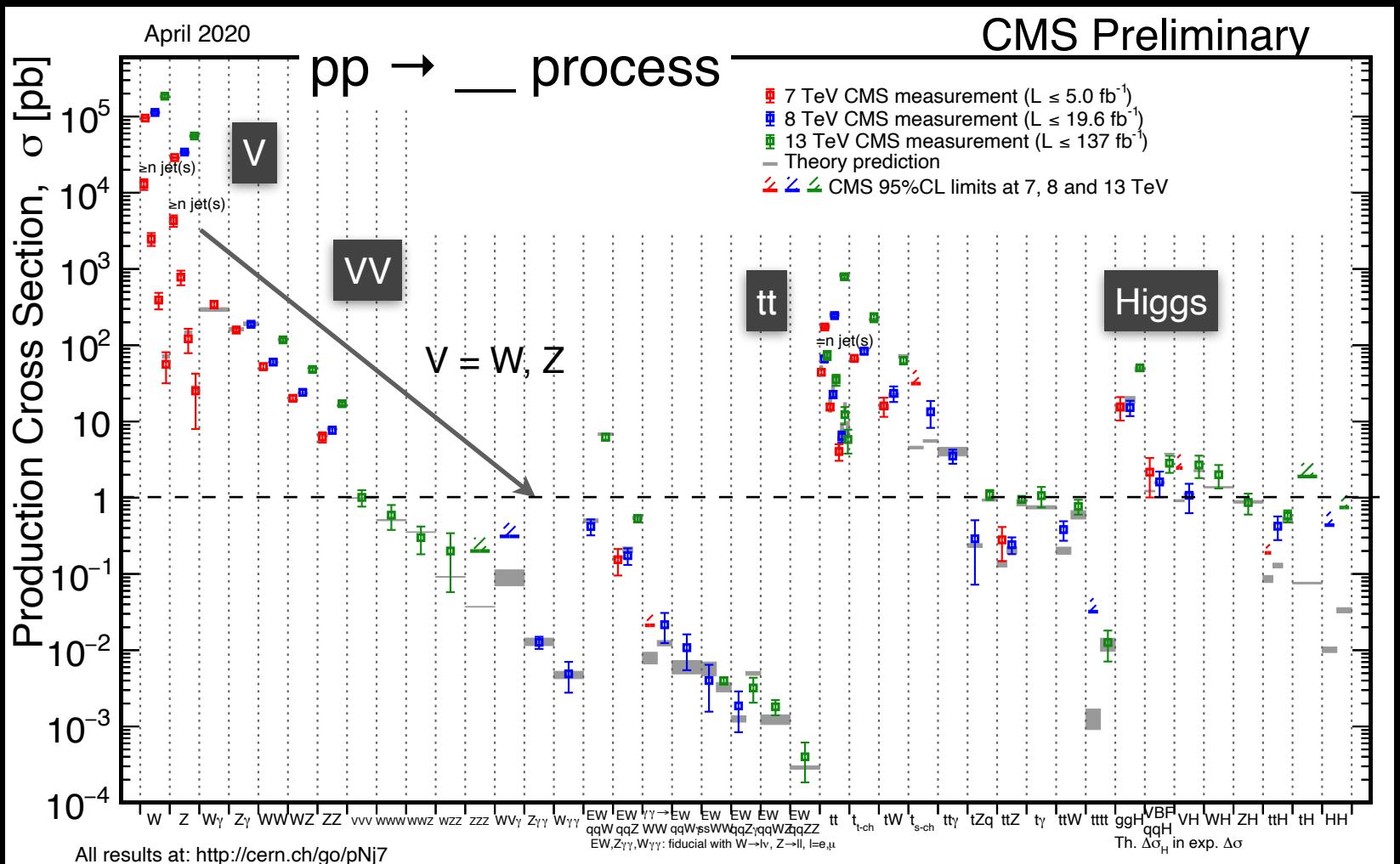
# Multi-X processes are rare and “heavy”

Chang  
UCSD



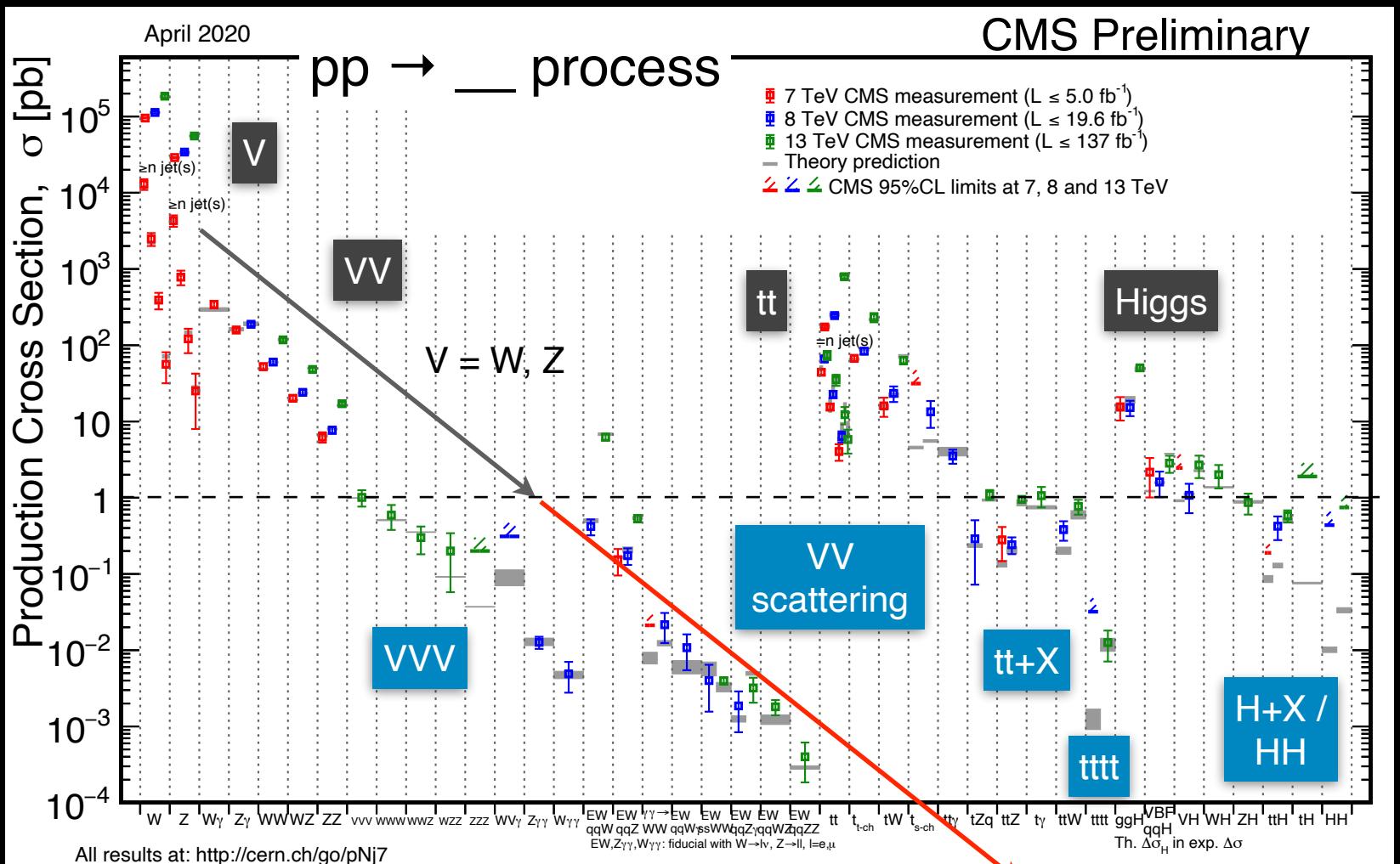
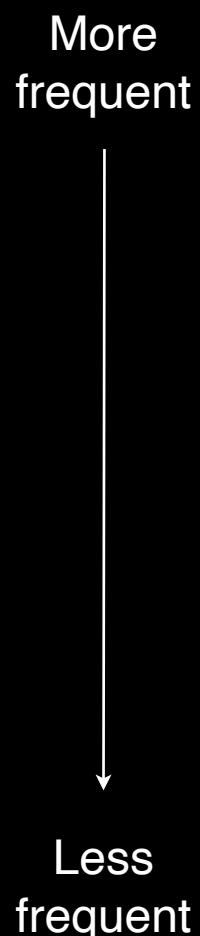
More frequent

↓  
Less frequent



# Multi-X processes are rare and “heavy”

**Chang**  
**UCSP**



## *multi-massive-X productions*

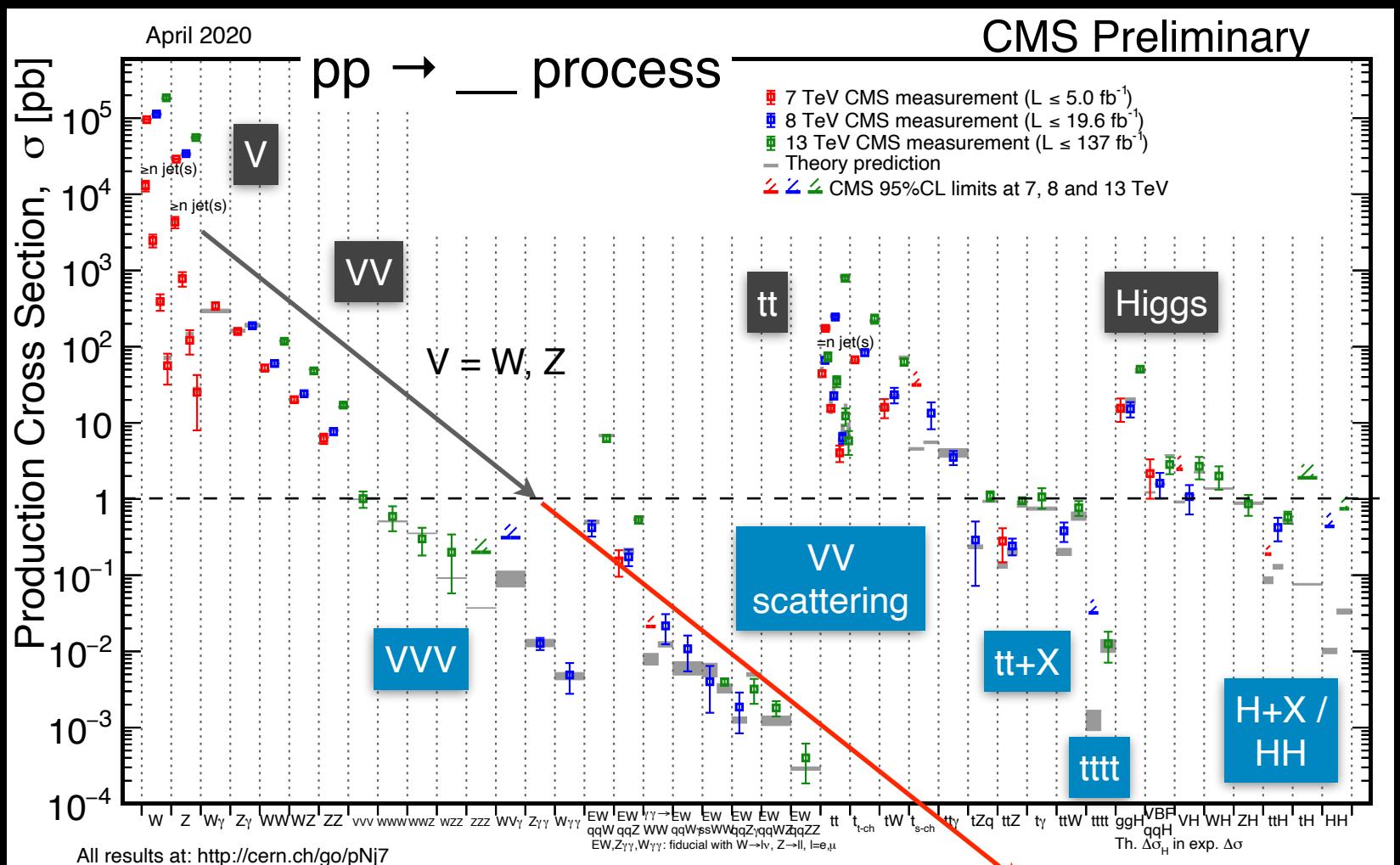
$X = t, W, Z, H$

# Multi-X processes are rare and “heavy”

Chang  
UCSD



More frequent  
↓  
Less frequent



Massive ::  $M_{\text{top}}, M_W, M_Z, M_H$  all  $\sim 100 \text{ GeV}$

*multi-massive-X productions*  
 $X = t, W, Z, H$

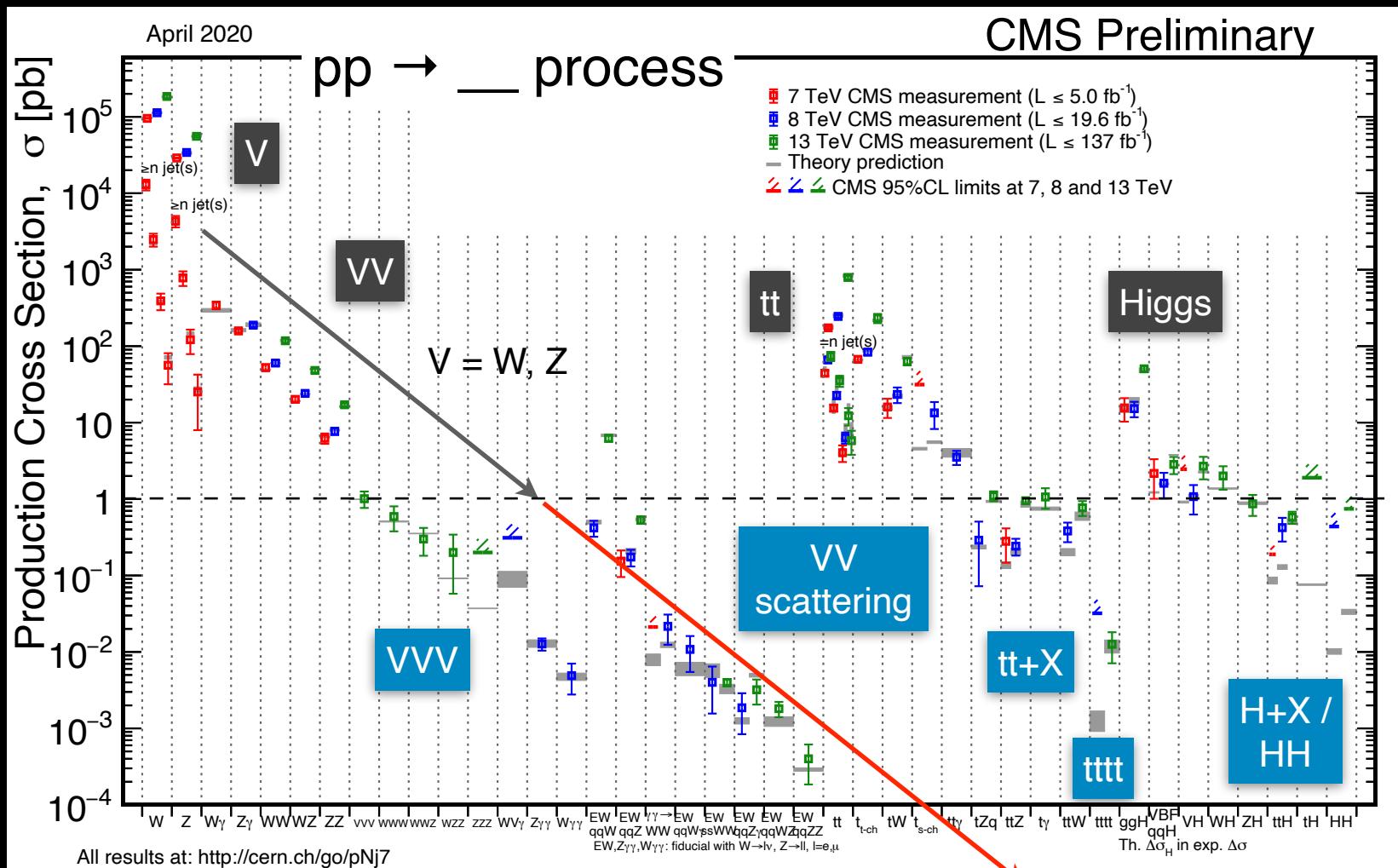
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Chang  
UCSD



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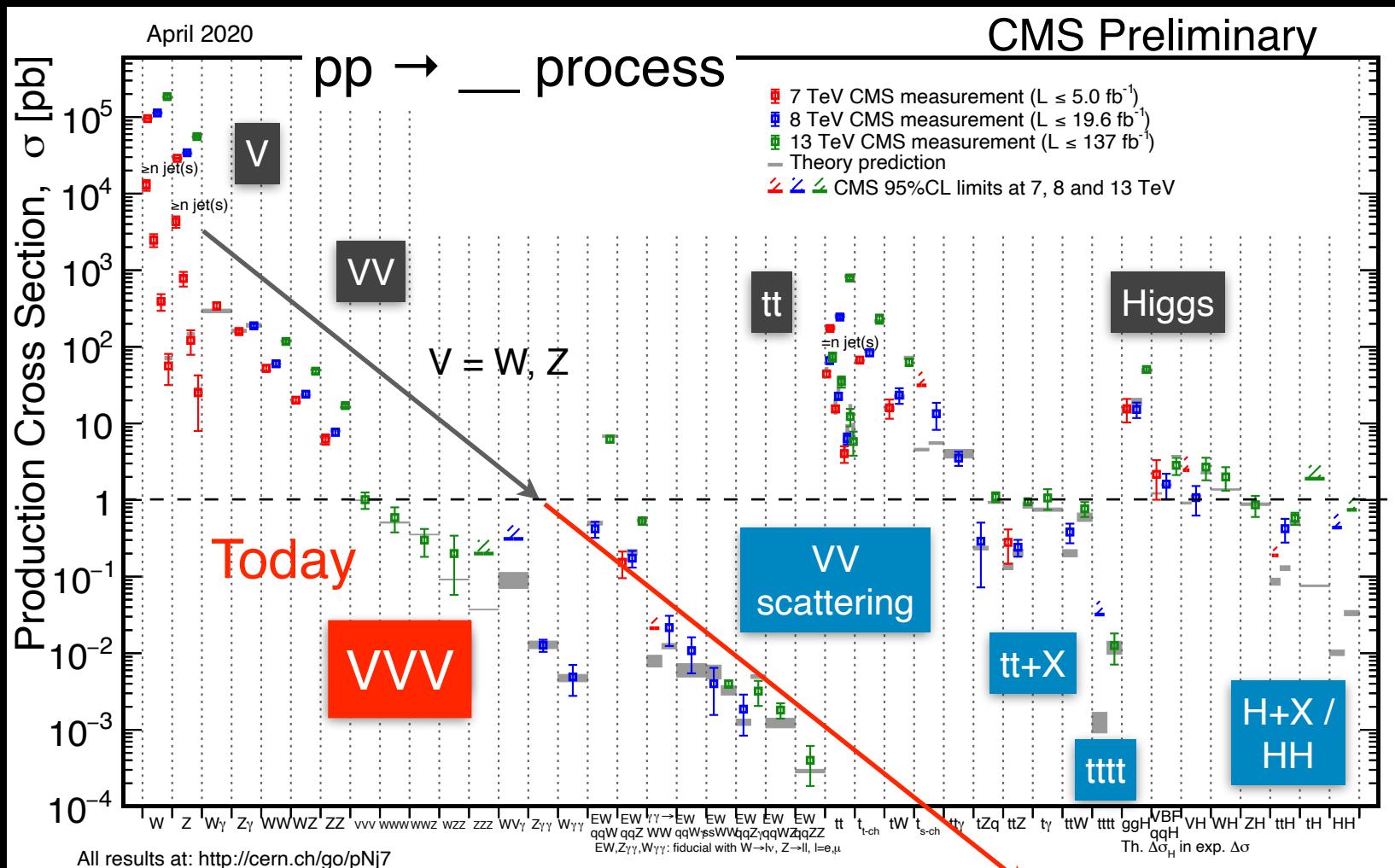
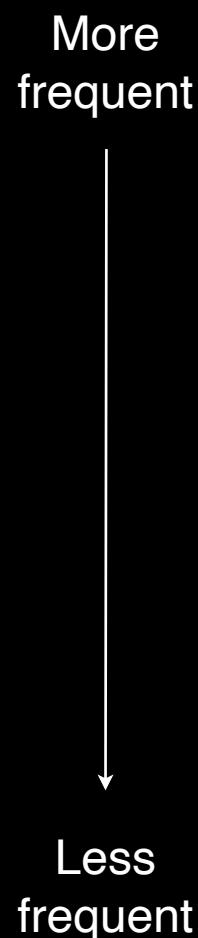


Massive :: M<sub>t</sub>, M<sub>w</sub>, M<sub>Z</sub>, M<sub>H</sub> all  $\sim 100 \text{ GeV}$

*multi-massive-X productions*  
 $X = t, W, Z, H$

Below picobarn most SM processes are electroweak multi-X production

# Multi-X processes are rare and “heavy”



Massive ::  $M_{top}$ ,  $M_W$ ,  $M_Z$ ,  $M_H$  all  $\sim 100$  GeV

# *multi-massive-X productions*

$X = t, W, Z, H$

Below picobarn most SM processes are electroweak multi-X production



Higgs discovery was a big triumph

Building on discovery, we must verify multi-boson interactions

Studying multi-boson production probes multi-boson interactions

Multi-boson productions are “heavy” and *rare*

It requires large and energetic pp collisions data

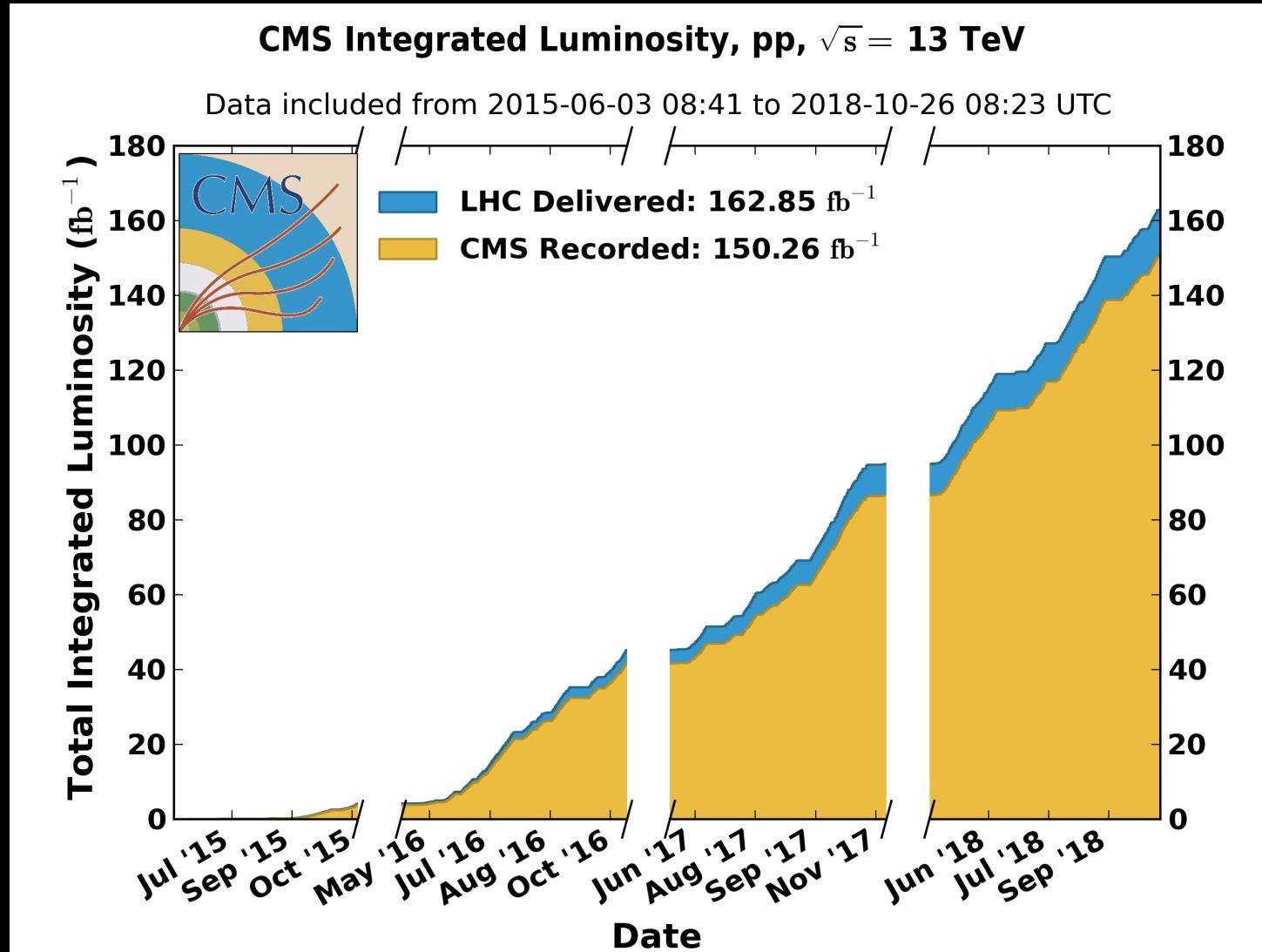
⇒ *We need the LHC to probe multi-boson interactions*

# We need LHC's large and energetic pp collision data

because **rare**

because **"heavy"**

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Multiply by 1000 to get the number of events produced for a picobarn process

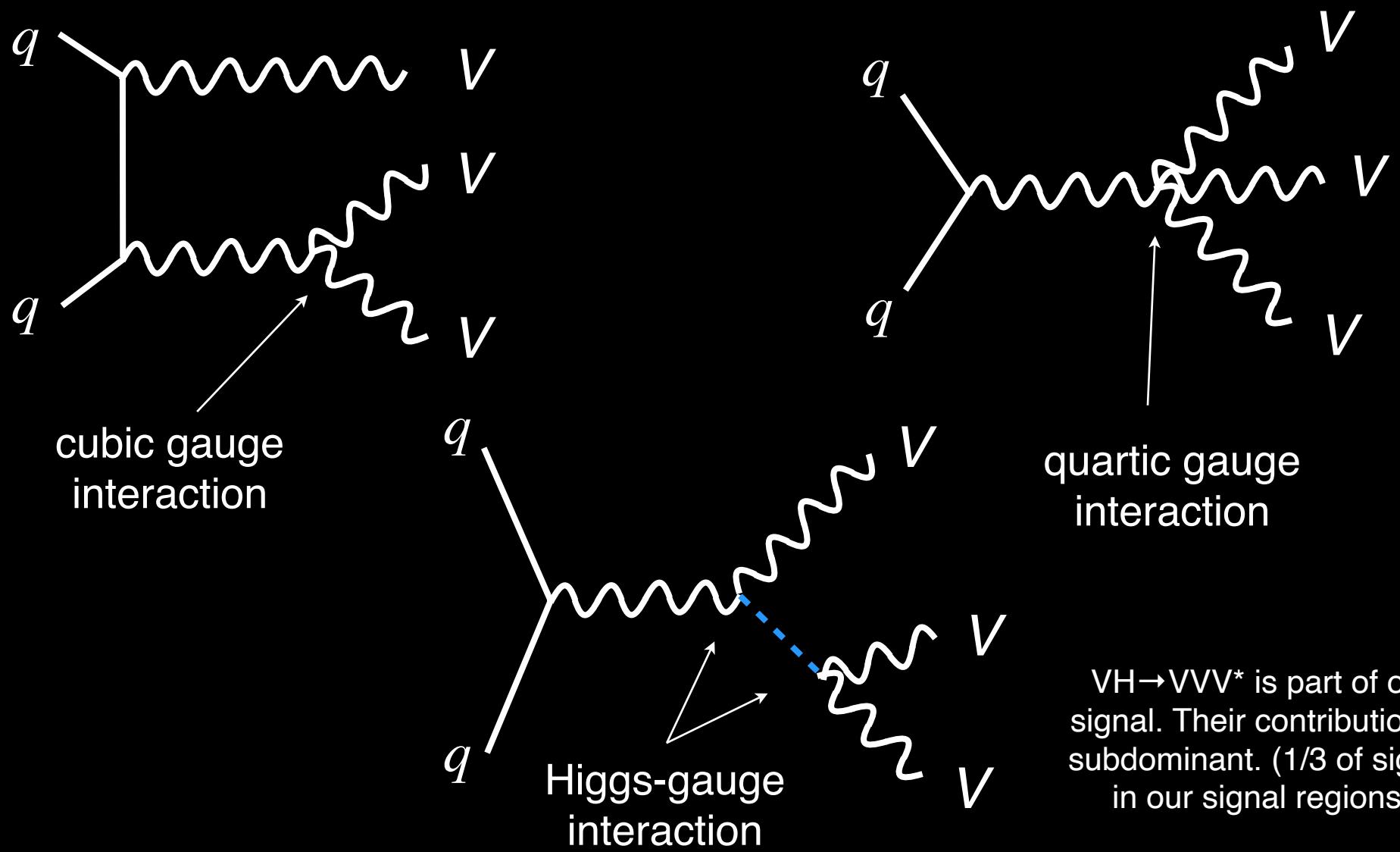
During Run 2, CMS recorded  $150 \text{ fb}^{-1}$  of which  $137 \text{ fb}^{-1}$  have been validated as good quality data useable for physics analysis

$\sim 10^{16}$  pp collisions

LHC's large data enables us to study rare EW multi-X processes

# Physics of VVV production ( $V = W, Z$ )

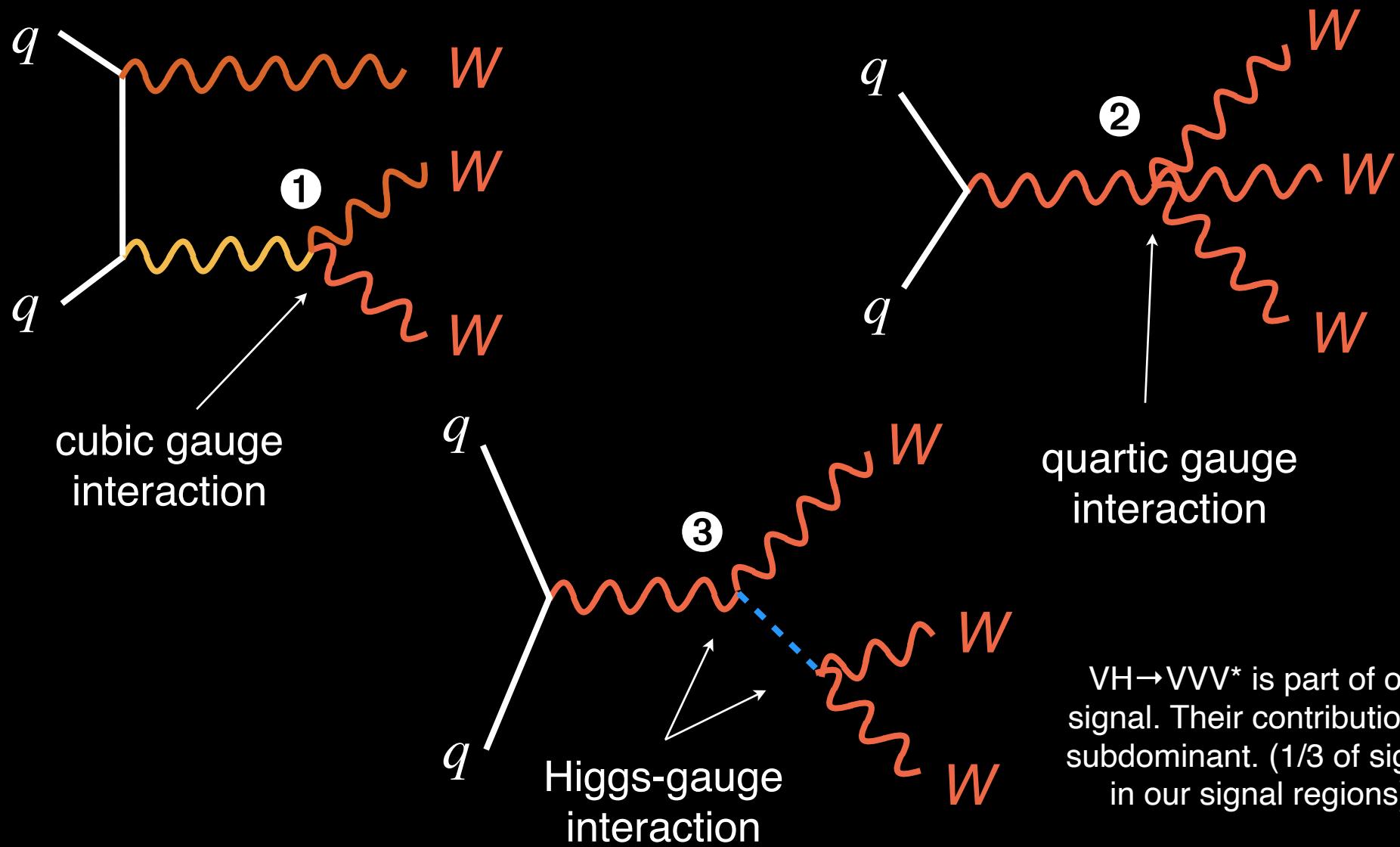
Chang  
UCSD



$VH \rightarrow VVV^*$  is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

Triboson process has access to studying many multi-*boson* interactions

# Physics of VVV production ( $V = W, Z$ )

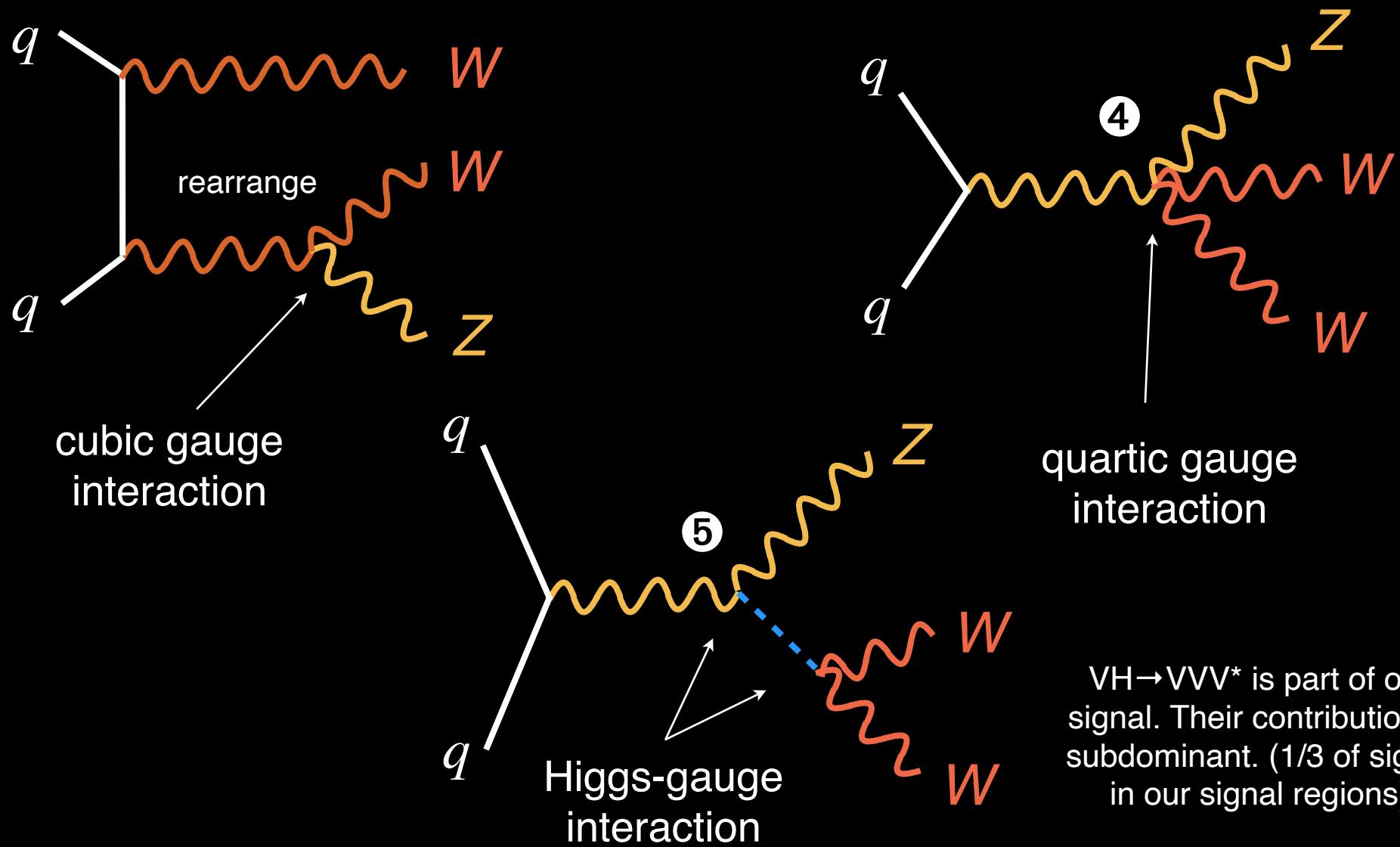


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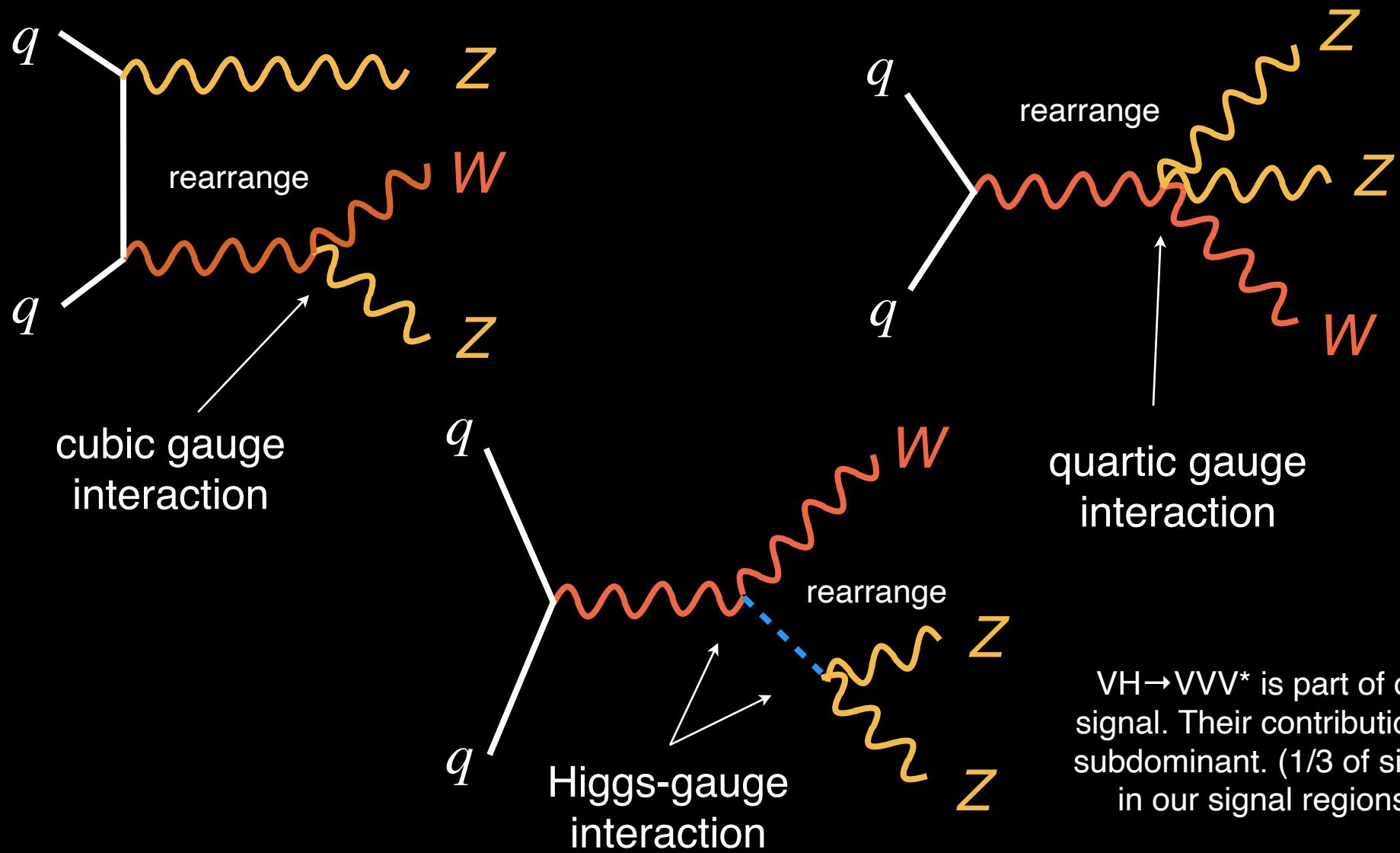
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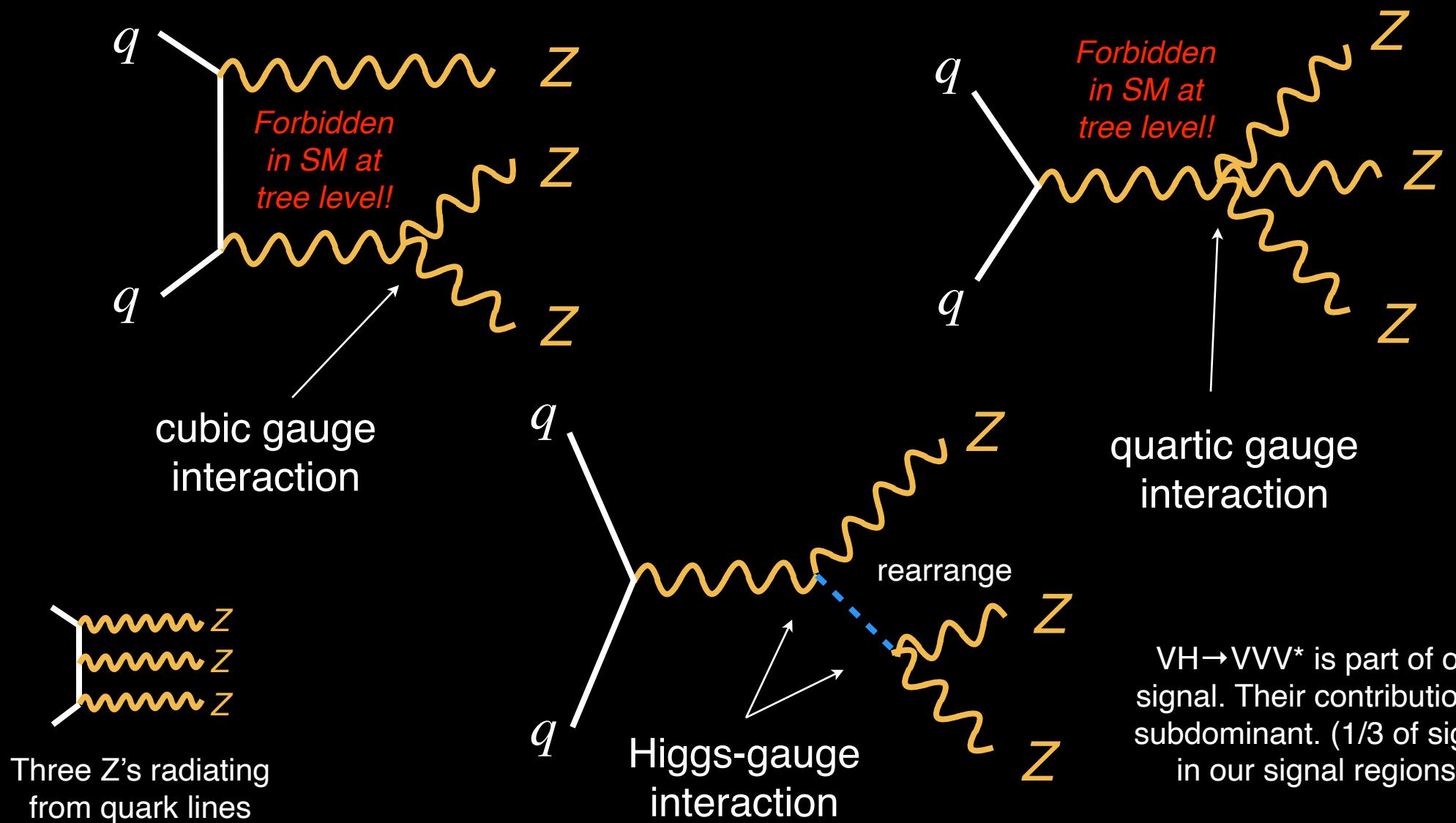
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Triboson process has access to studying many multi-*boson* interactions

# Physics of VVV production ( $V = W, Z$ )

Chang  
UCSD



Triboson process has access to studying many multi-*boson* interactions



We are targeting all possible VVV productions w/ or w/o Higgs:

- $\text{pp} \rightarrow \text{WWW}$
- $\text{pp} \rightarrow \text{WWZ}$
- $\text{pp} \rightarrow \text{WZZ}$
- $\text{pp} \rightarrow \text{ZZZ}$

And the combined production of all  $\text{pp} \rightarrow \text{VVV}$

# Previous work on VVV physics

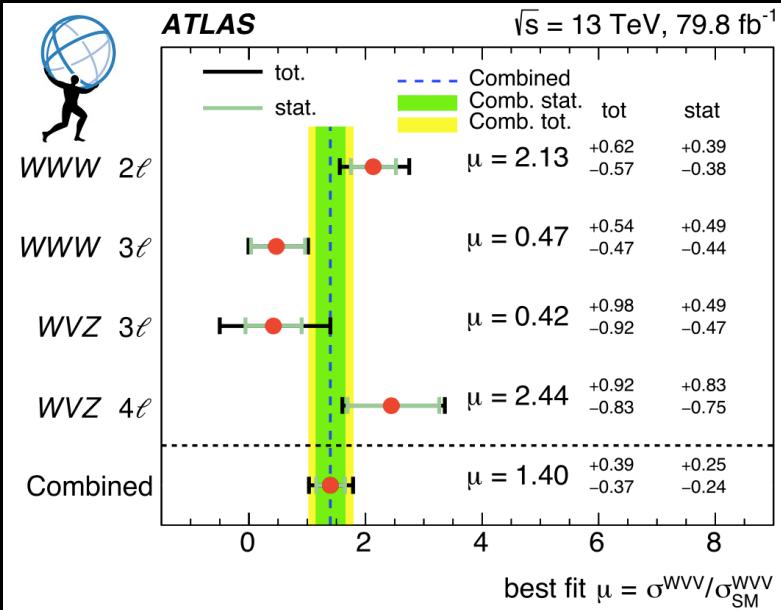
Chang  
UCSD



- ATLAS searched for WWW in 8 TeV:  $0.96\sigma$  ( $1.05\sigma$ ) arXiv:1610.05088
- CMS searched for WWW in 13 TeV  $36 \text{ fb}^{-1}$ :  $0.6\sigma$  ( $1.78\sigma$ ) arXiv:1905.04246
- ATLAS searched for VVV in 13 TeV  $80 \text{ fb}^{-1}$ :  $4.1\sigma$  ( $3.1\sigma$ ) arXiv:1903.10415

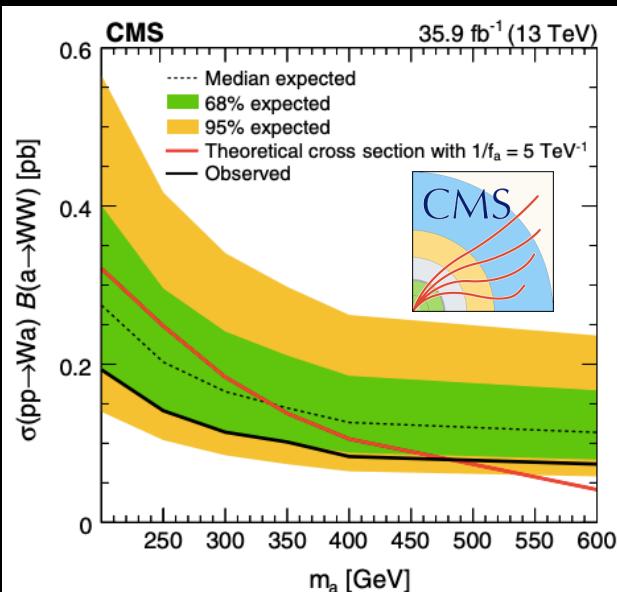
VVV evidence

VVV evidence



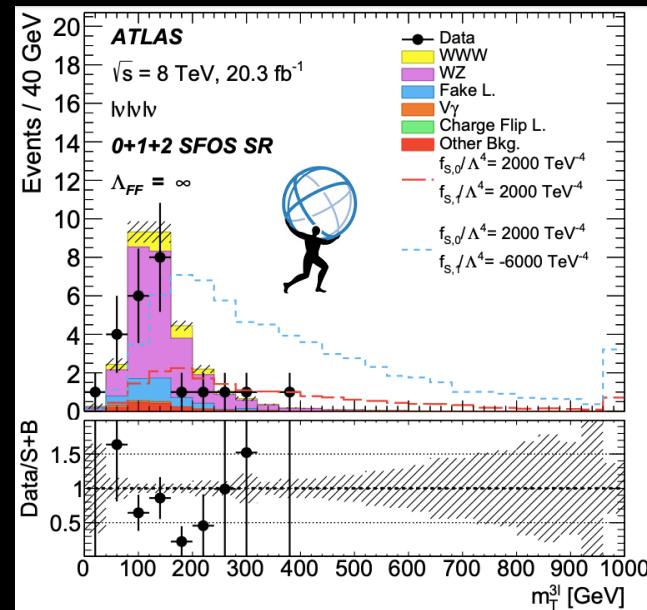
arXiv:1903.10415

Axion-like-particle  
triboson signature limit



arXiv:1905.04246

SMEFT Dim8 operator limit



arXiv:1610.05088

Both ATLAS and CMS have been searching for triboson processes and using them to test SM and constrain new physics

# Decay of W, Z bosons

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UCSD



## Quarks

$u$ up	$c$ charm	$t$ top
$d$ down	$s$ strange	$b$ bottom

$e$ electron	$\mu$ muon	$\tau$ tau
$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino

## Leptons

## Forces

$Z$ Z boson	$\gamma$ photon
$W$ W boson	$g$ gluon

# Decay of W, Z bosons

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UCSD



## Quarks

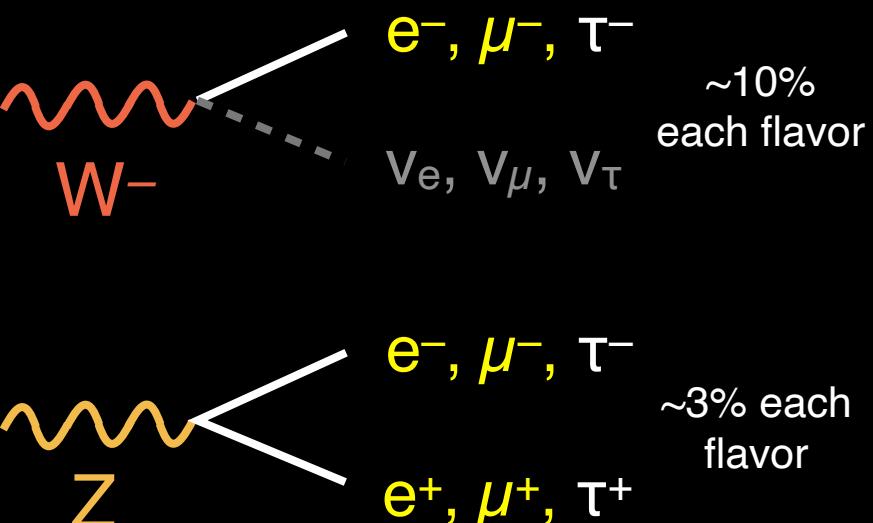
$u$ up	$c$ charm	$t$ top
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Once produced W, Z can decay to leptons

## Forces

$e$ electron	$\mu$ muon	$\tau$ tau
$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino

## Leptons



# Decay of W, Z bosons

Chang  
UCSD



## Quarks

u	c	t
down	charm	top

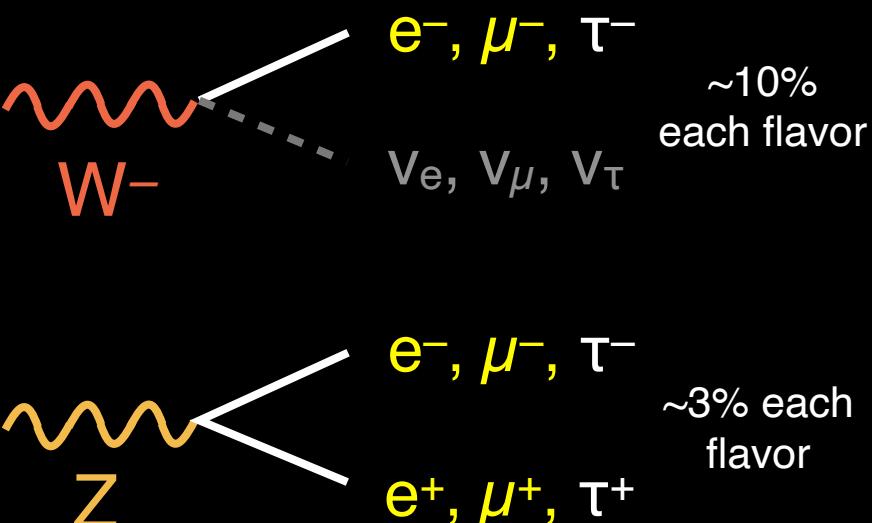
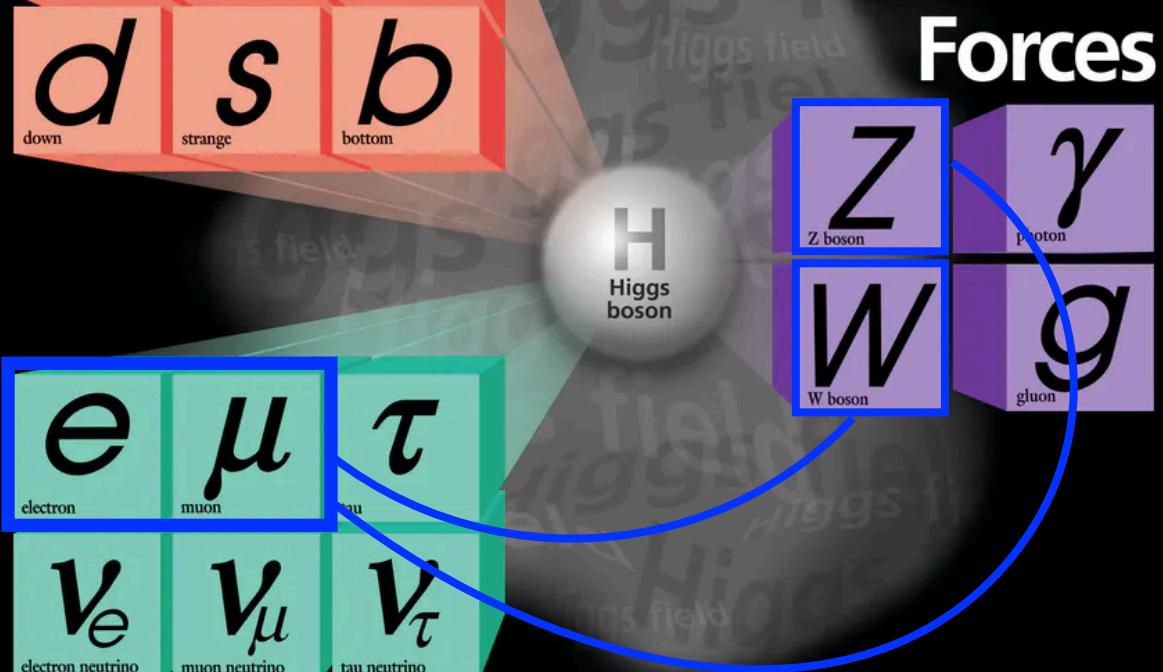
e	$\mu$	$\tau$
electron	muon	tau

$\nu_e$	$\nu_\mu$	$\nu_\tau$
electron neutrino	muon neutrino	tau neutrino

## Leptons

Once produced W, Z can decay to leptons



$\tau$  decays in the detector:

$$\begin{aligned}\tau &\rightarrow e, \mu + 2\nu \\ \text{or} \\ \tau &\rightarrow \text{hadrons} + \nu\end{aligned}$$

\*\*We include e,  $\mu$  from  $\tau$ 's from W/Z decays in the analysis

# Decay of W, Z bosons

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## Quarks

u	c	t
down	charm	top

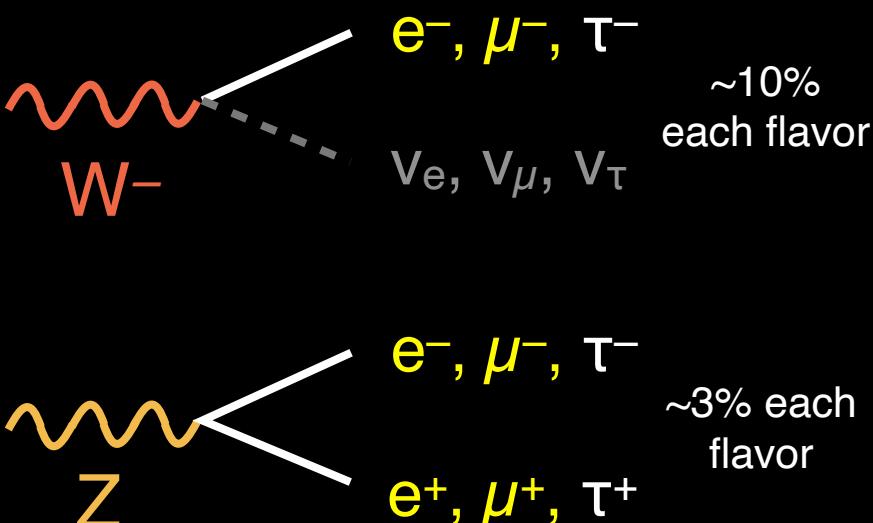
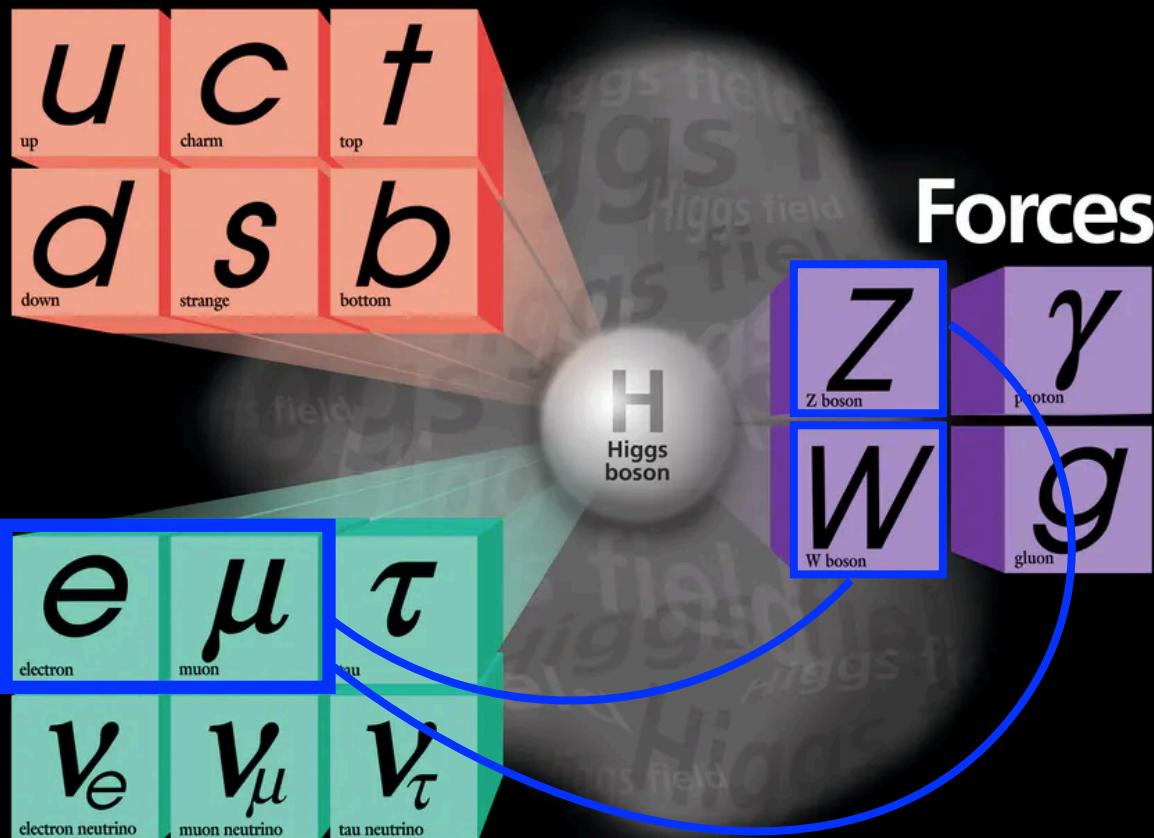
e	$\mu$	$\tau$
electron	muon	tau

$\nu_e$	$\nu_\mu$	$\nu_\tau$
electron neutrino	muon neutrino	tau neutrino

## Leptons

Once produced W, Z can decay to leptons



$\tau$  decays in the detector:

$$\begin{aligned}\tau &\rightarrow e, \mu + 2\nu \\ \text{or} \\ \tau &\rightarrow \text{hadrons} + \nu\end{aligned}$$

\*\*We include e,  $\mu$  from  $\tau$ 's from W/Z decays in the analysis

W's and Z's produced can be identified via electrons and muons

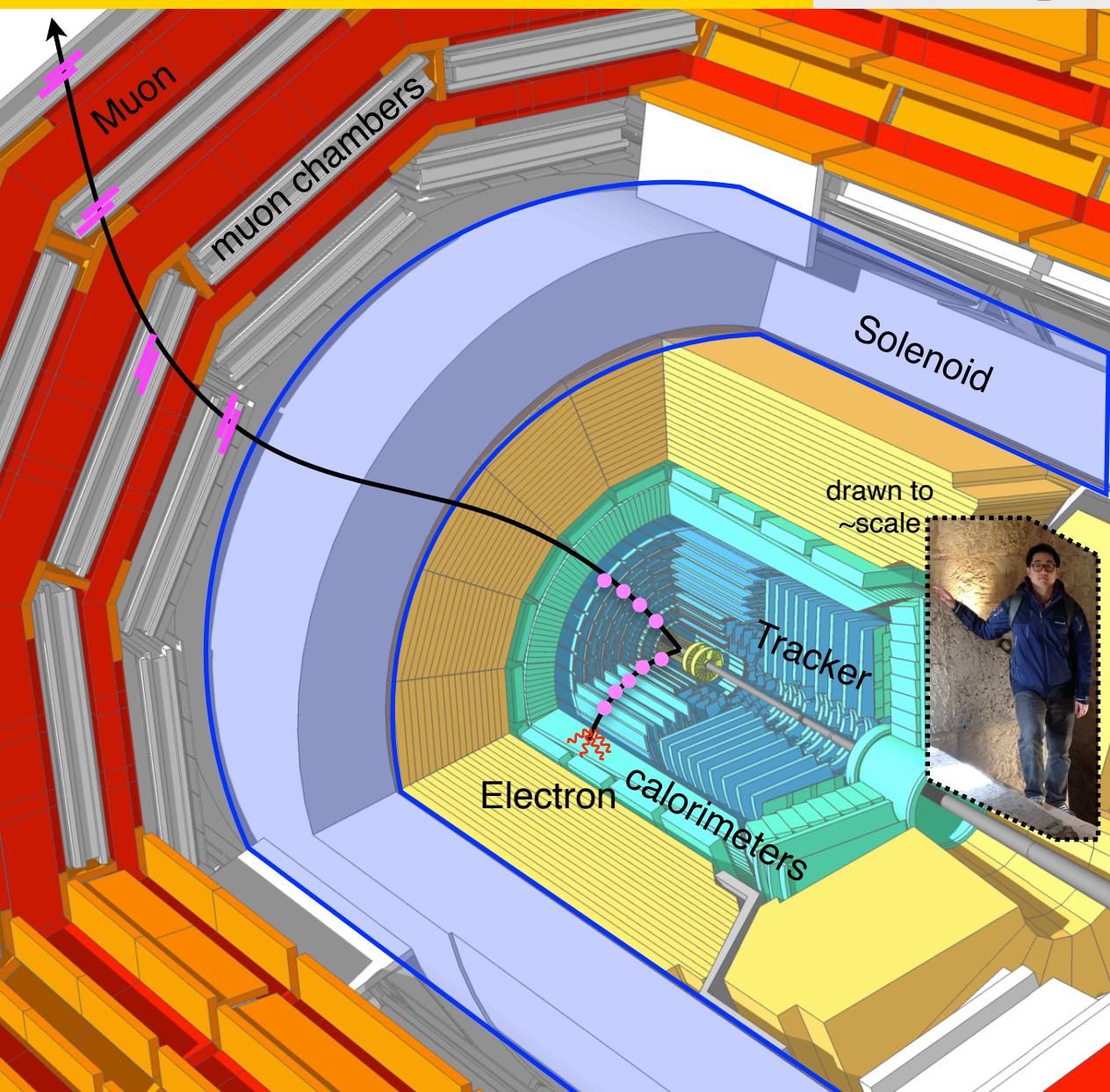
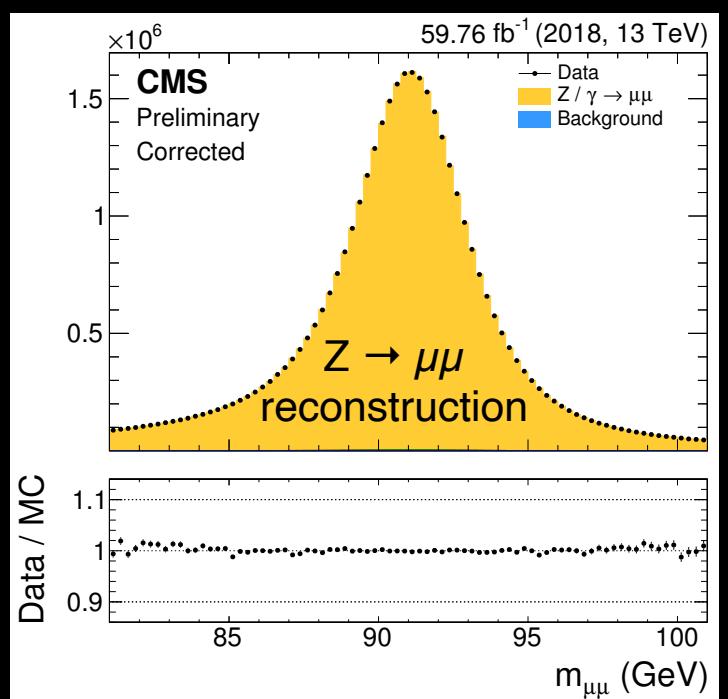
# CMS detector measures leptons very well

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e/ $\mu$  among the best measured particles at CMS by combining tracker, calorimeter, and chambers measurements

(1-2% resolution for well measured ones)



Excellent lepton reconstruction and simulation at CMS

# Classifying leptons' origins

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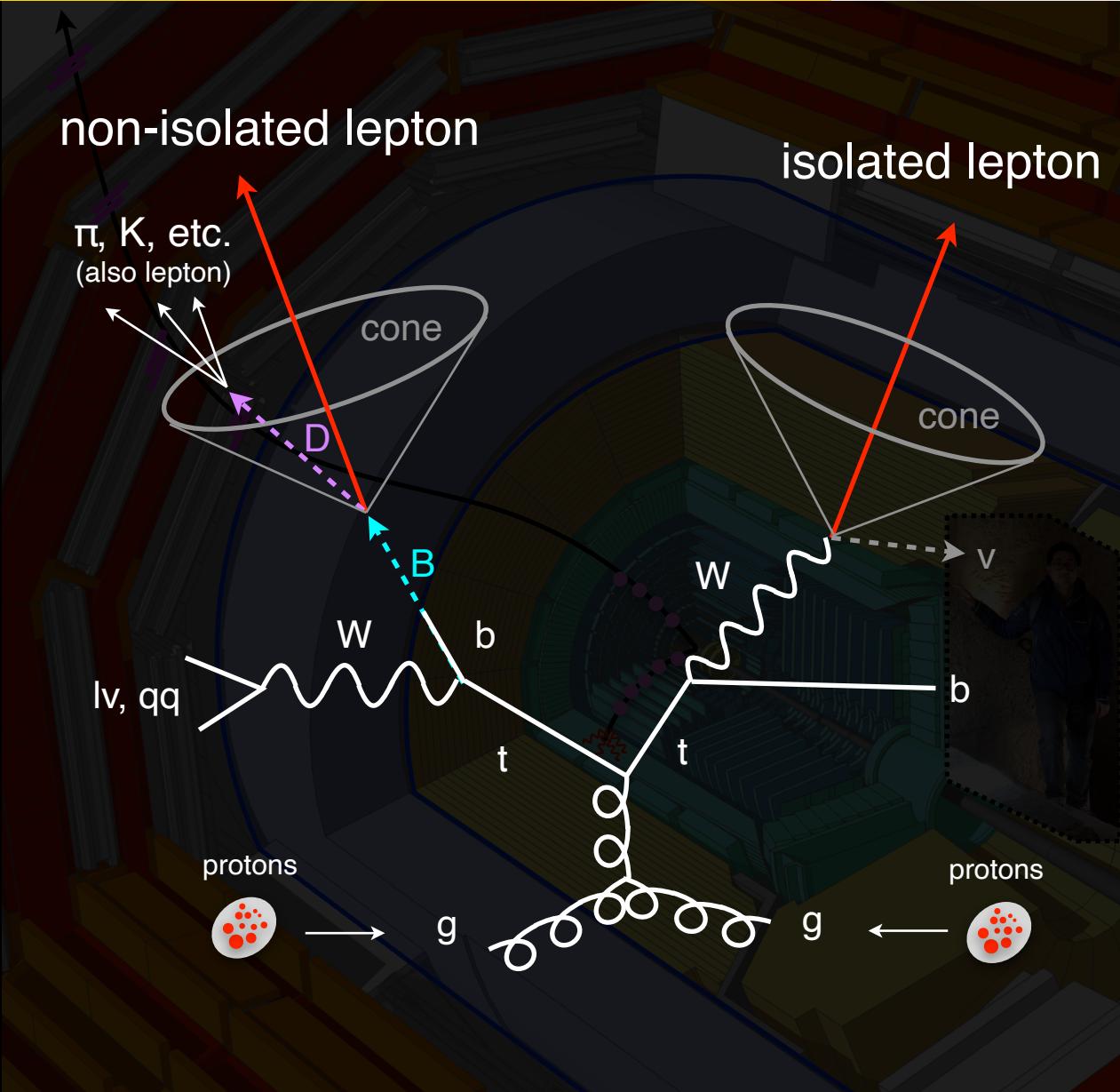


Identifying leptons is not enough

We need to further classify the origin

$$\text{Isolation} = \frac{\sum \text{"stuff" in cone } P_T}{P_{T,\text{Lepton}}}$$

N.B. electrons and muons have different effects (muons are cleaner)



Use isolation to discriminate against leptons from heavy flavor decay

Dubbed "fake lepton"

# Basics of VVV analysis methodology

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- We are targeting  $WWW$ ,  $WWZ$ ,  $WZZ$ ,  $ZZZ$
- $W$  and  $Z$  can be identified through  $e$  and  $\mu$
- Important to measure  $e$  and  $\mu$  (but only from  $W$  and  $Z$ !)  
    ⇒ e.g. by using isolation

Study lepton physics of LHC for VVV search

# 4 steps to VVV observation

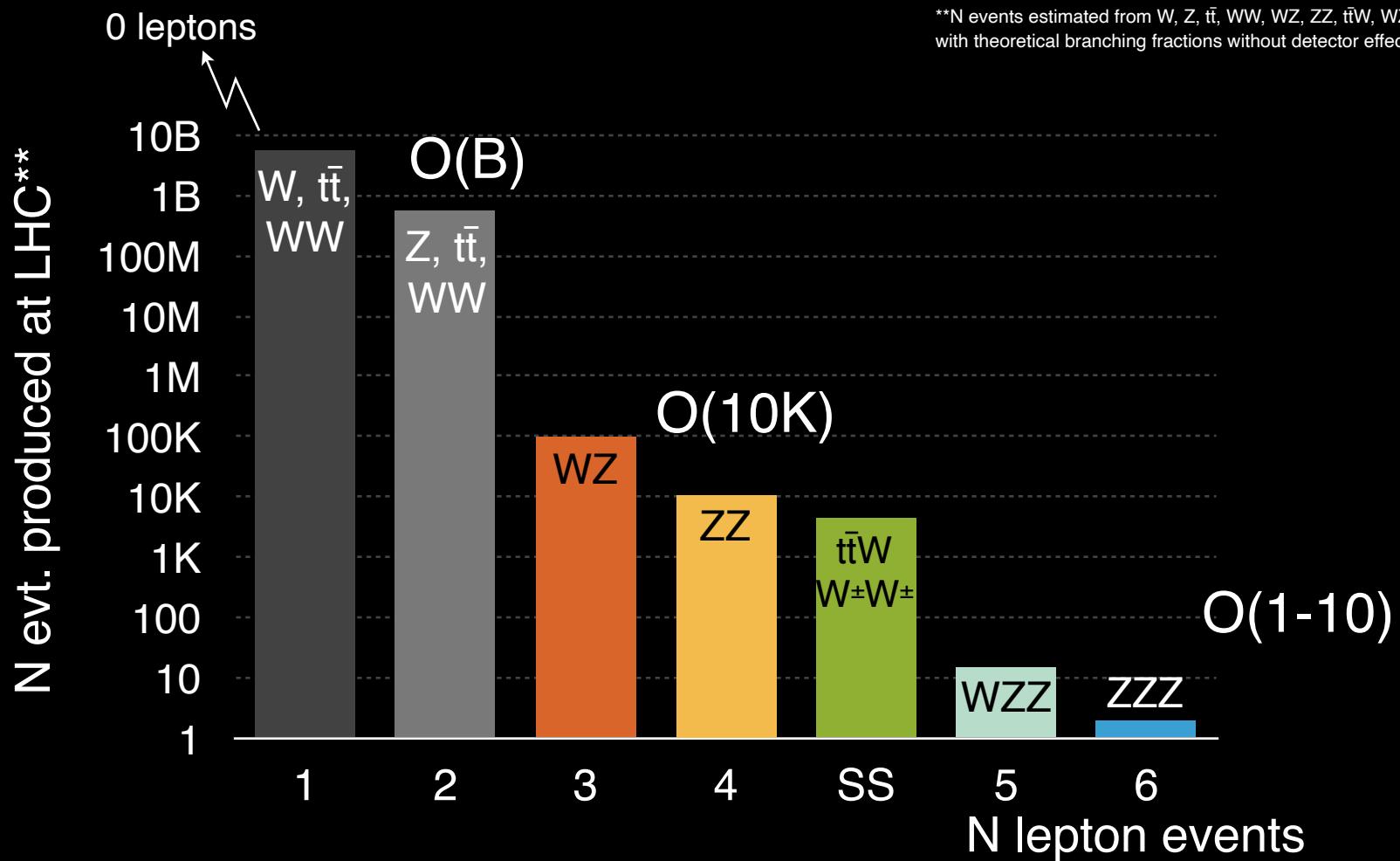


1. Organize analyses by leptons (likely) from W / Z
    - N leptons in the event
    - Flavor of the leptons
  2. Additional background suppression through smart choices
  3. Reliably estimate the size of residual backgrounds
  4. Observe VVV!
- Smart humans and  
smart machines  
(Both cut / BDT)
- 

# Lepton physics at the LHC



\*\*N events estimated from W, Z,  $t\bar{t}$ , WW, WZ, ZZ,  $t\bar{t}W$ , WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring  $\tau \rightarrow e, \mu$



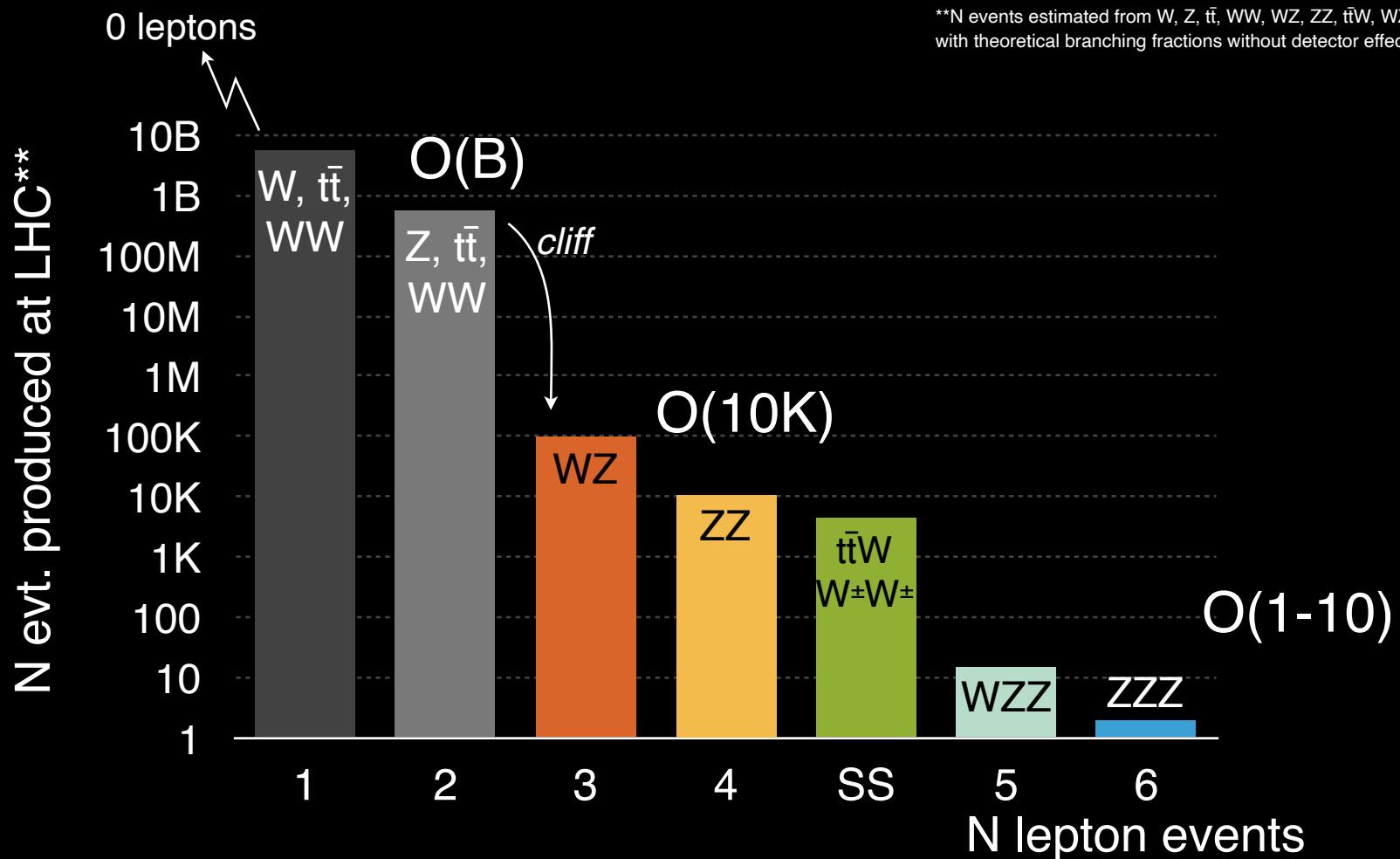
The more leptons produced the lower the rate (i.e. lower bkg.)

Useful to organize physics analyses by N leptons

# Lepton physics at the LHC



\*\*N events estimated from W, Z,  $t\bar{t}$ , WW, WZ, ZZ,  $t\bar{t}W$ , WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring  $\tau \rightarrow e, \mu$



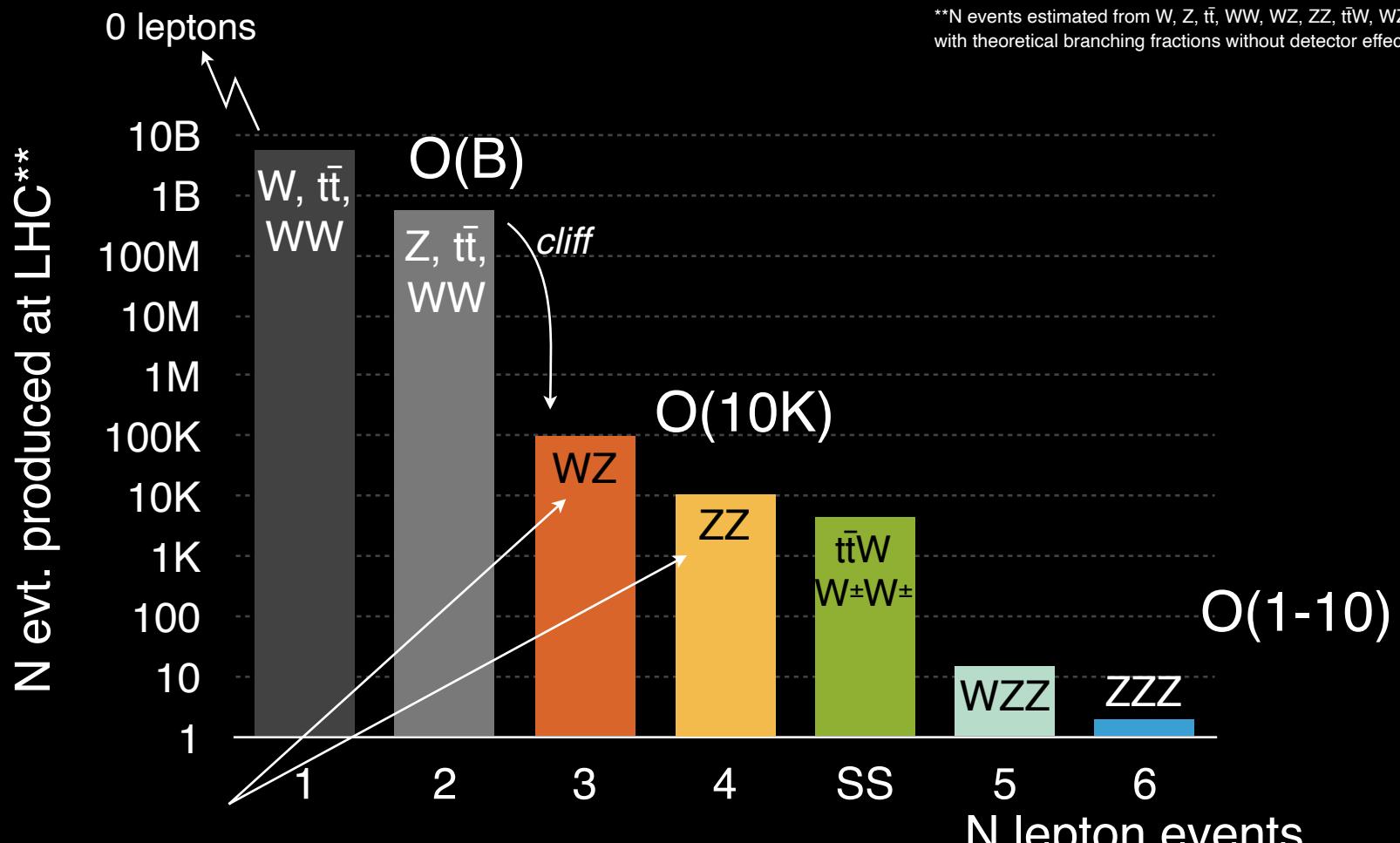
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Useful to organize physics analyses by N leptons

# Lepton physics at the LHC



\*\*N events estimated from W, Z,  $t\bar{t}$ , WW, WZ, ZZ,  $t\bar{t}W$ , WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring  $\tau \rightarrow e, \mu$



N.B.  $WZ \rightarrow 3l \sim 100k$ ,  $ZZ \rightarrow 4l \sim 10k$

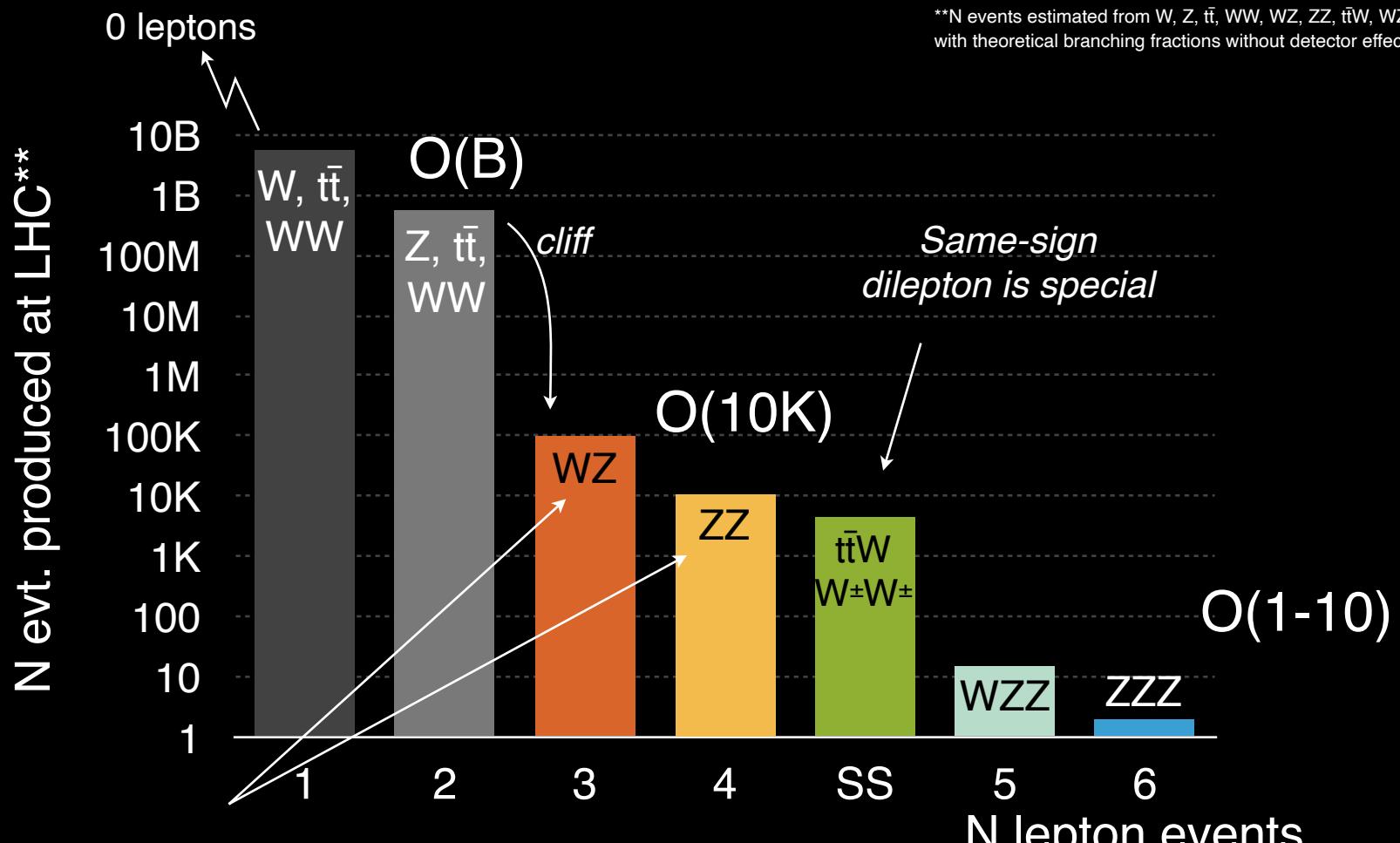
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Useful to organize physics analyses by N leptons

# Lepton physics at the LHC



\*\*N events estimated from W, Z,  $t\bar{t}$ , WW, WZ, ZZ,  $t\bar{t}W$ , WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring  $\tau \rightarrow e, \mu$



N.B.  $WZ \rightarrow 3l \sim 100k$ ,  $ZZ \rightarrow 4l \sim 10k$

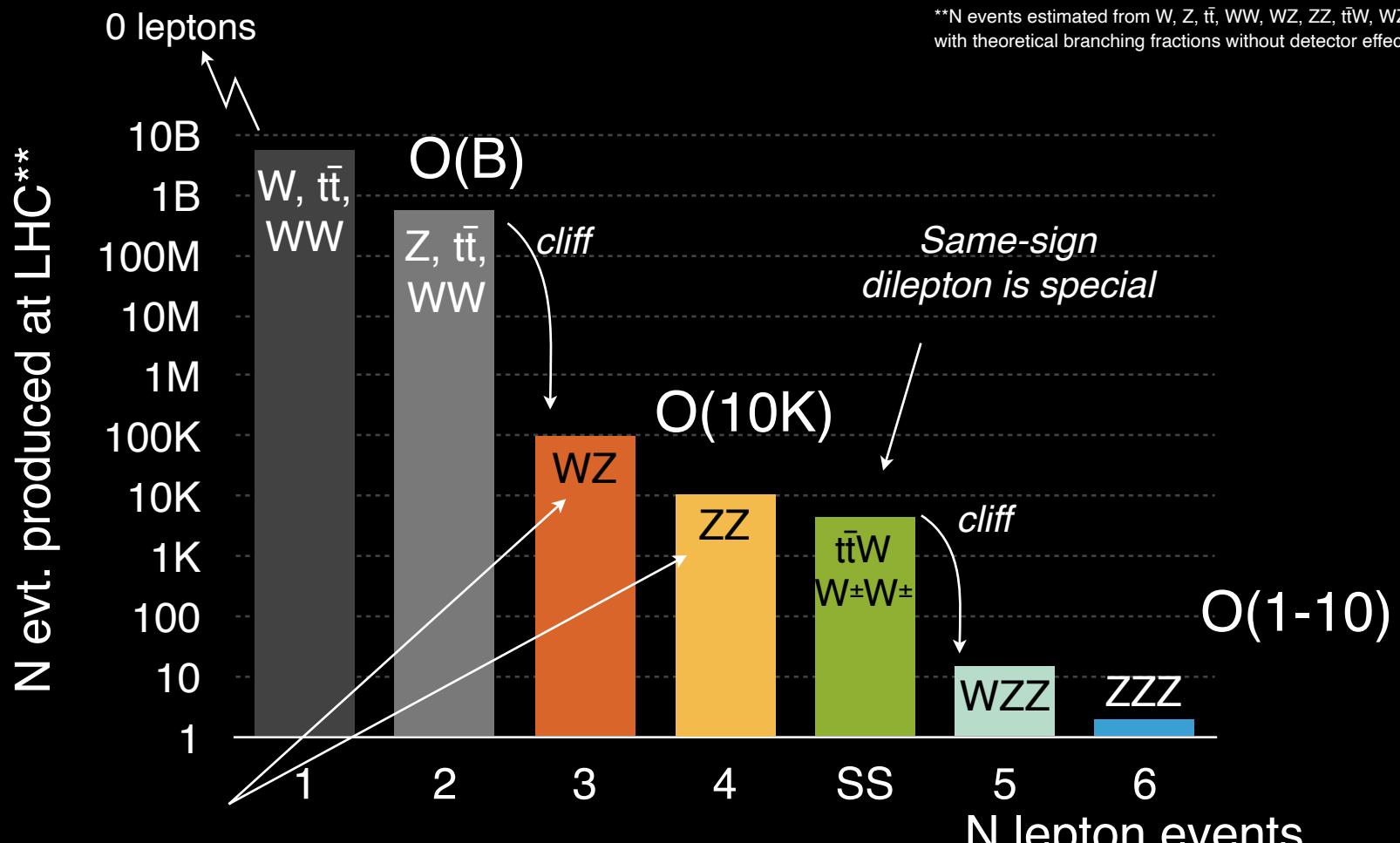
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Useful to organize physics analyses by N leptons

# Lepton physics at the LHC



\*\*N events estimated from W, Z,  $t\bar{t}$ , WW, WZ, ZZ,  $t\bar{t}W$ , WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring  $\tau \rightarrow e, \mu$



N.B.  $WZ \rightarrow 3l \sim 100k$ ,  $ZZ \rightarrow 4l \sim 10k$

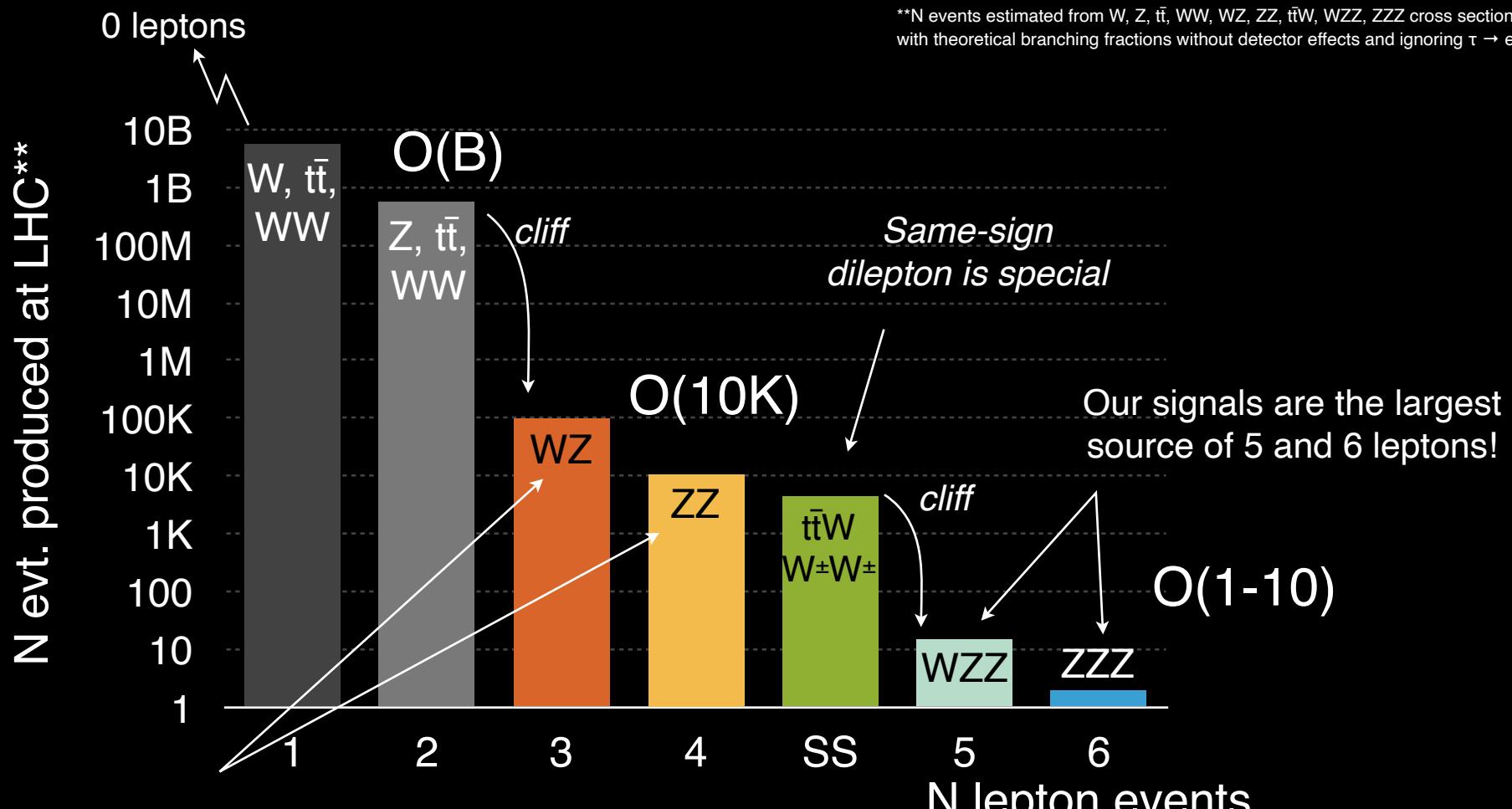
The more leptons produced the lower the rate (i.e. lower bkg.)

Useful to organize physics analyses by N leptons

# Lepton physics at the LHC



\*\*N events estimated from W, Z,  $t\bar{t}$ , WW, WZ, ZZ,  $t\bar{t}W$ , WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring  $\tau \rightarrow e, \mu$



N.B.  $WZ \rightarrow 3l \sim 100k$ ,  $ZZ \rightarrow 4l \sim 10k$

The more leptons produced the lower the rate (i.e. lower bkg.)

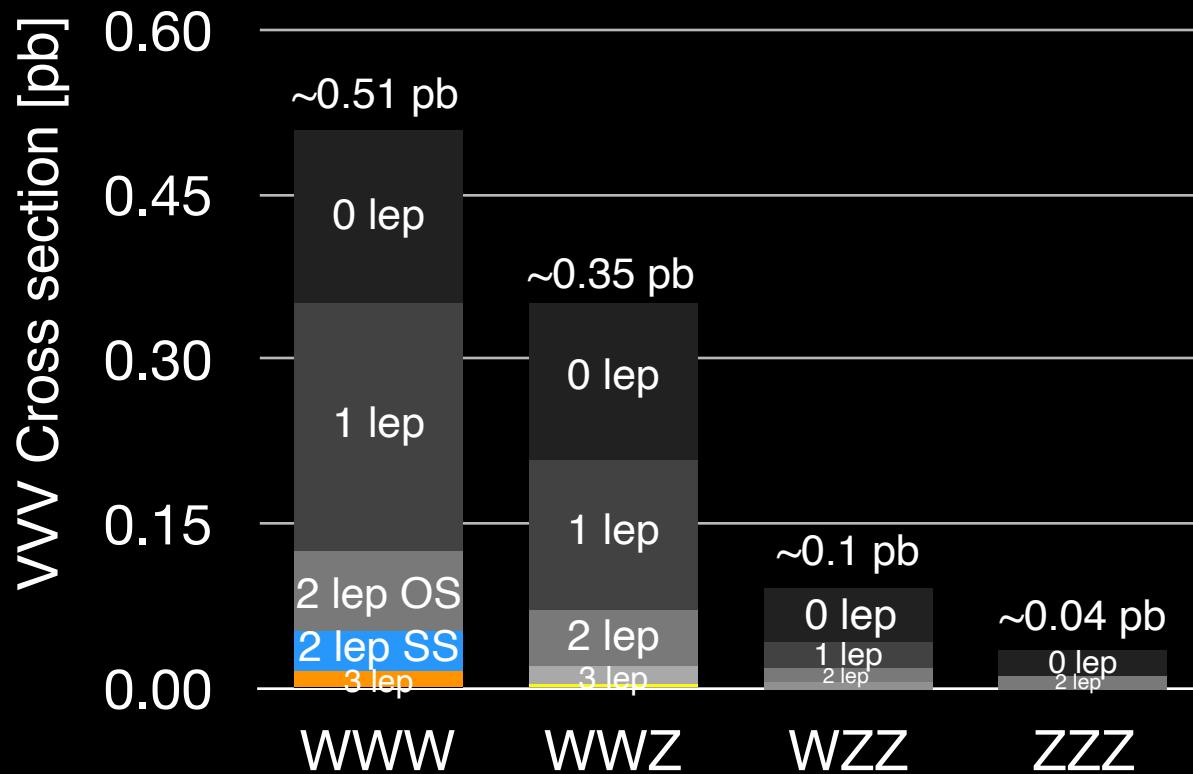
Useful to organize physics analyses by N leptons

# VVV channels in # of leptons

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Production cross section decreases with more Z's

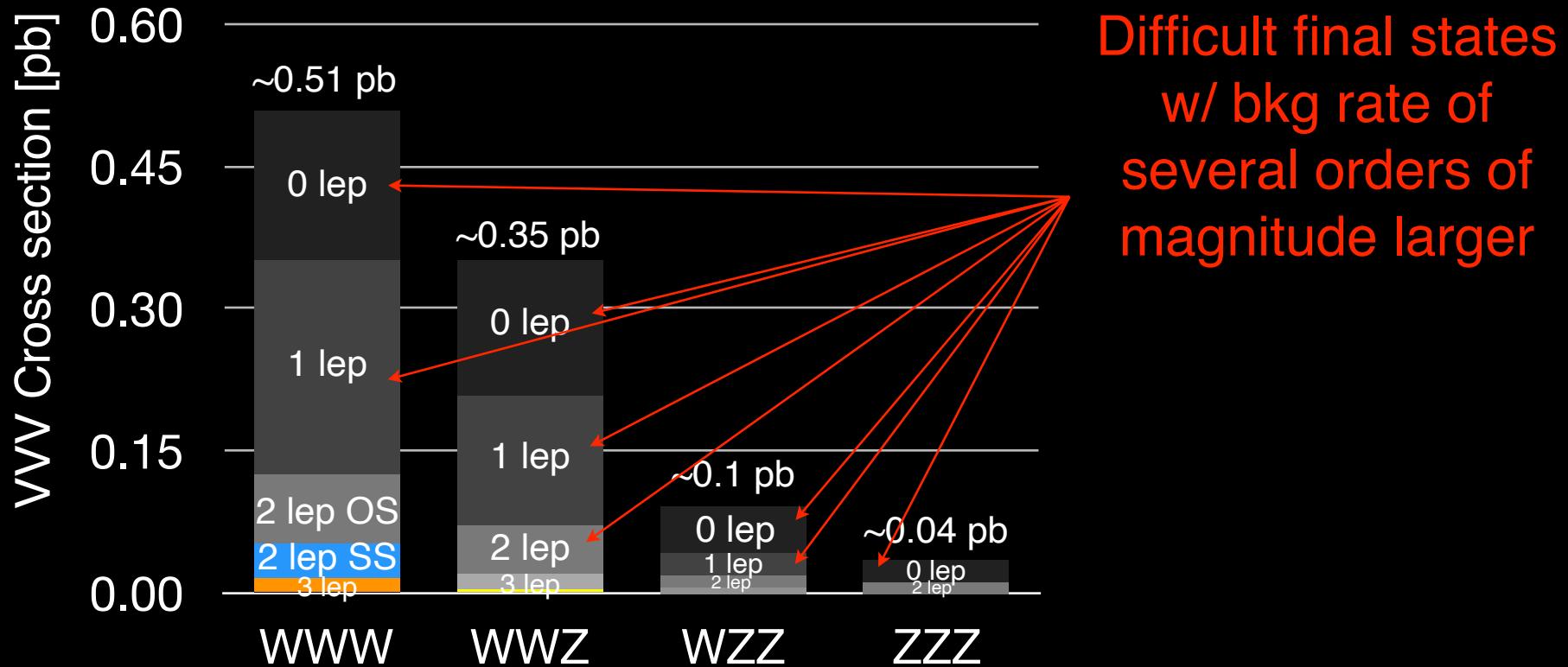


Viable final states have O(fb) or less cross sections

# VVV channels in # of leptons



Production cross section decreases with more Z's



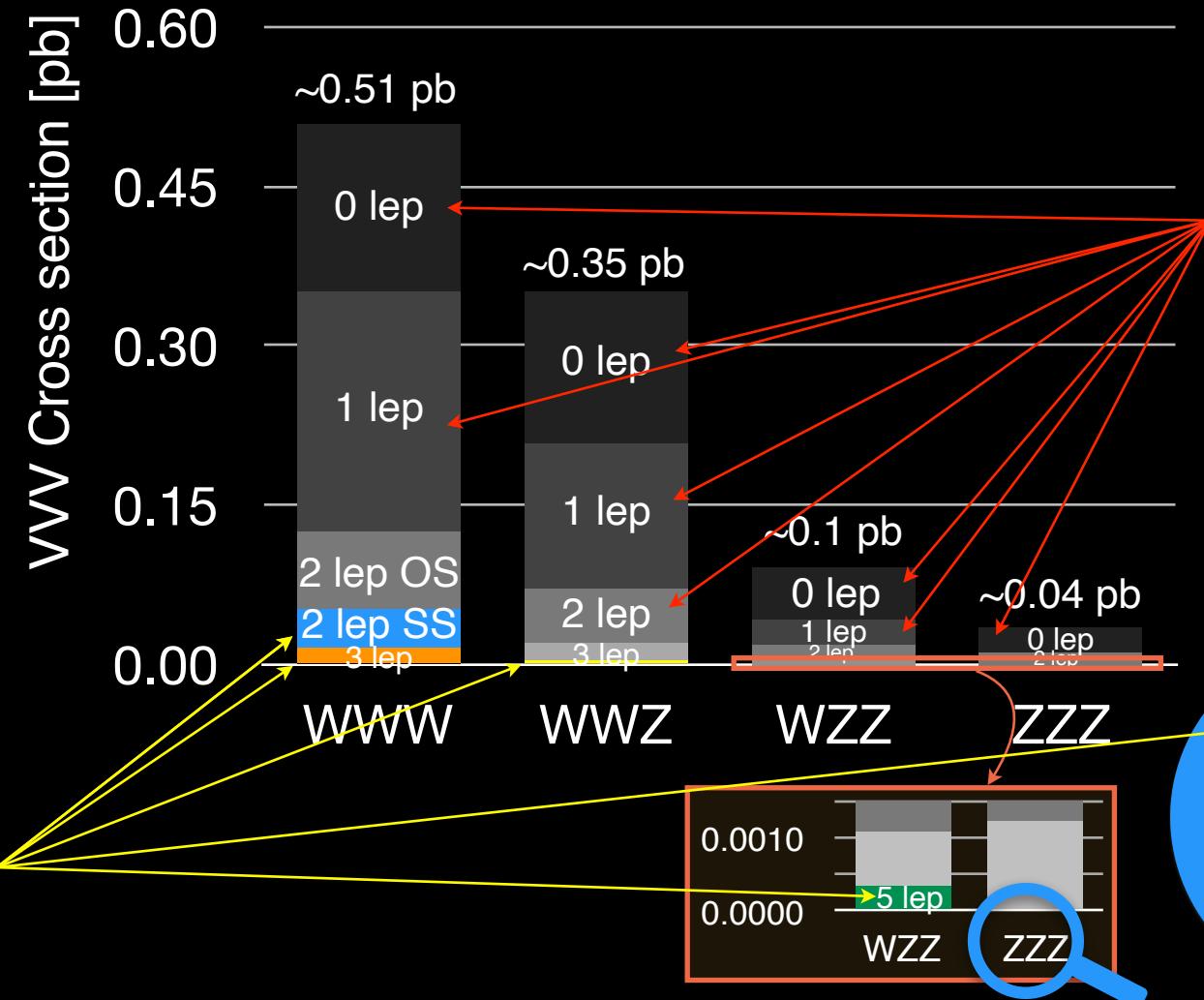
Viable final states have O(fb) or less cross sections

# VVV channels in # of leptons

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Production cross section decreases with more Z's



Difficult final states  
w/ bkg rate of  
several orders of  
magnitude larger

$ZZZ \rightarrow 6L$   
( $L = e, \mu$ )

**11 attobarn**  
(~1.5 events produced  
at Run 2 of LHC)

Viable final states have  $O(\text{fb})$  or less cross sections

# VVV analyses overview by N leptons

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Target “fully” leptonic final states to go after first observation

One exception

	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \rightarrow l^\pm \nu$ $W^\pm \rightarrow l^\pm \nu$ $W^\mp \rightarrow qq$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
	~2.5k evt.	~700 evt.	~140 evt.	~15 evt.	~1.5 evt.

Different modes populate different N lepton bins

Some cross contamination between N lepton bins exists but is small

# Backgrounds in each N lepton region

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	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \rightarrow l^\pm \nu$ $W^\pm \rightarrow l^\pm \nu$ $W^\mp \rightarrow qq$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
Dominant Bkgs.		$WZ \rightarrow l\nu ll$ $t\bar{t} \rightarrow bb + ll + X$ $\downarrow \text{fake } l$	$ZZ \rightarrow llll$ $ttZ \rightarrow llll + bbX$		

N.B.  $WZ \rightarrow 3l \sim 100k$ ,  $ZZ \rightarrow 4l \sim 10k$

Once separated by N leptons dominant bkg. source becomes apparent

# Backgrounds in each N lepton region



	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \rightarrow l^\pm \nu$ $W^\pm \rightarrow l^\pm \nu$ $W^\mp \rightarrow q\bar{q}$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
Dominant Bkgs.	$WZ \rightarrow l^\pm \nu  ^\pm \cancel{l^\mp}$ $t\bar{t} \rightarrow bb + l + X$ $\downarrow \text{fake } l$	$WZ \rightarrow l\nu ll$ $t\bar{t} \rightarrow bb + ll + X$ $\downarrow \text{fake } l$	$ZZ \rightarrow ll ll$ $ttZ \rightarrow ll ll + bbX$		

N.B.  $WZ \rightarrow 3l \sim 100k$ ,  $ZZ \rightarrow 4l \sim 10k$

Once separated by N leptons dominant bkg. source becomes apparent

# Backgrounds in each N lepton region



	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \rightarrow l^\pm \nu$ $W^\pm \rightarrow l^\pm \nu$ $W^\mp \rightarrow qq$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
Dominant Bkgs.	$WZ \rightarrow l^\pm \nu l^\pm \bar{l}^+$ $t\bar{t} \rightarrow bb + l + X$ $\hookdownarrow \text{fake } l$	$WZ \rightarrow l\nu ll$ $\hookdownarrow \text{fake } l$	$ZZ \rightarrow ll ll$ $t\bar{t}Z \rightarrow ll ll + bbX$	$ZZ \rightarrow ll ll$ $+ \text{fake lep}$	$ZZ \rightarrow ll ll$ $+ 2 \text{ fake lep}$

N.B.  $WZ \rightarrow 3l \sim 100k$ ,  $ZZ \rightarrow 4l \sim 10k$

Once separated by N leptons dominant bkg. source becomes apparent

# Backgrounds in each N lepton region



	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \rightarrow l^\pm \nu$ $W^\pm \rightarrow l^\pm \nu$ $W^\mp \rightarrow qq$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
Dominant Bkgs.	$WZ \rightarrow l^\pm \nu l^\pm \bar{l}^\mp$ $t\bar{t} \rightarrow bb + l + X$ $\hookdownarrow \text{fake } l$	$WZ \rightarrow l\nu ll$ $t\bar{t} \rightarrow bb + ll + X$ $\hookdownarrow \text{fake } l$	$ZZ \rightarrow ll ll$ $ttZ \rightarrow ll ll + bbX$	$ZZ \rightarrow ll ll$ $+ \text{fake lep}$	$ZZ \rightarrow ll ll$ $+ 2 \text{ fake lep}$
<b>WW v. Z</b>					

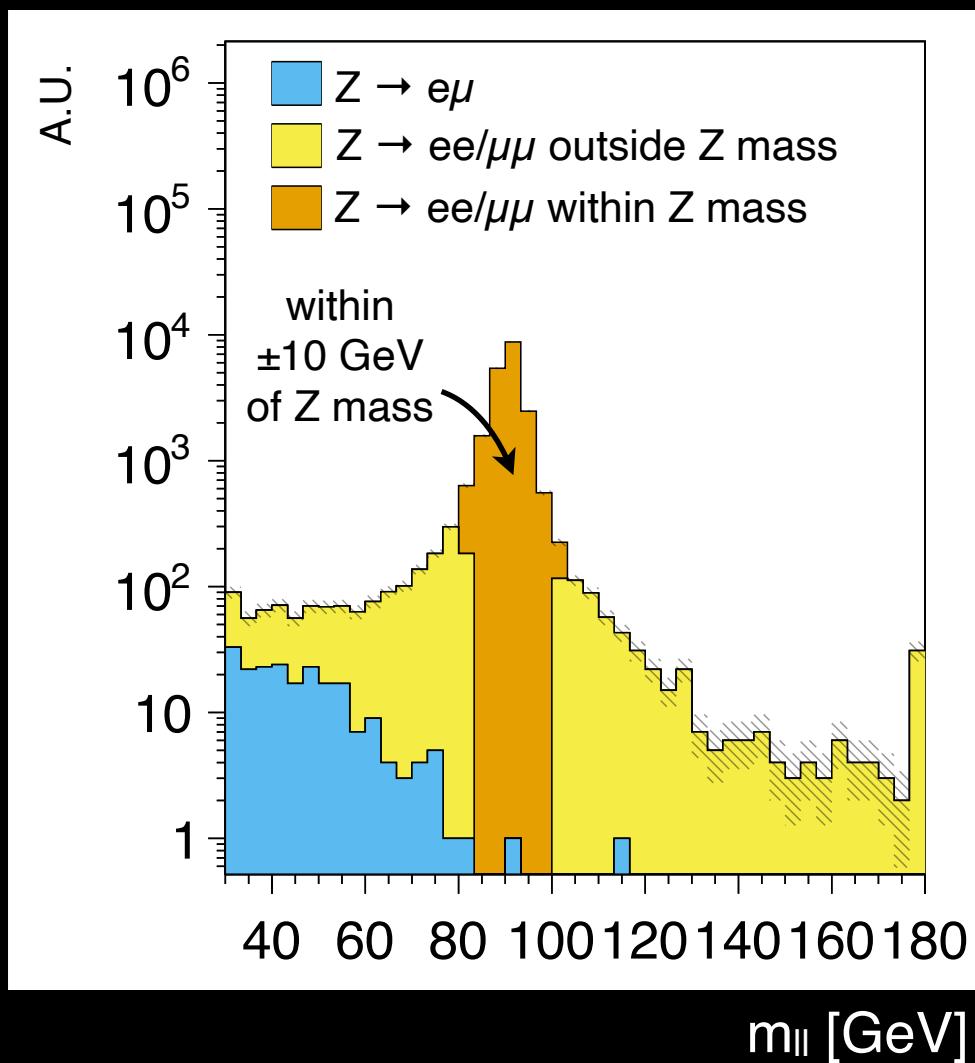
N.B.  $WZ \rightarrow 3l \sim 100k$ ,  $ZZ \rightarrow 4l \sim 10k$

Selection on flavor and b tag will further reduce bkg.

Once separated by N leptons dominant bkg. source becomes apparent

# Features of $Z \rightarrow ll$ decay

Plot of dilepton mass from  $Z \rightarrow ll$  decay



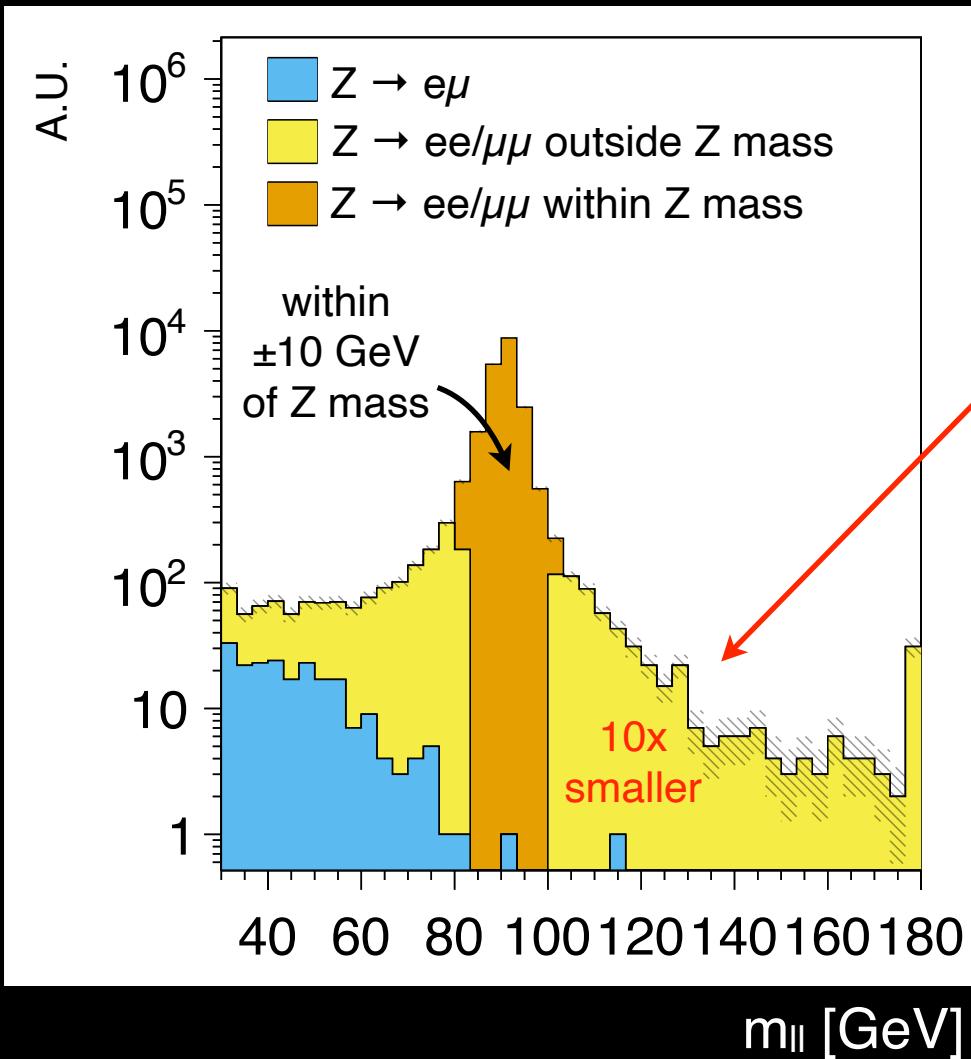
\*\*Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV  $P_T$  cuts

$Z$  decays predominantly to  $ee/\mu\mu$  on-shell

# Features of $Z \rightarrow ll$ decay



Plot of dilepton mass from  $Z \rightarrow ll$  decay



If one selects  $|m_{ll} - m_Z| > 10$  GeV of  $ee/\mu\mu$  final state  $Z$  is reduced by an order of magnitude

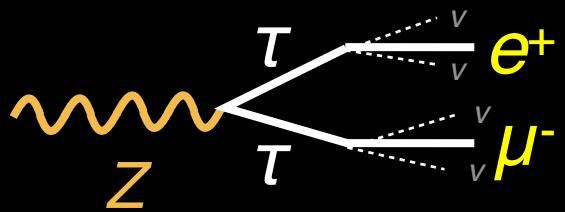
\*\*Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV  $P_T$  cuts

$Z$  decays predominantly to  $ee/\mu\mu$  on-shell

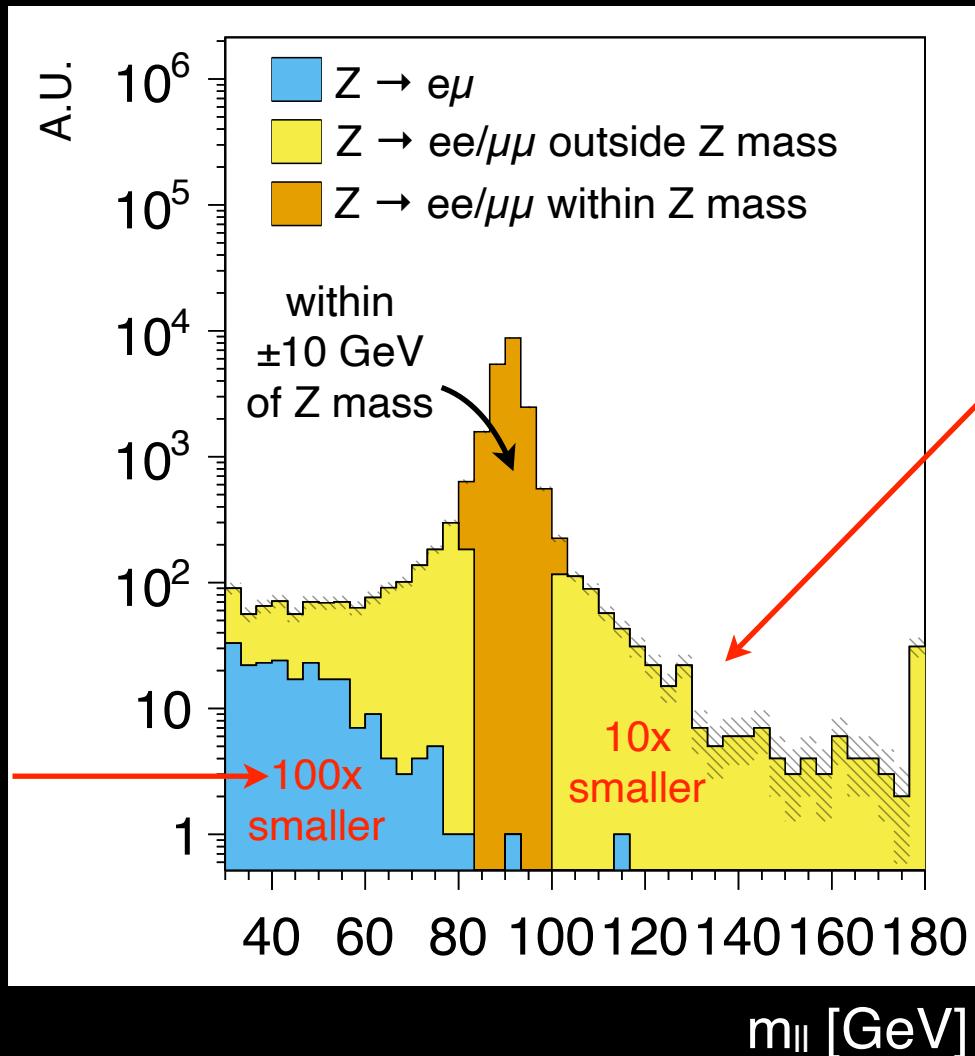
# Features of $Z \rightarrow ll$ decay



Plot of dilepton mass from  $Z \rightarrow ll$  decay



If one selects  $e\mu$  final state,  $Z$  is reduced by **2 orders** of magnitude ( $e, \mu$  from  $\tau$  are soft)



If one selects  $lm_{ll} - m_Z > 10$  GeV of  $ee/\mu\mu$  final state  $Z$  is reduced by **an order** of magnitude

\*\*Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV  $P_T$  cuts

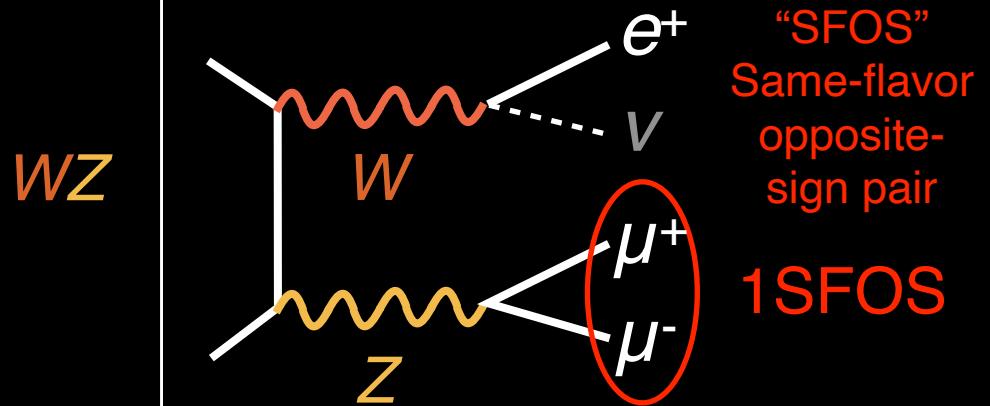
$Z$  decays predominantly to  $ee/\mu\mu$  on-shell

# Reducing VV background by flavor choice

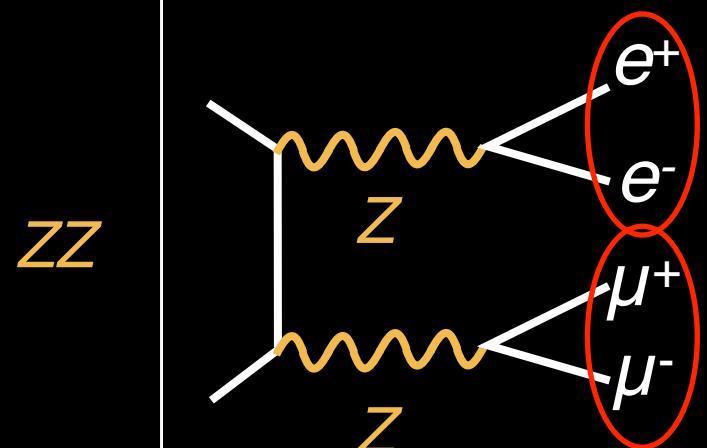
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Higher VV rate



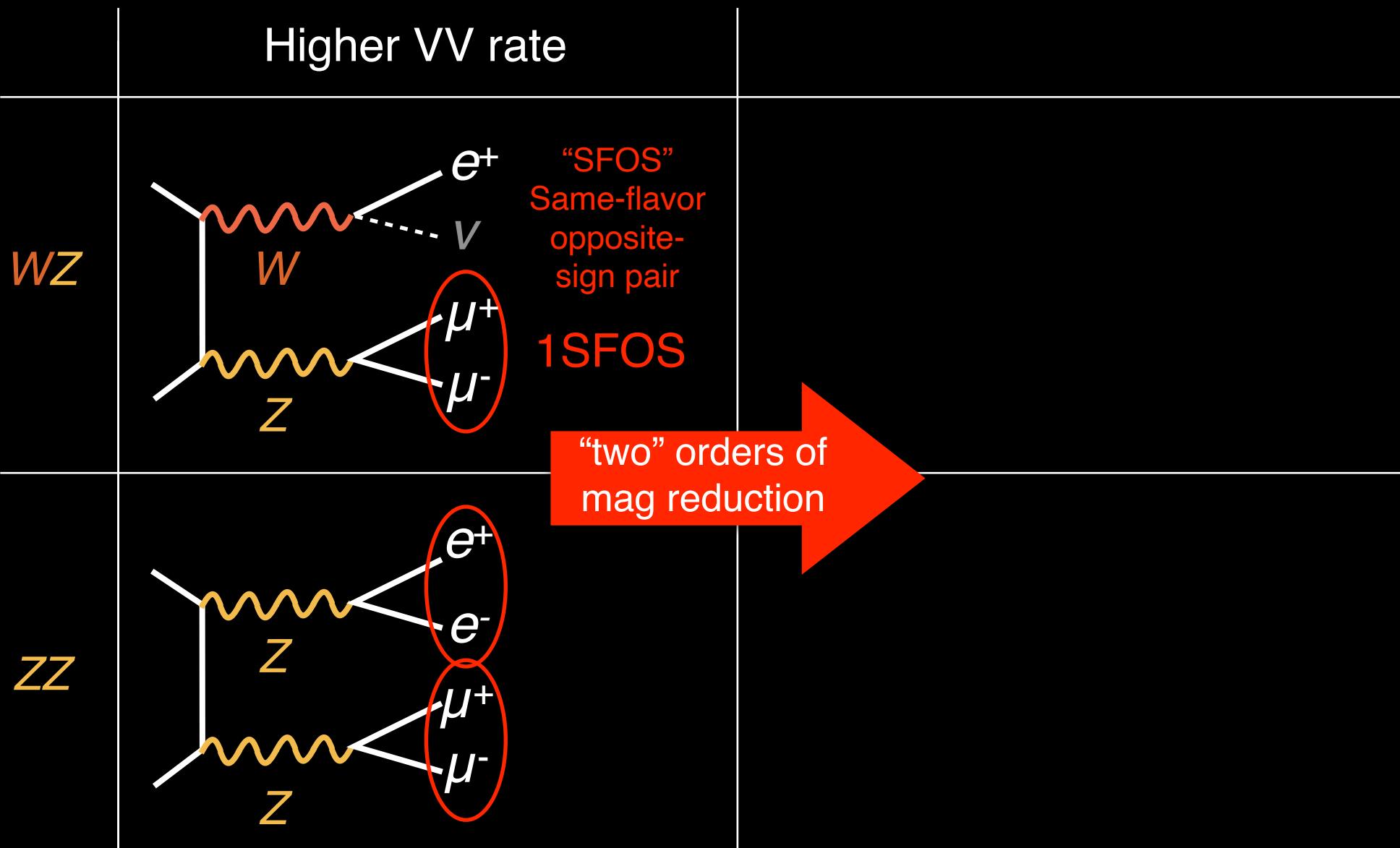
“SFOS”  
Same-flavor  
opposite-sign pair  
**1SFOS**



Selecting away from  $Z \rightarrow$ SFOS decay reduces background

# Reducing VV background by flavor choice

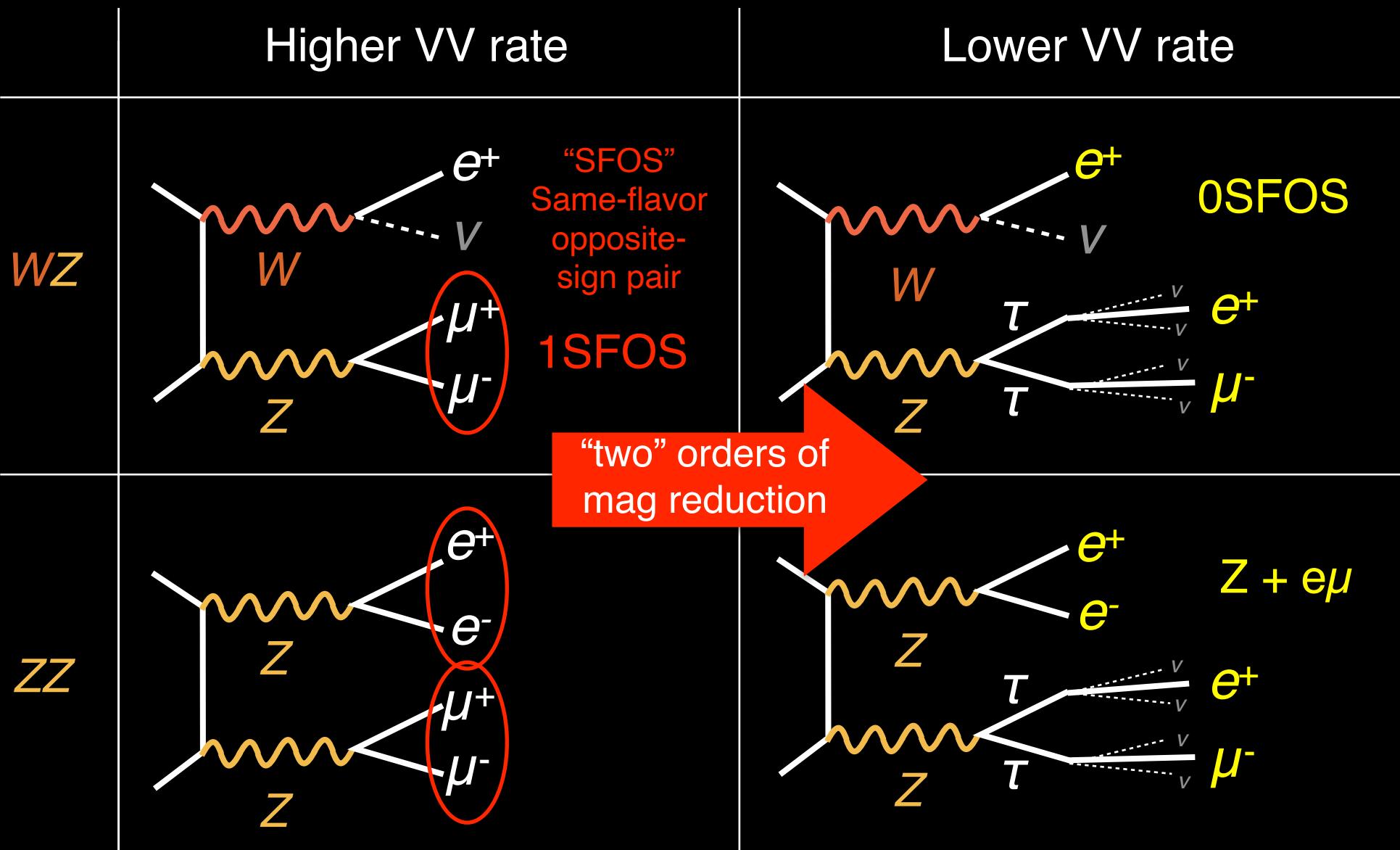
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Selecting away from  $Z \rightarrow$ SFOS decay reduces background

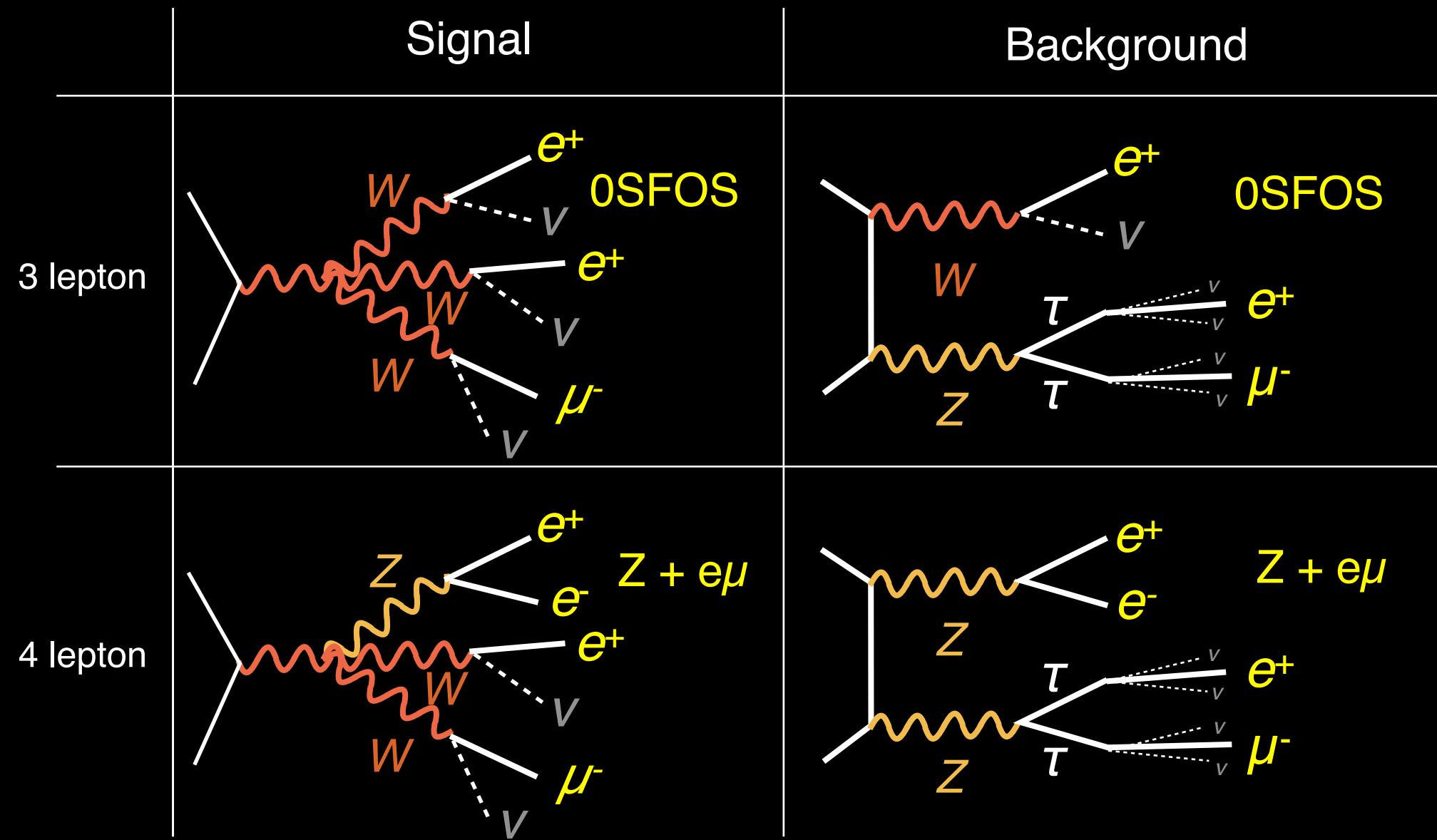
# Reducing VV background by flavor choice

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Selecting away from  $Z \rightarrow$ SFOS decay reduces background

# Signal is not affected by flavor choice



Signal does not have reduction due to specific flavor choice shown above

# Splitting signal regions by lepton flavors

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	3 leptons	4 leptons	
Signals	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	
	Split by # of SFOS e.g. 0: $e^\pm\mu^\mp e^\pm$ 1: $e^\pm e^\mp \mu^\pm$ 2: $e^\pm e^\mp e^\pm$	tag $Z \rightarrow ll$ then split $WW \rightarrow ee/\mu\mu$ v. $WW \rightarrow e\mu$	

**3 categories 2 categories\***

\* marked ones will be further split

Each N lepton analyses are further split by flavors

# Splitting signal regions by lepton flavors



Same-sign 2 leptons		3 leptons	4 leptons	5 leptons	6 leptons
signals	$W^\pm \rightarrow l^\pm \nu$ $W^\pm \rightarrow l^\pm \nu$ $W^\mp \rightarrow qq$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
Split by $ee/e\mu/\mu\mu$		Split by # of SFOS  e.g. 0: $e^\pm \mu^\mp e^\pm$ 1: $e^\pm e^\mp \mu^\pm$ 2: $e^\pm e^\mp e^\pm$	tag $Z \rightarrow ll$ then split $WW \rightarrow ee/\mu\mu$ v. $WW \rightarrow e\mu$		Not enough statistics single bin
N.B. $\mu$ is cleaner than $e$					
3 categories*	3 categories	2 categories*	1 category	1 category	

\* marked ones will be further split

Each N lepton analyses are further split by flavors

# 4 steps to VVV observation

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3

1. Organize analyses by leptons (likely) from W / Z

- N leptons in the event
- Flavor of the leptons

Smart humans and  
smart machines  
(Both cut / BDT)



2. Additional background suppression through smart choices
3. Reliably estimate the size of residual backgrounds
4. Observe VVV!

# Event selections

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## same-sign selection

Variable	$m_{jj}$ -in and $m_{jj}$ -out	1j
Trigger	Signal triggers, tab. 3.2	
Signal leptons	Exactly 2 tight SS leptons with $p_T > 25 \text{ GeV}$	
Additional leptons	No additional very loose lepton	
Isolated tracks	No additional isolated tracks	
Jets	$\geq 2$ jets	1 jet
b-tagging	no b-tagged jets and soft b-tag objects	
$m_{\ell\ell}$	$> 20 \text{ GeV}$	
$m_{\ell\ell}$	$ m_{\ell\ell} - m_Z  > 20 \text{ GeV}$ if $e^\pm e^\pm$	
$p_T^{\text{miss}}$	$> 45 \text{ GeV}$	
$m_{jj}$ (leading jets)	$< 500 \text{ GeV}$	—
$\Delta\eta_{jj}$ (leading jets)	$< 2.5$	—
$m_{jj}$ (closest $\Delta R$ )	$65 < m_{jj} < 95 \text{ GeV}$ or $ m_{jj} - 80 \text{ GeV}  \geq 15 \text{ GeV}$	—
$\Delta R_{\ell j}^{\min}$	—	$< 1.5$
$m_T^{\max}$	$> 90 \text{ GeV}$ if not $\mu^\pm \mu^\pm$	$> 90 \text{ GeV}$

## Three leptons selection

Variable	0 SFOS	1 and 2 SFOS
Trigger	Signal triggers, tab. 3.2	
Signal leptons	3 tight leptons with charge sum = $\pm 1e$	
$p_T > 25/25/25 \text{ GeV}$	$p_T > 25/20/20 \text{ GeV}$	
Additional leptons	No additional very loose lepton	
$m_{\text{SFOS}}$	$m_{\text{SFOS}} > 20 \text{ GeV}$ and $ m_{\text{SFOS}} - m_Z  > 20 \text{ GeV}$	
$m_{\ell\ell\ell}$	$ m_{\ell\ell\ell} - m_Z  > 10 \text{ GeV}$	
SF lepton mass	$> 20 \text{ GeV}$	—
Dielectron mass	$ m_{ee} - m_Z  > 20 \text{ GeV}$	—
Jets	$\leq 1$ jet	0 jets
b-tagging	No b-tagged jets and soft b-tag objects	
$\Delta\phi(\vec{p}_T(\ell\ell\ell), \vec{p}_T^{\text{miss}})$	—	$> 2.5$
$p_T(\ell\ell\ell)$	—	$> 50 \text{ GeV}$
$m_T^{3\text{rd}}$ (1 SFOS) or $m_T^{\max}$ (2 SFOS)	—	$> 90 \text{ GeV}$

## Four leptons selection

Variable	e $\mu$ category	ee / $\mu\mu$ category
Preselection		Selections in Table 20
W candidate lepton flavors	e $\mu$	ee / $\mu\mu$
$m_{\ell\ell}$	Separated into 4 bins in $(0, 40, 60, 100, \infty)$	$ m_{\ell\ell} - m_Z  > 10 \text{ GeV}$
$m_{T2}$	$m_{T2} > 25 \text{ GeV}$ (for $m_{\ell\ell} > 100 \text{ GeV}$ )	...
$p_{T,4\ell}$ and $p_T^{\text{miss}}$	...	No $p_{T,4\ell}$ cuts and $p_T^{\text{miss}} > 120 \text{ GeV}$ (Bin A) $p_{T,4\ell} > 70 \text{ GeV}$ and $70 < p_T^{\text{miss}} < 120 \text{ GeV}$ (Bin B) $40 < p_{T,4\ell} < 70 \text{ GeV}$ and $70 < p_T^{\text{miss}} < 120 \text{ GeV}$ (Bin C)

5/6L will be explained later

This is the full selections but I will not go in details for every single one

# Event selections

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## same-sign selection

Variable	$m_{jj}$ -in and $m_{jj}$ -out	1j
Trigger	Signal triggers, tab. 3.2	
Signal leptons	Exactly 2 tight SS leptons with $p_T > 25 \text{ GeV}$	
Additional leptons	No additional very loose lepton	
Isolated tracks	No additional isolated tracks	
Jets	$\geq 2$ jets	1 jet

Split by N leptons  
and requiring “Tight” leptons

$\Delta\eta_{JJ}$ (leading jets)	<2.5	—
$m_{jj}$ (closest $\Delta R$ )	$65 < m_{jj} < 95 \text{ GeV}$ or $ m_{jj} - 80 \text{ GeV}  \geq 15 \text{ GeV}$	—
$\Delta R_{\ell j}^{\min}$	—	<1.5
$m_T^{\max}$	>90 GeV if not $\mu^\pm\mu^\pm$	>90 GeV

## Three leptons selection

Variable	0 SFOS	1 and 2 SFOS
Trigger	Signal triggers, tab. 3.2	
Signal leptons	3 tight leptons with charge sum = $\pm 1e$	
$p_T$	$p_T > 25/25/25 \text{ GeV}$	$p_T > 25/20/20 \text{ GeV}$
Additional leptons	No additional very loose lepton	
$m_{SFOS}$	$m_{SFOS} > 20 \text{ GeV}$ and $ m_{SFOS} - m_Z  > 20 \text{ GeV}$	
$m_{\ell\ell\ell}$	$ m_{\ell\ell\ell} - m_Z  > 10 \text{ GeV}$	—
SF lepton mass	—	—
Dielectron mass	$ m_{ee} - m_Z  > 20 \text{ GeV}$	—
Jets	$\leq 1$ jet	0 jets
b-tagging	No b-tagged jets and soft b-tag objects	
$\Delta\phi(\vec{p}_T(\ell\ell\ell), \vec{p}_T^{\text{miss}})$	—	>2.5
$p_T(\ell\ell\ell)$	—	>50 GeV
$m_T^{3\text{rd}}$ (1 SFOS) or $m_T^{\max}$ (2 SFOS)	—	>90 GeV

## Four leptons selection

Variable	e $\mu$ category	ee / $\mu\mu$ category
Preselection		
W candidate lepton flavors	e $\mu$	Selections in Table 20
$m_{\ell\ell}$	Separated into 4 bins in $(0, 40, 60, 100, \infty)$	ee / $\mu\mu$
$m_{T2}$	$m_{T2} > 25 \text{ GeV}$ (for $m_{\ell\ell} > 100 \text{ GeV}$ )	$ m_{\ell\ell} - m_Z  > 10 \text{ GeV}$
$p_{T,4\ell}$ and $p_T^{\text{miss}}$	...	...
		No $p_{T,4\ell}$ cuts and $p_T^{\text{miss}} > 120 \text{ GeV}$ (Bin A)
		$p_{T,4\ell} > 70 \text{ GeV}$ and $70 < p_T^{\text{miss}} < 120 \text{ GeV}$ (Bin B)
		$40 < p_{T,4\ell} < 70 \text{ GeV}$ and $70 < p_T^{\text{miss}} < 120 \text{ GeV}$ (Bin C)

5/6L will be  
explained later

But already you can notice a few things

# Event selections

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## same-sign selection

Variable	$m_{jj}$ -in and $m_{jj}$ -out	1j
Trigger	Signal triggers, tab. 3.2	
Signal leptons	Exactly 2 tight SS leptons with $p_T > 25$ GeV	
Additional leptons	No additional very loose lepton	
Isolated tracks	No additional isolated tracks	
Jets	$\geq 2$ jets	1 jet
b-tagging	no b-tagged jets and soft b-tag objects	
$m_{\ell\ell}$	$> 20$ GeV	
$m_{\ell\ell}$	$ m_{\ell\ell} - m_Z  > 20$ GeV if $e^\pm e^\pm$	
$p_T^{\text{miss}}$	$> 45$ GeV	
$m_{jj}$ (leading jets)	$< 500$ GeV	—
$\Delta\eta_{jj}$ (leading jets)	$< 2.5$	—
$m_{jj}$ (closest $\Delta R$ )	$65 < m_{jj} < 95$ GeV or $ m_{jj} - 80$ GeV $  \geq 15$ GeV	—
$\Delta R_{\ell j}^{\min}$	—	$< 1.5$
$m_T^{\max}$	$> 90$ GeV if not $\mu^\pm \mu^\pm$	$> 90$ GeV

## Three leptons selection

Variable	0 SFOS	1 and 2 SFOS
Trigger	Signal triggers, tab. 3.2	
Signal leptons	2 tight leptons with charge sum = $\pm 1e$	
Additional leptons	No additional leptons	
$m_{\text{SFOS}}$		$> 20$ GeV
$m_{\ell\ell\ell}$		
SF lepton mass		
Dielectron mass		
Jets		
b-tagging		
$\Delta\phi(\vec{p}_T(\ell\ell\ell), \vec{p}_T^{\text{miss}})$	—	$> 2.5$
$p_T(\ell\ell\ell)$	—	$> 50$ GeV
$m_T^{3\text{rd}}$ (1 SFOS) or $m_T^{\max}$ (2 SFOS)	—	$> 90$ GeV

## Four leptons selection

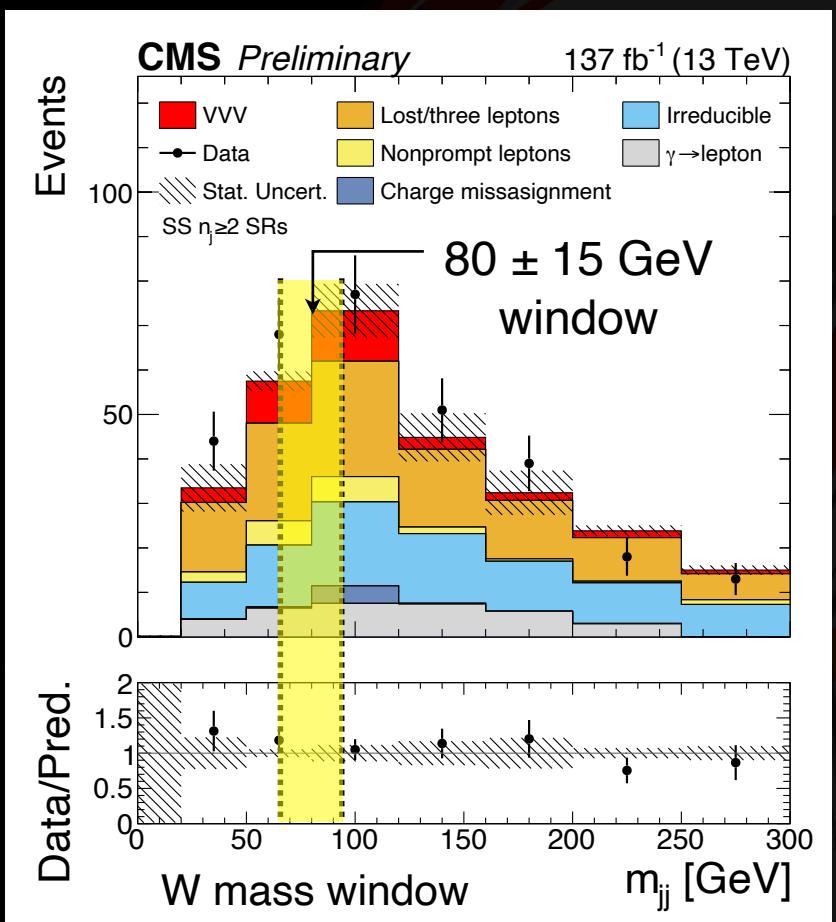
Variable	e $\mu$ category		ee / $\mu\mu$ category	
	Preselection	Selections in Table 20	ee / $\mu\mu$	
W candidate lepton flavors	e $\mu$			
$m_{\ell\ell}$	Separated into 4 bins in $(0, 40, 60, 100, \infty)$		$ m_{\ell\ell} - m_Z  > 10$ GeV	
$m_{T2}$	$m_{T2} > 25$ GeV (for $m_{\ell\ell} > 100$ GeV)		...	
$p_{T,4\ell}$ and $p_T^{\text{miss}}$	...		No $p_{T,4\ell}$ cuts and $p_T^{\text{miss}} > 120$ GeV (Bin A)	
			$p_{T,4\ell} > 70$ GeV and $70 < p_T^{\text{miss}} < 120$ GeV (Bin B)	
			$40 < p_{T,4\ell} < 70$ GeV and $70 < p_T^{\text{miss}} < 120$ GeV (Bin C)	

5/6L will be explained later

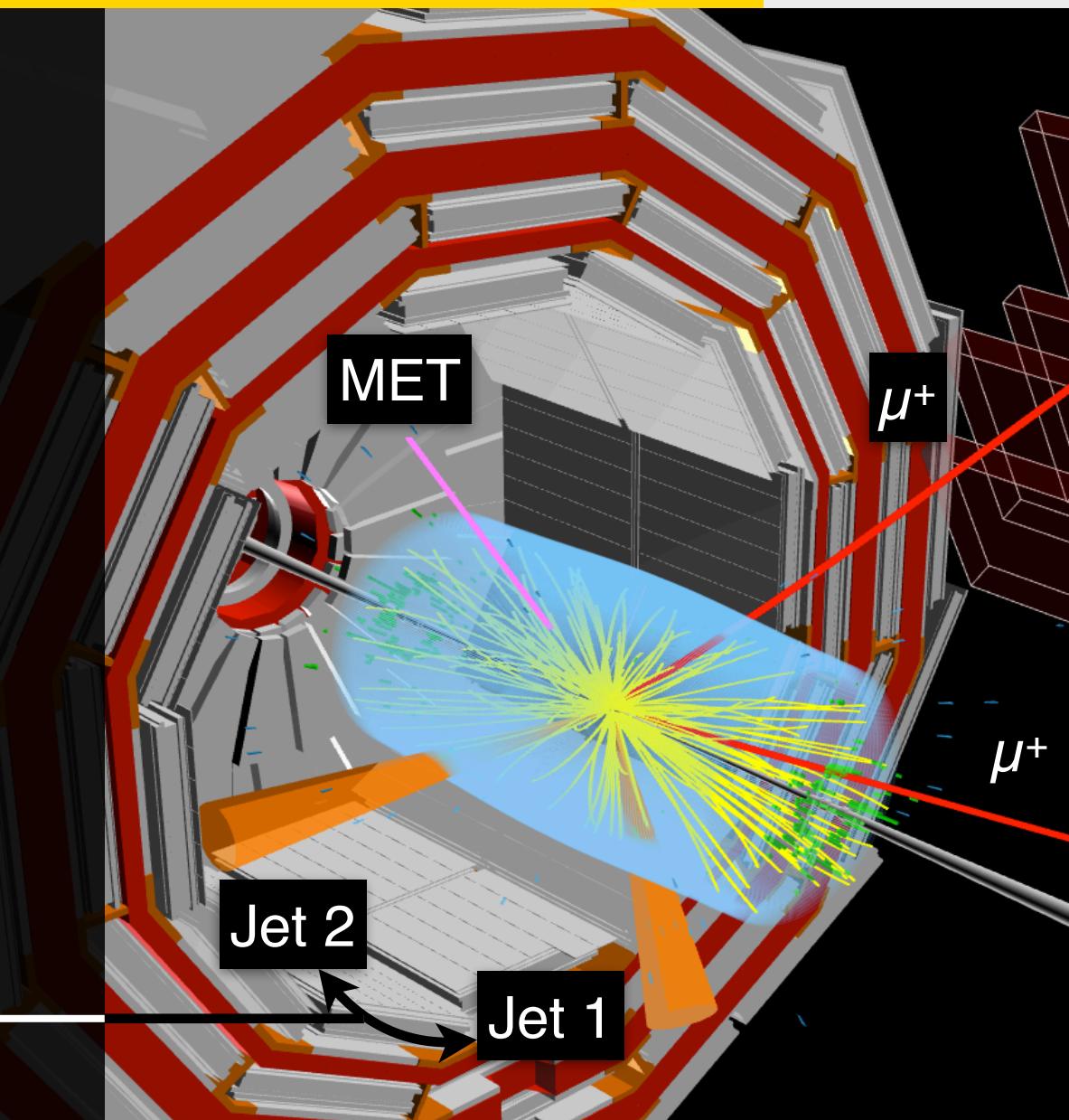
But I will highlight these 5 points in the coming slides

# Reconstruct $W \rightarrow qq$ in $WWW \rightarrow l^\pm l^\pm qq$

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N.B. some signals are outside the window. So we consider  $m_{jj\text{-out}}$  and also 1 jet only events



dijet invariant mass for signal peaks around W mass

# Kinematic endpoints for 3 leptons

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Separated by # of SFOS pairs:

- 0 SFOS (**low bkg.**)
- 1 SFOS
- 2 SFOS

0SFOS is by far the cleanest

For 1SFOS it is clear which one is from W:

$$\frac{e^\pm e^\mp}{Z} \quad \frac{\mu^\pm}{W} \quad \frac{\mu^\pm \mu^\mp}{Z} \quad \frac{e^\pm}{W}$$

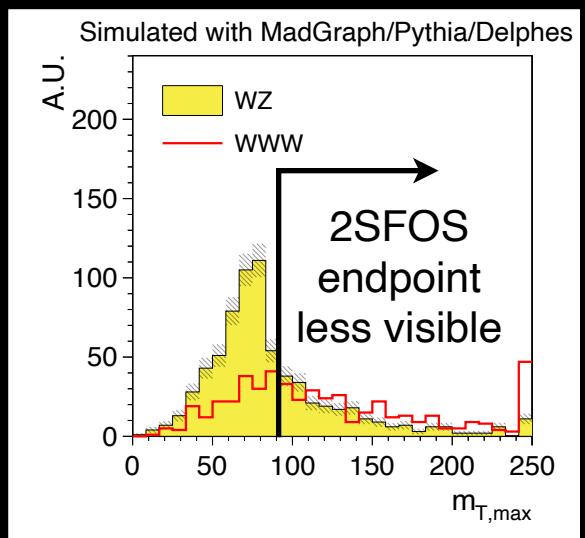
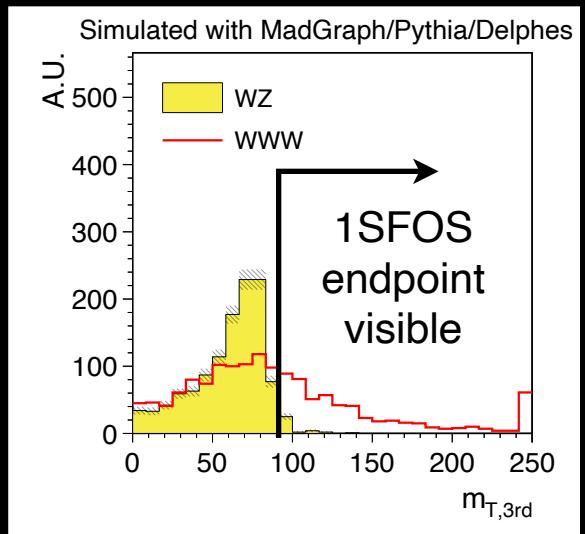
For 2SFOS it is less clear which one is from W:

$$\frac{e^\pm e^\mp}{W?} \quad \frac{e^\pm}{W?} \quad \frac{\mu^\pm \mu^\mp}{W?} \quad \frac{\mu^\pm}{W?}$$

Take max  $m_T$  computed from either leptons

$\Rightarrow$  3 signal regions for 3 leptons

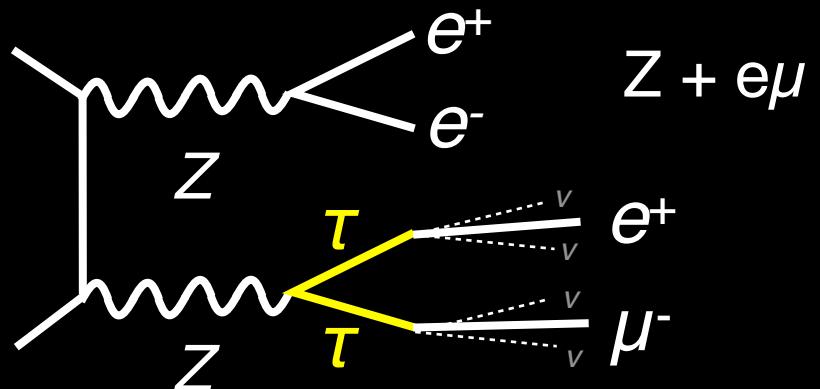
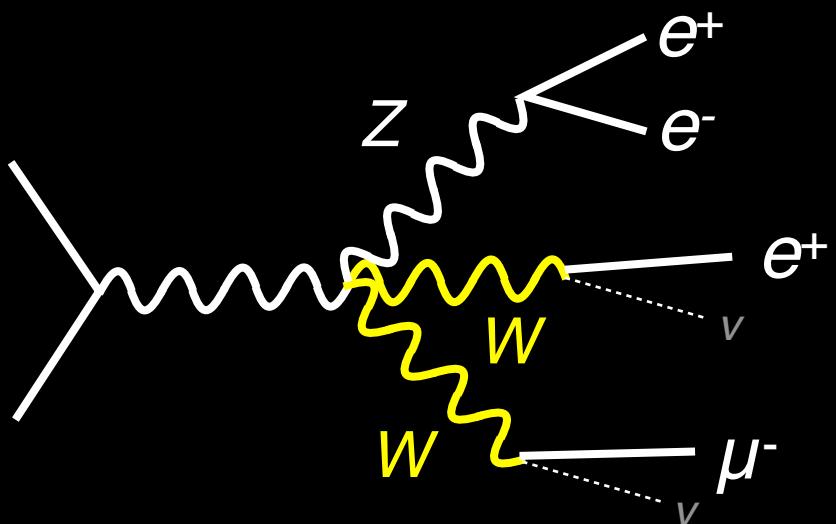
$m_T^{3\text{rd}}$ (1 SFOS) or $m_T^{\max}$ (2 SFOS)	$>90\text{ GeV}$
--	------------------



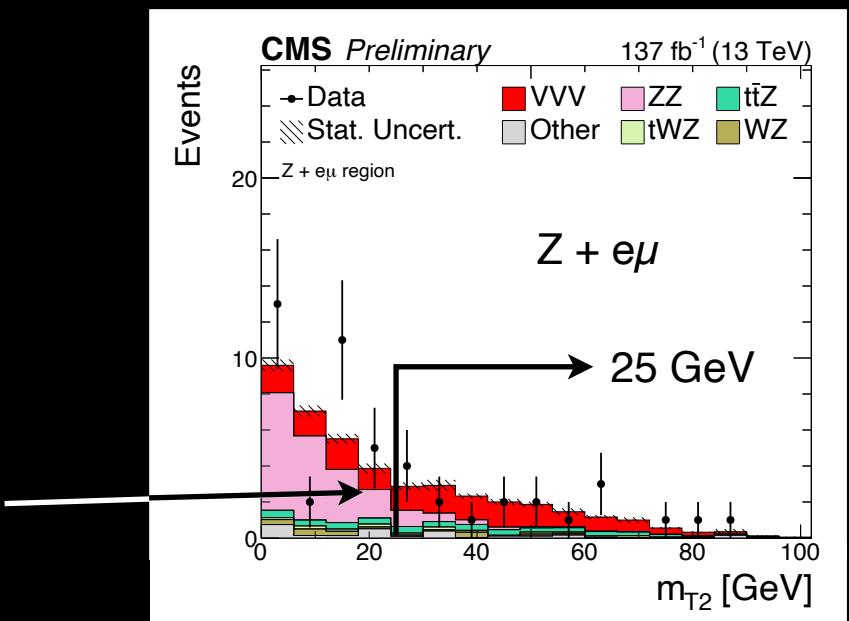
By flavor, W lepton can be identified and kinematic endpoints can be used

# Kinematic endpoints for 4 leptons

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- Utilize  $m_{T2}$  variable: generalization of  $m_T$  for multiple missing particles
- $m_{T2}$  is sensitive to the end points of  $m_W$  from  $ZWW \rightarrow ll\ell\mu$
- $m_{T2}$  is sensitive to the end points of  $m_\tau$  from  $ZZ \rightarrow ll\tau\tau \rightarrow ll\ell\mu$



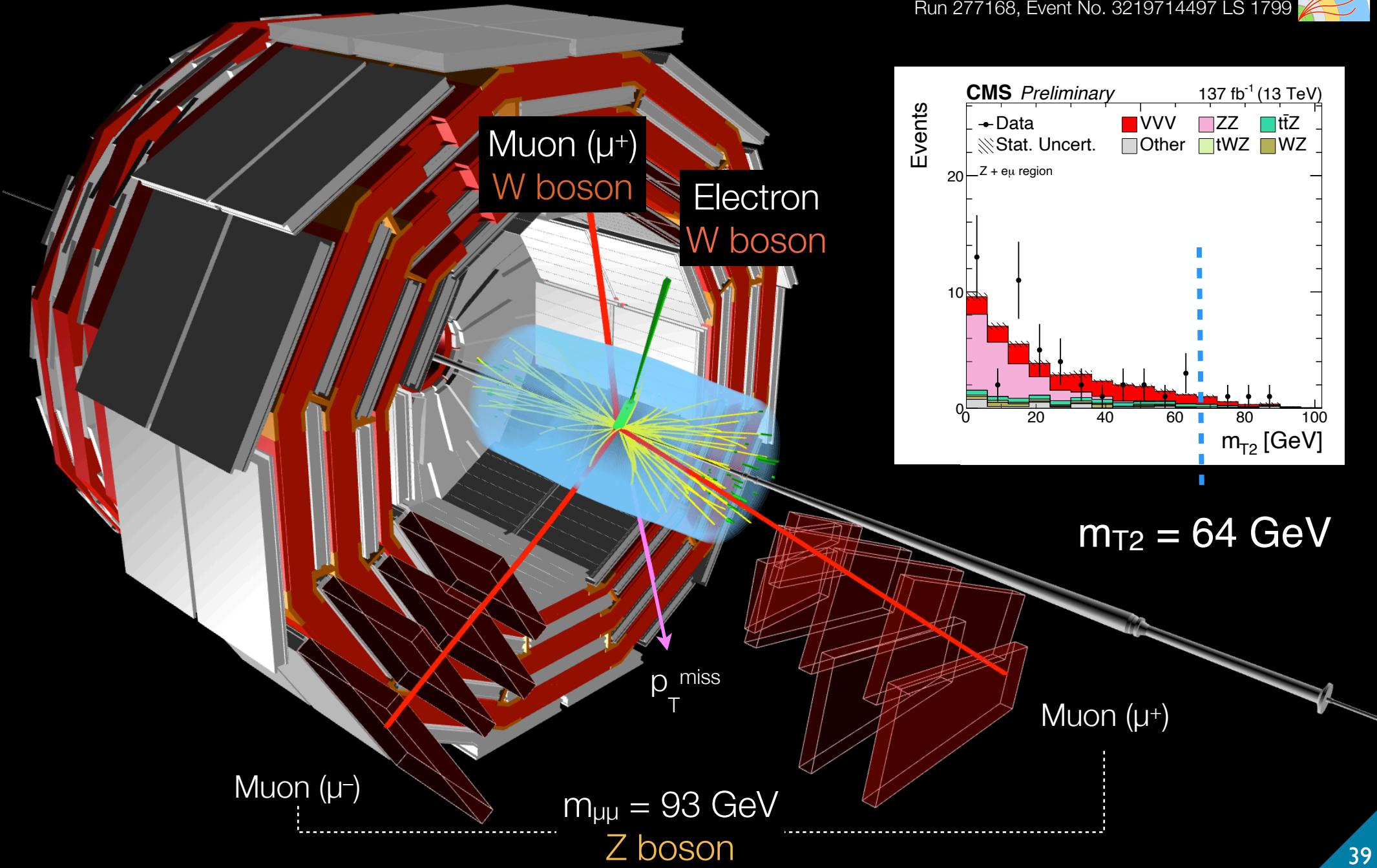
Exploit differences between  $Z \rightarrow ll$  v.  $WW \rightarrow llvv$

# 4 lepton event

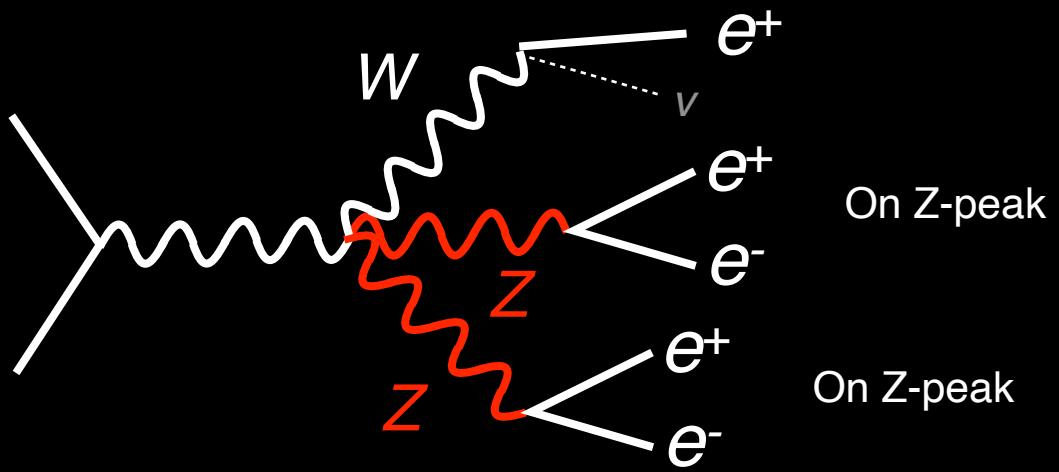
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CMS experiment at the LHC, CERN  
Data recorded: 2016-Jul-23 08:13:27.898048 GMT  
Run 277168, Event No. 3219714497 LS 1799



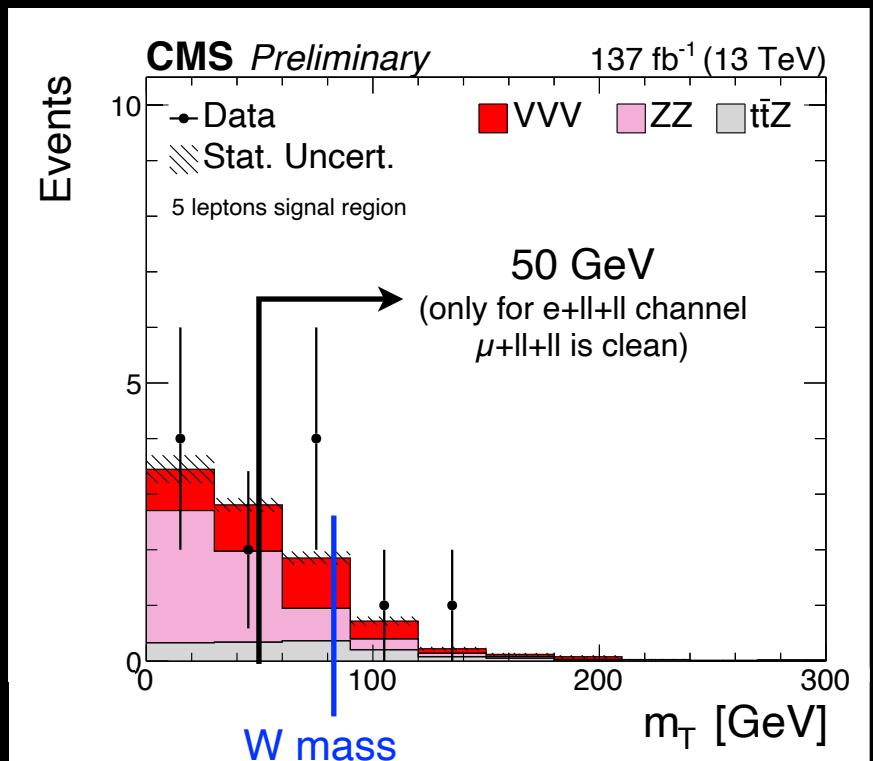
# 5 leptons target $WZZ$ signal



Require the 5 lepton events to contain two SFOS pair consistent with  $Z$  mass

The dominant background is  $ZZ \rightarrow ll ll$   
plus a fake lepton

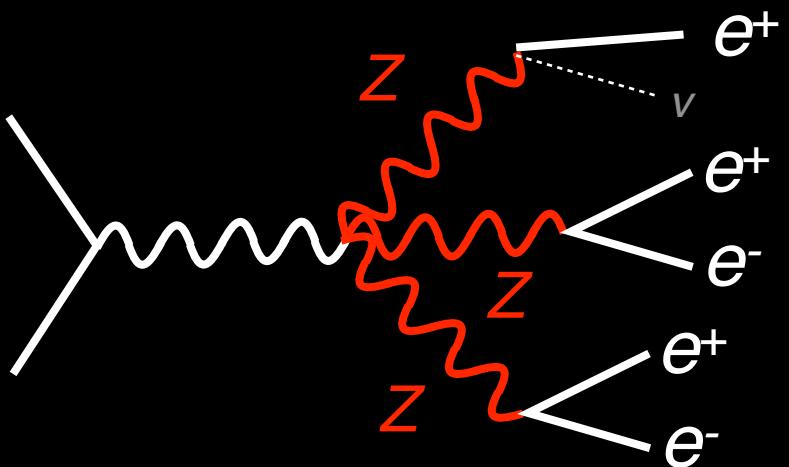
The fake lepton has low transverse mass while the signal's  $W$  has transverse mass peaking at  $W$  mass



Cut-and-count of one bin

# 6 leptons target ZZZ process

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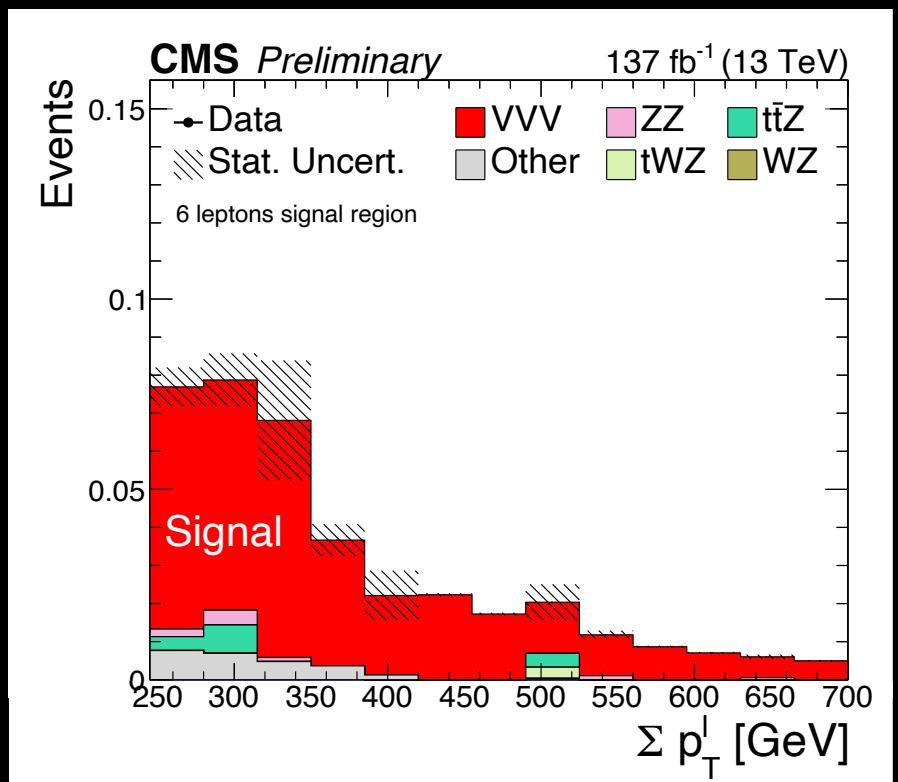


Select at least 6 leptons

Require  $\Sigma p_T \geq 250$  GeV

Less than 1 event expected

Very clean channel



Not enough stats, so search inclusively

# 4 steps to VVV observation

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3

1. Organize analyses by leptons (likely) from W / Z

- N leptons in the event
- Flavor of the leptons

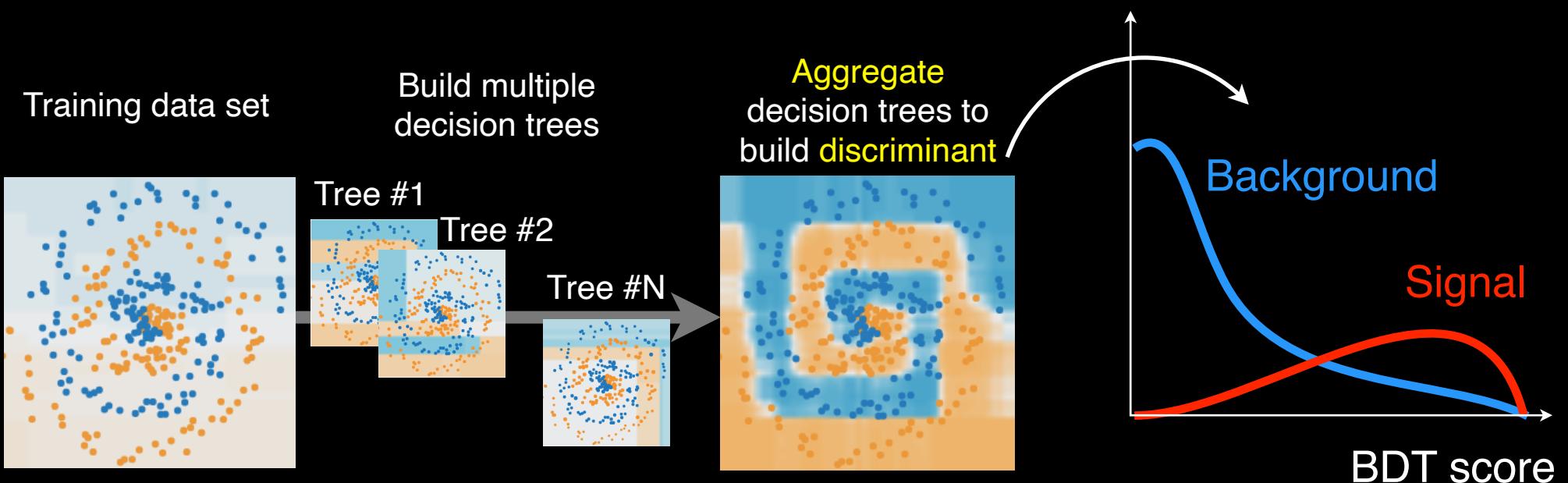
Smart humans and  
smart machines  
(Both cut / BDT)



2. Additional background suppression through smart choices
3. Reliably estimate the size of residual backgrounds
4. Observe VVV!

# Machine learning technique

Boosted decision tree is widely used in many analyses at the LHC



[https://arogozhnikov.github.io/2016/07/05/gradient\\_boosting\\_playground.html](https://arogozhnikov.github.io/2016/07/05/gradient_boosting_playground.html)

Train dedicated boosted decision trees to maximize sensitivity

# Overview of BDT



	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \rightarrow l^\pm \nu$ $W^\pm \rightarrow l^\pm \nu$ $W^\mp \rightarrow q\bar{q}$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
Dominant Bkgs.	$WZ \rightarrow l^\pm \nu l^\pm l^\mp$ $t\bar{t} \rightarrow bb + l + X$ $\downarrow$ fake $l$	$WZ \rightarrow l\nu ll$ $t\bar{t} \rightarrow bb + ll + X$ $\downarrow$ fake $l$	$ZZ \rightarrow ll ll$ $t\bar{t}Z \rightarrow ll ll + bbX$	$ZZ \rightarrow ll ll$ $+ \text{fake lep}$	$ZZ \rightarrow ll ll$ $+ 2 \text{ fake lep}$
	“Prompt” bkgs.	“Fake” bkgs.	$t\bar{t}Z$ bkg. $ZZ$ bkg.	No BDT trained for 5/6 leptons (not enough stats)	

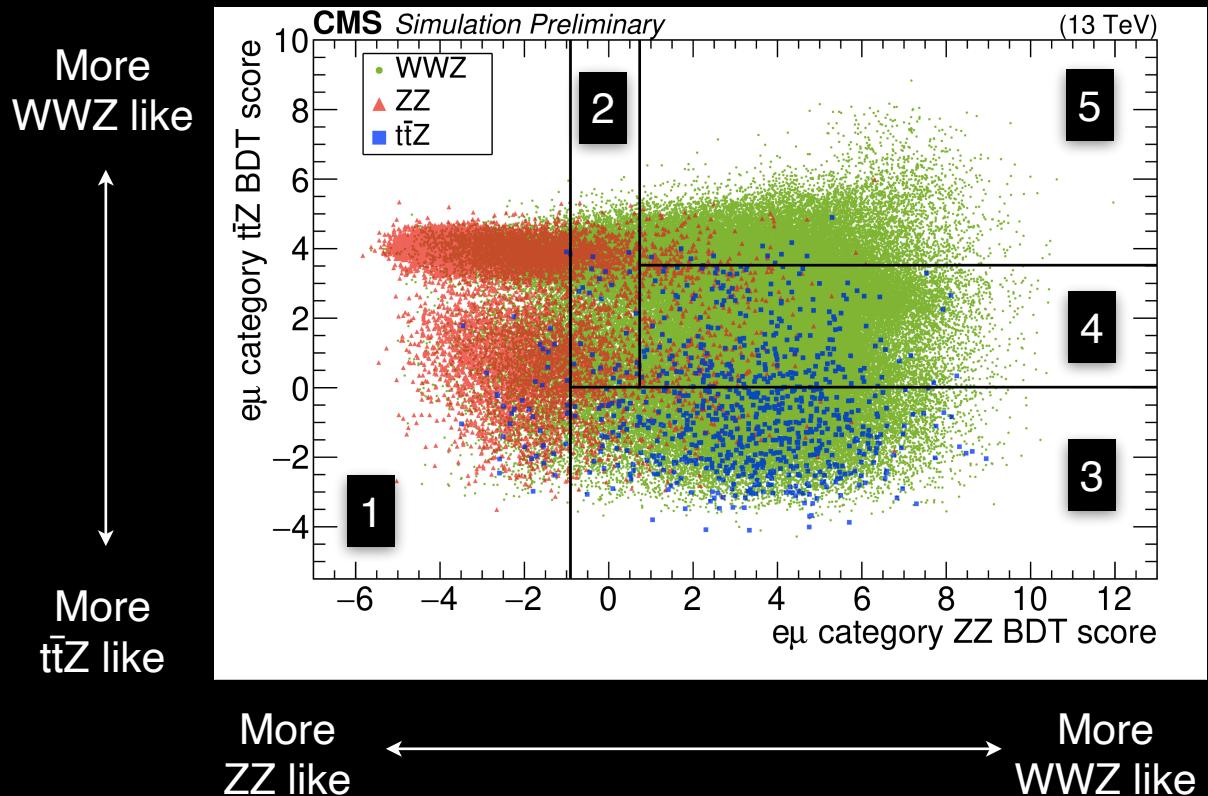
Train different BDTs against different backgrounds

# WWZ BDTs for 4 leptons analysis

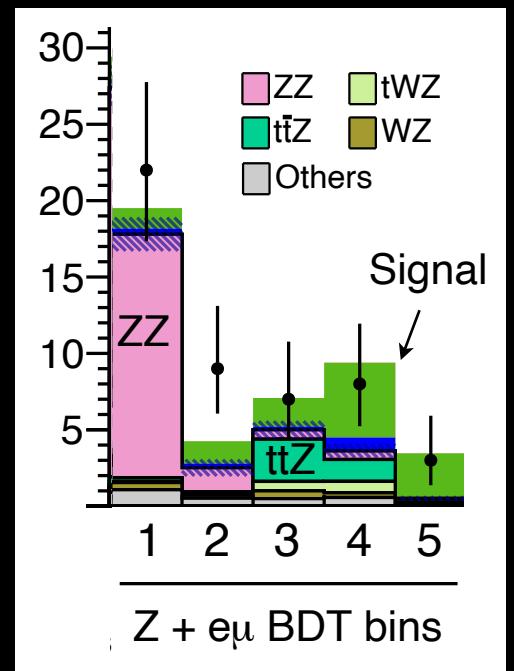
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2D plane in BDT scores for 4 lepton  
 $Z \rightarrow ll + e\mu$  event category



5 bins are created from 2D planes



\*\*For  $Z \rightarrow ll + ee/\mu\mu$  event category, 2 bins are created (not shown)

Created multiple bins in BDTs to maximize sensitivity

# ~~4~~ steps to VVV observation

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~~3~~  
2

1. Organize analyses by leptons (likely) from W / Z
  - N leptons in the event
  - Flavor of the leptons
2. Additional background suppression through smart choices
3. Reliably estimate the size of residual backgrounds
4. Observe VVV!

Smart humans and  
smart machines  
(Both cut / BDT)



# Background estimation in a nutshell

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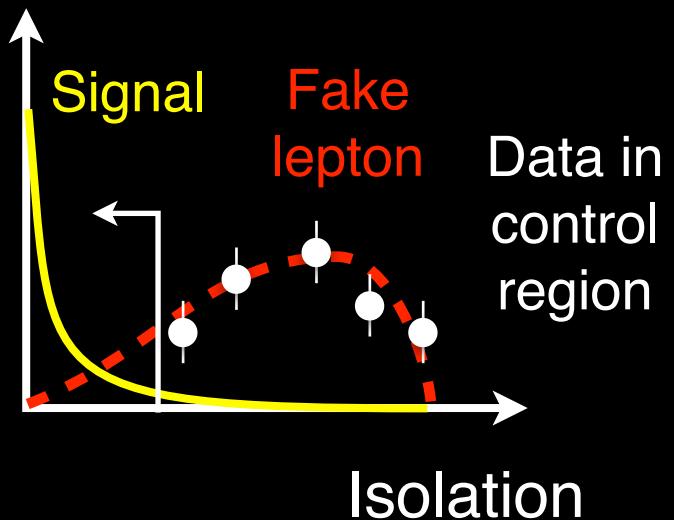
Identify which discriminant most reduces the background

Then, reliably extrapolate across the discriminant phase-space

Background estimations in essence are simple extrapolations

# Lepton isolation example

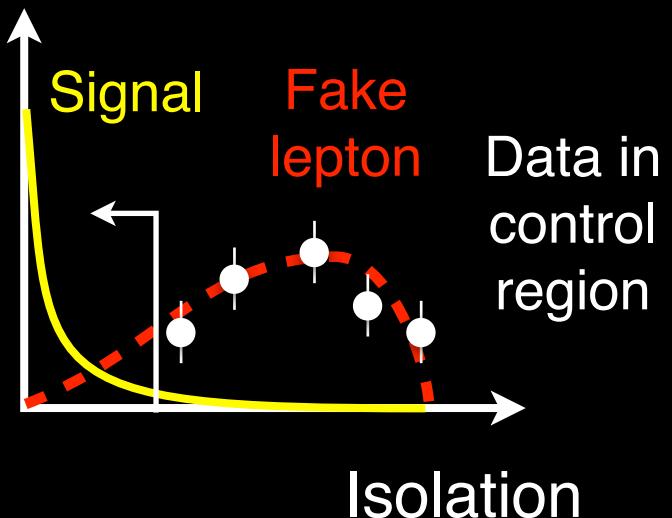
Lepton isolation to discriminate  
signal from fake leptons



# Lepton isolation example

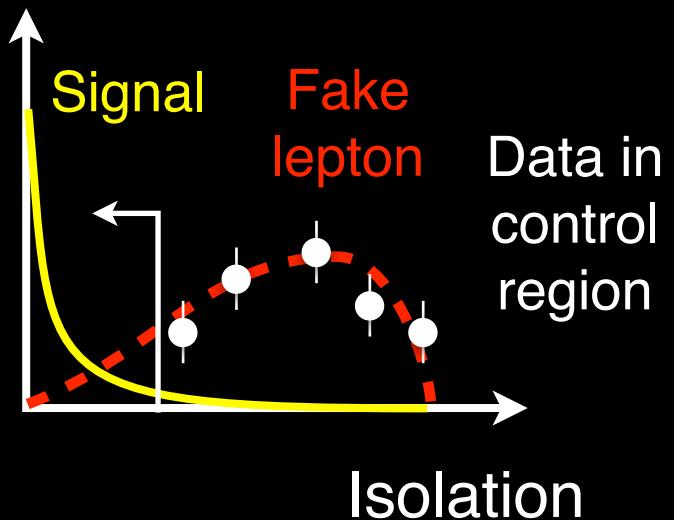
Lepton isolation to discriminate signal from fake leptons

If I can reliably measure two things:



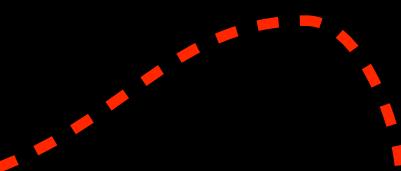
# Lepton isolation example

Lepton isolation to discriminate signal from fake leptons



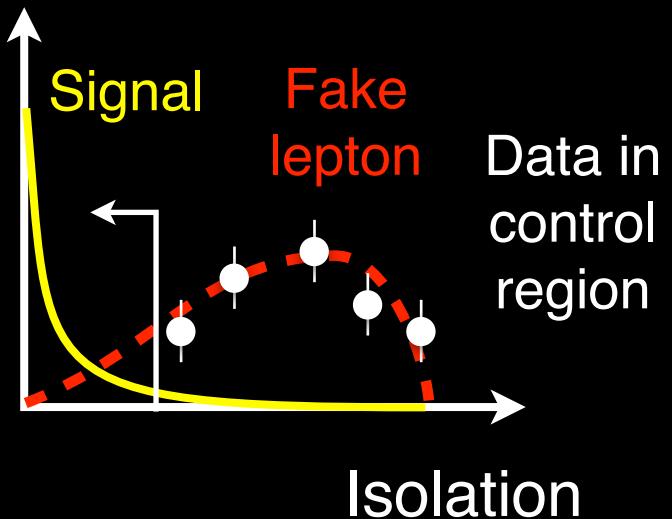
If I can reliably measure two things:

① “Shape”



# Lepton isolation example

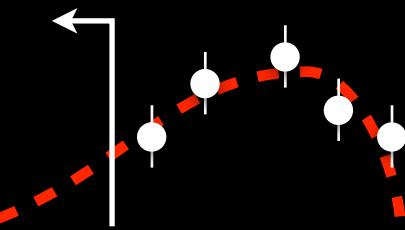
Lepton isolation to discriminate signal from fake leptons



If I can reliably measure two things:

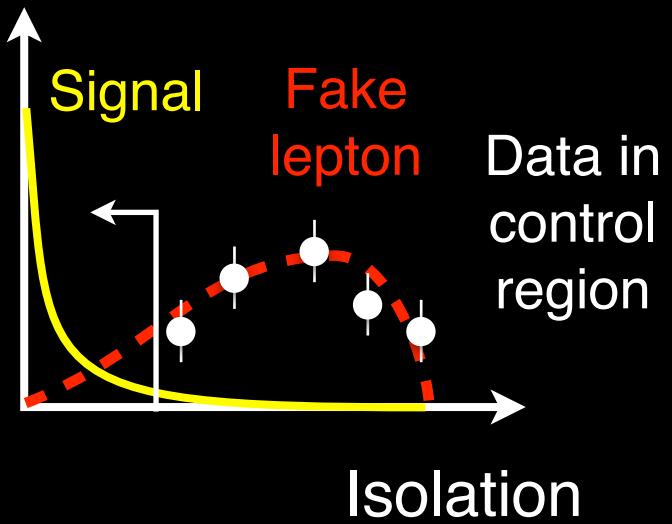
① “Shape”

② Data events



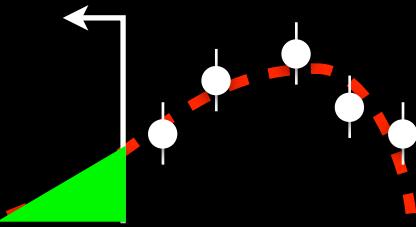
# Lepton isolation example

Lepton isolation to discriminate signal from fake leptons



If I can reliably measure two things:

① “Shape”

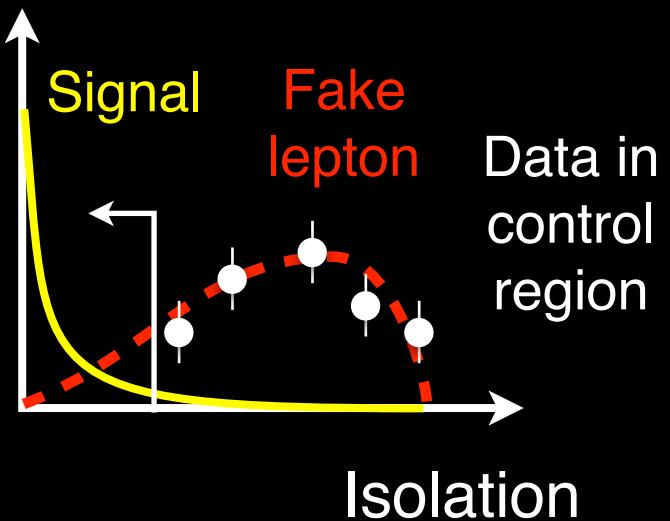


② Data events

③ Estimate residual amount of backgrounds via extrapolation

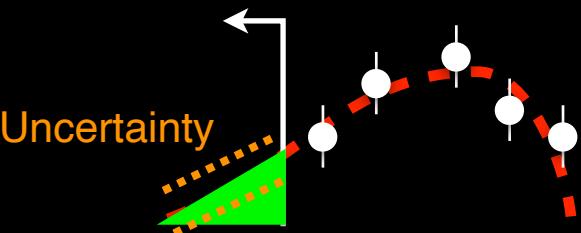
# Lepton isolation example

Lepton isolation to discriminate signal from fake leptons



If I can reliably measure two things:

① “Shape”



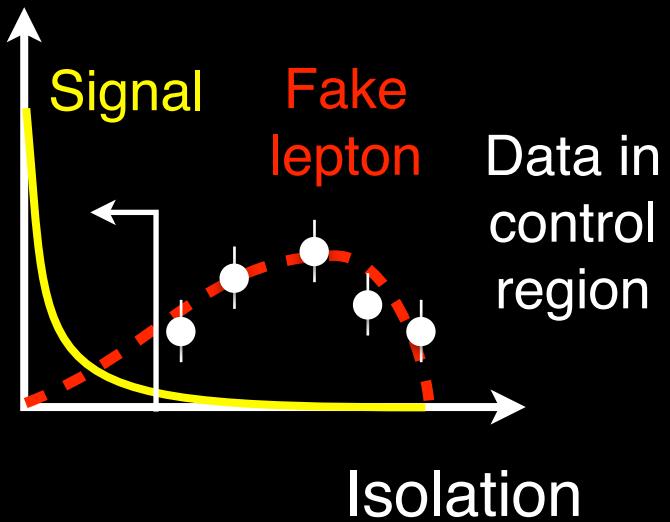
② Data events

③ Estimate residual amount of backgrounds via extrapolation

“Uncertain-ness” in extrapolation becomes your source of systematics  
(e.g. data statistics, theory error, experimental error, etc.)

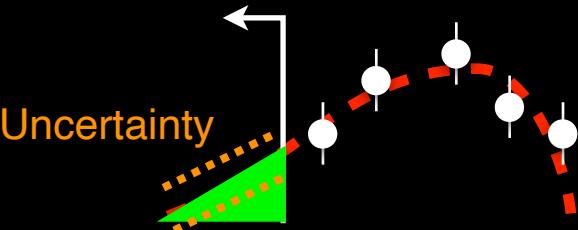
# Lepton isolation example

Lepton isolation to discriminate signal from fake leptons



If I can reliably measure two things:

① “Shape”



② Data events

③ Estimate residual amount of backgrounds via extrapolation

“Uncertain-ness” in extrapolation becomes your source of systematics  
(e.g. data statistics, theory error, experimental error, etc.)

Reliably extrapolate across the method used to suppress background to estimate the size of residual backgrounds in signal region

# Background estimations in VVV analysis

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Types of backgrounds	Suppressed via	Bkg. estimation
Fake leptons	Isolation	Reliably extrapolate across isolation
Irreducible	Smart flavor choices	Reliably extrapolate across flavor
Backgrounds with $b$ jets	$b$ tagging	Reliably extrapolate across $b$ tagging
Lost leptons	Removing events with 3rd lepton	Reliably extrapolate across N leptons

Reliably extrapolate across the method used to suppress background to estimate the size of residual backgrounds in signal region

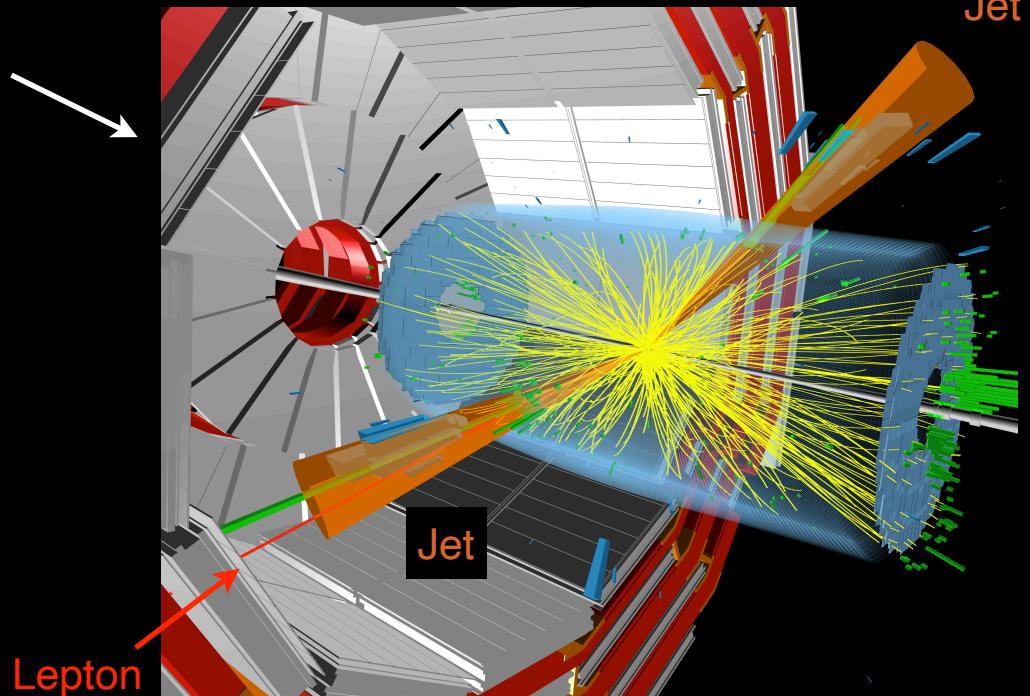
# Fake lepton backgrounds

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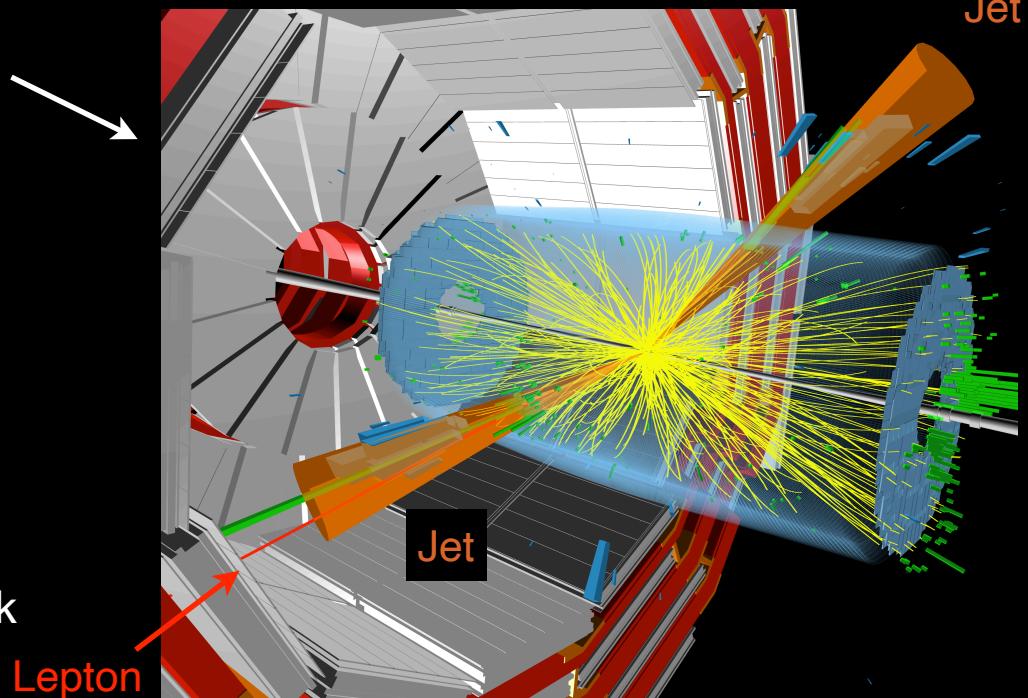
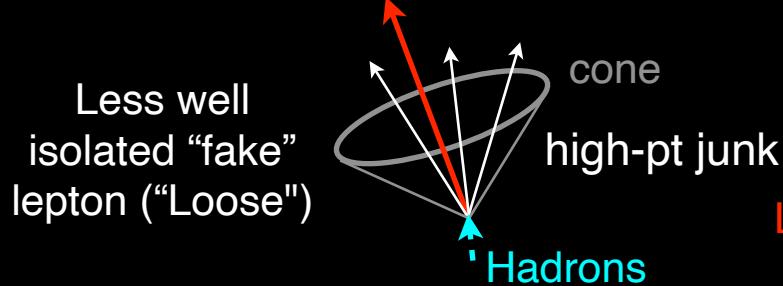
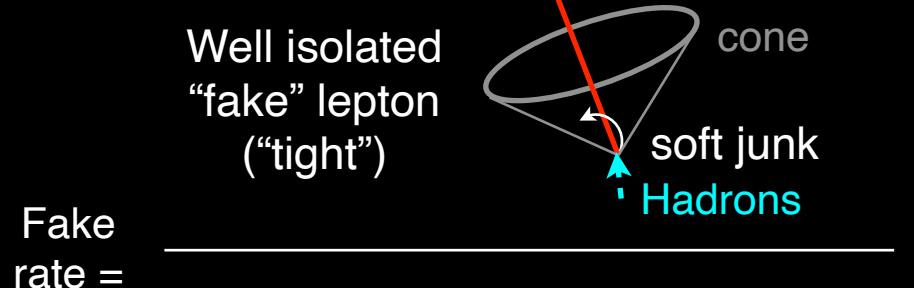
# Fake lepton backgrounds

Pick one lepton events with phase space dominated by QCD (dijet) events



# Fake lepton backgrounds

Pick one lepton events with phase space dominated by QCD (dijet) events



# Fake lepton backgrounds

Pick one lepton events with phase space dominated by QCD (dijet) events

Well isolated  
“fake” lepton  
(“tight”)



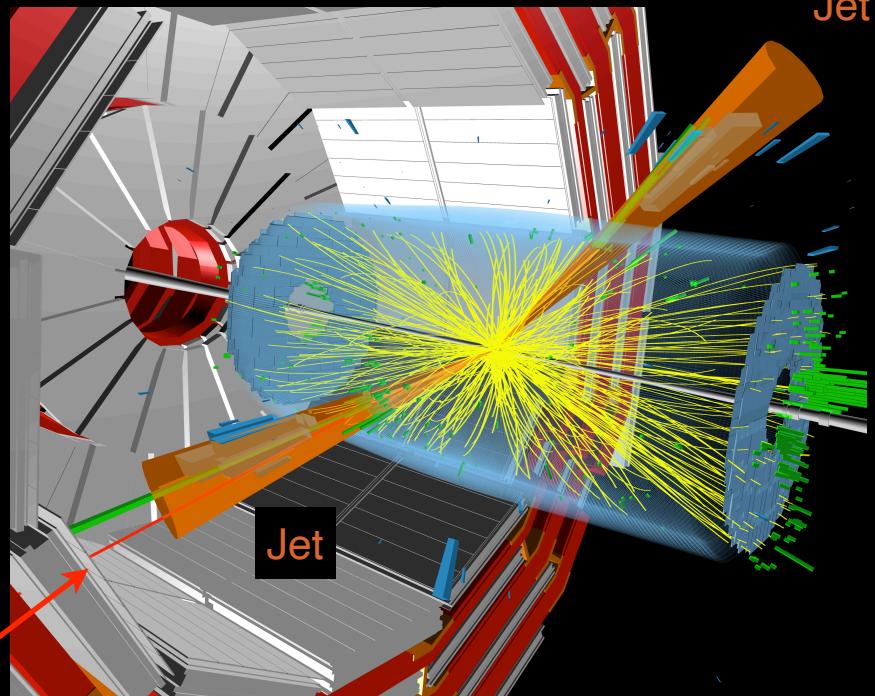
Fake  
rate =

Less well  
isolated “fake”  
lepton (“Loose”)



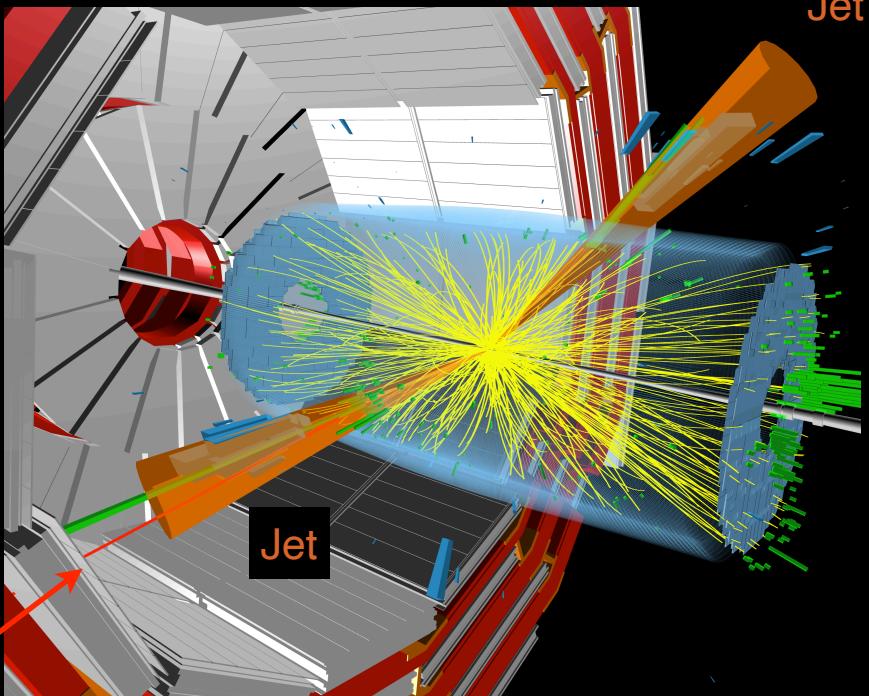
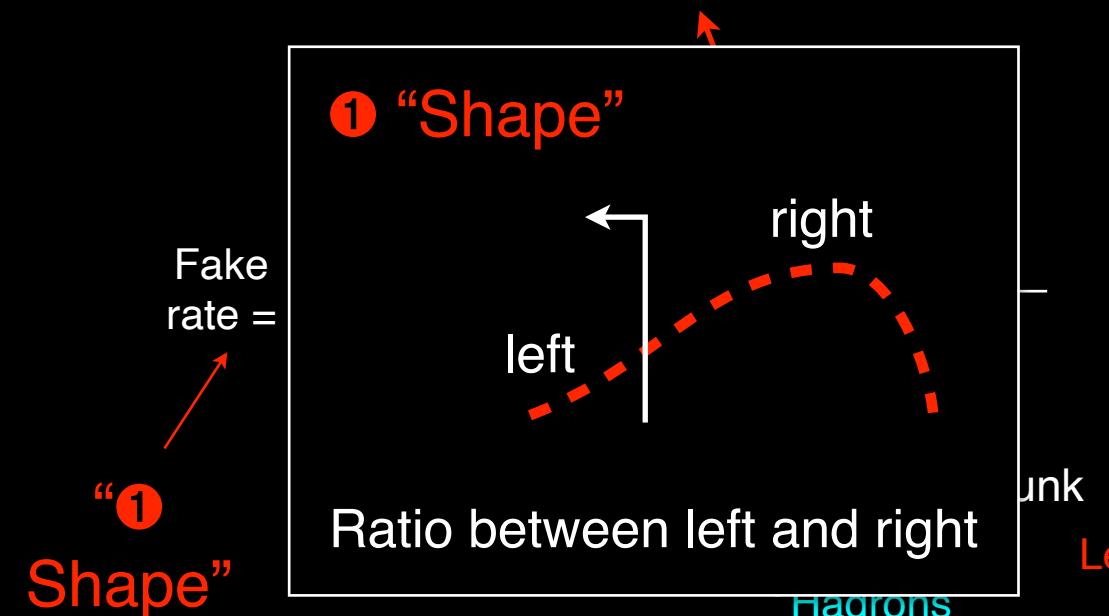
①

Shape



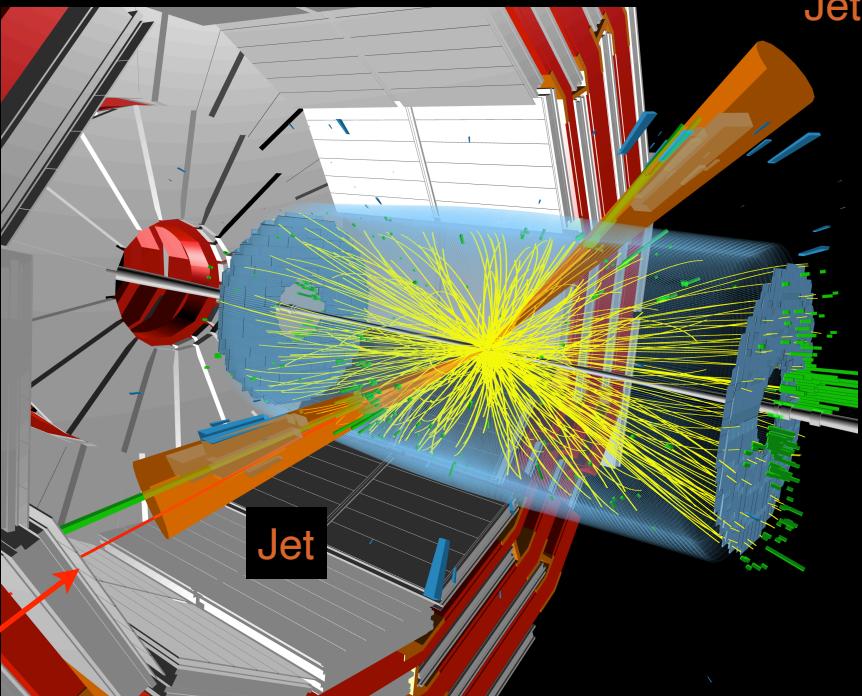
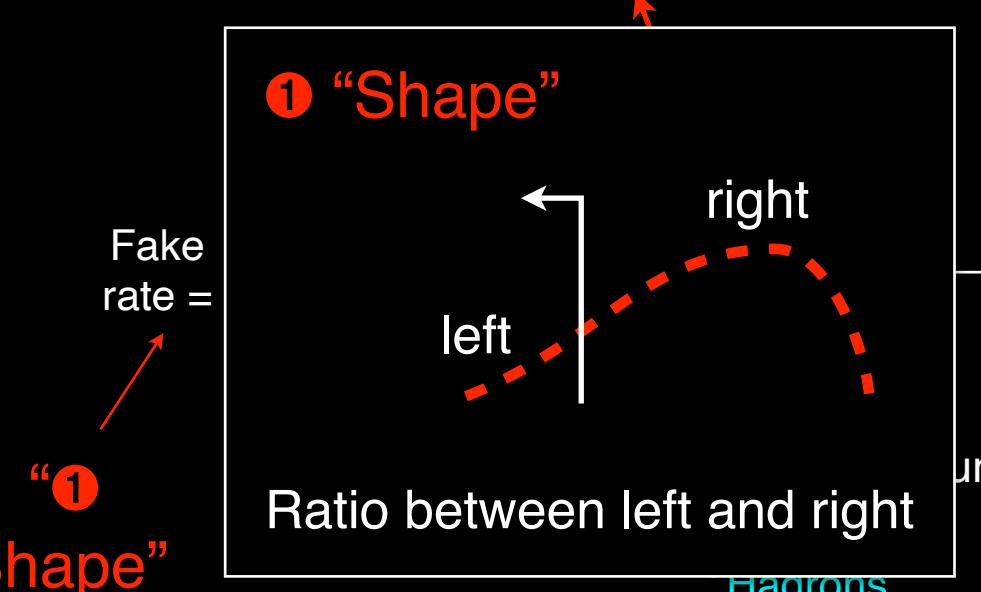
# Fake lepton backgrounds

Pick one lepton events with phase space dominated by QCD (dijet) events



# Fake lepton backgrounds

Pick one lepton events with phase space dominated by QCD (dijet) events



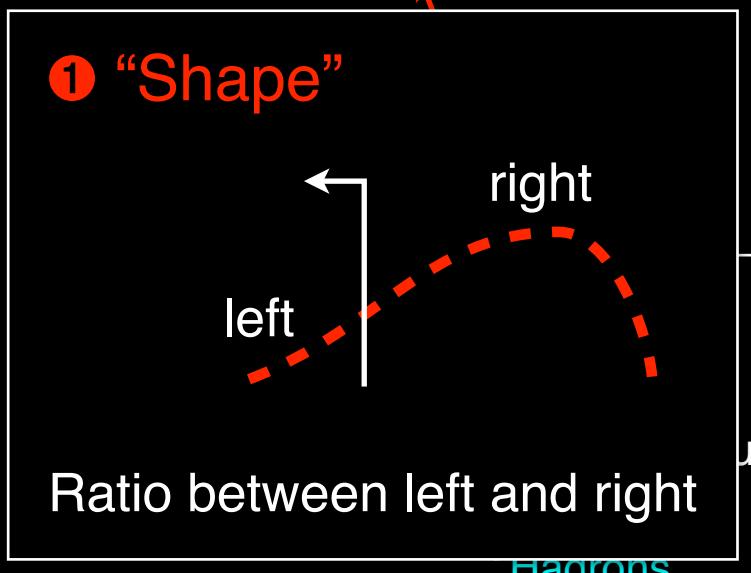
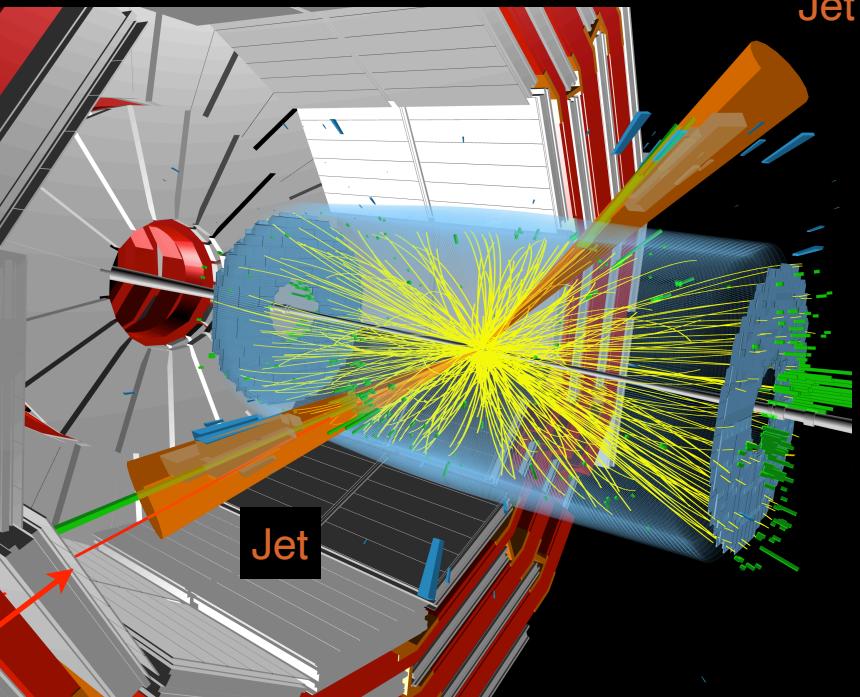
Fake rate is then applied to signal like region with “Loose”-ly identified leptons

“Side band” in isolation

“② Data in CR”

# Fake lepton backgrounds

Pick one lepton events with phase space dominated by QCD (dijet) events



Fake rate is then applied to signal like region with “Loose”-ly identified leptons

Underlying effects ( $P_T$  of quarks) that govern fake rate are not measurable  
⇒ Source of systematics (~30%)

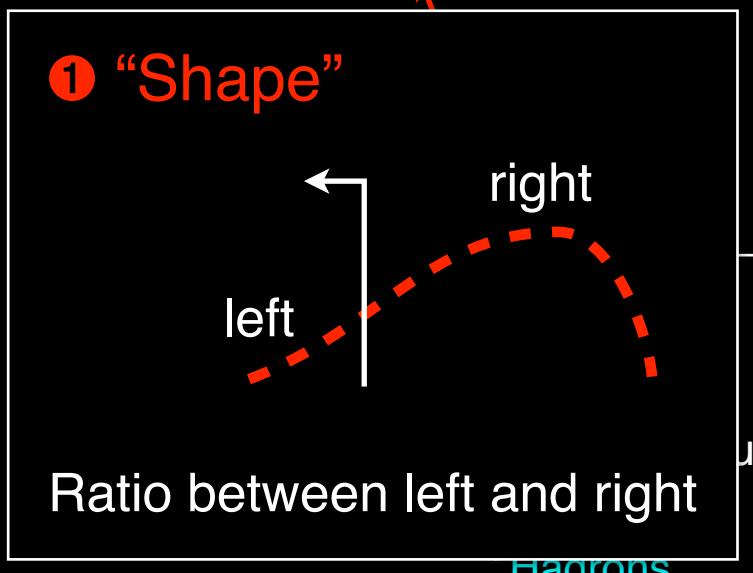
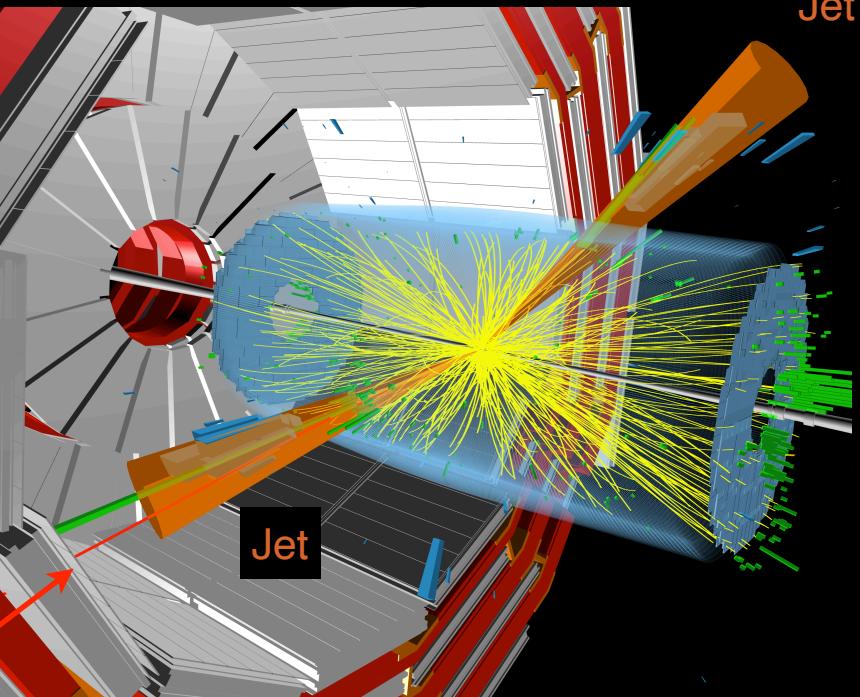
"Side band" in isolation

↑

“② Data in CR”

# Fake lepton backgrounds

Pick one lepton events with phase space dominated by QCD (dijet) events



Fake rate is then applied to signal like region with “Loose”-ly identified leptons

Underlying effects ( $P_T$  of quarks) that govern fake rate are not measurable  
⇒ Source of systematics (~30%)

"Side band" in isolation  
↑  
“② Data in CR”

Estimate fake lepton by measuring fake rate from QCD events

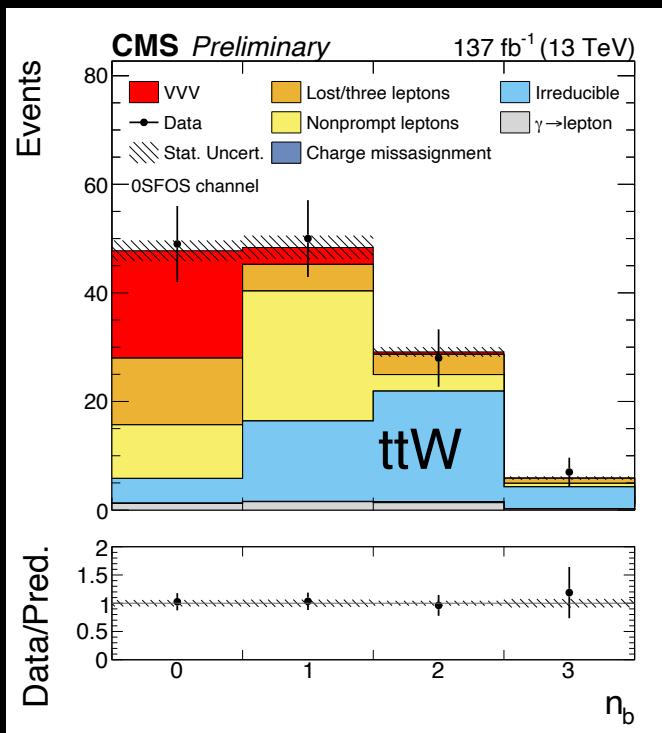
# Backgrounds with $b$ jets / irreducible

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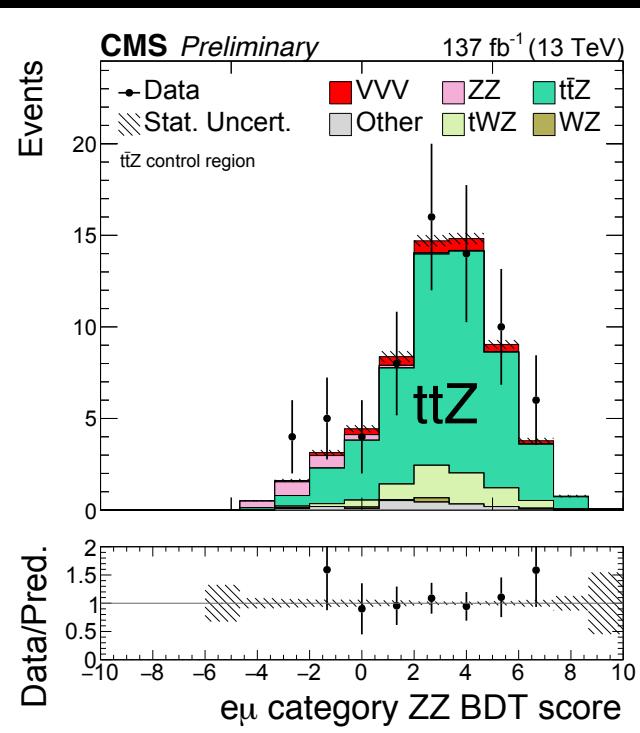


Devise control regions and extrapolate to signal region

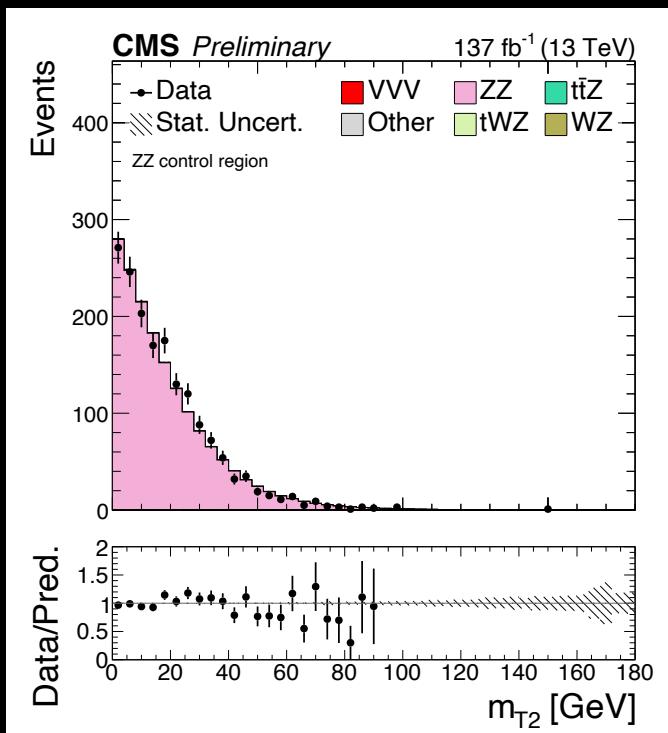
$N_b$  in 3 lepton



4 lepton BDT score  
 $Z \rightarrow ll + e\mu + b$  jets



4 lepton  $m_{T2}$   
 $Z \rightarrow ll + ee/\mu\mu$



Extrapolate across  $N_b$  tag ( $\sim 10\%$ )

Extrapolate across flavor  
(uncertainty  $\sim 5\%$ )

Extrapolate from control region to estimate backgrounds

# 4 steps to VVV observation



1. Organize analyses by leptons (likely) from W / Z
  - N leptons in the event
  - Flavor of the leptons
2. Additional background suppression through smart choices
3. Reliably estimate the size of residual backgrounds
4. Observe VVV!

Smart humans and  
smart machines  
(Both cut / BDT)



# Putting it all together

	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \rightarrow l^\pm \nu$	$W \rightarrow l\nu$	$W \rightarrow l\nu$	$W \rightarrow l\nu$	$Z \rightarrow ll$
	$W^\pm \rightarrow l^\pm \nu$	$W \rightarrow l\nu$	$W \rightarrow l\nu$	$Z \rightarrow ll$	$Z \rightarrow ll$
	$W^+ \rightarrow qq$	$W \rightarrow l\nu$	$Z \rightarrow ll$	$Z \rightarrow ll$	$Z \rightarrow ll$
Split Flavor	3	3	2	1	1
Channel specific splits	mjj-in mjj-out 1J	-	Split in kinematics or BDT	-	-
Total	9 bins	3 bins	7 bins	1 bin	1 bin

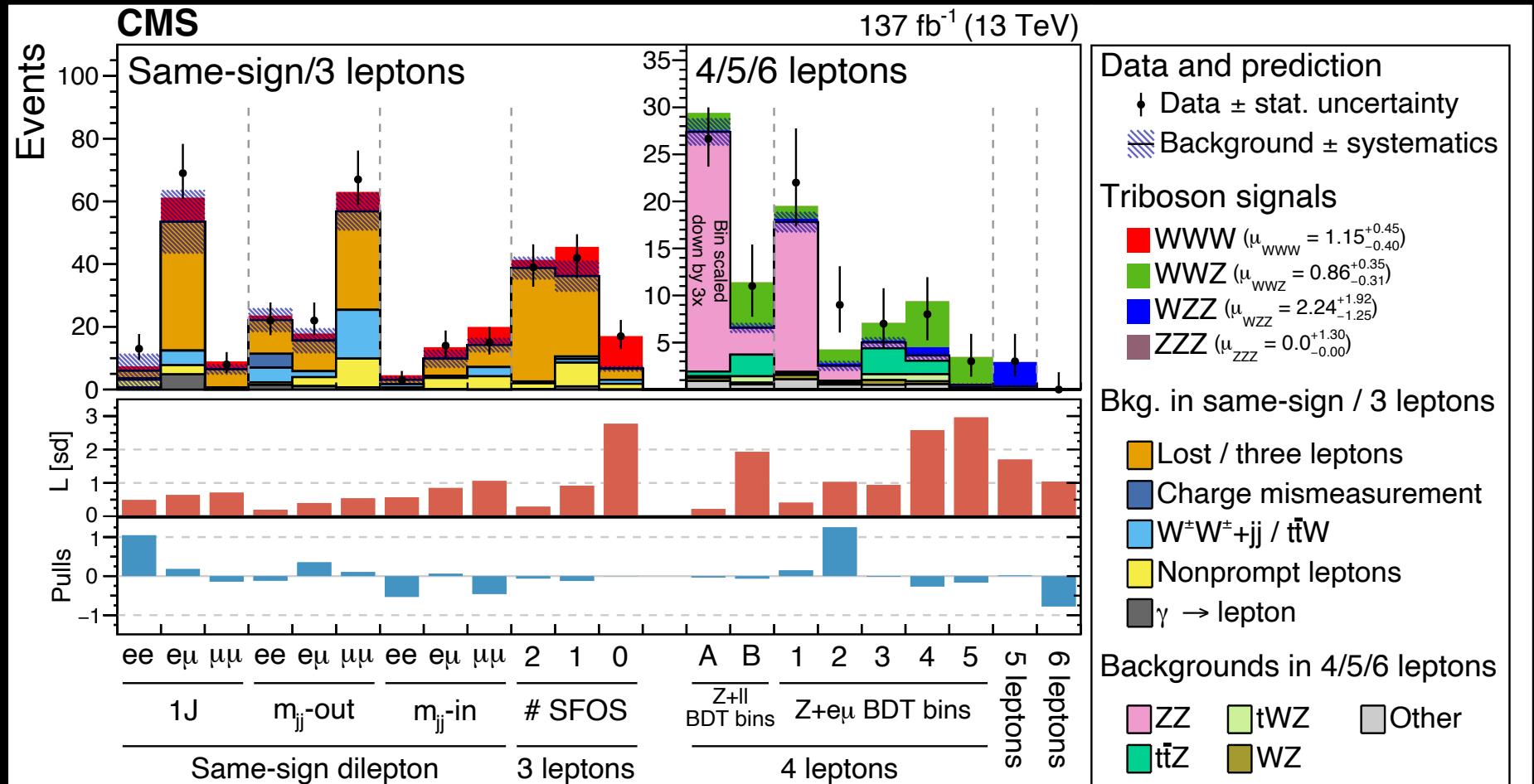
Total of 21 bins

# Results (BDT-based analysis)

Chang  
UCSD



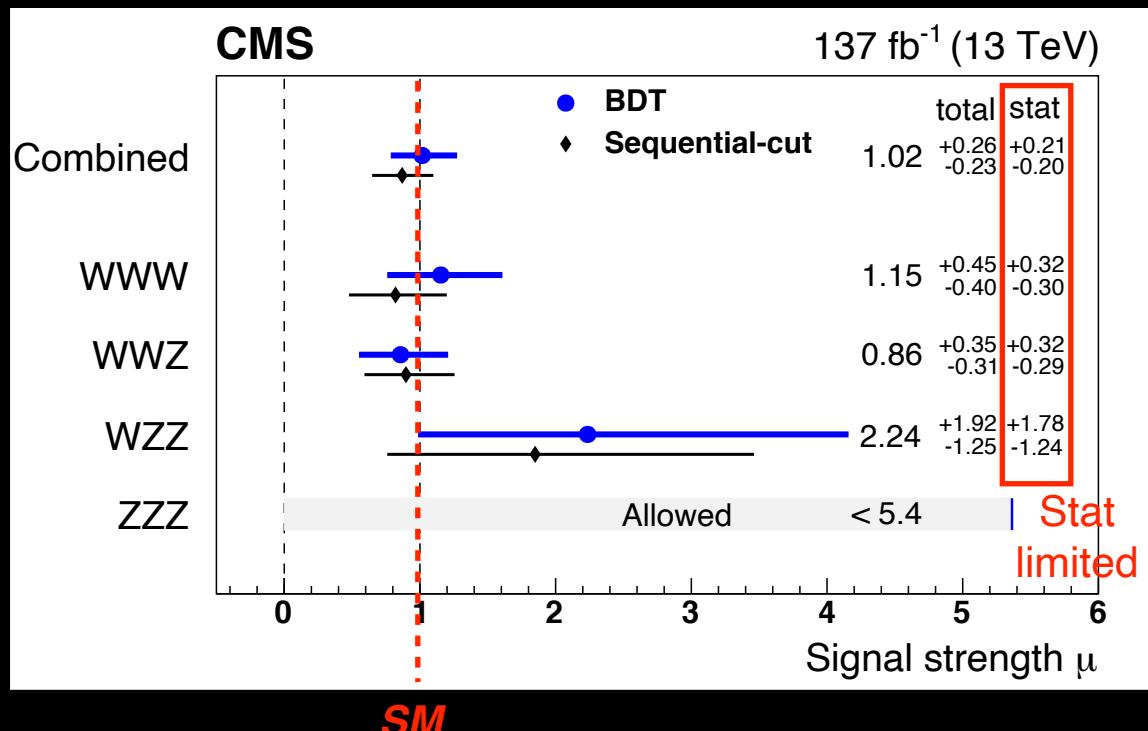
Measured cross section  
Theoretical cross section



BDT-based analysis is more sensitive so this is our main result

# Results

VVV mode	Significance [ $\sigma$ ]
WWW	3.3 (3.1)
WWZ	3.4 (4.1)
WZZ	1.7 (0.7)
ZZZ	0 (0.9)
Combined	5.7 (5.9)

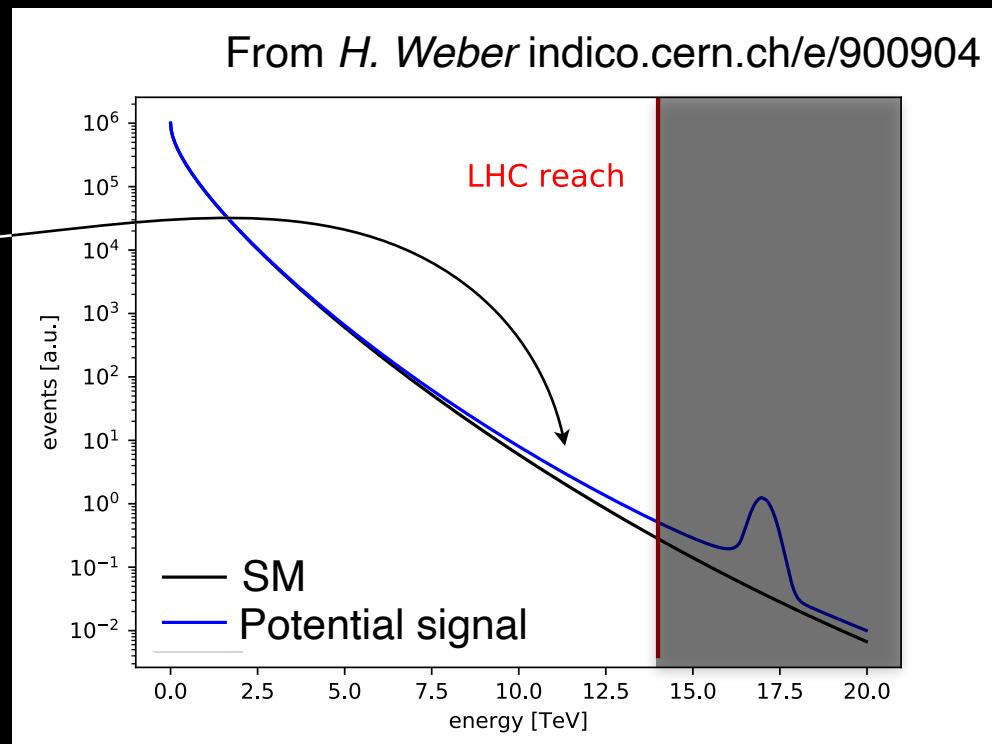
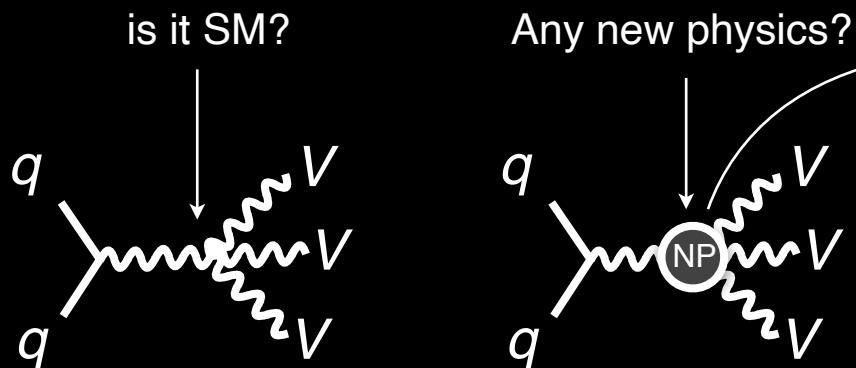


- We have observed production of three massive gauge boson for the first time!
- We also found evidences separately for the WWW and WWZ production.
- The cross sections are compatible with the standard model expectation.

First observation of VVV and evidences for WWW and WWZ productions

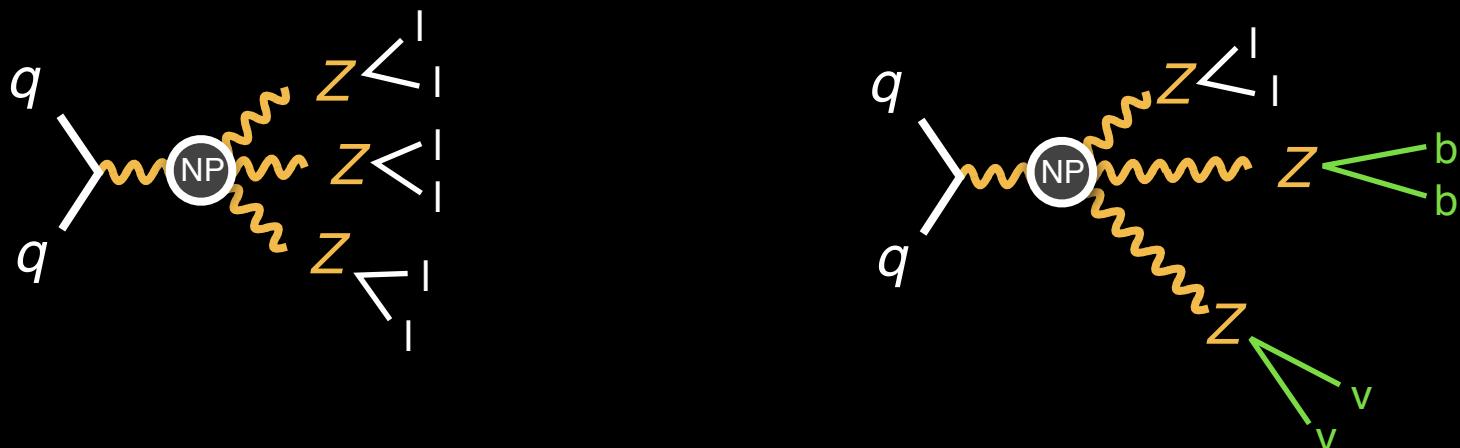
# Using VVV as a tool

Now that we have established VVV production we can use it to test SM and also search new physics (cf. Four fermion interaction with Fermi constant)



Establishment of VVV production opens up a new physics program

# Fully leptonic v. Semi leptonic channel



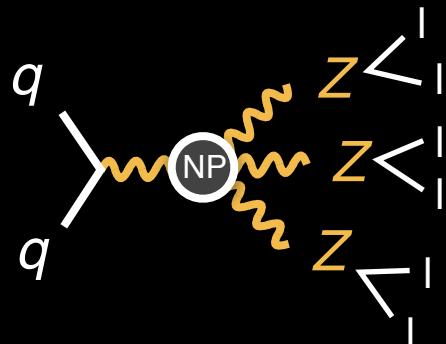
If BSM exists, effects are same

- Physics of  $V \rightarrow ff$  is well understood
- We have now established  $pp \rightarrow VVV$  production in “fully” leptonic decay
- Therefore, there ought to be  $pp \rightarrow VVV \rightarrow$  semi-leptonic
  - ⇒ If new physics alters  $pp \rightarrow VVV$ , it will alter fully / semi leptonic the same

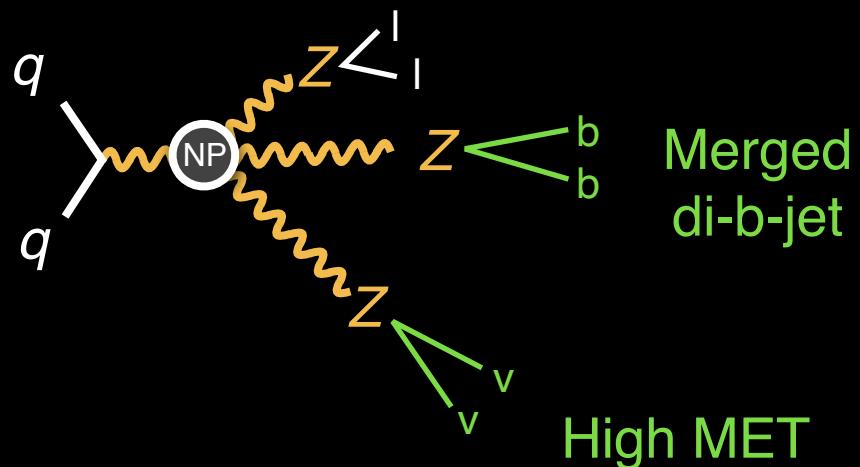
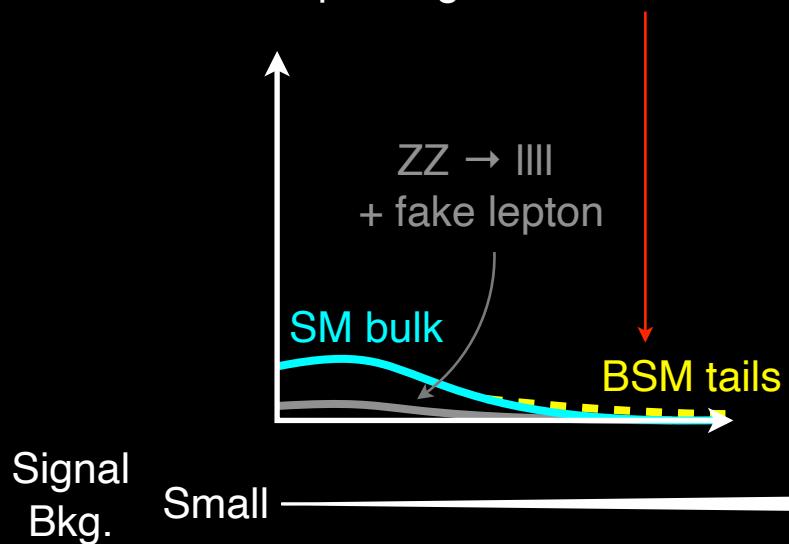
$VVV \rightarrow$  semi-leptonic ought to have same physics as  $VVV \rightarrow$  fully leptonic

# Fully leptonic v. Semi leptonic channel

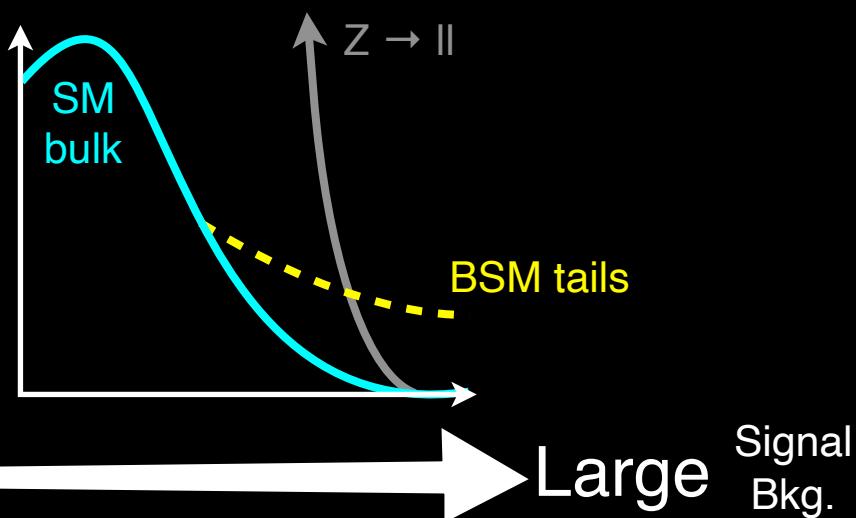
Chang  
UCSD



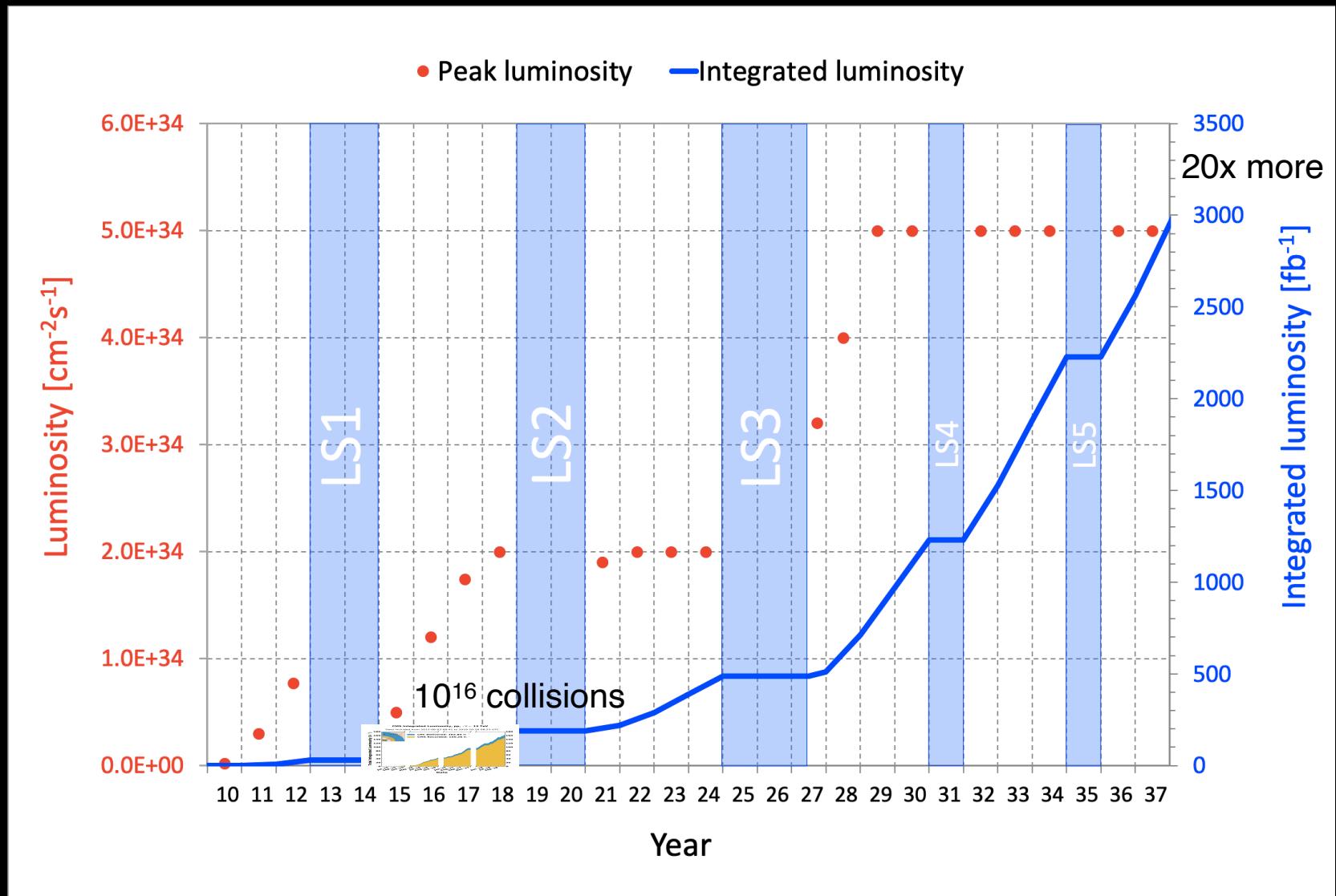
Clean channel for discovery but probing tail is **difficult**



Bkg is larger but distinct high  $P_T$  feature can **discriminate** bkg.



We can probe  $VVV \rightarrow$  semi-leptonic for new physics



We've only seen ~5% of the total data LHC will provide in its lifetime

# More multi-massive-X processes for future

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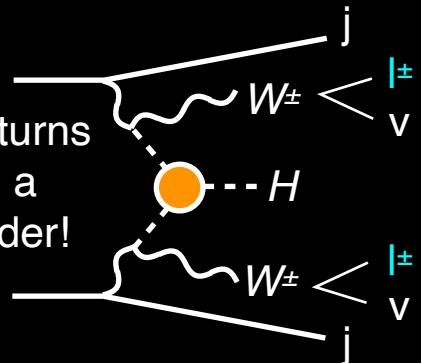


# listing a few multi-massive-X processes with **same-sign**

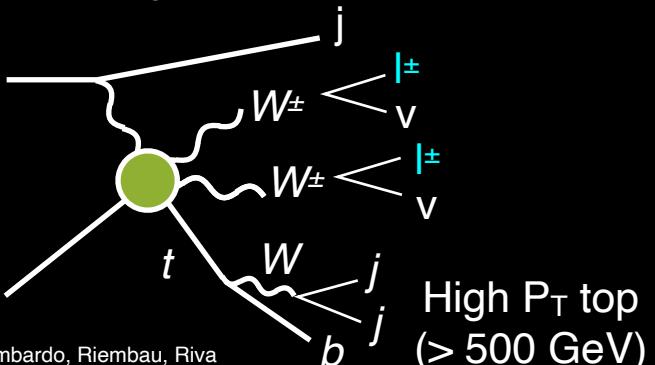
$pp \rightarrow W^\pm W^\pm H$

## *Same-sign is special*

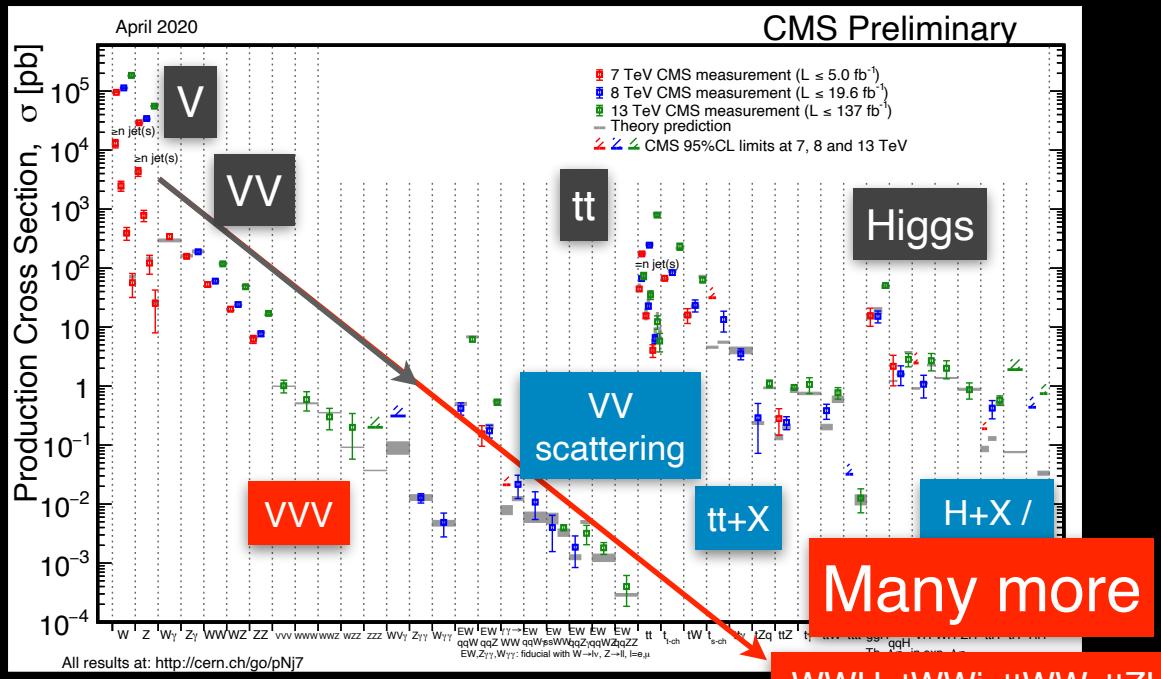
## Same-sign turns LHC into a Higgs collider!



$pp \rightarrow tW^\pm W^\pm j$



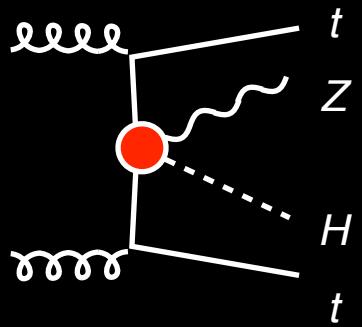
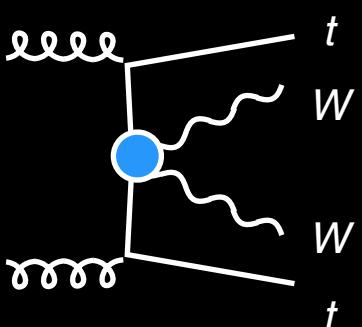
arXiv:1812.09299 Henning, Lombardo, Riembau, Riva  
arXiv:1511.03674 Dror, Farina, Salvioni, Serra  
arXiv:1904.05637 Maltoni, Mantani, Mimasu



# Many more

$pp \rightarrow ttWW$

pp → ttZH



There are many more multi-massive-X production to be explored at LHC



- First observation of  $VVV$  production was made by CMS collaboration
- Also found evidences for  $WWW$  and  $WWZ$
- first hints for  $WZZ$  production and no hints for  $ZZZ$  yet
- The measured cross section is compatible with SM
- This establishes  $VVV$  process and opens a unique opportunity to test SM
- New physics can be also searched
- LHC will continue to probe electroweak interactions in various  $VVV$  channel

CERN Courier

**CERN COURIER** Reporting on international high-energy physics

The first observation of the combined production of three massive vector bosons was reported by CMS

The first observation of the combined production of three massive vector bosons ( $V$ ,  $W$  or  $Z$ ) was reported by the CMS experiment. In the nearly 40 years that have followed, the first observation of the combined production of three massive vector bosons ( $V$ ,  $W$  or  $Z$ ) was reported by the CMS experiment. In the nearly 40 years that have followed, the first observation of the combined production of three massive vector bosons ( $V$ ,  $W$  or  $Z$ ) was reported by the CMS experiment. In the nearly 40 years that have followed,

This paper is 1000th paper submitted by CMS!



*"CMS is the first experiment in the history of high energy physics to reach this outstanding total of papers and with only a fraction of the data that the LHC anticipates to produce in its lifetime. The LHC accelerator at CERN will operate for another two decades."*



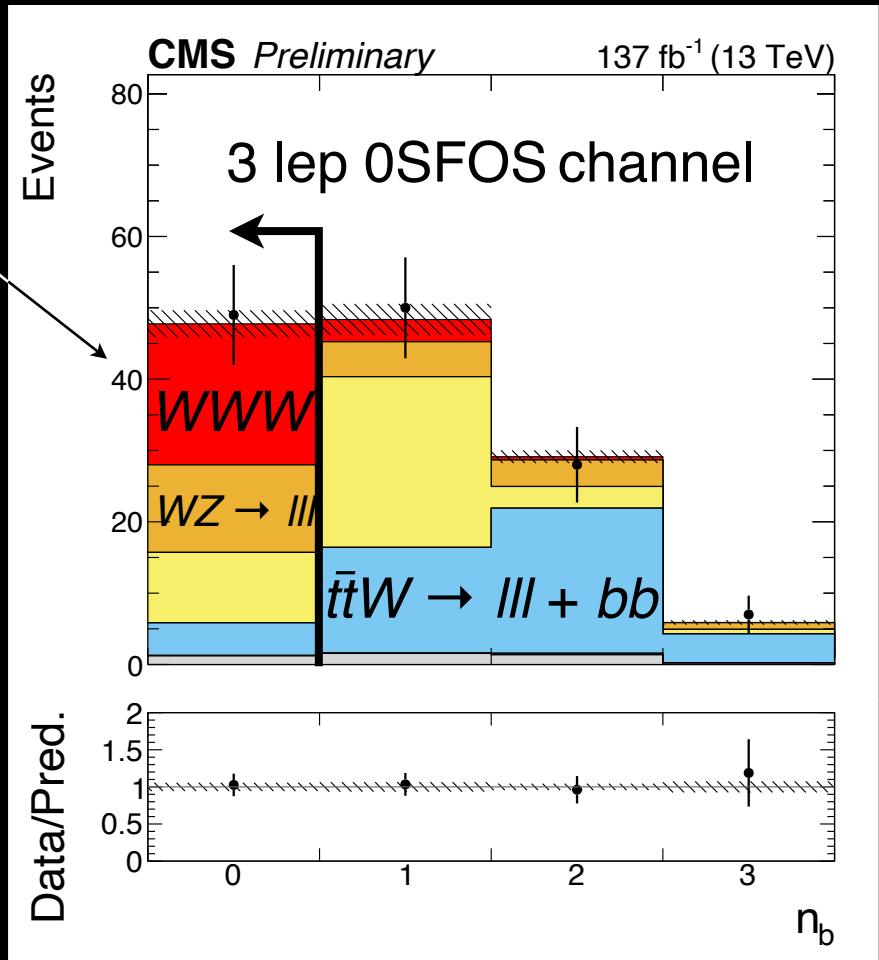
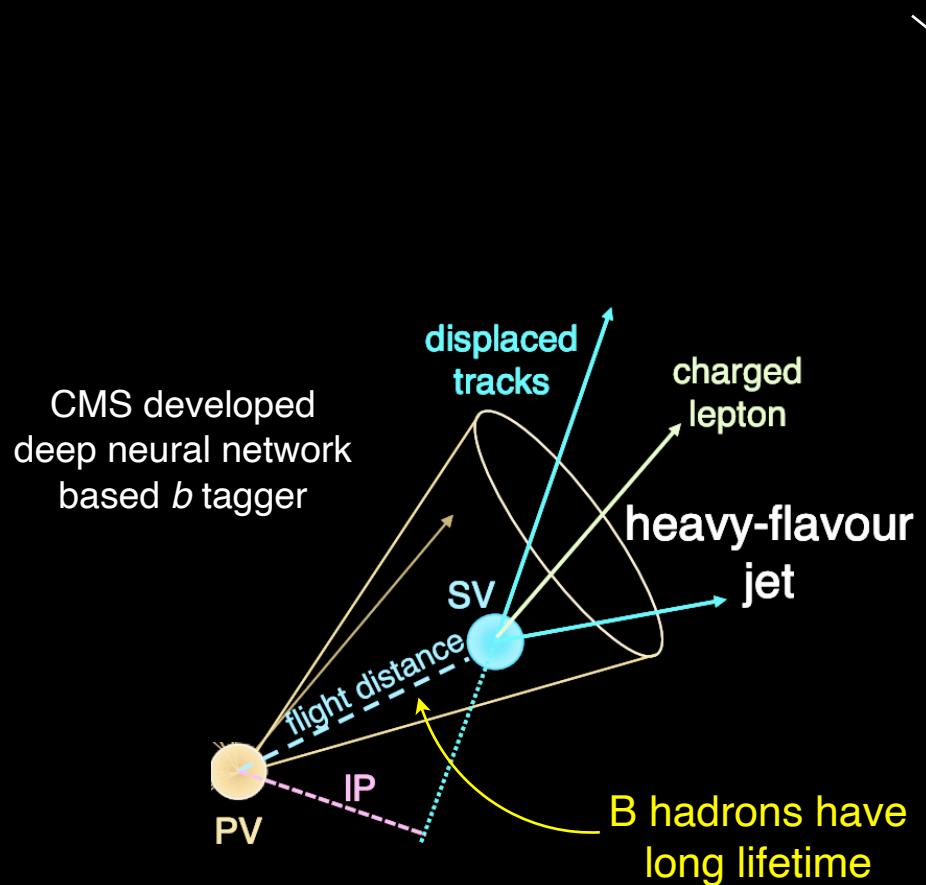
# Backup

# Rejecting events with $b$ jets

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UCSD



EW processes generally do not come  
with  $b$  jets  $\Rightarrow$  Require # of  $b = 0$



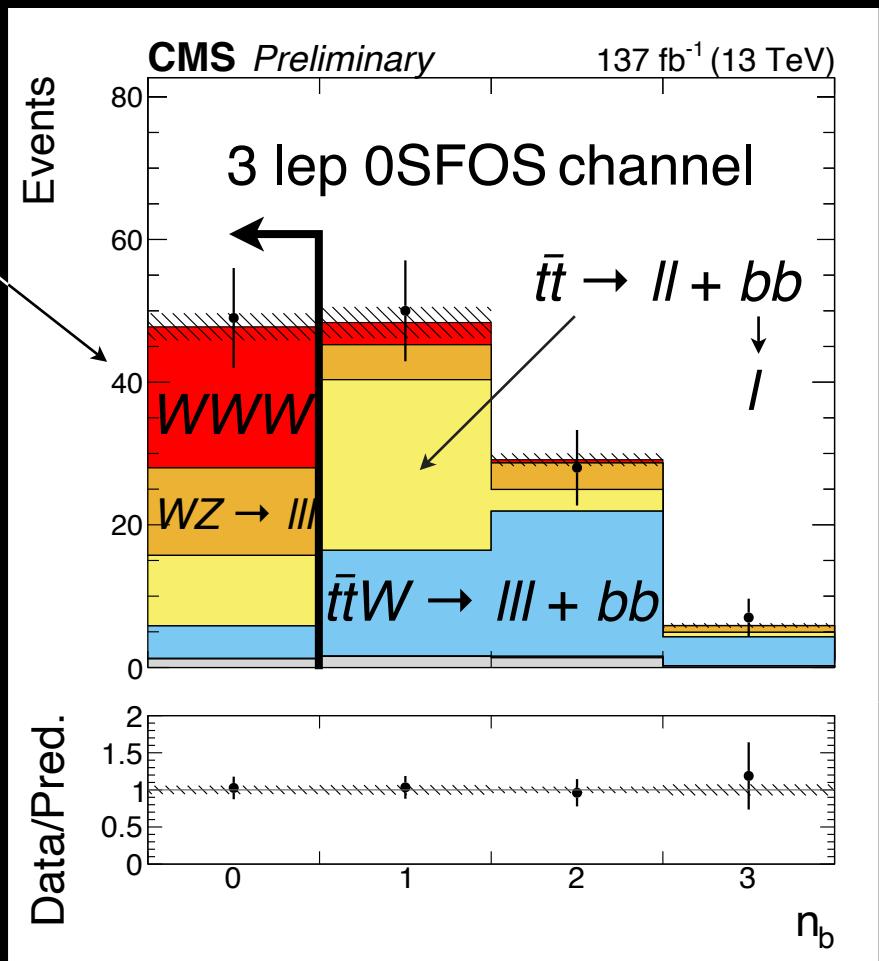
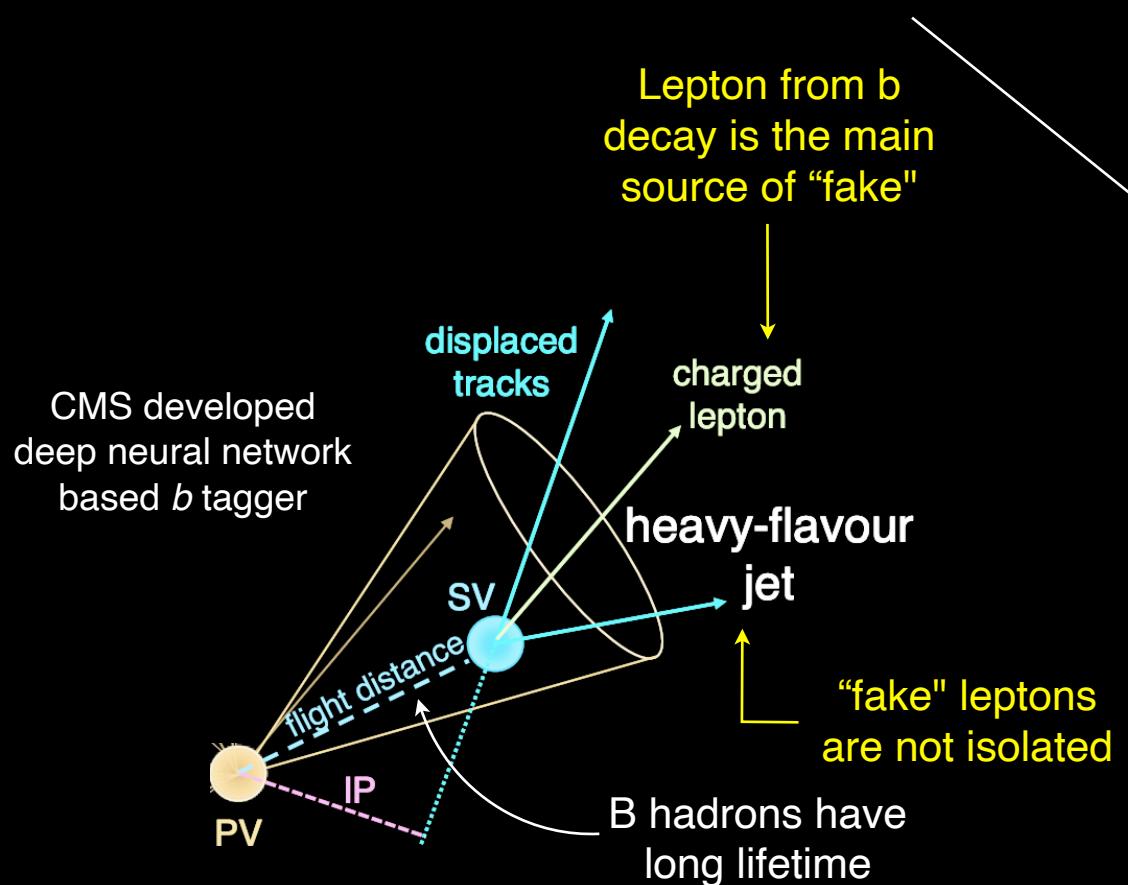
Signals do not have  $b$  jets

# Added benefit of rejecting events with b

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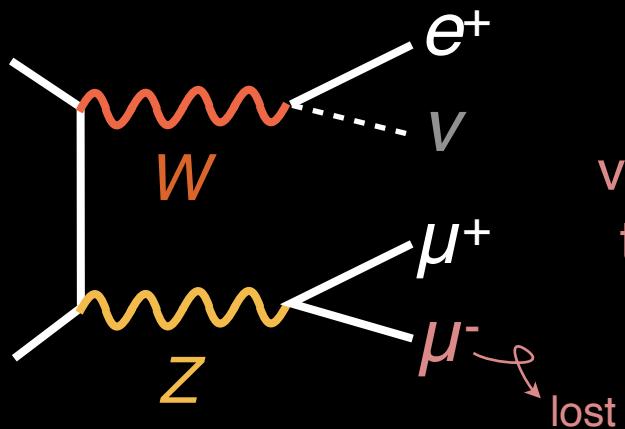


EW processes generally do not come  
with b jets  $\Rightarrow$  Require # of b = 0



Signals do not have  $b$  jets

# WZ background in same-sign channel



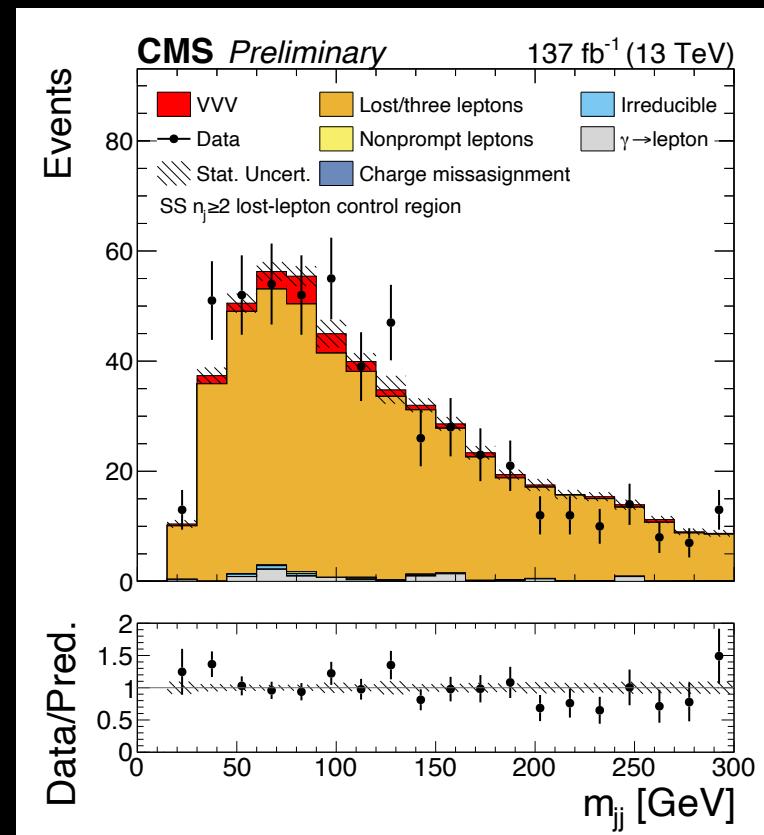
enters signal region  
via lost lepton  $\Rightarrow$  Need  
to understand lepton  
finding efficiency

Lepton finding efficiency is well modeled by MC  
(factors:  $P_T$ ,  $\eta$ , lepton ID)

Construct a control region with 3 leptons and  
extrapolate across 3 lepton  $\rightarrow$  2 leptons

Experimental systematics assigned

Control region data statistics dominates  
uncertainty (20%)



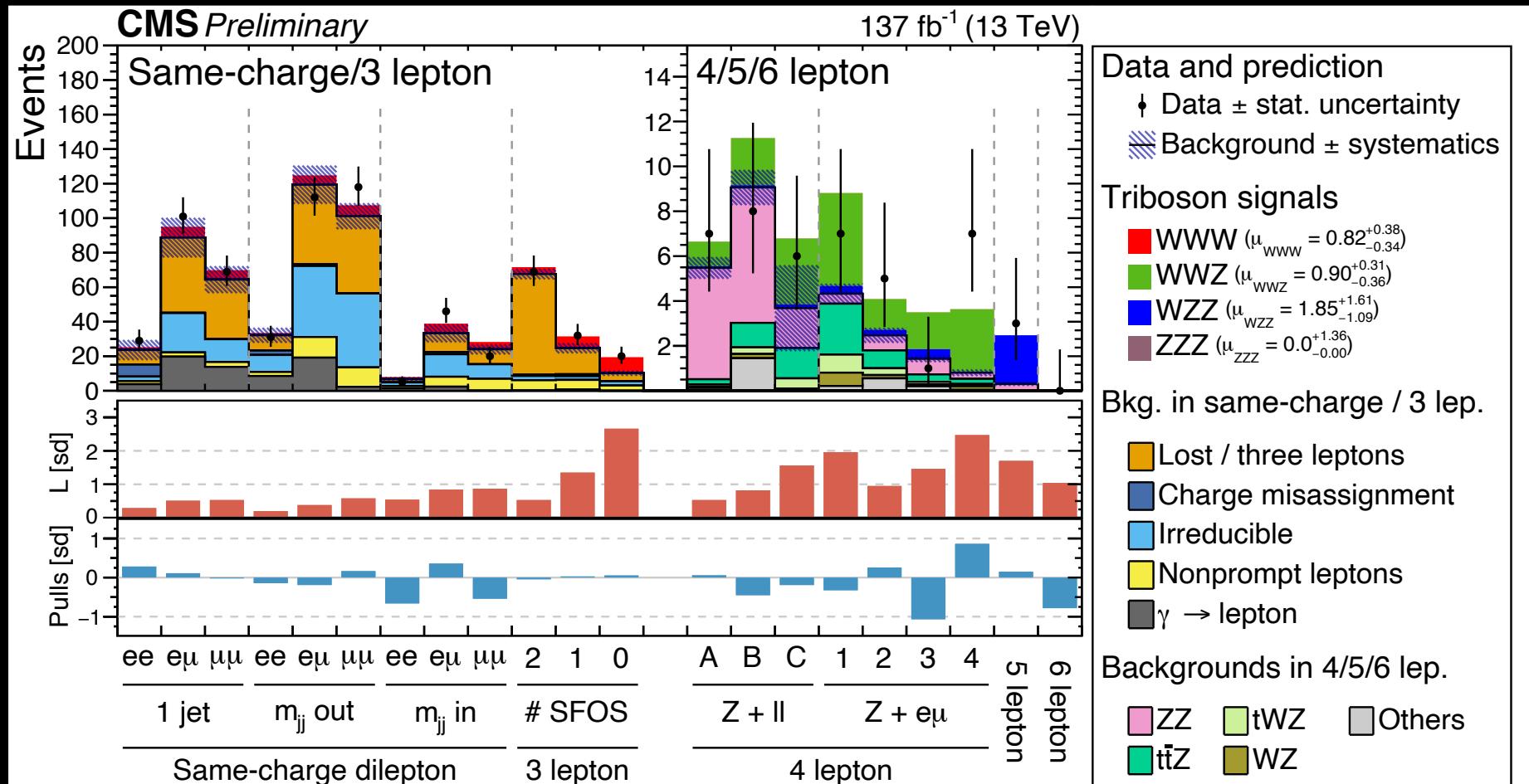
Estimate lost lepton background by extrapolating across # of leptons

# Results (Cut-based analysis)

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Measured cross section  
 $\frac{\text{Signal strength } \mu =}{\text{Theoretical cross section}}$



9 bins

3 bins

7 bins

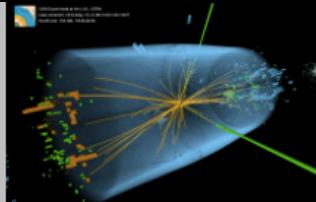
1 1

More sensitive bins are generally to the right

Cut-based analysis is also reported for cross check and completeness  
 (also easier to understand by theorists if re-interpreted)



## Compact Muon Solenoid LHC, CERN



Visit us: [CMS Public Website](#), [CMS Physics](#) ; Contact us: [CMS Publications Committee](#)

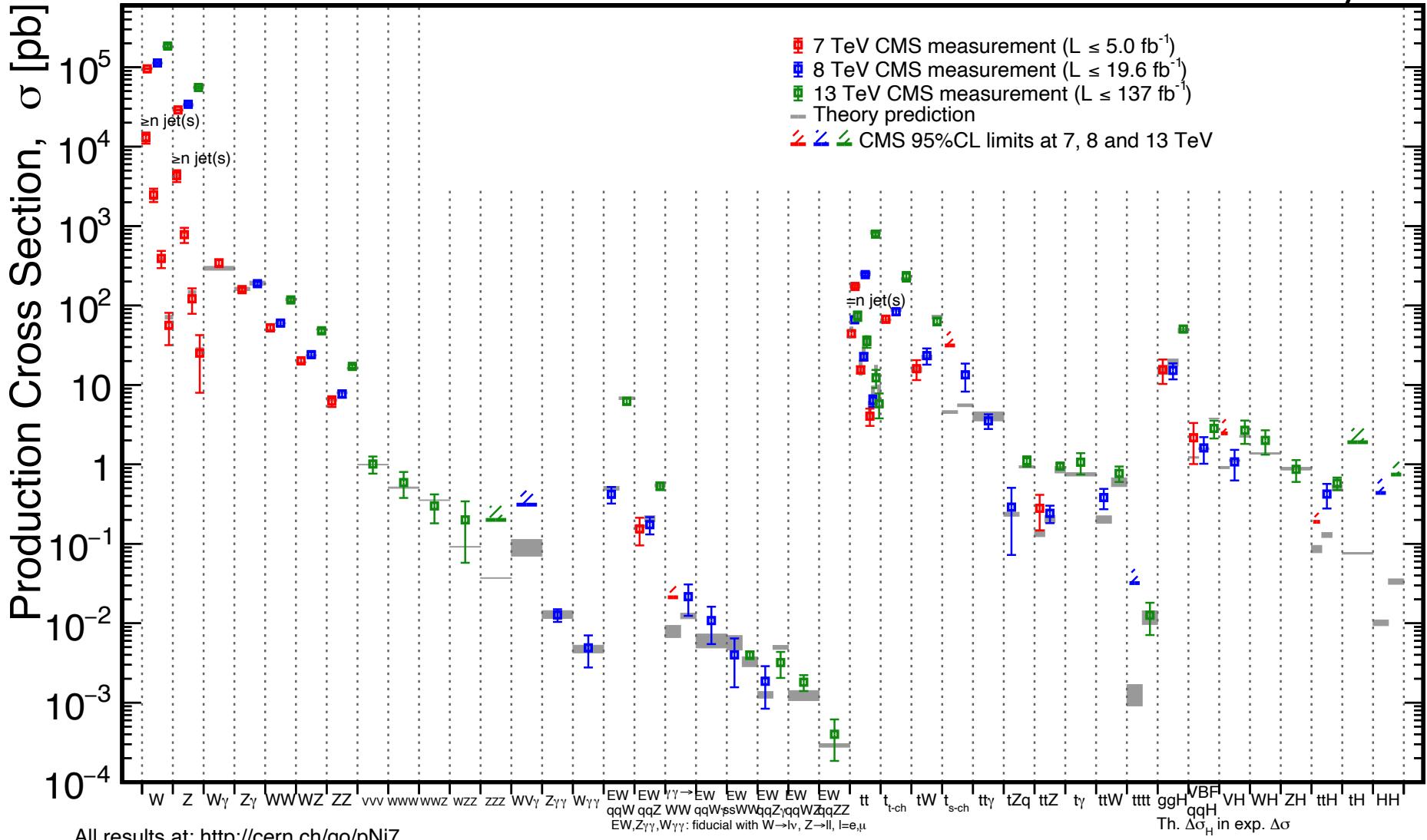
## CMS Publications

1000	<a href="#">SMP-19-014</a>	Observation of the production of three massive gauge bosons at $\sqrt{s} = 13$ TeV	Submitted to PRL	19 June 2020
999	<a href="#">HIN-19-001</a>	Evidence for top quark production in nucleus-nucleus collisions	Submitted to NP	19 June 2020
998	<a href="#">TRG-17-001</a>	Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JINST	18 June 2020



April 2020

CMS Preliminary





Quantities	WWW	WWZ	WZZ	ZZZ
$\sigma_{pp \rightarrow VVV \text{ non-VH}} (\text{fb})$	216.0	165.1	55.7	14.0
$\sigma_{VH \rightarrow VVV} (\text{fb})$	293.4	188.9	36.0	23.1
$\sigma_{\text{total}} (\text{fb})$	509.4	354.0	91.6	37.1
$\mathcal{B}_{VVV \rightarrow SS} (\%)$	7.16	-	-	-
$\mathcal{B}_{VVV \rightarrow 3\ell} (\%)$	3.46	4.82	6.37	-
$\mathcal{B}_{VVV \rightarrow 4\ell} (\%)$	-	1.16	0.81	3.22
$\mathcal{B}_{VVV \rightarrow 5\ell} (\%)$	-	-	0.39	-
$\mathcal{B}_{VVV \rightarrow 6\ell} (\%)$	-	-	-	0.13
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow SS} (\text{fb})$	36.4	-	-	-
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow 3\ell} (\text{fb})$	17.6	17.1	5.83	-
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow 4\ell} (\text{fb})$	-	4.12	0.74	1.19
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow 5\ell} (\text{fb})$	-	-	0.36	-
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow 6\ell} (\text{fb})$	-	-	-	0.05
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow SS} \times 137 \text{ fb}^{-1} (N_{\text{evts}})$	4987	-	-	-
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow 3\ell} \times 137 \text{ fb}^{-1} (N_{\text{evts}})$	2411	2343	799	-
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow 4\ell} \times 137 \text{ fb}^{-1} (N_{\text{evts}})$	-	564	101	163
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow 5\ell} \times 137 \text{ fb}^{-1} (N_{\text{evts}})$	-	-	49.3	-
$\sigma_{\text{total}} \times \mathcal{B}_{VVV \rightarrow 6\ell} \times 137 \text{ fb}^{-1} (N_{\text{evts}})$	-	-	-	6.85

# SS / 3L preselection

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Features	SS + $\geq 2j$	SS + 1j	Selections
Triggers	Select events passing dilepton triggers		
Number of leptons	Select events with 2 (3) leptons passing SS-ID ( $3\ell$ -ID) for SS ( $3\ell$ ) final states		
Number of leptons	Select events with 2 (3) leptons passing veto-ID for SS ( $3\ell$ ) final states		
Isolated tracks	No additional isolated tracks		—
b-tagging		no b-tagged jets and soft b-tag objects	
Jets	$\geq 2$ jets	1 jet	$\leq 1$ jet
$m_{JJ}$ (leading jets)		<500 GeV	—
$\Delta\eta_{JJ}$ (leading jets)		<2.5	—
$m_{\ell\ell}$		>20 GeV	—
$m_{\ell\ell}$	$ m_{\ell\ell} - m_Z  > 20$ GeV if $e^\pm e^\pm$		
$m_{\text{SFOS}}$	—	—	$m_{\text{SFOS}} > 20$ GeV
$m_{\text{SFOS}}$	—	—	$ m_{\text{SFOS}} - m_Z  > 20$ GeV
$m_{\ell\ell\ell}$	—	—	$ m_{\ell\ell\ell} - m_Z  > 10$ GeV

# SS selection



Variable	$m_{jj}$ -in and $m_{jj}$ -out	1j
Trigger	Signal triggers, tab. 3.2	
Signal leptons	Exactly 2 tight SS leptons with $p_T > 25 \text{ GeV}$	
Additional leptons	No additional very loose lepton	
Isolated tracks	No additional isolated tracks	
Jets	$\geq 2$ jets	1 jet
b-tagging	no b-tagged jets and soft b-tag objects	
$m_{\ell\ell}$		$> 20 \text{ GeV}$
$m_{\ell\ell}$		$ m_{\ell\ell} - m_Z  > 20 \text{ GeV}$ if $e^\pm e^\pm$
$p_T^{\text{miss}}$		$> 45 \text{ GeV}$
$m_{JJ}$ (leading jets)	$< 500 \text{ GeV}$	—
$\Delta\eta_{JJ}$ (leading jets)	$< 2.5$	—
$m_{jj}$ (closest $\Delta R$ )	$65 < m_{jj} < 95 \text{ GeV}$ or $ m_{jj} - 80 \text{ GeV}  \geq 15 \text{ GeV}$	—
$\Delta R_{\ell j}^{\min}$	—	$< 1.5$
$m_T^{\max}$	$> 90 \text{ GeV}$ if not $\mu^\pm \mu^\pm$	$> 90 \text{ GeV}$

# 3L selection



Variable	0 SFOS	1 and 2 SFOS
Trigger	Signal triggers, tab. 3.2	
Signal leptons	3 tight leptons with charge sum = $\pm 1e$ $p_T > 25/25/25 \text{ GeV}$	$p_T > 25/20/20 \text{ GeV}$
Additional leptons	No additional very loose lepton	
$m_{\text{SFOS}}$	$m_{\text{SFOS}} > 20 \text{ GeV}$ and $ m_{\text{SFOS}} - m_Z  > 20 \text{ GeV}$	
$m_{\ell\ell\ell}$		$ m_{\ell\ell\ell} - m_Z  > 10 \text{ GeV}$
SF lepton mass	$> 20 \text{ GeV}$	—
Dielectron mass	$ m_{ee} - m_Z  > 20 \text{ GeV}$	—
Jets	$\leq 1 \text{ jet}$	0 jets
b-tagging	No b-tagged jets and soft b-tag objects	
$\Delta\phi(\vec{p}_T(\ell\ell\ell), \vec{p}_T^{\text{miss}})$	—	$> 2.5$
$p_T(\ell\ell\ell)$	—	$> 50 \text{ GeV}$
$m_T^{\text{3rd}} \text{ (1 SFOS) or } m_T^{\text{max}} \text{ (2 SFOS)}$	—	$> 90 \text{ GeV}$

# 4L preselection



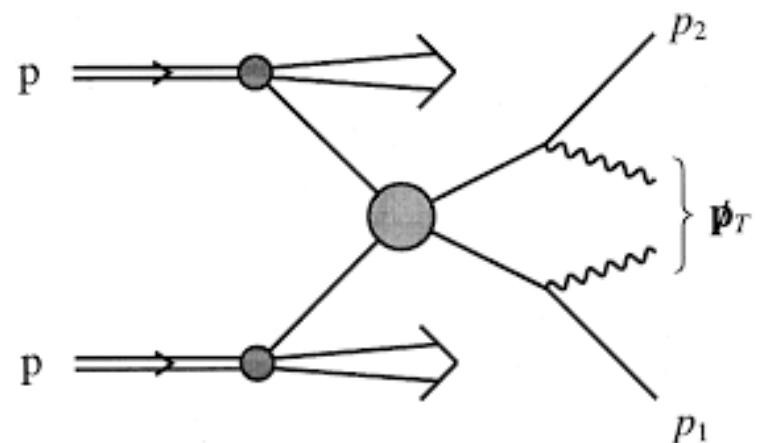
Features	Selections
Number of leptons	Select events with 4 leptons passing common veto-ID
Triggers	Select events passing dilepton triggers
Z lepton	Find opposite charge lepton pairs, passing ZID, closest to $m_Z$ Require Z leptons to have $p_T > 25, 15$ GeV
W lepton	Require that leftover leptons are opposite charge and pass WID Require W leptons to have $p_T > 25, 15$ GeV
Low mass resonances	Require any opposite charge pair invariant mass to be greater than 12 GeV
b-tagged jets	no b-tagged jet
Z mass window	Require invariant mass of the Z leptons to be within 10 GeV of Z boson mass

# 4L selection



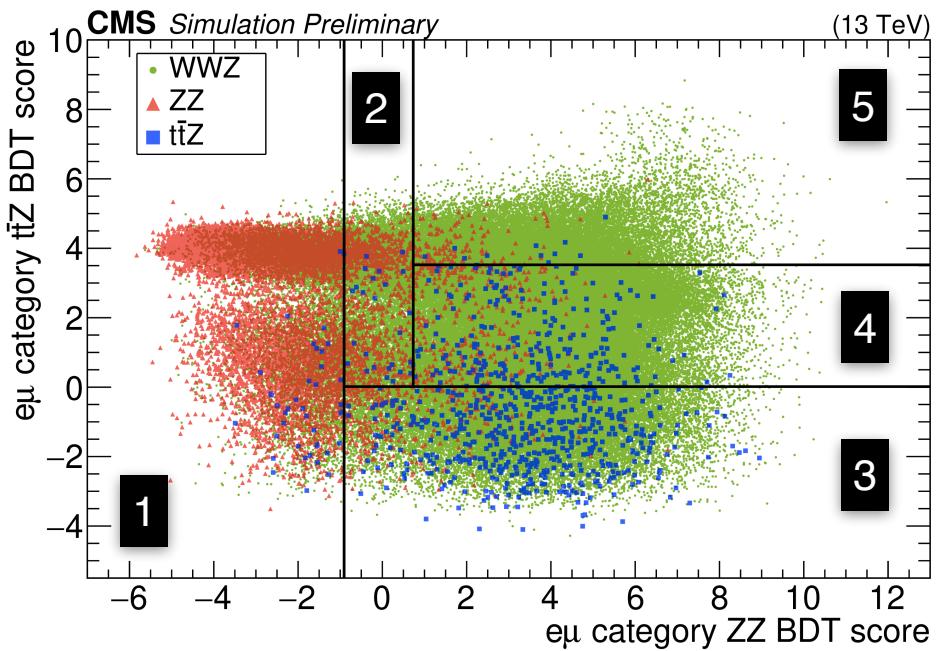
Variable	e $\mu$ category	ee/ $\mu\mu$ category
Preselection	Selections in Table 20	
W candidate lepton flavors	e $\mu$	ee/ $\mu\mu$
$m_{\ell\ell}$	Separated into 4 bins in $(0, 40, 60, 100, \infty)$	$ m_{\ell\ell} - m_Z  > 10 \text{ GeV}$
$m_{T2}$	$m_{T2} > 25 \text{ GeV}$ (for $m_{\ell\ell} > 100 \text{ GeV}$ )	...
$p_{T,4\ell}$ and $p_T^{\text{miss}}$	...	No $p_{T,4\ell}$ cuts and $p_T^{\text{miss}} > 120 \text{ GeV}$ (Bin A) $p_{T,4\ell} > 70 \text{ GeV}$ and $70 < p_T^{\text{miss}} < 120 \text{ GeV}$ (Bin B) $40 < p_{T,4\ell} < 70 \text{ GeV}$ and $70 < p_T^{\text{miss}} < 120 \text{ GeV}$ (Bin C)

$$m_{T2} = \min_{\vec{p}_T^{\nu(1)} + \vec{p}_T^{\nu(2)} = \vec{p}_T^{\text{miss}}} \left[ \max \left( m_T^{(1)}(\vec{p}_T^{\nu(1)}, \vec{p}_T^e), m_T^{(2)}(\vec{p}_T^{\nu(2)}, \vec{p}_T^\mu) \right) \right]$$

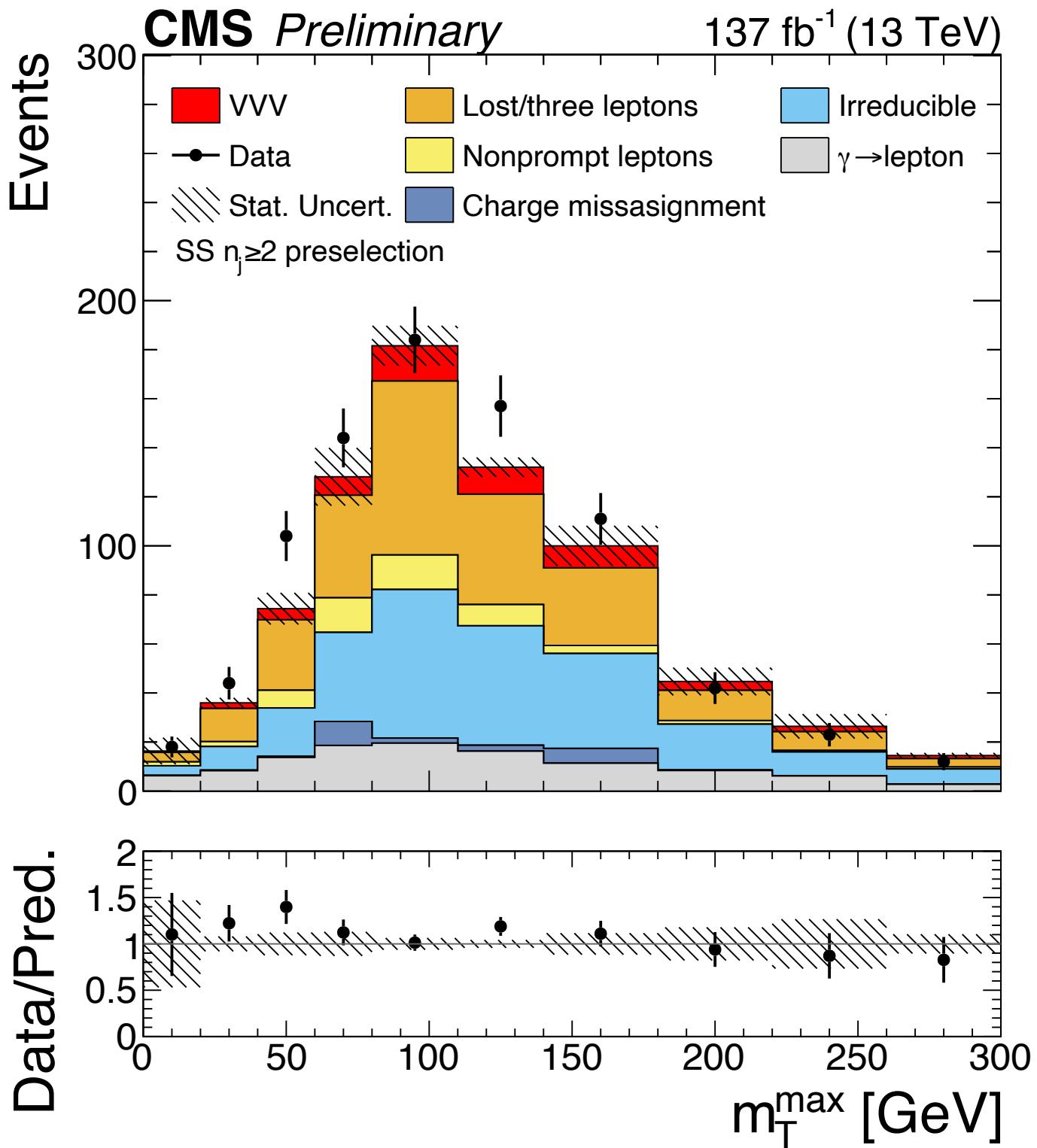


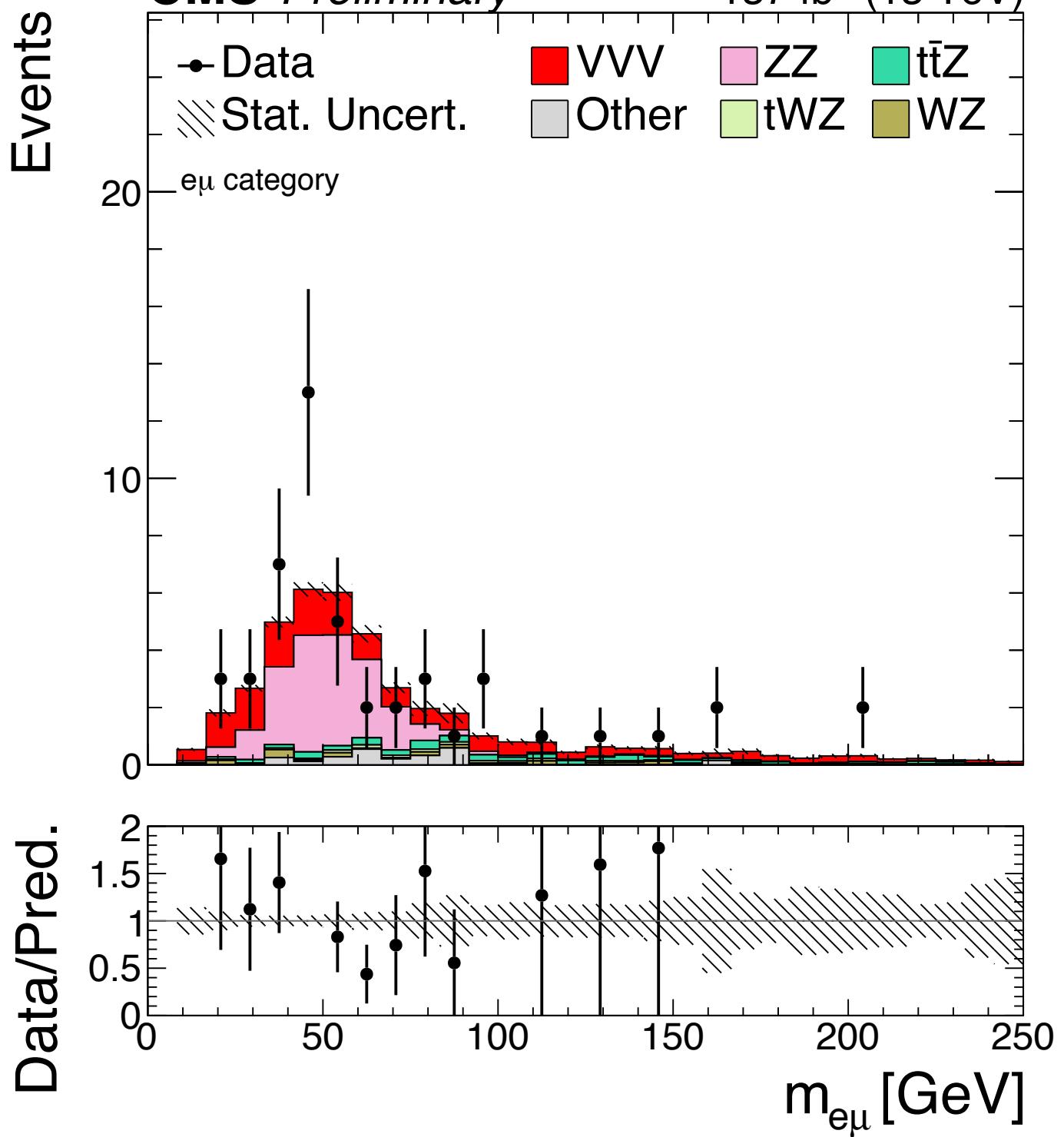
For  $WW \rightarrow llvv$  sub-system of  $WWZ$ , endpoint is at  $m_W$

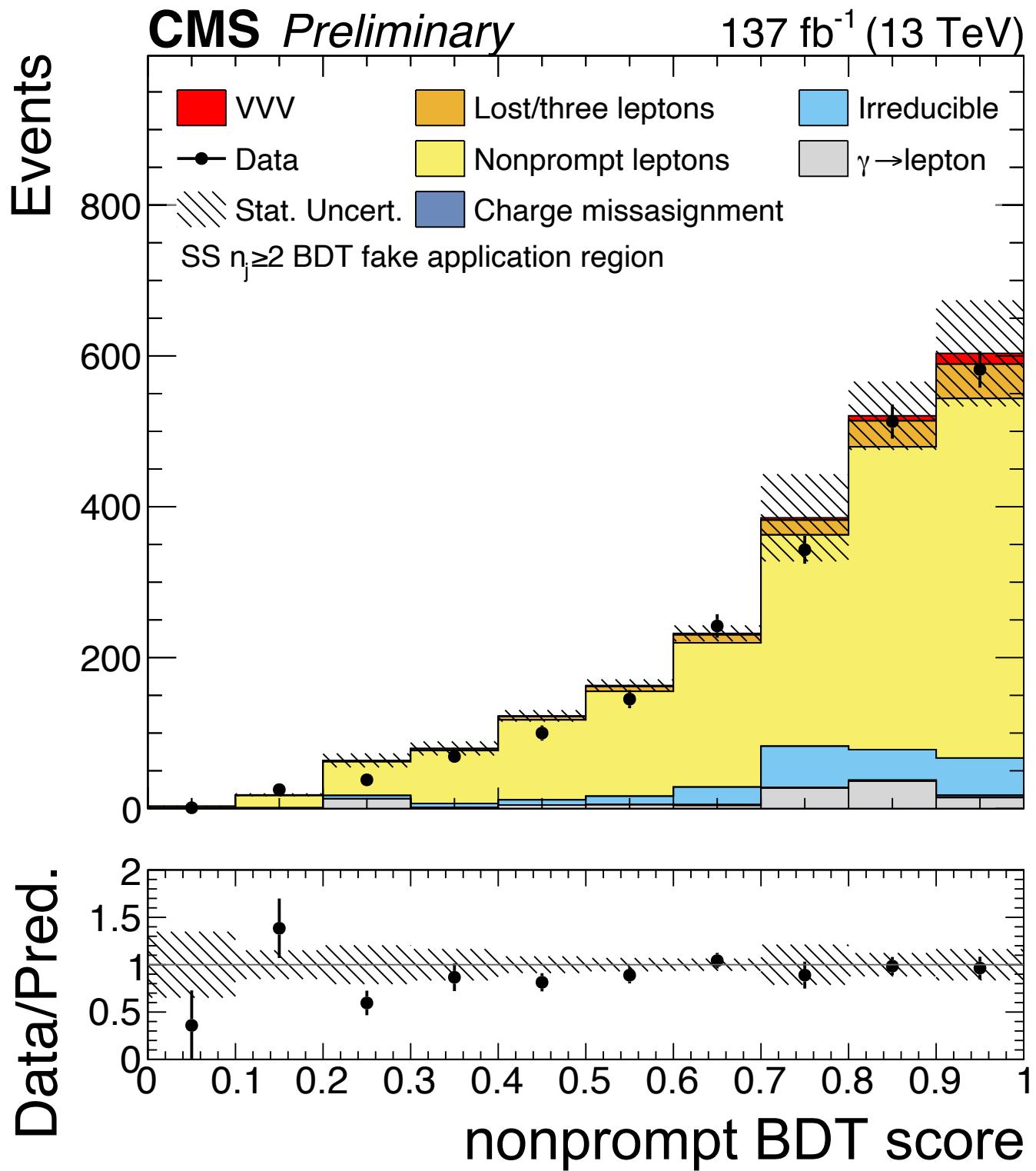
For  $Z \rightarrow \tau\tau \rightarrow llvvvv$  sub-system of  $ZZ$ , endpoint is at  $m_\tau$

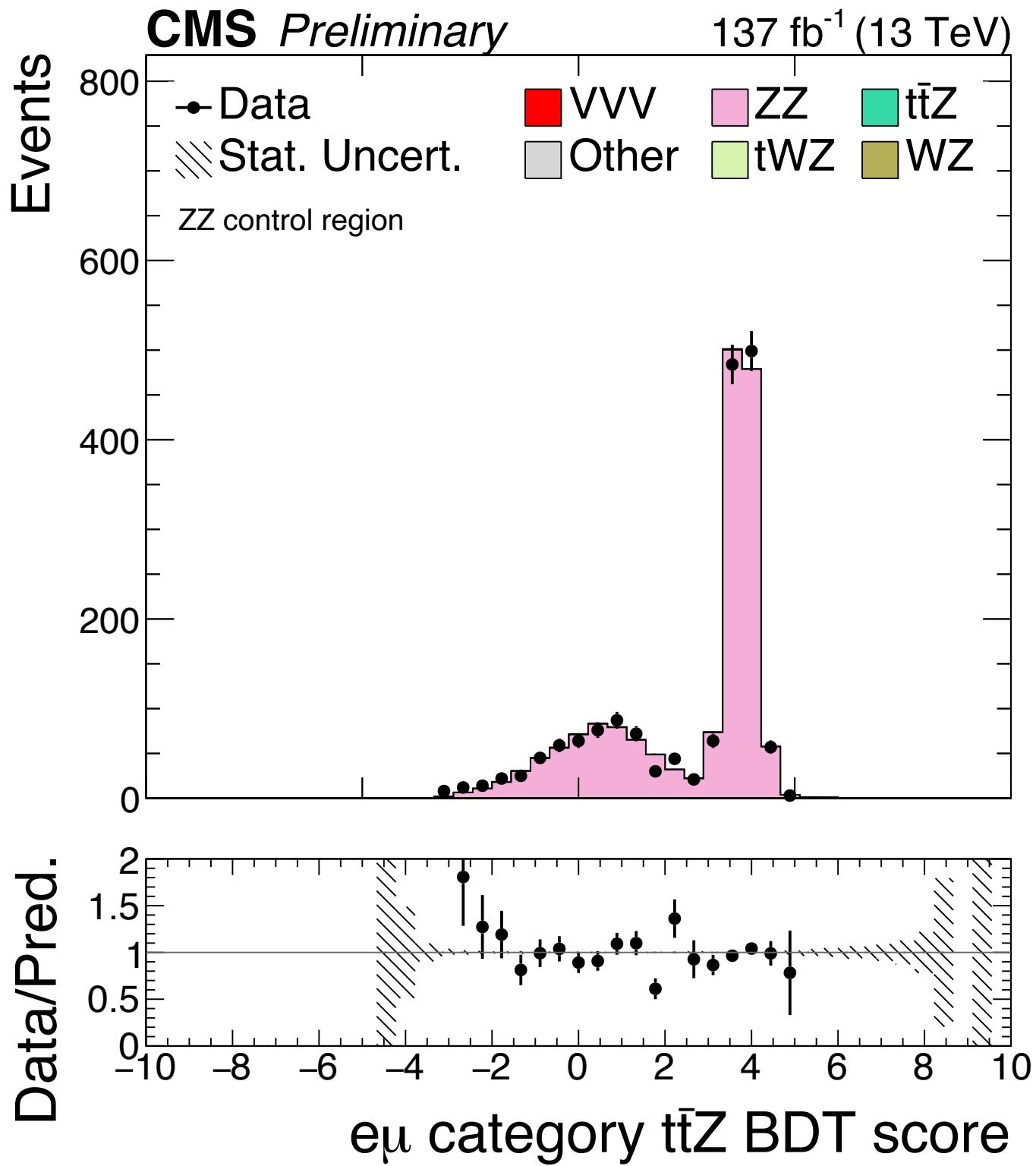


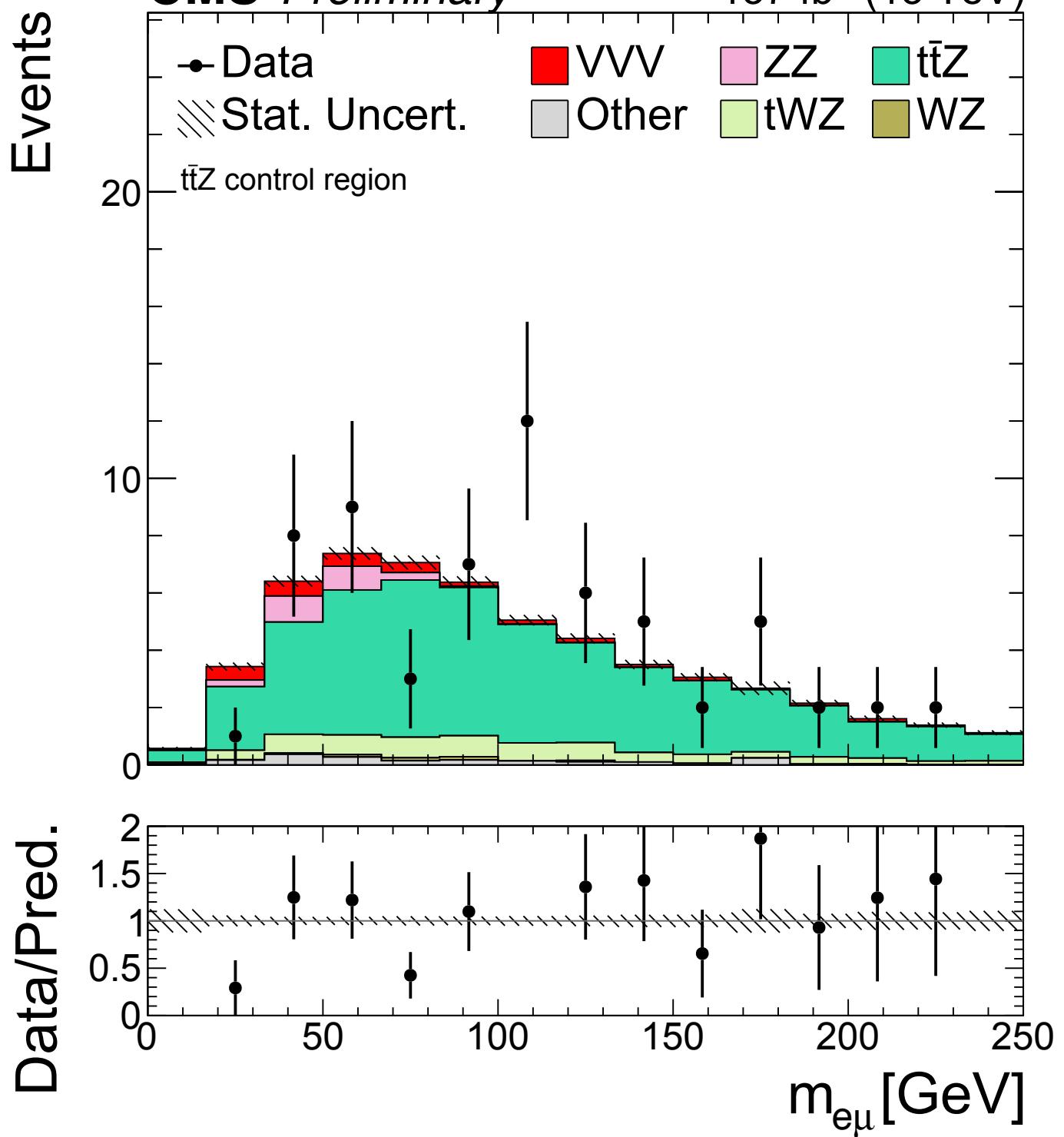
	ZZ BDT range	t̄Z BDT range
eμ BDT bin 1	(-∞, -0.908 )	(-∞ , ∞ )
eμ BDT bin 2	(-0.908 , ∞ )	(-∞ , 0.015 )
eμ BDT bin 3	(-0.908 , 0.733 )	(0.015 , ∞ )
eμ BDT bin 4	(0.733 , ∞ )	(0.015 , 3.523 )
eμ BDT bin 5	(0.733 , ∞ )	(3.523 , ∞ )
ee/μμ BDT bin A	(0 , 3 )	-
ee/μμ BDT bin B	(3 , ∞ )	-













Process	Higgs boson contributions as signal		Higgs boson contributions as background	
	sequential-cut	BDT-based	sequential-cut	BDT-based
WWW	2.5 (2.9)	3.3 (3.1)	1.0 (1.8)	1.6 (1.9)
WWZ	3.5 (3.6)	3.4 (4.1)	0.9 (2.2)	1.3 (2.2)
WZZ	1.6 (0.7)	1.7 (0.7)	1.7 (0.8)	1.7 (0.8)
ZZZ	0.0 (0.9)	0.0 (0.9)	0.0 (0.9)	0.0 (0.9)
VVV	5.0 (5.4)	5.7 (5.9)	2.3 (3.5)	2.9 (3.5)



Process	Higgs boson contributions as signal		Higgs boson contributions as background	
	sequential-cut	BDT-based	sequential-cut	BDT-based
WZZ	5.2 (3.7 <sup>+2.2</sup> <sub>-1.3</sub> )	6.1 (3.8 <sup>+2.2</sup> <sub>-1.3</sub> )	5.8 (3.7 <sup>+2.3</sup> <sub>-1.3</sub> )	5.8 (3.7 <sup>+2.3</sup> <sub>-1.3</sub> )
ZZZ	5.4 (6.0 <sup>+4.6</sup> <sub>-2.6</sub> )	5.4 (6.2 <sup>+4.9</sup> <sub>-2.7</sub> )	5.6 (6.3 <sup>+5.3</sup> <sub>-2.8</sub> )	5.7 (6.3 <sup>+5.3</sup> <sub>-2.8</sub> )



Signal region	SS $m_{jj}$ -in				SS $m_{jj}$ -out				SS 1j			$3\ell$		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	0 SFOS	1 SFOS	2 SFOS		
Lost/three $\ell$	1.4±0.9	5.5±1.6	7.0±1.7	10.7±2.6	9.7±3.6	31.4±3.8	2.5±1.1	41.0±6.1	5.8±1.6	3.5±0.7	25.6±4.2	36.1±3.1		
Irreducible	1.0±0.1	0.6±0.1	2.9±0.2	4.7±0.4	1.9±0.2	15.5±1.2	0.4±0.0	4.6±0.2	0.5±0.1	1.3±0.1	1.2±0.1	0.3±0.0		
Nonprompt $\ell$	0.6±0.6	3.6±2.4	4.2±1.5	0.8±1.0	2.8±1.5	9.1±4.5	2.5±5.2	2.9±1.4	0.2±0.1	1.8±0.5	7.5±2.3	1.8±1.1		
Charge flips	<0.1	<0.1	<0.1	4.5±2.5	<0.1	<0.1	<0.1	0.1±0.1	<0.1	<0.1	0.8±1.2	0.3±0.1		
$\gamma \rightarrow$ nonprompt $\ell$	0.1±0.2	0.1±0.4	<0.1	1.4±0.5	1.1±0.4	0.7±0.4	0.6±1.2	4.8±8.0	<0.1	<0.1	1.0±0.4	0.1±1.5		
Background sum	3.1±1.1	9.8±2.9	14.2±2.3	22.1±3.8	15.6±4.0	56.8±6.0	6.0±5.4	53.5±10.1	6.4±1.6	6.6±0.9	36.2±5.0	38.7±3.6		
WWW onshell	0.9±0.4	2.3±0.9	4.6±1.7	0.9±0.4	1.0±0.6	3.3±1.3	0.3±0.2	1.2±0.4	0.4±0.2	6.7±2.4	4.3±1.6	1.8±0.7		
WH $\rightarrow$ WWW	0.4±0.3	1.3±0.9	1.2±0.5	0.5±0.3	1.3±1.3	2.7±1.2	1.1±0.8	6.5±3.1	2.2±1.1	3.4±1.6	5.0±2.1	0.6±0.6		
WWW total	1.3±0.5	3.7±1.3	5.8±1.7	1.5±0.5	2.3±1.4	6.0±1.7	1.4±0.8	7.7±3.1	2.5±1.1	10.1±2.9	9.3±2.6	2.4±0.9		
WWZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2±0.1	<0.1	<0.1		
ZH $\rightarrow$ WWZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1±0.1	0.1±0.1	<0.1		
WWZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3±0.1	0.1±0.1	<0.1		
WZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
WH $\rightarrow$ WZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
WZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
ZZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
ZH $\rightarrow$ ZZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
ZZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
VVV onshell	0.9±0.4	2.3±0.9	4.6±1.7	0.9±0.4	1.0±0.6	3.3±1.3	0.3±0.2	1.2±0.4	0.4±0.2	6.9±2.4	4.3±1.6	1.8±0.7		
VH $\rightarrow$ VVV	0.4±0.3	1.3±0.9	1.2±0.5	0.5±0.3	1.3±1.3	2.7±1.2	1.1±0.8	6.5±3.1	2.2±1.1	3.6±1.6	5.1±2.1	0.6±0.6		
VVV total	1.3±0.5	3.7±1.3	5.8±1.7	1.5±0.5	2.3±1.4	6.0±1.7	1.4±0.8	7.7±3.1	2.5±1.1	10.4±2.9	9.3±2.6	2.4±0.9		
Total	4.4±1.2	13.5±3.2	20.0±2.9	23.6±3.8	17.8±4.2	62.7±6.3	7.4±5.5	61.2±10.6	9.0±2.0	17.0±3.0	45.5±5.6	41.1±3.7		
Observed	3	14	15	22	22	67	13	69	8	17	42	39		



Signal region	$4\ell e\mu$					$4\ell ee/\mu\mu$		$5\ell$	$6\ell$
	bin 1	bin 2	bin 3	bin 4	bin 5	bin A	bin B		
ZZ	$15.9 \pm 1.0$	$1.6 \pm 0.1$	$0.6 \pm 0.1$	$0.6 \pm 0.1$	$0.2 \pm 0.0$	$76.4 \pm 4.3$	$2.9 \pm 0.3$	$0.30 \pm 0.09$	$0.01 \pm 0.01$
t̄Z	$0.2 \pm 0.1$	$0.1 \pm 0.1$	$2.8 \pm 0.5$	$1.4 \pm 0.2$	$0.1 \pm 0.1$	$1.5 \pm 0.3$	$2.3 \pm 0.3$	$<0.01$	$<0.01$
tWZ	$0.1 \pm 0.1$	$0.1 \pm 0.1$	$0.6 \pm 0.1$	$0.7 \pm 0.1$	$0.1 \pm 0.1$	$0.5 \pm 0.1$	$0.7 \pm 0.1$	$<0.01$	$<0.01$
WZ	$0.5 \pm 0.2$	$0.2 \pm 0.2$	$0.5 \pm 0.2$	$0.3 \pm 0.3$	$0.1 \pm 0.1$	$1.0 \pm 0.4$	$0.2 \pm 0.1$	$<0.01$	$<0.01$
Other	$1.1 \pm 0.4$	$0.5 \pm 0.5$	$0.5 \pm 0.2$	$0.6 \pm 0.2$	$<0.1$	$2.7 \pm 0.6$	$0.5 \pm 0.2$	$<0.01$	$<0.01$
Background sum	$17.8 \pm 1.1$	$2.5 \pm 0.5$	$5.0 \pm 0.6$	$3.6 \pm 0.4$	$0.5 \pm 0.1$	$82.2 \pm 4.3$	$6.6 \pm 0.5$	$0.30 \pm 0.09$	$0.01 \pm 0.01$
WWW onshell	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.01$	$<0.01$
WH → WWW	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.01$	$<0.01$
WWW total	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.01$	$<0.01$
WWZ onshell	$0.3 \pm 0.1$	$0.4 \pm 0.2$	$1.4 \pm 0.7$	$3.6 \pm 1.5$	$1.0 \pm 0.5$	$2.7 \pm 1.2$	$3.2 \pm 1.4$	$<0.01$	$<0.01$
ZH → WWZ	$1.1 \pm 0.5$	$1.1 \pm 0.5$	$0.5 \pm 0.2$	$1.3 \pm 0.5$	$1.8 \pm 0.8$	$2.9 \pm 1.2$	$1.5 \pm 0.6$	$<0.01$	$<0.01$
WWZ total	$1.3 \pm 0.5$	$1.5 \pm 0.5$	$1.9 \pm 0.8$	$4.9 \pm 1.6$	$2.9 \pm 0.9$	$5.6 \pm 1.7$	$4.7 \pm 1.5$	$<0.01$	$<0.01$
WZZ onshell	$0.2 \pm 0.2$	$0.1 \pm 0.1$	$0.2 \pm 0.2$	$0.4 \pm 0.4$	$0.1 \pm 0.1$	$0.5 \pm 0.4$	$0.2 \pm 0.2$	$2.62 \pm 1.82$	$0.03 \pm 0.05$
WH → WZZ	$0.2 \pm 0.3$	$0.2 \pm 0.3$	$<0.1$	$0.5 \pm 0.5$	$<0.1$	$<0.1$	$<0.1$	$<0.01$	$<0.01$
WZZ total	$0.4 \pm 0.3$	$0.3 \pm 0.3$	$0.2 \pm 0.2$	$0.9 \pm 0.7$	$0.1 \pm 0.1$	$0.5 \pm 0.4$	$0.2 \pm 0.2$	$2.62 \pm 1.82$	$0.03 \pm 0.05$
ZZZ onshell	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.01$	$<0.01$
ZH → ZZZ	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.01$	$<0.01$
ZZZ total	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.1$	$<0.01$	$<0.01$
VVV onshell	$0.5 \pm 0.2$	$0.4 \pm 0.2$	$1.6 \pm 0.8$	$4.0 \pm 1.5$	$1.1 \pm 0.5$	$3.2 \pm 1.3$	$3.4 \pm 1.4$	$2.62 \pm 1.82$	$0.03 \pm 0.05$
VH → VVV	$1.2 \pm 0.5$	$1.3 \pm 0.6$	$0.5 \pm 0.2$	$1.7 \pm 0.8$	$1.8 \pm 0.8$	$2.9 \pm 1.2$	$1.5 \pm 0.6$	$<0.01$	$<0.01$
VVV total	$1.7 \pm 0.6$	$1.7 \pm 0.6$	$2.1 \pm 0.8$	$5.8 \pm 1.7$	$3.0 \pm 0.9$	$6.1 \pm 1.8$	$4.8 \pm 1.5$	$2.62 \pm 1.82$	$0.03 \pm 0.05$
Total	$19.5 \pm 1.2$	$4.2 \pm 0.8$	$7.1 \pm 1.0$	$9.4 \pm 1.8$	$3.5 \pm 0.9$	$88.2 \pm 4.7$	$11.4 \pm 1.6$	$2.92 \pm 1.82$	$0.04 \pm 0.05$
Observed	22	9	7	8	3	80	11	3	0



Signal region	SS $m_{jj}$ -in				SS $m_{jj}$ -out				SS 1j				$3\ell$		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	0 SFOS	1 SFOS	2 SFOS			
Lost/three $\ell$	1.8 $\pm$ 0.4	10.9 $\pm$ 2.0	8.7 $\pm$ 1.0	8.8 $\pm$ 1.7	46.0 $\pm$ 6.2	44.8 $\pm$ 4.4	8.4 $\pm$ 1.3	43.5 $\pm$ 4.4	34.5 $\pm$ 2.7	4.6 $\pm$ 0.8	15.1 $\pm$ 1.5	58.3 $\pm$ 2.4			
Irreducible	2.1 $\pm$ 0.4	13.0 $\pm$ 3.6	8.4 $\pm$ 1.4	9.8 $\pm$ 1.4	41.1 $\pm$ 4.5	42.8 $\pm$ 4.7	2.6 $\pm$ 0.6	22.8 $\pm$ 8.6	13.2 $\pm$ 1.9	2.5 $\pm$ 0.9	2.2 $\pm$ 1.2	2.5 $\pm$ 0.8			
Nonprompt $\ell$	1.3 $\pm$ 0.9	5.8 $\pm$ 2.4	6.8 $\pm$ 2.2	2.3 $\pm$ 1.3	12.0 $\pm$ 6.1	11.2 $\pm$ 3.8	1.8 $\pm$ 2.9	2.4 $\pm$ 1.3	2.8 $\pm$ 1.1	3.0 $\pm$ 0.9	5.7 $\pm$ 1.6	5.9 $\pm$ 1.6			
Charge flips	<0.1	1.2 $\pm$ 2.0	<0.1	2.6 $\pm$ 1.6	1.0 $\pm$ 0.5	<0.1	6.9 $\pm$ 4.7	0.2 $\pm$ 0.1	<0.1	<0.1	1.1 $\pm$ 1.3	0.7 $\pm$ 0.2			
$\gamma \rightarrow$ nonprompt $\ell$	1.4 $\pm$ 0.4	2.3 $\pm$ 0.9	0.1 $\pm$ 0.8	8.6 $\pm$ 3.1	19.2 $\pm$ 5.1	2.3 $\pm$ 0.9	3.8 $\pm$ 1.1	19.7 $\pm$ 6.0	13.8 $\pm$ 7.0	<0.1	0.6 $\pm$ 0.7	0.2 $\pm$ 0.3			
Background sum	6.7 $\pm$ 1.2	33.3 $\pm$ 5.2	24.0 $\pm$ 2.9	32.1 $\pm$ 4.3	119 $\pm$ 11	101 $\pm$ 8	23.6 $\pm$ 5.8	88.7 $\pm$ 11.4	64.4 $\pm$ 7.8	10.1 $\pm$ 1.5	24.7 $\pm$ 2.9	67.6 $\pm$ 3.1			
WWW onshell	1.0 $\pm$ 0.5	3.3 $\pm$ 1.5	3.5 $\pm$ 1.6	0.9 $\pm$ 0.5	3.9 $\pm$ 1.8	4.1 $\pm$ 1.9	0.5 $\pm$ 0.3	1.8 $\pm$ 0.8	1.7 $\pm$ 0.9	5.9 $\pm$ 2.6	3.8 $\pm$ 1.7	2.5 $\pm$ 1.2			
WH $\rightarrow$ WWW	0.2 $\pm$ 0.3	1.9 $\pm$ 1.5	0.6 $\pm$ 0.4	0.4 $\pm$ 0.4	1.3 $\pm$ 0.8	1.7 $\pm$ 1.0	0.8 $\pm$ 0.5	4.5 $\pm$ 2.7	3.3 $\pm$ 2.0	3.0 $\pm$ 1.7	2.7 $\pm$ 1.5	1.3 $\pm$ 0.8			
WWW total	1.2 $\pm$ 0.6	5.1 $\pm$ 2.2	4.1 $\pm$ 1.6	1.3 $\pm$ 0.6	5.3 $\pm$ 2.0	5.7 $\pm$ 2.1	1.4 $\pm$ 0.6	6.3 $\pm$ 2.8	5.0 $\pm$ 2.2	8.8 $\pm$ 3.1	6.6 $\pm$ 2.3	3.8 $\pm$ 1.4			
WWZ onshell	0.1 $\pm$ 0.1	0.3 $\pm$ 0.2	0.2 $\pm$ 0.1	<0.1	<0.1	0.1 $\pm$ 0.1	0.1 $\pm$ 0.1	<0.1	<0.1	0.3 $\pm$ 0.2	0.2 $\pm$ 0.2	0.2 $\pm$ 0.1			
ZH $\rightarrow$ WWZ	0.1 $\pm$ 0.1	<0.1	<0.1	<0.1	<0.1	0.3 $\pm$ 0.3	<0.1	<0.1	0.4 $\pm$ 0.4	0.2 $\pm$ 0.1	<0.1	<0.1			
WWZ total	0.1 $\pm$ 0.2	0.3 $\pm$ 0.2	0.2 $\pm$ 0.1	<0.1	<0.1	0.4 $\pm$ 0.3	0.1 $\pm$ 0.1	<0.1	0.4 $\pm$ 0.4	0.4 $\pm$ 0.2	0.2 $\pm$ 0.2	0.2 $\pm$ 0.1			
WZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
WH $\rightarrow$ WZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
WZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
ZZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
ZH $\rightarrow$ ZZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
ZZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
VVV onshell	1.0 $\pm$ 0.5	3.5 $\pm$ 1.5	3.7 $\pm$ 1.6	0.9 $\pm$ 0.5	3.9 $\pm$ 1.8	4.2 $\pm$ 1.9	0.6 $\pm$ 0.3	1.8 $\pm$ 0.8	1.7 $\pm$ 0.9	6.1 $\pm$ 2.6	4.0 $\pm$ 1.8	2.7 $\pm$ 1.2			
VH $\rightarrow$ VVV	0.3 $\pm$ 0.3	1.9 $\pm$ 1.5	0.6 $\pm$ 0.4	0.4 $\pm$ 0.4	1.3 $\pm$ 0.8	2.0 $\pm$ 1.0	0.8 $\pm$ 0.5	4.5 $\pm$ 2.7	3.7 $\pm$ 2.0	3.1 $\pm$ 1.7	2.7 $\pm$ 1.5	1.3 $\pm$ 0.8			
VVV total	1.3 $\pm$ 0.6	5.4 $\pm$ 2.2	4.2 $\pm$ 1.6	1.3 $\pm$ 0.6	5.3 $\pm$ 2.0	6.1 $\pm$ 2.1	1.4 $\pm$ 0.6	6.3 $\pm$ 2.8	5.4 $\pm$ 2.2	9.3 $\pm$ 3.1	6.8 $\pm$ 2.3	3.9 $\pm$ 1.4			
Total	8.0 $\pm$ 1.3	38.7 $\pm$ 5.6	28.2 $\pm$ 3.4	33.5 $\pm$ 4.4	125 $\pm$ 11	107 $\pm$ 8	25.0 $\pm$ 5.8	95.0 $\pm$ 11.8	69.8 $\pm$ 8.1	19.4 $\pm$ 3.4	31.4 $\pm$ 3.7	71.5 $\pm$ 3.4			
Observed	5	46	20	31	112	118	29	101	69	20	32	69			



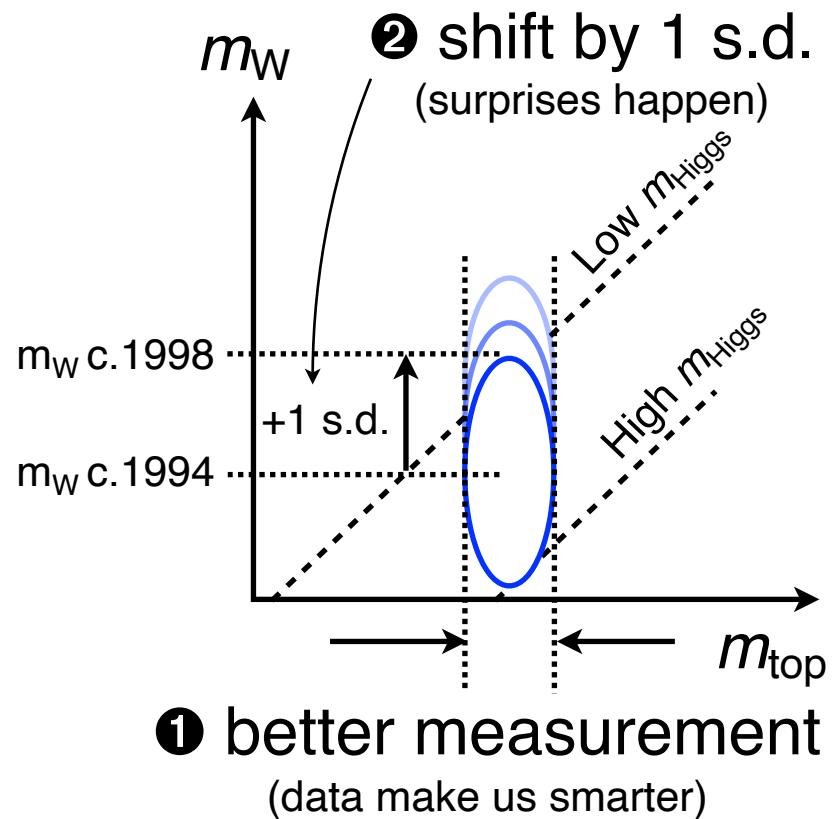
Signal region	4ℓ eμ					4ℓ ee/μμ		5ℓ	6ℓ
	bin 4	bin 3	bin 2	bin 1	bin A	bin B	bin C		
ZZ	0.3±0.0	0.7±0.0	0.7±0.0	0.4±0.0	1.8±0.2	6.0±0.6	5.0±0.5	0.30±0.08	0.01±0.01
t̄Z	0.2±0.0	0.3±0.1	0.8±0.1	2.3±0.4	1.4±0.2	1.1±0.2	0.2±0.0	<0.01	<0.01
tWZ	0.1±0.1	0.1±0.1	0.3±0.0	0.8±0.1	0.5±0.1	0.3±0.1	0.1±0.1	<0.01	<0.01
WZ	0.2±0.1	0.1±0.1	0.1±0.2	0.6±0.2	<0.1	0.2±0.1	0.1±0.1	<0.01	<0.01
Other	<0.1	0.2±0.1	0.6±0.3	0.2±0.1	<0.1	1.4±0.5	0.1±0.1	<0.01	<0.01
Background sum	0.8±0.1	1.4±0.1	2.5±0.3	4.3±0.4	3.7±1.9	9.1±0.8	5.5±0.5	0.30±0.08	0.01±0.01
WWW onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WH → WWW	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WWW total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WWZ onshell	0.5±0.2	0.5±0.2	1.1±0.4	4.0±1.6	2.1±0.9	1.2±0.4	0.6±0.2	<0.01	<0.01
ZH → WWZ	2.3±0.9	1.1±0.4	0.3±0.1	0.1±0.1	0.8±0.3	0.9±0.4	0.5±0.2	<0.01	<0.01
WWZ total	2.8±0.9	1.6±0.5	1.4±0.4	4.1±1.6	2.9±1.0	2.1±0.6	1.1±0.3	<0.01	<0.01
WZZ onshell	<0.1	0.1±0.1	0.1±0.1	0.4±0.3	0.2±0.2	0.1±0.1	0.1±0.1	2.17±1.46	0.03±0.04
WH → WZZ	<0.1	0.4±0.3	0.1±0.2	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WZZ total	<0.1	0.4±0.4	0.2±0.2	0.4±0.3	0.2±0.2	0.1±0.1	0.1±0.1	2.17±1.46	0.03±0.04
ZZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
ZH → ZZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
ZZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
VVV onshell	0.5±0.2	0.6±0.2	1.2±0.4	4.4±1.6	2.3±0.9	1.3±0.5	0.7±0.2	2.17±1.46	0.03±0.04
VH → VVV	2.3±0.9	1.5±0.5	0.4±0.3	0.1±0.1	0.8±0.3	0.9±0.4	0.5±0.2	<0.01	<0.01
VVV total	2.8±0.9	2.1±0.6	1.6±0.5	4.5±1.6	3.1±1.0	2.2±0.6	1.2±0.3	2.17±1.46	0.03±0.04
Total	3.6±0.9	3.5±0.6	4.1±0.6	8.8±1.7	6.8±2.1	11.3±1.0	6.6±0.6	2.47±1.46	0.04±0.04
Observed	7	1	5	7	6	8	7	3	0

# History lesson

Chang  
UCSD

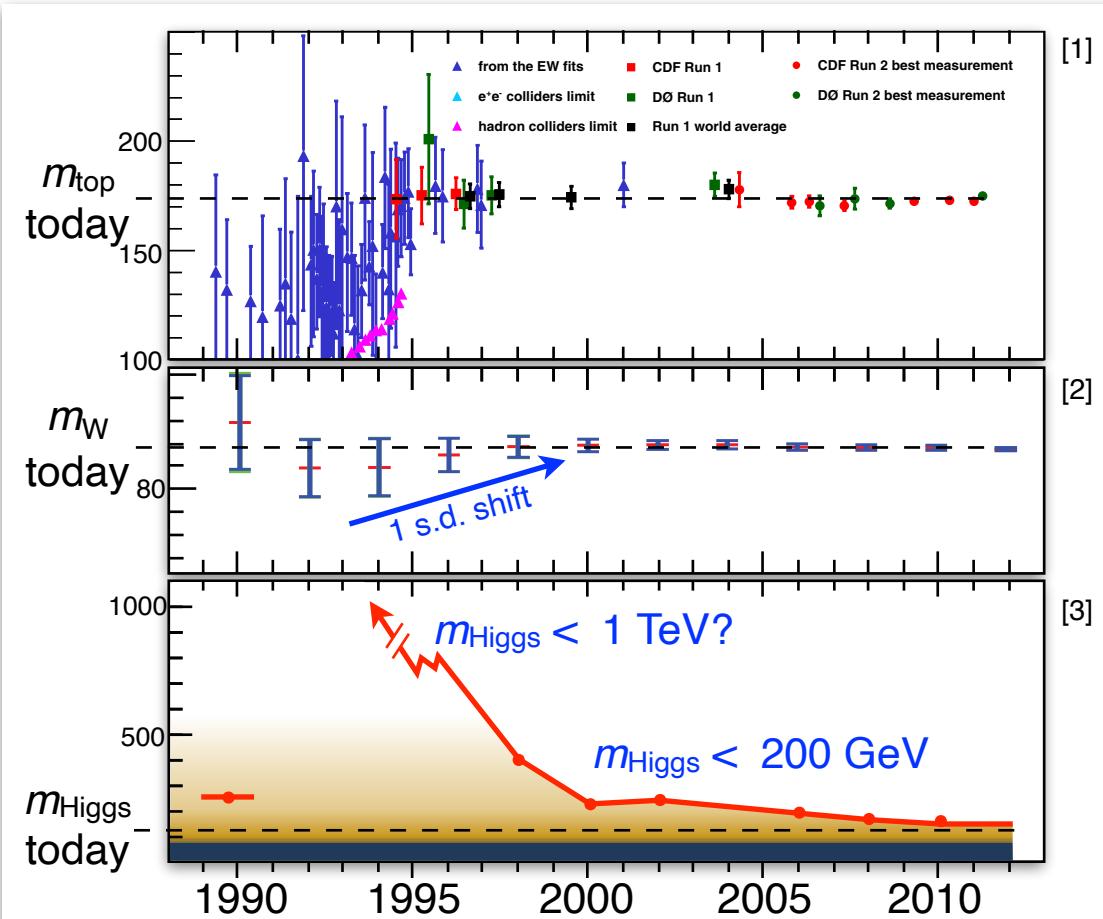


$m_{\text{top}}$  vs.  $m_W$  and  $m_{\text{Higgs}}$



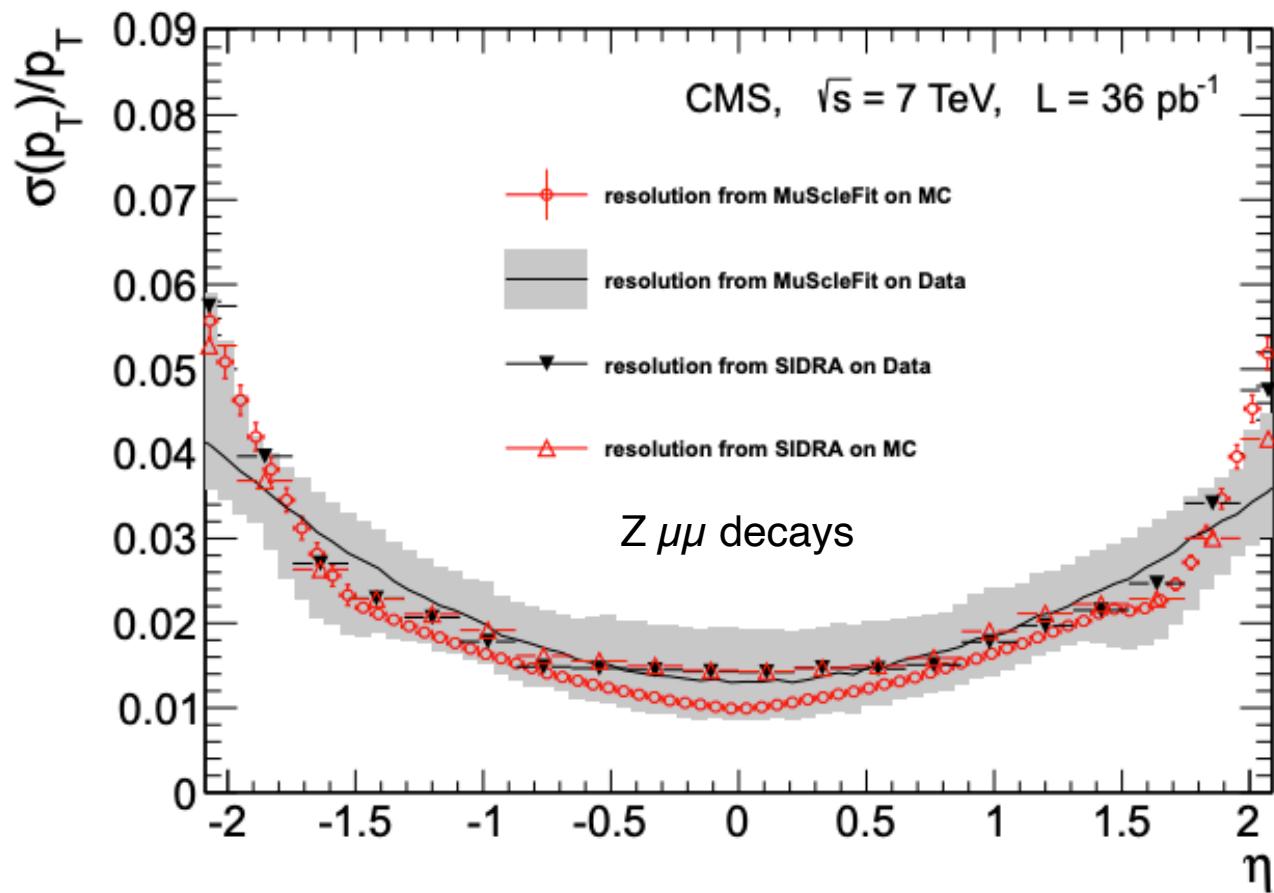
...after analysis of Run I data, ... ②  $m_W$  shifted a full s.d. ... the  $m_{\text{Higgs}}$  must be ③ much lower than anyone had anticipated. ... Surprises happen.

– D. Amidei, R. Brock Fermi news 1/17/2003



History tells us with more data we get smarter; also surprises happen

# Muon resolution

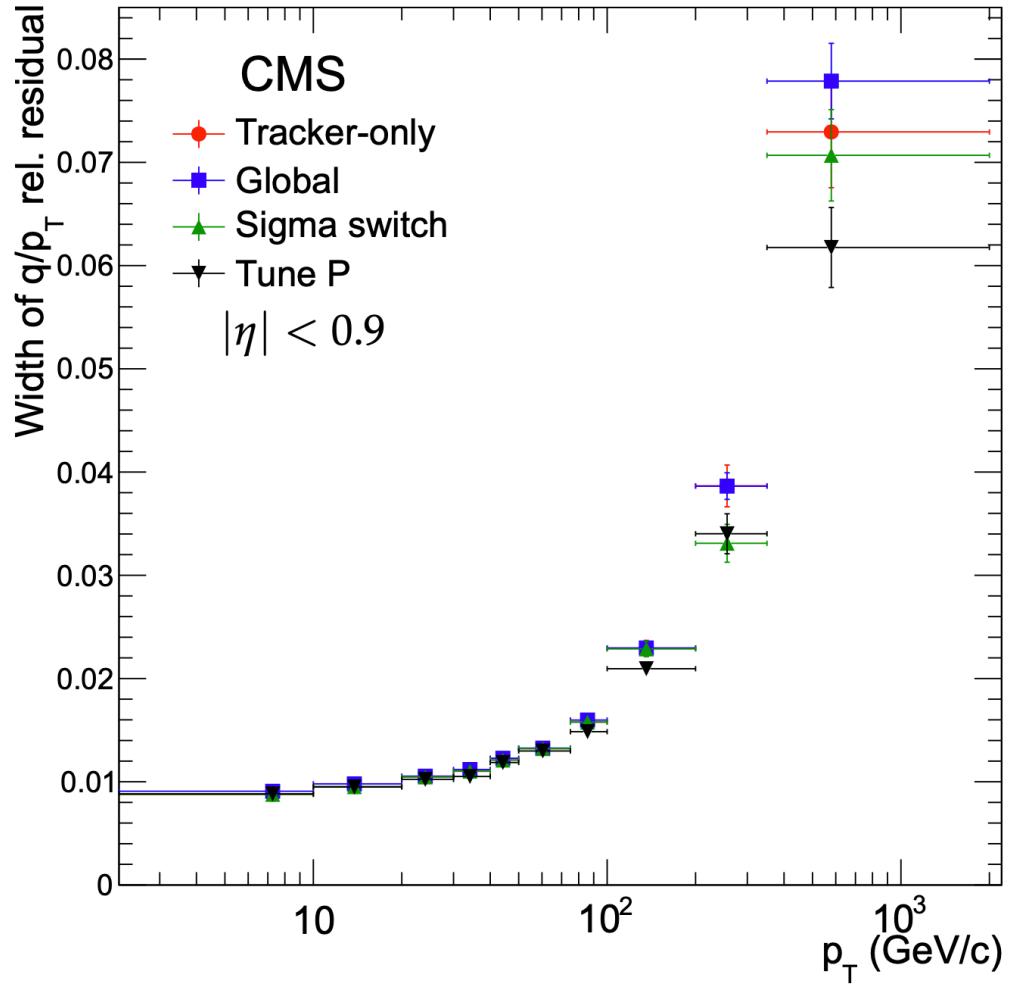


ment with the results obtained from simulation. The  $\sigma(p_T)/p_T$  averaged over  $\phi$  and  $\eta$  varies in  $p_T$  from  $(1.8 \pm 0.3(\text{stat.}))\%$  at  $p_T = 30 \text{ GeV}/c$  to  $(2.3 \pm 0.3(\text{stat.}))\%$  at  $p_T = 50 \text{ GeV}/c$ , again in good agreement with the expectations from simulation.

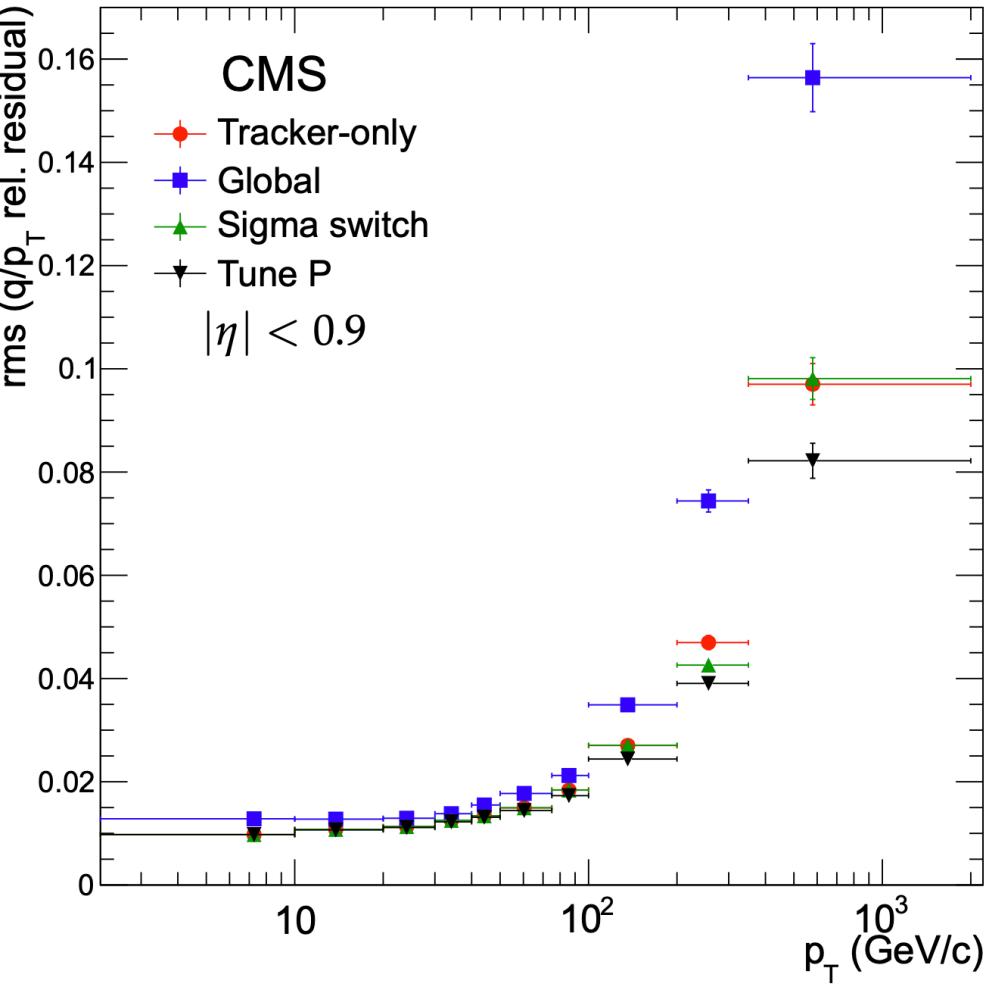
<https://arxiv.org/pdf/1206.4071.pdf>

# Muon resolution

<https://arxiv.org/pdf/1206.4071.pdf>



(a)



(b)



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## Physics > Instrumentation and Detectors

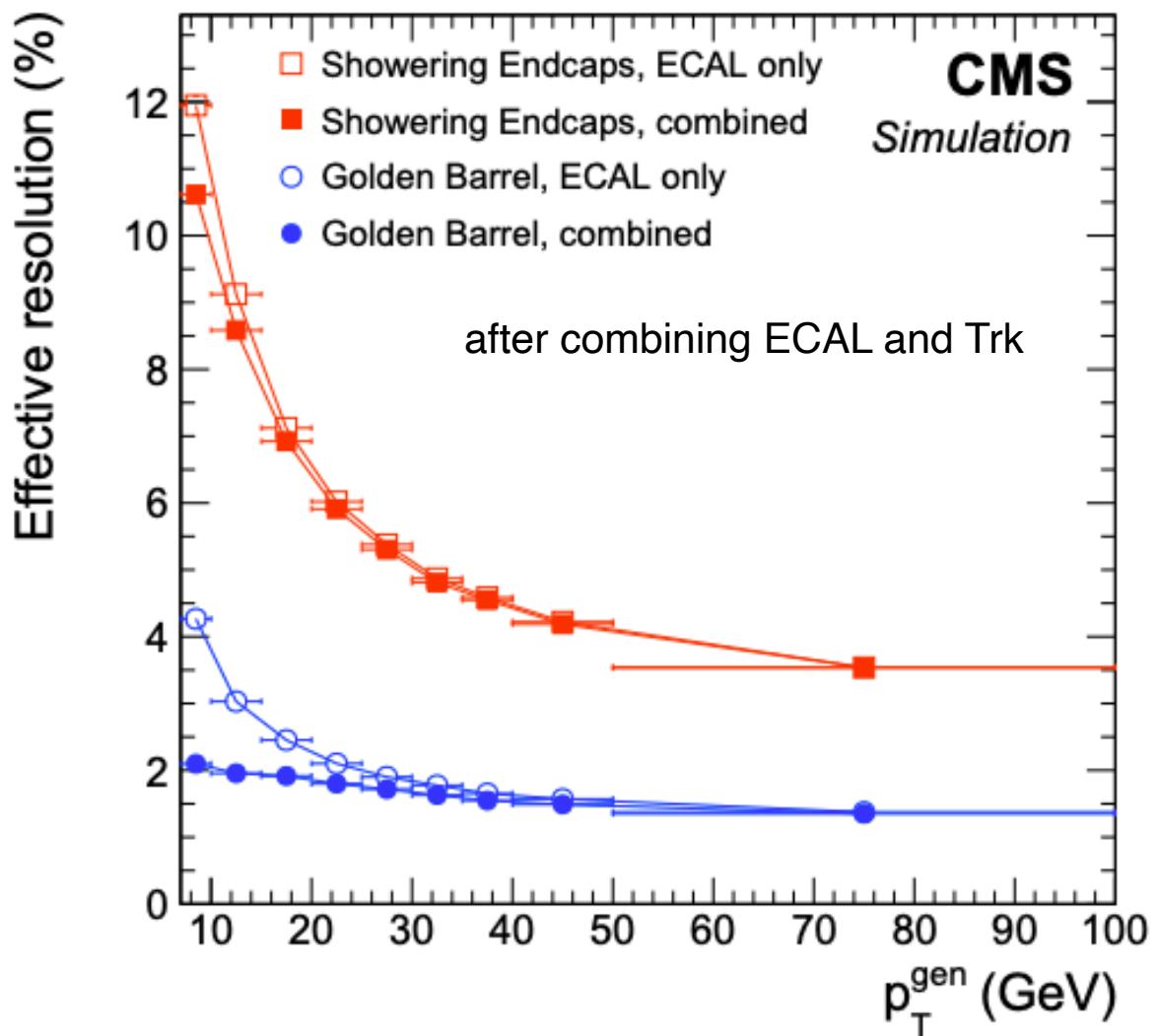
[Submitted on 9 Feb 2015 ([v1](#)), last revised 1 Jul 2015 (this version, v2)]

# Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8 \text{ TeV}$

CMS Collaboration

The performance and strategies used in electron reconstruction and selection at CMS are presented based on data corresponding to an integrated luminosity of 19.7 inverse femtobarns, collected in proton–proton collisions at  $\sqrt{s} = 8 \text{ TeV}$  at the CERN LHC. The paper focuses on prompt isolated electrons with transverse momenta ranging from about 5 to a few 100 GeV. A detailed description is given of the algorithms used to cluster energy in the electromagnetic calorimeter and to reconstruct electron trajectories in the tracker. The electron momentum is estimated by combining the energy measurement in the calorimeter with the momentum measurement in the tracker. Benchmark selection criteria are presented, and their performances assessed using Z, Upsilon, and J/psi decays into electron–positron pairs. The spectra of the observables relevant to electron reconstruction and selection as well as their global efficiencies are well reproduced by Monte Carlo simulations. The momentum scale is calibrated with an uncertainty smaller than 0.3%. The momentum resolution for electrons produced in Z boson decays ranges from 1.7 to 4.5%, depending on electron pseudorapidity and energy loss through bremsstrahlung in the detector material.

# Electron resolution



<https://twiki.cern.ch/twiki/pub/CMSPublic/BTV13TeV2017FIRST2018/PT30GeV.pdf>

