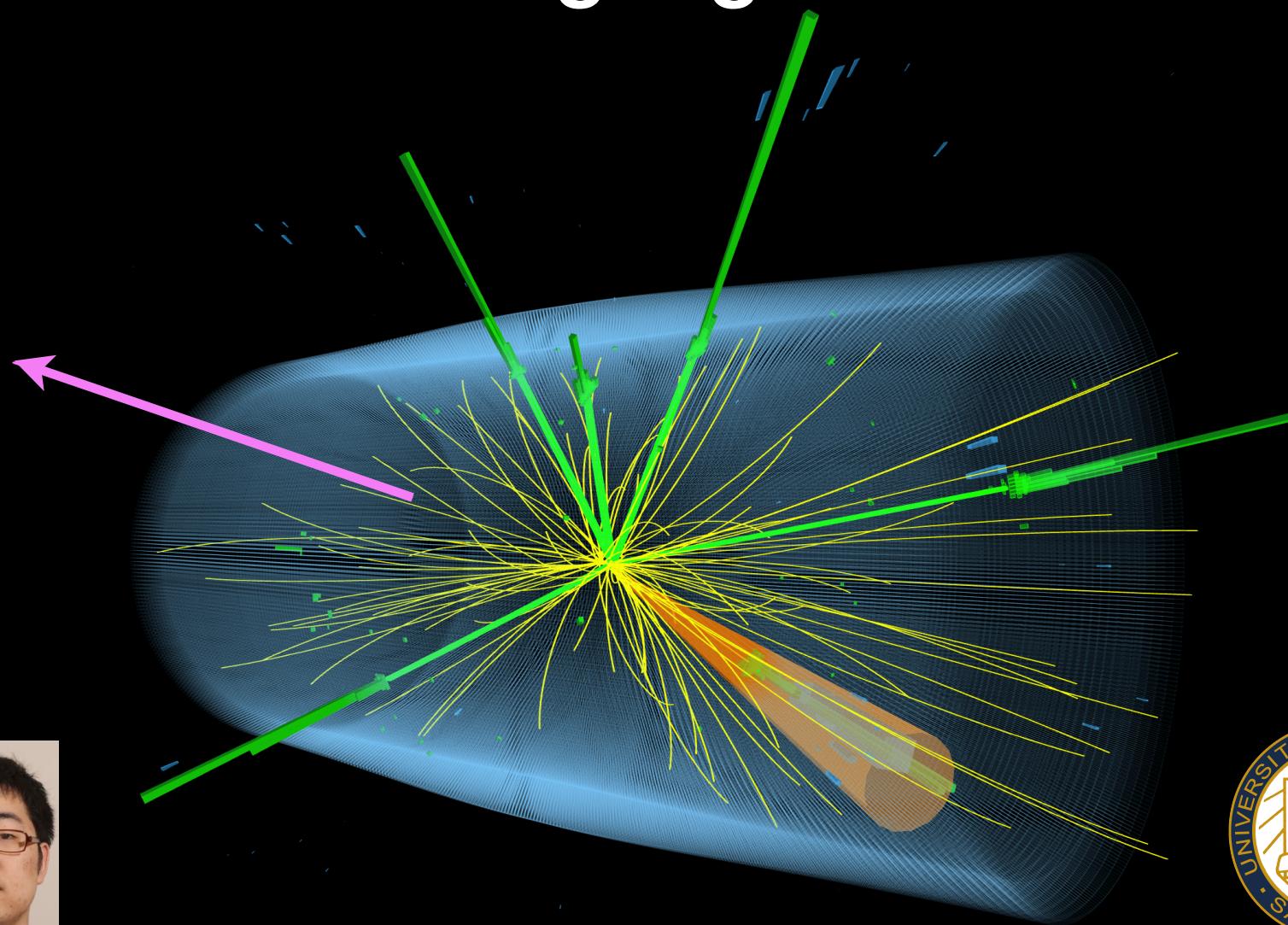


First observation of production of three massive gauge bosons

$V = W, Z$



Philip
Chang

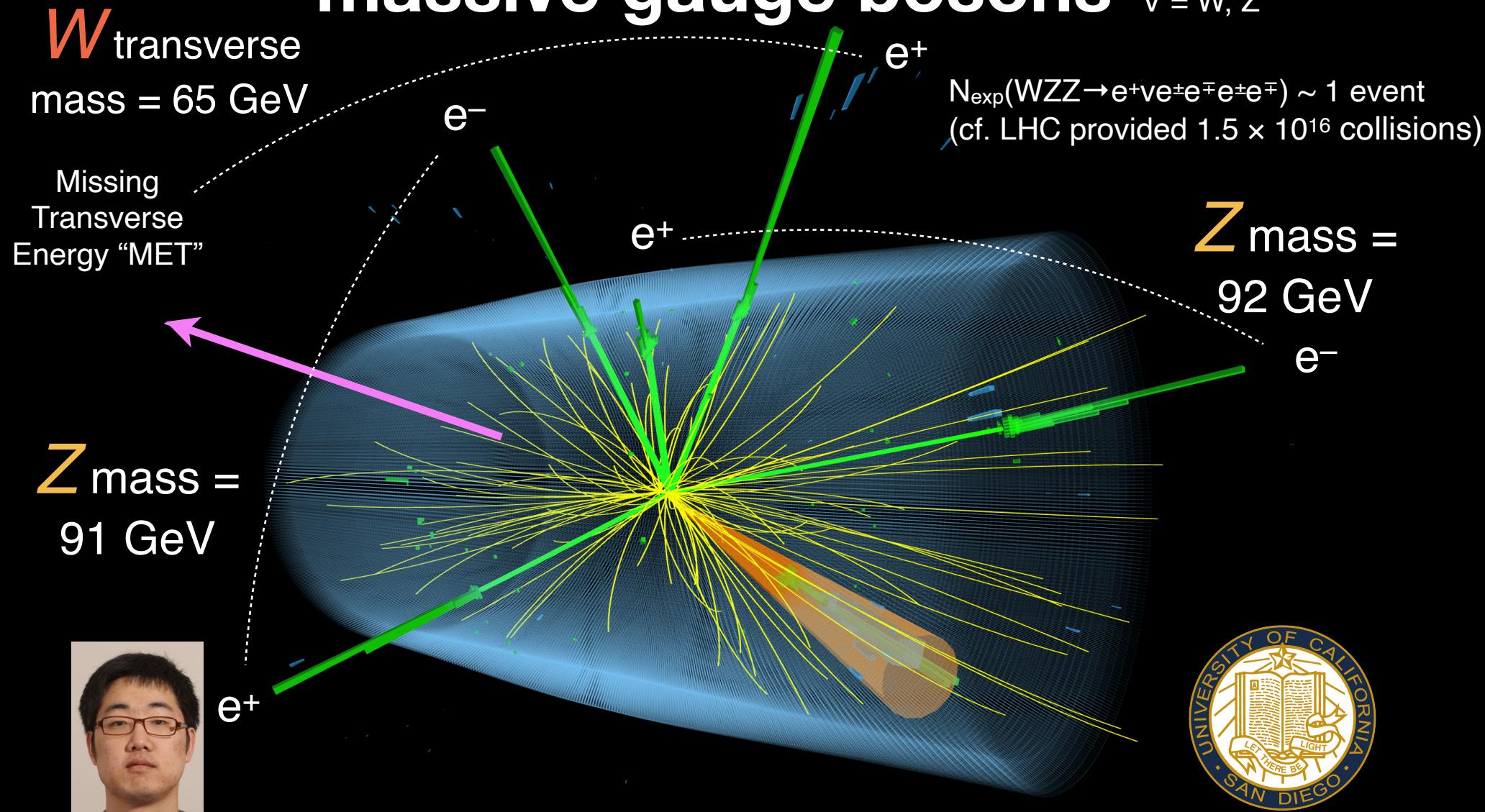
Korea Univ. HEP Seminar
July 2, 2020



Univ. of California
San Diego

First observation of production of three massive gauge bosons

$V = W, Z$



Philip
Chang

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San Diego

Discovery of Higgs boson

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July 4, 2012

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe



Discovery advanced our knowledge of origin of mass in a major way

More work to be done in electroweak sector

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Quarks

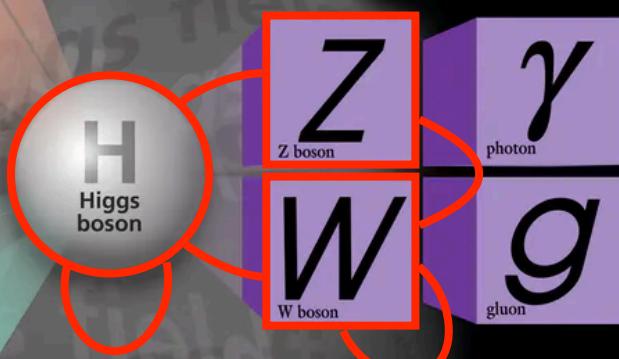
u	c	t
up	charm	top

e	μ	τ
electron	muon	tau
ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

Leptons

massive bosons

Forces



- Is it the only Higgs boson?
(or are there more?)
- Are multi-*bosons* interactions SM?
- Are there more states involved in electroweak symmetry breaking?
- Is the Higgs potential SM?

Many more to be studied on electroweak sector at the LHC

Multi-*boson* electroweak interactions

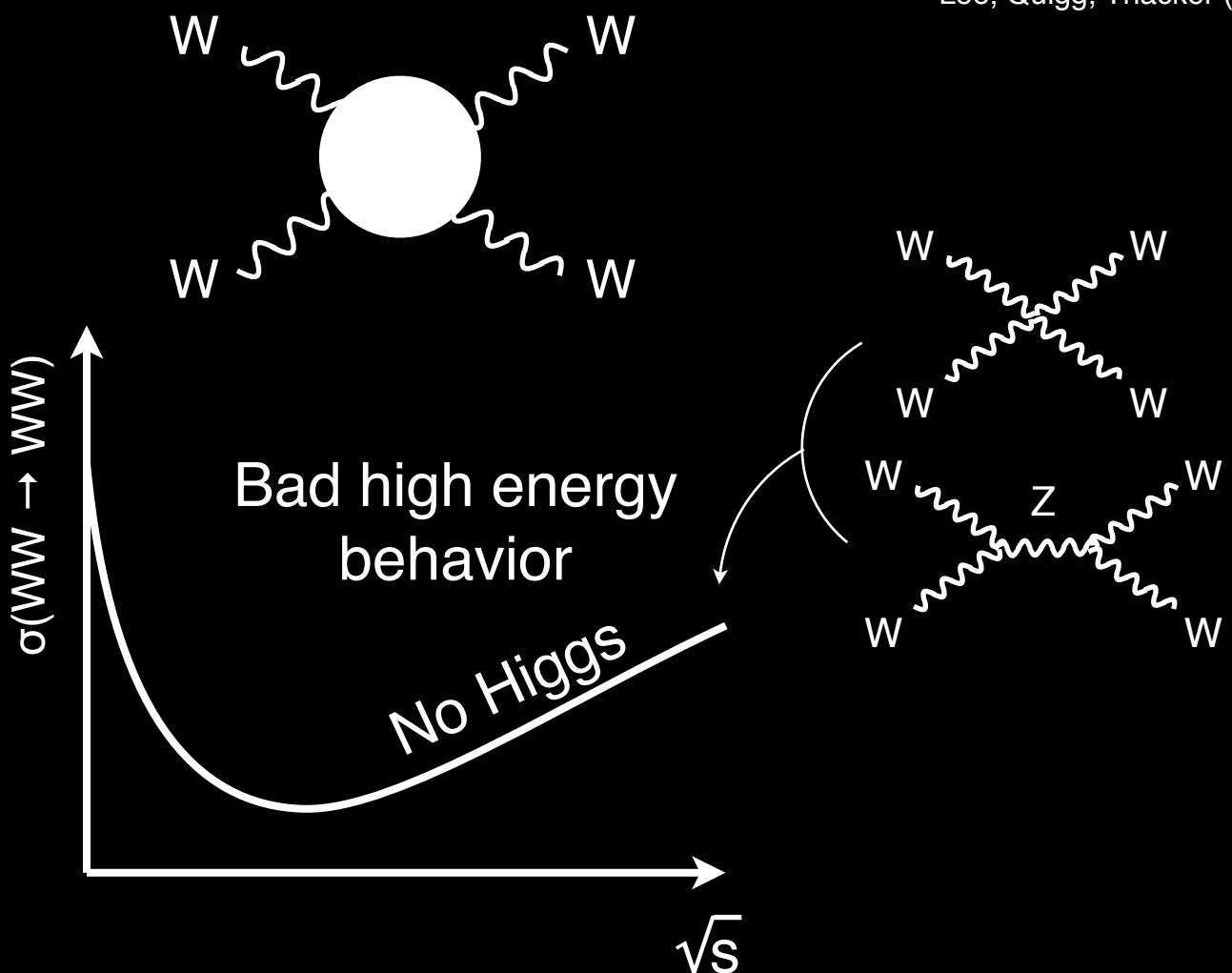
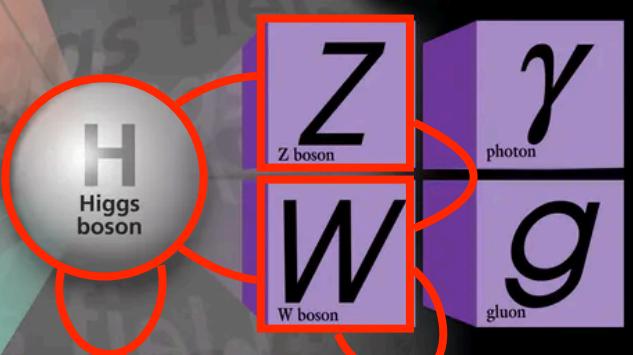
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Lee, Quigg, Thacker (1977)

massive bosons

Forces



Multi-*boson* electroweak interactions

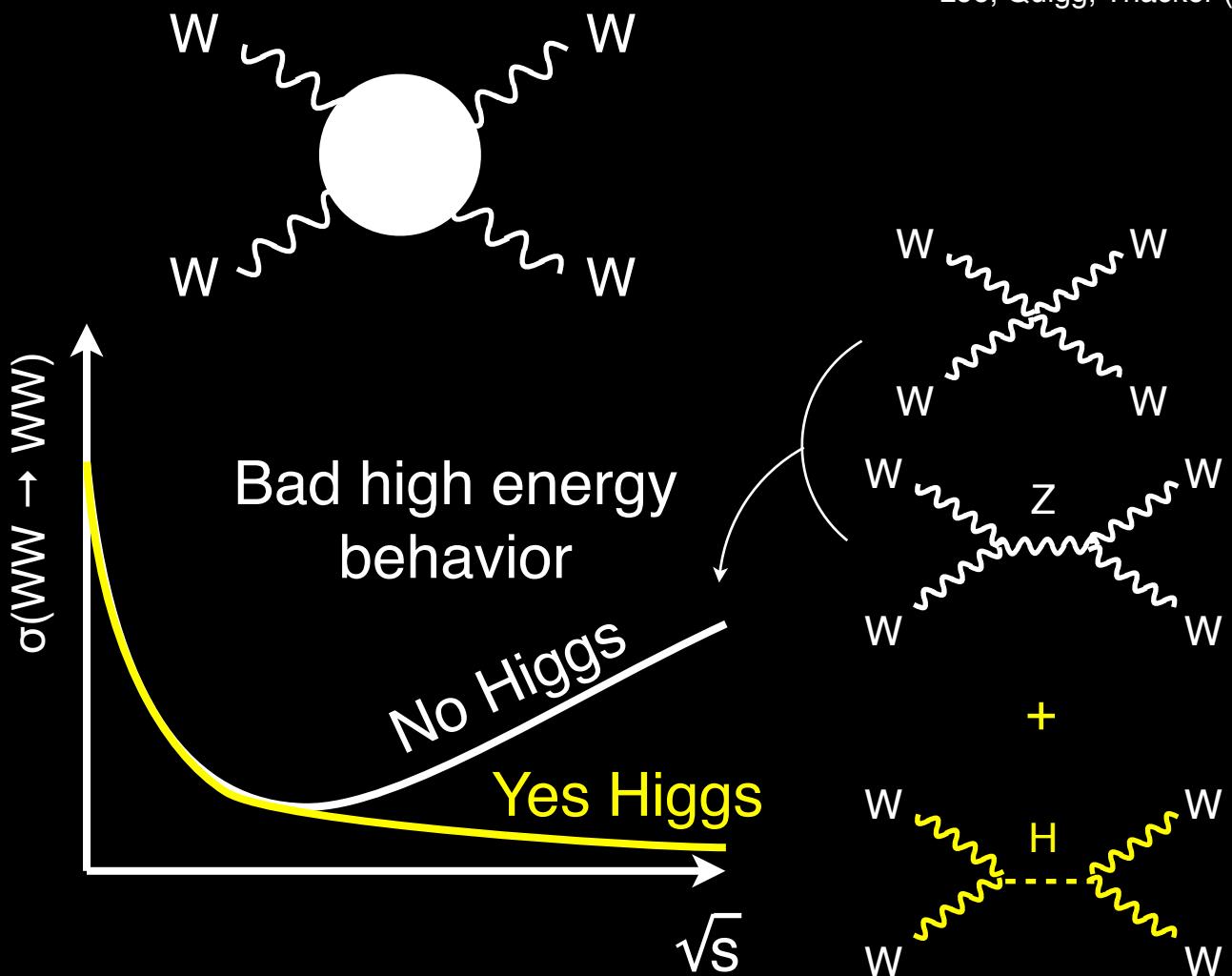
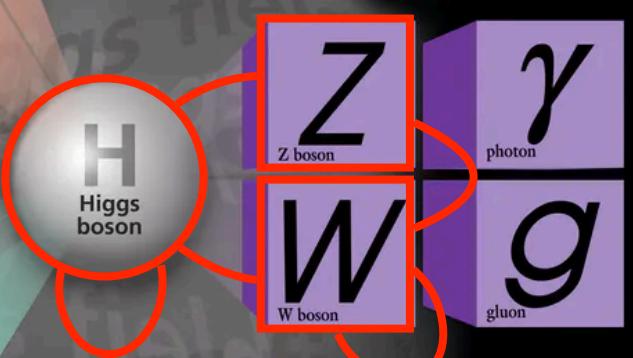
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massive bosons

Forces



Multi-*boson* electroweak interactions

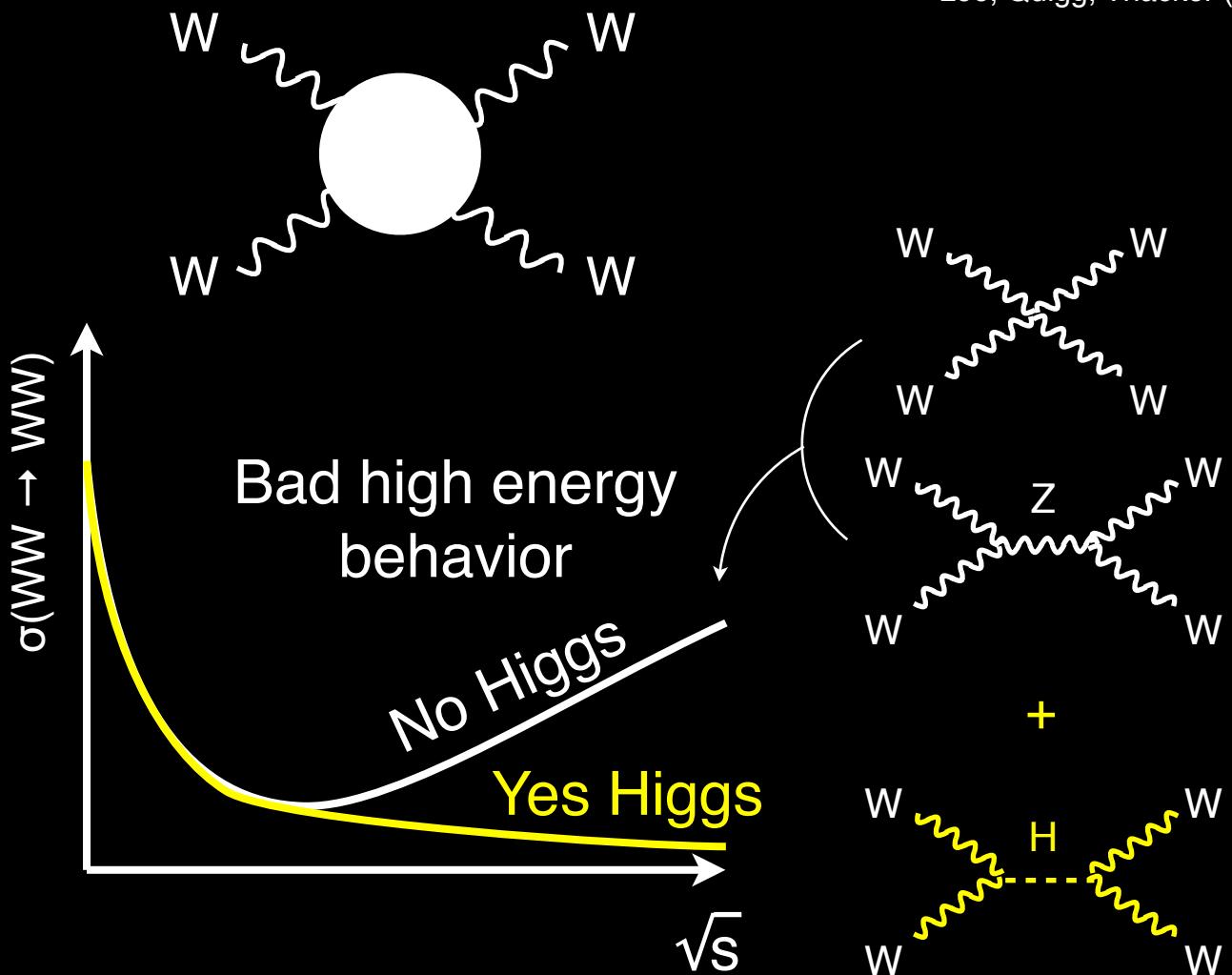
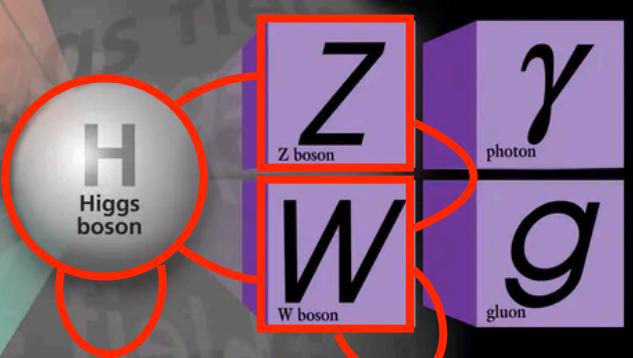
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Lee, Quigg, Thacker (1977)

massive bosons

Forces



Is this picture all SM-like?

Multi-*boson* electroweak interactions

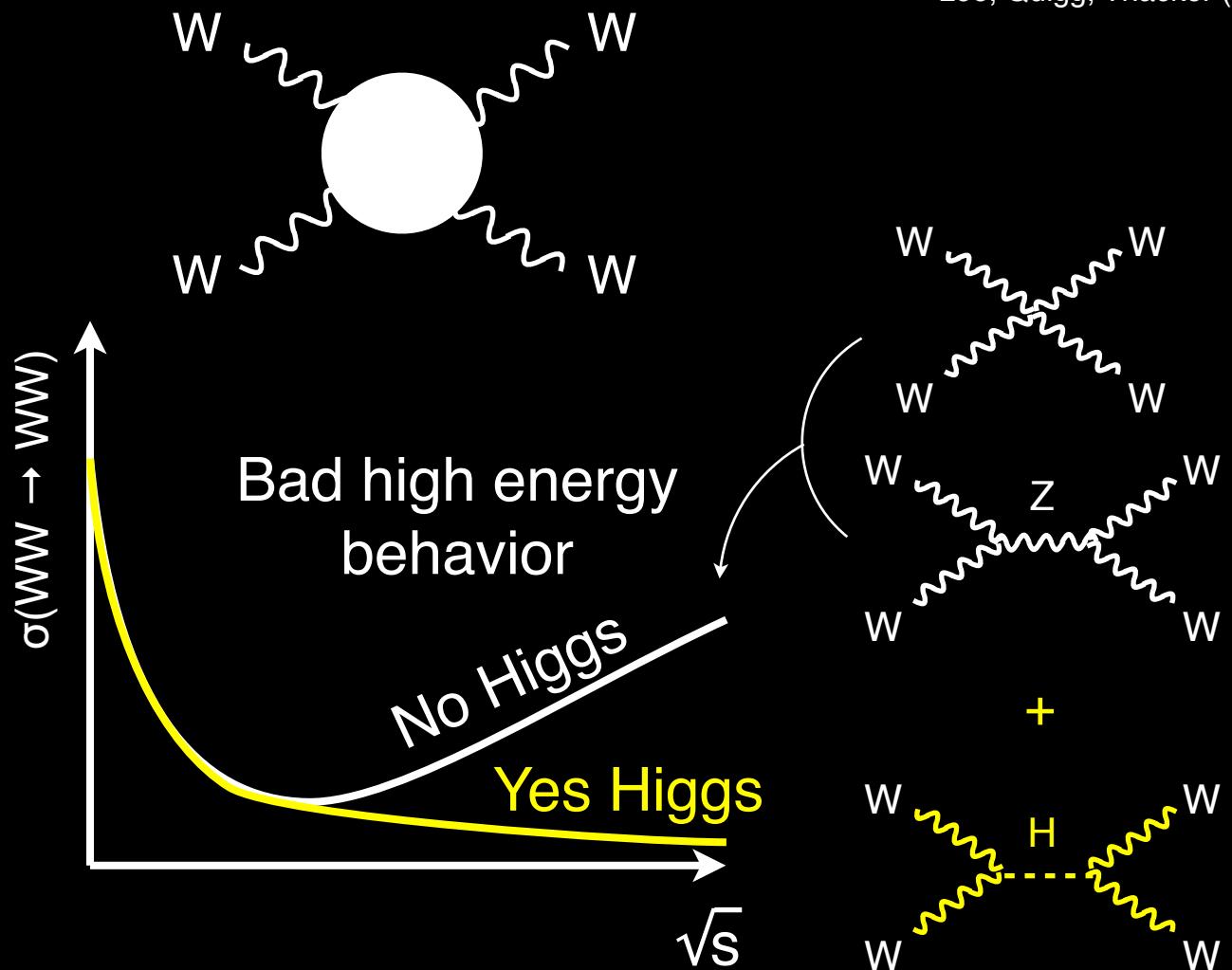
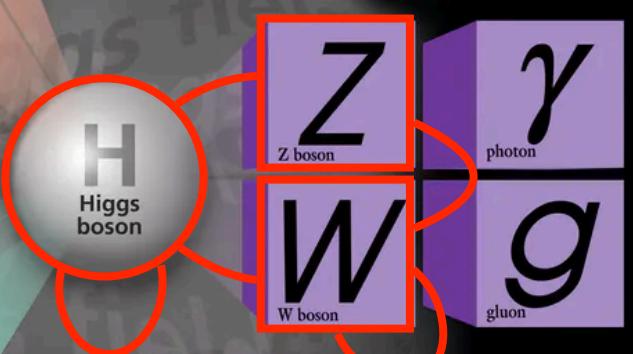
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Lee, Quigg, Thacker (1977)

massive bosons

Forces

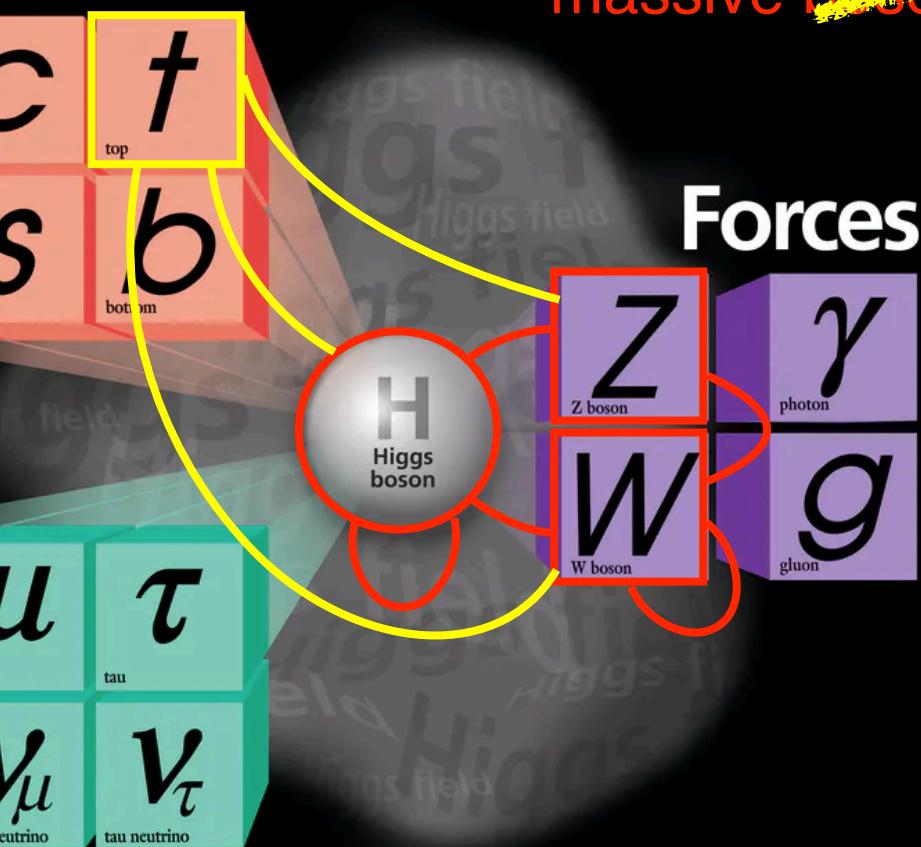


Is this picture all SM-like?

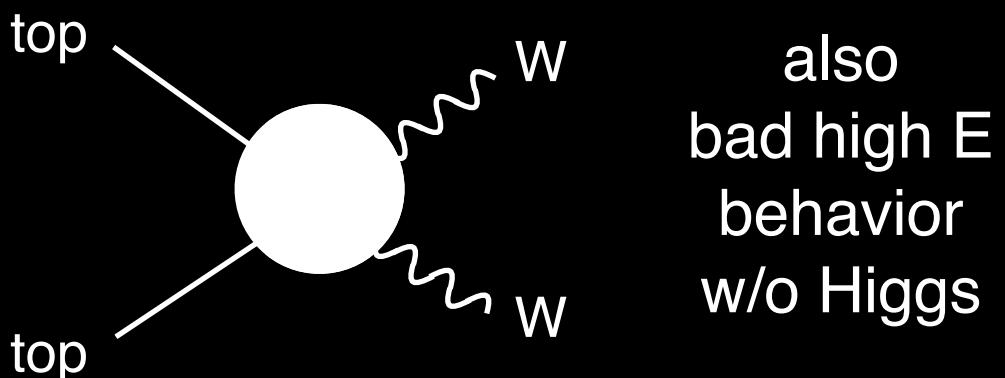
Higgs boson is integral to the multi-*boson* interactions

Multi-X electroweak interactions

Top is also connected



massive bosons -X



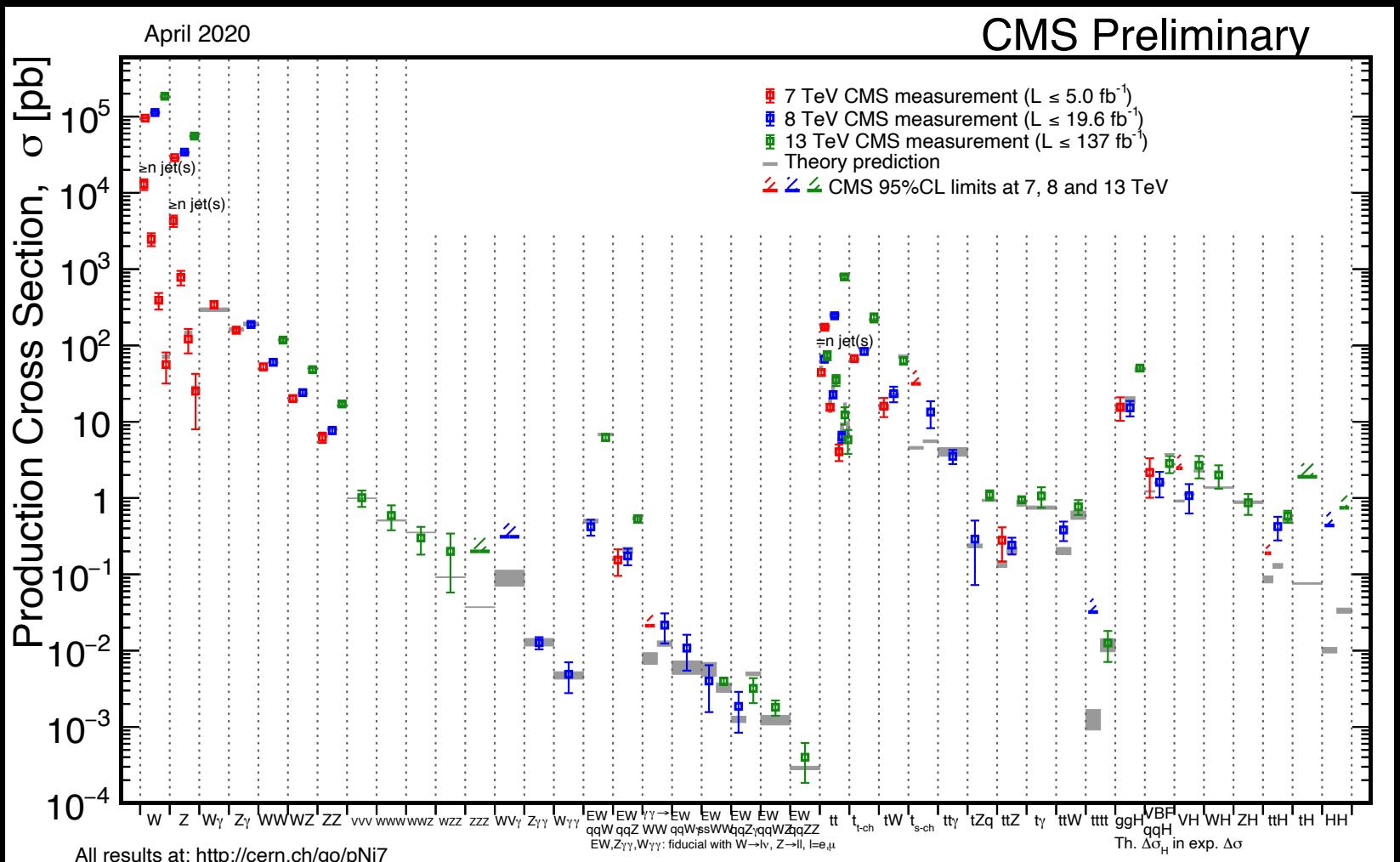
1978 (way) before top/W/Z/Higgs discovery
Chanowitz, Furman, Hinchliffe

F, W^\pm , Z and H become “sthenons” in the sense of Appelquist and Bjorken [4] : they couple strongly to one another ^{*1} 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

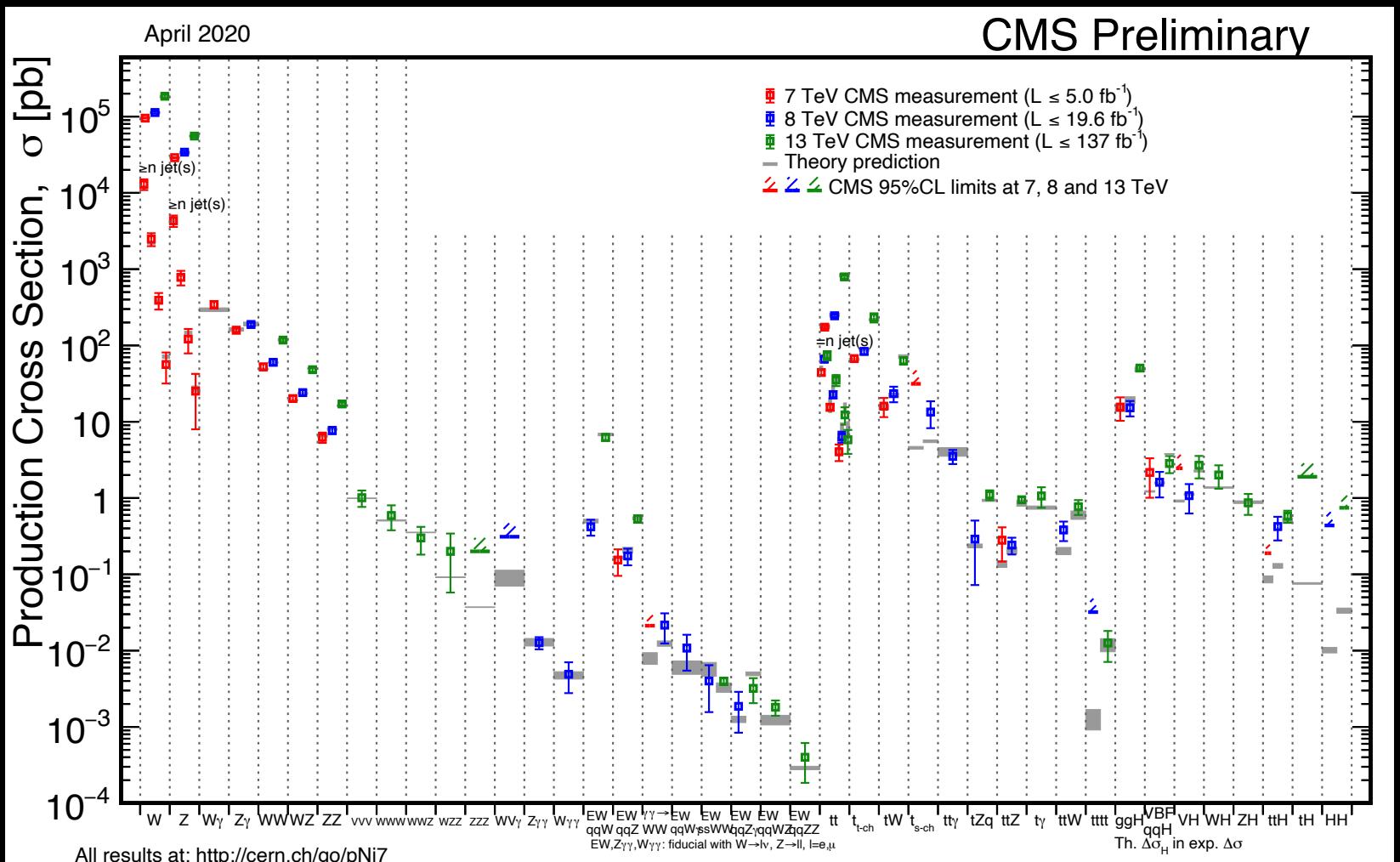
Multi-X processes are rare and “heavy”

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Multi-X processes are rare and “heavy”

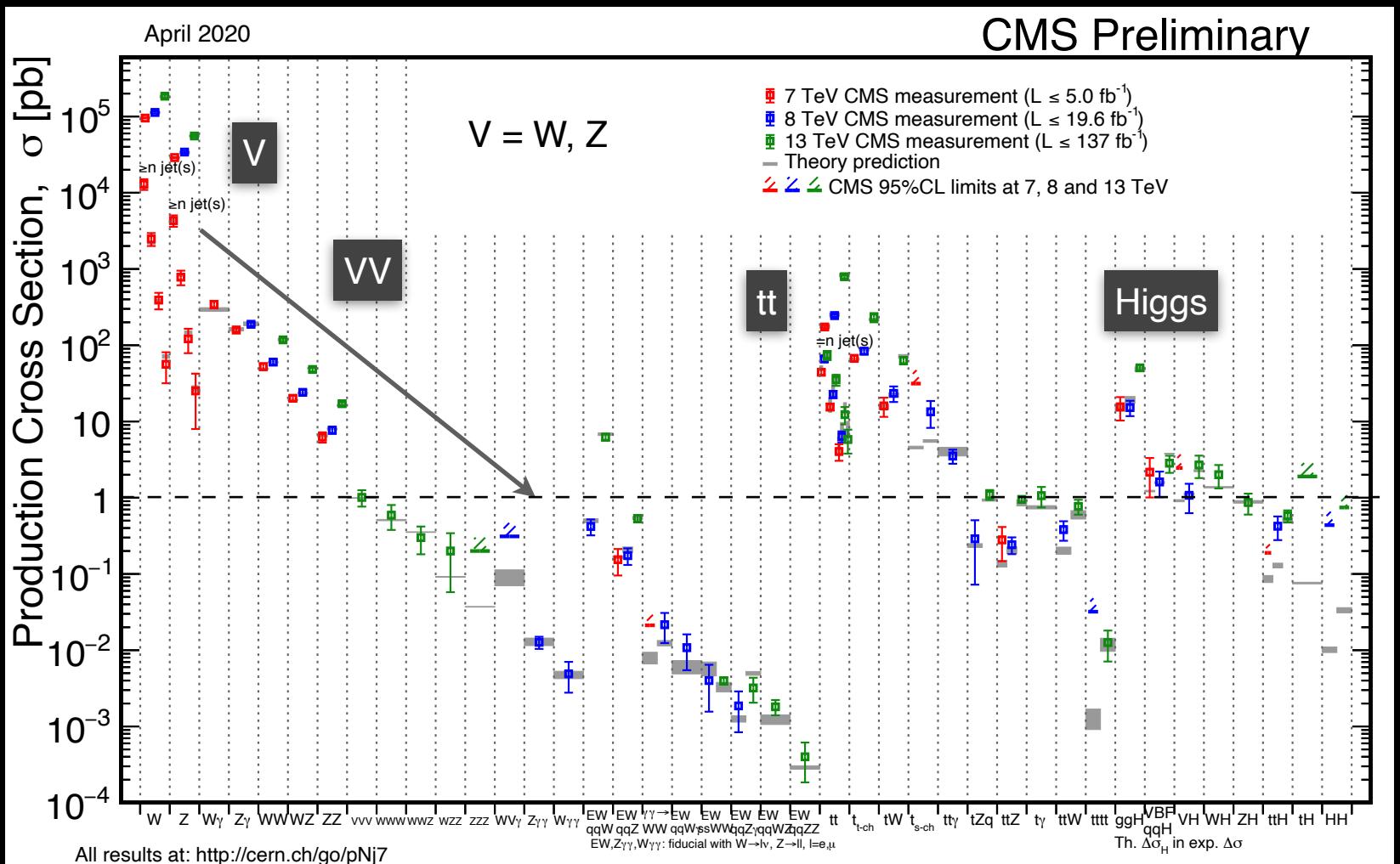
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N.B. xsec \times decay BR can be even smaller

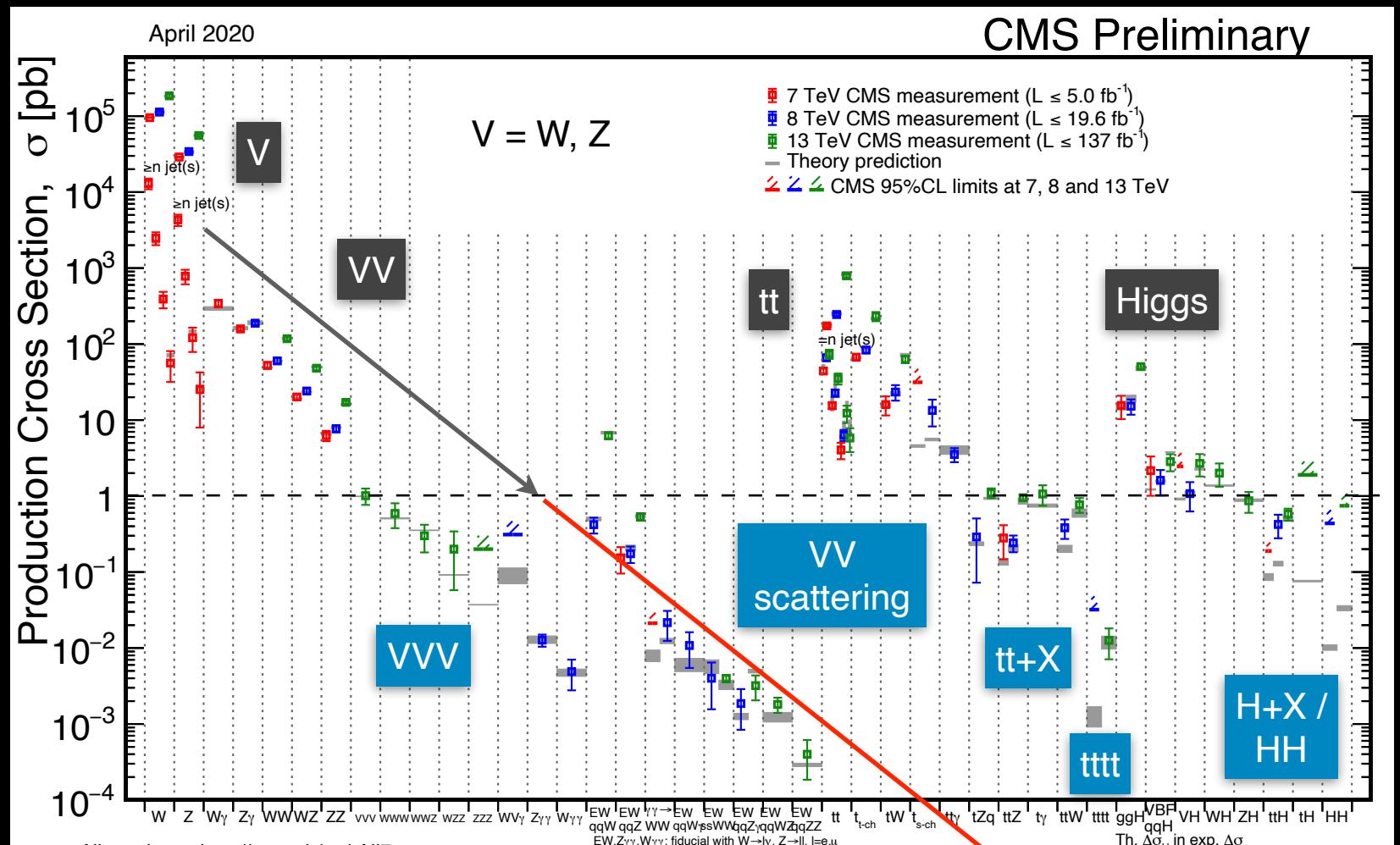
Multi-X processes are rare and “heavy”

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Multi-X processes are rare and “heavy”

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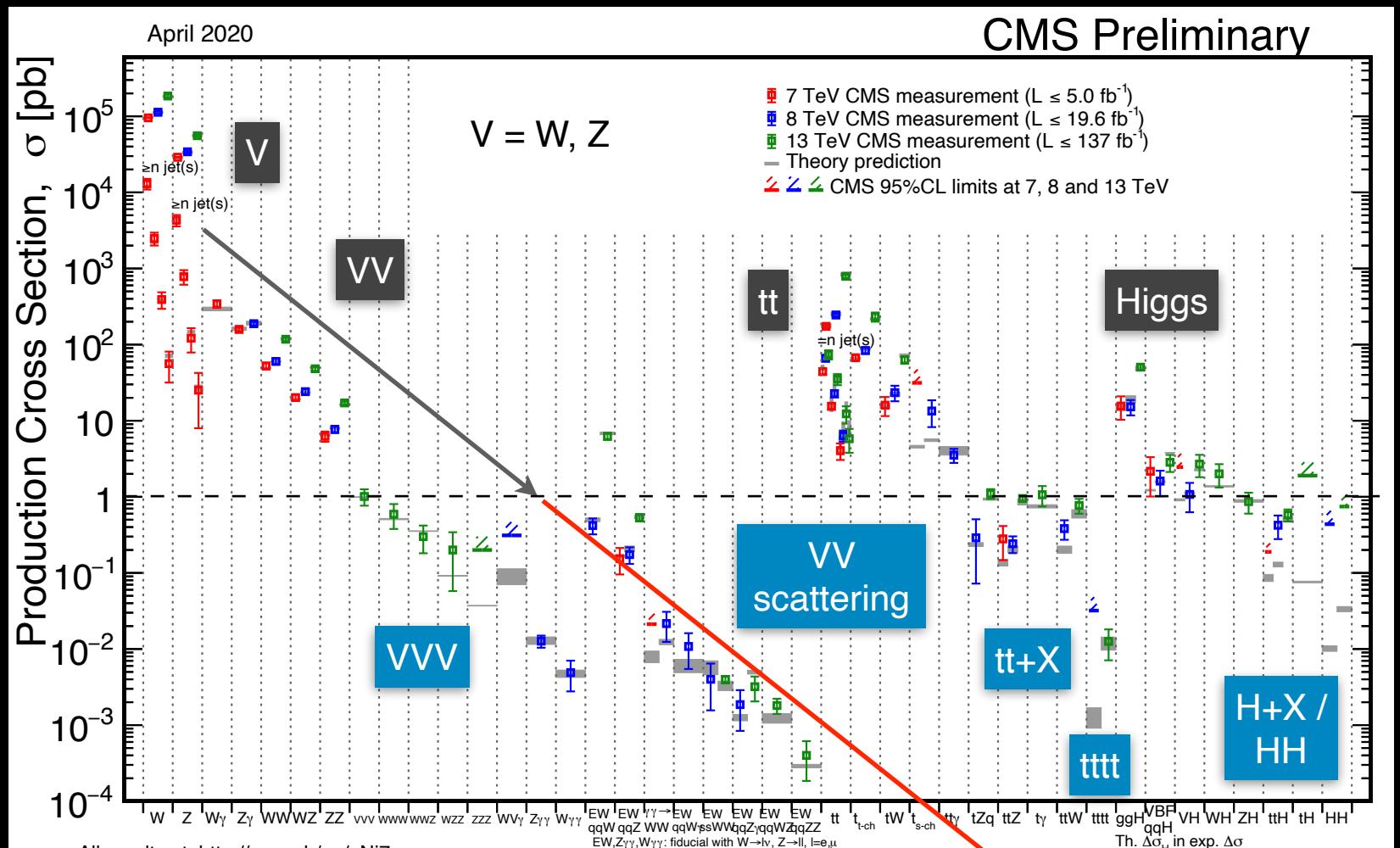
multi-massive-X productions

$X = t, W, Z, H$

Multi-X processes are rare and “heavy”



Rarer (and “heavier”) events



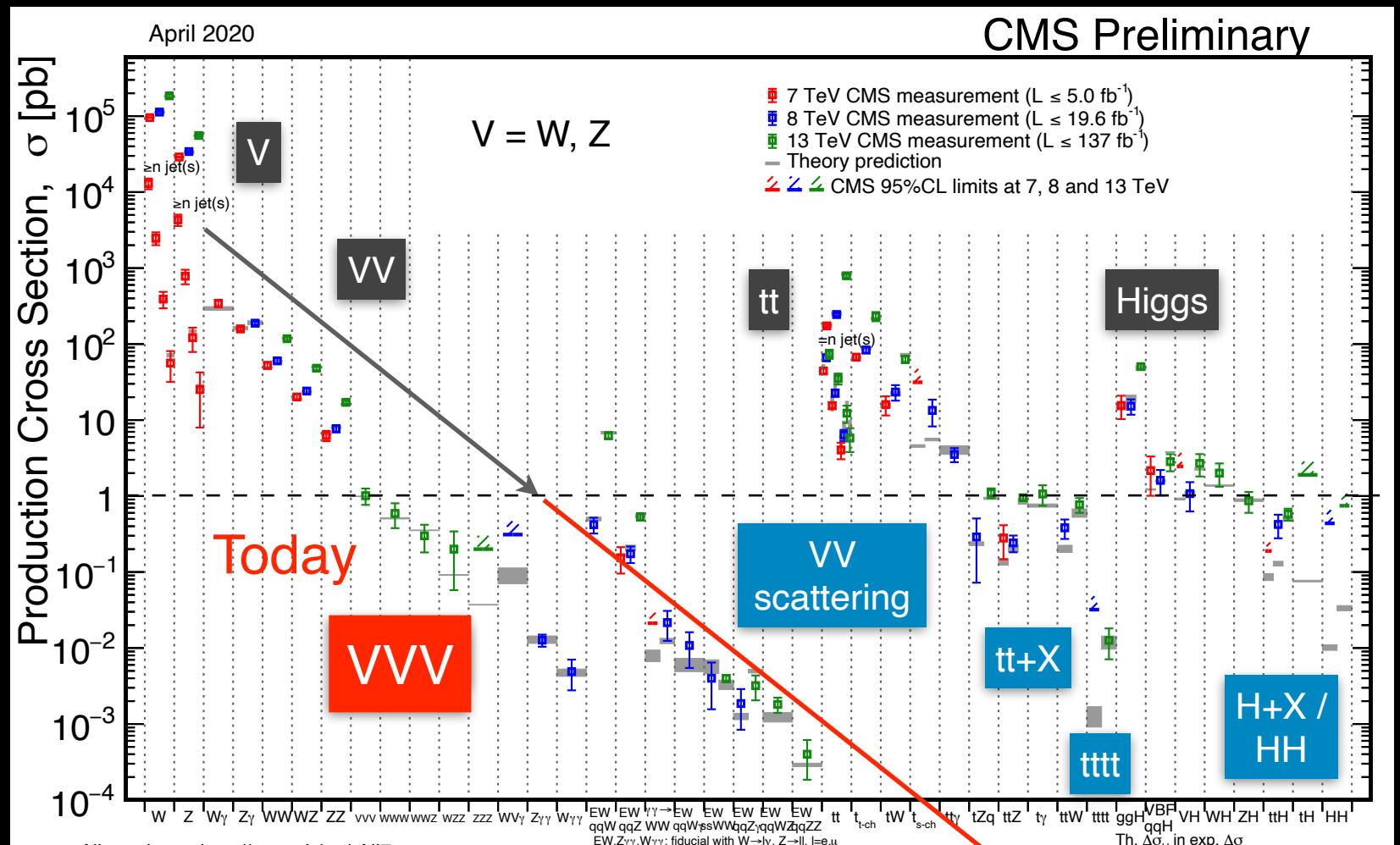
multi-massive-X productions

$X = t, W, Z, H$

Below picobarn most SM processes are electroweak multi-X production

Multi-X processes are rare and “heavy”

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multi-massive-X productions

$X = t, W, Z, H$

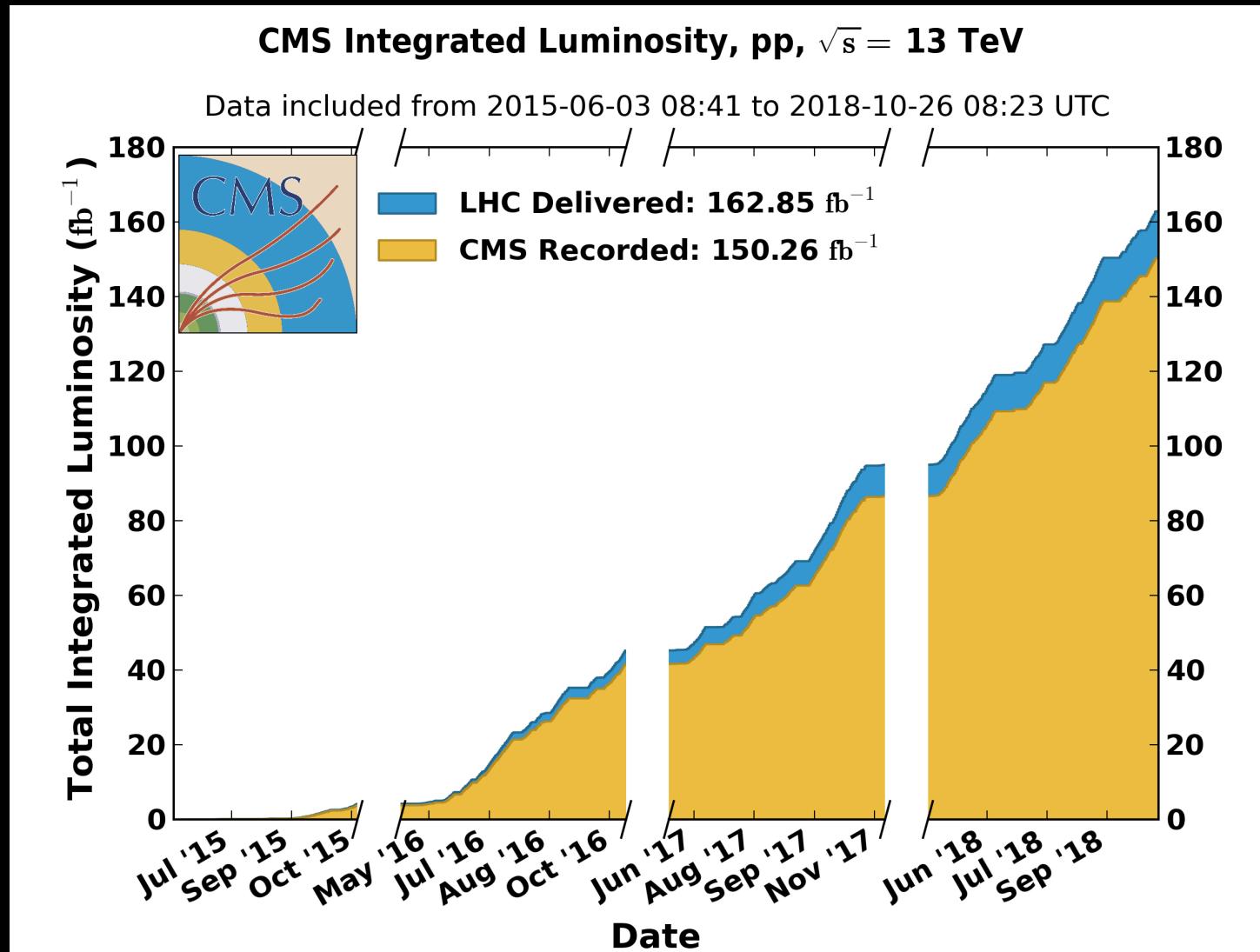
Below picobarn most SM processes are electroweak multi-X production

We need LHC's large and energetic pp collision data

because **rare**

because **"heavy"**

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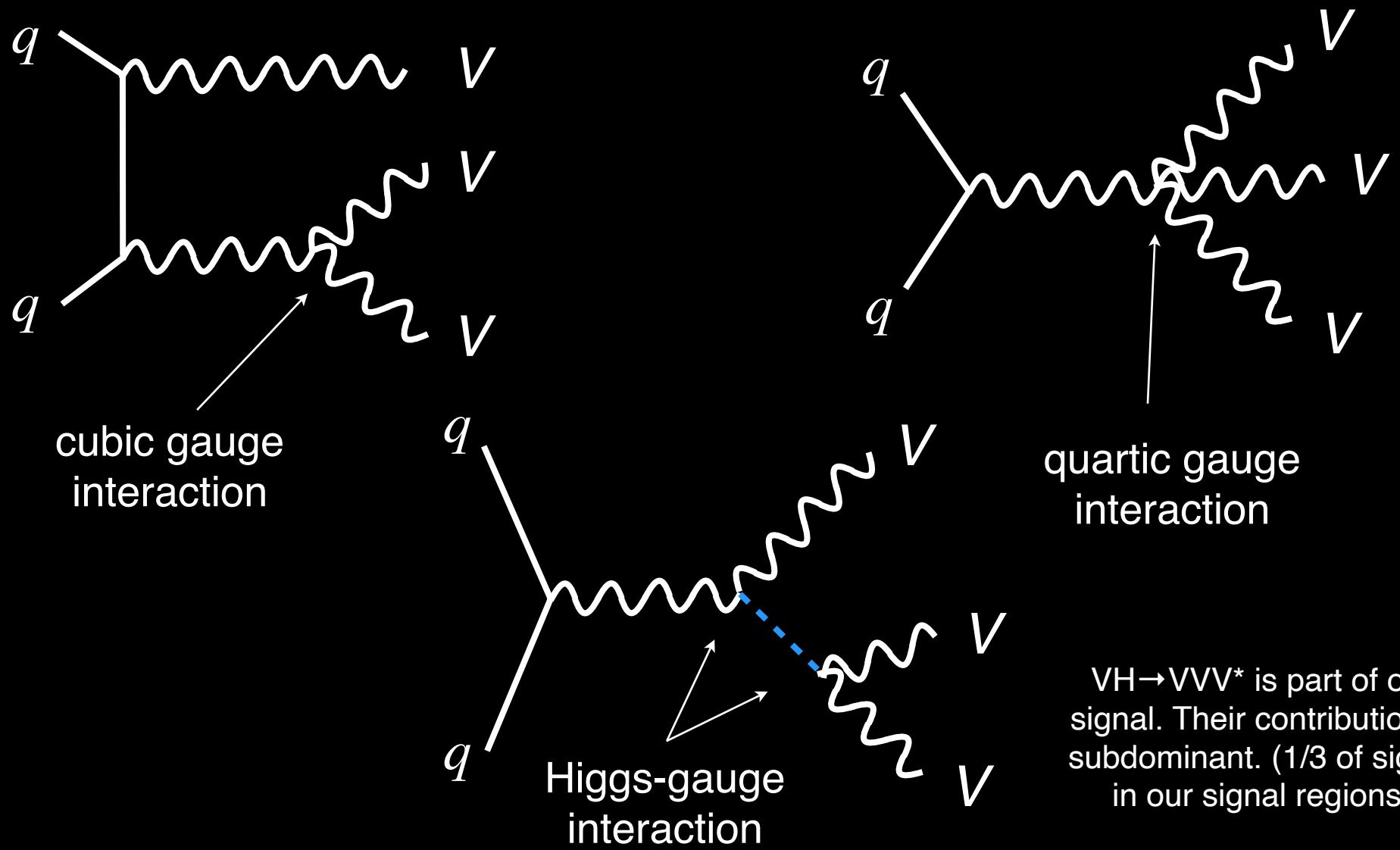
Multiply by 1000 to get the number of events produced for a picobarn process

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

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

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

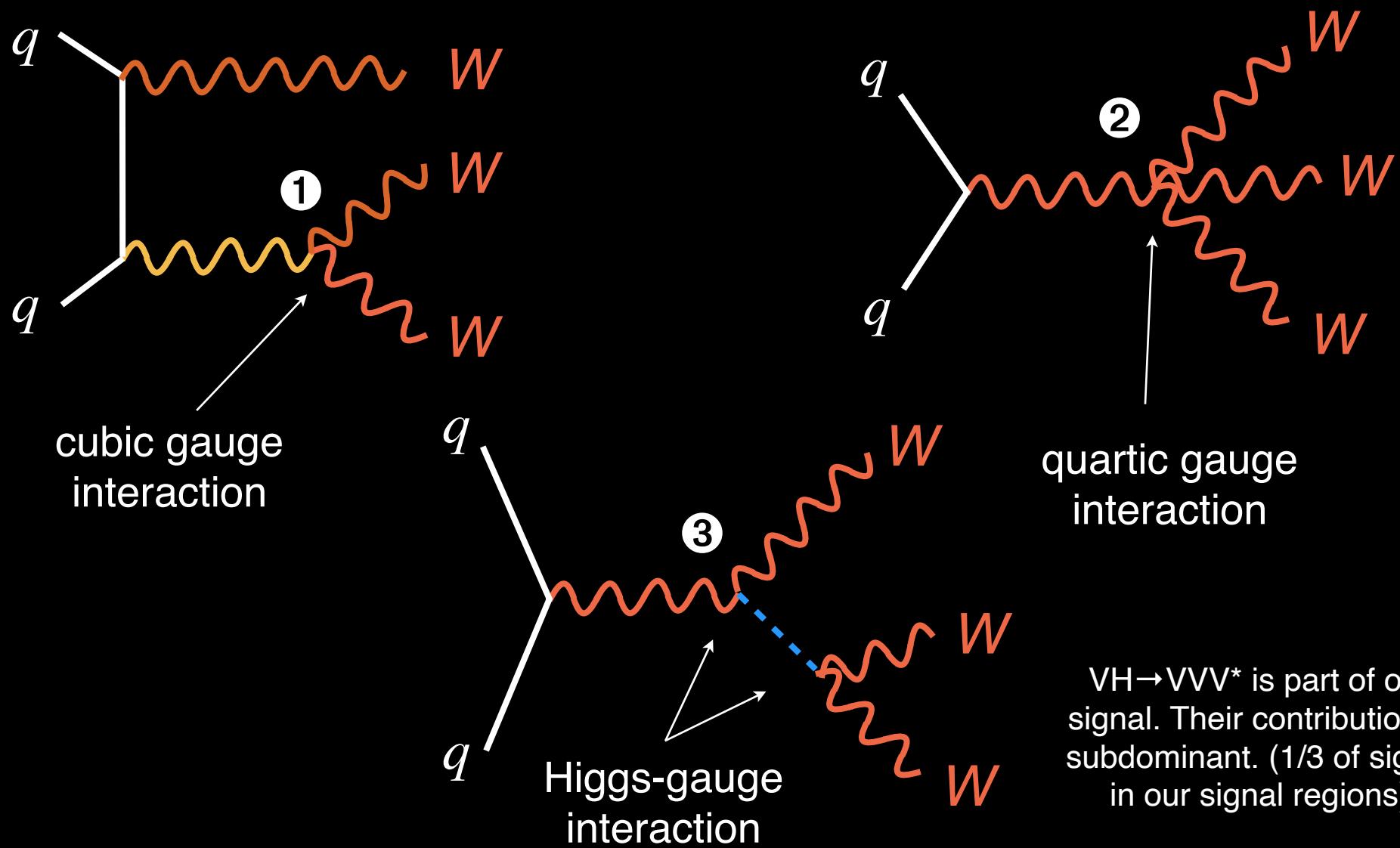
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$VH \rightarrow VVV^*$ is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

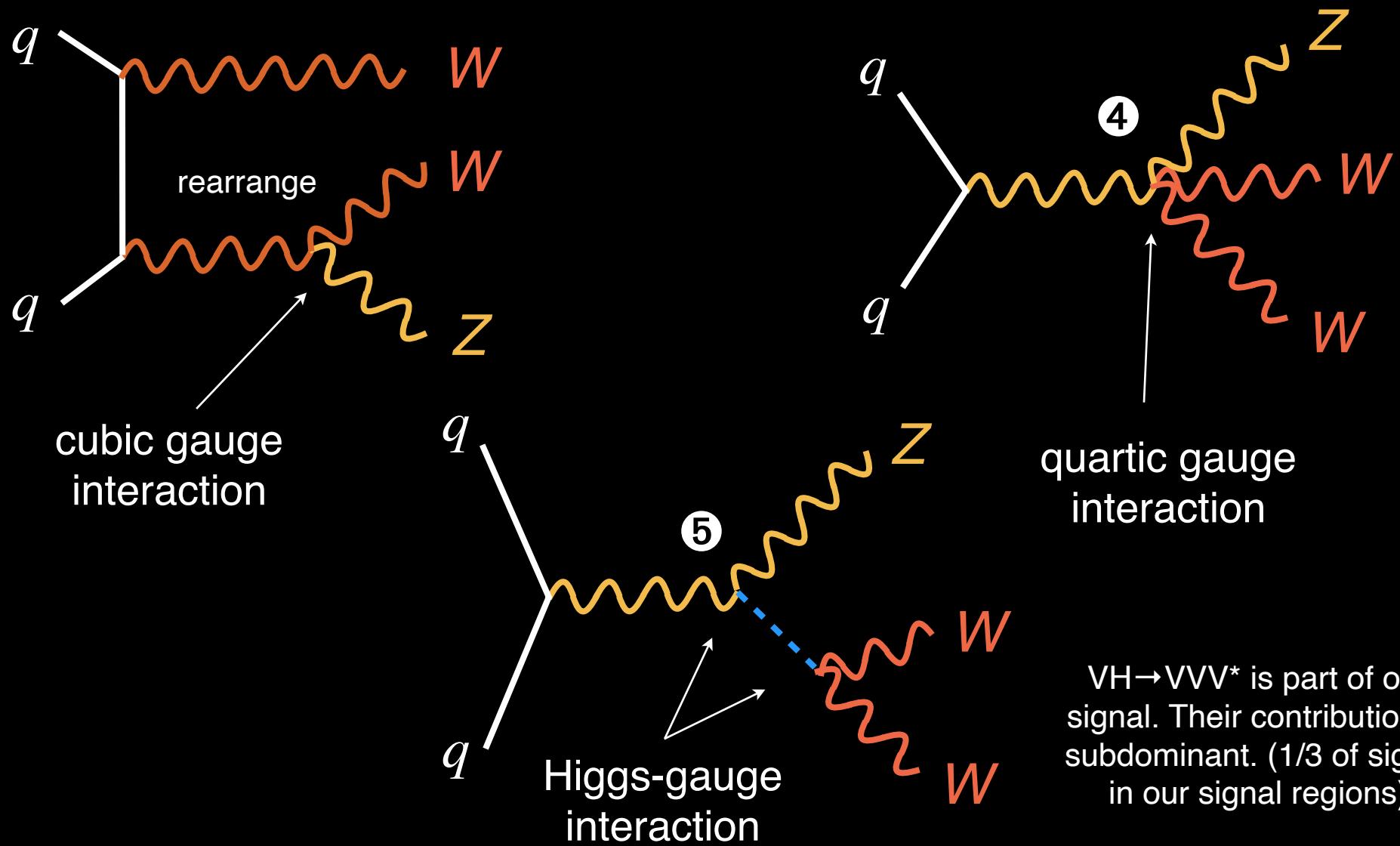
Triboson process has access to studying many multi-*boson* interactions

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



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

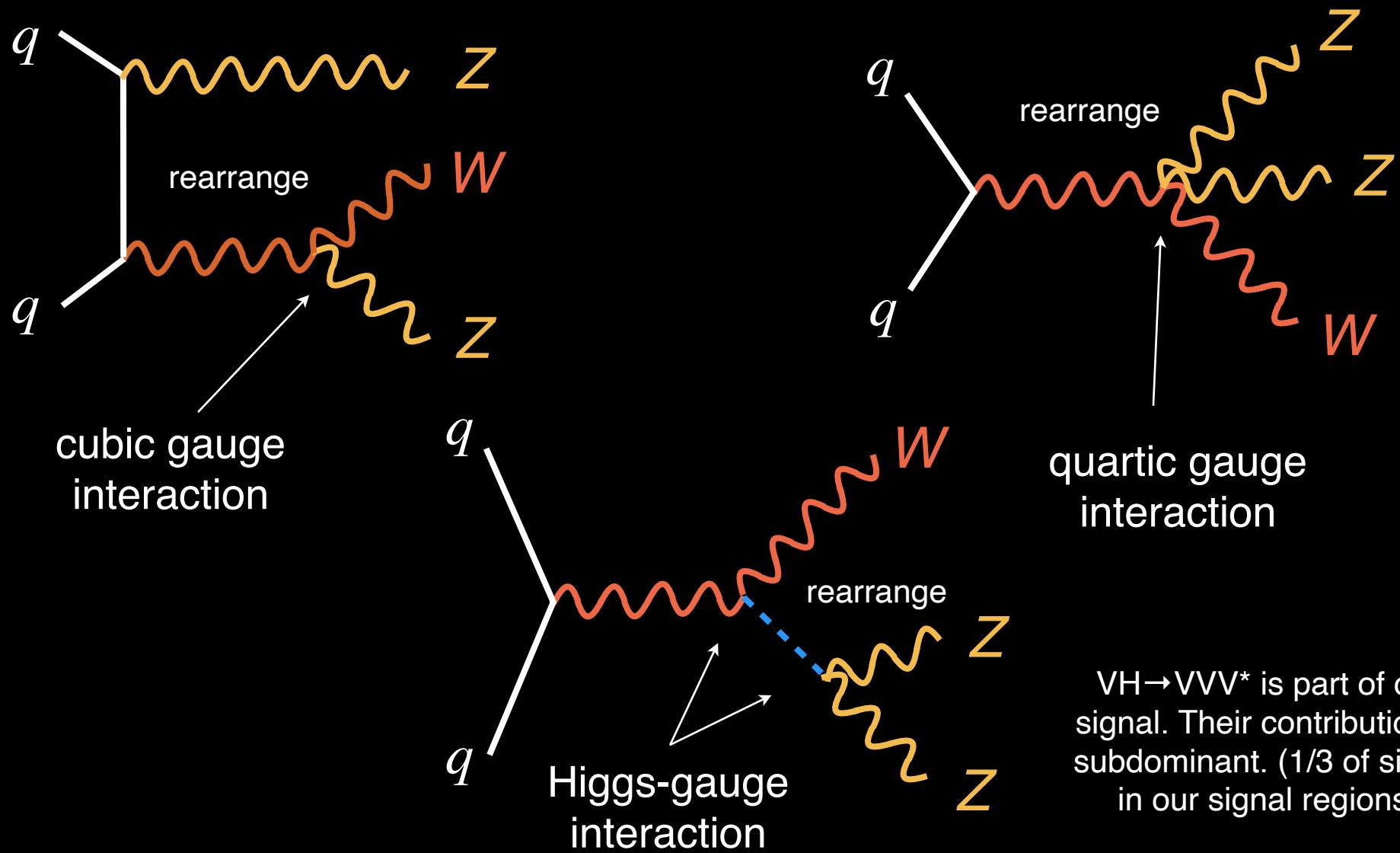
Physics of VVV production ($V = W, Z$)



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

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

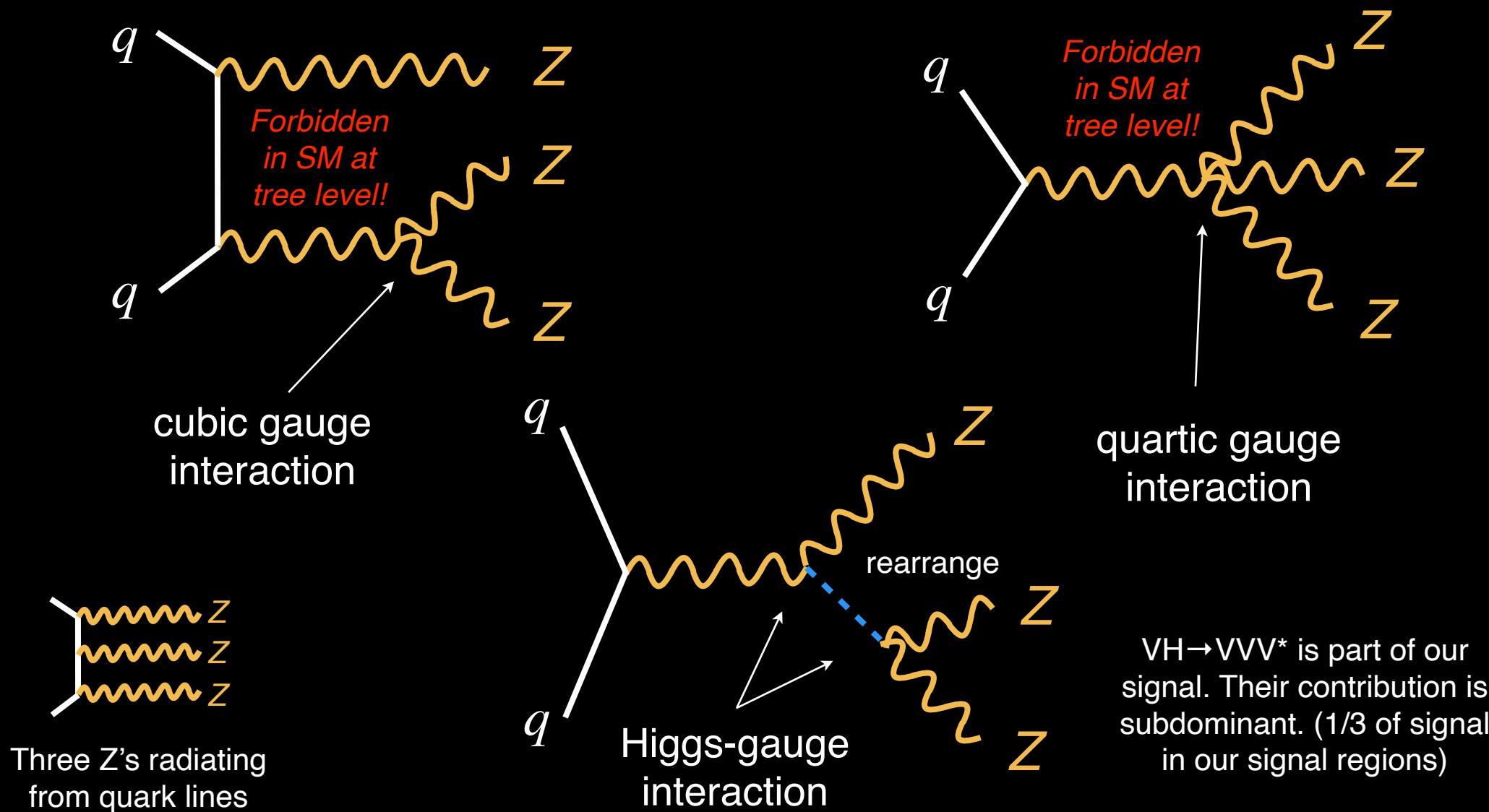
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Triboson process has access to studying many multi-*boson* interactions

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

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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

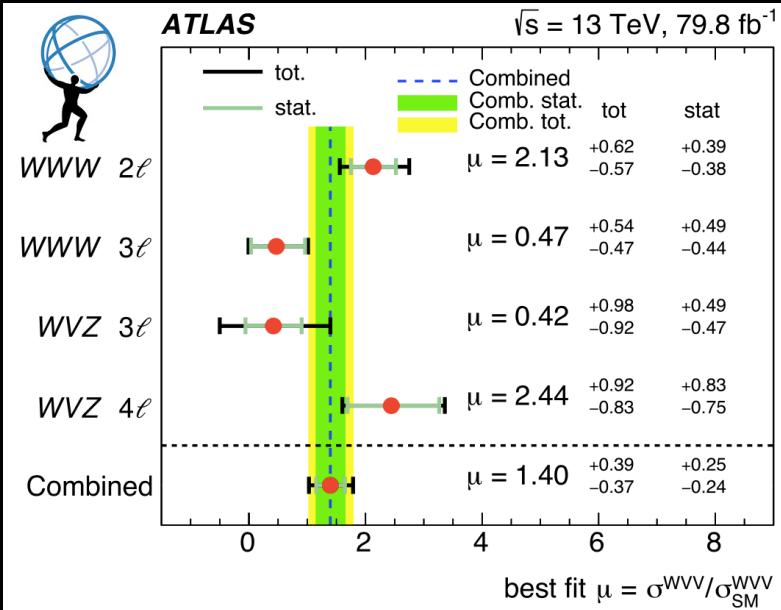
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- ATLAS searched for WWW in 8 TeV: 0.96σ (1.05σ) arXiv:1610.05088
- CMS searched for WWW in 13 TeV 36 fb^{-1} : 0.6σ (1.78σ) arXiv:1905.04246
- ATLAS searched for VVV in 13 TeV 80 fb^{-1} : 4.1σ (3.1σ) arXiv:1903.10415

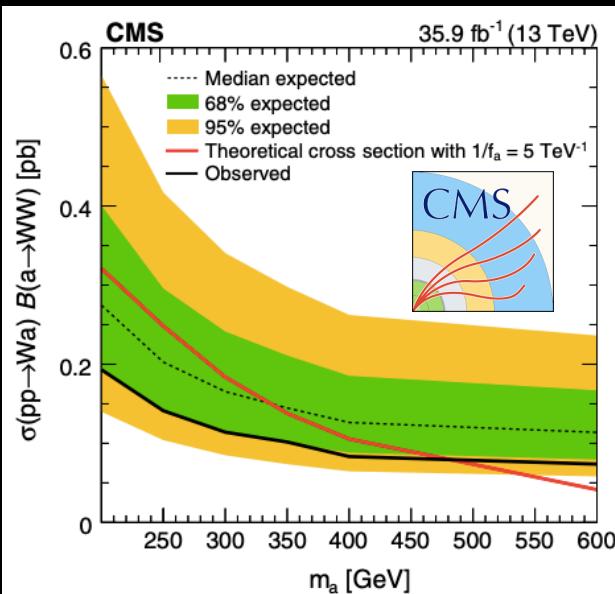
VVV evidence

VVV evidence



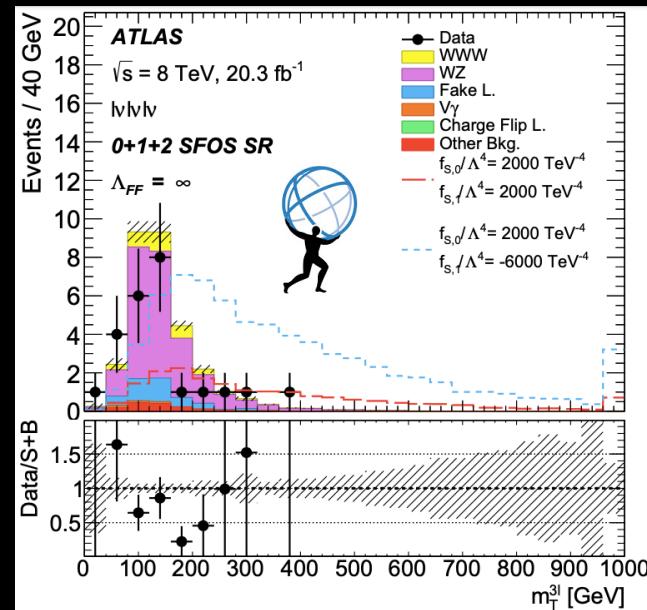
arXiv:1903.10415

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

Forces

Z Z boson	γ photon
W W boson	g gluon

e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Leptons

Decay of W, Z bosons

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Quarks

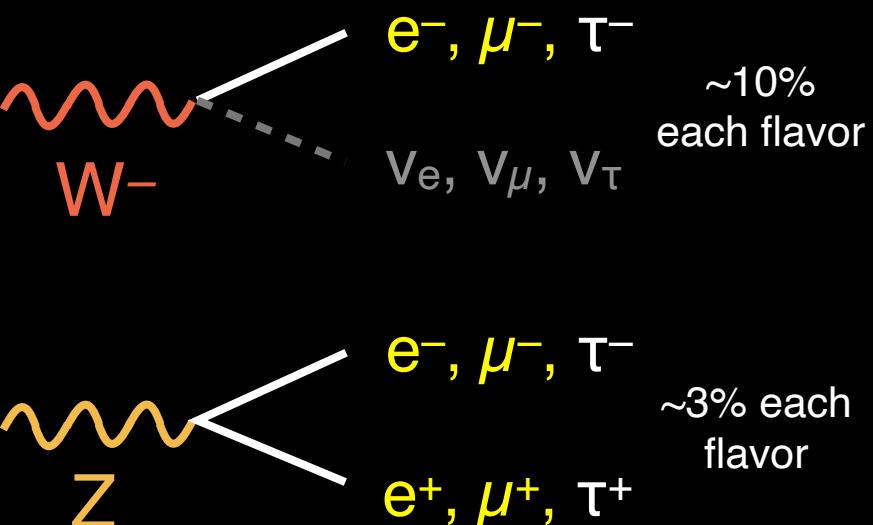
u up	c charm	t top
d down	s strange	b bottom

Once produced W, Z can decay to leptons

Forces

e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Leptons



Decay of W, Z bosons

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Quarks

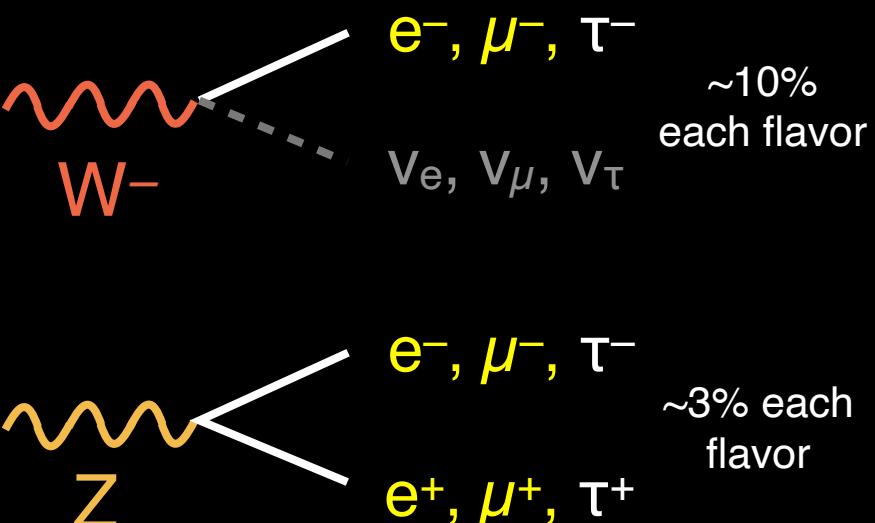
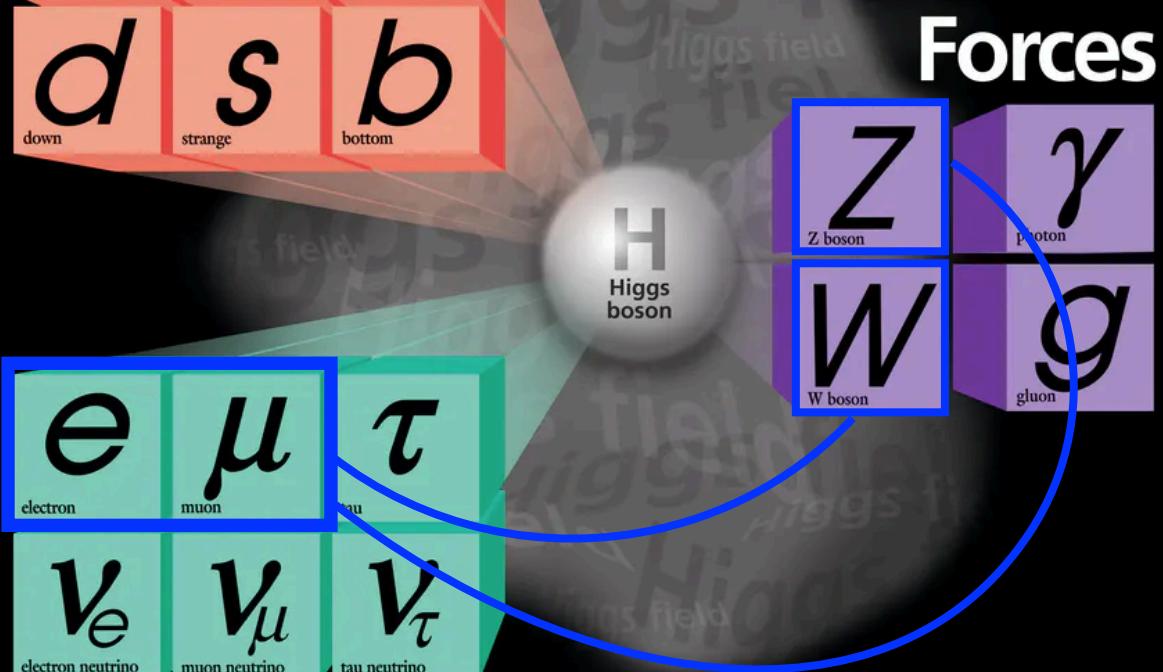
u	c	t
down	charm	top

e	μ	τ
electron	muon	tau

ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

Leptons

Once produced W, Z can decay to leptons



τ decays in the detector:

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

**We include e, μ from τ 's from W/Z decays in the analysis

Decay of W, Z bosons

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Quarks

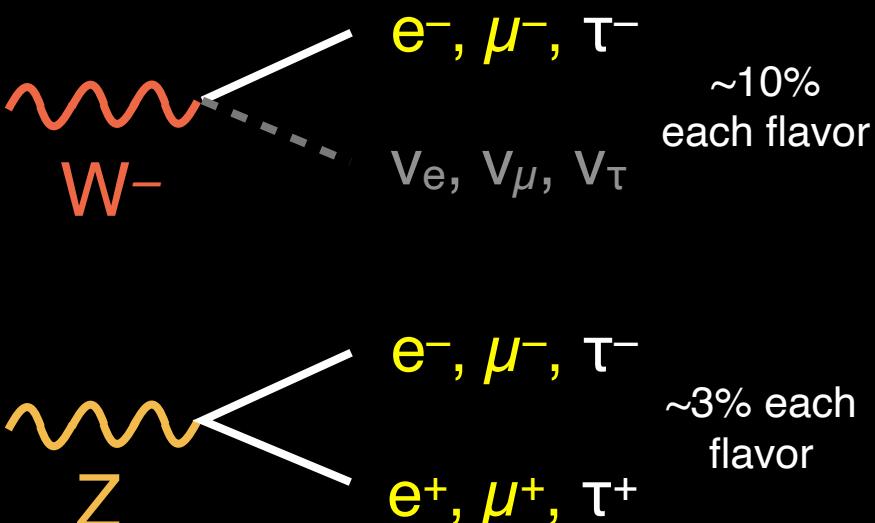
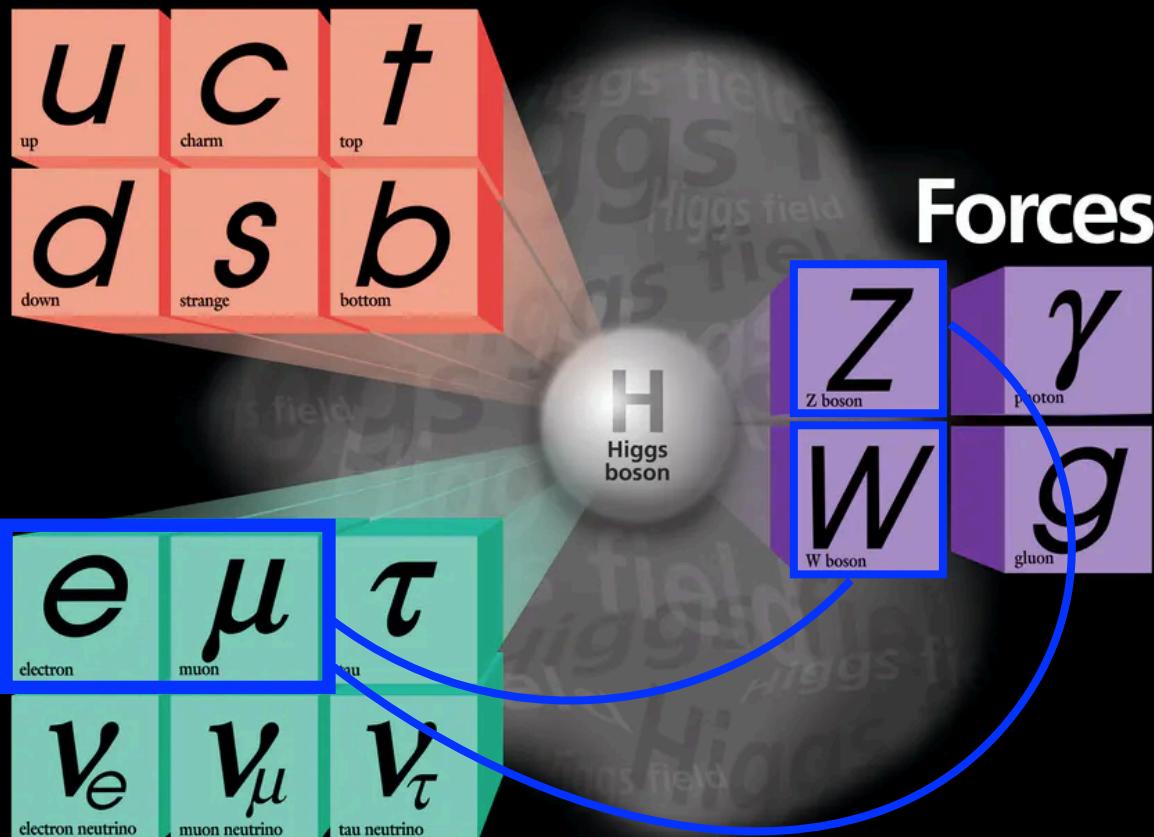
u	c	t
down	charm	top

e	μ	τ
electron	muon	tau

ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

Leptons

Once produced W, Z can decay to leptons



τ decays in the detector:

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**We include e, μ from τ 's from W/Z decays in the analysis

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

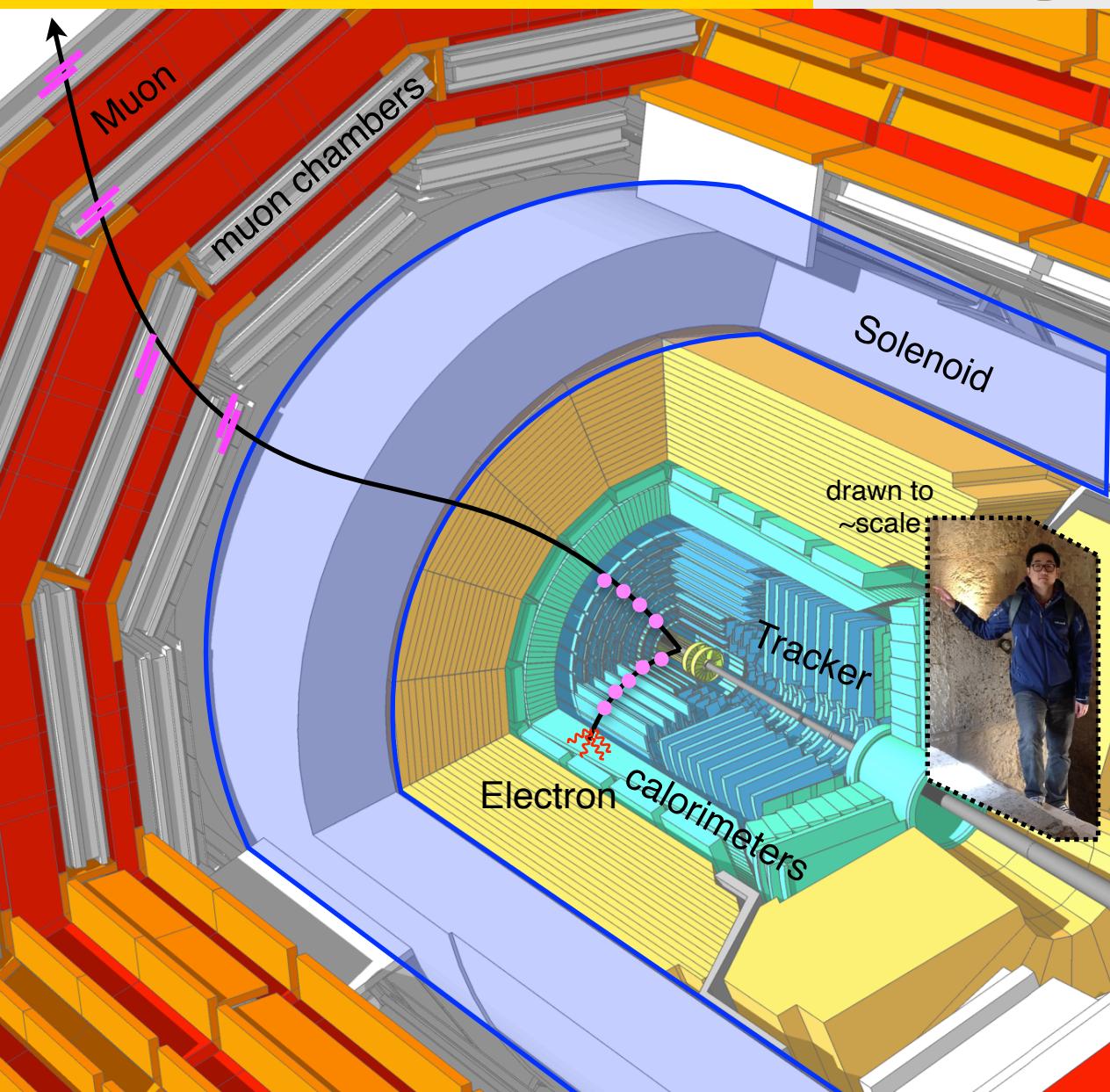
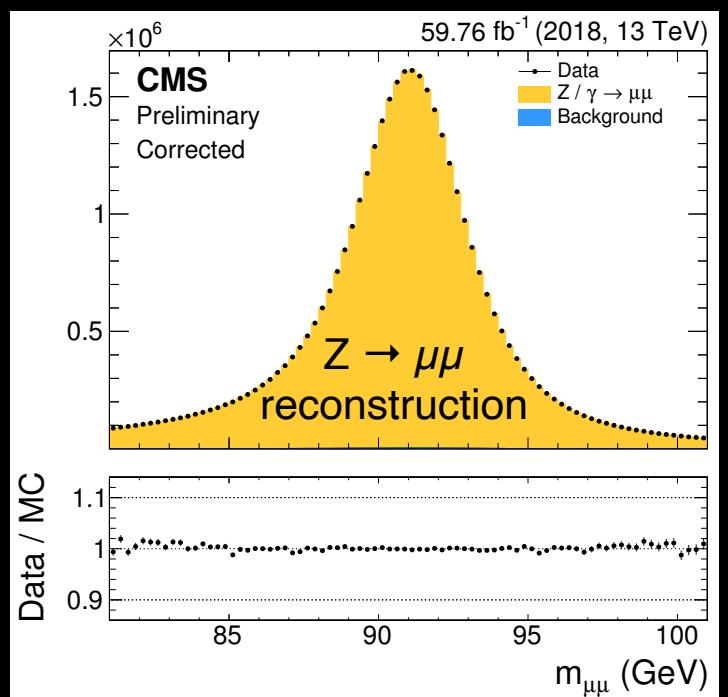
CMS detector measures leptons very well

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e/ μ 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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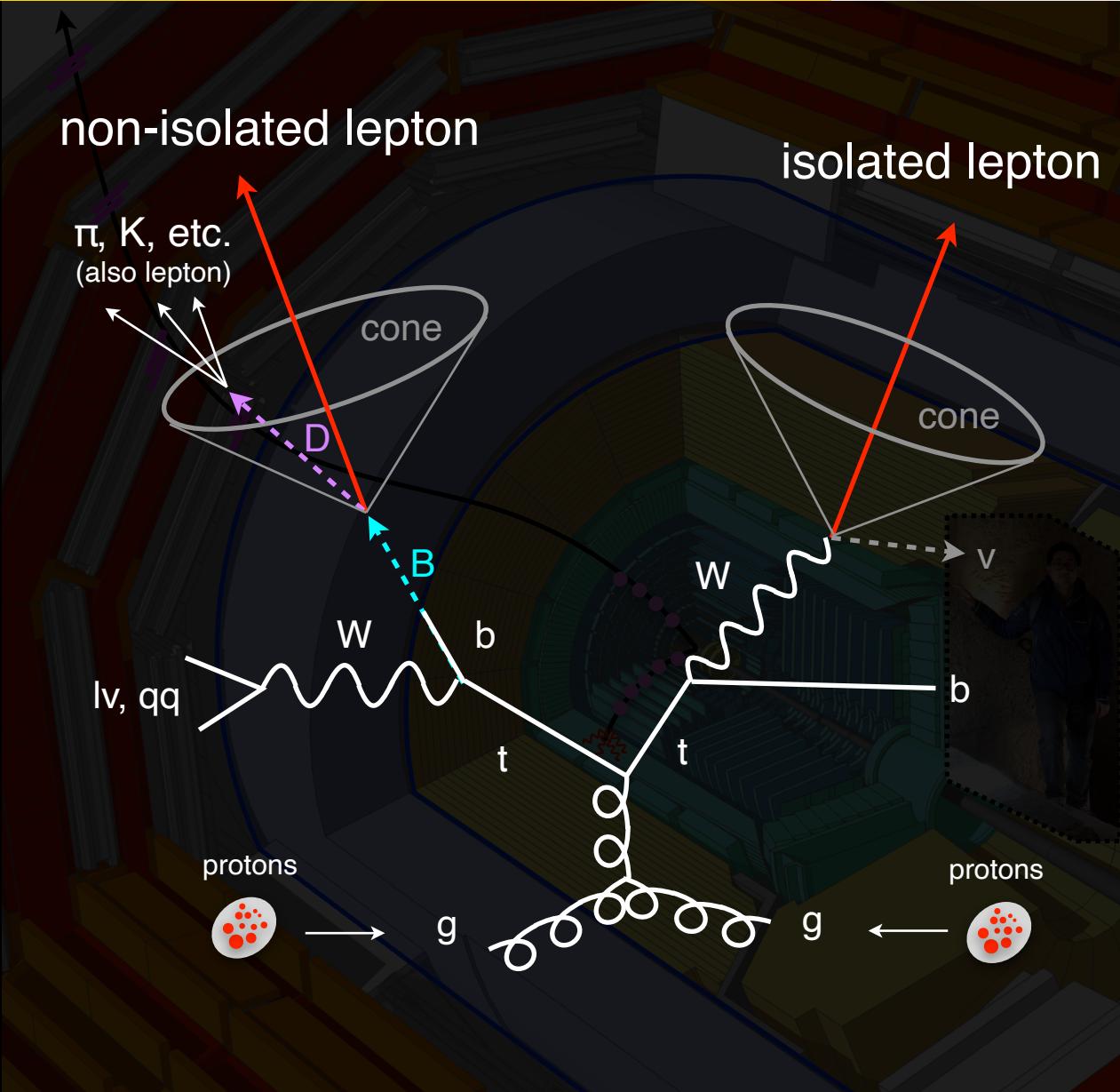


Identifying leptons is not enough

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 μ
- Important to measure e and μ (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!

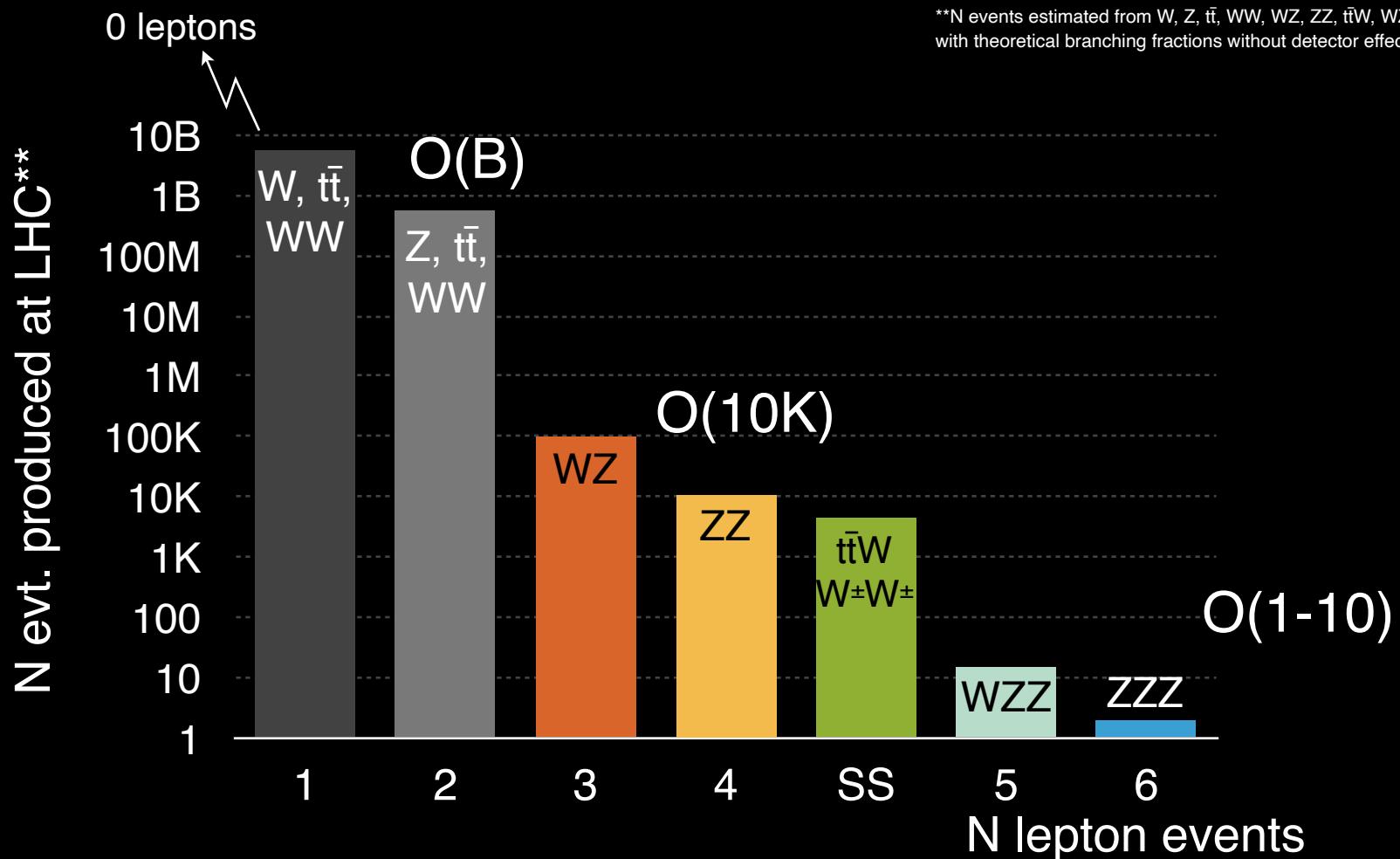
Smart humans and
smart machines
(Both cut / BDT)



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 $\tau \rightarrow e, \mu$



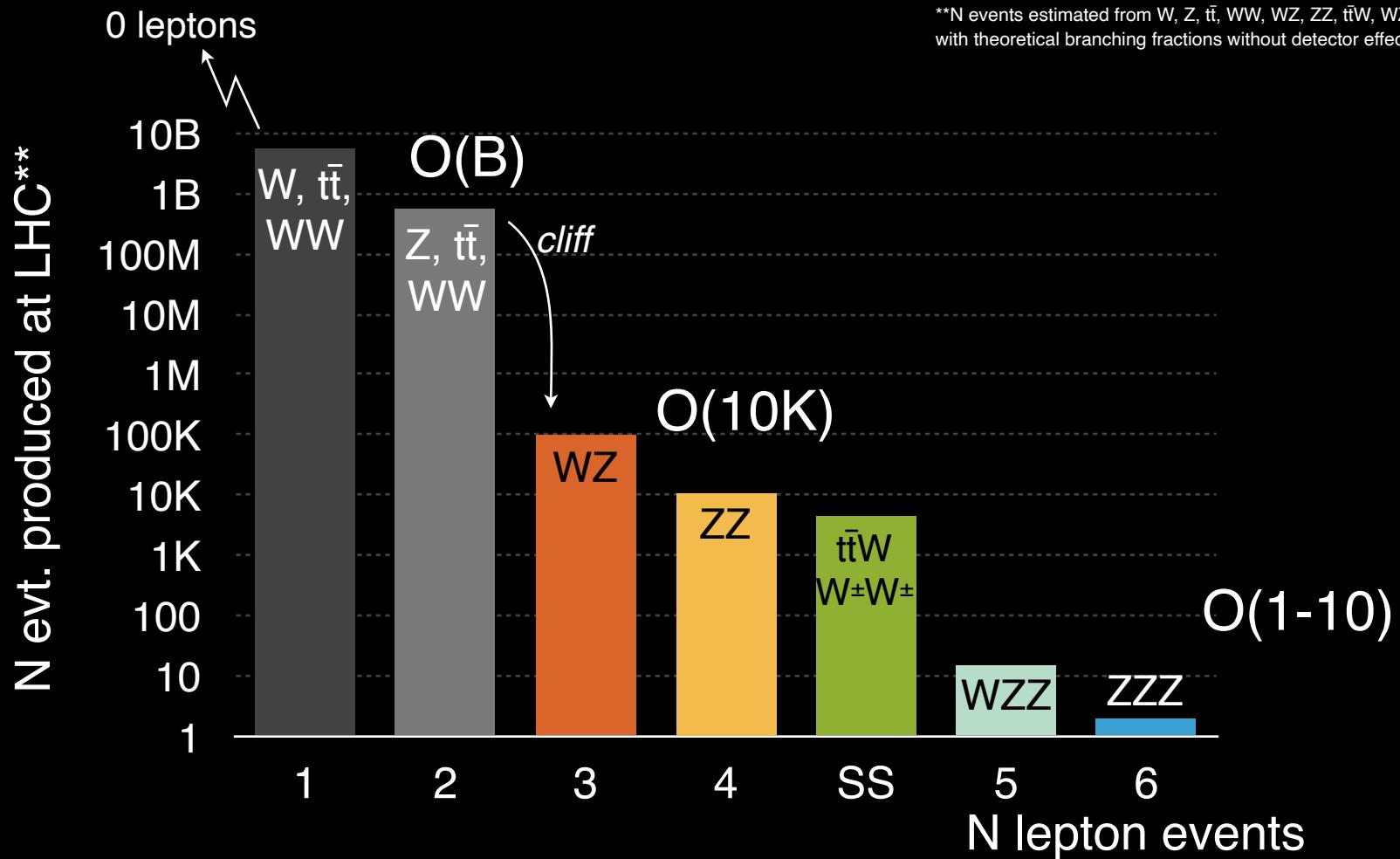
The more leptons produced the lower the rate (i.e. lower bkg.)

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 $\tau \rightarrow e, \mu$



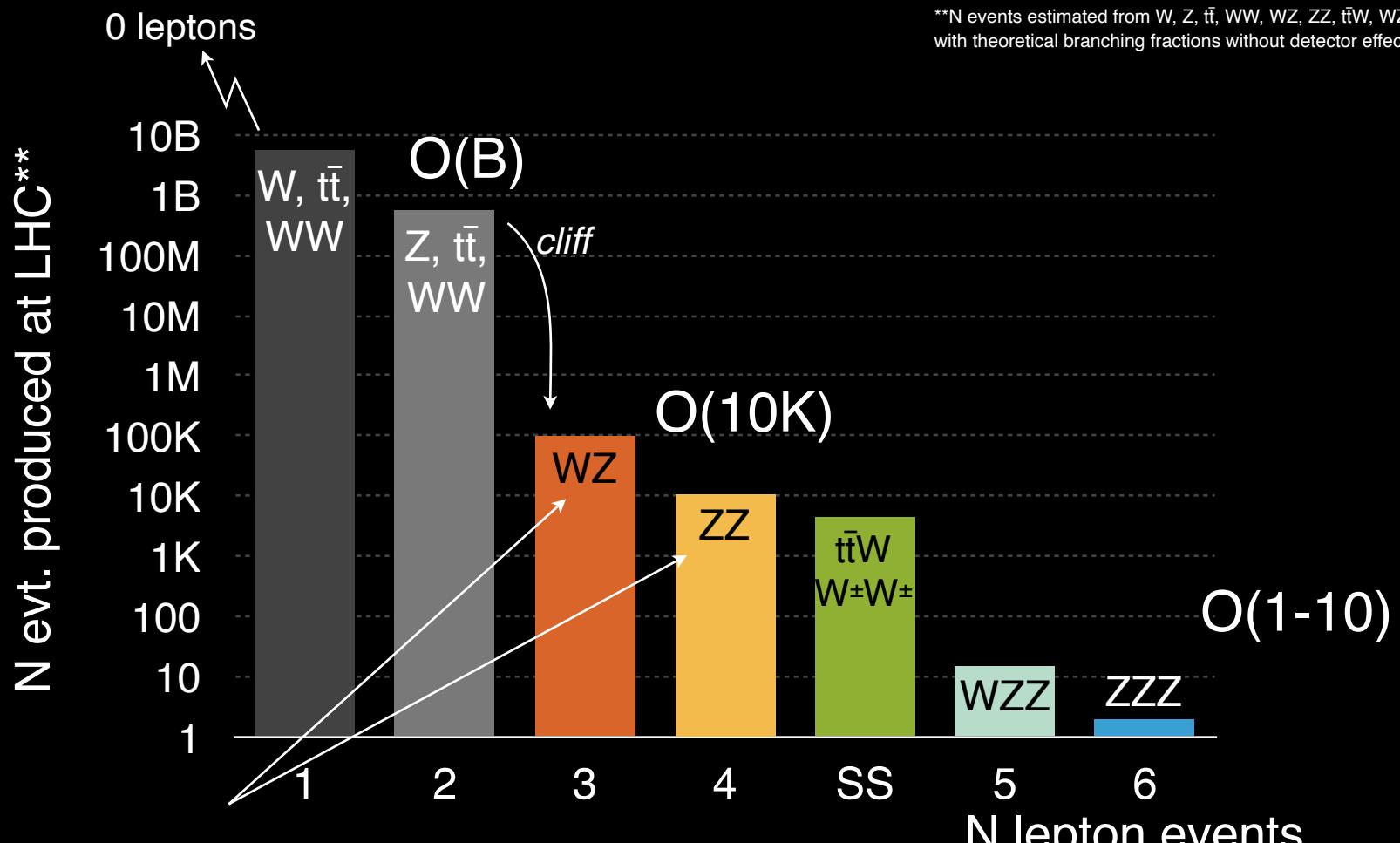
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N.B. $WZ \rightarrow 3l \sim 100k$, $ZZ \rightarrow 4l \sim 10k$

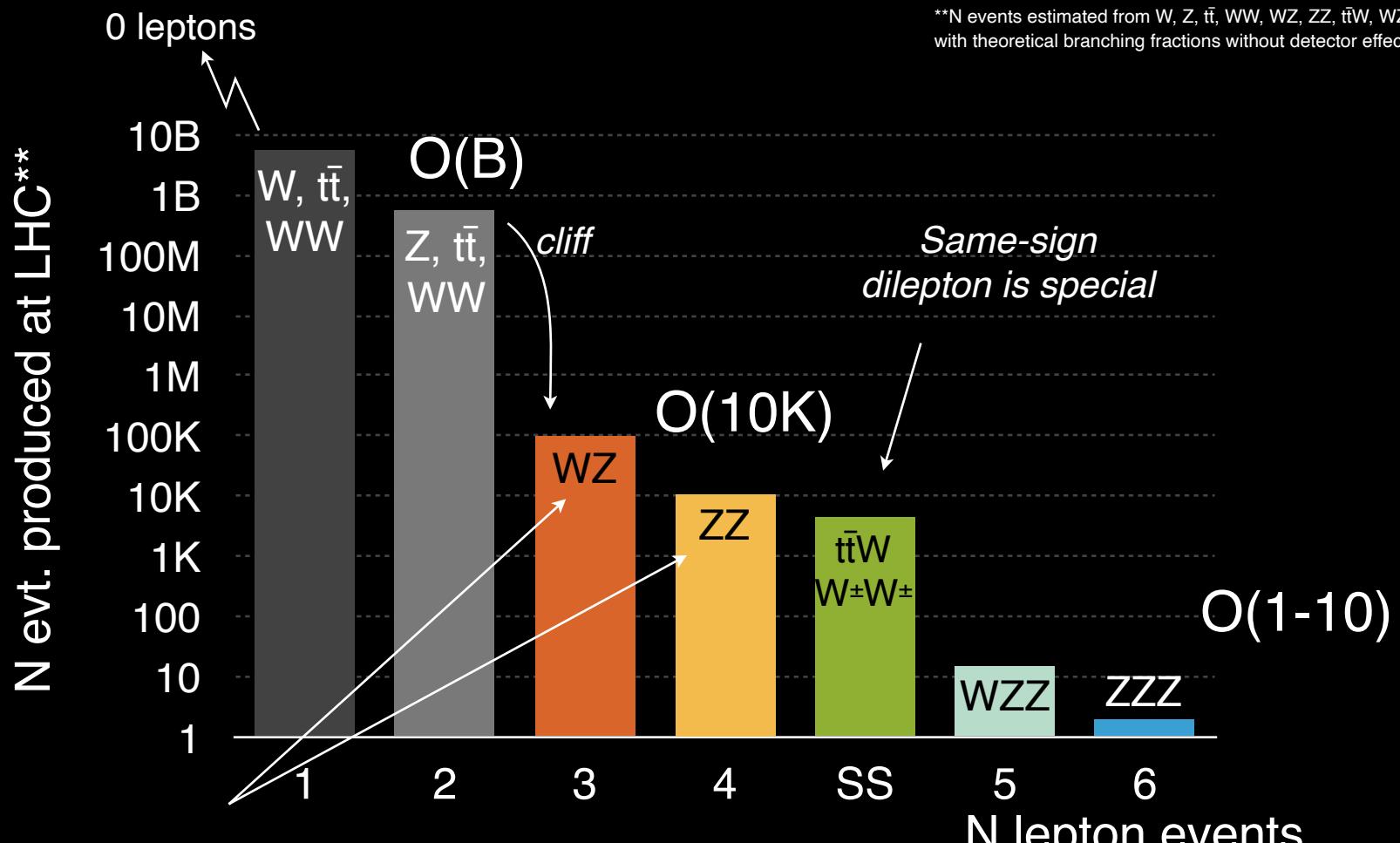
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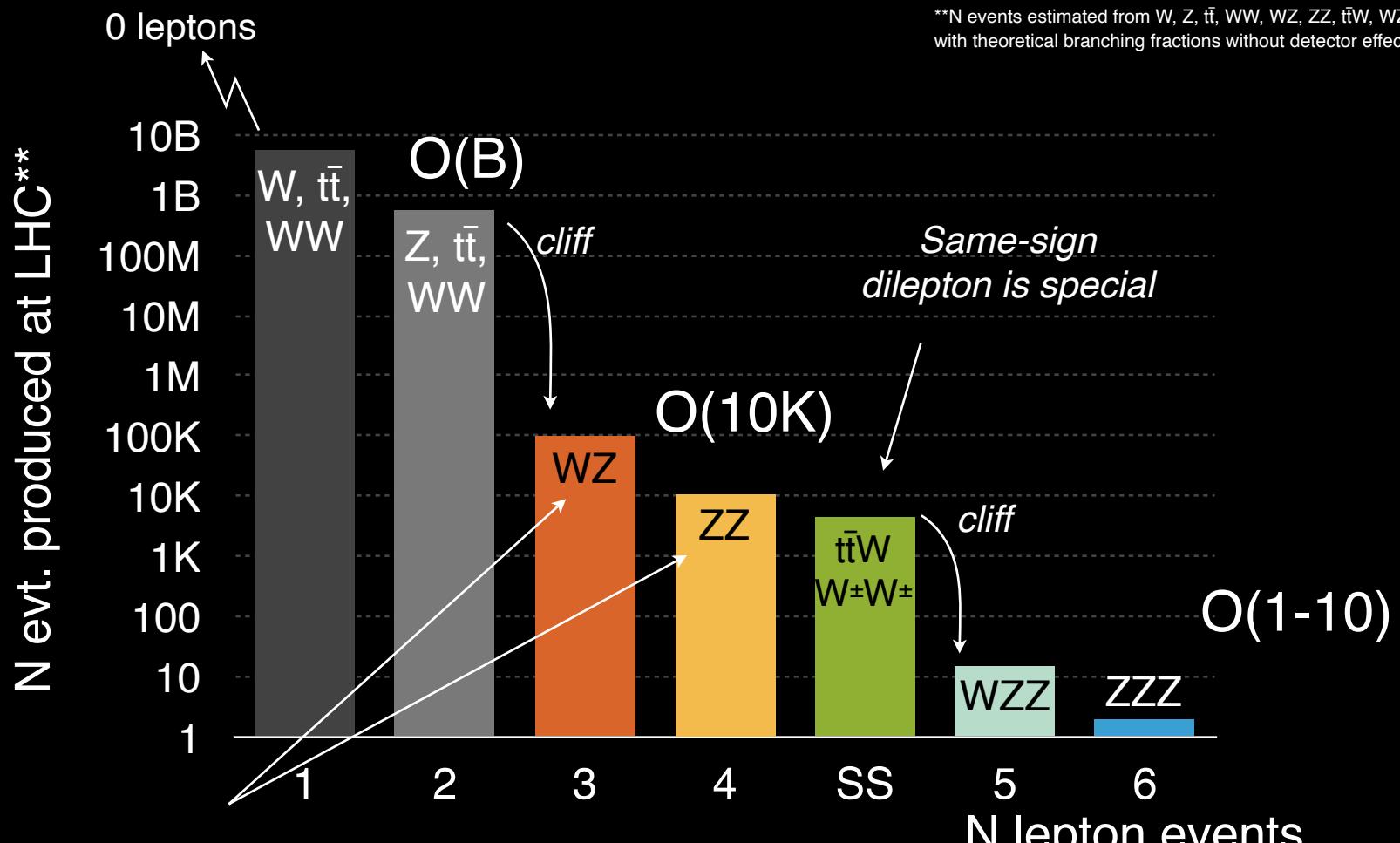
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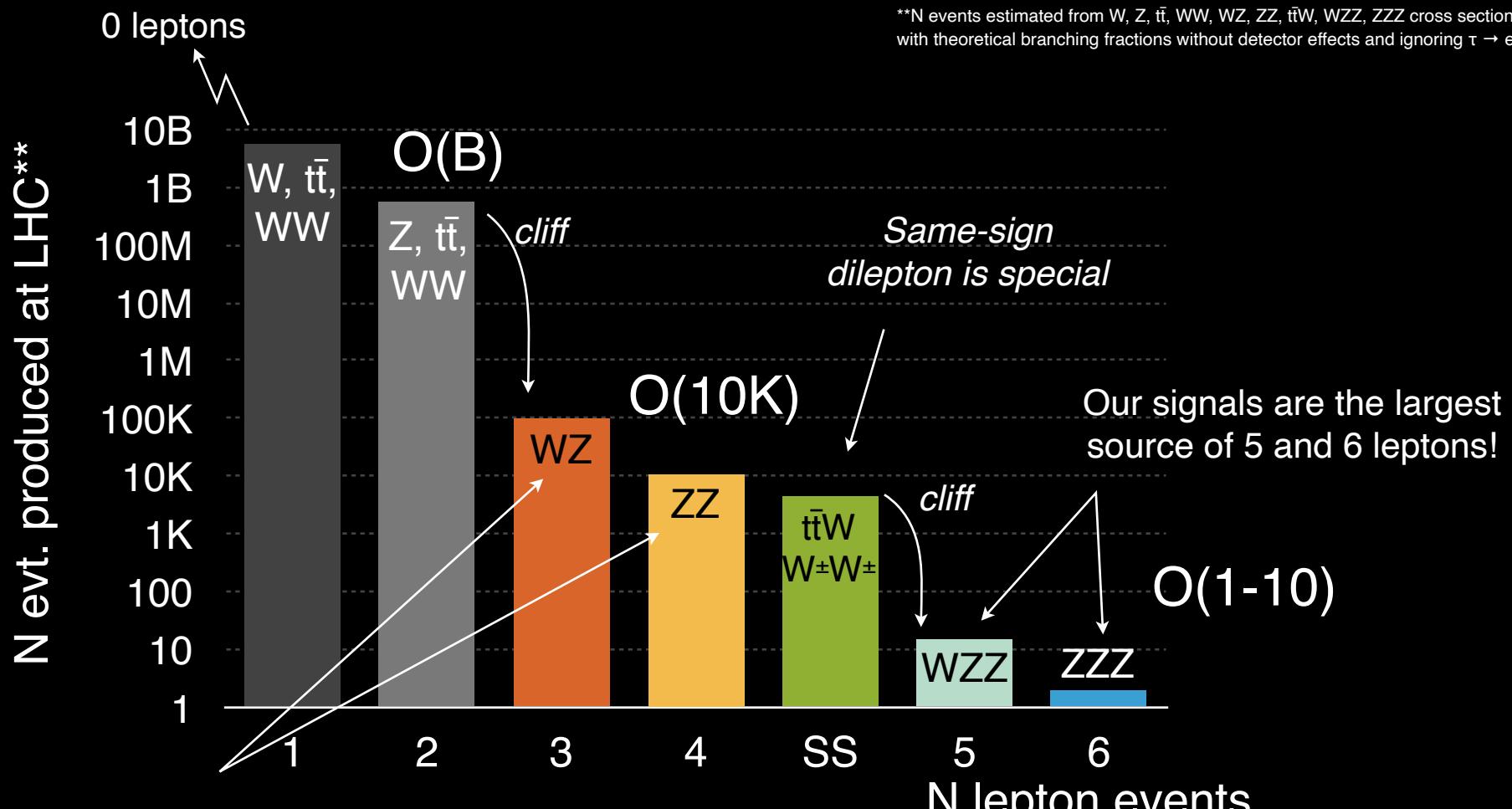
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Lepton physics at the LHC



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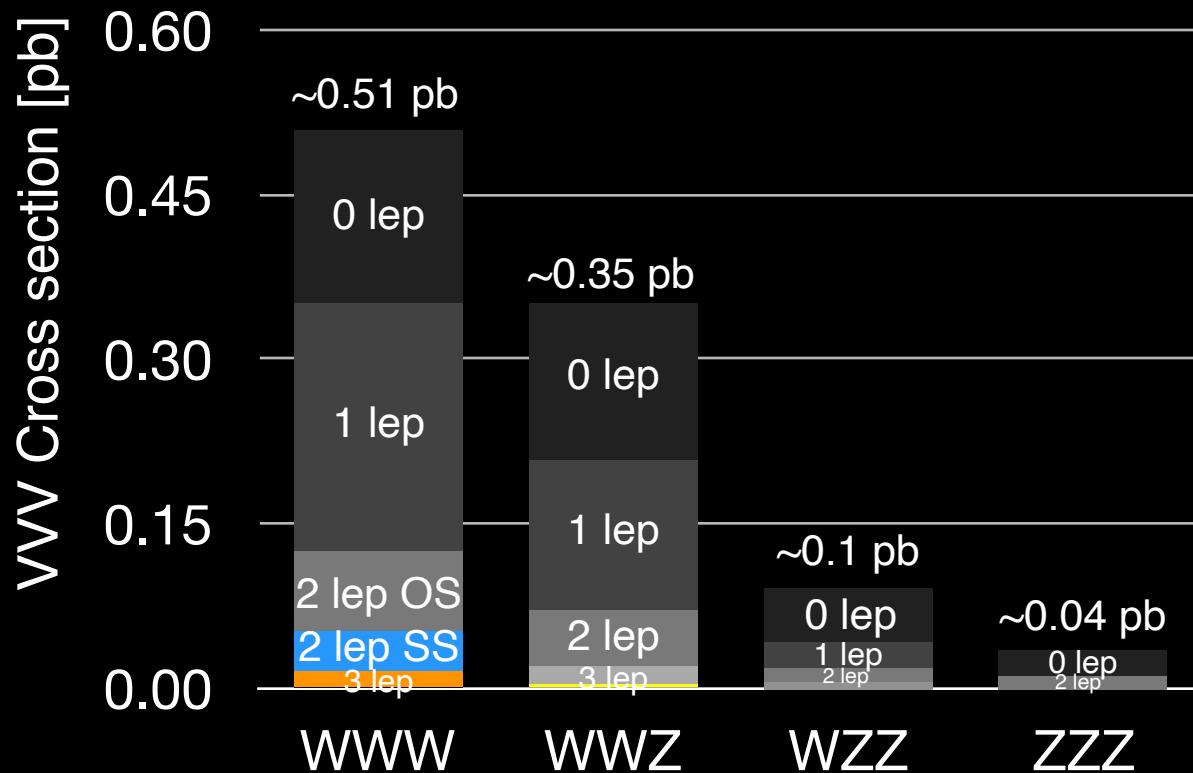
Useful to organize physics analyses by N leptons

VVV channels in # of leptons

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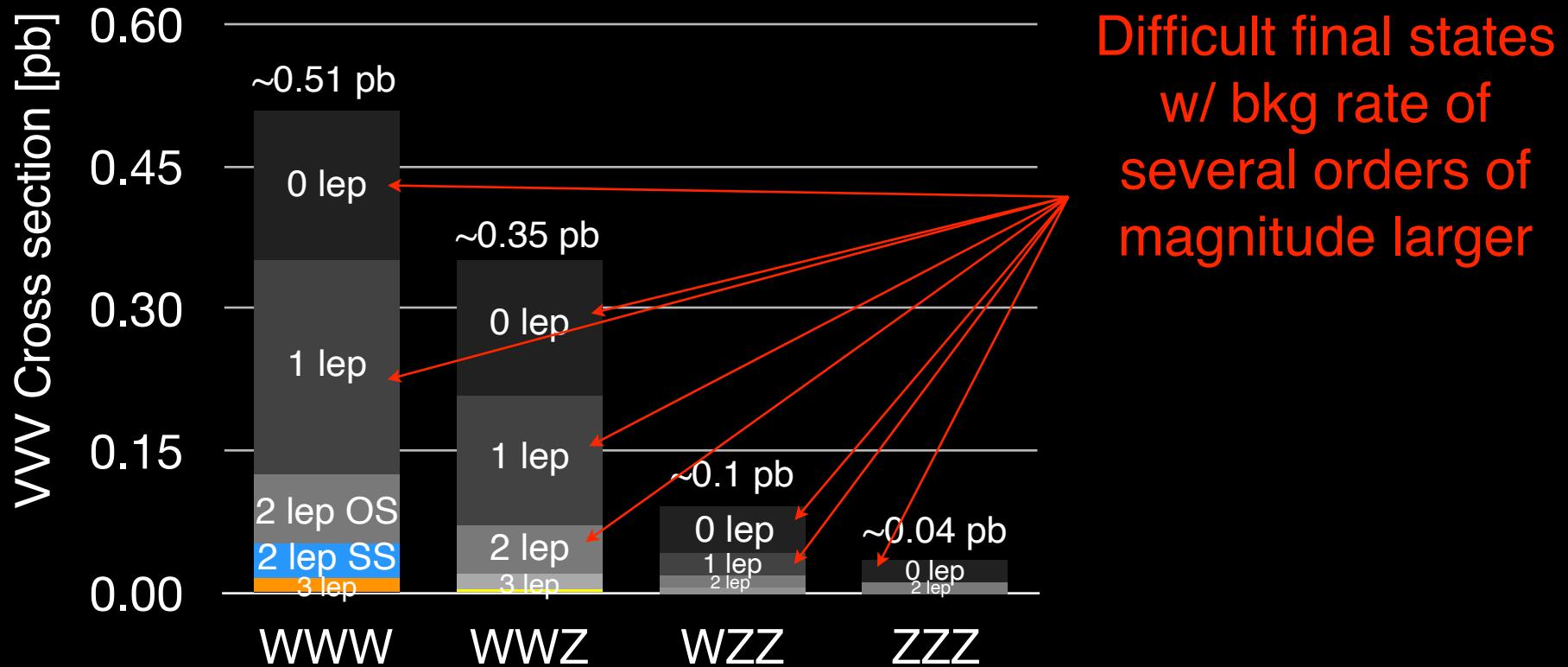
Production cross section decreases with more Z's



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

VVV channels in # of leptons

Production cross section decreases with more Z's



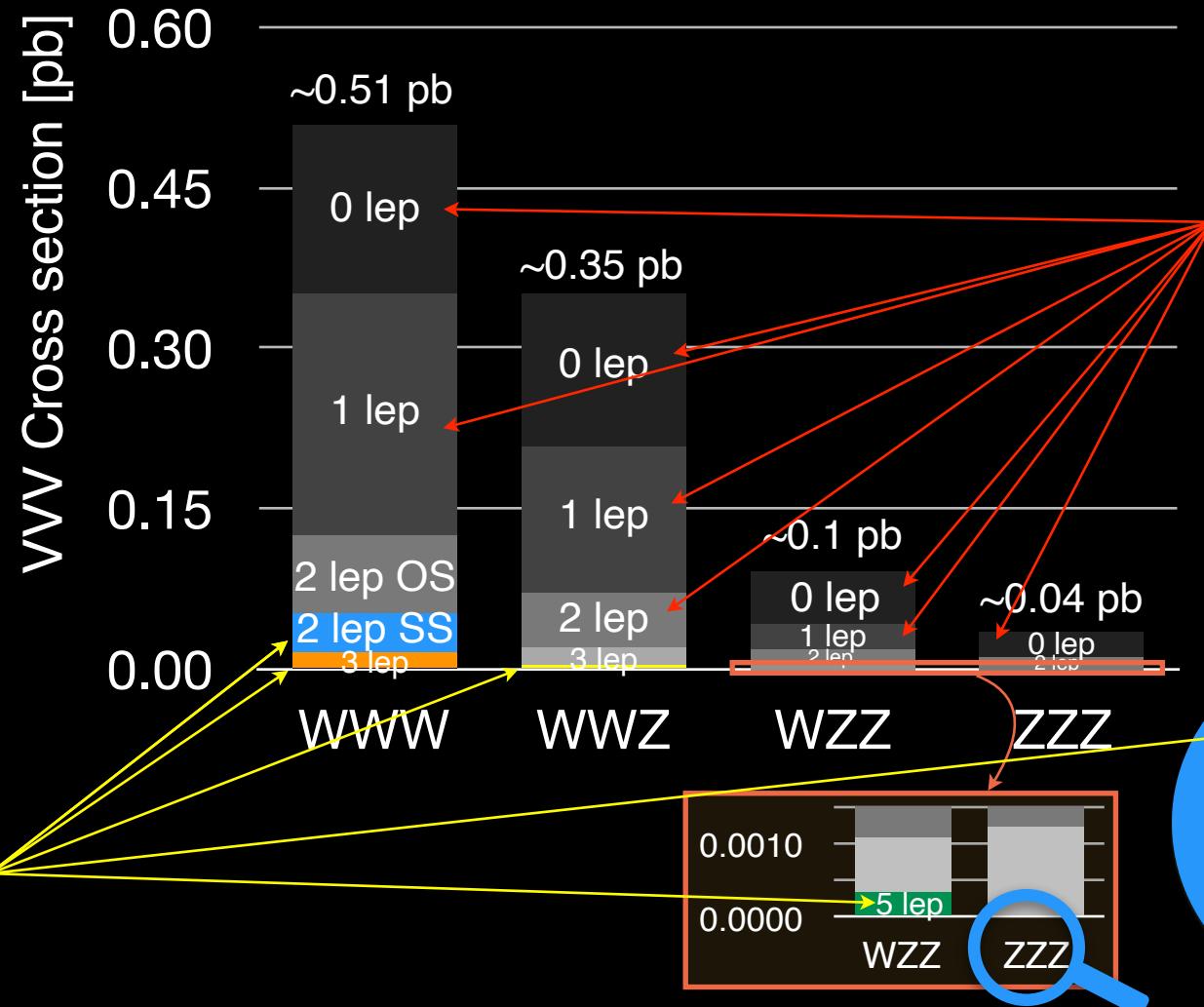
Viable final states have O(fb) or less cross sections

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

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

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.	$WZ \rightarrow l^\pm \nu l^\pm \bar{l}^\mp$ $t\bar{t} \rightarrow bb + l + X$ $\hookdownarrow \text{fake } l$	$WZ \rightarrow l\nu ll$ $t\bar{t} \rightarrow bb + ll + X$ $\hookdownarrow \text{fake } l$	$ZZ \rightarrow ll ll$ $ttZ \rightarrow ll ll + bbX$	$ZZ \rightarrow ll ll$ $+ \text{fake lep}$	$ZZ \rightarrow ll ll$ $+ 2 \text{ fake lep}$
WW v. Z					

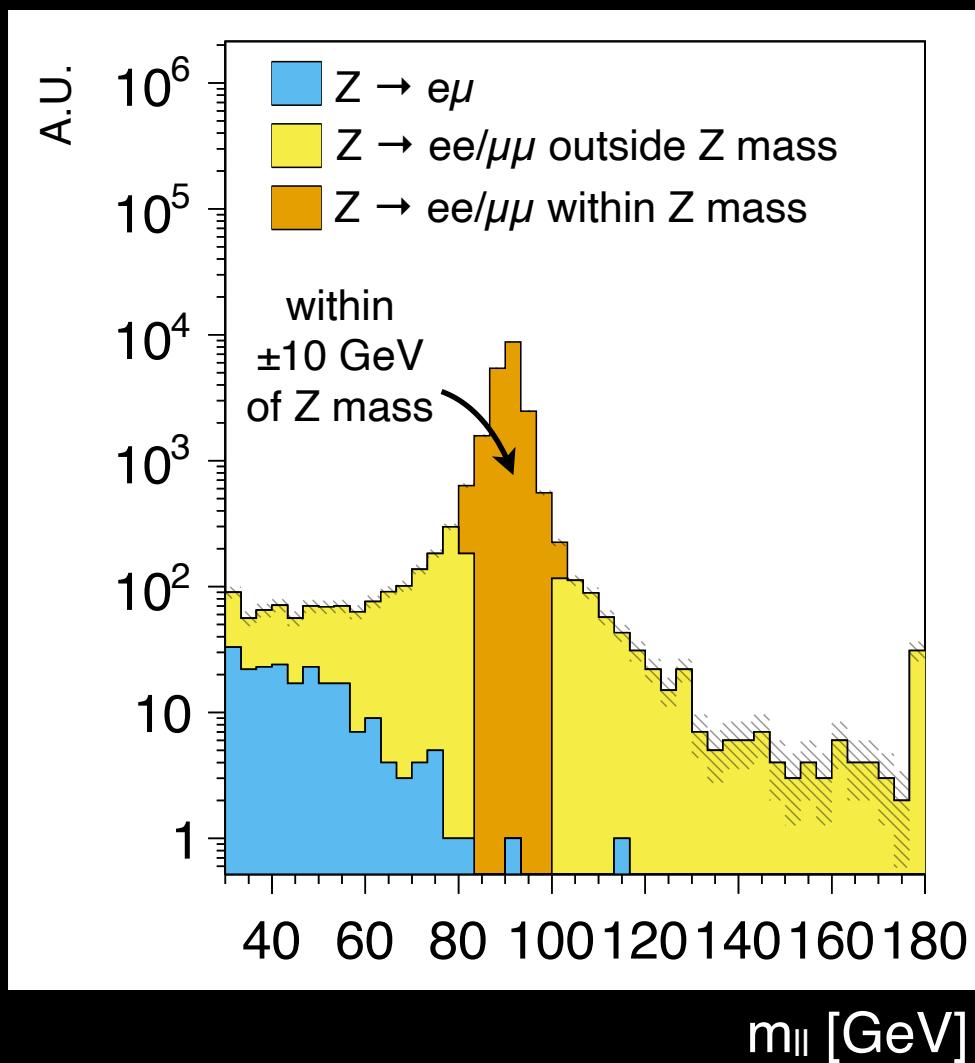
N.B. $WZ \rightarrow 3l \sim 100k$, $ZZ \rightarrow 4l \sim 10k$

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

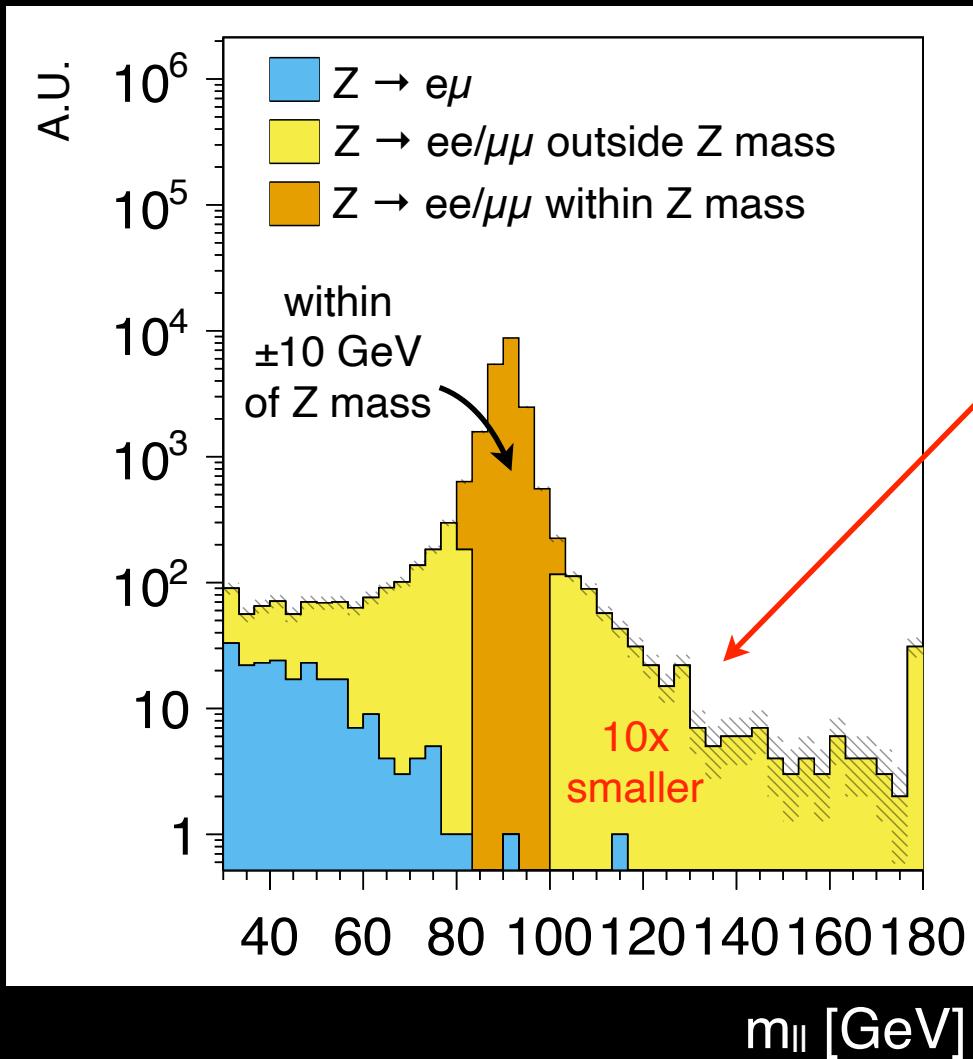
Z decays predominantly to $ee/\mu\mu$ on-shell

Features of $Z \rightarrow ll$ decay

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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

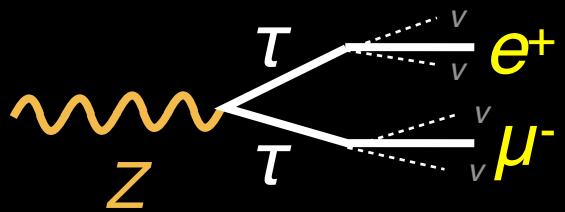
**Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV P_T cuts

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

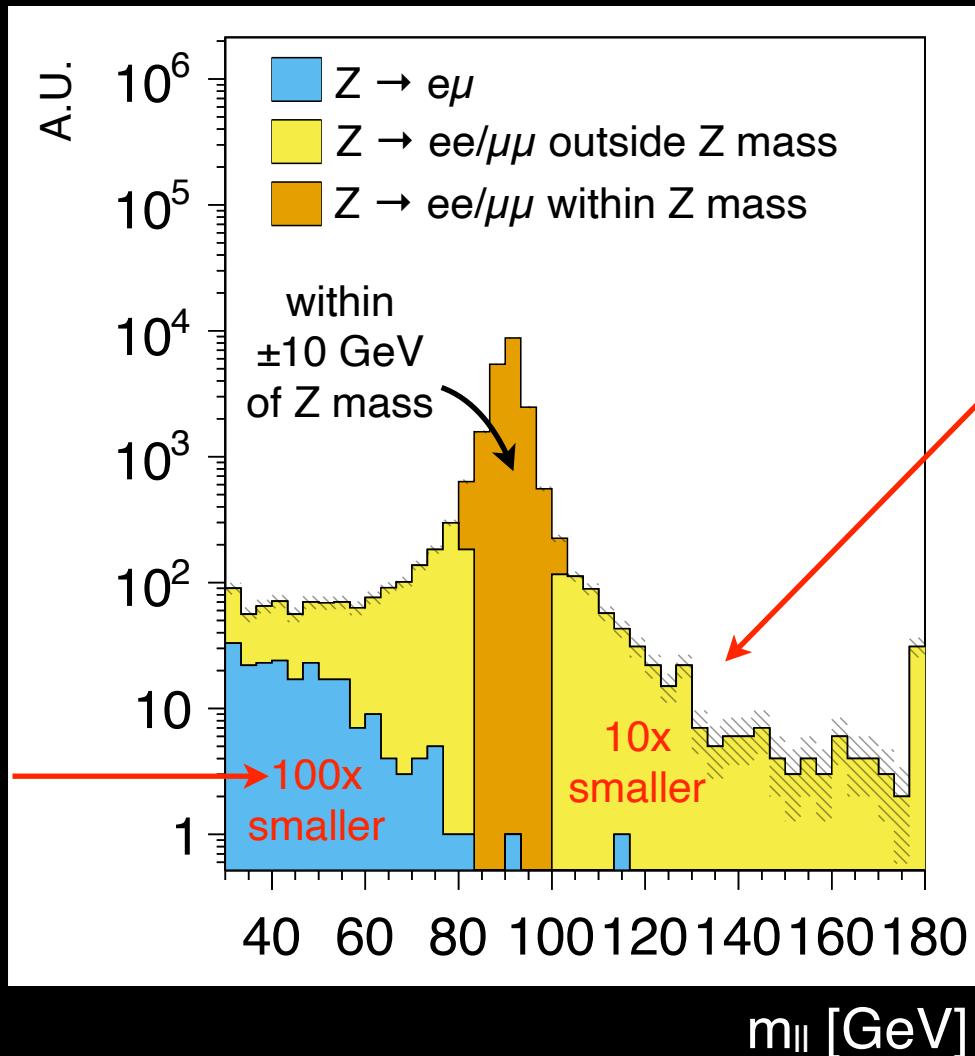
Features of $Z \rightarrow ll$ decay



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, μ from τ are soft)



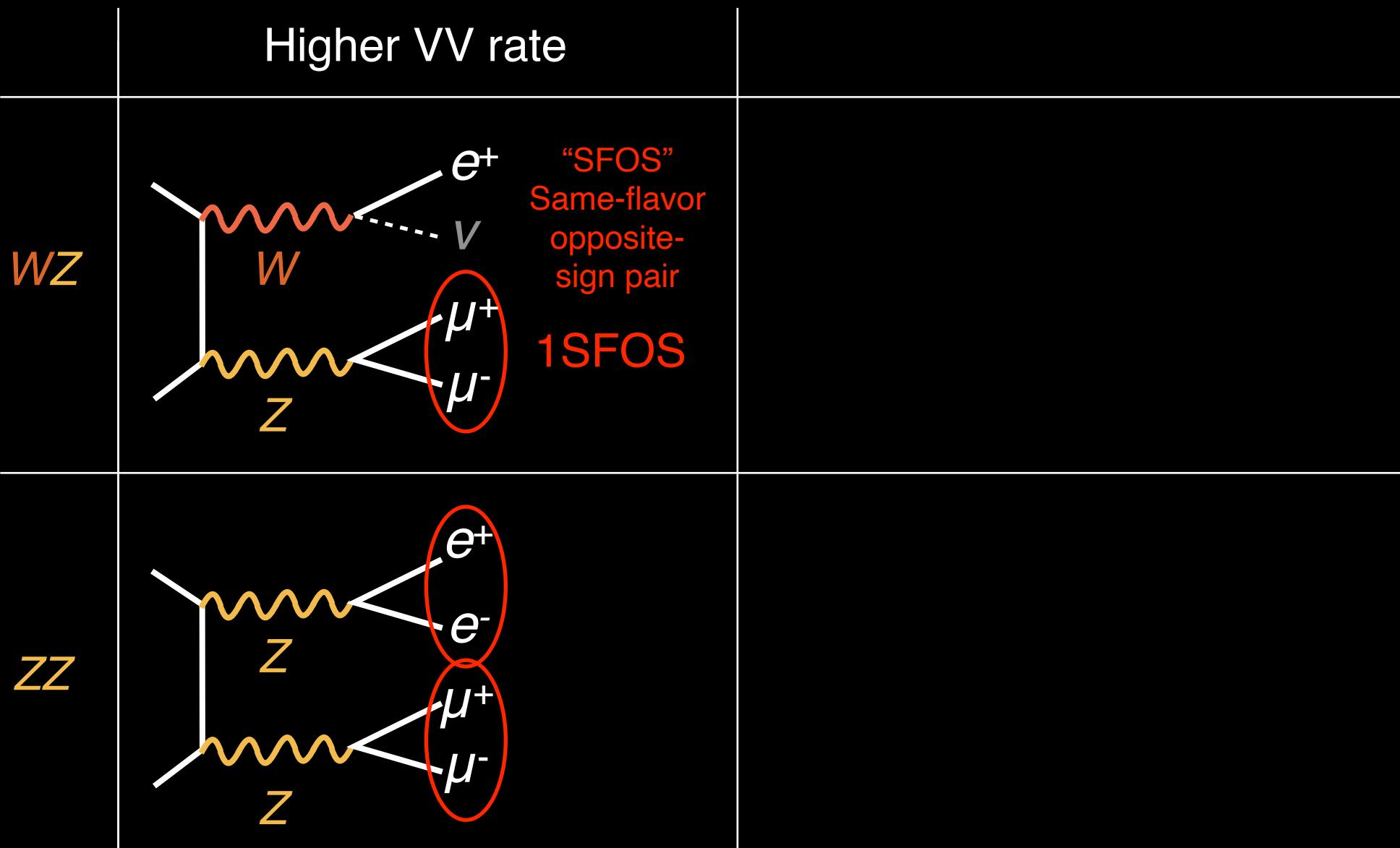
If one selects $lm_{ll} - m_Z > 10$ GeV of $ee/\mu\mu$ final state Z is reduced by **an order** of magnitude

**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

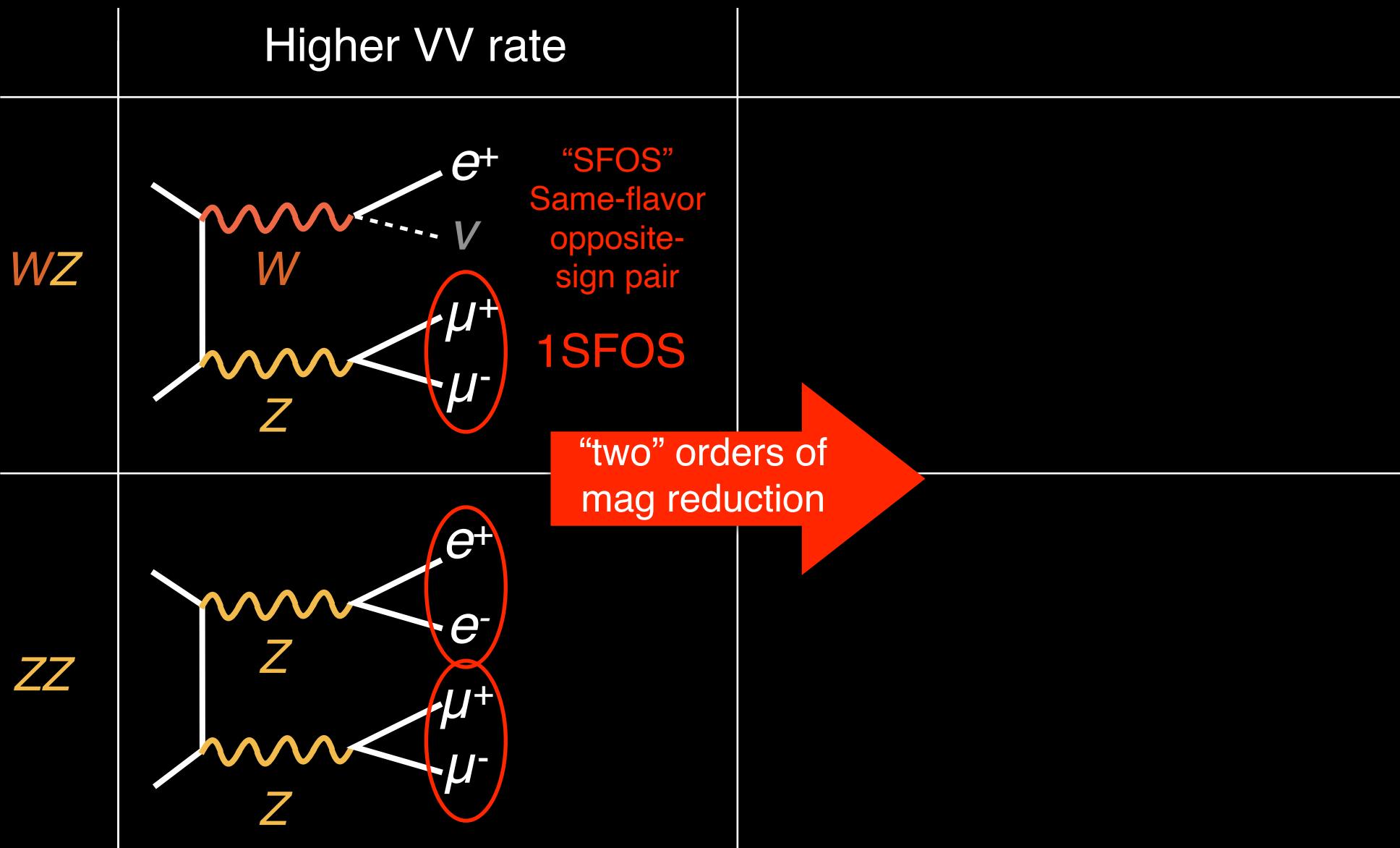
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Selecting away from $Z \rightarrow$ SFOS decay reduces background

Reducing VV background by flavor choice

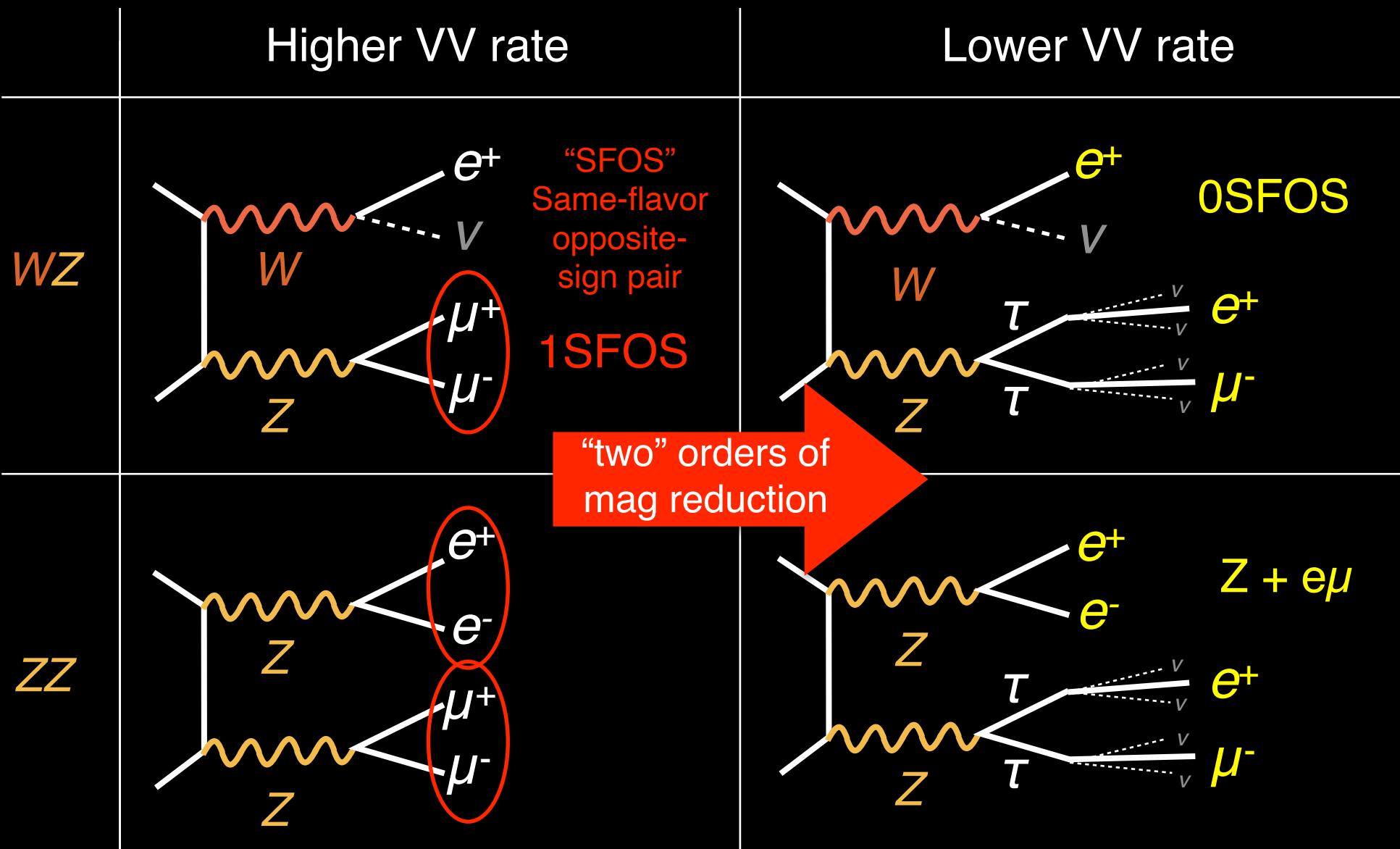
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Selecting away from $Z \rightarrow$ SFOS decay reduces background

Reducing VV background by flavor choice

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

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. μ 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	≥ 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^{miss}	$> 45 \text{ GeV}$	
m_{jj} (leading jets)	$< 500 \text{ GeV}$	—
$\Delta\eta_{jj}$ (leading jets)	< 2.5	—
m_{jj} (closest ΔR)	$65 < m_{jj} < 95 \text{ GeV}$ 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_{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	≤ 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 μ category	ee / $\mu\mu$ category
Preselection		Selections in Table 20
W candidate lepton flavors	e μ	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^{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	≥ 2 jets	1 jet

Split by N leptons
and requiring “Tight” leptons

$\Delta\eta_{JJ}$ (leading jets)	<2.5	—
m_{jj} (closest ΔR)	$65 < m_{jj} < 95 \text{ GeV}$ 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	≤ 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 μ category	ee / $\mu\mu$ category
Preselection		
W candidate lepton flavors	e μ	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^{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 $p_T > 25 \text{ GeV}$	
Additional leptons	No additional very loose lepton	
Isolated tracks	No additional isolated tracks	
Jets	≥ 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^{miss}	$> 45 \text{ GeV}$	
m_{jj} (leading jets)	$< 500 \text{ GeV}$	—
$\Delta\eta_{jj}$ (leading jets)	< 2.5	—
m_{jj} (closest ΔR)	$65 < m_{jj} < 95 \text{ GeV}$ or $ m_{jj} - 80 \text{ GeV} \geq 15 \text{ GeV}$	—
$\Delta R_{\ell j}^{\text{min}}$	—	< 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	2 tight leptons with charge sum = $\pm 1e$	
Additional leptons	$20 \text{ GeV} < p_T < 30 \text{ GeV}$	
m_{SFOS}		
$m_{\ell\ell\ell}$		
SF lepton mass		
Dielectron mass		
Jets		
b-tagging		
$\Delta\phi(\vec{p}_T(\ell\ell\ell), \vec{p}_T^{\text{miss}})$	—	> 2.5
$p_T(\ell\ell\ell)$	—	$> 50 \text{ GeV}$
$m_T^{3\text{rd}}$ (1 SFOS) or m_T^{max} (2 SFOS)	—	$> 90 \text{ GeV}$

Four leptons selection

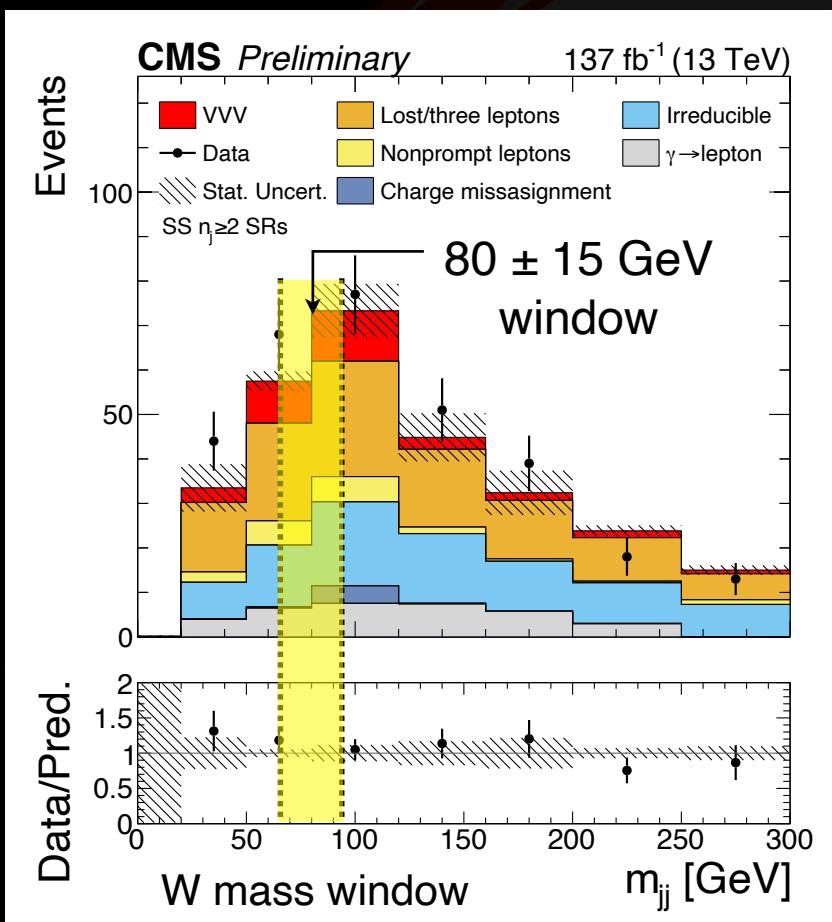
Variable	e μ category		ee / $\mu\mu$ category	
	Preselection	Selections in Table 20	ee / $\mu\mu$	
W candidate lepton flavors	e μ			
$m_{\ell\ell}$	Separated into 4 bins in $(0, 40, 60, 100, \infty)$		$ m_{\ell\ell} - m_Z > 10 \text{ GeV}$	
m_{T2}	$m_{T2} > 25 \text{ GeV}$ (for $m_{\ell\ell} > 100 \text{ GeV}$)		...	
$p_{T,4\ell}$ and p_T^{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

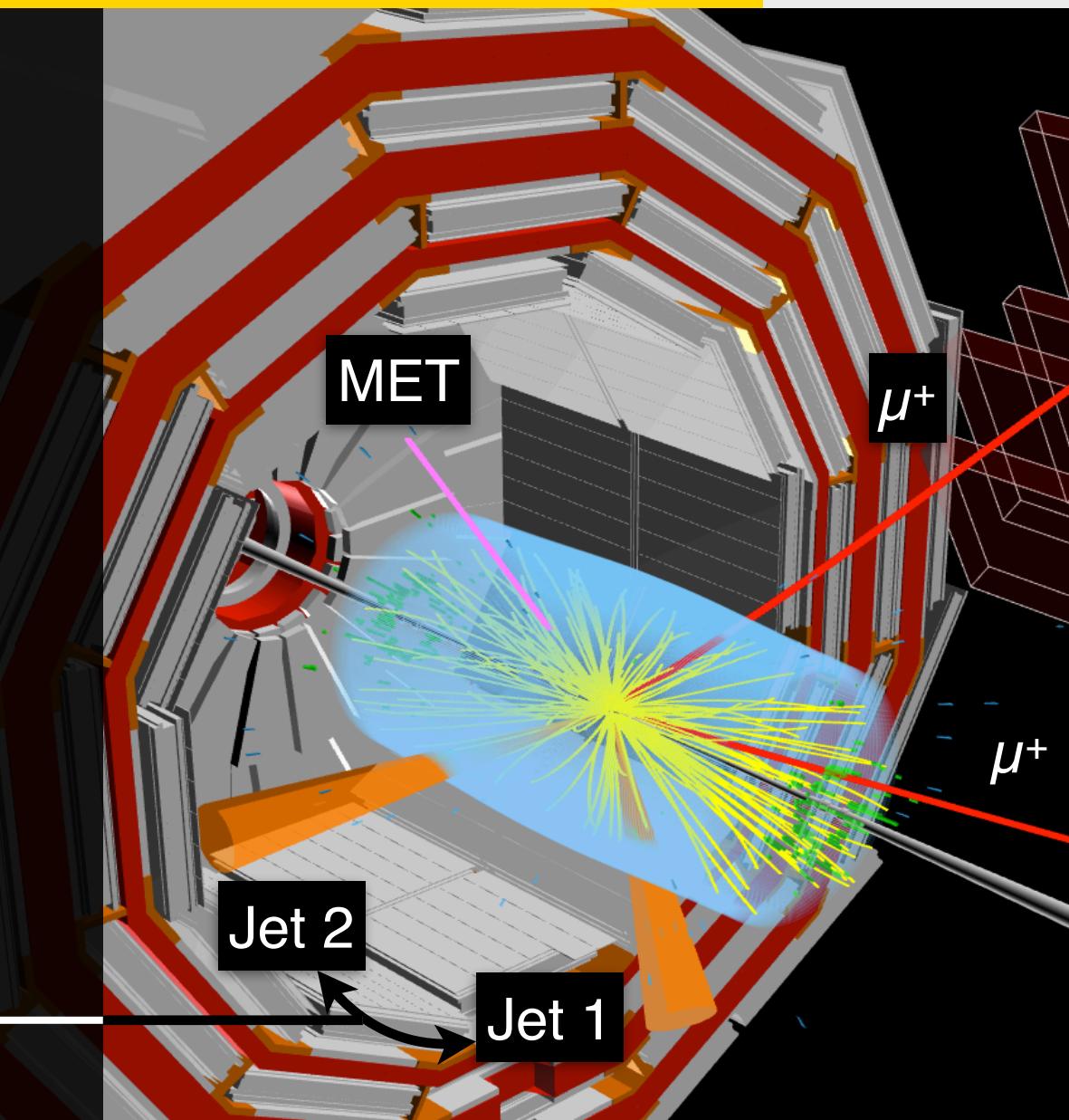
But I will highlight these 5 points in the coming slides

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:

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

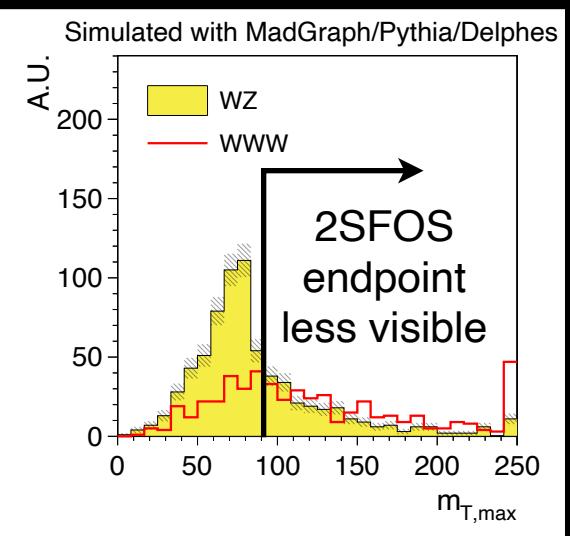
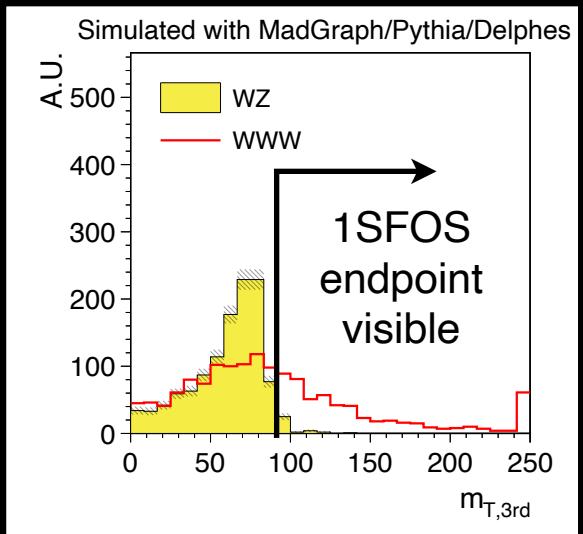
For 2SFOS it is less clear which one is from W:

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

Take max m_T computed from either leptons

\Rightarrow 3 signal regions for 3 leptons

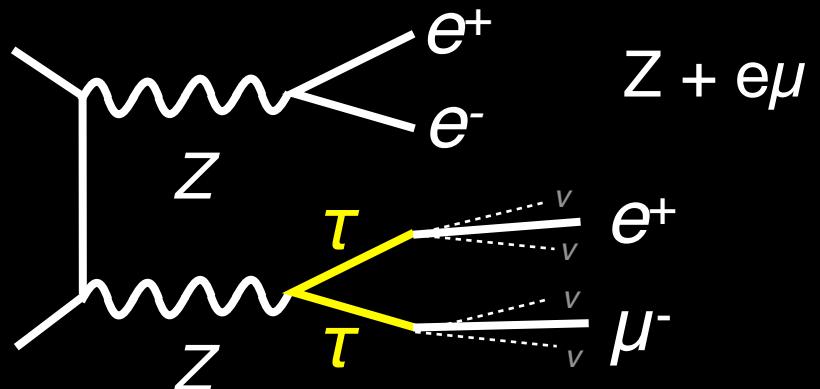
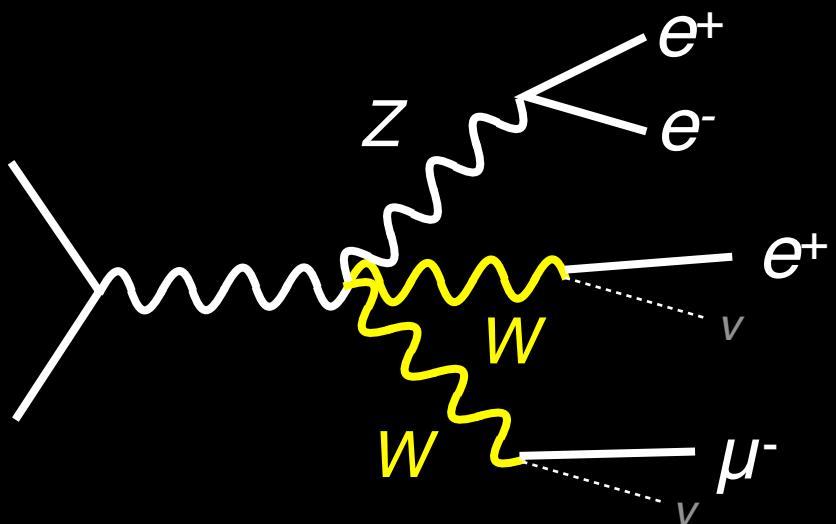
$m_T^{3\text{rd}}$ (1 SFOS) or m_T^{\max} (2 SFOS)	$>90\text{ GeV}$
--	------------------



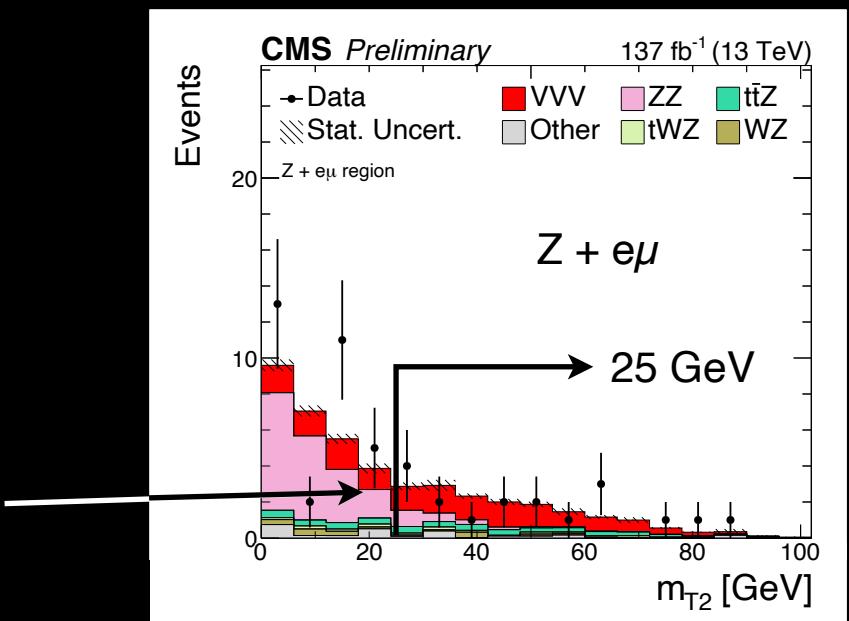
By flavor, W lepton can be identified and kinematic endpoints can be used

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_τ from $ZZ \rightarrow ll\tau\tau \rightarrow ll\ell\mu$



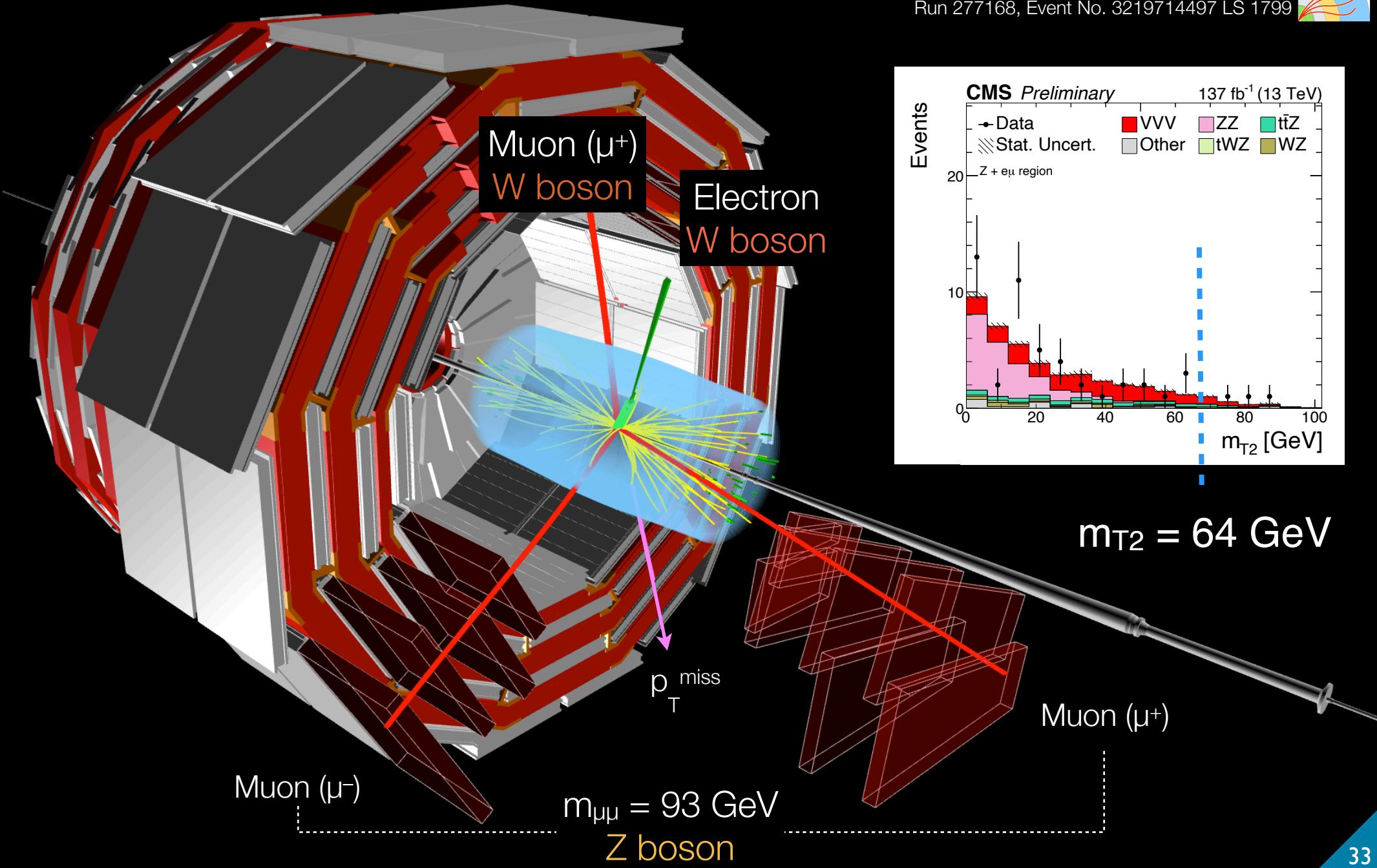
Exploit differences between $Z \rightarrow ll$ v. $WW \rightarrow llvv$

4 lepton event

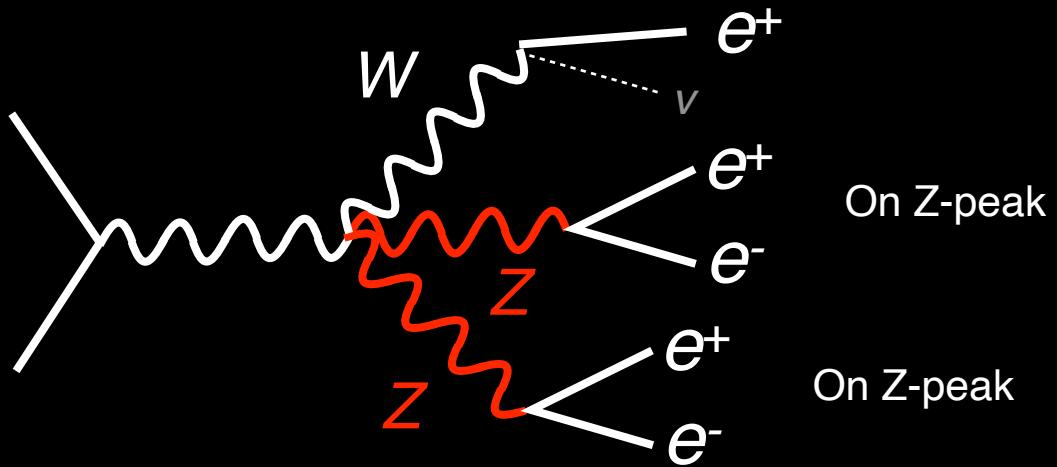
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CMS experiment at the LHC, CERN
Data recorded: 2016-Jul-23 08:13:27.898048 GMT
Run 277168, Event No. 3219714497 LS 1799



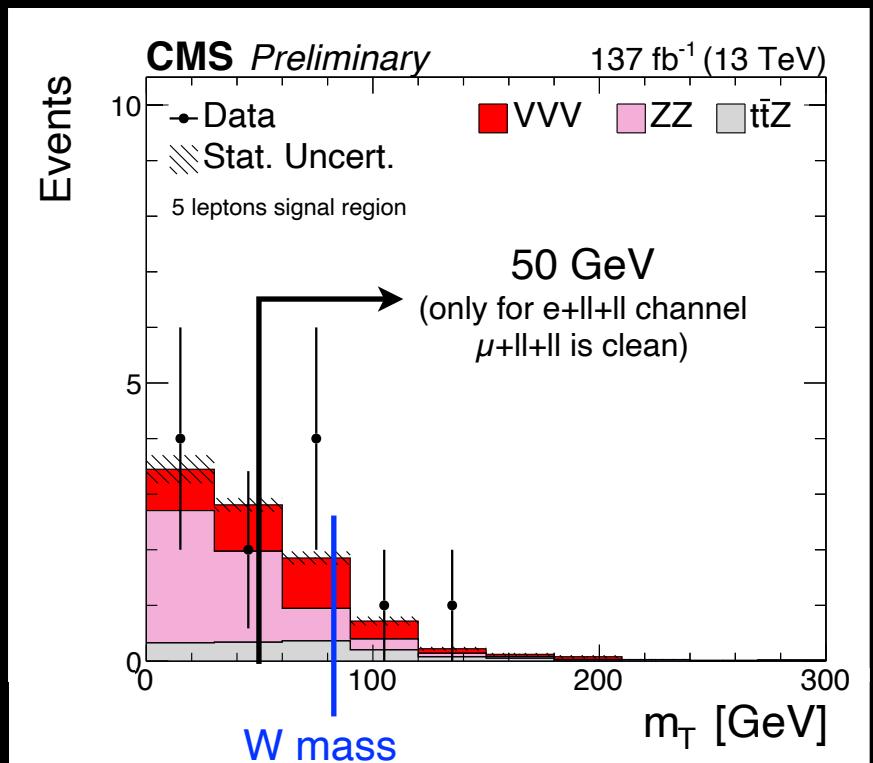
5 leptons target WZZ signal



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

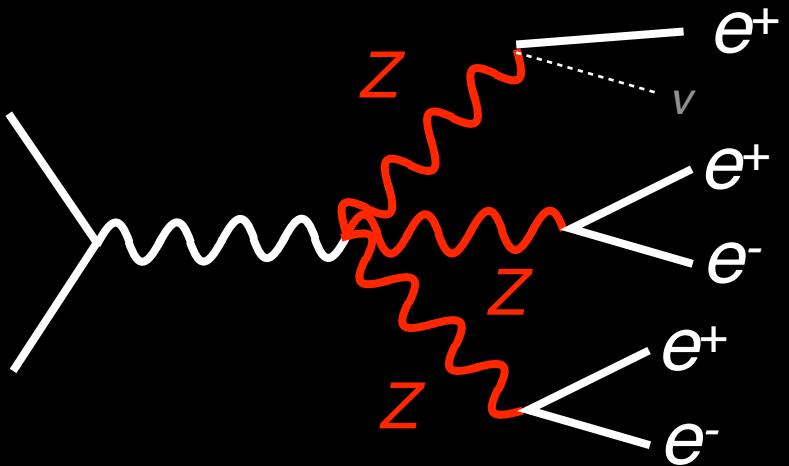
The fake lepton has low transverse mass while the signal's W has transverse mass peaking at W mass



Cut-and-count of one bin

6 leptons target ZZZ process

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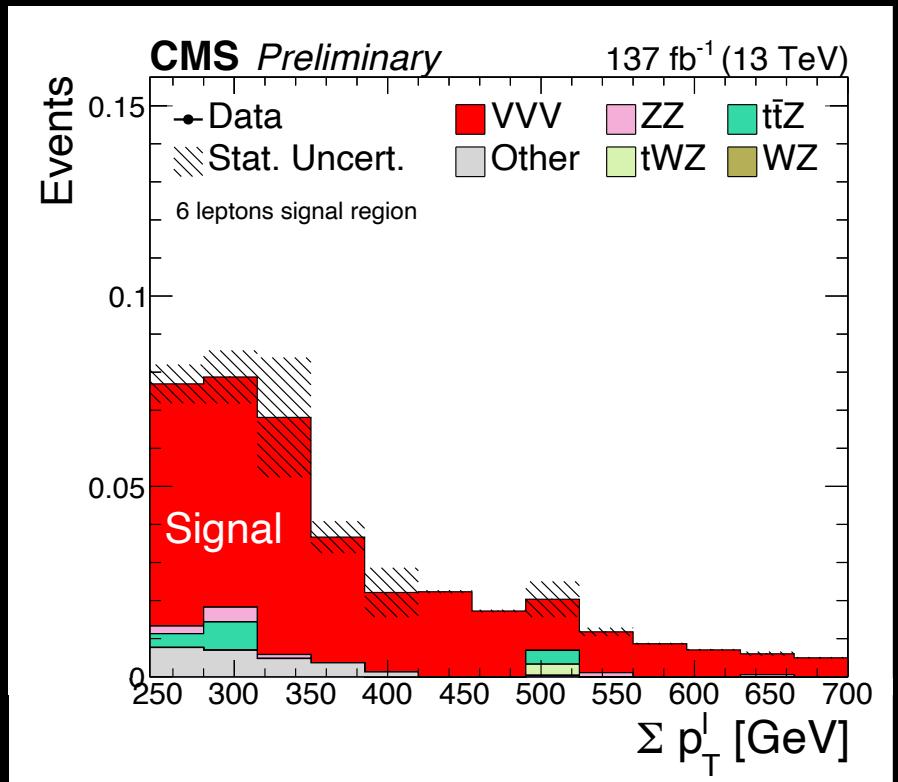


Select at least 6 leptons

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

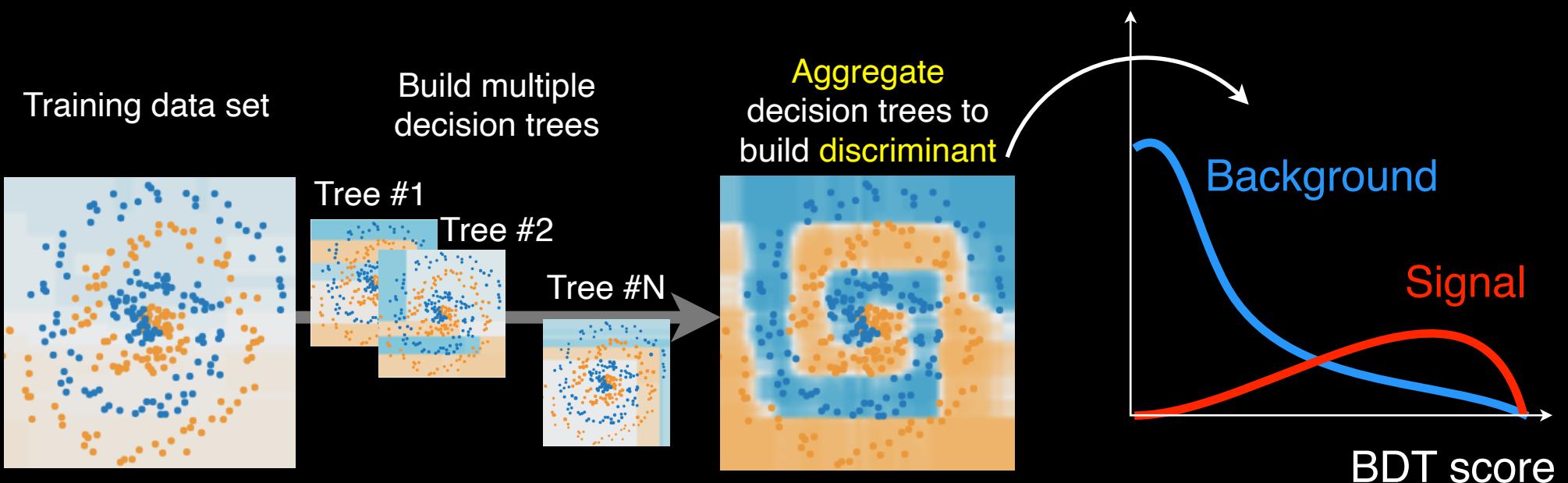
Smart humans and
smart machines
(Both cut / BDT)



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

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)	

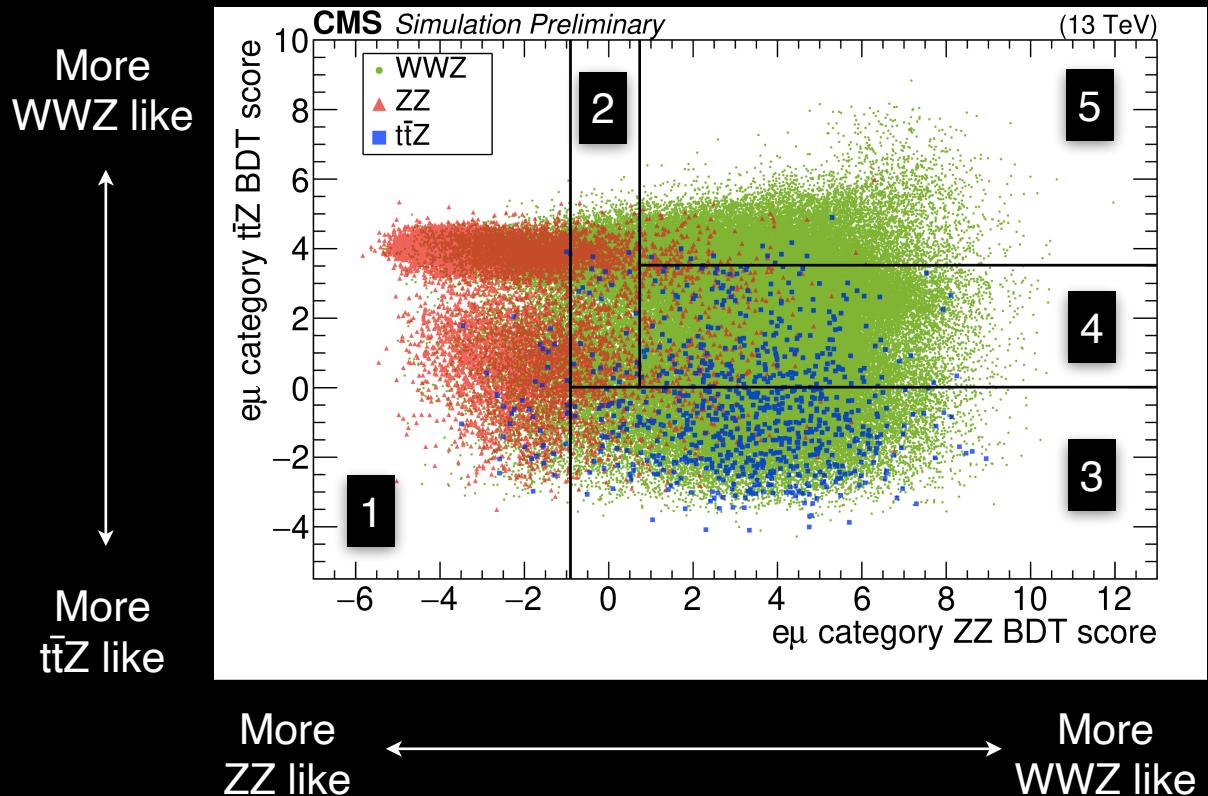
Train different BDTs against different backgrounds

WWZ BDTs for 4 leptons analysis

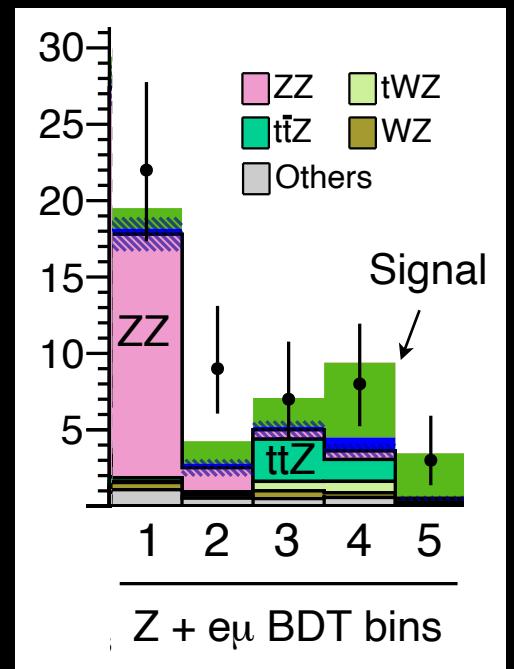
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2D plane in BDT scores for 4 lepton
 $Z \rightarrow ll + e\mu$ event category



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

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!

Background estimation in a nutshell

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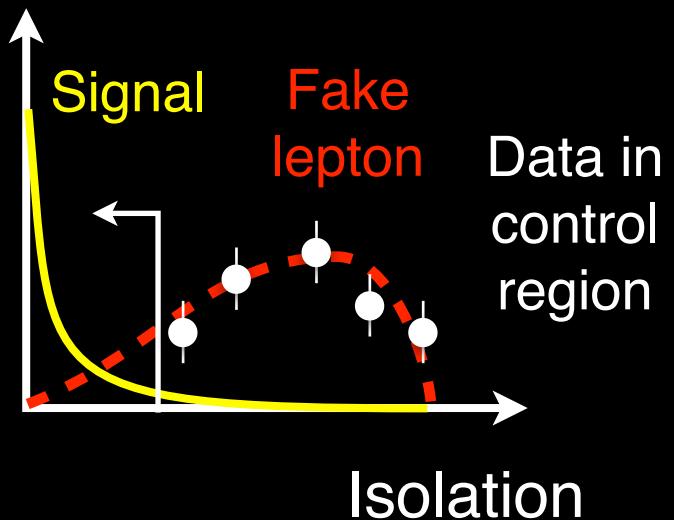
Identify which discriminant most reduces the background

Then, reliably extrapolate across the discriminant phase-space

Background estimations in essence are simple extrapolations

Lepton isolation example

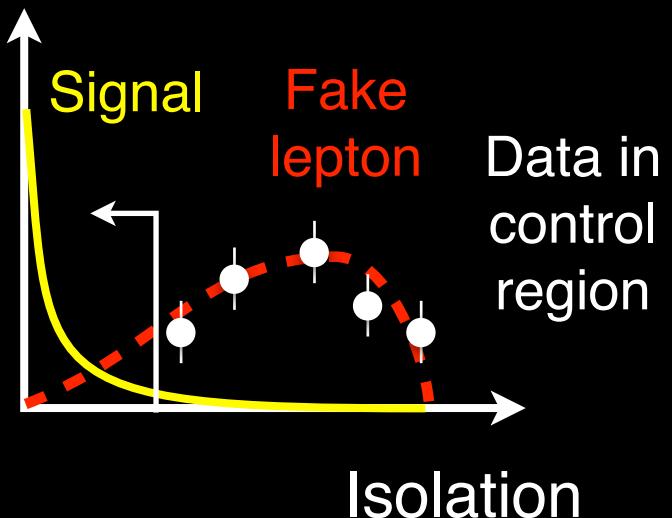
Lepton isolation to discriminate
signal from fake leptons



Lepton isolation example

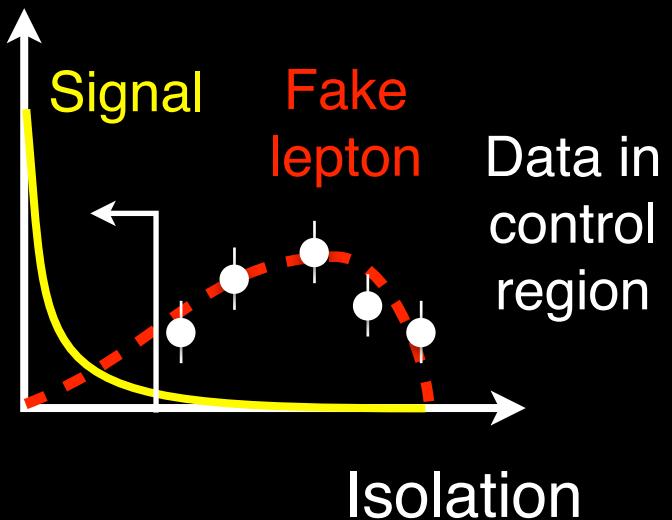
Lepton isolation to discriminate signal from fake leptons

If I can reliably measure two things:



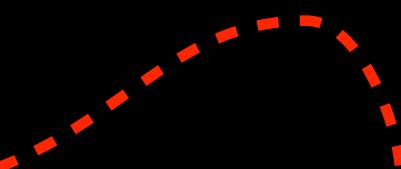
Lepton isolation example

Lepton isolation to discriminate signal from fake leptons



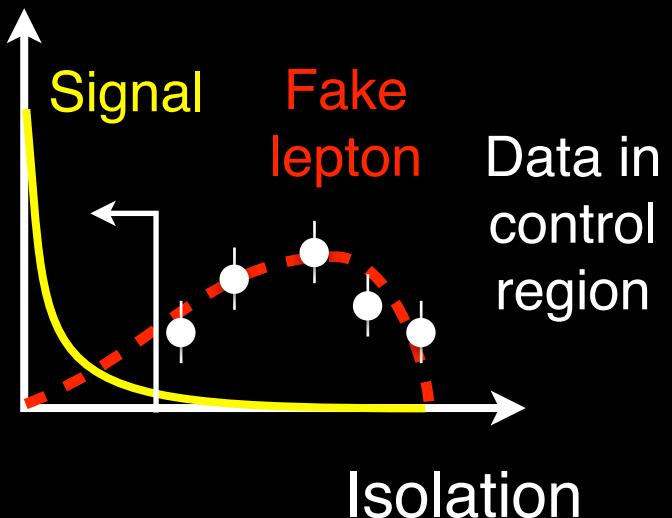
If I can reliably measure two things:

① “Shape”



Lepton isolation example

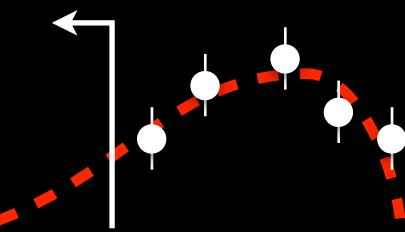
Lepton isolation to discriminate signal from fake leptons



If I can reliably measure two things:

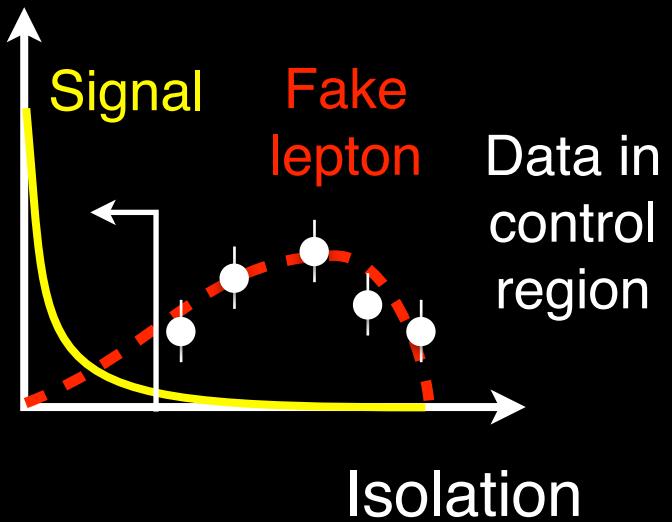
① “Shape”

② Data events



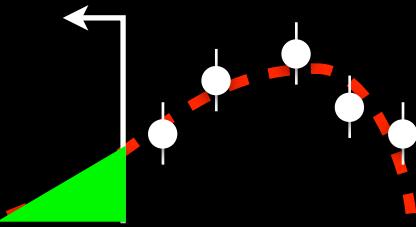
Lepton isolation example

Lepton isolation to discriminate signal from fake leptons



If I can reliably measure two things:

① “Shape”

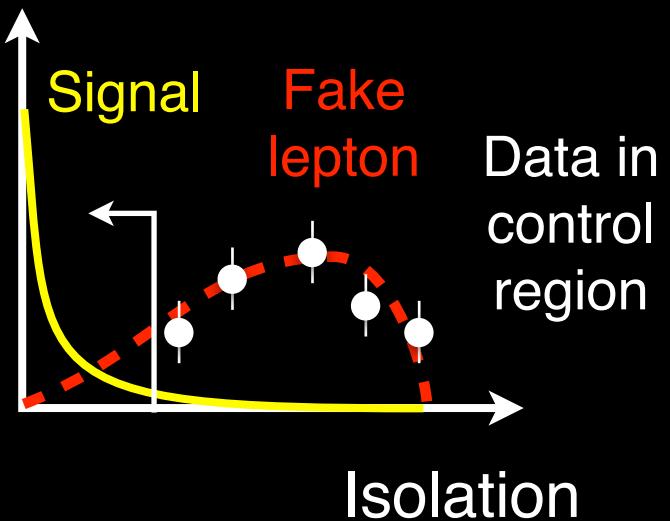


② Data events

③ Estimate residual amount of backgrounds via extrapolation

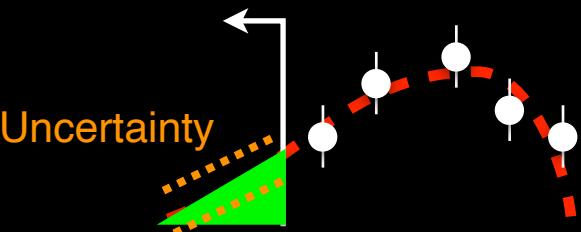
Lepton isolation example

Lepton isolation to discriminate signal from fake leptons



If I can reliably measure two things:

① “Shape”



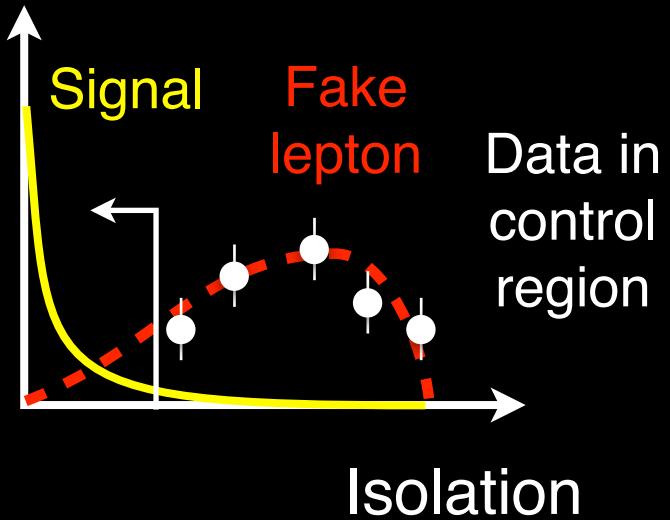
② Data events

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.)

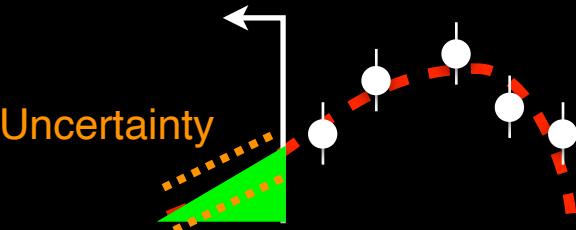
Lepton isolation example

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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UCSD



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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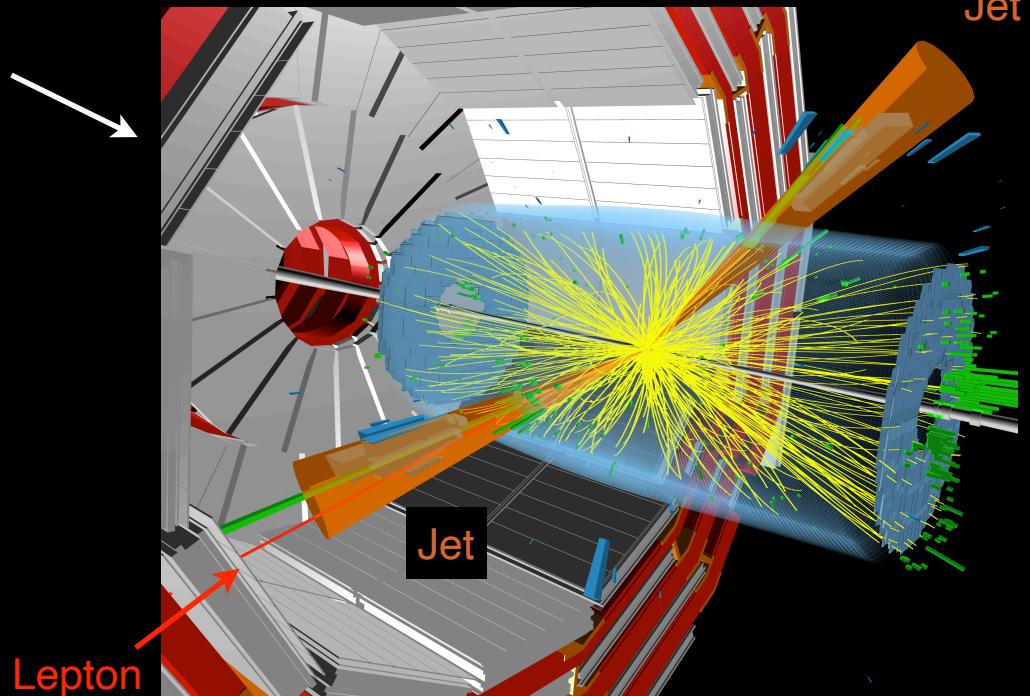


Fake lepton backgrounds

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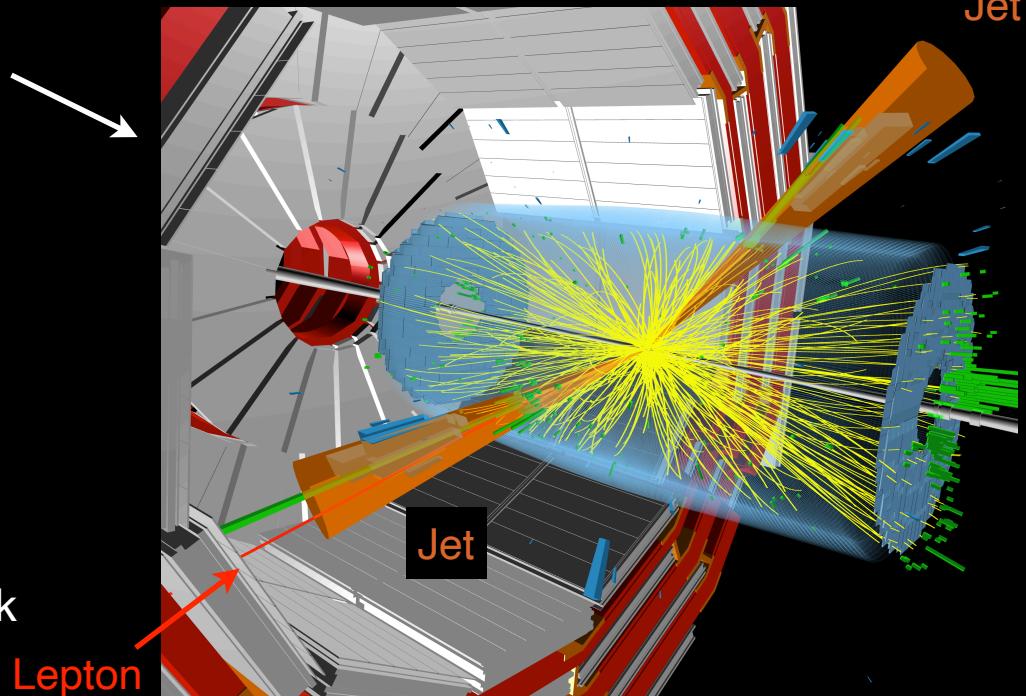
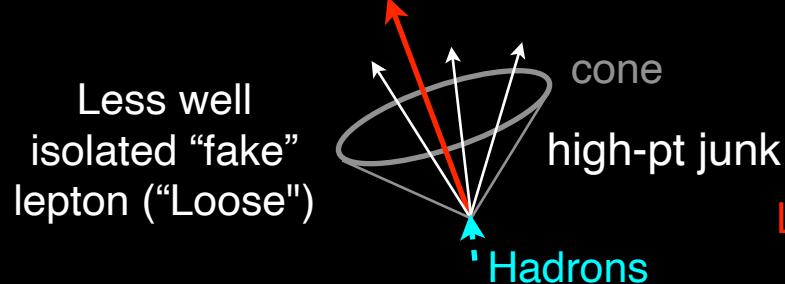
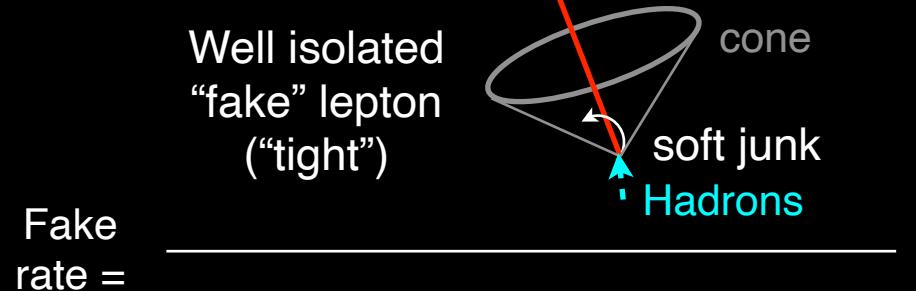


Pick one lepton events with phase space dominated by QCD (dijet) events



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”)



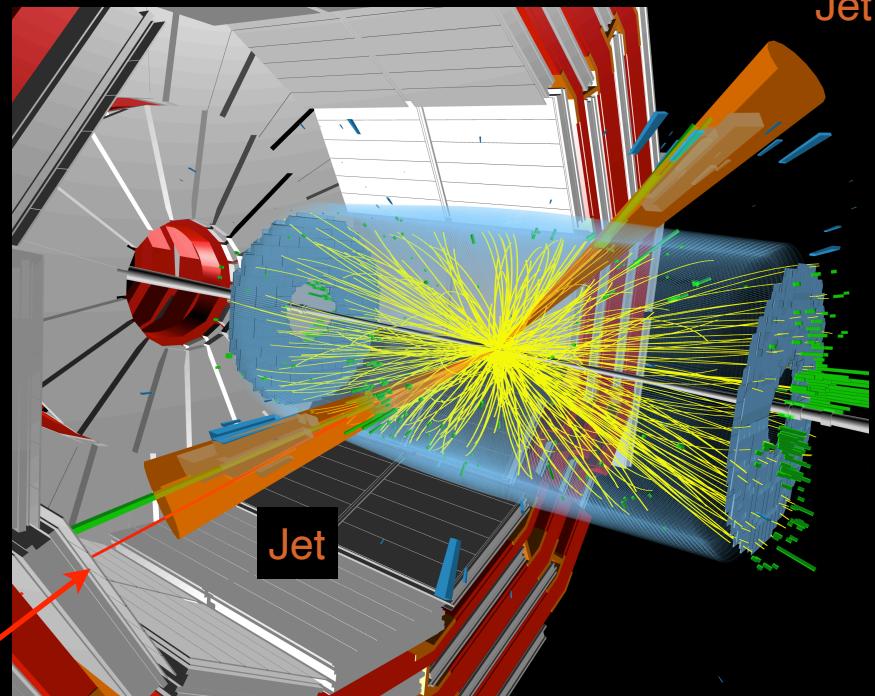
Fake
rate =

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



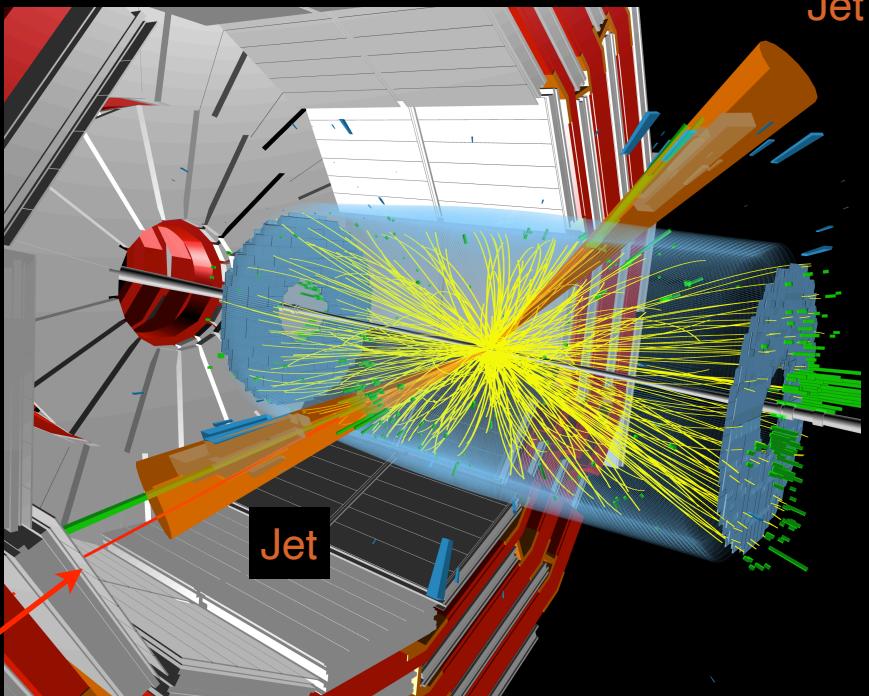
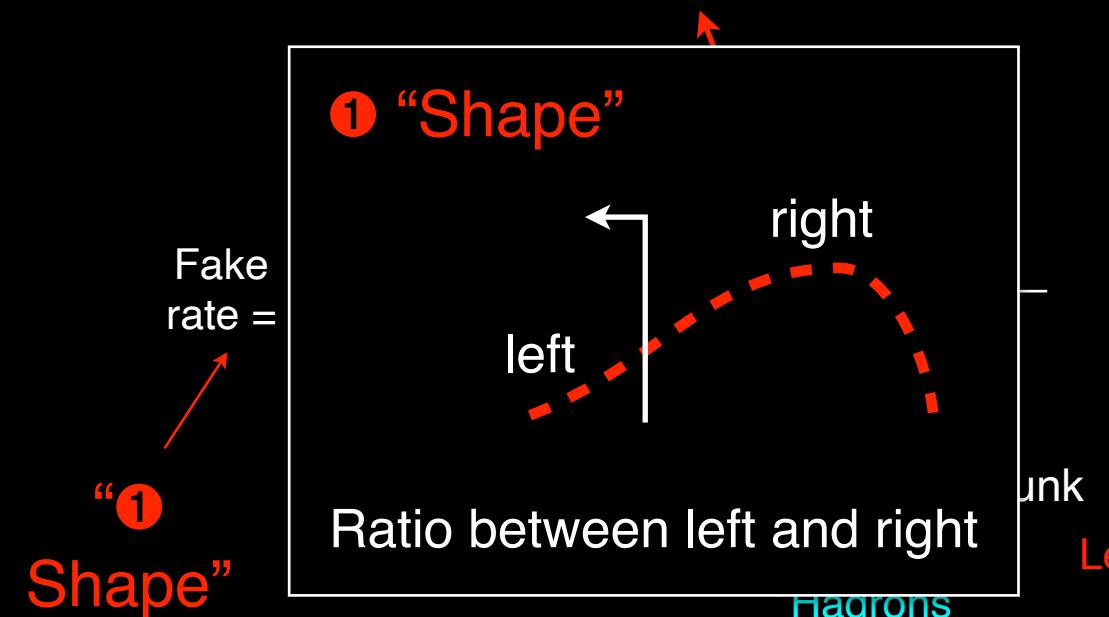
①

Shape



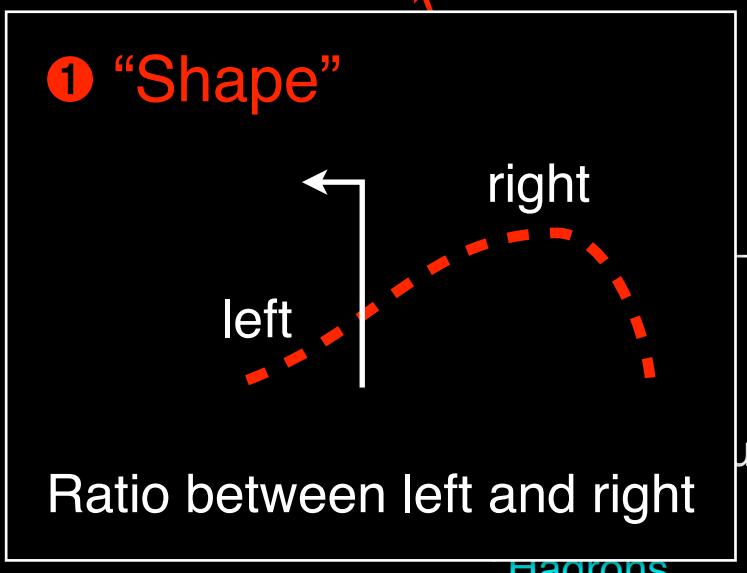
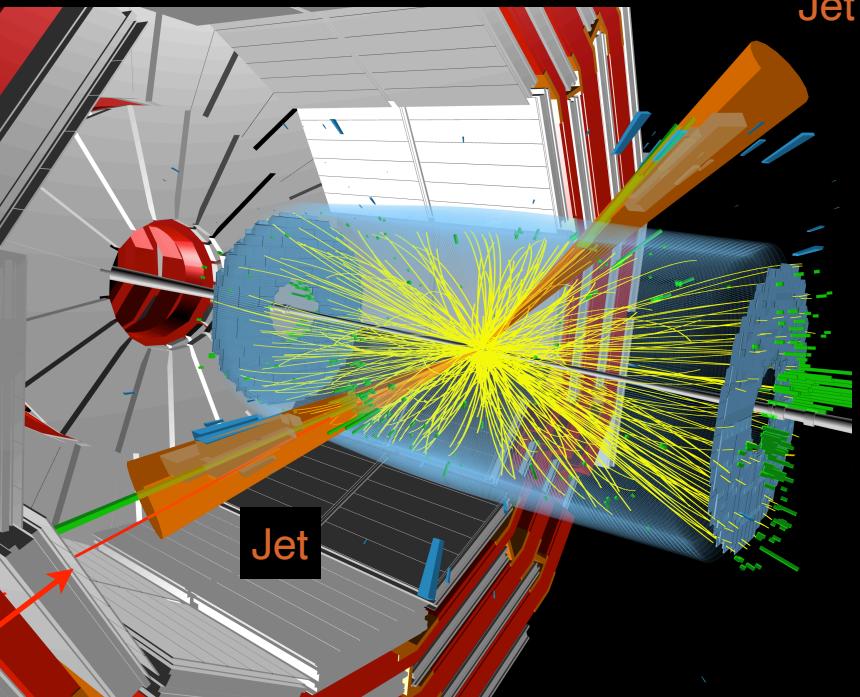
Fake lepton backgrounds

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



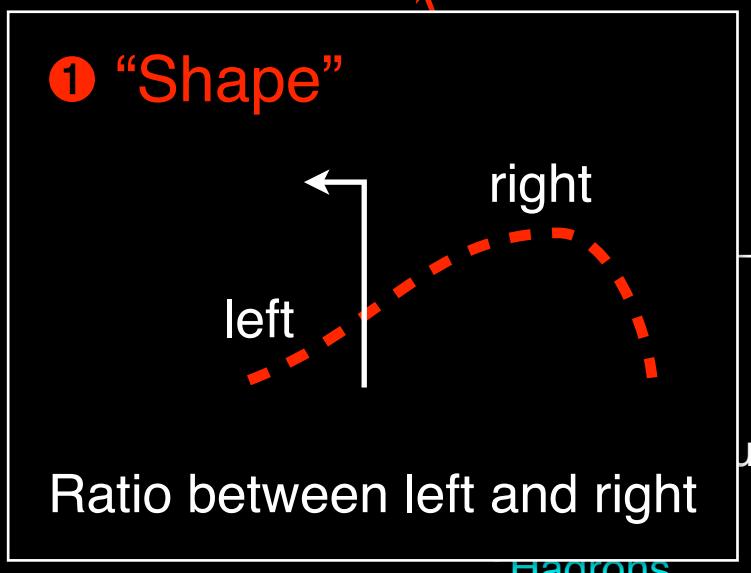
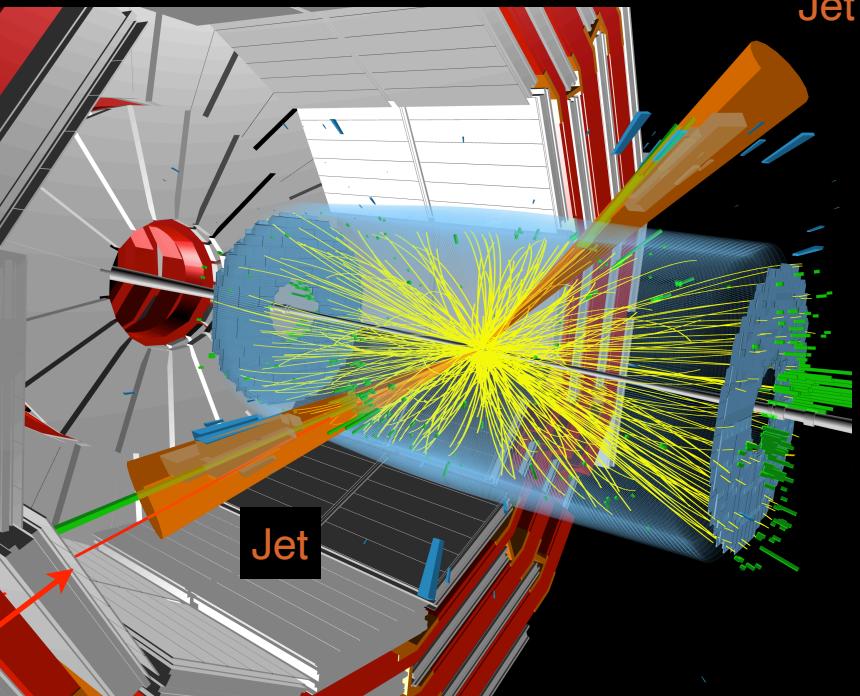
Fake rate is then applied to signal like region with “Loose”-ly identified leptons

“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%)

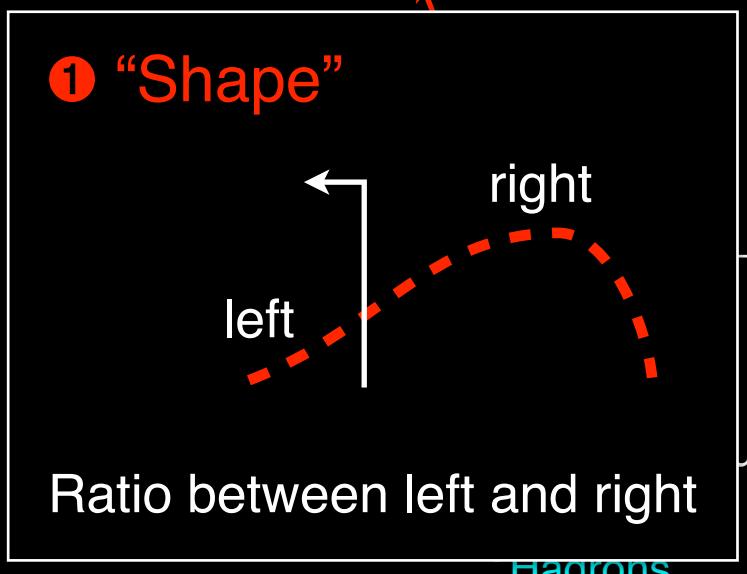
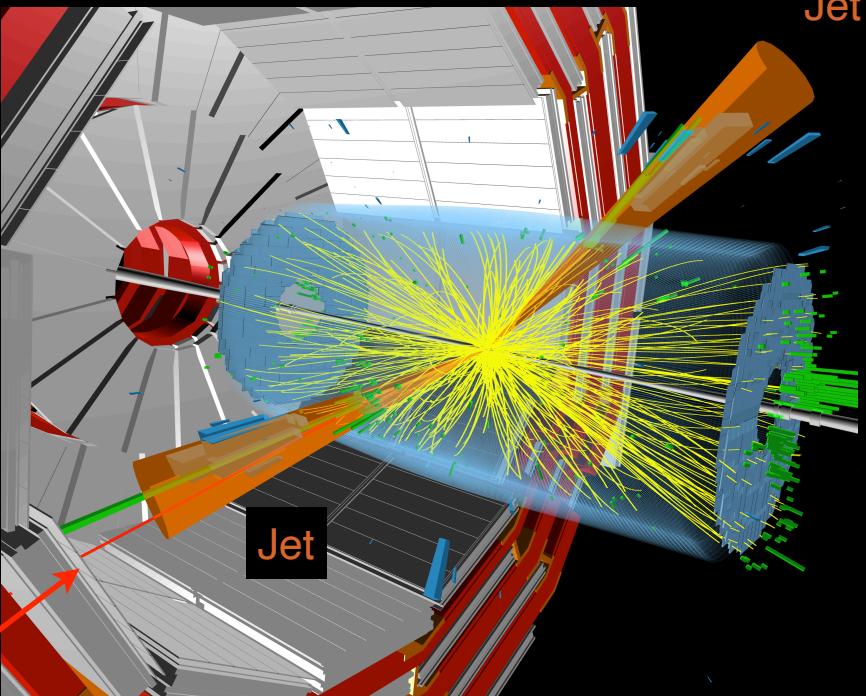
“Side band” in isolation

↑

“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

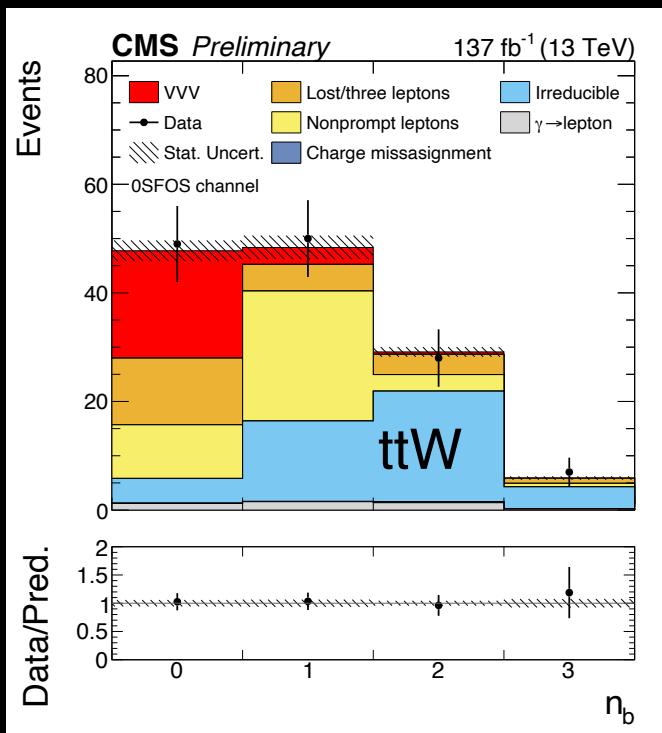
Backgrounds with b jets / irreducible

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UCSD

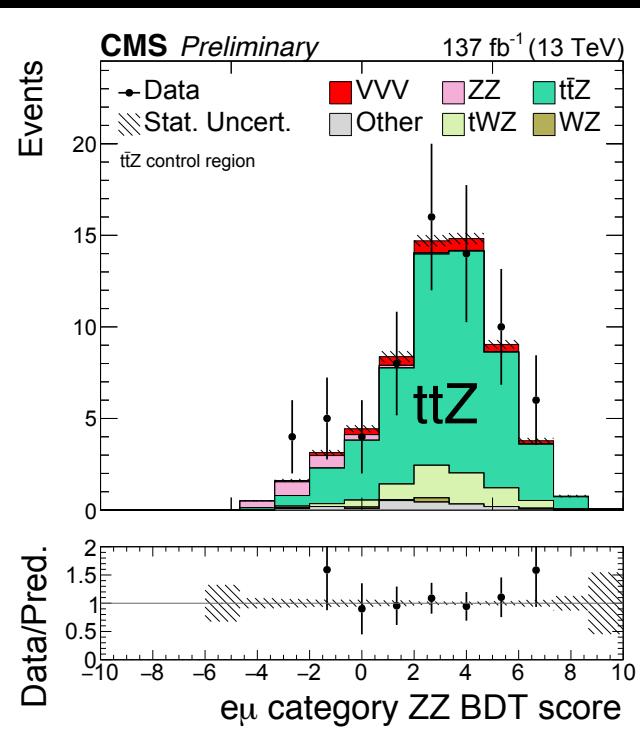


Devise control regions and extrapolate to signal region

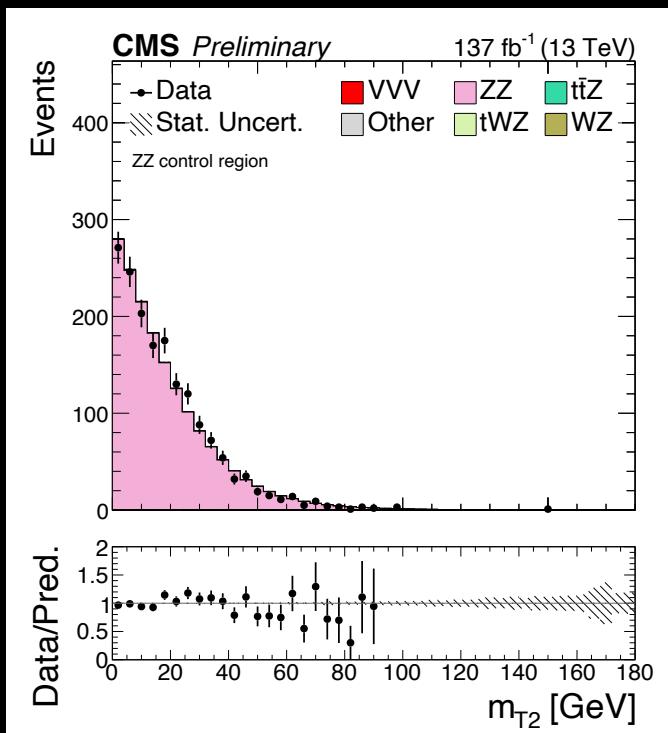
N_b in 3 lepton



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

Smart humans and
smart machines
(Both cut / BDT)



2. Additional background suppression through smart choices

3. Reliably estimate the size of residual backgrounds

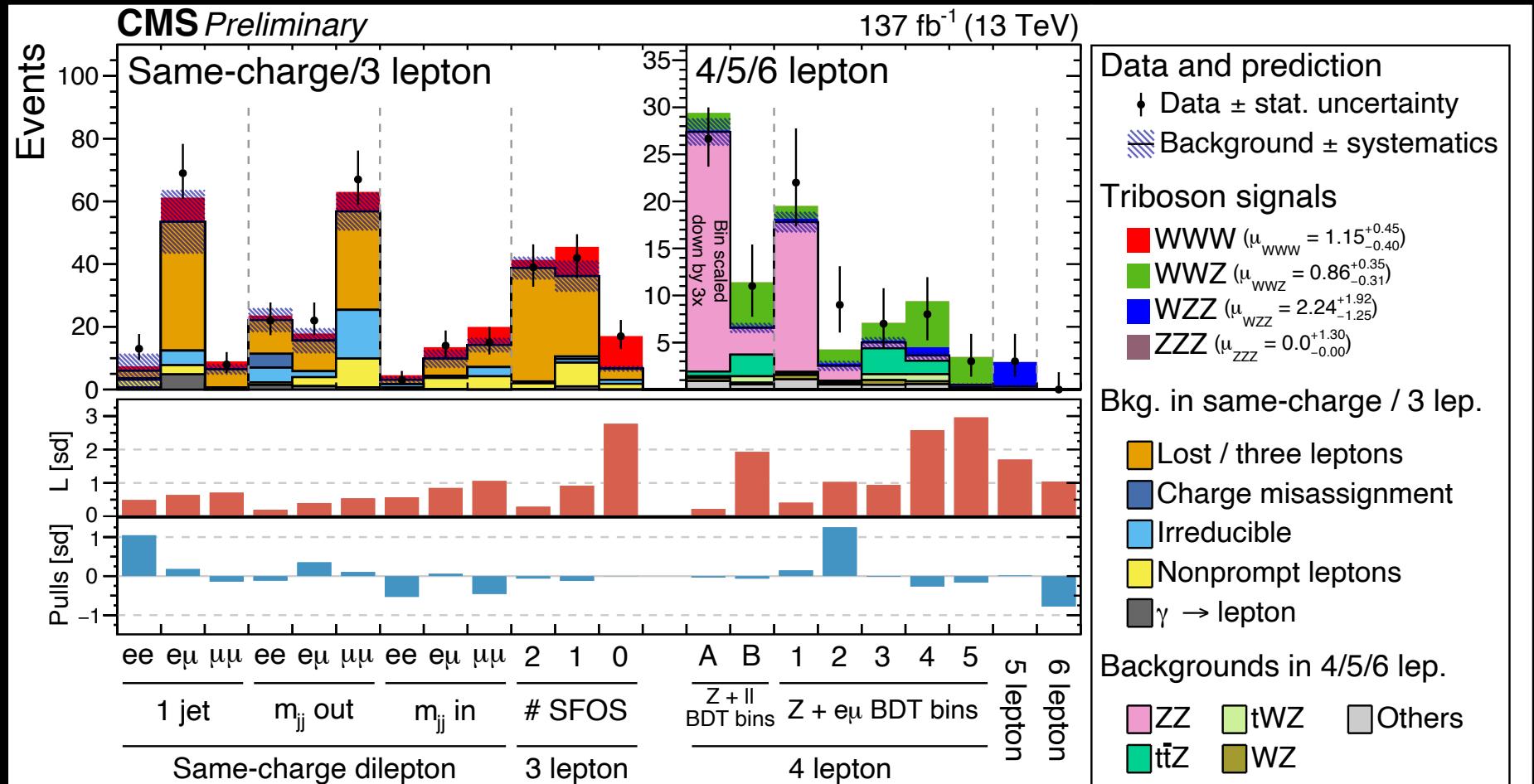
4. Observe VVV!

Results (BDT-based analysis)

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Measured cross section
Theoretical cross section



9 bins

3 bins

7 bins

1 1

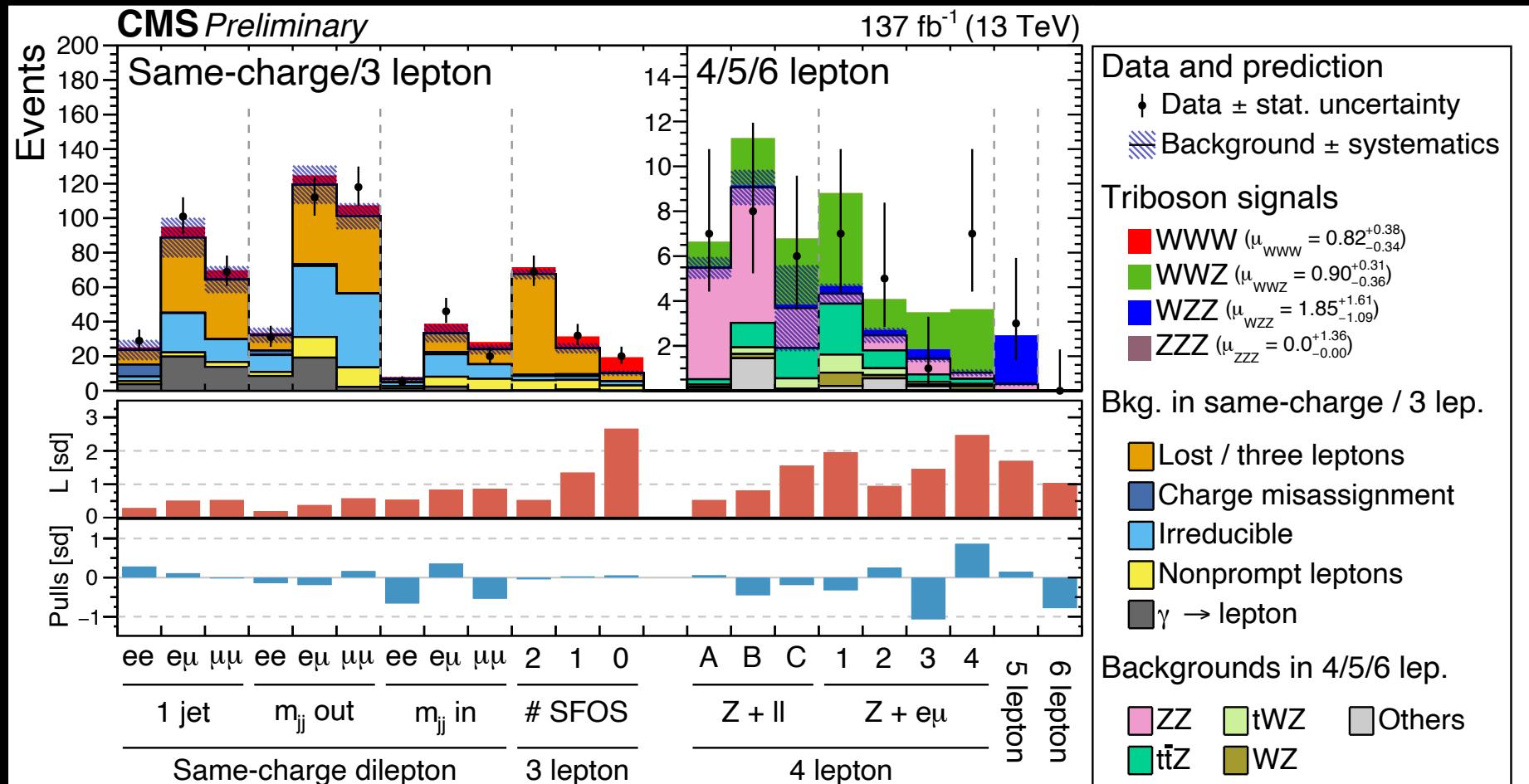
More sensitive bins are generally to the right

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

Results (Cut-based analysis)



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

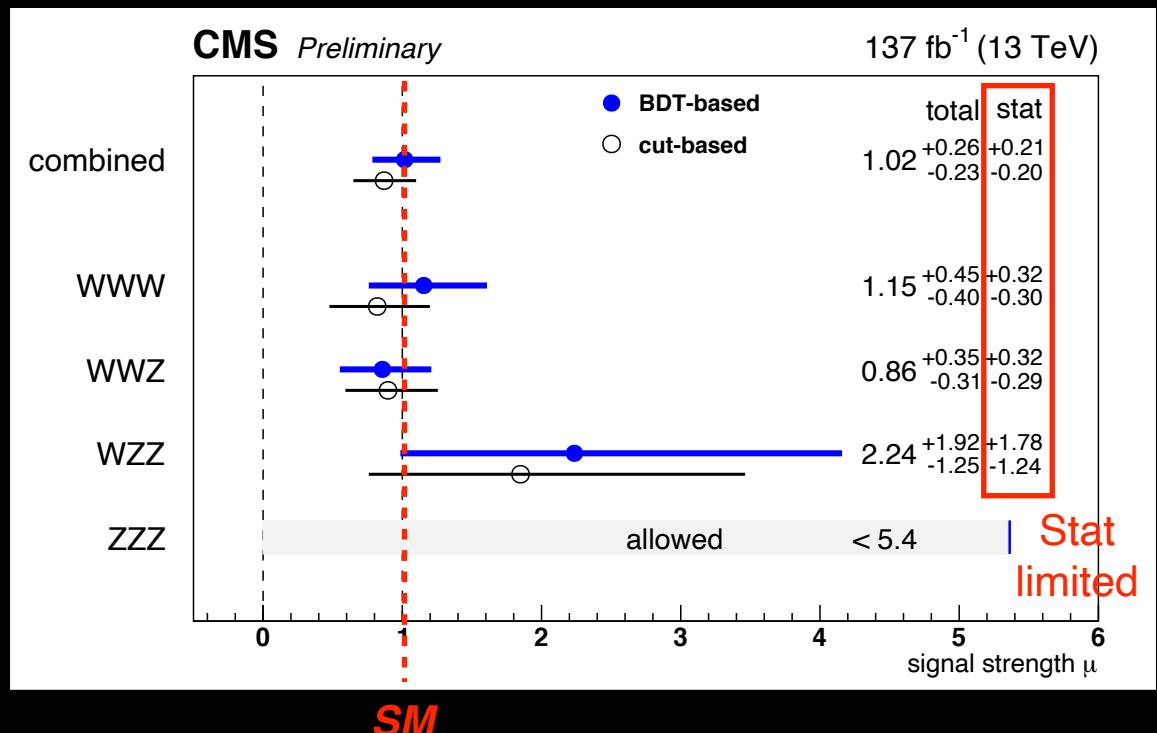


More sensitive bins are generally to the right

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

Results

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



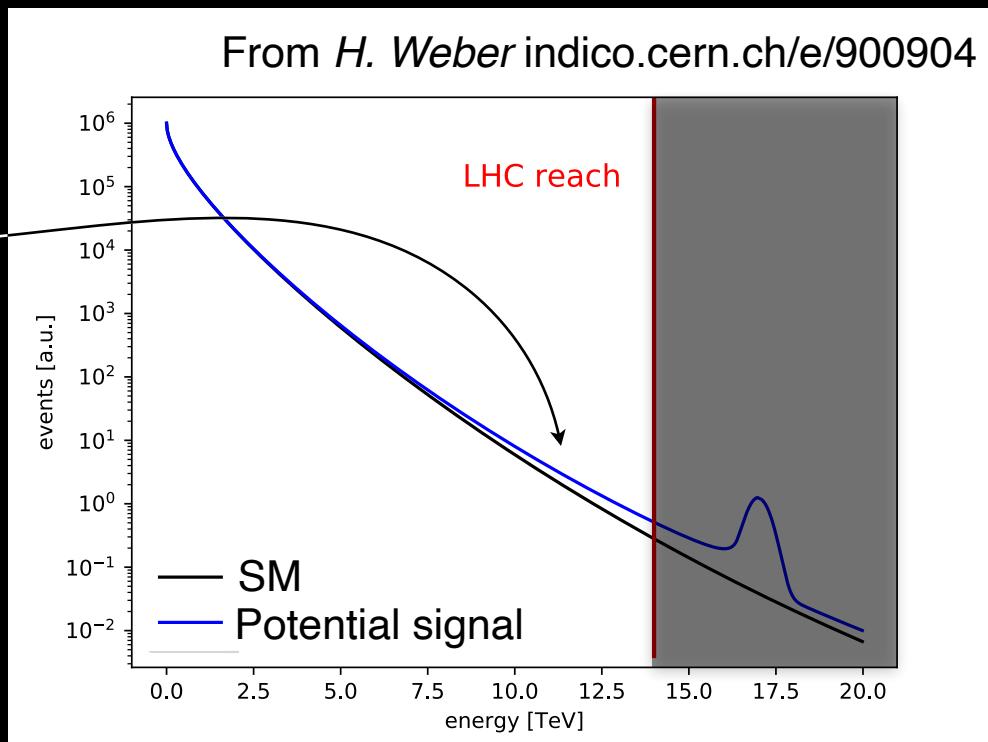
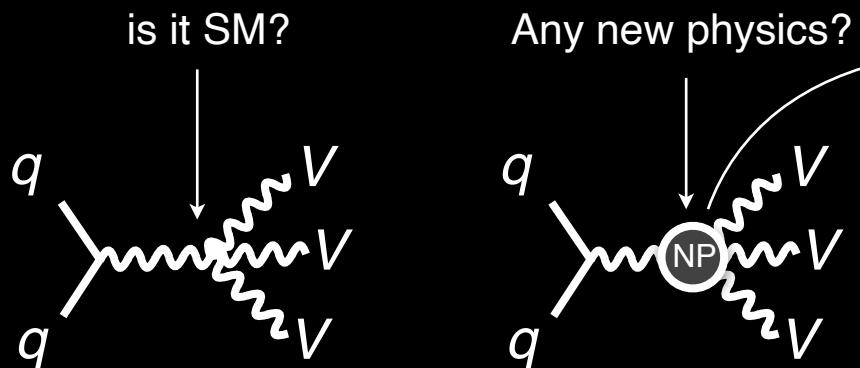
$$\text{Signal strength } \mu = \frac{\text{Measured cross section}}{\text{Theoretical cross section}}$$

- 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

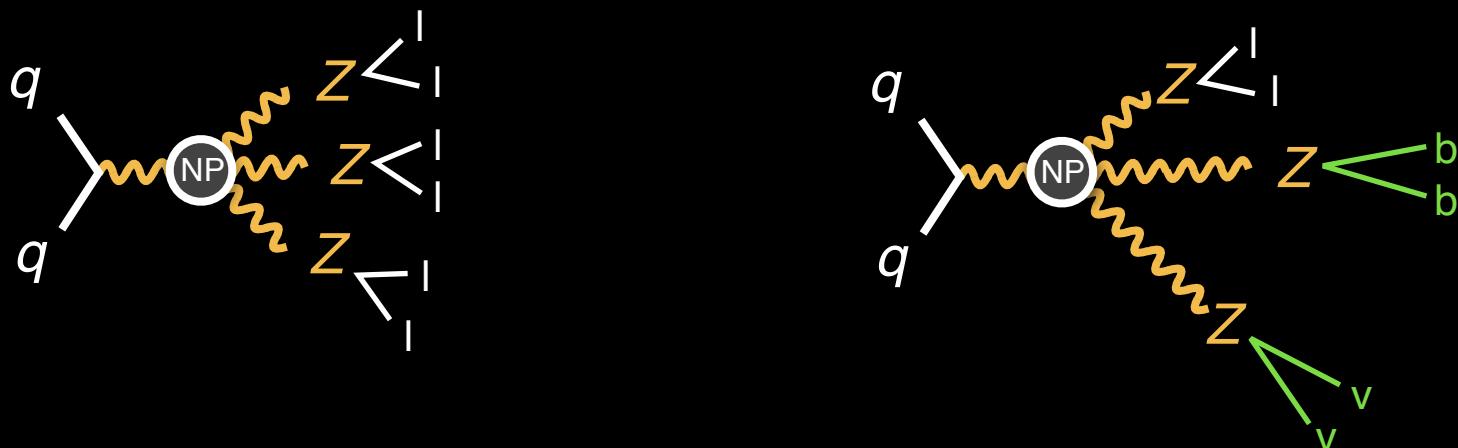
Now that we have established VVV production we can use it to test SM and also search new physics (cf. Four fermion interaction with Fermi constant)



Establishment of VVV production opens up a new physics program

Fully leptonic v. Semi leptonic channel

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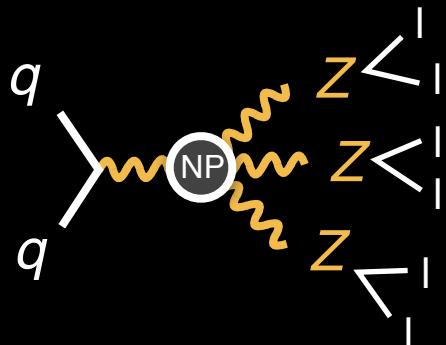
└─ If BSM exists, effects are same ─┘

- 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

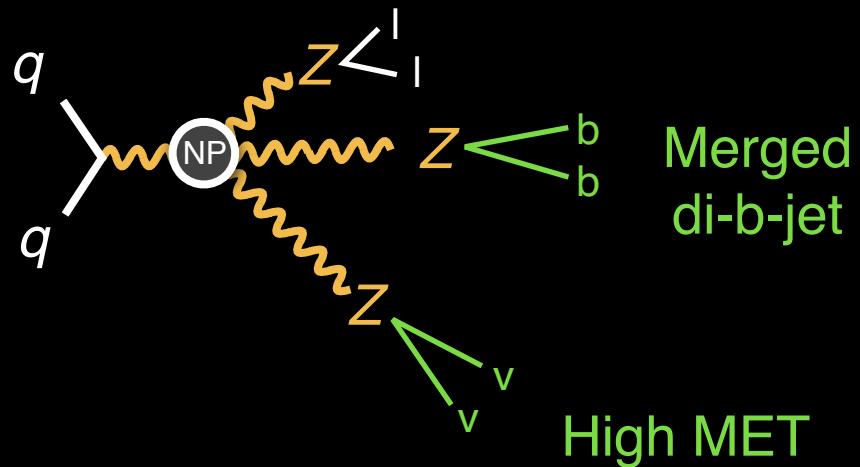
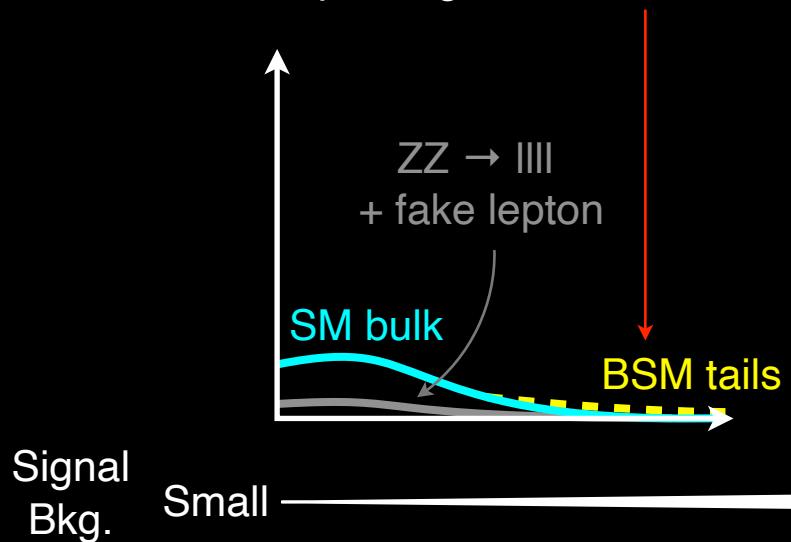
$VVV \rightarrow$ semi-leptonic ought to have same physics as $VVV \rightarrow$ fully leptonic

Fully leptonic v. Semi leptonic channel

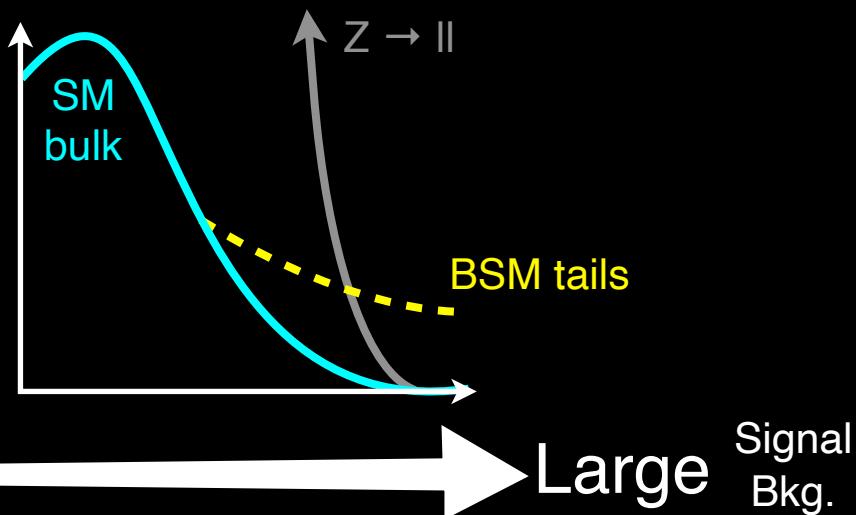
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Clean channel for discovery but probing tail is **difficult**



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



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

More multi-massive-X processes for future

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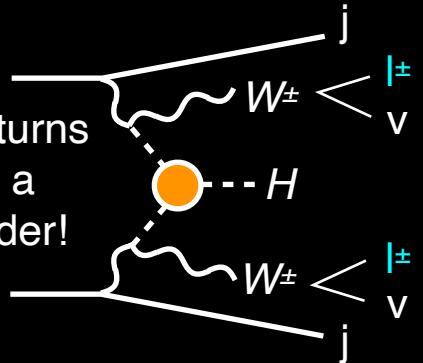


listing a few multi-massive-X processes with same-sign

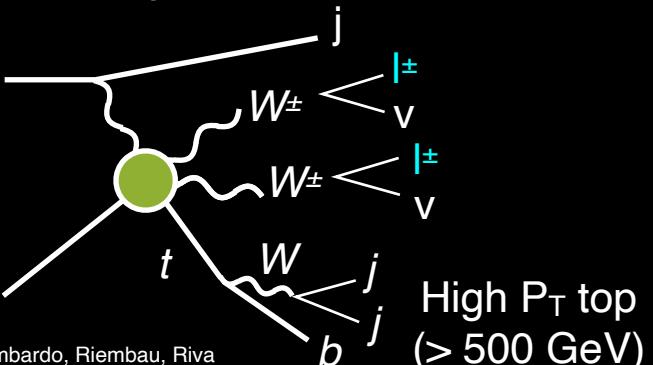
$pp \rightarrow W^\pm W^\pm H$

Same-sign is special

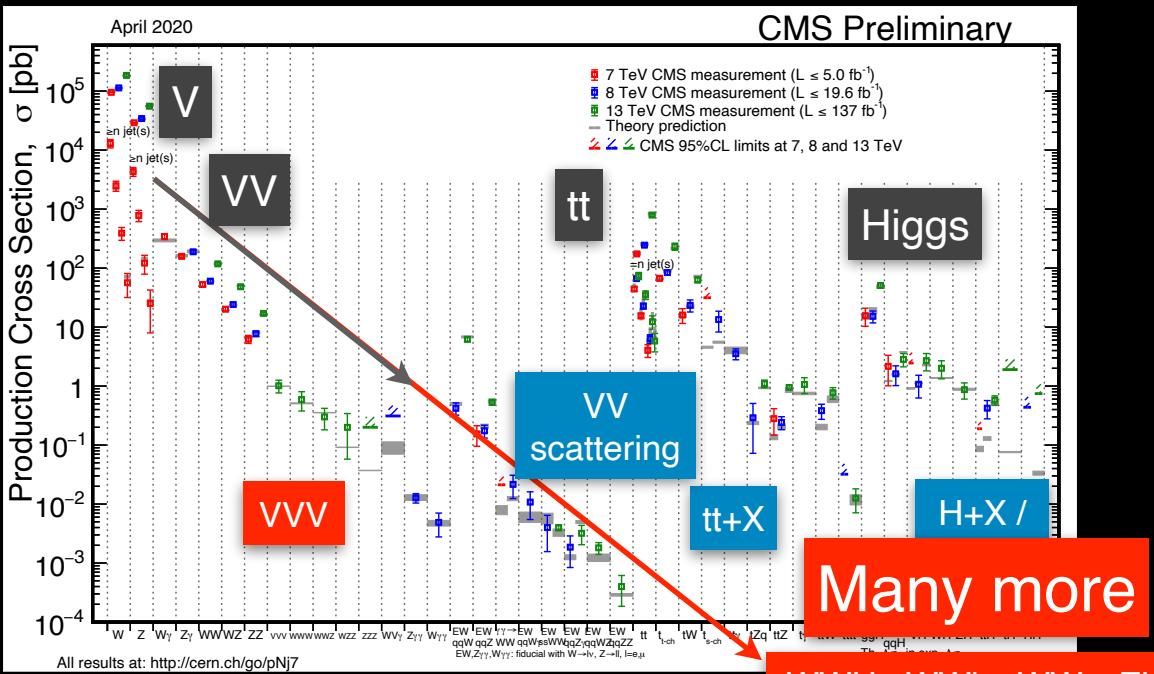
Same-sign turns LHC into a Higgs collider!



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



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

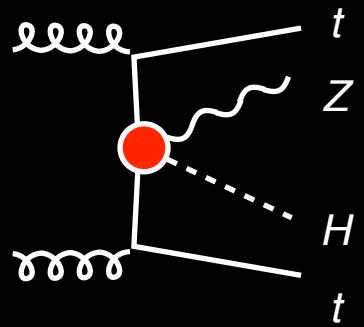
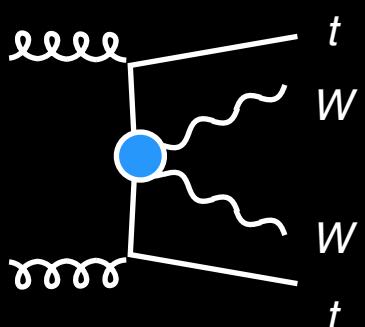


Many more

WWH, tWWj, ttWW, ttZH

$pp \rightarrow ttWW$

$pp \rightarrow ttZ\bar{H}$



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

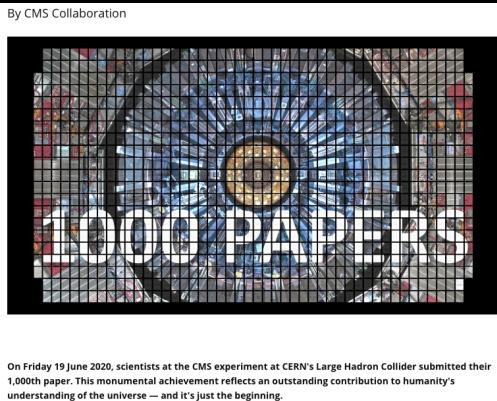
Summary



- First observation of VVV productions 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



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.”



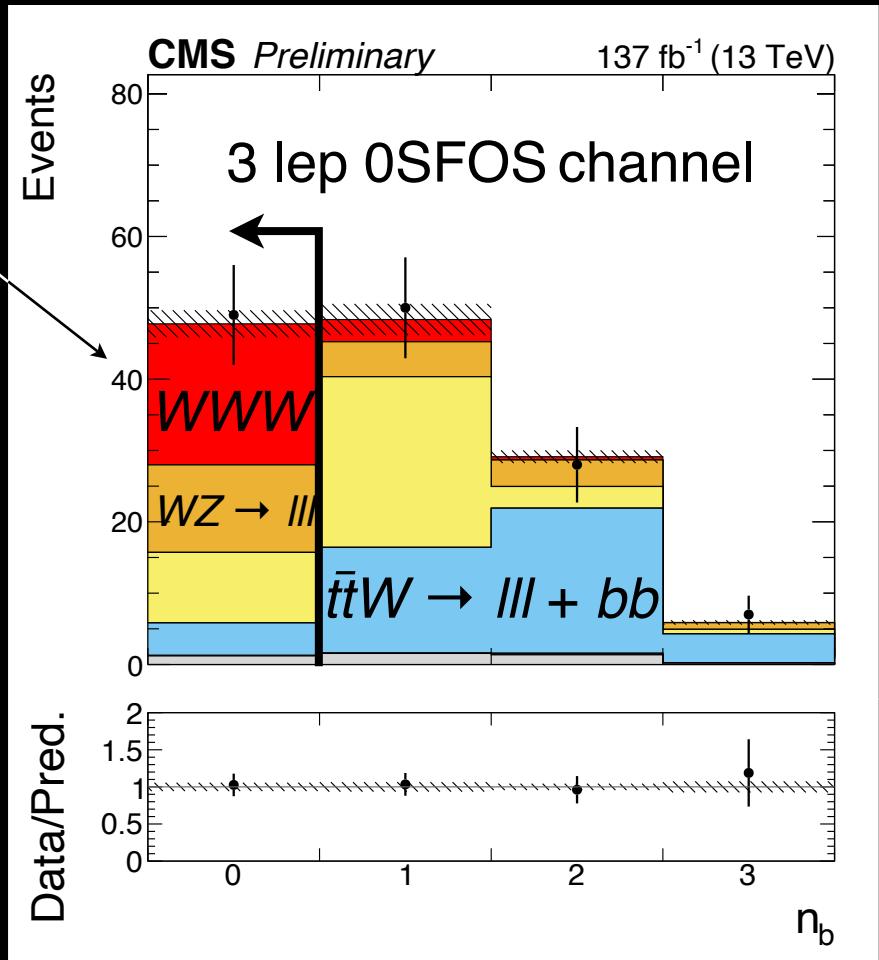
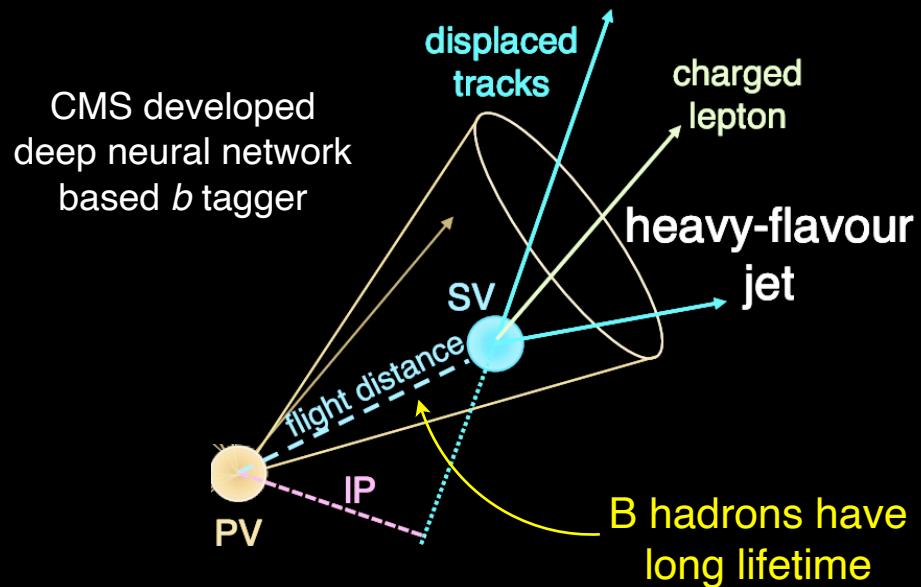
Backup

Rejecting events with b jets

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



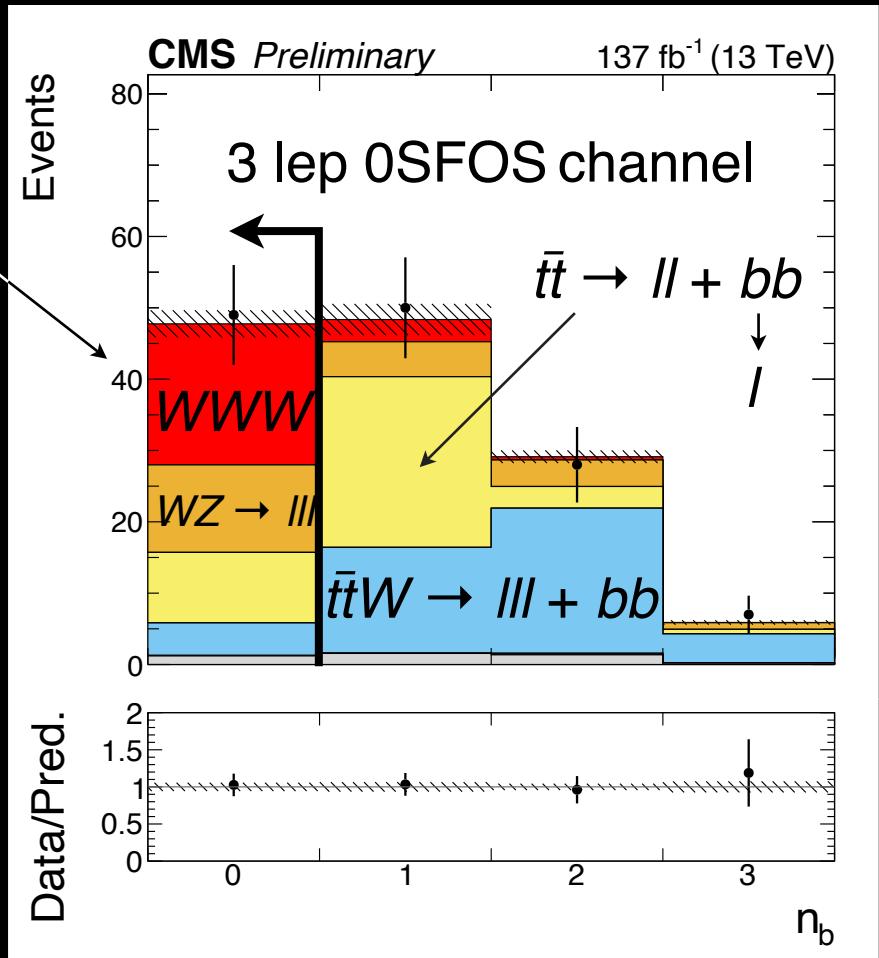
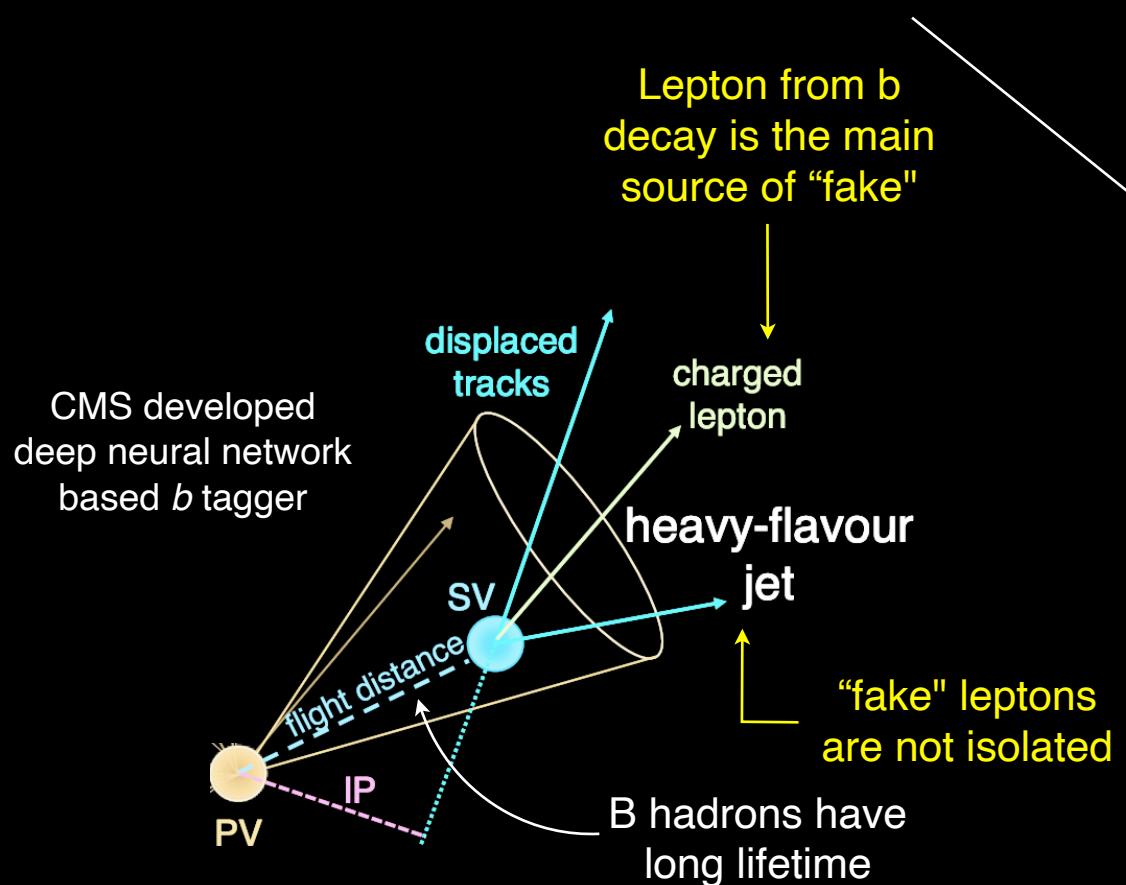
Signals do not have b jets

Added benefit of rejecting events with b

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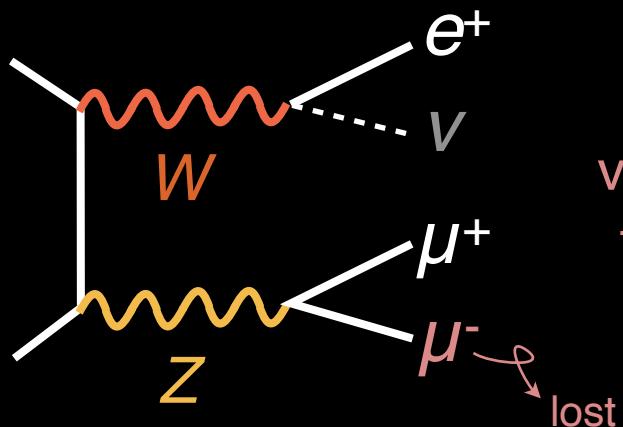


EW processes generally do not come
with b jets \Rightarrow Require # of b = 0



Signals do not have b jets

WZ background in same-sign channel



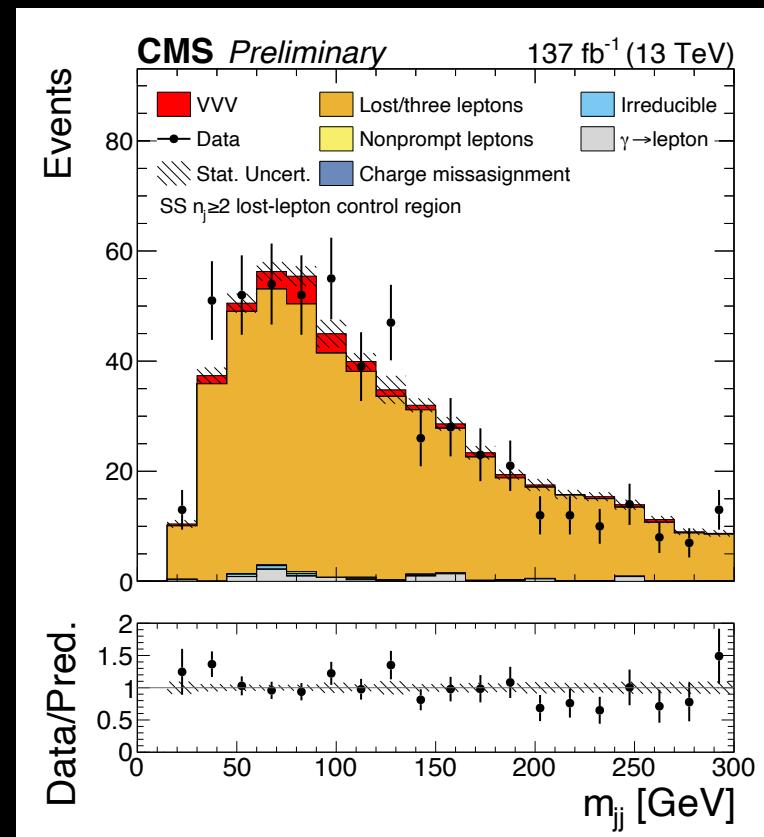
enters signal region
via lost lepton \Rightarrow Need
to understand lepton
finding efficiency

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

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

Experimental systematics assigned

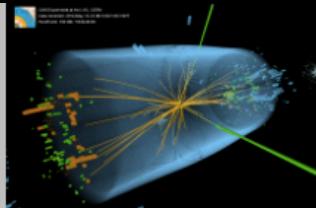
Control region data statistics dominates
uncertainty (20%)



Estimate lost lepton background by extrapolating across # of leptons



Compact Muon Solenoid LHC, CERN



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

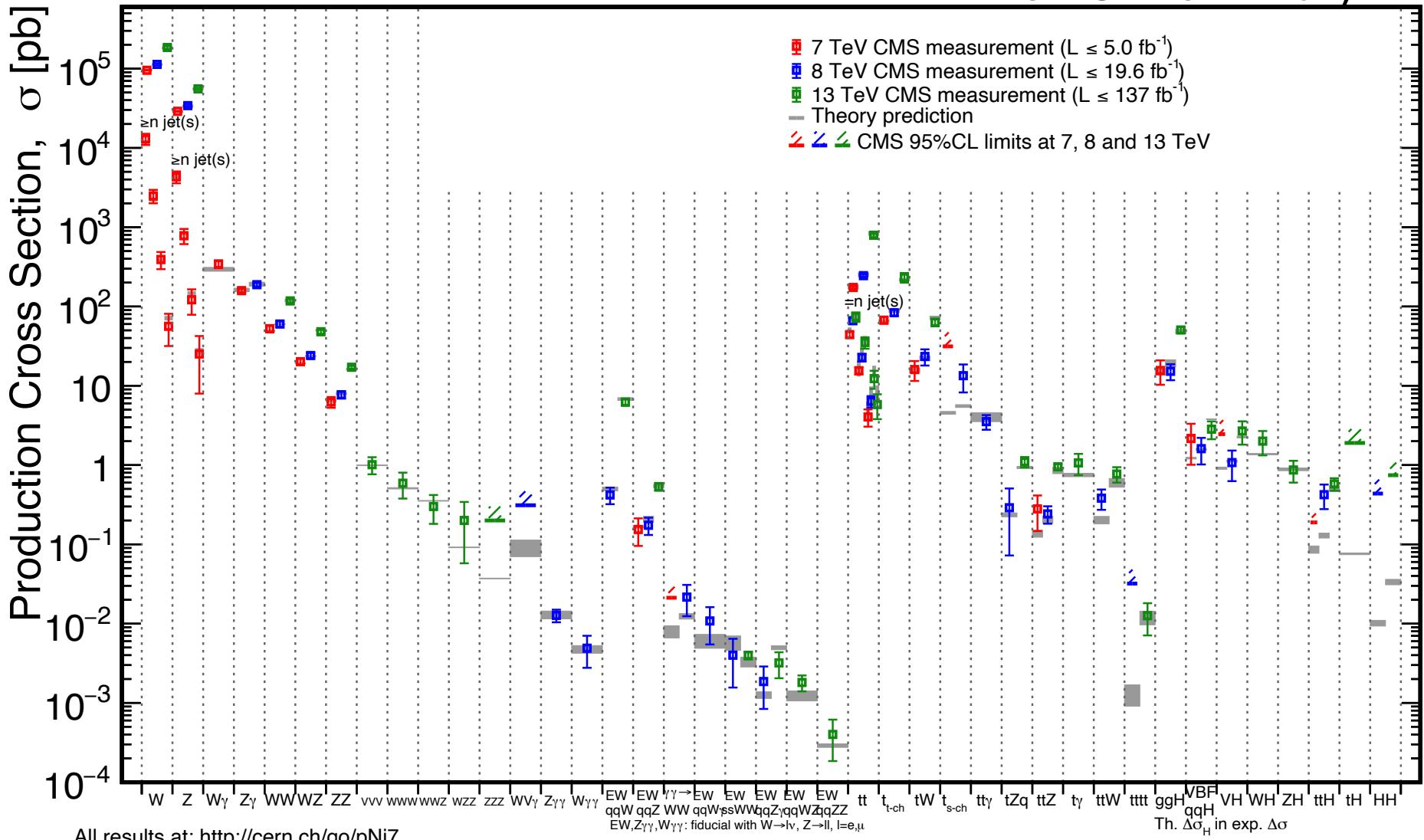
CMS Publications

1000	SMP-19-014	Observation of the production of three massive gauge bosons at $\sqrt{s} = 13$ TeV	Submitted to PRL	19 June 2020
999	HIN-19-001	Evidence for top quark production in nucleus-nucleus collisions	Submitted to NP	19 June 2020
998	TRG-17-001	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
			3ℓ
Triggers	Select events passing dilepton triggers		
Number of leptons	Select events with 2 (3) leptons passing SS-ID (3ℓ -ID) for SS (3ℓ) final states		
Number of leptons	Select events with 2 (3) leptons passing veto-ID for SS (3ℓ) final states		
Isolated tracks	No additional isolated tracks		
b-tagging	no b-tagged jets and soft b-tag objects		
Jets	≥ 2 jets	1 jet	≤ 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_{SFOS}	—	—	$m_{\text{SFOS}} > 20$ GeV
m_{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	≥ 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^{miss}		$> 45 \text{ GeV}$
m_{JJ} (leading jets)	$< 500 \text{ GeV}$	—
$\Delta\eta_{JJ}$ (leading jets)	< 2.5	—
m_{jj} (closest ΔR)	$65 < m_{jj} < 95 \text{ GeV}$ 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_{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



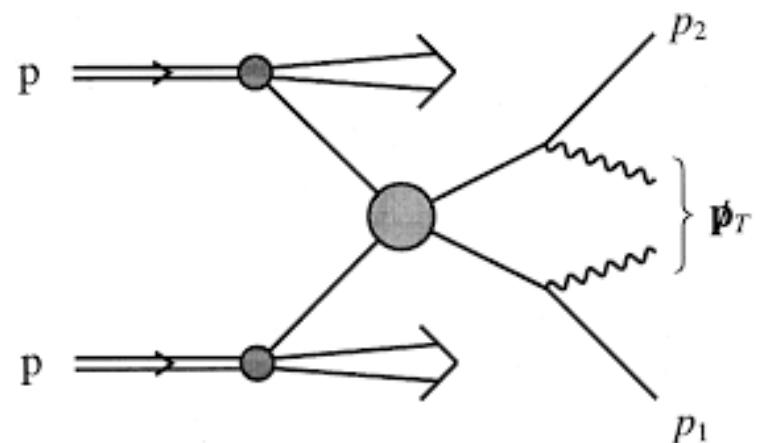
Features	Selections
Number of leptons	Select events with 4 leptons passing common veto-ID
Triggers	Select events passing dilepton triggers
Z lepton	Find opposite charge lepton pairs, passing ZID, closest to m_Z Require Z leptons to have $p_T > 25, 15$ GeV
W lepton	Require that leftover leptons are opposite 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



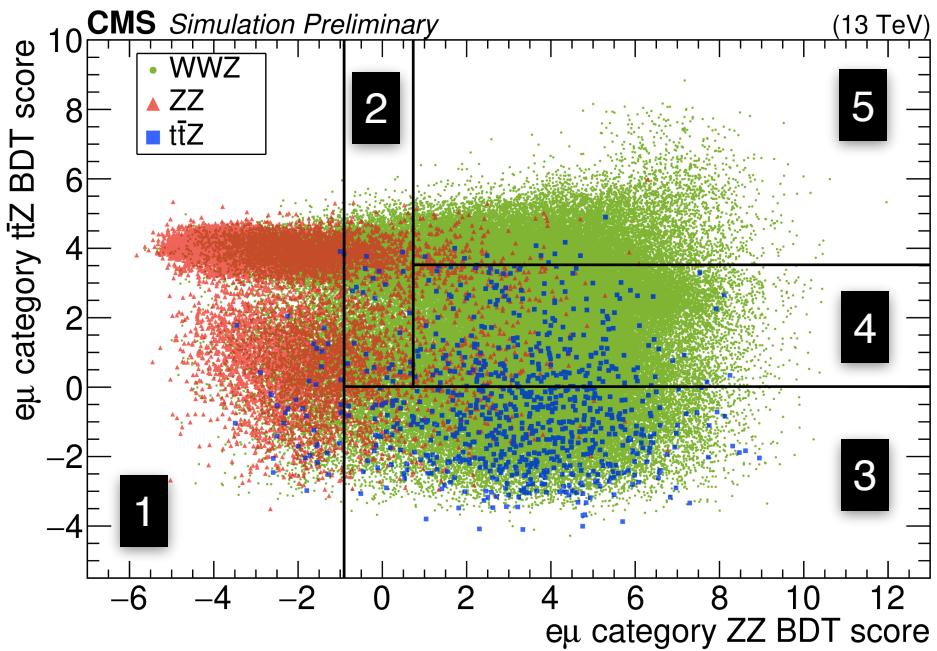
Variable	e μ category	ee/ $\mu\mu$ category
Preselection	Selections in Table 20	
W candidate lepton flavors	e μ	ee/ $\mu\mu$
$m_{\ell\ell}$	Separated into 4 bins in $(0, 40, 60, 100, \infty)$	$ m_{\ell\ell} - m_Z > 10 \text{ GeV}$
m_{T2}	$m_{T2} > 25 \text{ GeV}$ (for $m_{\ell\ell} > 100 \text{ GeV}$)	...
$p_{T,4\ell}$ and p_T^{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)

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

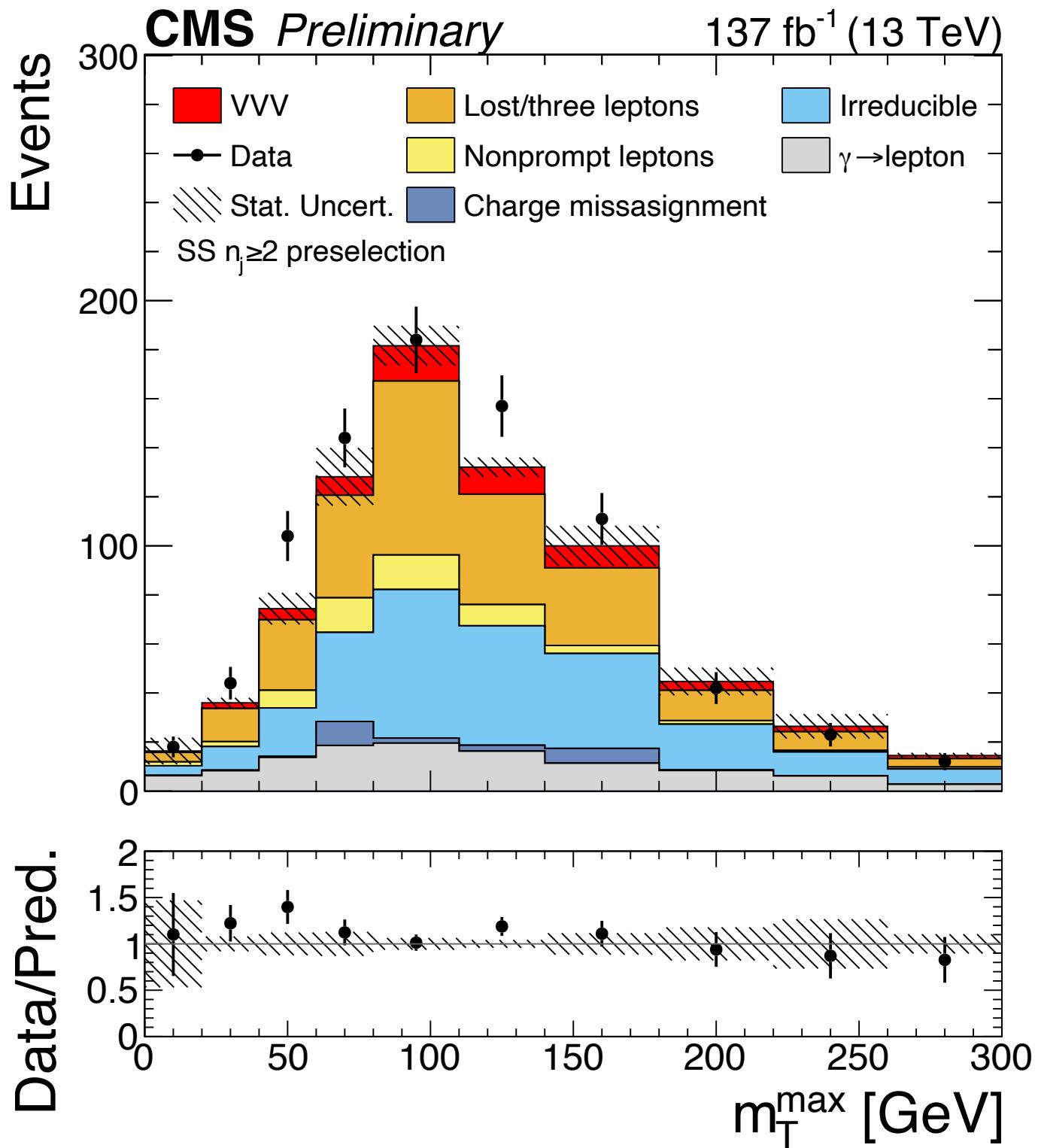


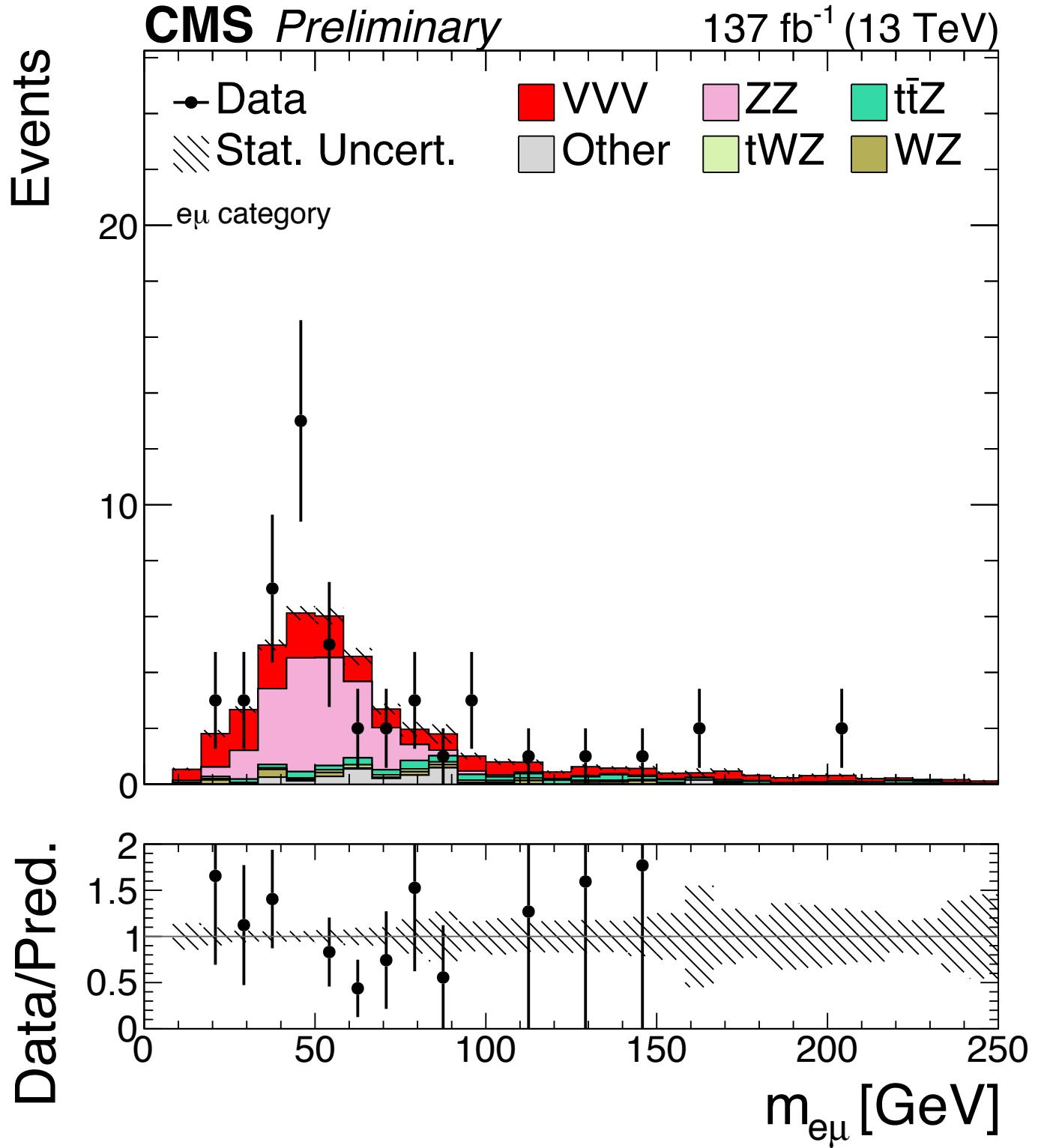
For $WW \rightarrow llvv$ sub-system of WWZ , endpoint is at m_W

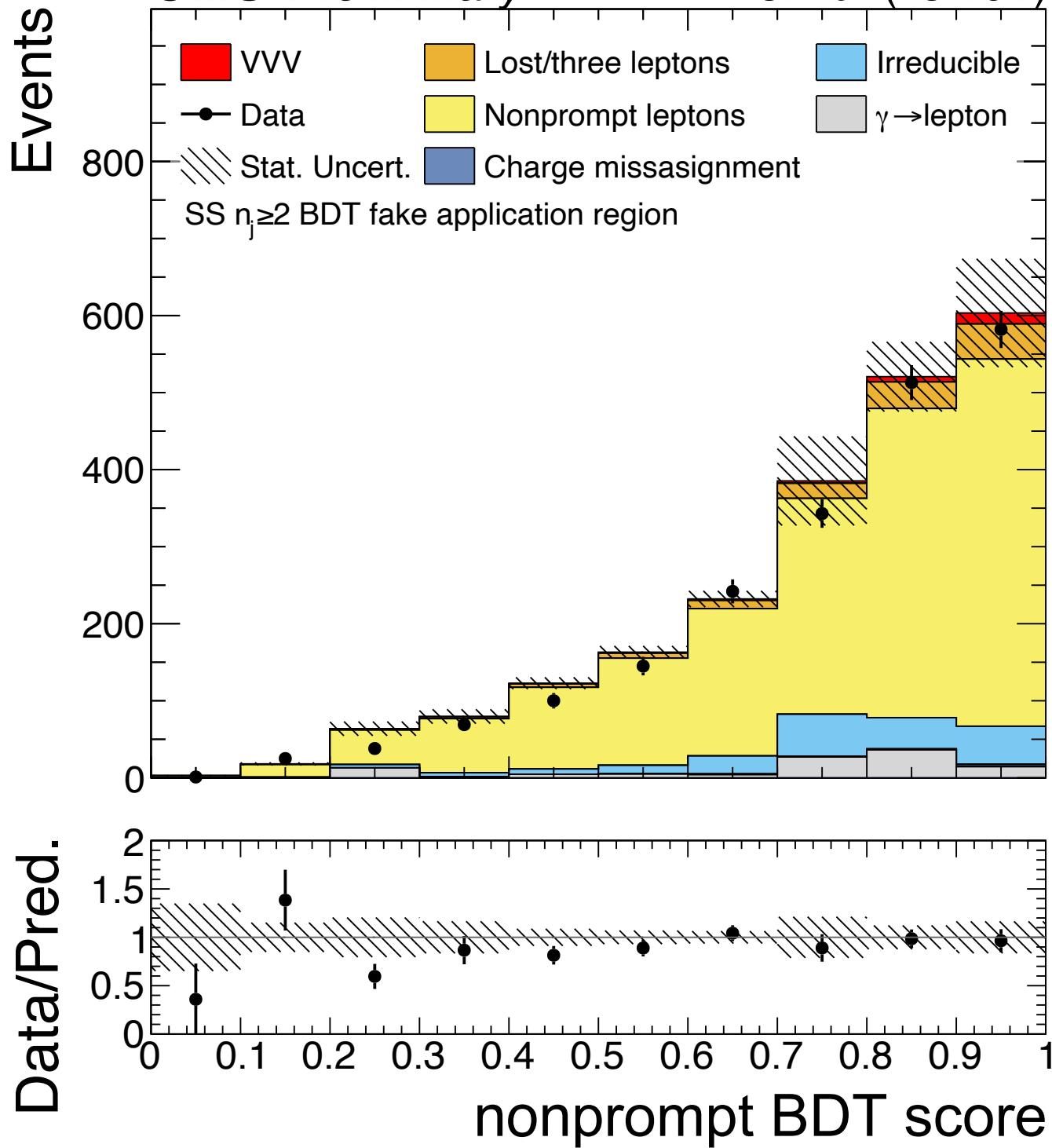
For $Z \rightarrow \tau\tau \rightarrow llvvvv$ sub-system of ZZ , endpoint is at m_τ

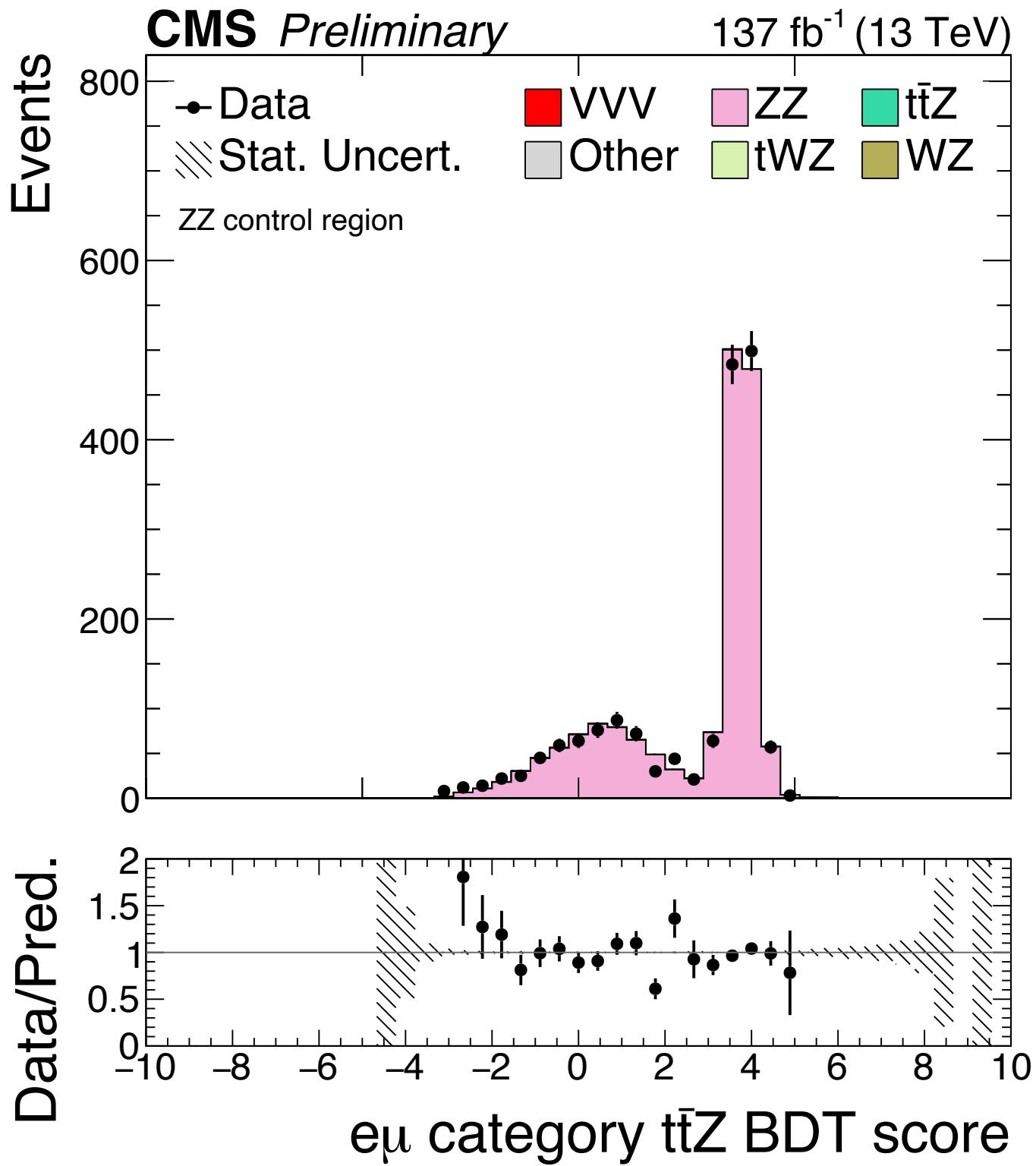


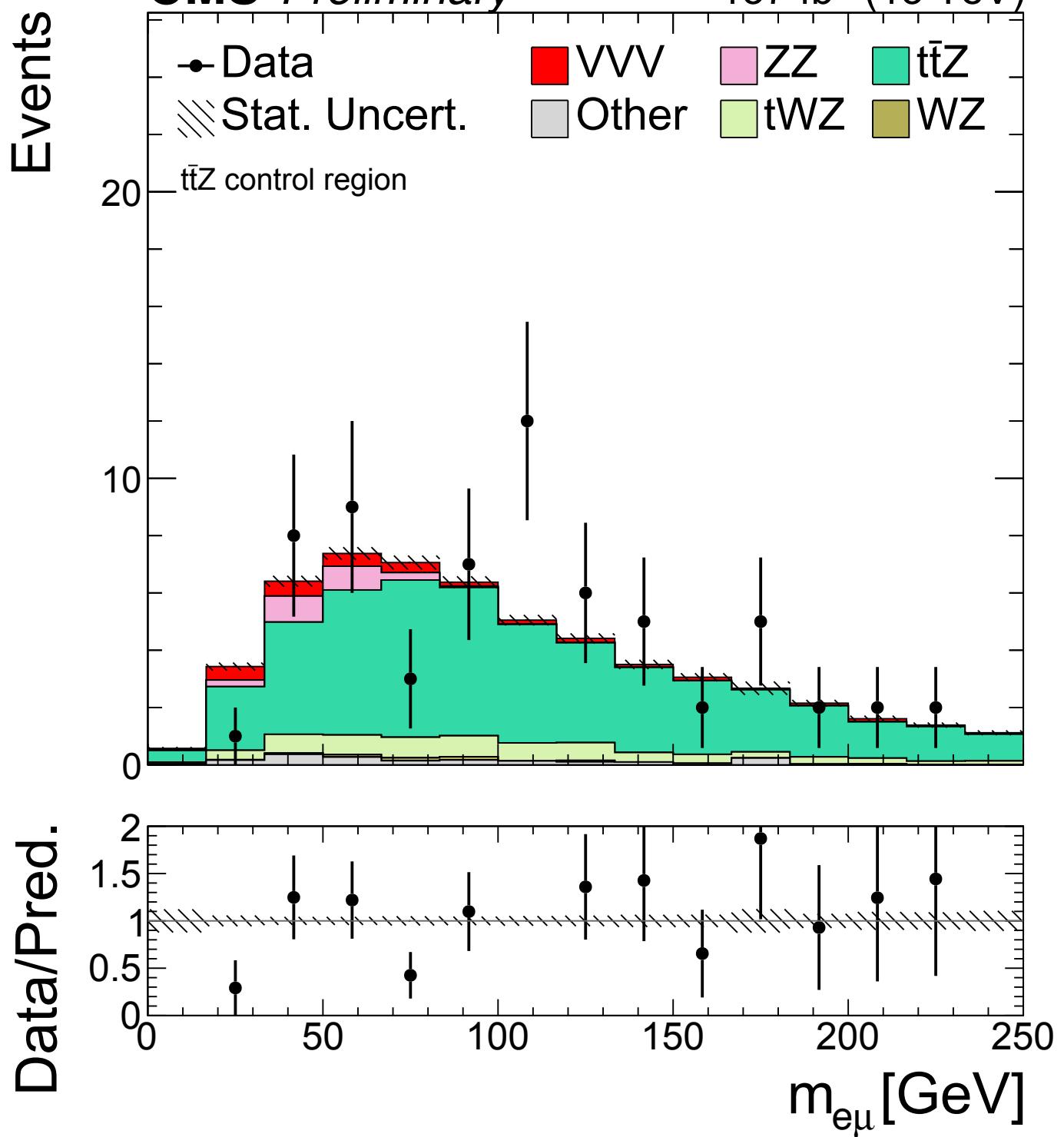
	ZZ BDT range	t̄Z BDT range
eμ BDT bin 1	(-∞, -0.908)	(-∞ , ∞)
eμ BDT bin 2	(-0.908 , ∞)	(-∞ , 0.015)
eμ BDT bin 3	(-0.908 , 0.733)	(0.015 , ∞)
eμ BDT bin 4	(0.733 , ∞)	(0.015 , 3.523)
eμ BDT bin 5	(0.733 , ∞)	(3.523 , ∞)
ee/μμ BDT bin A	(0 , 3)	-
ee/μμ BDT bin B	(3 , ∞)	-













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 ^{+2.2} _{-1.3})	6.1 (3.8 ^{+2.2} _{-1.3})	5.8 (3.7 ^{+2.3} _{-1.3})	5.8 (3.7 ^{+2.3} _{-1.3})
ZZZ	5.4 (6.0 ^{+4.6} _{-2.6})	5.4 (6.2 ^{+4.9} _{-2.7})	5.6 (6.3 ^{+5.3} _{-2.8})	5.7 (6.3 ^{+5.3} _{-2.8})



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



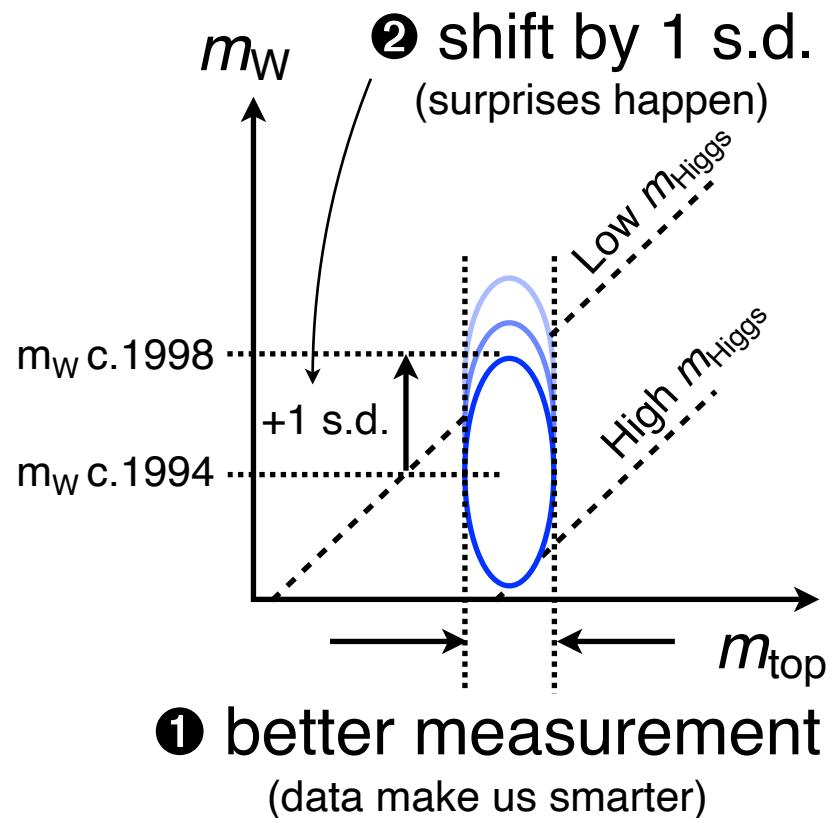
Signal region	SS m_{jj} -in				SS m_{jj} -out				SS 1j				3ℓ		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	0 SFOS	1 SFOS	2 SFOS			
Lost/three ℓ	1.8 \pm 0.4	10.9 \pm 2.0	8.7 \pm 1.0	8.8 \pm 1.7	46.0 \pm 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 ℓ	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 ℓ	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

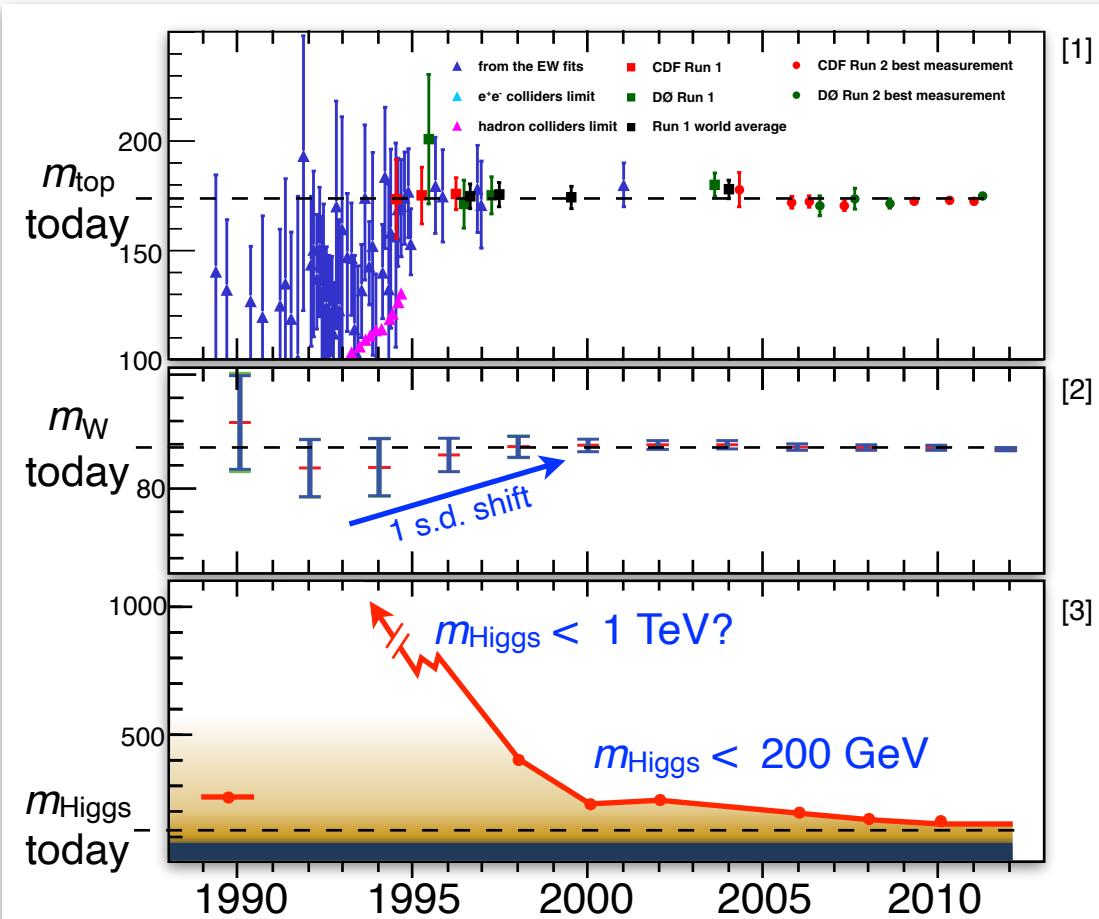
History lesson

m_{top} vs. m_W and m_{Higgs}



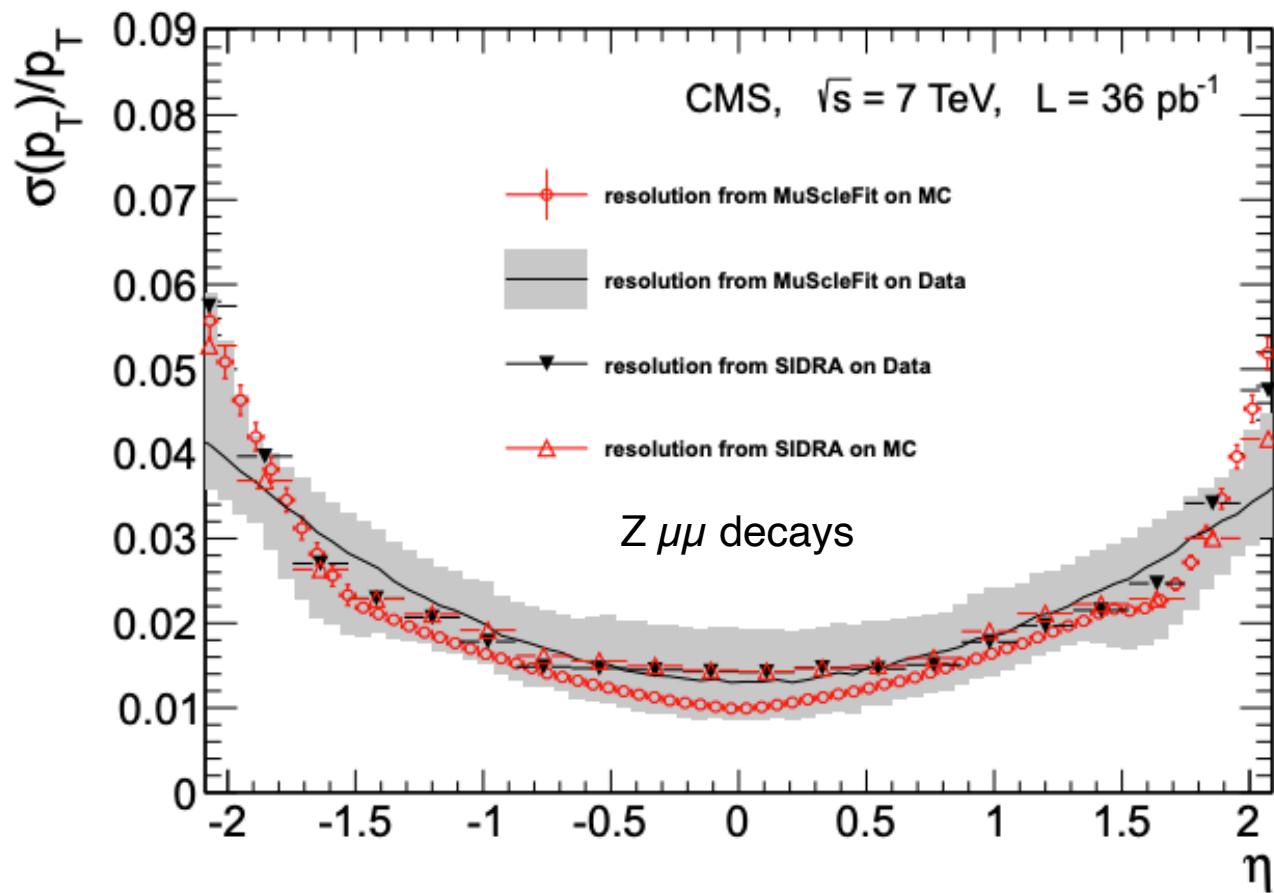
...after analysis of Run I data, ... **②** m_W shifted a full s.d. ... the m_{Higgs} must be **③** much lower than anyone had anticipated. ... Surprises happen.

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



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

Muon resolution

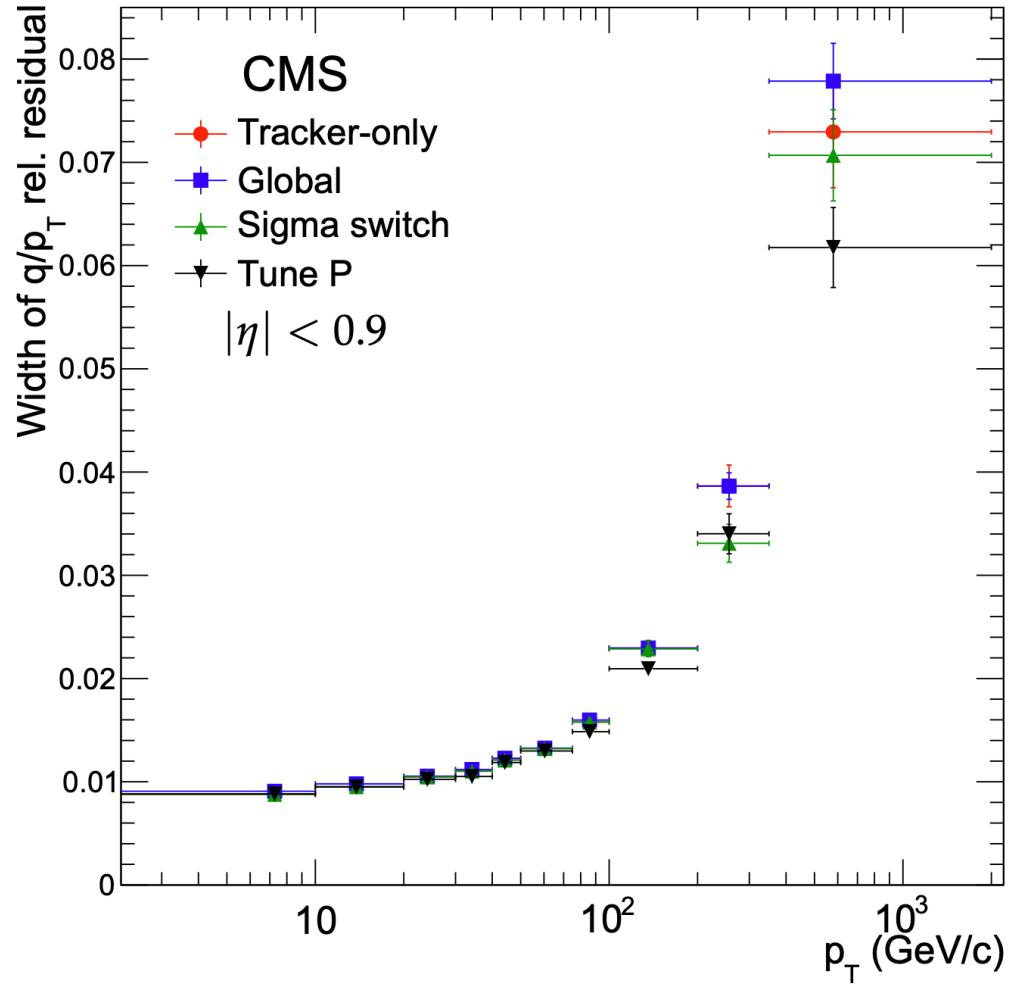


ment with the results obtained from simulation. The $\sigma(p_T)/p_T$ averaged over ϕ and η varies in p_T from $(1.8 \pm 0.3(\text{stat.}))\%$ at $p_T = 30 \text{ GeV}/c$ to $(2.3 \pm 0.3(\text{stat.}))\%$ at $p_T = 50 \text{ GeV}/c$, again in good agreement with the expectations from simulation.

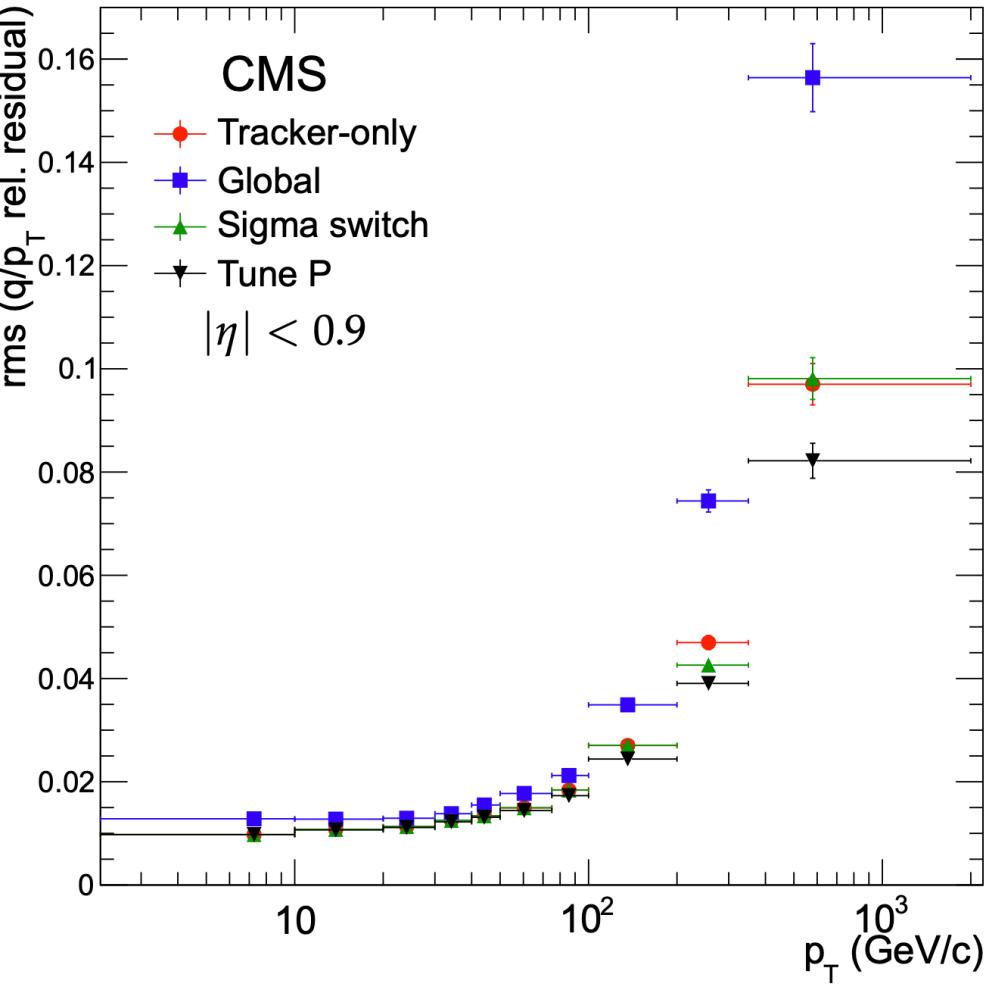
<https://arxiv.org/pdf/1206.4071.pdf>

Muon resolution

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



(a)



(b)



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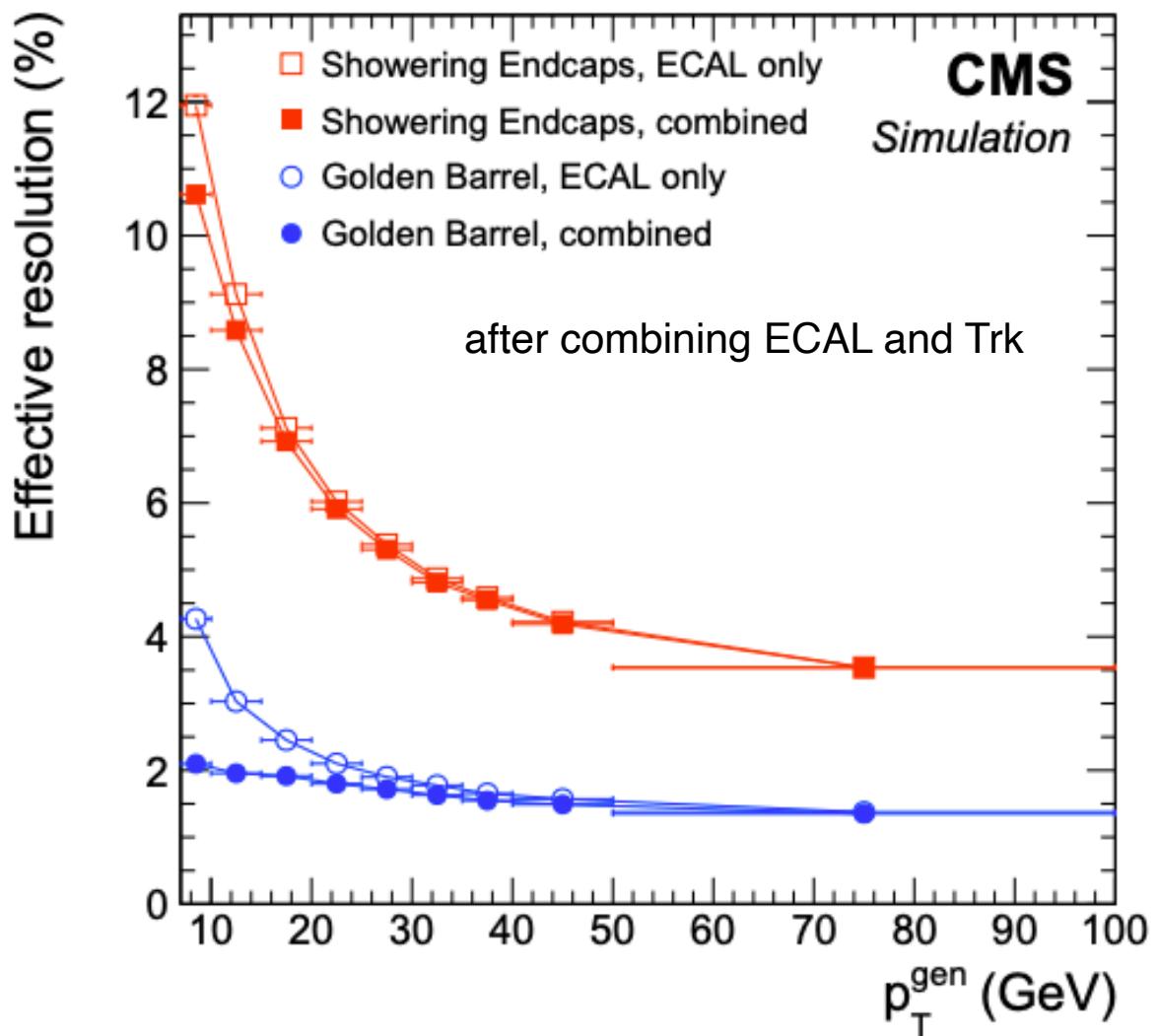
[Submitted on 9 Feb 2015 ([v1](#)), last revised 1 Jul 2015 (this version, v2)]

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

