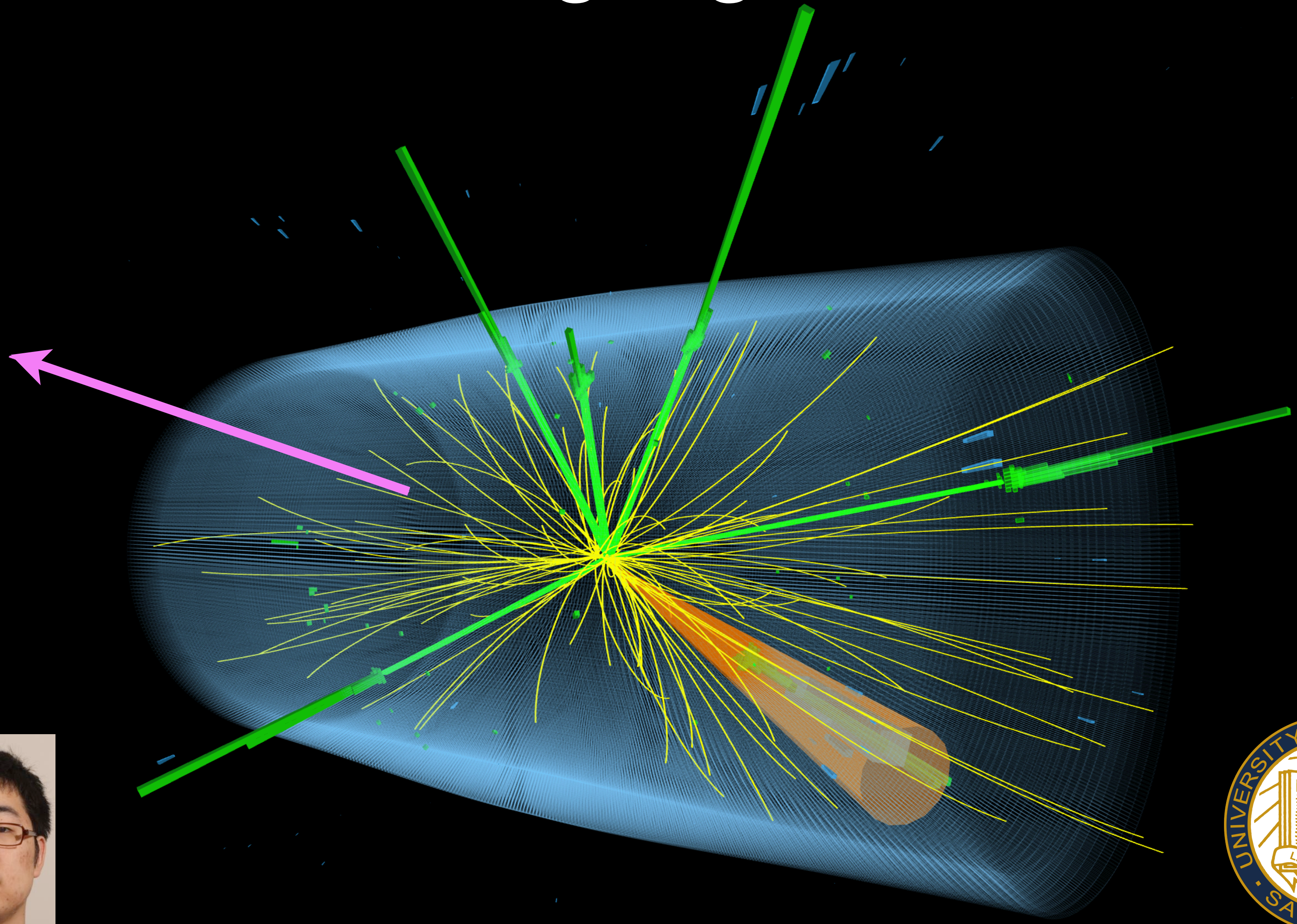
First observation of production of three massive gauge bosons

V = W, Z



Philip
Chang

Kyungpook National University
Center for High Energy Physics
August 5, 2020

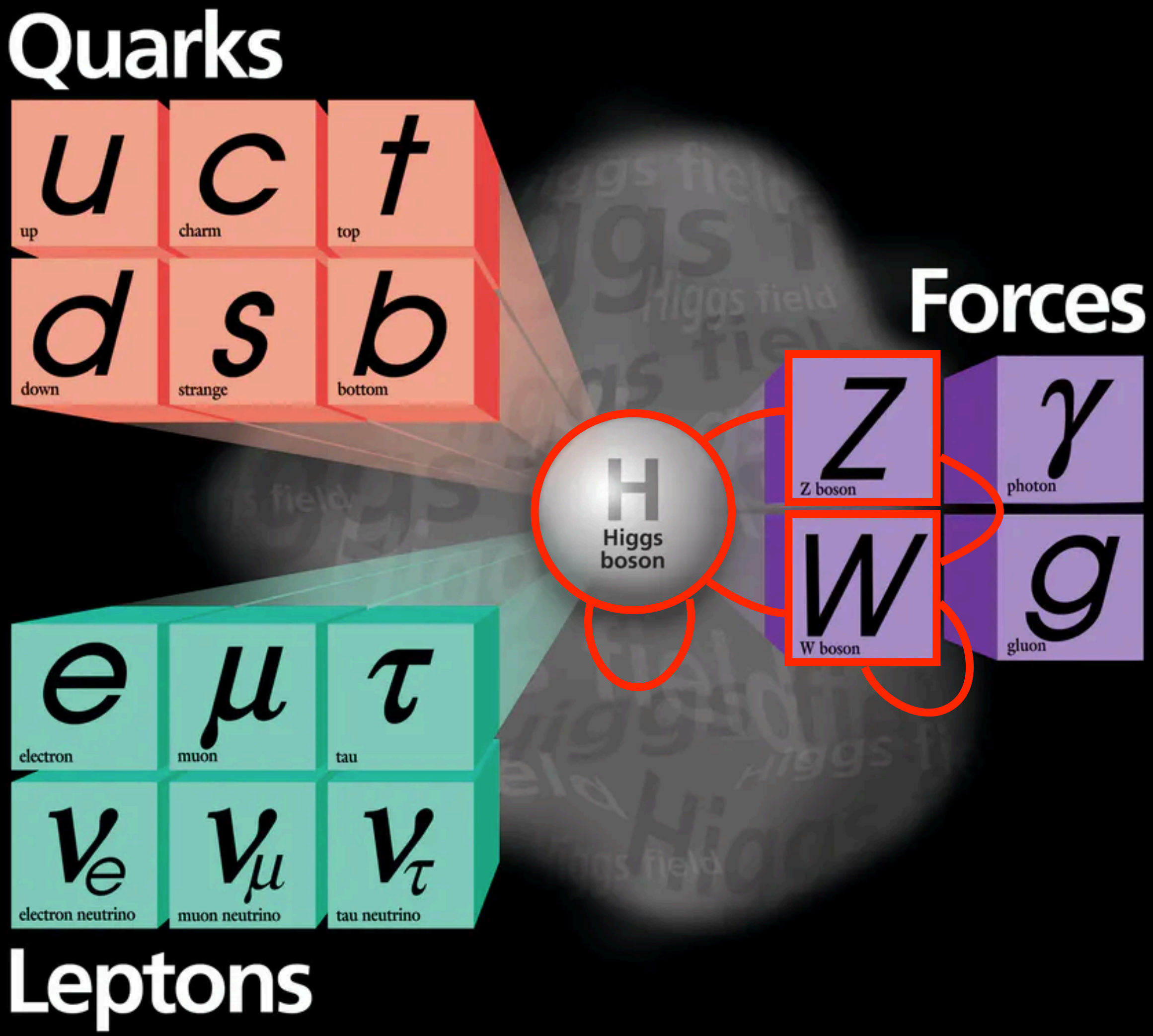
Univ. of California
San Diego

Discovery of Higgs boson

July 4, 2012

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

More work to be done in electroweak sector



- 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 interaction (MBI) at high E

Lee, Quigg, Thacker (1977)

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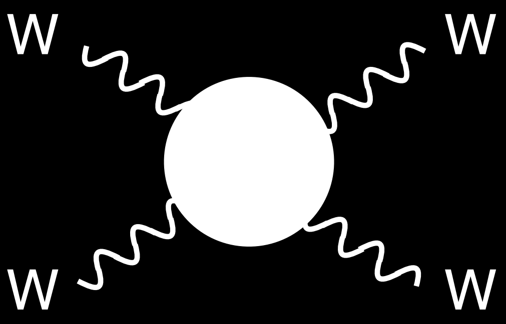
WW scattering



Multi-boson interaction (MBI) at high E

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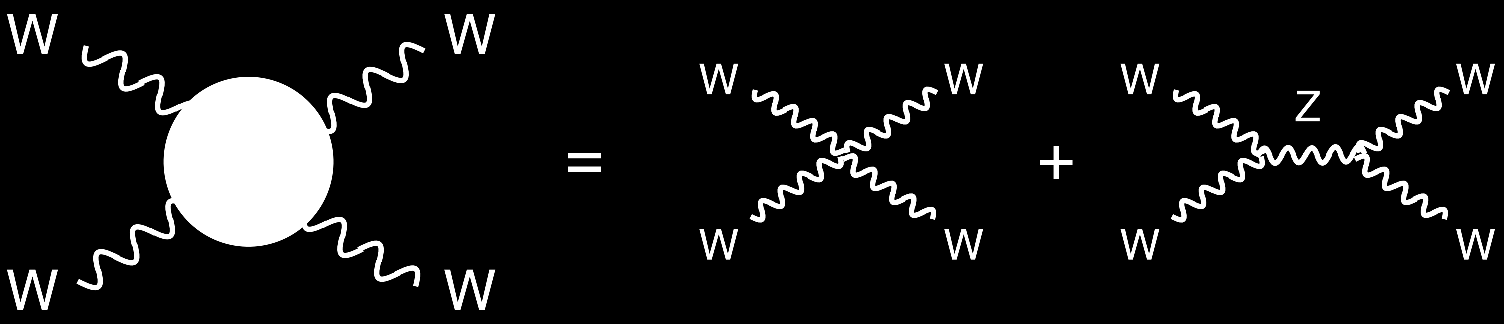
$$P(WW \rightarrow WW) \sim E^2$$

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



Bad high energy behavior

Multi-boson interaction (MBI) at high E

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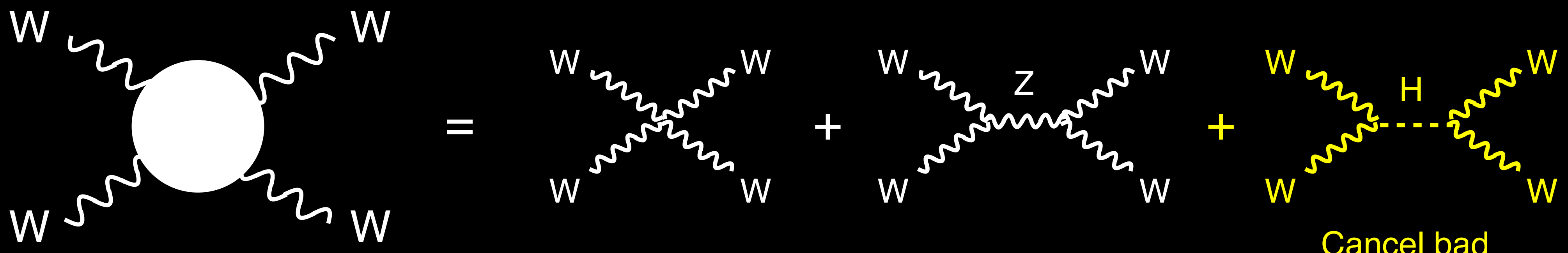
With Higgs P < 1



Bad high energy behavior

Cancel bad
high E behavior

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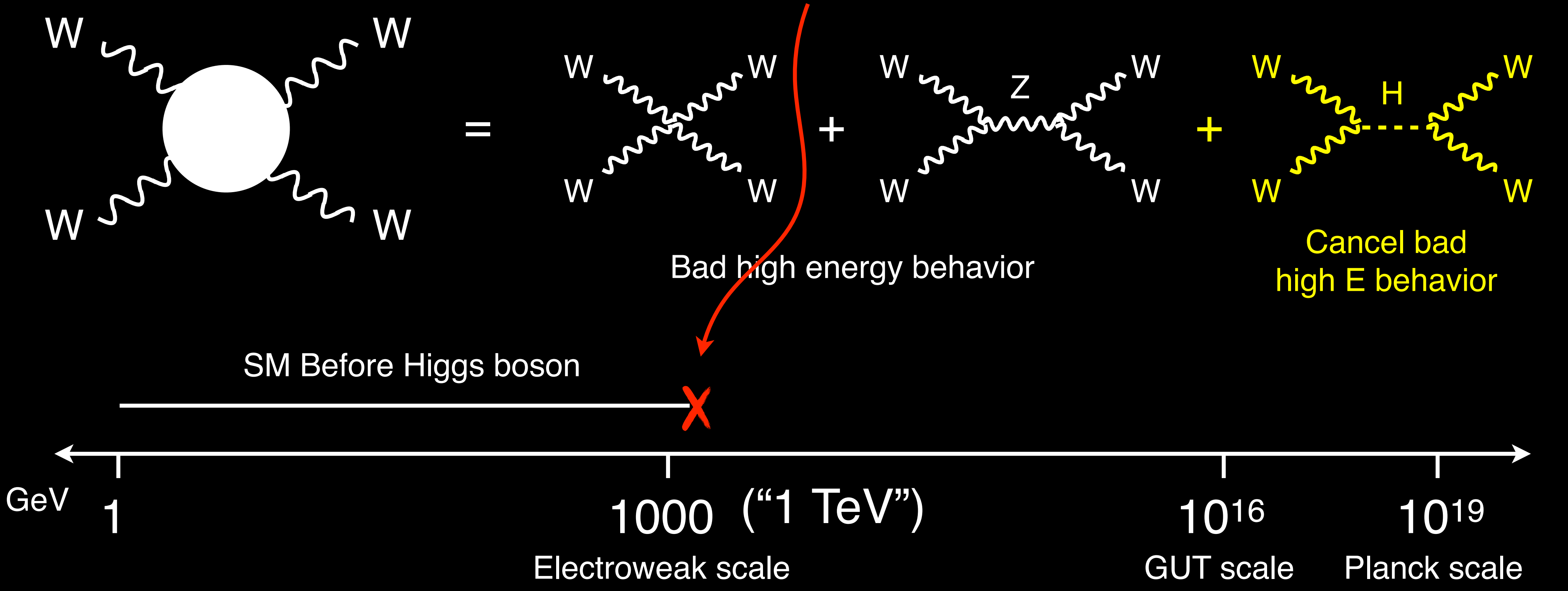

Bad high energy behavior

Cancel bad
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SM Before Higgs boson

Electroweak scale

GUT scale

Planck scale

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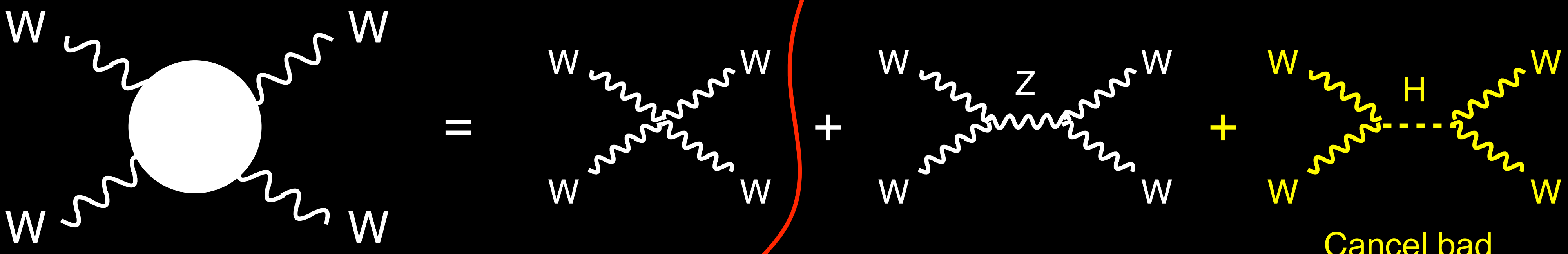

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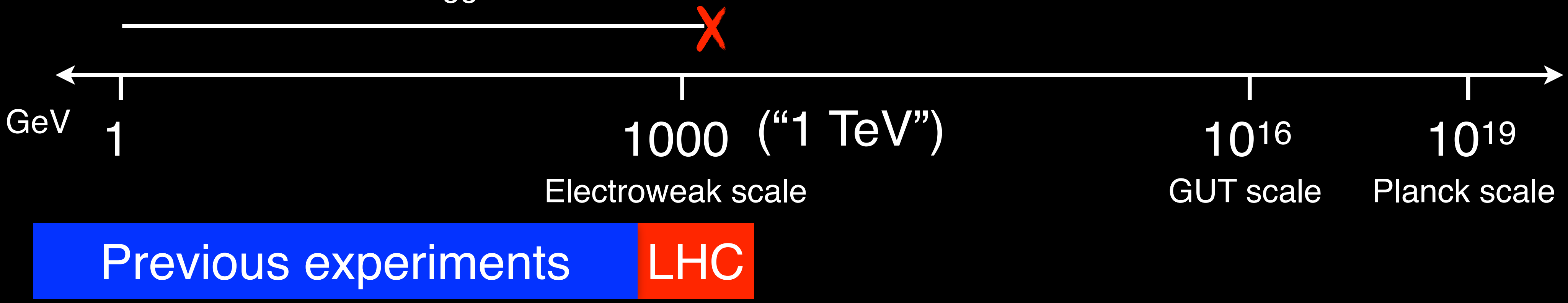

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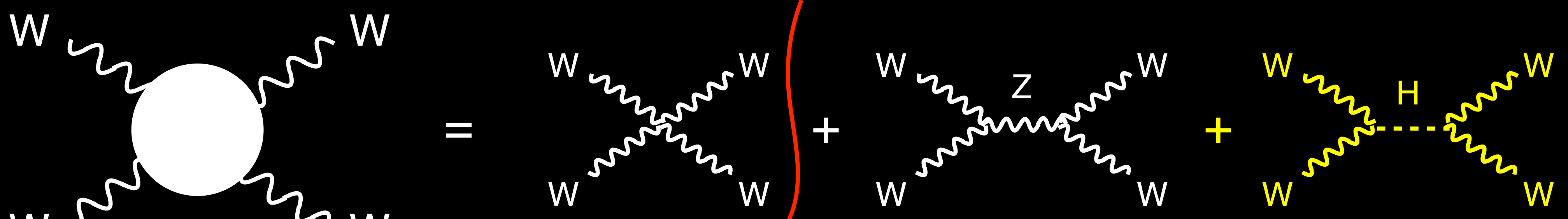

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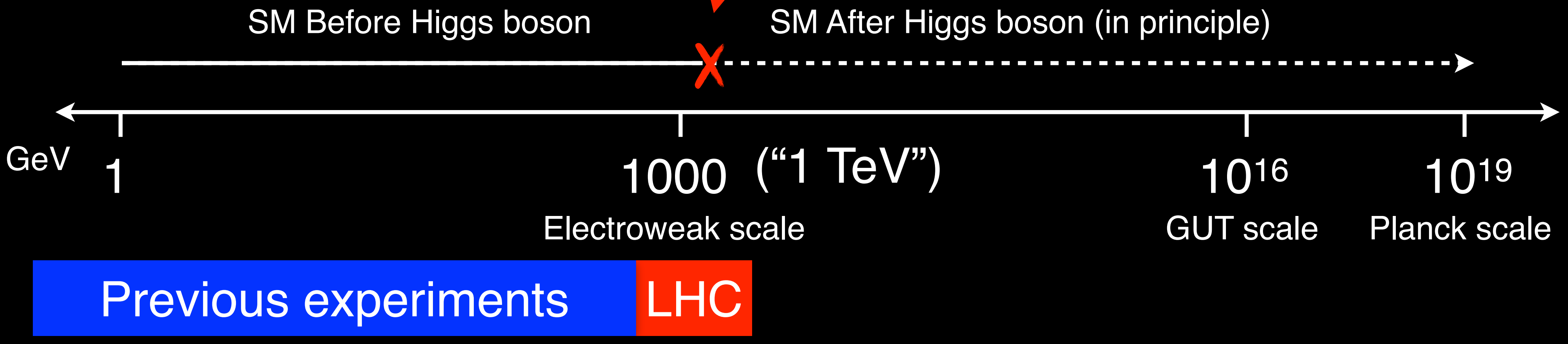

SM Before Higgs boson

SM After Higgs boson (in principle)

GeV 1

1000 (“1 TeV”)
Electroweak scale

10^{16}
GUT scale

10^{19}
Planck scale

Previous experiments | LHC

Multi-boson interaction (MBI) at high E

Lee, Quigg, Thacker (1977)

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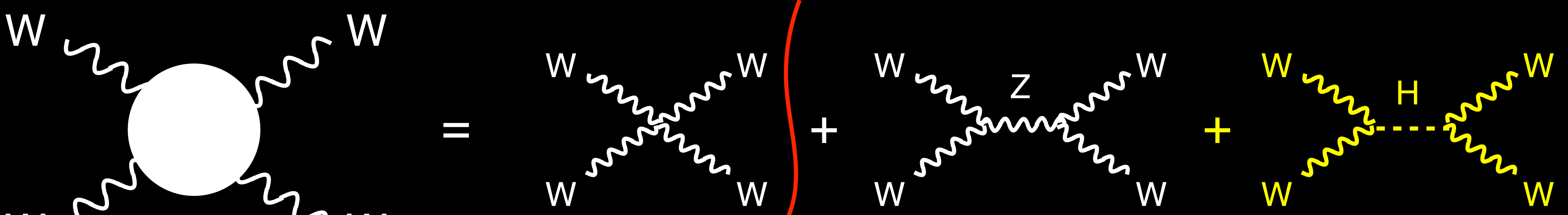

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Previous experiments	LHC

Is this picture all true?

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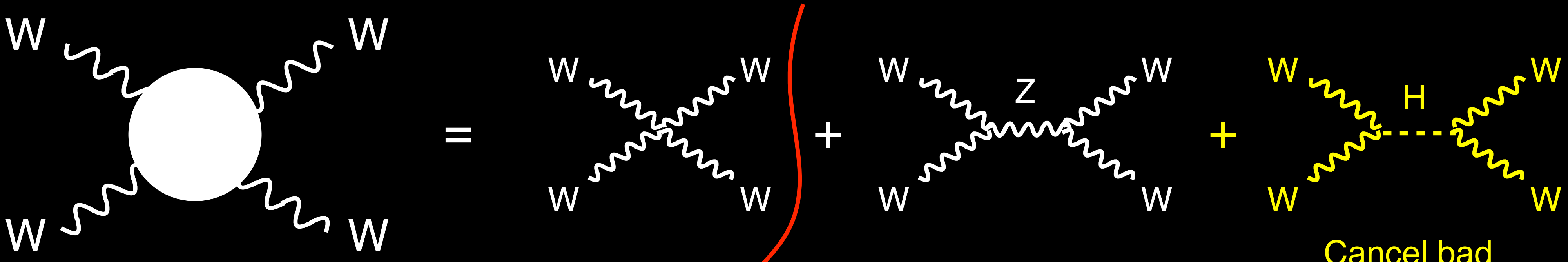

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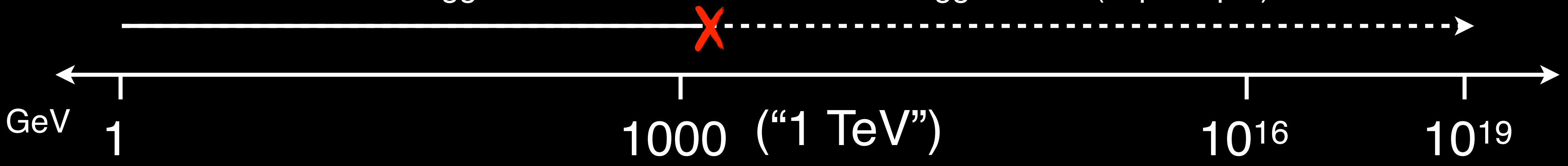


Electroweak scale

GUT scale

Planck scale

Previous experiments | LHC

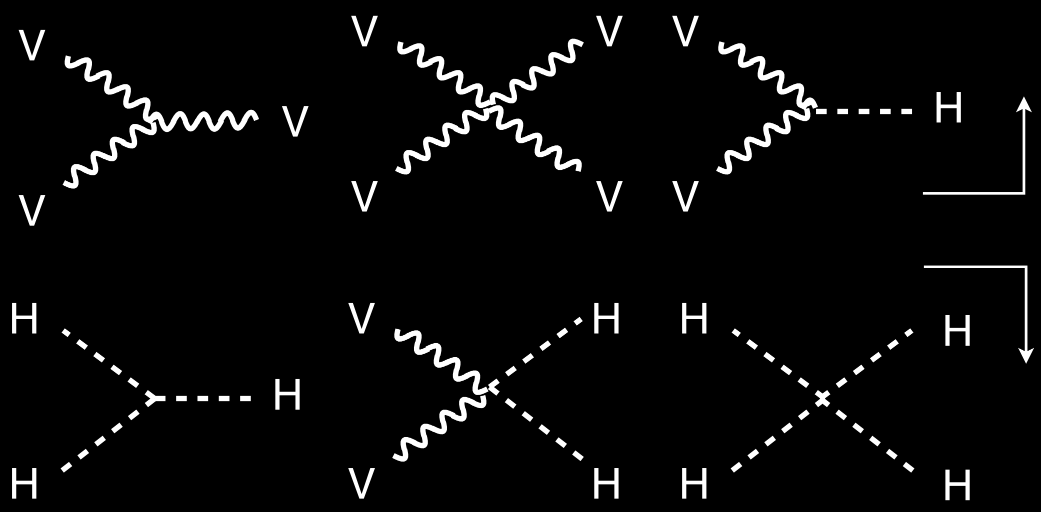
Is this picture all true?

Crucial test of electroweak theory

Remaining questions in electroweak sector

List of multi-boson interactions

V = W, Z



LHC has started to probe

Not yet probed very well

- 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? H1, H2, … ??)
- If so, what are their role in the electroweak symmetry breaking?

Remaining questions in electroweak sector

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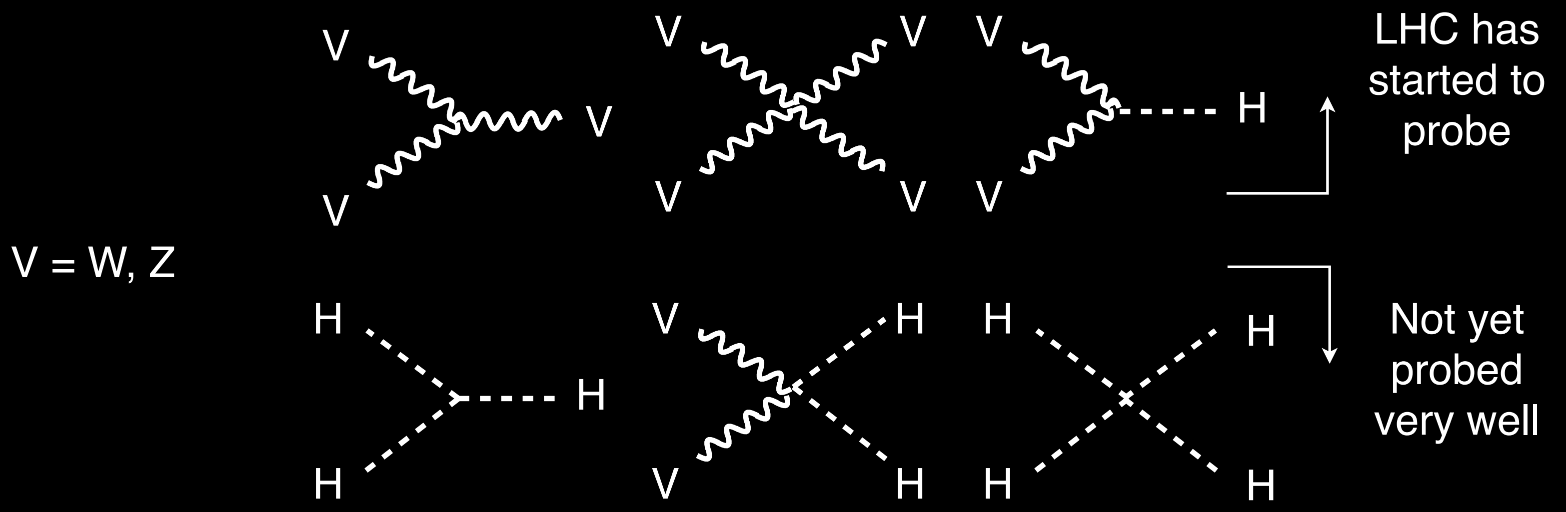

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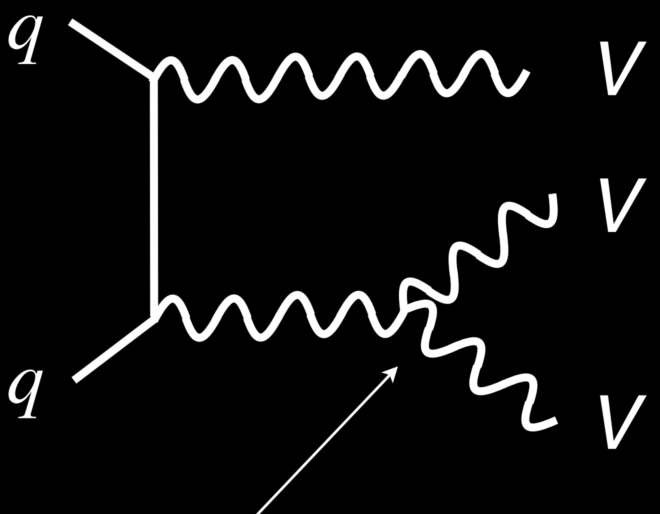
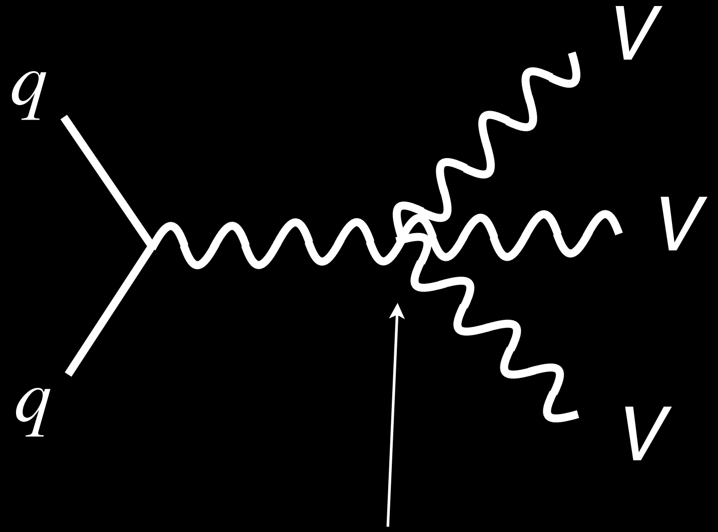
Studying multi-boson interactions can answer these questions

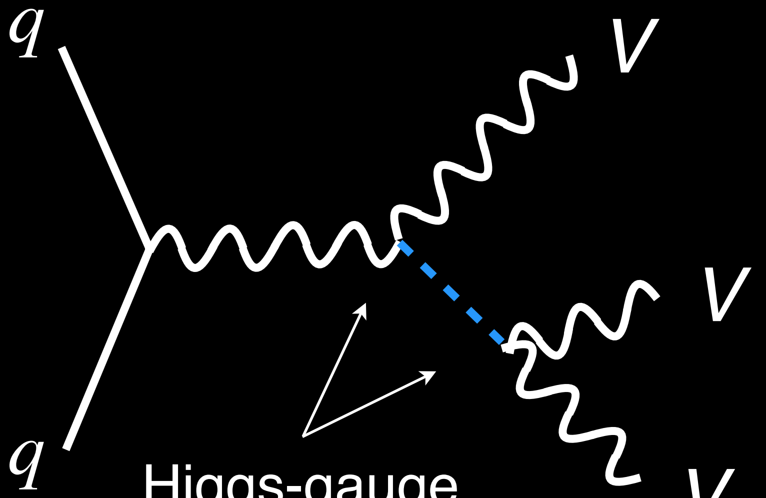
Physics of VVV production (V = W, Z)



cubic gauge interaction



quartic gauge interaction



Higgs-gauge interaction

Four VVV modes

- WWW
- WWZ
- WZZ
- ZZZ

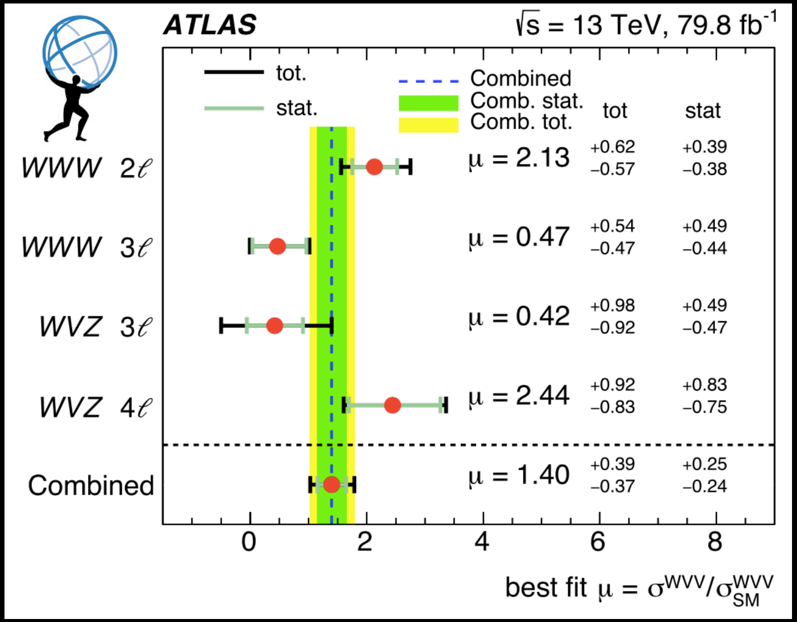
VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

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

Previous work on VVV physics

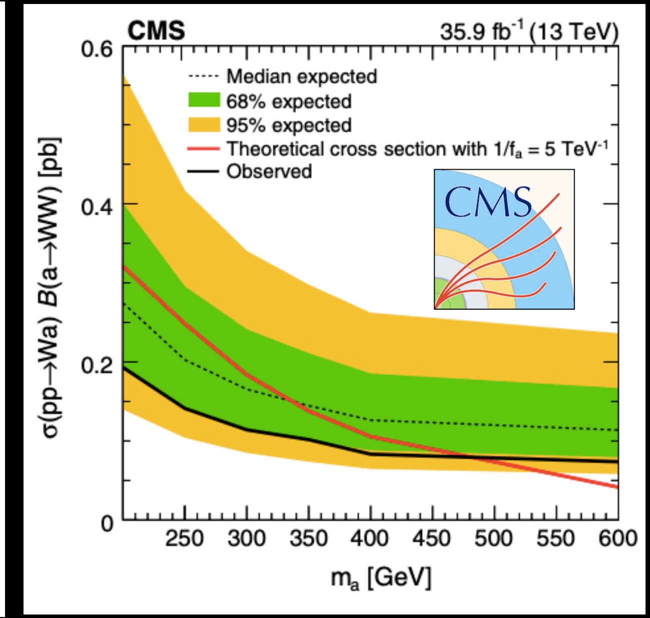
- ATLAS searched for WWW in 8 TeV: 0.96σ (1.05σ) arXiv:1610.05088
- CMS searched for WWW in 13 TeV 36 fb^{-1}: 0.6σ (1.78σ) arXiv:1905.04246
- ATLAS searched for VVV in 13 TeV 80 fb^{-1}: 4.1σ (3.1σ) arXiv:1903.10415

VVV evidence



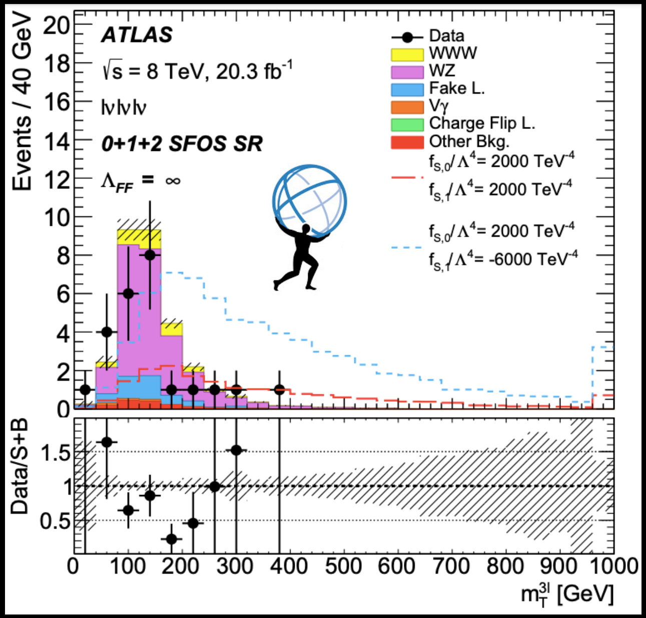
arXiv:1903.10415

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

VVV production at LHC

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

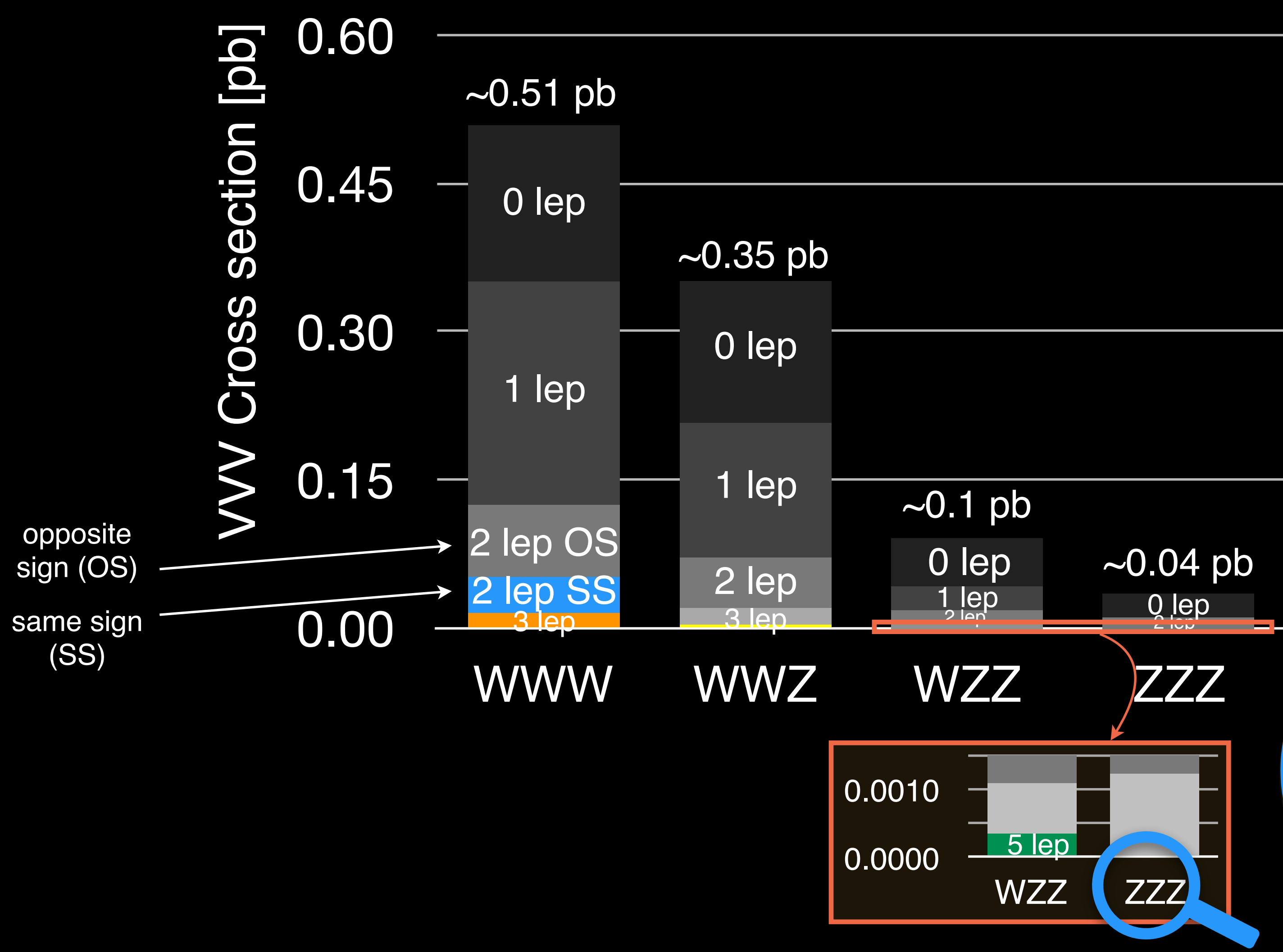
- pp→WWW
- pp→WWZ
- pp→WZZ
- pp→ZZZ

And the combined production of all pp→VVV

Targeting VVV as a main result but also individual production modes

VVV channels in # of leptons

Production cross section decreases with more Z's



ZZZ → 6L

(L = e, μ)

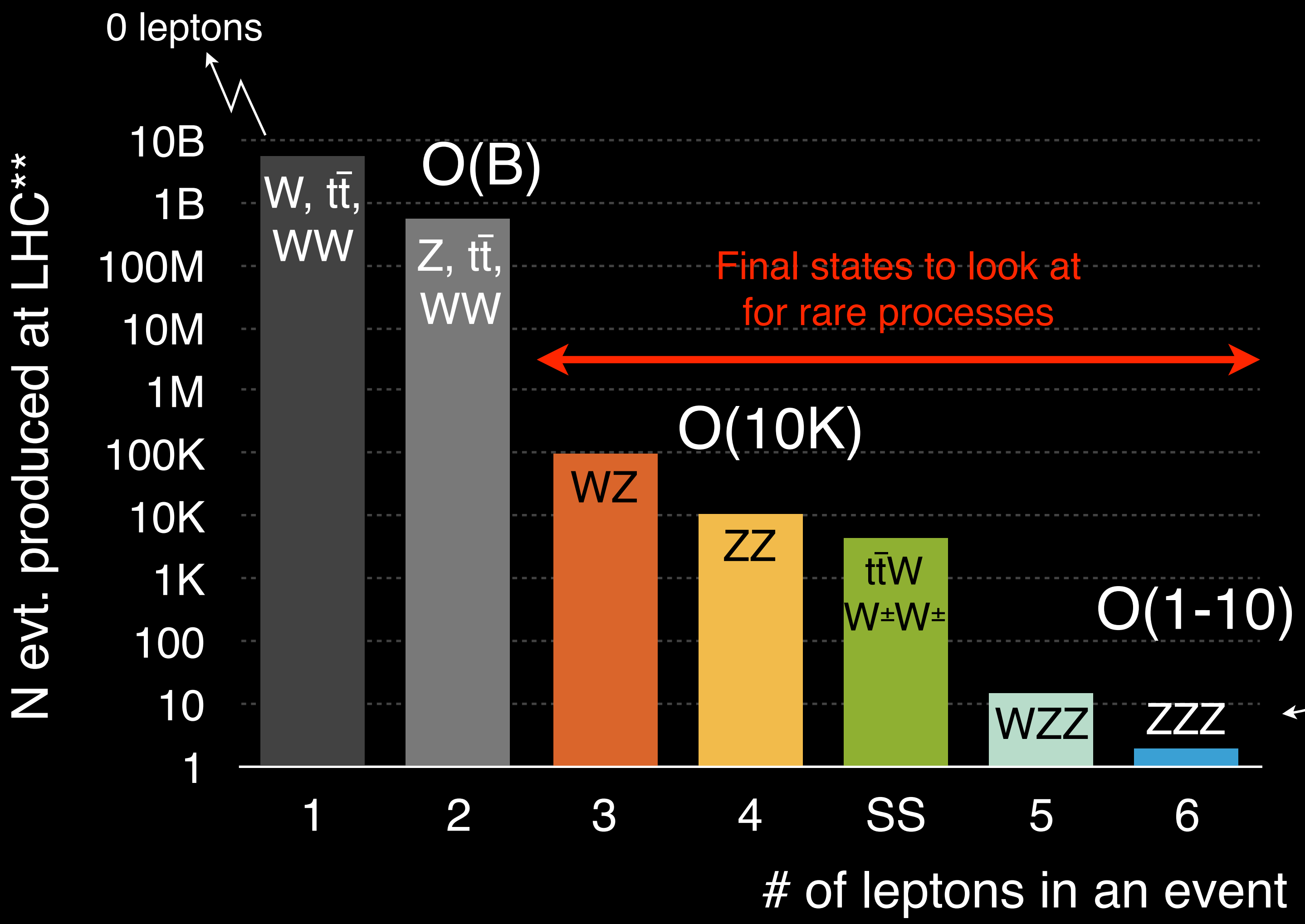
11 attobarn

(~1.5 events produced at Run 2 of LHC)

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

Overview of 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 $\tau \rightarrow e, \mu$



If one only looks at 5 or 6 lepton events, there will be very small backgrounds

Target large # of lepton events for multi-boson productions (∵ lower bkg.)

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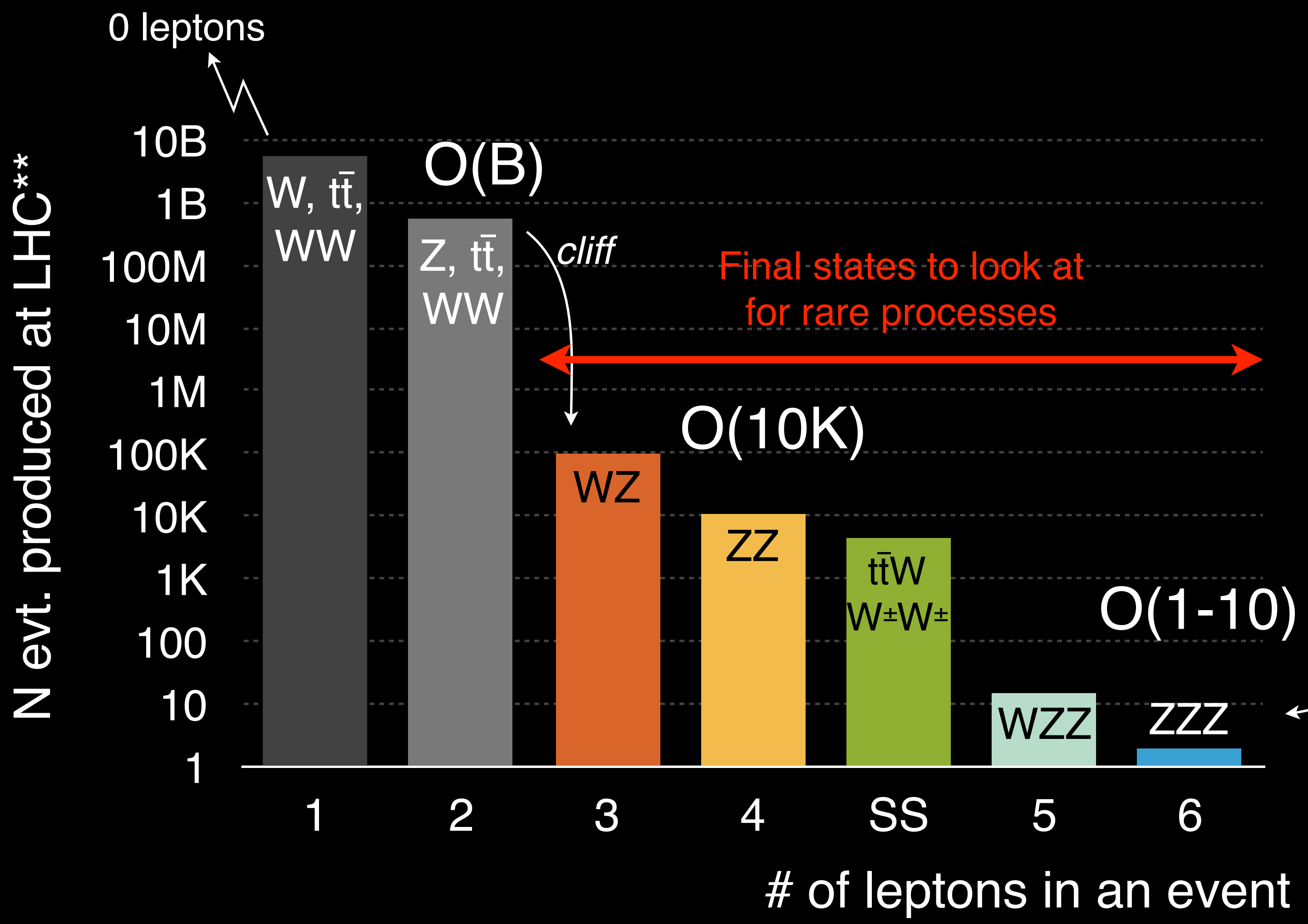

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Chang
UCSD

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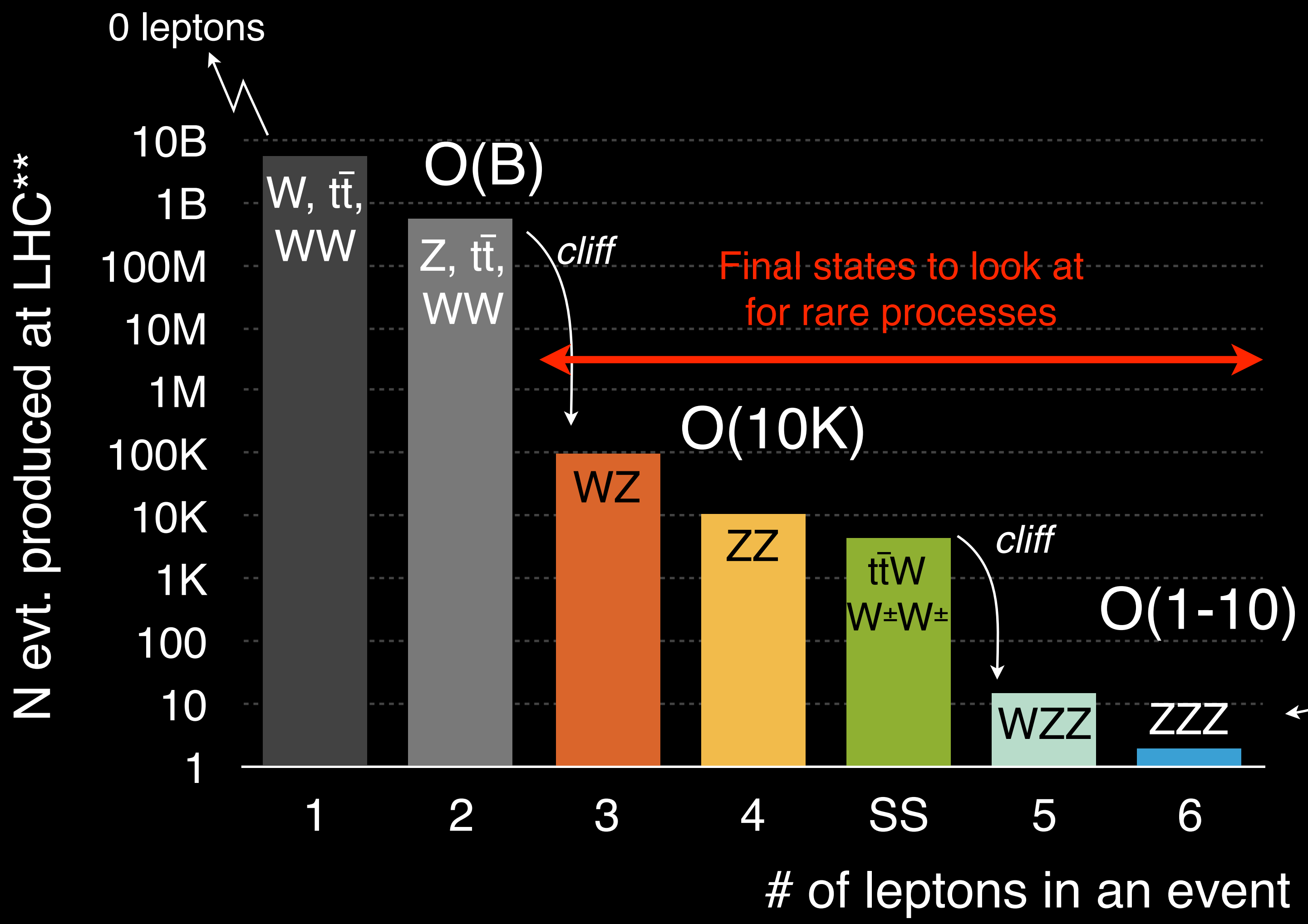

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VVV channels in # of leptons

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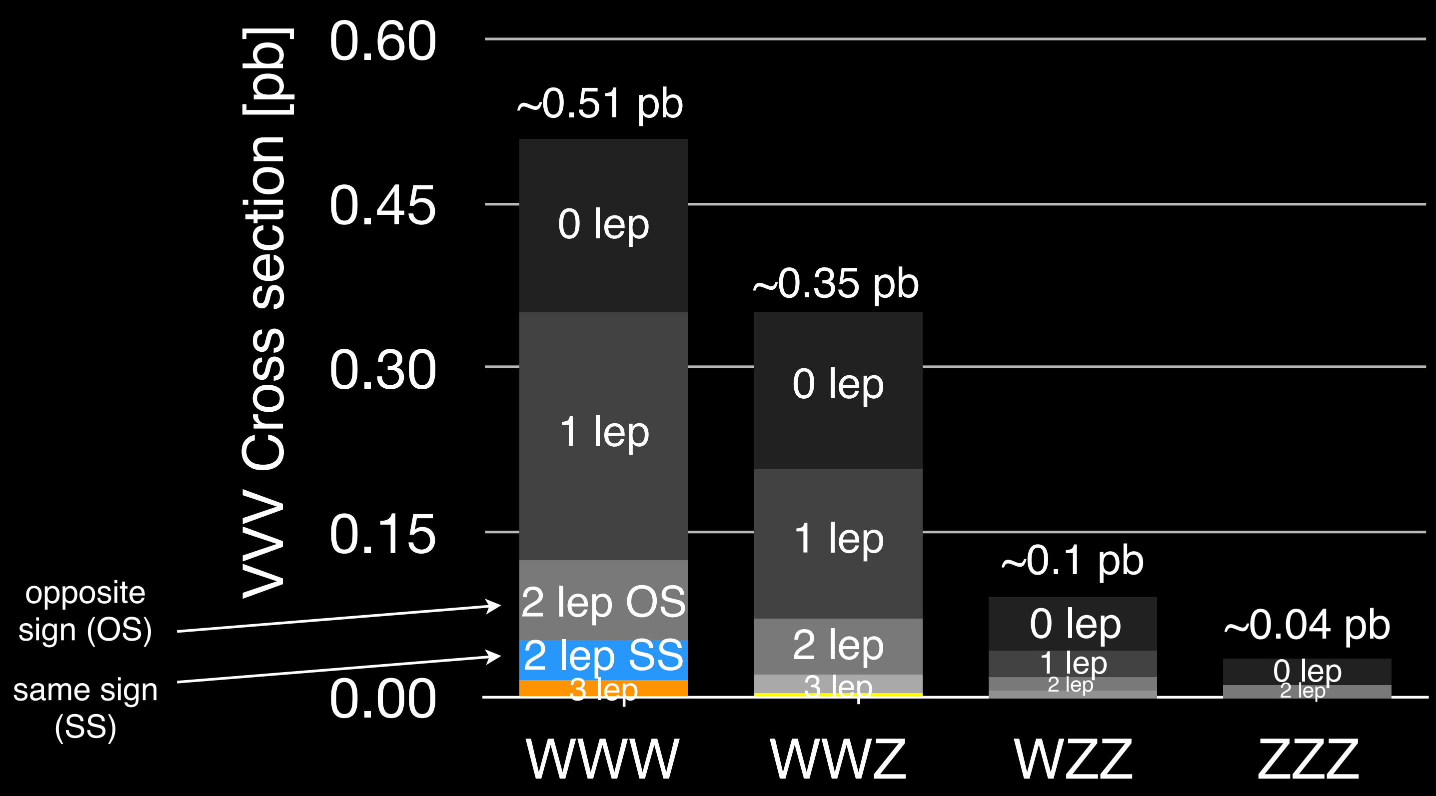

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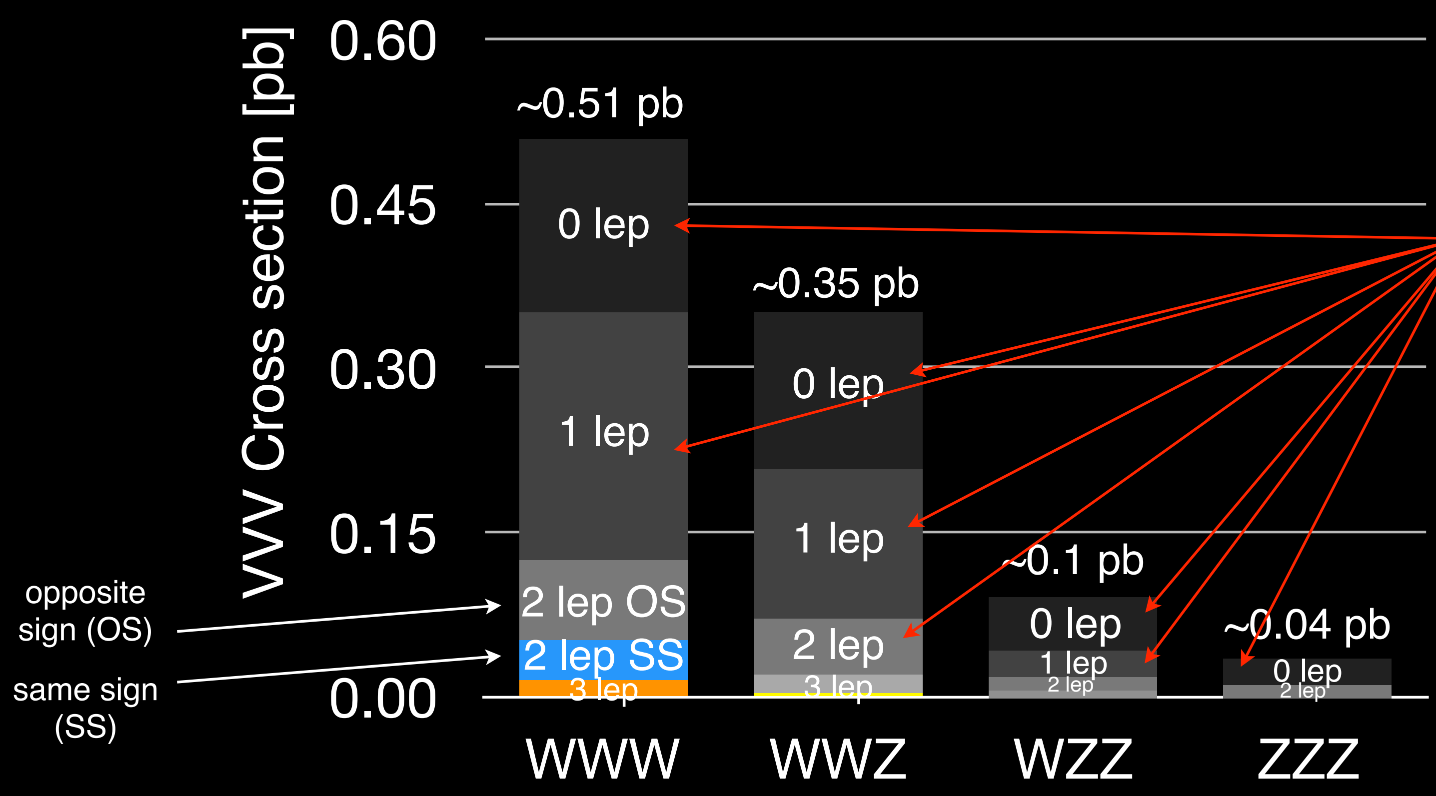

Difficult final states w/ bkg rate of several orders of magnitude larger

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

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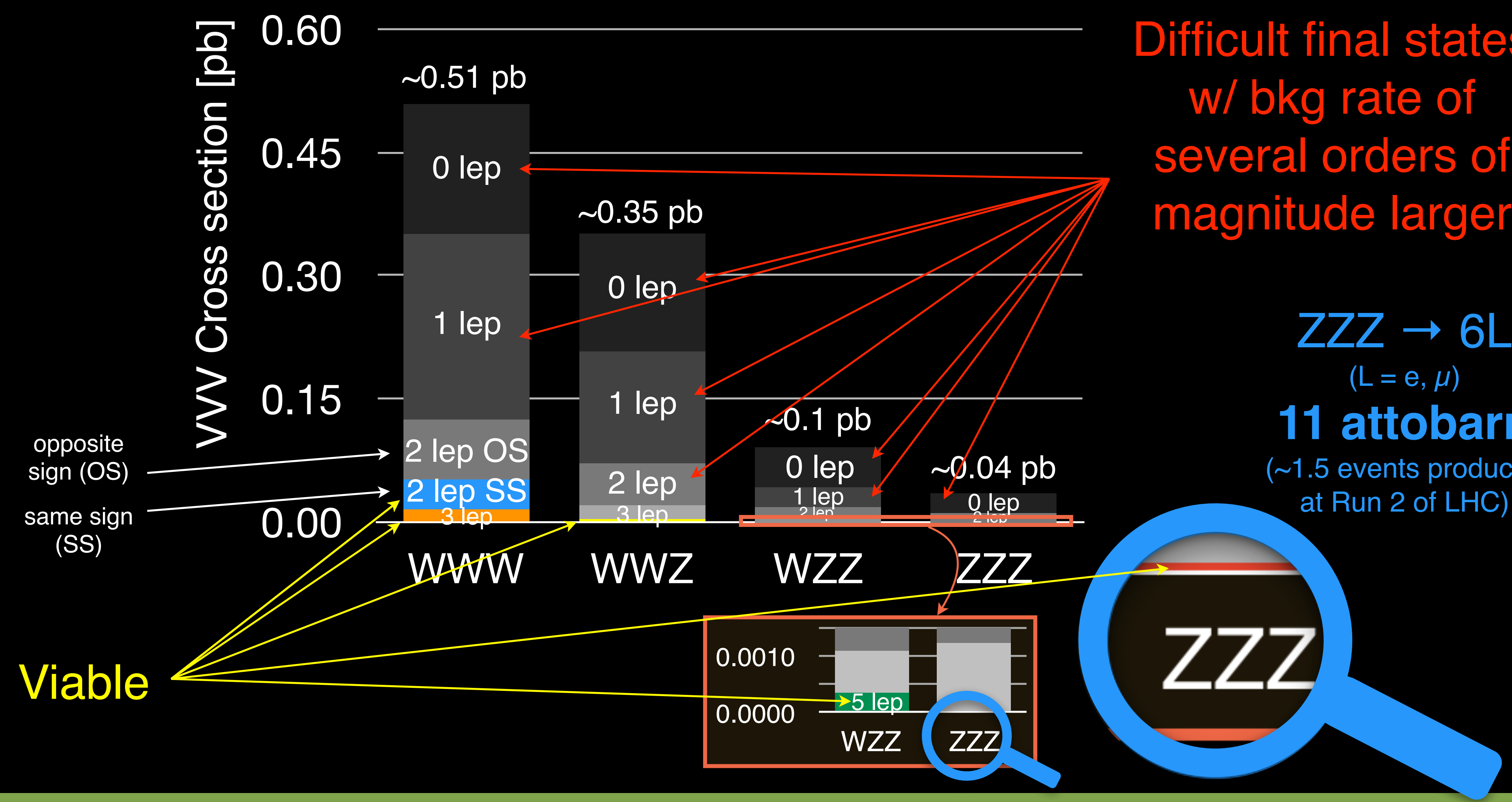

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ZZZ → 6L

(L = e, μ)

11 attobarn

(~1.5 events produced at Run 2 of LHC)

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

VVV analyses overview by N leptons

Target "fully" leptonic final states to go after first observation

One exception

	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Targeted signal	$W^{\pm} \to l^{\pm}\nu$ $W^{\pm} \to l^{\pm}\nu$ $W^{\mp} \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
	~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

Overview of the analysis

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

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	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
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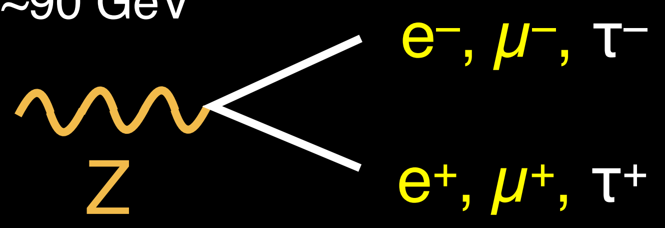
Dominant Bkgs.	~2.5k evt. lost $WZ \to l^\pm\nu l^\pm l^\mp$ $\bar{t}t \to bb + ll + X$ ↳ fake l	~700 evt. $WZ \to l\nu ll$ $\bar{t}t \to bb + ll + X$ ↳ fake l	~140 evt. $ZZ \to llll$ $ttZ \to llll + \mathrm{bbX}$	~15 evt. $ZZ \to llll$ + fake lep	~1.5 evt. $ZZ \to llll$ + 2 fake lep

N.B. same-sign ~O(few k), WZ→3l ~100k, ZZ→4l ~10k

Separate the analysis categories by N of leptons

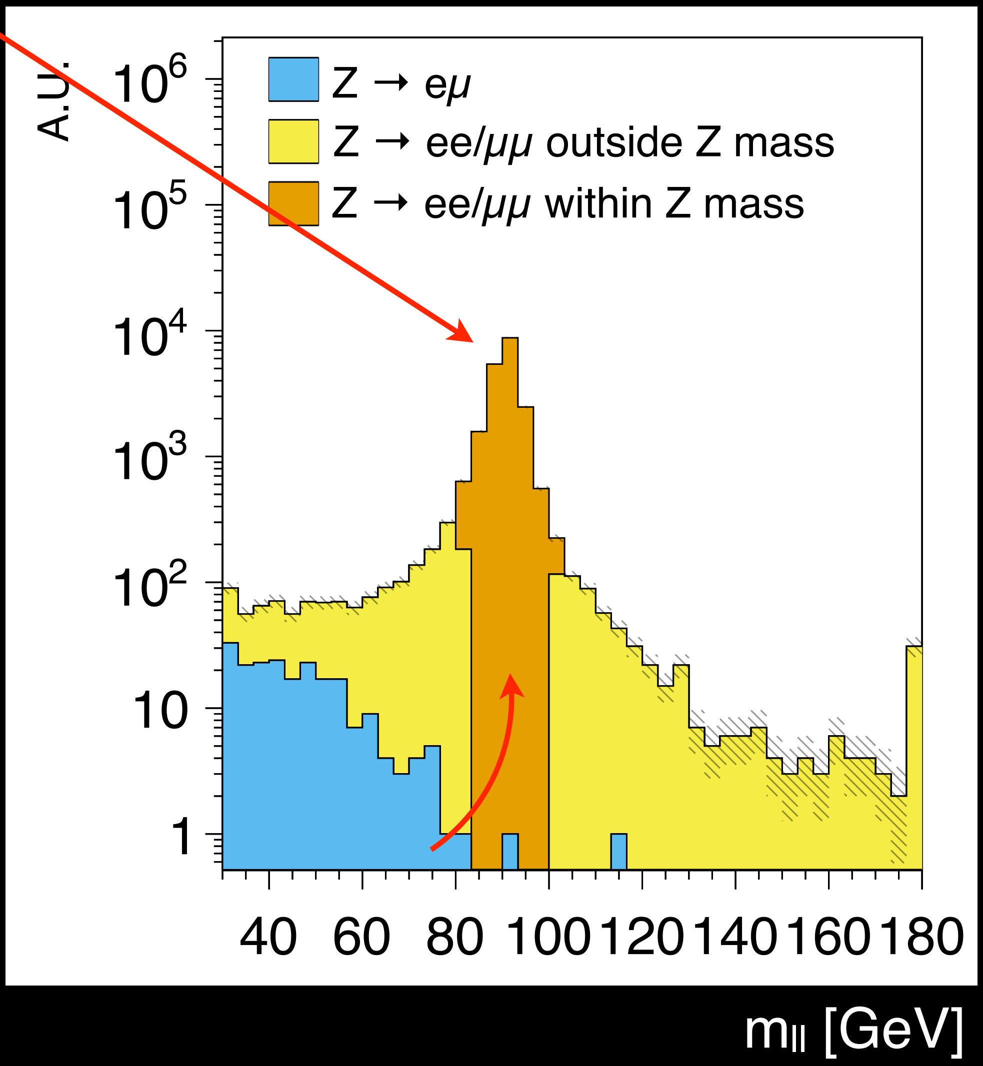
Features of Z → ll decay

mass of Z
~90 GeV



~3% each flavor

Plot of dilepton mass from Z→ll decay

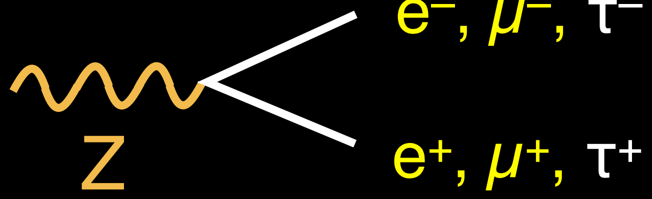


**Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV P_T cuts

Z decays predominantly to ee/*μμ* on-shell

Features of $Z \to ll$ decay

mass of Z
~90 GeV



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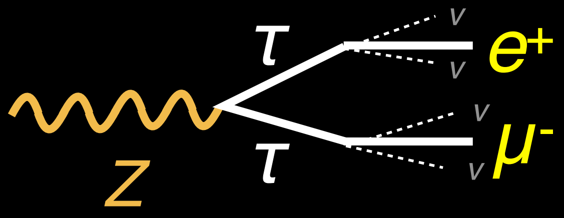
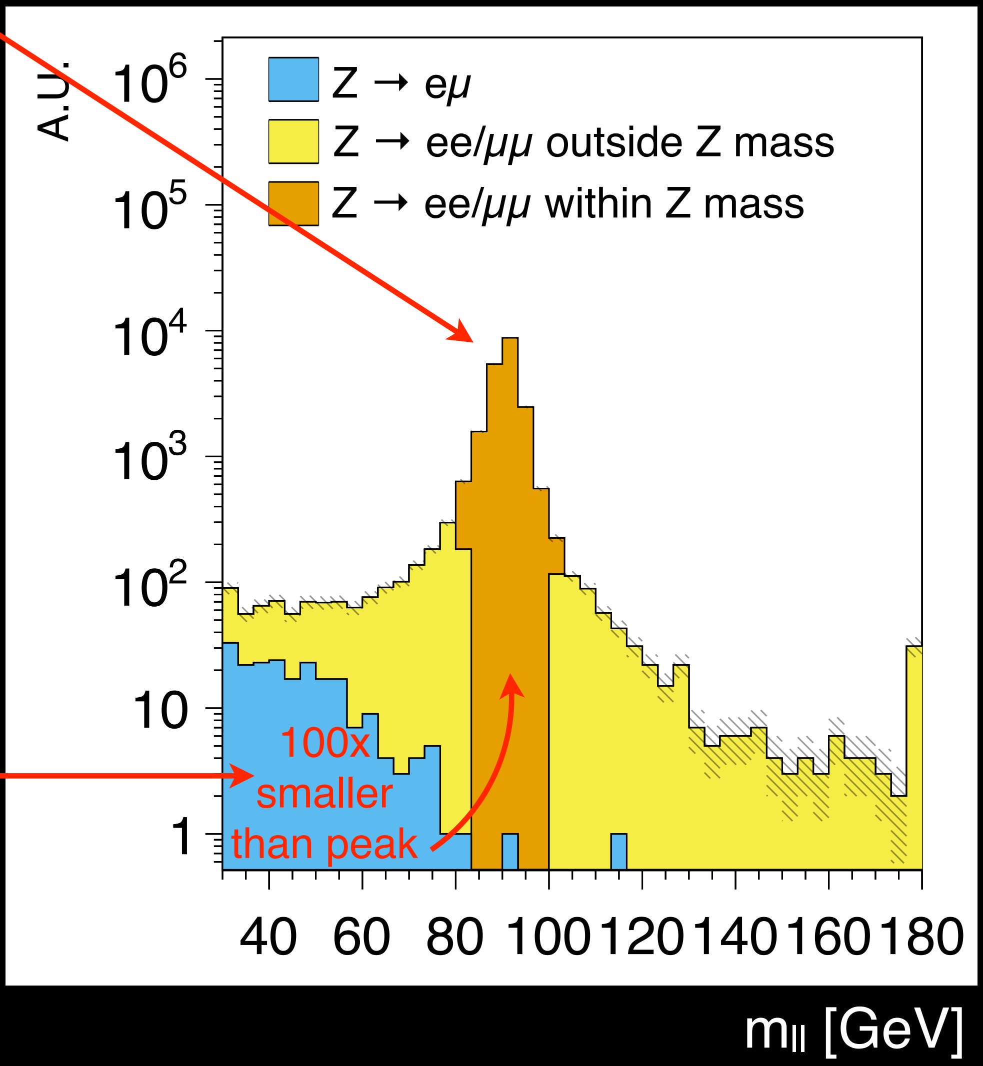


If one selects $e\mu$ final state, Z is reduced by 2 orders of magnitude
(e, μ from τ are soft)

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



100x smaller than peak

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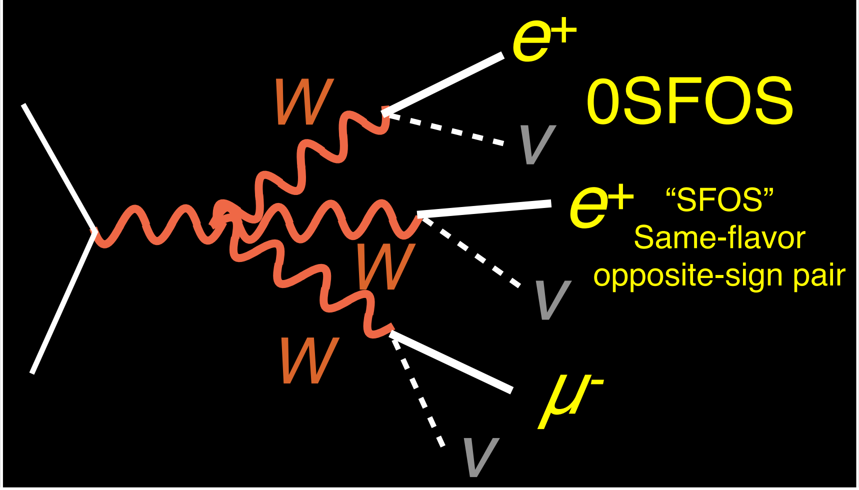
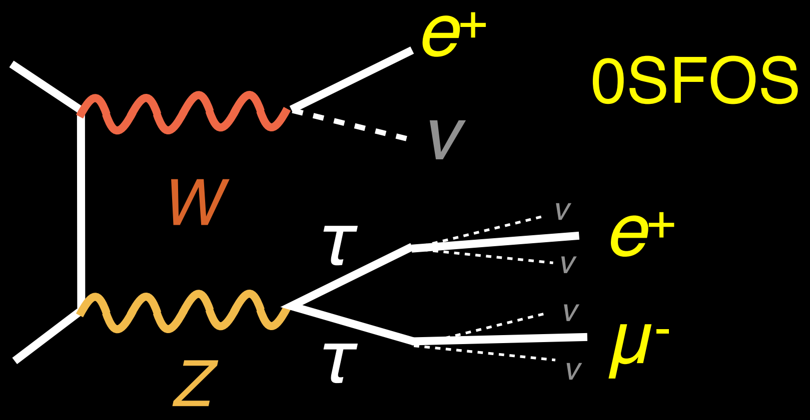
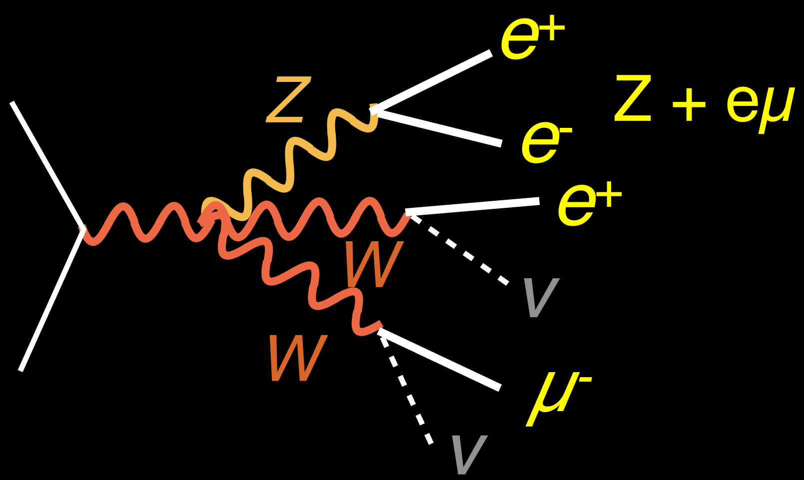
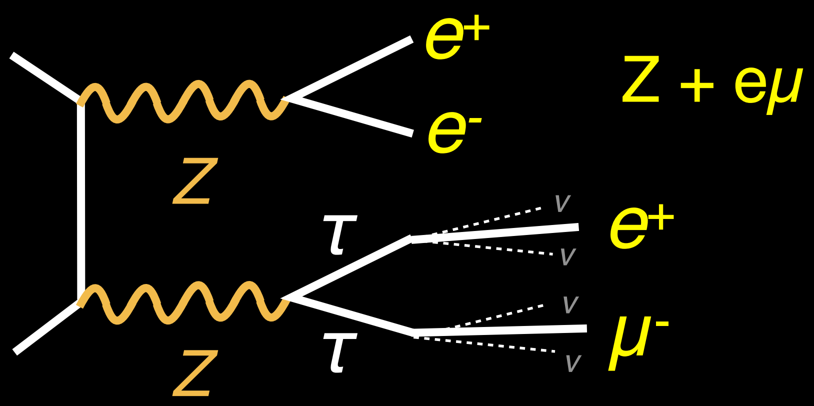
Z decays predominantly to $ee/\mu\mu$ on-shell

Flavor choices

	Signal	Background
3 lepton	 0SFOS “SFOS” Same-flavor opposite-sign pair	 0SFOS
4 lepton	 Z + eμ	 Z + eμ

Backgrounds are suppressed via disfavored decay topology of Z→ττ→eμ

Splitting signal regions by lepton flavors

	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Targeted signal	$W^{\pm} \rightarrow l^{\pm}\nu$ $W^{\pm} \rightarrow l^{\pm}\nu$ $W^{\mp} \rightarrow qq$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
	Split by ee/eμ/$\mu\mu$ N.B. μ is “cleaner” than e	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→ll then split WW→ee/$\mu\mu$ v. WW→eμ	Not enough statistics single bin	
	3 categories*	3 categories	2 categories*	1 category	1 category

* marked ones will be further split

Each N lepton analysis is further split by flavors

Splitting signal regions by lepton flavors

	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Targeted signal	$W^\pm$ $W^\pm$ $W^\mp \to qq$ Also have BDT-based analysis	Also have BDT-based analysis $W \to l\nu$	Also have BDT-based analysis $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
	Split by ee/eμ/$\mu\mu$ N.B. μ is "cleaner" than e	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→ll then split WW→ee/$\mu\mu$ v. WW→eμ	Not enough statistics single bin	
	3 categories*	3 categories	2 categories*	1 category	1 category

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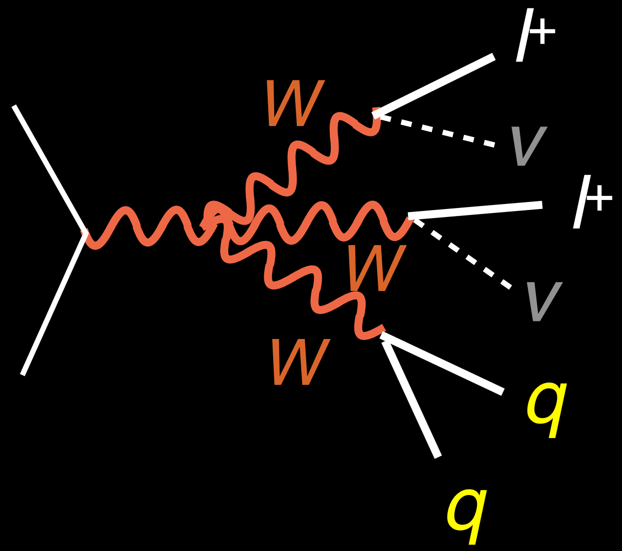
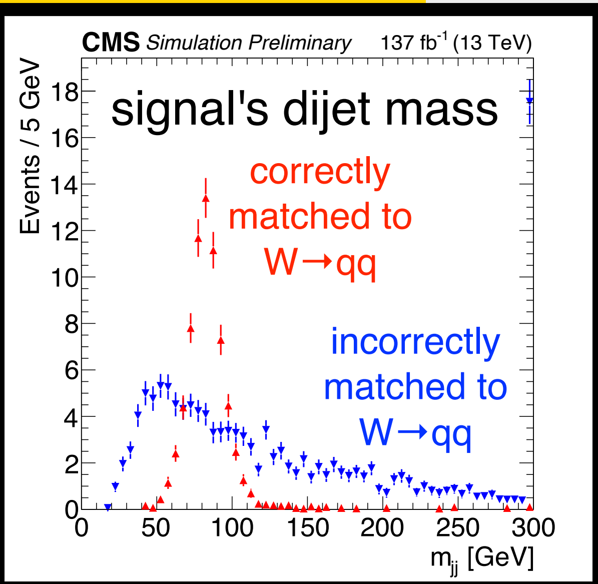
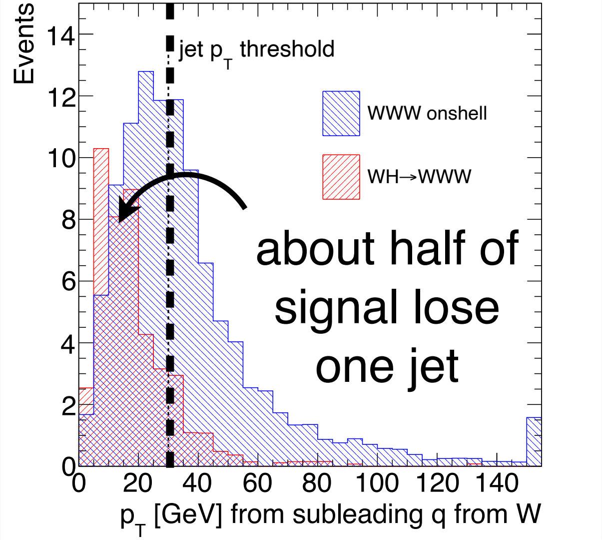
Same-sign channel categorization





- $N_J \geq 2$
  - Two jets satisfy $|m_{jj} - m_W| < 15$ GeV (**m_{jj}-in**)
  - Two jets satisfy $|m_{jj} - m_W| \geq 15$ GeV (**m_{jj}-out**)
- $N_J = 1$
  - Only one jet exists (**1J**)

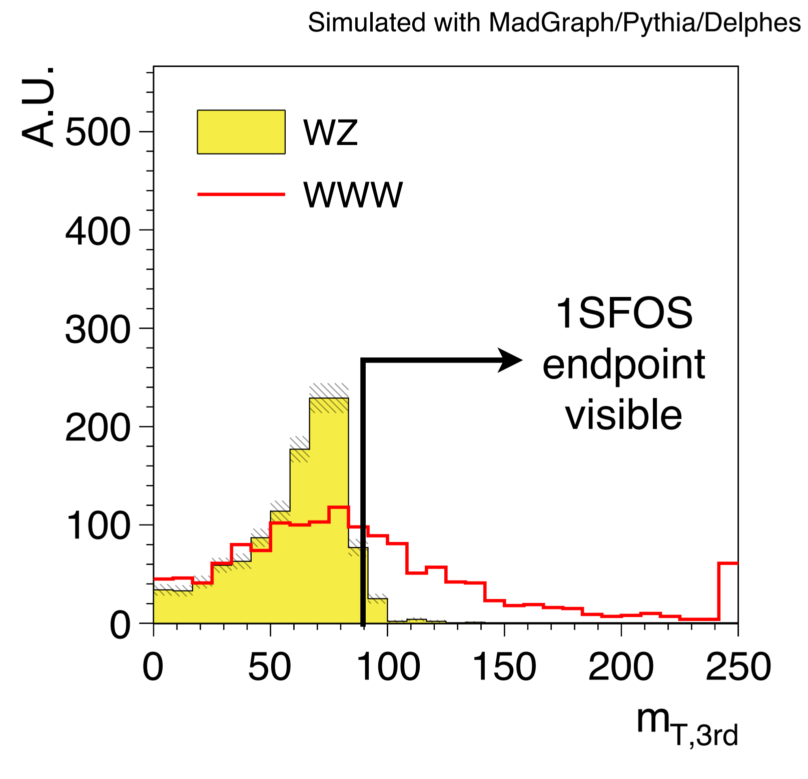


3 additional categories (m_{jj}-in, m_{jj}-out, 1J) each split by ee/eμ/μμ

⇒ Total of 9 signal regions for same-sign analysis

Kinematic endpoints for 3 leptons

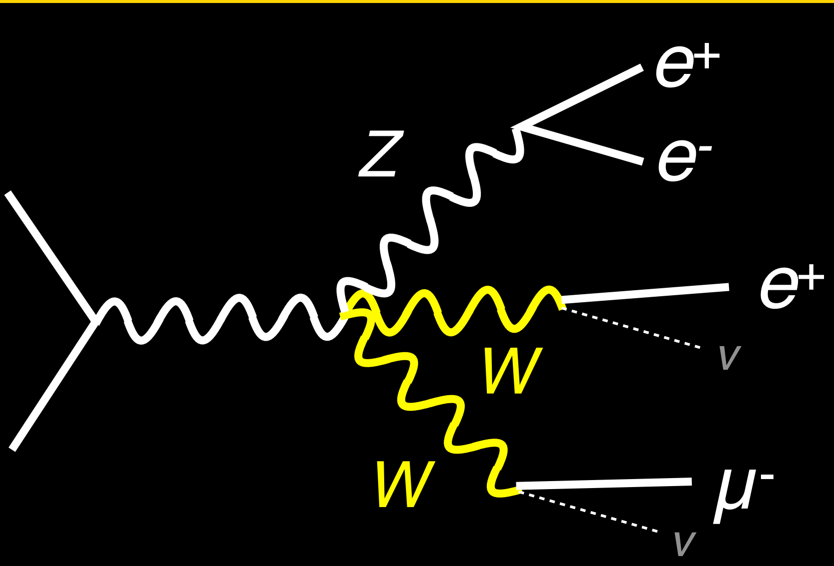
- Separated by # of SFOS pairs:
  - 0 SFOS (low bkg.)
  - 1 SFOS
  - 2 SFOS
- 0SFOS is by far the cleanest
- One can further reduce WZ backgrounds in other SFOS channels
- e.g. For 1SFOS it is clear which lepton is from W: $\underbrace{e^{\pm}e^{\mp}}_{Z}\ \underbrace{\mu^{\pm}}_{W}\quad \underbrace{\mu^{\pm}\mu^{\mp}}_{Z}\ \underbrace{e^{\pm}}_{W}$

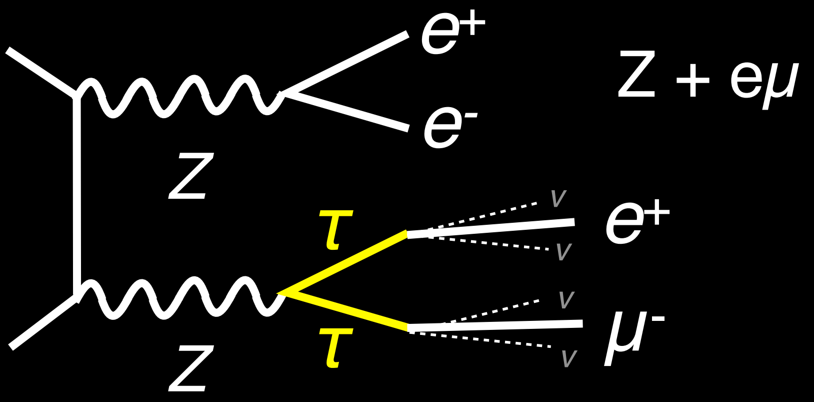


- (Similar strategy employed for 2SFOS)

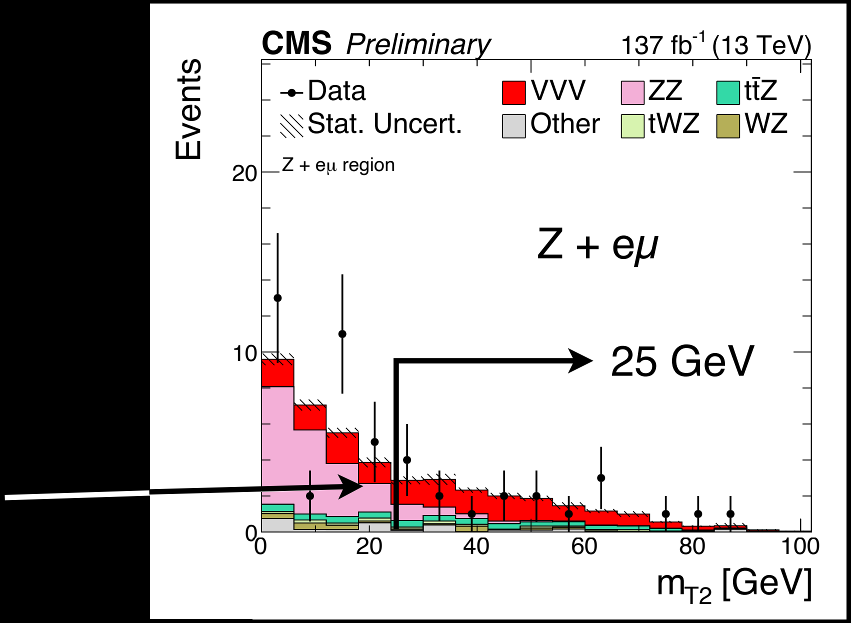
By flavor, W lepton can be identified and kinematic endpoints can be used
⇒ Total of 3 signal regions for 3 lepton analysis

Kinematic endpoints for 4 leptons





- 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→lleμ
- m_{T2} is sensitive to the end points of m_τ from ZZ→llττ→lleμ



Exploit differences between Z → ll v. WW → lνlν

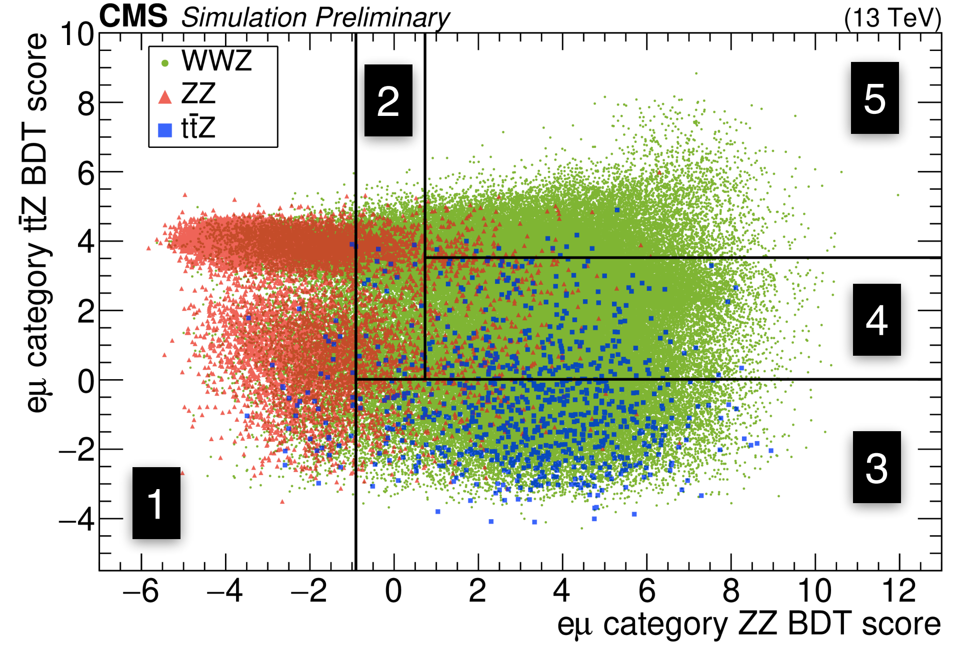
WWZ BDTs for 4 leptons analysis

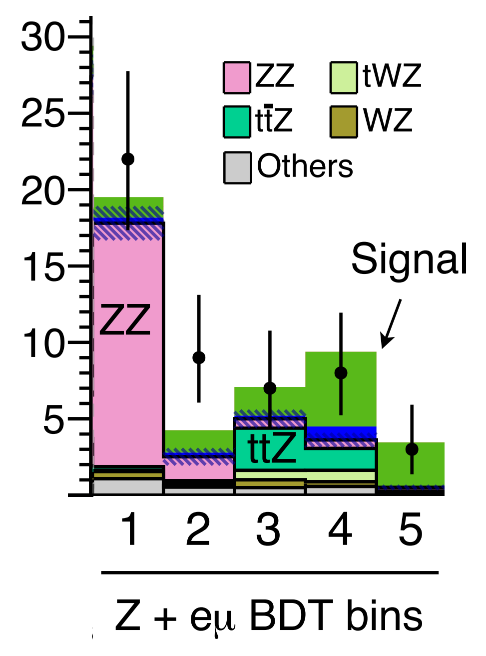
Trained two BDTs: WWZ v. ZZ and WWZ v. ttZ
Below shows the 2D plane in BDT scores

5 bins are created from 2D planes

More WWZ like

More $t\bar{t}Z$ like





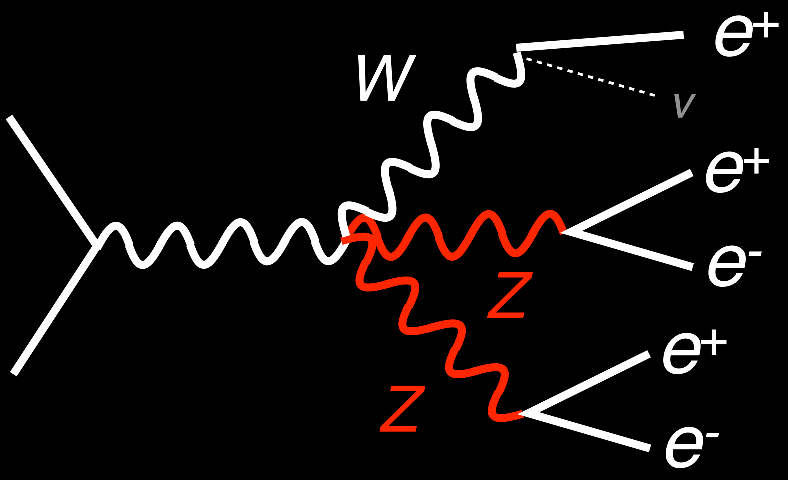
More ZZ like

More WWZ like

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

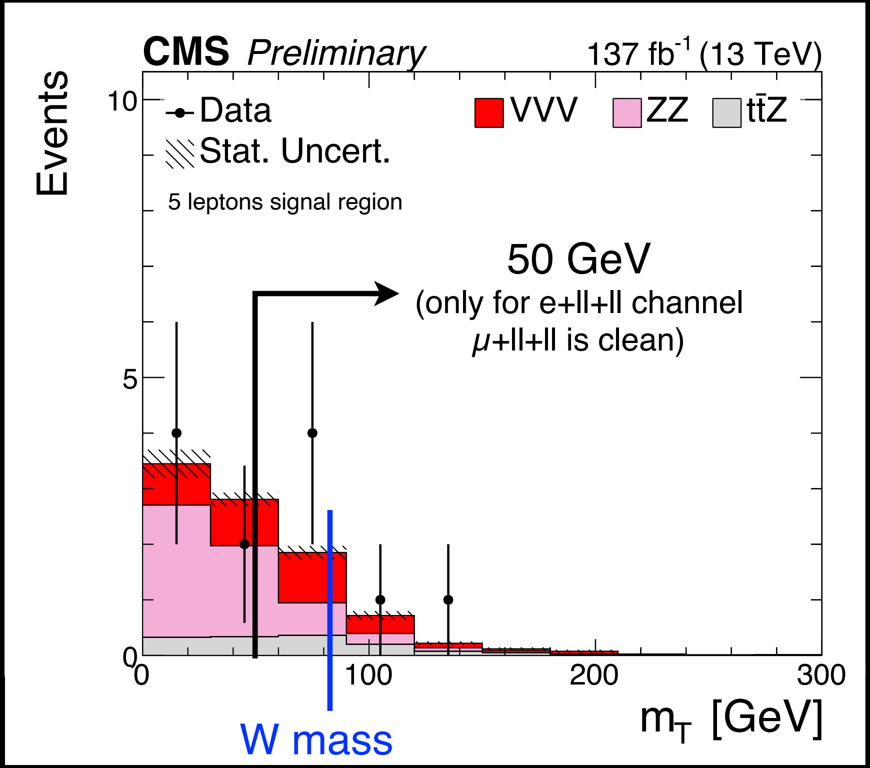
Created multiple bins in BDTs to maximize sensitivity
⇒ Total of 7 signal regions for 4 lepton analysis

5 leptons



On Z-peak

On Z-peak



50 GeV
(only for e+ll+ll channel
μ+ll+ll is clean)

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

The dominant background is *ZZ* → llll plus a fake lepton

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

Simple cut-and-count ⇒ Total of 1 bin in 5 lepton

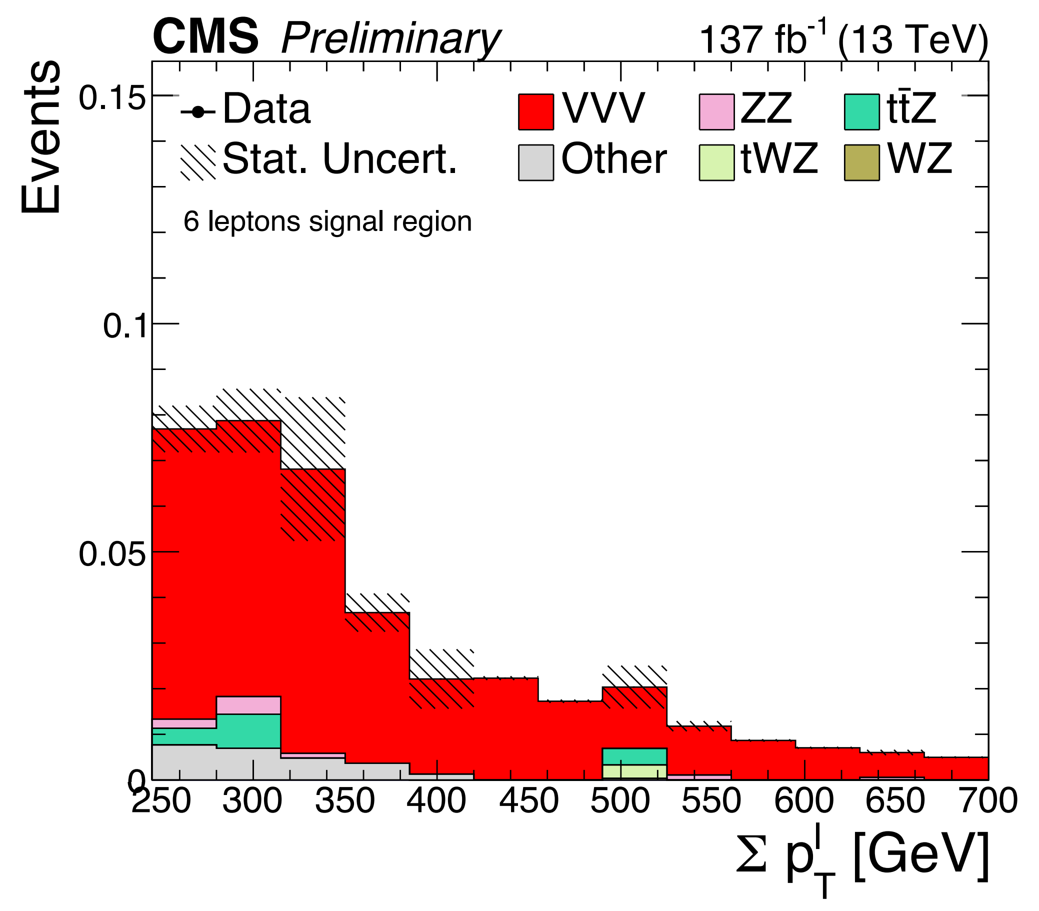
6 leptons

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 ⇒ Total of 1 bin in 6 lepton

Putting it all together

	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^{\pm} \to l^{\pm}\nu$ $W^{\pm} \to l^{\pm}\nu$ $W^{\mp} \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
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

Background estimations

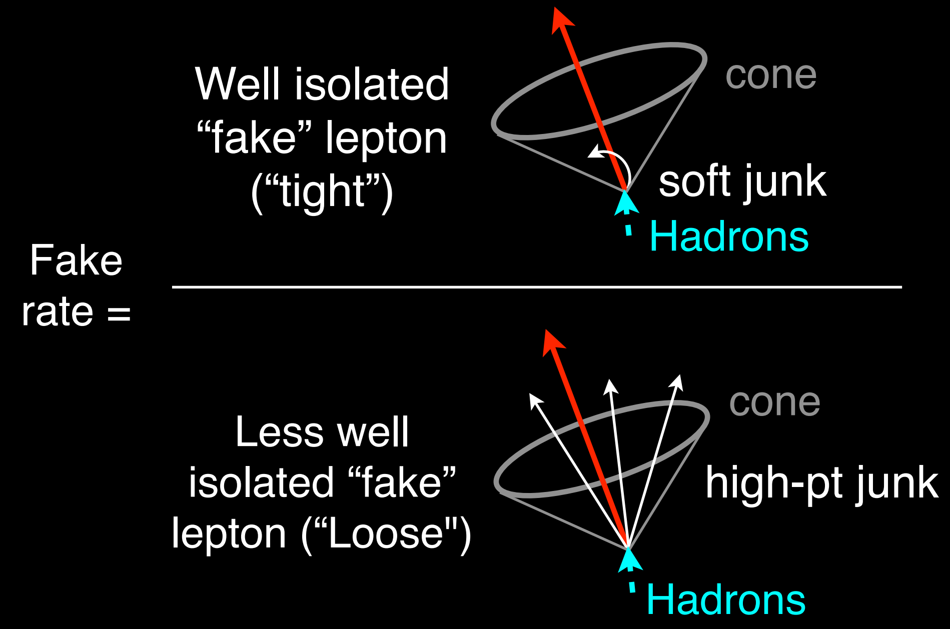
	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Dominant Bkgs.	$WZ \rightarrow l^{\pm}\nu l^{\pm}\overset{\text{lost}}{l^{\mp}}$ $t\bar{t} \rightarrow bb + l + X$ ↳ fake l	$WZ \rightarrow l\nu ll$ $t\bar{t} \rightarrow bb + ll + X$ ↳ fake l	$ZZ \rightarrow llll$ $ttZ \rightarrow llll + \text{bbX}$	$ZZ \rightarrow llll$ + fake lep	$ZZ \rightarrow llll$ + 2 fake lep

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

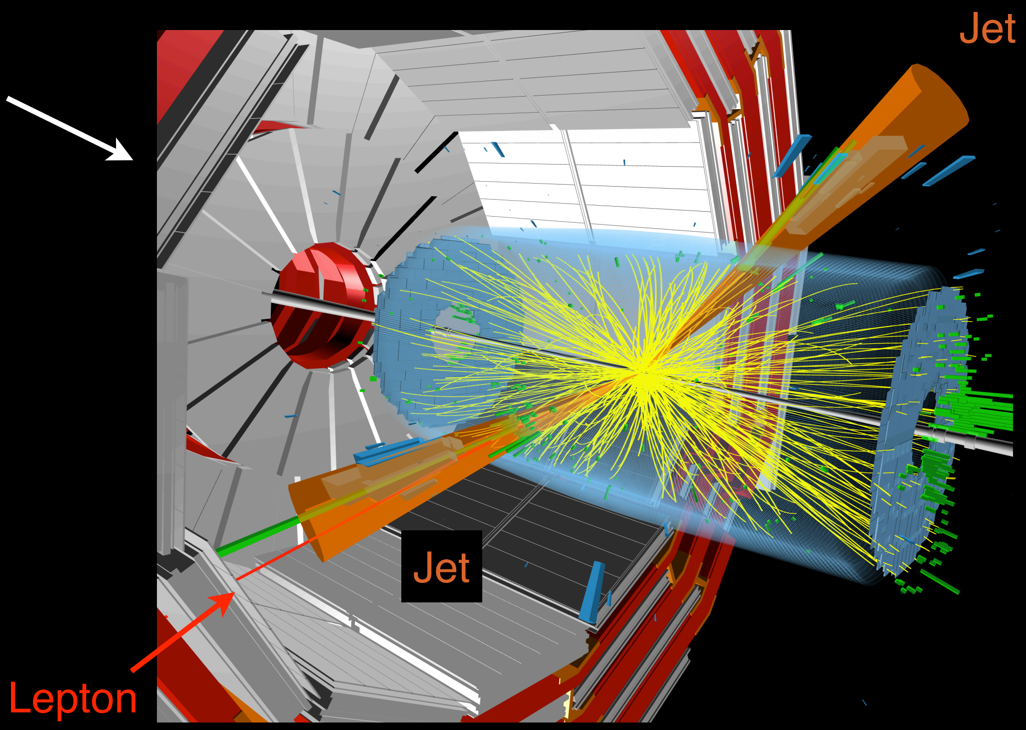
Reliably extrapolate across the method used to suppress background to estimate the size of residual backgrounds in signal region

Fake lepton backgrounds

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



Fake rate = Well isolated “fake” lepton (“tight”) / Less well isolated “fake” lepton (“Loose")



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

"Side band" in isolation

Underlying effects (P_T of quarks) that govern fake rate are not measurable

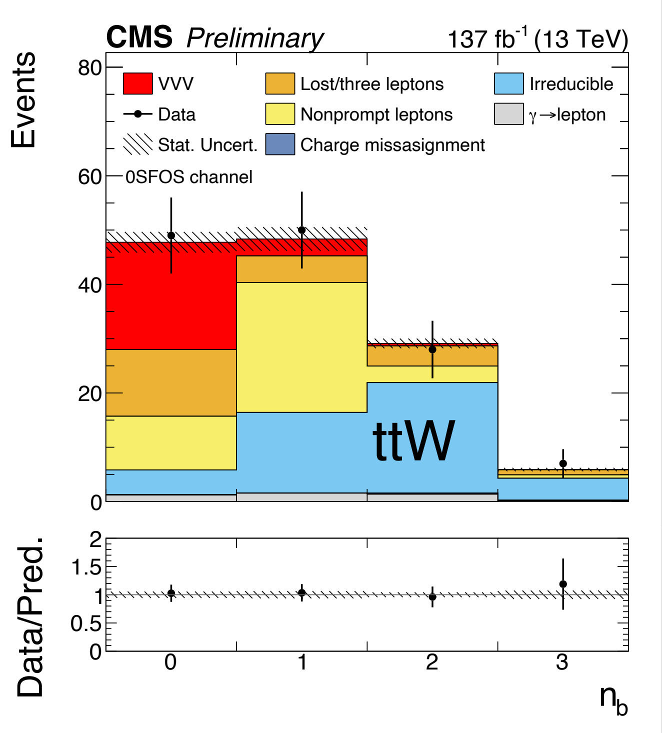
⇒ Source of systematics (~30%)

Estimate fake lepton by measuring fake rate from QCD events

Backgrounds with *b* jets / irreducible

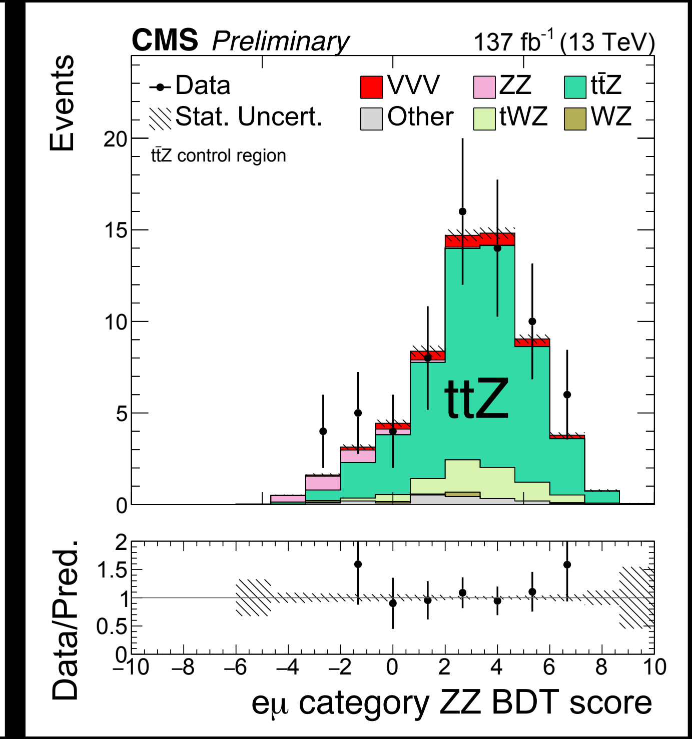
Devise control regions and extrapolate to signal region

N_b in 3 lepton

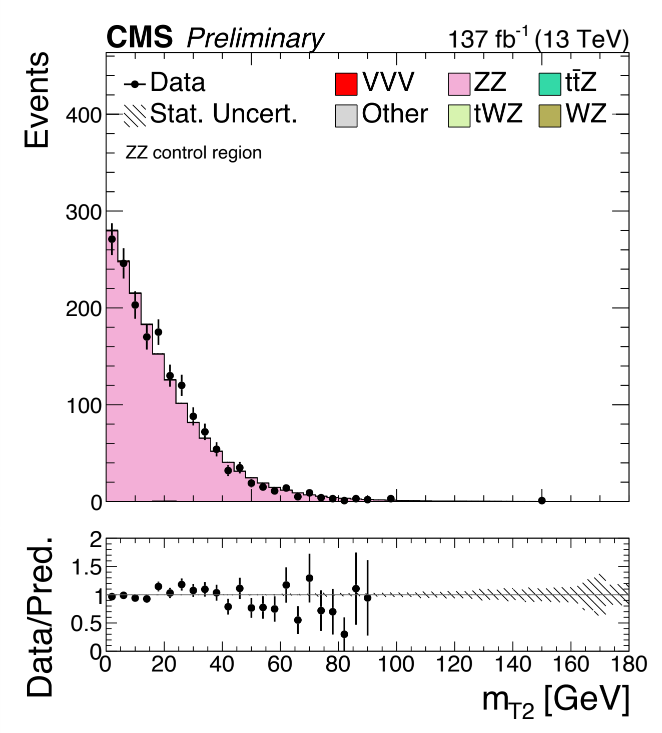


Extrapolate across N_b tag (~10%)

4 lepton BDT score
Z→ll + e*μ* + *b* jets



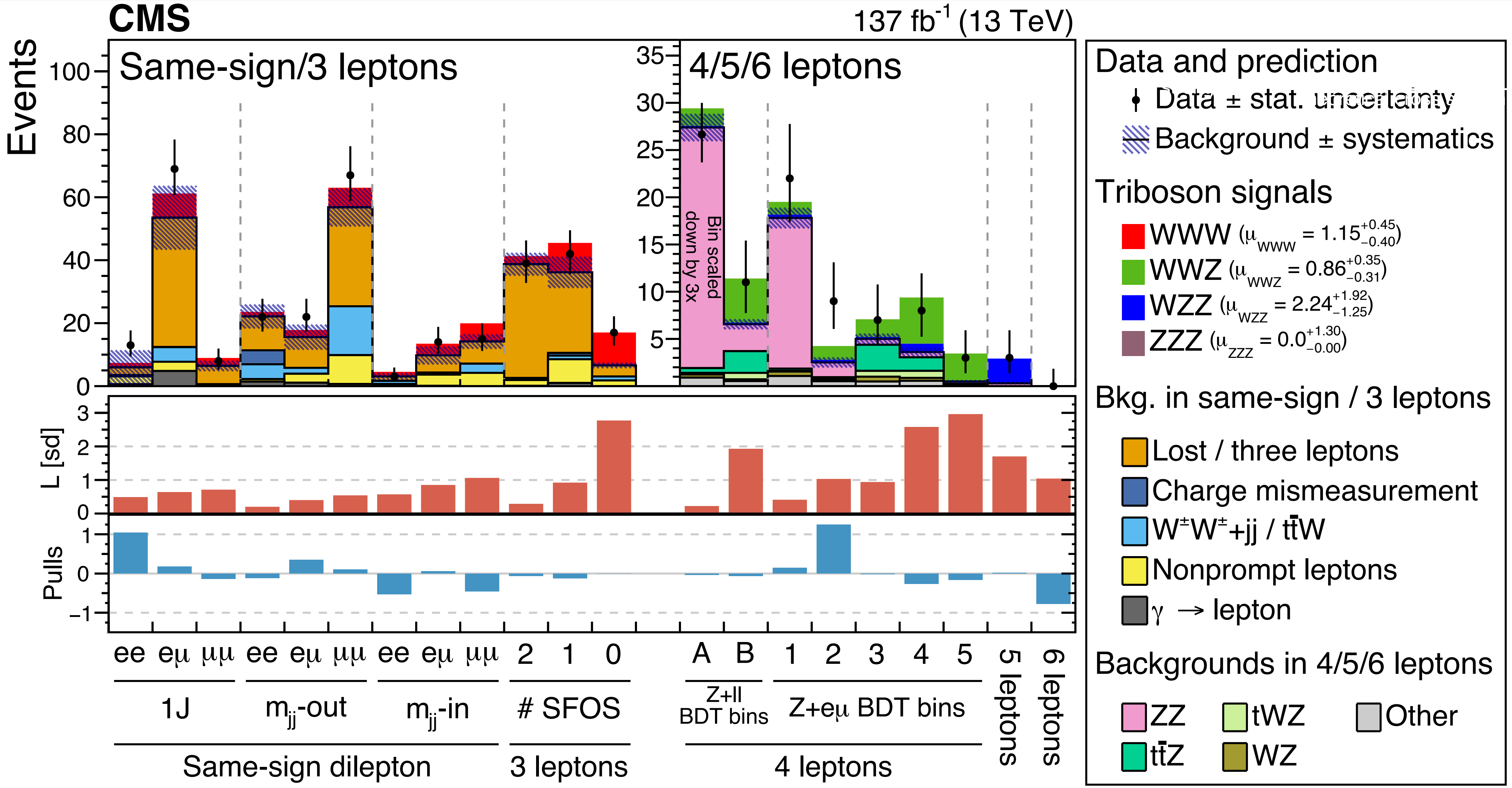
4 lepton m_{T2}
Z→ll + ee/*μμ*



Extrapolate across flavor
(uncertainty ~5%)

Extrapolate from control region to estimate backgrounds

Results

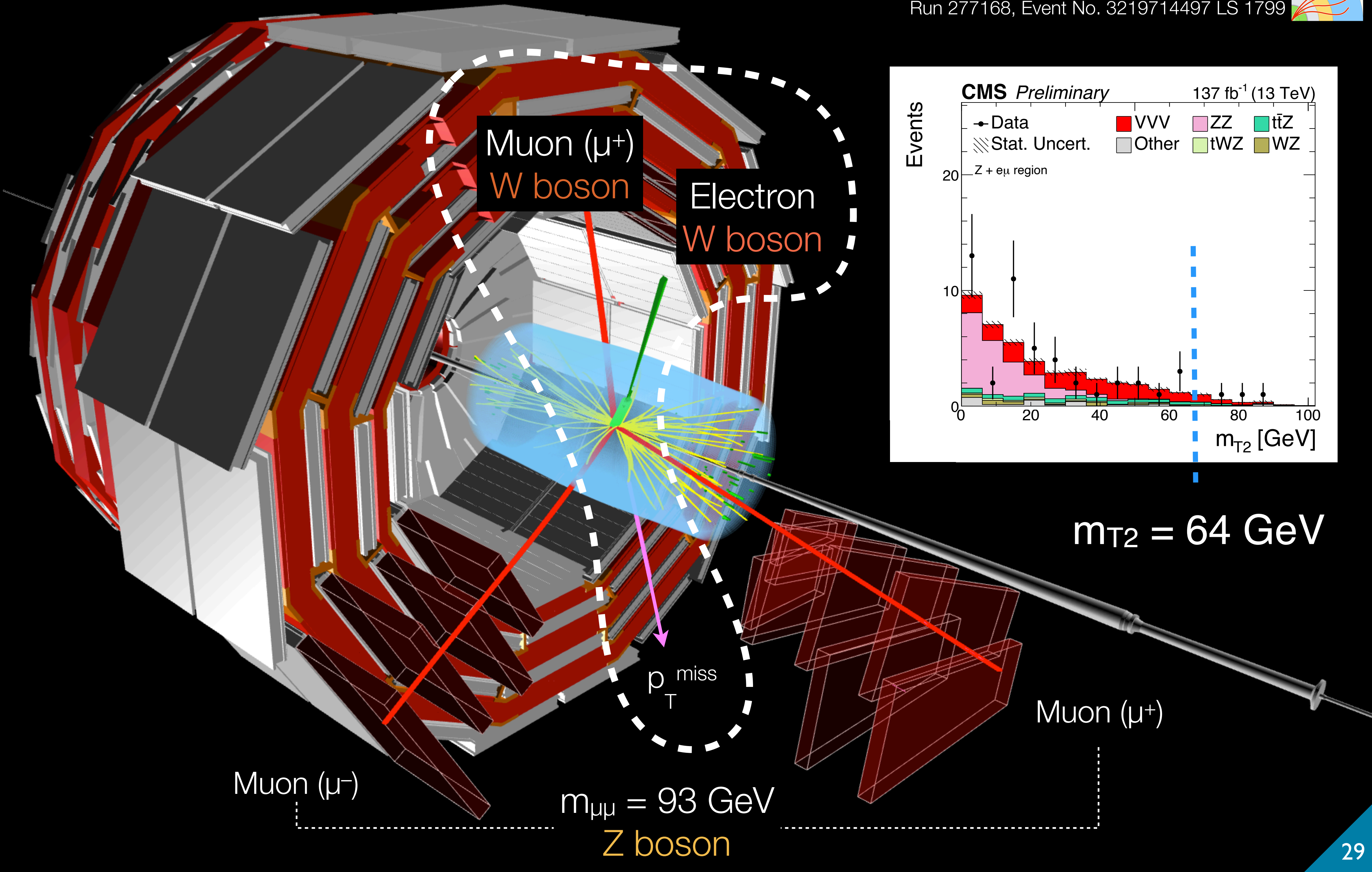


9 bins 3 bins 7 bins 1 1

More sensitive bins are generally to the right

4 lepton event

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



m_{T2} = 64 GeV

$m_{\mu\mu}$ = 93 GeV

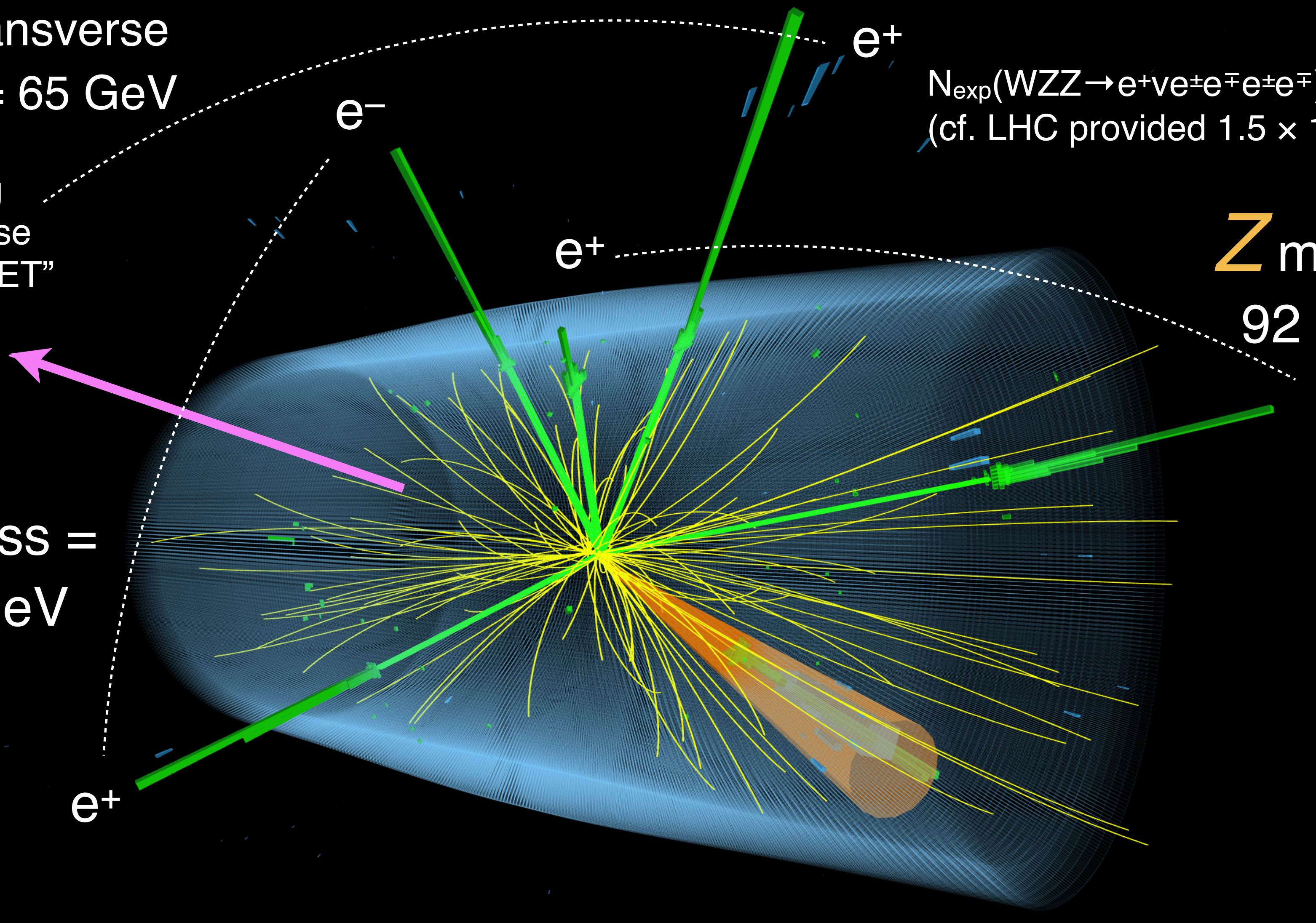
Z boson

5 lepton event

CMS experiment at the LHC, CERN
Data recorded: 2016-Oct-09 21:24:05.010240 GMT
Run 282735, Event No. 989682042 LS 491

V = W, Z

$N_{exp}(WZZ \rightarrow e^{+}\nu e^{\pm}e^{\mp}e^{\pm}e^{\mp}) \sim 1$ event
(cf. LHC provided 1.5×10^{16} collisions)



W transverse mass = 65 GeV

Missing Transverse Energy “MET”

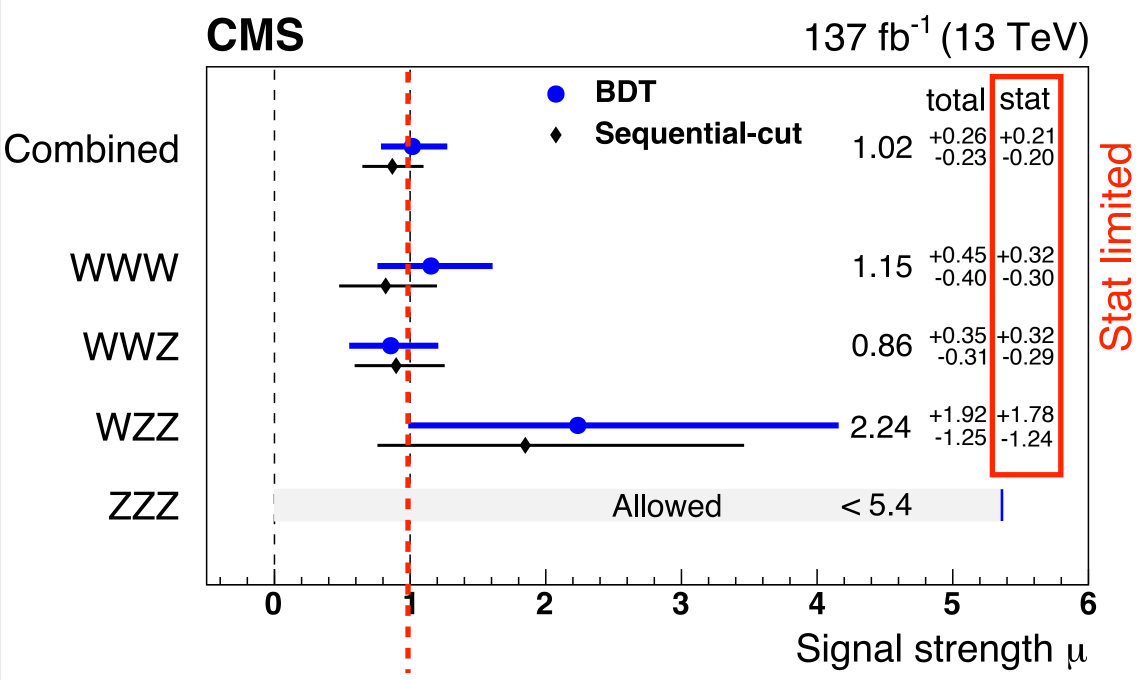
Z mass = 92 GeV

Z mass = 91 GeV

Results

O(10) events only
⇒ measure total cross section

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)



SM

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

- 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.

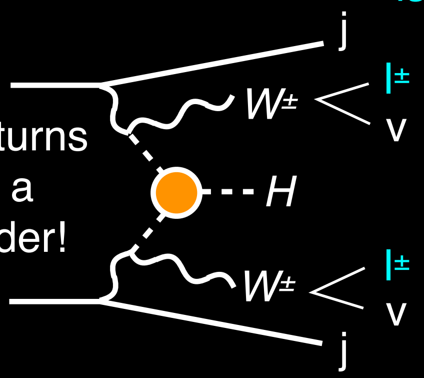
First observation of VVV and evidences for WWW and WWZ productions

More multi-massive-X processes for future

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

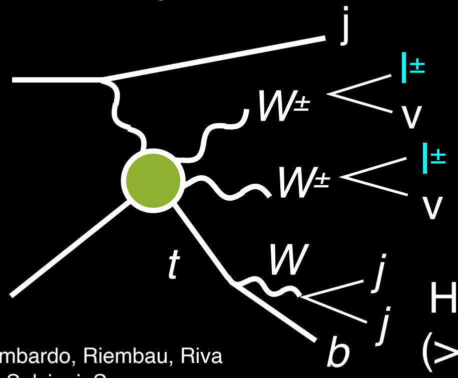
pp → $W^\pm W^\pm H$

Same-sign is special



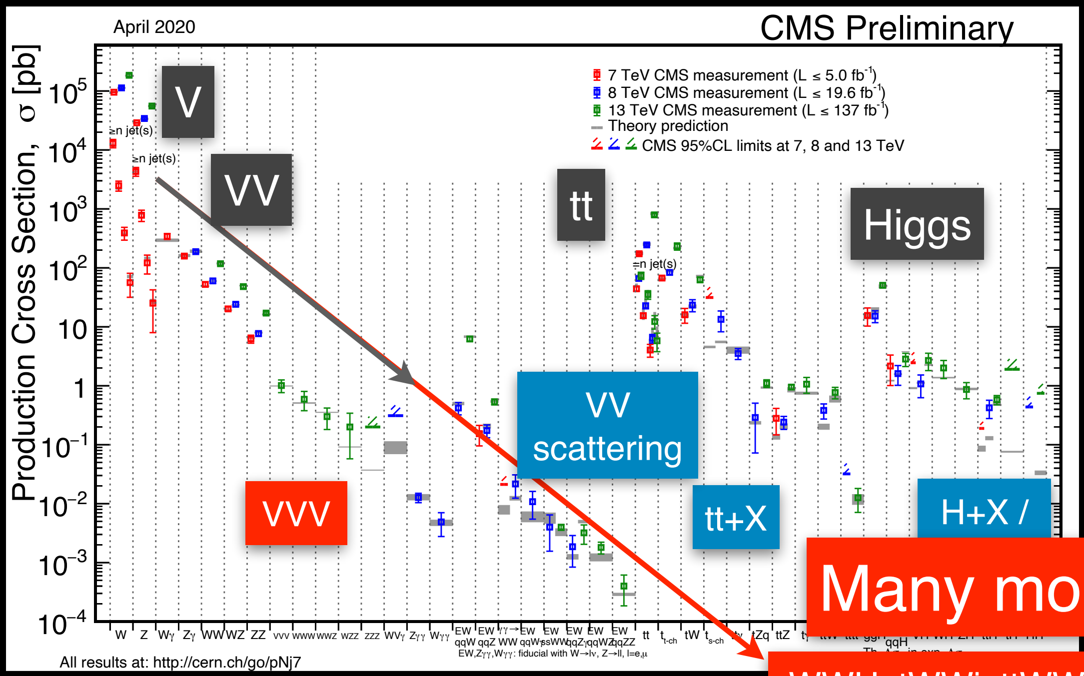
Same-sign turns LHC into a Higgs collider!

pp → $tW^\pm W^\pm j$



High P_T top (> 500 GeV)

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



V

VV

tt

Higgs

VVV

VV scattering

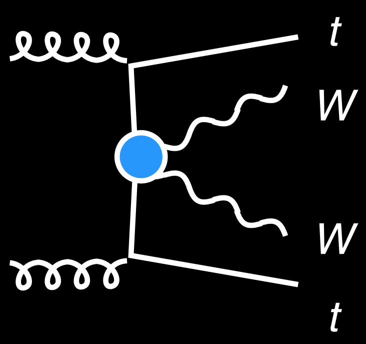
tt+X

H+X /

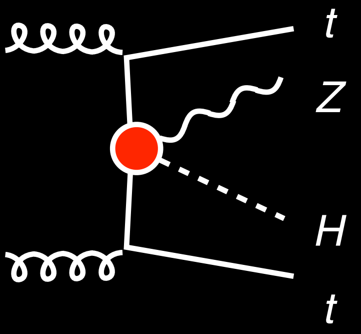
Many more

WWH, tWWj. ttWW, ttZH

pp → ttWW



pp → ttZH

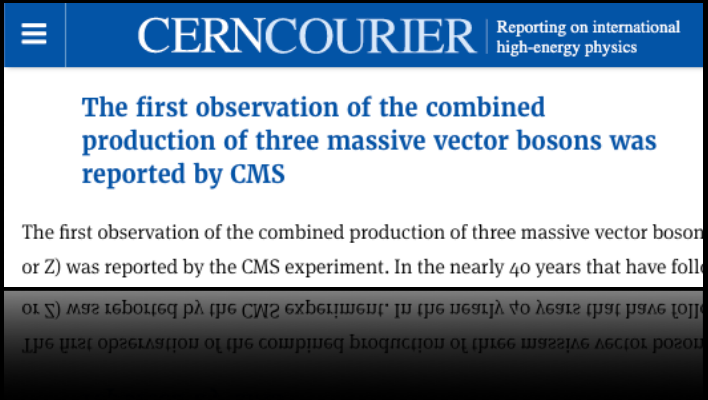


There are many more multi-massive-X production to be explored at LHC

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

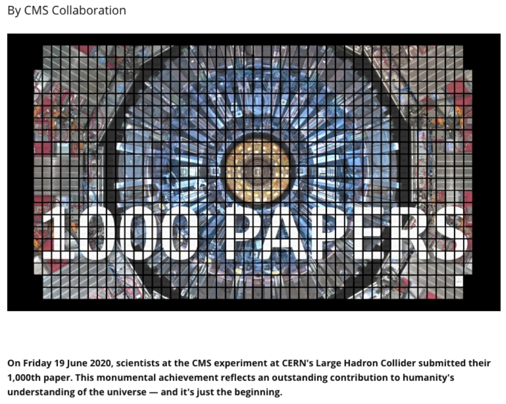


CERNCOURIER Reporting on international high-energy physics

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 boson
or Z) was reported by the CMS experiment. In the nearly 40 years that have foll

This paper is 1000th paper submitted by CMS!



By CMS Collaboration

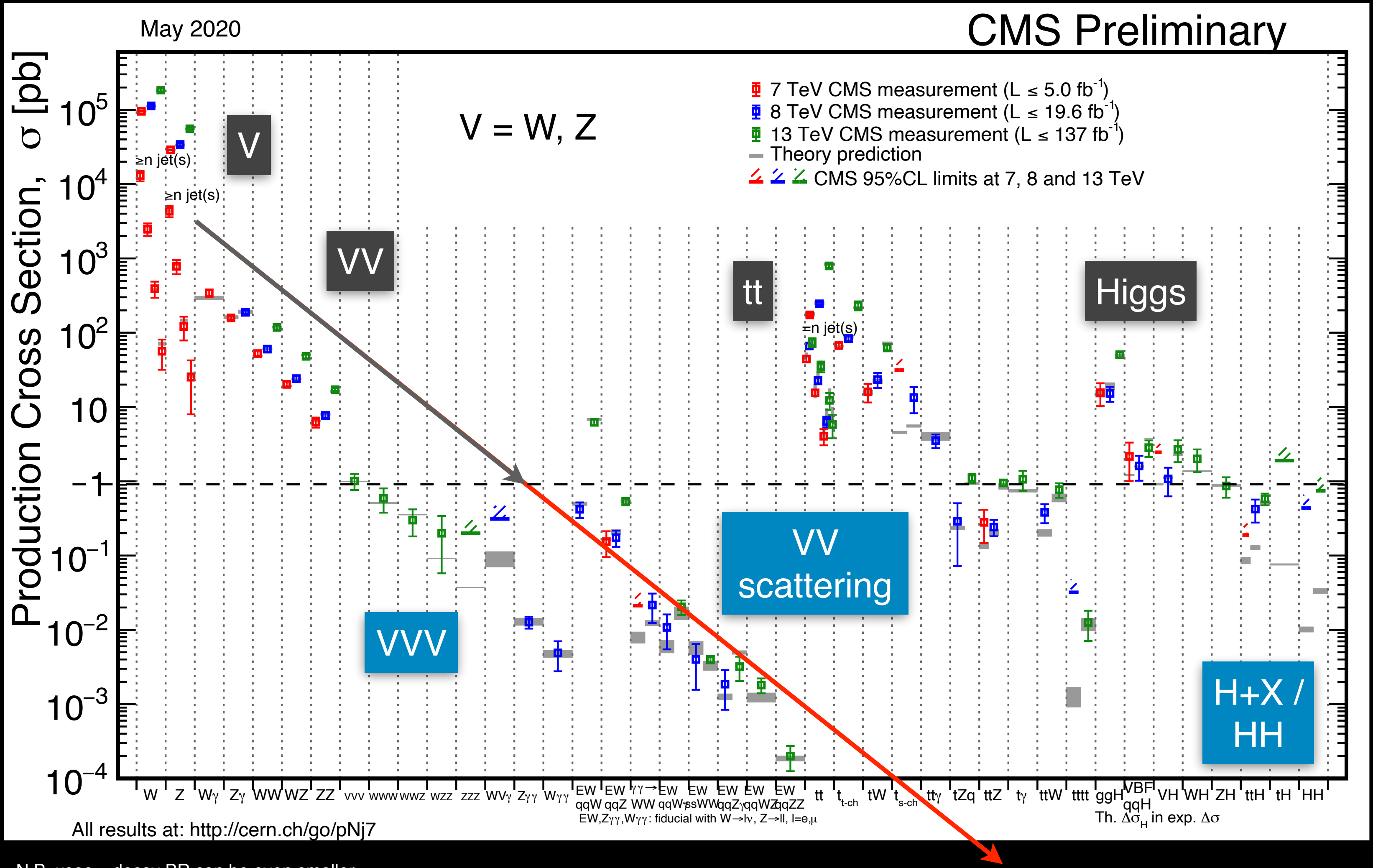
On Friday 19 June 2020, scientists at the CMS experiment at CERN's Large Hadron Collider submitted their 1,000th paper. This monumental achievement reflects an outstanding contribution to humanity's understanding of the universe — and it's just the beginning.

“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

Rare multi-boson processes

Rarer events



N.B. xsec × decay BR can be even smaller

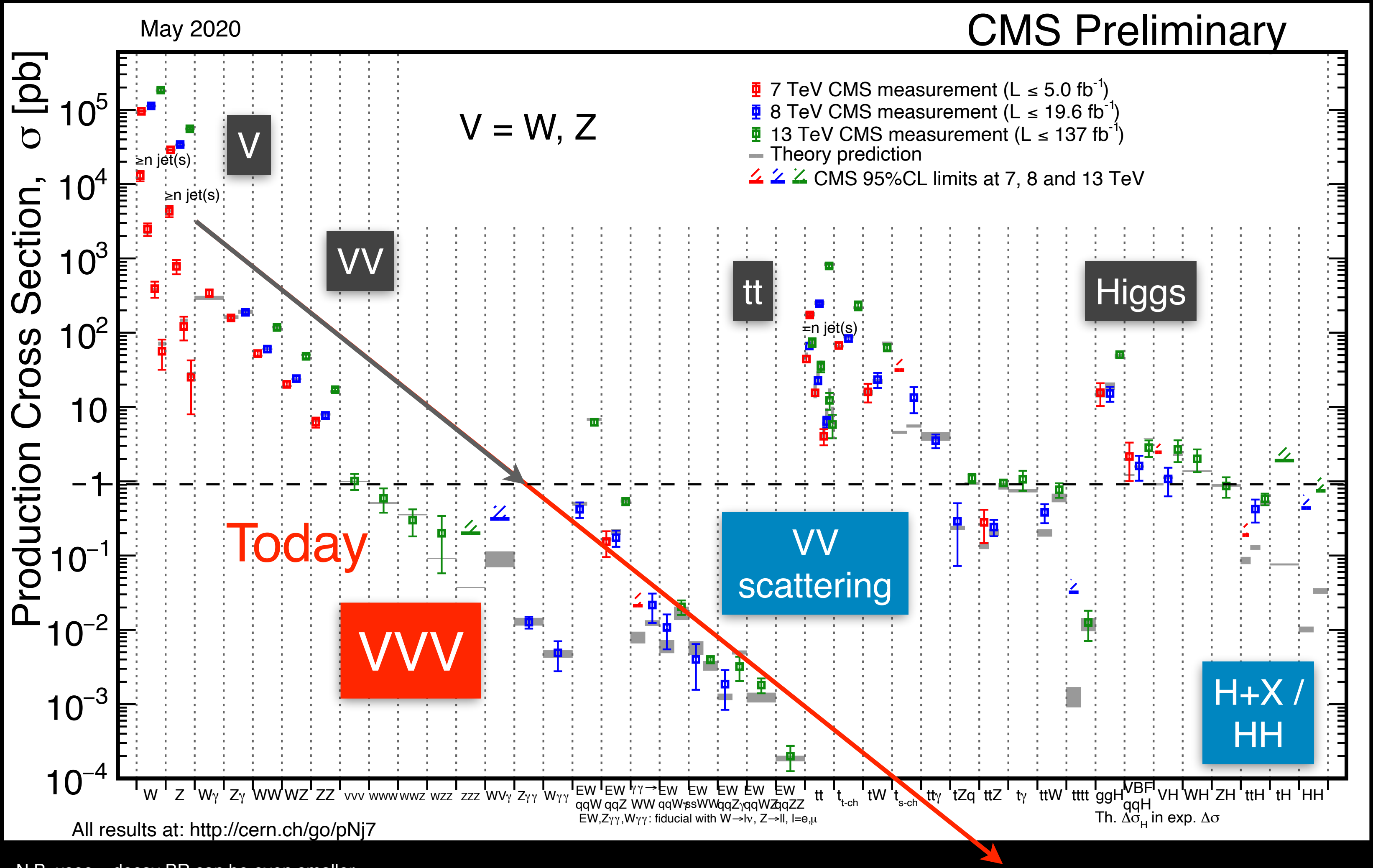
Multi-boson processes

X = W, Z, H

Electroweak multi-boson processes are rare and require LHC

Rare multi-boson processes

Rarer events



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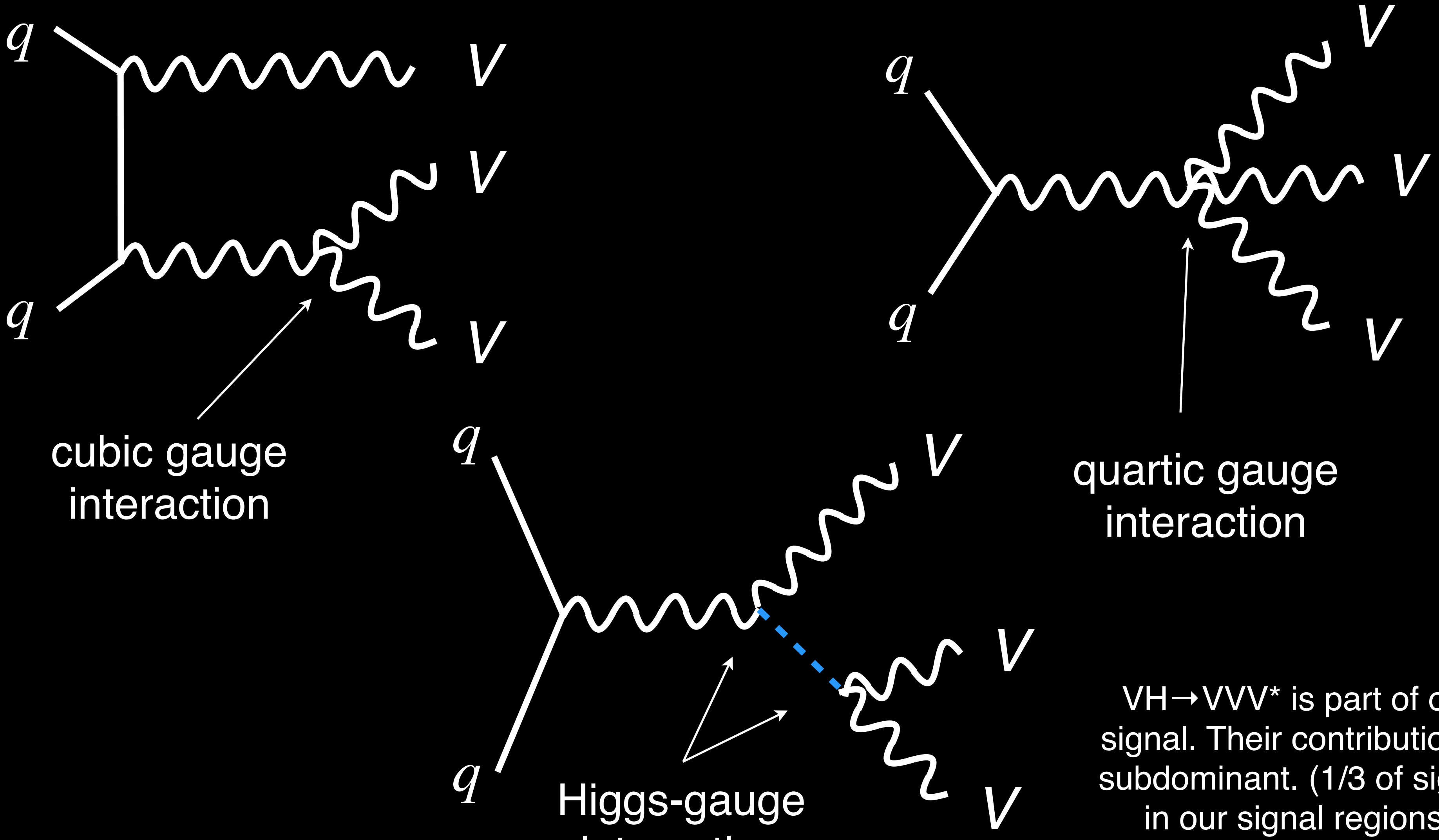
Multi-boson processes

X = W, Z, H

Electroweak multi-boson processes are rare and require LHC

Physics of VVV production (V = W, Z)



cubic gauge interaction

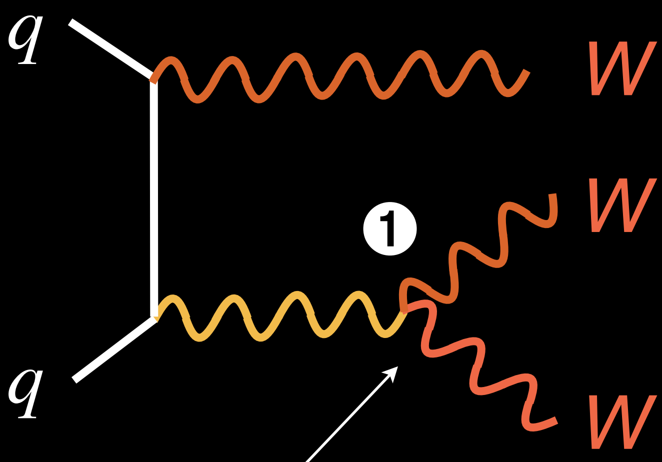
quartic gauge interaction

Higgs-gauge interaction

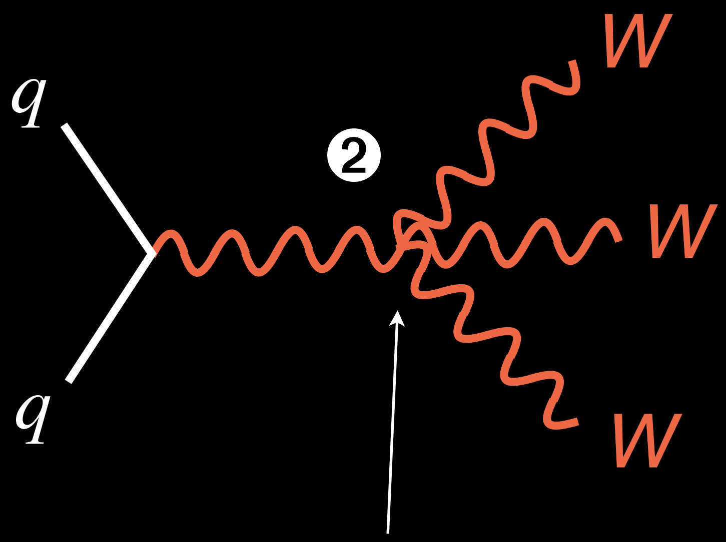
VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

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

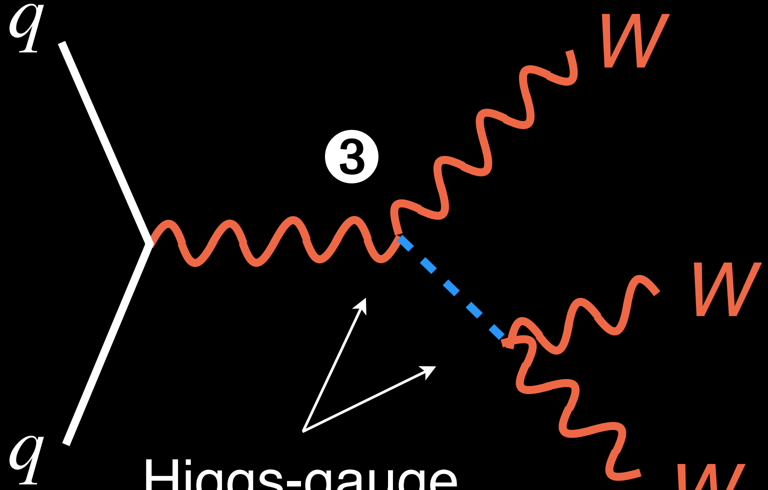
Physics of VVV production (V = W, Z)



cubic gauge interaction



quartic gauge interaction



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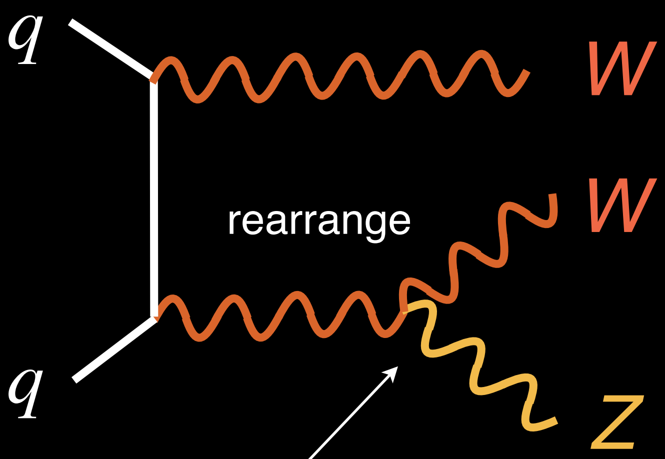
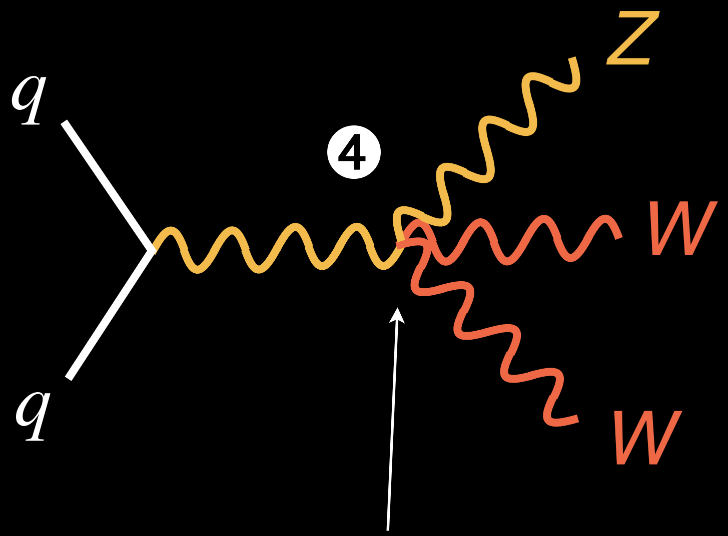
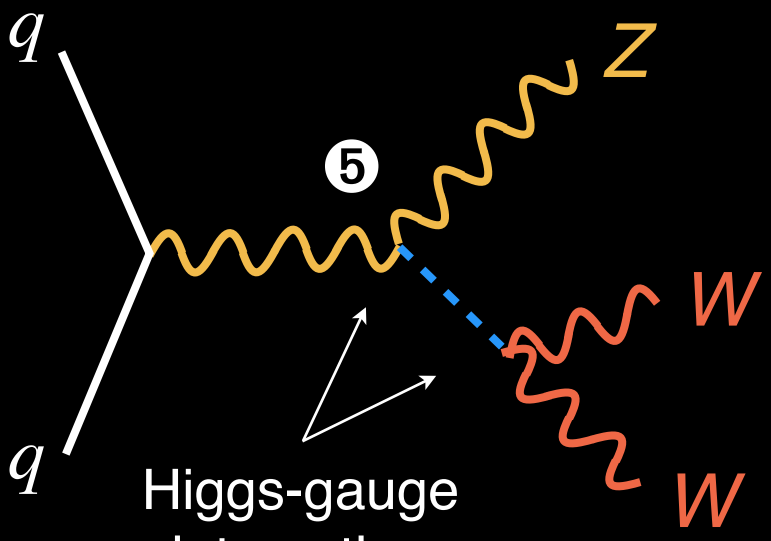


cubic gauge interaction



quartic gauge interaction



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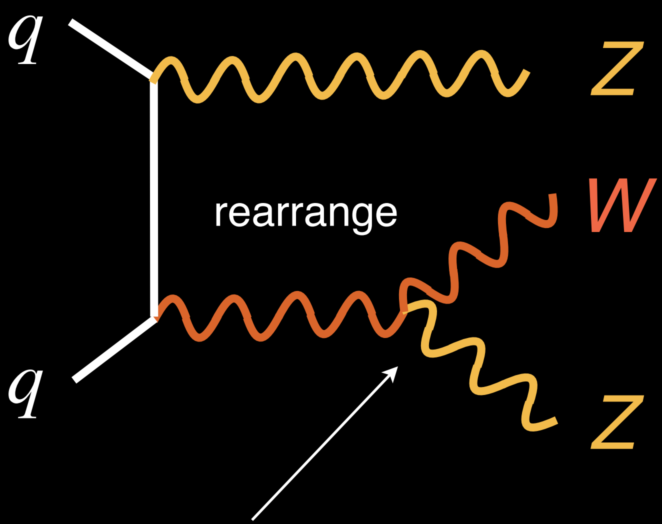
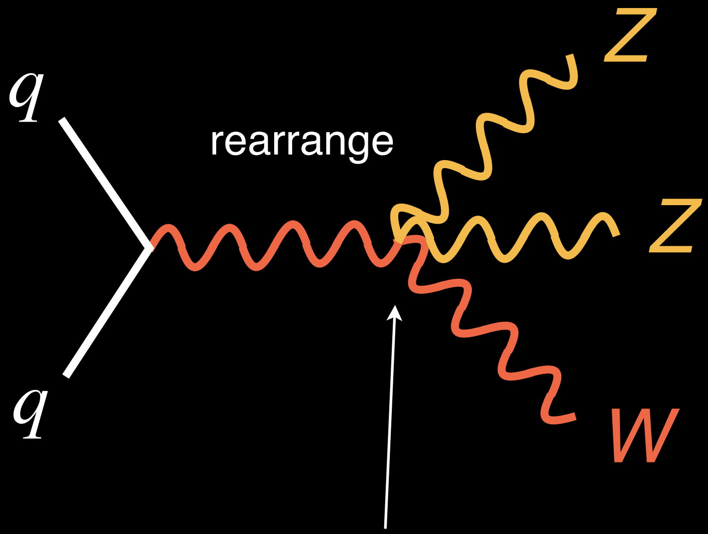
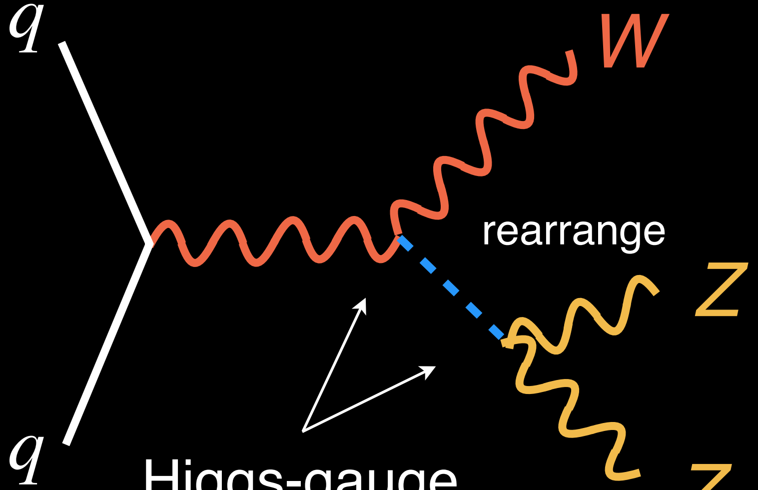


cubic gauge interaction



quartic gauge interaction



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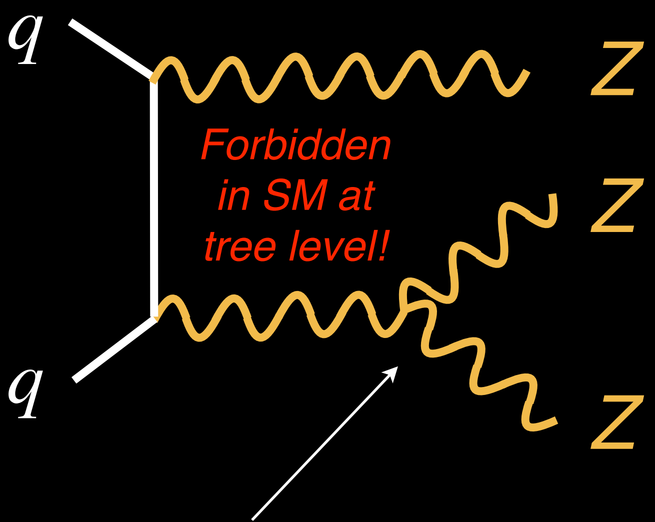
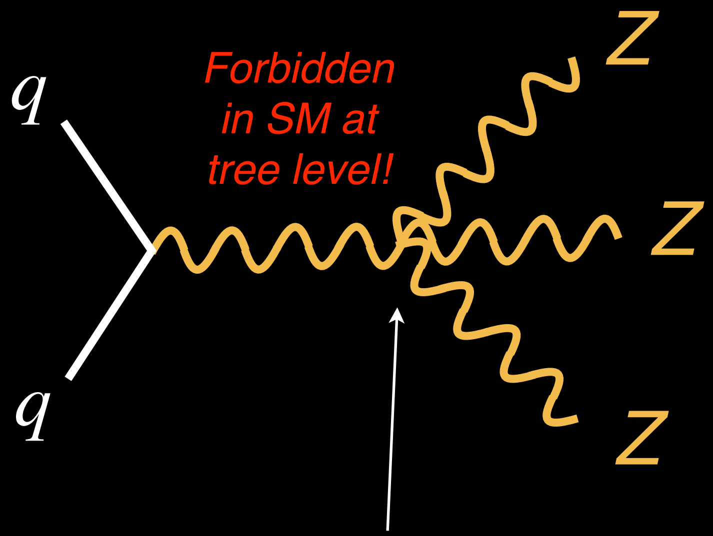
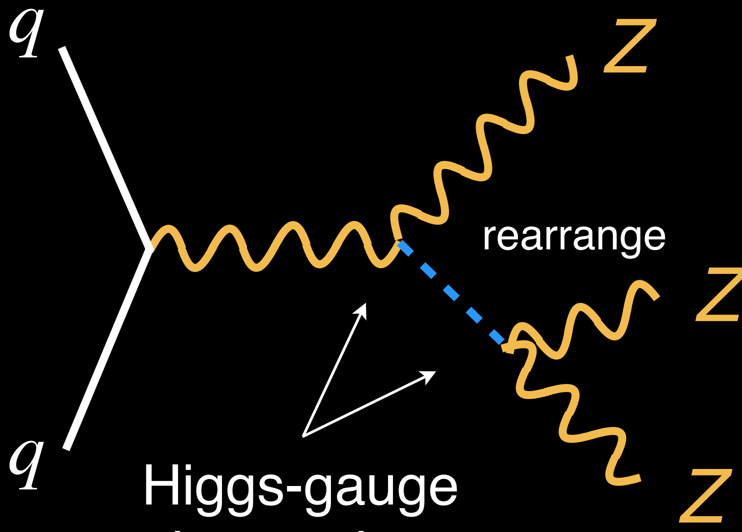


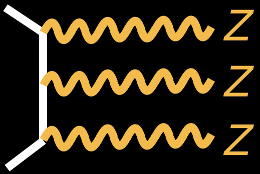
cubic gauge
interaction



quartic gauge
interaction



Higgs-gauge
interaction



Three Z's radiating
from quark lines

VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

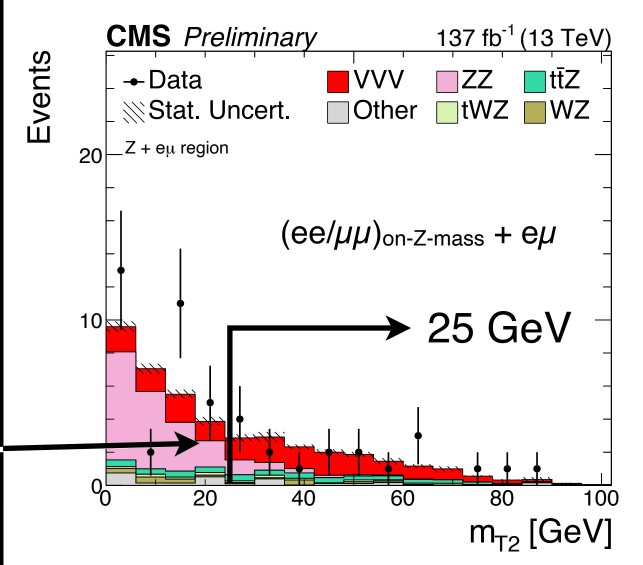
Triboson process has access to studying many multi-*boson* interactions

Kinematic endpoints for 4 leptons

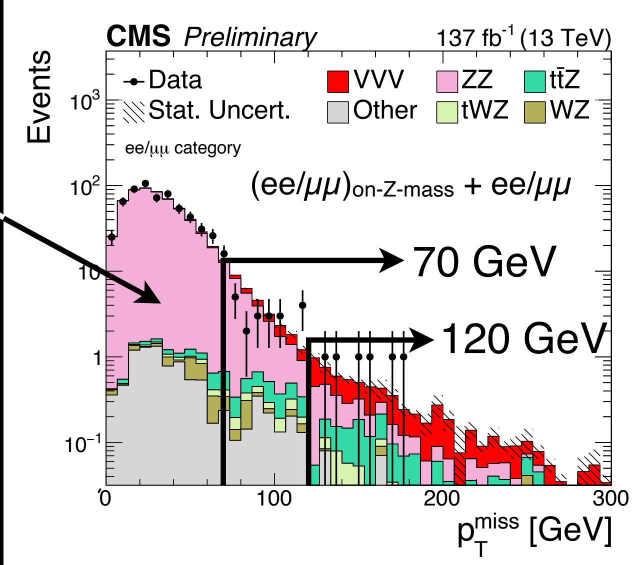
Events are separated into 2 categories by flavor:

- "e*μ* channel": (ee/*μμ*)$_{\text{on-Z-mass}}$ + e*μ* (low bkg.)
- "ee/*μμ* channel": (ee/*μμ*)$_{\text{on-Z-mass}}$ + ee/*μμ*

e*μ* channel utilizes m_{T2} variable, which is a generalization of m_T for multiple missing particles. m_{T2} is sensitive to the end points of m_τ from ZZ→llττ



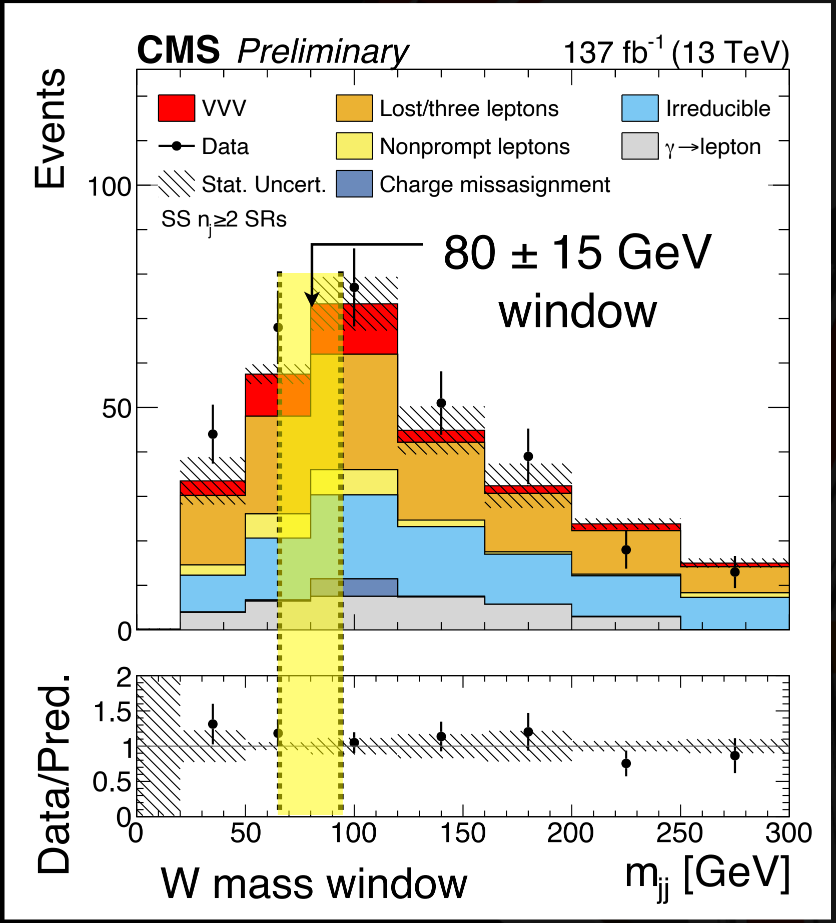
ZZ bkg in ee/*μμ* have low missing energy



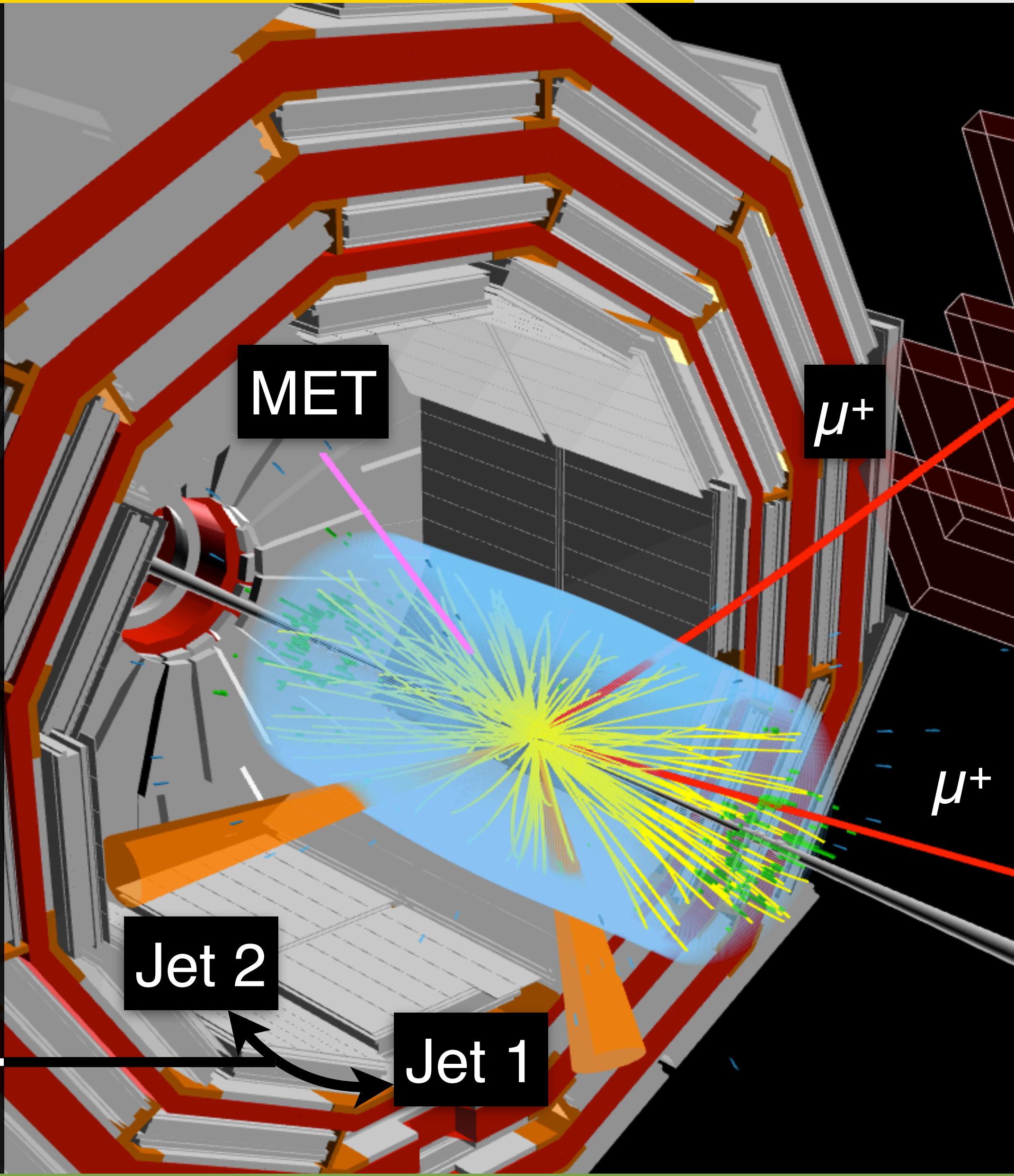
Combine these and a few more kinematic variables to form total of 7 signal regions for 4 lepton analysis

Exploit differences between Z → ll v. WW → lvlv

Reconstruct W→qq in WWW → l±l±qq

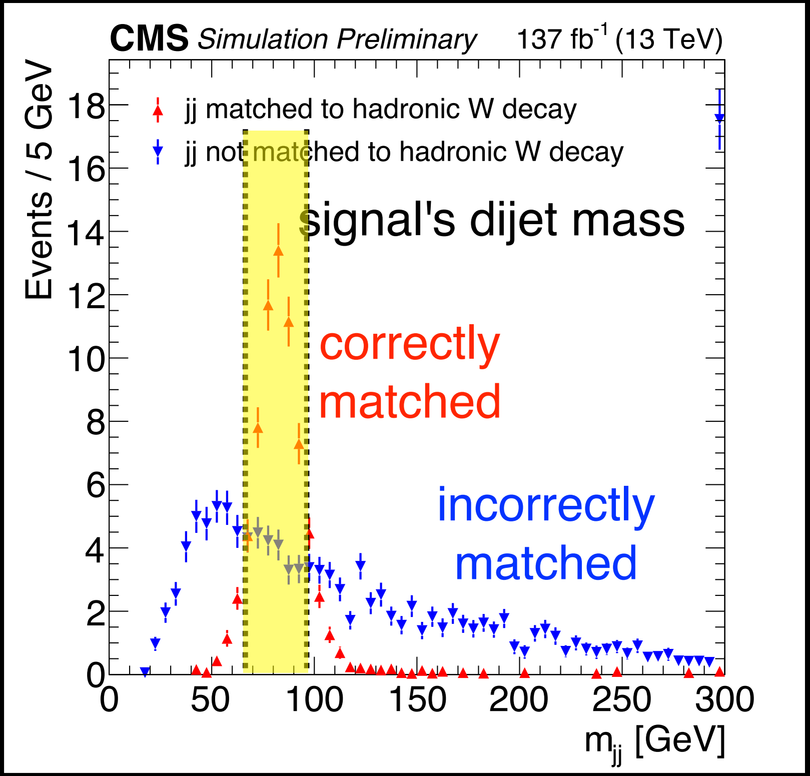


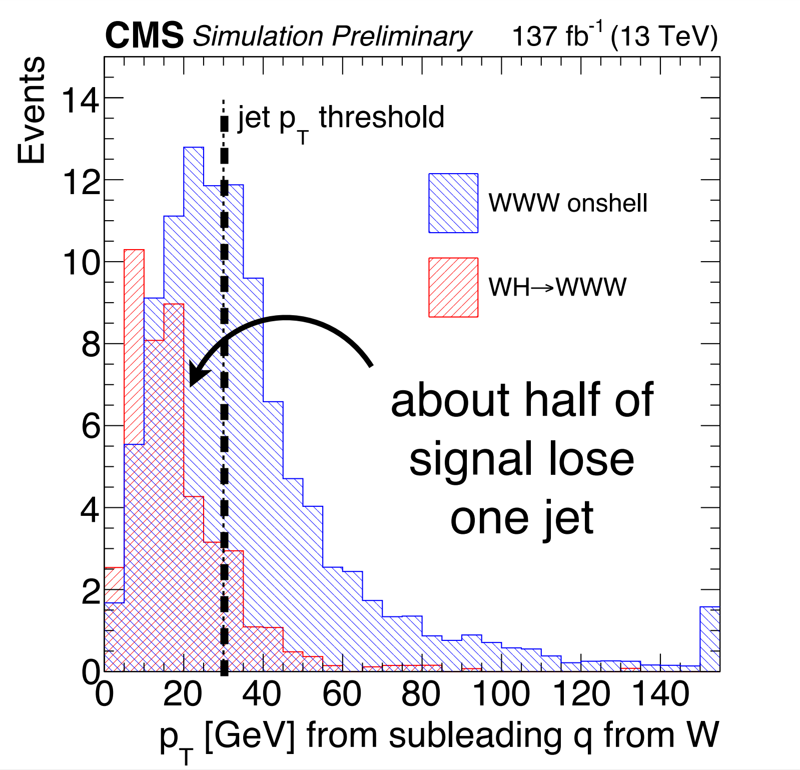
N.B. some signals are
outside the window
(See next slide)



dijet invariant mass for signal peaks around W mass

Difficulties in jet final states





Difficult to match W → qq
⇒ Select off-W-mass peak region

Difficult to reconstruct both jets
⇒ Select 1 jet (1J) events

2 additional categories (m_{jj}-in, m_{jj}-out, 1J) each split by *ee*/*eμ*/*μμ*
⇒ Total of 9 signal regions for same-sign analysis

We cover wide range of possible jet final states to maximize sensitivity

Kinematic endpoints for 4 leptons

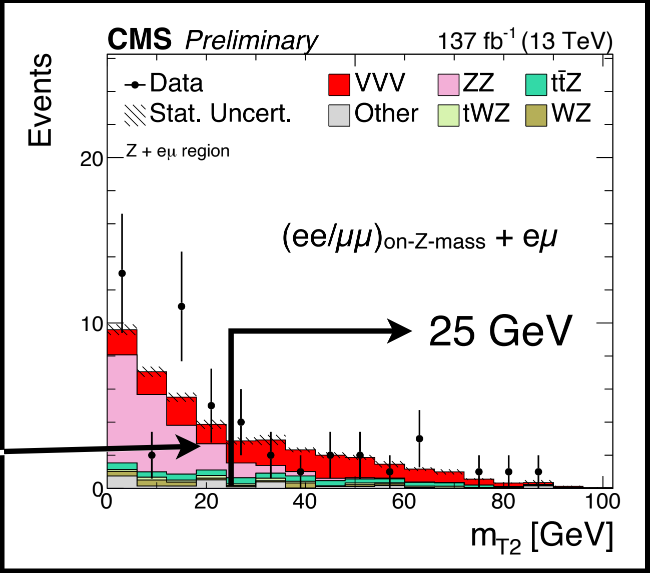
Events are separated into 2 categories by flavor:

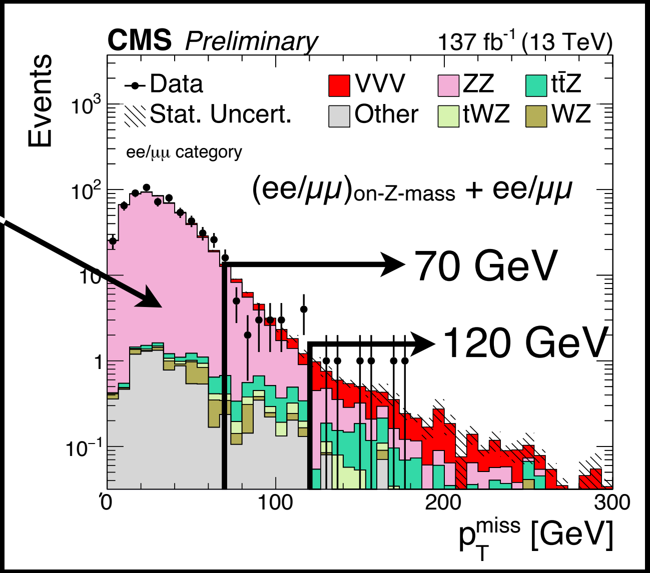
- "eμ channel": $(ee/\mu\mu)_{\text{on-Z-mass}}$ + eμ (low bkg.)
- "ee/$\mu\mu$ channel": $(ee/\mu\mu)_{\text{on-Z-mass}}$ + ee/$\mu\mu$

eμ channel utilizes m_{T2} variable, which is a generalization of m_T for multiple missing particles. m_{T2} is sensitive to the end points of m_τ from ZZ→llττ

ZZ bkg in ee/$\mu\mu$ have low missing energy

Combine these and a few more kinematic variables to form total of 7 signal regions for 4 lepton analysis

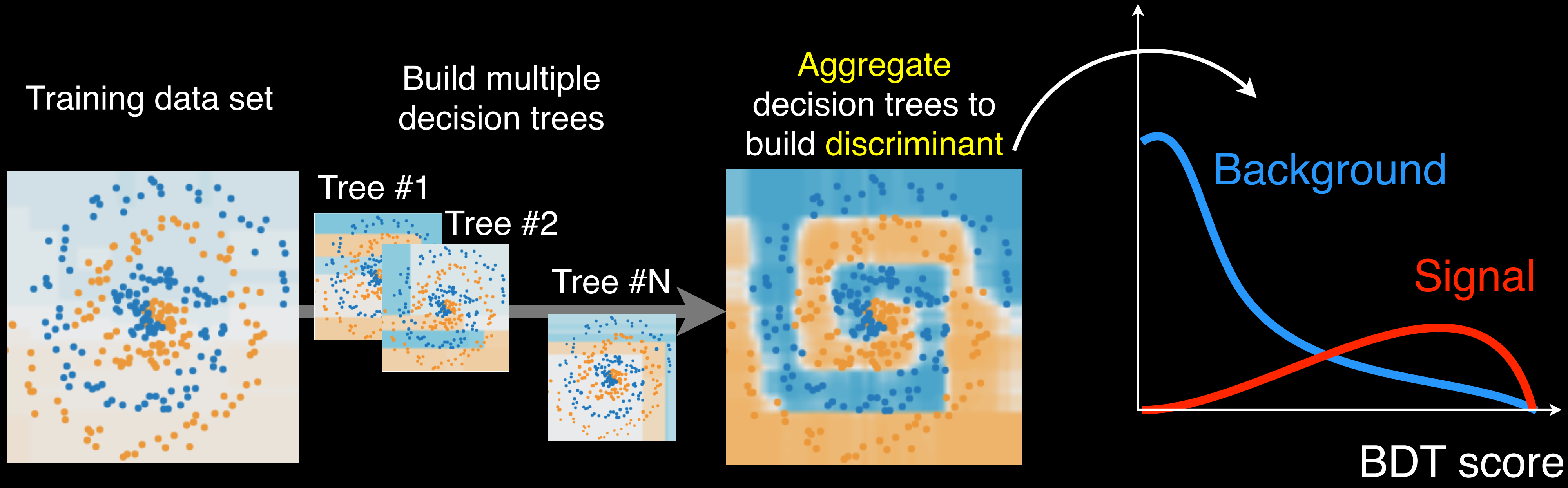




Exploit differences between Z → ll v. WW → lvlv

Boosted decision tree

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



Training data set

Build multiple decision trees

Tree #1

Tree #2

Tree #N

Aggregate decision trees to build discriminant

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	$W^{\pm} \to l^{\pm}\nu$ $W^{\pm} \to l^{\pm}\nu$ $W^{\mp} \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
Dominant Bkgs.	lost $WZ \to l^{\pm}\nu l^{\pm}l^{\mp}$ $t\bar{t} \to bb + l + X$ ↳ fake l	$WZ \to l\nu ll$ $t\bar{t} \to bb + ll + X$ ↳ fake l	$ZZ \to llll$ $ttZ \to llll + bbX$	$ZZ \to llll$ + fake lep	$ZZ \to llll$ + 2 fake lep

“Prompt” bkgs.

“Fake” bkgs.

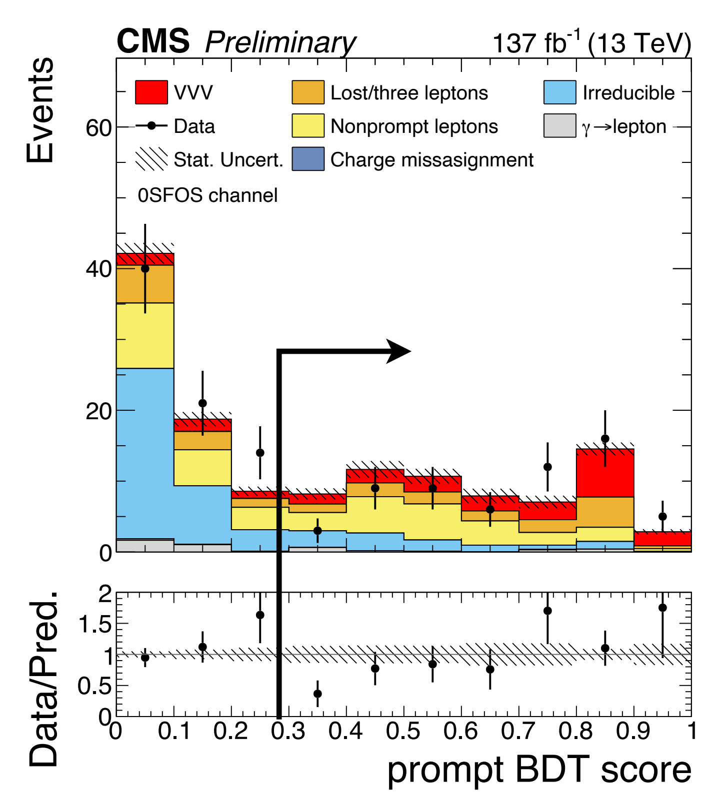
$t\bar{t}Z$ bkg.

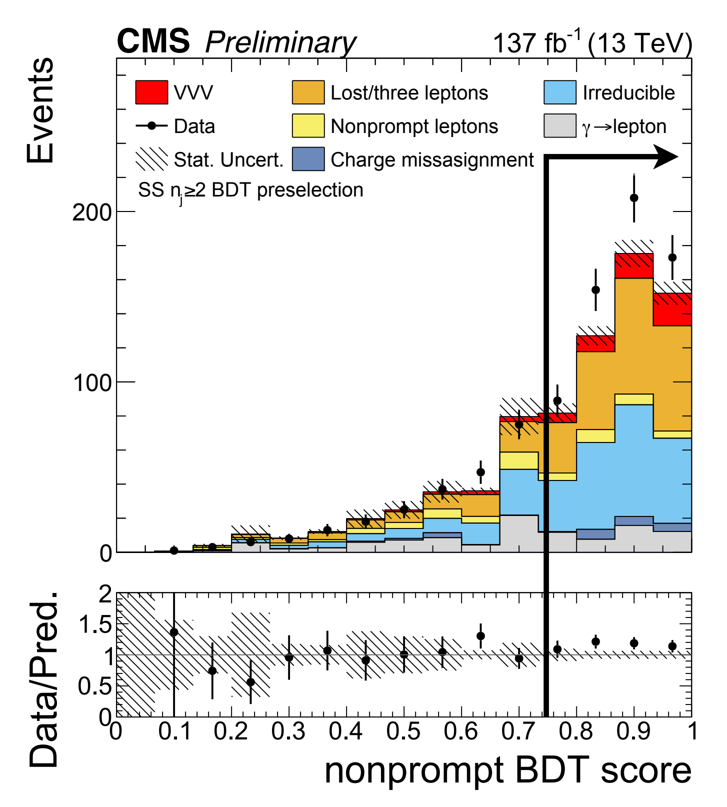
ZZ bkg.

No BDT trained for
5/6 leptons (not
enough stats)

Train different BDTs against different backgrounds

WWW BDTs: Same-Sign / 3 leptons



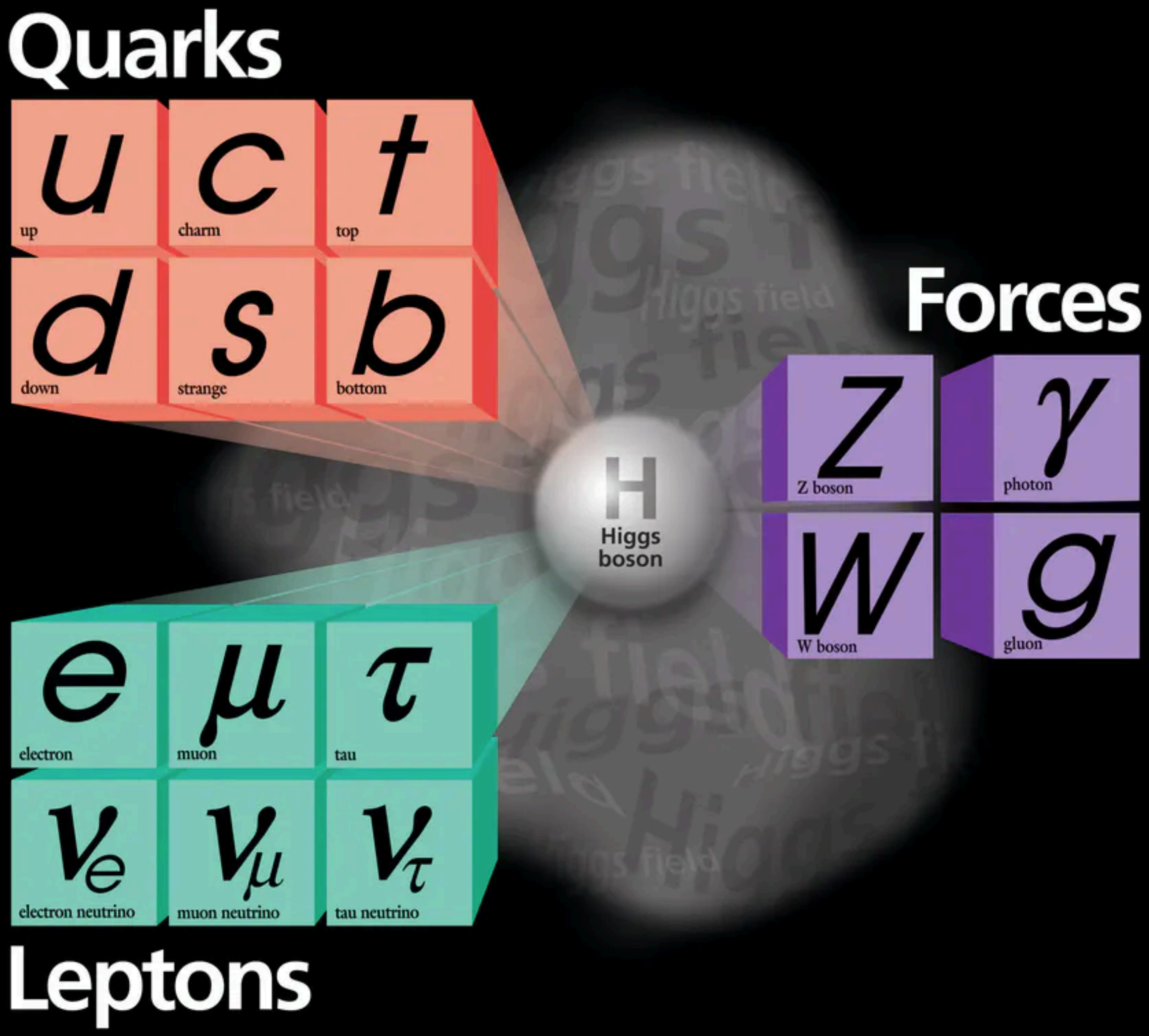


Maintained same categorizations but cut on BDT to maximize sensitivity

Total number of bins stayed same (9 for same-sign, 3 for 3 leptons)

Cut on each BDT scores to create a high sensitivity bin

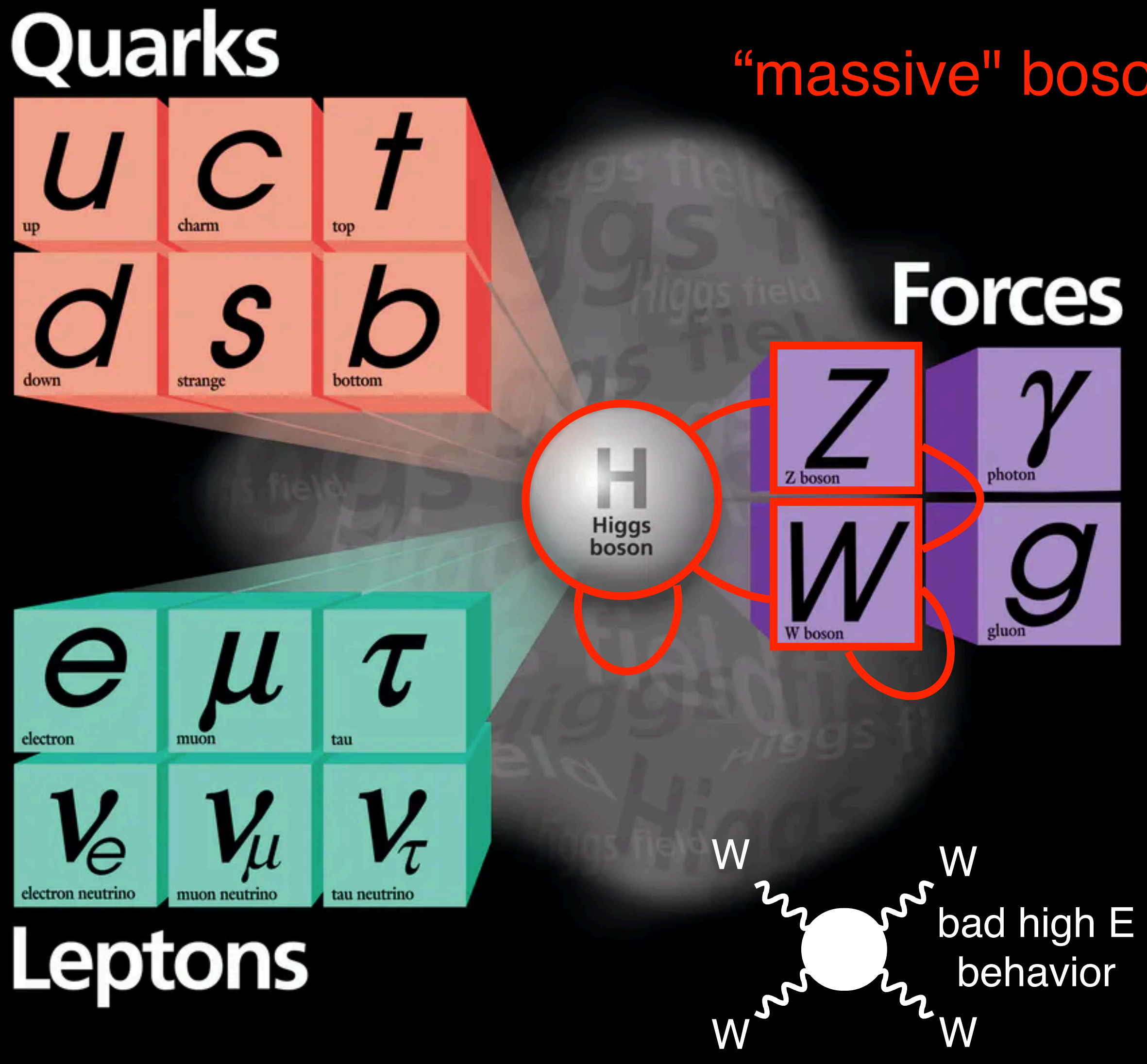
More work to be done in electroweak sector



- 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

More work to be done in electroweak sector



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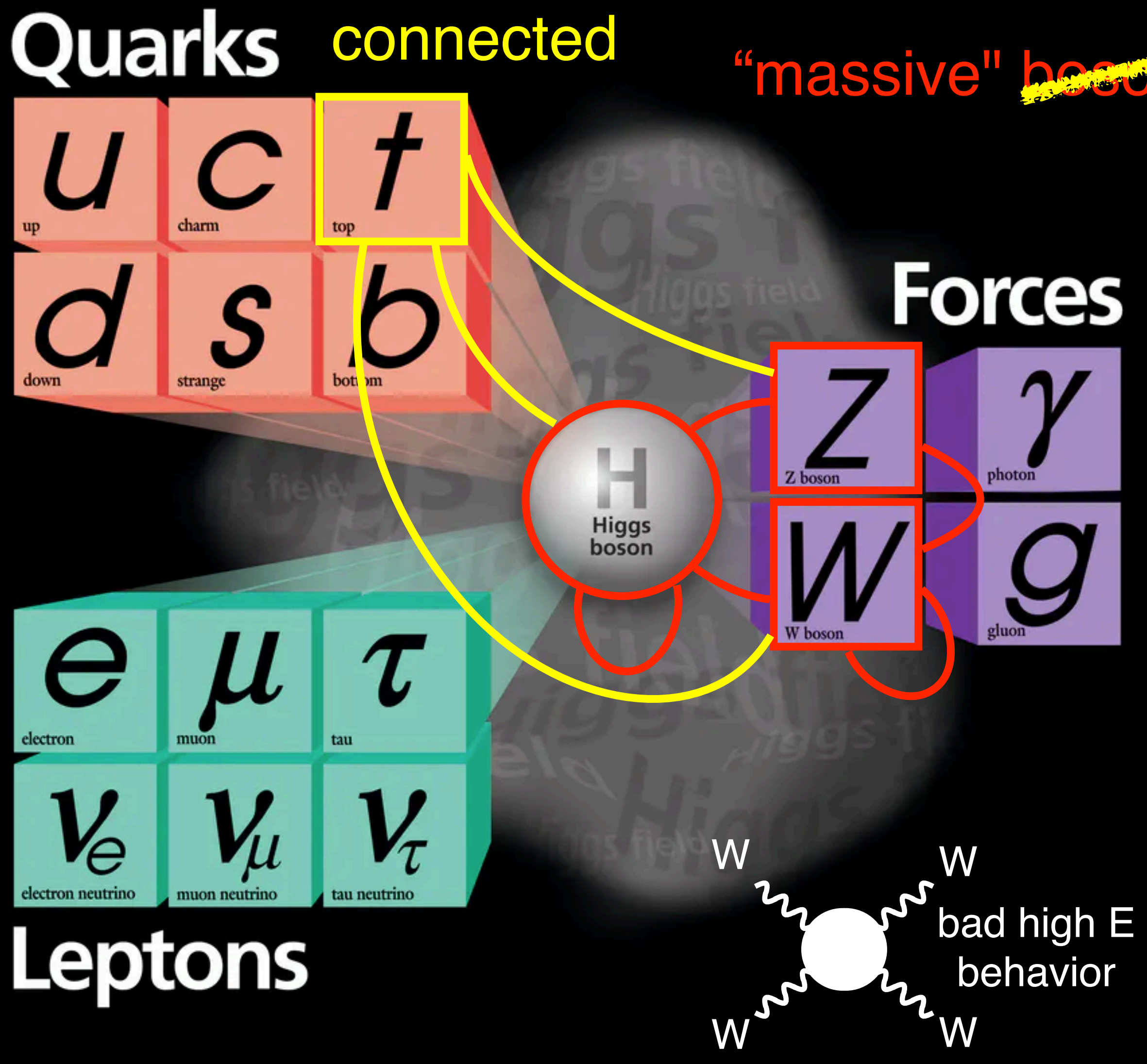
Many more to be studied on electroweak sector at the LHC

More work to be done in electroweak sector



Top is also connected

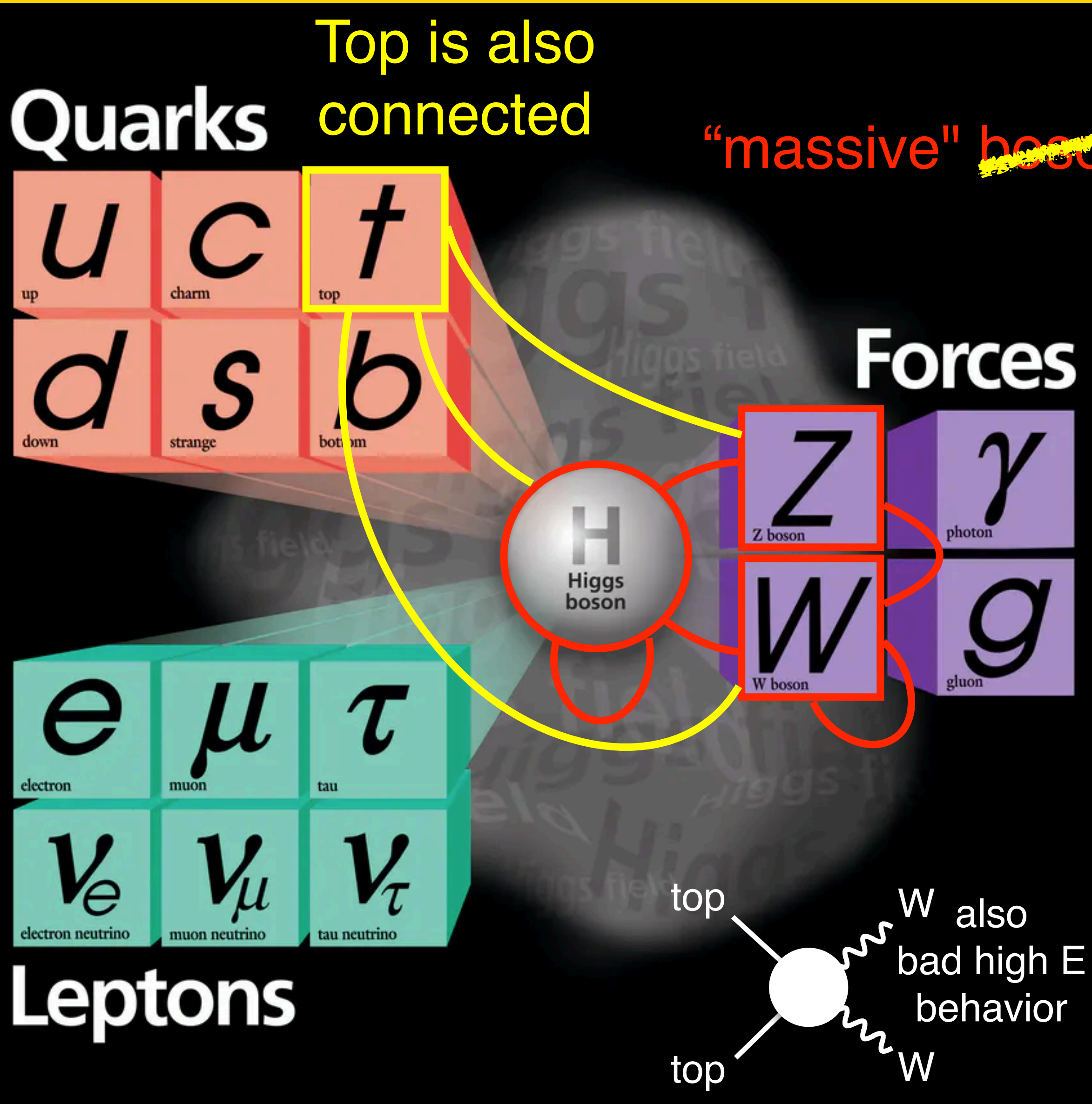
“massive" ~~bosons~~ -X

bad high E behavior

- 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

More work to be done in electroweak sector



Top is also connected

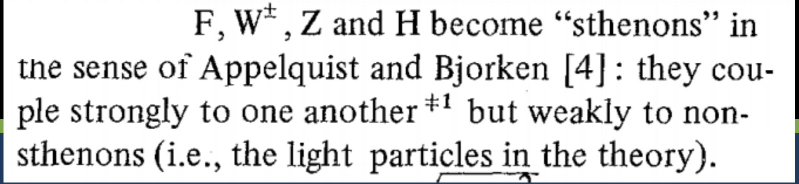
“massive" ~~bosons~~ -X

W also bad high E behavior

- 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?

1978 (way) before top/W/Z/Higgs discovery

Chanowitz, Furman, Hinchliffe

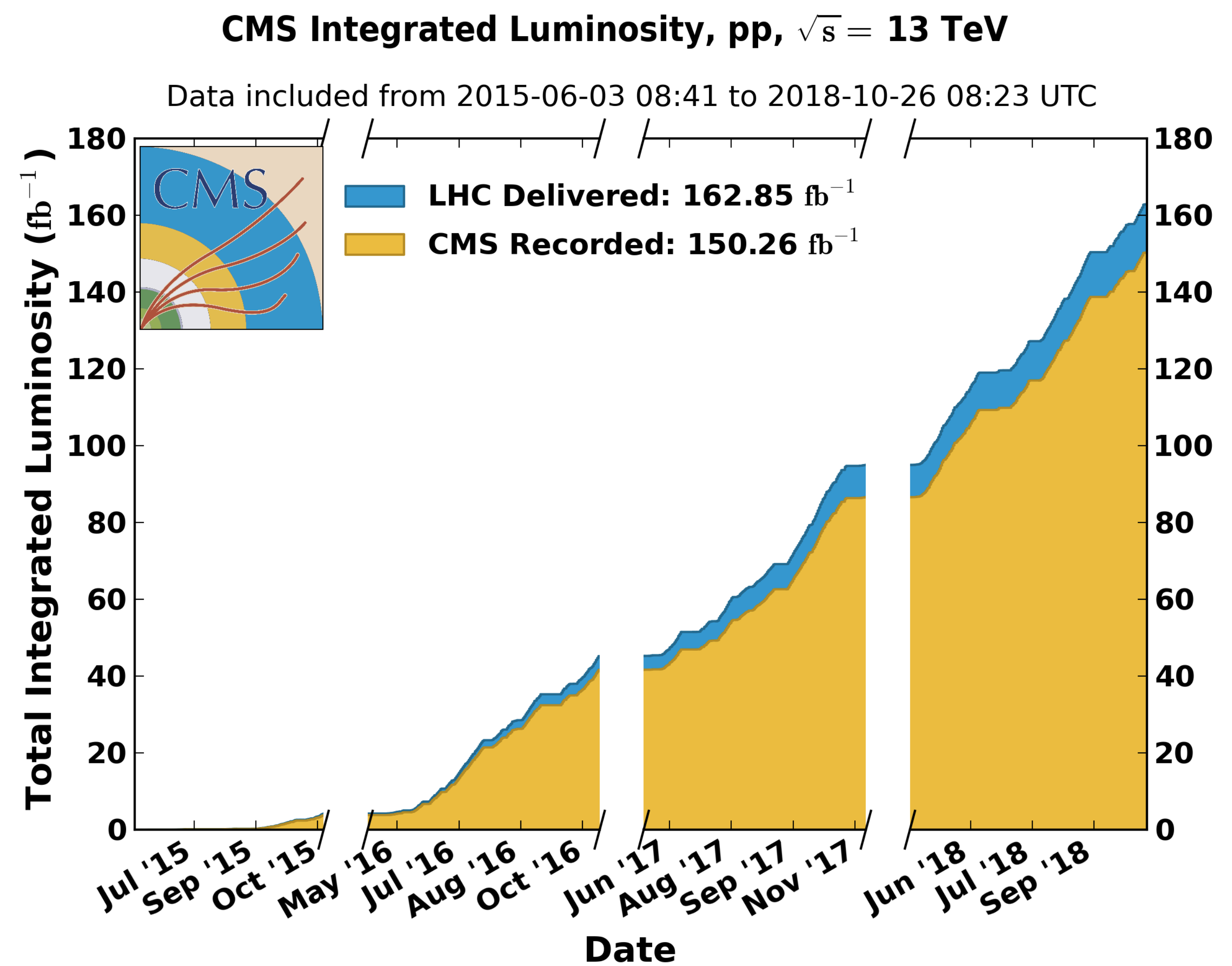


F, $W^\pm$, Z and H become “sthenons” in the sense of Appelquist and Bjorken [4]: they couple strongly to one another[‡1] but weakly to non-sthenons (i.e., the light particles in the theory).

Many more to be studied on electroweak sector at the LHC

We need LHC's large and energetic pp collision data

because rare because "heavy"



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

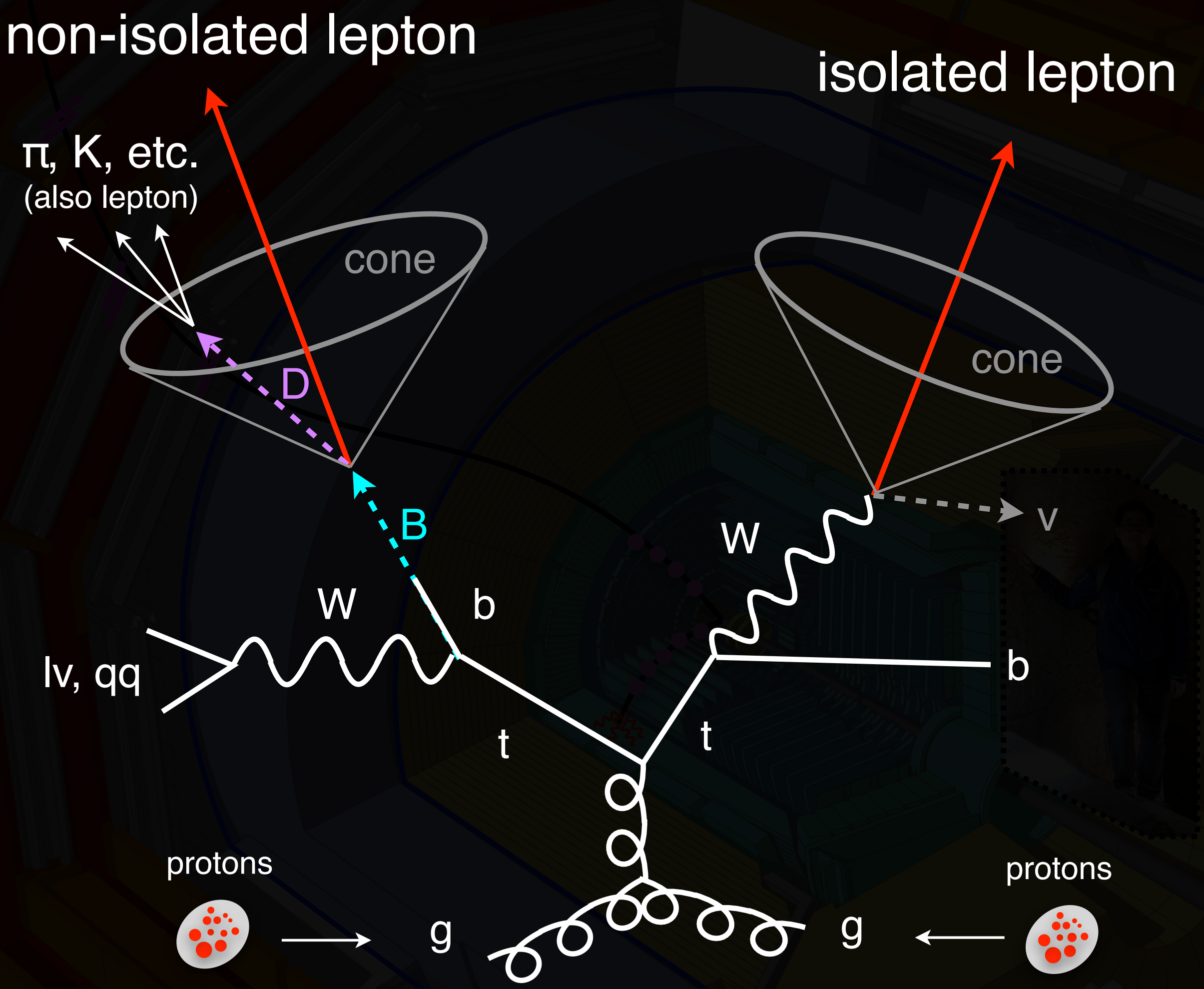
Classifying leptons' origins

Identifying leptons is not enough

We need to further classify the origin

$$\text{Isolation} = \frac{\Sigma_{\text{“stuff” in cone}} P_T}{P_{T,\text{Lepton}}}$$

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

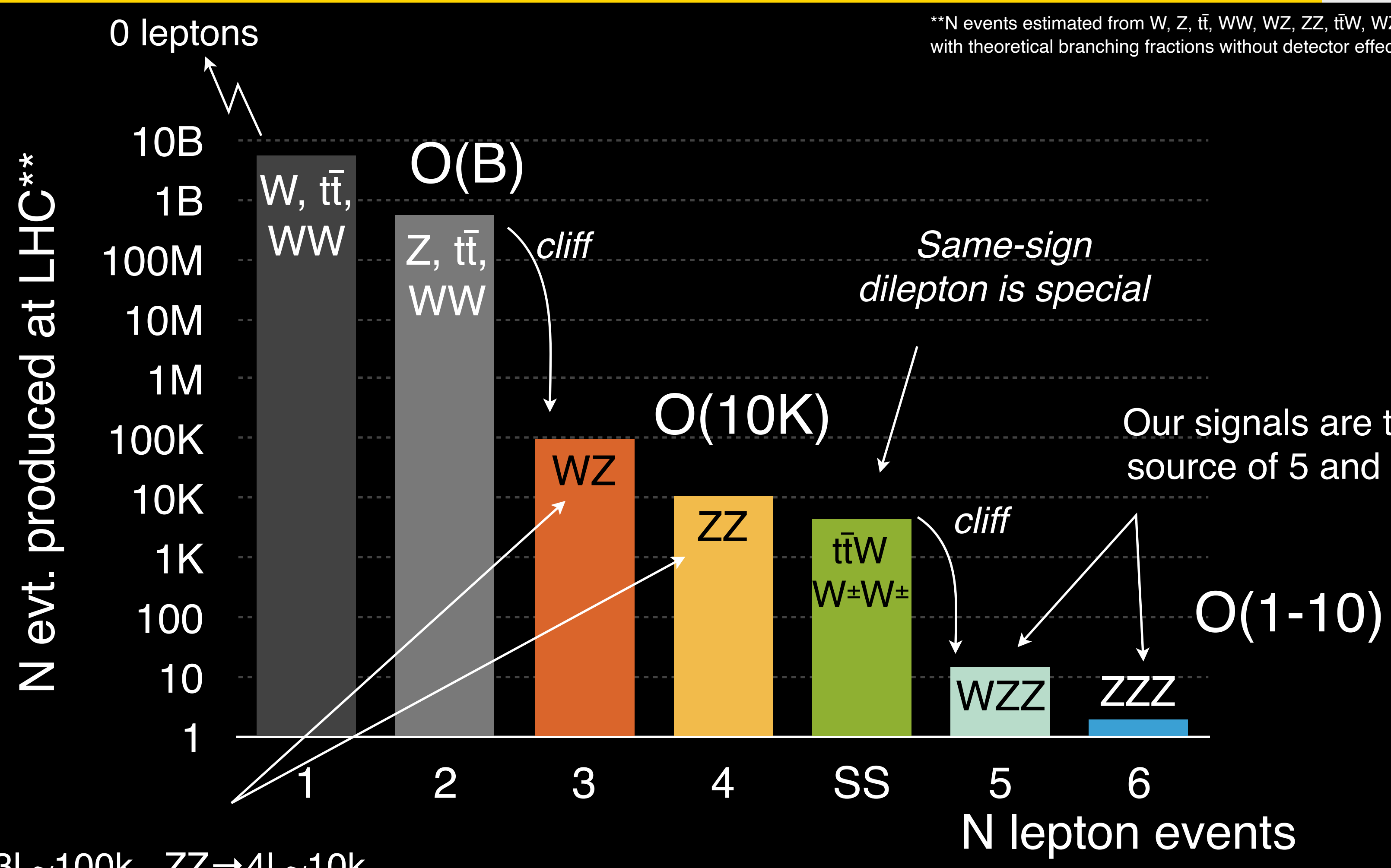


Use isolation to discriminate against leptons from heavy flavor decay

Dubbed “fake lepton”

Lepton physics at the LHC

**N events estimated from W, Z, tt̄, WW, WZ, ZZ, tt̄W, WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring τ → e, μ



Our signals are the largest source of 5 and 6 leptons!

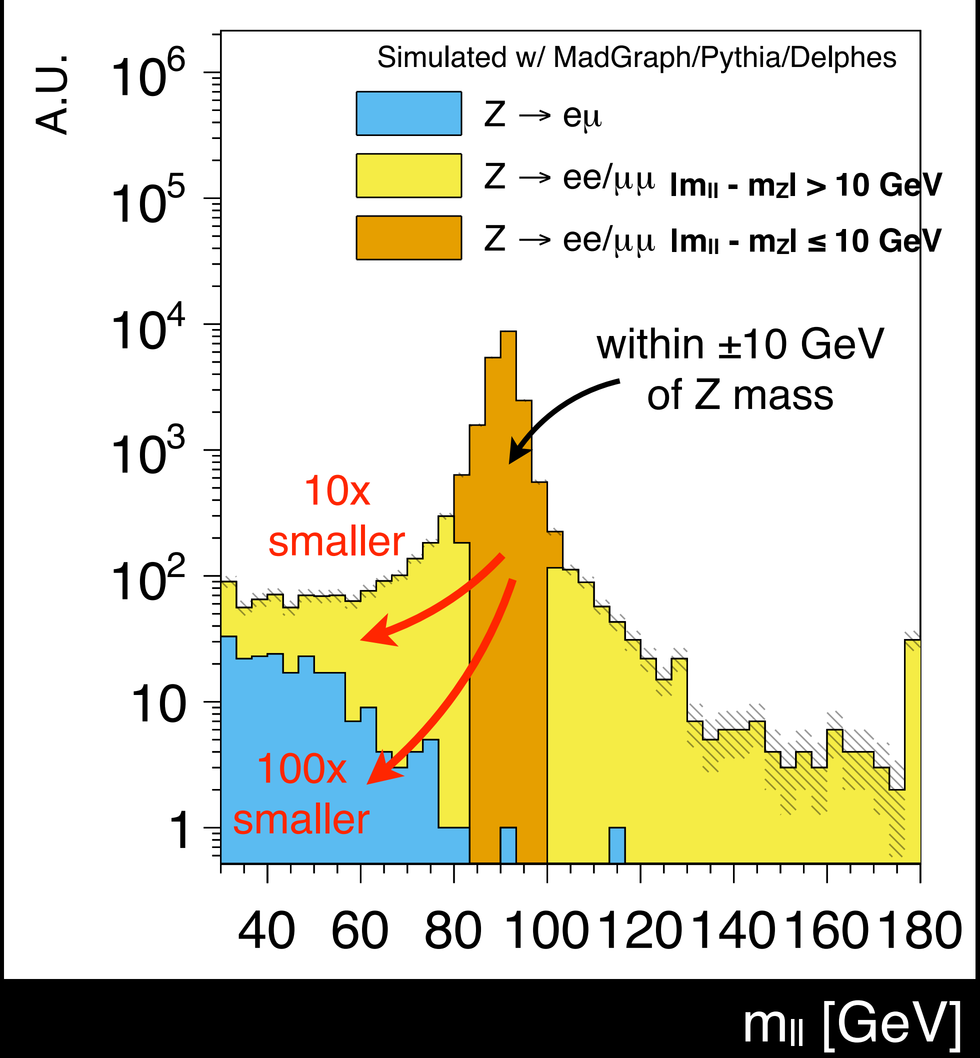
N.B. WZ→3l ~100k, ZZ→4l ~10k

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

Useful to organize physics analyses by N leptons

Exploiting Z → ll features

dilepton invariant mass of Z → 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

If one selects eμ final state, *Z* is reduced by 2 orders of magnitude
(e, μ from τ are soft)

⇒ *ZZ* suppressed in 4 leptons: ee/$\mu\mu$ + eμ
WZ suppressed in $e^{\pm}\mu^{\mp}e^{\pm}$
↑
0 “SFOS”
(Zero same-flavor opposite sign pair)

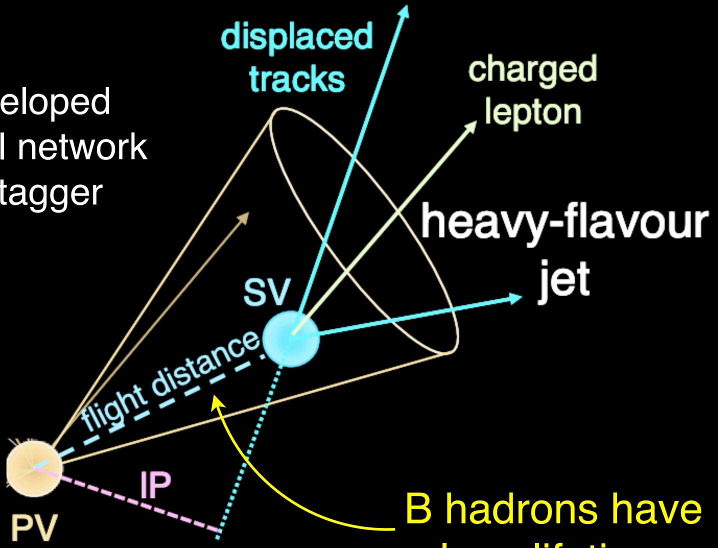
i.e. “ee” or “$\mu\mu$”

Z decays predominantly to ee/$\mu\mu$ ⇒ select away from *Z* → ee/$\mu\mu$

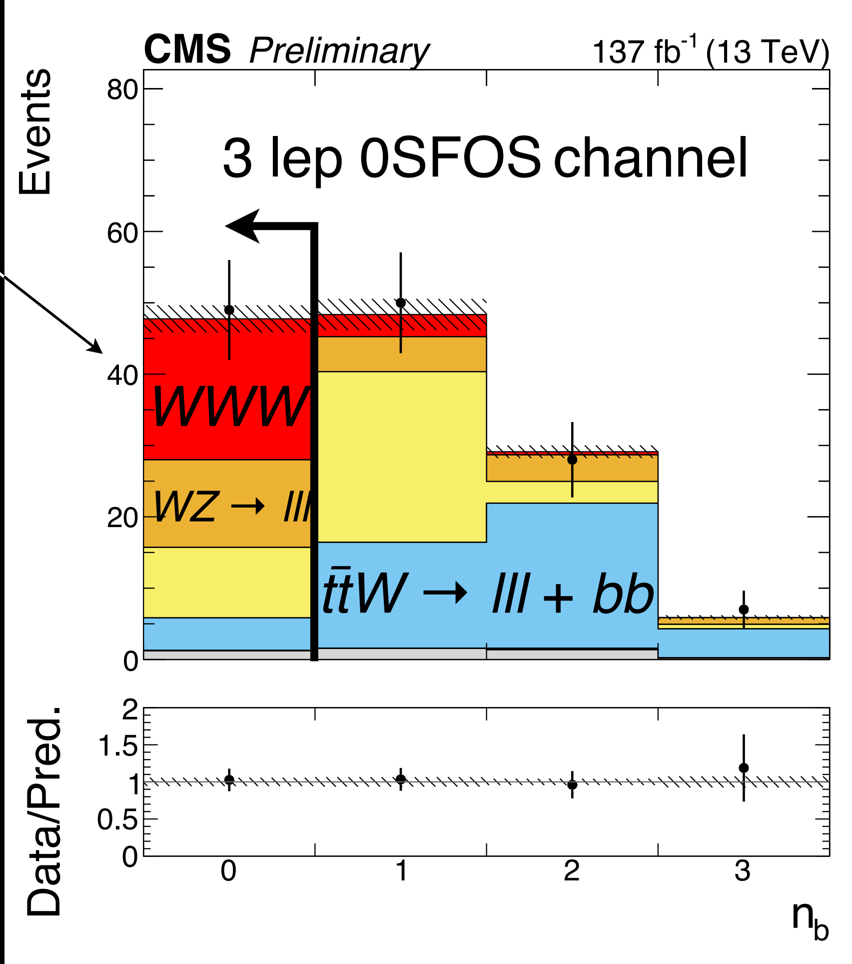
Rejecting events with *b* jets

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

CMS developed deep neural network based *b* tagger



B hadrons have long lifetime



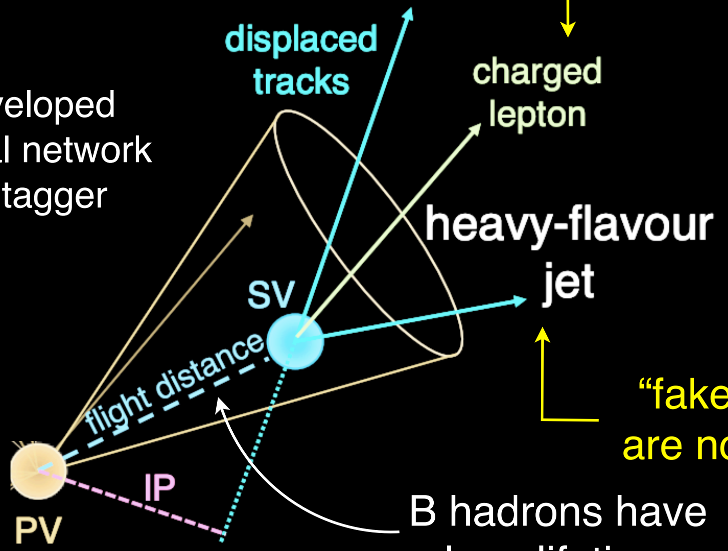
Signals do not have *b* jets

Added benefit of rejecting events with b

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

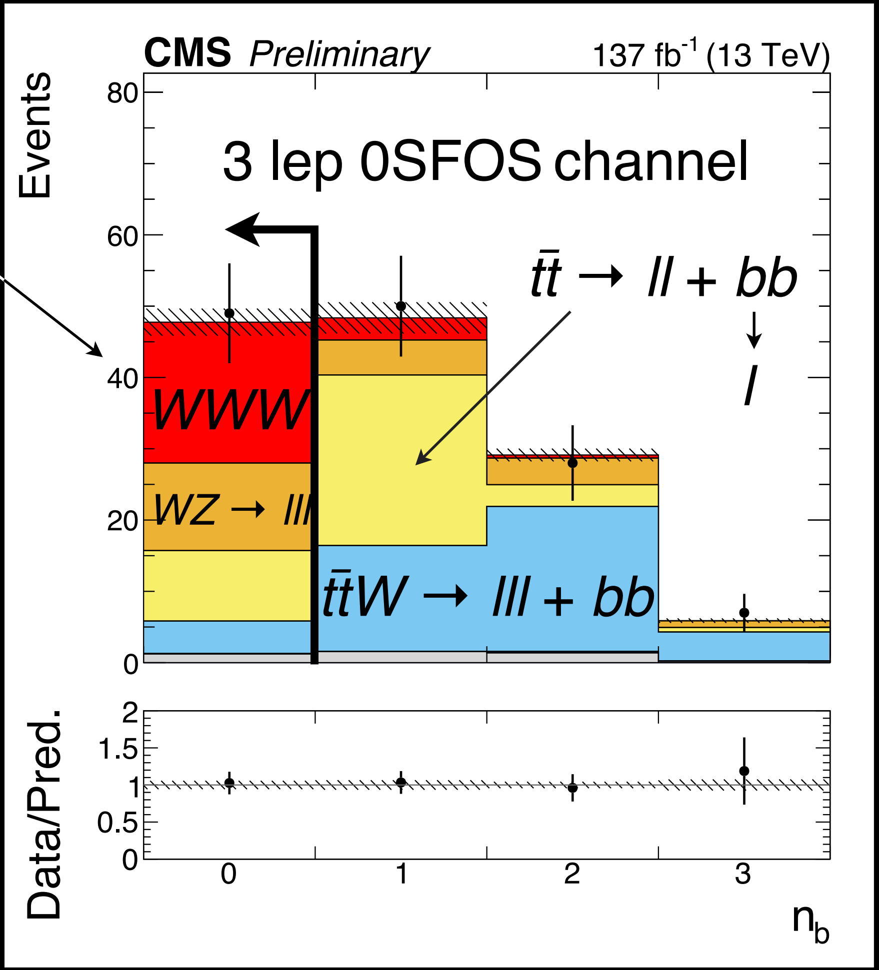
Lepton from b decay is the main source of “fake"

CMS developed deep neural network based *b* tagger



“fake" leptons are not isolated

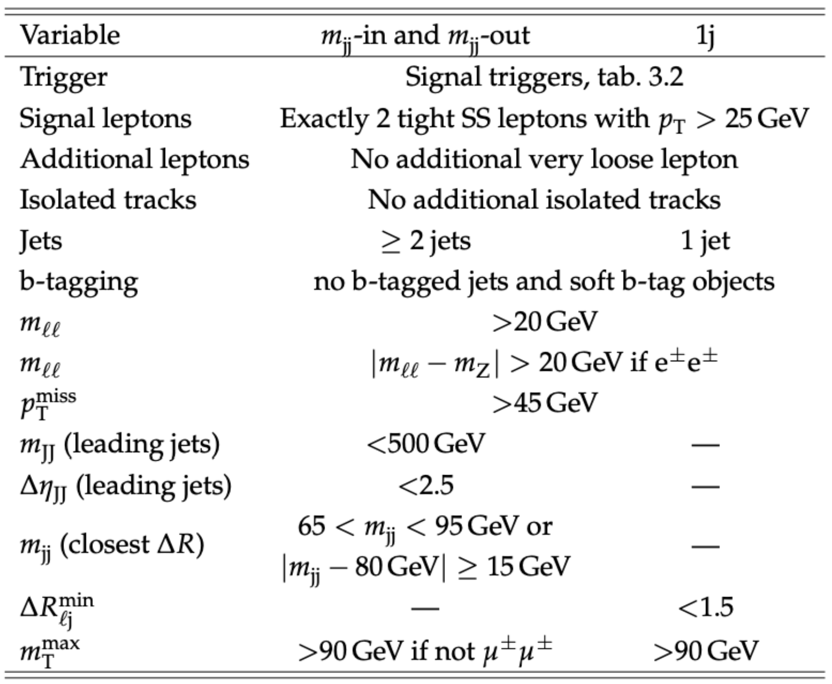
B hadrons have long lifetime



Signals do not have *b* jets

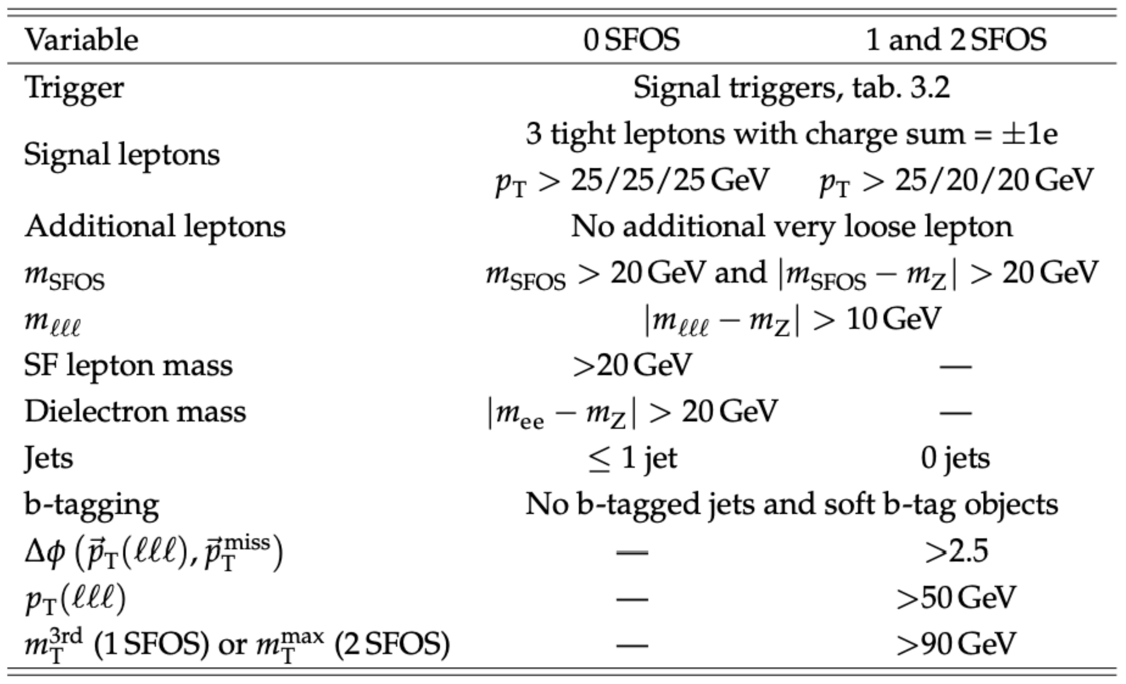
Event selections

same-sign selection



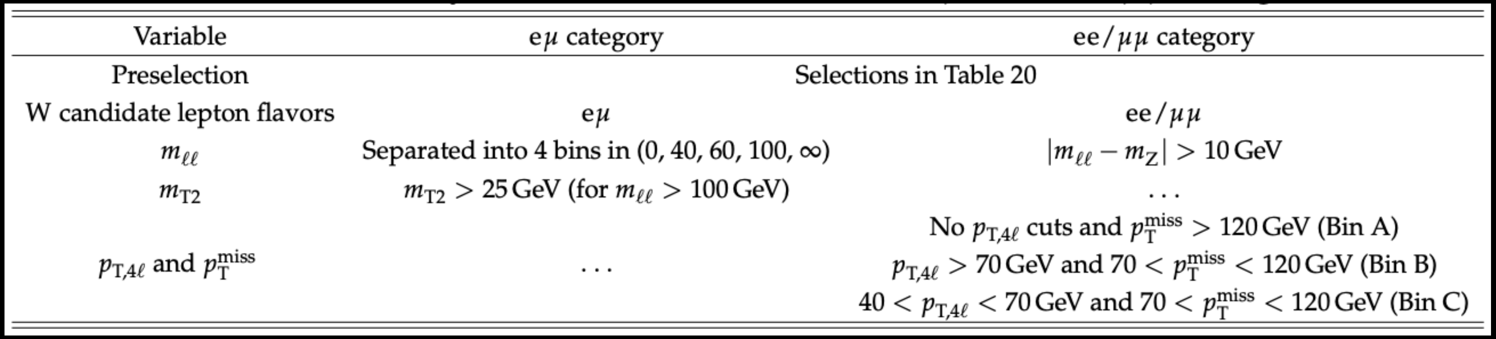
Variable	m_{jj}-in and m_{jj}-out	1j
Trigger	Signal triggers, tab. 3.2	
Signal leptons	Exactly 2 tight SS leptons with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$	
Additional leptons	No additional very loose lepton	
Isolated tracks	No additional isolated tracks	
Jets	≥ 2 jets	1 jet
b-tagging	no b-tagged jets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

Three leptons selection



Variable	0 SFOS	1 and 2 SFOS
Trigger	Signal triggers, tab. 3.2	
Signal leptons	3 tight leptons with charge sum = ± 1e $p_{\mathrm{T}} > 25/25/25\,\mathrm{GeV}$	$p_{\mathrm{T}} > 25/20/20\,\mathrm{GeV}$
Additional leptons	No additional very loose lepton	
m_{SFOS}	$m_{\mathrm{SFOS}} > 20\,\mathrm{GeV}$ and $\lvert m_{\mathrm{SFOS}} - m_{\mathrm{Z}} \rvert > 20\,\mathrm{GeV}$	
$m_{\ell\ell\ell}$	$\lvert m_{\ell\ell\ell} - m_{\mathrm{Z}} \rvert > 10\,\mathrm{GeV}$	
SF lepton mass	$>20\,\mathrm{GeV}$	—
Dielectron mass	$\lvert m_{\mathrm{ee}} - m_{\mathrm{Z}} \rvert > 20\,\mathrm{GeV}$	—
Jets	≤ 1 jet	0 jets
b-tagging	No b-tagged jets and soft b-tag objects	
$\Delta\phi\left(\vec{p}_{\mathrm{T}}(\ell\ell\ell), \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$	—	>2.5
$p_{\mathrm{T}}(\ell\ell\ell)$	—	$>50\,\mathrm{GeV}$
$m_{\mathrm{T}}^{\mathrm{3rd}}$ (1 SFOS) or $m_{\mathrm{T}}^{\mathrm{max}}$ (2 SFOS)	—	$>90\,\mathrm{GeV}$

Four leptons selection



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

5/6L will be explained later

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

Lost lepton background

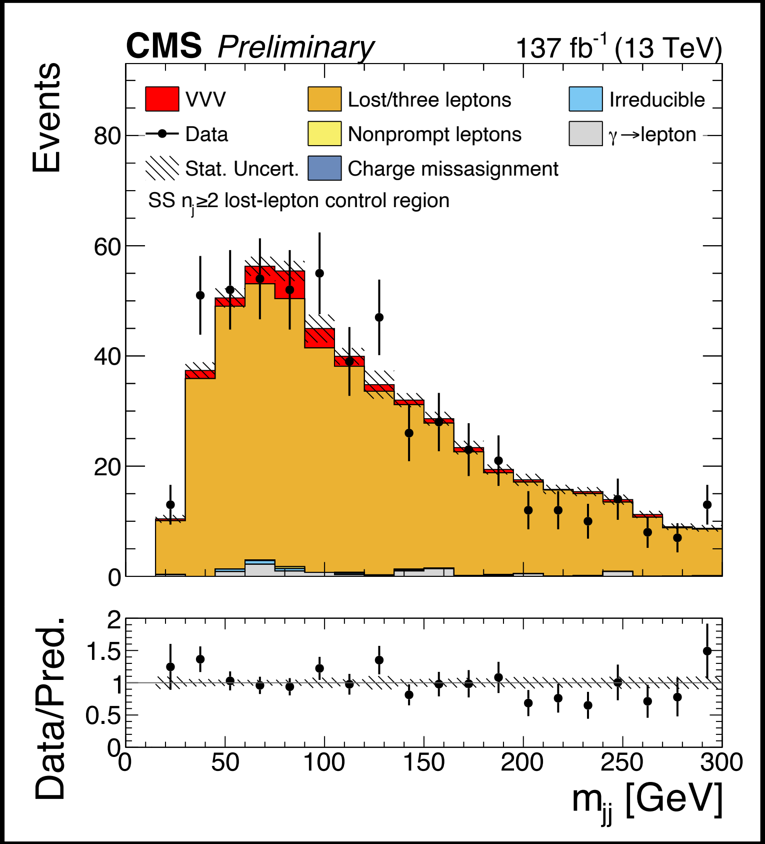
Lepton finding efficiency is well modeled by MC

(factors: P_T, η, lepton ID)

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

Experimental systematics assigned

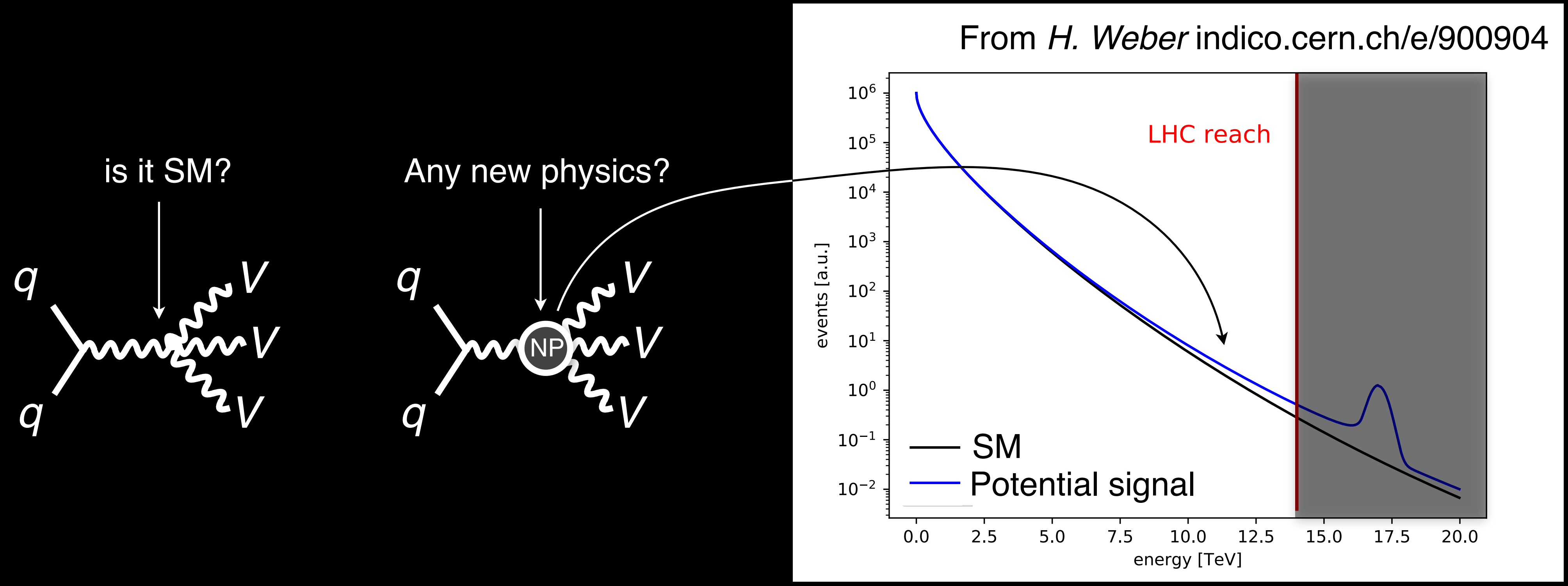
Control region data statistics dominates uncertainty (20%)



Estimate lost lepton background by extrapolating across # of leptons

Using VVV as a tool

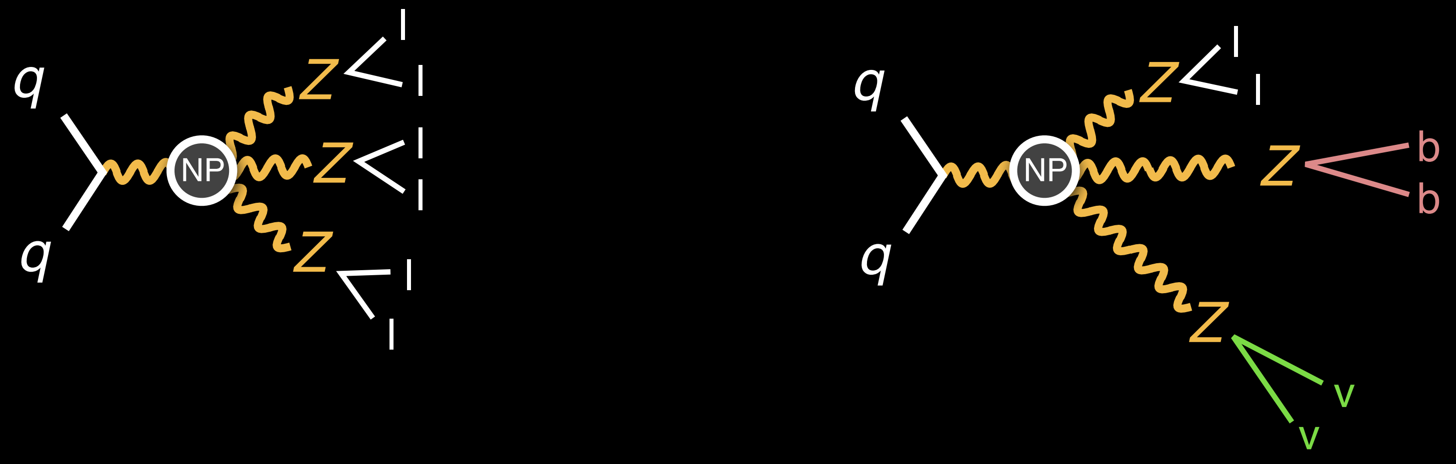
Now that we have established VVV production we can use it to test SM and also search new physics (cf. Four fermion interaction with Fermi constant)



From *H. Weber* indico.cern.ch/e/900904

Establishment of VVV production opens up a new physics program

Fully leptonic v. Semi leptonic channel



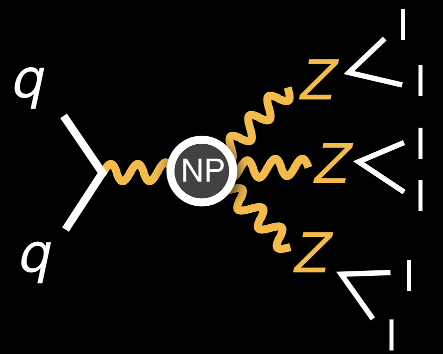
If BSM exists, effects are same

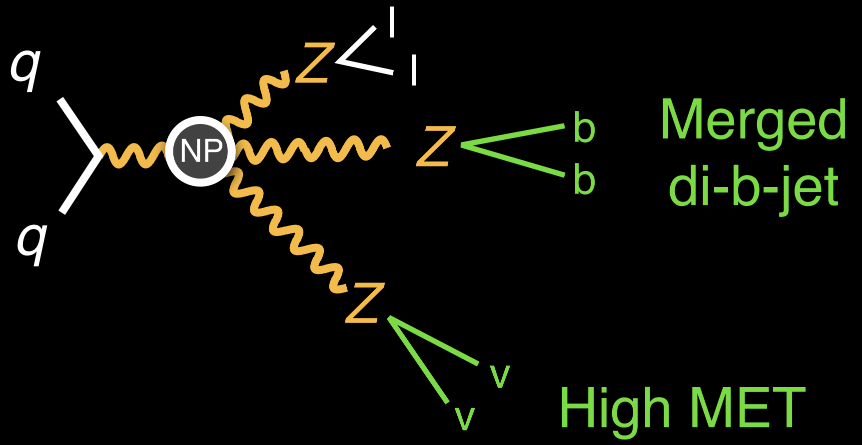
- Physics of V → ff is well understood
- We have now established pp → VVV production in "fully" leptonic decay
- Therefore, there ought to be pp → VVV → semi-leptonic

⇒ If new physics alters pp → VVV, it will alter fully / semi leptonic the same

VVV → semi-leptonic ought to have same physics as VVV → fully leptonic

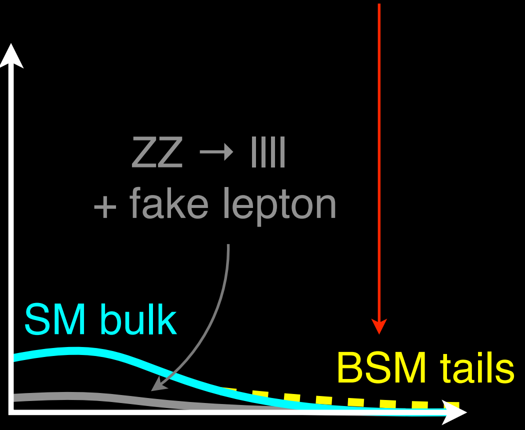
Fully leptonic v. Semi leptonic channel

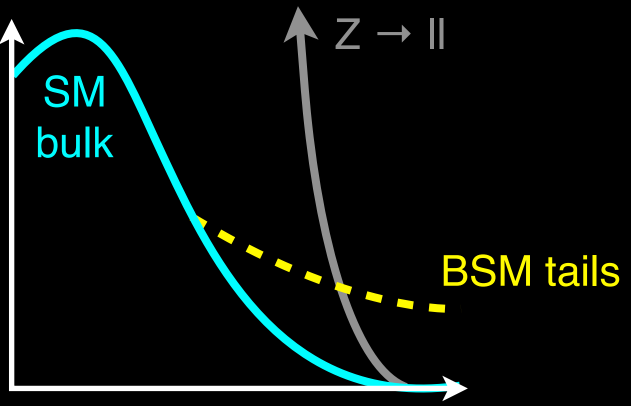




Clean channel for
discovery but
probing tail is difficult

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





We can probe VVV → semi-leptonic for new physics

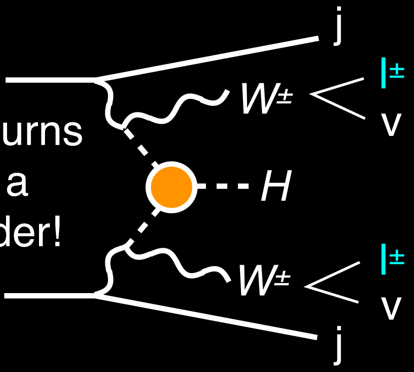
More multi-massive-X processes for future

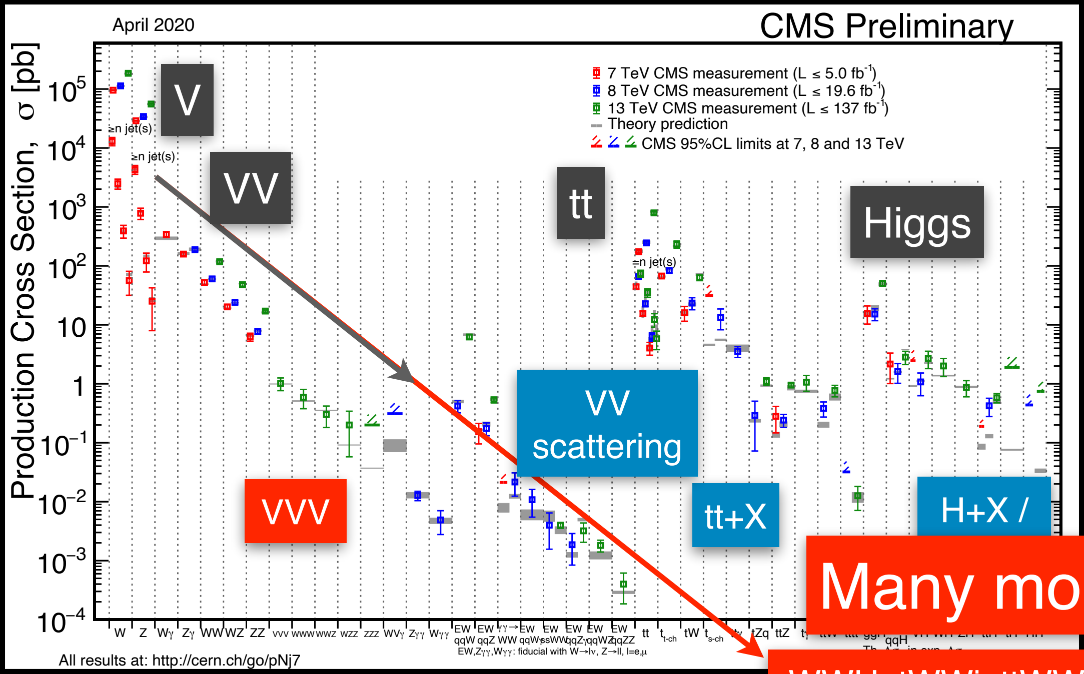
listing a few multi-massive-X processes with same-sign

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

Same-sign is special

Same-sign turns LHC into a Higgs collider!

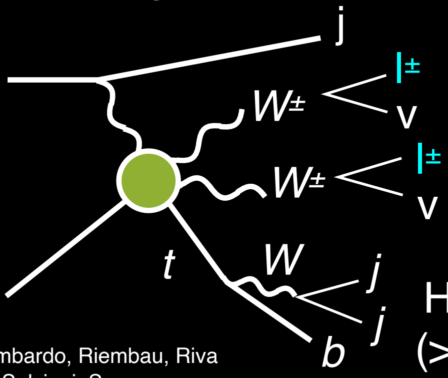




Many more

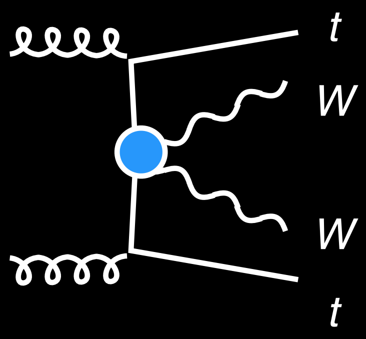
WWH, tWWj. ttWW, ttZH

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

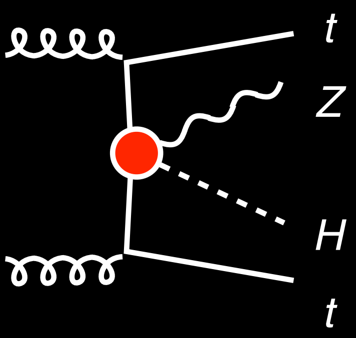


High P_T top (> 500 GeV)

$pp \rightarrow ttWW$



$pp \rightarrow ttZH$

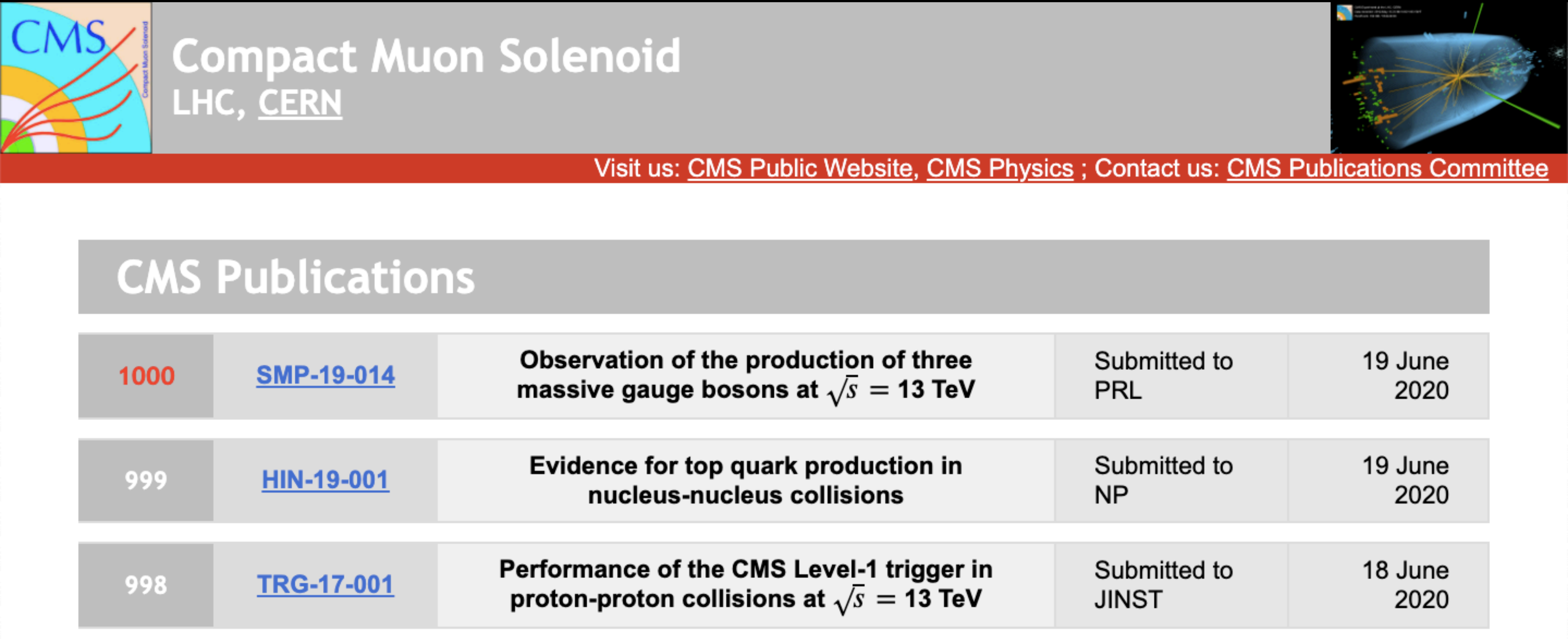


arXiv:1812.09299 Henning, Lombardo, Riembau, Riva
arXiv:1511.03674 Dror, Farina, Salvioni, Serra
arXiv:1904.05637 Maltoni, Mantani, Mimasu

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

Title

Chang
UCSD



Compact Muon Solenoid

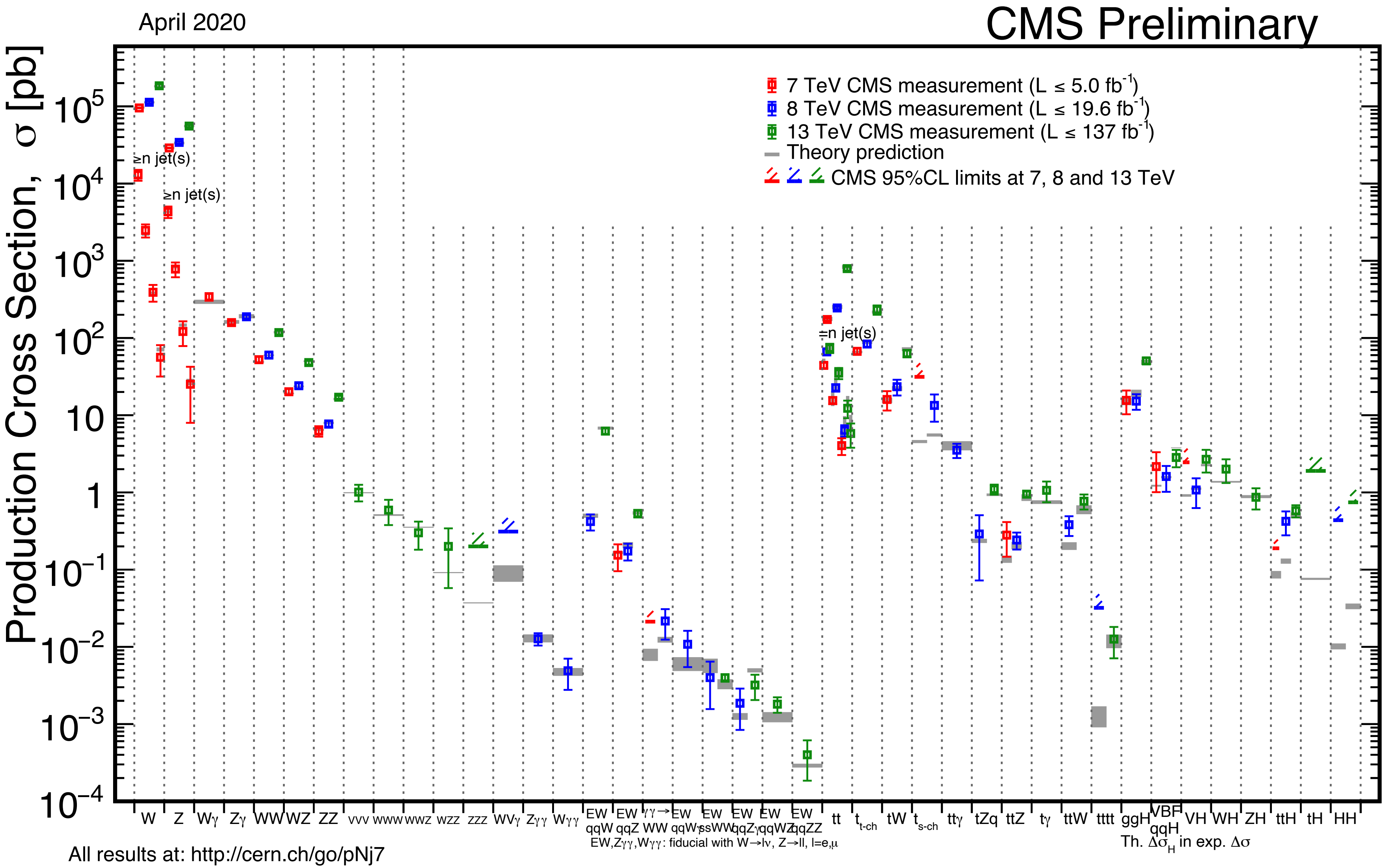
LHC, CERN

Visit us: CMS Public Website, CMS Physics ; Contact us: CMS Publications Committee

CMS Publications

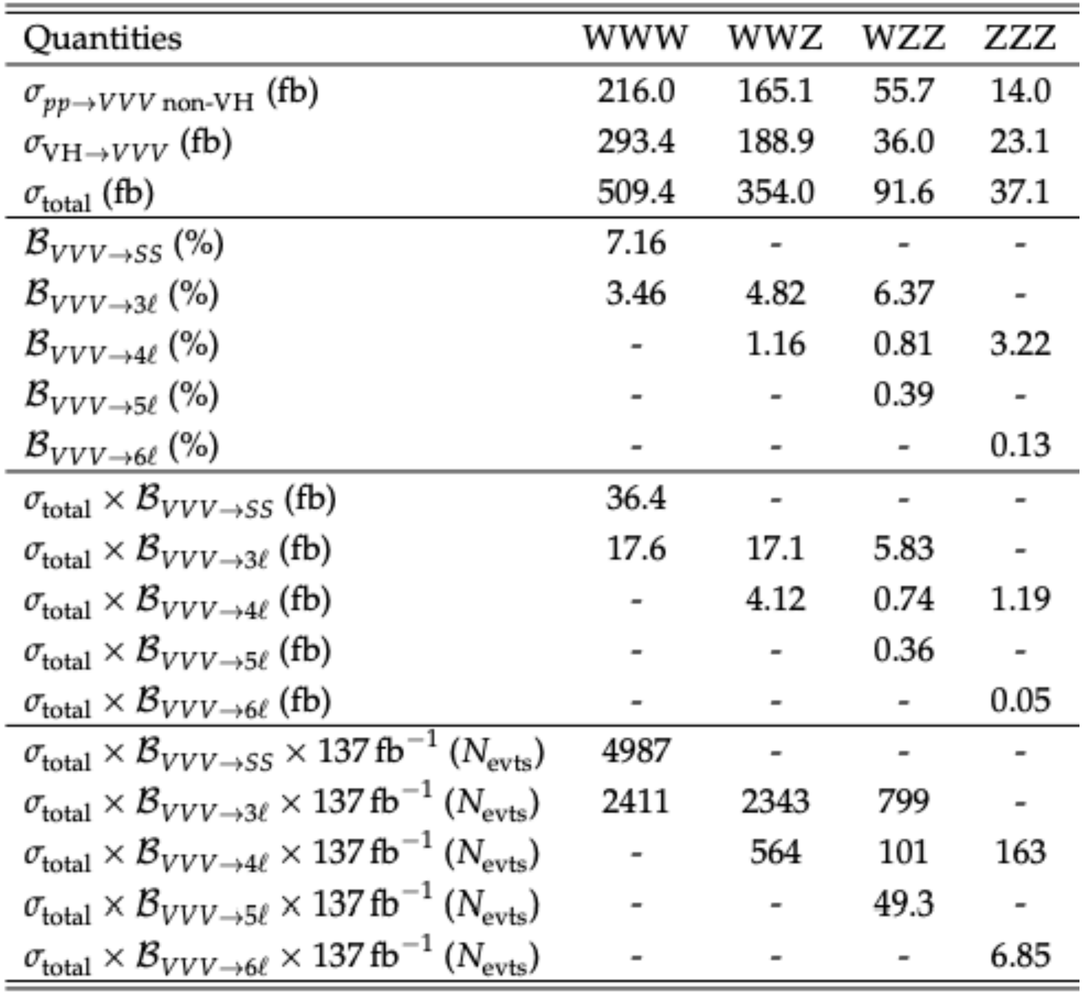
1000	SMP-19-014	**Observation of the production of three massive gauge bosons at $\sqrt{s} = 13$ TeV**	Submitted to PRL	19 June 2020
999	HIN-19-001	**Evidence for top quark production in nucleus-nucleus collisions**	Submitted to NP	19 June 2020
998	TRG-17-001	**Performance of the CMS Level-1 trigger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

Title



All results at: http://cern.ch/go/pNj7

Title

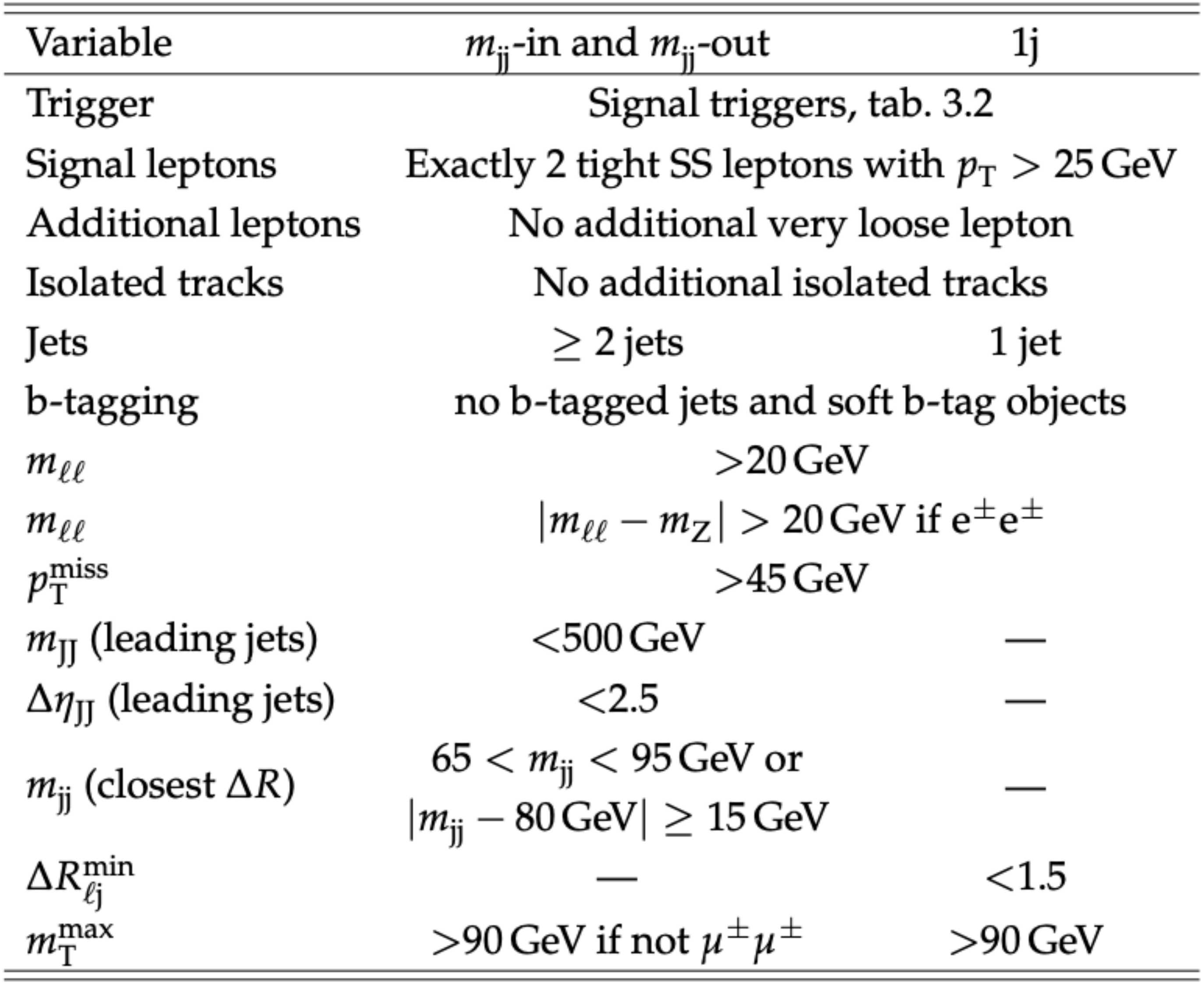


Quantities	WWW	WWZ	WZZ	ZZZ
$\sigma_{pp\to VVV\text{ non-VH}}$ (fb)	216.0	165.1	55.7	14.0
$\sigma_{\text{VH}\to VVV}$ (fb)	293.4	188.9	36.0	23.1
σ_{total} (fb)	509.4	354.0	91.6	37.1
$\mathcal{B}_{VVV\to SS}$ (%)	7.16	-	-	-
$\mathcal{B}_{VVV\to 3\ell}$ (%)	3.46	4.82	6.37	-
$\mathcal{B}_{VVV\to 4\ell}$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

SS / 3L preselection

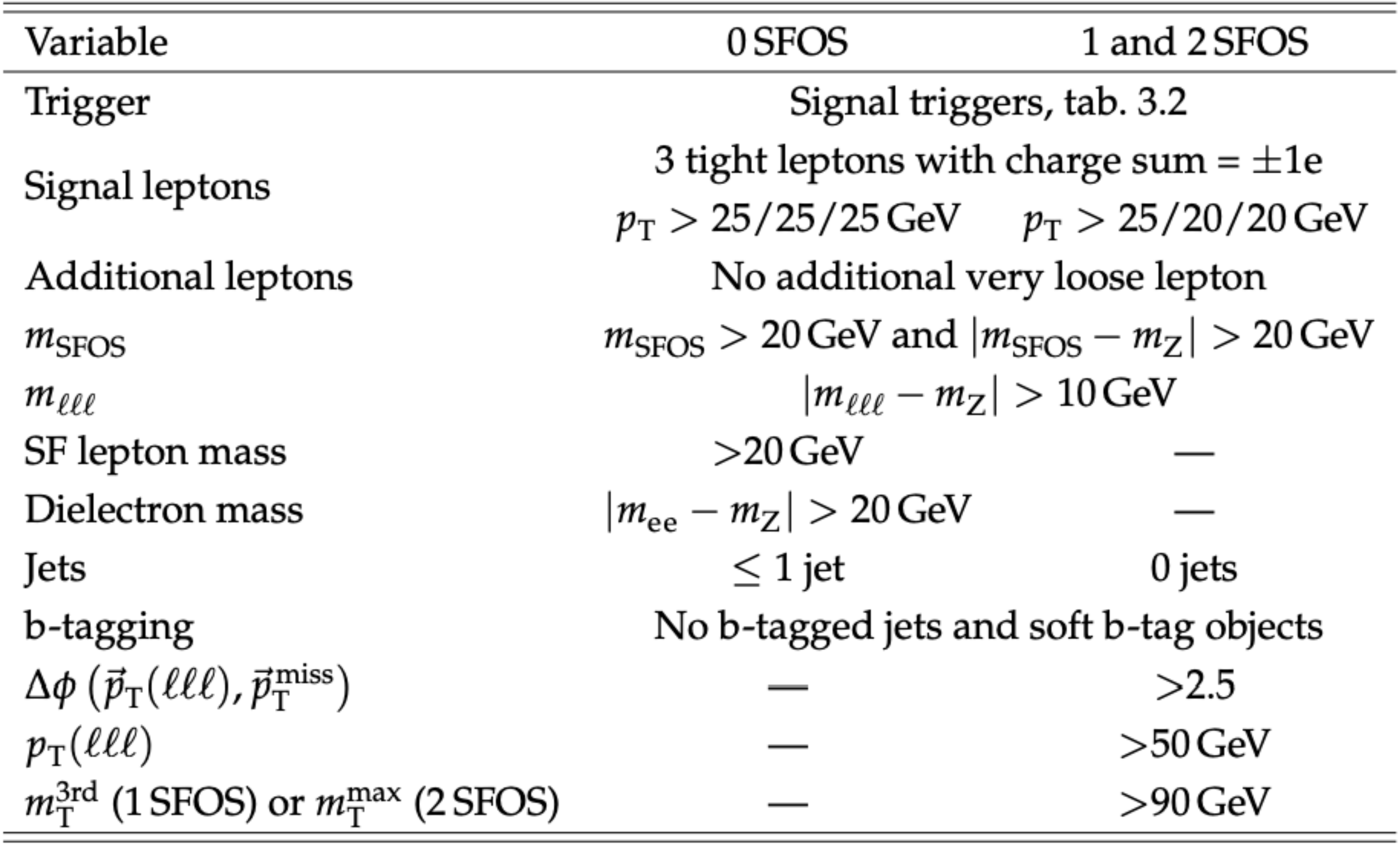
Features	Selections		
	SS + $\geq$2j	SS + 1j	3ℓ
Triggers	Select events passing dilepton triggers		
Number of leptons	Select events with 2 (3) leptons passing SS-ID (3ℓ-ID) for SS (3ℓ) final states		
Number of leptons	Select events with 2 (3) leptons passing veto-ID for SS (3ℓ) final states		
Isolated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

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 $p_T > 25\,\mathrm{GeV}$	
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	
$m_{\ell\ell}$	$>20\,\mathrm{GeV}$	
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert > 20\,\mathrm{GeV}$ if $e^{\pm}e^{\pm}$	
p_T^{miss}	$>45\,\mathrm{GeV}$	
m_{JJ} (leading jets)	$<500\,\mathrm{GeV}$	—
$\Delta\eta_{JJ}$ (leading jets)	<2.5	—
m_{jj} (closest ΔR)	$65 < m_{jj} < 95\,\mathrm{GeV}$ or $\lvert m_{jj} - 80\,\mathrm{GeV} \rvert \geq 15\,\mathrm{GeV}$	—
$\Delta R_{\ell j}^{min}$	—	<1.5
m_T^{max}	$>90\,\mathrm{GeV}$ if not $\mu^{\pm}\mu^{\pm}$	$>90\,\mathrm{GeV}$

3L selection

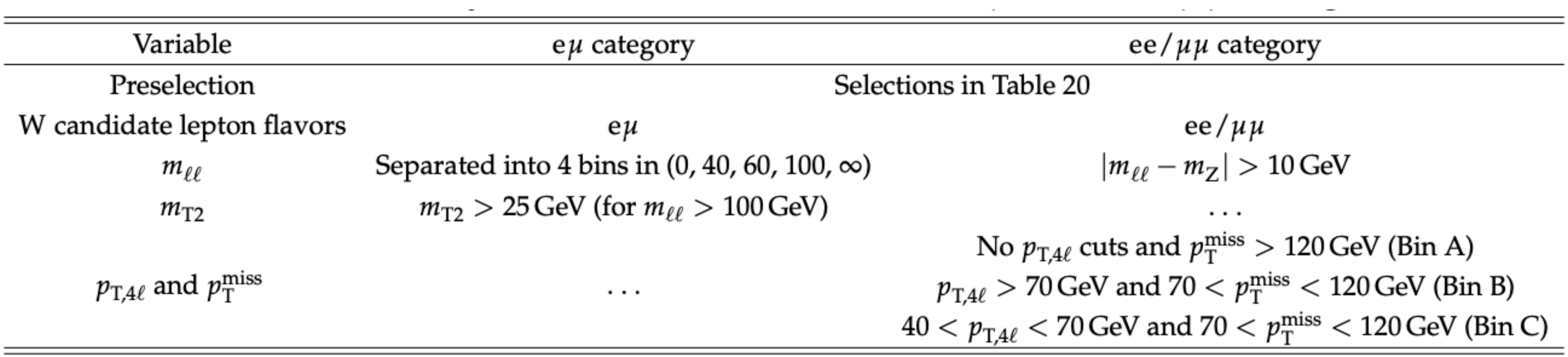


Variable	0 SFOS	1 and 2 SFOS
Trigger	Signal triggers, tab. 3.2	
Signal leptons	3 tight leptons with charge sum = ±1e $p_{\mathrm{T}} > 25/25/25$ GeV	$p_{\mathrm{T}} > 25/20/20$ GeV
Additional leptons	No additional very loose lepton	
m_{SFOS}	$m_{\mathrm{SFOS}} > 20$ GeV and $\lvert m_{\mathrm{SFOS}} - m_{\mathrm{Z}} \rvert > 20$ GeV	
$m_{\ell\ell\ell}$	$\lvert m_{\ell\ell\ell} - m_{\mathrm{Z}} \rvert > 10$ GeV	
SF lepton mass	>20 GeV	—
Dielectron mass	$\lvert m_{\mathrm{ee}} - m_{\mathrm{Z}} \rvert > 20$ GeV	—
Jets	≤ 1 jet	0 jets
b-tagging	No b-tagged jets and soft b-tag objects	
$\Delta\phi\left(\vec{p}_{\mathrm{T}}(\ell\ell\ell), \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$	—	>2.5
$p_{\mathrm{T}}(\ell\ell\ell)$	—	>50 GeV
$m_{\mathrm{T}}^{\mathrm{3rd}}$ (1 SFOS) or $m_{\mathrm{T}}^{\mathrm{max}}$ (2 SFOS)	—	>90 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

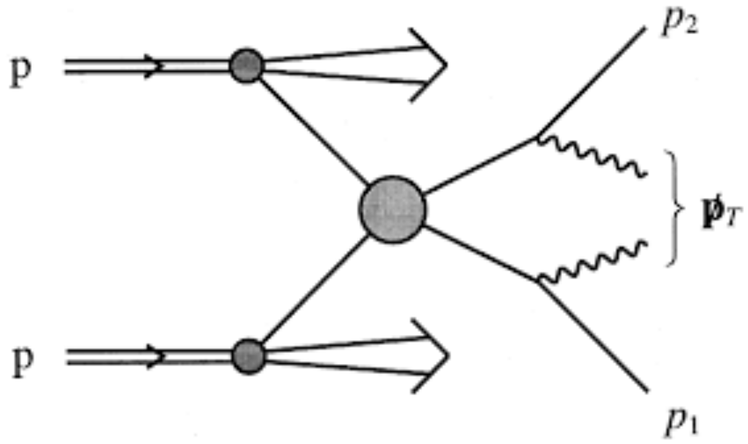
4L selection



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 $(0, 40, 60, 100, \infty)$	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\text{GeV}$
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}

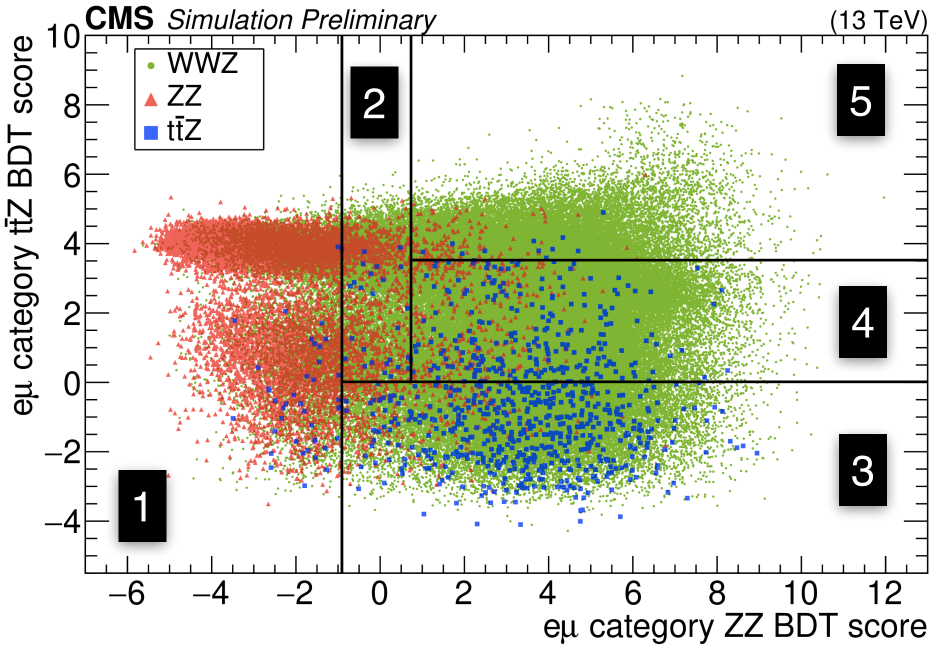
$$m_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\nu(1)} + \vec{p}_{\mathrm{T}}^{\nu(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max\left(m_{\mathrm{T}}^{(1)}(\vec{p}_{\mathrm{T}}^{\nu(1)}, \vec{p}_{\mathrm{T}}^{\mathrm{e}}), m_{\mathrm{T}}^{(2)}(\vec{p}_{\mathrm{T}}^{\nu(2)}, \vec{p}_{\mathrm{T}}^{\mu})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



For WW→ lvlv sub-system of WWZ, endpoint is at m_W

For Z→ττ→llvvvv sub-system of ZZ, endpoint is at $m_τ$

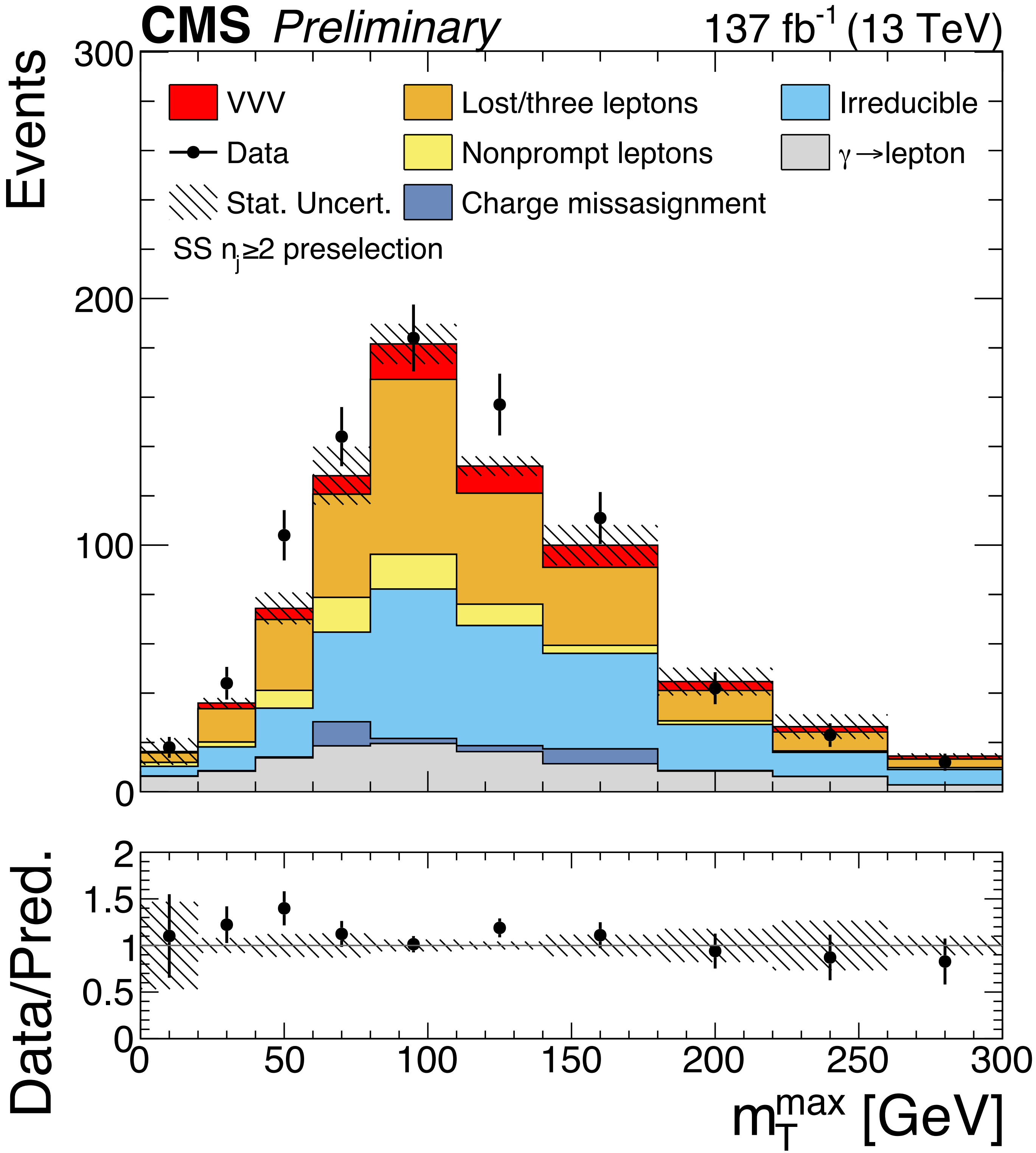
Title



	ZZ BDT range	$t\bar{t}Z$ 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/$\mu\mu$ BDT bin A	(0 , 3)	-
ee/$\mu\mu$ BDT bin B	(3 , ∞)	-

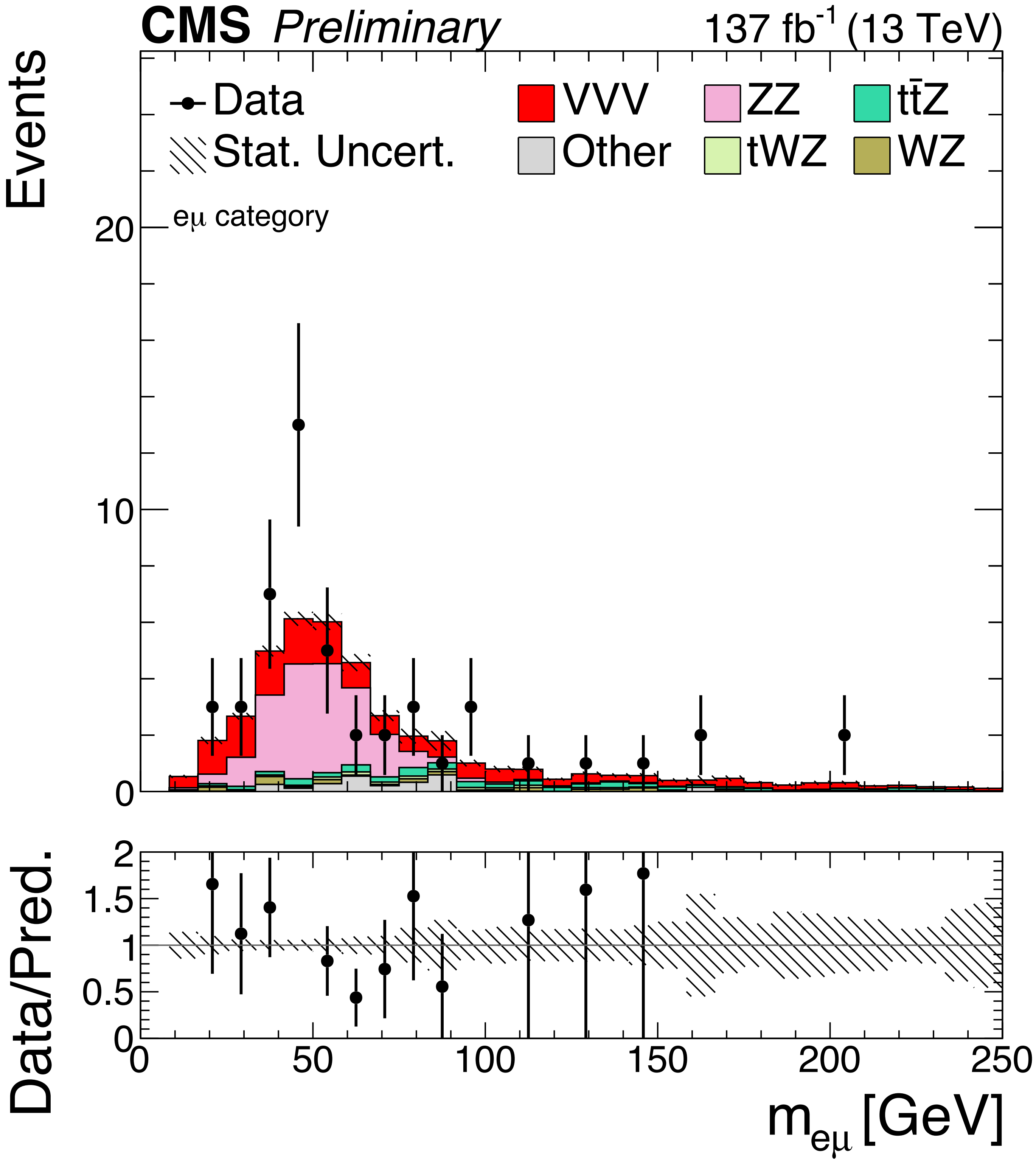
Title

Chang
UCSD

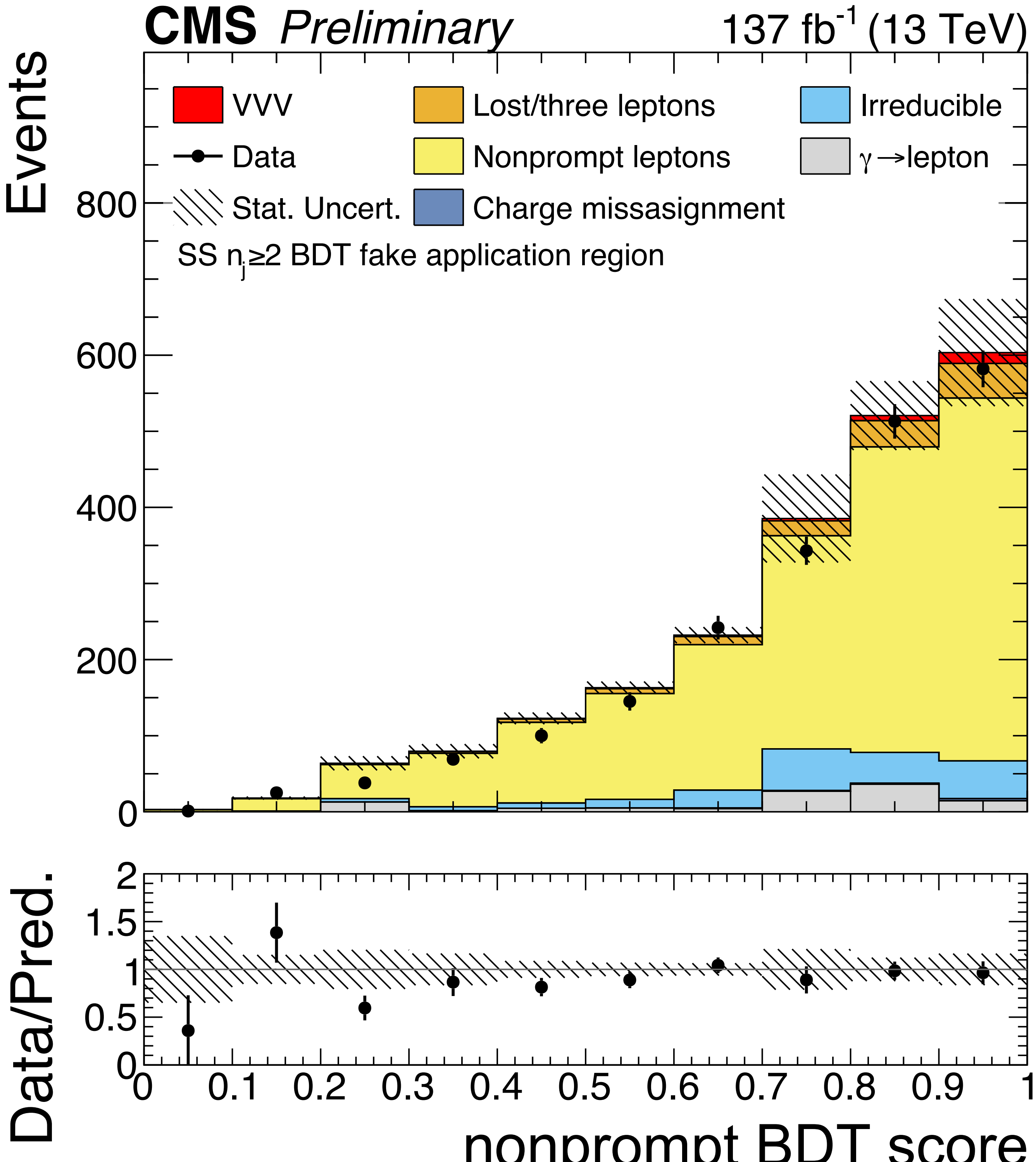


Title

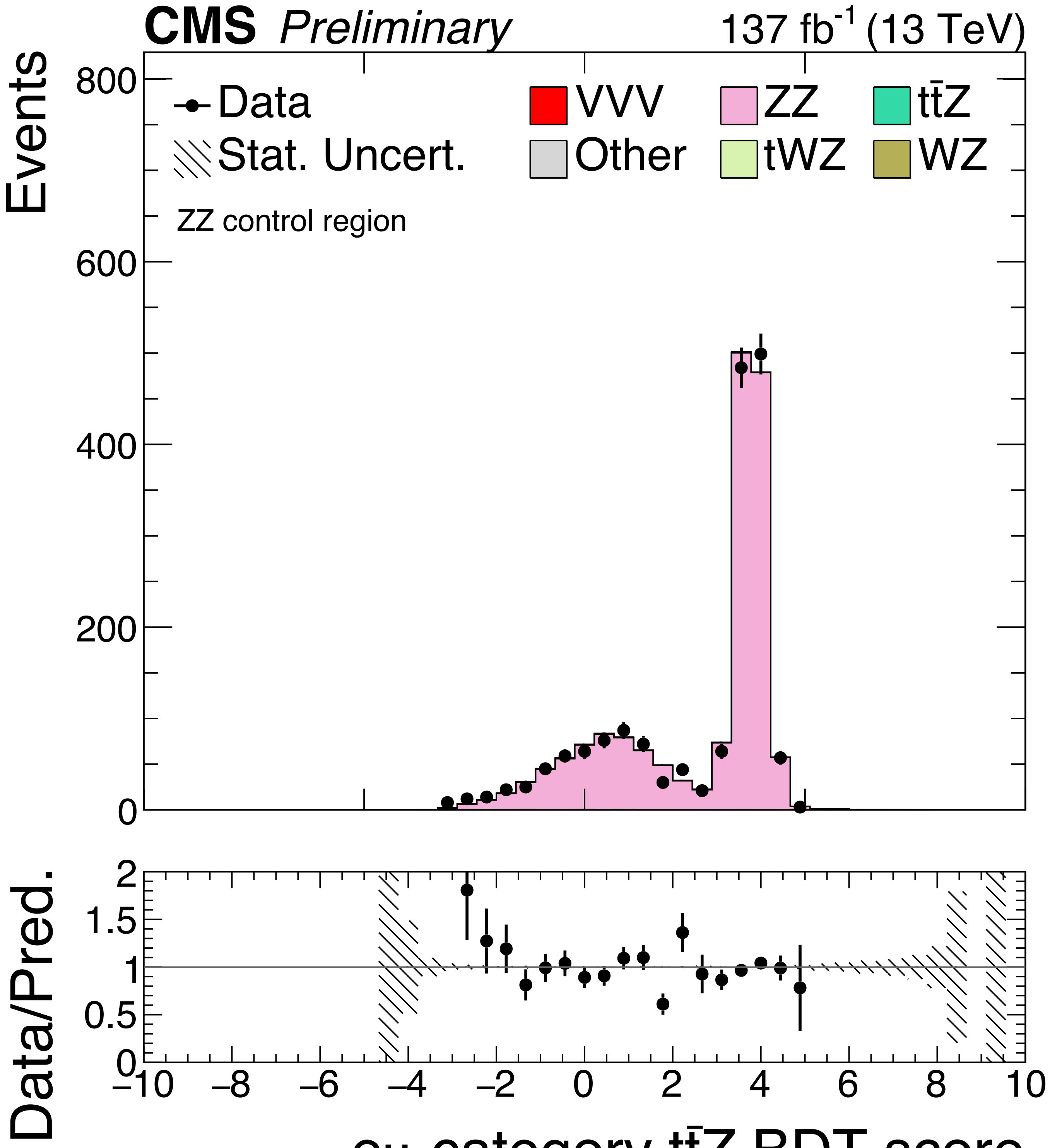
Chang
UCSD



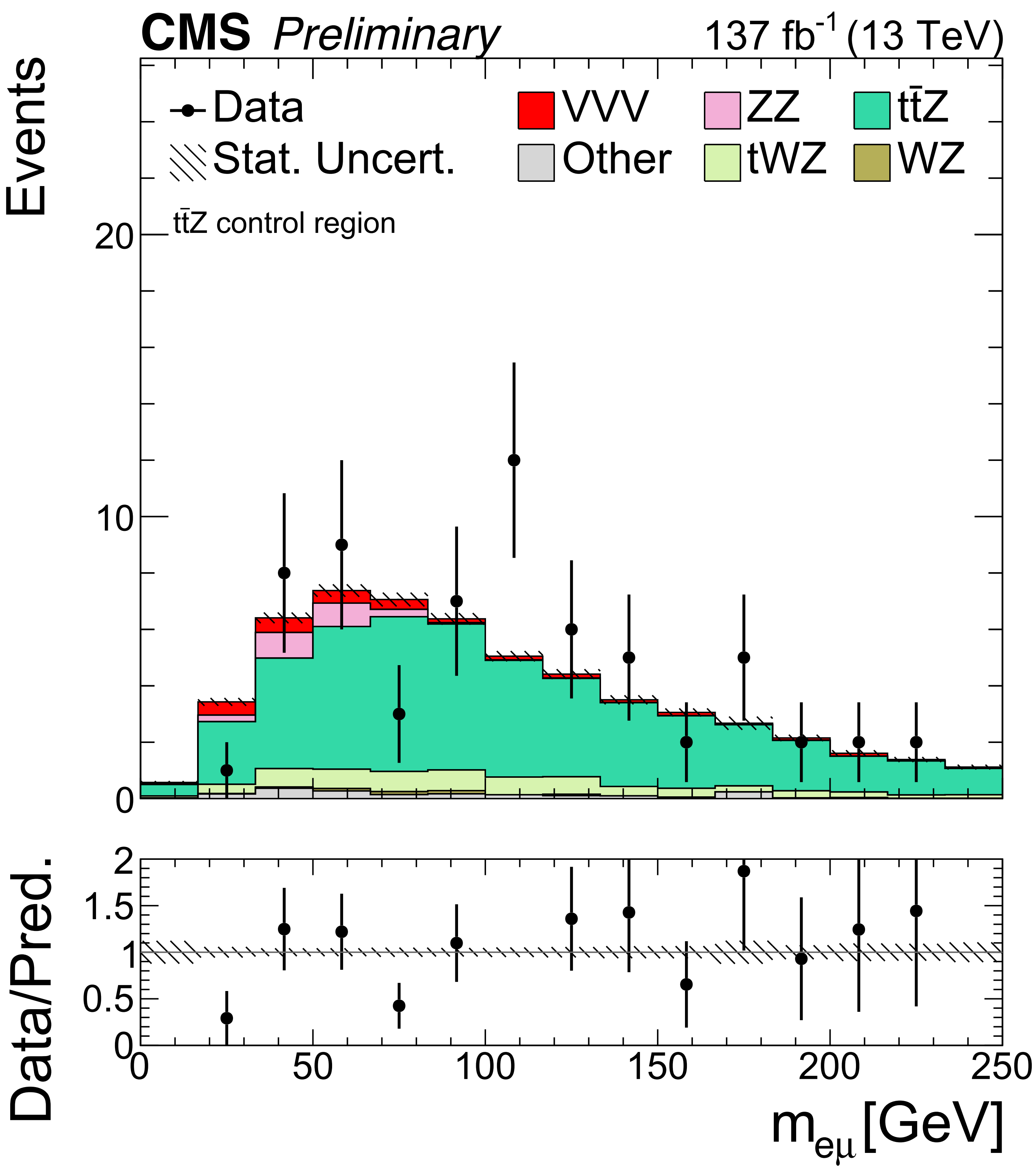
Title


CMS Preliminary
137 fb^{-1} (13 TeV)
VVV
Lost/three leptons
Irreducible
Data
Nonprompt leptons
γ→lepton
Stat. Uncert.
Charge missasignment
SS n$_j$≥2 BDT fake application region
Events
0
200
400
600
800
Data/Pred.
0
0.5
1
1.5
2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
nonprompt BDT score

Title


CMS Preliminary
137 fb^{-1} (13 TeV)
Events
800
600
400
200
0
Data
Stat. Uncert.
VVV
Other
ZZ
tWZ
tt̄Z
WZ
ZZ control region
Data/Pred.
2
1.5
1
0.5
0
−10
−8
−6
−4
−2
0
2
4
6
8
10
eμ category tt̄Z BDT score

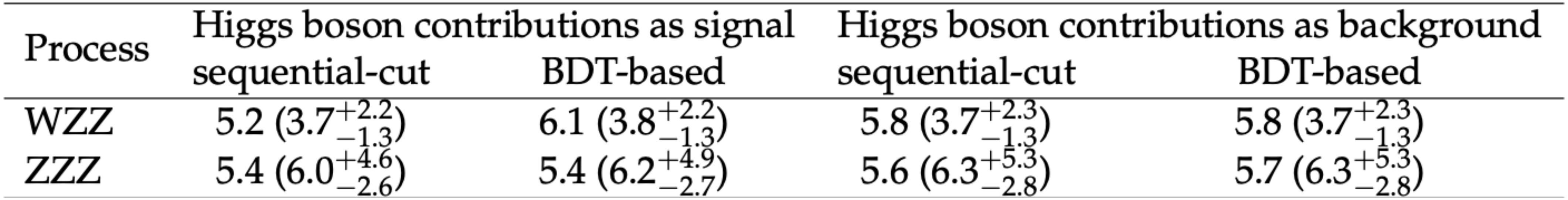
Title


CMS Preliminary
137 fb^{-1} (13 TeV)
Data
Stat. Uncert.
VVV
Other
ZZ
tWZ
t$\bar{t}$Z
WZ
t$\bar{t}$Z control region
Events
20
10
0
Data/Pred.
2
1.5
1
0.5
0
0
50
100
150
200
250
$m_{e\mu}$ [GeV]

Title

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)

Title



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 ($6.3^{+5.3}_{-2.8}$)

Title

Signal region	SS m_{jj}-in $e^{\pm}e^{\pm}$	SS m_{jj}-in $e^{\pm}\mu^{\pm}$	SS m_{jj}-in $\mu^{\pm}\mu^{\pm}$	SS m_{jj}-out $e^{\pm}e^{\pm}$	SS m_{jj}-out $e^{\pm}\mu^{\pm}$	SS m_{jj}-out $\mu^{\pm}\mu^{\pm}$	SS 1j $e^{\pm}e^{\pm}$	SS 1j $e^{\pm}\mu^{\pm}$	SS 1j $\mu^{\pm}\mu^{\pm}$	3ℓ 0 SFOS	3ℓ 1 SFOS	3ℓ 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 → 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 → 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 → 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 → 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 → 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

Title

Signal			4ℓ eμ			4ℓ ee/$\mu\mu$		5ℓ	6ℓ
region	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
$t\bar{t}Z$	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

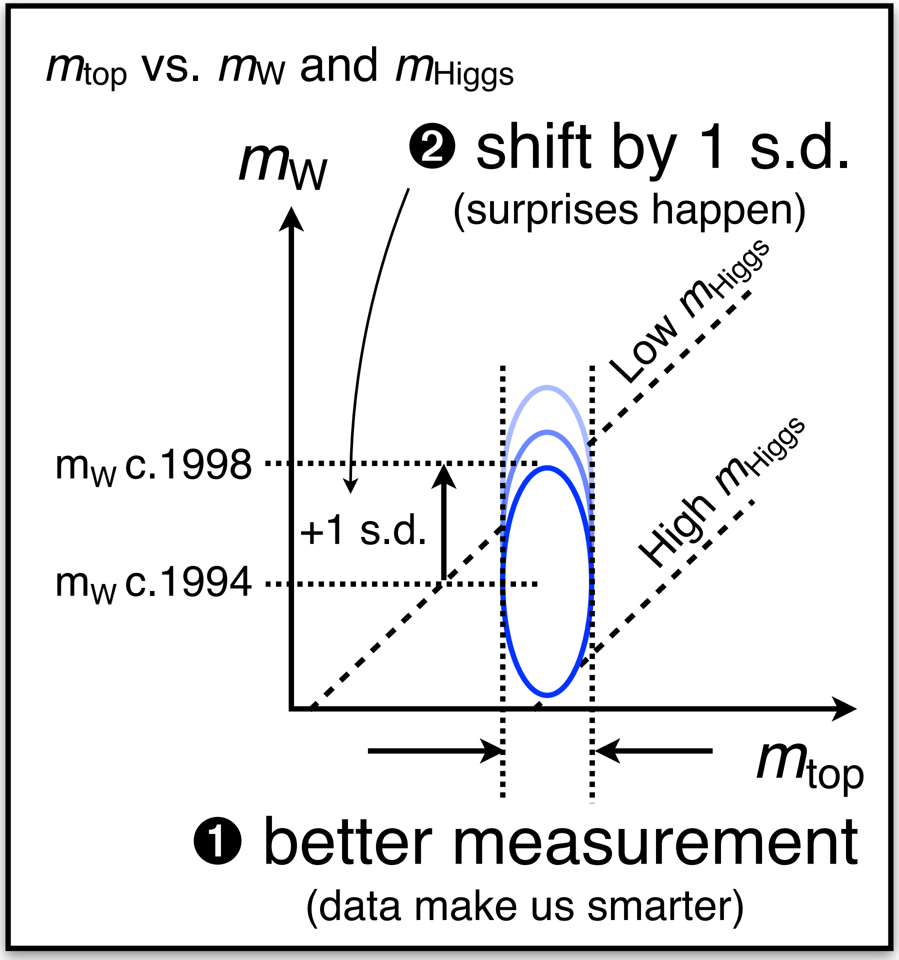
Title

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

Title

Signal	4ℓ $e\mu$				4ℓ ee/$\mu\mu$			5ℓ	6ℓ
region	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
$t\bar{t}Z$	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

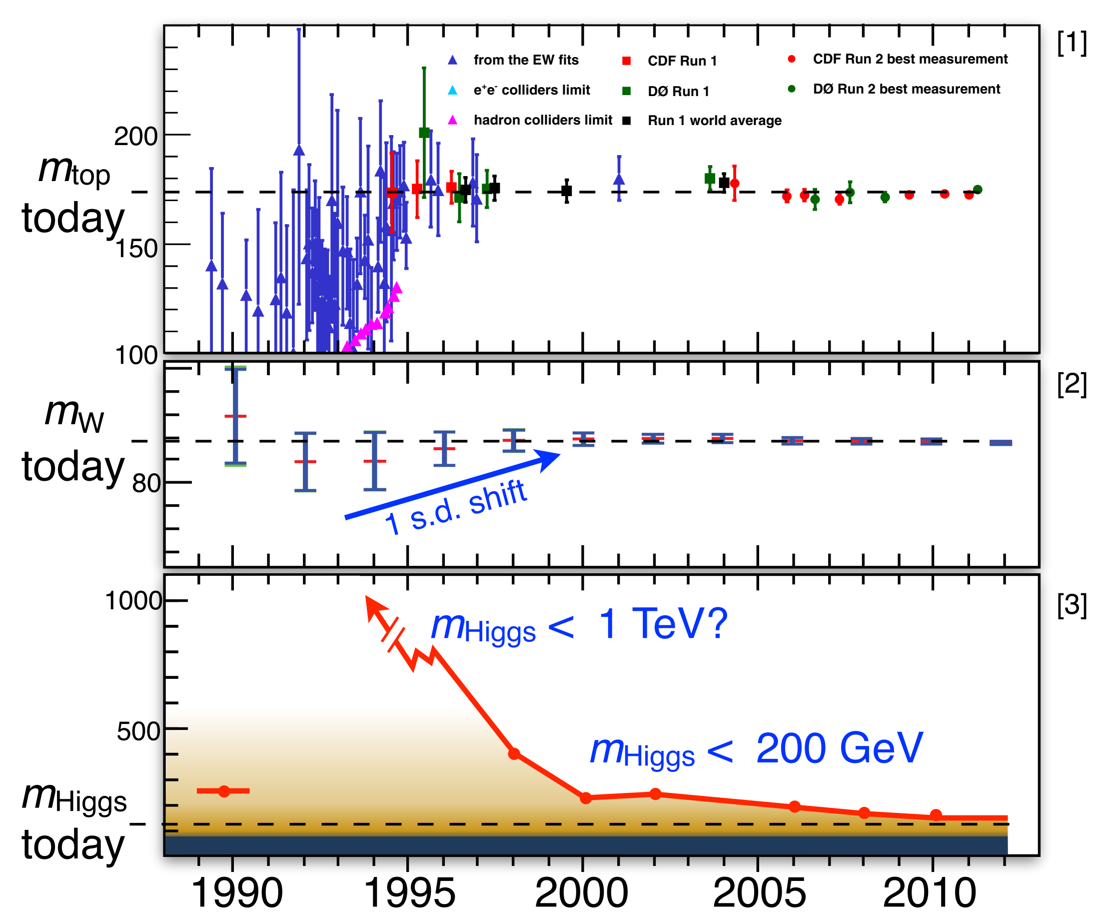
History lesson



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

❷ shift by 1 s.d.
(surprises happen)

❶ better measurement
(data make us smarter)

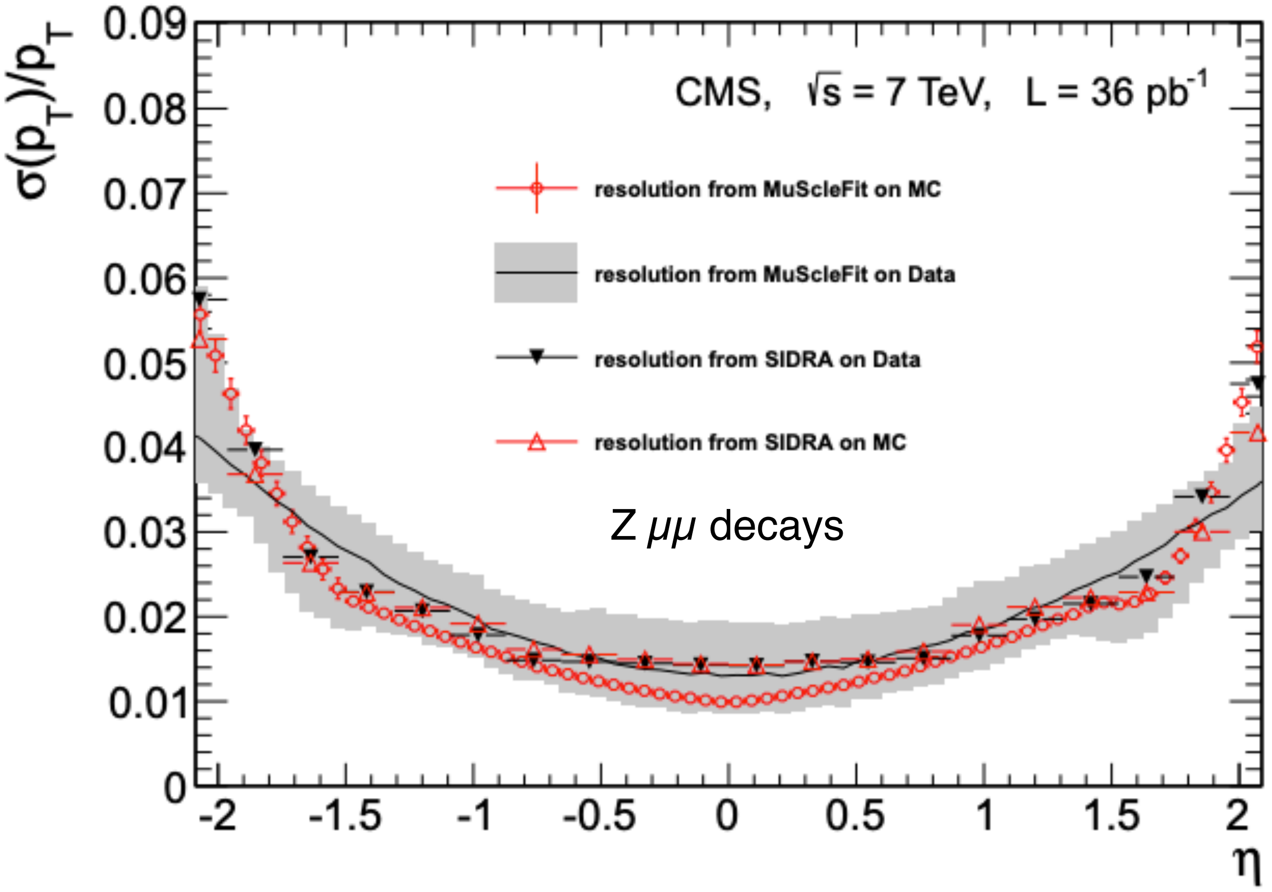


…after analysis of Run I data, … ❷ m_W shifted a full s.d. … the m_{Higgs} must be ❸ much lower than anyone had anticipated. … Surprises happen.

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

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

Muon resolution

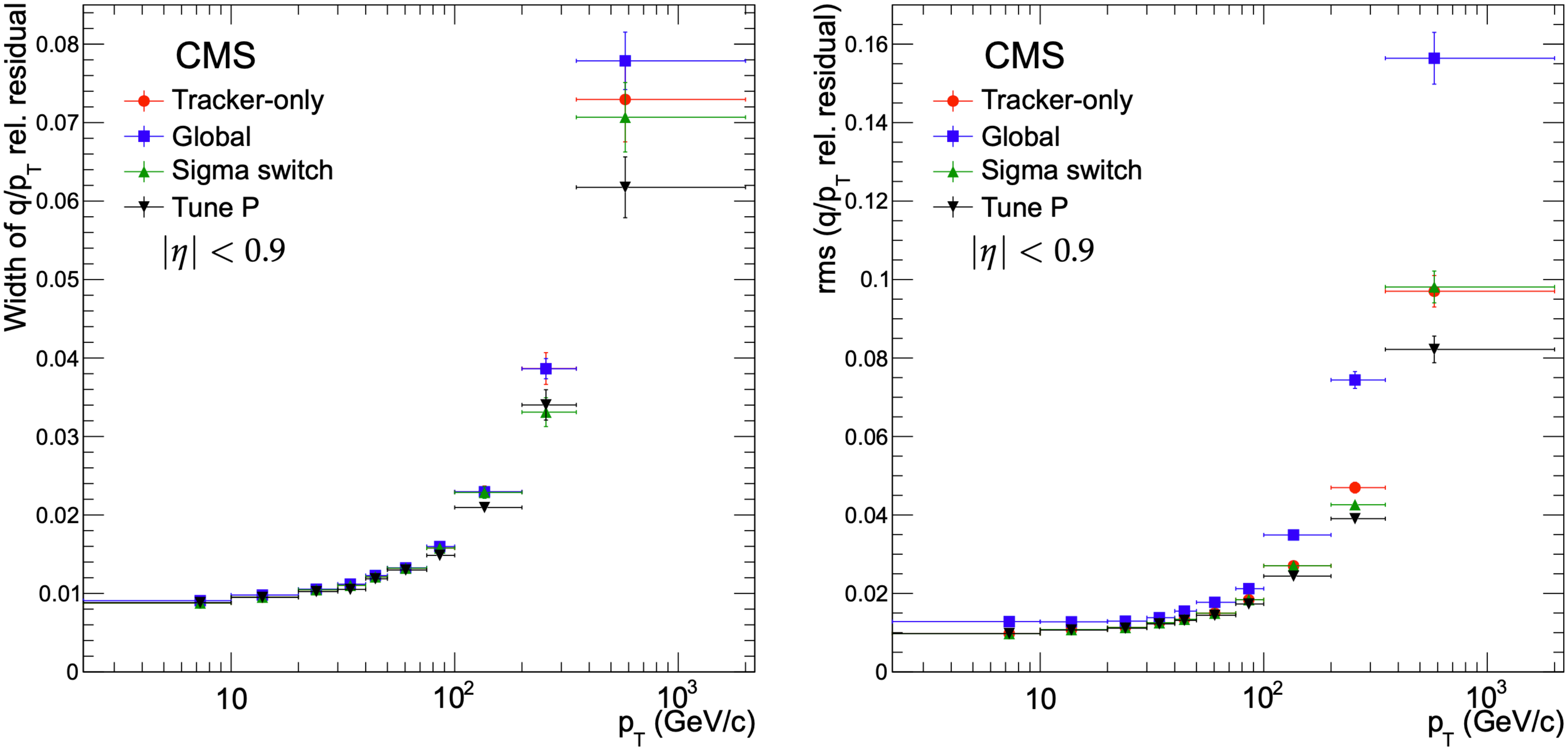


ment with the results obtained from simulation. The $\sigma(p_T)/p_T$ averaged over ϕ and η varies in p_T from $(1.8 \pm 0.3(\text{stat.}))\%$ at $p_T = 30\,\text{GeV}/c$ to $(2.3 \pm 0.3(\text{stat.}))\%$ at $p_T = 50\,\text{GeV}/c$, again in good agreement with the expectations from simulation.

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

Muon resolution

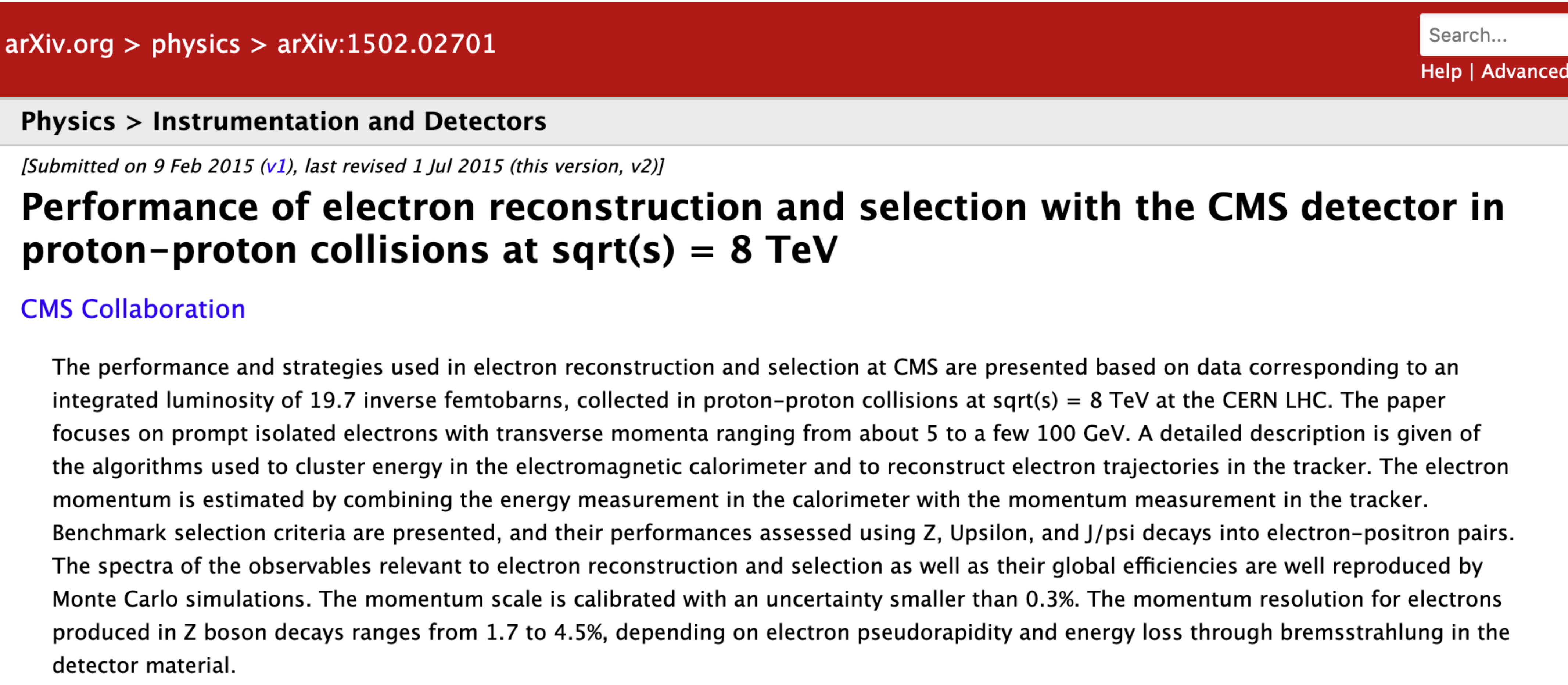
https://arxiv.org/pdf/1206.4071.pdf



(a)

(b)

Electron resolution



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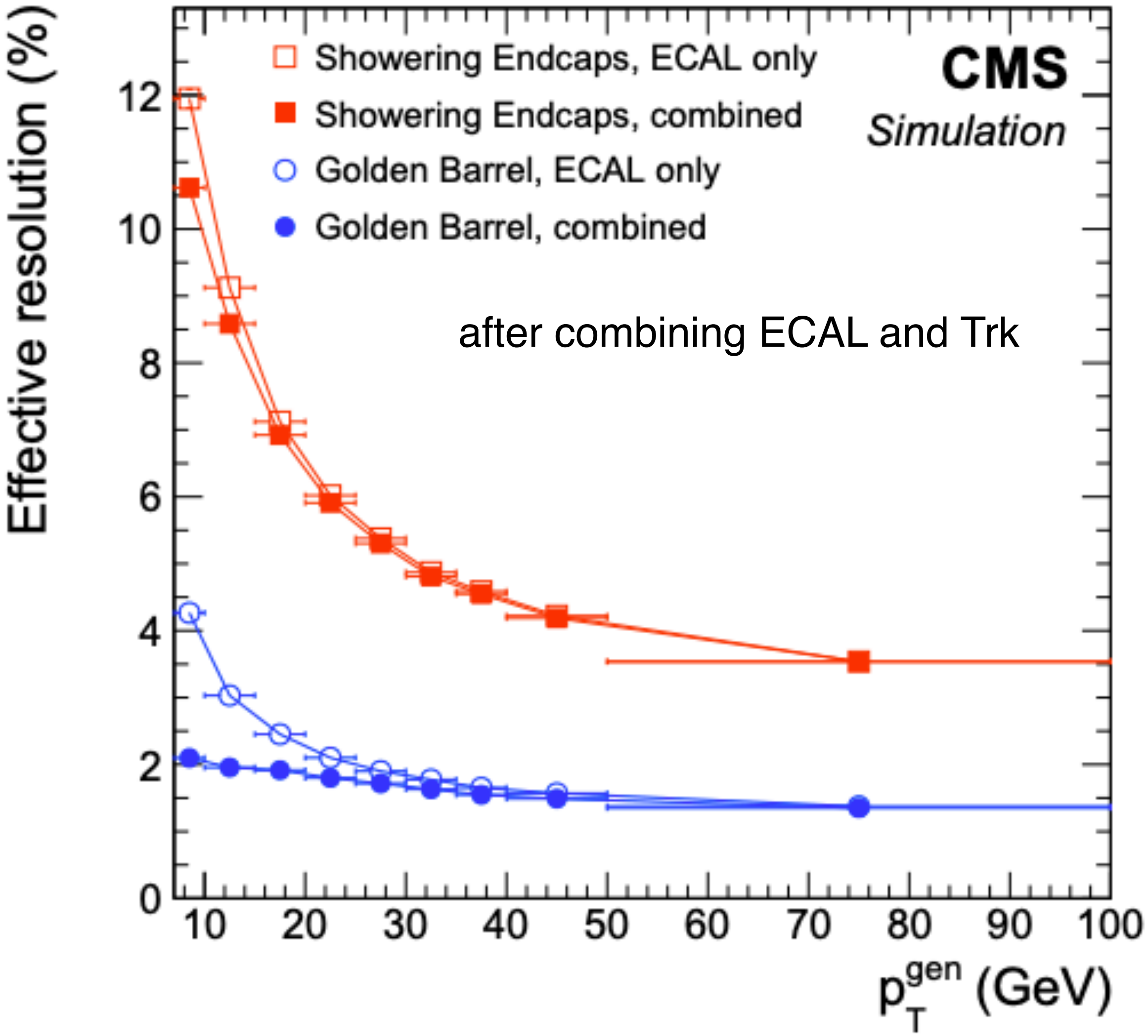
[Submitted on 9 Feb 2015 (v1), last revised 1 Jul 2015 (this version, v2)]

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



after combining ECAL and Trk

b tagging

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