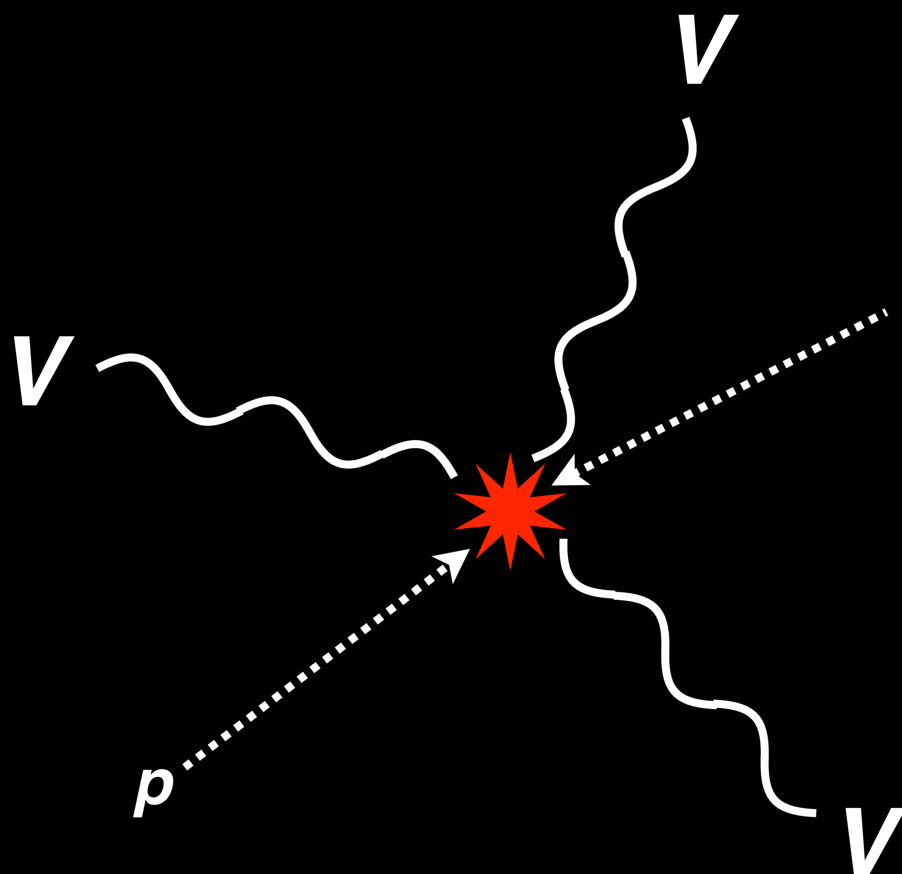
First observation of production of three massive gauge bosons ($V = W, Z$)



Philip Chang

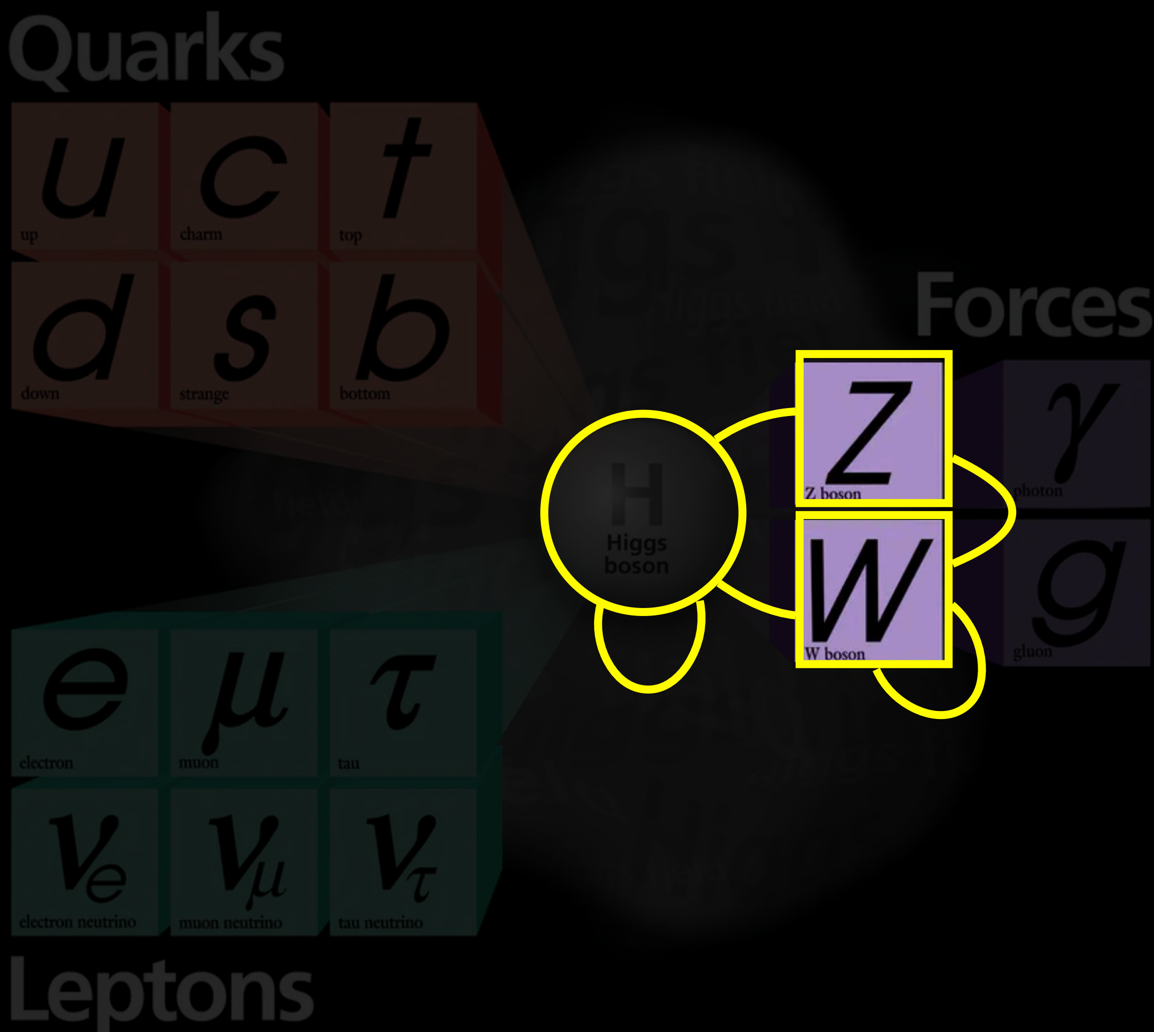
Univ. of California San Diego

KIAS Seminar
August 14, 2020

Outline

- Why study multi-boson interactions (MBI)?
- How do we study MBI at LHC
- Triboson result from CMS
- Future direction of multi-boson physics

Electroweak sector of Standard Model

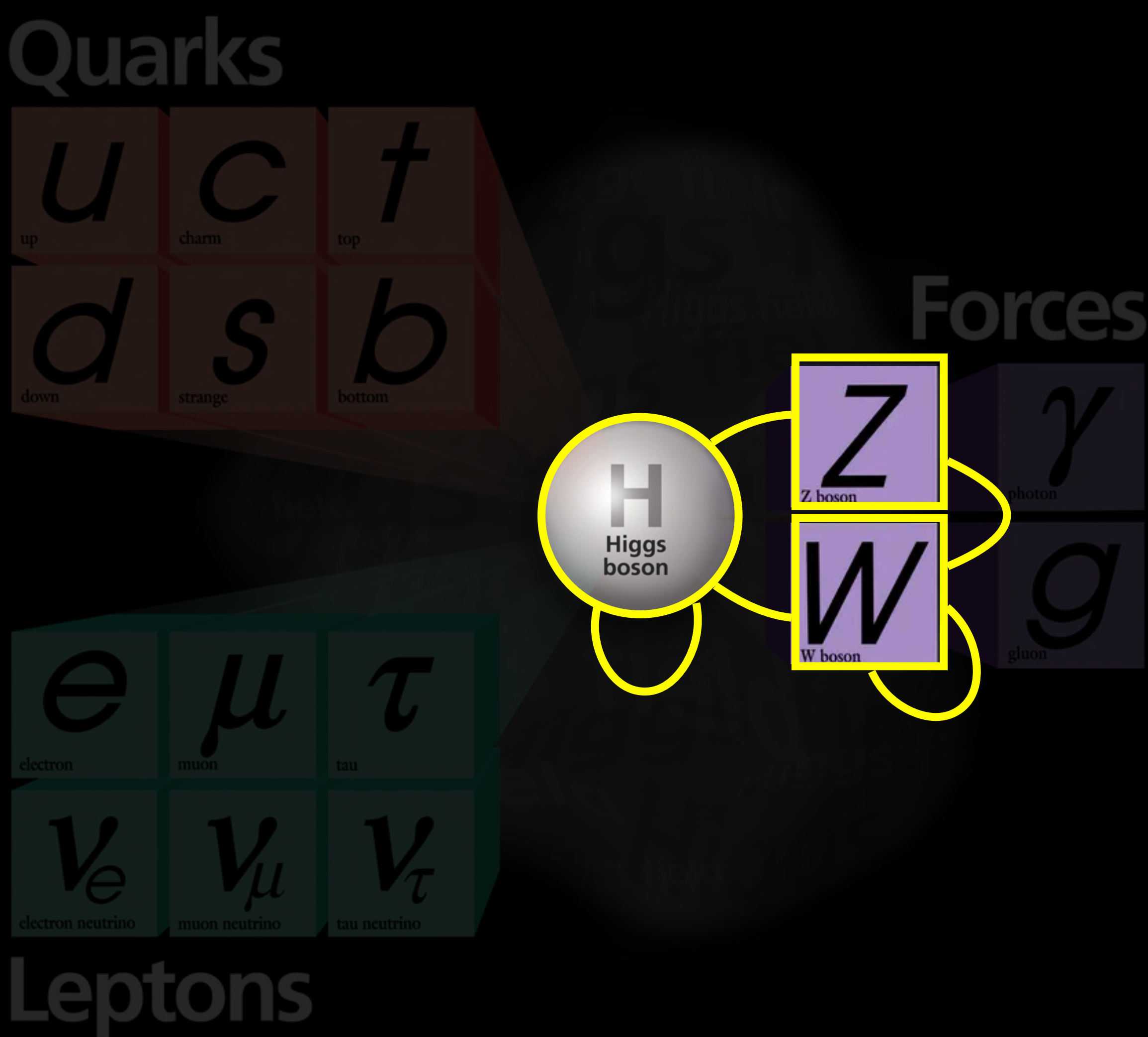


Spin 1

- Mass of W is 80 GeV (≠ 0)
- Mass of Z is 91 GeV (≠ 0)

⇒ EW symmetry is broken

Electroweak sector of Standard Model



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- Mass of H is 125 GeV

⇒ We must build upon this discovery to understand electroweak sector

Electroweak sector of Standard Model

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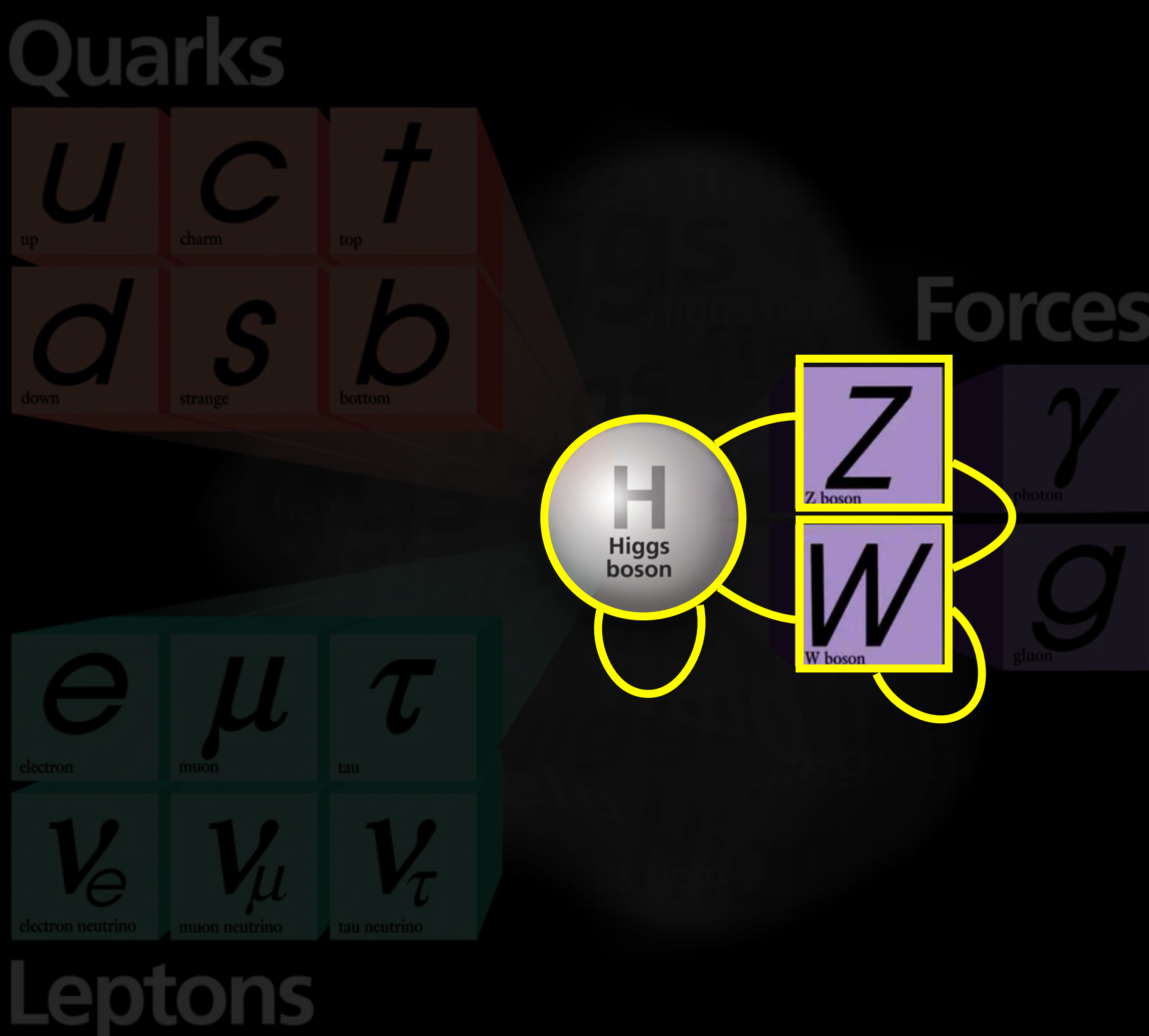

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We must understand the W, Z, H and their interactions

Multi-boson interaction (MBI) at high E

Lee, Quigg, Thacker (1977)

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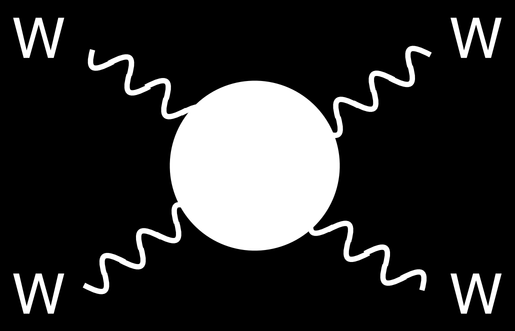
WW scattering



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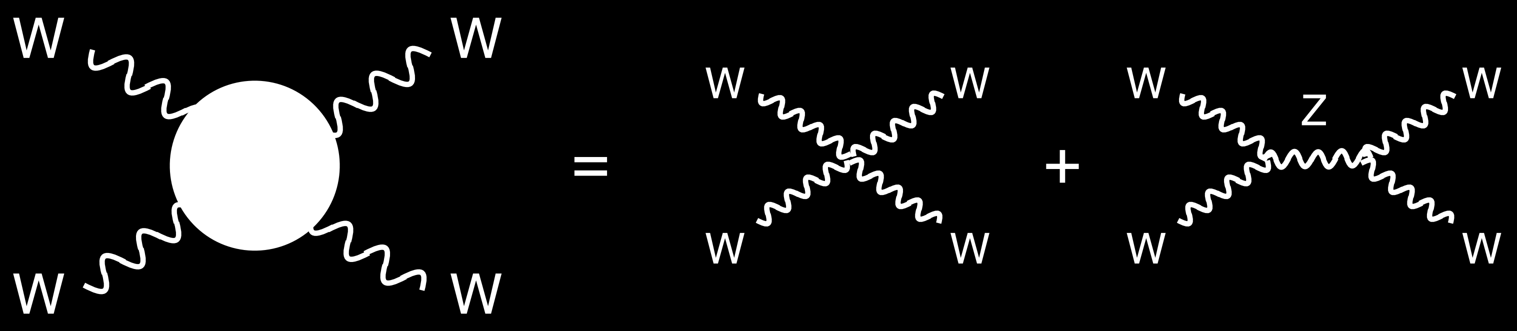
$P(WW \rightarrow WW) \sim E^2$
(i.e. ***at high E***, $P > 1$)



Bad high energy behavior

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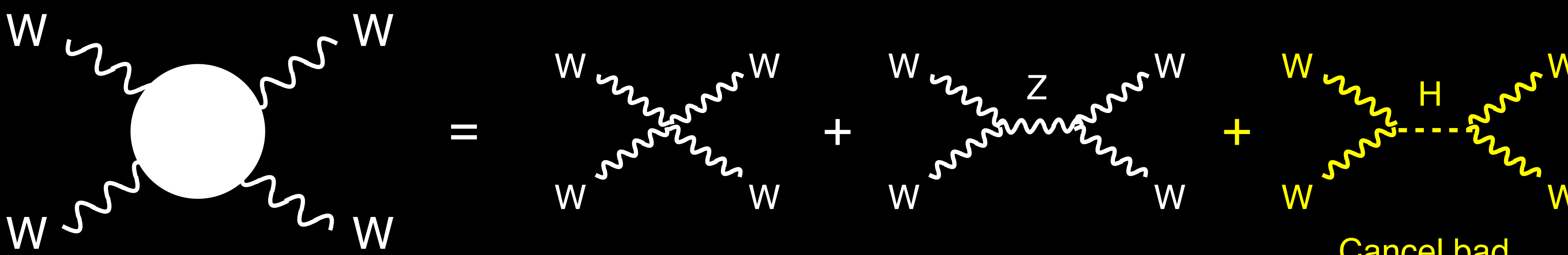
With Higgs P < 1



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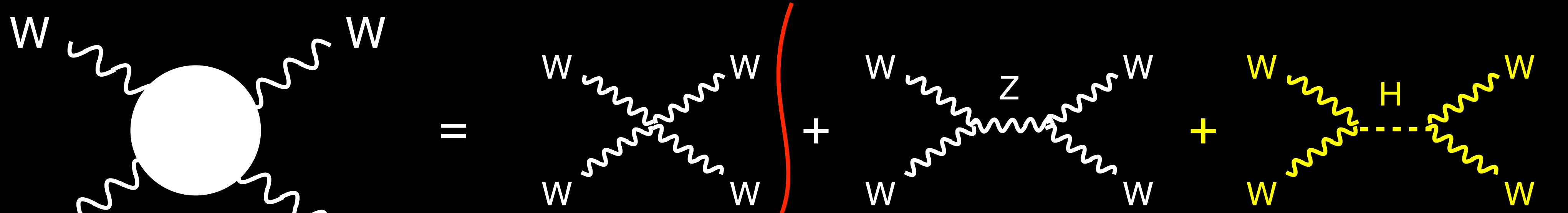

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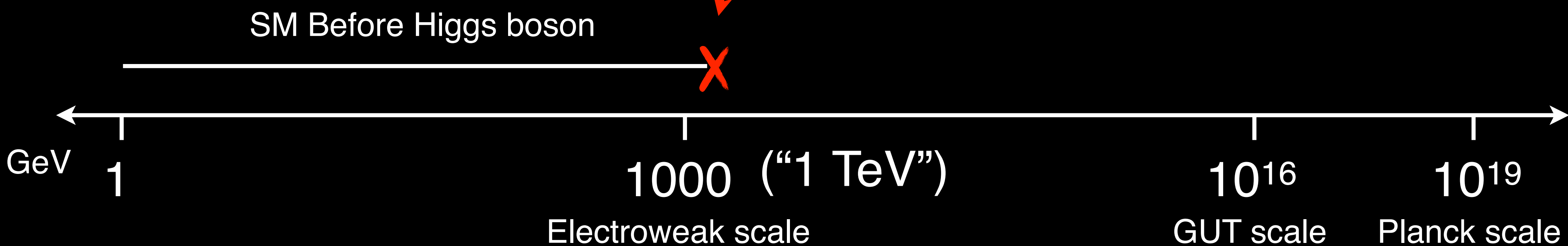

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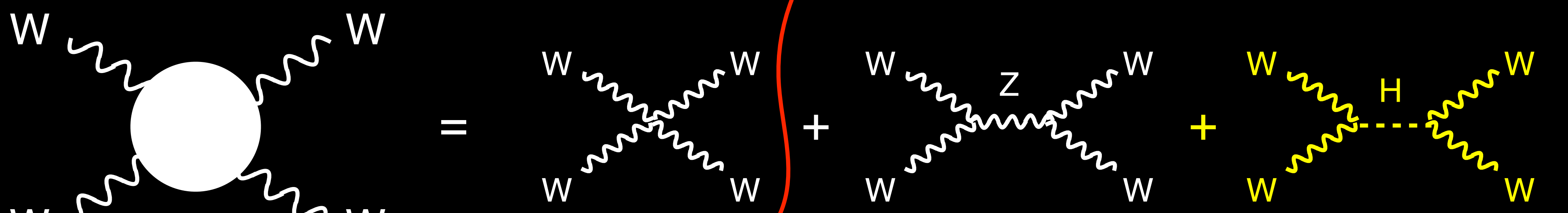

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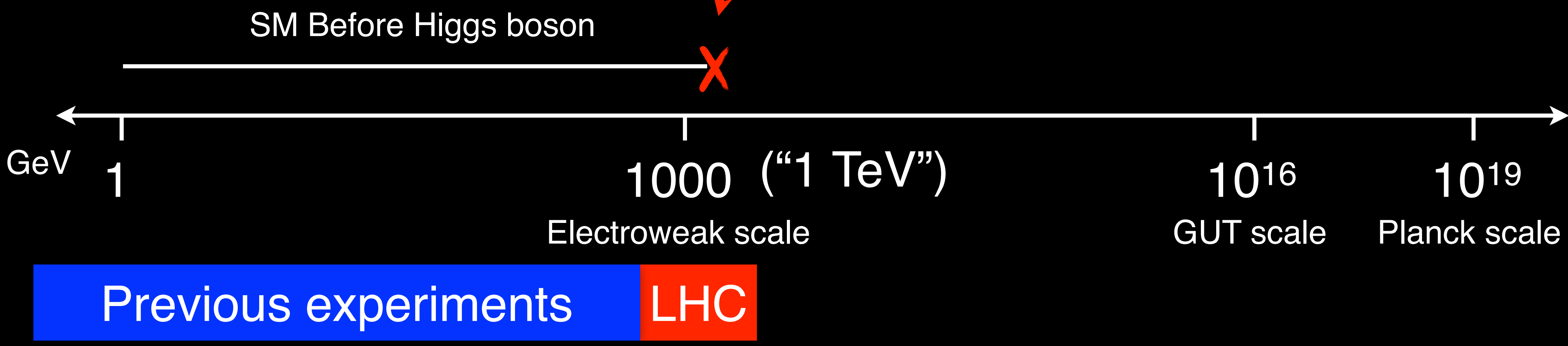

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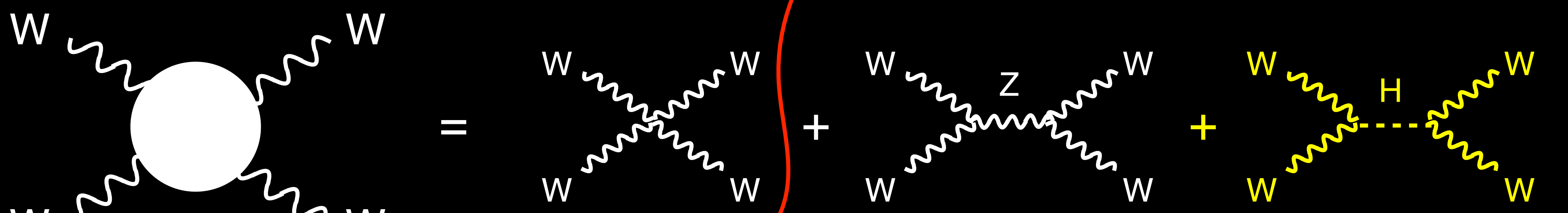

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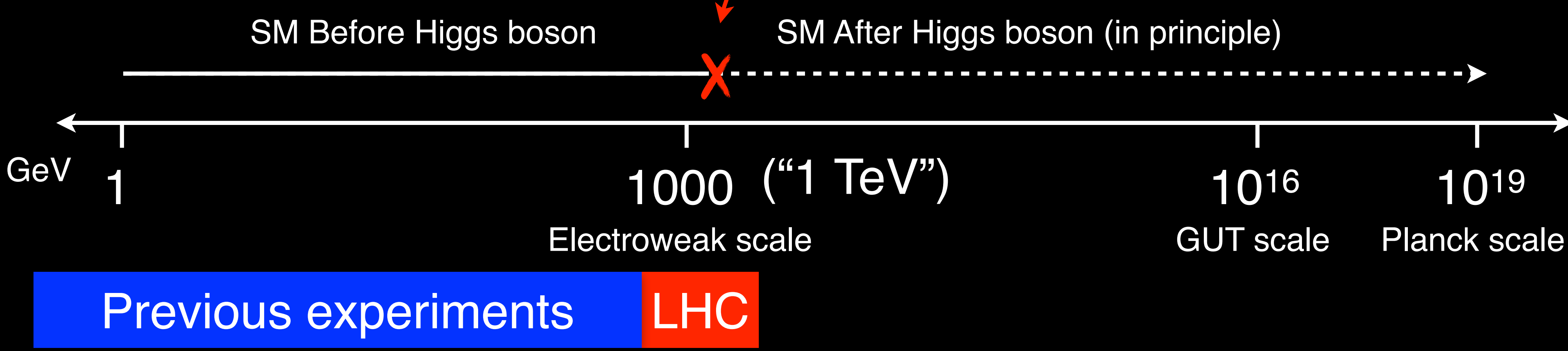

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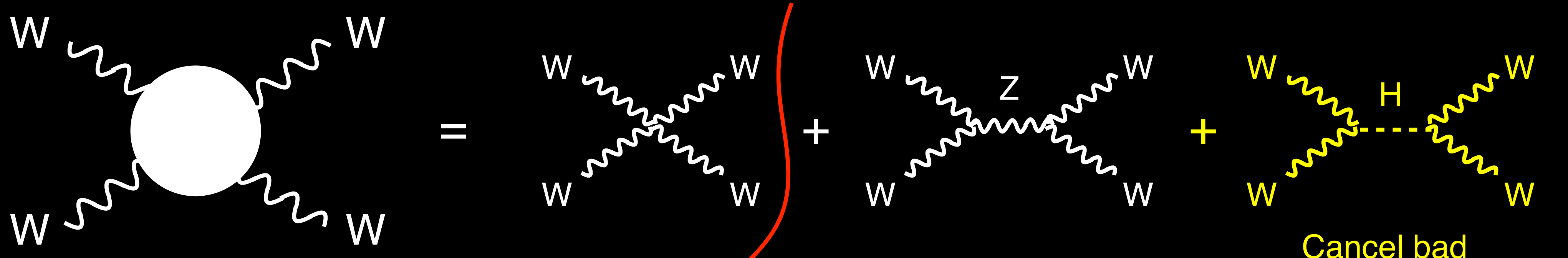

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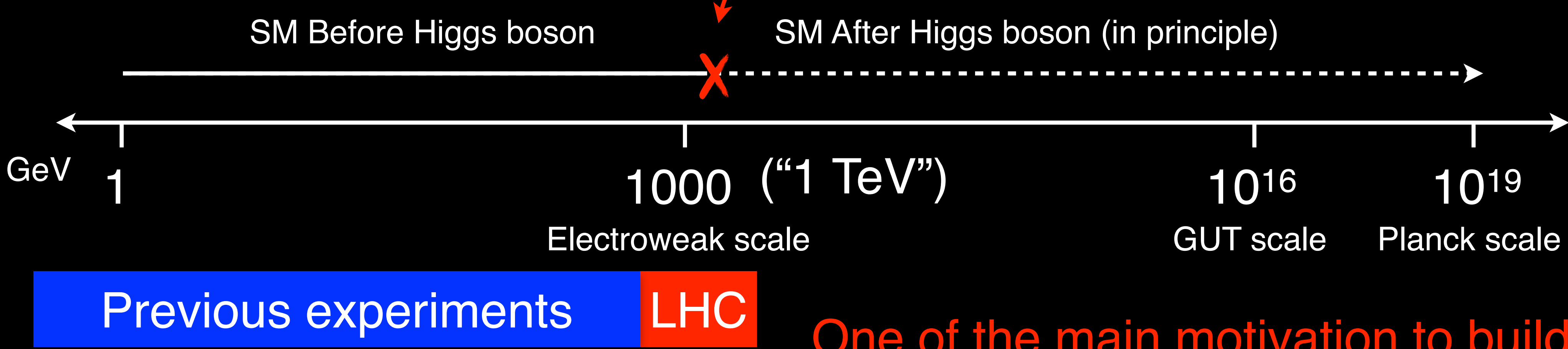

One of the main motivation to build
LHC to probe physics at the TeV range

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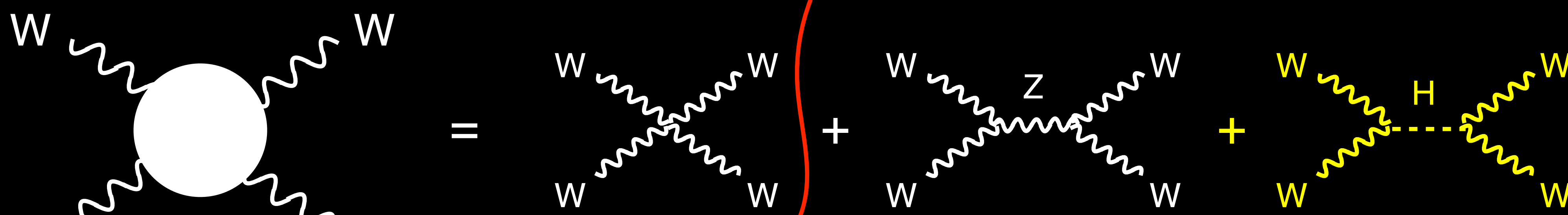

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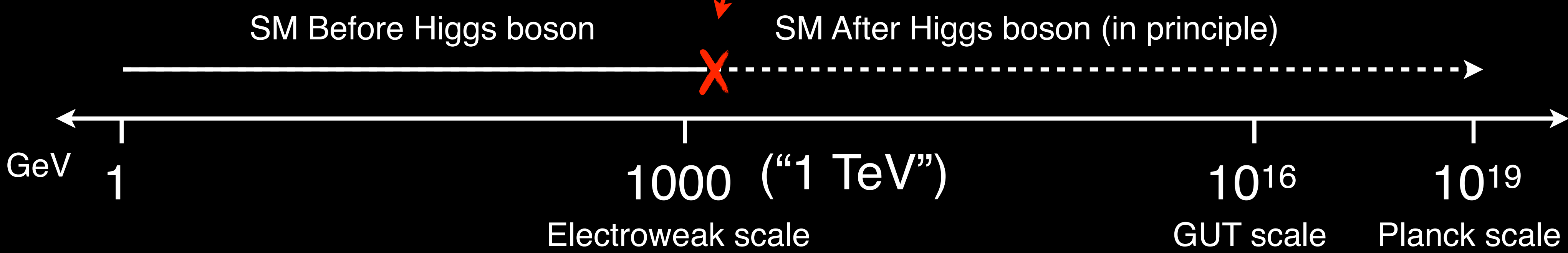
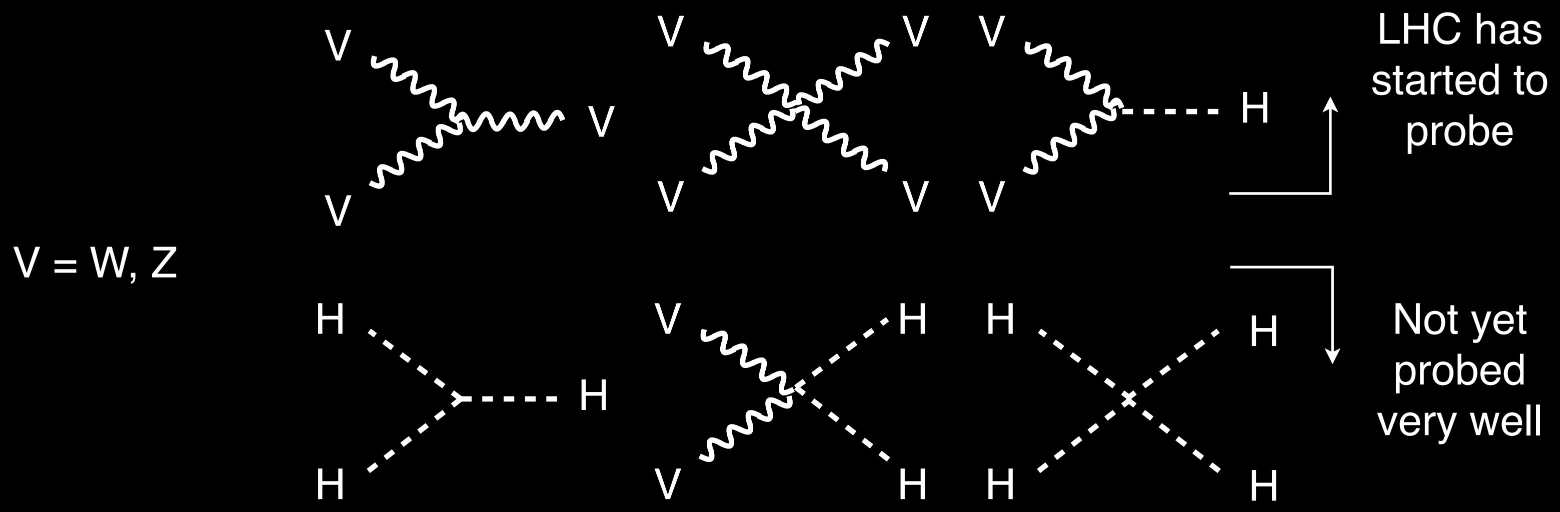


Previous experiments | LHC

One of the main motivation to build
LHC to probe physics at the TeV range

Is the interaction and couplings all SM-like?
⇒ Crucial test of electroweak theory

Various multi-boson interactions



- Are multi-*bosons* interactions SM? (including Higgs self-coupling)
  - (Deep implications, e.g. baryogenesis, stability of the universe.)
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- If so, what are their role in the electroweak symmetry breaking?

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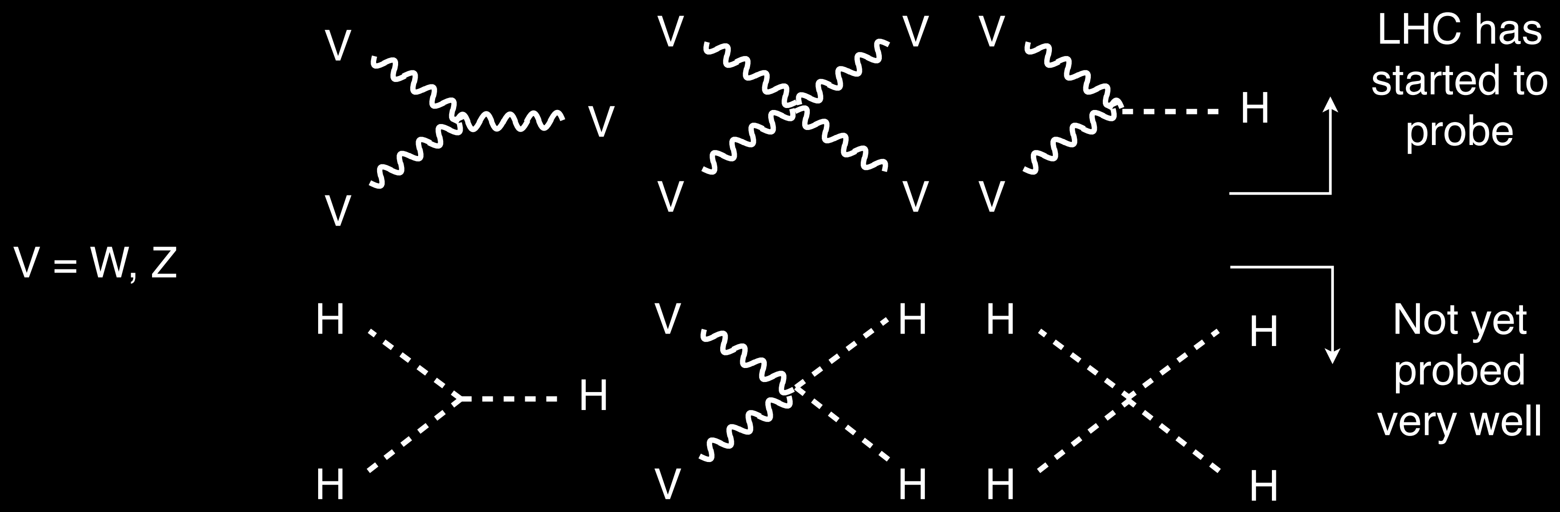

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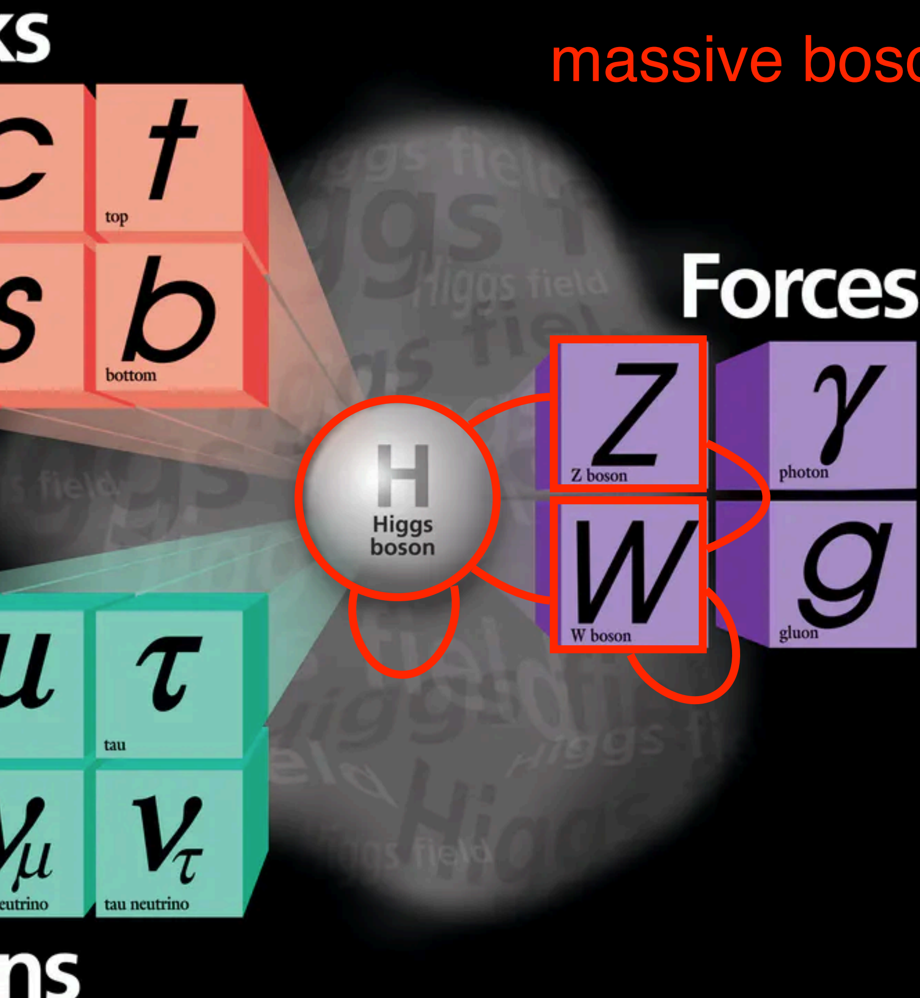
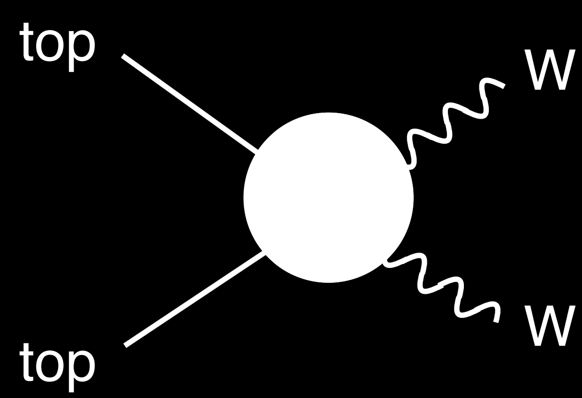
Studying multi-boson productions helps answering these questions

Multi-*X* electroweak interactions

massive bosons





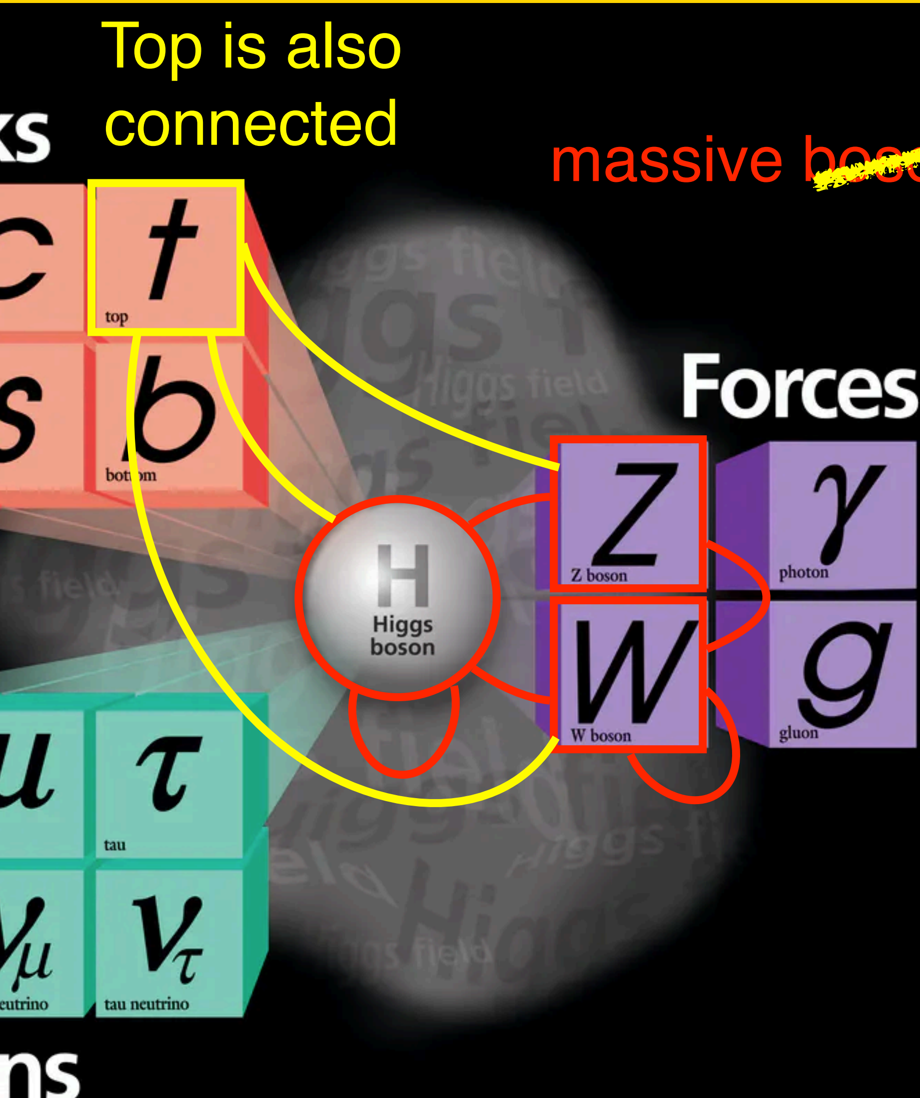
also
bad high E
behavior
w/o Higgs

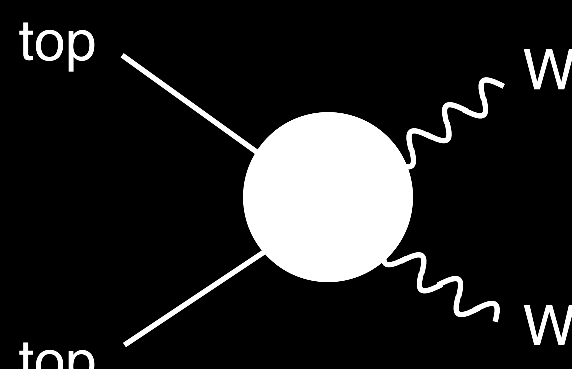
1978 (way) before top/W/Z/Higgs discovery
Chanowitz, Furman, Hinchliffe

F, $W^{\pm}$, Z and H become "sthenons" in the sense of Appelquist and Bjorken [4]: they couple strongly to one another ‡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* electroweak interactions





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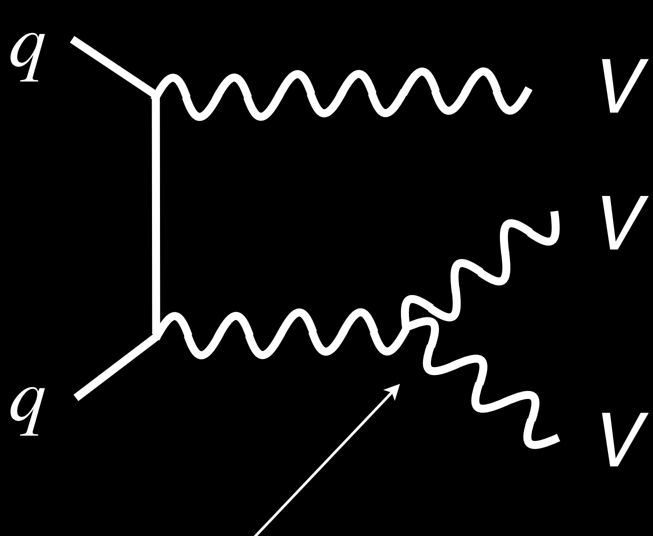
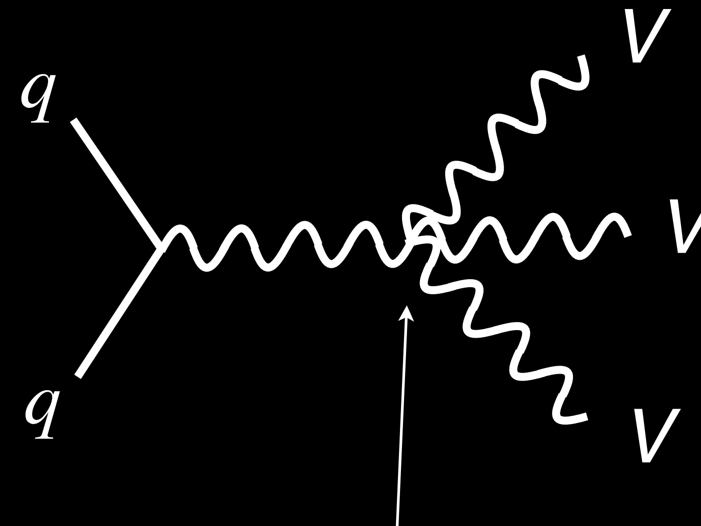
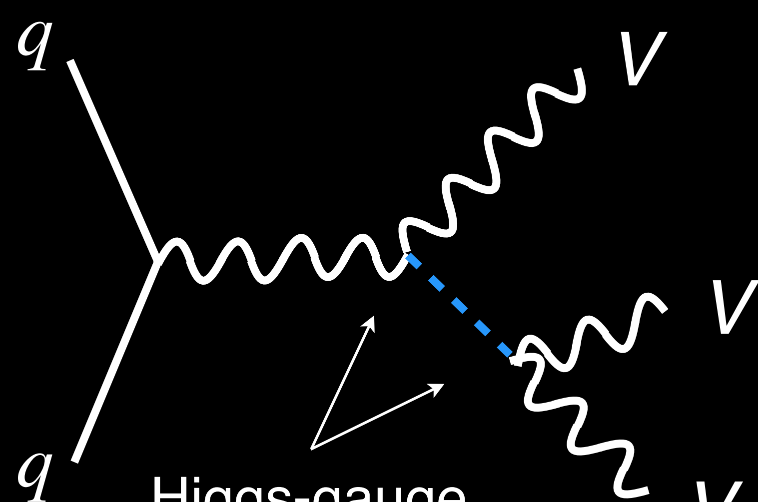
Physics of VVV production (V = W, Z)



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

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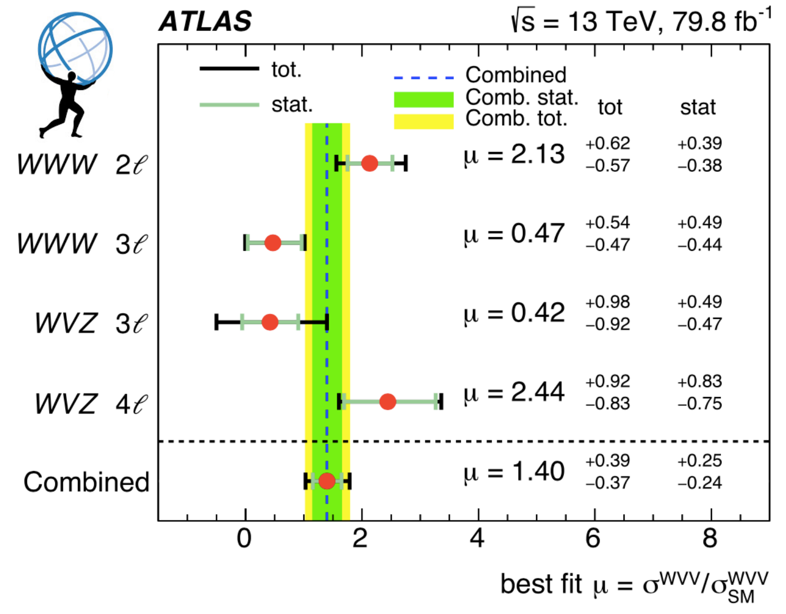
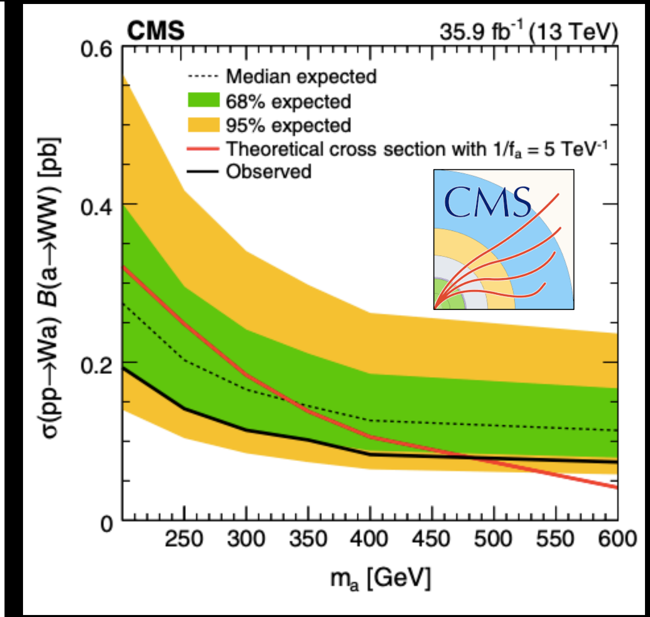
- ATLAS searched for WWW in 8 TeV: 0.96σ (1.05σ) arXiv:1610.05088
- CMS searched for WWW in 13 TeV 36 fb^{-1}: 0.6σ (1.78σ) arXiv:1905.04246
- ATLAS searched for VVV in 13 TeV 80 fb^{-1}: 4.1σ (3.1σ) arXiv:1903.10415

VVV evidence



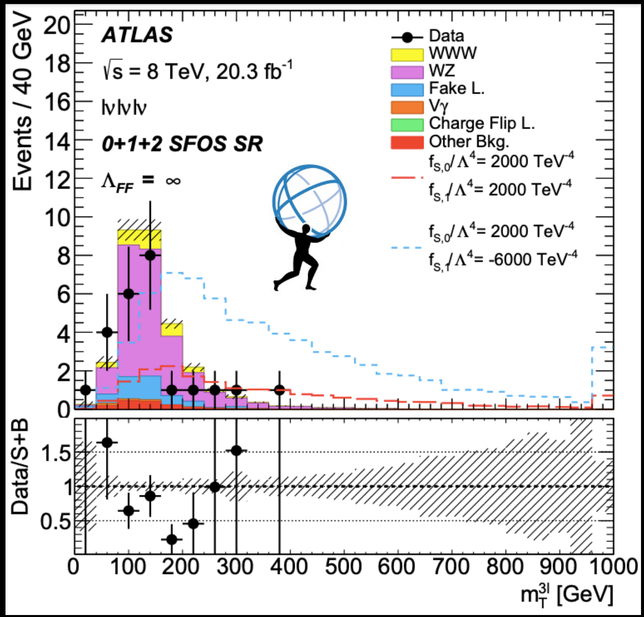
arXiv:1903.10415

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

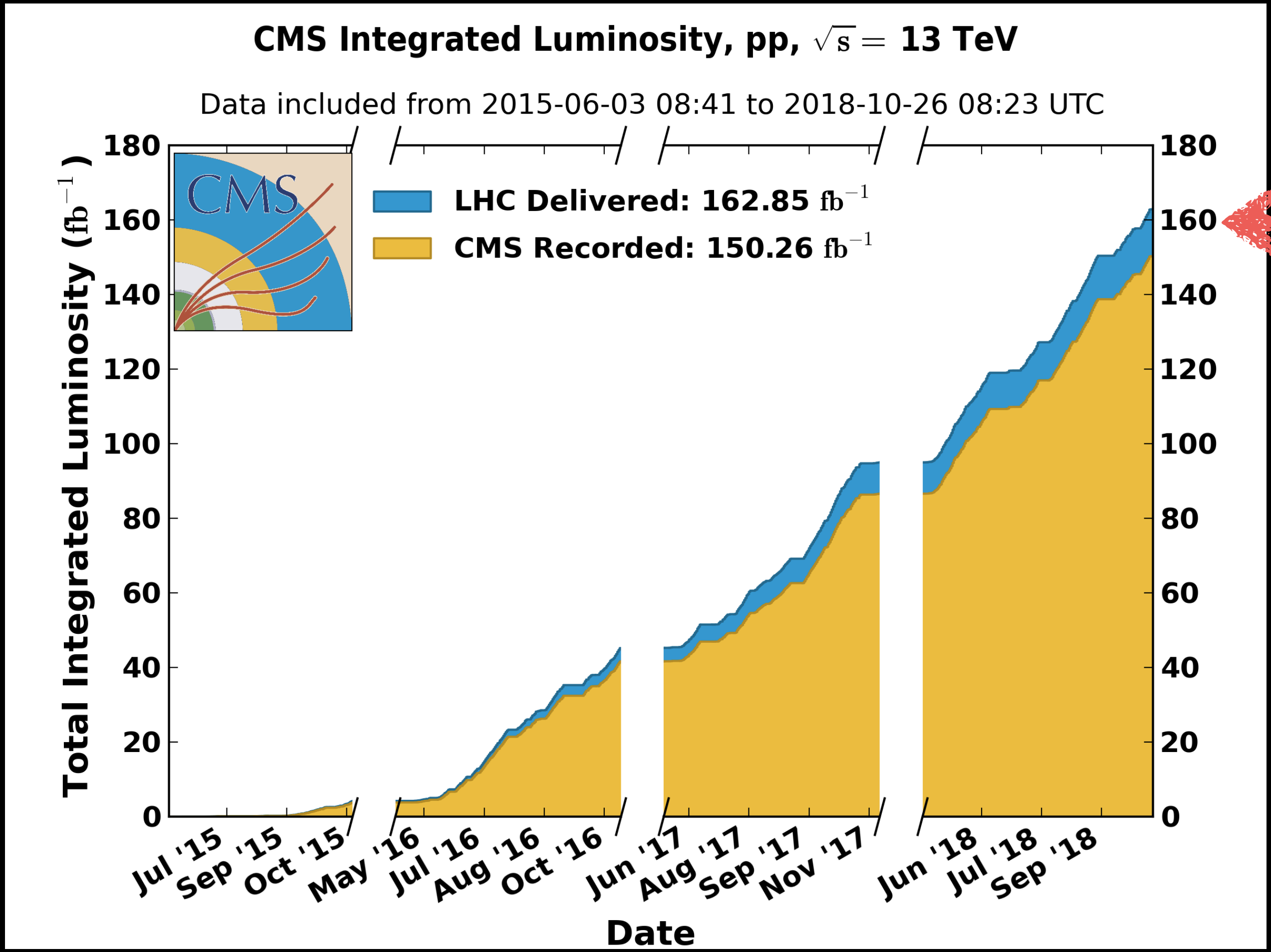
We are targeting all possible VVV productions w/ or w/o Higgs:

- pp→WWW
- pp→WWZ
- pp→WZZ
- pp→ZZZ

And the combined production of all pp→VVV

Data collected by LHC experiment

Total amount of pp collision data delivered by LHC, and recorded by CMS experiment



~15 quadrillion pp collisions

From 2015 to 2018, CMS experiment recorded around 15 quadrillion *pp* collision events

⇒ ~5k - 50k Tri-boson processes

LHC's large provides large and energetic pp collision data set to study rare multi-boson processes

VVV channels in # of leptons

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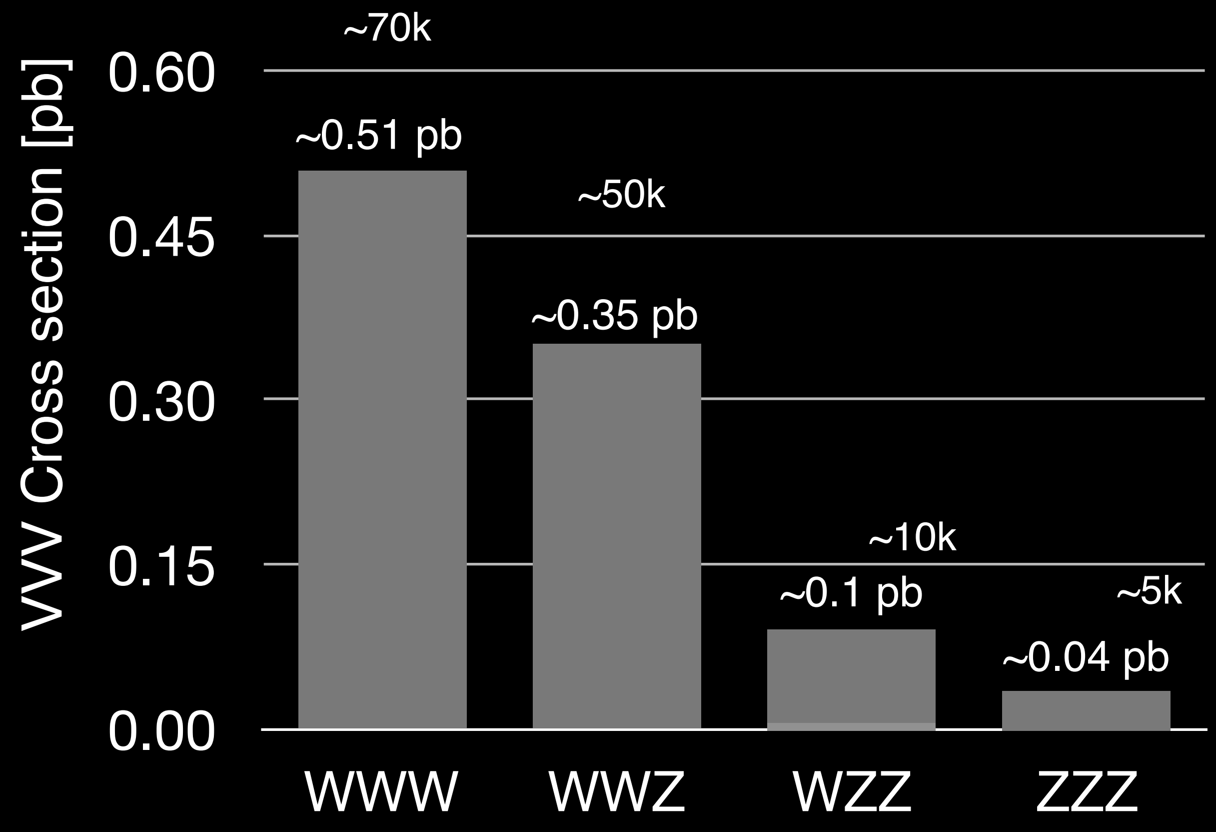
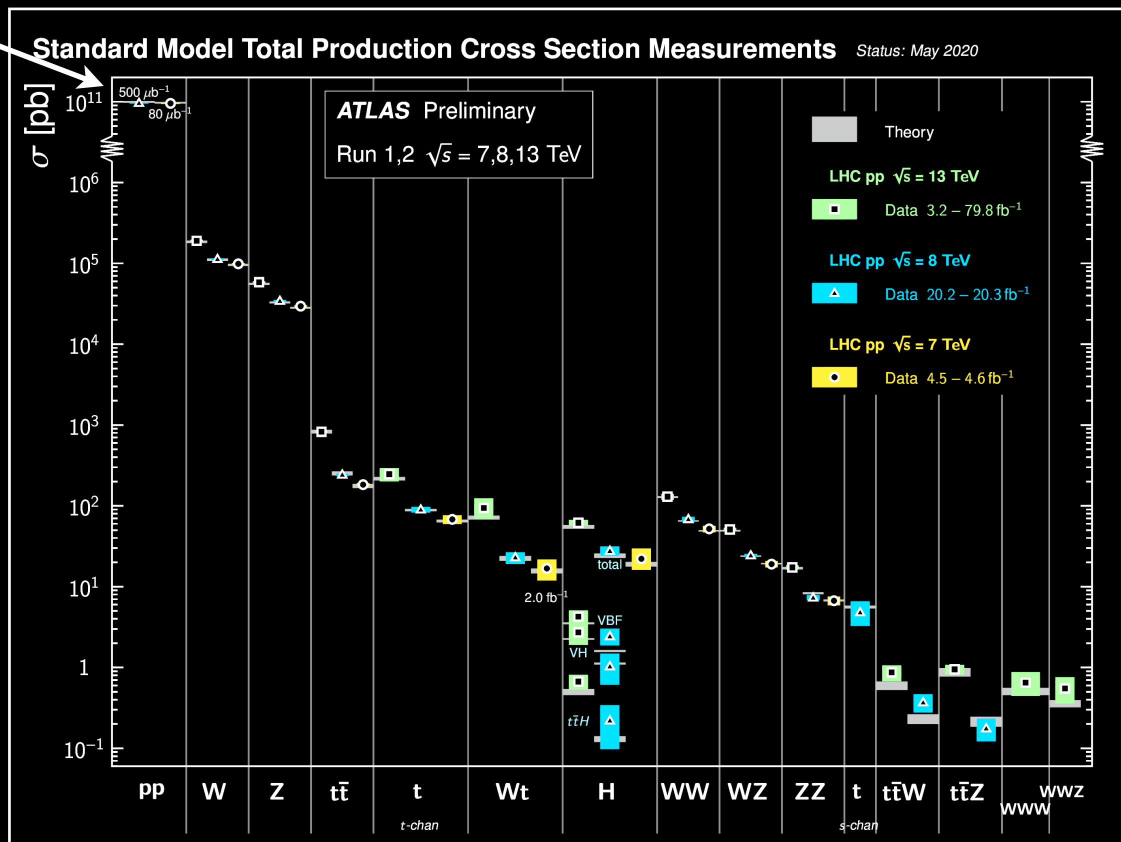
Production cross section decreases with more Z's



Less than 0.5 pb each VVV process (~5k to ~70k produced)

EWK multi-boson processes are rare

If total cross section is “1”



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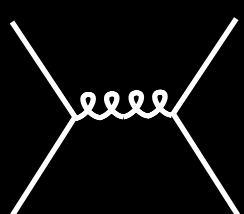

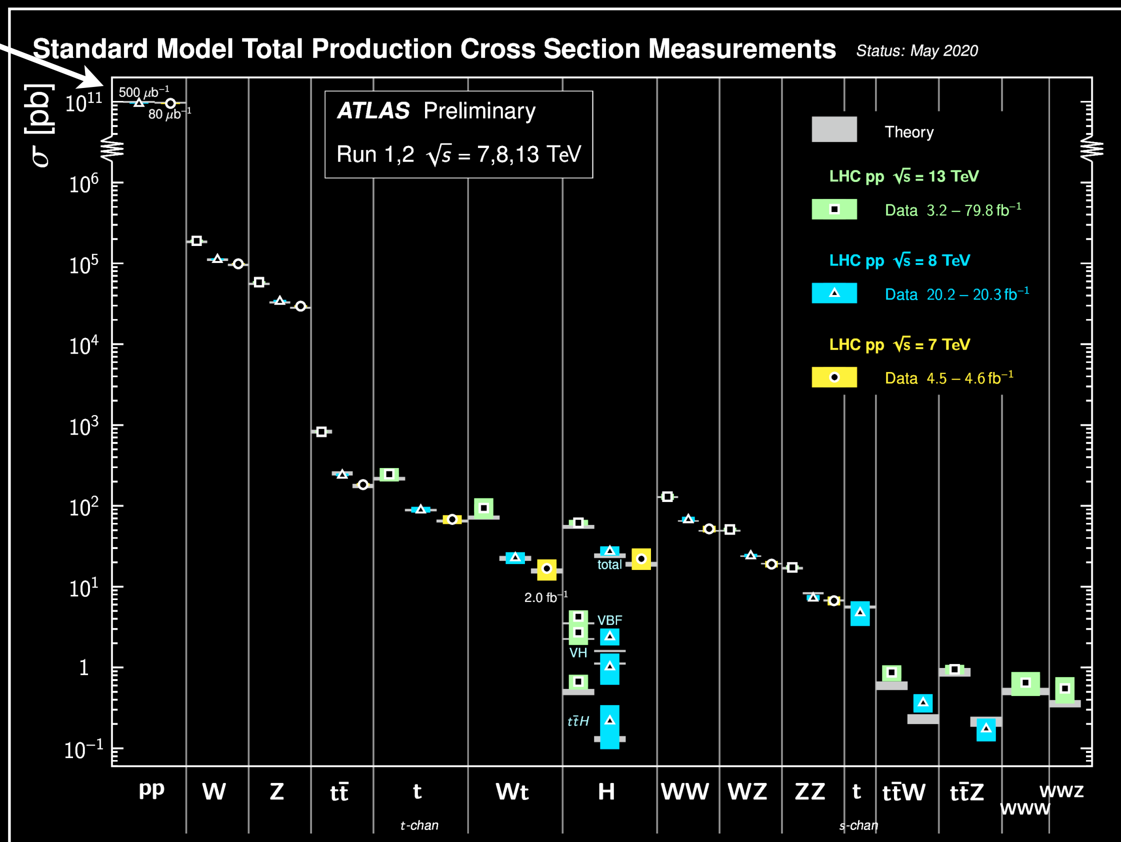

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Single boson production ~ $\frac{1}{\sim 1\text{-}10 \text{ Million}}$

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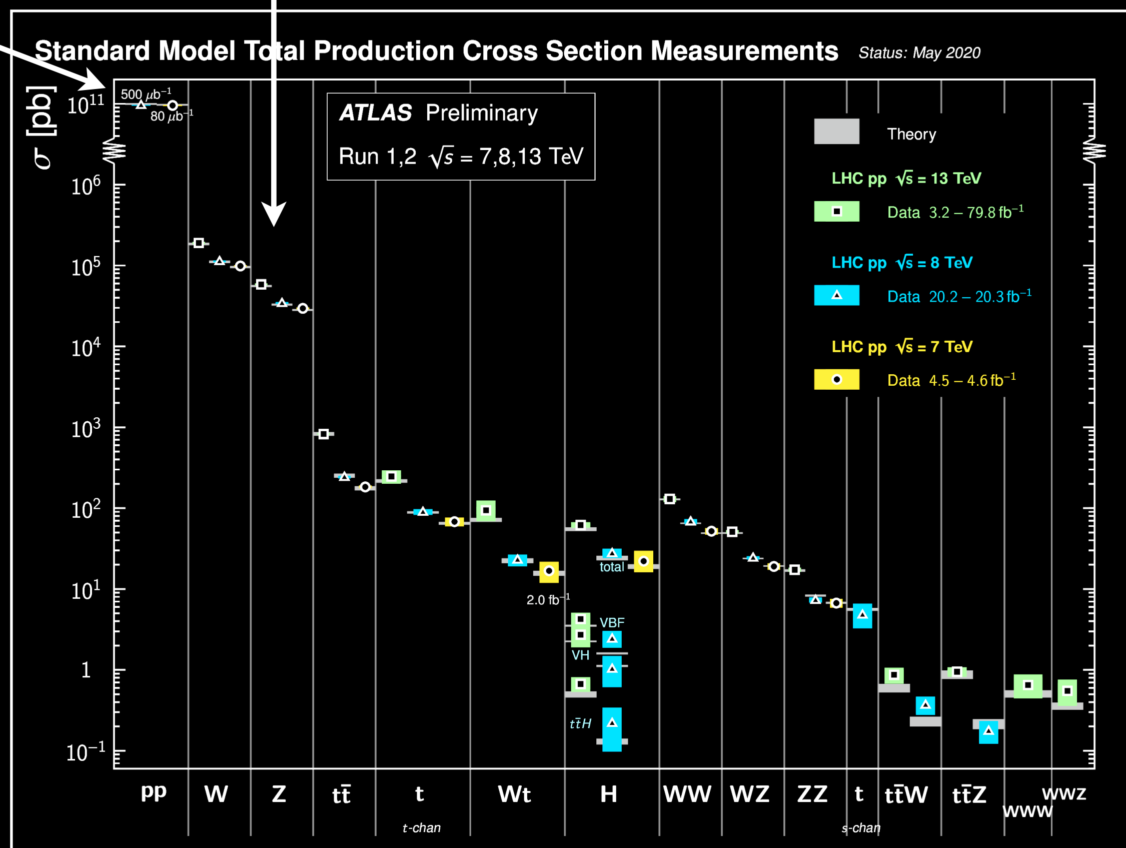

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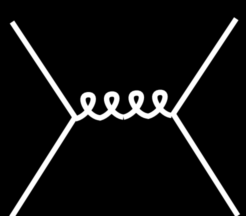

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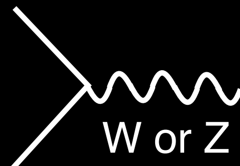
Single boson production ~ $\frac{1}{\sim 1\text{-}10 \text{ Million}}$

Top quark events ~ $\frac{1}{\sim 100 \text{ Million}}$



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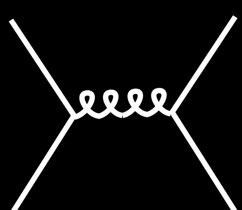

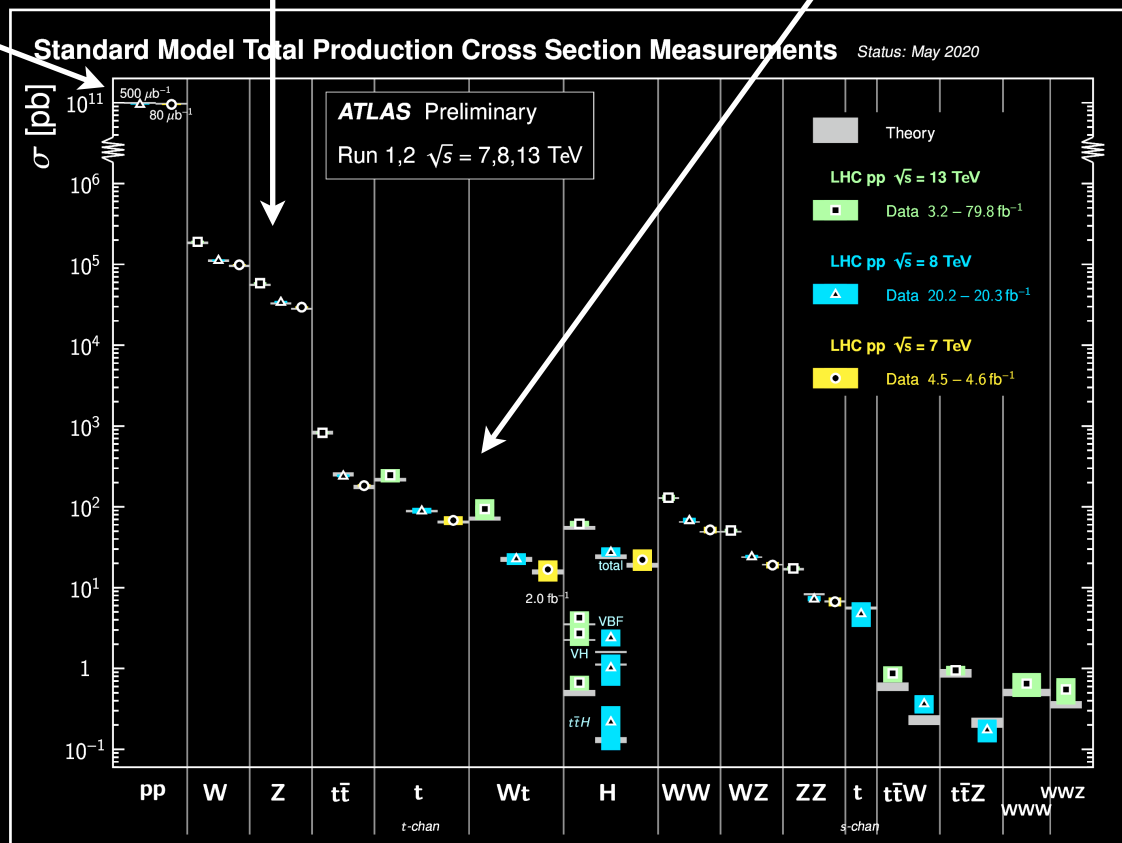

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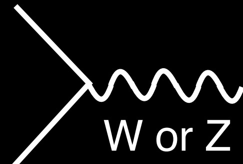

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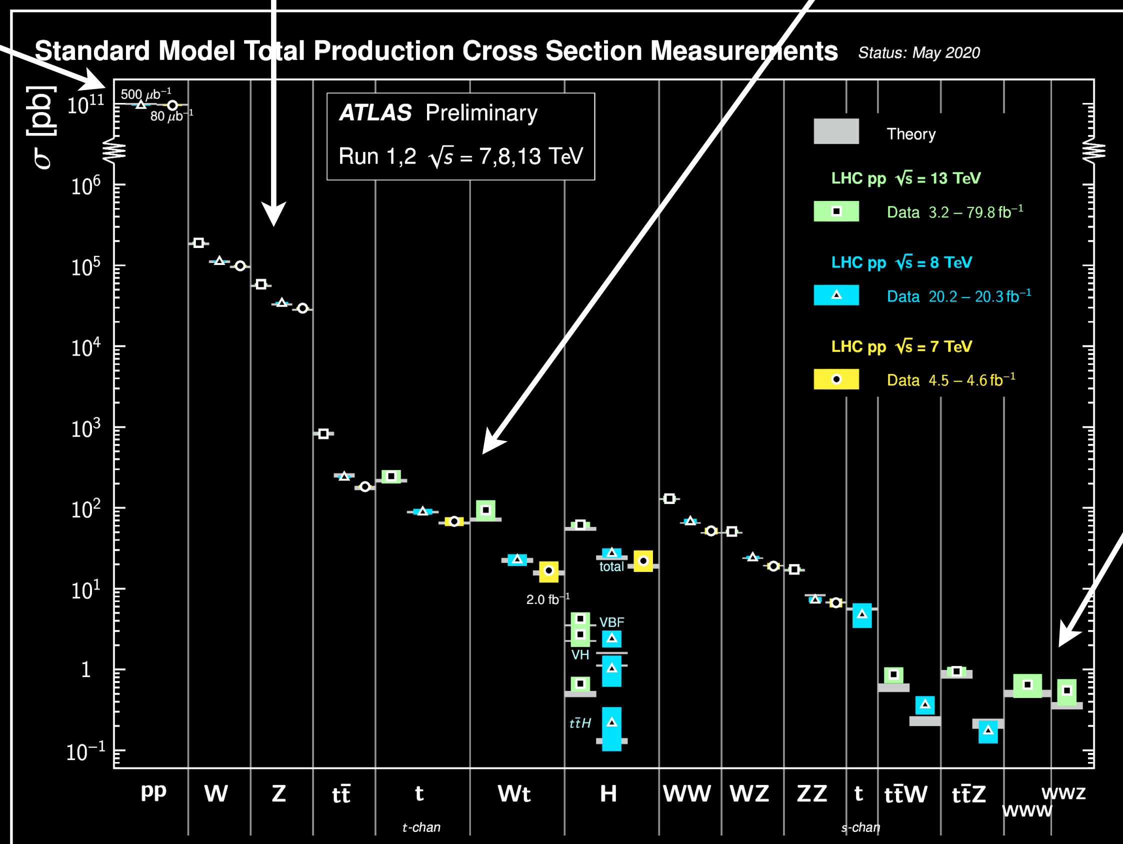
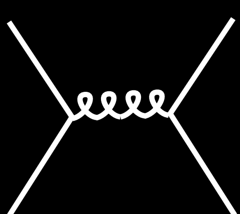




Tri-boson processes ~ $\dfrac{1}{\sim \text{Trillion}}$ or rarer

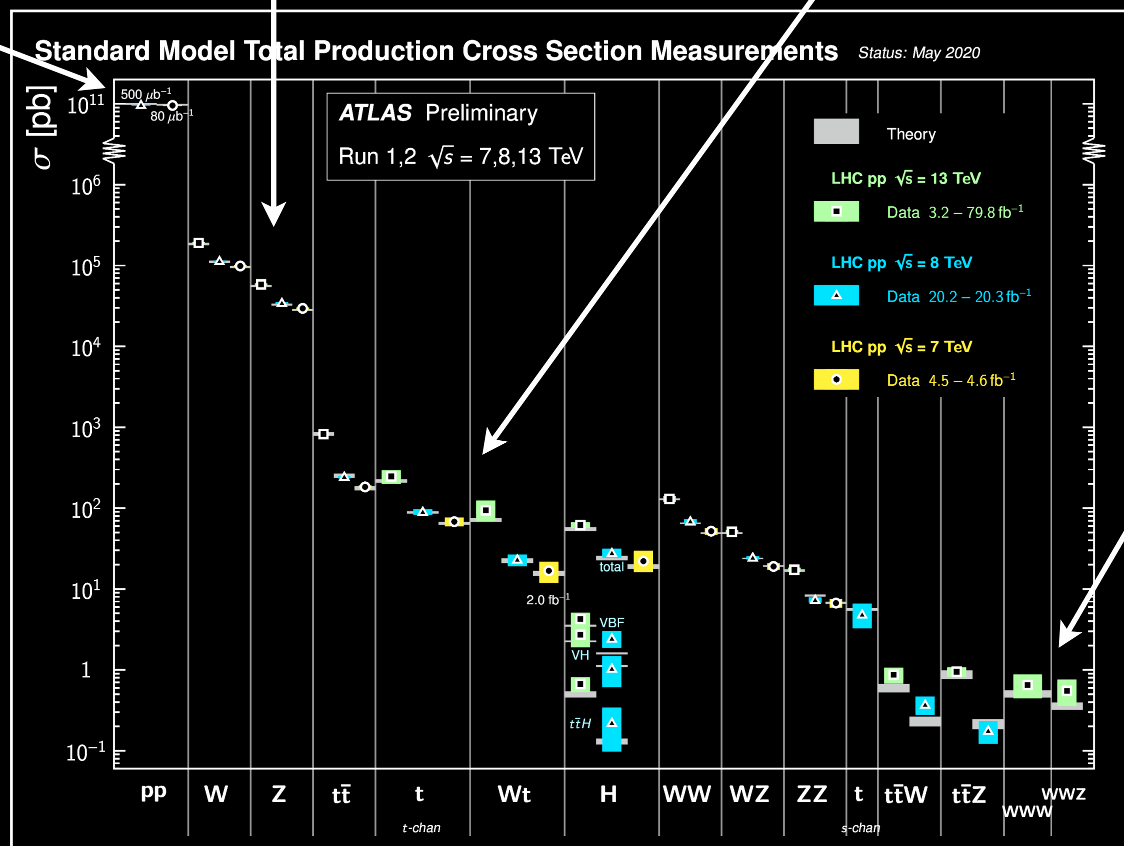
EWK multi-boson processes are rare

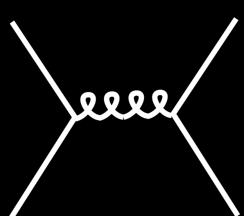
Single boson production ~ $\frac{1}{\text{~1-10 Million}}$

Top quark events ~ $\frac{1}{\text{~100 Million}}$

If total cross section is "1"

Majority are QCD events





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Need to have large number of *pp* collisions to study MBI

EWK multi-boson processes are rare

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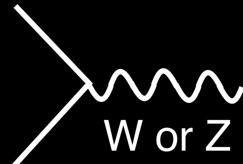
Top quark events ~ $\frac{1}{\sim 100 \text{ Million}}$



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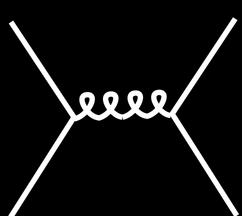
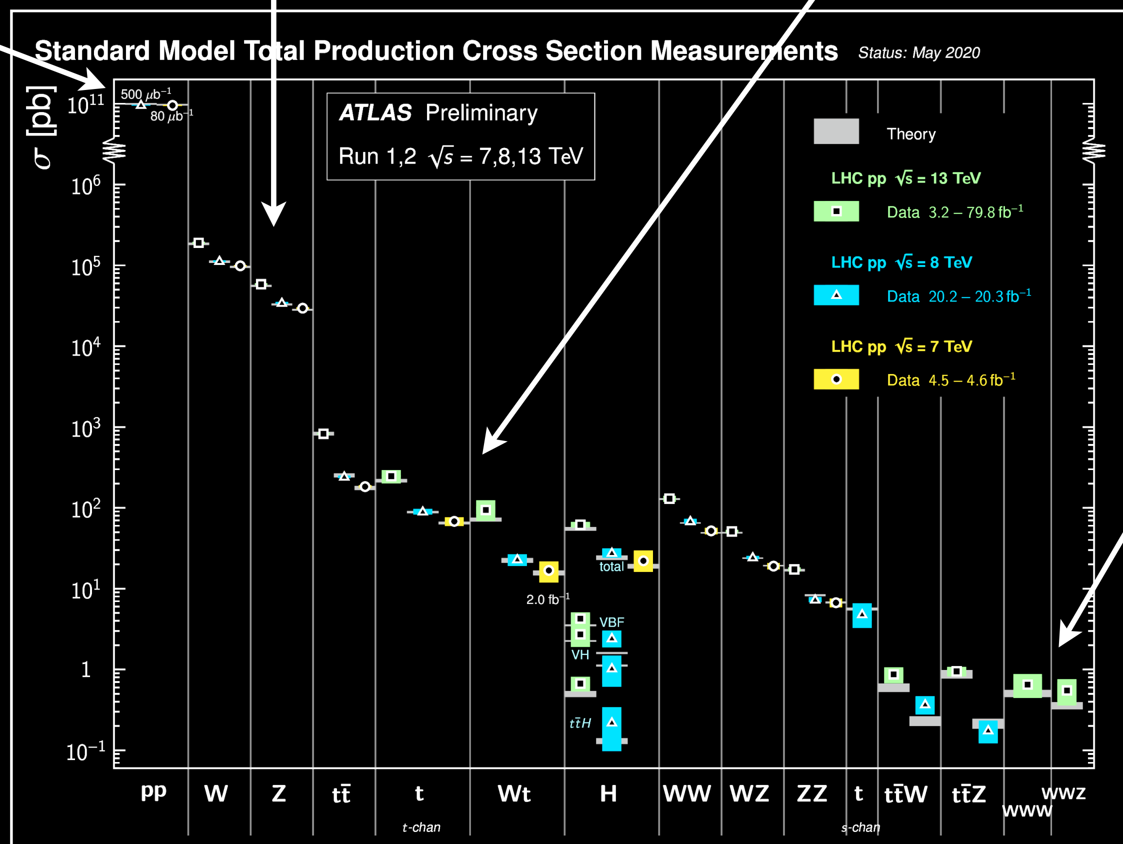


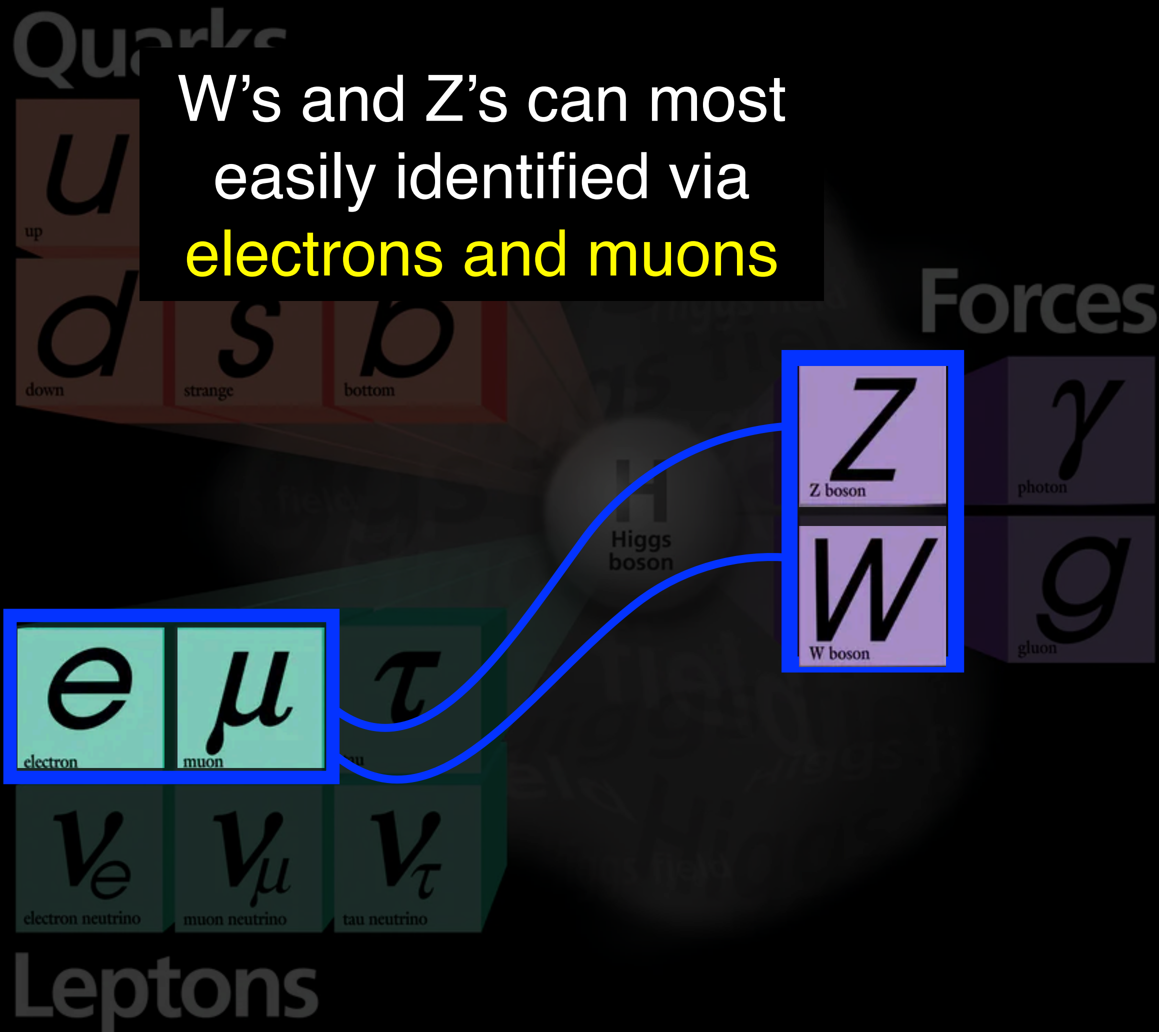


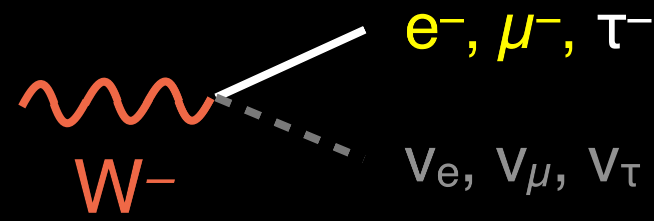
Tri-boson processes ~ $\frac{1}{\sim \text{Trillion}}$ or rarer

Need to have large number of *pp* collisions to study MBI
(Also energetic since N × ~100 GeV particles)

Decay of W, Z bosons

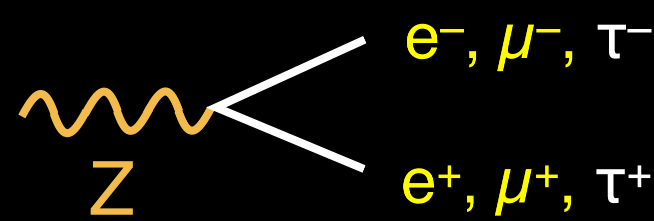
W's and Z's can most easily identified via electrons and muons





BR ~10% each flavor

Branchng ratio (BR)



BR ~3% each flavor

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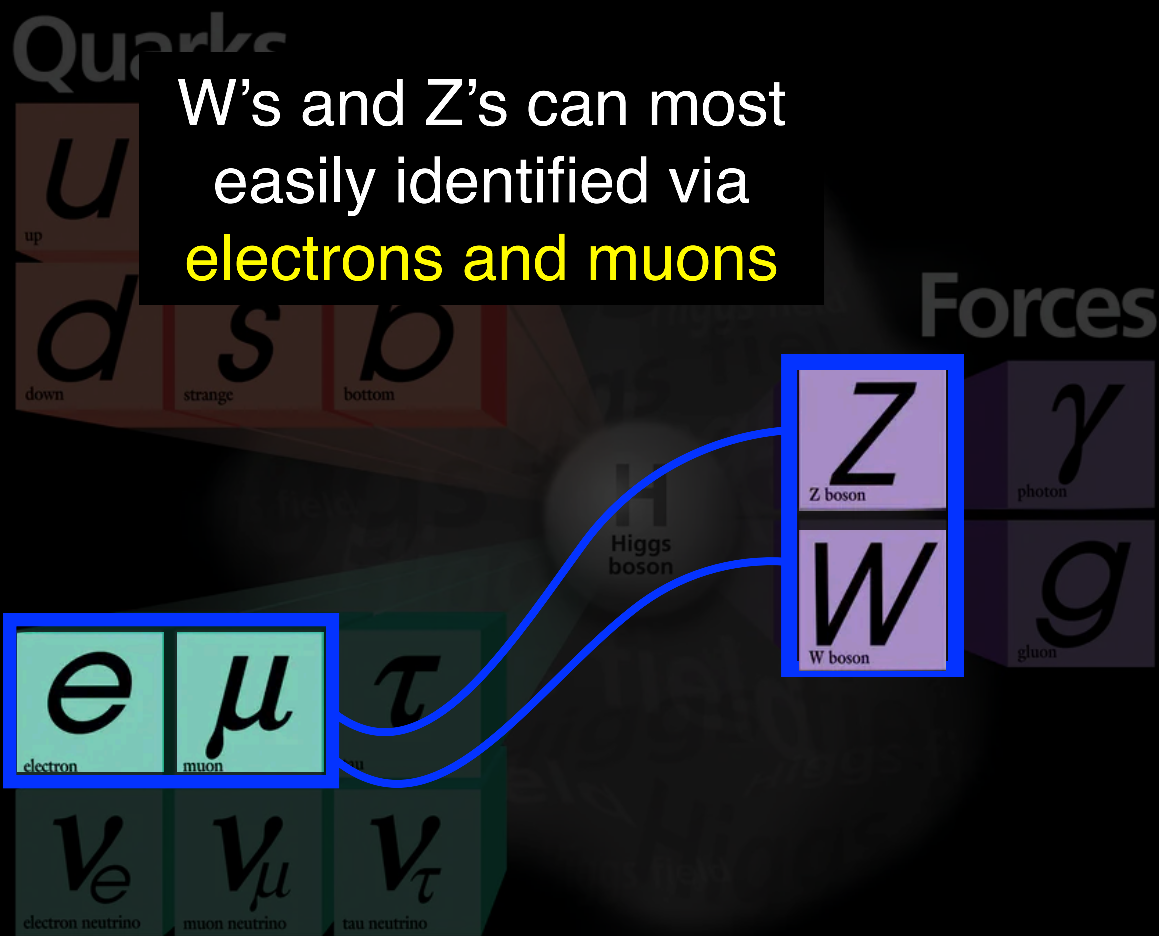

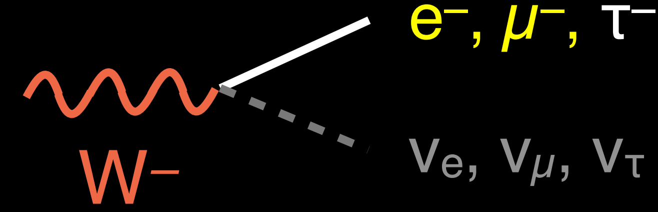

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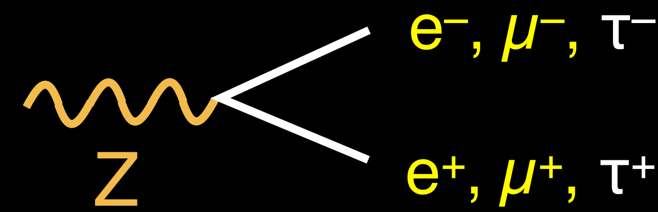


BR ~3% each flavor

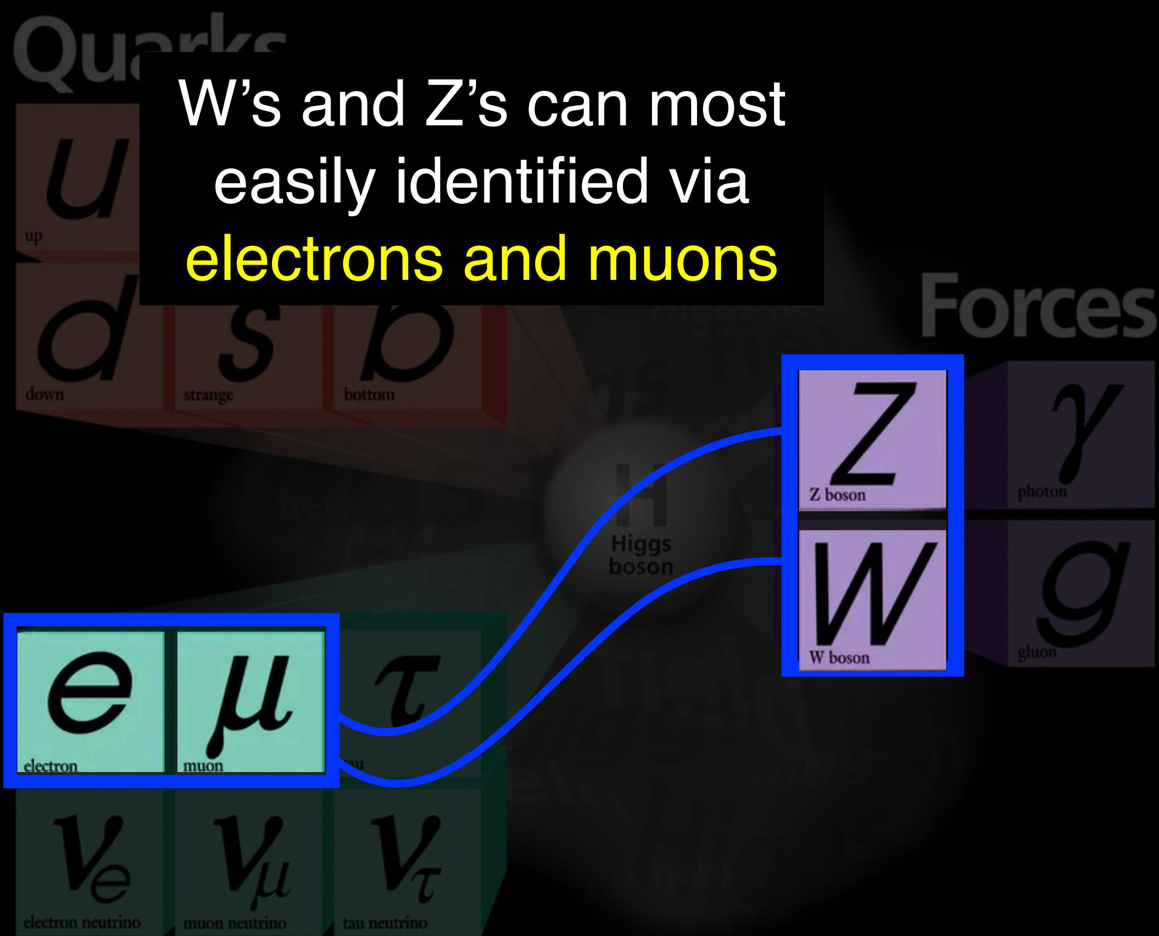
e.g. If all W's from pp → WWW decays to e or μ's ⇒ O(100s) events

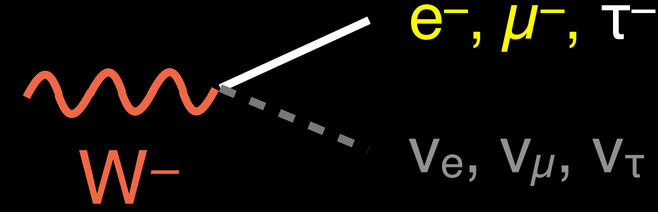
If all Z's from pp → ZZZ decays to e or μ's ⇒ ~2 events

(more details in later slides)

Decay of W, Z bosons

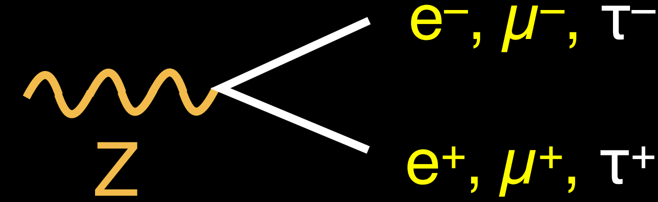
W's and Z's can most easily identified via electrons and muons





BR ~10% each flavor

Branchng ratio (BR)



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(more details in later slides)

W's and Z's can be identified via e and μ (but pay the price of BR)

Decay of W, Z bosons

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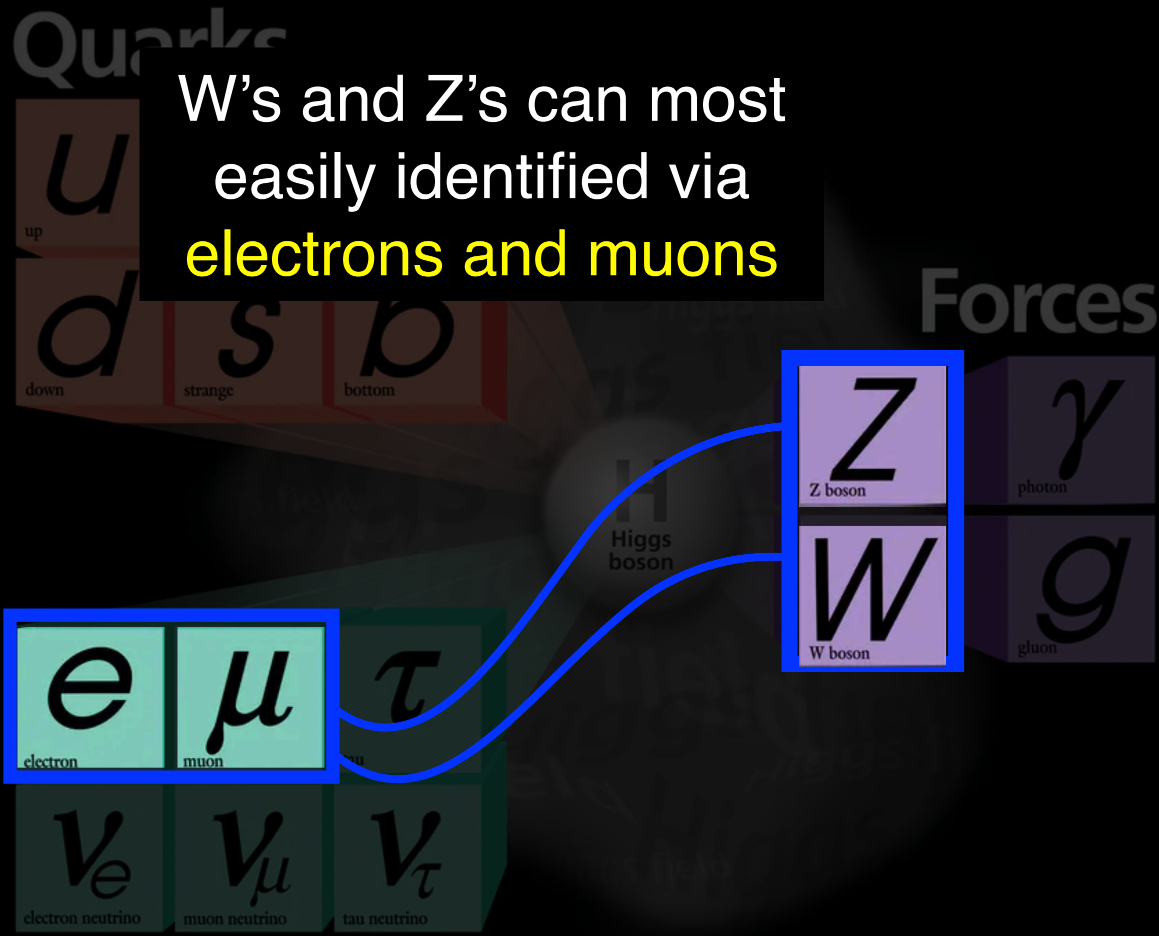

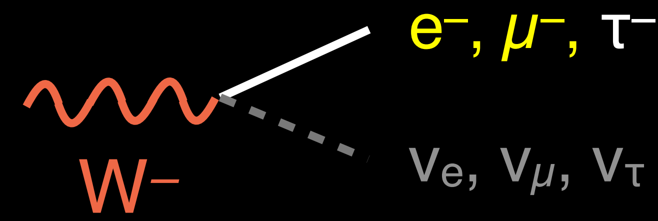

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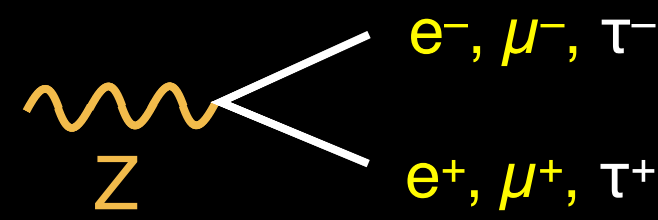
Branchng ratio (BR)



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(more details in later slides)

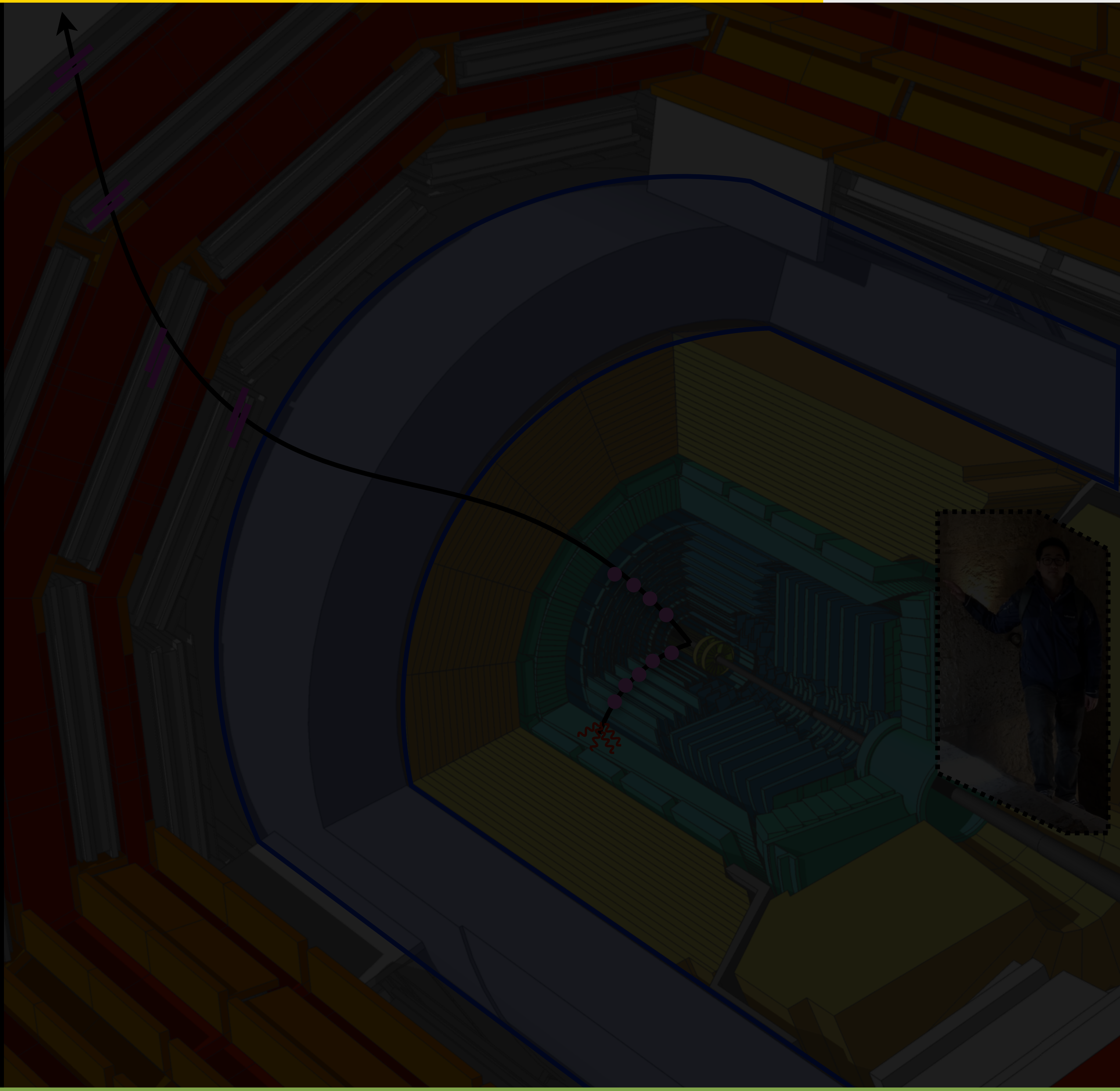
W's and Z's can be identified via e and μ (but pay the price of BR)

⇒ Crucial to identify e and μ well

Classifying leptons' origins

Identifying leptons is not enough

We need to further classify the origin



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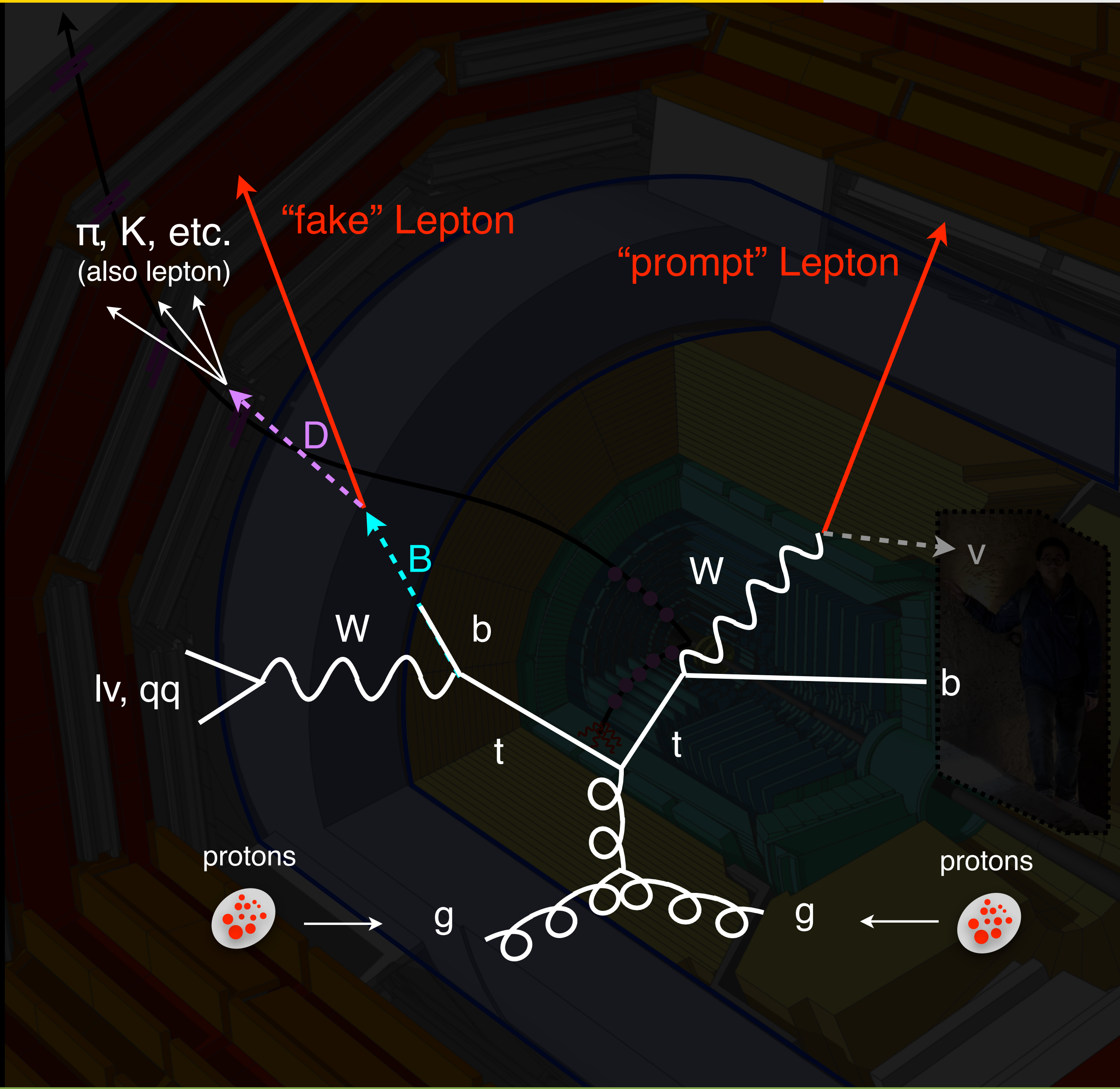

Classifying leptons' origins

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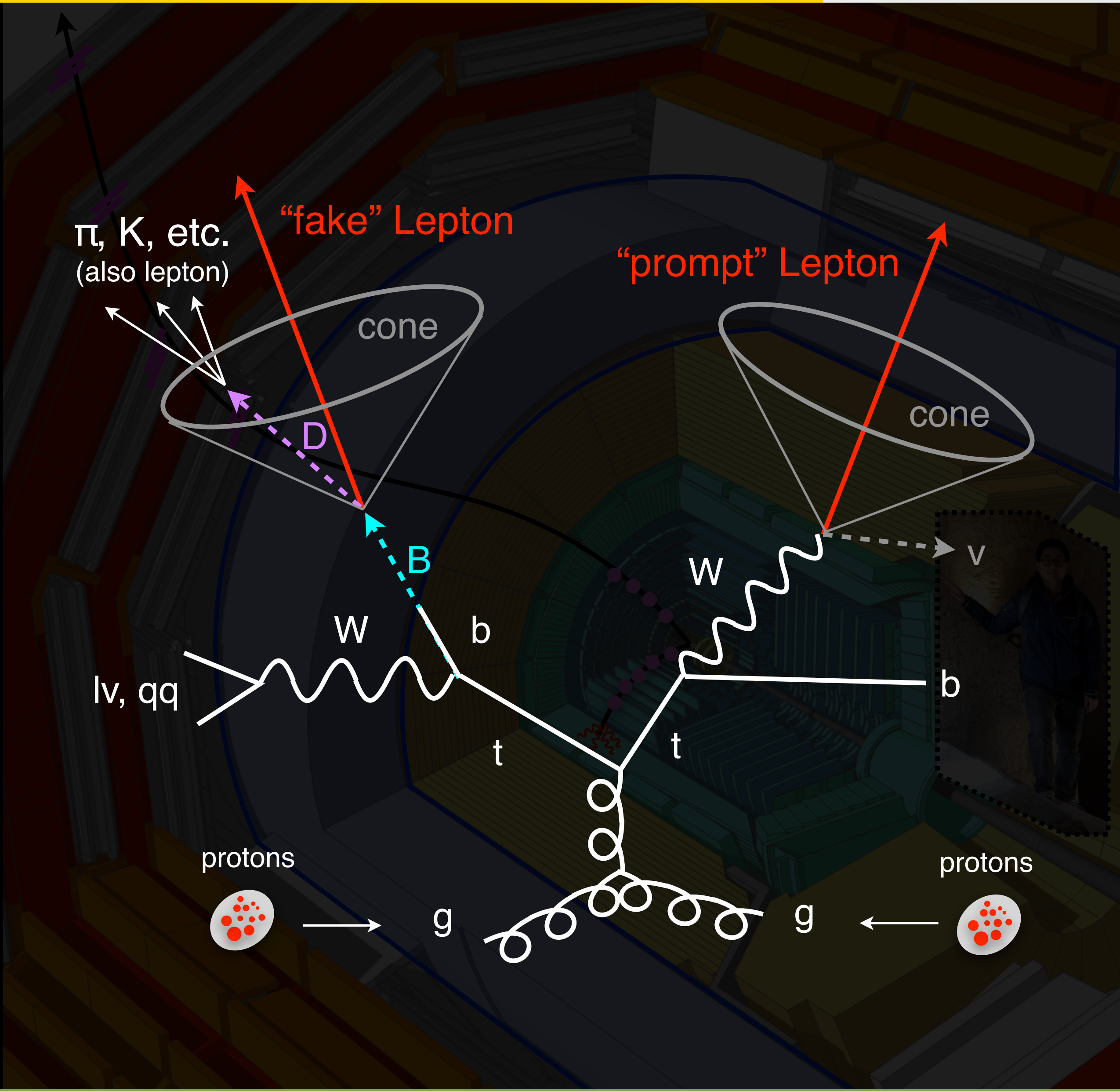
$$\text{Isolation} = \frac{\Sigma_{\text{"stuff" in cone}} P_T}{P_{T,\text{Lepton}}}$$



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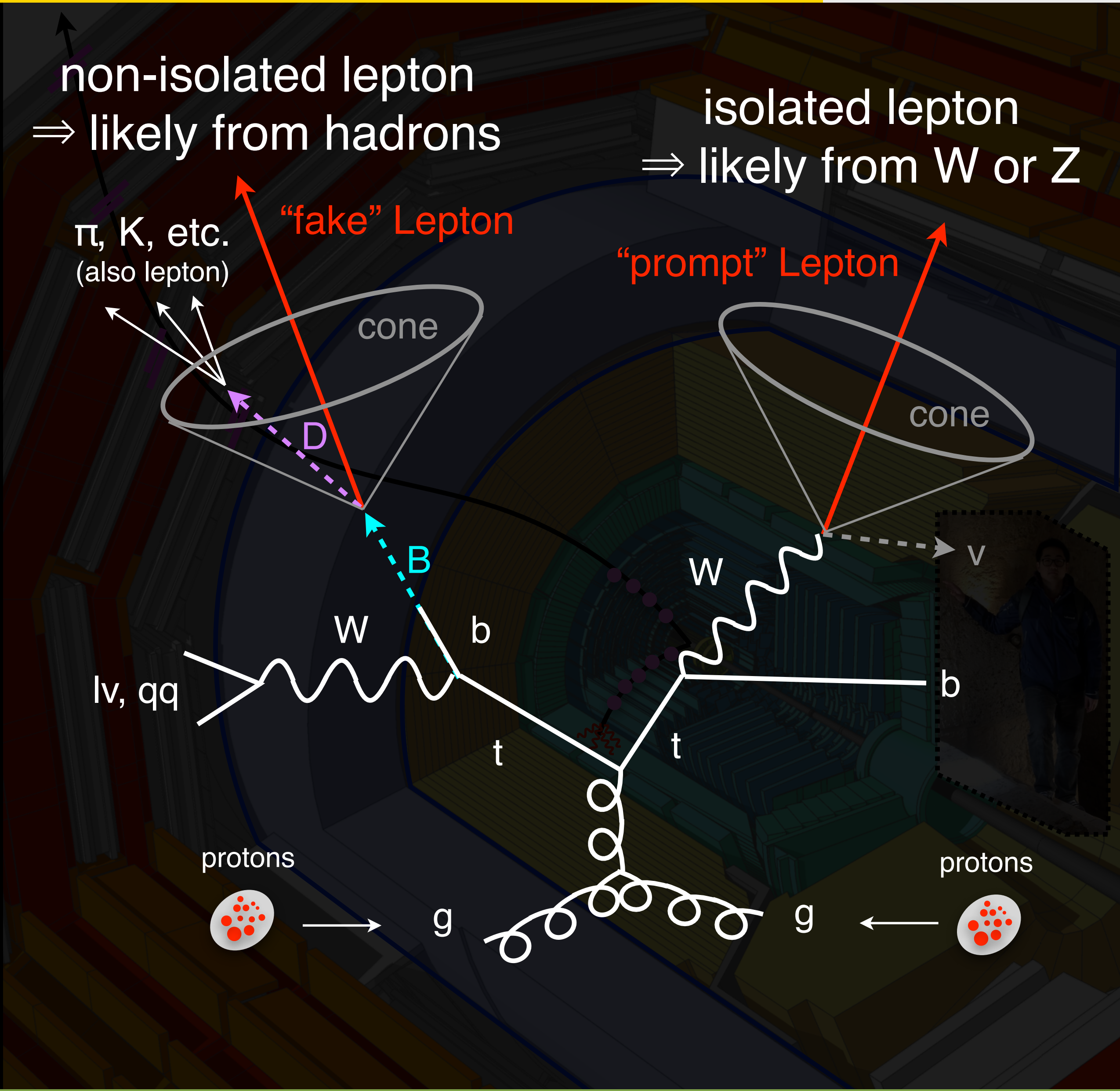

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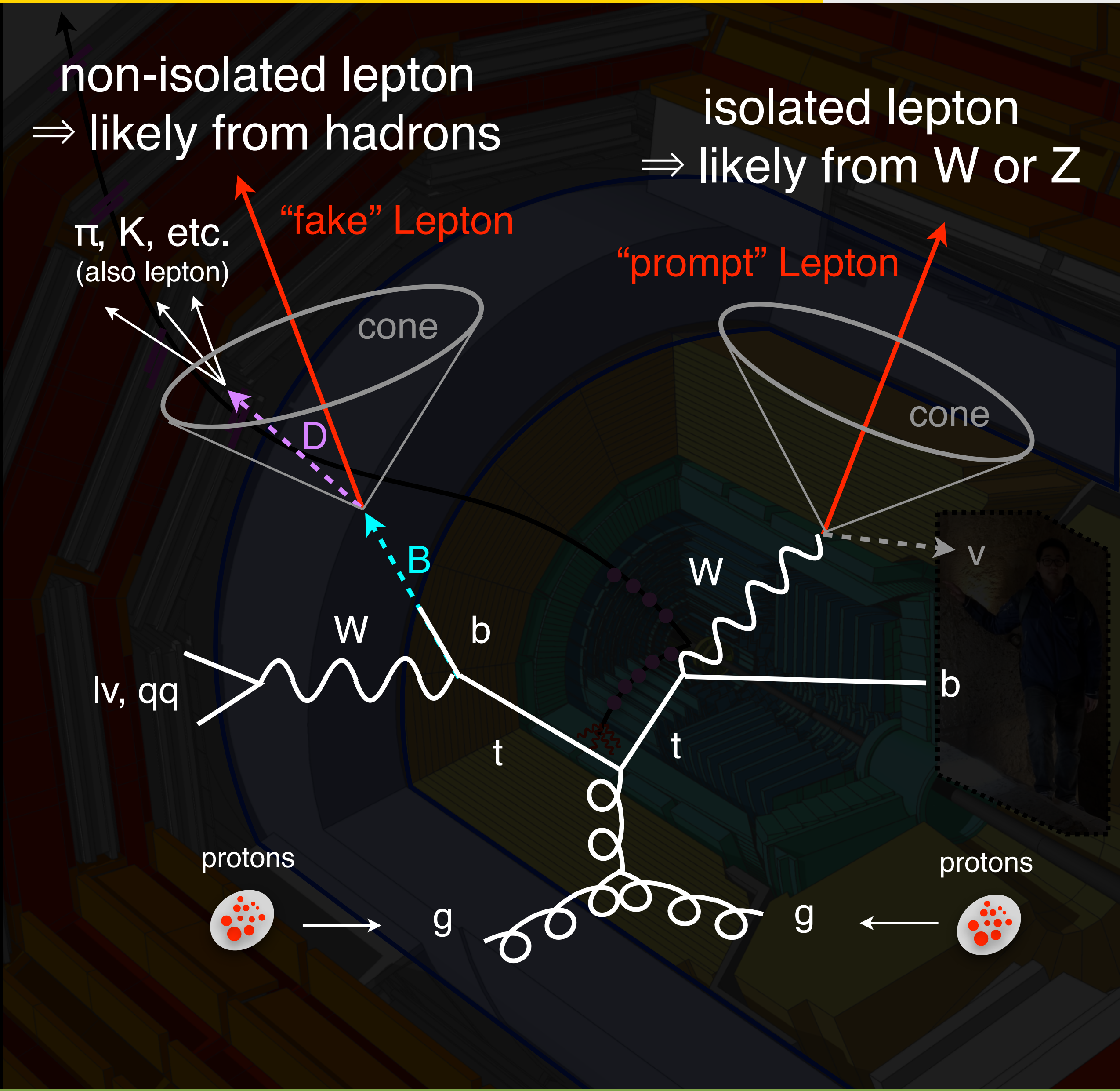
N.B. electrons and muons have different effects (muons are cleaner)



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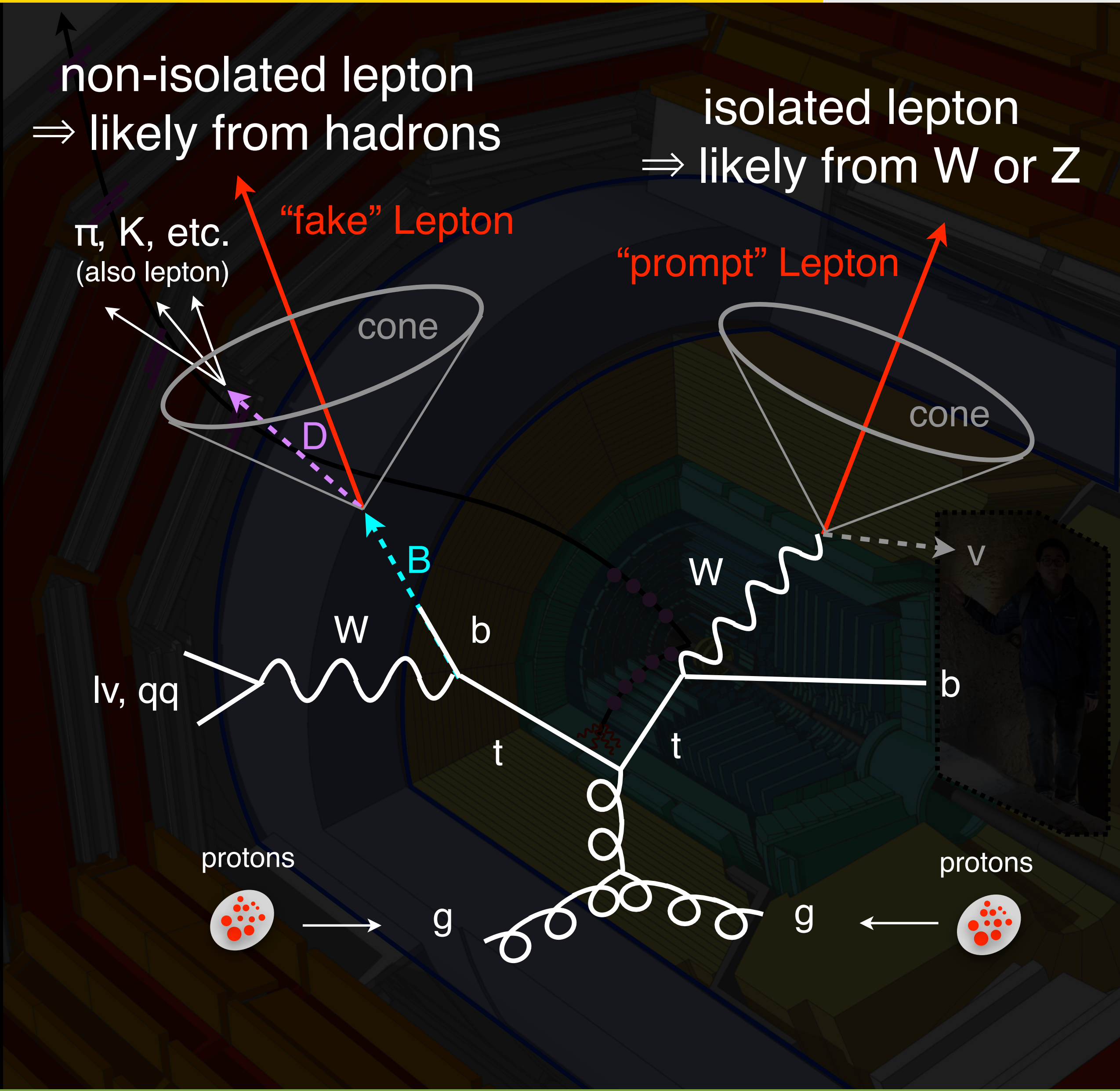


Use isolation to discriminate against leptons from heavy flavor decay

Dubbed “fake lepton”

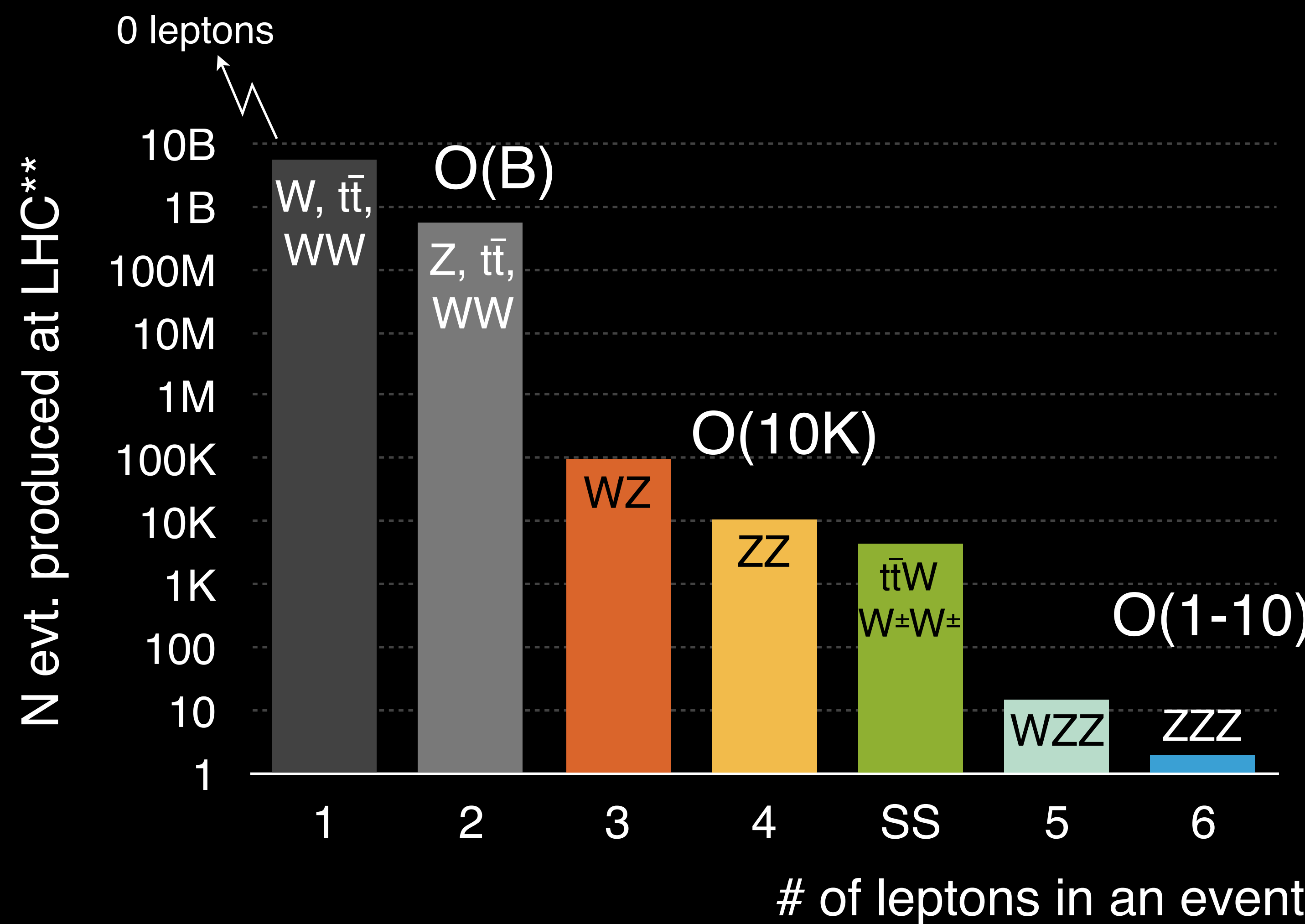
4 steps to VVV observation

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)

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 $\tau \to e, \mu$



Overview of lepton physics at the LHC

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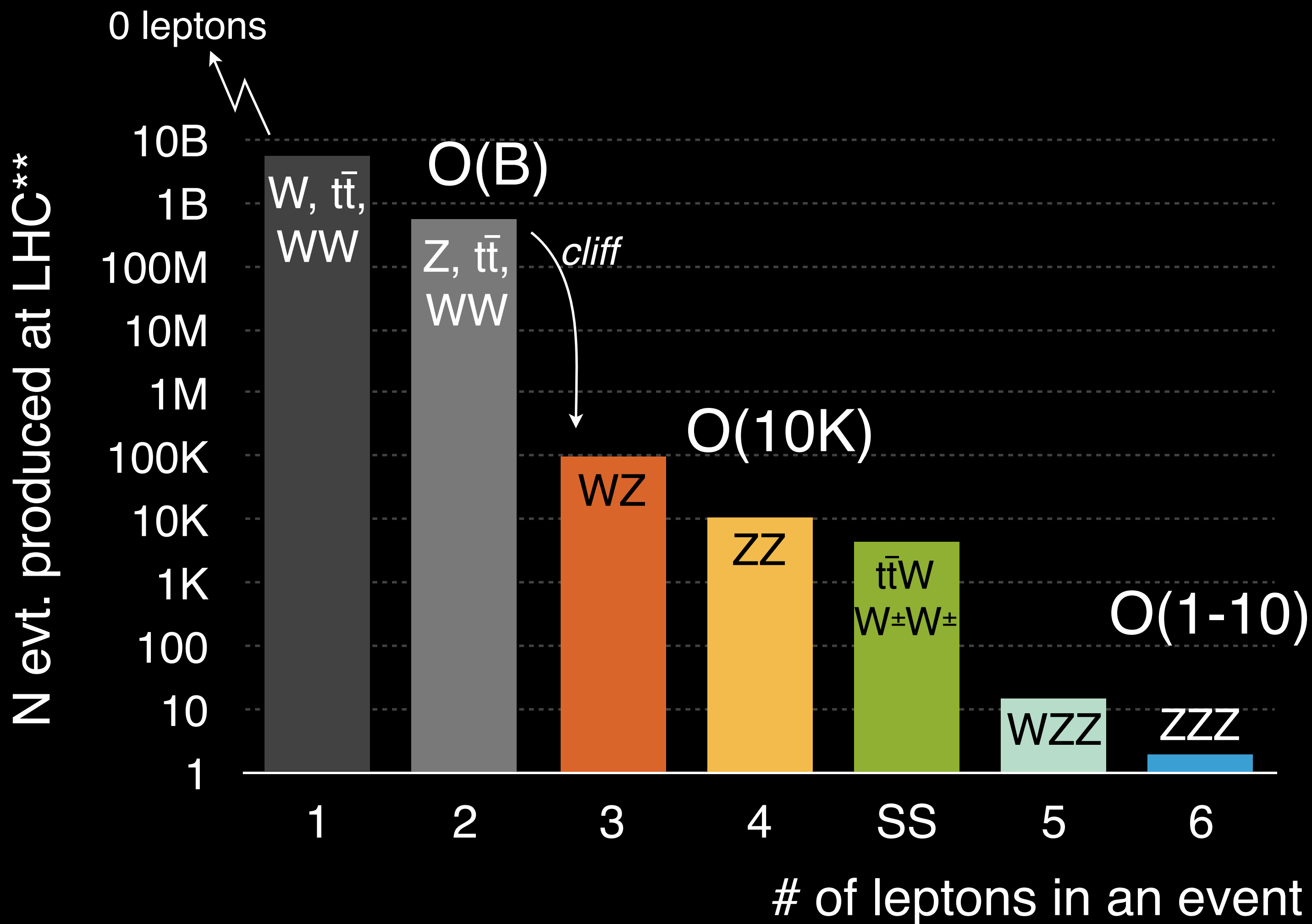

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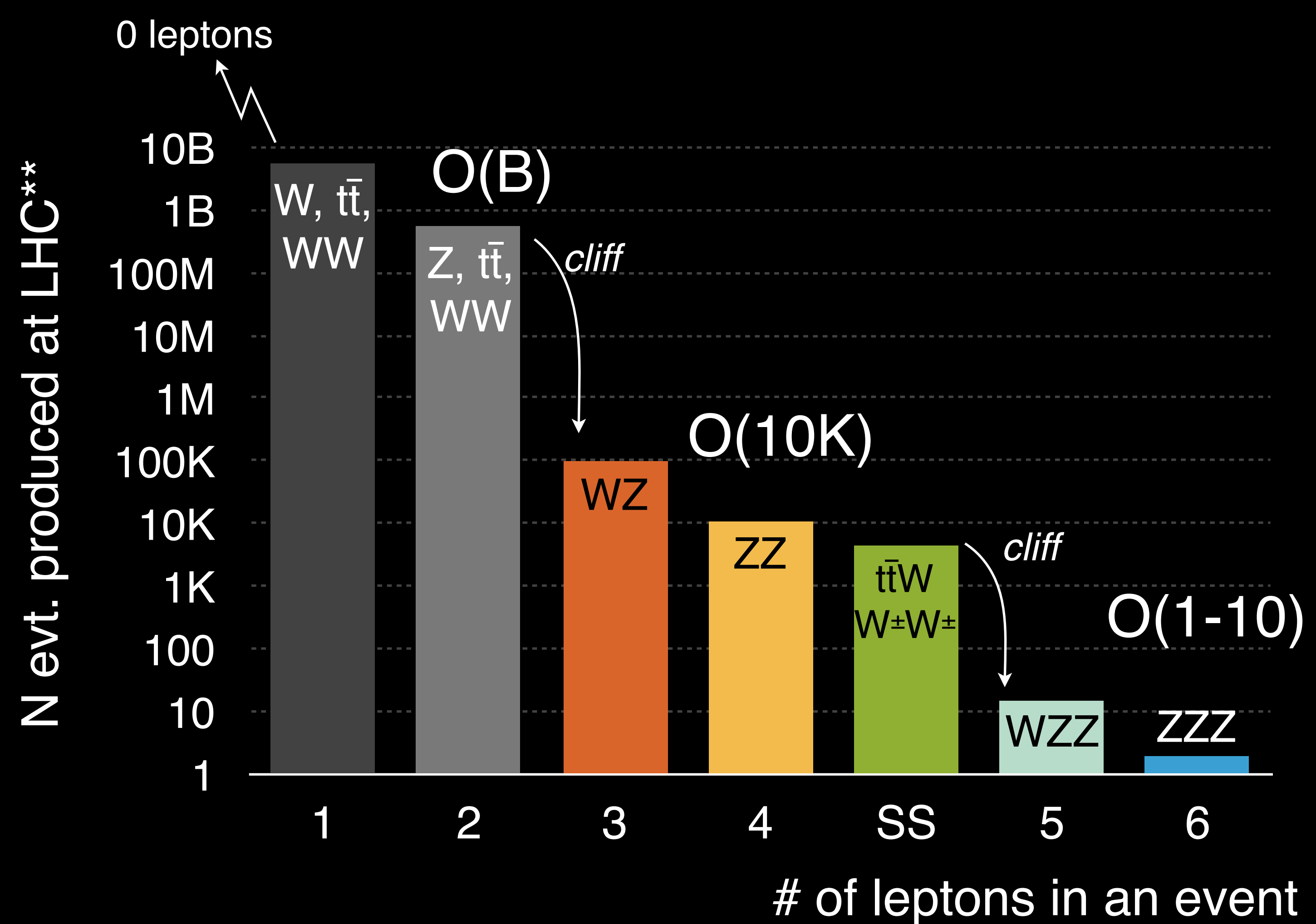

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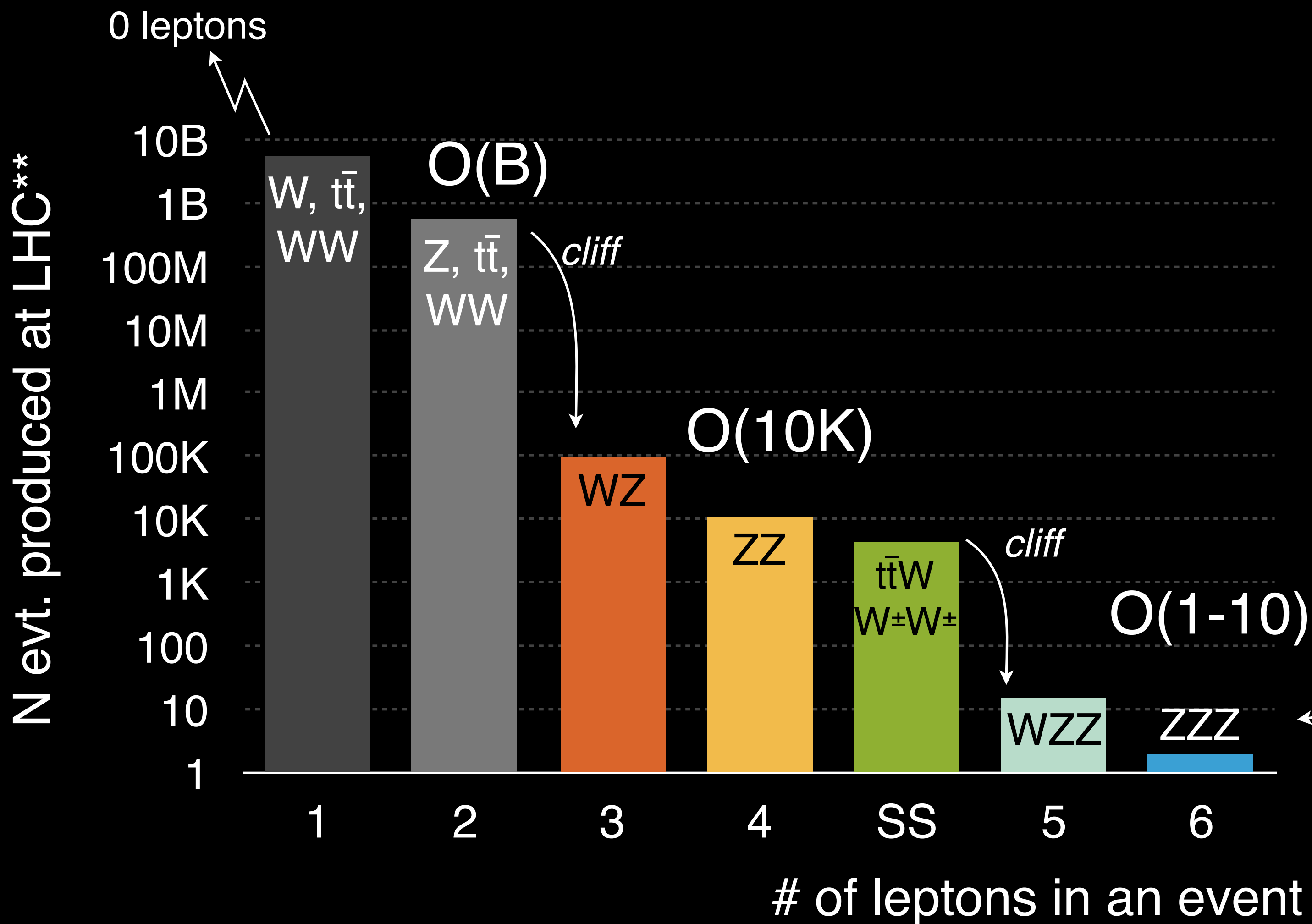

If one only looks at 5 or 6 lepton events, there will be very small backgrounds

Overview of lepton physics at the LHC

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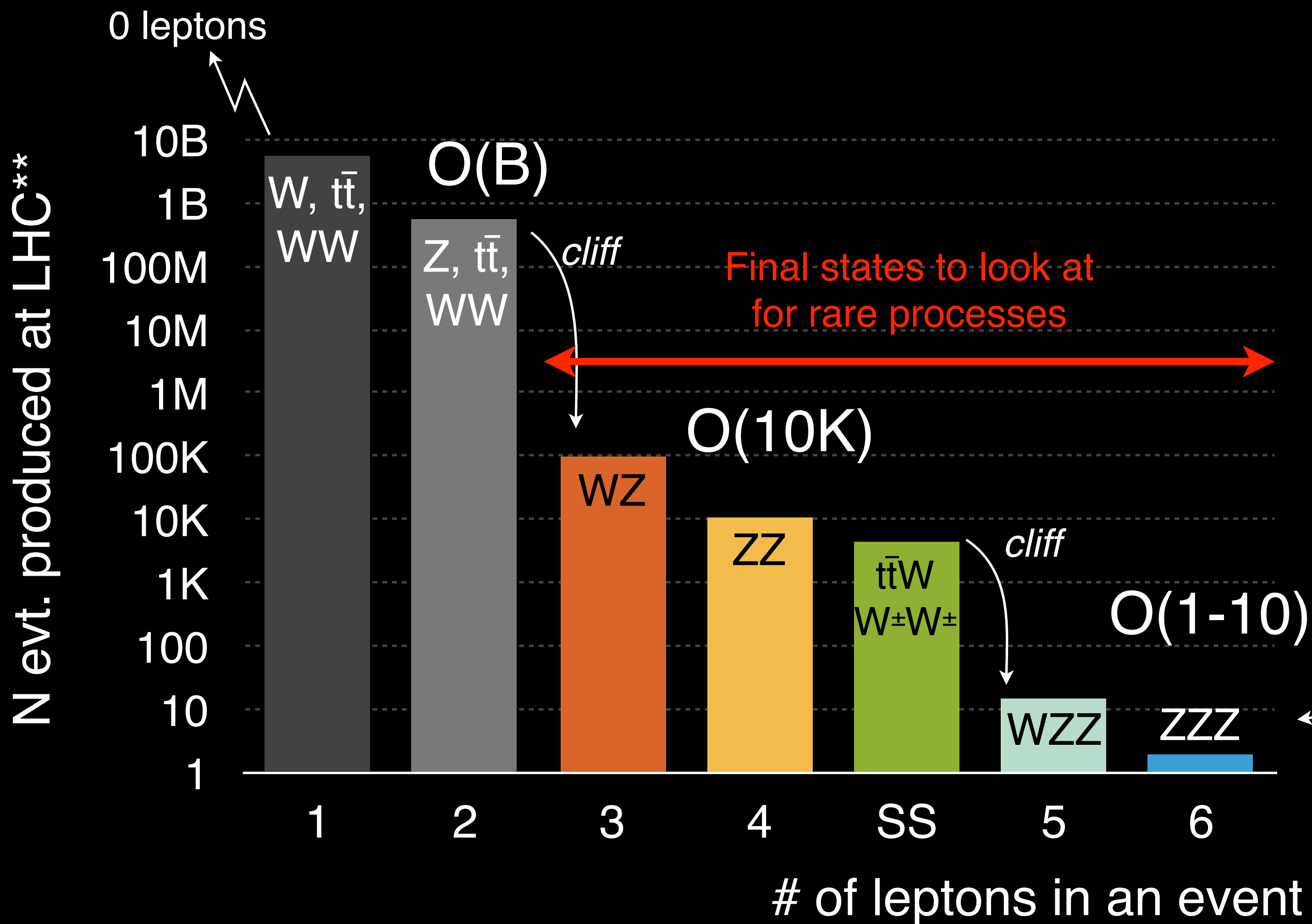

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Overview of lepton physics at the LHC

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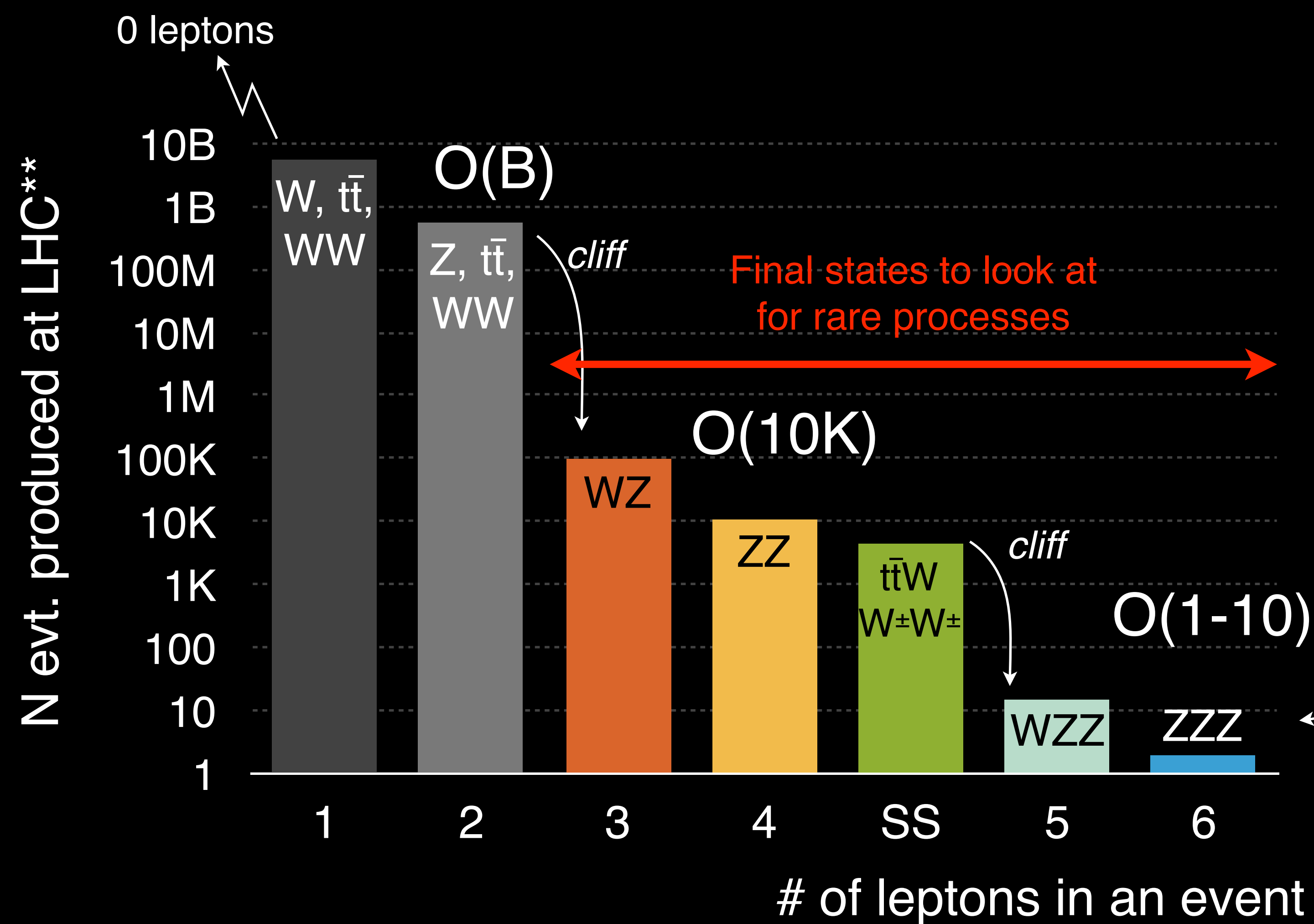
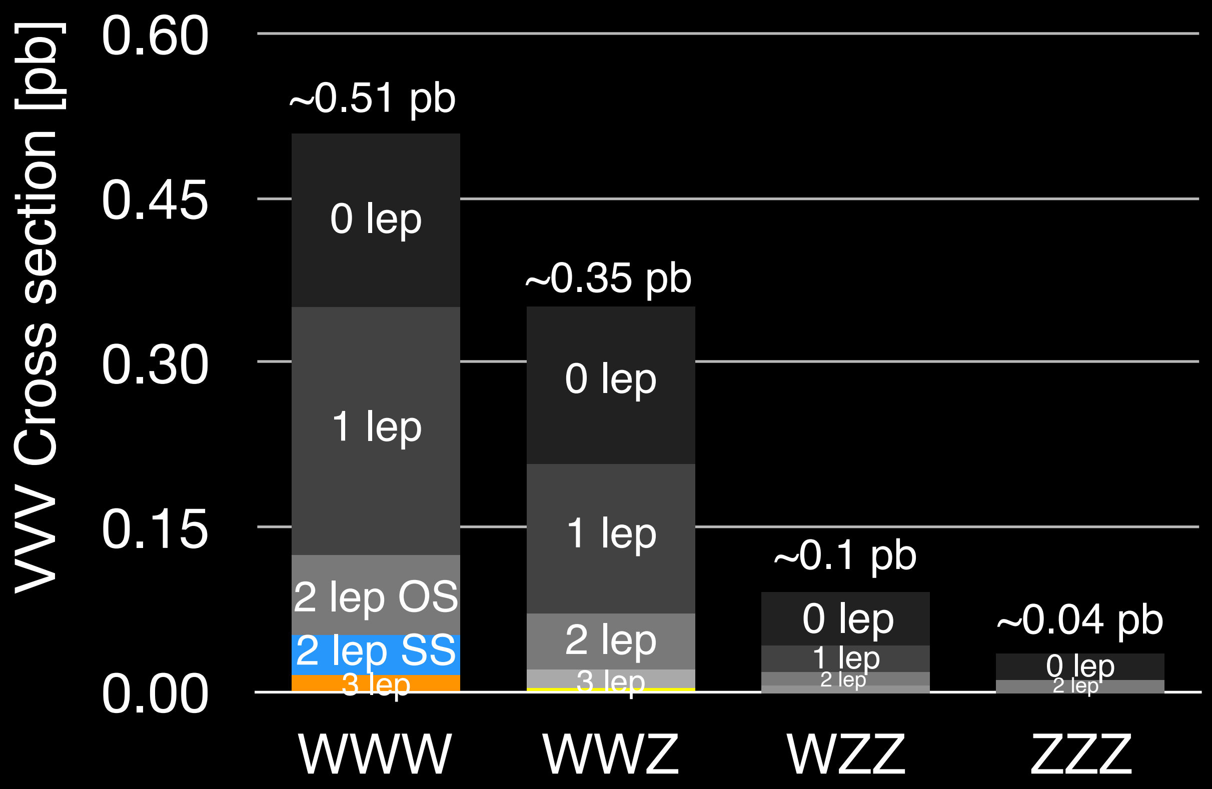


If one only looks at 5 or 6 lepton events, there will be very small backgrounds

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

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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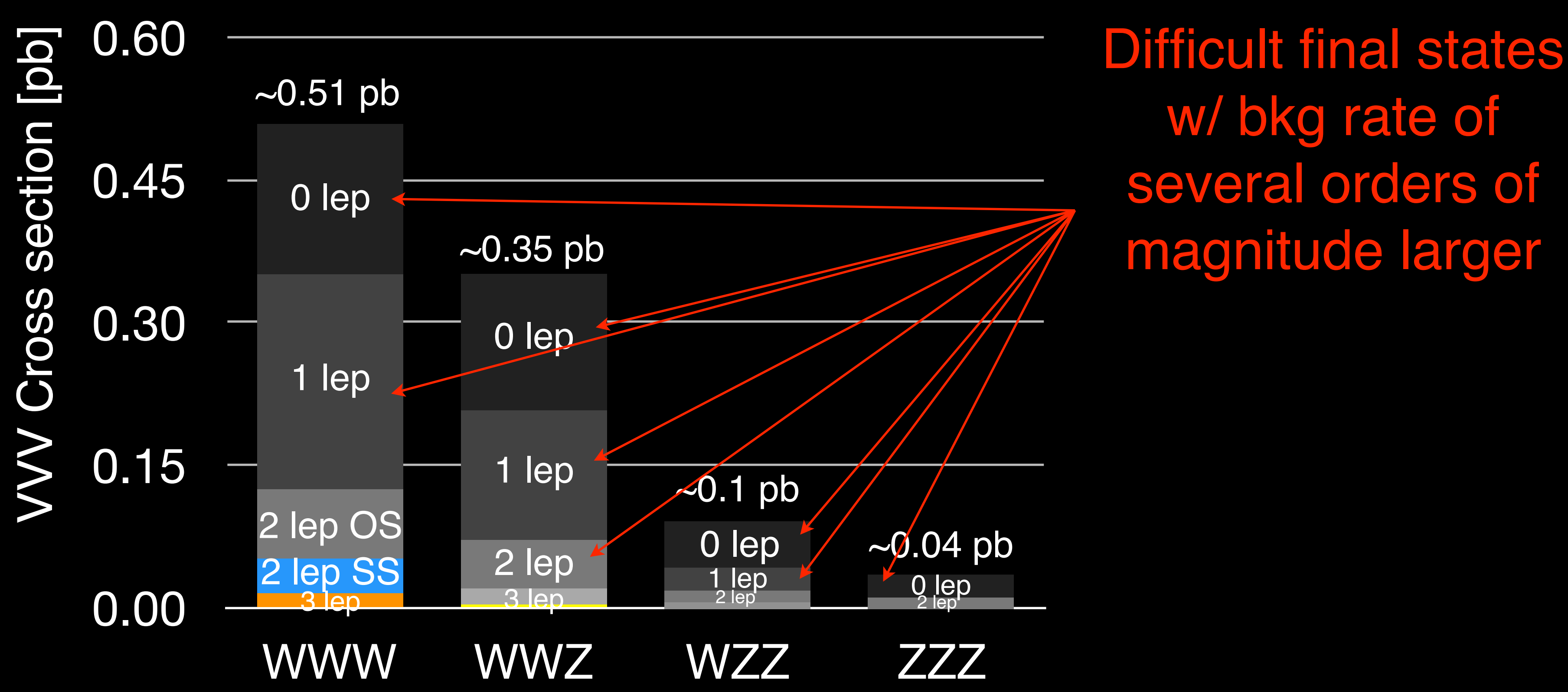
Production cross section decreases with more Z's



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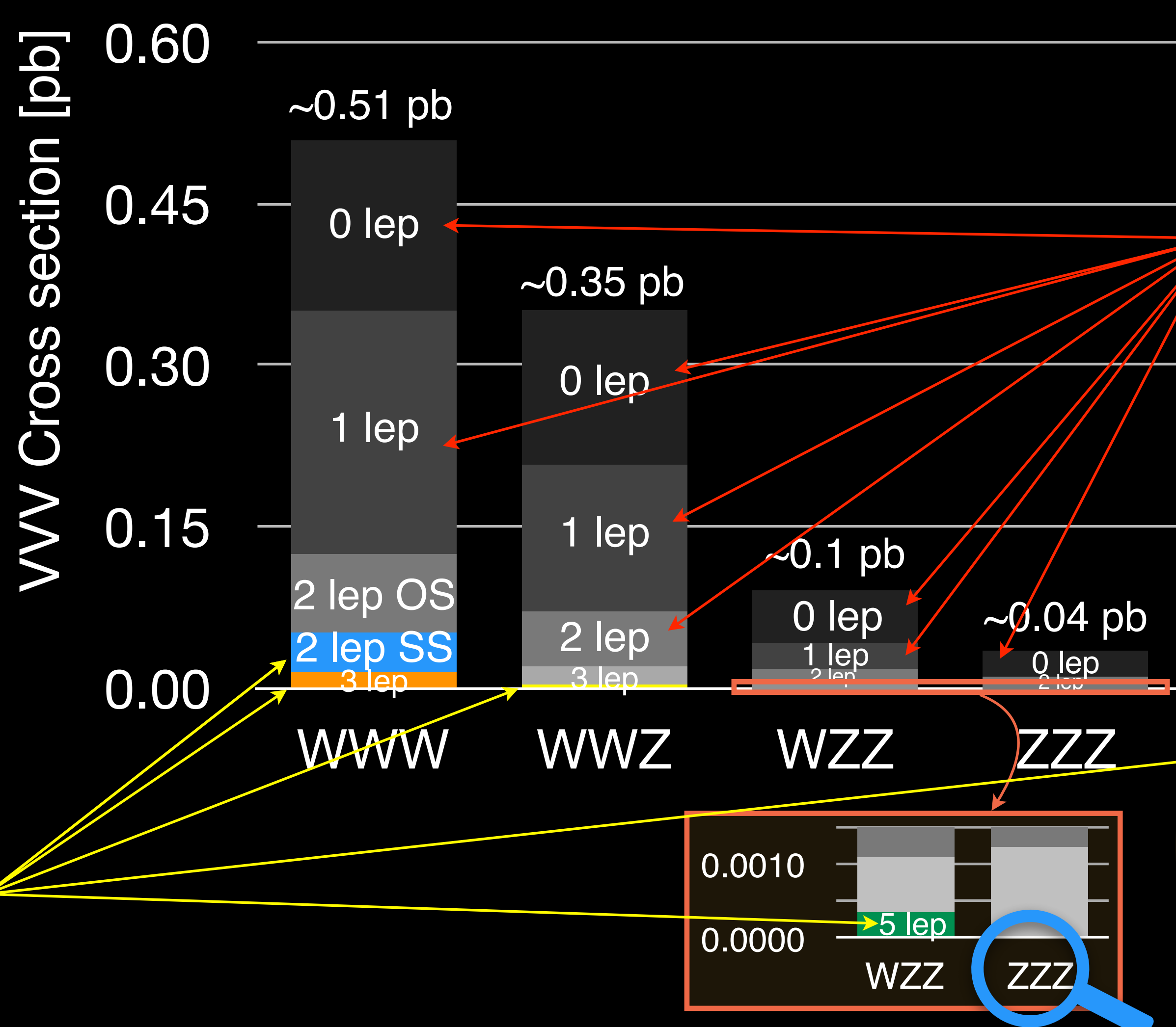

Difficult final states w/ bkg rate of several orders of magnitude larger

Viable

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
Signals	$W^{\pm} \to l^{\pm}\nu$ $W^{\pm} \to l^{\pm}\nu$ $W^{\mp} \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
	~2.5k evt.	~700 evt.	~140 evt.	~15 evt.	~1.5 evt.

~5k - 50k produced → ~few to ~few k after BR

**Before acceptance and lepton ID efficiency applied

VVV analyses overview by N leptons

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

One exception (→ Same-sign)

	Same-sign	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \to l^\pm\nu$ $W^\pm \to l^\pm\nu$ $W^\mp \to qq$ ~2.5k evt.	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$ ~700 evt.	$W \to l\nu$ $W \to l\nu$ $Z \to ll$ ~140 evt.	$W \to l\nu$ $Z \to ll$ $Z \to ll$ ~15 evt.	$Z \to ll$ $Z \to ll$ $Z \to ll$ ~1.5 evt.
Dominant Bkgs.	$WZ \to l^\pm\nu l^\pm l^\mp$ (lost: $l^\mp$) $t\bar{t} \to bb + ll + X$ ↳ fake l	WZ→3l ~100k $WZ \to l\nu ll$ $t\bar{t} \to bb + ll + X$ ↳ fake l	ZZ→4l ~10k $ZZ \to llll$ $ttZ \to llll$ + bbX	$ZZ \to llll$ + fake lep	$ZZ \to llll$ + 2 fake lep

VVV analyses overview by N leptons

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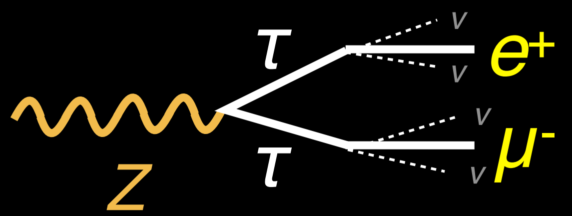
Signals	$W^\pm \to l^\pm \nu$ $W^\pm \to l^\pm \nu$ $W^\mp \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
	~2.5k evt.	~700 evt.	~140 evt.	~15 evt.	~1.5 evt.
Dominant Bkgs.	$WZ \to l^\pm \nu l^\pm l^\mp$ ($l^\mp$ lost) $t\bar{t} \to bb + ll + X$ ↳ fake l	WZ→3l ~100k $WZ \to l\nu ll$ $t\bar{t} \to bb + ll + X$ ↳ fake l	ZZ→4l ~10k $ZZ \to llll$ $ttZ \to llll$ + bbX	$ZZ \to llll$ + fake lep	$ZZ \to llll$ + 2 fake lep

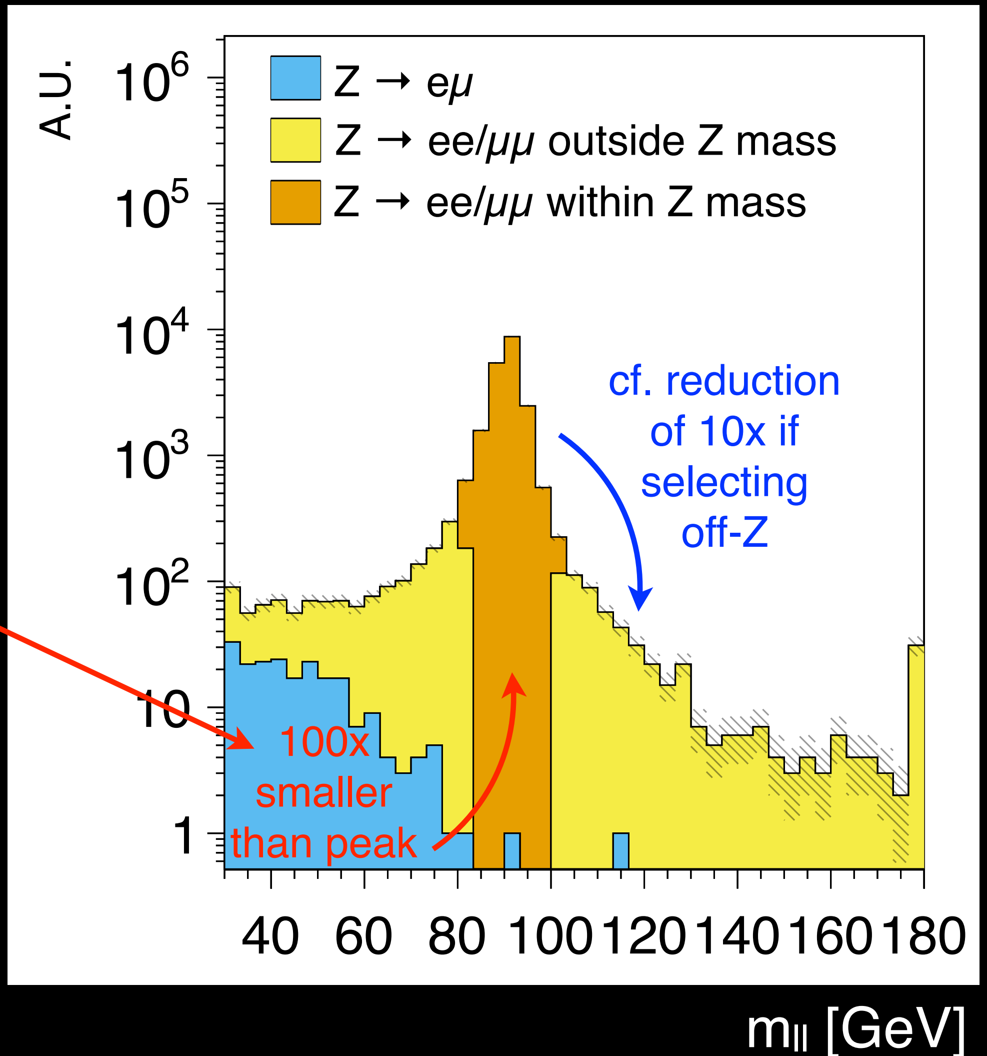
Different modes populate different N lepton bins
Some cross contamination between N lepton bins exists but is small

Features of Z → ll decay



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

Plot of dilepton mass from Z→ll decay

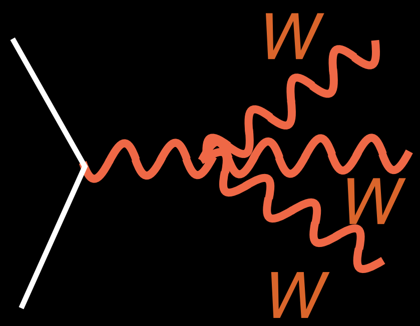


**Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV P_T cuts

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

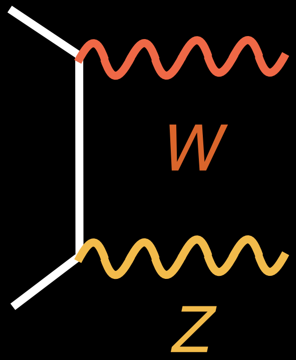
Flavor choices

WWW signal



pp → WWW

Background

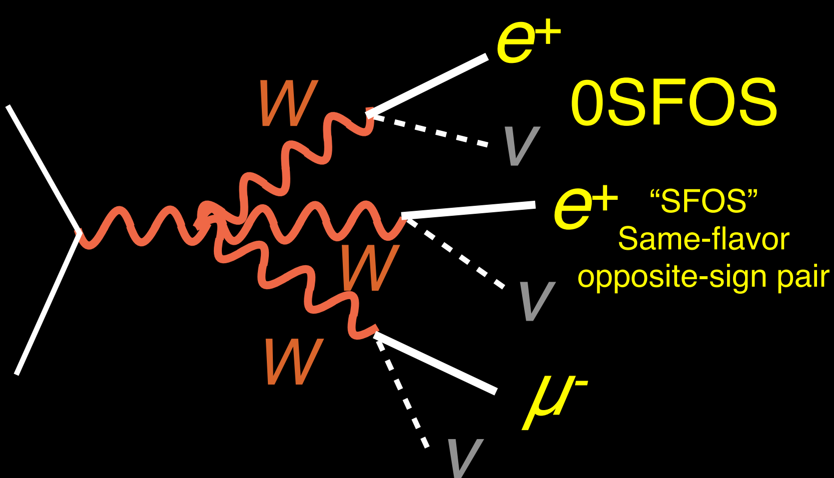


pp → WZ

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

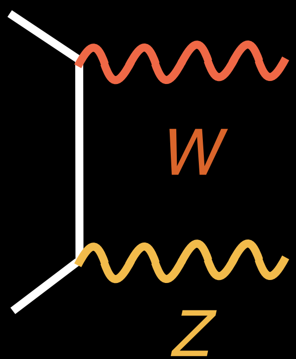
Flavor choices

WWW signal



$pp \to WWW \to e^+e^+\mu^-$

Background

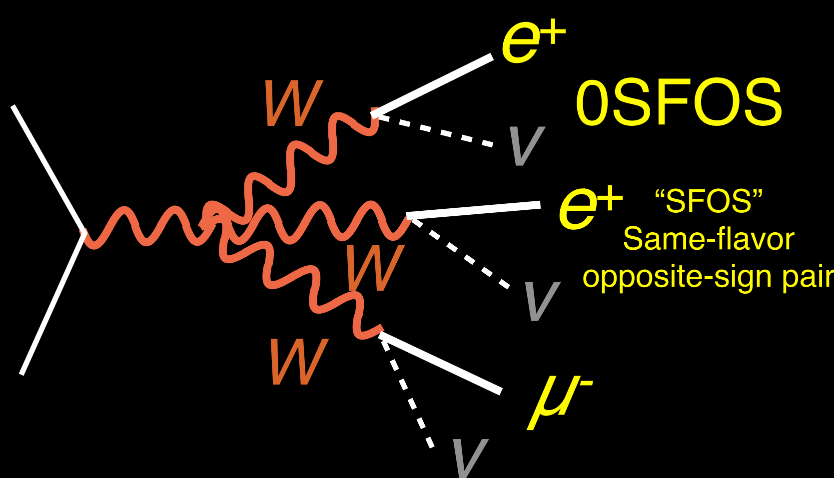


$pp \to WZ$

Backgrounds are suppressed via disfavored decay topology of $Z \to \tau\tau \to e\mu$

Flavor choices

WWW signal



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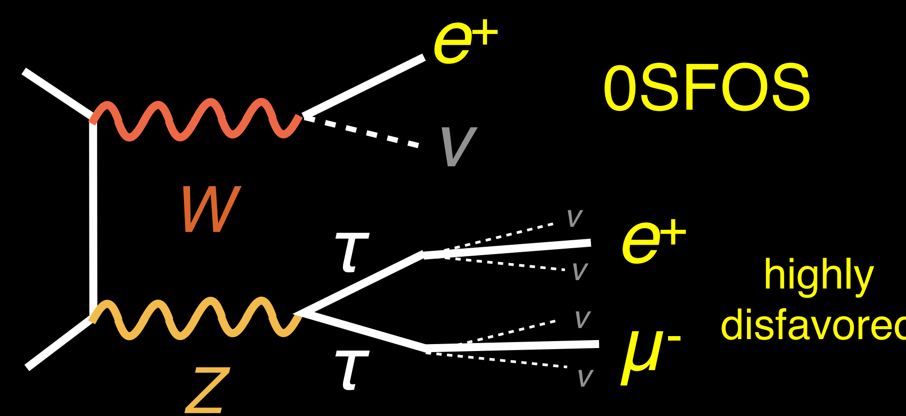

pp → WWW → $e^+e^+\mu^-$

pp → WZ → $e^+e^+\mu^-$

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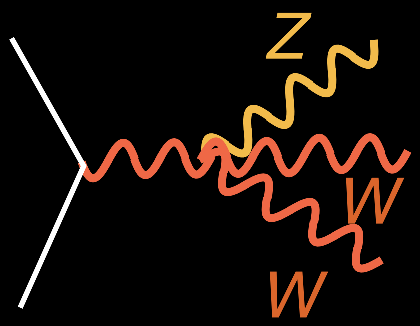
Flavor choices

WWW signal



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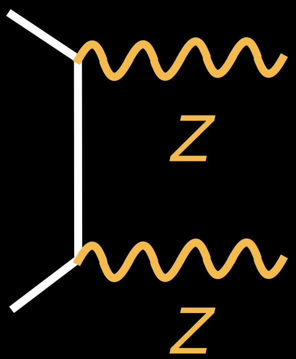

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Flavor choices

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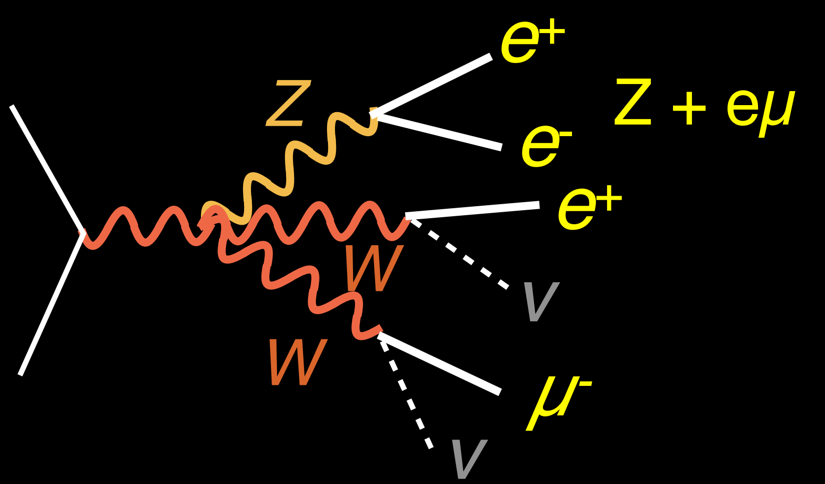
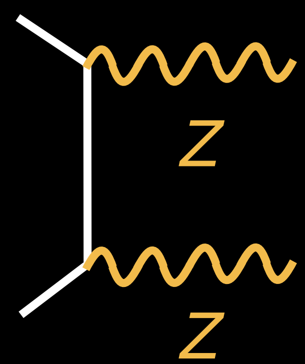


$pp \rightarrow ZWW \rightarrow (e^+e^-)\, e^+\mu^-$

tagged-Z

Background

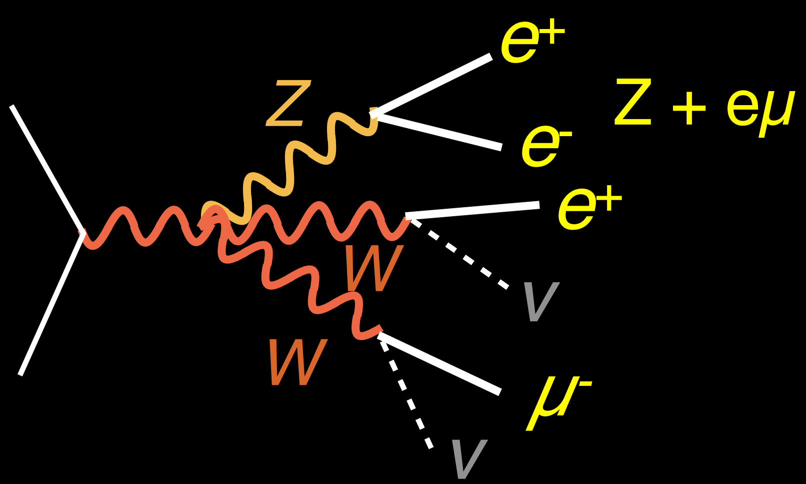


$pp \rightarrow ZZ$

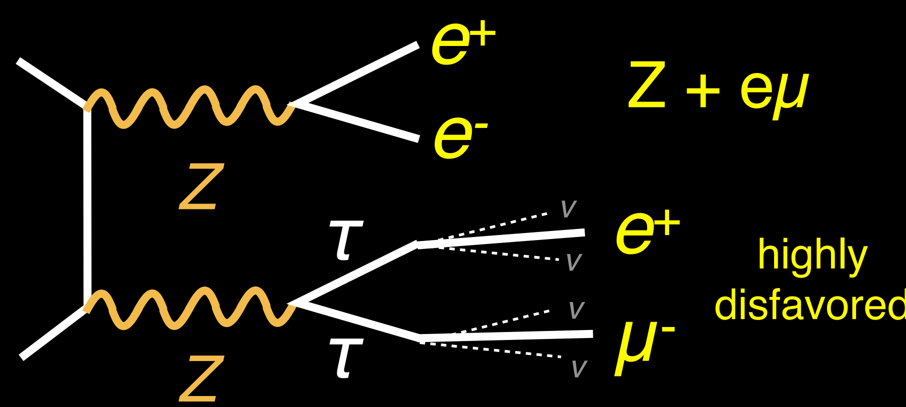
Backgrounds are suppressed via disfavored decay topology of $Z \rightarrow \tau\tau \rightarrow e\mu$

Flavor choices

WWW signal



Background



pp → ZWW → (e$^+$e$^-$) e$^+$$\mu^-$

tagged-Z

pp → ZZ → (e$^+$e$^-$) e$^+$$\mu^-$

tagged-Z

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

Splitting signal regions by lepton flavors

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		3 leptons	4 leptons		
Targeted signal		$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$		

3 leptons	4 leptons
Split by # of SFOS e.g. 0: $e^{\pm}e^{\pm}\mu^{\mp}$ 1: $e^{\pm}e^{\mp}\mu^{\pm}$ 2: $e^{\pm}e^{\mp}e^{\pm}$	tag $Z \to ll$ then split $WW \to ee/\mu\mu$ v. $WW \to e\mu$
3 categories	2 categories*

* 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	$W^\pm \to l^\pm \nu$ $W^\pm \to l^\pm \nu$ $W^\mp \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
	Split by ee/eμ/$\mu\mu$ (N.B. μ is "cleaner" than e) Further split by jets (viz. on-W, off-W, 1J)	Split by # of SFOS e.g. 0: $e^\pm e^\pm \mu^\mp$ 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	
	9 categories	3 categories	2 categories*	1 category	1 category

* marked ones will be further split

Each N lepton analysis is further split by flavors

~~4~~ 3 steps to VVV observation

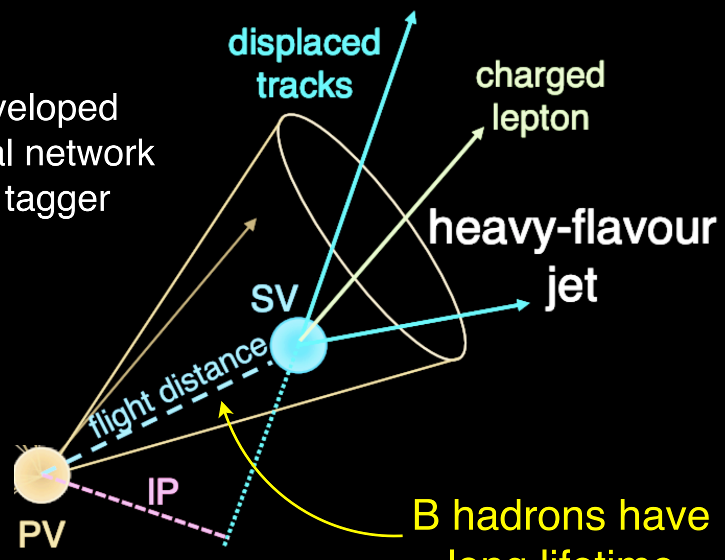
1. Organize analyses by leptons (likely) from W / Z
   - N leptons in the event
   - Flavor of the leptons
2. Additional background suppression through smart choices
3. Reliably estimate the size of residual backgrounds
4. Observe VVV!

Smart humans and smart machines (Both cut / BDT)

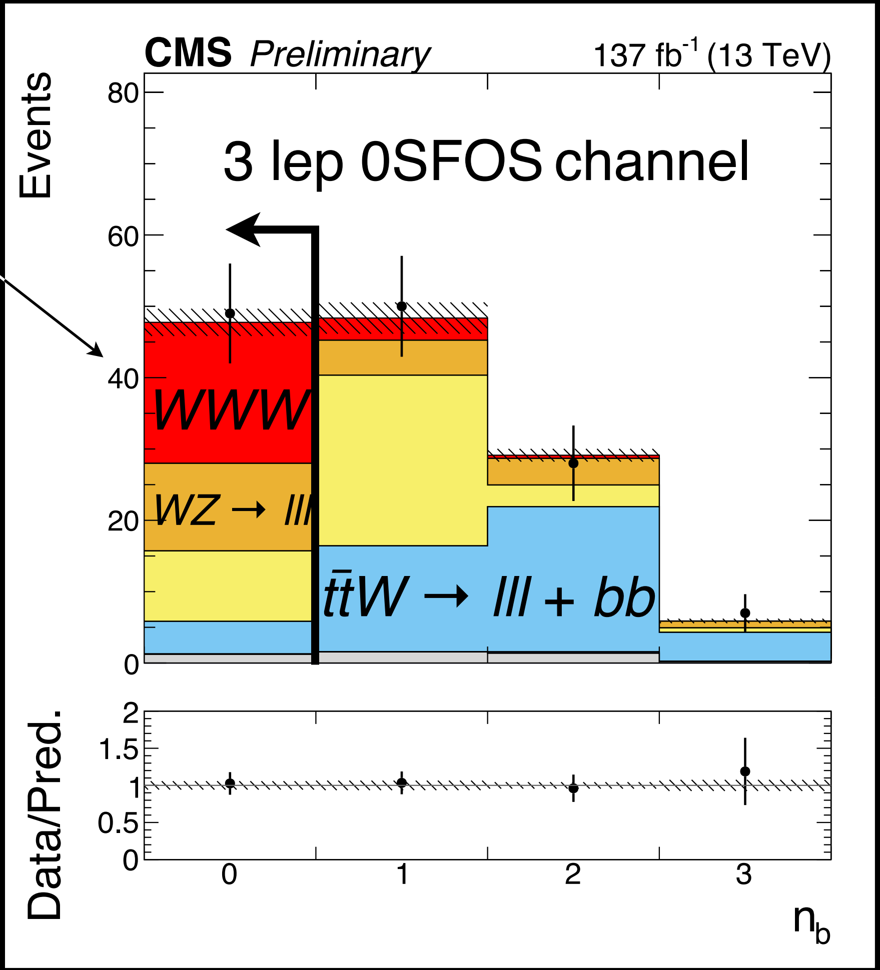
b tagging

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

CMS developed deep neural network based *b* tagger



After 0SFOS preselection



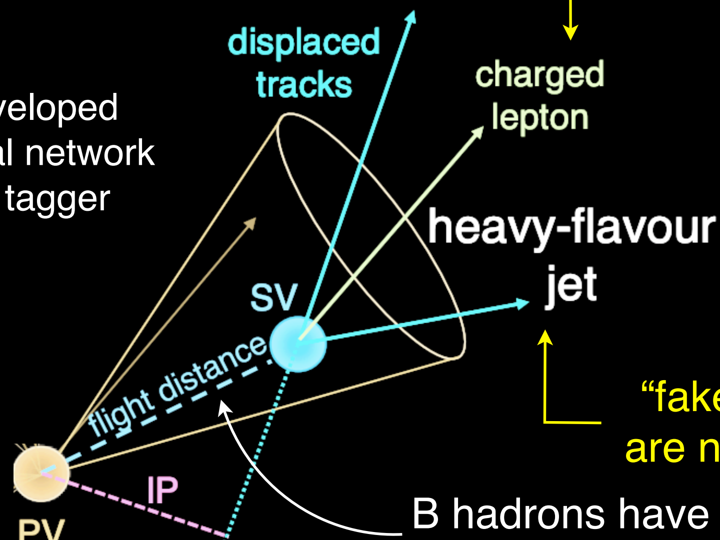
Signals do not have *b* jets

Added benefit of rejecting events with b

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

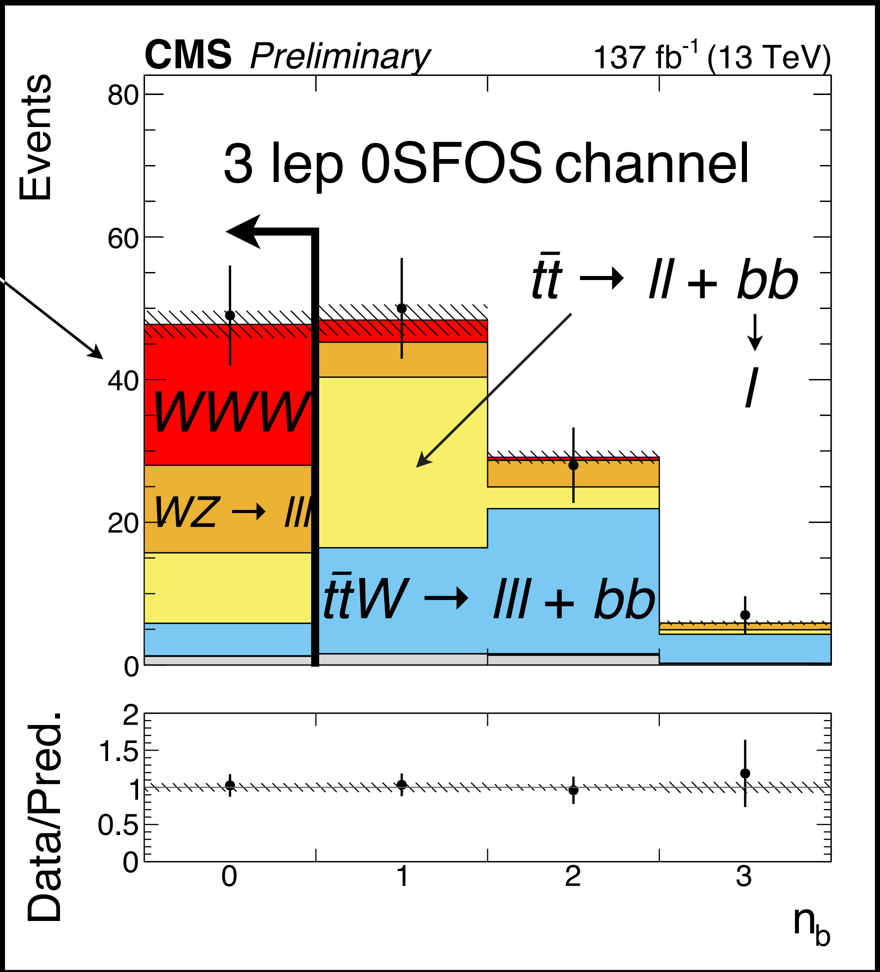
CMS developed deep neural network based *b* tagger

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



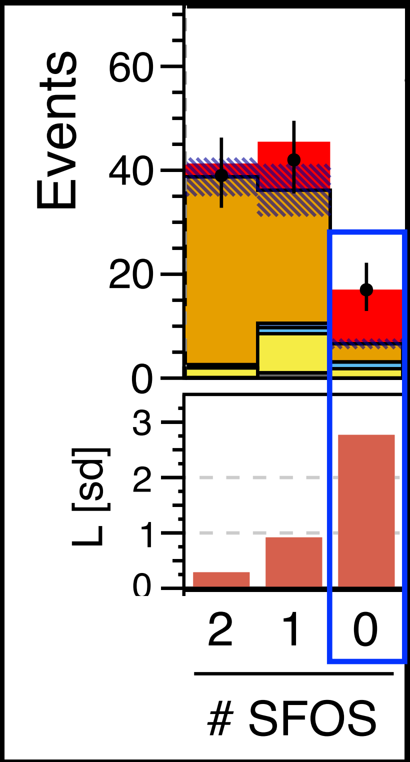
“fake" leptons are not isolated

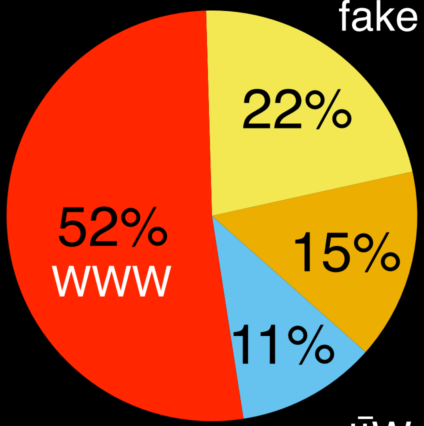
B hadrons have long lifetime



Signals do not have *b* jets

Summary of 3 lepton analysis





- ~10s of WWW events
- 0SFOS dominates in sensitivity
- Statistics limited (but systematics are becoming important)

Kinematic endpoints for 4 leptons

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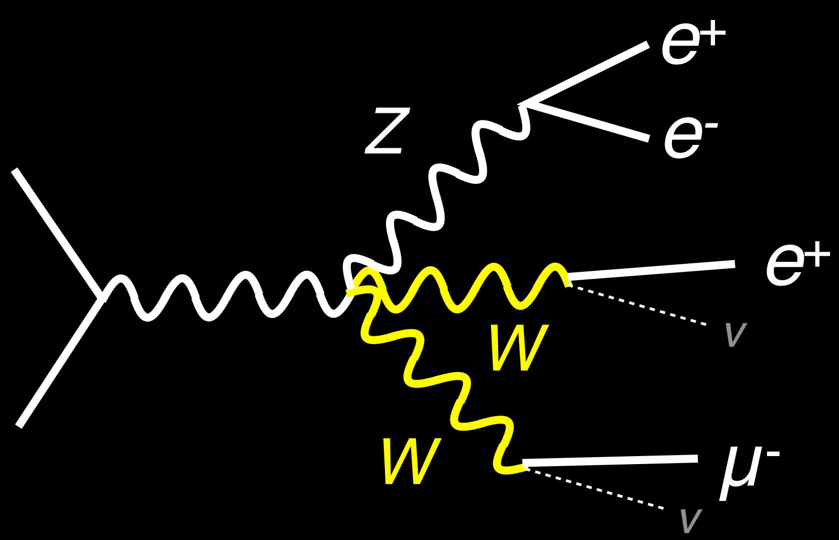
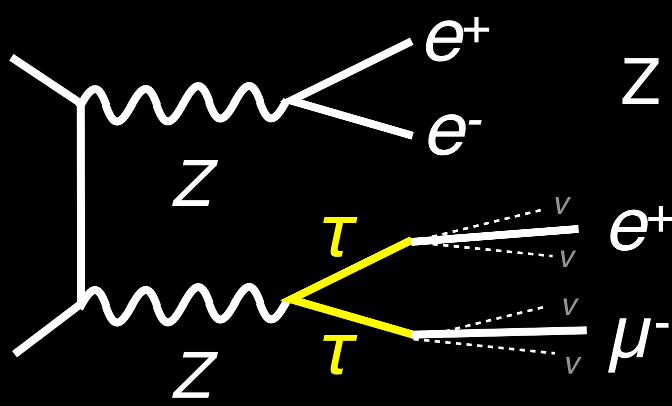
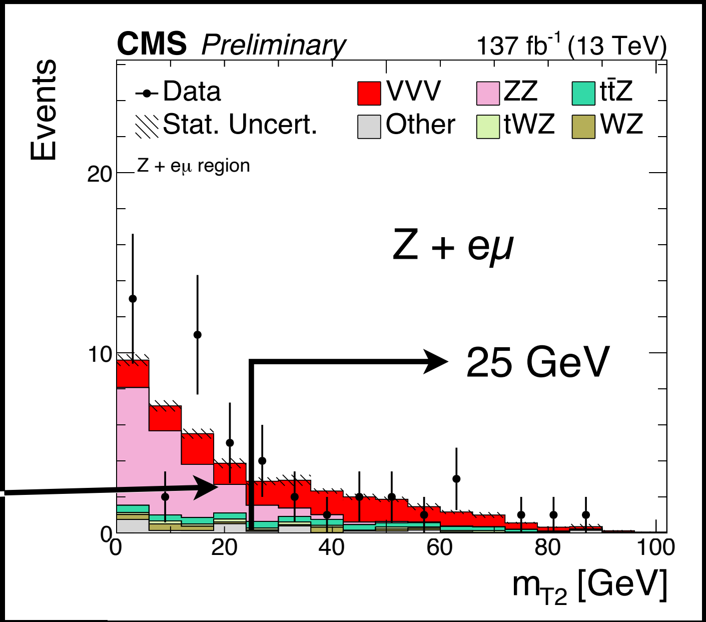


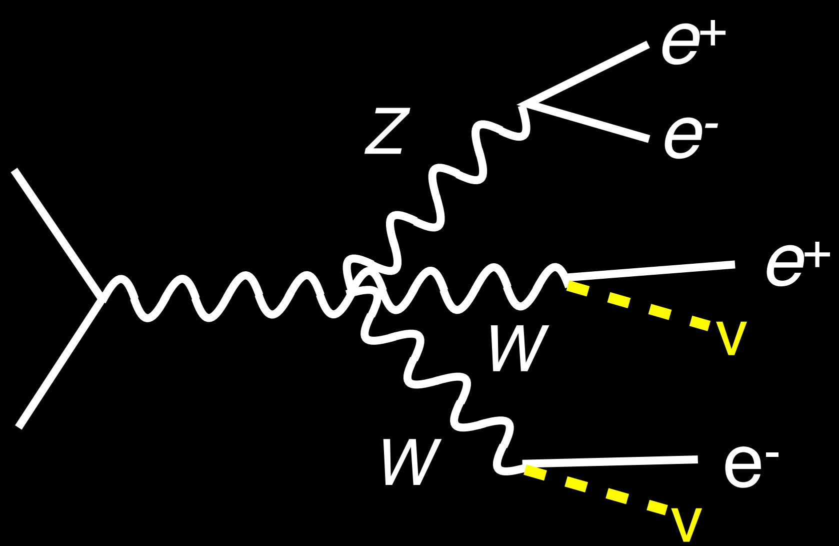


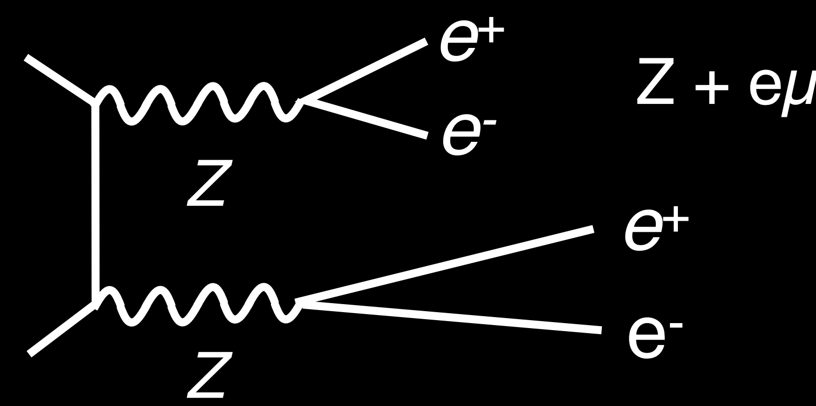
- Recap: 4L split to Z+eμ, Z+ee/$\mu\mu$
- Utilize m_{T2} variable: generalization of m_T for multiple missing particles
- m_{T2} is sensitive to the end points of m_W from ZWW→lleμ
- m_{T2} is sensitive to the end points of m_τ from ZZ→ll$\tau\tau$→lleμ



Exploit differences between Z → ll v. WW → lνlν

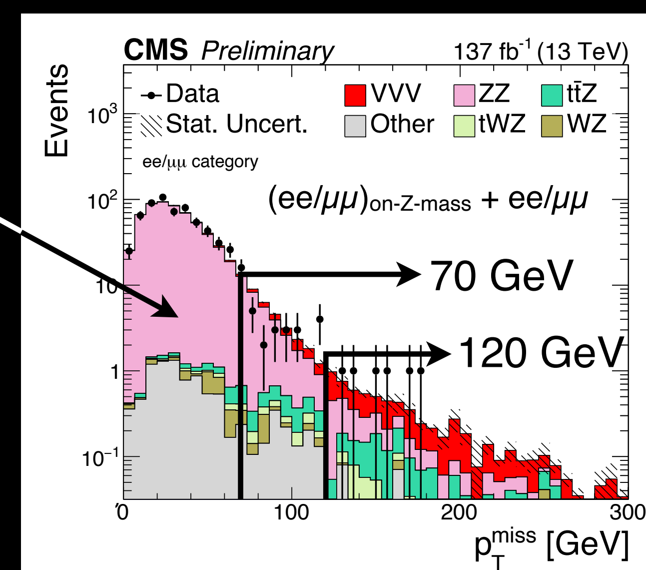
Kinematic endpoints for 4 leptons





WWZ contains 2 neutrinos:
WWZ → 4 lepton + 2 neutrino

ZZ bkg in Z + ee/*μμ* does not have missing energy ⇒ populates at low MET



Exploit differences between Z → ll v. WW → lνlν

WWZ BDTs for 4 leptons analysis

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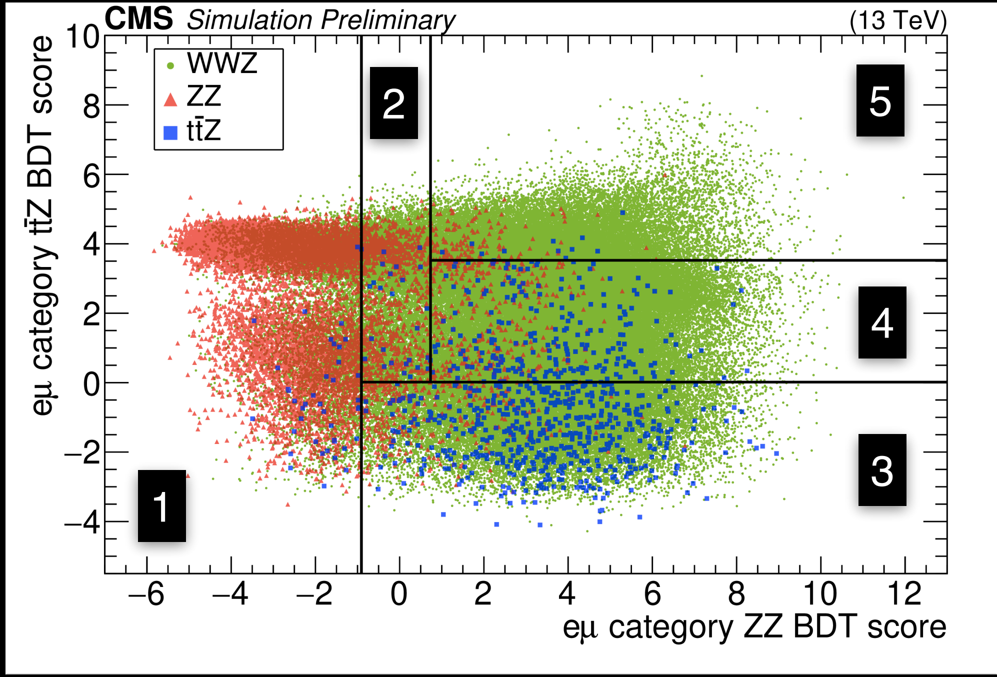
Trained two BDTs: WWZ v. ZZ and WWZ v. ttZ
Below shows the 2D plane in BDT scores

More WWZ like

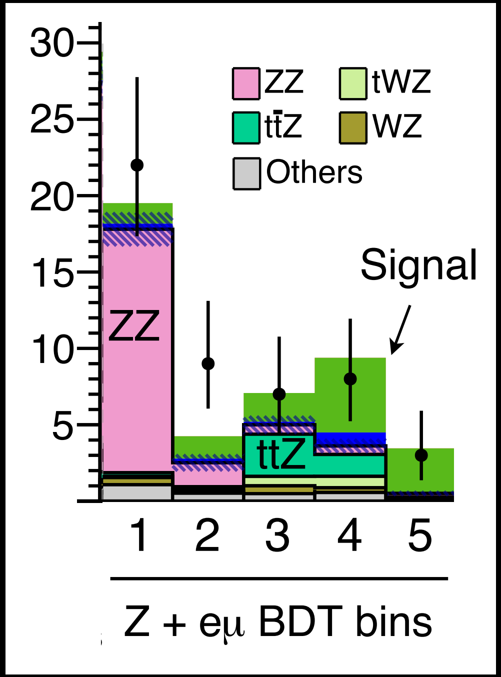
More $t\bar{t}Z$ like



More ZZ like

More WWZ like

5 bins are created from 2D planes

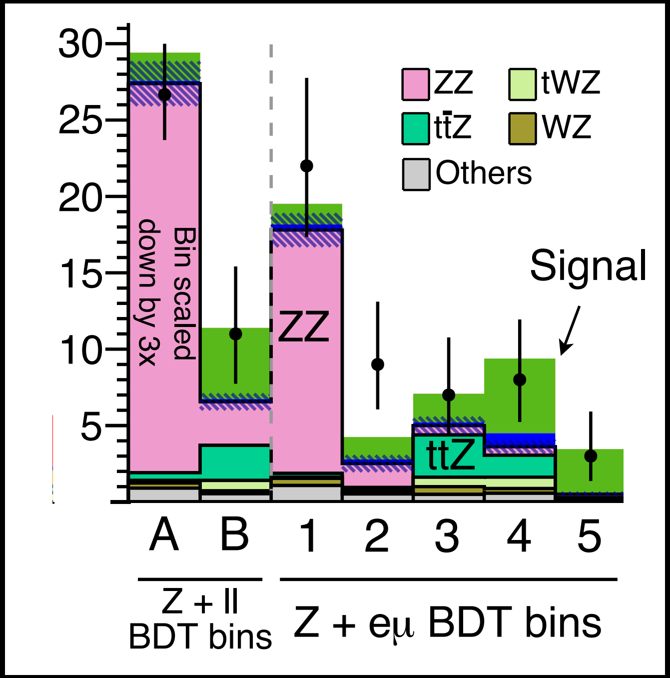


**For Z→ll + ee/$\mu\mu$ event category, 2 bins are created (not shown)

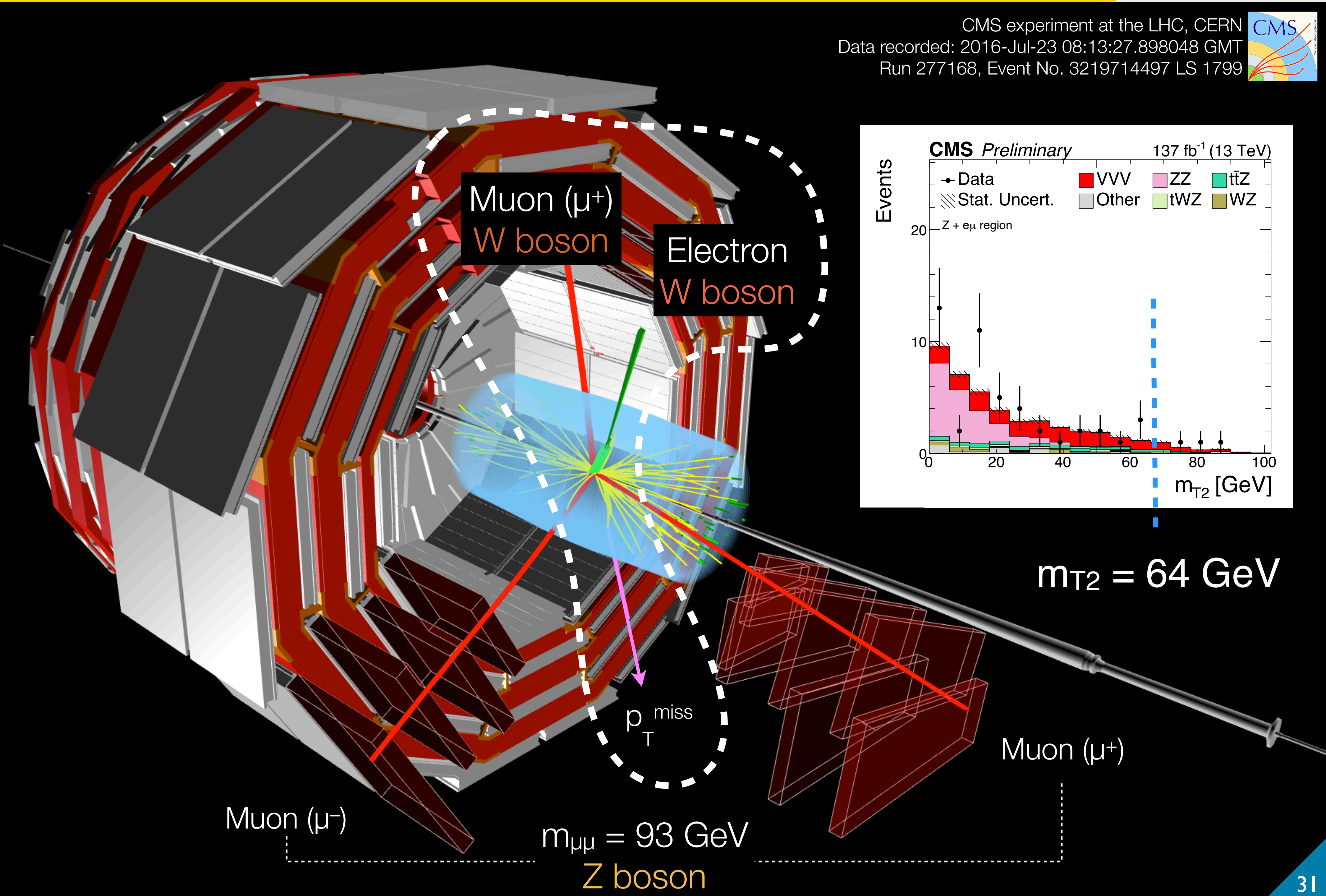
Created multiple bins in BDTs to maximize sensitivity
⇒ Total of 7 signal regions for 4 lepton analysis

Summary of 4 lepton

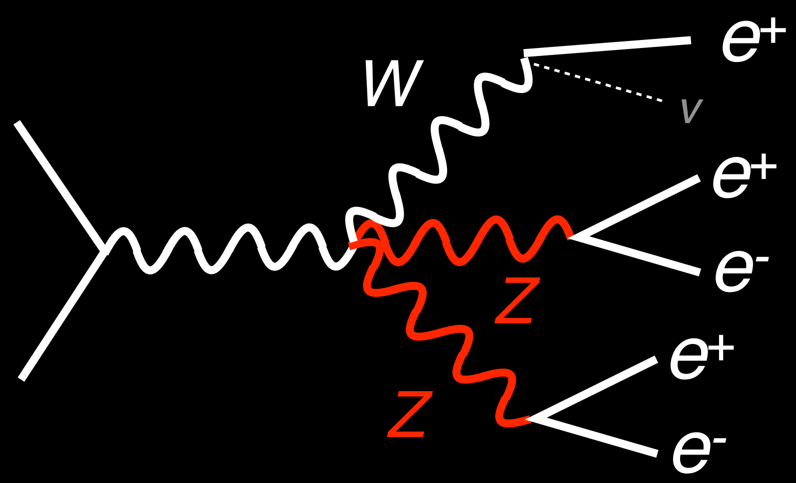
- O(10) WWZ events
- Z + *eμ* bins are most sensitive
- Statistics limited
- main backgrounds are ZZ and tt̄Z
  - ZZ ~5% uncertainty
    - Extrapolation across lepton flavor
  - tt̄Z ~30% uncertainty
    - Dominated by CR statistics
    - b-tagging uncertainty ~10%



4 lepton event



Very rare 5 lepton events



- Once you make signal selection there aren't much background left
    - Two on-Z requirement + 5th lepton with high M_T
- Expected total of 2 events with 3:1 signal to background ratio
- And we've observed 3 events
- Only now becoming accessible to study!

5 lepton events are clean and are becoming accessible for the first time

5 lepton event display

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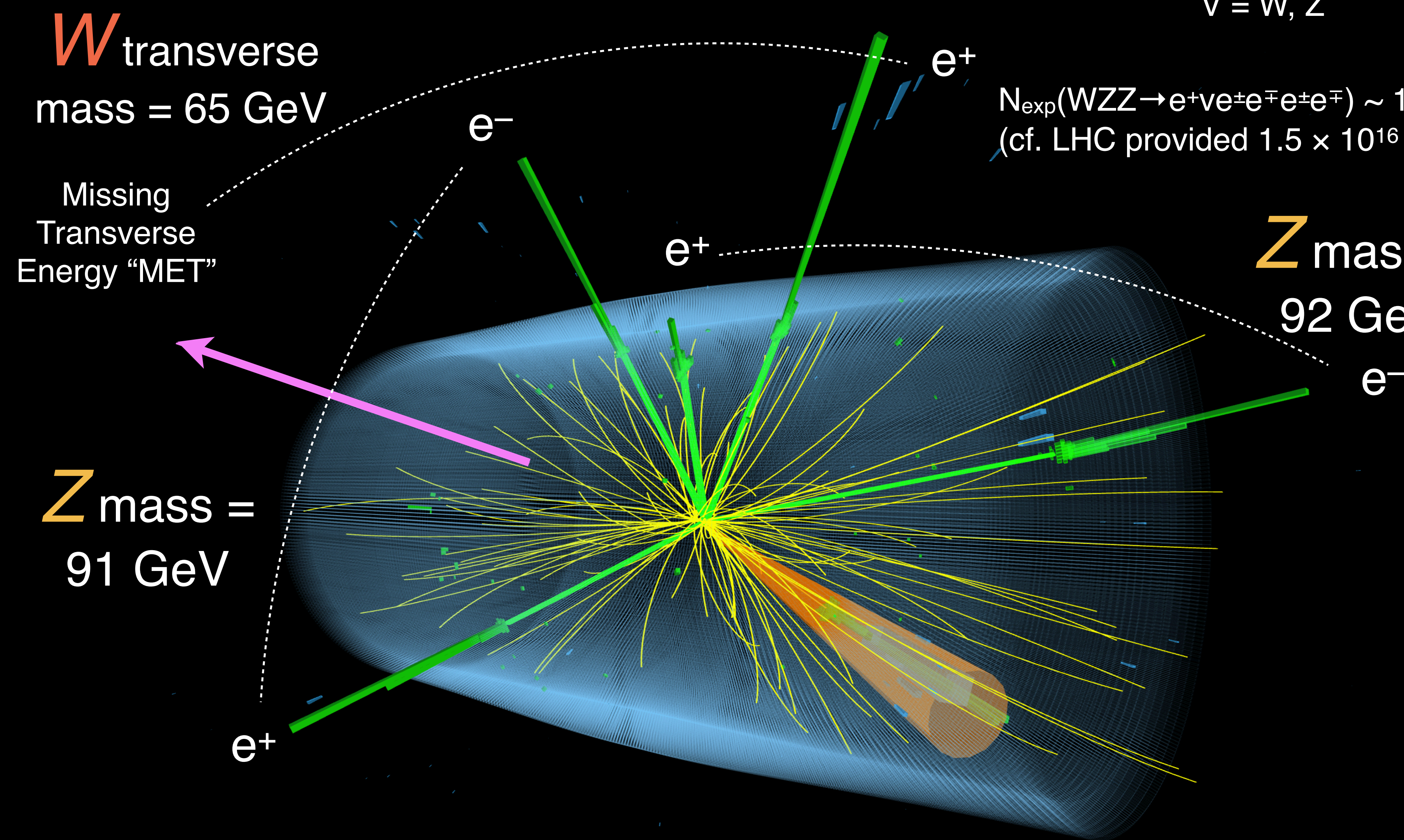
CMS experiment at the LHC, CERN
Data recorded: 2016-Oct-09 21:24:05.010240 GMT
Run 282735, Event No. 989682042 LS 491

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)



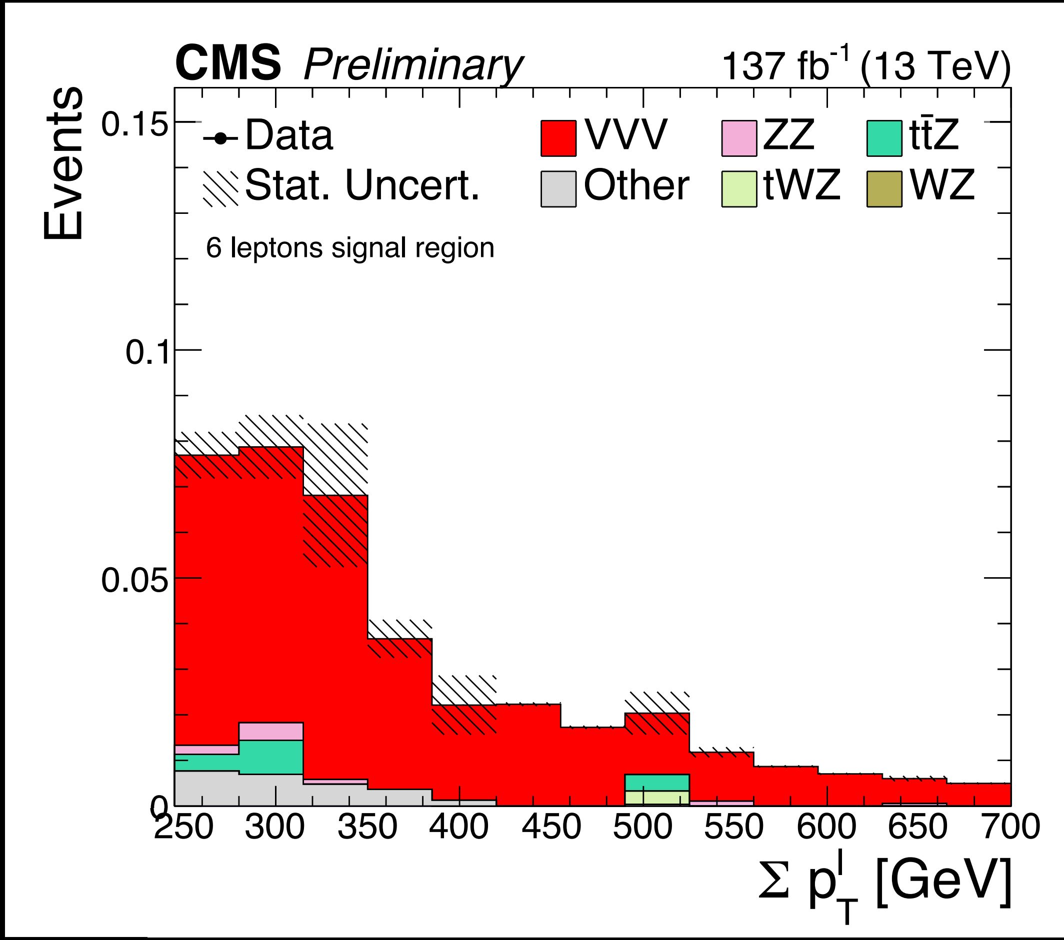
6 leptons

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

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	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

Results (BDT-based analysis)

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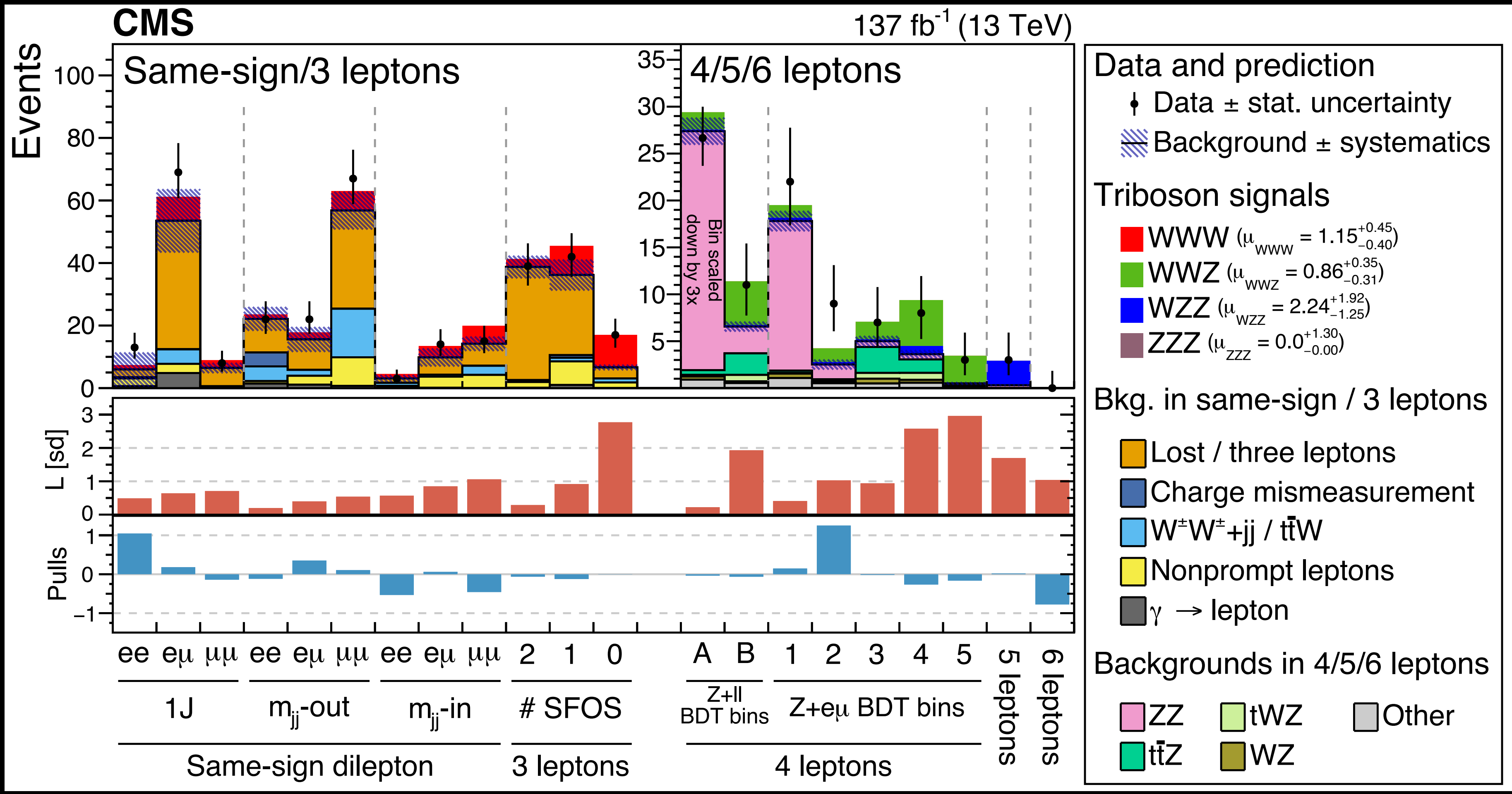
Signal strength $\mu = \frac{\text{Measured cross section}}{\text{Theoretical cross section}}$



9 bins 3 bins 7 bins 1 1

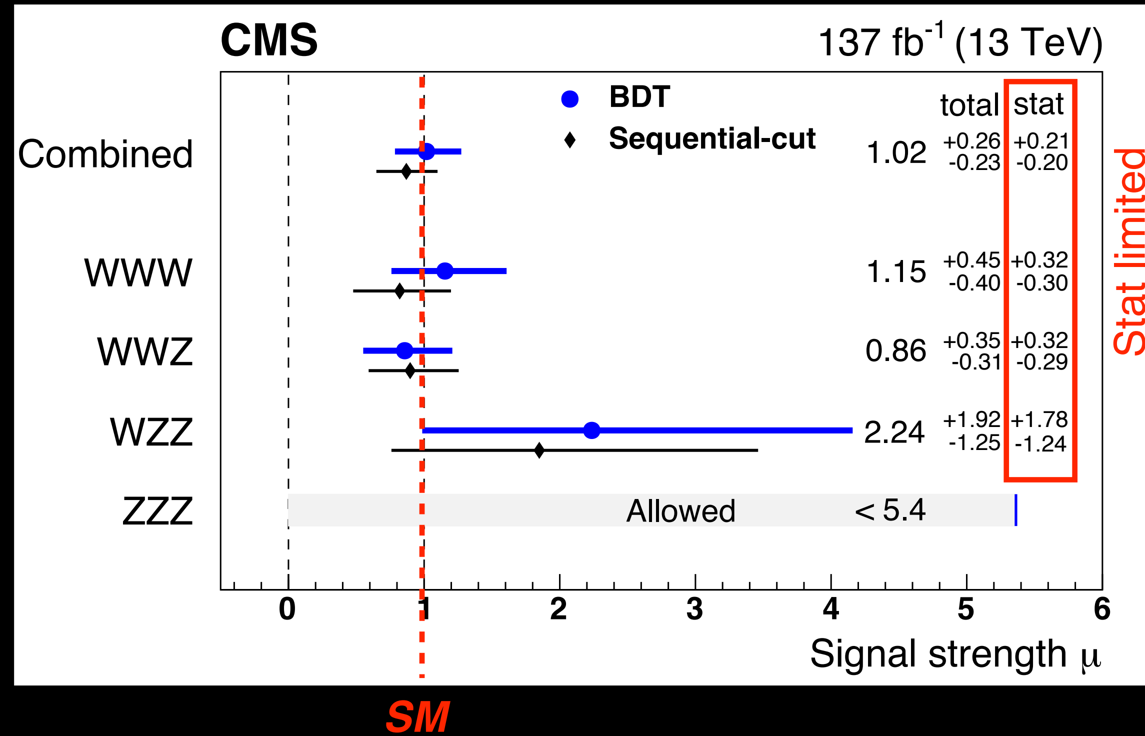
More sensitive bins are generally to the right

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

Results

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)



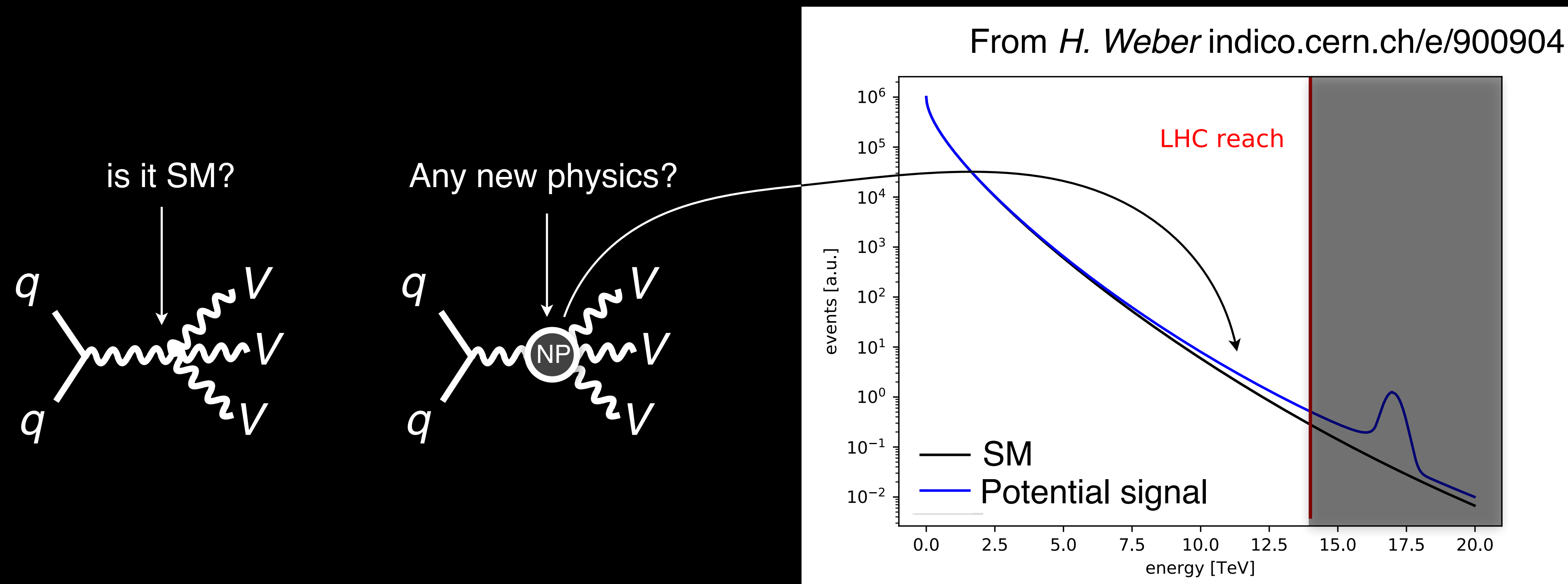
$$\text{Signal strength } \mu = \frac{\text{Measured cross section}}{\text{Theoretical cross section}}$$

- 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

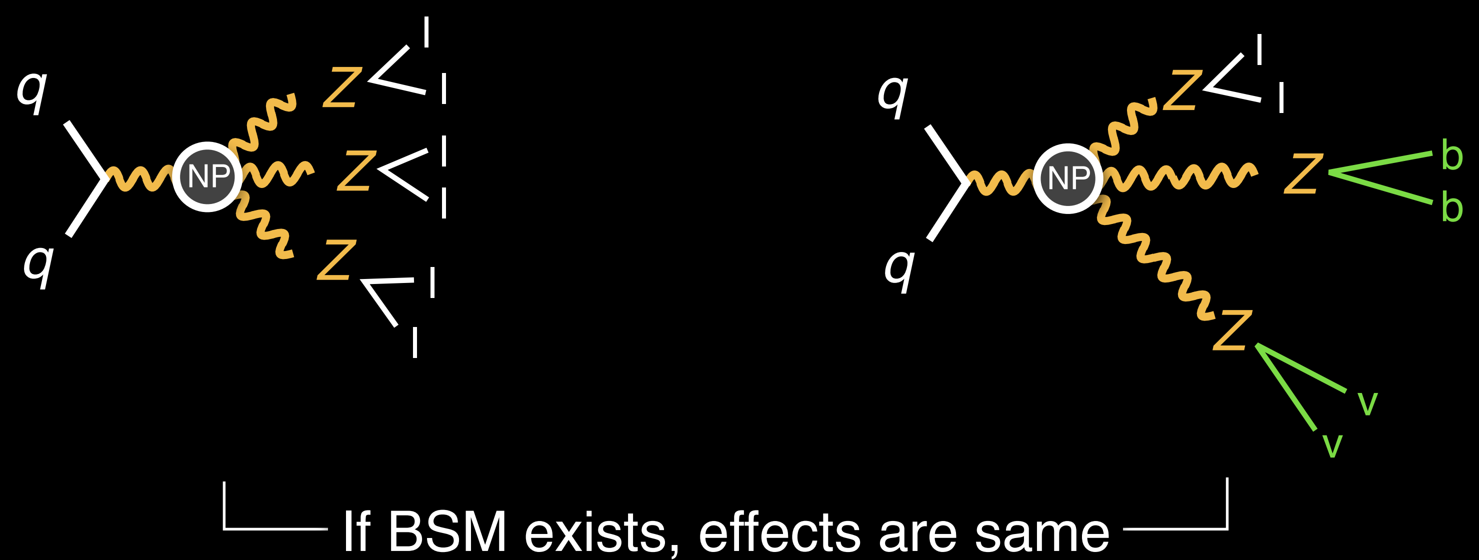
Using VVV as a tool

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



- 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

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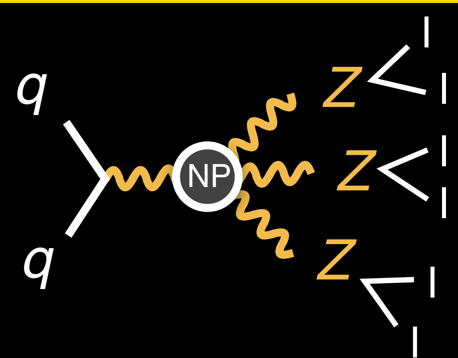
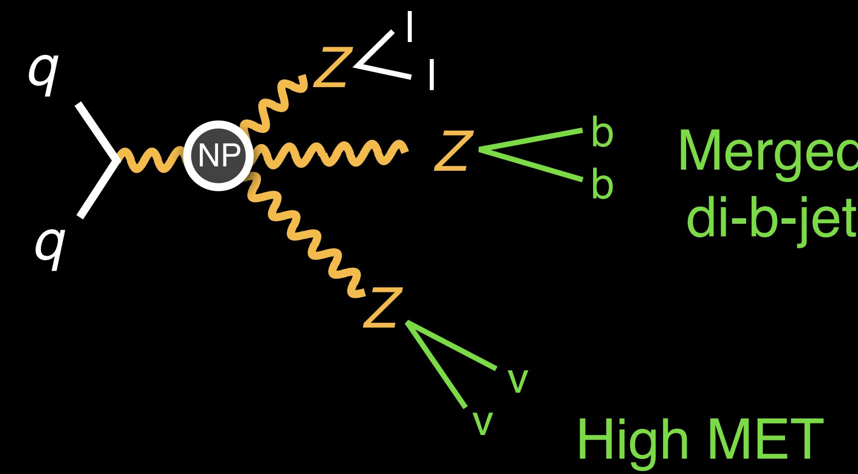
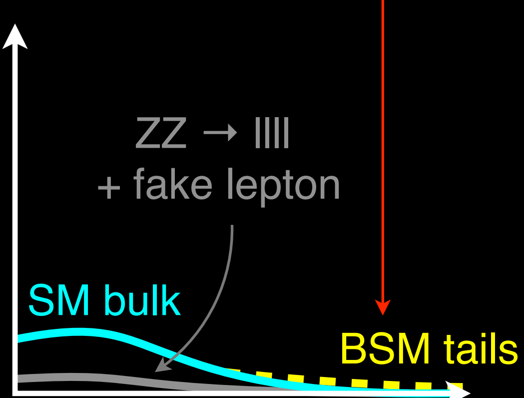
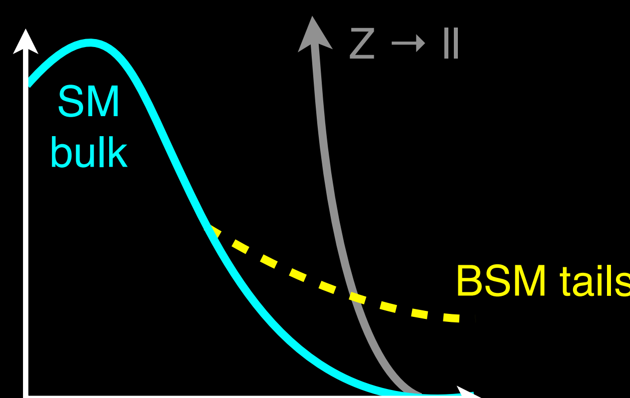


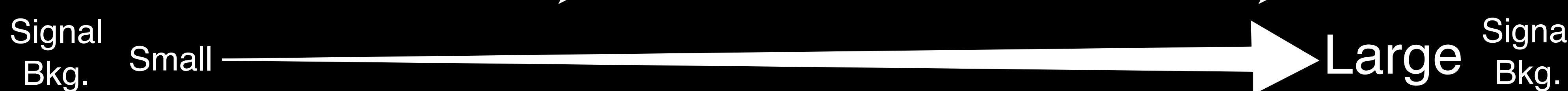


Clean channel for discovery but probing tail is difficult

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

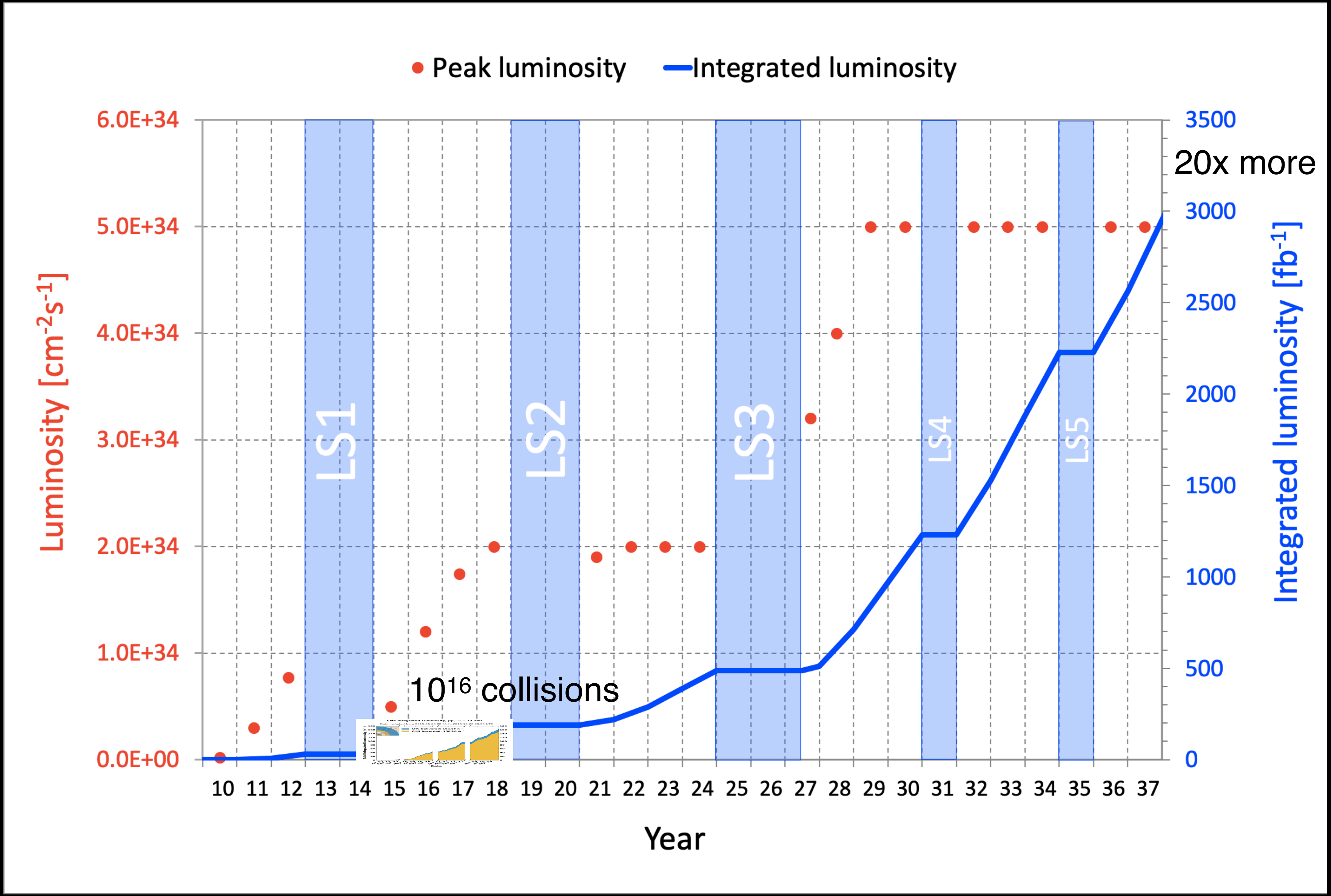






We can probe VVV → semi-leptonic for new physics

HL-LHC



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

Vector boson scattering

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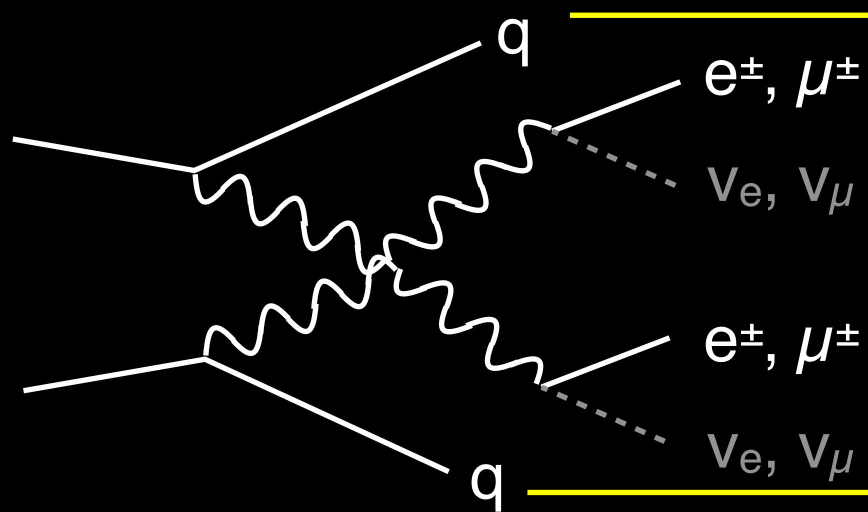
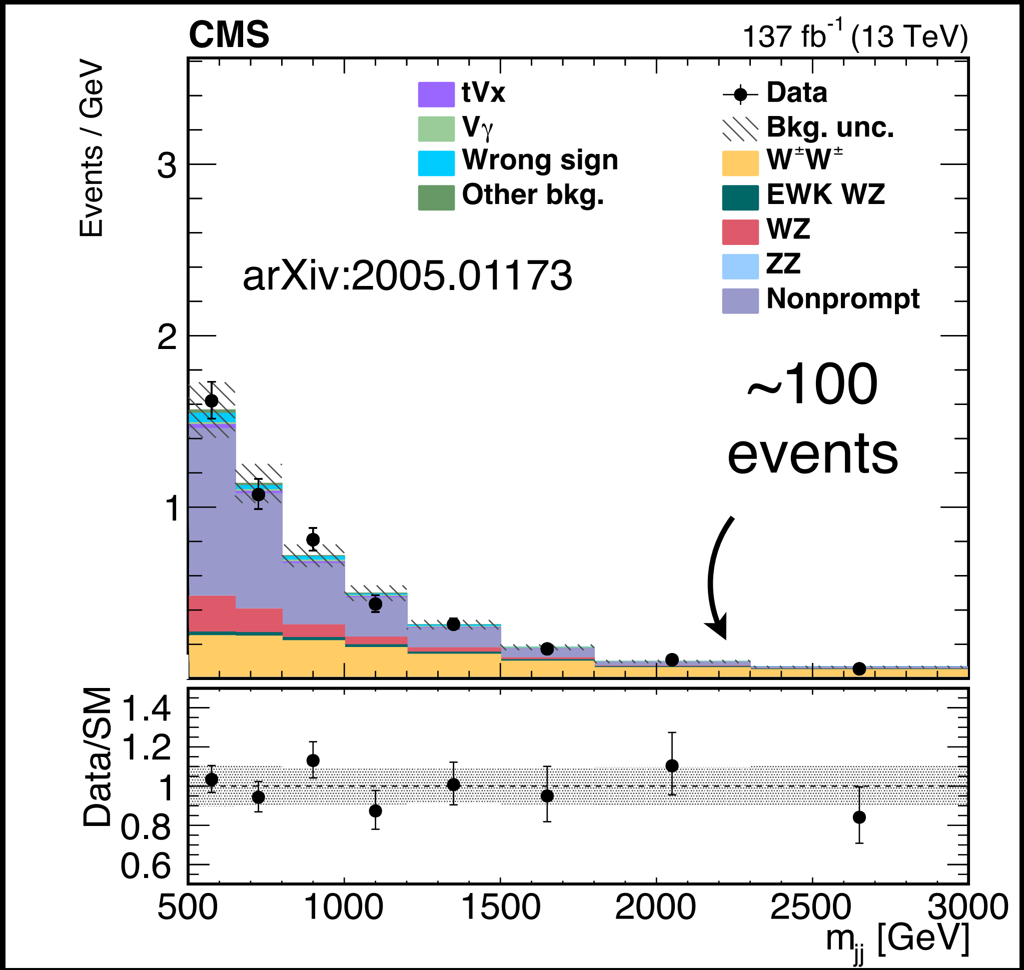
WW scattering



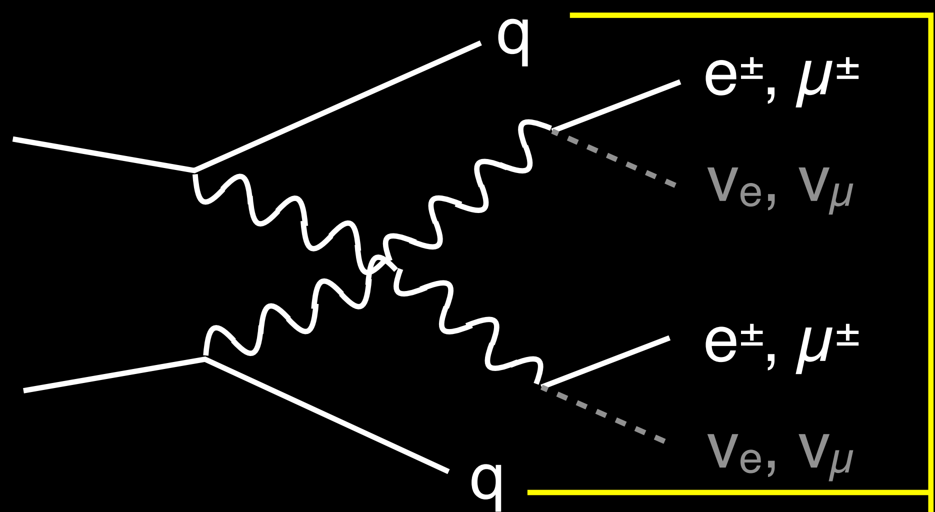
Same-sign dilepton + 2 quarks



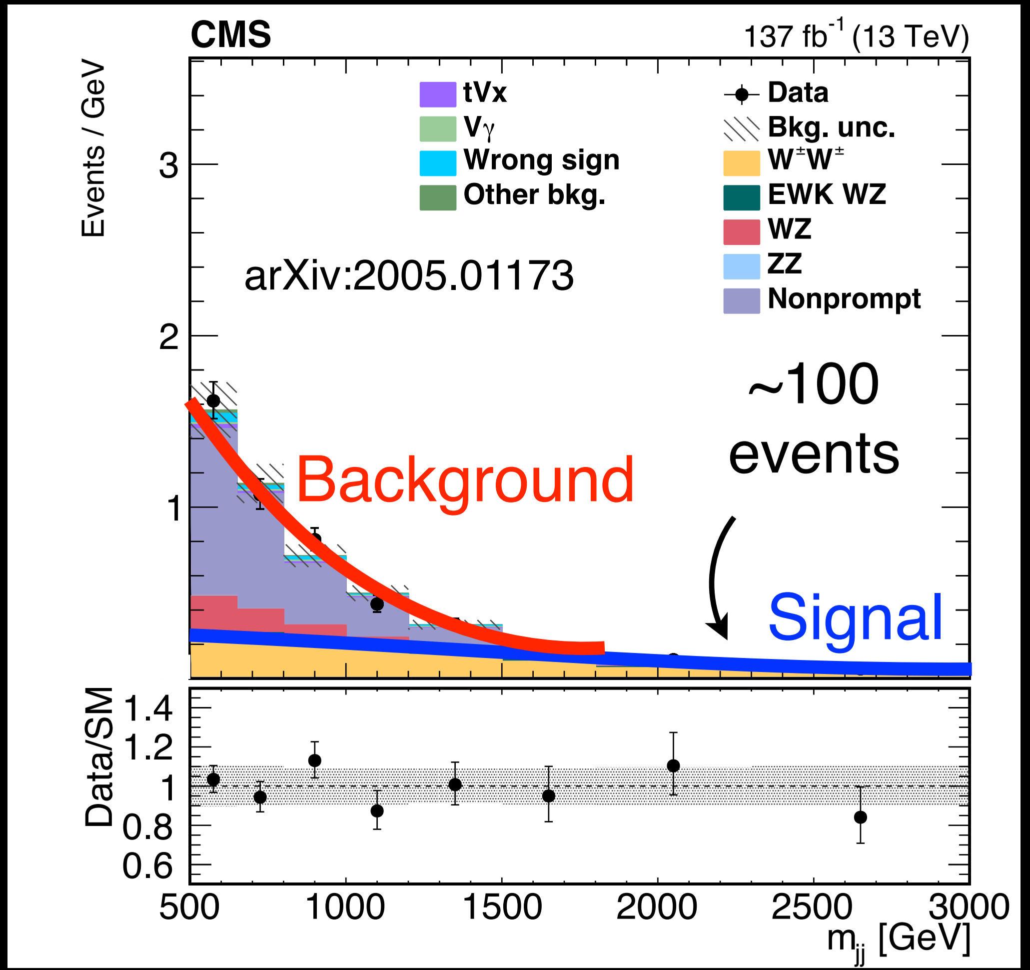
Two jets from VBS process tend to have relatively high invariant mass

Vector boson scattering

WW scattering



Same-sign dilepton + 2 quarks



Two jets from VBS process tend to have relatively high invariant mass

WW scattering results

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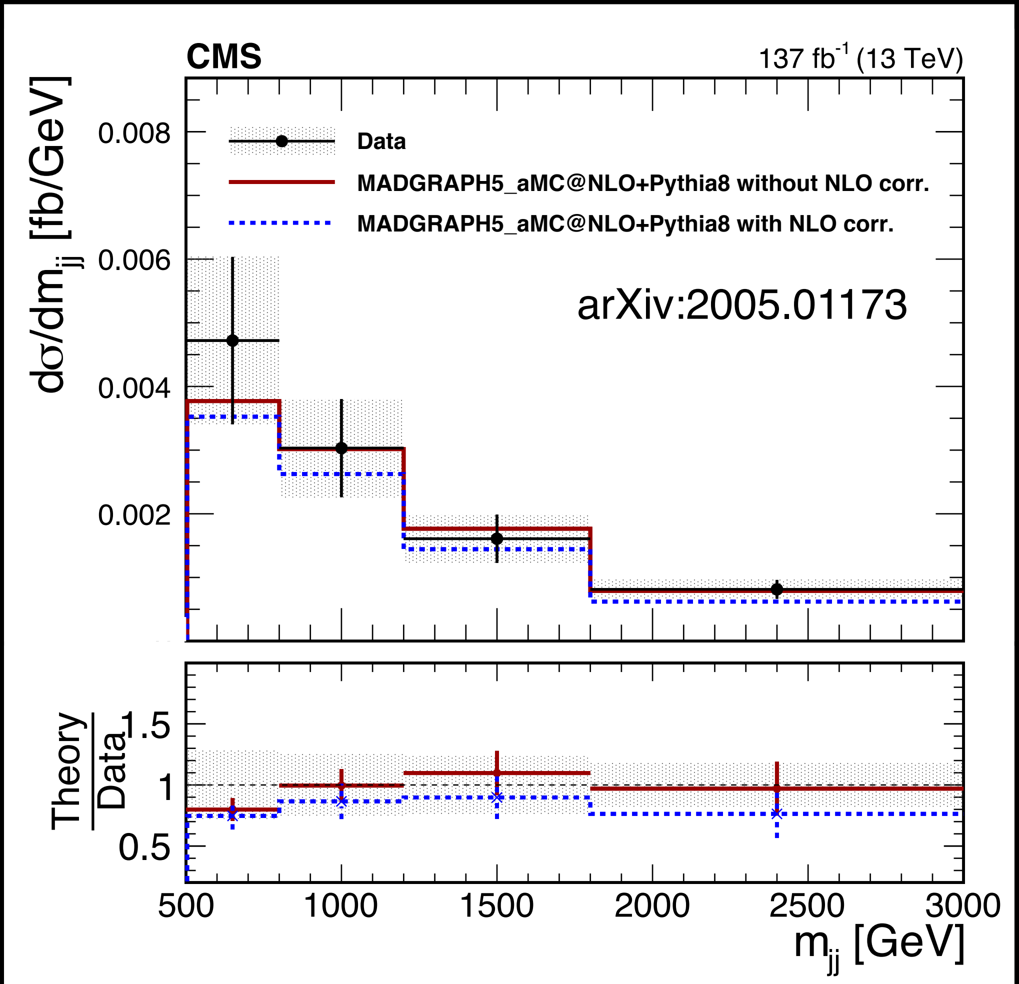

- O(100) events observed
- Measure the production rates as a function of important variables
- The measured cross section is compatible with the SM
- (Small fraction are $W_L W_L$ scattering)

WW scattering cross section has been measured and found to be consistent with SM

Future of multi-boson interaction

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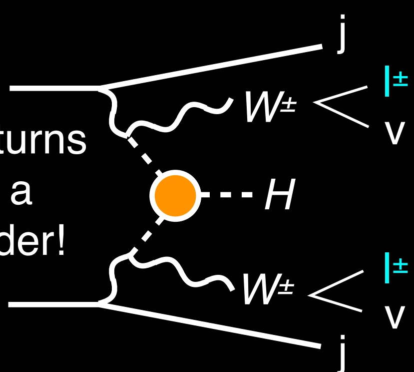
$pp \rightarrow W^{\pm}W^{\pm}H\, jj$

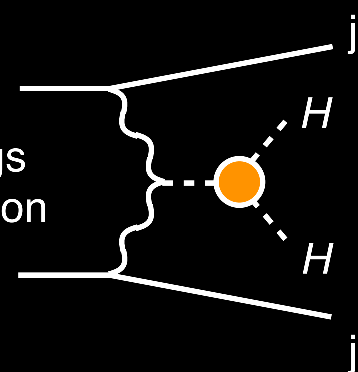
Same-sign turns LHC into a Higgs collider!



Same sign

$pp \rightarrow HH\, jj$

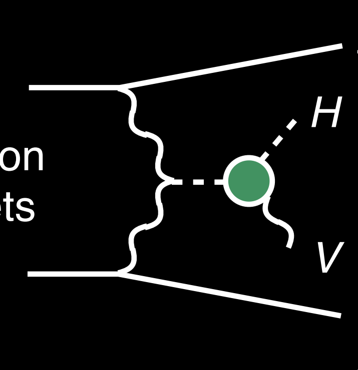
Di-higgs production



Same-sign / 0SFOS
or +++/- - - 3L

$pp \rightarrow VH\, jj$

VH production with VBS jets



Same-sign / 0SFOS

arXiv:1812.09299 Henning, Lombardo, Riembau, Riva
arXiv:2006.09374 Stolarski, Wu

There are many more rare events that we should search for and study

More multi-massive-X processes for future

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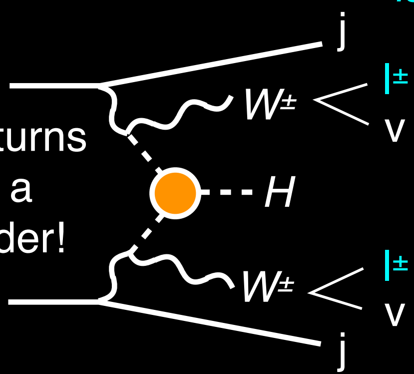
listing a few multi-massive-X processes with same-sign

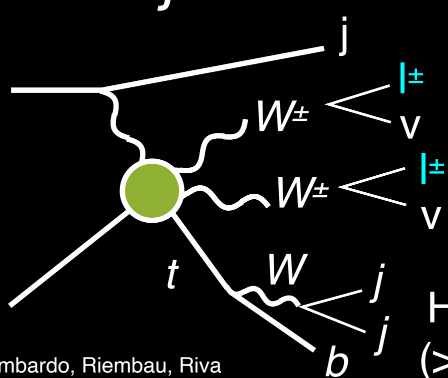
Same-sign is special

$pp \to W^\pm W^\pm H$

Same-sign turns LHC into a Higgs collider!

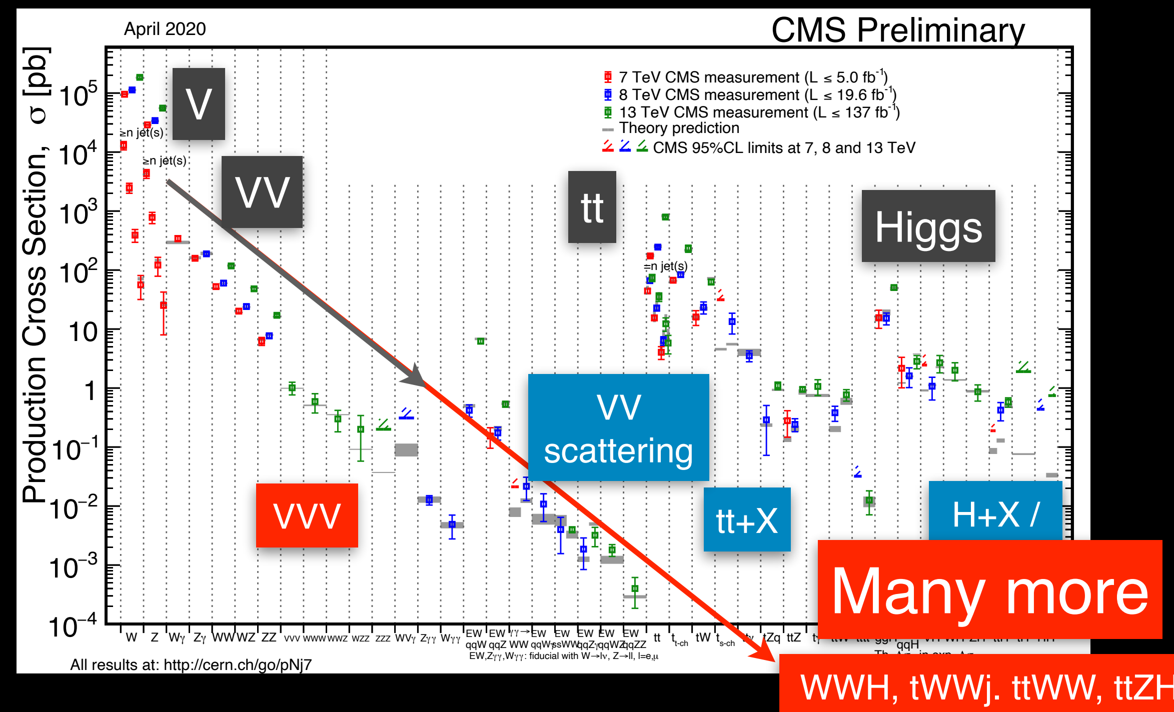


$pp \to t W^\pm W^\pm j$

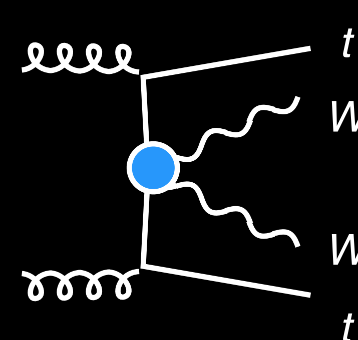


High P_T top (> 500 GeV)

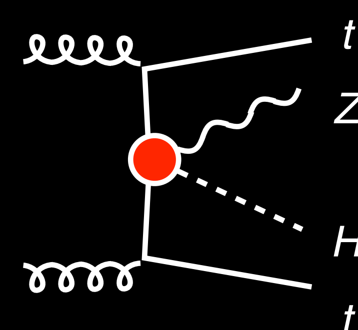
arXiv:1812.09299 Henning, Lombardo, Riembau, Riva
arXiv:1511.03674 Dror, Farina, Salvioni, Serra
arXiv:1904.05637 Maltoni, Mantani, Mimasu



$pp \to ttWW$



$pp \to ttZH$



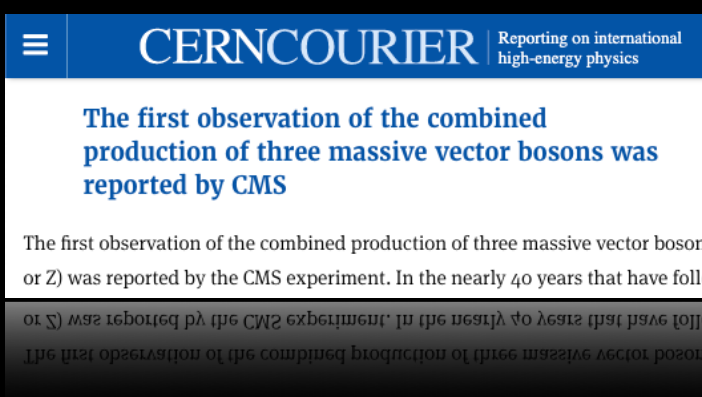
There are many more multi-massive-X production to be explored at LHC

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

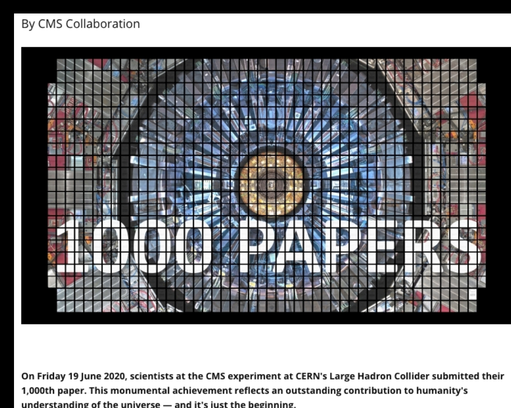
This paper is 1000th paper submitted by CMS!

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



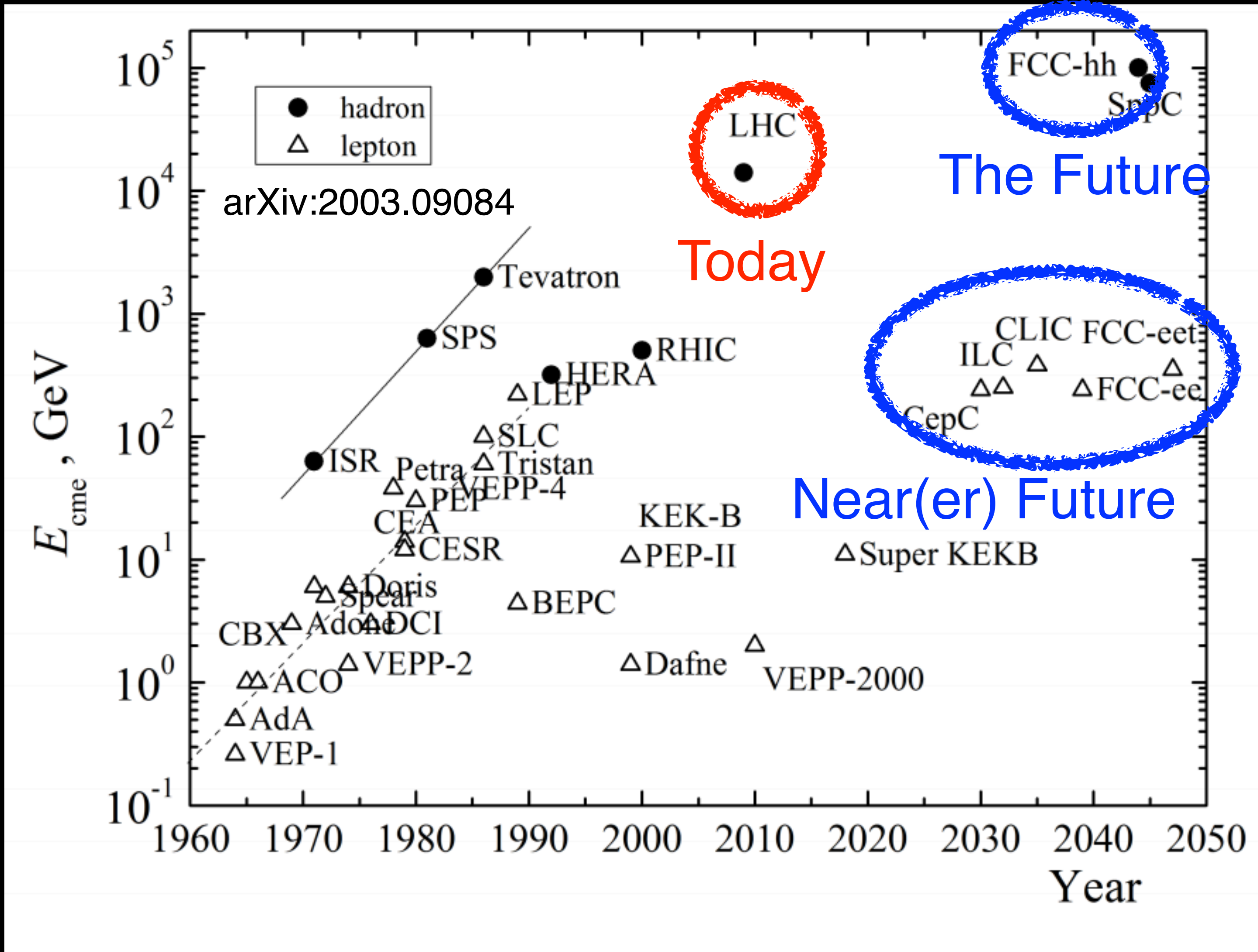
"CMS is the first experiment in the history of high energy physics to reach this outstanding total of papers and with only a fraction of the data that the LHC anticipates to produce in its lifetime. The LHC accelerator at CERN will operate for another two decades."

Backup

What to change for Run 3

- Lepton ID for many lepton final states
    - Custom isolation only useful for same-sign / 3 lepton final states
    - Less than ideal for 5 / 6 lepton, which will be more important in Run 3
- Split interpretation by channels and vertex
    - Split WWW / WWZ / WZZ / ZZZ
    - Further split by VH v. VVV
        - WWW v. WH→WWW
        - WWZ v. ZH→ZWW
        - WZZ v. WH→WZZ
        - ZZZ v. ZH→ZZZ
- Work towards combination with other VBS channel
    - e.g. In theory, WWW and VBS same-sign WW cannot be separated
        - Breaks gauge invariance if remove diagram by hand

Future colliders



"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least **100 TeV** …"

— 2020 Update of the European Strategy for Particle Physics

Ultimately FCC-hh with 100 TeV collider will map out the Higgs potential

Lepton collider multi-boson physics

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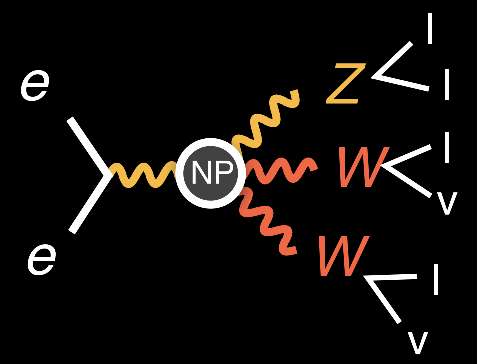
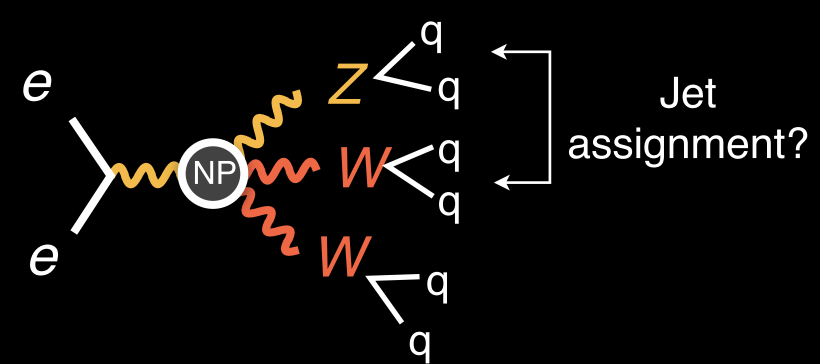


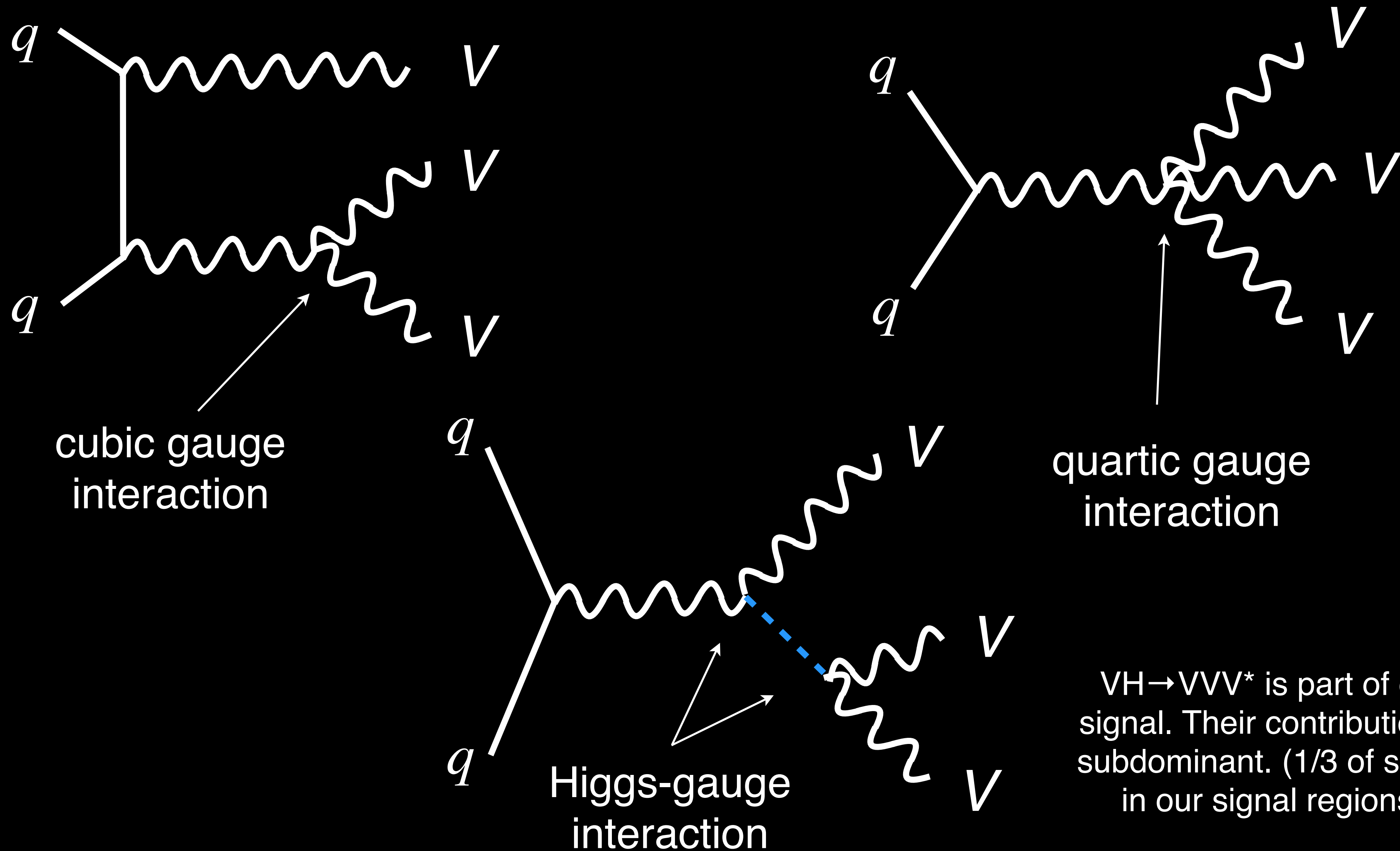


Multi-lepton → Multi-jet final states

⇒ W / Z → qq separation important
⇒ Hadronic calorimeter important (resolution)

**SM process will likely proceed via ZH

Physics of VVV production (V = W, Z)



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)

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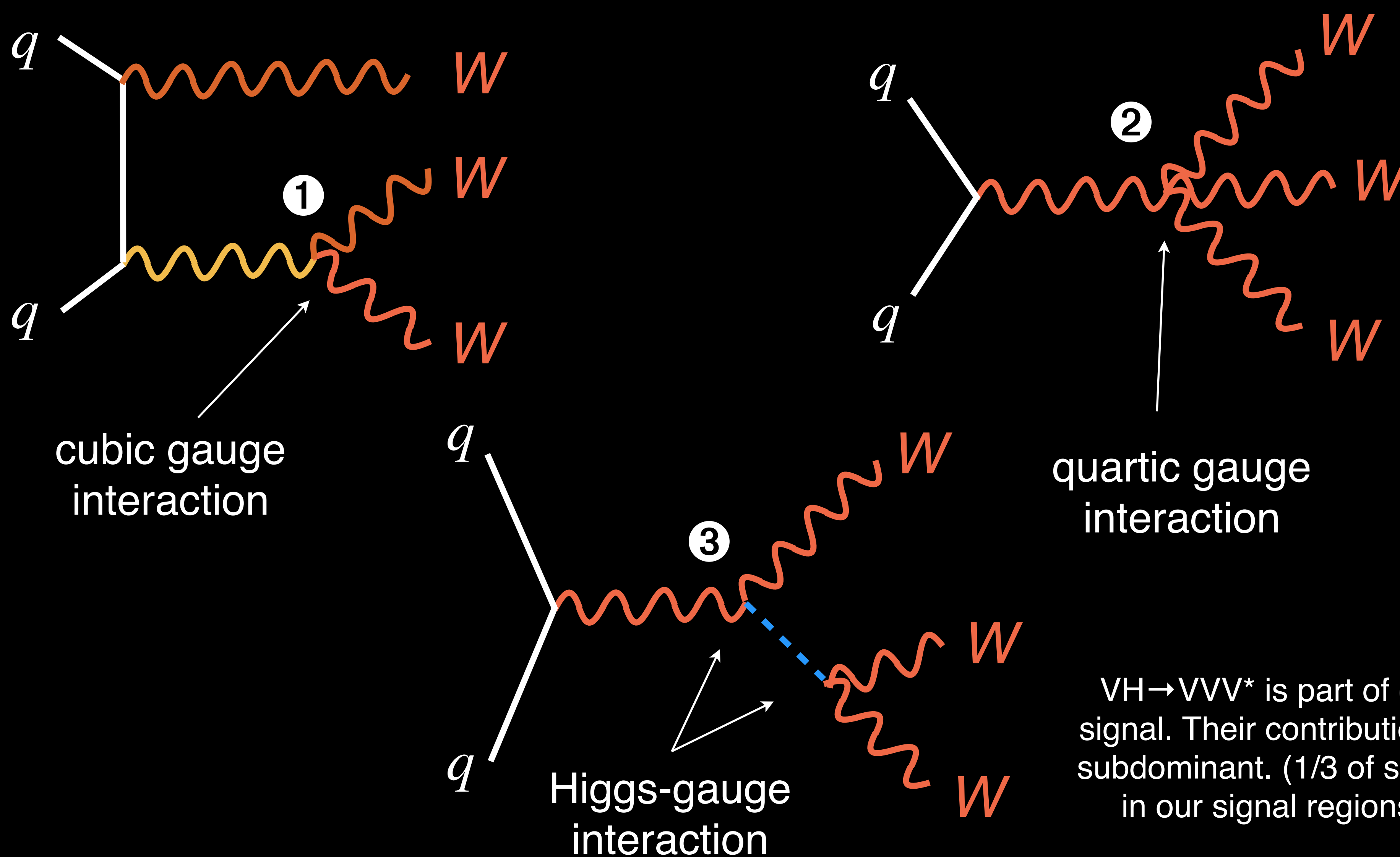

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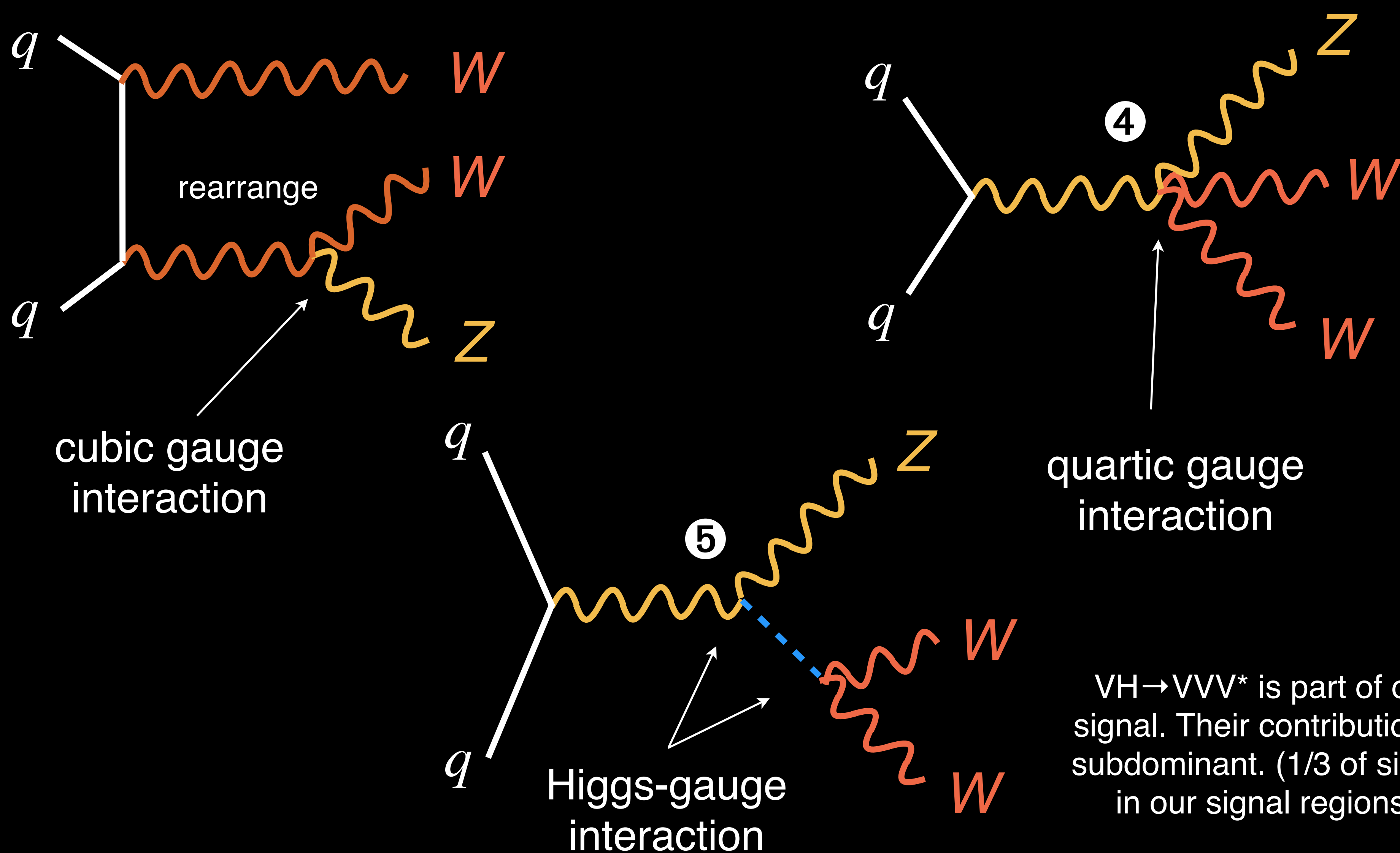

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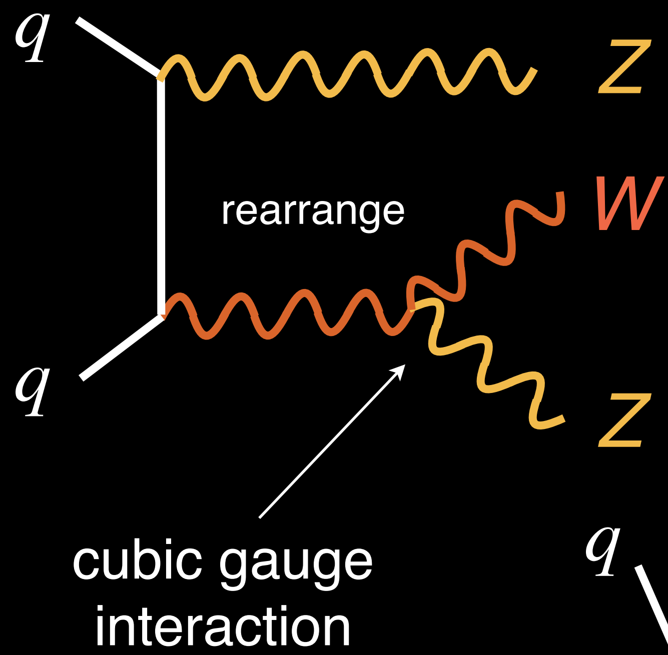

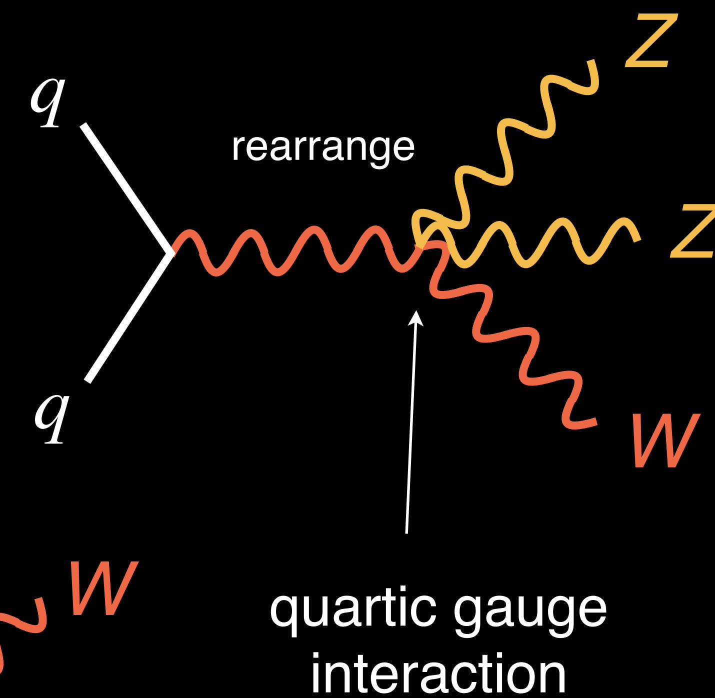

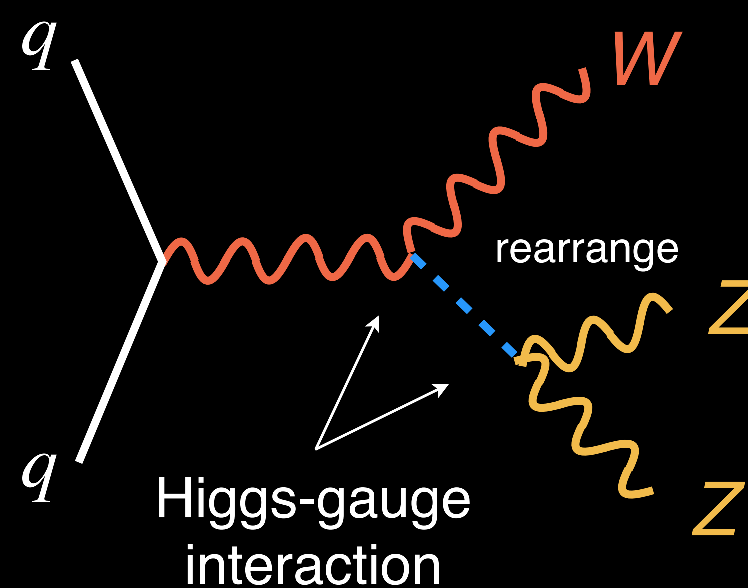

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Physics of VVV production (V = W, Z)

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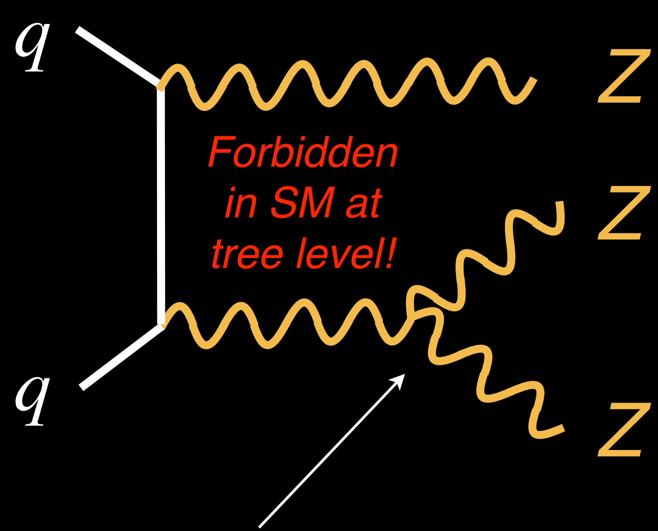
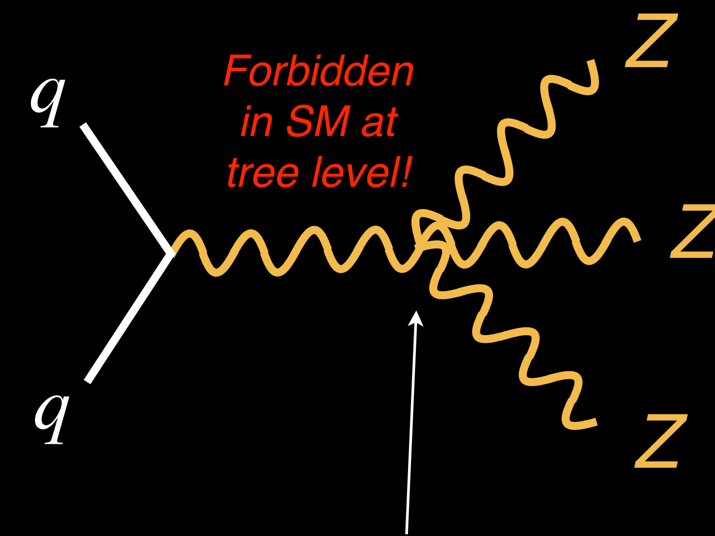
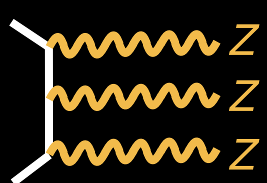


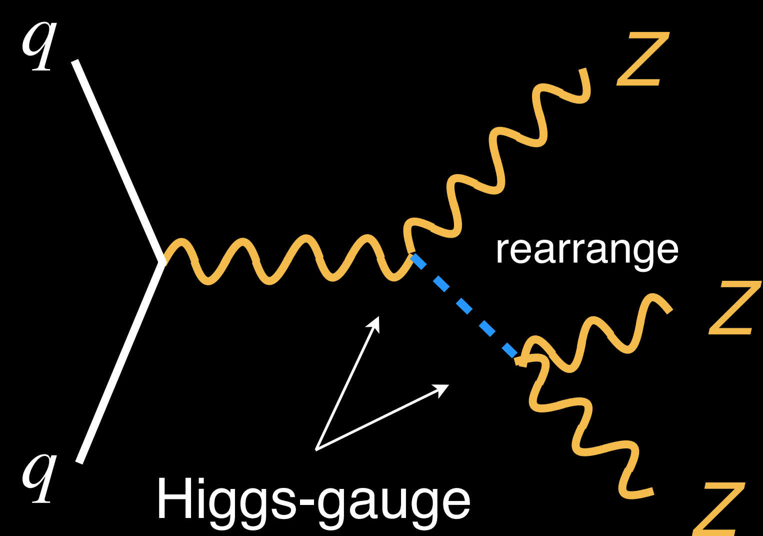
cubic gauge interaction



quartic gauge interaction



Three Z's radiating from quark lines

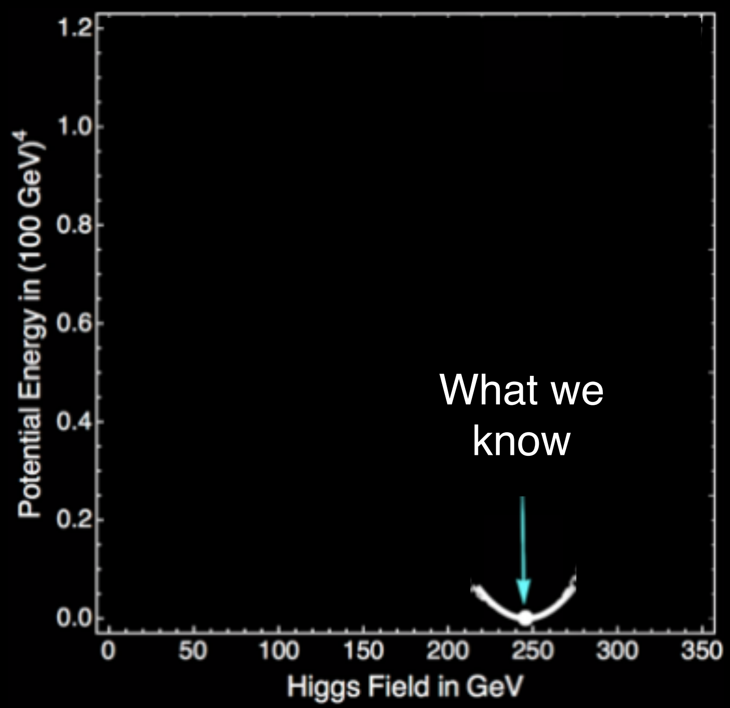


Higgs-gauge interaction

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

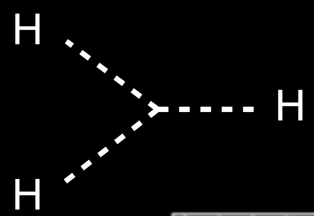
Higgs potential

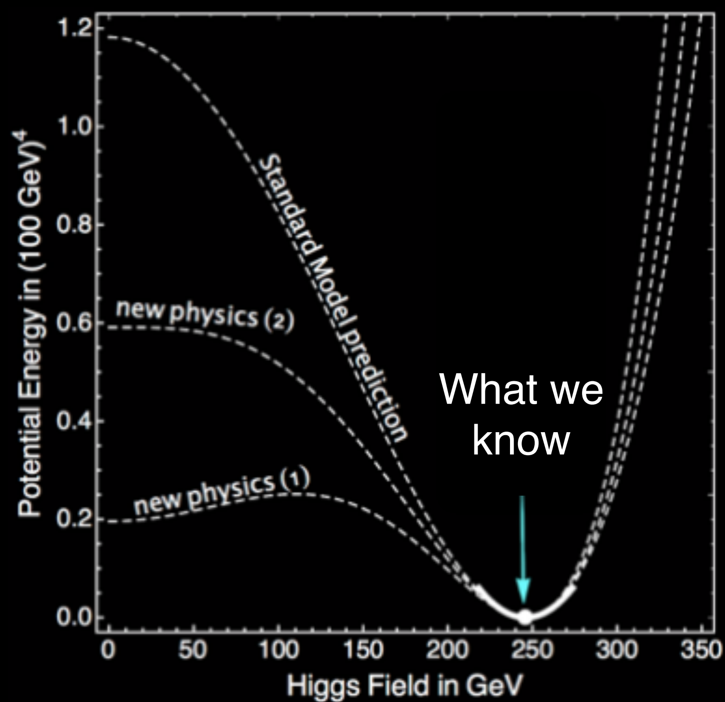


How is electroweak symmetry broken?

https://indico.cern.ch/event/687651/contributions/3403318/attachments/1851013/3038718/LHCP2019_TheoryVision_Craig.pdf

Higgs potential





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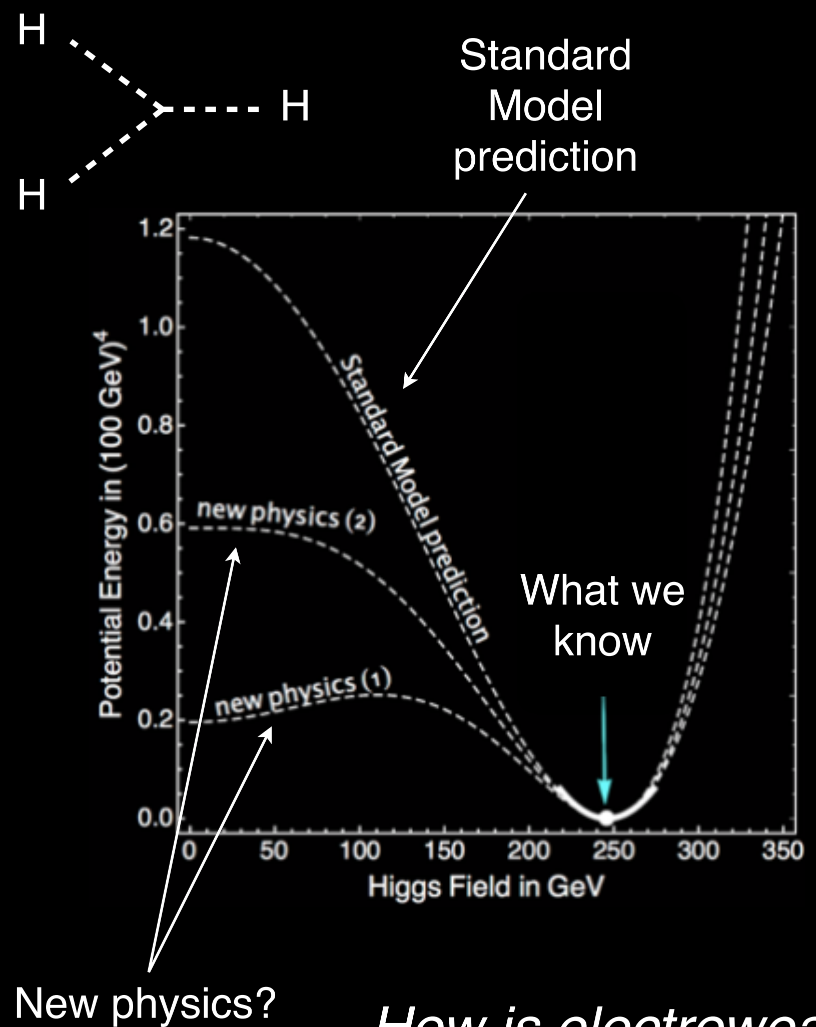
Higgs potential



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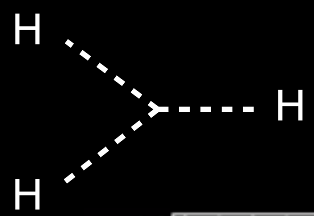
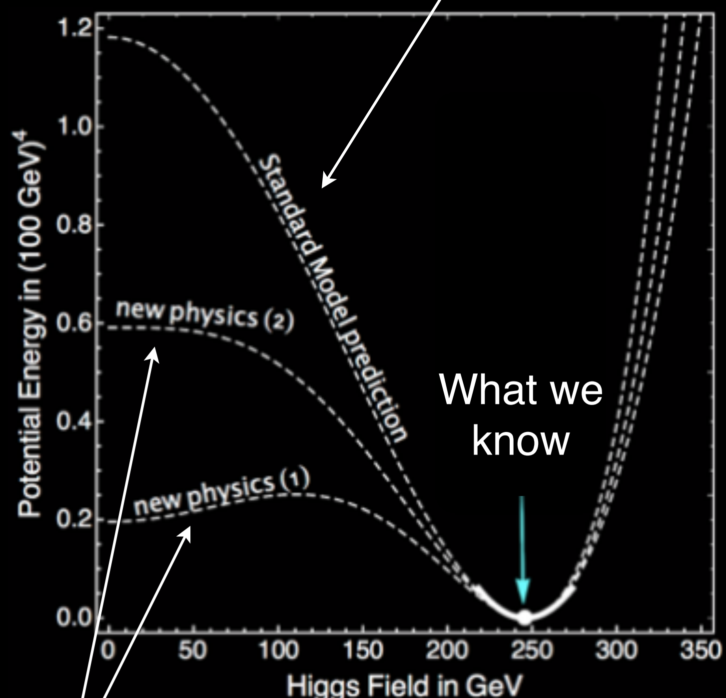


Standard Model prediction

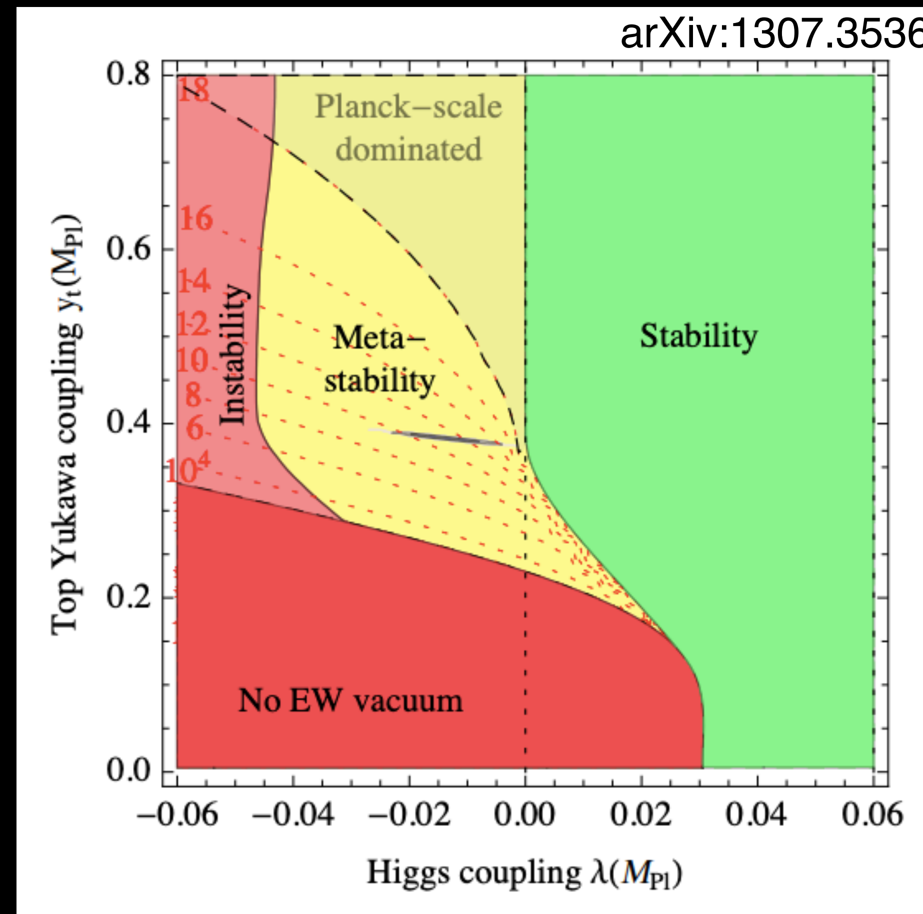


What we know

New physics?

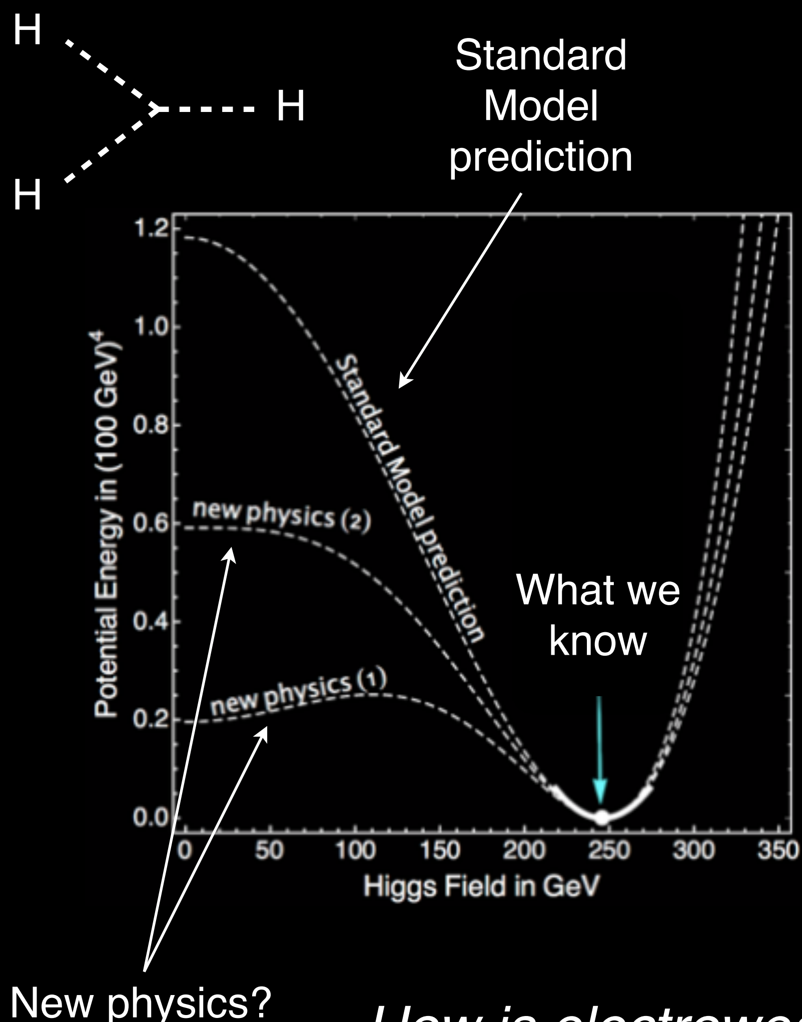
How is electroweak symmetry broken?

What is the fate of the universe?

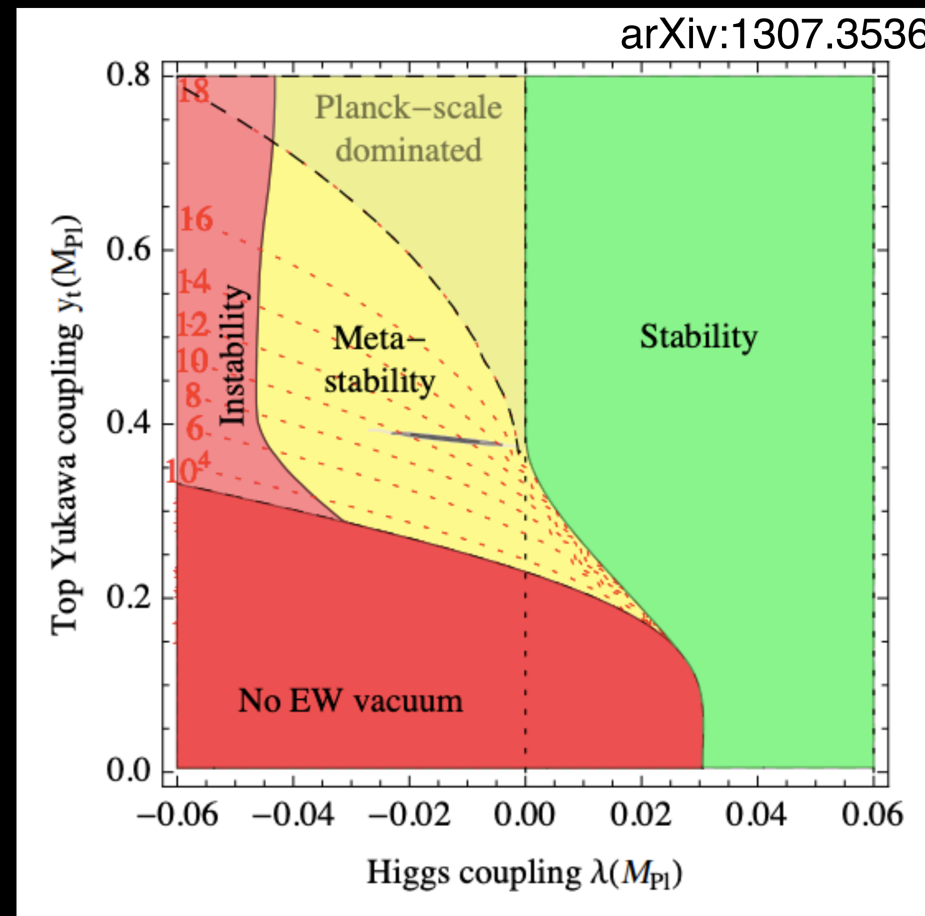


https://indico.cern.ch/event/687651/contributions/3403318/attachments/1851013/3038718/LHCP2019_TheoryVision_Craig.pdf

Higgs potential



What is the fate of the universe?

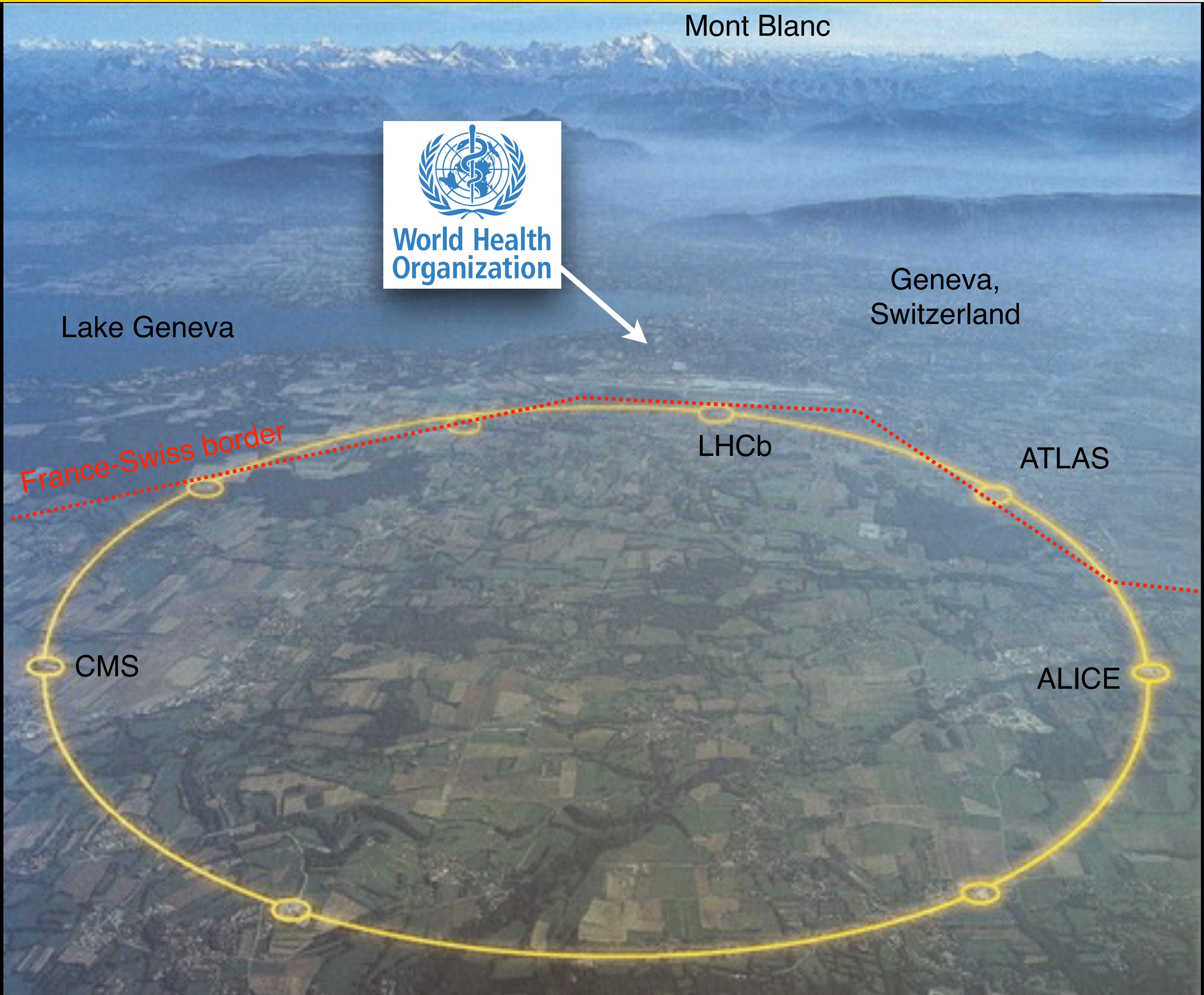


How is electroweak symmetry broken?

https://indico.cern.ch/event/687651/contributions/3403318/attachments/1851013/3038718/LHCP2019_TheoryVision_Craig.pdf

Understanding Higgs potential have deep implications to cosmology

Large Hadron Collider at CERN



Large Hadron Collider at CERN

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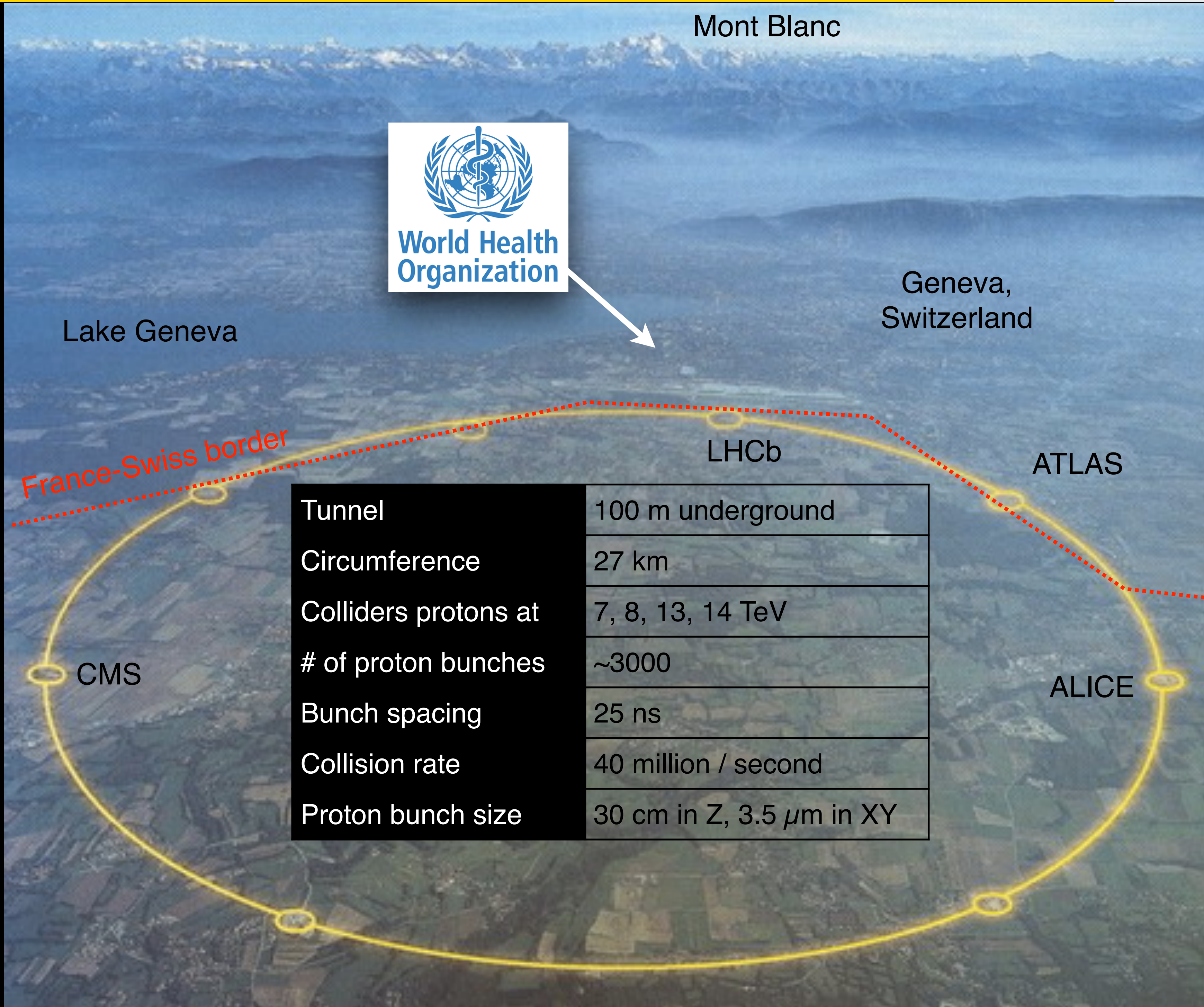
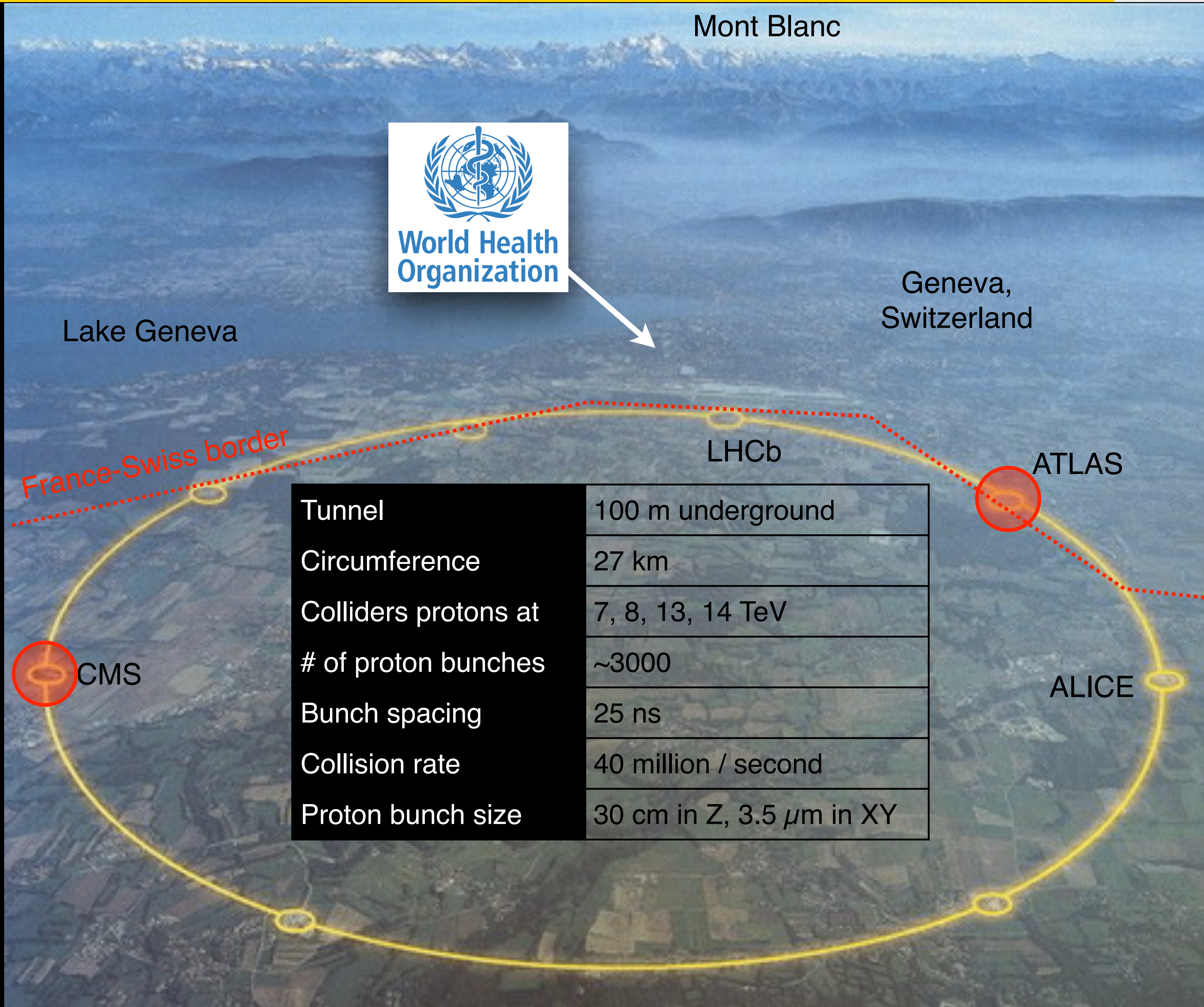
UCSD



Tunnel	100 m underground
Circumference	27 km
Colliders protons at	7, 8, 13, 14 TeV
# of proton bunches	~3000
Bunch spacing	25 ns
Collision rate	40 million / second
Proton bunch size	30 cm in Z, 3.5 μm in XY

Large Hadron Collider at CERN



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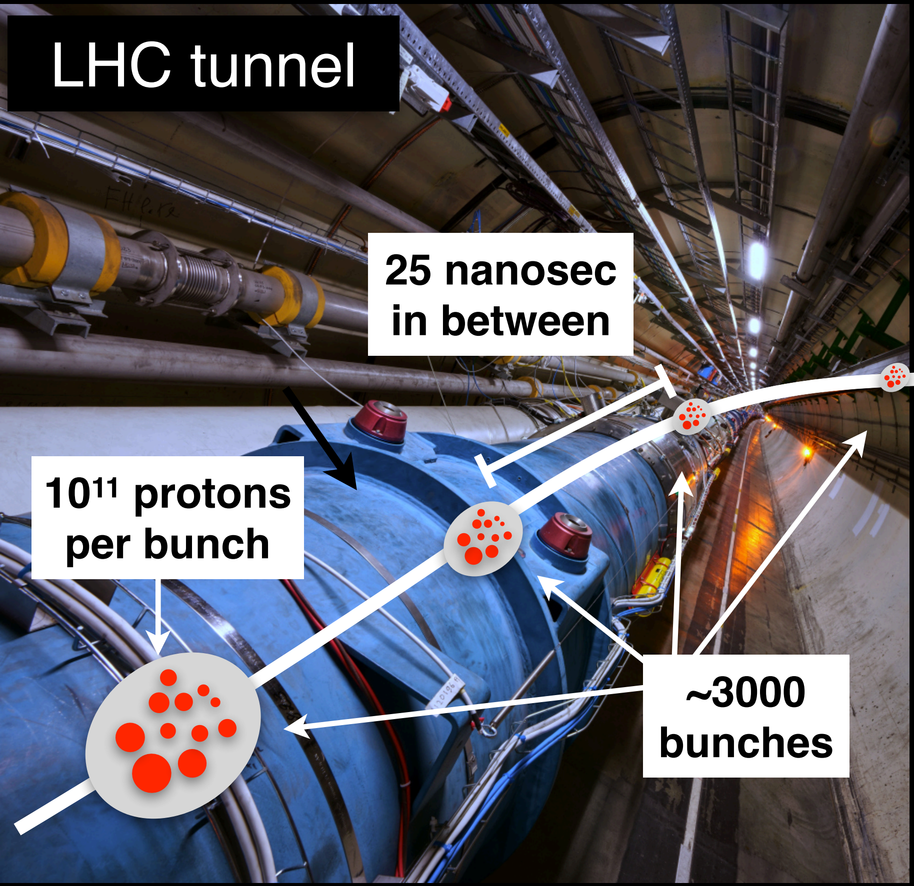
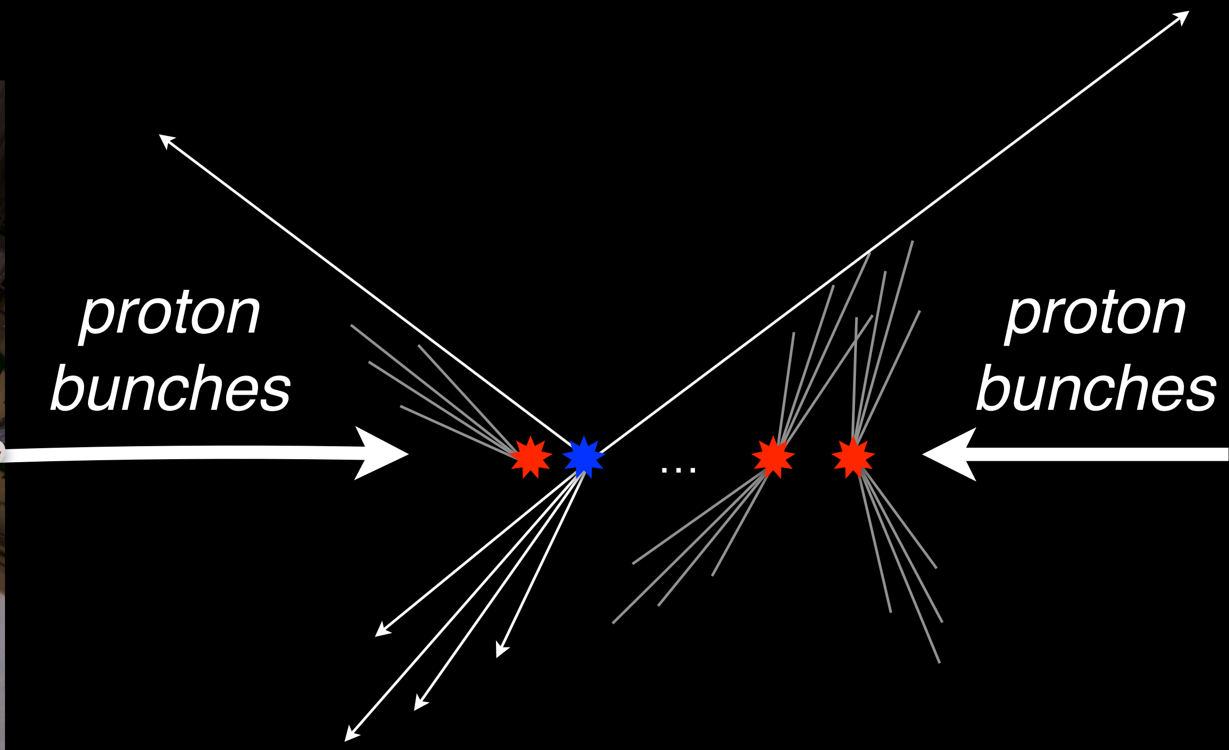
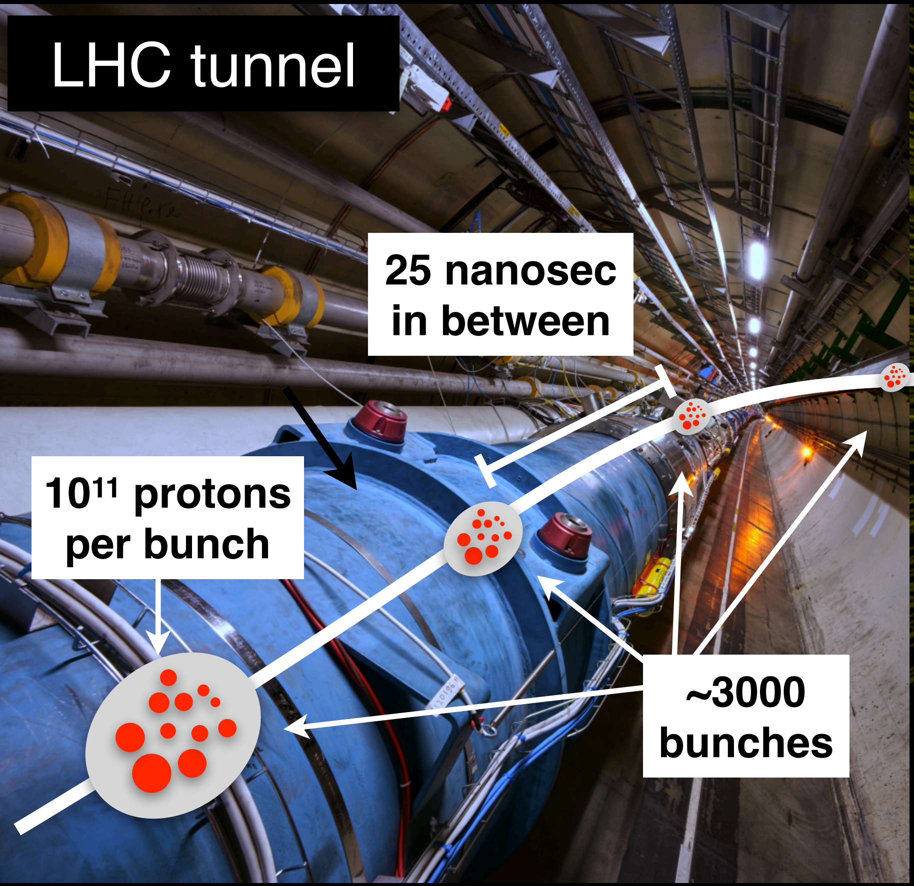
Proton beam collision at the LHC

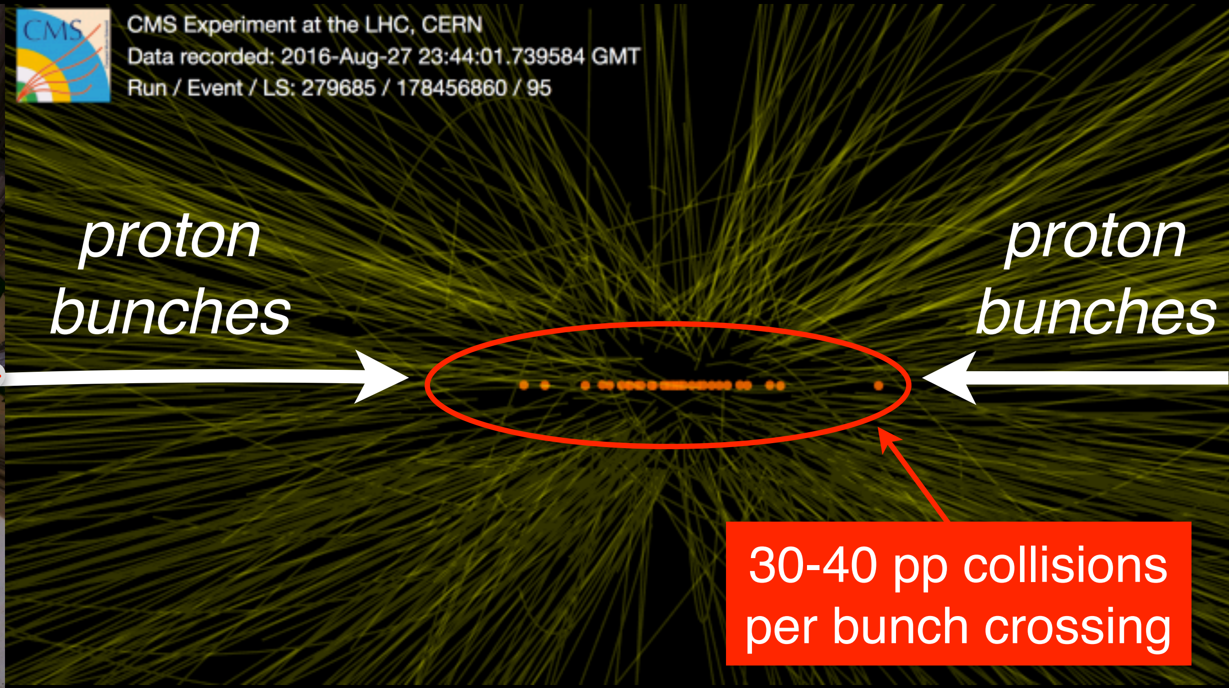




LHC provides highest energy *pp* collisions ever recorded

Proton beam collision at the LHC





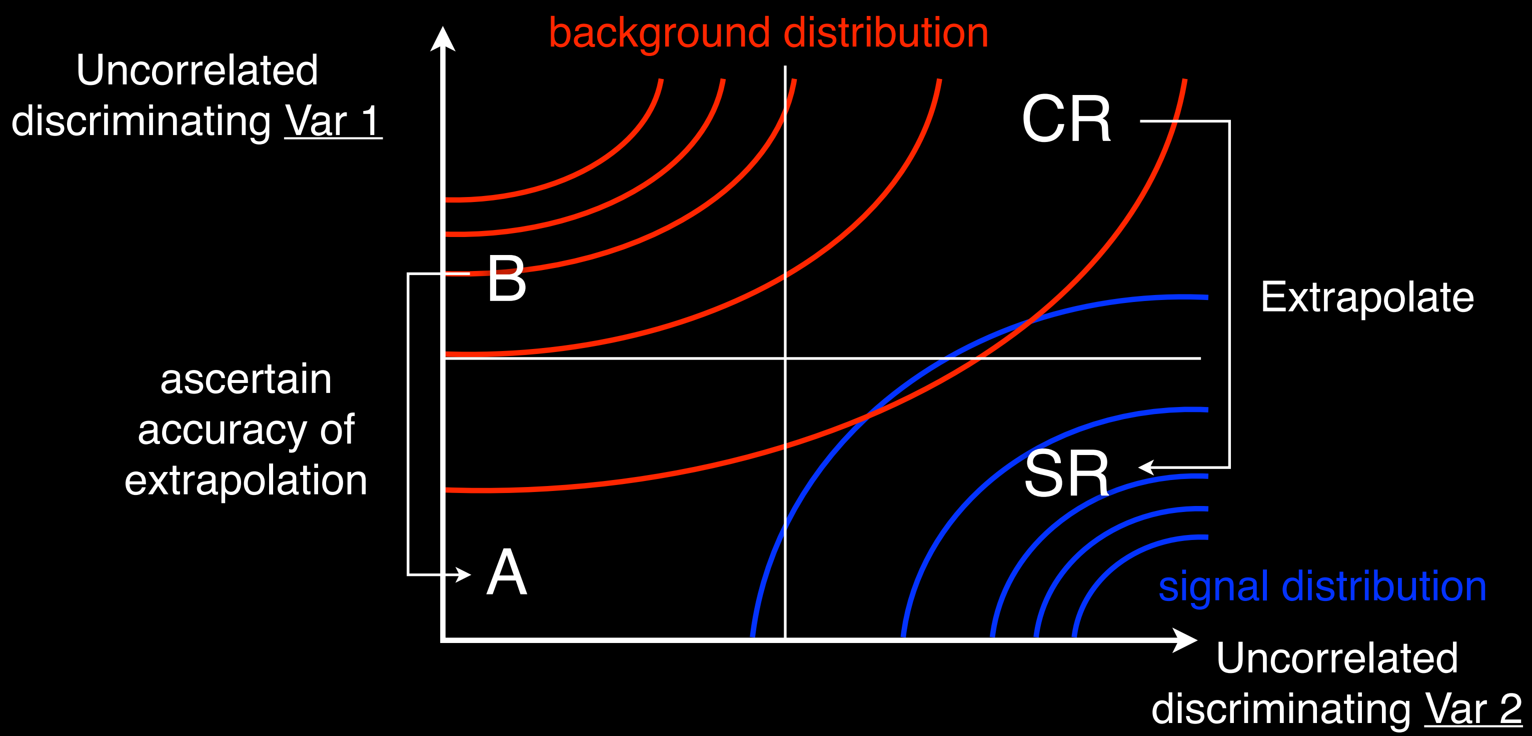
(35 pp collisions) × (40 MHz) =
~1.5 billions *pp* collisions per second

Large dataset of

LHC provides highest energy *pp* collisions ever recorded

Typical search strategy

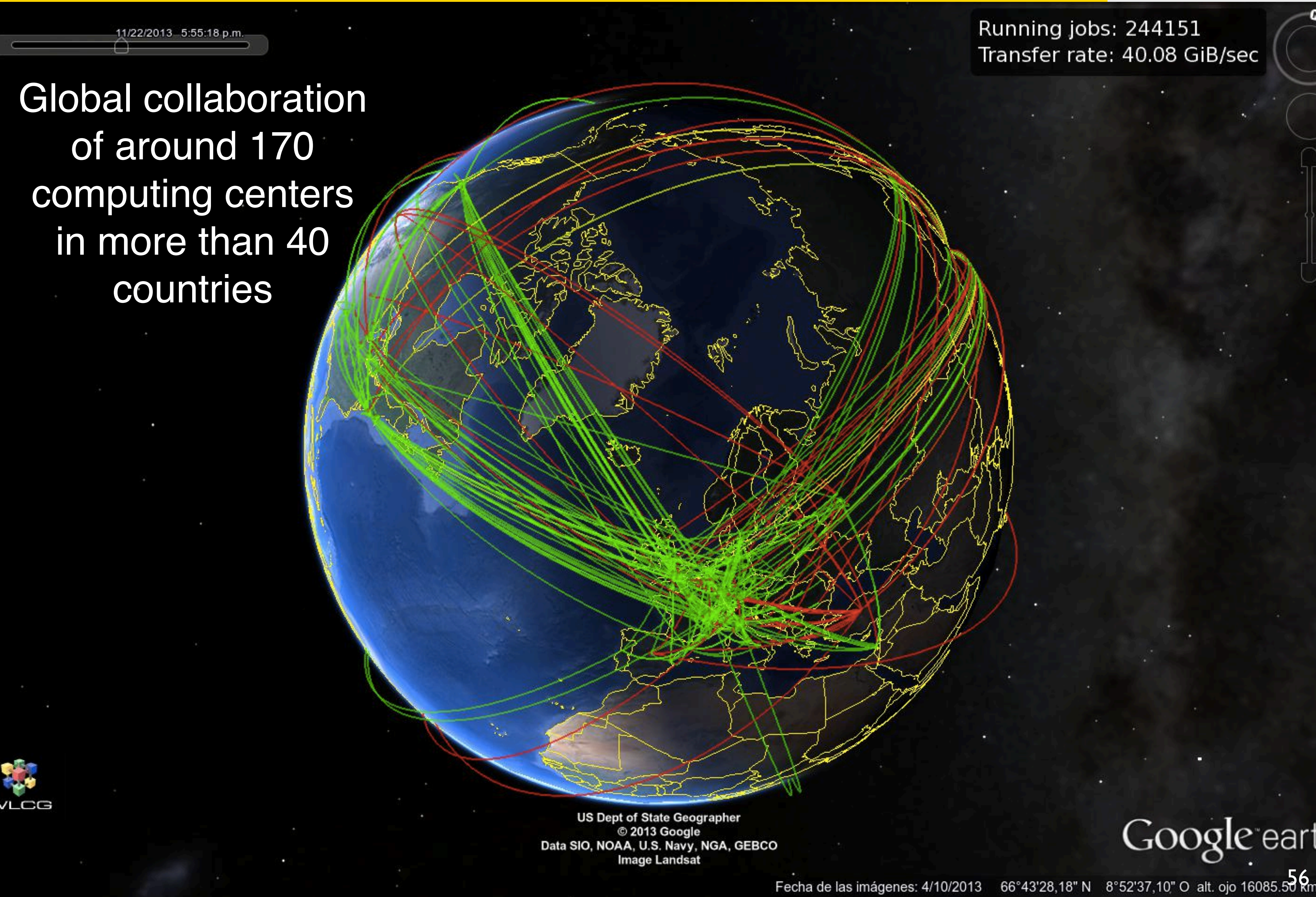
1. Define low background signal regions (SRs)
2. Estimate background yields by extrapolating from bkg. enriched control region (CR)
3. Ascertain accuracy of the extrapolation from a different sample



Make smart choices (brains) then execute to deliver (brawns)

Worldwide LHC Computing Grid (Brawns)

Global collaboration of around 170 computing centers in more than 40 countries



Details on the operation

Detectors have ~70M channels

× few bytes per channel

× 40 MHz event rate

× 1/1000 zero-suppression

⇒ O(10) TB / s

× "one" year (4×10^6 secs)

⇒ O(100) Exabyte / year

× 1/100,000 event filtering

⇒ ~5 PB / year

After some processing e.g. CMS provides ~10 PB of data and simulation for analysis

This is reprocessed twice a year

Then this is further reduced by x10 and is processed monthly

Then we further reduce it x5 and can be done in a ~week

And then we further reduce it ~few TB that can be processed daily

Recent results in multi-boson physics

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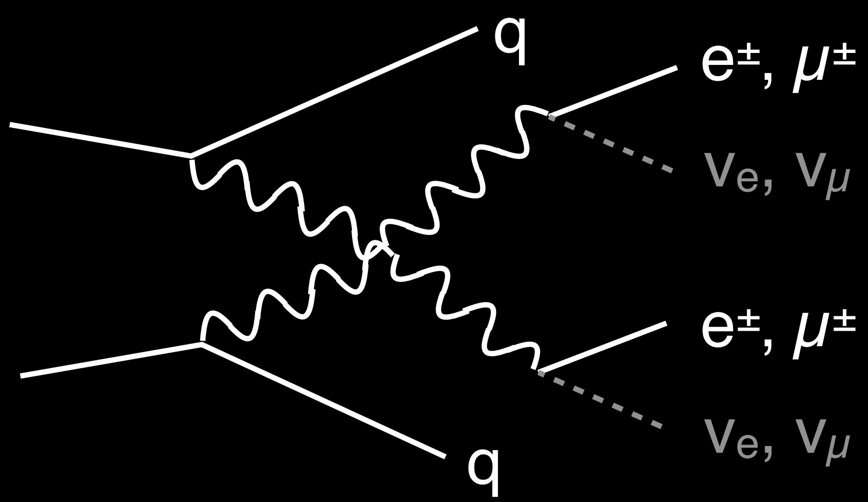
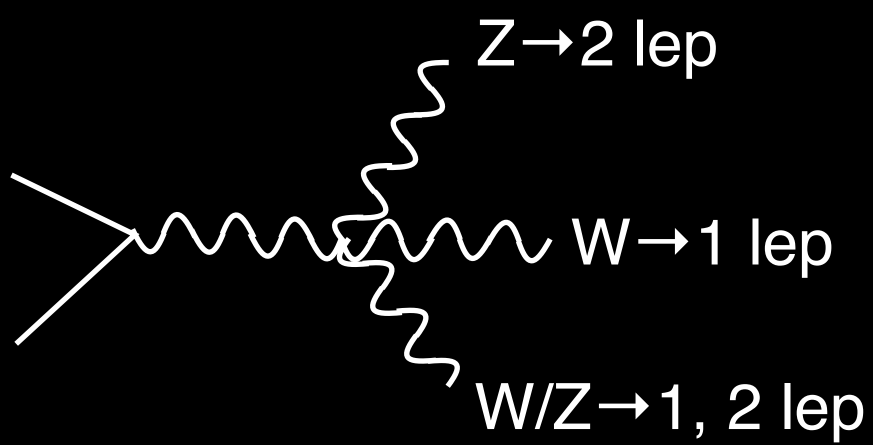
- Several important results have come out recently from both ATLAS and CMS
- I will highlight a few (from CMS)
- (Disclaimer: Rest of the talk from here on will focus mostly on CMS)

WW scattering



Same-sign dilepton + 2 quarks

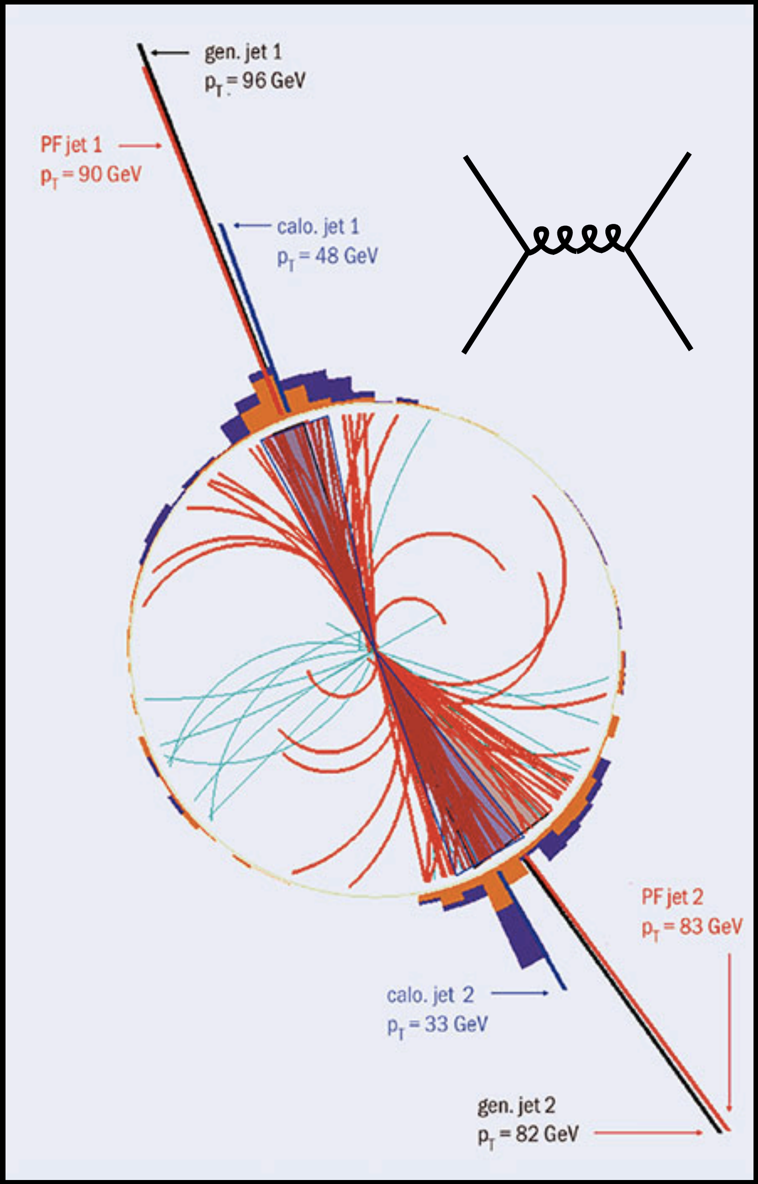
Tri-boson process



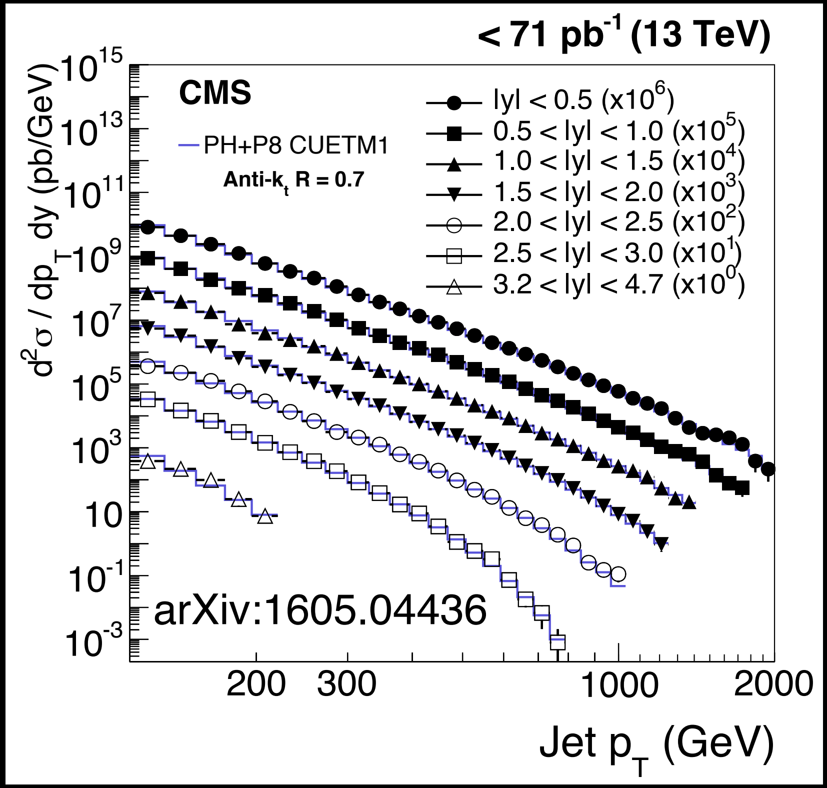
4 or 5 leptons

⇒ electrons, muons, and jets reconstructions are crucial

Jet formation and identification



Quarks and gluons produced from pp collisions manifest as a "jet" of particles



Excellent jet reconstruction and simulation

Jets from vector boson scattering

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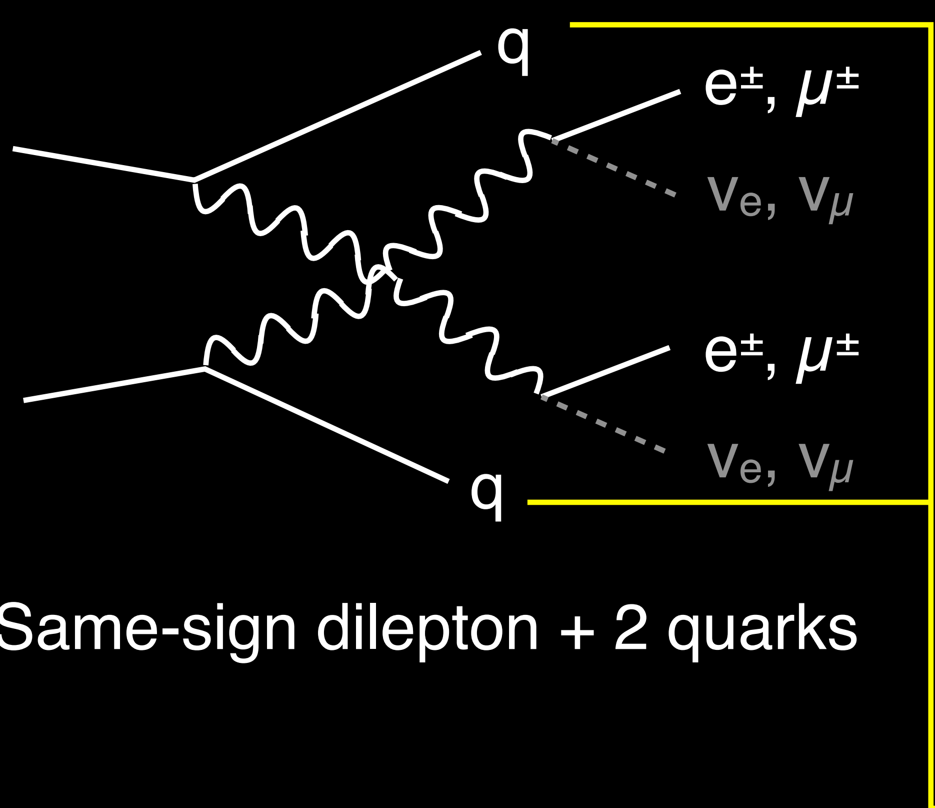
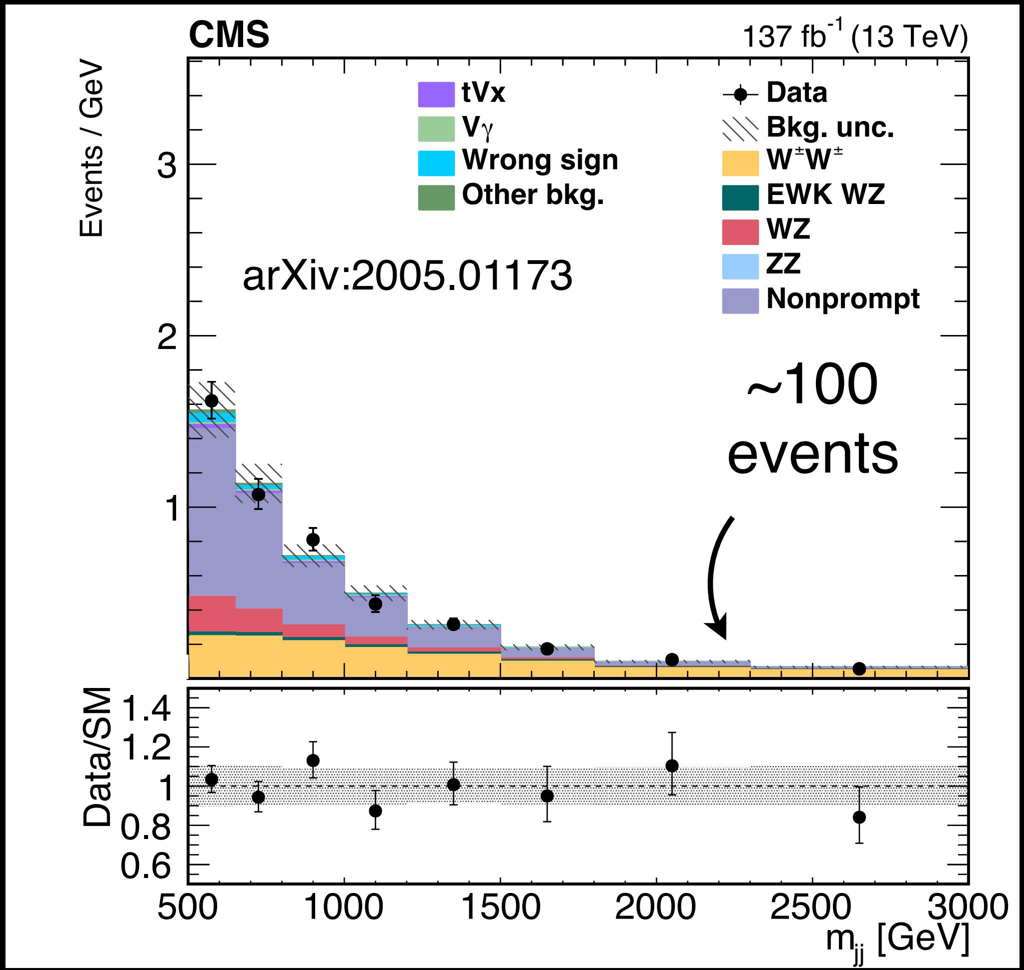
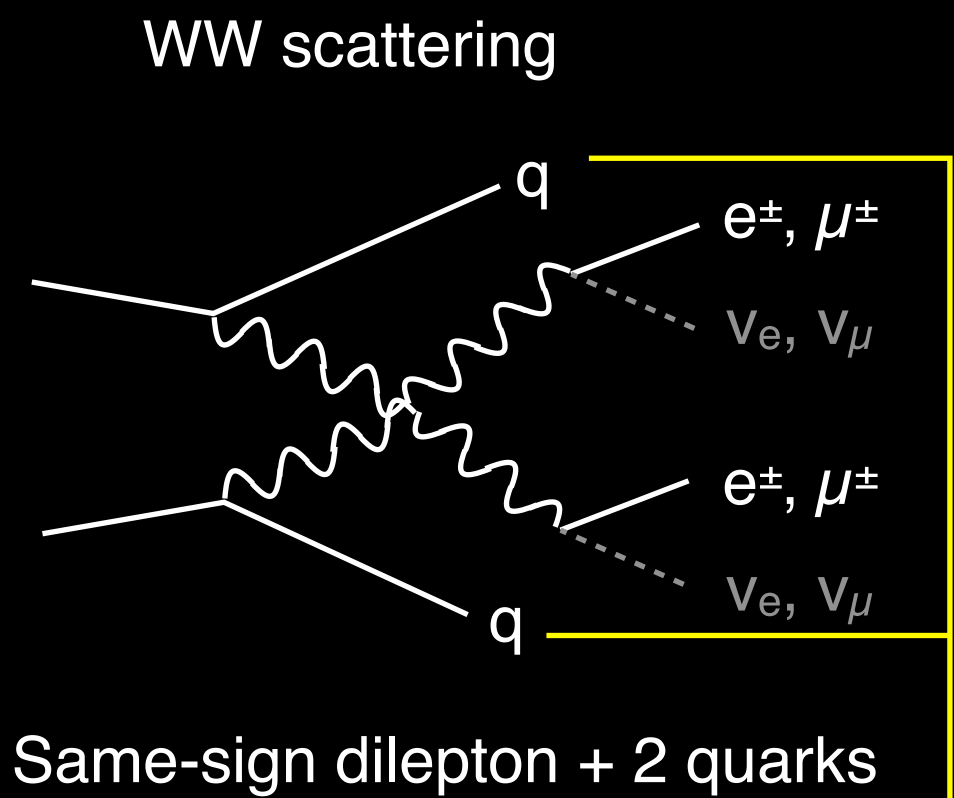
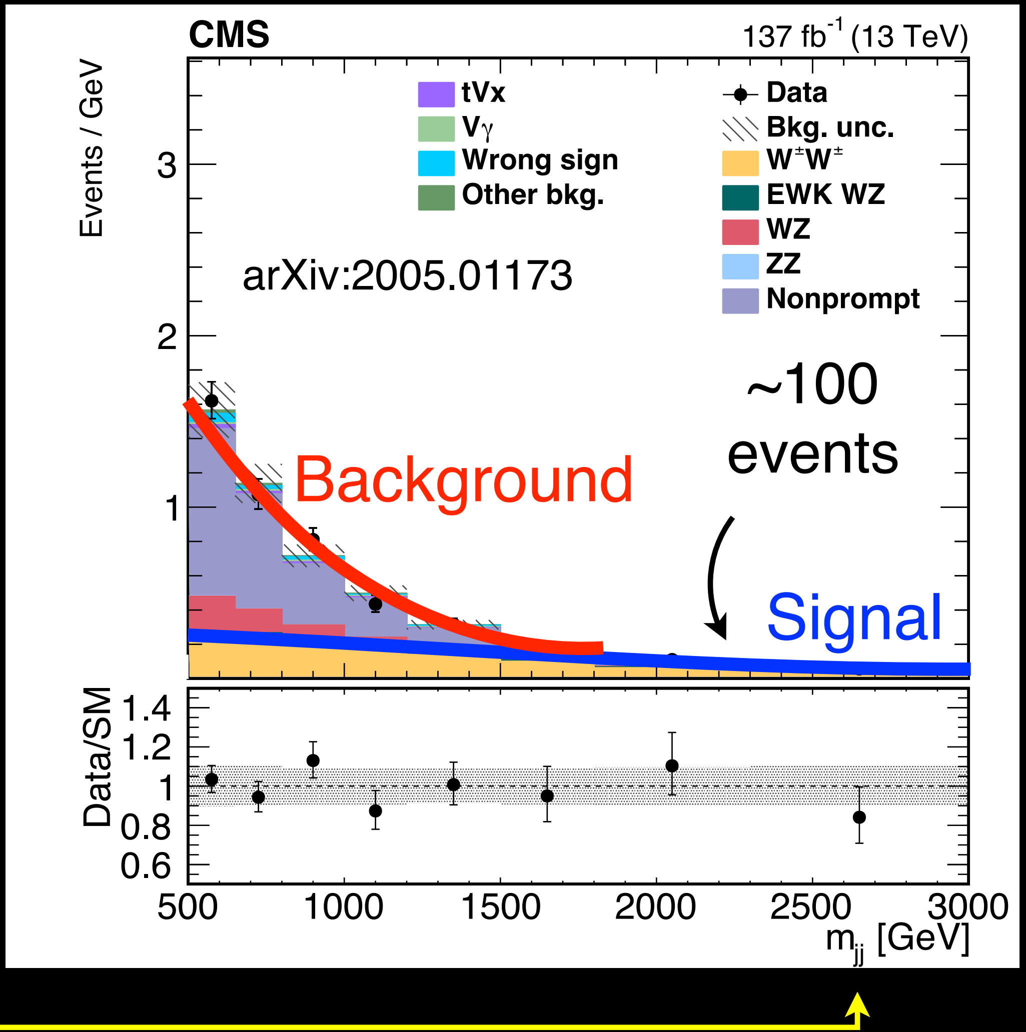




Two jets from VBS process tend to have relatively high invariant mass

Jets from vector boson scattering



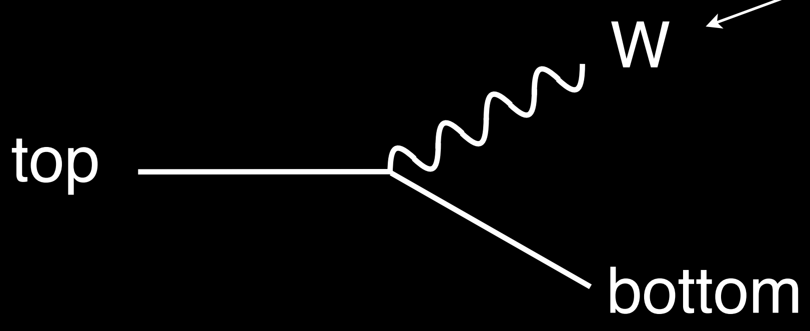


Two jets from VBS process tend to have relatively high invariant mass

Top quark decay features

Top quark is produced more abundantly than multi-bosons (see slide 9 for typical rates)

Produces W bosons that are not of our interest



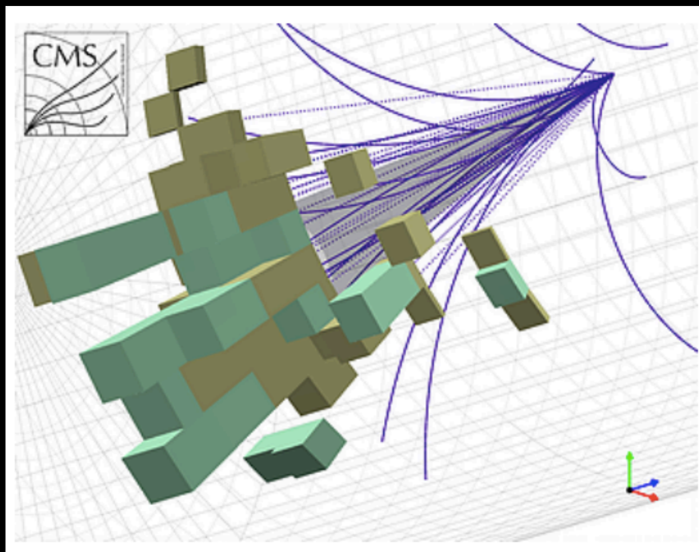
When produced top quark decays ~100% of the time to b quark and a W boson

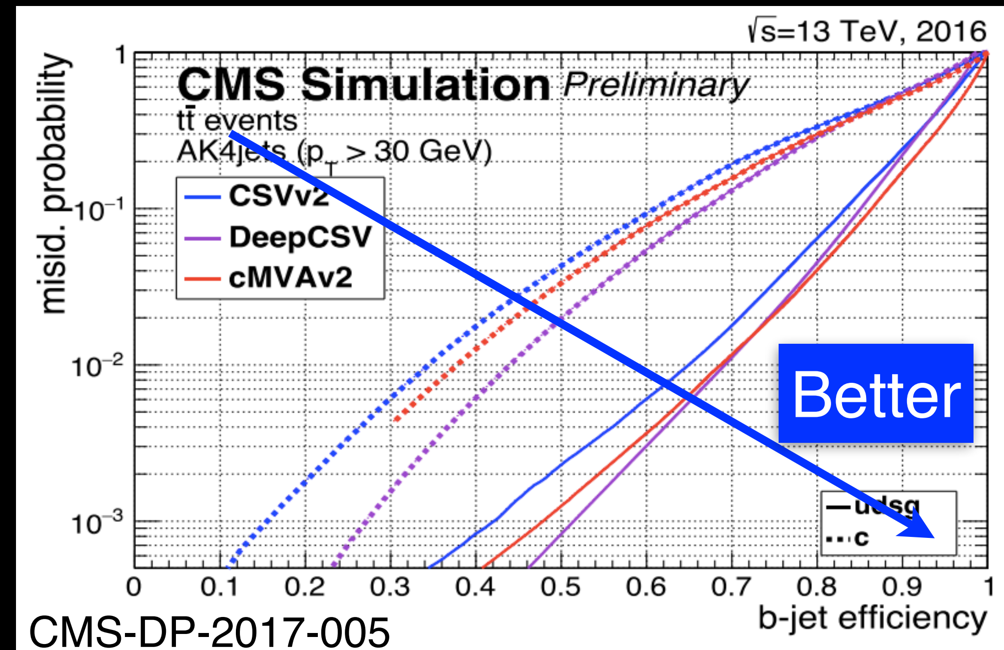
bottom quark has a long-lifetime (flight distance ~ 100s of μm)

⇒ Tag bottom quark and reject events with bottom quarks

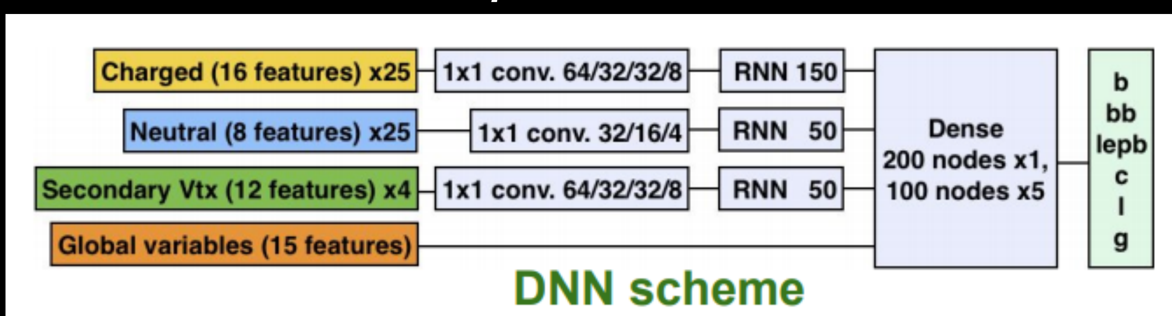
Machine learning in LHC

Was this from bottom quark?



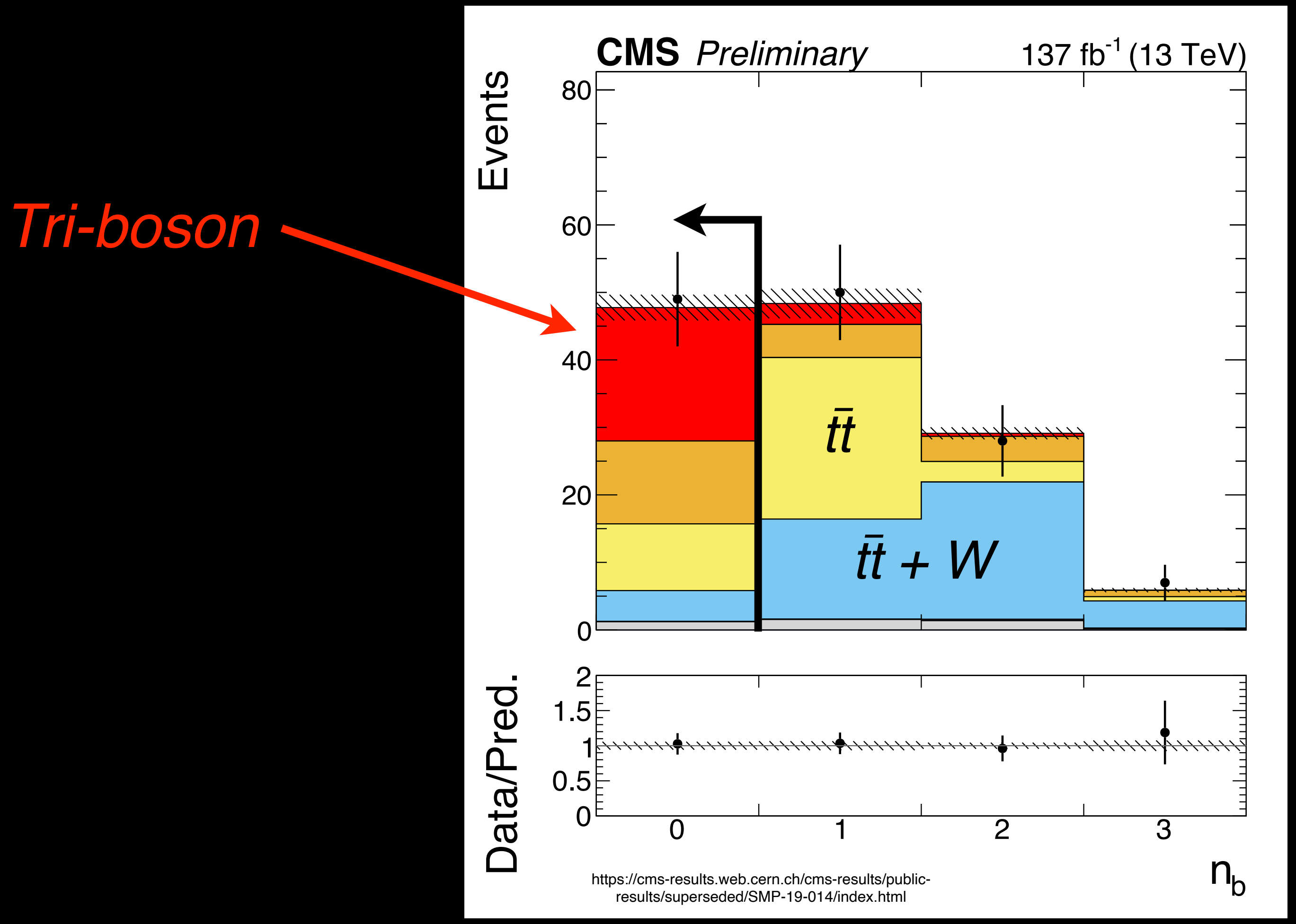


Train deep neural network



b-tagging via machine learning is one of many successful application of ML that is continually growing in particle physics

b quark jets tagging



Number of b-tagged jets in the event

Reject events with bottom quark to reduced backgrounds from top quark

WW scattering results

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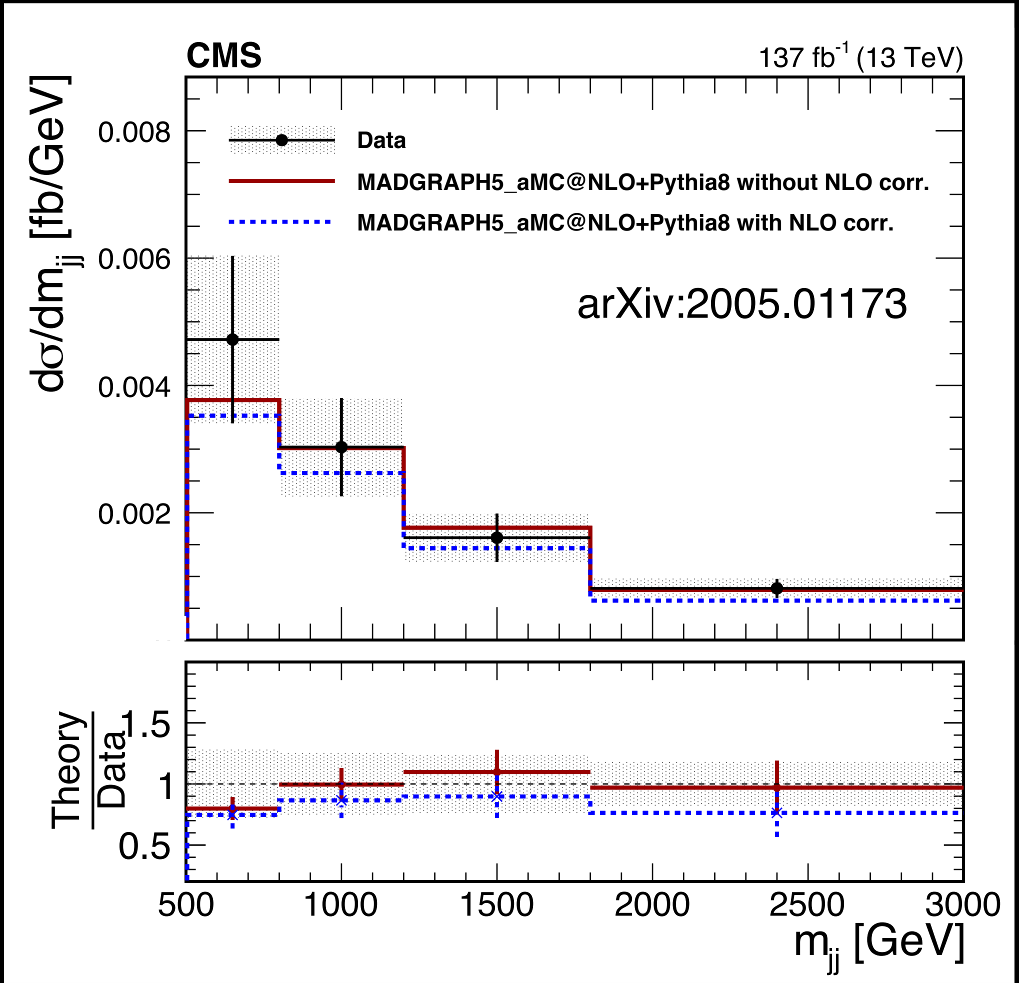

- O(100) events observed
- Measure the production rates as a function of important variables
- The measured cross section is compatible with the SM

WW scattering cross section has been measured and found to be consistent with SM

Reconstruct W→qq in WWW → l±l±qq

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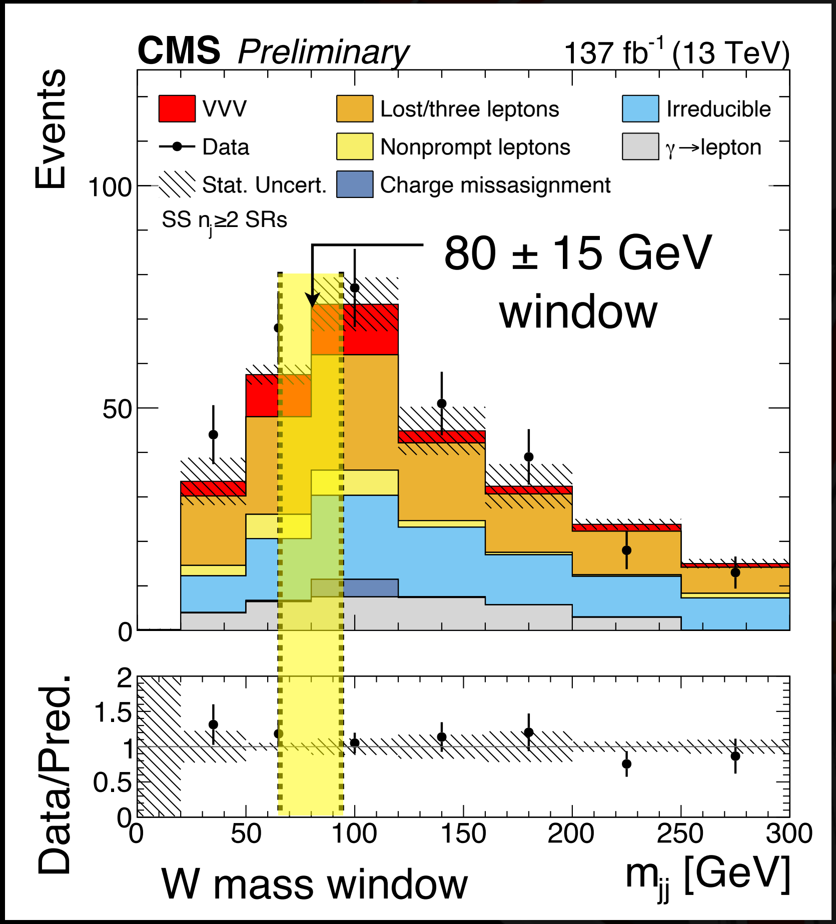
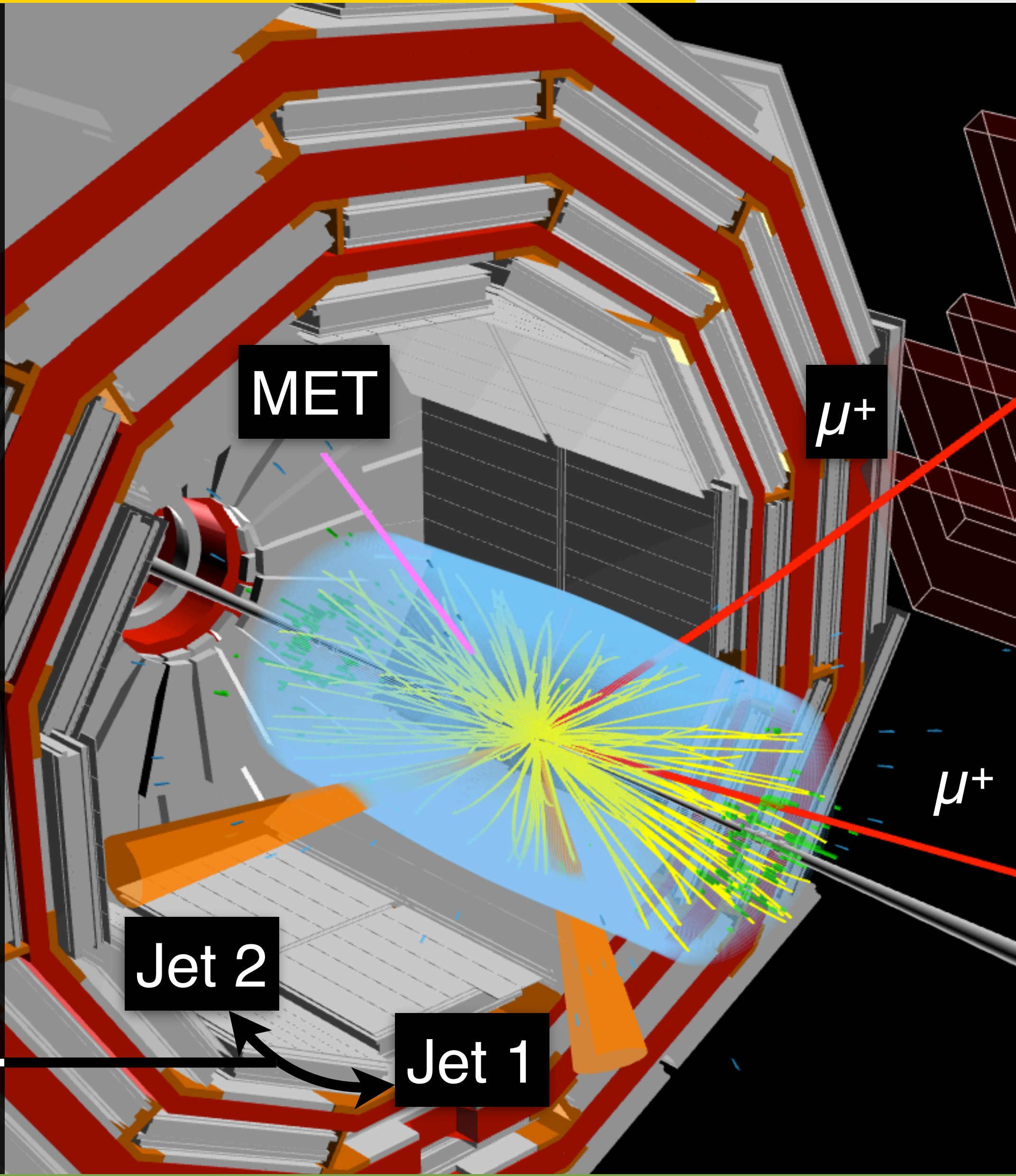
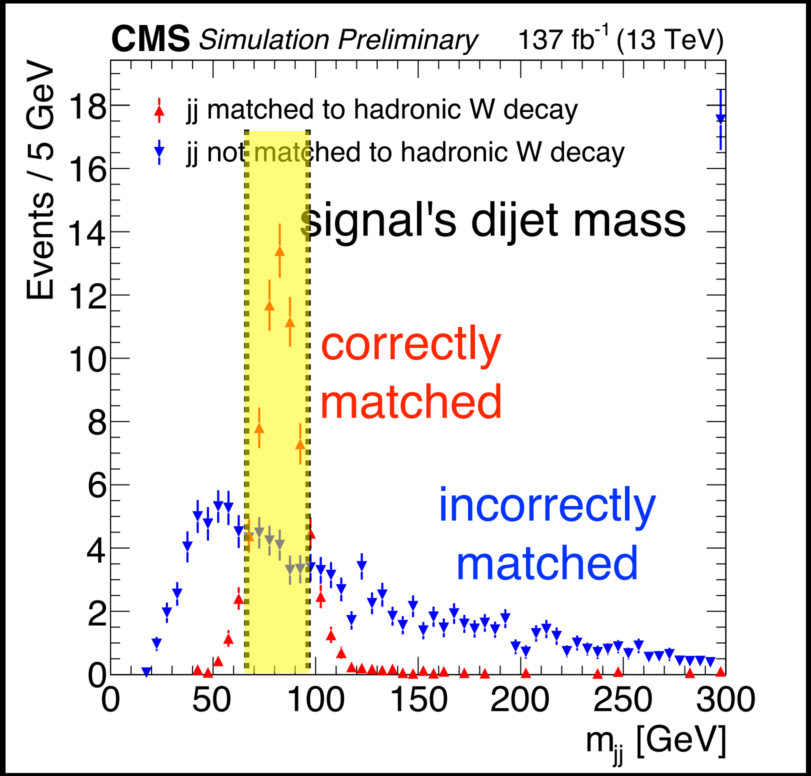


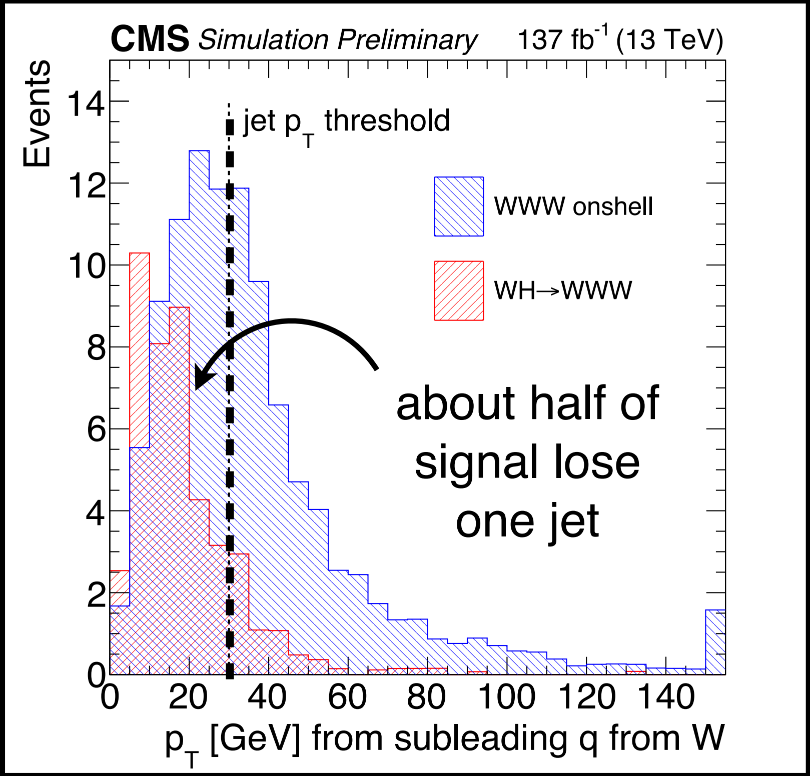
N.B. some signals are outside the window (See next slide)



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

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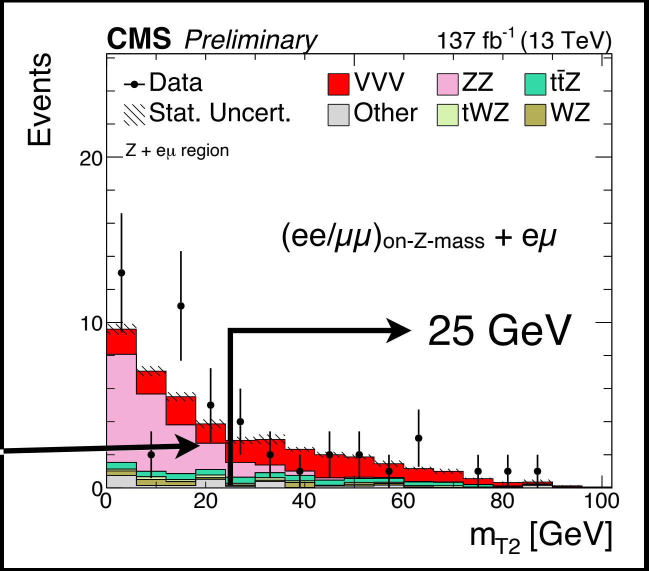
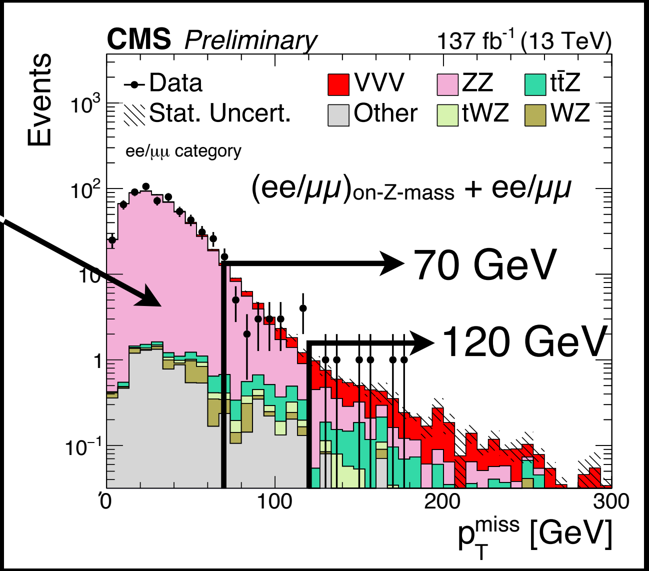
Events are separated into 2 categories by flavor:

- "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 $ZZ \rightarrow ll\tau\tau$



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 $Z \rightarrow ll$ v. $WW \rightarrow l\nu l\nu$

5 leptons

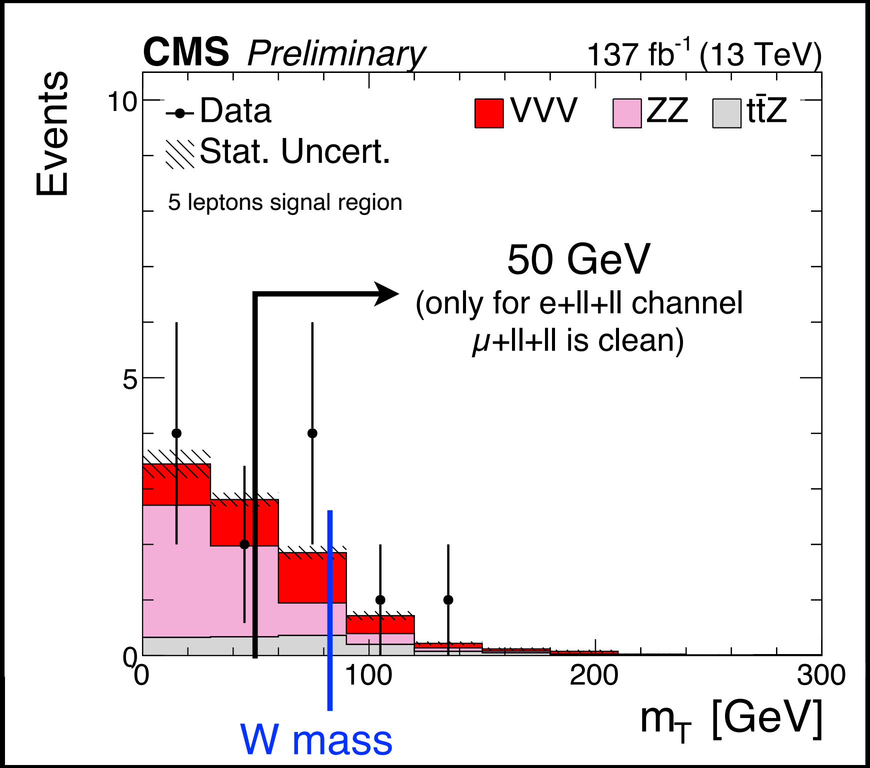
5 leptons target W **Z Z** signal

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

Cut-and-count of one bin



Exploit the features of W → lν decay

Background estimations

	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Dominant Bkgs.	$WZ \to l^{\pm}\nu l^{\pm}l^{\mp}$ (lost $l^{\mp}$) $t\bar{t} \to bb + l + X$ ↳ 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

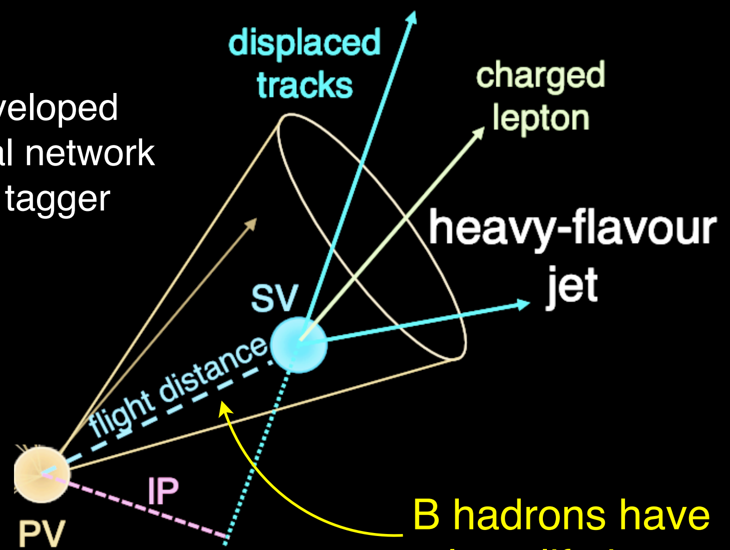
Types of backgrounds	Suppressed via	Bkg. estimation
Fake leptons	Isolation	Reliably extrapolate across isolation
Backgrounds with *b* jets	*b* tagging	Reliably extrapolate across *b* tagging
Lost leptons	Removing events with 3rd lepton	Reliably extrapolate across N leptons
Irreducible	Smart flavor choices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

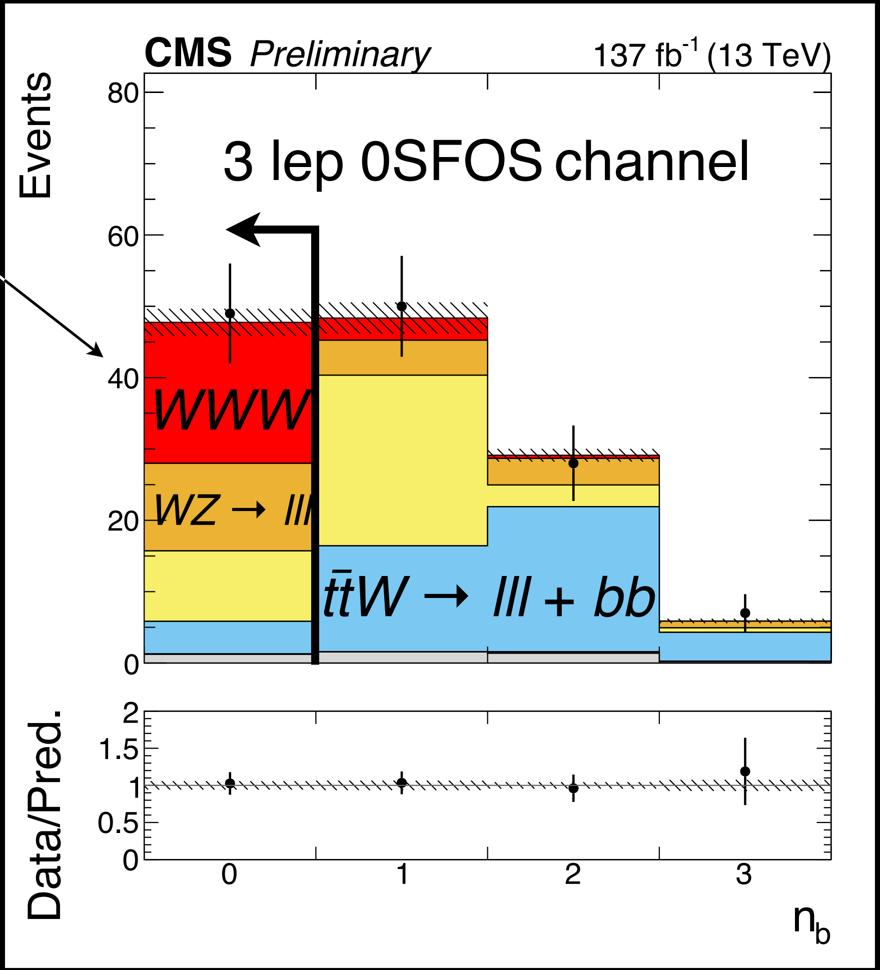
Reliably extrapolate across the method used to suppress background to estimate the size of residual backgrounds in signal region

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





Signals do not have *b* jets

Added benefit of rejecting events with b

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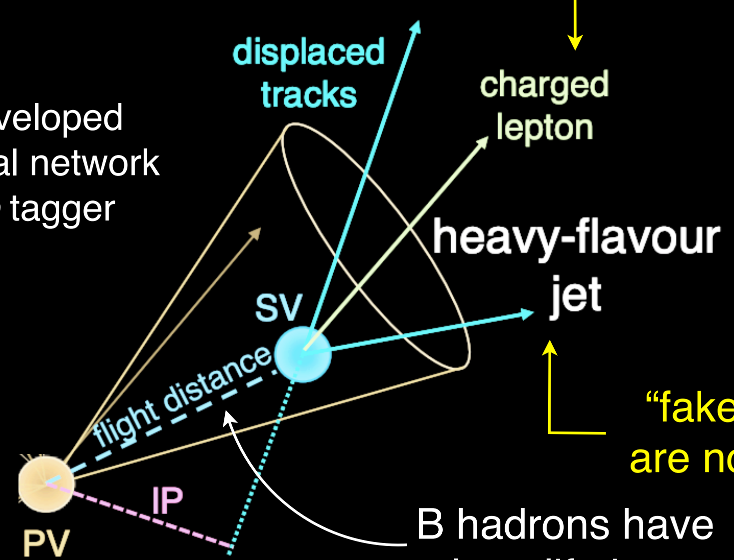
EW processes generally do not come with b jets ⇒ Require # of b = 0

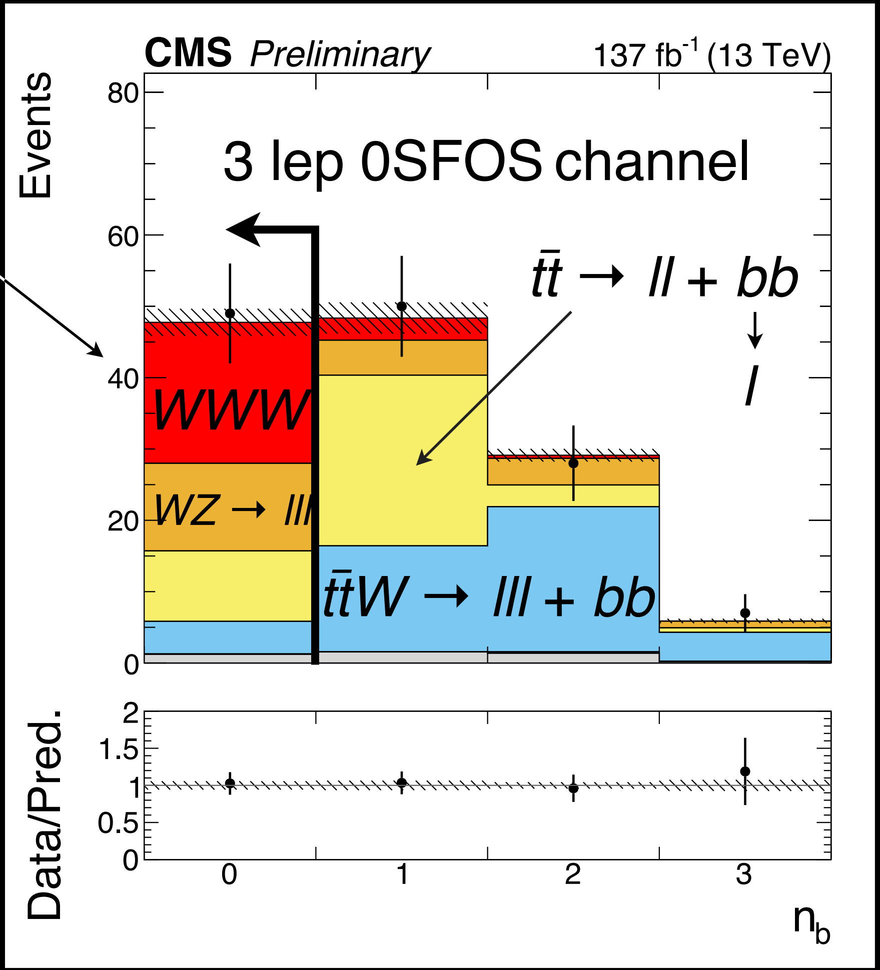
Lepton from b decay is the main source of “fake"

CMS developed deep neural network based *b* tagger



“fake" leptons are not isolated

B hadrons have long lifetime



Signals do not have *b* jets

WZ background in same-sign channel

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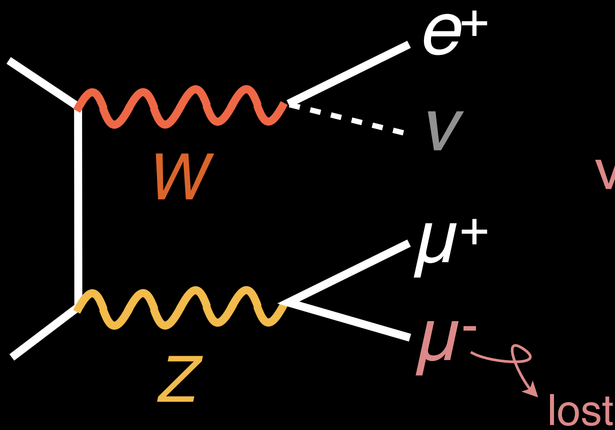


enters signal region via lost lepton ⇒ Need to understand lepton finding efficiency

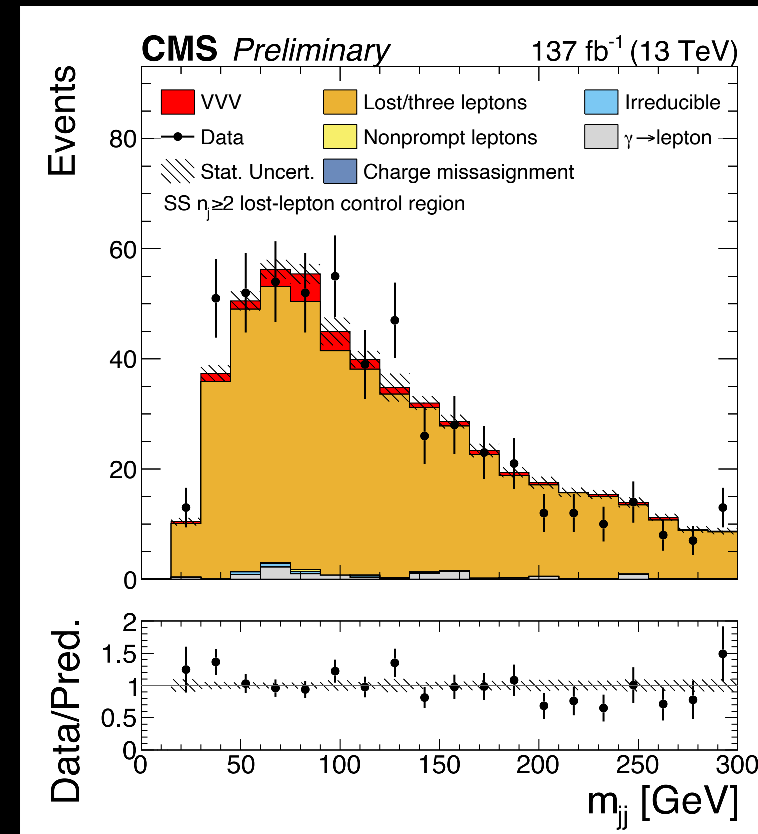
Lepton finding efficiency is well modeled by MC

(factors: P_T, η, lepton ID)

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

Experimental systematics assigned

Control region data statistics dominates uncertainty (20%)



Estimate lost lepton background by extrapolating across # of leptons

Results (Cut-based analysis)

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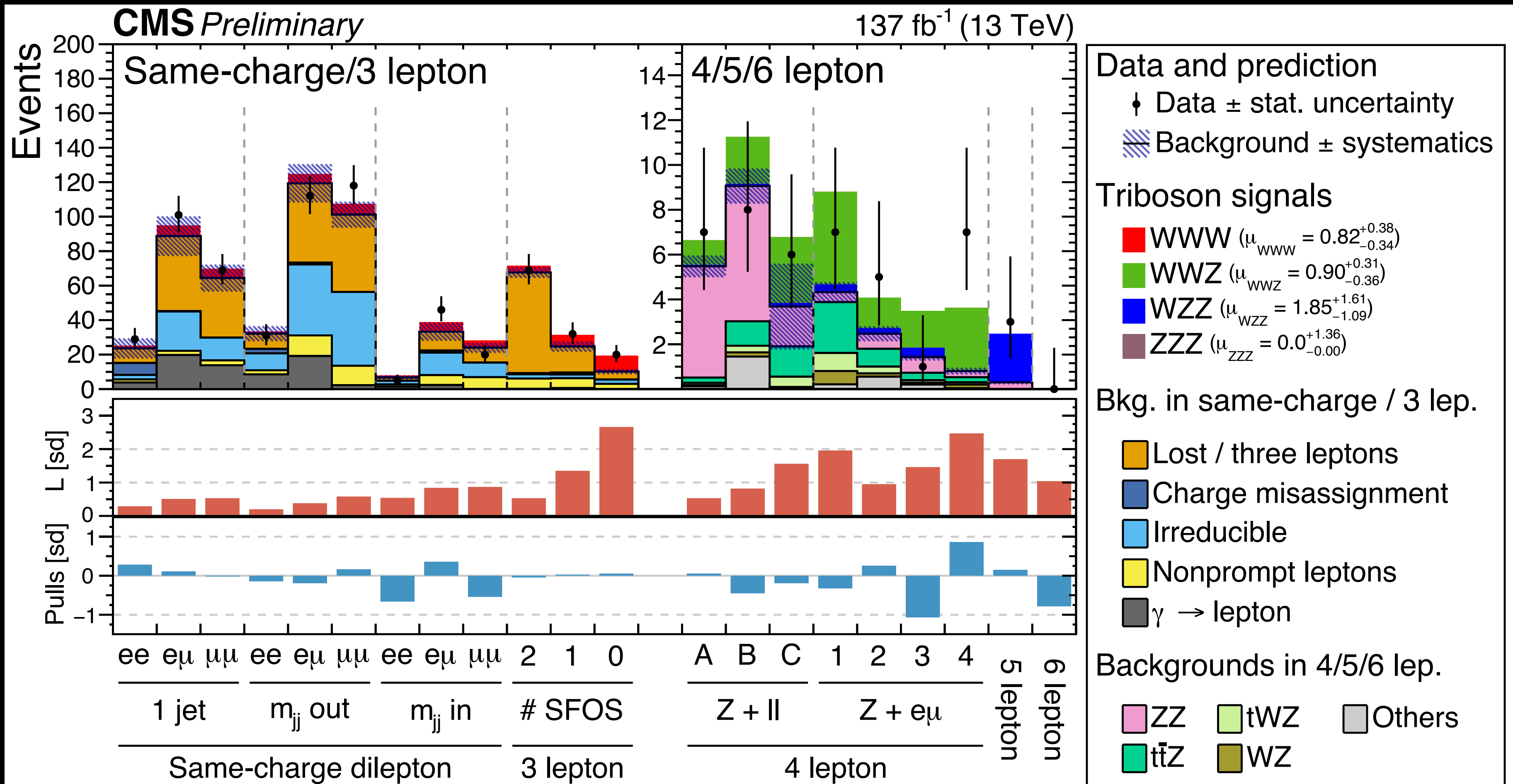
$$\text{Signal strength } \mu = \frac{\text{Measured cross section}}{\text{Theoretical cross section}}$$



9 bins 3 bins 7 bins 1 1

More sensitive bins are generally to the right

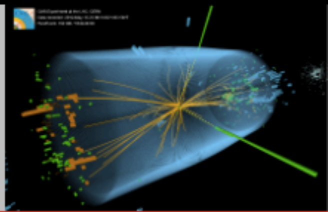
Cut-based analysis is also reported for cross check and completeness

(also easier to understand by theorists if re-interpreted)

Title

Compact Muon Solenoid

LHC, CERN



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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

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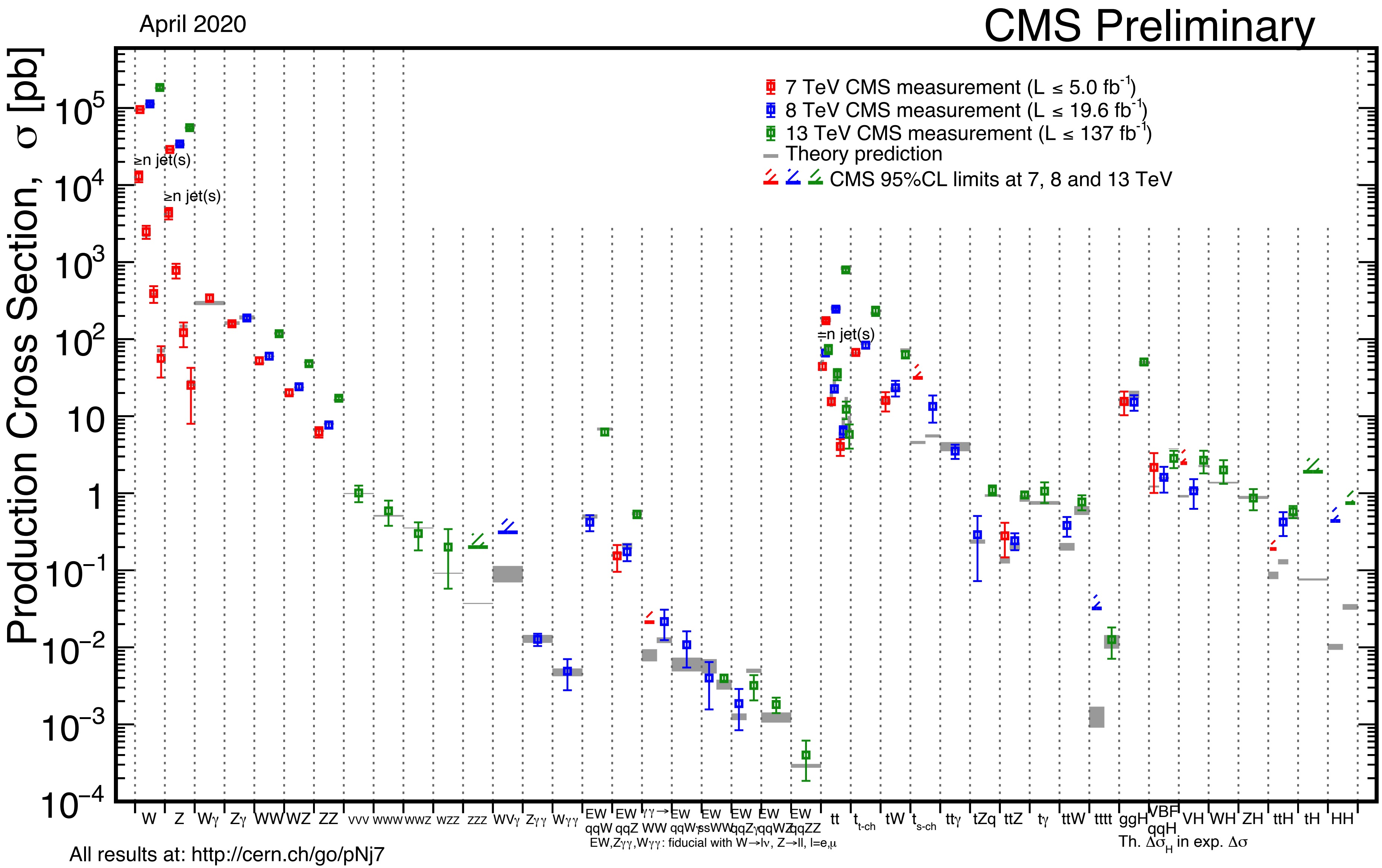

Title

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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

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

3L selection

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

4L preselection

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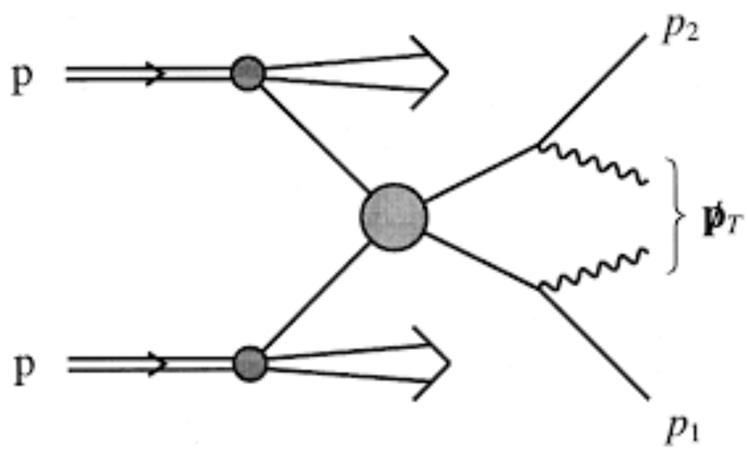
Features	Selections
Number of leptons	Select events with 4 leptons passing common veto-ID
Triggers	Select events passing dilepton triggers
Z lepton	Find opposite charge lepton pairs, passing ZID, closest to m_Z Require Z leptons to have $p_T > 25, 15$ GeV
W lepton	Require that leftover leptons are opposite 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 $p_{T}^{miss} > 120\,\text{GeV}$ (Bin A) $p_{T,4\ell} > 70\,\text{GeV}$ and $70 < p_{T}^{miss} < 120\,\text{GeV}$ (Bin B) $40 < p_{T,4\ell} < 70\,\text{GeV}$ and $70 < p_{T}^{miss} < 120\,\text{GeV}$ (Bin C)

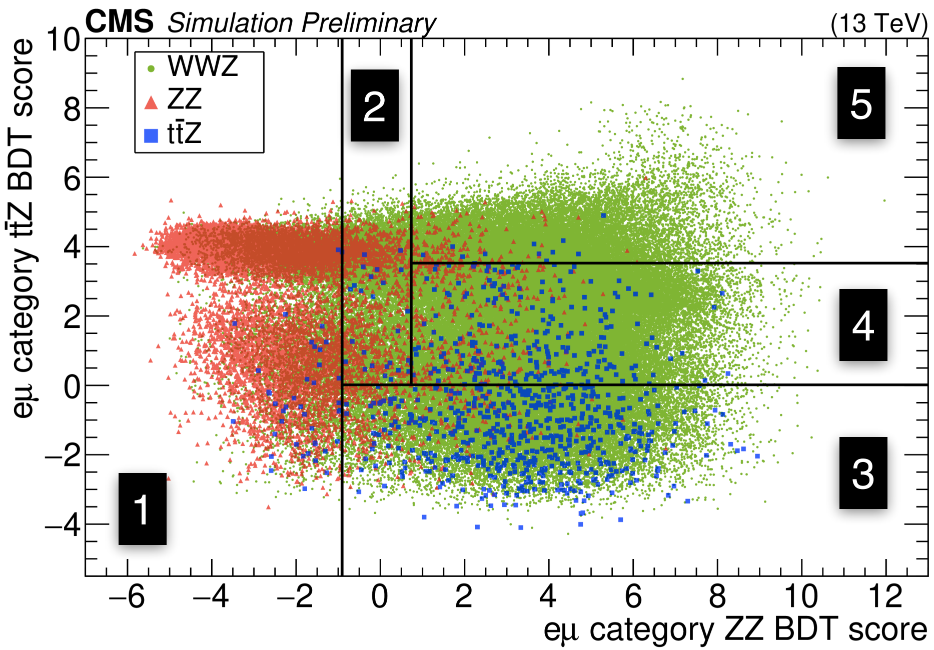
$$m_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\nu(1)} + \vec{p}_{\mathrm{T}}^{\nu(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max \left(m_{\mathrm{T}}^{(1)}(\vec{p}_{\mathrm{T}}^{\nu(1)}, \vec{p}_{\mathrm{T}}^{\mathrm{e}}), m_{\mathrm{T}}^{(2)}(\vec{p}_{\mathrm{T}}^{\nu(2)}, \vec{p}_{\mathrm{T}}^{\mu})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



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

For Z→ττ→llνννν 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 , ∞)	-

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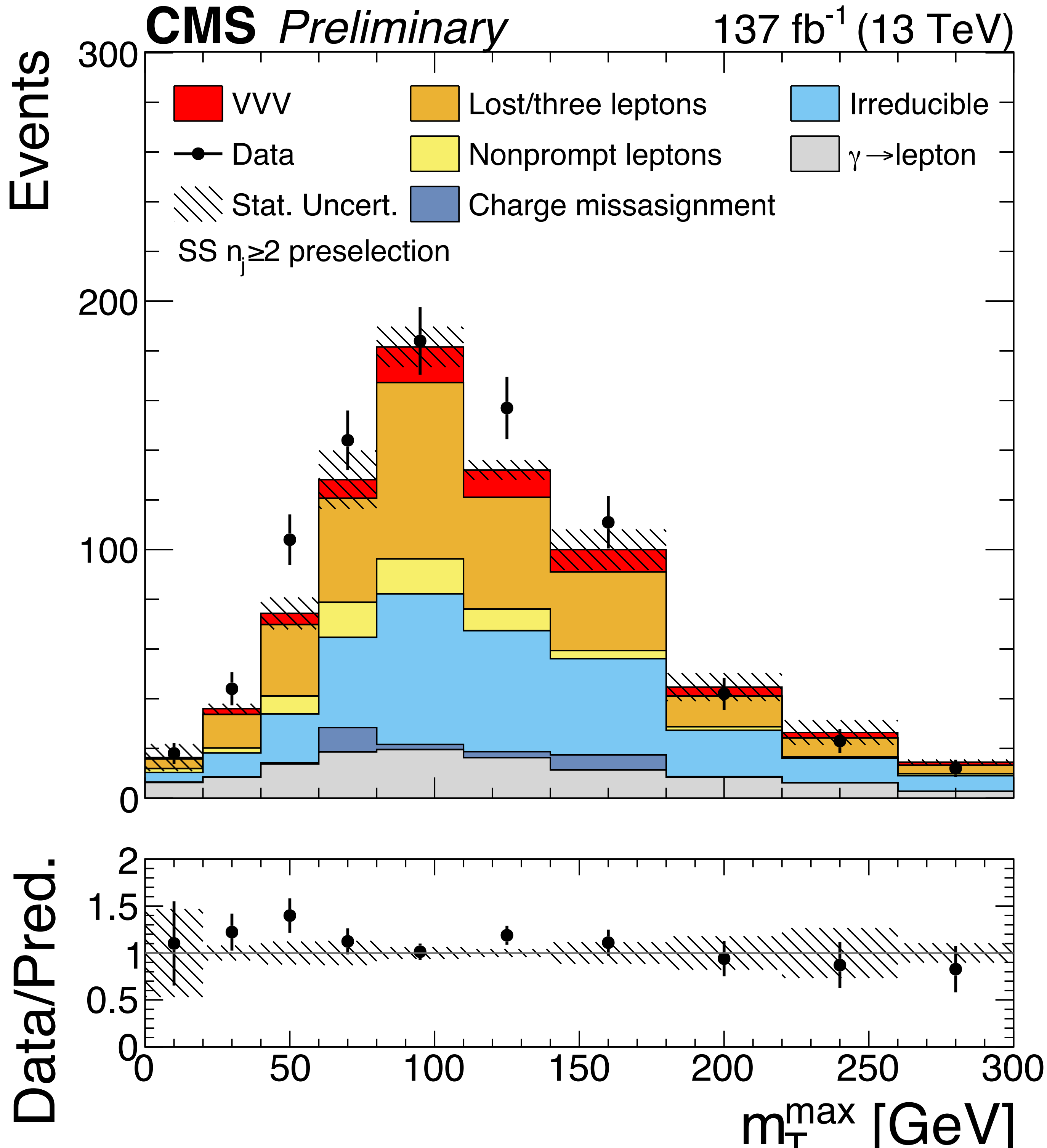
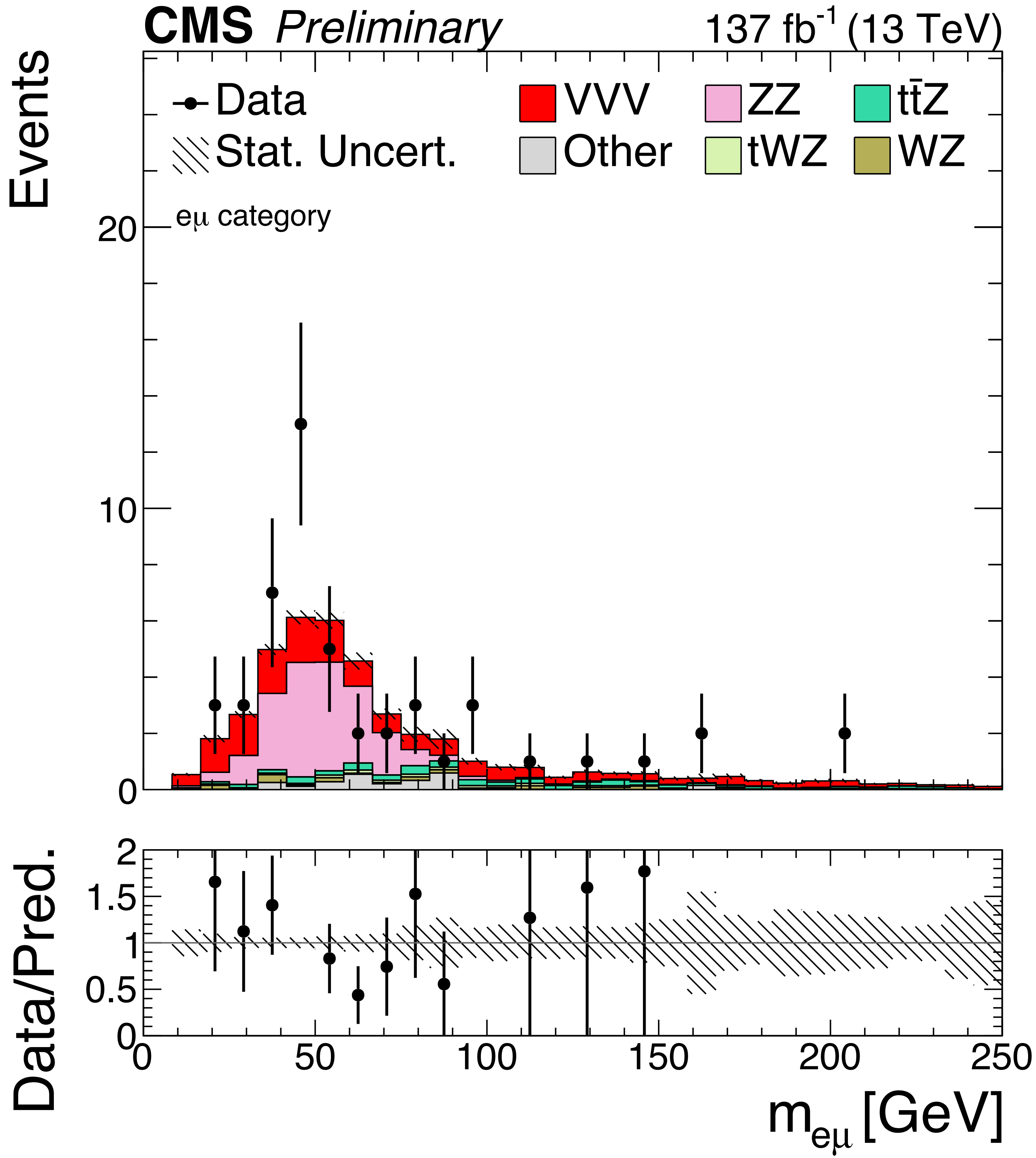
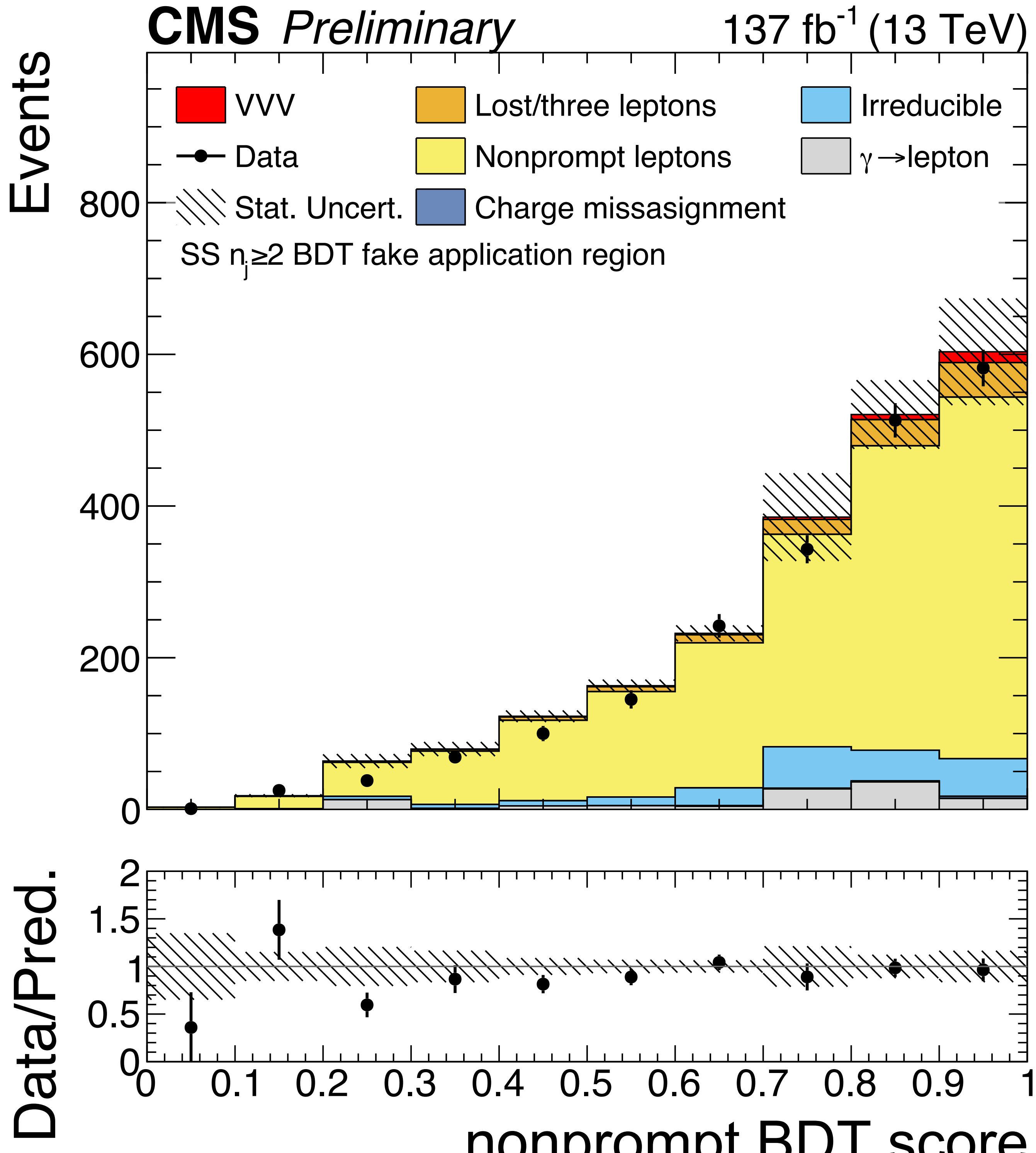


Title


CMS Preliminary
137 fb-1 (13 TeV)
Data
Stat. Uncert.
VVV
Other
ZZ
tWZ
tt̄Z
WZ
eμ category
Events
Data/Pred.
meμ [GeV]

Title



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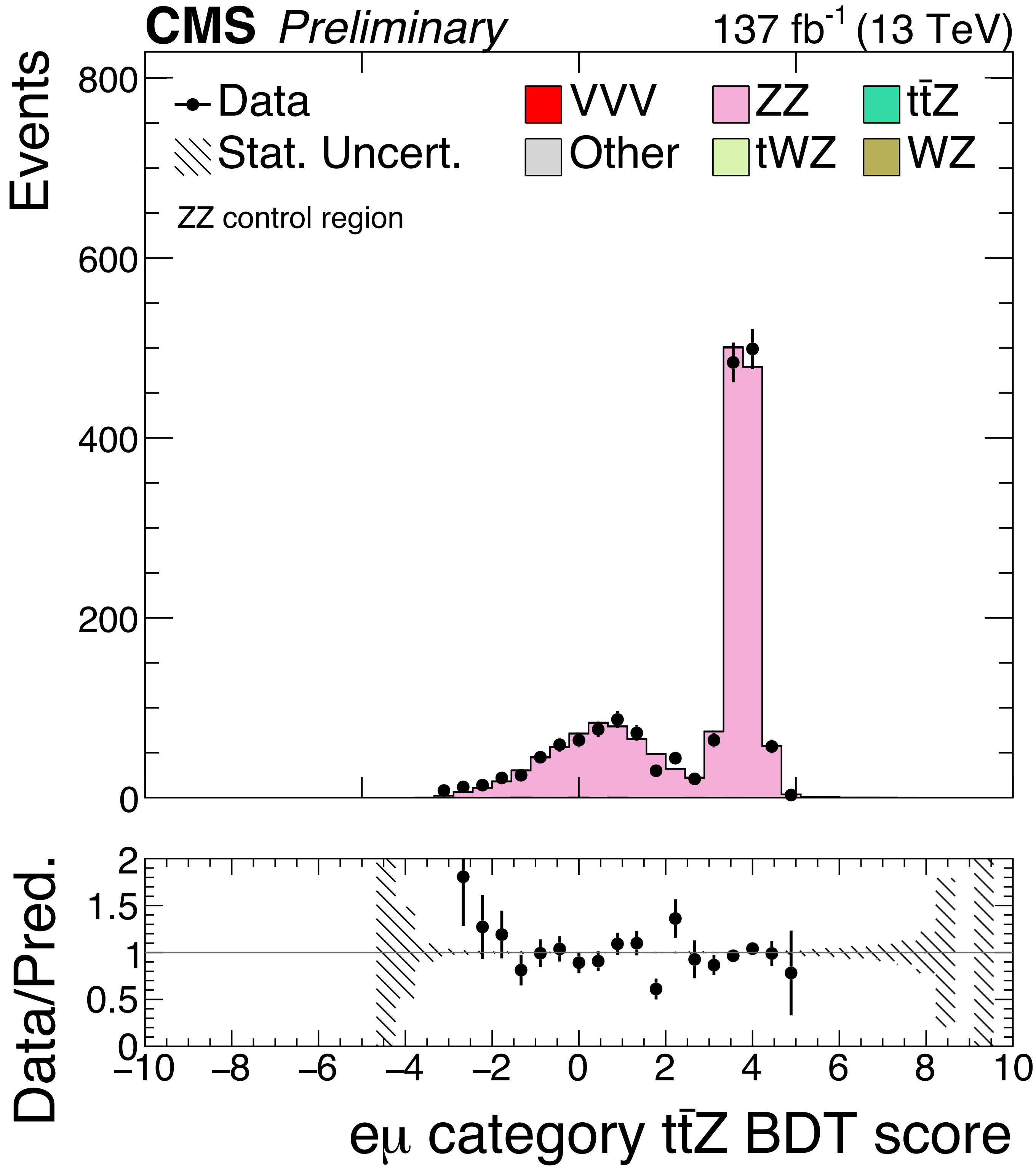
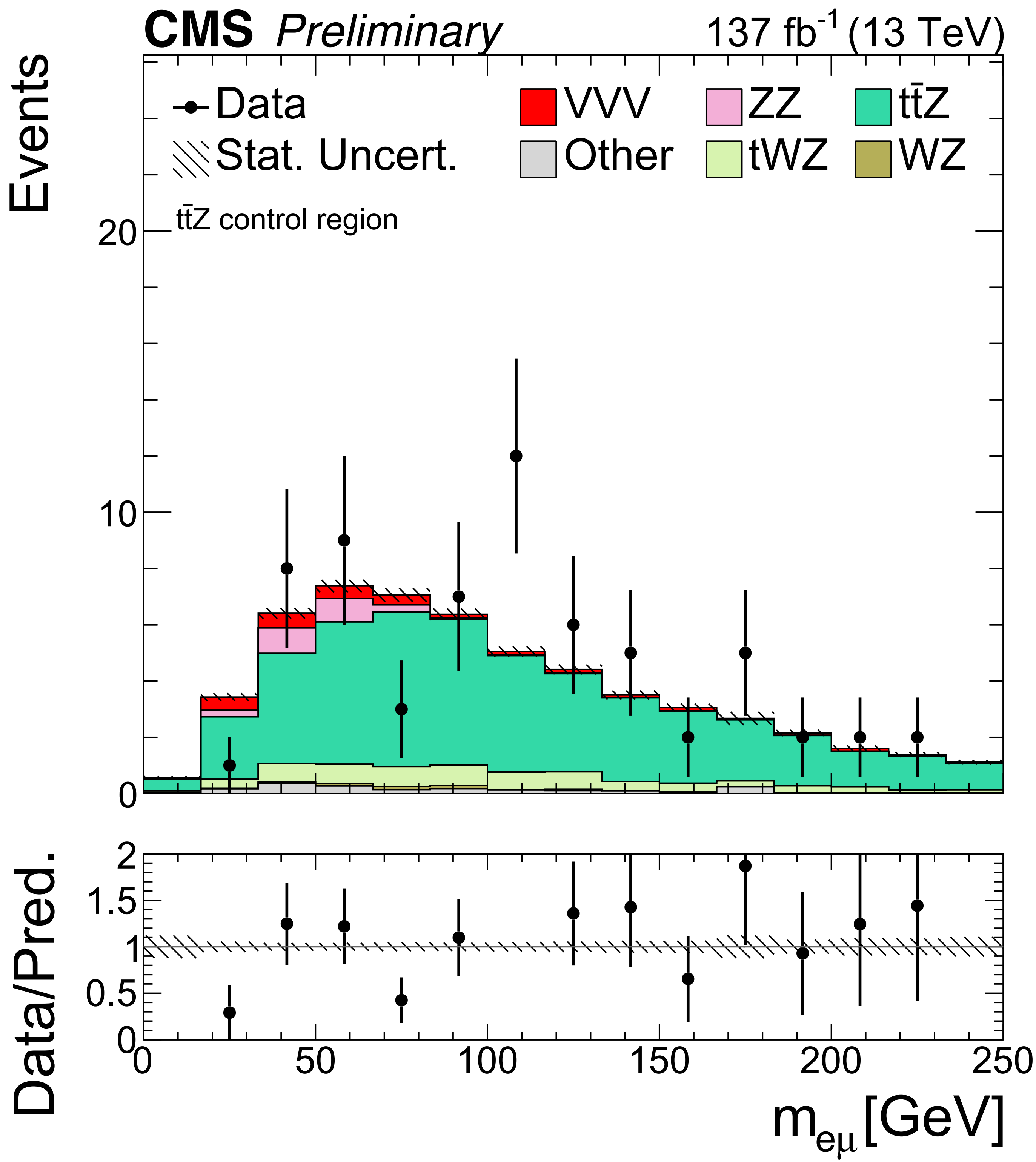
Title



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

Title



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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 $\rightarrow$ 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

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Signal region	4ℓ eμ bin 1	bin 2	bin 3	bin 4	bin 5	4ℓ ee/μμ bin A	bin B	5ℓ	6ℓ
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

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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	1.8±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

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Signal region	4ℓ eμ bin 4	4ℓ eμ bin 3	4ℓ eμ bin 2	4ℓ eμ bin 1	4ℓ ee/μμ bin A	4ℓ ee/μμ bin B	4ℓ ee/μμ bin C	5ℓ	6ℓ
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

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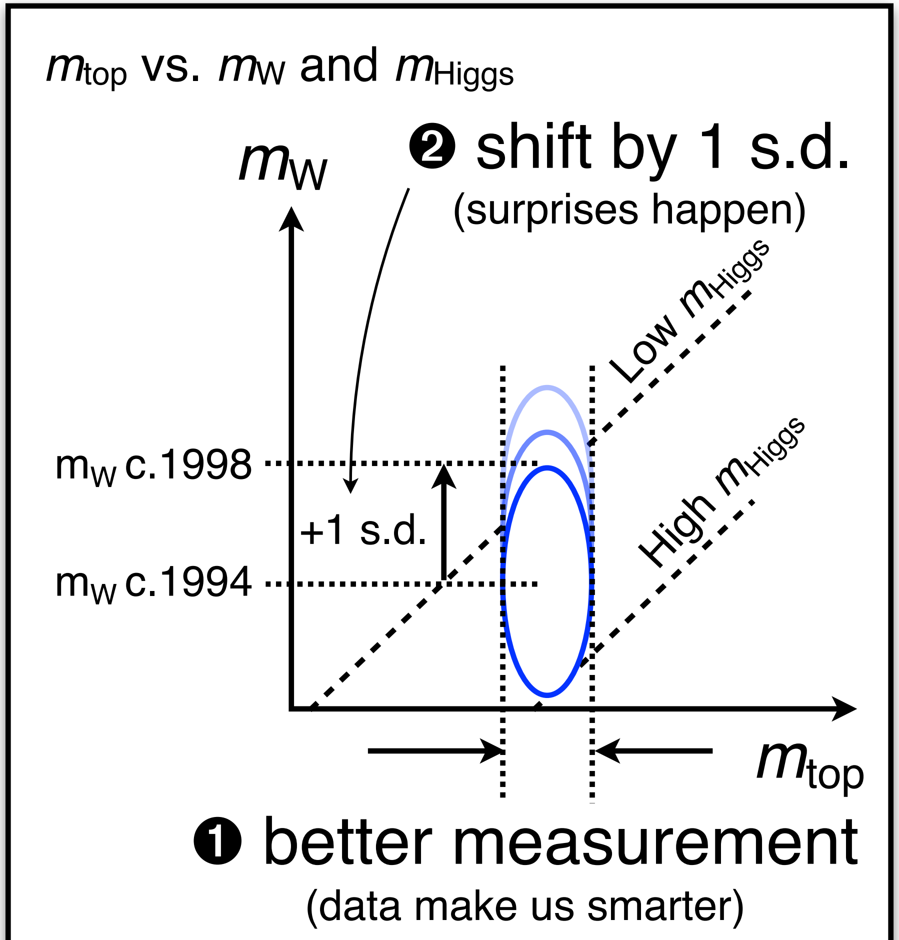
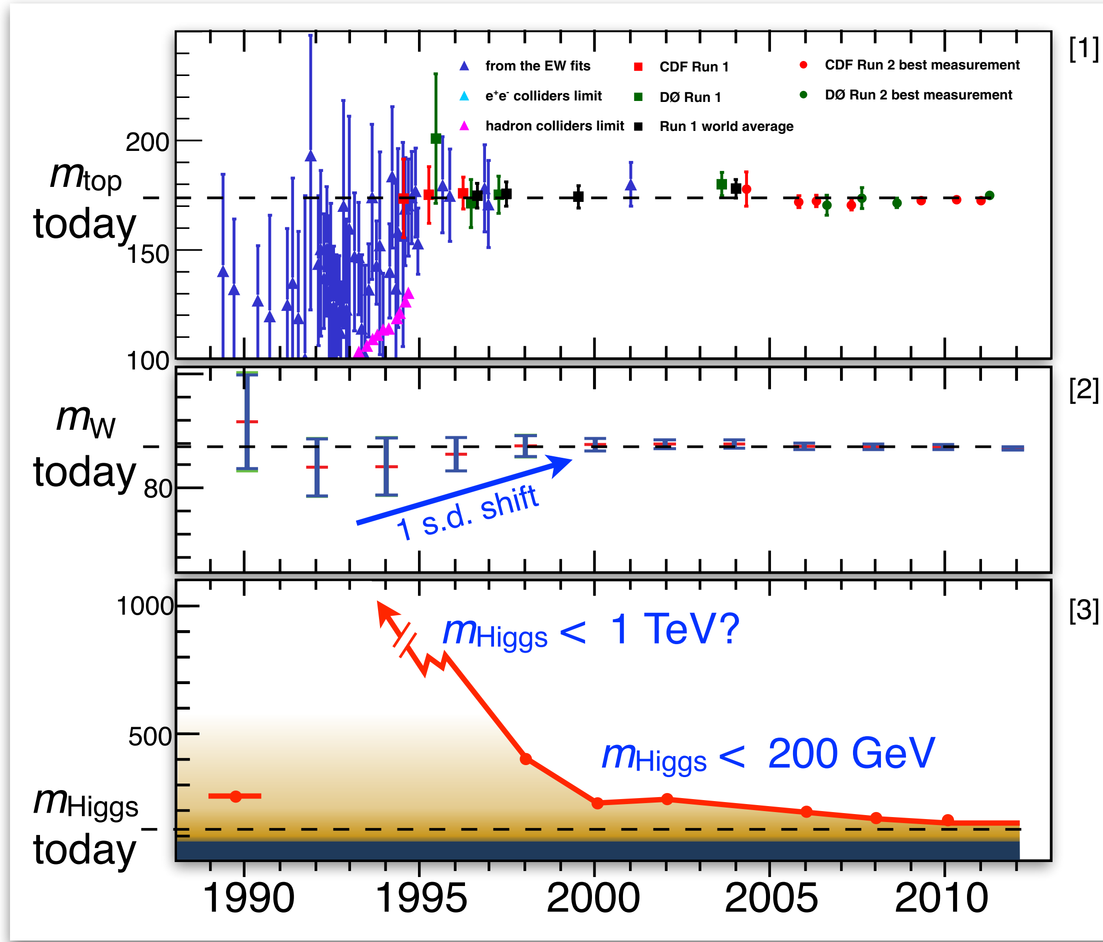


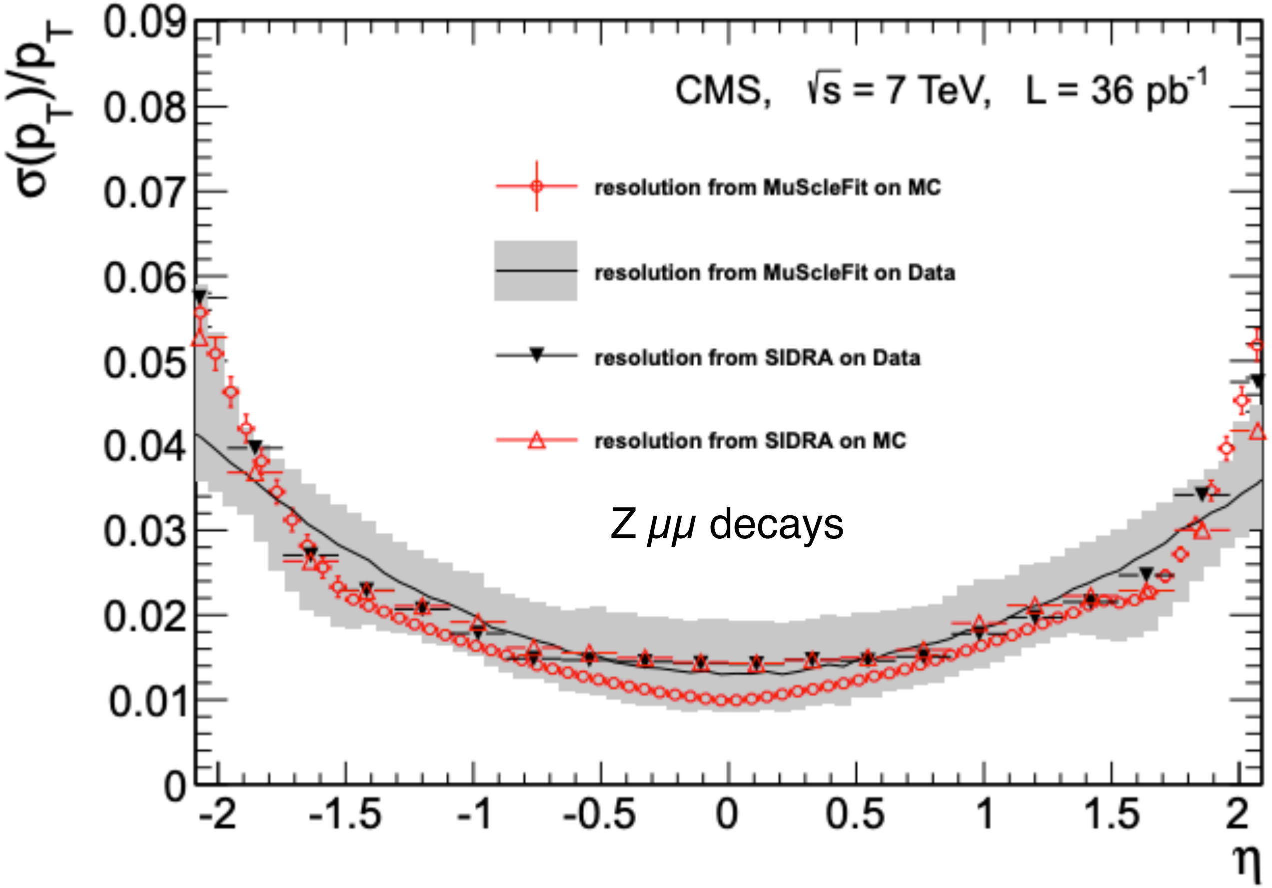


…after analysis of Run I data, … ❷ <u>m_W shifted a full s.d.</u> … the m_{Higgs} must be ❸ <u>much lower than anyone had anticipated.</u> … Surprises happen.

– 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

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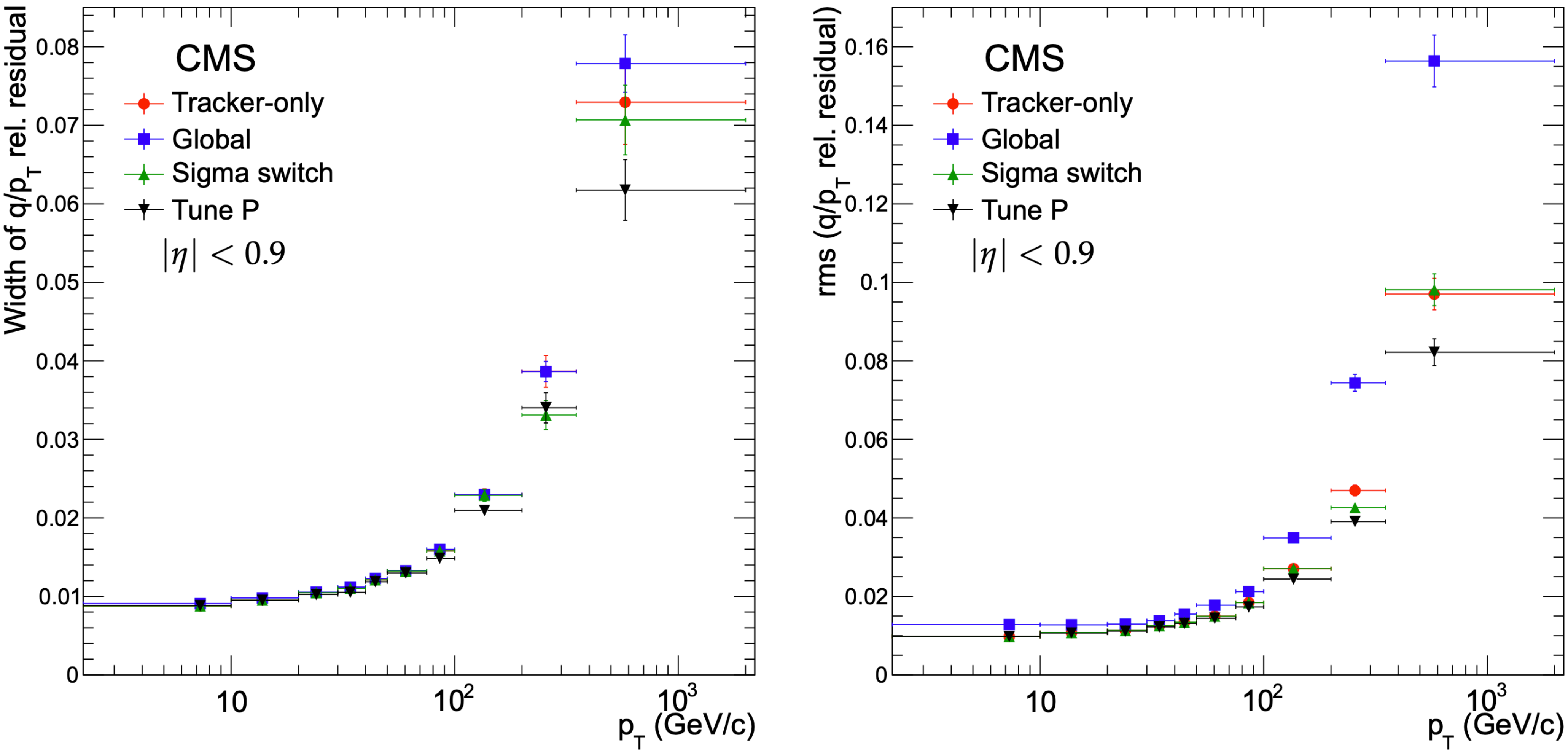
https://arxiv.org/pdf/1206.4071.pdf



(a) (b)

arXiv.org > physics > arXiv:1502.02701

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Physics > Instrumentation and Detectors

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

Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at sqrt(s) = 8 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

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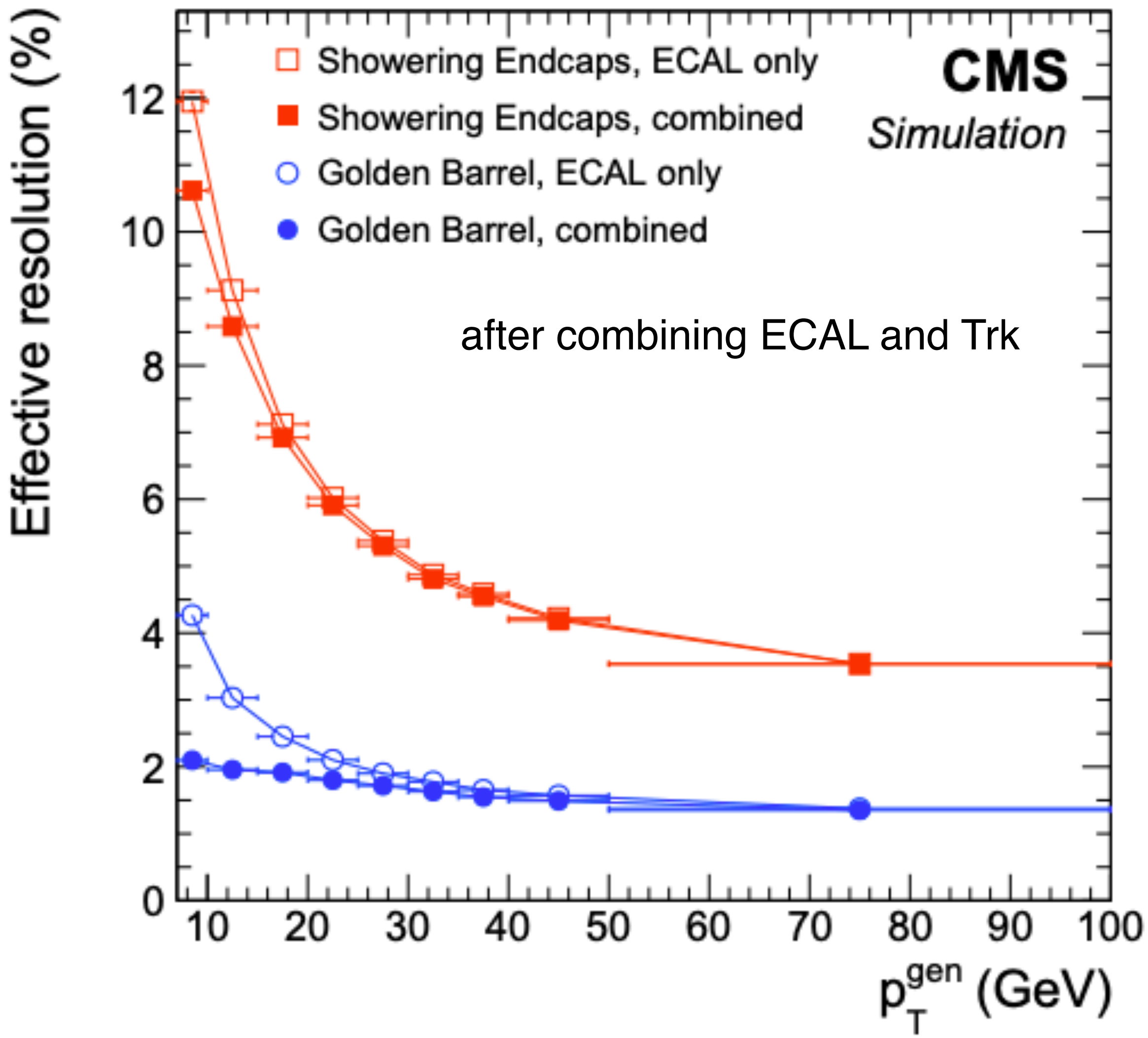
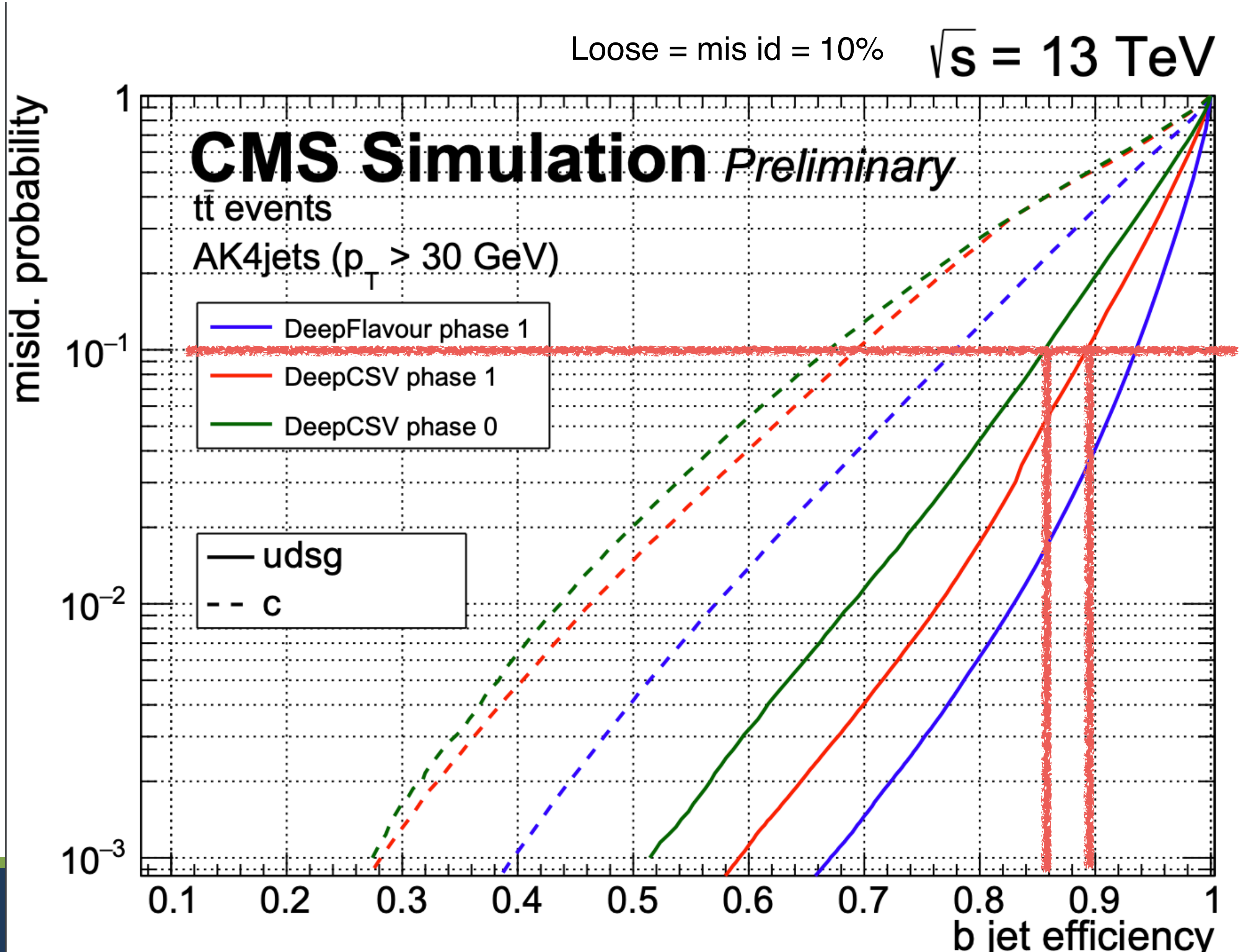


b tagging

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



Electroweak sector

$$\mathcal{L}_\phi = D_\mu \phi^\dagger D_\mu \phi + \mu^2(\phi\phi^\dagger) - \frac{\lambda}{4}(\phi\phi^\dagger)^2 - \frac{1}{4}W^{i\mu\nu}W^i_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}$$

$$\phi(x) = \begin{pmatrix} 0 \\ \frac{v+H(x)}{2} \end{pmatrix}$$

$$D_\mu = \partial_\mu + i\tfrac{g}{2}\sigma_j W^j_\mu + 2ig' Y B_\mu$$

$$\begin{aligned}\mathcal{L}_\phi = &\frac{1}{2}(\partial_\mu H \partial^\mu H) - \mu^2 H^2 \\ &-\frac{1}{4}(\partial_\mu W_{i\nu} - \partial_\nu W_{i\mu})(\partial^\mu W_i^\nu - \partial^\nu W_i^\mu) \\ &+\frac{1}{8}g^2 v^2 (W_{1\mu}W^{1\mu} + W_{2\mu}W^{2\mu}) \\ &+\frac{1}{8}v^2(gW_{3\mu} - g'B_\mu)(gW_3^\mu - g'B^\mu) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}\end{aligned}$$