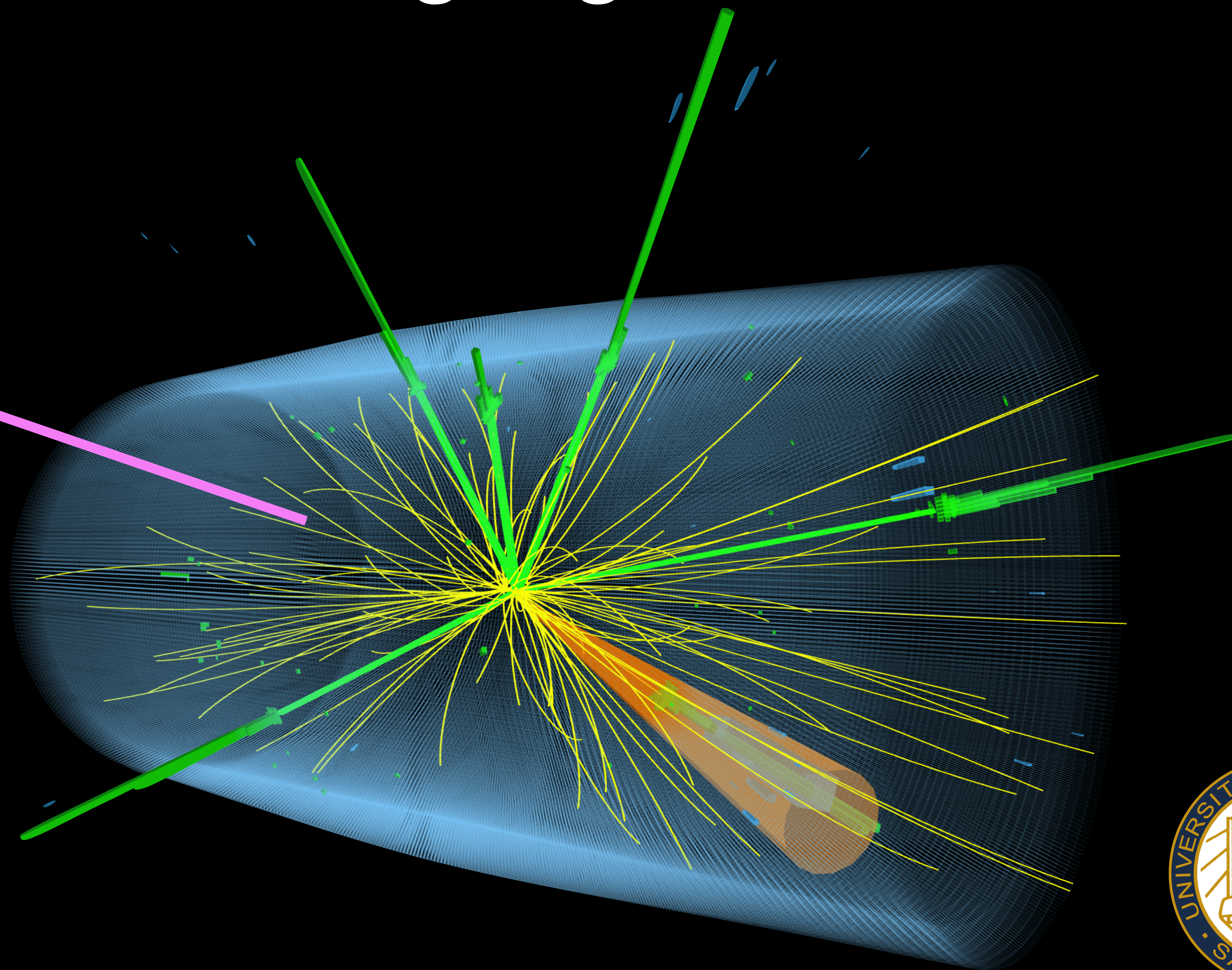
First observation of the production of three massive gauge bosons at CMS



Philip Chang

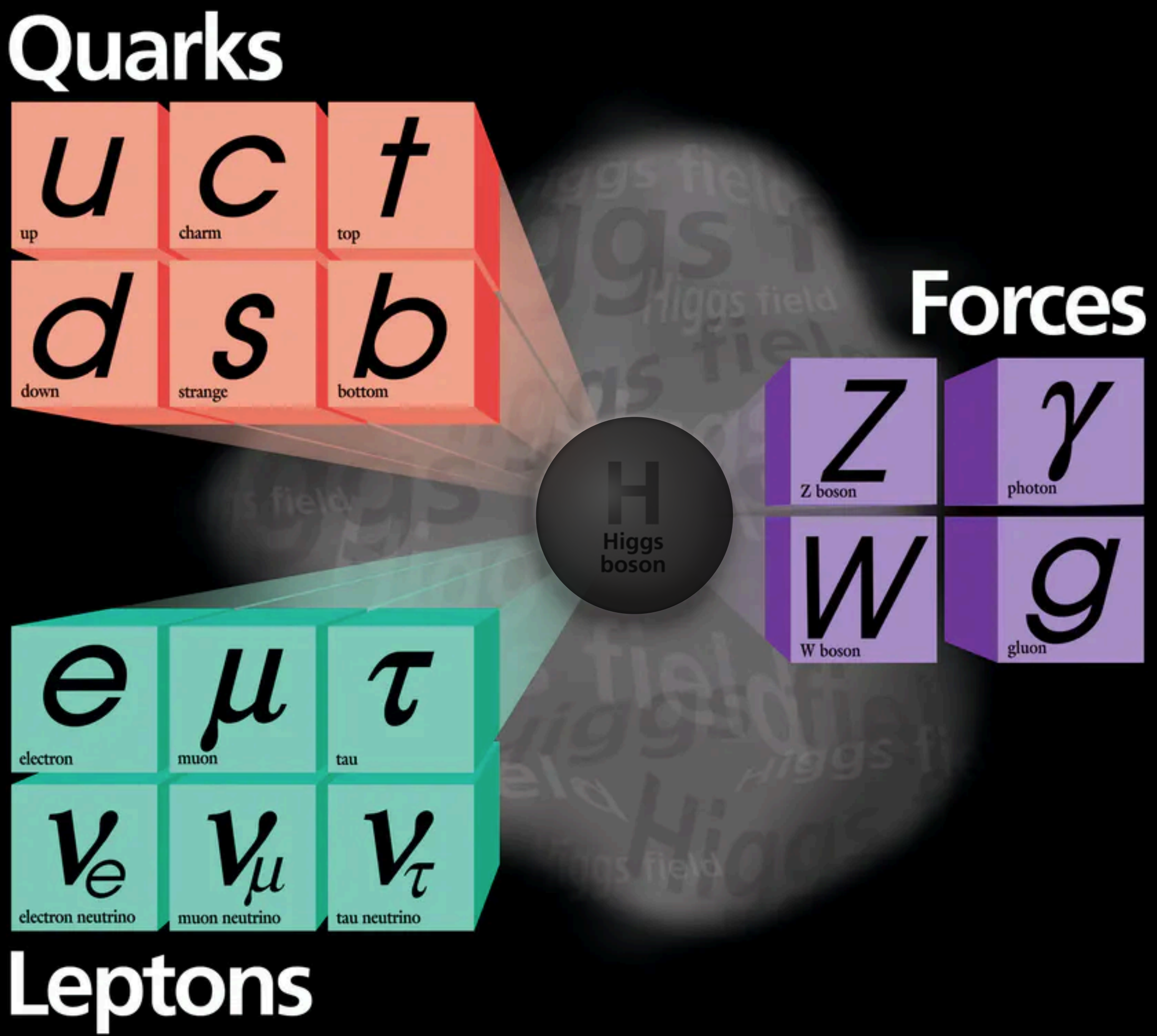
Fermilab W&C Seminar
September 4, 2020

Univ. of California
San Diego

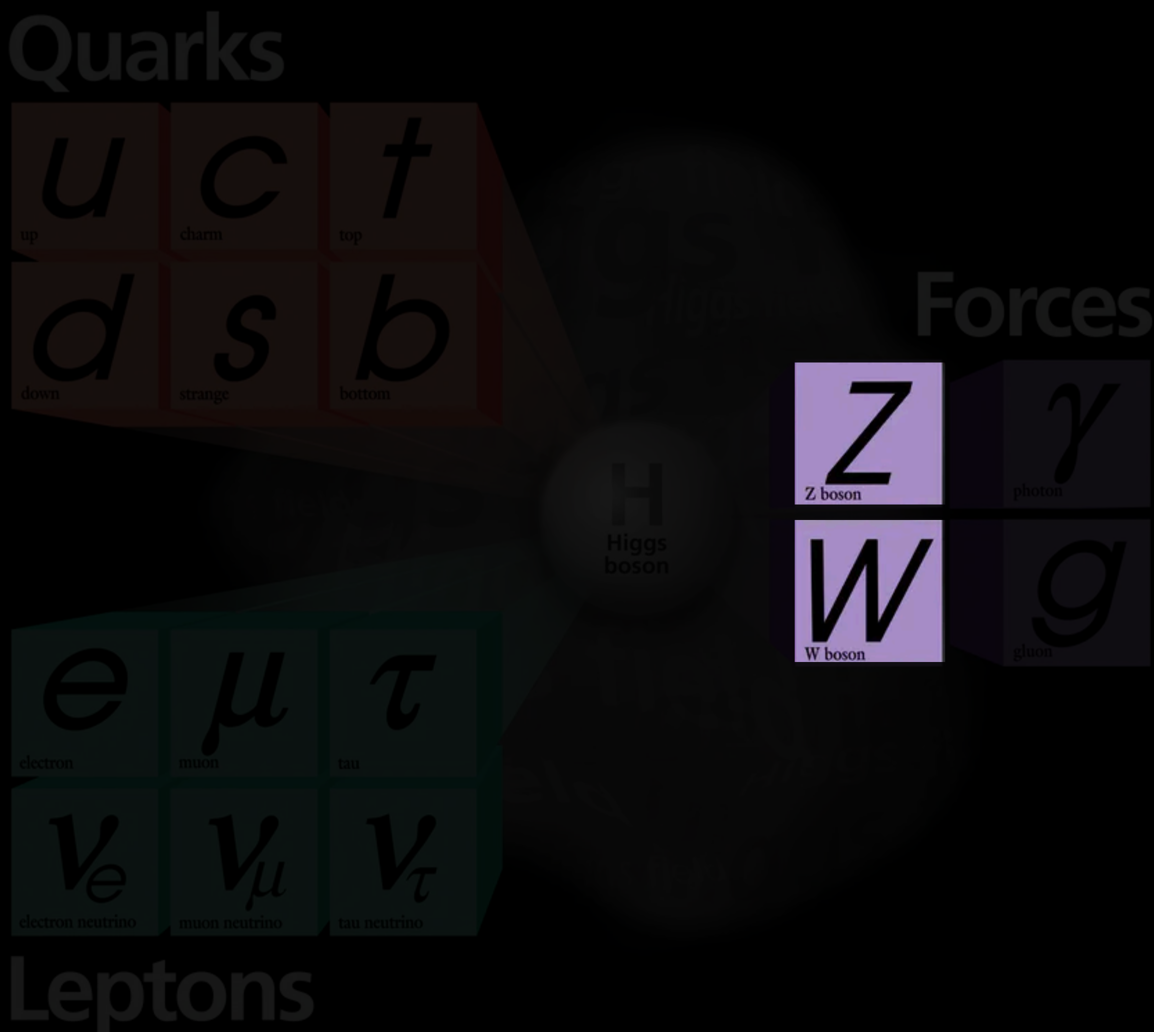
Outline

- Electroweak sector of SM
- Why study rare multi-boson productions?
- CMS's VVV analysis and results
- Future directions

Completing the Standard Model



Completing the Standard Model

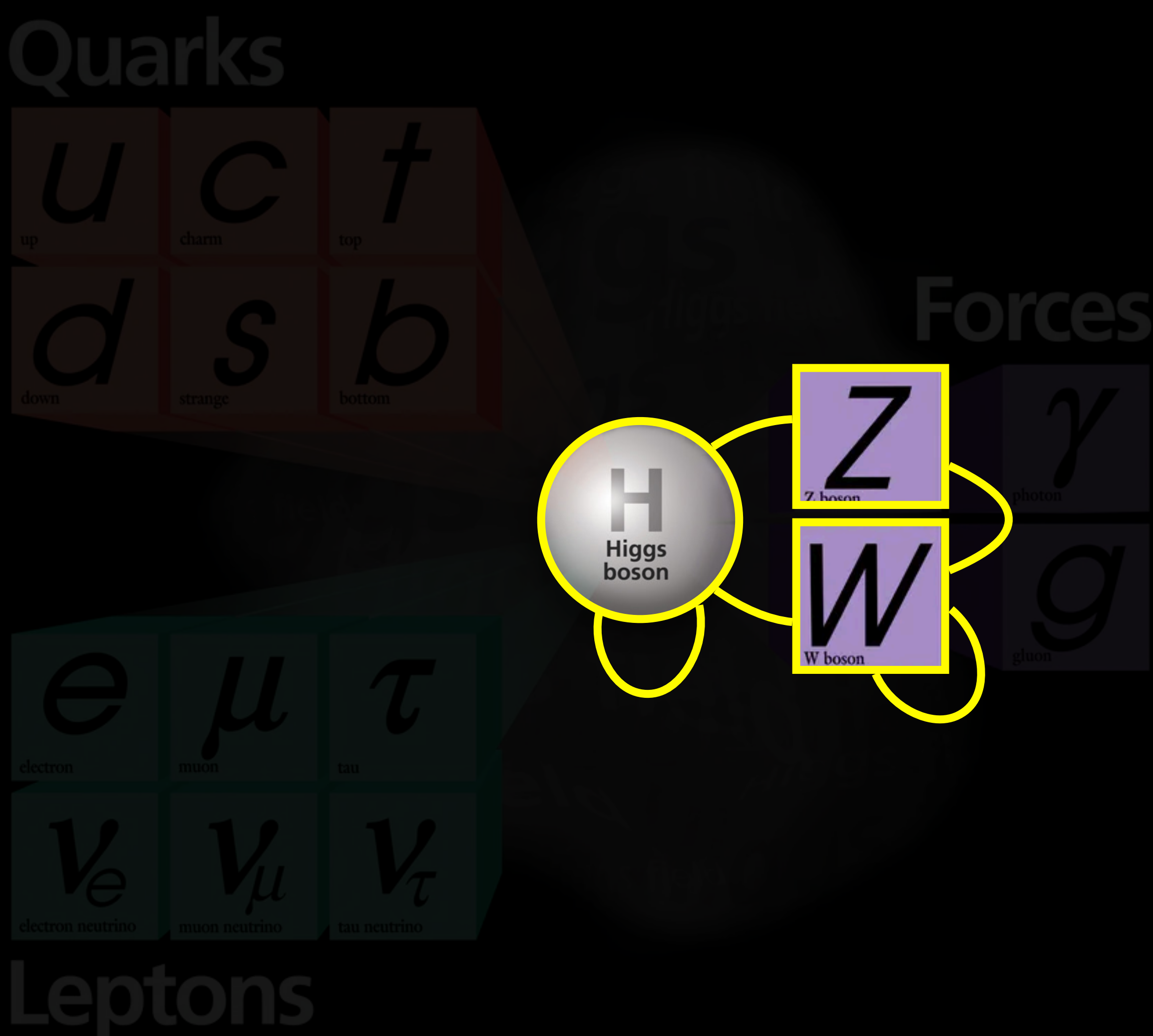


Spin 1

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

⇒ EW symmetry is broken

Completing the Standard Model



Spin 1
- Mass of W is 80 GeV (≠ 0)
- Mass of Z is 91 GeV (≠ 0)

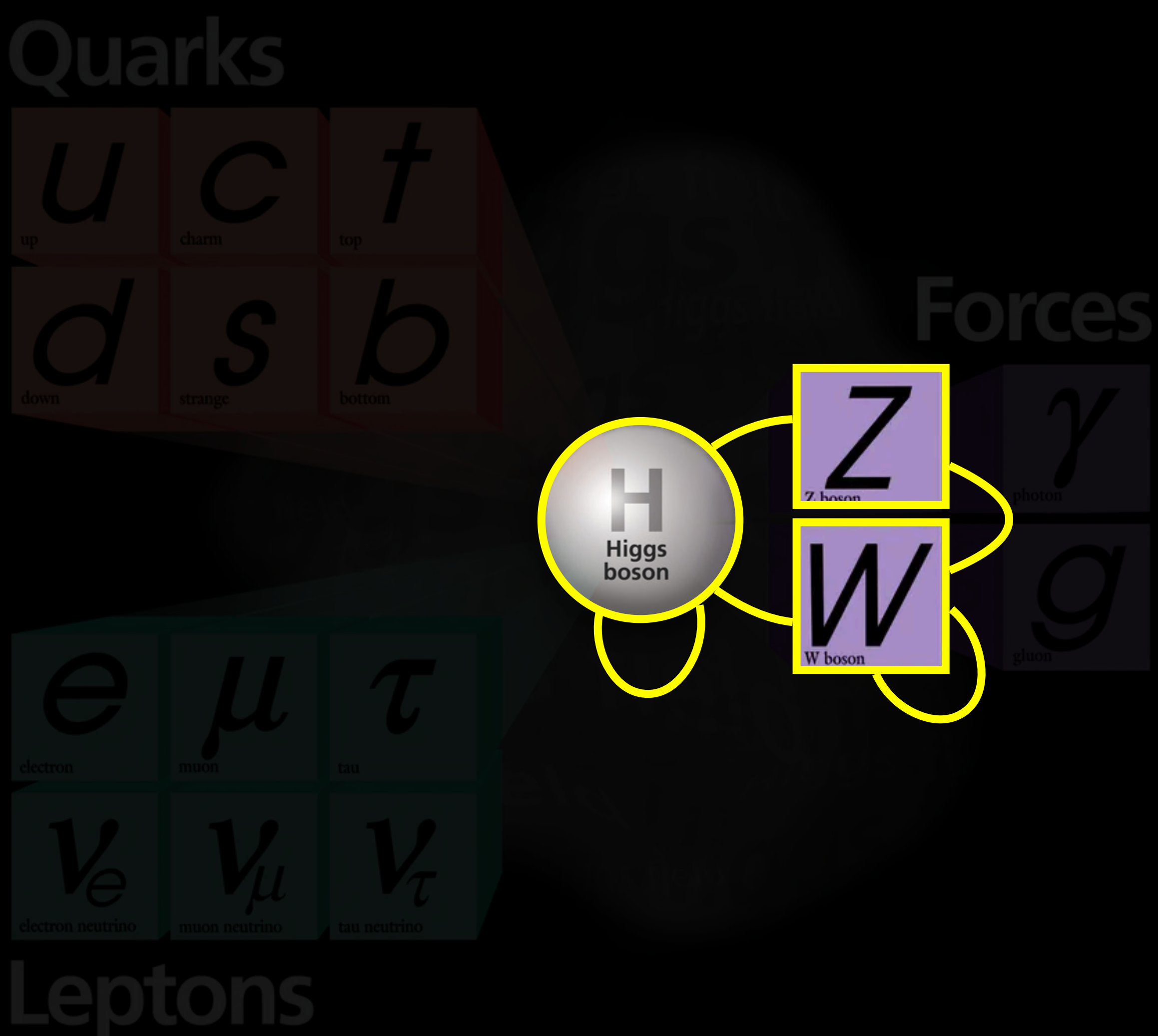
⇒ EW symmetry is broken

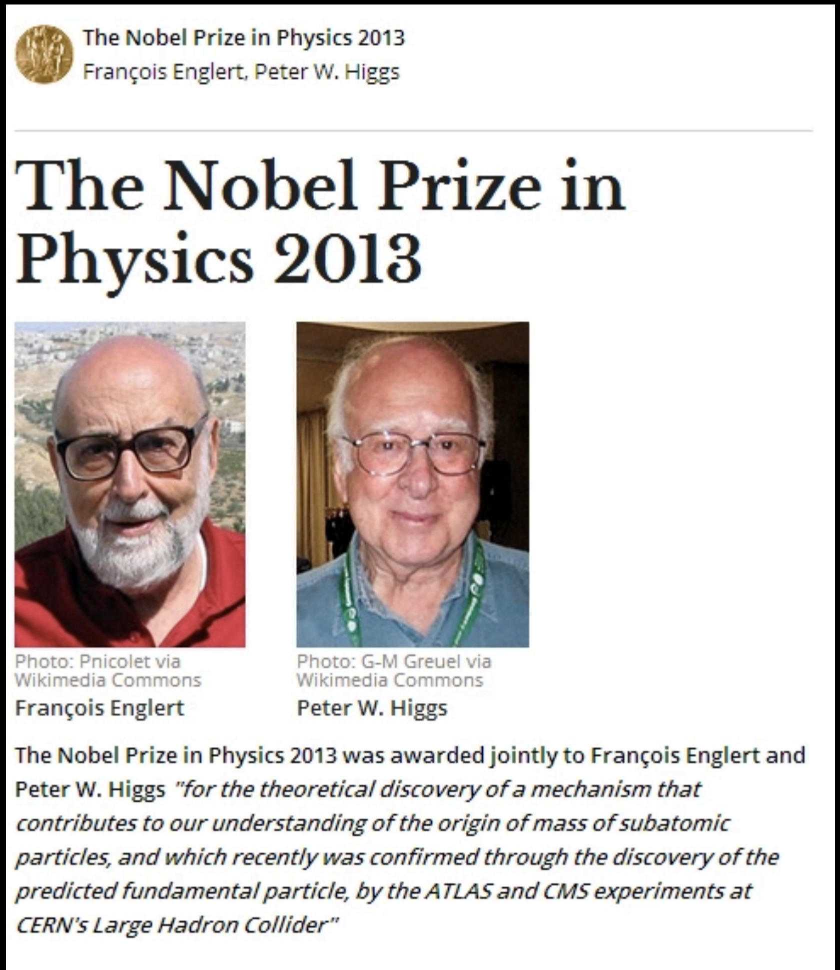
Spin 0
- Agent of electroweak symmetry breaking
- Higgs discovery (2012)

⇒ Completes the EW sector

Last missing piece of the SM has been found

Completing the Standard Model




The Nobel Prize in Physics 2013
François Englert, Peter W. Higgs

The Nobel Prize in Physics 2013

Photo: Pnicolet via Wikimedia Commons
François Englert

Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

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

Last missing piece of the SM has been found

Completing the electroweak sector

≠

Understanding the electroweak sector

More work to be done in electroweak sector

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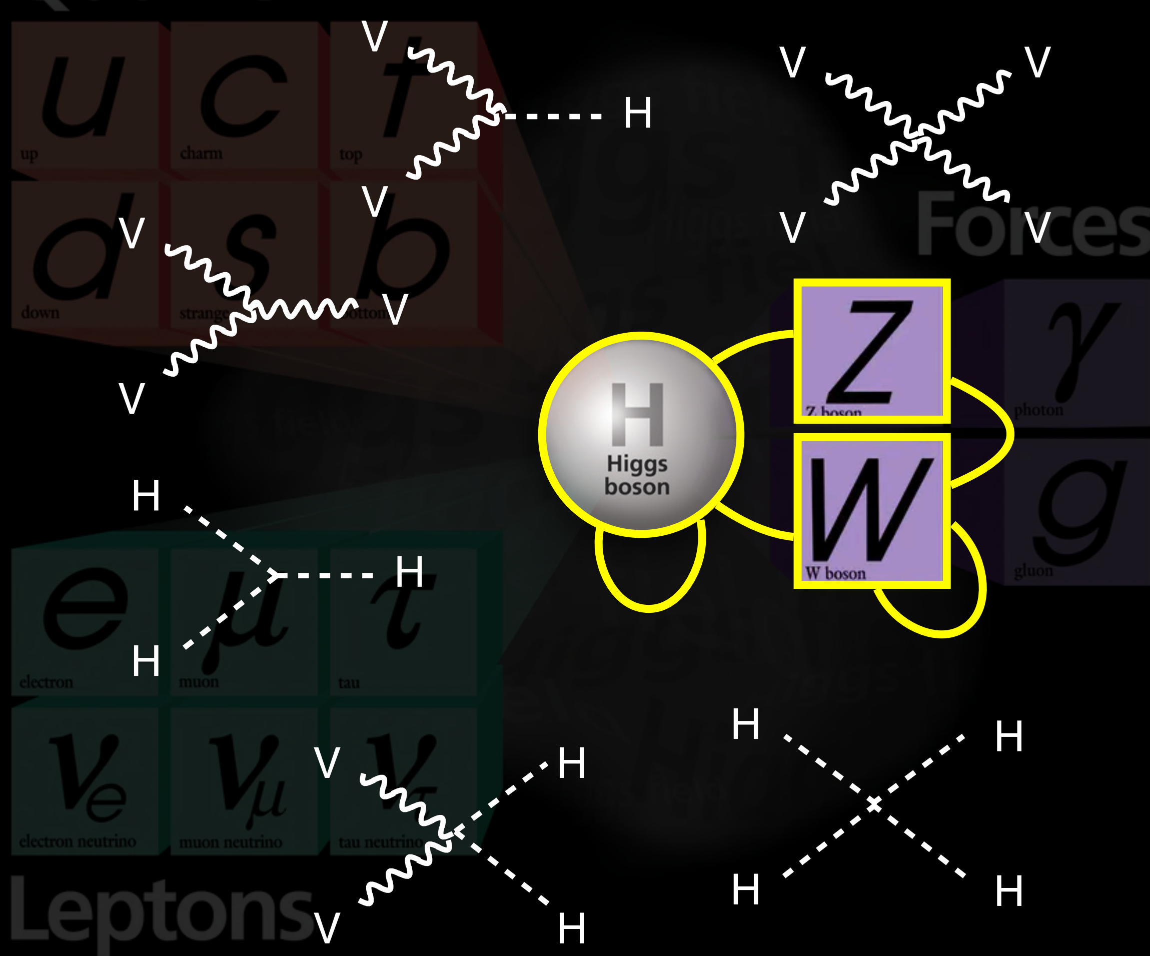
List of multi-boson interactions (MBIs)



- Are multi-*bosons* interactions SM?
- Is it the only Higgs boson? (or are there more? H_1, H_2, $H^{\pm}$, … ??)
- If so, what are their role in the electroweak symmetry breaking?
- Is the Higgs potential SM-like?

Now, we must understand the electroweak sector

More work to be done in electroweak sector

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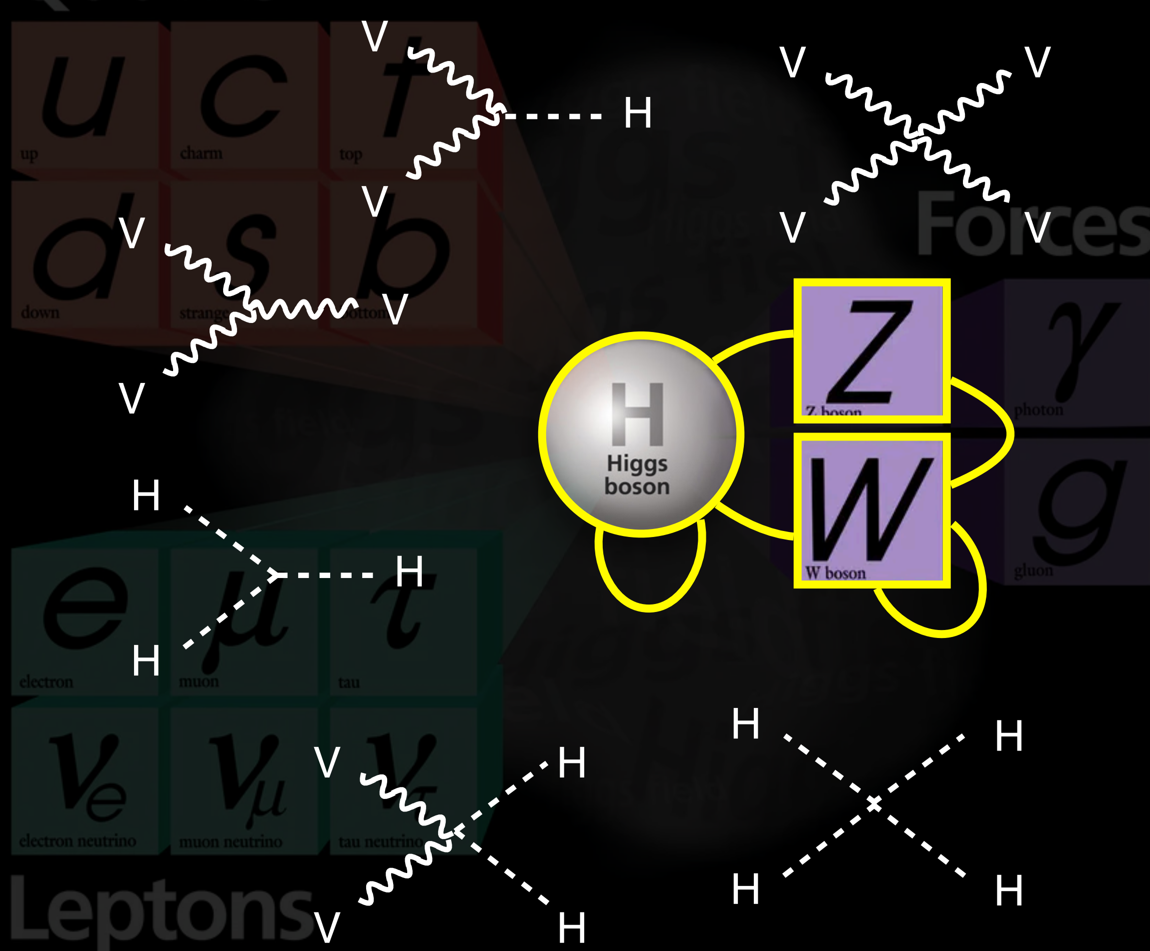

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- If so, what are their role in the electroweak symmetry breaking?
- Is the Higgs potential SM-like?

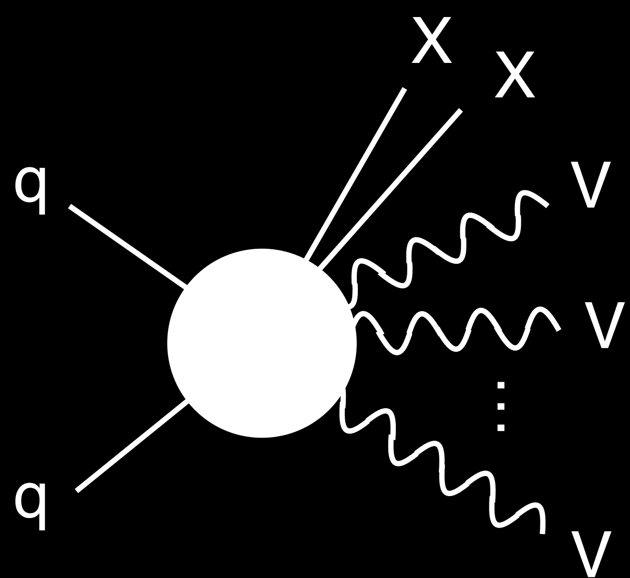
- These Qs have deep implications
    - How/Why is EWSB broken?
    - Could EWPT be first order?
    - Baryogenesis?
    - Stability of the universe?

Now, we must understand the electroweak sector

Studying multi-boson interactions (MBI)

Consider multi-object production process
(i.e. 2 → 2, 3, 4, … scattering processes)

pp → nV + mX



Studying multi-boson interactions (MBI)

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Consider multi-object production process
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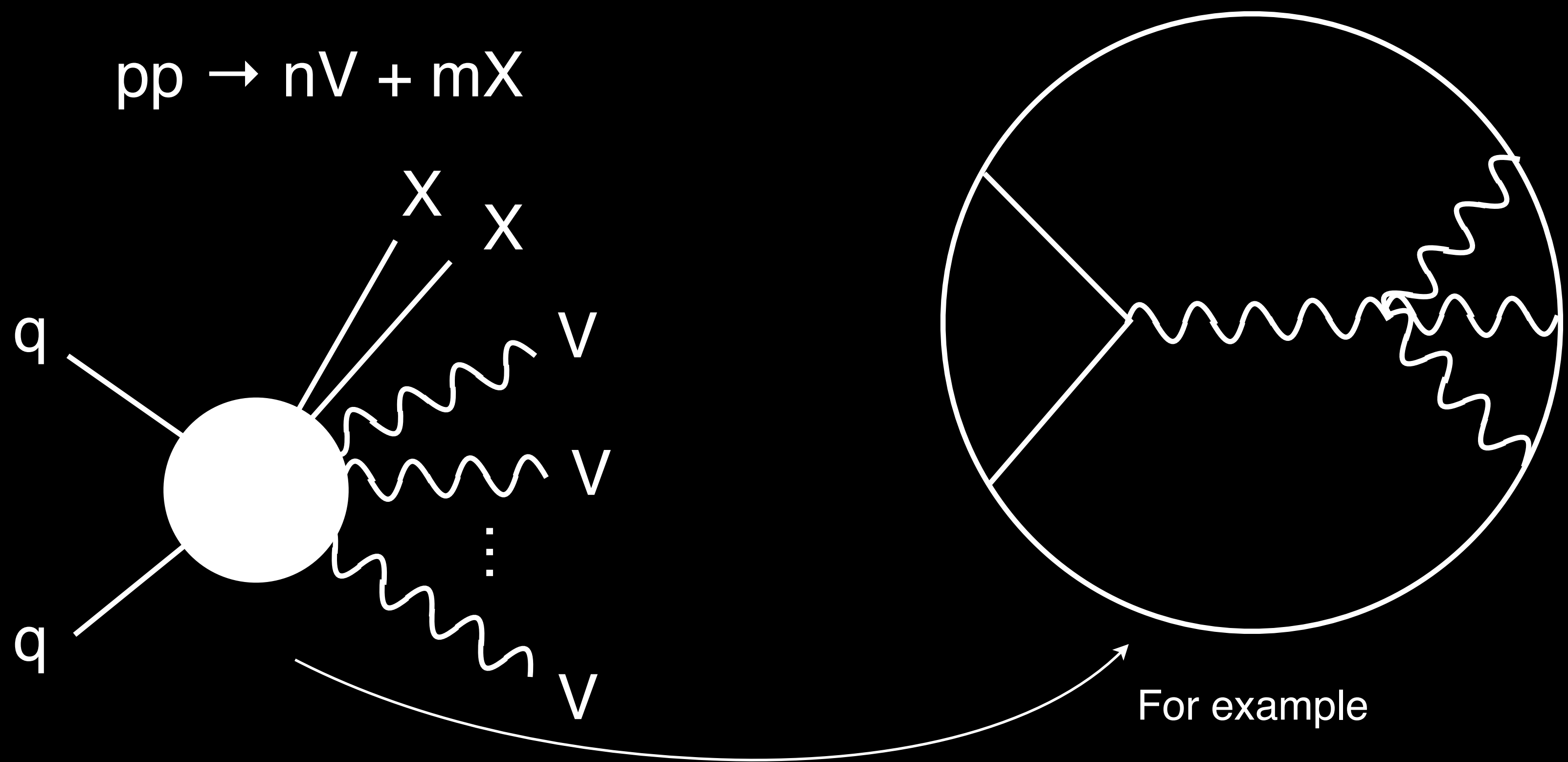
Can probe quartic gauge coupling

pp → nV + mX



For example

Details of MBI determine the multi-boson production rate

Studying multi-boson interactions (MBI)

Consider multi-object production process
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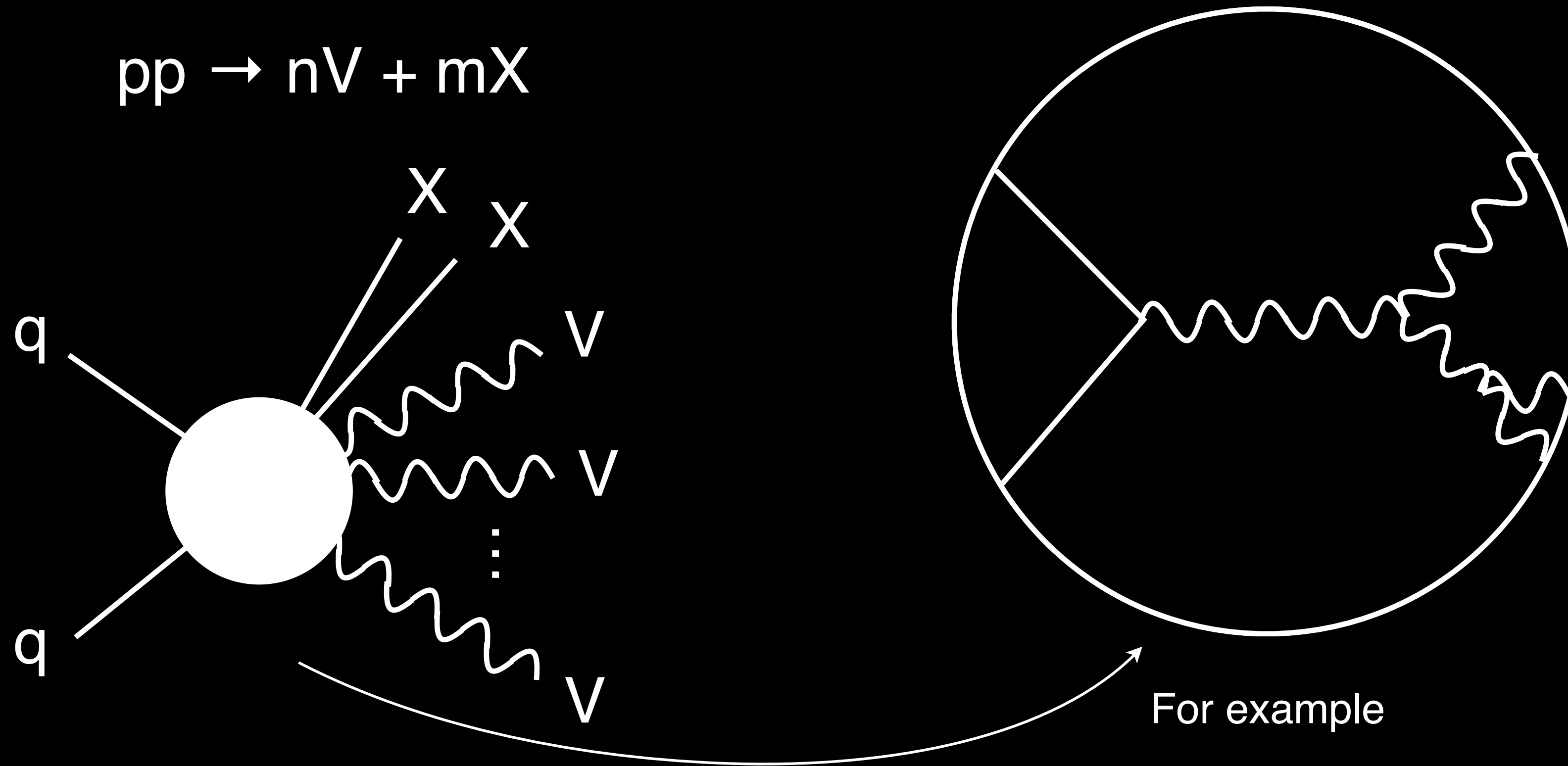
Can also probe
cubic-gauge coupling

pp → nV + mX



Details of MBI determine the multi-boson production rate

Studying multi-boson interactions (MBI)

Consider multi-object production process
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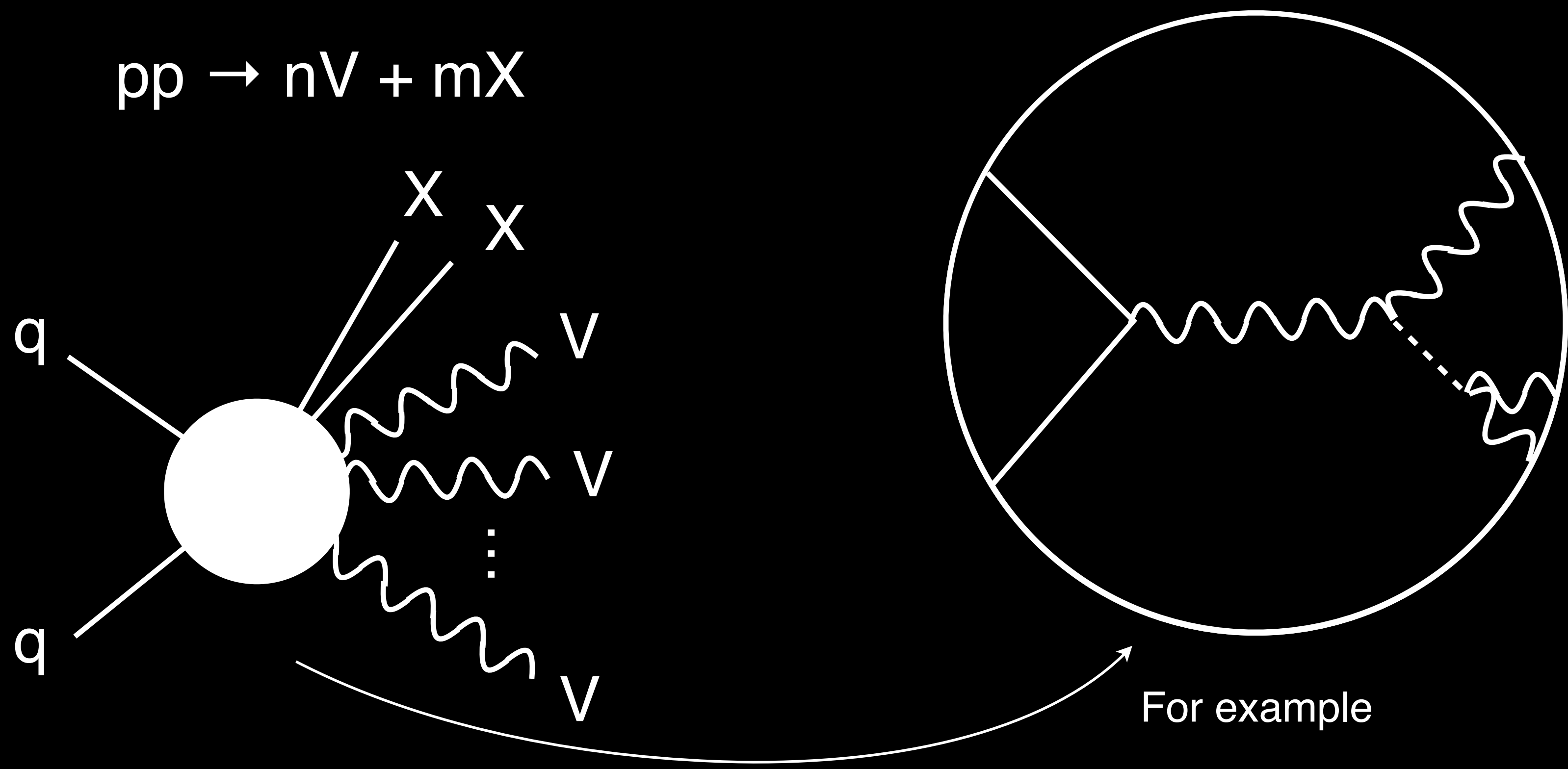
Can also probe Higgs-gauge coupling

$pp \to nV + mX$



Details of MBI determine the multi-boson production rate

Studying multi-boson interactions (MBI)

Consider multi-object production process
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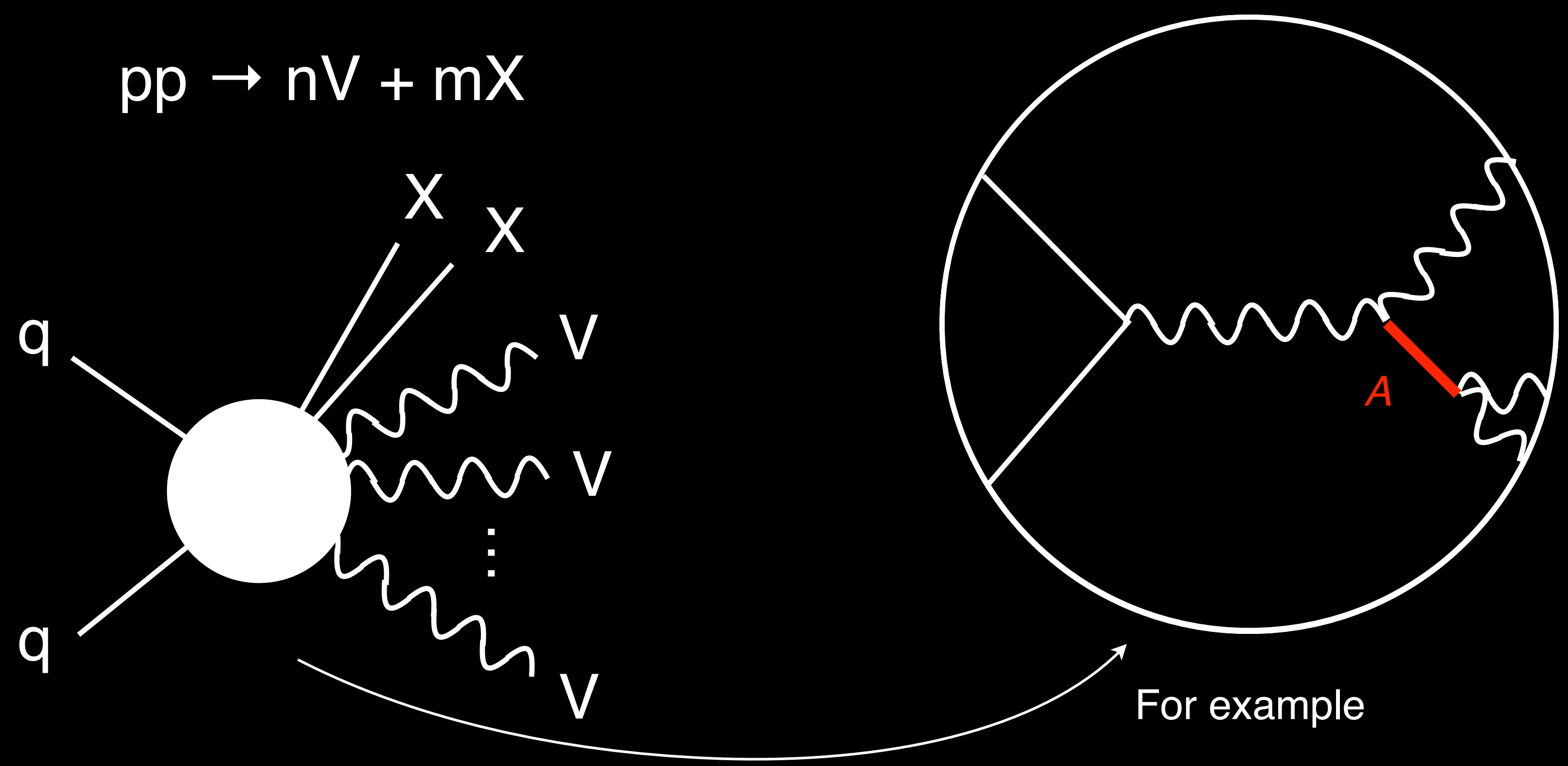
Perhaps new physics is present that alters the dynamics of EW sector

pp → nV + mX



Details of MBI determine the multi-boson production rate
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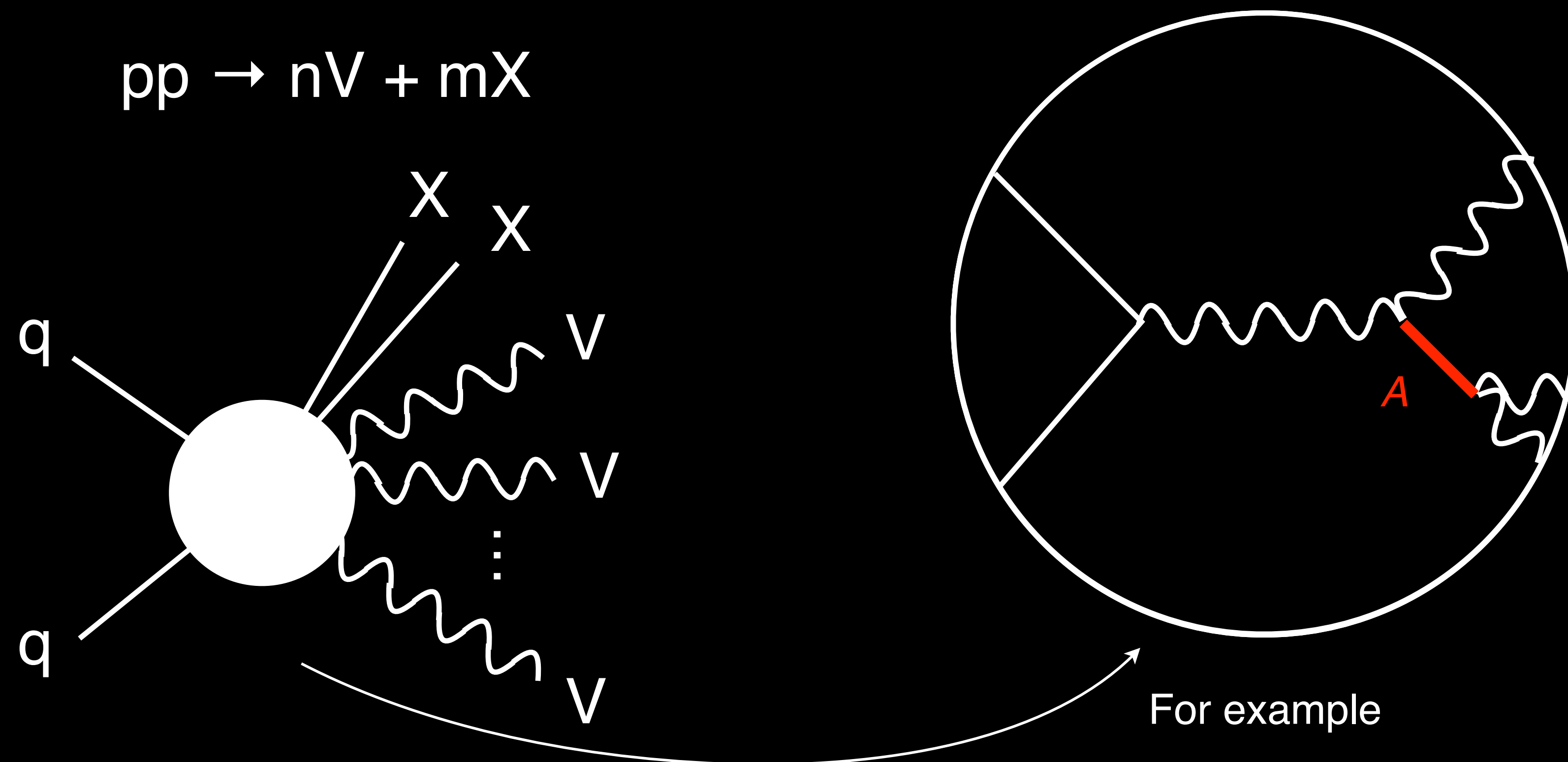

Details of MBI determine the multi-boson production rate
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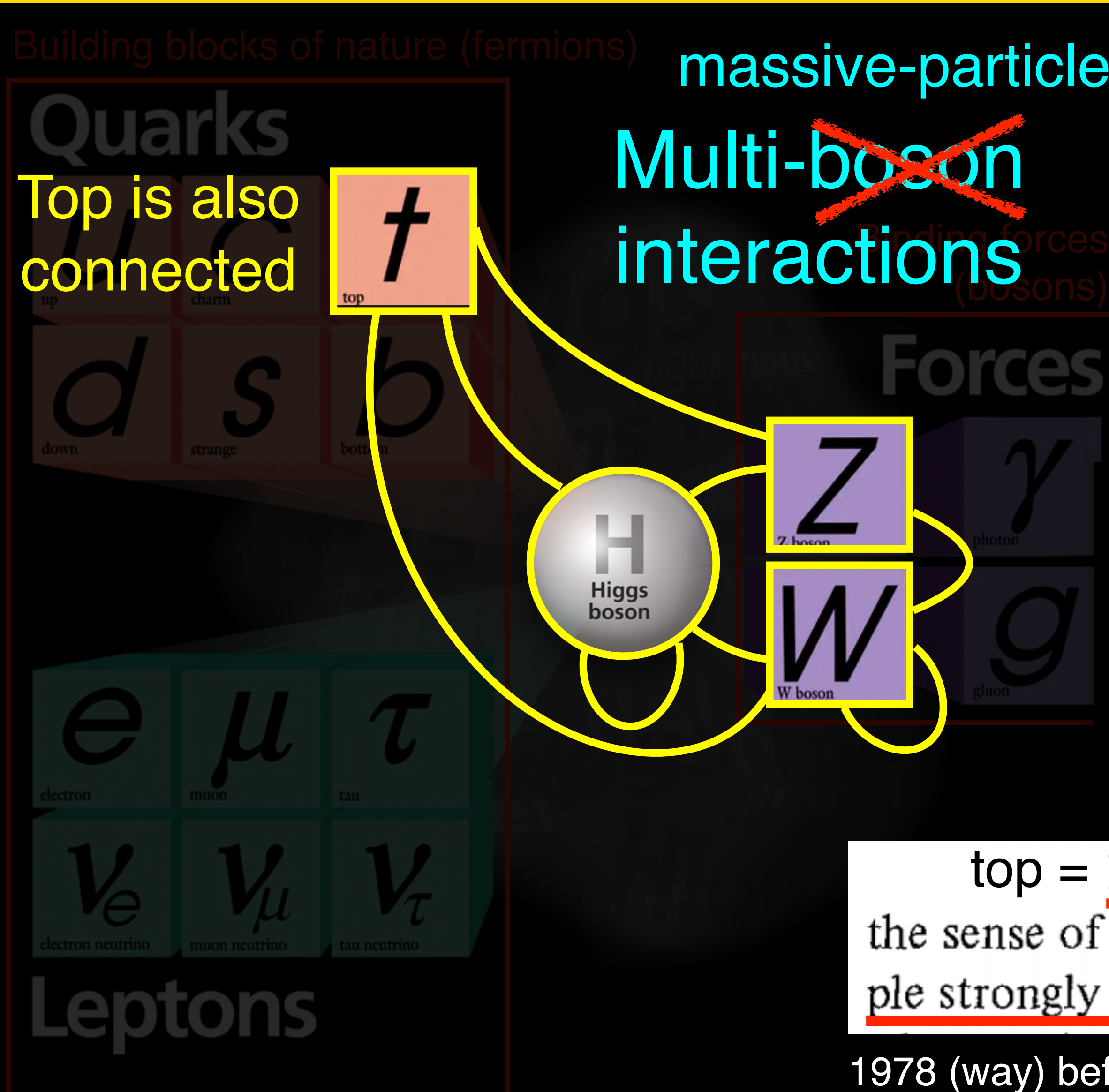
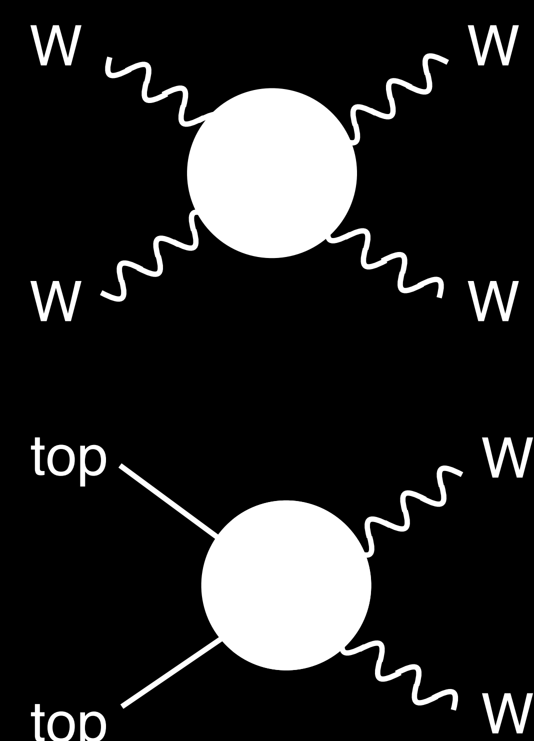
Study multi-boson production to study MBI

Quick aside…





Bad high energy behavior

Lee, Quigg, Thacker (1977)

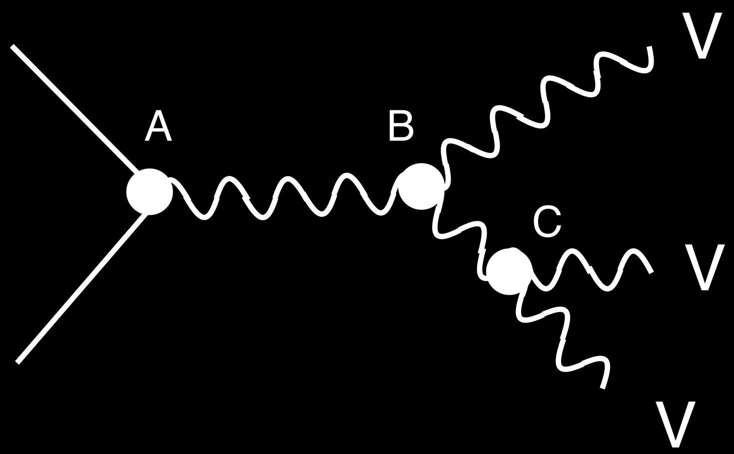
Also bad high energy behavior

top = 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-

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

Multi-X (X = t, W, Z, H) interactions must be studied

Experimental challenge



$m_V \approx \sim 100$ GeV

Multi-boson productions (MBP) are *rare*

rare because need to produce multiple massive particles

rare because involves multiple electroweak vertices

Three massive gauge boson rate ~ 10 / Trillion pp collisions

Probing MBP requires large data set

Cross sections at LHC

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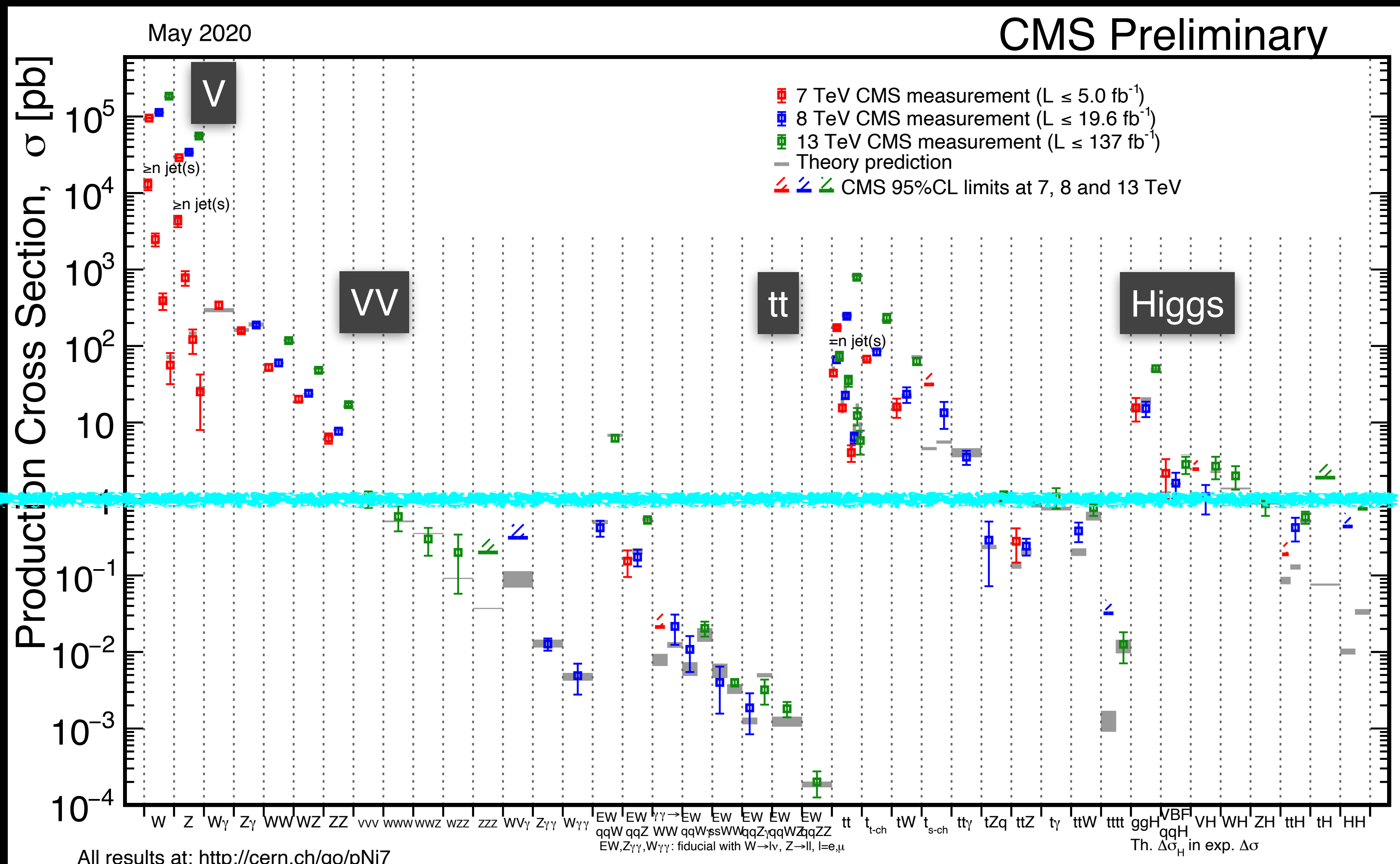
1 pb
≈
10 / Trillion
pp collisions



Rarer

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

Cross sections at LHC

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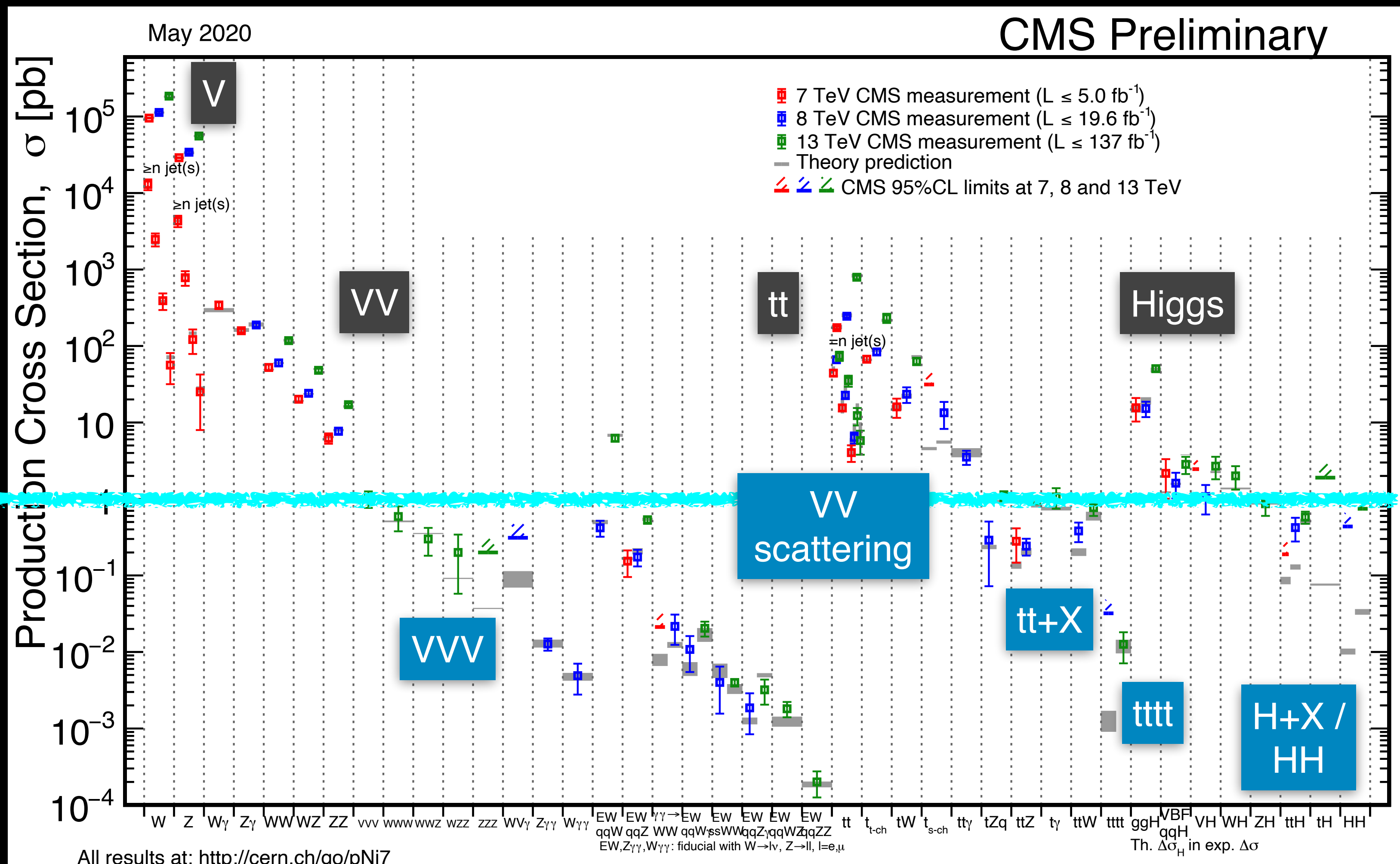

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multi-"massive"-particles processes
X = t, W, Z, H

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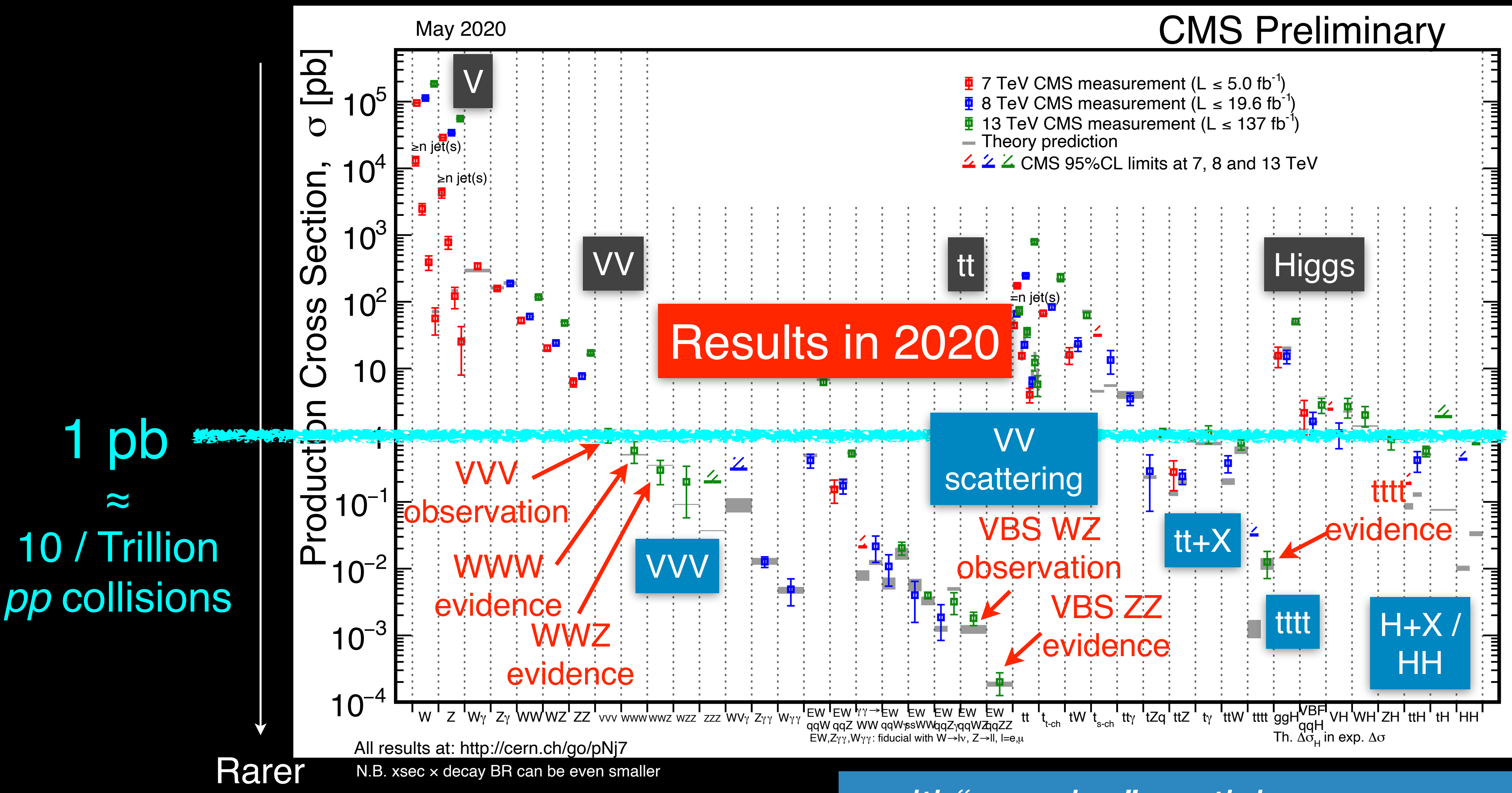

multi-"massive"-particles processes
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Recent rapid progress in finding new final states

Cross sections at LHC

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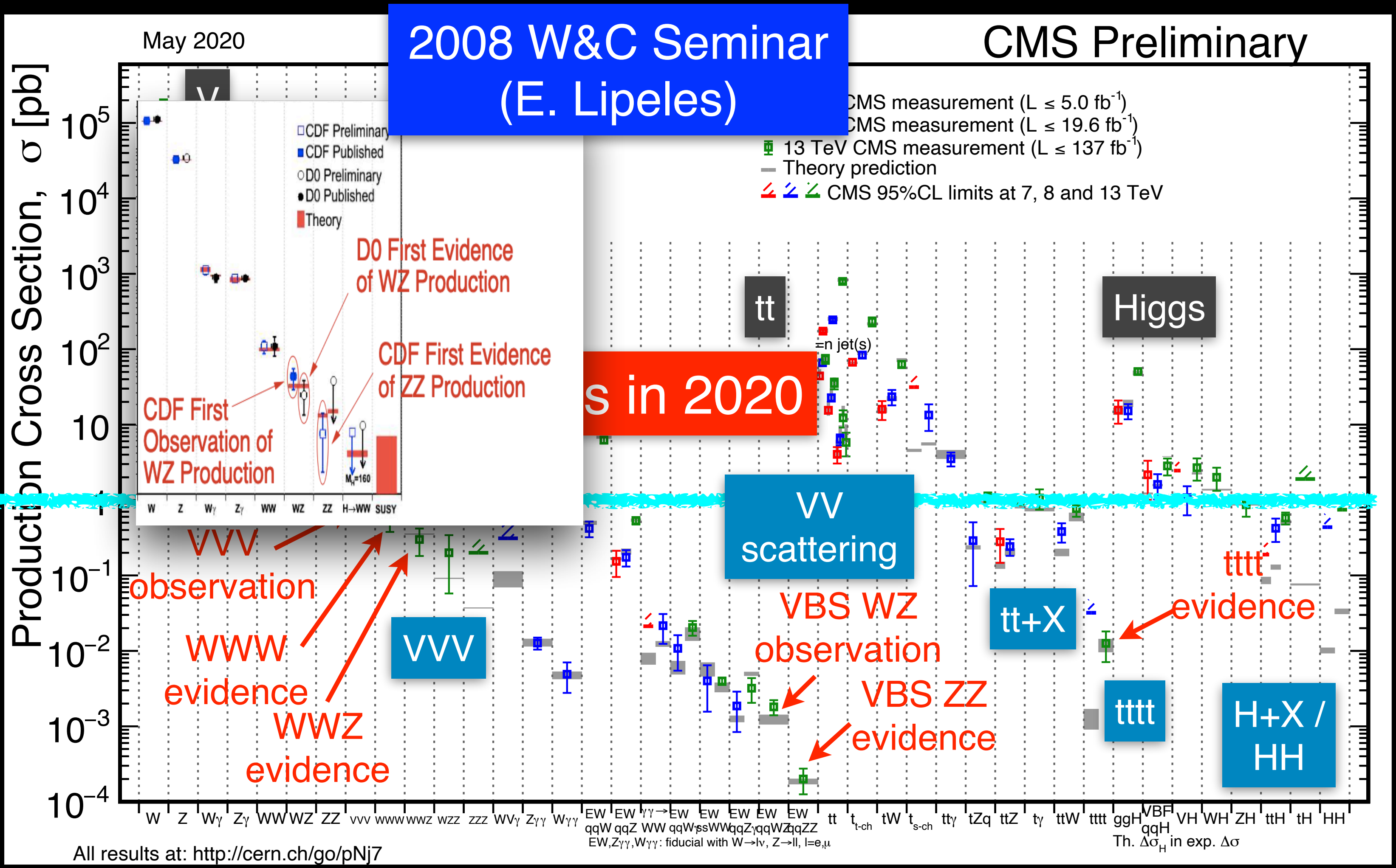

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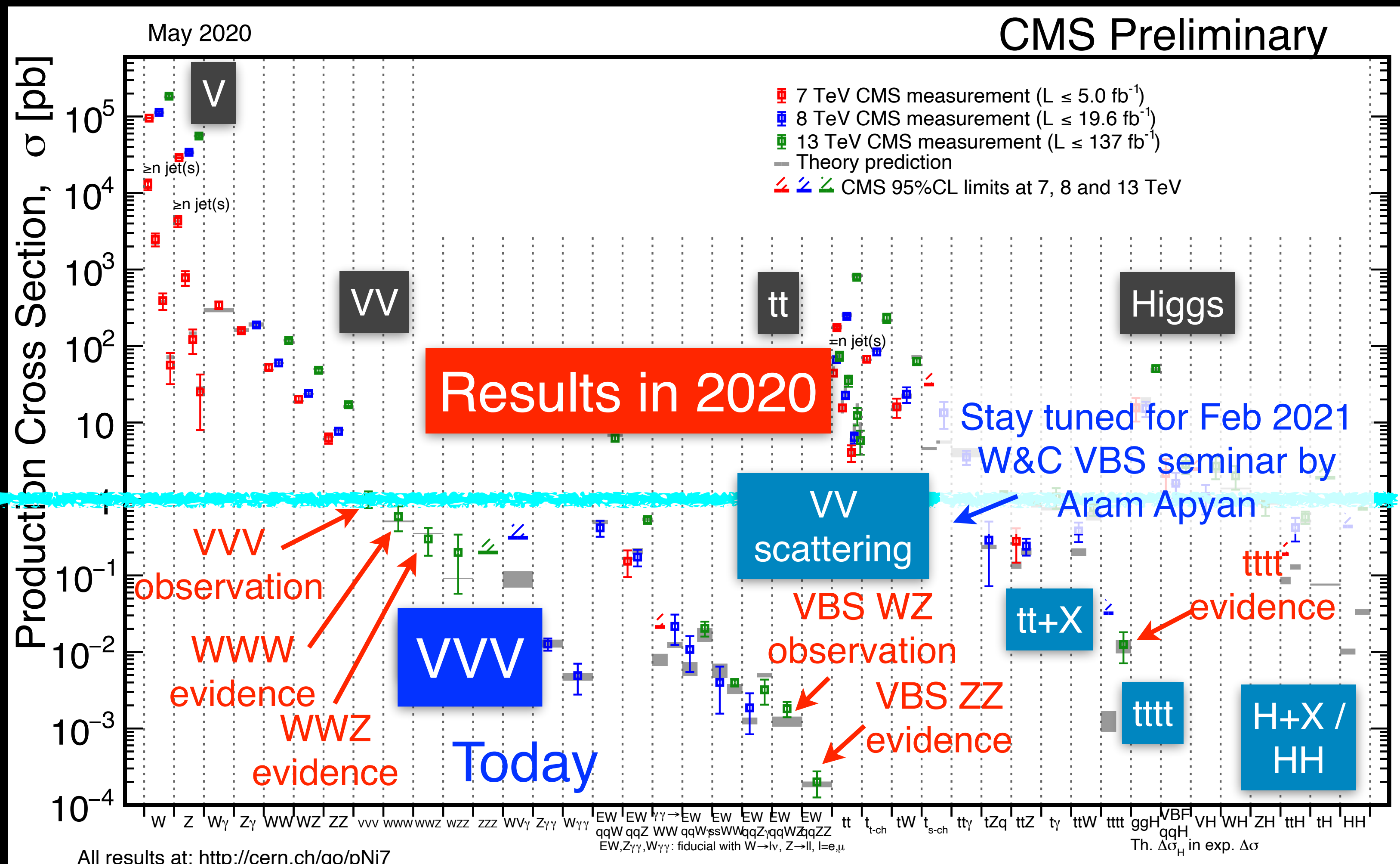

Rarer

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Recent rapid progress in finding new final states

MBIs in VVV production (V = W, Z)

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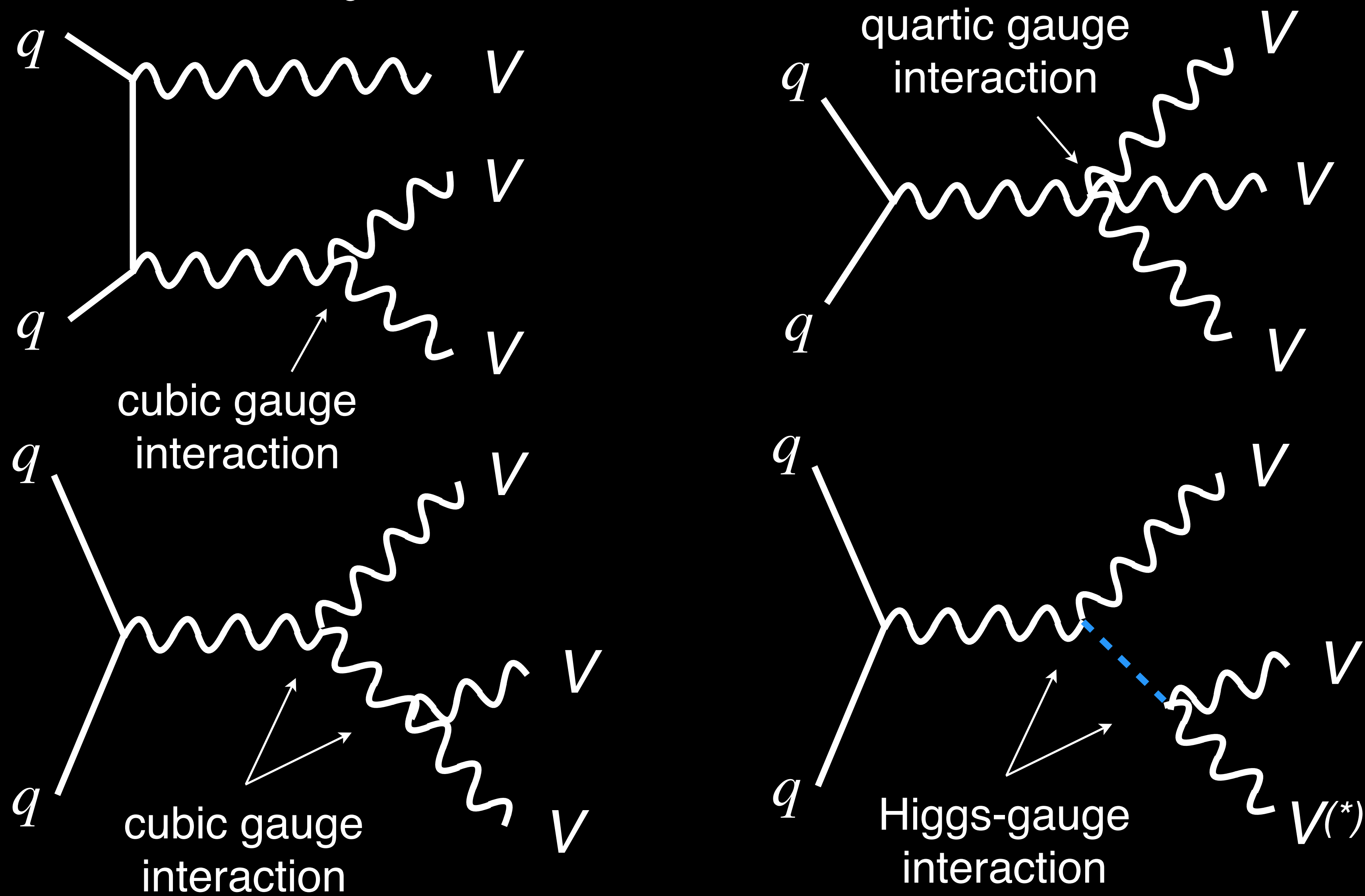
**Non-exhaustive set of VVV diagrams



Triboson processes contain many interesting MBIs

VVV production at LHC

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Targeting all VVV productions:

- pp→WWW
- pp→WWZ
- pp→WZZ
- pp→ZZZ

And the combined production of all pp→VVV

Today: Aim to establish VVV production with 5σ

Previous work on VVV physics

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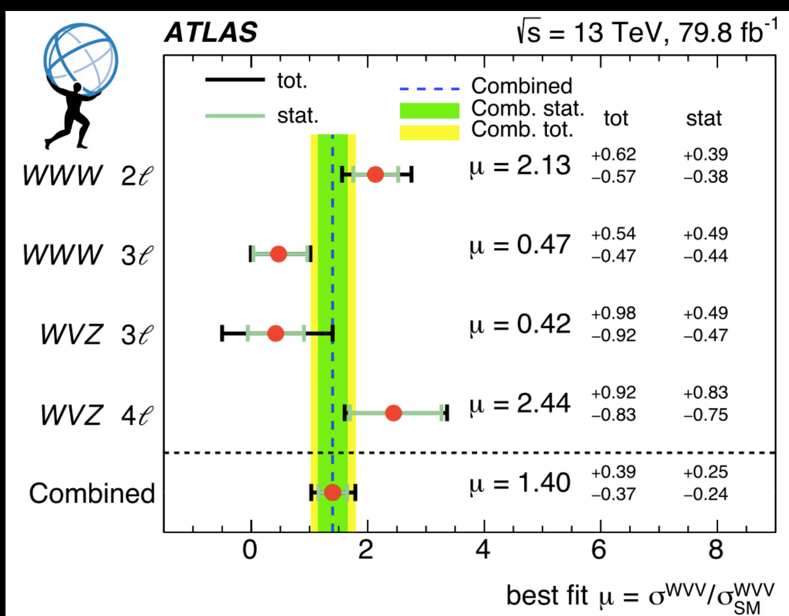
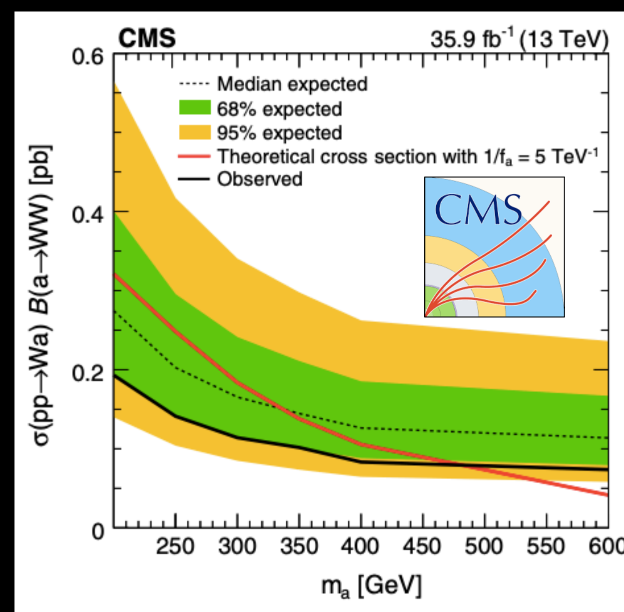
- ATLAS searched for WWW in 8 TeV: 0.96σ (1.05σ) arXiv:1610.05088
- CMS searched for WWW in 13 TeV 36 fb^{-1}: 0.6σ (1.78σ) arXiv:1905.04246
- ATLAS searched for VVV in 13 TeV 80 fb^{-1}: 4.1σ (3.1σ) arXiv:1903.10415

VVV evidence



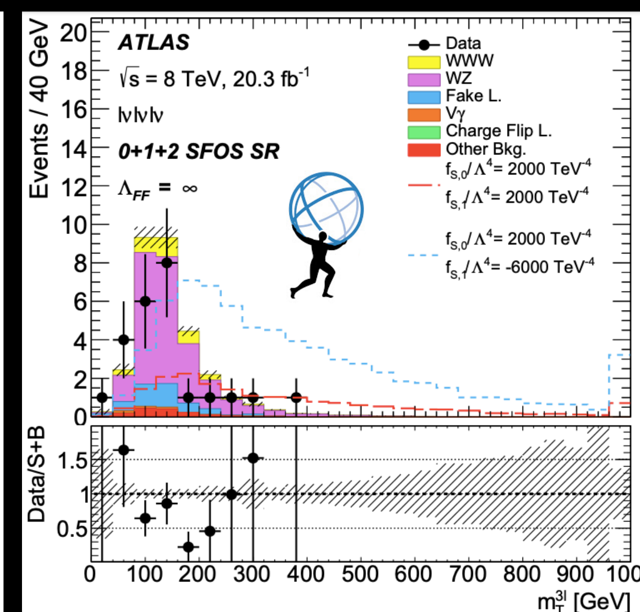
arXiv:1903.10415

Axion-like-particle triboson signature limit



arXiv:1905.04246

SMEFT Dim8 operator limit

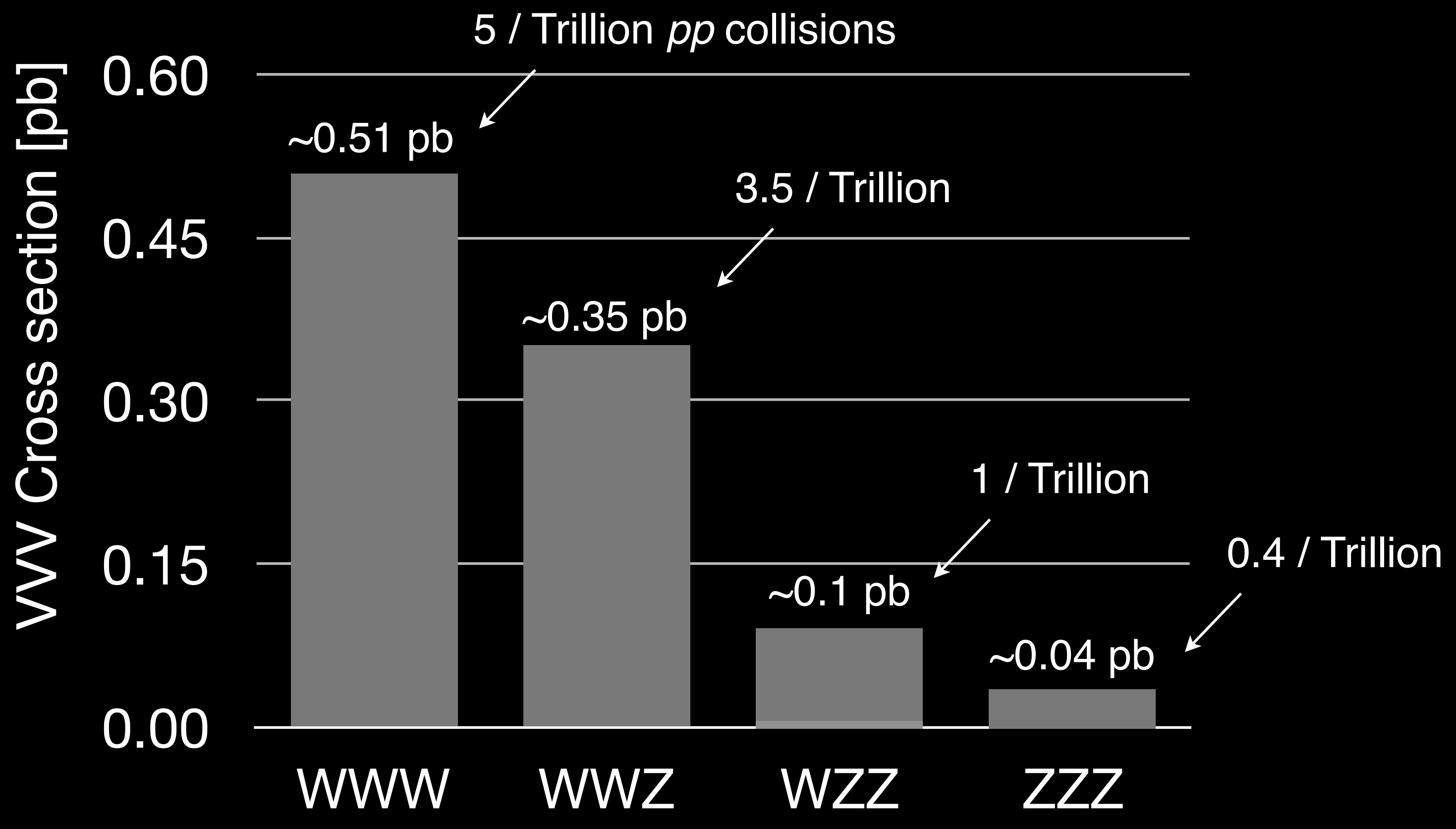


arXiv:1610.05088

ATLAS / CMS have studied VVV to test SM / BSM

VVV production cross section and rate

Production cross section decreases with more Z's



< 0.5 pb each VVV mode (rate @ LHC ~ few / Trillion)

LHC Run 2 data set

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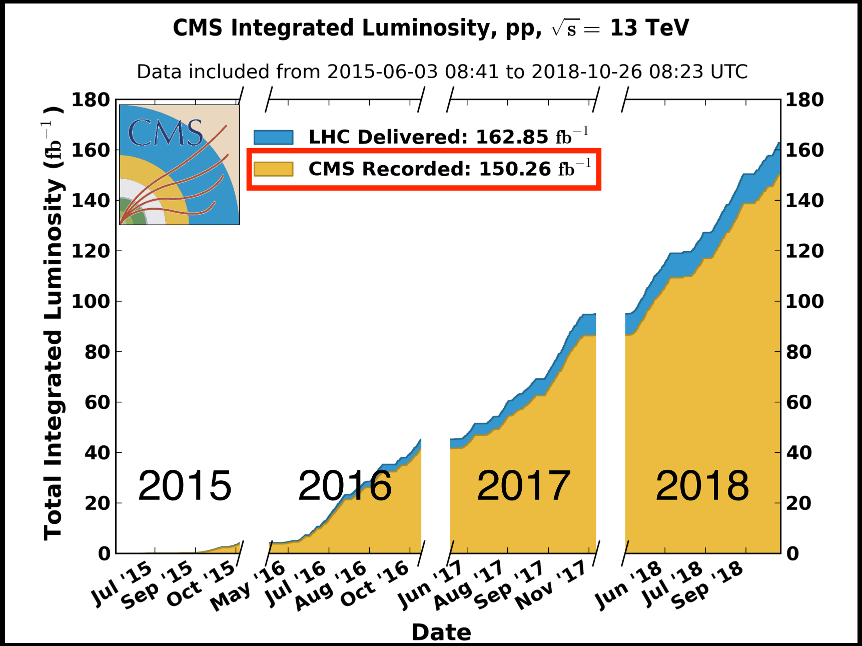
From 2015 to 2018, CMS recorded 15000 Trillion pp collisions of which ~13700 Trillions are marked *good for analysis*

⇒ Total of 135K VVV events (between from 5K to 70K per mode)

More *pp* collisions



Time

VVV	N / Trillion	N total
VVV	10	135K
WWW	5	70K
WWZ	3.5	48K
WZZ	1	13K
ZZZ	0.4	5K

LHC's large data set provides ~135K VVV events

But how do we select the interesting O(1k-10k) events out of 10^{16} pp collision events?

⇒ Select events with specific features present in multi-boson but not in other background events

Experimental signature of W, Z bosons

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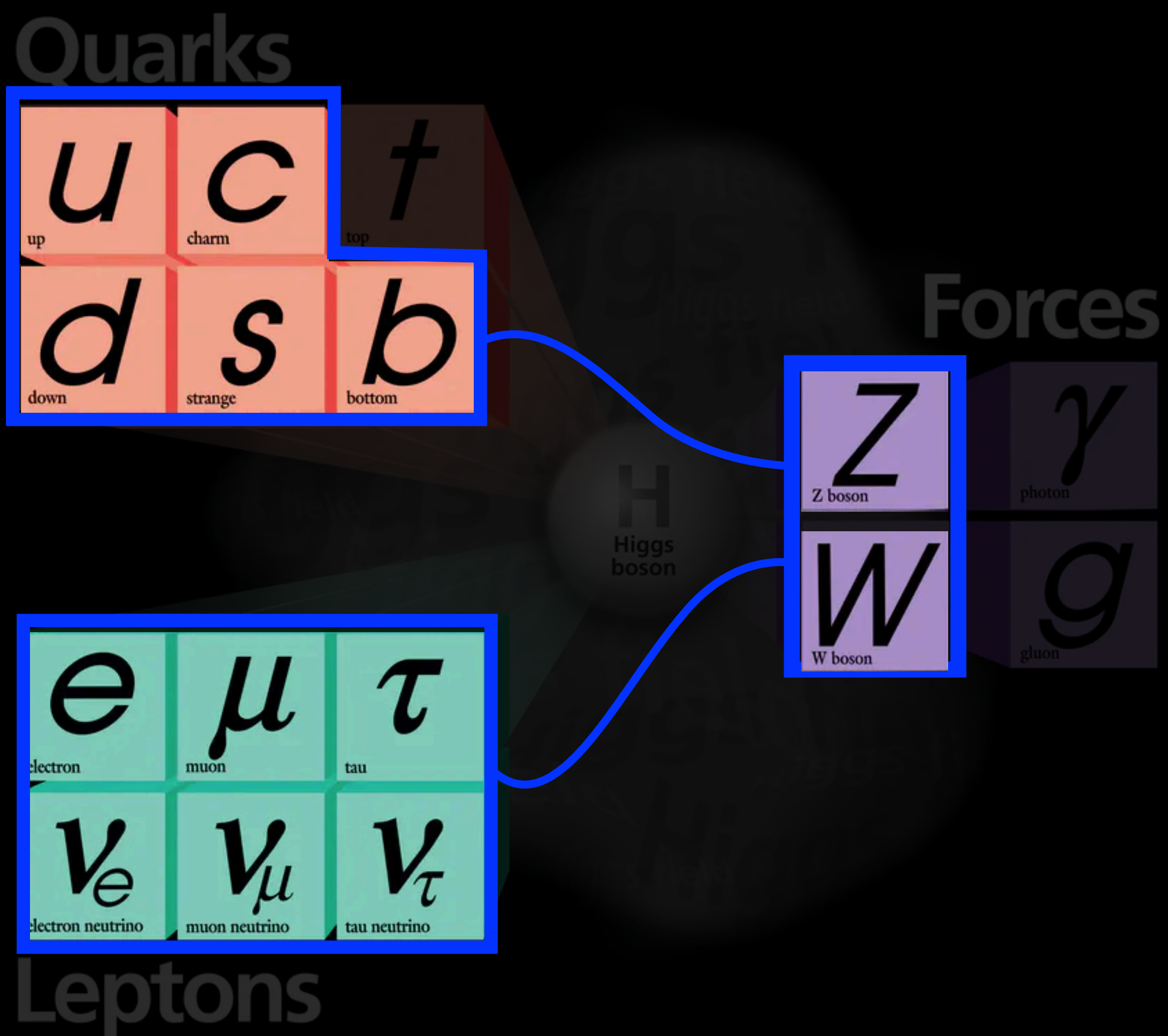
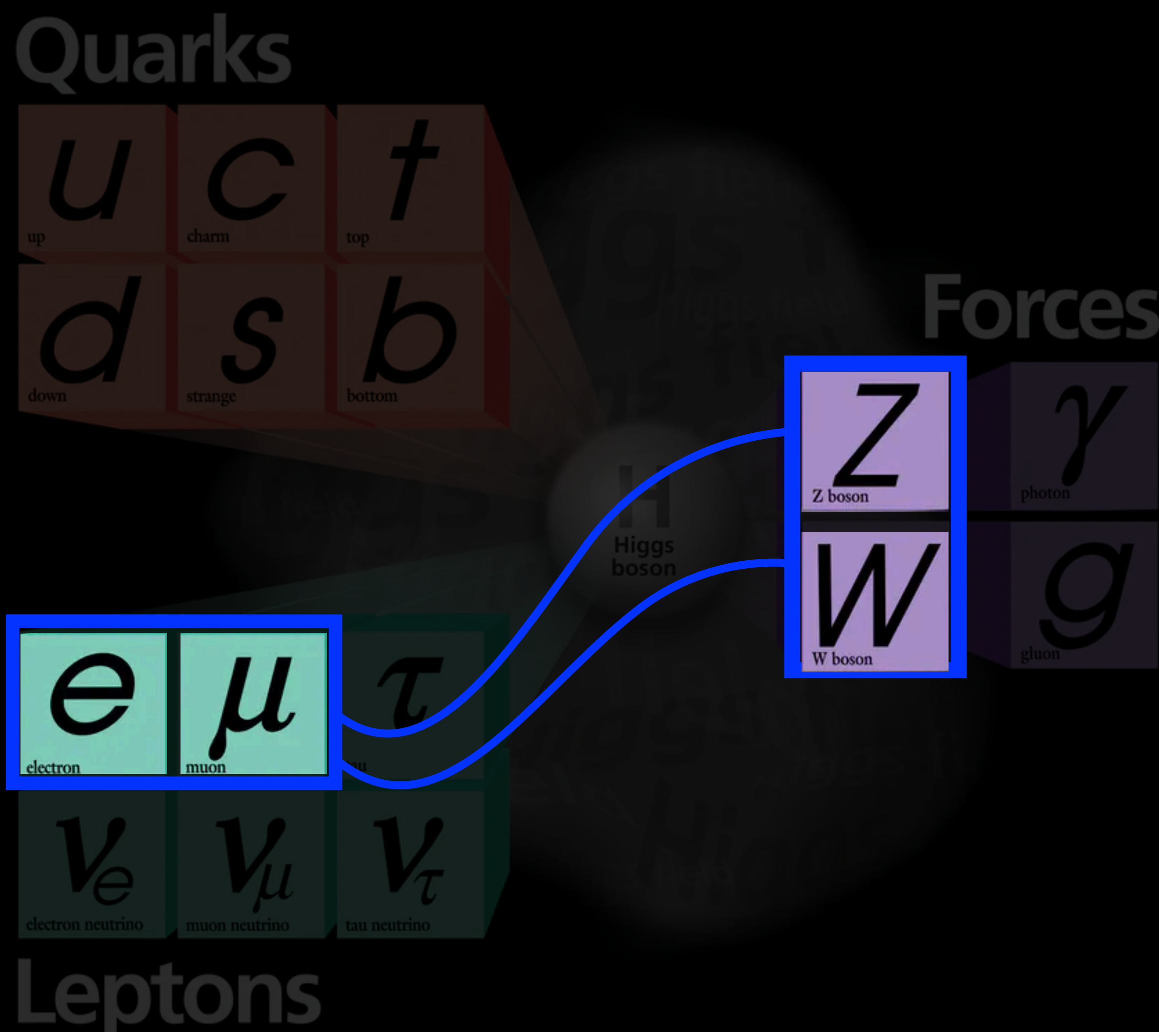
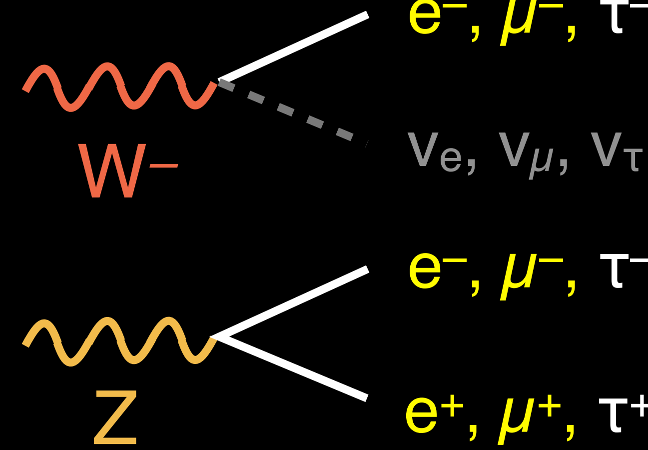


W's and Z's can decay to various quarks or lepton pairs

Experimental signature of W, Z bosons





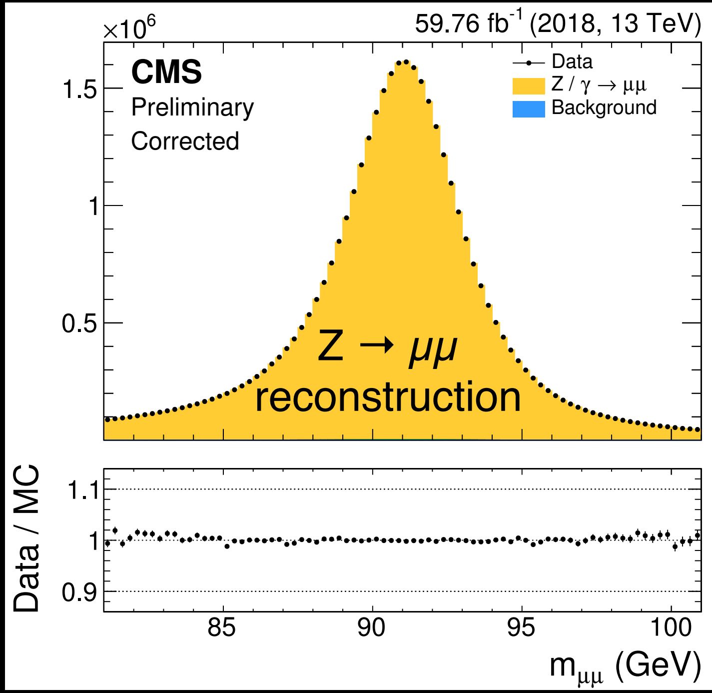
But W's and Z's can most easily identified via electrons and muons

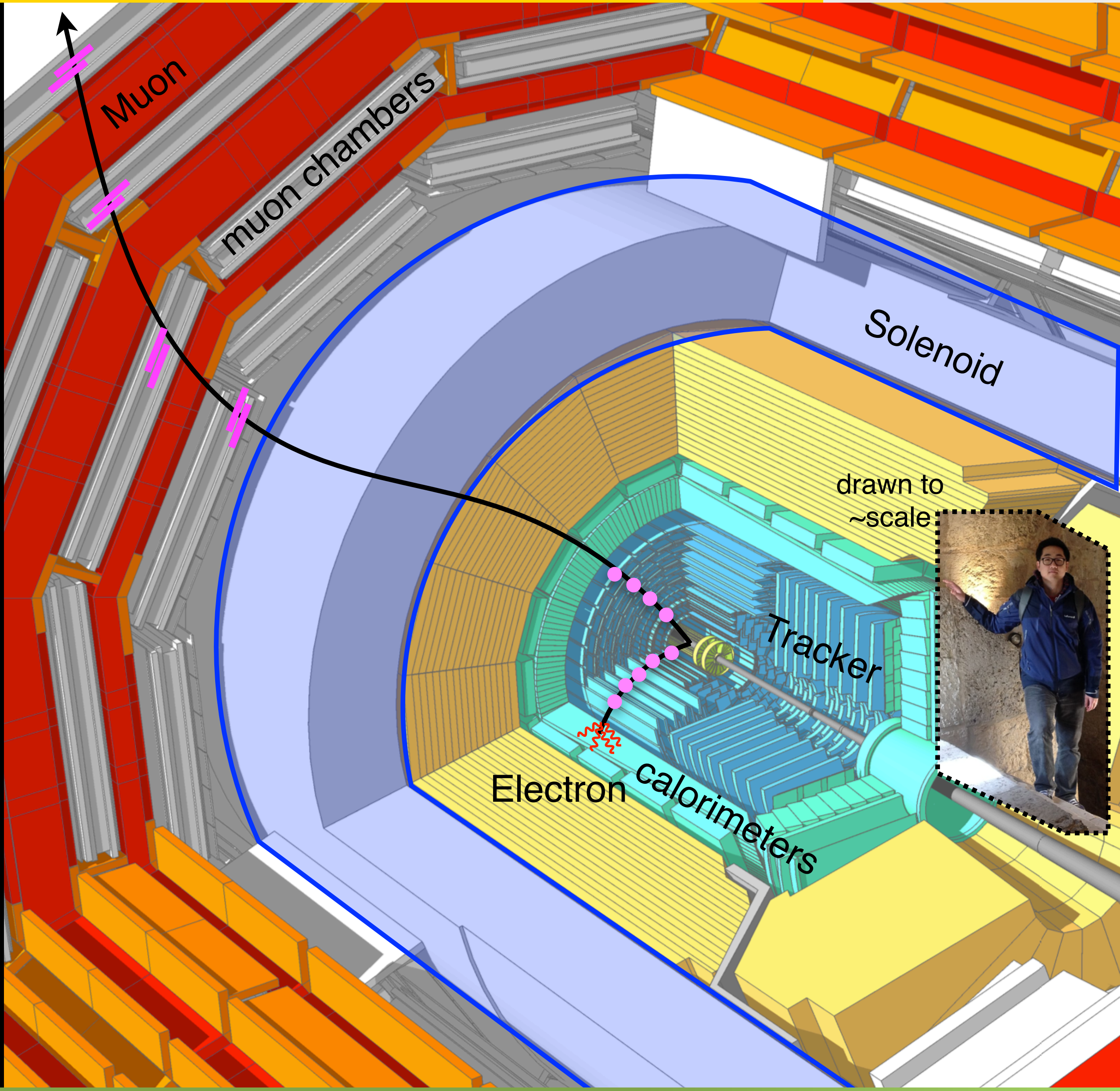
∴ Multiple W's and Z's
⇒ Multiple e's and μ's

W/Z's can be identified via e and μ

CMS detector measures e/μ very well

e/μ among the best measured particles at CMS by combining tracker, calorimeter, and chambers measurements
(1-2% resolution for well measured ones)



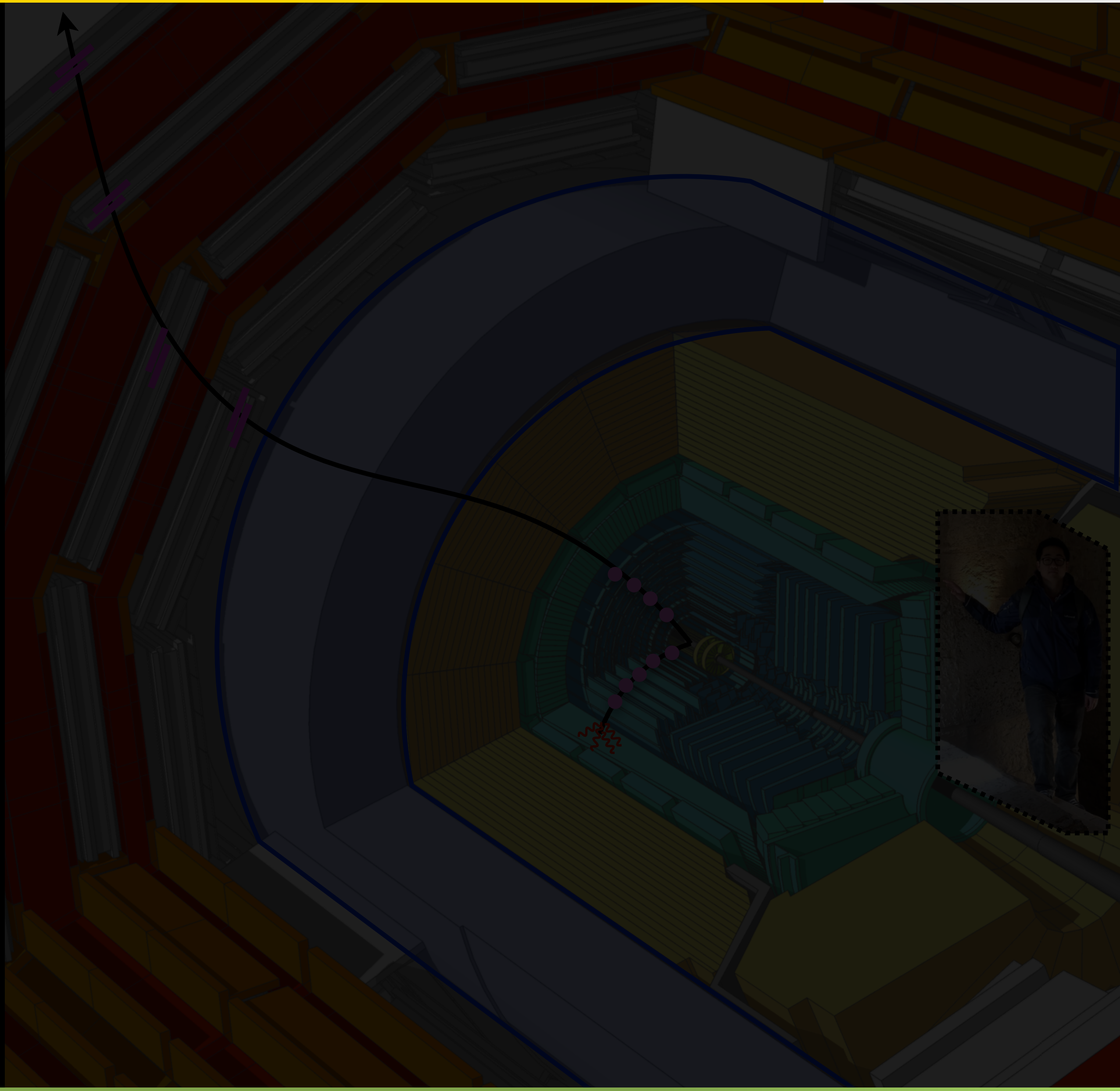


Excellent e/μ reconstruction and simulation at CMS

Classifying leptons' origins

Identifying e/μ is not enough

We need to further classify the origin



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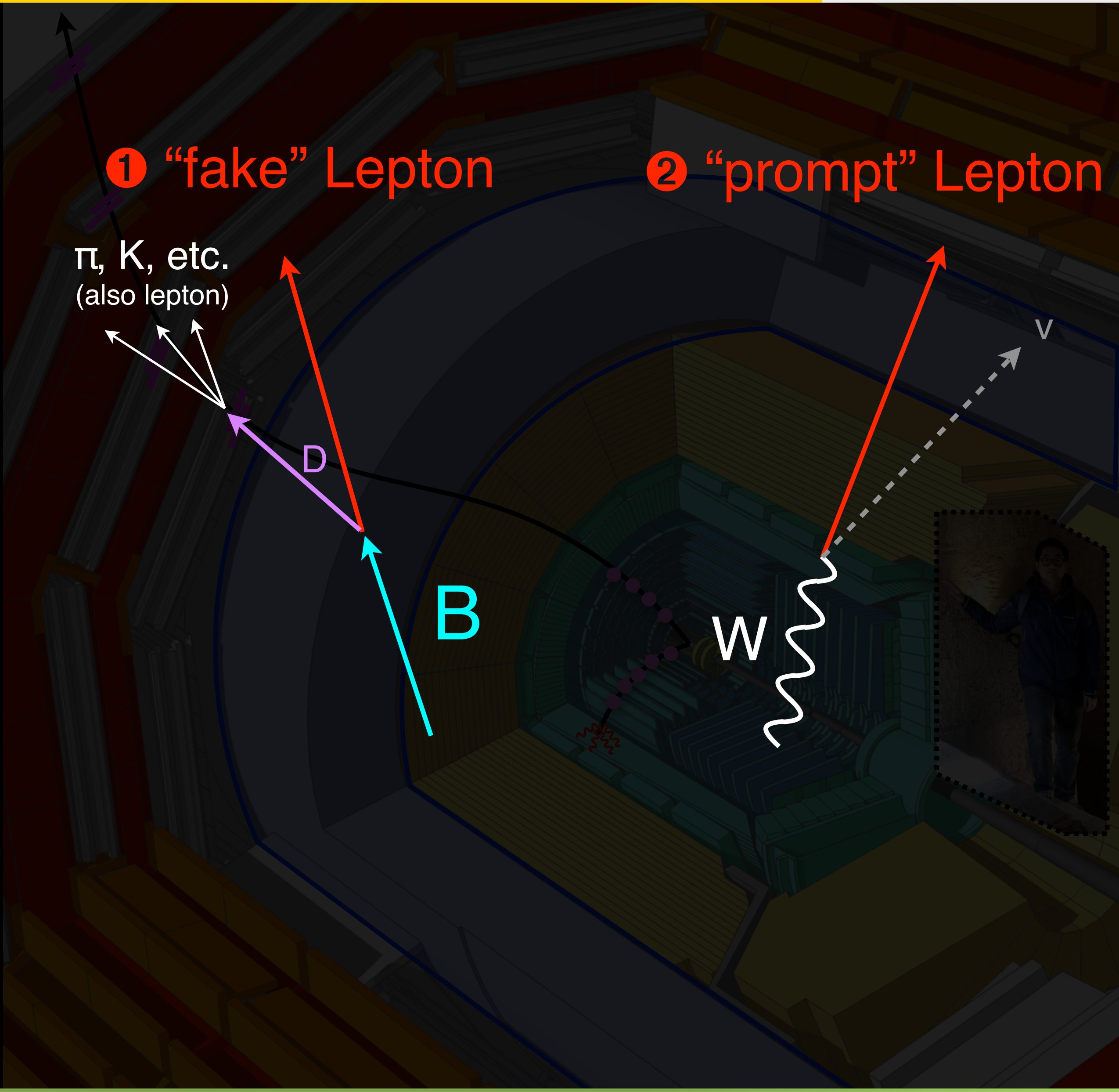

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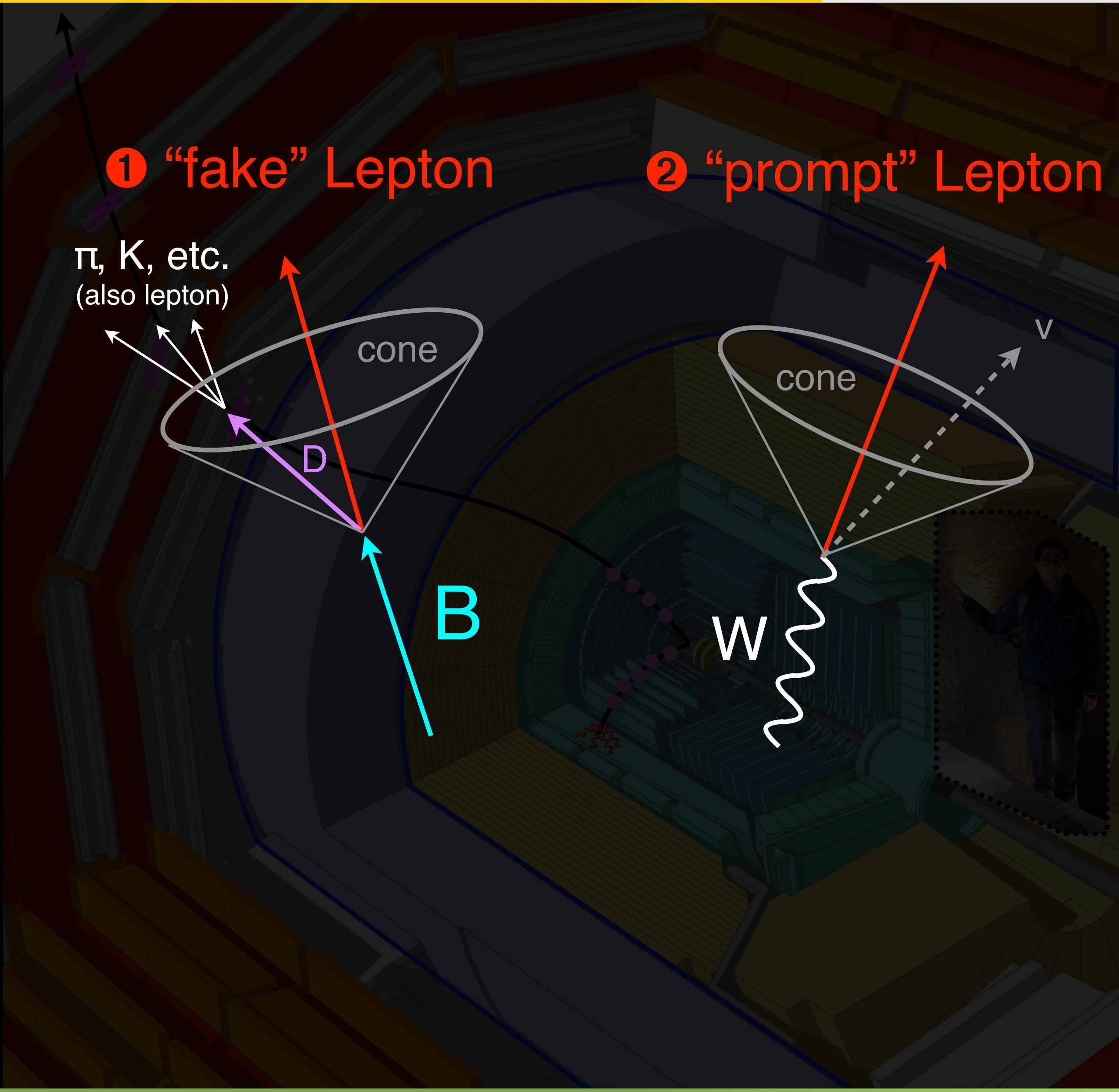
$$\text{Isolation} = \frac{\Sigma_{\text{“stuff” in cone}} P_T}{P_{T,\text{Lepton}}}$$



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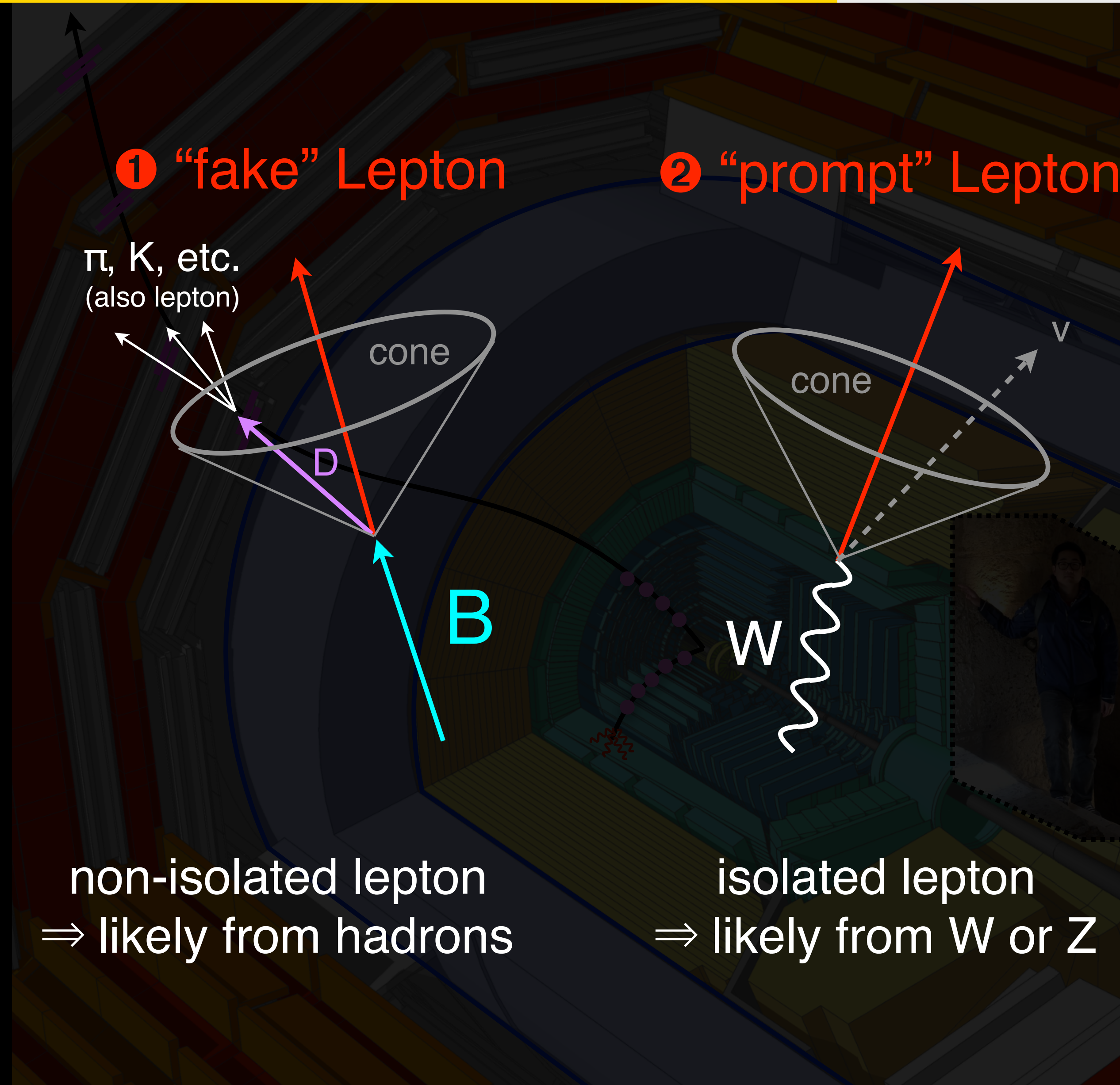

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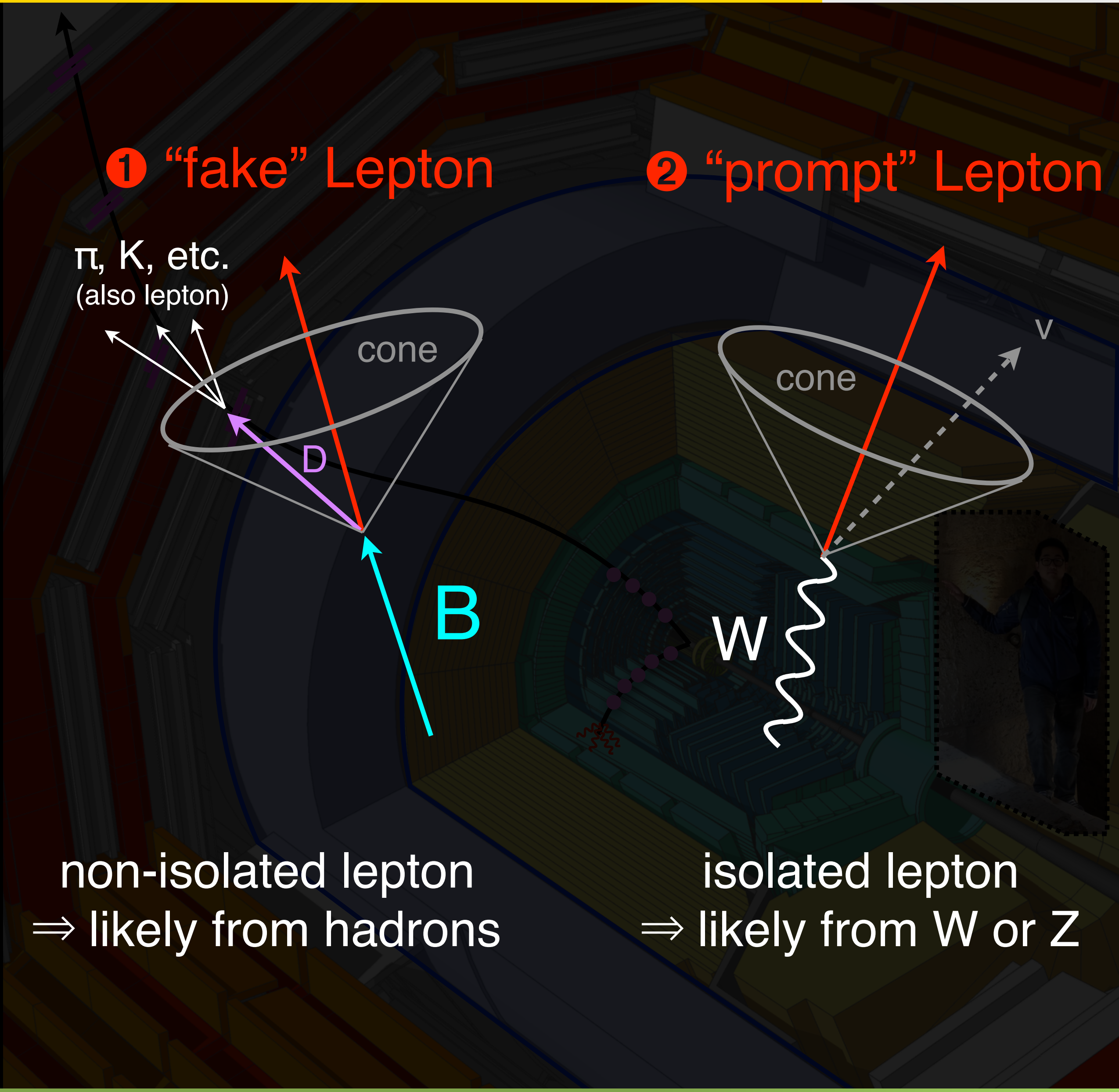

Use isolation to suppress leptons from hadrons

5 steps to VVV observation

1. Organize analyses by # of leptons (likely) from W / Z
2. Categorize by flavor of the leptons
3. Additional background suppression through smart choices
4. Reliably estimate the size of residual backgrounds
5. Observe VVV!

Smart humans and smart machines (Both cut / BDT)

Fully leptonic decay channels of VVV

Inclusive number of events

VVV	#
WWW	70K
WWZ	48K
WZZ	13K
ZZZ	5K

**Expected # of events in Run 2

Fully leptonic decay channels of VVV

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- Fraction of W, Z decays to e or μ:
- BR(W → e or μ) = 21%
- BR(Z → ee or $\mu\mu$) = 7%

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→

cf. Run 1 had ~55 WWW evt.

Number of events when all V's decay to e or μ

VVV → N leptons	Total BR	%	#
WWW → 3 lepton + 3v	$(21\%)^3$	1	700
WWZ → 4 lepton + 2v	$(21\%)^2(7\%)$	0.3	150
WZZ → 5 lepton + 1v	$(21\%)(7\%)^2$	0.1	15
ZZZ → 6 lepton	$(7\%)^3$	0.03	1.5

Run 2 data set allows to study various VVV modes for the first time

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ZZZ → 6 lepton	$(7\%)^3$	0.03	1.5

Run 2 data set allows to study various VVV modes for the first time

**Expected # of events in Run 2

Fully leptonic channels ~ a few to hundreds of events

Semi-leptonic decay channels of VVV

Percentage of semi-leptonic decay events
(i.e. 0, 1, or 2 leptons)

VVV	Total	%	Example
WWW	70K	99.0	WWW → jj jj jj
WWZ	48K	99.7	WWZ → lv jj jj
WZZ	13K	99.9	WZZ → ll jj jj
ZZZ	5K	99.97	ZZZ → ll jj vv

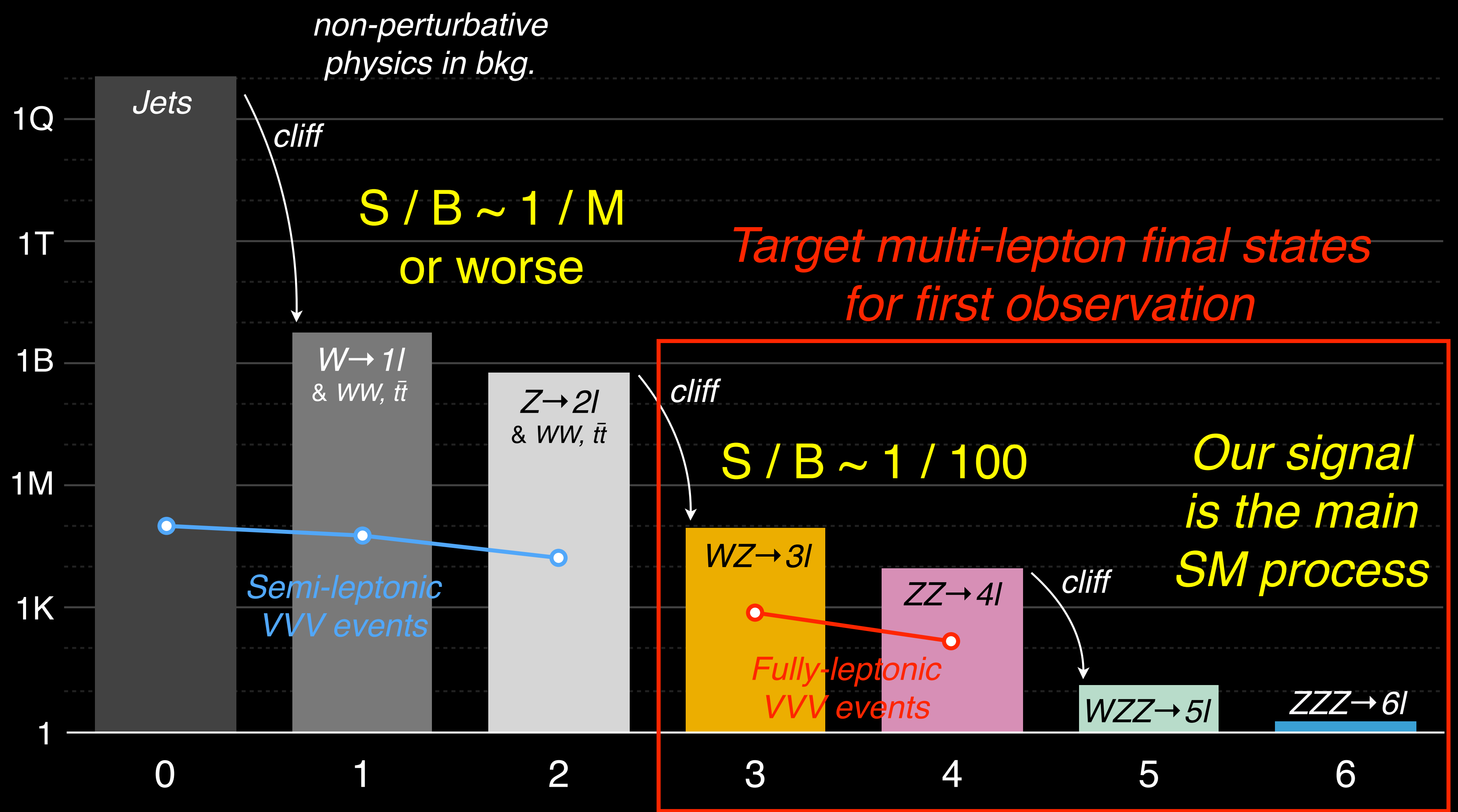
In contrast, majority of the events decay with ≤ 2 leptons

**Expected # of events in Run 2

Majority of the decays are semi-leptonic decays

Choosing lepton channels to use

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



Target multi-lepton final states for first observation

Divide and conquer

		3 leptons	4 leptons	5 leptons	6 leptons
Signals		$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
		~700 evt.	~140 evt.	~15 evt.	~1.5 evt.

***Minor cross-contamination exists (but negligible) and are taken care of properly at the final statistics procedure

Signals get disentangled by # of lepton bins

Divide and conquer

	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.

Only hadronic decay

**SM does not produce same-sign dilepton very often

***Minor cross-contamination exists (but negligible) and are taken care of properly at the final statistics procedure

Signals get disentangled by # of lepton bins

Disclaimer

There are many channels in this analysis (21 channels)

I will highlight few categories with high sensitivity

3 leptons 0SFOS channel
4 leptons Z + eμ channel

5 steps to VVV observation

1. ~~Organize analyses by # of leptons (likely) from W / Z~~
2. Categorize by flavor of the leptons
3. Additional background suppression through smart choices
4. Reliably estimate the size of residual backgrounds
5. Observe VVV!

Smart humans and smart machines (Both cut / BDT)

Dominant background

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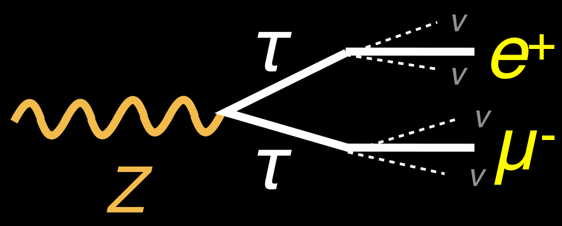
	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$ ~700 evt.	$W \to l\nu$ $W \to l\nu$ $Z \to ll$ ~140 evt.	$W \to l\nu$ $Z \to ll$ $Z \to ll$ ~15 evt.	$Z \to ll$ $Z \to ll$ $Z \to ll$ ~1.5 evt.
Dominant Bkgs.	$WZ \to l\nu ll$ ~100K evt.	$ZZ \to llll$ ~10K evt.	$ZZ \to llll$ + fake lep "× 10^{-3}"	$ZZ \to llll$ + 2 fake lep "× 10^{-6}"
S / B	~1 / 100	~1 / 100	~1 / 1**	>> 1**

How to improve S / B by ~100?

**fake lepton is "~per mille" effect

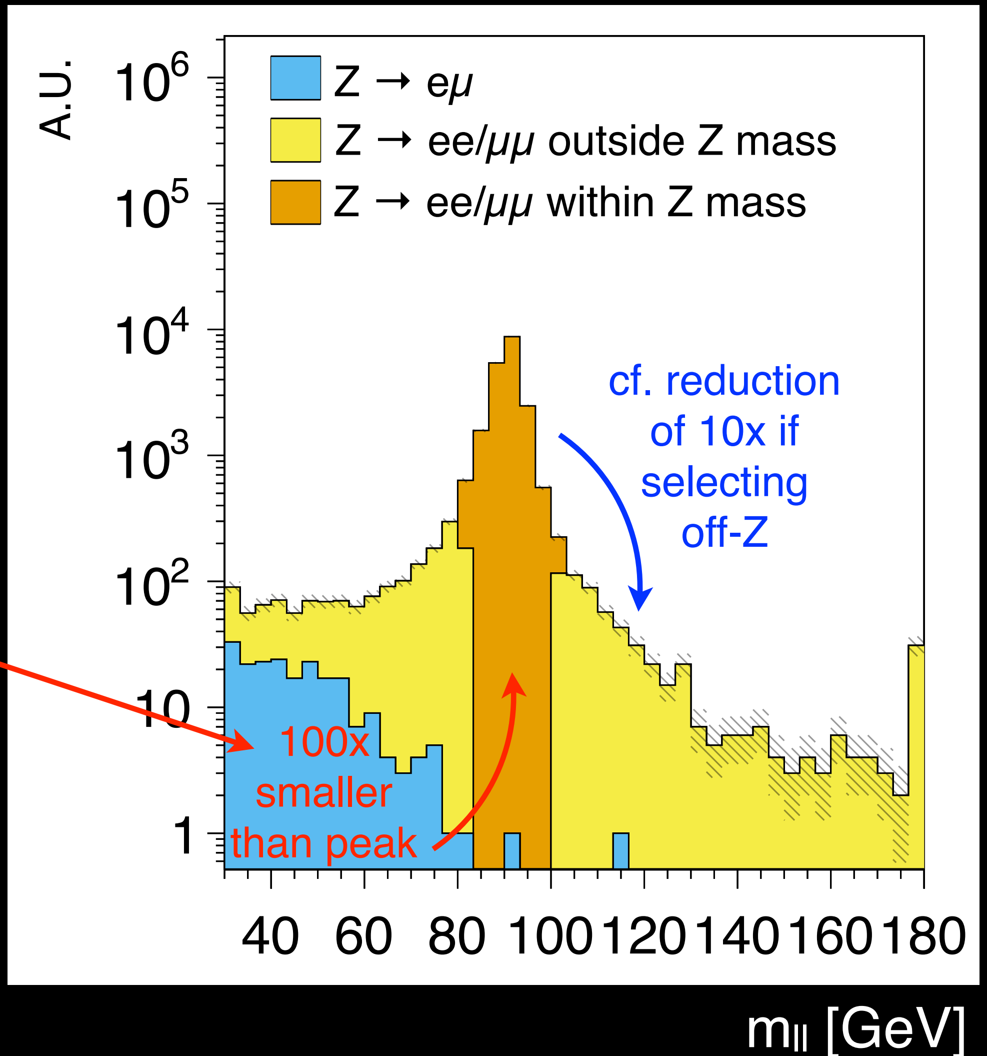
Dominant background is diboson process (WZ, ZZ)

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

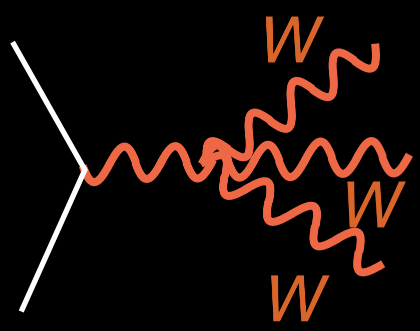


**Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV P_T cuts

Z decays predominantly to ee/μμ on-shell

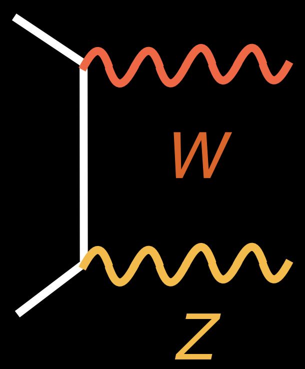
Flavor choices

WWW signal



pp → WWW

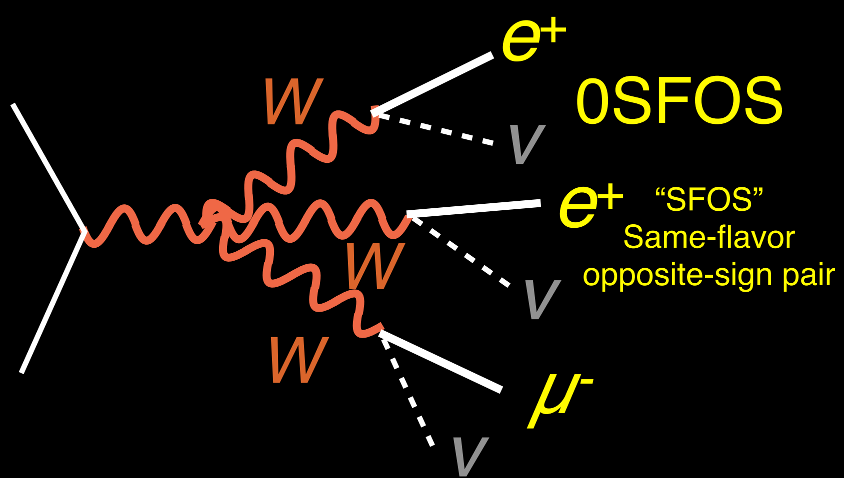
Background



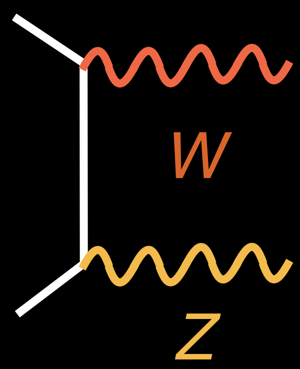
pp → WZ

Flavor choice can suppress WZ by 100x

WWW signal



Background



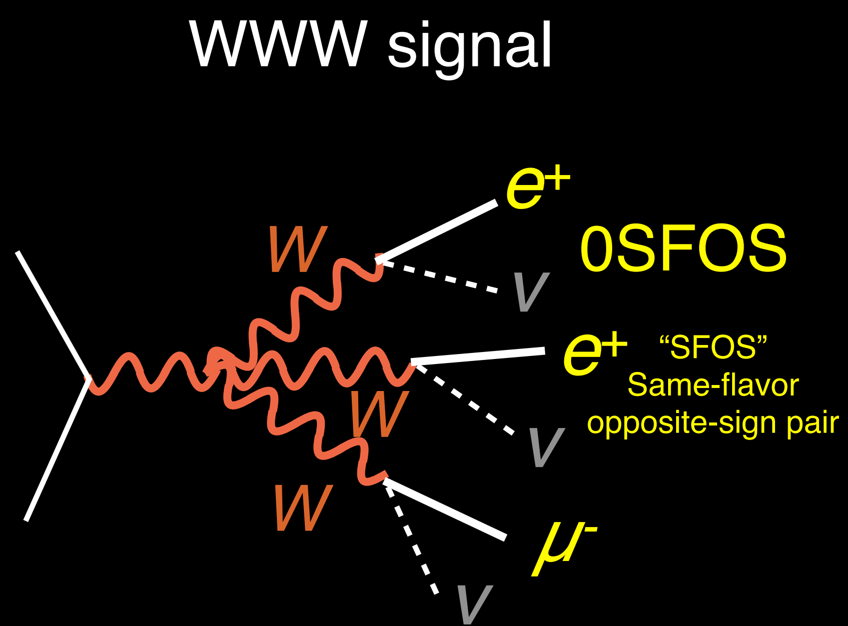
$pp \to WWW \to e^+e^+\mu^-$

$pp \to WZ$

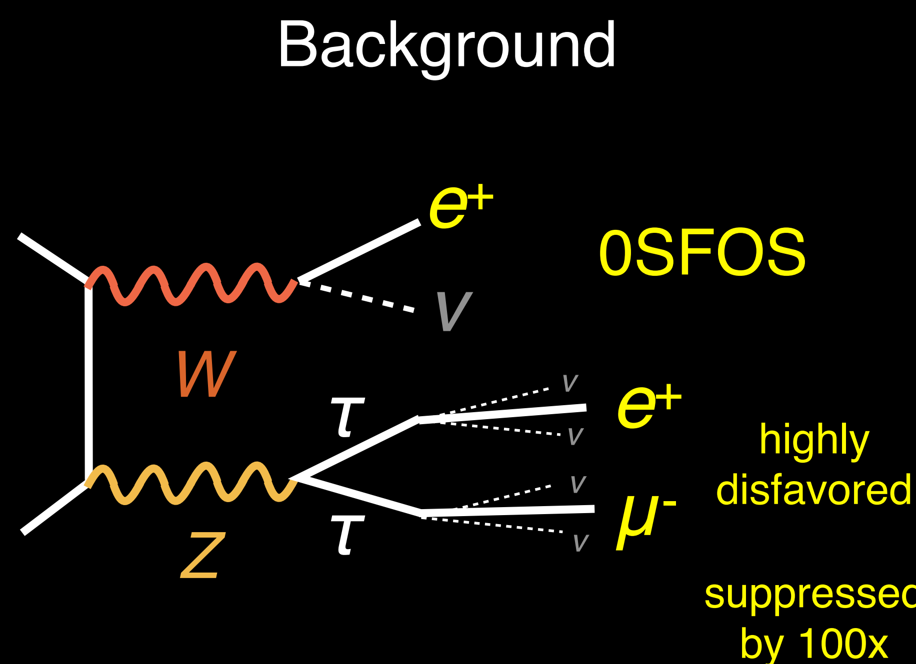
Same for
$e^-e^-\mu^+$, $\mu^+\mu^+e^-$, $\mu^-\mu^-e^+$

Flavor choice can suppress WZ by 100x

Flavor choices



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



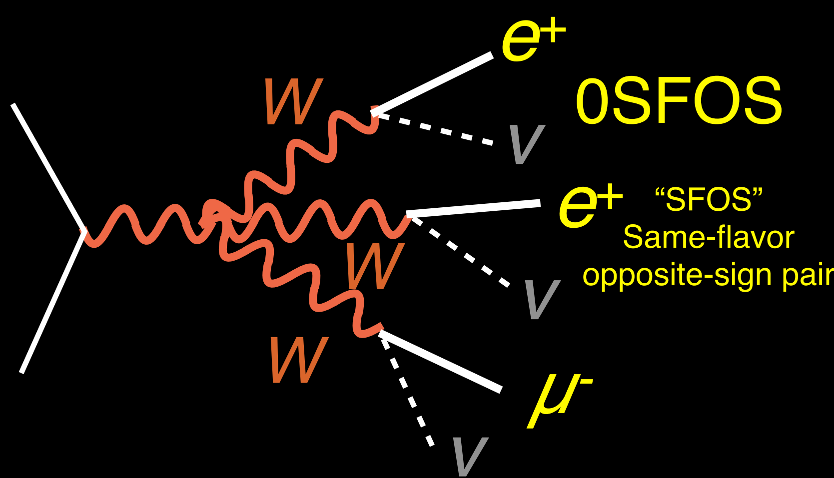
$pp \to WZ \to e^+e^+\mu^-$

Same for
$e^-e^-\mu^+$, $\mu^+\mu^+e^-$, $\mu^-\mu^-e^+$

Flavor choice can suppress WZ by 100x

Flavor choices

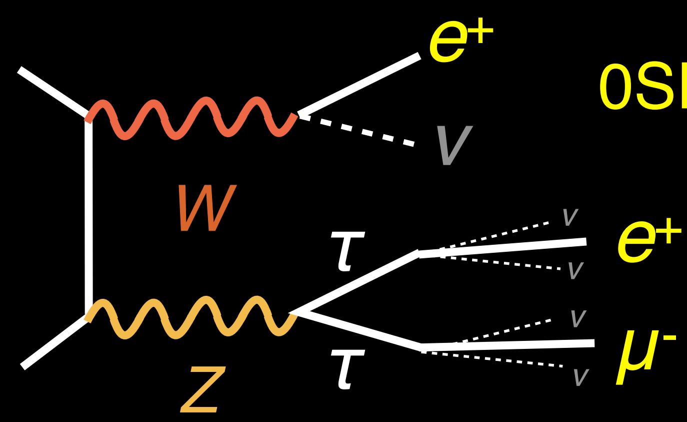
WWW signal



pp → WWW → $e^+e^+\mu^-$

Same for
$e^-e^-\mu^+$, $\mu^+\mu^+e^-$, $\mu^-\mu^-e^+$

Background



highly
disfavored

suppressed
by 100x

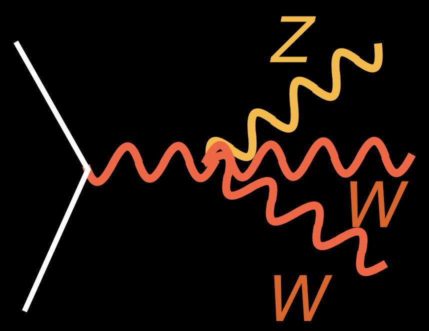
pp → WZ → $e^+e^+\mu^-$

⇒ 0SFOS channel

Flavor choice can suppress WZ by 100x

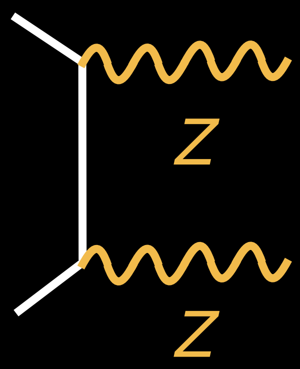
Flavor choices

WWZ signal



pp → ZWW

Background

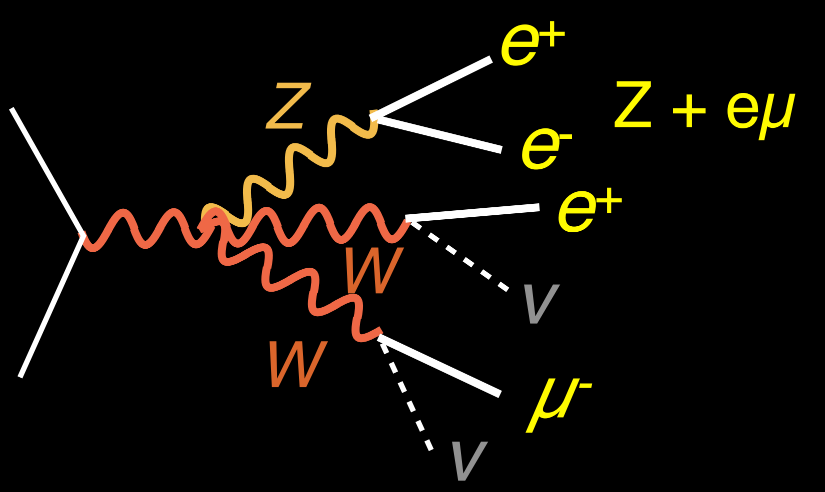


pp → ZZ

Flavor choice can suppress ZZ by 100x

Flavor choices

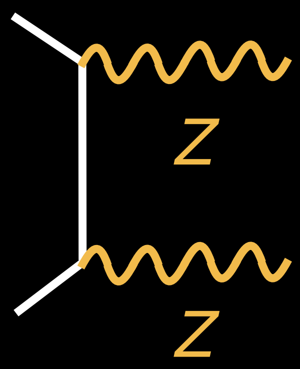
WWZ signal



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

tagged-Z

Background



$pp \rightarrow ZZ$

Same for
$(e^+e^-)\, e^-\mu^+$, $(\mu^+\mu^-)\, e^+\mu^-$, $(\mu^+\mu^-)\, e^-\mu^+$

Flavor choice can suppress ZZ by 100x

Flavor choices

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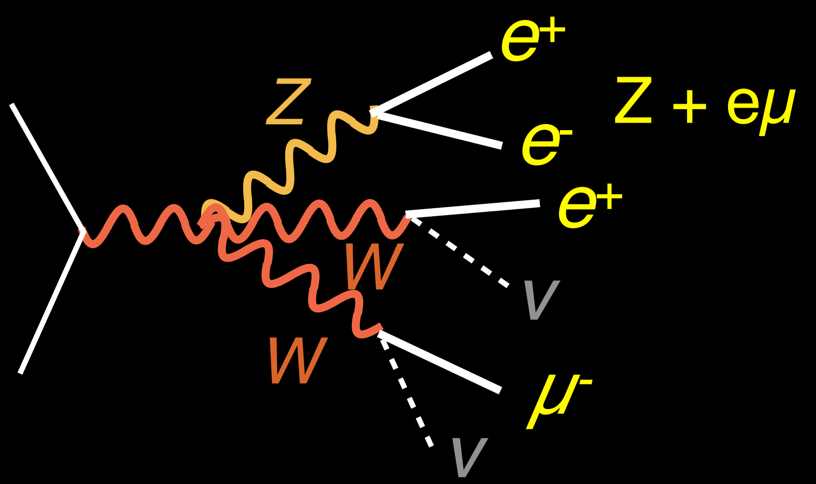
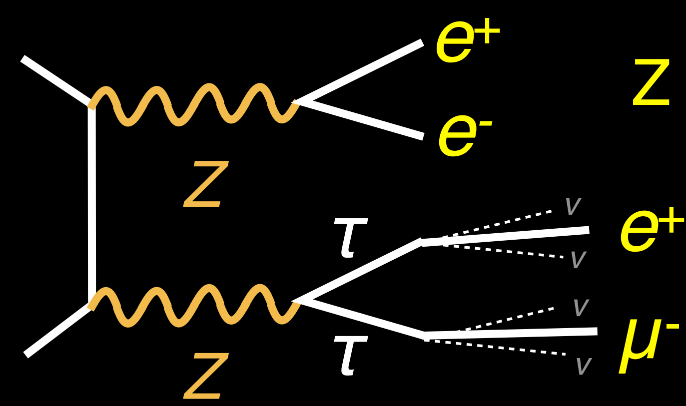
WWZ signal



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

tagged-Z

Background



highly disfavored

suppressed by 100x

$pp \to ZZ \to (e^+e^-)\, e^+\mu^-$

tagged-Z

Same for
$(e^+e^-)\, e^-\mu^+$, $(\mu^+\mu^-)\, e^+\mu^-$, $(\mu^+\mu^-)\, e^-\mu^+$

Flavor choice can suppress ZZ by 100x

Flavor choices

Chang
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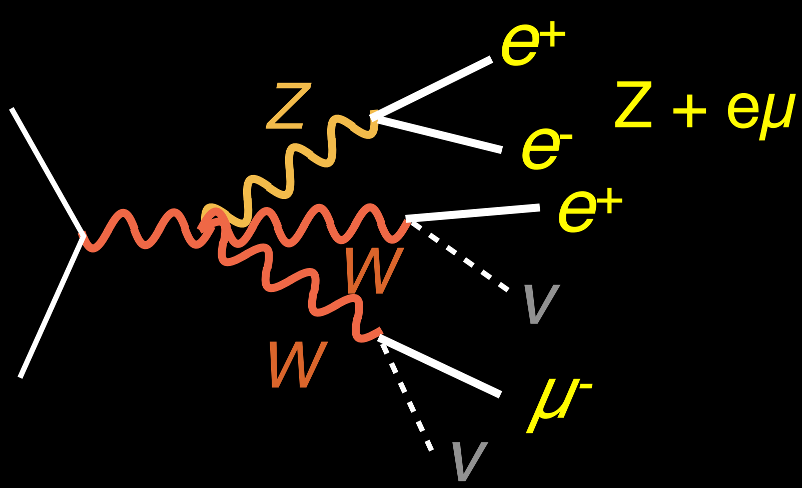
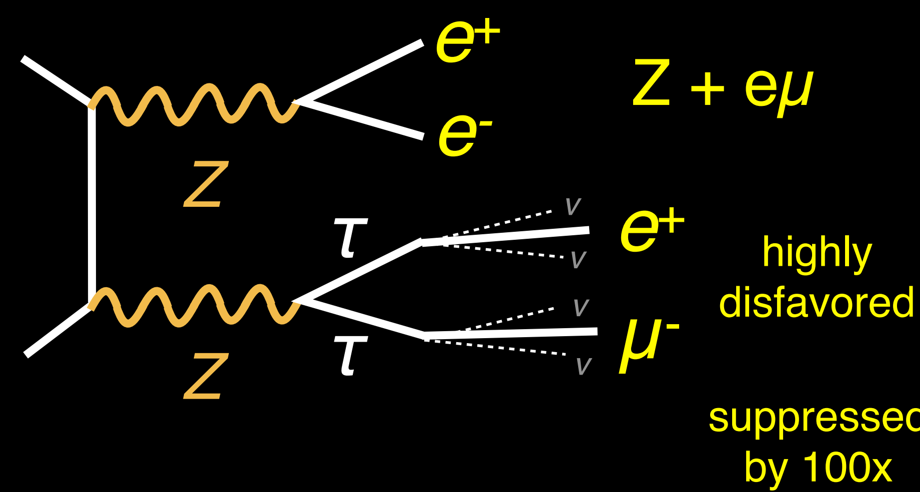
WWZ signal



Background



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

tagged-Z

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

tagged-Z

Same for
$(e^+e^-)\, e^-\mu^+$, $(\mu^+\mu^-)\, e^+\mu^-$, $(\mu^+\mu^-)\, e^-\mu^+$

$\Rightarrow$ Z + eμ channel

Flavor choice can suppress ZZ by 100x

5 steps to VVV observation

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

2. ~~Categorize by flavor of the leptons~~

Smart humans and smart machines (Both cut / BDT)

3. Additional background suppression through smart choices

4. Reliably estimate the size of residual backgrounds

5. Observe VVV!

b tagging

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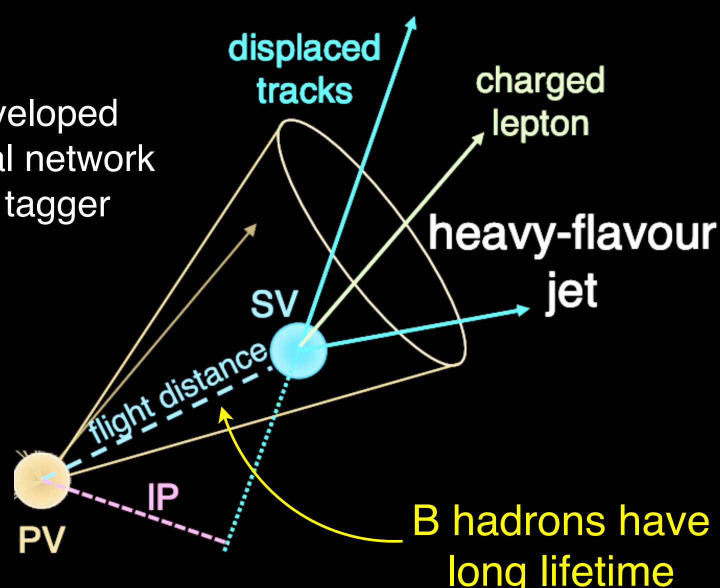
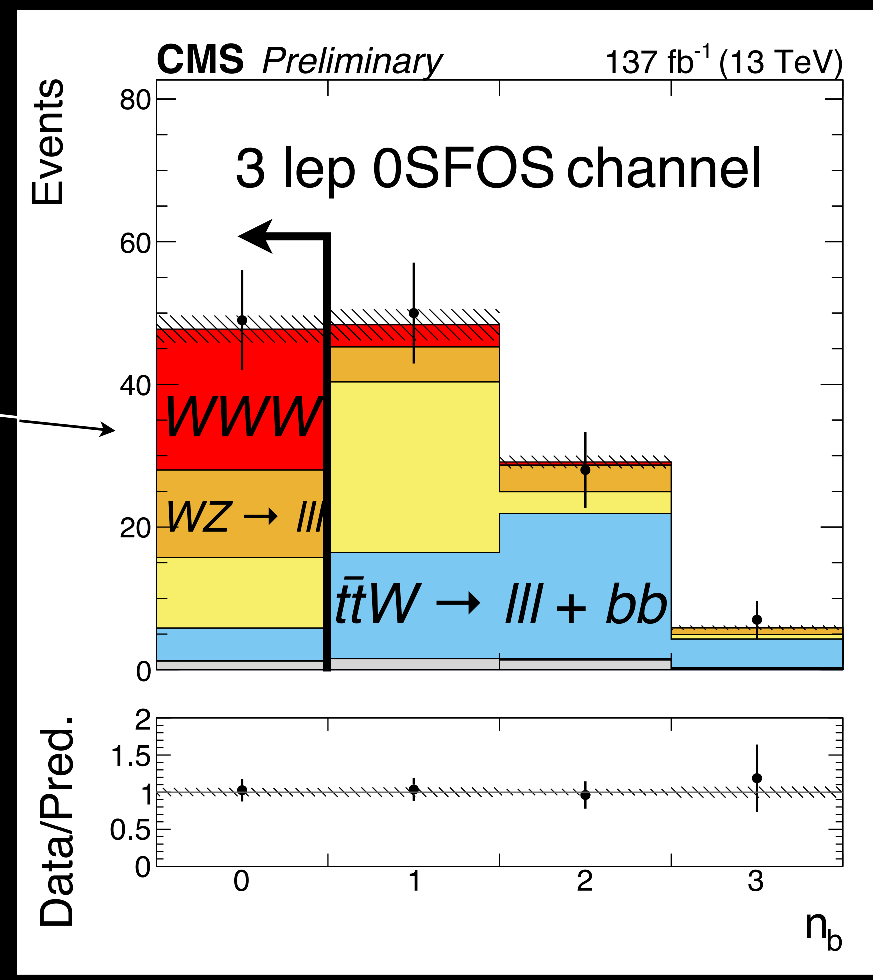
- As expected, WWW v. WZ ~ same order
- But additional backgrounds of "$t\bar{t}$ + X"
  - These bkgs have *b jets*
- Signals (EW process) generally do not come with b jets
- **⇒ Require # of b = 0**

CMS developed deep neural network based *b* tagger



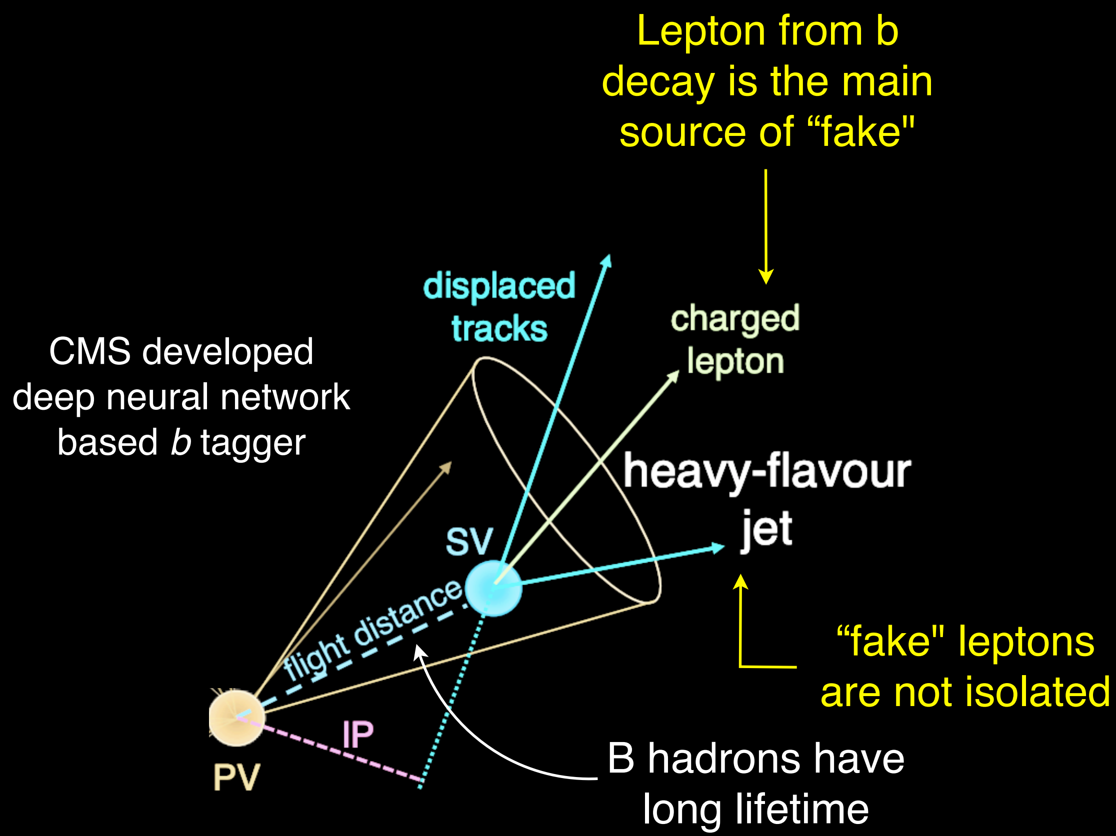
After 0SFOS preselection



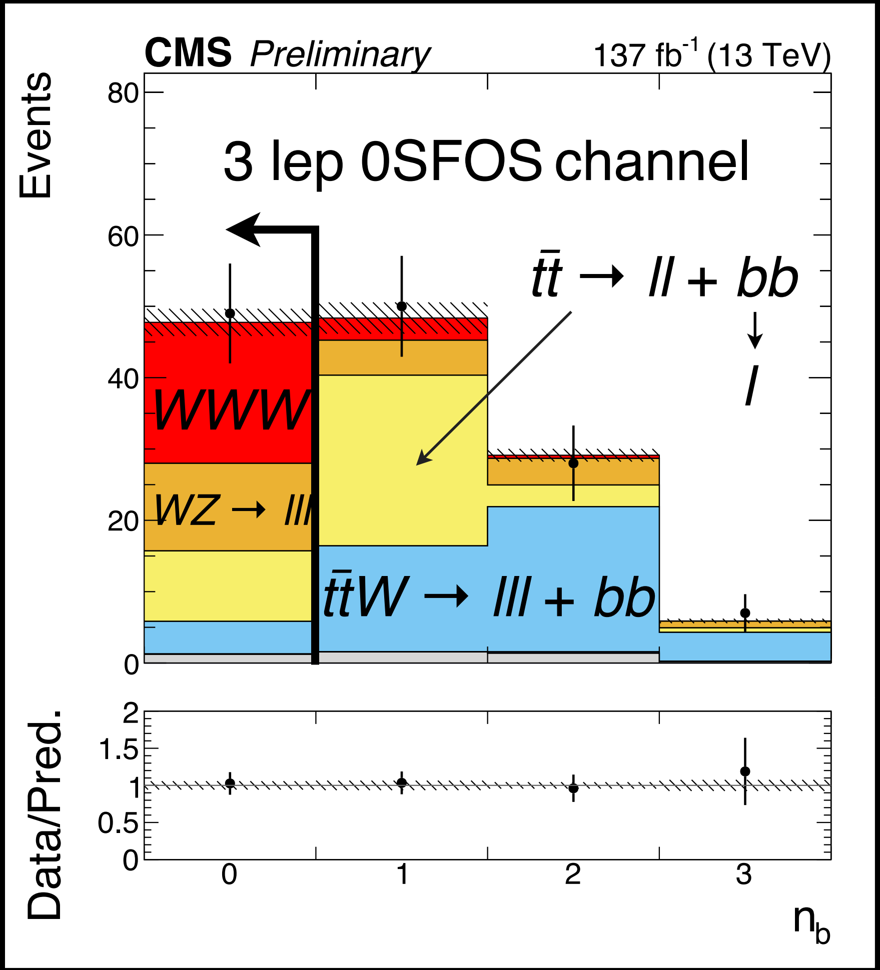
Reject N_b = 0 events to reduce $t\bar{t}$+X backgrounds

Added benefit of rejecting events with b

- Fake leptons mainly come from b jets
- Major source of b jets is $t\bar{t}$
- ⇒ **Rejecting $t\bar{t}$ reduces fake lepton**



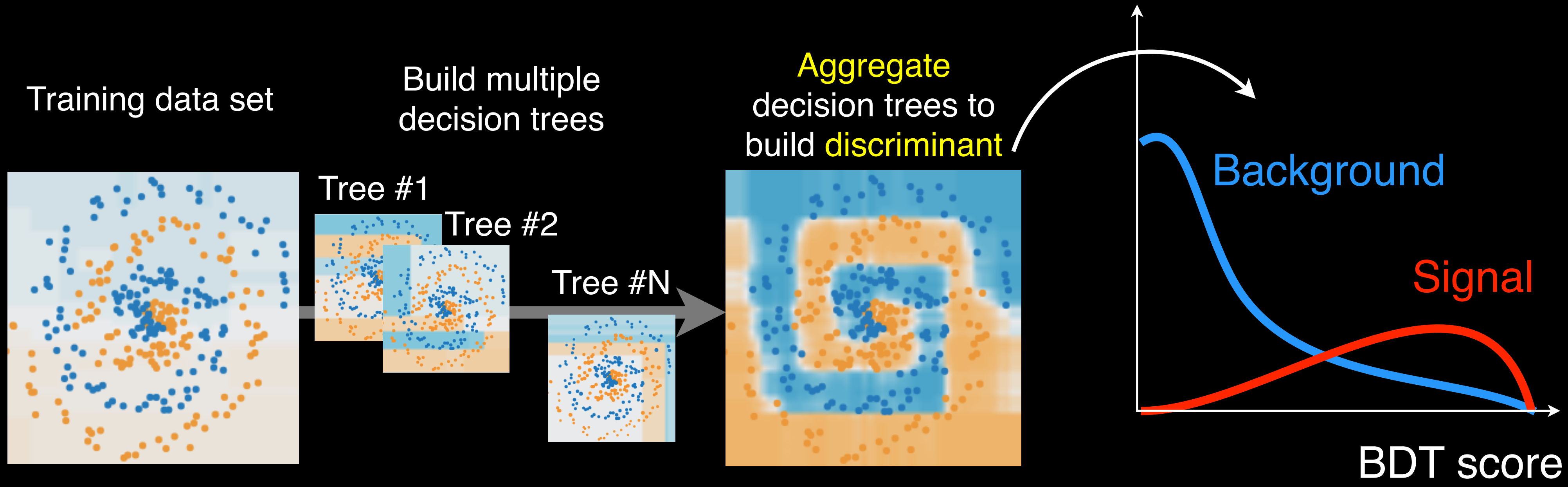
After 0SFOS preselection



Rejecting $N_b = 0$ events also reduces fake lepton bkgs.

Boosted decision tree

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

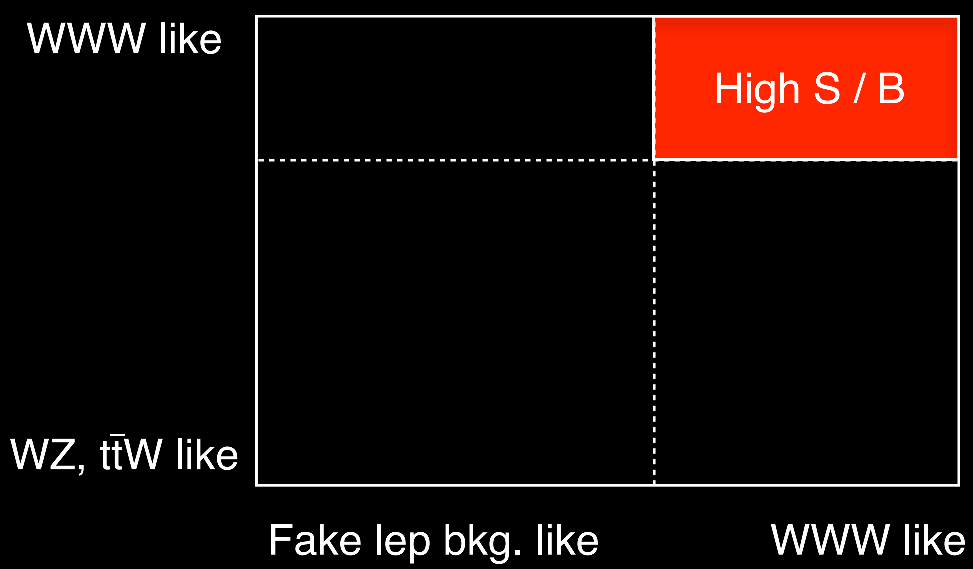


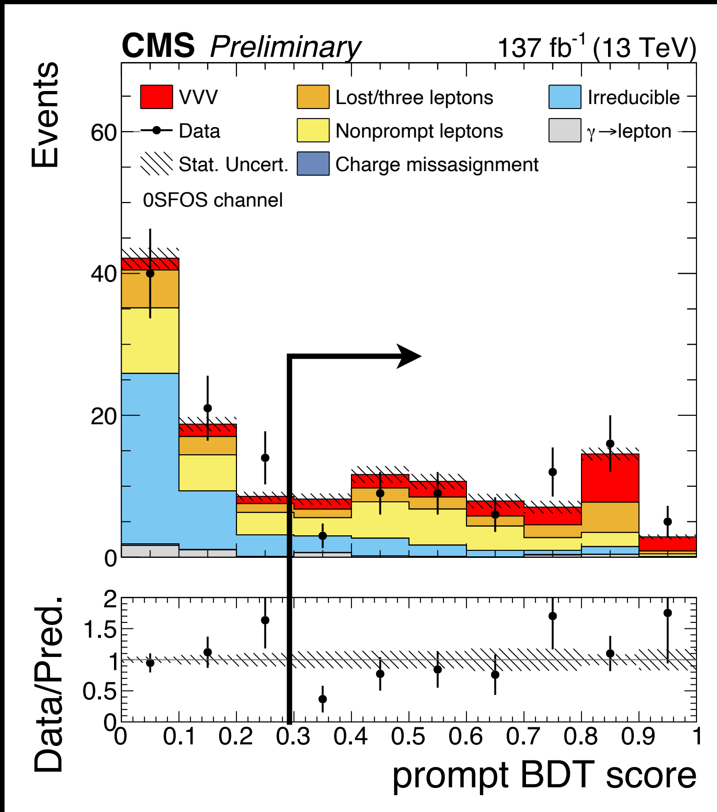
https://arogozhnikov.github.io/2016/07/05/gradient_boosting_playground.html

Train dedicated BDTs to maximize sensitivity

Applying BDT method to 0SFOS

- 10+ kinematics variables used to train BDT
- Two different bkg categories were targeted
  - Fake lepton backgrounds
  - "Prompt backgrounds" (e.g. WZ, $t\bar{t}W$)





2D BDT used to maximize sensitivity

Summary of 0SFOS channel

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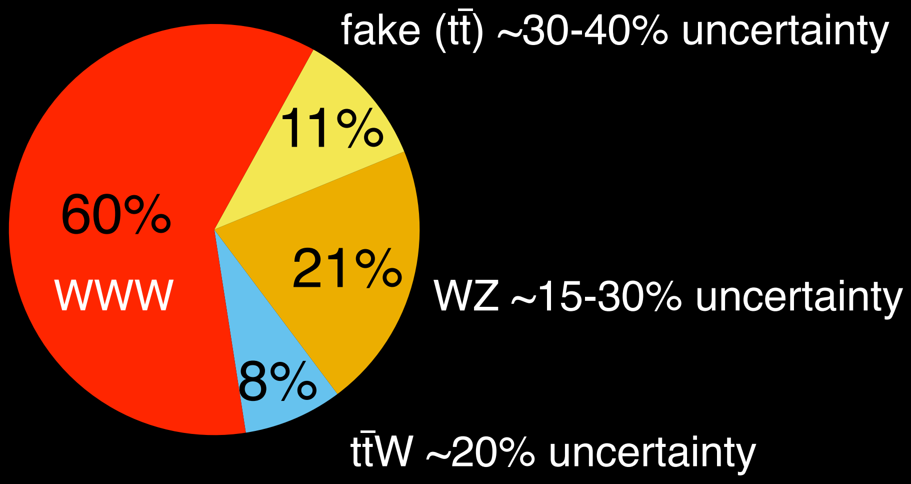
WWW	Fake	WZ	$t\bar{t}W$	Total B	S / B
10.1	1.8	3.5	1.3	6.6	1.5

cf. 700 total WWW → 3l

- 10 WWW events
- Statistics limited
- But systematics are becoming important
- 0SFOS sensitivity ~2.8 σ
- WWW sensitivity 3.1 σ (combined with other channels)

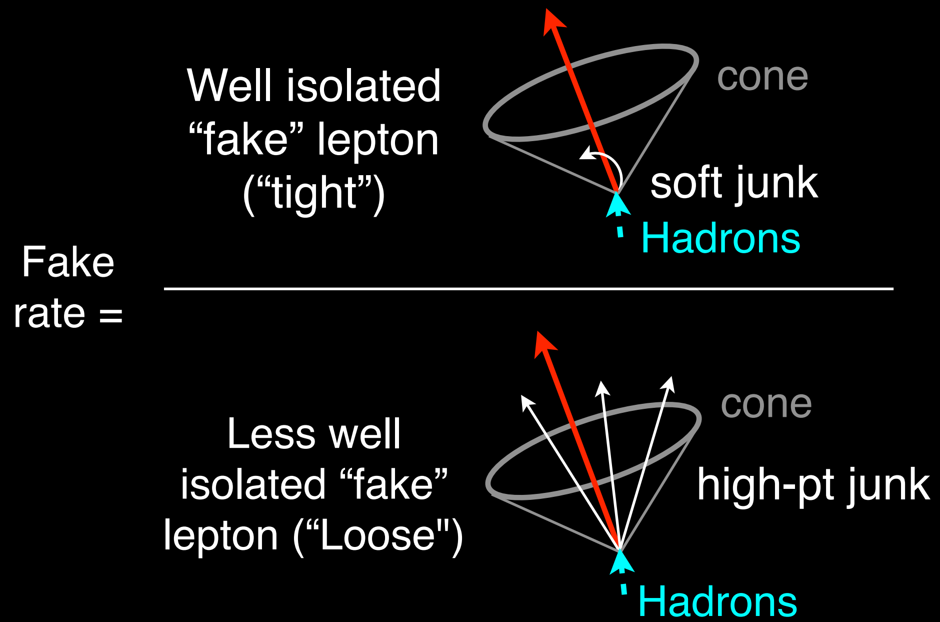
0SFOS composition

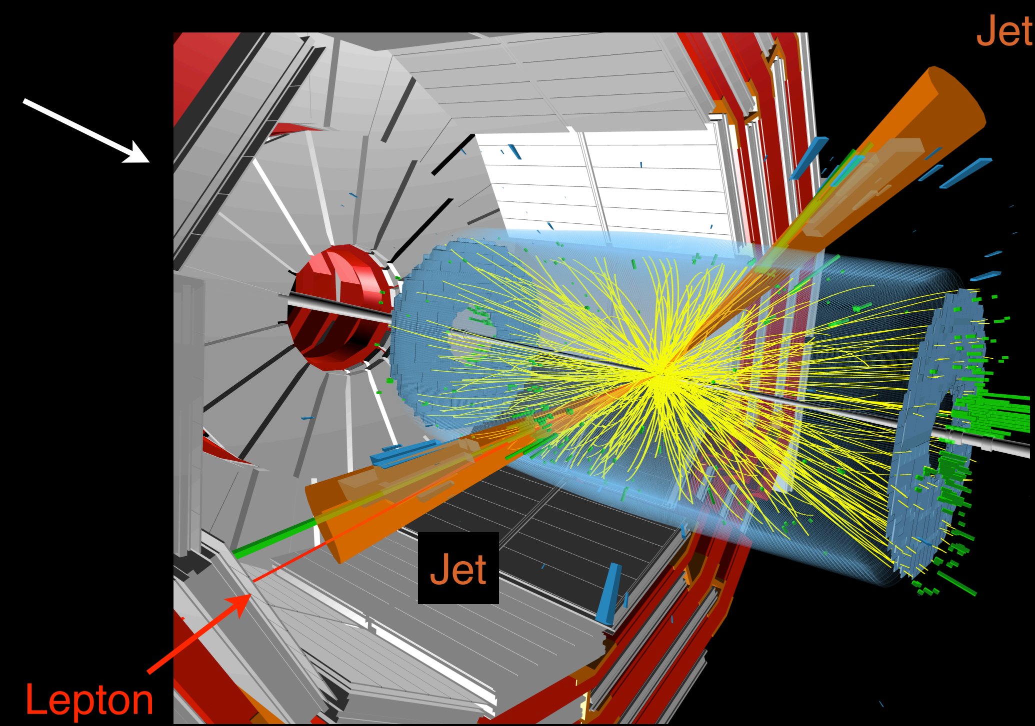


WWW expected sensitivity of 3.1 σ

Fake lepton backgrounds

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





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

"Side band" in isolation

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

⇒ Source of systematics (~30-40%)

Estimate fake lep bkg. via fake rate from QCD events

Additional fake background rejection

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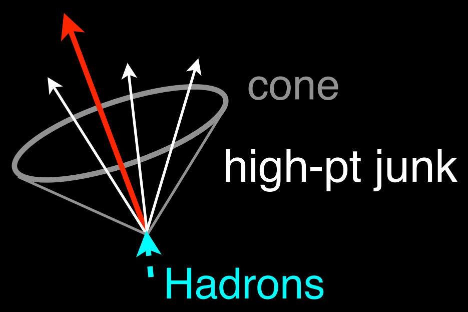
Standard Isolation = $\dfrac{\Sigma_{\text{“stuff” in cone}} P_T}{P_{T,\text{Lepton}}}$

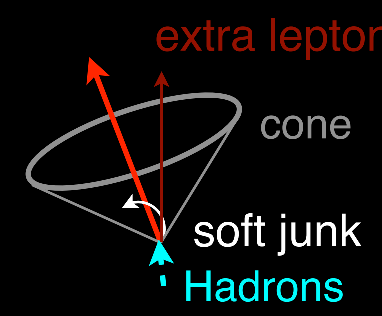
Neutral hadron, charged hadron, neutral EM components are included but not extra leptons

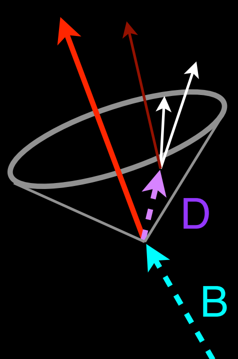
Less well isolated “fake” lepton (“Loose")



Cutting hard on standard isolation biases fake leptons to have extra leptons

Well isolated “fake” lepton (“tight”)





extra lepton primarily comes from D decay

$\Rightarrow$

Modified Isolation = $\dfrac{\Sigma_{\text{“stuff”+extra leptons in cone}} P_T}{P_{T,\text{Lepton}}}$

Developed custom isolation to further reject fake lepton

Kinematic endpoints for Z + $e\mu$ (4 lepton)

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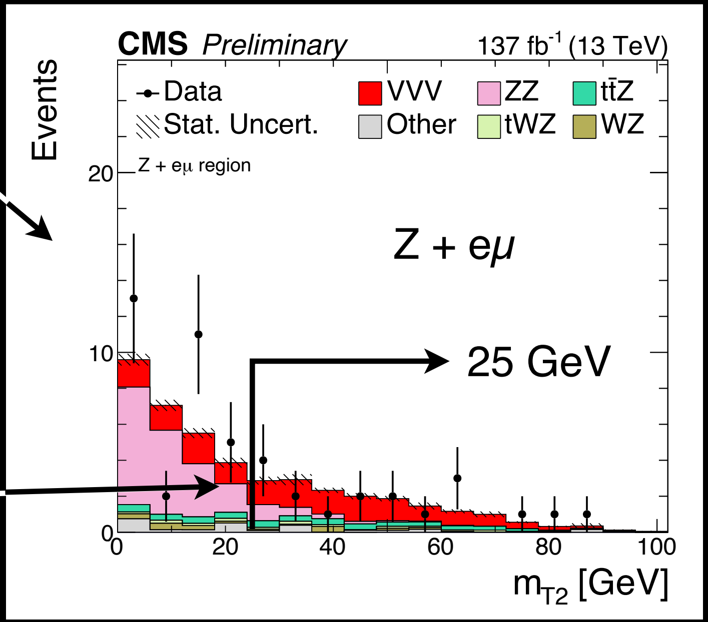
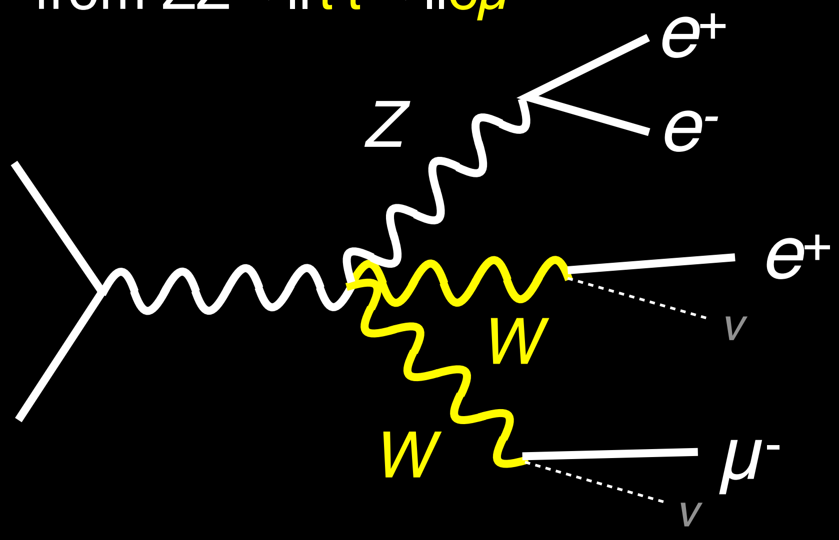
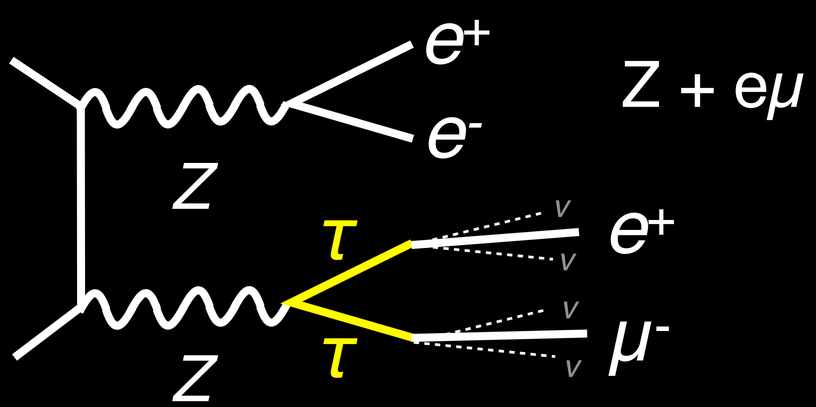
- As expected ZWW v. ZZ ~same order
- $t\bar{t}Z$ suppressed via b tagging
- Utilize m_{T2} variable
- m_{T2} is sensitive to the end points of m_W from ZWW→ll$e\mu$
- m_{T2} is sensitive to the end points of m_τ from ZZ→llττ→ll$e\mu$







Exploit differences between Z → ll v. WW → lvlv

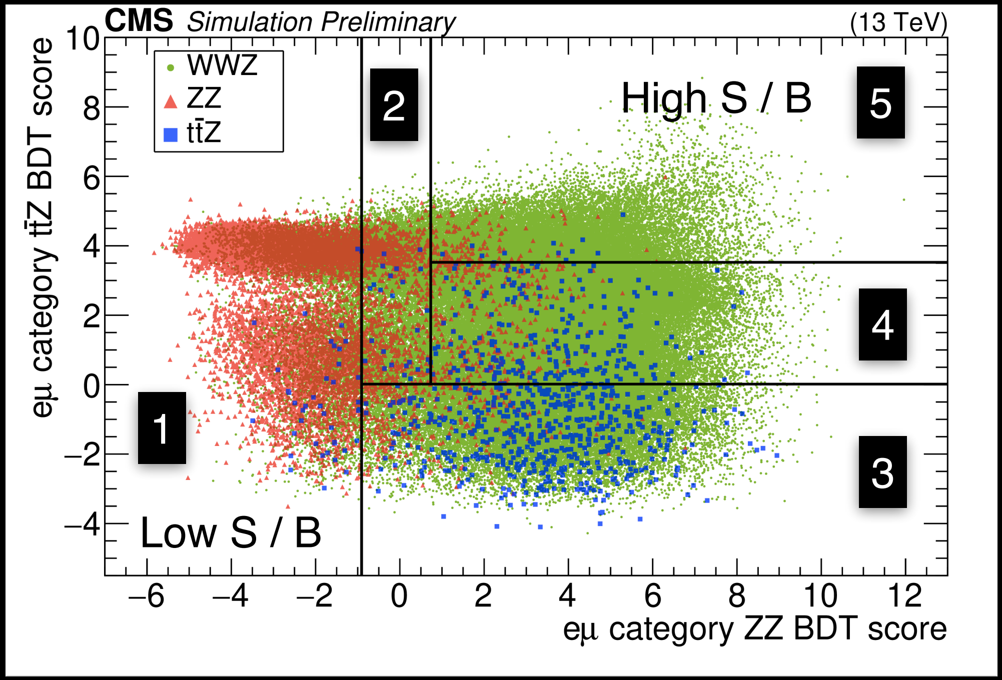
Applying BDT method to Z + $e\mu$ channel

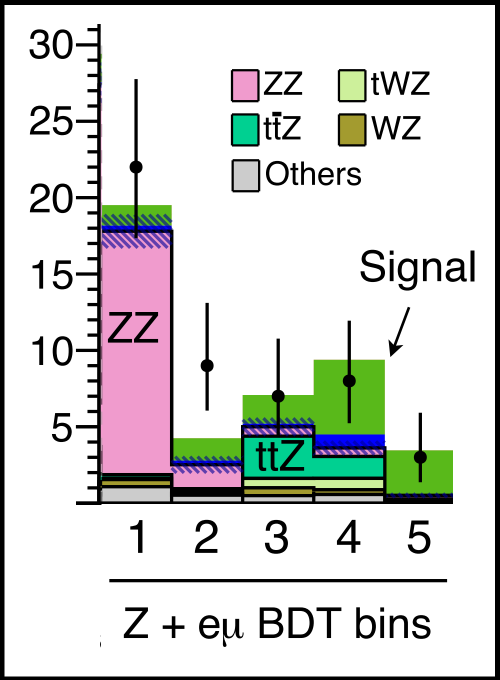
Trained two BDTs: WWZ v. ZZ and WWZ v. ttZ
Below shows the 2D plane in BDT scores

5 bins are created from 2D planes

More WWZ like

More $t\bar{t}Z$ like





More ZZ like ⟷ More WWZ like

2D BDT used to maximize sensitivity

Summary of Z + eμ

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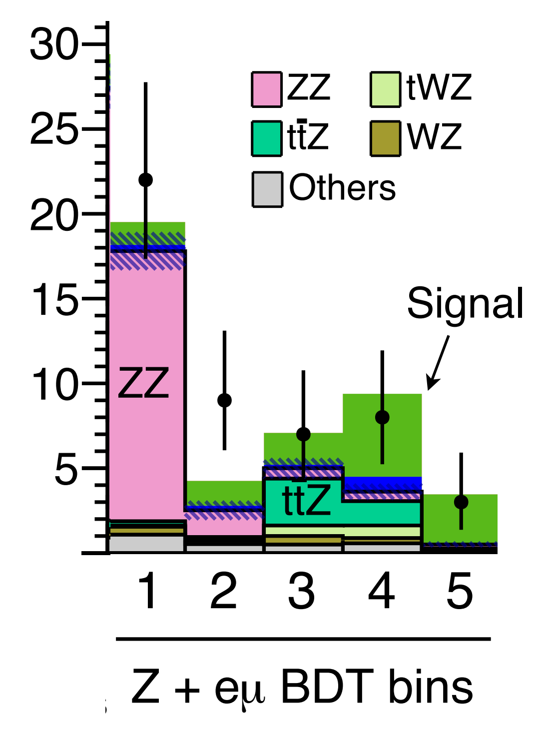
UCSD

BDT #	WWZ	ZZ	ttZ	tWZ	WZ	Total B	S / B
5	2.9	0.2	0.1	0.1	0.1	0.5	5.8
4	4.9	0.6	1.4	0.7	0.3	3.6	1.4

cf. 700 total WWZ → 150

- Statistics limited
- Main backgrounds are ZZ and $t\bar{t}Z$
  - ZZ ~5% uncertainty
  - $t\bar{t}Z$ ~30% uncertainty
- Z + e*μ* sensitivity ~4 σ
- Combined WWZ sensitivity 4.1 σ



WWZ expected sensitivity of 4.1 σ

WWZ event candidate (Z + eμ channel)

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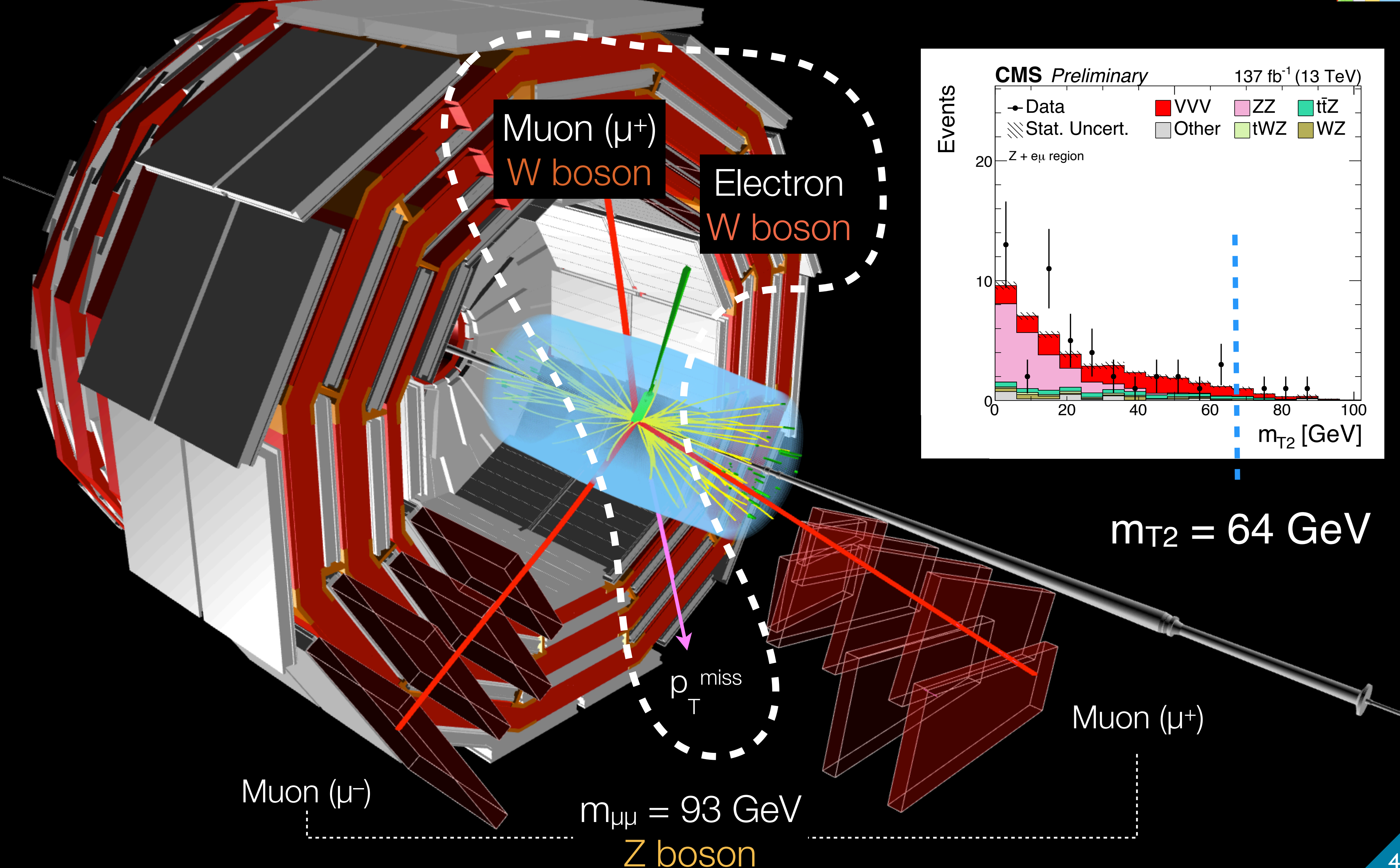
CMS experiment at the LHC, CERN
Data recorded: 2016-Jul-23 08:13:27.898048 GMT
Run 277168, Event No. 3219714497 LS 1799



ZZ and $t\bar{t}Z$ bkg. control regions (CR)

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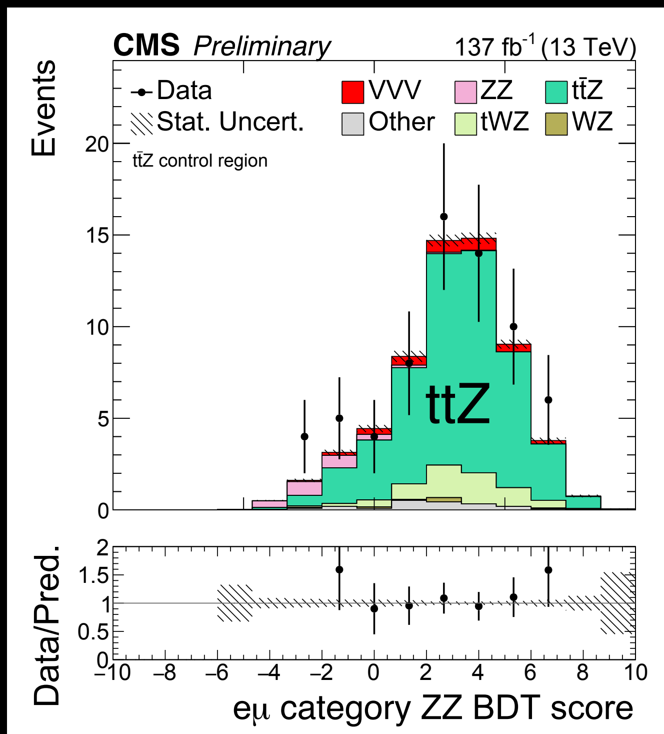
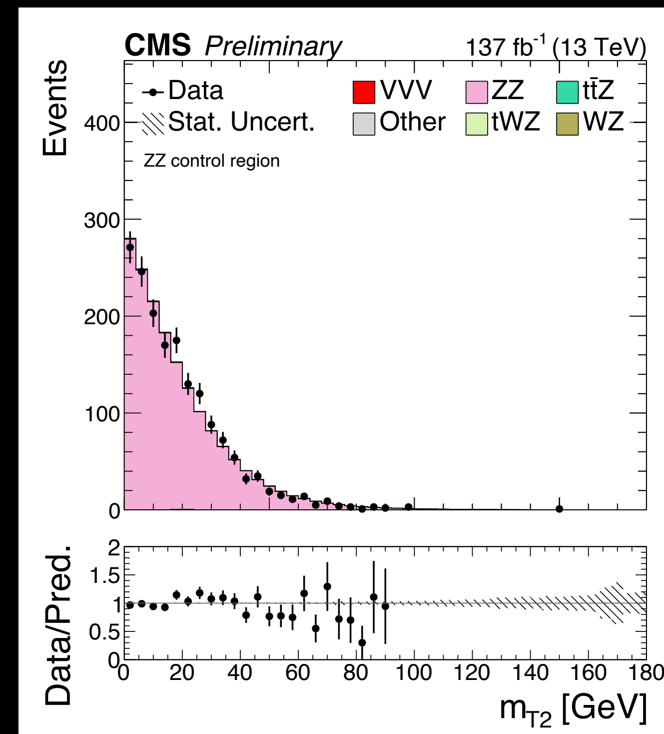
Devise control regions and extrapolate to signal region

$t\bar{t}Z$ CR (invert b jet veto requirement)



ZZ CR (invert "eμ selection")



Extrapolate across N_b tag (unc. ~10%)
Data statistical unc. dominates (unc. ~30%)

Extrapolate across flavor
(uncertainty ~5%)

Extrapolate from CR to estimate backgrounds

5 lepton event display

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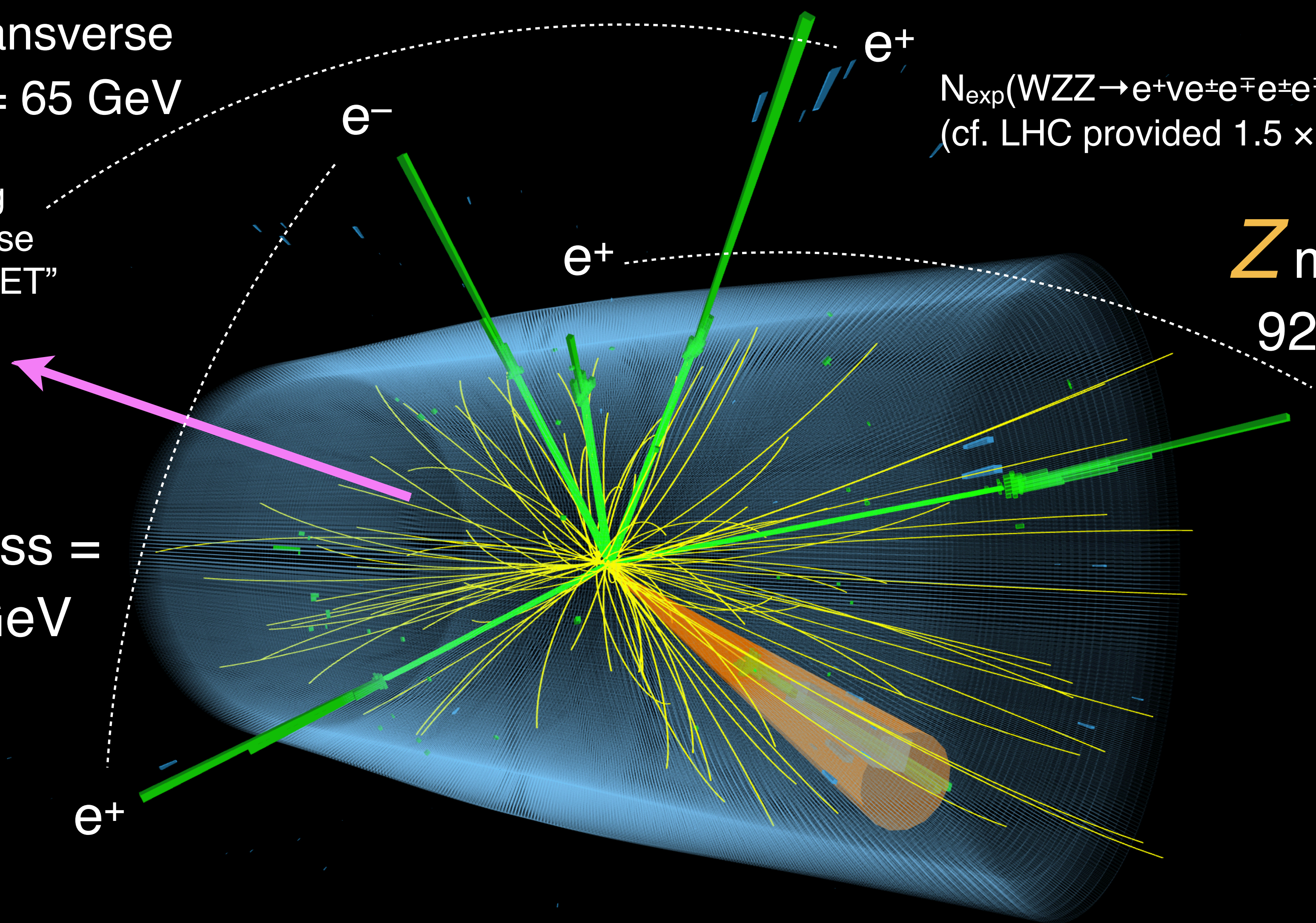
CMS experiment at the LHC, CERN
Data recorded: 2016-Oct-09 21:24:05.010240 GMT
Run 282735, Event No. 989682042 LS 491

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)



5 steps to VVV observation

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

2. ~~Categorize by flavor of the leptons~~

Smart humans and smart machines (Both cut / BDT)

3. ~~Additional background suppression through smart choices~~

4. ~~Reliably estimate the size of residual backgrounds~~

5. Observe VVV!

Putting it altogether

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	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \to l^\pm \nu$ $W^\pm \to l^\pm \nu$ $W^\mp \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
Total	9 bins	3 bins	7 bins	1 bin	1 bin
		0SFOS most sensitive	Z + eμ most sensitive	Single bin each	

- 21-bin fit w/ following scenarios:
  - All VVV signal combined with single signal strength
  - WWW, WWZ, WZZ, ZZZ w/ 4 different signal strength
- In both cases, also consider VH as signal v. background

21-bin fit; 2 signal scenarios: VVV combined, separate

Results (BDT-based analysis)

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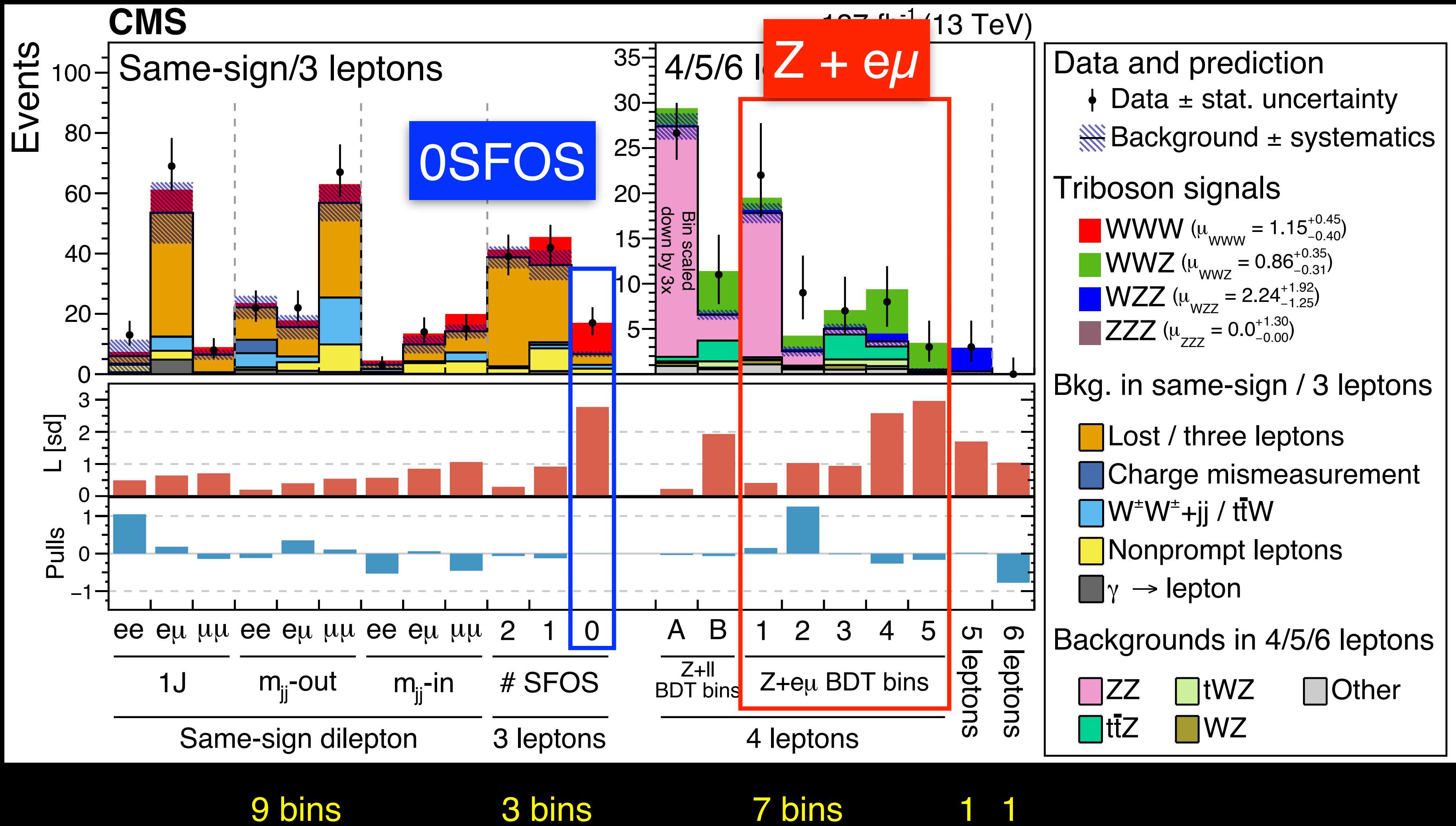
Signal strength $\mu = \frac{\text{Measured cross section}}{\text{Theoretical cross section}}$

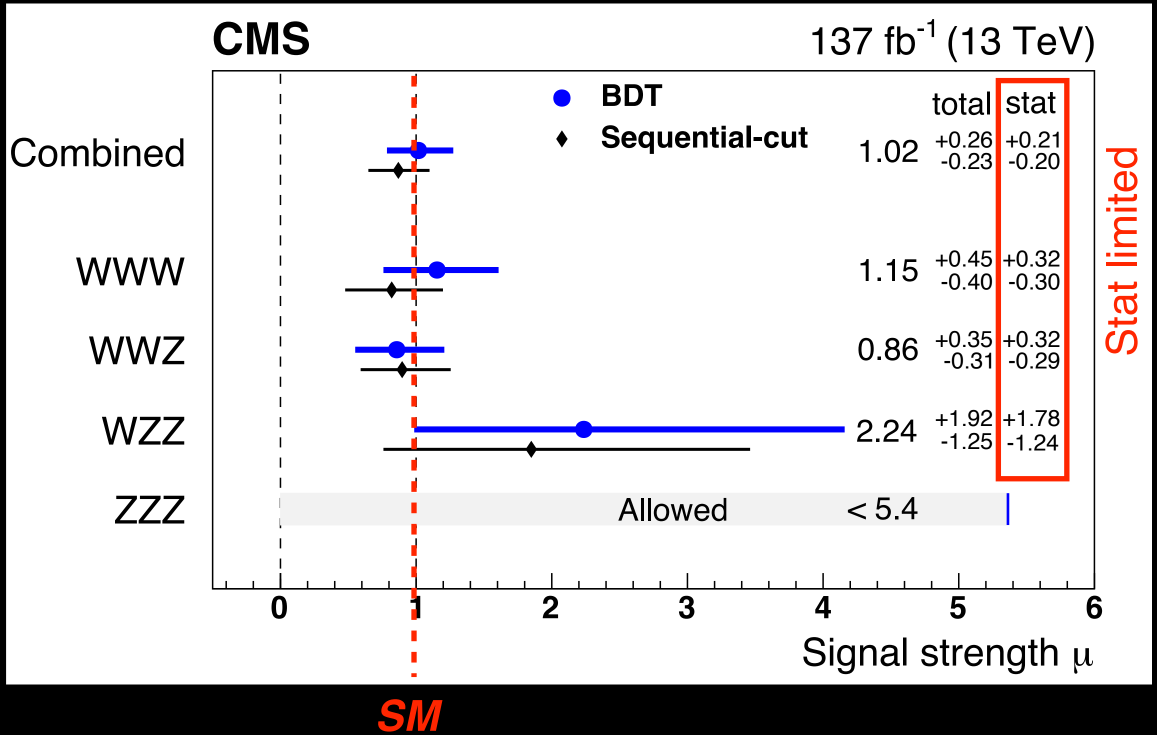


More sensitive bins are generally to the right

BDT-based analysis final result (cut-based backup)

O(10) events only
⇒ measure total cross section

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



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

- 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 VVV observation VVV and WWW, WWZ evidence

Using VVV as a tool

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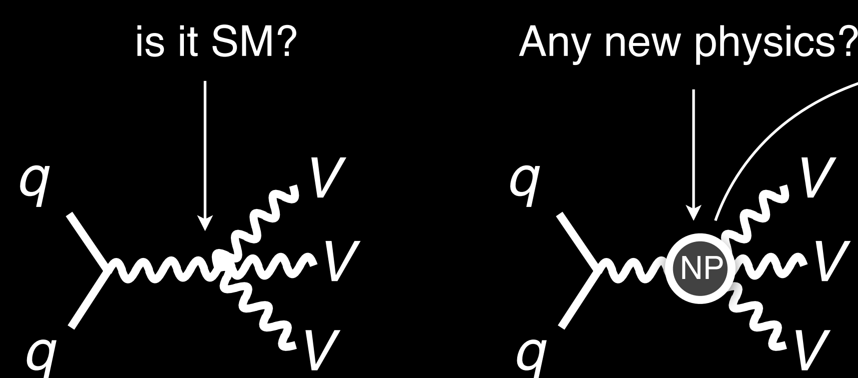
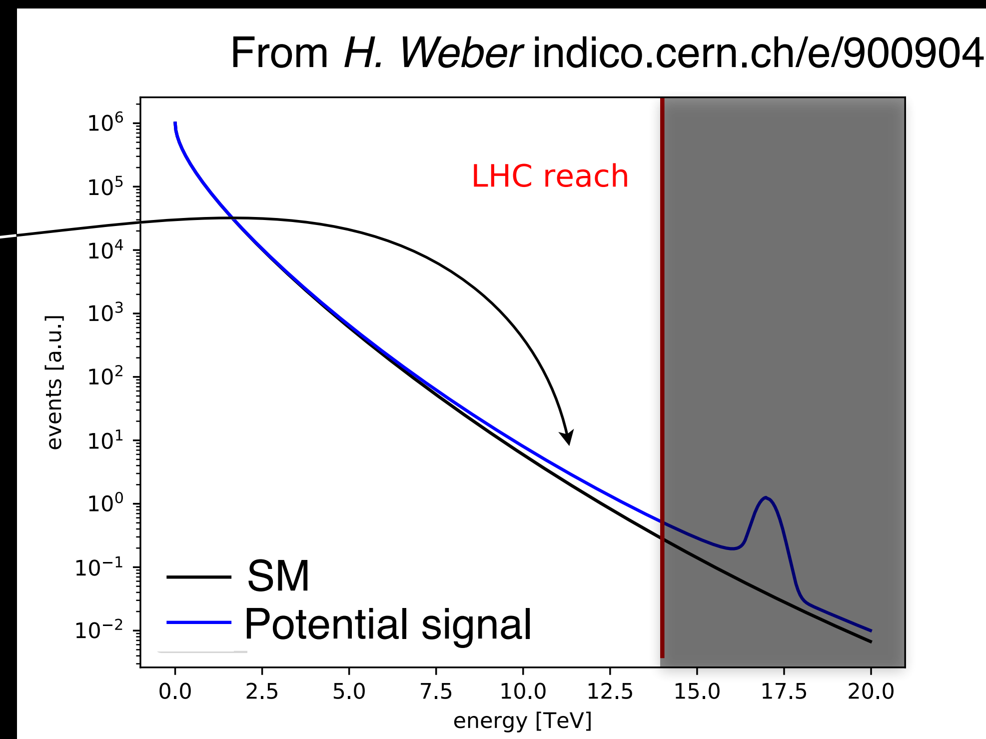
Now that we have established VVV production we can use it to test SM and also search new physics (cf. Four fermion interaction with Fermi constant)





Establishment of VVV opens up a new physics program

Uncovered semi-leptonic final states

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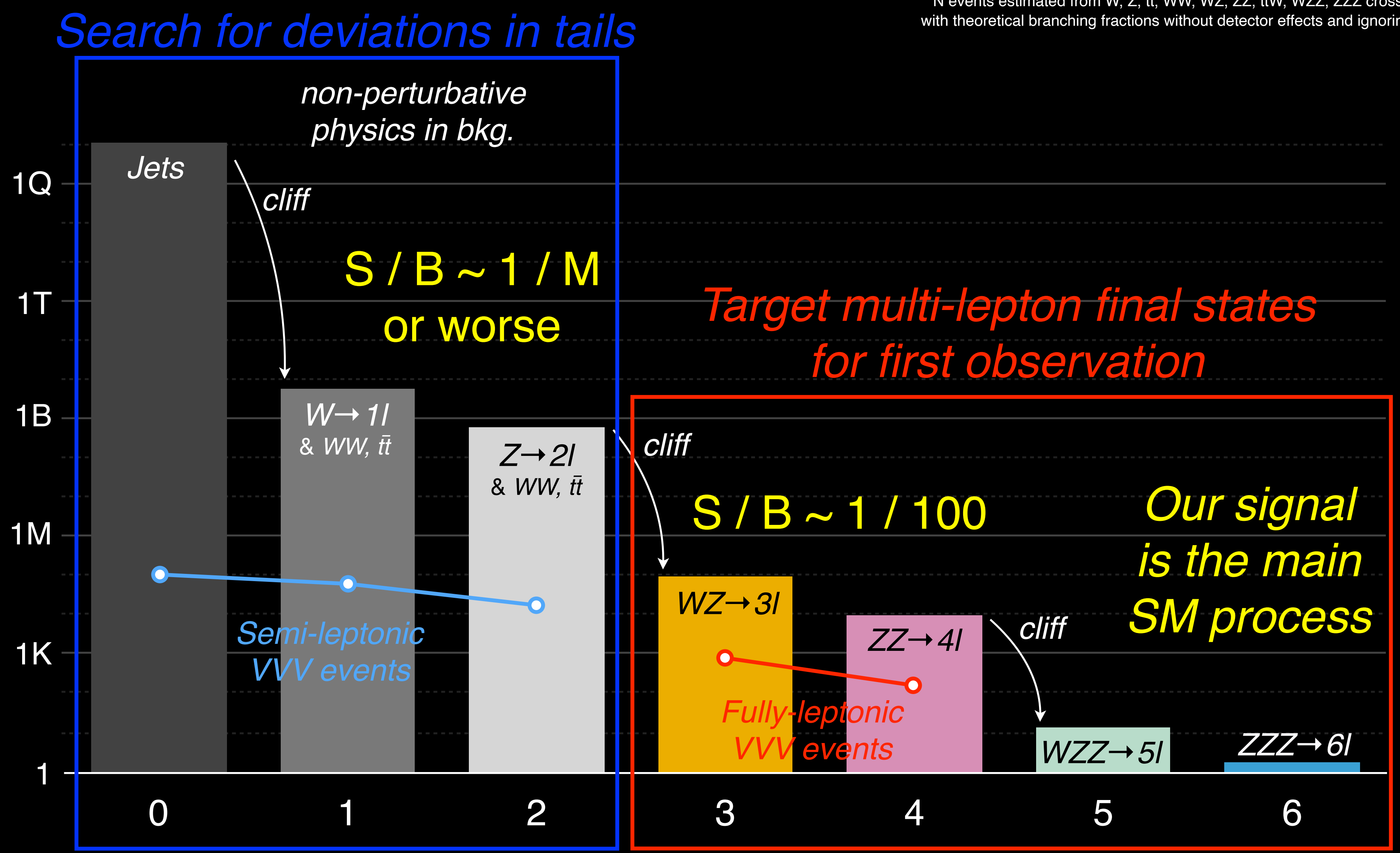
**N events estimated from W, Z, tt̄, WW, WZ, ZZ, tt̄W, WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring τ → e, μ



Target semi-leptonic final states for tail search

Fully leptonic v. Semi leptonic channel

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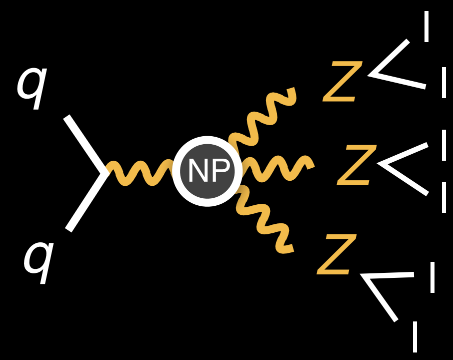
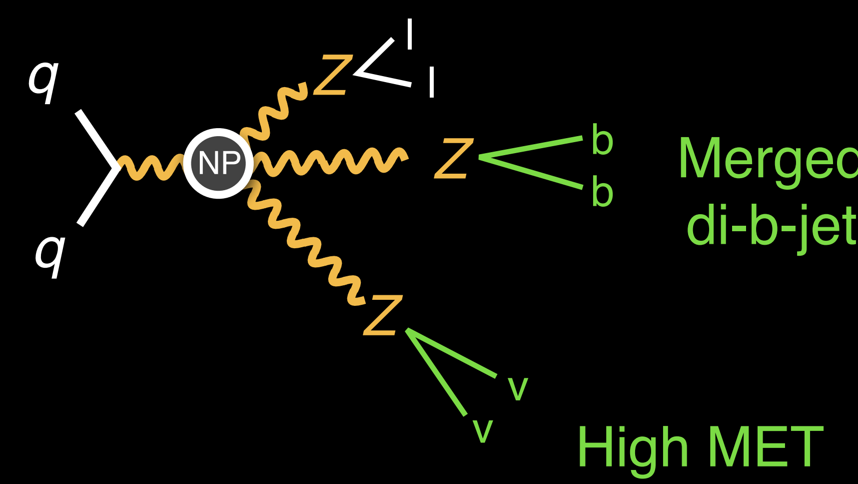
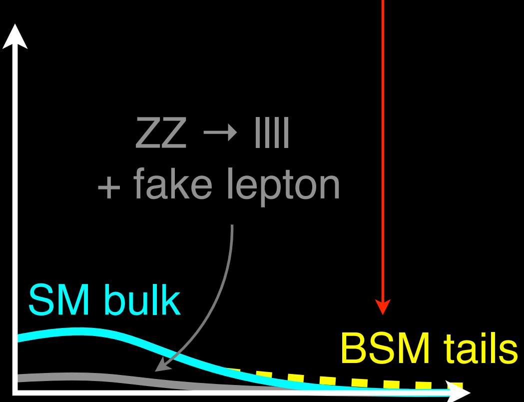
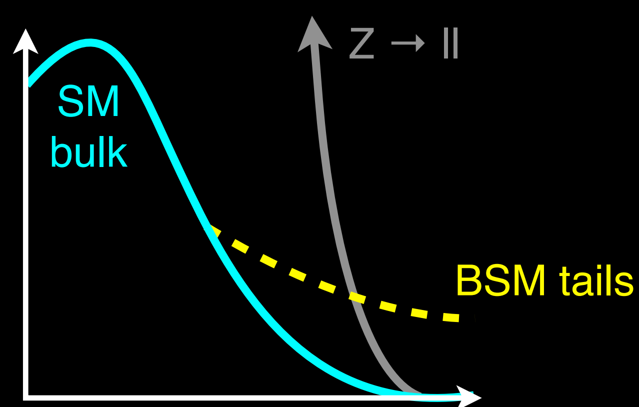


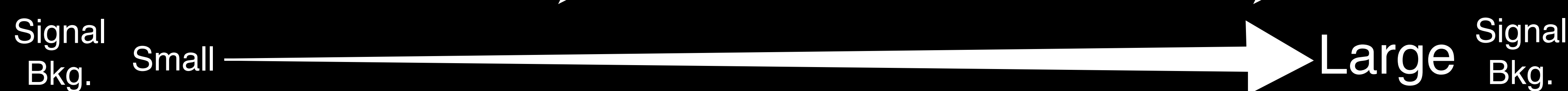


Clean channel for discovery but probing tail is difficult

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







NP effects could be exploited in semi-leptonic channels

HL-LHC

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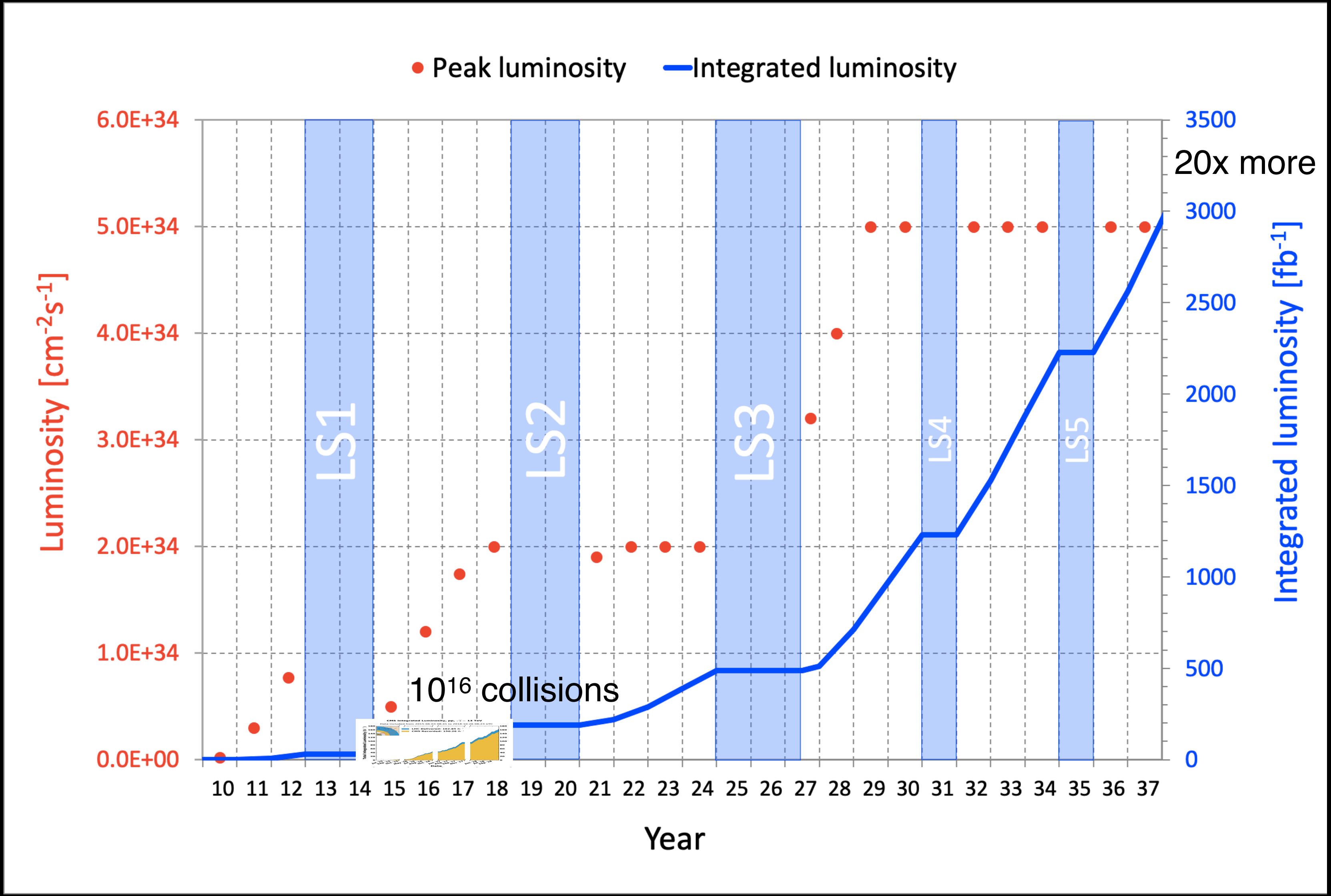


We've only seen ~5% of the total planned LHC data

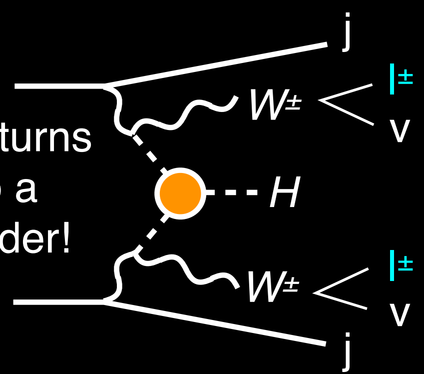
Future multi-boson analyses

arXiv:1812.09299 Henning, Lombardo, Riembau, Riva
arXiv:1511.03674 Dror, Farina, Salvioni, Serra
arXiv:1904.05637 Maltoni, Mantani, Mimasu
arXiv:2006.09374 Stolarski, Wu
arXiv:2009.01249 LHC Higgs WG Note

listing a few additional rare multi-boson processes

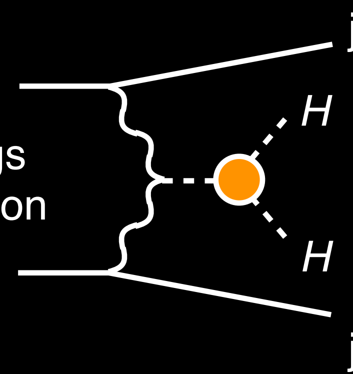
$pp \to W^{\pm}W^{\pm}H\,jj$

Same-sign turns LHC into a Higgs collider!



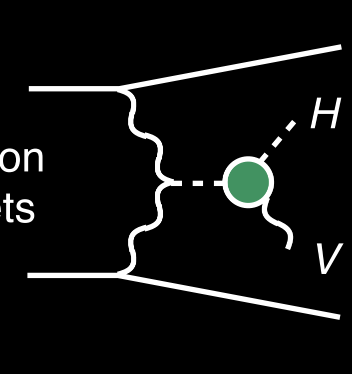
$pp \to HH\,jj$

Di-higgs production



$pp \to VH\,jj$

VH production with VBS jets



Rich set of final states to cover w/ LHC data set

Future multi-~~boson~~ massive-X analyses

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arXiv:1812.09299 Henning, Lombardo, Riembau, Riva
arXiv:1511.03674 Dror, Farina, Salvioni, Serra
arXiv:1904.05637 Maltoni, Mantani, Mimasu
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listing a few additional rare multi-~~boson~~ massive-X processes

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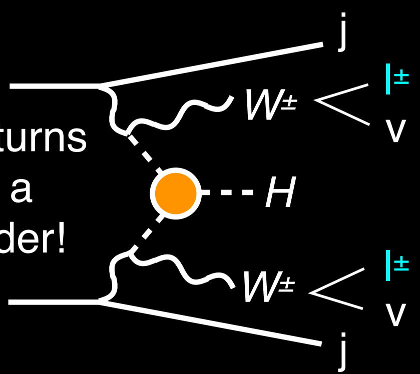
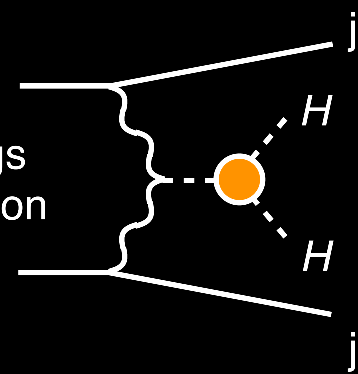


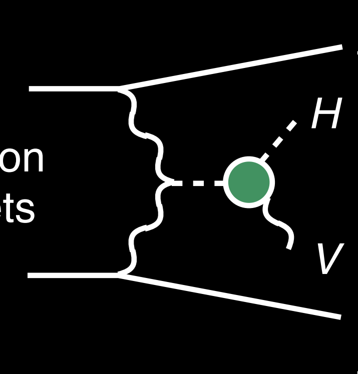
$pp \to HH\,jj$

Di-higgs production

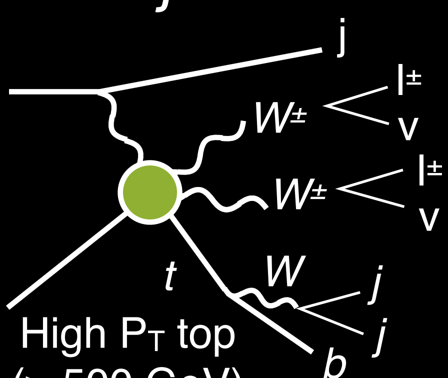


$pp \to VH\,jj$

VH production with VBS jets

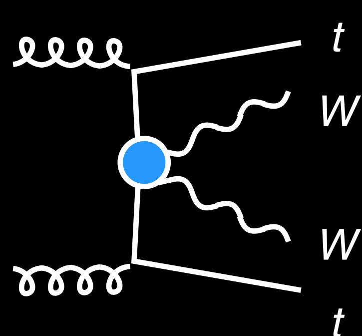


$pp \to tW^{\pm}W^{\pm}j$

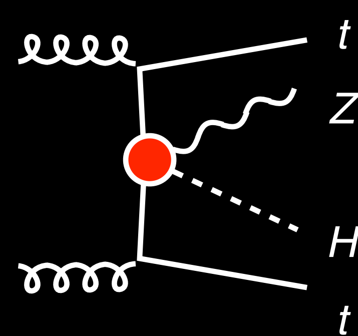


High P_T top (> 500 GeV)

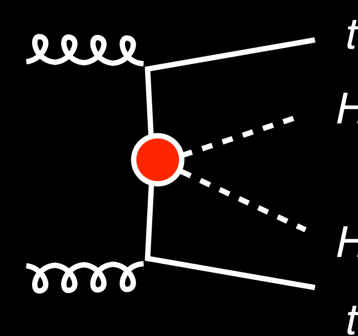
$pp \to ttWW$



$pp \to ttZH$



$pp \to ttHH$



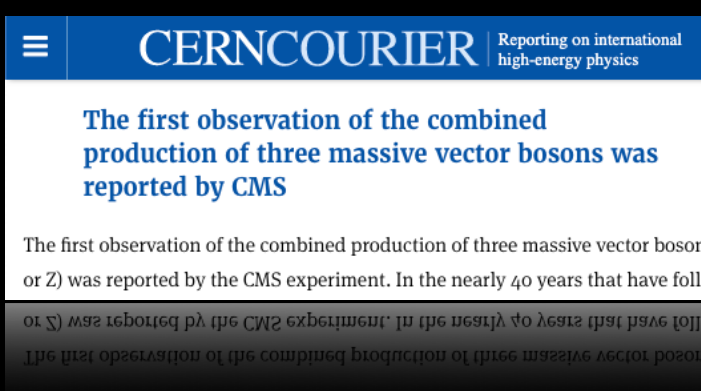
Rich set of final states to cover w/ LHC data set

Summary

- EW sector is complete, now we must understand EW sector
- To understand EW sector we study rare multi-boson production
- First observation of VVV productions was made by CMS collaboration
- Also found evidences for WWW and WWZ
- The measured cross section is compatible with SM
- LHC experiments will continue to probe various VVV channel
- Also LHC experiments will continue to search for new final states of rare multi-massive-particle processes

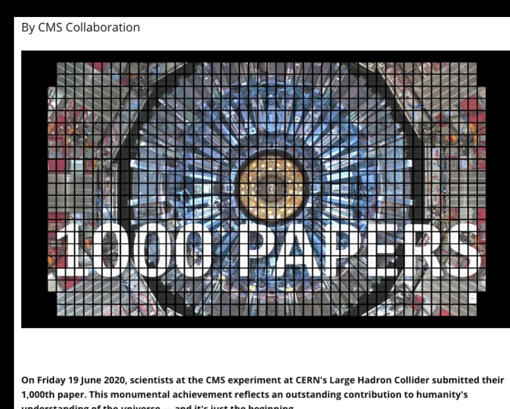
This paper is 1000th paper submitted by CMS!
Accepted as PRL editor's suggestions!

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

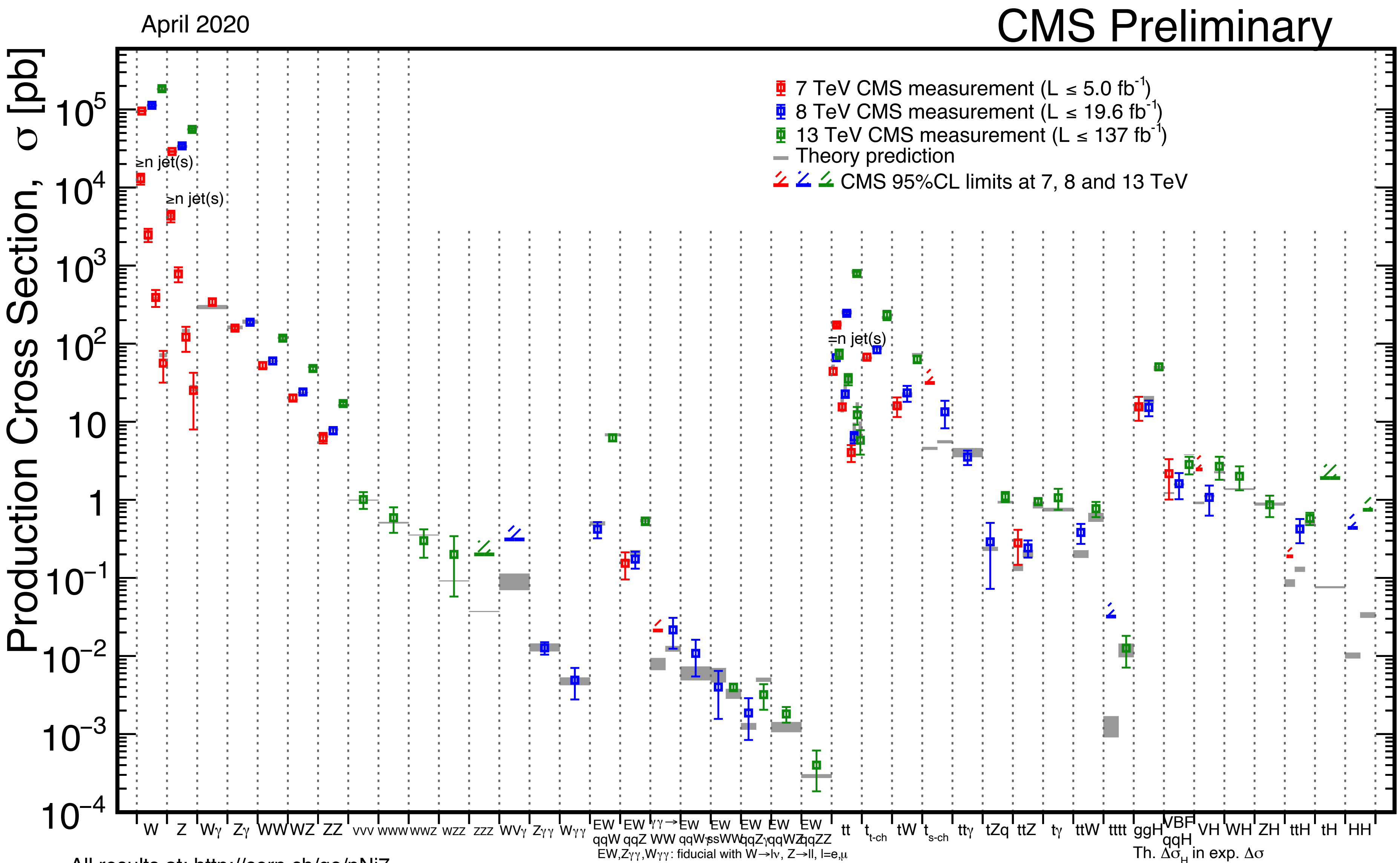
The first observation of the combined production of three massive vector boson
or Z) was reported by the CMS experiment. In the nearly 40 years that have foll



"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

Title



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

Title

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

SS / 3L preselection

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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		—
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert > 20$ GeV if $e^{\pm}e^{\pm}$		—
m_{SFOS}	—	—	$m_{SFOS} > 20$ GeV
m_{SFOS}	—	—	$\lvert m_{SFOS} - m_Z \rvert > 20$ GeV
$m_{\ell\ell\ell}$	—	—	$\lvert m_{\ell\ell\ell} - m_Z \rvert > 10$ 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	
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert > 20$ 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 $\lvert m_{jj} - 80\,\mathrm{GeV} \rvert \geq 15$ 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

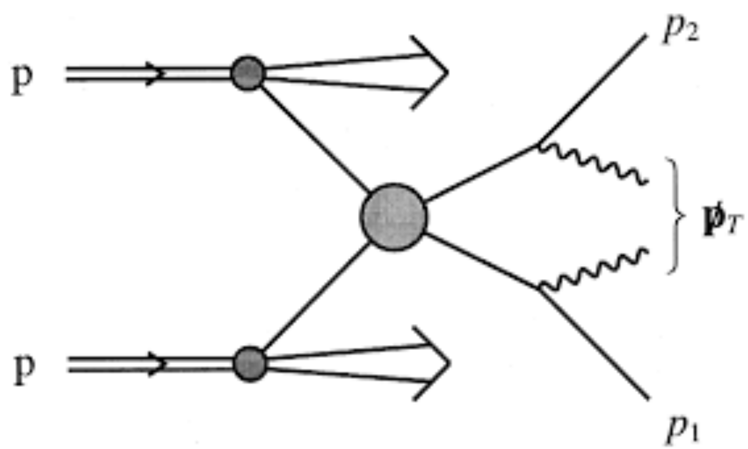
4L preselection

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

4L selection

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

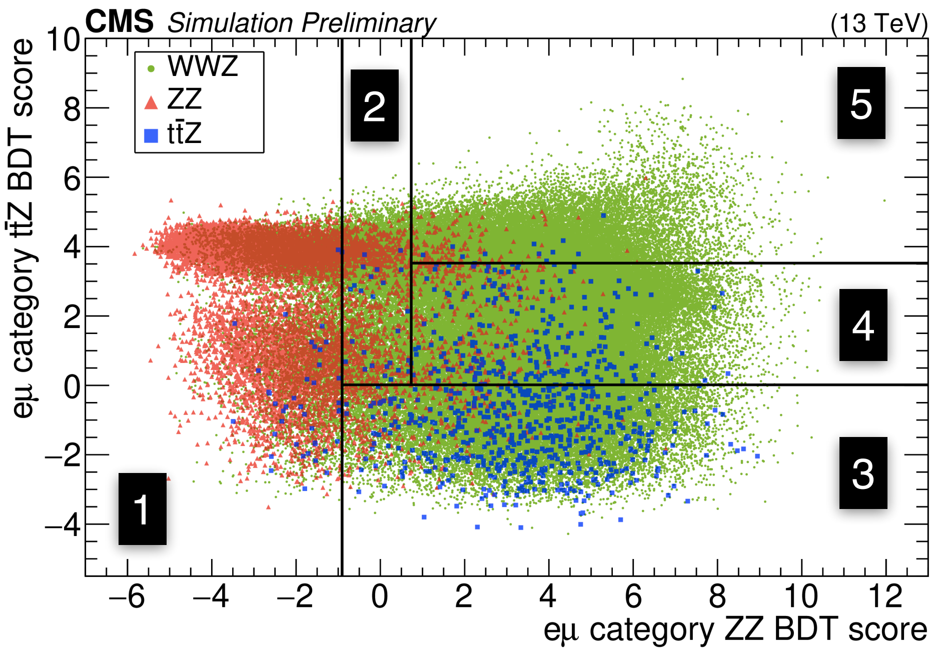
$$m_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\nu(1)} + \vec{p}_{\mathrm{T}}^{\nu(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max \left(m_{\mathrm{T}}^{(1)}(\vec{p}_{\mathrm{T}}^{\nu(1)}, \vec{p}_{\mathrm{T}}^{\mathrm{e}}), m_{\mathrm{T}}^{(2)}(\vec{p}_{\mathrm{T}}^{\nu(2)}, \vec{p}_{\mathrm{T}}^{\mu})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



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

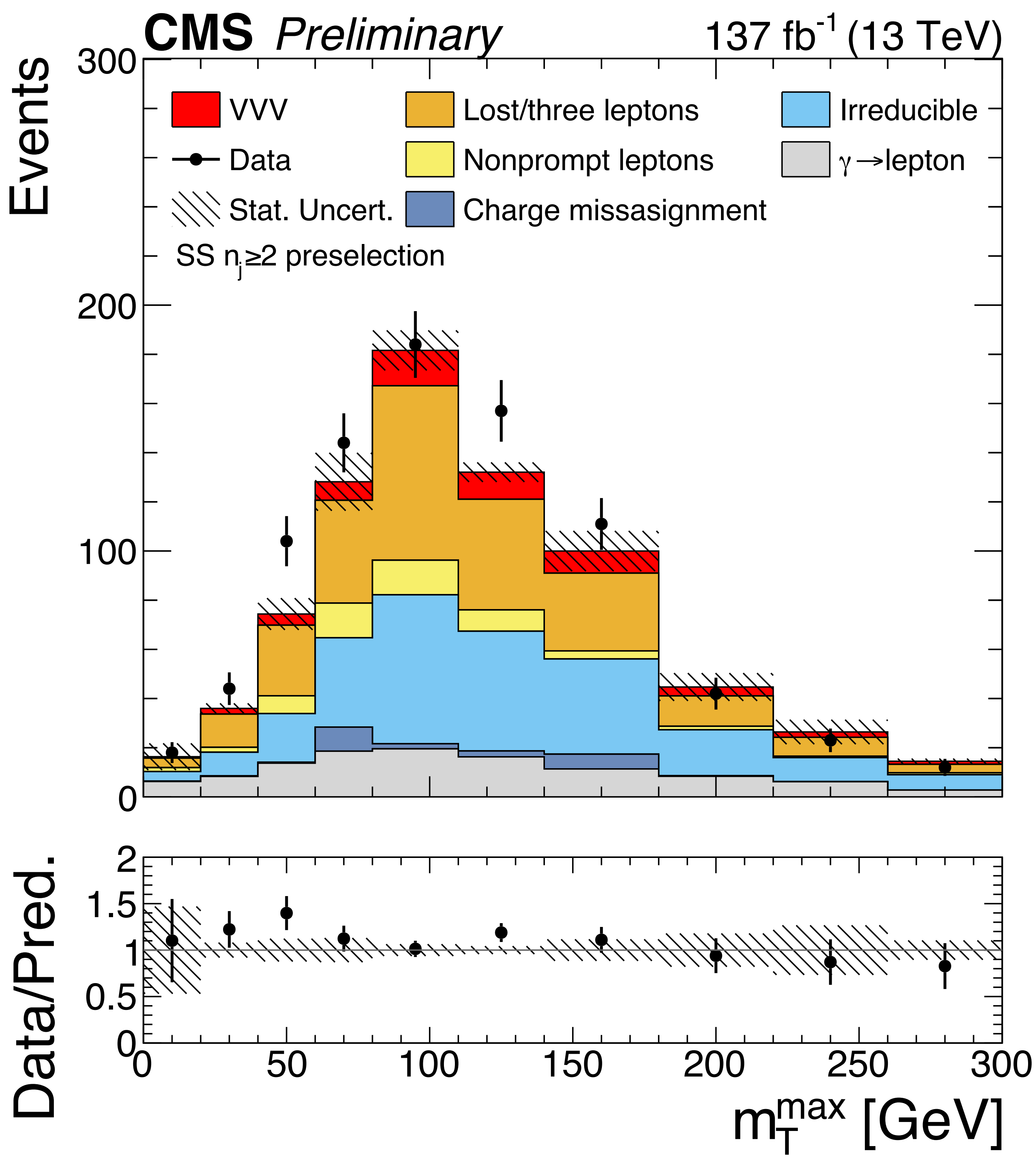
For Z→ττ→llvvvv sub-system of ZZ, endpoint is at m_τ

Title



	ZZ BDT range	$t\bar{t}Z$ BDT range
eμ BDT bin 1	(-∞, -0.908)	(-∞ , ∞)
eμ BDT bin 2	(-0.908 , ∞)	(-∞ , 0.015)
eμ BDT bin 3	(-0.908 , 0.733)	(0.015 , ∞)
eμ BDT bin 4	(0.733 , ∞)	(0.015 , 3.523)
eμ BDT bin 5	(0.733 , ∞)	(3.523 , ∞)
ee/$\mu\mu$ BDT bin A	(0 , 3)	-
ee/$\mu\mu$ BDT bin B	(3 , ∞)	-

Title



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Title

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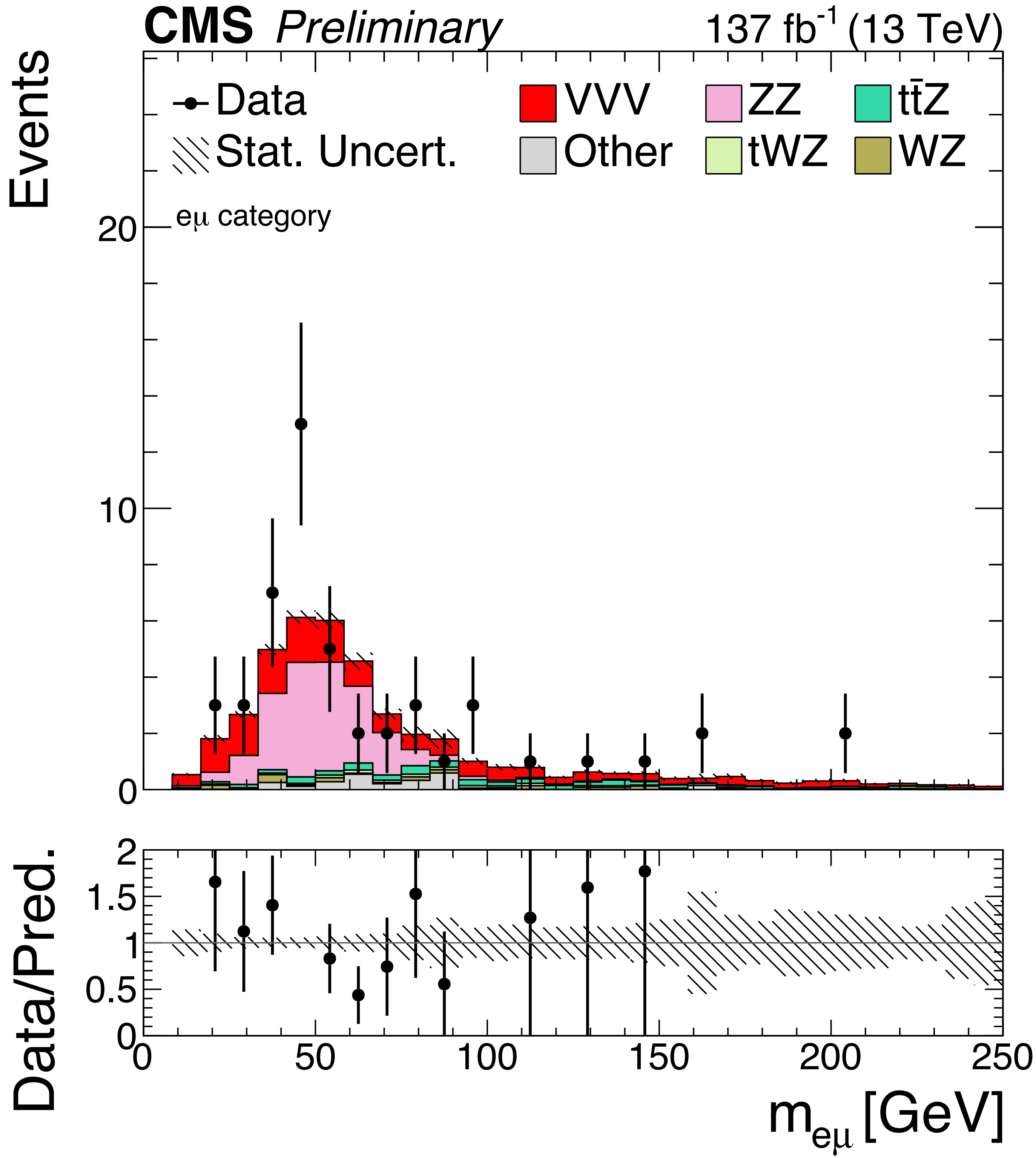

Title

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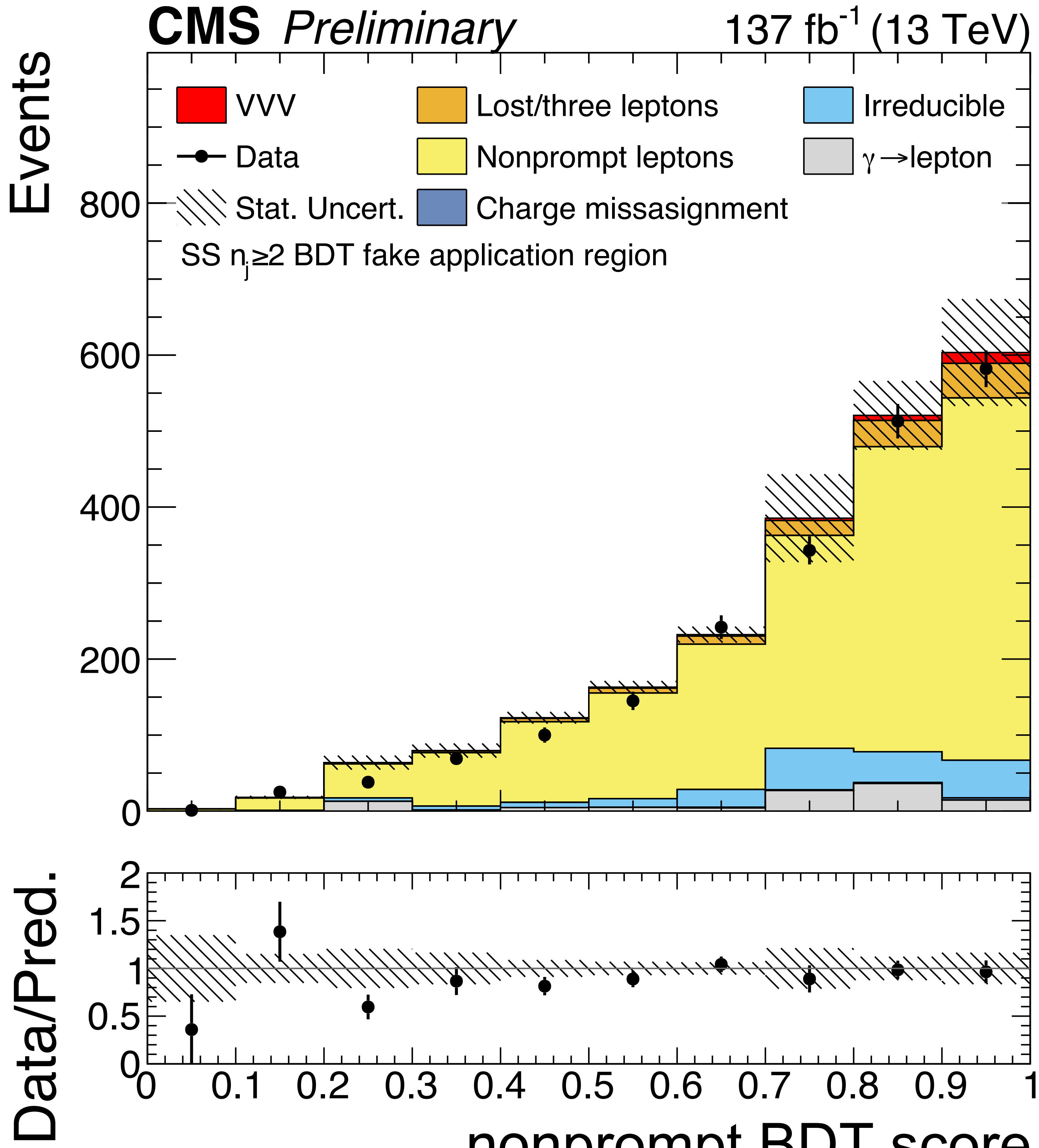

Title

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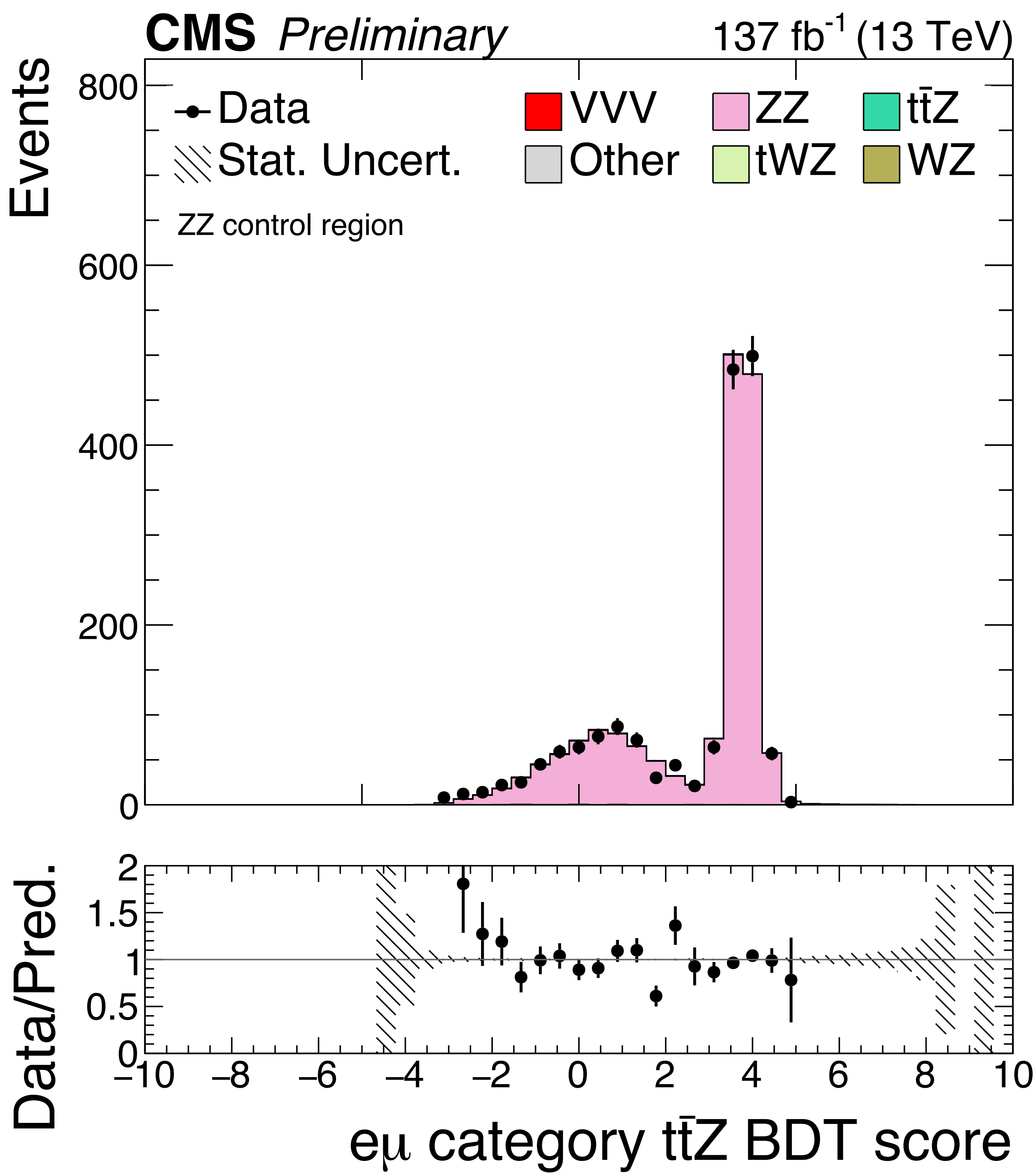
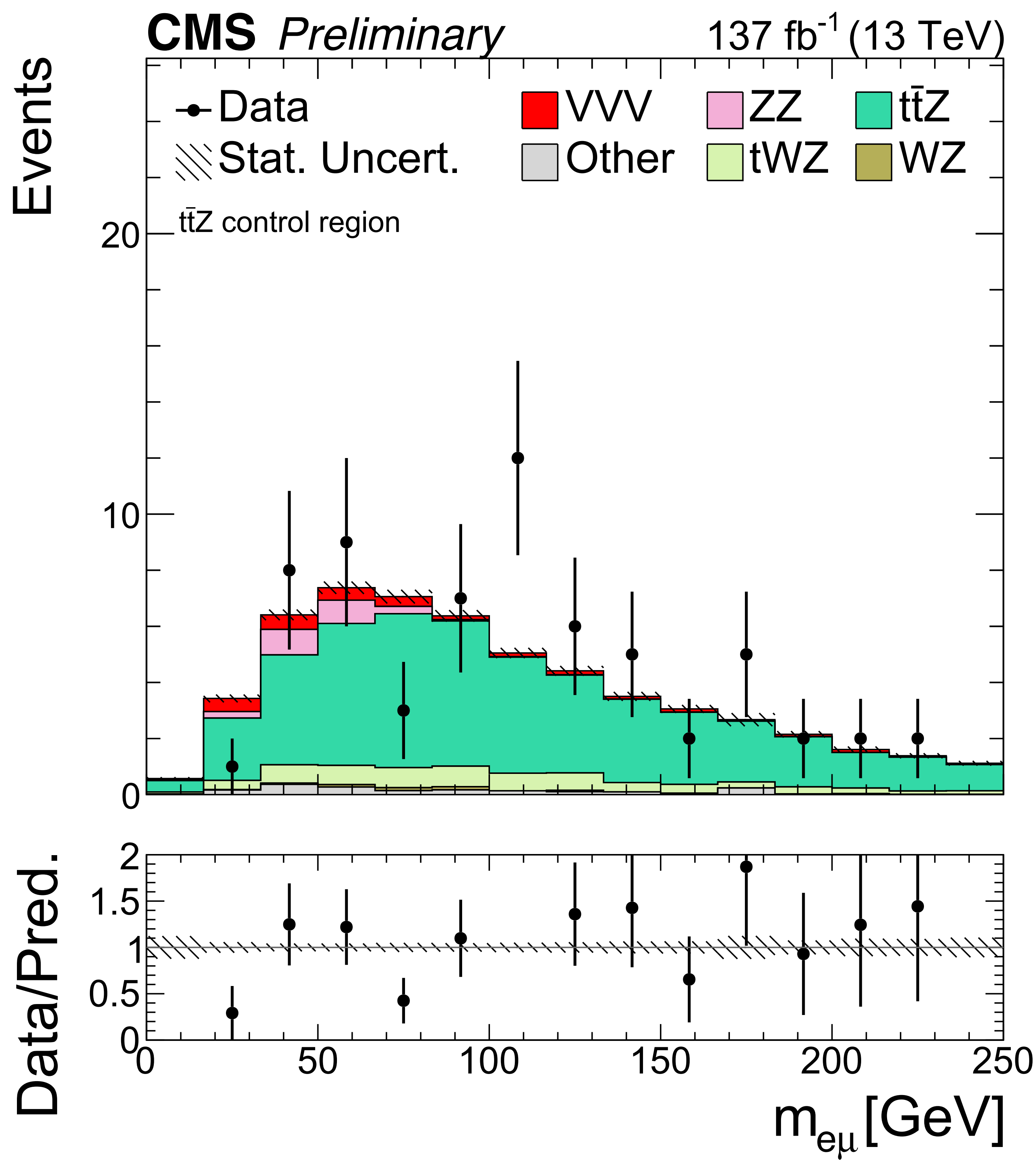


Title


CMS Preliminary
137 fb-1 (13 TeV)
Data
Stat. Uncert.
VVV
Other
ZZ
tWZ
tt̄Z
WZ
tt̄Z control region
Events
Data/Pred.
m_eμ [GeV]
0
10
20
0
0.5
1
1.5
2
0
50
100
150
200
250

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

Signal region	bin 1	bin 2	bin 3	bin 4	bin 5	bin A	bin B	5ℓ	6ℓ
	4ℓ $e\mu$					4ℓ ee/$\mu\mu$			
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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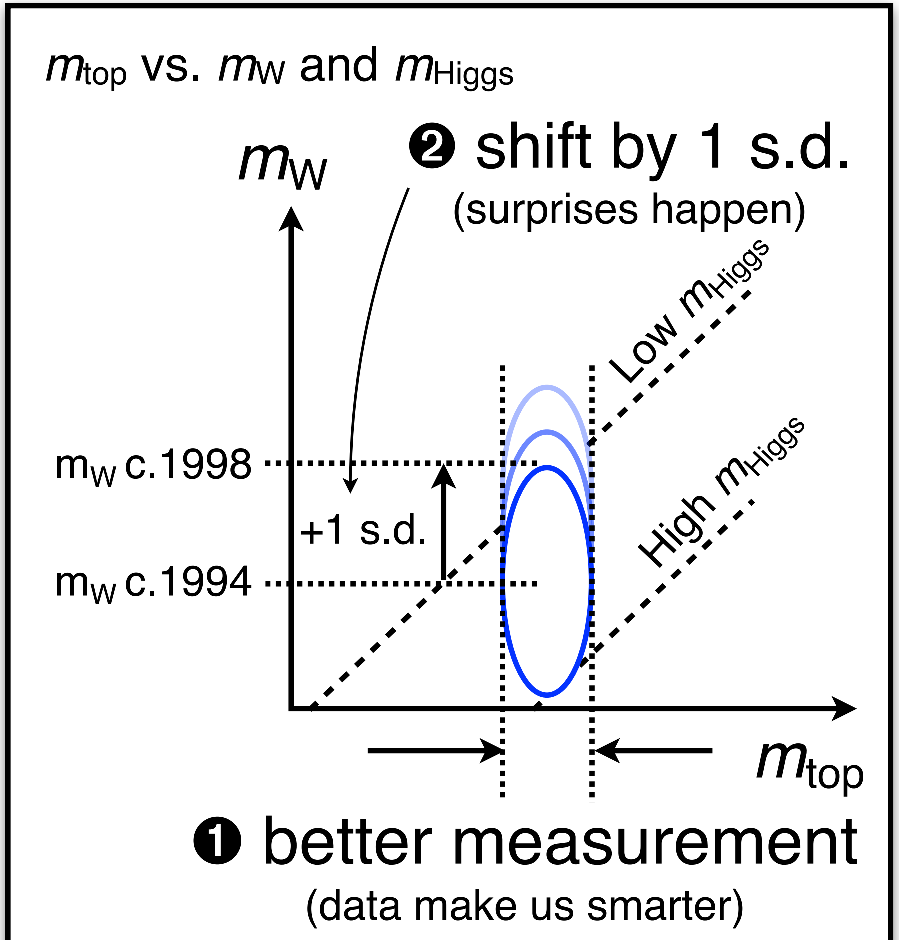
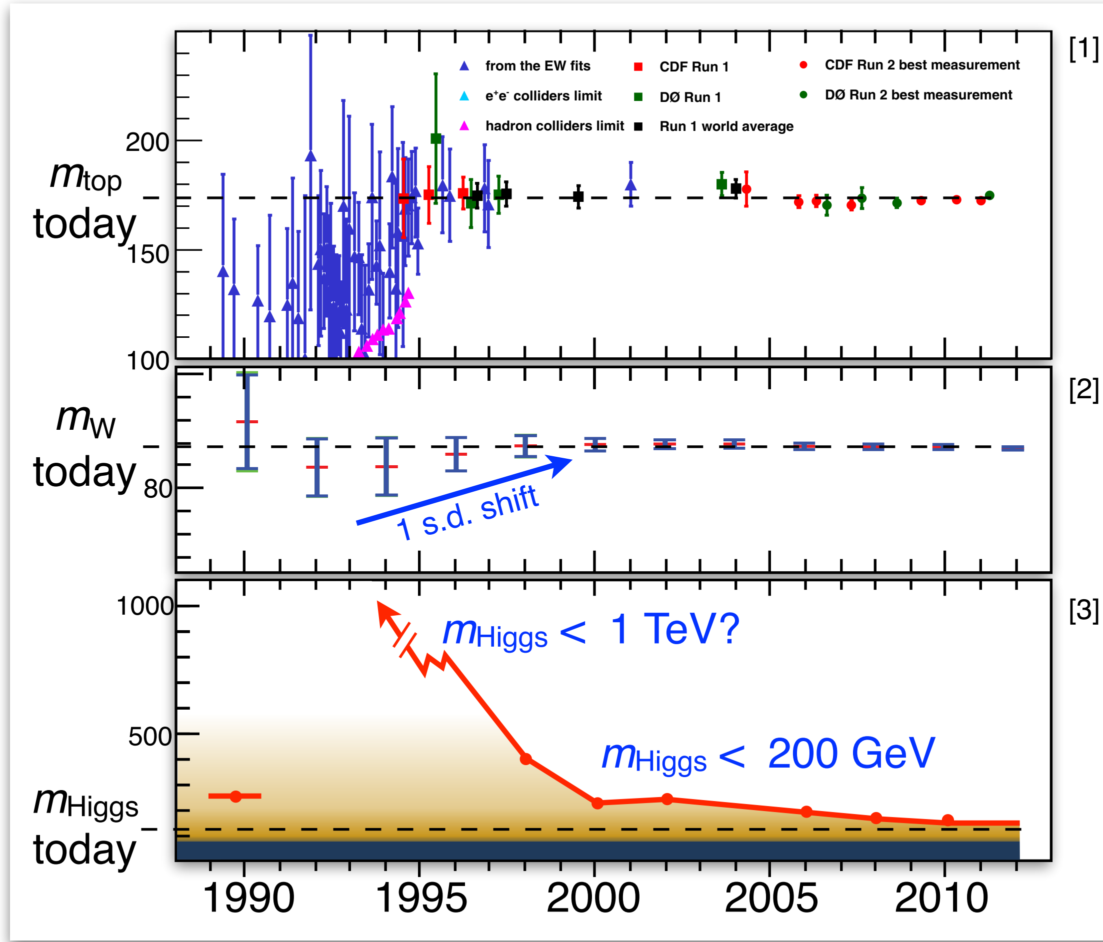
Signal region	SS m_{jj}-in $e^{\pm}e^{\pm}$	SS m_{jj}-in $e^{\pm}\mu^{\pm}$	SS m_{jj}-in $\mu^{\pm}\mu^{\pm}$	SS m_{jj}-out $e^{\pm}e^{\pm}$	SS m_{jj}-out $e^{\pm}\mu^{\pm}$	SS m_{jj}-out $\mu^{\pm}\mu^{\pm}$	SS 1j $e^{\pm}e^{\pm}$	SS 1j $e^{\pm}\mu^{\pm}$	SS 1j $\mu^{\pm}\mu^{\pm}$	3ℓ 0 SFOS	3ℓ 1 SFOS	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
$\gamma \to$ 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 $\to$ 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 $\to$ 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 $\to$ 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 $\to$ 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 $\to$ VVV	0.3±0.3	1.9±1.5	0.6±0.4	0.4±0.4	1.3±0.8	2.0±1.0	0.8±0.5	4.5±2.7	3.7±2.0	3.1±1.7	2.7±1.5	1.3±0.8
VVV total	1.3±0.6	5.4±2.2	4.2±1.6	1.3±0.6	5.3±2.0	6.1±2.1	1.4±0.6	6.3±2.8	5.4±2.2	9.3±3.1	6.8±2.3	3.9±1.4
Total	8.0±1.3	38.7±5.6	28.2±3.4	33.5±4.4	125±11	107±8	25.0±5.8	95.0±11.8	69.8±8.1	19.4±3.4	31.4±3.7	71.5±3.4
Observed	5	46	20	31	112	118	29	101	69	20	32	69

Title

Signal 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



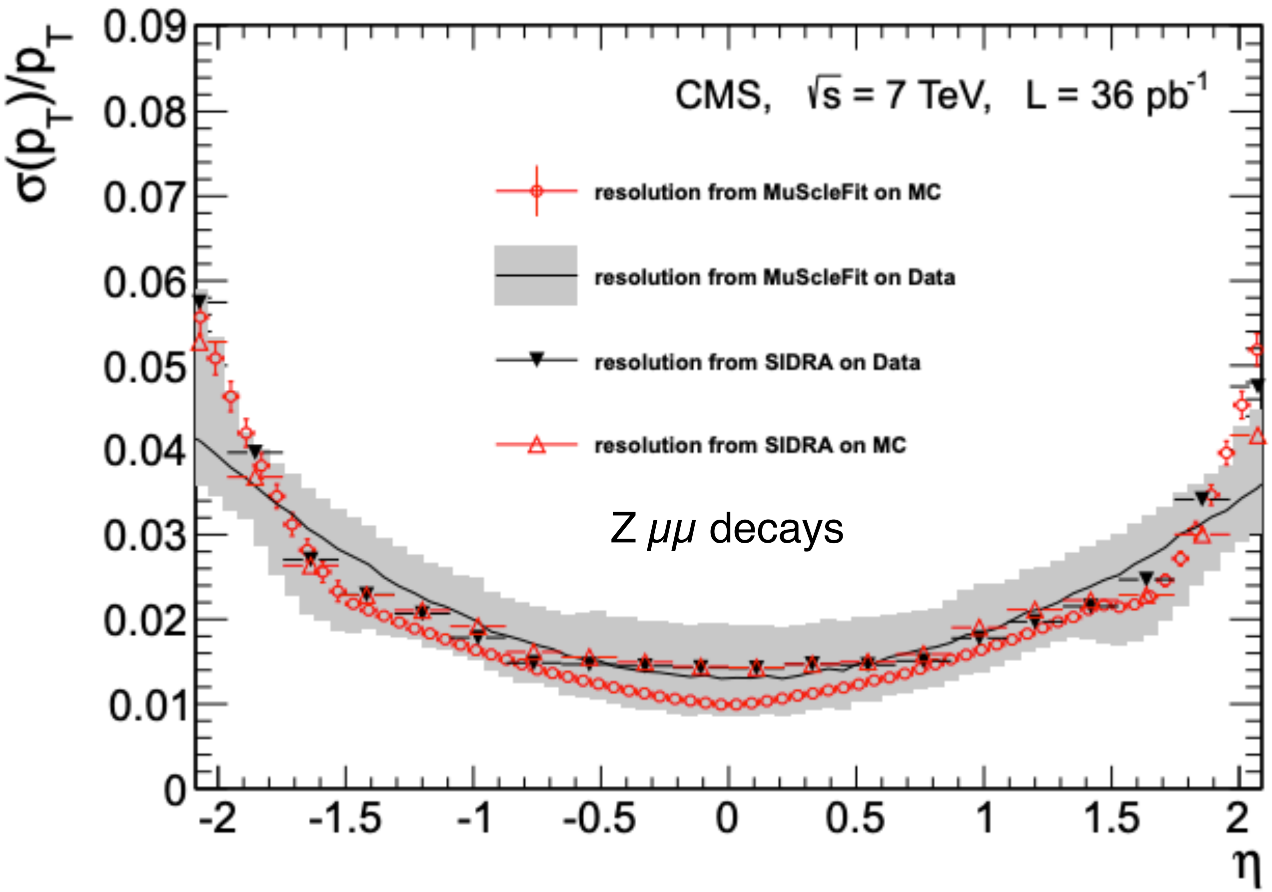


…after analysis of Run I data, … ❷ m_W shifted a full s.d. … the m_{Higgs} must be ❸ much lower than anyone had anticipated. … Surprises happen.

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

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

Muon resolution



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

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

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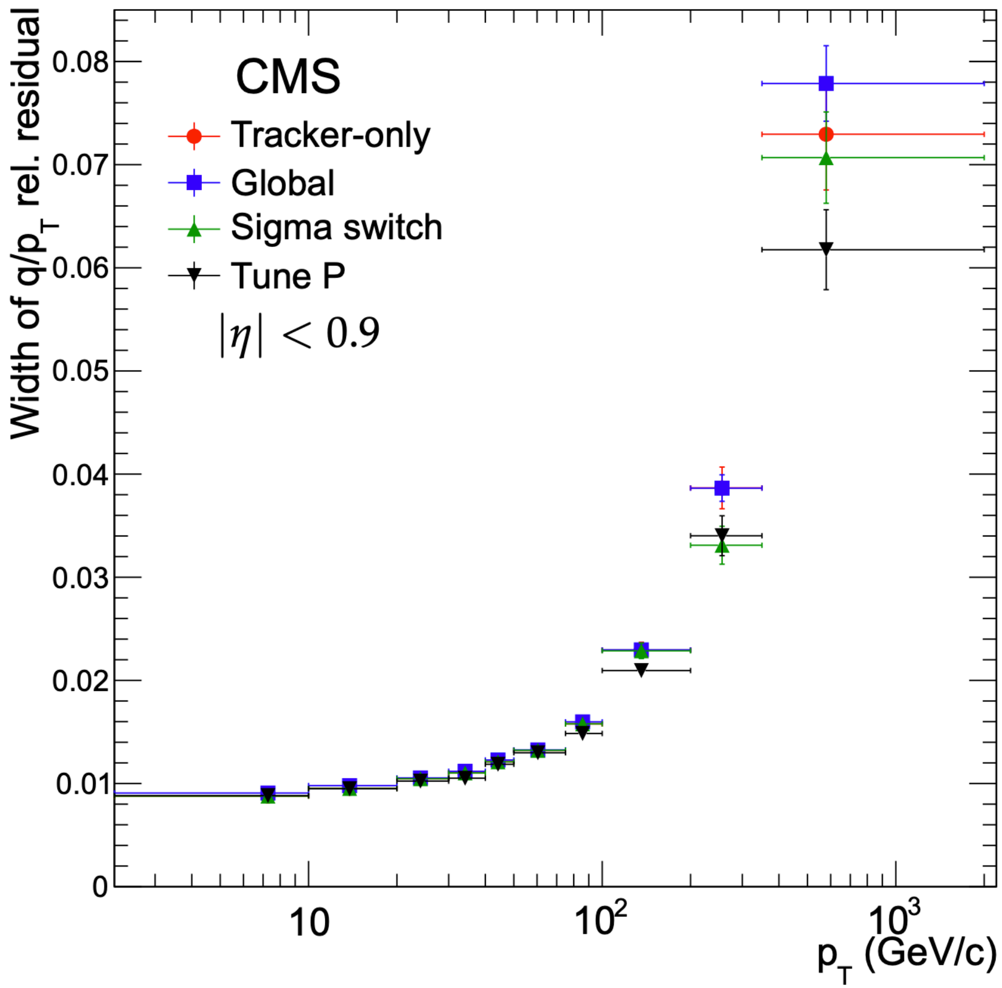
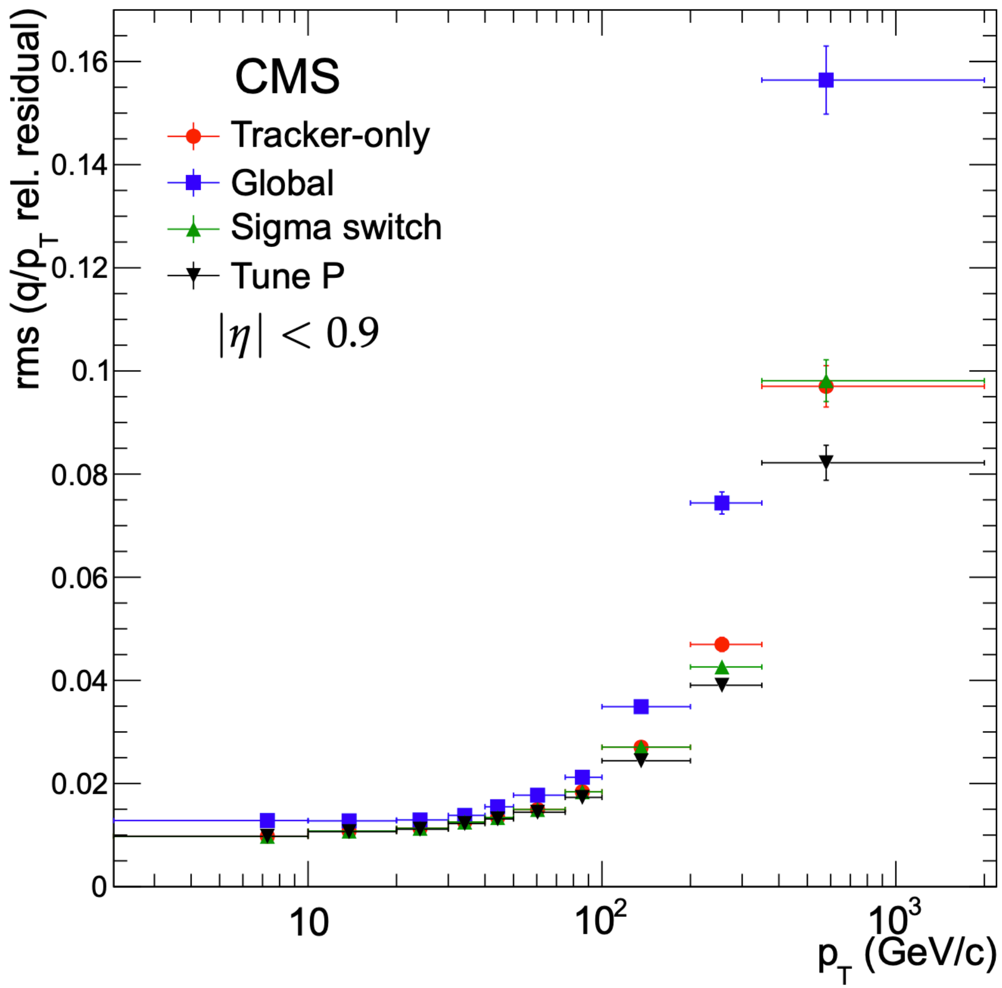
https://arxiv.org/pdf/1206.4071.pdf



(a)



(b)

Electron resolution

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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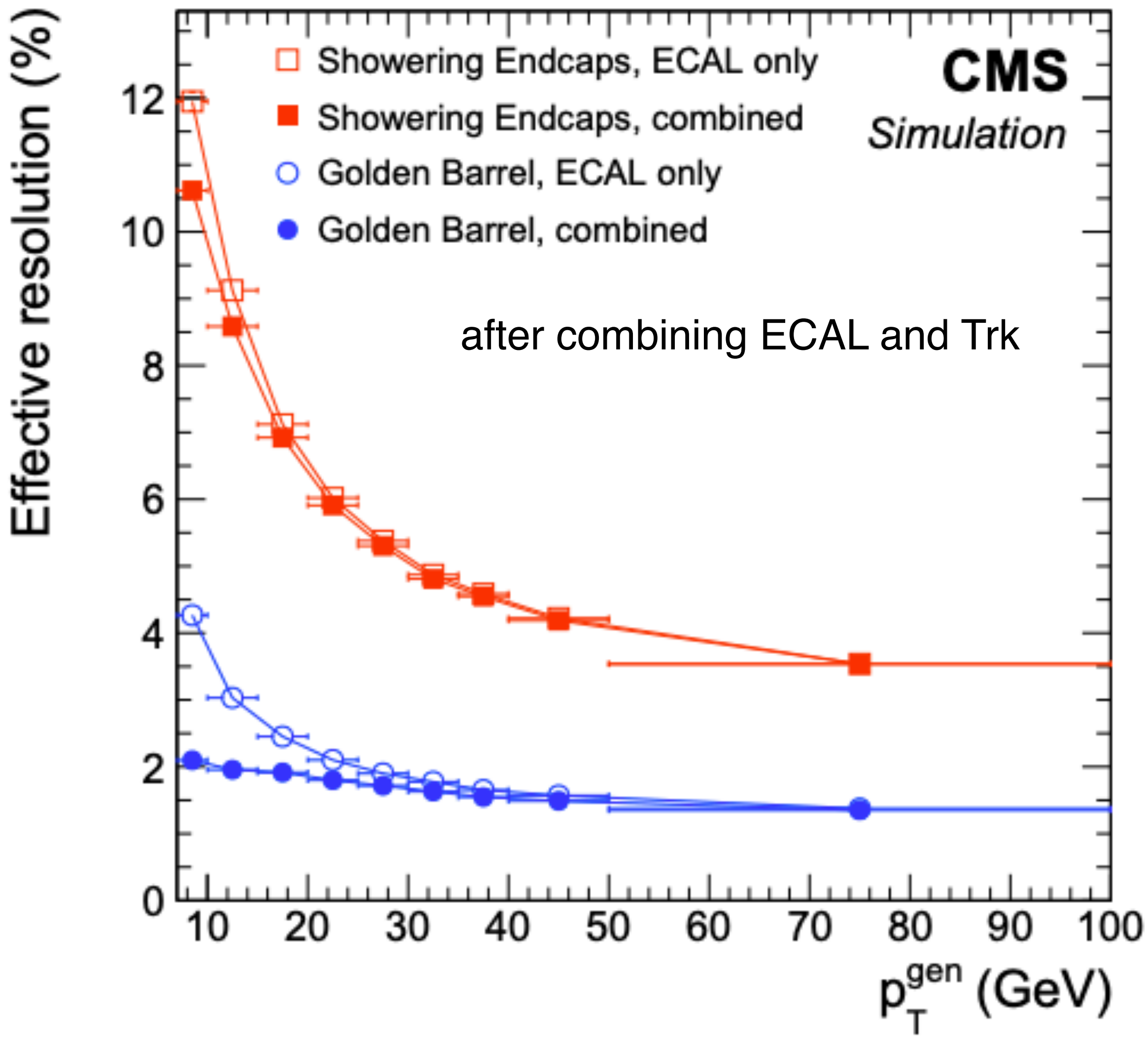
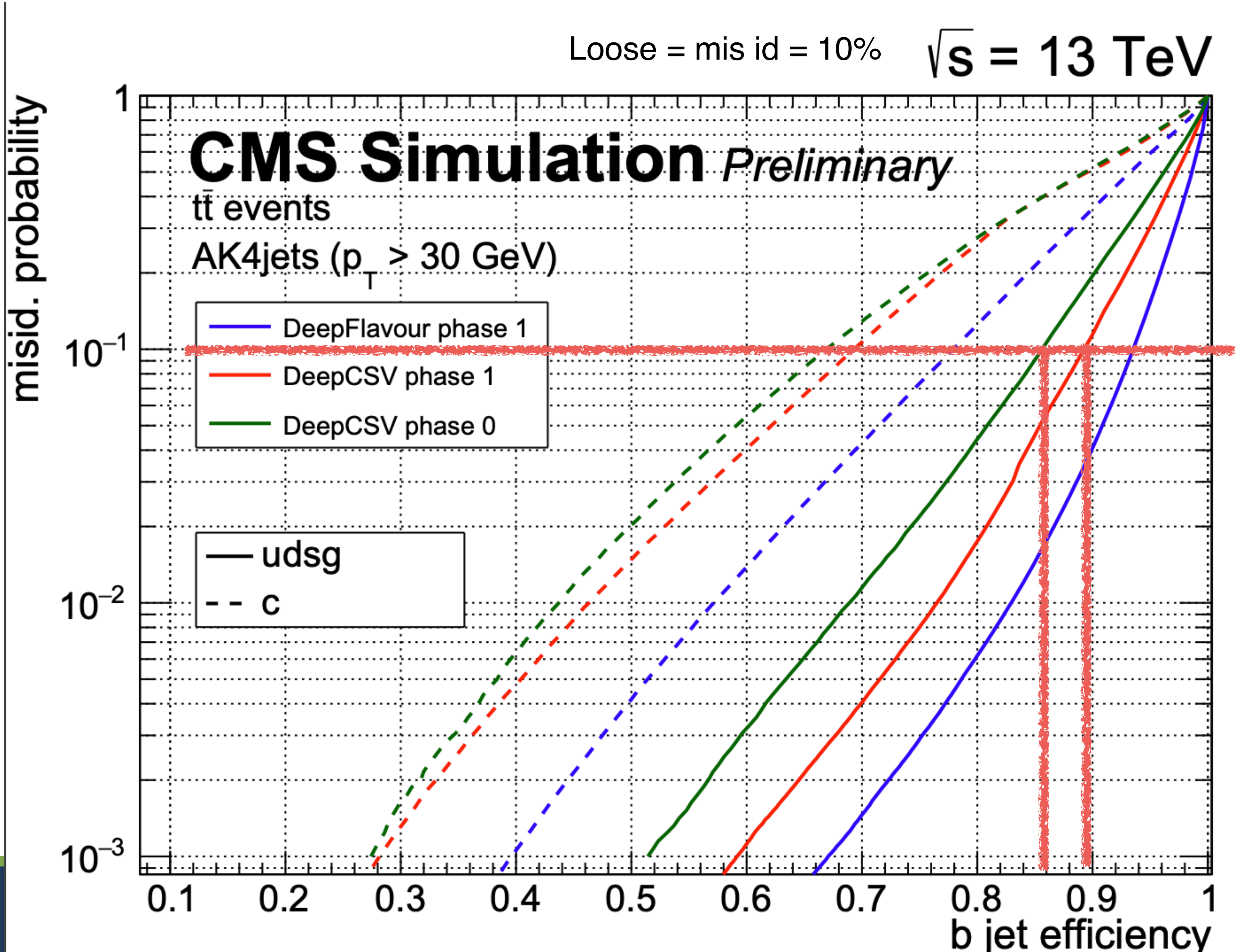


b tagging

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



Electroweak sector

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

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

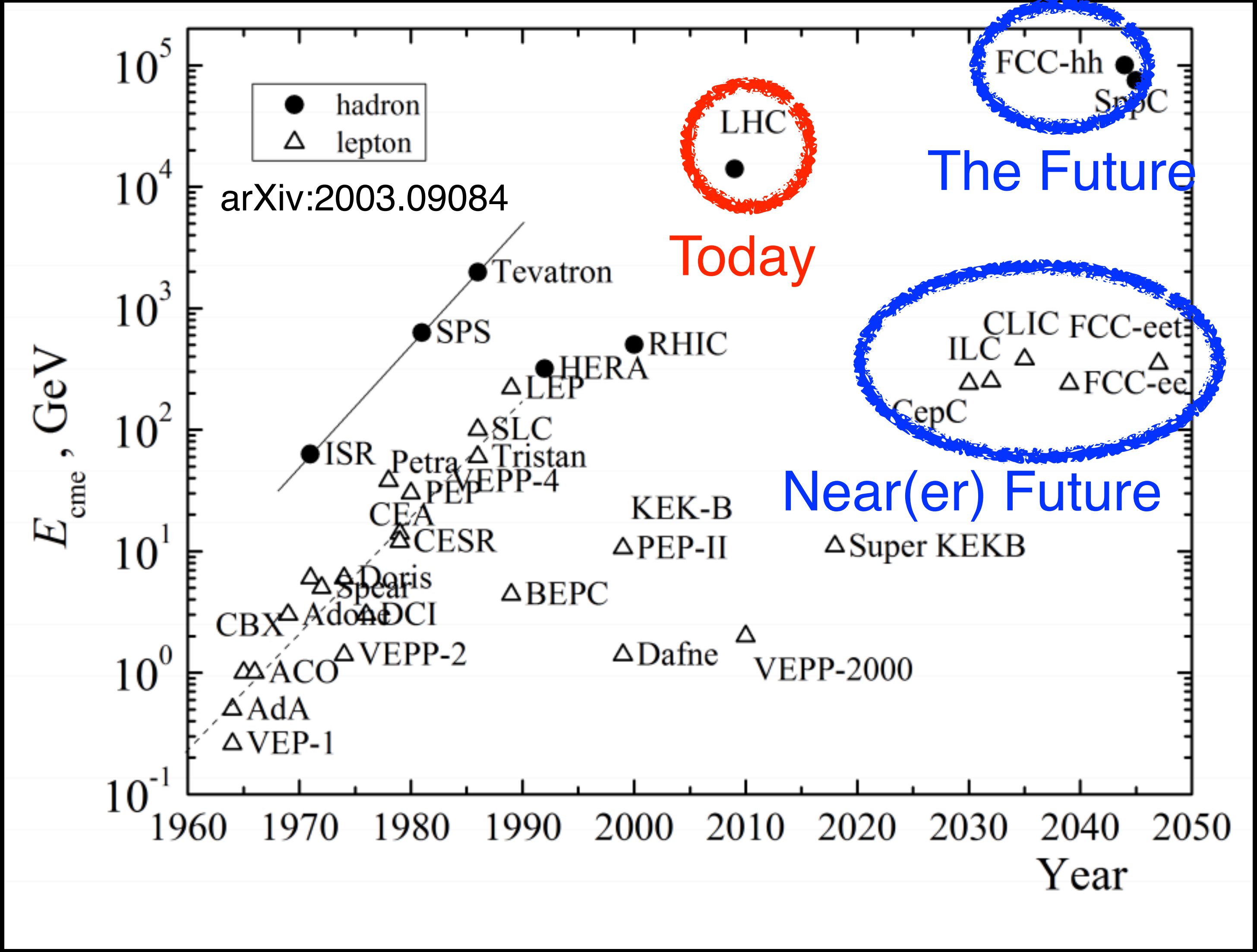
$$D_\mu = \partial_\mu + i\tfrac{g}{2}\sigma_j W^j_\mu + 2ig'YB_\mu$$

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

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

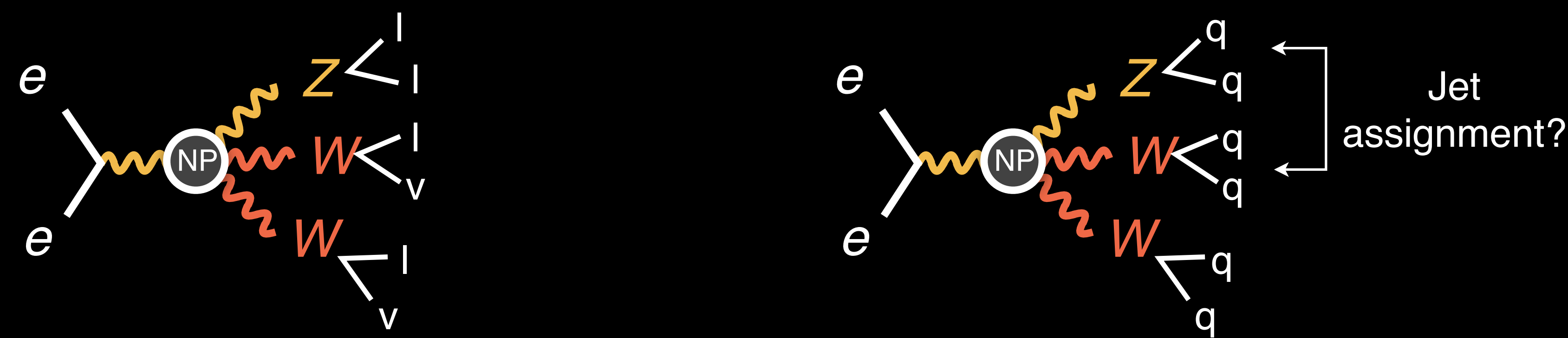


"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a <u>centre-of-mass energy of at least **100 TeV**</u> …"

— 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



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)

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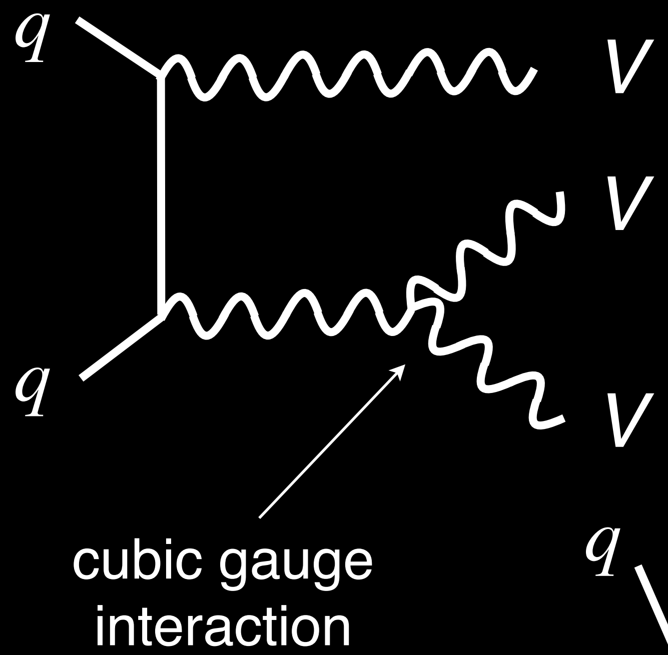
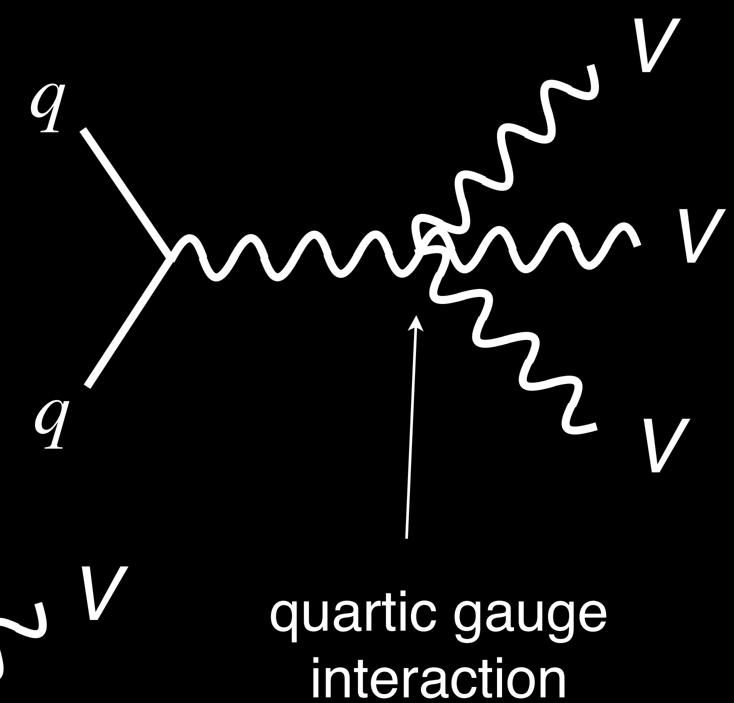
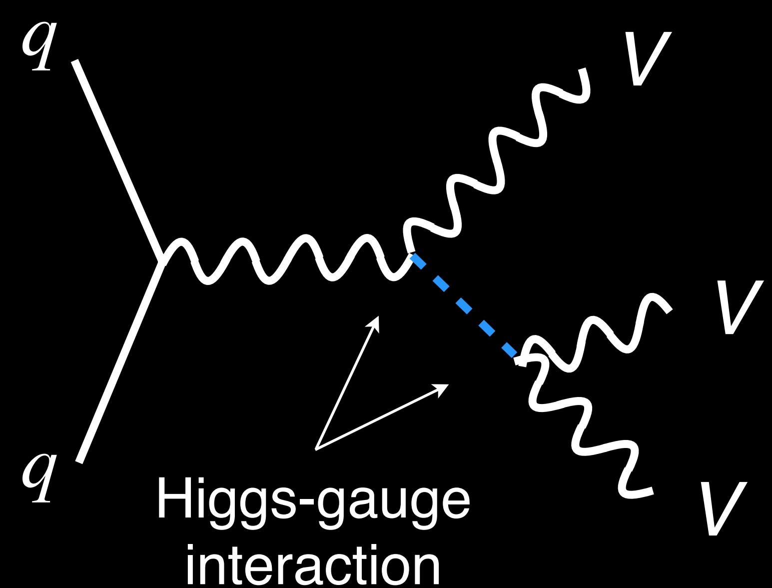


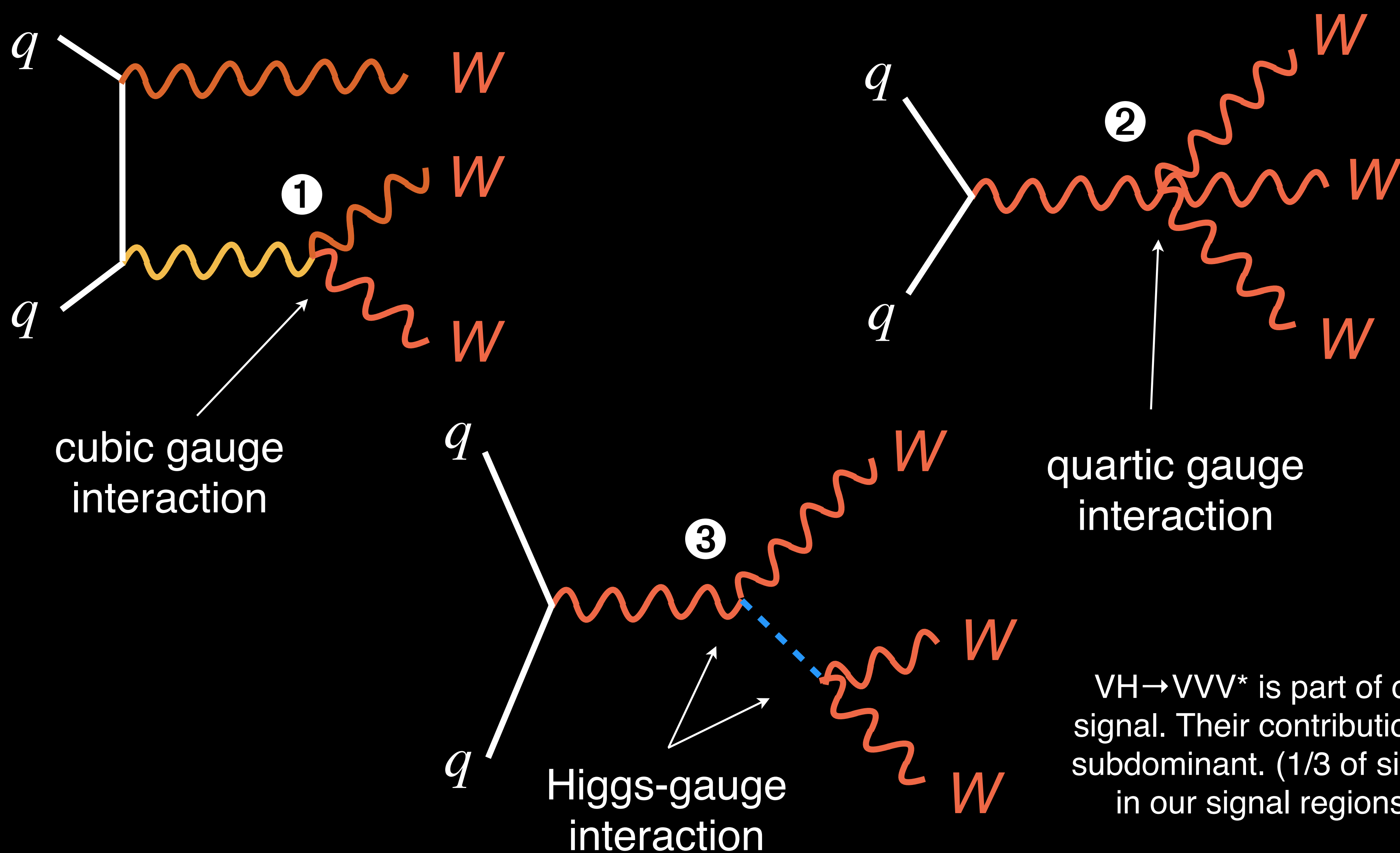




VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

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

Physics of VVV production (V = W, Z)



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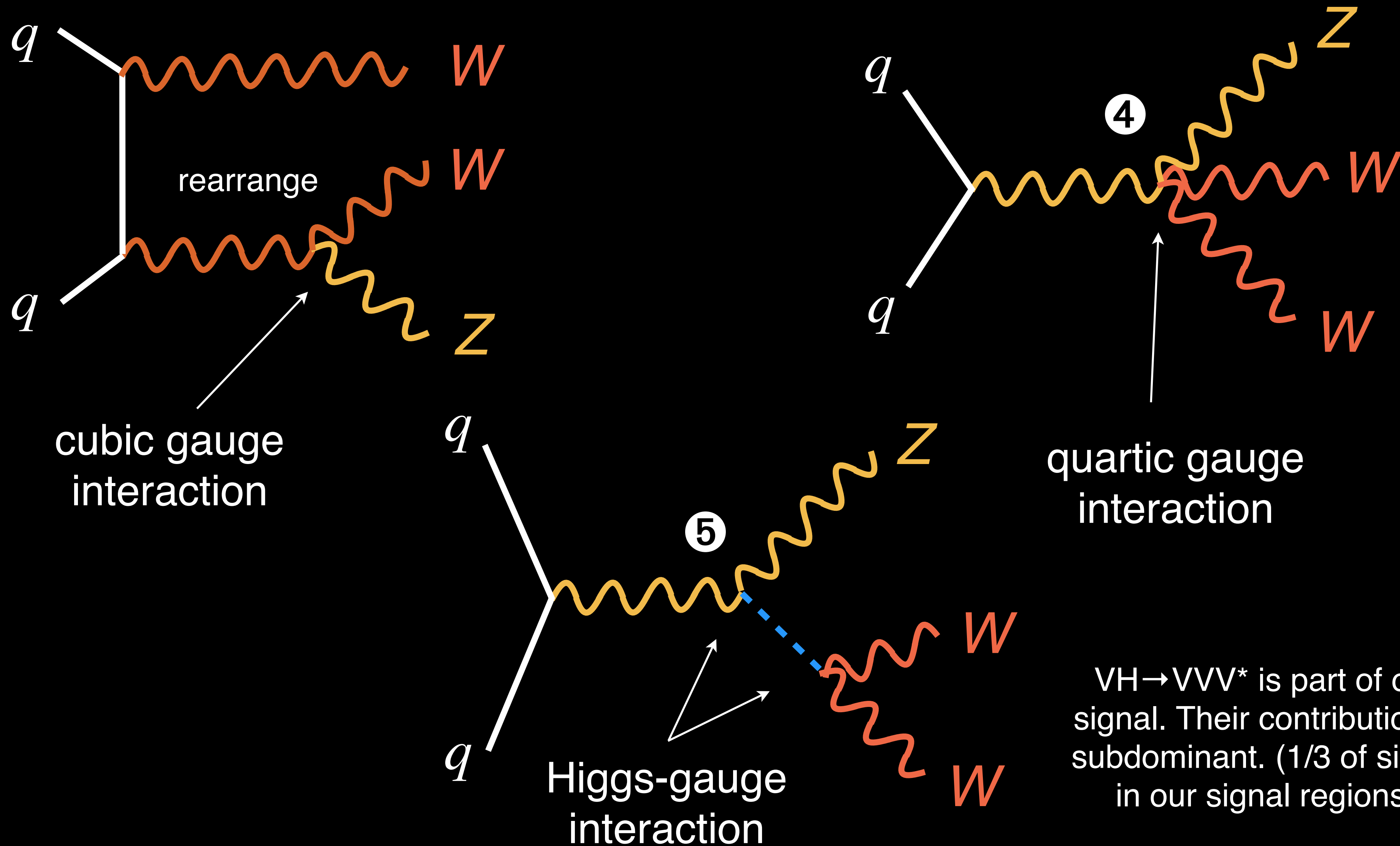

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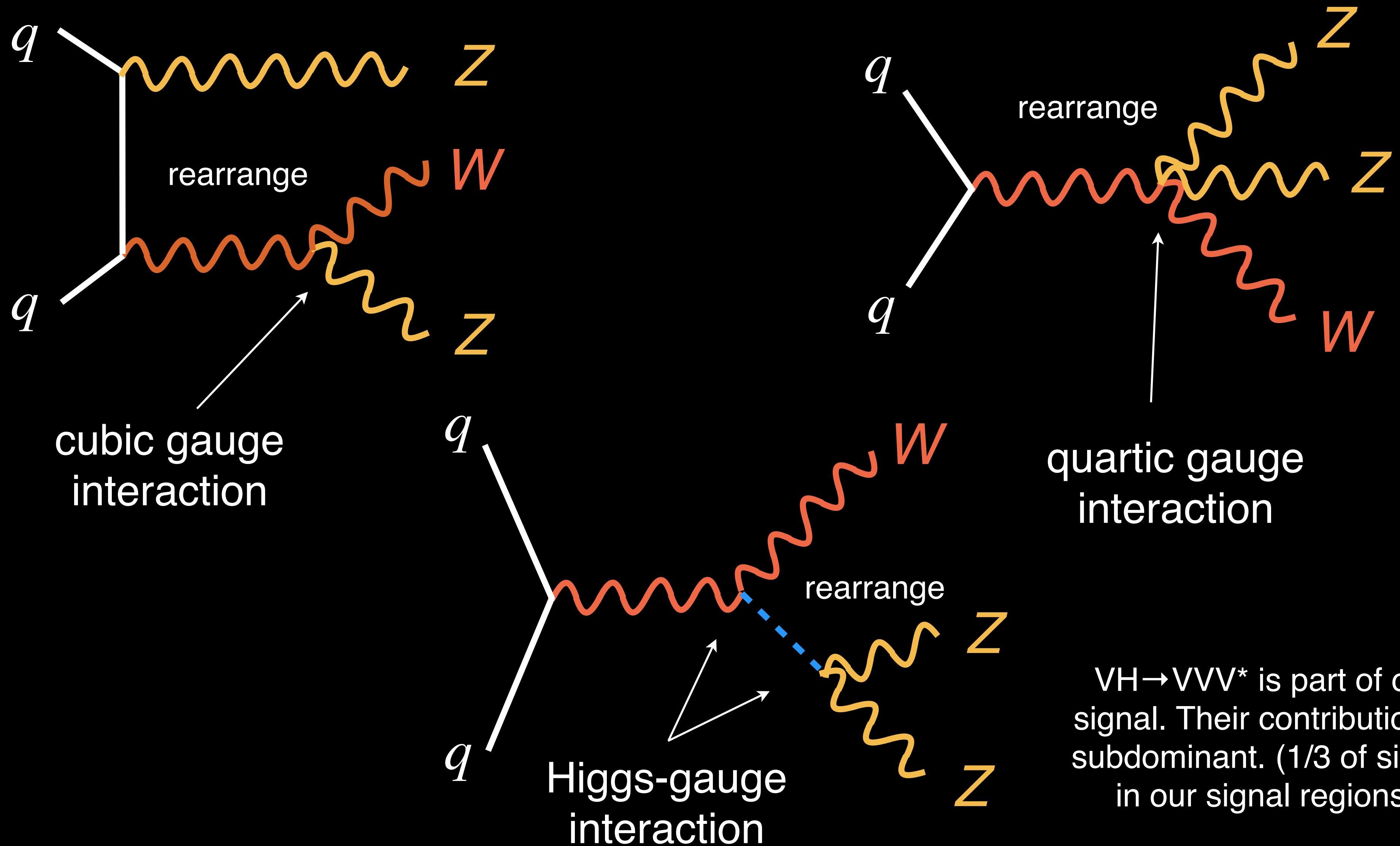

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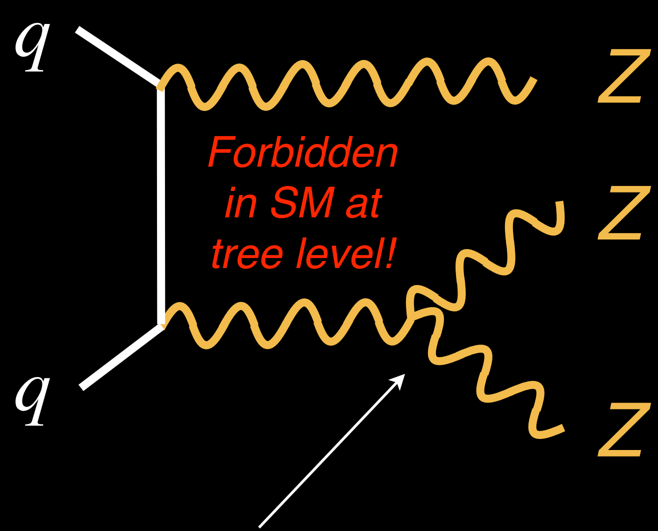
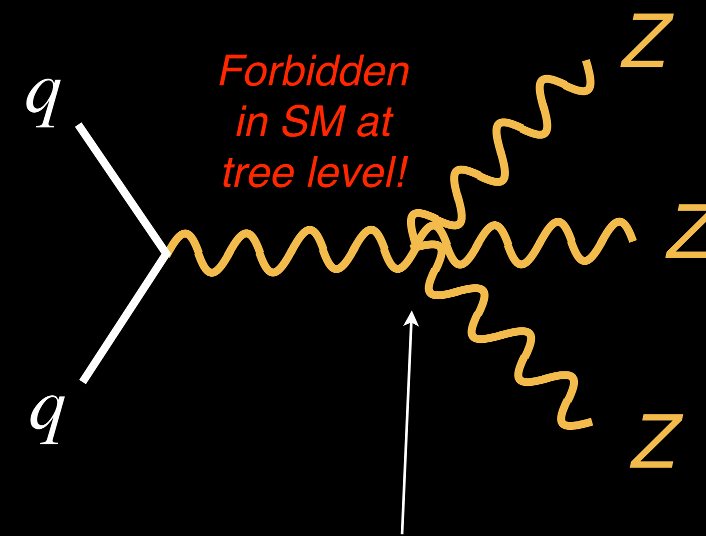
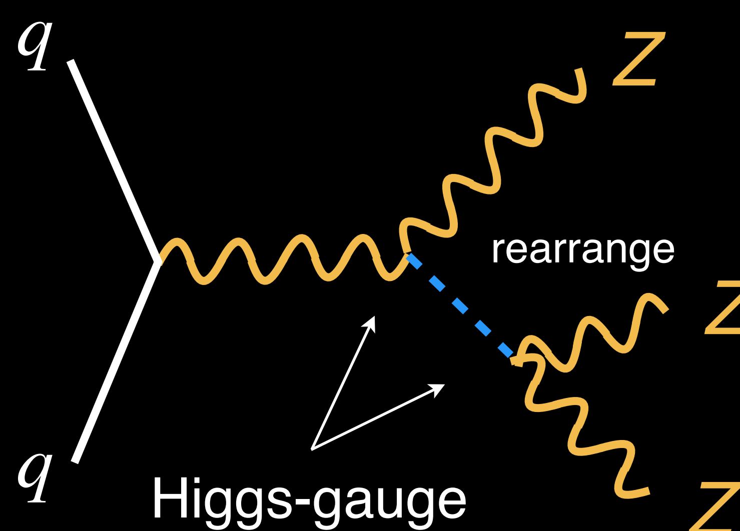


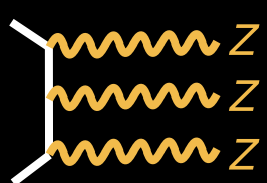
cubic gauge
interaction



quartic gauge
interaction



Higgs-gauge
interaction

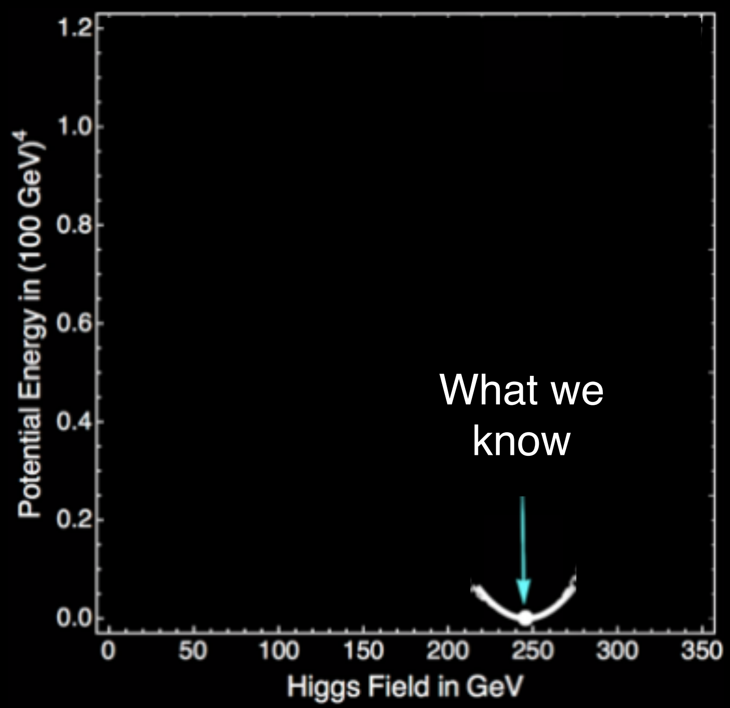


Three Z's radiating
from quark lines

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

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

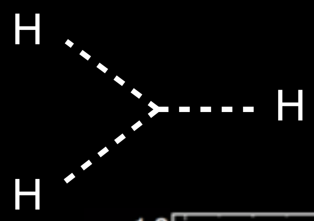
Higgs potential

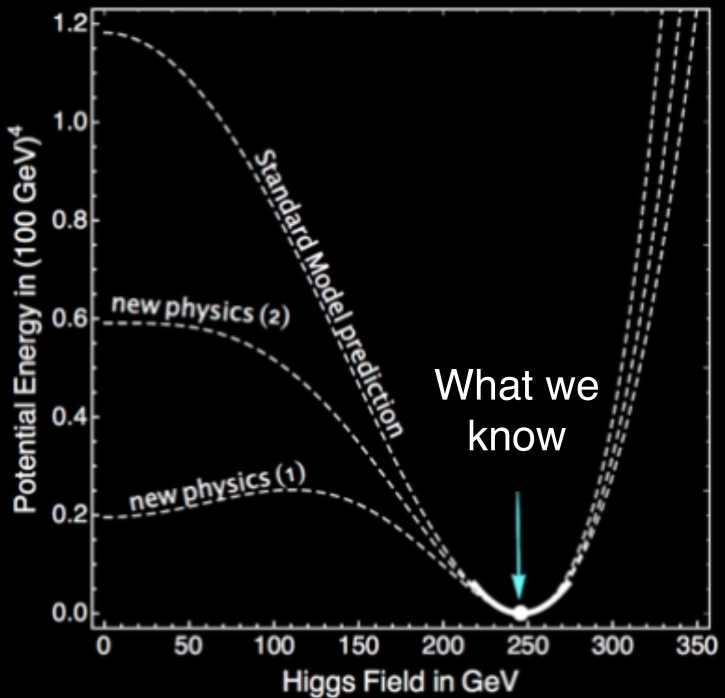


How is electroweak symmetry broken?

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

Higgs potential





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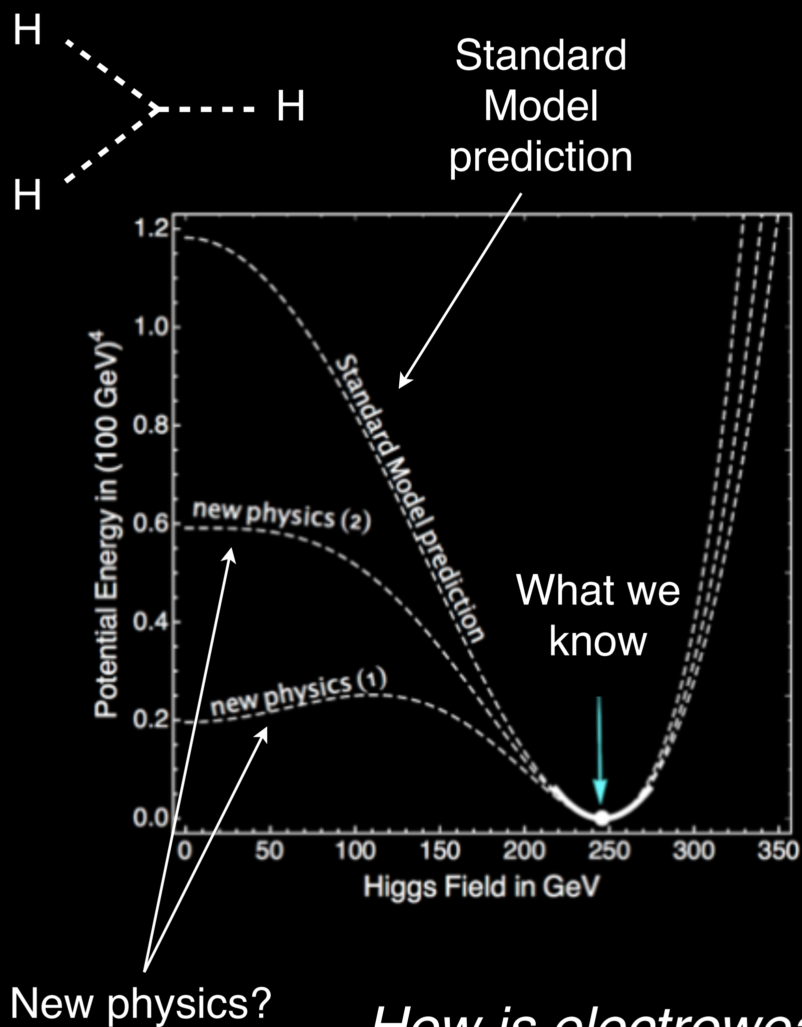

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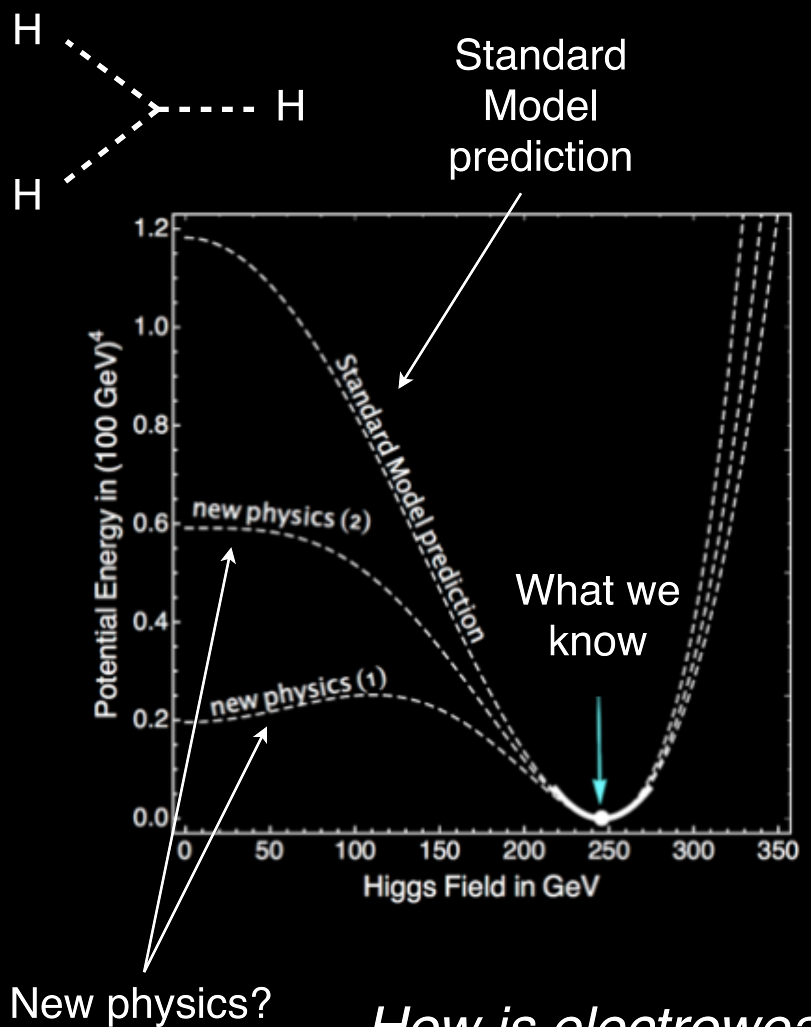
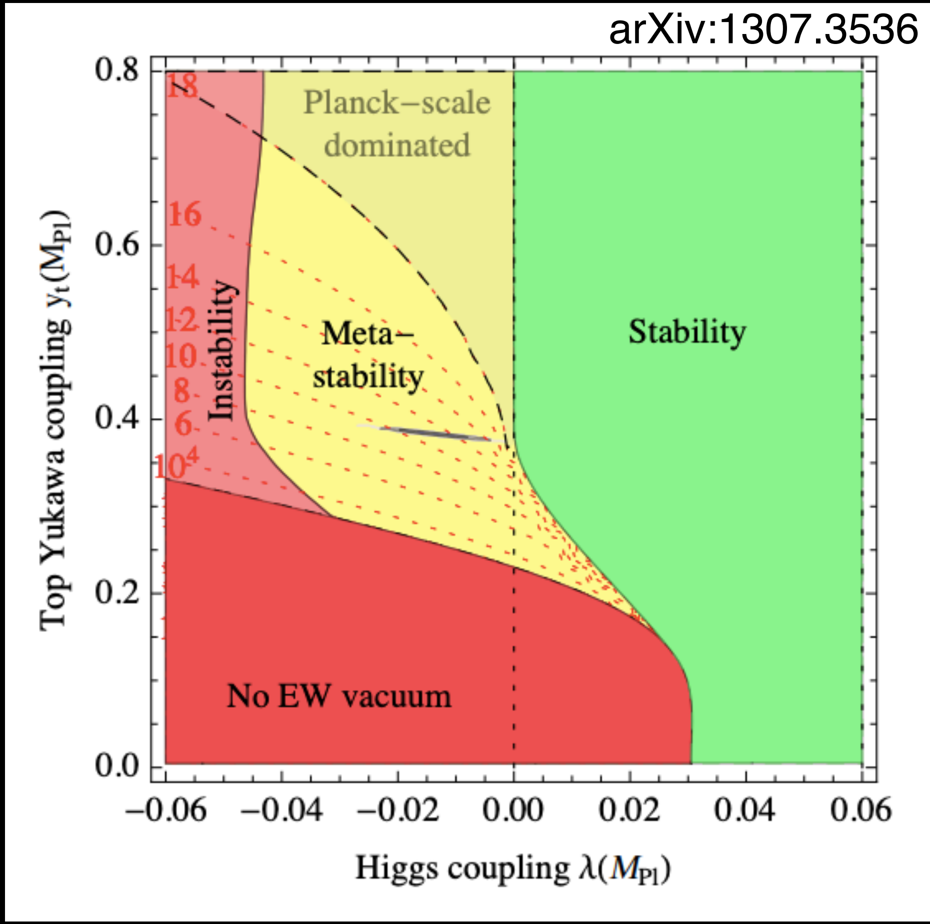
Higgs potential



How is electroweak symmetry broken?

What is the fate of the universe?



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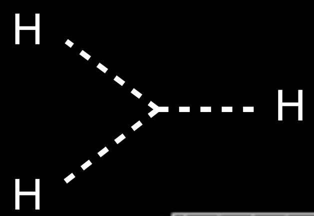
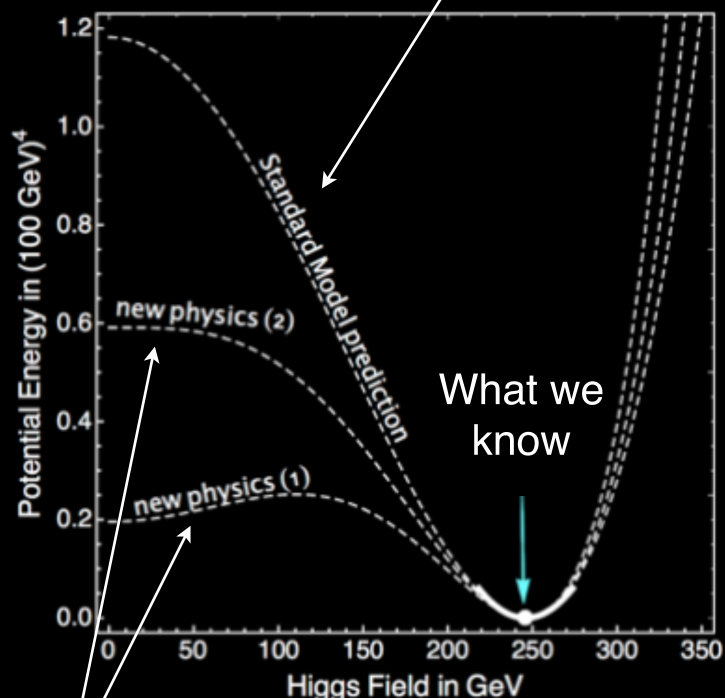
Higgs potential



Standard Model prediction

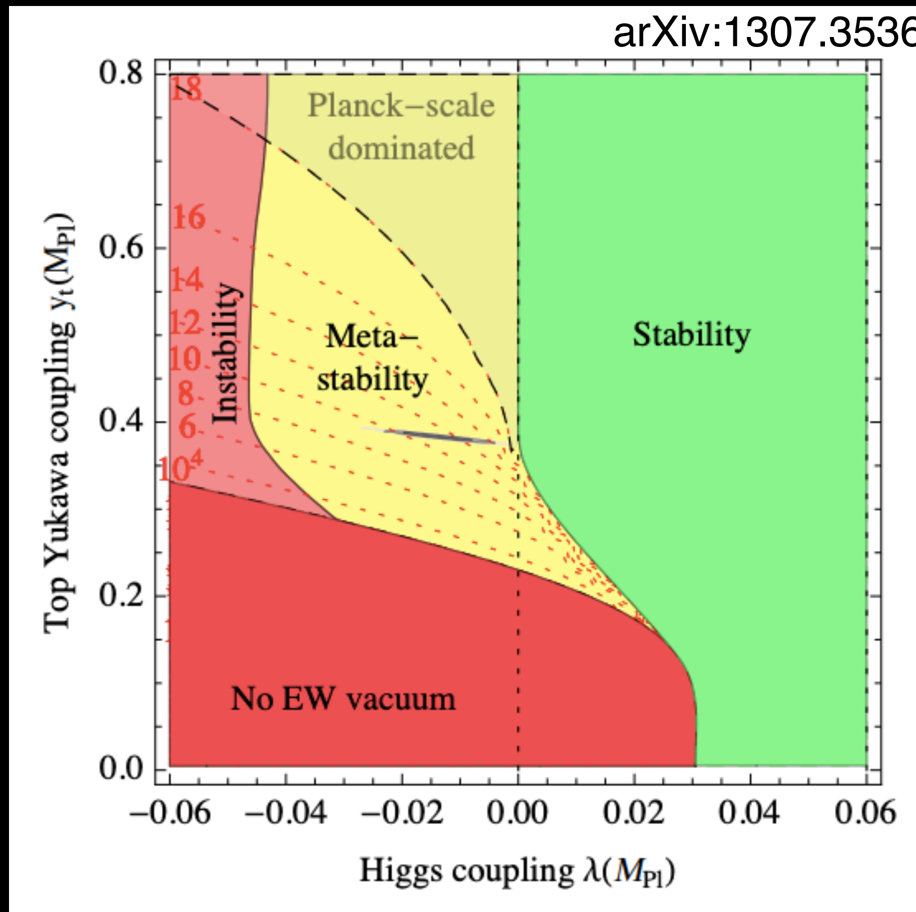


What we know

New physics?

How is electroweak symmetry broken?

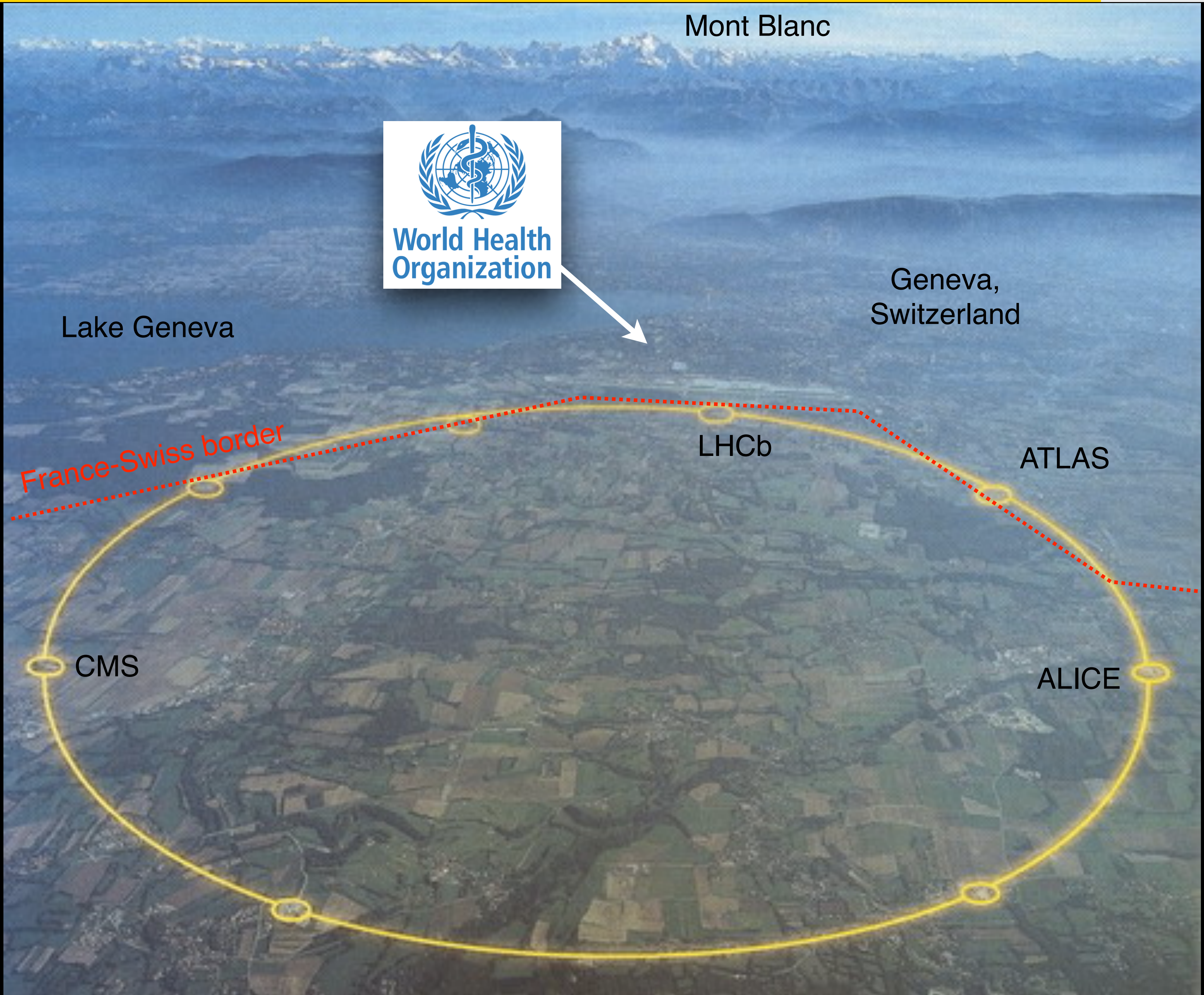
What is the fate of the universe?



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

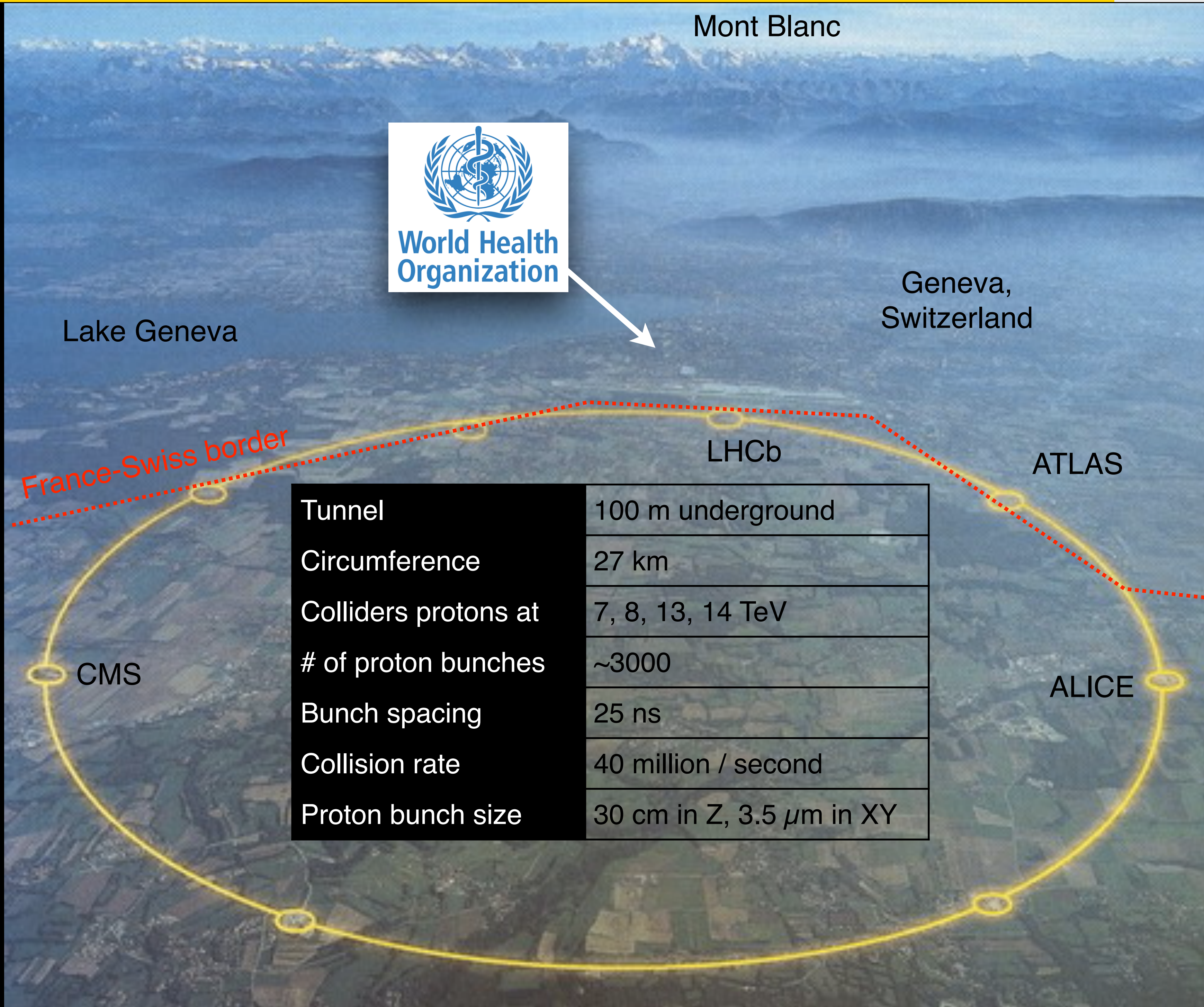
Understanding Higgs potential have deep implications to cosmology

Large Hadron Collider at CERN



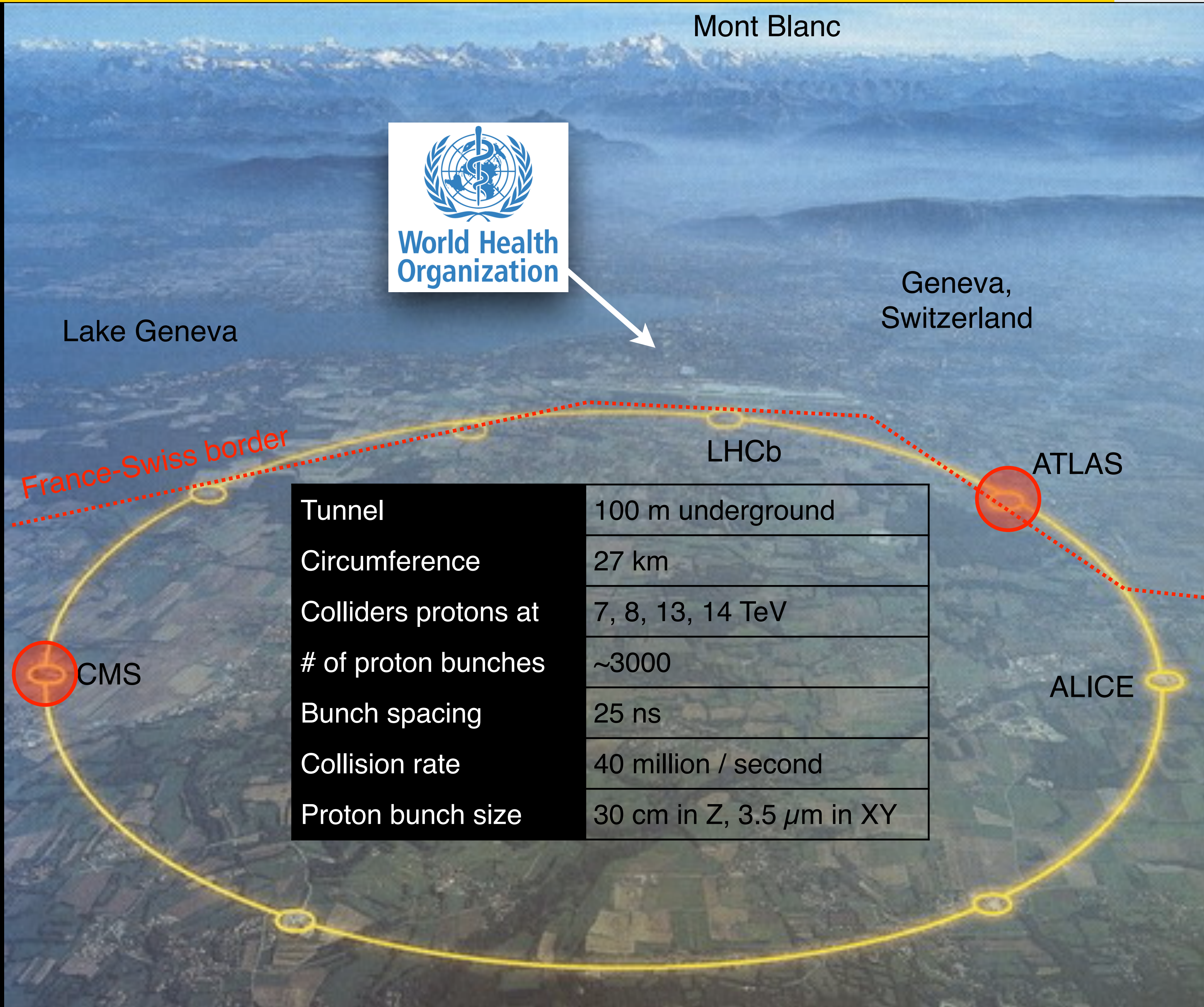
Large Hadron Collider at CERN

Chang
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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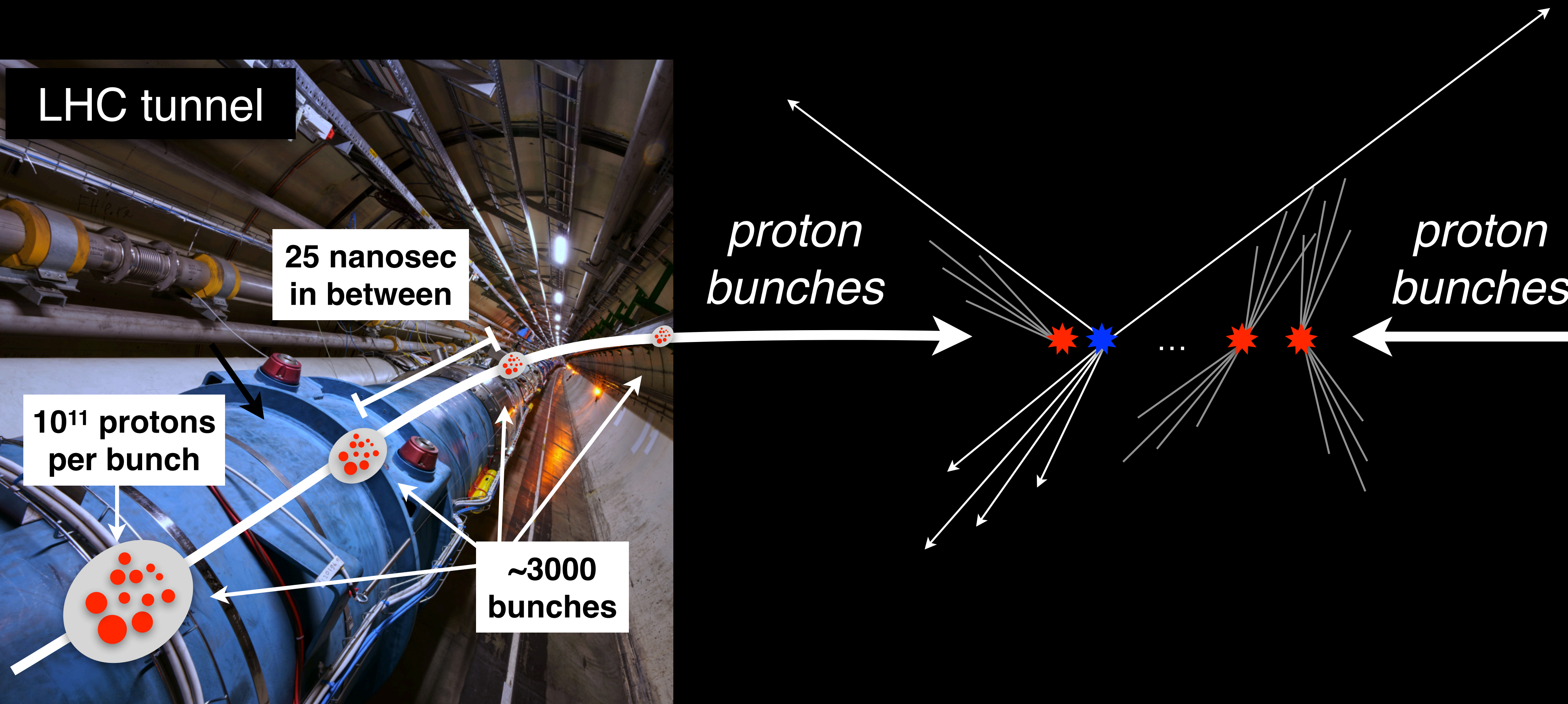
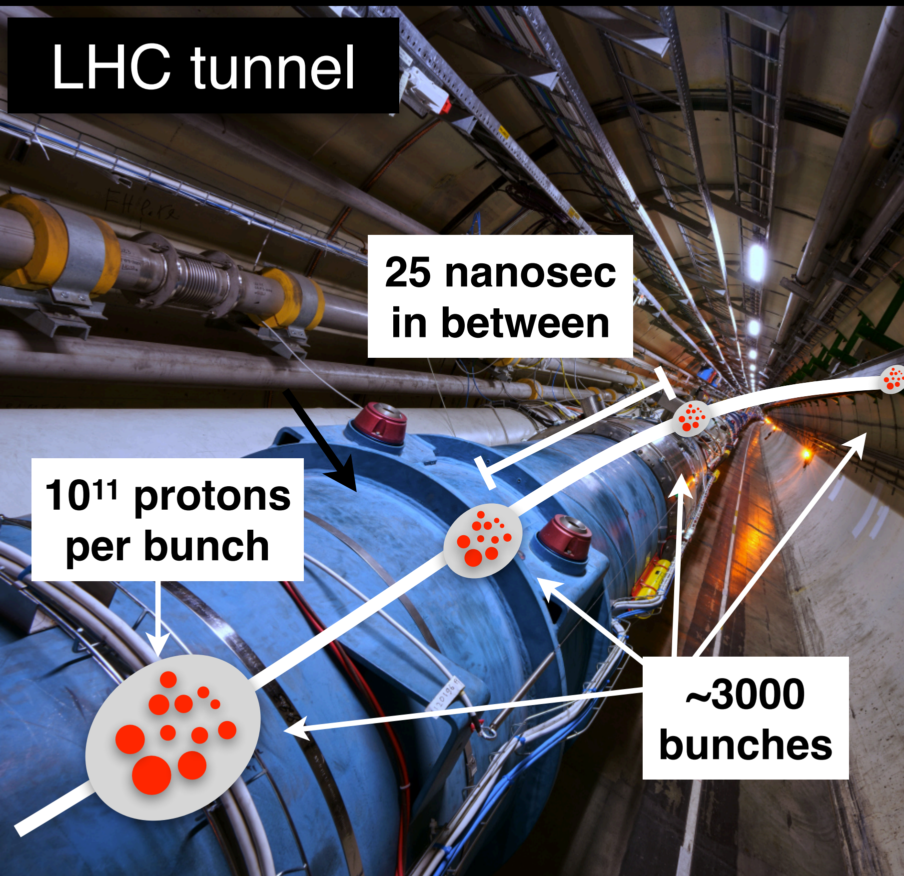
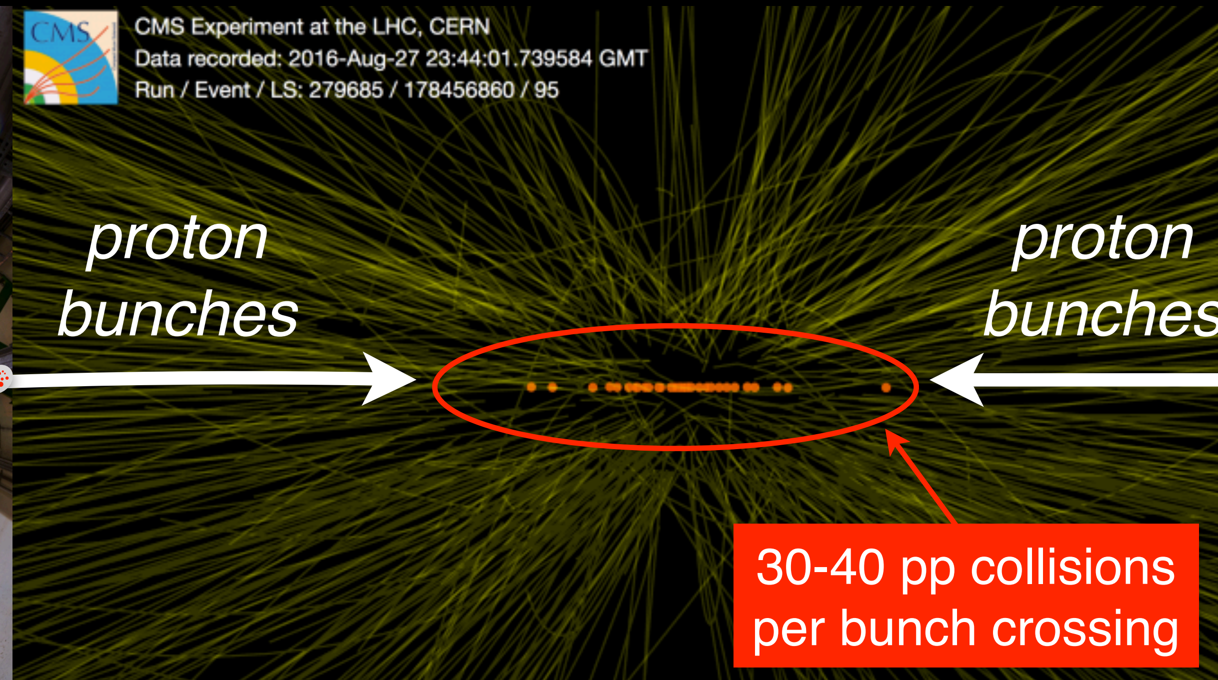
Proton beam collision at the LHC



LHC provides highest energy *pp* collisions ever recorded

Proton beam collision at the LHC





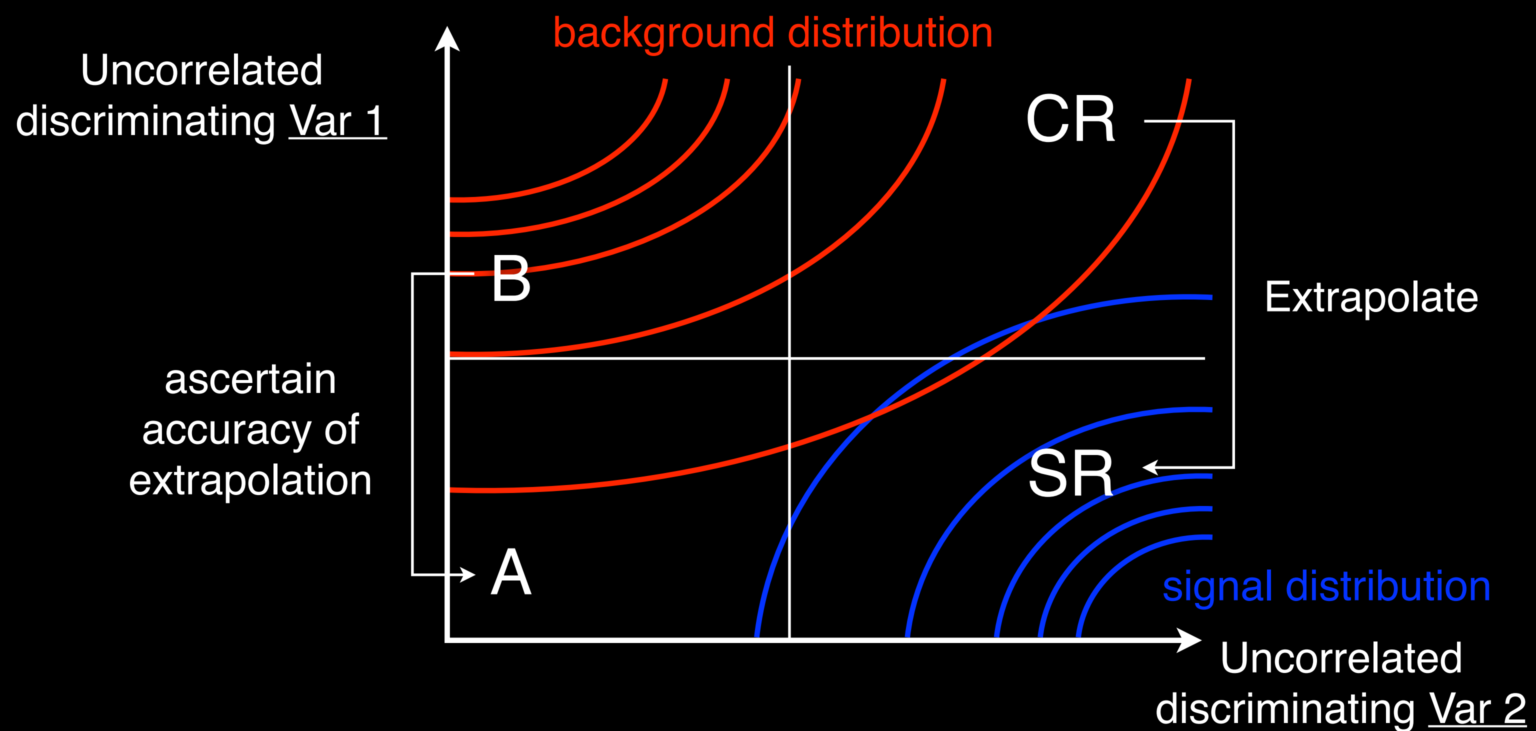
(35 pp collisions) × (40 MHz) =
~1.5 billions *pp* collisions per second

Large dataset of

LHC provides highest energy *pp* collisions ever recorded

Typical search strategy

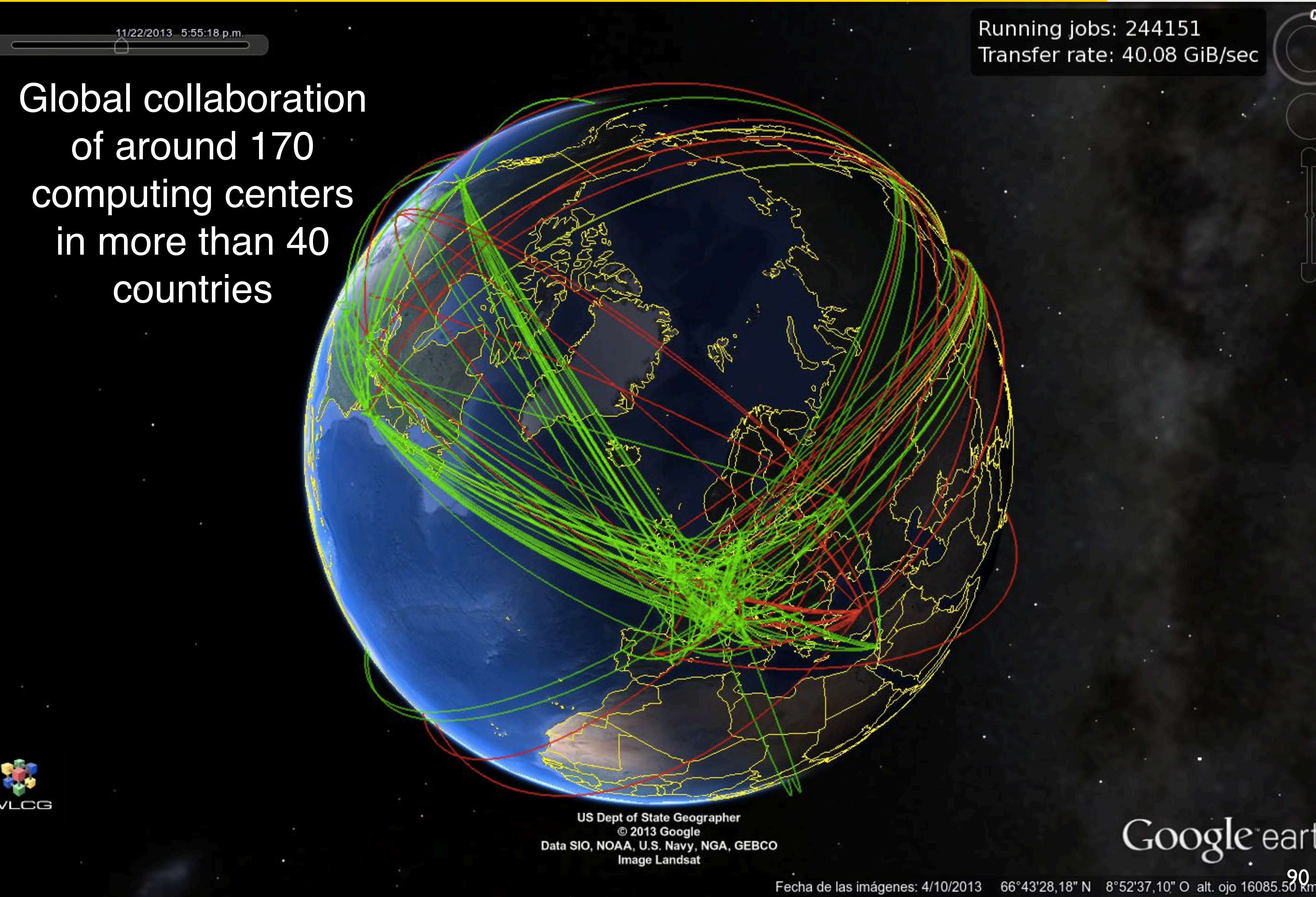
1. Define low background signal regions (SRs)
2. Estimate background yields by extrapolating from bkg. enriched control region (CR)
3. Ascertain accuracy of the extrapolation from a different sample



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

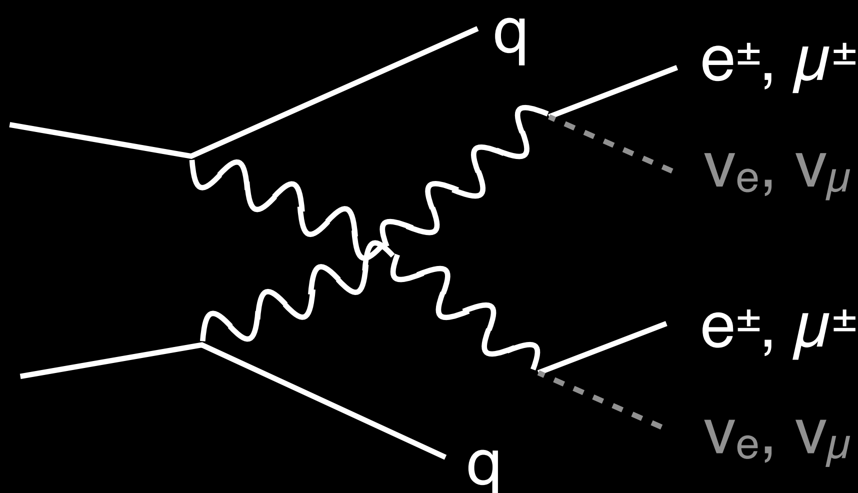
Then we further reduce it x5 and can be done in a ~week

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

Recent results in multi-boson physics

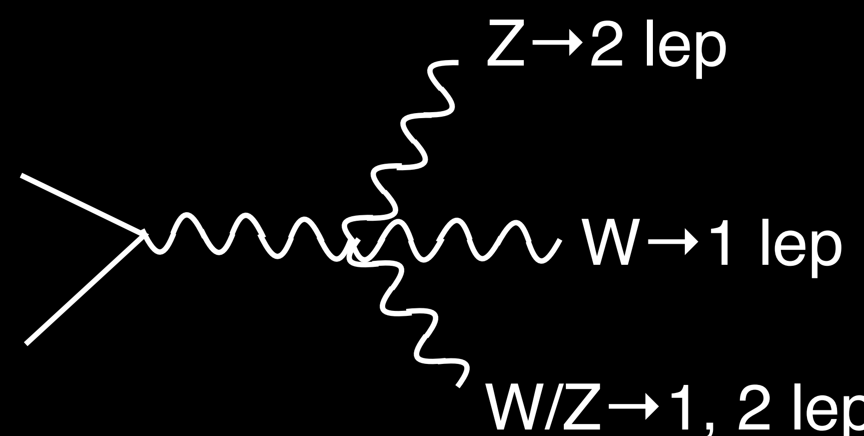
- Several important results have come out recently from both ATLAS and CMS
- I will highlight a few (from CMS)
- (Disclaimer: Rest of the talk from here on will focus mostly on CMS)

WW scattering



Same-sign dilepton + 2 quarks

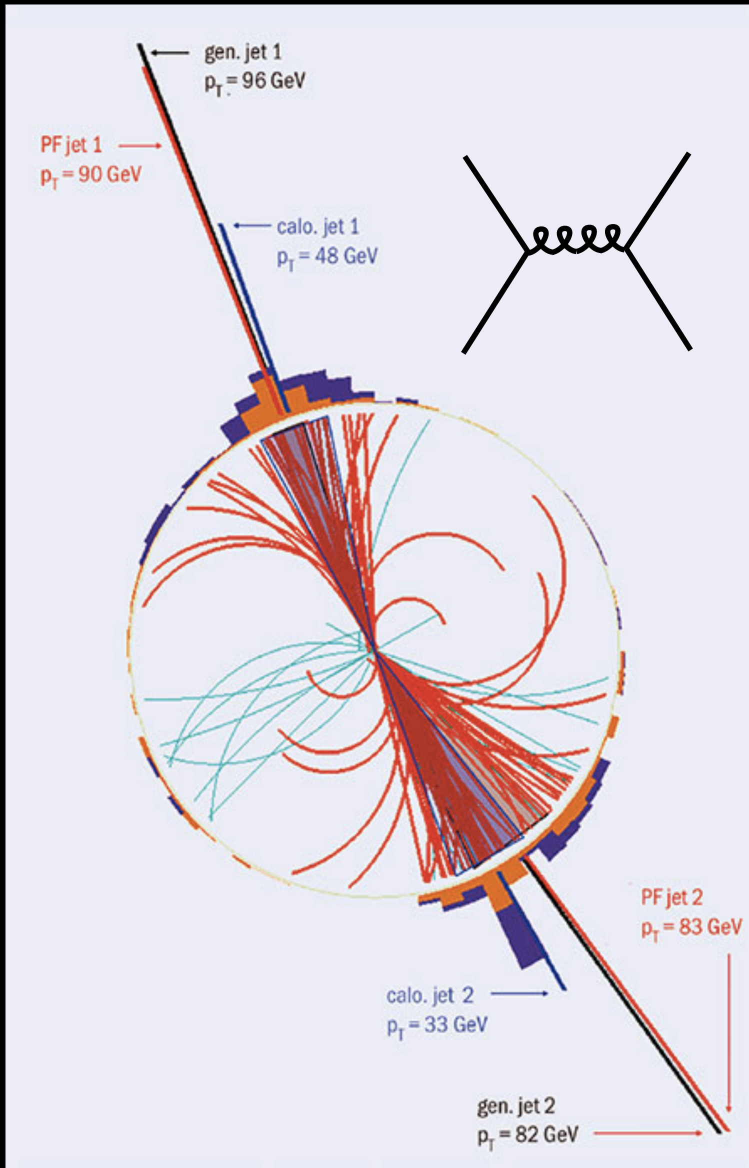
Tri-boson process



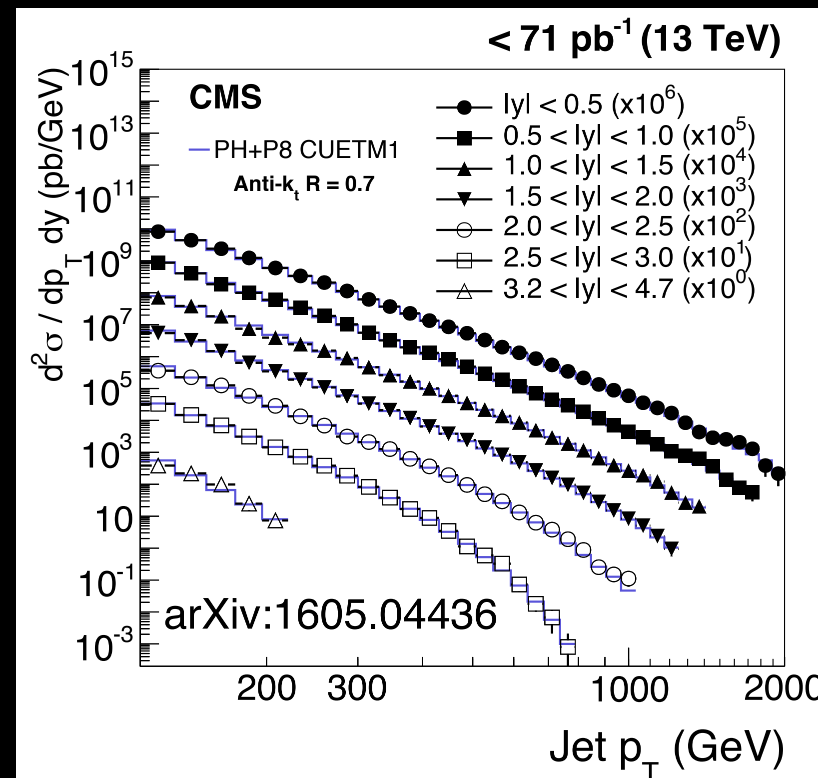
4 or 5 leptons

⇒ electrons, muons, and jets reconstructions are crucial

Jet formation and identification



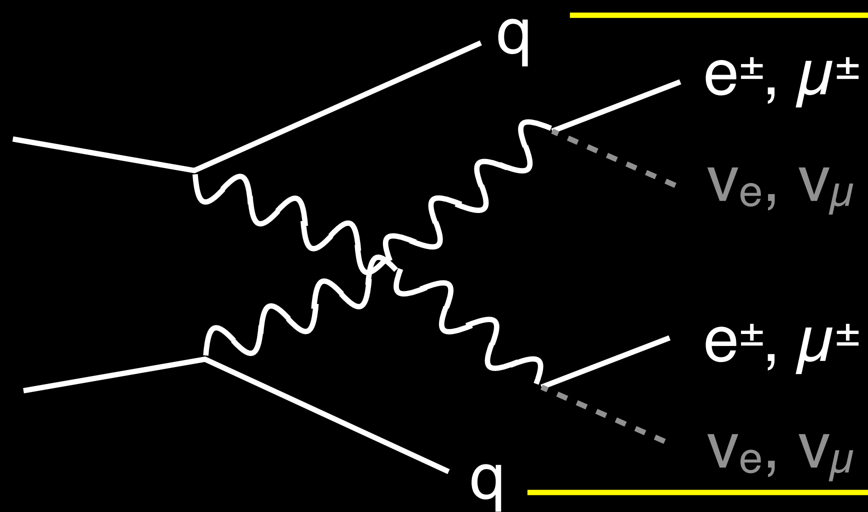
Quarks and gluons produced from pp collisions manifest as a “jet” of particles



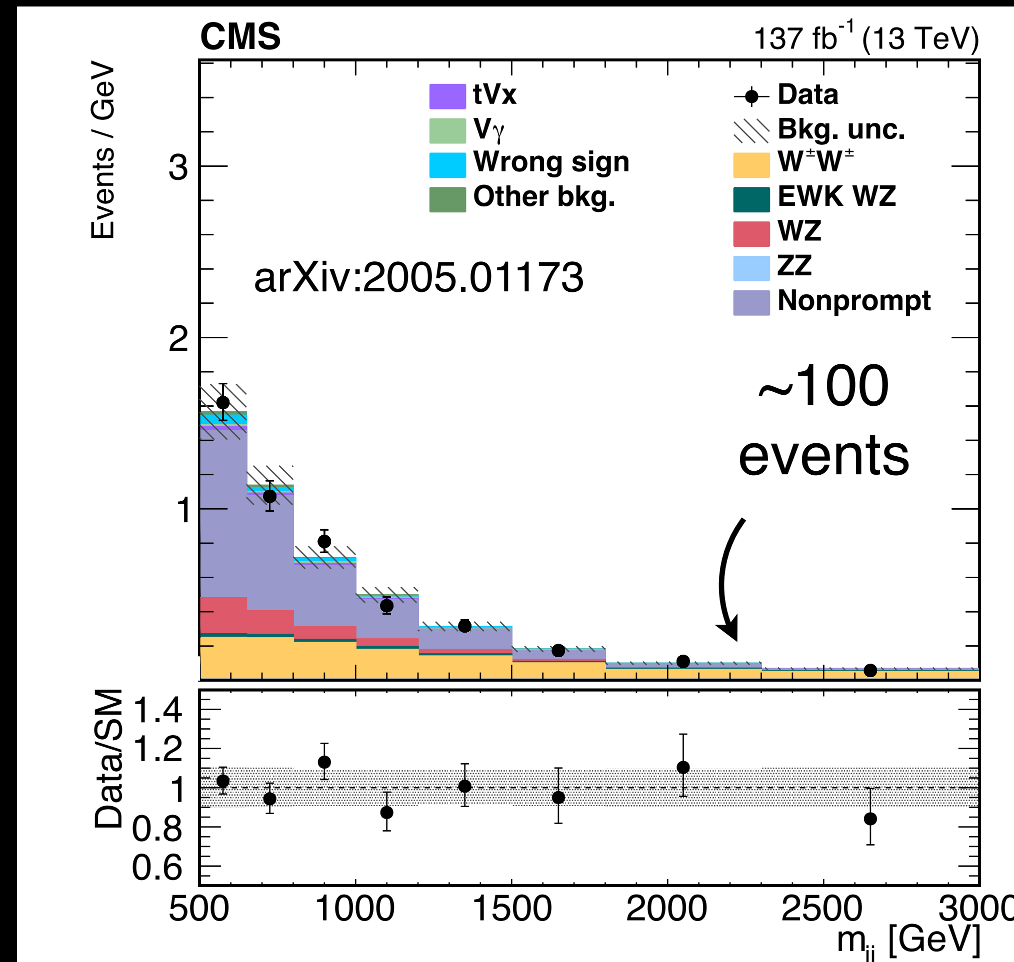
Excellent jet reconstruction and simulation

Jets from vector boson scattering

WW scattering

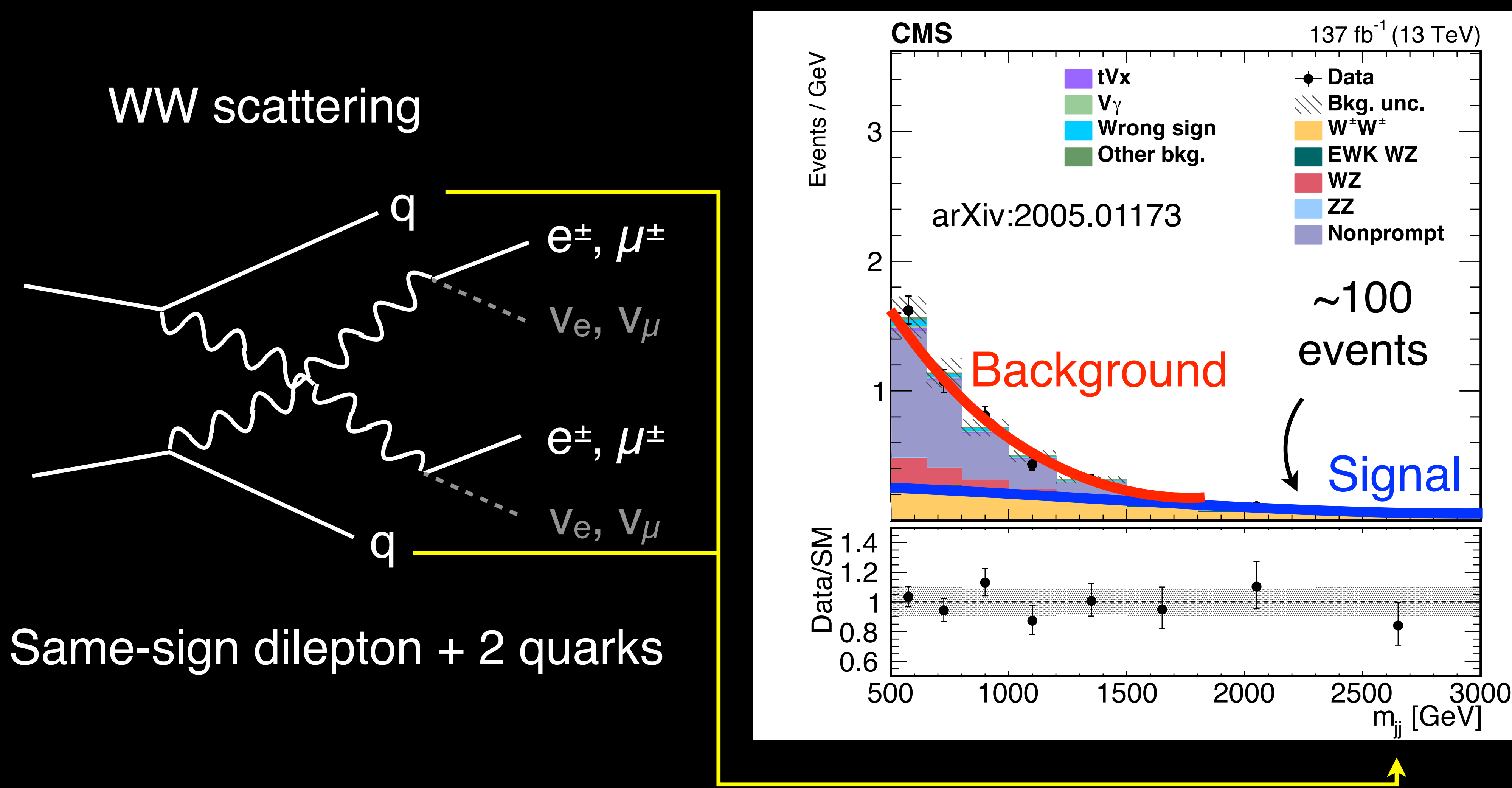


Same-sign dilepton + 2 quarks



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

Jets from vector boson scattering

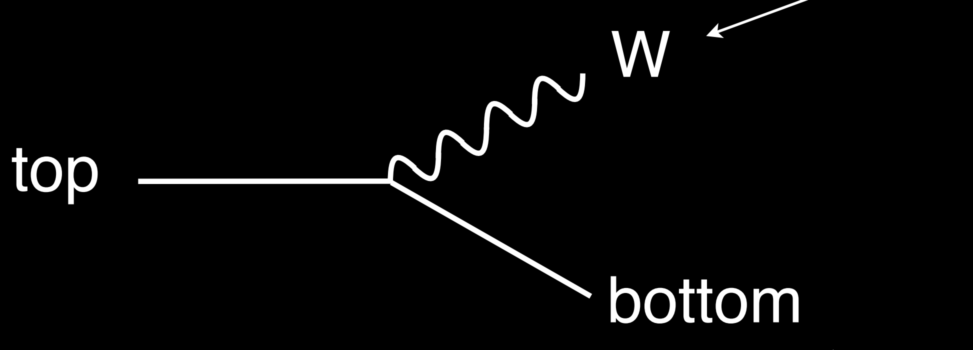


Two jets from VBS process tend to have relatively high invariant mass

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



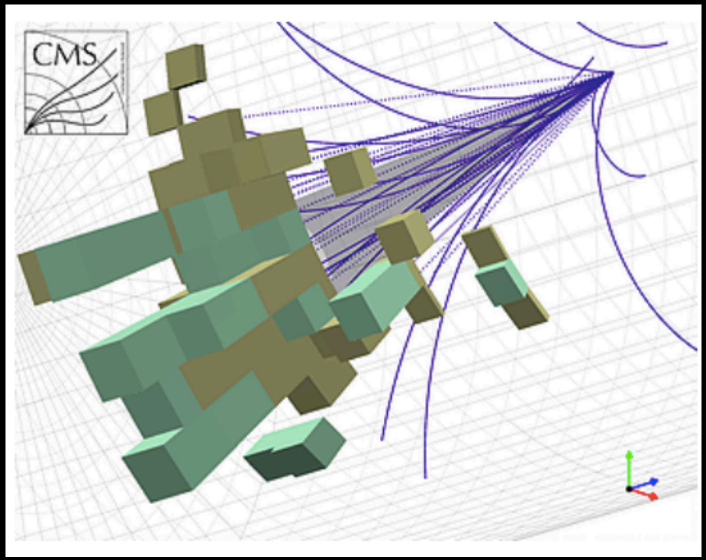
When produced top quark decays ~100% of the time to b quark and a W boson

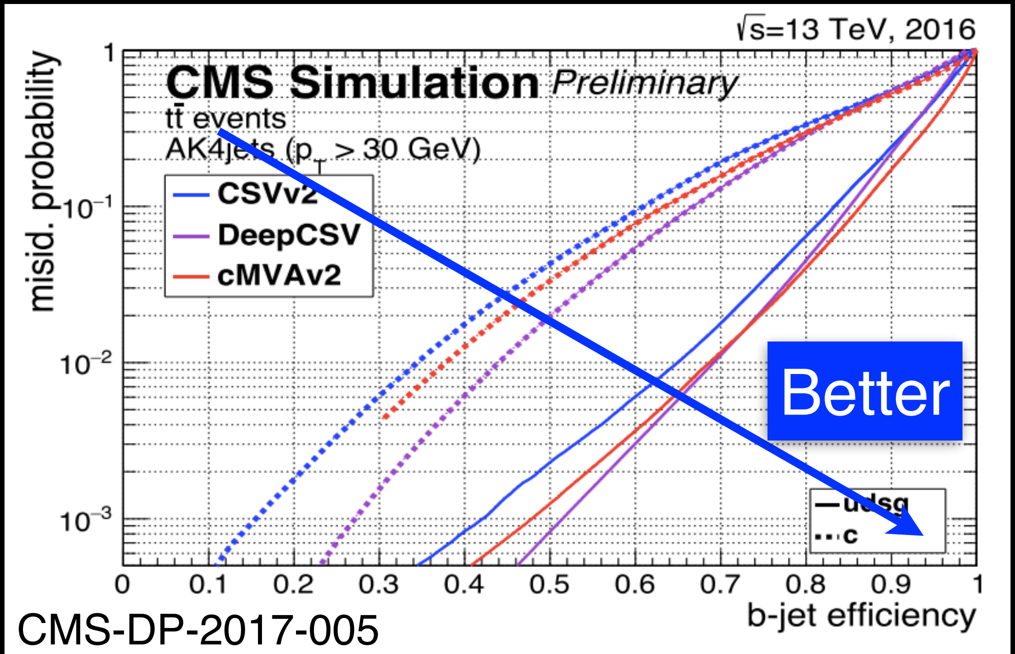
bottom quark has a long-lifetime (flight distance ~ 100s of μm)

⇒ Tag bottom quark and reject events with bottom quarks

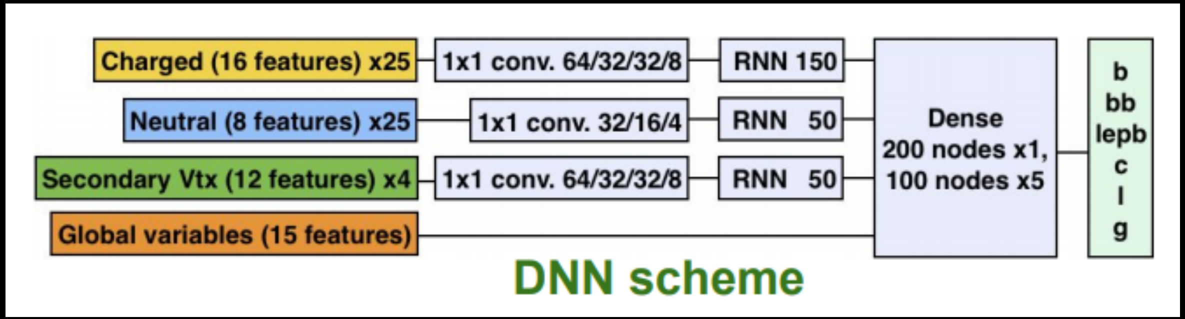
Machine learning in LHC

Was this from bottom quark?



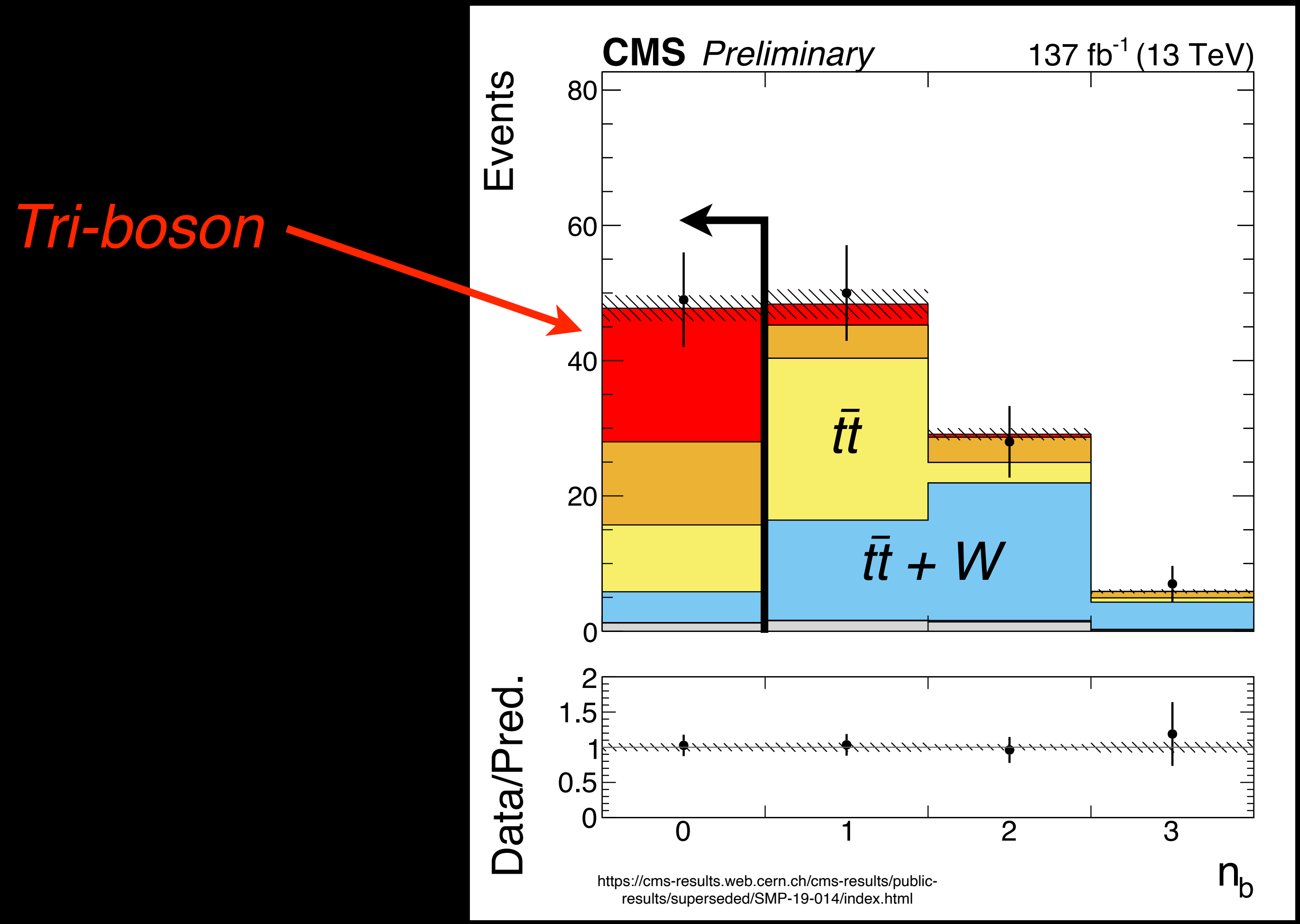


Train deep neural network



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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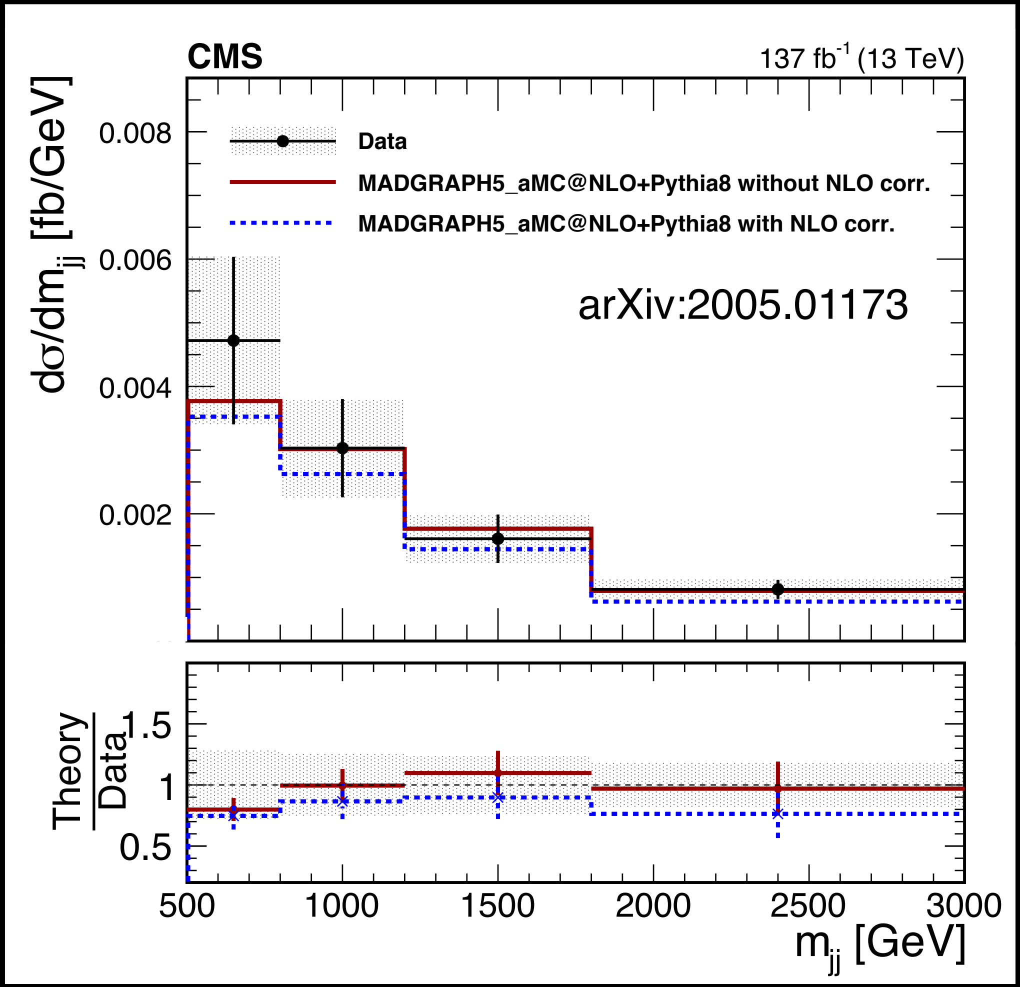

- O(100) events observed
- Measure the production rates as a function of important variables
- The measured cross section is compatible with the SM

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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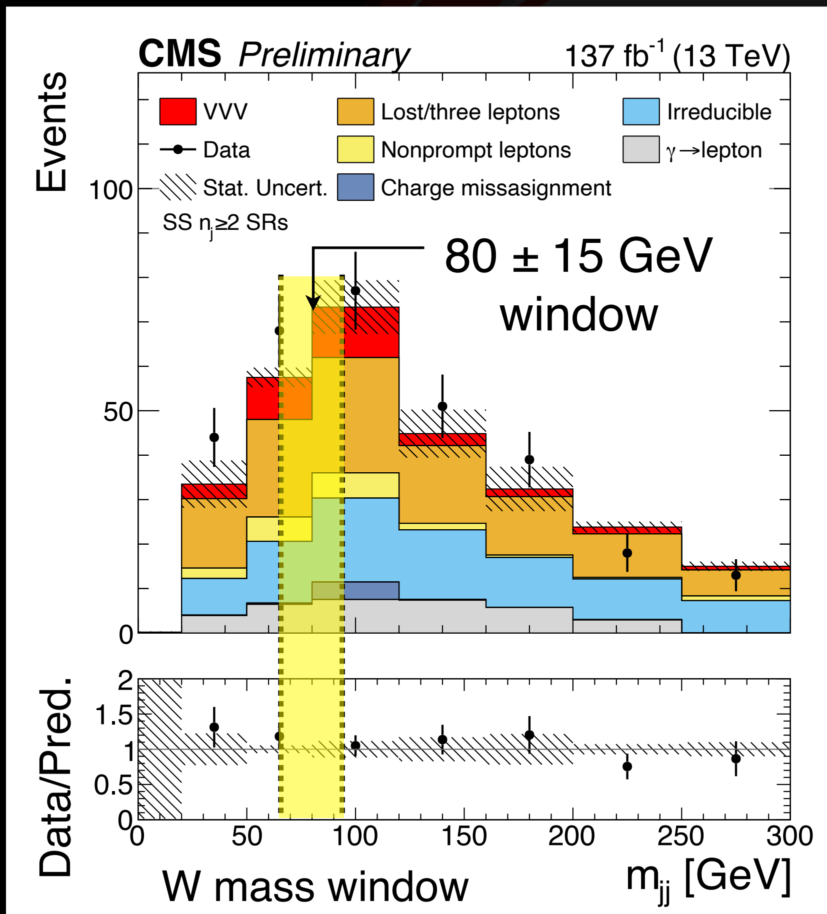
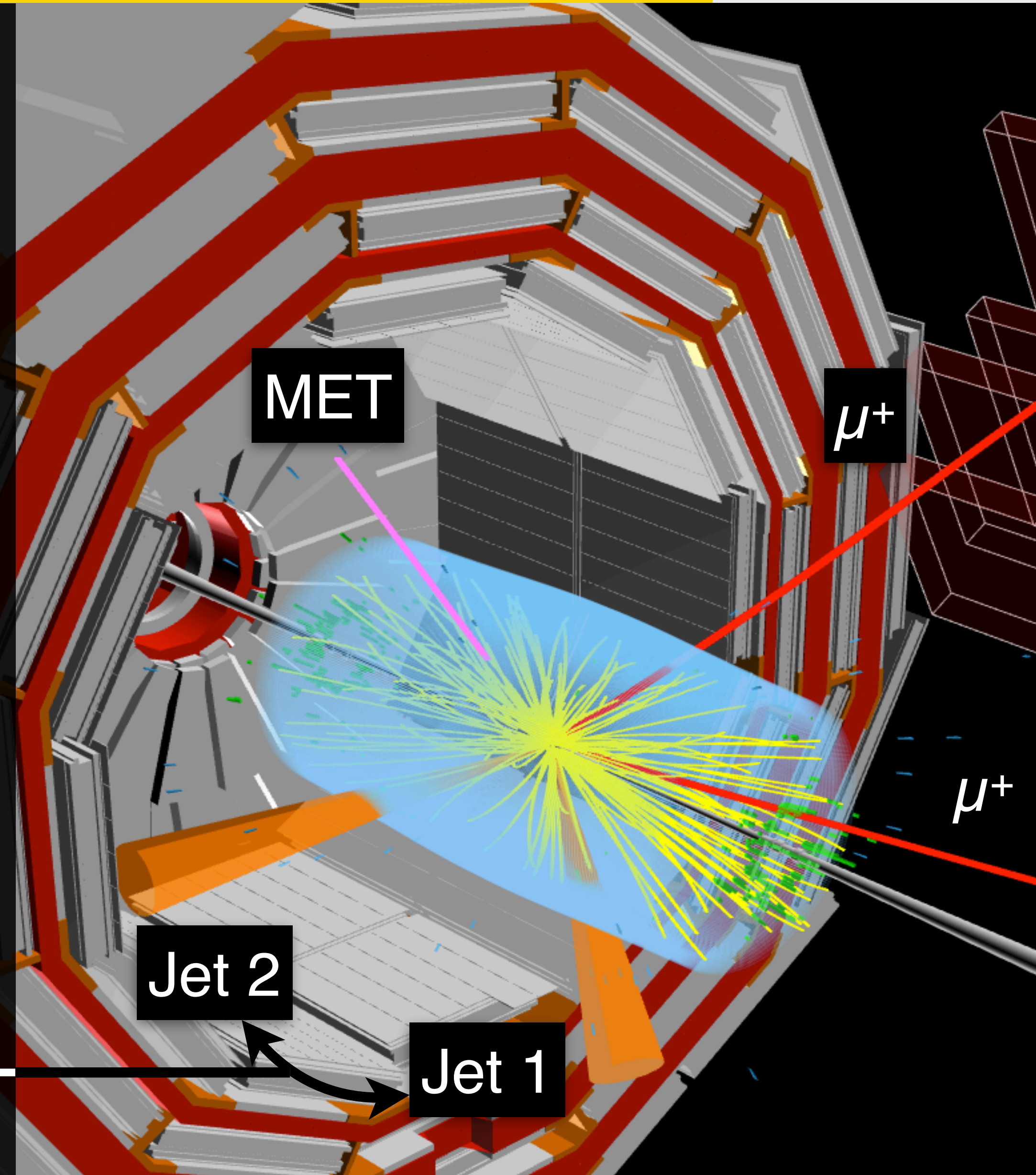
UCSD

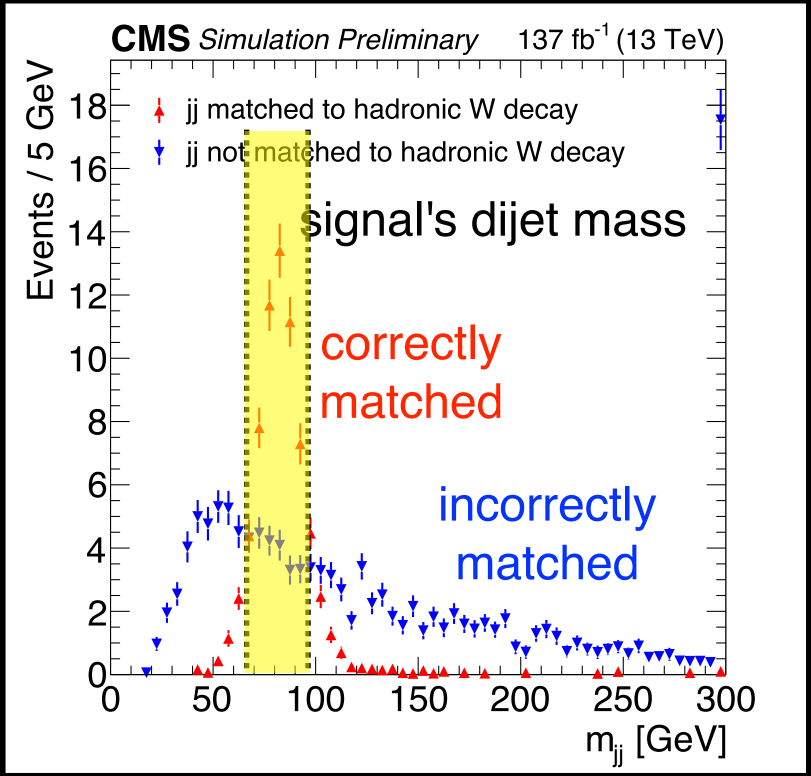


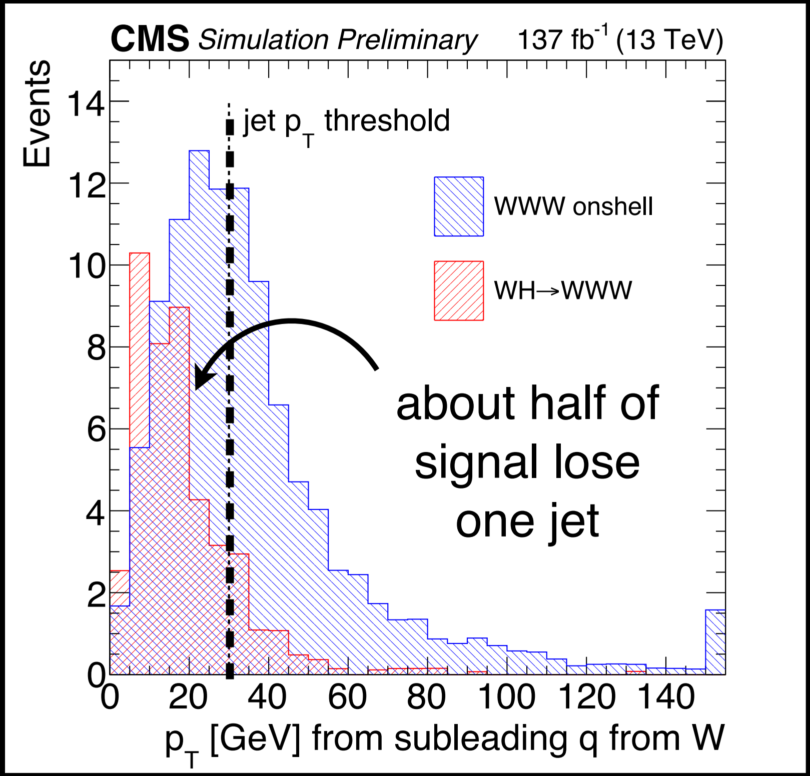
N.B. some signals are outside the window (See next slide)



dijet invariant mass for signal peaks around W mass

Difficulties in jet final states





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

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

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

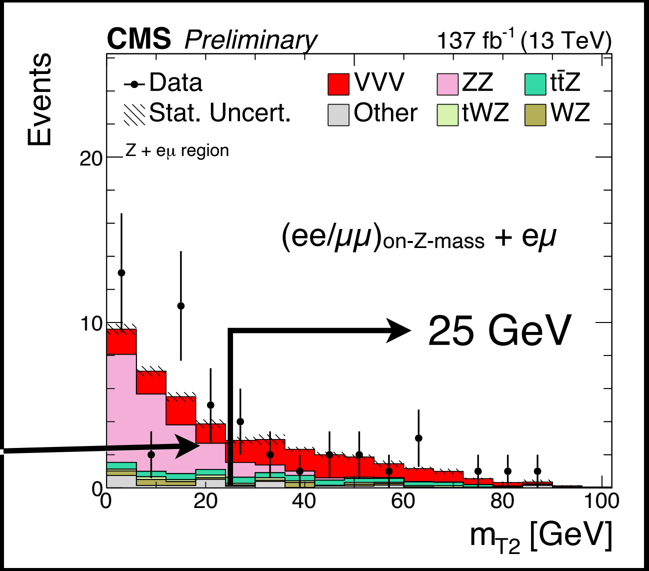
We cover wide range of possible jet final states to maximize sensitivity

Kinematic endpoints for 4 leptons

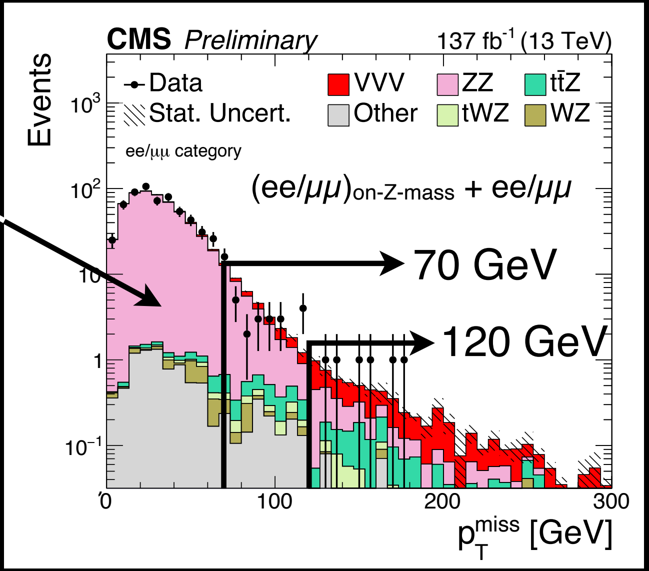
Events are separated into 2 categories by flavor:

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

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



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

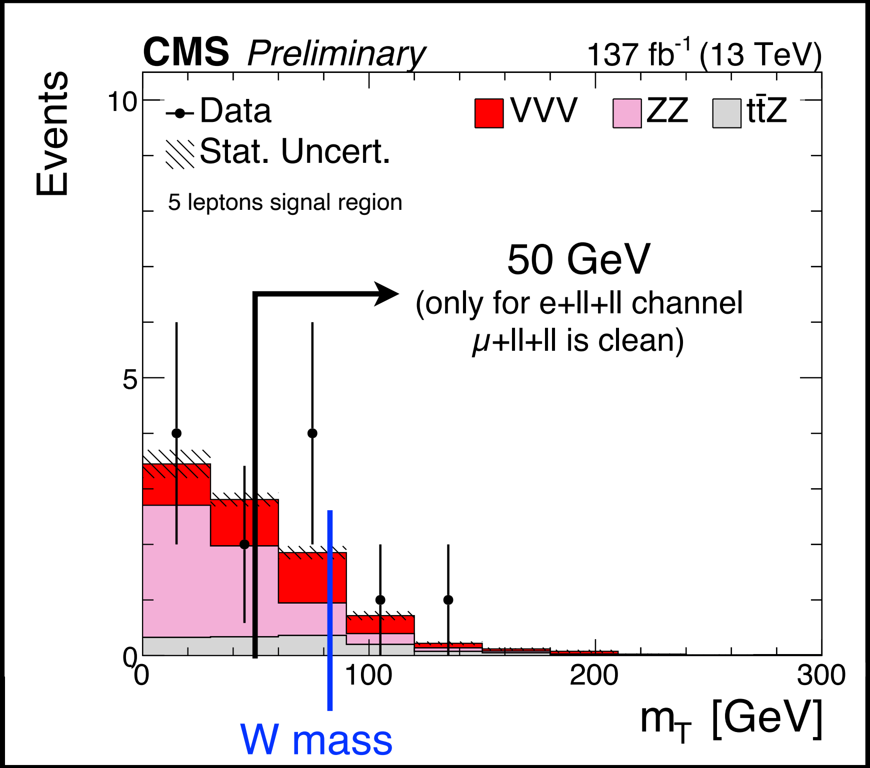
5 leptons target W **Z Z** signal

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

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

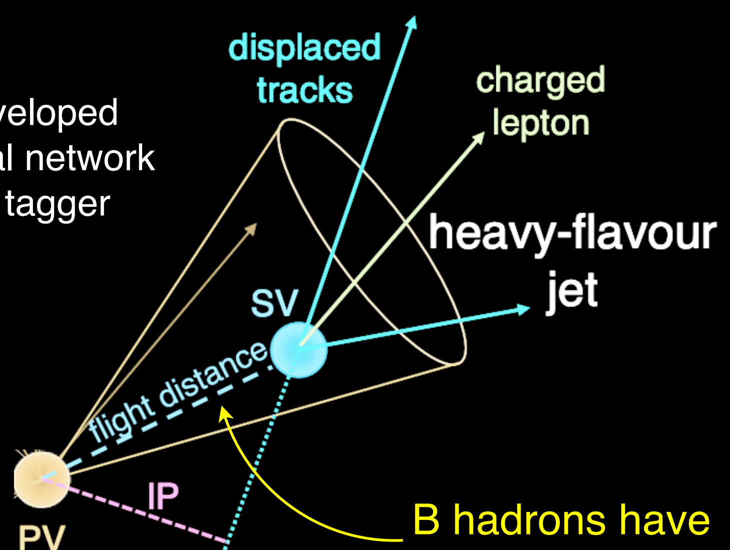
Types of backgrounds	Suppressed via	Bkg. estimation
Fake leptons	Isolation	Reliably extrapolate across isolation
Backgrounds with *b* jets	*b* tagging	Reliably extrapolate across *b* tagging
Lost leptons	Removing events with 3rd lepton	Reliably extrapolate across N leptons
Irreducible	Smart flavor choices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

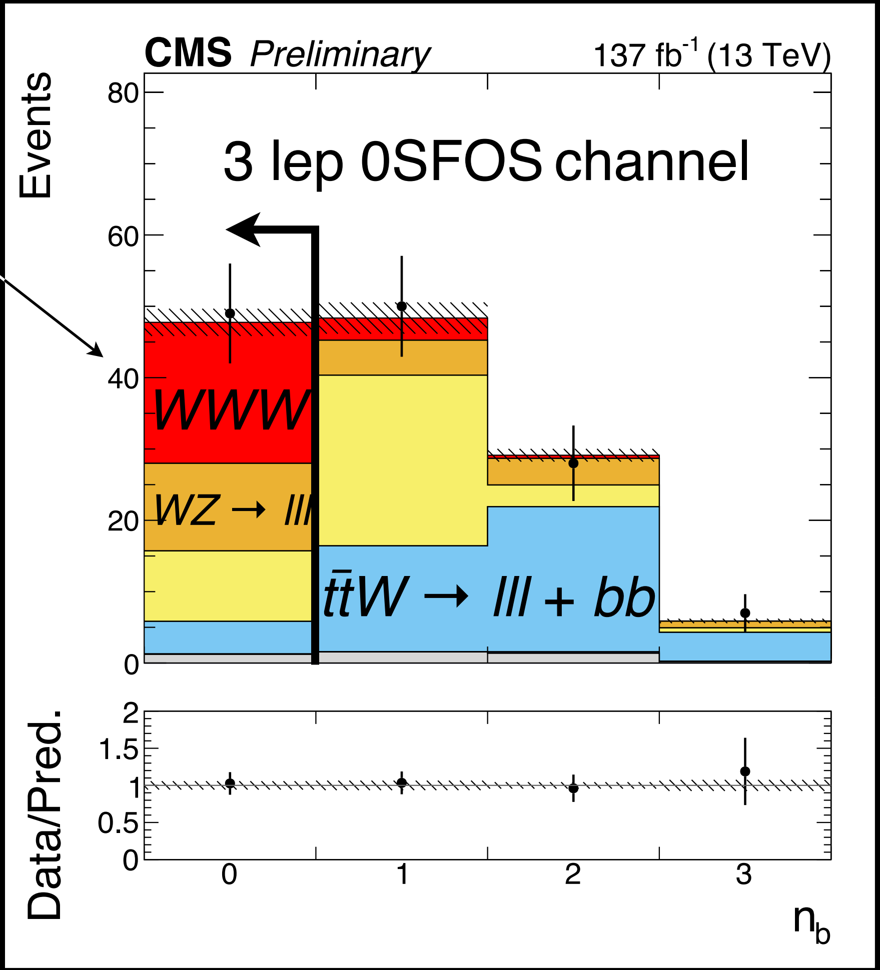
Reliably extrapolate across the method used to suppress background to estimate the size of residual backgrounds in signal region

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

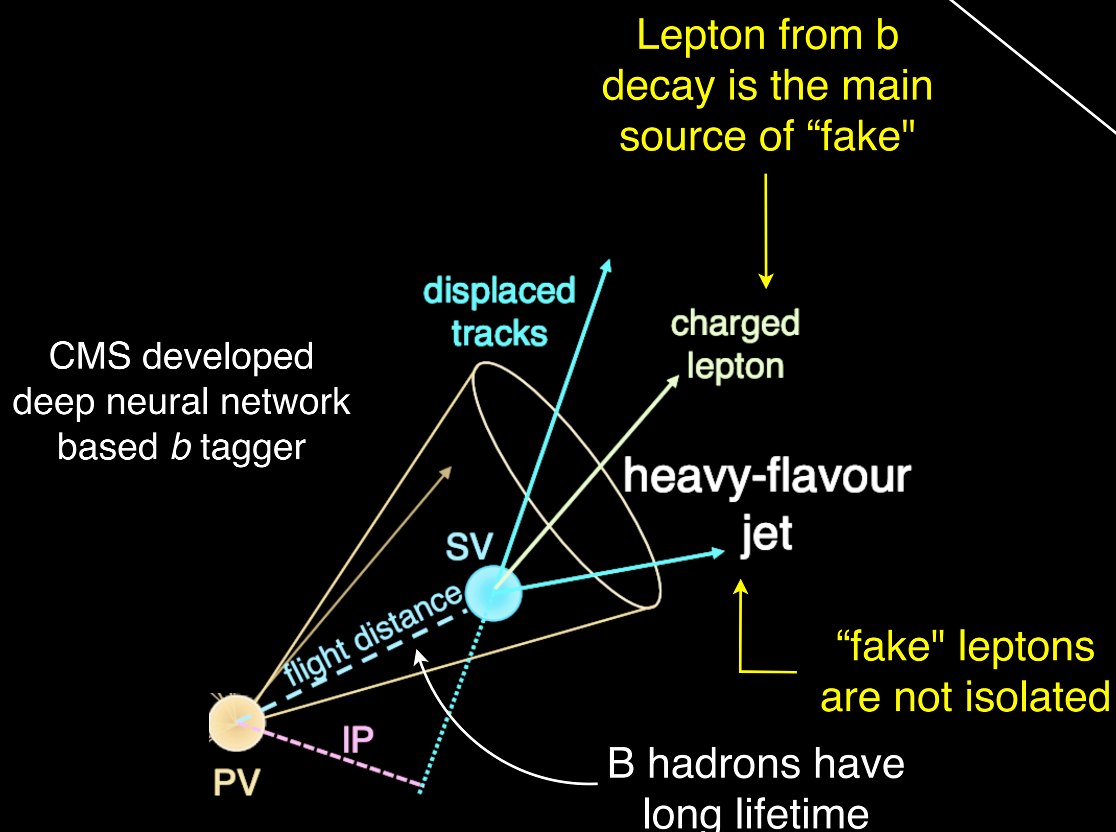


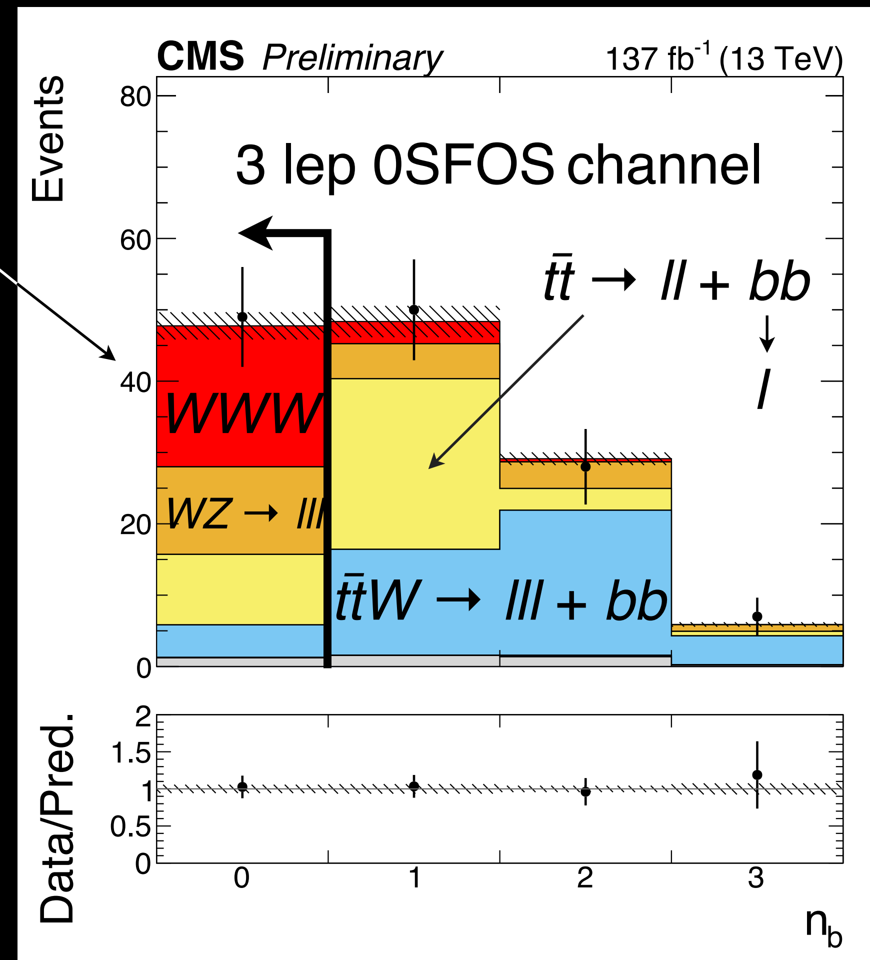


Signals do not have *b* jets

Added benefit of rejecting events with b

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





Signals do not have *b* jets

WZ background in same-sign channel

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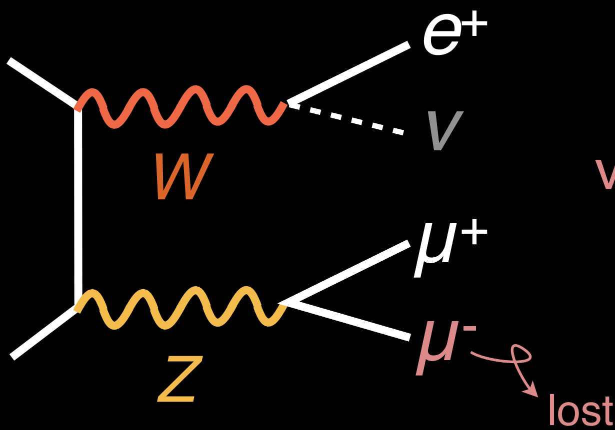
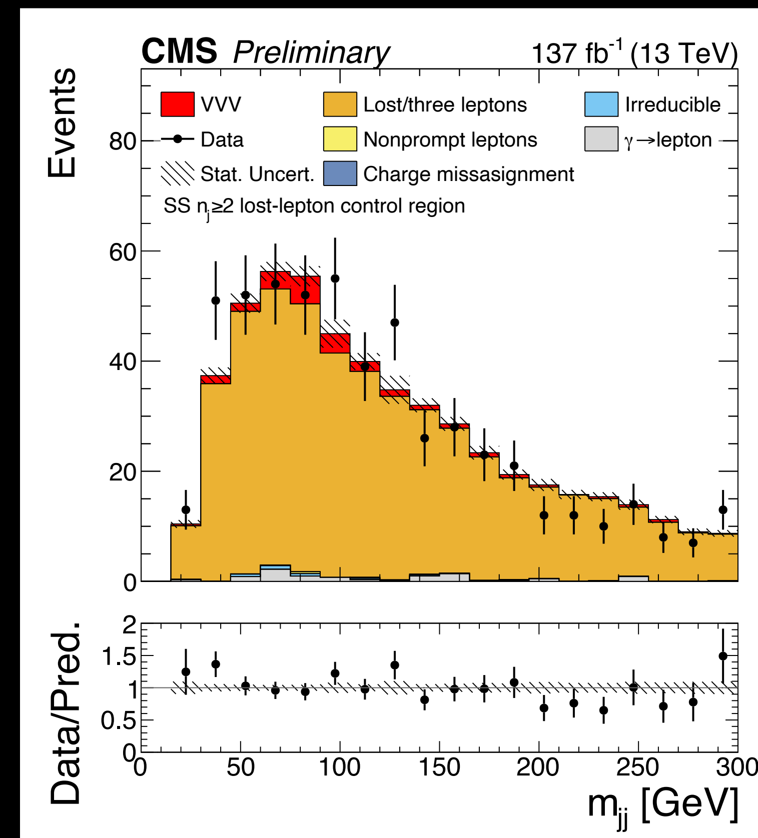


enters signal region via lost lepton ⇒ Need to understand lepton finding efficiency



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

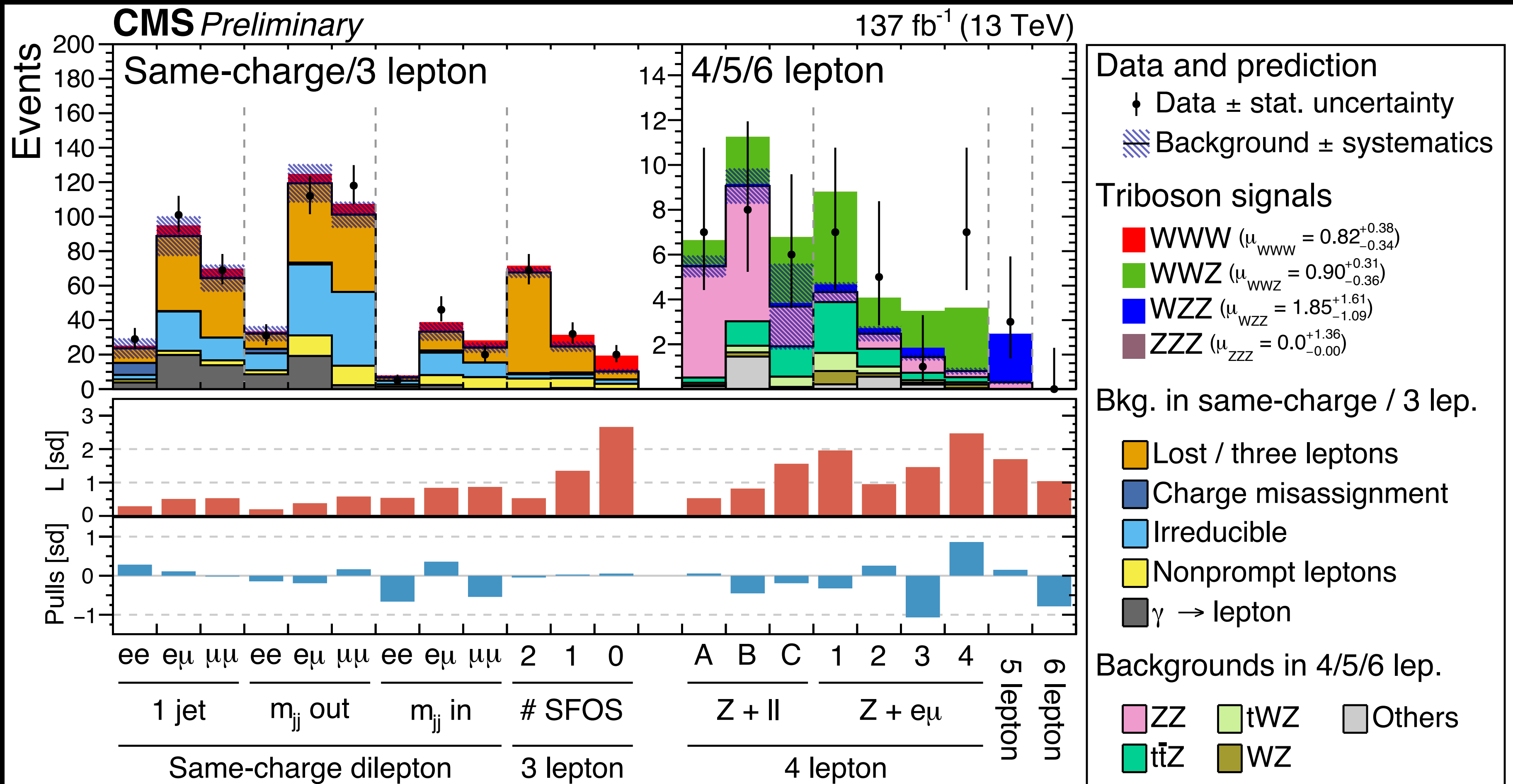
Experimental systematics assigned

Control region data statistics dominates uncertainty (20%)

Estimate lost lepton background by extrapolating across # of leptons

Results (Cut-based analysis)

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)

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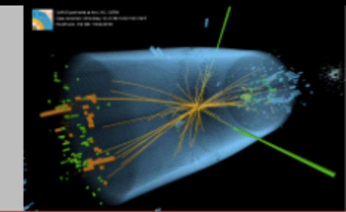
Compact Muon Solenoid

LHC, CERN



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