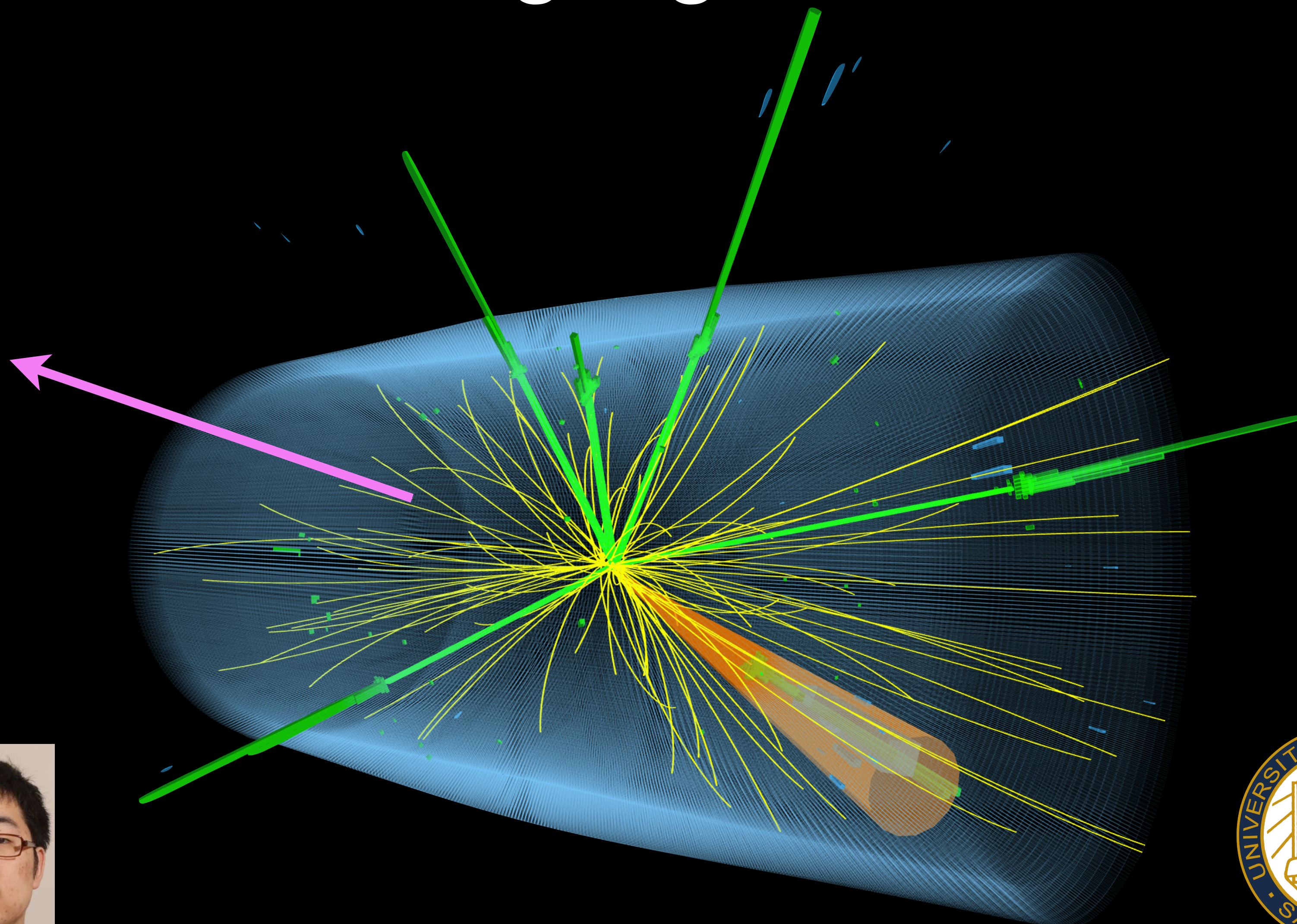
First observation of the production of three massive gauge bosons at CMS



Philip Chang

HEP seminar UPenn
September 30, 2020

Univ. of California San Diego

Outline

Chang UCSD

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

Completing the Standard Model

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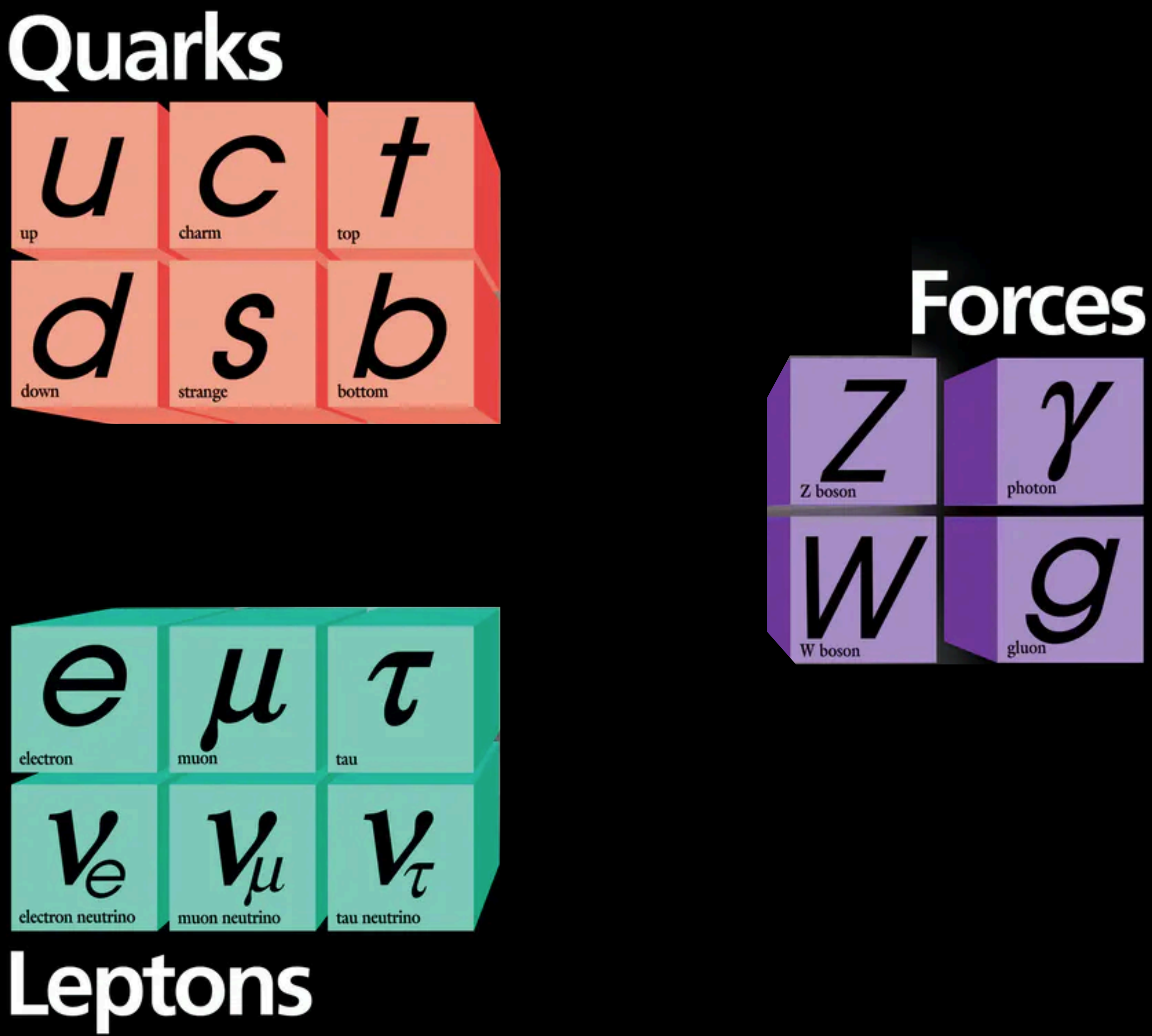
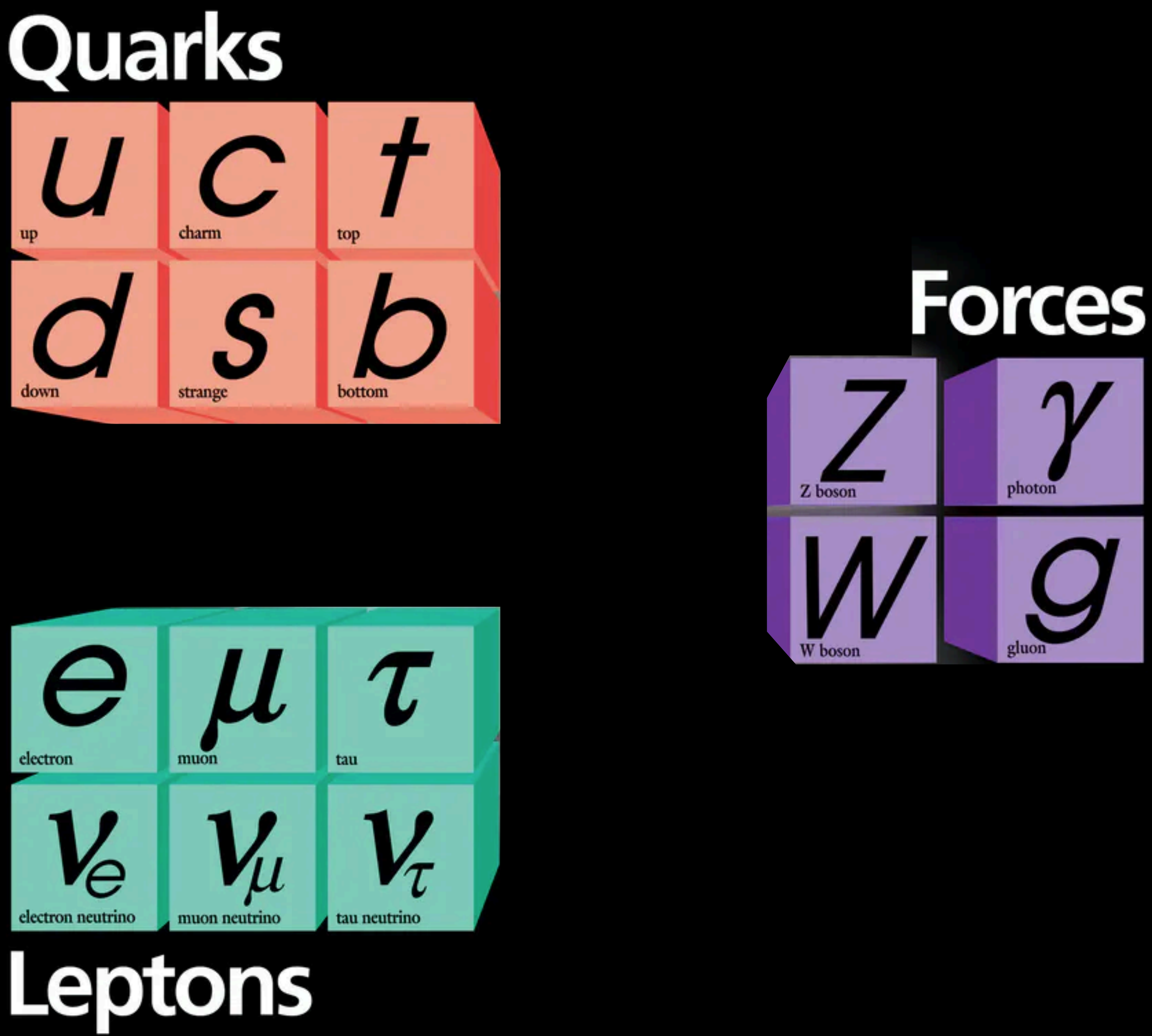


Completing the Standard Model

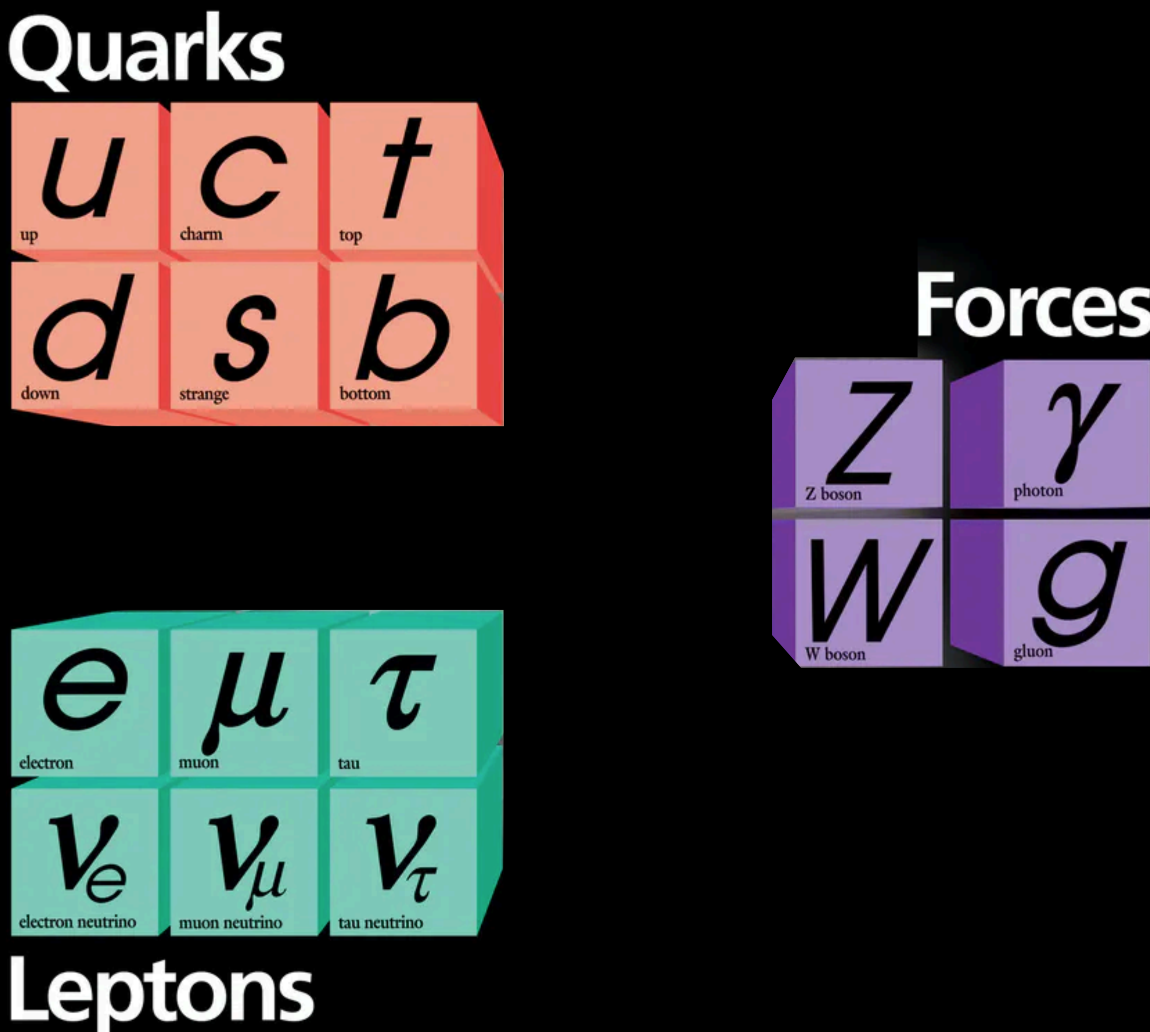


Spin 1

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

⇒ EW symmetry is broken

Completing the Standard Model



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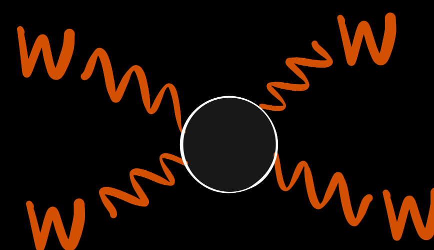
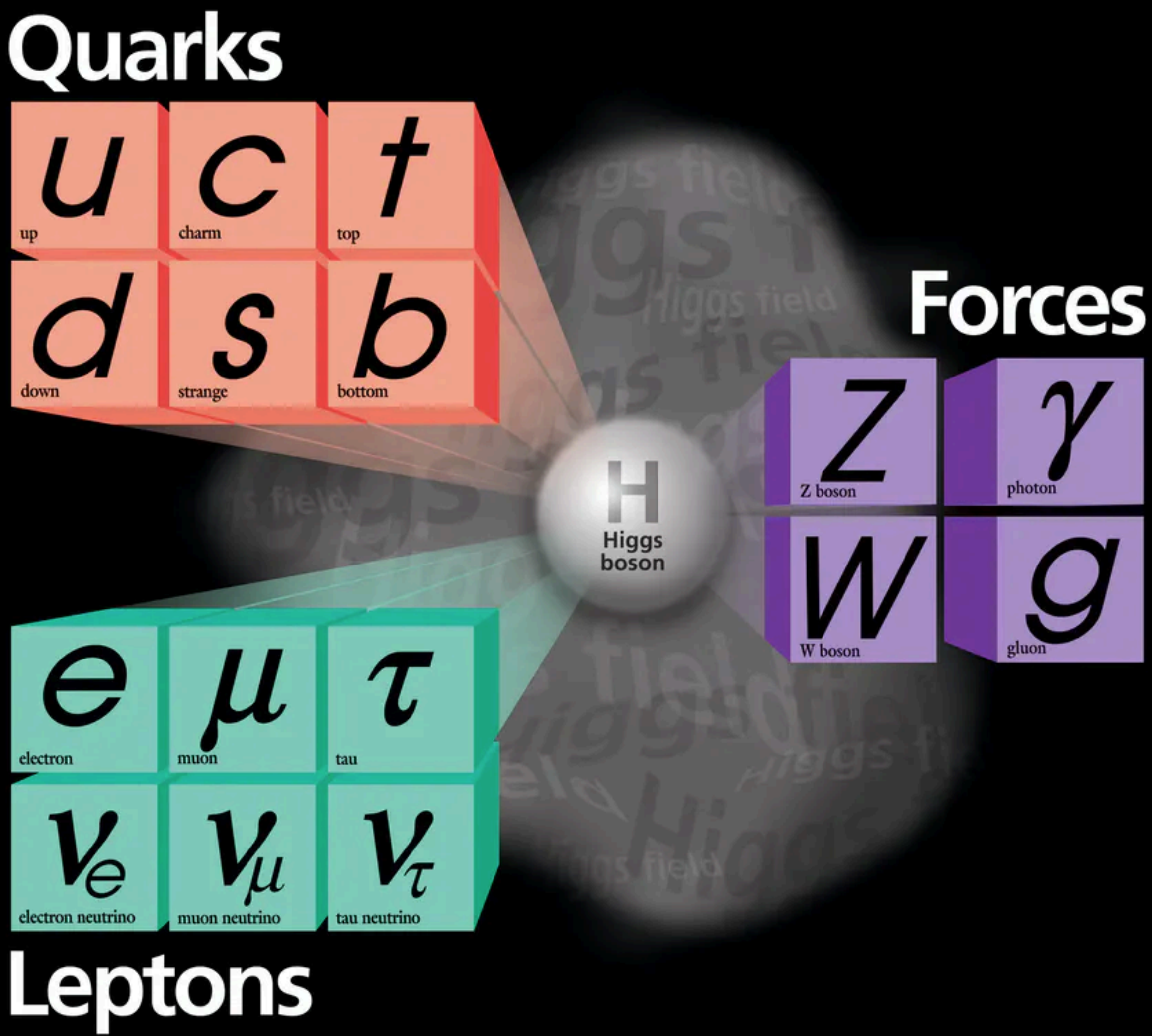


bad ~high energy behavior
(Lee, Quigg, Thacker 1977)

Completing the Standard Model



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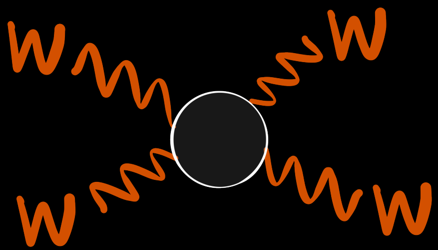

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Spin 0

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

Completing the Standard Model

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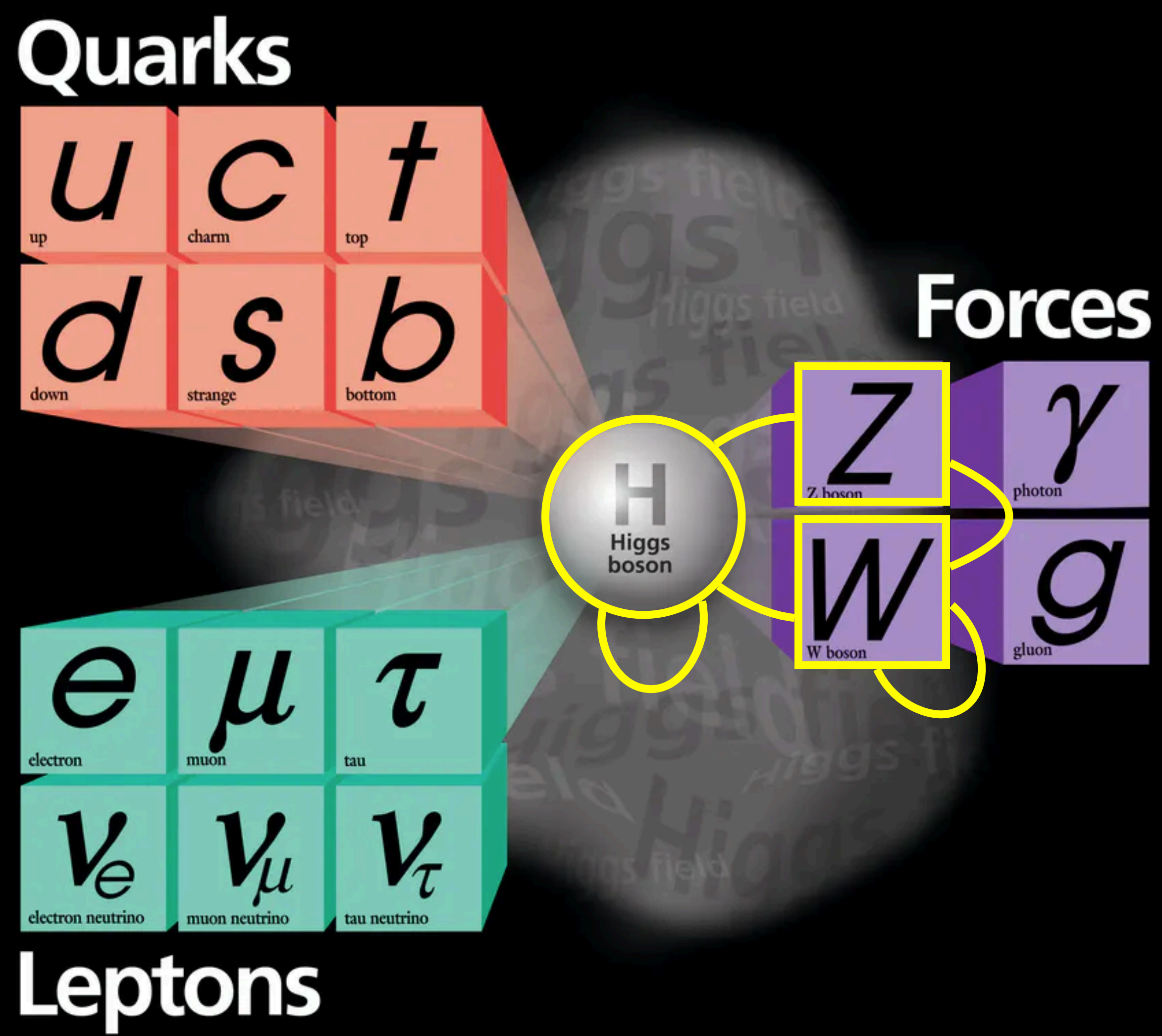

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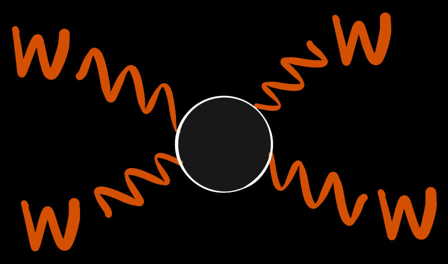

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Spin 0

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

⇒ Completes the EW sector

Last missing piece of the SM has been found

Completing the electroweak sector

≠

Understanding the electroweak sector

More work to be done in electroweak sector

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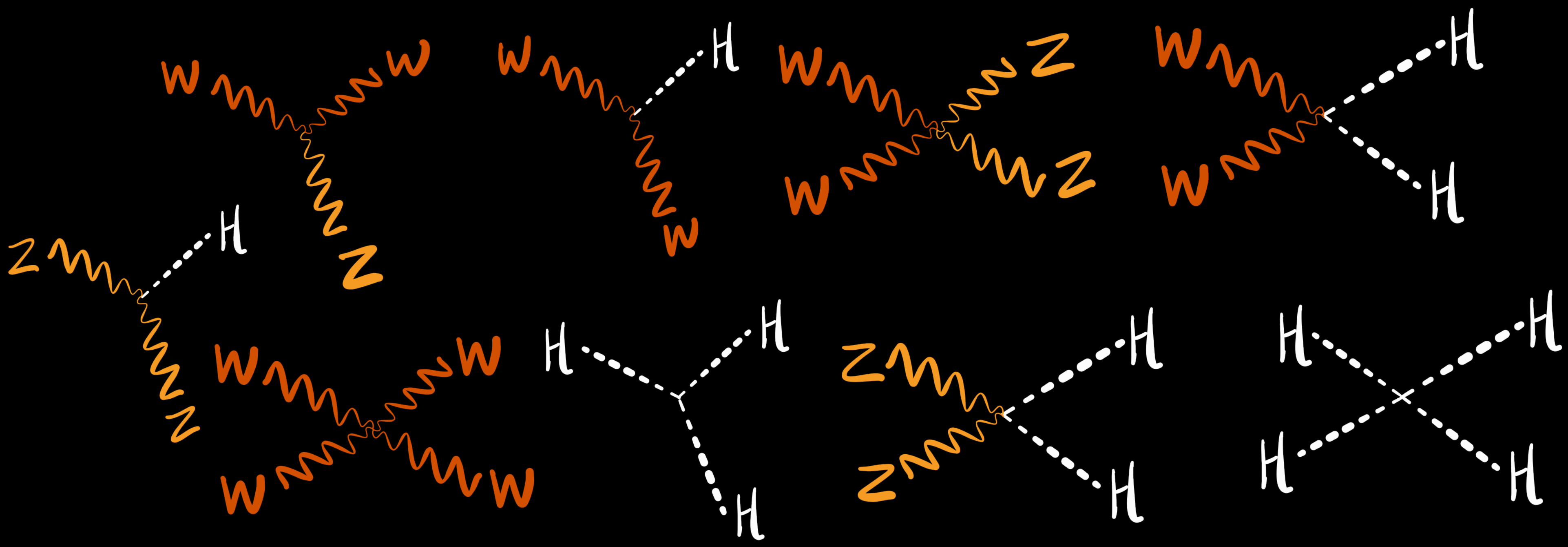
List of multi-(massive)-boson interactions

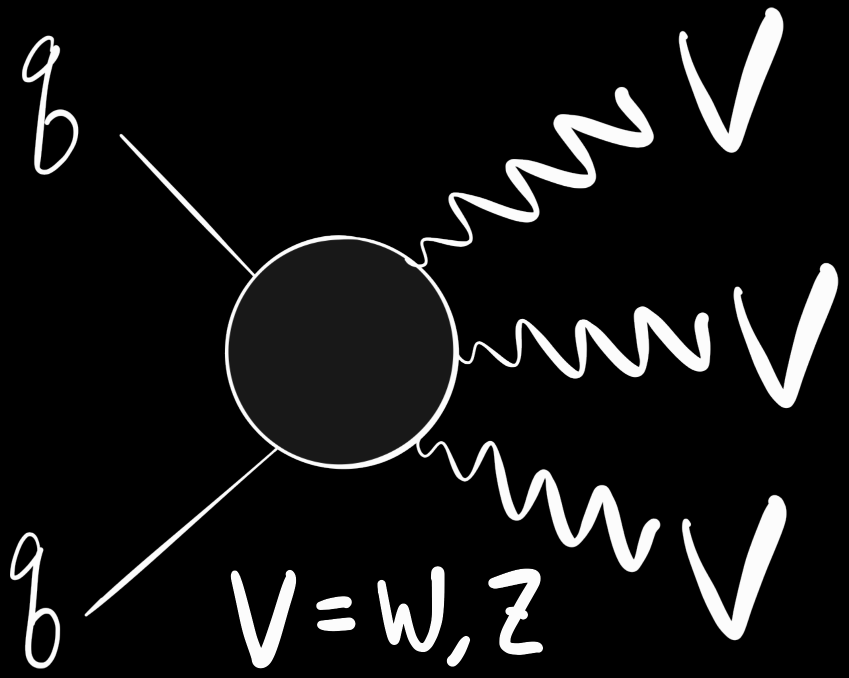


- Are multi-*bosons* interactions SM?
- Is it the only Higgs boson? (or are there more? H_1, H_2, $H^{\pm}$, … ??)
- If so, what are their role in the electroweak symmetry breaking?

Now, we must understand the electroweak sector

Multi-boson production process

Consider multi-boson *production* process
Many diagrams contribute to the process



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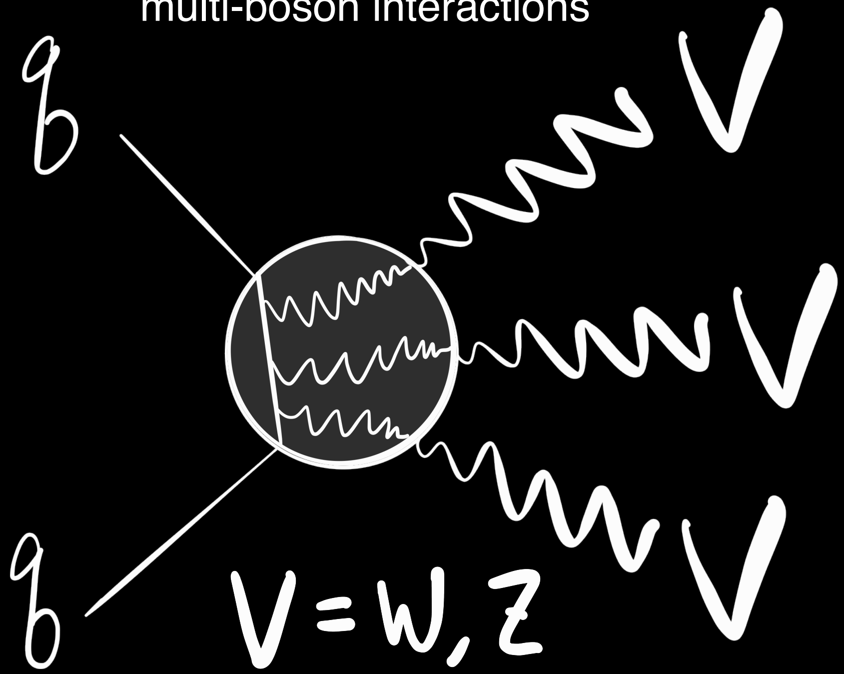
some diagrams are without multi-boson interactions



Multi-boson production process

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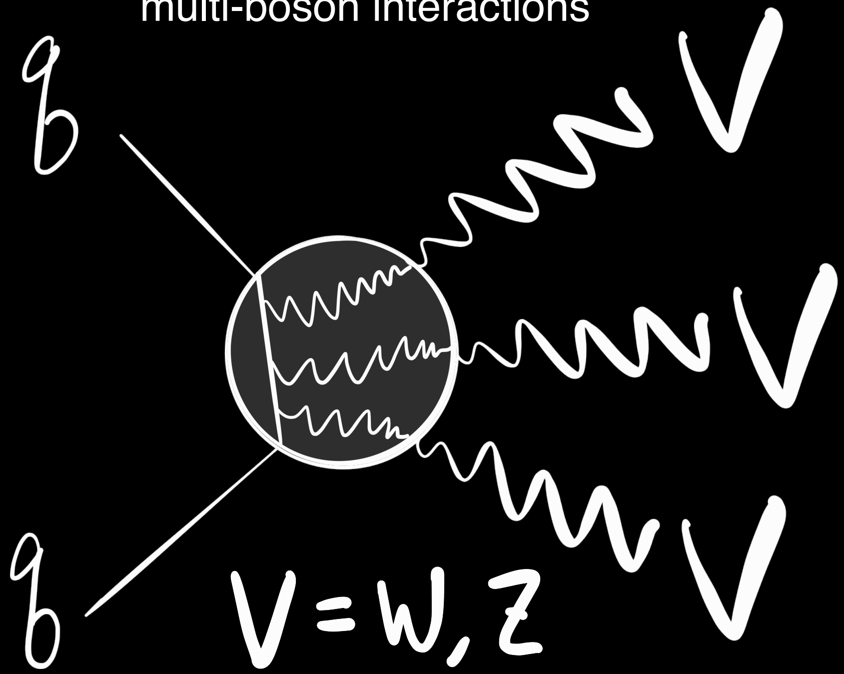

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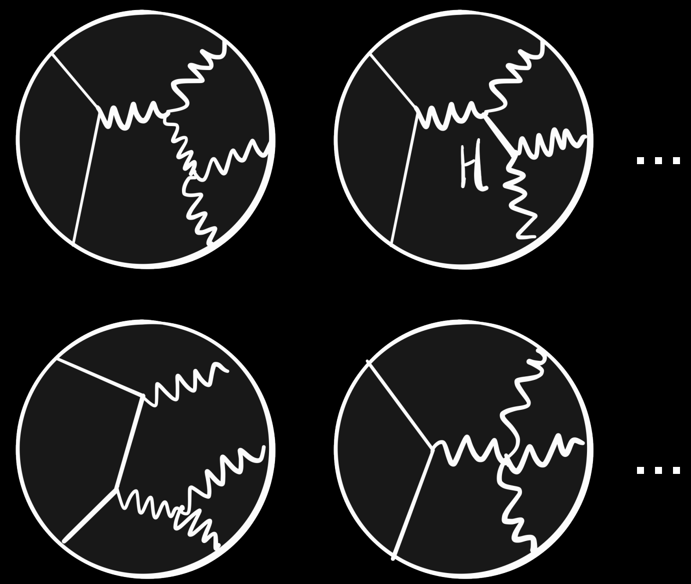

Details of multi-boson interaction determine multi-boson production rate

Study multi-boson production to study MBI

Multi-boson production process

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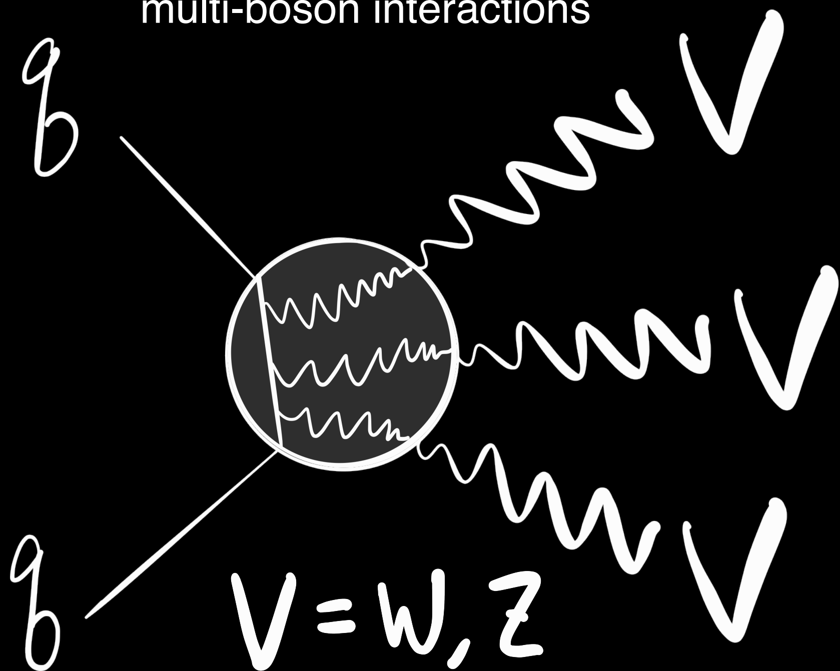
Consider multi-boson *production* process
Many diagrams contribute to the process

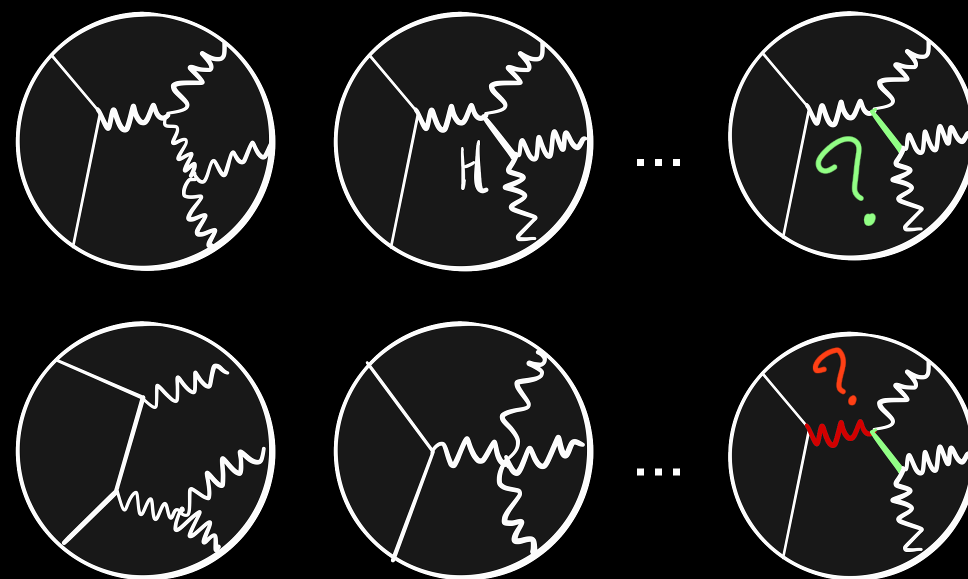
N. Craig, A. Hook, S. Kasko 1805.06538
K. Agashe, J. Colins, P. Du, S. Hong, D. Kim, R. K. Mishra 1711.09920

some diagrams are without multi-boson interactions



some diagrams are with multi-boson interactions

new physics?



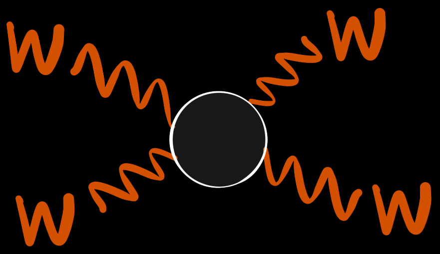
Details of multi-boson interaction determine multi-boson production rate

⇒ If new physics, dynamics of EW sector could be altered

Study multi-boson production to study MBI

Quick aside…

We must understand multi-boson interactions



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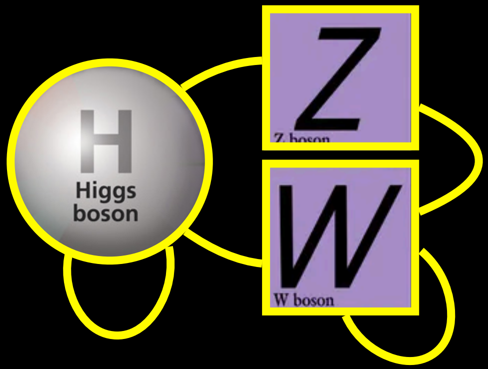
(Lee, Quigg, Thacker 1977)



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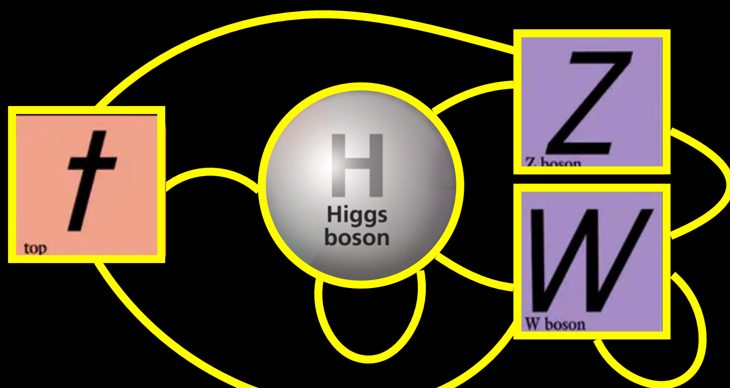
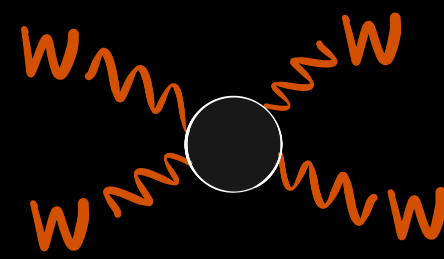
massive-particle



Top quark is
also connected!



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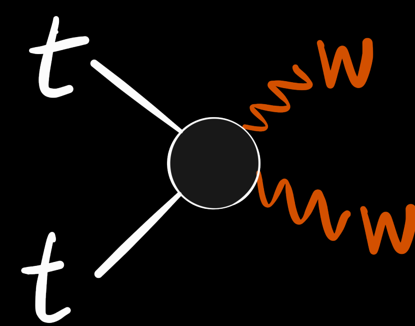

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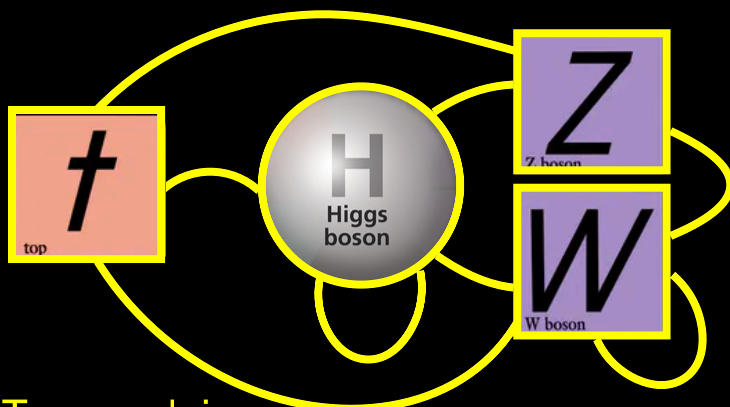

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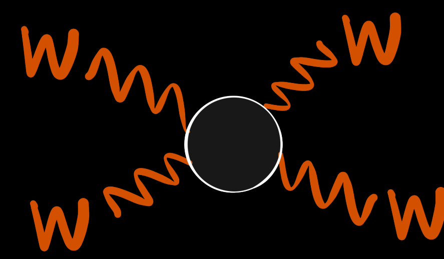

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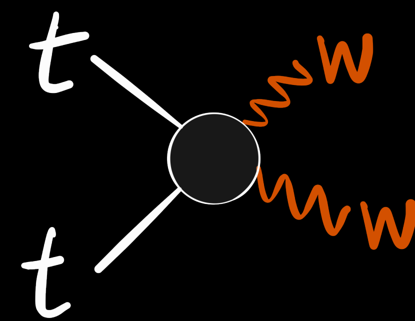

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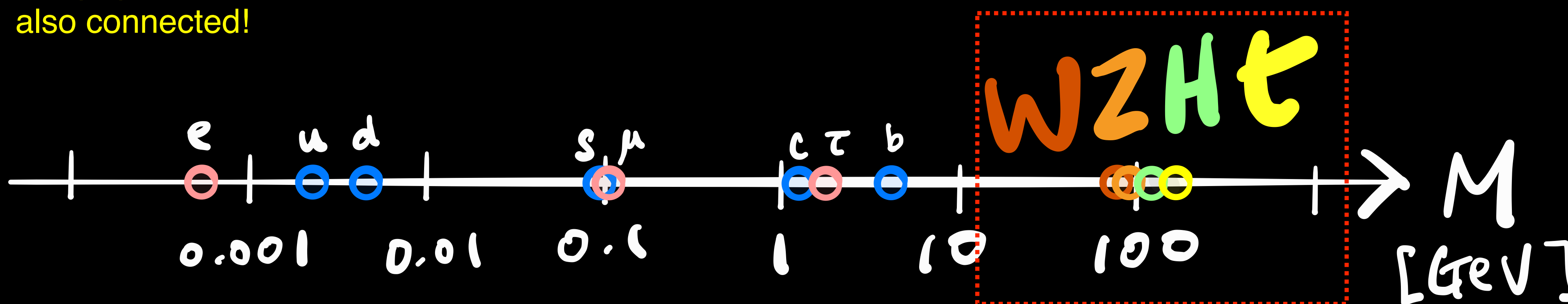

Quick aside…

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We must understand
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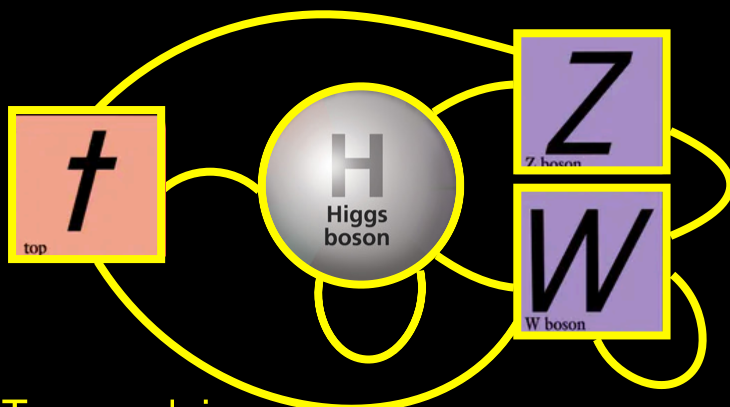

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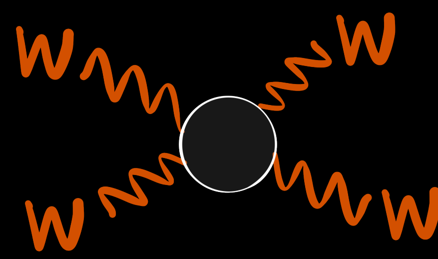

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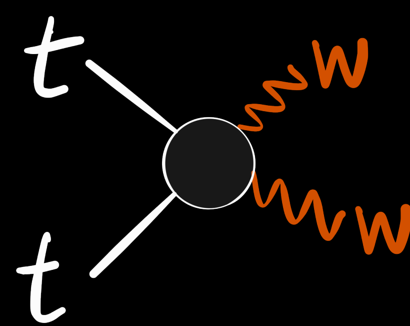

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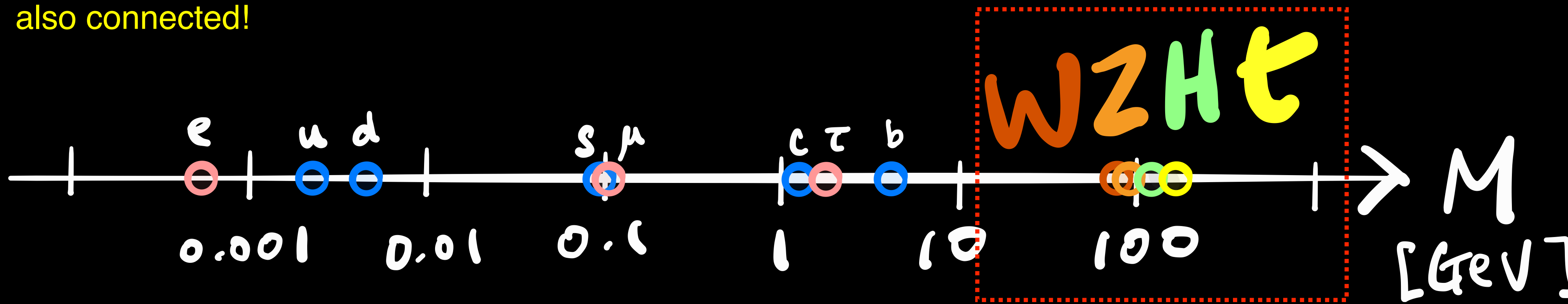
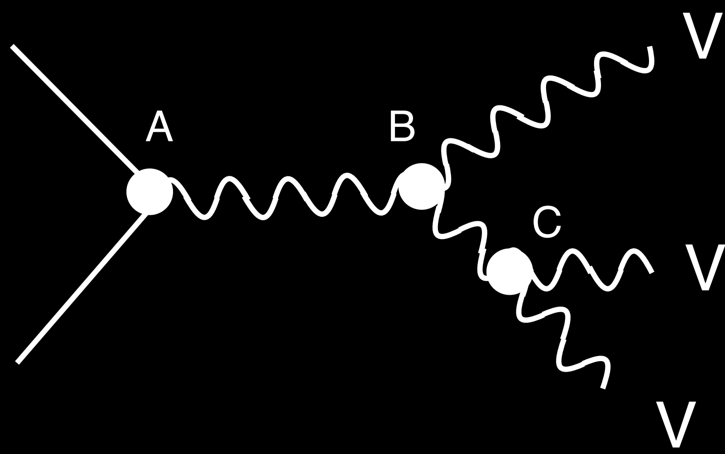


Multi-X ($X = W, Z, H, t$) interactions must be studied

Experimental challenge



$m_V \approx \sim 100$ GeV

Multi-boson productions (MBP) are *rare*

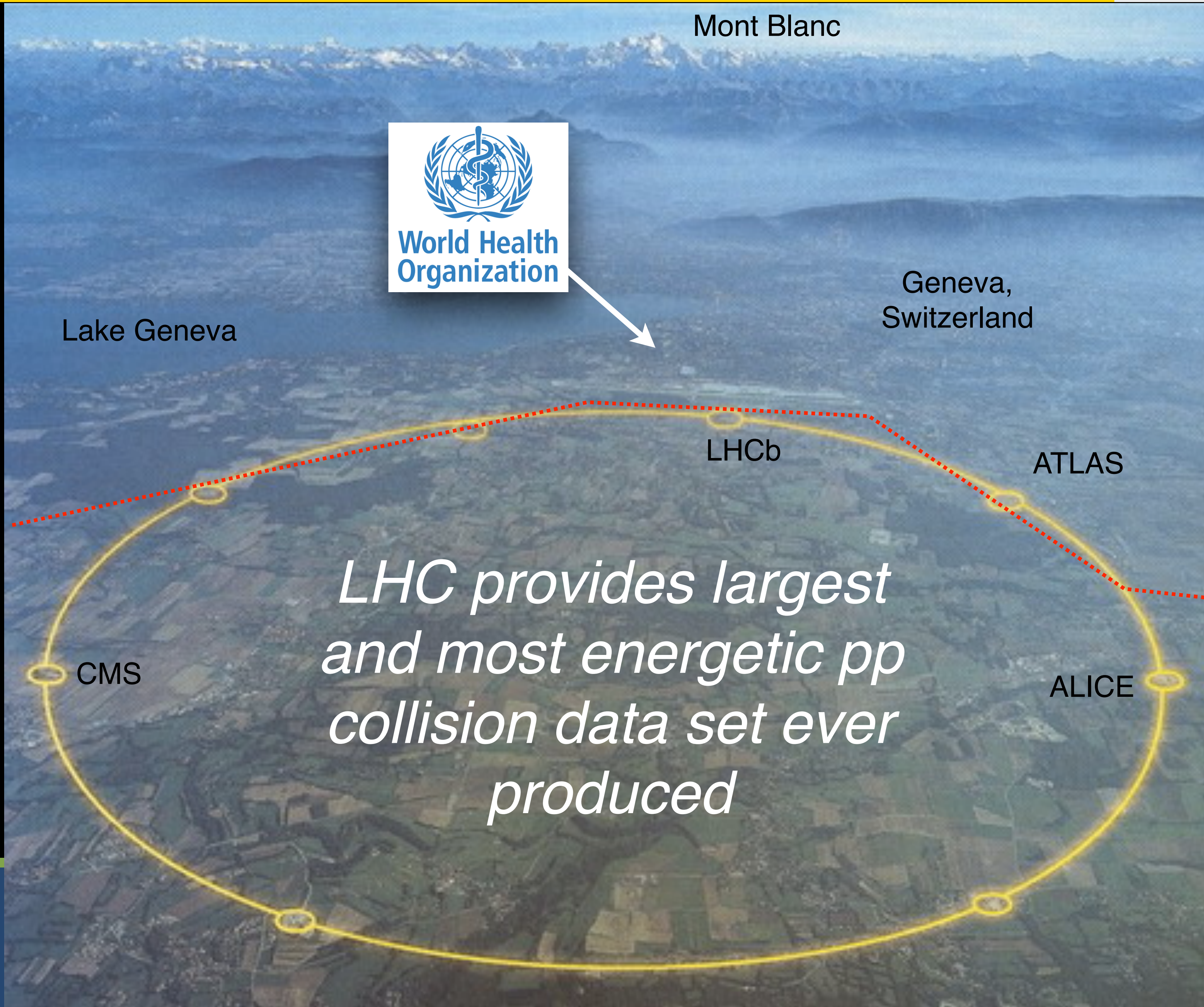
rare because need to produce multiple massive particles

rare because involves multiple electroweak vertices

Three massive gauge boson rate ~ 10 / Trillion pp coll. @ LHC

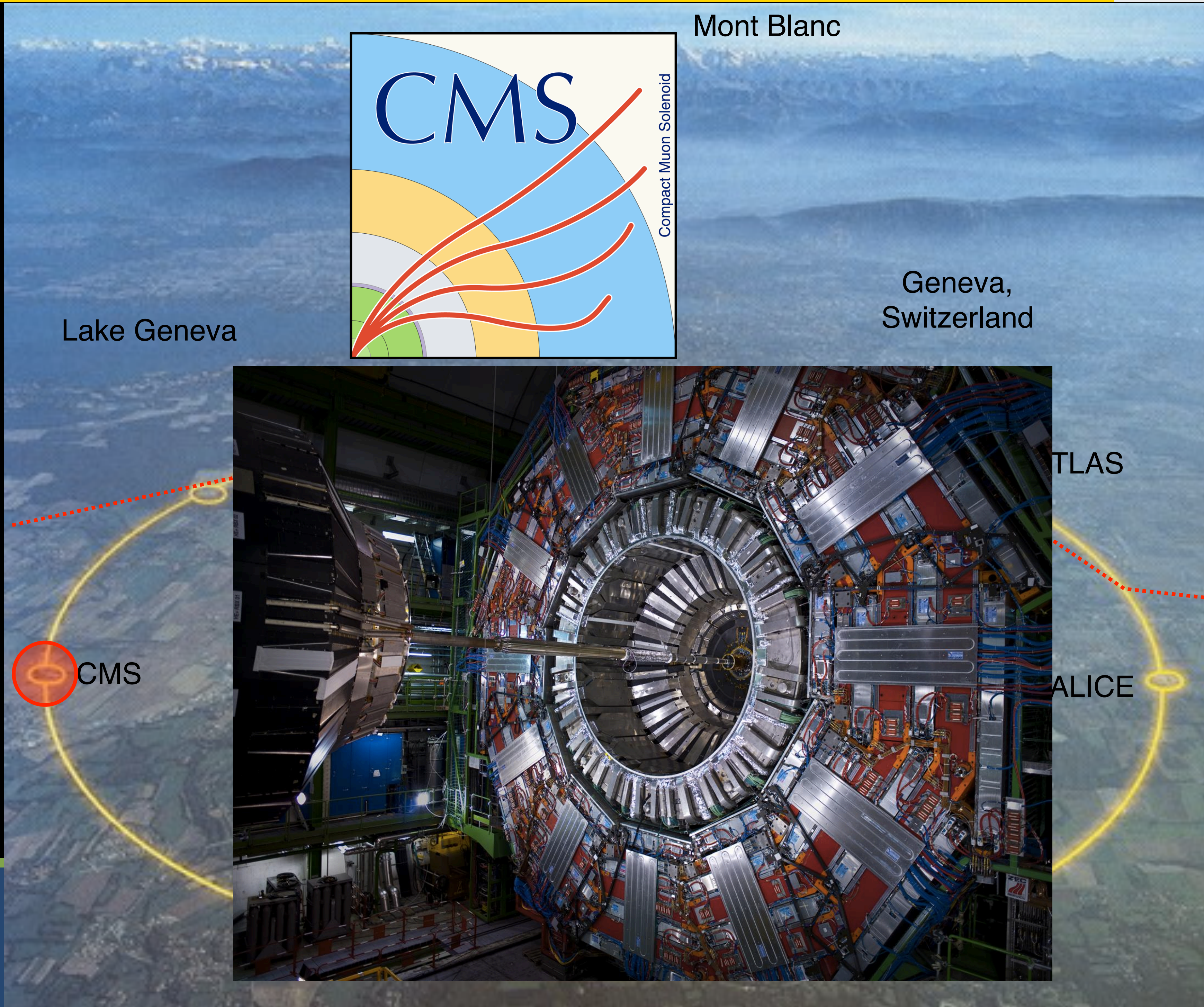
Probing MBP requires energetic and large data set

Large Hadron Collider at CERN



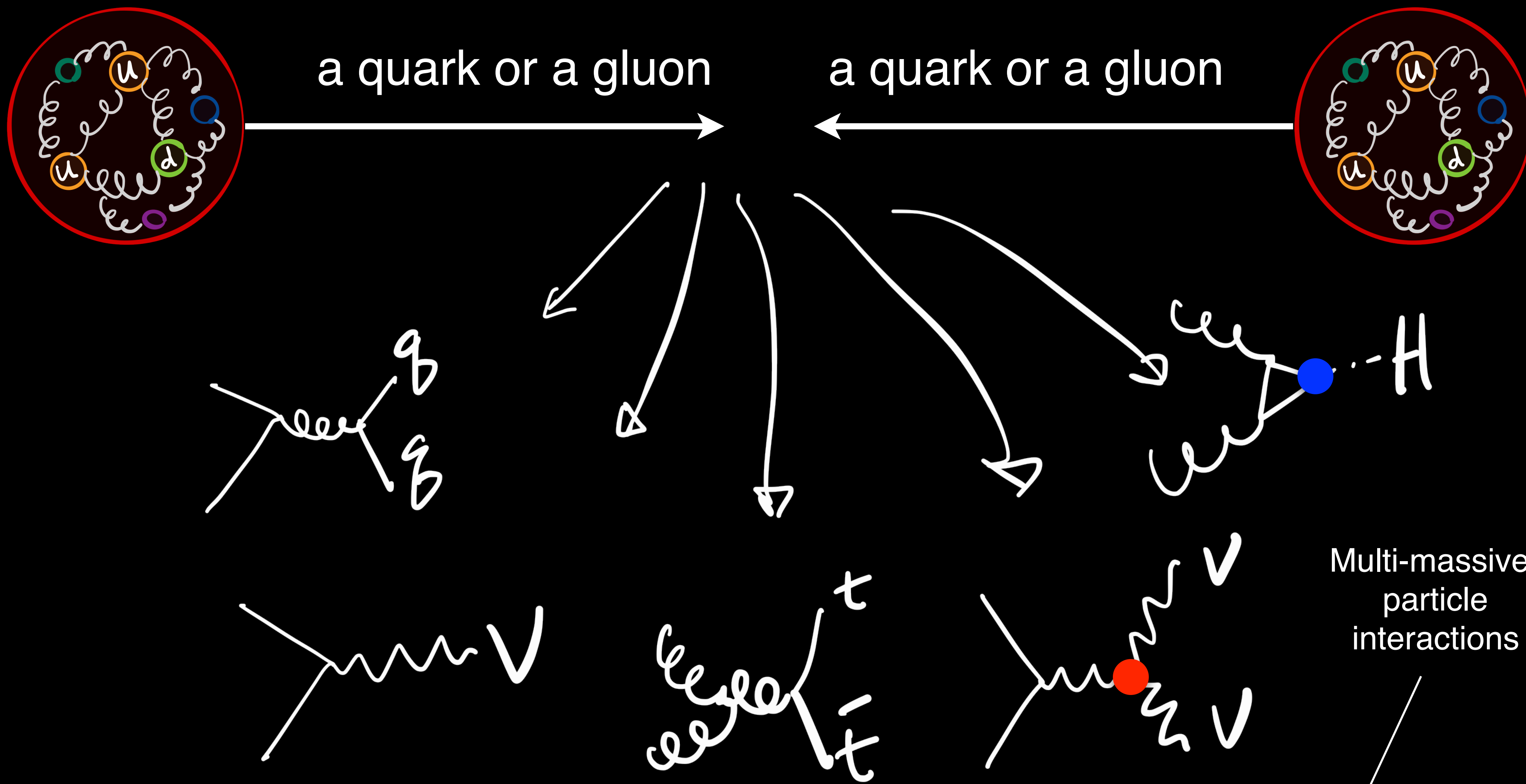
LHC provides largest and most energetic pp collision data set ever produced

Large Hadron Collider at CERN



LHC pp collision processes

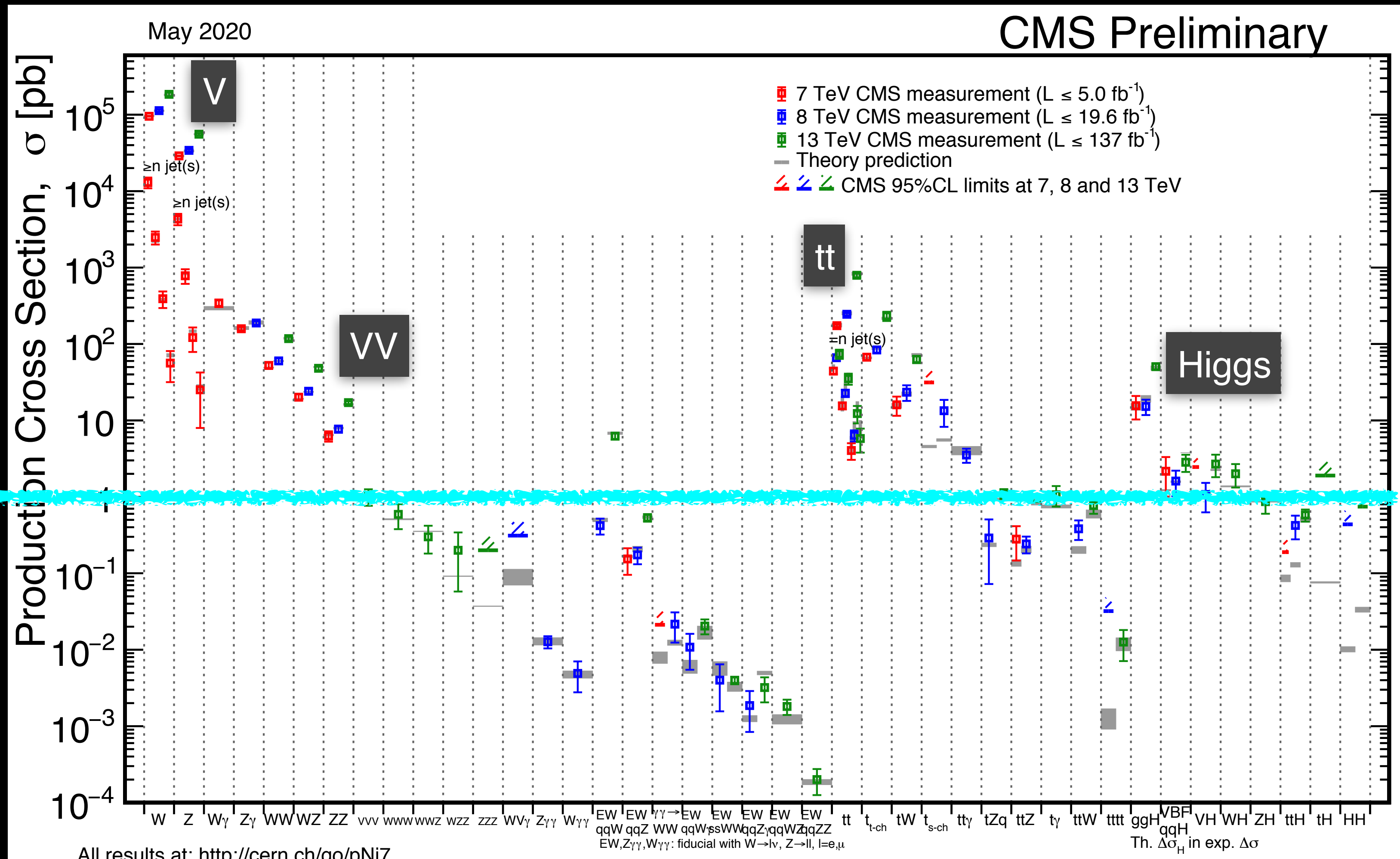
Proton is a bag of quarks and gluons



Multi-massive-particle interactions

Common LHC processes rarely involve MMPIs

Cross sections at LHC



1 pb

≈

10 / Trillion

pp collisions

Rarer

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

Cross sections at LHC

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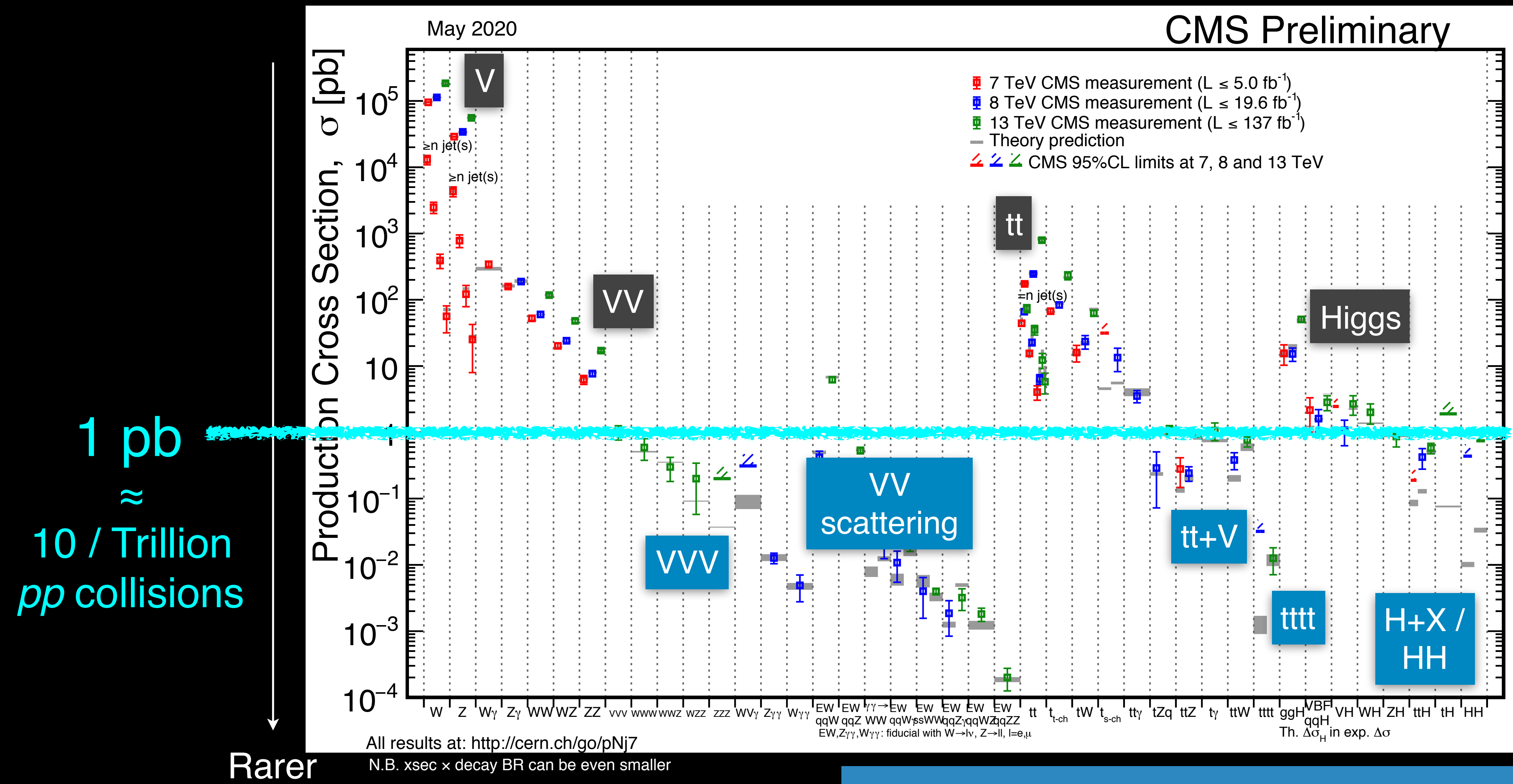

N.B. xsec × decay BR can be even smaller

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

Cross sections at LHC

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1 pb
≈
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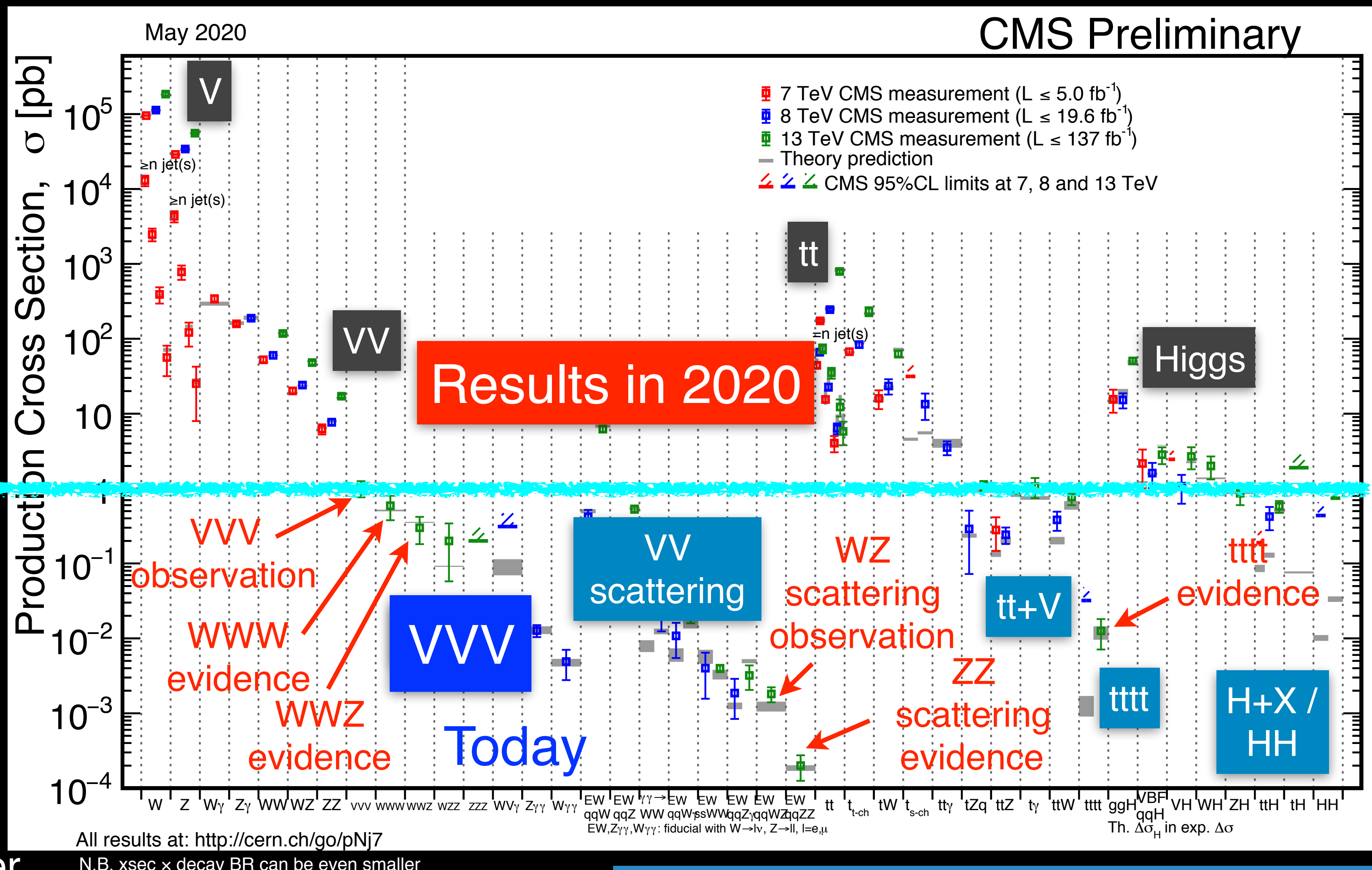
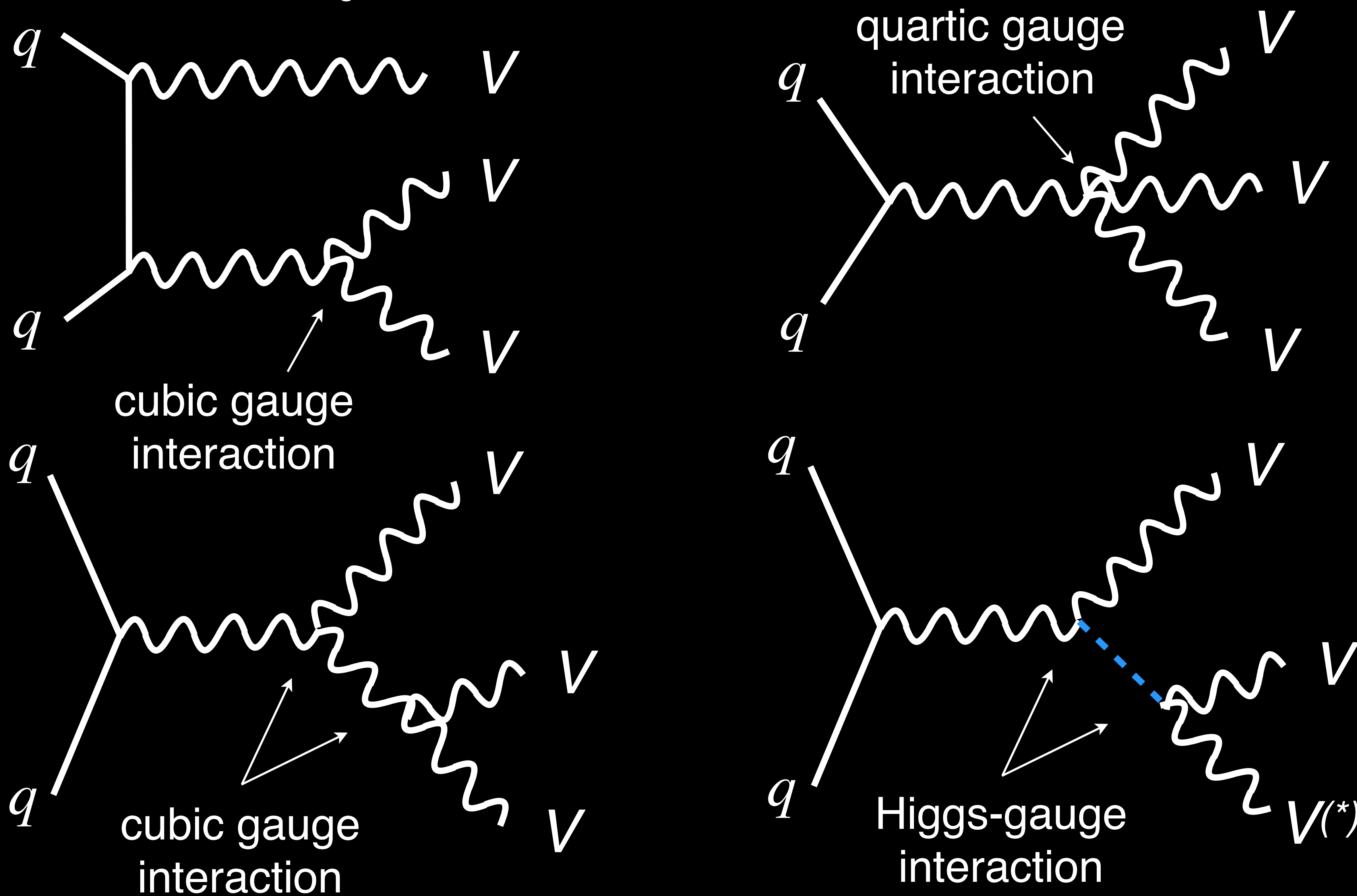


multi-“massive”-particles processes
X = t, W, Z, H

Recent rapid progress in finding new final states

MBIs in VVV production (V = W, Z)

**Non-exhaustive set of VVV diagrams



Triboson processes contain many interesting MBIs

VVV production at LHC

Targeting all VVV productions:

- pp→WWW
- pp→WWZ
- pp→WZZ
- pp→ZZZ

And the combined production of all pp→VVV

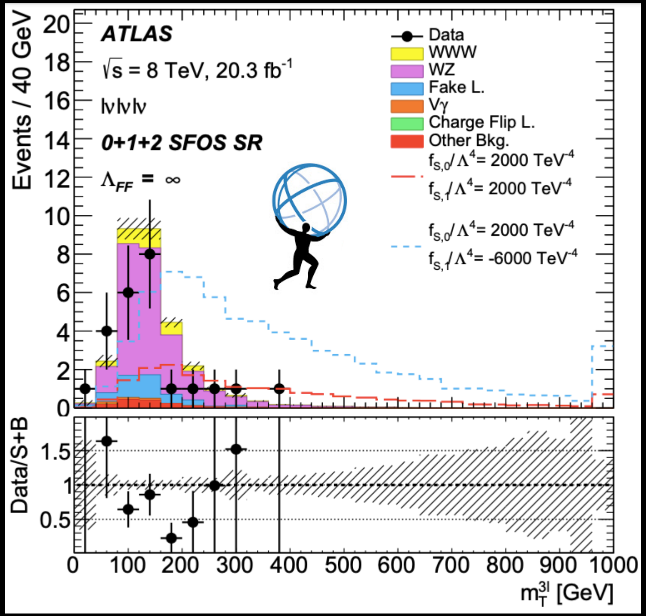
Today: Aim to establish VVV production with 5σ

Previous work on VVV physics

Previous work on VVV physics

- ATLAS searched for WWW in 8 TeV: 0.96σ (1.05σ) arXiv:1610.05088

SMEFT Dim8 operator limit



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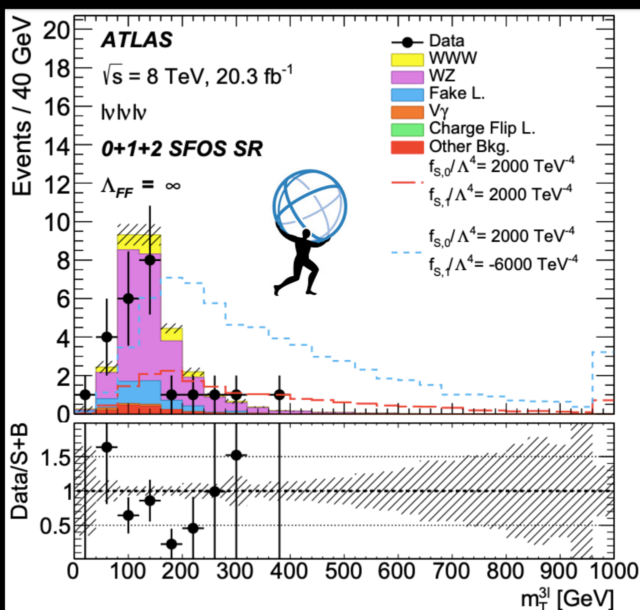
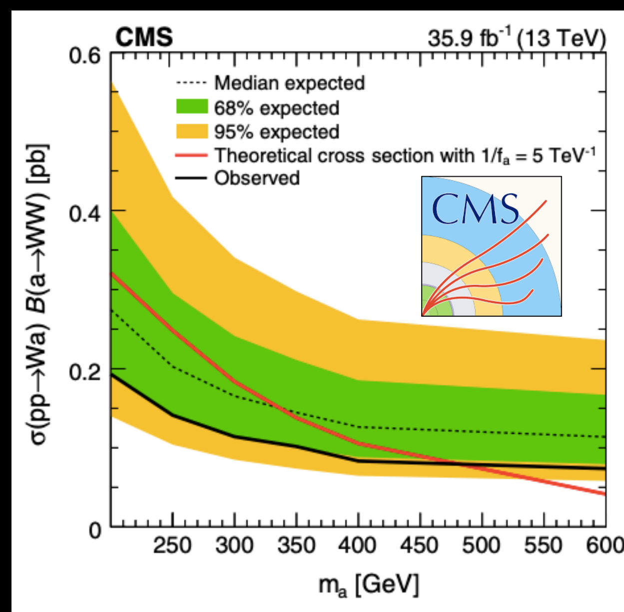


arXiv:1610.05088

Axion-like-particle triboson signature limit



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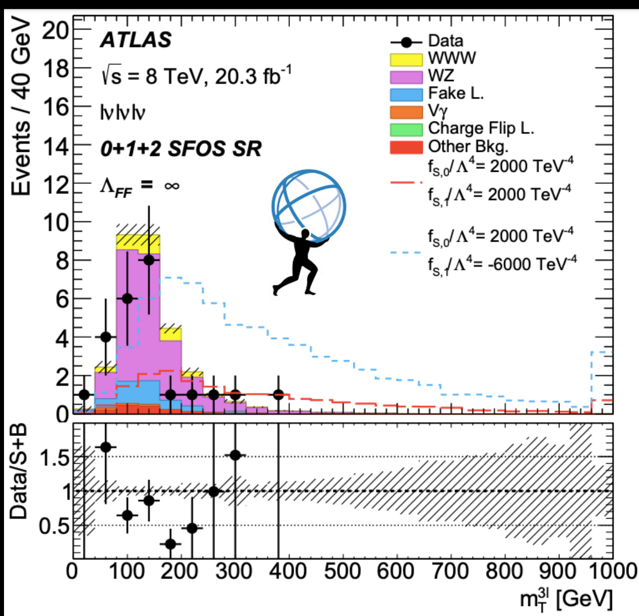

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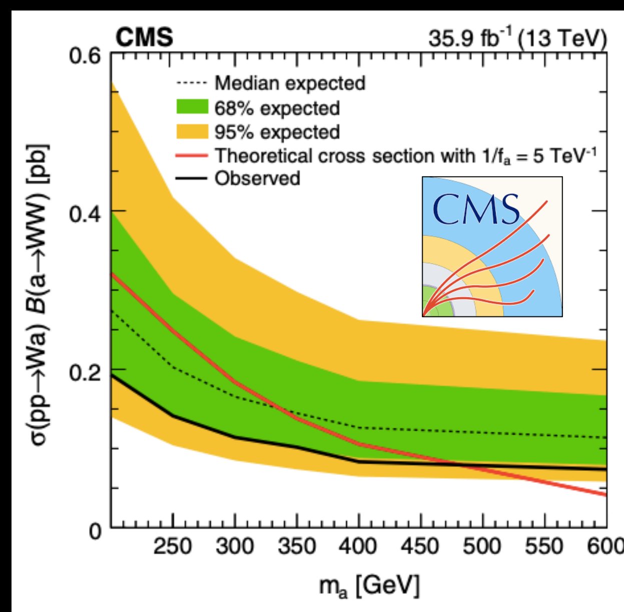

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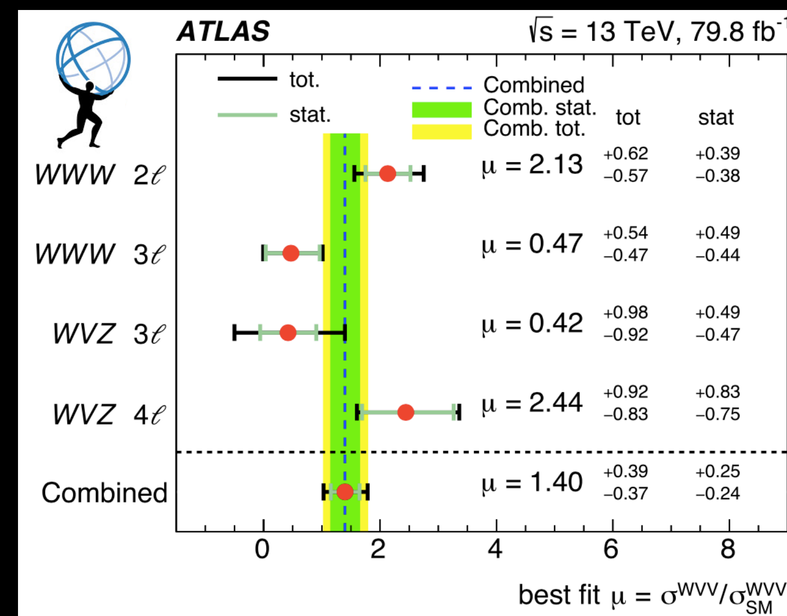
VVV evidence



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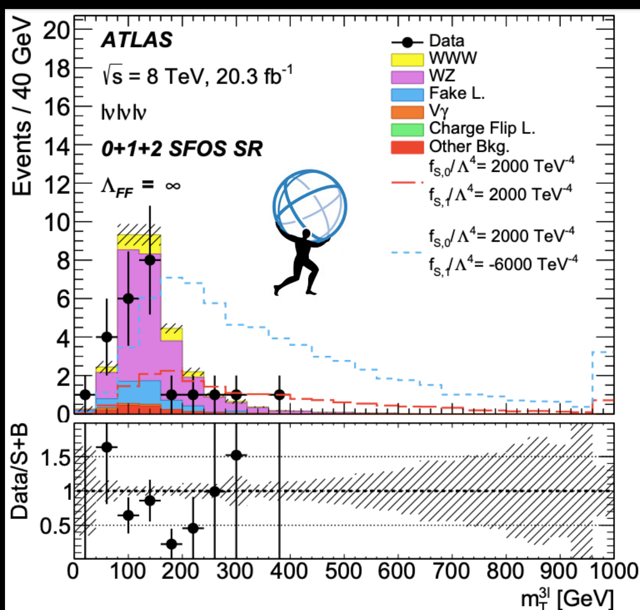

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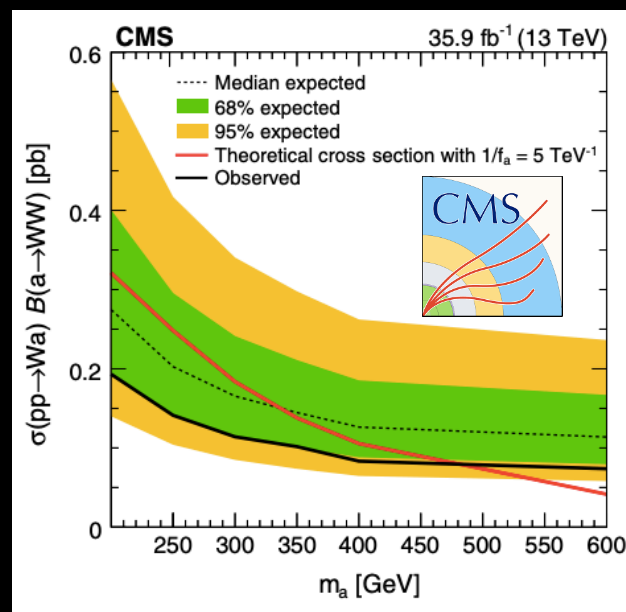

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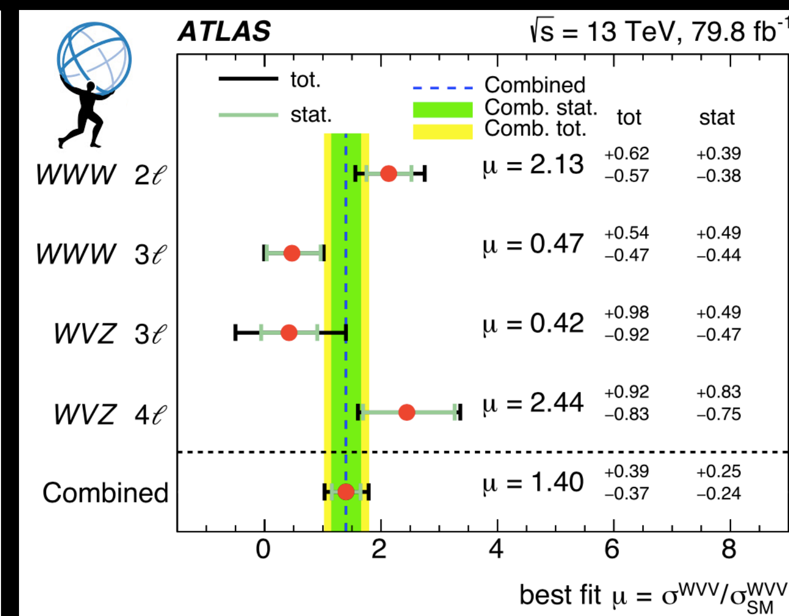

arXiv:1903.10415

ATLAS / CMS have studied VVV to test SM / BSM

VVV production cross section and rate

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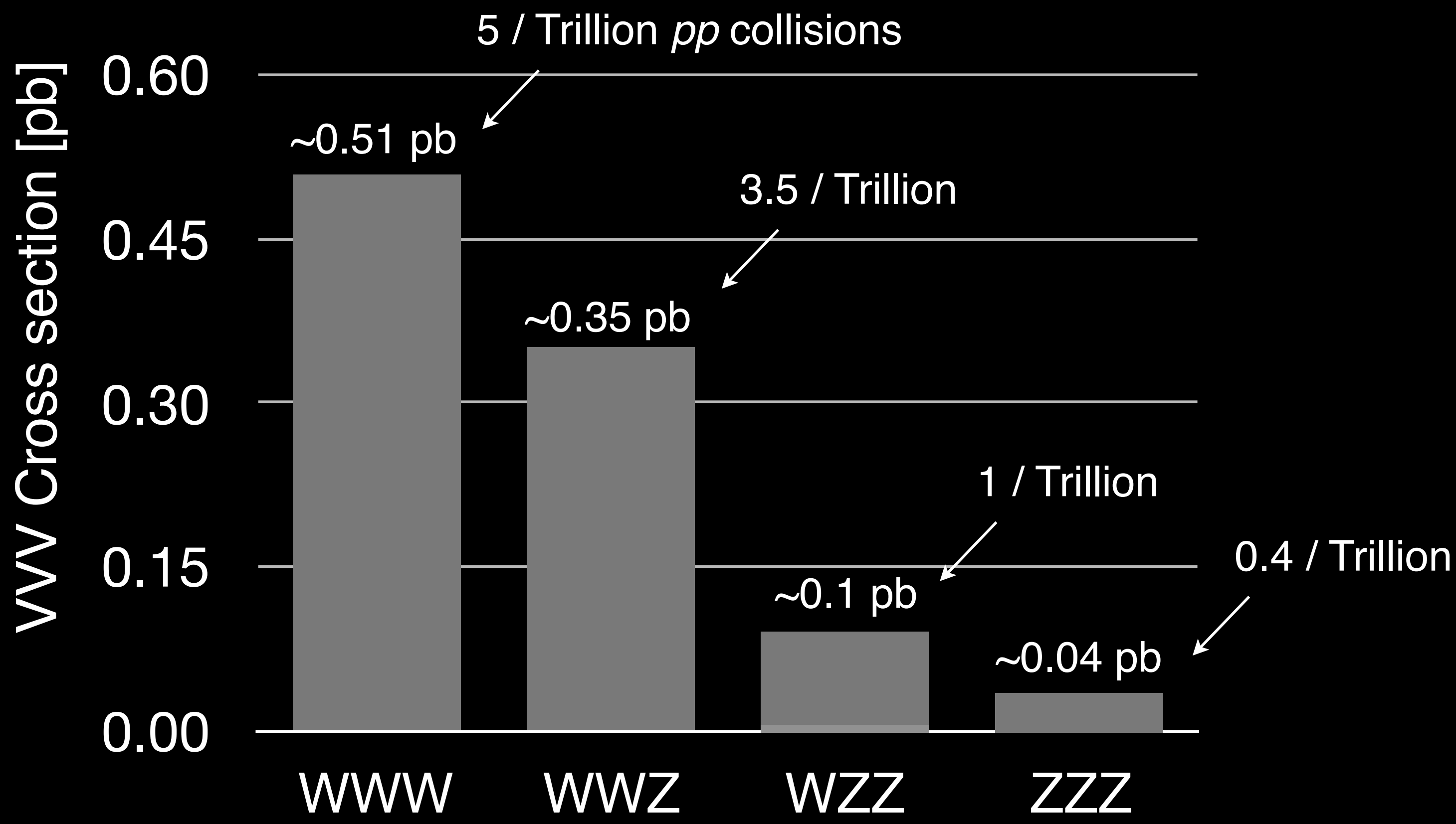
Production cross section decreases with more Z's



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

LHC Run 2 data set

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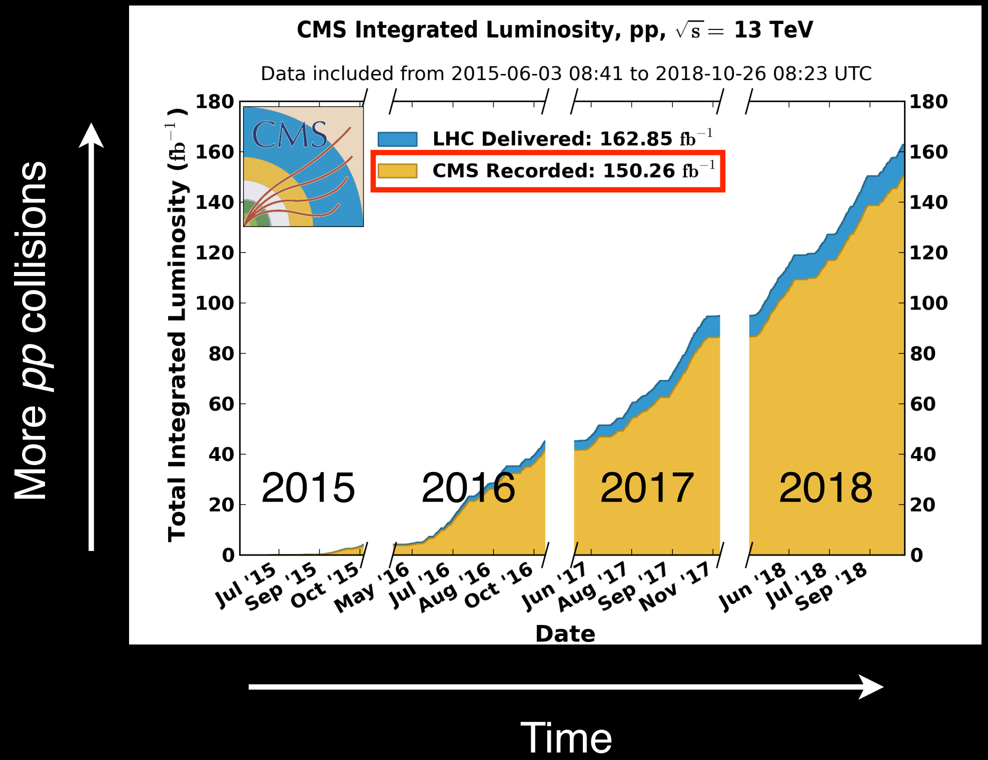
- Run 2 data set
- 15000 Trillion pp collisions
- of which ~13700 Trillions are marked "*good for analysis*"

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



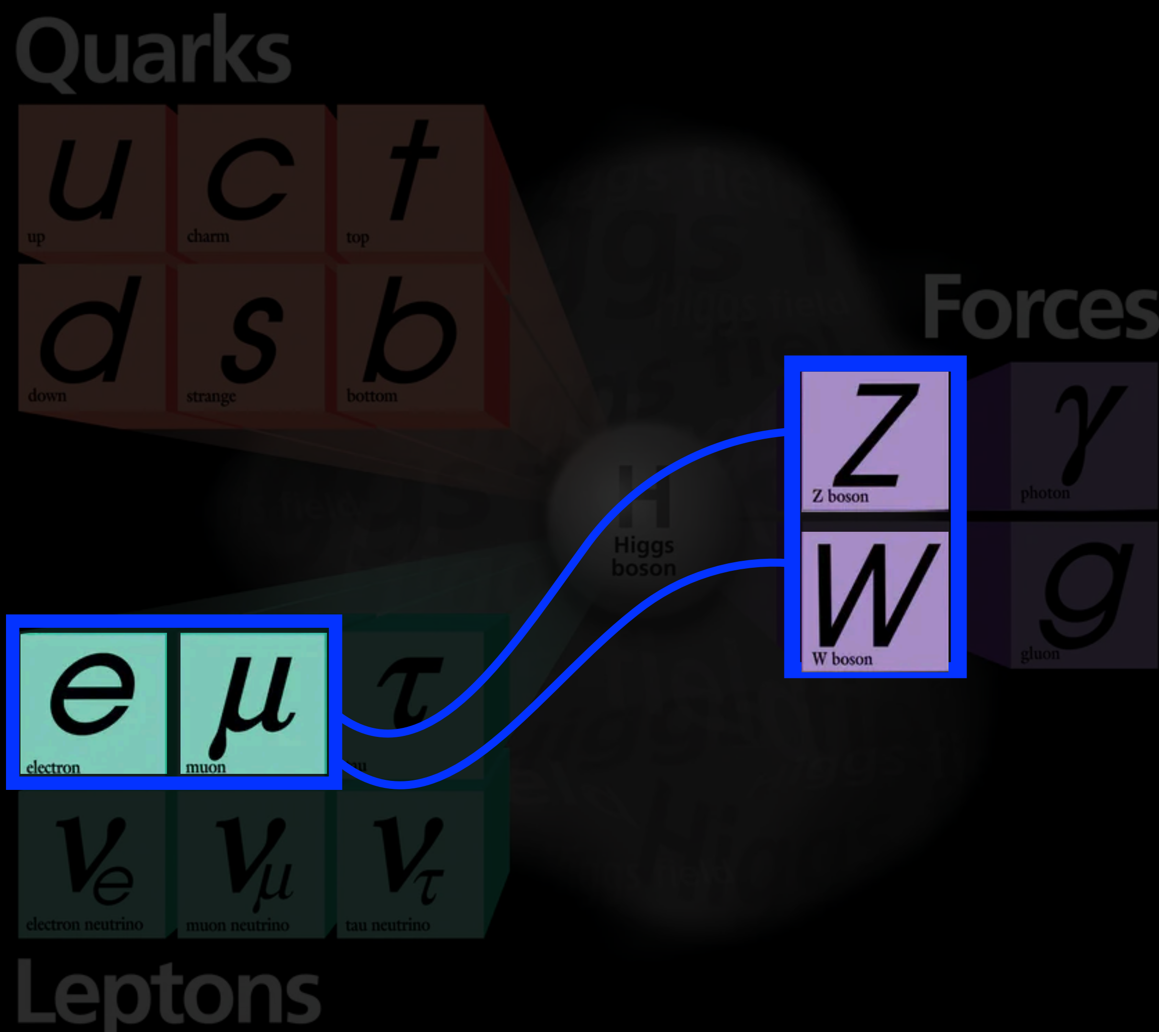
VVV	N / Trillion	N total
VVV	10	135K
WWW	5	70K
WWZ	3.5	48K
WZZ	1	13K
ZZZ	0.4	5K

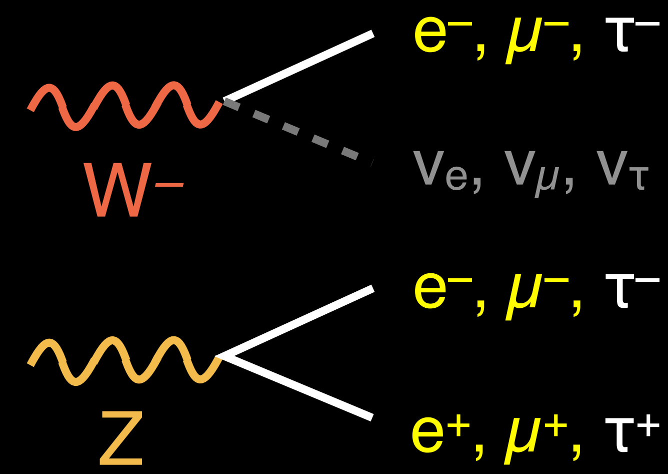
LHC's large data set provides ~135K VVV events

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





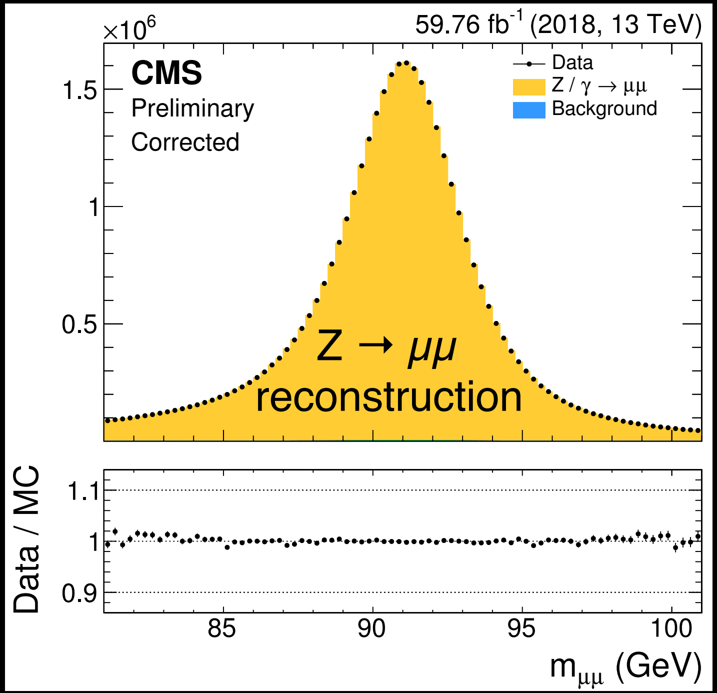
W's and Z's can most easily identified via electrons and muons

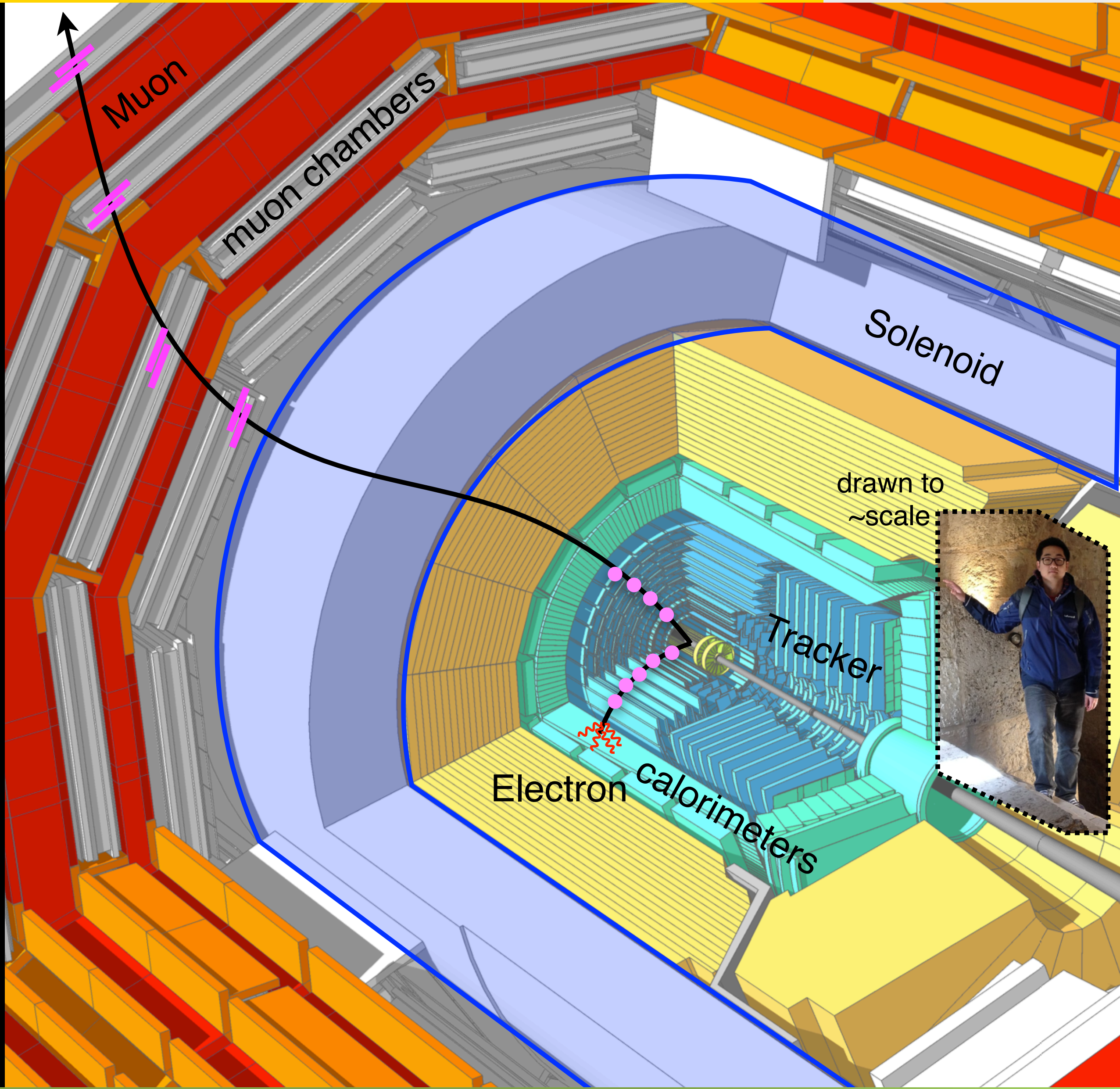
∴ Multiple W's and Z's
⇒ Multiple e's and μ's

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)



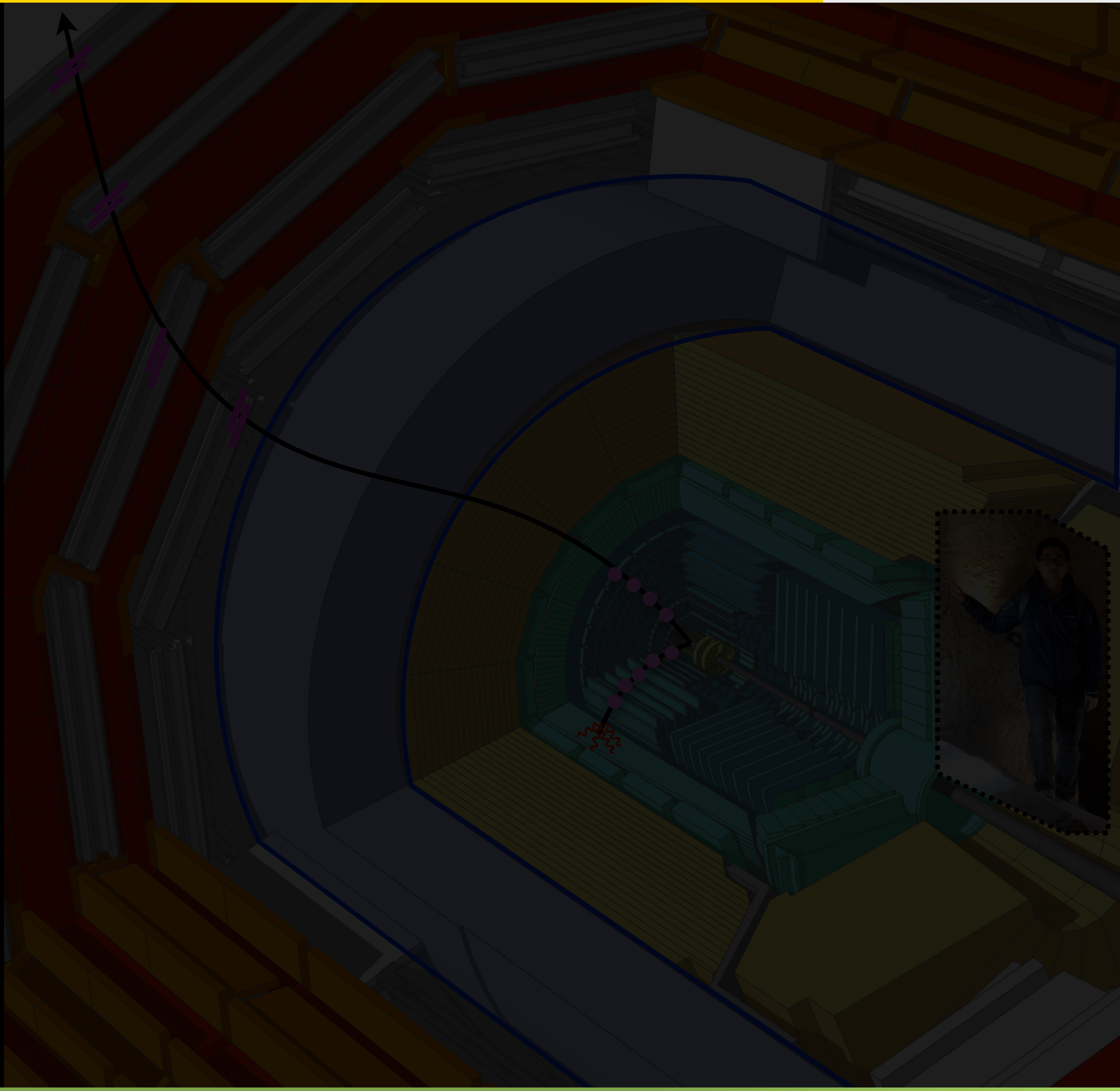


Excellent e/μ reconstruction and simulation at CMS

Classifying leptons' origins

Identifying e/μ is not enough

We need to further classify the origin



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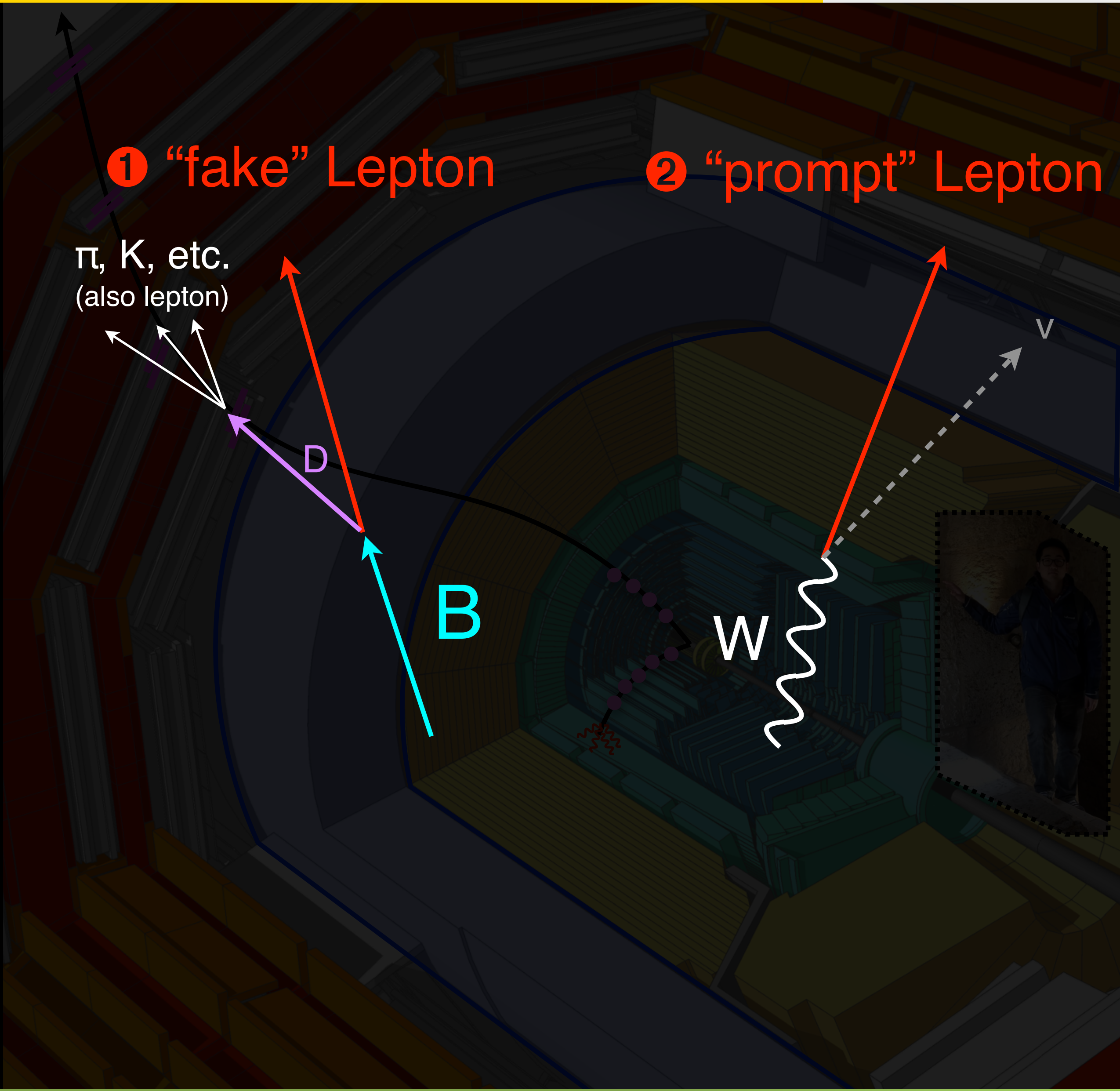
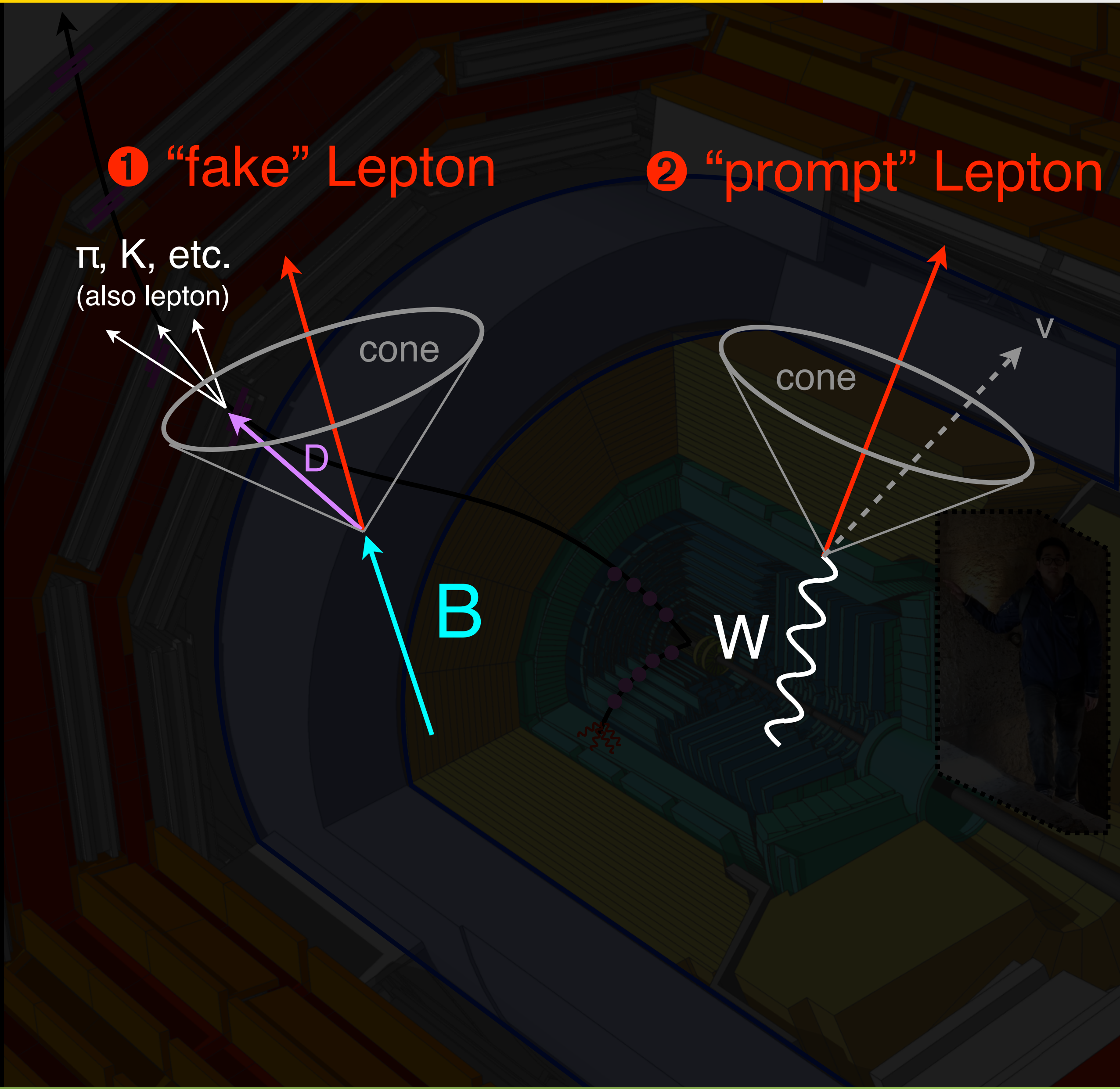


Classifying leptons' origins

Identifying e/μ is not enough

We need to further classify the origin

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



Classifying leptons' origins

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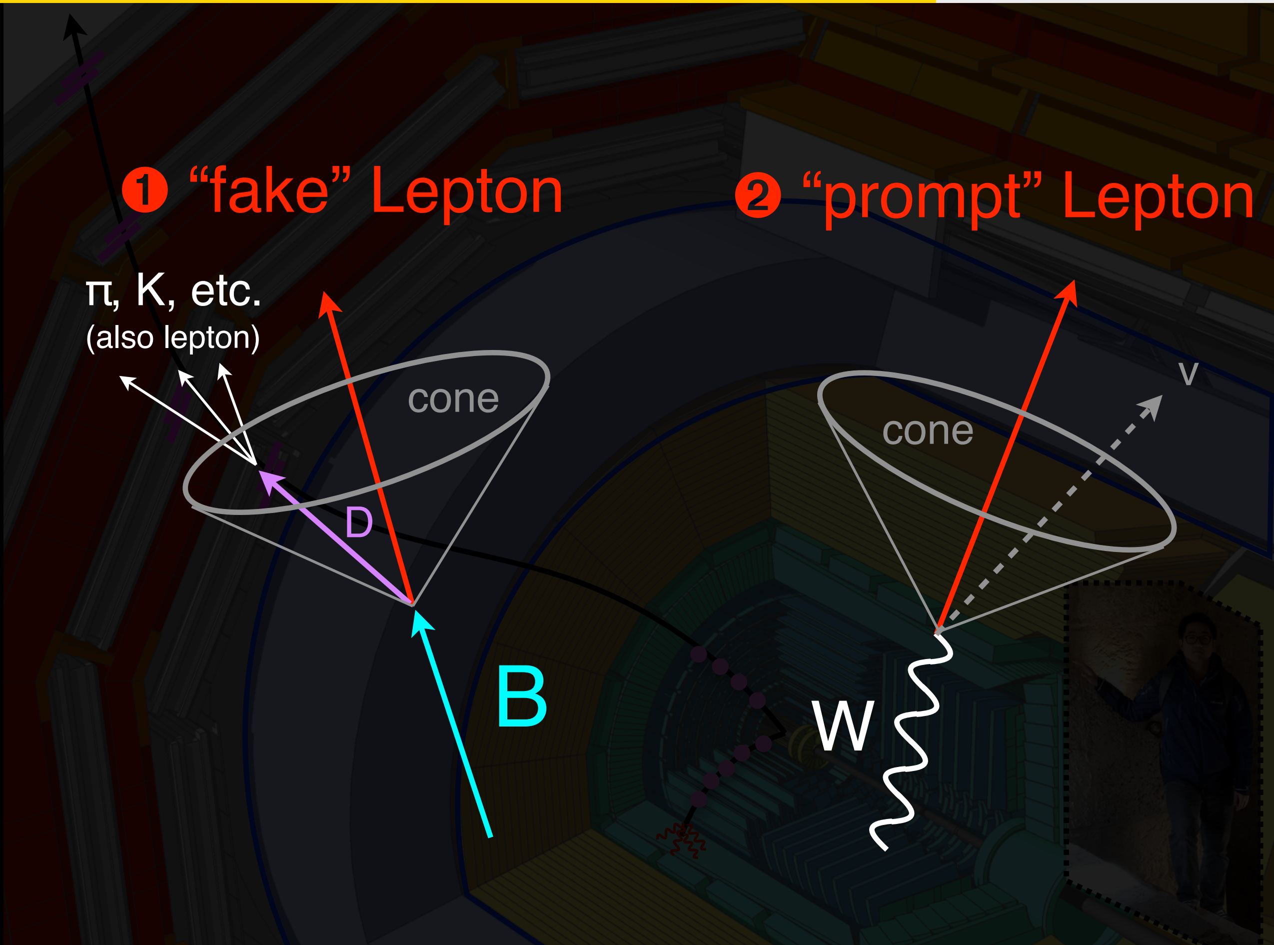

non-isolated lepton
⇒ likely from hadrons

isolated lepton
⇒ likely from W or Z

Classifying leptons' origins

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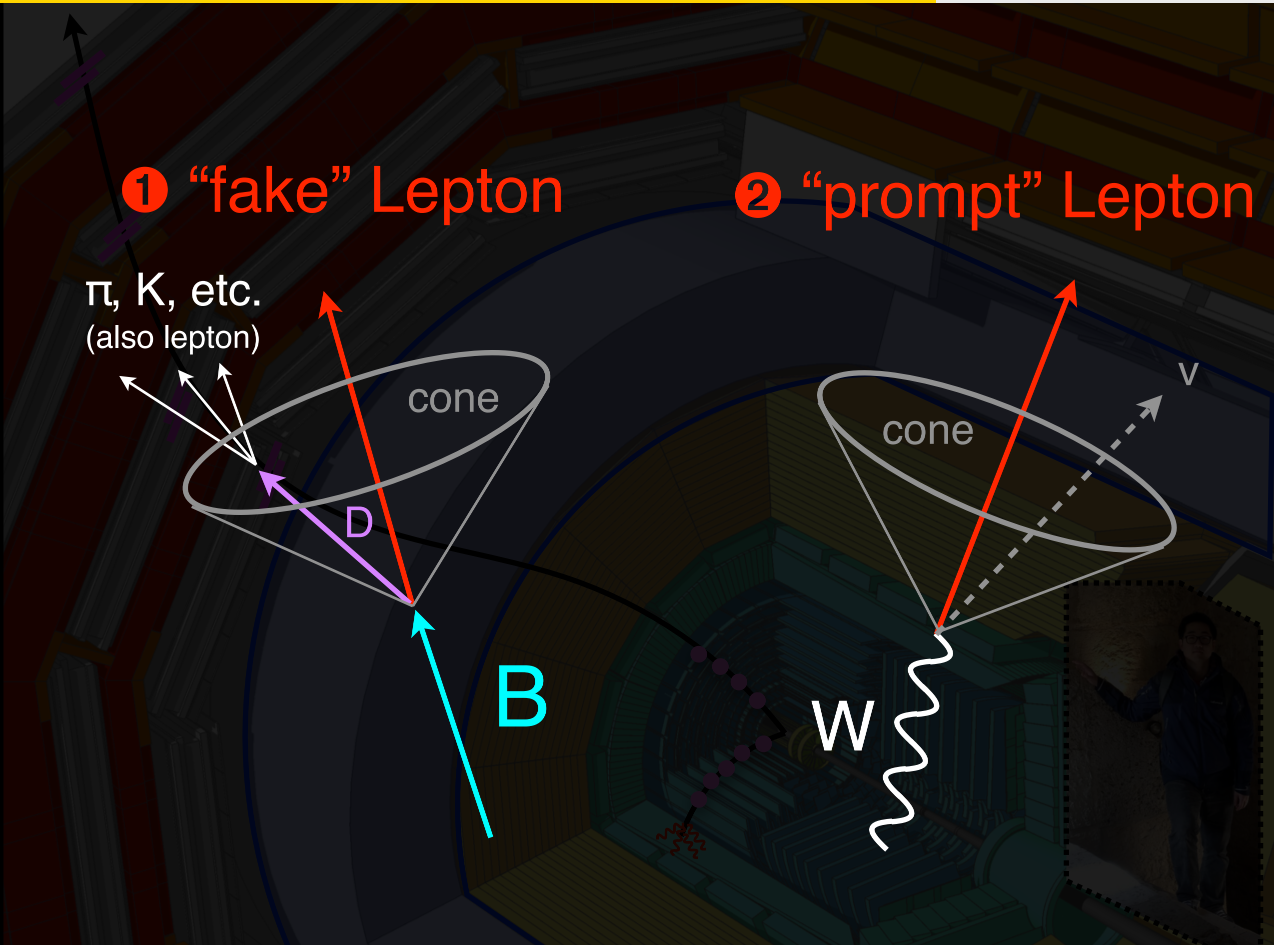

non-isolated lepton
⇒ likely from hadrons

isolated lepton
⇒ likely from W or Z

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

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

Inclusive number of events

VVV	#
WWW	70K
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WZZ	13K
ZZZ	5K

→

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cf. Run 1 had ~55 WWW evt.

Inclusive number of events

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

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

**Expected # of events in Run 2

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$ZZZ \rightarrow$ 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

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

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

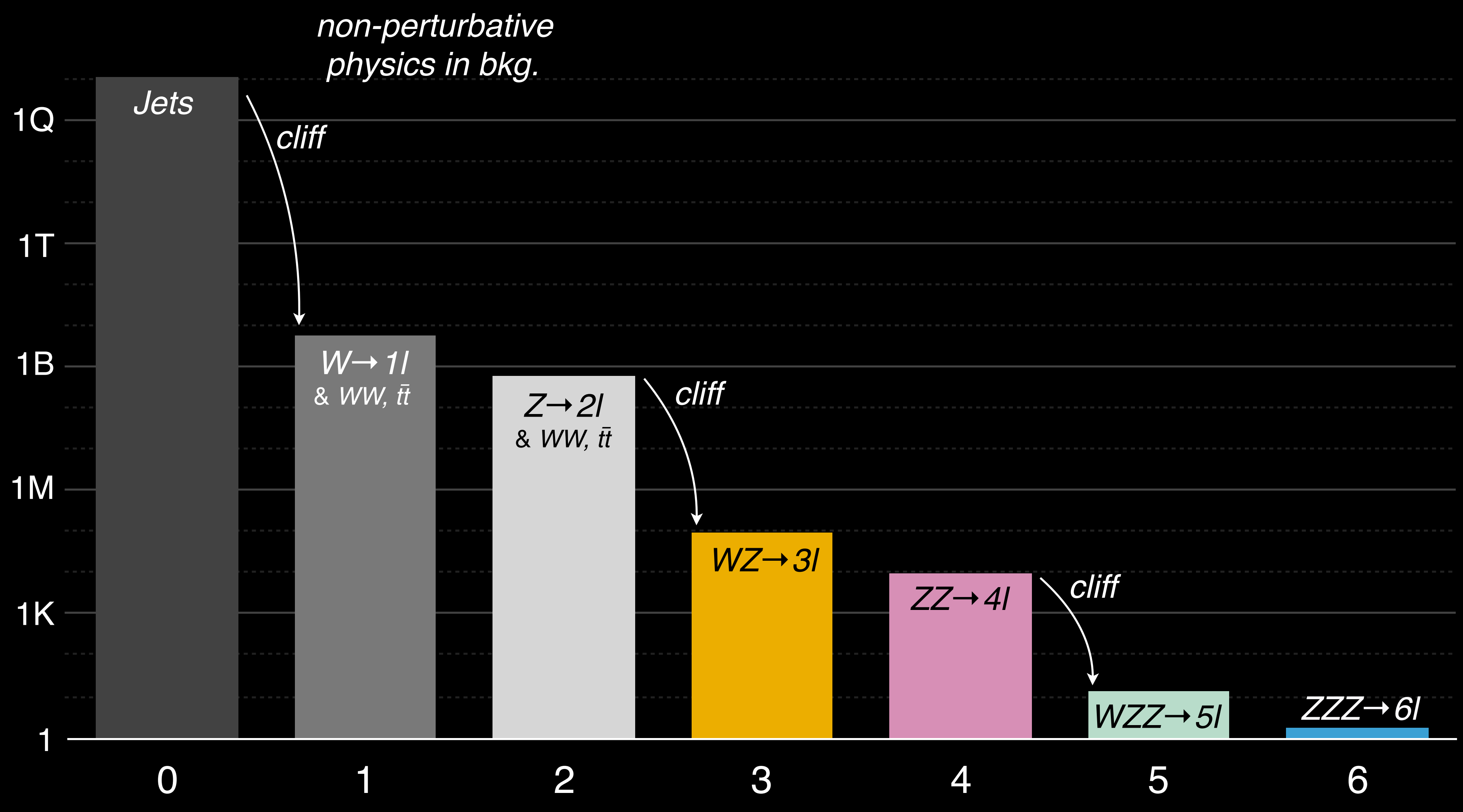
VVV	Total	%	Example
WWW	70K	99.0	WWW → jj jj jj
WWZ	48K	99.7	WWZ → lv jj jj
WZZ	13K	99.9	WZZ → ll jj jj
ZZZ	5K	99.97	ZZZ → ll jj vv

**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 $\tau \to e, \mu$



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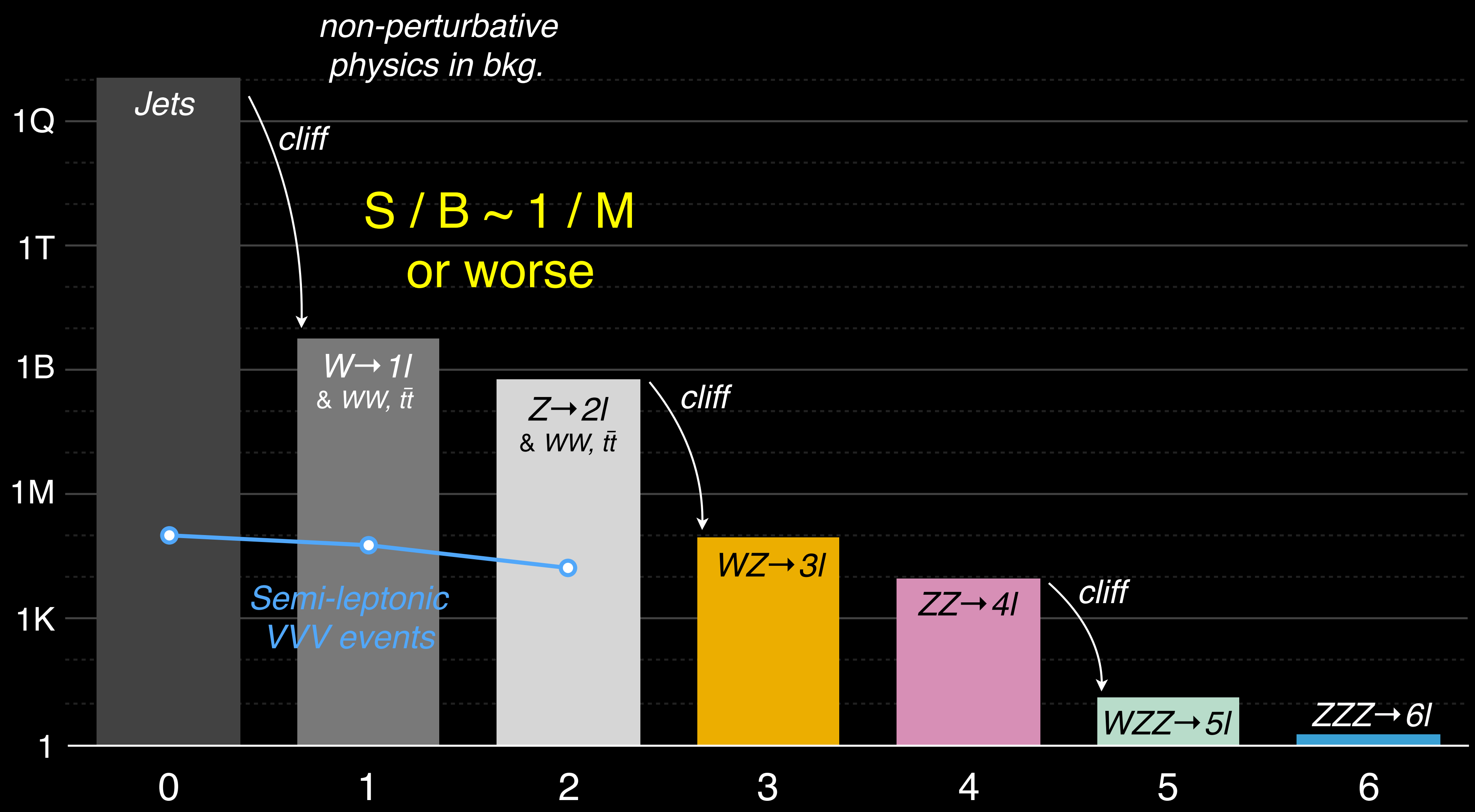

Choosing lepton channels to use

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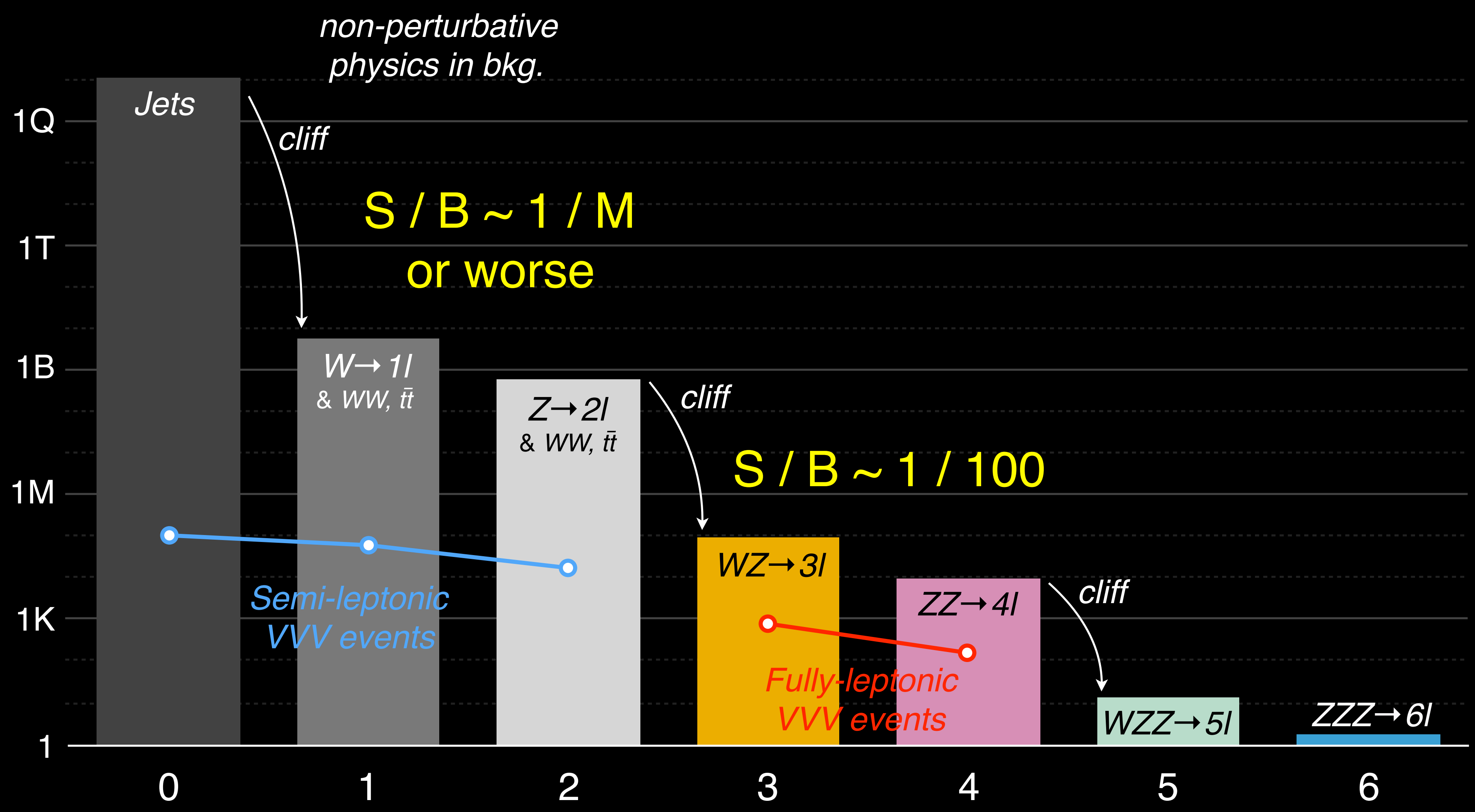
UCSD

**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 $\tau \to e, \mu$



Choosing lepton channels to use

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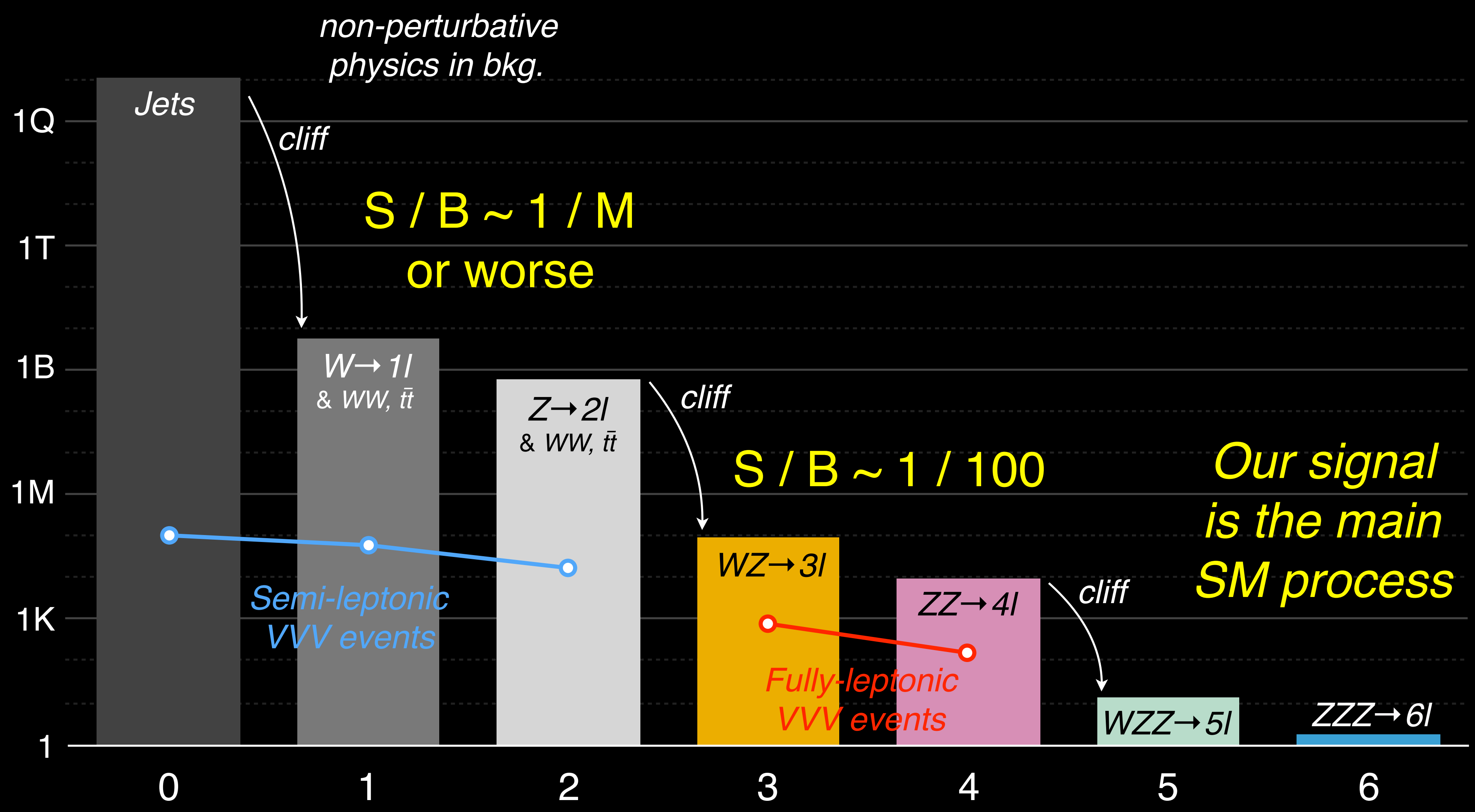
UCSD

**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 $\tau \rightarrow e, \mu$



Choosing lepton channels to use

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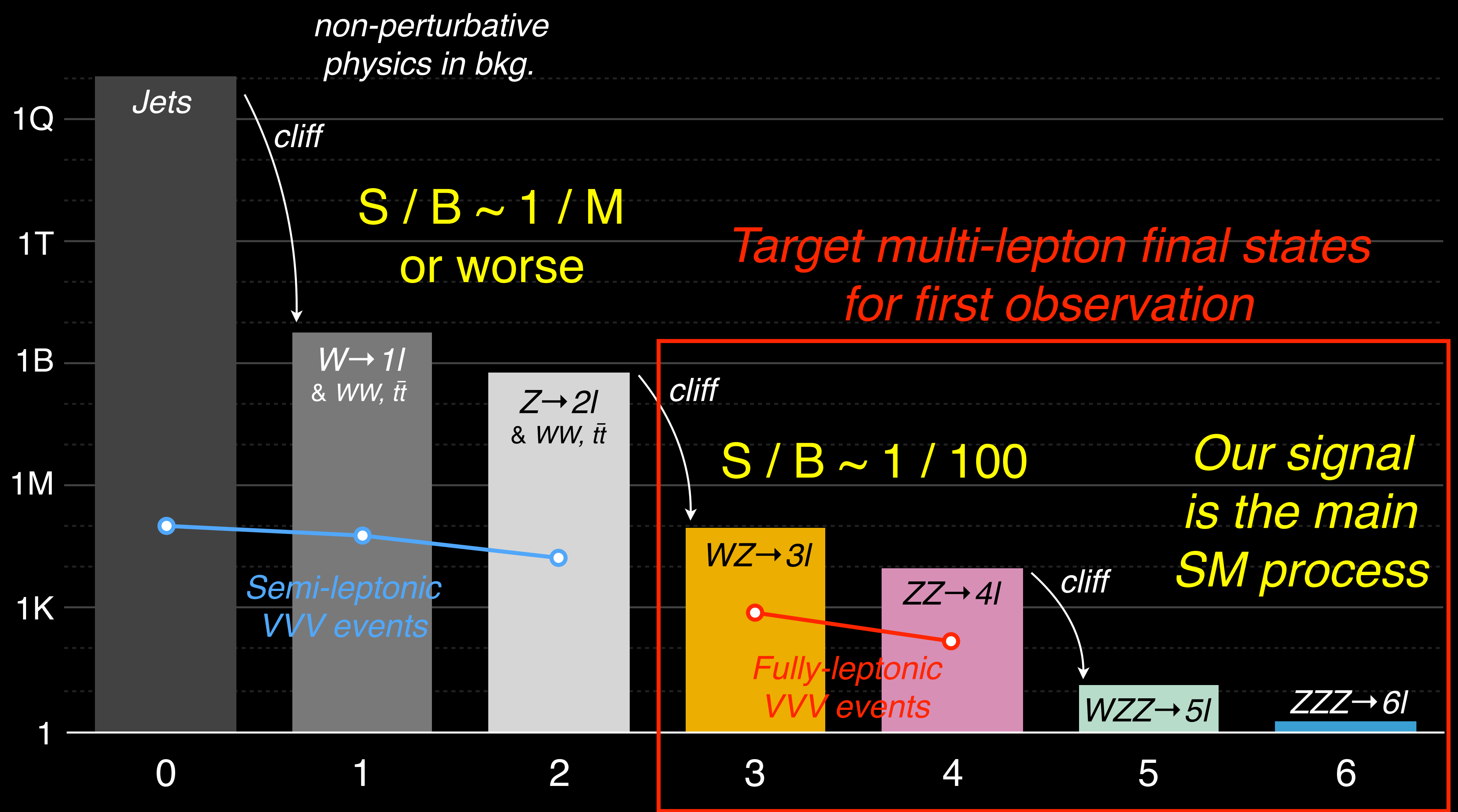

Target multi-lepton final states for first observation

Divide and conquer

		3 leptons	4 leptons	5 leptons	6 leptons
Signals		$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
		~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 channels

5 steps to VVV observation

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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!

Dominant background

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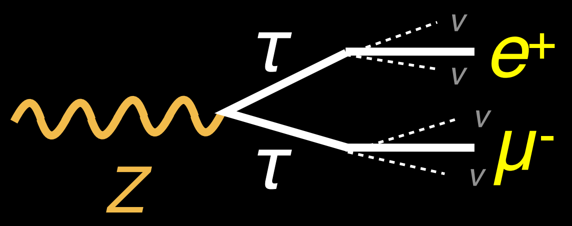
	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$ ~700 evt.	$W \to l\nu$ $W \to l\nu$ $Z \to ll$ ~140 evt.	$W \to l\nu$ $Z \to ll$ $Z \to ll$ ~15 evt.	$Z \to ll$ $Z \to ll$ $Z \to ll$ ~1.5 evt.
Dominant Bkgs.	$WZ \to l\nu ll$ ~100K evt.	$ZZ \to llll$ ~10K evt.	$ZZ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

How to improve S / B by ~100?

**fake lepton is "~per mille" effect

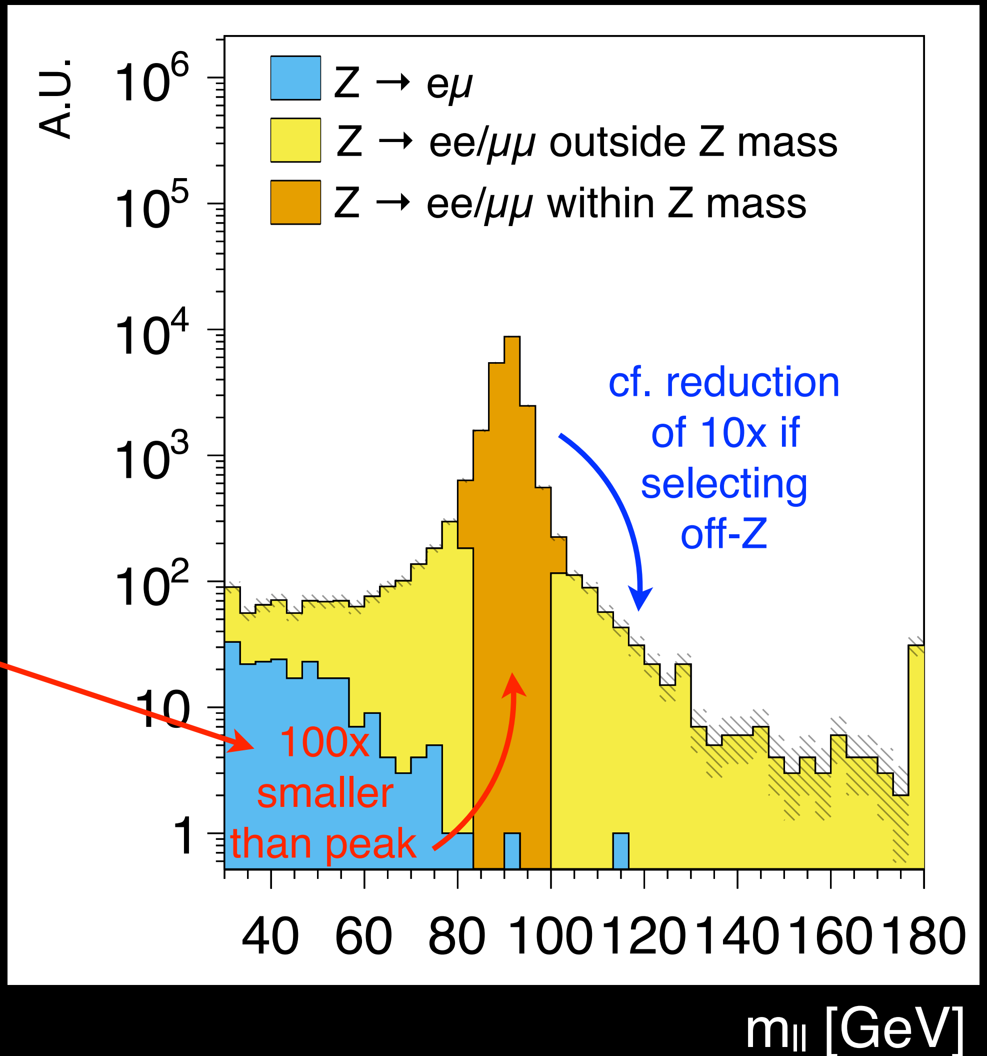
Dominant background is diboson process (WZ, ZZ)

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

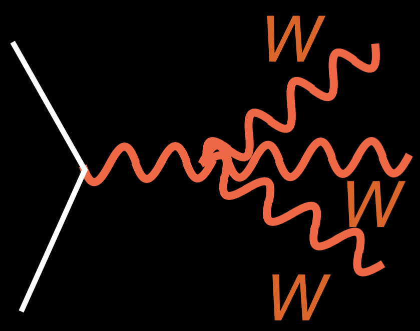


**Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV P_T cuts

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

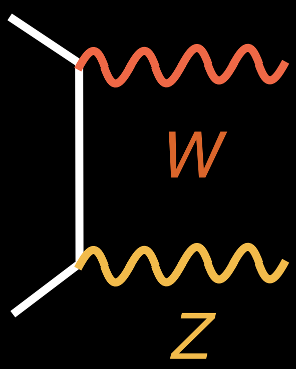
Flavor choices

WWW signal



pp → WWW

Background



pp → WZ

Flavor choice can suppress WZ by 100x

Flavor choices

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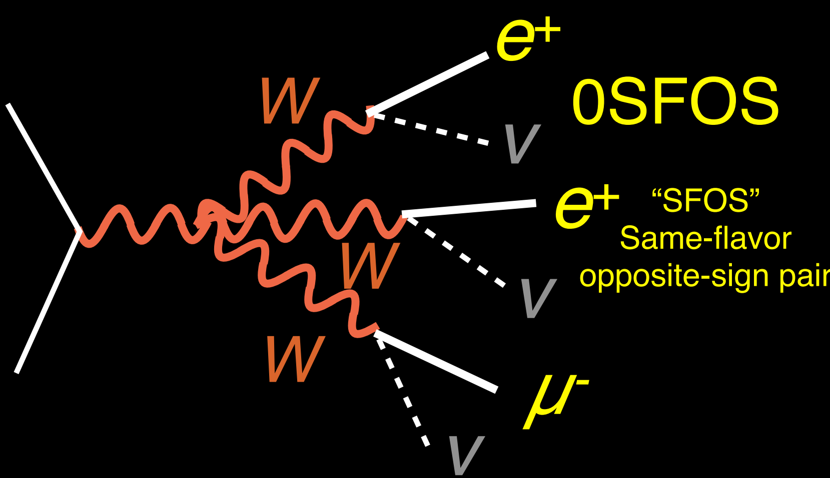
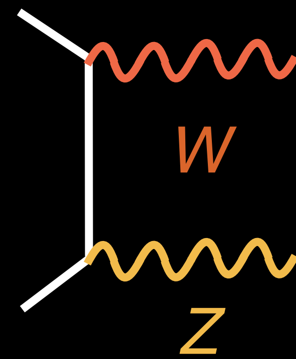
WWW signal



Background



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

$pp \rightarrow WZ$

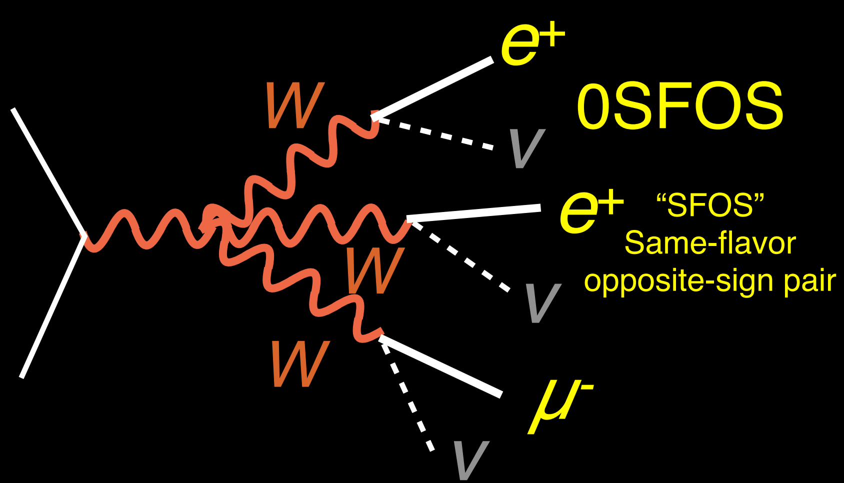
Same for
$e^-e^-\mu^+$, $\mu^+\mu^+e^-$, $\mu^-\mu^-e^+$

Flavor choice can suppress WZ by 100x

Flavor choices

Chang
UCSD

WWW signal



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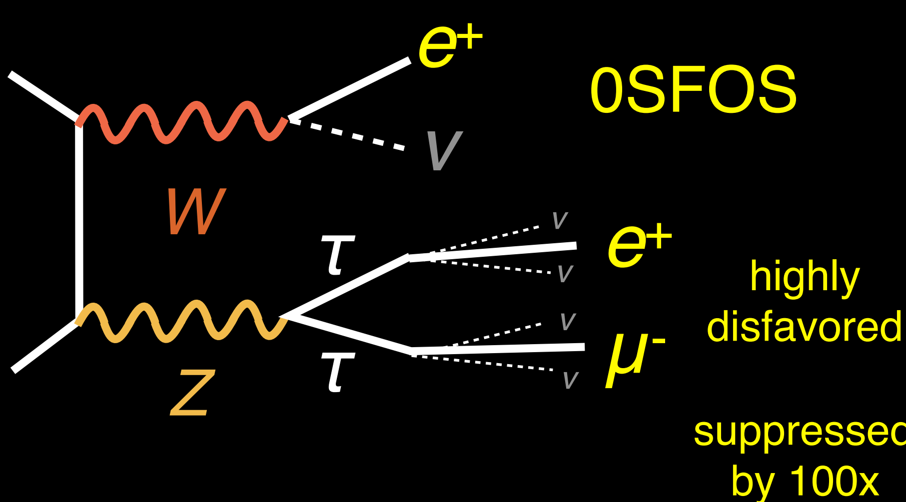

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Flavor choices

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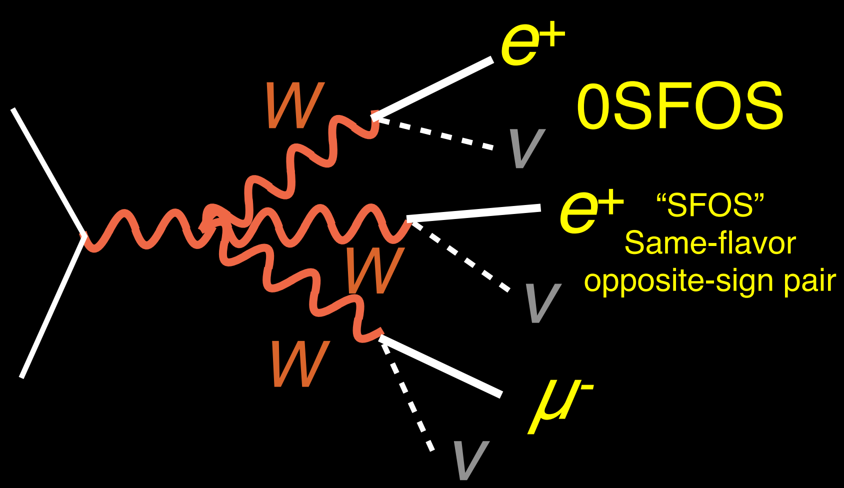
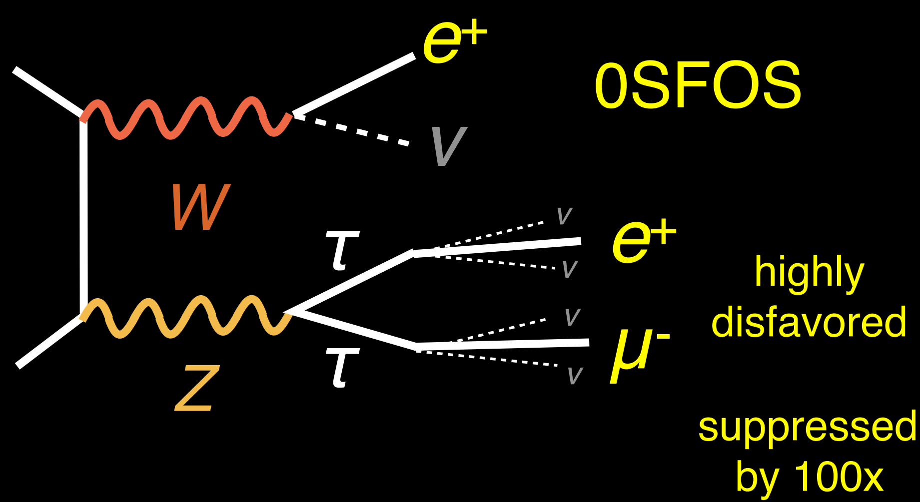


$pp \to WWW \to e^+e^+\mu^-$

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

Background



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

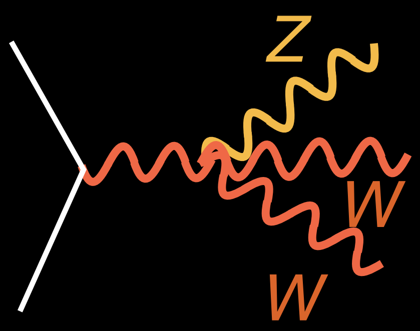
⇒ 0SFOS channel

Flavor choice can suppress WZ by 100x

Flavor choices

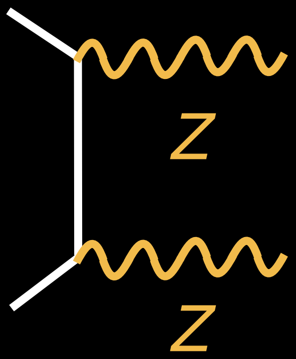
Chang
UCSD

WWZ signal



pp → ZWW

Background



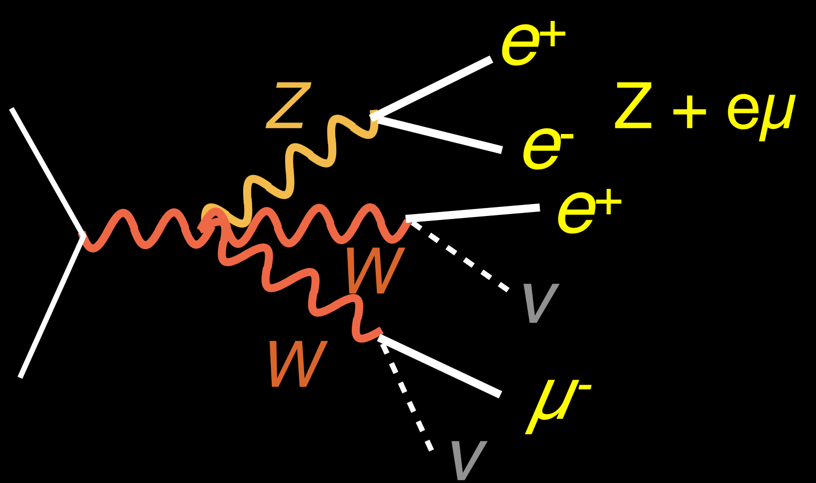
pp → ZZ

Flavor choice can suppress ZZ by 100x

Flavor choices

Chang
UCSD

WWZ signal



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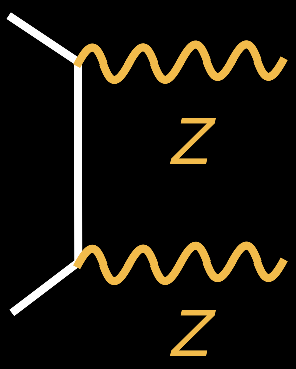


pp → ZWW → $(e^+e^-)\ e^+\mu^-$

tagged-Z

pp → ZZ

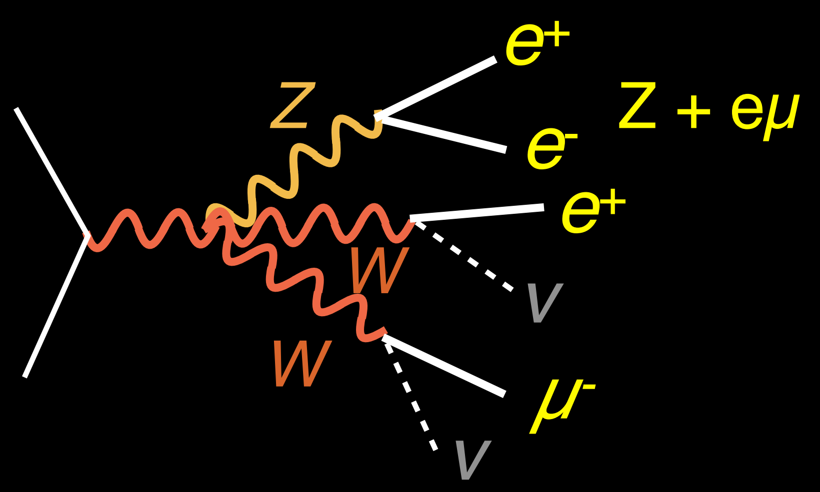
Same for
$(e^+e^-)\ e^-\mu^+$, $(\mu^+\mu^-)\ e^+\mu^-$, $(\mu^+\mu^-)\ e^-\mu^+$

Flavor choice can suppress ZZ by 100x

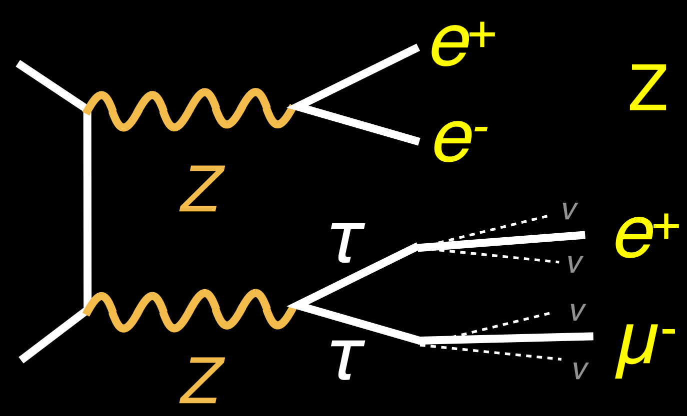
Flavor choices

Chang
UCSD

WWZ signal



Background



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tagged-Z

Same for
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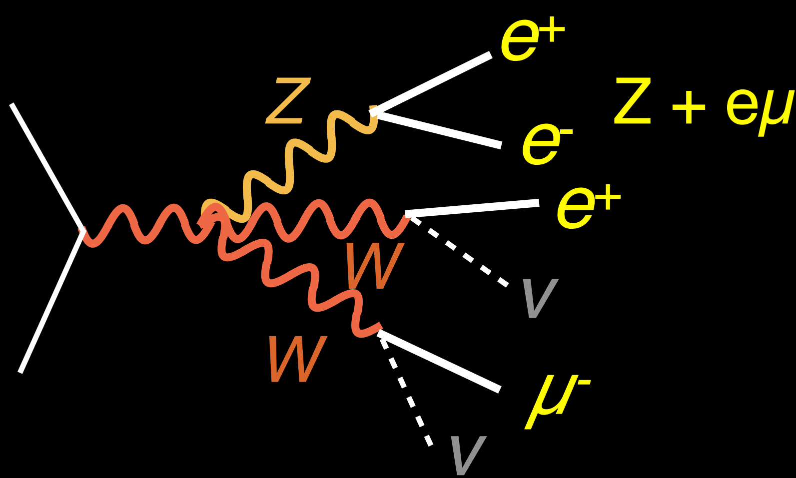
Flavor choice can suppress ZZ by 100x

Flavor choices

WWZ signal

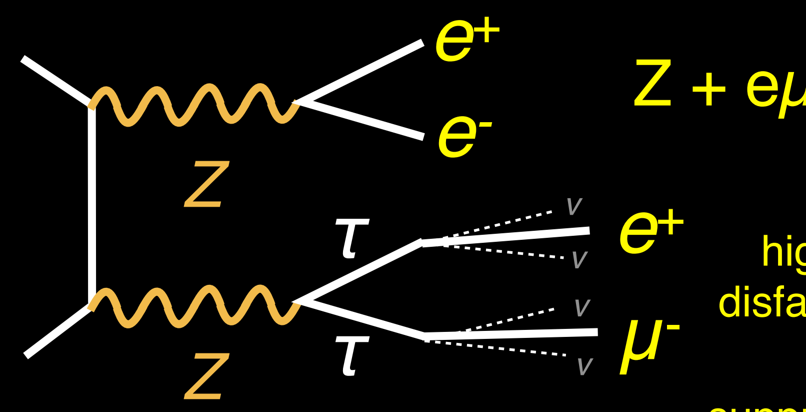


$pp \rightarrow ZWW \rightarrow (e^+e^-)\, e^+\mu^-$

tagged-Z

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

Background



highly disfavored

suppressed by 100x

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

tagged-Z

$\Rightarrow$ Z + eμ channel

Flavor choice can suppress ZZ by 100x

5 steps to VVV observation

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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

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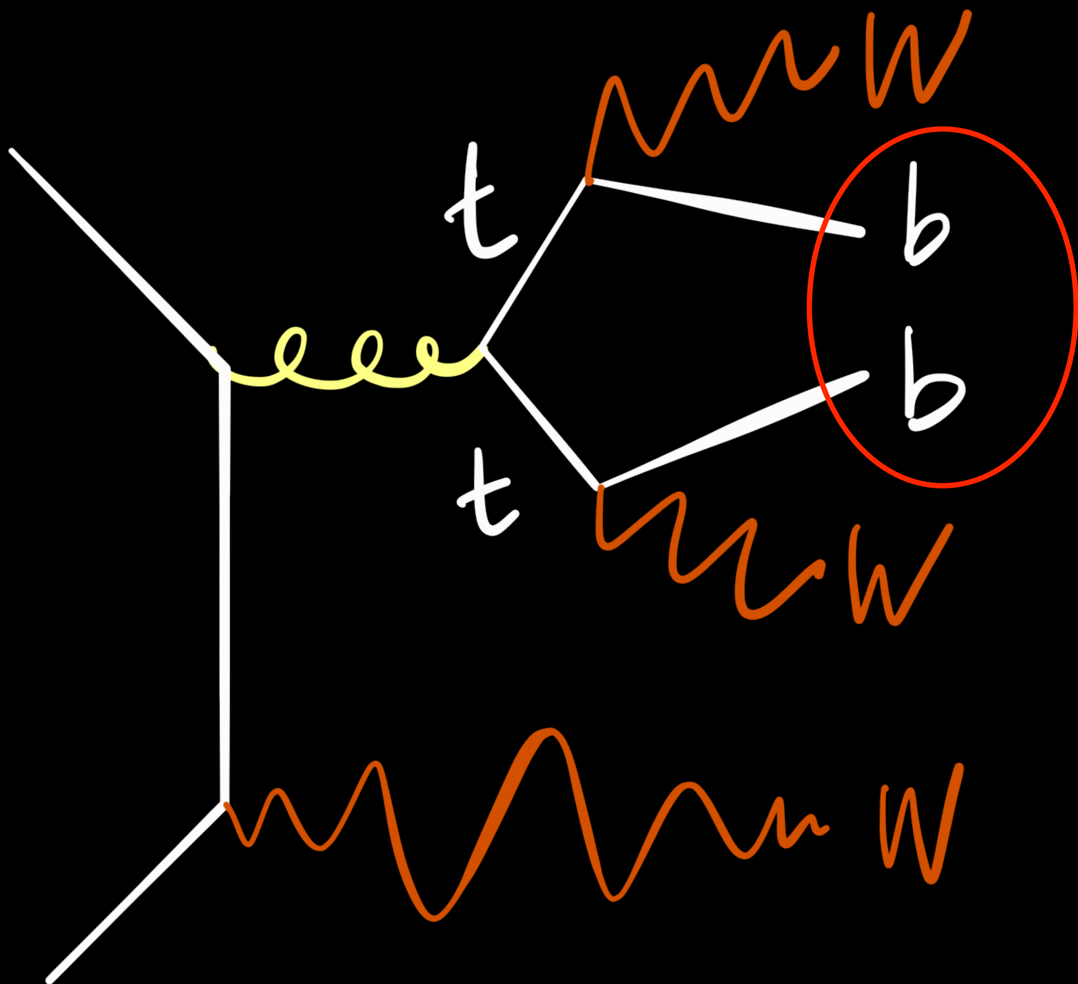
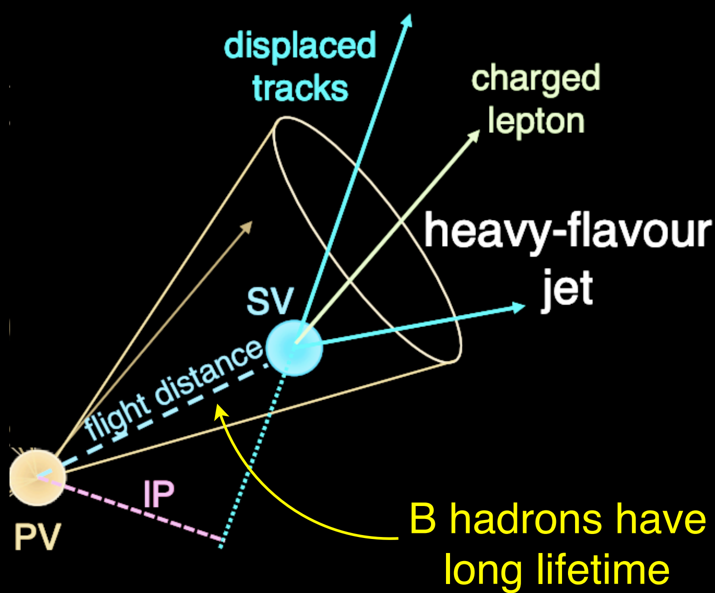
$t\bar{t}$ (+ X) backgrounds

$t\bar{t}$ (+ X) are second dominant bkg sources and **they have b quarks**



CMS developed deep neural network based *b* tagger

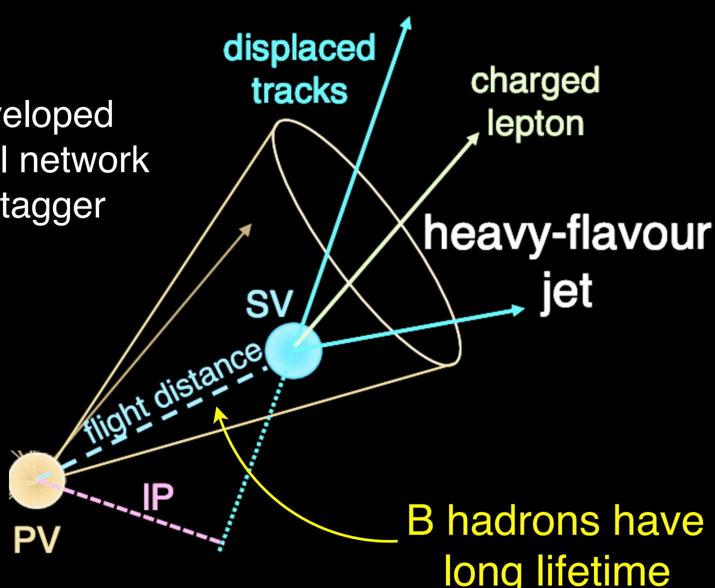


$t\bar{t}$ (+ X) backgrounds contain b quarks

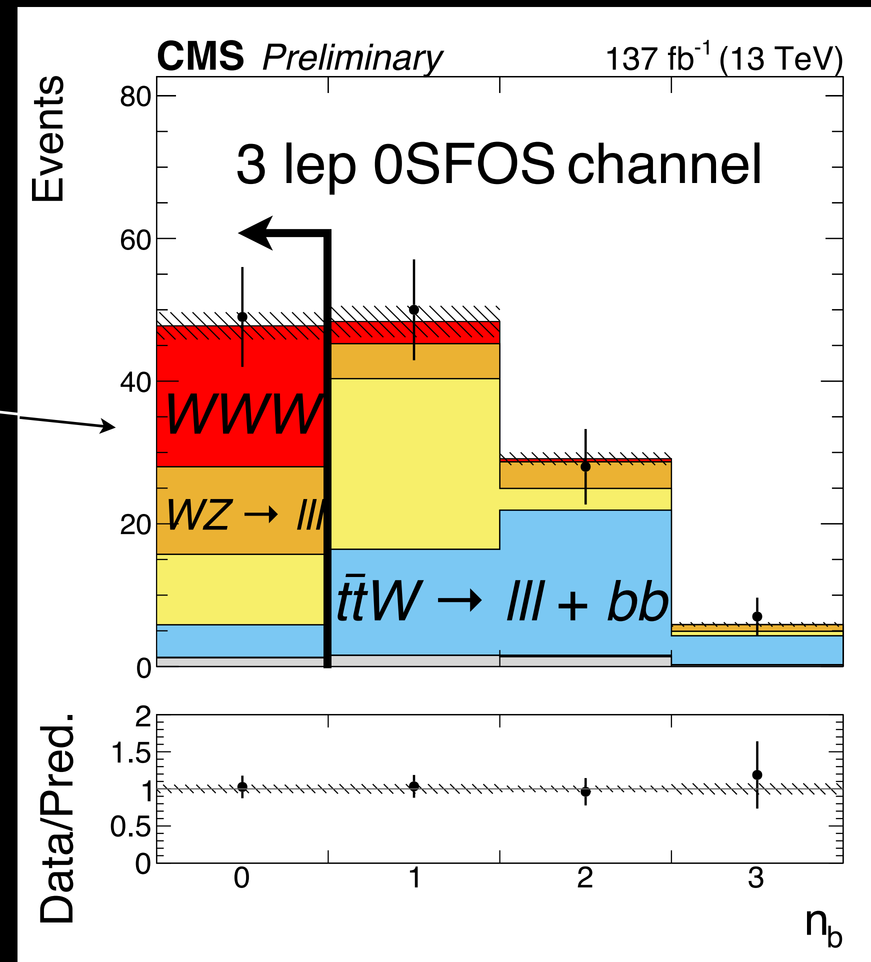
b tagging

- 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

Boosted decision tree

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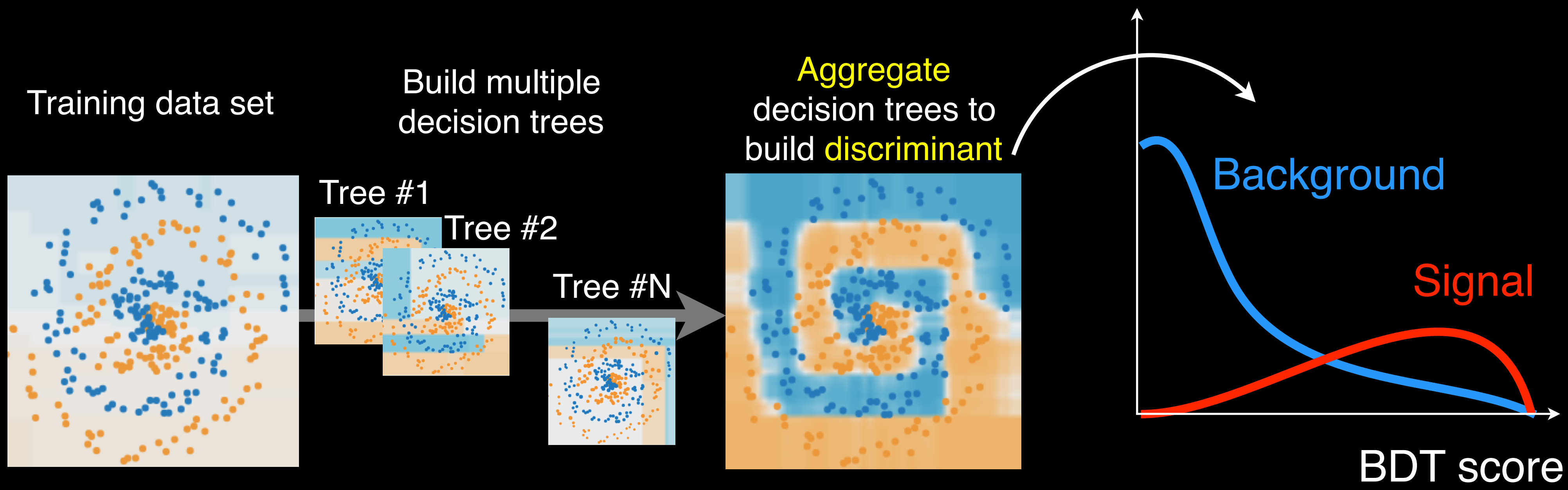
Boosted decision tree is widely used in many analyses at the LHC

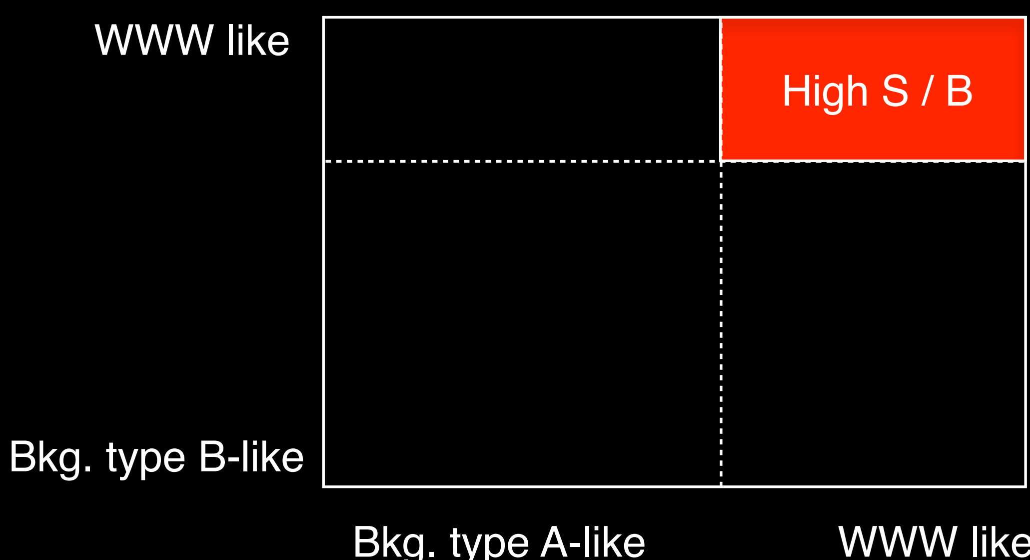


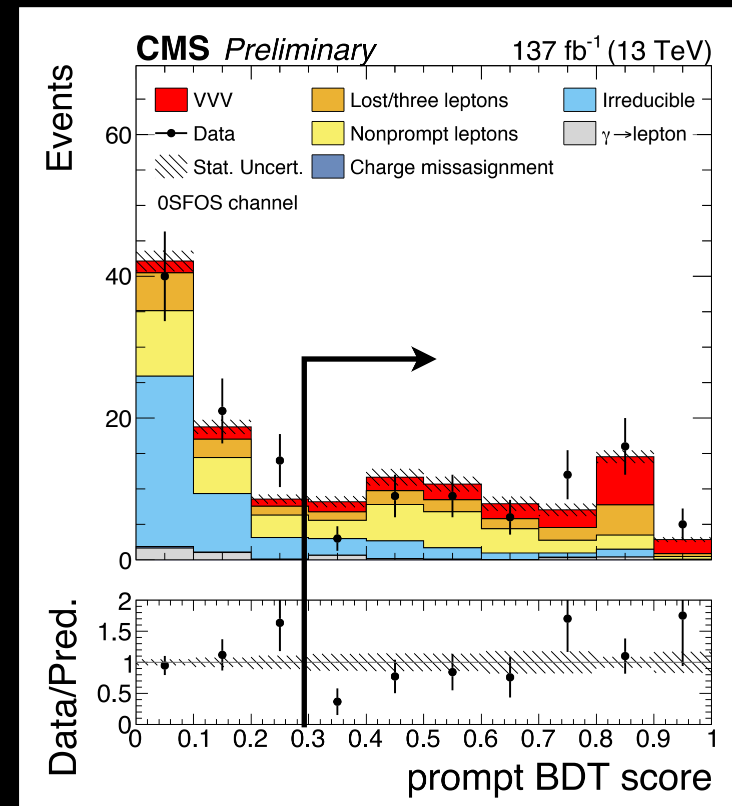
https://arogozhnikov.github.io/2016/07/05/gradient_boosting_playground.html

Train dedicated BDTs to maximize sensitivity

Applying BDT method to 0SFOS

- 10+ kinematics variables used to train BDT
- Two different bkg categories were targeted
  - Type A: Fake lepton backgrounds
    - $t\bar{t}$, DY
  - Type B: Non-Fake lepton backgrounds
    - $t\bar{t}W$, WZ





2D BDT used to maximize sensitivity

Summary of 0SFOS channel

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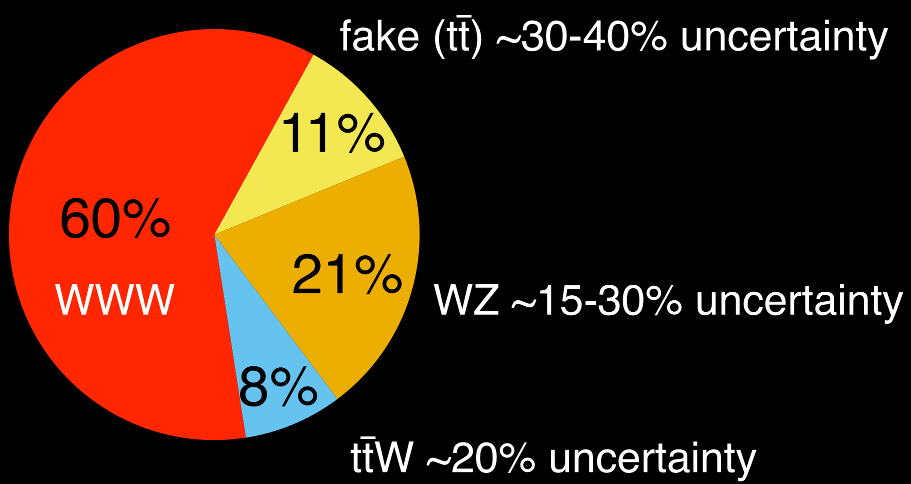
WWW	Fake	WZ	$t\bar{t}W$	Total B	S / B
10.1	1.8	3.5	1.3	6.6	1.5

cf. 700 total WWW → 3l

- 10 WWW events
- Statistics limited
- But systematics are becoming important
  - syst. err / stat. err ≈ 1:1
- 0SFOS sensitivity ~2.8 σ
- WWW sensitivity 3.1 σ (combined with other channels)

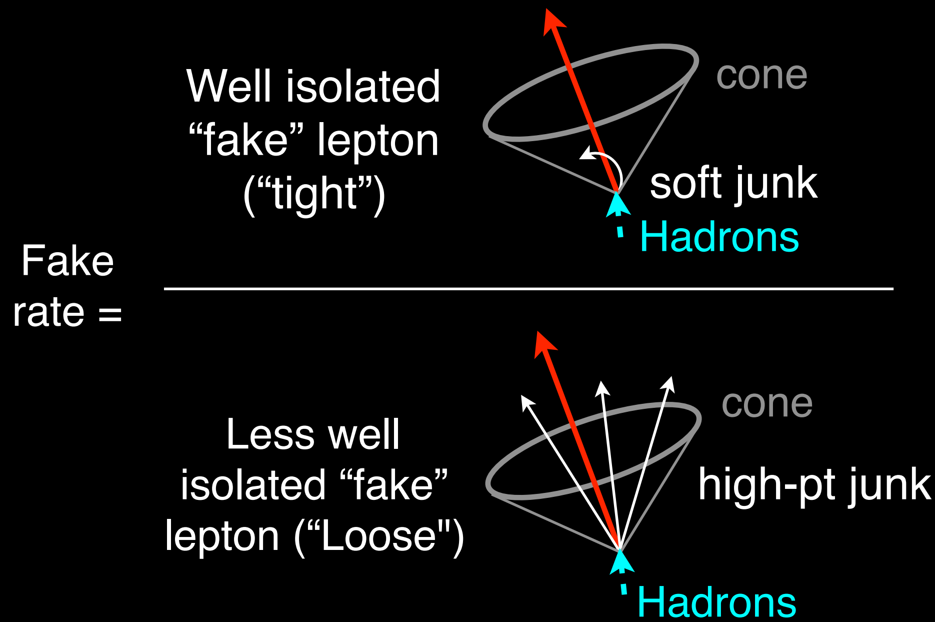
0SFOS composition

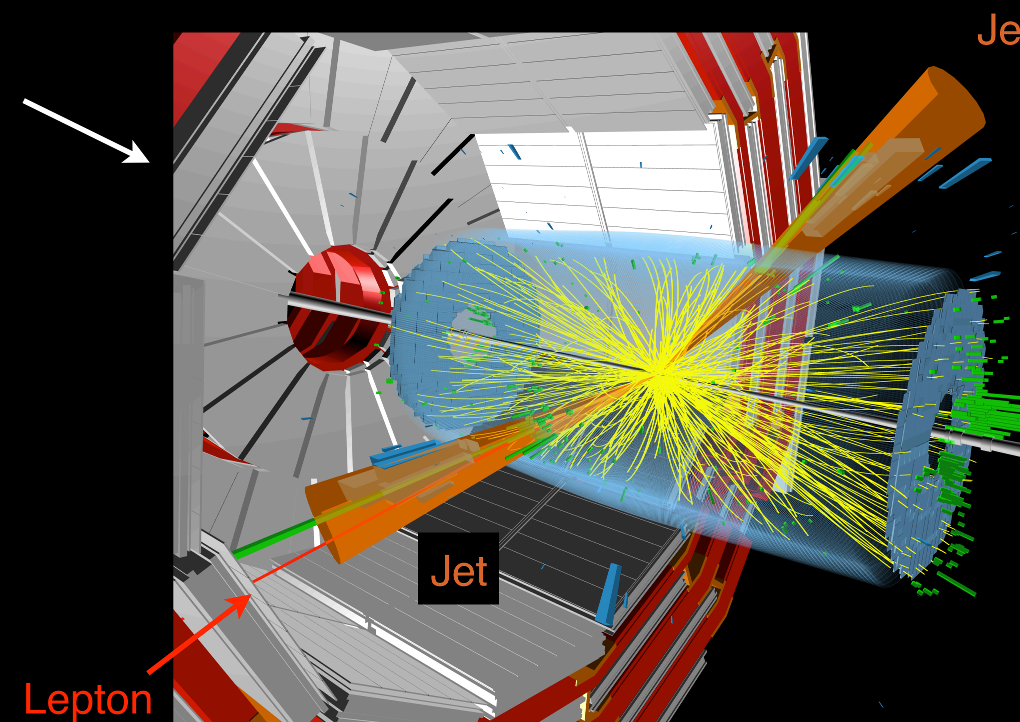


WWW expected sensitivity of 3.1 σ

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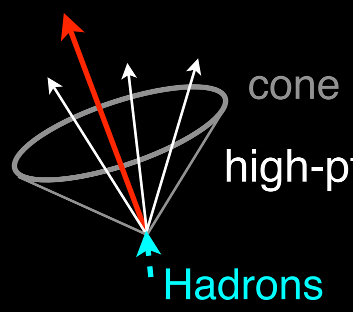
$$\text{Standard Isolation} = \frac{\sum_{\text{“stuff” in cone}} P_T}{P_{T,\text{Lepton}}}$$

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

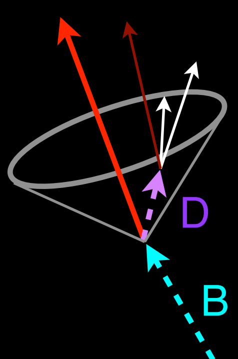
---

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

$\Longrightarrow$

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

Developed custom isolation to further reject fake lepton

Kinematic endpoints for Z + eμ (4 lepton)

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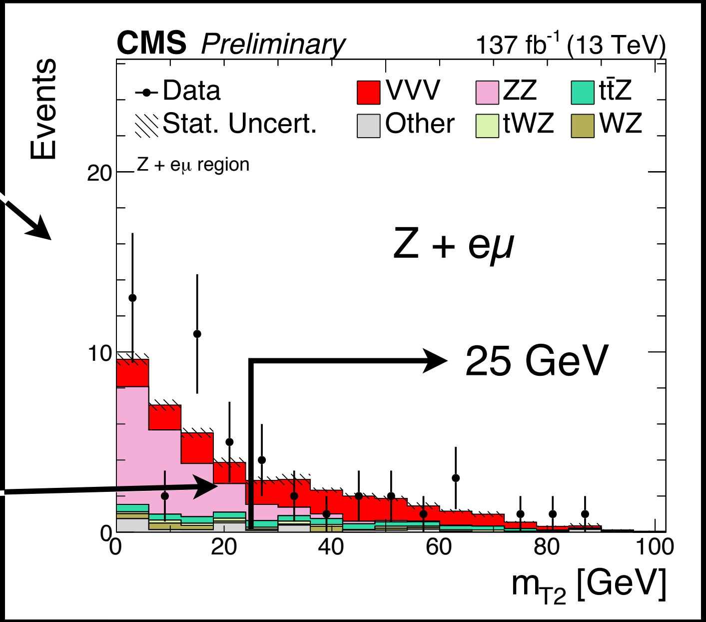
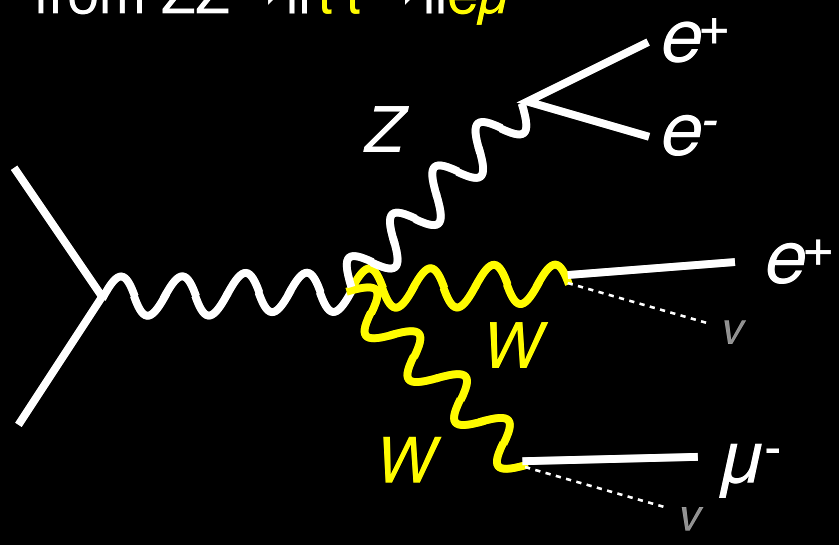
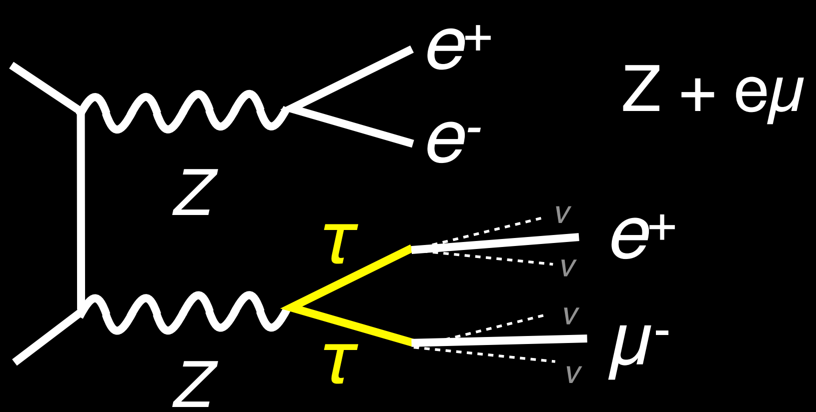
- As expected ZWW v. ZZ ~same order
- $t\bar{t}Z$ suppressed via b tagging
- Utilize m_{T2} variable
- m_{T2} is sensitive to the end points of m_W from ZWW→lleμ
- m_{T2} is sensitive to the end points of m_τ from ZZ→llττ→lleμ







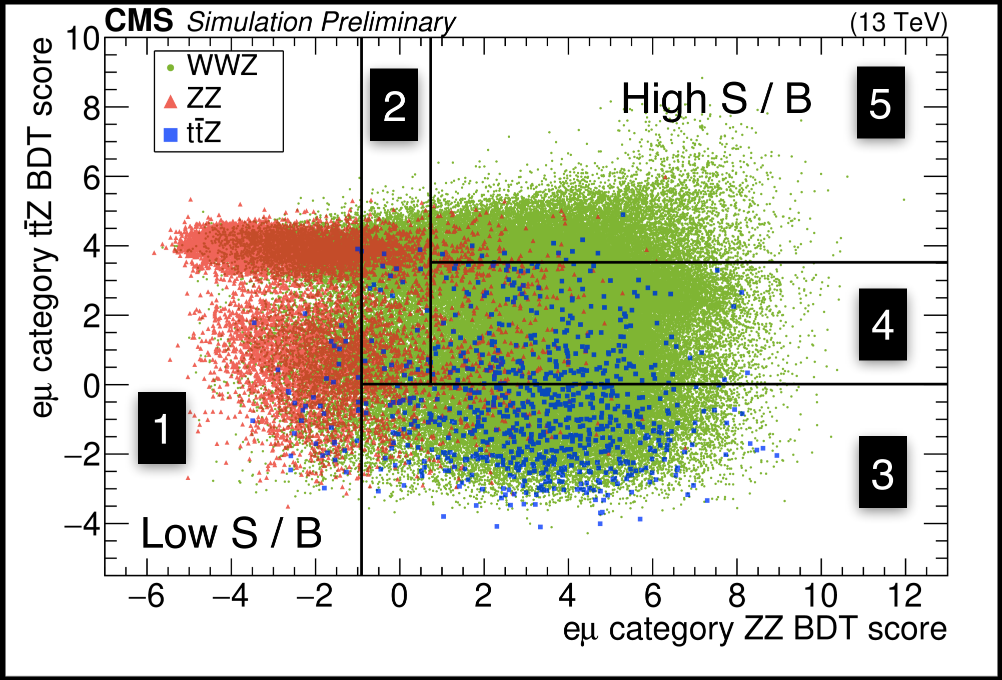
Exploit differences between Z → ll v. WW → lνlν

Applying BDT method to Z + eμ channel

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

More WWZ like

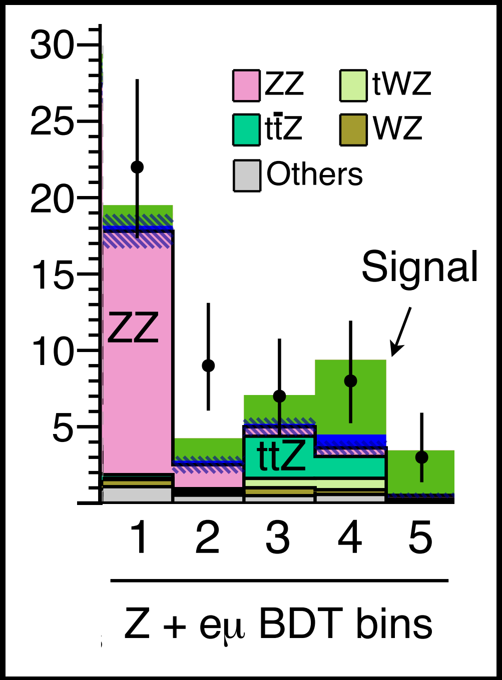
More $t\bar{t}Z$ like



More ZZ like

More WWZ like

5 bins are created from 2D planes



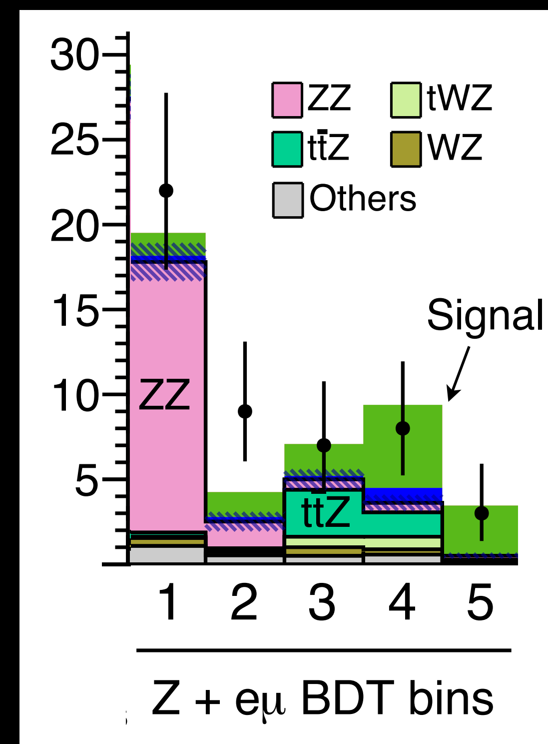
2D BDT used to maximize sensitivity

Summary of Z + *eμ*

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. 150 total WWZ → 4l

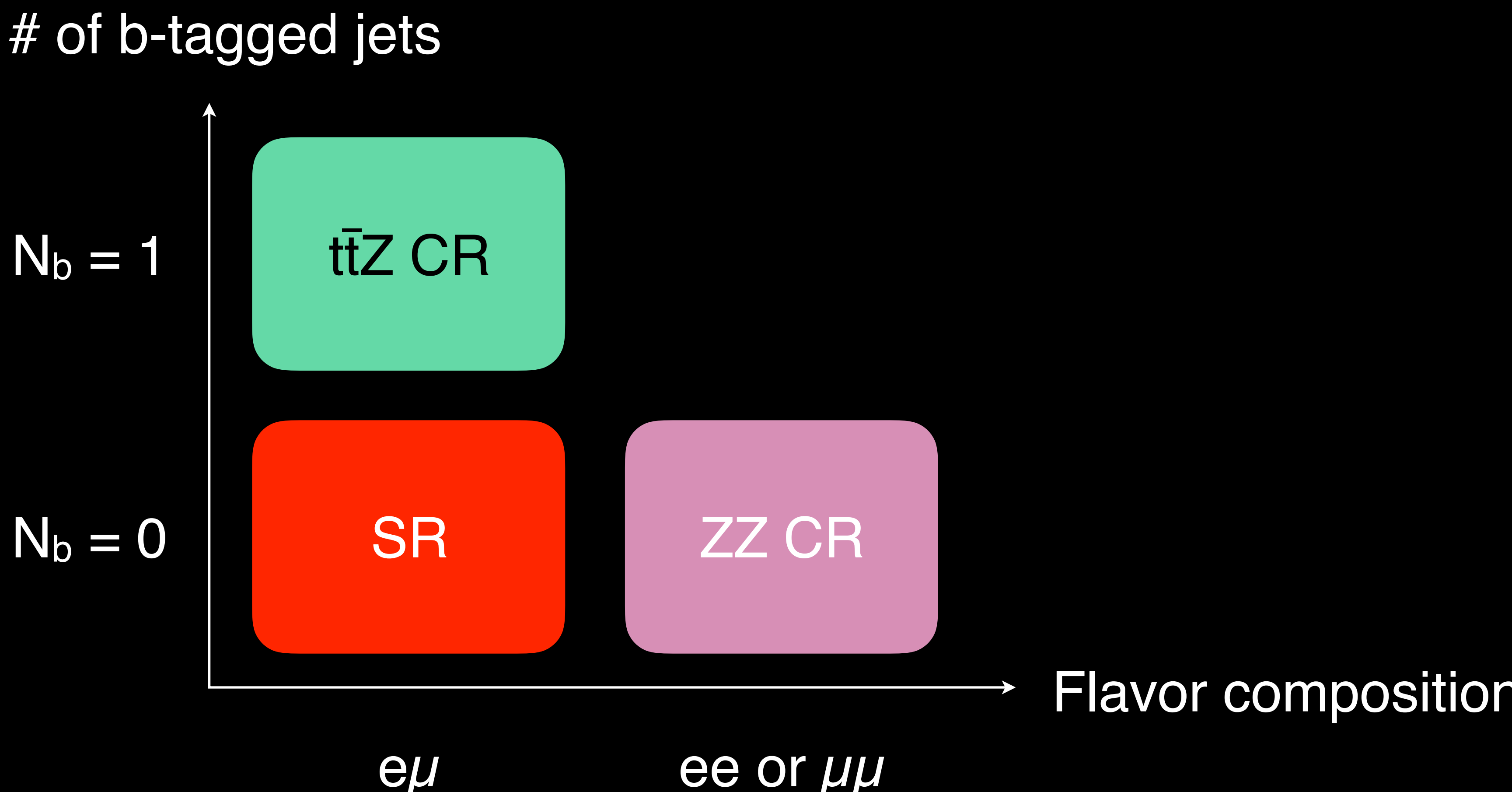
- Statistics limited
- Main backgrounds are ZZ and $t\bar{t}Z$
    - ZZ ~5% uncertainty
    - $t\bar{t}Z$ ~30% uncertainty
- Z + *eμ* sensitivity ~4 σ
- Combined WWZ sensitivity 4.1 σ



WWZ expected sensitivity of 4.1 σ

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

Devise control regions and extrapolate to signal region



Extrapolate from CR to estimate backgrounds

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

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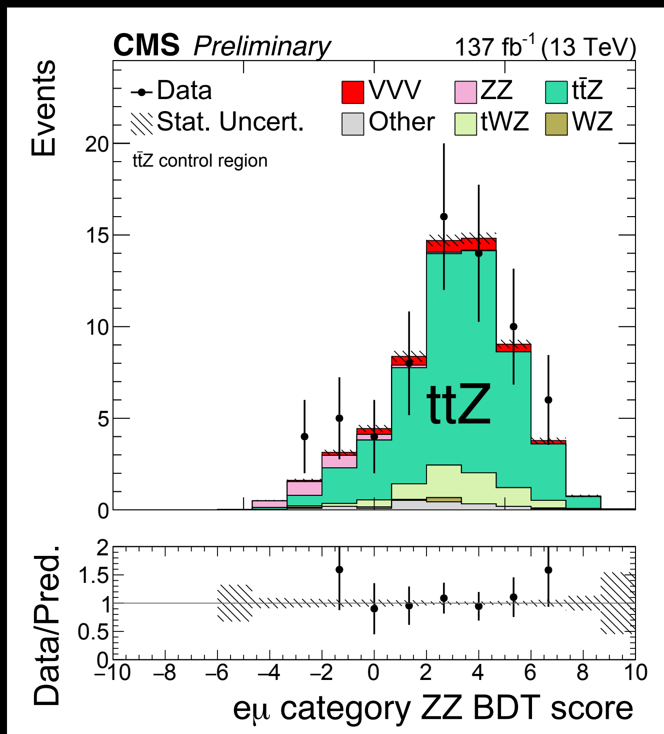
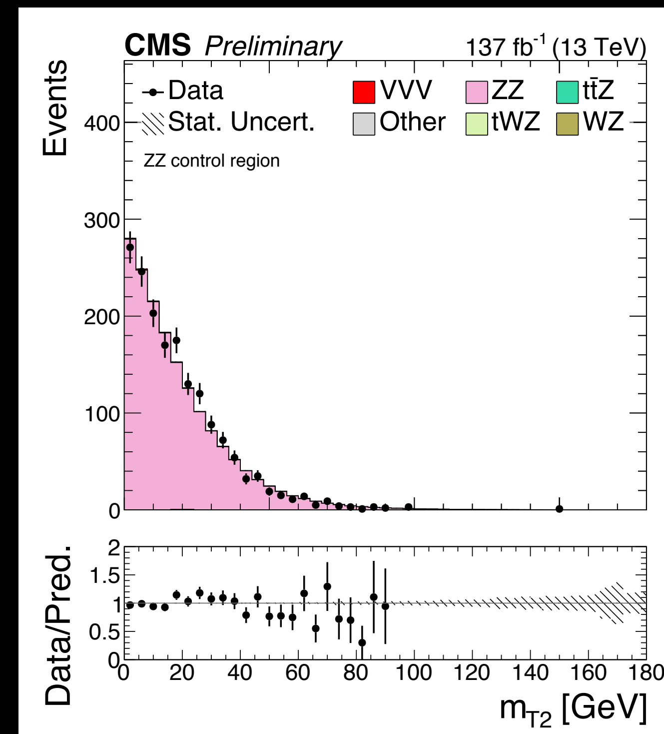
Devise control regions and extrapolate to signal region

$t\bar{t}Z$ 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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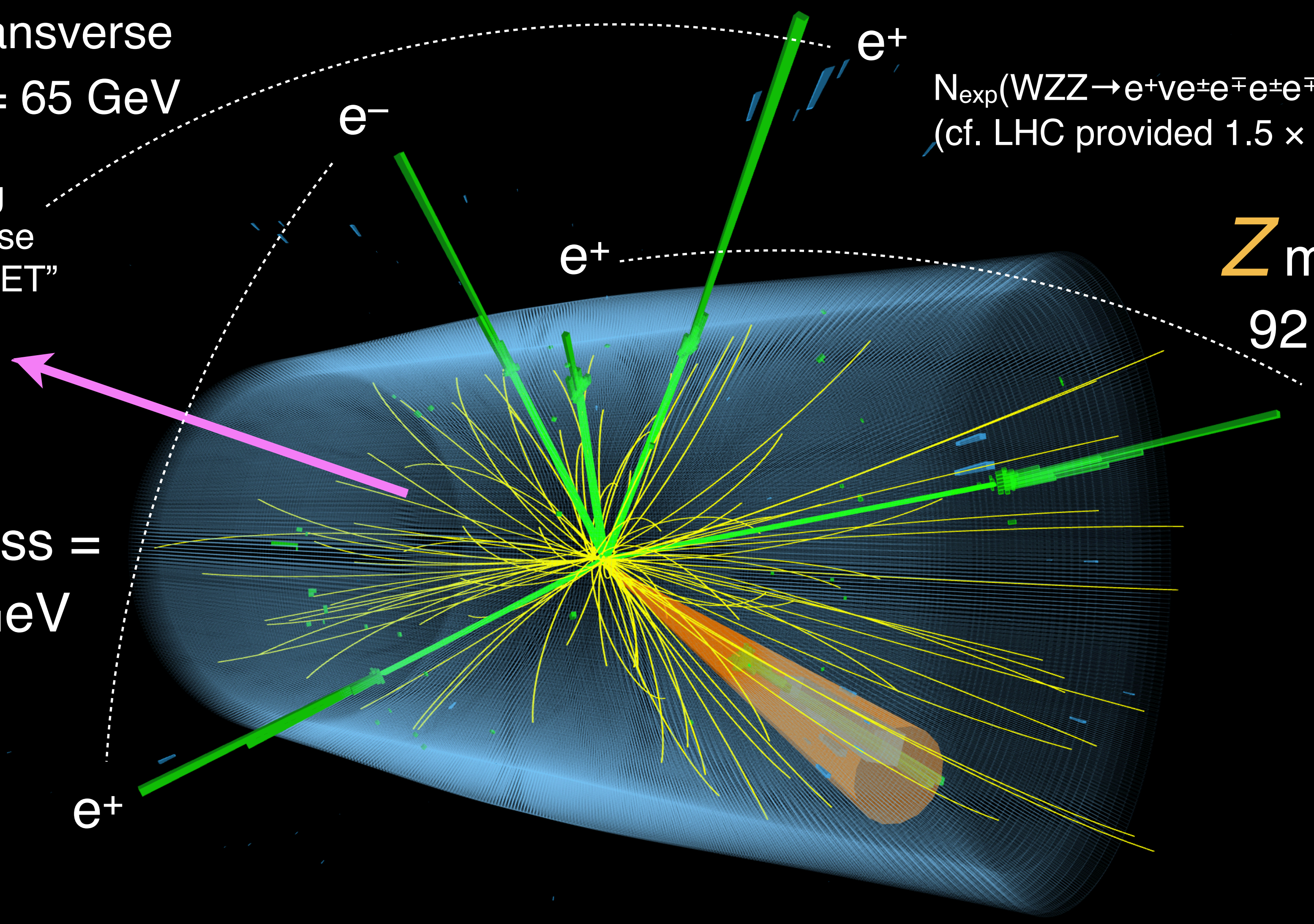
CMS experiment at the LHC, CERN
Data recorded: 2016-Oct-09 21:24:05.010240 GMT
Run 282735, Event No. 989682042 LS 491

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

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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

	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^{\pm} \rightarrow l^{\pm}\nu$ $W^{\pm} \rightarrow l^{\pm}\nu$ $W^{\mp} \rightarrow qq$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $W \rightarrow l\nu$	$W \rightarrow l\nu$ $W \rightarrow l\nu$ $Z \rightarrow ll$	$W \rightarrow l\nu$ $Z \rightarrow ll$ $Z \rightarrow ll$	$Z \rightarrow ll$ $Z \rightarrow ll$ $Z \rightarrow ll$
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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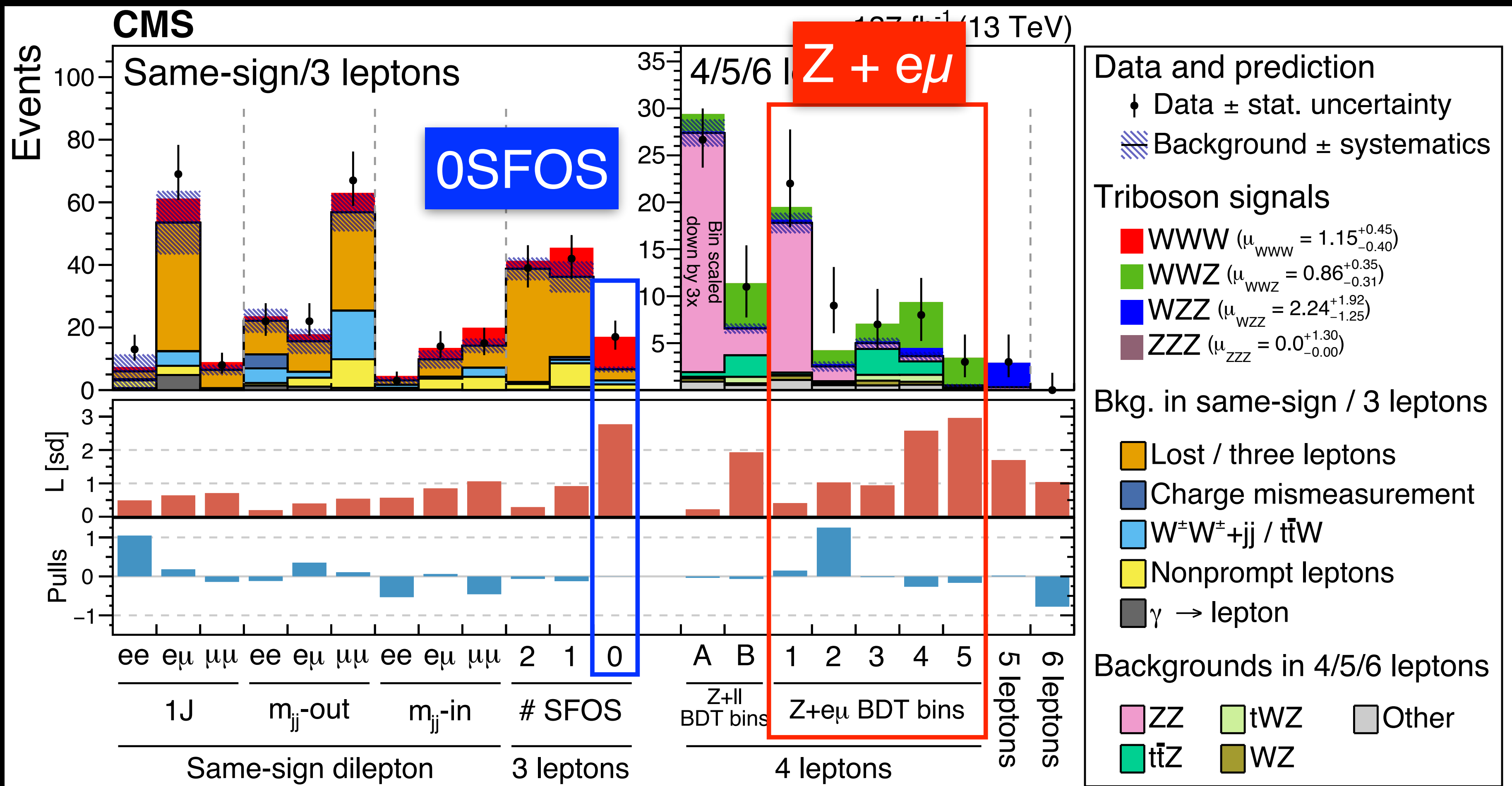
Signal strength $\mu = \frac{\text{Measured cross section}}{\text{Theoretical cross section}}$



9 bins 3 bins 7 bins 1 1

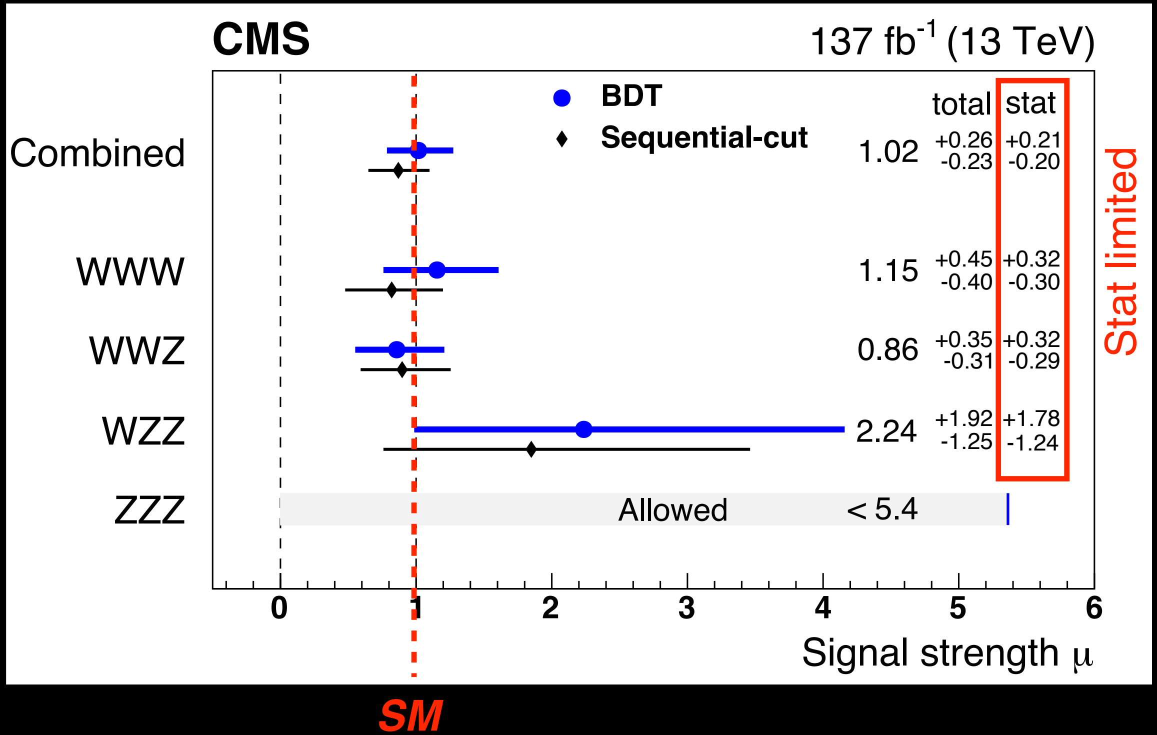
More sensitive bins are generally to the right

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

Results

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)



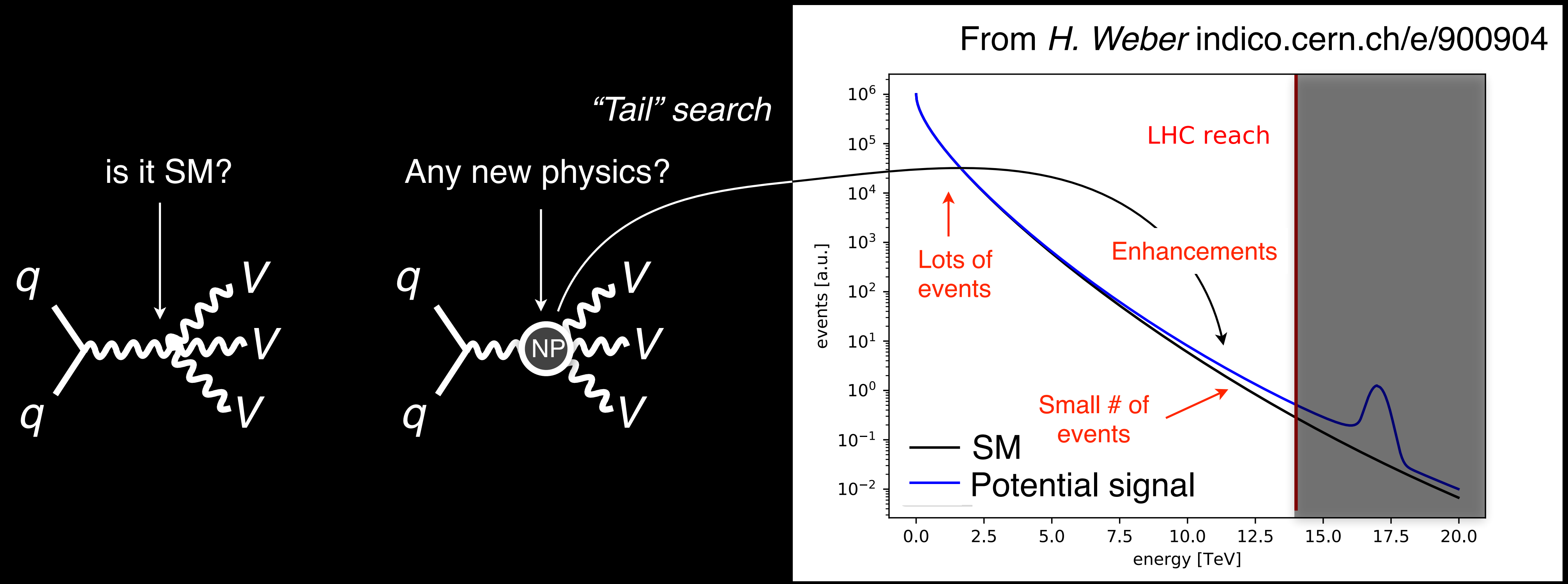
$$\text{Signal strength } \mu = \frac{\text{Measured cross section}}{\text{Theoretical cross section}}$$

- 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

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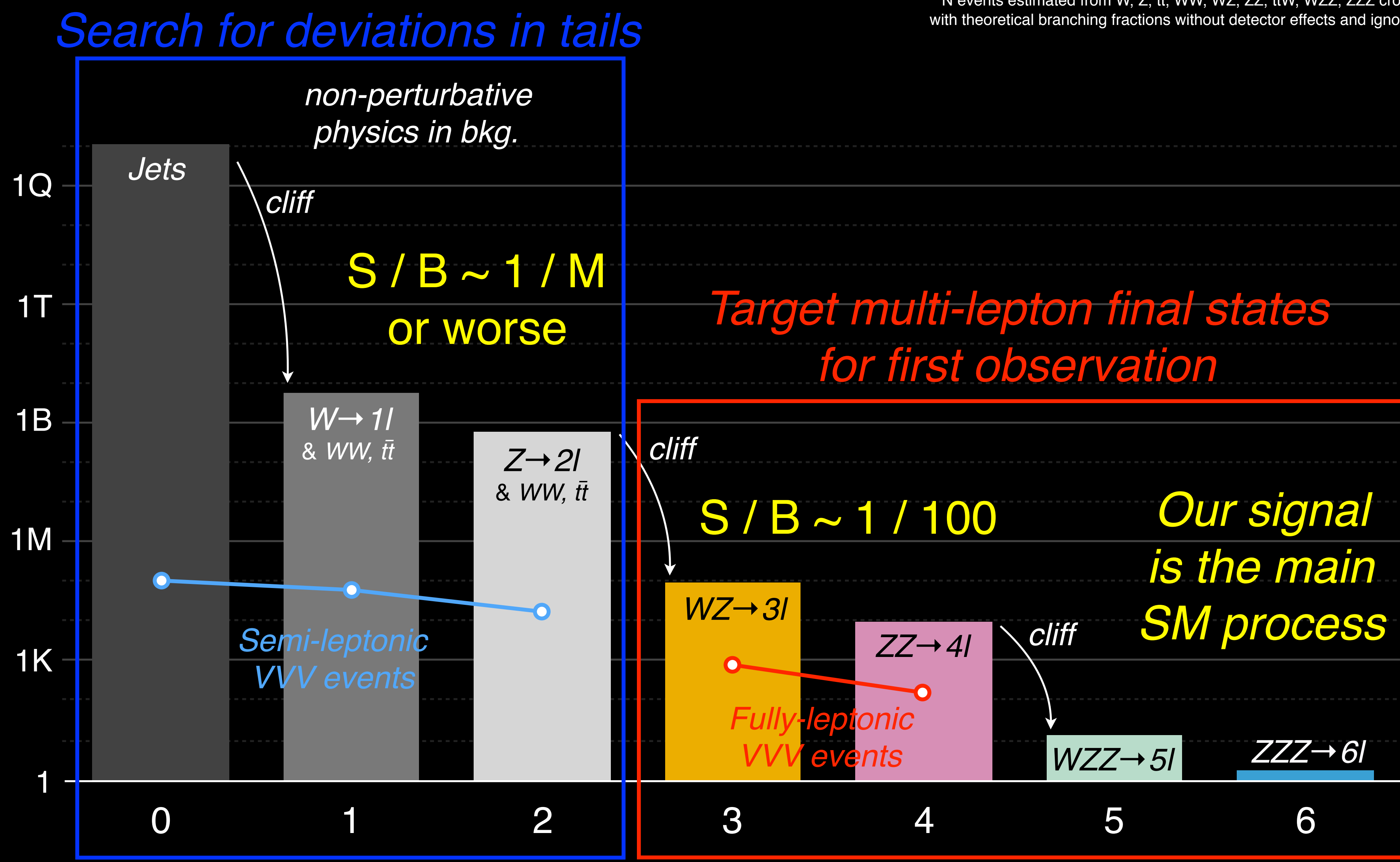
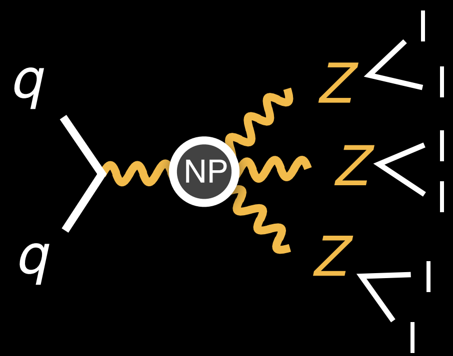
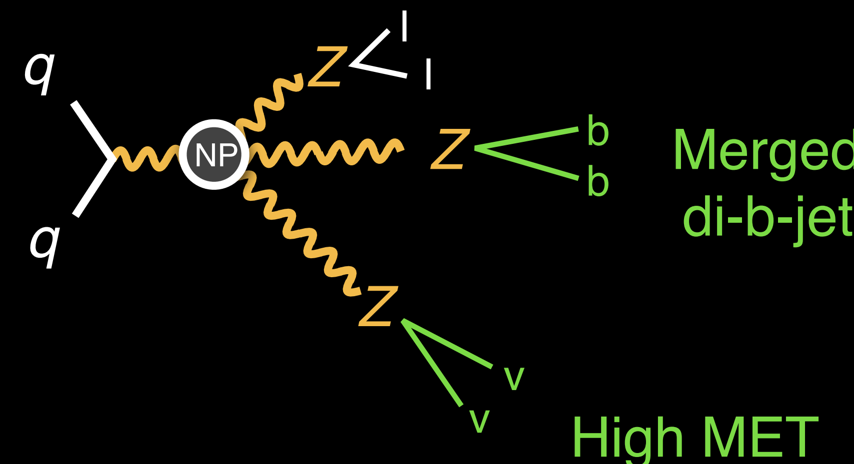
**N events estimated from W, Z, $t\bar{t}$, WW, WZ, ZZ, $t\bar{t}$W, WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring $\tau \rightarrow e, \mu$



Target semi-leptonic final states for tail search

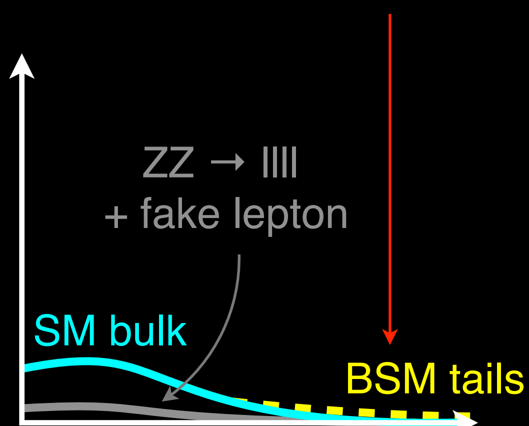
Fully leptonic v. Semi leptonic channel

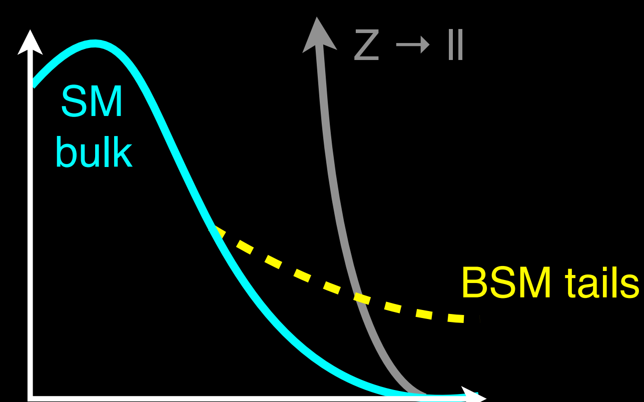




Clean channel for discovery but probing tail is difficult due to small total # of events

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





Also resonance could be here too

NP effects could be exploited in semi-leptonic channels

VVV as a probe to constrain new physics

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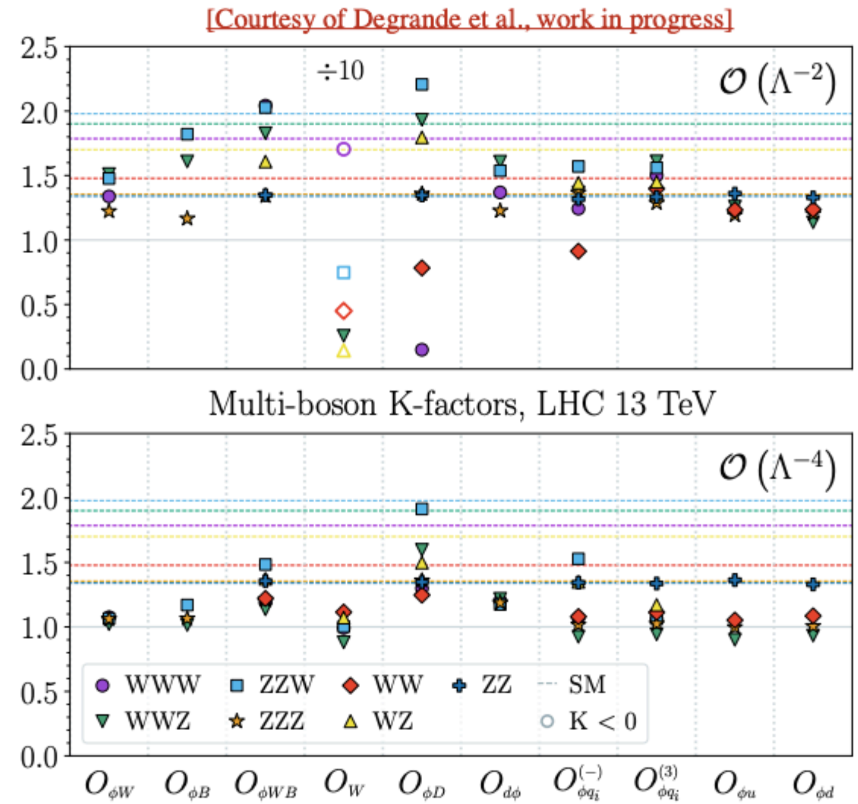
Fabio Maltoni (Plenary Theory talk at ICHEP)

VVV measurement

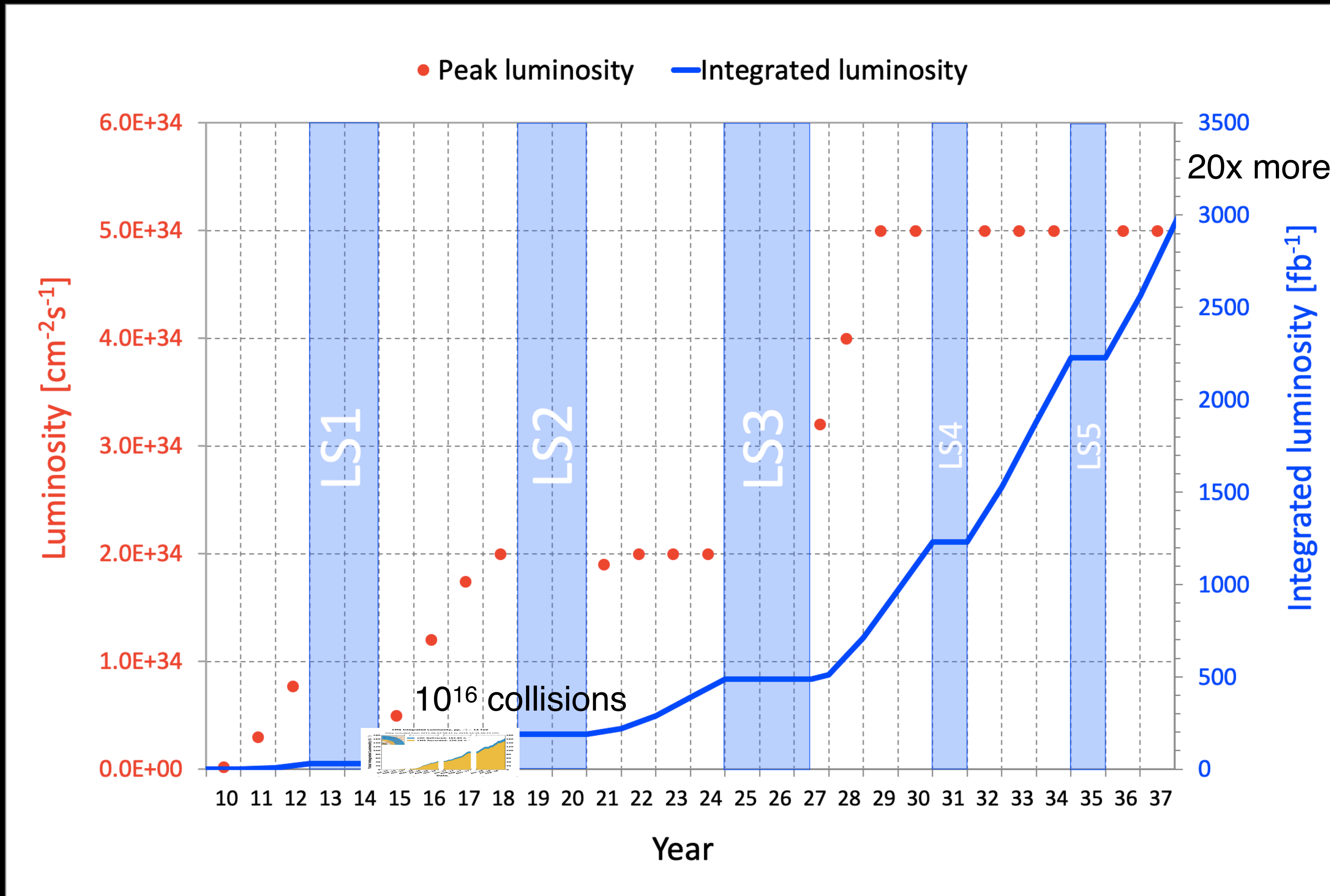
the 1000th CMS paper

- VVV observed by CMS in the multi-lepton final state by combining various channels.
- VVV known at NLO in QCD in the SM.
- Now prediction at NLO QCD in the SMEFT for VVV production at the LHC are available.
- K-factors show a non-trivial behaviour.
- An interesting outcome is the large K-factor of O_W opening the possibility of bounding it here, instead of by using differential distributions in WW.



VVV suggested as a new window to constrain BSM

HL-LHC



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

Future multi-boson analyses

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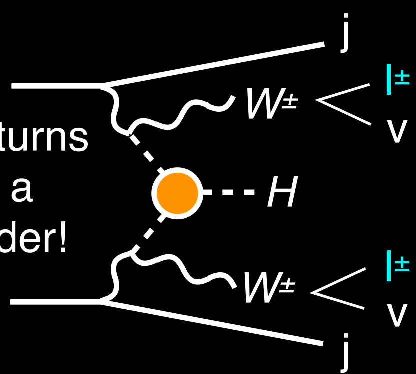
arXiv:1812.09299 Henning, Lombardo, Riembau, Riva
arXiv:1511.03674 Dror, Farina, Salvioni, Serra
arXiv:1904.05637 Maltoni, Mantani, Mimasu
arXiv:2006.09374 Stolarski, Wu
arXiv:2009.01249 LHC Higgs WG Note

listing a few additional rare multi-boson processes

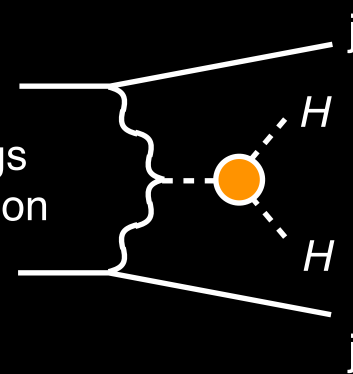
$pp \to W^{\pm}W^{\pm}H\,jj$

Same-sign turns LHC into a Higgs collider!



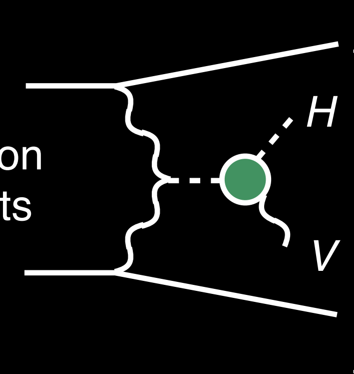
$pp \to HH\,jj$

Di-higgs production



$pp \to VH\,jj$

VH production with VBS jets



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

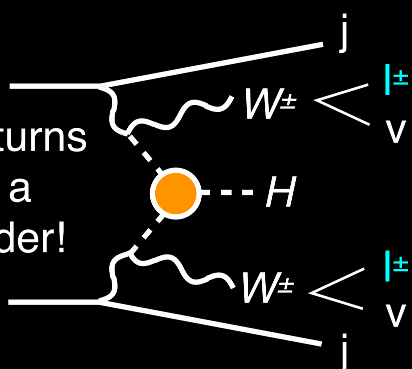
Future multi-~~boson~~ massive-X analyses

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~~ massive-X processes

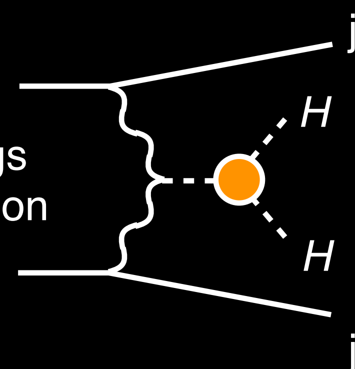
$pp \rightarrow W^{\pm}W^{\pm}H\,jj$

Same-sign turns LHC into a Higgs collider!



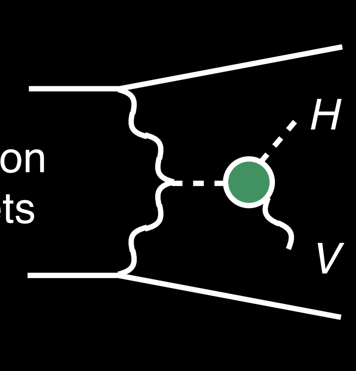
$pp \rightarrow HH\,jj$

Di-higgs production



$pp \rightarrow VH\,jj$

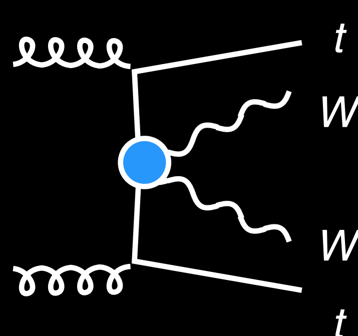
VH production with VBS jets



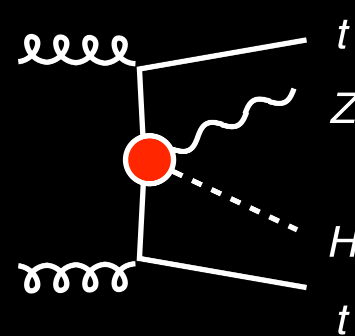
$pp \rightarrow tW^{\pm}W^{\pm}j$

High P_T top (> 500 GeV)

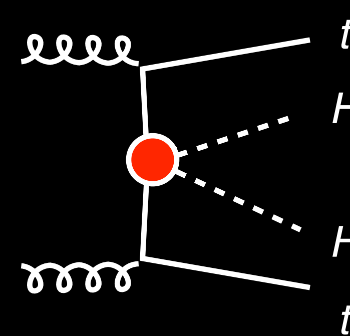
$pp \rightarrow ttWW$



$pp \rightarrow ttZH$



$pp \rightarrow ttHH$



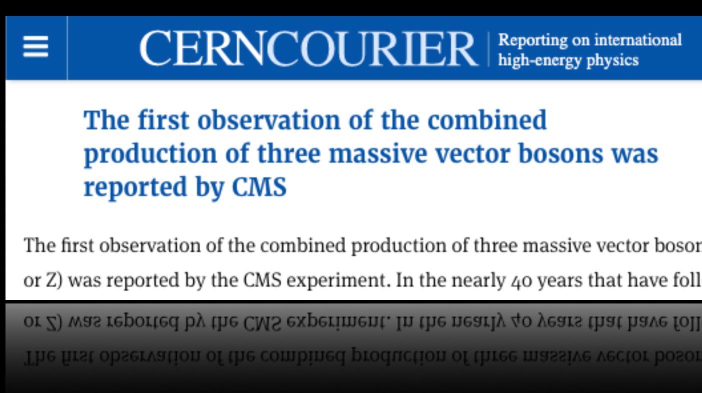
Rich set of final states to cover w/ LHC data set

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!

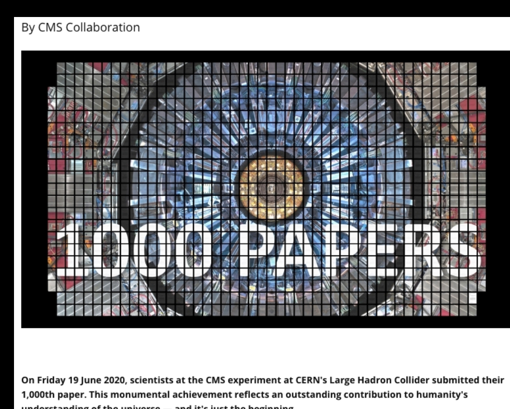
CERN Courier



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

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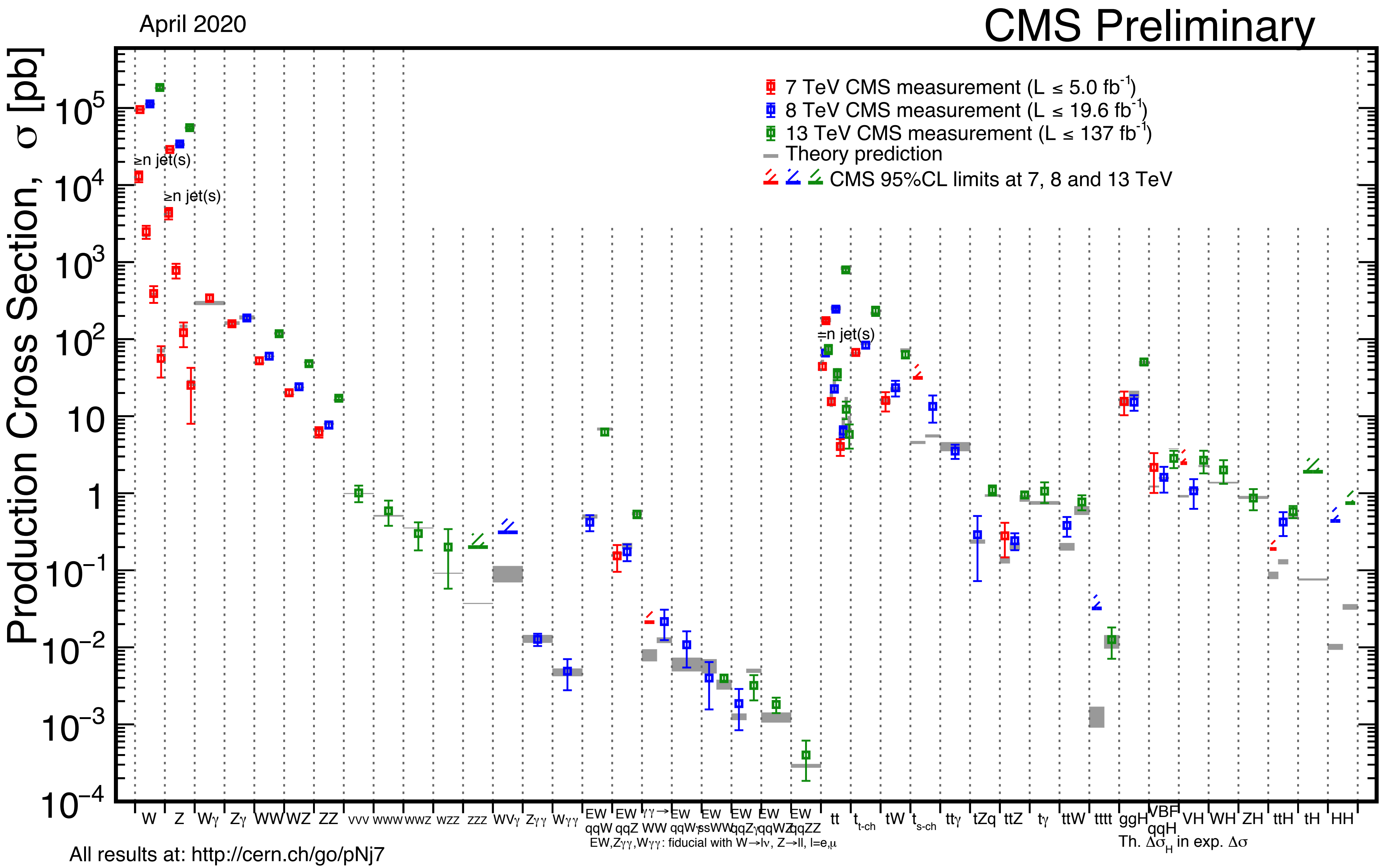

Title

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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		—
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert > 20$ 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

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

3L selection

Variable	0 SFOS	1 and 2 SFOS
Trigger	Signal triggers, tab. 3.2	
Signal leptons	3 tight leptons with charge sum = $\pm 1e$	
	$p_T > 25/25/25$ 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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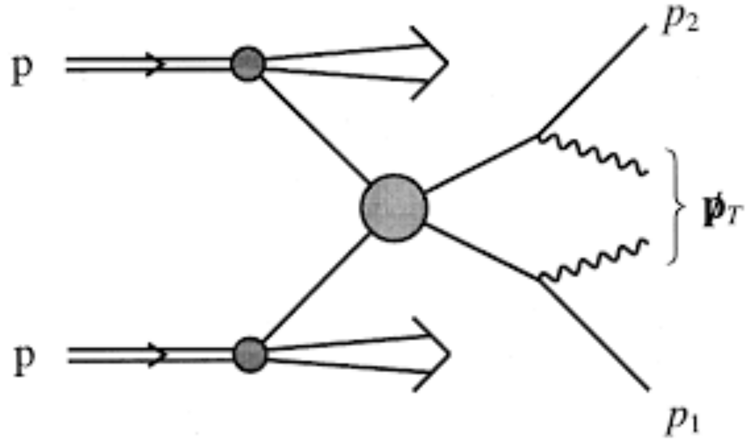
UCSD

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

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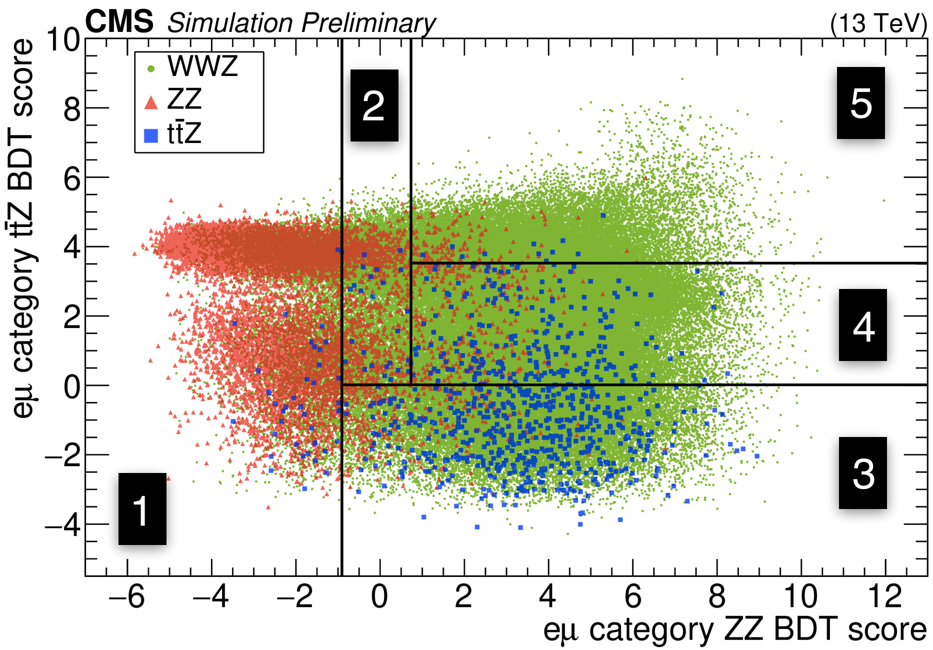
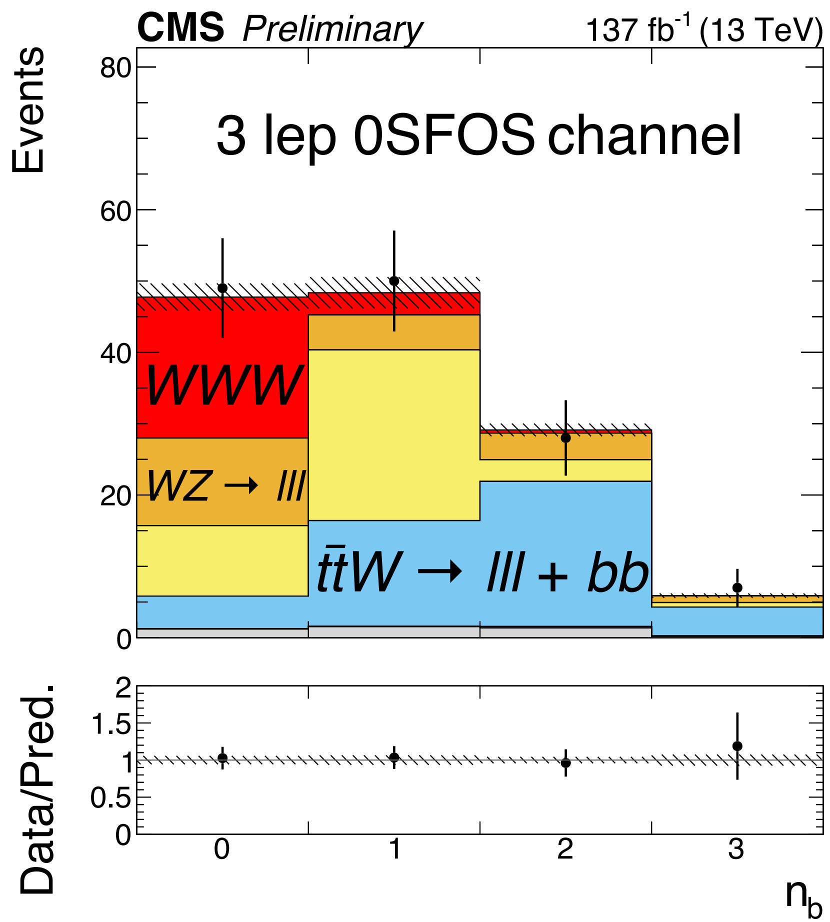


	ZZ BDT range	$t\bar{t}Z$ BDT range
eμ BDT bin 1	(-∞, -0.908)	(-∞ , ∞)
eμ BDT bin 2	(-0.908 , ∞)	(-∞ , 0.015)
eμ BDT bin 3	(-0.908 , 0.733)	(0.015 , ∞)
eμ BDT bin 4	(0.733 , ∞)	(0.015 , 3.523)
eμ BDT bin 5	(0.733 , ∞)	(3.523 , ∞)
ee/$\mu\mu$ BDT bin A	(0 , 3)	-
ee/$\mu\mu$ BDT bin B	(3 , ∞)	-

Title


CMS Preliminary
137 fb-1 (13 TeV)
3 lep 0SFOS channel
Events
WWW
WZ → lll
t̄tW → lll + bb
Data/Pred.
n_b
0
1
2
3

Title

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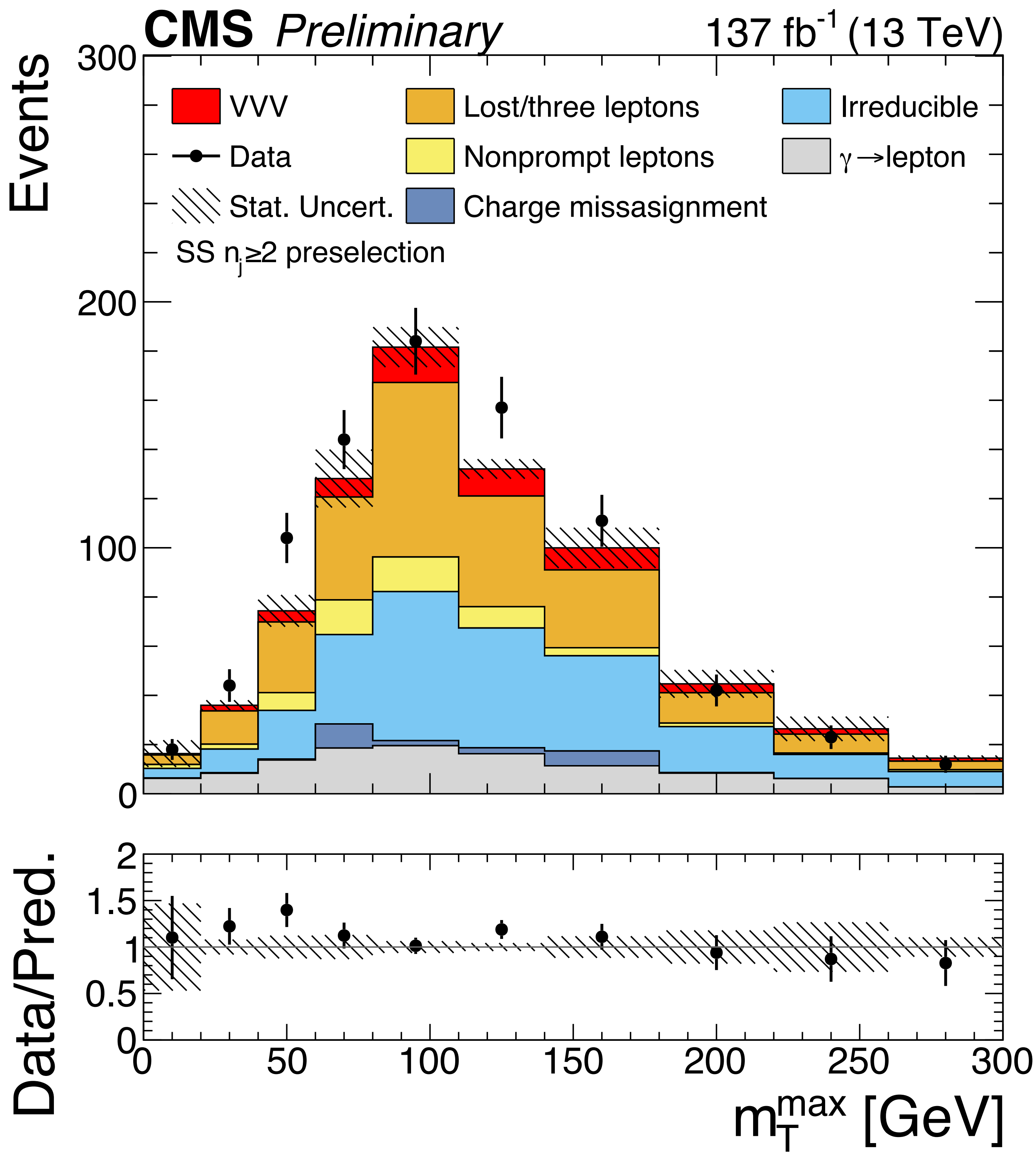
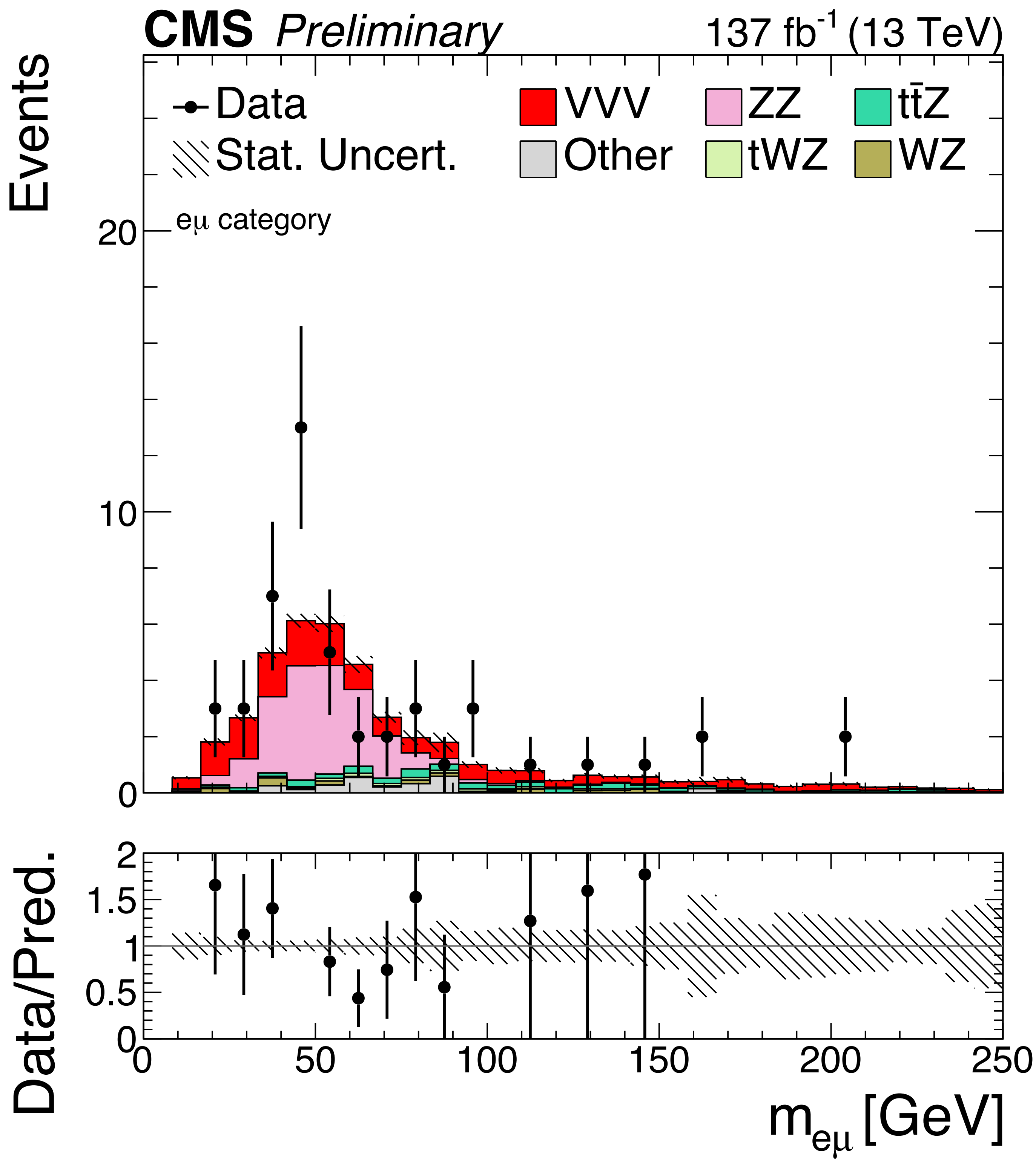
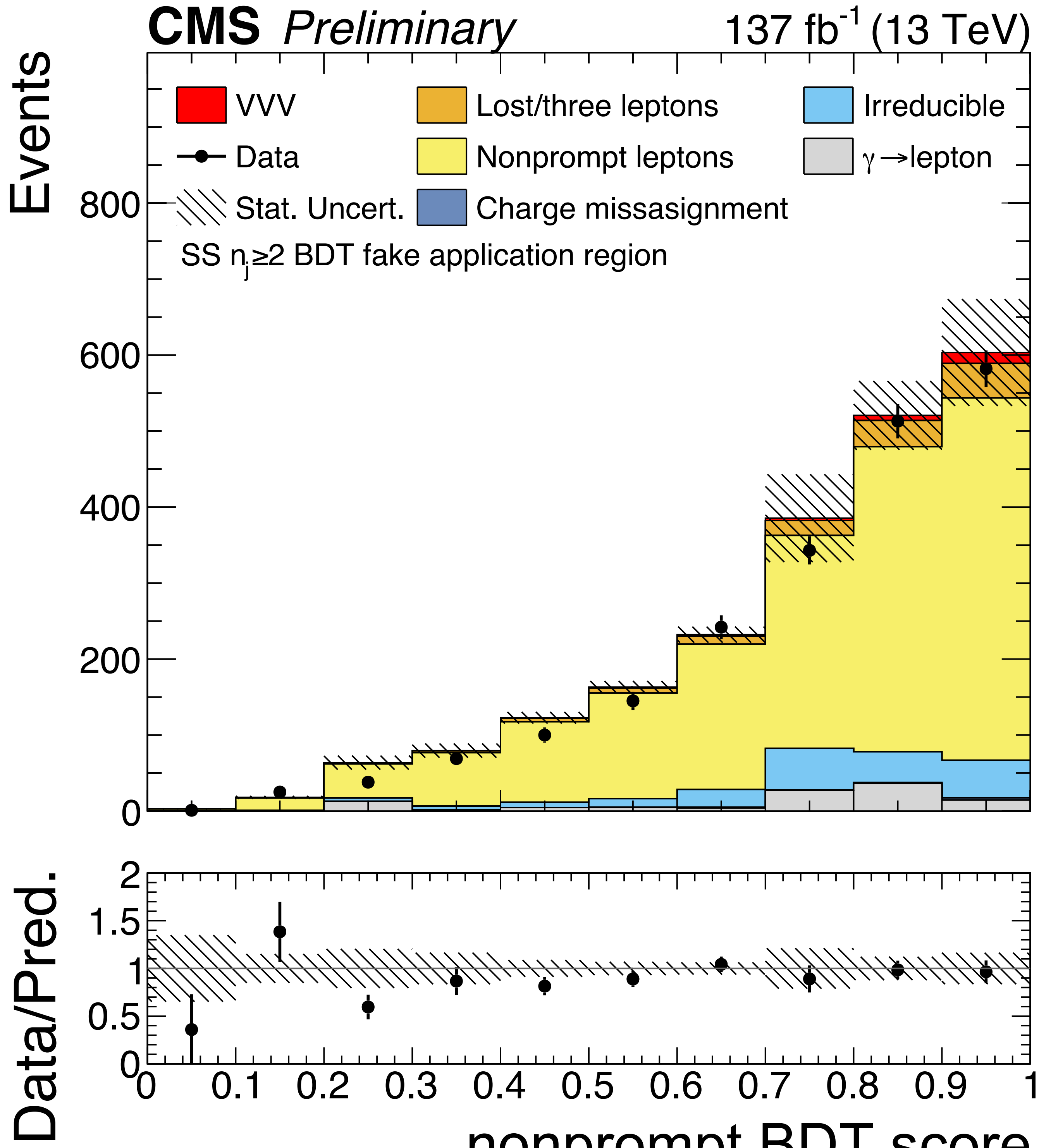


Title


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

Title



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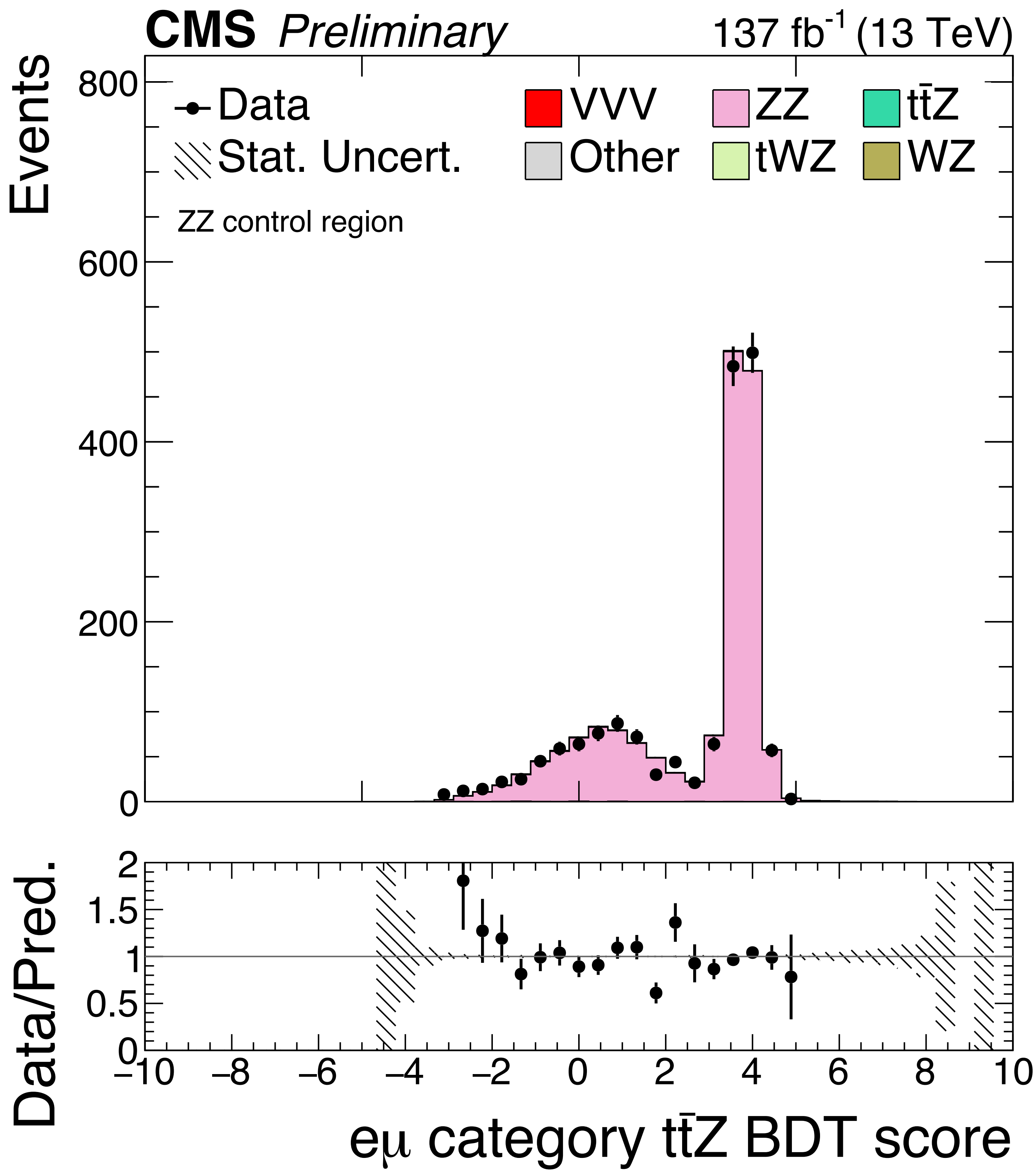
Title



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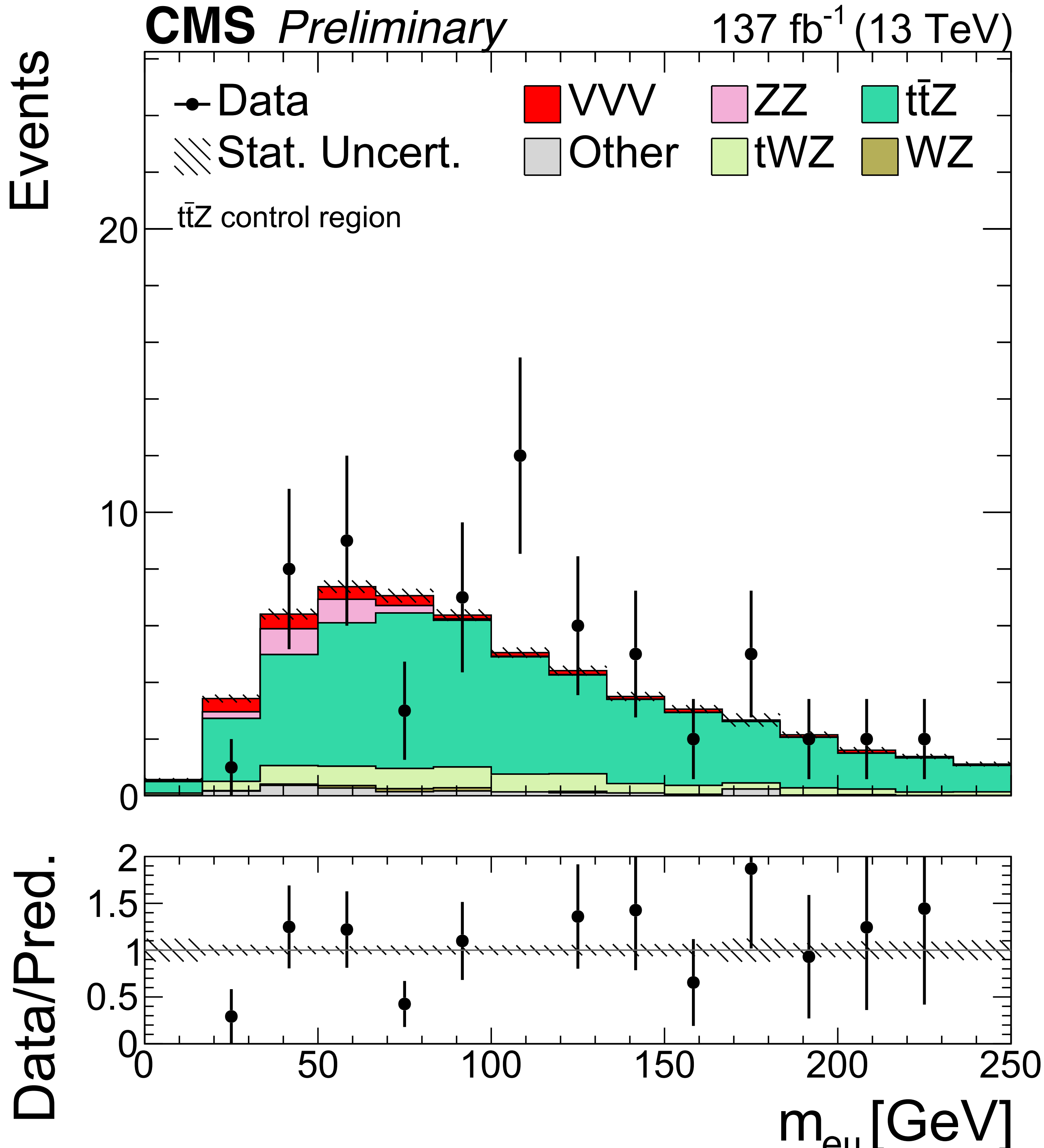
Title


CMS Preliminary
137 fb-1 (13 TeV)
Data
Stat. Uncert.
VVV
Other
ZZ
tWZ
tt̄Z
WZ
tt̄Z control region
Events
Data/Pred.
meμ [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 $e^{\pm}e^{\pm}$	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

Title

Signal	SS m_{jj}-in			SS m_{jj}-out			SS 1j			3ℓ		
region	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	0 SFOS	1 SFOS	2 SFOS
Lost/three ℓ	1.8±0.4	10.9±2.0	8.7±1.0	8.8±1.7	46.0±6.2	44.8±4.4	8.4±1.3	43.5±4.4	34.5±2.7	4.6±0.8	15.1±1.5	58.3±2.4
Irreducible	2.1±0.4	13.0±3.6	8.4±1.4	9.8±1.4	41.1±4.5	42.8±4.7	2.6±0.6	22.8±8.6	13.2±1.9	2.5±0.9	2.2±1.2	2.5±0.8
Nonprompt ℓ	1.3±0.9	5.8±2.4	6.8±2.2	2.3±1.3	12.0±6.1	11.2±3.8	1.8±2.9	2.4±1.3	2.8±1.1	3.0±0.9	5.7±1.6	5.9±1.6
Charge flips	<0.1	1.2±2.0	<0.1	2.6±1.6	1.0±0.5	<0.1	6.9±4.7	0.2±0.1	<0.1	<0.1	1.1±1.3	0.7±0.2
$\gamma \to$ 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

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Signal region	4ℓ eμ				4ℓ ee/μμ			5ℓ	6ℓ
	bin 4	bin 3	bin 2	bin 1	bin A	bin B	bin C		
ZZ	0.3±0.0	0.7±0.0	0.7±0.0	0.4±0.0	1.8±0.2	6.0±0.6	5.0±0.5	0.30±0.08	0.01±0.01
$t\bar{t}Z$	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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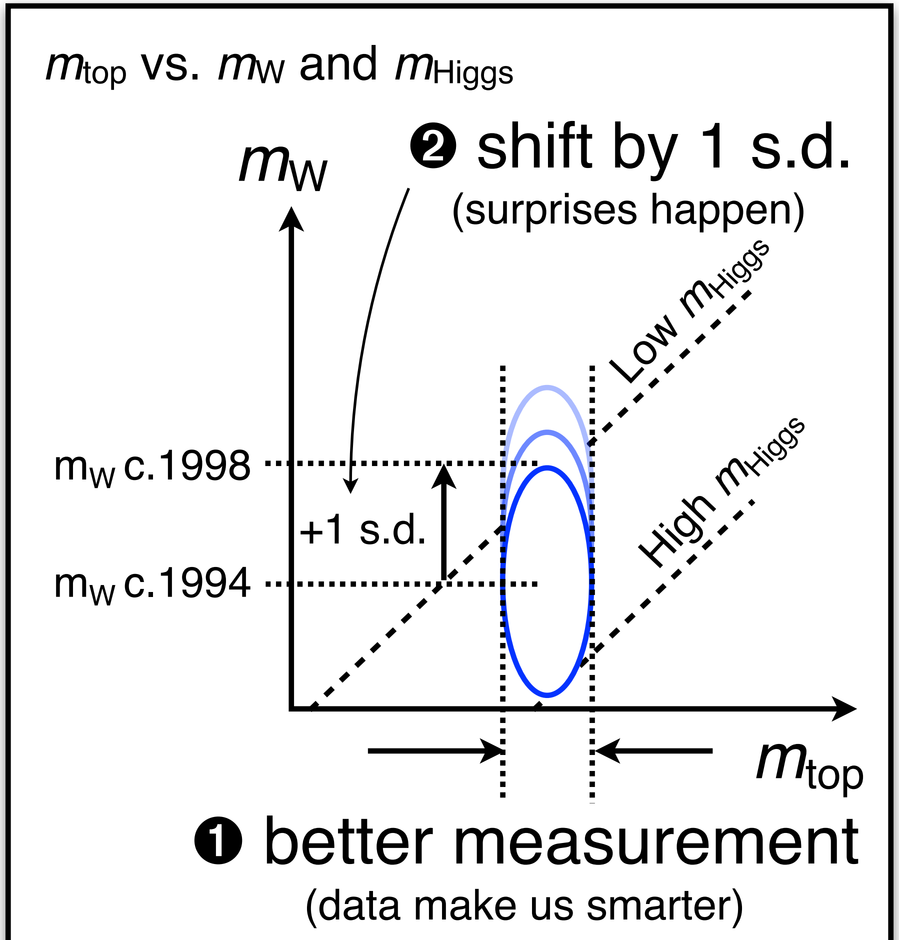
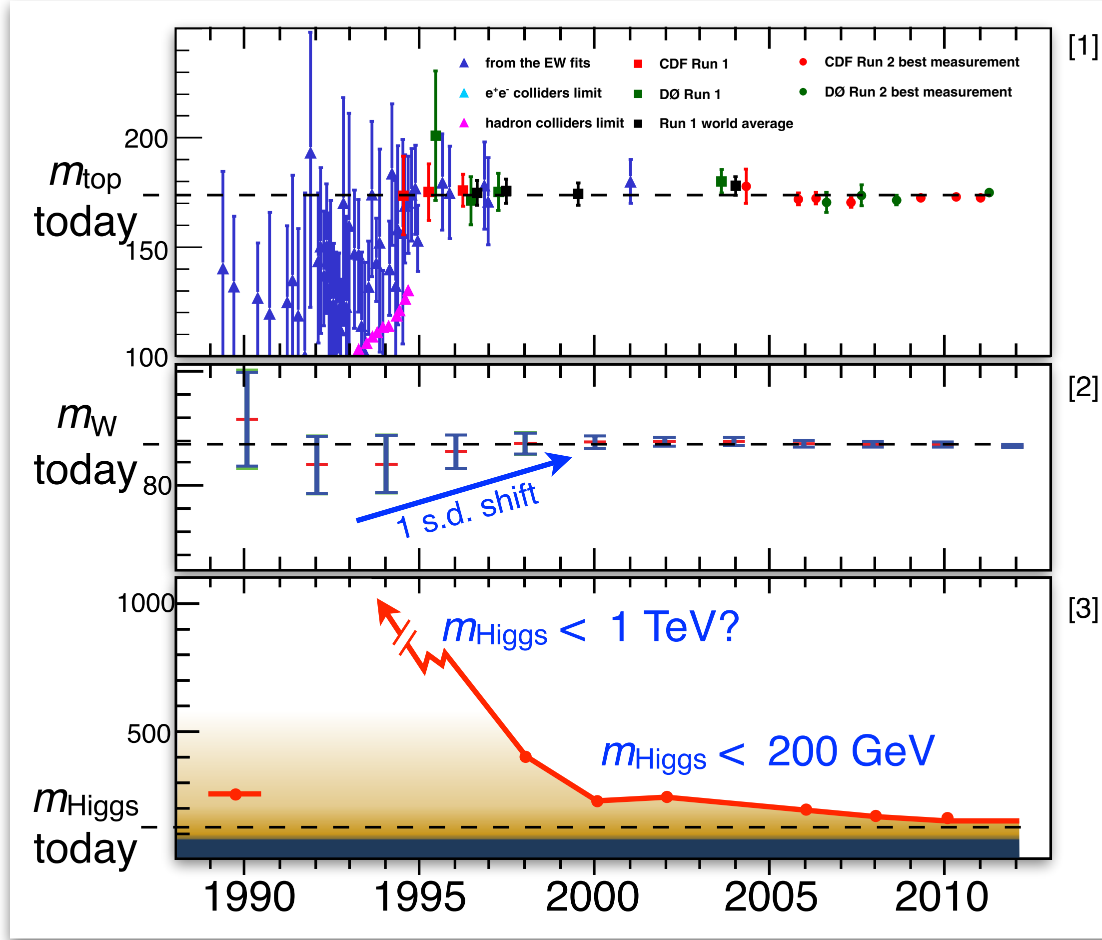


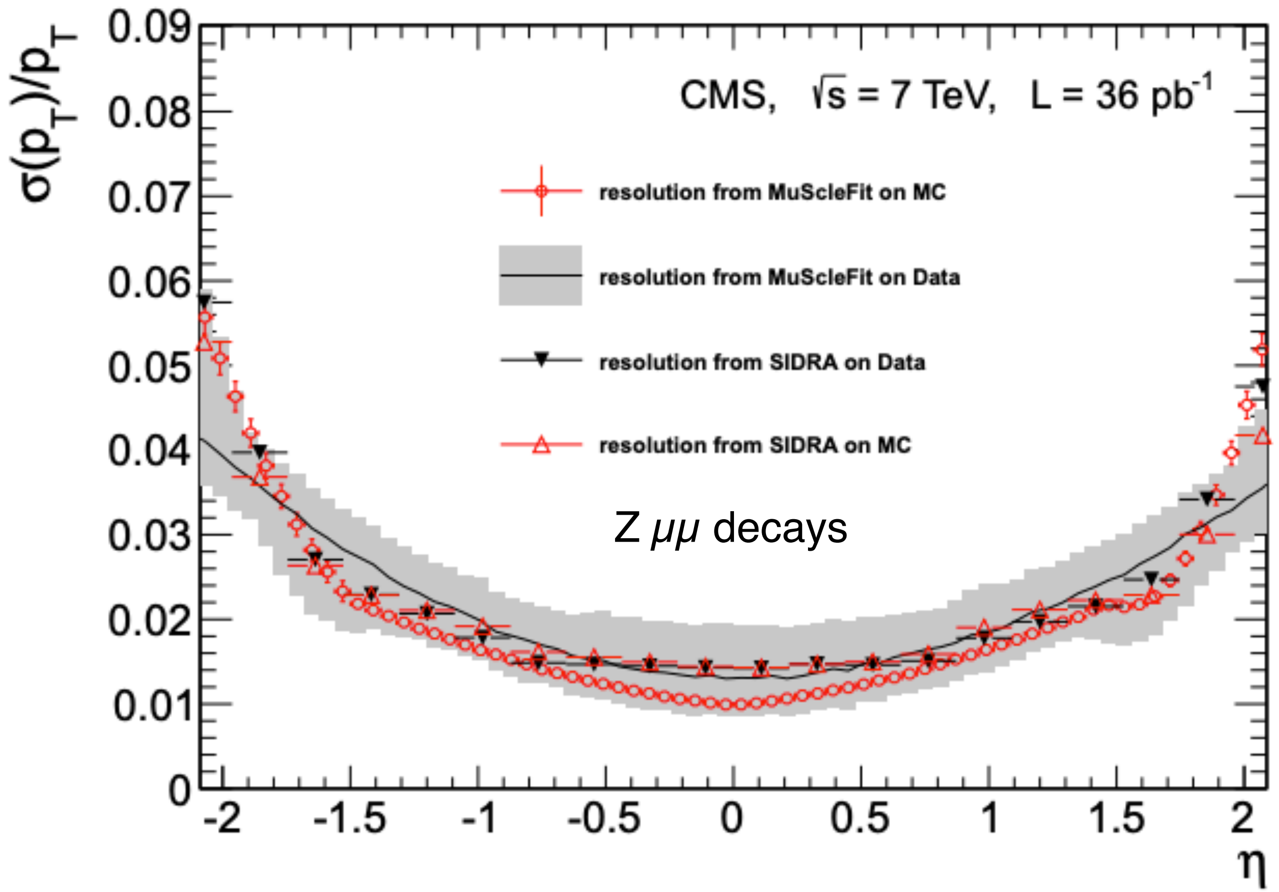


…after analysis of Run I data, … ❷ <u>m_W shifted a full s.d.</u> … the m_{Higgs} must be ❸ <u>much lower than anyone had anticipated.</u> … Surprises happen.

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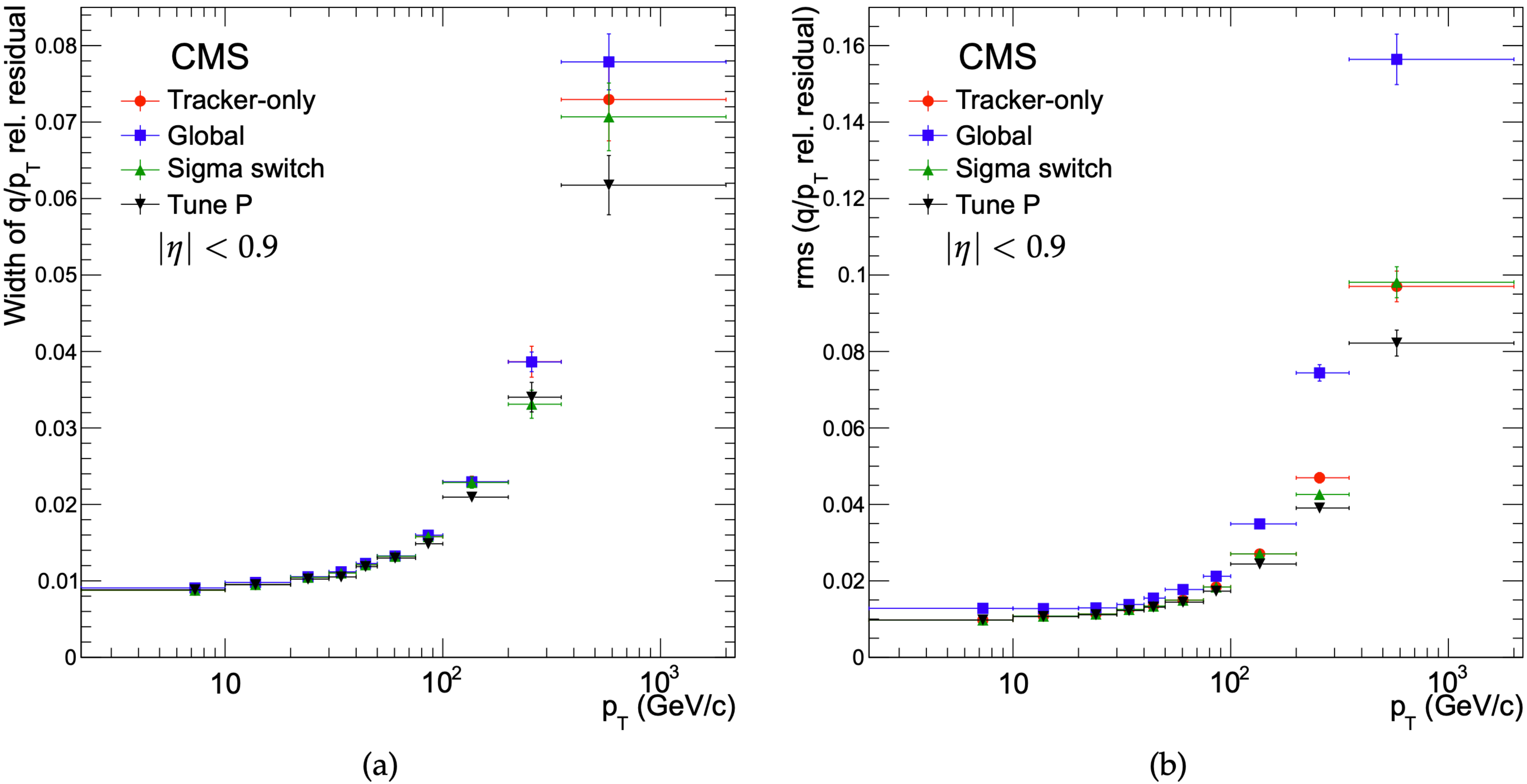
https://arxiv.org/pdf/1206.4071.pdf



arXiv.org > physics > arXiv:1502.02701

Search...
Help | Advanced

Physics > Instrumentation and Detectors

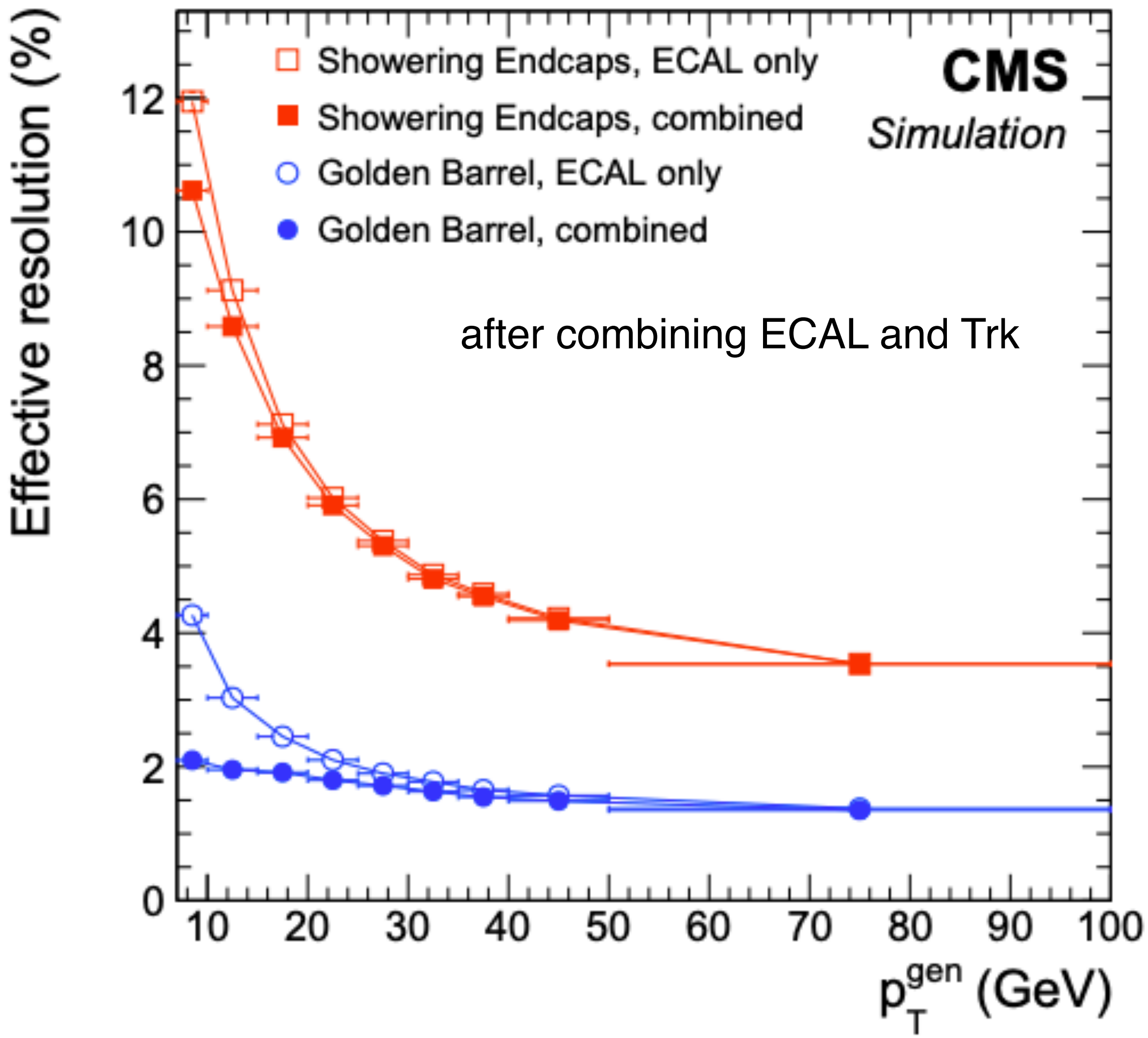
[Submitted on 9 Feb 2015 (v1), last revised 1 Jul 2015 (this version, v2)]

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

CMS Collaboration

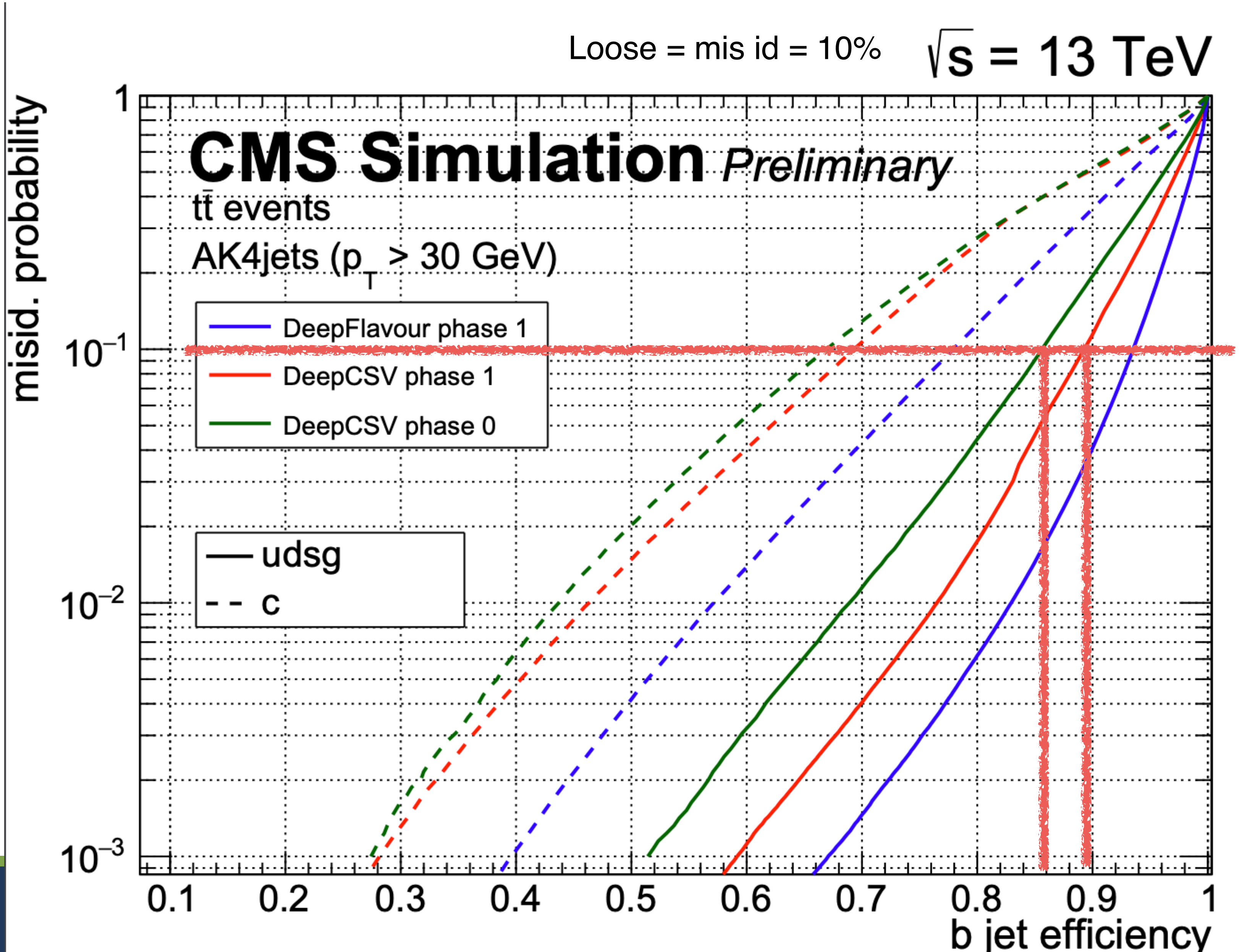
The performance and strategies used in electron reconstruction and selection at CMS are presented based on data corresponding to an integrated luminosity of 19.7 inverse femtobarns, collected in proton-proton collisions at sqrt(s) = 8 TeV at the CERN LHC. The paper focuses on prompt isolated electrons 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



b tagging

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



Electroweak sector

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

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

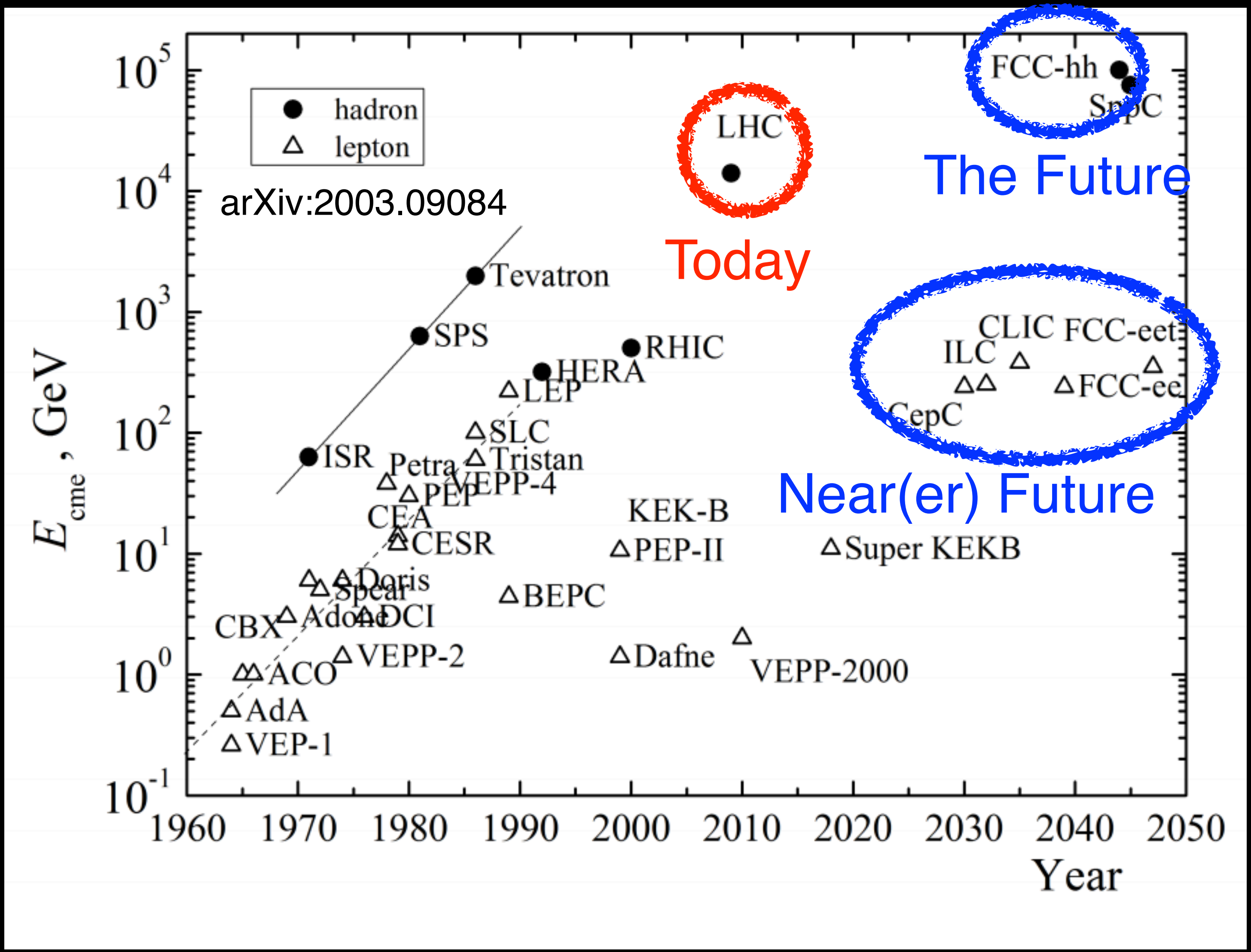
$$D_\mu = \partial_\mu + i\tfrac{g}{2}\sigma_j W^j_\mu + 2ig'YB_\mu$$

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

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

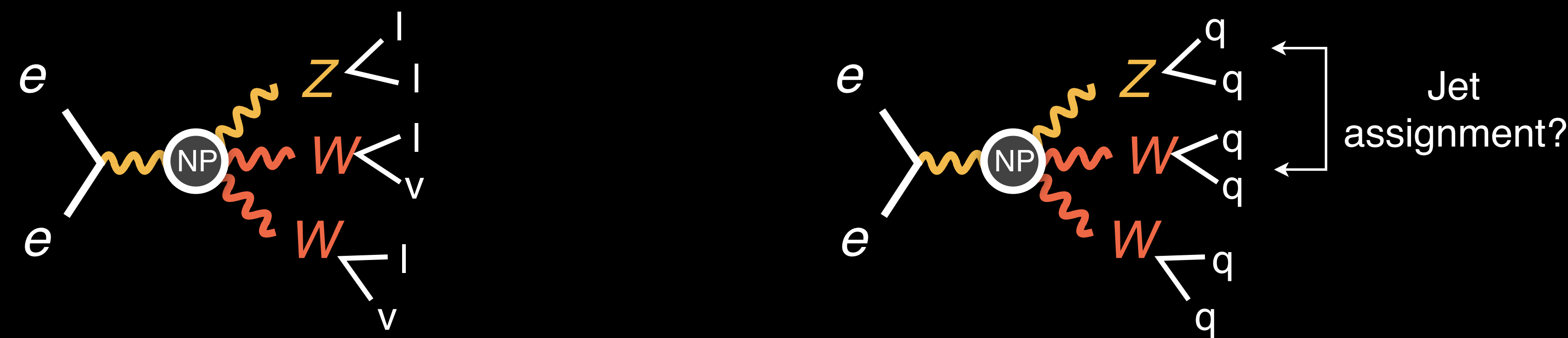


"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least **100 TeV** …"

— 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

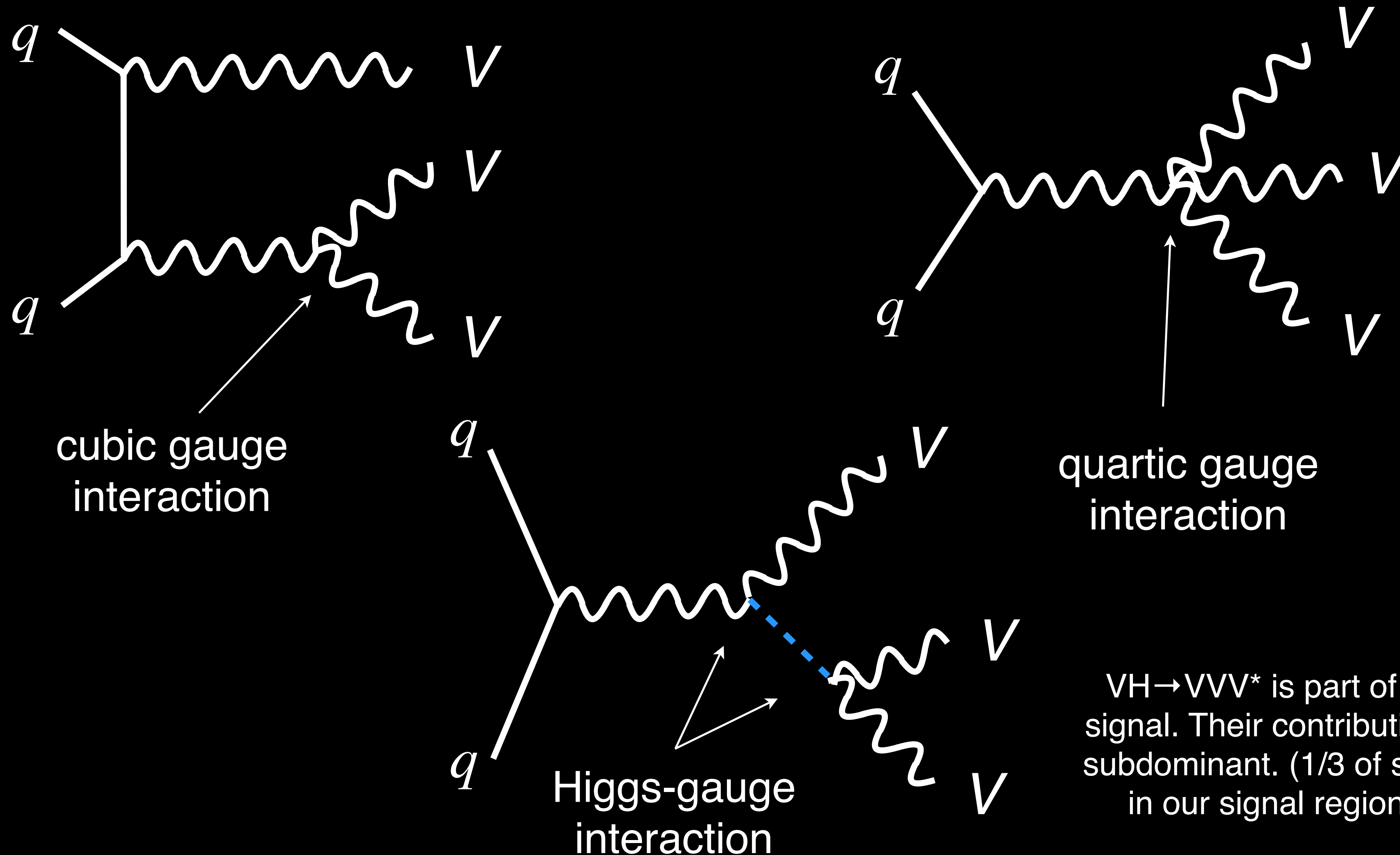


Multi-lepton → Multi-jet final states

⇒ 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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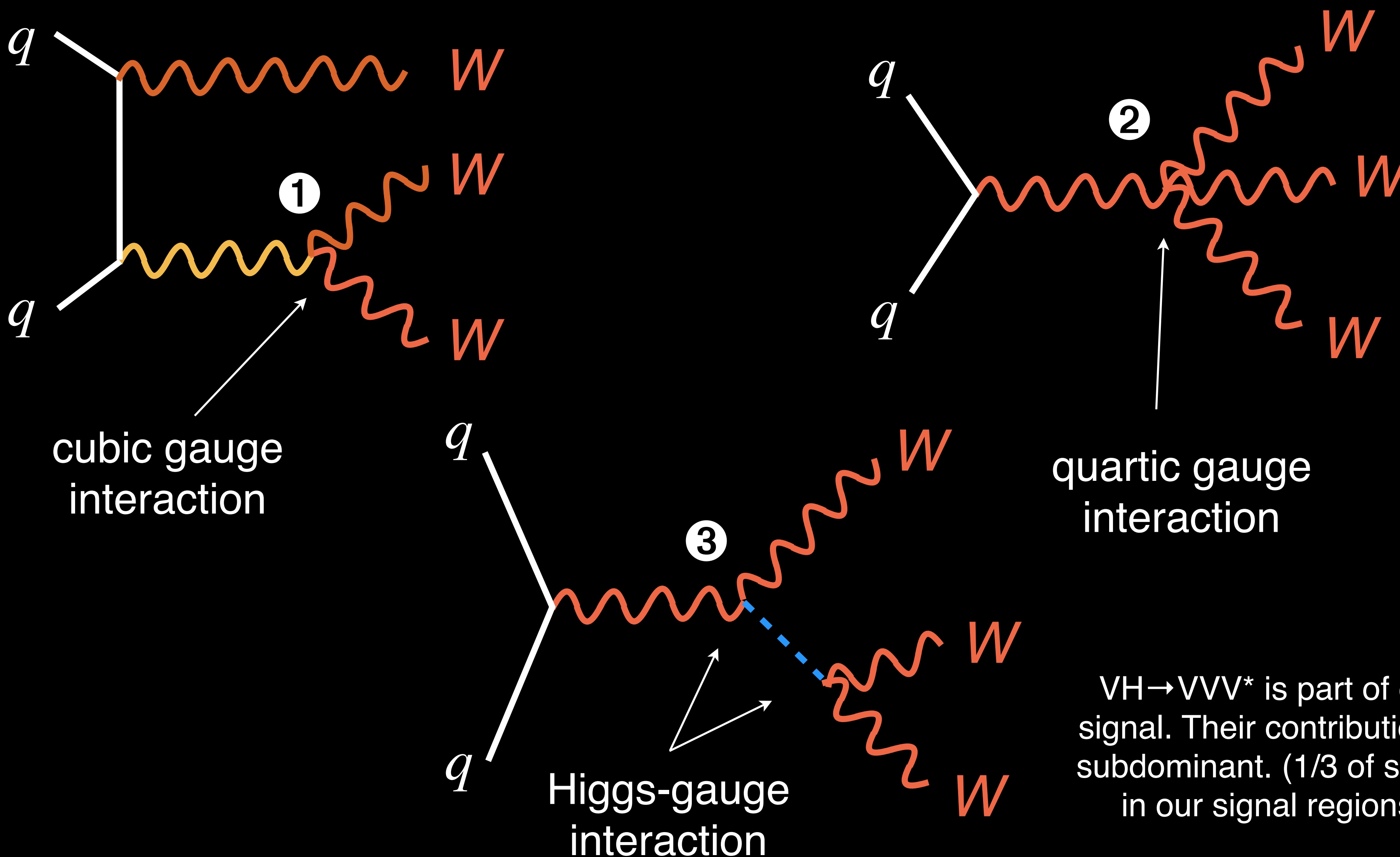

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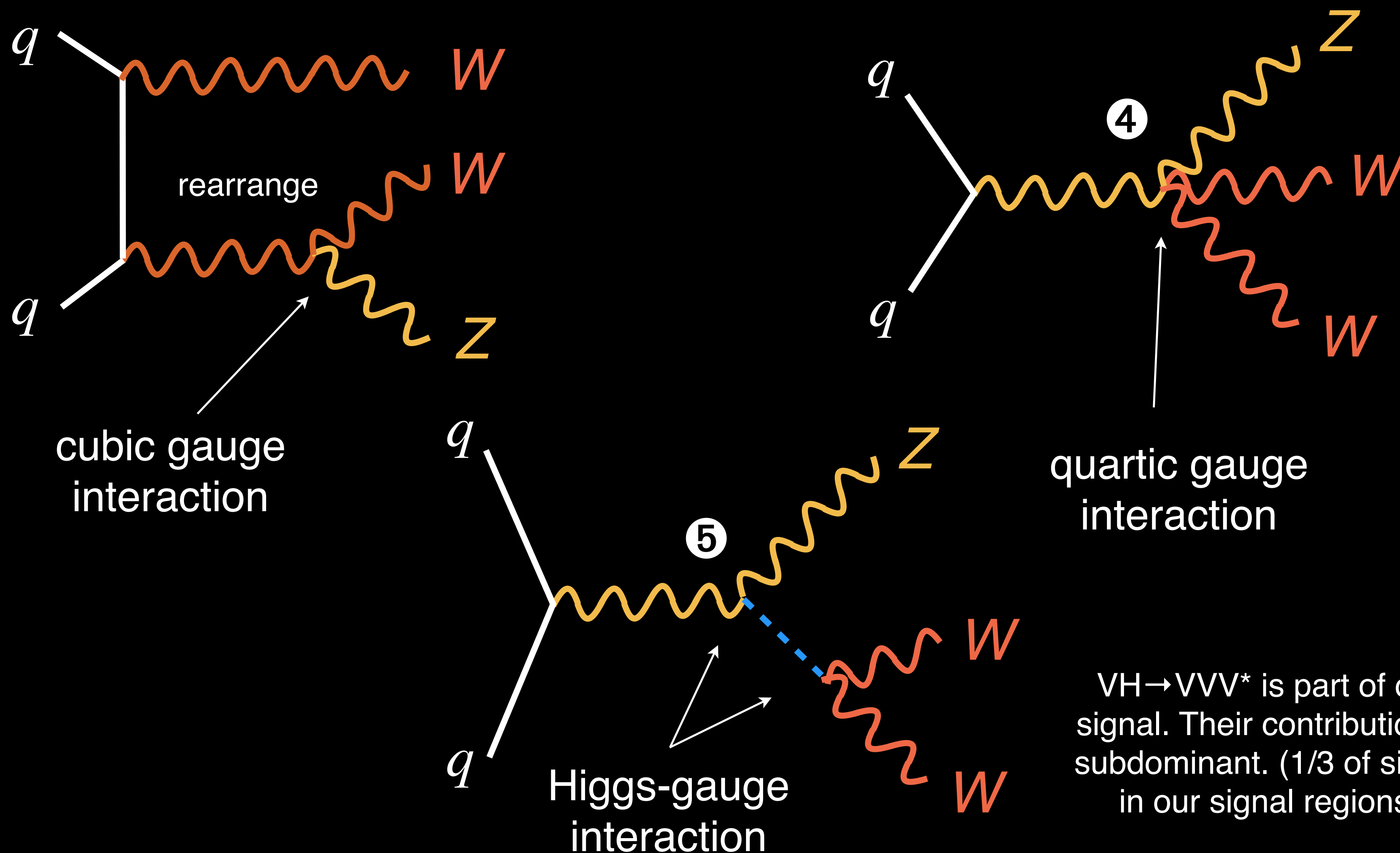

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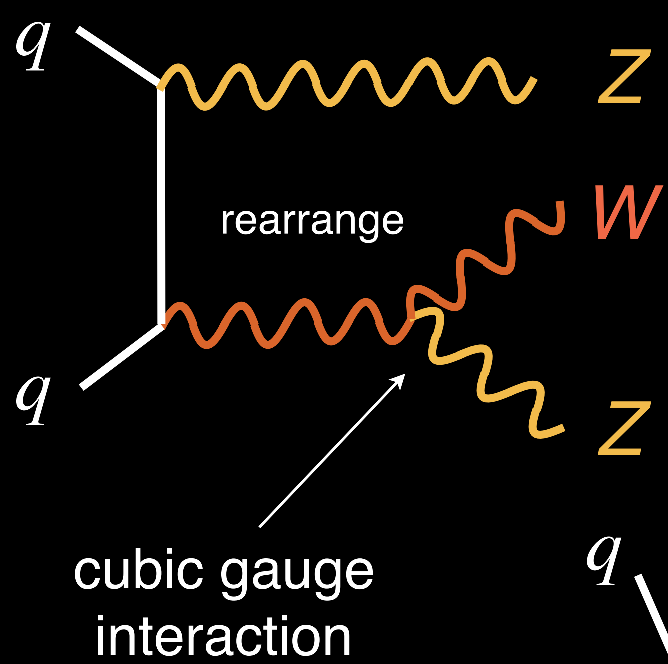

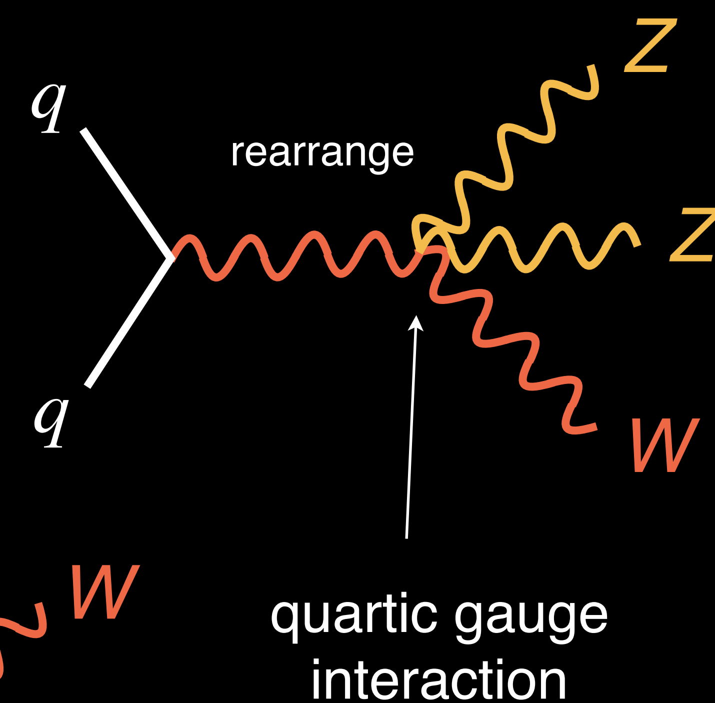

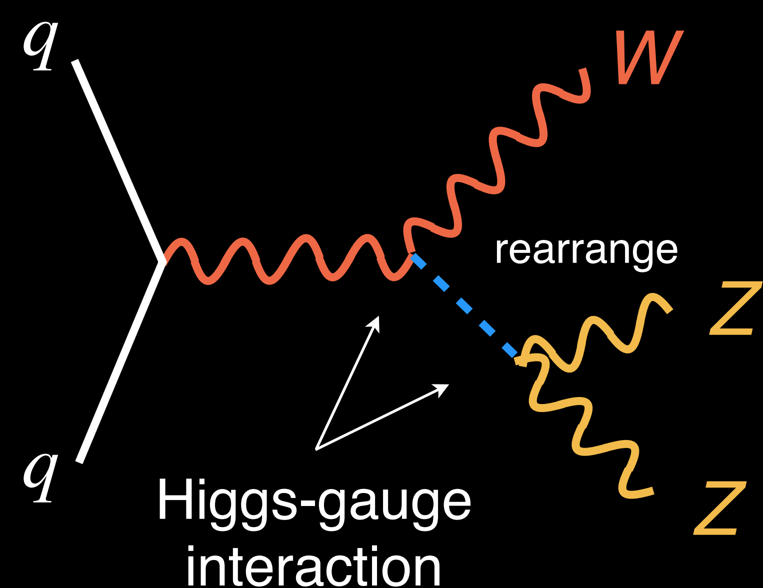

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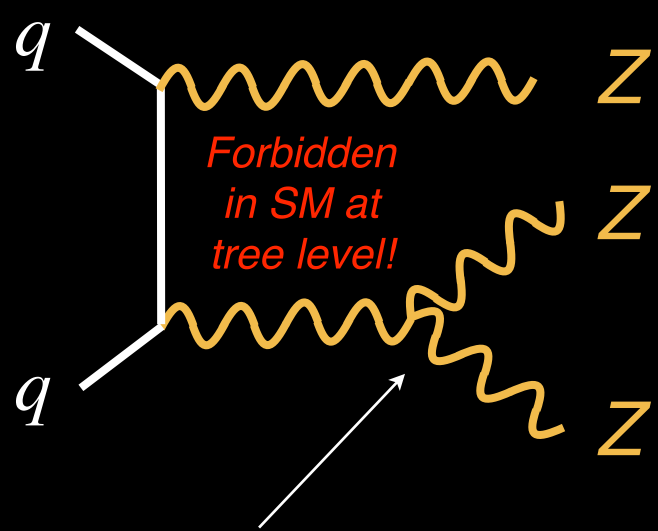
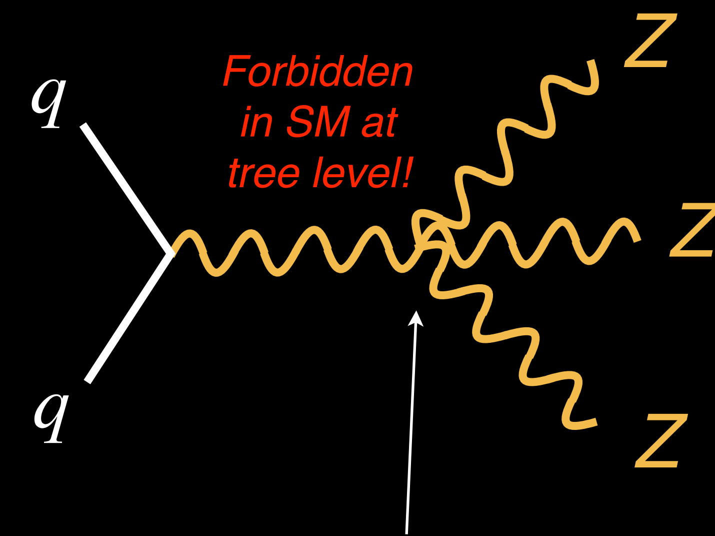
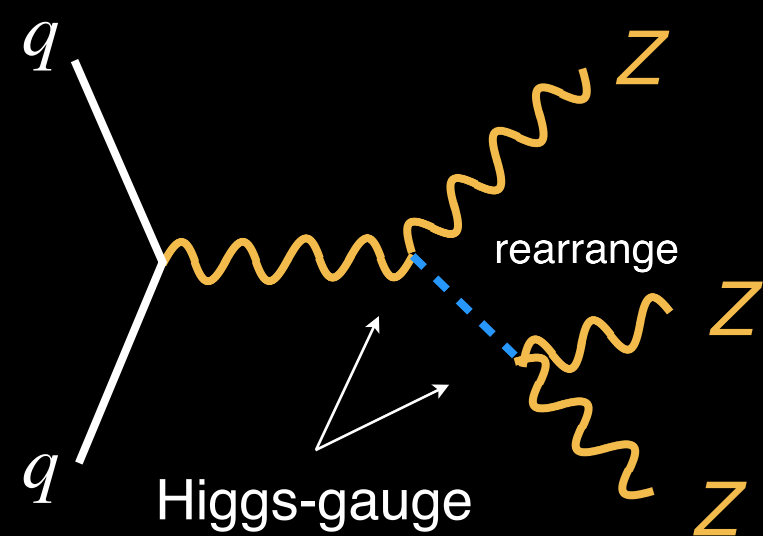


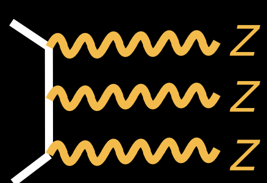
cubic gauge interaction



quartic gauge interaction



Higgs-gauge interaction

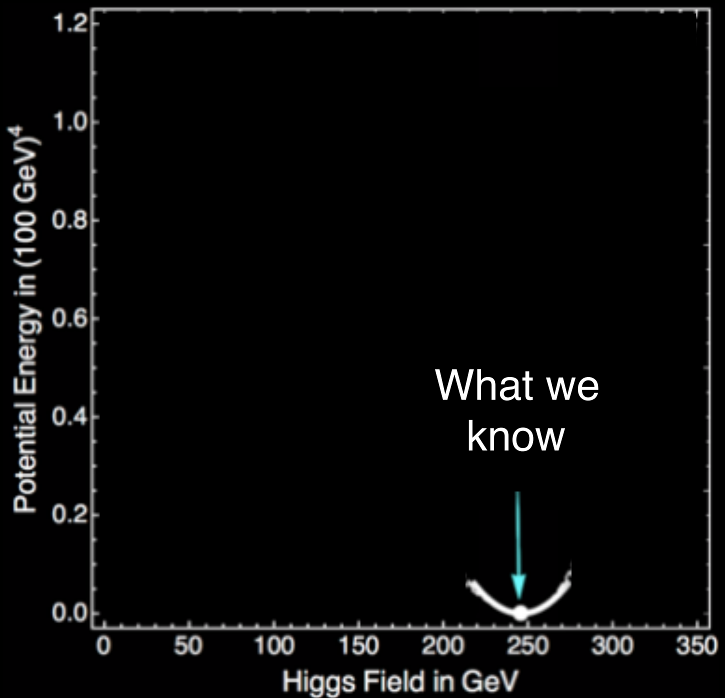


Three Z's radiating from quark lines

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

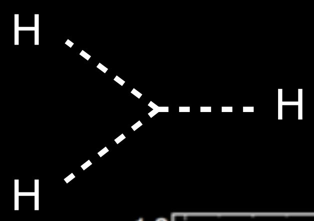
Higgs potential

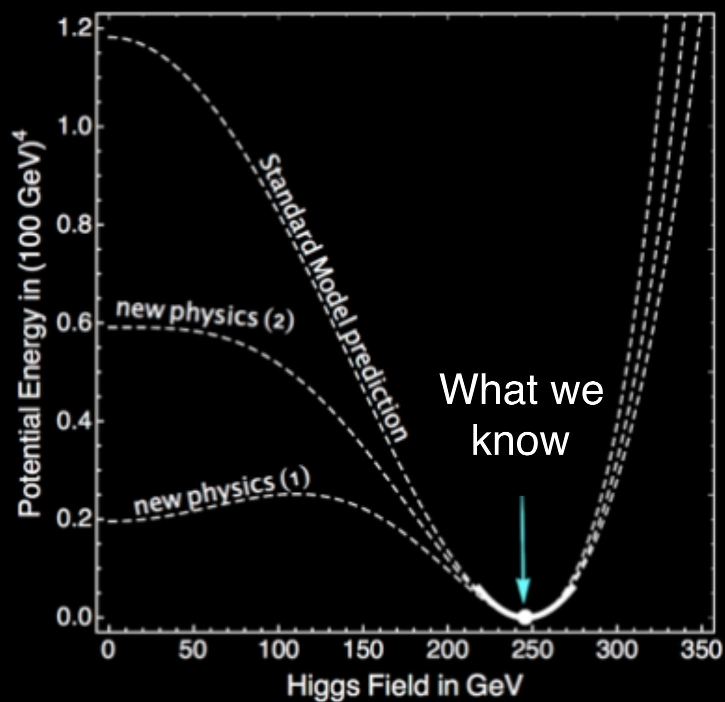


How is electroweak symmetry broken?

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

Higgs potential





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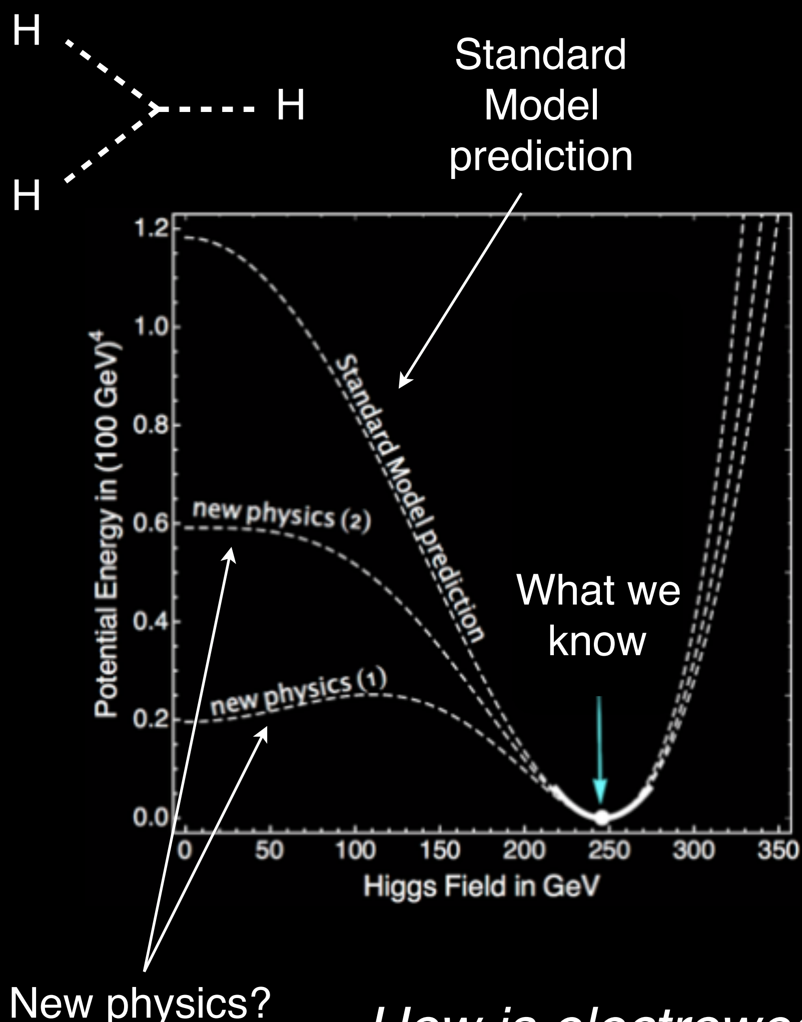
Higgs potential



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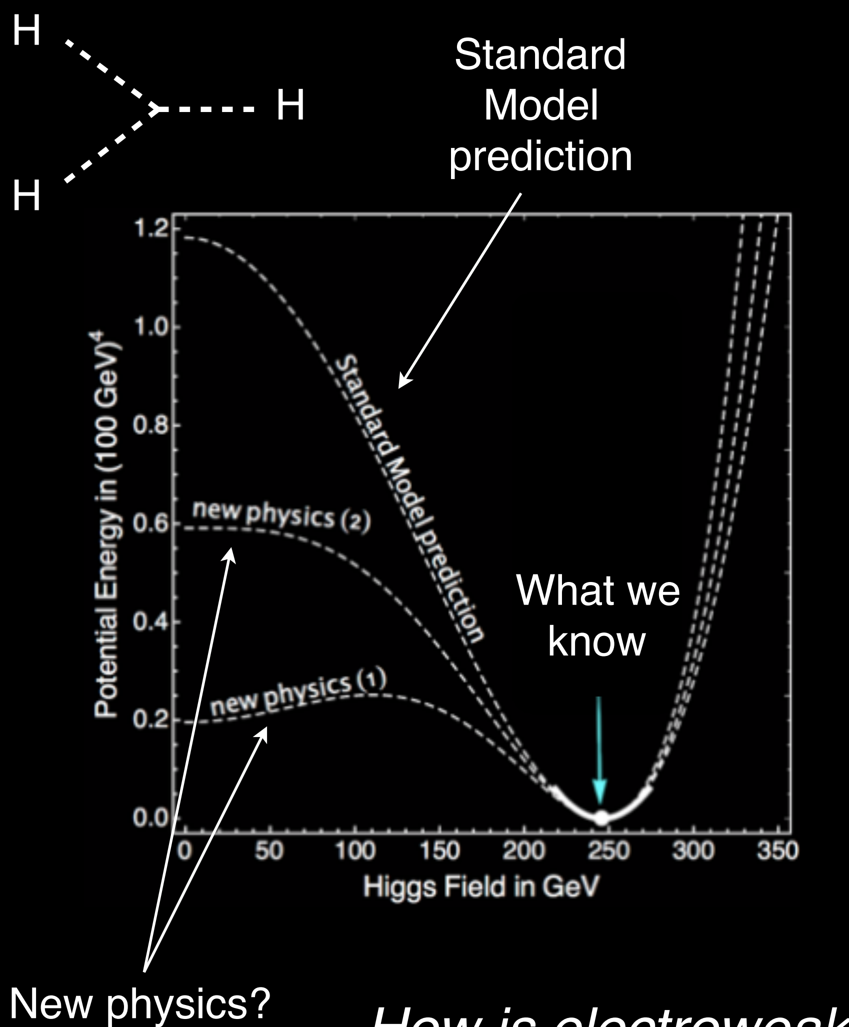
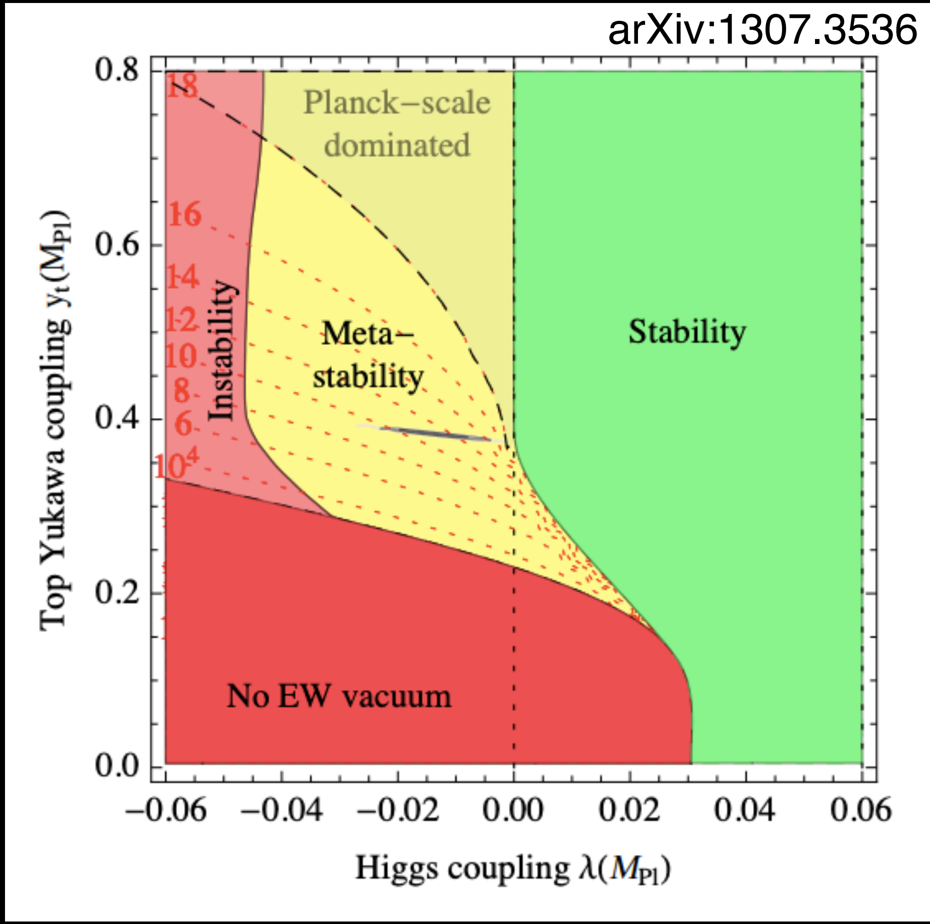
Higgs potential



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

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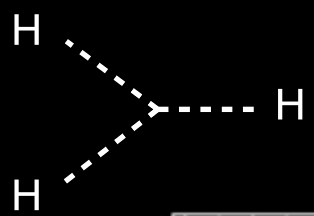
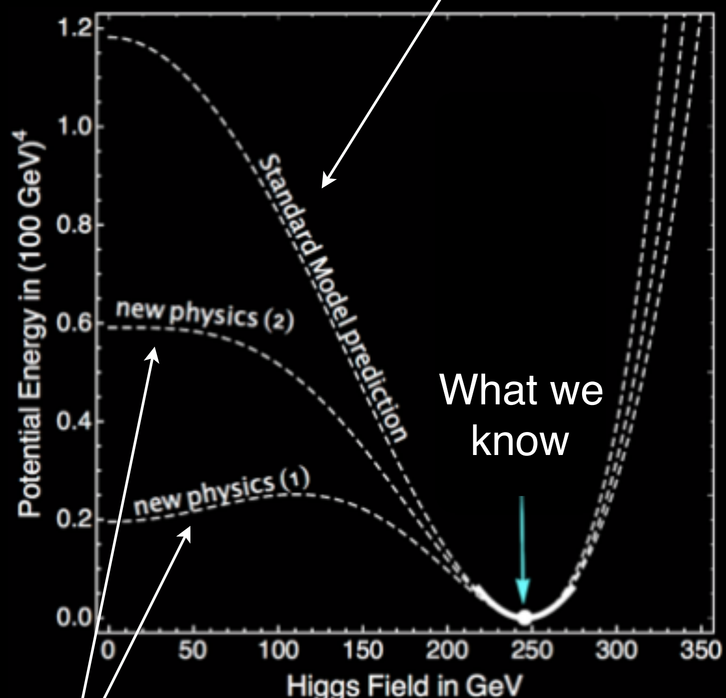


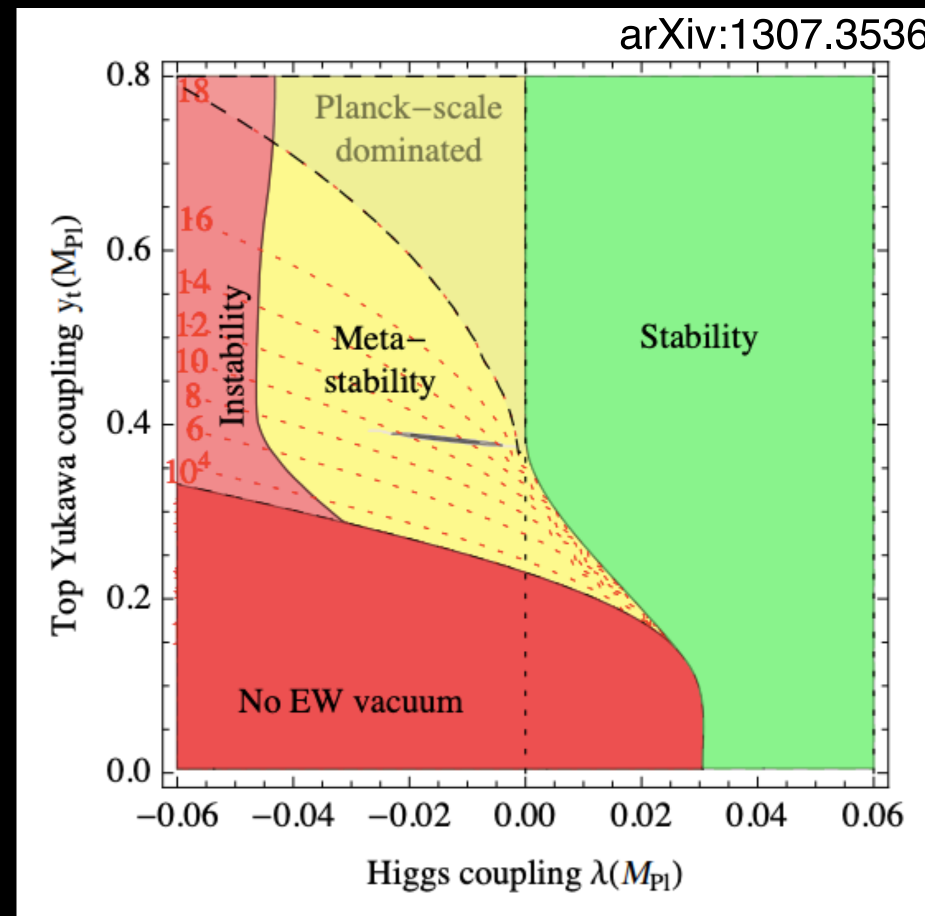
Standard Model prediction



New physics?

How is electroweak symmetry broken?

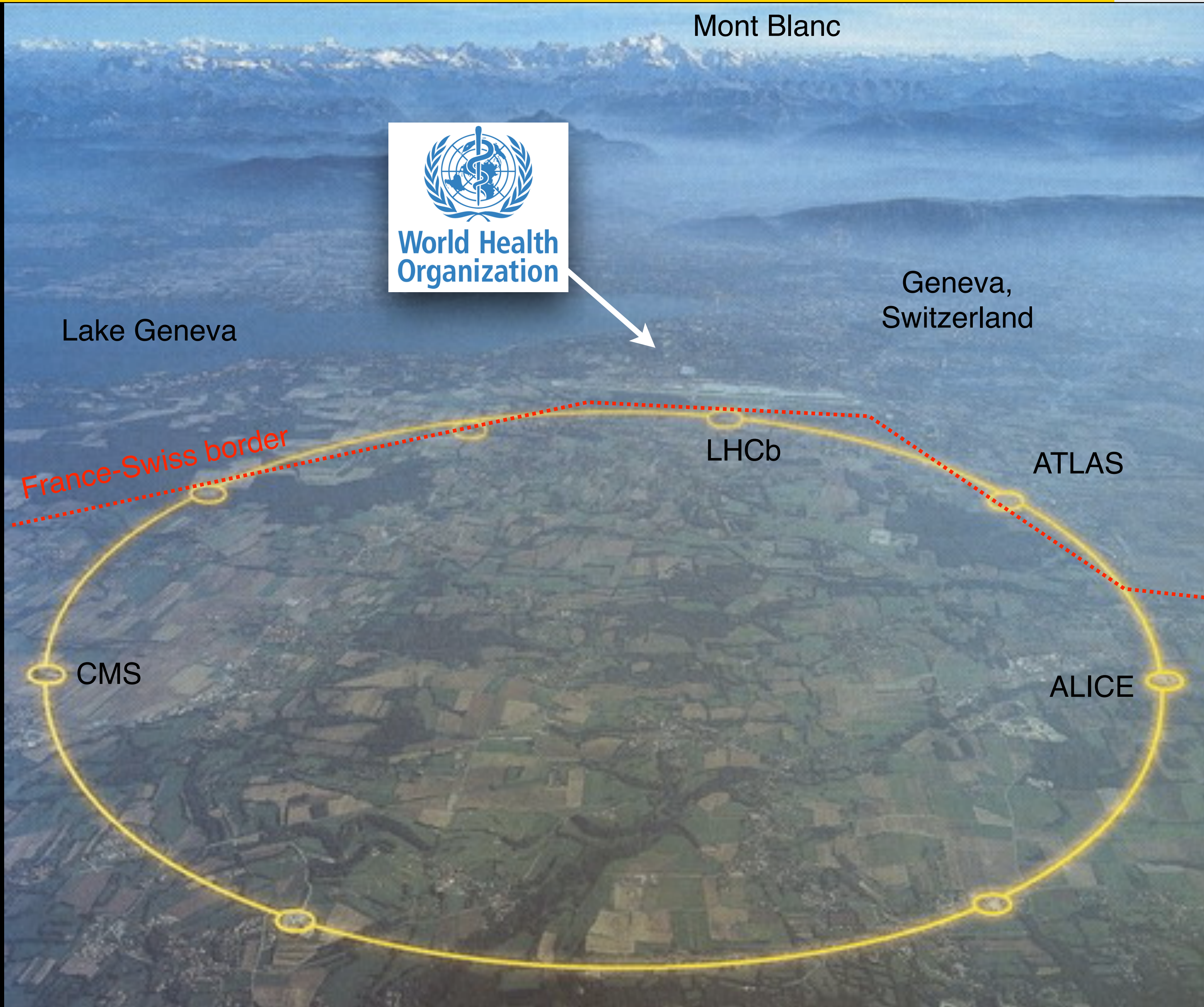
What is the fate of the universe?



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

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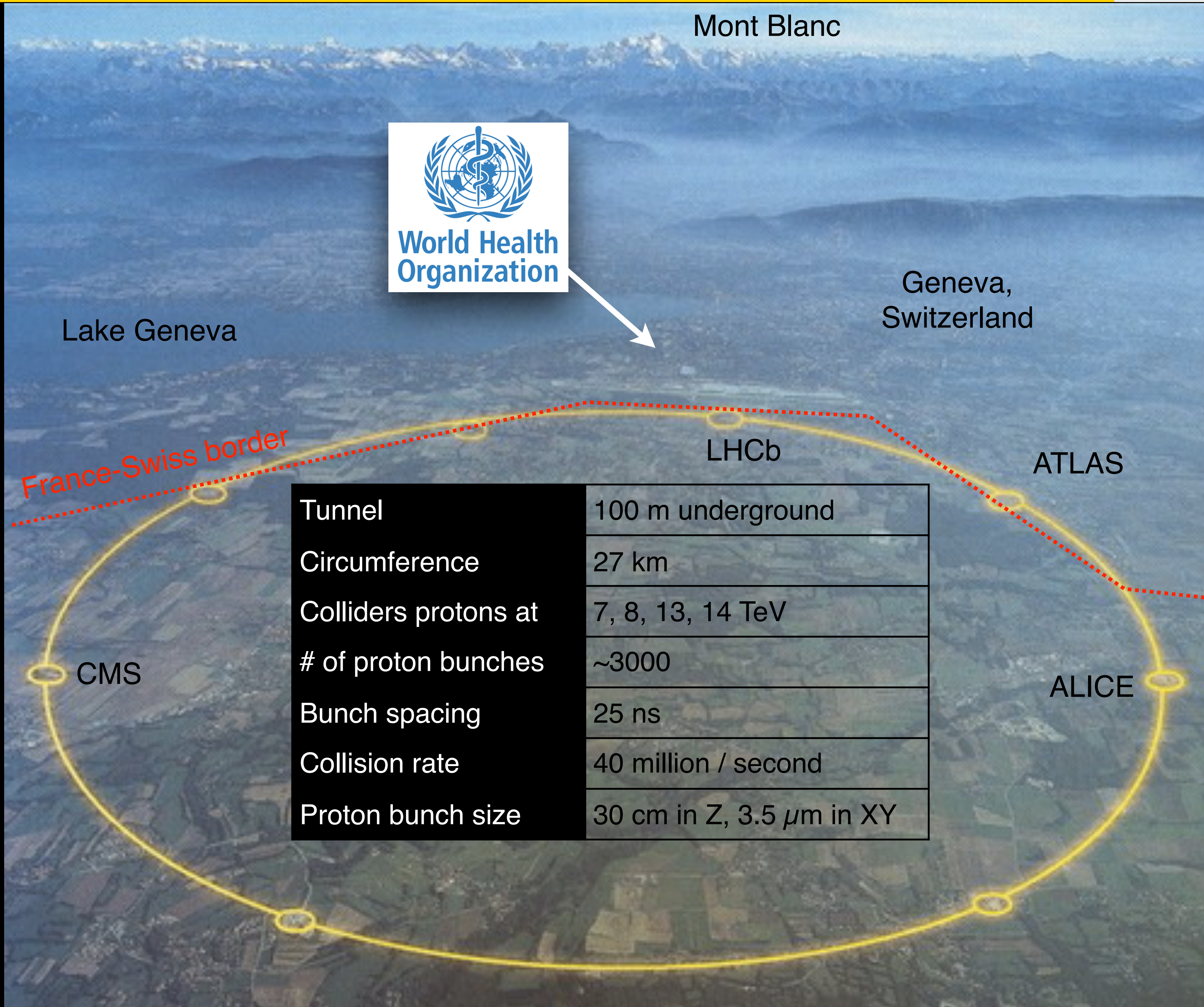
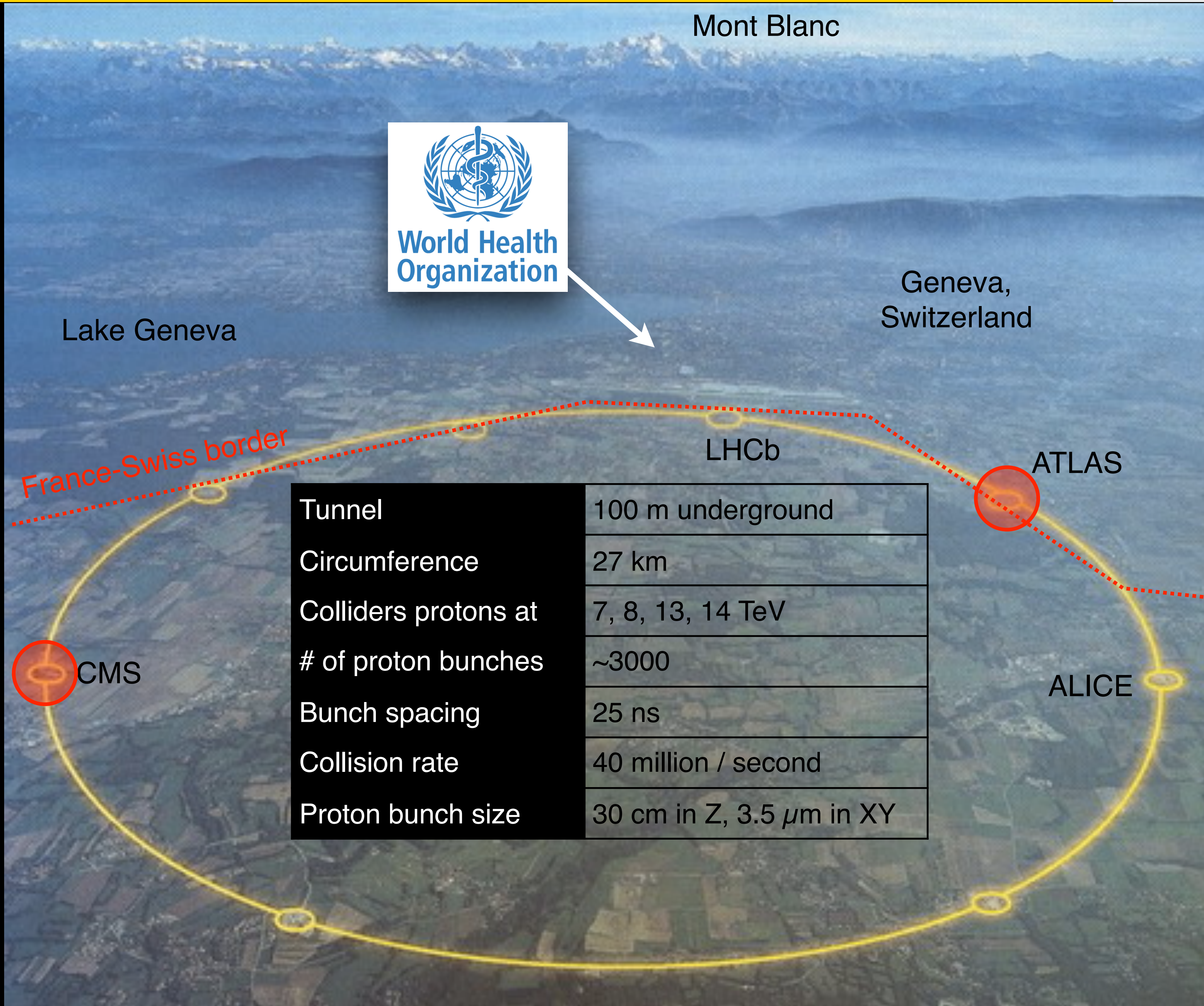


Tunnel	100 m underground
Circumference	27 km
Colliders protons at	7, 8, 13, 14 TeV
# of proton bunches	~3000
Bunch spacing	25 ns
Collision rate	40 million / second
Proton bunch size	30 cm in Z, 3.5 μm in XY

Large Hadron Collider at CERN



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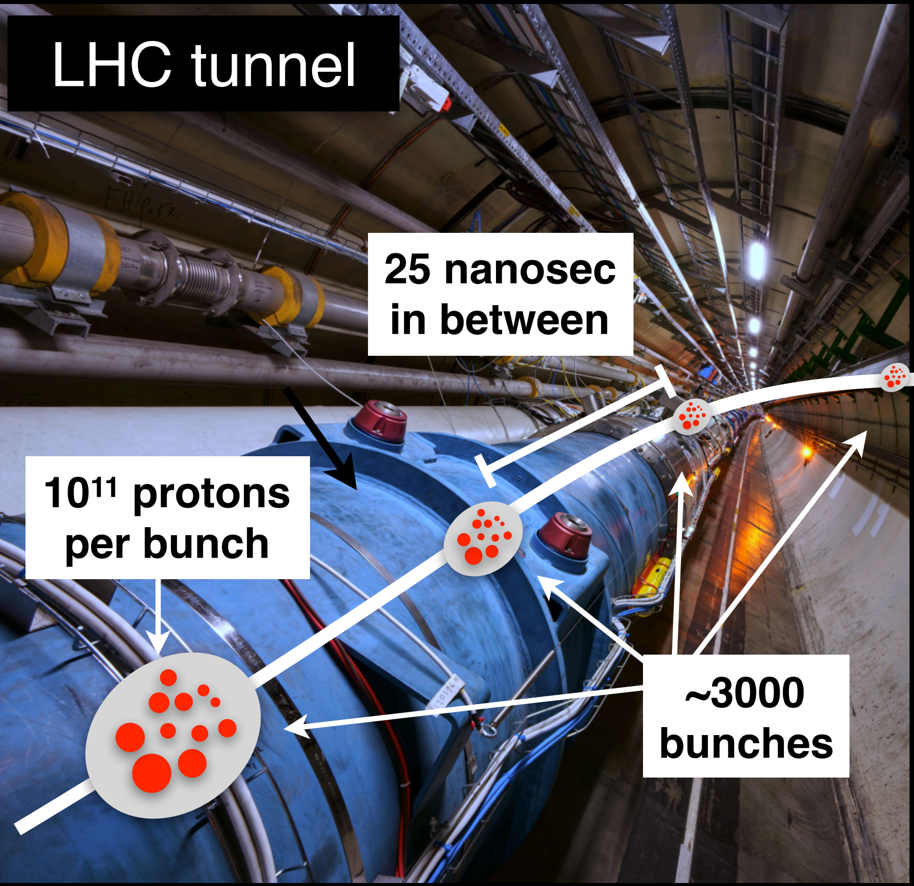
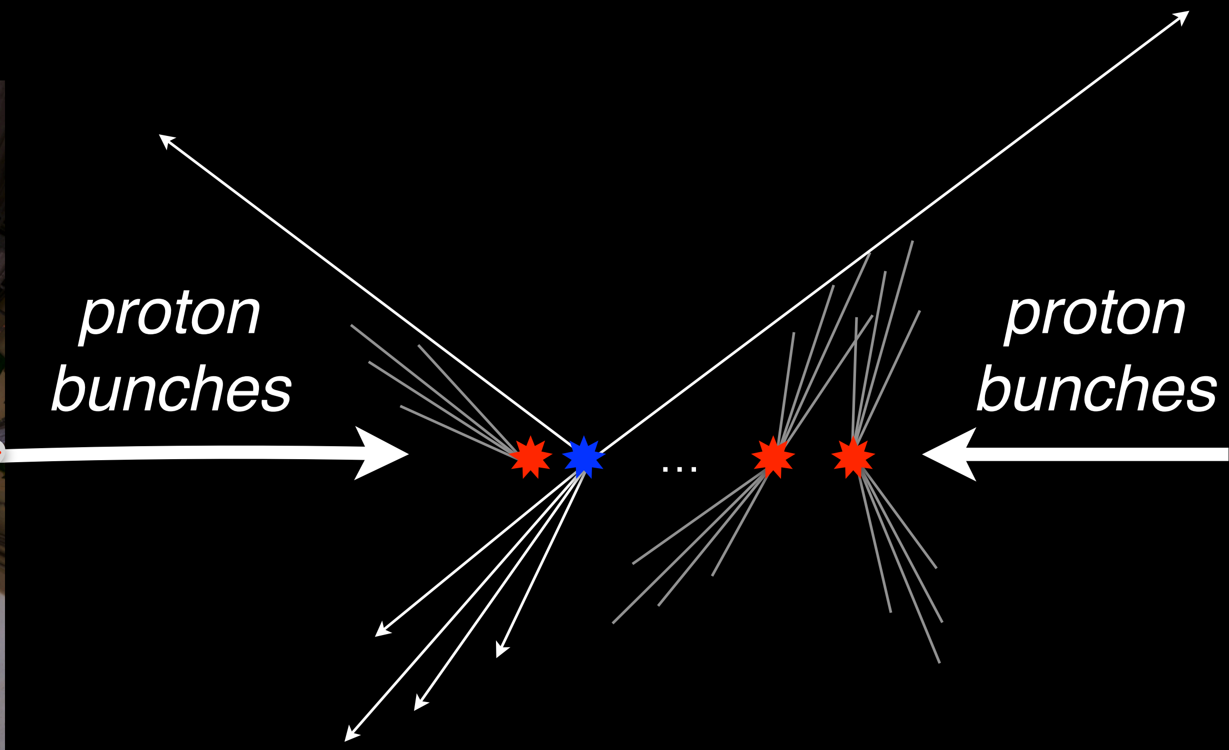
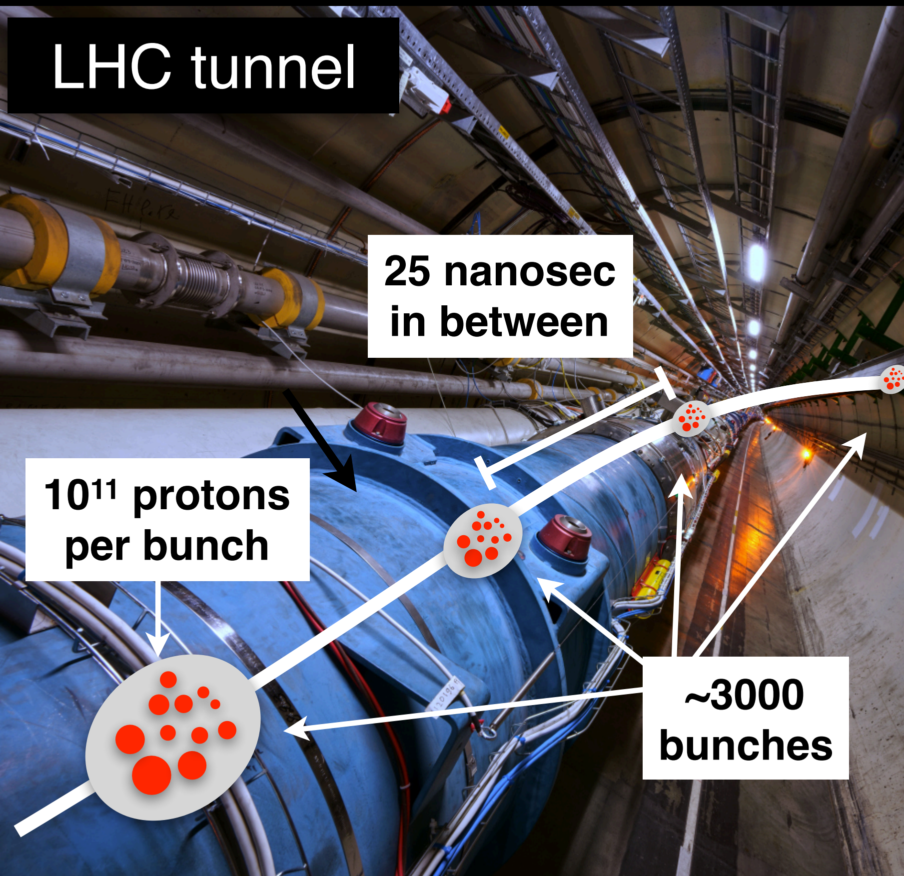
Proton beam collision at the LHC

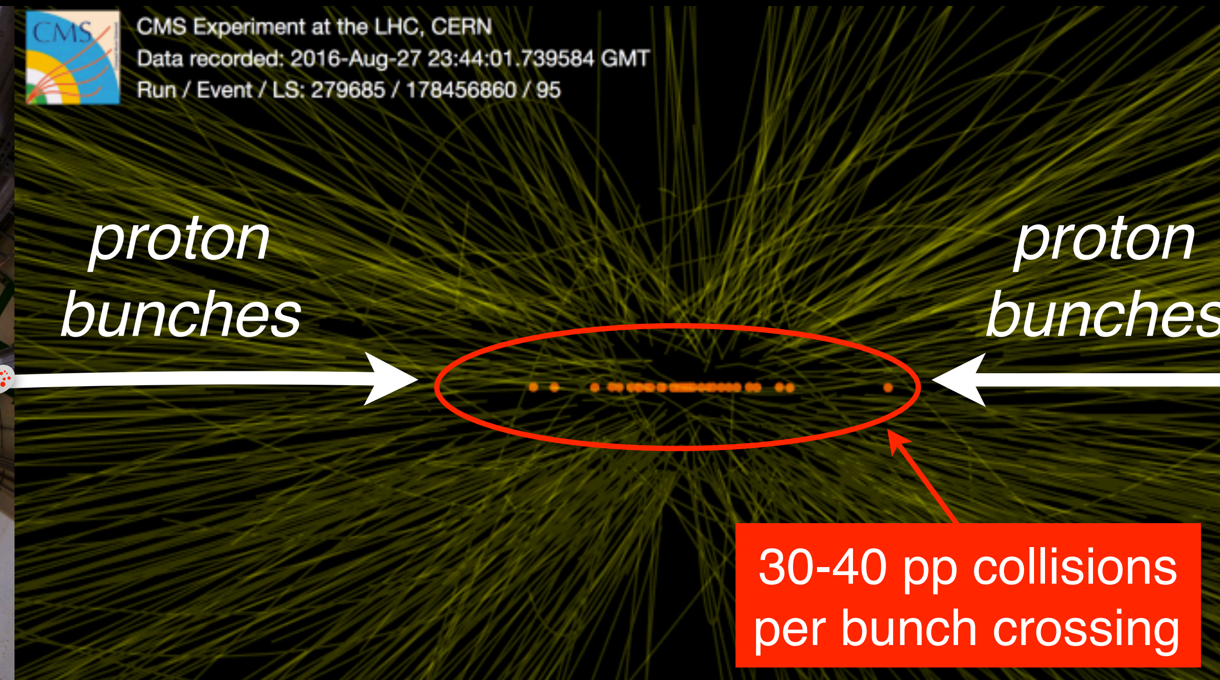




LHC provides highest energy *pp* collisions ever recorded

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

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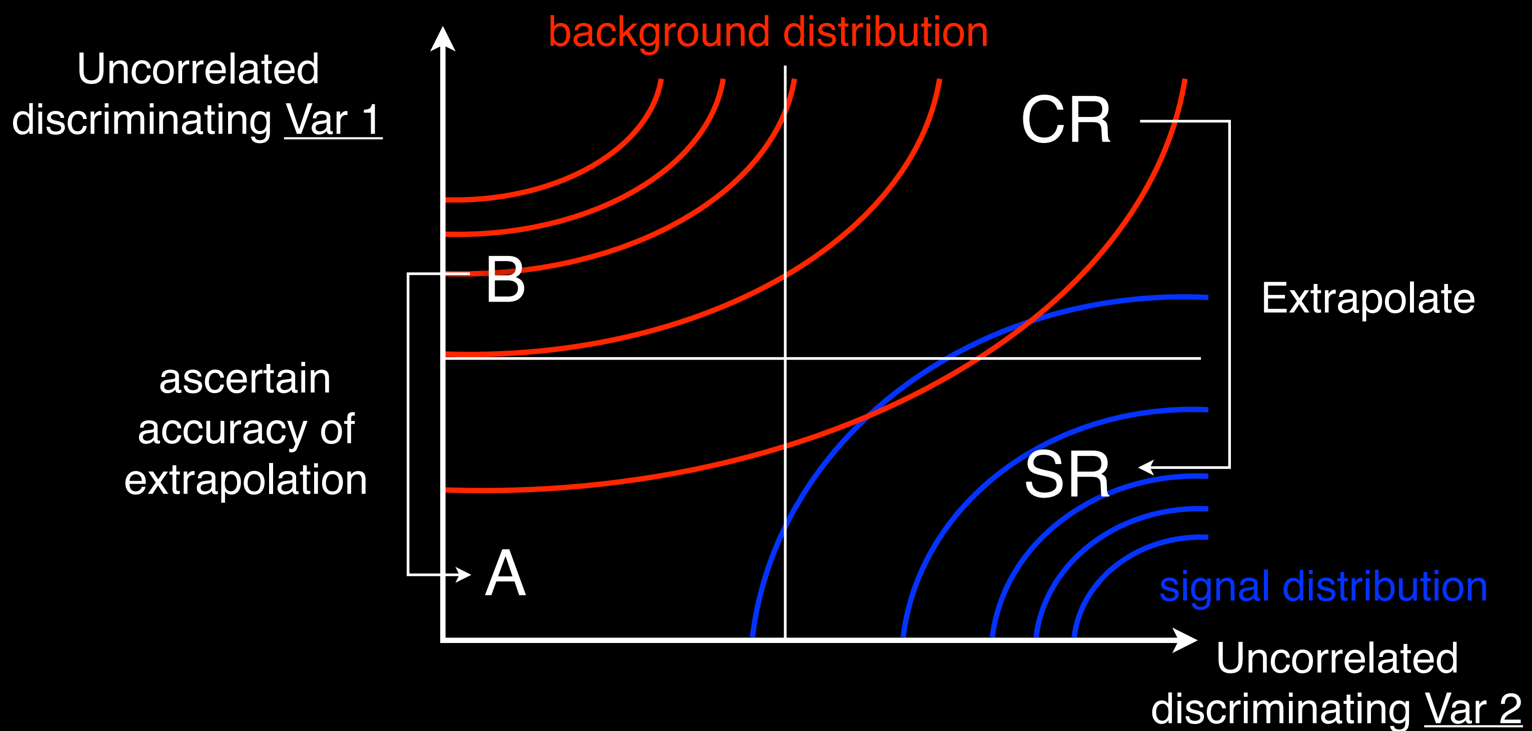
UCSD

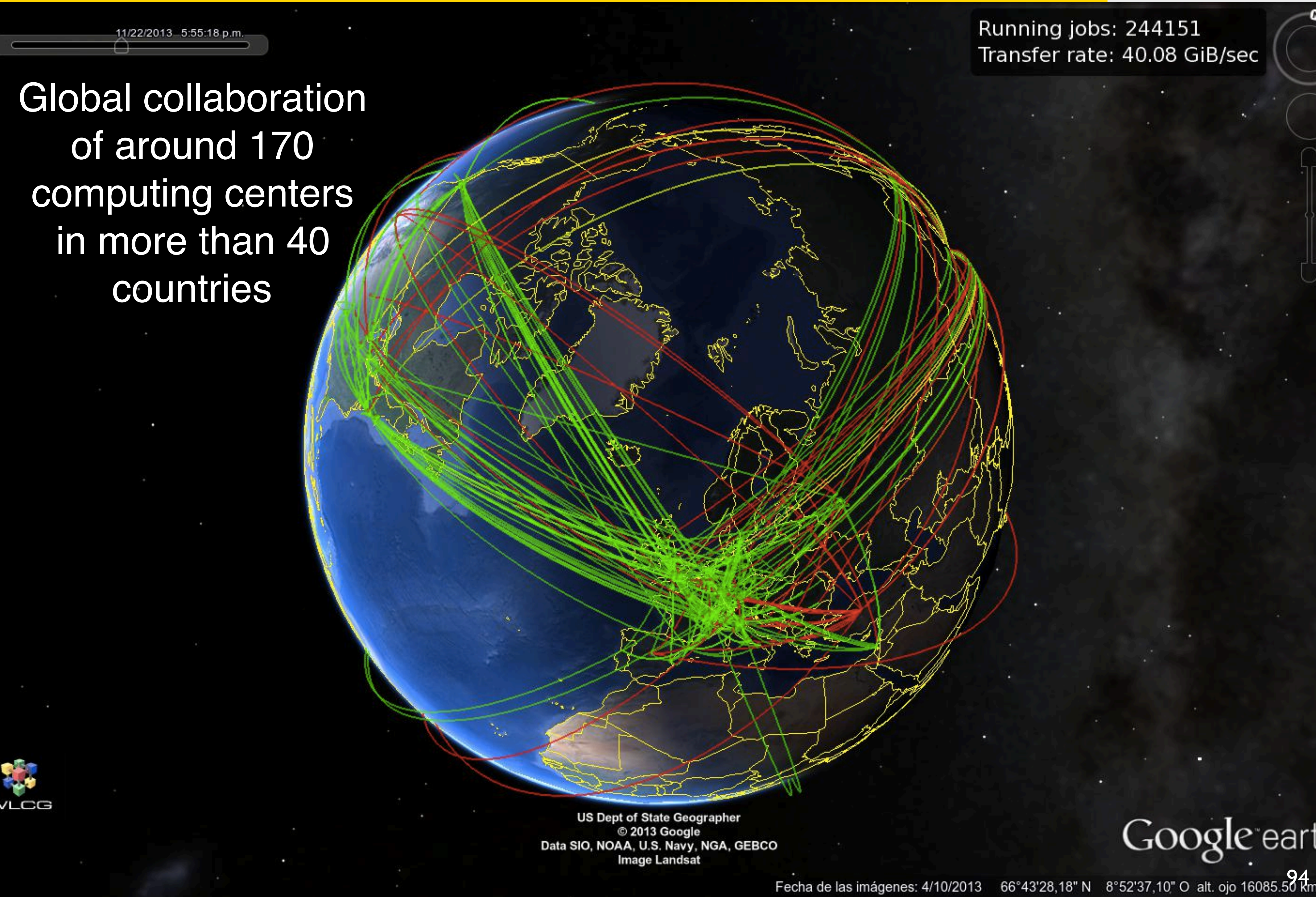
1. Define low background signal regions (SRs)
2. Estimate background yields by extrapolating from bkg. enriched control region (CR)
3. Ascertain accuracy of the extrapolation from a different sample



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

11/22/2013 5:55:18 p.m.

Running jobs: 244151
Transfer rate: 40.08 GiB/sec

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

WLCG

US Dept of State Geographer
© 2013 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat

Google earth

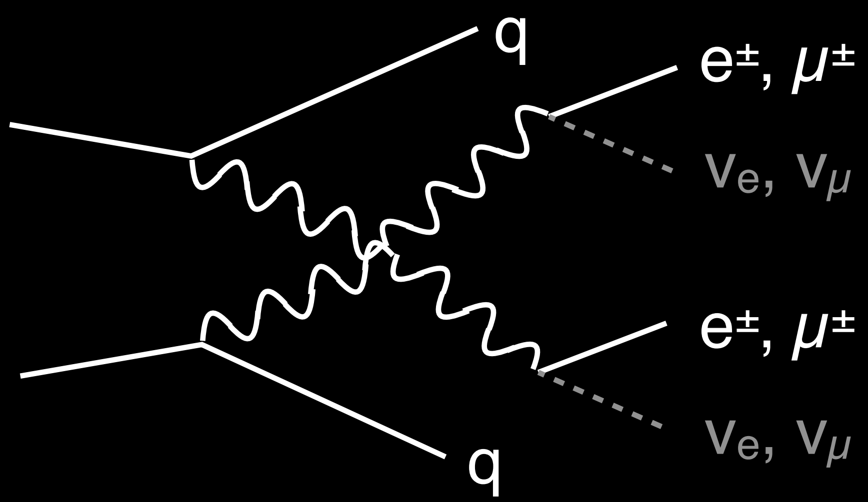
Fecha de las imágenes: 4/10/2013 66°43'28,18" N 8°52'37,10" O alt. ojo 16085.50 km

Recent results in multi-boson physics

Chang
UCSD

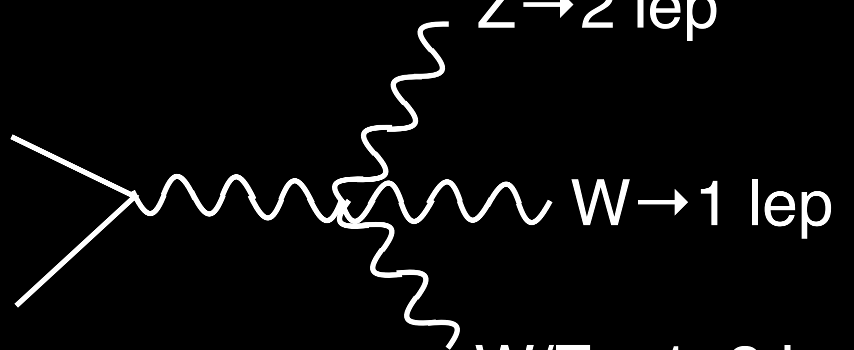
- Several important results have come out recently from both ATLAS and CMS
- I will highlight a few (from CMS)
- (Disclaimer: Rest of the talk from here on will focus mostly on CMS)

WW scattering



Same-sign dilepton + 2 quarks

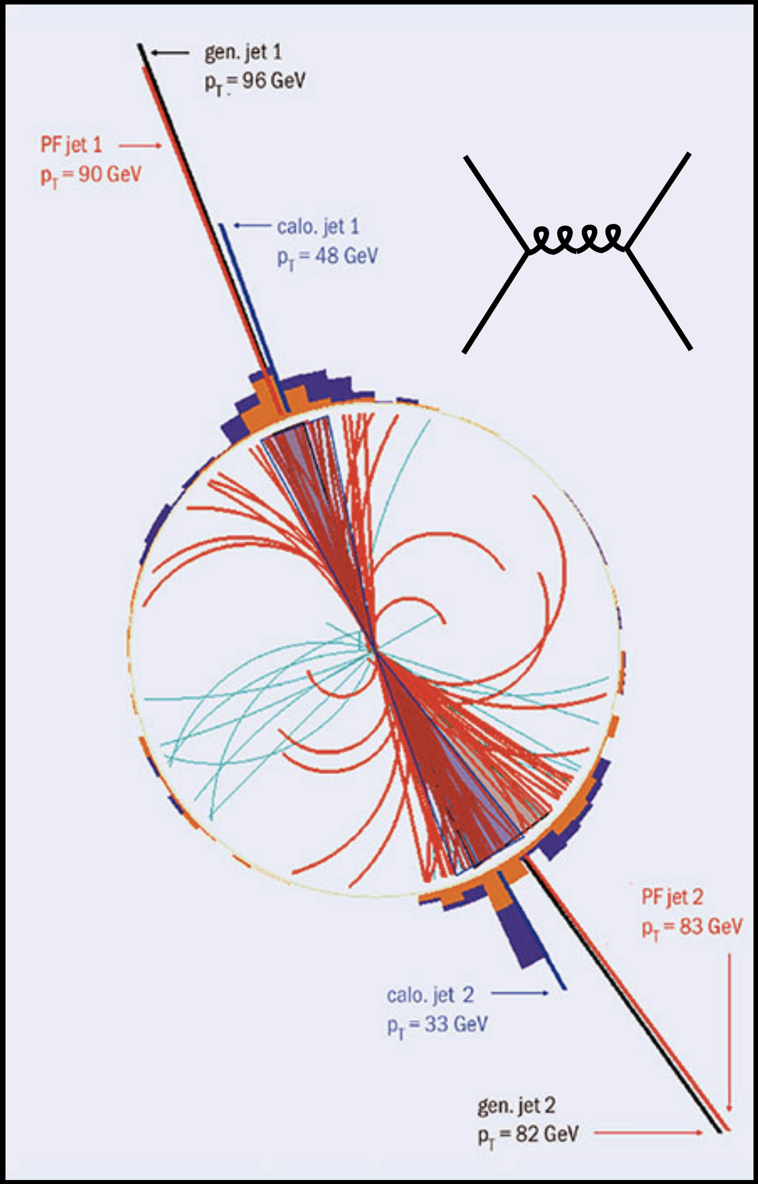
Tri-boson process



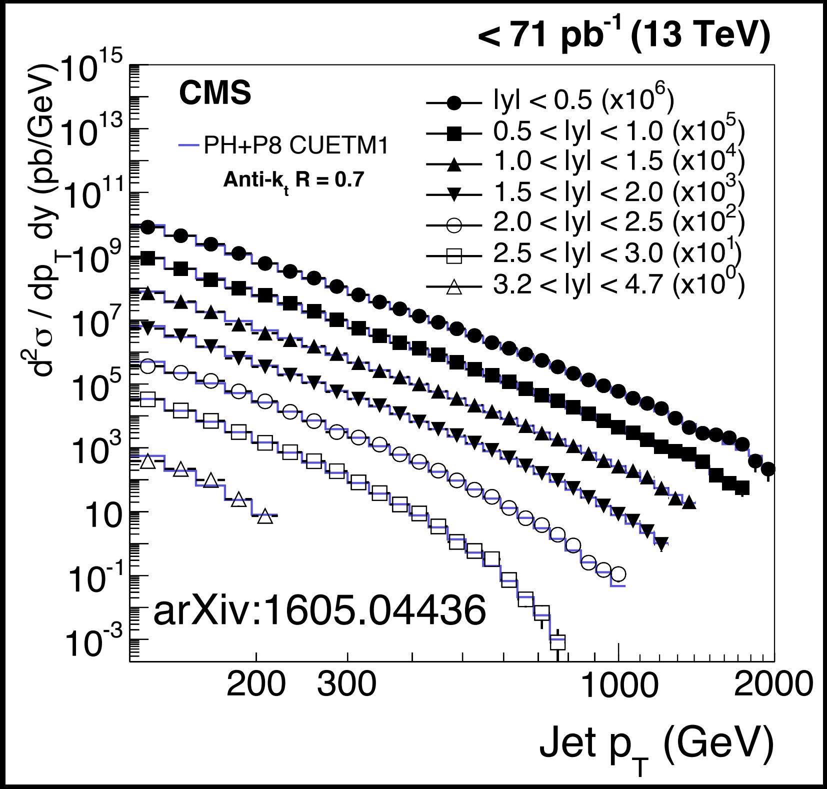
4 or 5 leptons

⇒ 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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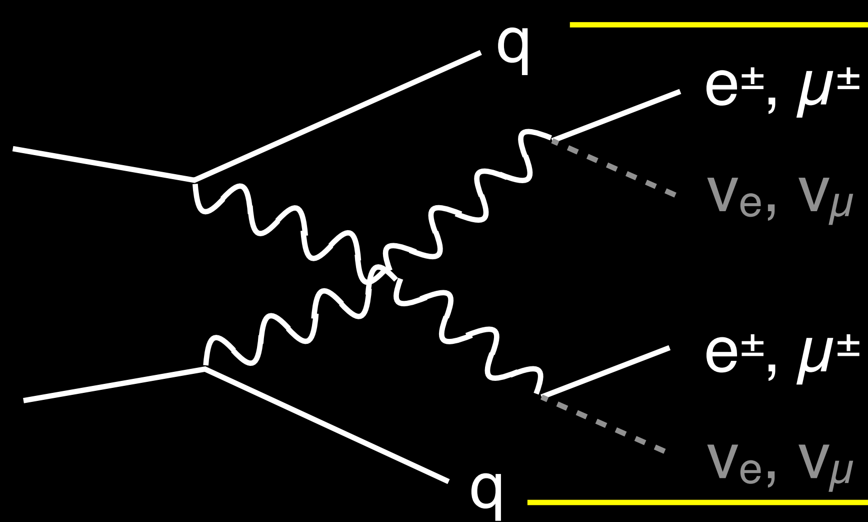
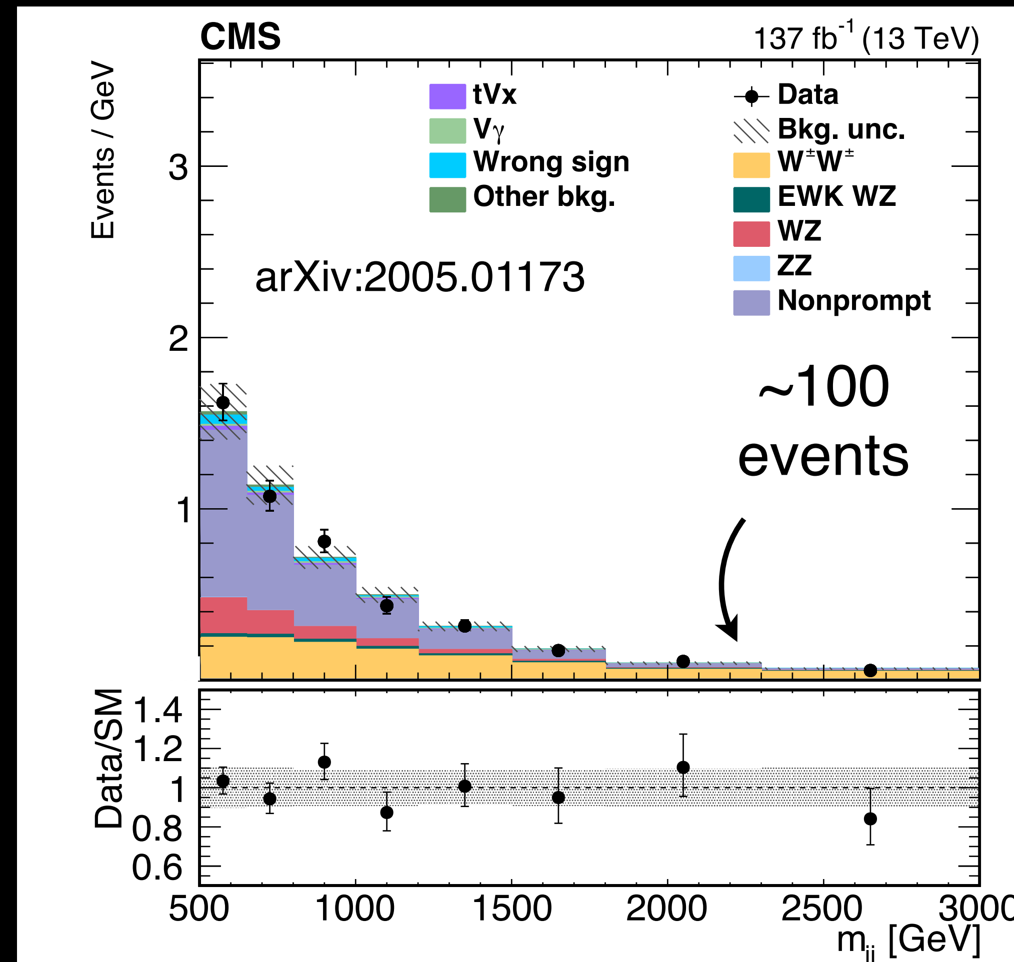
WW scattering



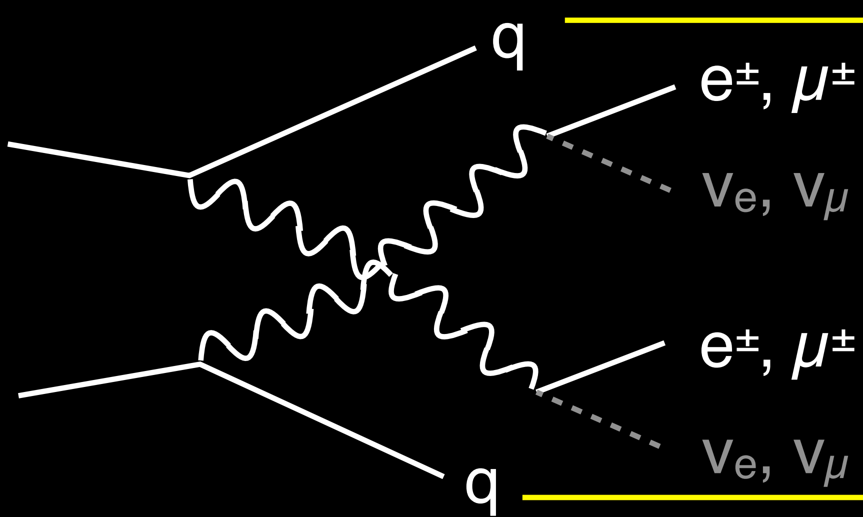
Same-sign dilepton + 2 quarks

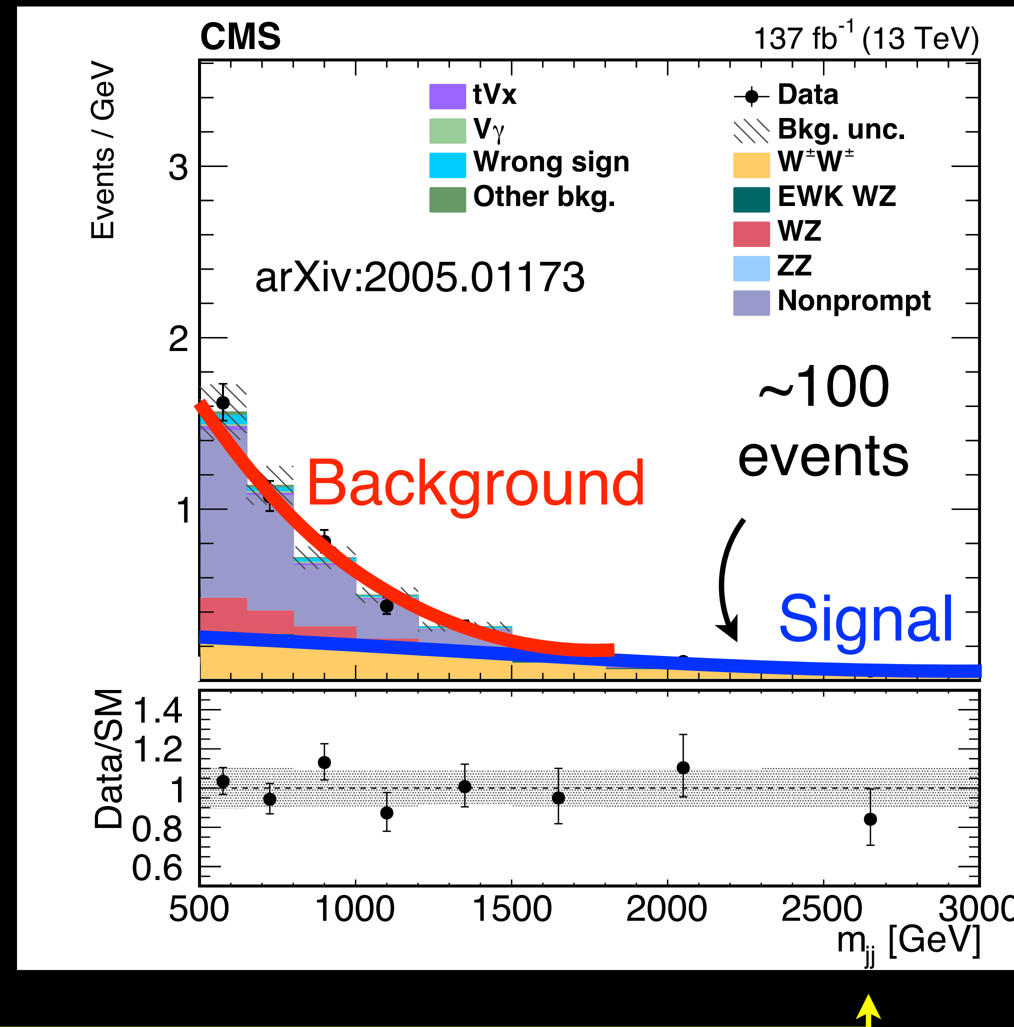


Two jets from VBS process tend to have relatively high invariant mass

Jets from vector boson scattering

WW scattering





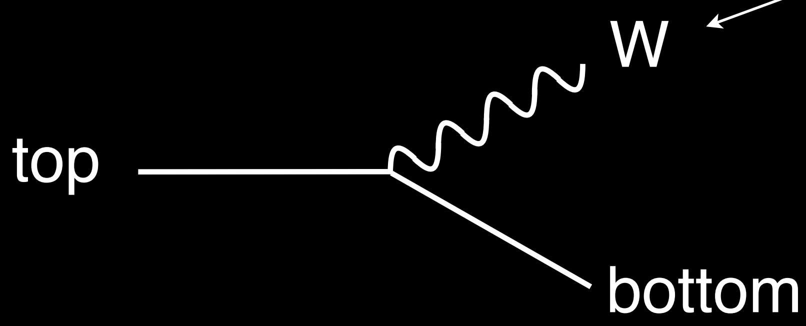
Same-sign dilepton + 2 quarks

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

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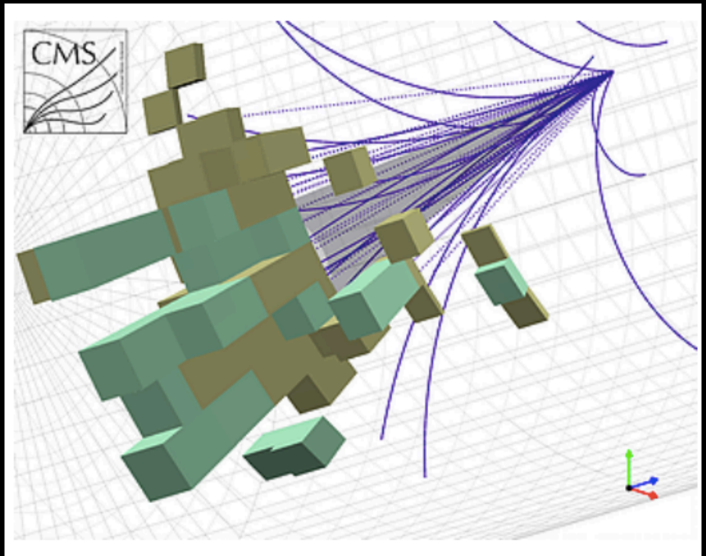
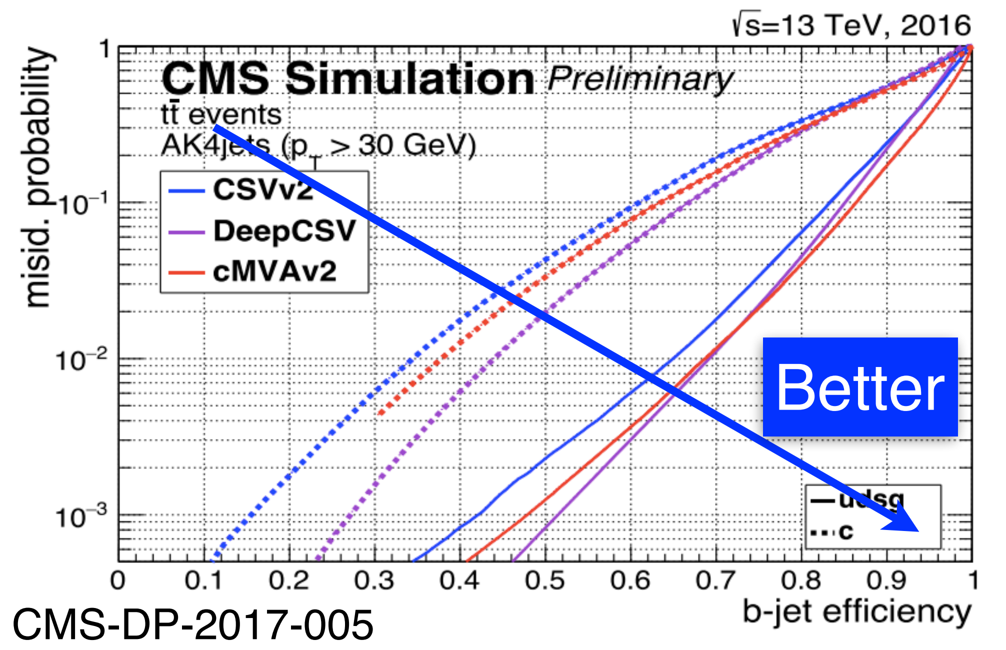
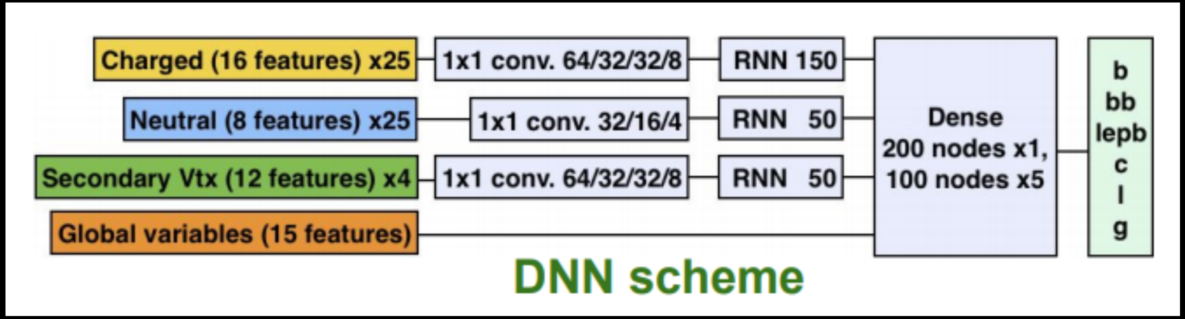
Was this from bottom quark?





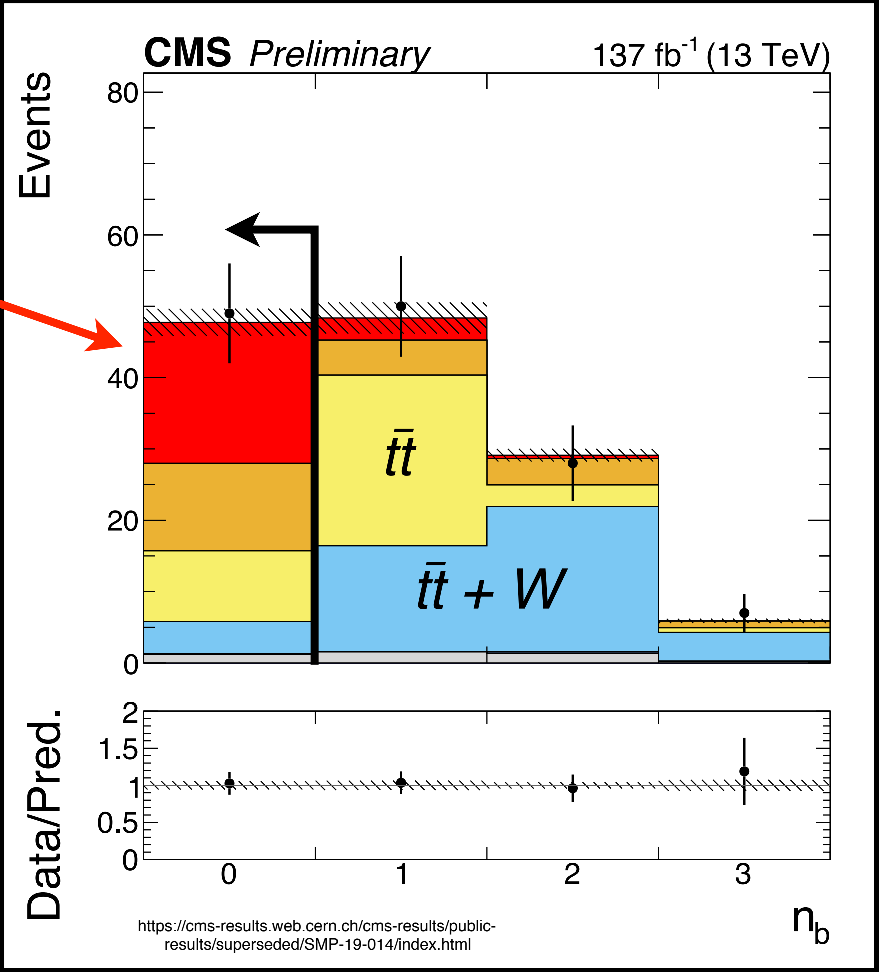
Train deep neural network



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

b quark jets tagging

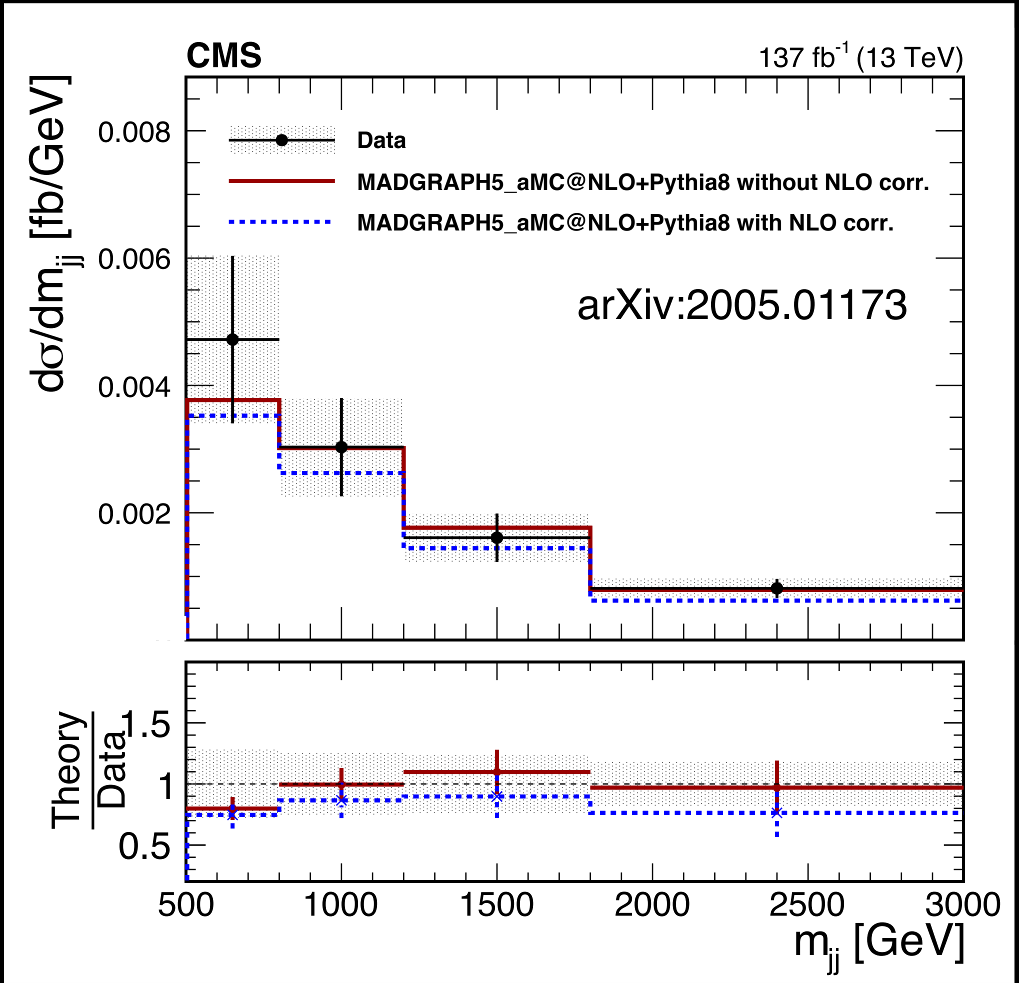
Tri-boson



Number of b-tagged jets in the event

Reject events with bottom quark to reduced backgrounds from top quark

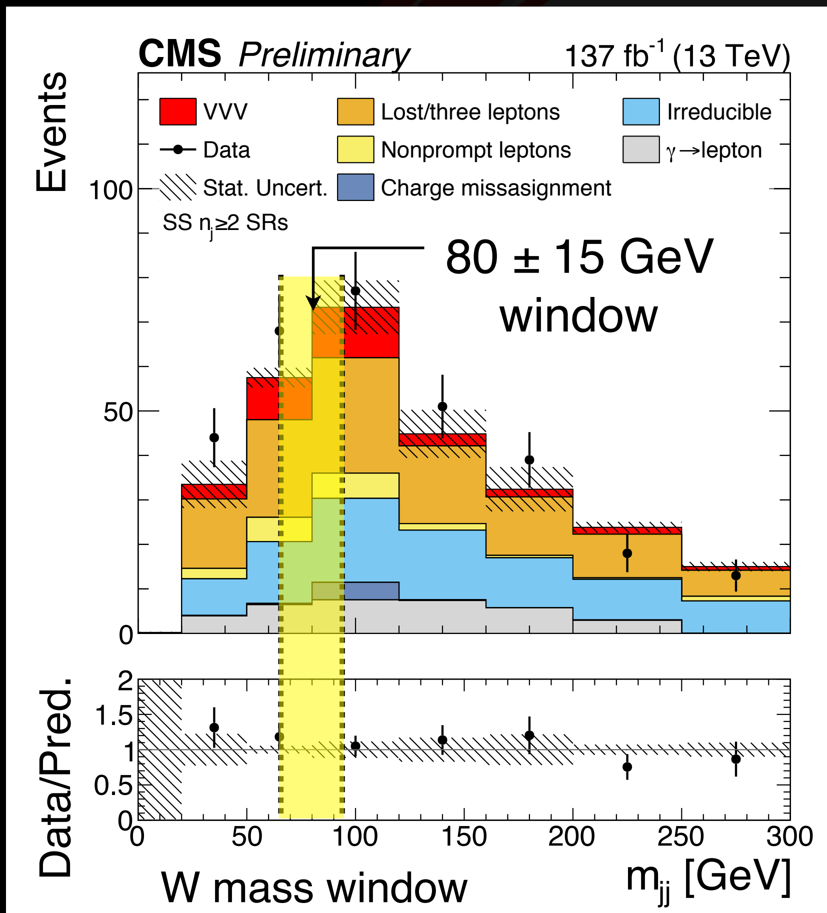
WW scattering results



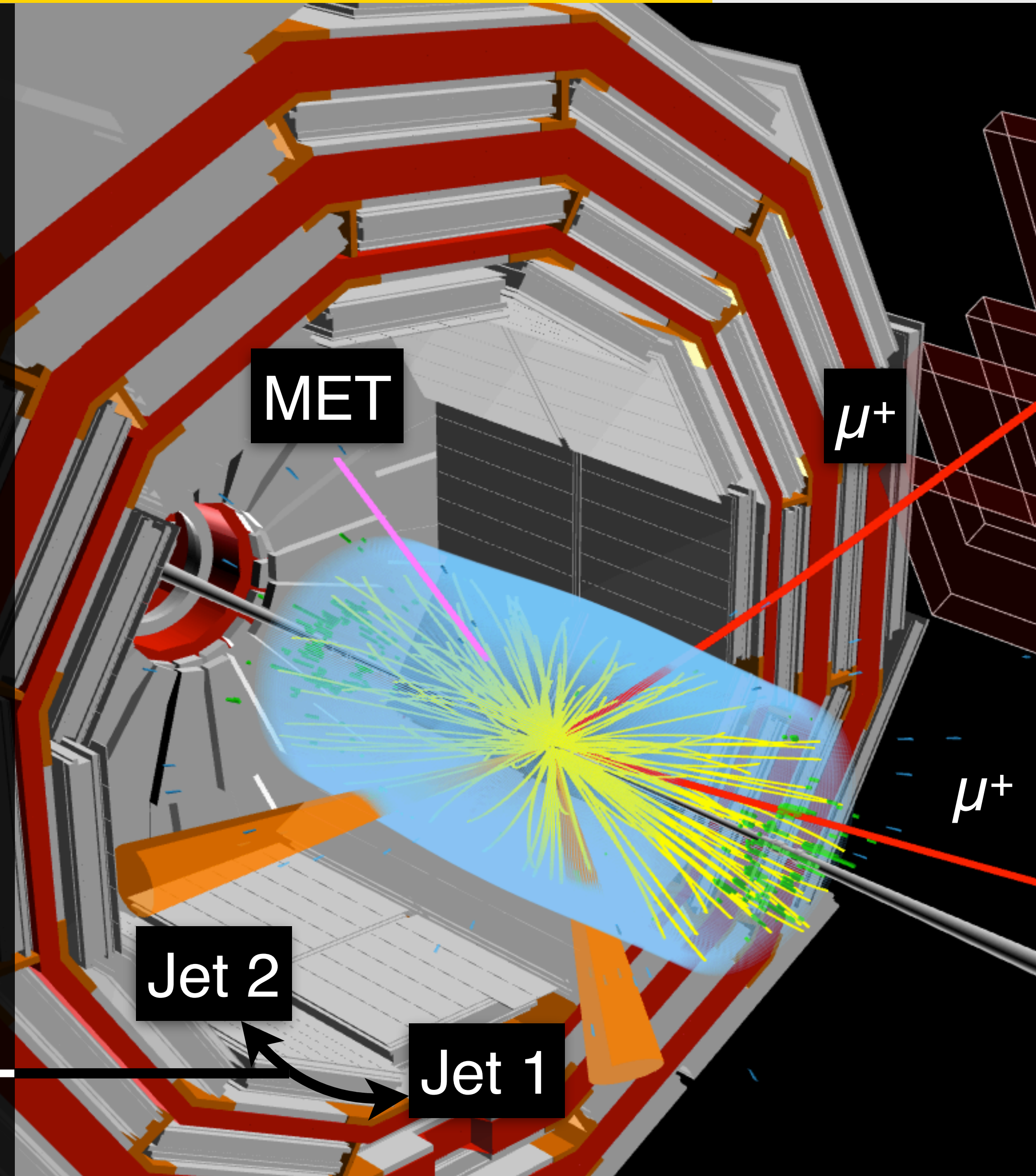
- O(100) events observed
- Measure the production rates as a function of important variables
- The measured cross section is compatible with the SM

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

Reconstruct W→qq in WWW → l±l±qq

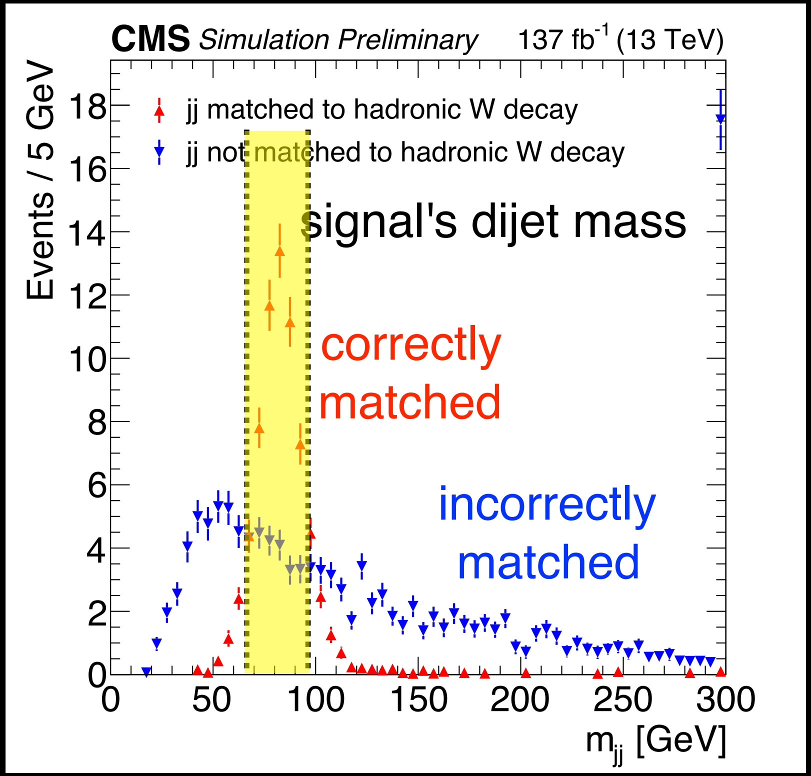


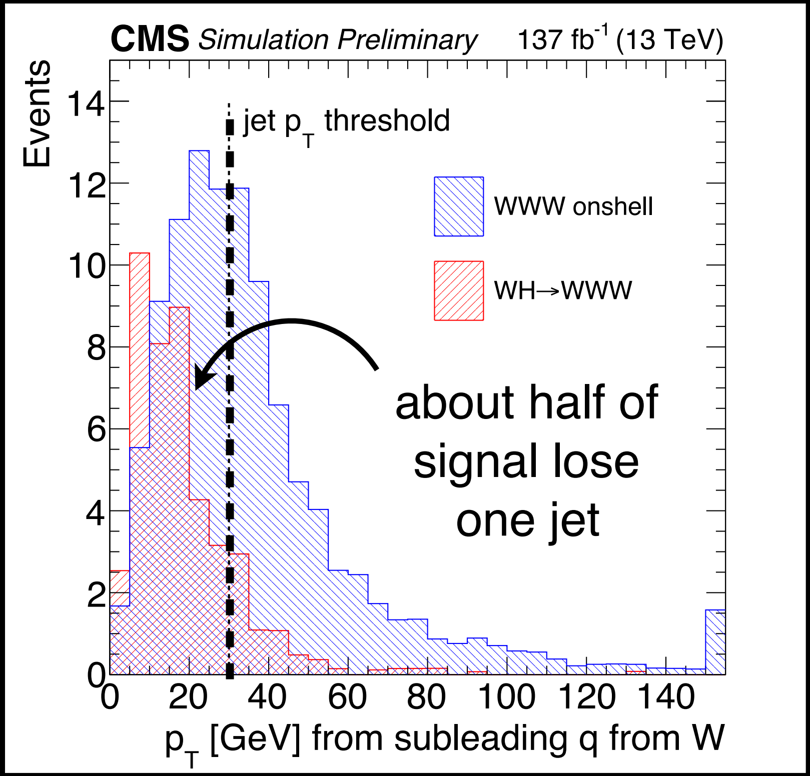
N.B. some signals are outside the window (See next slide)



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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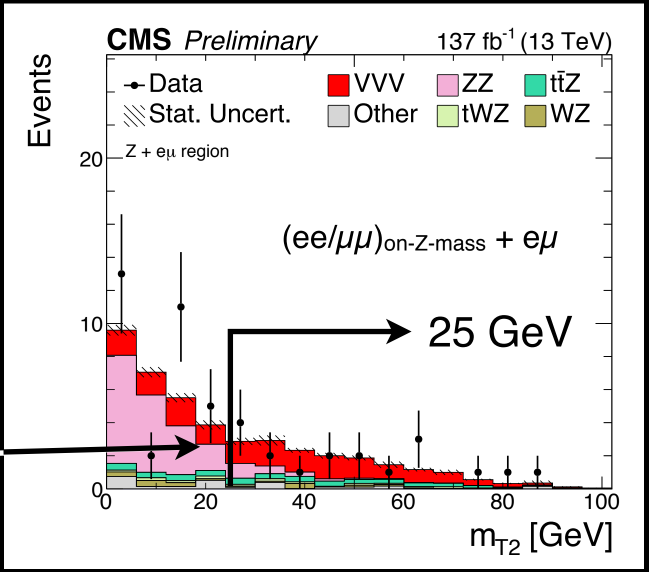
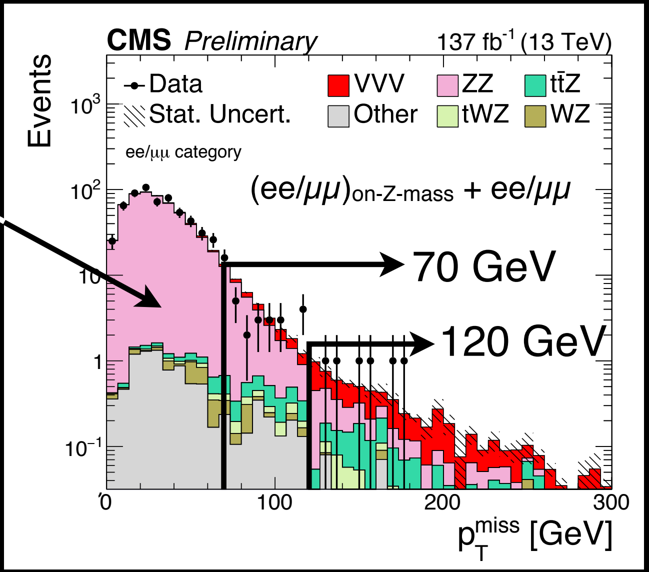
Events are separated into 2 categories by flavor:

- "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 $ZZ \to ll\tau\tau$



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

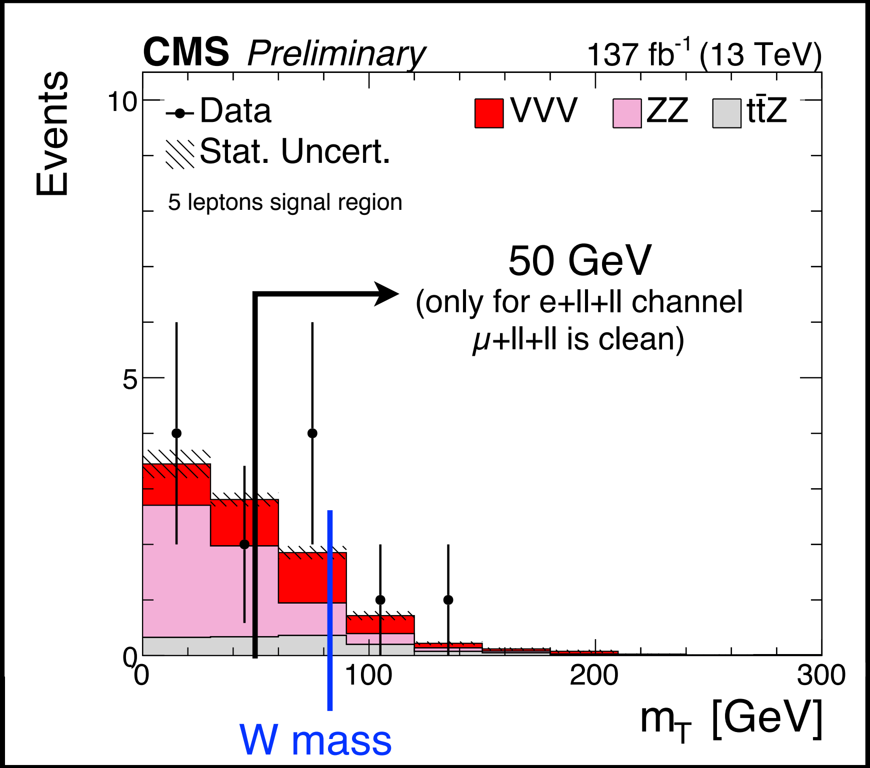
5 leptons target W **Z Z** signal

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.	$WZ \to l^{\pm}\nu l^{\pm}l^{\mp}$ (lost) $t\bar{t} \to bb + l + X$ ↳ 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

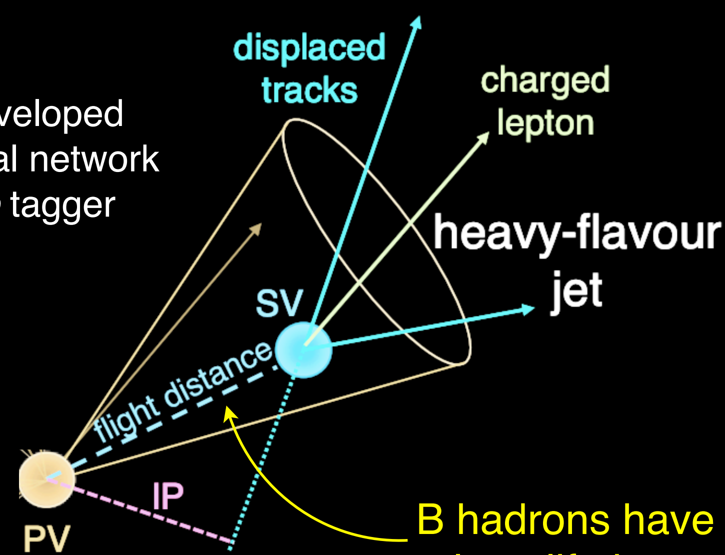
Types of backgrounds	Suppressed via	Bkg. estimation
Fake leptons	Isolation	Reliably extrapolate across isolation
Backgrounds with *b* jets	*b* tagging	Reliably extrapolate across *b* tagging
Lost leptons	Removing events with 3rd lepton	Reliably extrapolate across N leptons
Irreducible	Smart flavor choices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

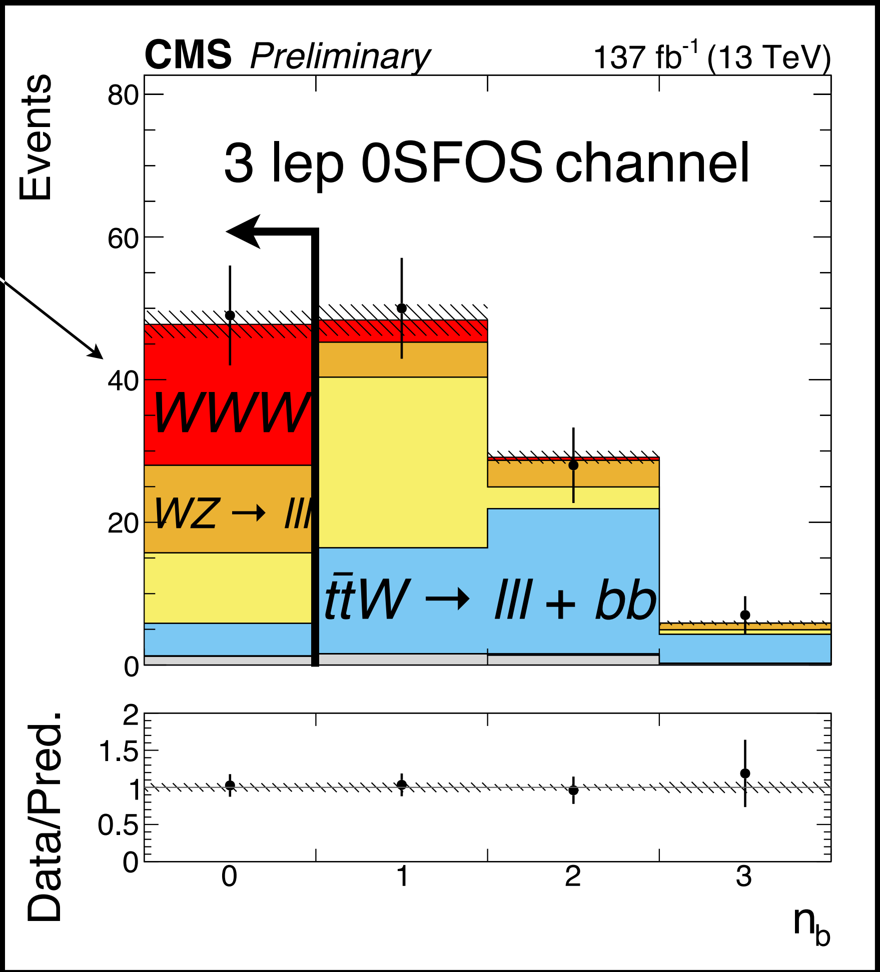
Reliably extrapolate across the method used to suppress background to estimate the size of residual backgrounds in signal region

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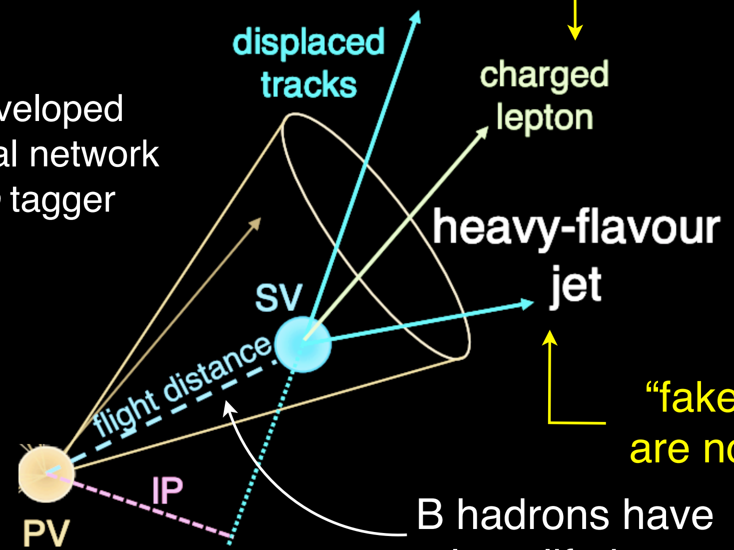
EW processes generally do not come with b jets ⇒ Require # of b = 0

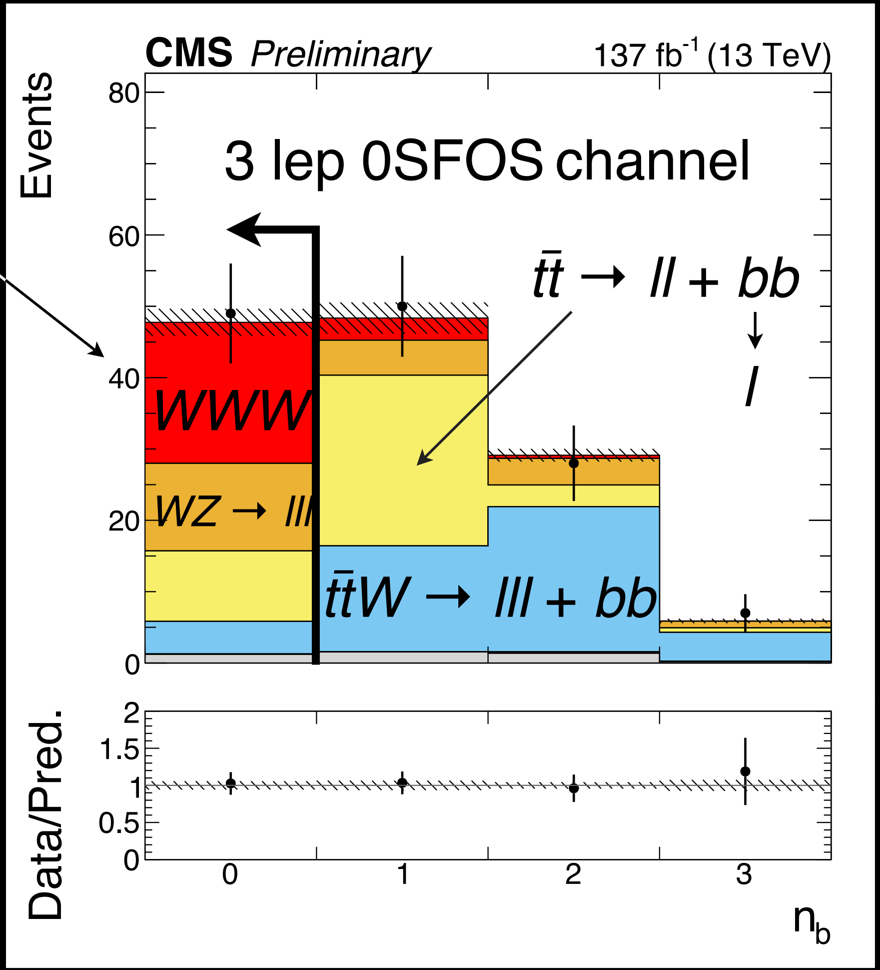
Lepton from b decay is the main source of “fake"



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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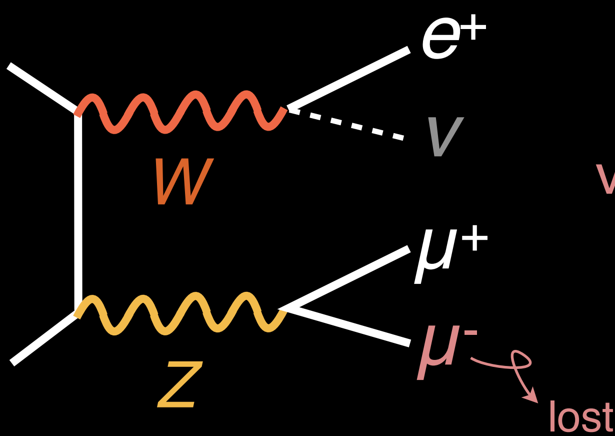
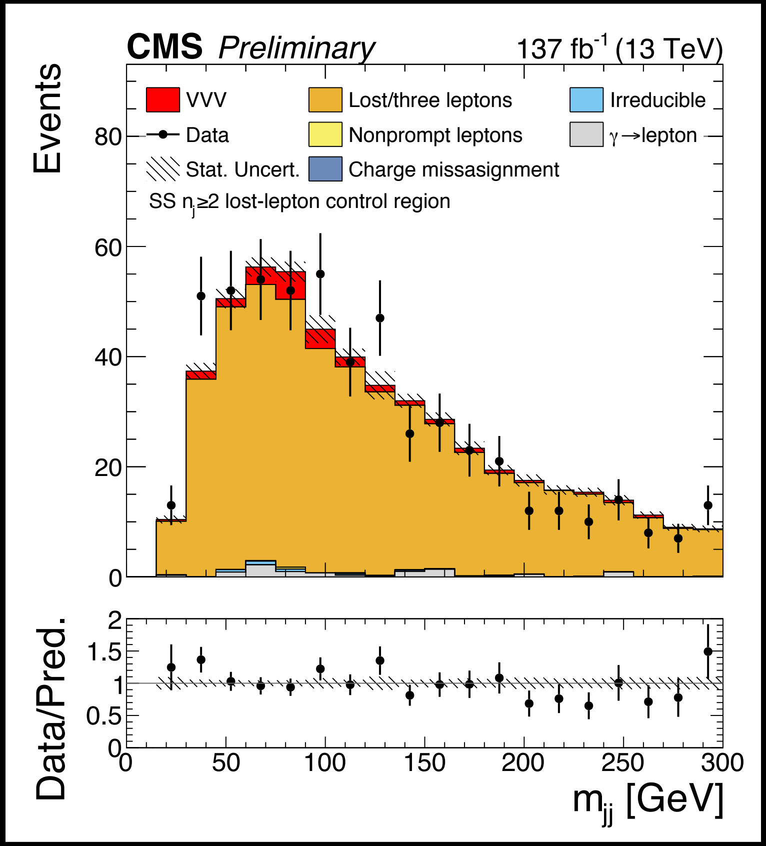


enters signal region via lost lepton ⇒ Need to understand lepton finding efficiency



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

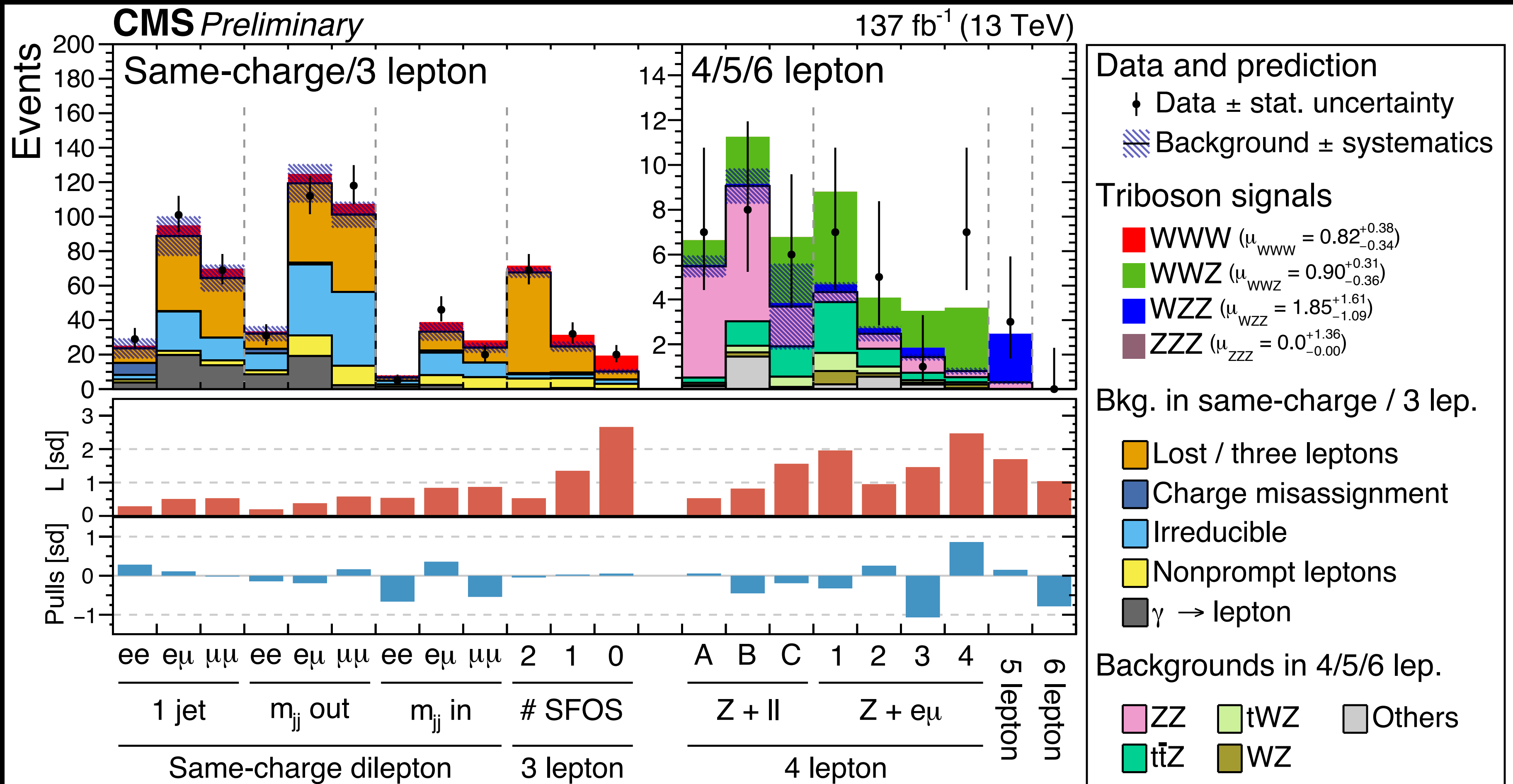
Experimental systematics assigned

Control region data statistics dominates uncertainty (20%)

Estimate lost lepton background by extrapolating across # of leptons

Results (Cut-based analysis)

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



9 bins 3 bins 7 bins 1 1

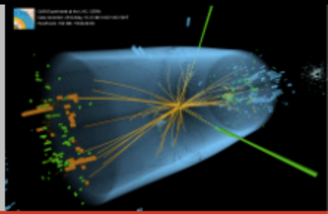
More sensitive bins are generally to the right

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

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

Compact Muon Solenoid

LHC, CERN



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