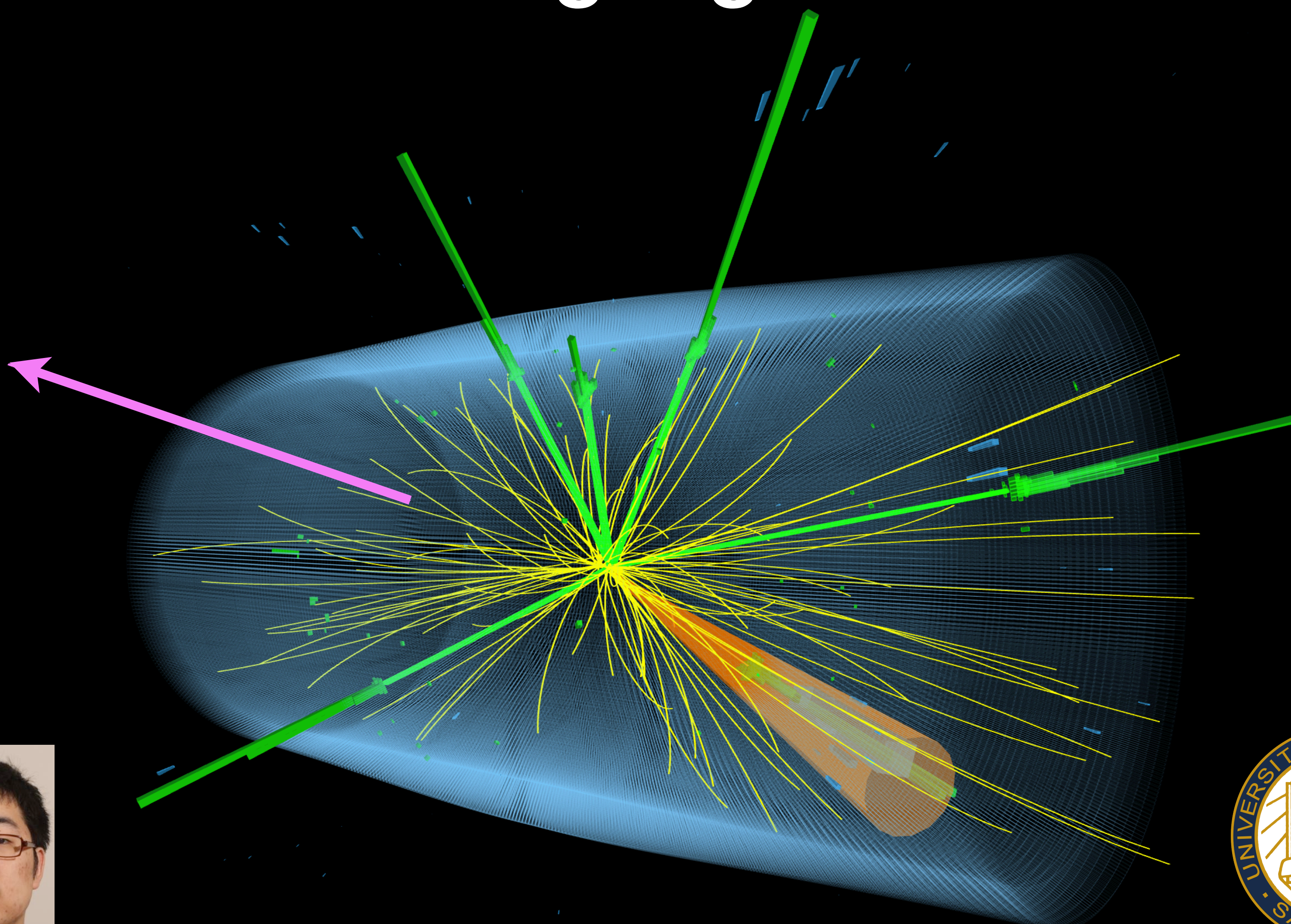
First observation of production of three massive gauge bosons

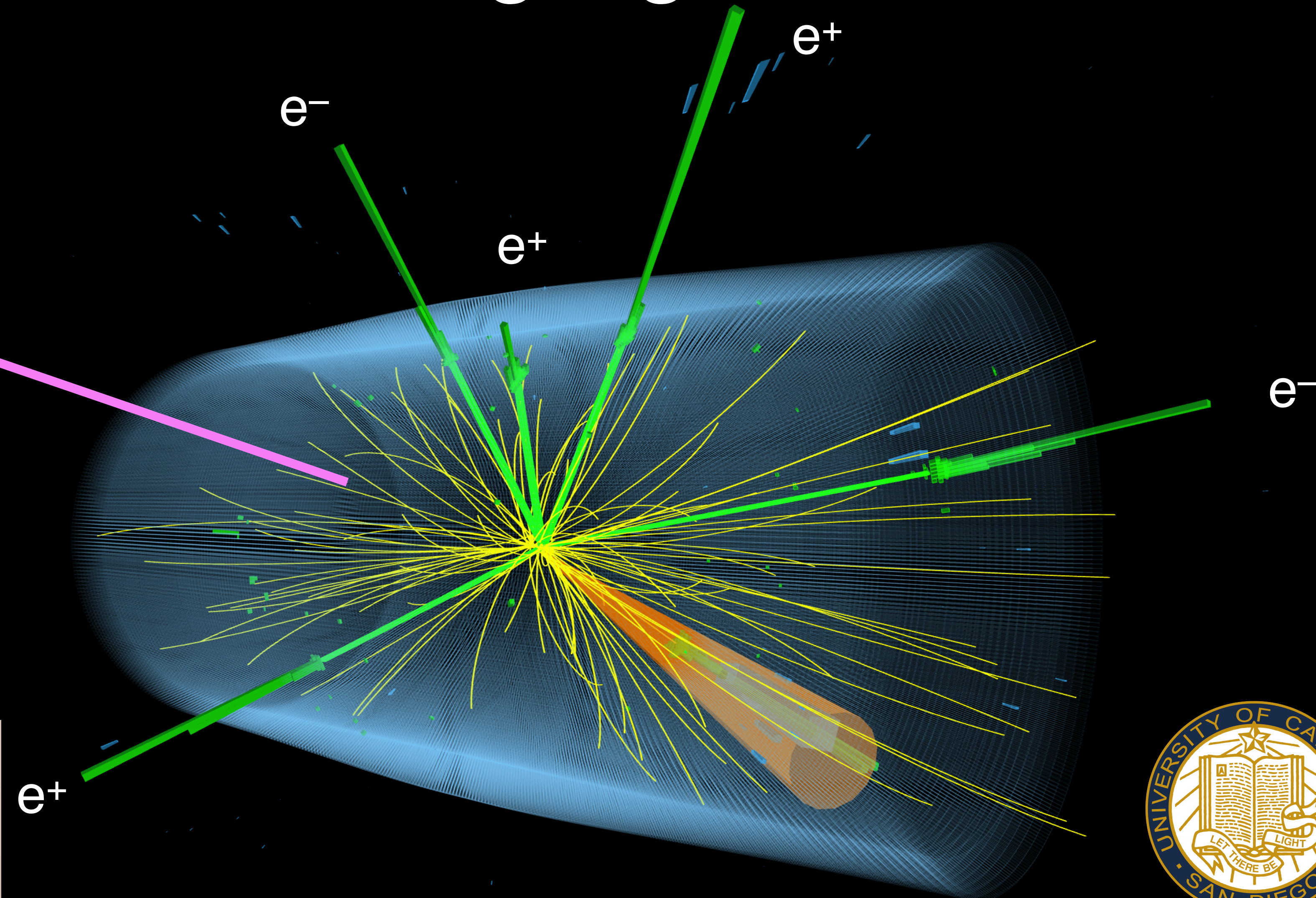


Philip
Chang

Harvard/MIT HEP Seminar
June 17, 2020

Univ. of California
San Diego

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

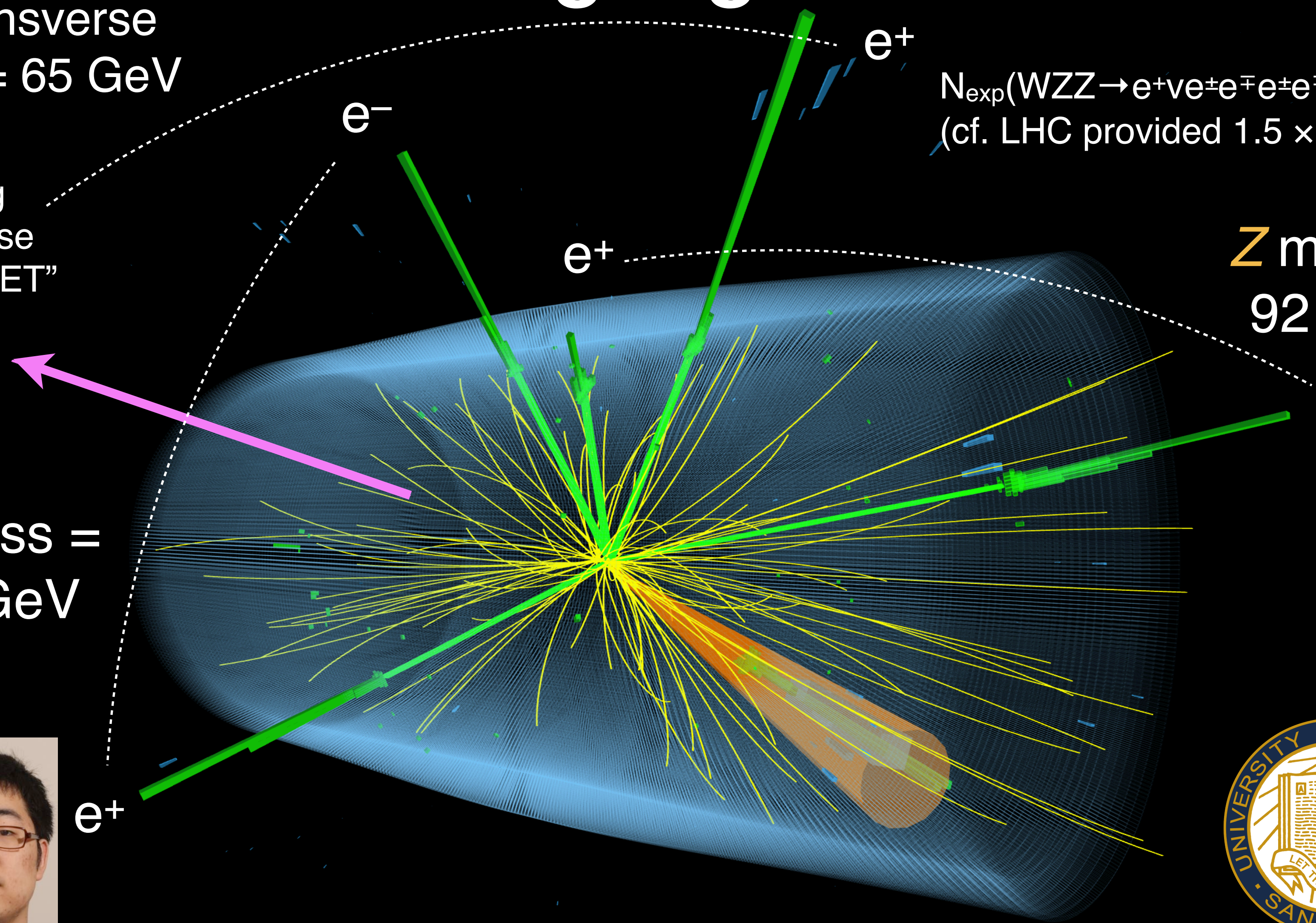


Philip Chang

Harvard/MIT HEP Seminar
June 17, 2020

Univ. of California San Diego

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



Philip Chang

Harvard/MIT HEP Seminar
June 17, 2020

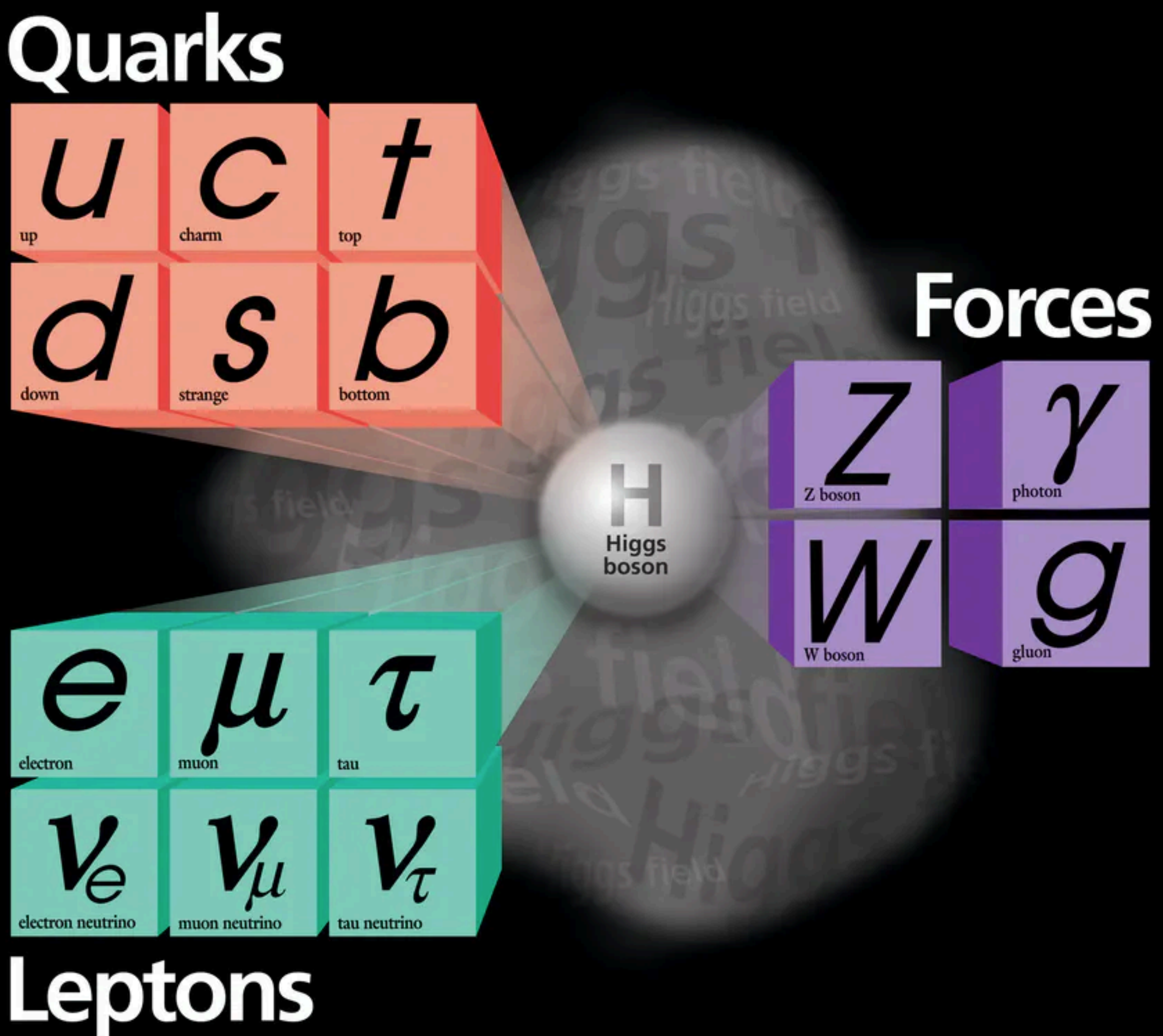
Univ. of California San Diego

Discovery of Higgs boson

July 4, 2012

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

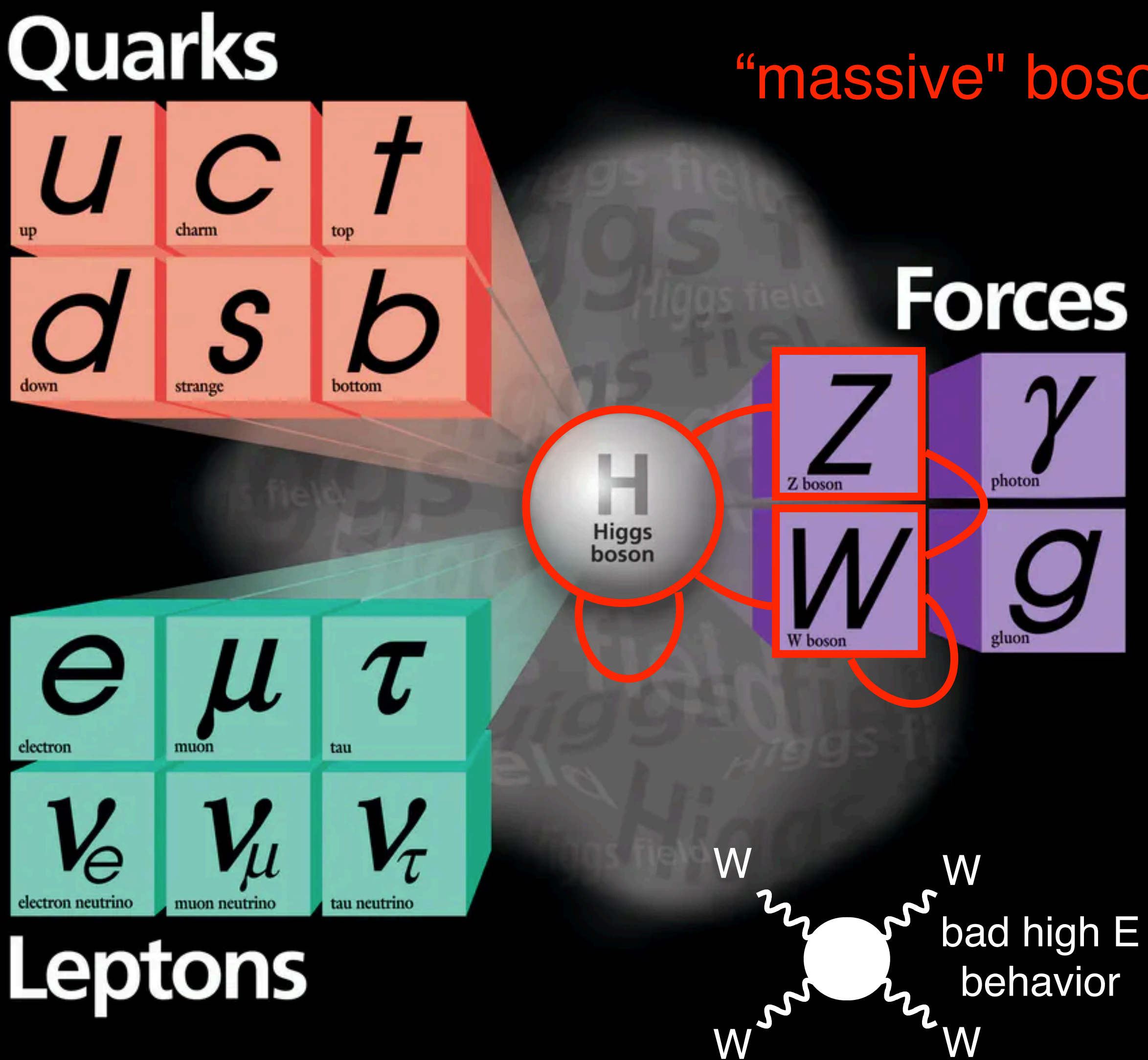
More work to be done in electroweak sector



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

Many more to be studied on electroweak sector at the LHC

More work to be done in electroweak sector

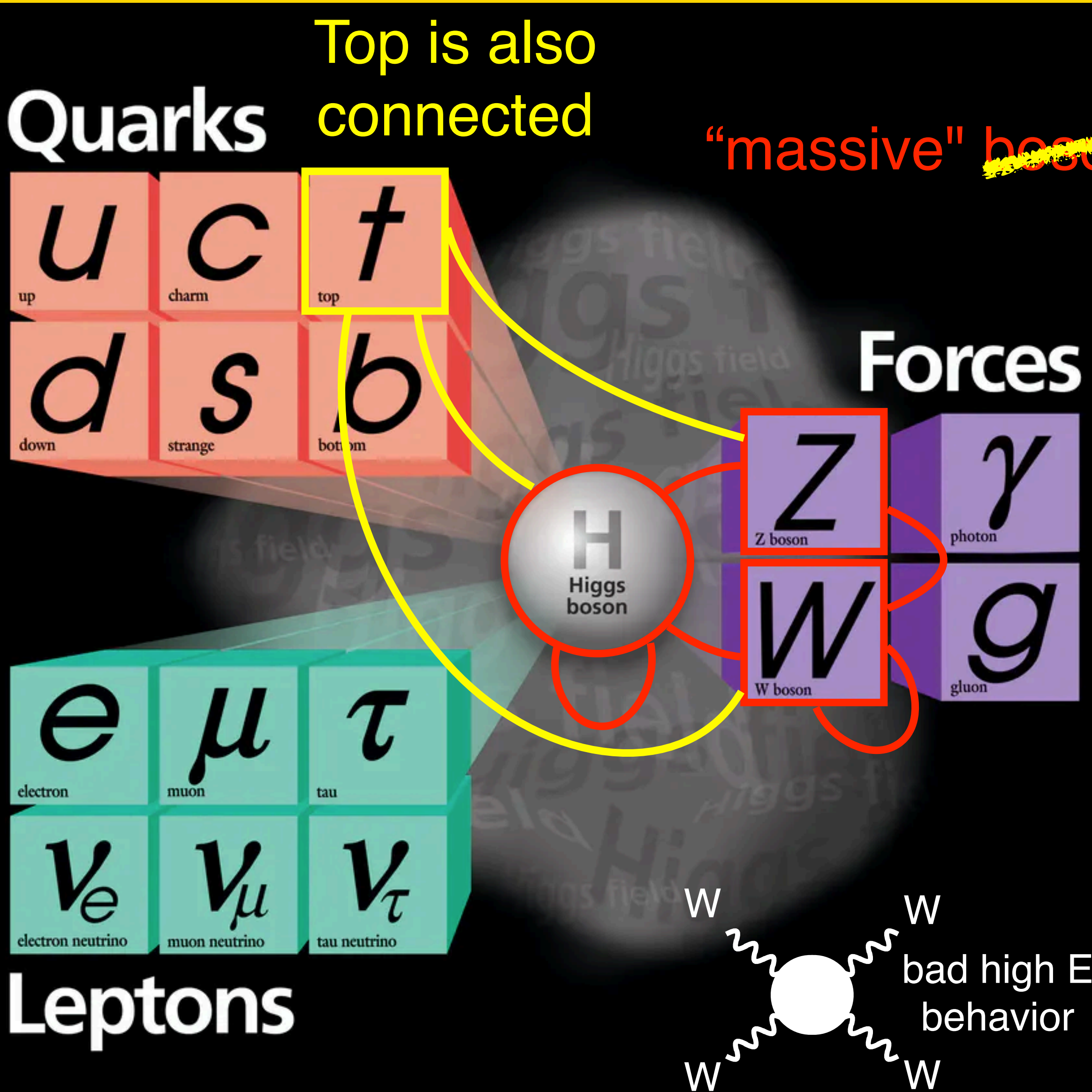


- Is it the only Higgs boson? (or are there more?)
- Are multi-*bosons* interactions SM?
- Are there more states involved in electroweak symmetry breaking?
- Is the Higgs potential SM?

Many more to be studied on electroweak sector at the LHC

More work to be done in electroweak sector

Chang
UCSD



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

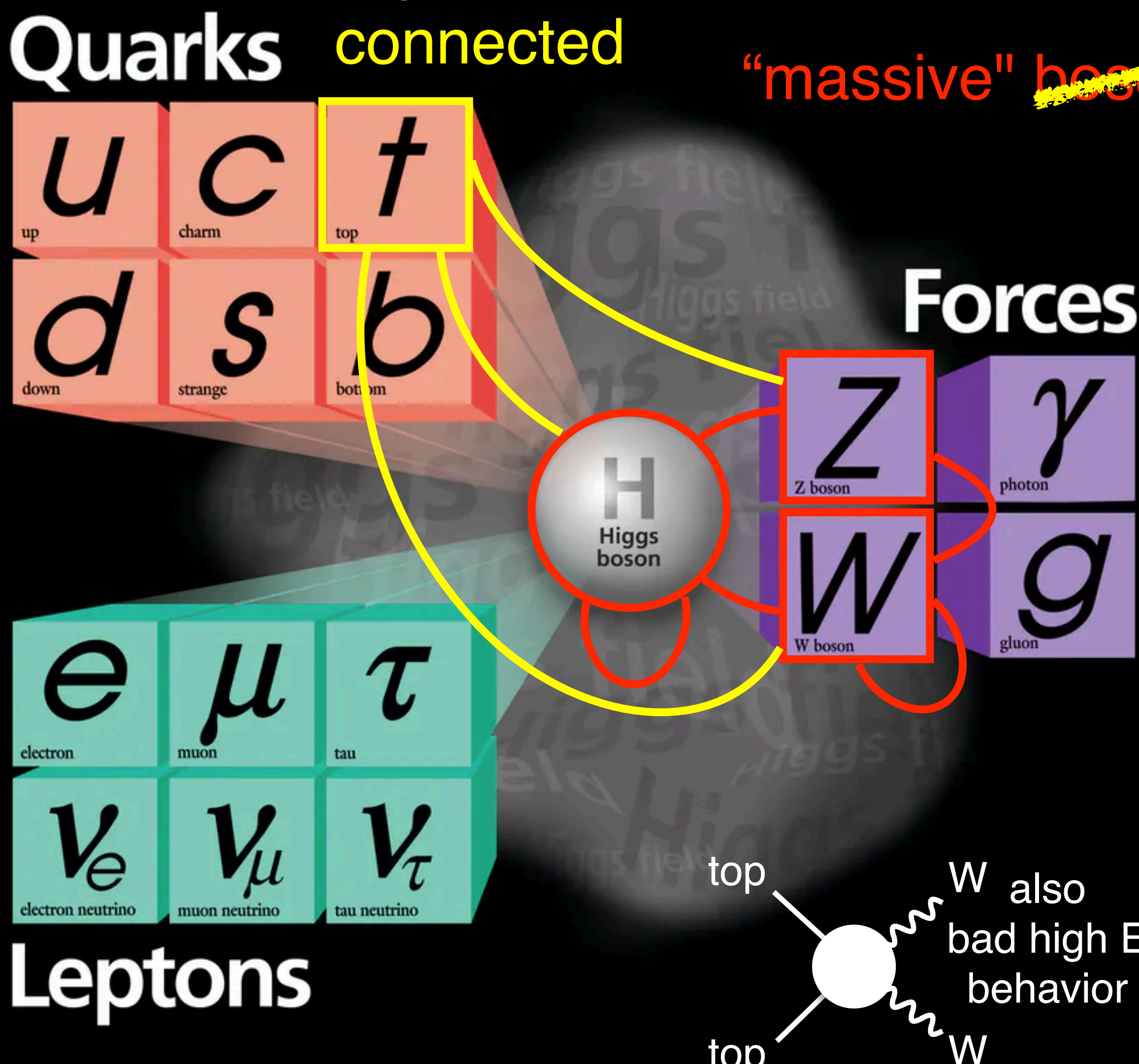
Many more to be studied on electroweak sector at the LHC

More work to be done in electroweak sector

Chang
UCSD

Top is also connected

“massive" ~~bosons~~ -X



also bad high E behavior

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

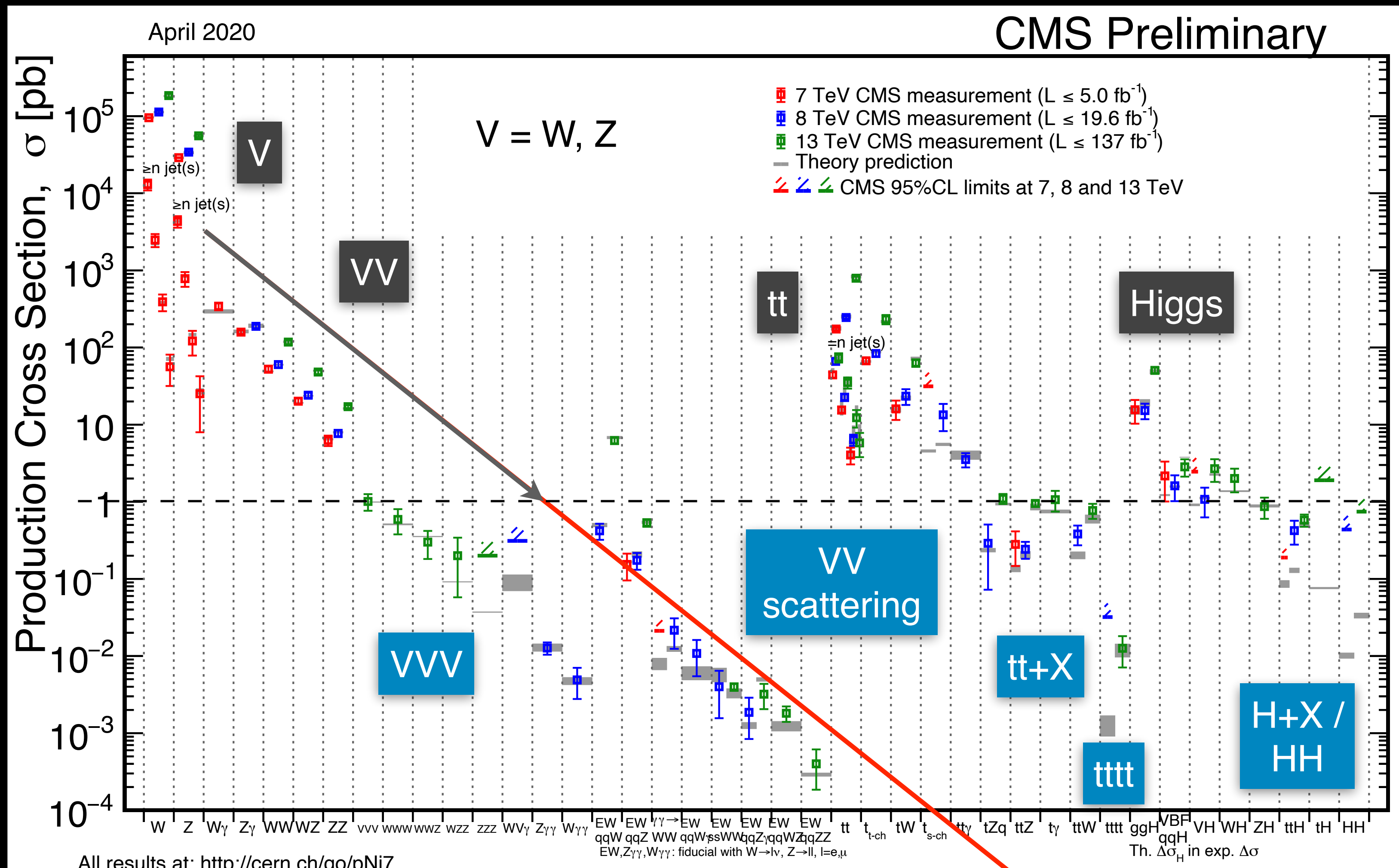
1978 (way) before top/W/Z/Higgs discovery
Chanowitz, Furman, Hinchliffe

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

Many more to be studied on electroweak sector at the LHC

Multi-"X" processes are rare and "heavy"

Rarer (and "heavier") events



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

multi-"massive"-X particles

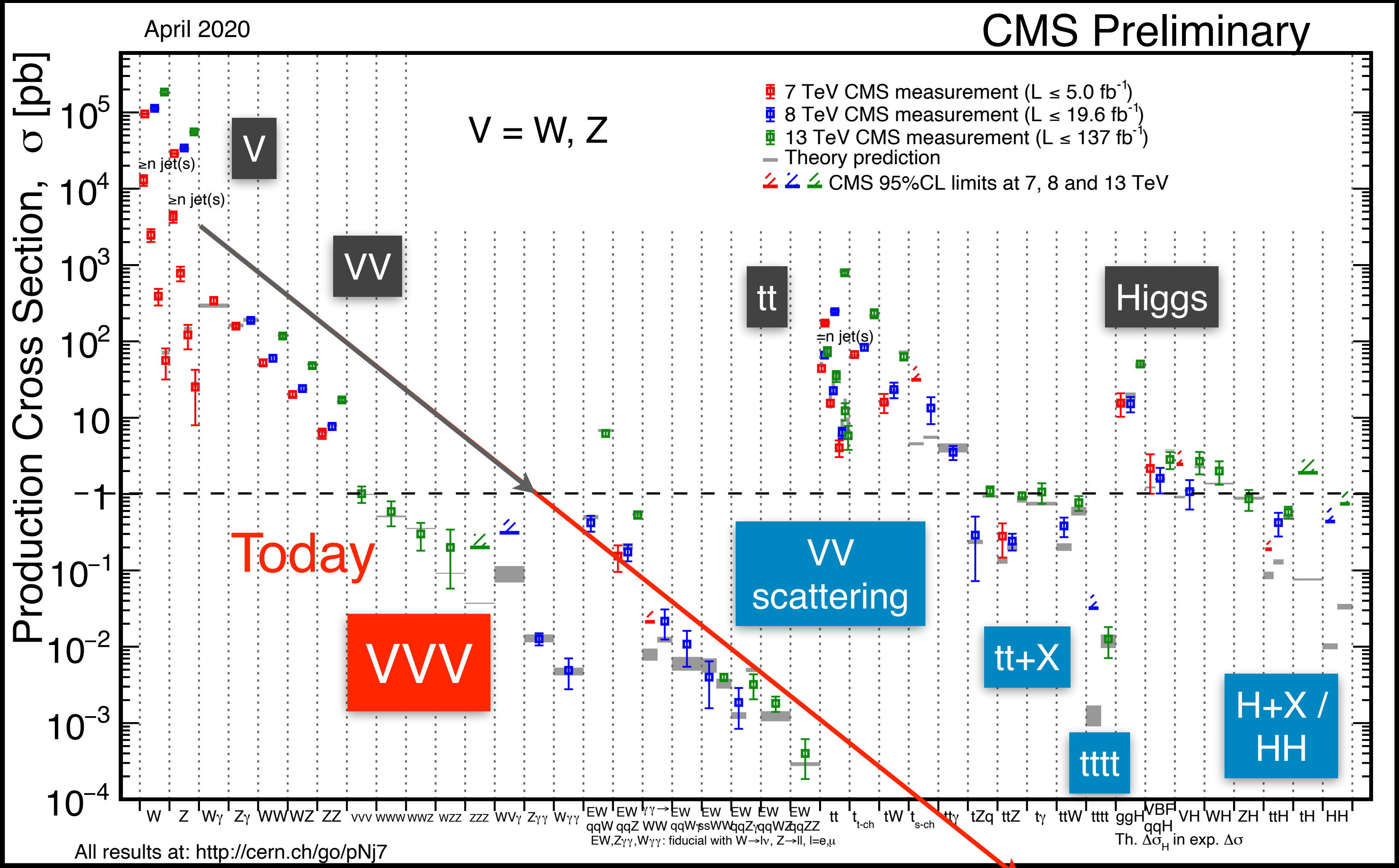
X = t, W, Z, H

Below picobarn most SM processes are electroweak multi-X production

Multi-“X” processes are rare and “heavy”

Chang
UCSD

Rarer (and “heavier”) events



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

multi-“massive"-X particles

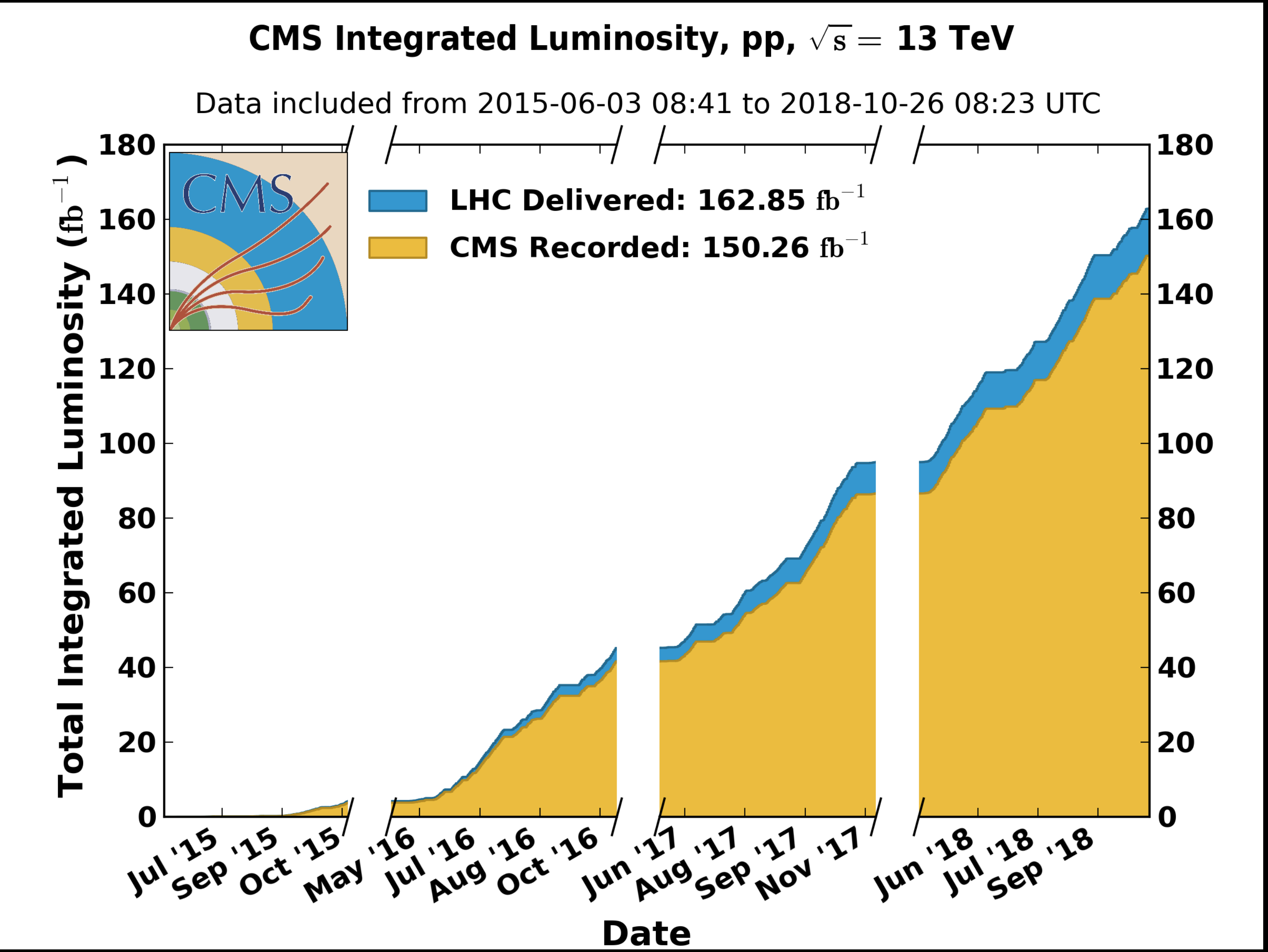
X = t, W, Z, H

Below picobarn most SM processes are electroweak multi-X production

We need LHC's large and energetic pp collision data

because rare — because "heavy"

Chang
UCSD

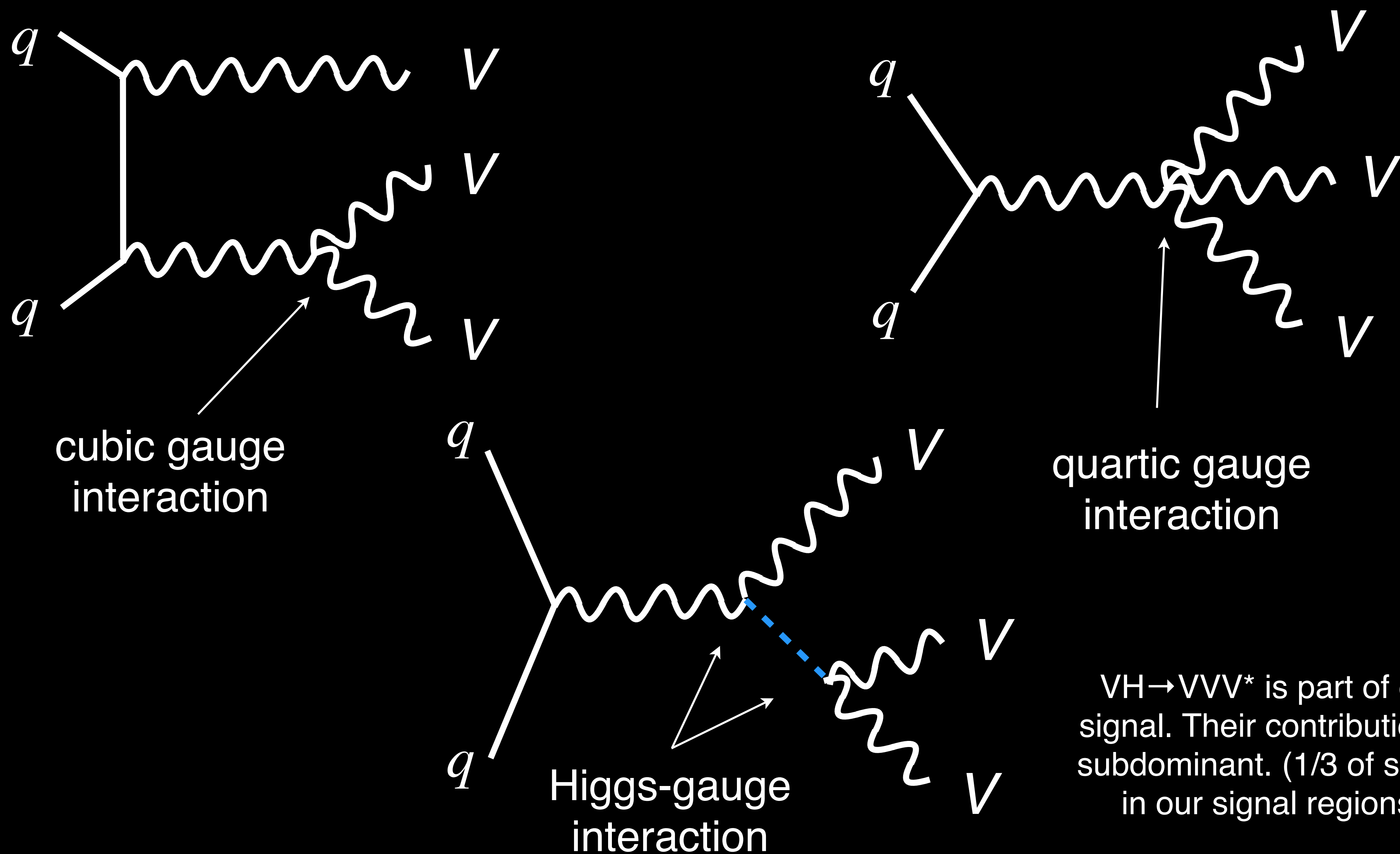


Multiply by 1000 to get the number of events produced for a picobarn process

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

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

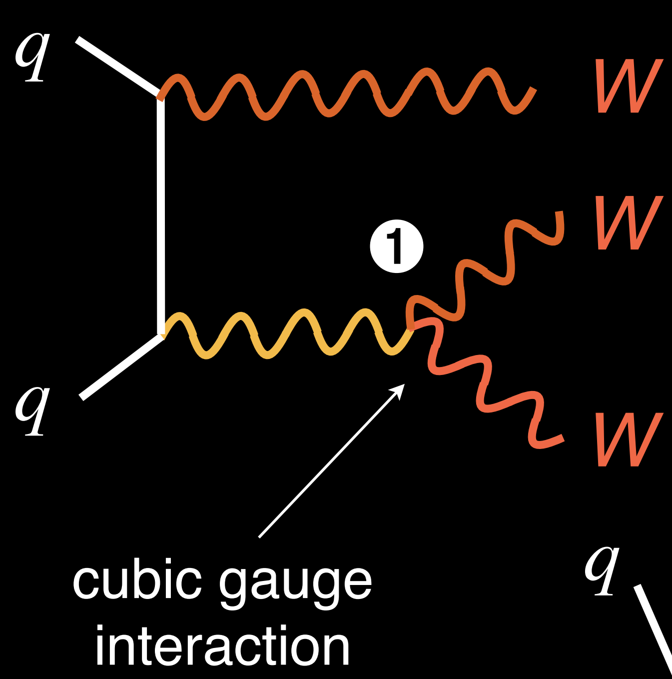
Physics of VVV production (V = W, Z)

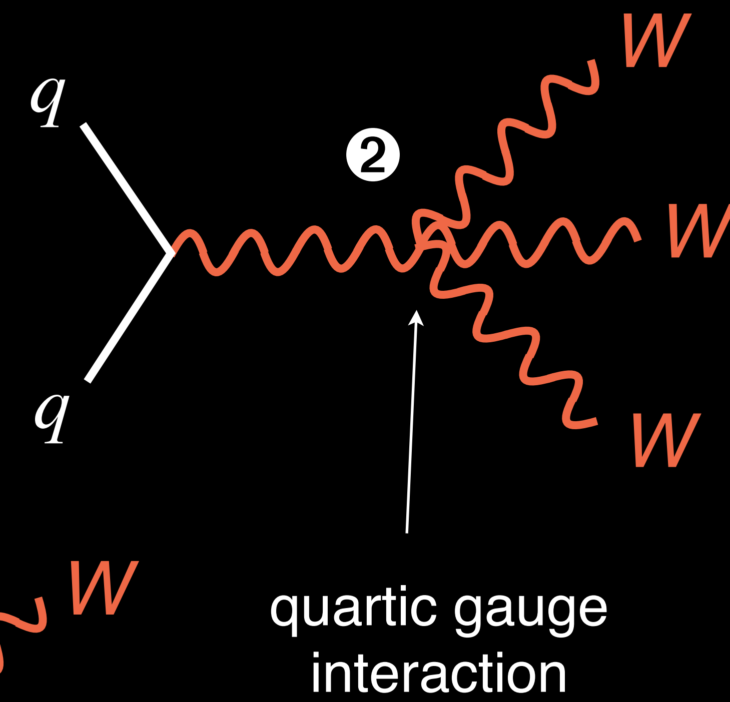


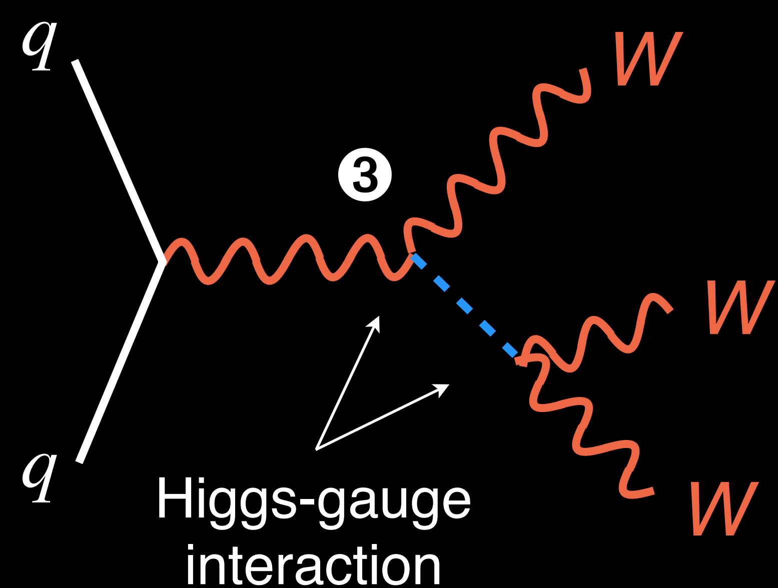
VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

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

Physics of VVV production (V = W, Z)





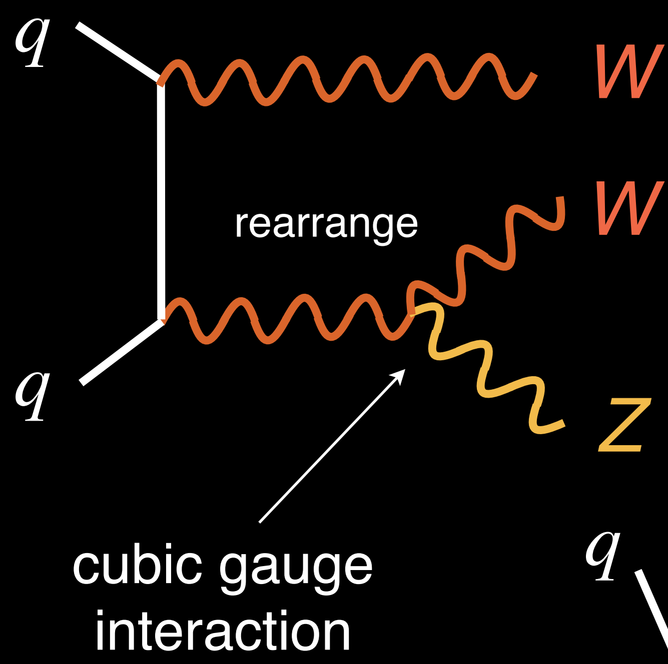


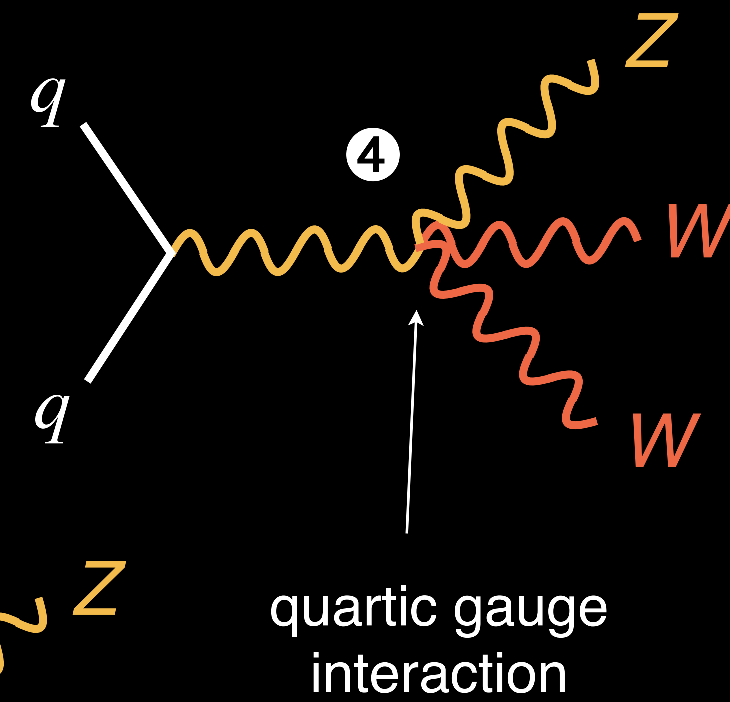
VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

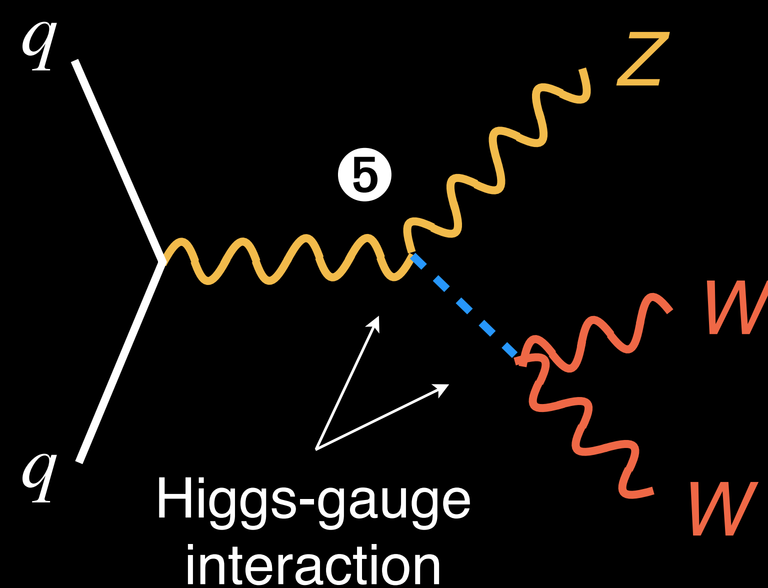
Triboson process has access to studying many multi-*boson* interactions

Physics of VVV production (V = W, Z)

Chang
UCSD



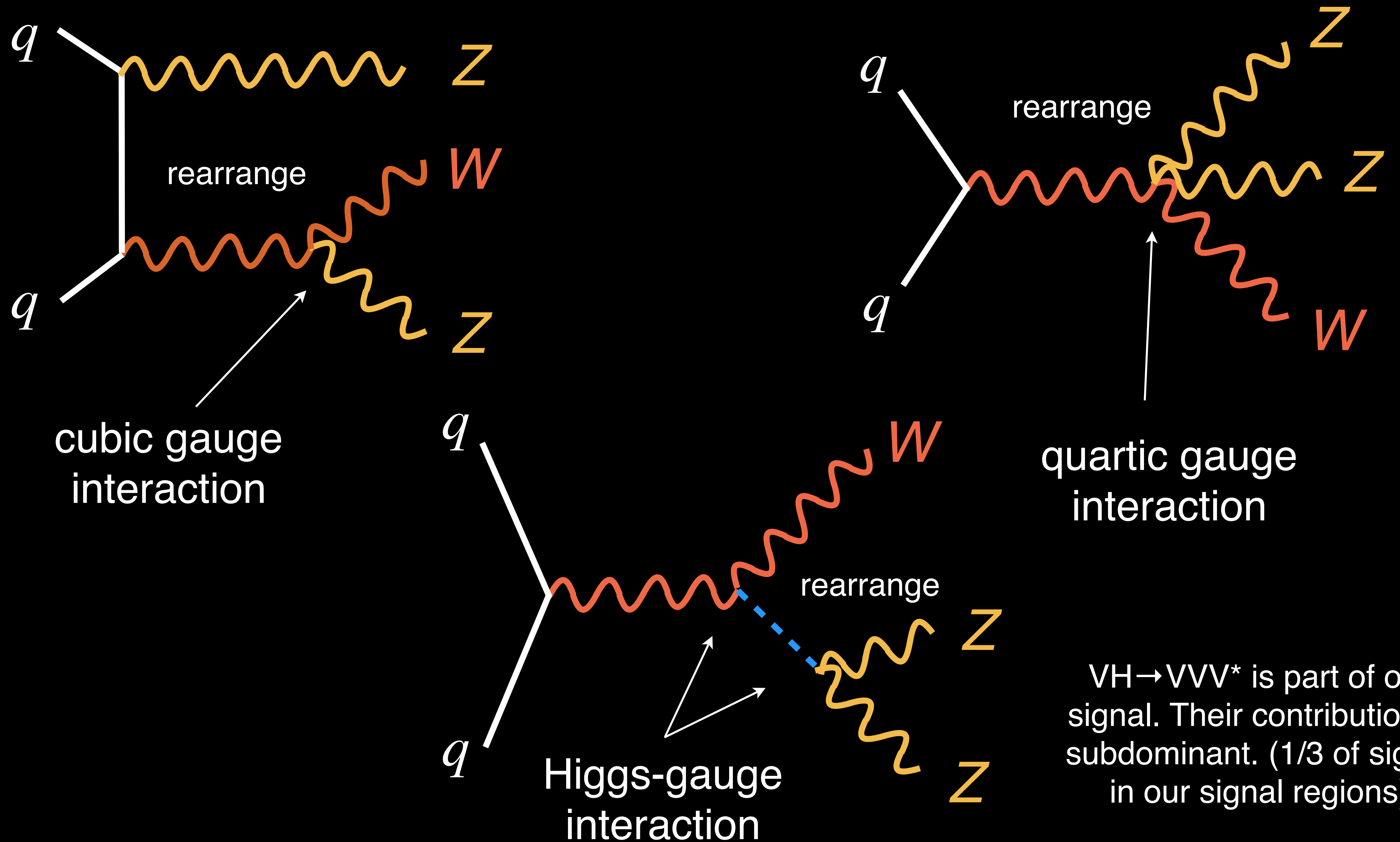




VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

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

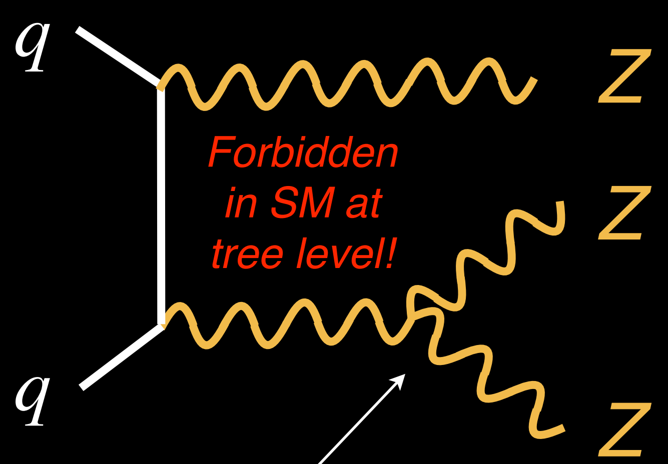
Physics of VVV production (V = W, Z)



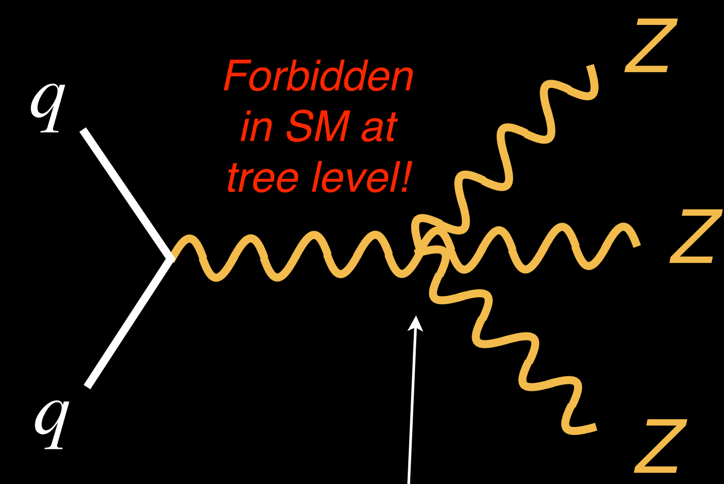
VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

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

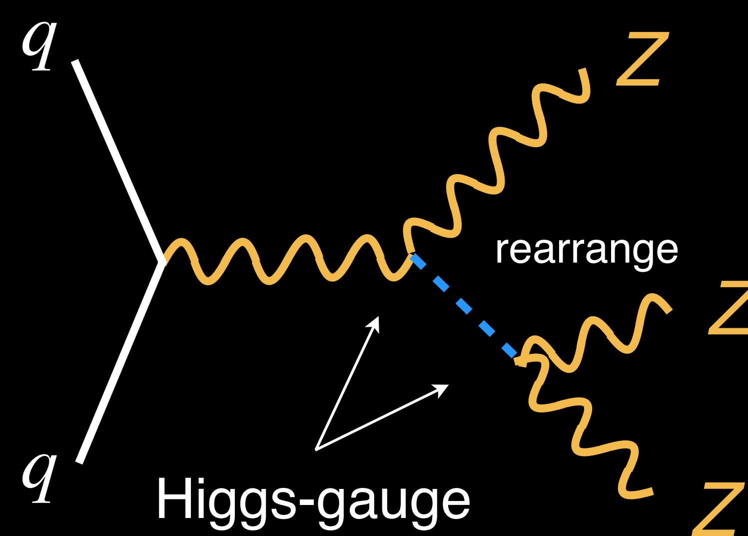
Physics of VVV production (V = W, Z)



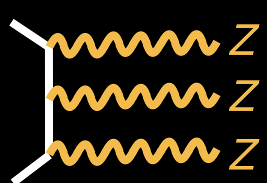
cubic gauge
interaction



quartic gauge
interaction



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)

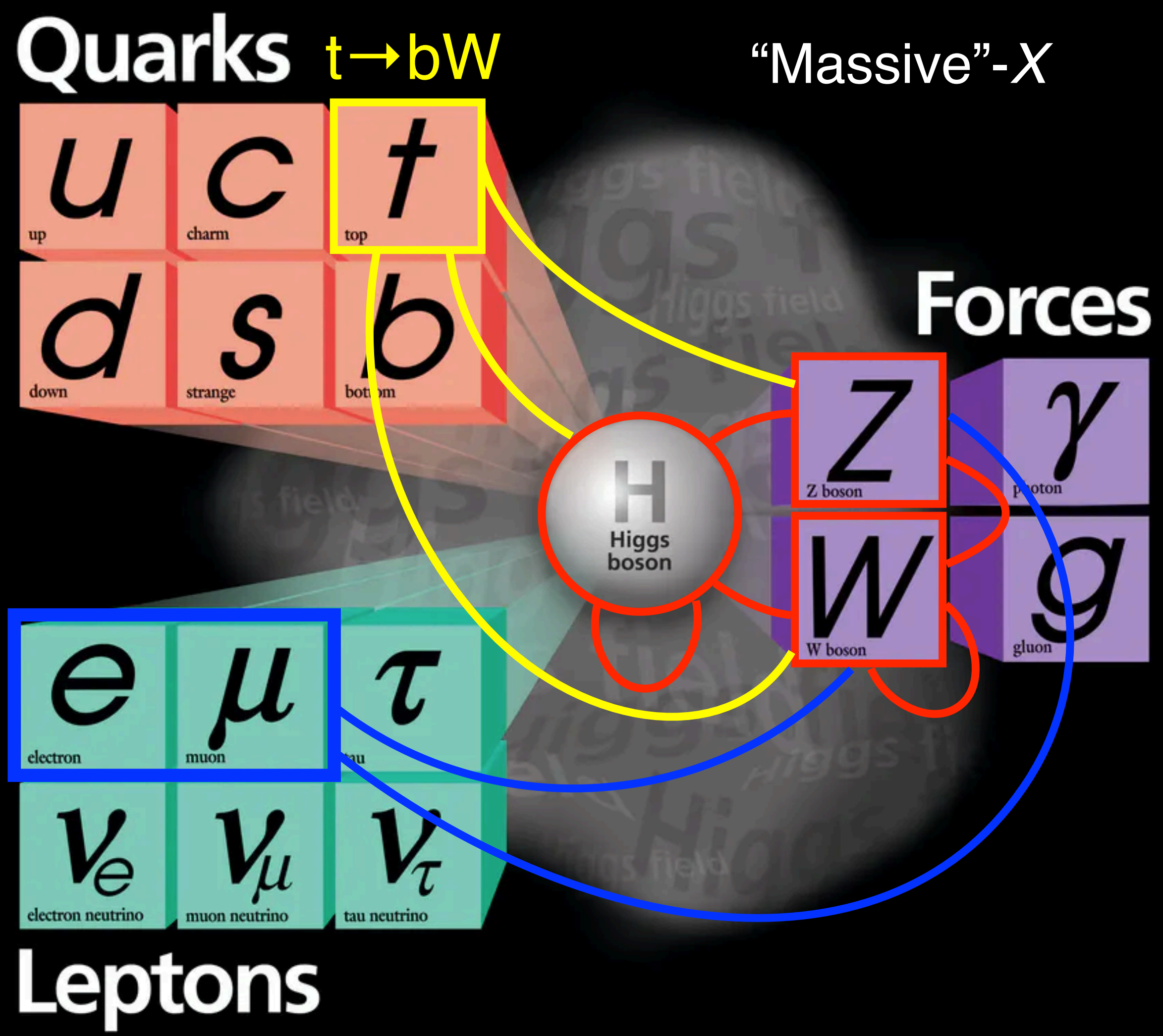
Triboson process has access to studying many multi-*boson* interactions

Decay of W, Z bosons

W → e/*μ* (~20%)
Z → ee/*μμ* (~7%)
We select leptons w/ transverse momentum (P_T) of > 25, 20, 10

τ decays in the detector
τ → e, *μ* + 2v
or
τ → hadrons + v

We include e, *μ* from τ's from W/Z decays in the analysis
But they have quite soft P_T and do not pass the P_T requirements



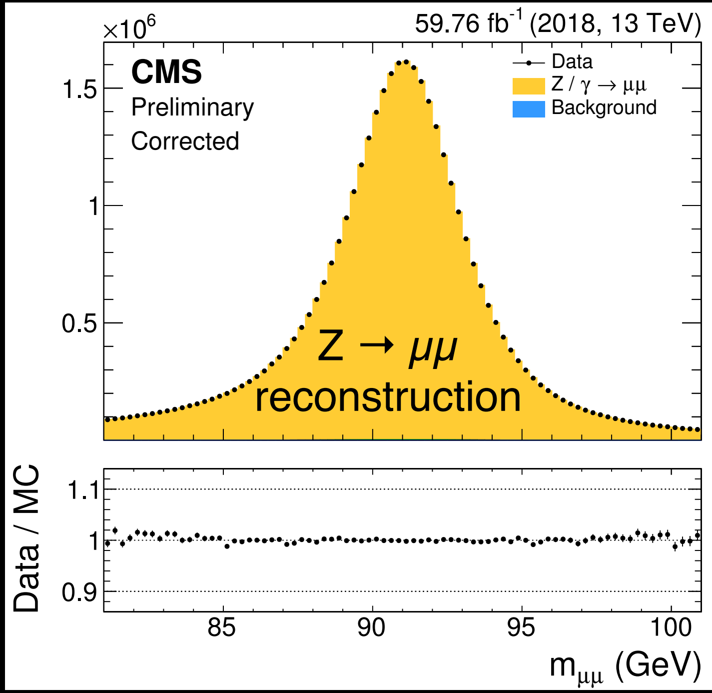
W's and Z's produced can be identified via electrons and muons

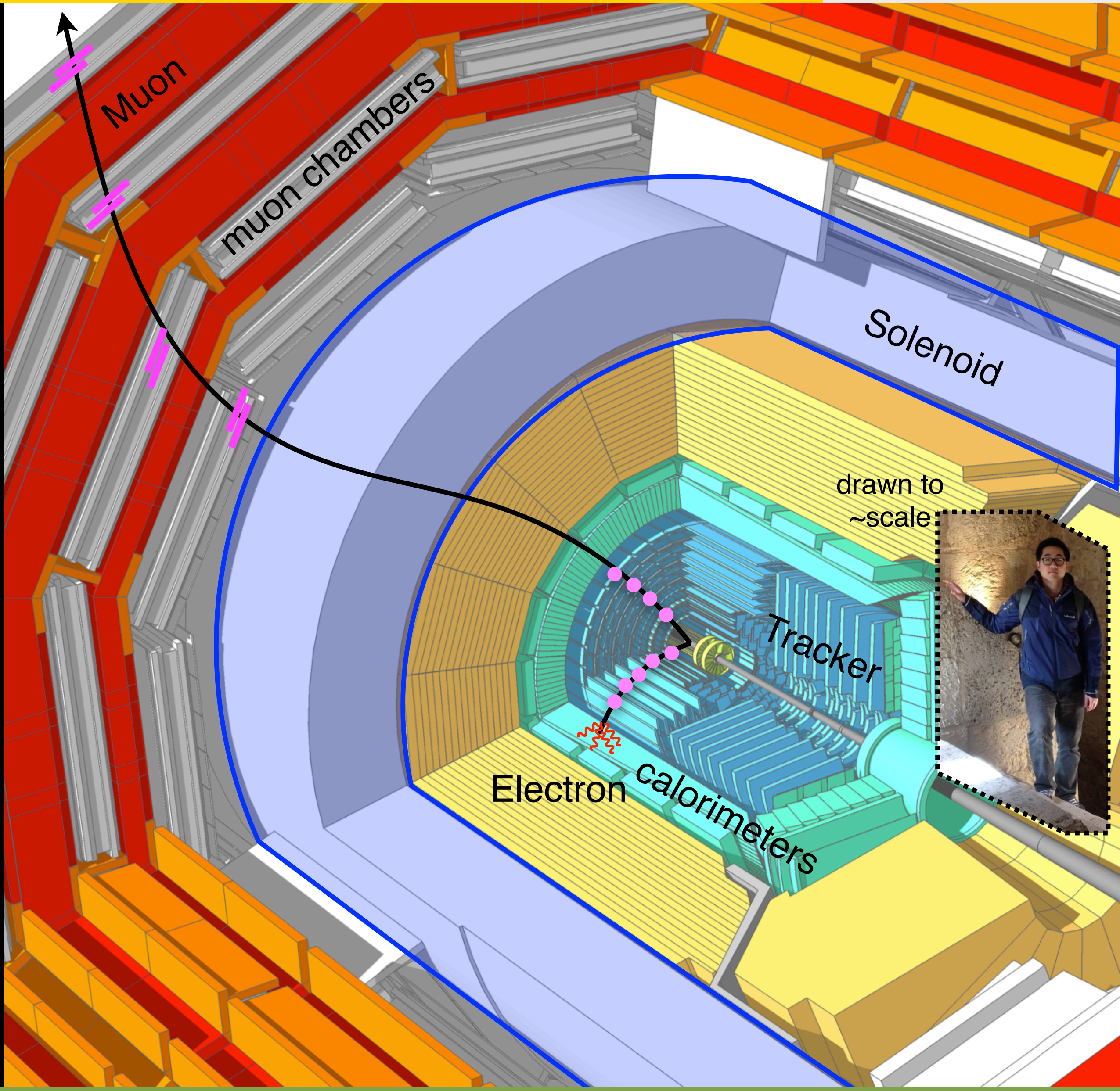
CMS detector measures leptons very well

Chang
UCSD

e/μ among the best measured particles at CMS by combining tracker, calorimeter, and chambers measurements

(1-2% resolution for well measured ones)





Excellent lepton reconstruction and simulation at CMS

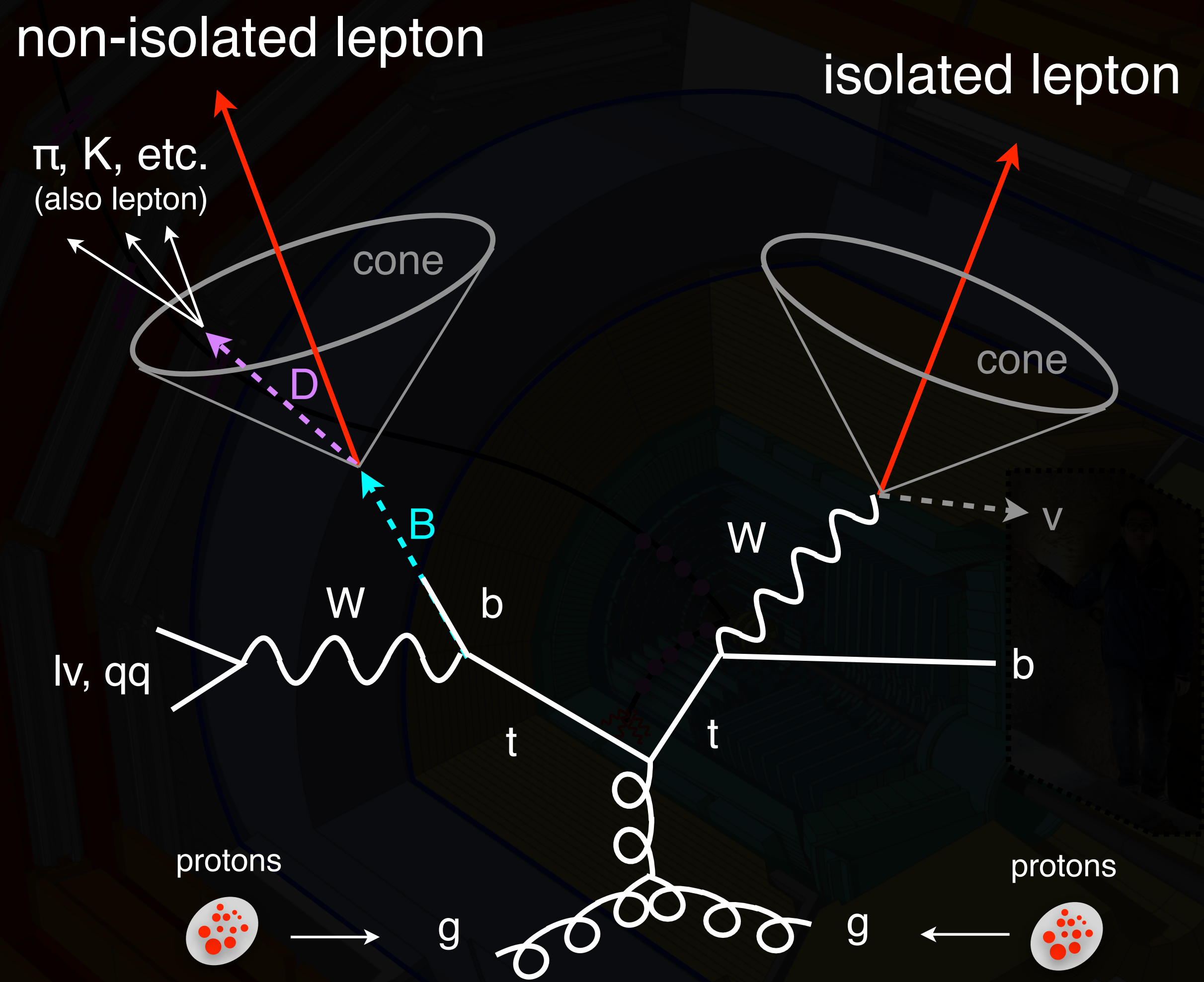
Classifying leptons' origins

Identifying leptons is not enough

We need to further classify the origin

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

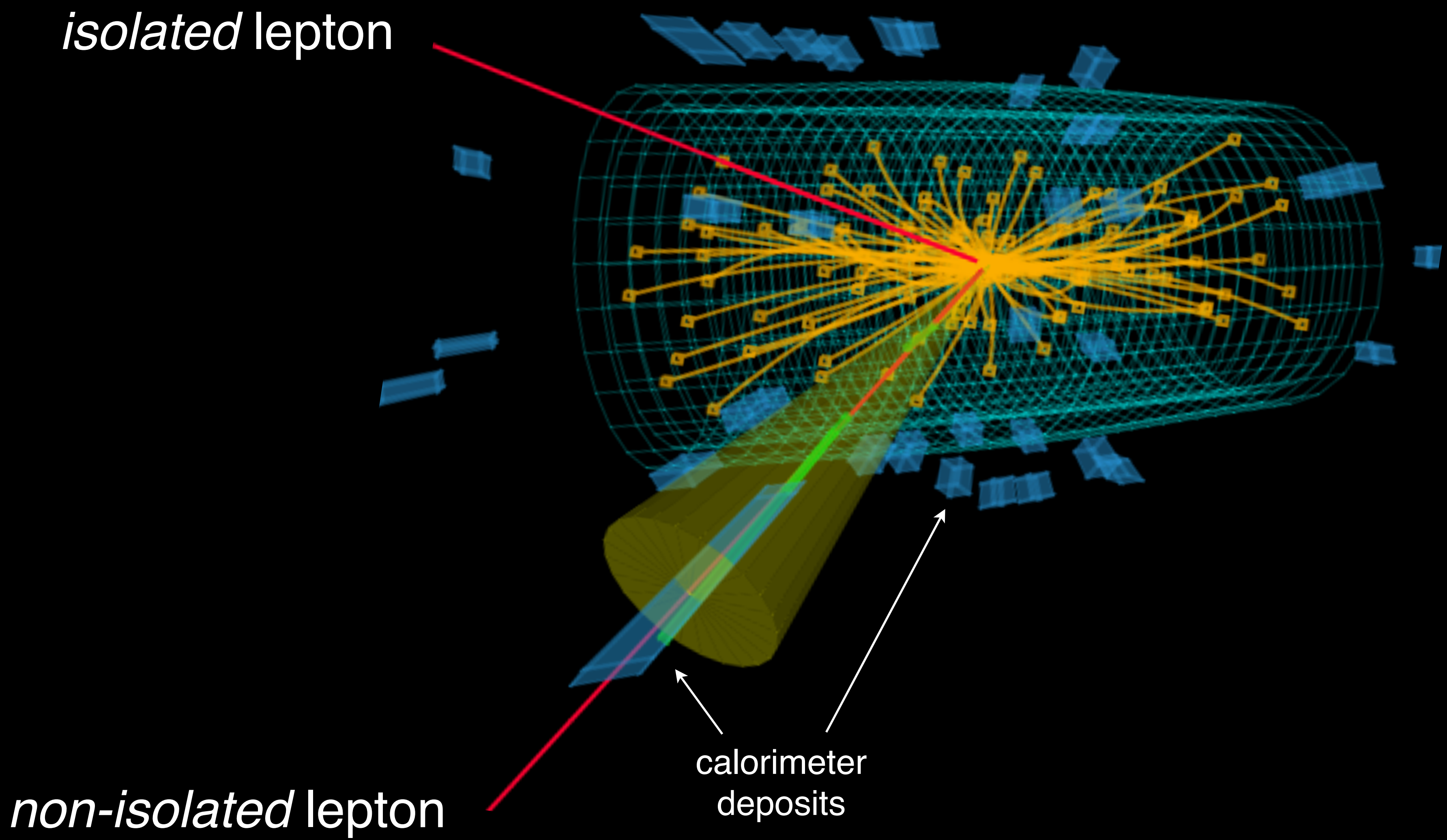
N.B. electrons and muons have different effects (muons are cleaner)



Use isolation to discriminate against leptons from heavy flavor decay

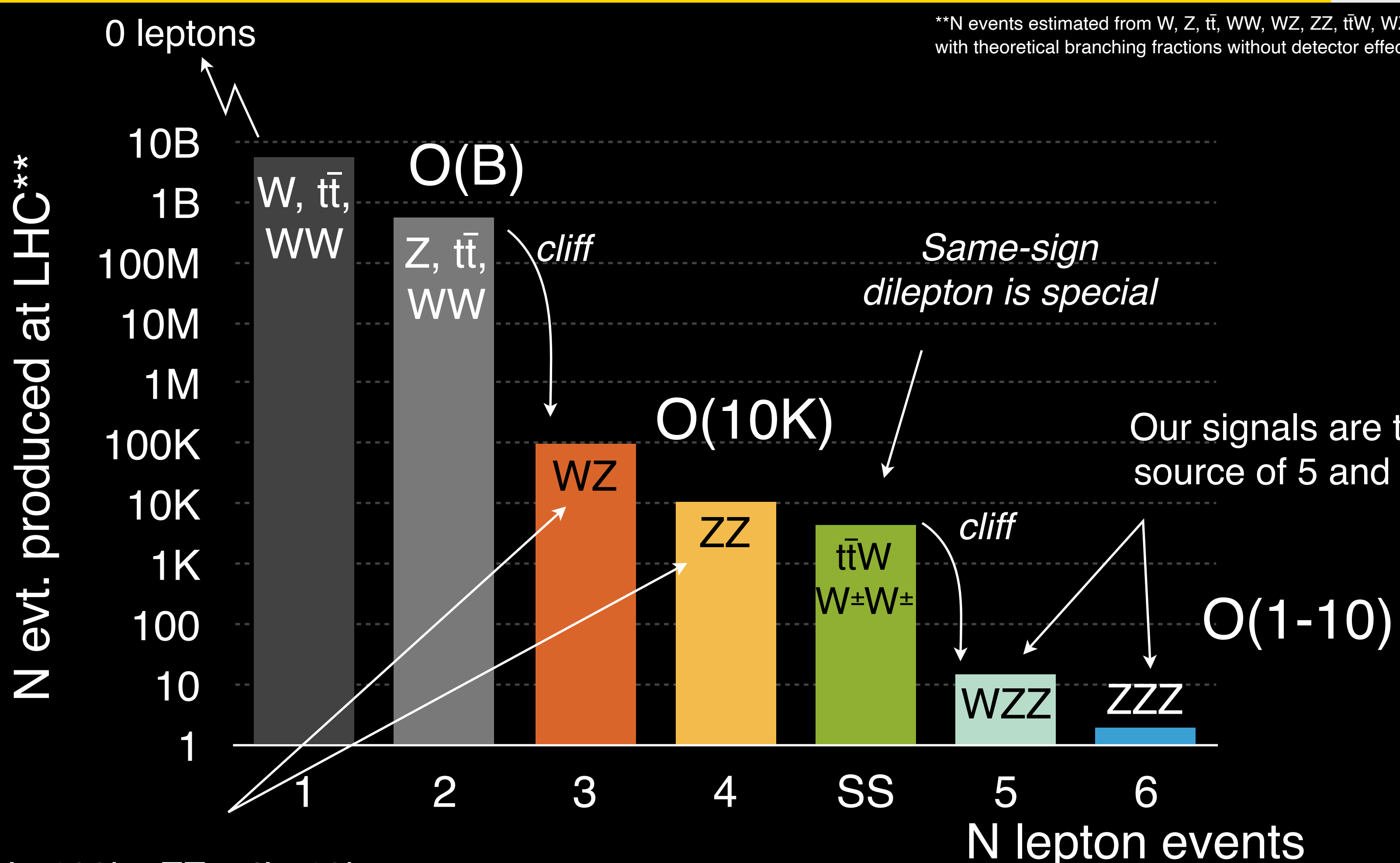
Dubbed “fake lepton”

Example


isolated lepton
non-isolated lepton
calorimeter
deposits

Lepton physics at the LHC

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



N.B. WZ→3l ~100k, ZZ→4l ~10k

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

Useful to organize physics analyses by N leptons

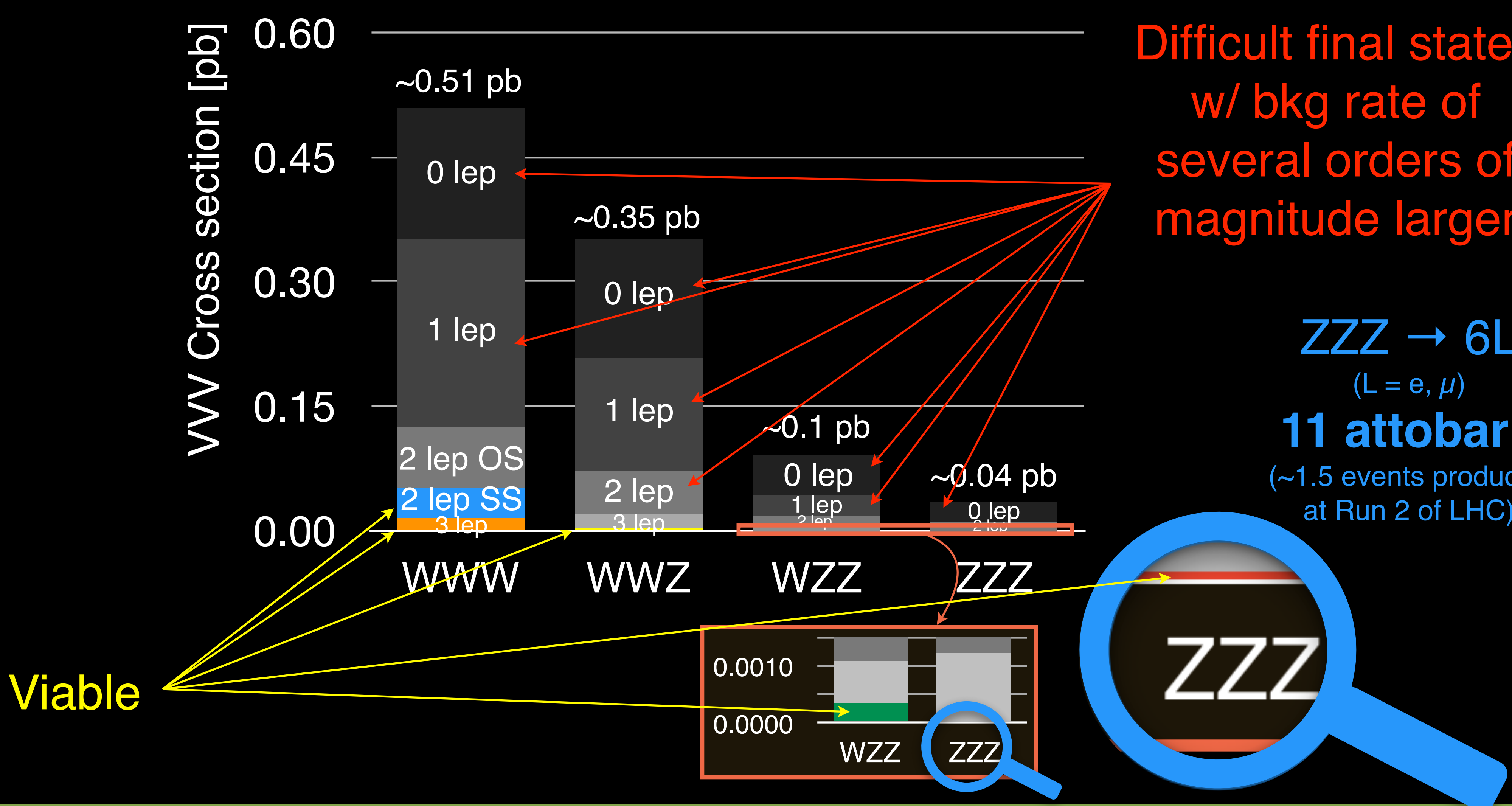
5 steps to VVV observation

1. Organize analyses by leptons (likely) from W / Z
    - N leptons in the event
    - Flavor of the leptons
2. Reject events with *b* jets
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)

VVV channels in # of leptons

Production cross section decreases with more Z's



ZZZ → 6L
(L = e, μ)
11 attobarn
(~1.5 events produced at Run 2 of LHC)

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

VVV analyses overview by N leptons

Chang
UCSD

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

One exception

Same-sign

	2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^\pm \to l^\pm \nu$ $W^\pm \to l^\pm \nu$ $W^\mp \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
	~2.5k evt.	~700 evt.	~140 evt.	~15 evt.	~1.5 evt.

Evt. # based on direct W, Z to e, μ decays
Numbers are higher if you add τ’s to e, μ

Different modes populate different N lepton bins

Some cross contamination between N lepton bins exist but is small

N.B. WZ→3l ~100k, ZZ→4l ~10k

We cover SS, 3, 4, 5, and 6 lepton final states

Backgrounds in each N lepton region

Chang
UCSD

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

N.B. WZ→3l ~100k, ZZ→4l ~10k

Once separated by N leptons dominant bkg. source becomes apparent

Backgrounds in each N lepton region

Chang
UCSD

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

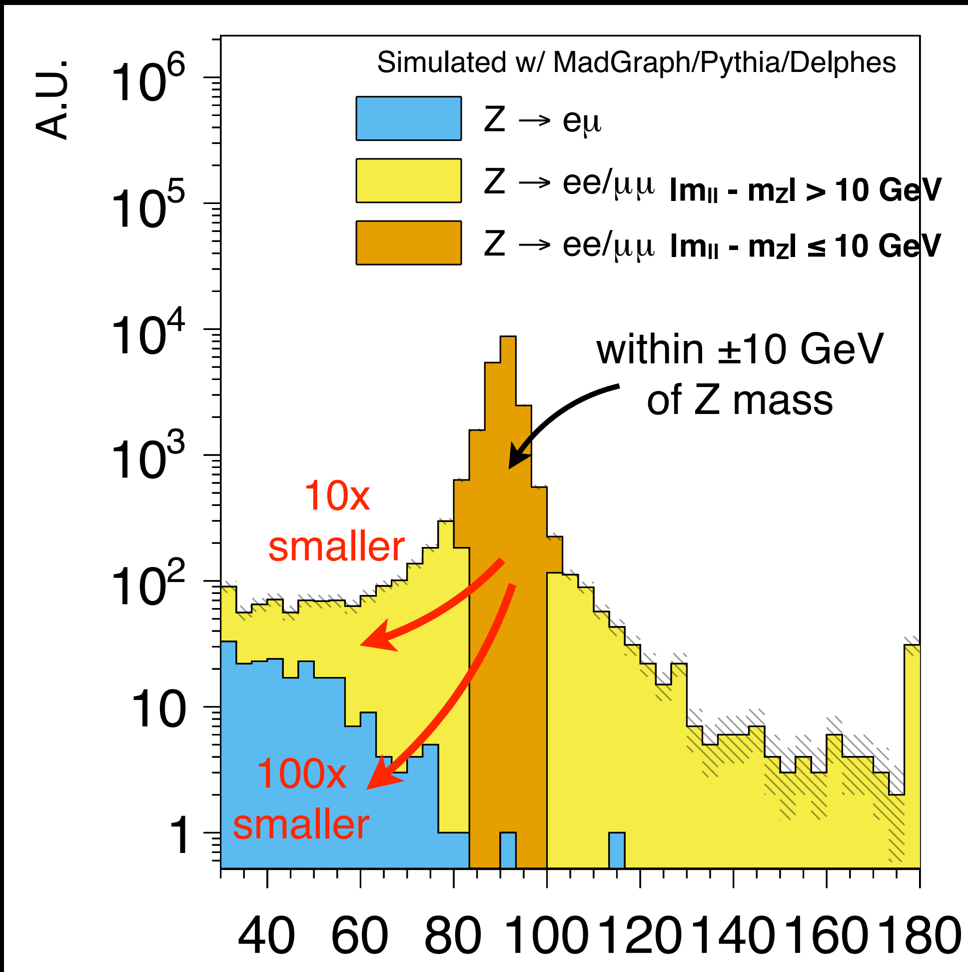
N.B. WZ→3l ~100k, ZZ→4l ~10k

Selection on flavor and b tag will further reduce bkgs.

Once separated by N leptons dominant bkg. source becomes apparent

Exploiting Z → ll features

dilepton invariant mass of Z → ll decay



m_{ll} [GeV]

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

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

⇒ *ZZ* suppressed in 4 leptons: ee/$\mu\mu$ + eμ
WZ suppressed in $e^{\pm}\mu^{\mp}e^{\pm}$

↑
0 “SFOS”
(Zero same-flavor opposite sign pair)

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

Splitting signal regions by lepton flavors

Chang
UCSD

	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^{\pm} \to l^{\pm}v$ $W^{\pm} \to l^{\pm}v$ $W^{\mp} \to qq$	$W \to lv$ $W \to lv$ $W \to lv$	$W \to lv$ $W \to lv$ $Z \to ll$	$W \to lv$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
	Split by ee/eμ/$\mu\mu$ N.B. μ is cleaner than e	Split by # of SFOS e.g. 0: $e^{\pm}\mu^{\mp}e^{\pm}$ 1: $e^{\pm}e^{\mp}\mu^{\pm}$ 2: $e^{\pm}e^{\mp}e^{\pm}$	tag Z→ll then split WW→ee/$\mu\mu$ v. WW→eμ	Not enough statistics single bin	
	3 categories*	3 categories	2 categories*	1 category	1 category

* marked ones will be further split

Each N lepton analyses are further split by flavors

~~5~~ steps to VVV observation

4

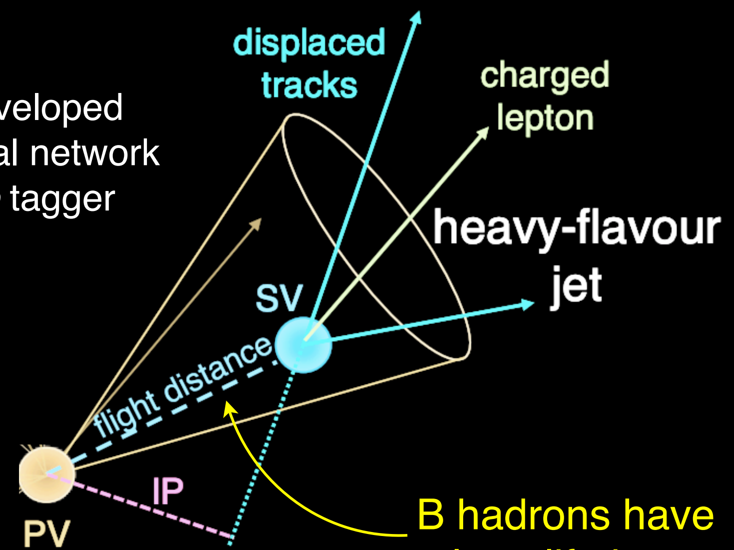
1. Organize analyses by “clean” leptons (likely) from W / Z
   - N leptons in the event
   - Flavor of the leptons
2. Reject events with *b* jets
3. Additional background suppression through smart choices
4. Reliably estimate the size of residual backgrounds
5. Observe VVV!

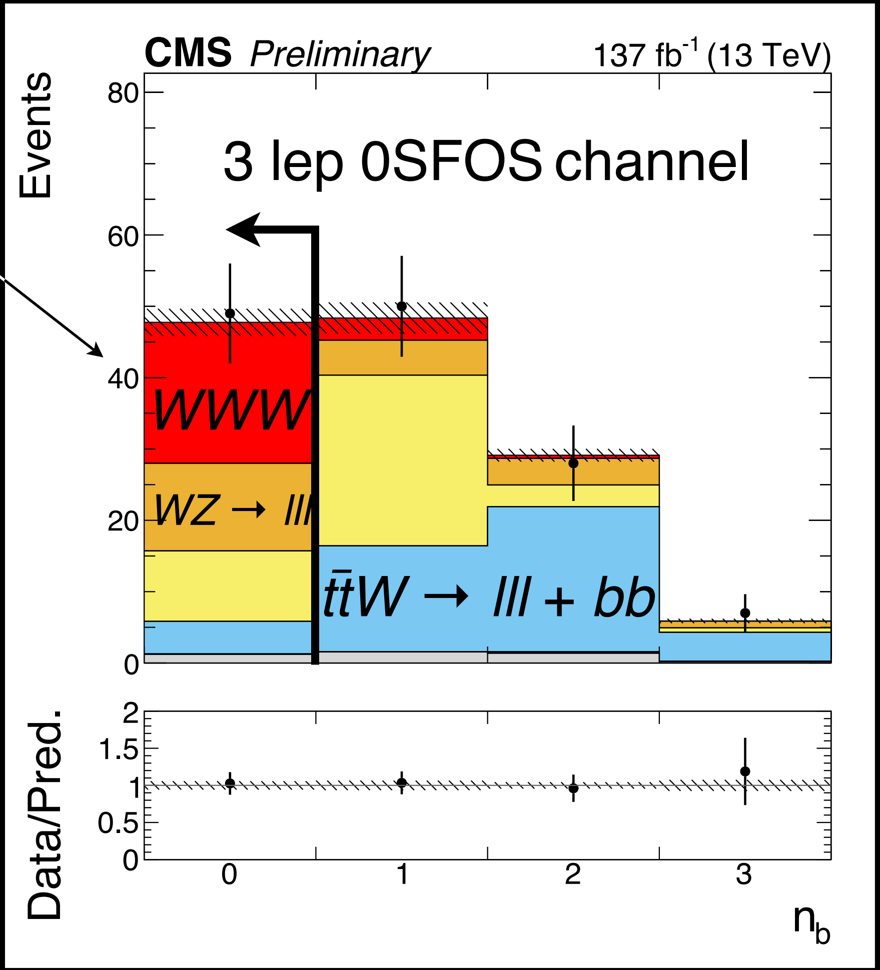
Smart humans and
smart machines
(Both cut / BDT)

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

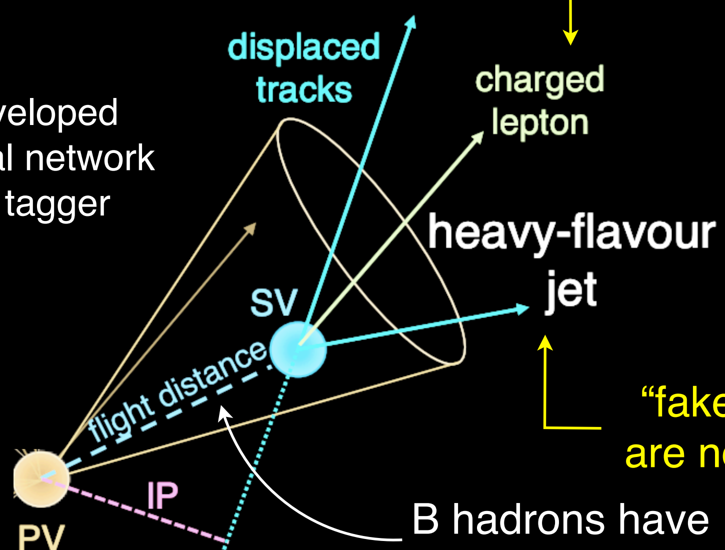
Added benefit of rejecting events with b

Chang
UCSD

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

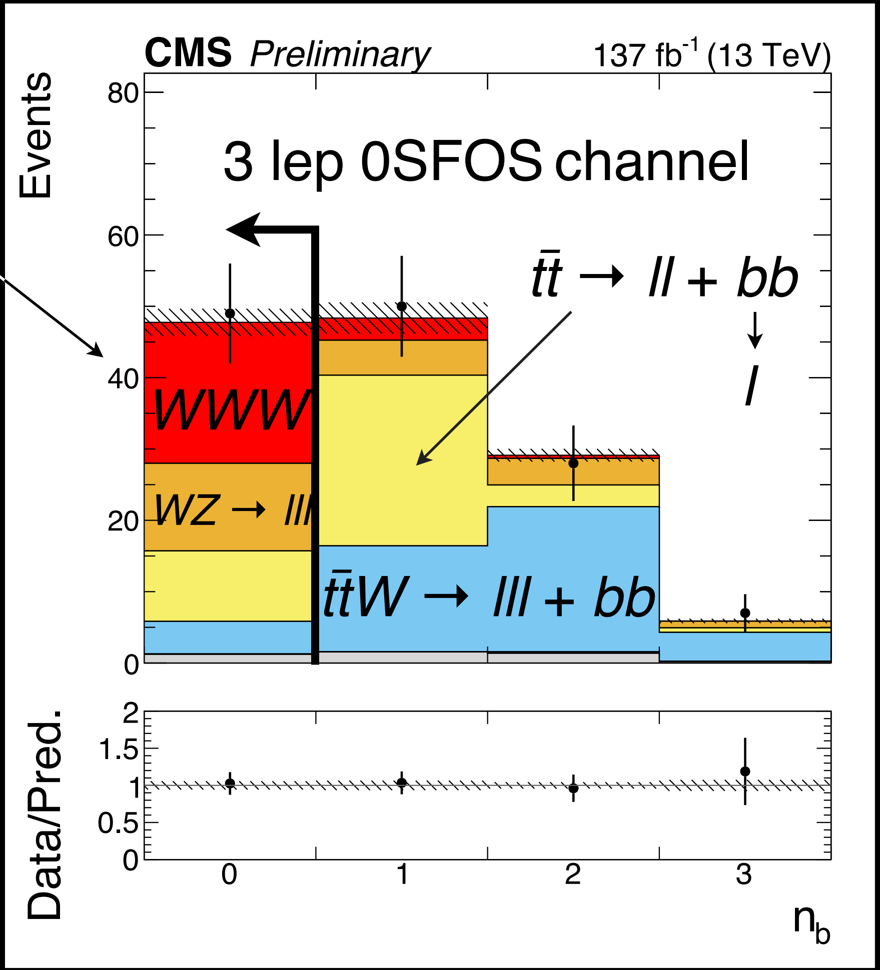
Lepton from b decay is the main source of “fake"

CMS developed deep neural network based *b* tagger



“fake" leptons are not isolated

B hadrons have long lifetime



Signals do not have *b* jets

~~5~~ steps to VVV observation

Chang
UCSD

~~4~~

3

1. Organize analyses by “clean” leptons (likely) from W / Z
   - N leptons in the event
   - Flavor of the leptons
2. Reject events with *b* jets
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)

Event selections

Chang UCSD

same-sign selection

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

Three leptons selection

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

Four leptons 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, ∞)	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV
m_{T2}	$m_{T2} > 25$ GeV (for $m_{\ell\ell} > 100$ GeV)	...
$p_{T,4\ell}$ and p_T^{miss}	...	No $p_{T,4\ell}$ cuts and $p_T^{miss} > 120$ GeV (Bin A) $p_{T,4\ell} > 70$ GeV and $70 < p_T^{miss} < 120$ GeV (Bin B) $40 < p_{T,4\ell} < 70$ GeV and $70 < p_T^{miss} < 120$ GeV (Bin C)

5/6L will be explained later

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

Event selections

Chang
UCSD

same-sign selection

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

Split by N leptons
and requiring “Tight” leptons

Three leptons selection

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

Split by channels

Four leptons selection

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

5/6L will be explained later

But already you can notice a few things

Event selections

Chang
UCSD

same-sign selection

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

Three leptons selection

Variable	0 SFOS	1 and 2 SFOS
Trigger	Signal triggers, tab. 3.2	
Signal leptons		±1e 0 GeV
Additional leptons		0 GeV
m_{SFOS}		
$m_{\ell\ell\ell}$		
SF lepton mass		
Dielectron mass		
Jets		
b-tagging		cts
$\Delta\phi\,(\vec{p}_T(\ell\ell\ell), \vec{p}_T^{\,miss})$	—	>2.5
$p_T(\ell\ell\ell)$	—	$>50\,\mathrm{GeV}$
m_T^{3rd} (1 SFOS) or m_T^{max} (2 SFOS)	—	$>90\,\mathrm{GeV}$

- Split by number of jets
- Dijet invariant mass: m_{jj}
- Transverse mass: m_T
- "S"transverse mass: m_{T2}
- Missing transverse energy

Four leptons selection

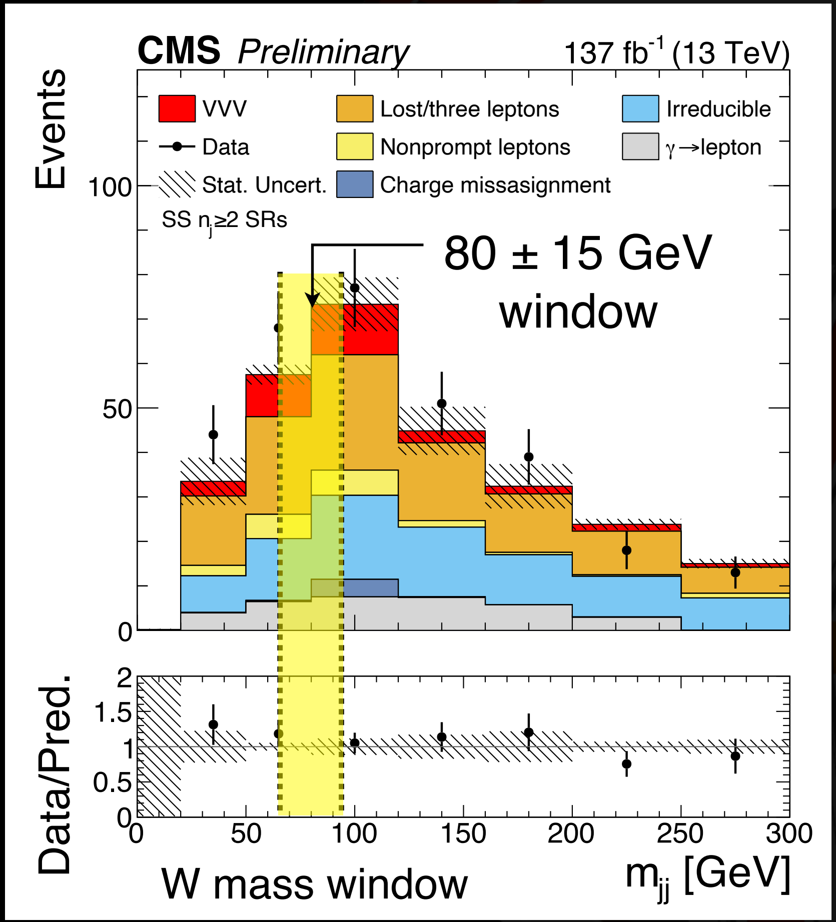
Variable	$e\mu$ category	$ee/\mu\mu$ category
Preselection	Selections in Table 20	
W candidate lepton flavors	$e\mu$	$ee/\mu\mu$
$m_{\ell\ell}$	Separated into 4 bins in $(0, 40, 60, 100, \infty)$	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\mathrm{GeV}$
m_{T2}	$m_{T2} > 25\,\mathrm{GeV}$ (for $m_{\ell\ell}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

5/6L will be explained later

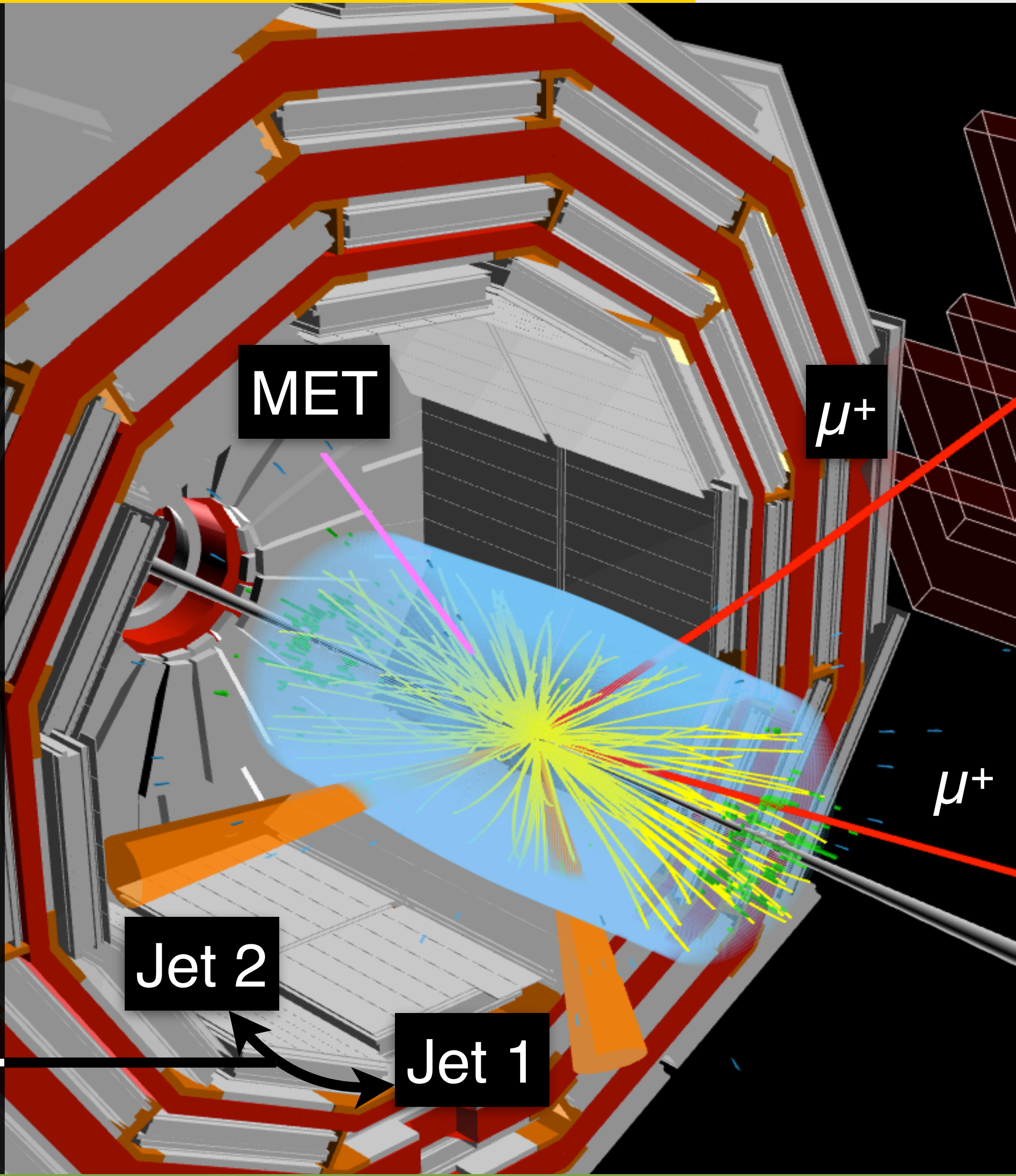
But I will highlight these 5 points in the coming slides

Reconstruct W→qq in WWW → l±l±qq

Chang
UCSD

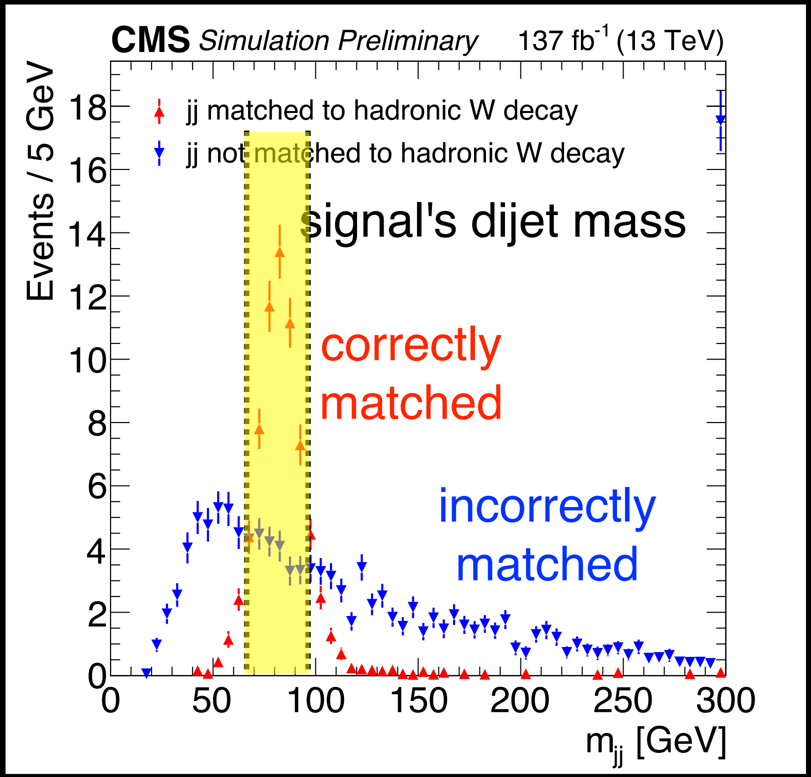


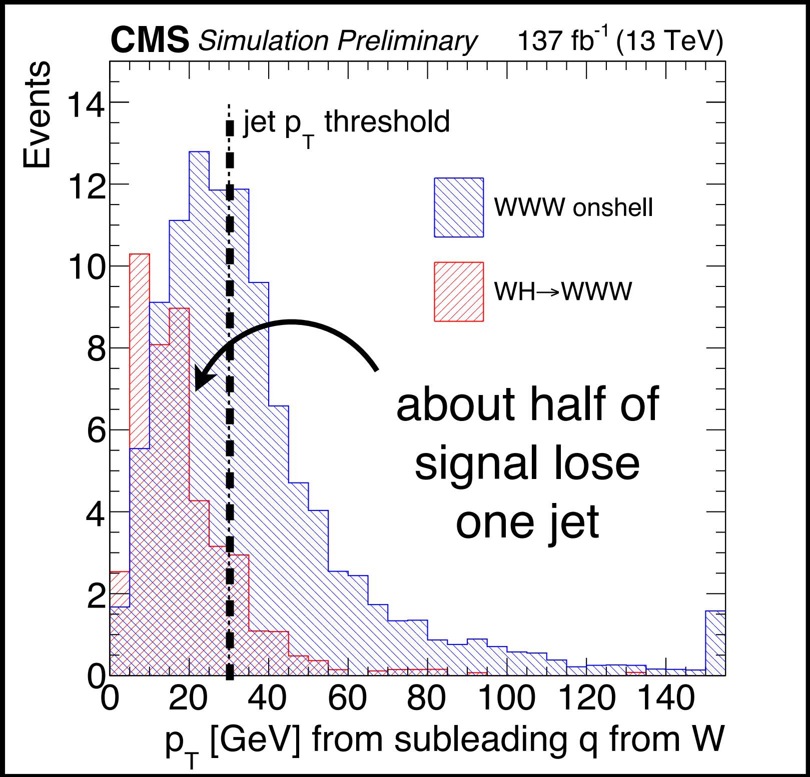
N.B. some signals are outside the window (See next slide)



dijet invariant mass for signal peaks around W mass

Difficulties in jet final states





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

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

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

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

Kinematic endpoints for 3 leptons

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

Separated by # of SFOS pairs:

- 0 SFOS (low bkg.)
- 1 SFOS
- 2 SFOS

0SFOS is by far the cleanest

For 1SFOS it is clear which one is from W:

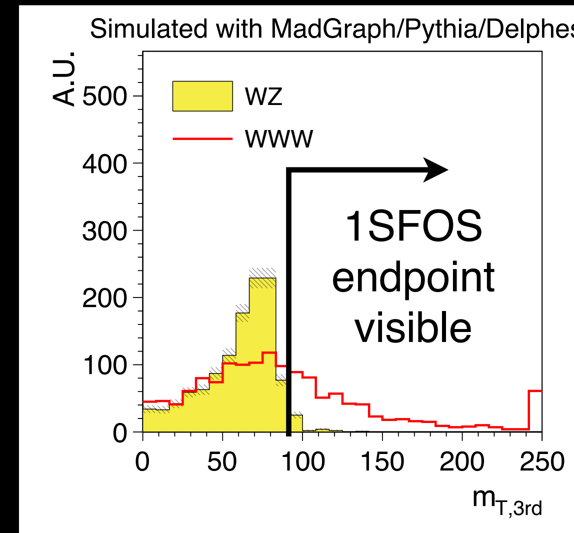
$\underbrace{e^\pm e^\mp}_{Z}\ \underbrace{\mu^\pm}_{W} \qquad \underbrace{\mu^\pm\mu^\mp}_{Z}\ \underbrace{e^\pm}_{W}$

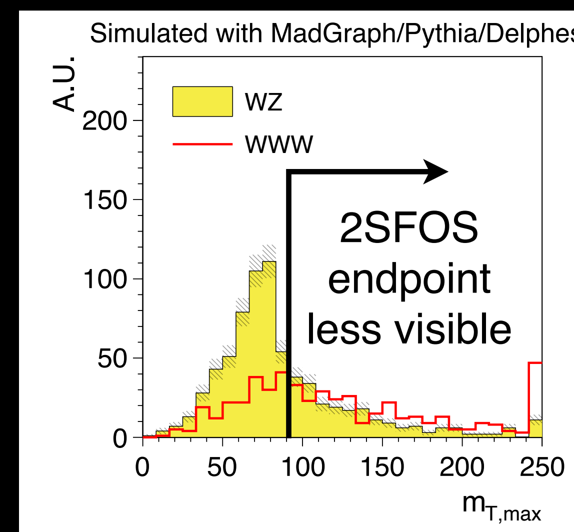
For 2SFOS it is less clear which one is from W:

$\underbrace{e^\pm}_{W?}\ \underbrace{e^\mp\ e^\pm}_{W?} \qquad \underbrace{\mu^\pm\ \mu^\mp}_{W?}\ \underbrace{\mu^\pm}_{W?}$

Take max m_T computed from either leptons

⇒ 3 signal regions for 3 leptons





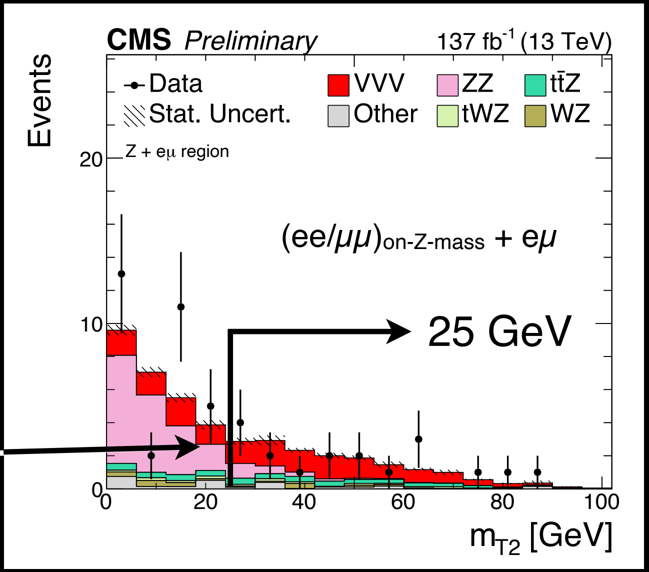
By flavor, W lepton can be identified and kinematic endpoints can be used

Kinematic endpoints for 4 leptons

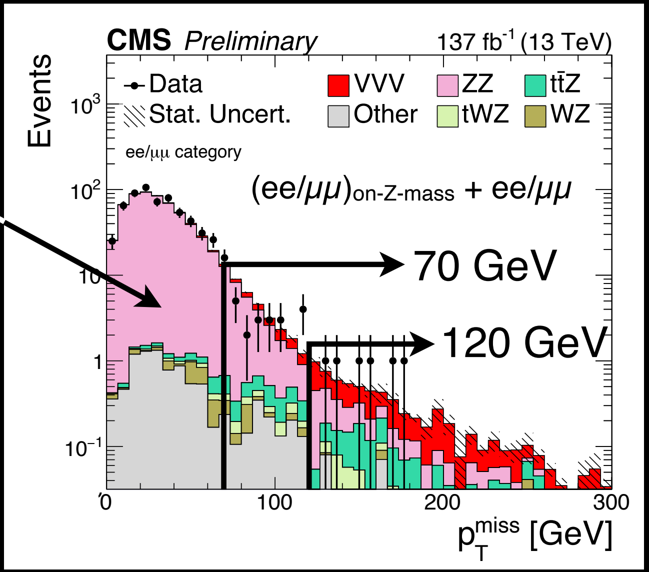
Events are separated into 2 categories by flavor:

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

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



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

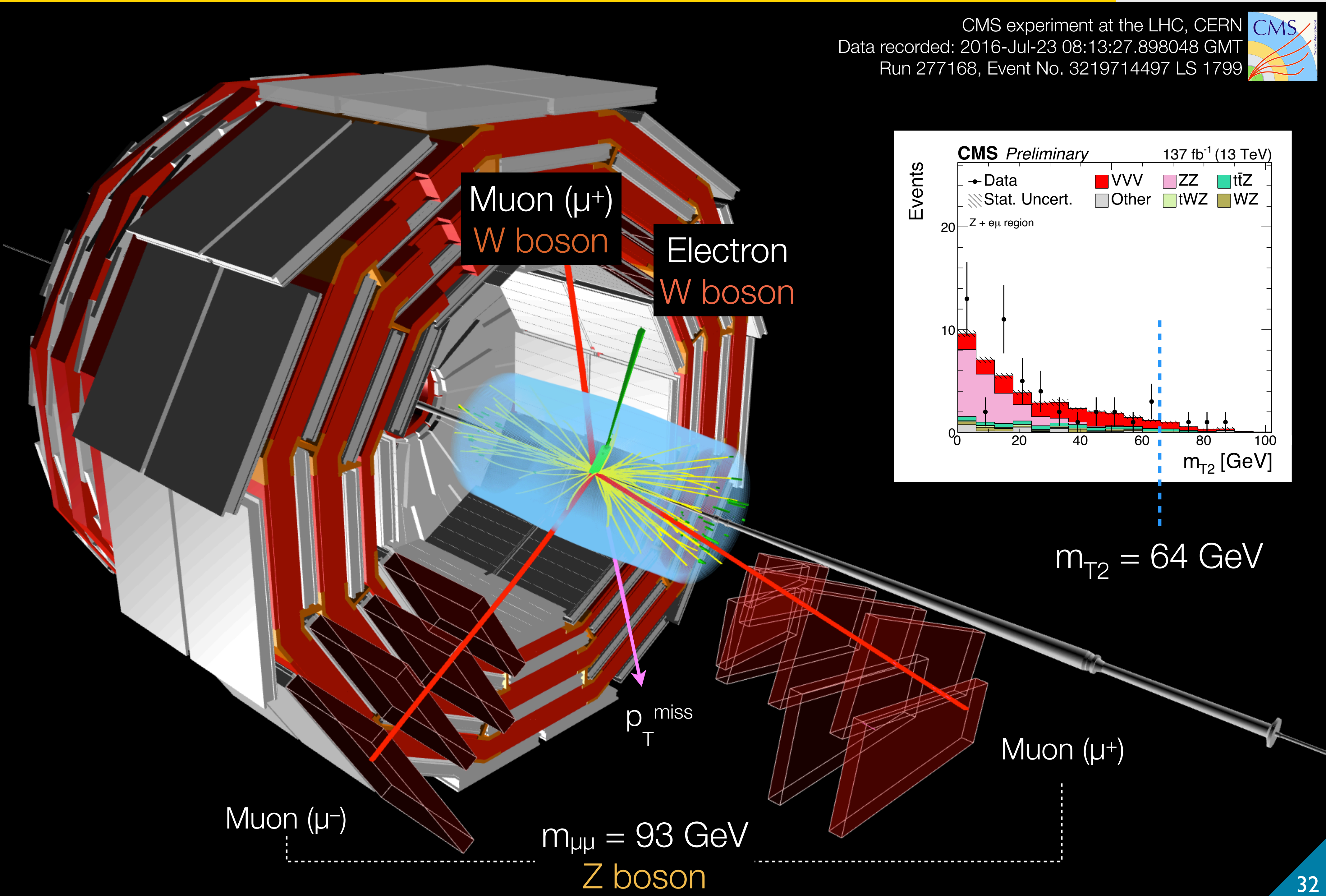


Combine these and a few more kinematic variables to form total of 7 signal regions for 4 lepton analysis

Exploit differences between $Z \to ll$ v. $WW \to l\nu l\nu$

4 lepton event

Chang
UCSD



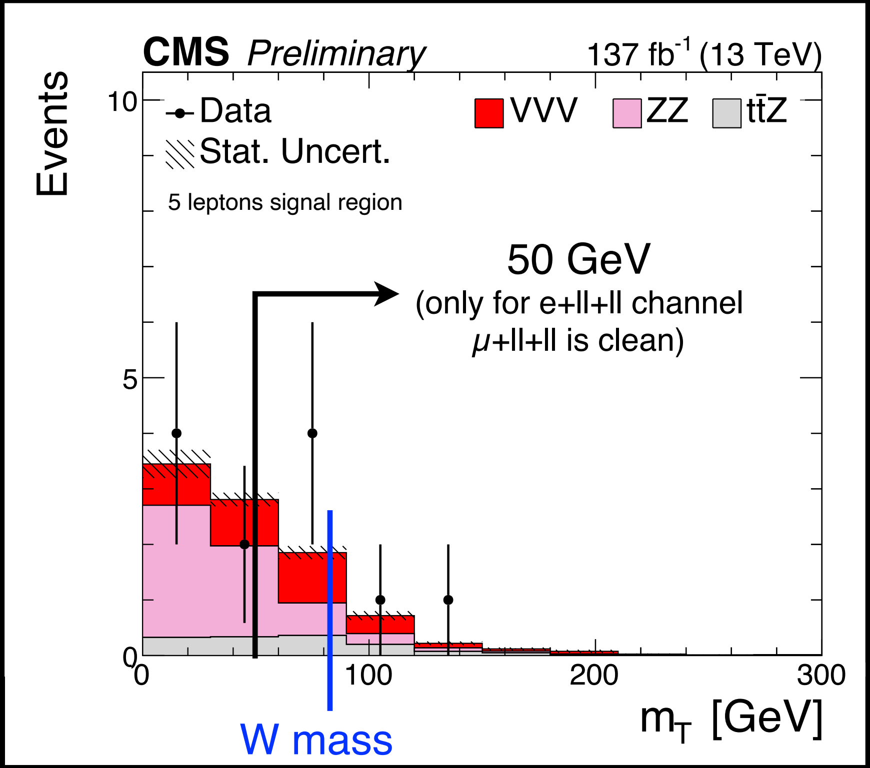
5 leptons

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

The dominant background is ZZ → llll plus a fake lepton

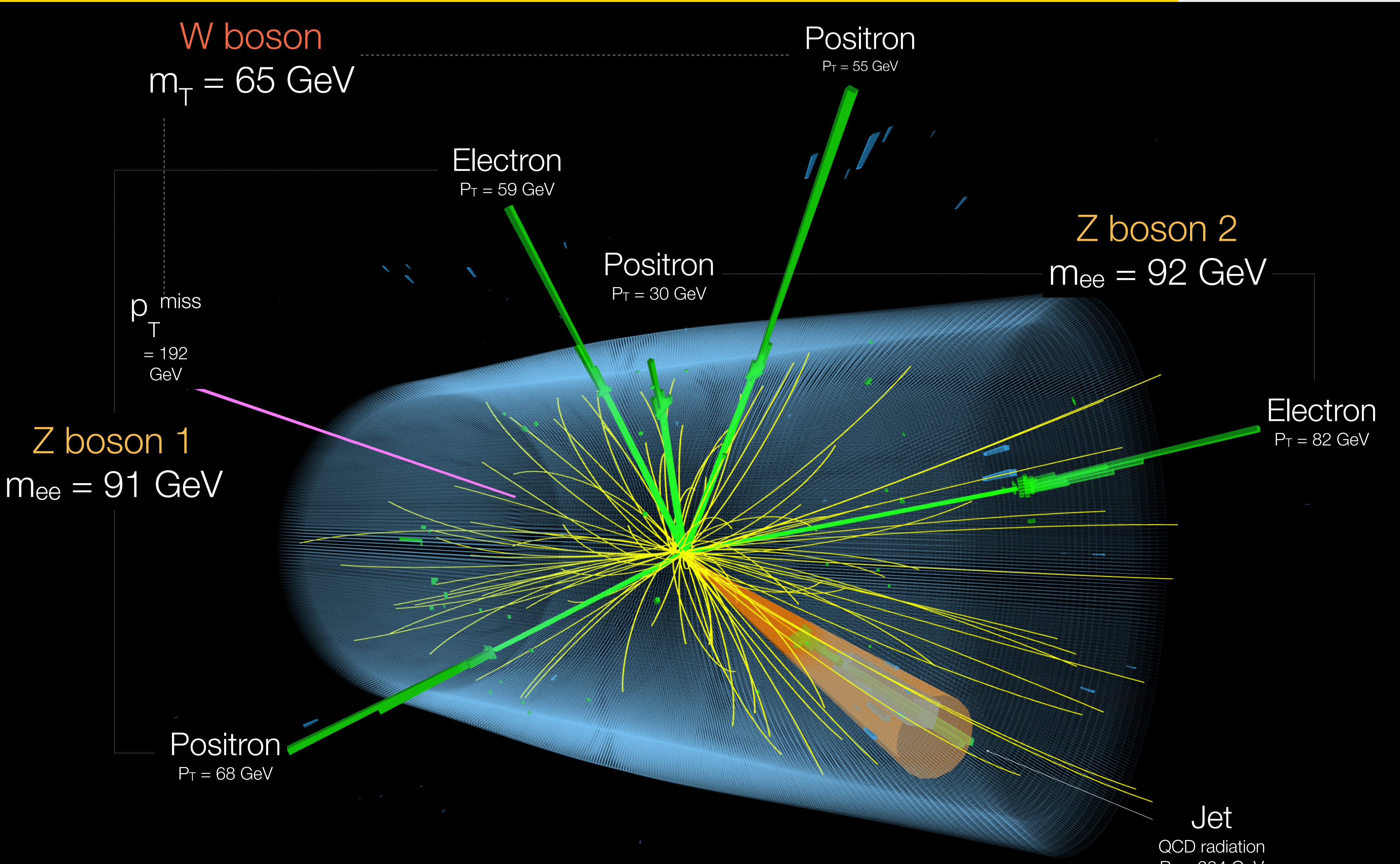
The fake lepton has low transverse mass while the signal's W has transverse mass peaking at W mass

Cut-and-count of one bin



Exploit the features of W → lν decay

5 lepton event



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

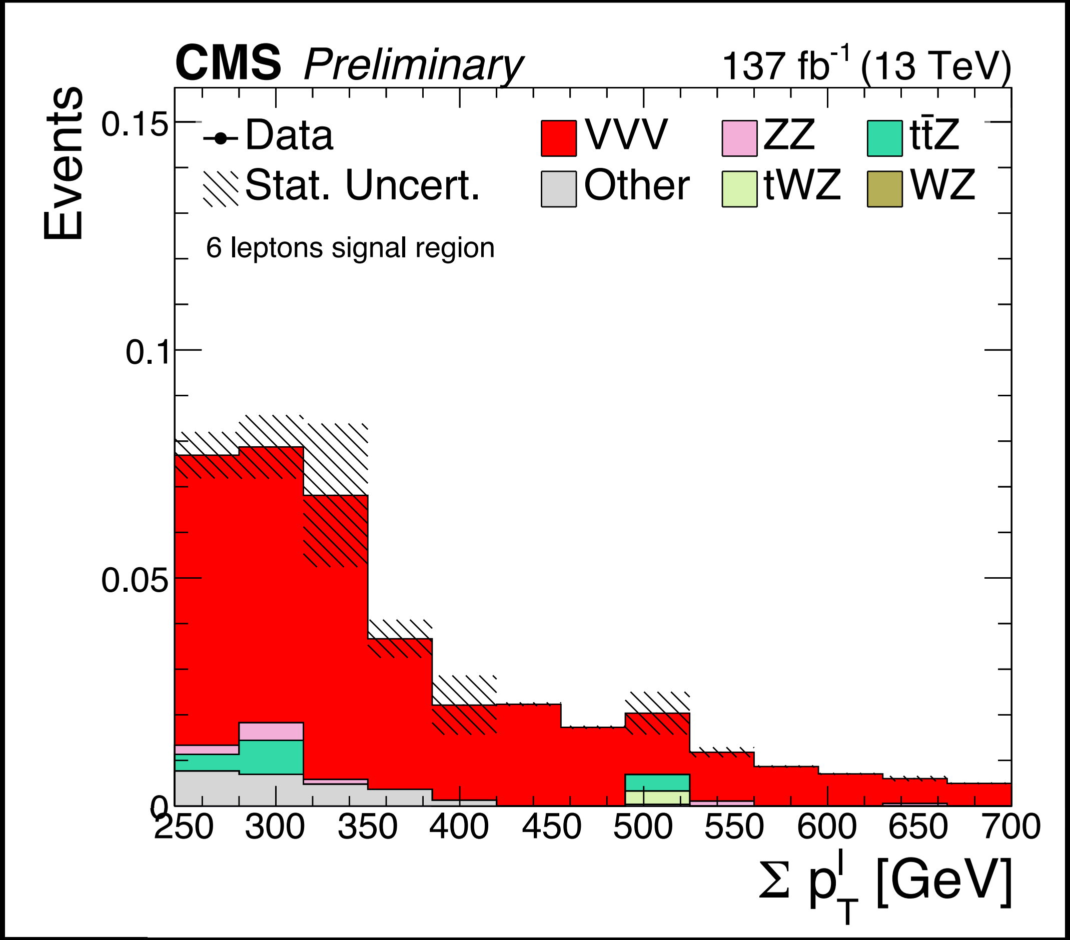
6 leptons

Select at least 6 leptons

Require $\Sigma P_T \geq 250$ GeV

Less than 1 event expected

Very clean channel



Not enough stats, so search inclusively

~~5~~ steps to VVV observation

~~4~~

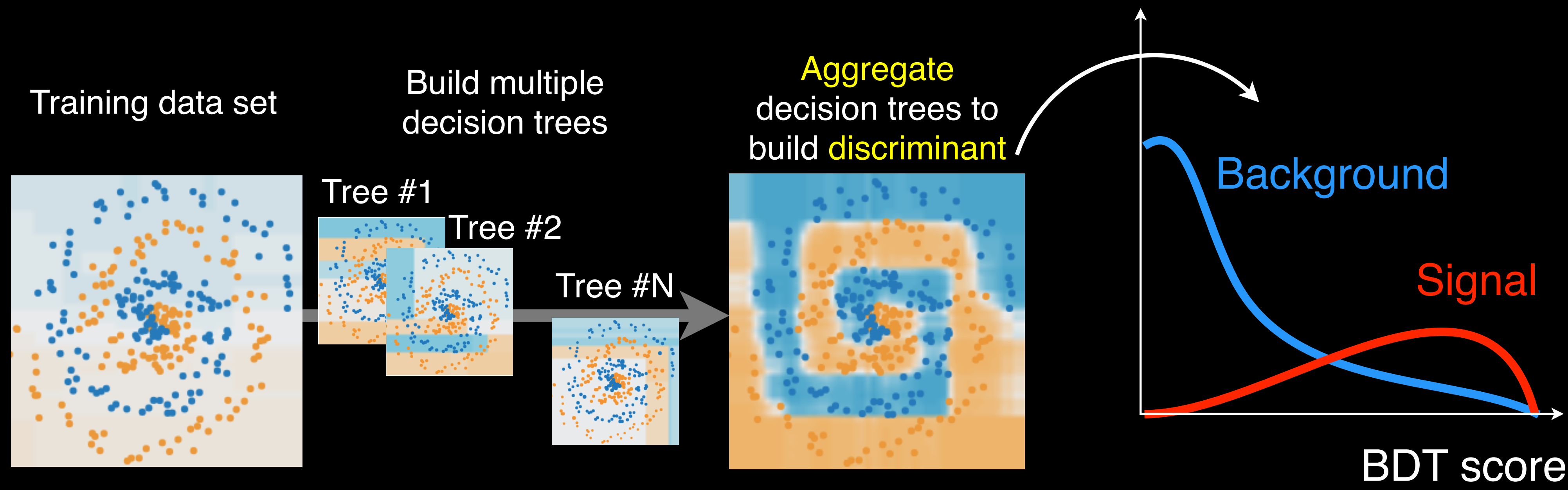
3

1. Organize analyses by "clean" leptons (likely) from W / Z
    - N leptons in the event
    - Flavor of the leptons
2. Reject events with *b* jets
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)

Boosted decision tree

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



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

Train dedicated boosted decision trees to maximize sensitivity

Overview of BDT

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

"Prompt" bkgs.

"Fake" bkgs.

$t\bar{t}Z$ bkg.

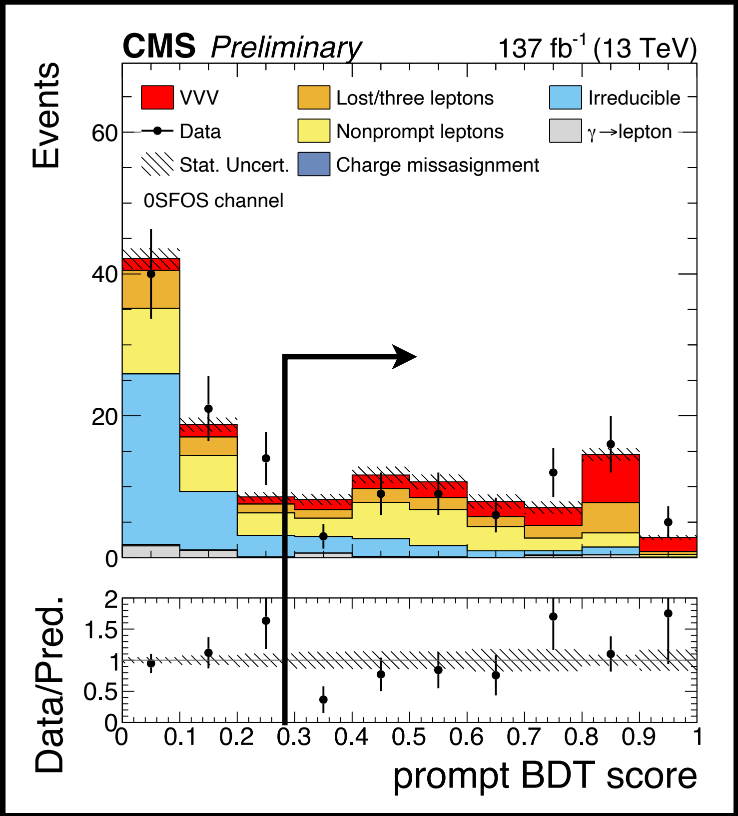
ZZ bkg.

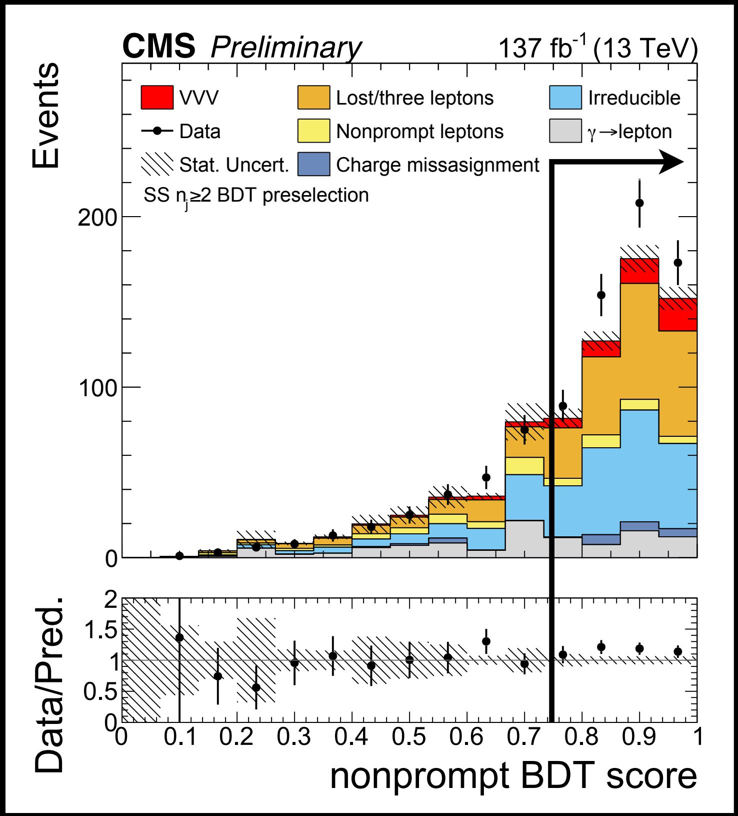
No BDT trained for 5/6 leptons (not enough stats)

Train different BDTs against different backgrounds

WWW BDTs: SS / 3 leptons

Chang
UCSD





Maintained same categorizations but cut on BDT to maximize sensitivity

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

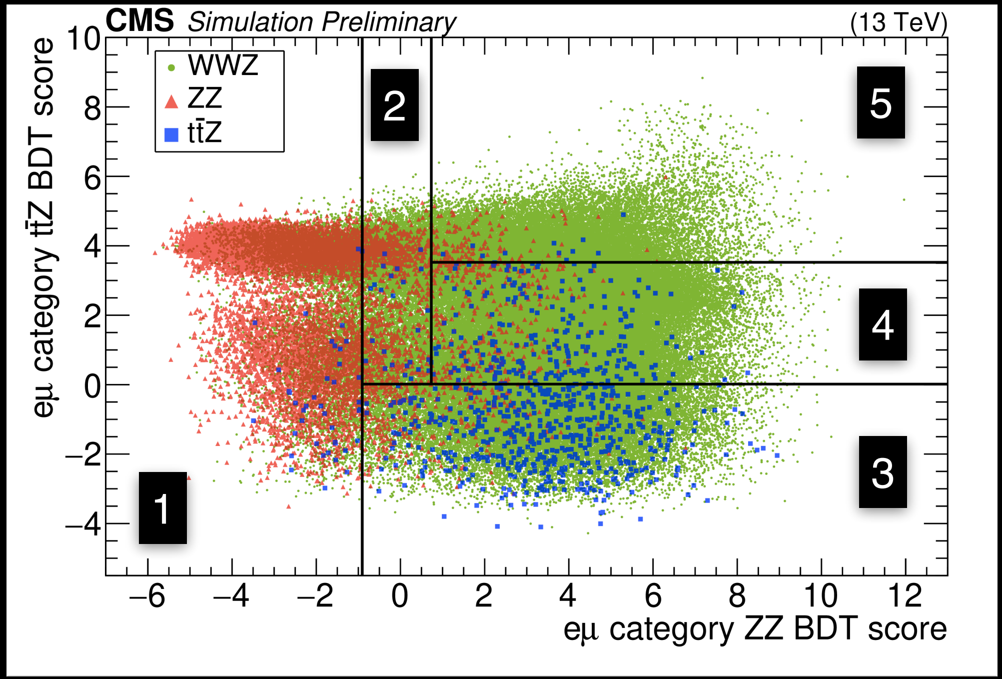
Cut on each BDT scores to create a high sensitivity bin

WWZ BDTs for 4 leptons analysis

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

More
WWZ like

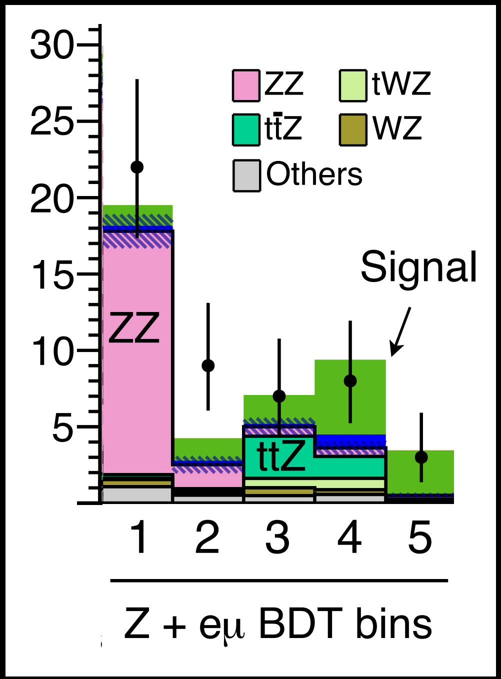
More
$t\bar{t}Z$ like



More
ZZ like

More
WWZ like

5 bins are created
from 2D planes



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

Created multiple bins in BDTs to maximize sensitivity

~~5~~ steps to VVV observation

Chang
UCSD

~~4~~

~~3~~ 2

1. Organize analyses by “clean” leptons (likely) from W / Z
   - N leptons in the event
   - Flavor of the leptons
2. Reject events with *b* jets
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)

Now two steps left

Background estimations

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

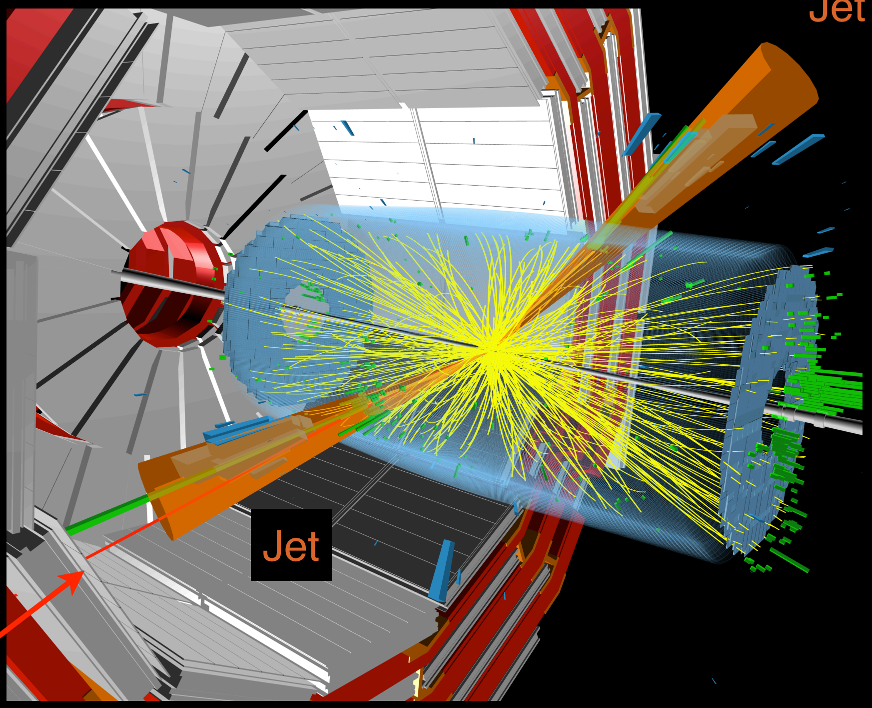
Types of backgrounds	Suppressed via	Bkg. estimation
Fake leptons	Isolation	Reliably extrapolate across isolation
Backgrounds with *b* jets	*b* tagging	Reliably extrapolate across *b* tagging
Lost leptons	Removing events with 3rd lepton	Reliably extrapolate across N leptons
Irreducible	Smart flavor choices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

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

Fake lepton backgrounds

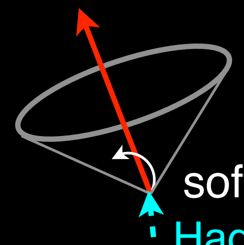
Chang
UCSD

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

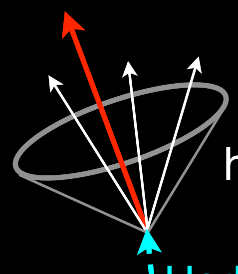


Fake rate =

Well isolated “fake” lepton (“tight”)



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



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

"Side band" in isolation

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

⇒ Source of systematics (~30%)

Estimate fake lepton by measuring fake rate from QCD events

Lost lepton background

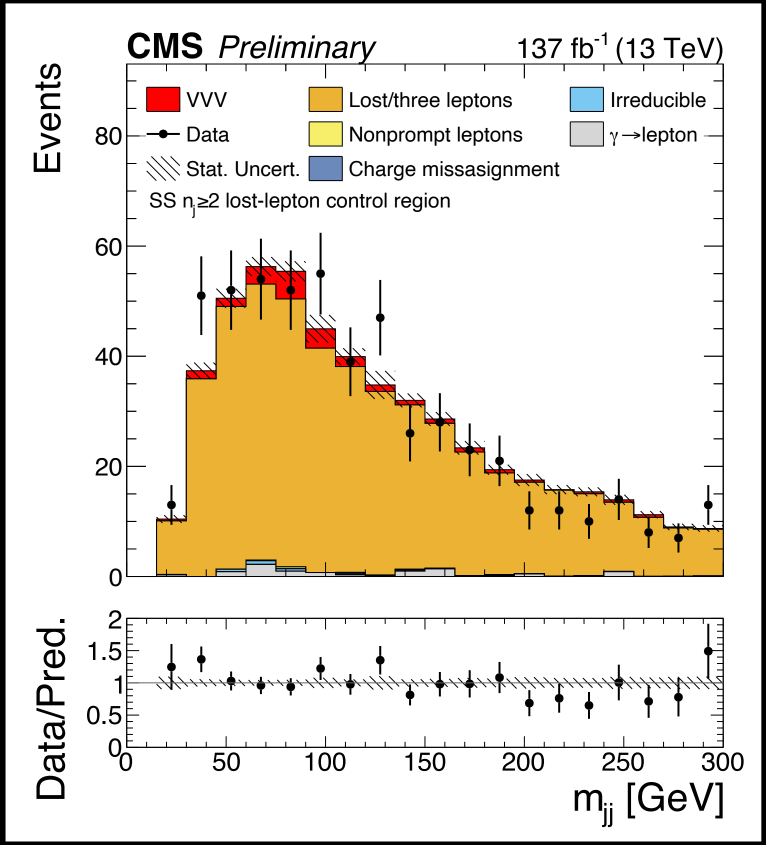
Lepton finding efficiency is well modeled by MC

(factors: P_T, η, lepton ID)

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

Experimental systematics assigned

Control region data statistics dominates uncertainty (20%)

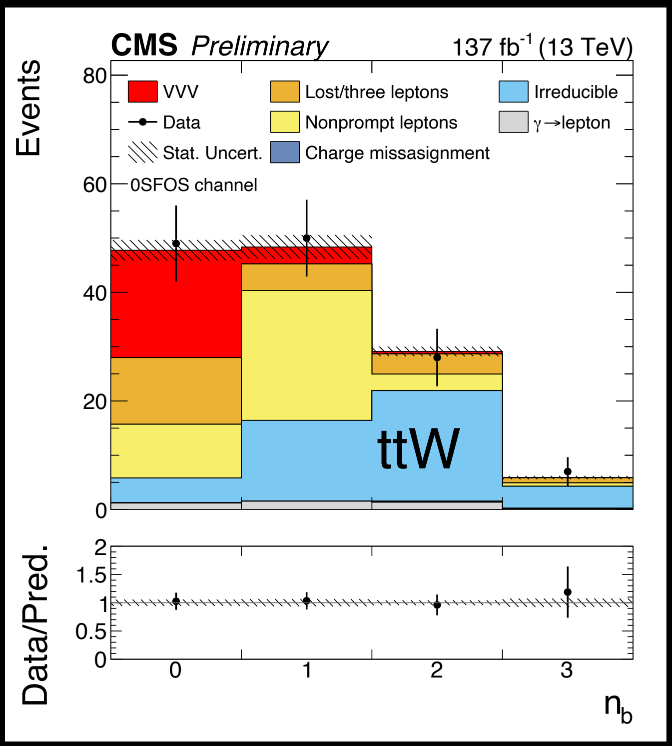


Estimate lost lepton background by extrapolating across # of leptons

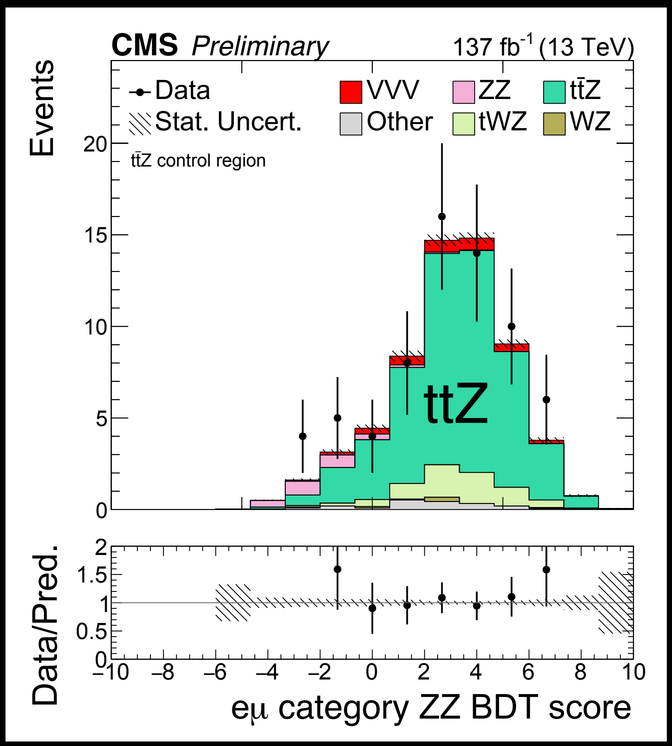
Backgrounds with *b* jets / irreducible

Devise control regions and extrapolate to signal region

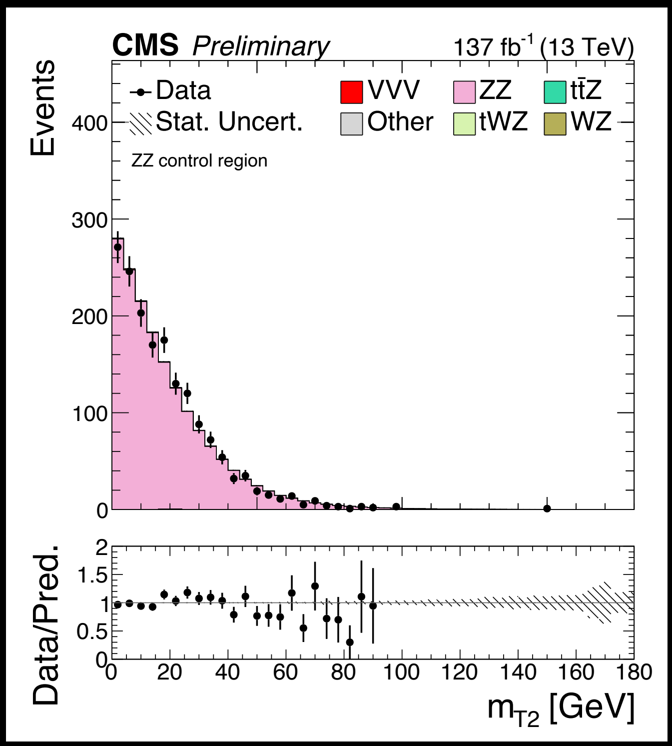
N_b in 3 lepton



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



4 lepton m_{T2}
Z→ll + ee/*μμ*



Extrapolate across N_b tag (~10%)

Extrapolate across flavor
(uncertainty ~5%)

Extrapolate from control region to estimate backgrounds

Putting it all together

Chang
UCSD

	Same-sign 2 leptons	3 leptons	4 leptons	5 leptons	6 leptons
Signals	$W^{\pm} \to l^{\pm}\nu$ $W^{\pm} \to l^{\pm}\nu$ $W^{\mp} \to qq$	$W \to l\nu$ $W \to l\nu$ $W \to l\nu$	$W \to l\nu$ $W \to l\nu$ $Z \to ll$	$W \to l\nu$ $Z \to ll$ $Z \to ll$	$Z \to ll$ $Z \to ll$ $Z \to ll$
Split Flavor	3	3	2	1	1
Channel specific splits	mjj-in mjj-out 1J	-	Split in kinematics or BDT	-	-
Total	9 bins	3 bins	7 bins	1 bin	1 bin

Total of 21 bins

~~5~~ steps to VVV observation

Chang
UCSD

~~4~~

~~3~~ ~~2~~ 1

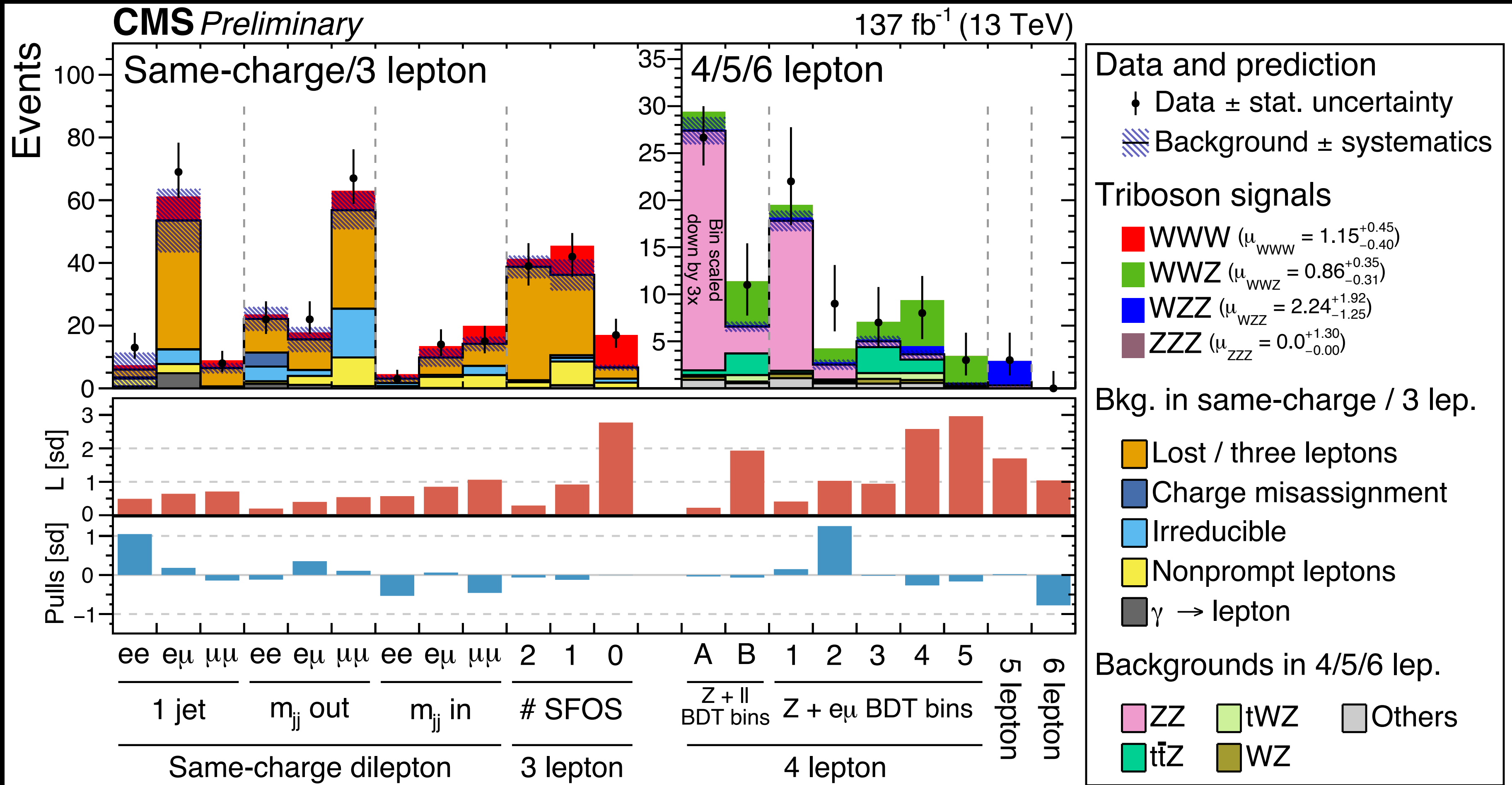
1. Organize analyses by "clean" leptons (likely) from W / Z
    - N leptons in the event
    - Flavor of the leptons
2. Reject events with *b* jets
3. Additional background suppression through smart choices
4. Reliably estimate the size of residual backgrounds
5. Observe VVV!

Let's observe!

Results (BDT-based analysis)

Chang
UCSD

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



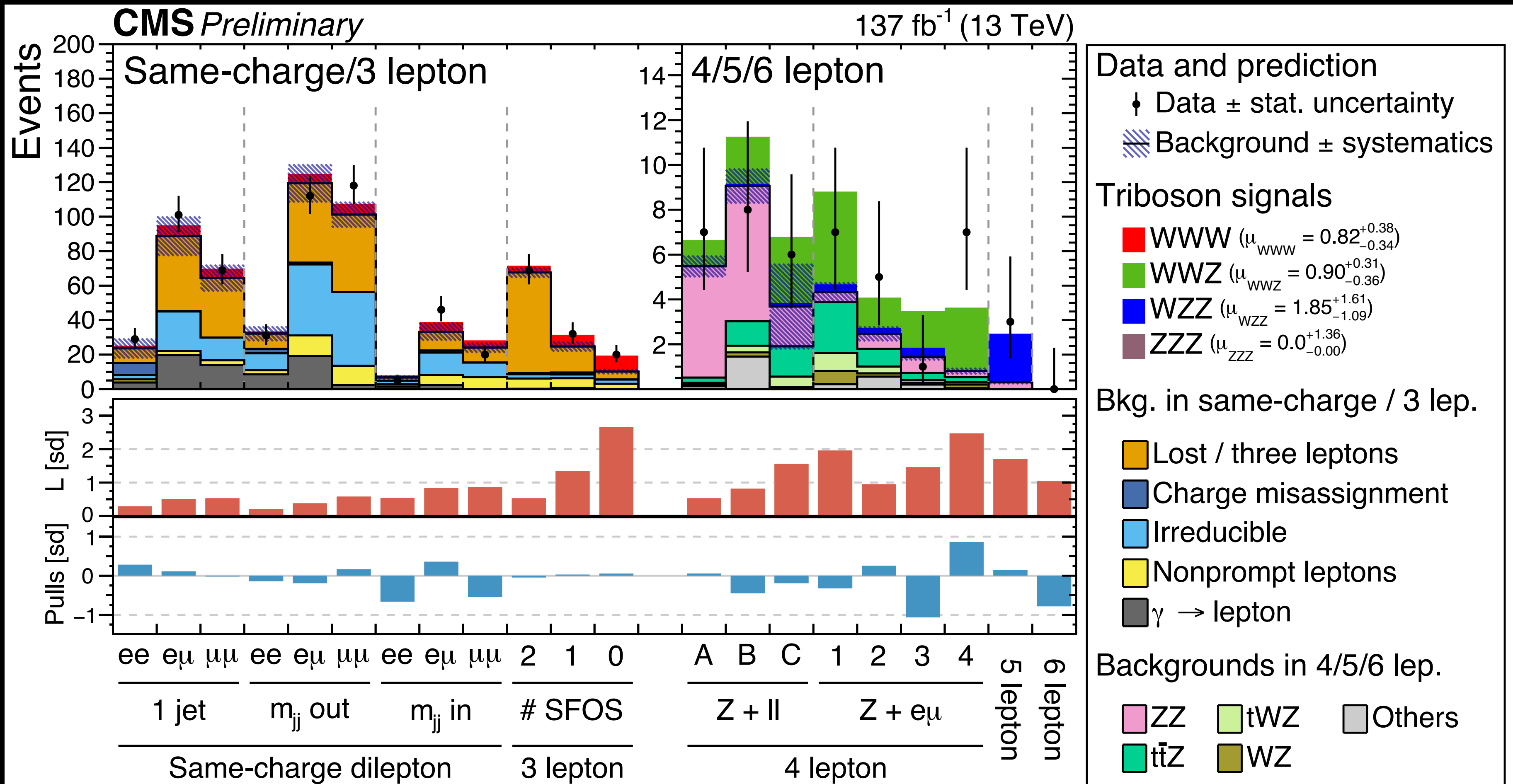
9 bins 3 bins 7 bins 1 1

More sensitive bins are generally to the right

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

Results (Cut-based analysis)

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



9 bins 3 bins 7 bins 1 1

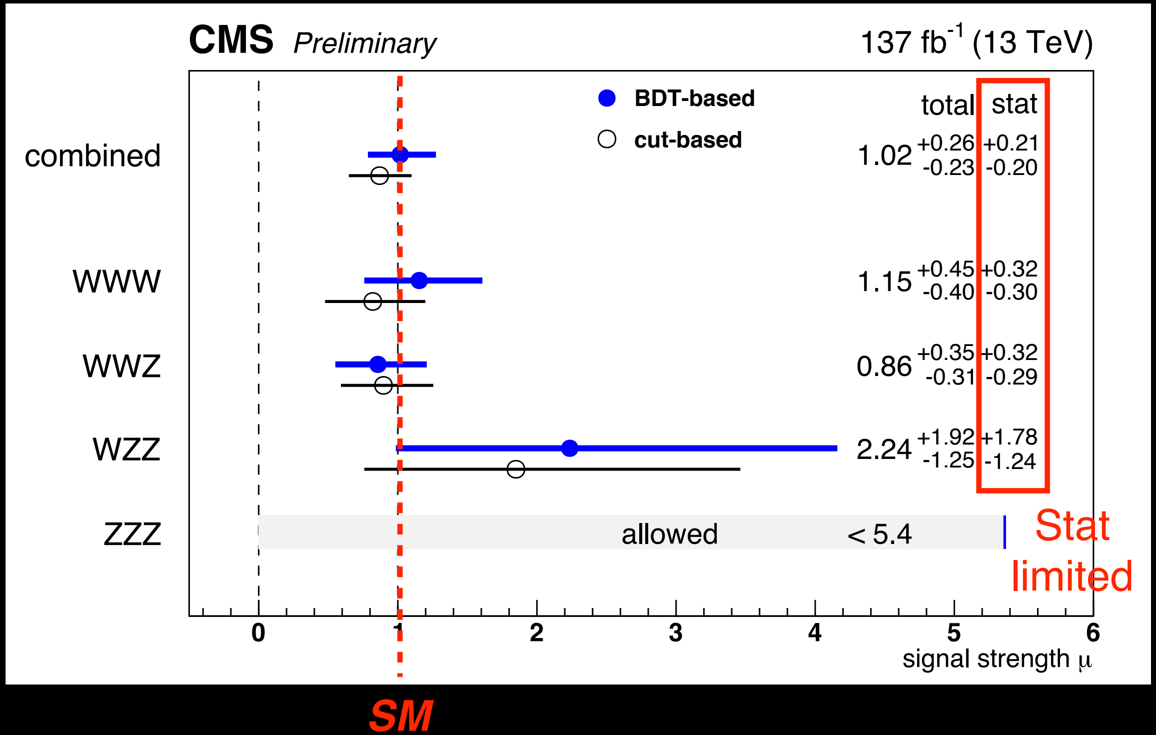
More sensitive bins are generally to the right

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

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

Results

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



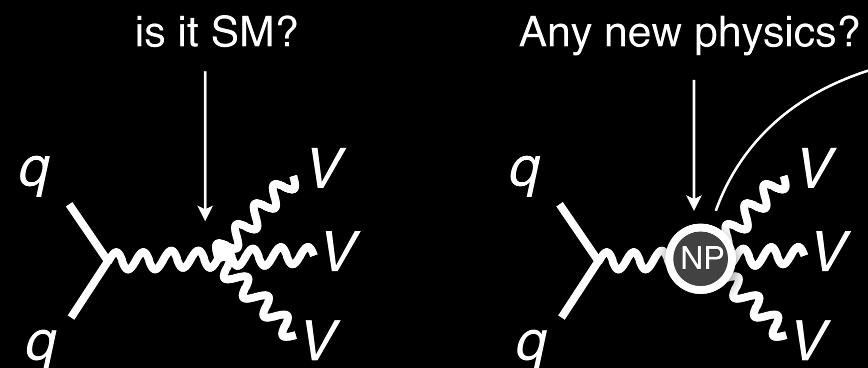
$$\text{Signal strength } \mu = \frac{\text{Measured cross section}}{\text{Theoretical cross section}}$$

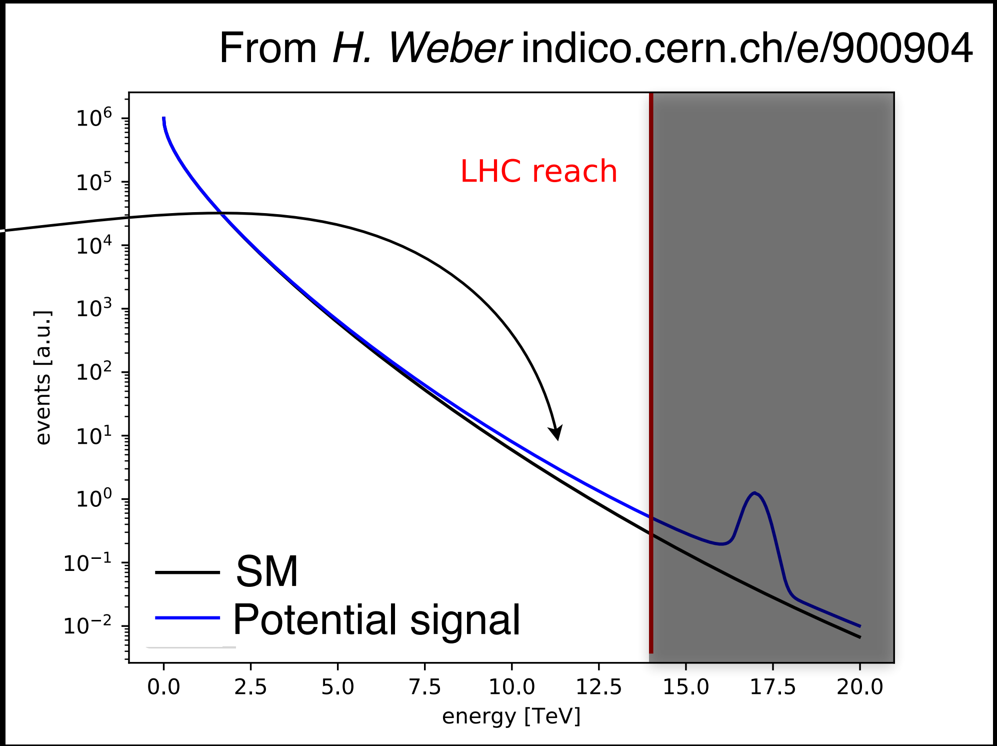
- We have observed production of three massive gauge boson for the first time!
- We also found evidences separately for the WWW and WWZ production.
- The cross sections are compatible with the standard model expectation.

First observation of VVV and evidences for WWW and WWZ productions

Using VVV as a tool

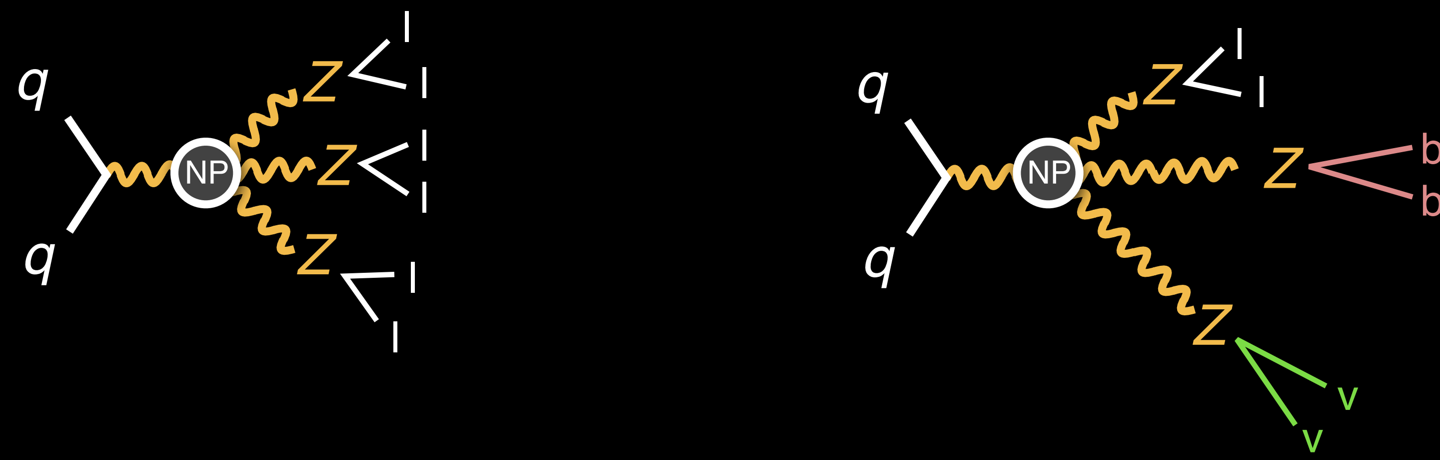
Now that we have established VVV production we can use it to test SM and also search new physics (cf. Four fermion interaction with Fermi constant)





Establishment of VVV production opens up a new physics program

Fully leptonic v. Semi leptonic channel



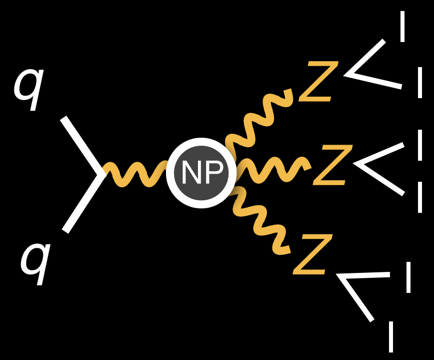
If BSM exists, effects are same

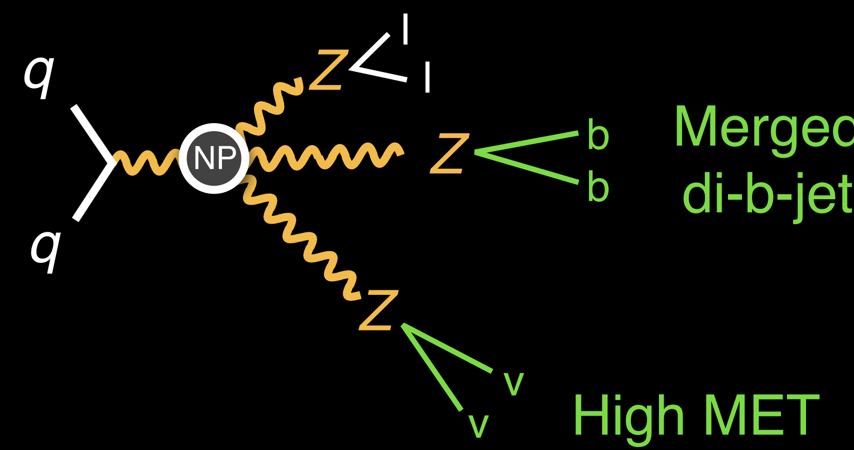
- Physics of V → ff is well understood
- We have now established pp → VVV production in “fully” leptonic decay
- Therefore, there ought to be pp → VVV → semi-leptonic

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

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

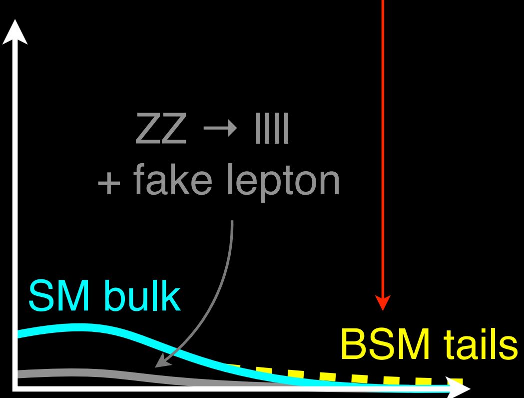
Fully leptonic v. Semi leptonic channel

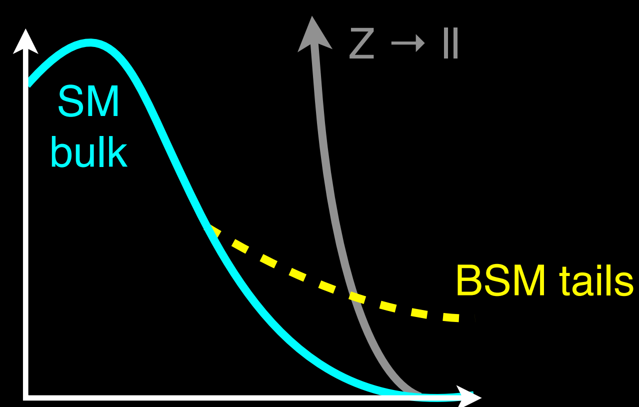




Clean channel for discovery but probing tail is difficult

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





Signal/Bkg. Small → Large Signal/Bkg.

We can probe VVV → semi-leptonic for new physics

More multi-massive-X processes for future

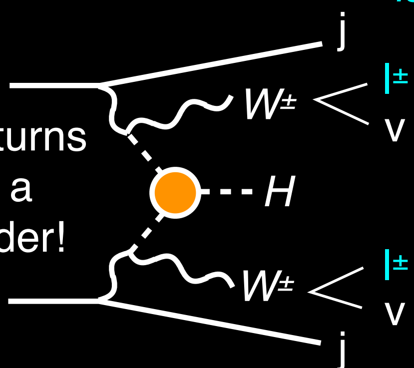
Chang
UCSD

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

pp → W±W±H

Same-sign is special

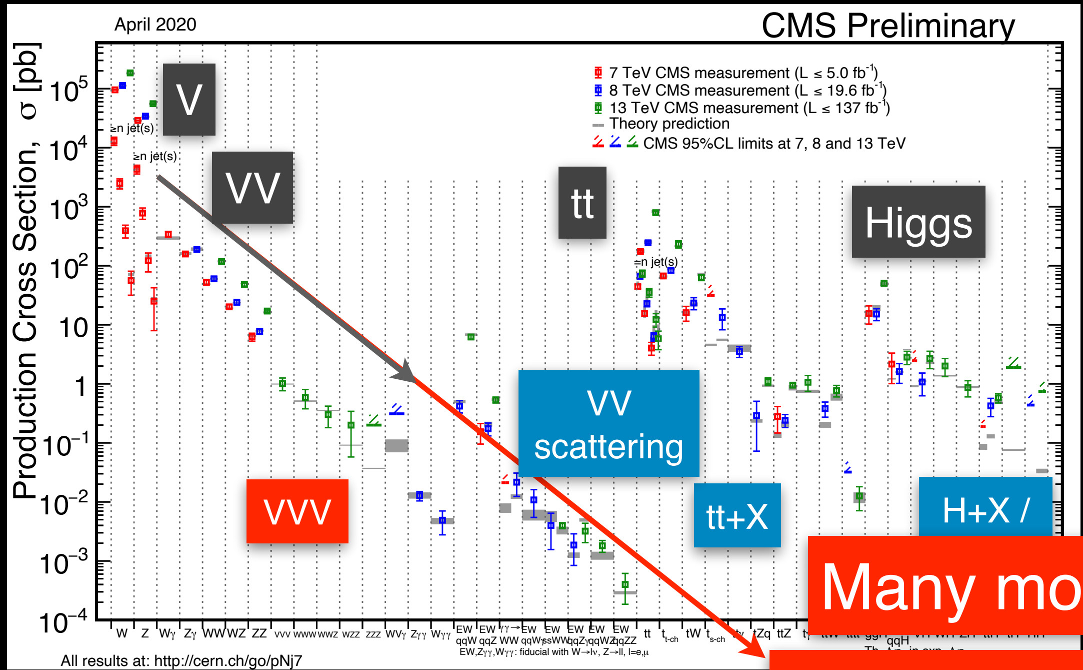
Same-sign turns LHC into a Higgs collider!



pp → tW±W±j

High P_T top (> 500 GeV)

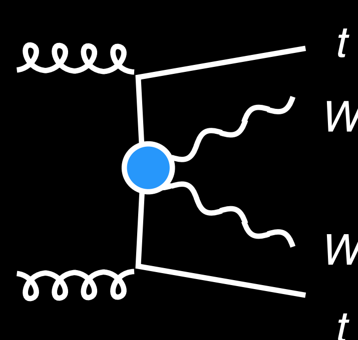
arXiv:1812.09299 Henning, Lombardo, Riembau, Riva
arXiv:1511.03674 Dror, Farina, Salvioni, Serra
arXiv:1904.05637 Maltoni, Mantani, Mimasu



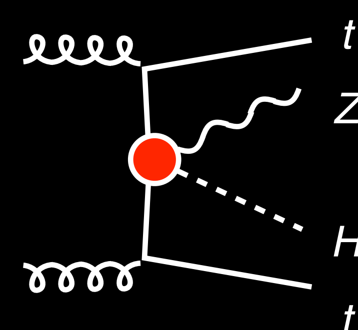
Many more

WWH, tWWj. ttWW, ttZH

pp → ttWW



pp → ttZH



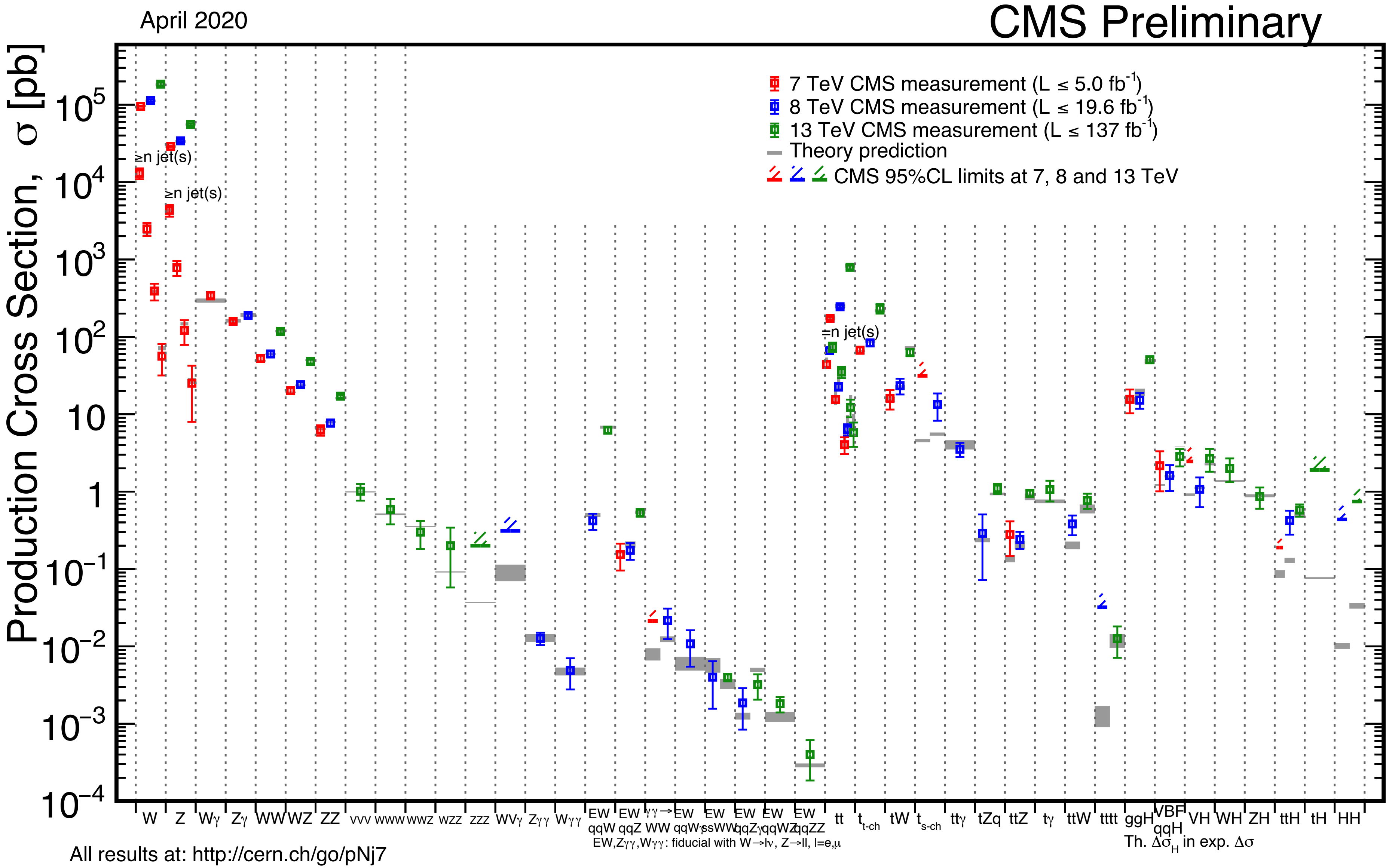
There are many more multi-massive-X production to be explored at LHC

Summary

- First observation of VVV productions was made by CMS collaboration
- Also found evidences for WWW and WWZ
- first hints for WZZ production and no hints for ZZZ yet
- The measured cross section is compatible with SM
- This establishes VVV process and opens a unique opportunity to test SM
- New physics can be also searched
- In the future, LHC will continue to probe electroweak interactions in various VVV channel
- Also, LHC will have to continue to probe unexplored electroweak productions of massive particles

Backup

Title


April 2020
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
13 TeV CMS measurement (L ≤ 137 fb^{-1})
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ VVV WWW WWZ WZZ ZZZ WVγ Zγγ Wγγ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqWZ EW qqZZ tt t$_{t\text{-ch}}$ tW t$_{s\text{-ch}}$ ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. $\Delta\sigma_H$ in exp. $\Delta\sigma$
All results at: http://cern.ch/go/pNj7

Title

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

SS / 3L preselection

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

SS selection

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

3L selection

Chang
UCSD

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}	$m_{\text{SFOS}} > 20$ GeV and $\lvert m_{\text{SFOS}} - m_Z \rvert > 20$ 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	
$\Delta\phi\left(\vec{p}_T(\ell\ell\ell), \vec{p}_T^{\,\text{miss}}\right)$	—	>2.5
$p_T(\ell\ell\ell)$	—	>50 GeV
m_T^{3rd} (1 SFOS) or m_T^{max} (2 SFOS)	—	>90 GeV

4L preselection

Chang
UCSD

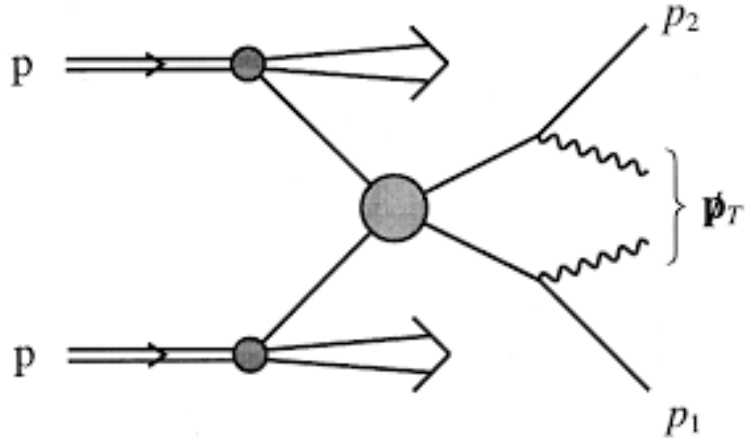
Features	Selections
Number of leptons	Select events with 4 leptons passing common veto-ID
Triggers	Select events passing dilepton triggers
Z lepton	Find opposite charge lepton pairs, passing ZID, closest to m_Z Require Z leptons to have $p_T > 25, 15$ GeV
W lepton	Require that leftover leptons are opposite 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 $(0, 40, 60, 100, \infty)$	$\|m_{\ell\ell} - m_Z\| > 10\,\text{GeV}$
m_{T2}	$m_{T2} > 25\,\text{GeV}$ (for $m_{\ell\ell} > 100\,\text{GeV}$)	...
$p_{T,4\ell}$ and p_T^{miss}	...	No $p_{T,4\ell}$ cuts and $p_T^{miss} > 120\,\text{GeV}$ (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)

Chang
UCSD

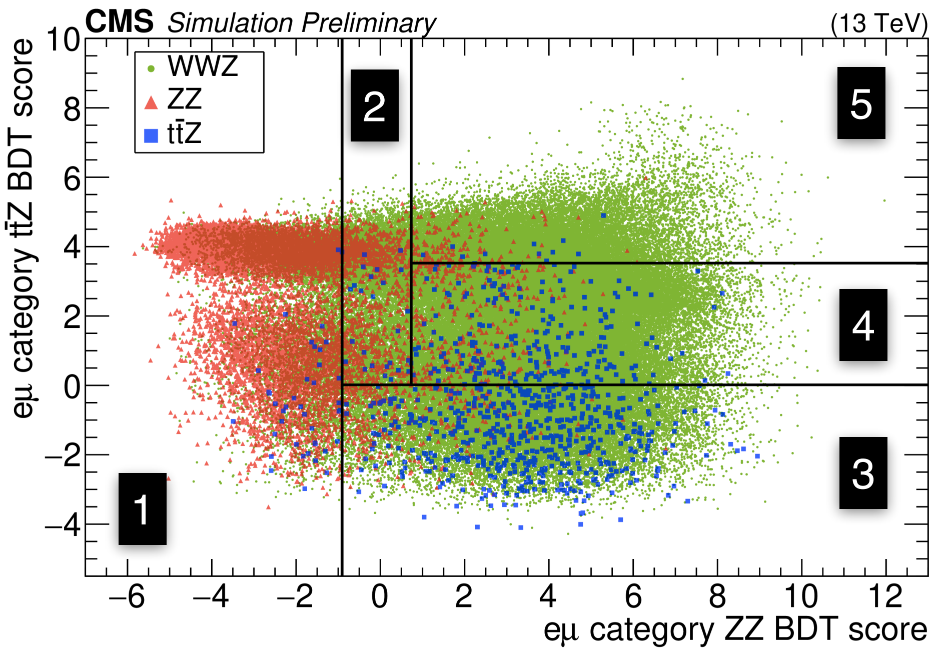
$$m_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\nu(1)} + \vec{p}_{\mathrm{T}}^{\nu(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max\left(m_{\mathrm{T}}^{(1)}(\vec{p}_{\mathrm{T}}^{\nu(1)}, \vec{p}_{\mathrm{T}}^{\mathrm{e}}), m_{\mathrm{T}}^{(2)}(\vec{p}_{\mathrm{T}}^{\nu(2)}, \vec{p}_{\mathrm{T}}^{\mu})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



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

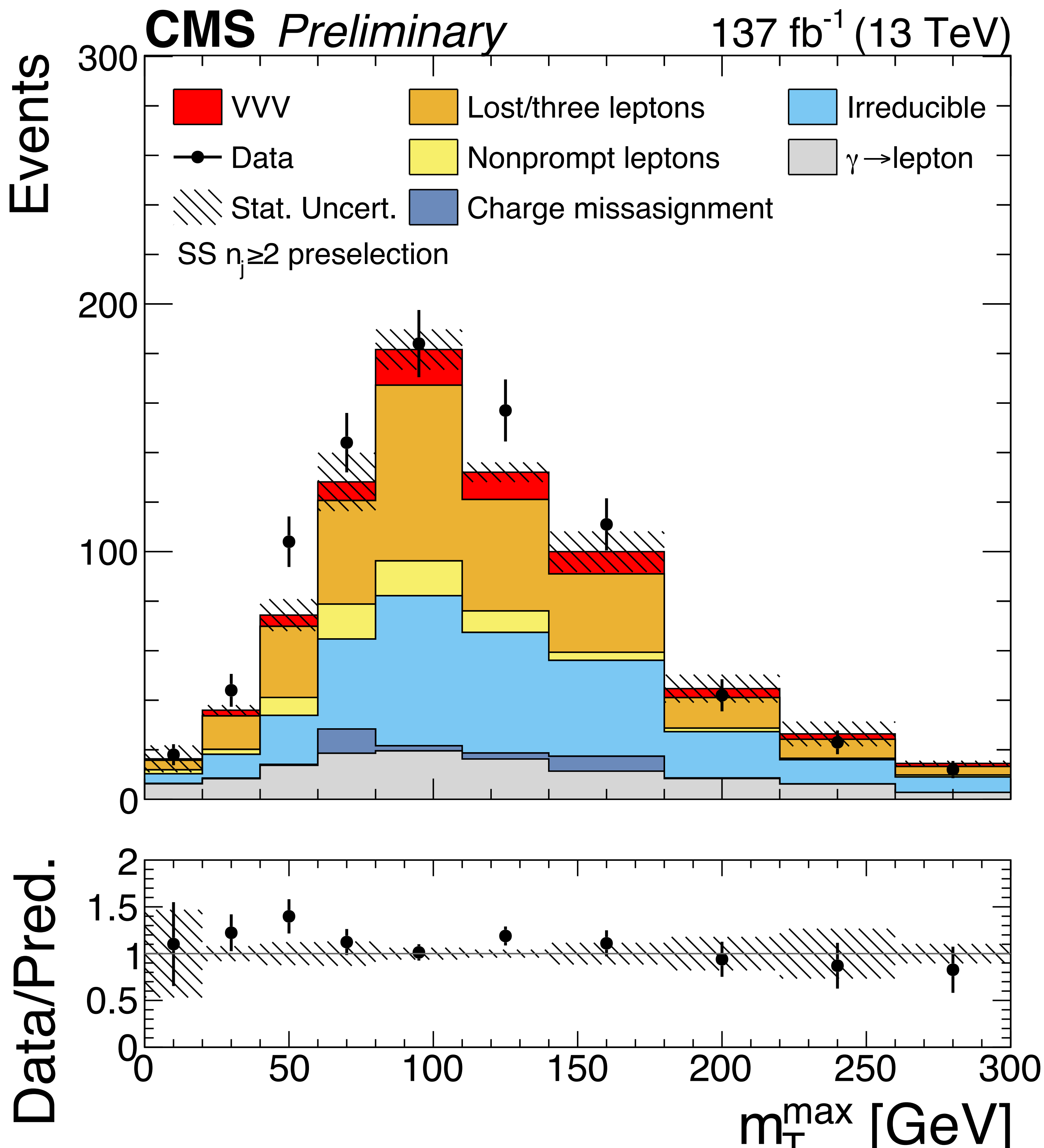
For Z→ττ→llvvvv sub-system of ZZ, endpoint is at m_τ

Title

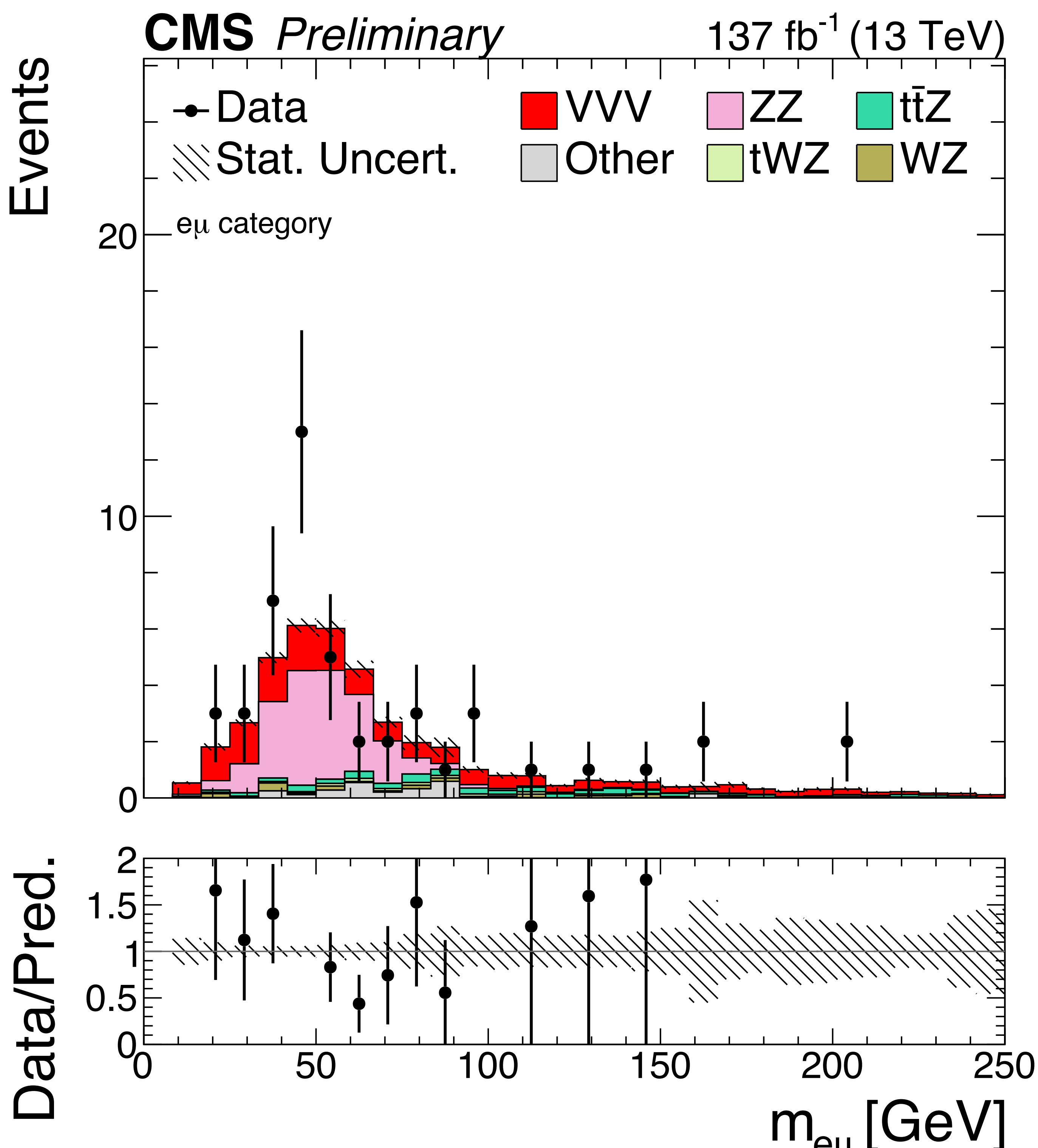


	ZZ BDT range	$t\bar{t}Z$ BDT range
eμ BDT bin 1	(-∞, -0.908)	(-∞ , ∞)
eμ BDT bin 2	(-0.908 , ∞)	(-∞ , 0.015)
eμ BDT bin 3	(-0.908 , 0.733)	(0.015 , ∞)
eμ BDT bin 4	(0.733 , ∞)	(0.015 , 3.523)
eμ BDT bin 5	(0.733 , ∞)	(3.523 , ∞)
ee/$\mu\mu$ BDT bin A	(0 , 3)	-
ee/$\mu\mu$ BDT bin B	(3 , ∞)	-

Title

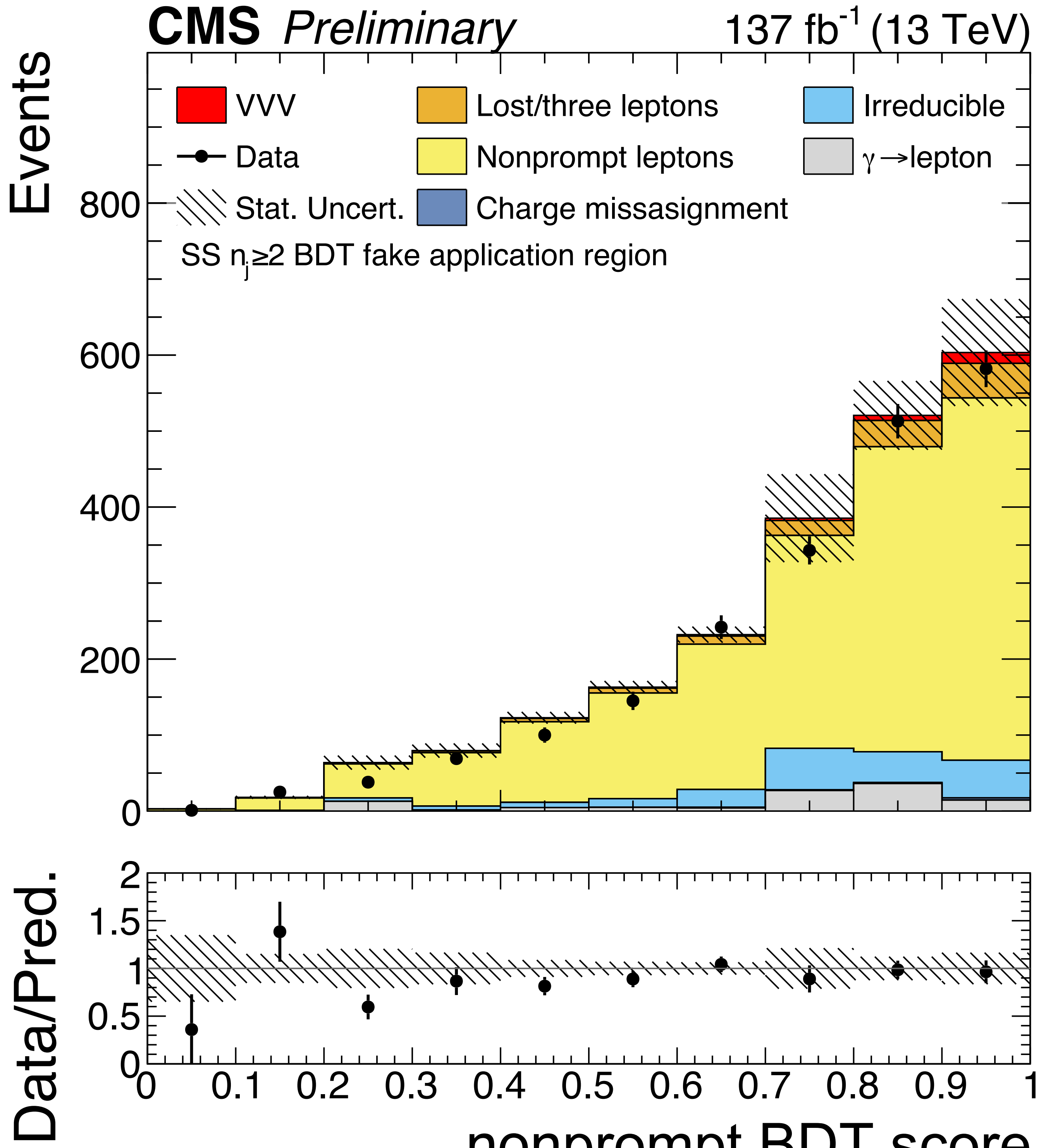

CMS Preliminary
137 fb-1 (13 TeV)
VVV
Lost/three leptons
Irreducible
Data
Nonprompt leptons
γ→lepton
Stat. Uncert.
Charge missassignment
SS nj≥2 preselection
Events
Data/Pred.
m_T^max [GeV]
0
100
200
300
0.5
1
1.5
2
50
150
250

Title



Chang
UCSD

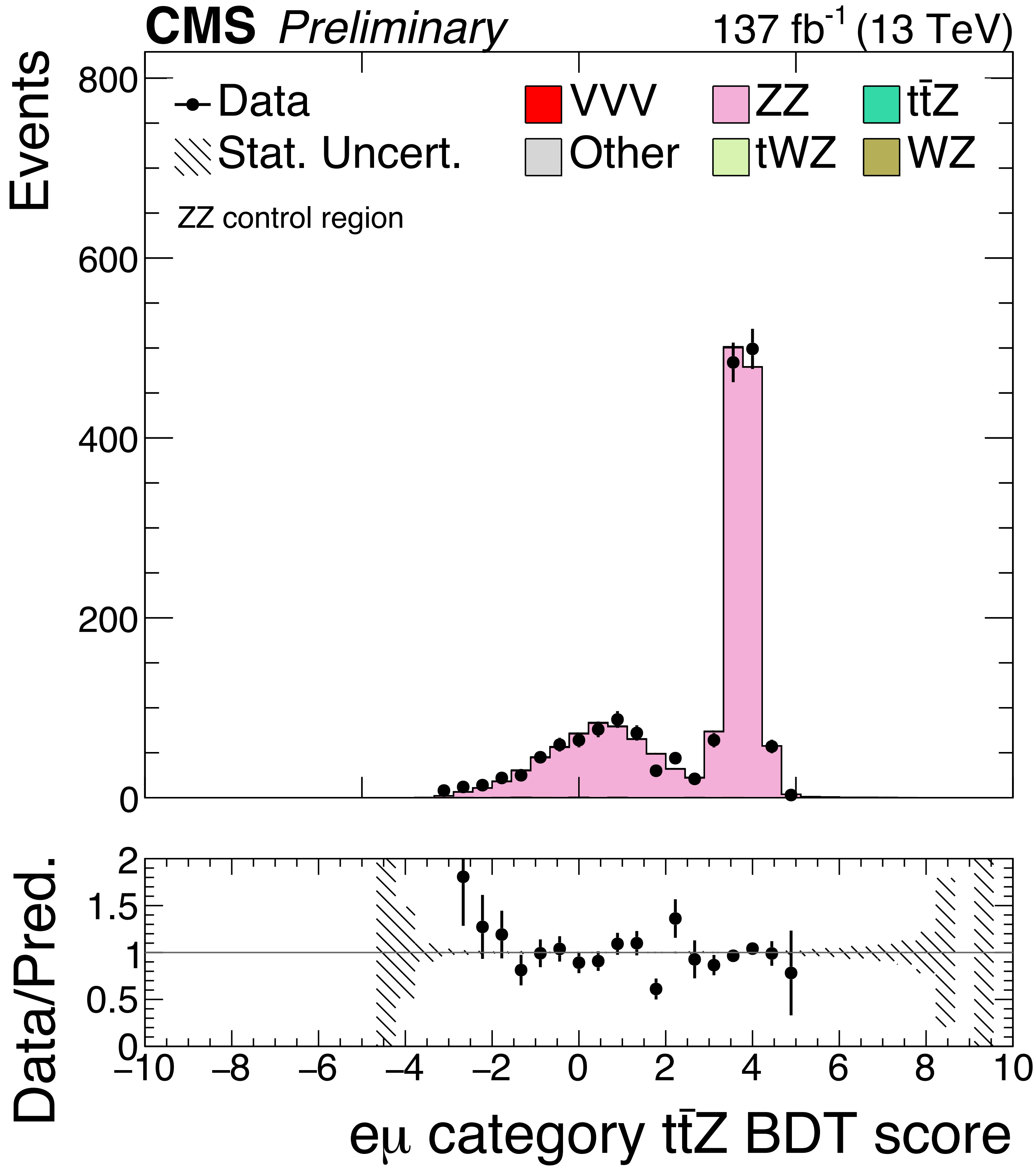
Title



Chang
UCSD

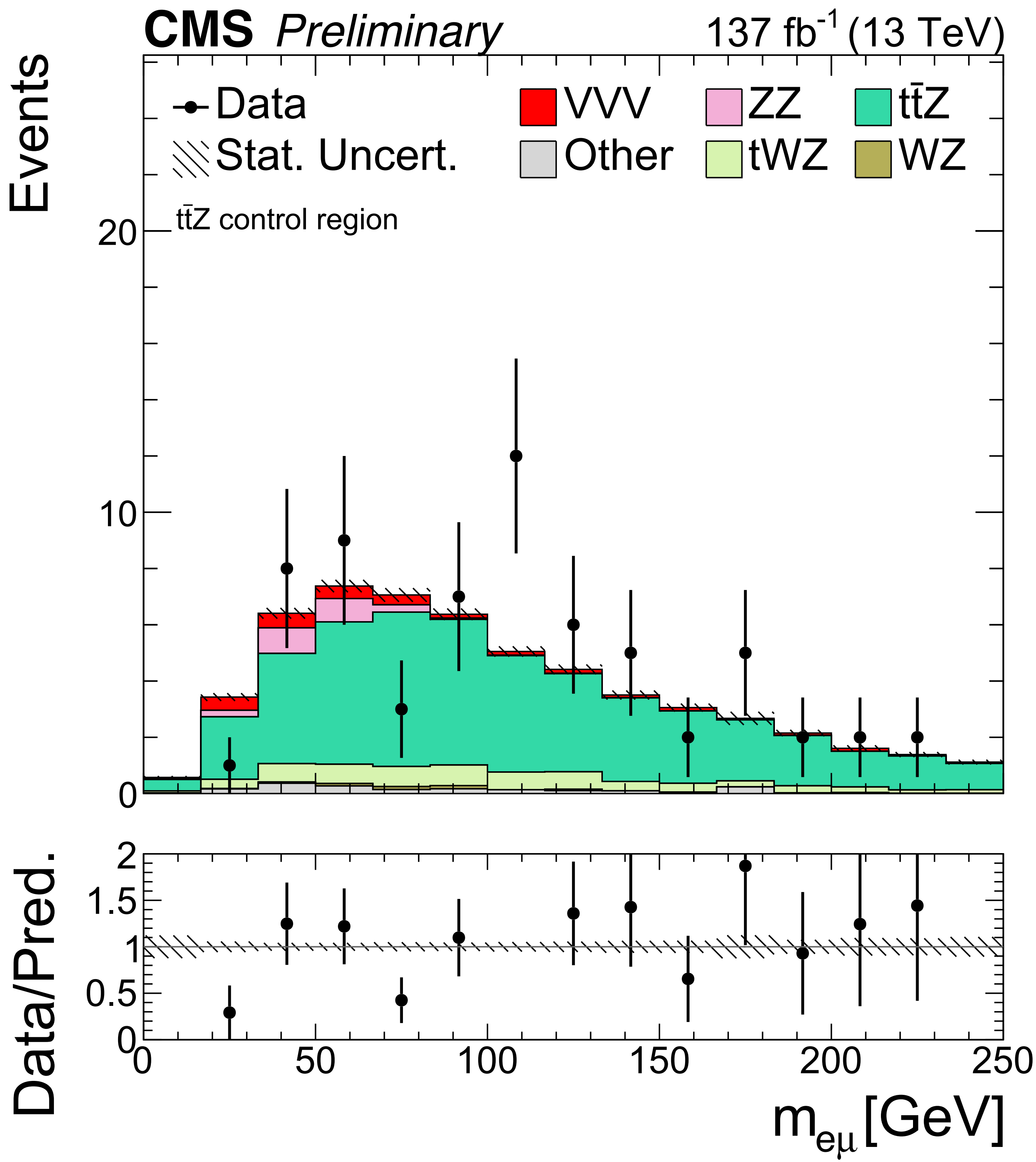
Title

Chang
UCSD



Title

Chang
UCSD



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

Chang
UCSD

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

Chang
UCSD

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

Title

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

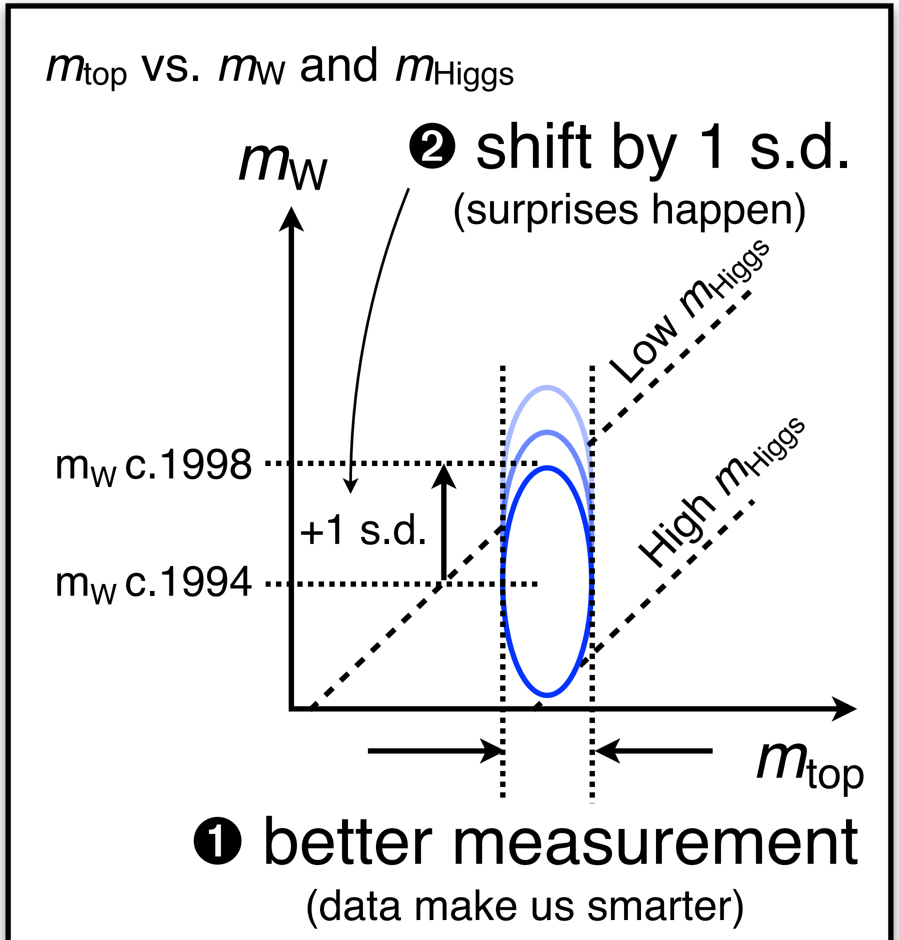
Chang
UCSD

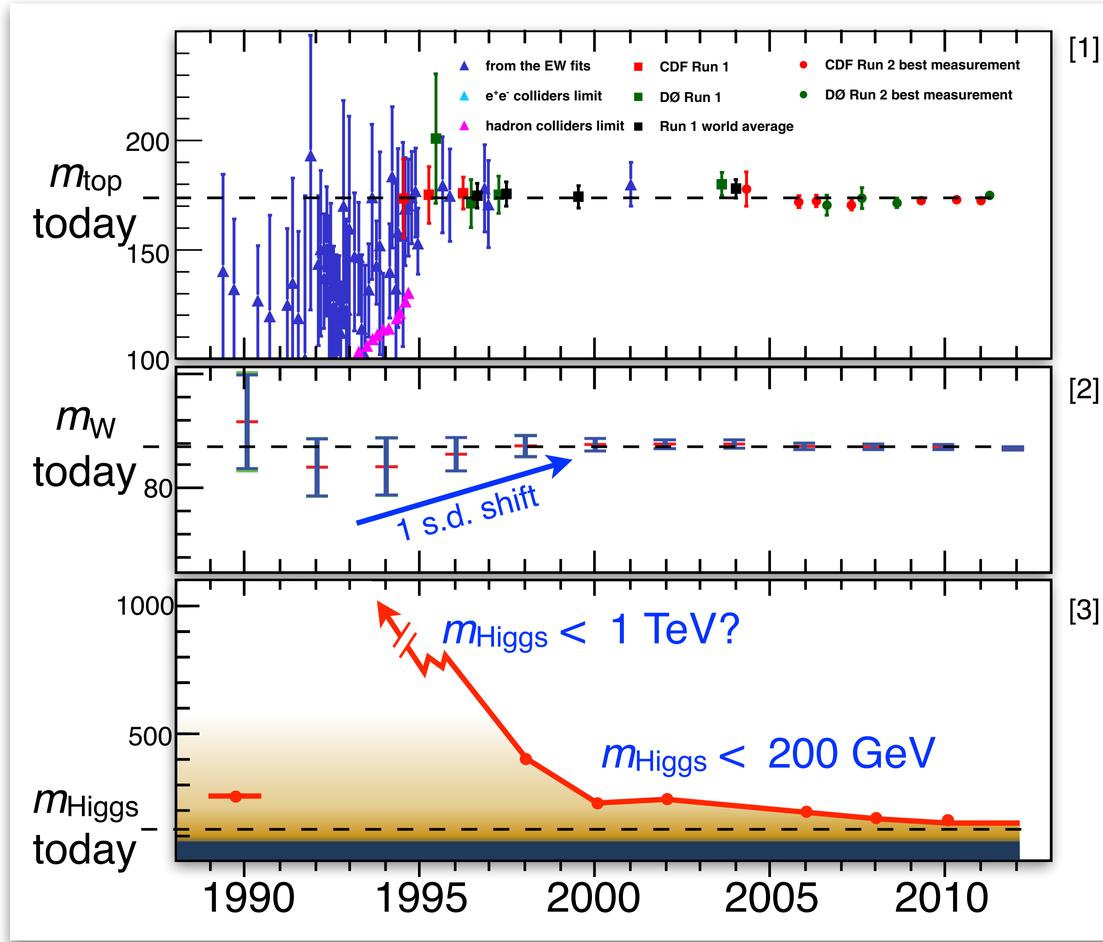
Signal	SS m_{jj}-in			SS m_{jj}-out			SS 1j			3ℓ		
region	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	0 SFOS	1 SFOS	2 SFOS
Lost/three ℓ	1.8±0.4	10.9±2.0	8.7±1.0	8.8±1.7	46.0±6.2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

Title

Signal region	4ℓ eμ bin 4	bin 3	bin 2	bin 1	4ℓ ee/μμ bin A	bin B	bin C	5ℓ	6ℓ
ZZ	0.3±0.0	0.7±0.0	0.7±0.0	0.4±0.0	1.8±0.2	6.0±0.6	5.0±0.5	0.30±0.08	0.01±0.01
$t\bar{t}Z$	0.2±0.0	0.3±0.1	0.8±0.1	2.3±0.4	1.4±0.2	1.1±0.2	0.2±0.0	<0.01	<0.01
tWZ	0.1±0.1	0.1±0.1	0.3±0.0	0.8±0.1	0.5±0.1	0.3±0.1	0.1±0.1	<0.01	<0.01
WZ	0.2±0.1	0.1±0.1	0.1±0.2	0.6±0.2	<0.1	0.2±0.1	0.1±0.1	<0.01	<0.01
Other	<0.1	0.2±0.1	0.6±0.3	0.2±0.1	<0.1	1.4±0.5	0.1±0.1	<0.01	<0.01
Background sum	0.8±0.1	1.4±0.1	2.5±0.3	4.3±0.4	3.7±1.9	9.1±0.8	5.5±0.5	0.30±0.08	0.01±0.01
WWW onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WH → WWW	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WWW total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WWZ onshell	0.5±0.2	0.5±0.2	1.1±0.4	4.0±1.6	2.1±0.9	1.2±0.4	0.6±0.2	<0.01	<0.01
ZH → WWZ	2.3±0.9	1.1±0.4	0.3±0.1	0.1±0.1	0.8±0.3	0.9±0.4	0.5±0.2	<0.01	<0.01
WWZ total	2.8±0.9	1.6±0.5	1.4±0.4	4.1±1.6	2.9±1.0	2.1±0.6	1.1±0.3	<0.01	<0.01
WZZ onshell	<0.1	0.1±0.1	0.1±0.1	0.4±0.3	0.2±0.2	0.1±0.1	0.1±0.1	2.17±1.46	0.03±0.04
WH → WZZ	<0.1	0.4±0.3	0.1±0.2	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WZZ total	<0.1	0.4±0.4	0.2±0.2	0.4±0.3	0.2±0.2	0.1±0.1	0.1±0.1	2.17±1.46	0.03±0.04
ZZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
ZH → ZZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
ZZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
VVV onshell	0.5±0.2	0.6±0.2	1.2±0.4	4.4±1.6	2.3±0.9	1.3±0.5	0.7±0.2	2.17±1.46	0.03±0.04
VH → VVV	2.3±0.9	1.5±0.5	0.4±0.3	0.1±0.1	0.8±0.3	0.9±0.4	0.5±0.2	<0.01	<0.01
VVV total	2.8±0.9	2.1±0.6	1.6±0.5	4.5±1.6	3.1±1.0	2.2±0.6	1.2±0.3	2.17±1.46	0.03±0.04
Total	3.6±0.9	3.5±0.6	4.1±0.6	8.8±1.7	6.8±2.1	11.3±1.0	6.6±0.6	2.47±1.46	0.04±0.04
Observed	7	1	5	7	6	8	7	3	0

History lesson



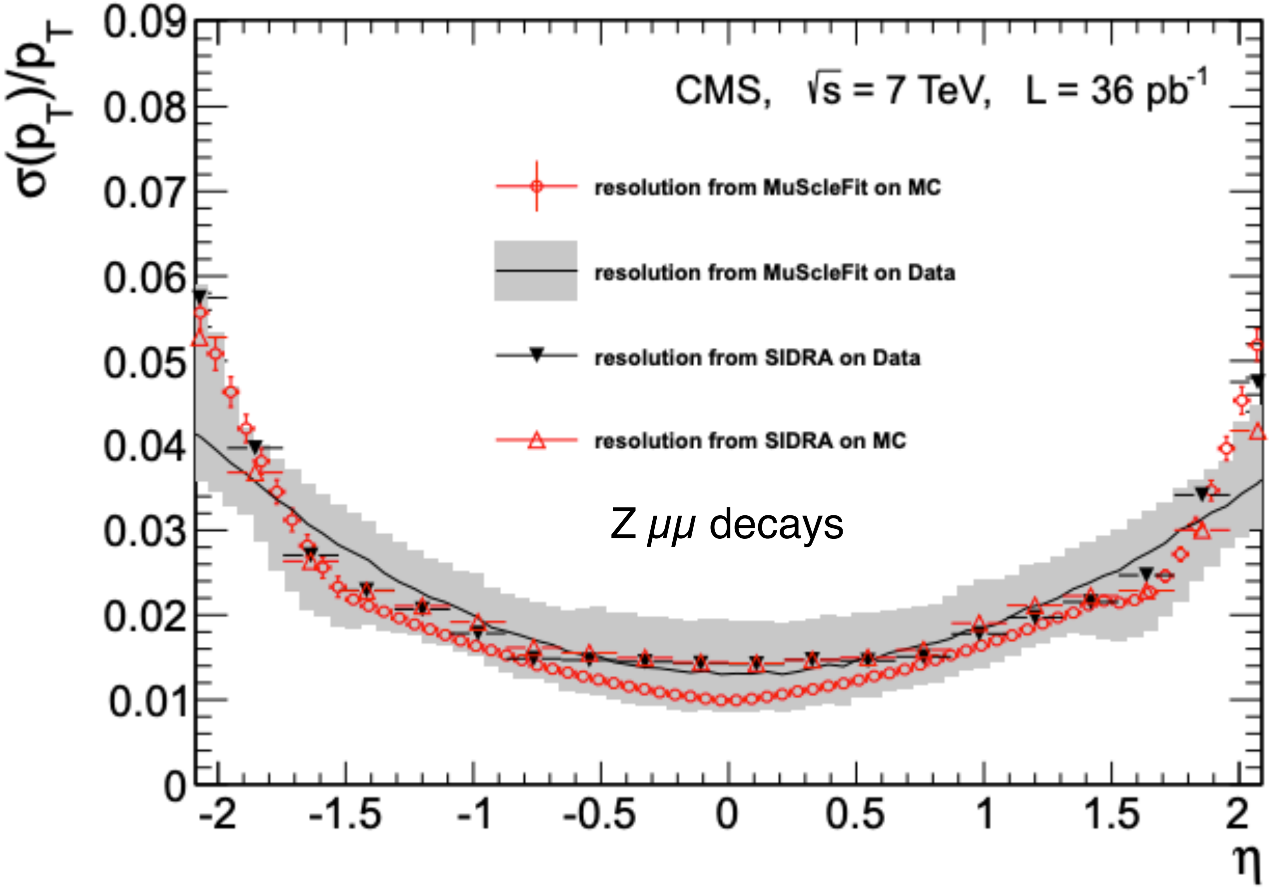


…after analysis of Run I data, … ❷ <u>m_W shifted a full s.d.</u> … the m_{Higgs} must be ❸ <u>much lower than anyone had anticipated.</u> … Surprises happen.

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

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

Muon resolution

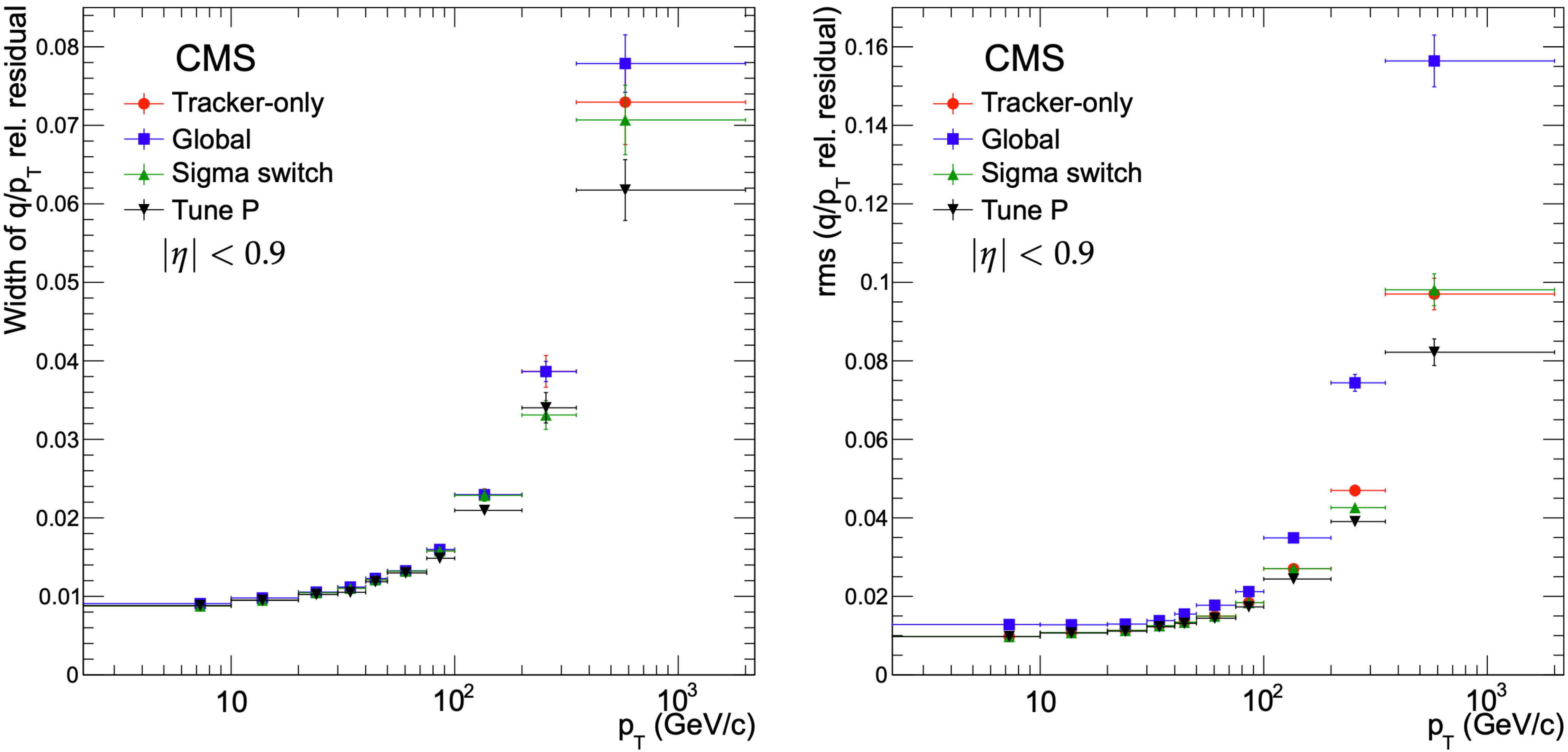


ment with the results obtained from simulation. The $\sigma(p_T)/p_T$ averaged over ϕ and η varies in p_T from $(1.8 \pm 0.3(\mathrm{stat.}))\%$ at $p_T = 30\,\mathrm{GeV}/c$ to $(2.3 \pm 0.3(\mathrm{stat.}))\%$ at $p_T = 50\,\mathrm{GeV}/c$, again in good agreement with the expectations from simulation.

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

Muon resolution

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



(a)

(b)

Electron resolution

arXiv.org > physics > arXiv:1502.02701

Search...
Help | Advanced

Physics > Instrumentation and Detectors

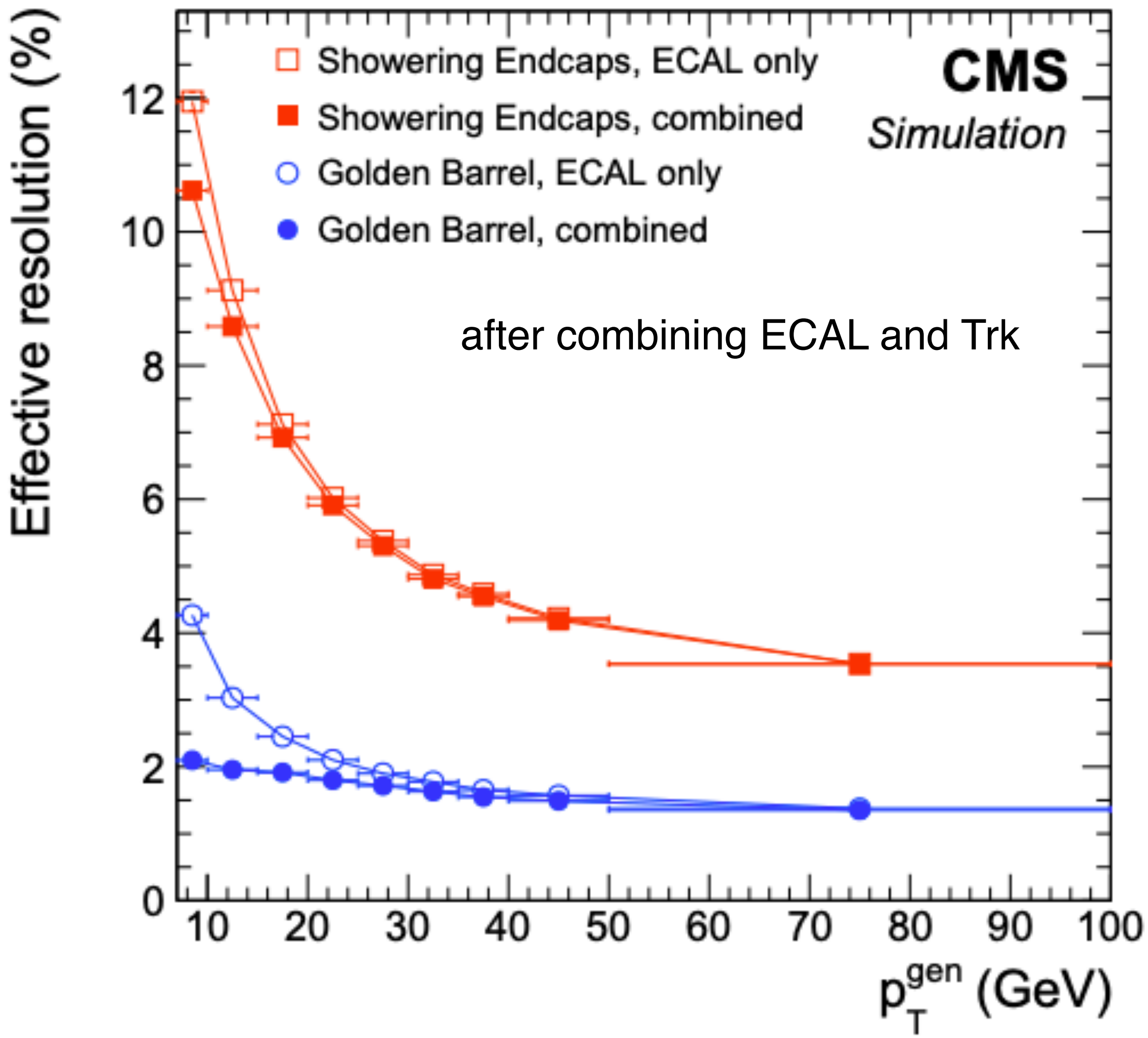
[Submitted on 9 Feb 2015 (v1), last revised 1 Jul 2015 (this version, v2)]

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



after combining ECAL and Trk

b tagging

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

Loose = mis id = 10%