Standard model electroweak measurements

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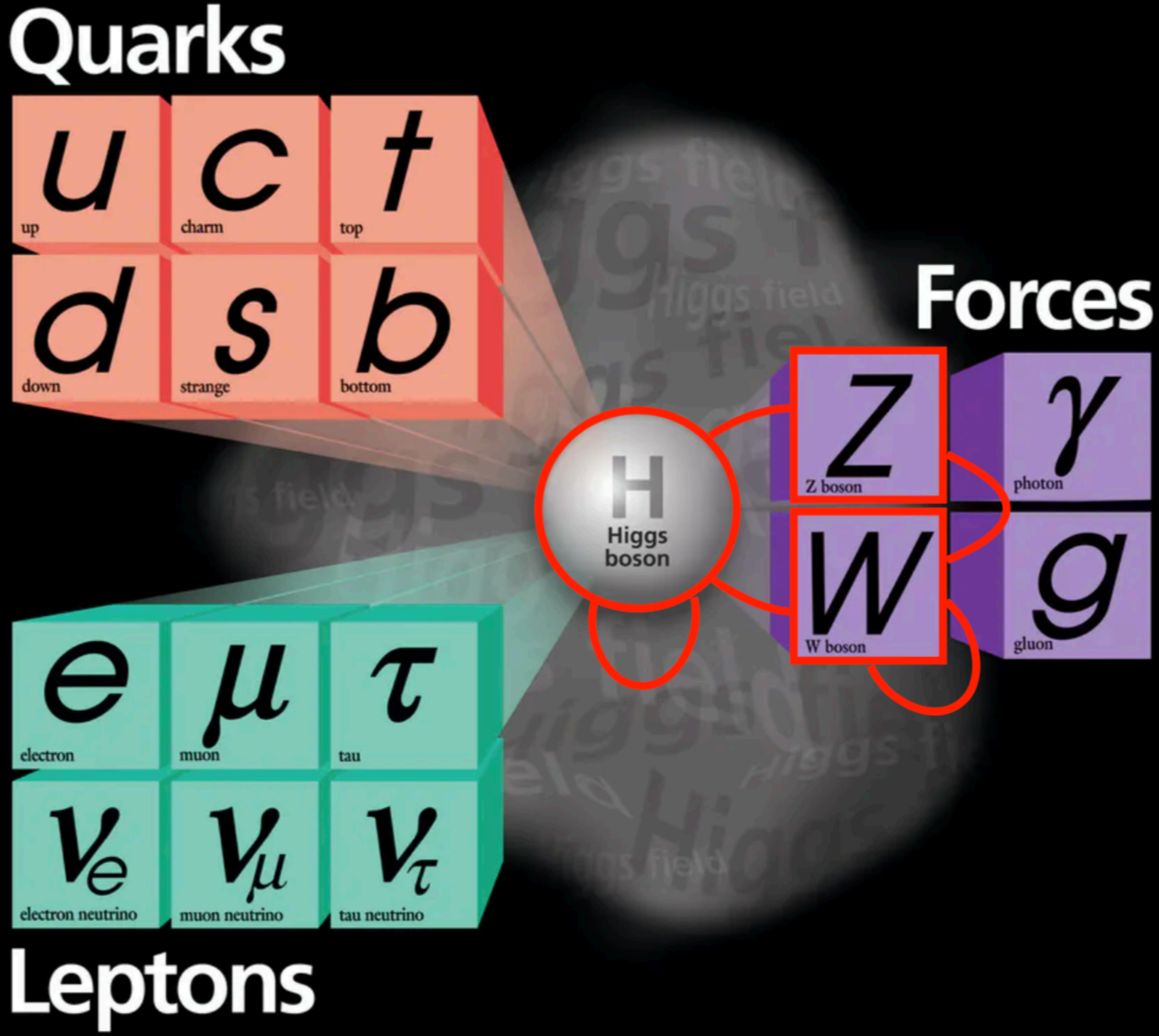
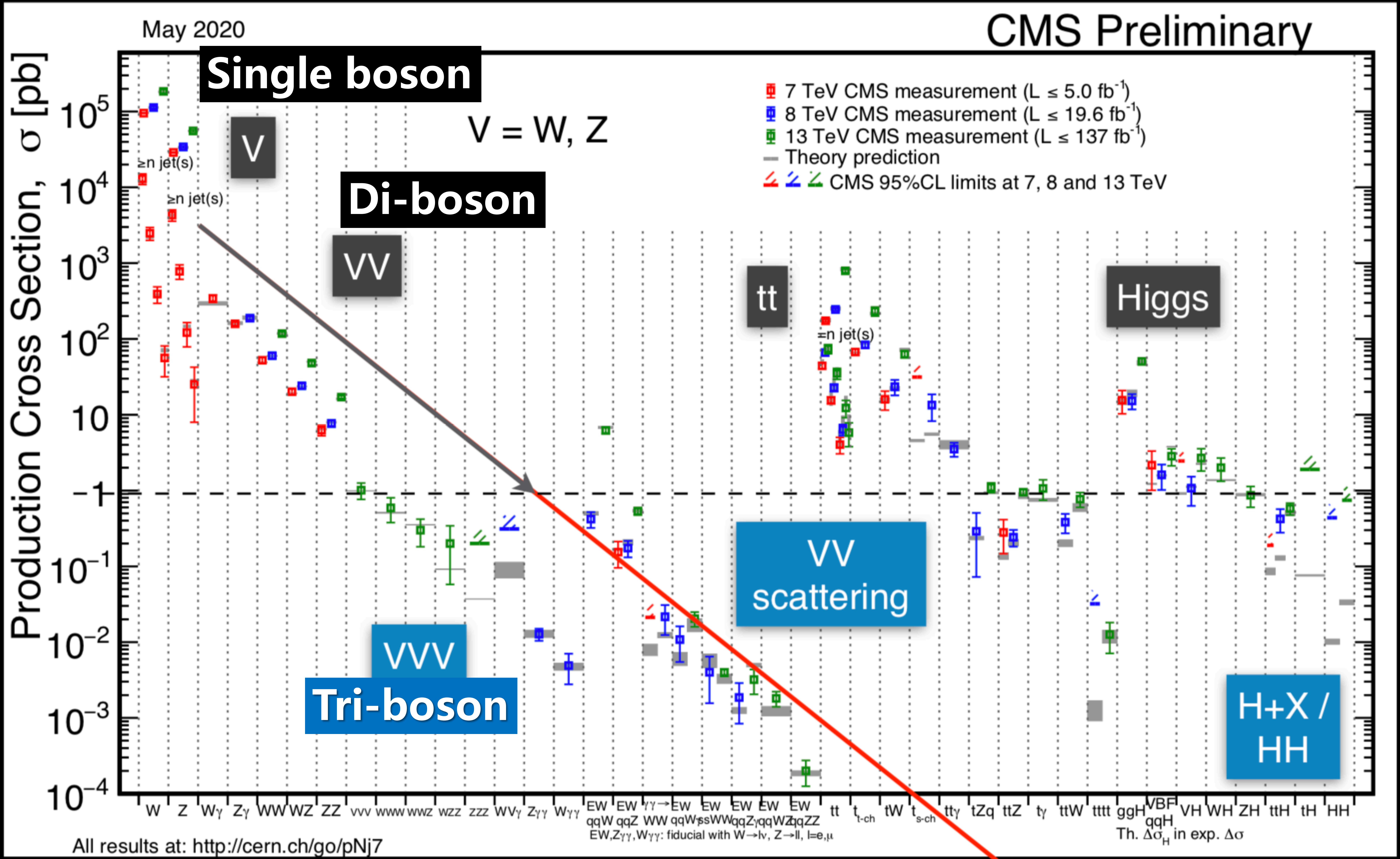
Introduction



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

Introduction



Rarer events

Multi-boson processes

Outline

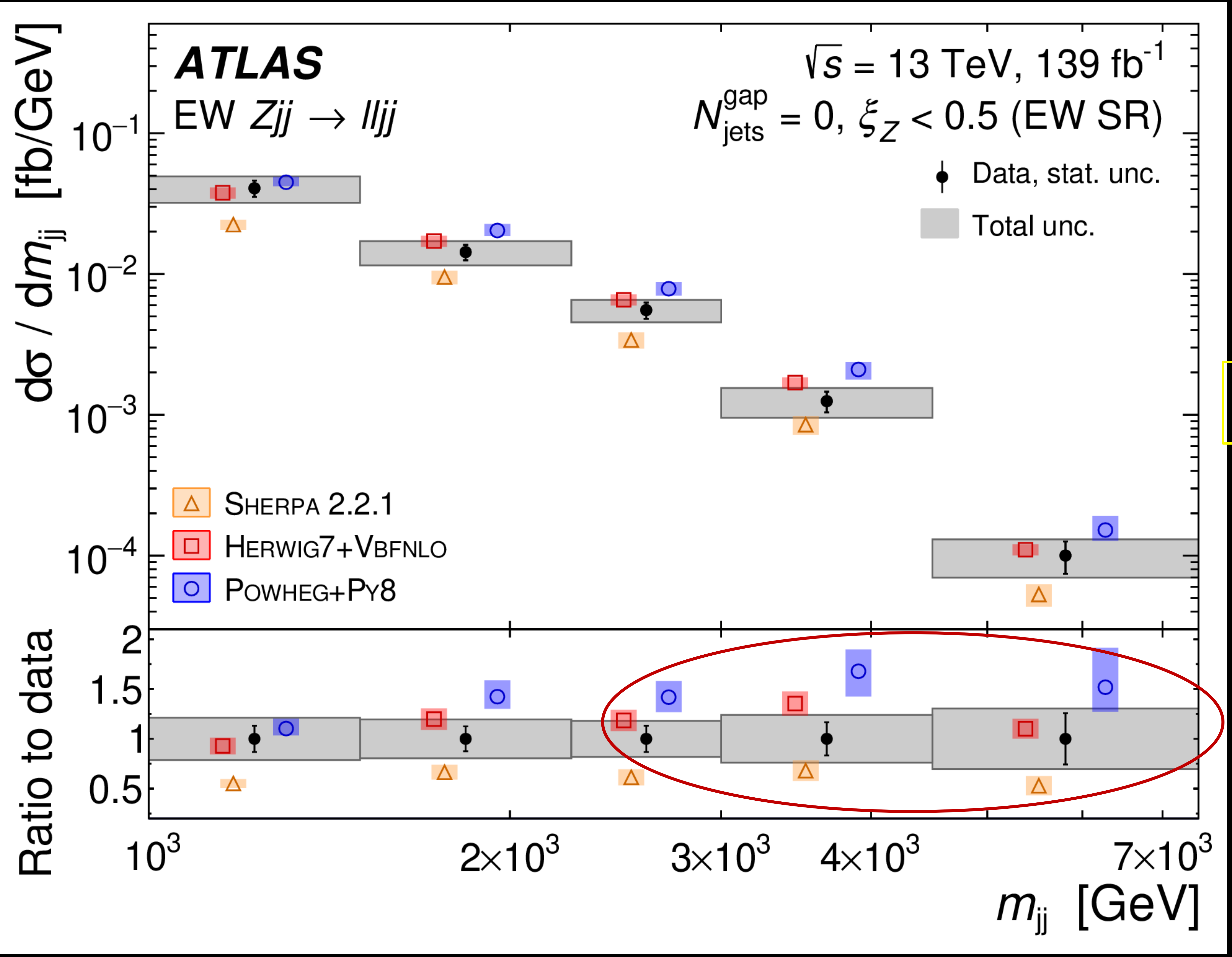
- **Single boson results**
- **Electroweak Z+dijets**

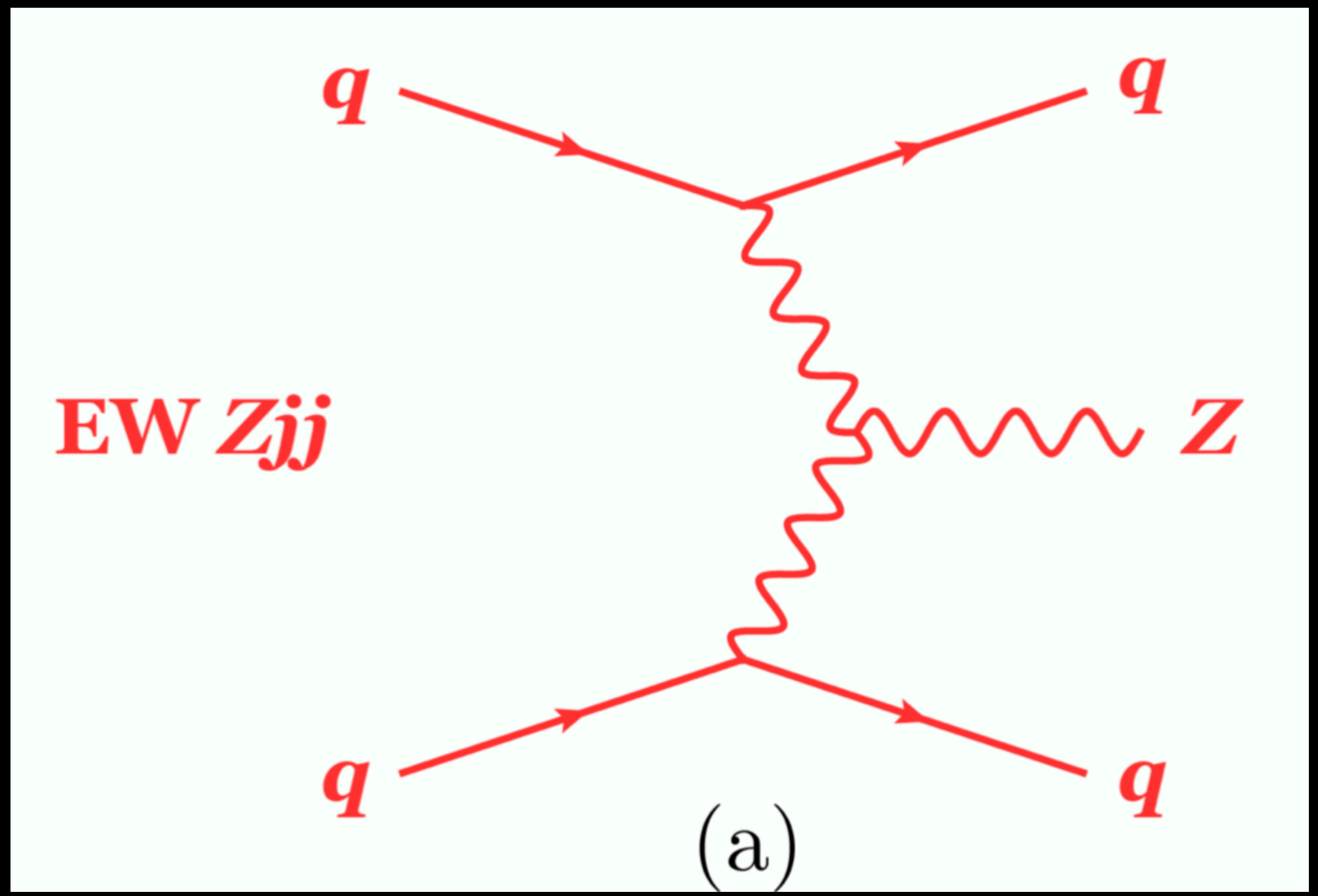
- **Diboson results**
- **Vector boson scattering**
- **$\gamma\gamma \rightarrow WW$ measurement**

- **Tri-boson results**
- **Three massive boson productions**

Electroweak Z+dijets (Vector boson fusion) arXiv:2006.15458

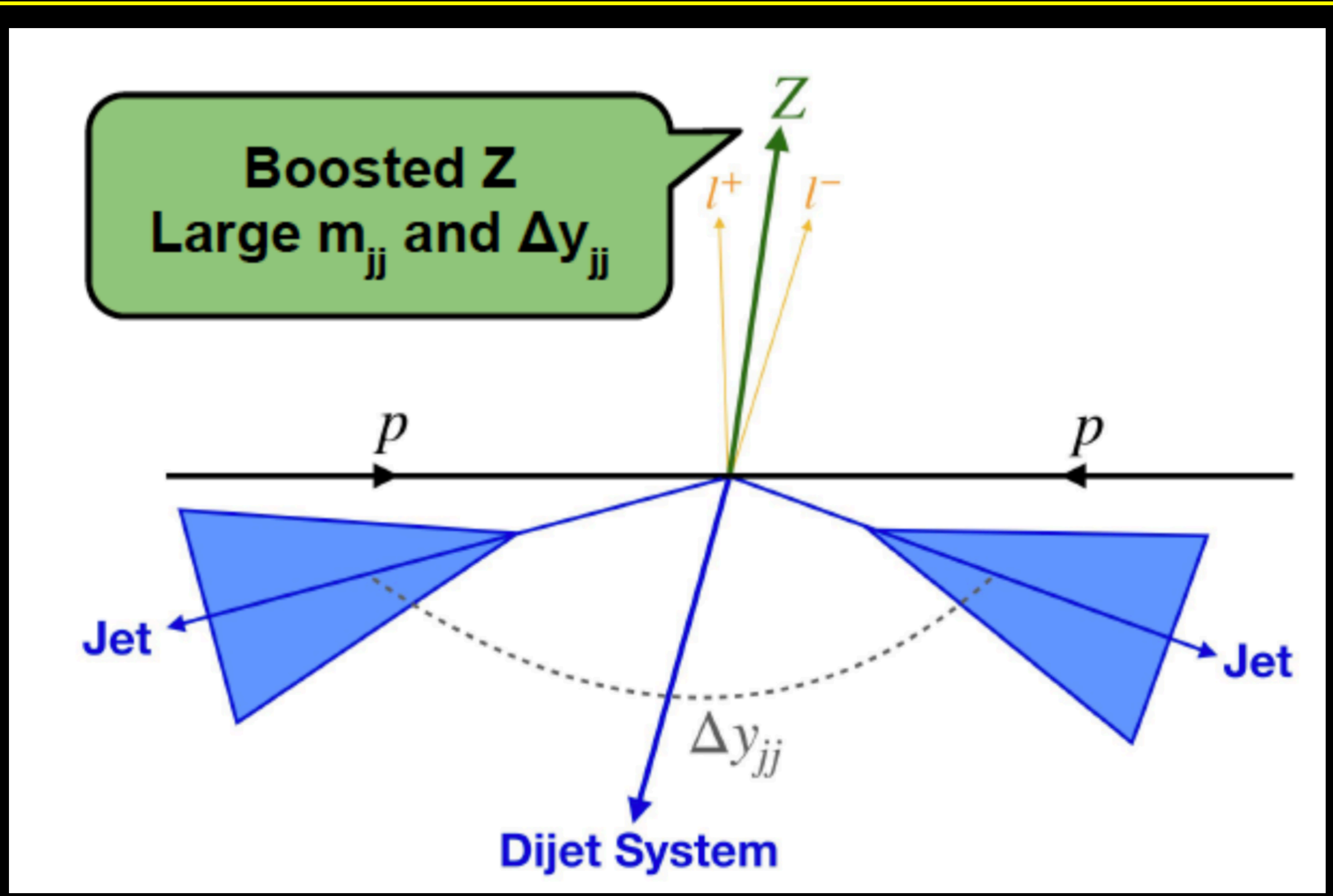
- Differential measurements of electroweak Z+dijets events by ATLAS with full run 2 data
- Syst. Unc dominated by QCD Z+jets modelling
- Herwig7+VBFNLO agrees with data
- PoweHeg +Pythia8 overestimates at high m_{jj}, high $|\Delta y_{jj}|$,





Measurements: 37.4 ± 3.5 (stat.) ± 5.5 (syst.) fb

Herwig7+VBFNLO :39.5 ± 3.4 (scale) ± 1.2 (PDF) fb



W+W− production

CMS-PAS-SMP-18-004

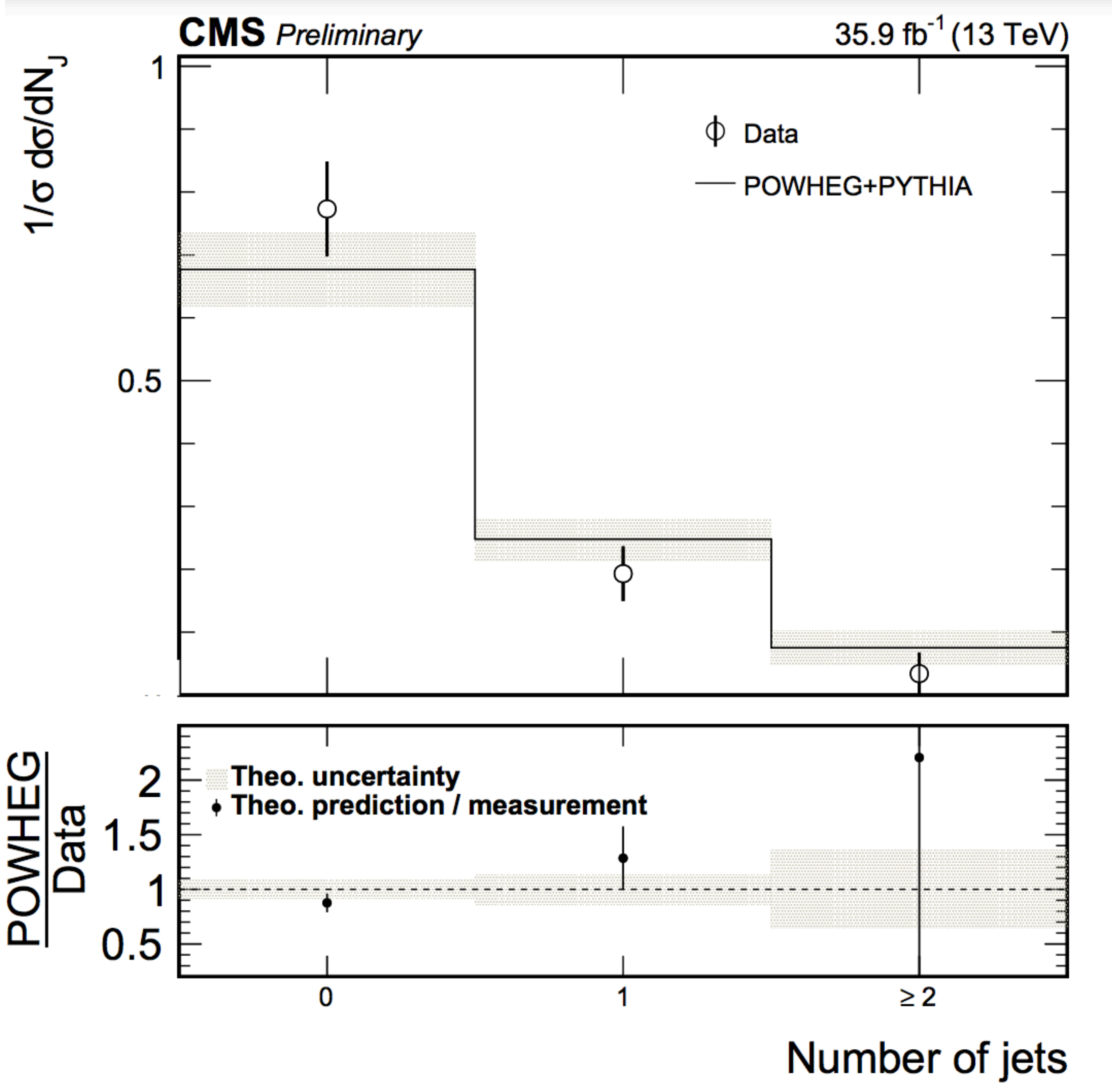
- **CMS:** W+W− measurements with **run II 36fb[-1]**
- Two random forest classifier for Drell-Yan and top background.
- Systematics dominated by **jet energy scale unc.** and **higher order QCD corrections unc.**

σ_{fid} **(measured)=** 1.529± 0.020 (stat)± 0.069 (syst)± 0.028 (theo) pb

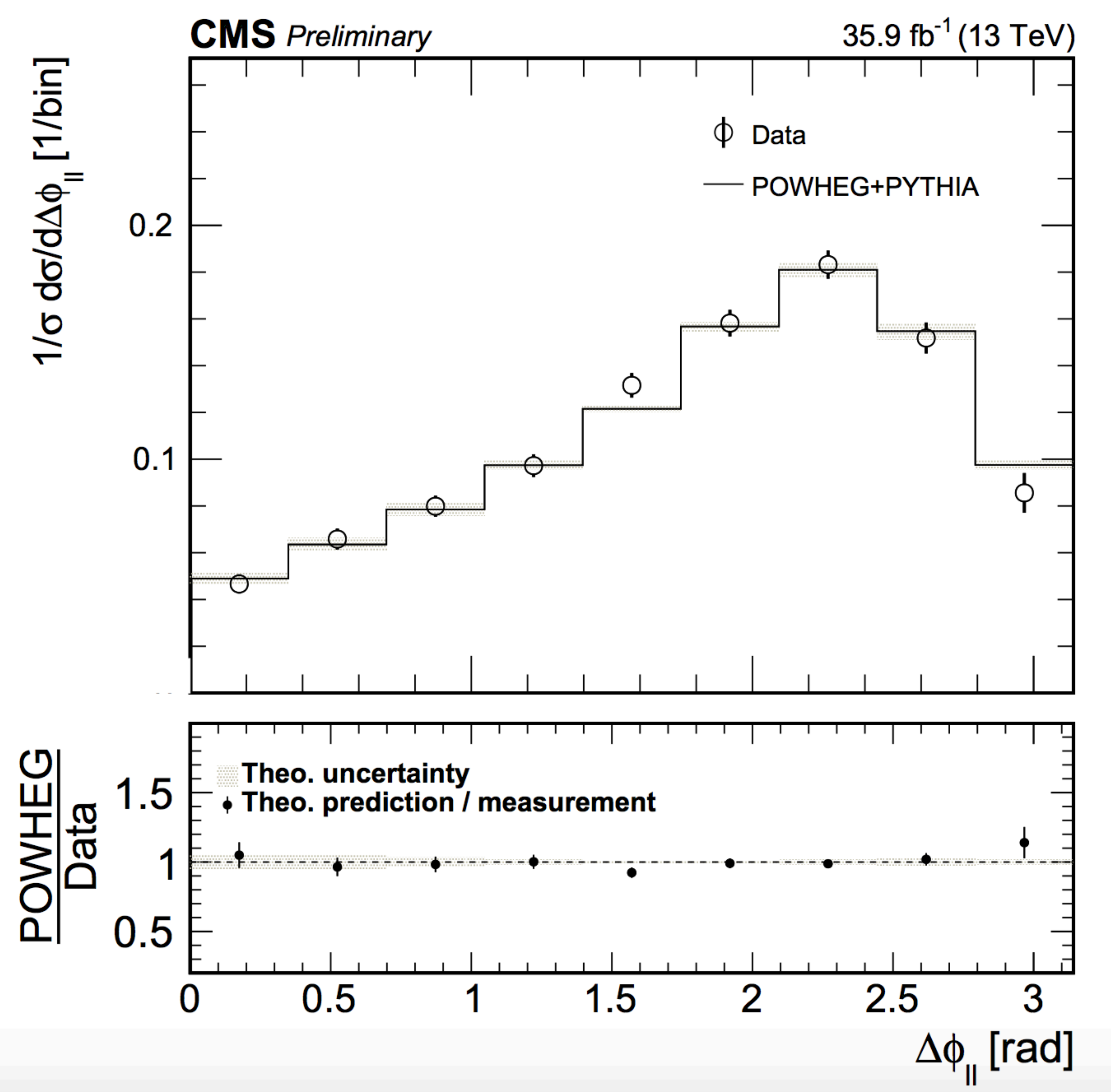
$\sigma_{fid\ NNLO}$ **(predicted)=** 1.531 ± 0.043 pb

Uncertainty source	(%)
Statistical uncertainty	1.2
$t\bar{t}$ normalization	2.0
Drell-Yan normalization	1.4
$W\gamma^*$ normalization	0.4
Nonprompt leptons normalization	1.9
Lepton efficiencies	2.1
b-tagging (b/c)	0.4
b-tagging (light)	1.0
Jet energy scale and resolution	2.3
Pileup	0.4
Simulation and data control regions sample size	1.0
Total experimental systematic uncertainty	4.6
QCD factorization and renormalization scales	0.4
Higher-order QCD corrections and p_T^{WW} distribution	1.4
PDFs	0.4
Underlying event modeling	0.5
Total theoretical systematic uncertainty	1.6
Luminosity	2.7
Total uncertainty	5.7

Number of jets



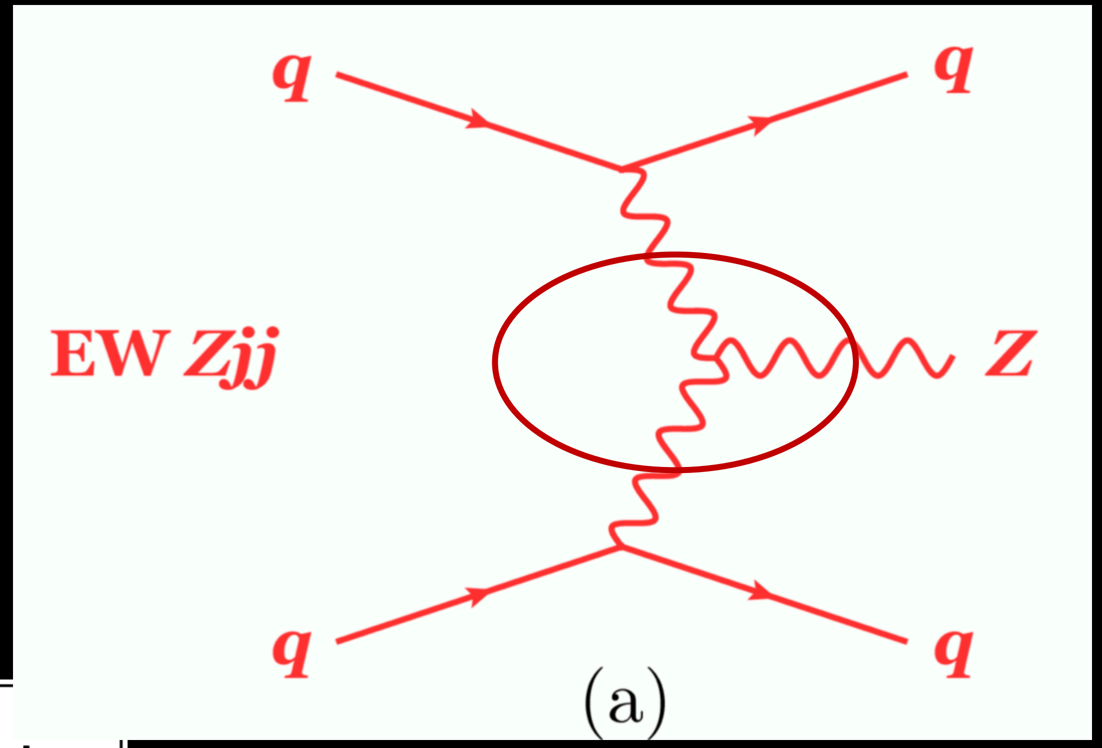
Di-lepton $\Delta\phi_{ll}$



Anomalous triple gauge couplings **(aTGCs)**

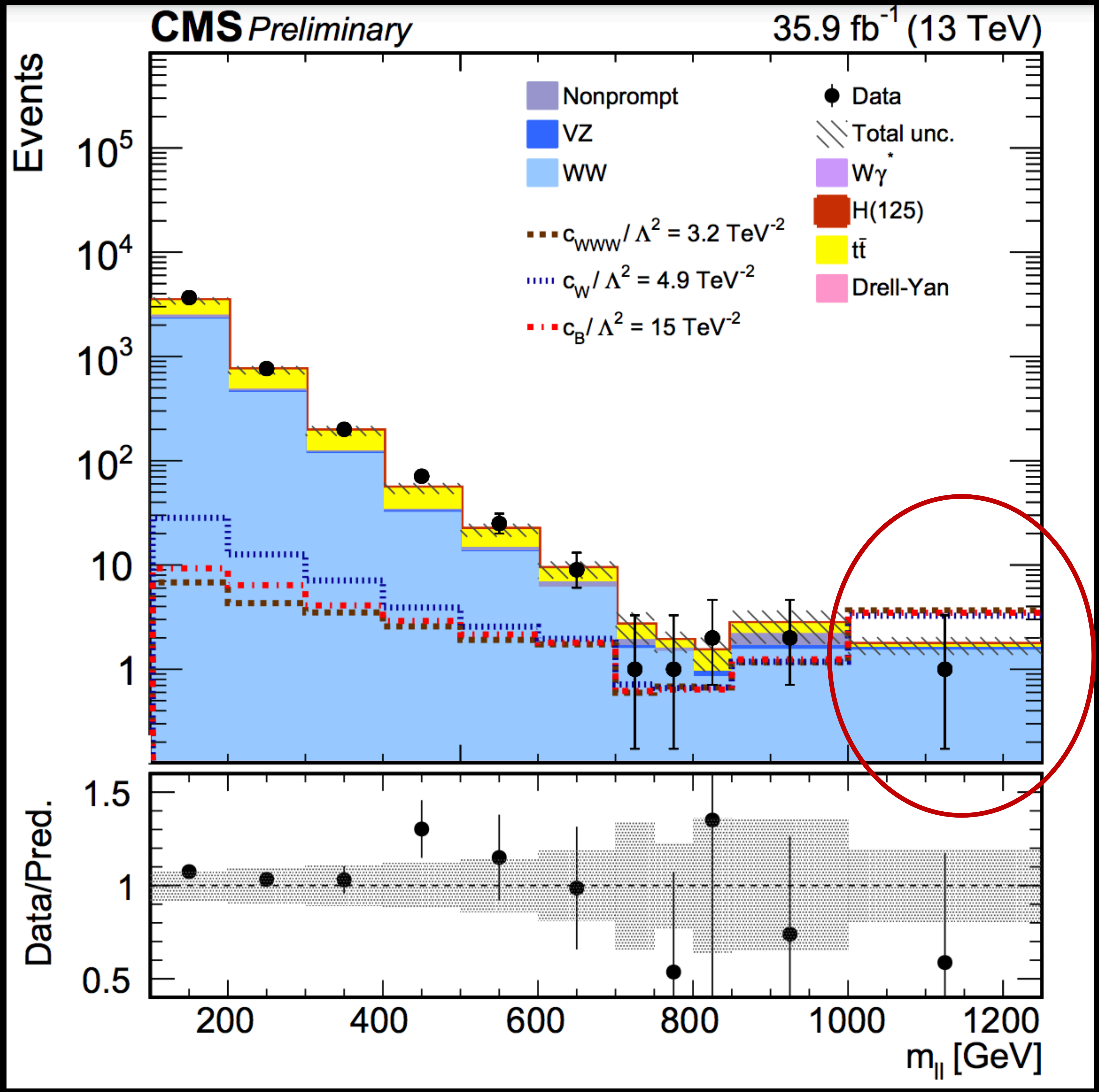
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_i \frac{C_{6i}}{\Lambda^2}\mathcal{O}_{6i} + \sum_j \frac{C_{8j}}{\Lambda^4}\mathcal{O}_{8j}$$

EWK Z+dijet



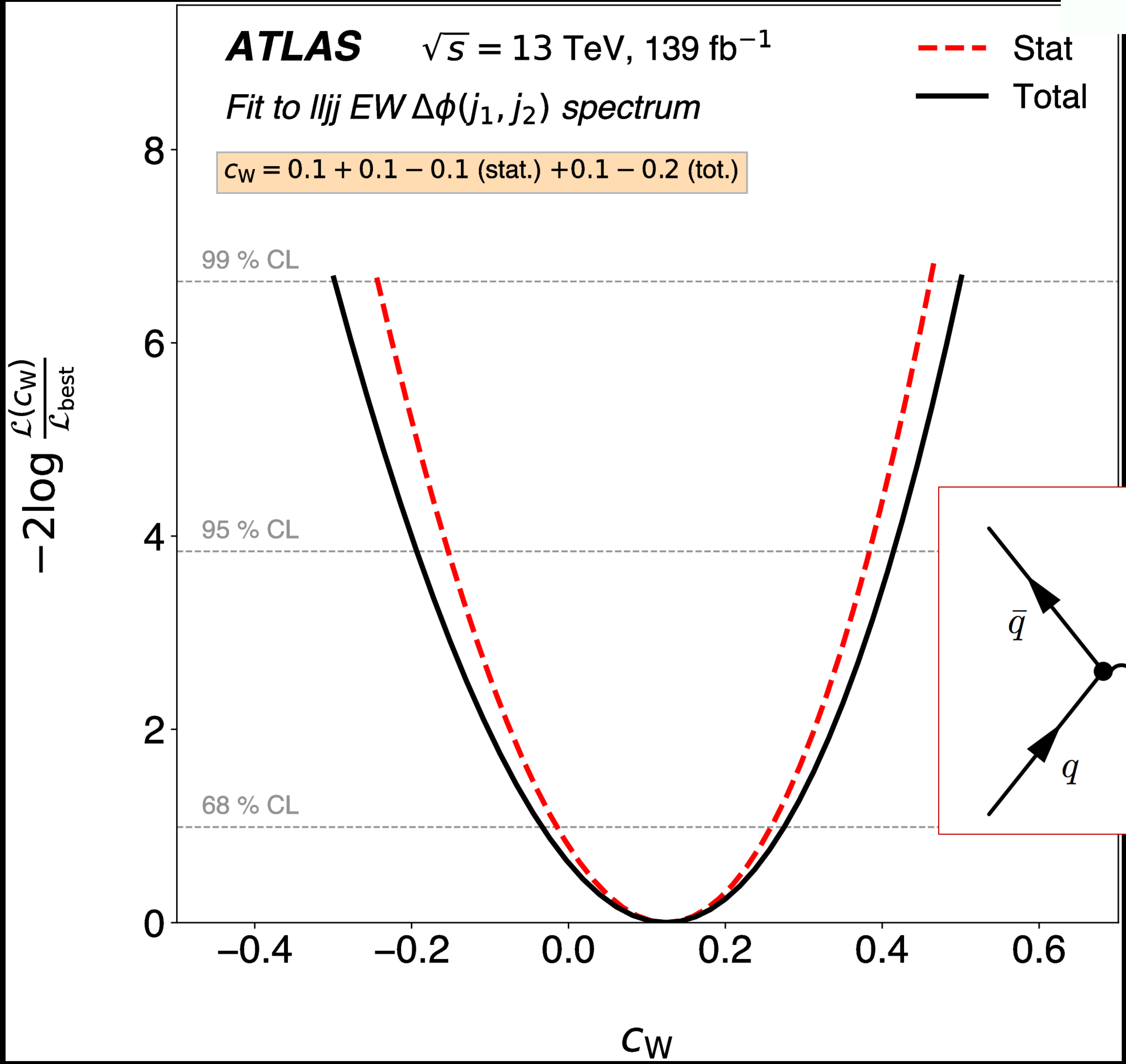
CMS: W+W– production

CMS-PAS-SMP-18-004

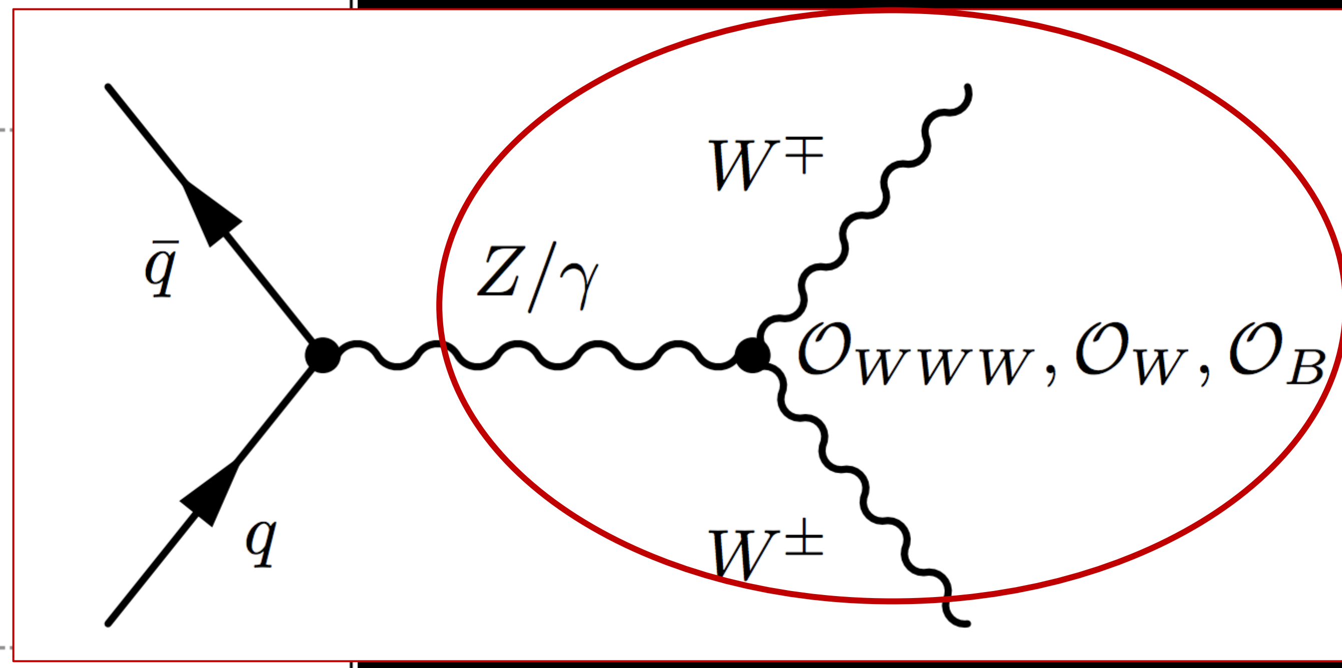


ATLAS: EWK Z+dijet

arXiv:2006.15458



aTGCs in W+W–



Motivation of Vector Boson Scattering

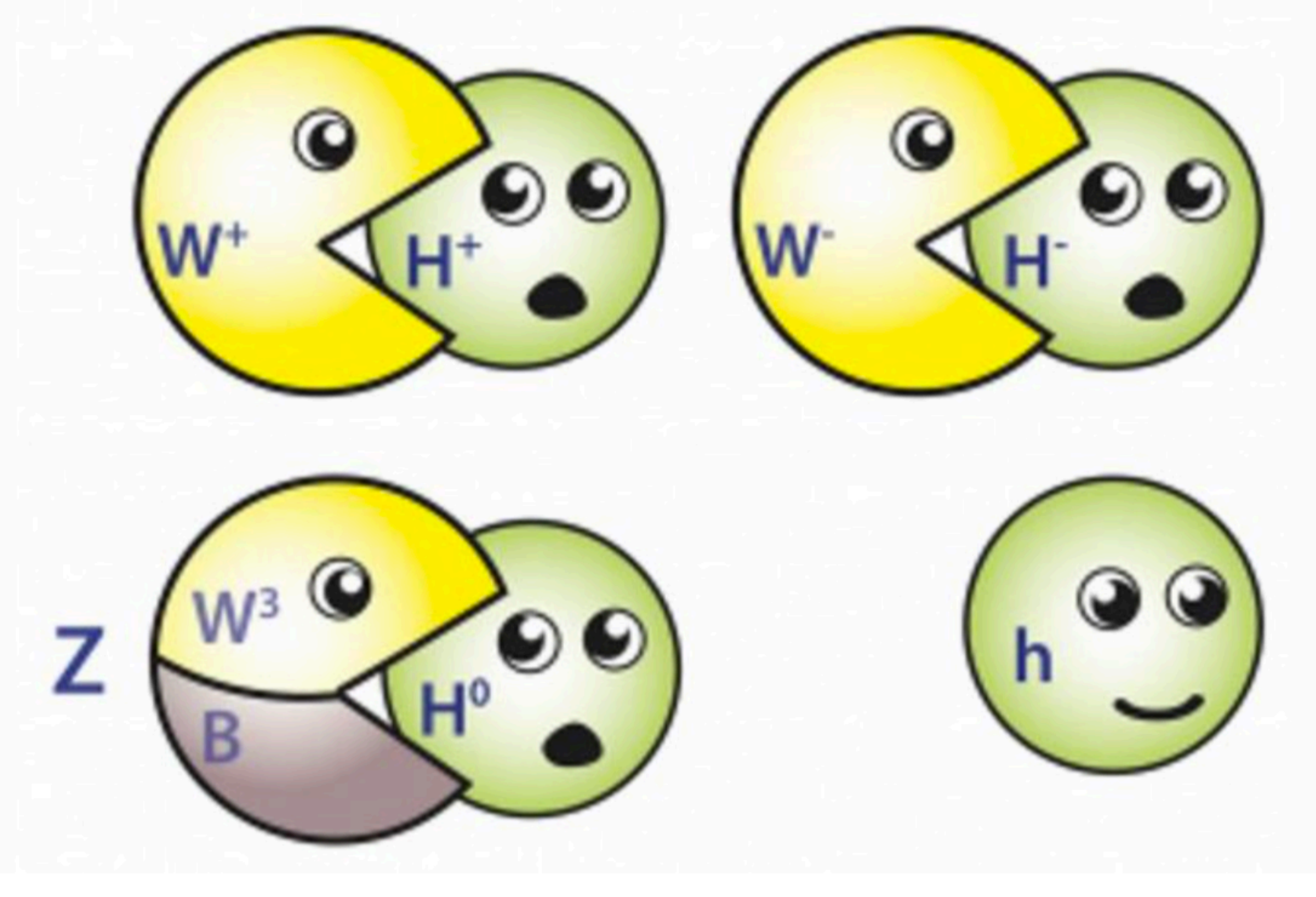
- Higgs Boson alone responsible for Electroweak Symmetry Breaking (EWSB)?

→additional Higgs bosons may still play a role in the EW symmetry breaking.

- Vector boson scattering (VBS) processes

→Key process to probe nature of EWSB

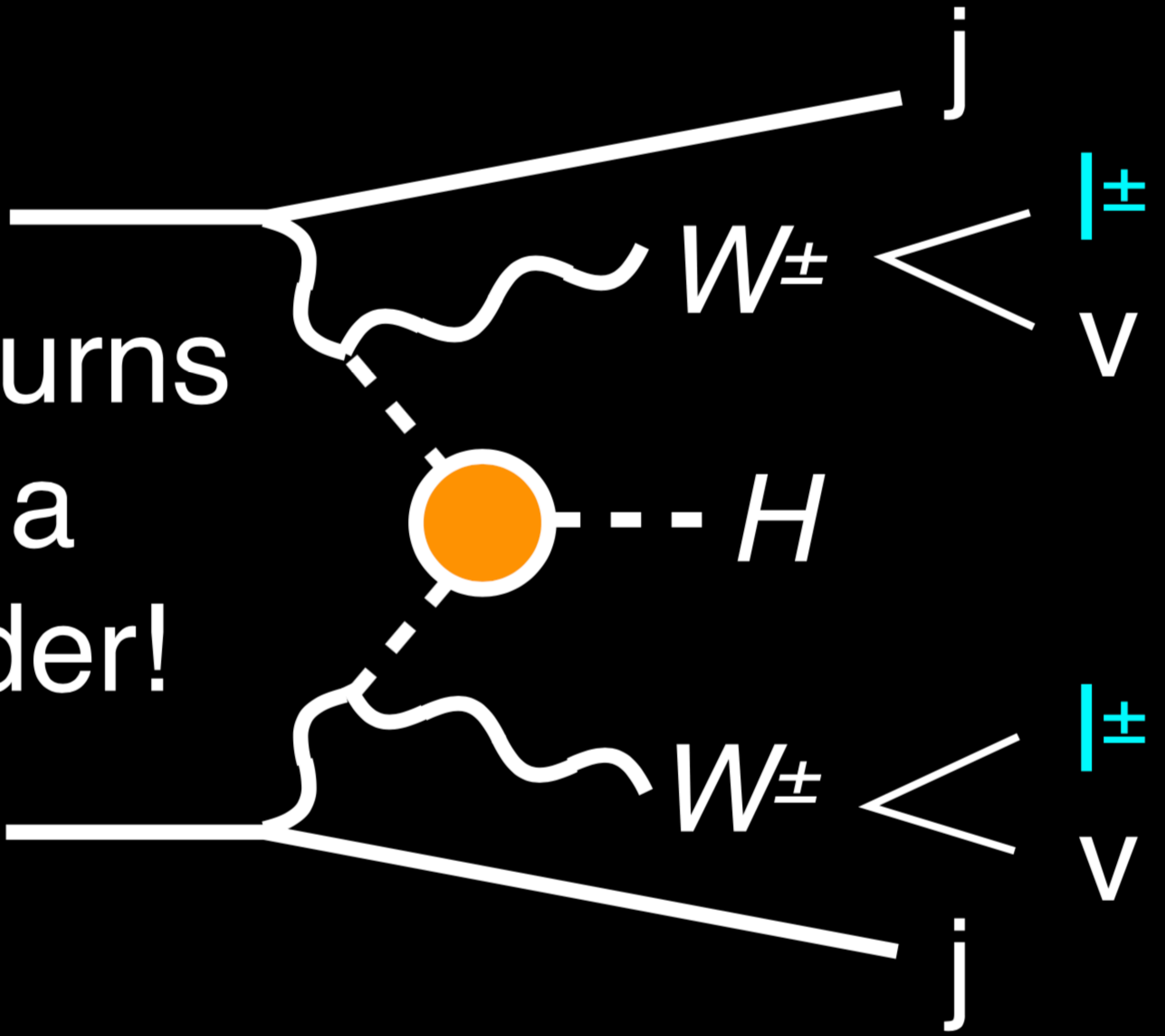
→complementary to direct Higgs boson measurements



- W and Z gauge bosons acquire longitudinal polarization via the Brout-Englert-Higgs mechanism：

→ 3 goldstone bosons $H^{\pm}$ and H^0 "eaten up" by W and Z

Same-sign turns LHC into a Higgs collider!



Polarization of WW pairs

- Two longitudinal polarized W pairs ($W_L W_L$)
- W pairs with one transversed (longitudinal) polarized , $W_T W_X$ ($W_L W_X$)
- Two transversed polarized W pairs ($W_T W_T$)

Unpolarized WW/WZ VBS Full Run II

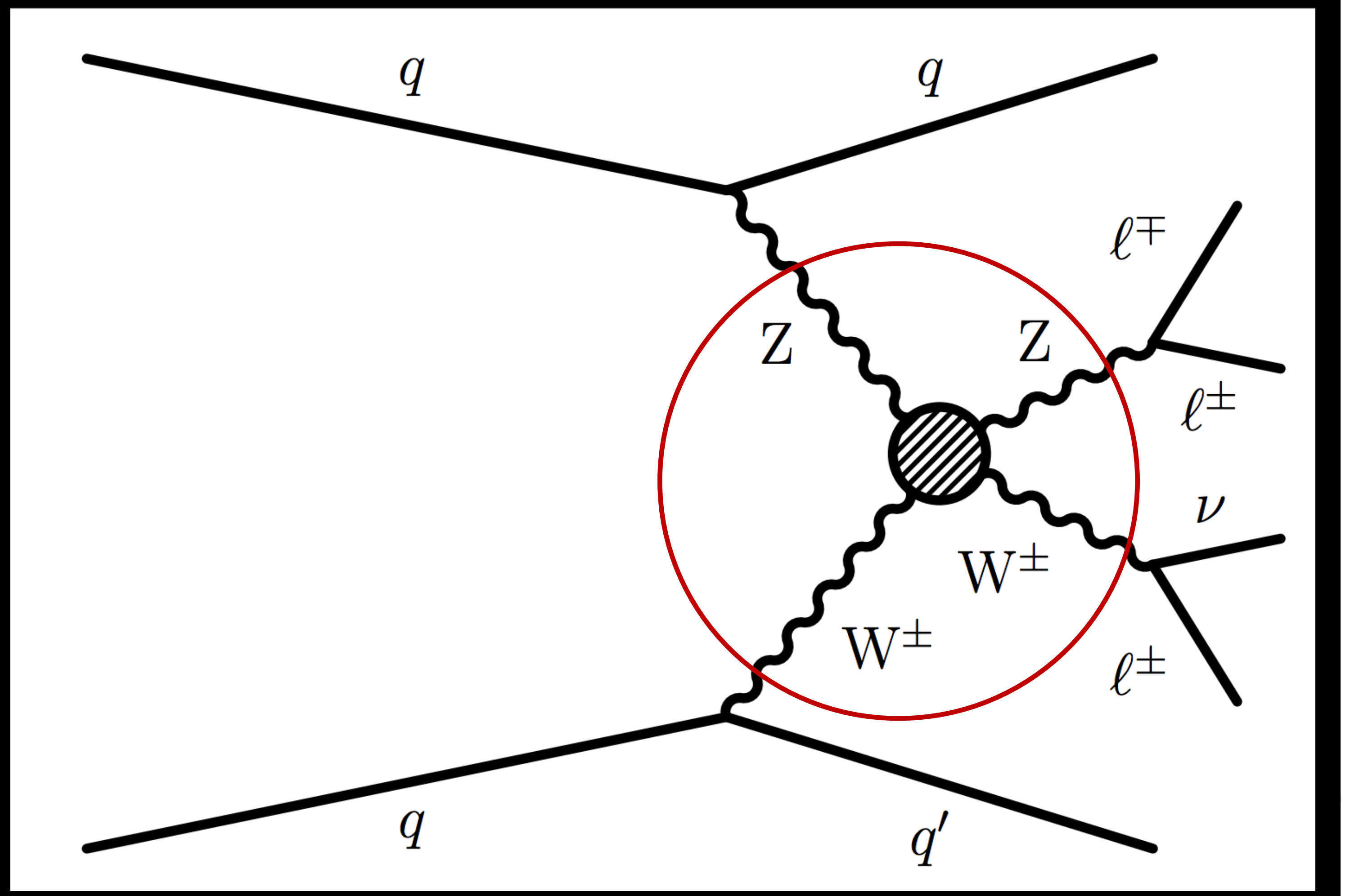
➢ **An observation of electroweak production of WZ boson pairs by CMS**

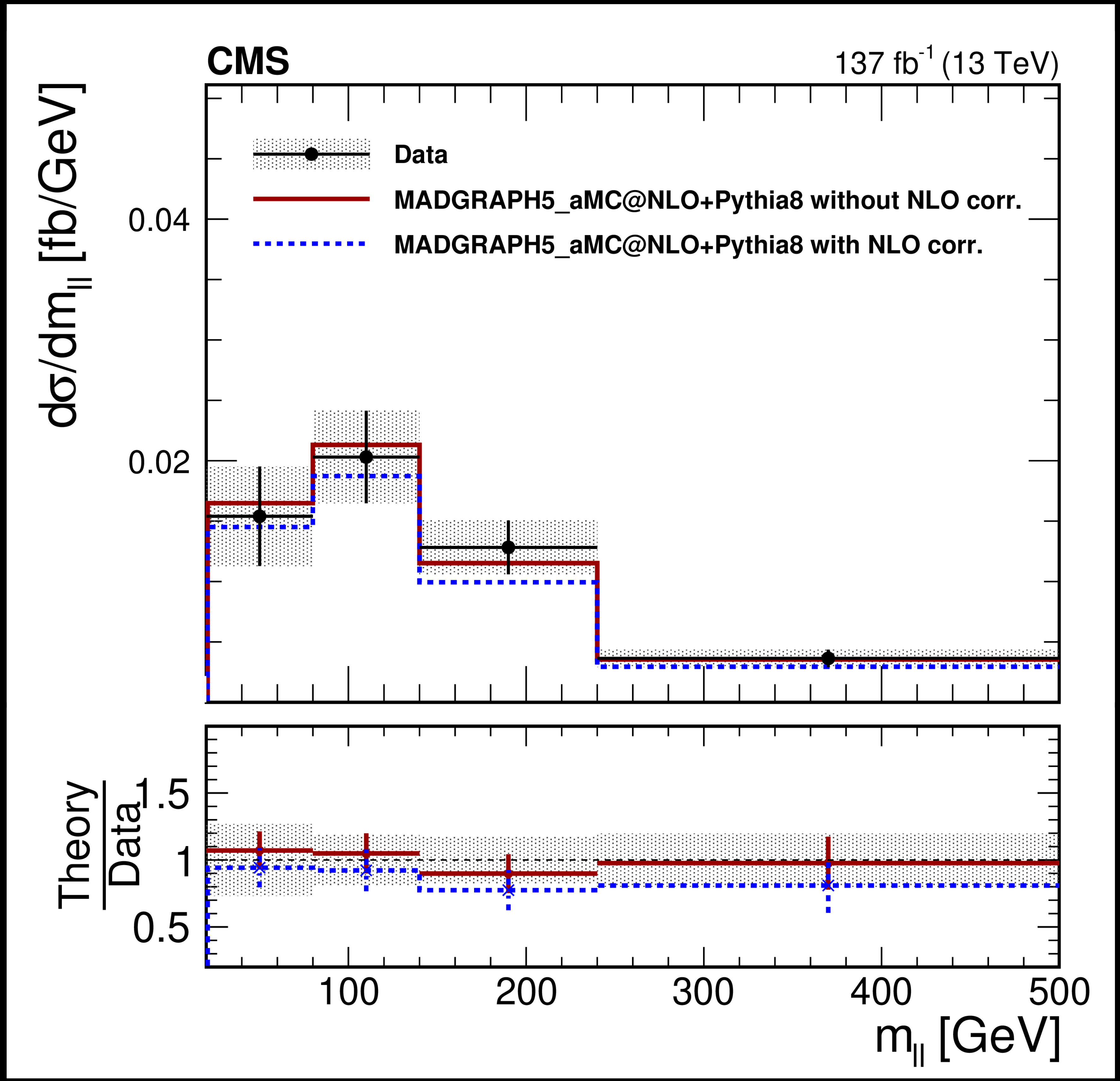
Event selection highlight
- ☐ 2 same-sign leptons (WW)
- ☐ 3 leptons (WZ)
- ☐ Dijet mass m_{jj} >500GeV

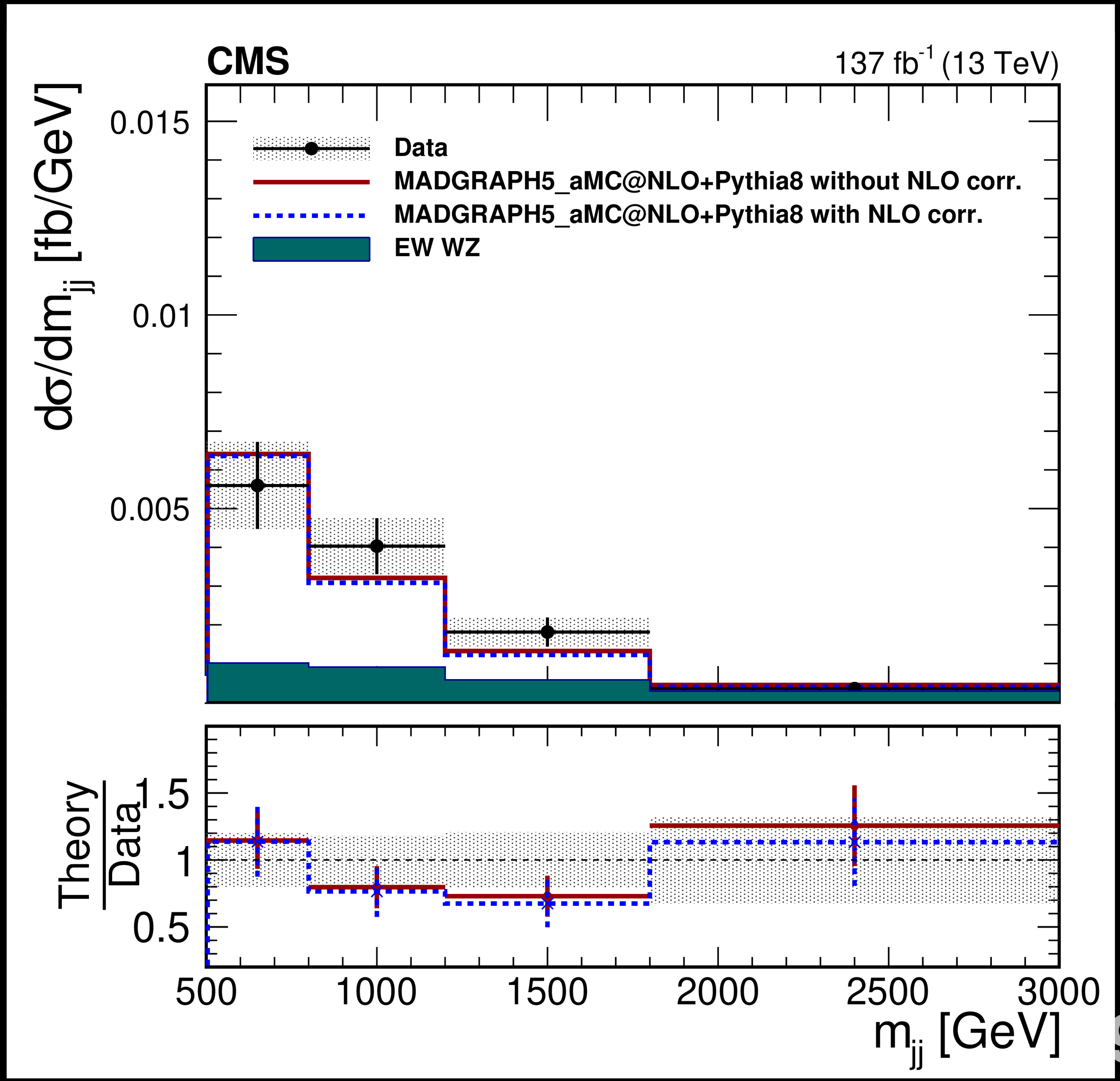
Observed (expected) Significance
EWK WZ: 6.8 (5.3)σ
EWK WW: far above 5 σ

Phys. Lett. B 809 (2020) 135710

WZ VBS







Polarized $W^{\pm}W^{\pm}$ VBS Full Run II

CMS PAS-SMP-20-006

- **First measurements of EW production cross sections of polarized $W^{\pm}W^{\pm}$**
- **1st Goal : measure two longitudinal polarized W pairs ($W_L W_L$)**
- **2nd goal: W pairs with at least one longitudinal polarized , $W_L W_X$**

Event selection highlight

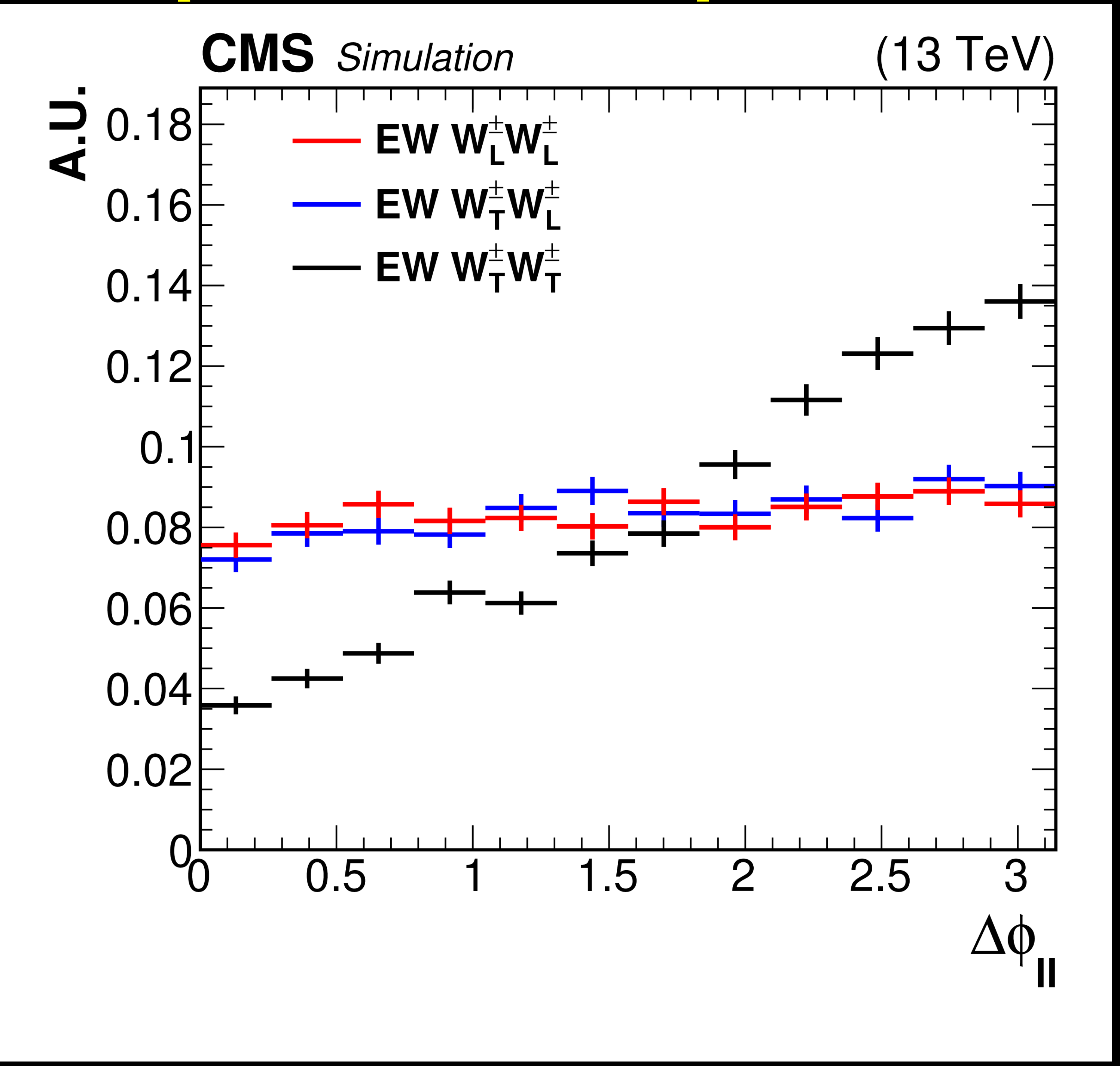
- 2 same-sign leptons
- Dijet mass m_{jj} >500GeV

Process	Yields in $W^{\pm}W^{\pm}$ SR
$W^{\pm}_L W^{\pm}_L$	16.0 ± 18.3
$W^{\pm}_L W^{\pm}_T$	63.1 ± 10.7
$W^{\pm}_T W^{\pm}_T$	110.1 ± 18.1

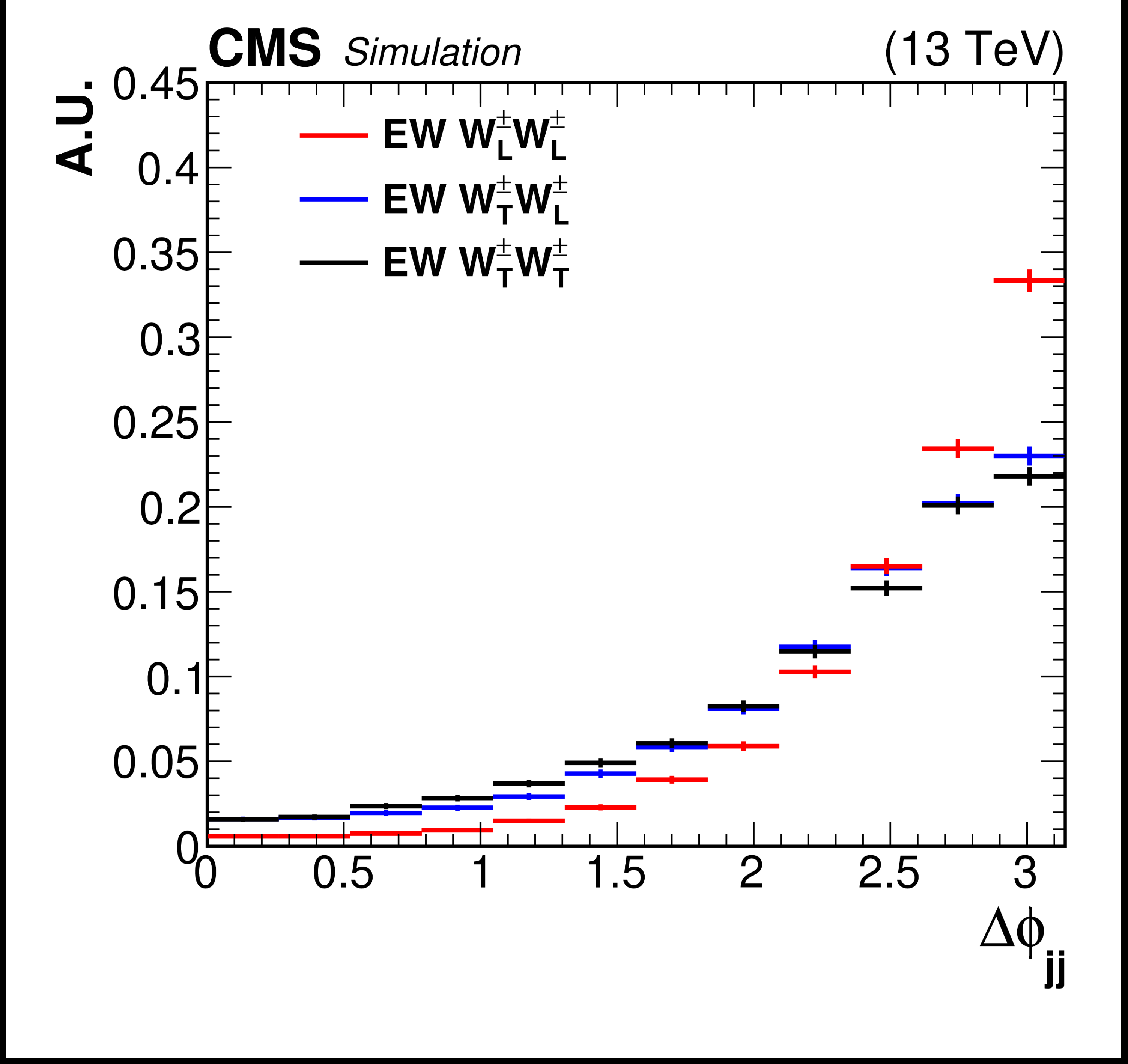
Multivariate Analysis

- Two Signal BDTs
  - measure $W_L W_L$ and $W_X W_T$
  - measure $W_L W_X$ and $W_T W_T$

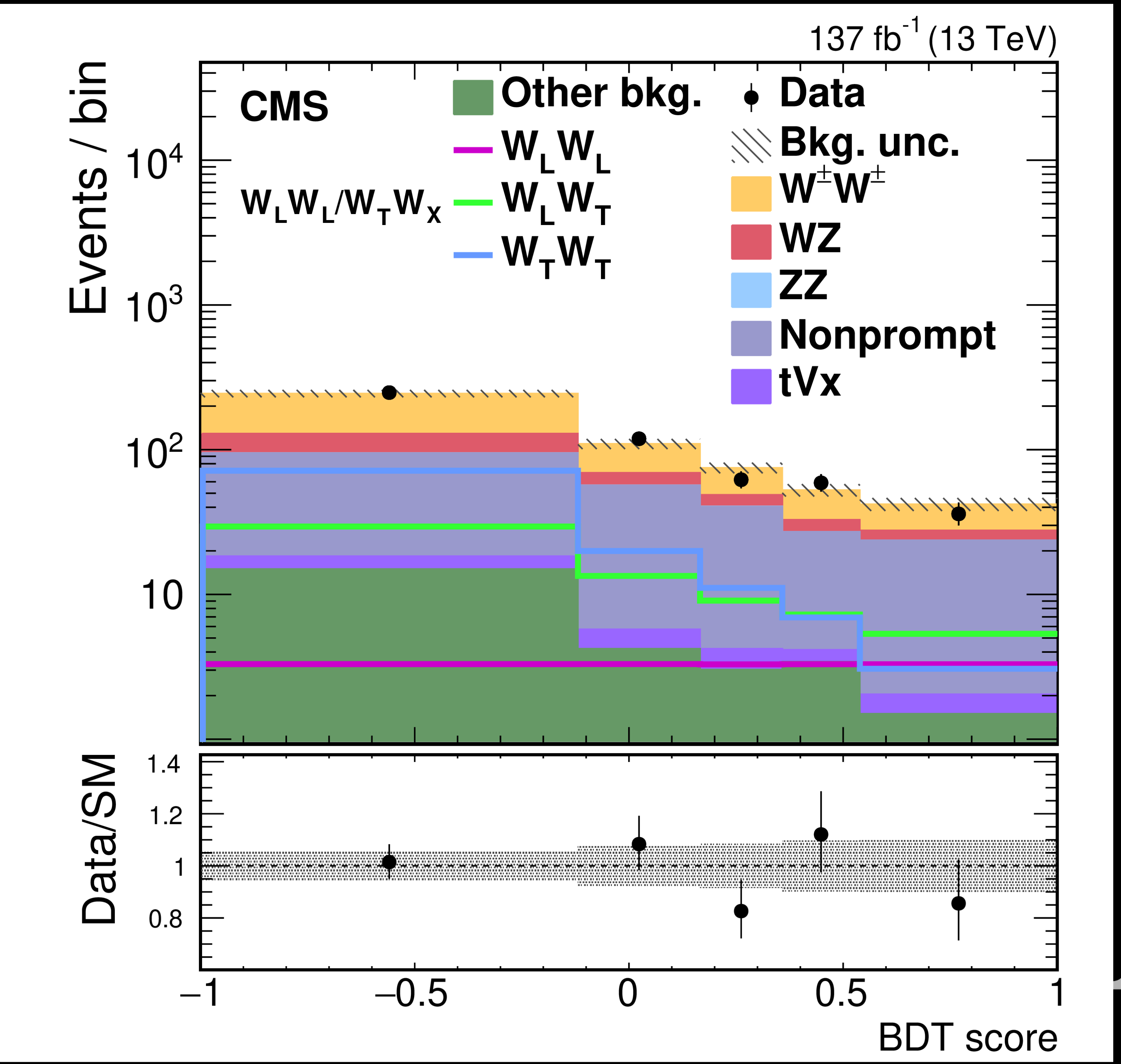
Δϕ between leptons



Δϕ between VBF jets



BDT score for $W_L W_L$ and $W_X W_T$



Polarized $W^{\pm}W^{\pm}$ VBS Full Run II

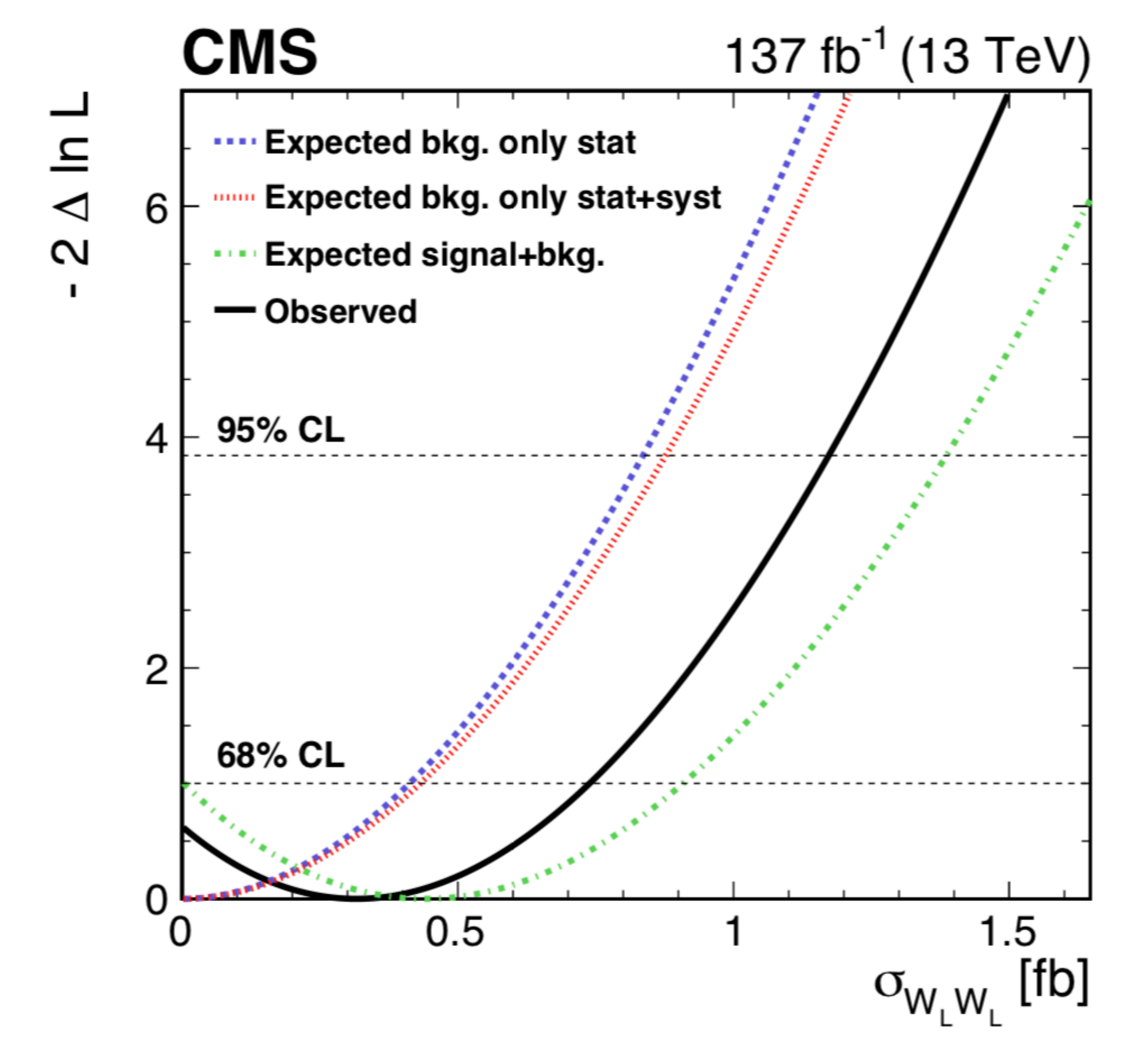
CMS PAS-SMP-20-006

- **First measurements of EW production cross sections of polarized $W^{\pm}W^{\pm}$**
- **need more data to observe two longitudinal polarized W pairs, W_LW_L**
- **Expected significance for W_LW_X is around 3 σ**

□ $W^{\pm}W^{\pm}$ center-of-mass Frame:
Observed (expected) significance: (W_LW_X) : 2.3 (3.1) σ

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_{X}W^{\pm}_{T}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^{\pm}_{T}W^{\pm}_{T}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

Searching for W_LW_L



□ China CMS(PKU) team is playing a leading role

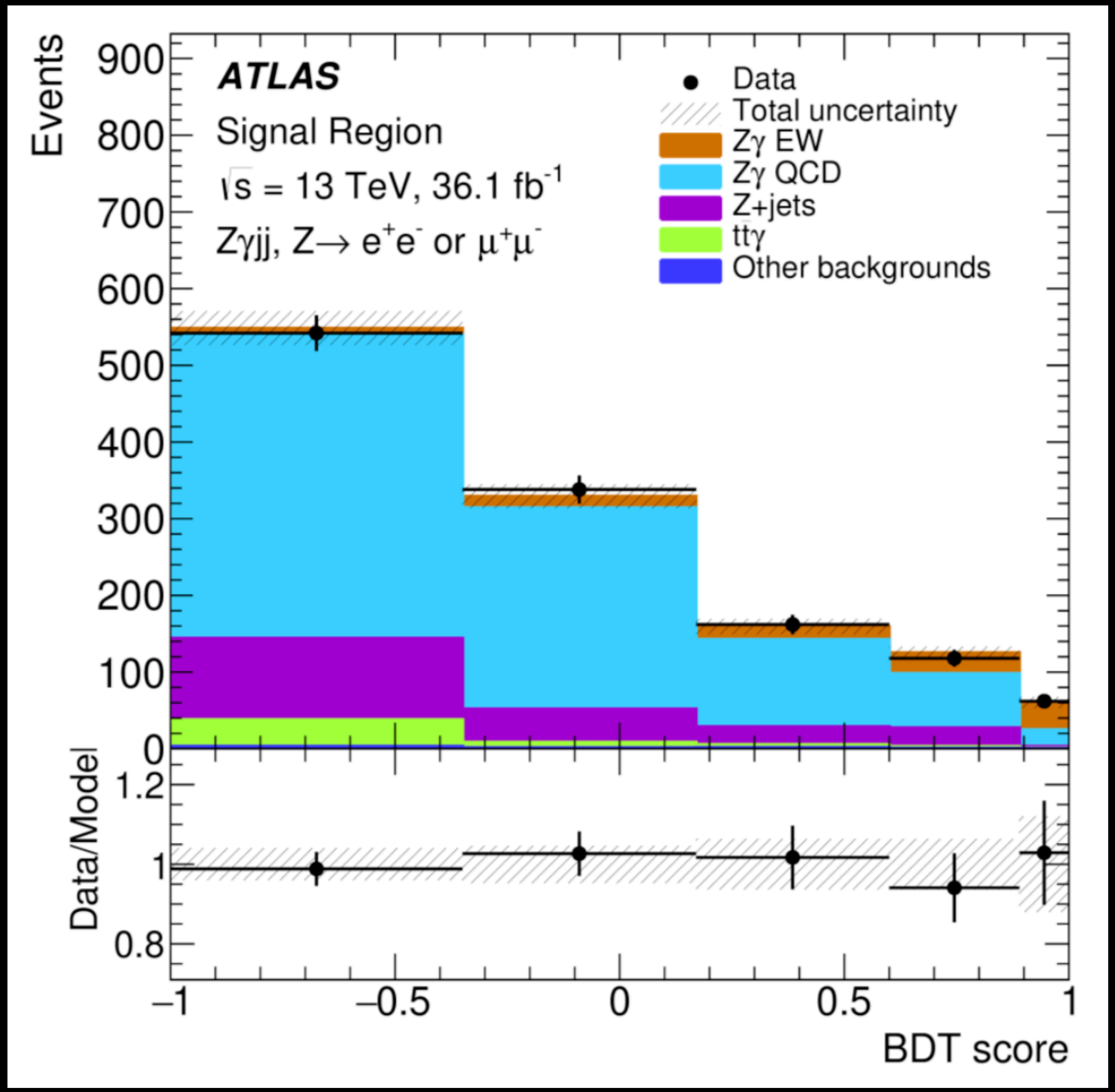
CMS Collaboration Highlight

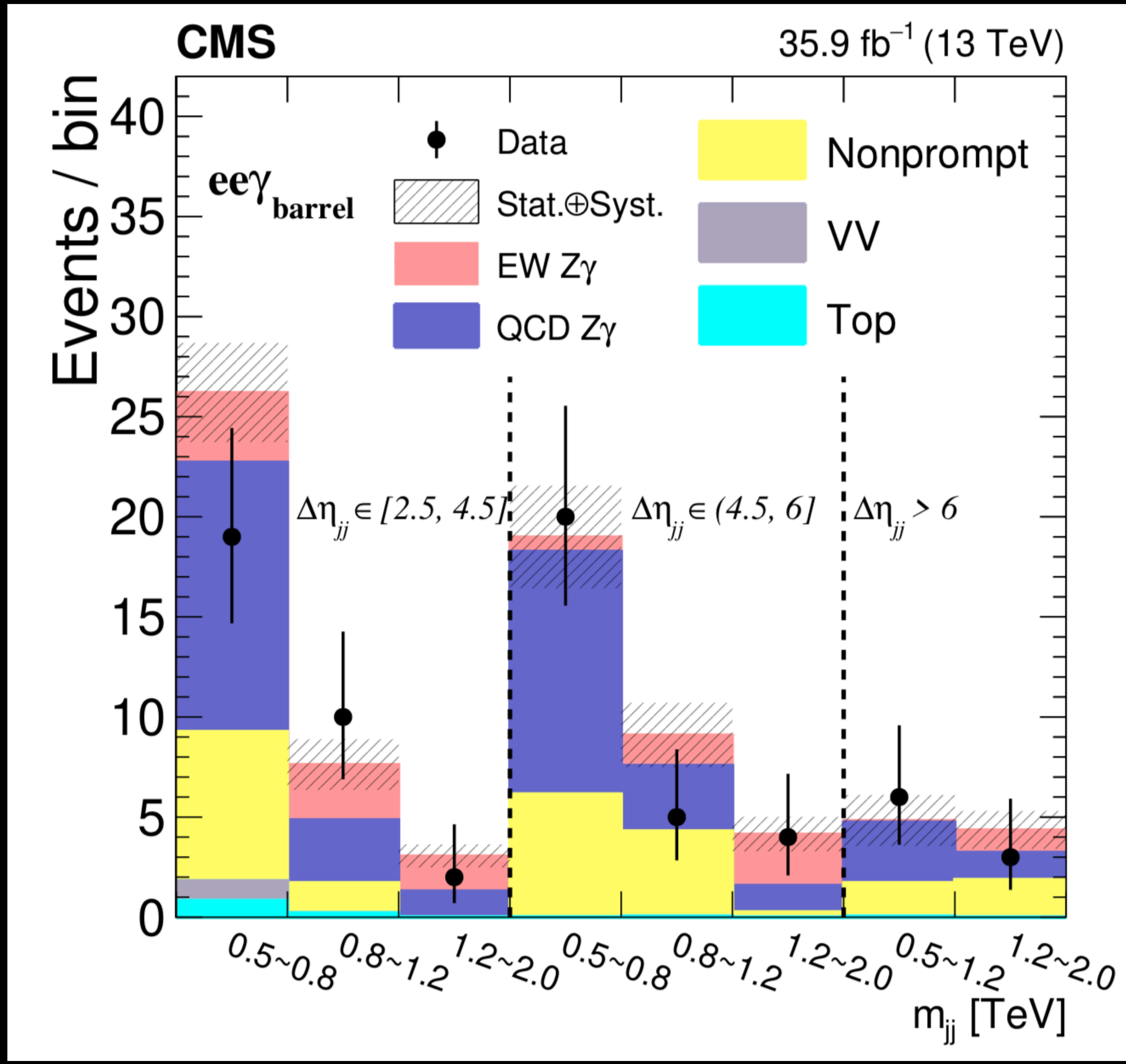
Boson-boson collider hiding inside proton-proton collisions

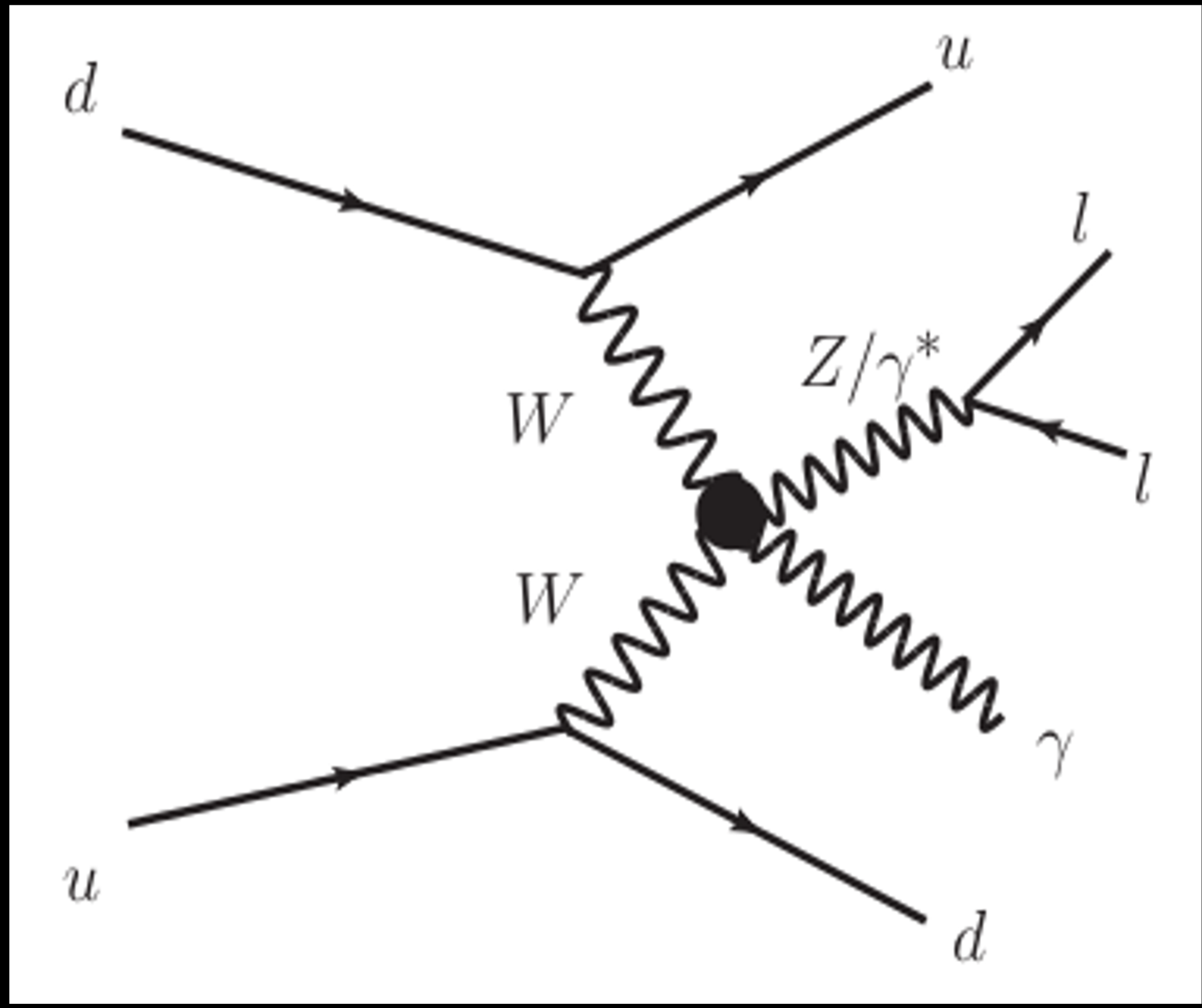
"These heavy boson-boson collisions inside the LHC provide physicists with a unique view of the subatomic world."

Zγ VBS

- **CMS: Observation of Zγ VBS processes (36 fb^{-1}), JHEP 06 (2020) 076**
  - →Observed (expected) significance: 5.5 (4.7)σ
  - → China CMS team (PKU) plays a leading role
- **ATLAS: Evidence of Zγ VBS processes (36 fb^{-1}), Phys. Lett. B 803 (2020) 135341**
  - →Observed (expected) significance: 4.1 (3.8)σ,
  - → China ATLAS team (TDLI) plays an important role



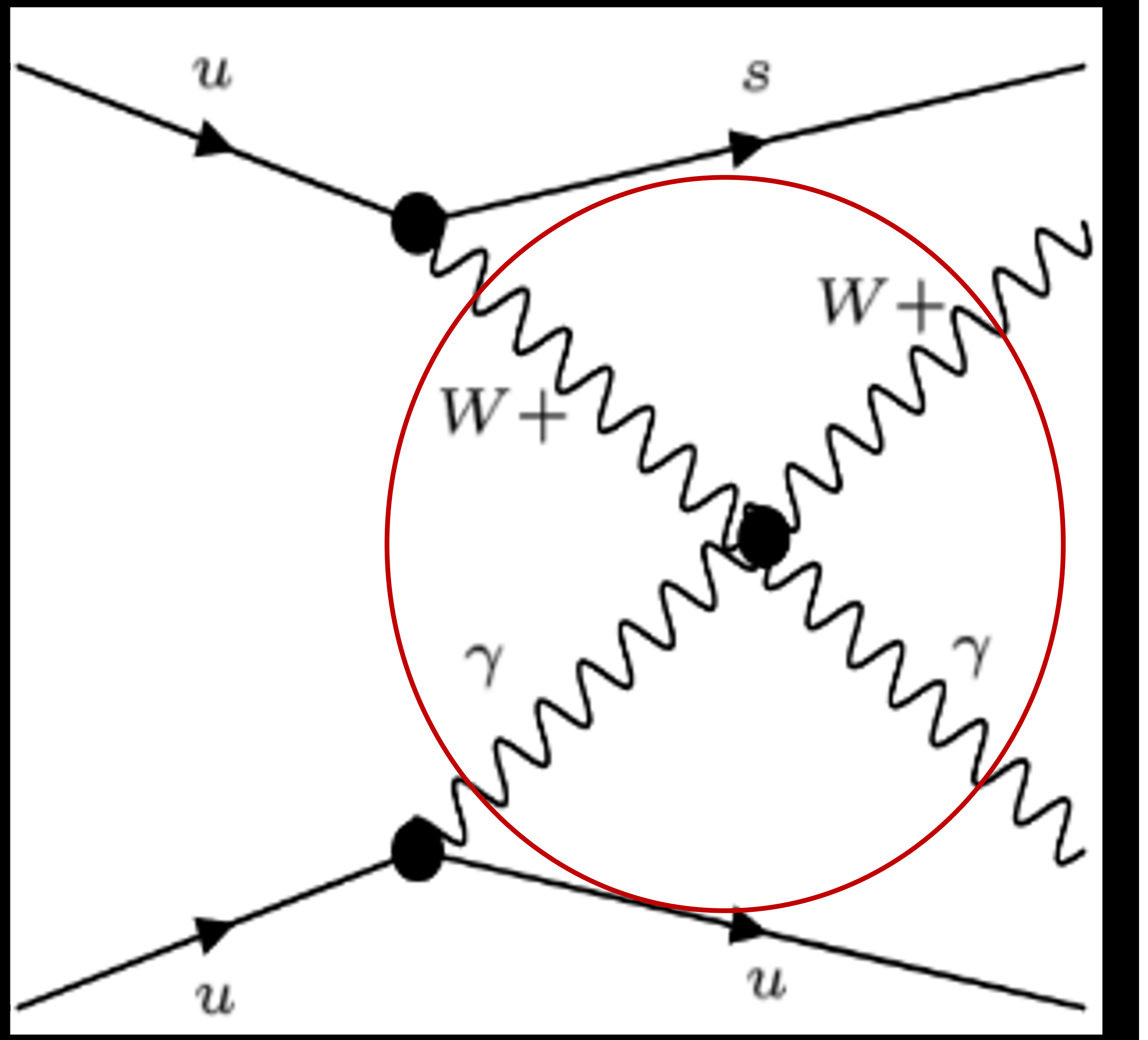


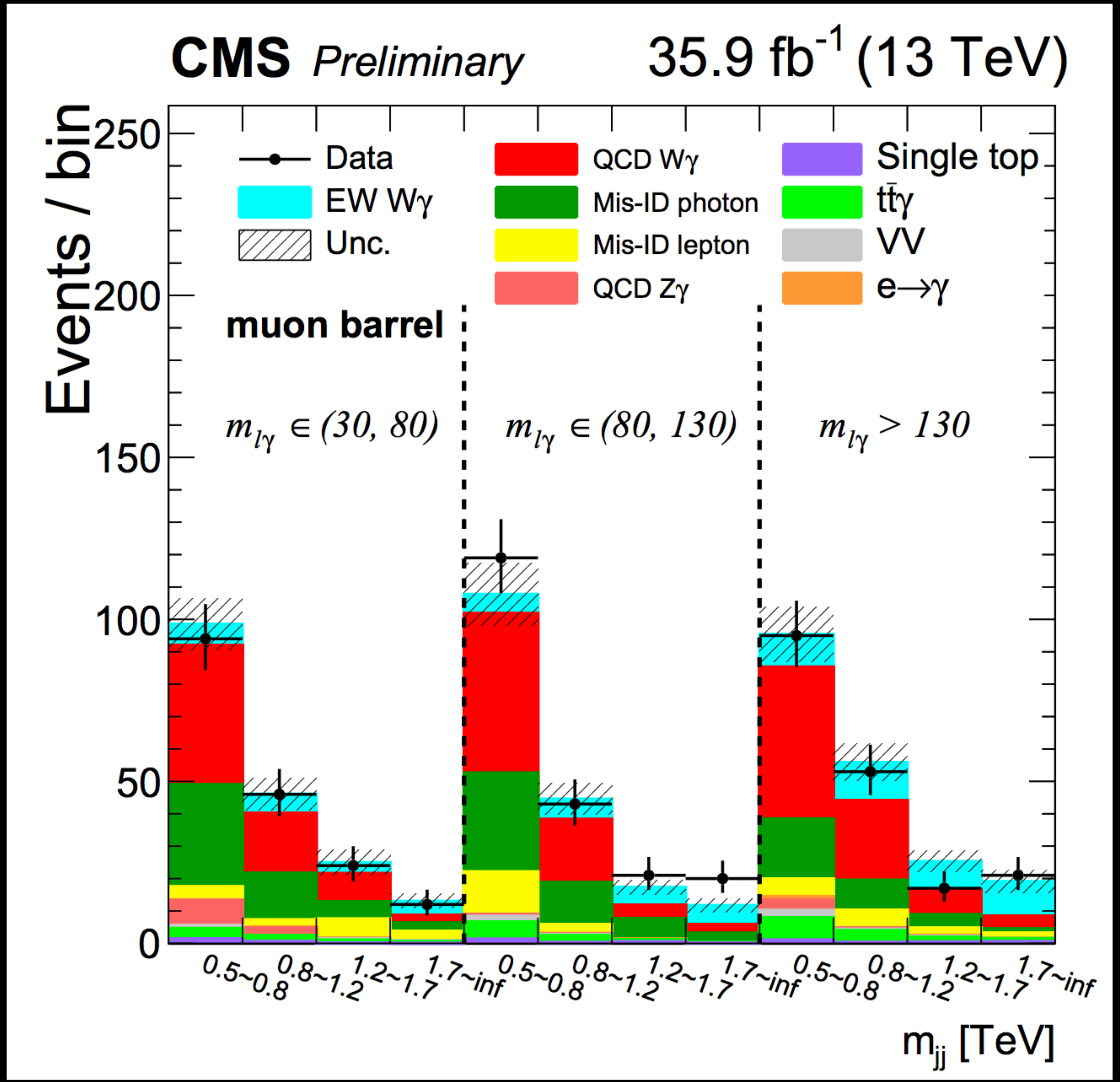


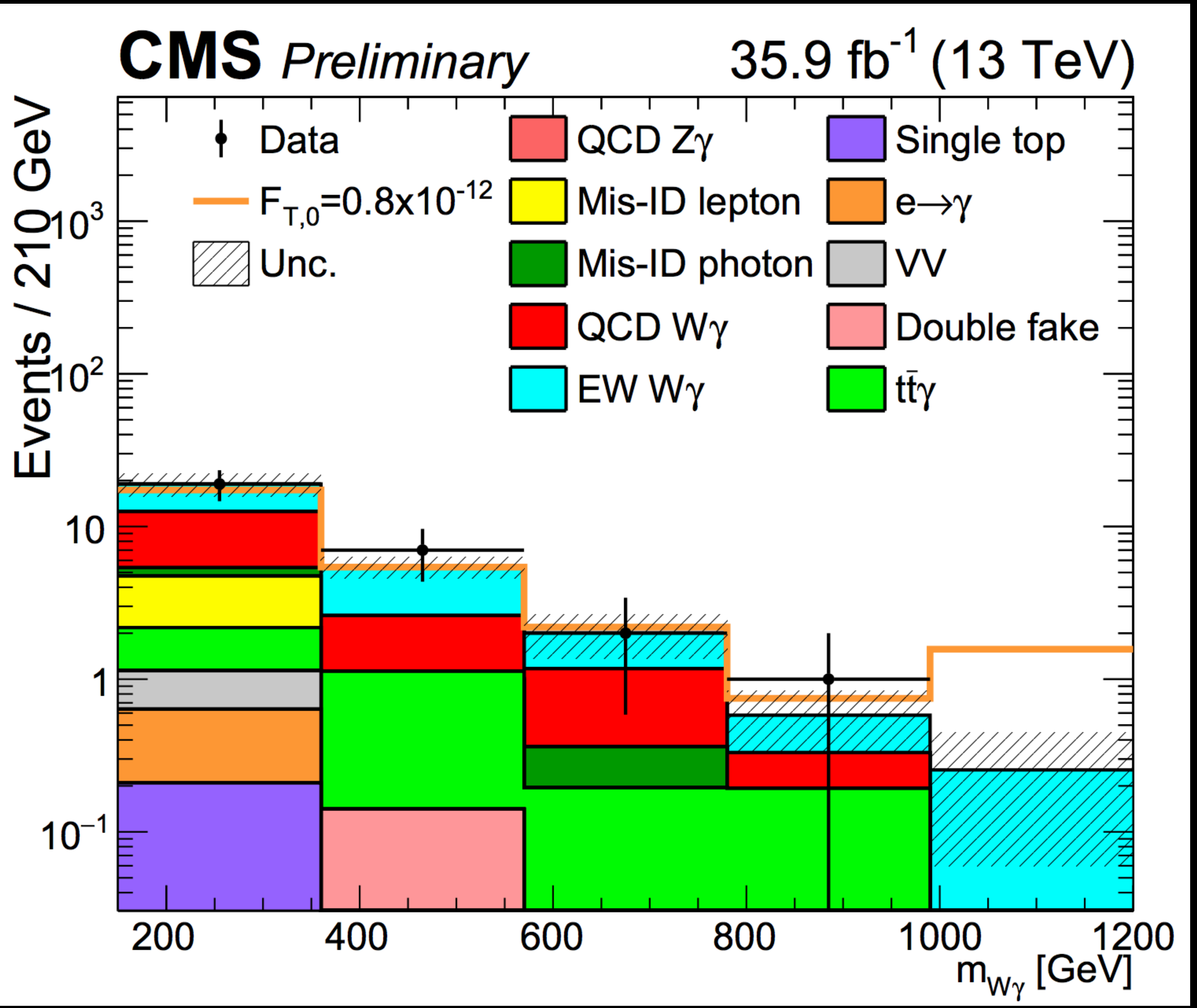
Wγ VBS

CMS-PAS-SMP-19-008

- **CMS: Observation of Wγ VBS processes** (run II 36 fb^{-1})
  - →Observed (expected) significance: **5.3 (4.8)σ,**
  - → use dijet mass(m_{jj}) and lepton+photon mass ($m_{l\gamma}$) to extract signal
  - → use Wγ mass ($m_{W\gamma}$) to search for anomalous quartic gauge couplings (aQGCs)
  - → China CMS team (PKU) plays a leading role

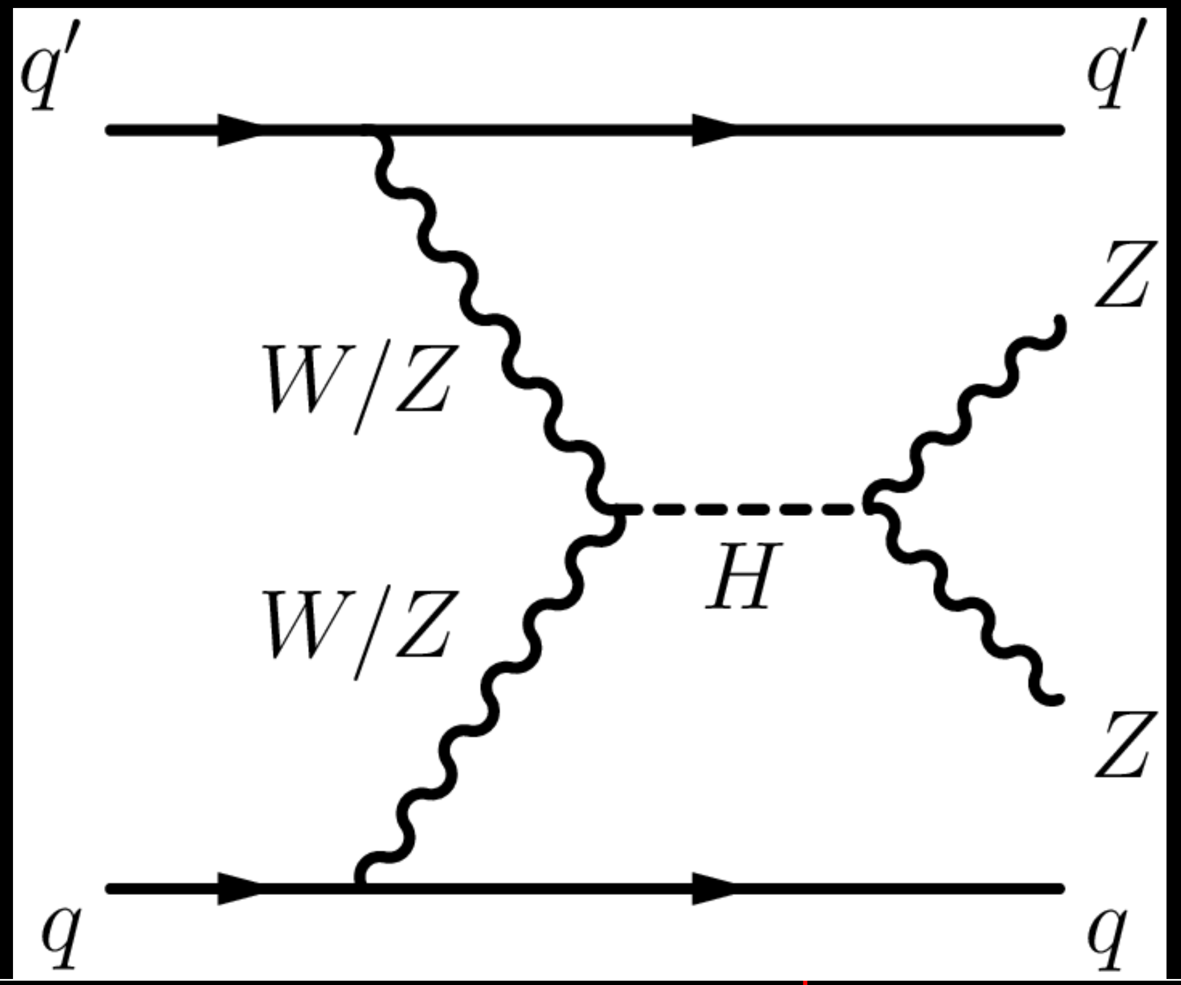




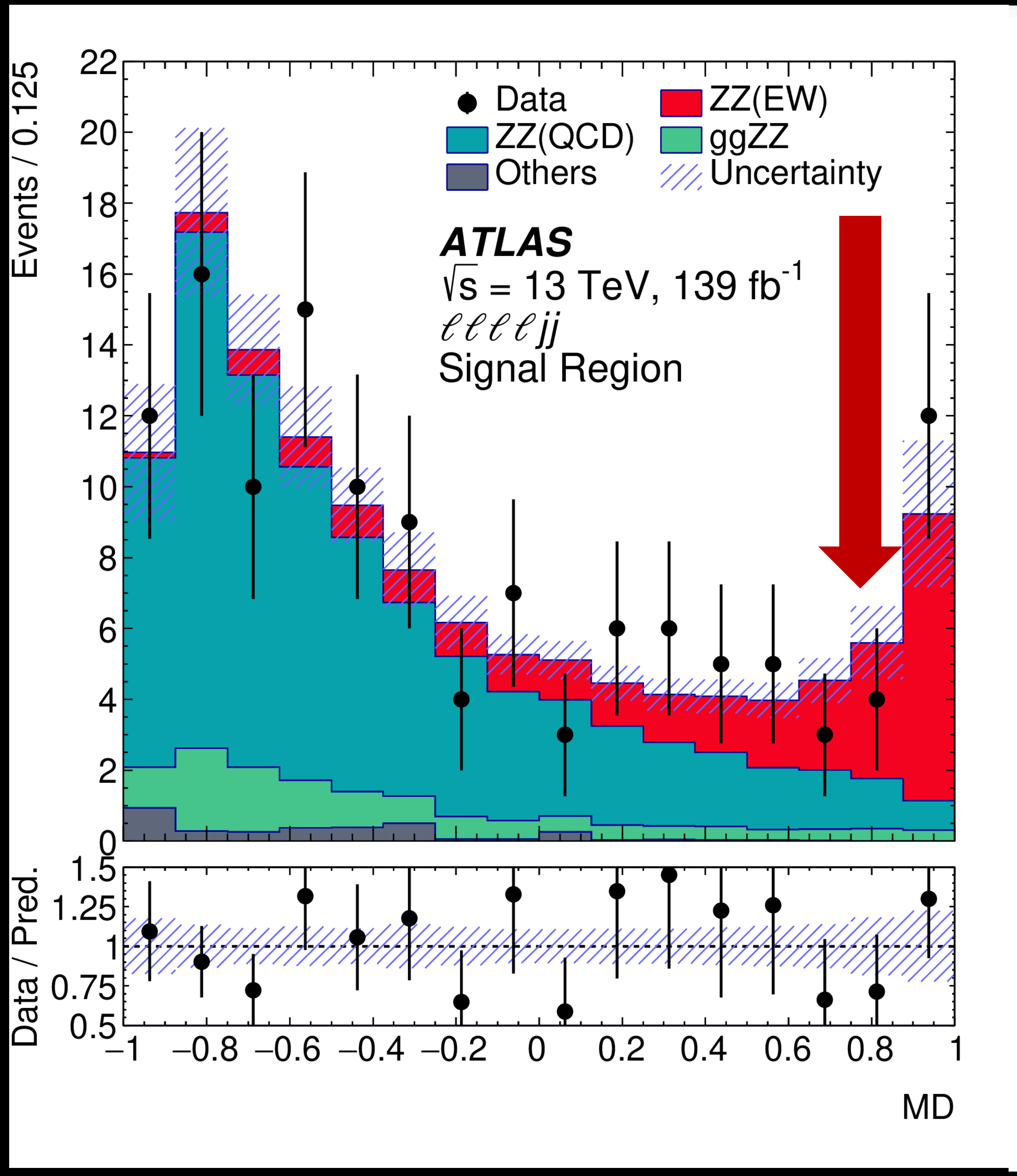


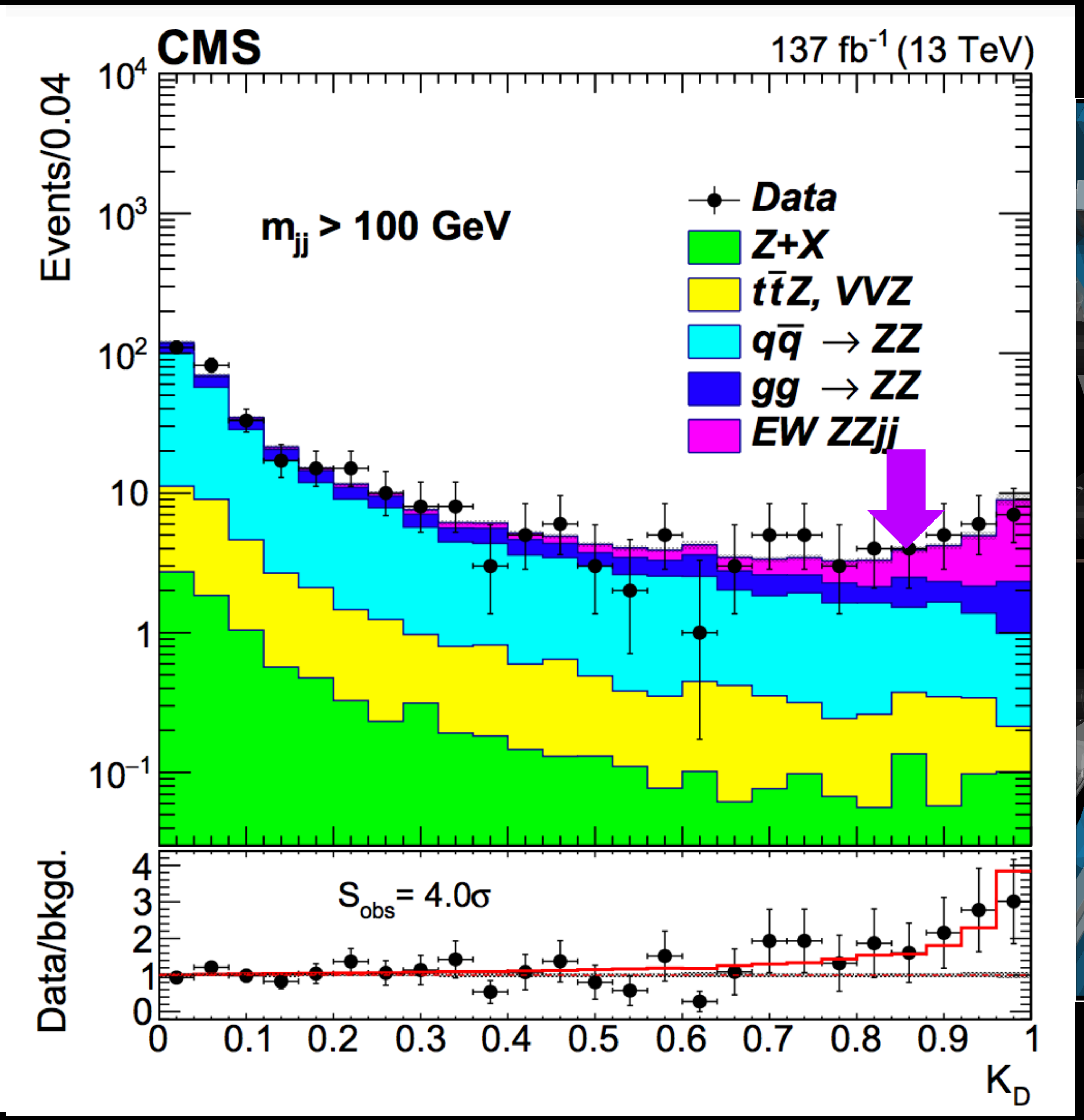
ZZ VBS Full Run II

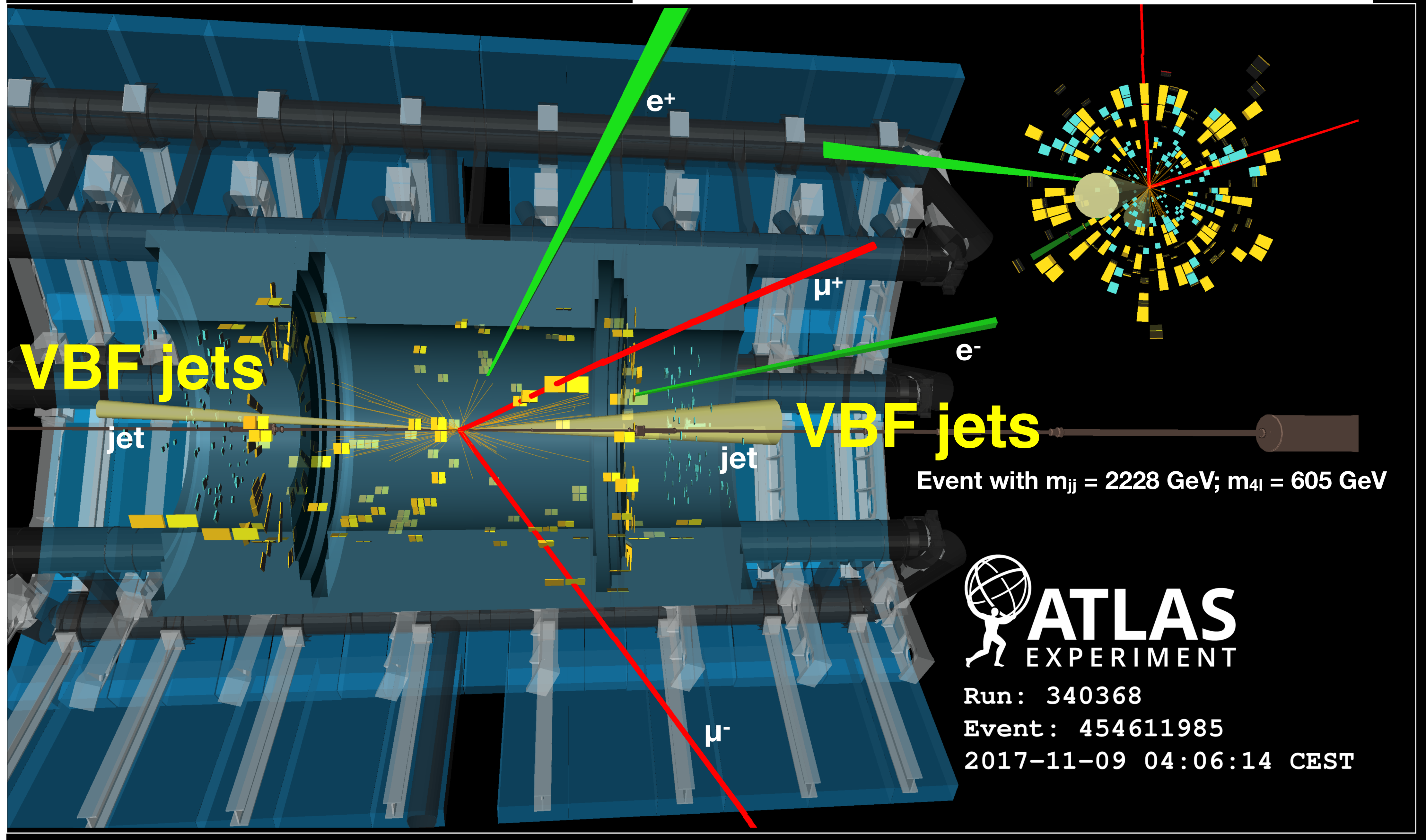
- ZZ VBS is rarest Vector boson scattering process
- **ATLAS: Observation of ZZ VBS processes (139 fb^{-1}), arXiv:2004.10612**
  - →Observed (expected) significance: **5.5 (4.3)σ,**
  - → China ATLAS team (USTC,TDLI) plays an leading role
- **CMS: Evidence for ZZ VBS processes (137 fb^{-1}), arXiv:2004.10612**
  - →Observed (expected) significance: **4.0 (3.5)σ**
  - →China CMS team (PKU) plays an important role



Multi-variable analysis output

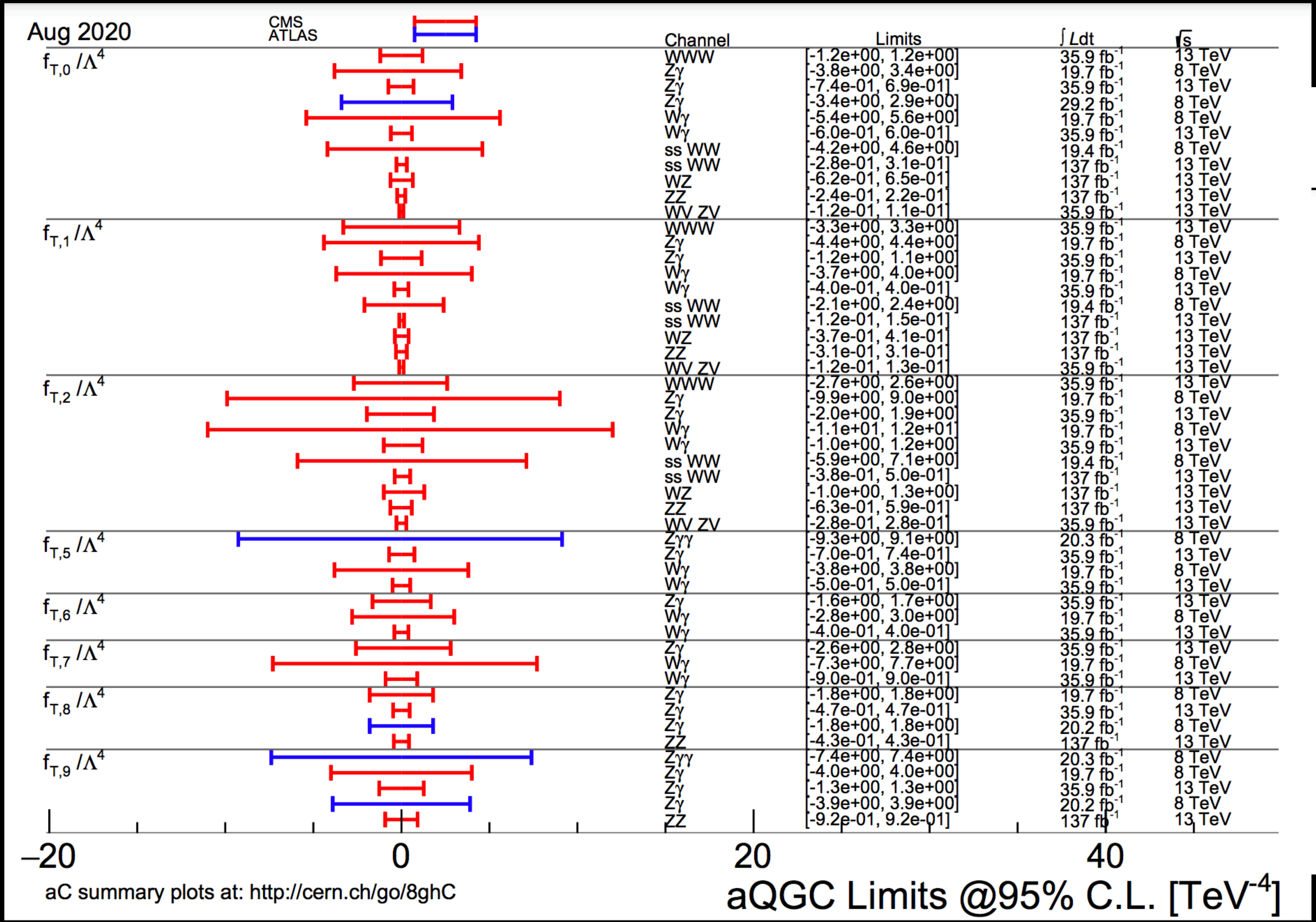


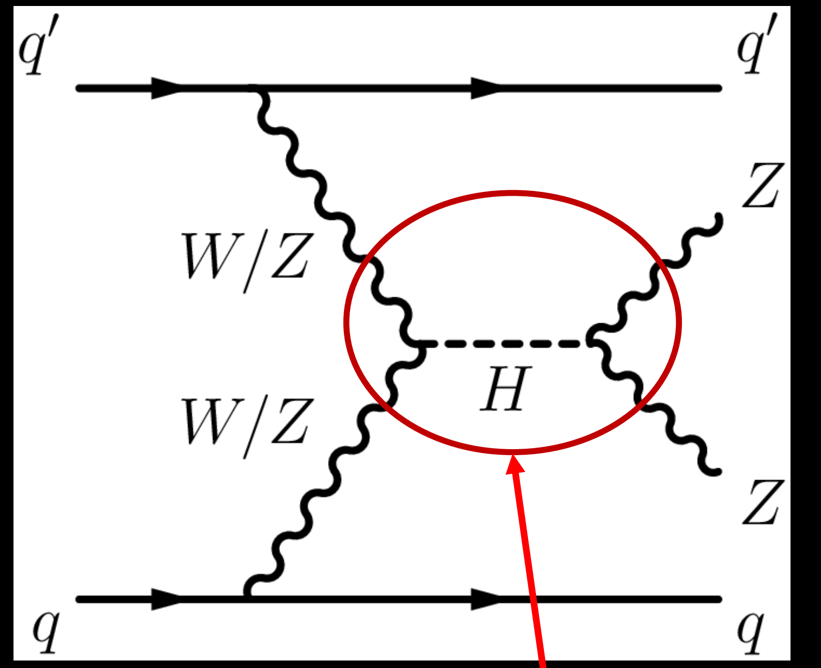




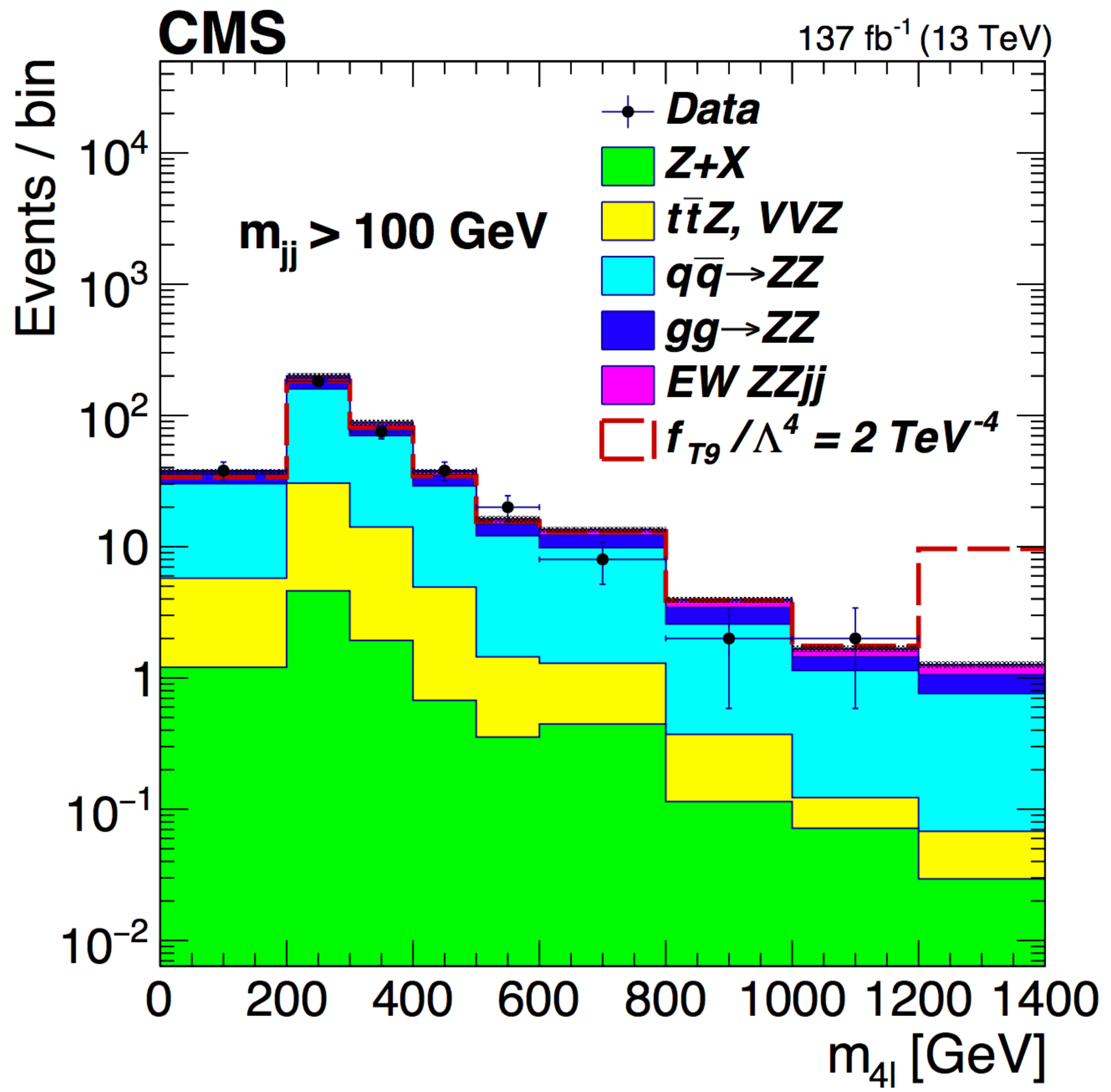
Anomalous quartic gauge couplings(aQGCs)

Combination on aQGCs limits with ATLAS/CMS results



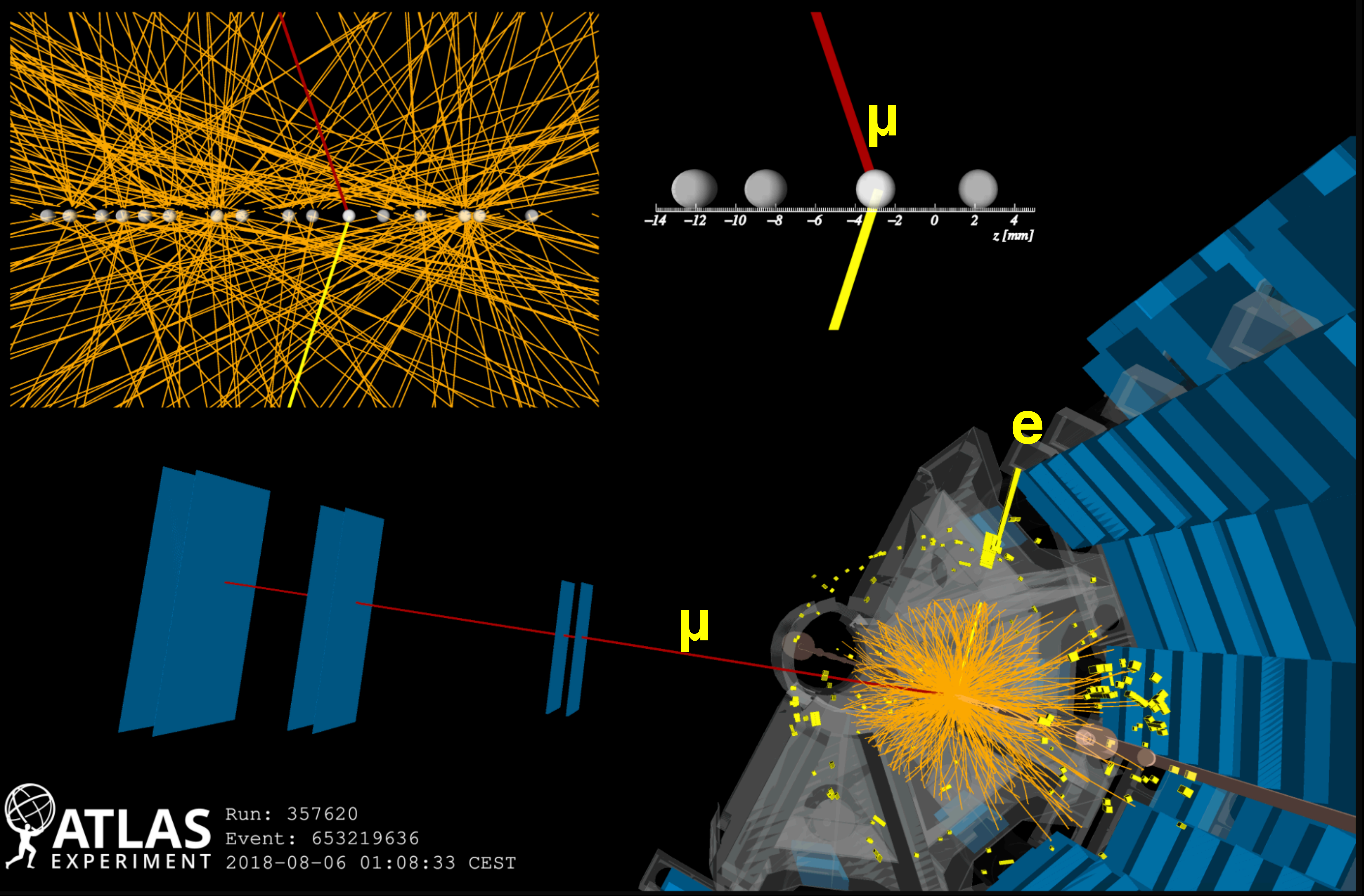


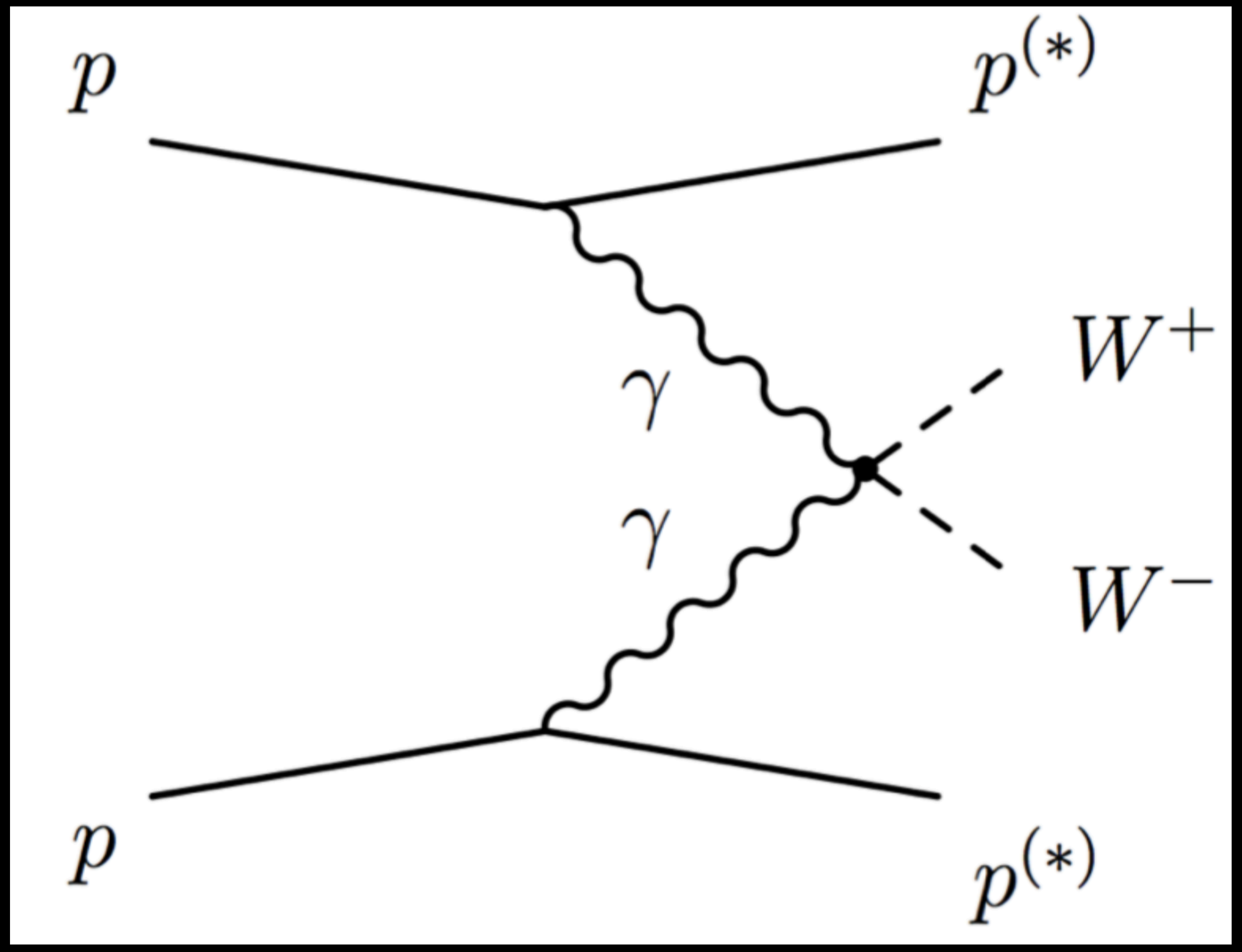
$$\mathcal{L}_{aQGC} = \sum_{i=0}^{2} \frac{f_{S_i}}{\Lambda^4} O_{S_i} + \sum_{j=0}^{7} \frac{f_{M_j}}{\Lambda^4} O_{M_j} + \sum_{k=0}^{9} \frac{f_{T_k}}{\Lambda^4} O_{T_k}$$



γγ→WW measurement in ATLAS

- **Rare electroweak process that probes SM γγWW vertex**
- **Key signature: No tracks near lepton vertex**
- **Event selection highlight : 1 electron + 1 μ, no additional tracks in primary vertex**



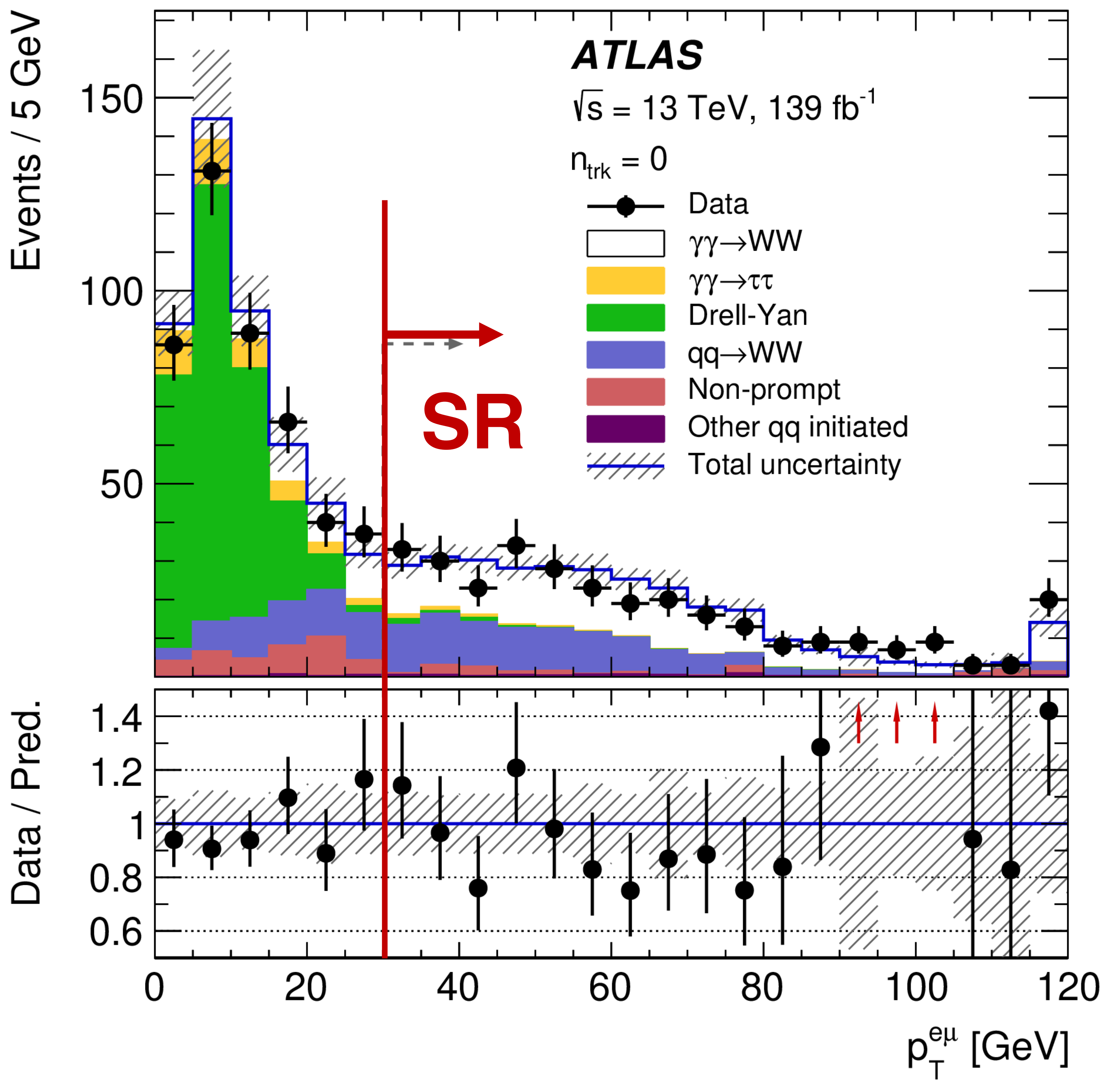


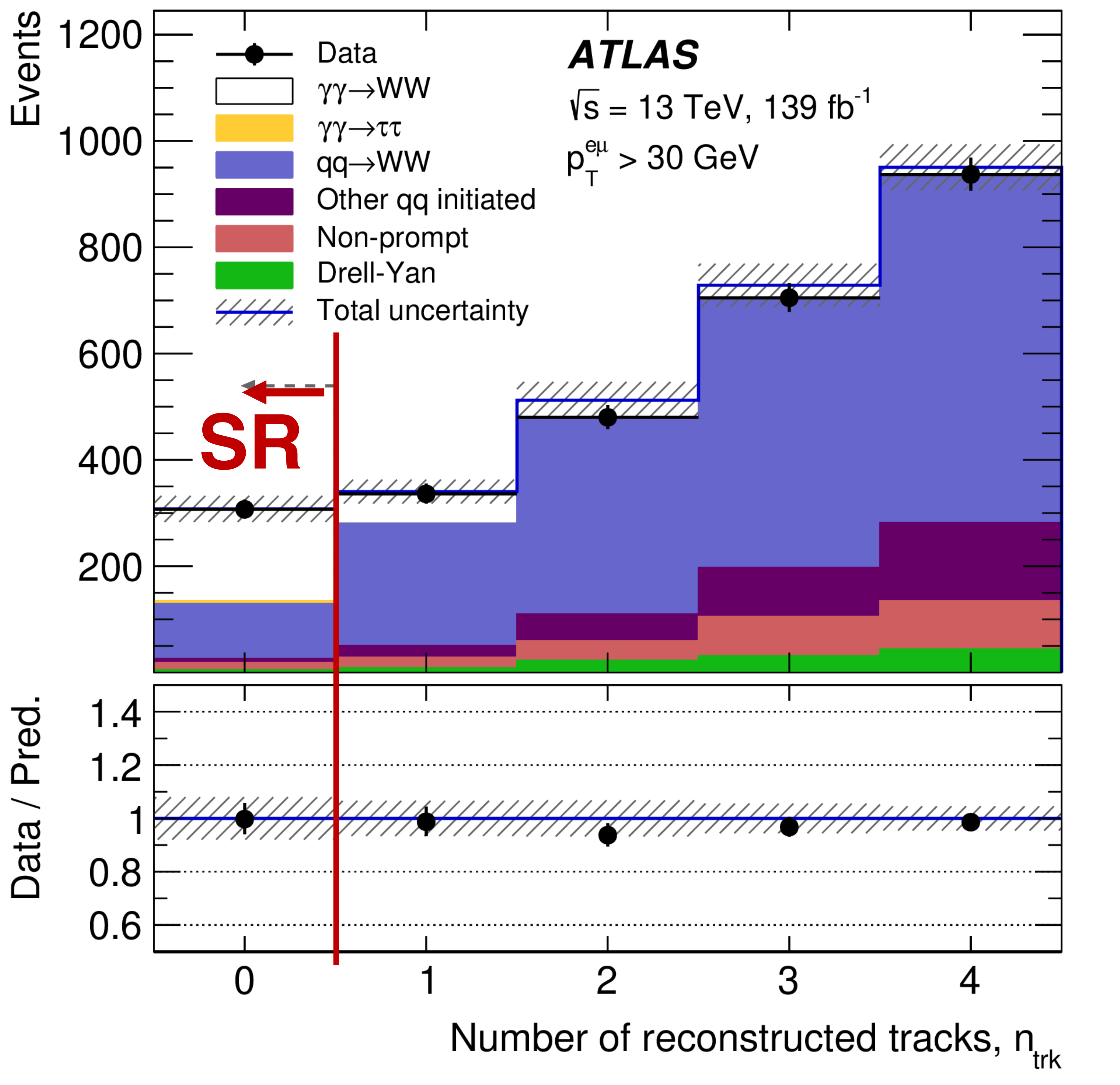
γγ→WW measurement in ATLAS (2)

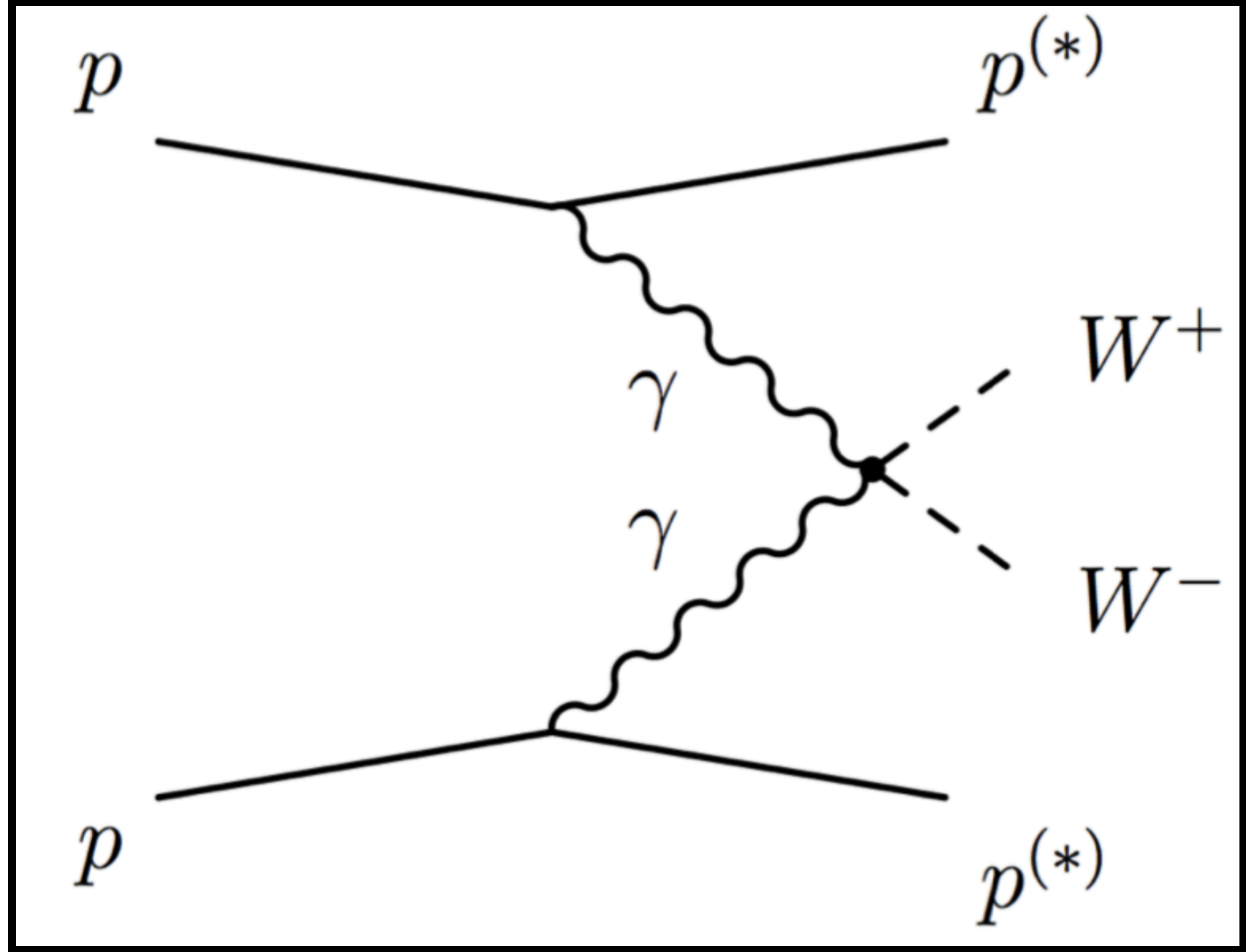
- **First observation of γγ→WW with a significance of 8.4σ (6.7σ expected)**
- **Event selection highlight : $p_T(e\mu)$>30GeV ($p_T(e\mu)$ as a Missing ET proxy)**

$p_T(e\mu)$

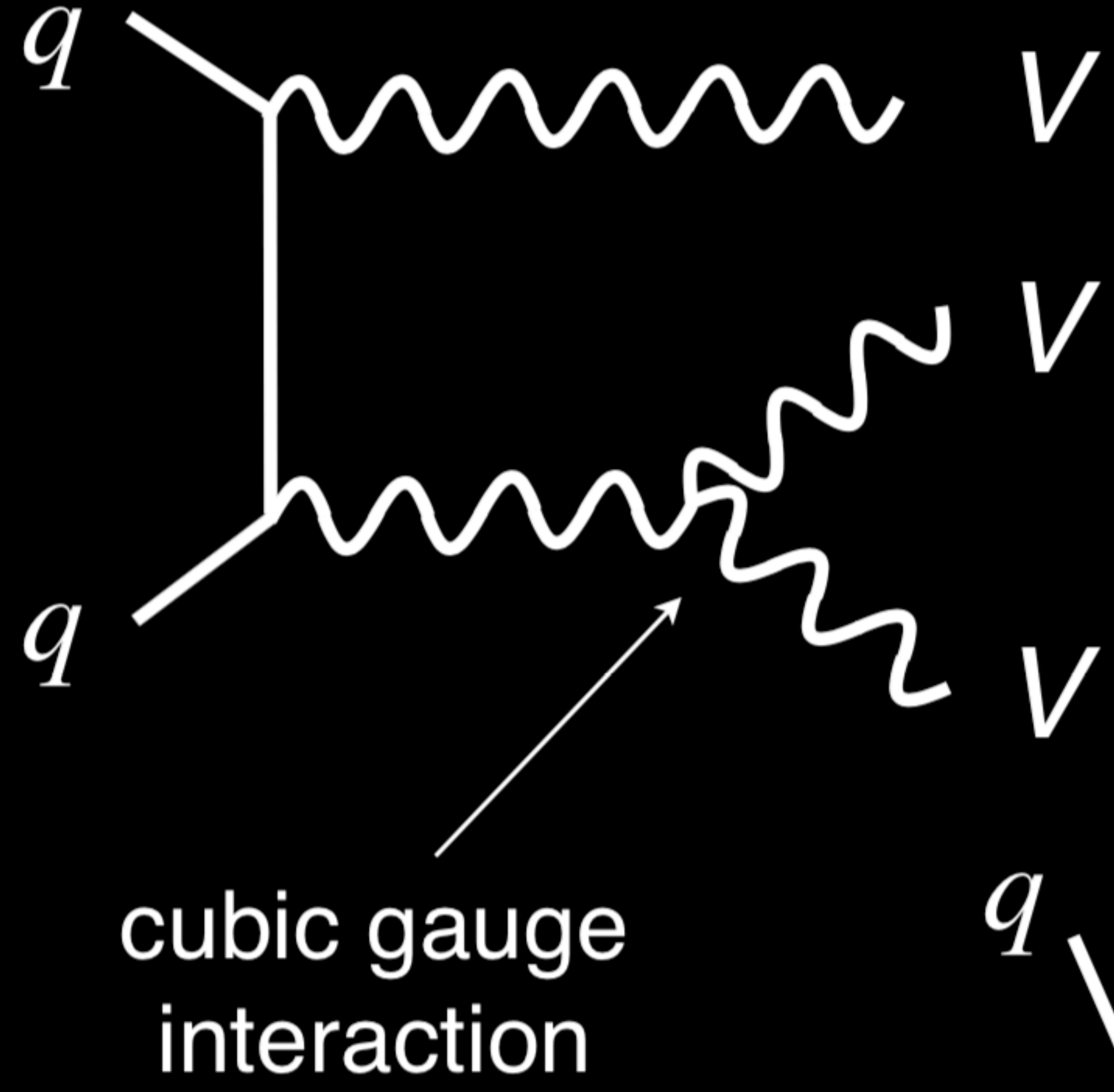
Number of additional tracks in vertex

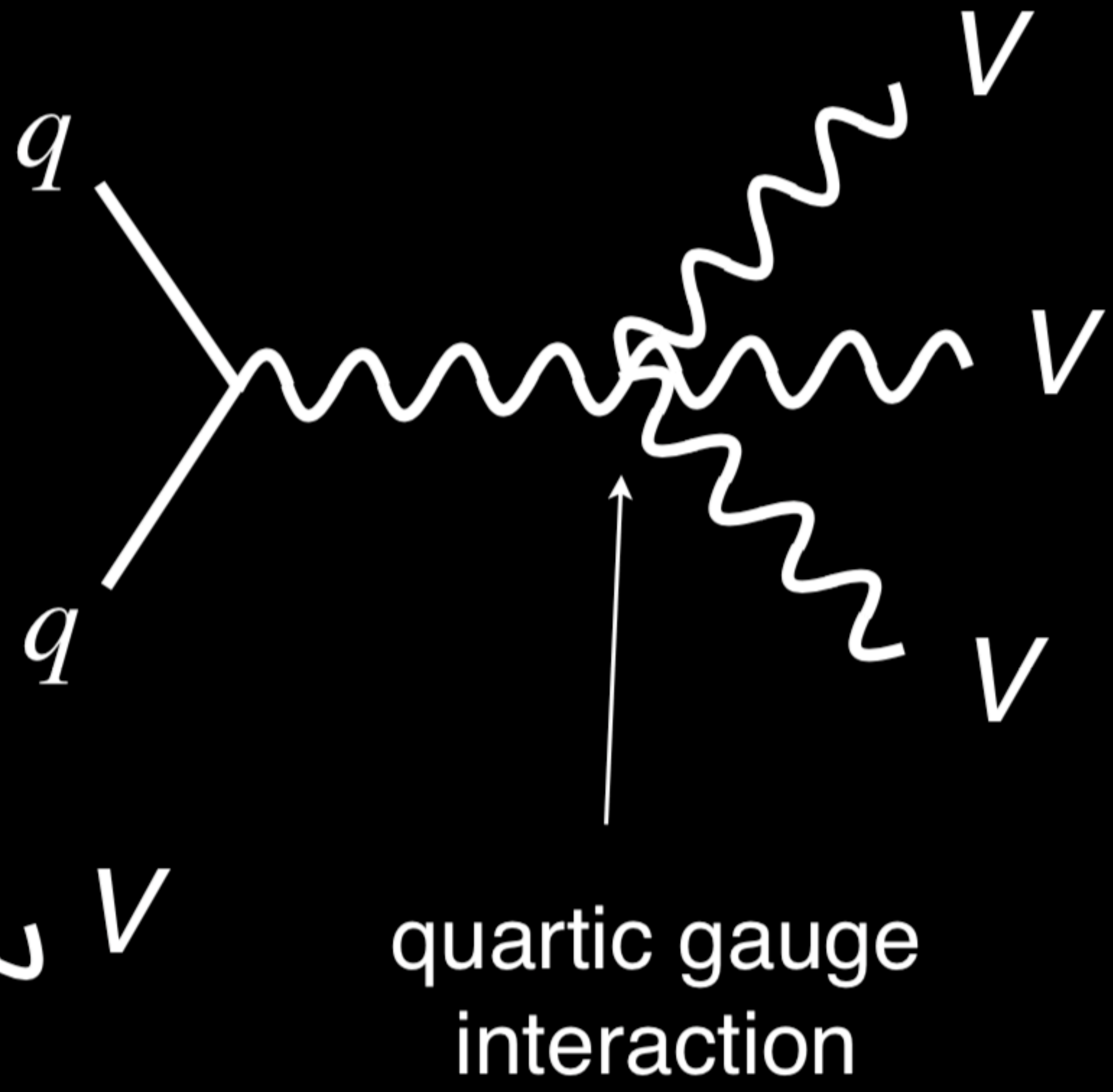


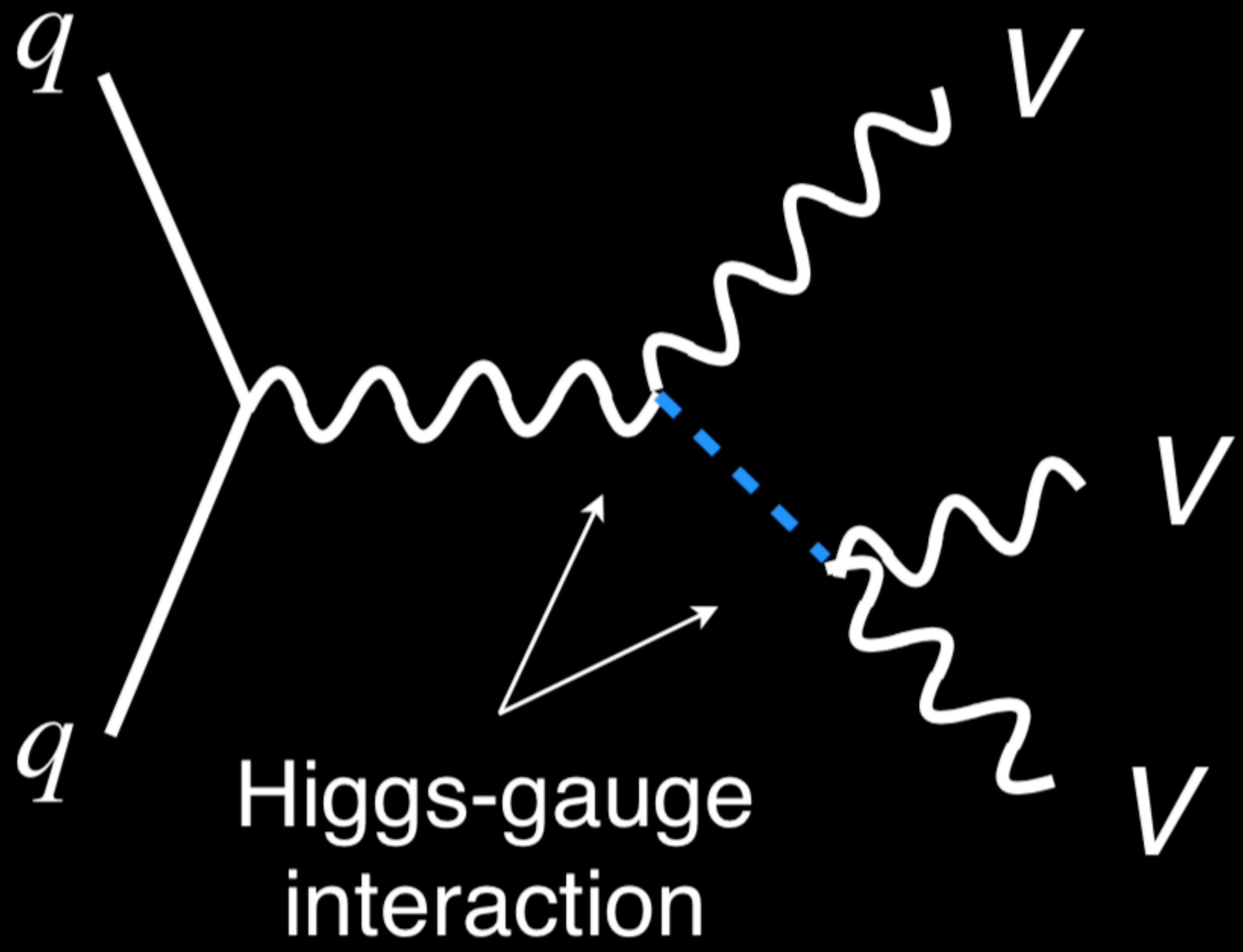




Tri-boson measurements







Four VVV modes

- WWW
- WWZ
- WZZ
- ZZZ

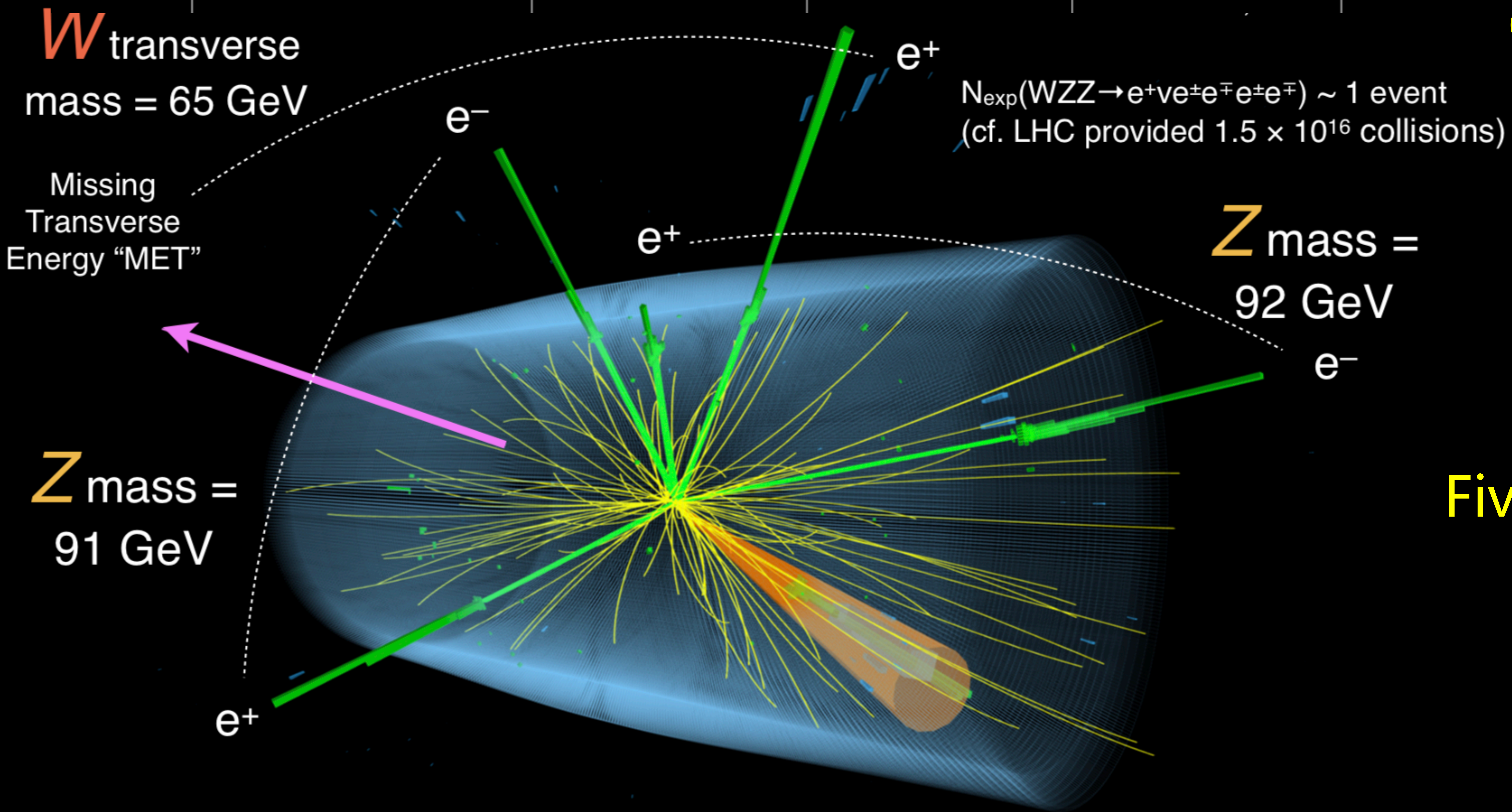
VH→VVV* is part of our signal. Their contribution is subdominant. (1/3 of signal in our signal regions)

Tri-boson measurements

PRL 125 (2020) 151802

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

CMS full runII analysis



Five lepton events

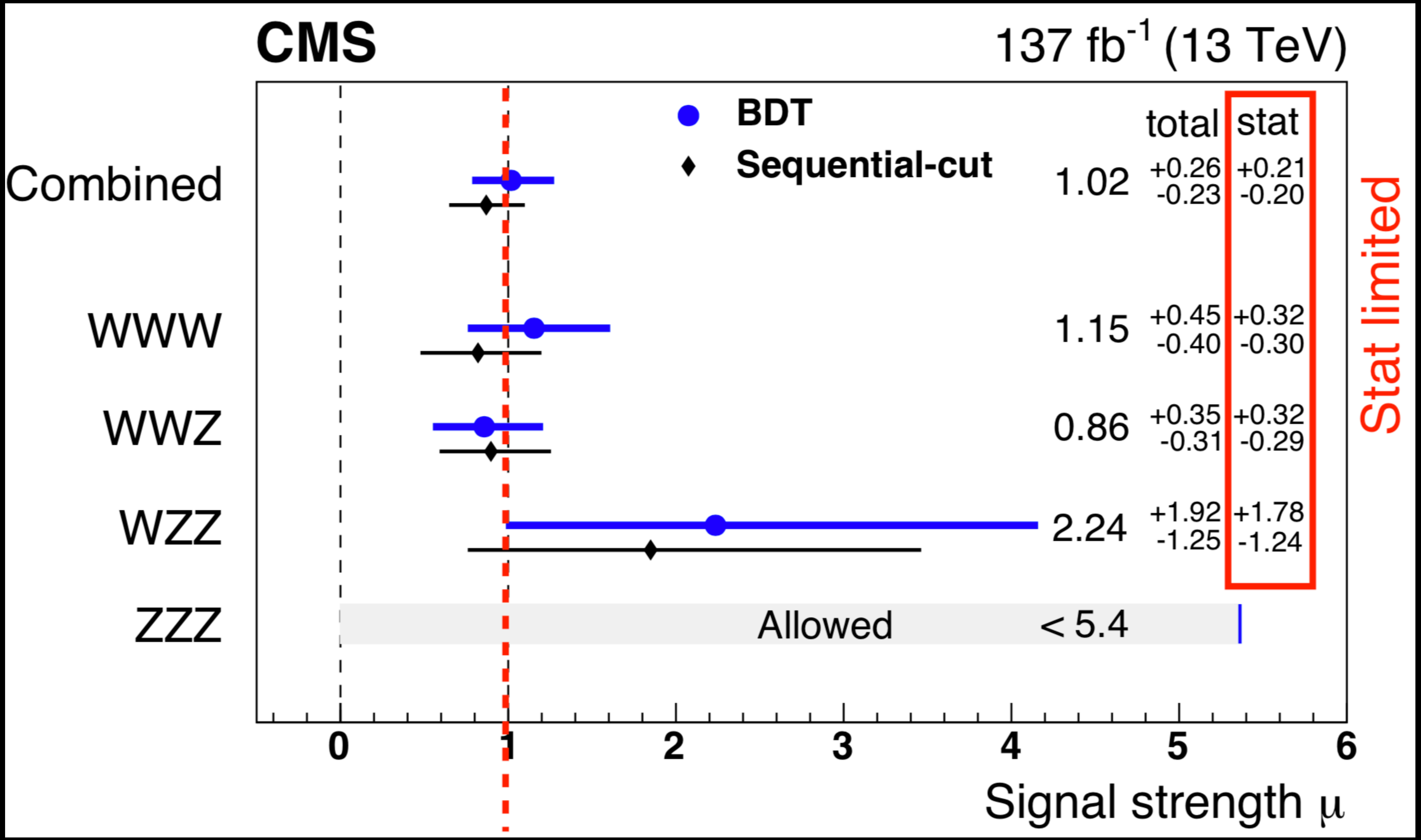
Tri-boson measurements

- CMS: **First observation** of three massive boson productions with full run II data
  → Observed expected significance 5.7σ (5.9σ), PRL 125 (2020) 151802
- ATLAS : Evidence for VVV in 13 TeV 80 fb^{-1}:
  → Observed expected significance 4.1σ (3.1σ), Phys. Lett. B 798 (2019) 134913

CMS Tri-boson observation

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

CMS Tri-boson combination

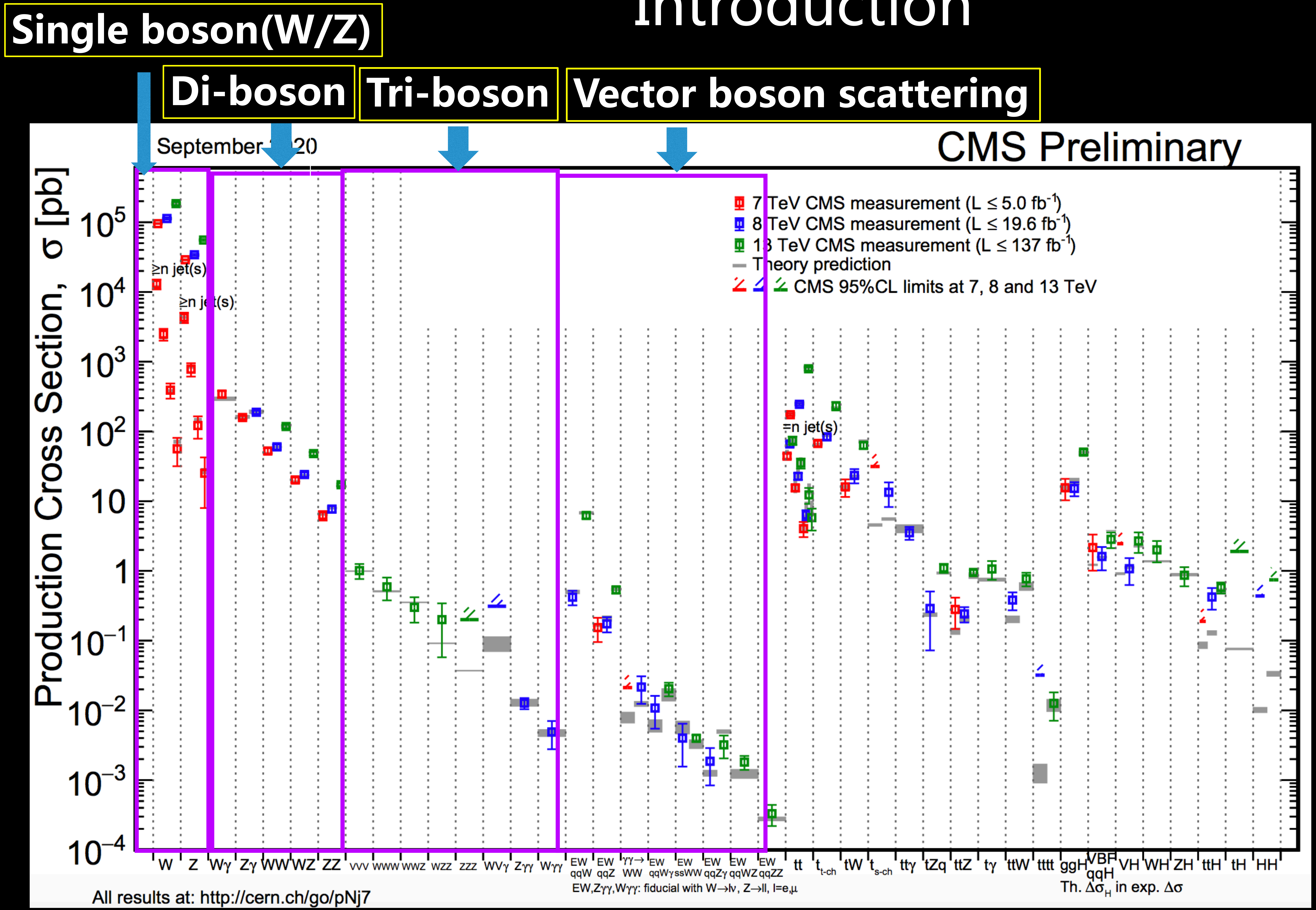


Summary

- **New observations in Vector Boson Scattering and Tri-Bosons productions**

- **Many measurements are becoming systematic limited with the full run II data**
  - **Theory uncertainty on W/Z+jets and diboson +jets became an important systematics**
  - **More differential measurements to improve MC modelling of VBF observations**

Introduction



Signal extraction of EWK Z+dijets

- EW Zjj is extracted by using different QCD Zjj generators:
- Different mismodelling before fits, but reach good data/MC agreement after fits