Recent Tests of the Standard Model in Multiboson final states

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on behalf of the ATLAS and CMS collaborations

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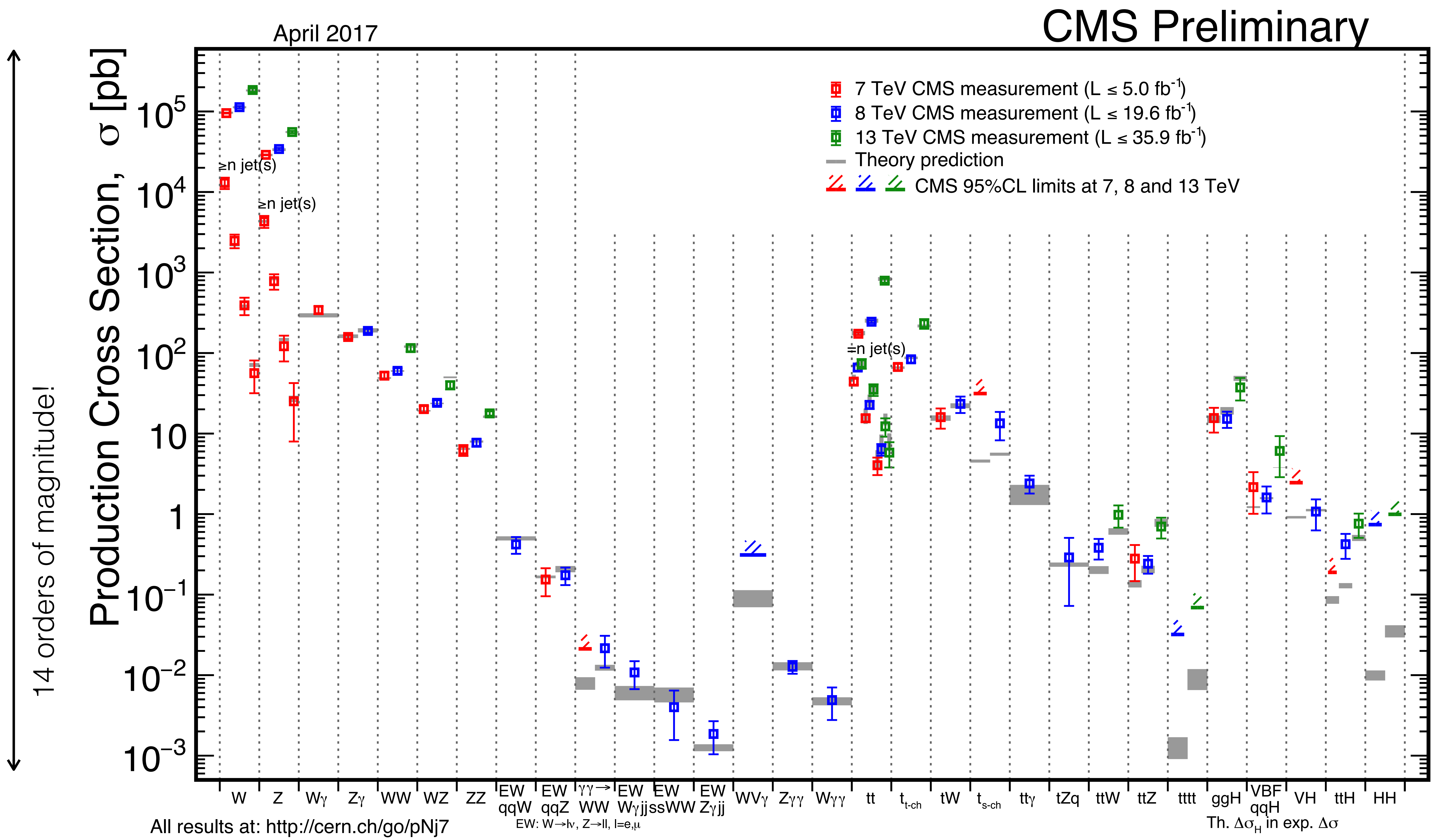
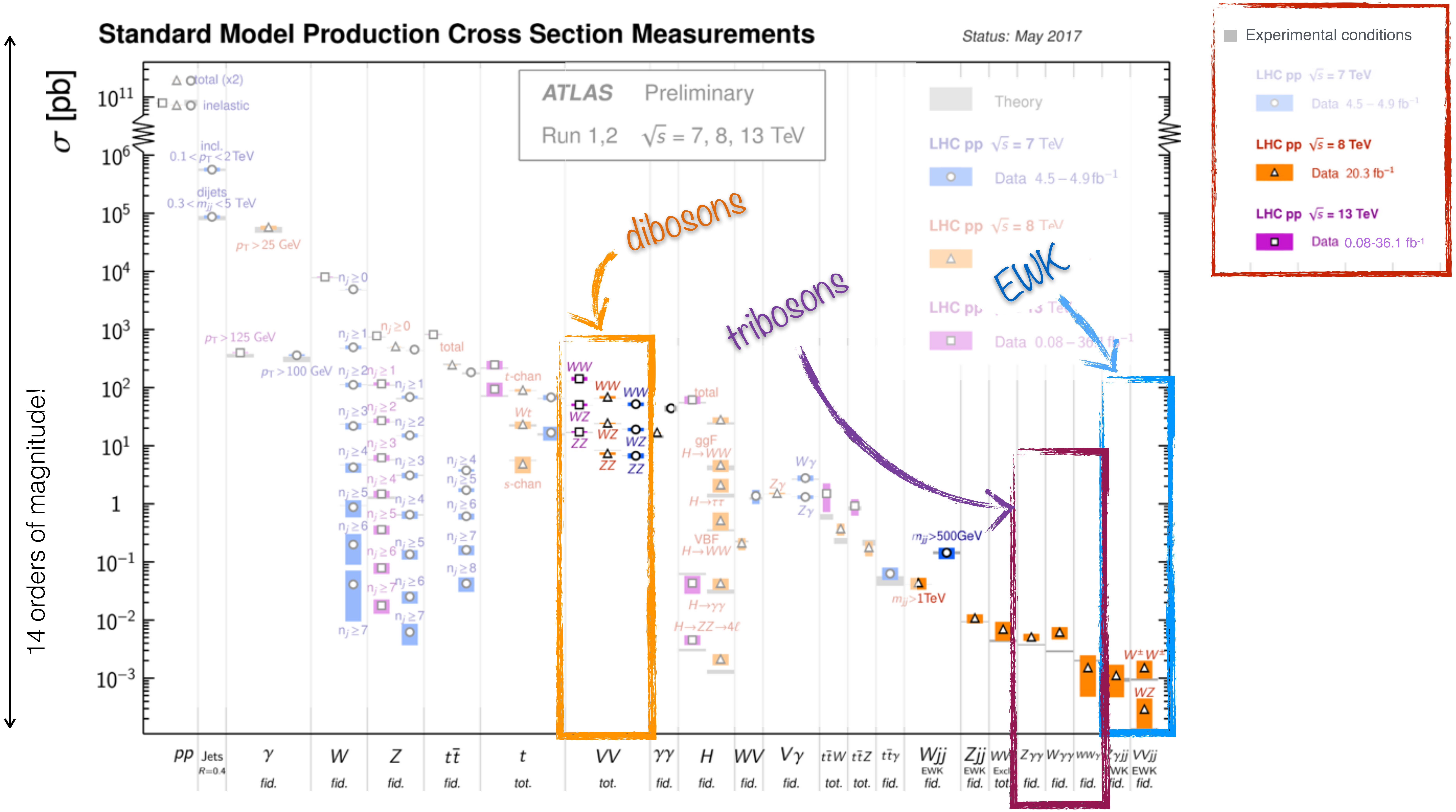
Standard Model landscape



- The Standard Model (SM), has been extensively studied and experimentally verified to an unprecedented precision
- There are still unanswered questions; which suggest that there might be New Physics
- SM physics measurements are important to these searches as they are the foundations on which new physics might sit on
- Gauge boson self-coupling (TGC/QGC) are very powerful tool for indirect searches of New Physics contributions

Outline : SM Electroweak landscape

- Introduction
- Dibosons
  - WW
  - WZ
  - ZZ
- Tribosons
- VBS
  - $Z\gamma$
  - ZZjj
  - ssWW
- aGCs
- Summary



Common signatures and backgrounds

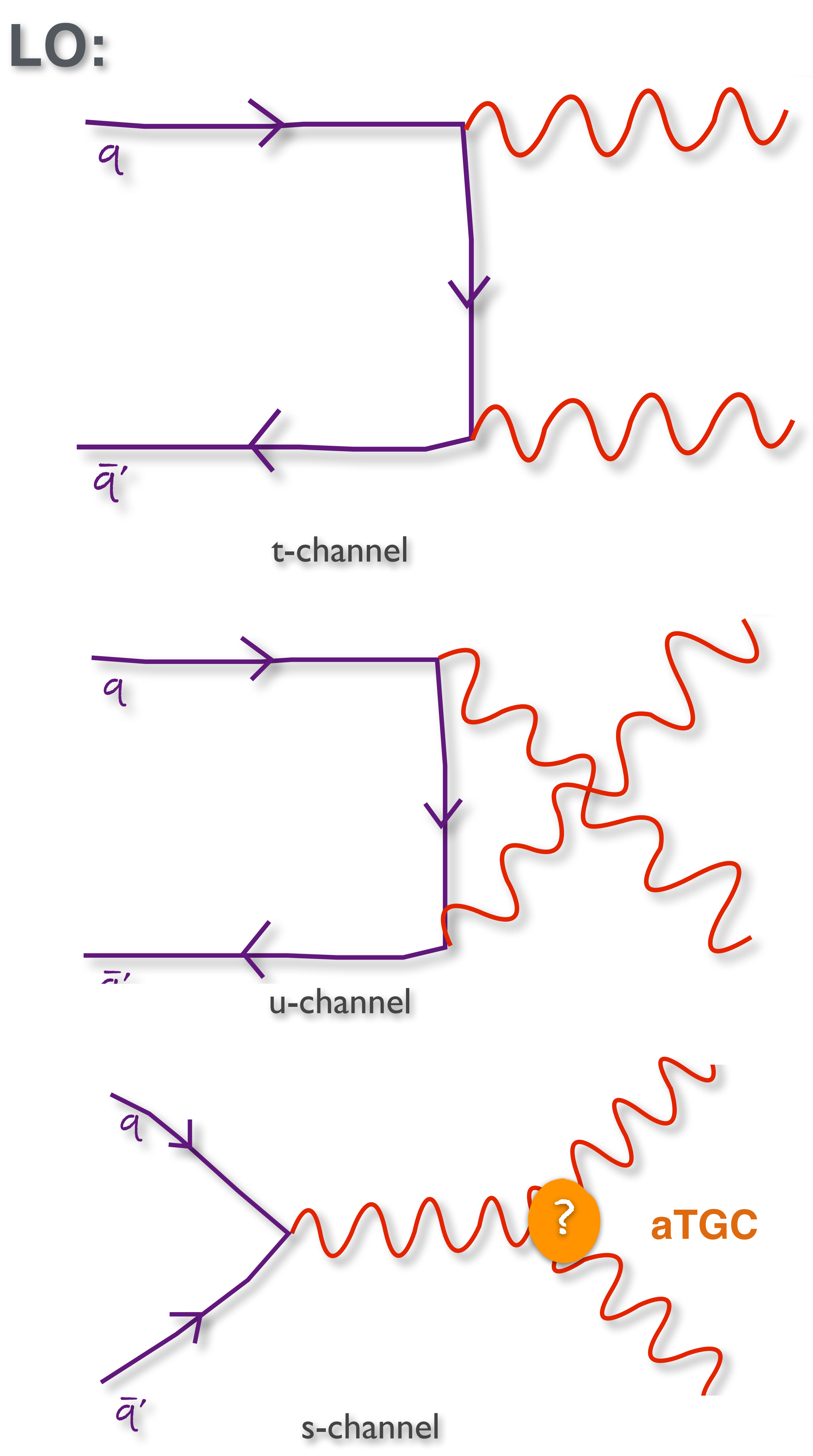
- Measurement of (multi)-boson processes involving combinations of W, Z and photons
- Focus on well-known and recent results of fully leptonic and semileptonic decays
- **Common signatures:**
  - High-p_T isolated electrons, muons and/or photons
  - When a $W \rightarrow \ell\nu$ or $Z \rightarrow \nu\bar{\nu}$ decay is involved :
    - Large E_T^{miss} cuts to account for the neutrino
  - High-p_T jets
- **Common backgrounds:**
  - Diboson processes can be backgrounds to each other → estimated mainly from MC
  - Lepton(s) from heavy flavor decays
  - Jet mis-identified as an electron or a photon
  - Bad E_T^{miss} reconstruction

(Lepton(s) from heavy flavor decays; Jet mis-identified as an electron or a photon; Bad E_T^{miss} reconstruction:) use data driven methods

Different data driven methods and control region definitions depend on the analysis.

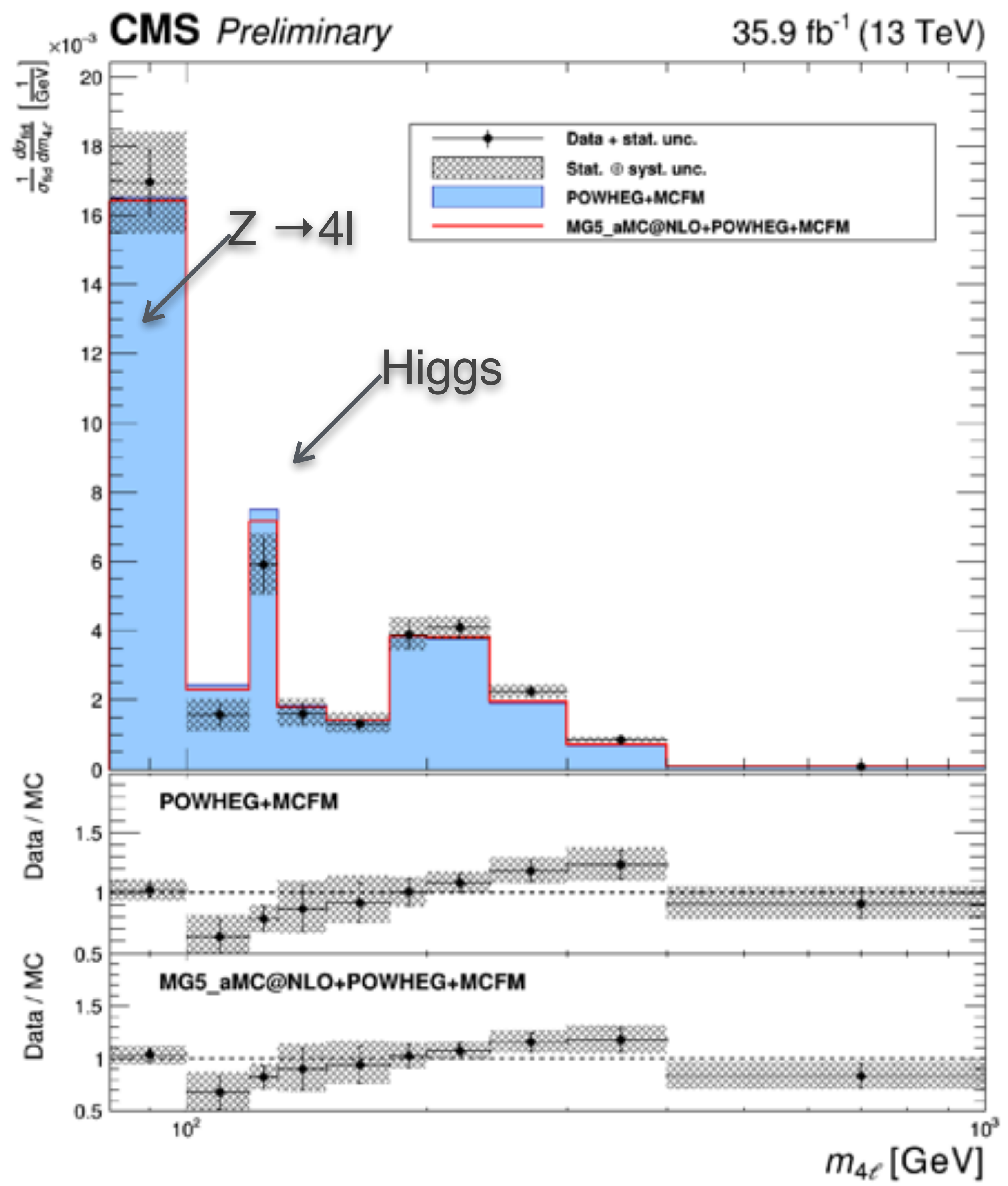
Dibosons

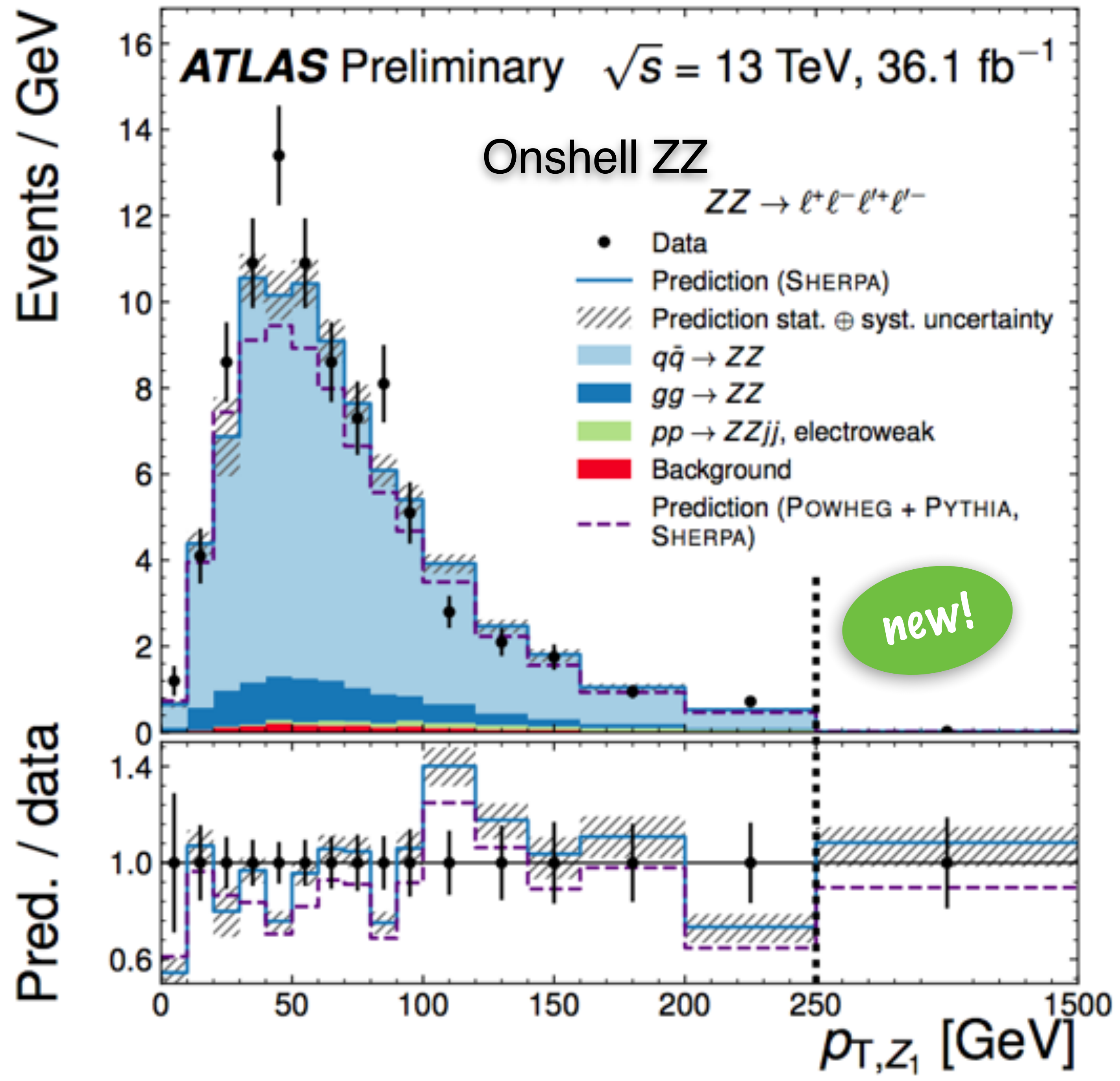
- Provides direct test of the electroweak sector of the SM at the TeV scale
  - Measurement of the fiducial, total and differential cross sections (few kinematic variables)
- Sensitive to new physics in the EW sector
  - Limits on anomalous Triple and Quartic Gauge Couplings (aTGC and aQGC)
- Irreducible background to Higgs and beyond-SM searches
- Test NLO EW corrections and of QCD calculations (NNLO)

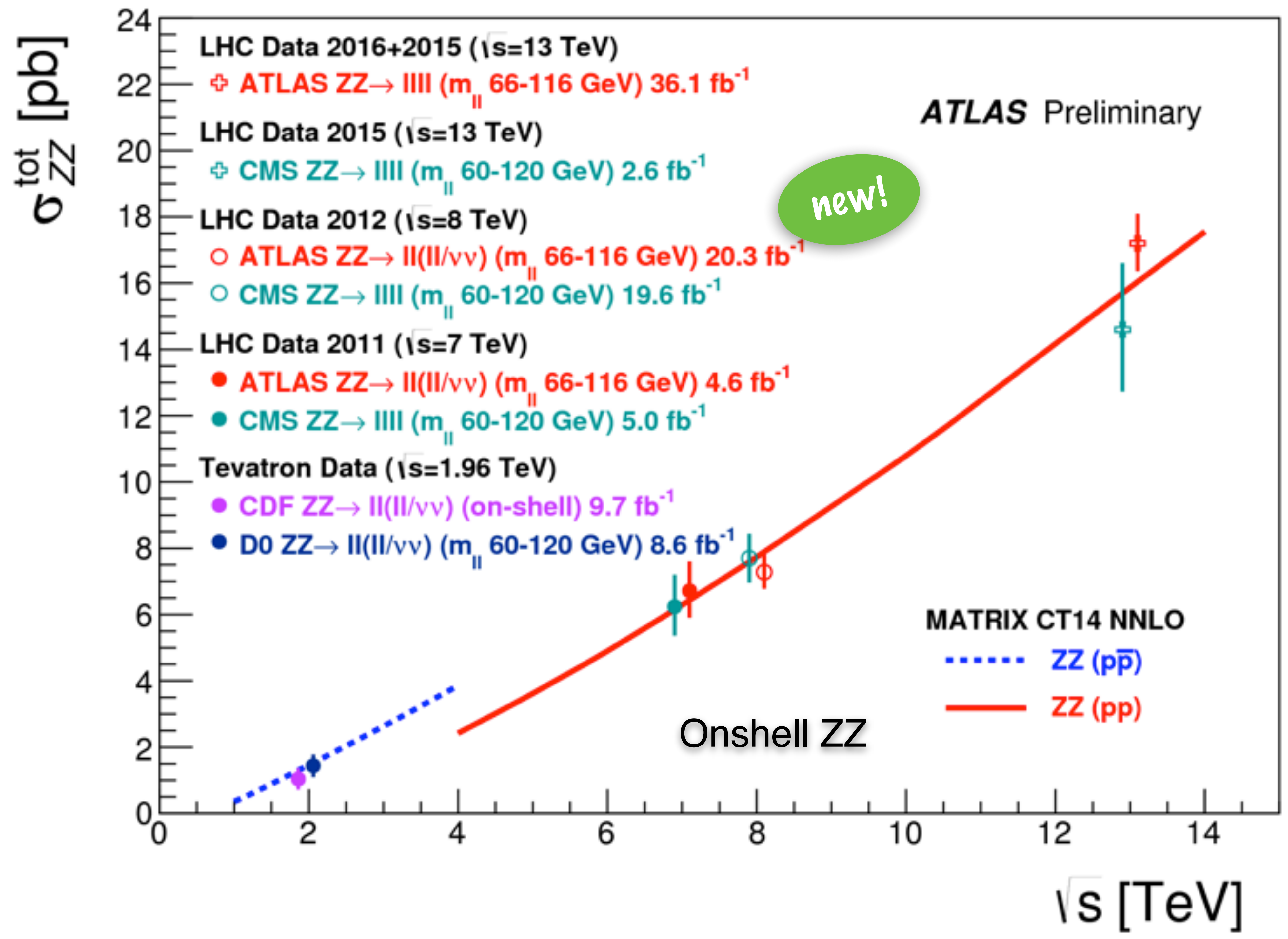


ZZ production cross section

- New results from ATLAS and CMS using the complete run 2 dataset!
- Two pairs of oppositely charged, same flavor leptons
  - minimal background of < 5% → All backgrounds are estimated using data driven techniques
  - small experimental uncertainties
- Good agreement of differential cross-sections with NNLO predictions



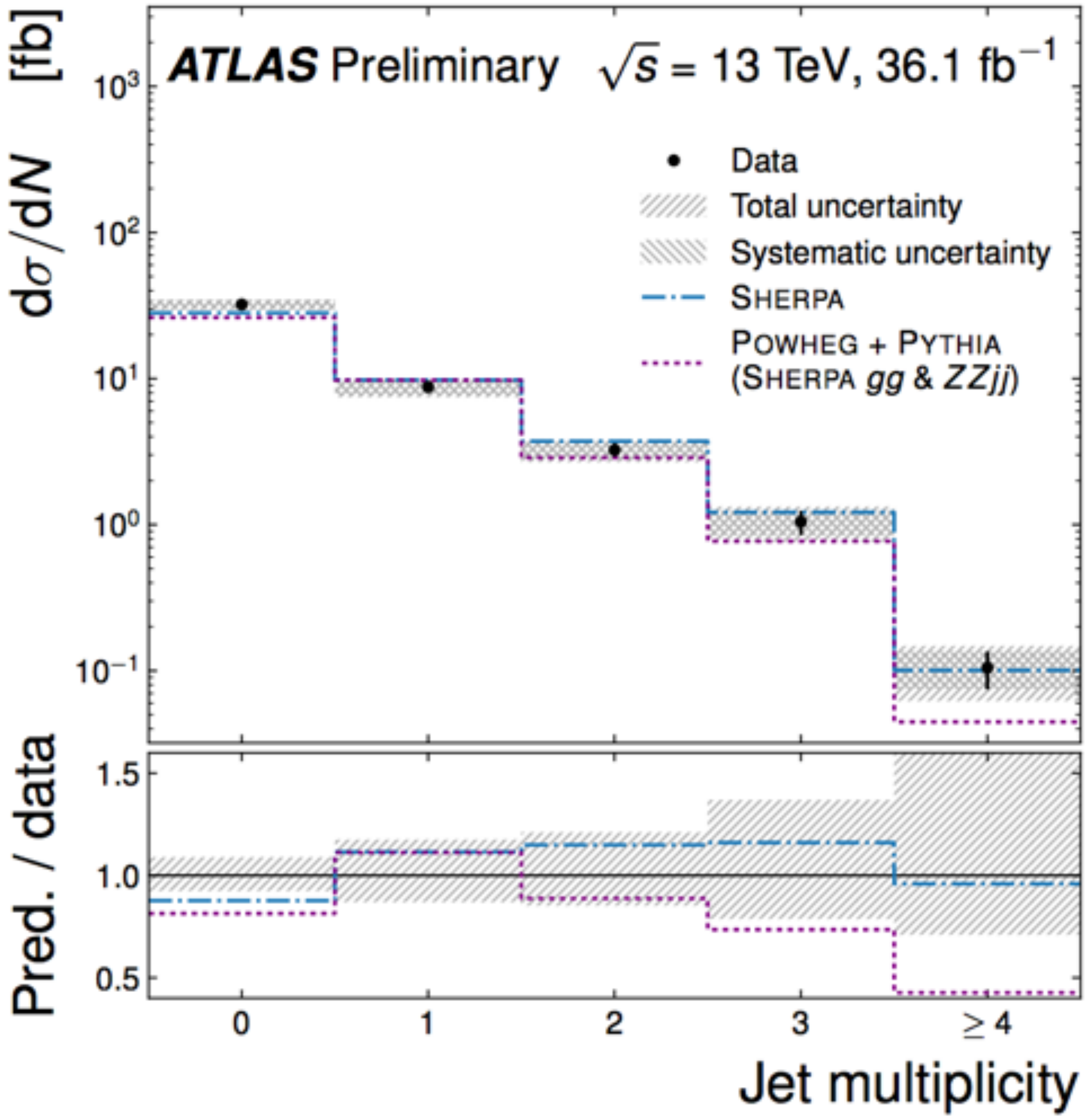


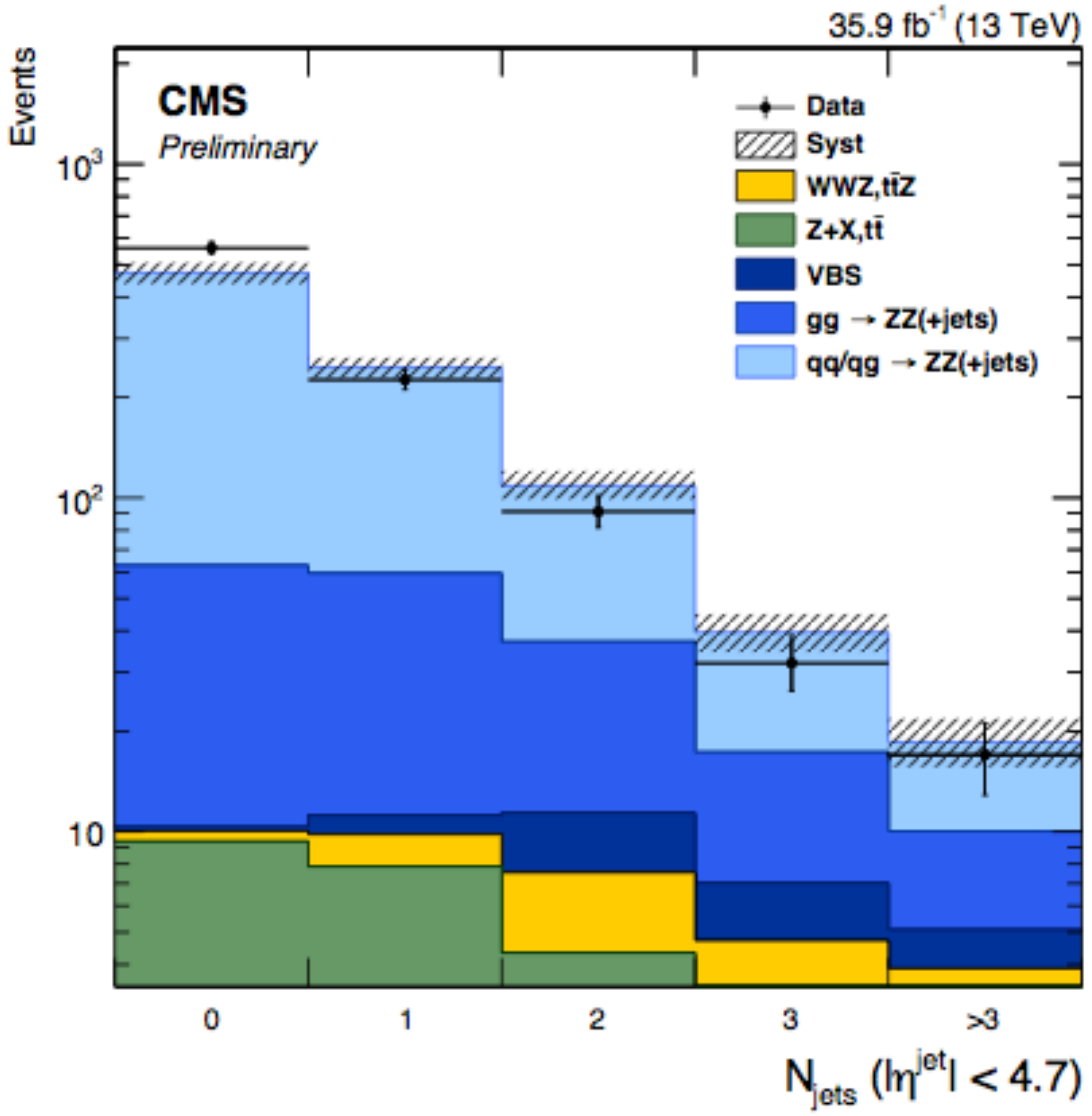


ZZ production cross section

new!

- Differential cross section measured in many observables, most for the first time e.g. Jet kinematics (highest pT jet), single lepton kinematics, dilepton kinematic
- Jet multiplicity results from ATLAS and CMS





- CMS cross section as a function of the jet multiplicity

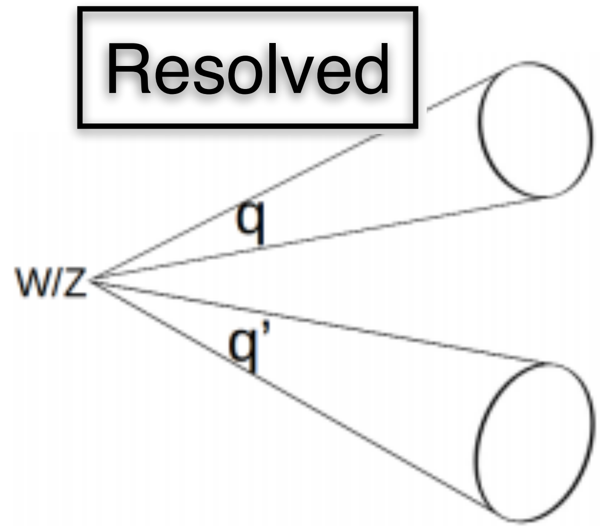
Number of jets ($\lvert\eta^{jet}\rvert < 4.7$)	Fiducial cross section [fb]	Theo. cross section [fb]
0	28.3 ± 1.3 (stat)$^{+1.7}_{-1.6}$ (syst) ± 0.7(lumi)	$23.6^{+0.8}_{-0.9}$
1	8.1 ± 0.8 (stat)$^{+0.8}_{-0.8}$ (syst) ± 0.2(lumi)	$9.7^{+0.4}_{-0.4}$
2	3.0 ± 0.5 (stat)$^{+0.3}_{-0.4}$ (syst) ± 0.1(lumi)	$4.0^{+0.3}_{-0.2}$
≥ 3	1.3 ± 0.4 (stat)$^{+0.3}_{-0.2}$ (syst)	$1.7^{+0.1}_{-0.1}$

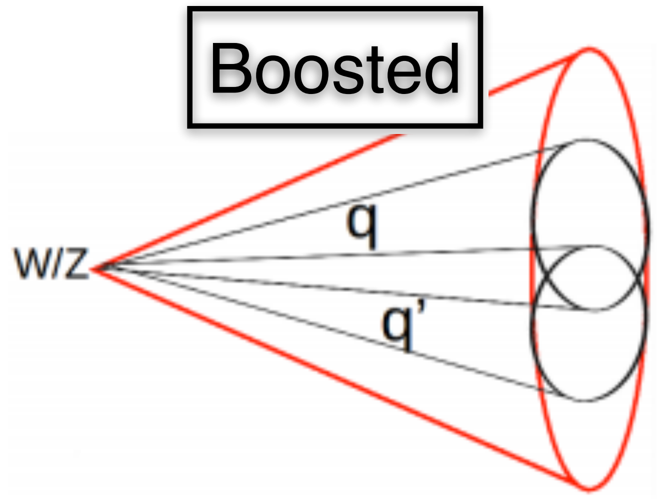
ATLAS: ATLAS-CONF-2017-031 CMS: CMS-PAS-SMP-16-019

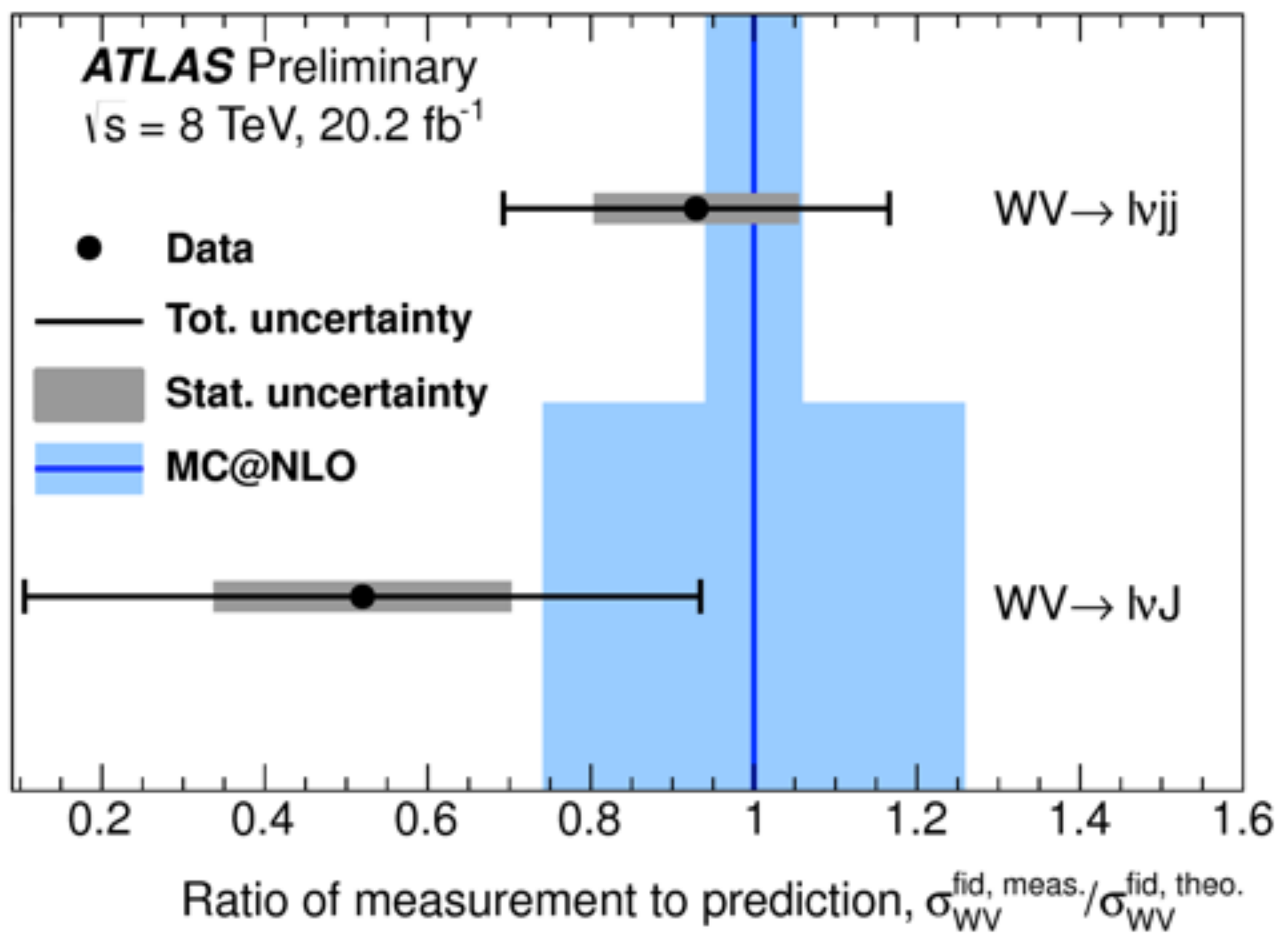
WW and WZ semileptonic

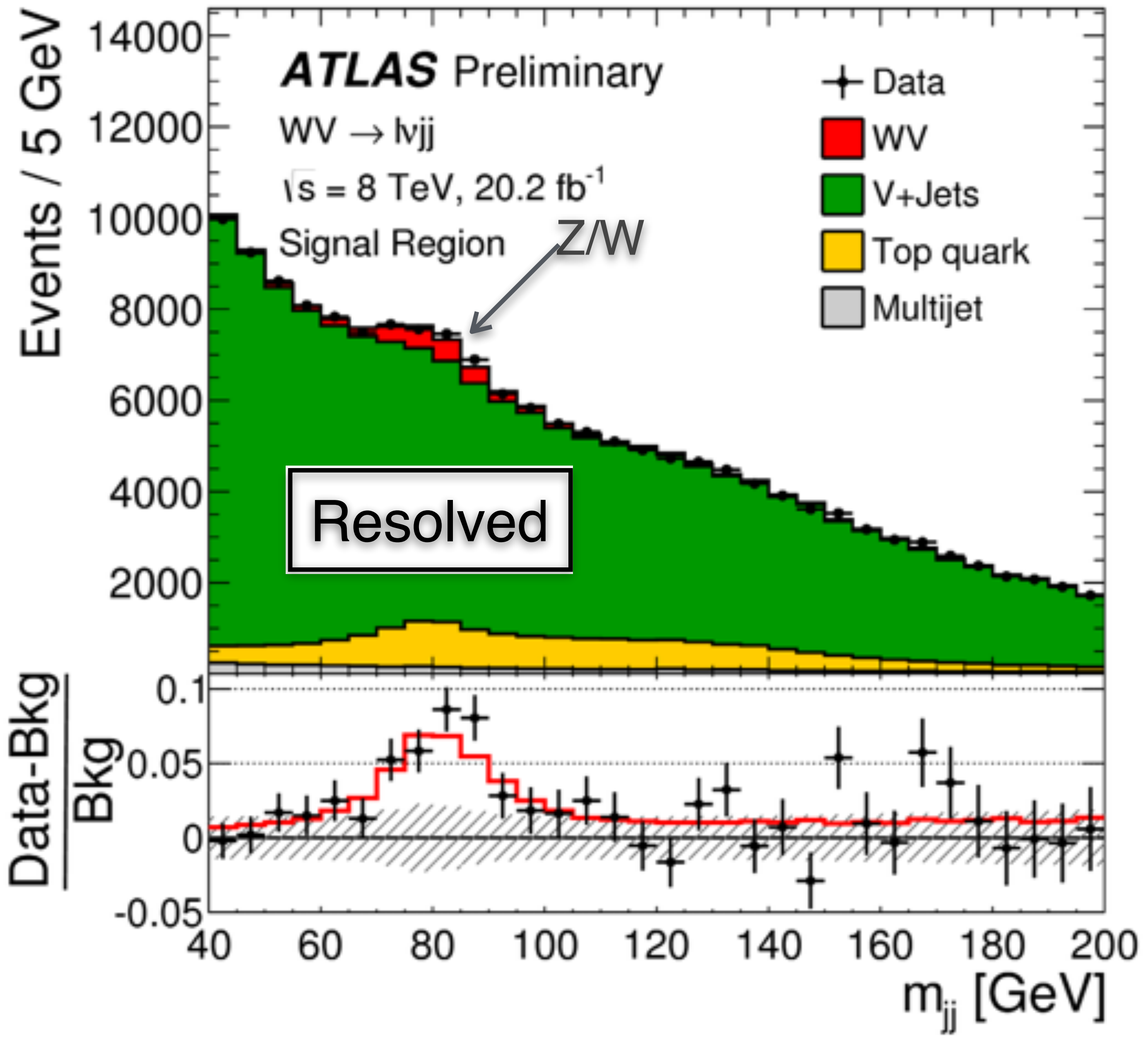
new!

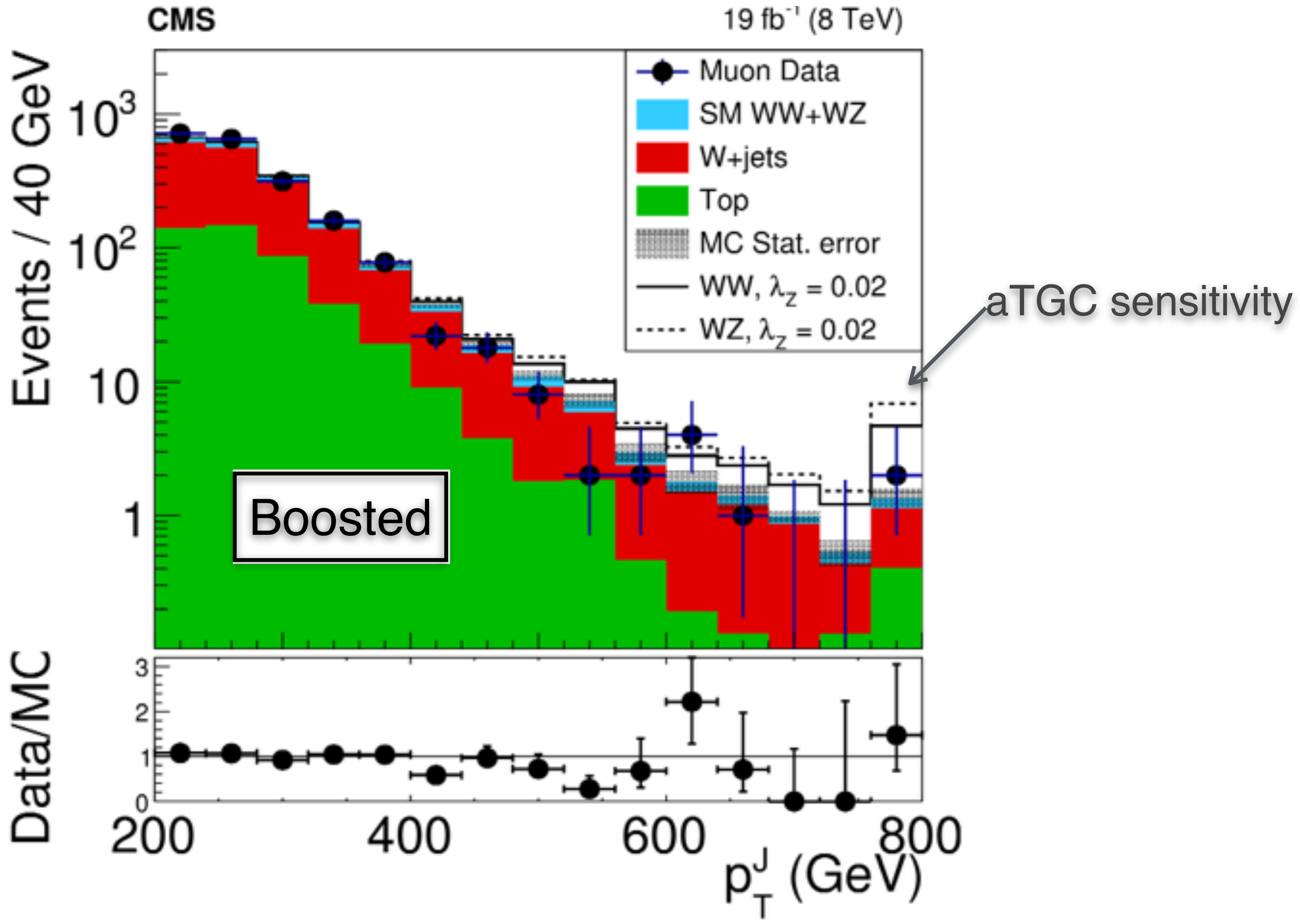
- Why measuring semi-leptonic when we have full leptonic ?
  - Branching fraction six times higher compared to fully-leptonic channel
  - Possible to probe higher pt(V) → more sensitive to aTGC
- Selection requires :
  - Isolated high pT lepton
  - High E_T^{miss}
  - Either 2 resolved jets or one boosted



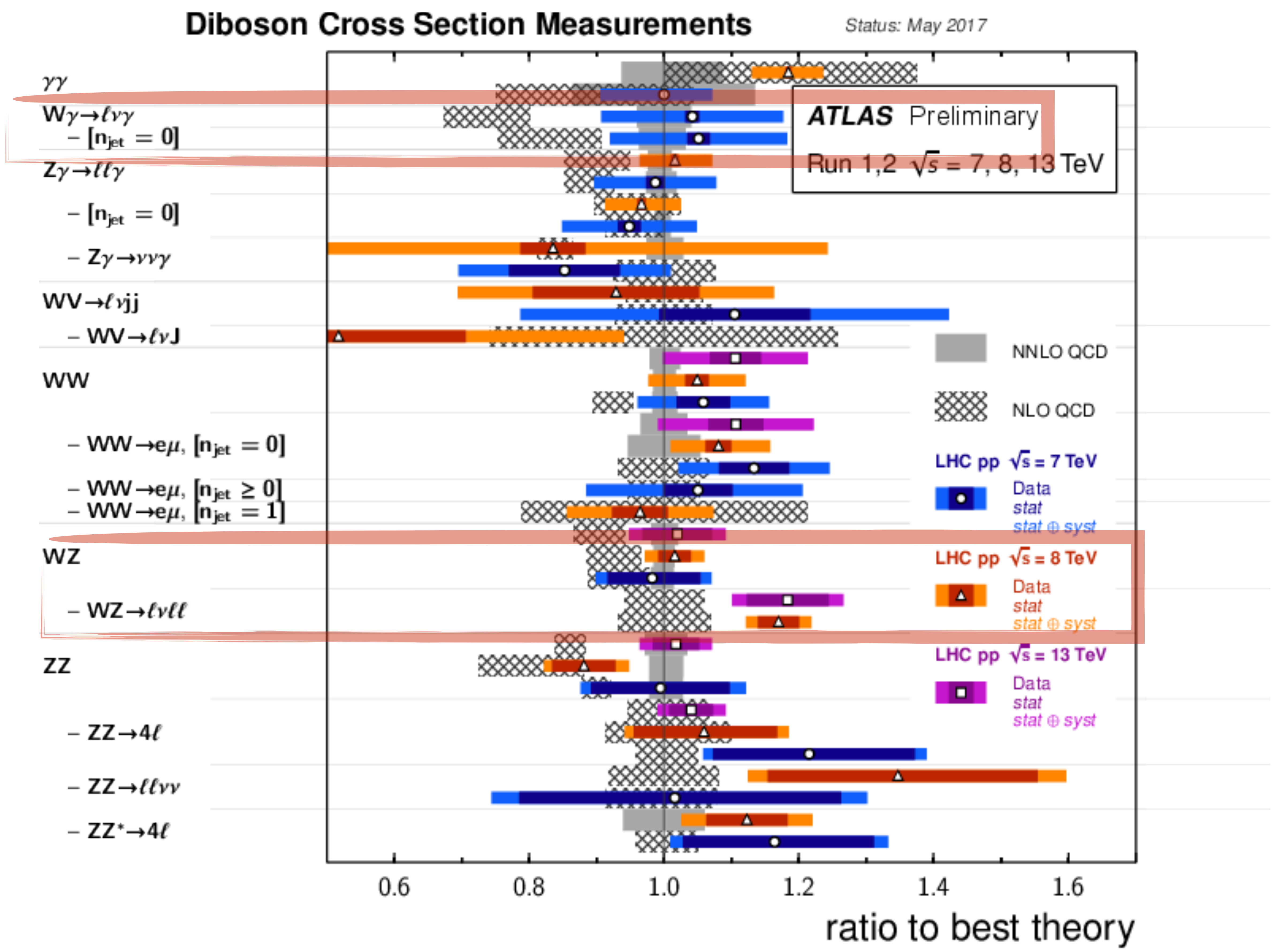


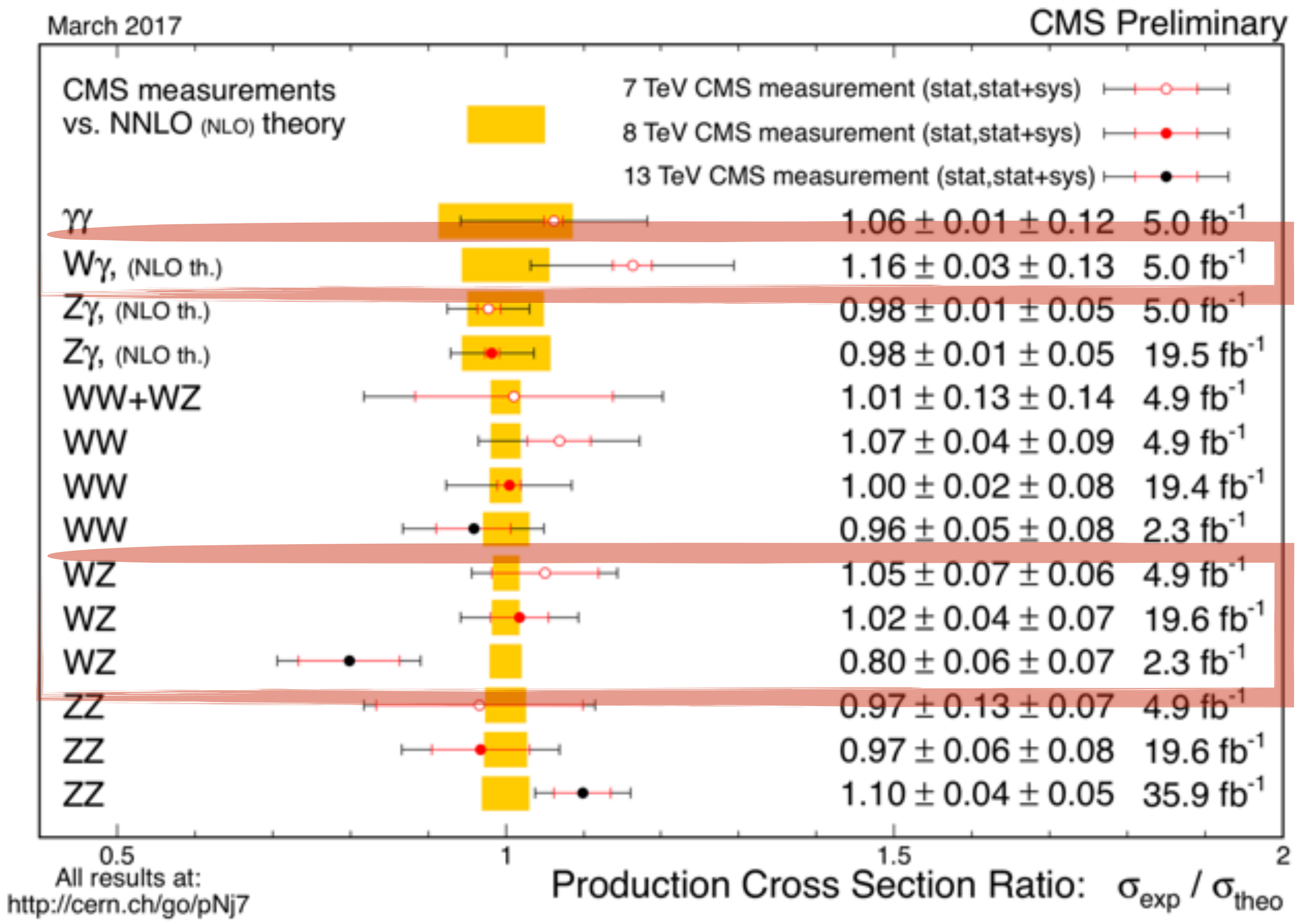






Dibosons production at the LHC

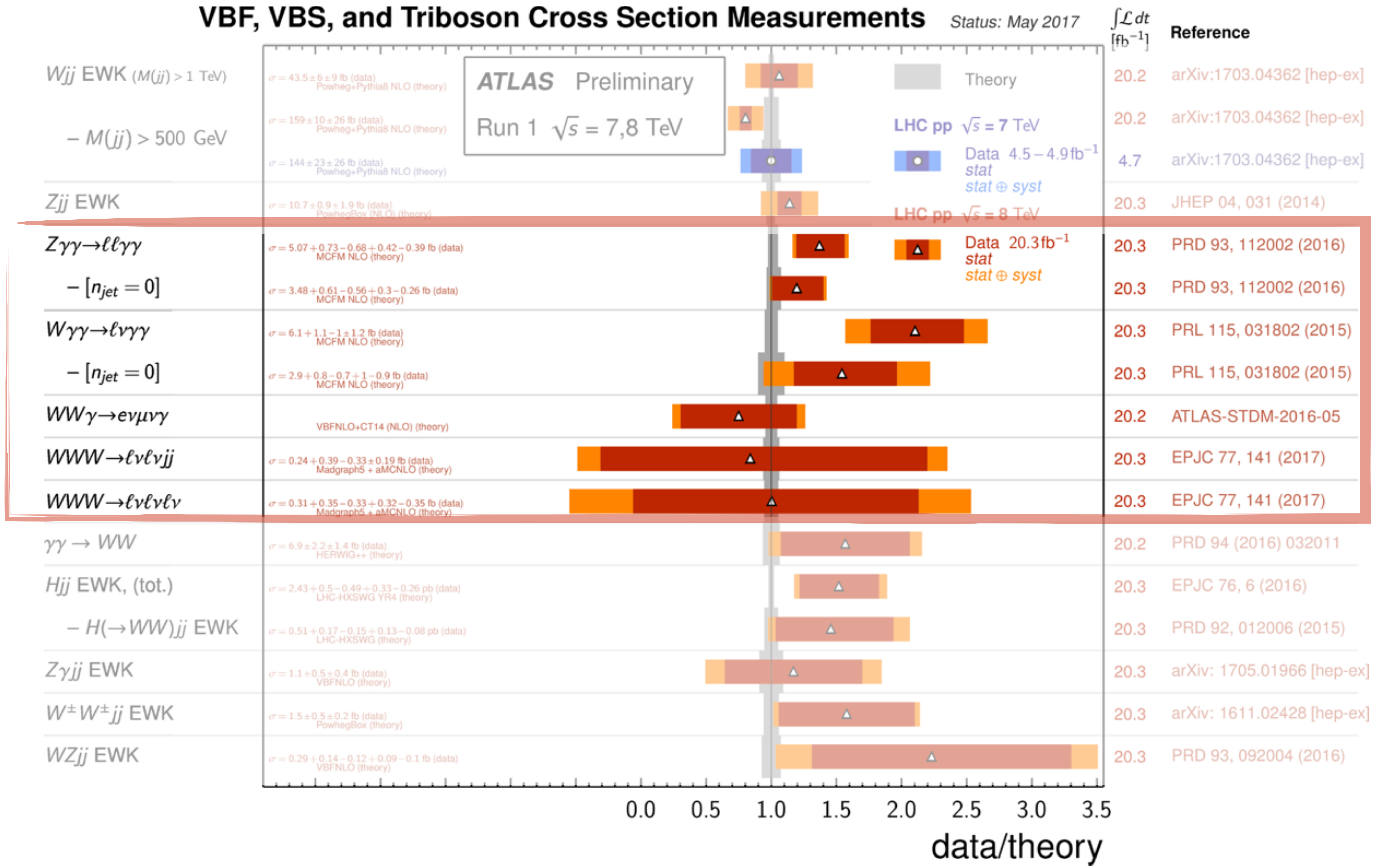




- Almost all recent measurements are limited by systematic uncertainties
- Generally good agreement between measurement and theory
  - NNLO QCD improves agreement substantially in some cases
    - New NNLO calculations for WZ (arXiv:1604.08576) and Vγ (arXiv:1504.01330)

Tribosons

new!



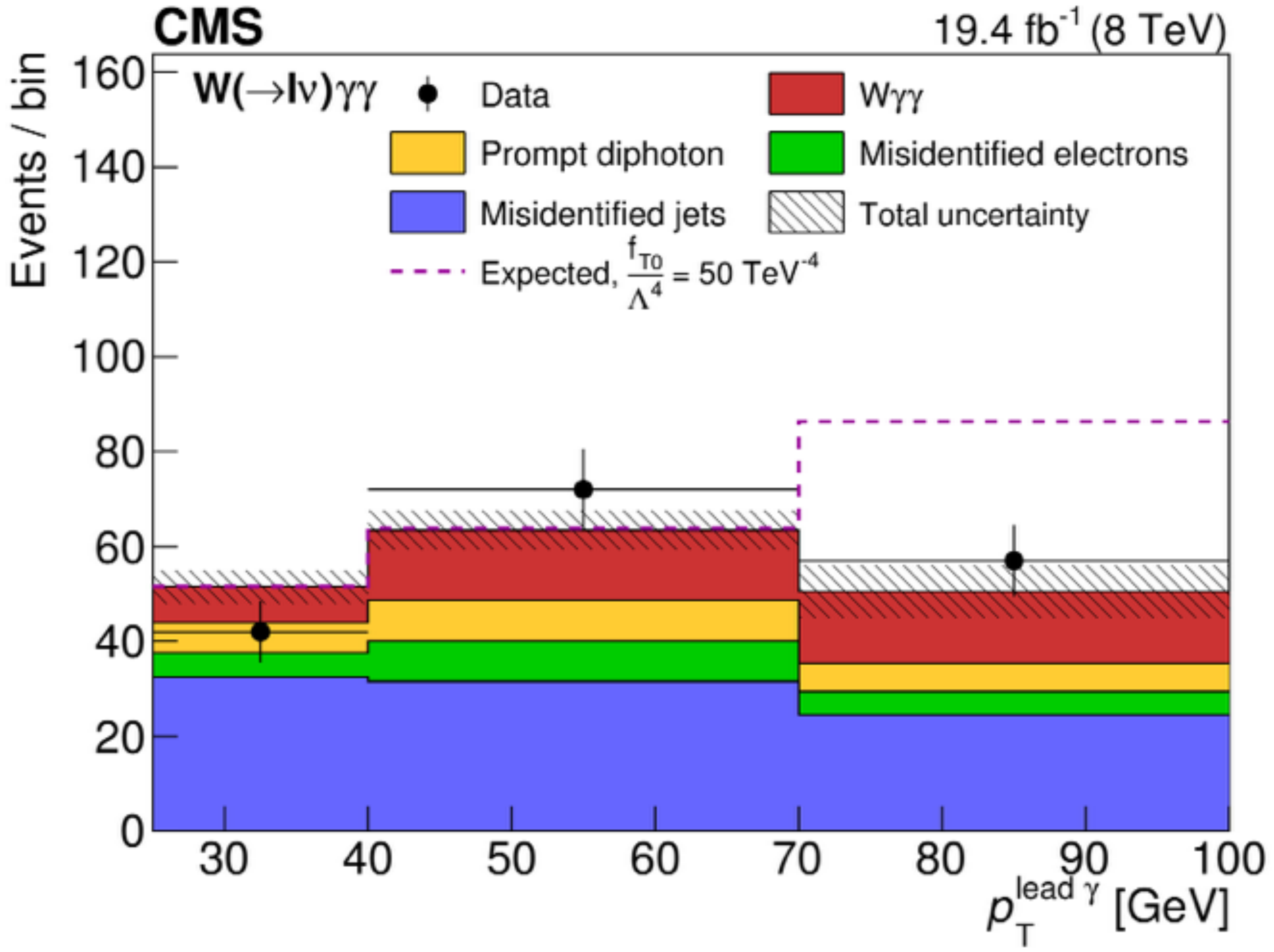
Tribosons : $W\gamma\gamma$ and Z $\gamma\gamma$

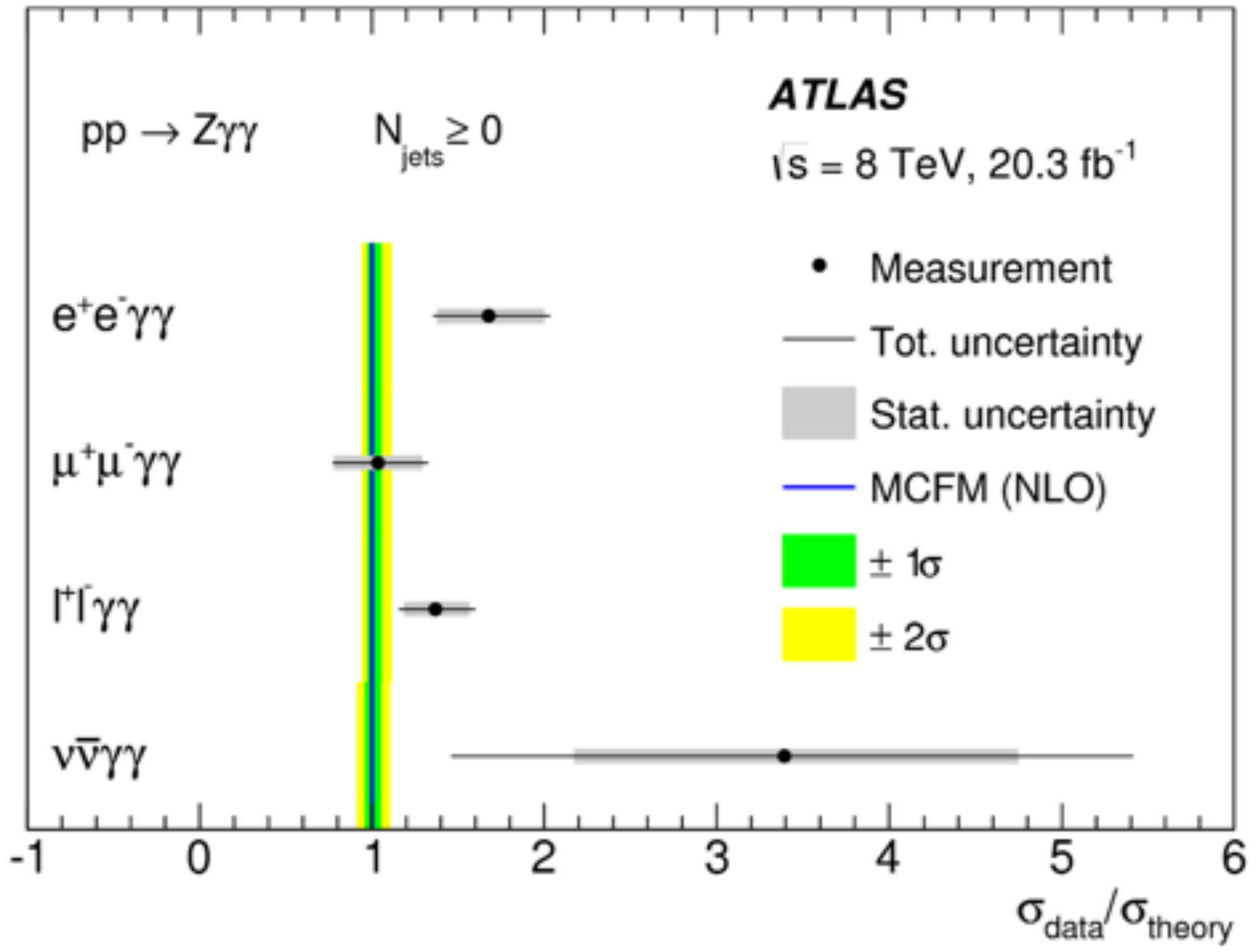
- New CMS W(ν)γγ / Z(ll)γγ production measurements at 8 TeV
- Zγγ (Wγγ) signal significance measured to be **5.9σ (2.6σ)**

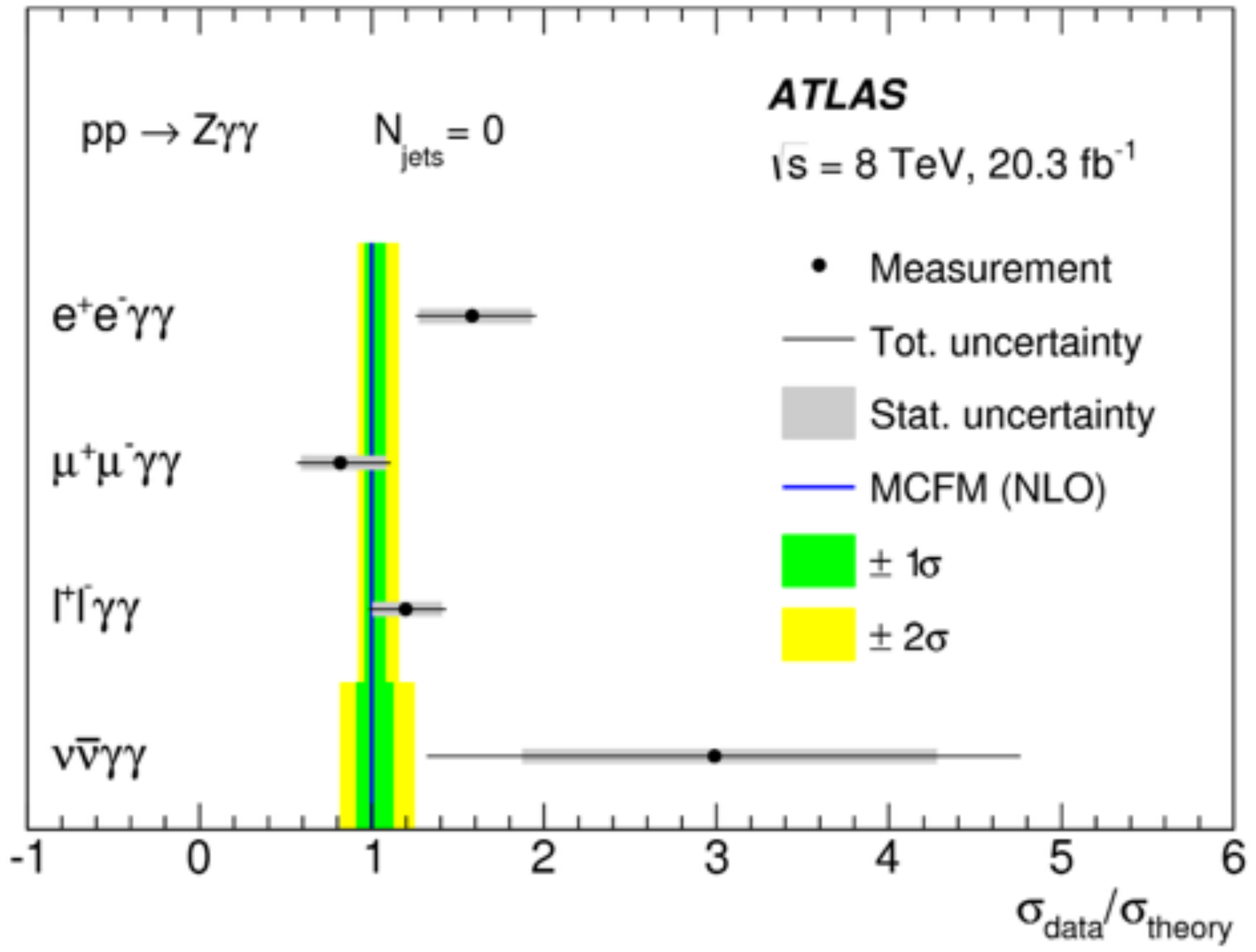
new!

Channel	Measured fiducial cross section
$W\gamma\gamma \to e^{\pm}\nu\gamma\gamma$	$4.2 \pm 2.0\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$W\gamma\gamma \to \mu^{\pm}\nu\gamma\gamma$	$6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})$ fb
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	$4.9 \pm 1.4\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$Z\gamma\gamma \to e^{+}e^{-}\gamma\gamma$	$12.5 \pm 2.1\,(\text{stat}) \pm 2.1\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \mu^{+}\mu^{-}\gamma\gamma$	$12.8 \pm 1.8\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	$12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb

Channel	Prediction
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	4.8 ± 0.5 fb
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	13.0 ± 1.5 fb







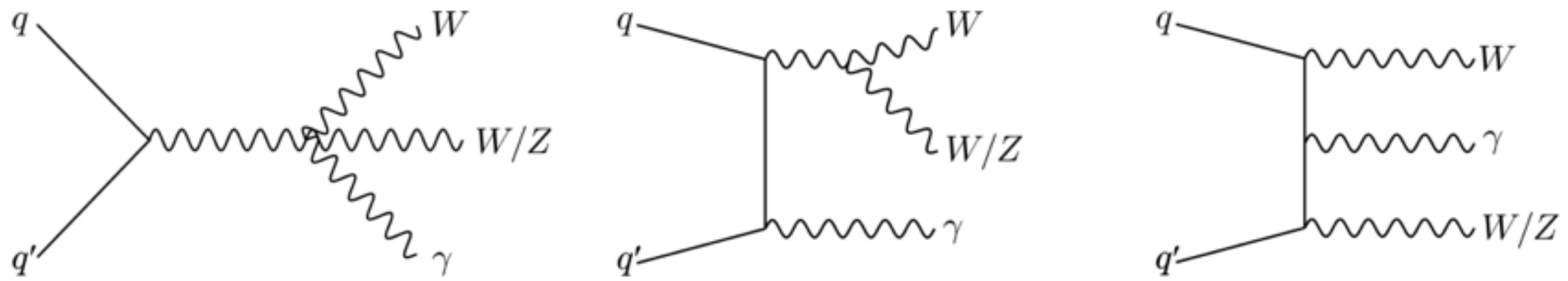
- Fiducial cross-sections consistent w/ NLO theory

ATLAS: arXiv:1604.05232 CMS: CMS-SMP-15-008

Tribosons : WWγ and WZγ

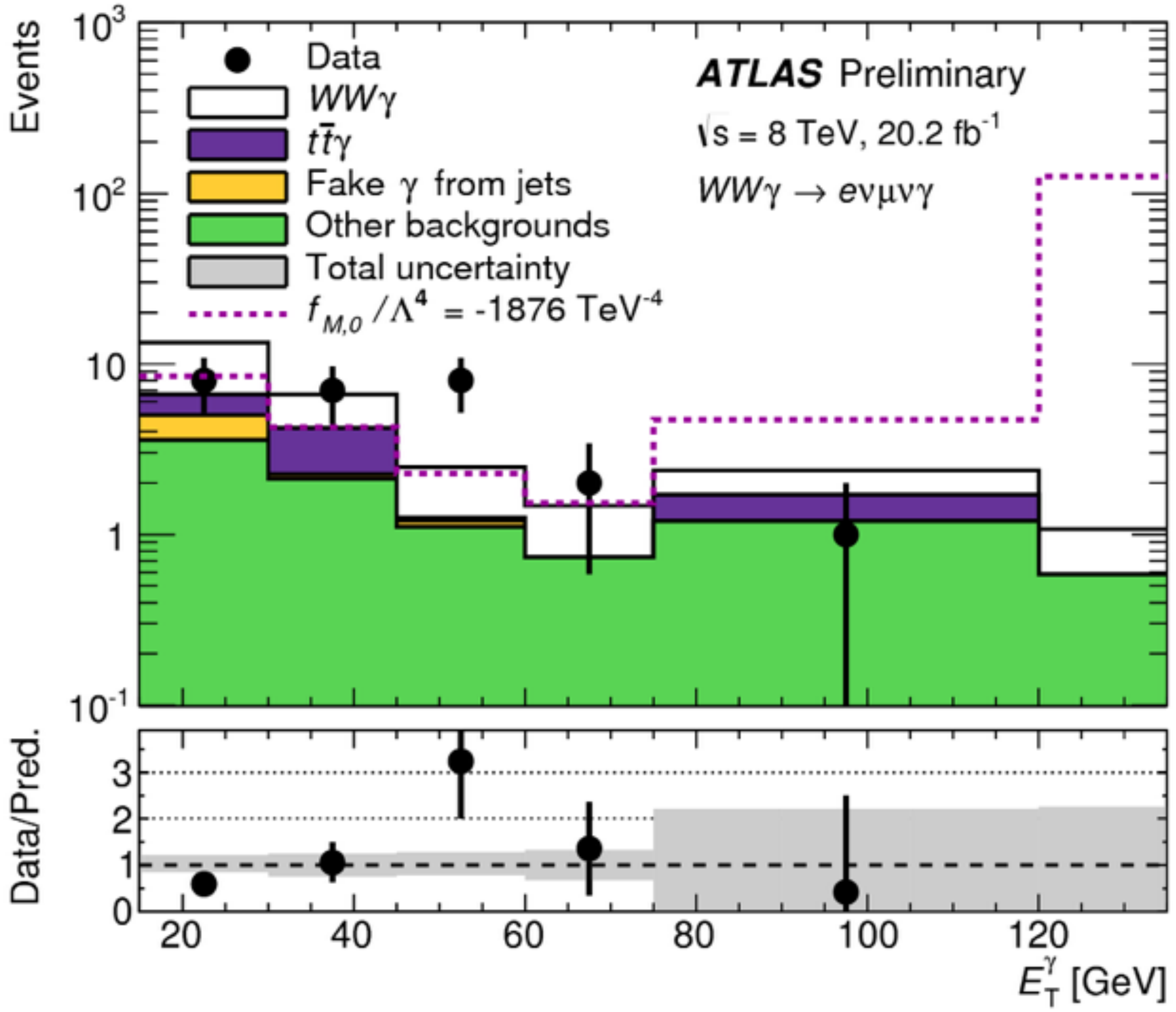
new!

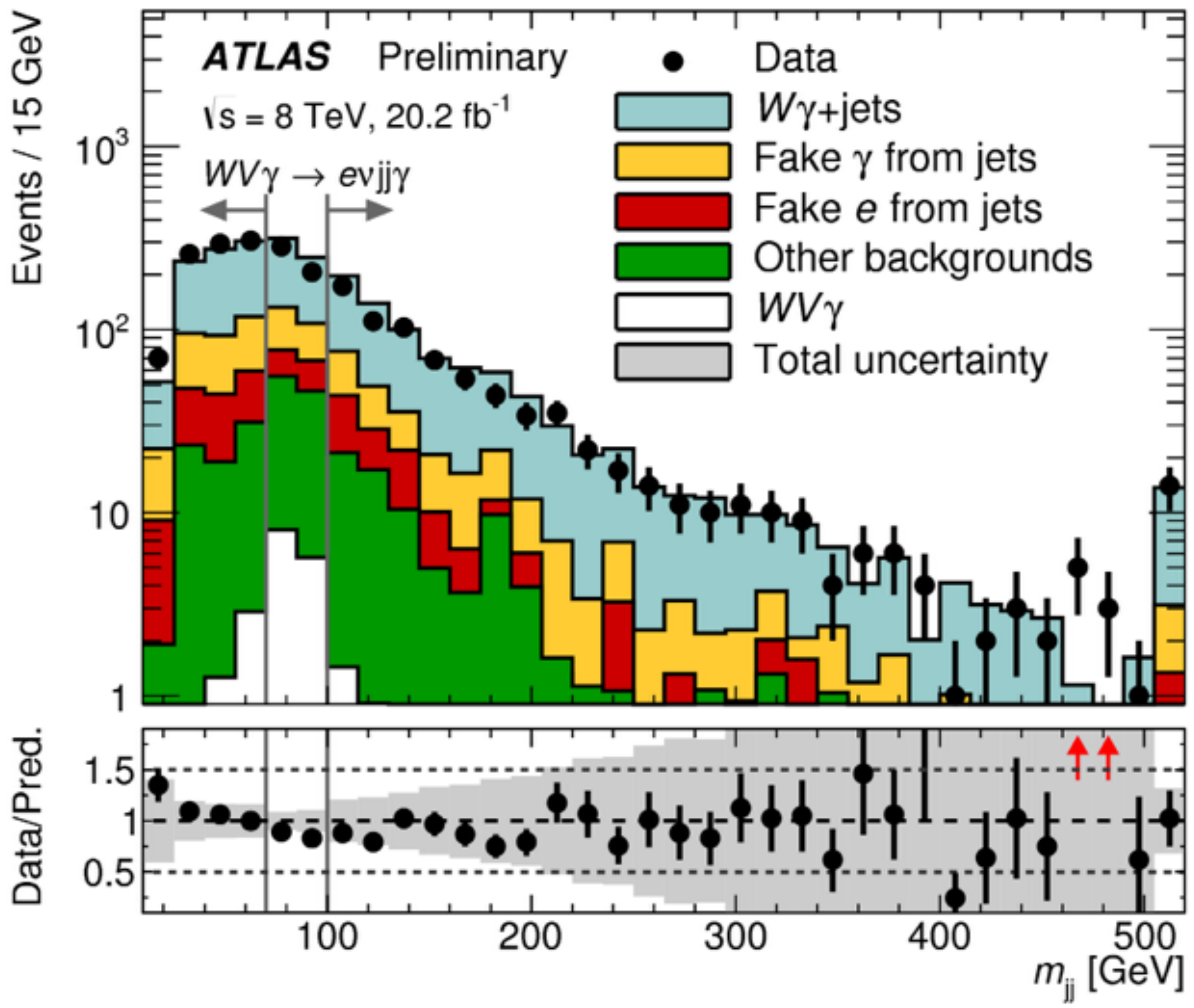
- New ATLAS WWγ / WZγ production measurement at 8 TeV
  - Fully leptonic final state used for the WWγ (e$\nu\mu\nu$ γ only) 0-jets
  - Semileptonic channel used for the WZγ
- The signal significance in the **the e$\nu\mu\nu\gamma$ final state** measured to be **1.4σ (1.6σ)**



$$\sigma_{\text{fid}}^{e\nu\mu\nu\gamma} = (1.5 \pm 0.9(\text{stat.}) \pm 0.5(\text{syst.}))\ \text{fb},$$

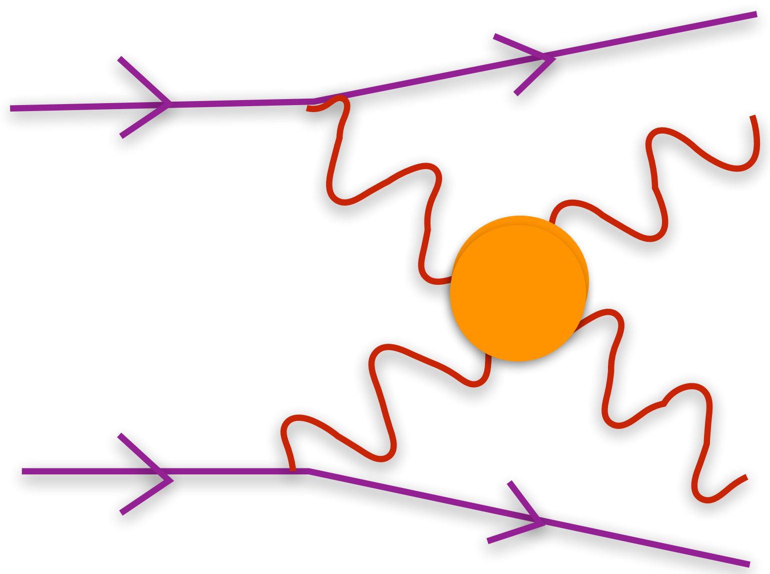
NLO prediction ~ 2.0 ± 0.1 fb





Electroweak production: Vector Bosons +2jets

VBS



- EWK V(V) + 2 jets production is essential to probe the nature of the EWSB
  - Characteristic signature: two high p_T jets in the forward-backward region with:
    - Large rapidity separation
    - Low hadronic activity in-between
- V(V) + 2 jets production is dominated by O(α_S^2) QCD processes
  - Evaluated from data in control region or from simultaneous fit
- ATLAS and CMS have shown observation of EWK V+2 jets

EWK measurements: VV+2jets	ATLAS	CMS	
	8 TeV	8 TeV	13 TeV
W	PRL 113, 141803, arxiv:1611.02428 **Evidence:** EWK signal significance 3.6σ (exp 2.3σ)	PRL 114 (2015) 051801 EWK signal significance 1.9σ (exp 2.9σ)	CMS PAS SMP-17-004 **Observation**: EWK signal significance 5.5σ (exp 5.7σ) new!
ZZ	-	SMP-16-019 EWK signal significance 2.7σ (exp 1.6σ) new!	-
W(lν)γ	-	CMS-PAS-SMP-14-011 EWK signal significance 2.7σ (exp 1.5σ)	-
Z(ll)γ	STDM-2015-21 EWK signal significance 2.0σ (exp 1.8σ) new!	CMS-PAS-SMP-14-018 **Evidence**: EWK signal significance 3.0σ (exp 2.1σ)	-
WZ	arxiv:1603.02151 EWK signal significance 2.0σ (exp 1.8σ)	-	-

Same-sign W bosons pair production in association with 2 jets

new!

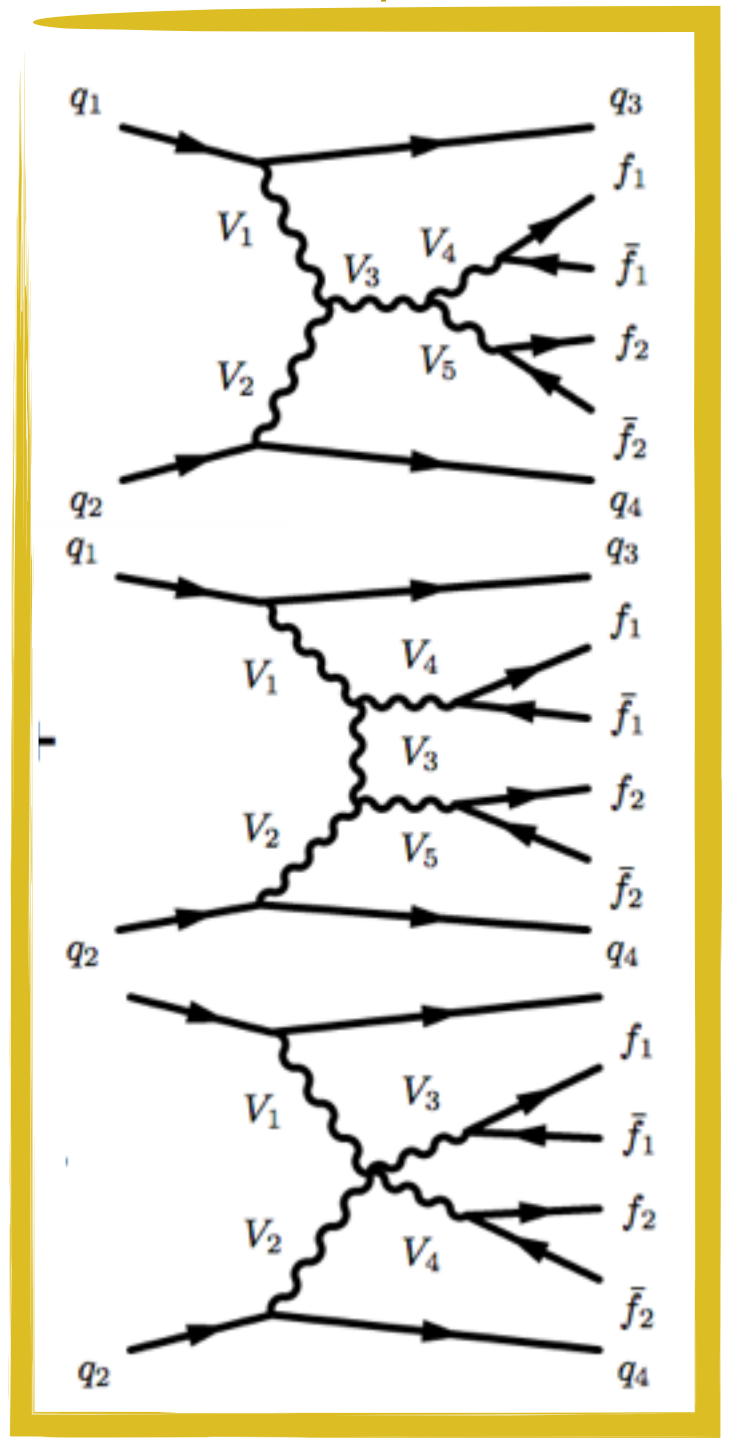
- $W^{\pm}W^{\pm}$ has highest EW/QCD ratio
- Clean signature by looking at the fully leptonic final state (W→ll l = μ,e,τ(μ,e decays))
- Few other backgrounds WZ and non prompt → constrained by control regions
- A two-dimensional fit fusing the mjj and mll
- **Observation of EWK ssWWjj production**
  - **Significance 5.7σ (exp 5.5σ)**

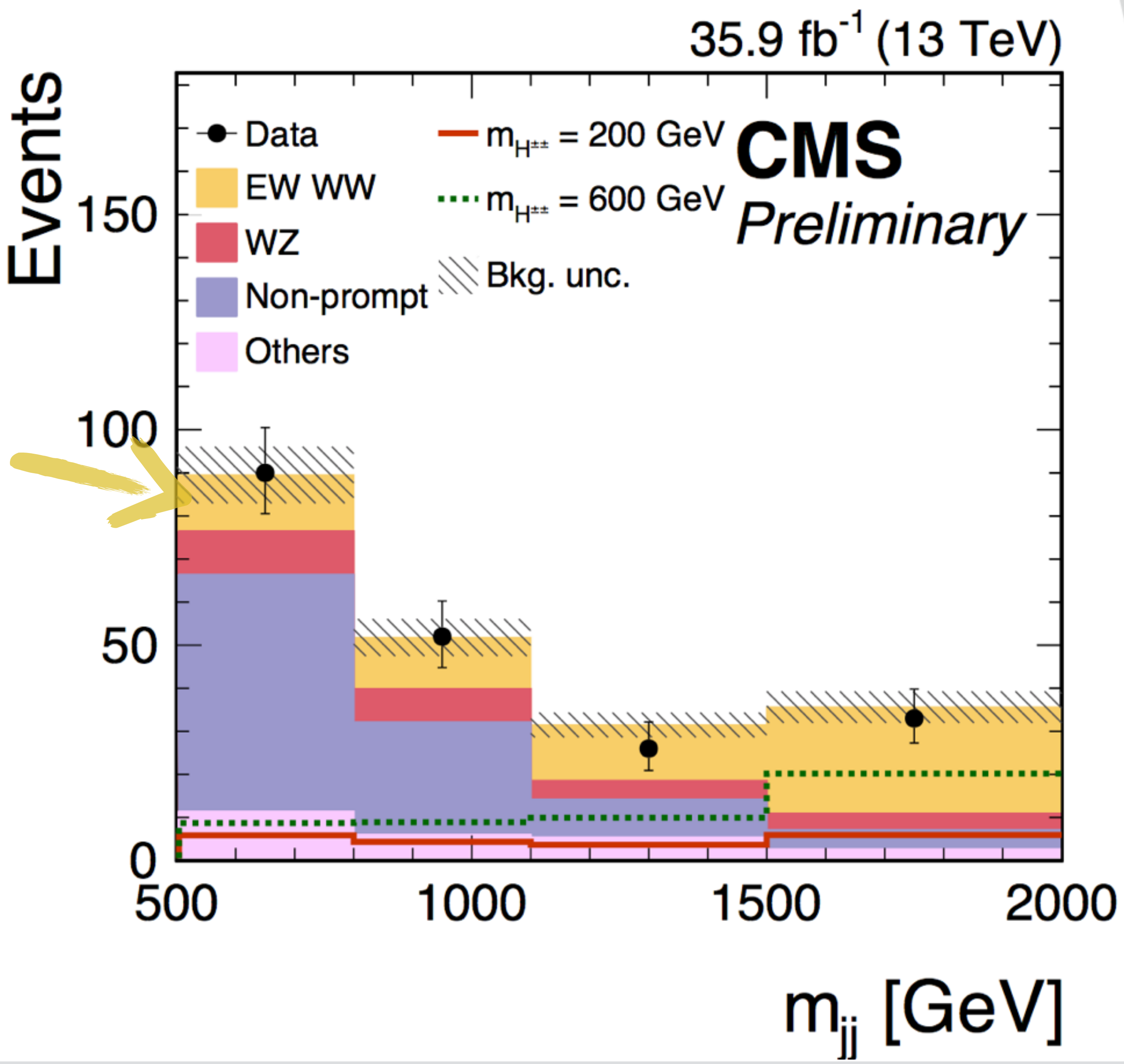
- Fiducial cross section measurement
  - M_{jj}>500GeV and $\Delta\eta_{jj}$>2.5

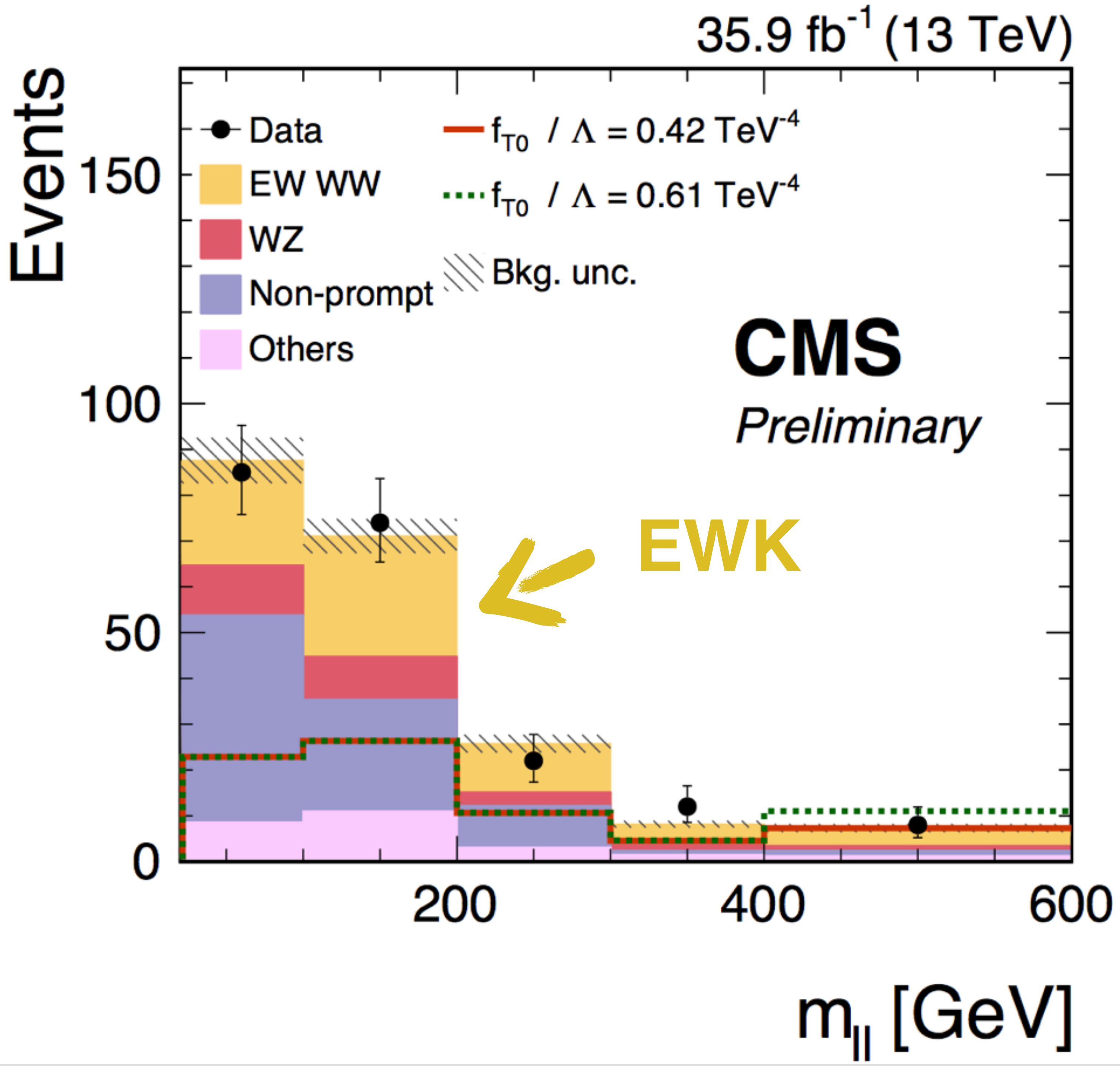
$$\sigma_{\text{fid}}(W^{\pm}W^{\pm}jj) = 3.83 \pm 0.66\,(\text{stat}) \pm 0.35\,(\text{syst})\,\text{fb}$$

LO prediction 4.25 ± 0.21 fb

Electroweak processes







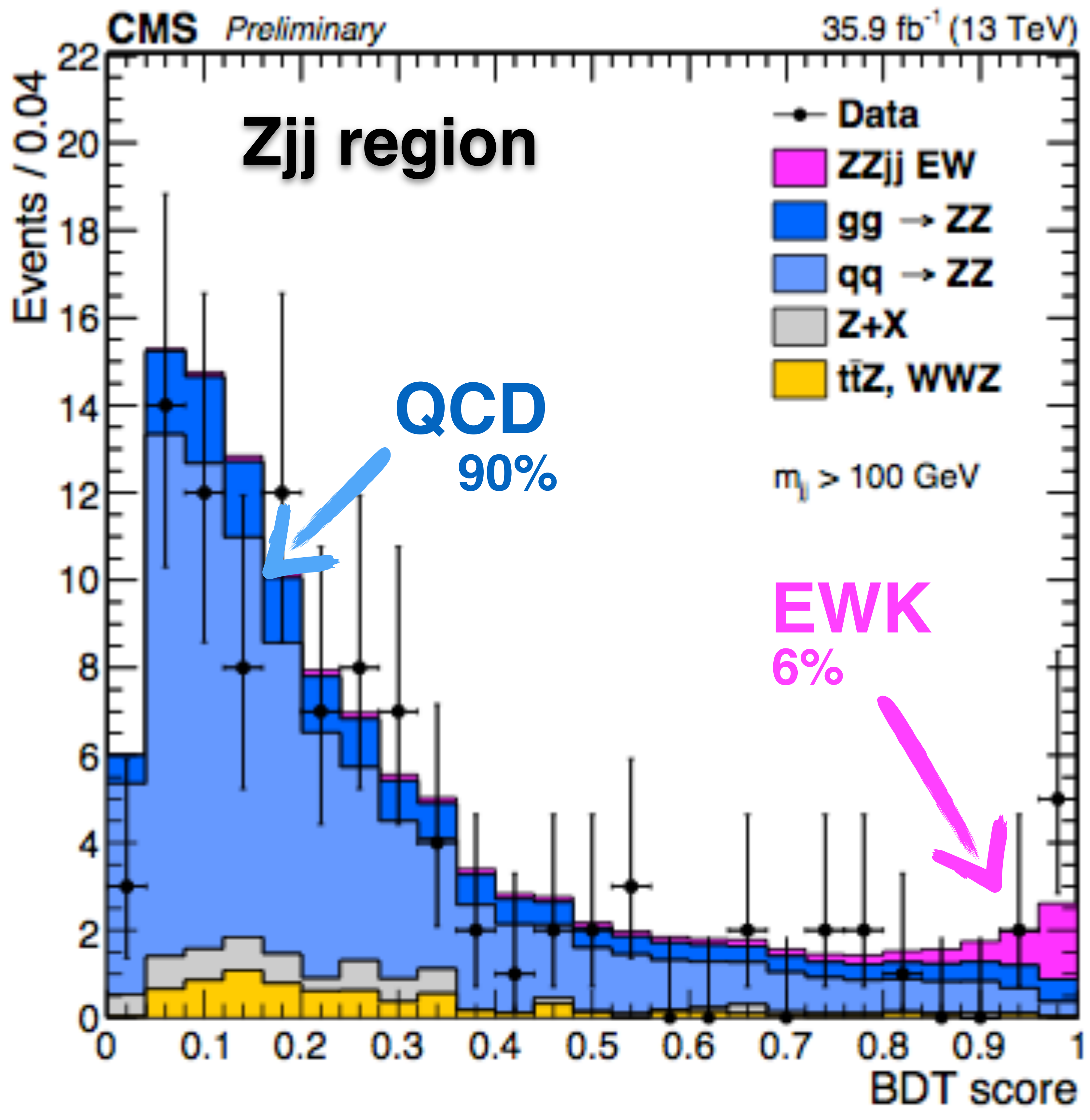
ZZjj production in association with 2 jets

new!

- Fully leptonic channel
- Two regions:
  - $M_{jj} > 100$ GeV **(Zjj region)**
  - $M_{jj} > 400$ GeV and $|\Delta\eta_{jj}| > 2.4$ **(VBS region)**
- BDT used in Zjj region to separate EWK and QCD (variables include mjj, $|\Delta\eta_{jj}|$, m_{ZZ}, Zeppenfeld variables of the two Z bosons, event balance $R_{p_T}^{hard}$ and others)
- EWK signal significance 2.7σ (exp 1.6σ)

$$\sigma_{\text{fid.}}(\text{EW pp} \to ZZjj \to \ell\ell\ell'\ell' jj) = 0.40^{+0.21}_{-0.16}(\text{stat.})^{+0.13}_{-0.09}(\text{syst.})\ \text{fb}$$

prediction 0.29 ± 0.03 fb

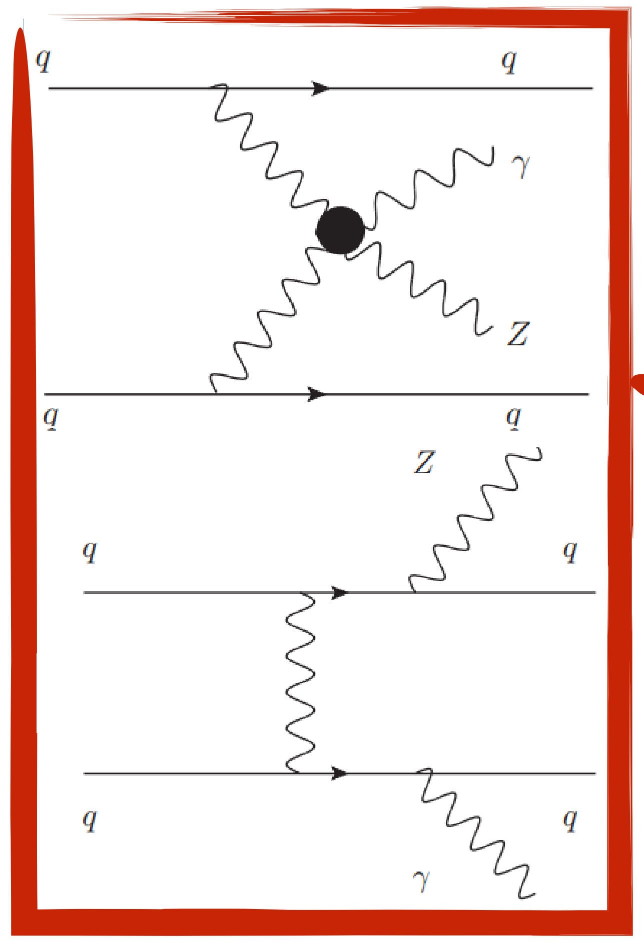


$Z\gamma$ EWK production in association with high mass di-jet system

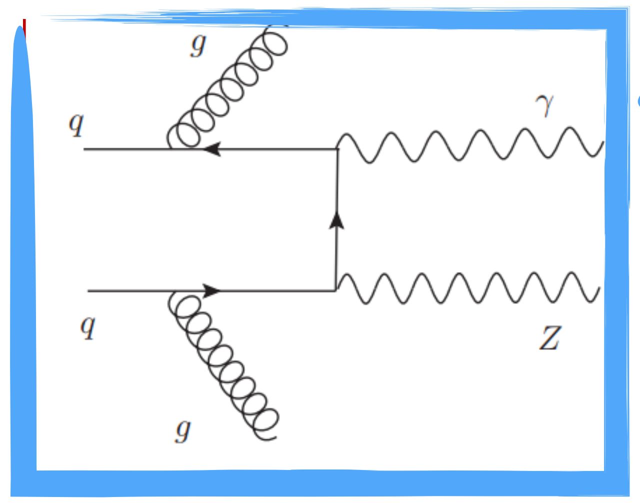
new!

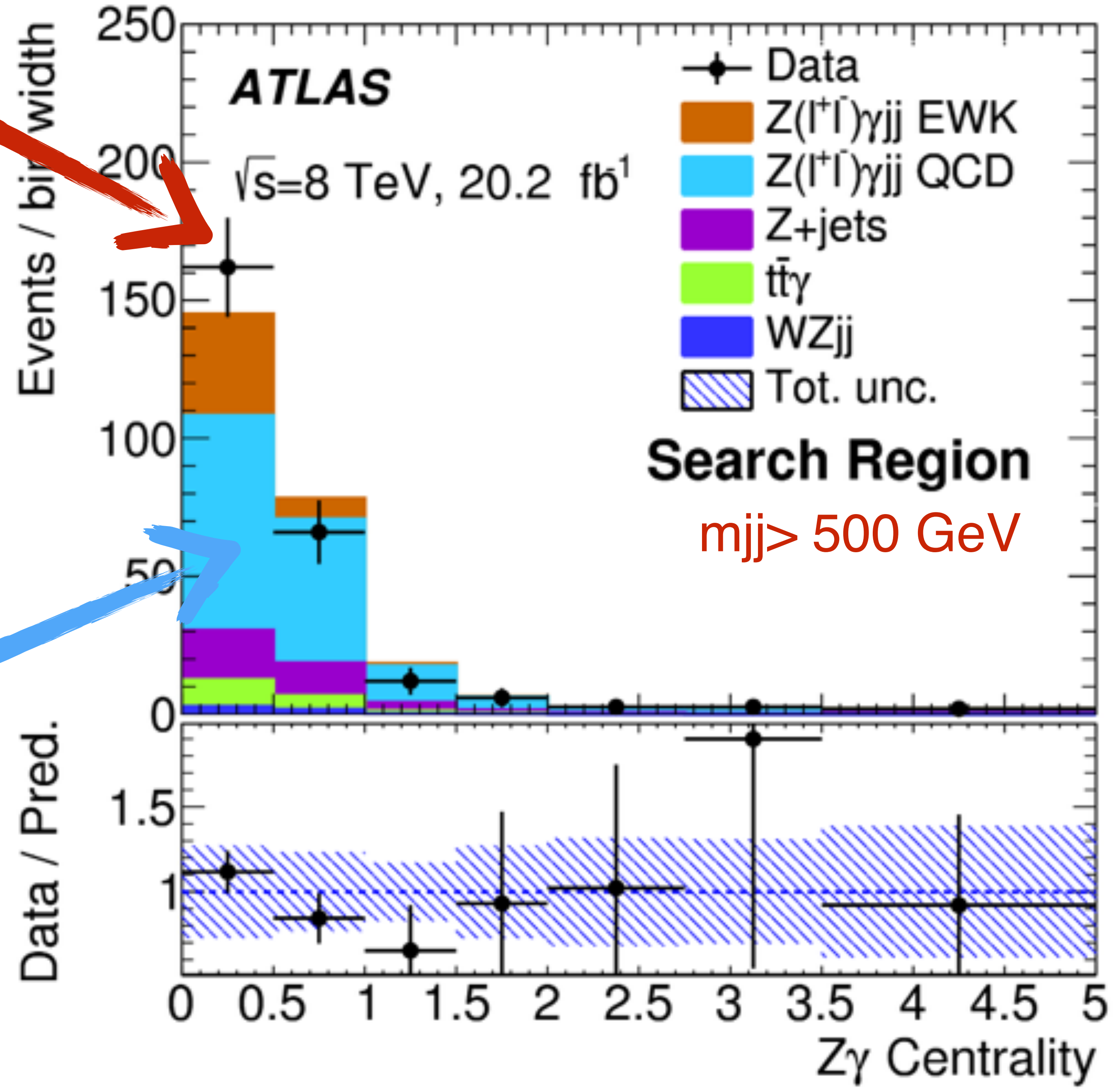
- Two channels: Z→ll and Z→νν
- Mjj cuts used to increase EWK sensitivity
- EWK only cross section extracted by fitting signal strength μ using centrality including control region→constrains on QCD part
- Observed EWK signal significance ~2σ

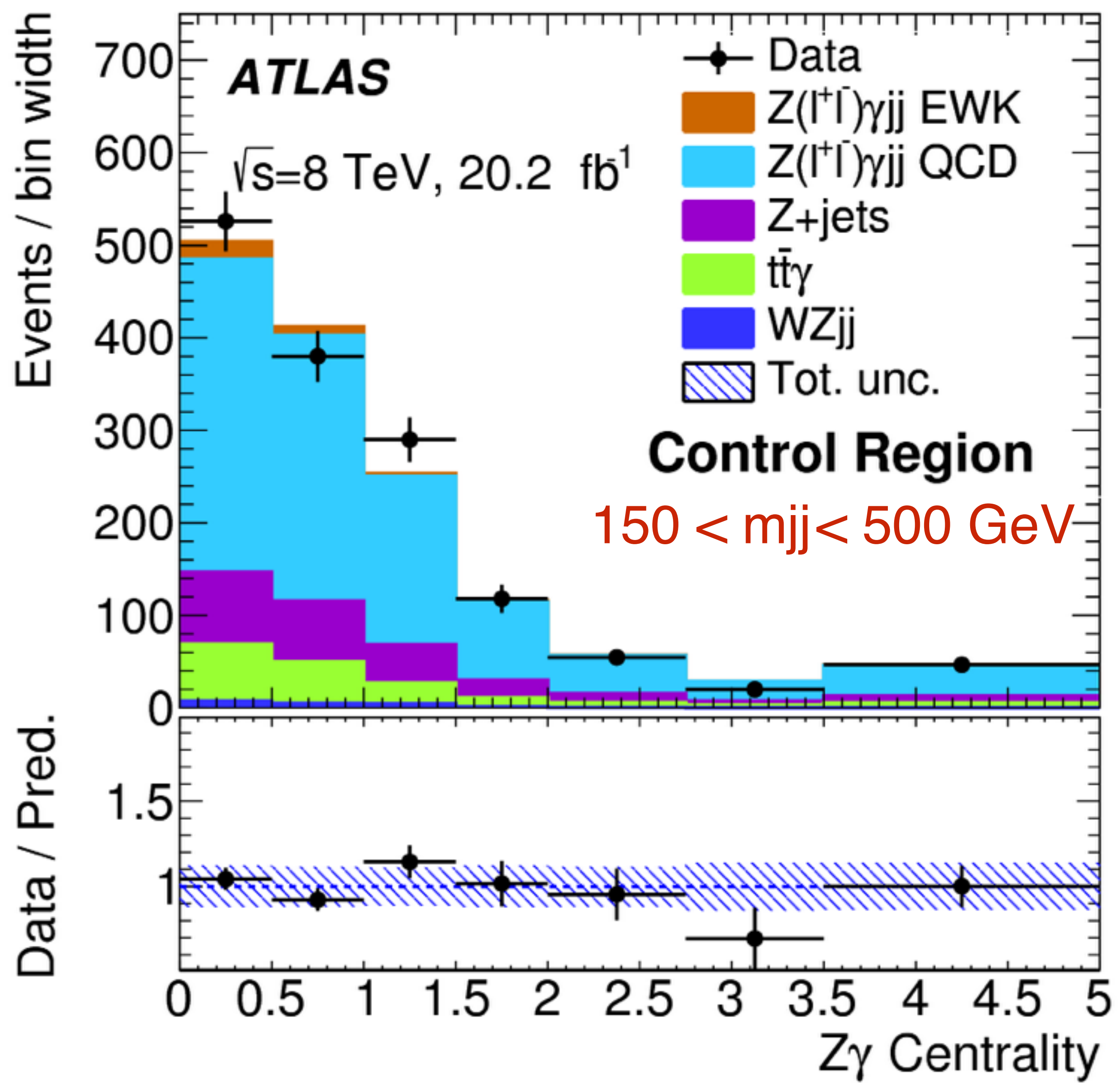
Electroweak processes

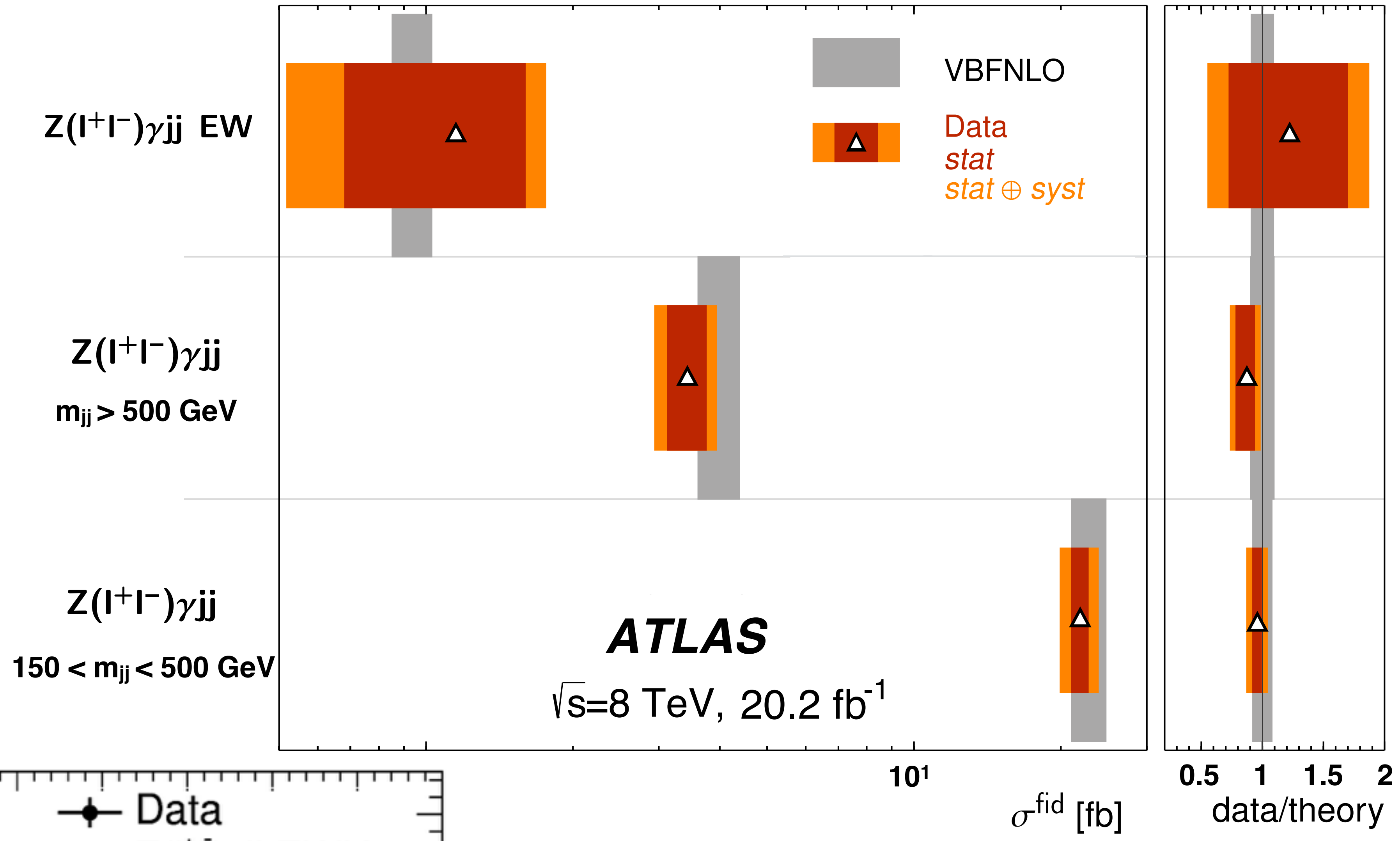


QCD processes







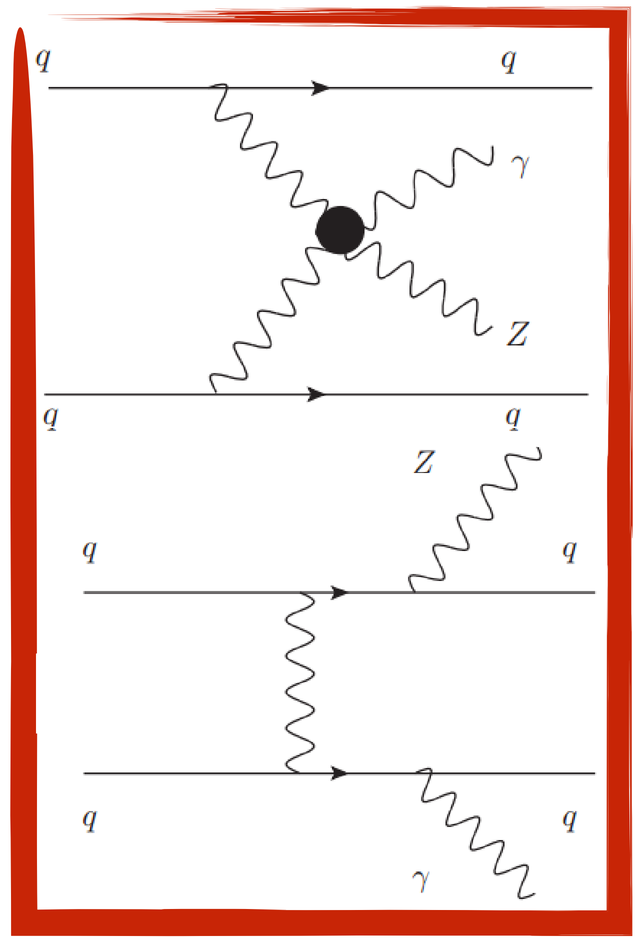


Data
Z(l⁺l⁻)γjj EWK
Z(l⁺l⁻)γjj QCD
Z+jets
tt̄γ
WZjj
Tot. unc.

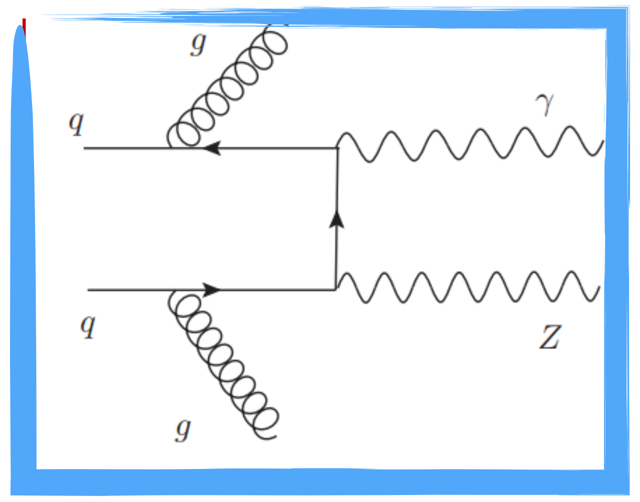
$Z\gamma$ EWK production in association with high mass di-jet system

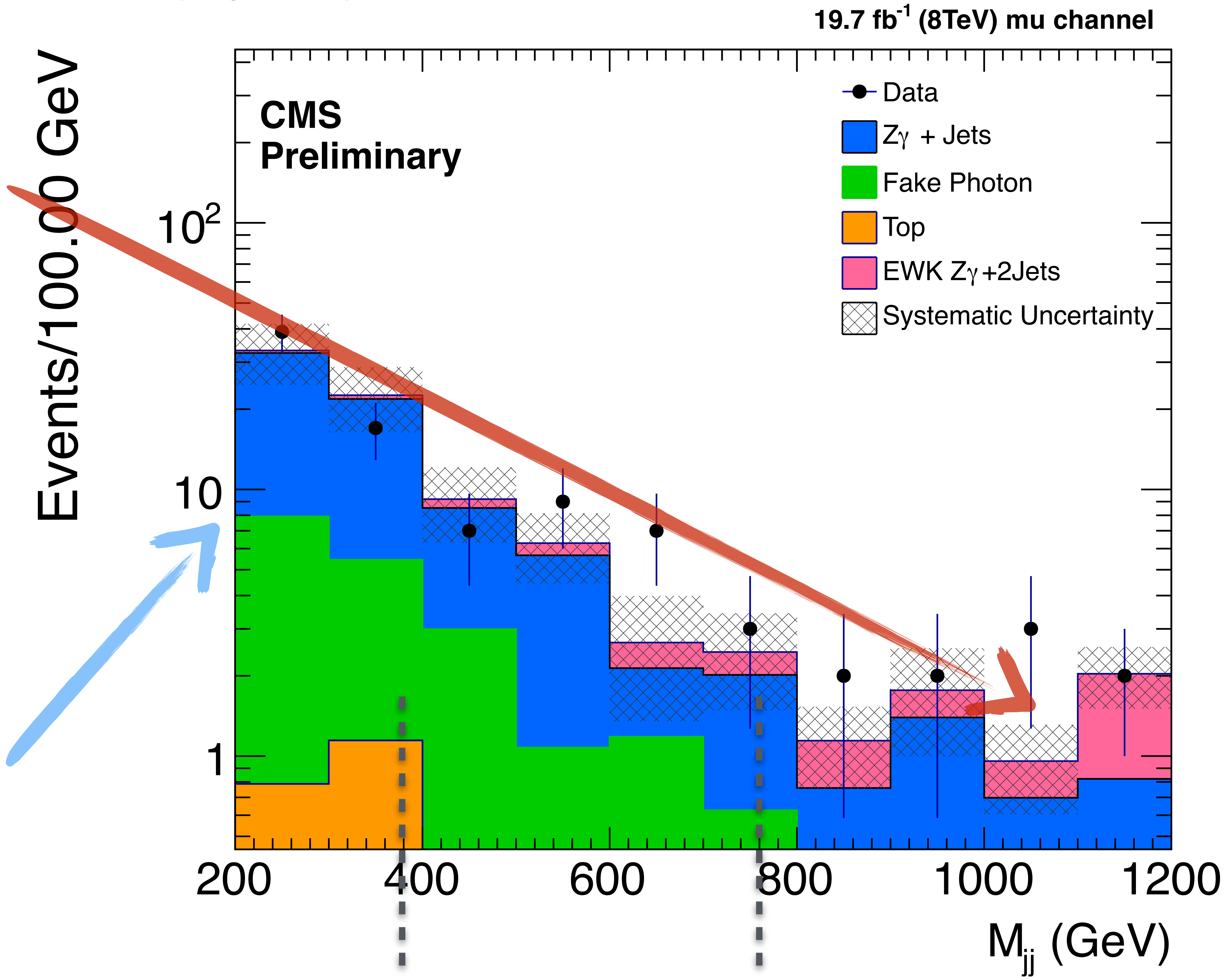
- Similar analysis from CMS
  - Leptonic channel $Z \rightarrow ll$ ($l = \mu, e$)
  - Two bins: 400 < mjj < 800 GeV; mjj > 800 GeV
- **Evidence of EWK $Z\gamma jj$ production**
  - Significance ~3σ (exp 2.1σ)

Electroweak processes



QCD processes

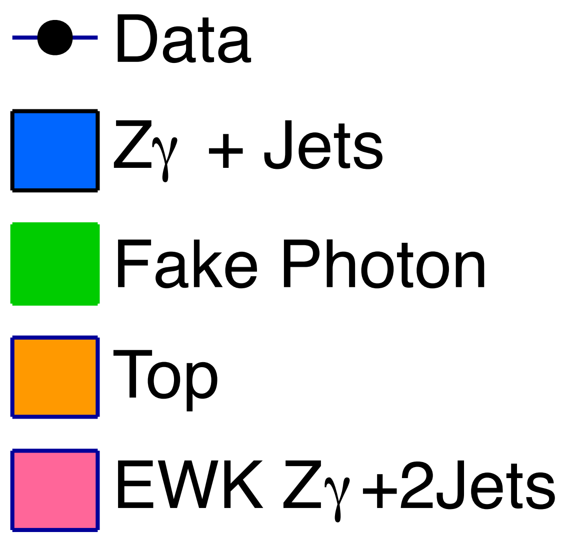




- Fiducial cross section measurement
  - M_{jj}>400GeV and $\Delta\eta_{jj}$>2.5

$$1.86^{+0.89}_{-0.75}(stat.)^{+0.41}_{-0.27}(sys.) \pm 0.05(lumi.)\ \text{fb}$$

LO prediction 1.26 ± 0.11(scale) ± 0.05(PDF) fb



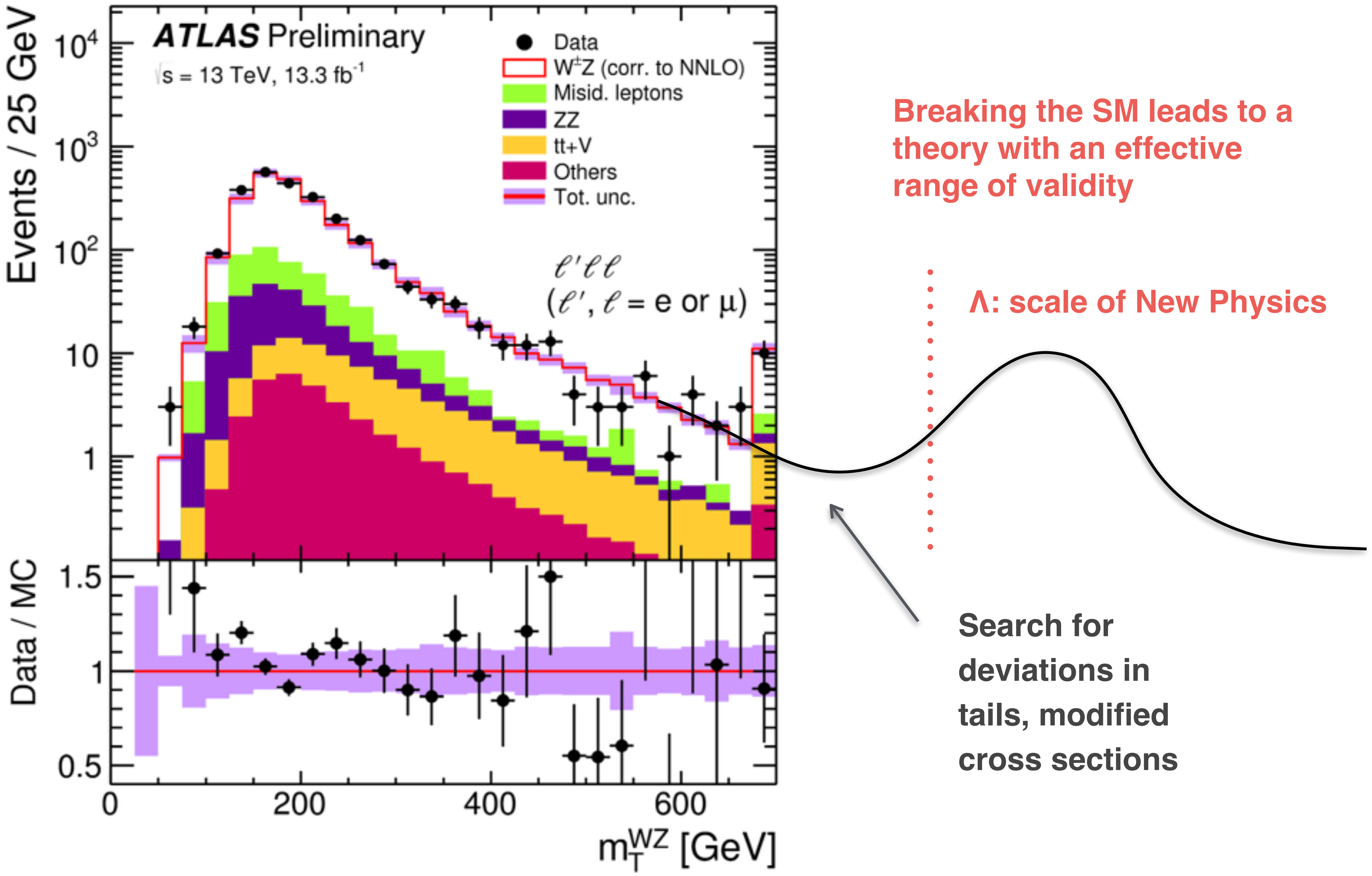
Look at beyond the SM physics

Introduction
Dibosons
WW
WZ
ZZ
Tribosons
VBS
Wjj
Zγ
ZZjj
aGCs
Summary

- Low energy effect from beyond SM physics can be modeled by effective theories (SM+higher dimension operators)
- Anomalous coupling approach: effective Lagrangian with anomalous triple or quartic gauge couplings (aTGC, aQGC)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

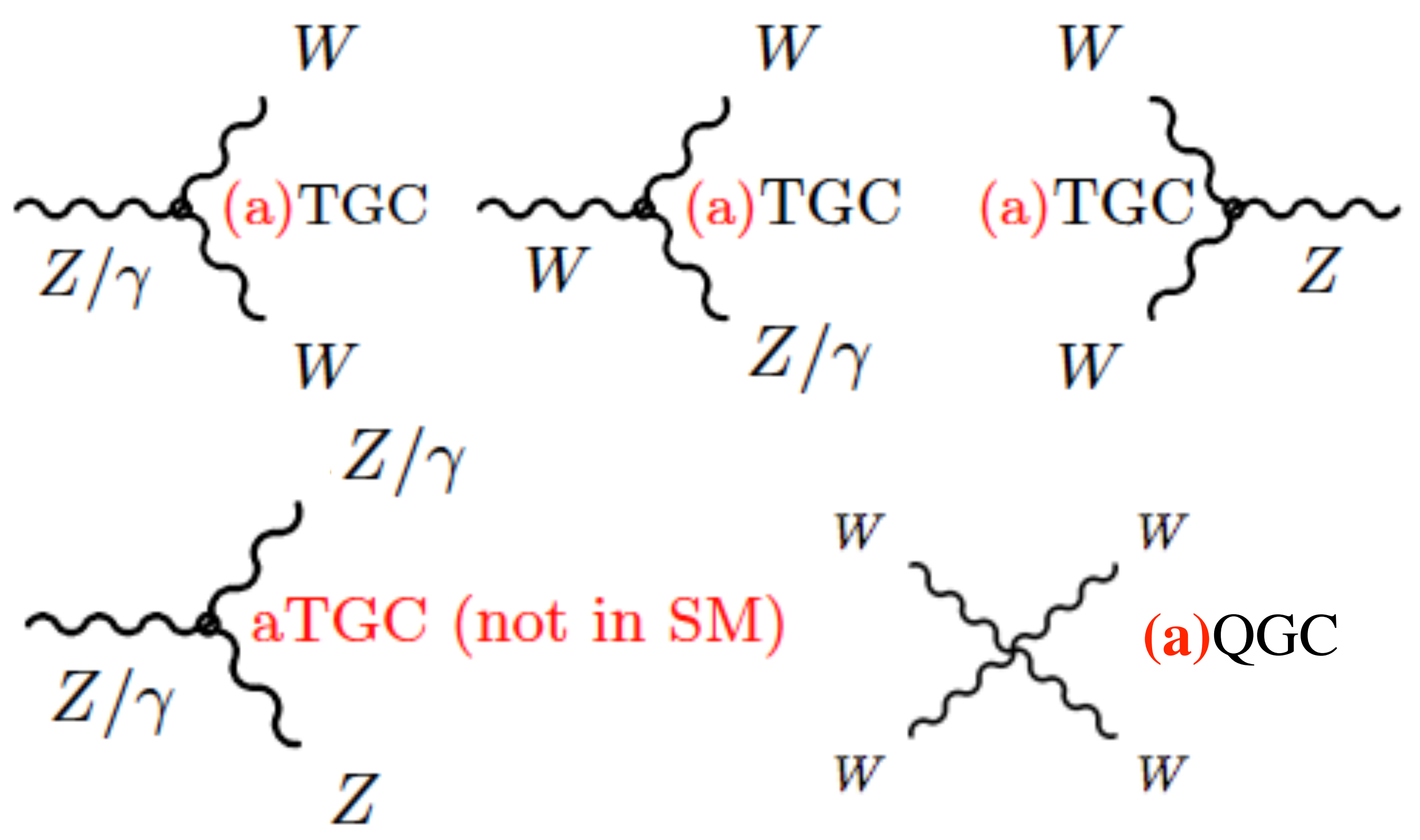
dimension d

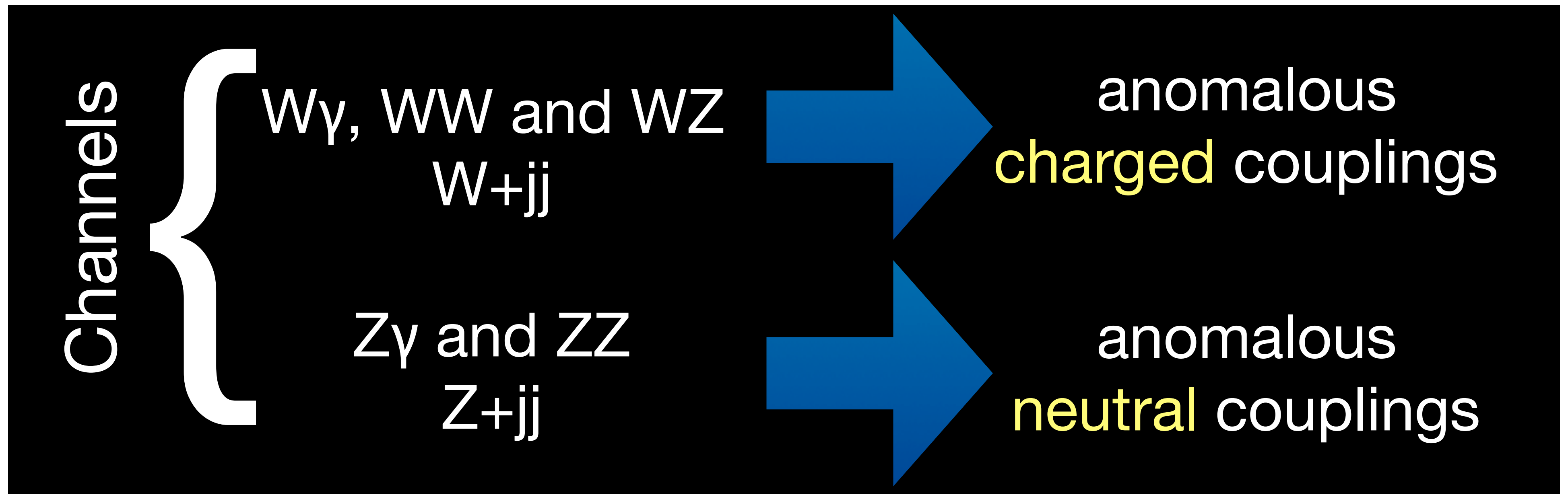


- Anomalous couplings manifest themselves as :
  - Enhanced production cross section
  - Modified kinematics distributions

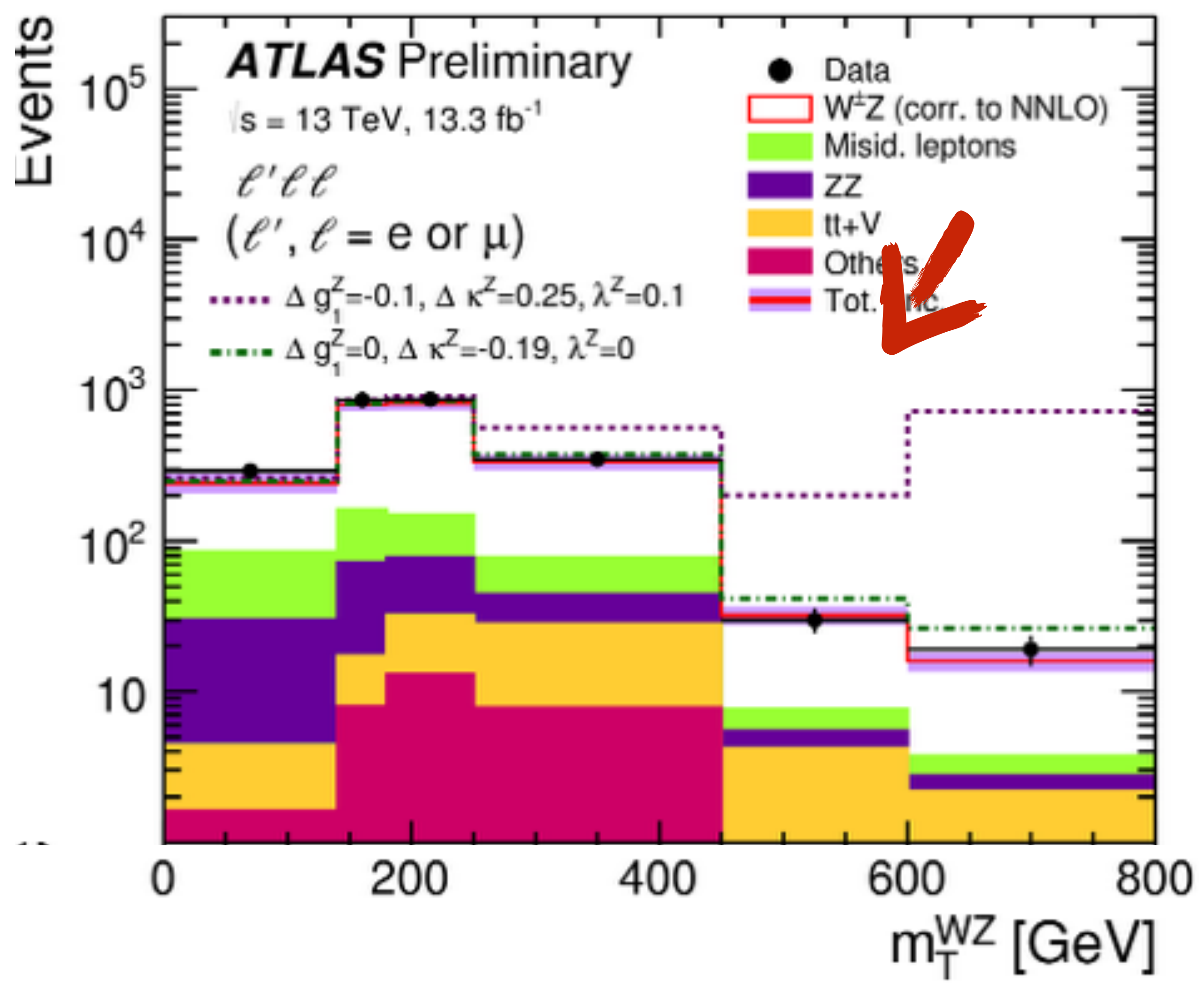
Anomalous gauge couplings

- A single channel is not sensible to all the parameters
  - Need to study various processes to put constraints on all operators

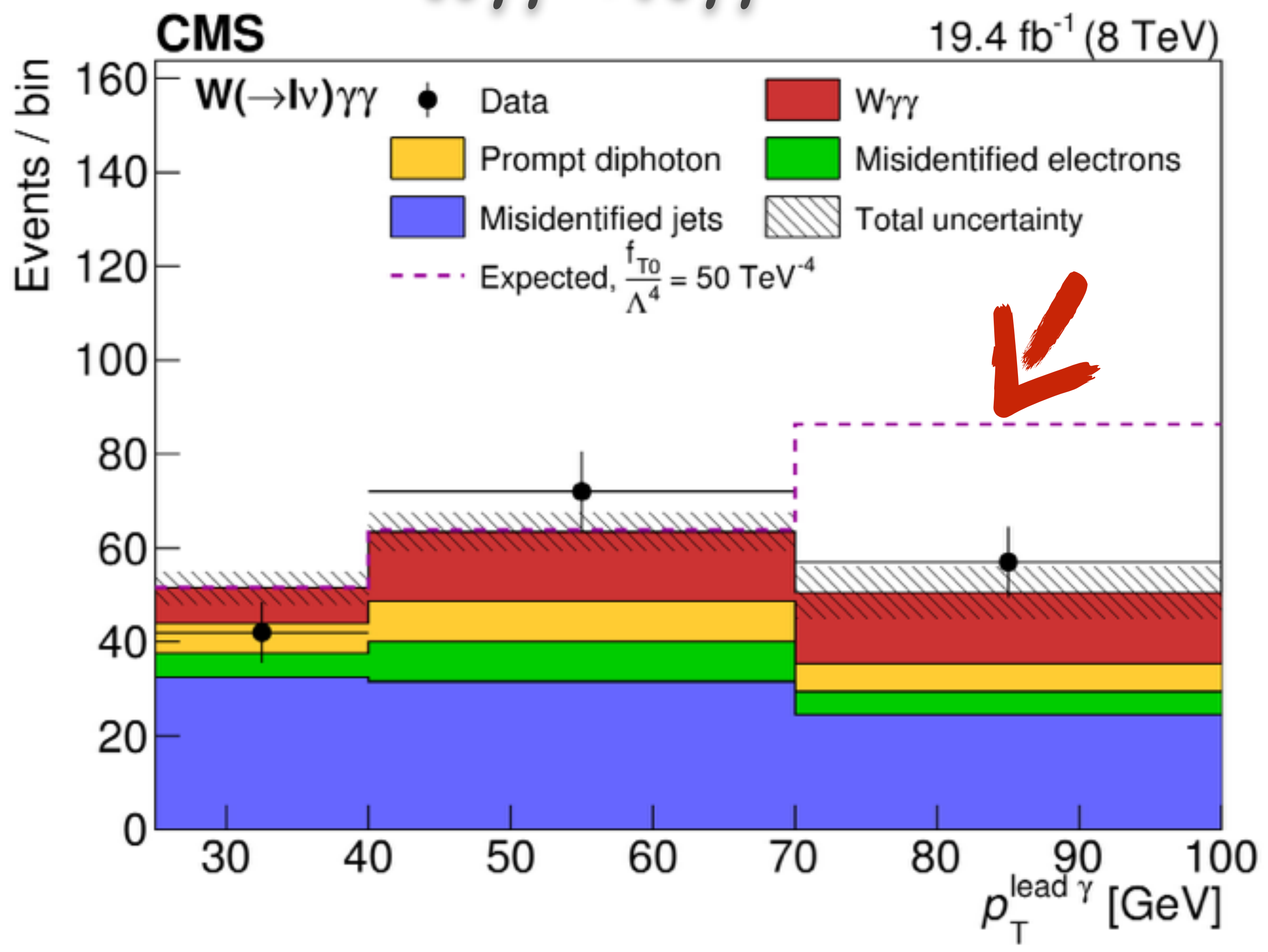




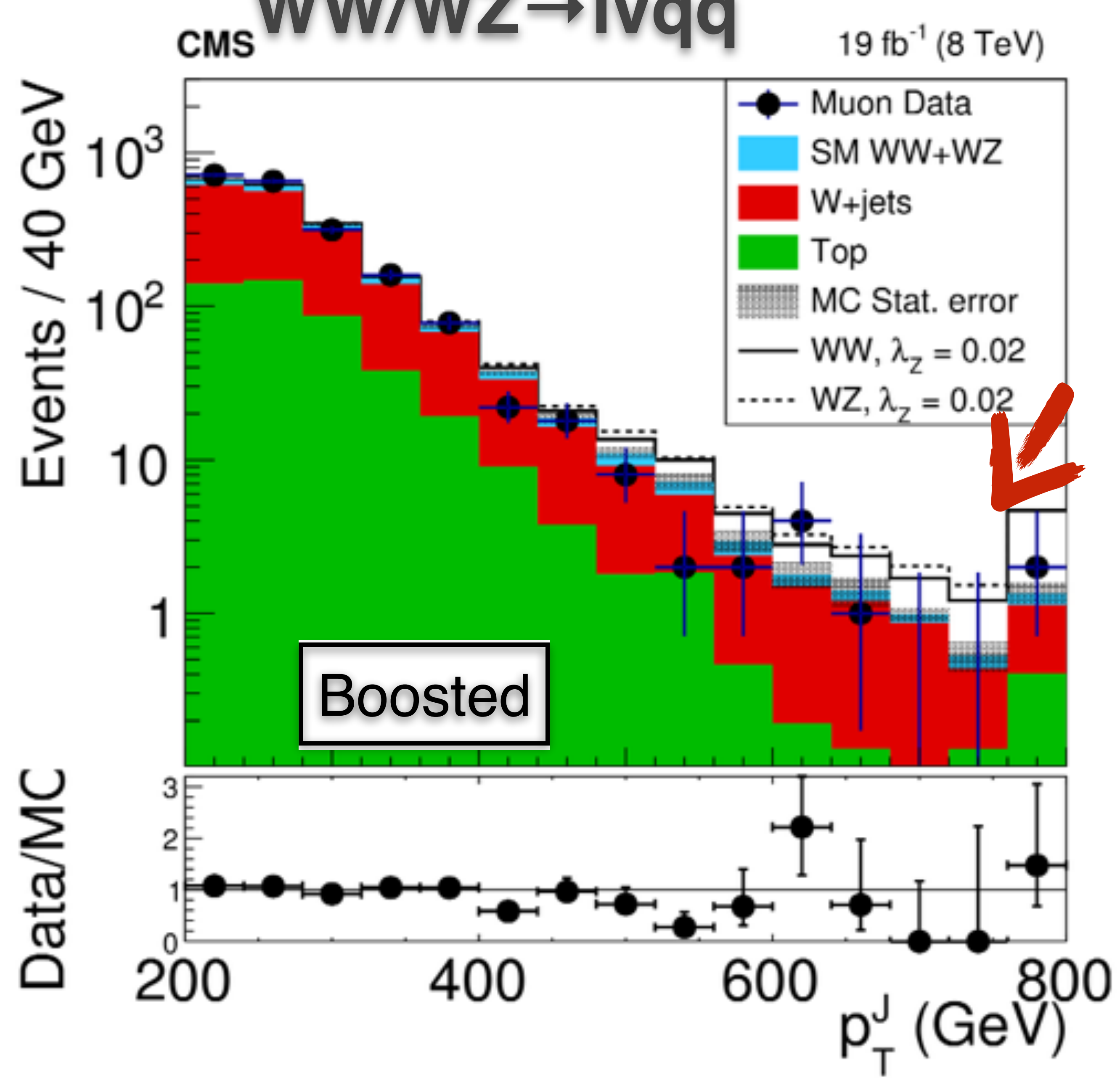
WZ→lνll



Wγγ→lνγγ

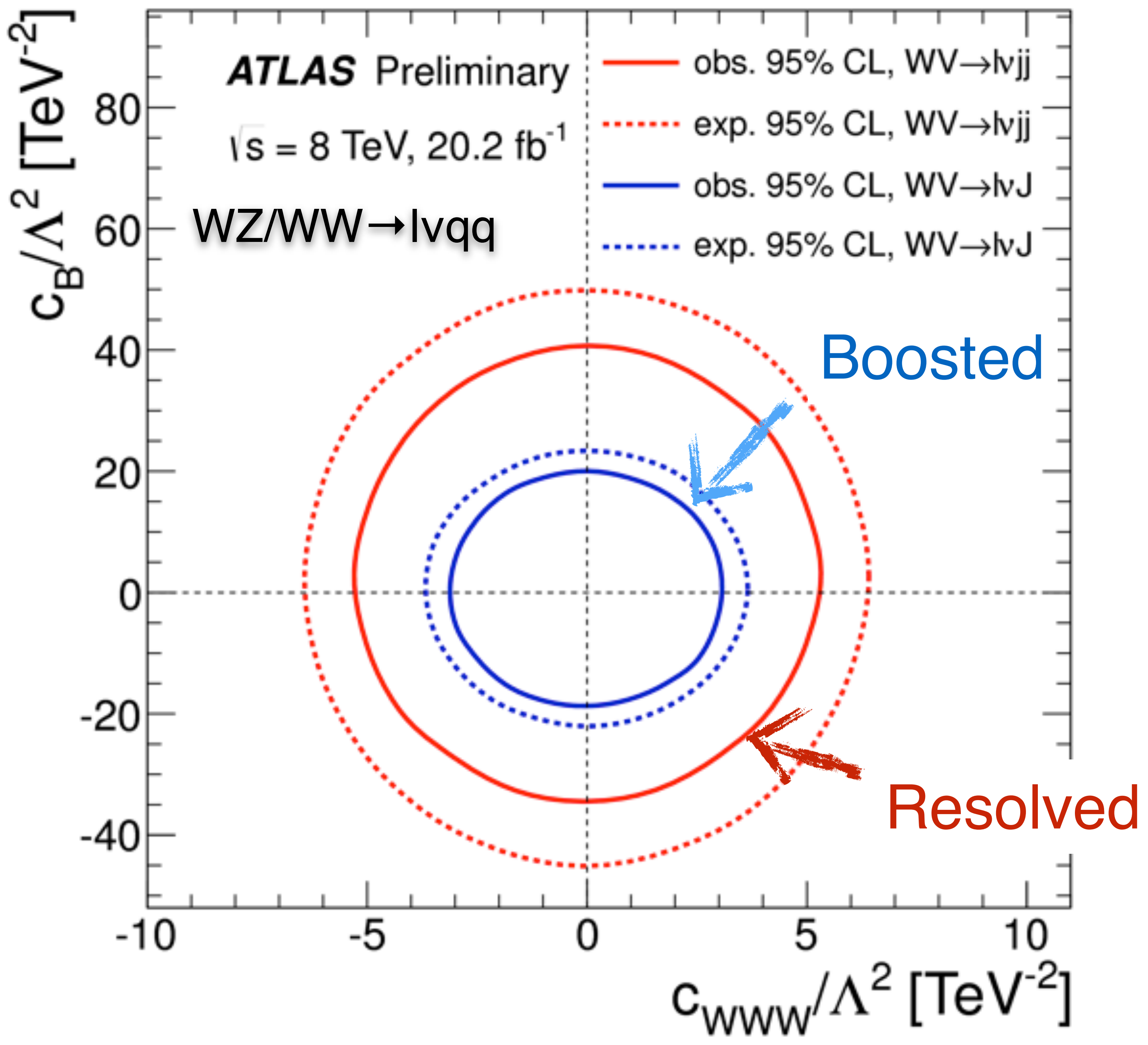


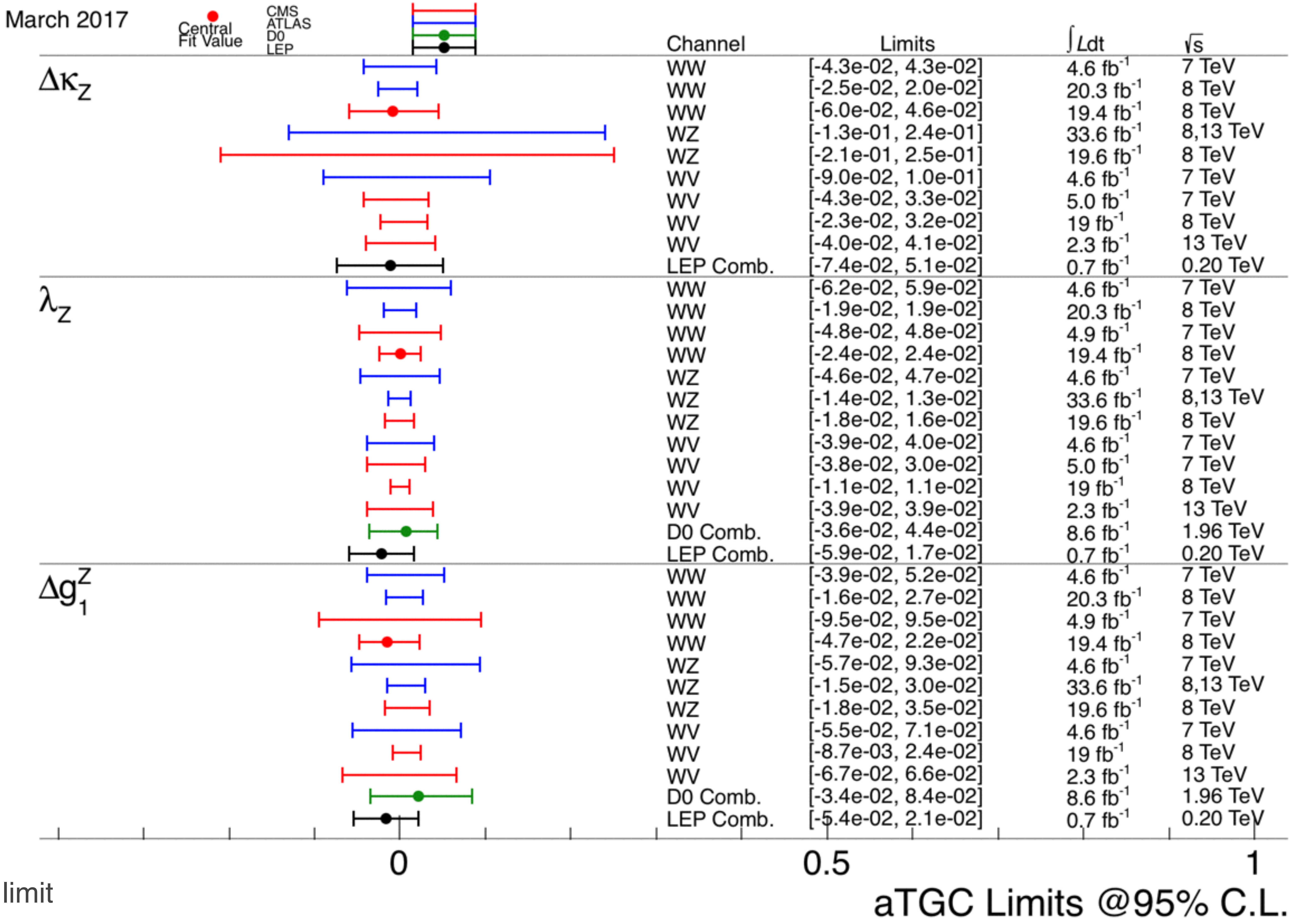
WW/WZ→lνqq



Charged aTGC

- Sensitivity depends on the reach of the channel
  - ex: WZ/WW semileptonic resolved and boosted analysis



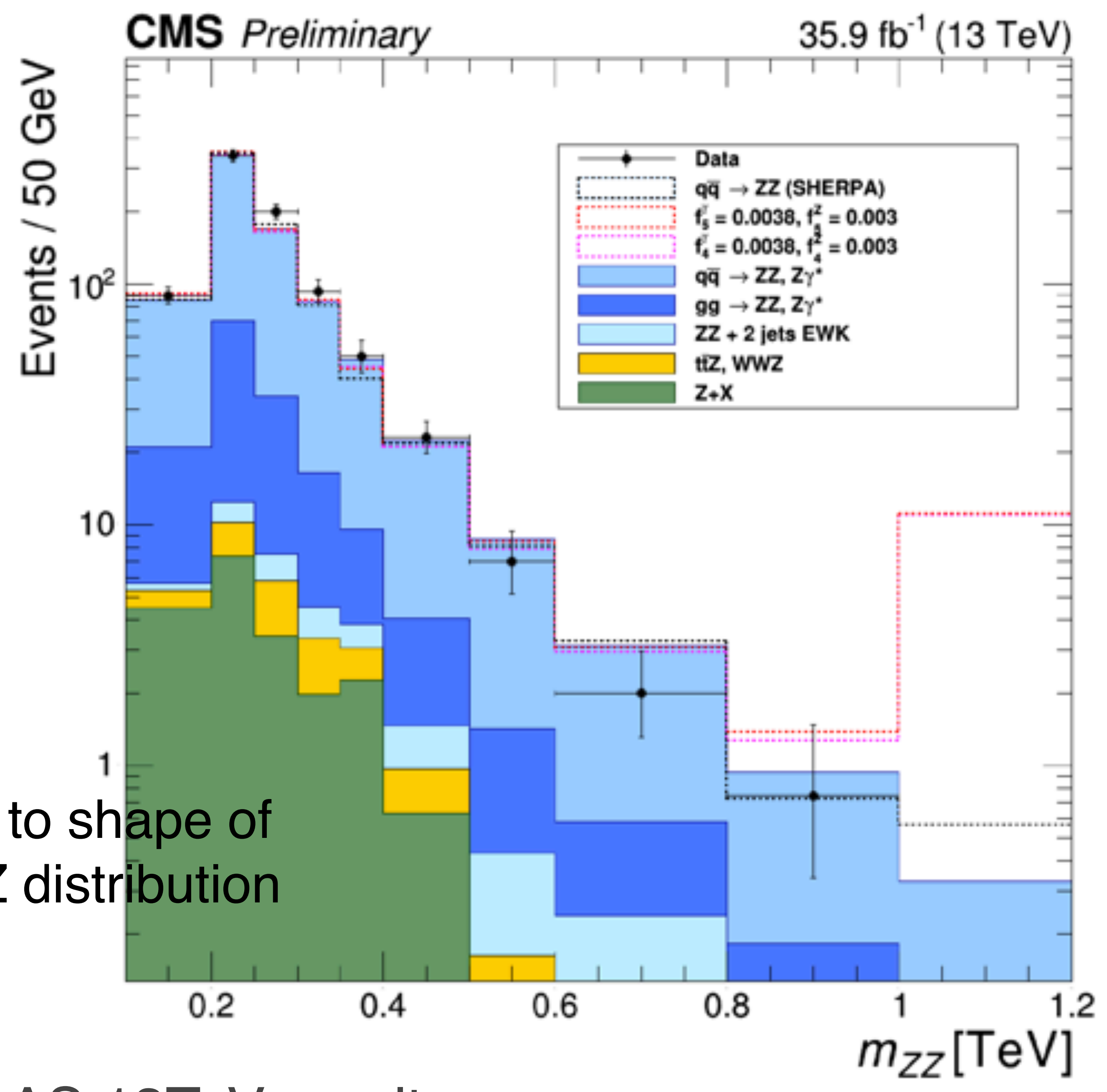


- LHC limits are already slightly better than LEP limit

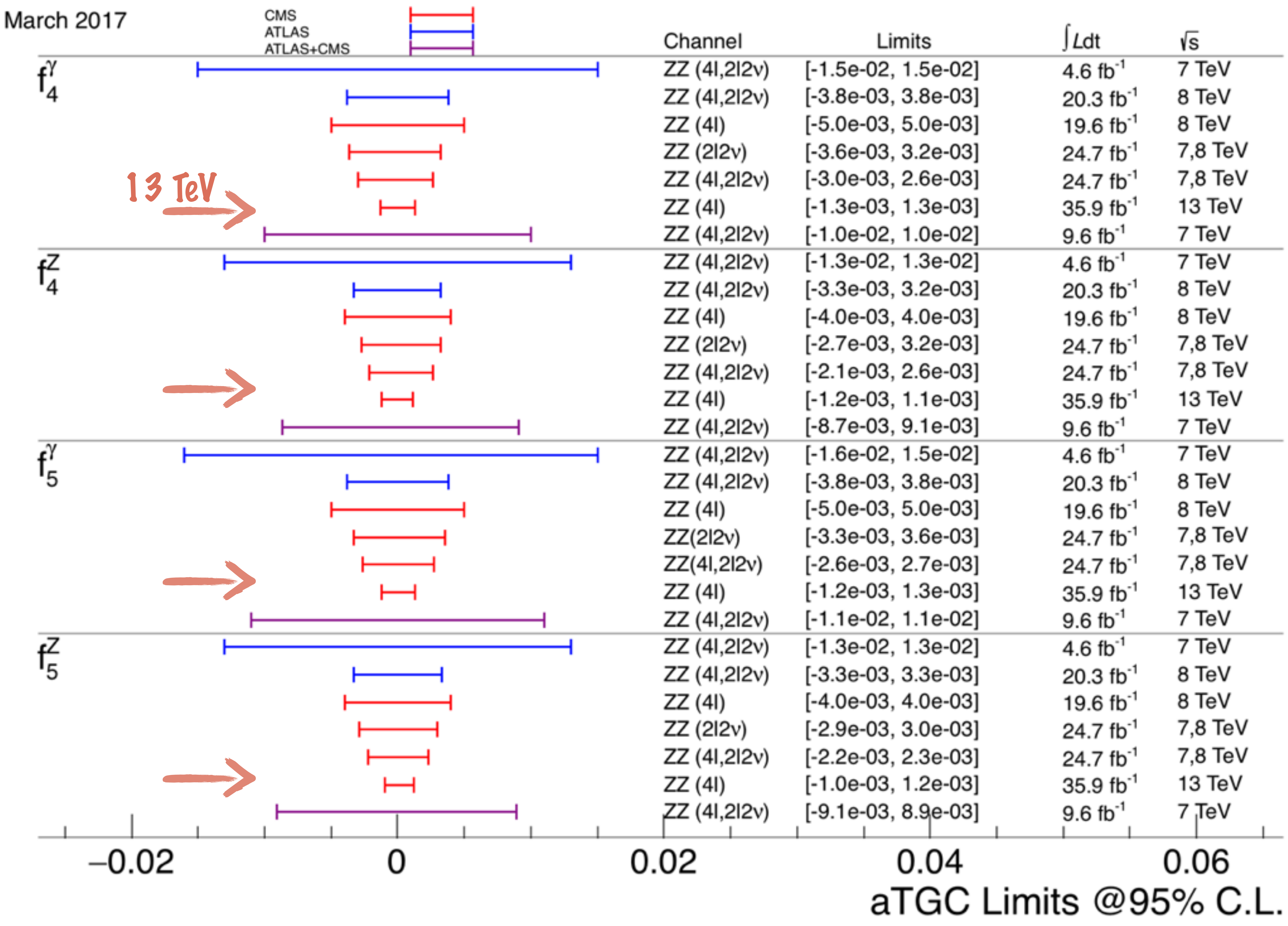
ATLAS : STDM-2015-23

Neutral aTGC

- LHC limits for neutral couplings are far stricter than LEP limits
- Large gain in sensitivity with increase of √s



Fits to shape of mZZ distribution



- ATLAS 13TeV results

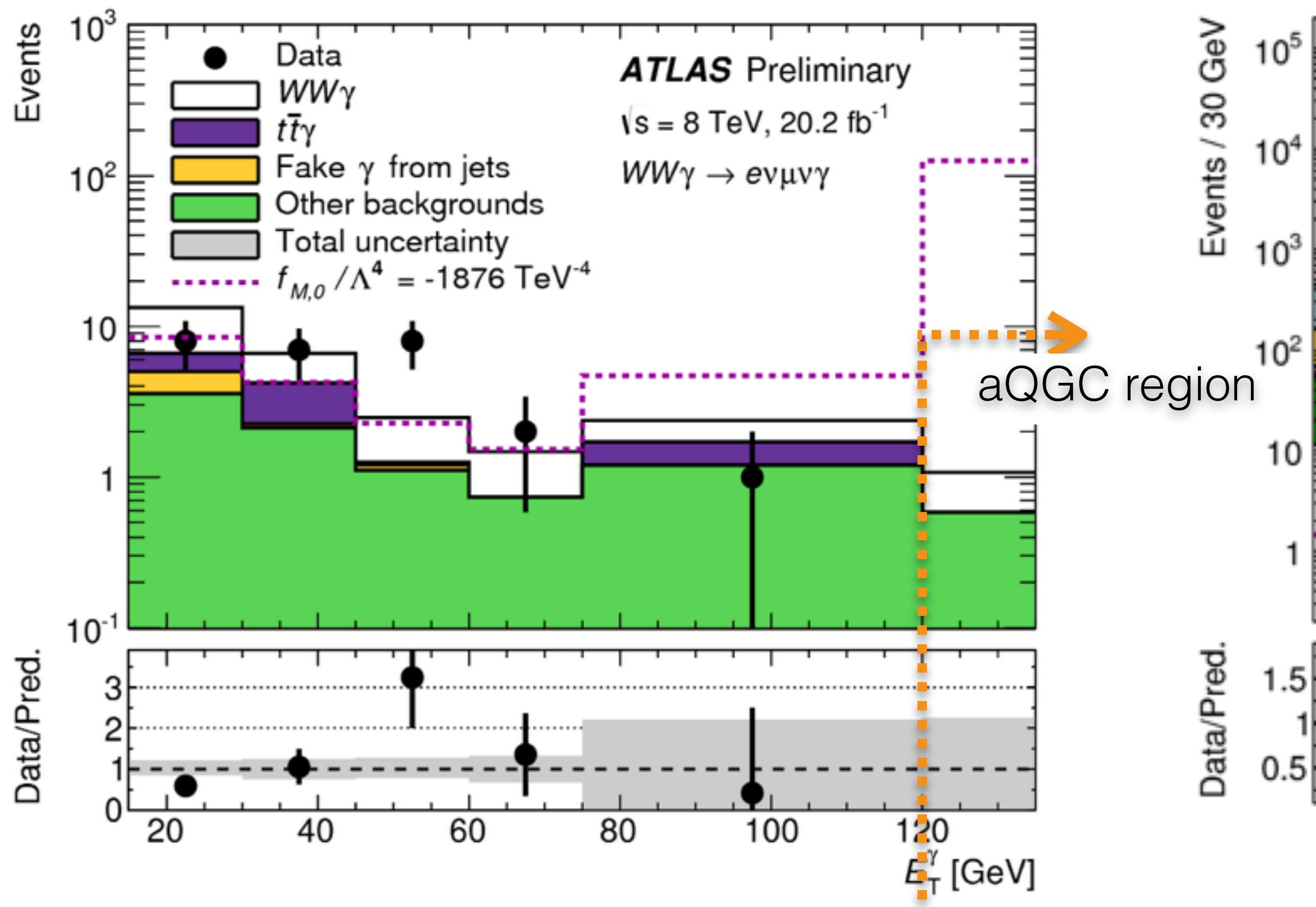
Coupling strength	Expected 95% CL [$\times 10^{-3}$]	Observed 95% CL [$\times 10^{-3}$]
f_4^γ	−2.4, 2.4	−1.8, 1.8
f_4^Z	−2.1, 2.1	−1.5, 1.5
f_5^γ	−2.4, 2.4	−1.8, 1.8
f_5^Z	−2.0, 2.0	−1.5, 1.5

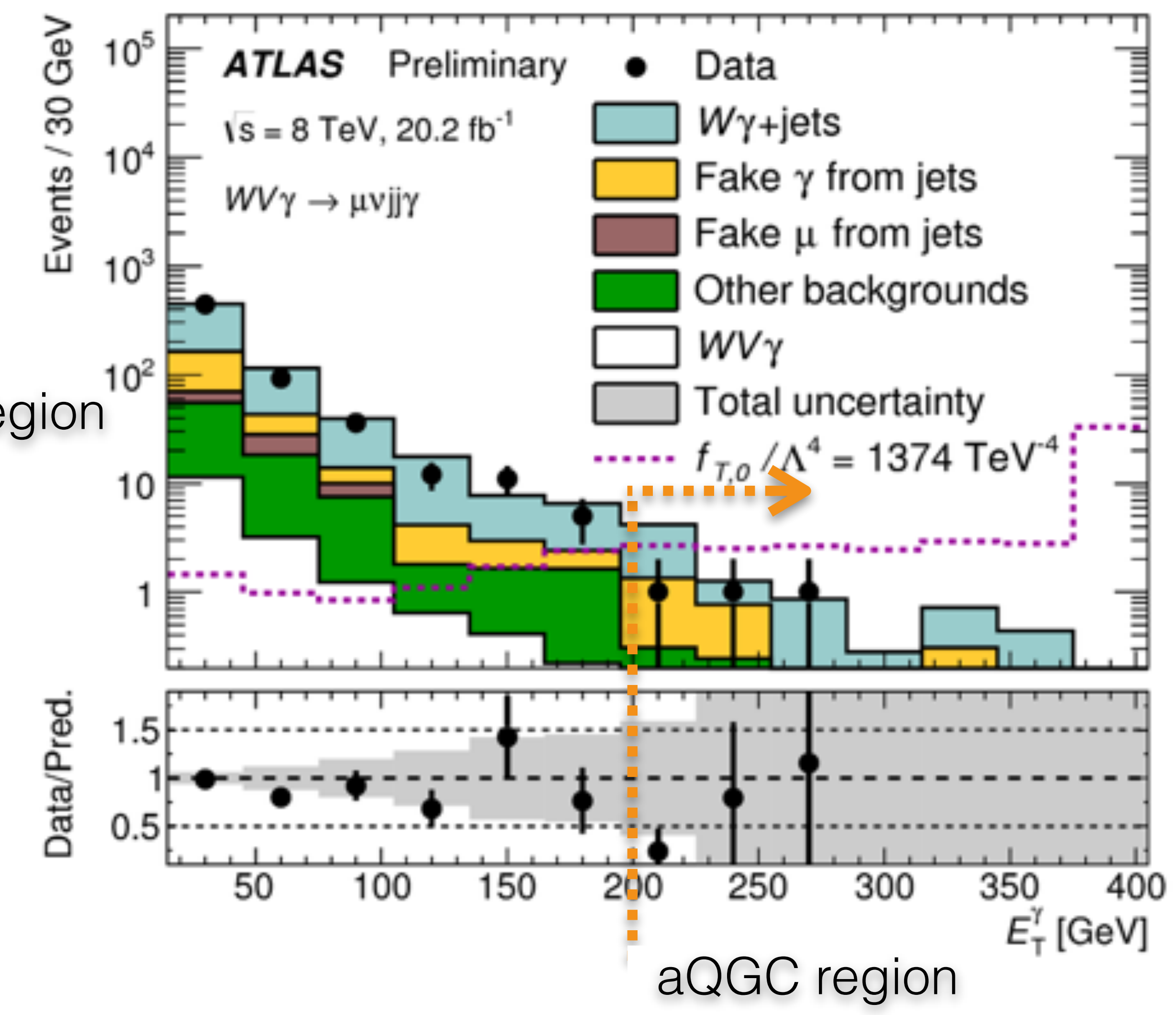
new!

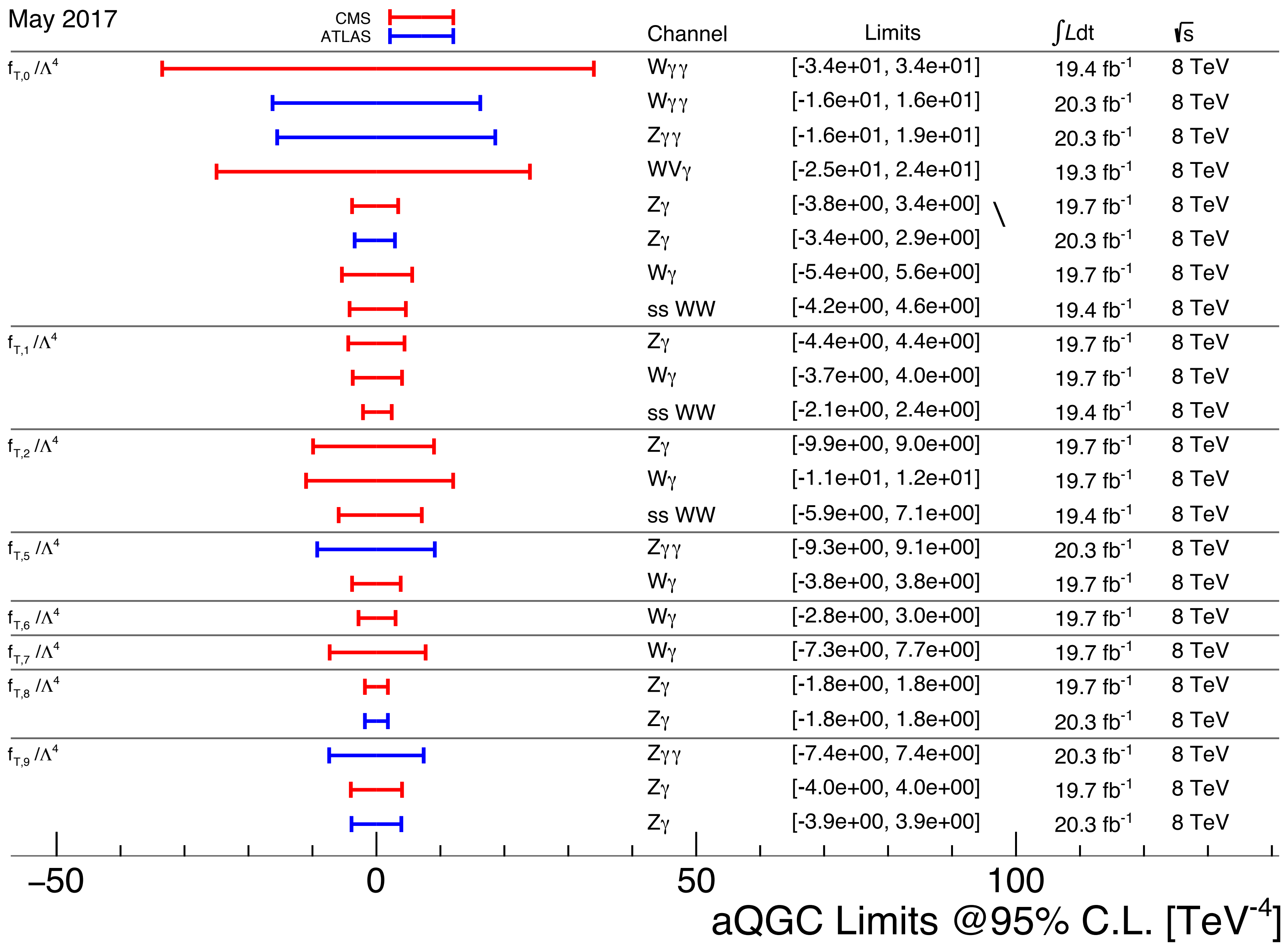
ATLAS: ATLAS-CONF-2017-031 CMS: CMS-PAS-SMP-16-017

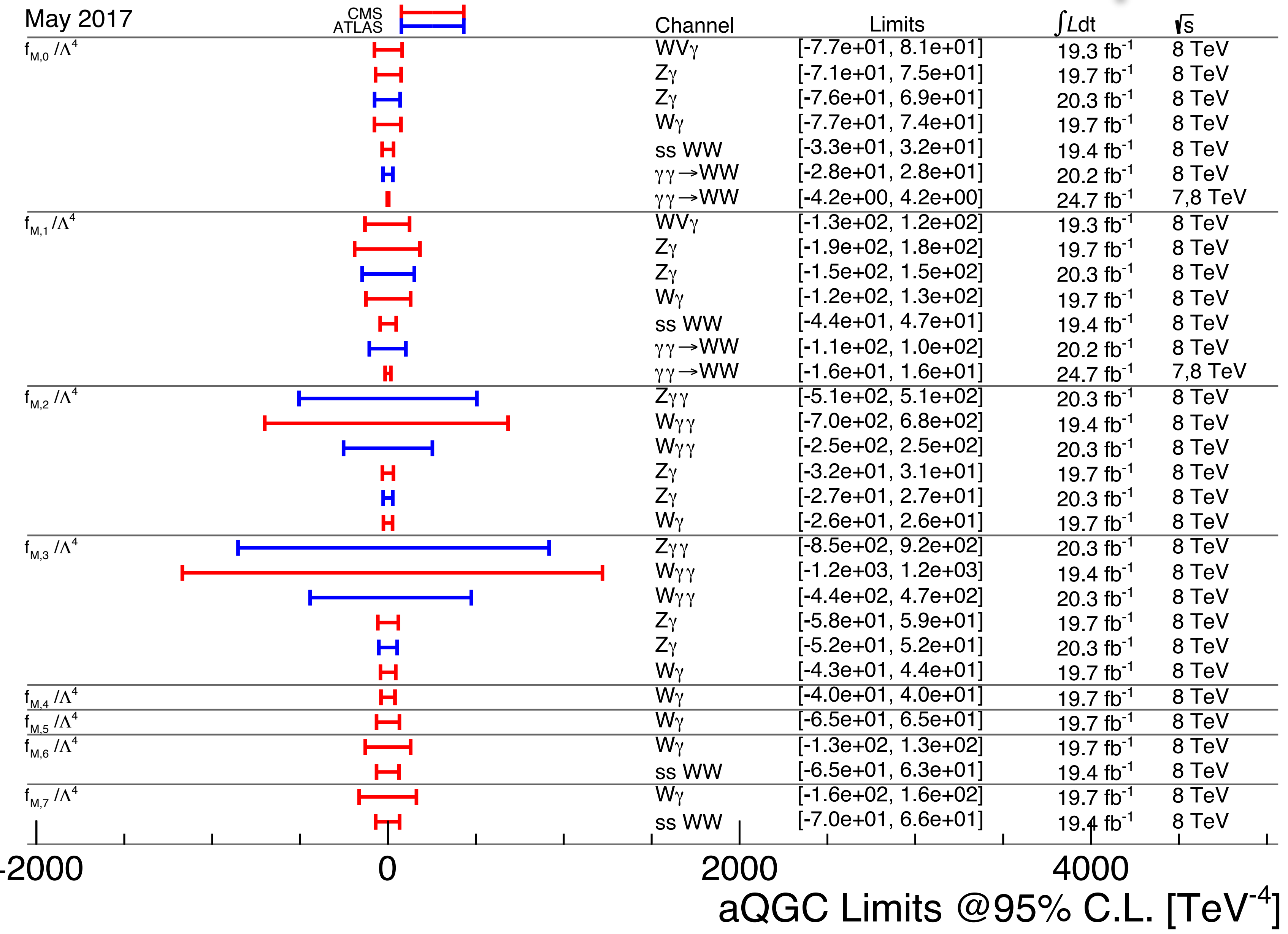
anomalous Quartic Gauge Couplings

- New physics could induce charged and neutral aQGCs
- Constraints are also derived using the dibosons and tribosons channels
  - aQGC fits use a more restrictive phase space with higher S/B but low statistics
- No deviations from the SM! we are eagerly awaiting the first 13 TeV results









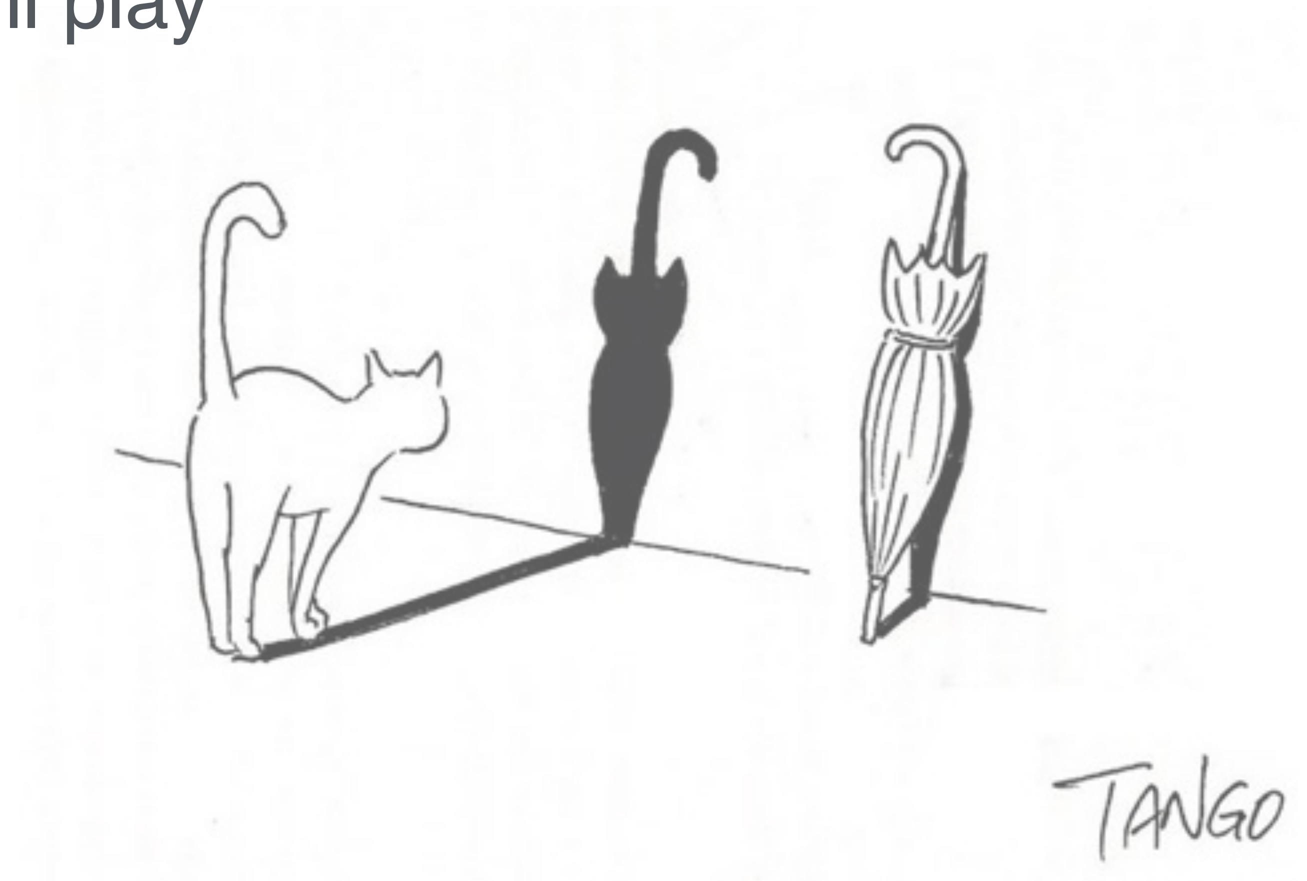
f_{Ti}: transverse

f_{Mi}: mixed longitudinal & transverse

ATLAS: ATLAS-STDM-2015-21

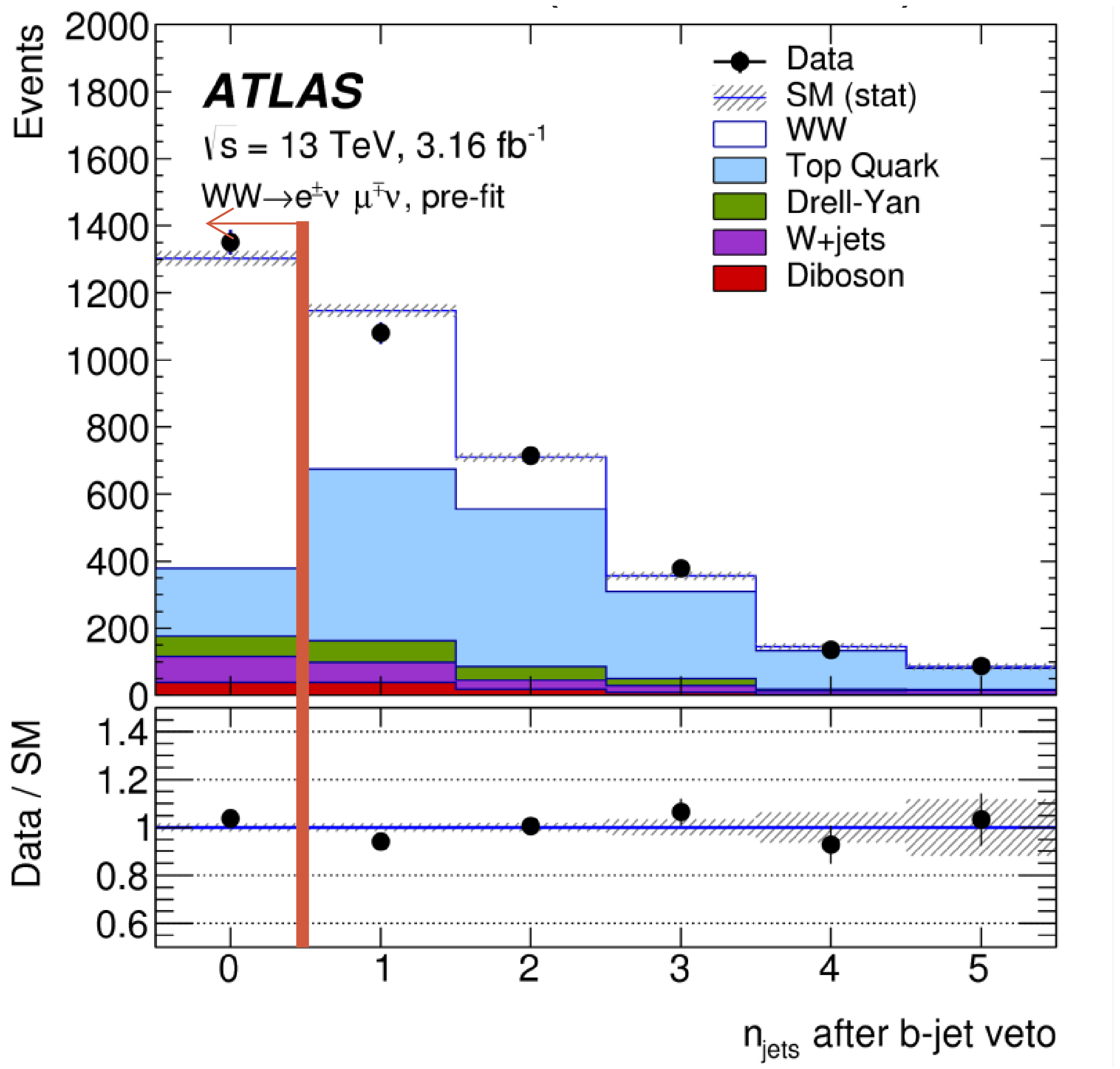
Closing remarks

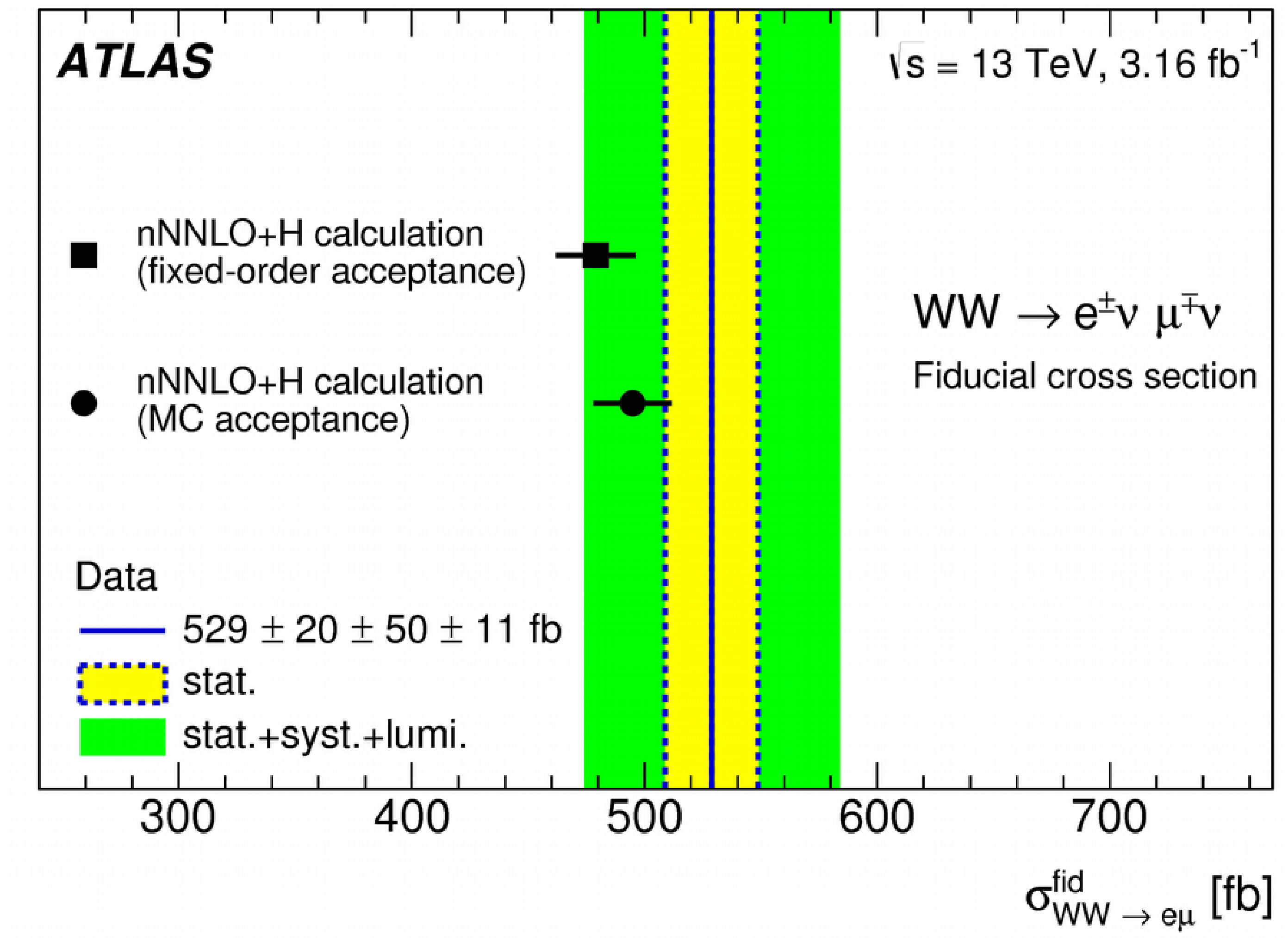
- The LHC proton-proton runs have produced exceptional Standard Model results at 7, 8 and 13 TeV
- The SM is more healthy than ever
  - The dibosons are there we started to see the tribosons, the production modes and couplings just fit, no sign of crack at the moment..
- 13 TeV data taking will soon be resumed and we have to continue looking!
  - Precision measurements will further challenge theorists for improved/higher-order predictions
  - New physics can be around the corner! The SM measurements and searches will play complementary role in this route



WW and WZ production cross sections

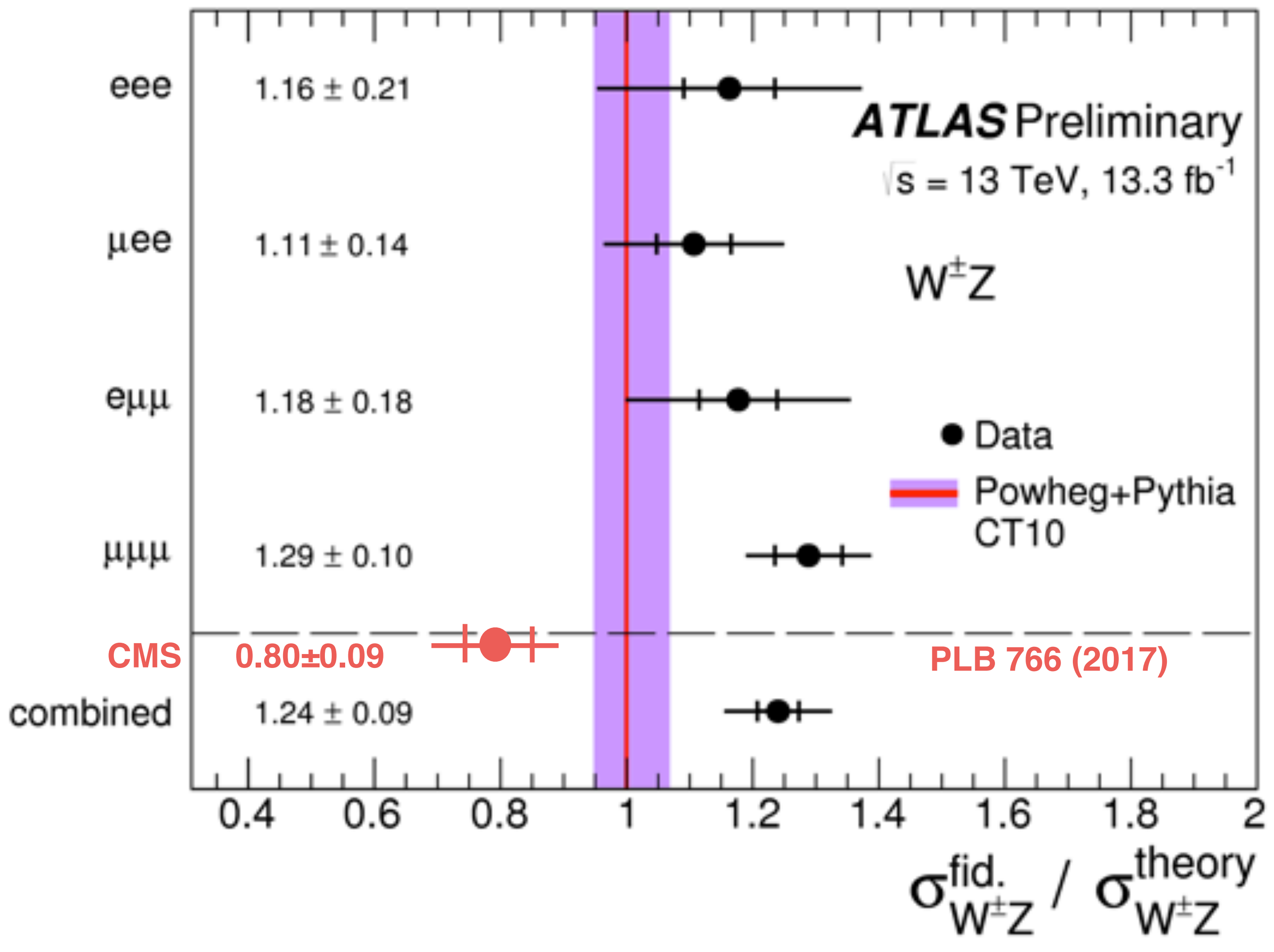
WW

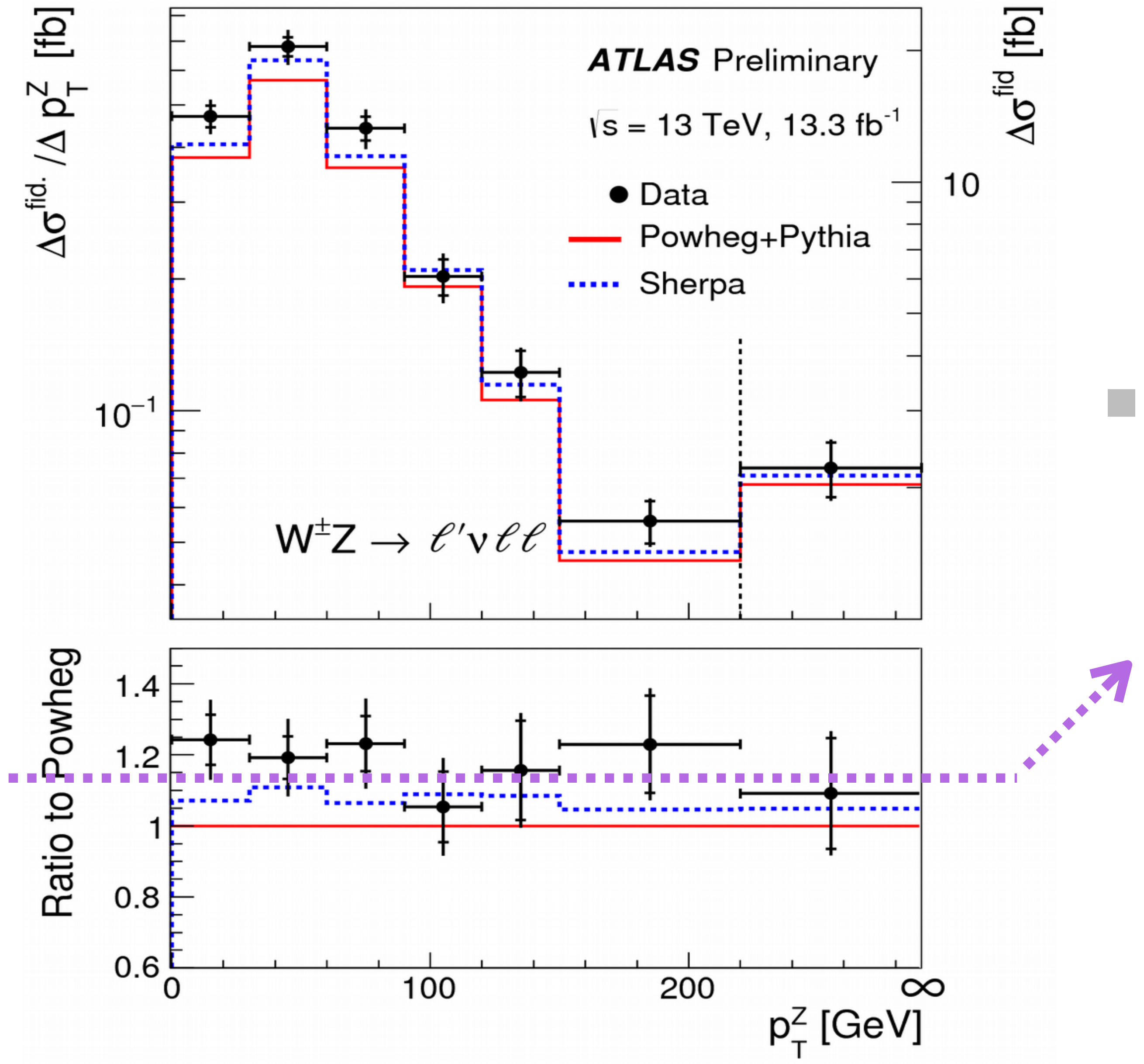




- Good agreement w/pred's (also in 13 TeV / 8 TeV ratio and WW+1jet 8 TeV)

WZ





- Comparison done with NLO theory
  - NNLO correction: ~11% higher