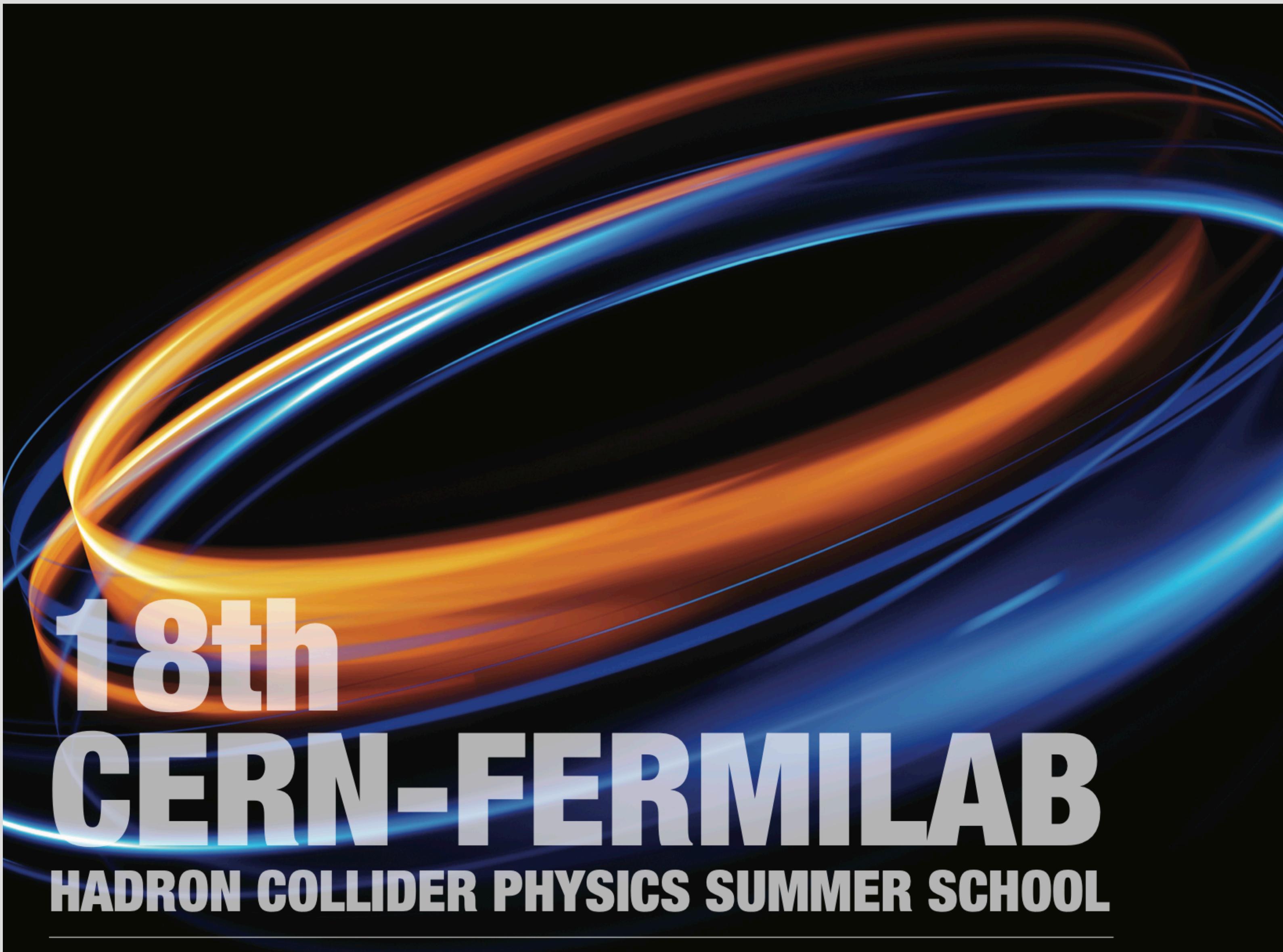


Experimental SM and Higgs Physics



18th
CERN-FERMILAB
HADRON COLLIDER PHYSICS SUMMER SCHOOL



Standard Model and Higgs

Lecture 2 *EW Precision at
Hadron Colliders*

Marumi Kado
Max Planck Institute for Physics

CERN-Fermilab School of Physics
August 28, 2023

Outline

2

Lecture 1: Basic concepts, QCD, jets and Z production

- Introduction (rather long)
- Luminosity and total cross section
- Jet production measurements and the measurement of the strong coupling constant
- Drell-Yan Z production and the measurements of the weak mixing angle and the strong coupling constant

Lecture 2: EW Precision at Hadron Colliders

- Drell-Yan W production and the W mass measurement
- Associated production of vector bosons and jets
- Multi-boson production (W, Z and photons)
- Top production and top properties measurements

Lecture 3: Higgs Physics

- Diboson channels for Higgs measurements
- Measuring the Yukawa couplings of the Higgs boson
- Differential and Simplified Template cross sections
- CP properties of the Higgs boson
- Invisible Higgs boson decays
- Rare Higgs boson decays

Lecture 4: More Higgs Physics and Global interpretation

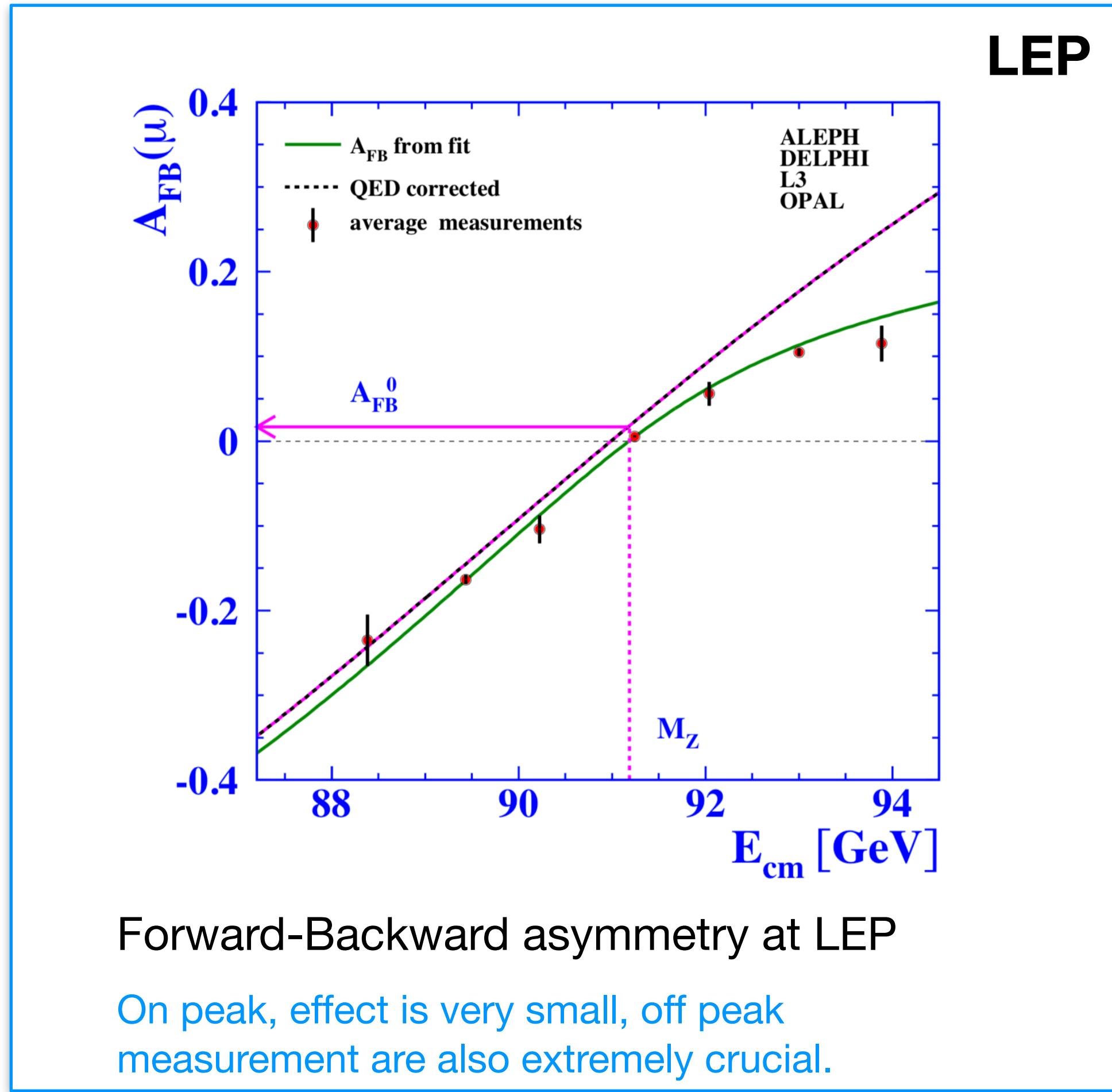
- Higgs couplings measurements
- The Yukawa coupling of the Higgs boson to charm quarks
- Off shell Higgs boson coupling and Higgs width
- Di-Higgs boson production and Higgs boson trilinear self coupling
- Precision EW Fit
- SMEFT Global fits
- Challenges for Run-3 and the HL-LHC

2

The AFB Asymmetry... Asymmetry

3

To illustrate the answer to the question in the previous lecture...



$$\frac{d\sigma}{d \cos \theta^*} = \frac{4\pi\alpha^2}{3\hat{s}} \left[\frac{3}{8}A(1 + \cos^2 \theta^*) + B \cos \theta^* \right]$$

Term coming from the Z/γ^* interference

Drell-Yan W boson production

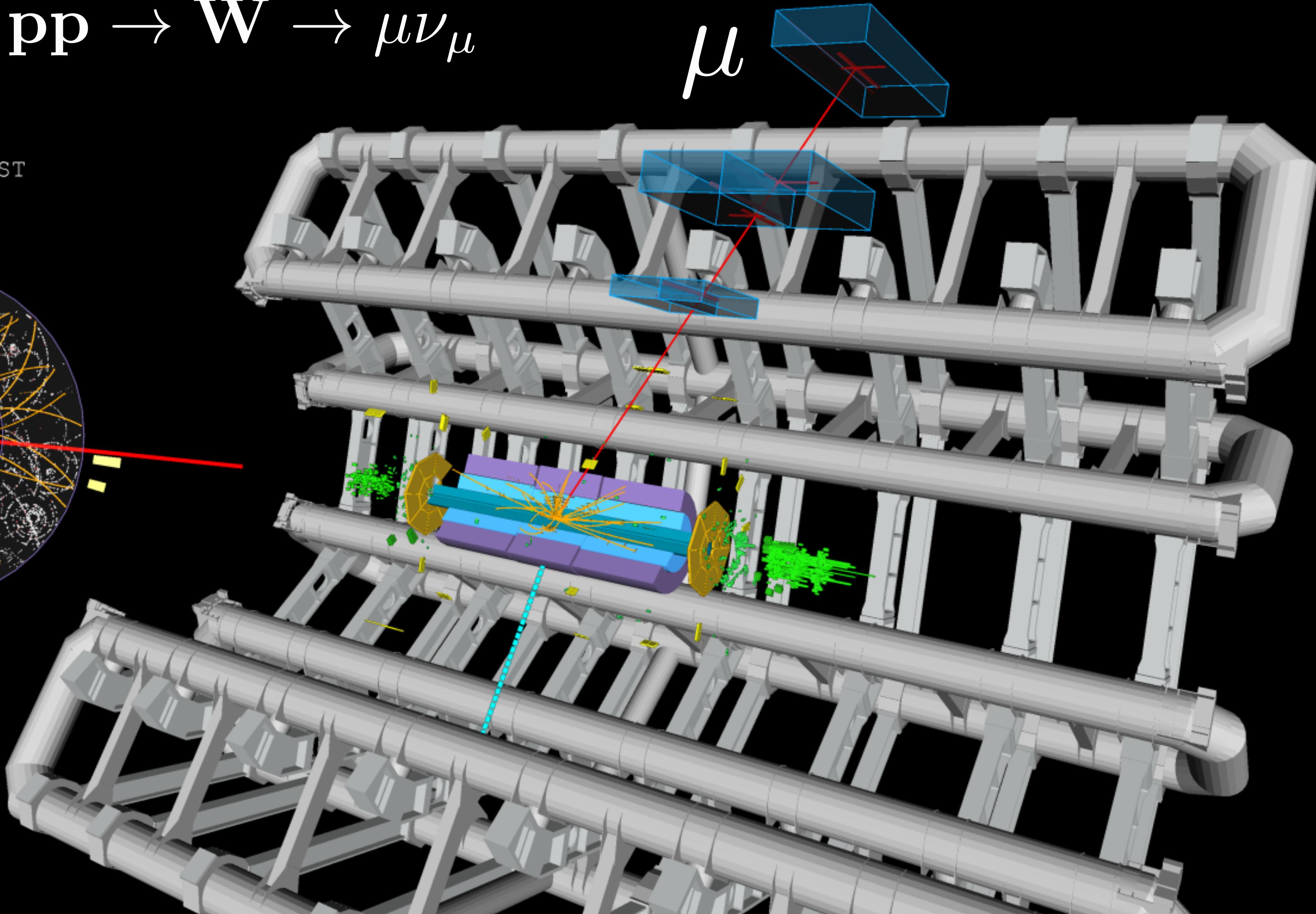
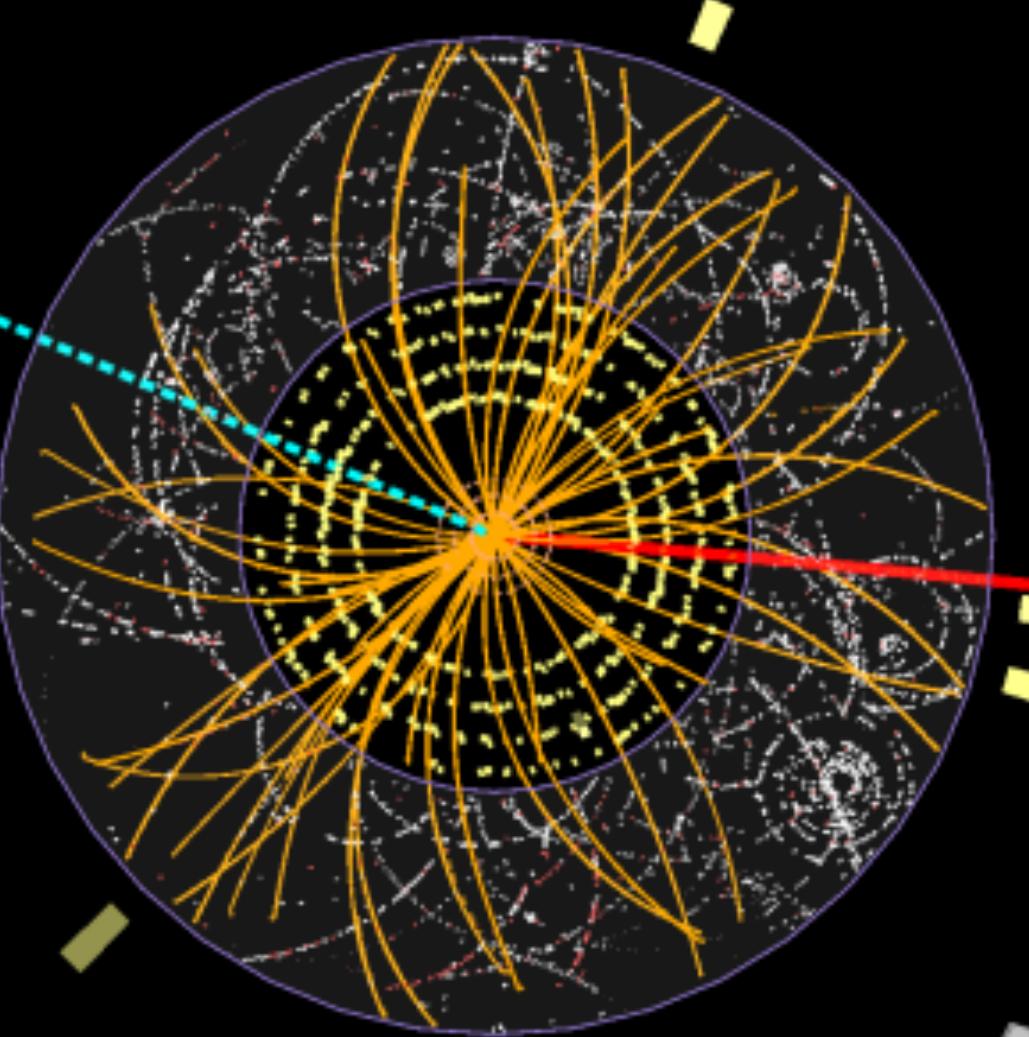


$pp \rightarrow W \rightarrow \mu\nu_\mu$

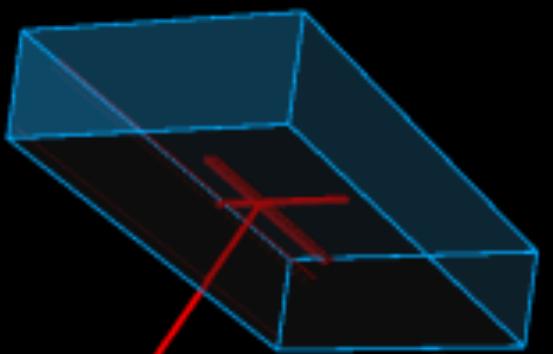
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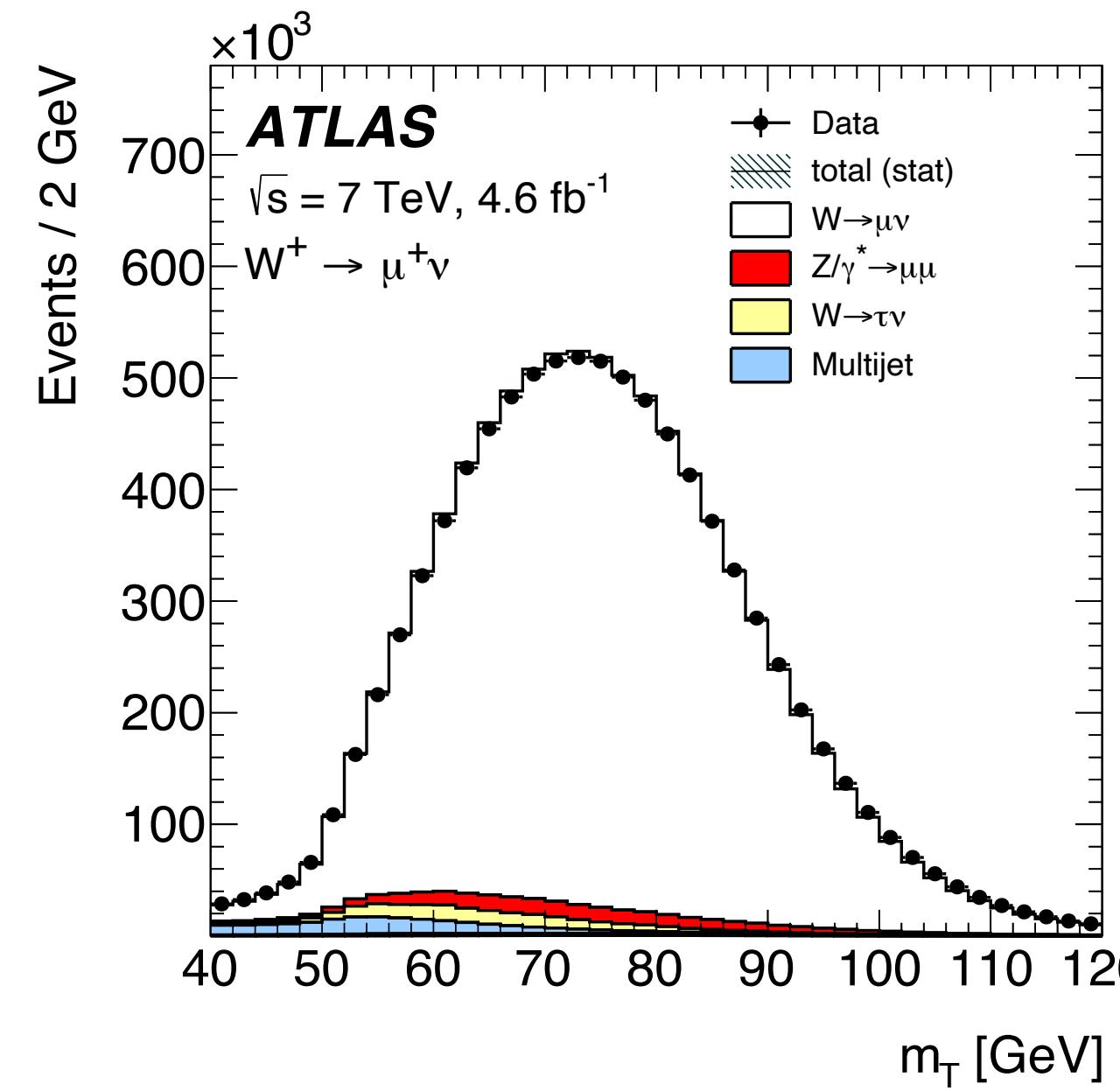
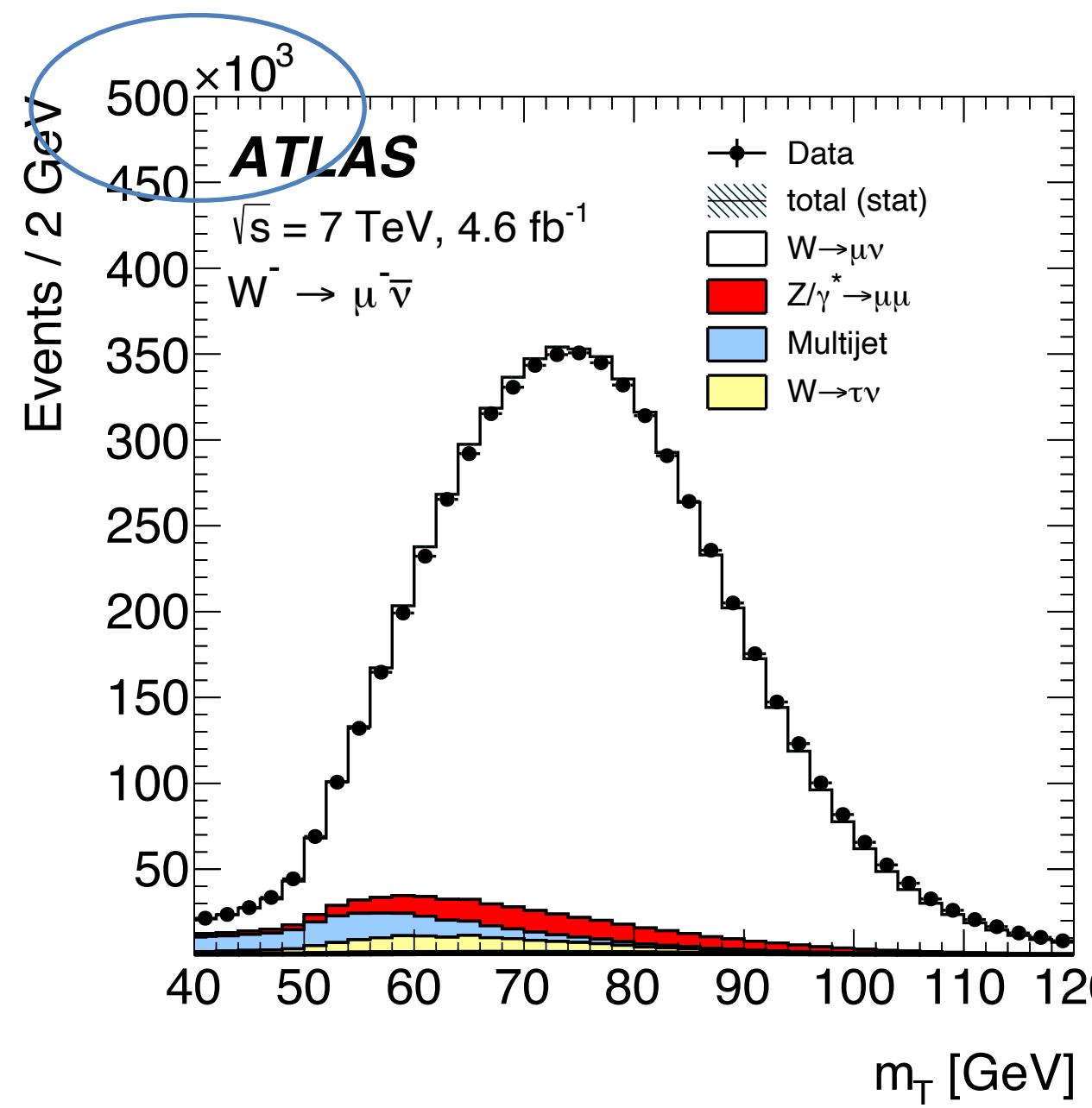


μ



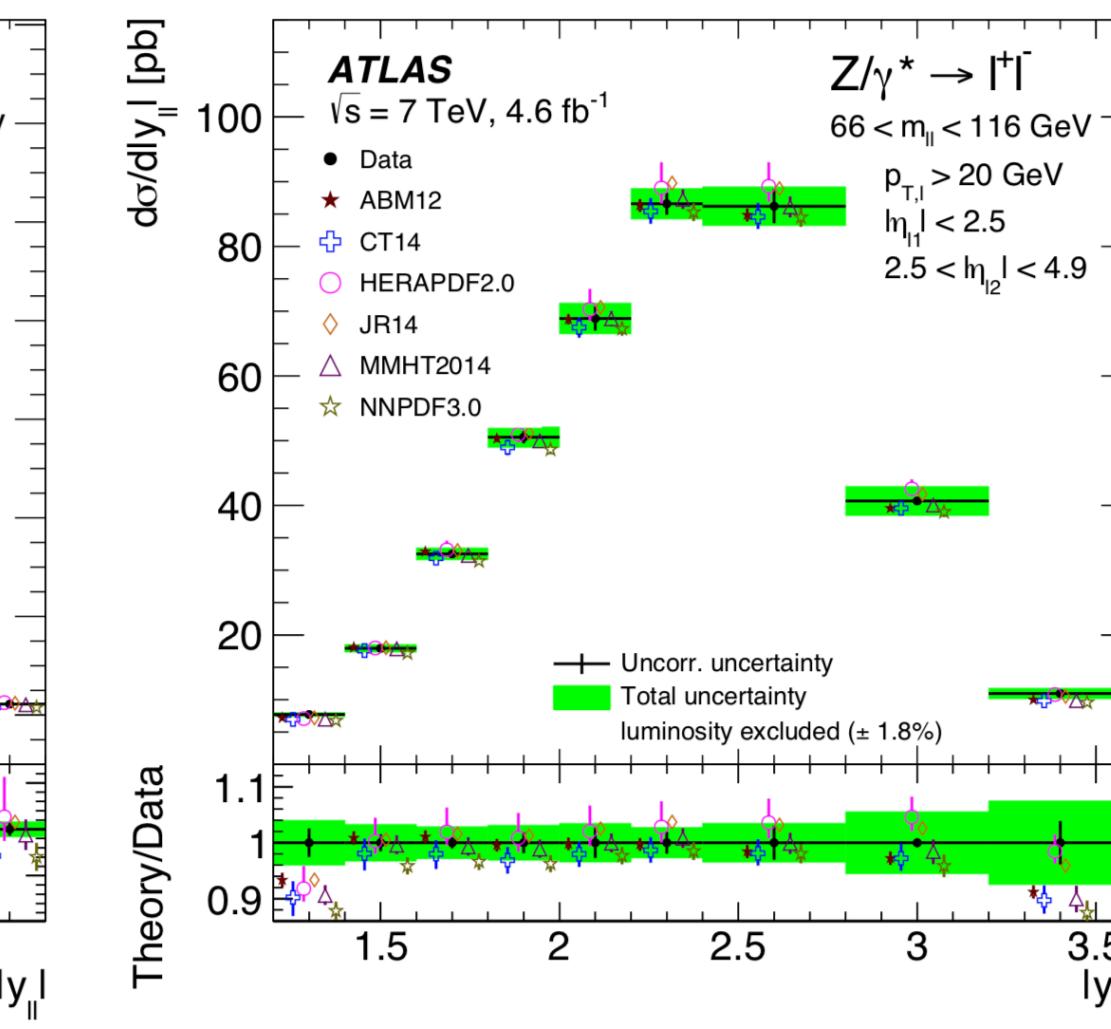
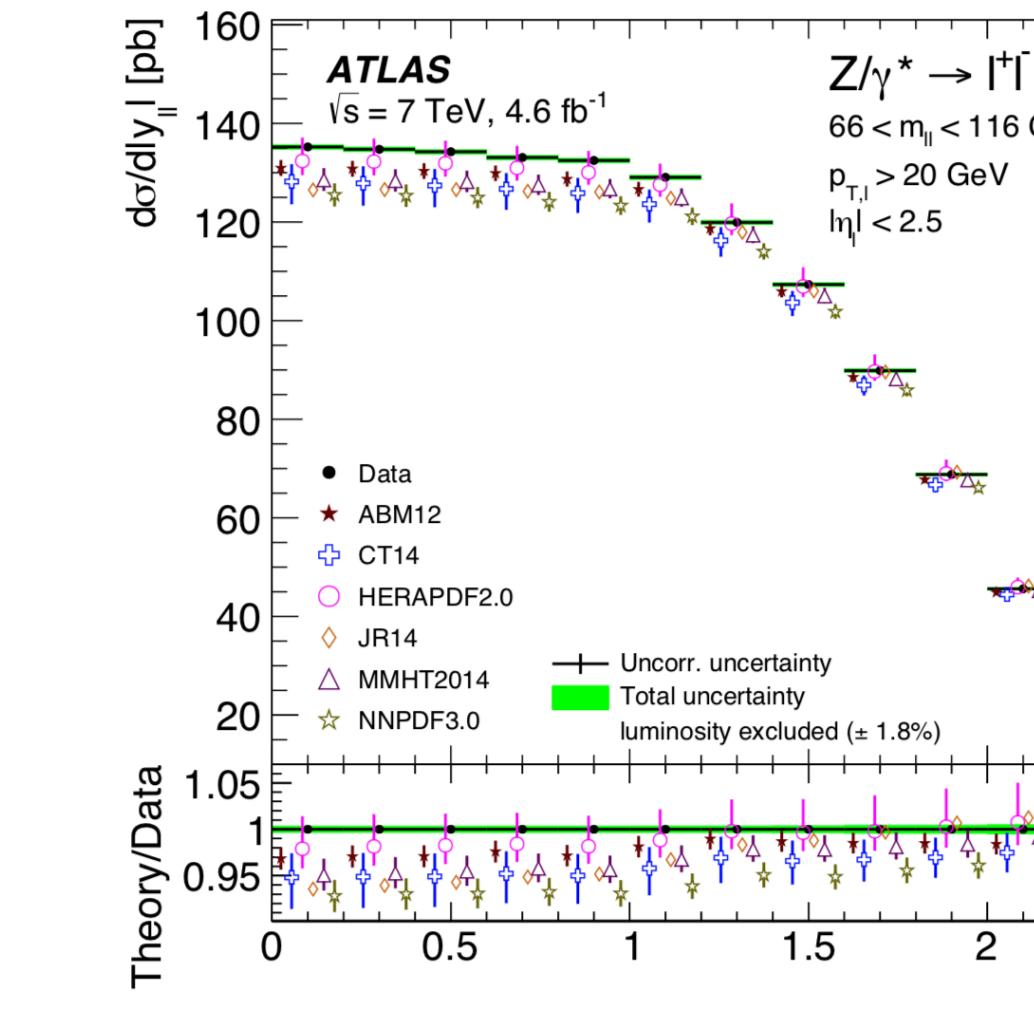
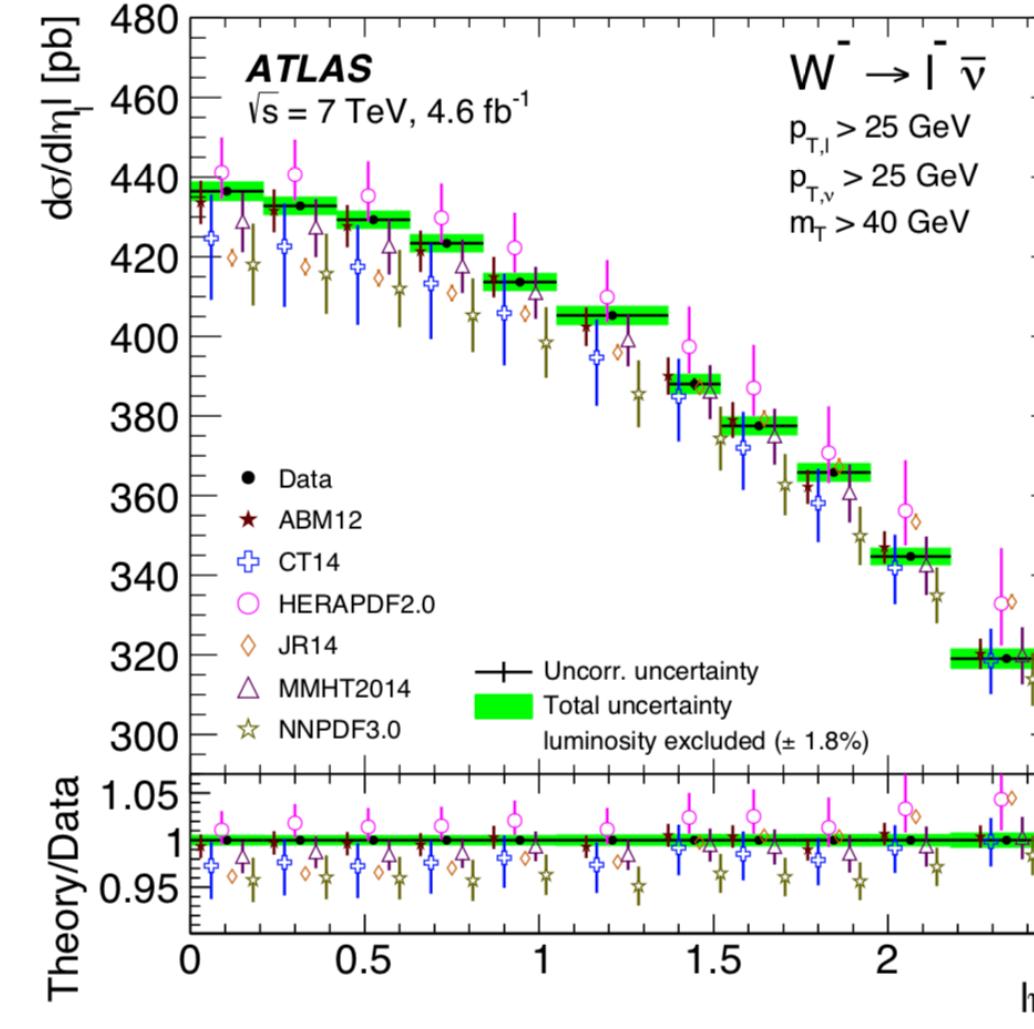
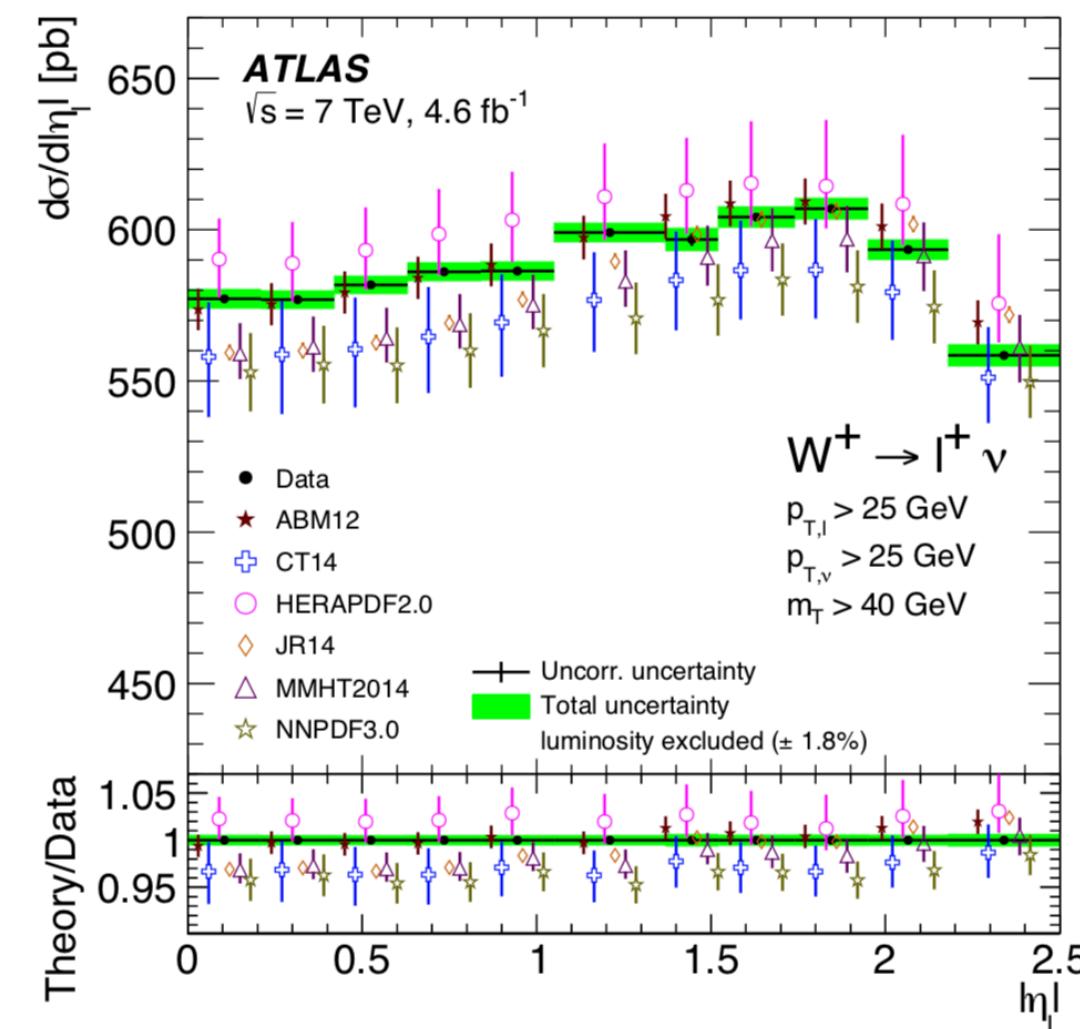
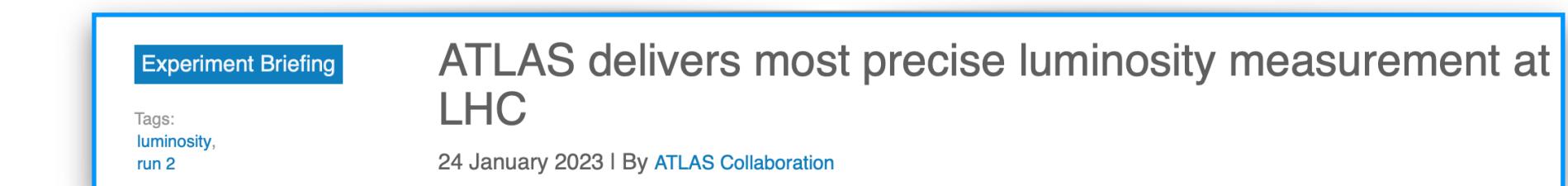
Inclusive Precision Vector Boson Production at the LHC

6



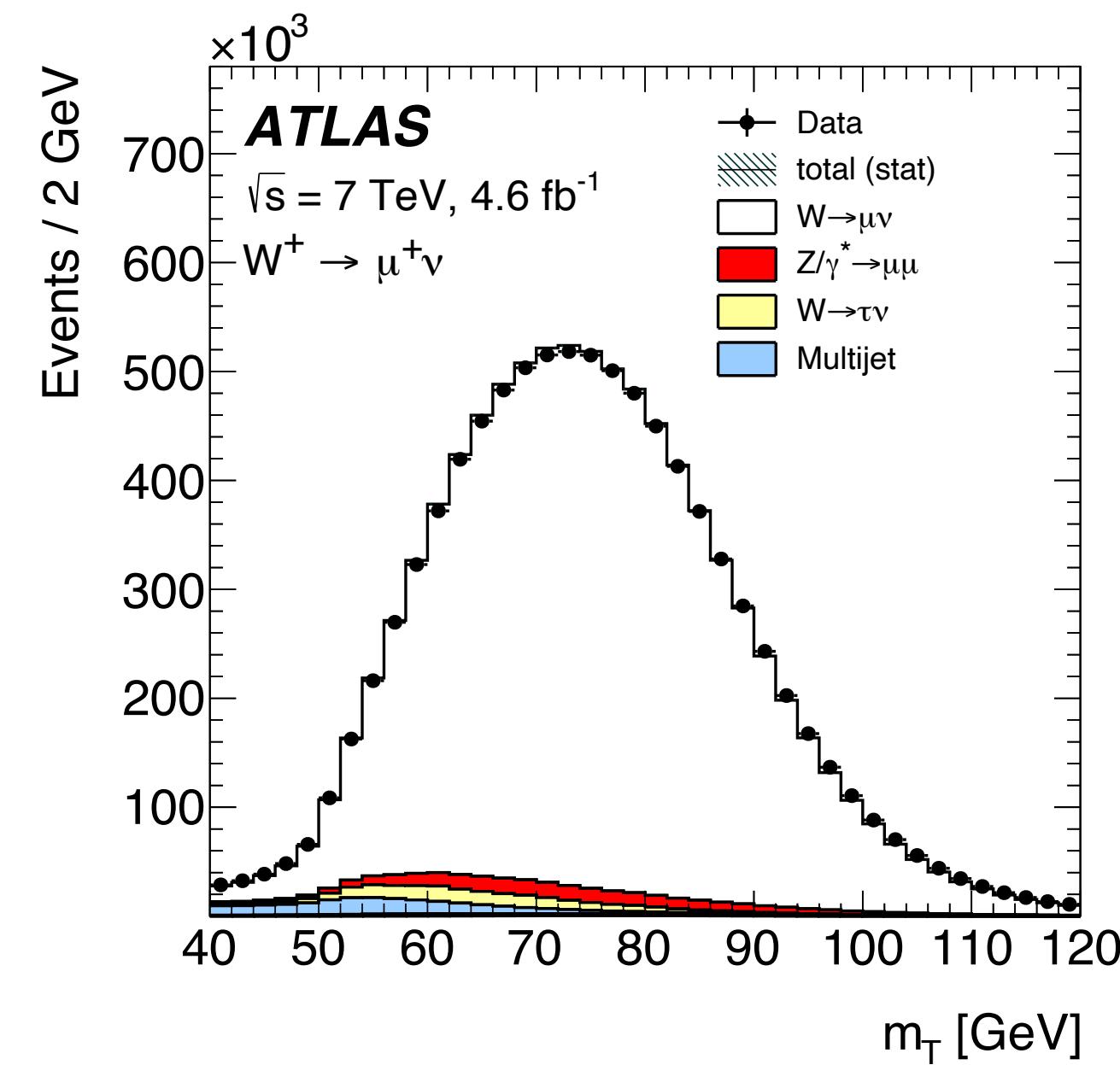
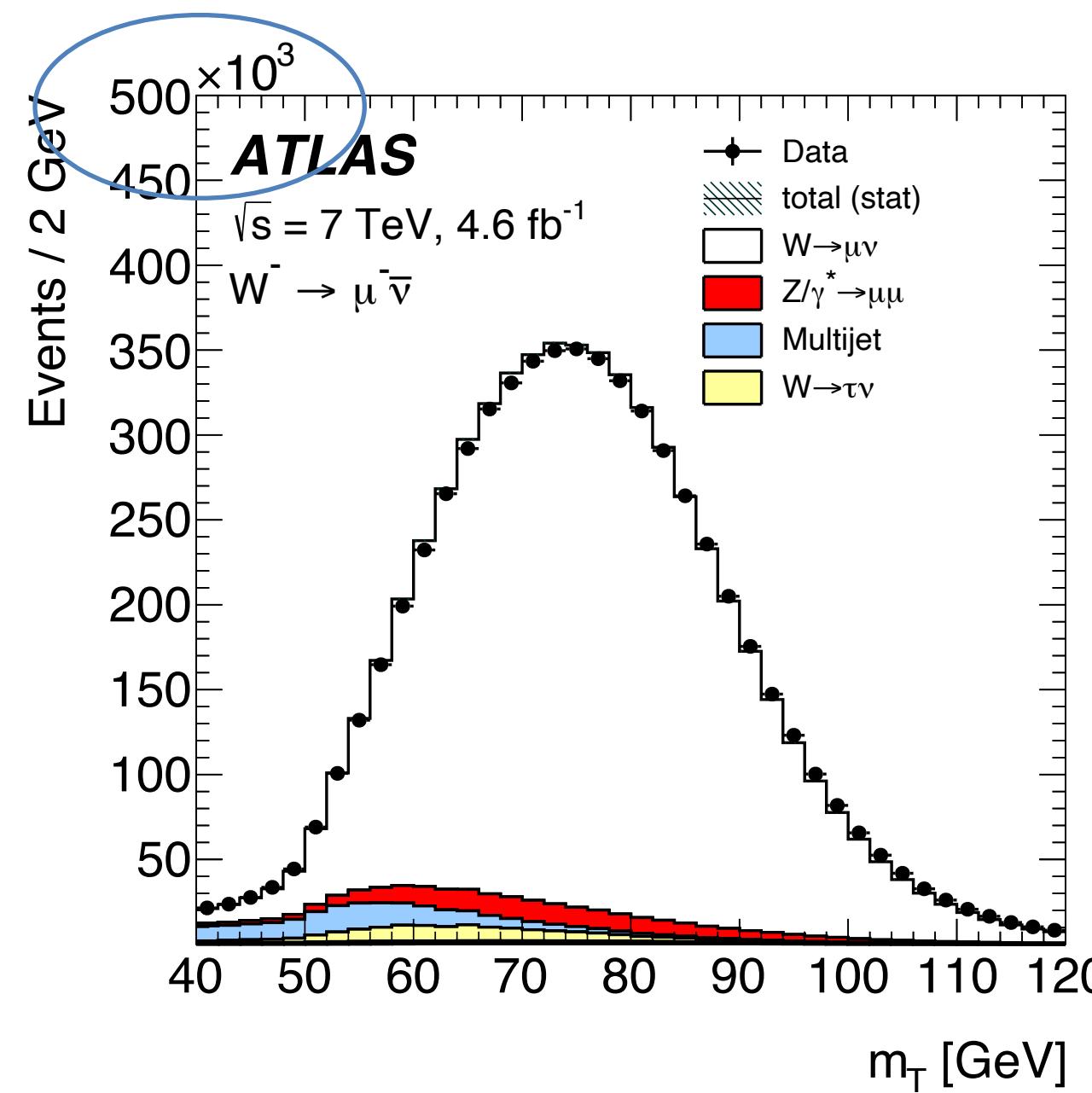
With a dataset of only 4.6 fb⁻¹ at **7 TeV**, approximately 15.5 M W^+ events and 10.4 W^- events (electrons and muons). **Low PU !**

Cross section measurement (as a function of rapidity) the uncertainty **completely dominated by luminosity uncertainty of 1.8% - Now reached less than 1% (see ATLAS briefing) !!!**



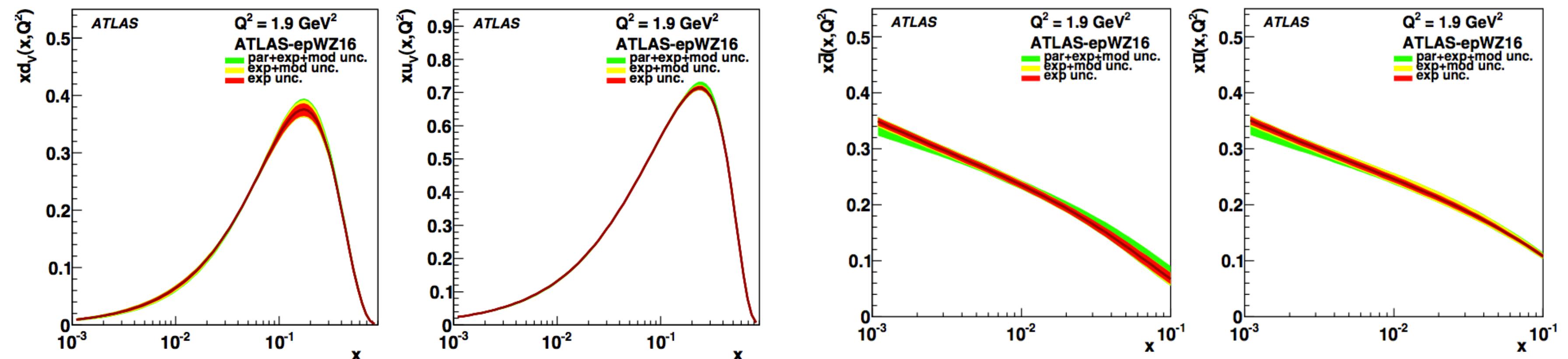
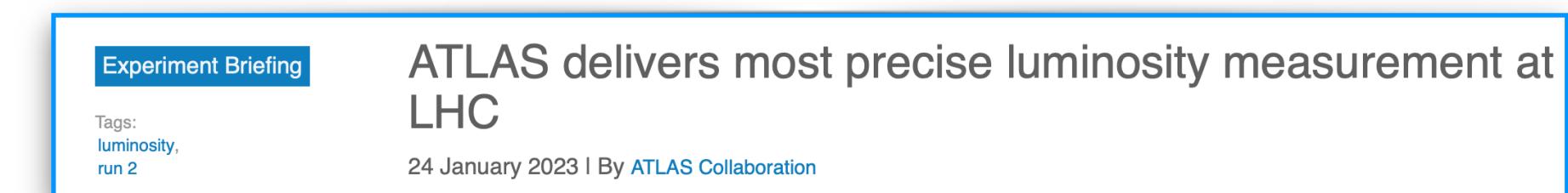
Inclusive Precision Vector Boson Production at the LHC

7



With a dataset of only 4.6 fb⁻¹ at **7 TeV**, approximately 15.5 M W^+ events and 10.4 W^- events (electrons and muons). **Low PU !**

Cross section measurement (as a function of rapidity) the uncertainty **completely dominated by luminosity uncertainty of 1.8% - Now reached less than 1% (see ATLAS briefing) !!!**

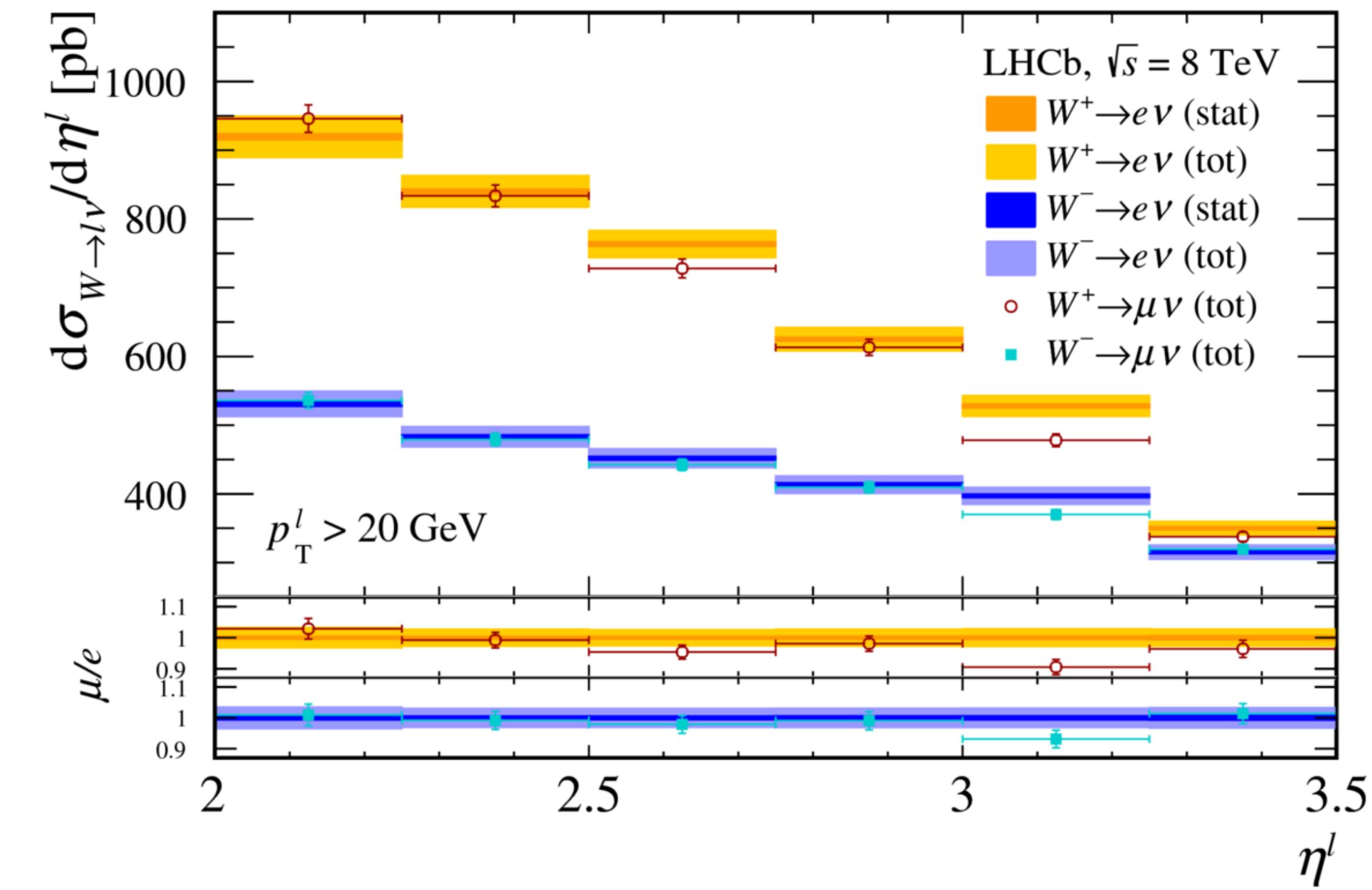
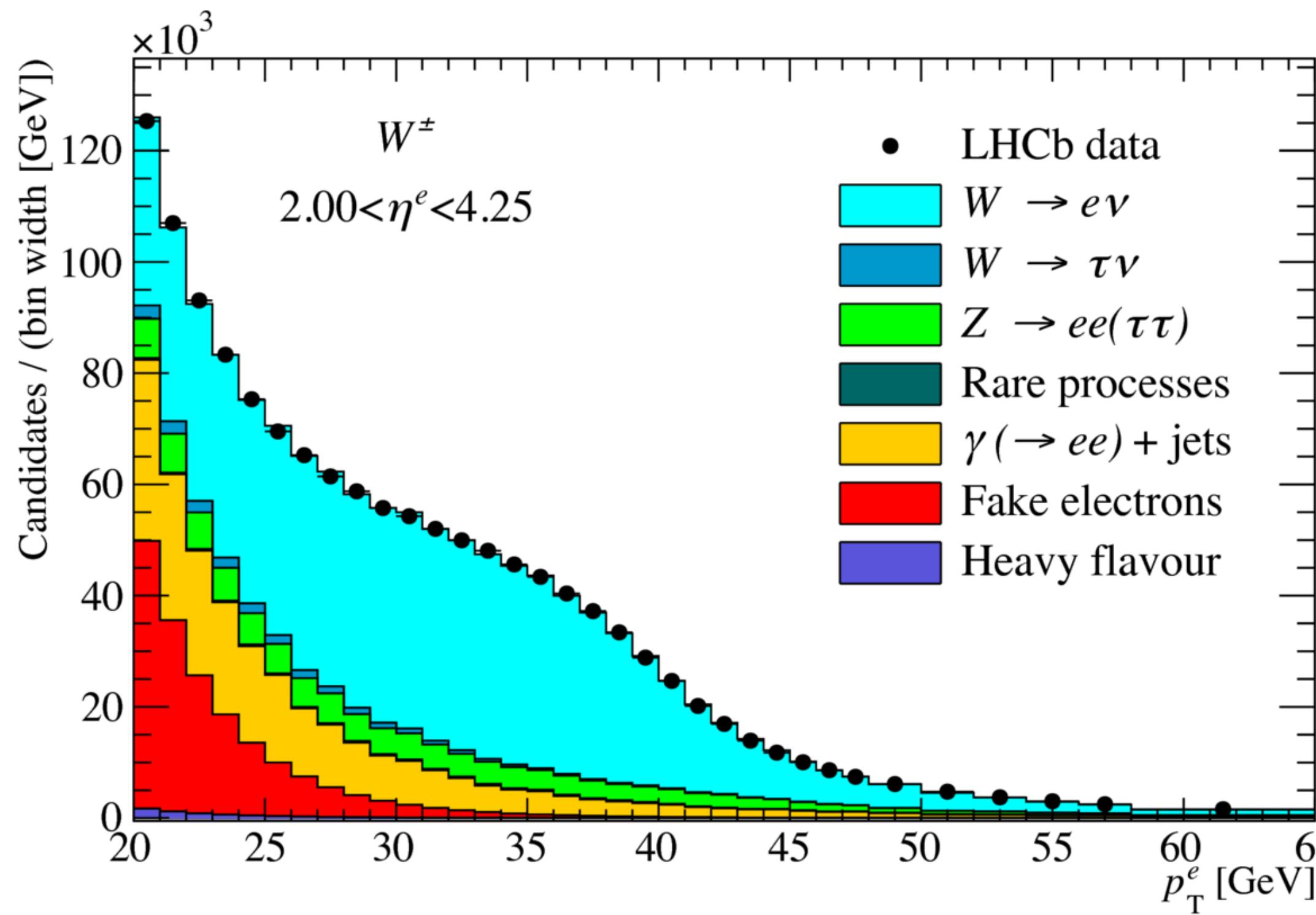


Using these cross section measurements and the Deep Inelastic Scattering data from Hera new set of PDFs can be estimated (ATLAS-epWZ16 same was done in CMS).

Inclusive Vector Boson Production at LHCb

LHCb

Precision W production measurements (at 8 TeV) complement the pseudo-rapidity distribution of the leptons in the [2-5] region.



Important complementarity for PDF fits.

ATLAS W Mass Measurement

Milestone measurement demonstrating the LHC capabilities in precision measurements!

Analysis strategy based on two kinematic distributions fitted in several categories

Decay channel	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$ \eta_\ell $ categories	$[0, 0.6], [0.6, 1.2], [1.8, 2.4]$	$[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]$

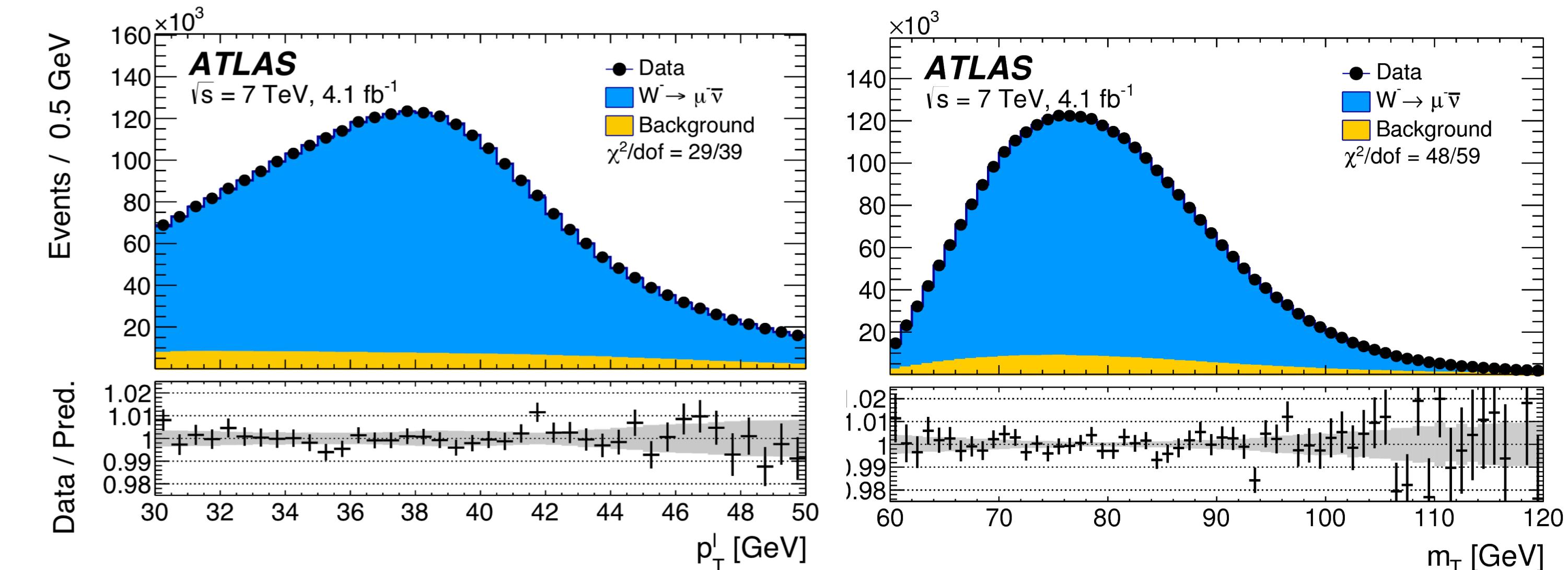
p_T^ℓ

Clean energy measurement, but more sensitive to the modelling of the W transverse momentum

m_T

Less sensitive to modelling but more difficult from to reconstruct (based on the missing transverse energy).

$$m_T = \sqrt{2p_T^\ell p_T^{miss} (1 - \cos \Delta\phi)}$$



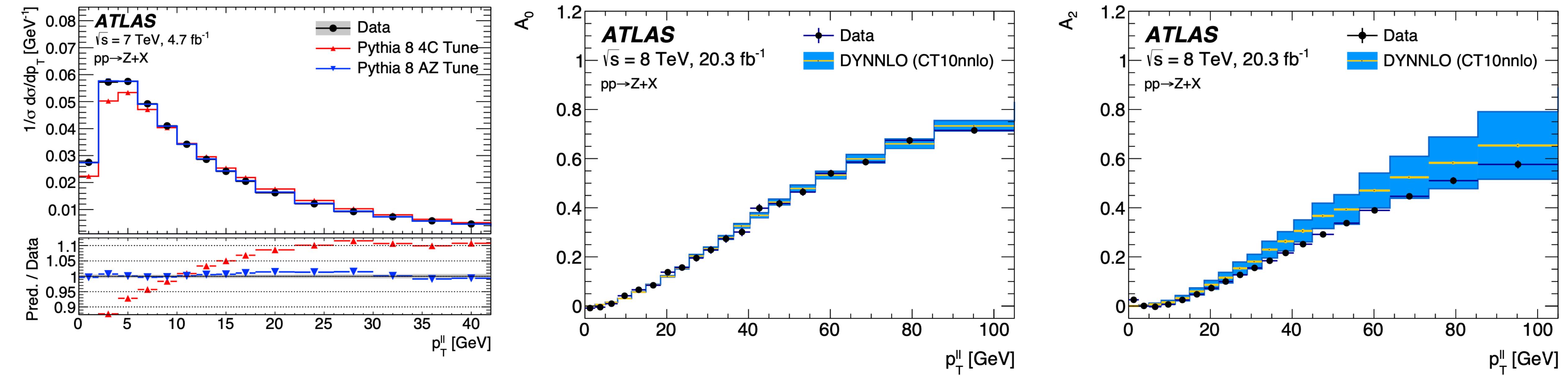
Prediction

- Reweighted fully simulated events using Powheg v1 – Pythia 8.170 – CT10 for HS (and CTEQ6L1 for PS) with AZNLO tune (QED ISR with Pythia 8 and FSR with Photos) – NLO EW effects not taken into account in baseline but uncertainty taken into account)
- Three steps reweighting procedure using factorized fully differential cross section:

$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{d\sigma(m)}{dm} \right] \left[\frac{d\sigma(y)}{dy} \right] \left[\frac{d\sigma(p_T, y)}{dp_T dy} \left(\frac{d\sigma(y)}{dy} \right)^{-1} \right] \left[(1 + \cos^2 \theta) + \sum_{i=0}^7 A_i(p_T, y) P_i(\cos \theta, \phi) \right]$$

- First reweight rapidity distribution to DYNNLO with CT10nnlo
- Then at given rapidity reweight in pT to Pythia 8 AZ tune
- Finally reweight to angular (A_i) coefficients estimated at $O(\alpha_s^2)$

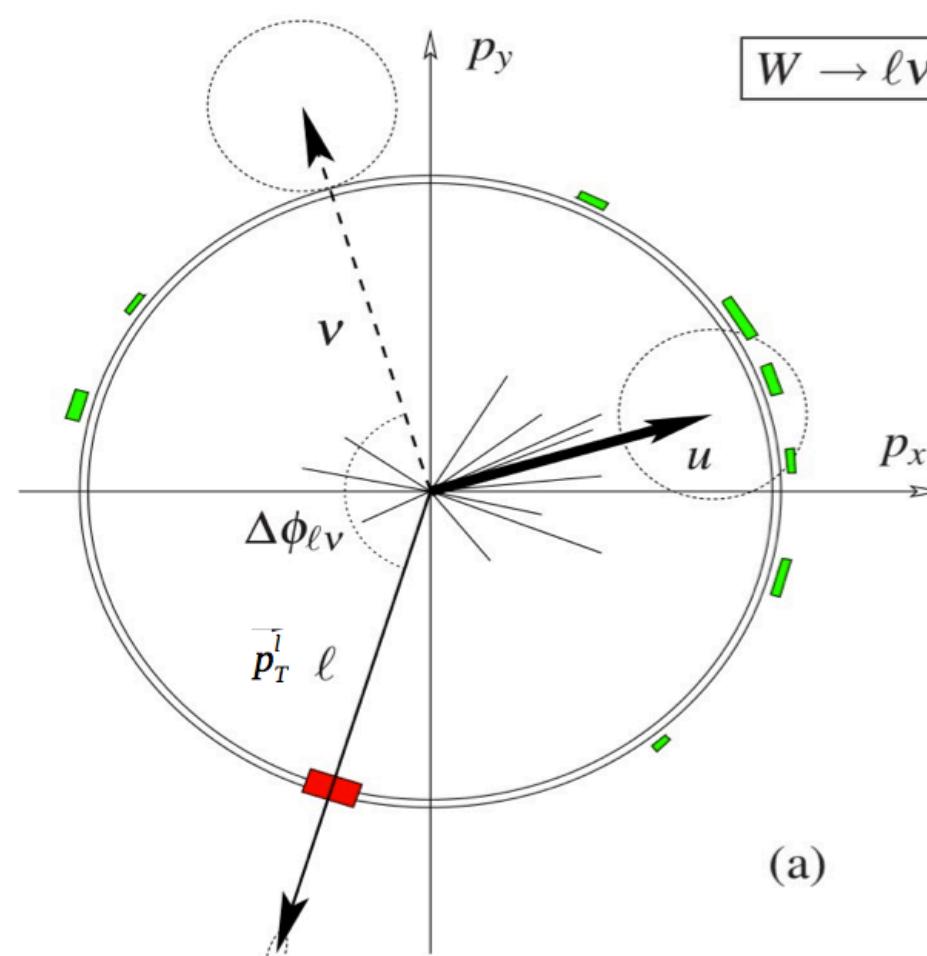
Uncertainty added for the small disagreement in A_2



Experimental Setup

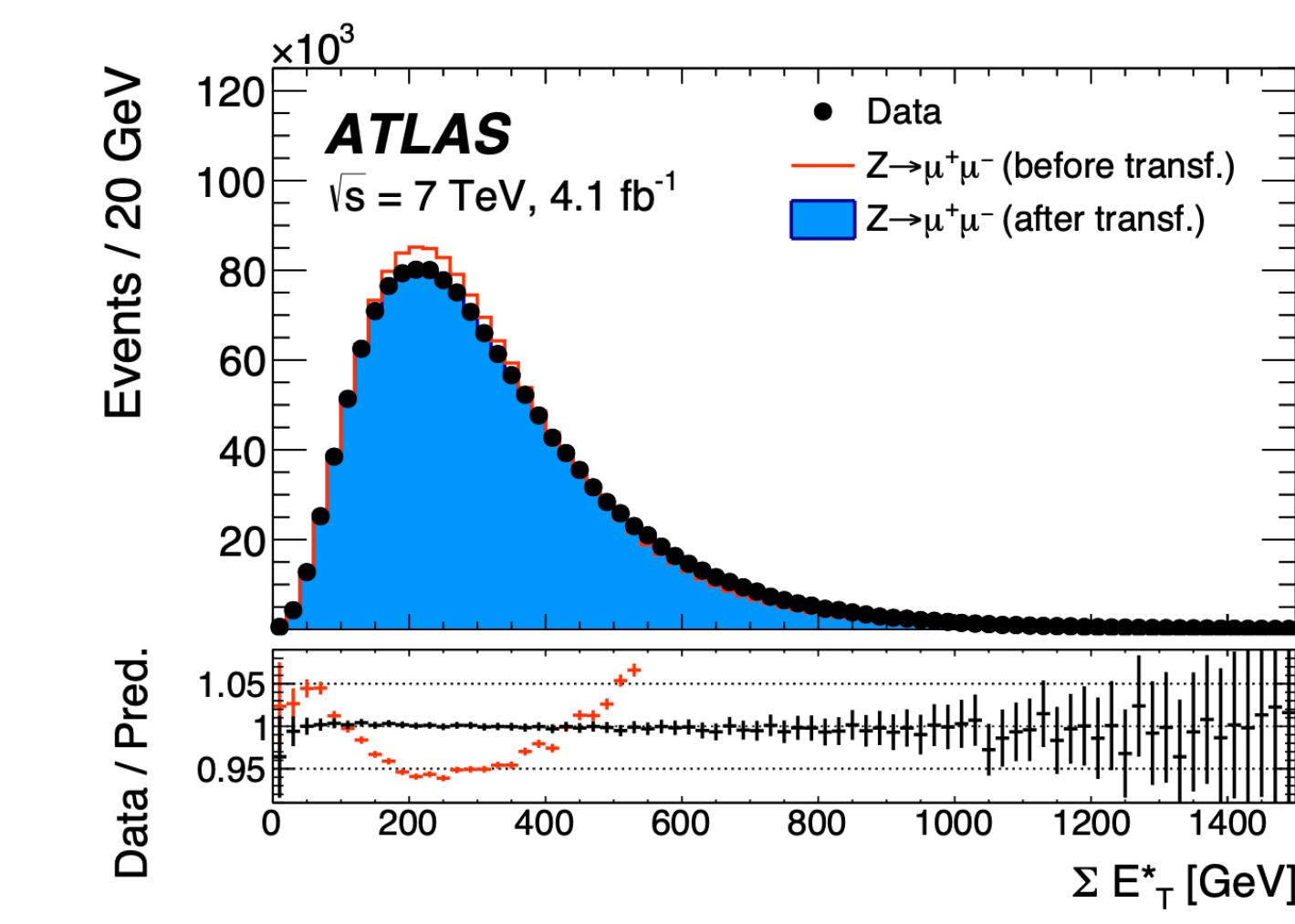
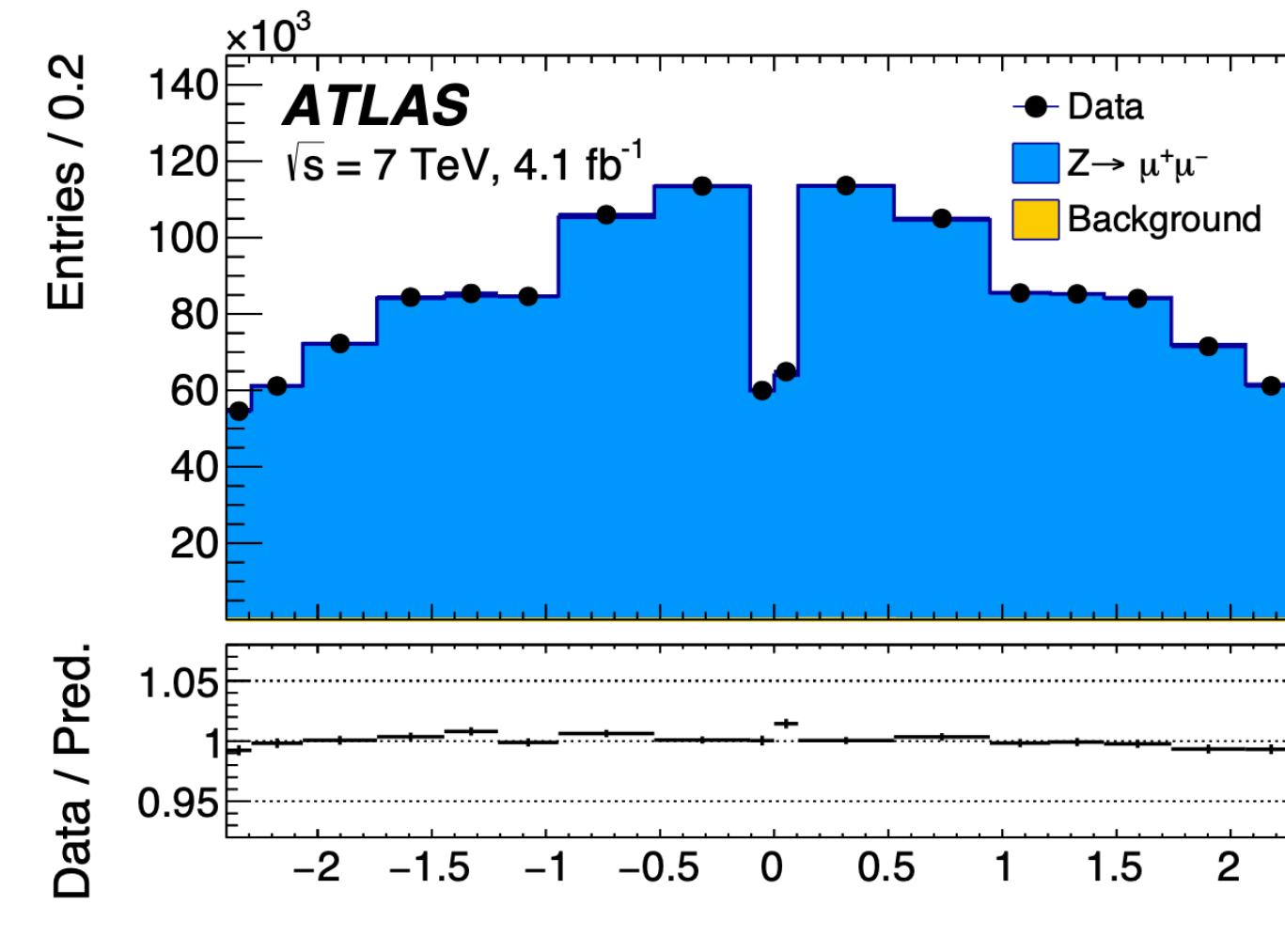
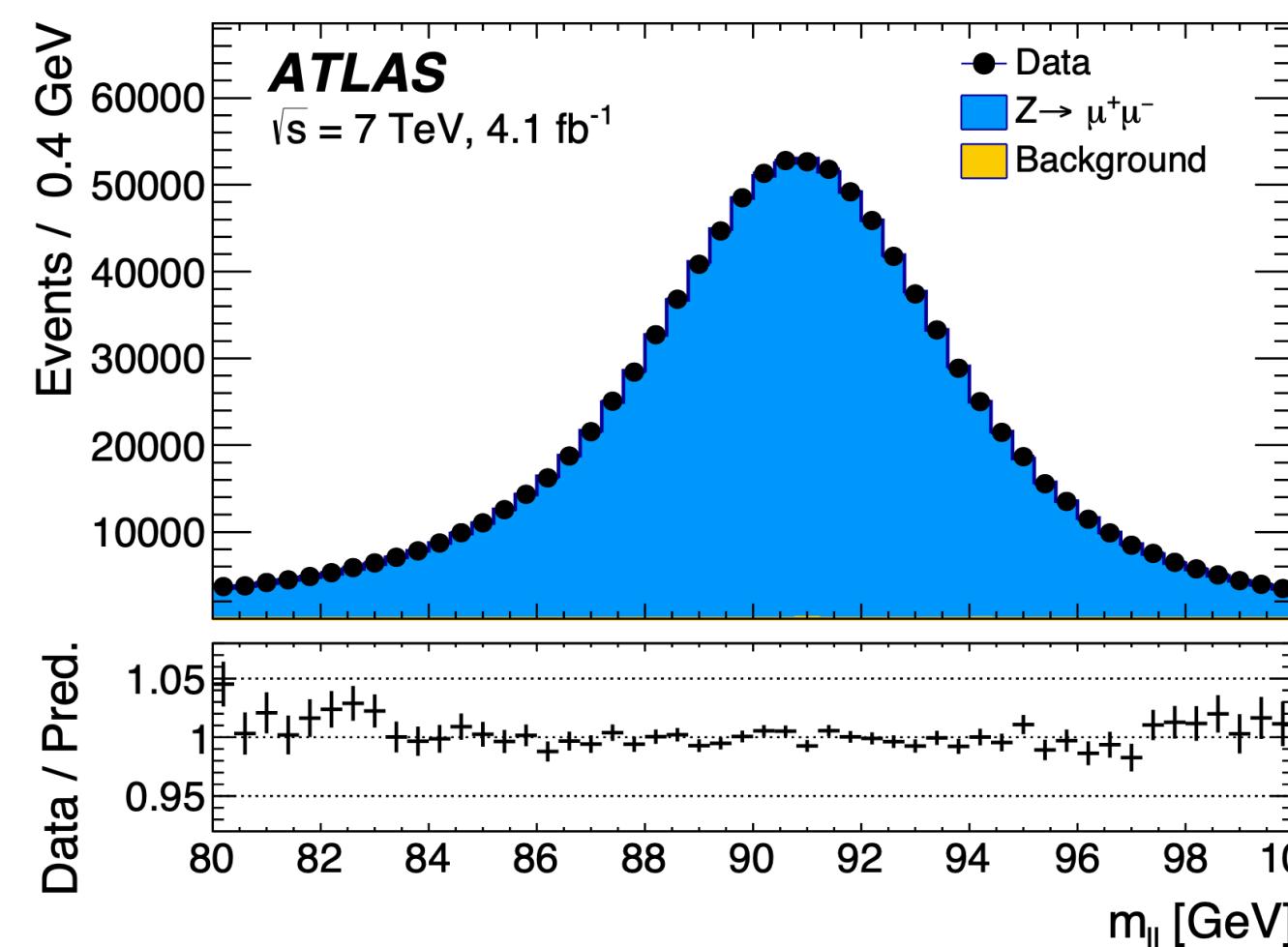
Dataset

- 7 TeV only, 4.6 fb⁻¹ (electrons) and 4.1 fb⁻¹ (muons) well probed data at moderate PU
- e, μ with pseudo-rapidity of 2.4 with transverse momentum > 30 GeV (MT > 60 GeV, MET > 30 GeV, recoil < 30 GeV)



$$\vec{p}_T^{\text{miss}} = -(\vec{p}_T^\ell + \vec{p}_T^\nu) \quad m_T = \sqrt{2p_T^\ell p_T^{\text{miss}}(1 - \cos \Delta\phi)}$$

- Specific improved calibration of leptons (**precision dominated by muons** - relatively low pT)
- Specific calibration of the recoil energy
 - First equalise PU multiplicities
 - Then correct for residual differences based on Z events

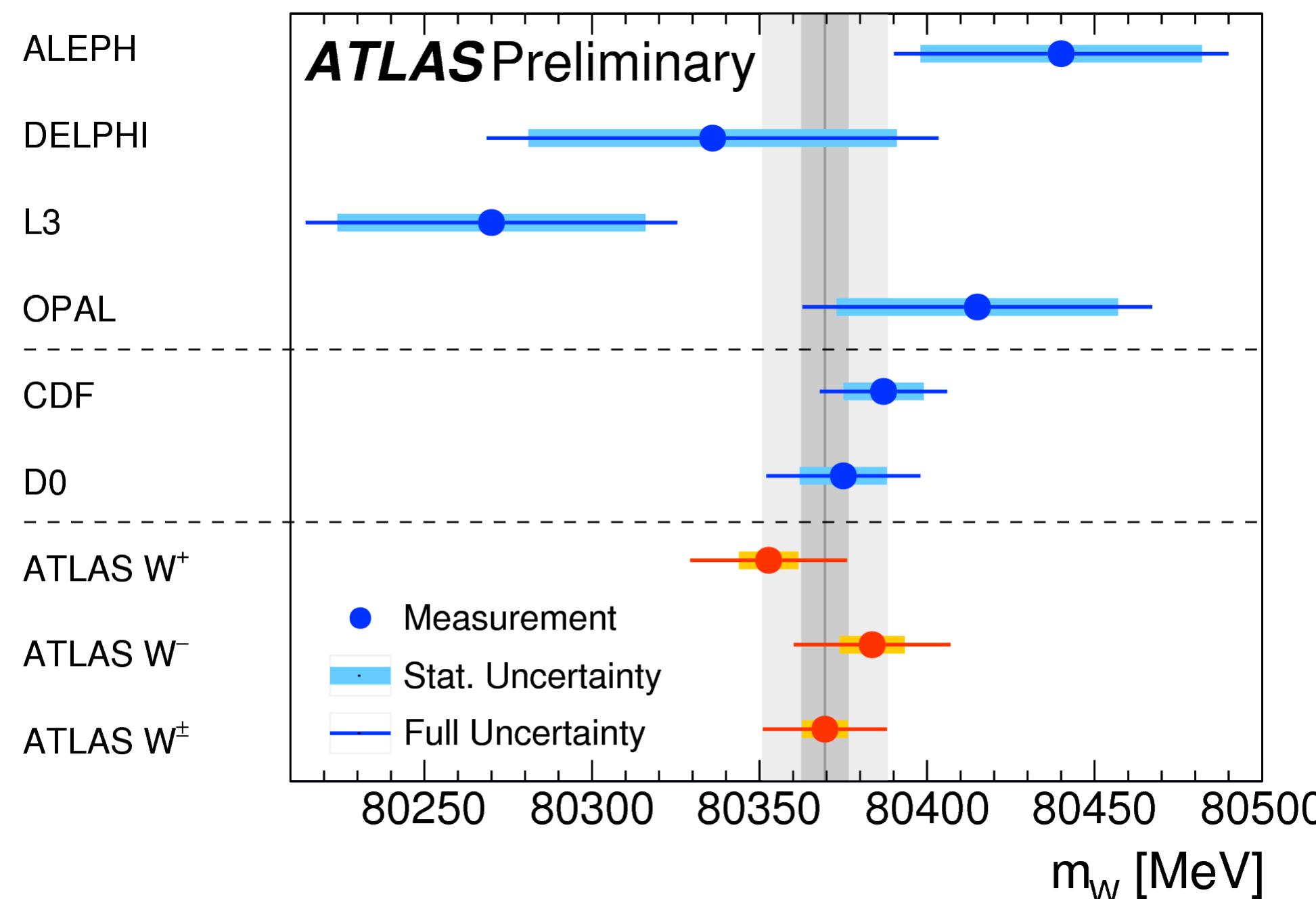


ATLAS W Mass Measurement

A Milestone measurement!

$$m_W = 80369.5 \pm 18.5 \text{ MeV}$$

$\pm 6.8 \text{ (Stat)} \pm 10.6 \text{ (Exp)} \pm 13.6 \text{ (Mod)} \text{ MeV}$



Modeling QCD and PDFs

W -boson charge Kinematic distribution	W^+		W^-		Combined	
	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
$\delta m_W \text{ [MeV]}$						
Fixed-order PDF uncertainty			13.1	14.9	12.0	14.2
AZ tune			3.0	3.4	3.0	3.4
Charm-quark mass			1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty			3.6	4.0	2.6	2.4
Angular coefficients			5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

PDF uncertainties: full CT10 variations but taking only effects affecting the W/Z ratio

Modeling EW

FSR and weak corrections sub-dominant

Experimental

Uncertainties dominated by lepton energy and momentum scale, and reconstruction and identification efficiencies

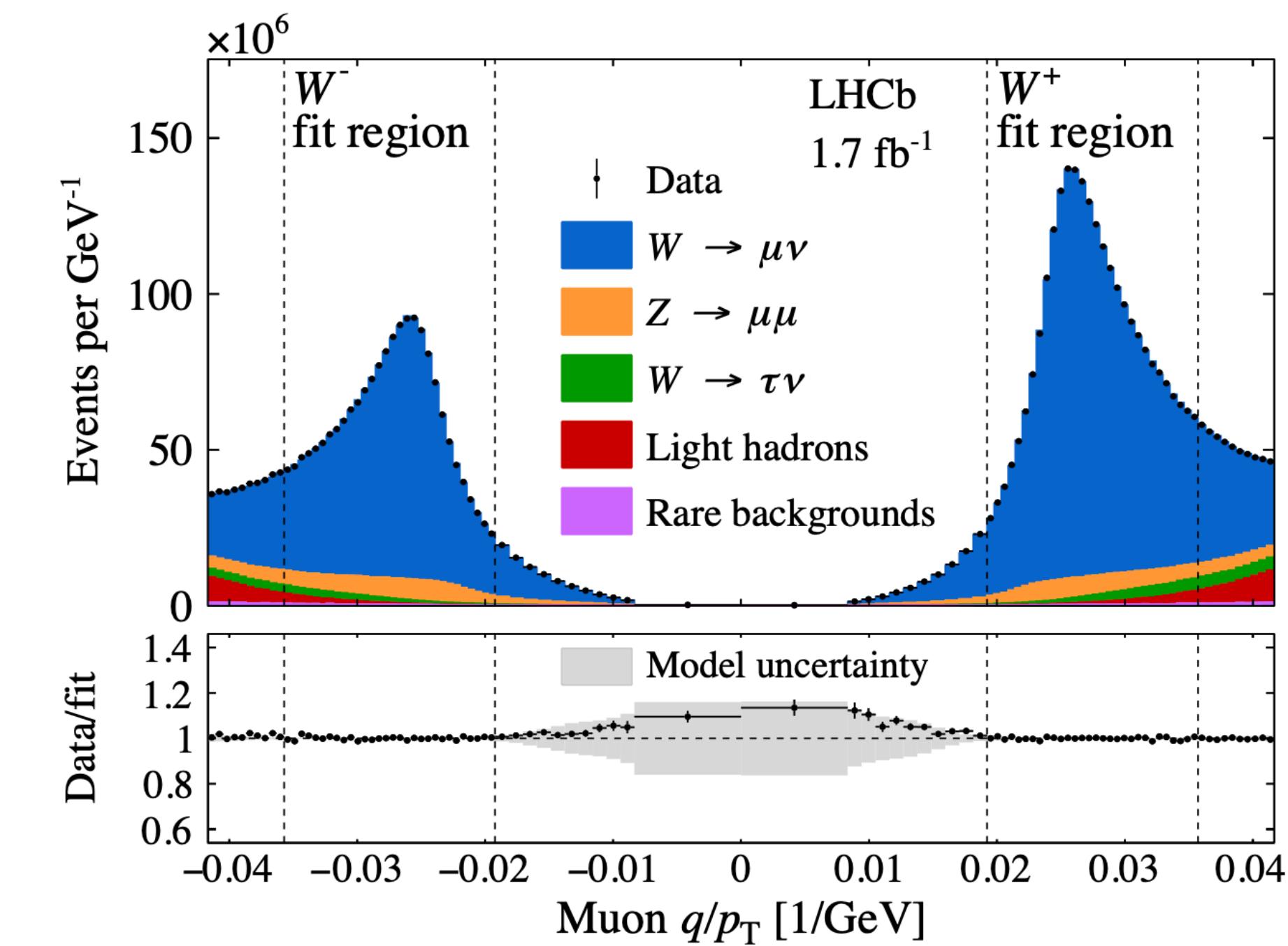
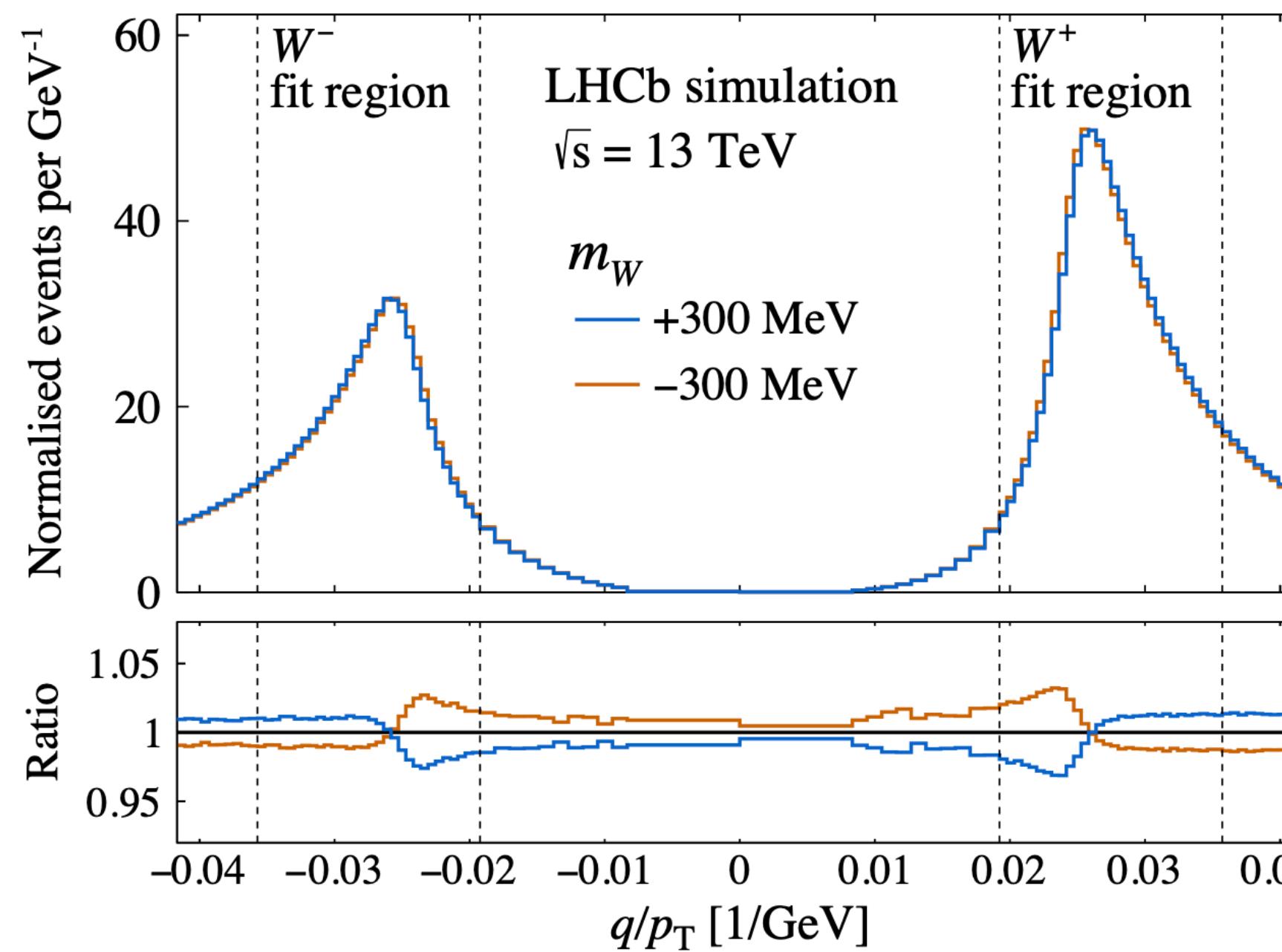
Sensitivity dominated by pT (individually 18.7 MeV uncertainty) w.r.t. MT (ind. 25.1 MeV uncertainty).

LHCb Measurement of the W Mass

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Measurement done using the q/p distribution (dominant in ATLAS as well) for W events and simultaneously the Collins-Soper ϕ^* distribution for the Z events:

$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M}$$



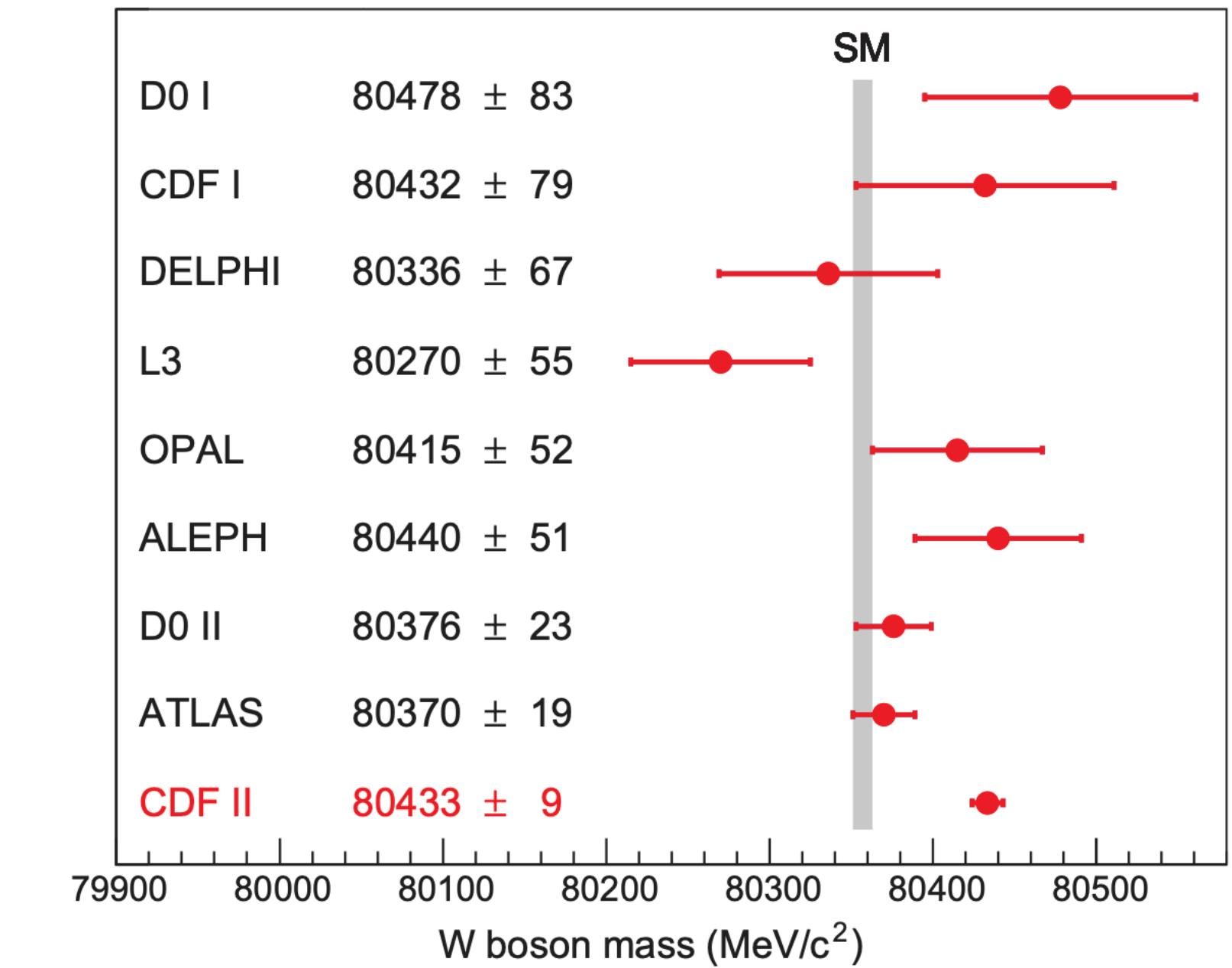
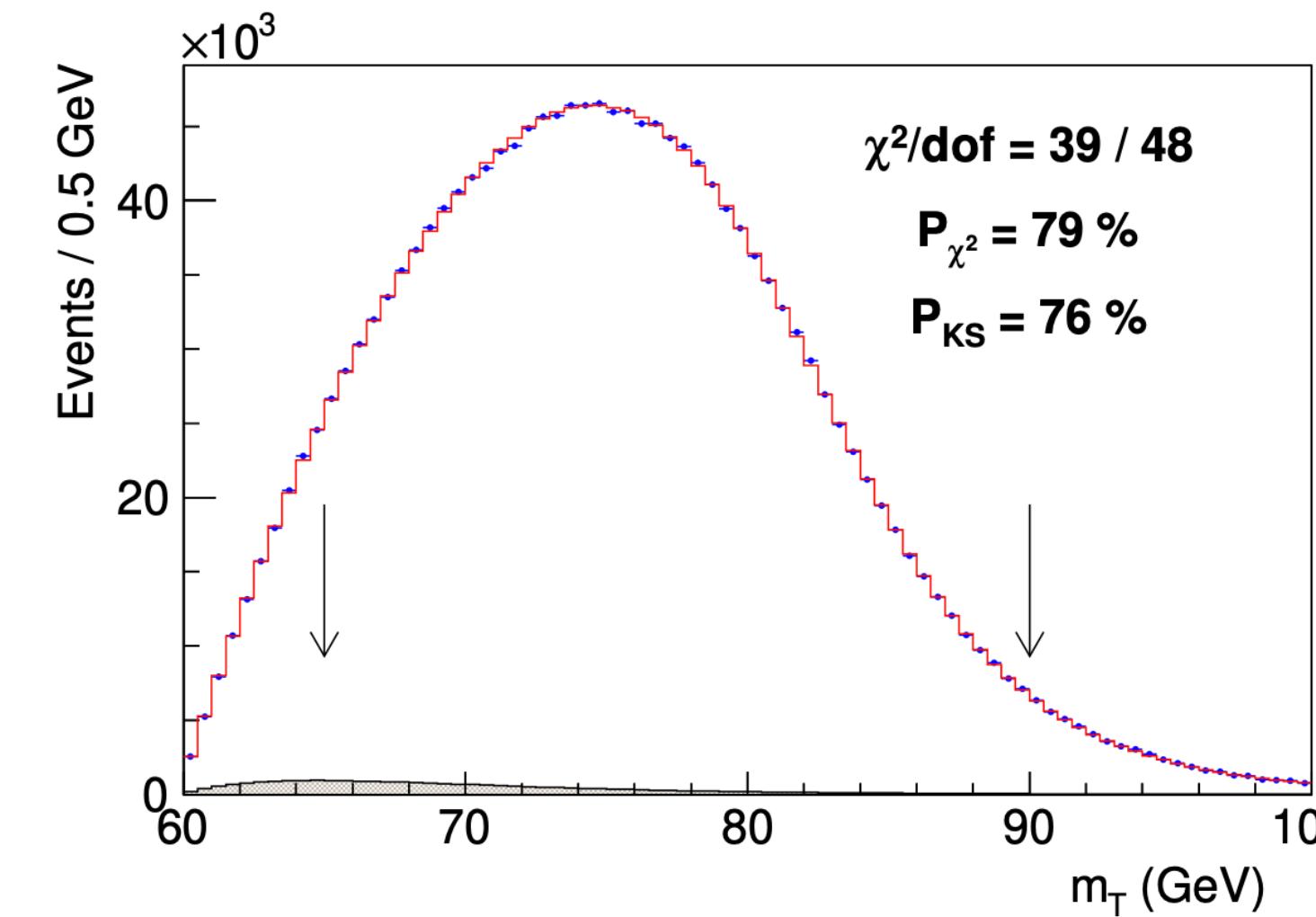
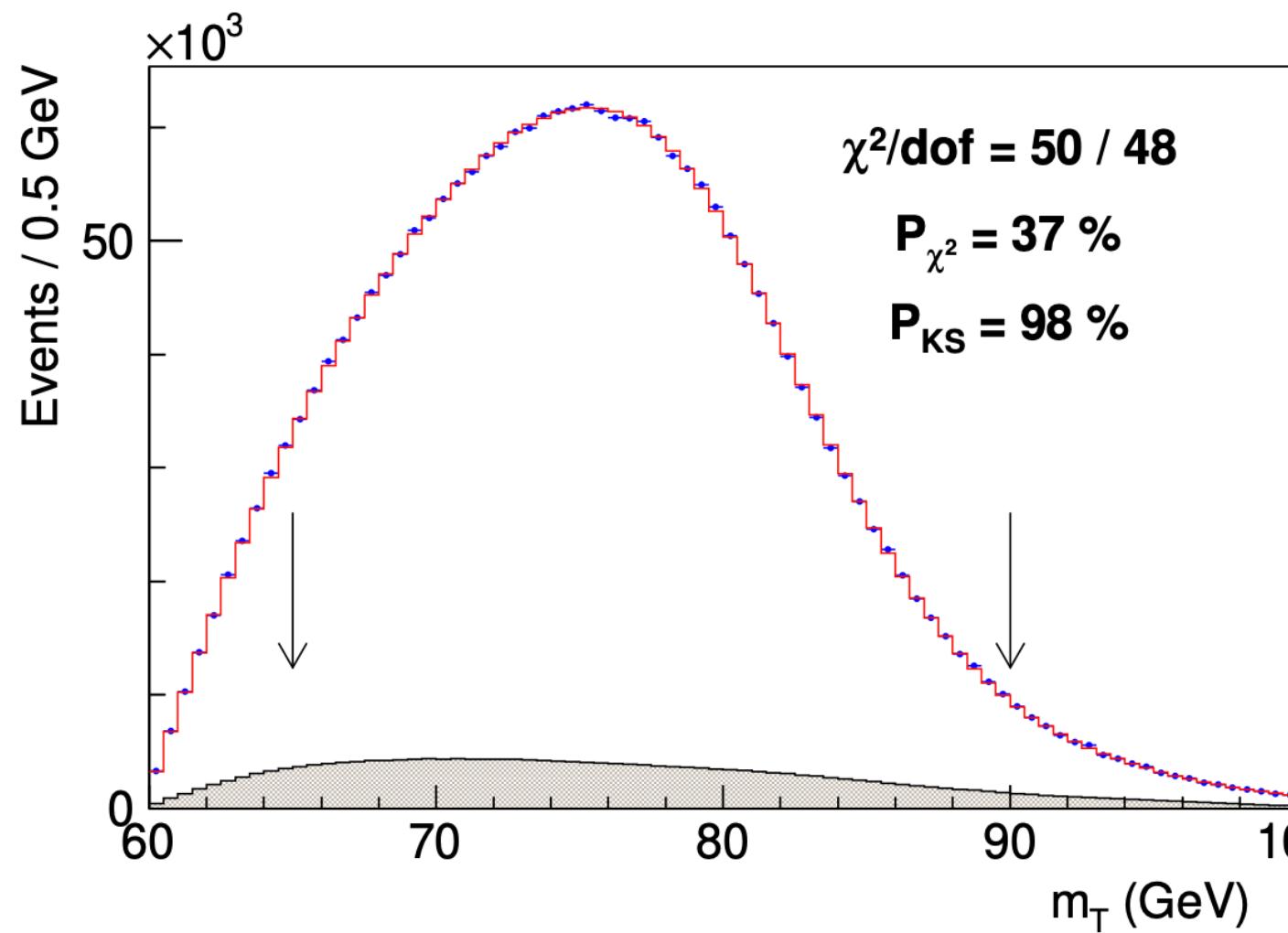
As for the case of ATLAS this **measurement relies on the fine calibration of the lepton energy scale**, savvy methods elaborated to correct for charge dependent curvature (sagitta) bias corrections using a pseudo mass definition.

$$\mathcal{M}^\pm = \sqrt{2p^\pm p_T^\pm \frac{p^\mp}{p_T^\pm} (1 - \cos\theta)}$$

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

CDF Mass Measurement

14



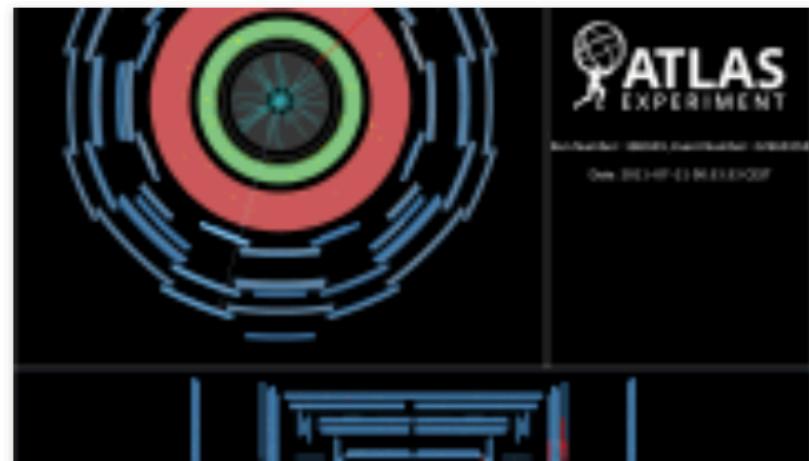
Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

- The tension with the CDF W mass with ATLAS only was at the 3.4σ level
- (Tension of CDF measurement with the SM 7σ)

Since an update of the W mass measurement was made by ATLAS...

W Mass Update - ATLAS

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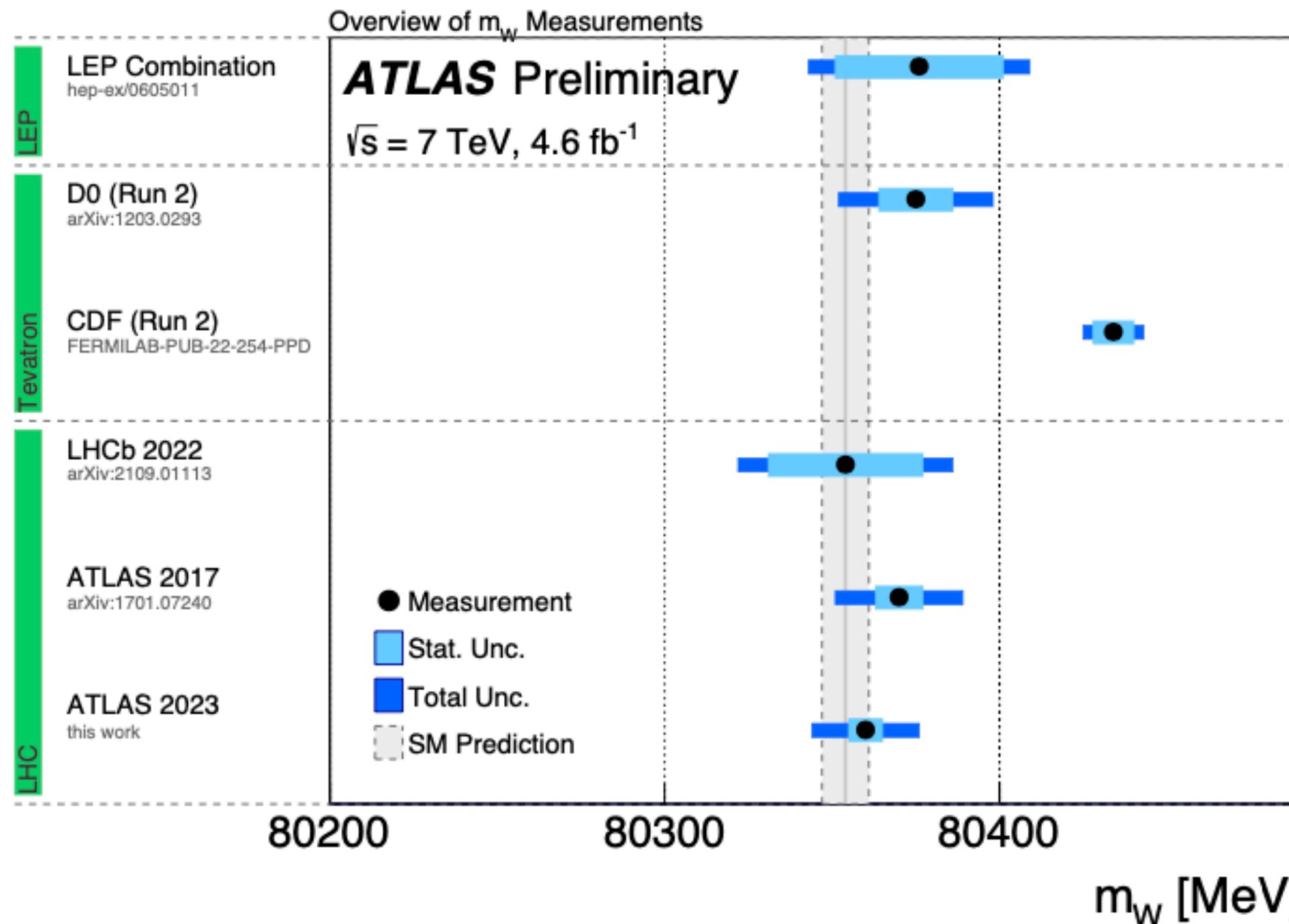
Improved ATLAS result weighs in on W boson

An improved ATLAS measurement of the W boson mass is in line with the Standard Model of particle physics

Press release | Physics | 23 March, 2023

CERN [press release](#)

Observed shift 10 MeV and precision improved by 16 MeV!



$$m_W = 80360 \pm 5_{\text{(stat.)}} \pm 15_{\text{(syst.)}} = 80360 \pm 16 \text{ MeV}$$

$$m_W = 80370 \pm 19 \text{ MeV}$$

Several small improvements, but mostly **relying on the huge analysis effort of the first 7 TeV result** but reformulated using the **profile likelihood paradigm**.

The tension with the CDF W mass increases to 4σ

Where do we go from here?

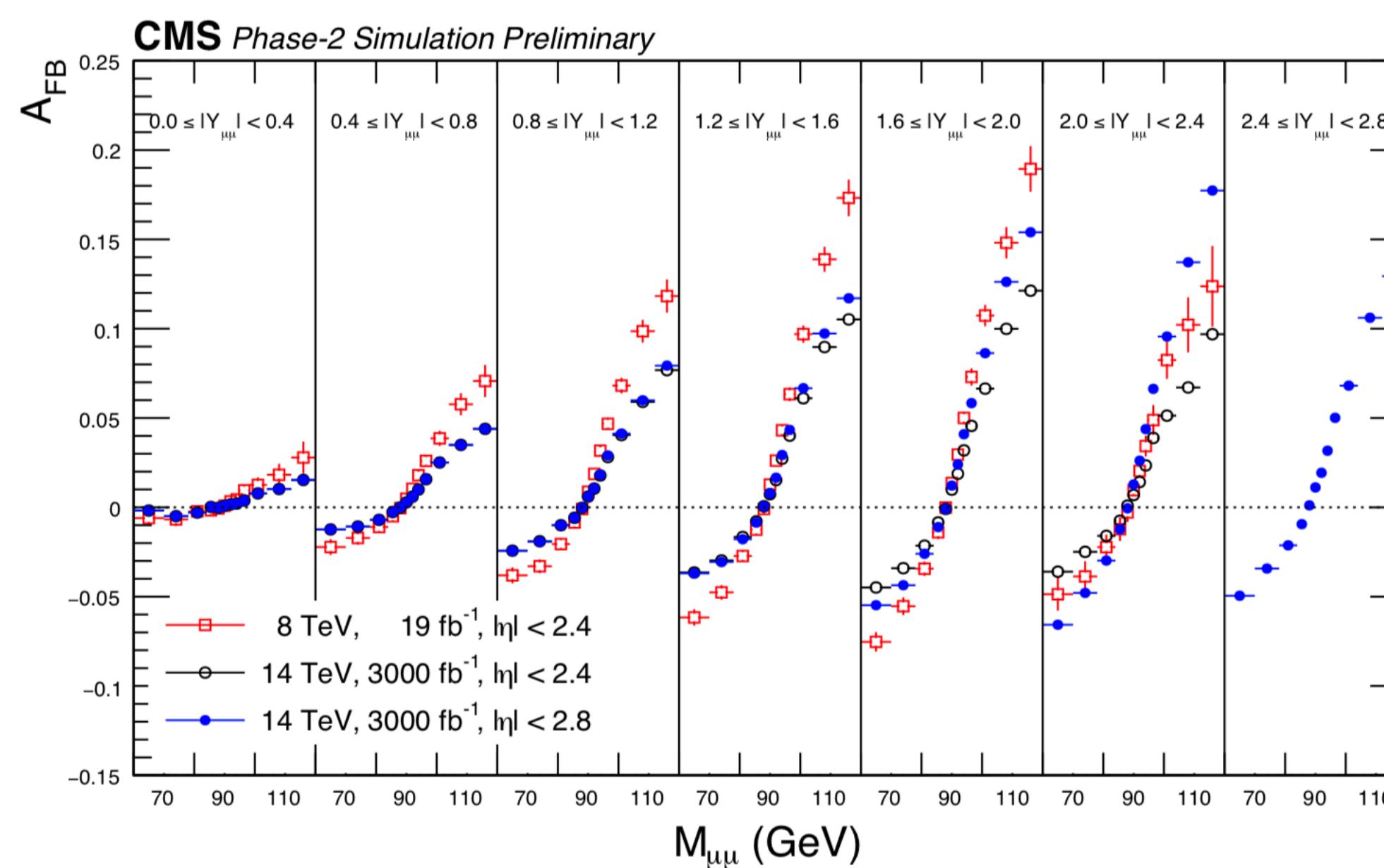
Significant evidence of measurement systematic bias: need a collective effort to understand this puzzle!

Reach at HL-LHC in EW Precision measurements

16

EW Mixing angle

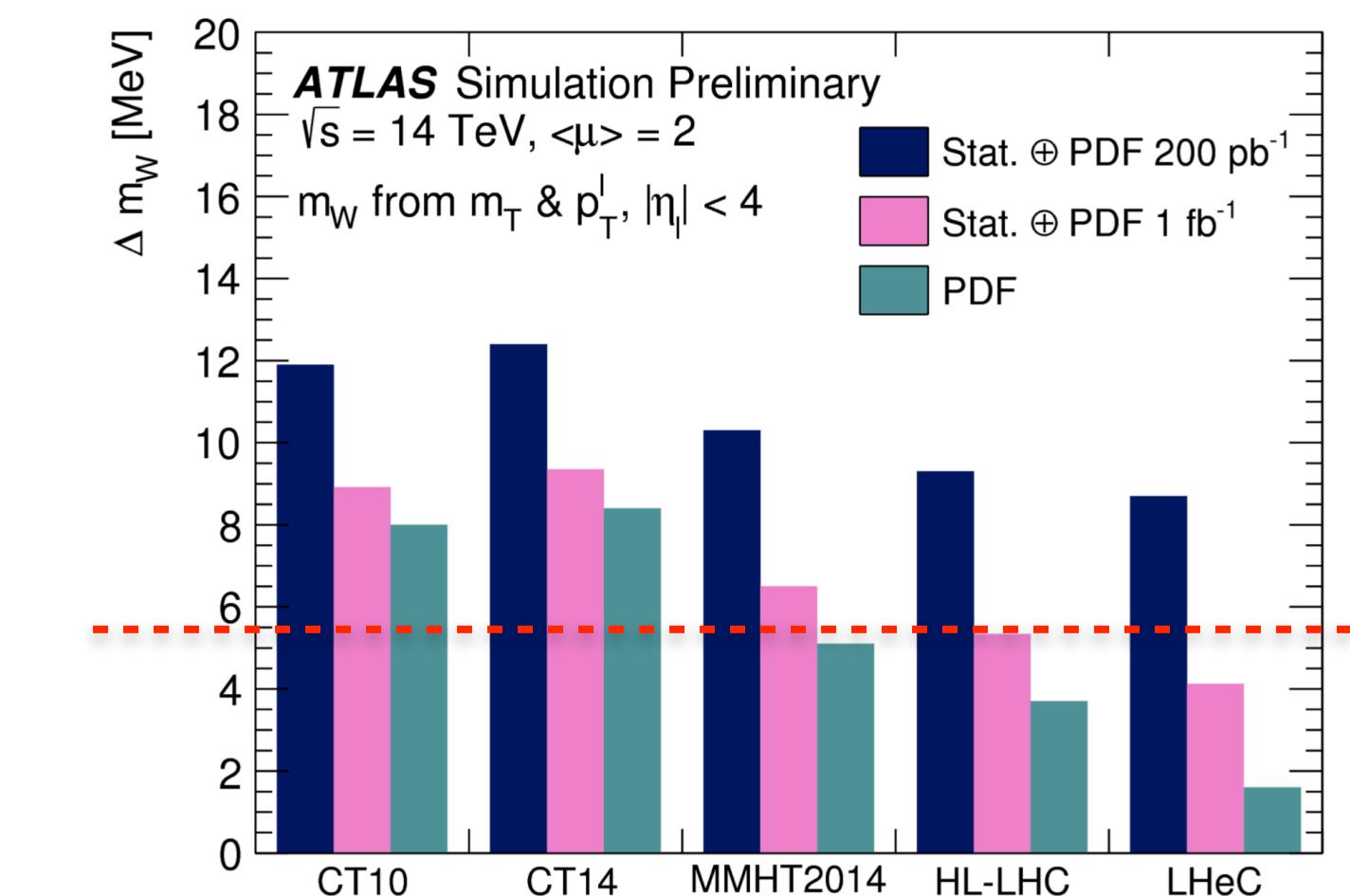
With the increased luminosity and muon acceptance in CMS (from eta 2.4 to 2.8 - for this study)



Individual measurements reach the level of the current World Average of **16 (10^{-5})** CMS estimate alone with muons.

W Mass

- Need for low PU (~ 2)
- Need from $\sim 200 \text{ pb}^{-1}$ (already a good start only approximately one week at 14 TeV) to 1 fb^{-1}
- Larger TRK acceptance: reduce PDF systematics

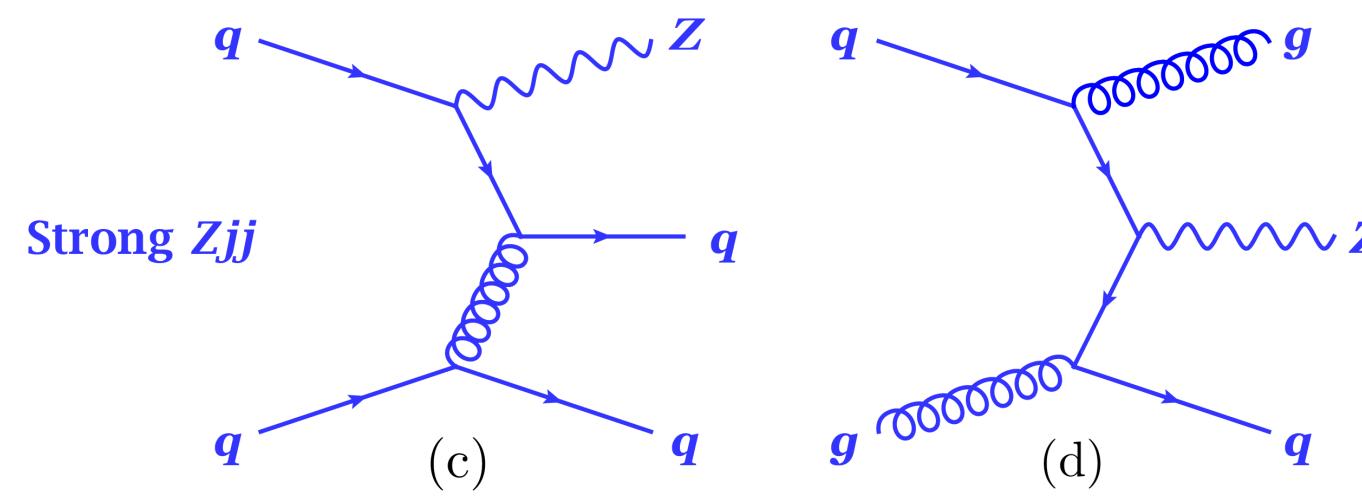


Precision reach at HL-LHC

$\sim 10 \text{ MeV}$ for 200 pb^{-1}
 $\sim 6 \text{ MeV}$ for 1 fb^{-1}
($\sim 4 \text{ MeV}$ with LHeC)

Vector Boson Production with Jets

QCD Vector boson and Jets

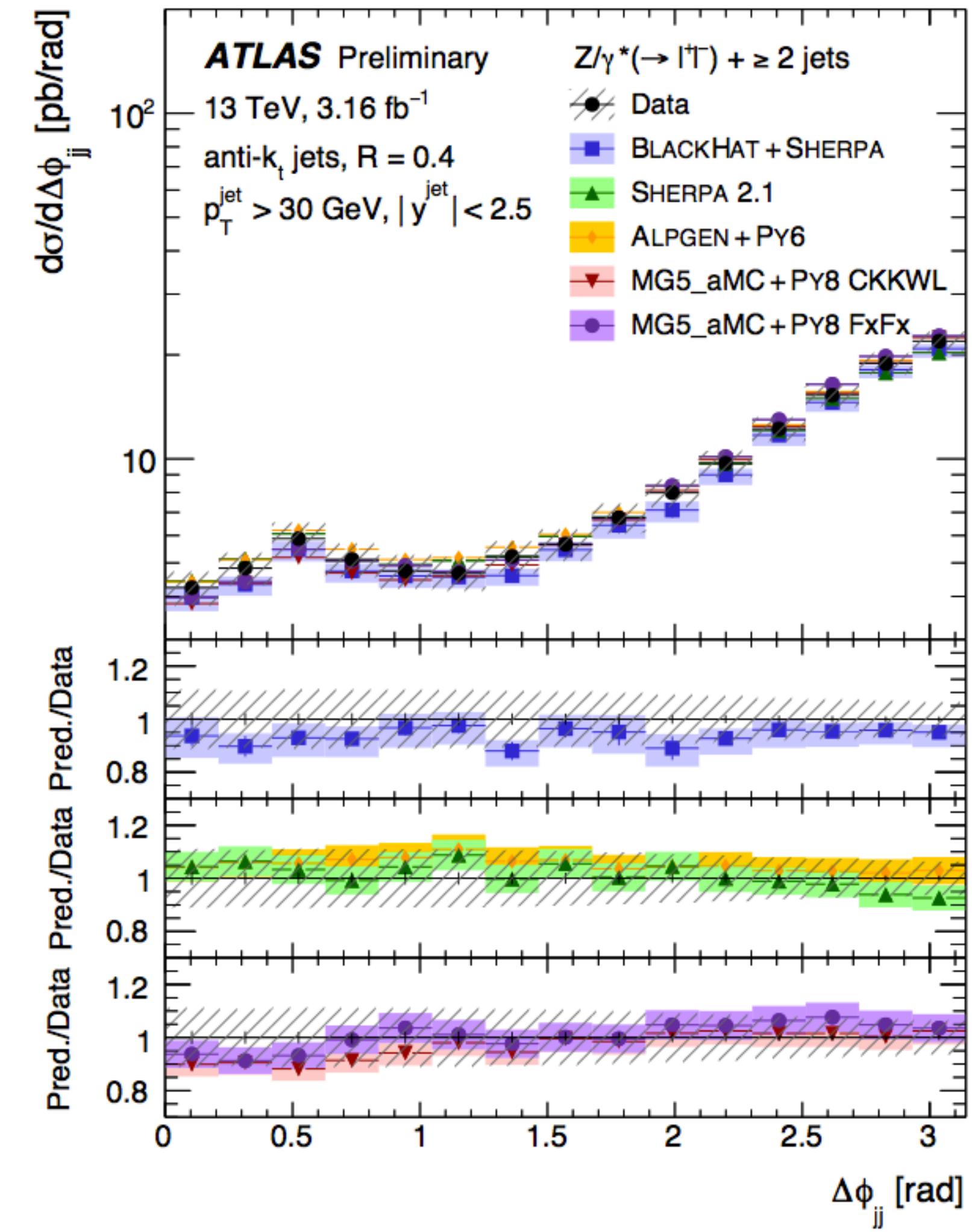
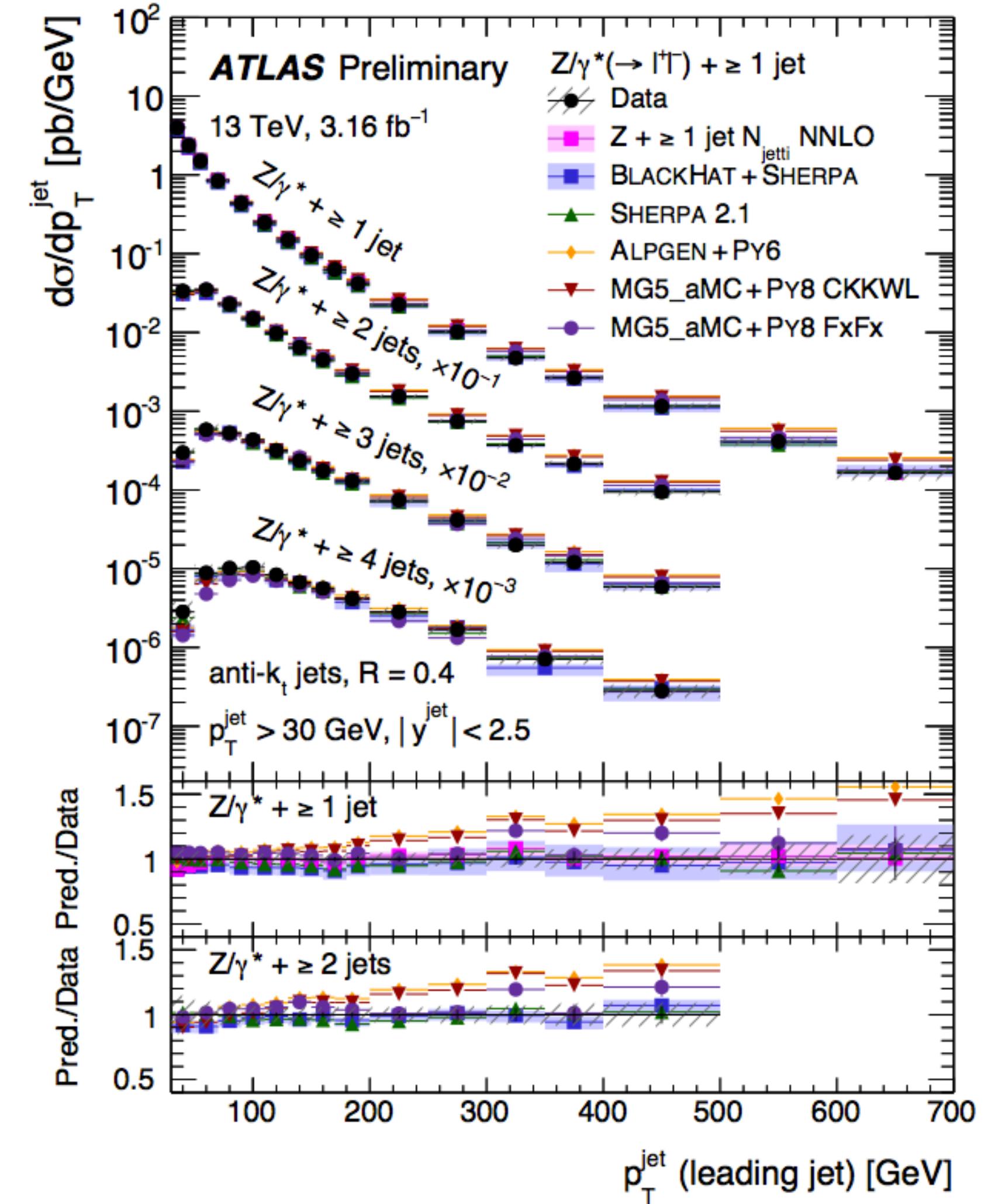


Vector boson production
Probing state-of-the-art Monte
Carlos

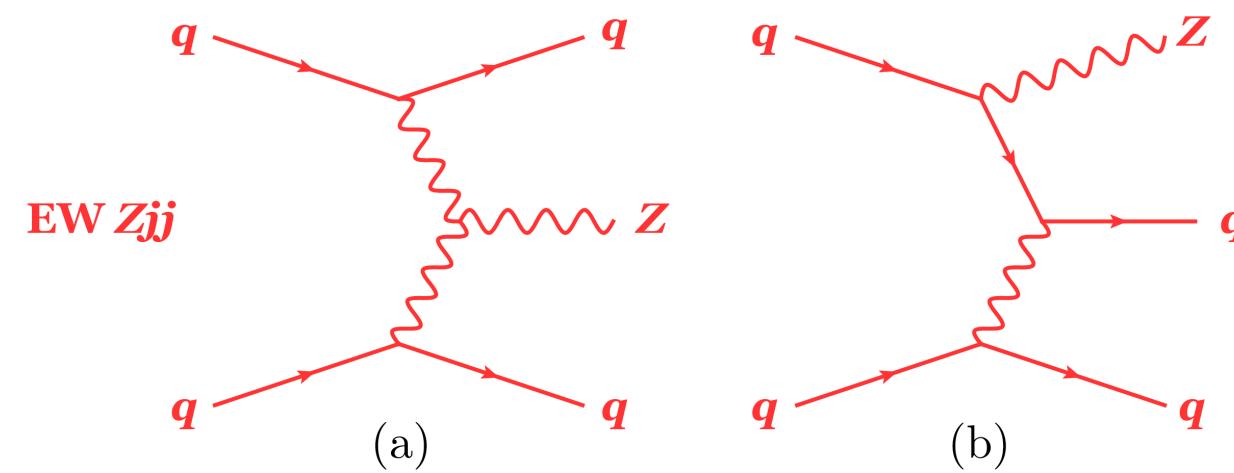
Essential ingredient (**ancillary**) of a
number of searches and measurements
(EW, top and Higgs physics in
particular)!

**Huge amount of work gone into
further improving and tuning the
MC modelling)!**

Level of sophistication made generation times
large (in some very specific cases even larger
than simulation)

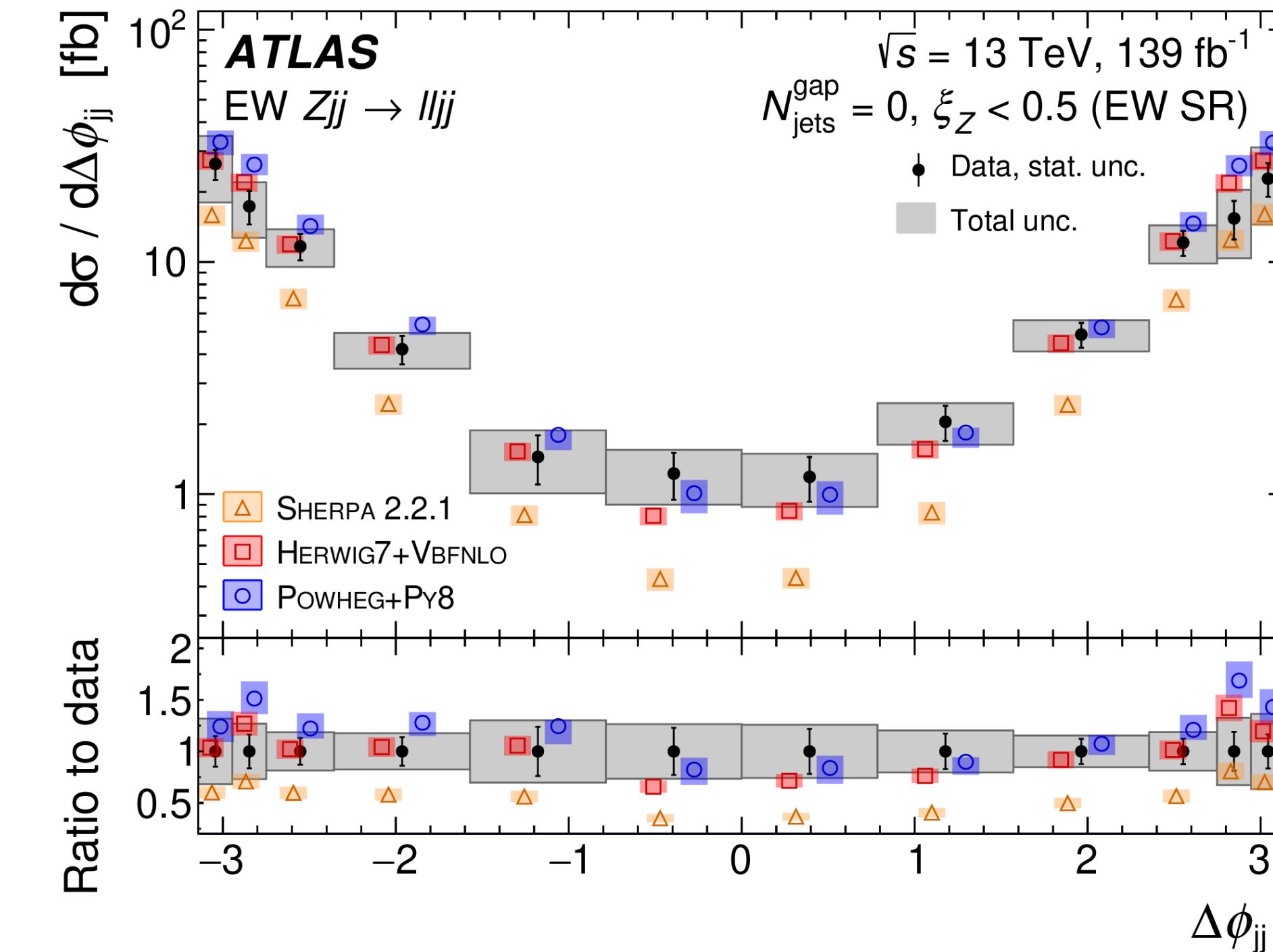
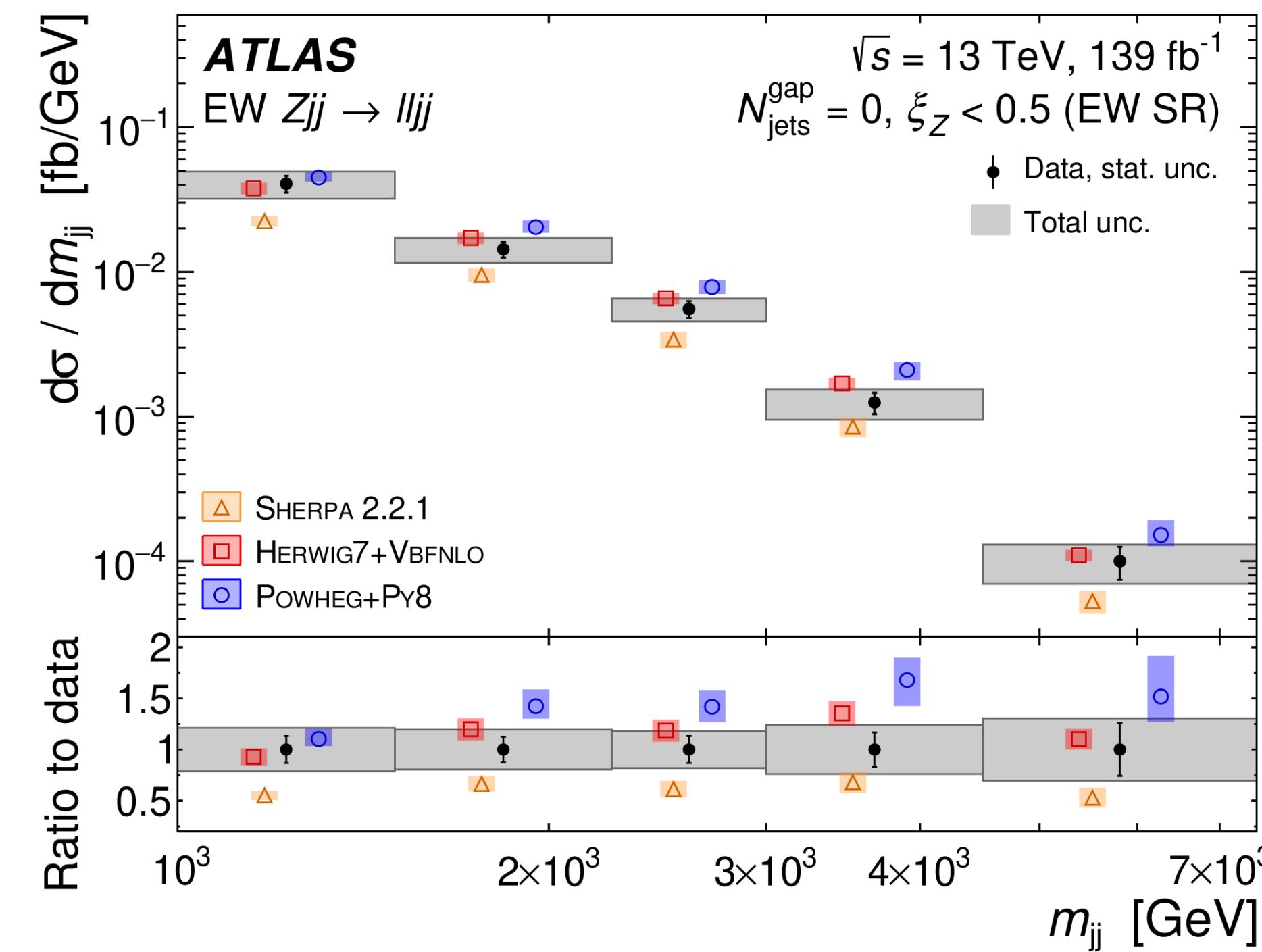


EW Vector boson and Jets



EW Vector boson production
Non trivial to isolate from QCD production

Essential ingredient for our understanding of color singlet EW production with forward tagging jets and Central Jet Veto.

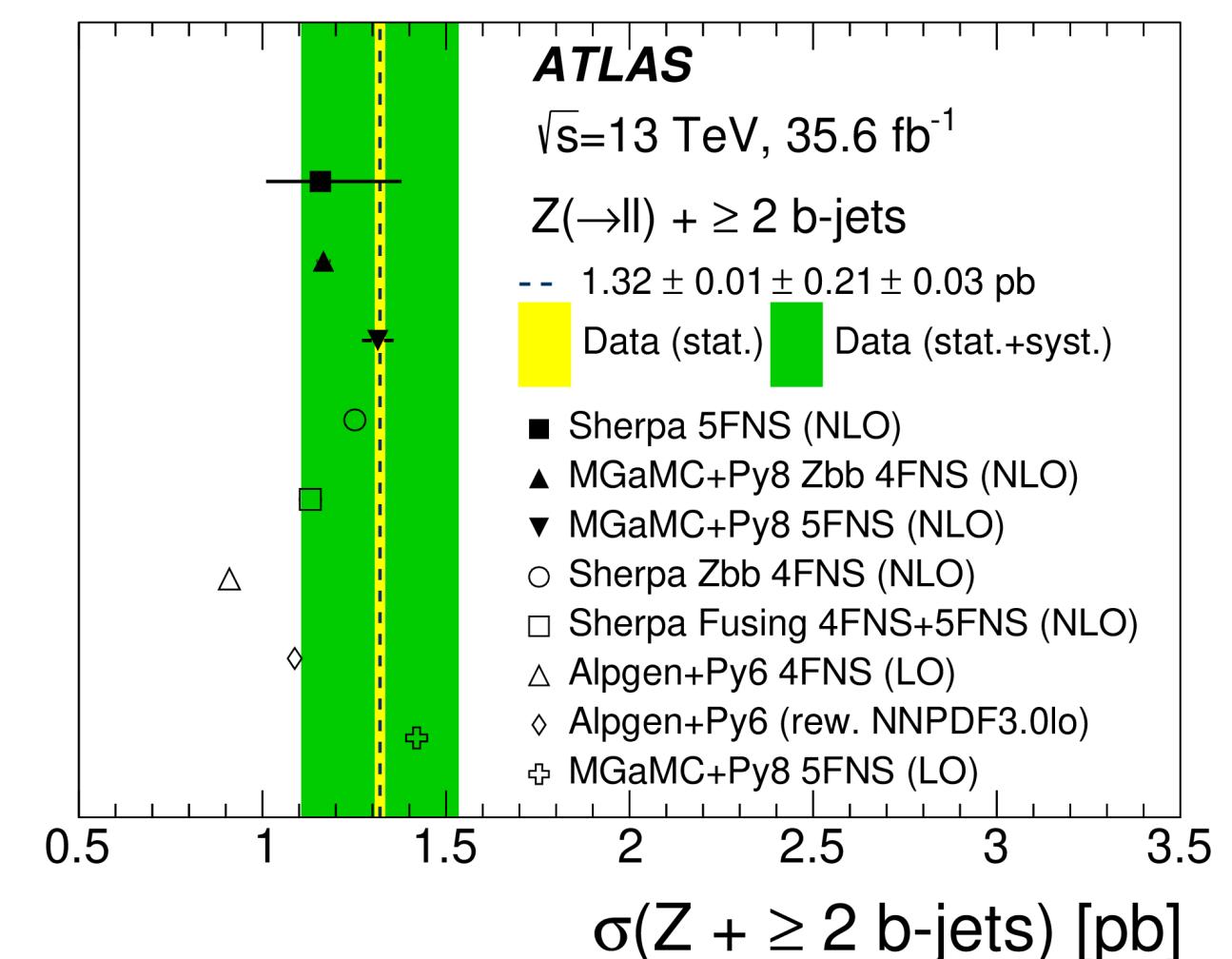
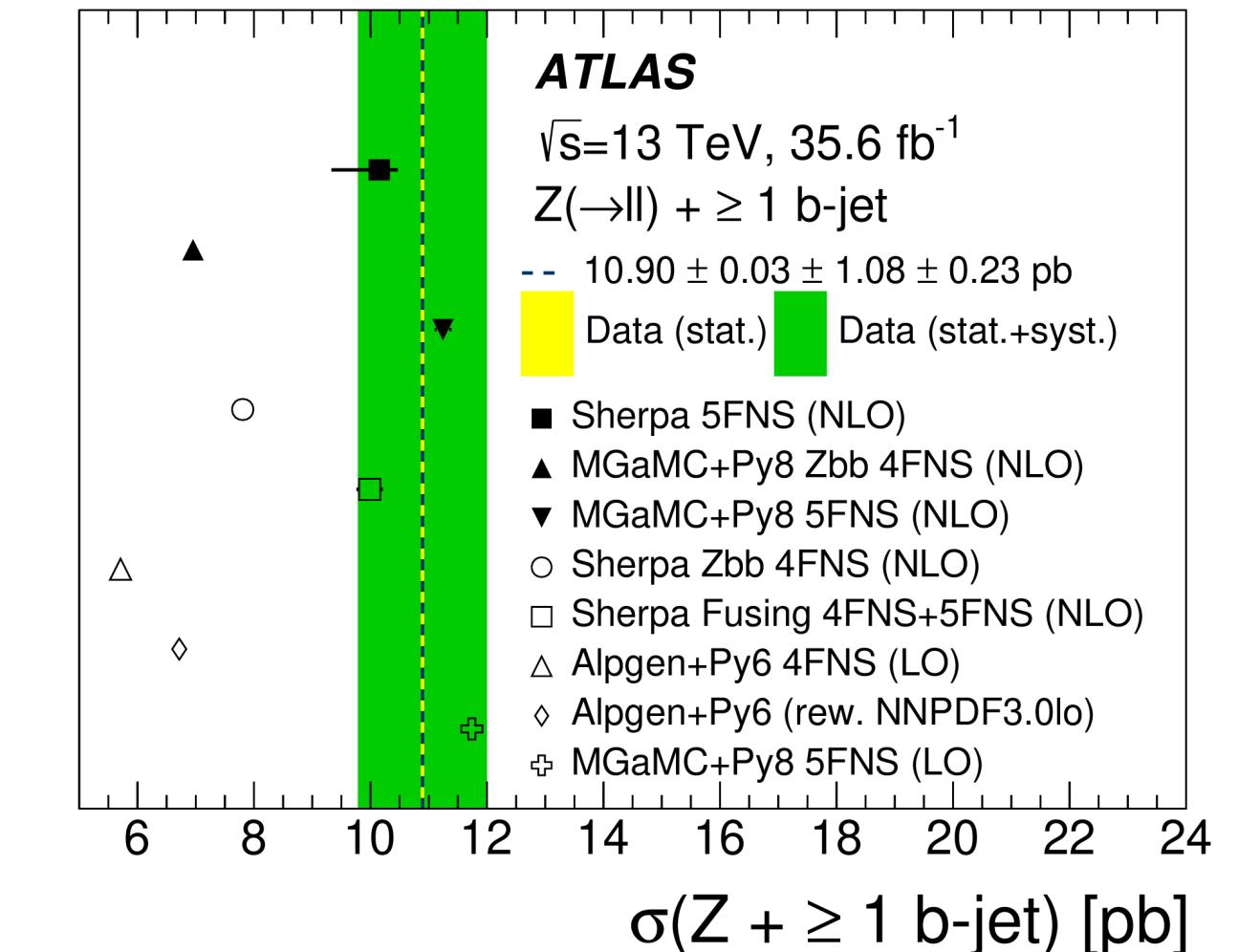
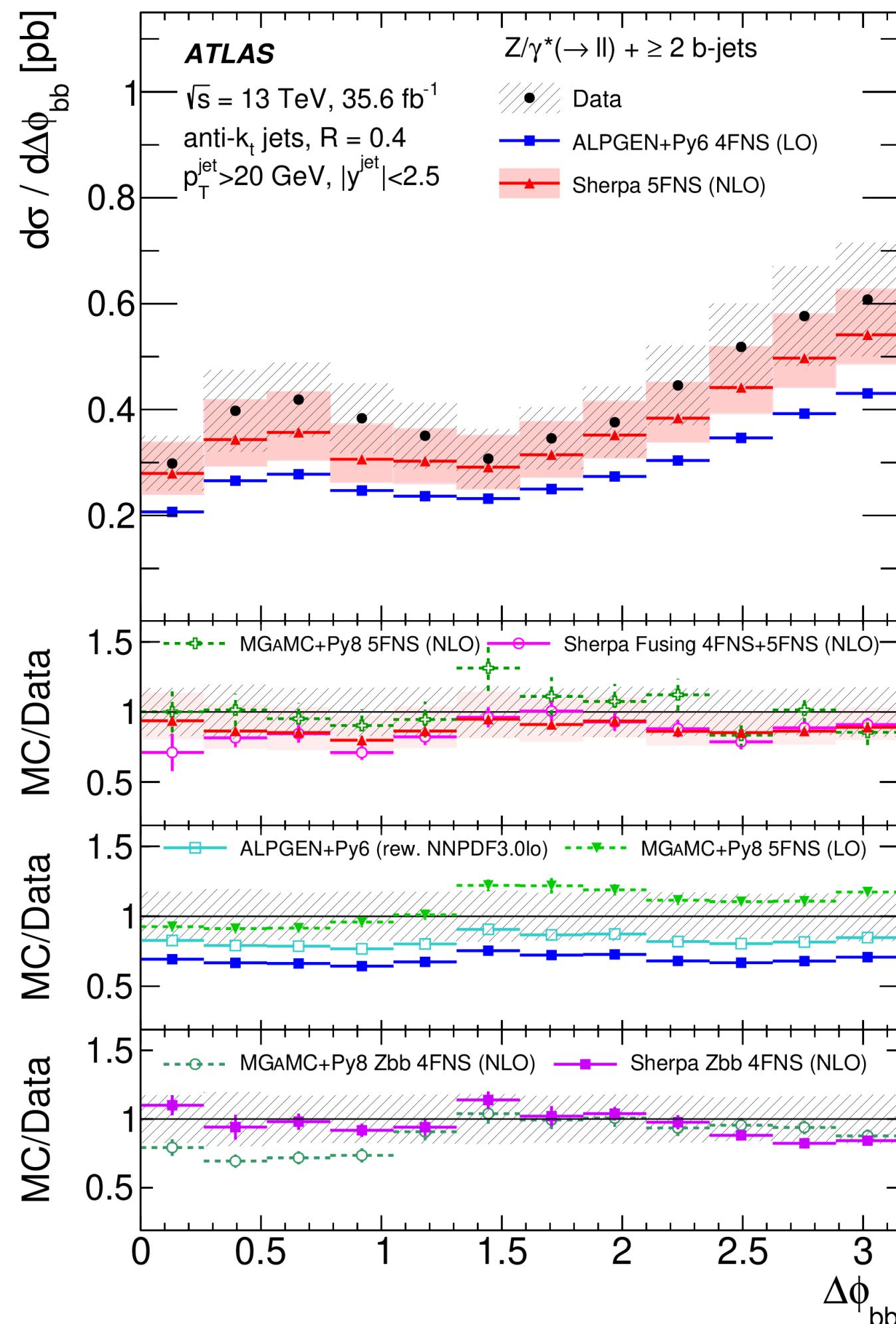
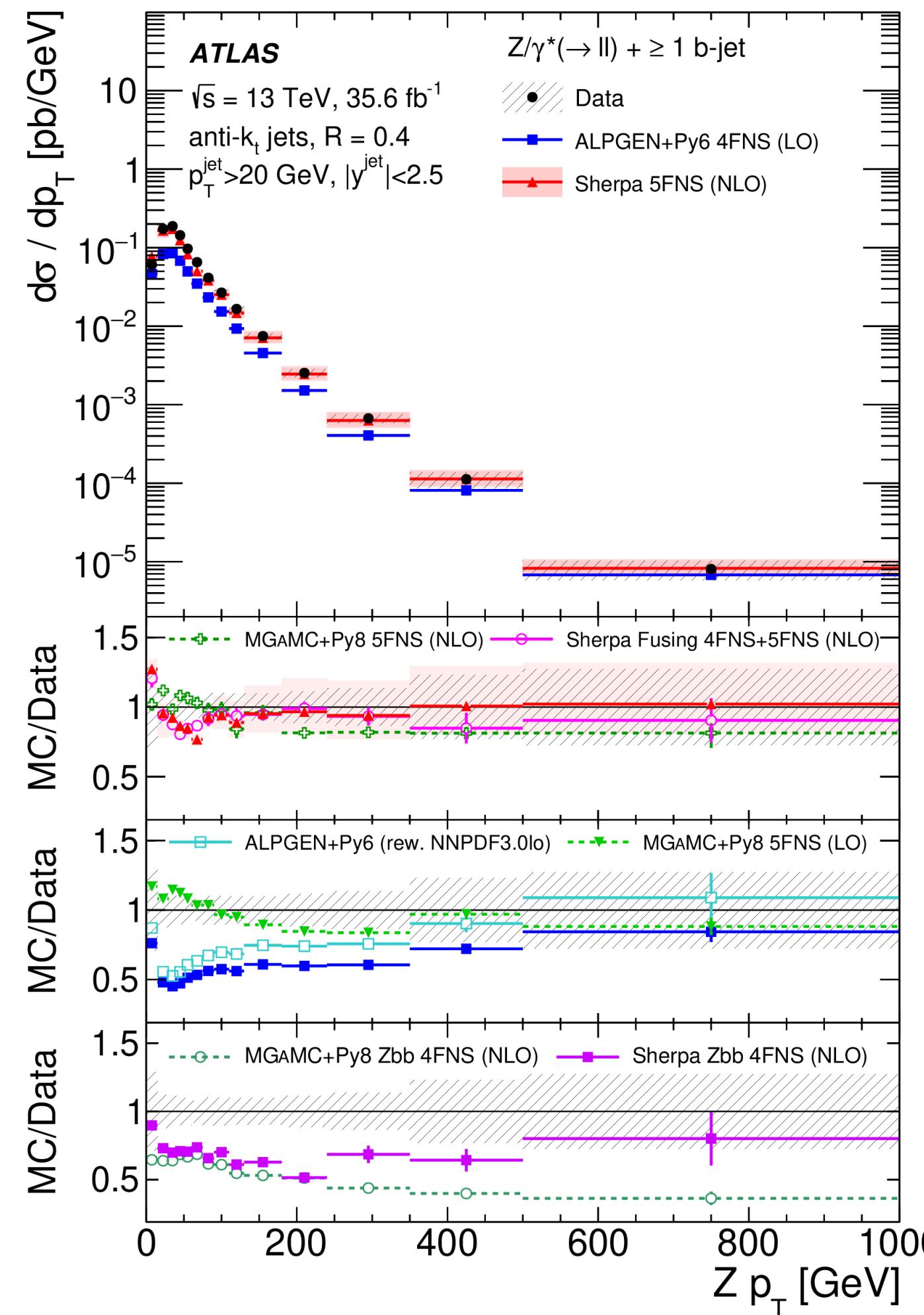


Z boson and 1 or 2 b-jets

Z boson production with b-jets

[2003.11960](#)

Essential background in the Higgs to b quarks measurements

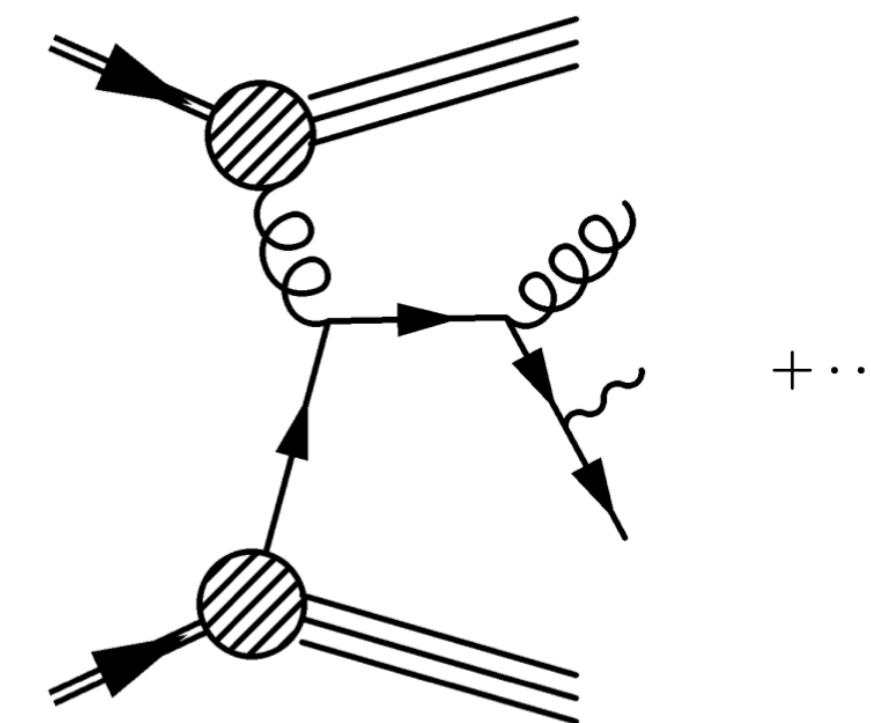


Multi boson production

Photon-jet Production

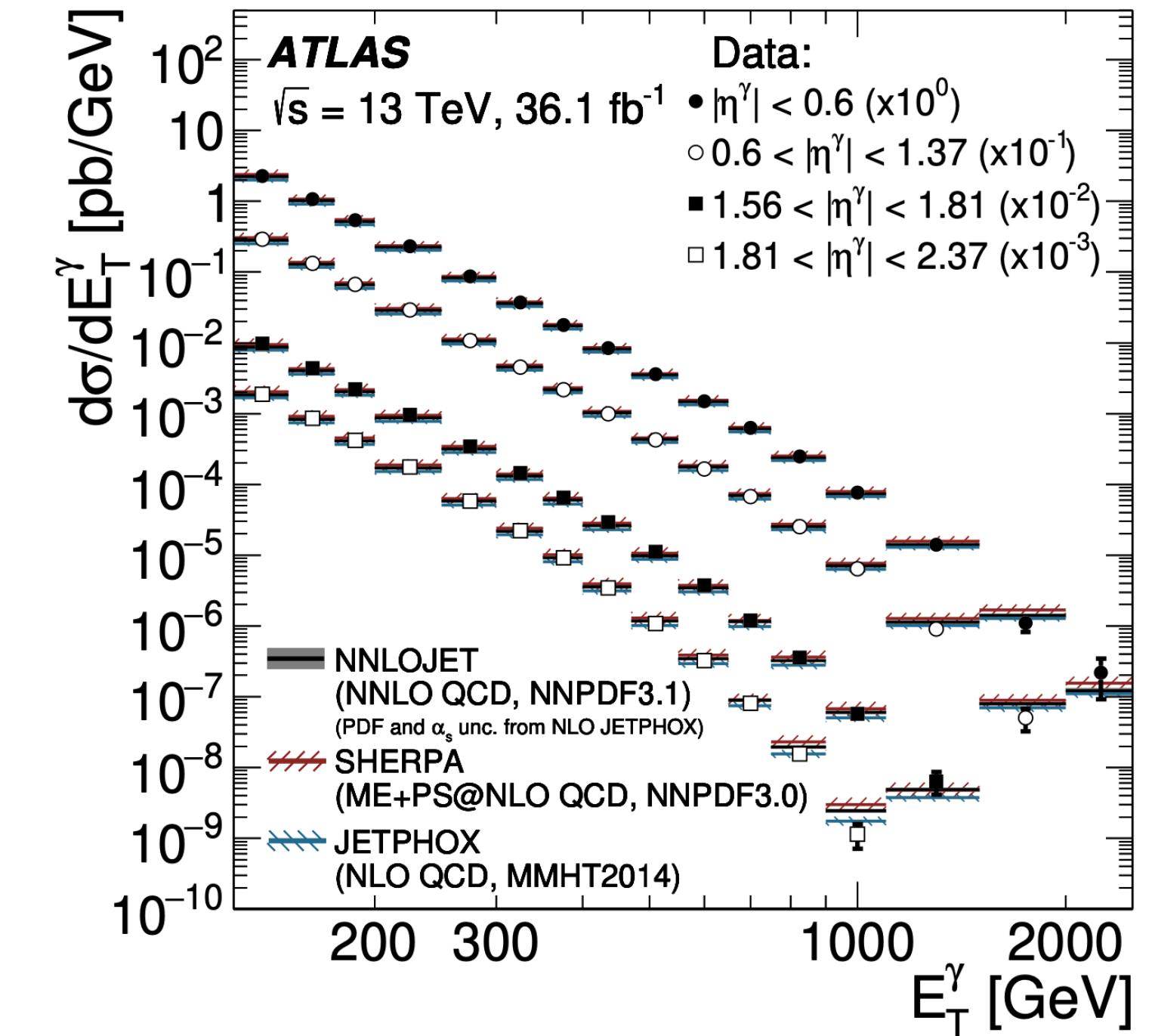
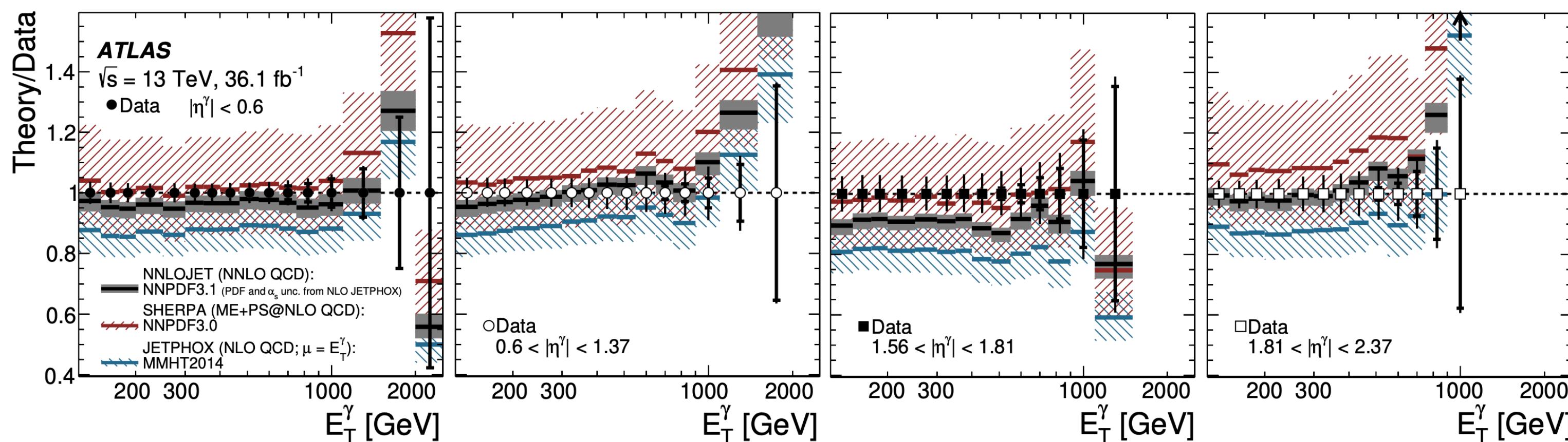
22

Photon-jet production is the largest reducible background in the measurements of the Higgs boson decays to two photons and is sensitive to gluon PDF!



Intricate process where the photon emission can be at parton level in the ME element or in the parton fragmentation.

The ME photon emission has a collinear divergence that can be eliminated by the Frixione isolation (used in Sherpa NLO QCD and in NNLOJET). The JetPhox Fixed Order TH calculation has a consistent calculation of cone isolation including the fragmentation component.

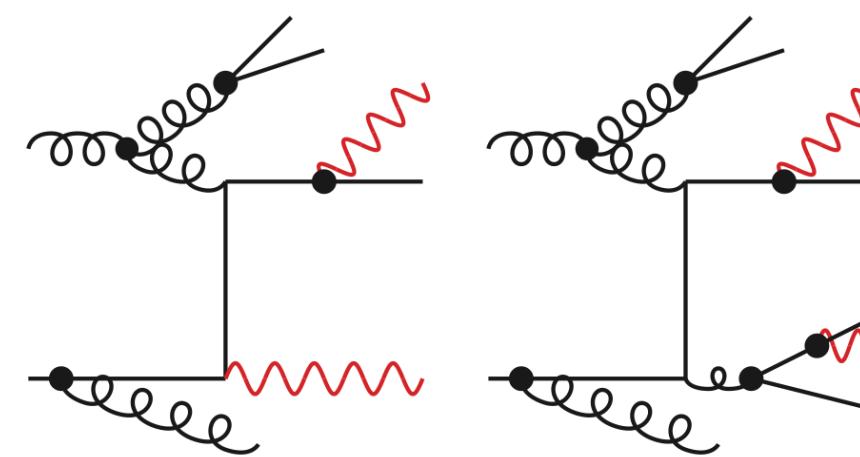


NLO descriptions already quite good, NNLO provides a significant improvement!

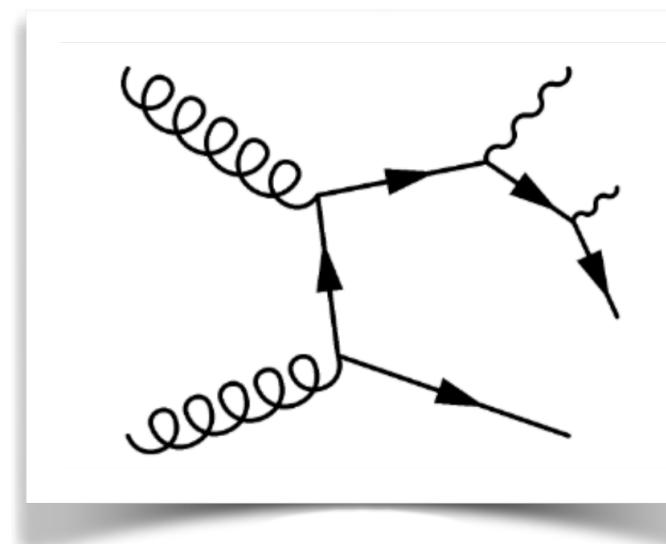
Diphoton Production Cross Section

23

Measuring diphoton production is not only an electromagnetic process also non trivial strong dynamics!

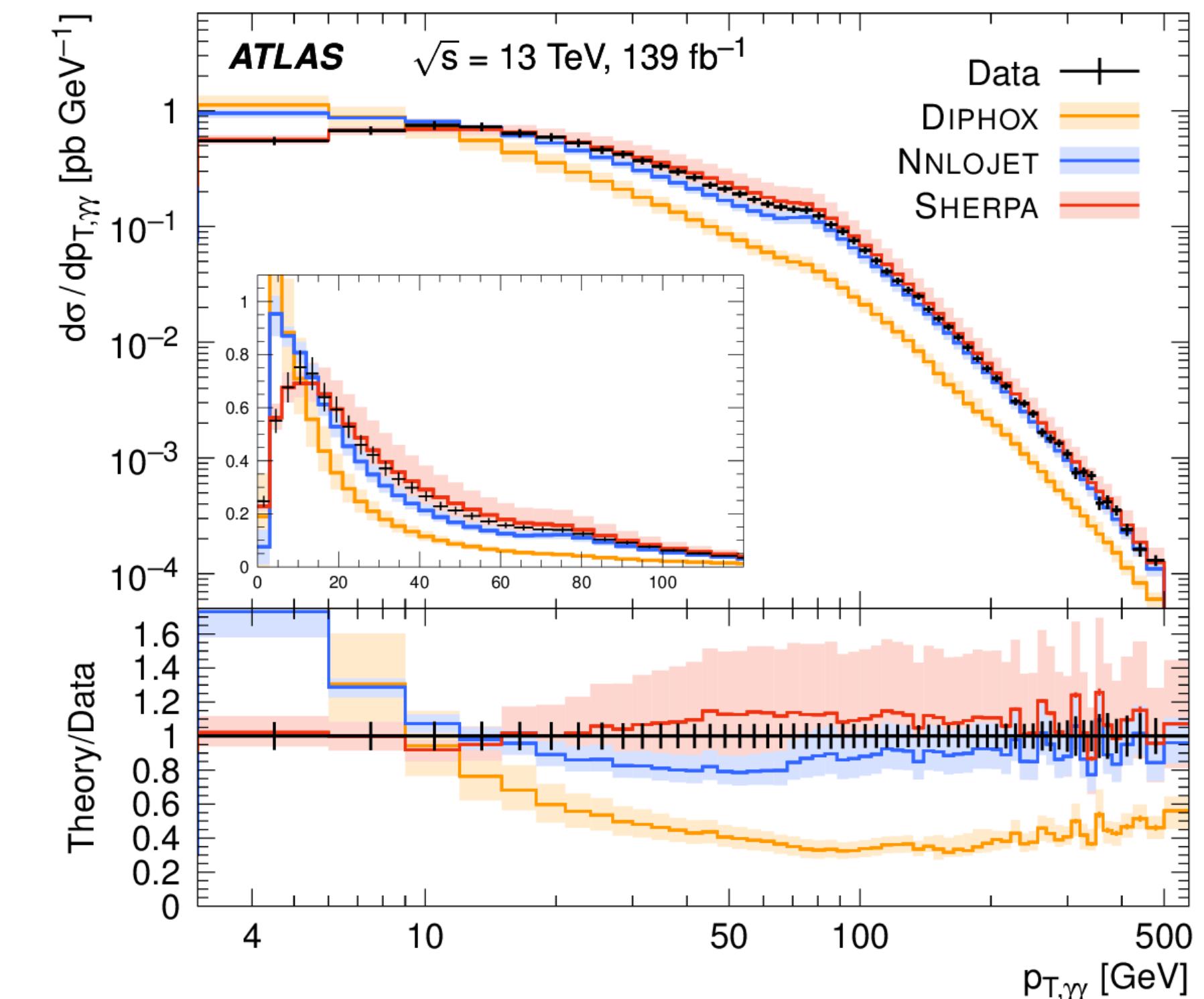
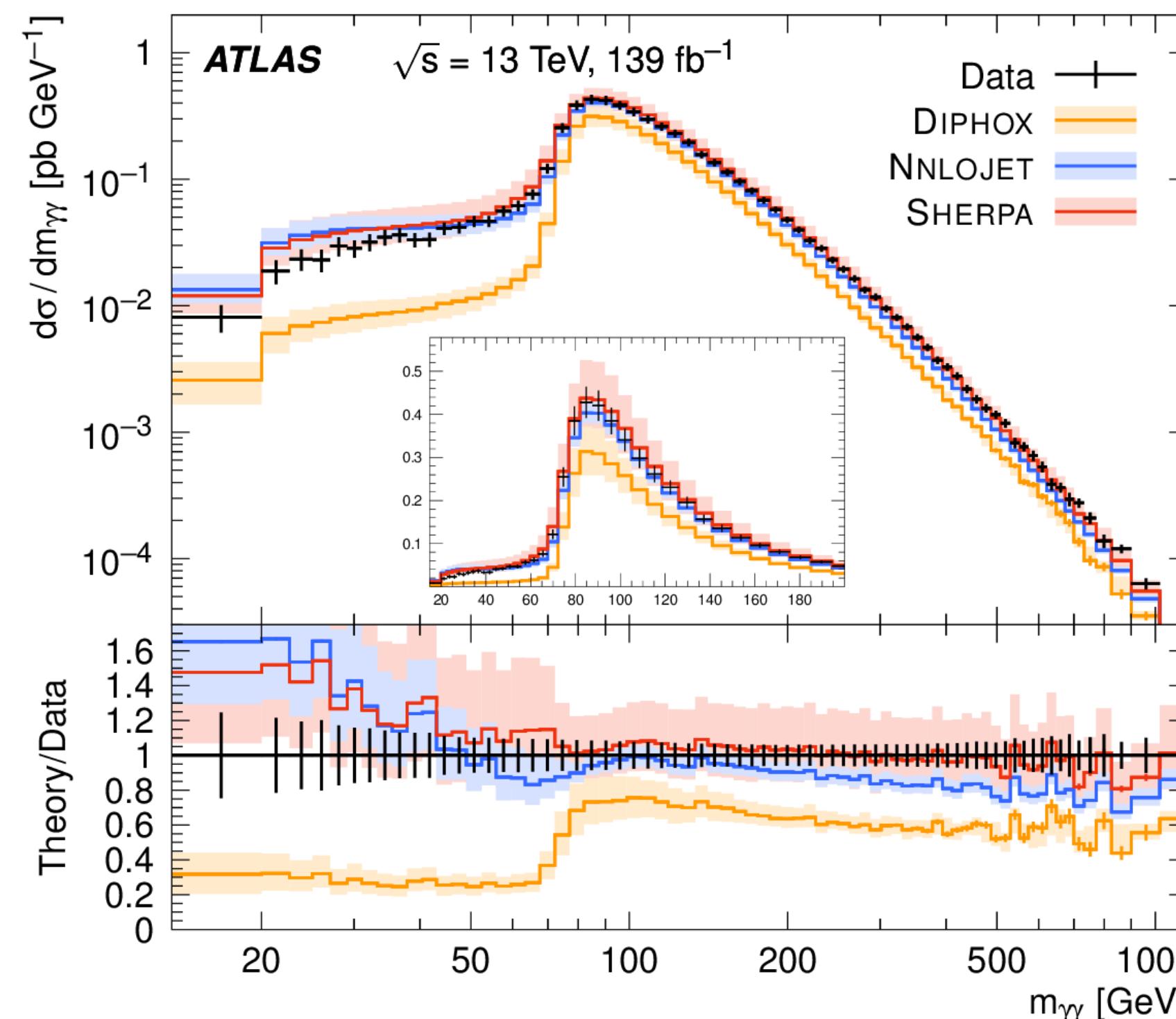


Estimate of PU events with two $\gamma - jet$ events in same bunch crossing
(estimated using photon conversions)



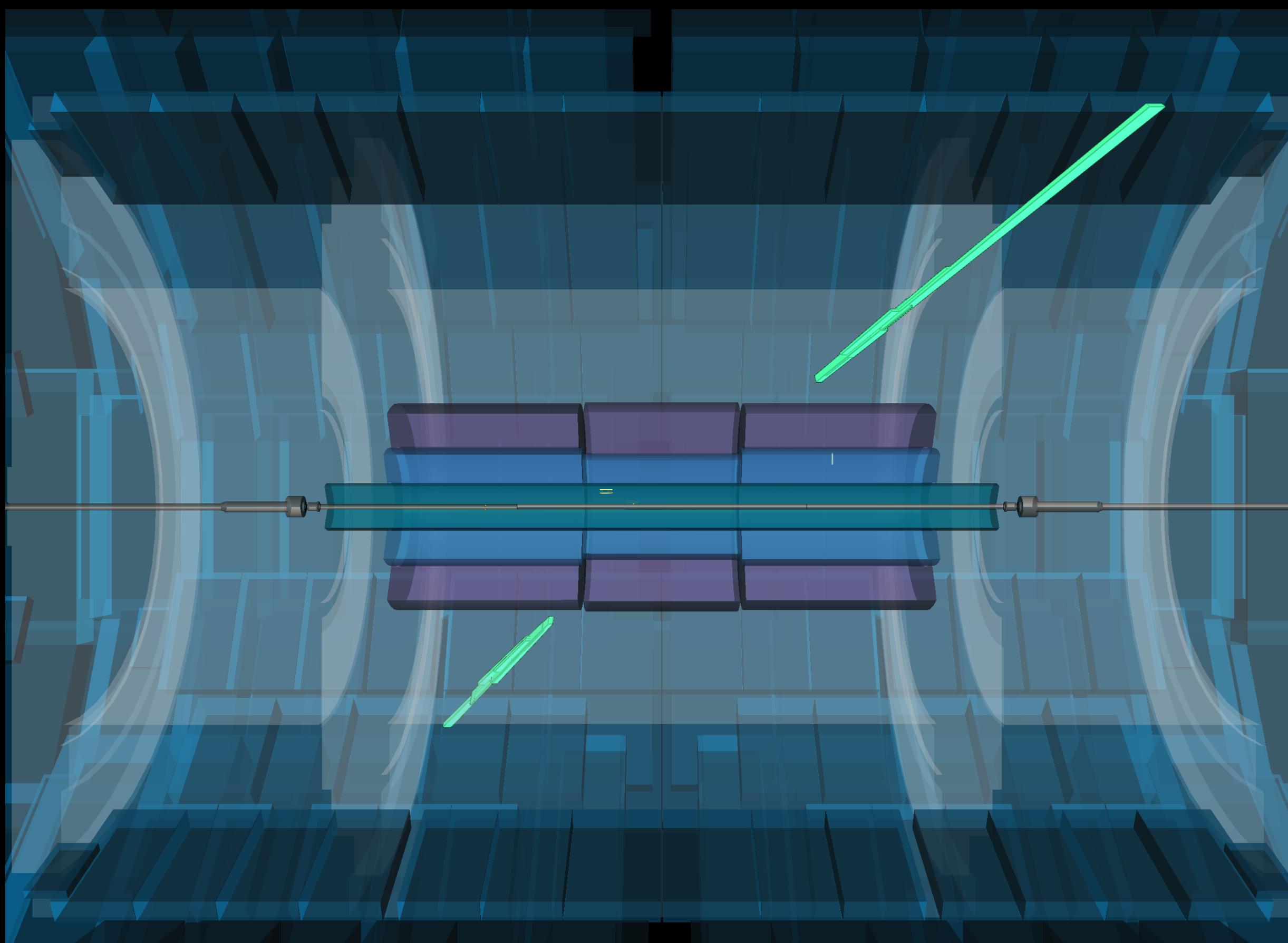
Intricate effects as peak in $p_{T,\gamma\gamma}$ from double emission and kinematic cuts

$$p_{T,\gamma_1(\gamma_2)} > 40 \text{ (30)}$$

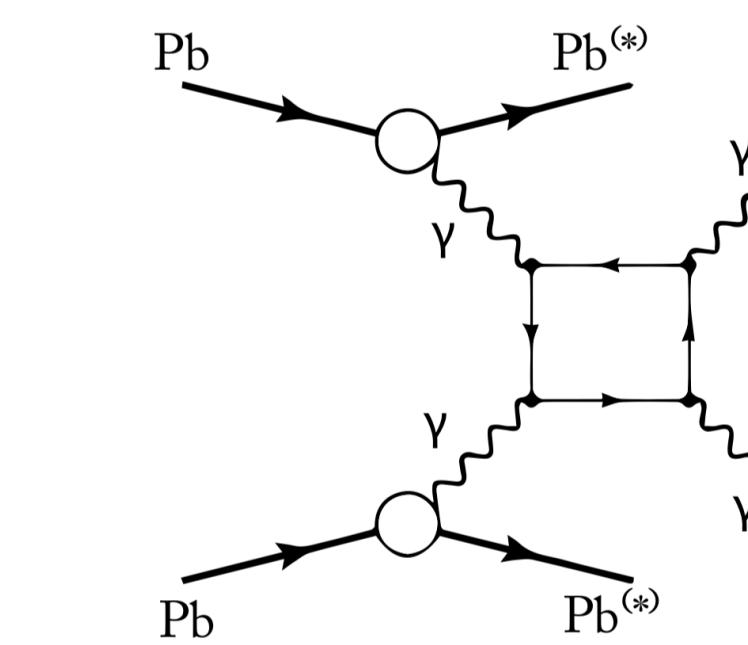


	Fixed-order accuracy					$gg \rightarrow \gamma\gamma$	Fragmentation		QCD res.	NP effects
	$\gamma\gamma$	+1j	+2j	+3j	+ ≥ 4j		single	double		
DIPHOX	NLO	LO	-	-	-	LO	NLO		-	-
NNLOJET	NNLO	NLO	LO	-	-	LO	-	-	-	-
SHERPA	NLO		LO		PS	LO	ME+PS		PS	✓

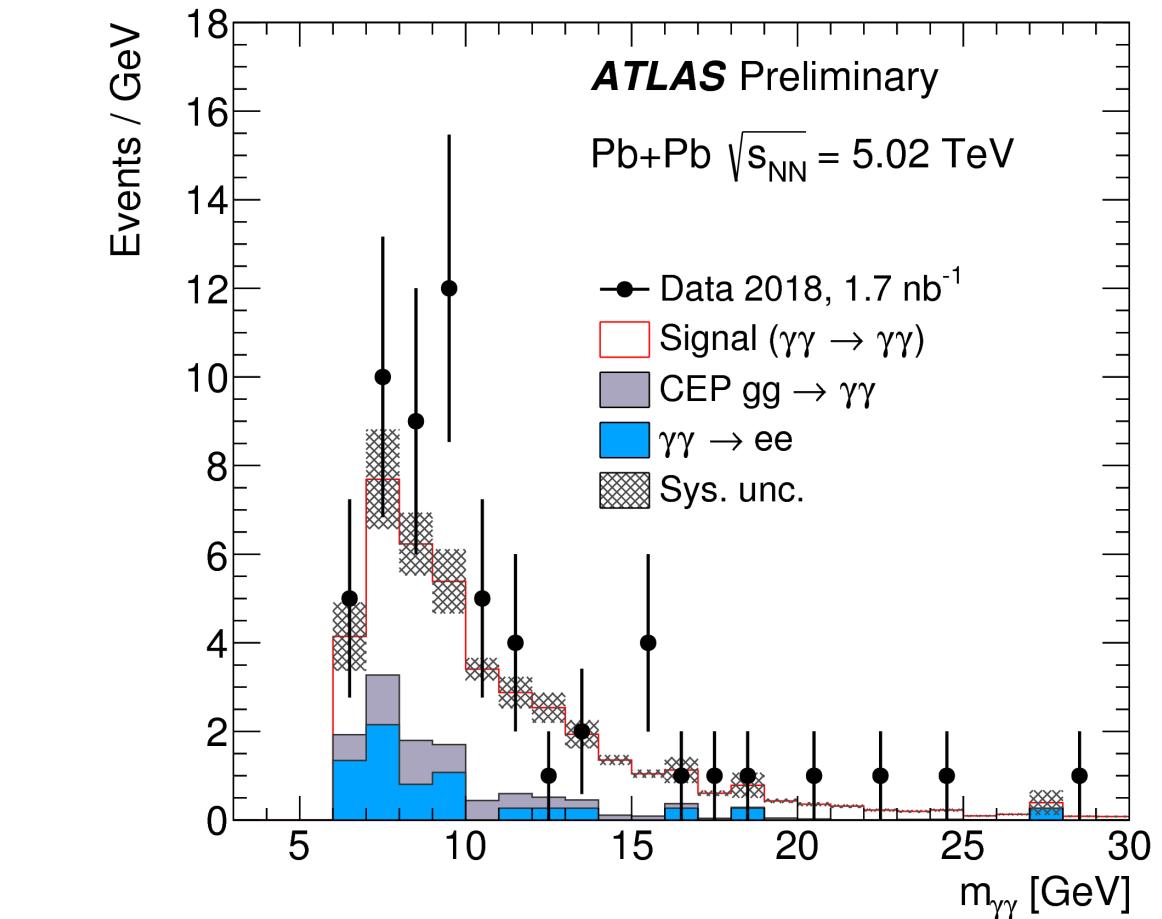
Photon Interactions in HI Events



Observation of **Light-by-light scattering** (Central Exclusive Production)

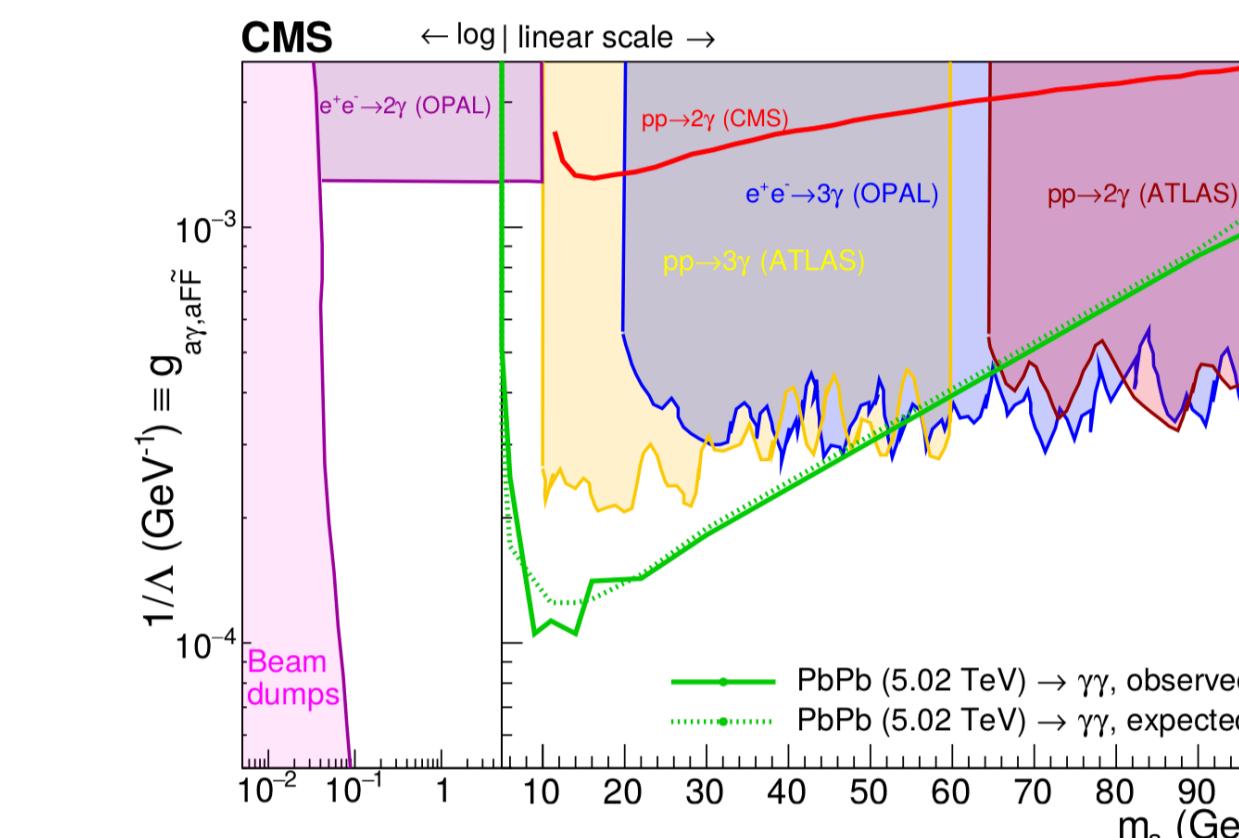


[Phys. Rev. Lett. 123 \(2019\) 052001](#)



Signal observed at more than 8 s.d.

$78 \pm 13 \text{ (stat.)} \pm 7 \text{ (syst.)} \pm 3 \text{ (lumi.) nb}$



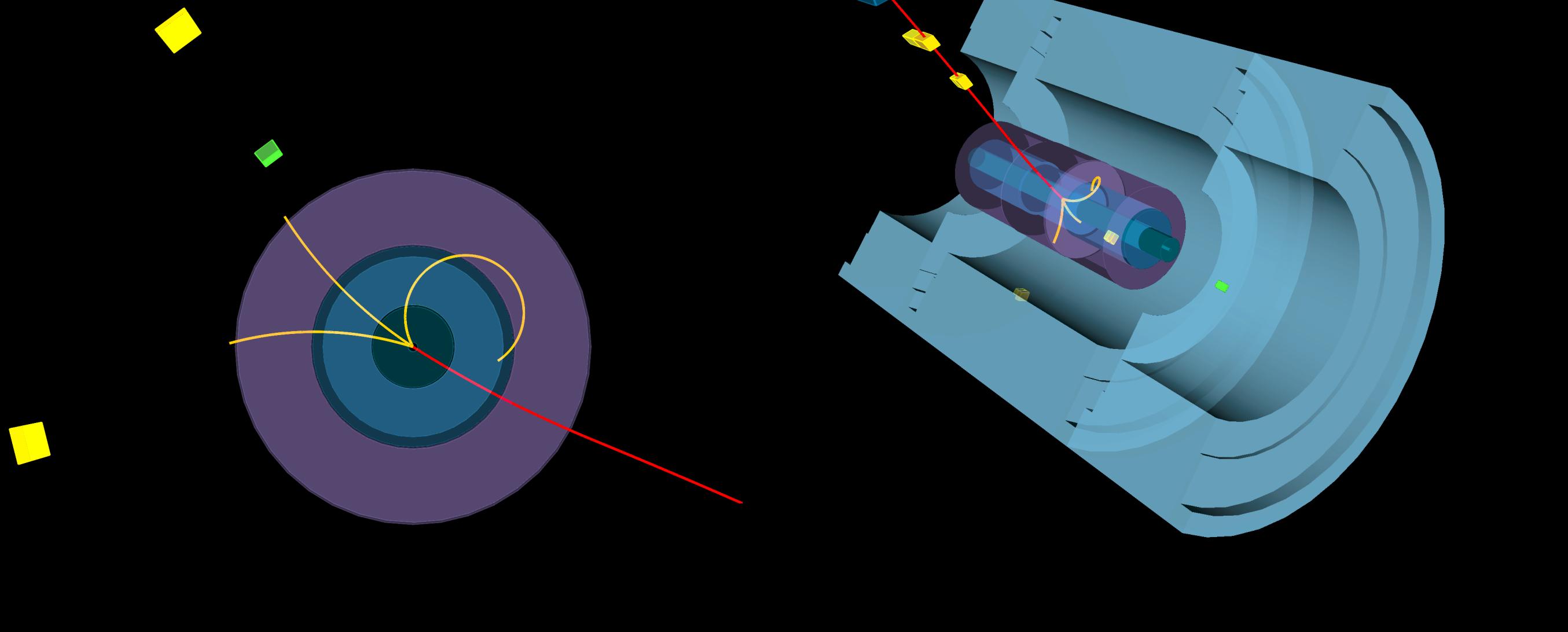
Constraints on ALP (Axion Like Particles) assuming sole coupling to photons.

CMS-FSQ-16-012

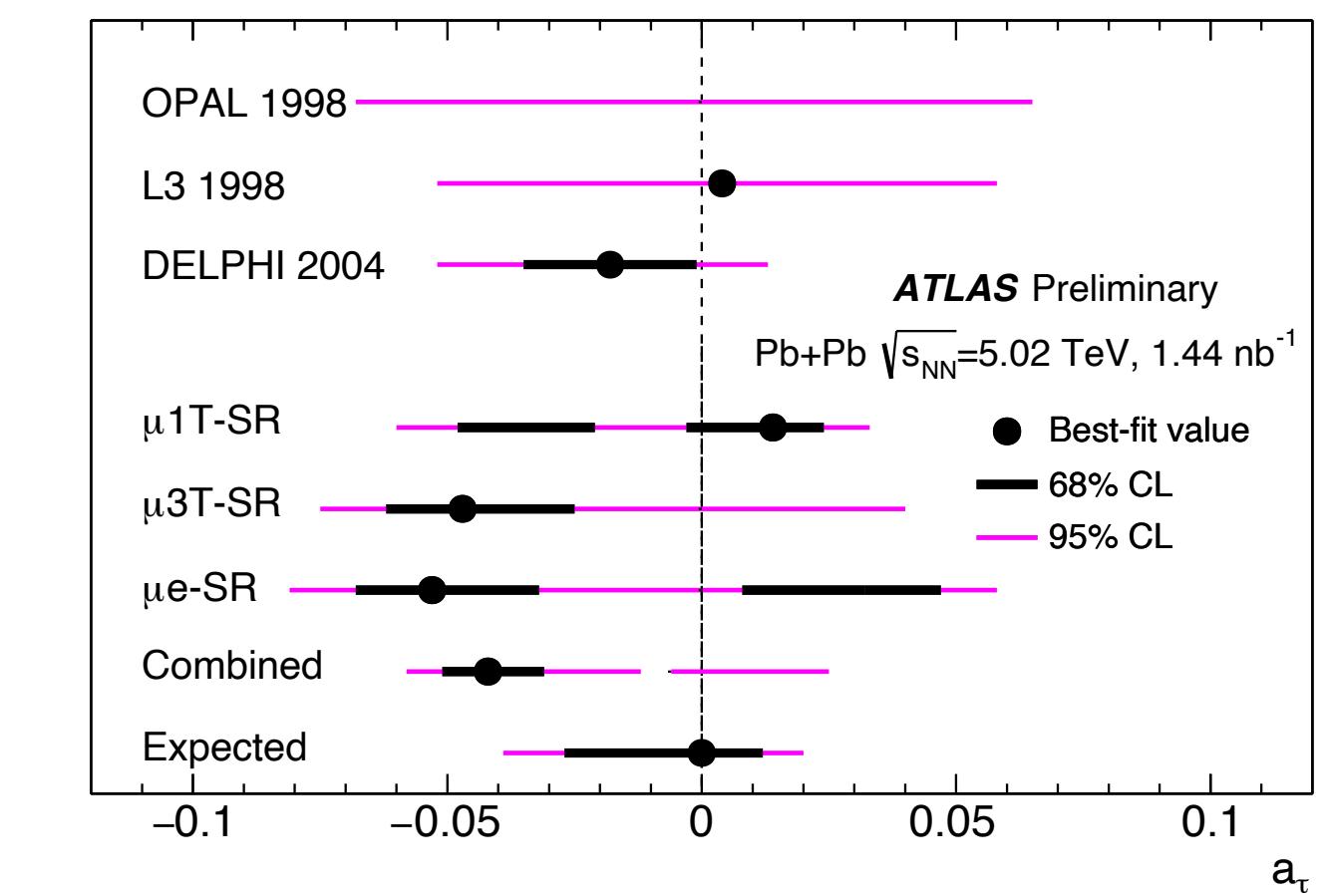
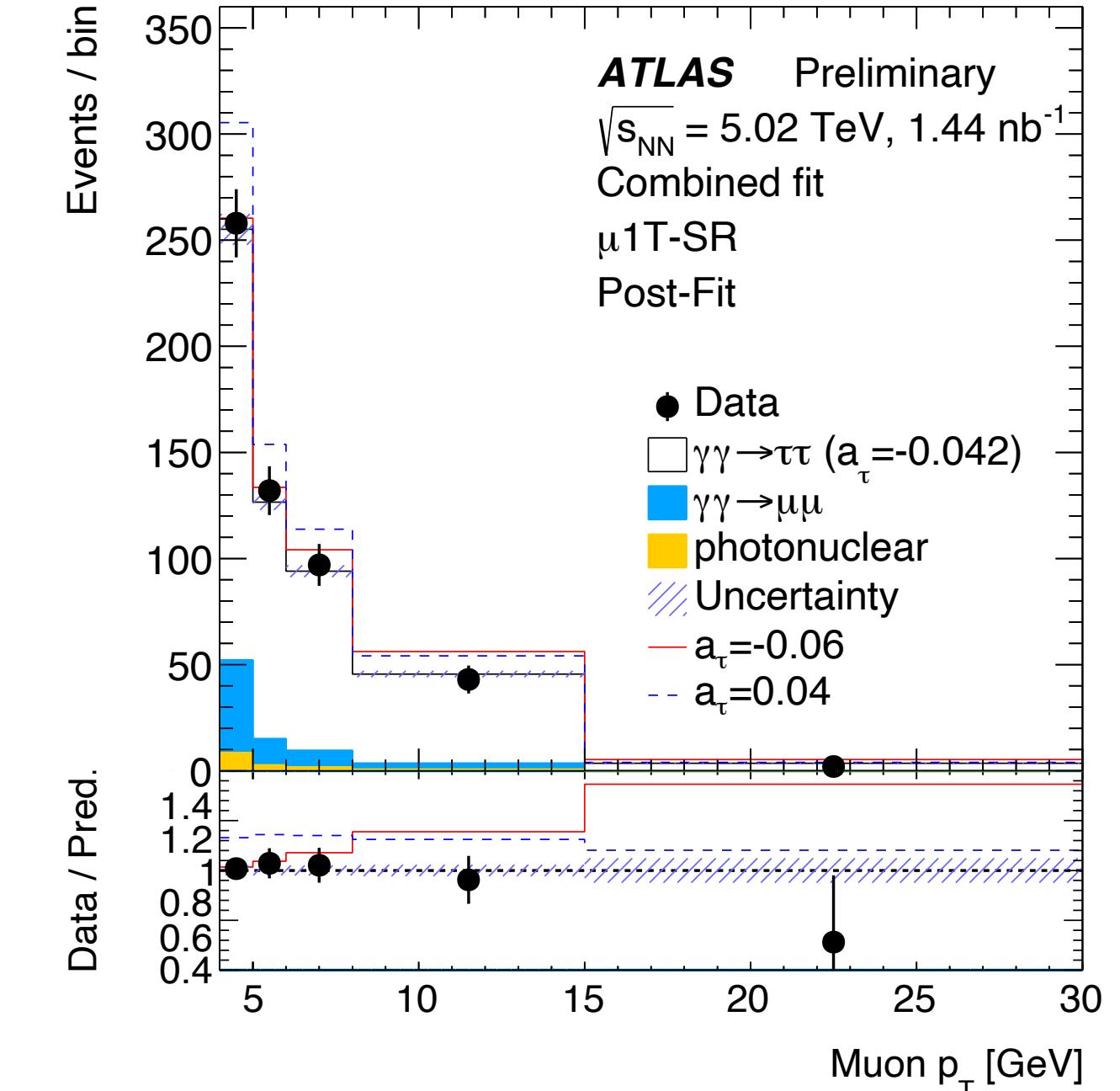
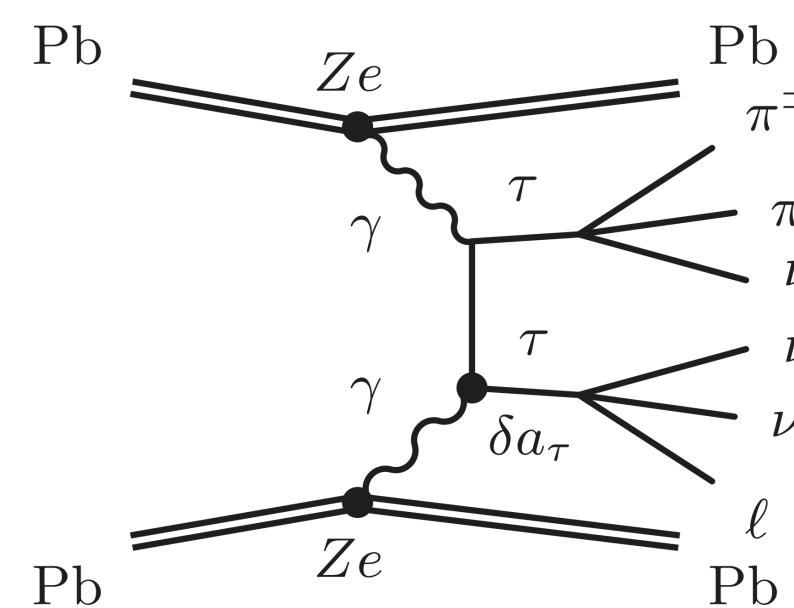
Tau magnetic moment and $\gamma\gamma \rightarrow \tau\tau$ Observation in PbPb



Run: 366268
Event: 3305670439
2018-11-18 16:09:33 CEST



Observation of $\gamma\gamma \rightarrow \tau\tau$ in Pb-Pb collisions and constraint on tau anomalous magnetic moment



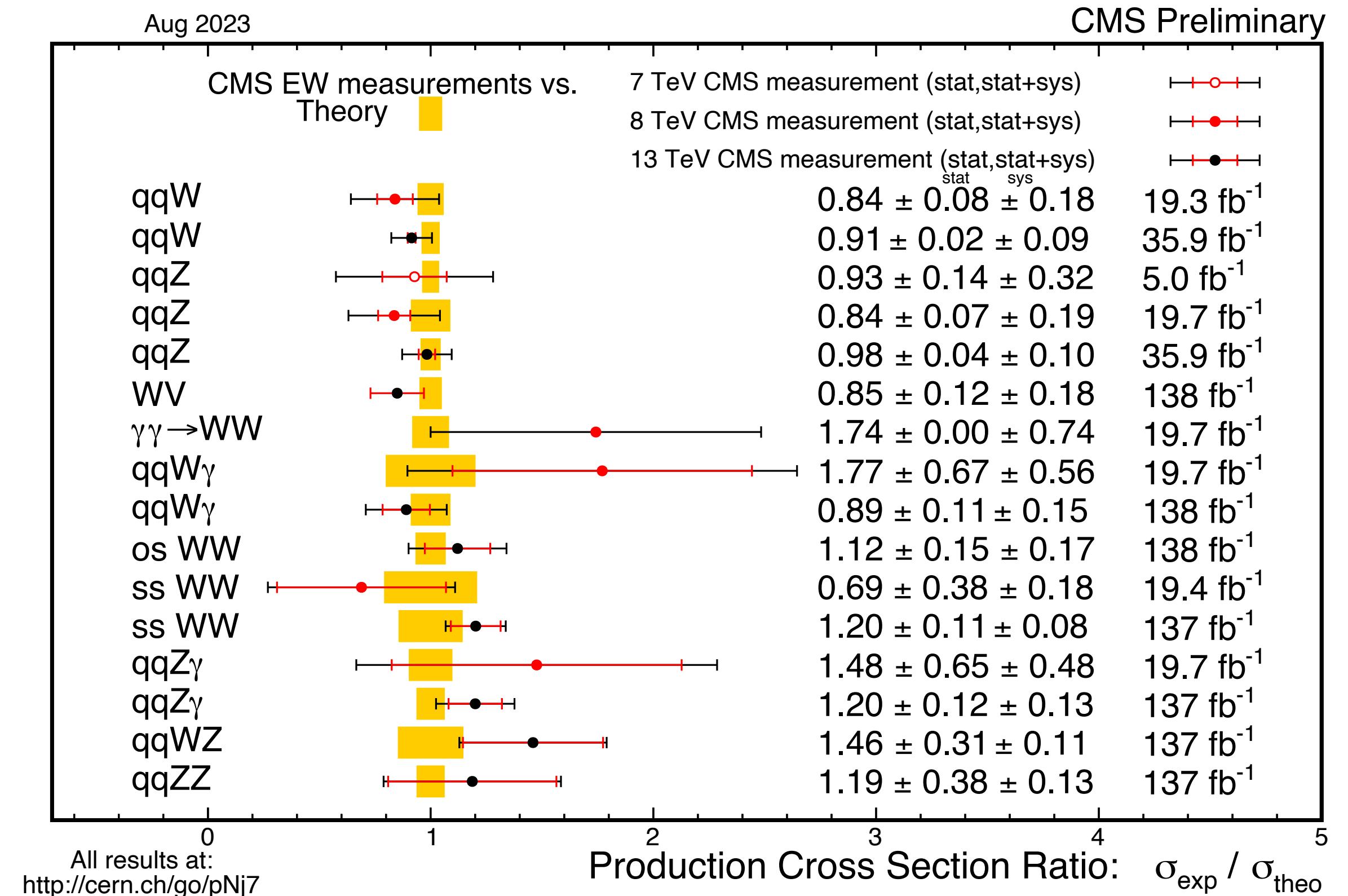
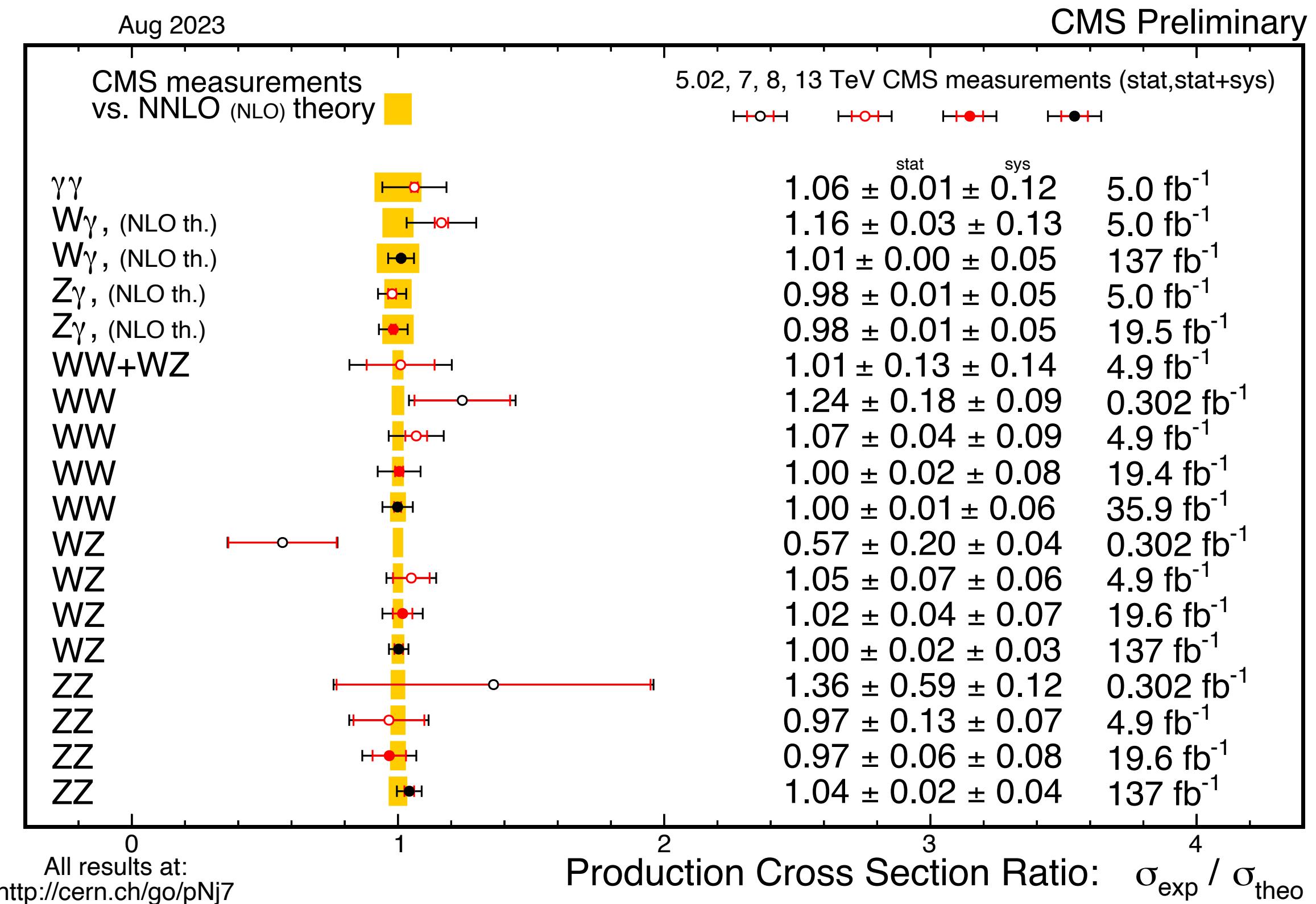
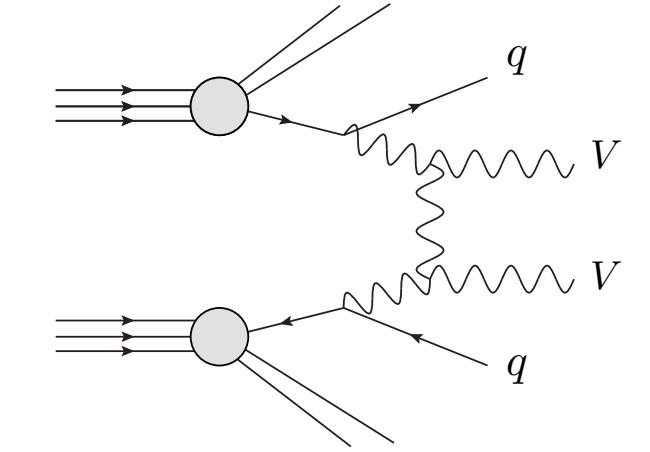
More di-boson measurements at the LHC

26

Large number of diboson processes measured in QCD and EW production which are key for to probe the electroweak Sector of the Standard Model.

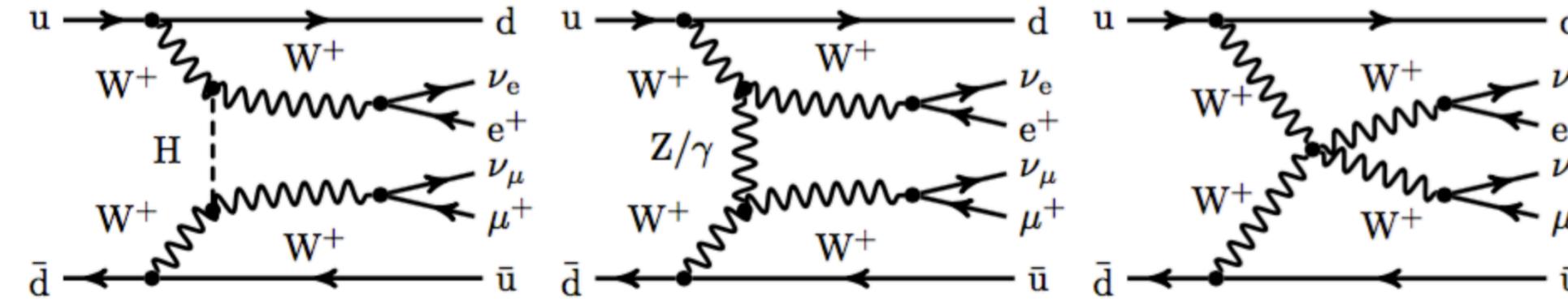
This will be further covered tomorrow when discussing Higgs physics.

VBS diboson production ($VVjj$)



EW Vector Boson Scattering

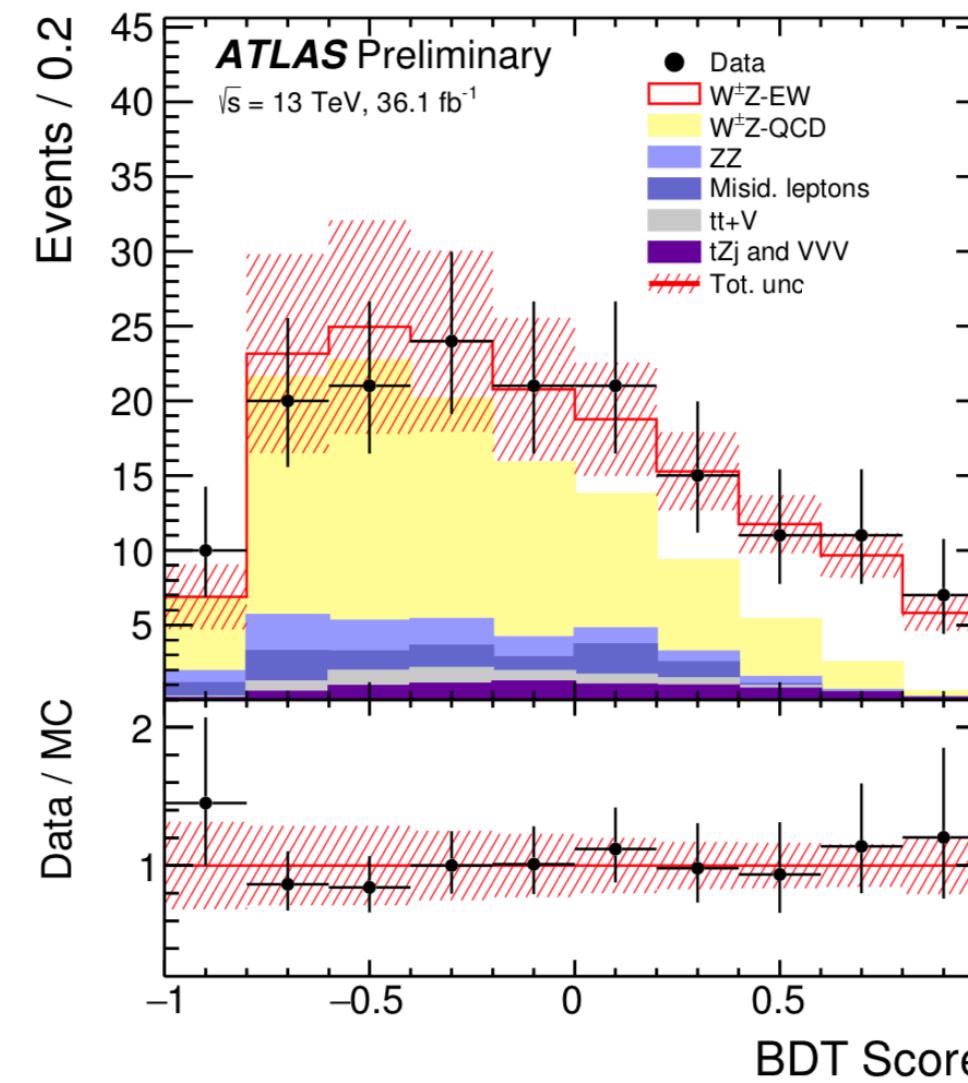
27



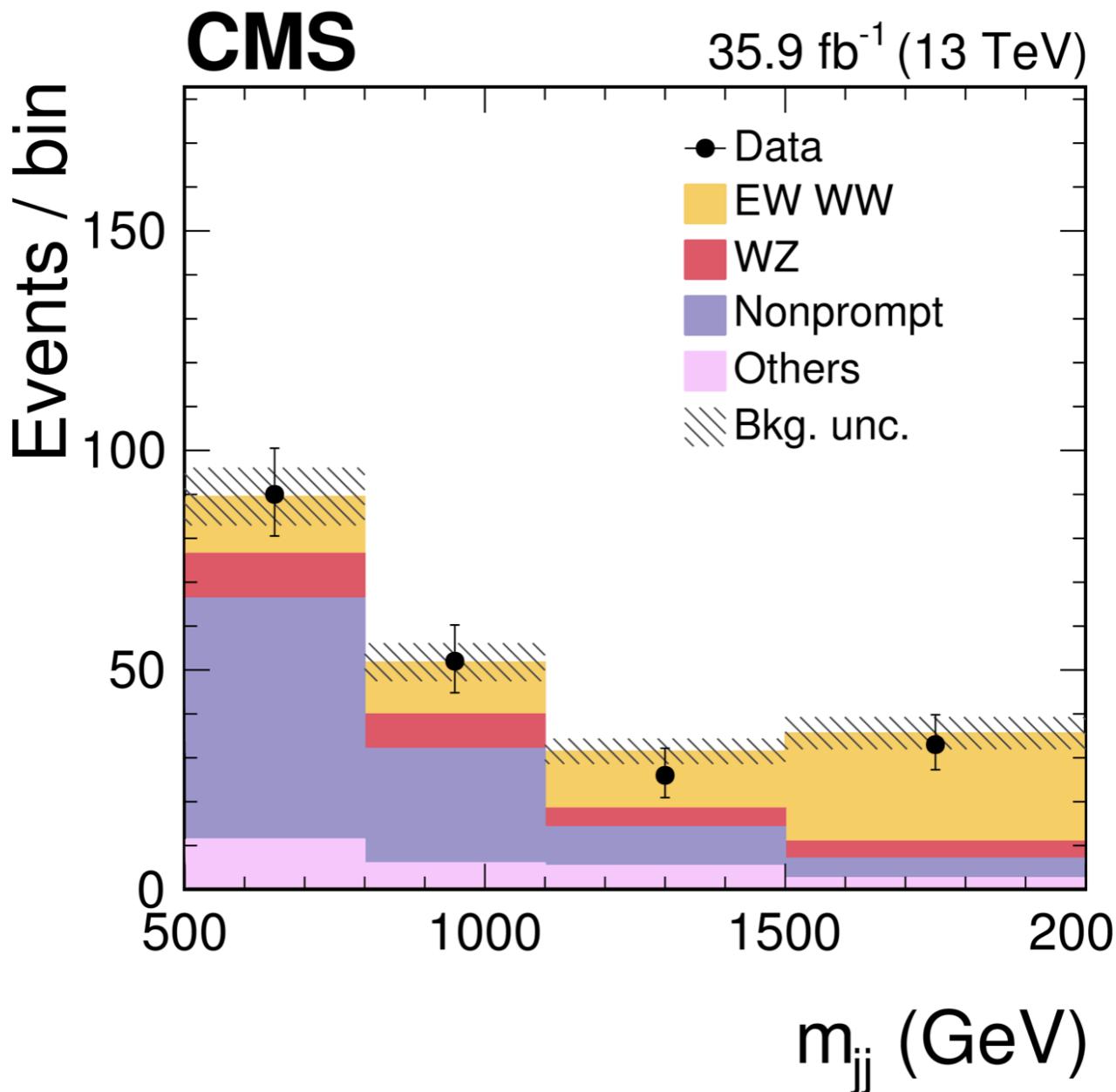
EW Vector Boson Scattering process

Unambiguously observed by both ATLAS and CMS (at more than 5σ) in the Same sign WW mode. Evidences in the WZ mode.

WZ 5.6σ (3.3σ)



WW 5.5σ (5.7σ)

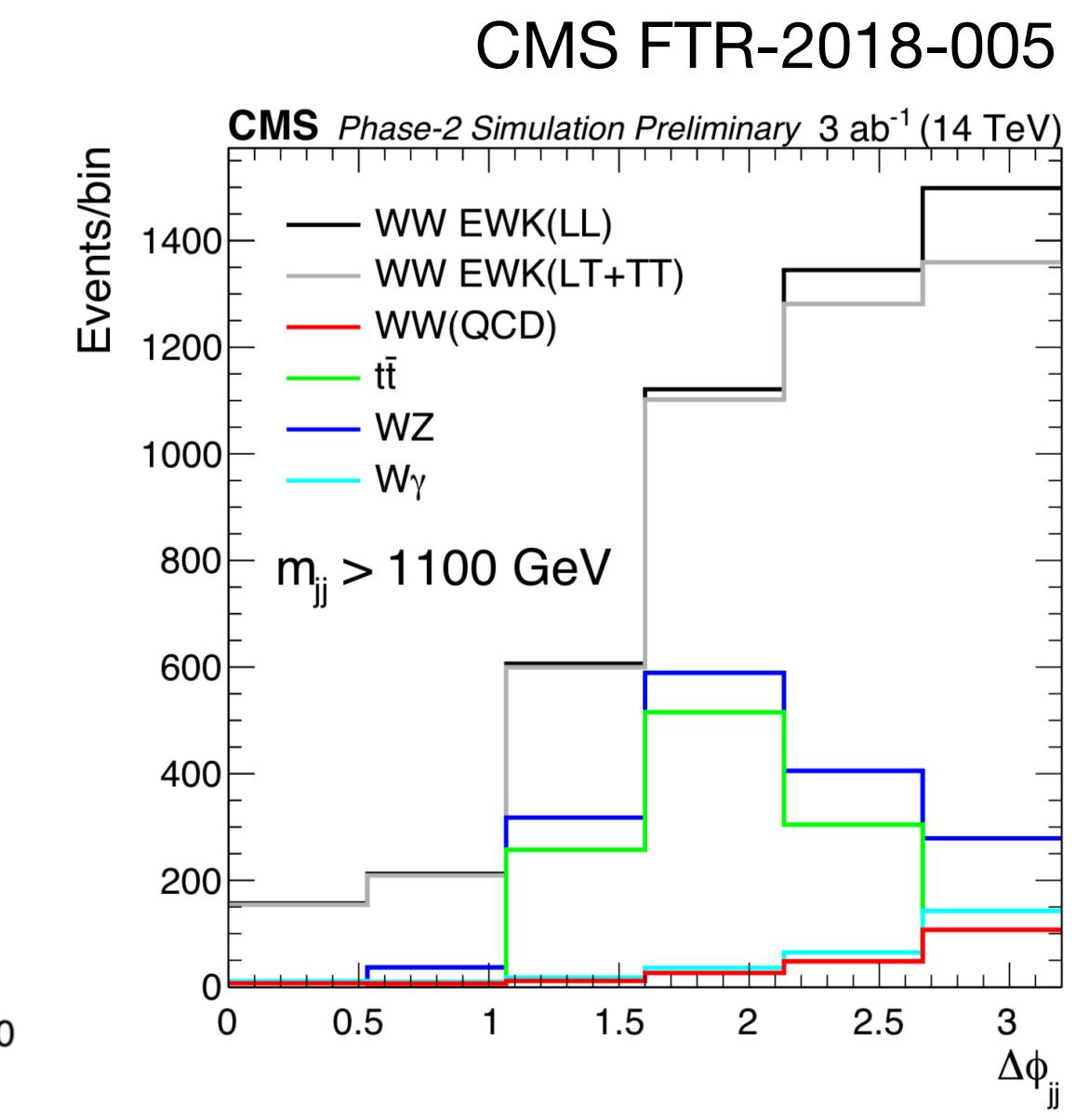
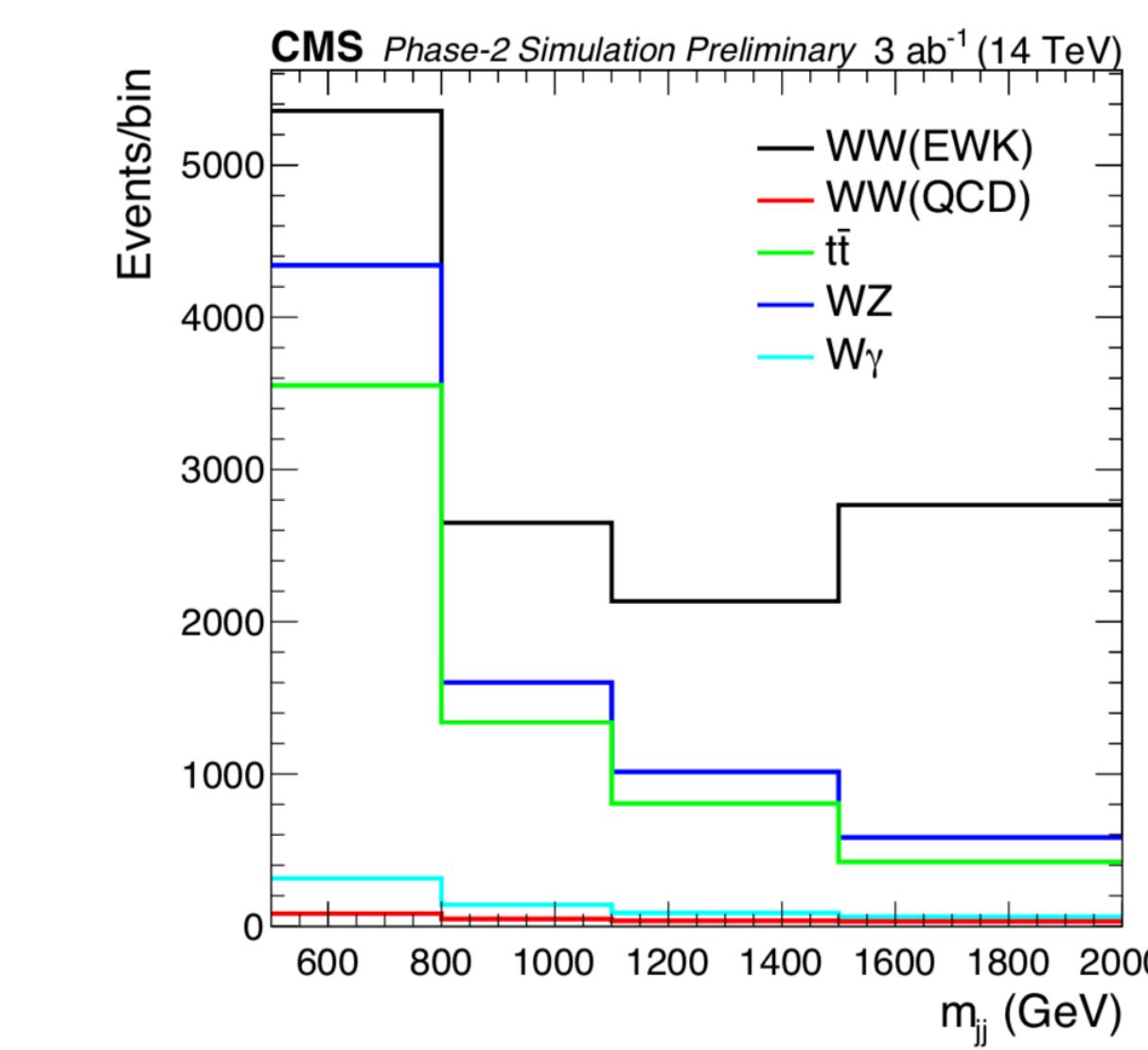


Longitudinal-Longitudinal Scattering

Important additional check of the EWSB sector.

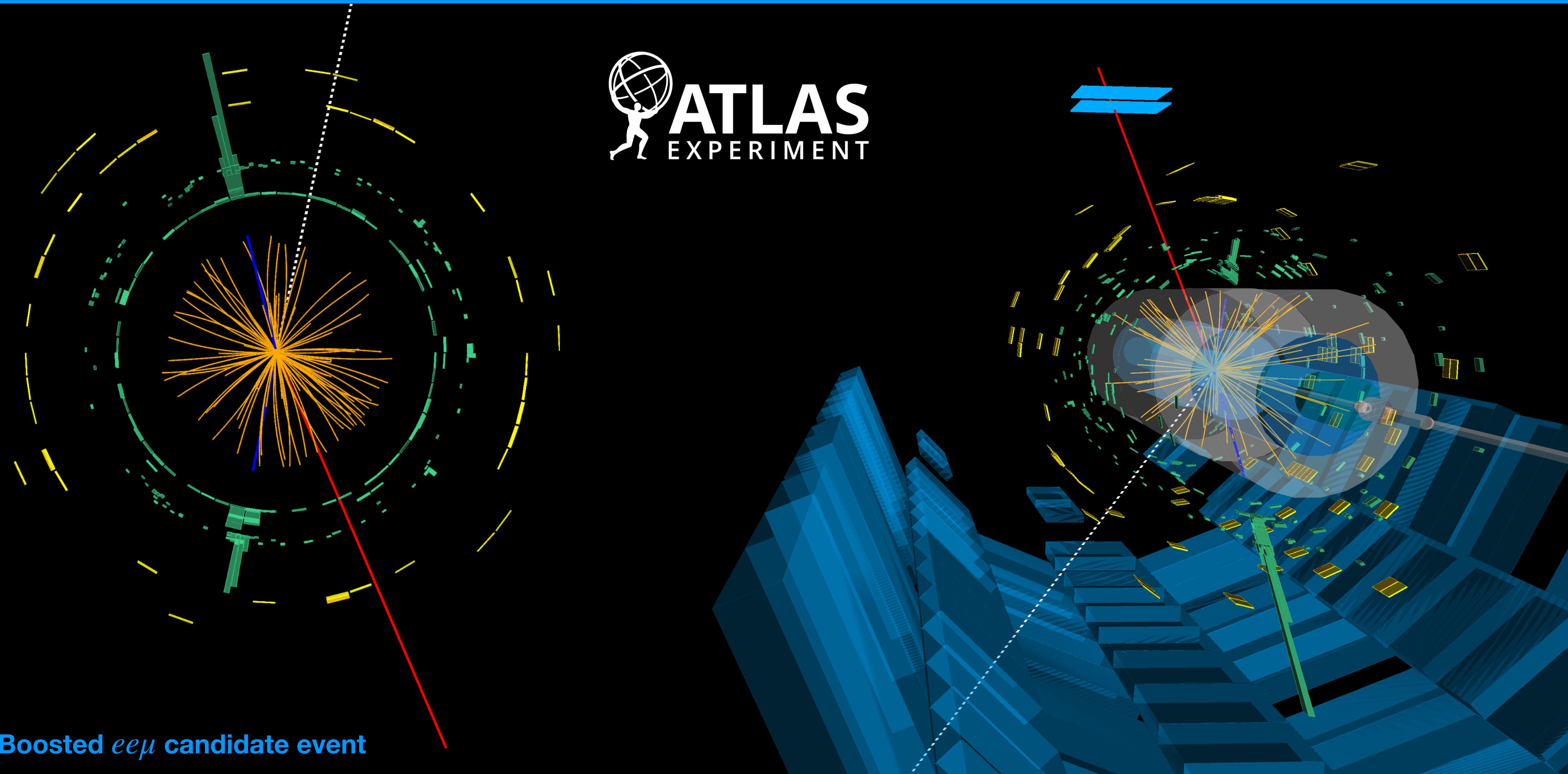
Suppressed from Higgs cancellation however with very large statistics and polarisation sensitive variables, there is sensitivity to SM LL signal almost 3σ for CMS alone.

With ATLAS and more channels WZ and ZZ well above 3σ



Tri-boson WWW Observation!

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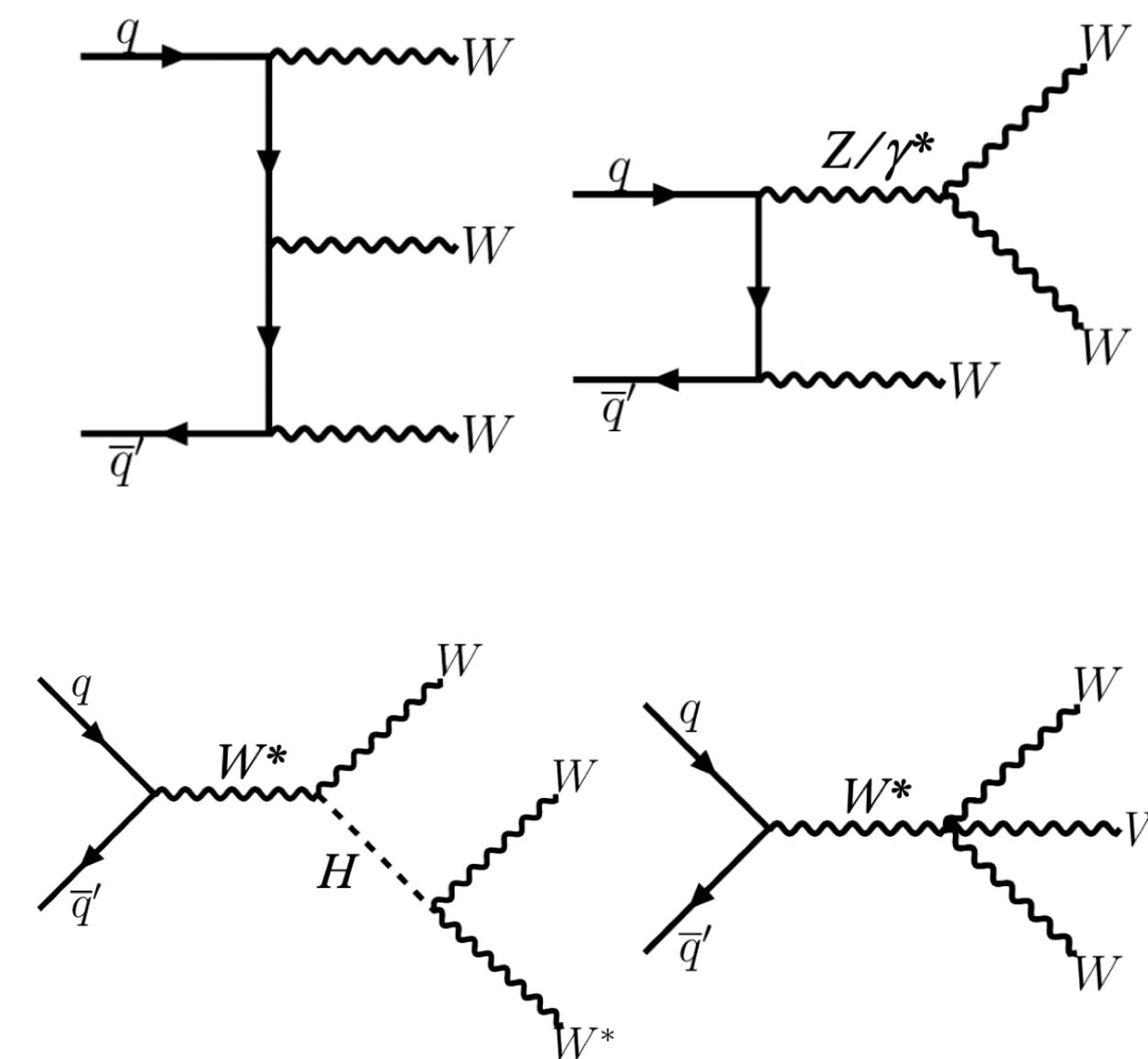


Triboson $W^\pm W^\mp W^\mp$ observation

29

Search for three W bosons production

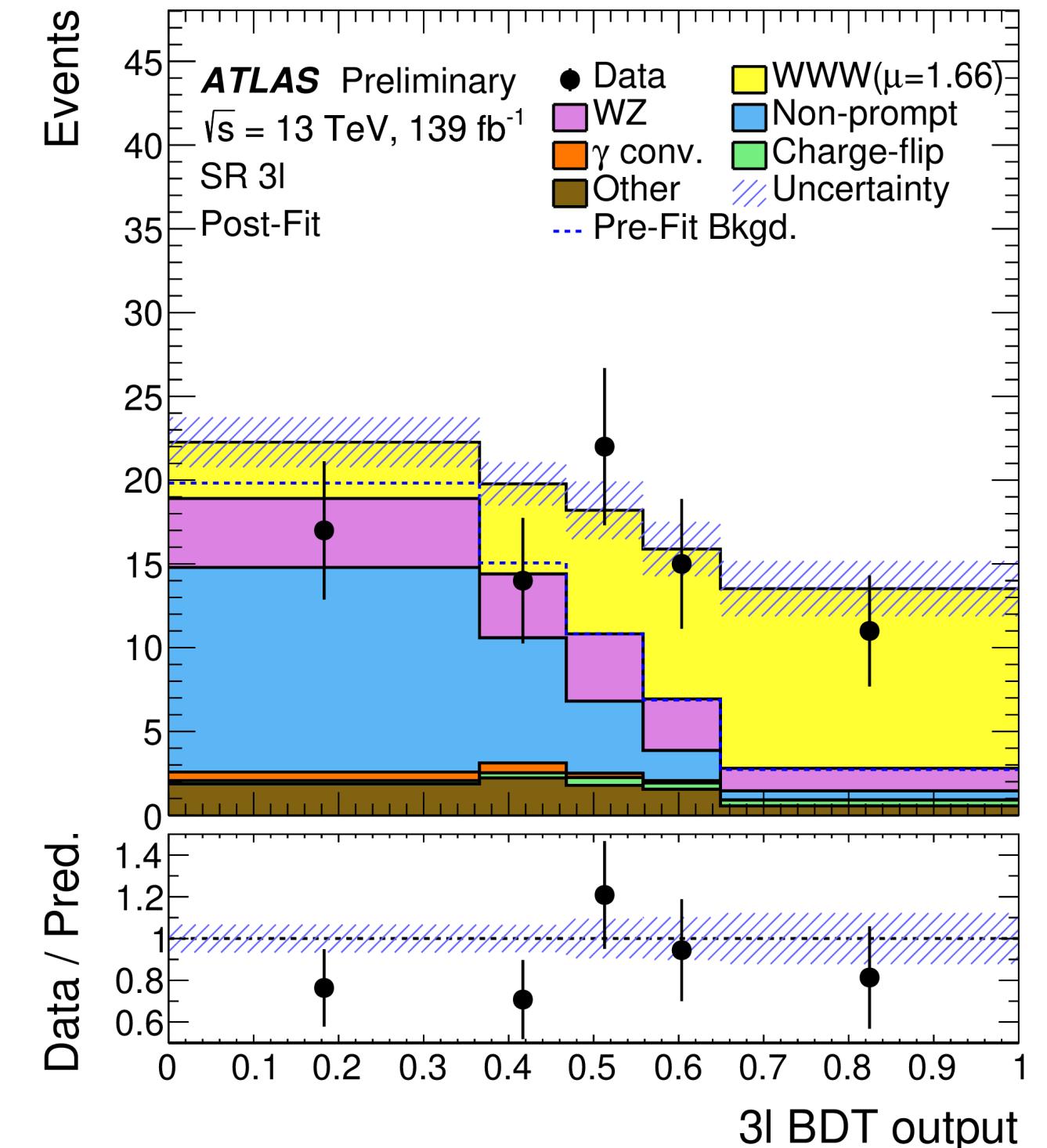
Last year shown observation of four top-quark production (see [talk](#)!)



First observation of $W^\pm W^\mp W^\mp$ at 8.2σ (5.4σ expected)!

Measured cross section:

$$\sigma(pp \rightarrow WWW) = 820 \pm 100 \text{ (stat.)} \pm 80 \text{ (syst.) fb}$$



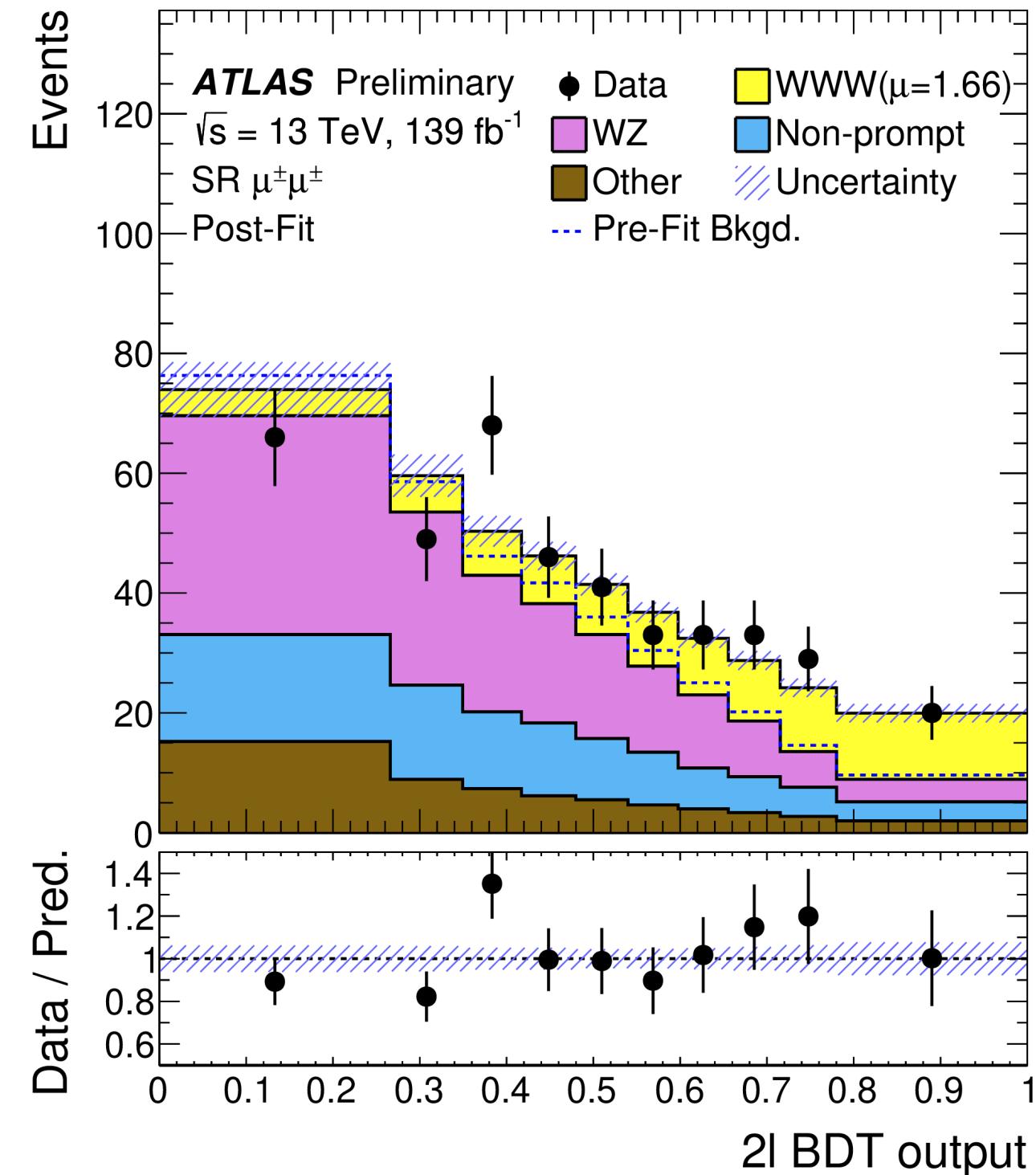
Same sign 2-lepton channel

$$\ell^\pm \nu \ell^\pm \nu jj$$

Predictions: $pp \rightarrow W^+ W^- W^-$

$$511 \pm 18 \text{ fb} \quad pp \rightarrow W^- W^+ W^+$$

$$pp \rightarrow WH \rightarrow WWW^* \quad 293^{+1}_{-2} \text{ (scale)}^{+6}_{-5} \text{ (PDF)} \pm 3 (\alpha_s) \text{ fb}$$



3-lepton channel

$$\ell^\pm \ell^\pm jj$$

$$76^{+4}_{-3} \text{ (scale)} \pm 2 \text{ (PDF) fb}$$

$$136^{+6}_{-5} \text{ (scale)} \pm 4 \text{ (PDF) fb}$$

Compatibility 2.6σ

Two recent Tri-Boson Observations!

30

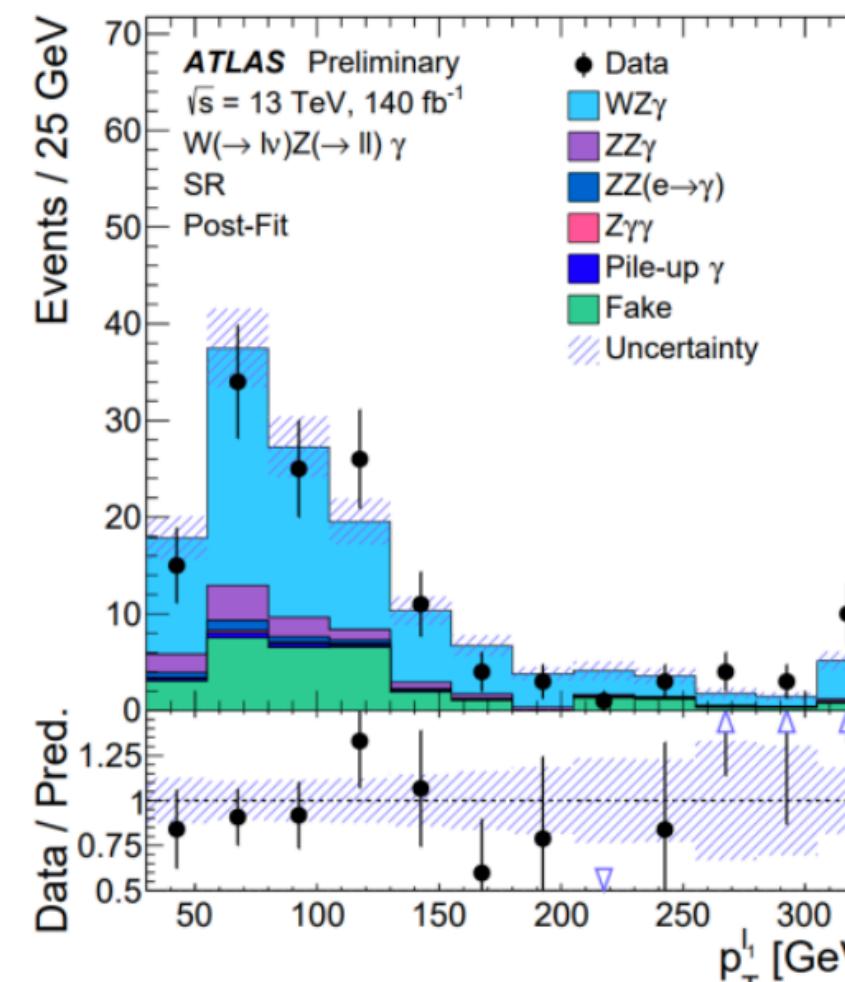
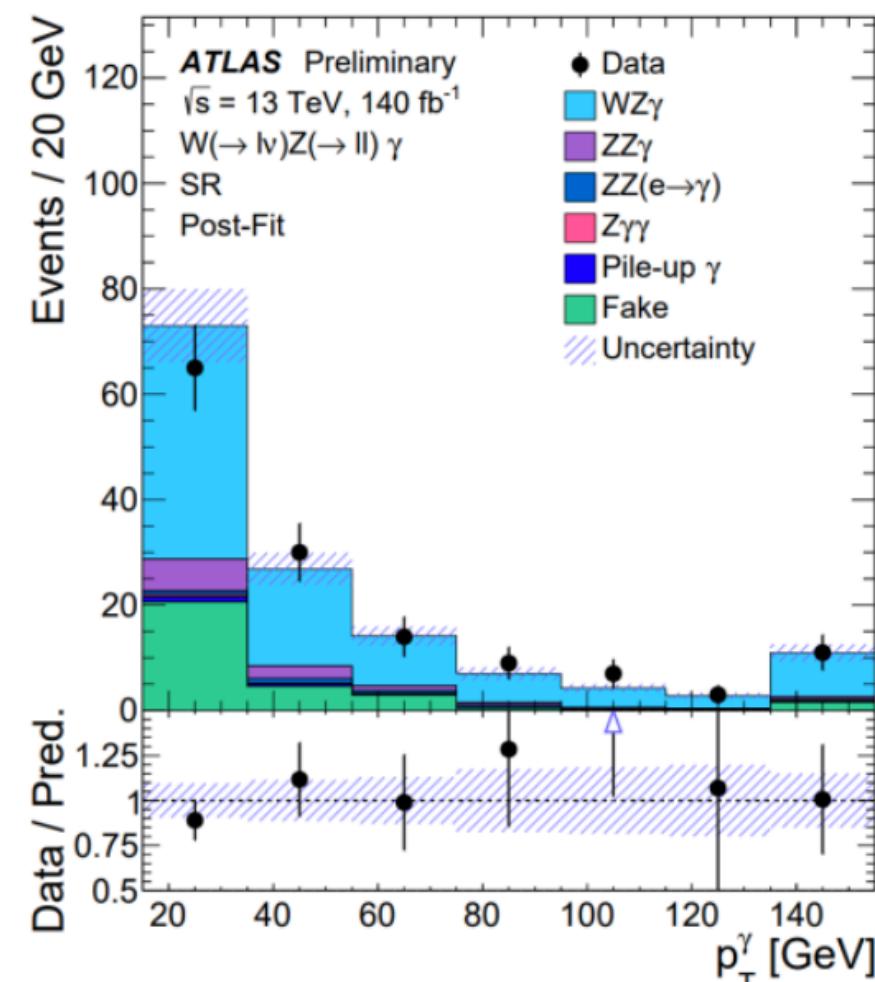
$WZ\gamma$ observation

Simultaneous fit with $\mu_{ZZ\gamma}, \mu_{ZZ}$

$WZ\gamma$ observed with 6.3σ

$$\sigma_{WZ\gamma} = 2.01 \pm 0.30 \text{ (stat.)} \pm 0.16 \text{ (syst.) fb}$$

Process	SR	$ZZ\gamma$ CR	$ZZ(e \rightarrow \gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e \rightarrow \gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Fake background	30 ± 6	-	-
Pile-up γ	1.9 ± 0.7	-	-
Total predicted	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33



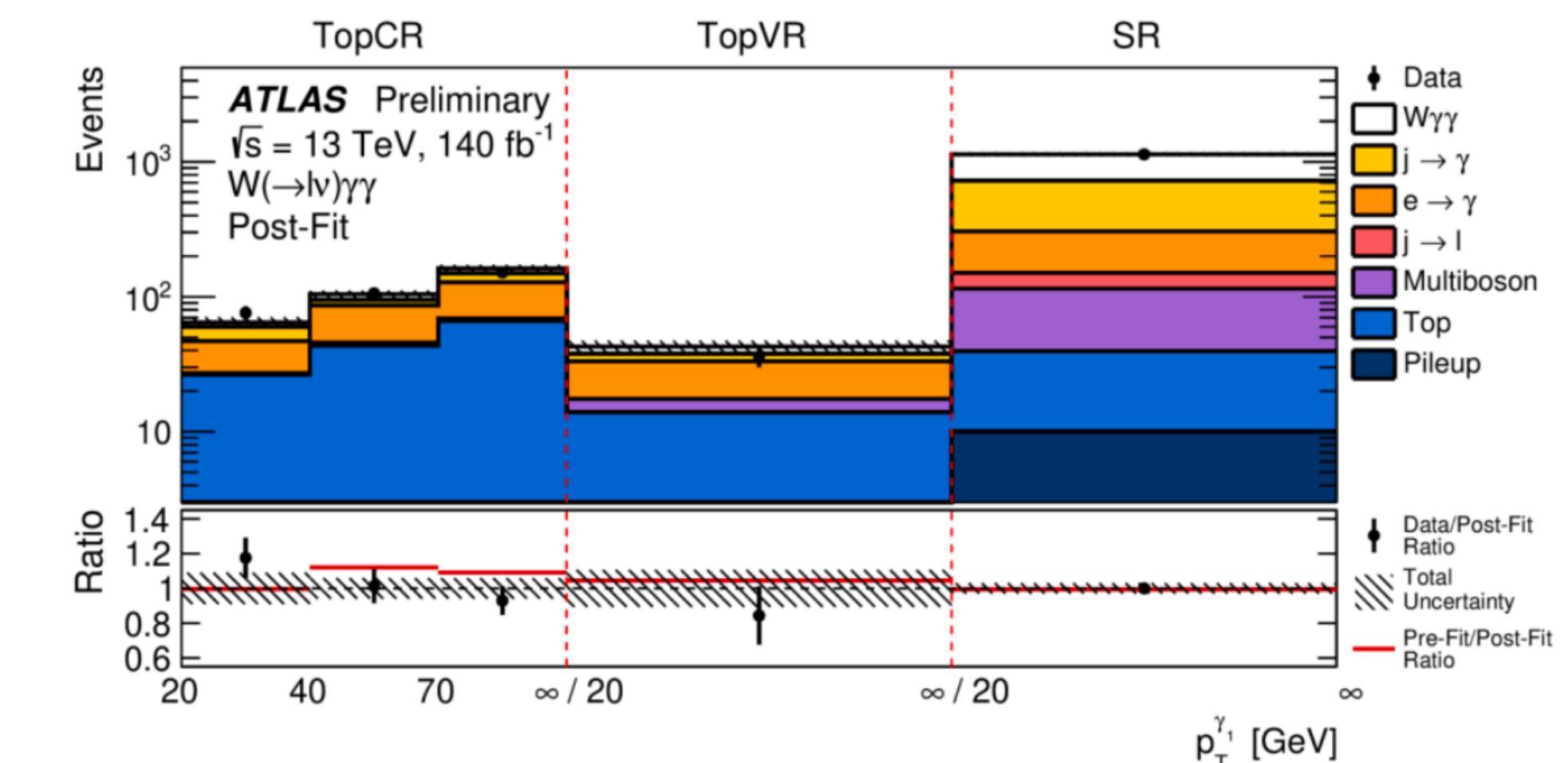
$W\gamma\gamma$ observation

data-driven Fake estimated in control regions

$WZ\gamma$ observed with 5.6σ

$$\sigma_{fid} = 12.1^{+2.5}_{-2.2} \text{ fb}^{-1}$$

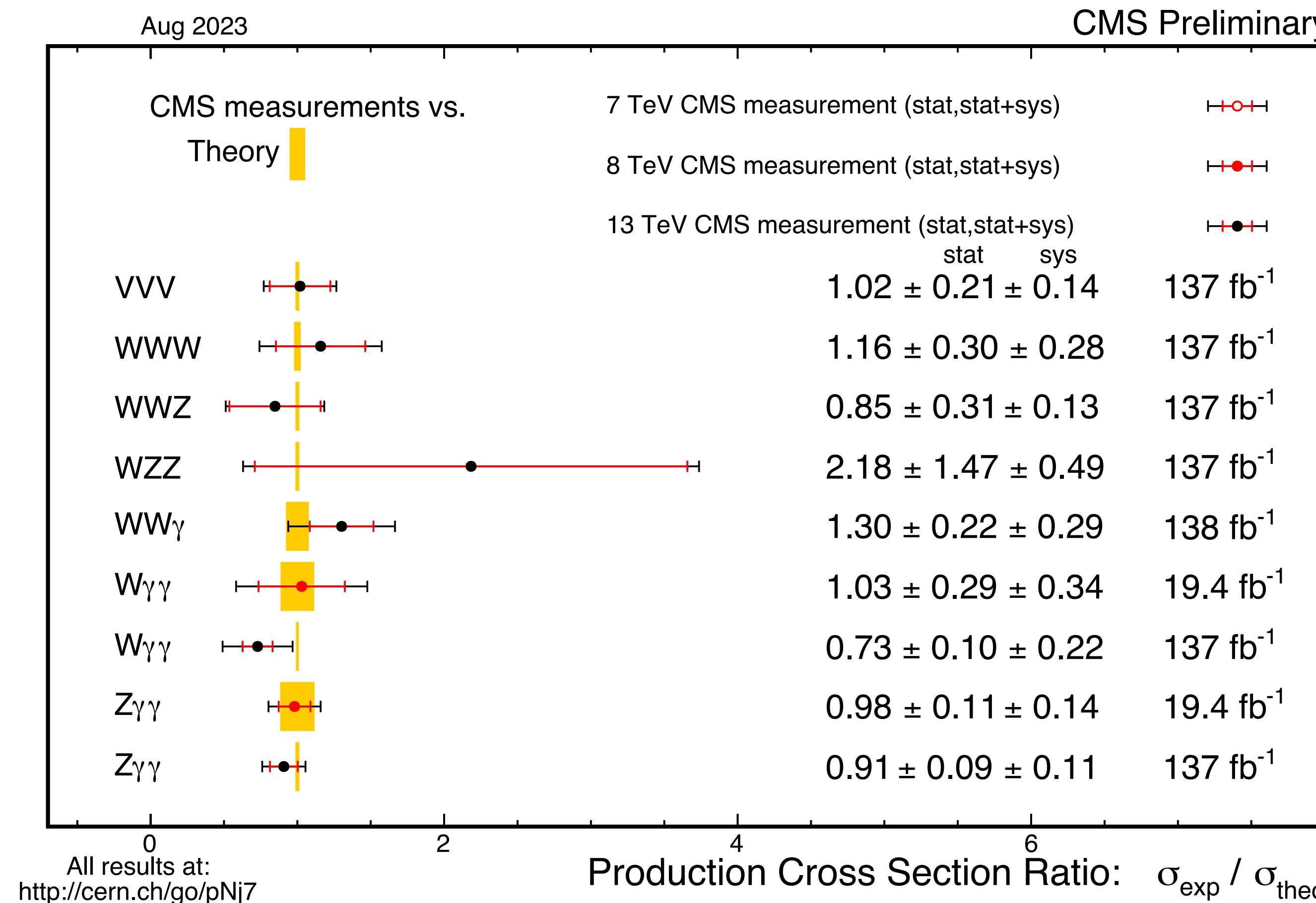
	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \rightarrow \gamma$	420 ± 50	42 ± 20
Misidentified $e \rightarrow \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \rightarrow \ell$	35 ± 10	-
Top ($t\bar{t}\gamma$, $tW\gamma$, $tq\gamma$)	30 ± 7	136 ± 32
Pileup	10 ± 5	-
Total	1136 ± 34	332 ± 18
Data	1136	333



Tri-boson Summary

31

Summary (for CMS) of tri-boson processes, with already large number of final states studied!

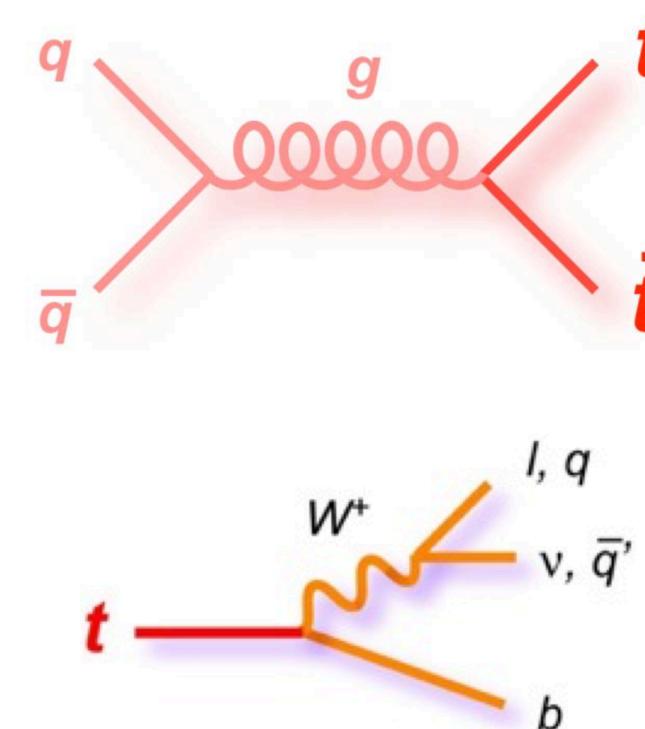


Top quark Production

Top pair production Cross Sections at the LHC

33

Top pair production is the main production mode at the LHC

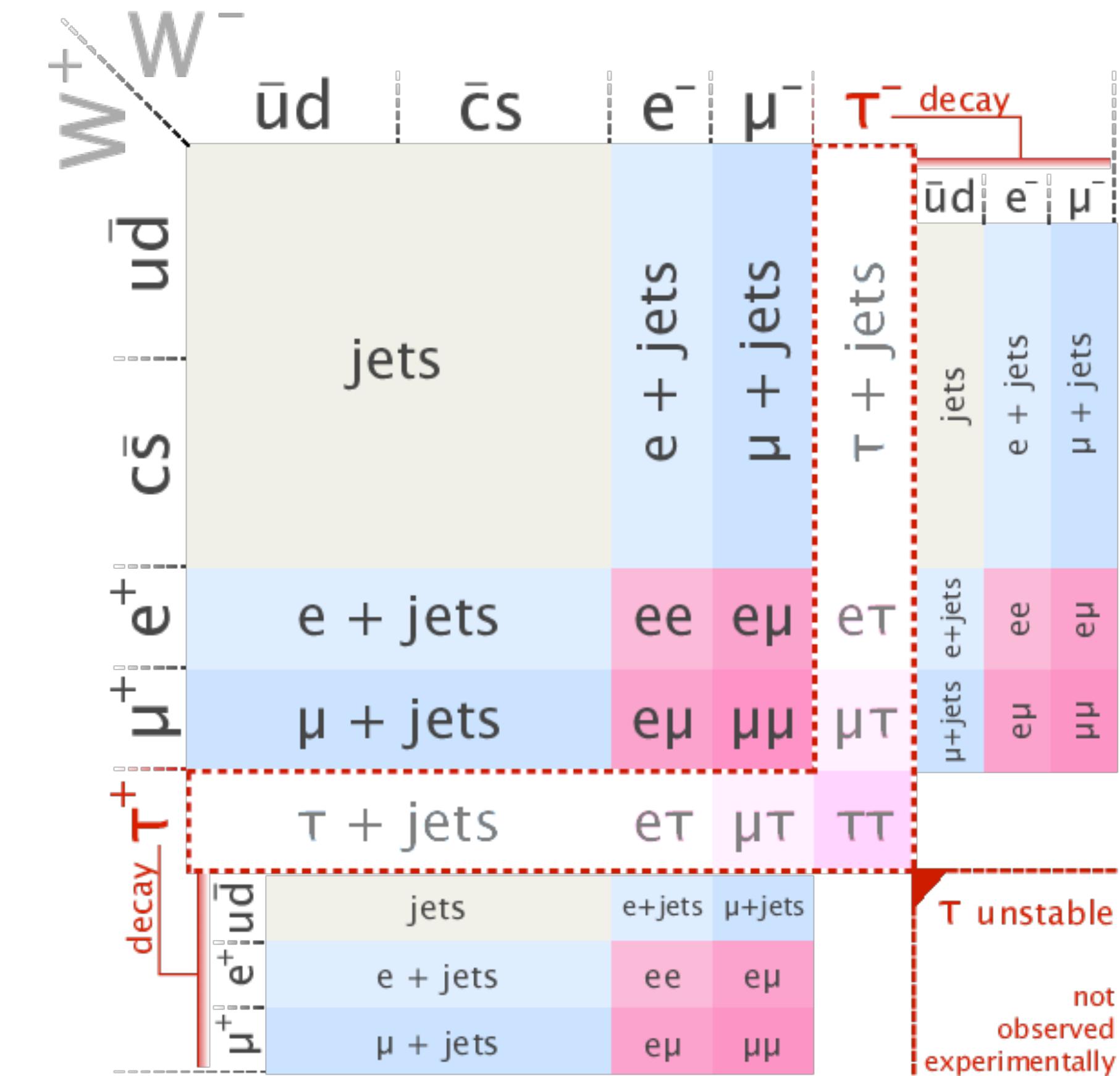


Each top quark decays mostly to a W and a b quark.

(Top pair production is a de-facto a higher order special di-boson process)

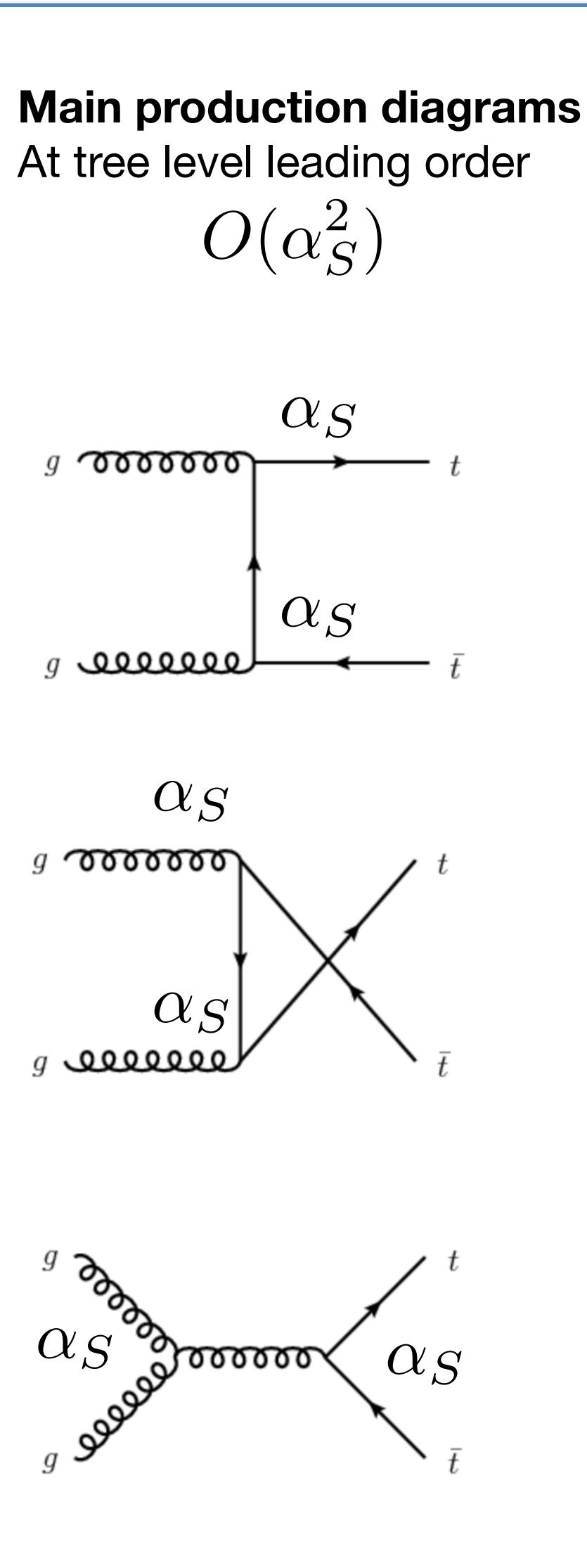
With possible decay modes of the W boson this gives rise to multitude of signatures (the most sensitive being the leptons-4jets)

$$\begin{aligned} Br(W \rightarrow \ell\nu) &= 10.9\% \\ Br(W \rightarrow \bar{u}\bar{d}, \bar{c}\bar{s}) &= 67.4\% \end{aligned}$$

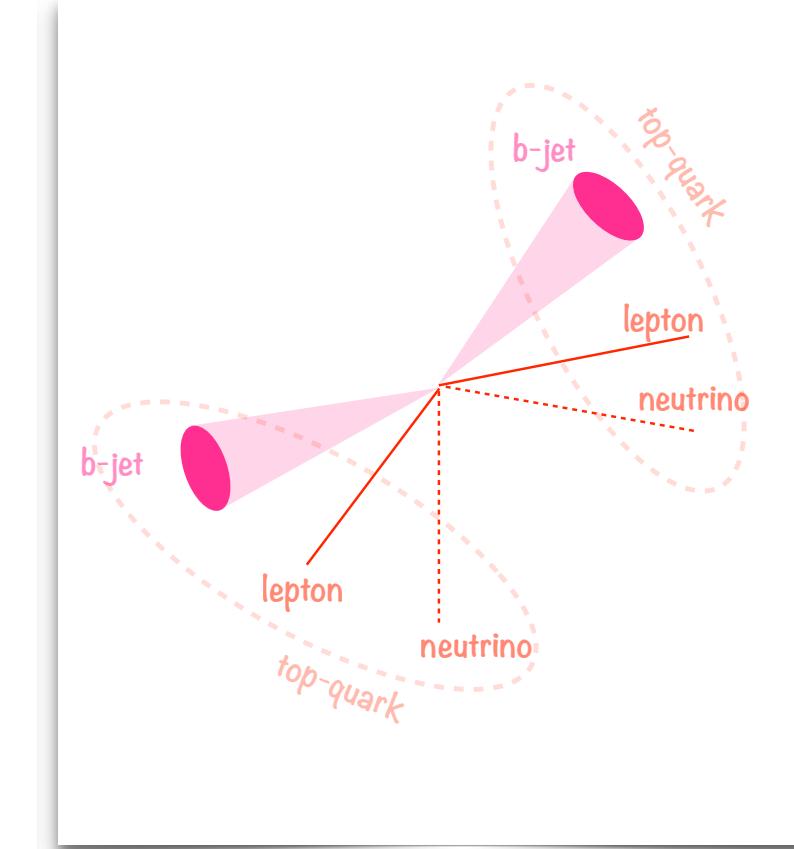
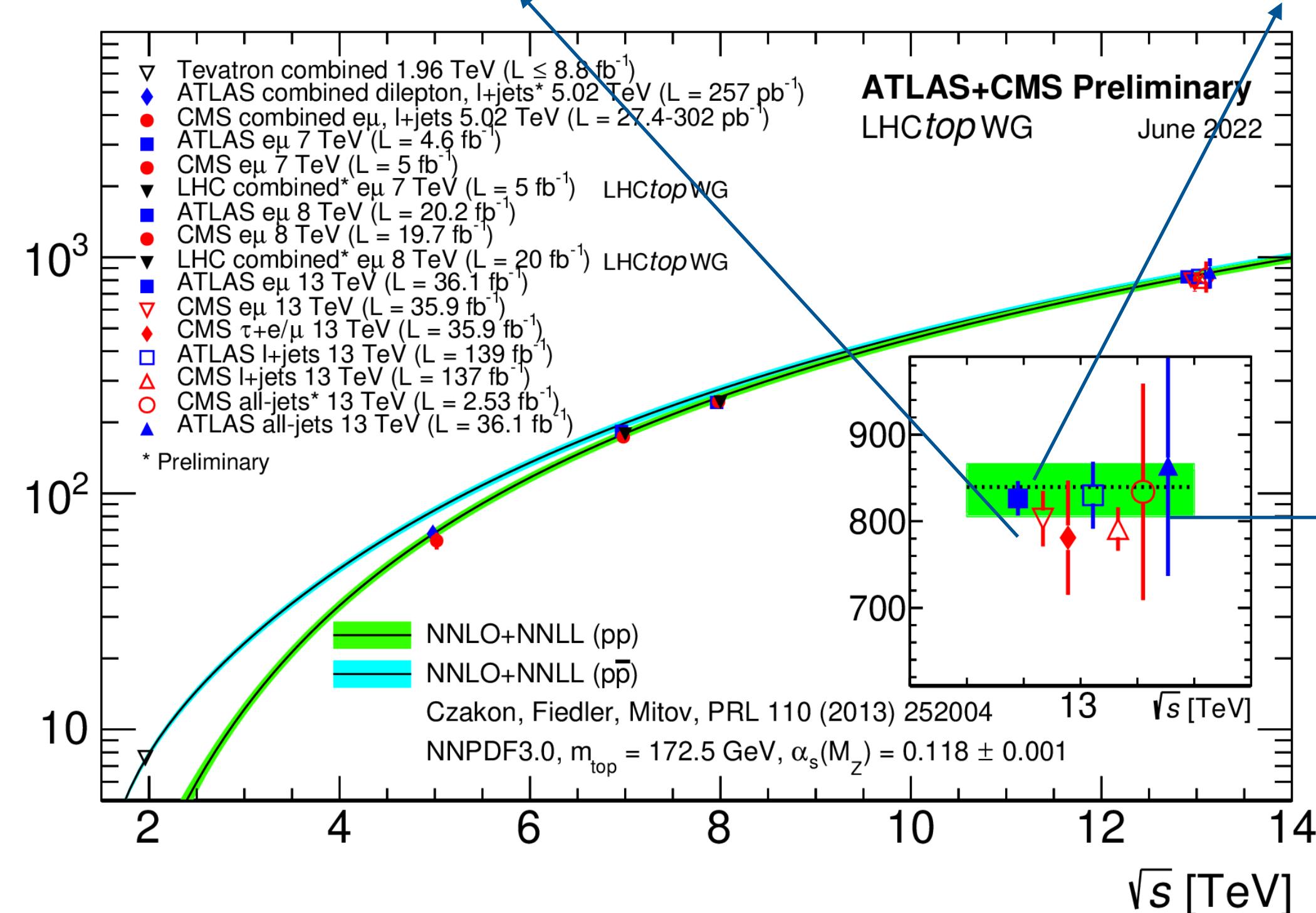


Top pair production Cross Sections at the LHC

34

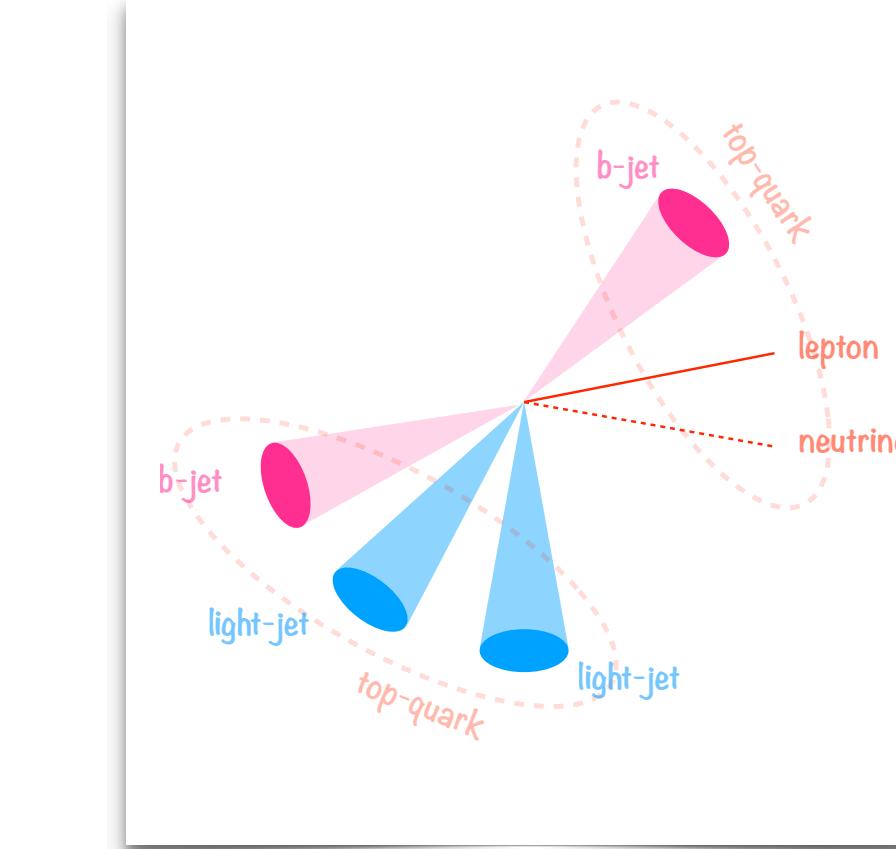


Inclusive $t\bar{t}$ cross section [pb]



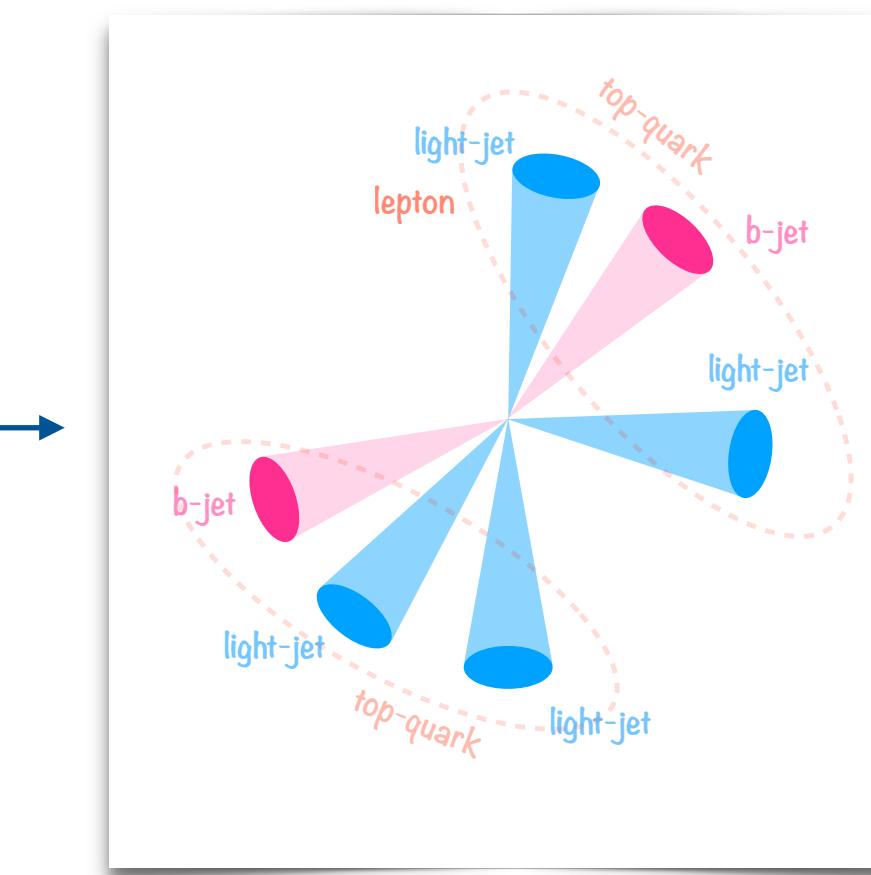
Di-lepton topology:

Precise determination of cross section in the different flavour electron-muon channel in particular. Excellent signal to background ratio. Lower stats (4%).



Semi-leptonic topology:

Best compromise between statistics (30%) and signal to background ratio.



Full hadronic topology:

Largest stats (50%) but larger multi-jet background and large combinatorial.

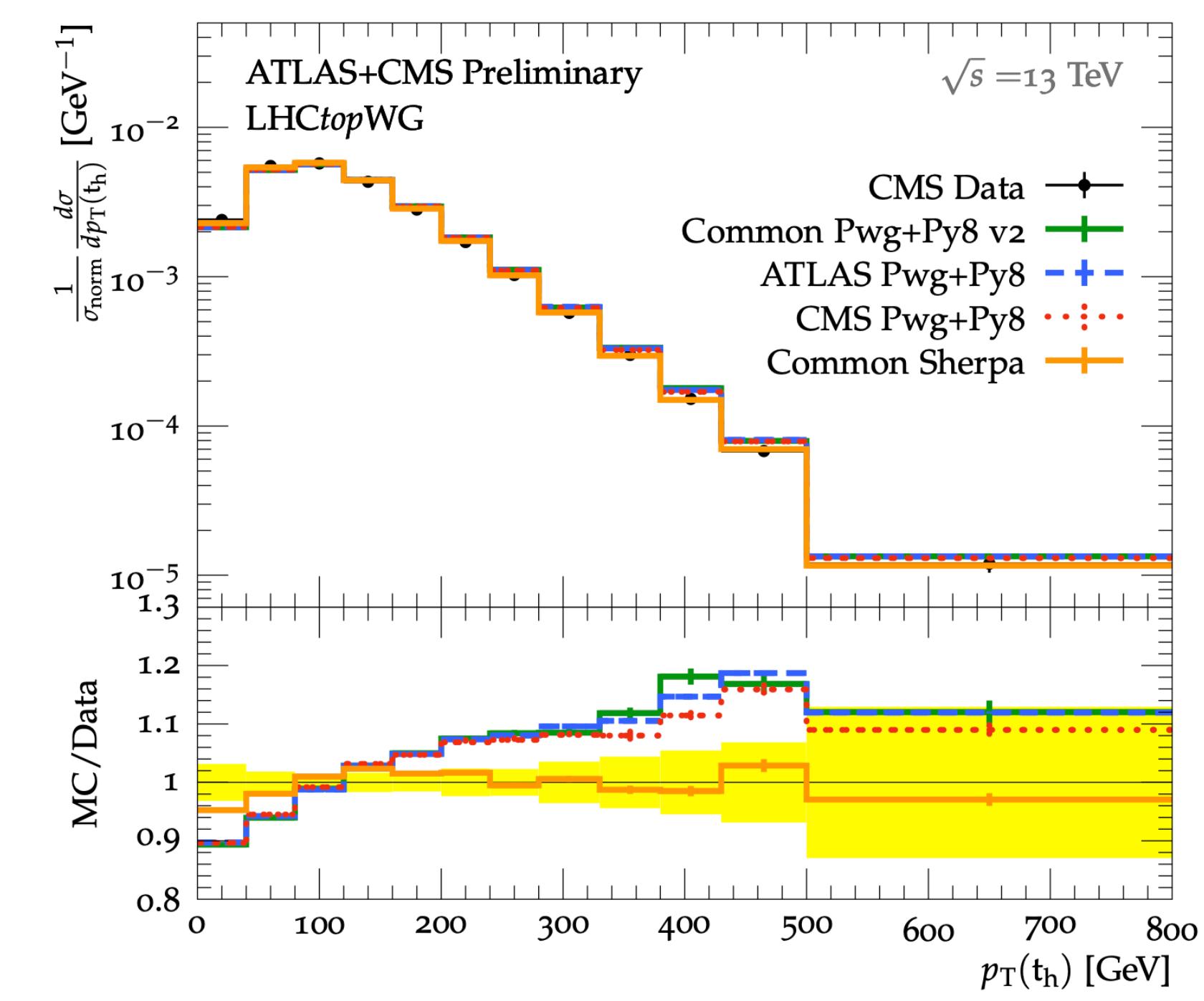
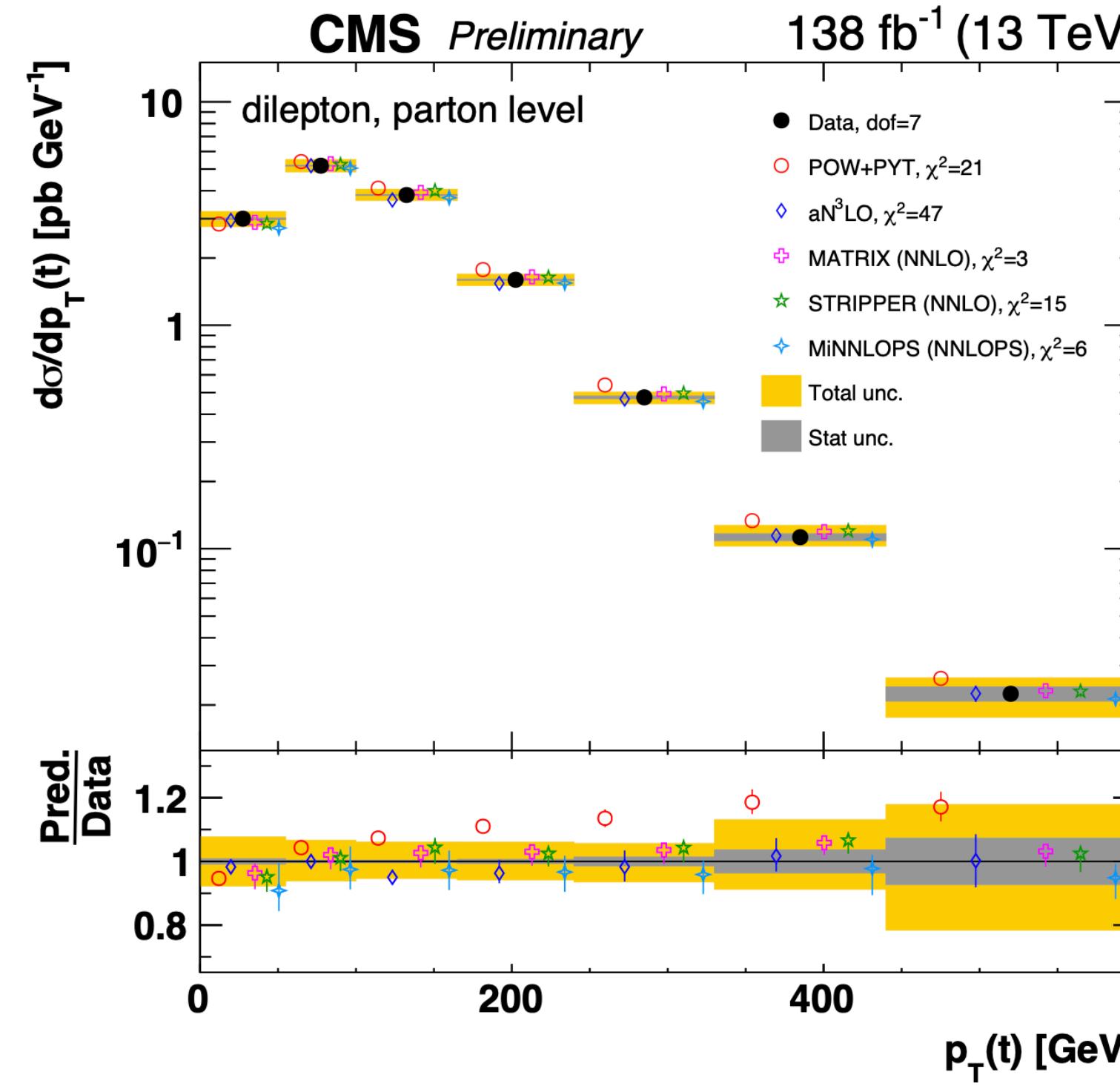
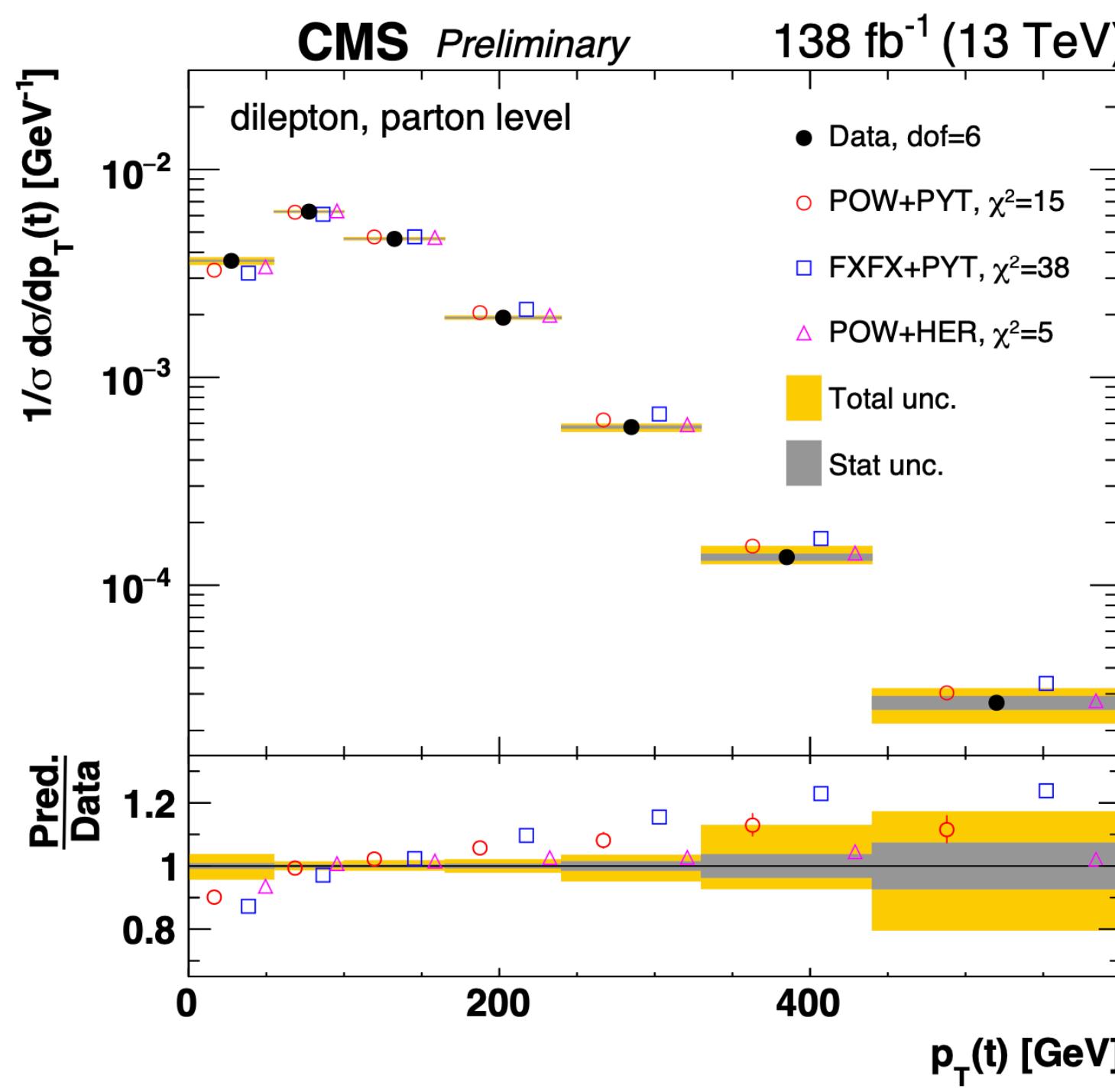
Top Modelling

35

Excerpts from recent top pair production differential cross section measurements:

“NLO Monte Carlo generally fail to describe a large fraction of the measured cross sections. The calculations predict the top quark and antiquark to have harder transverse momentum and more central rapidity distributions than observed in the data.”

“NNLO model provides a data description quality that is on average comparable but not better than that of the NLO MC models”.

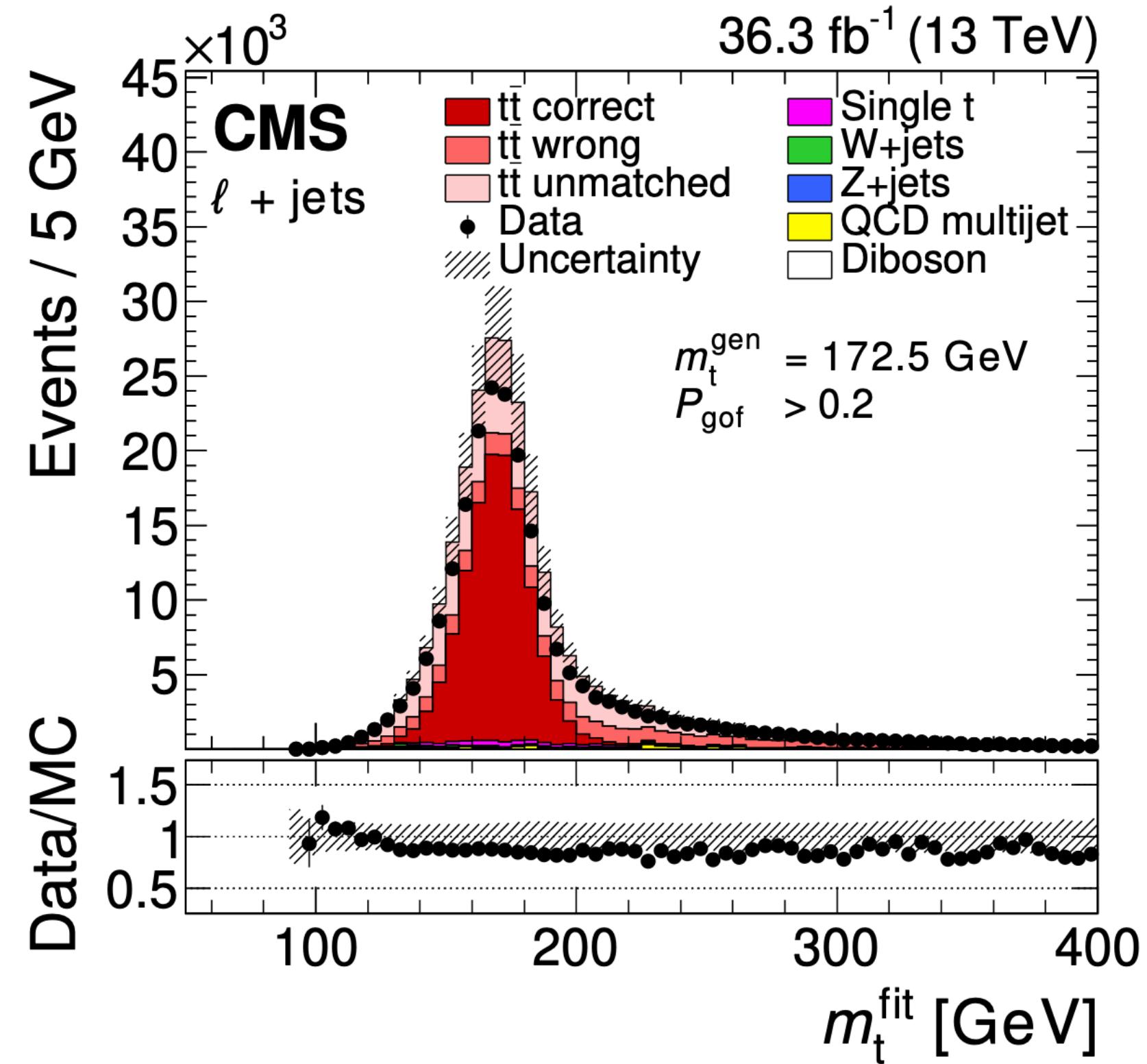


Common TH, ATLAS and CMS effort to address this modelling challenge

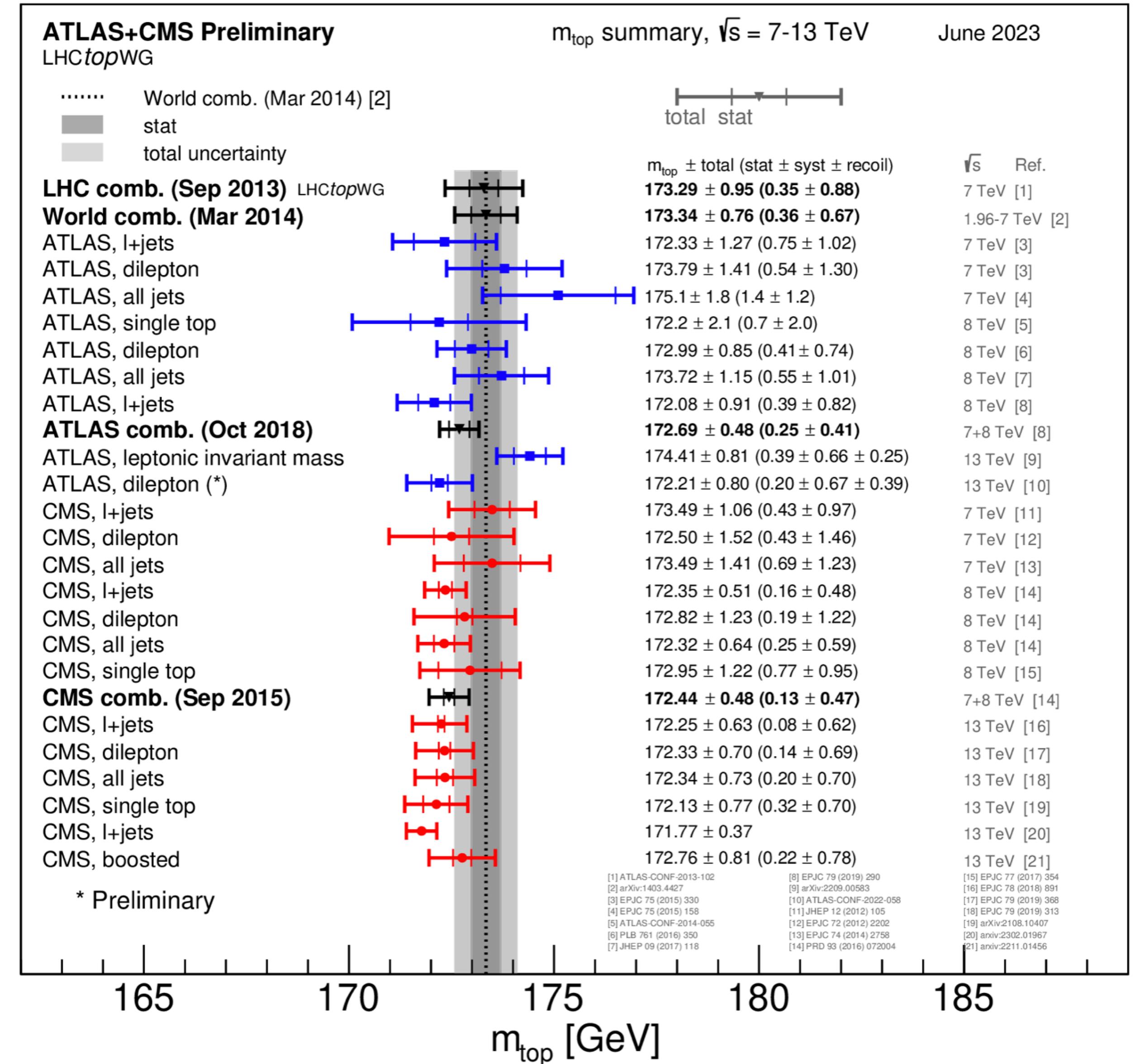
Direct Top Mass Measurements

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Most precise individual direct top mass measurement



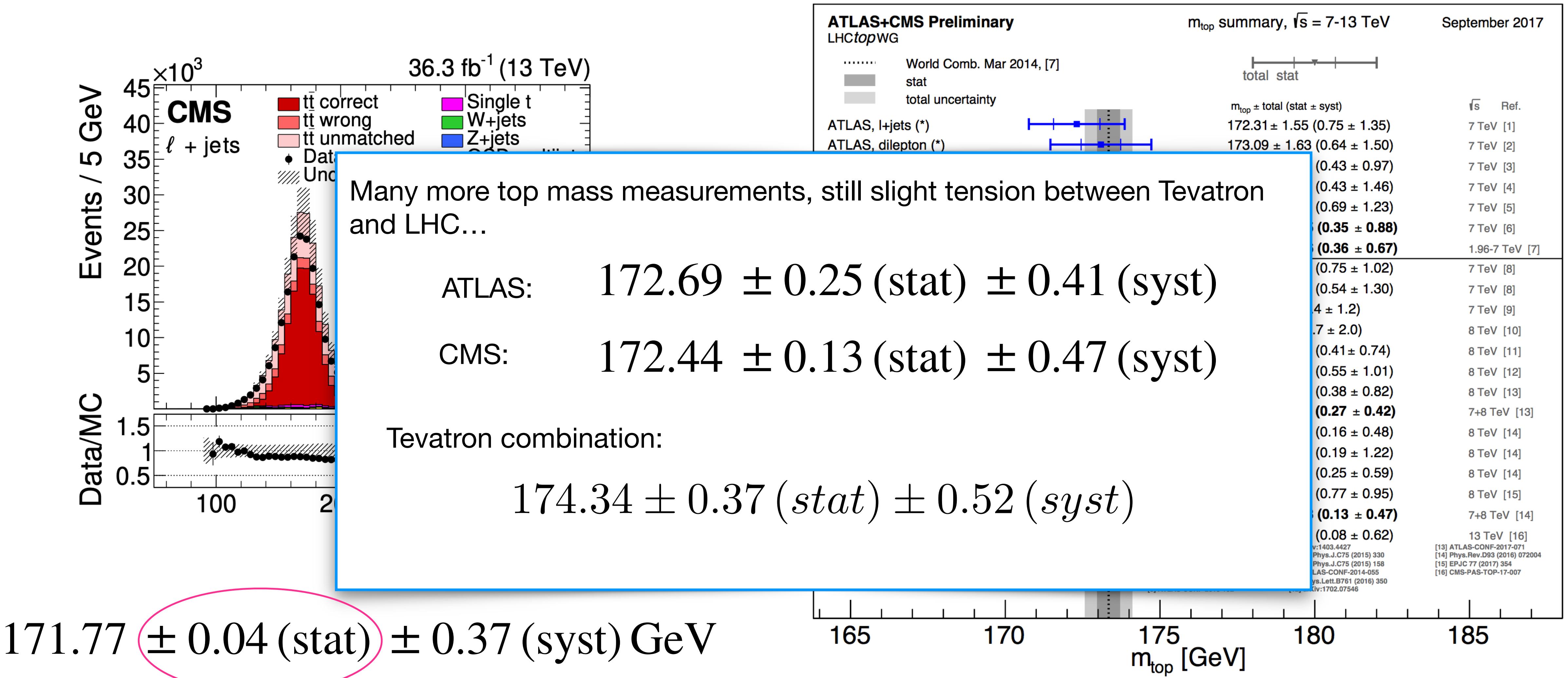
$171.77 \pm 0.04 \text{ (stat)} \pm 0.37 \text{ (syst)} \text{ GeV}$



Direct Top Mass Measurements

37

Most precise individual top mass from CMS

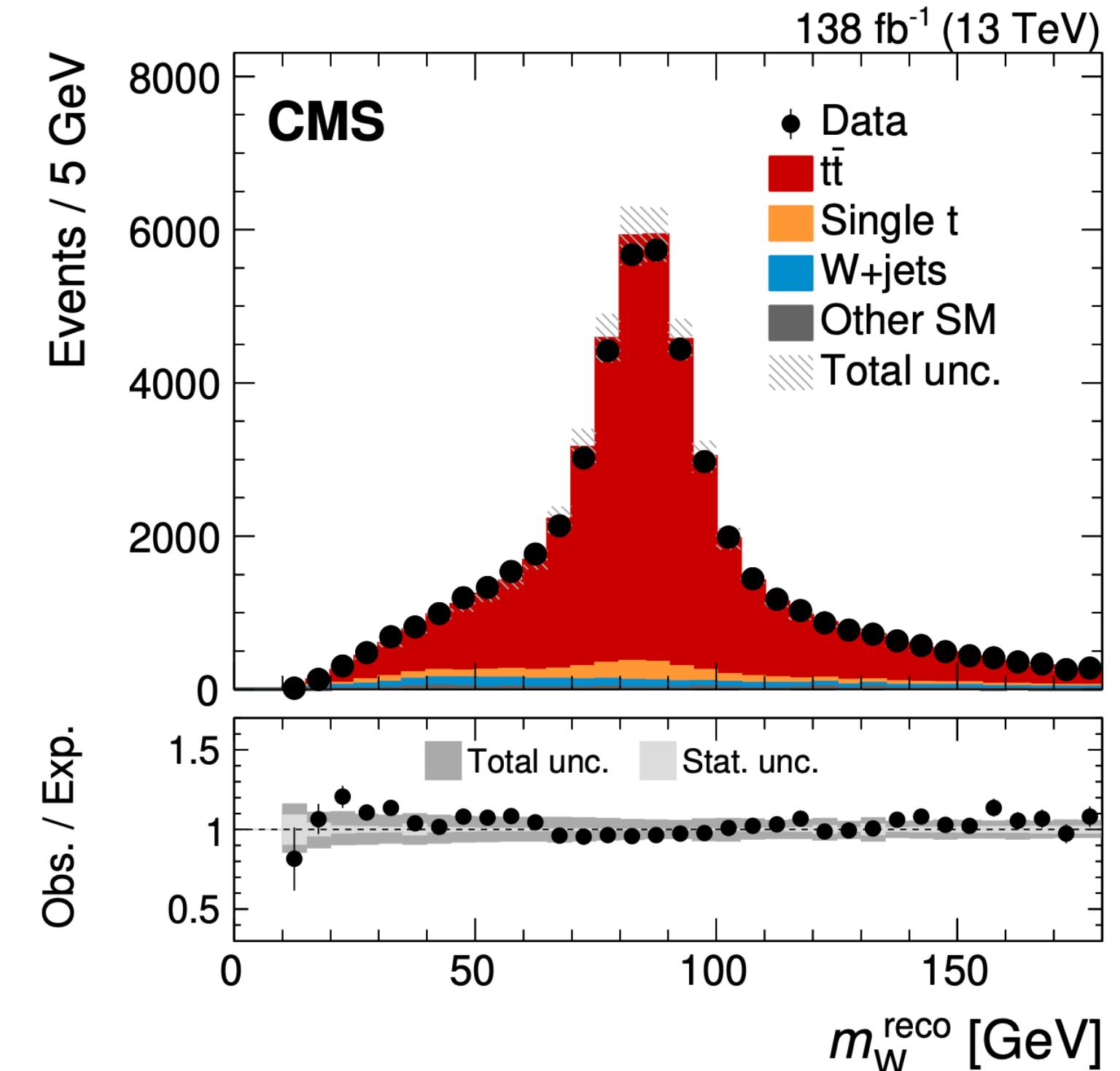
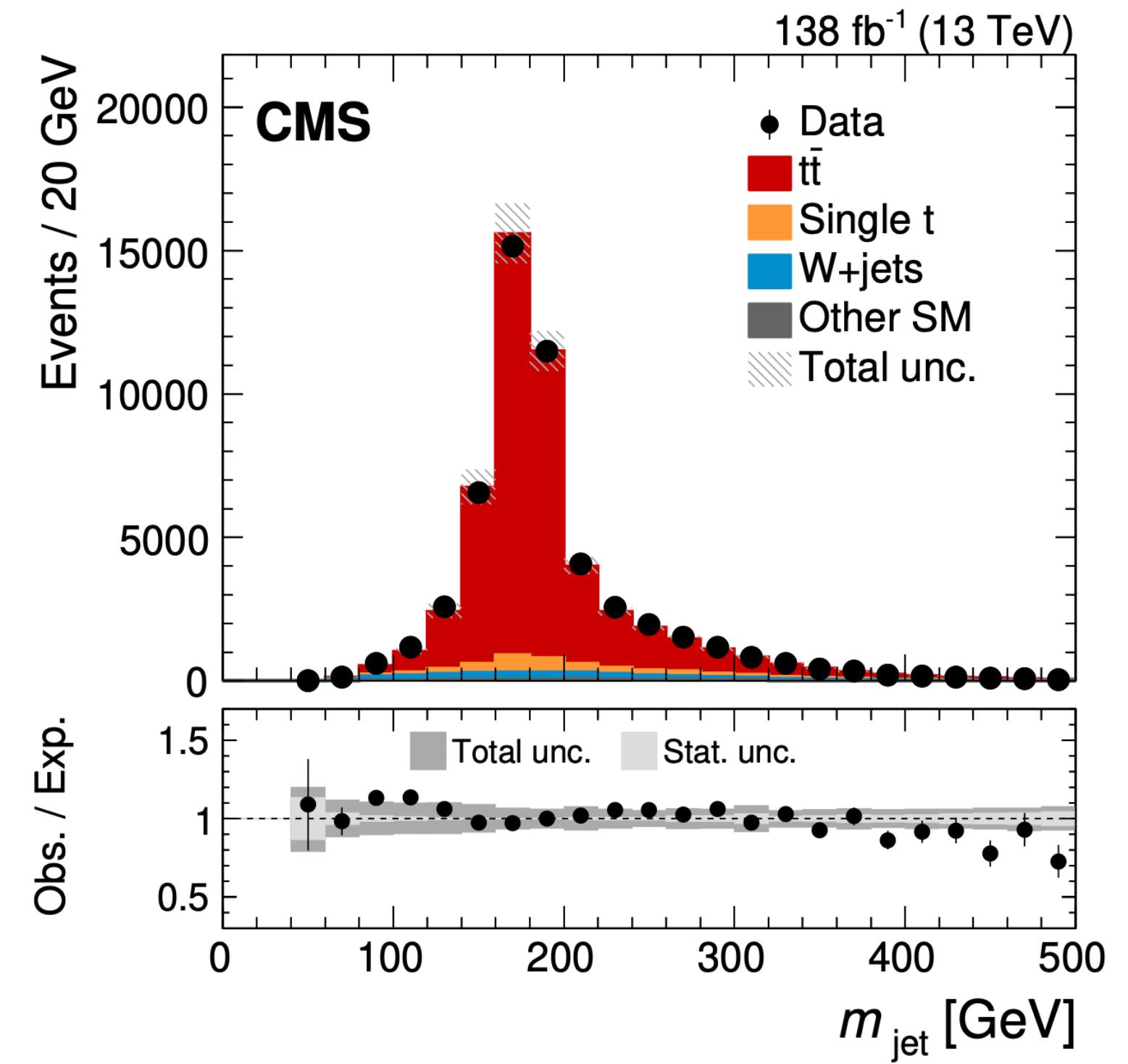
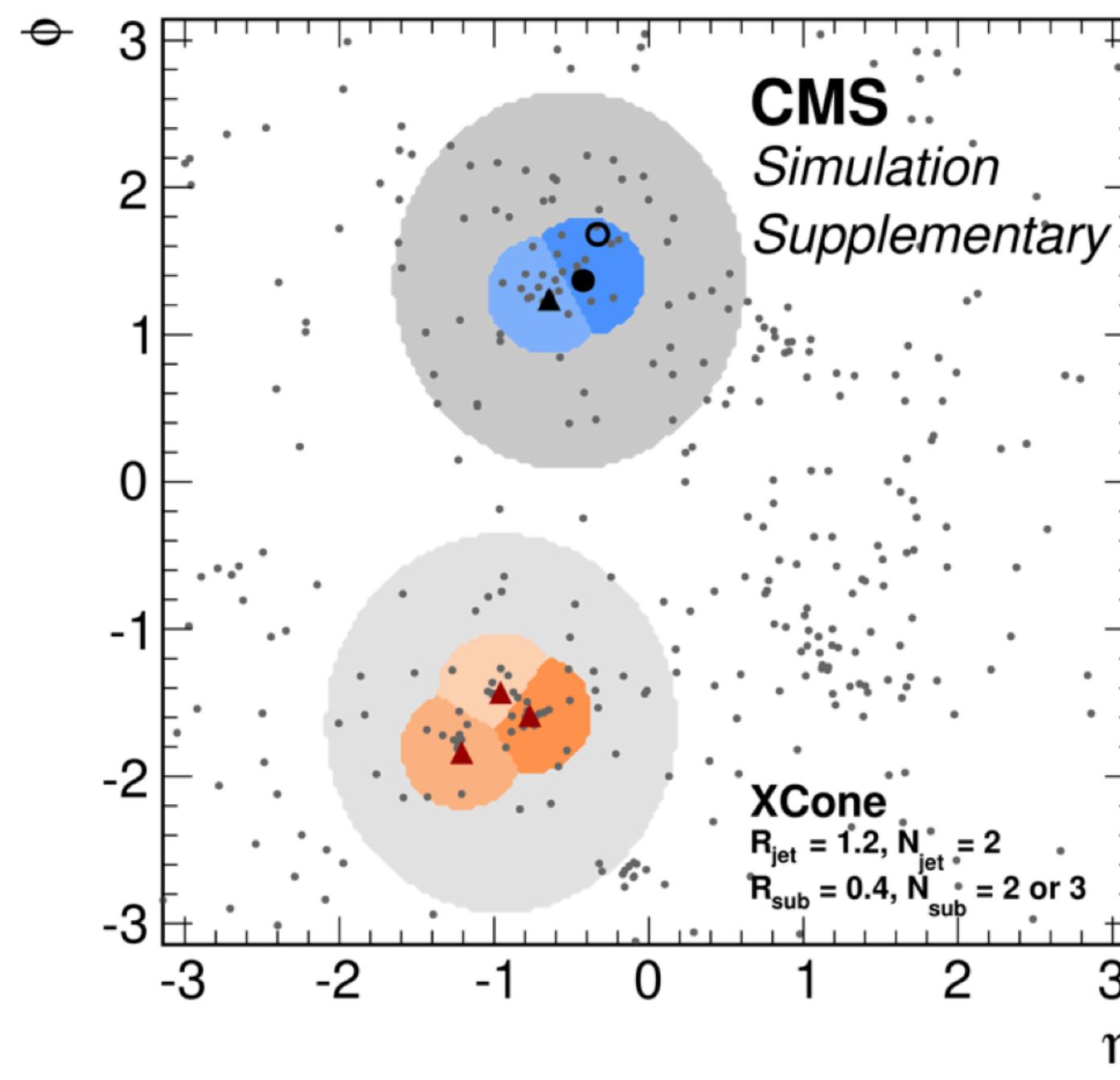


Boosted (top) Tagging



Boosted jet reconstruction with substructure has become a very active and exciting field! (See this summer's [Boost](#) conference at LBNL)

First introduced for Higgs boson reconstruction (Butterworth, Davison, Rubin and Salam - [paper](#))



Tagging of hadronically decaying boosted heavy particles (W, Z, Higgs and top) has led to large improvements in the performance of the reconstruction of these objects and subsequently in a vast number of measurements and searches!

Direct Top Mass Measurements

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Some basic and key concepts

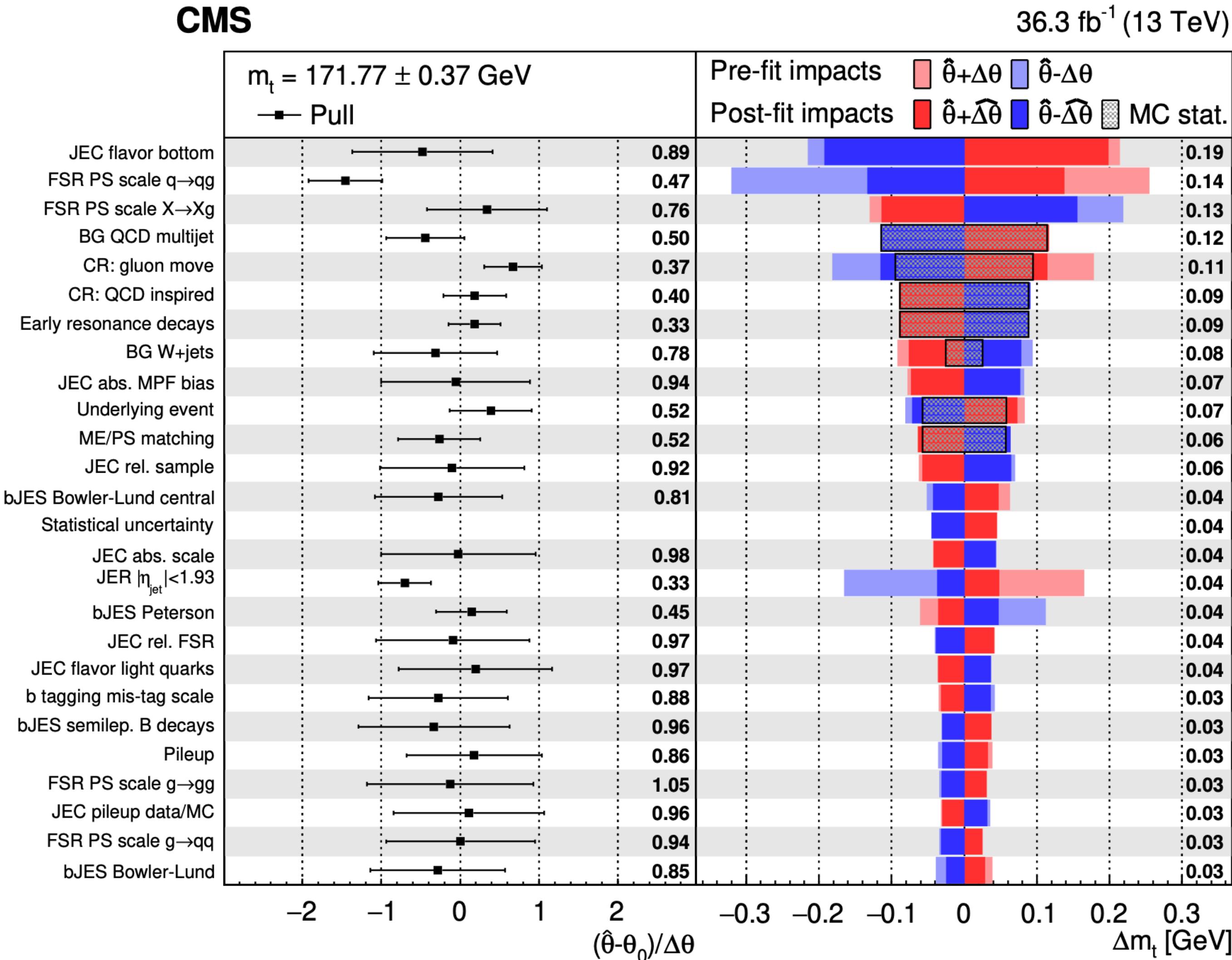
- 1.- The correct assignment of b-jets to each top is essential to the measurement of the top mass.
- 2.- Observables are either the mass of the 3-jet qqb system or the ℓb system depending on the W decay.
- 3.- The W mass can be used to calibrate in-situ the jets from the hadronic W decays.
- 4.- The b-jet energy scale is a key element in the measurement of the top mass.

Taking a closer look at the top mass table!

- 1.- l-jets channels have reached excellent statistical precision.
- 2.- The di-lepton channel also the statistical uncertainty is now sub-dominant.
- 3.- There are significant differences in systematic uncertainties between ATLAS and CMS.
- 4.- New channels for the ‘direct’ mass measurement are investigated (single-top production, boosted top).

Digression on the Profiling Paradigm

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1.- The dominant systematic uncertainties are b-JES and modelling.

2.- **Impact of MC uncertainties or limited MC stats**
(this is a growingly important issue in a large number of analyses!)

3.- Profiling paradigm is a subject of debate (different approaches between ATLAS and CMS).

Personal view on profiling: as long as a single parameter is not overwhelmingly dominating the uncertainty, the specific distribution chosen should not matter so much (in the limit of large number of parameters, the central limit theorem should correctly lead to a gaussian distribution of the overall uncertainty). In the case of an outstanding systematic, there is no problem in not profiling it.

Digression on the Mass Measurement

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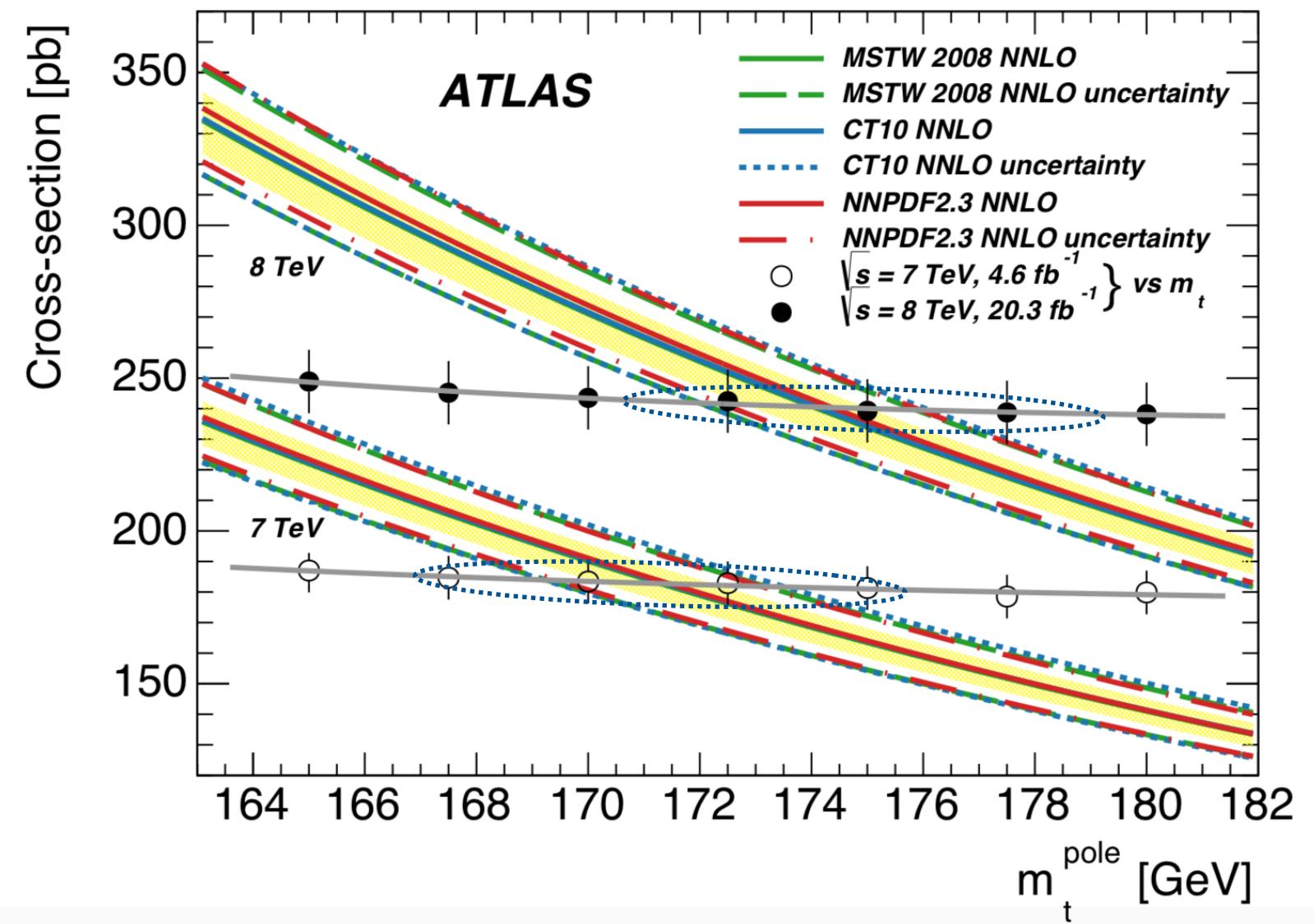
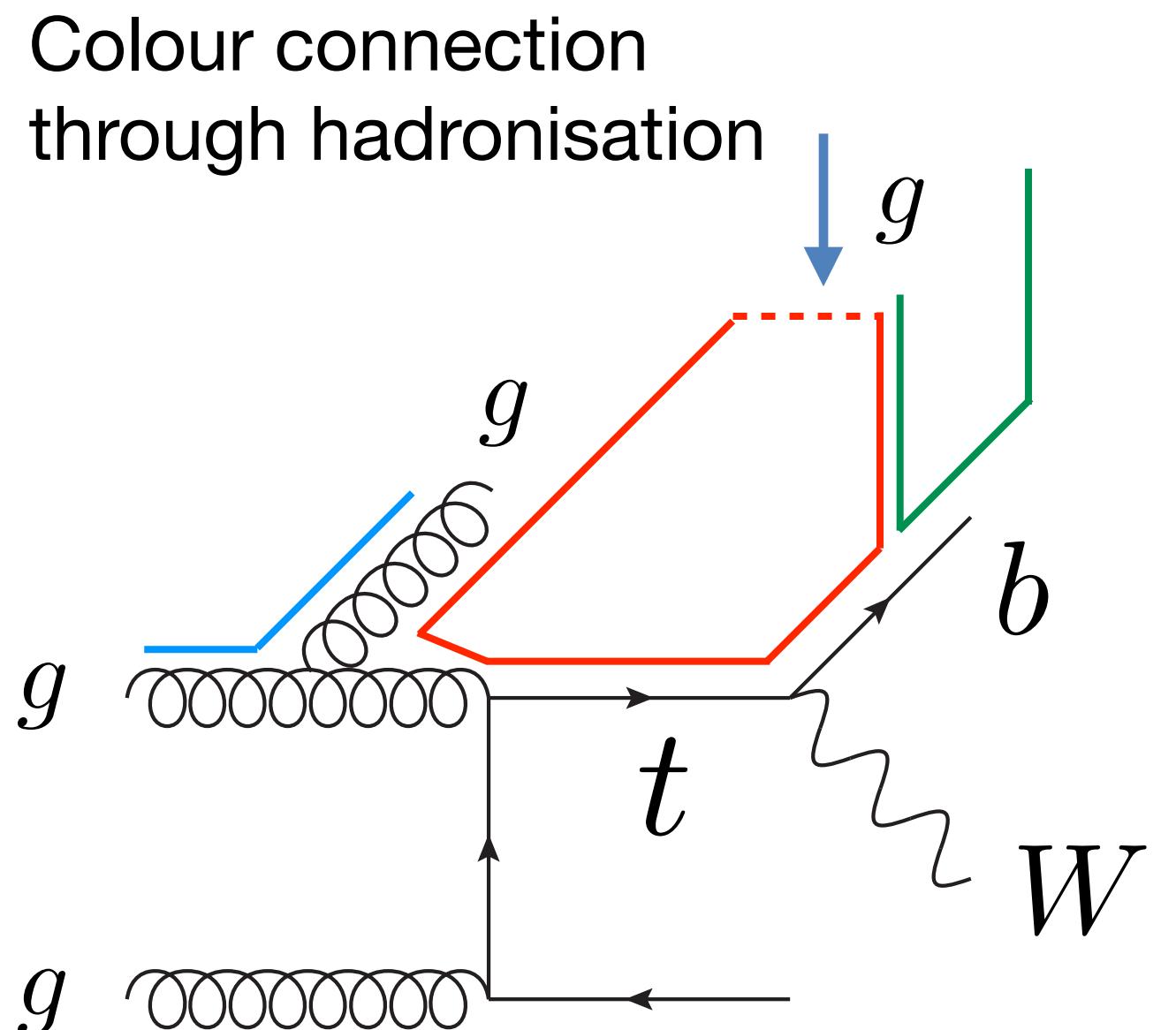
The relation between the Monte Carlo template used to fit the mass spectrum and the Field Theoretical parameter of the pole mass is not straightforward.

The top is coloured, so it is impossible to unambiguously associate every object in the final state to it!

These ambiguities lead to an uncertainty on the top mass measurement varying between 1 GeV and 200 MeV.

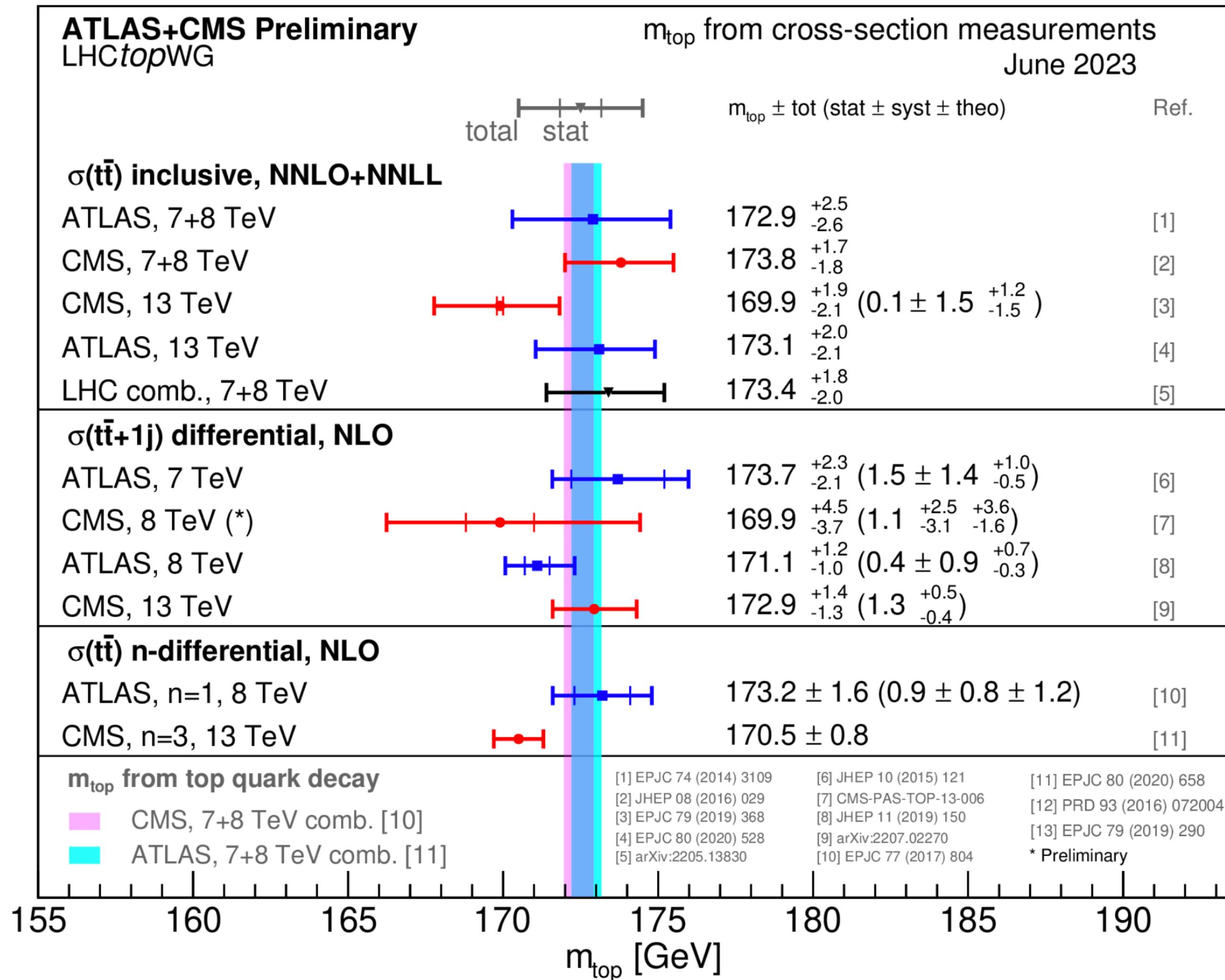
The pole mass can be measured using observables that are not dependent on the detailed reconstruction of the top system.

e.g. the pole mass can be measured using the top production cross section (at the cost of introducing a dependence on the production prediction).



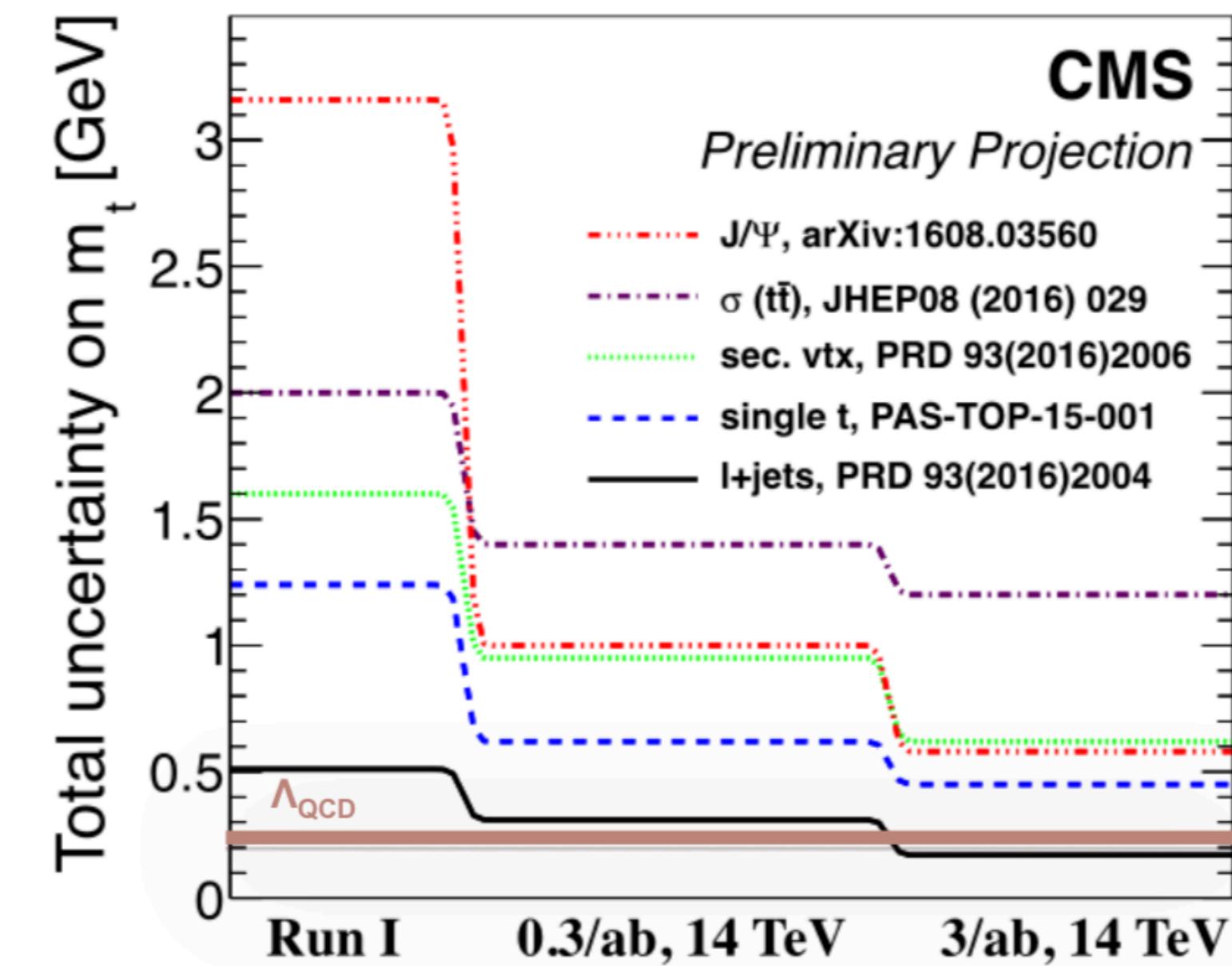
Digression on the Mass Measurement

42



Measurements from cross sections will be limited by prediction uncertainties and luminosity.

Study of the reach in precision at HL-LHC



Reaching a floor in the precision on the top mass at around HL-LHC Lambda QCD ~ 180 MeV

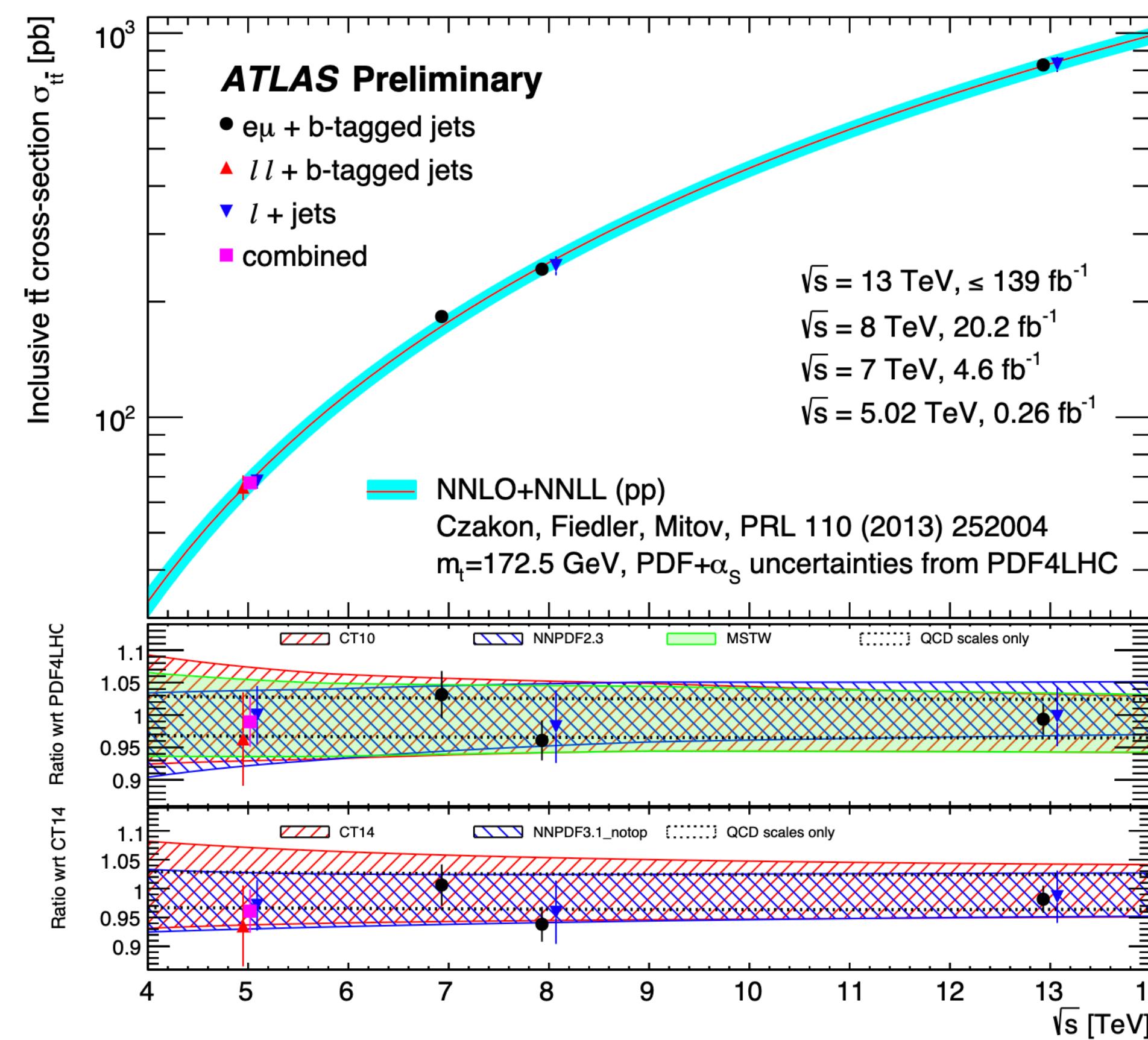
Top Pair Production at 5.02 TeV

43

Top pair production cross section measurement at 5.02 TeV

New lepton-jets measurement and combination with earlier di-lepton channel in low PU runs at 5.02 TeV

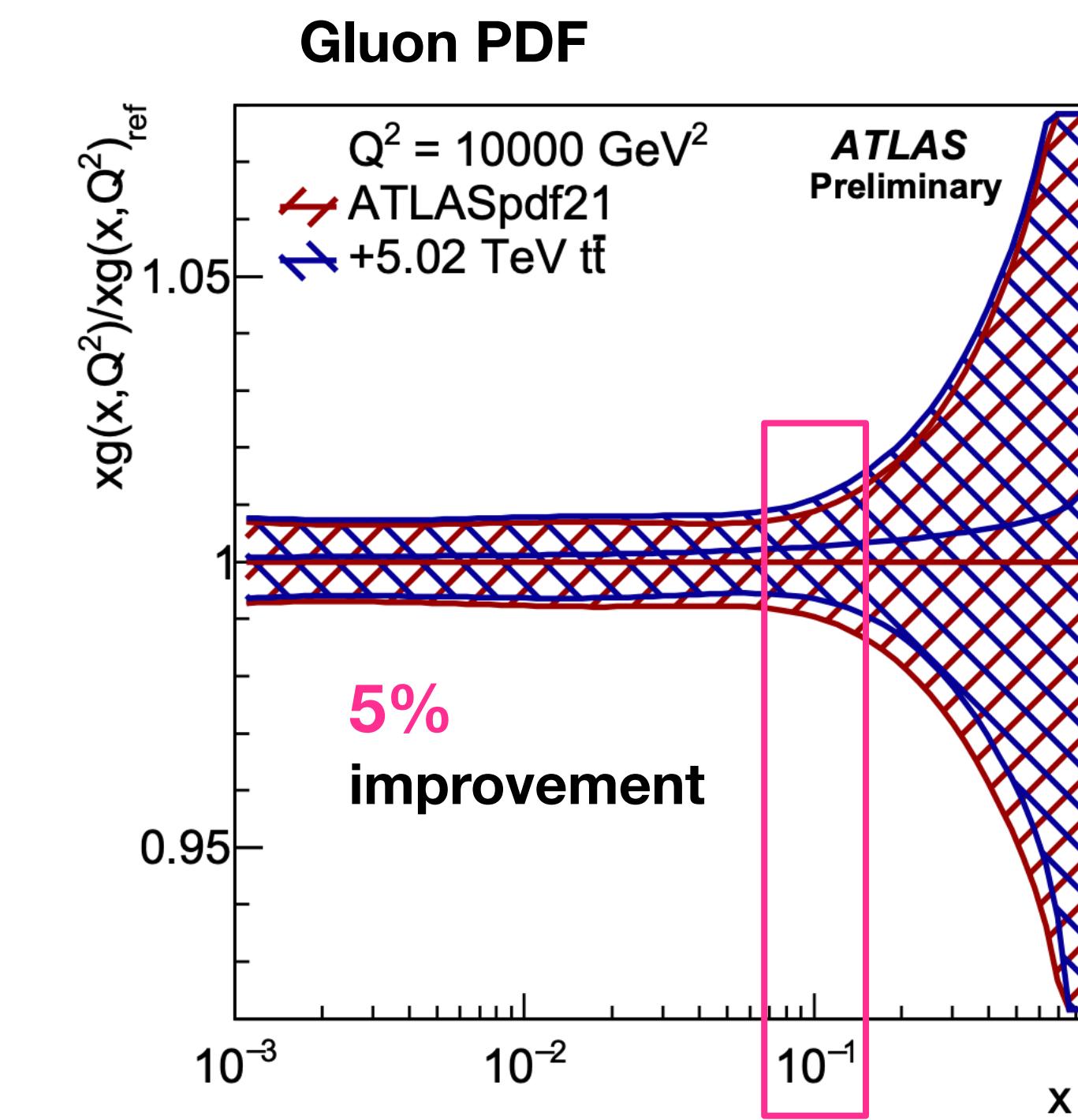
Excellent precision reached with small dataset of 0.26 fb^{-1}



$$\sigma_{t\bar{t}} = 67.5 \pm 0.9 \text{ (stat.)} \pm 2.3 \text{ (syst.)} \\ \pm 1.1 \text{ (lumi.)} \pm 0.2 \text{ (beam) pb}$$

In excellent agreement with the NNLO-NNLL TOP++ prediction

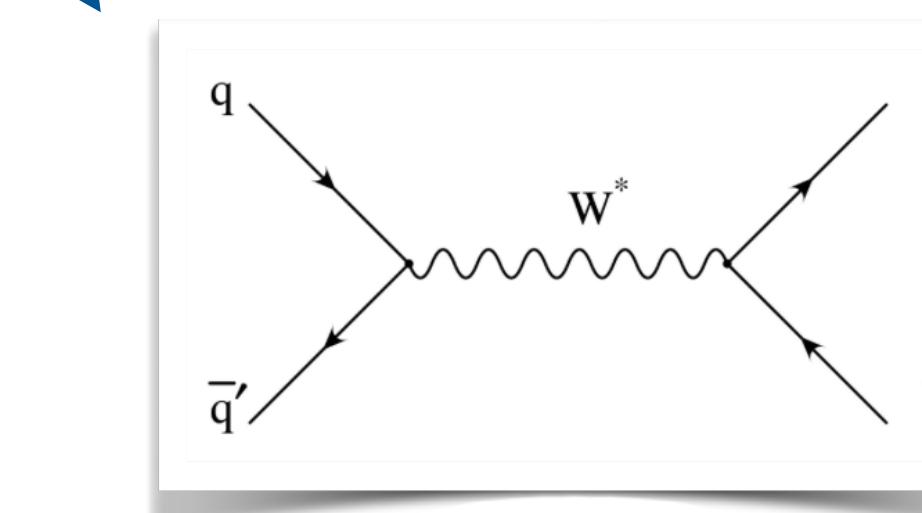
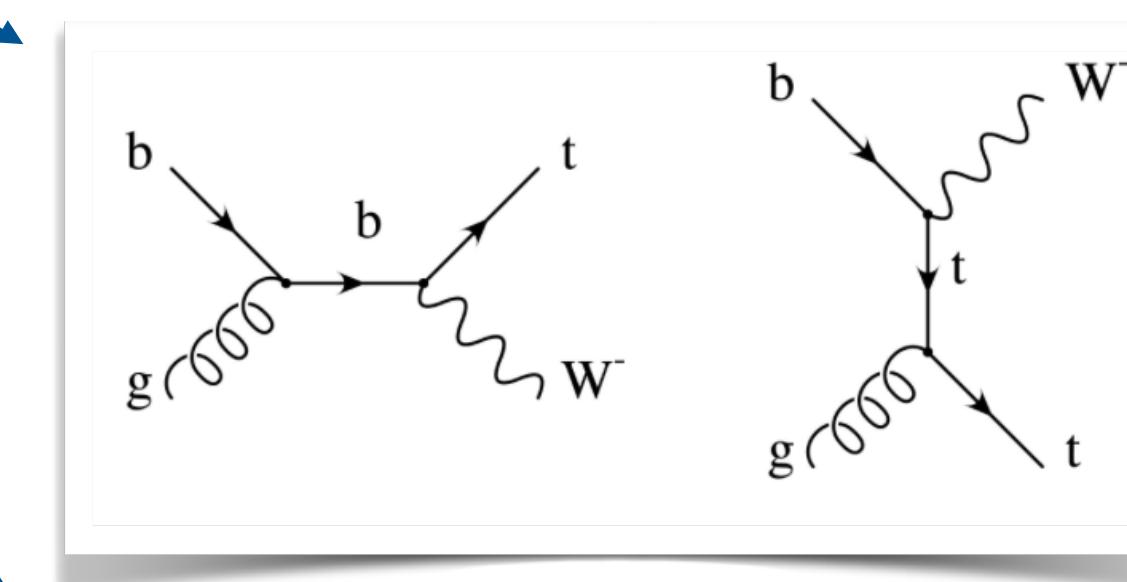
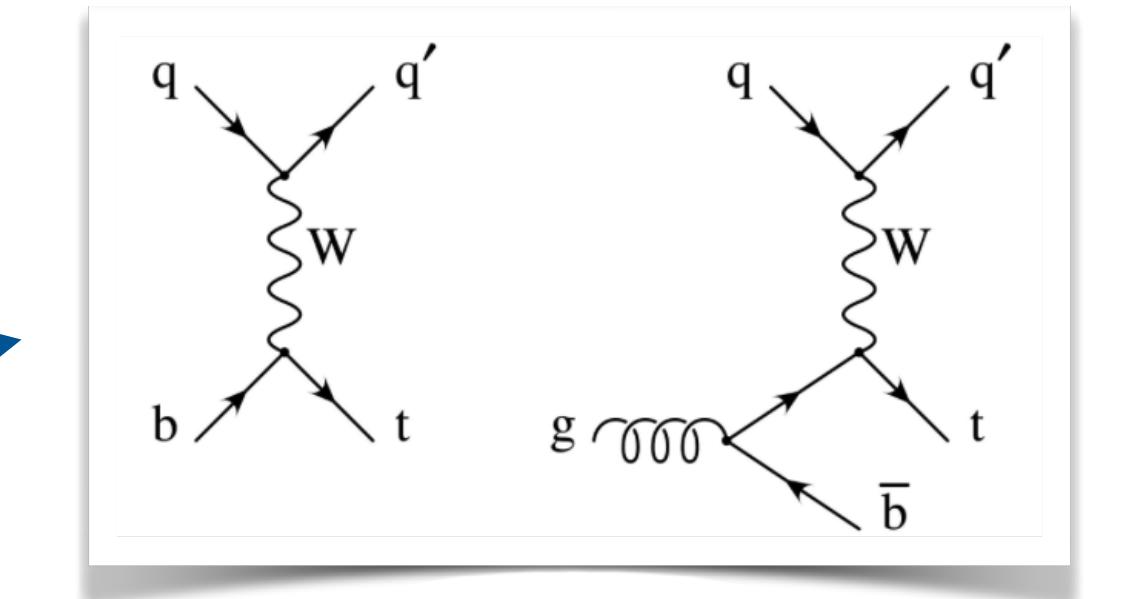
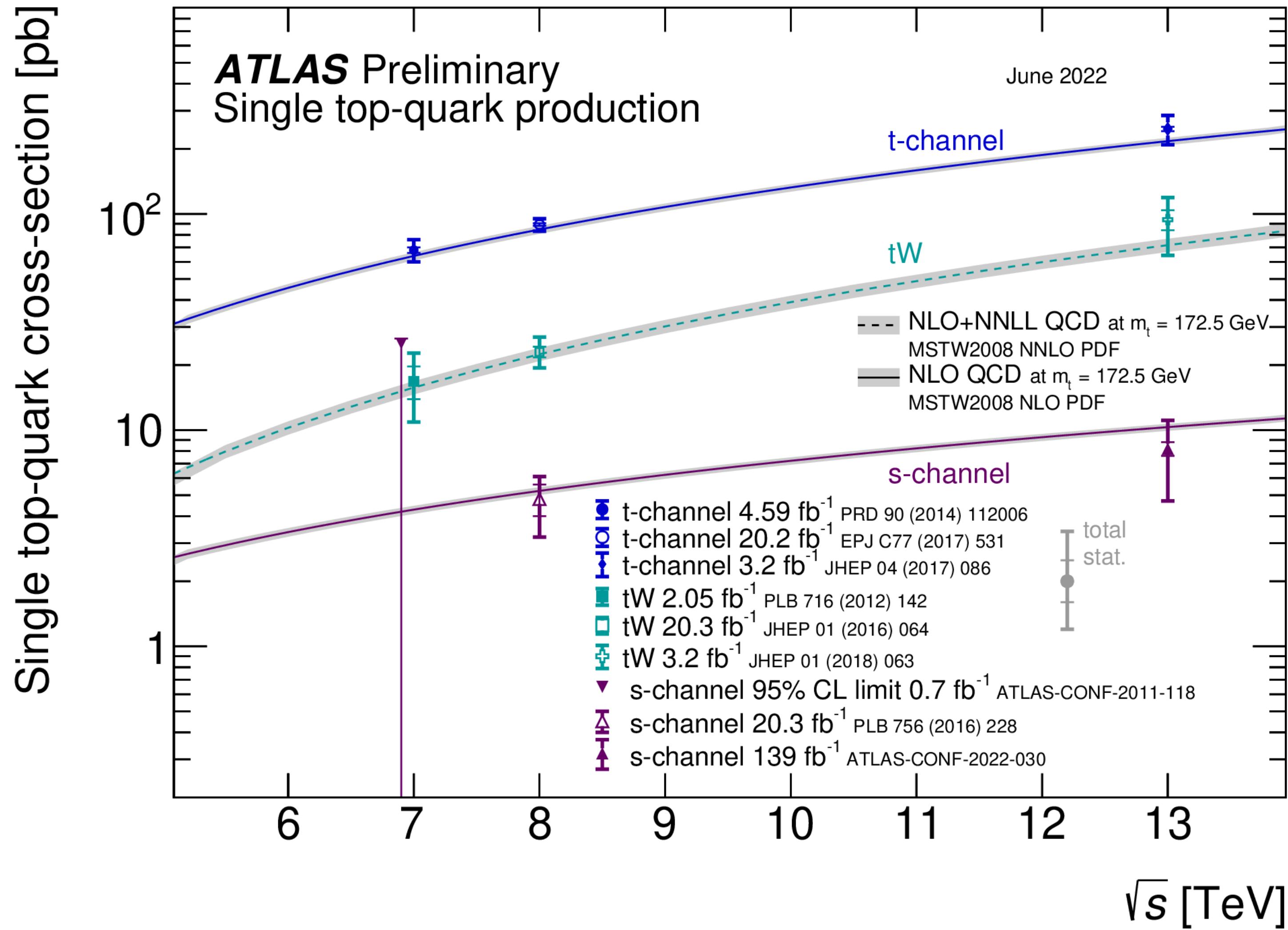
$$68.2 \pm 4.8^{+1.9}_{-2.3} \text{ pb}$$



Important feedback to improve Higgs precision measurements

Single-top production Cross Sections

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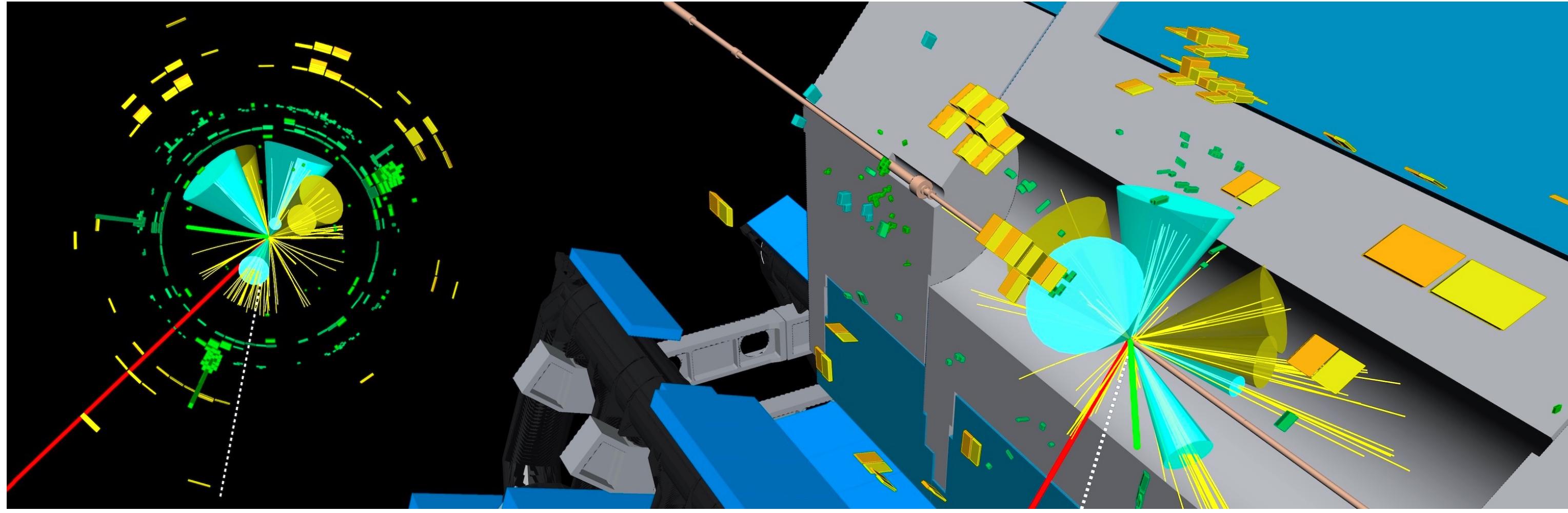


S-channel is particularly difficult even at Run 2 due to low cross section also larger top backgrounds!

More intricate Processes and Top Properties

Four top Production at LHC

46

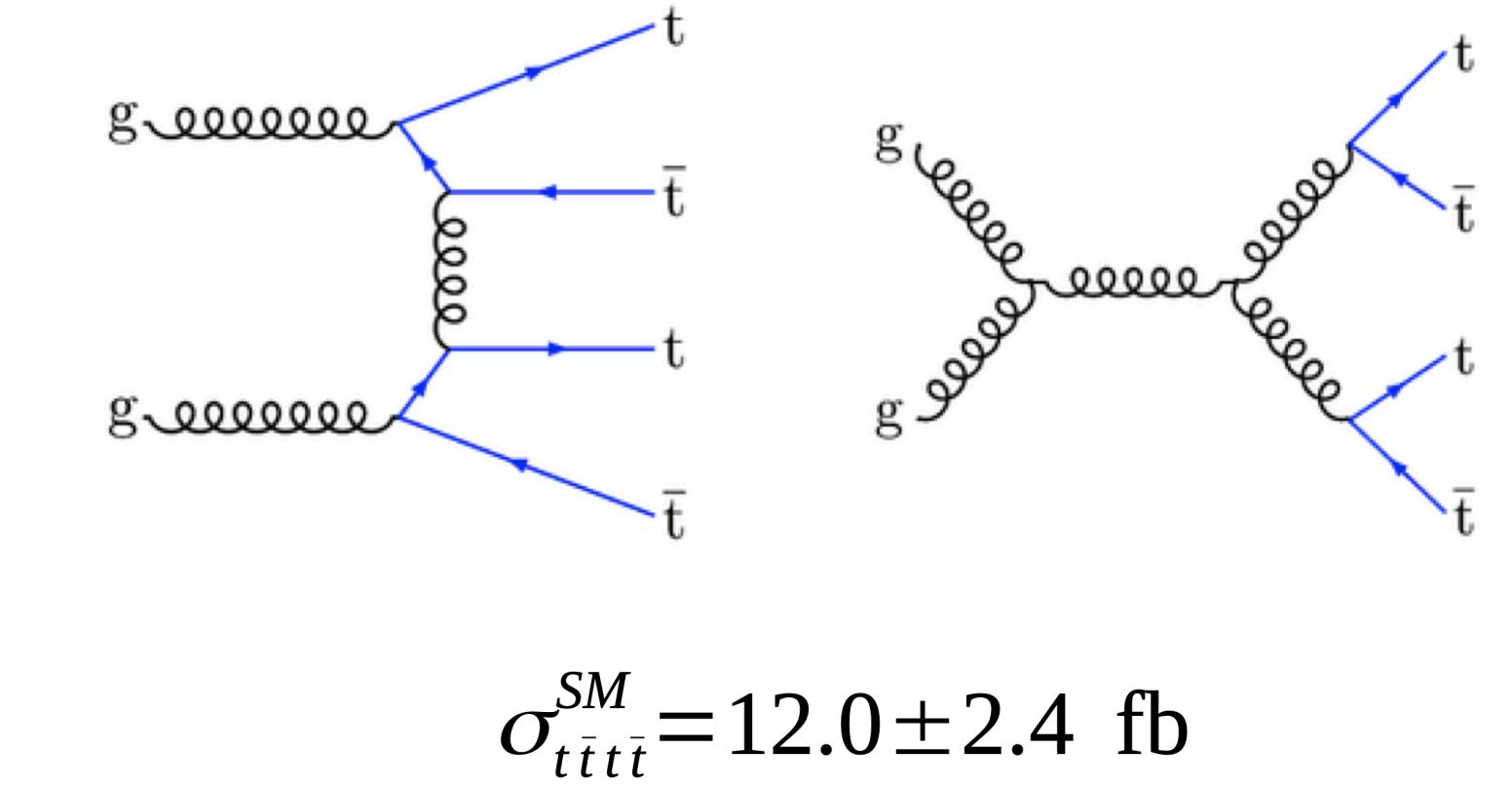
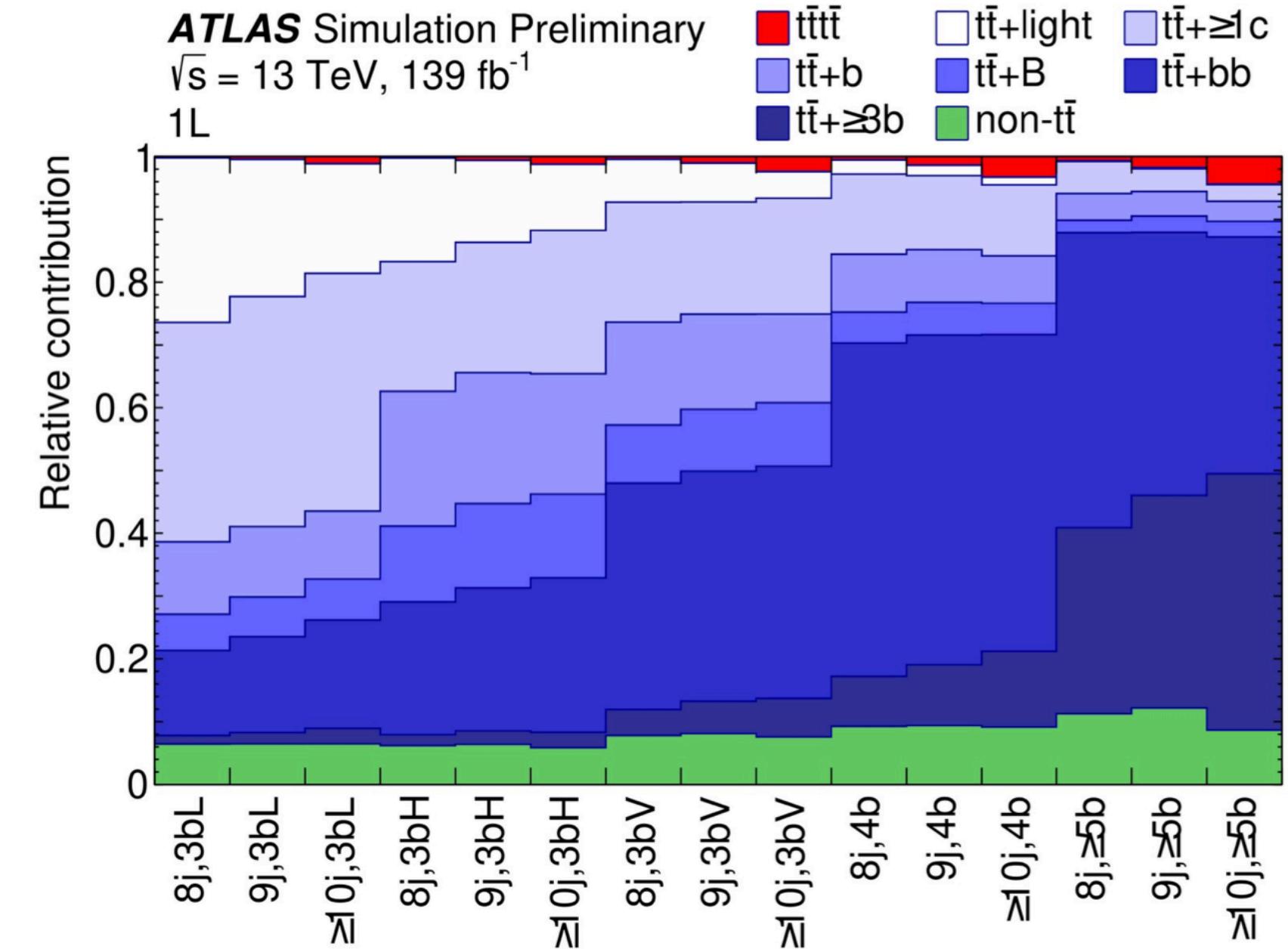


Final state with four W bosons
and four b jets!

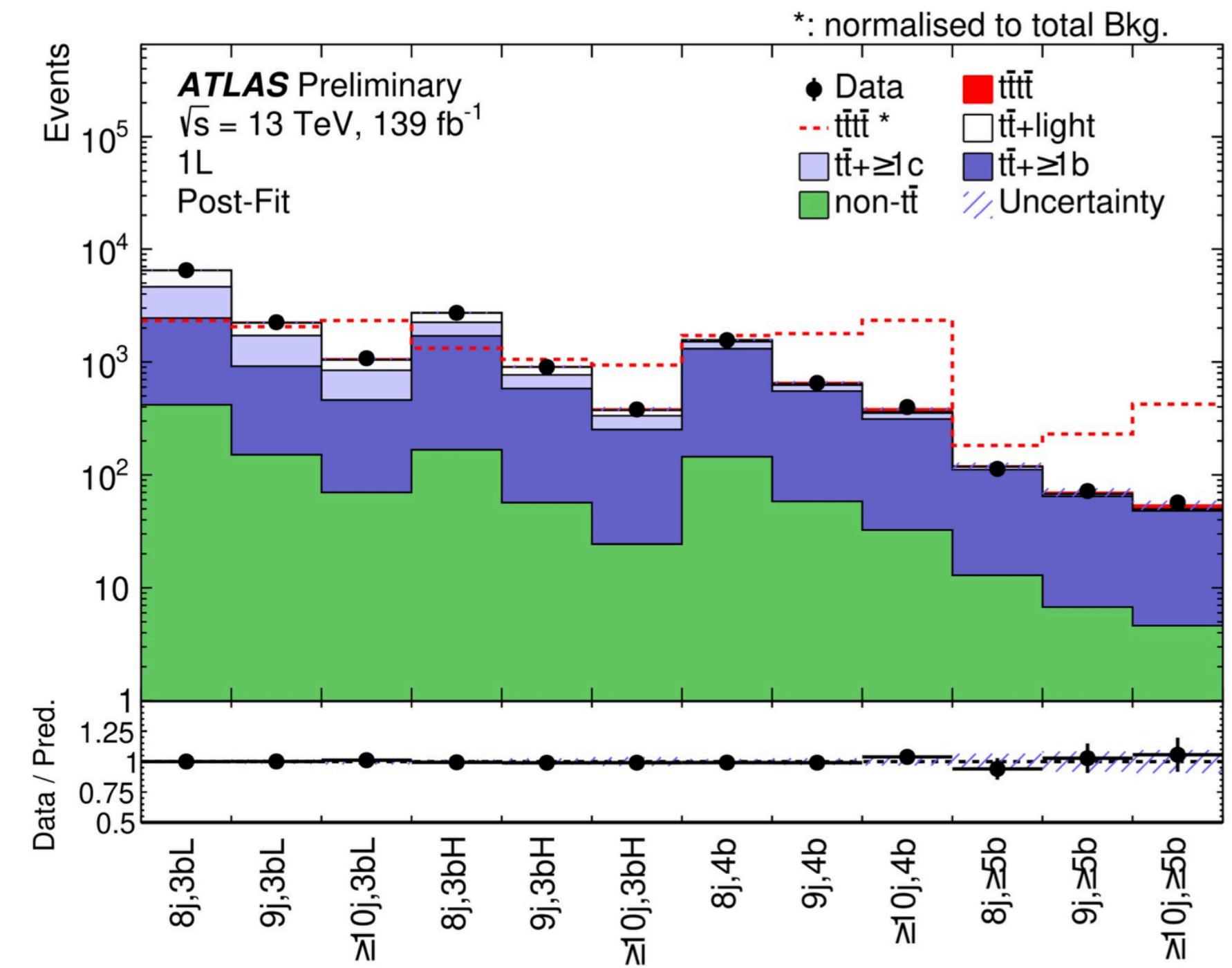
New intricate search channel: 1
lepton (and 2 leptons opposite
sign) with up 10 jets and 5 b-jets!!

57% of the four top events!

Much more intricate than the 2
Same sign leptons (larger
systematics - from tt-HF modelling)!



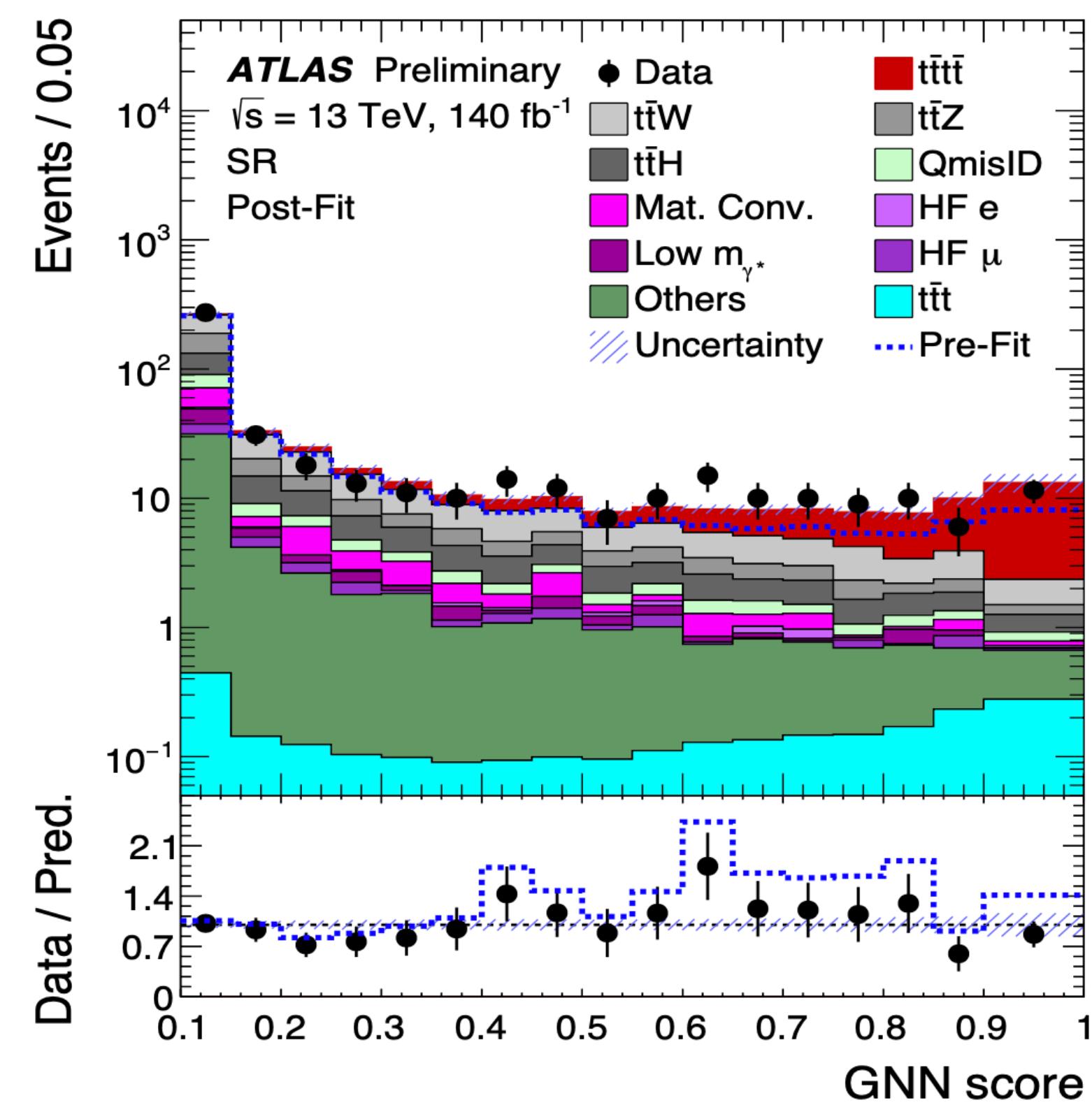
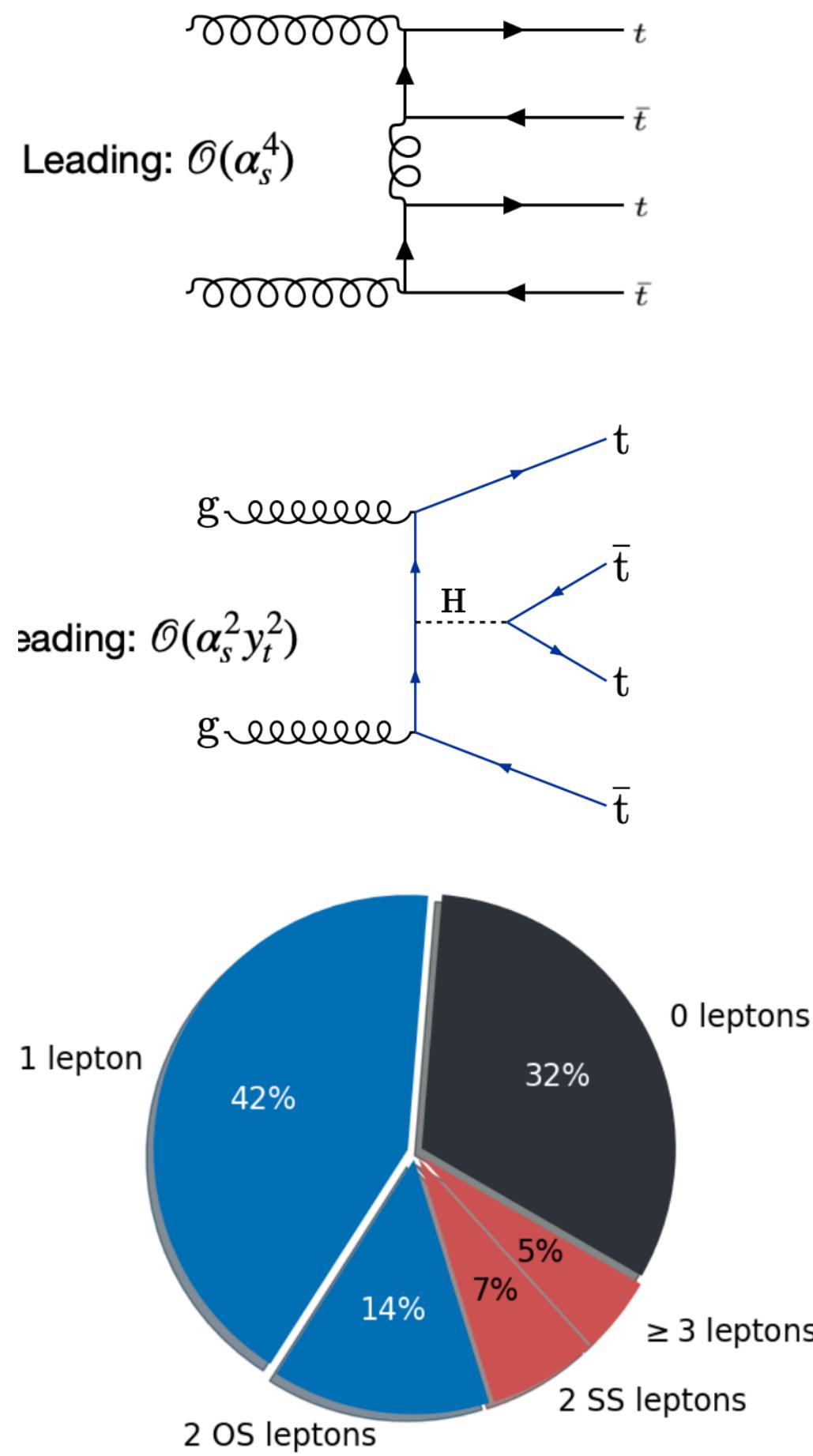
$$\sigma_{t\bar{t}t\bar{t}}^{SM} = 12.0 \pm 2.4 \text{ fb}$$



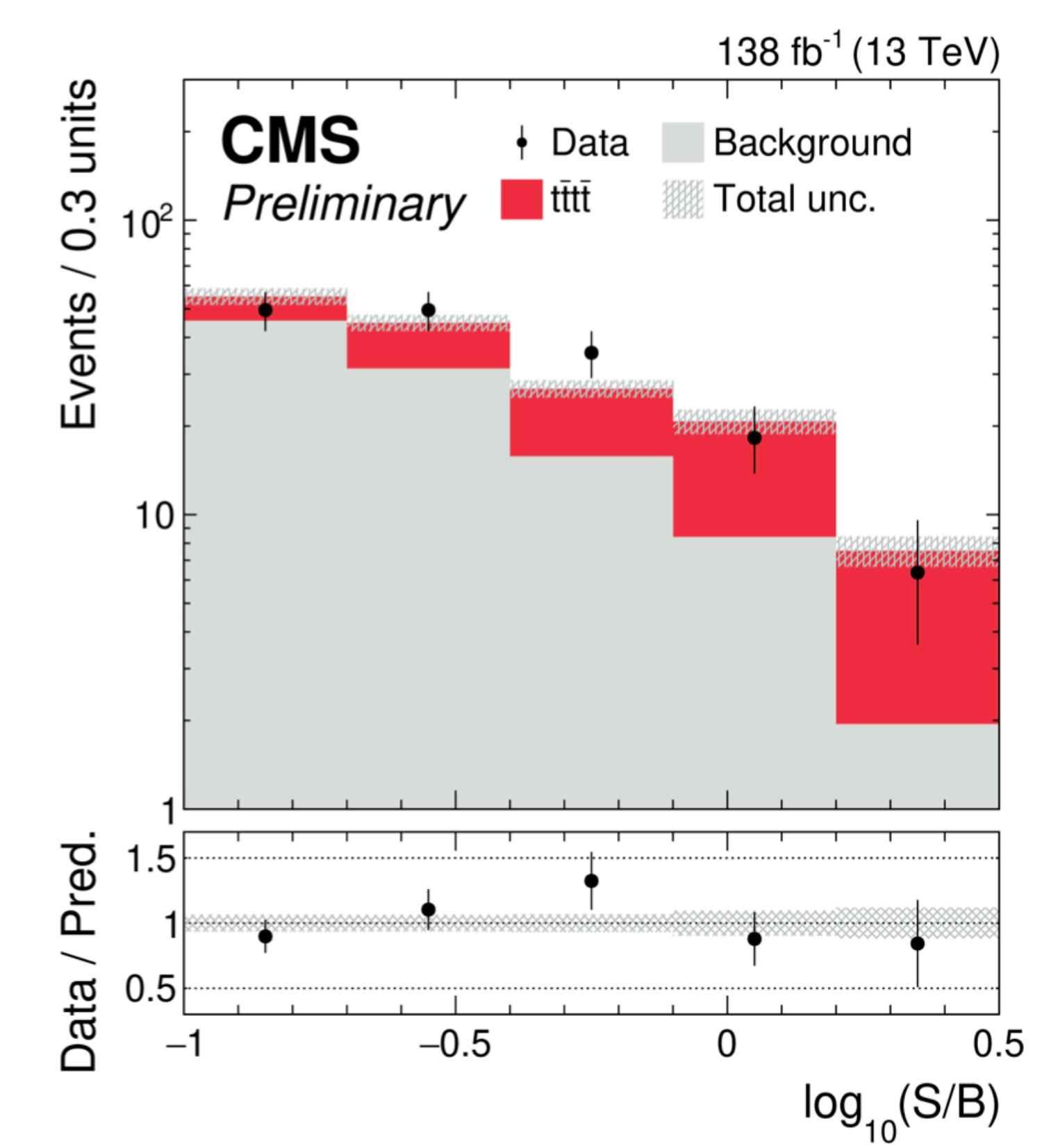
Four top Production Observation!

47

(Independent) Observation by ATLAS and CMS of 4 top production!



6.1 (4.3) σ observed (expected)

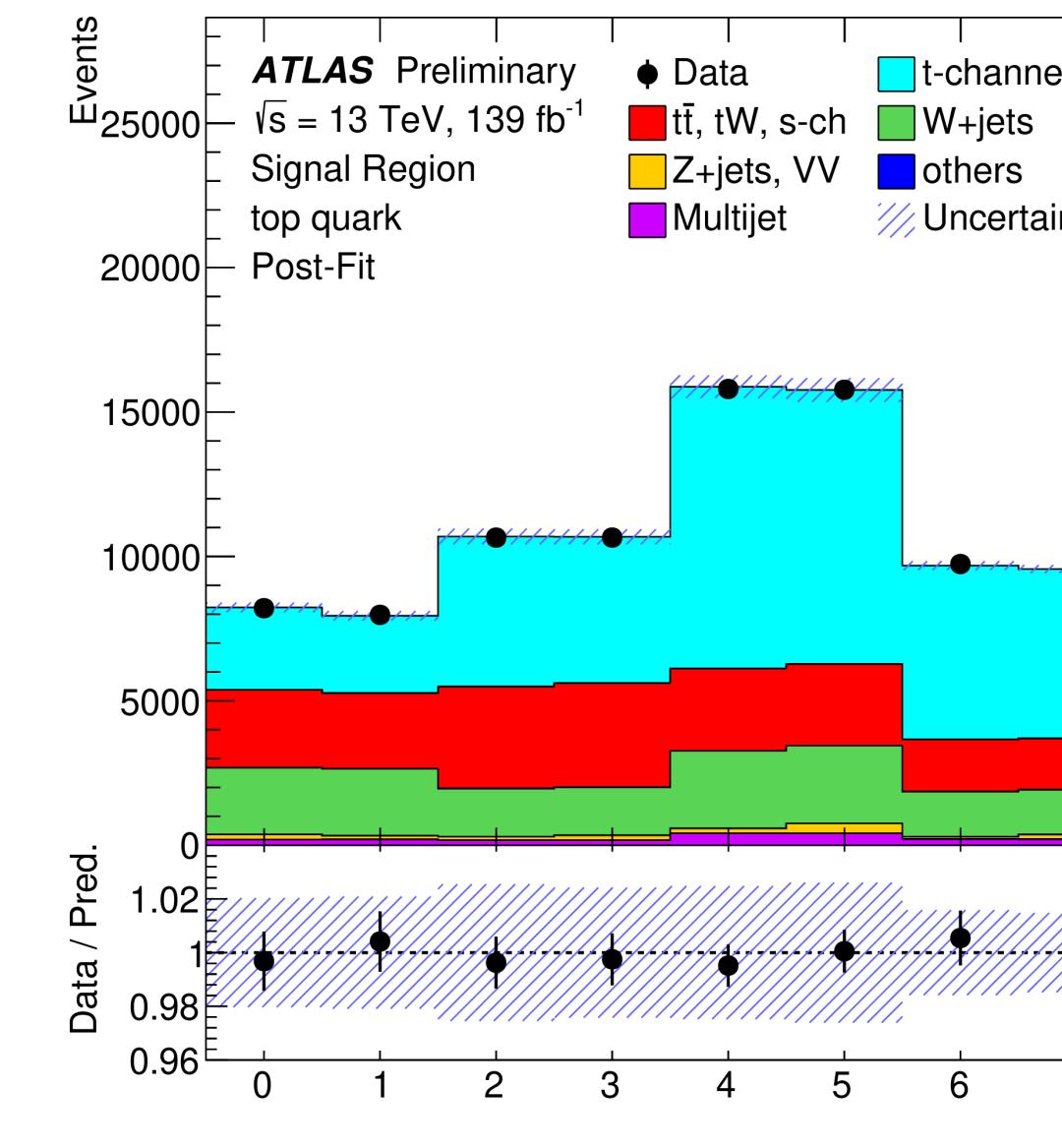
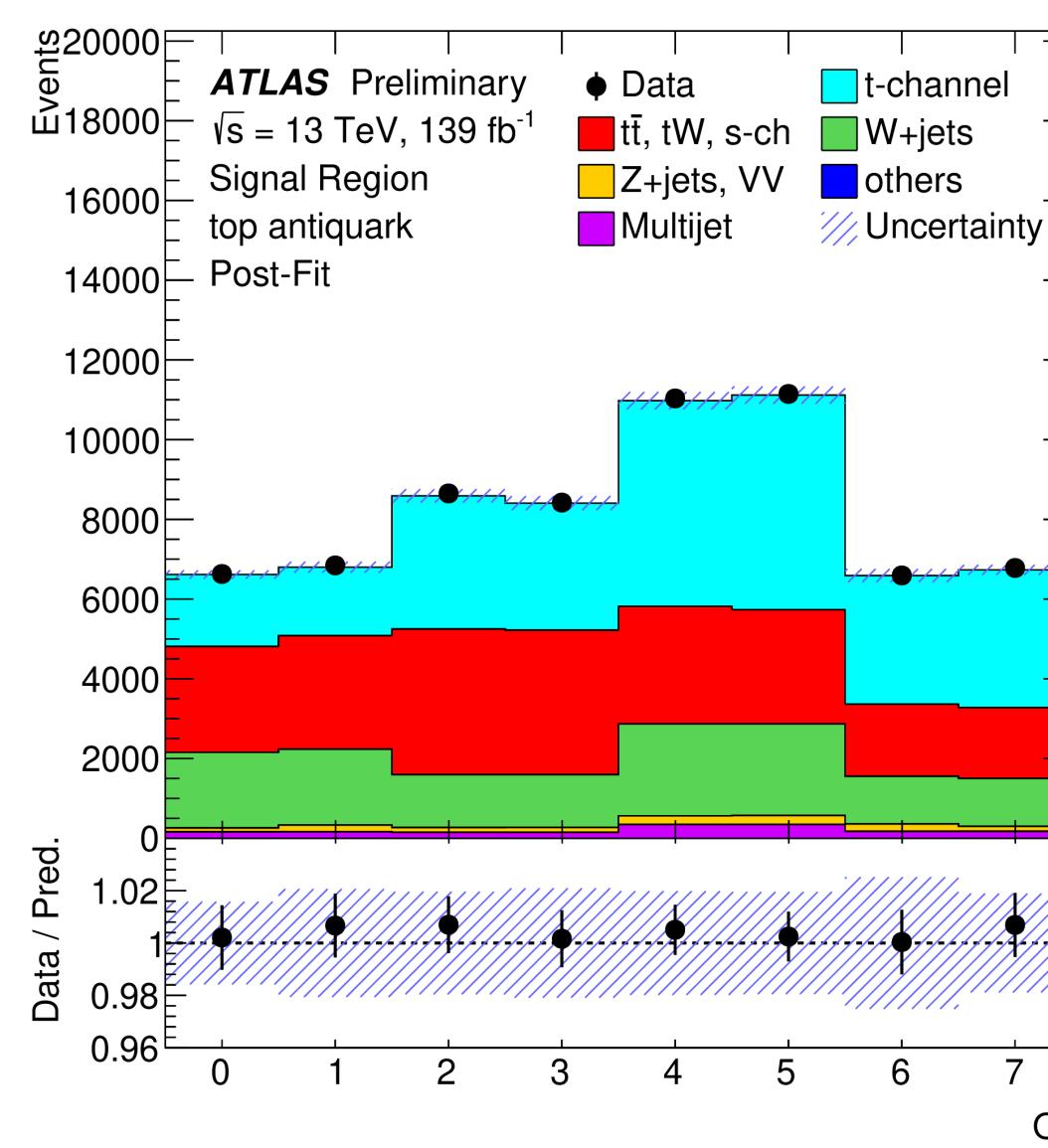
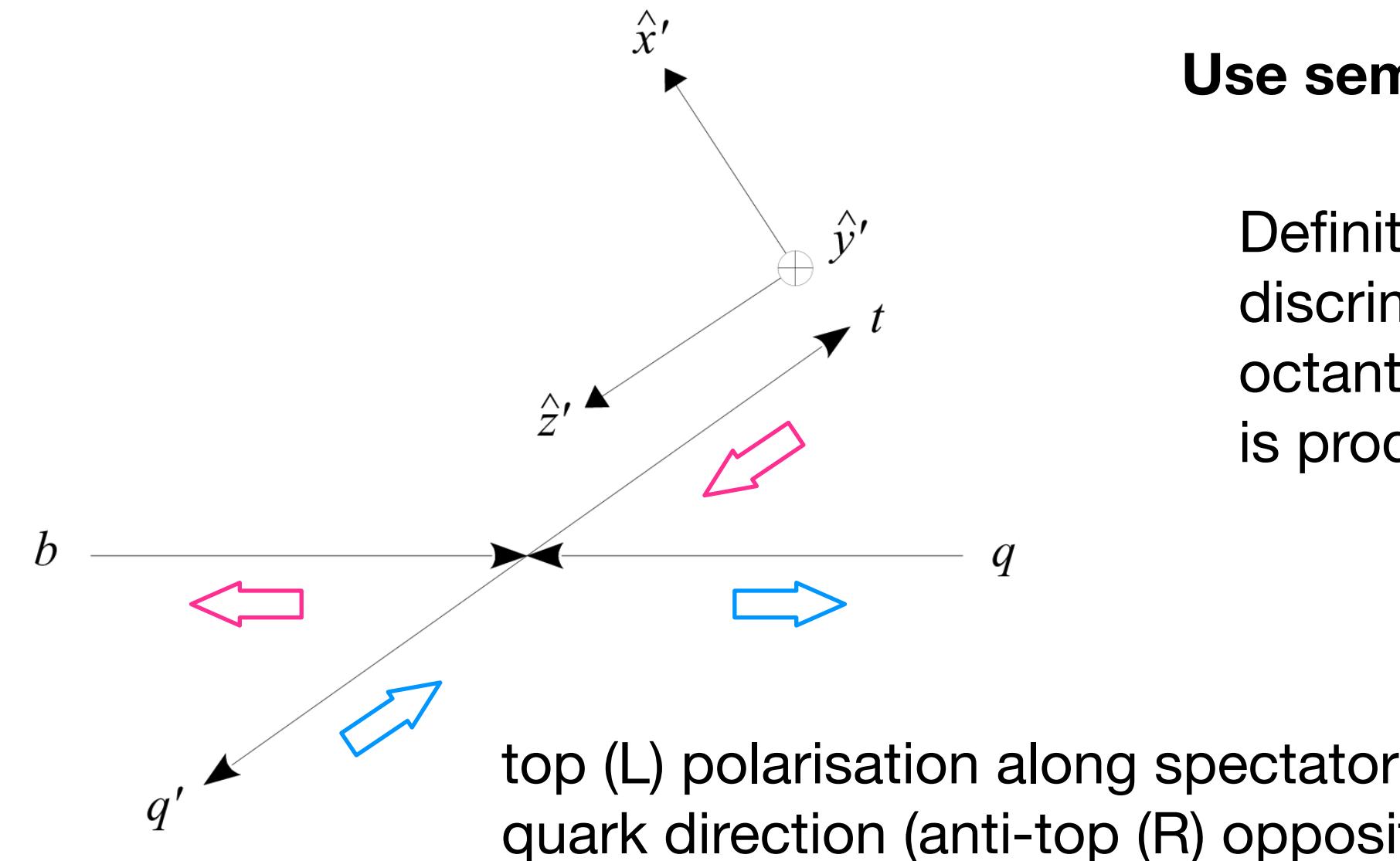
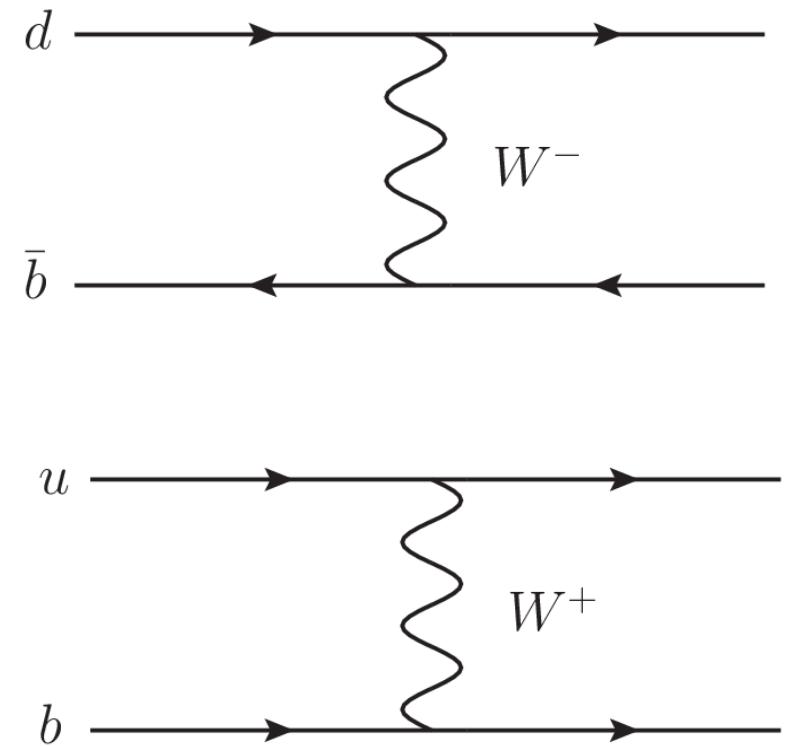


5.5 (4.9) σ observed (expected)

Top Polarisation in Single Top production

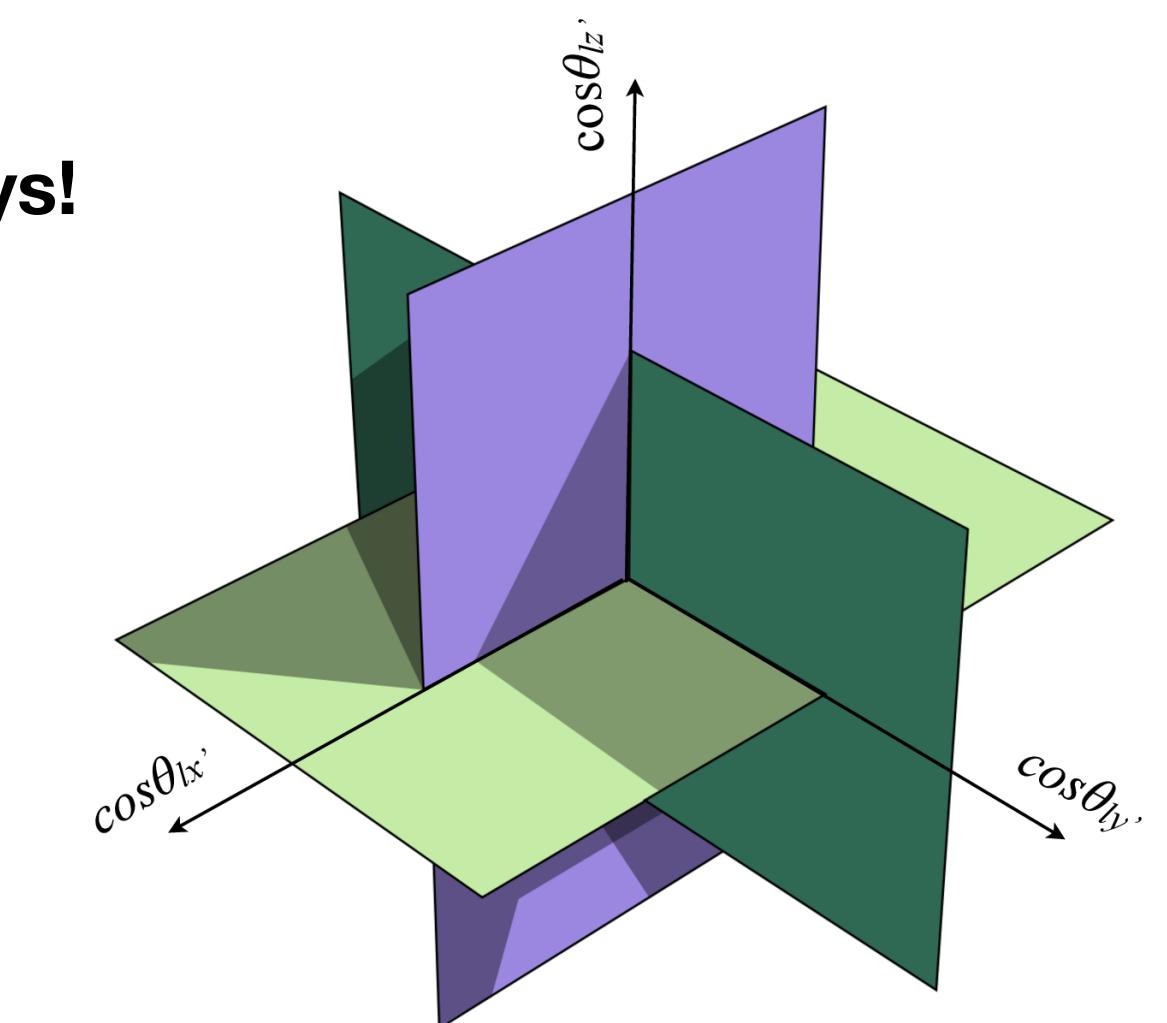
48

V-A coupling induces polarised production of single top quarks:



Use semi-leptonic top decays!

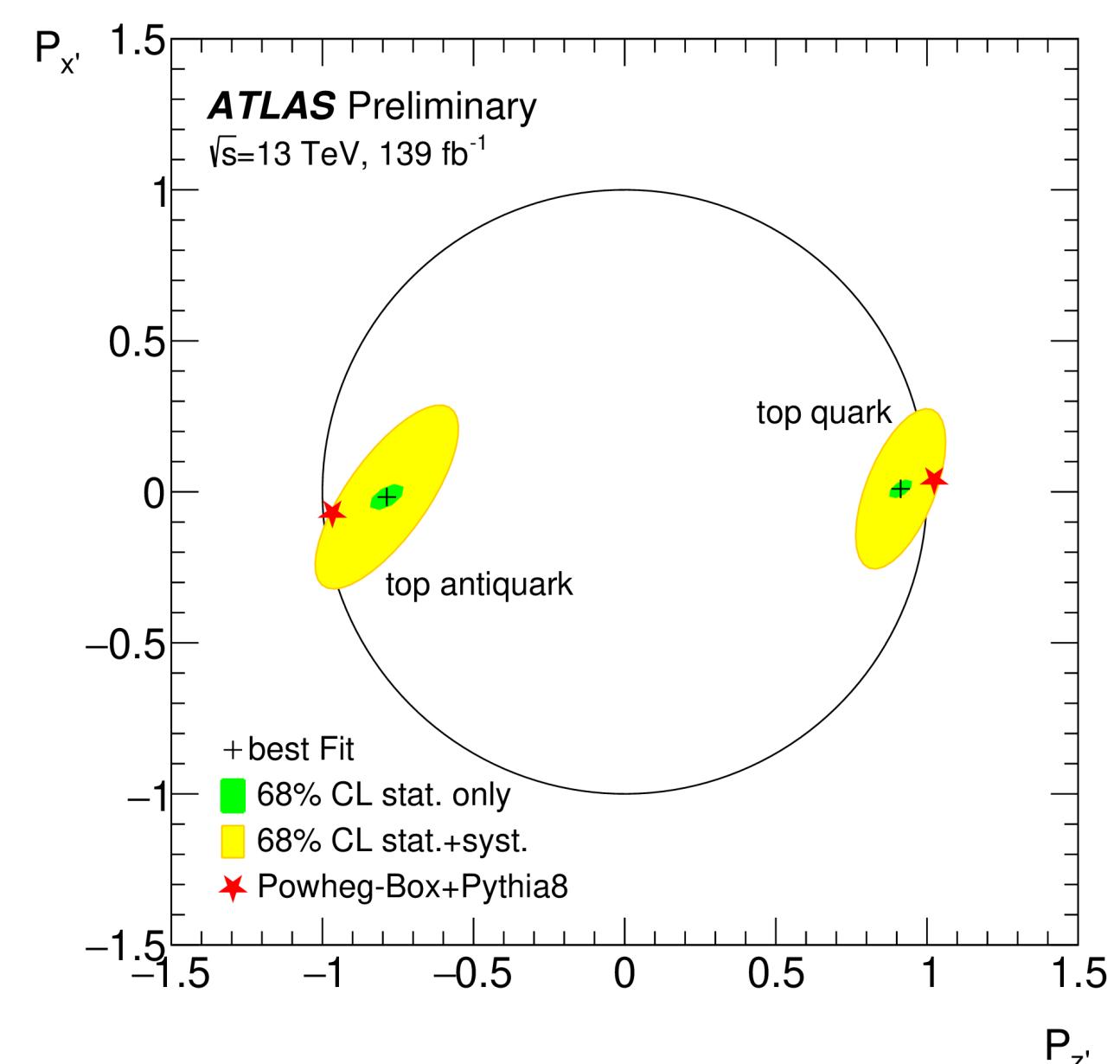
Definition of a 3D discriminant based on the octant in which the lepton is produced!



Fit to the polarisations P_x , P_y , P_z done using a parametrisation of this octant variable.

P_y is sensitive to CP violating effects

P_x is sensitive to NLO QCD effects

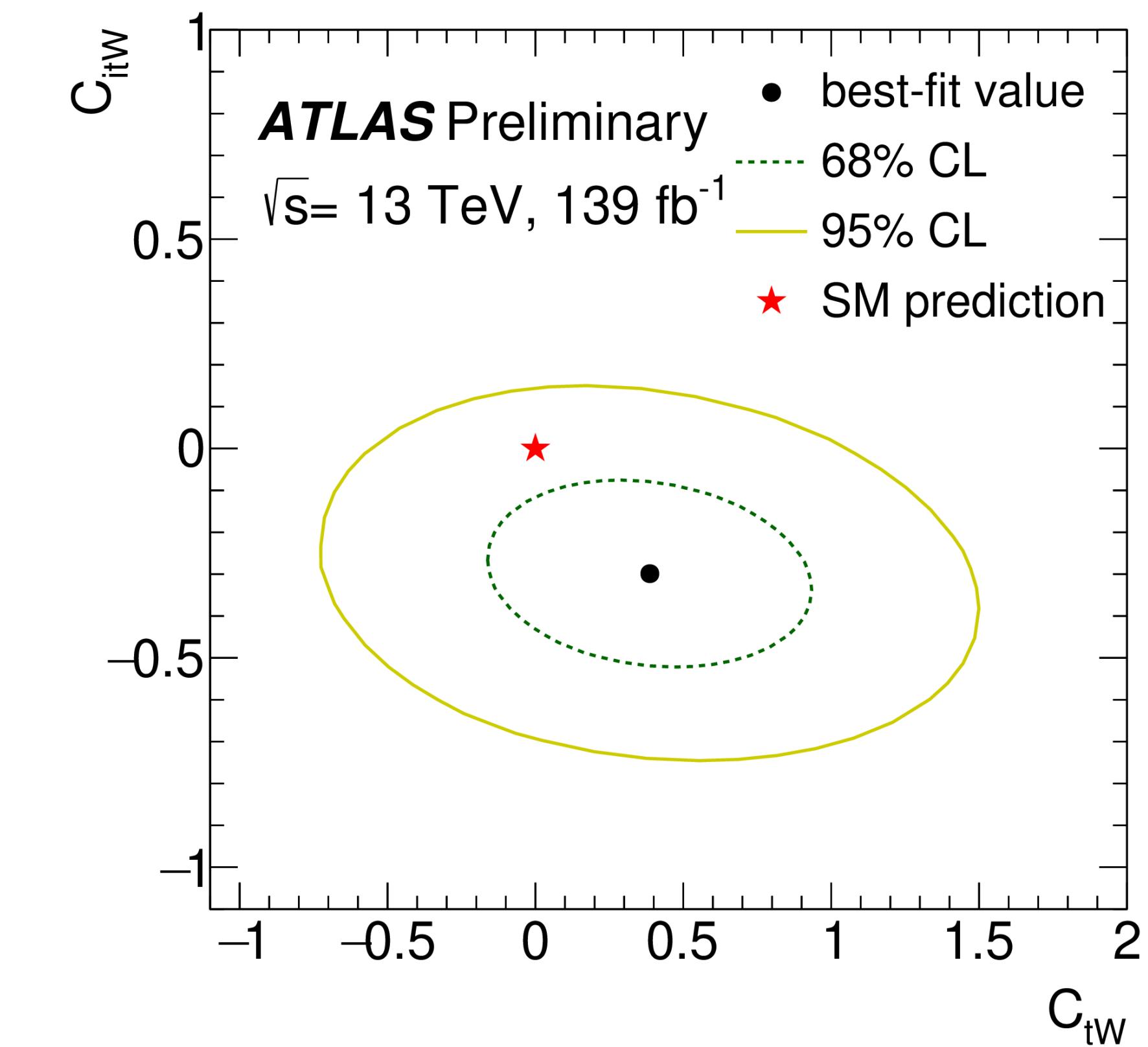
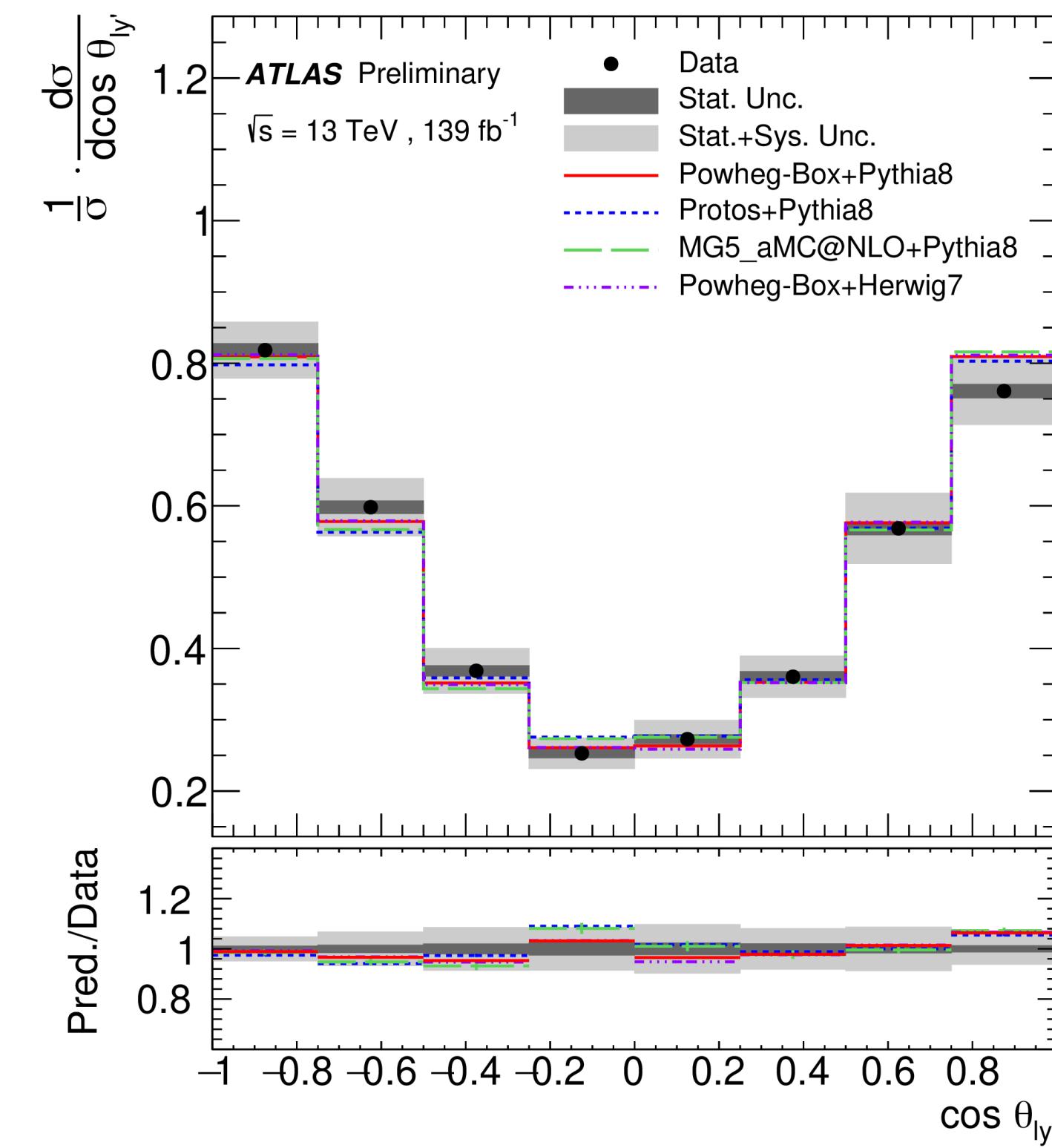
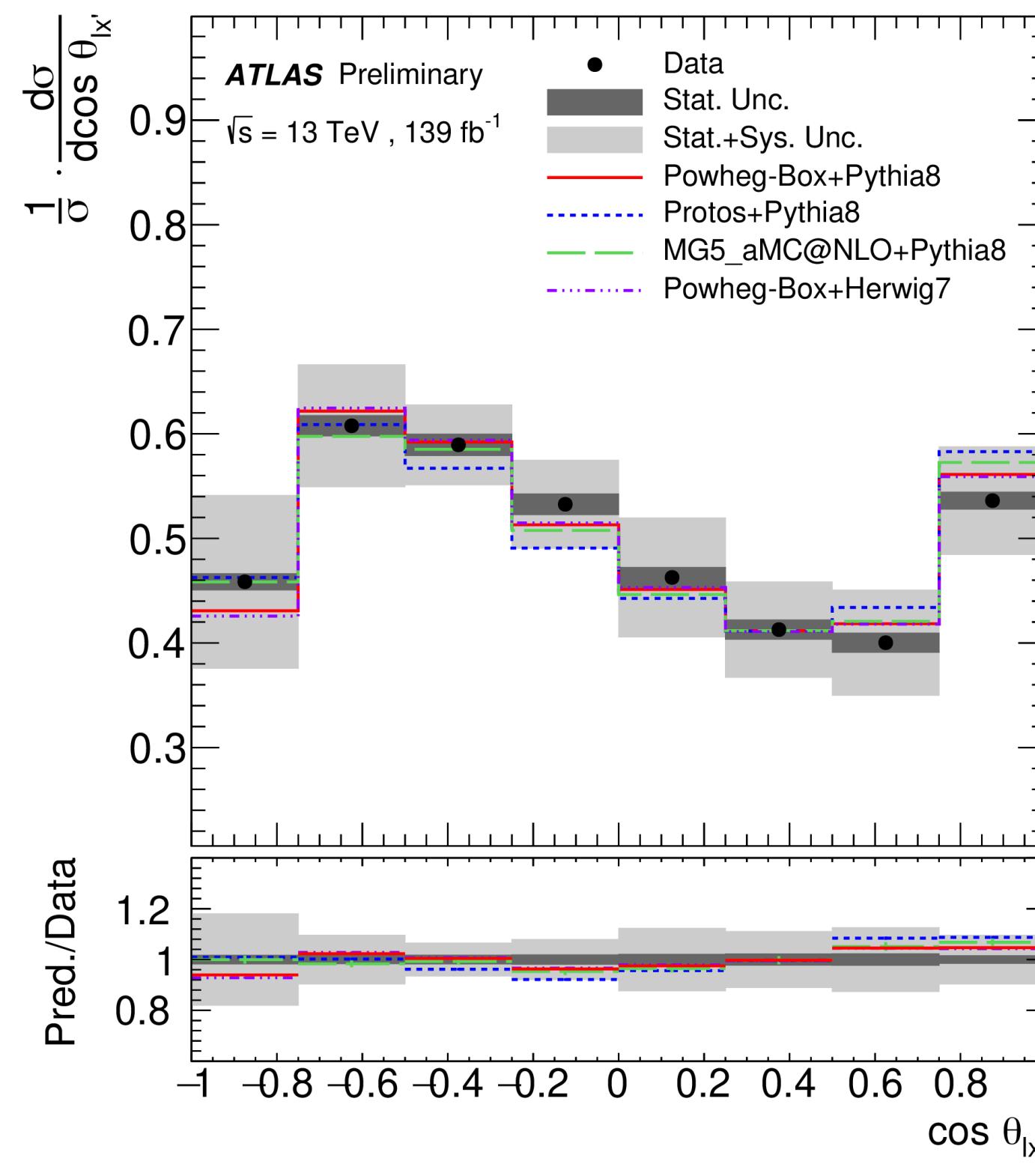


Top Polarisation in Single Top production

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Differential cross sections in $\cos \theta_{\ell x}$ and $\cos \theta_{\ell y}$ unfolded to particle level are also measured.

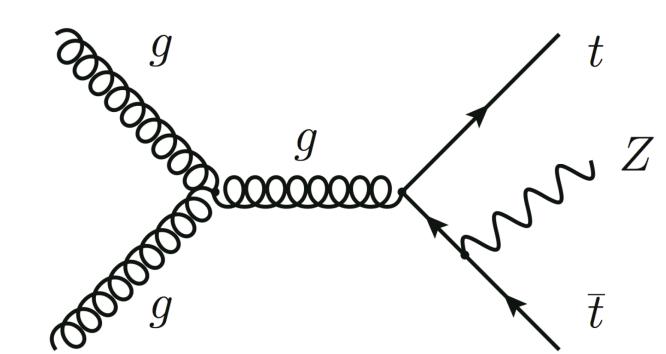
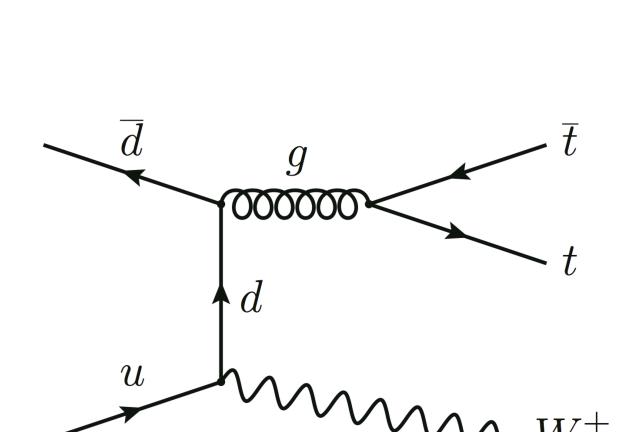
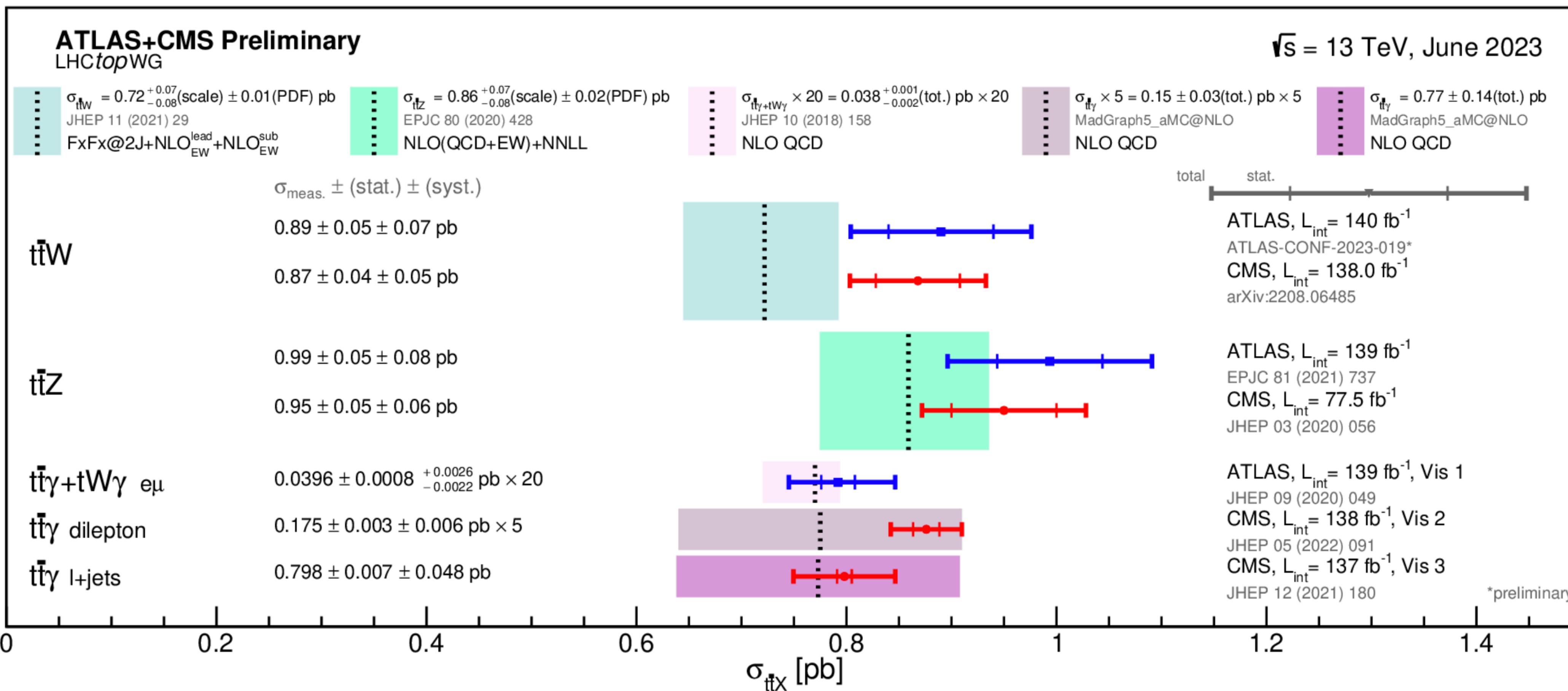
EFT Wilson coefficients for anomalous Dim. 6 tW coupling CP conserving and CP violating are fit simultaneously to the unfolded differential cross section measurements.



Top Pair Associated Production

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Very important ancillary measurements for many Higgs measurements (e.g. ttH ML) and searches!



Different processes ttW
ISR only and ttγ (ISR and
FSR)

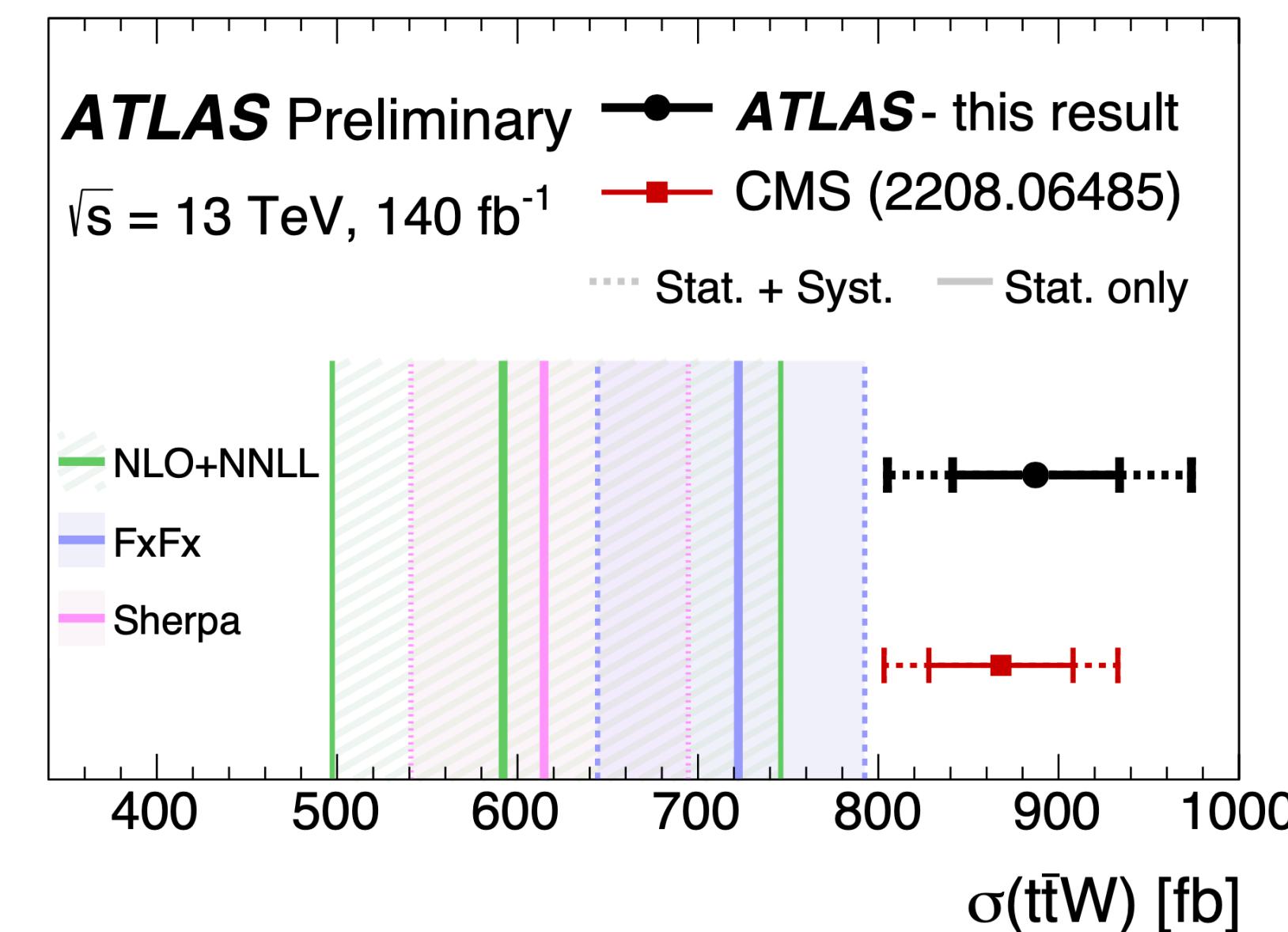
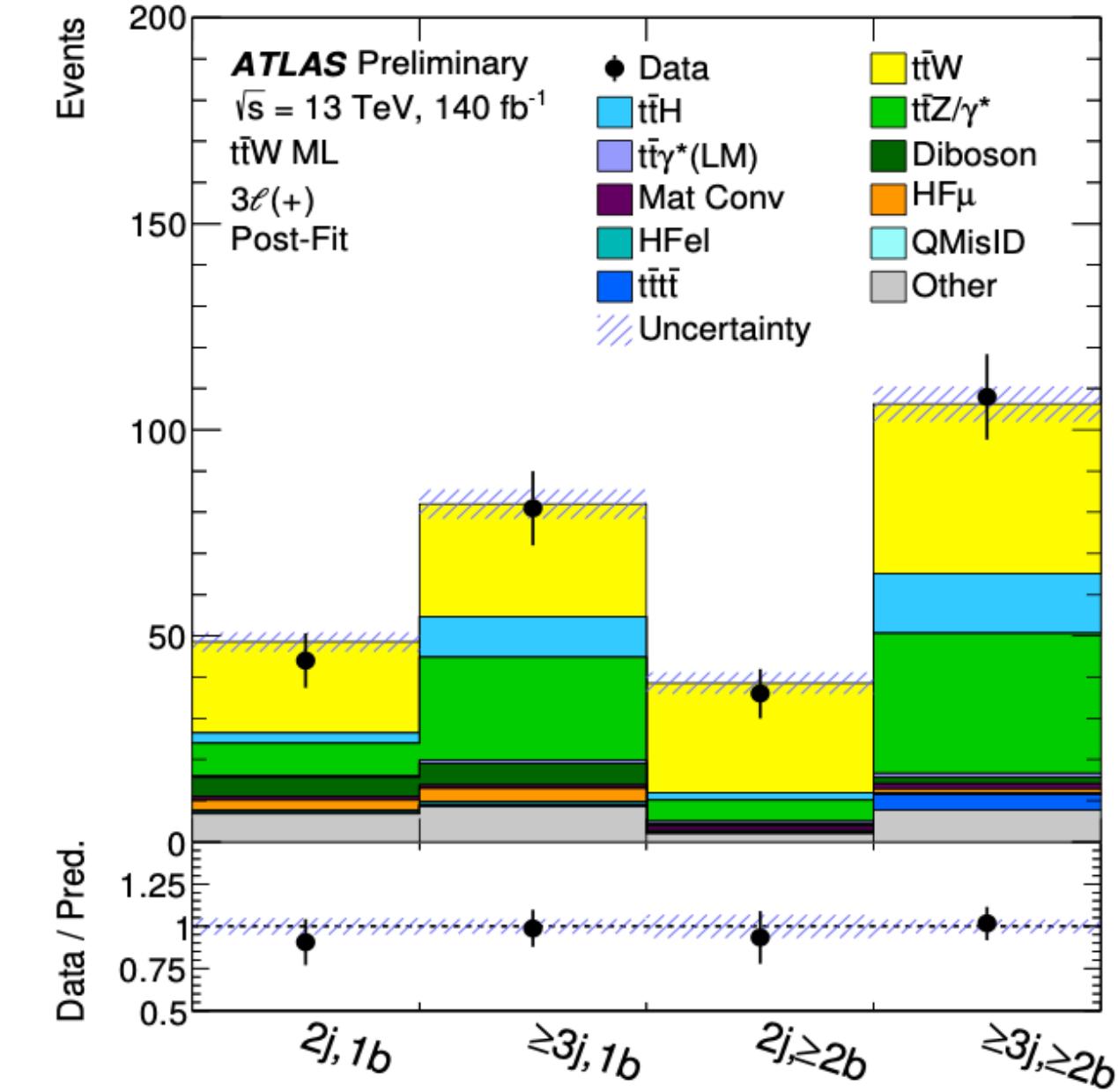
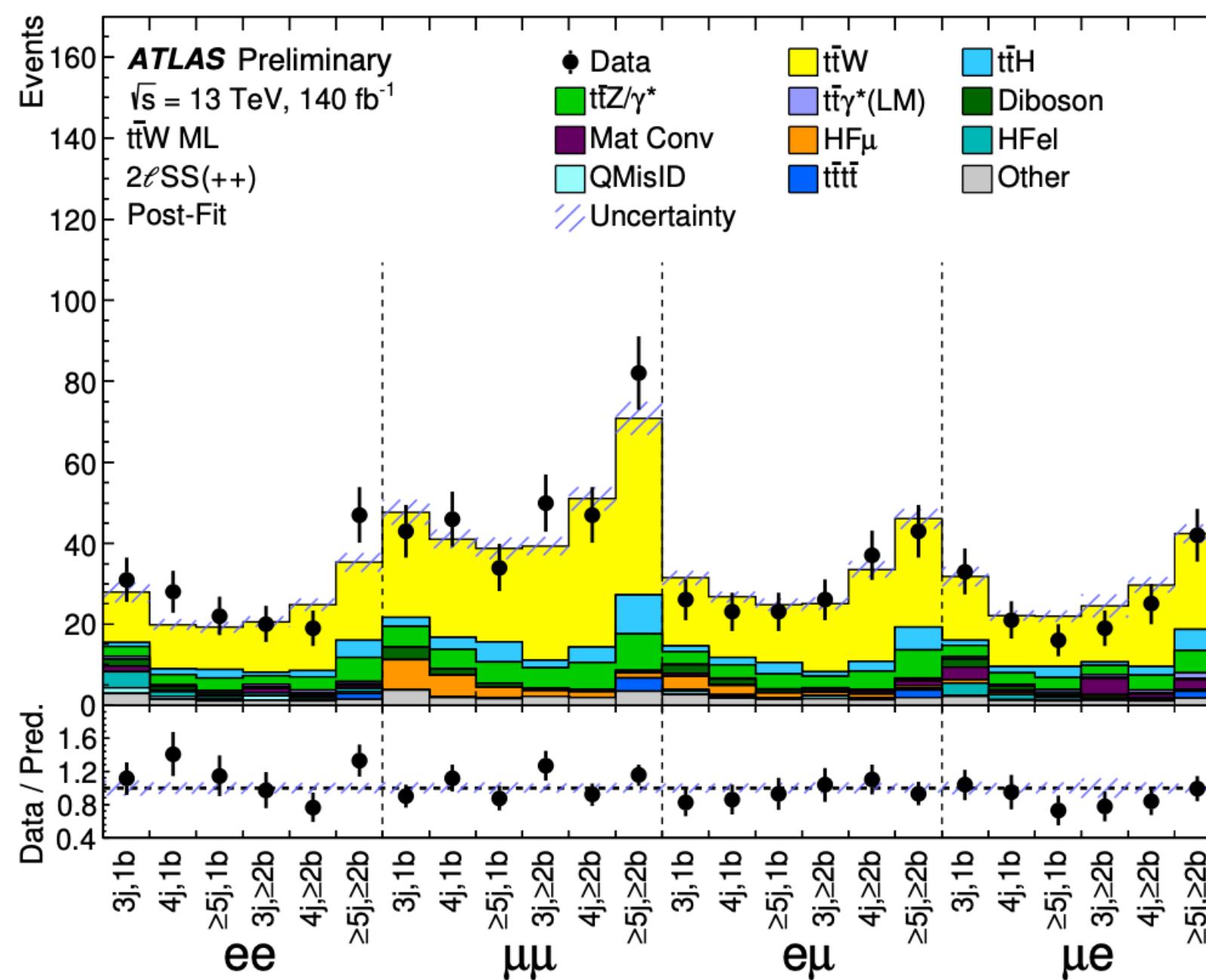
Associated production with a photon sensitive to the top quark charge.

Top Associated Production

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ATLAS Measurement of the $t\bar{t}W$ inclusive and differential cross sections (in 2 same sign leptons channel and 3 leptons)

- Long standing discrepancies
- Critical ancillary measurement for very large number of measurements (e.g. $t\bar{t}H$)



consistent at 1.5σ with theory calculation

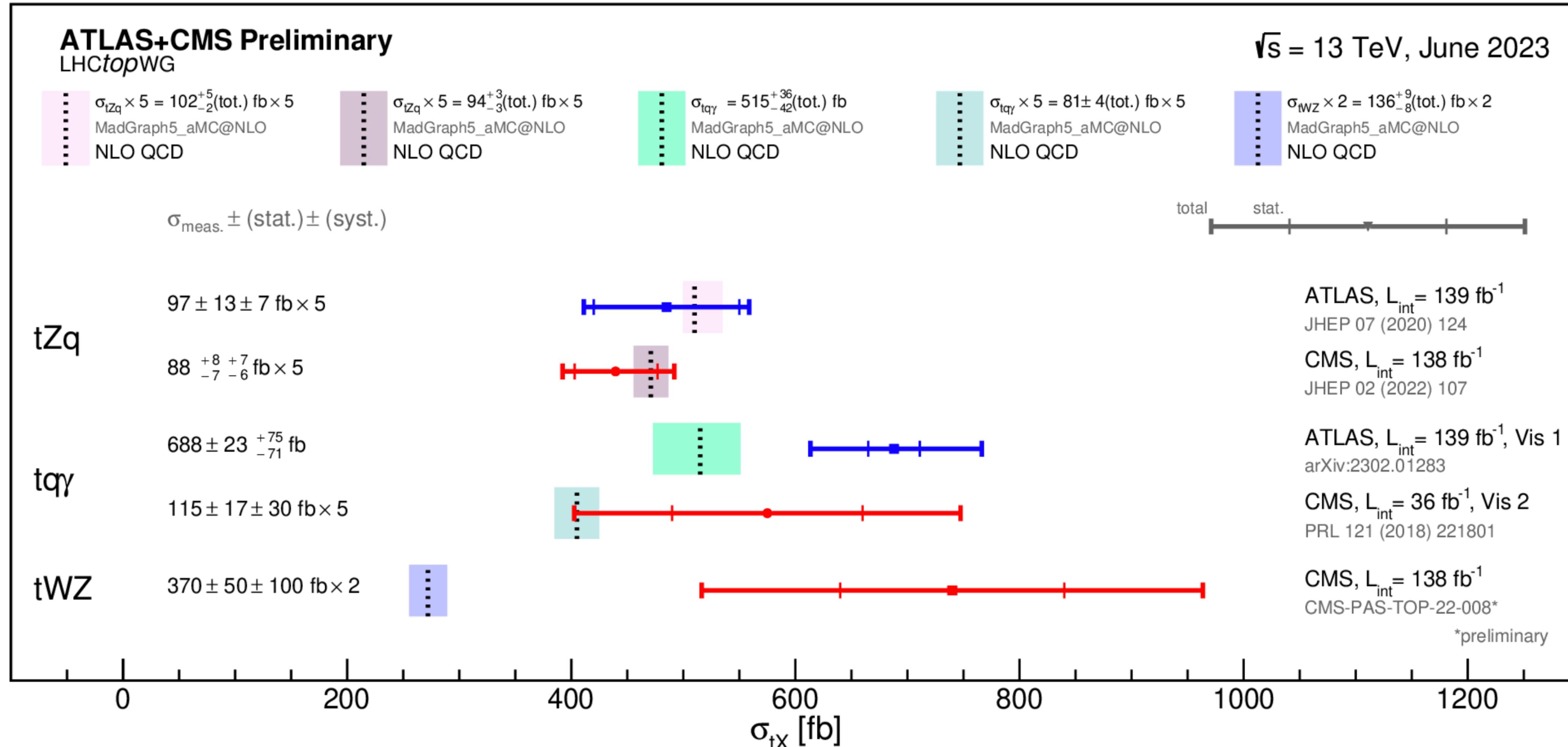
$\sigma_{t\bar{t}W} = 722^{+70}_{-78}$ (scale) ± 7 (PDF) fb

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$\sigma_{t\bar{t}W} = 890 \pm 50 \text{ (stat)} \pm 70 \text{ (syst)} \text{ fb}$
9% relative uncertainty

Single Top Associated Production

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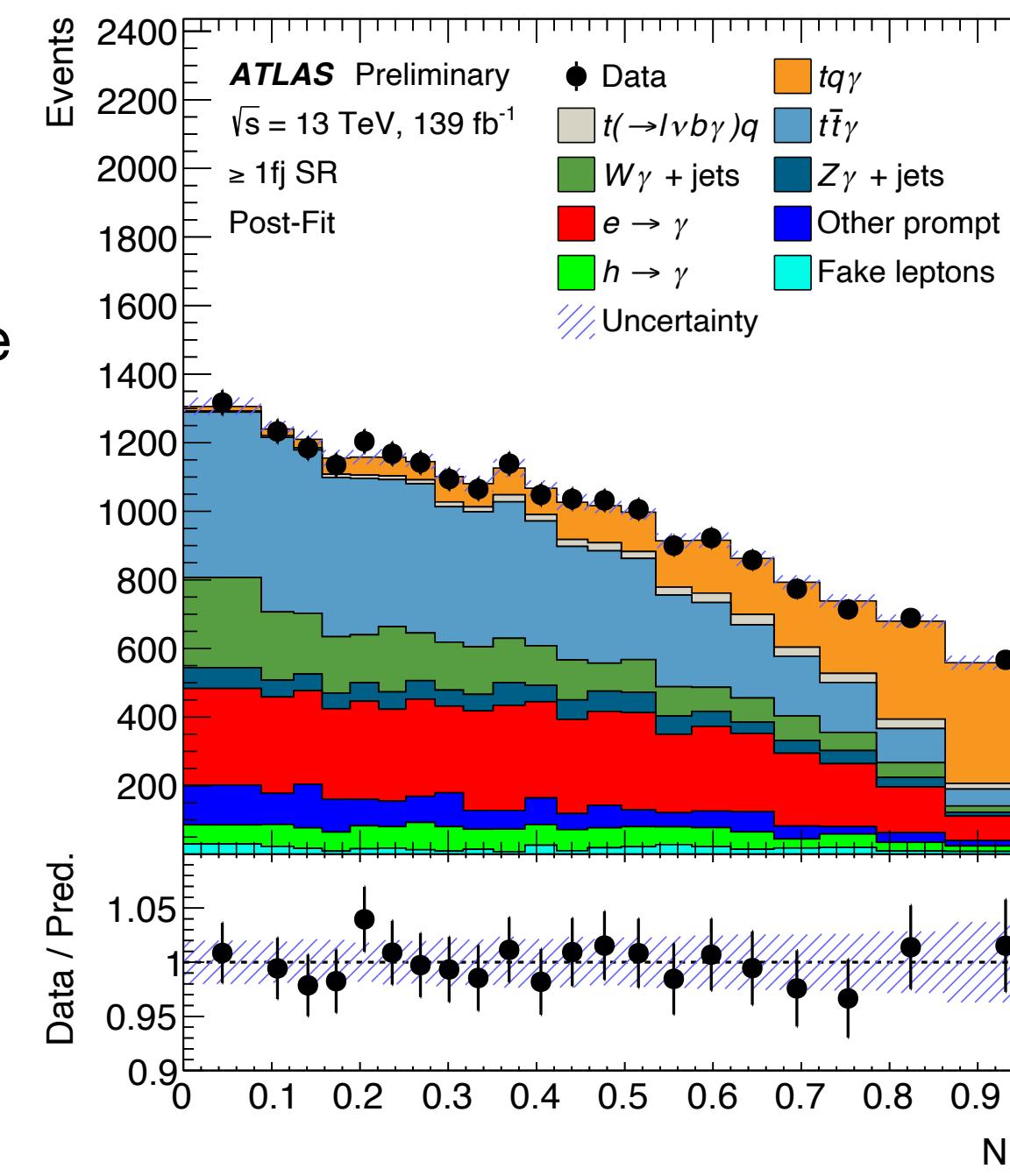
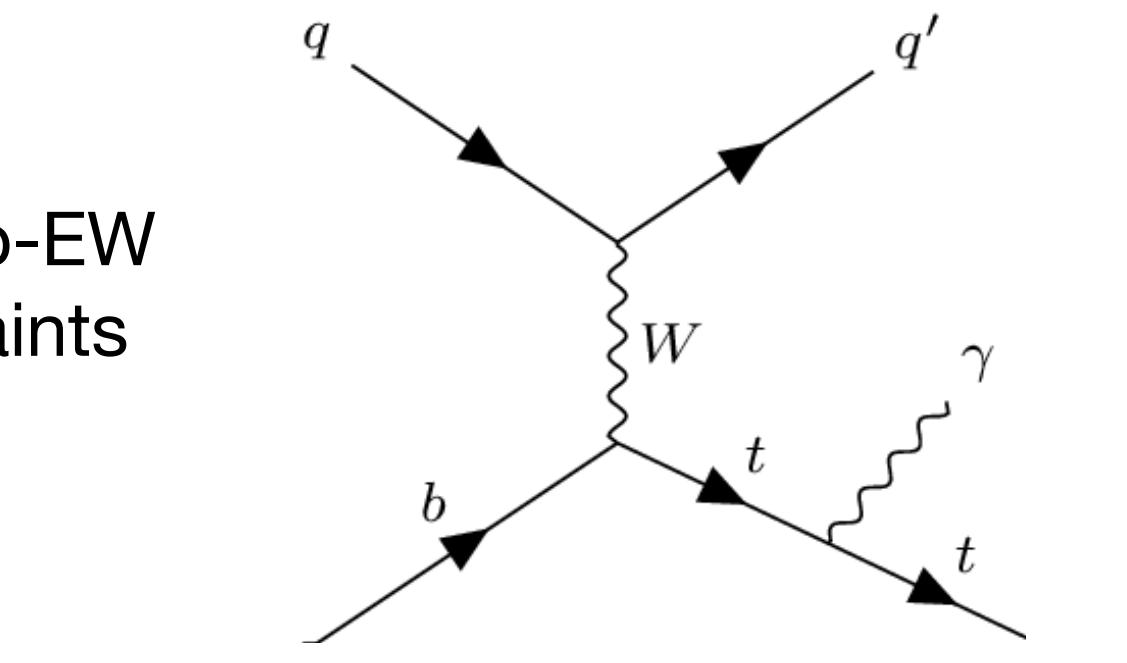
Rare single top production

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Rare single top process observation

$tq\gamma$ Single-top quark and a photon

Powerful probe of top-EW coupling (and constraints on new physics)



Search in the semi-leptonic top decay mode

Requires 1-forward jet

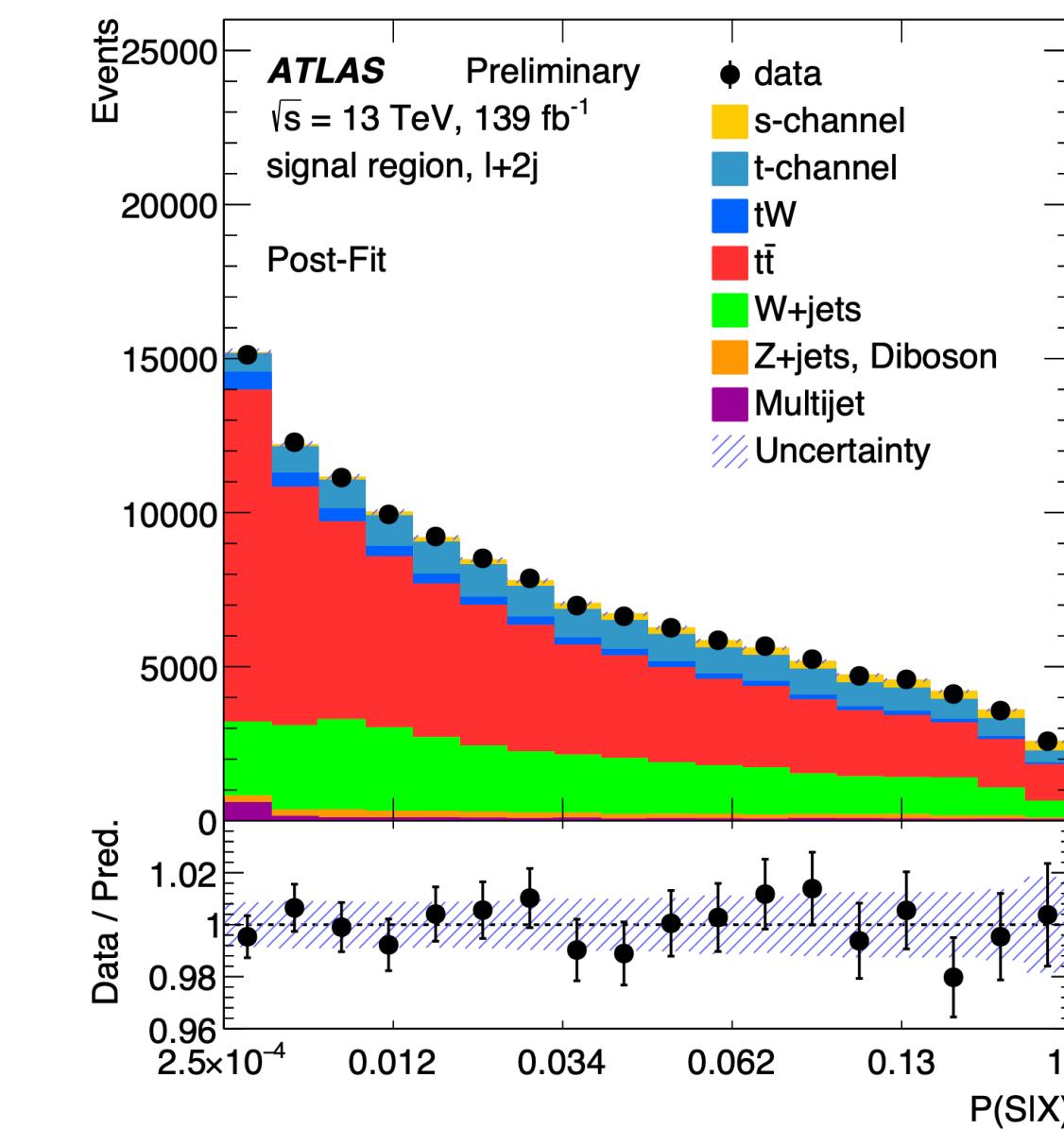
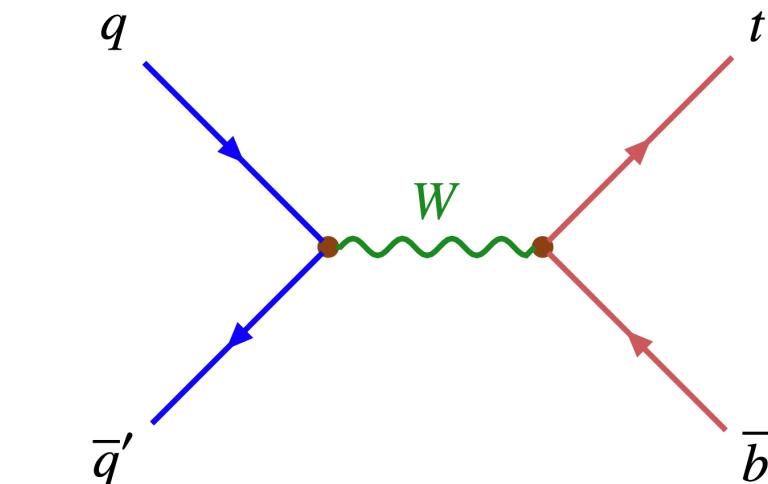
$$2.5 < |\eta_{\text{jet}}| < 4.5$$

S-channel single top production

More challenging at higher energies to the smaller relative increase w.r.t. top pairs

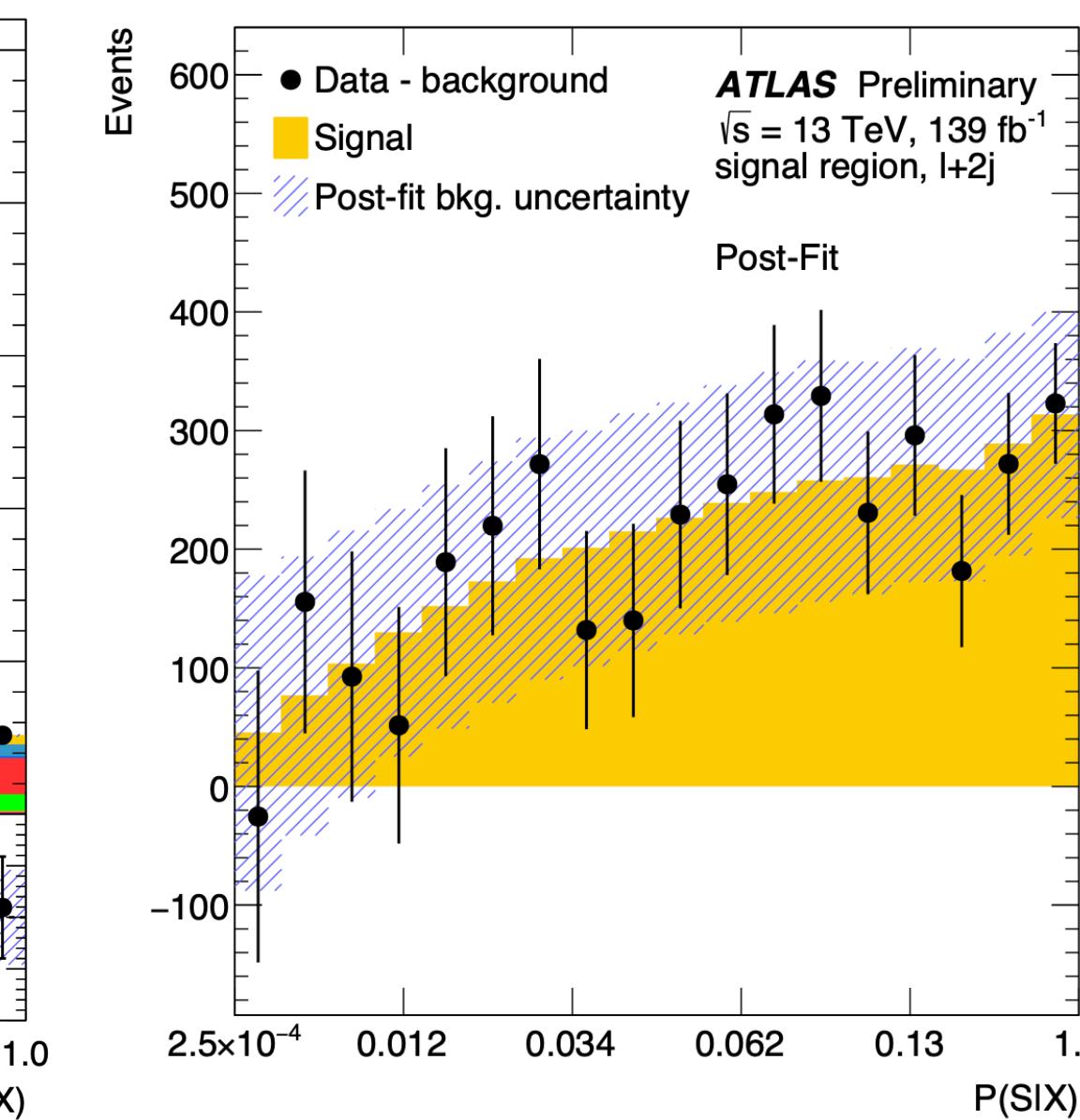
Lowest cross-section measurement of all single-top processes!

Same sensitivity as Run 1 with 7 times more data!



Matrix Element Probability for a given event X to be a signal event S $P(S|X)$

Measurement dominated by systematic uncertainties:



3.3 σ Observed (3.9 σ expected)

Prediction at NLO QCD

$$\sigma_s = 8.2^{+3.5}_{-2.9} \text{ pb}$$

$$\sigma_s^{SM} = 10.3 \pm 0.4 \text{ pb}$$

Main systematic:

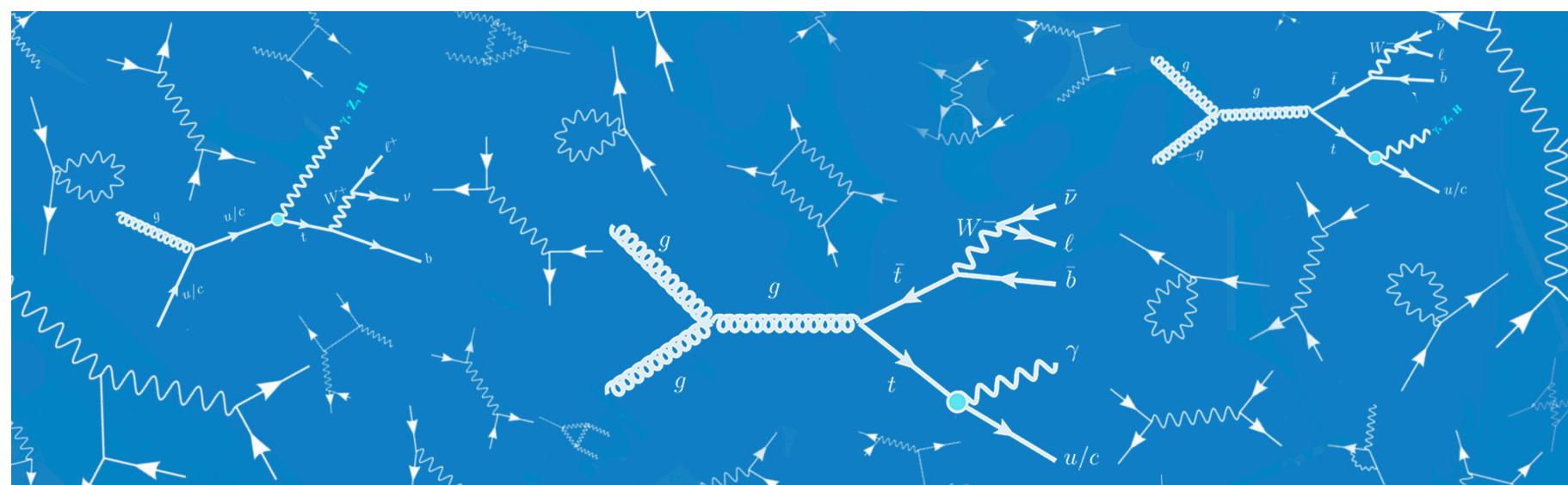
W-jets and top modelling

Jet energy scale and resolution

Top FCNC Decays

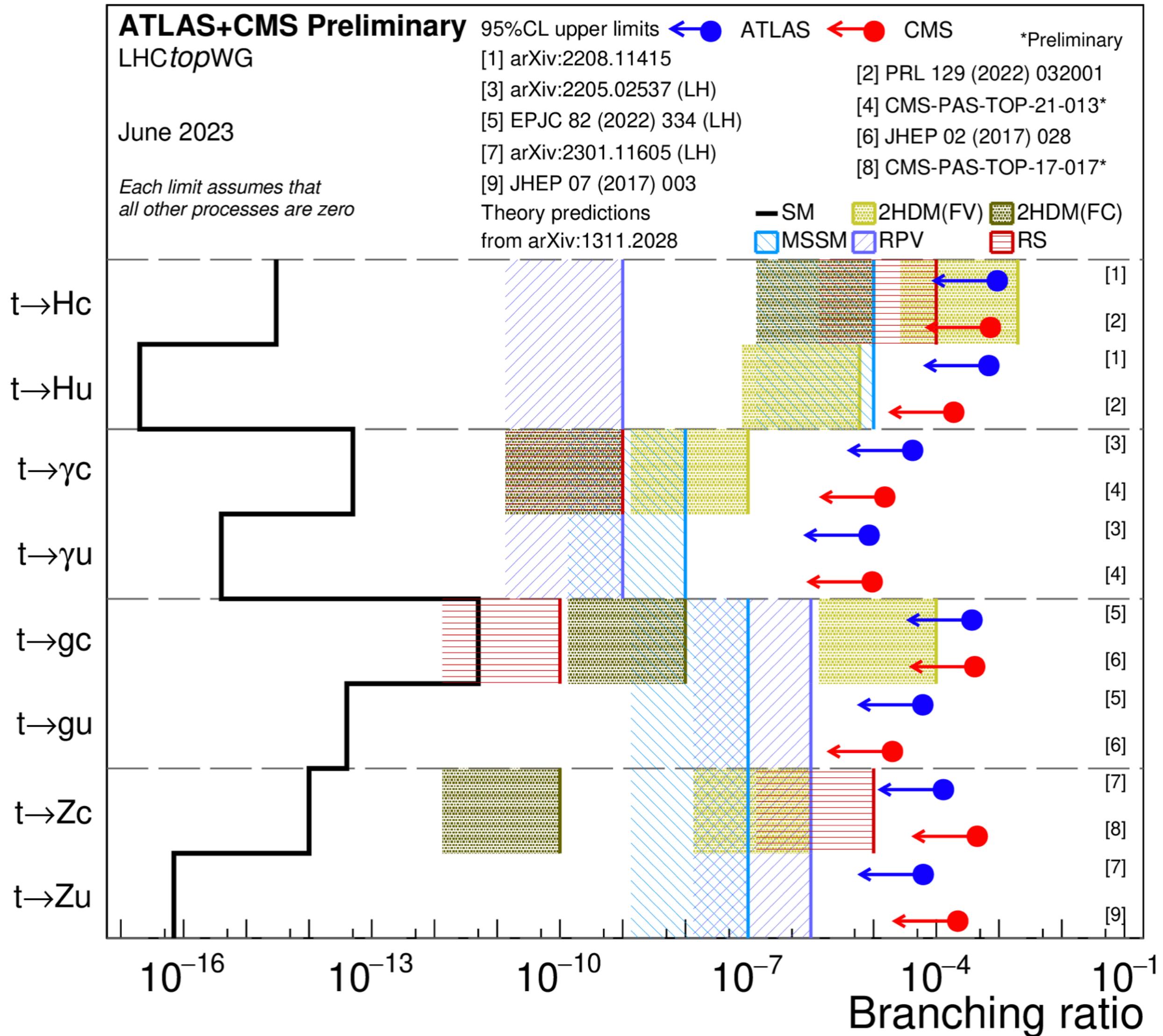
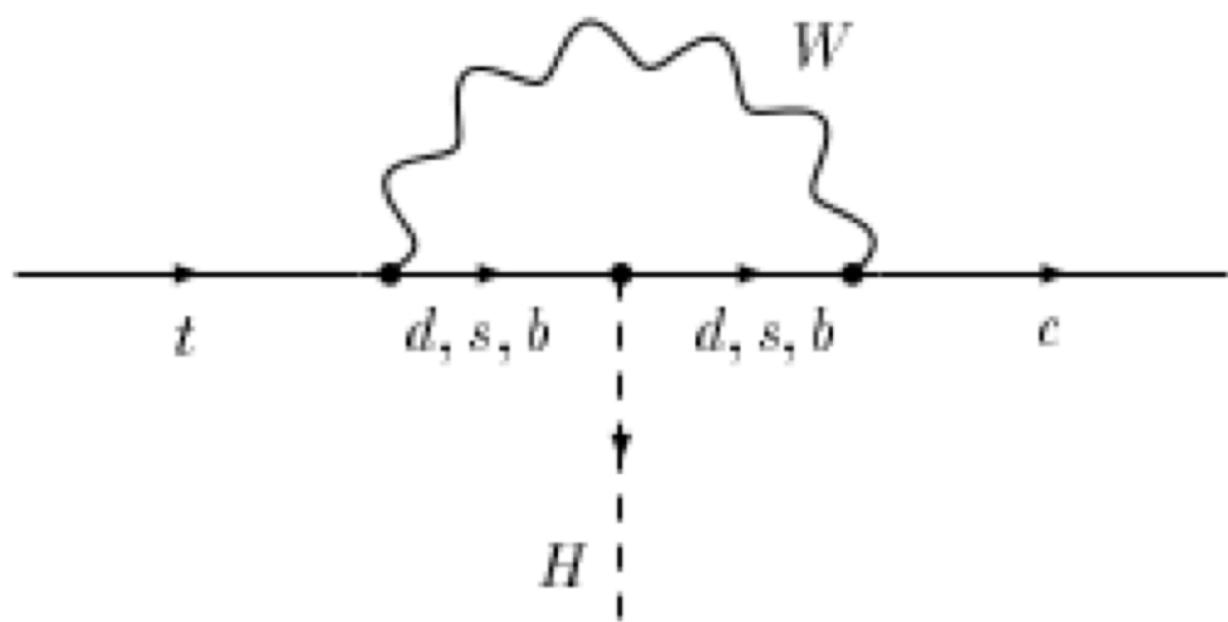
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Looking for top quarks going against the current!



ATLAS Physics [Briefing](#)

Rare top quark decays include CKM suppressed 2-body Ws(d) or N-body decays, FCNCs are greatly suppressed but could also be strongly enhanced due to BSM physics!

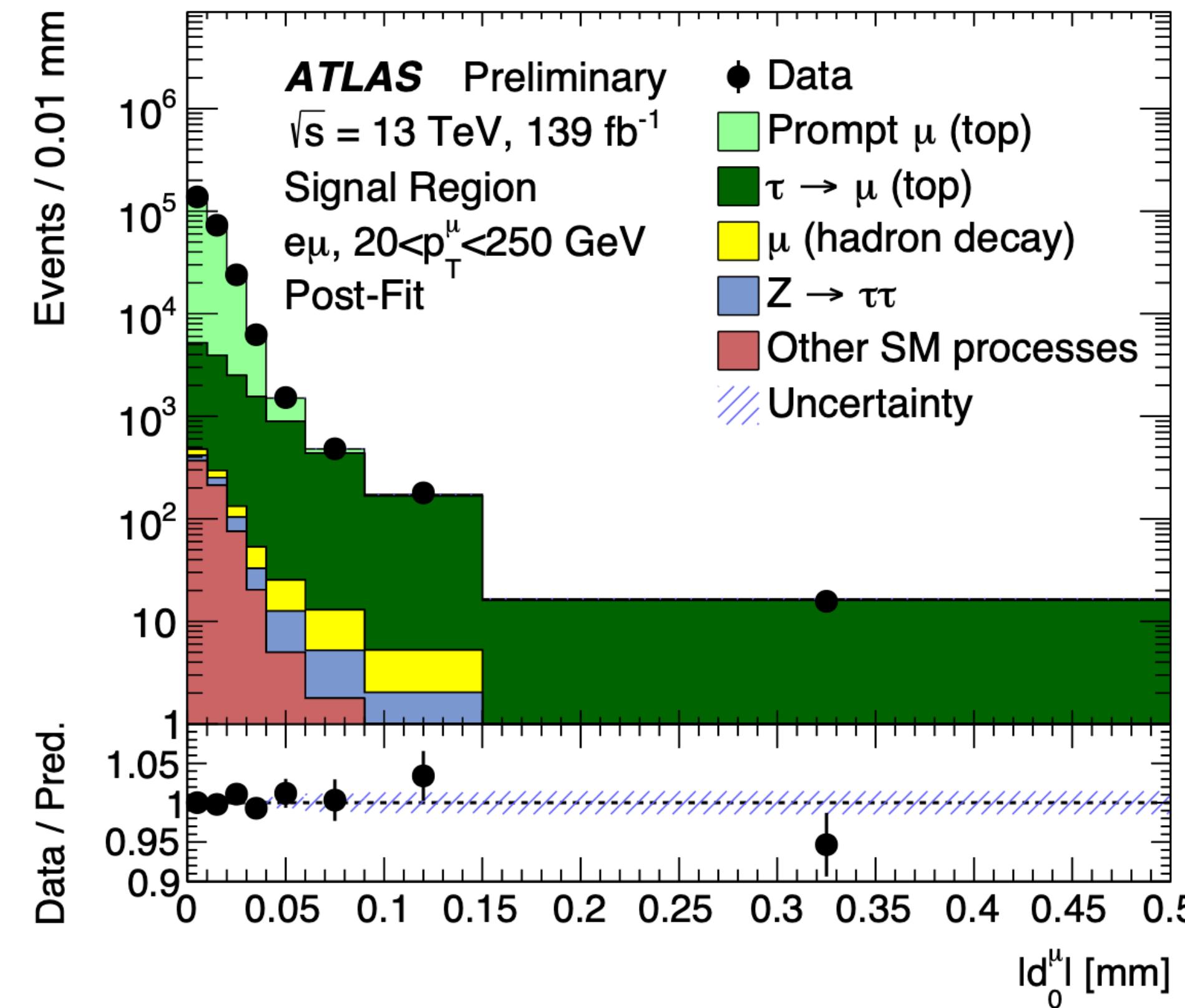


Measurement of Lepton Universality, W's from top

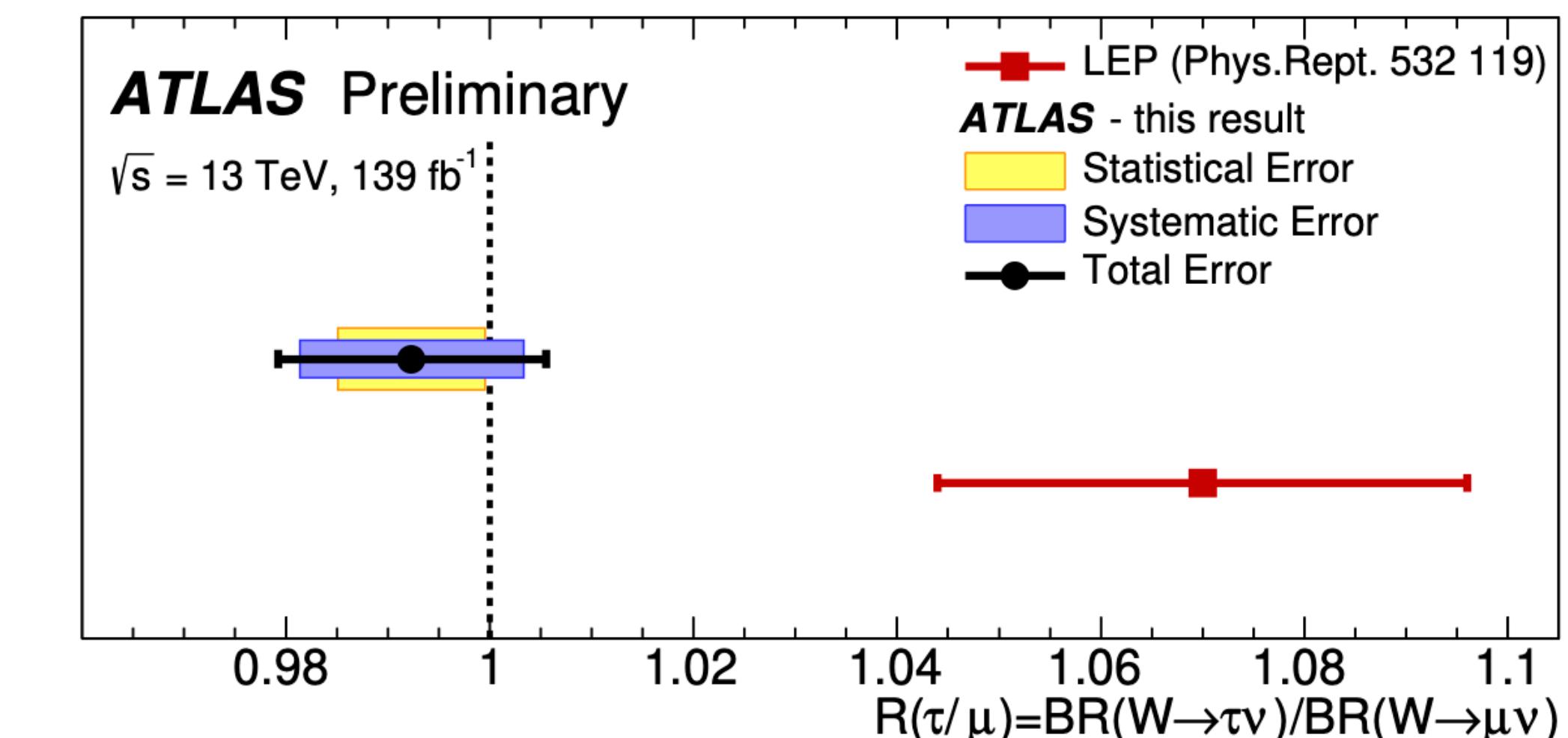
W boson decays to taus and muons

Probing a long standing 2.7 standard deviation discrepancy (since LEP)

See [ATLAS press release](#)



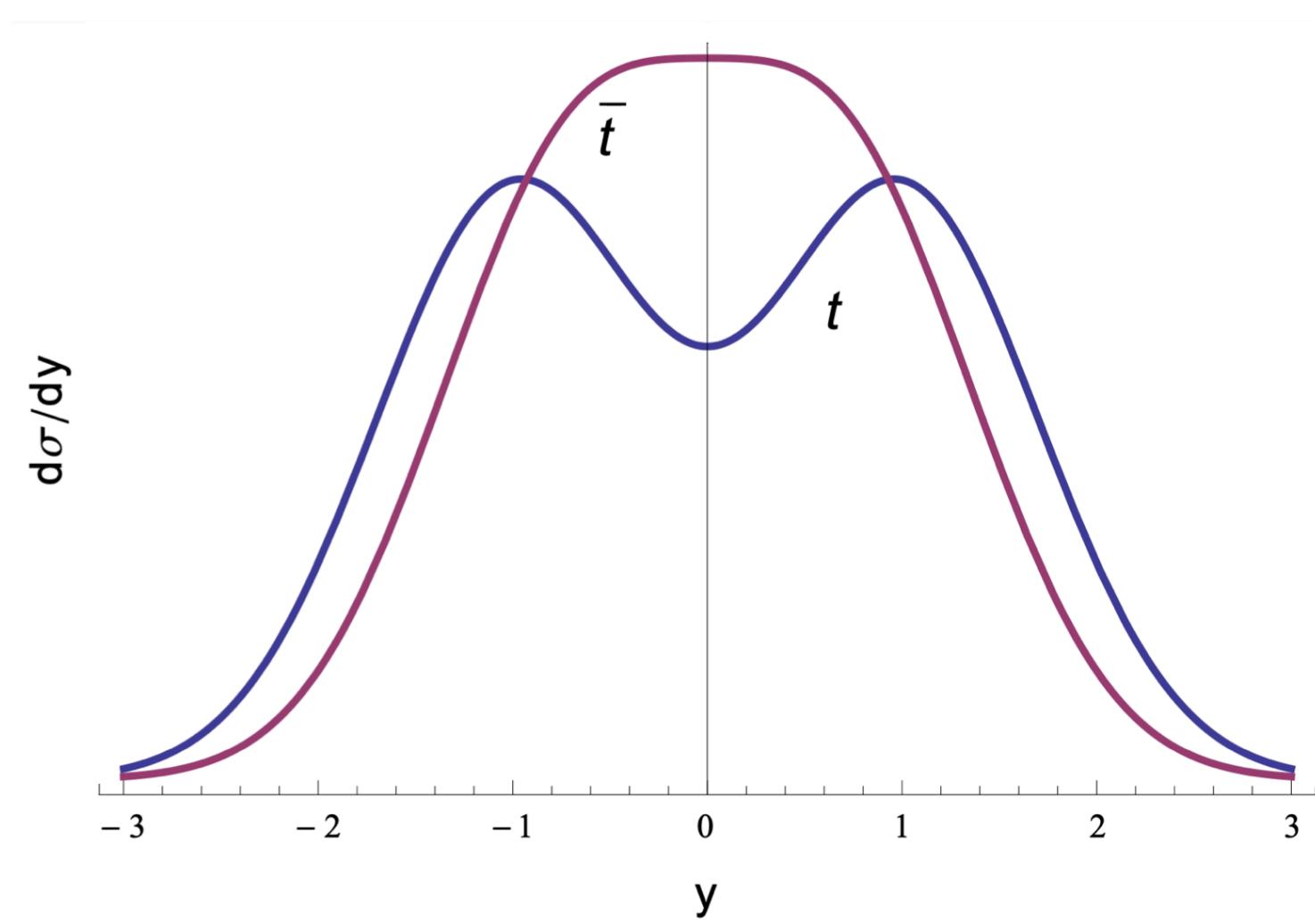
Using top pair production as a pure source of W bosons and investigating those tau decays to muons (from their impact parameter).



Top Charge Asymmetry

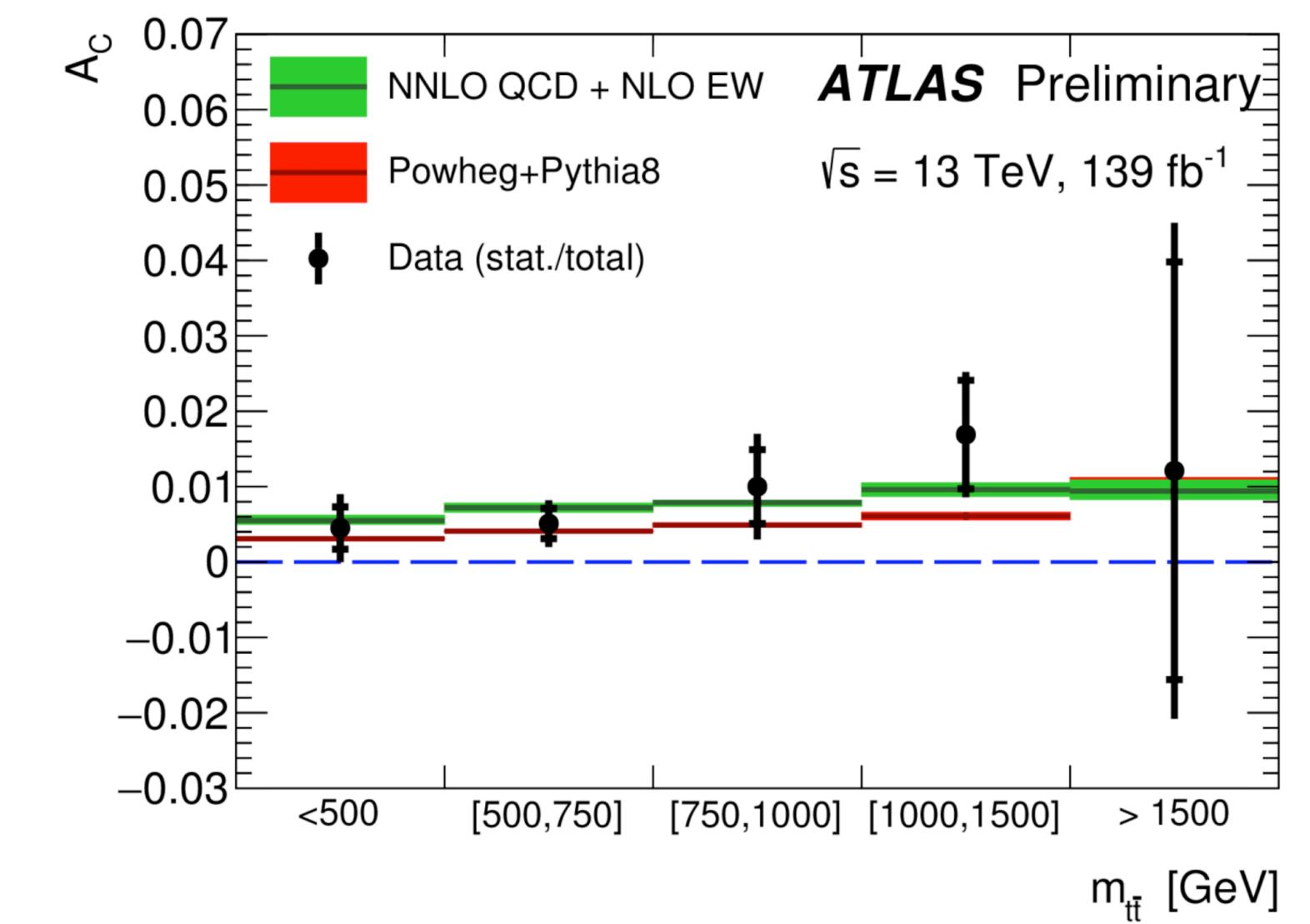
While at the Tevatron there is a forward-backward asymmetry between t and \bar{t} at the LHC the asymmetry in charge makes t to be produced more centrally and \bar{t} more forward. See [ATLAS Briefing](#).

The charge asymmetry arises from the interference at tree level $q\bar{q} \rightarrow t\bar{t}g$ (between ISR and FSR) and in $q\bar{q} \rightarrow t\bar{t}$ in the interference between the s-channel lowest level diagram and the box. The effect grows with the invariant mass of the $t\bar{t}$ system.



$$A_C^{t\bar{t}} = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

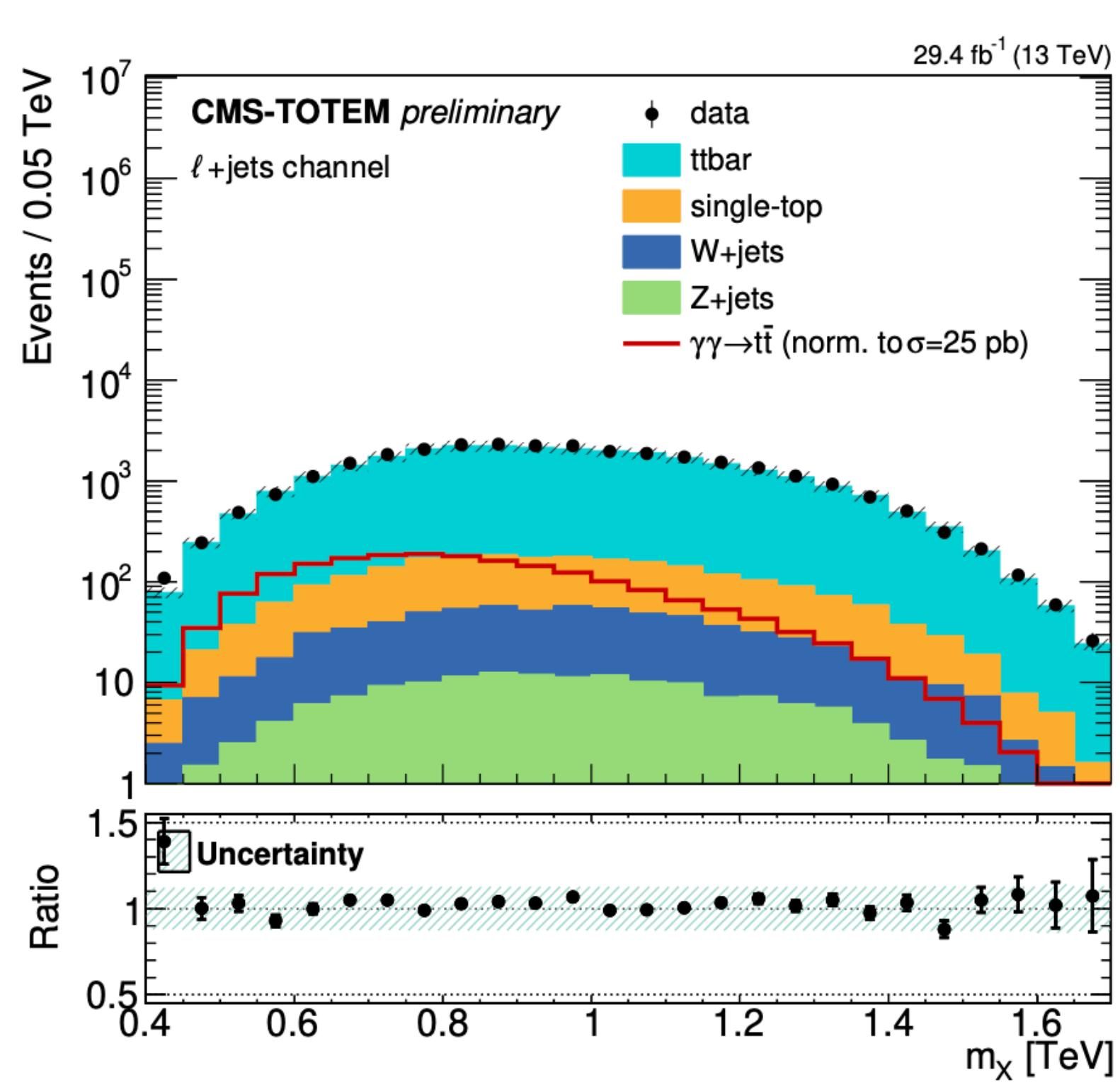
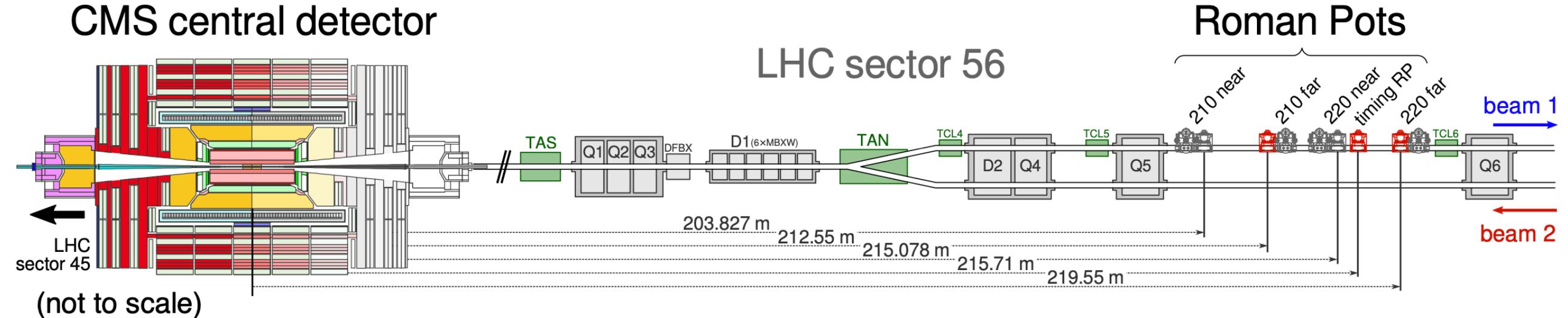
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



Effect observed at the 4 s.d. level

$$A_C = 0.0060 \pm 0.0015$$

Top Exclusive Production



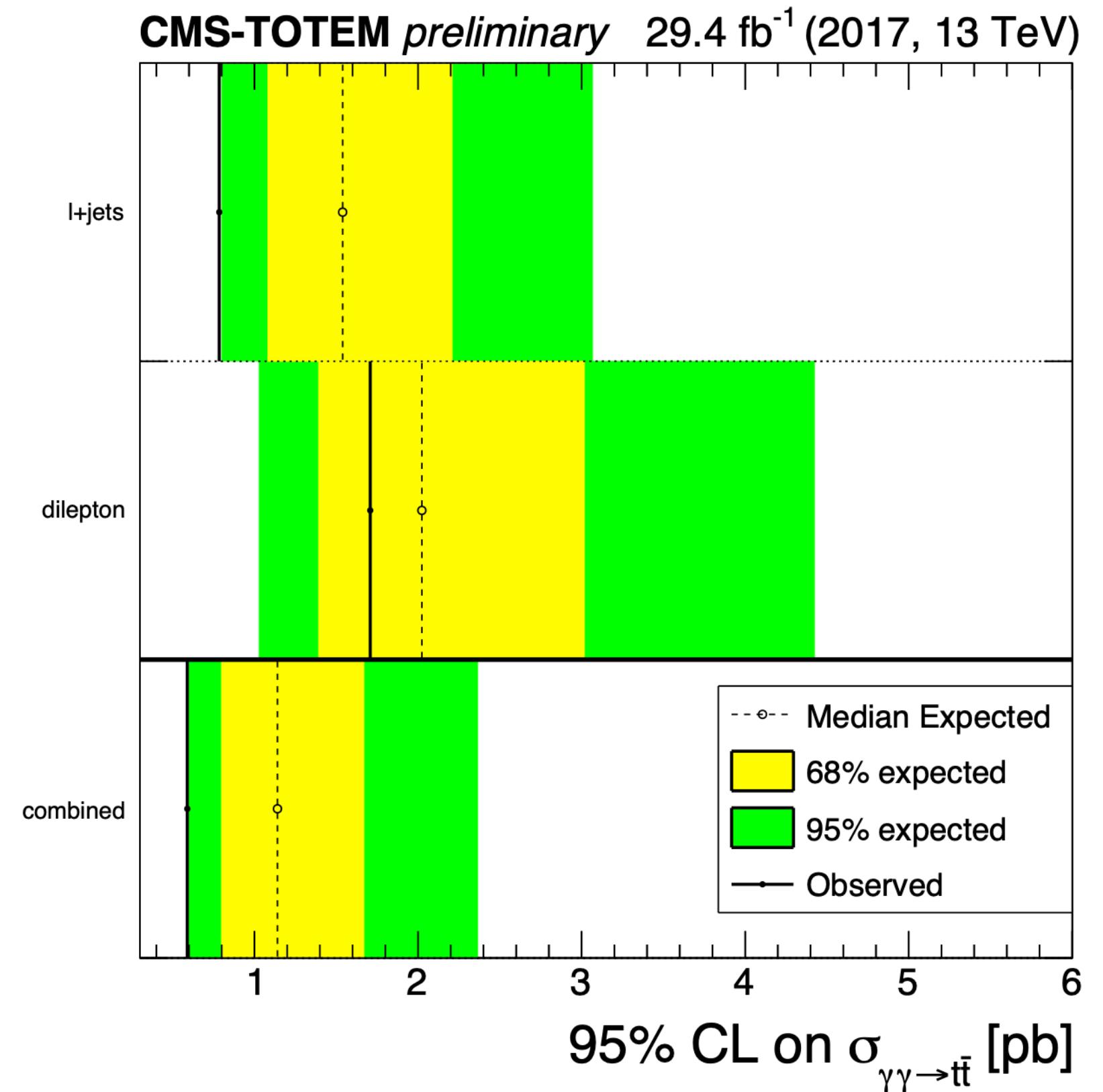
With discrimination form the forward proton tagging.

$$M_X = \sqrt{s\xi_1\xi_2}$$

Where ξ_1, ξ_2 are the fractional momentum loss of the intact protons in $pp \rightarrow p t \bar{t} p$

This process is sensitive to anomalous EM couplings of the top quark.

Example of exclusive measurement in pp collisions with tagged protons in high luminosity running using CT-PPS (CMS-TOTEM Precision Proton Spectrometer)

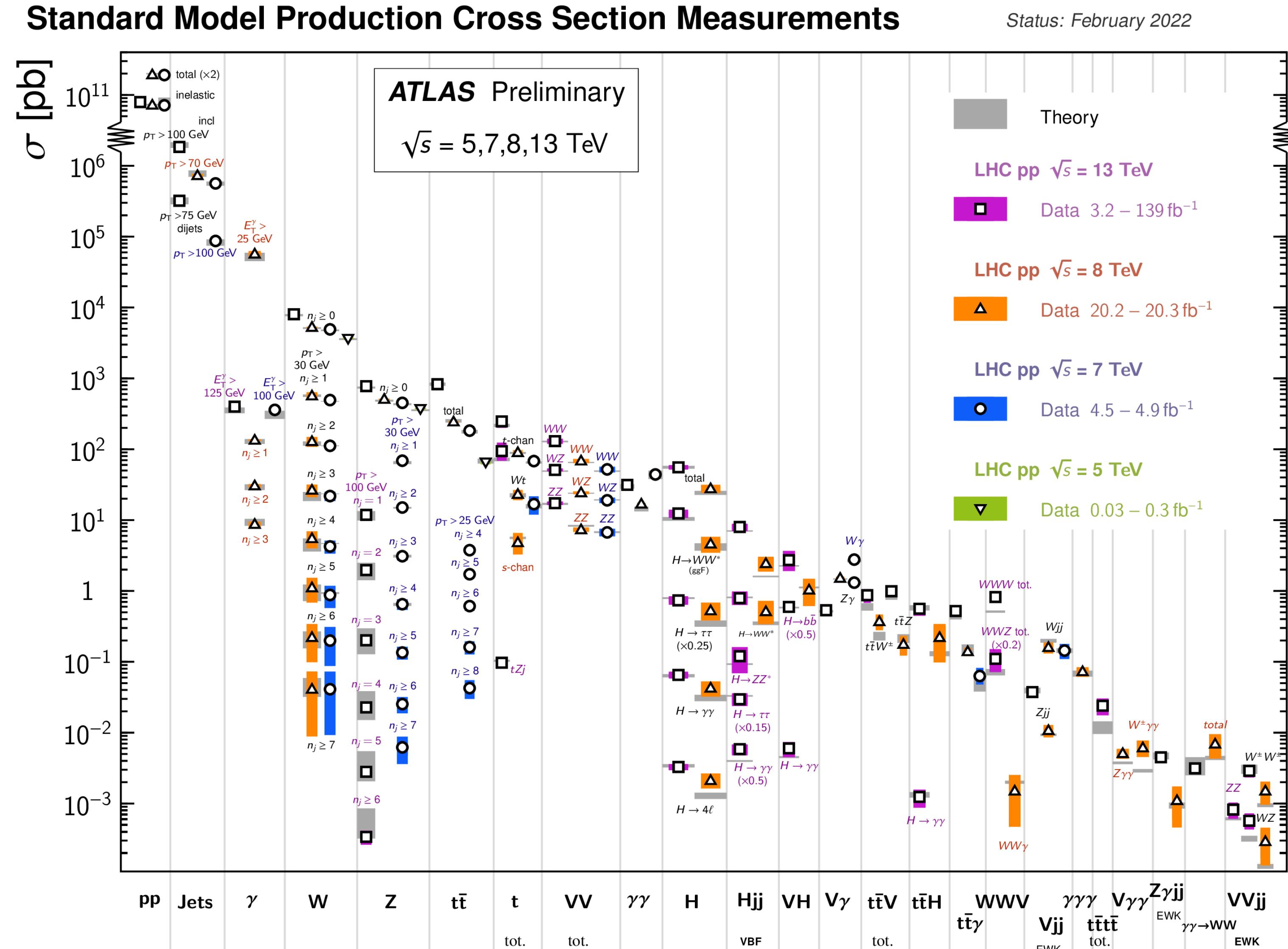


Global PDF Fit
Putting Everything Together...

Cross Section Measurements

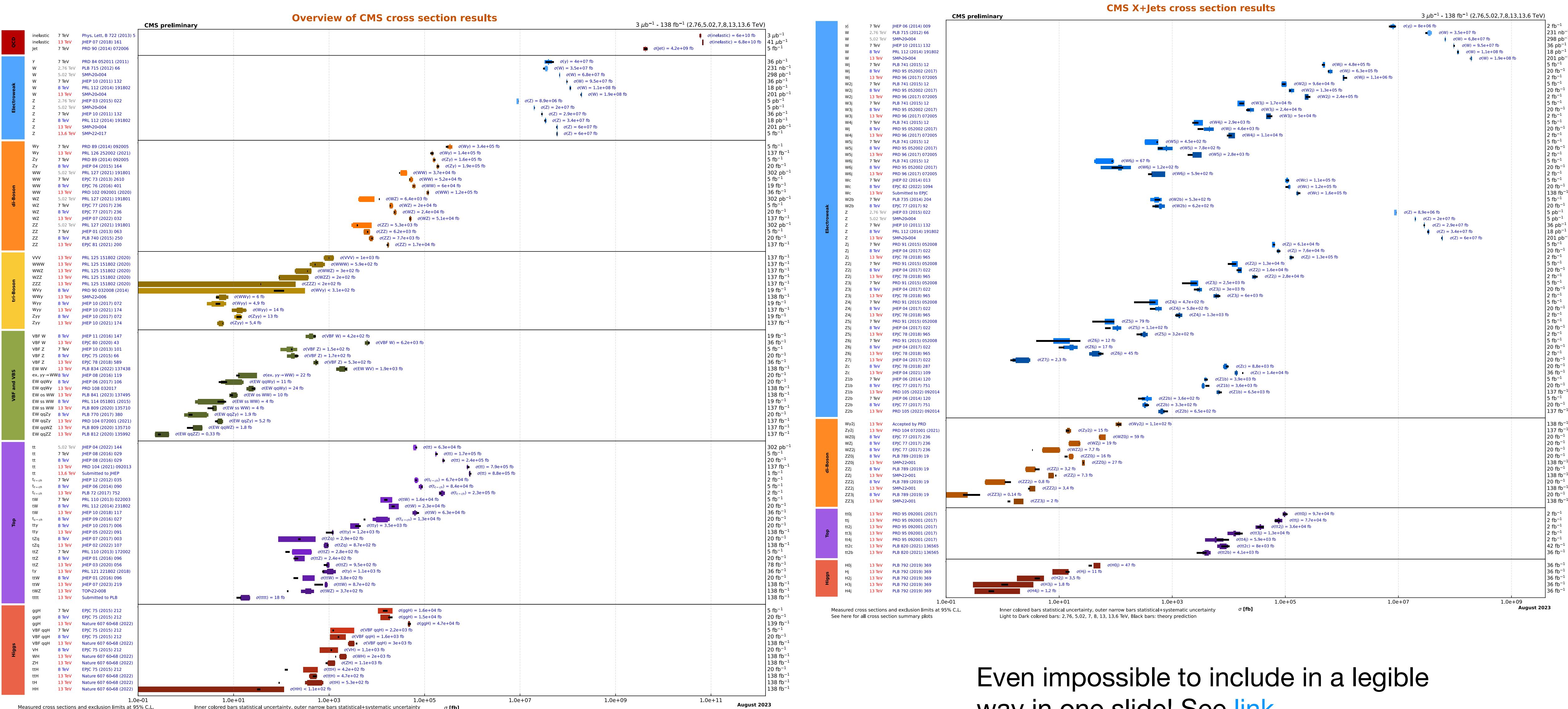
59

Vast number of cross section measurements made at the LHC



Cross Section Measurements

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even impossible to include in a legible
way in one slide! See [link](#).

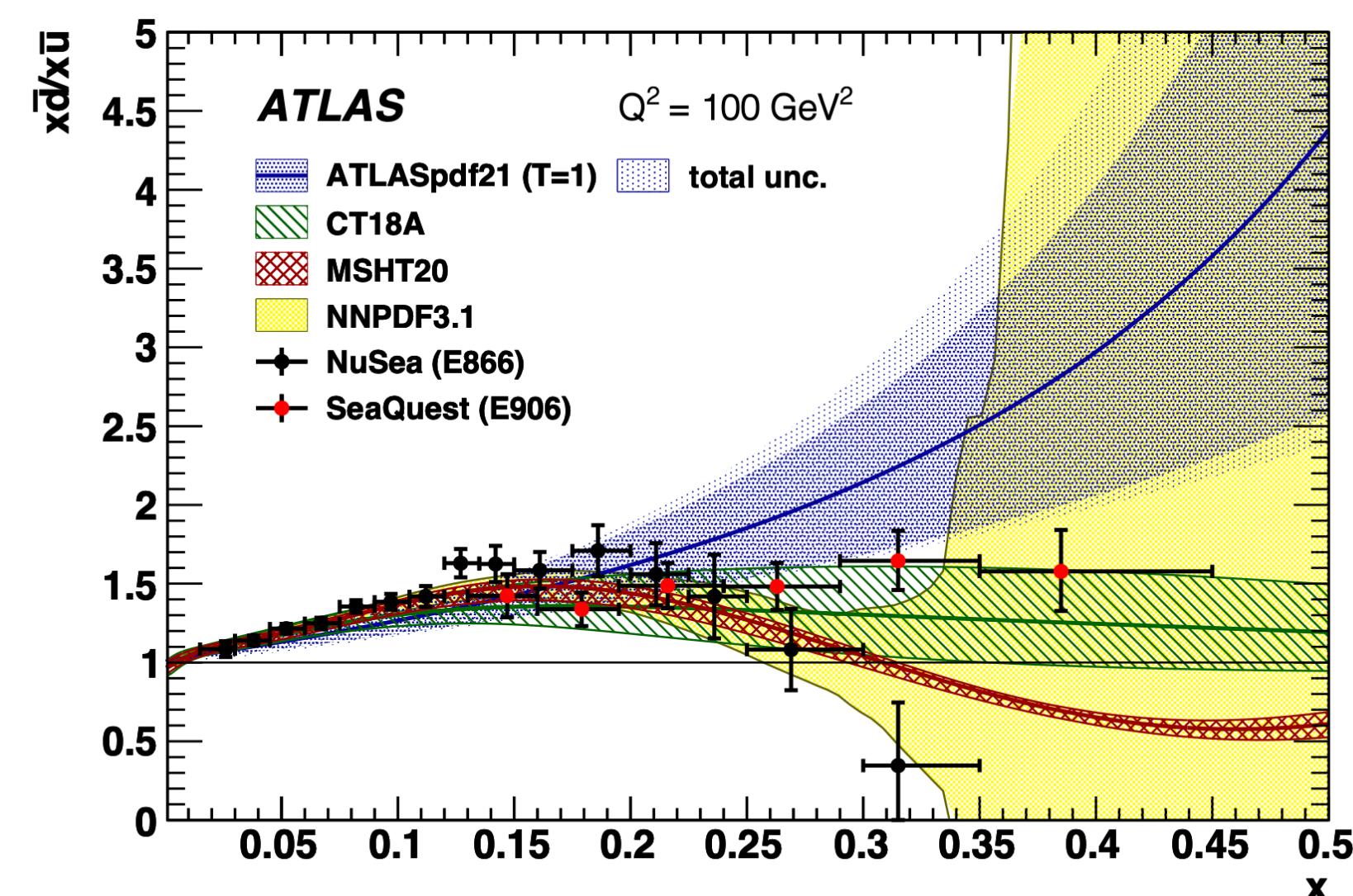
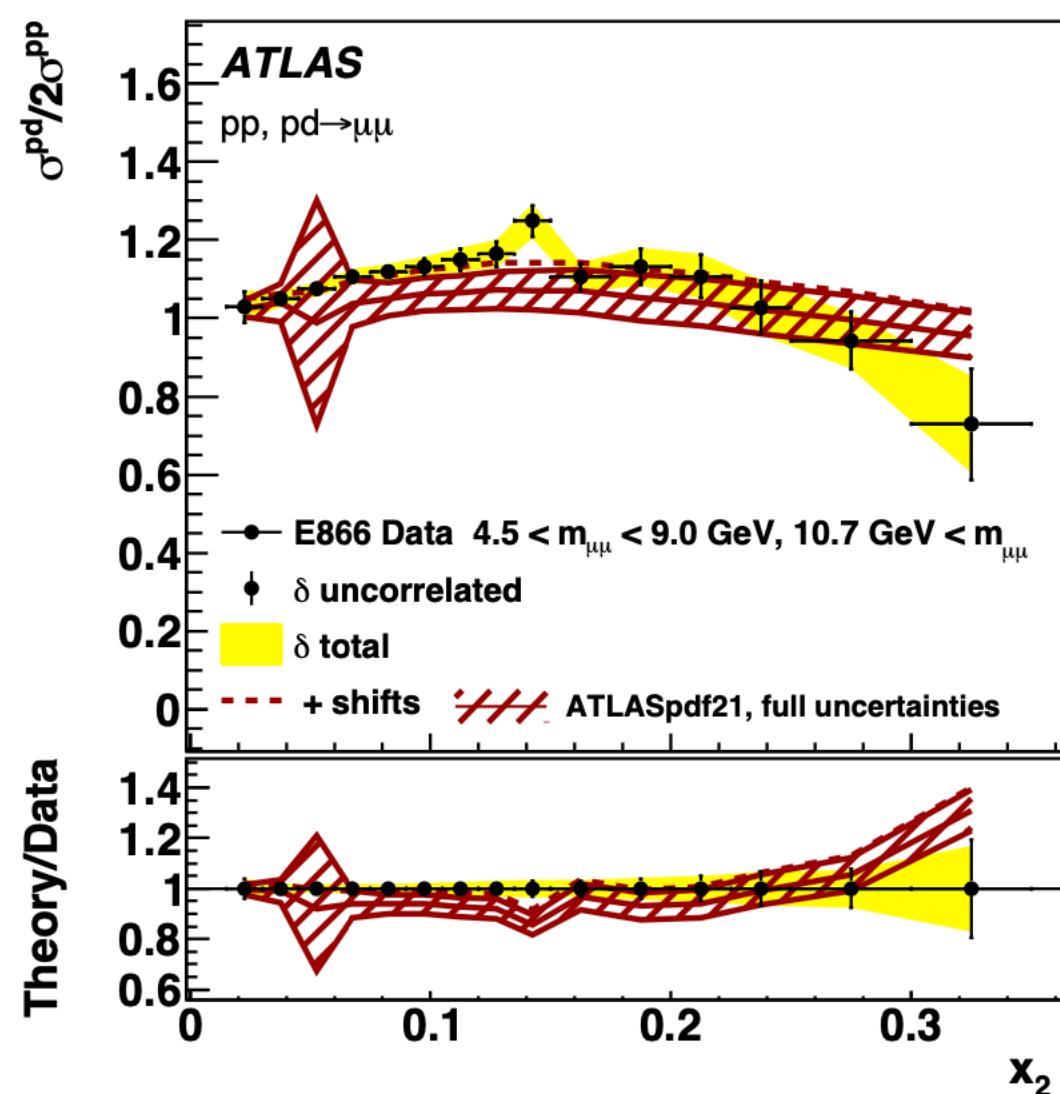
Global PDF Fits

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ATLAS PDF fit

Using exclusively HERA ep data and selected ATLAS measurements with the addition of **W, Z (+jets), tt, jets, photon** differential cross section measurements (fit done at NNLO in QCD, NLO in EW)

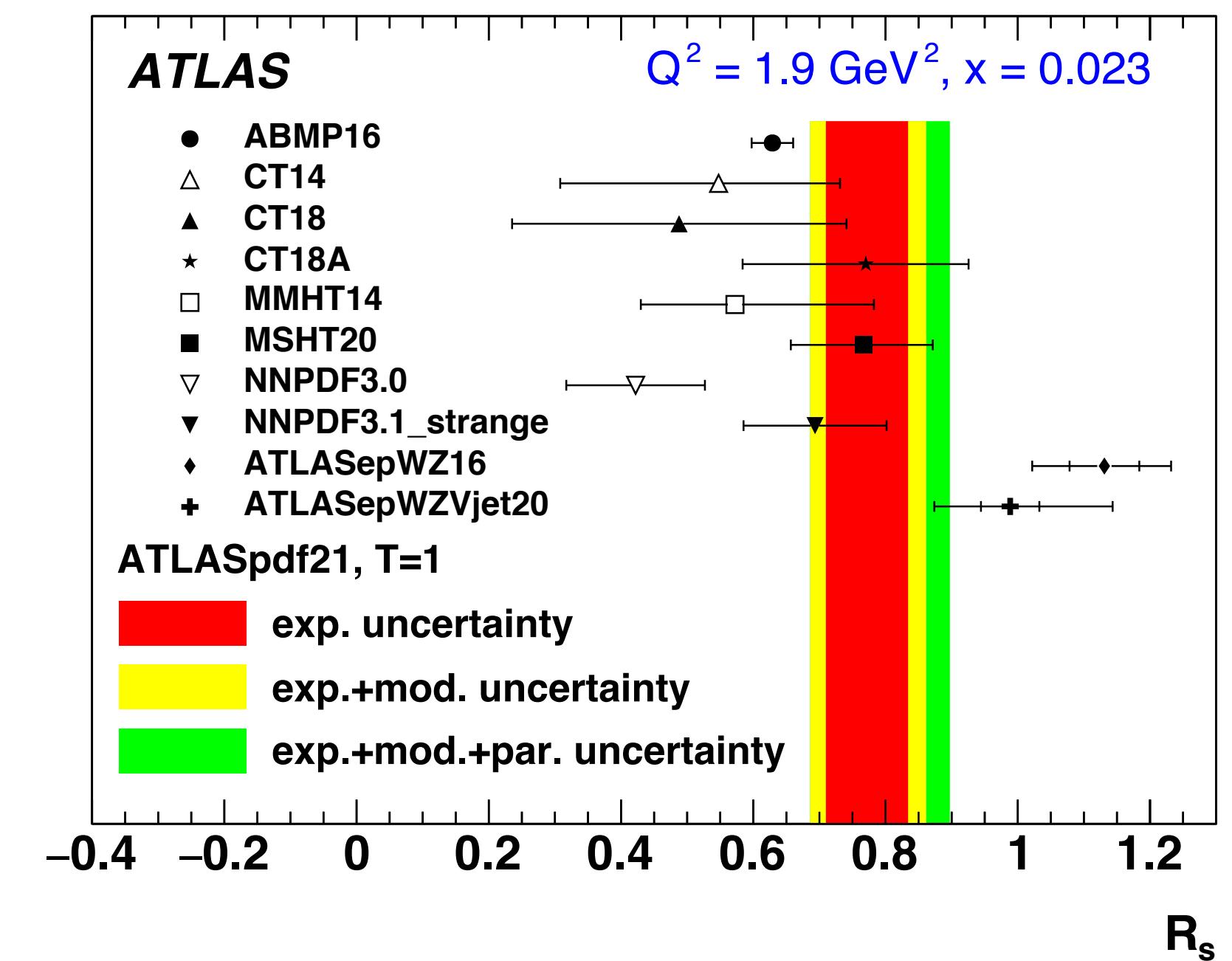
Light sea-quark contributions



ATLAS data can be used to predict pD fixed target DY cross sections

Check relative densities of \bar{u} and \bar{d} sea contributions compatible with recent SeaQuest data E906 (at high x) than with NuSea (E866)

Strange quark composition



Improvement w.r.t. previous ATLAS PDFs

V+jets data suppresses R_s at high x (with effect on low x), as well as improved low- x parametrisation