Overview of the Standard Model Measurements with the ATLAS Detector

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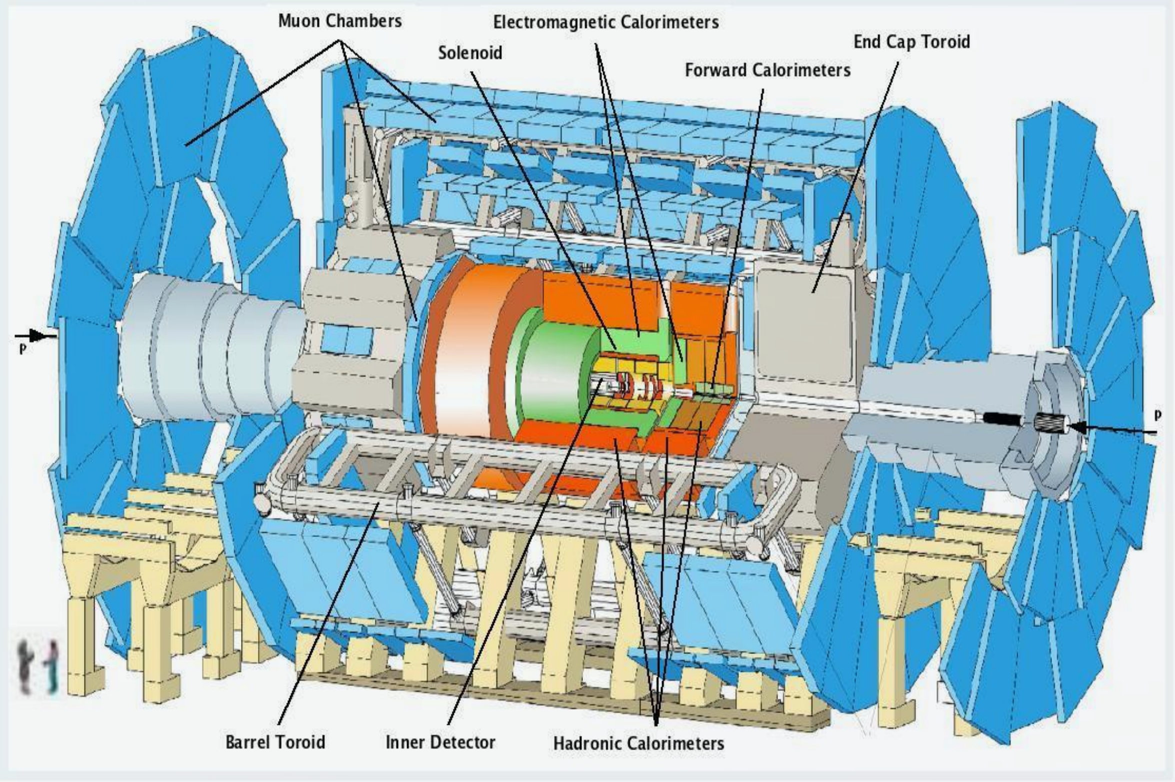
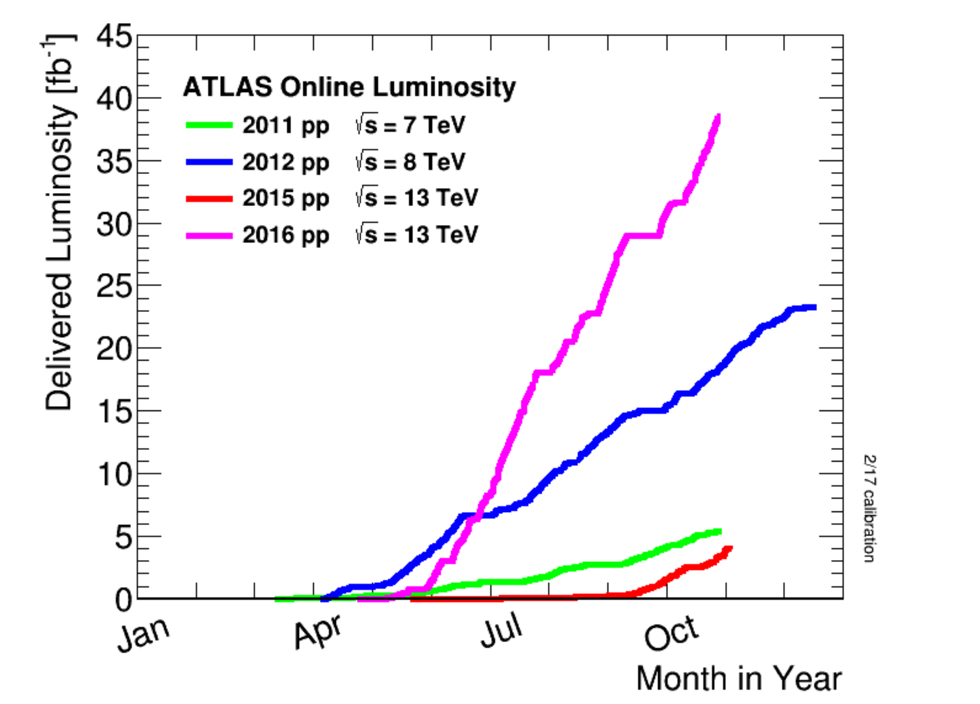
ON BEHALF OF THE ATLAS COLLABORATION

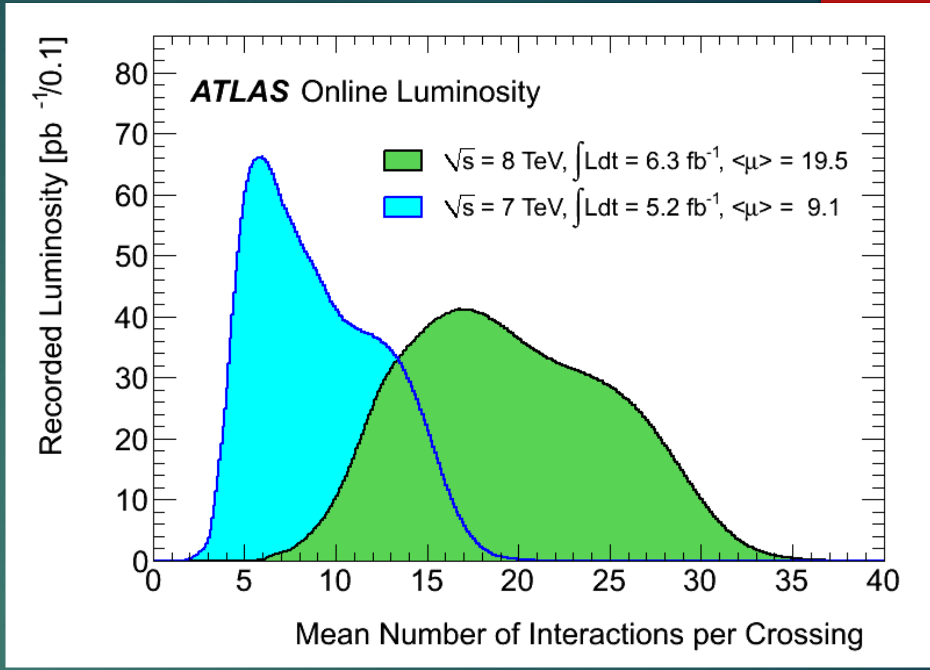
Outline

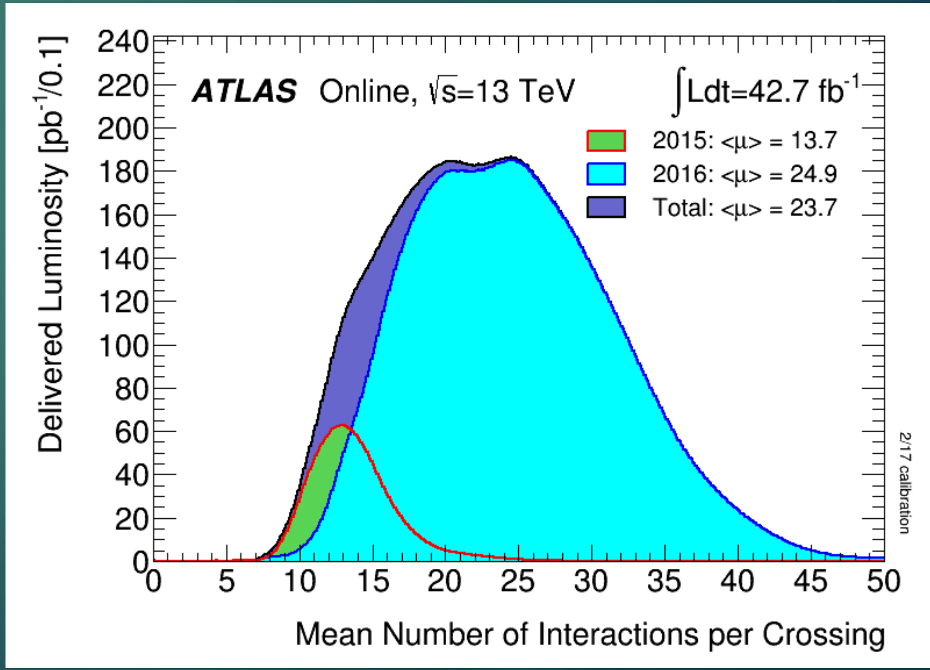
- Measurements of the fundamental SM parameters
  - m_W, $\sin\theta_W$, α_s
- Production cross sections
  - QCD (jets and photons)
    - Inclusive jet production at 8 TeV
    - Inclusive photon and di-photon
    - 4-jet differential
  - Electroweak: multi-bosons
    - W/Z physics
    - Diboson(WW, WZ, ZZ, VBS $Z\gamma$)
    - Triboson (WWW, $WV\gamma$)



Data samples







Part I: determination of m_W, $\sin\theta_W$, α_s

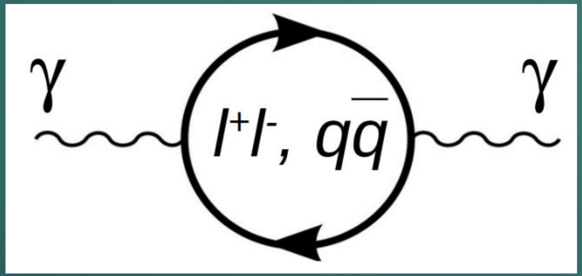
ariXiv:1701.07240

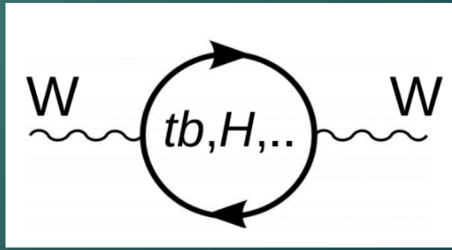
Measurement of W mass at ATLAS

- m_W created by EWSB
- Sensitive to high order corrections from top and Higgs

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

$$\Delta r = \Delta\alpha - \tan\theta_W \Delta\rho(m_{top}) + \Delta r^{SM}_{rem}(m_{top}, m_H) + \ldots$$

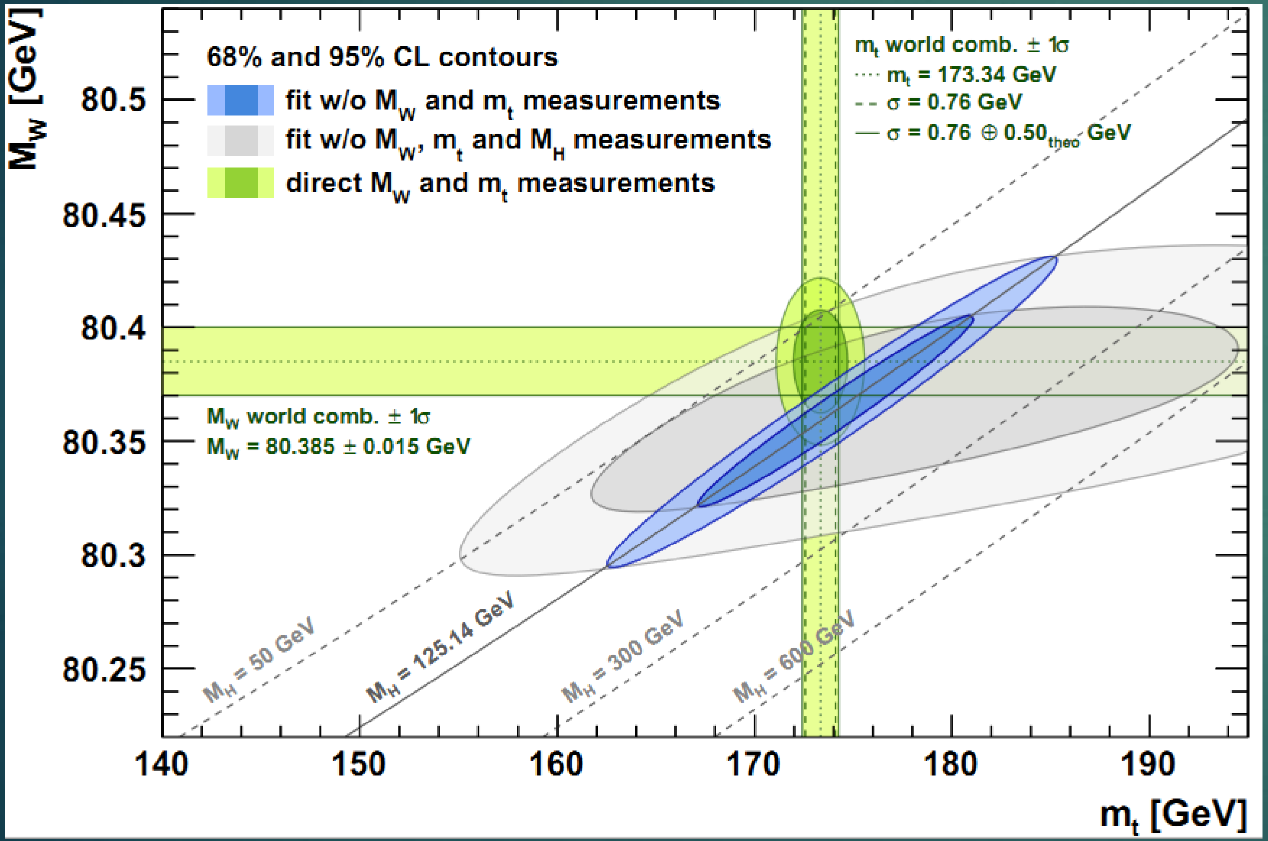




Precise measurement of m_W →test the consistency of the SM

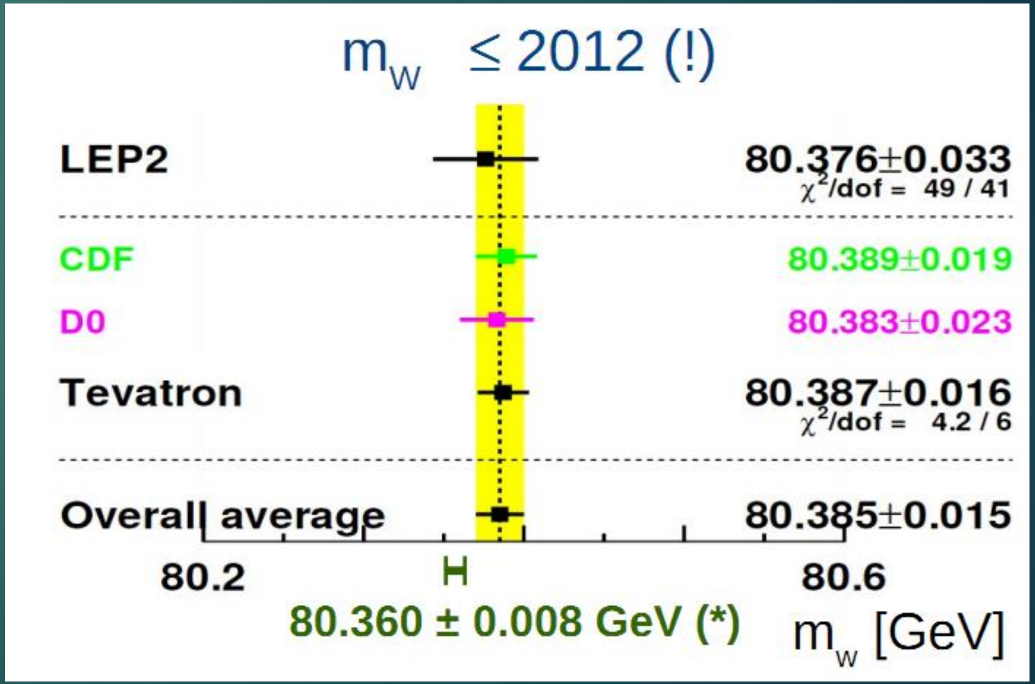
arXiv:1407.3792

Global fit (2014)



	Measurement	SM Prediction (*)
m_H	125.09 ± 0.24	102.8 ± 26.3
m_{top}	172.84 ± 0.70	176.6 ± 2.5
m_W	80.385 ± 0.015	80.360 ± 0.008

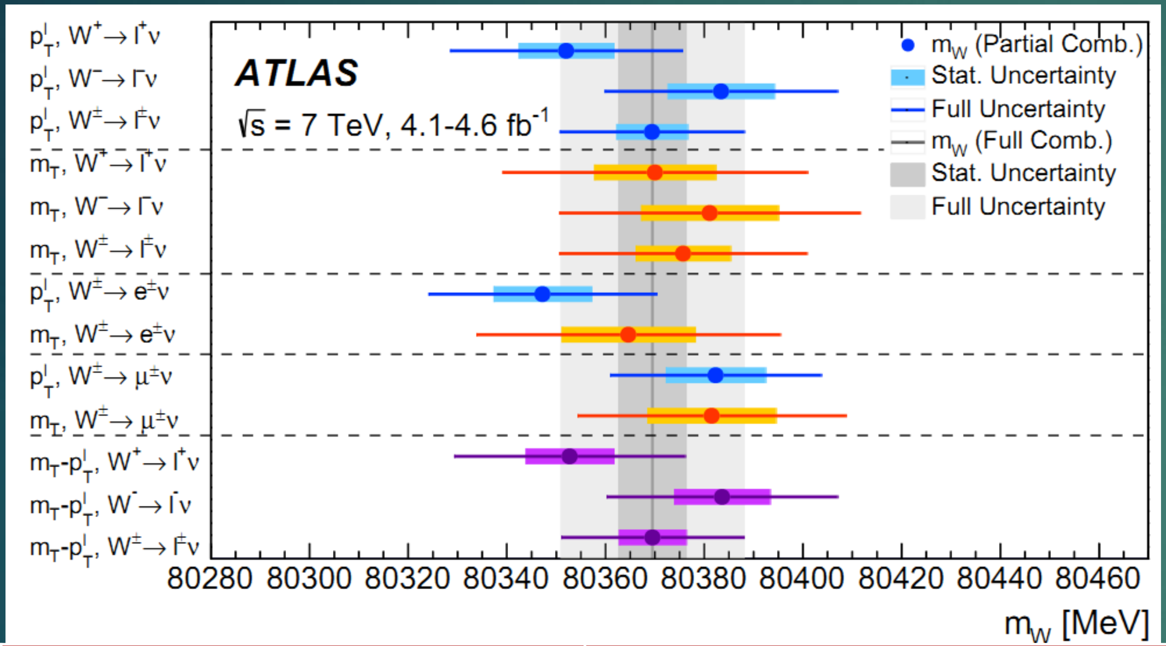
(*) arXiv:1608.01509



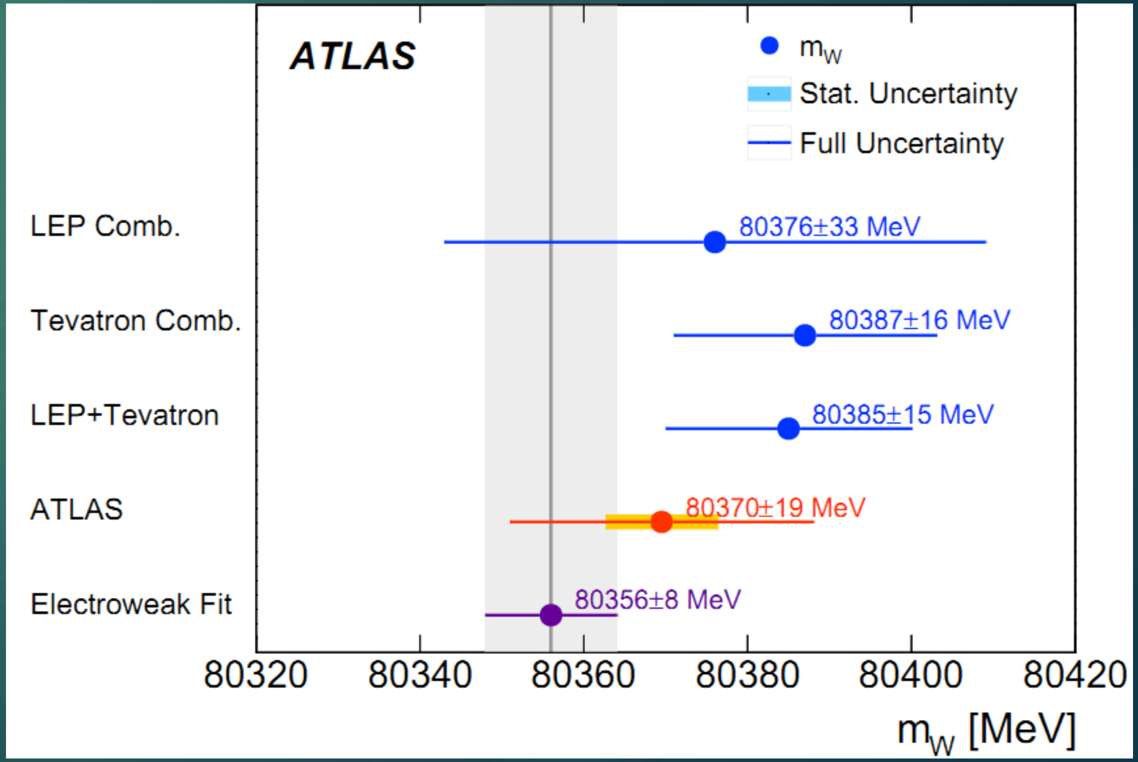
m_W can give strongest constraints

New measurement

- 2011 data (7 TeV 4.6 fb^{-1})
- Electron channel: 7.8 M events
- Muon channel: 5.9 M events
- Fit to p_T^l, m_T to obtain the m_W



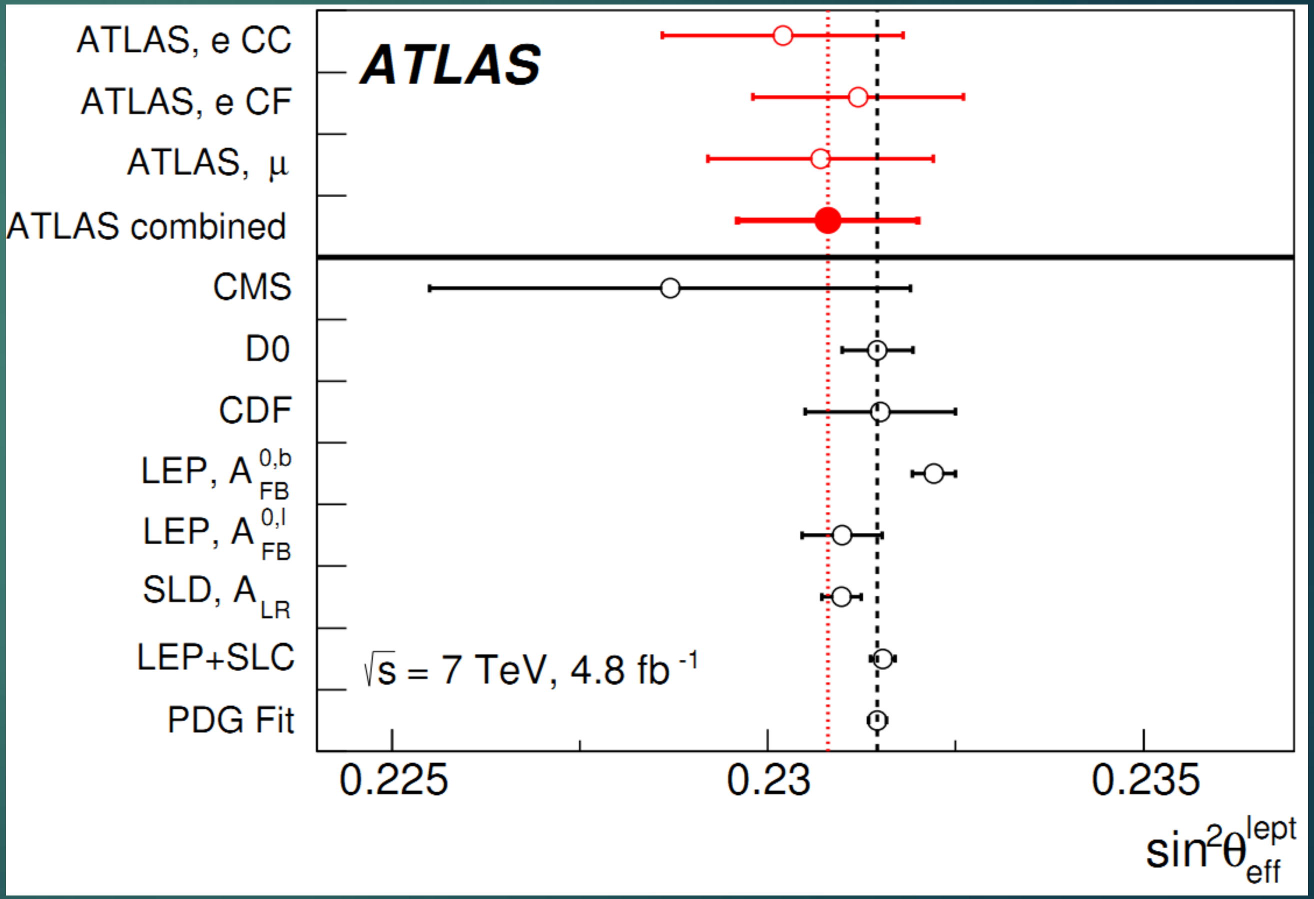
Effects	Uncertainties
Stat.	7 MeV
Expt. Syst.	11 MeV
Mod. Syt.	14 MeV



θ_W and AFB

JHEP09(2015)049

- Charge forward-backward symmetry $q\bar{q} \rightarrow Z/\gamma^* \rightarrow l^+l^-$events can be used to extract θ_W
- Fitting measured AFB with MC templates with varied sinθ_W
- Use ATLAS-epWZ12 LO PDF
- PDF uncertainty dominates



Measurement of α_s from TEEC

- Transverse Energy-Energy Correlation (TEEC) and its asymmetry (ATEEC) sensitive to α_s (infrared safe).
- Defined as E_T reweighted opening angles

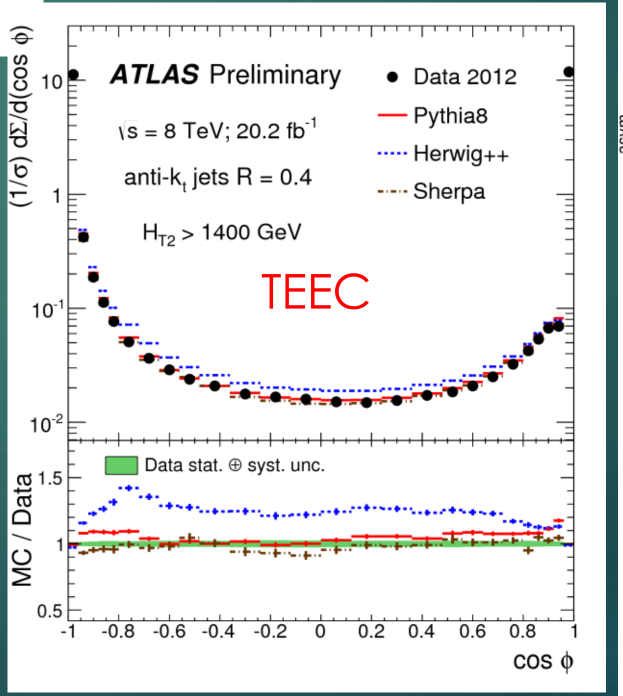
$$\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}\,dx_{Tj}\,d\cos\phi}\, x_{Ti}\, x_{Tj}\, dx_{Ti}\, dx_{Tj}$$

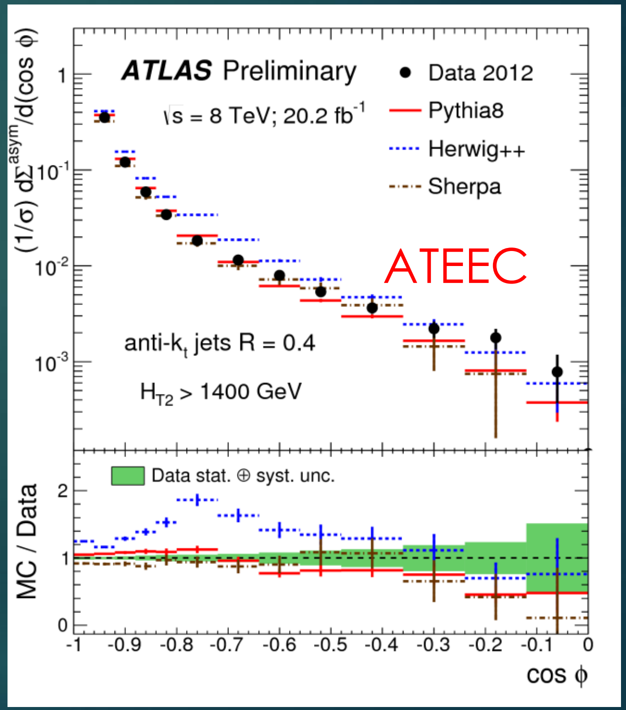
$$= \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{\left(\sum_k E_{Tk}^{A}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

N: Number of multi-jet events

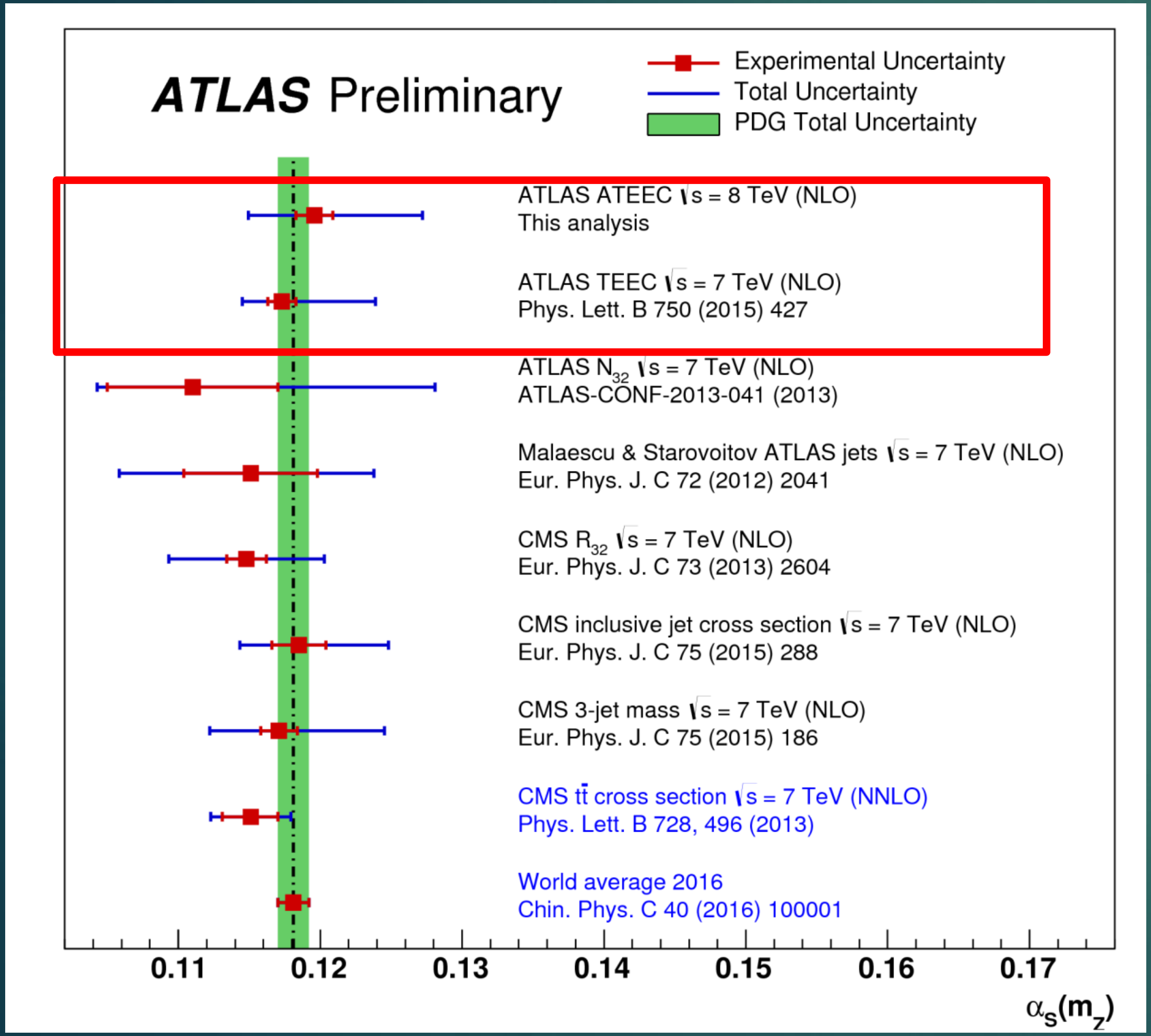
$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

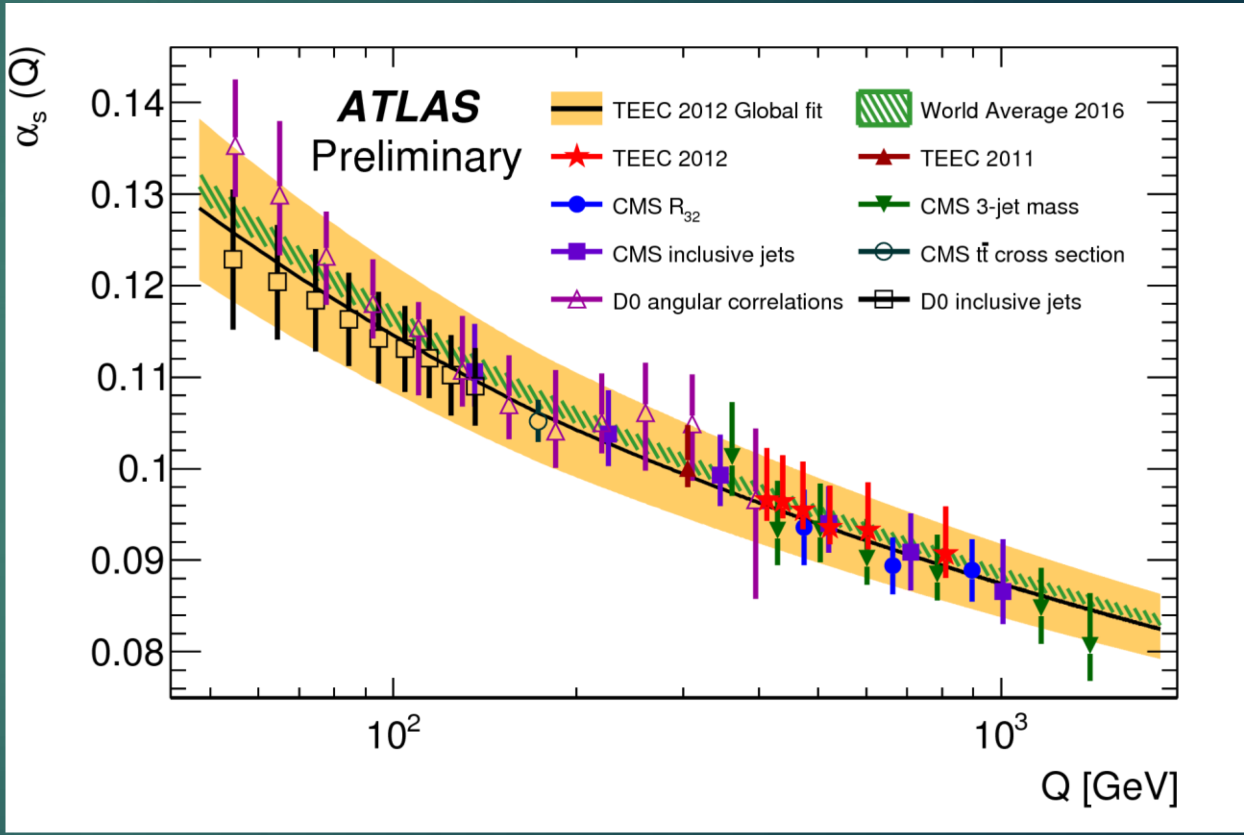
Herwig++ off
Sherpa OK





Determination of α_s

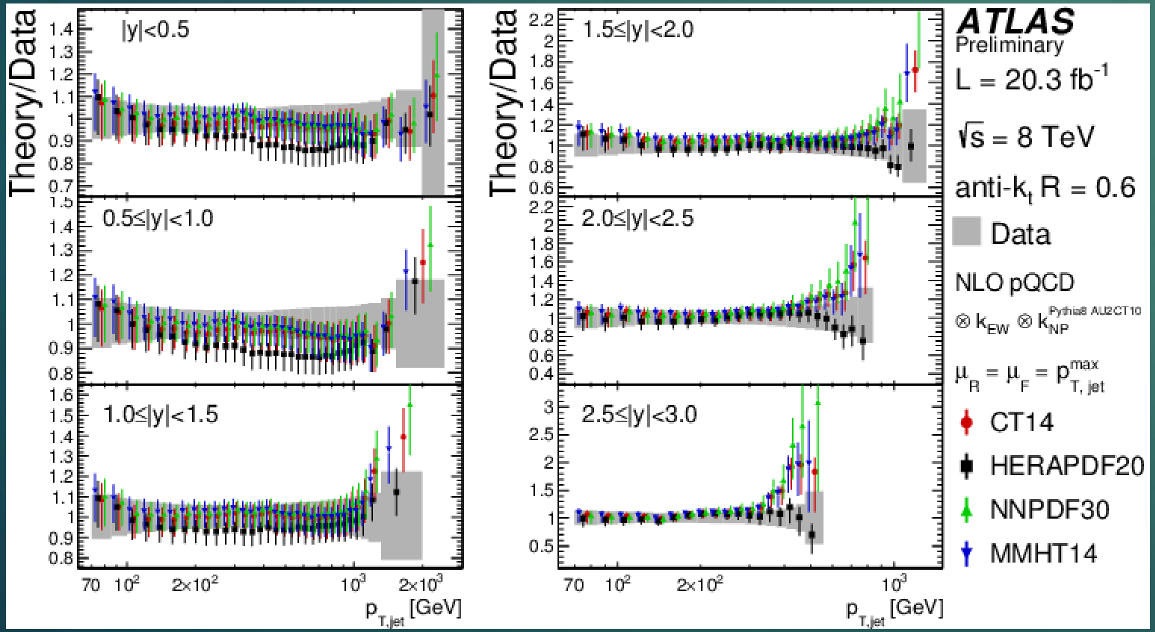




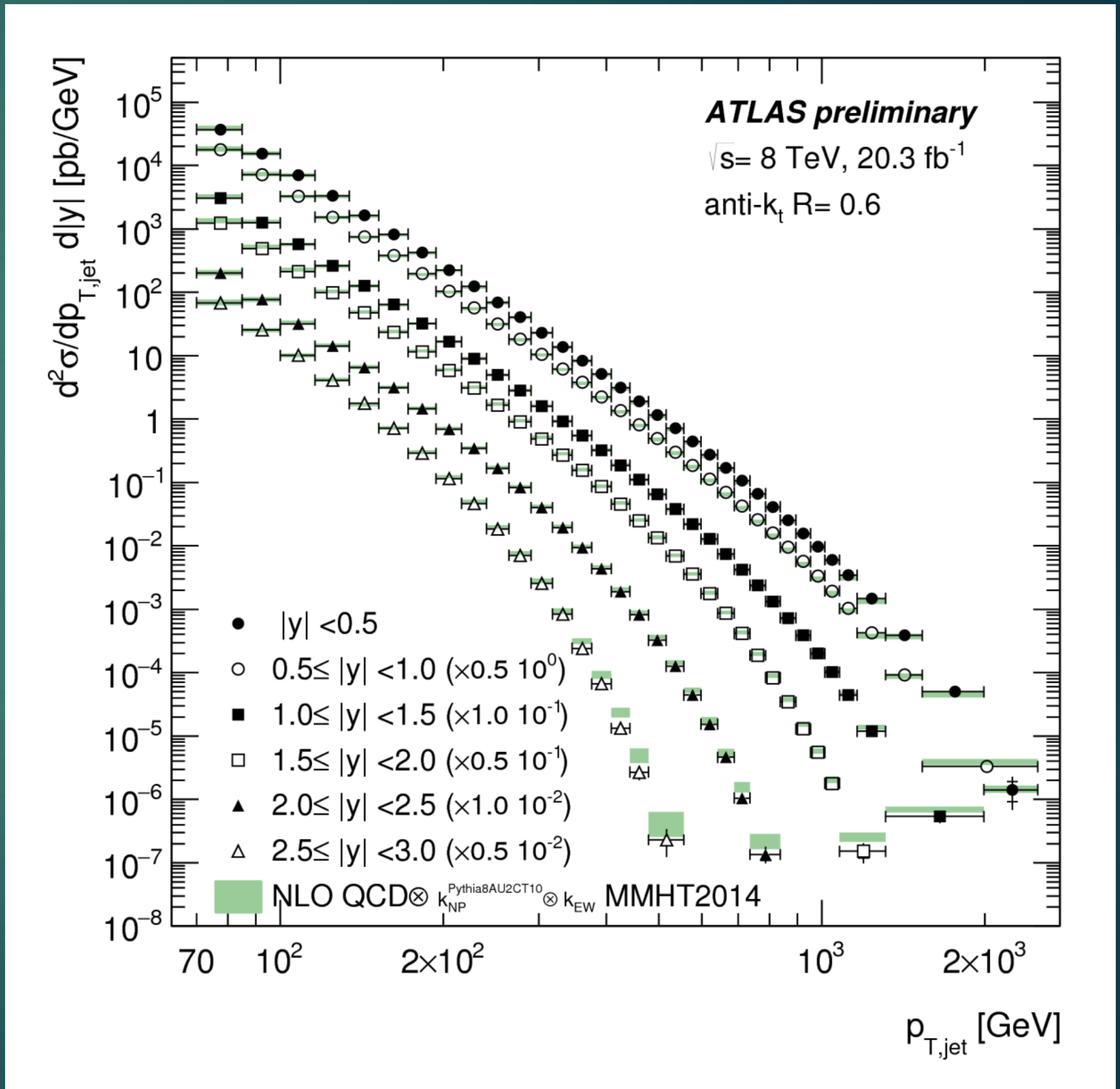
Part II: QCD (Jets and photons)

Inclusive jet cross sections at 8 TeV

- Test of QCD(strong coupling, PDF…)
- Directly probe physics at the shortest distance accessible



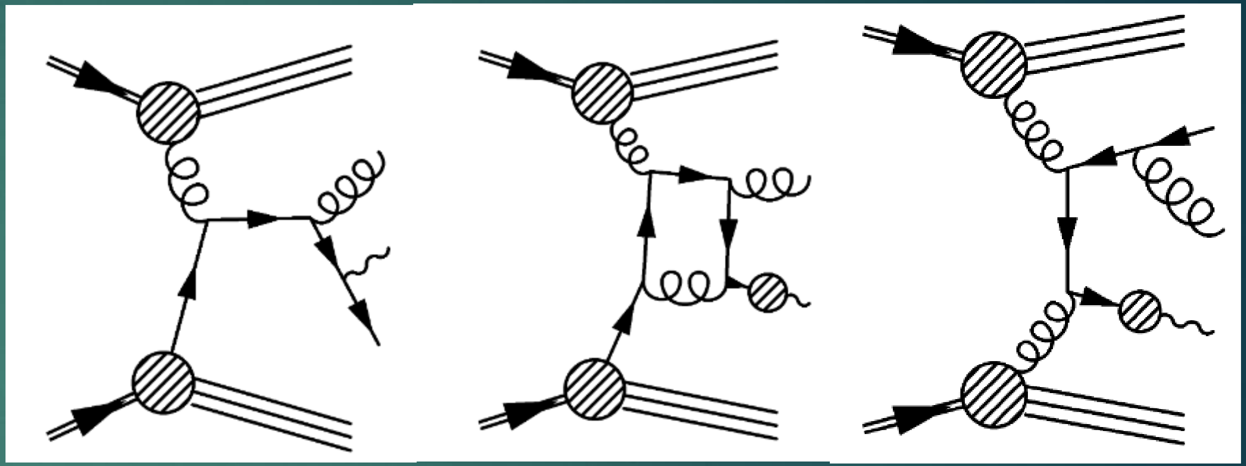
NLOJet++



arXiv:1701.06882

Inclusive photon production

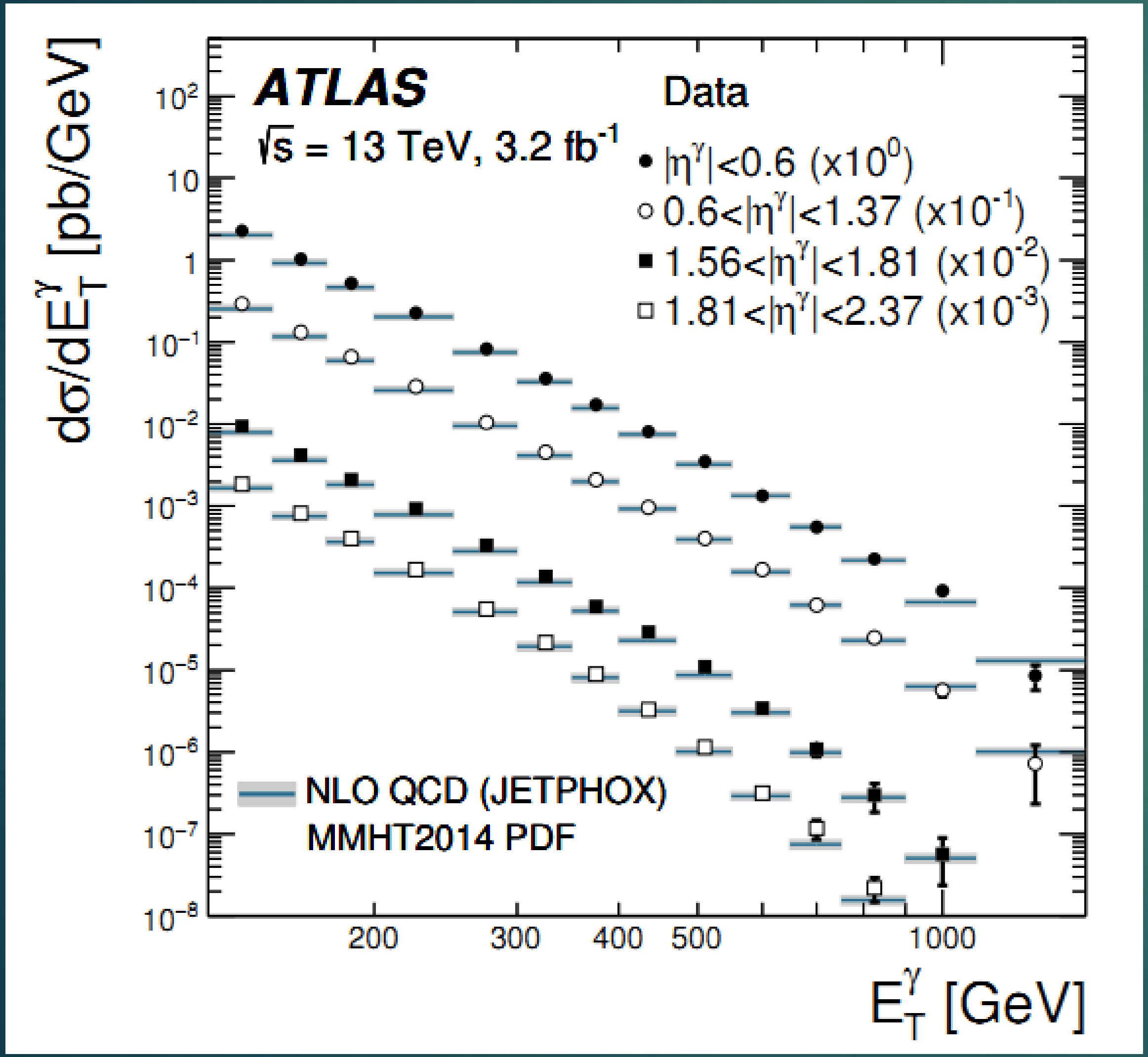
- Important test ground for pQCD and MC tools
  - Parton radiation, fragmentation, resummation of threshold logs

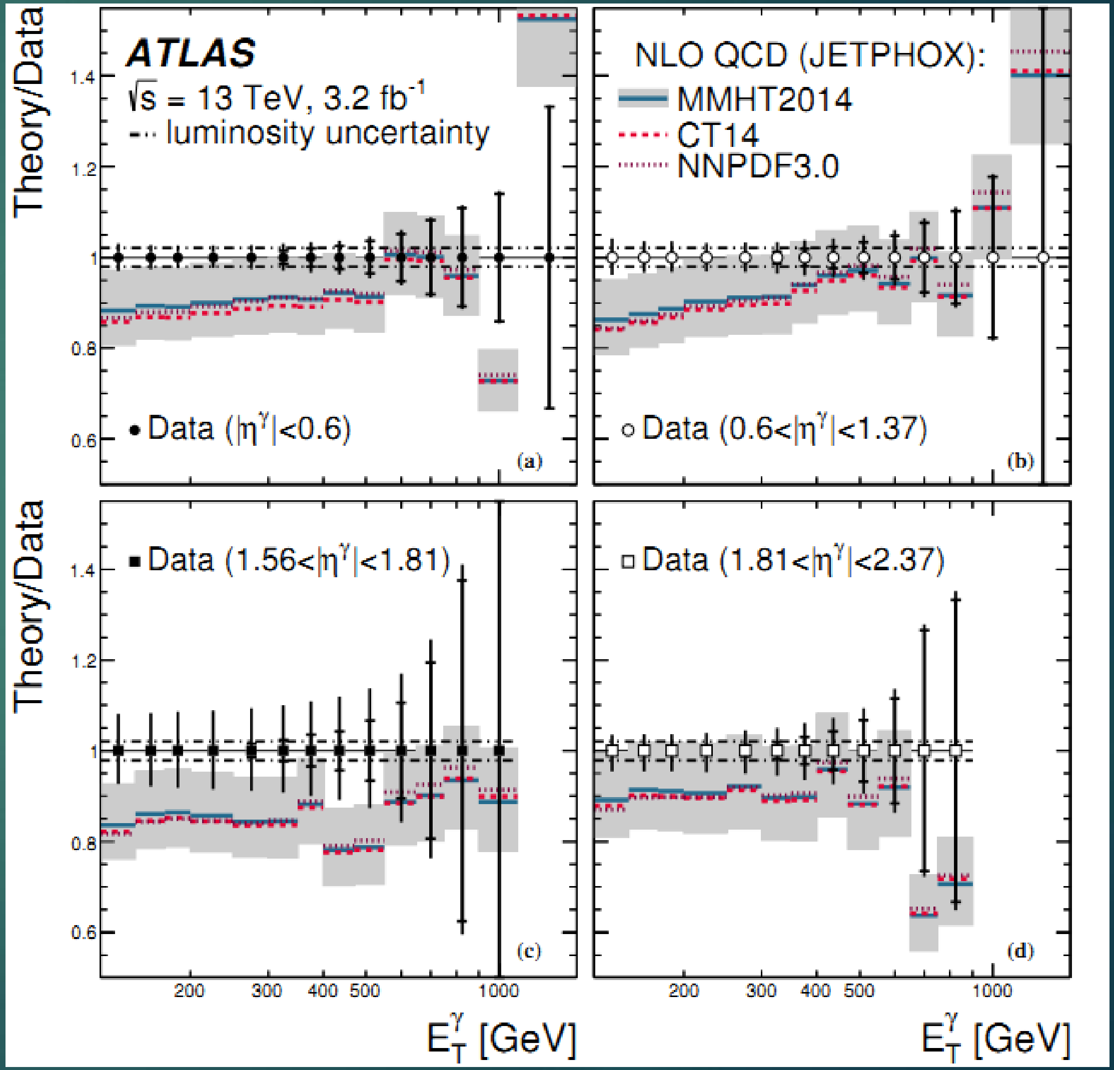


13 TeV, 3.2 fb^{-1}

	Phase-space region			
Requirement on E_T^γ	$E_T^\gamma > 125$ GeV			
Isolation requirement	$E_T^{iso} < 4.8 + 4.2 \cdot 10^{-3} \cdot E_T^\gamma$ [GeV]			
Requirement on $\lvert\eta^\gamma\rvert$	$\lvert\eta^\gamma\rvert < 0.6$	$0.6 < \lvert\eta^\gamma\rvert < 1.37$	$1.56 < \lvert\eta^\gamma\rvert < 1.81$	$1.81 < \lvert\eta^\gamma\rvert < 2.37$
Number of events	356 604	480 466	140 955	275 483

Comparison with theory

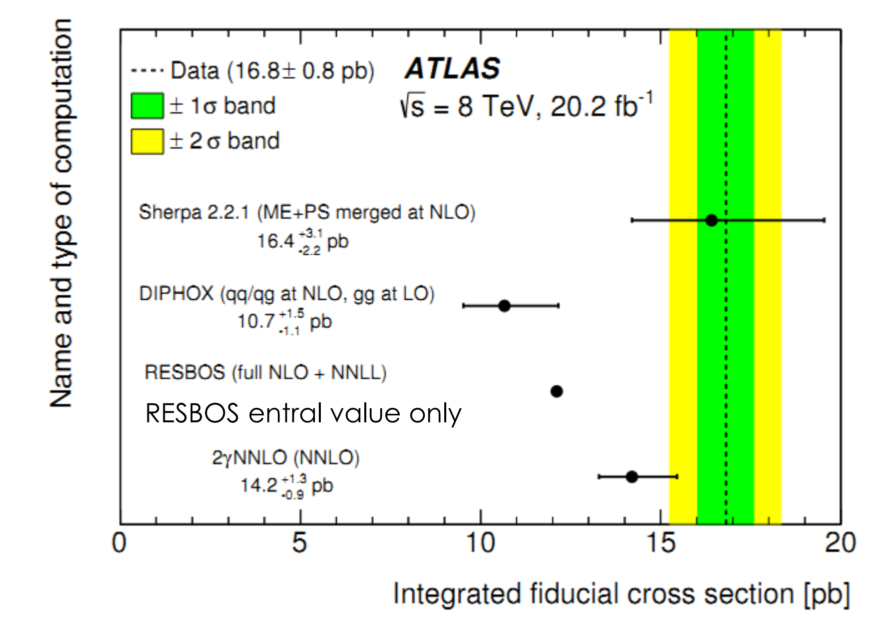


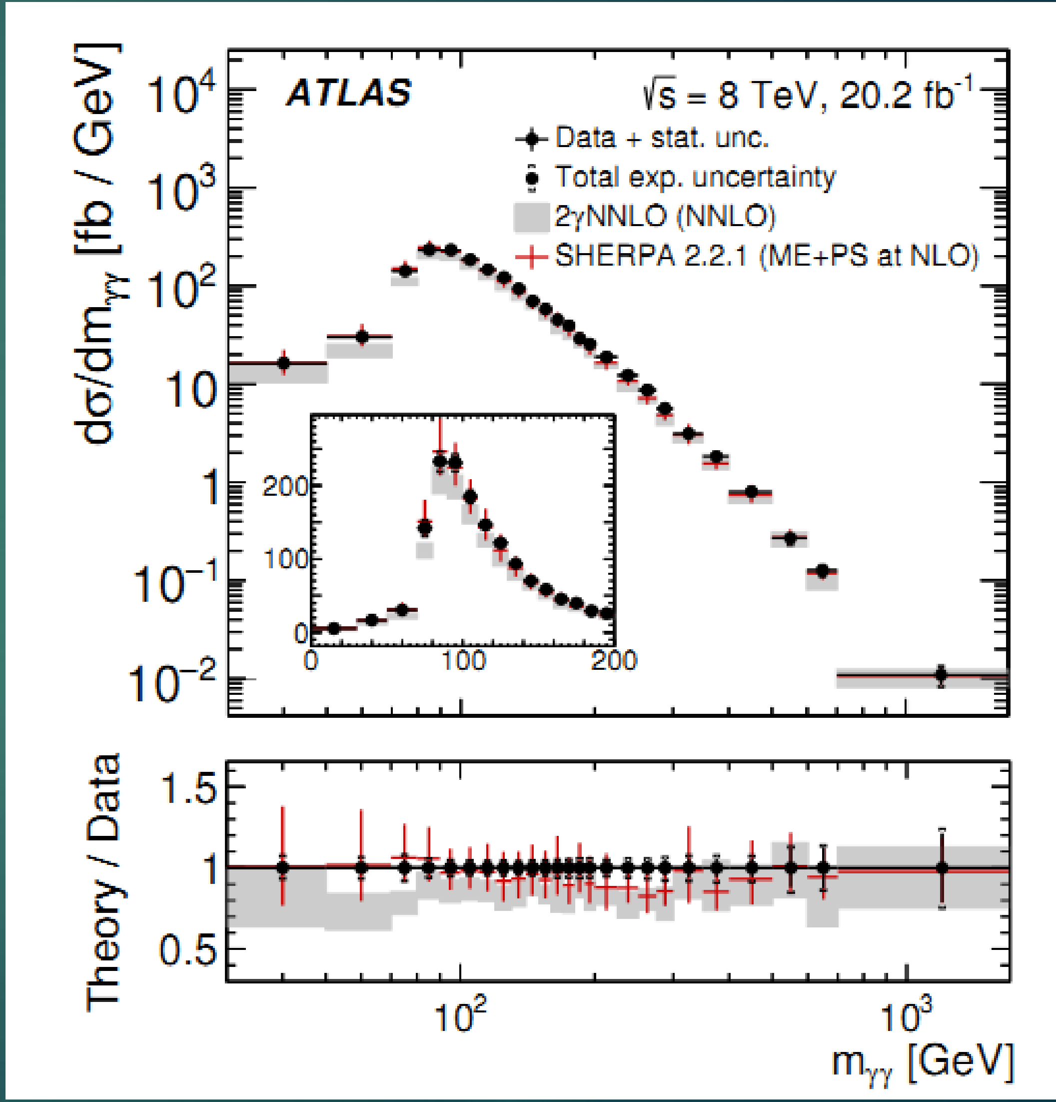


arXiv:1704.03839

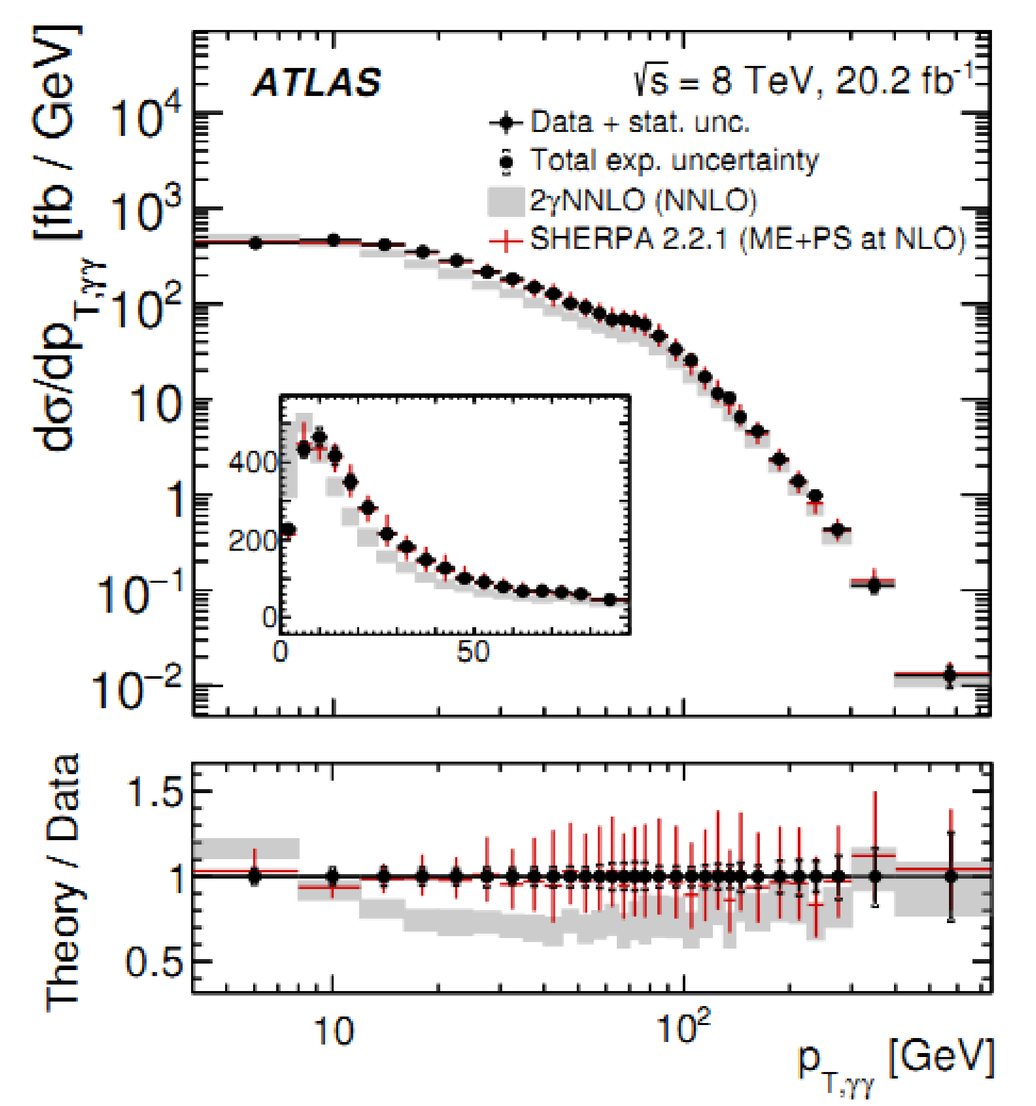
Production of photon pairs

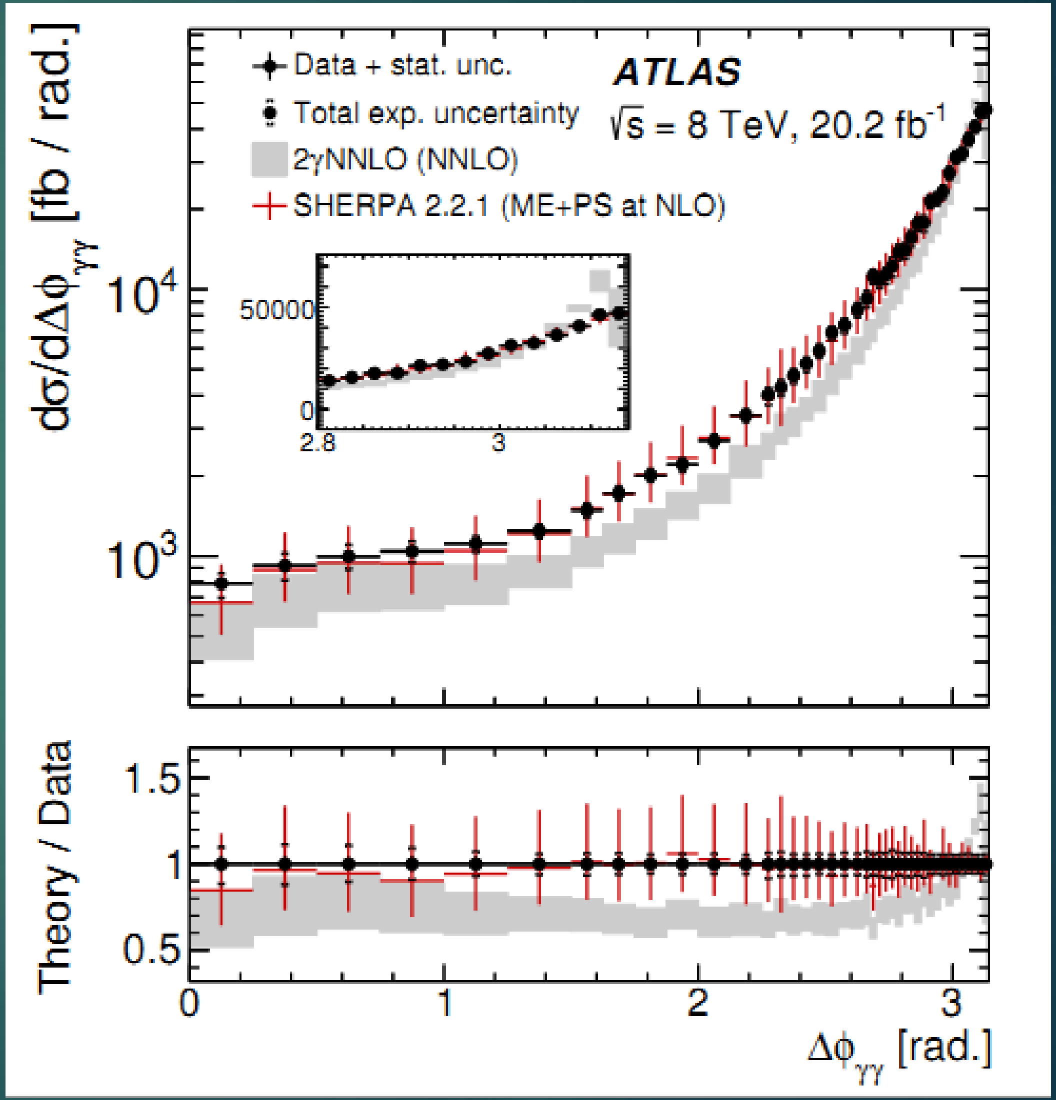
- Important test of pQCD
- Important background for $H \to \gamma\gamma$
- $E_{T1} > 40$ GeV, $E_{T2} > 30$ GeV, $\Delta R > 0.4$





P_T and $\Delta\varphi$



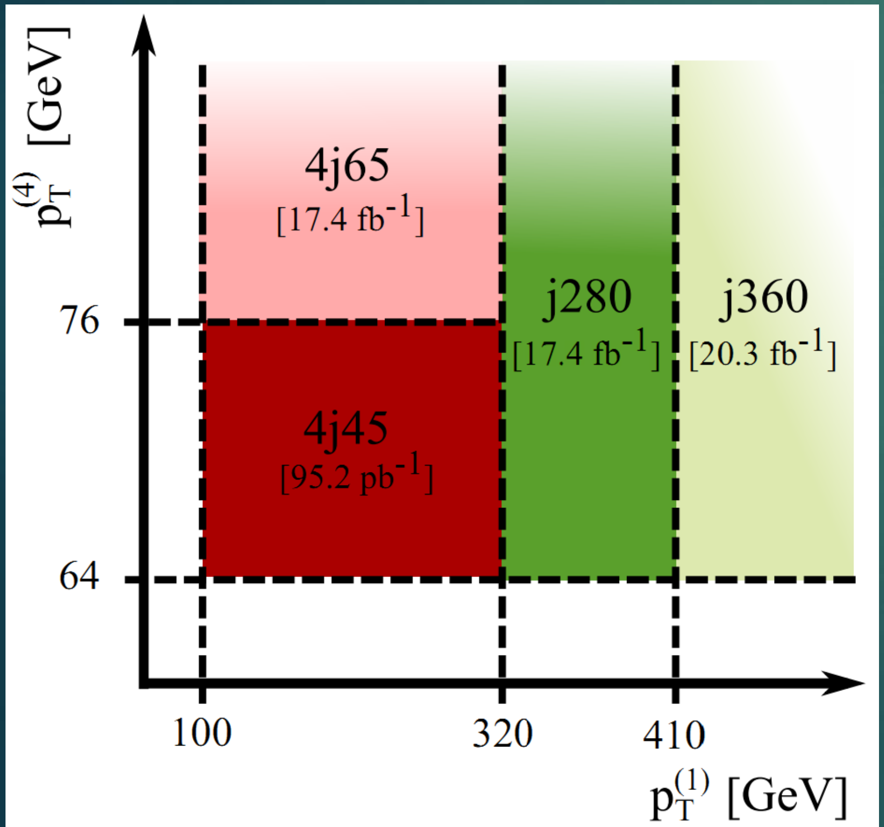


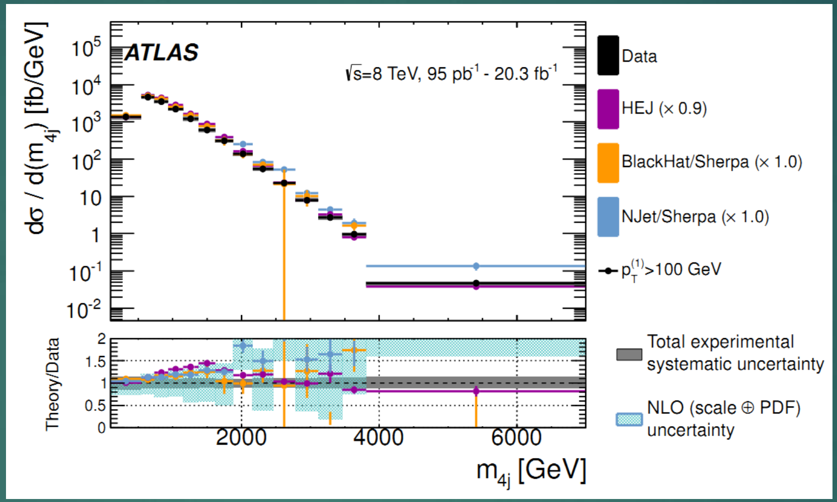
JHEP12(2015)105

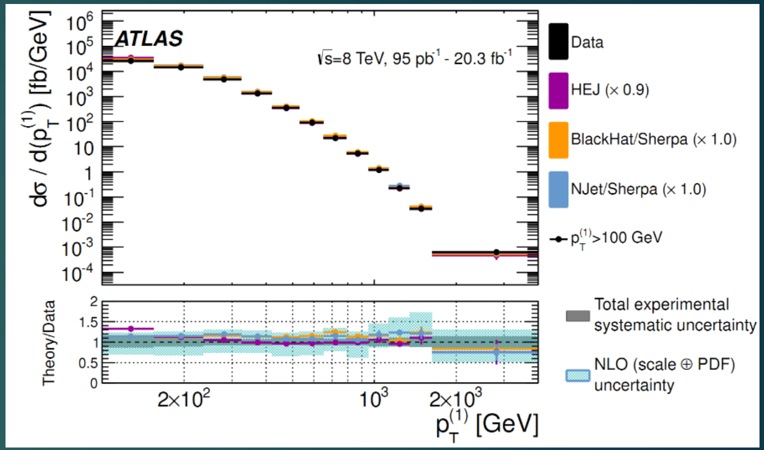
4-jet differential cross section

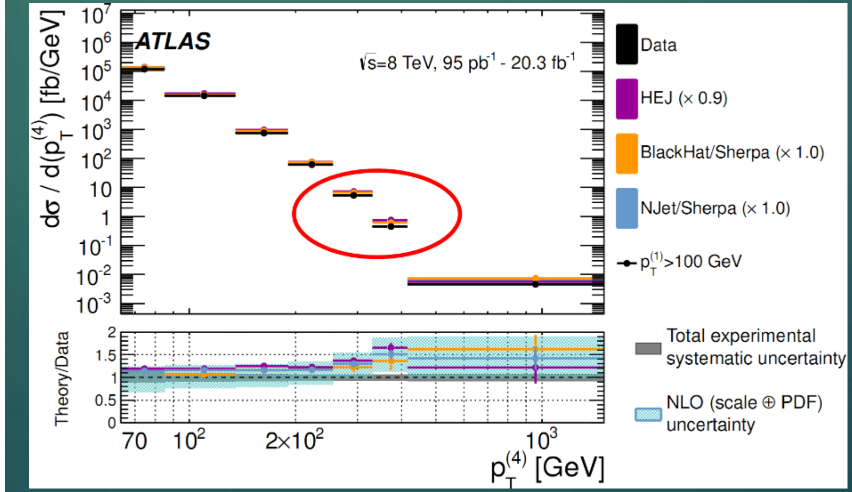
- Test pQCD

Triggers





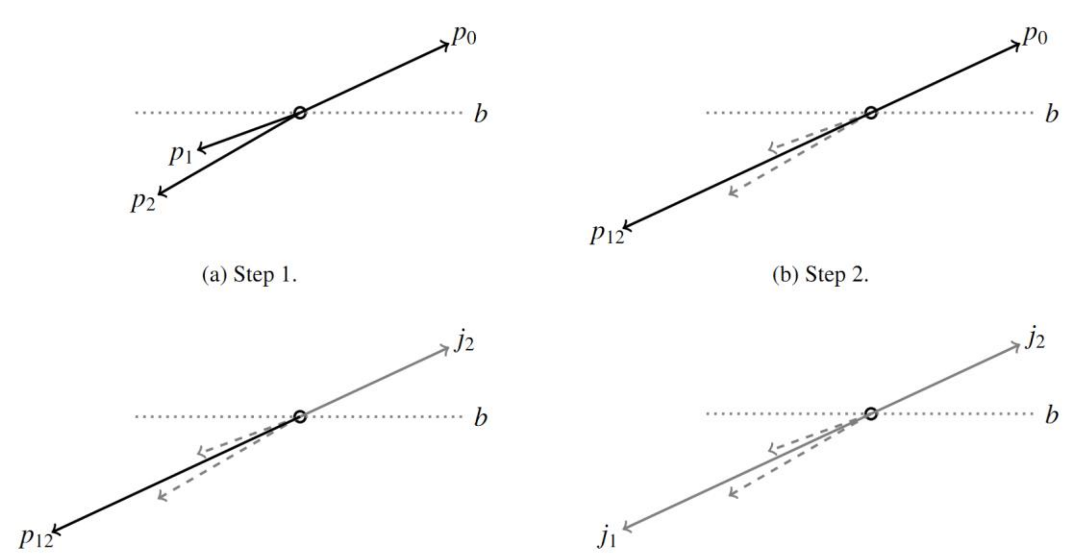




- Unfolded distributions compared with predictions
- Generally good agreements, except PT(4)

K_T splitting scales

- Complementary point of view on jets
- (Track-)Jet production rates on different resolution scales
- Use $Z/\gamma^* \to l^+l^-$ to select the events



(a) Step 1. (b) Step 2. (c) Step 3. (d) Step 4.

Quick review on K_T algorithm:

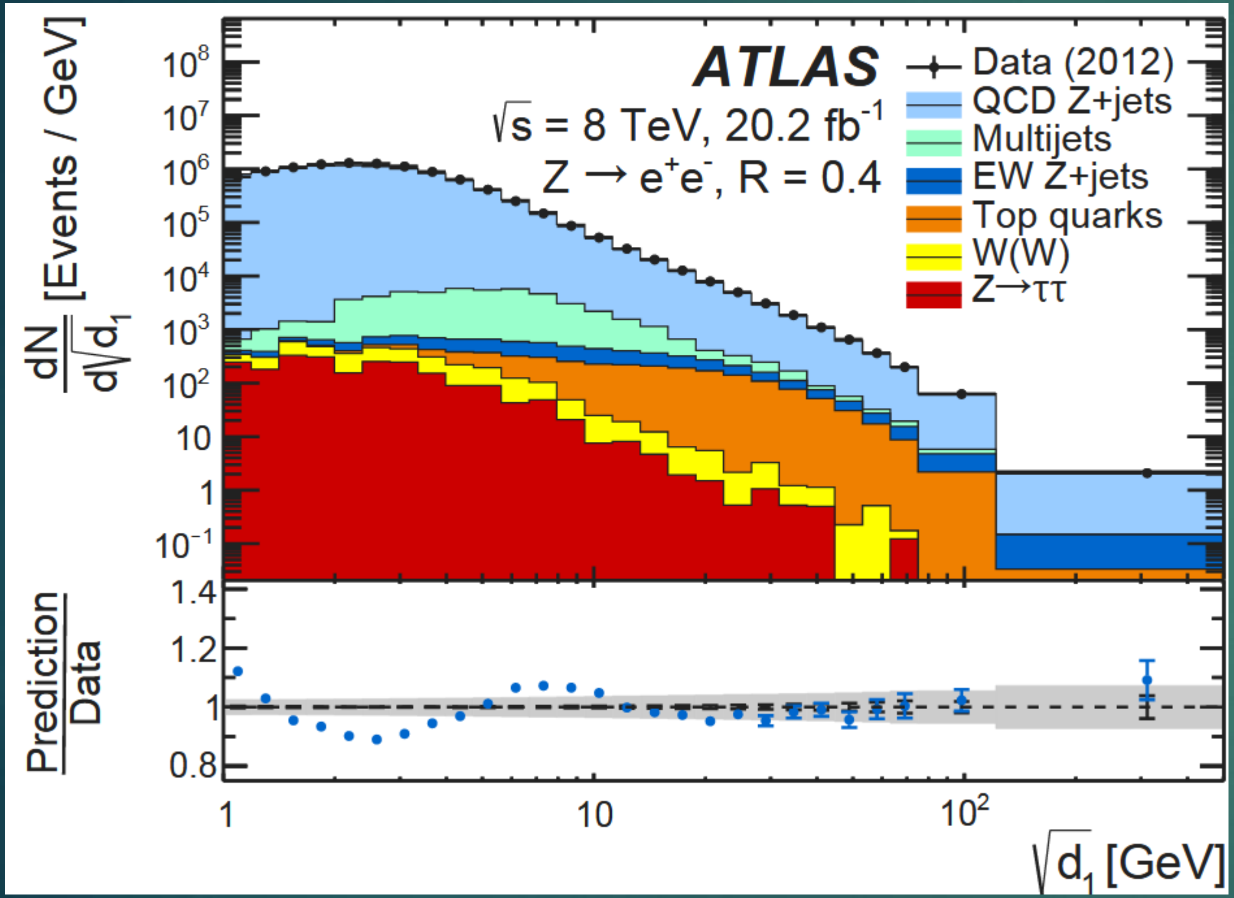
$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{ib} = p_{\mathrm{T},i}^2$$

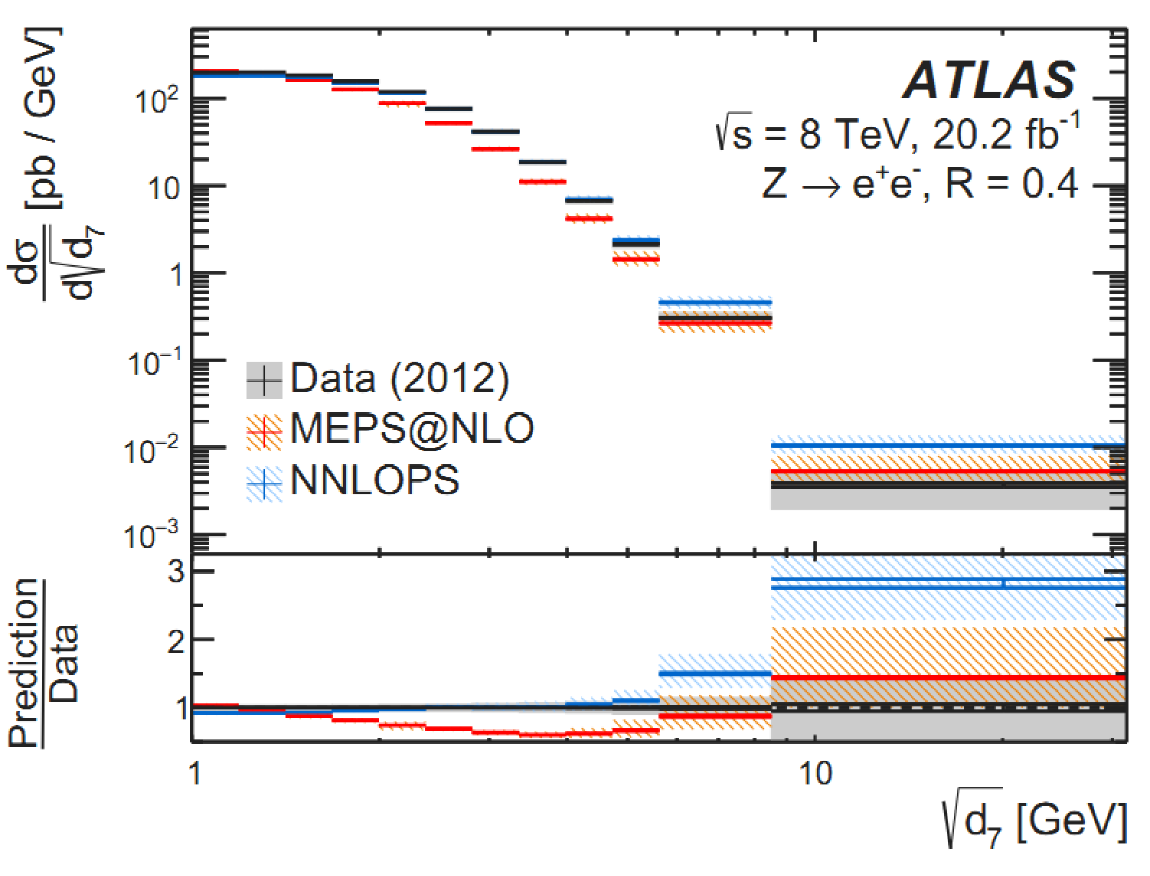
$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

merge (i_0,j_0) if d_{i0j0} is minimum,
k : number of momenta left in the input list

Results

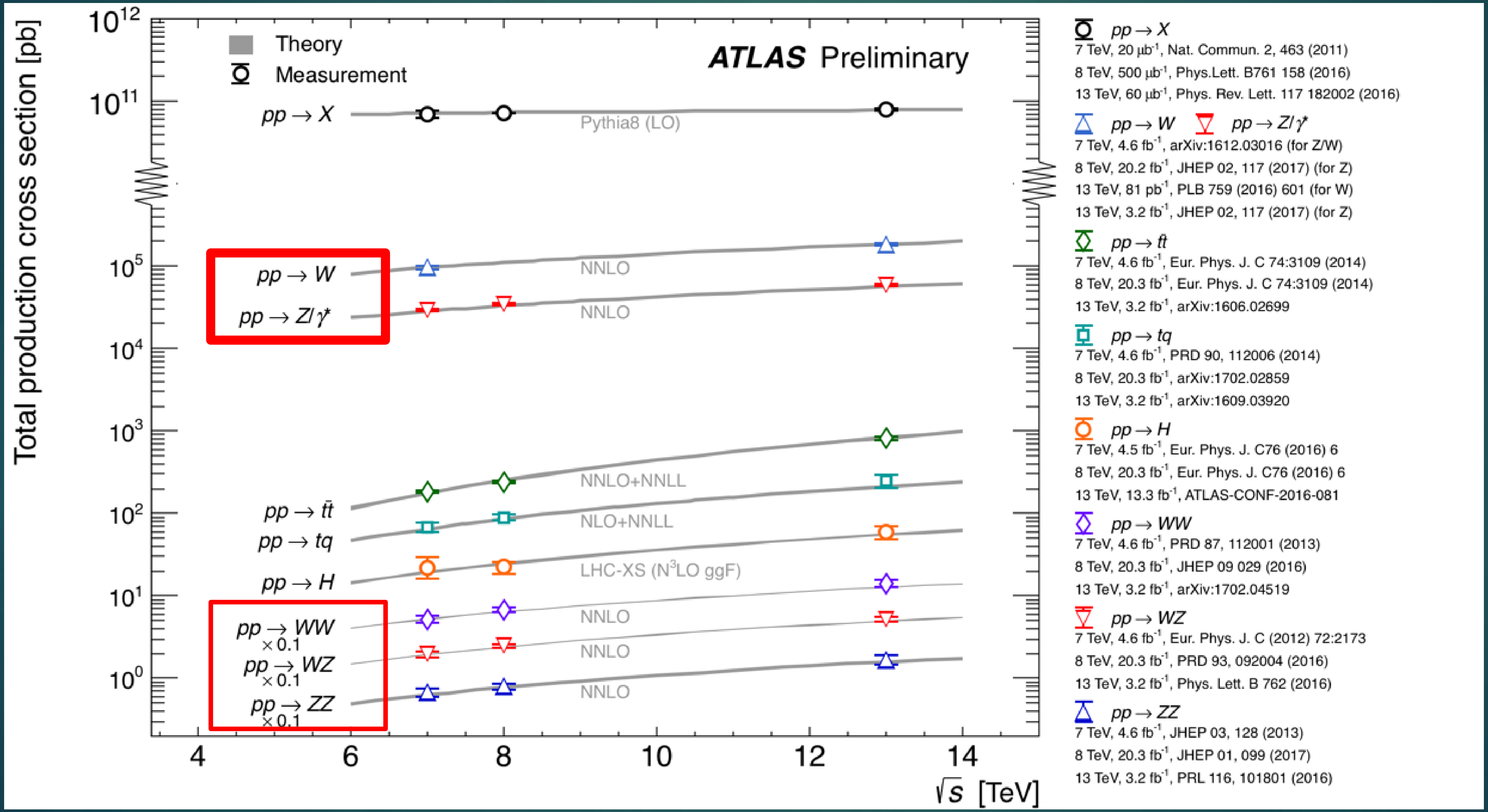


Detector level : d1
Purity : ~99%



Unfolded to charged-particle level
No generators can fully describe the data

Part III: Electroweak

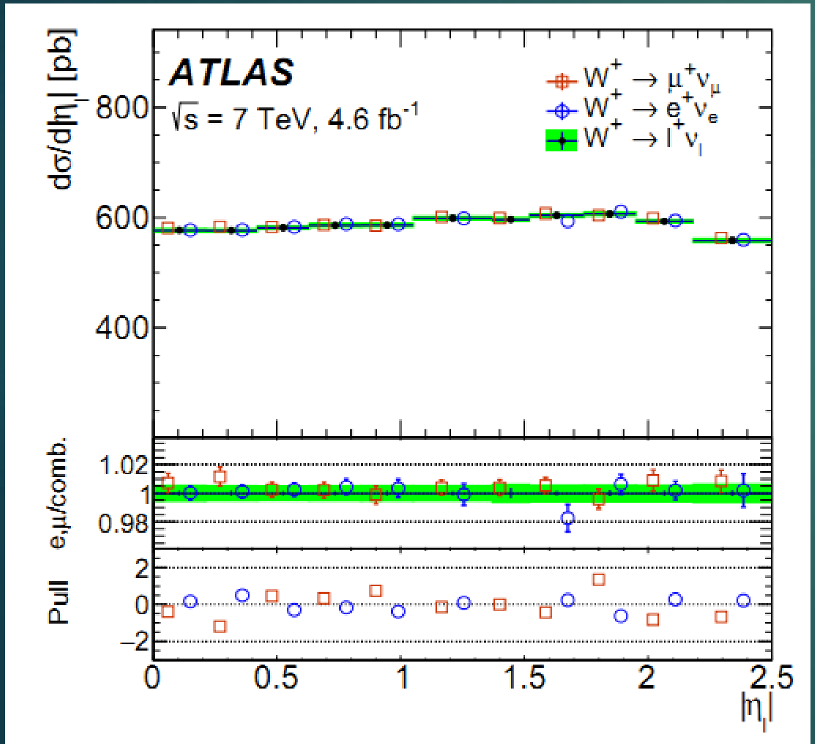


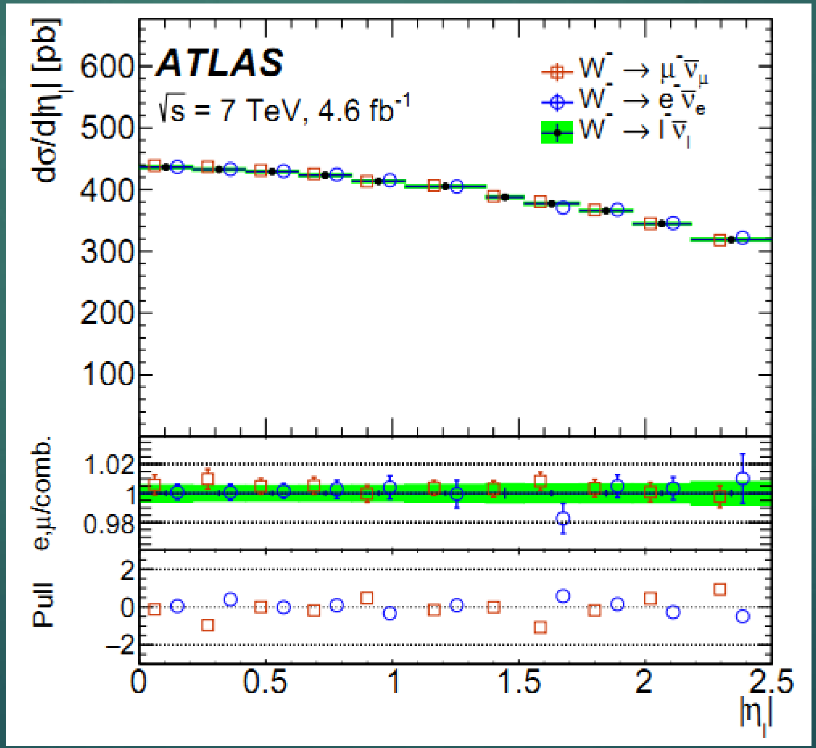
Picture from ATLAS SM Summary

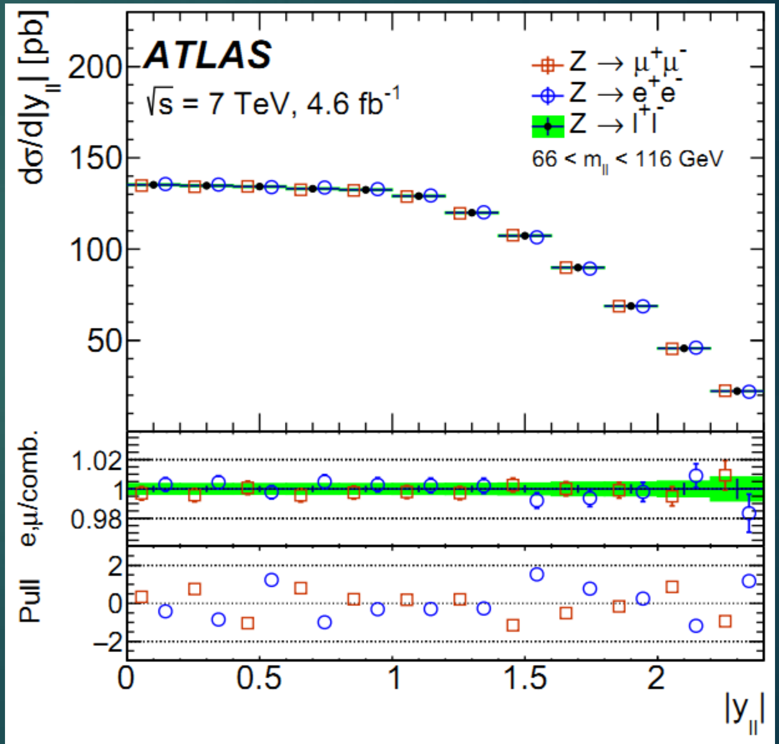
[Eur. Phys. J. C 77 (2017) 367]

W/Z cross sections

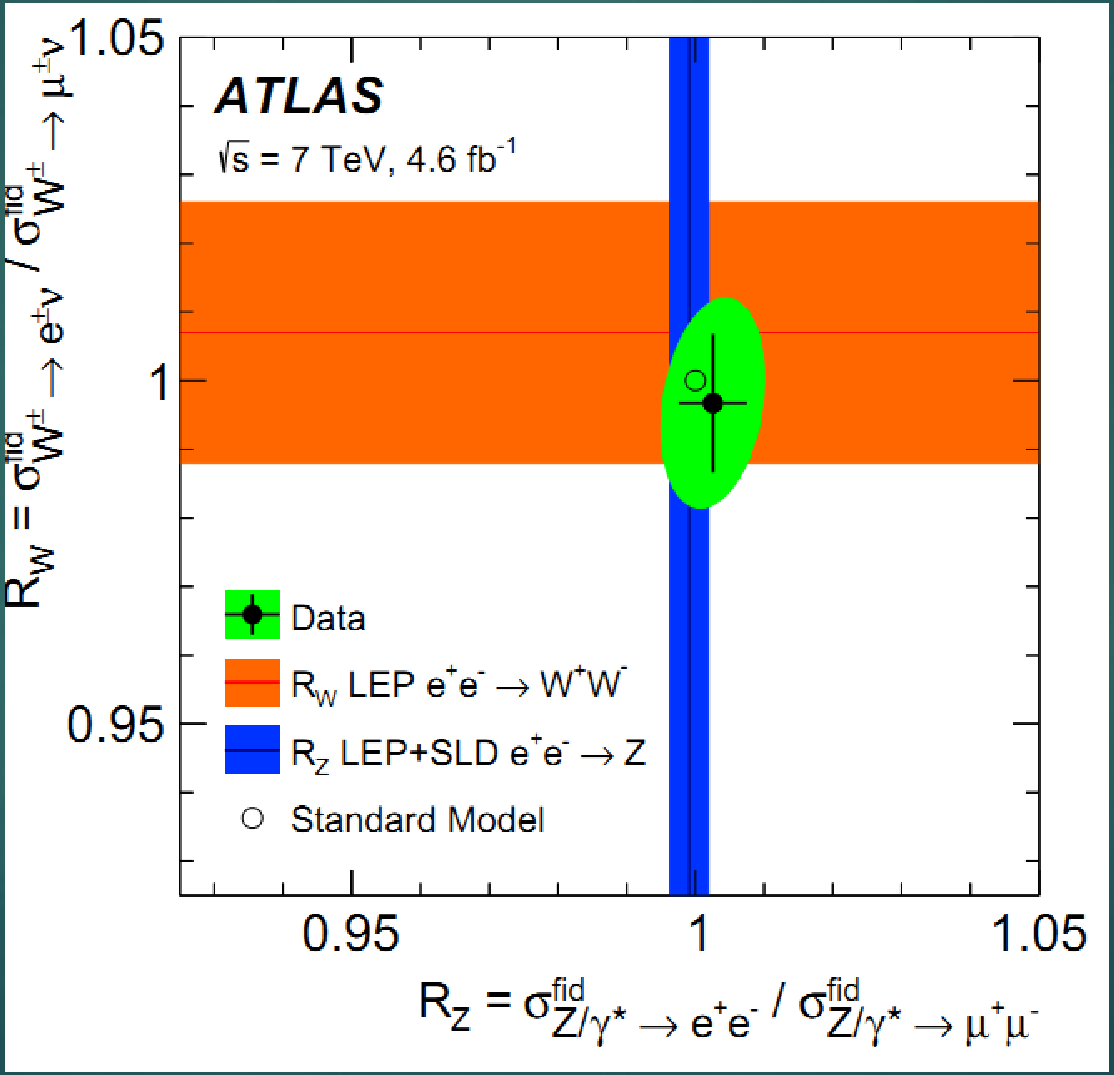
- Standard Candles of the hadron colliders
- Can study EWK physics as well as QCD effects



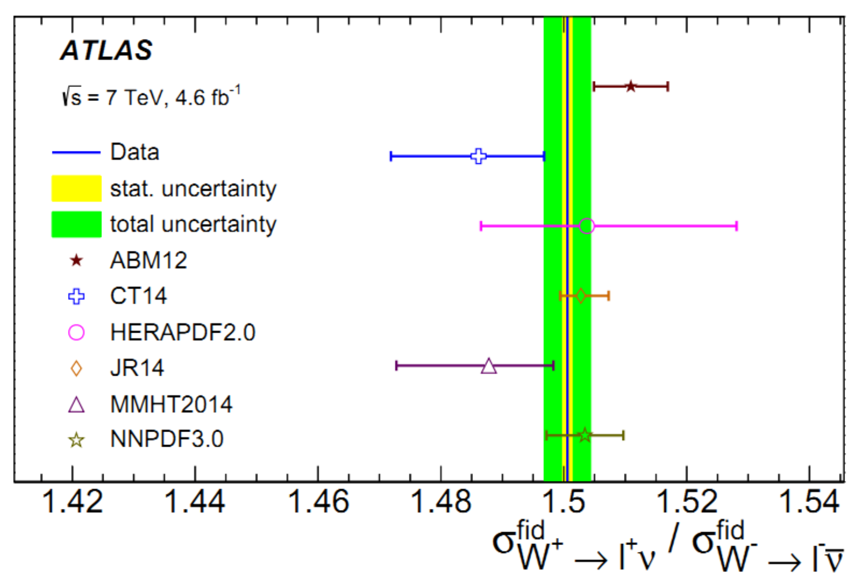


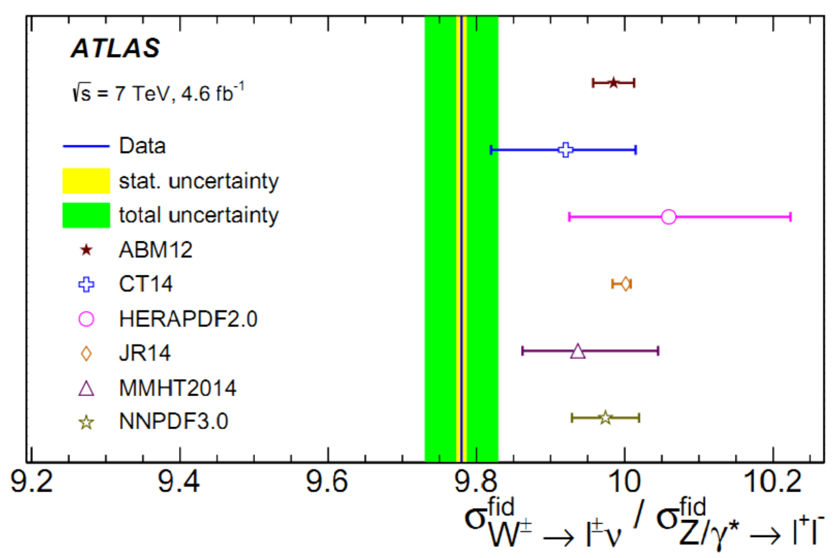


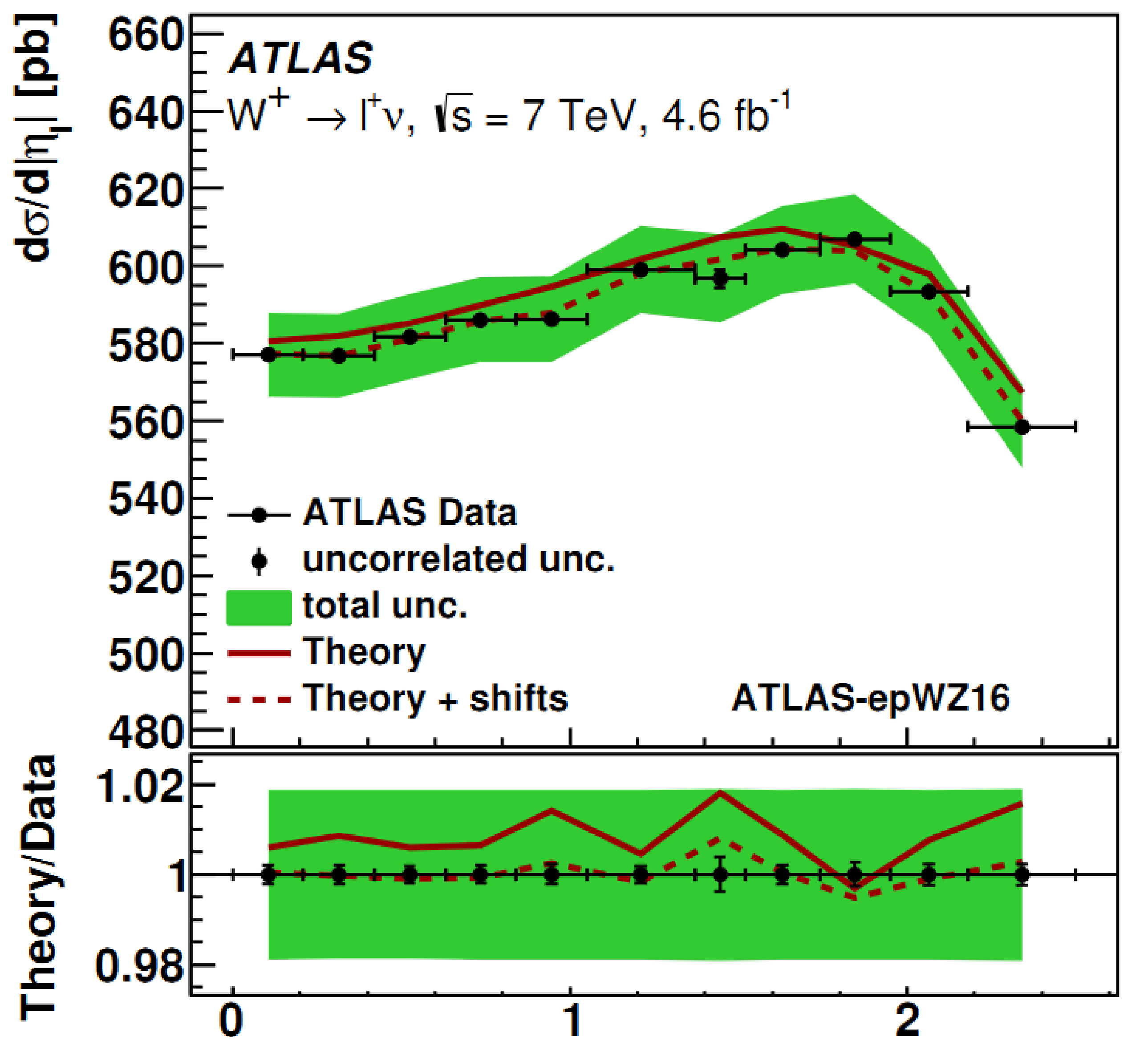
Test of electron/muon universality



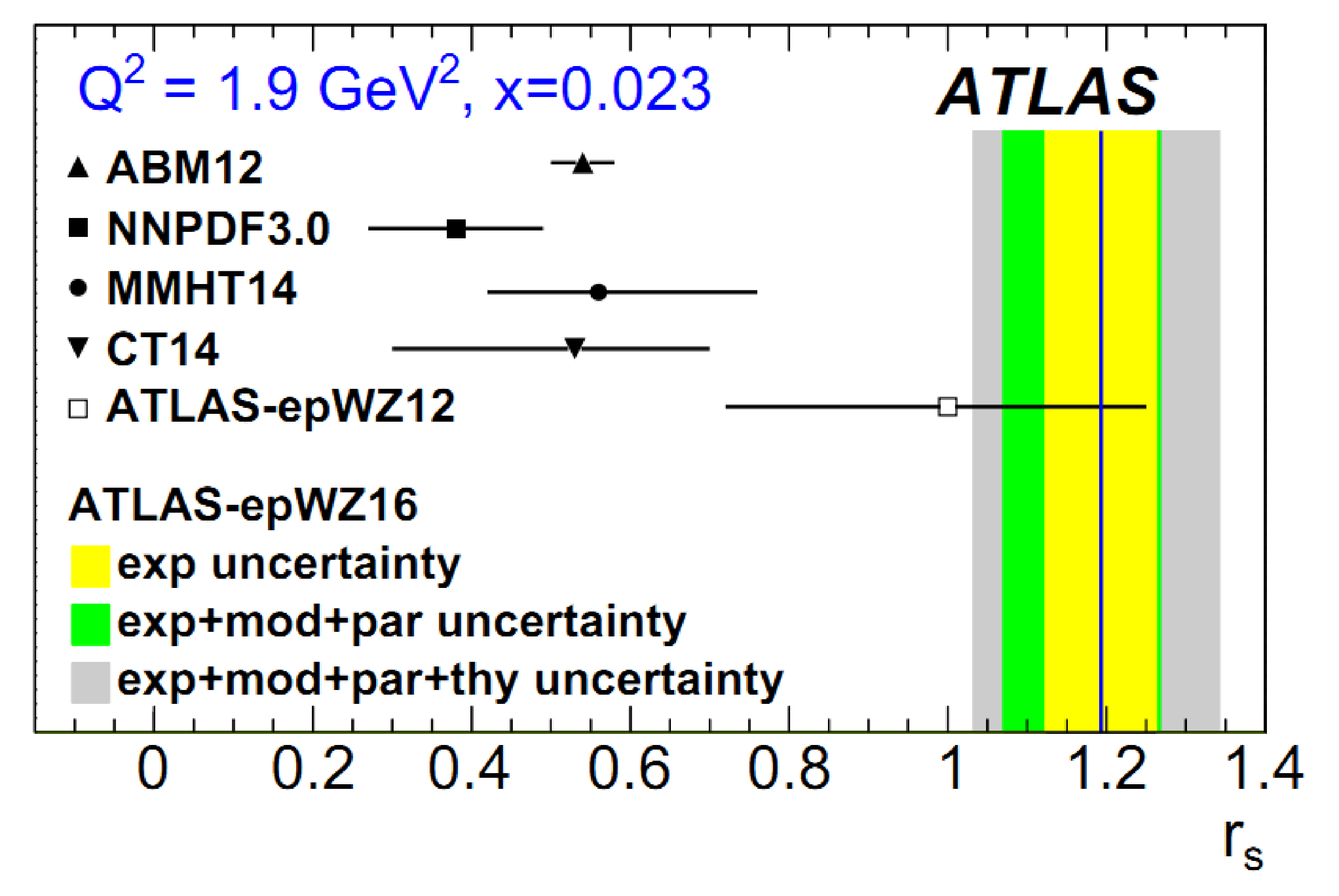
Constraining the PDF







More strangeness at low x

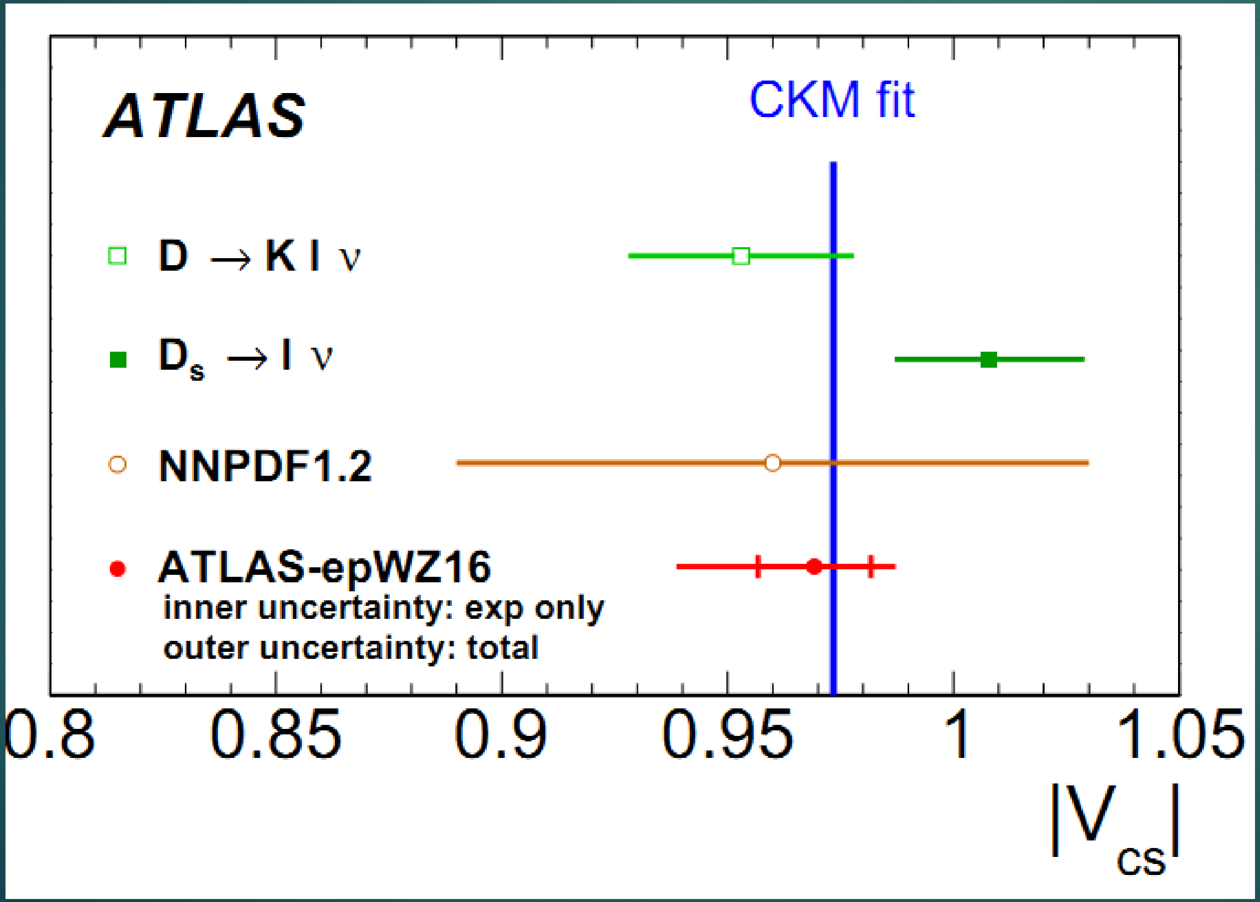


$$r_s = \frac{s + \bar{s}}{2\bar{d}} = 1.19 \pm 0.07\,(\mathrm{exp})$$

$$\pm\, 0.02\,(\mathrm{mod})\; {}^{+0.02}_{-0.10}\,(\mathrm{par})$$

Constrain |Vcs| with W

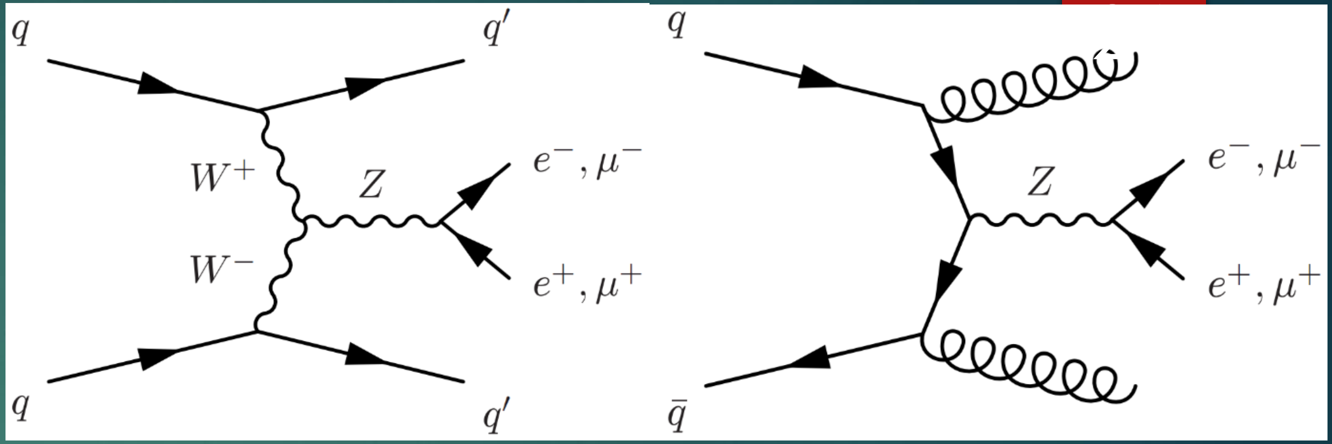
- Allow |Vcs| to vary freely in the PDF fit

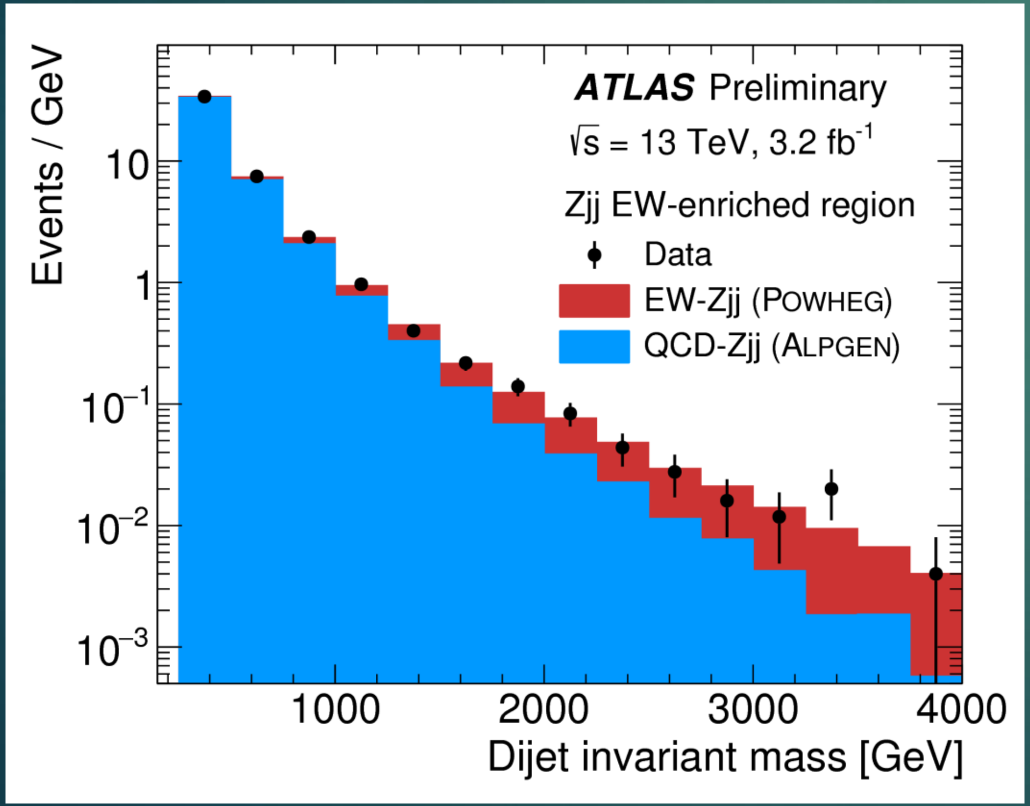


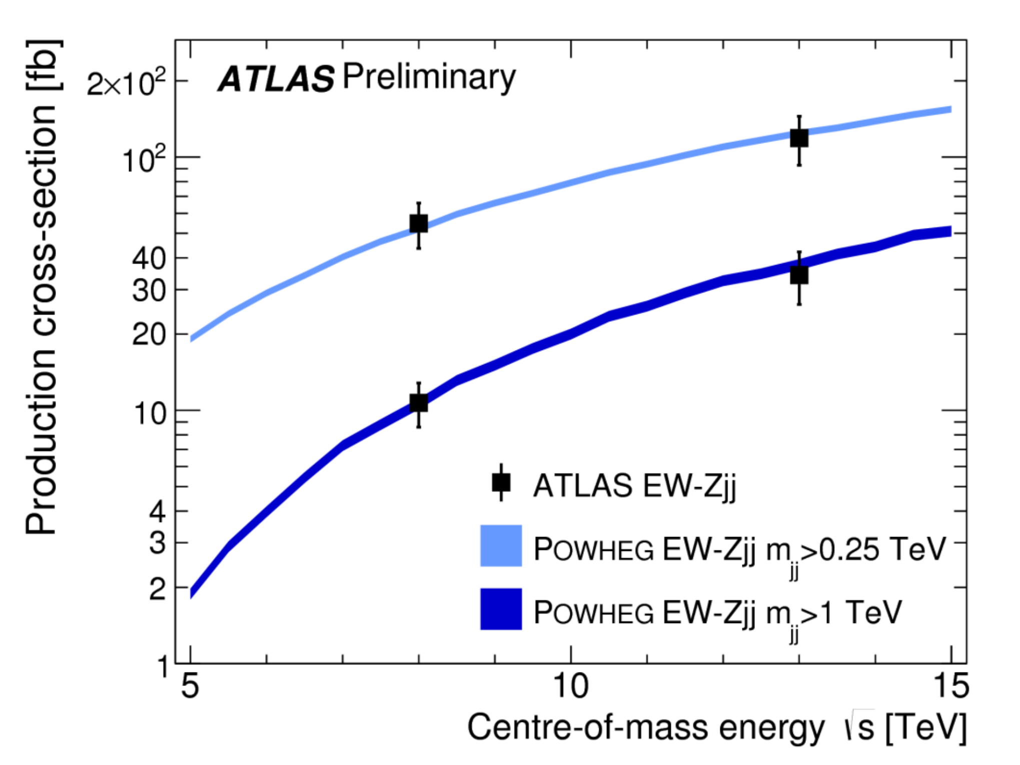
STDM-2016-09

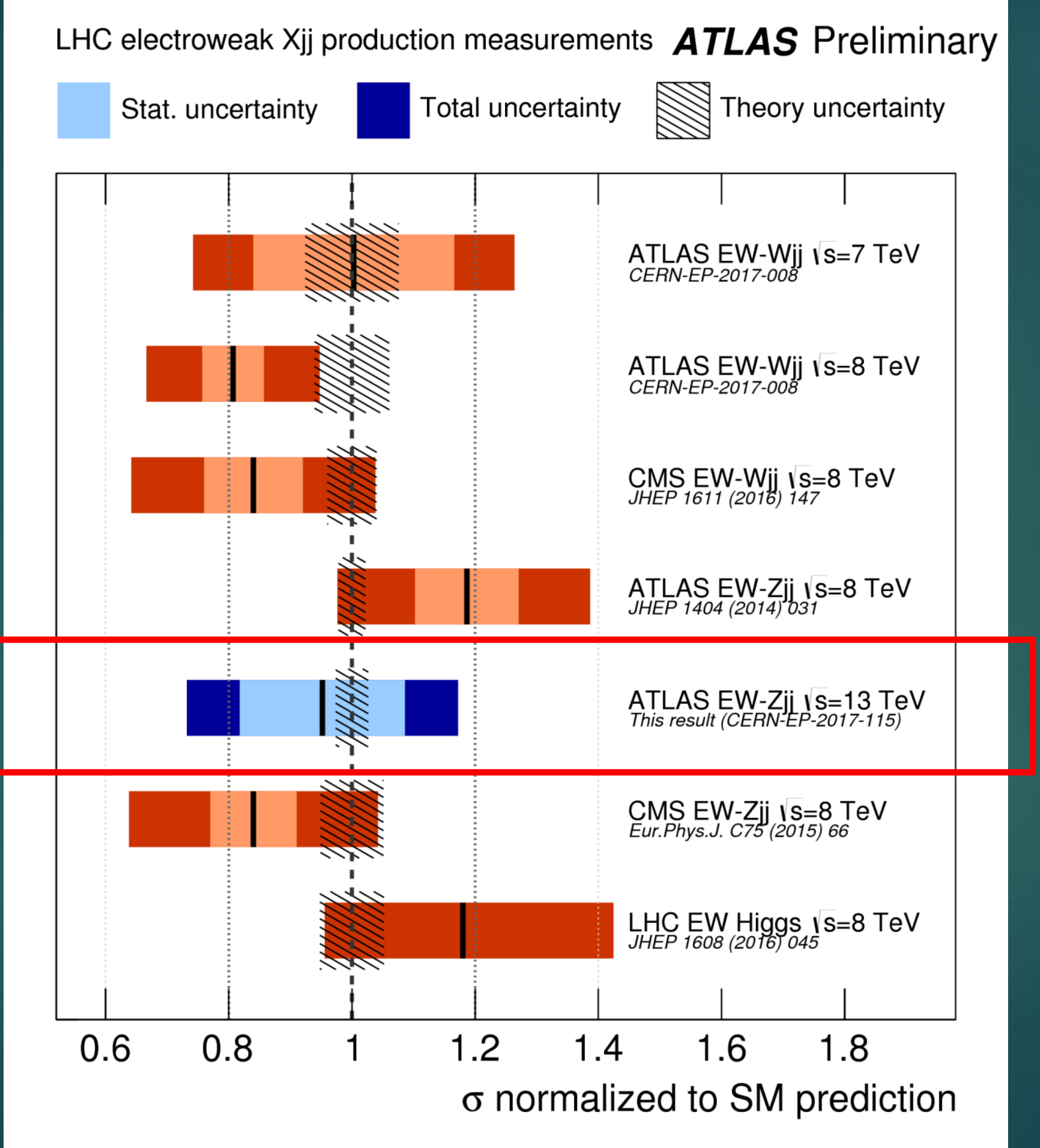
VBS Z production

- Standard candle to calib. VBS tag
- Sensitive to aGC







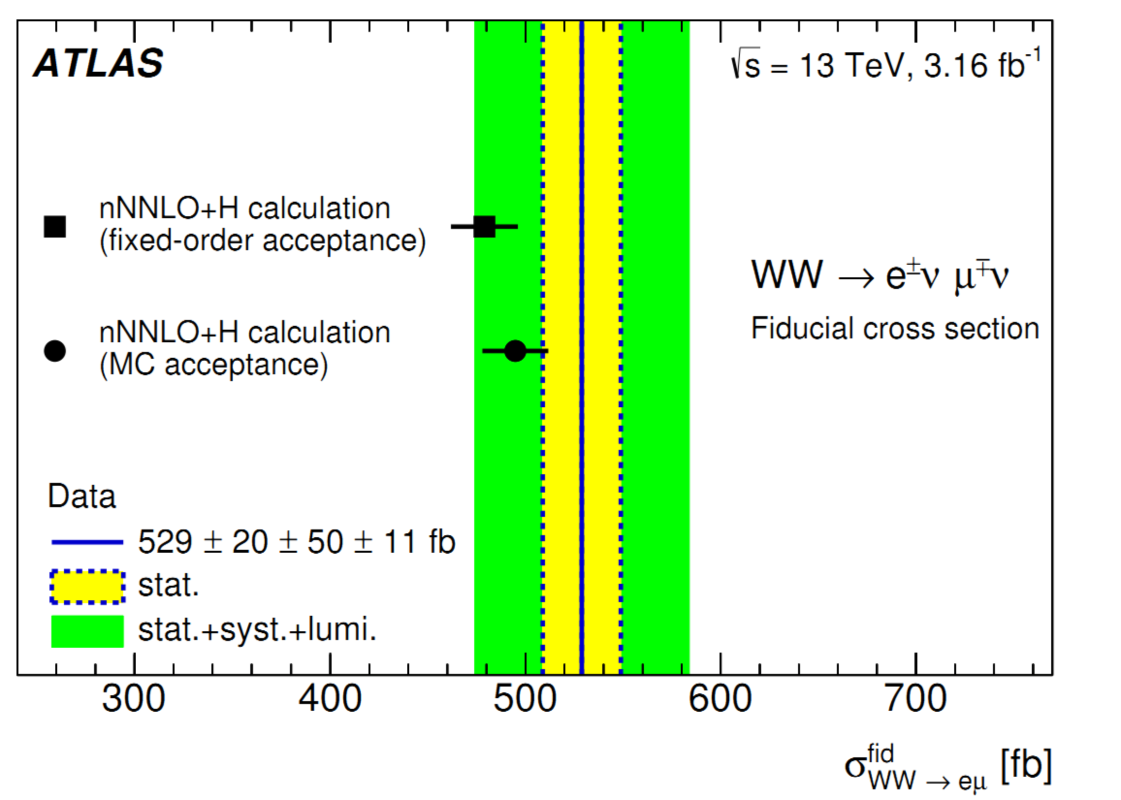

LHC electroweak Xjj production measurements
ATLAS Preliminary
Stat. uncertainty
Total uncertainty
Theory uncertainty
ATLAS EW-Wjj √s=7 TeV
CERN-EP-2017-008
ATLAS EW-Wjj √s=8 TeV
CERN-EP-2017-008
CMS EW-Wjj √s=8 TeV
JHEP 1611 (2016) 147
ATLAS EW-Zjj √s=8 TeV
JHEP 1404 (2014) 031
ATLAS EW-Zjj √s=13 TeV
This result (CERN-EP-2017-115)
CMS EW-Zjj √s=8 TeV
Eur.Phys.J. C75 (2015) 66
LHC EW Higgs √s=8 TeV
JHEP 1608 (2016) 045
0.6
0.8
1
1.2
1.4
1.6
1.8
σ normalized to SM prediction

WW production

- Sensitive to gauge boson interactions and QCD
- Important background for BSM
- Measurement with 3.2fb^{-1}, $e\mu$ final state, in fiducial region

Fiducial selection requirement	Cut value
p_T^{ℓ}	> 25 GeV
$\lvert\eta_\ell\rvert$	< 2.5
$m_{e\mu}$	> 10 GeV
Number of jets with $p_T > 25(30)$ GeV, $\lvert\eta\rvert < 2.5(4.5)$	0
$E_{\mathrm{T,\,Rel}}^{\mathrm{miss}}$	> 15 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 20 GeV

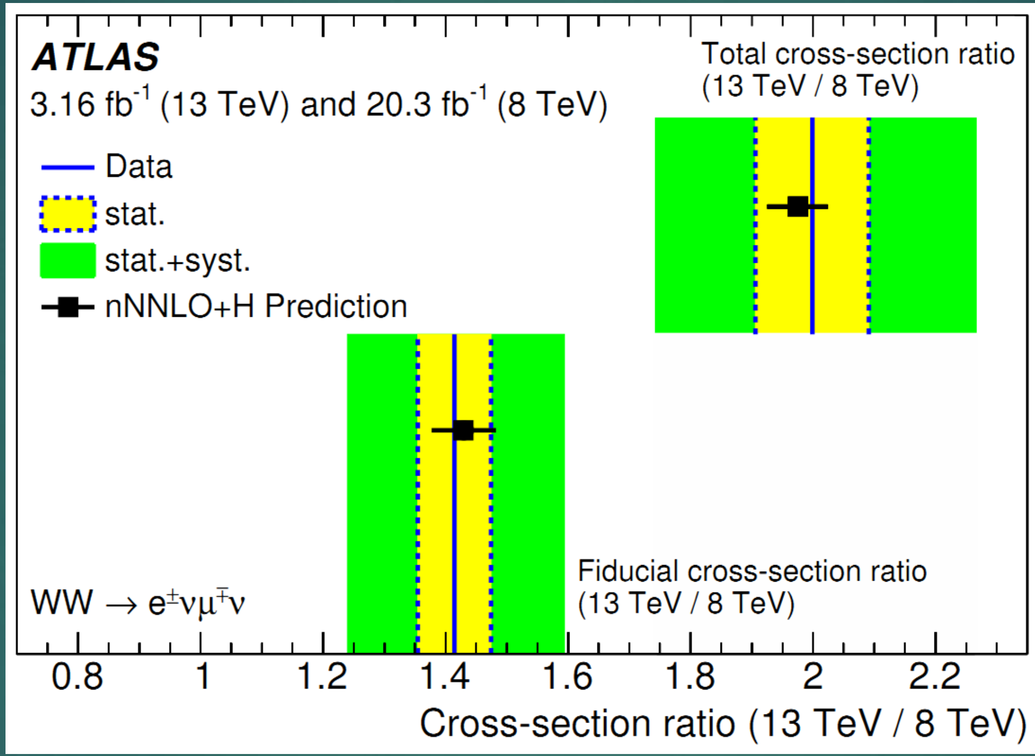
$pp \to WW$ sub-process	Order of α_s	σ_{WW}^{tot} [pb]	A [%]	$\sigma_{WW\to e\mu}^{fid}$ [fb]
$q\bar{q}$	$\mathcal{O}(\alpha_s^2)$	111.1 ± 2.8	16.20 ± 0.13	$422\ ^{+12}_{-11}$
gg (non-resonant)	$\mathcal{O}(\alpha_s^3)$	$6.82\ ^{+0.42}_{-0.55}$	$28.1\ ^{+2.7}_{-2.3}$	44.9 ± 7.2
$gg \to H \to WW$	$\mathcal{O}(\alpha_s^5)$ tot. / $\mathcal{O}(\alpha_s^3)$ fid.	$10.45\ ^{+0.61}_{-0.79}$	4.5 ± 0.6	11.0 ± 2.1
$q\bar{q}$ + gg (non-resonant) + $gg \to H \to WW$	nNNLO+H	$128.4\ ^{+3.5}_{-3.8}$	$15.87\ ^{+0.17}_{-0.14}$	478 ± 17



Ratio of 13/8 TeV

13 TeV: arXiv:1702.04519

8 TeV: JHEP09(2016)029

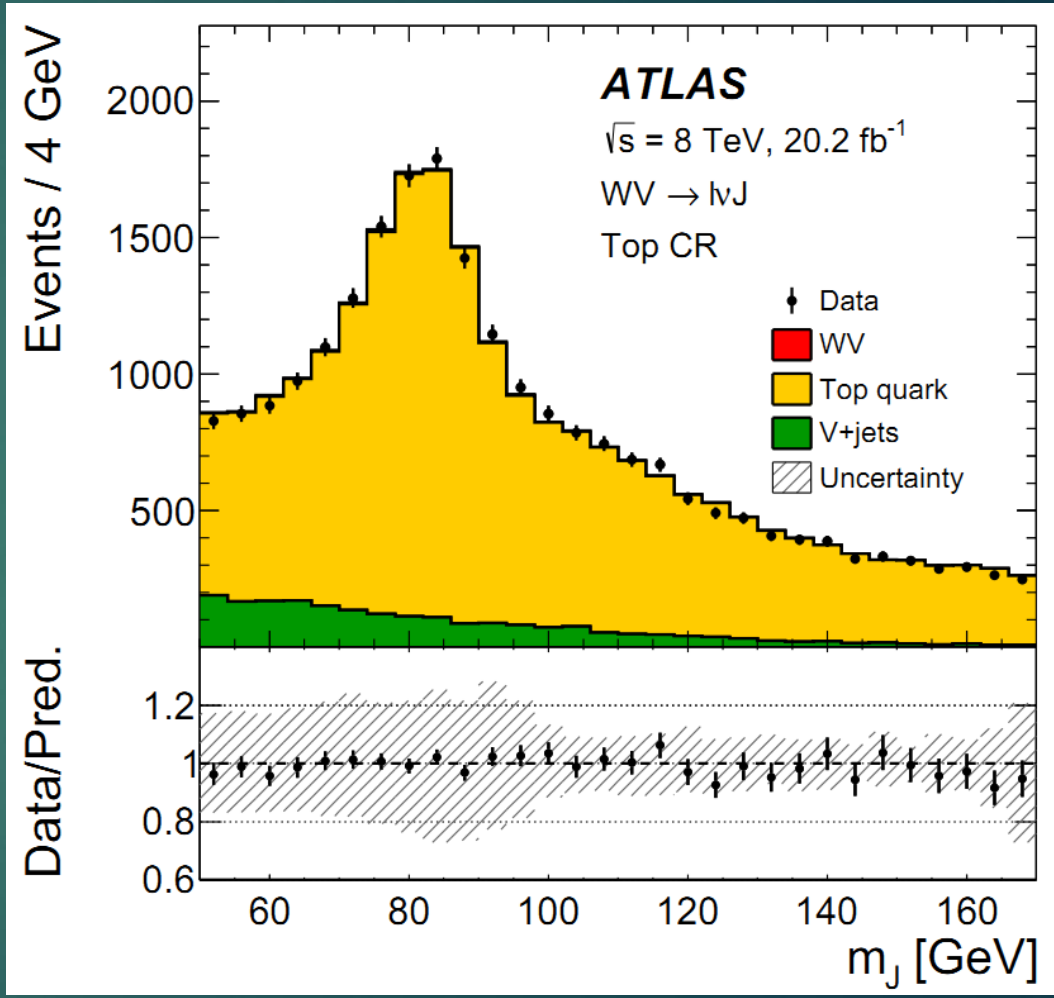


$$\frac{\sigma^{\mathrm{fid}}_{13\ \mathrm{TeV},WW\to e\mu}}{\sigma^{\mathrm{fid}}_{8\ \mathrm{TeV},WW\to e\mu}} = 1.41 \pm 0.06\ (\mathrm{stat.}) \pm 0.16\ (\mathrm{syst.}) \pm 0.04(\mathrm{lumi.})$$

arXiv:1706.01702

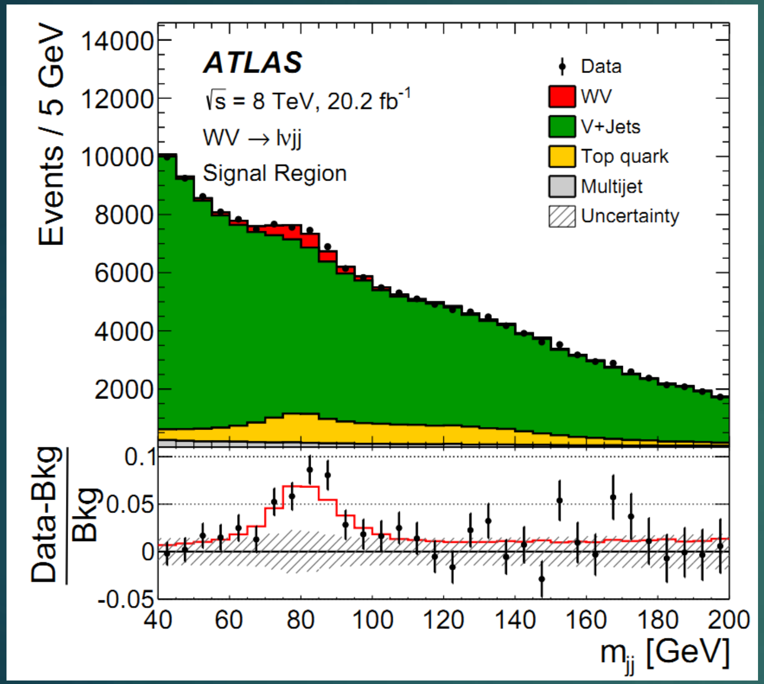
WV(V=W,Z) semi-leptonic decay

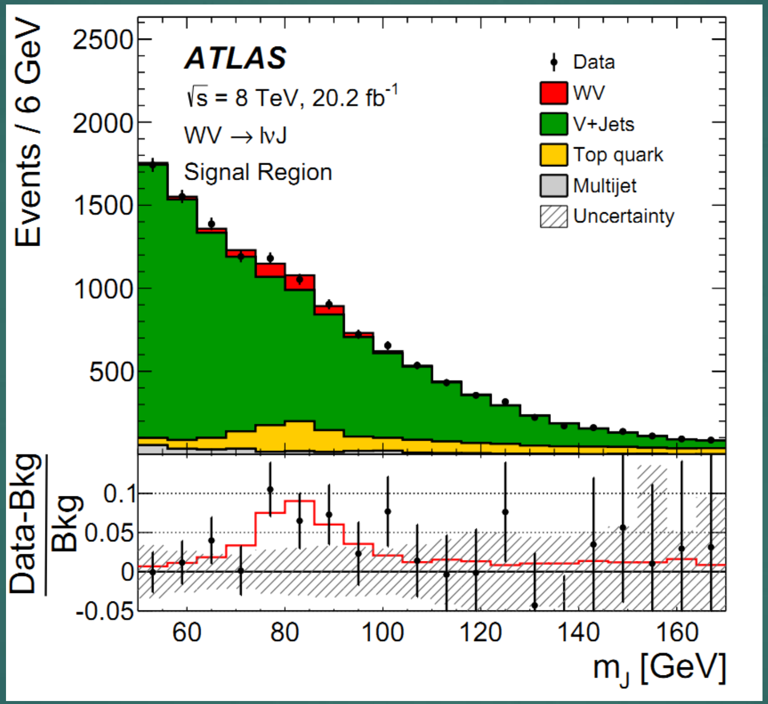
- V→qq' reconstructed in resolved (jj) or merged/large-R (J) jets
- Compared to leptonic decay:
  - Large background ☹
  - ~6X higher in BF ☺
  - No neutrino for W☺

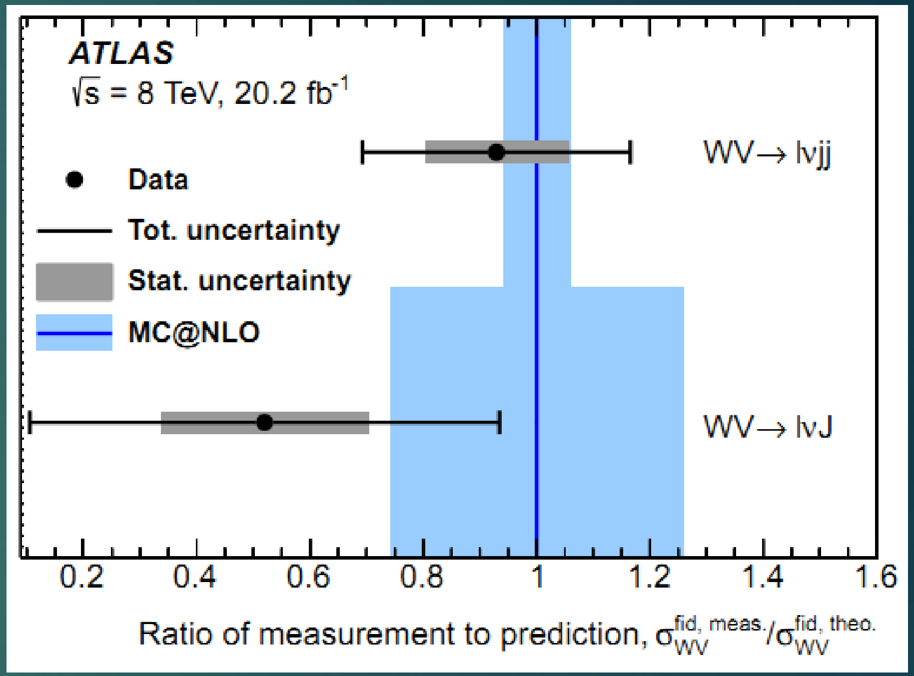


Top control region :
one b-tagged jet and dR(j,J) > 1.0

Signal regions



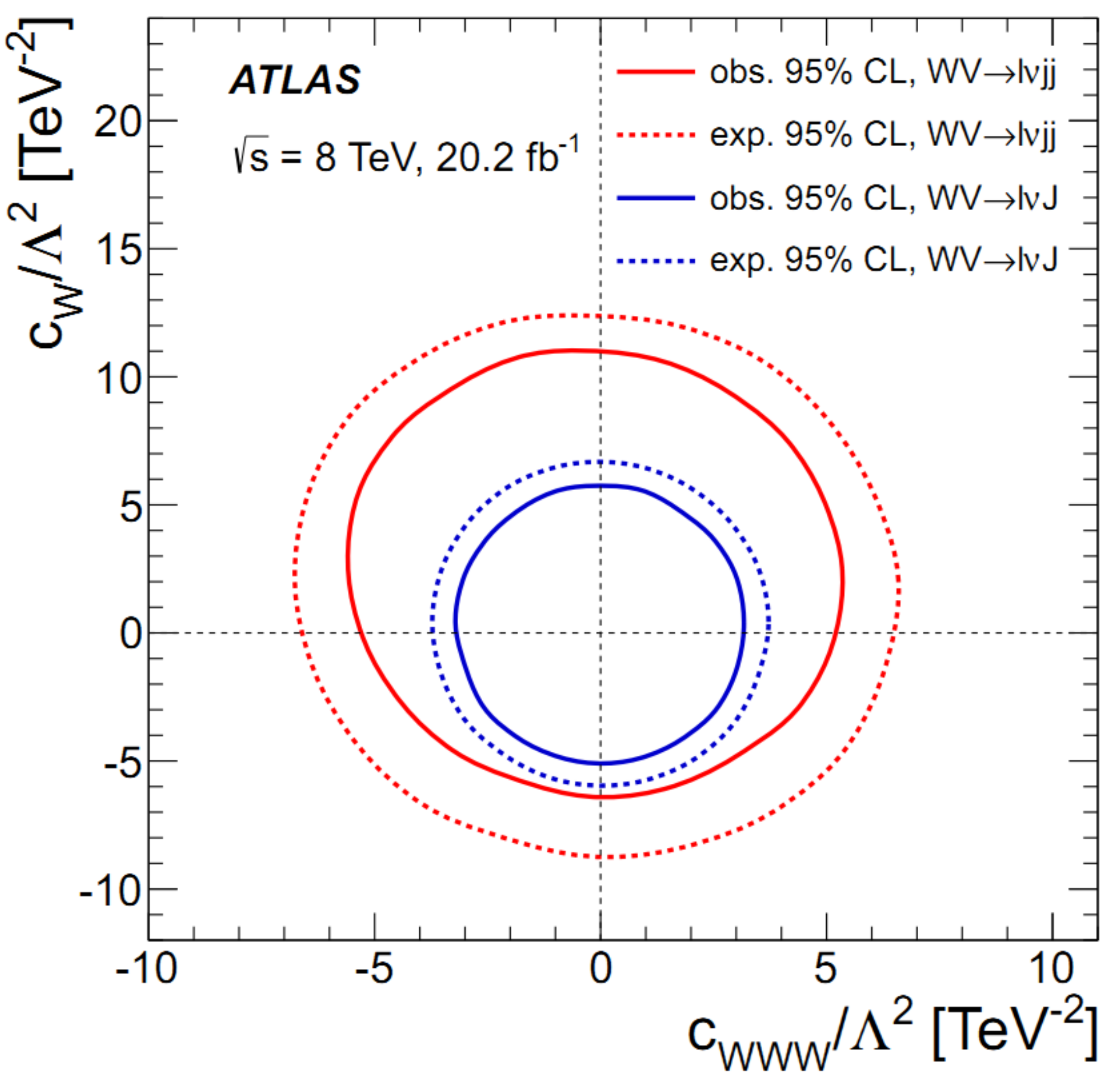


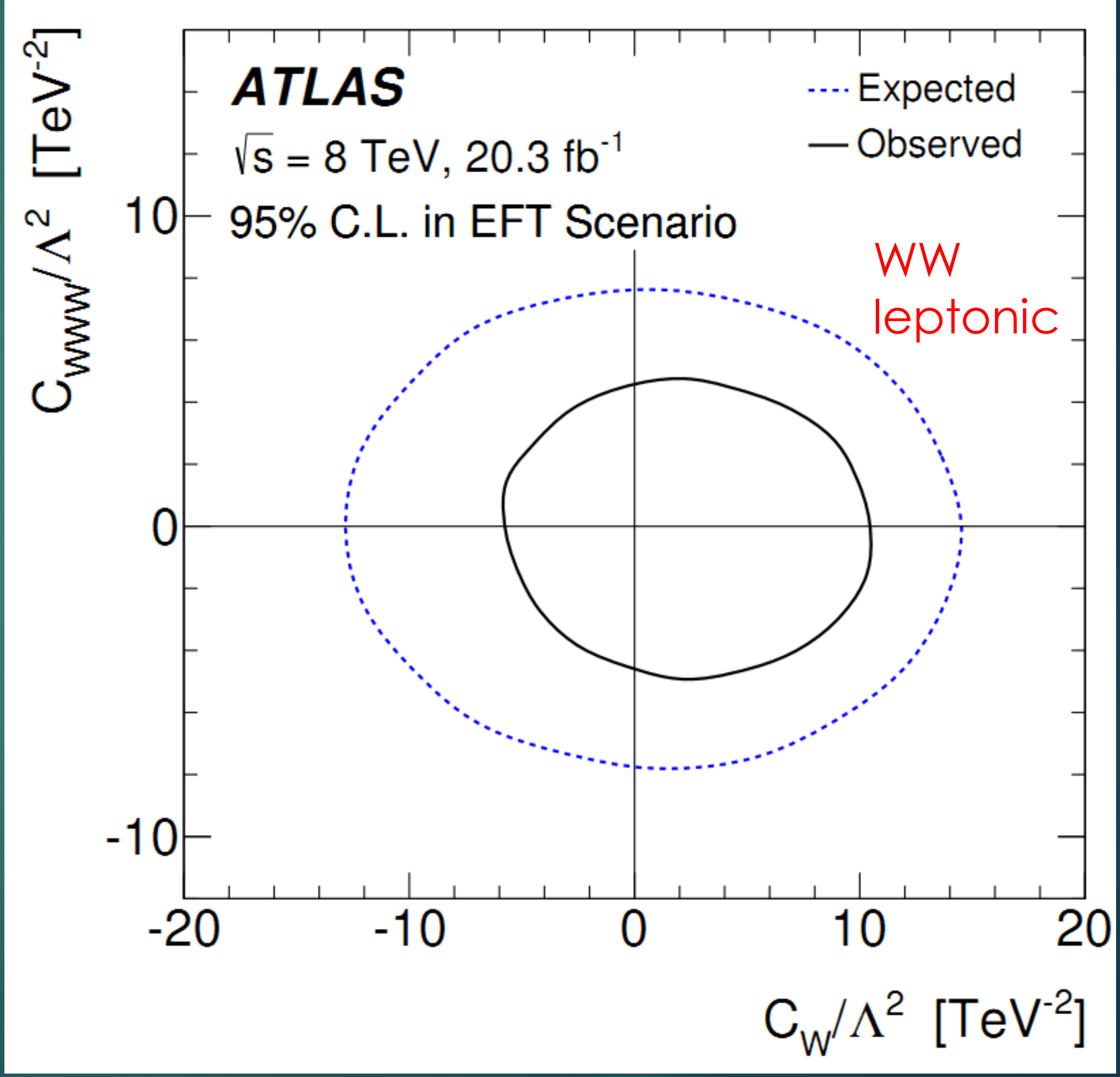


4.5 sigma

1.3 sigma

Limits on aGC





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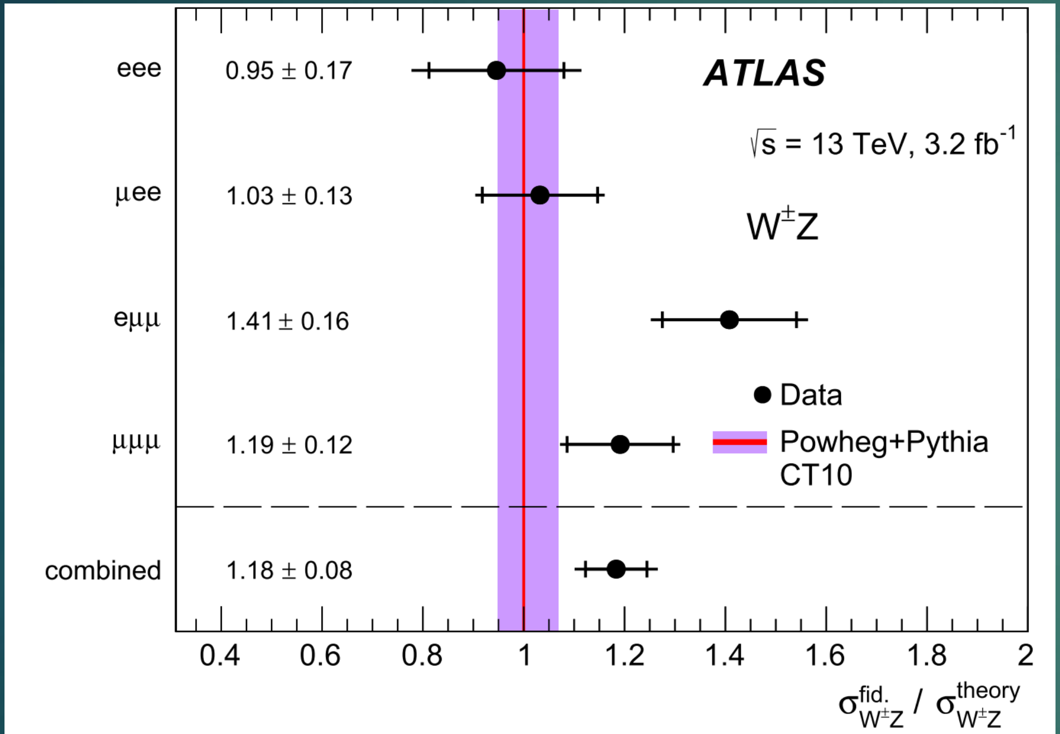
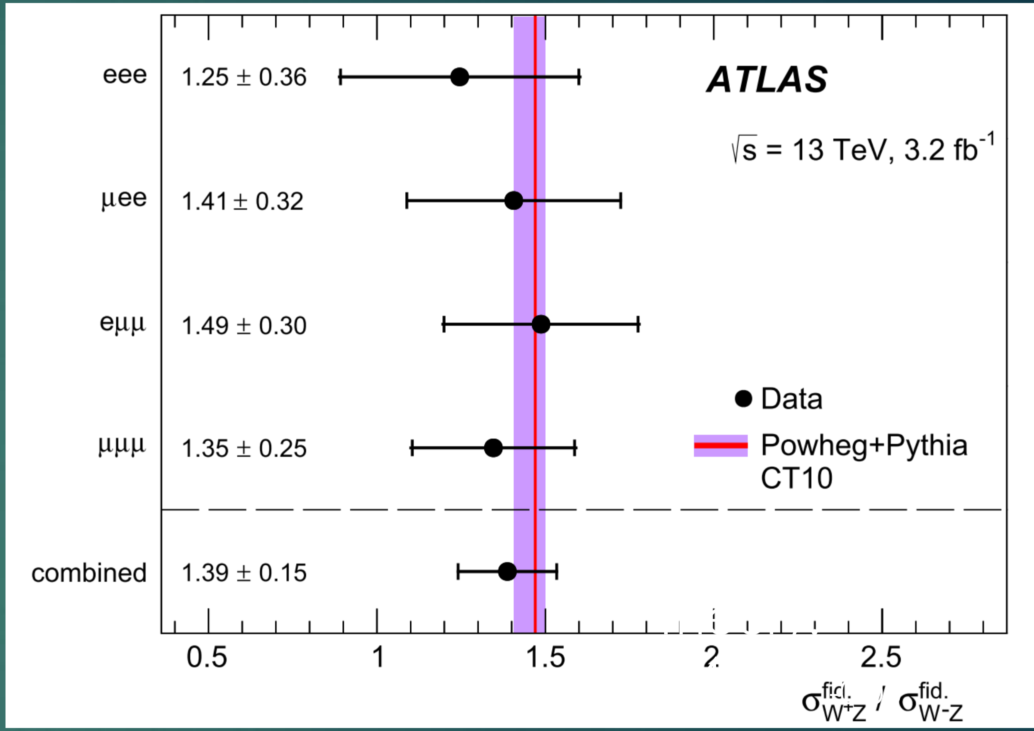
WZ cross section at 13 TeV

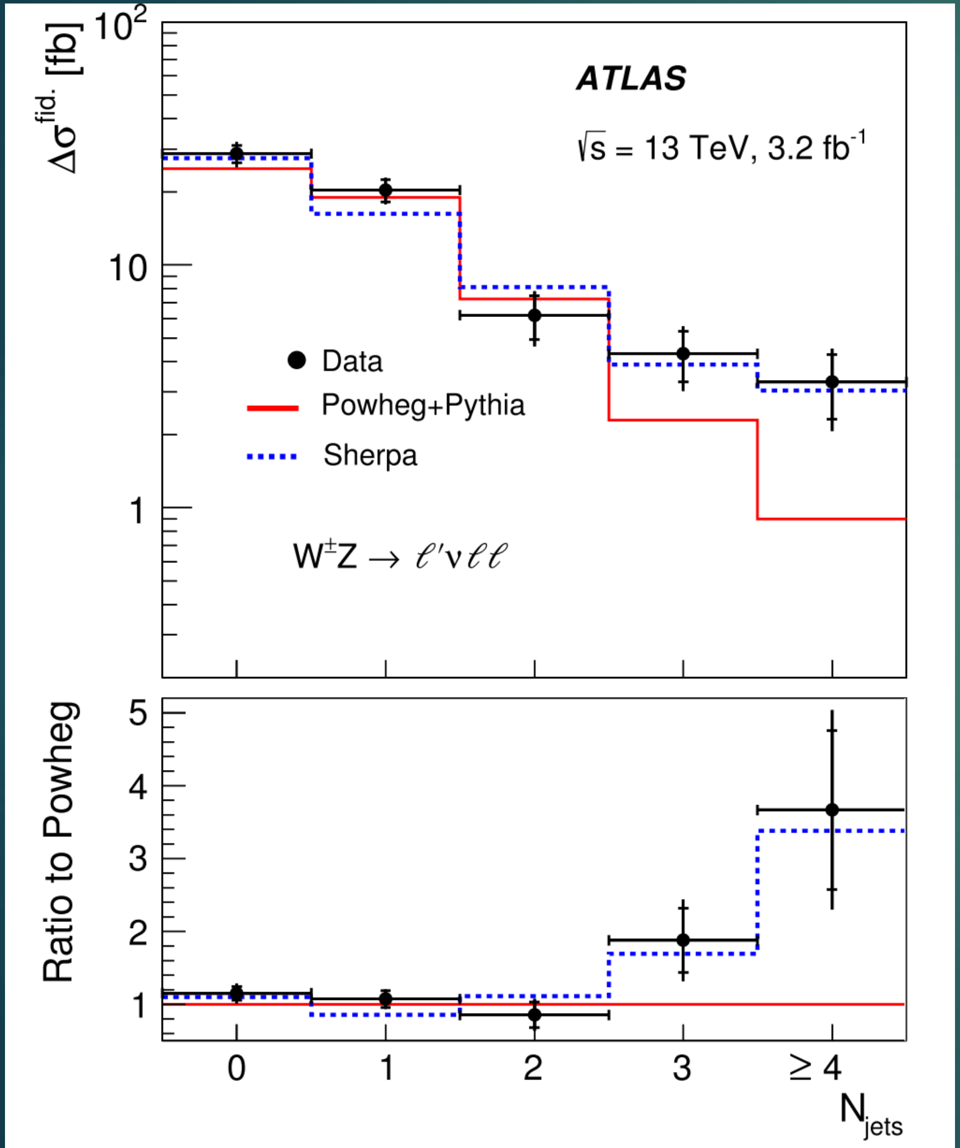




$$\frac{\sigma_{W^{\pm}Z}^{\text{fid.,13 TeV}}}{\sigma_{W^{\pm}Z}^{\text{fid.,8 TeV}}} = 1.80 \pm 0.10\,(\text{stat.}) \pm 0.08\,(\text{sys.}) \pm 0.06\,(\text{lumi.})$$

POWHEG-PYTHIA: 1.78+-0.03

Jet multi. and NNLO cross section



- Scale to full phase space:

  50.6±2.6(stat) ±2.0(sys) ±0.9(th) ±1.2(lumi) pb
- MATRIX (NNLO) prediction:

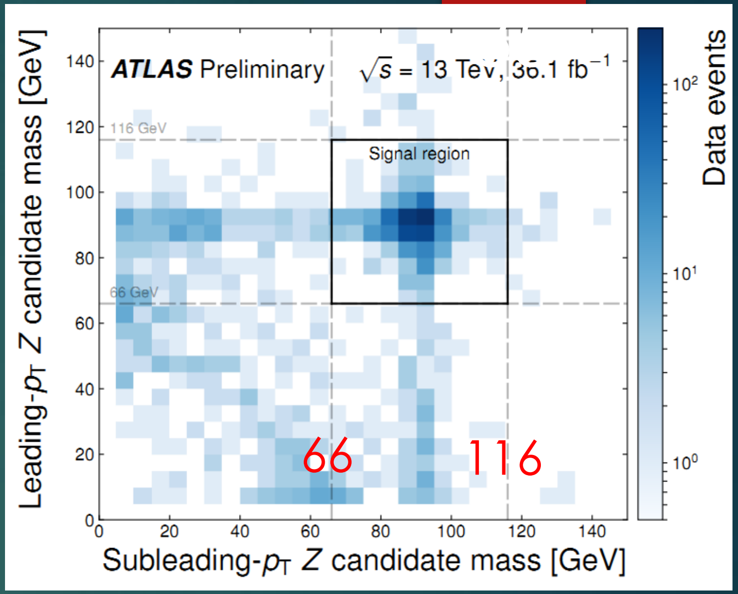
  $48.2^{+1.1}_{-1.0}$ pb

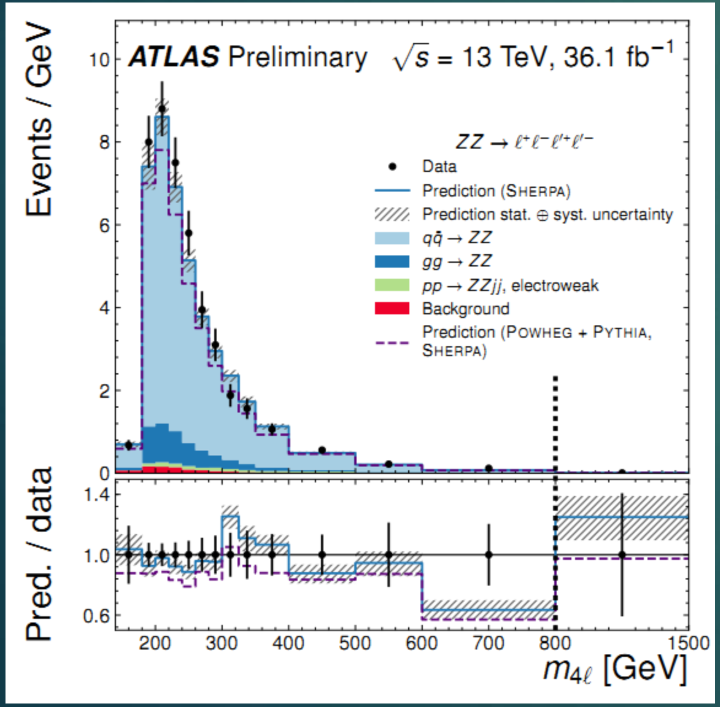
- Sherpa provides a good description of the jet multiplicity

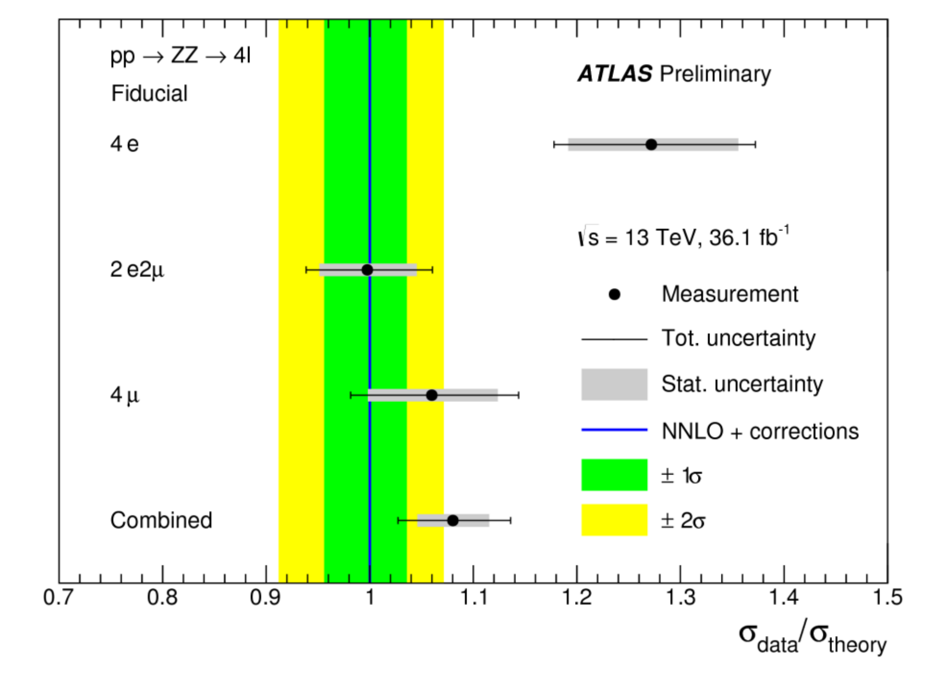
Phys. Rev. Lett. 116, 101801 (2016)
ATLAS-CONF-2017-031

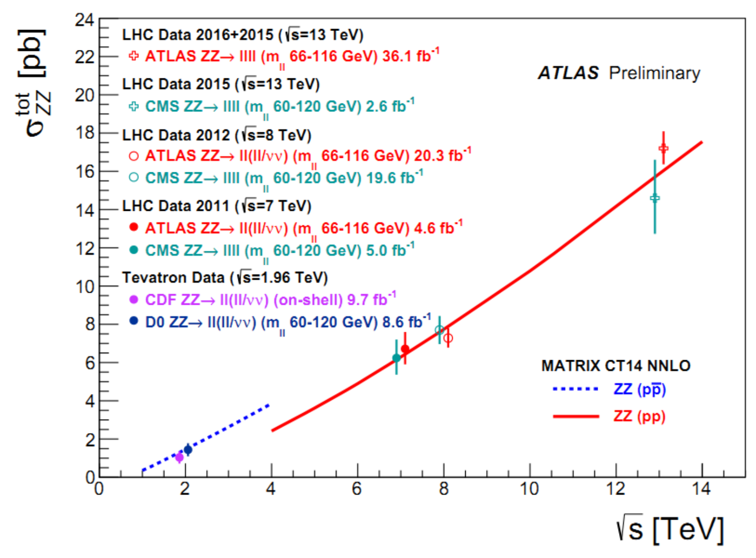
ZZ production at 13 TeV

- Test EWK at highest energies
- Cross section doubled from 8 to 13 TeV
- Important background for Higgs and BSM

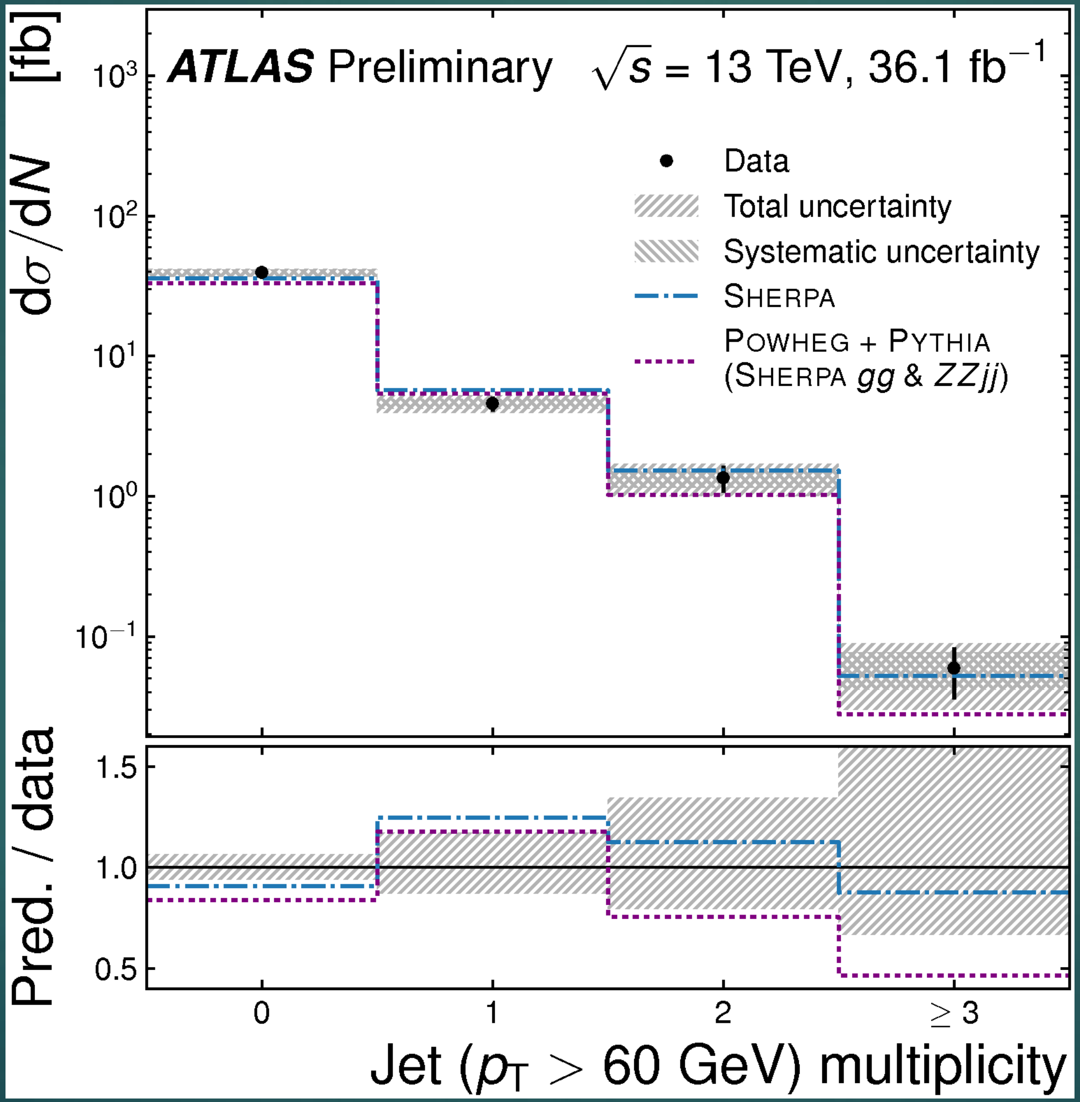






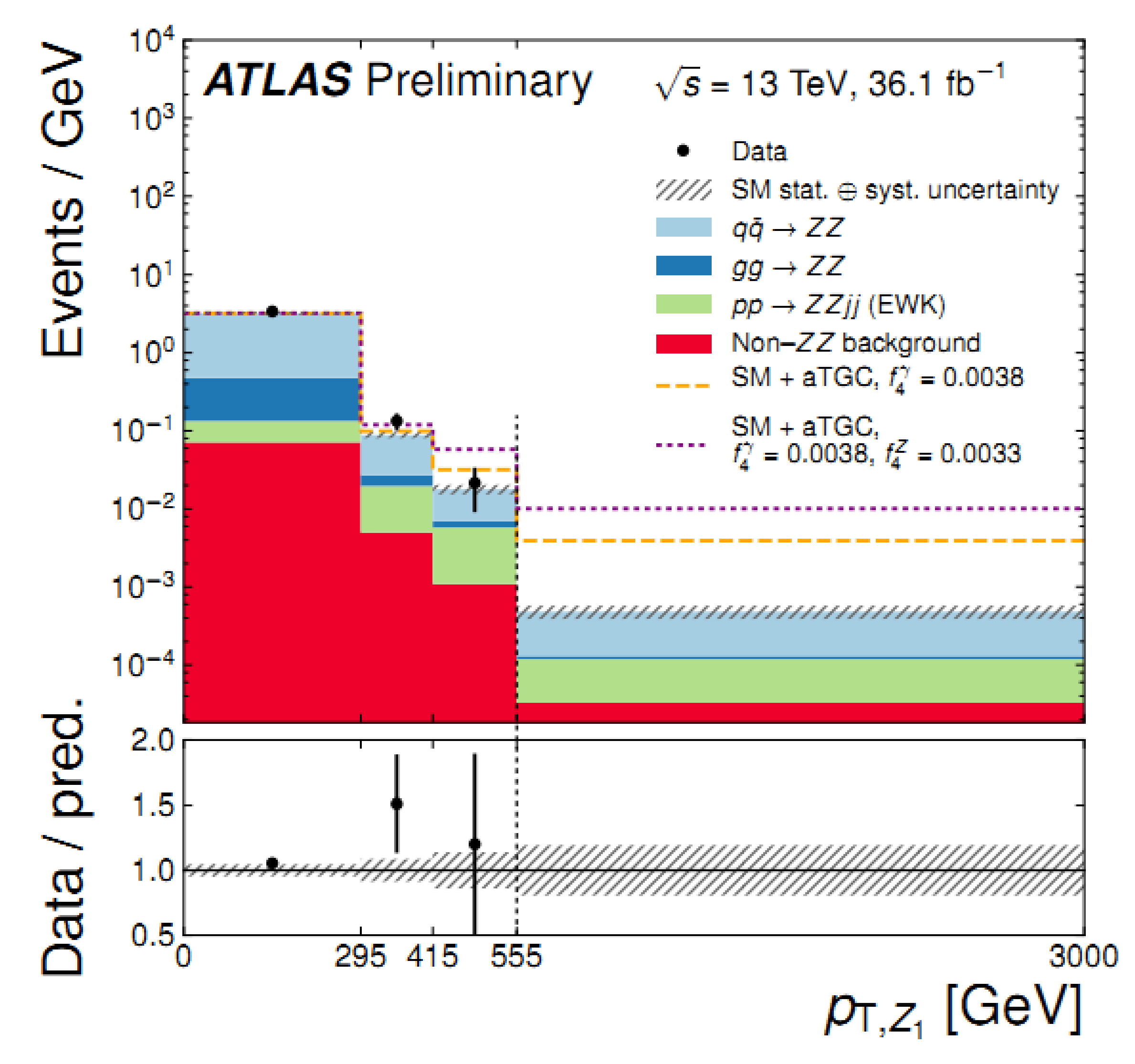


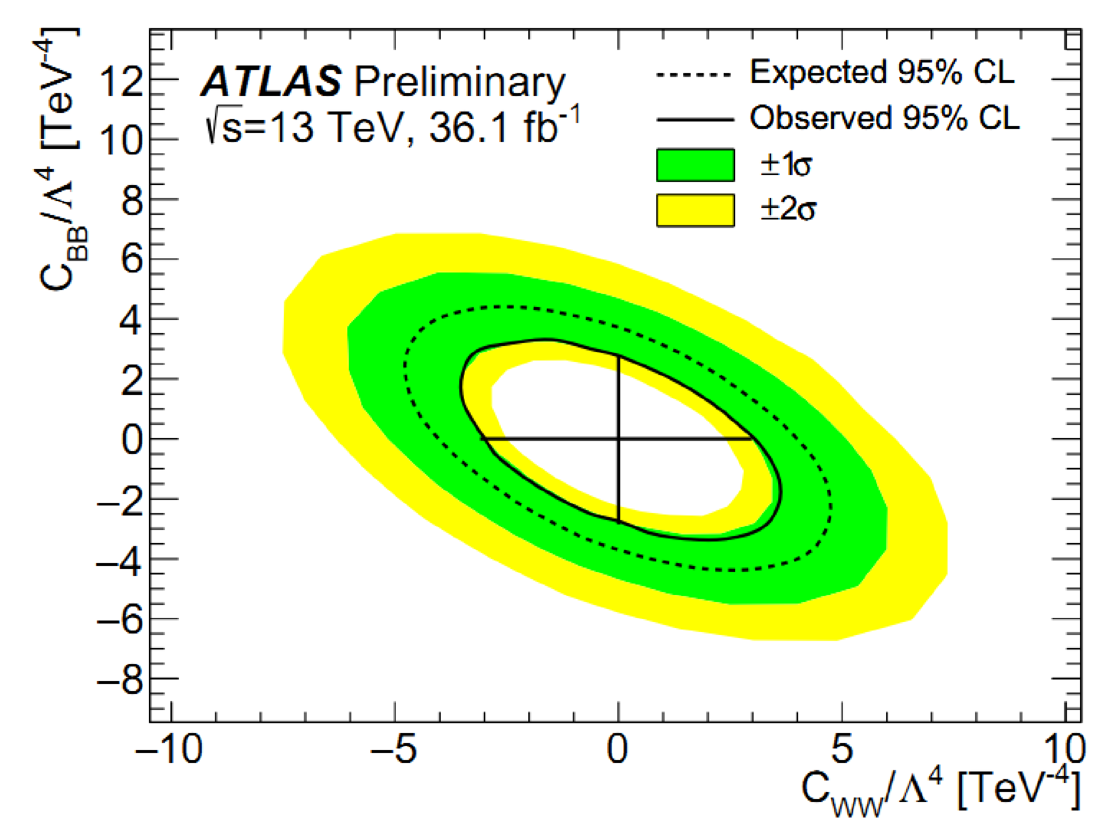
Jet multiplicity in ZZ events



SHERPA ~ OK
POWHEG+PYTHIA off at ≥ 3

Limits on anomalous couplings

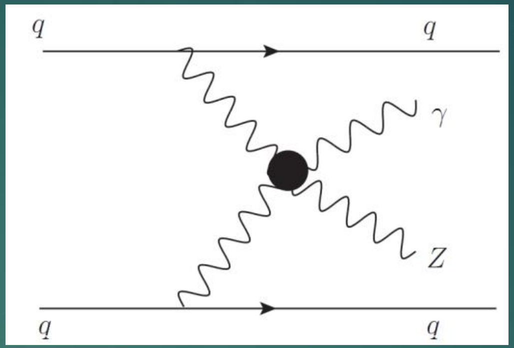


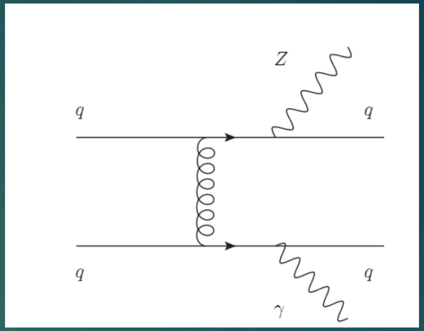


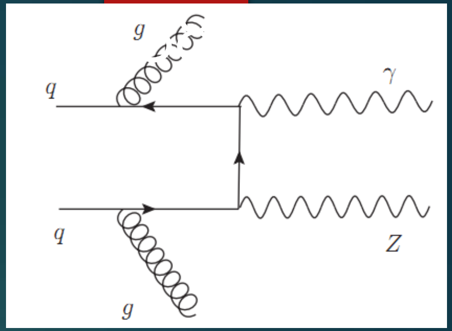
EFT parameter	Expected 95% CL [TeV^{-4}]	Observed 95% CL [TeV^{-4}]
$C_{\tilde{B}W}/\Lambda^4$	−8.1, 8.1	−5.9 , 5.9
C_{WW}/Λ^4	−4.0, 4.0	−3.0 , 3.0
C_{BW}/Λ^4	−4.4, 4.4	−3.3 , 3.3
C_{BB}/Λ^4	−3.7, 3.7	−2.7 , 2.8

VBS $Z\gamma$

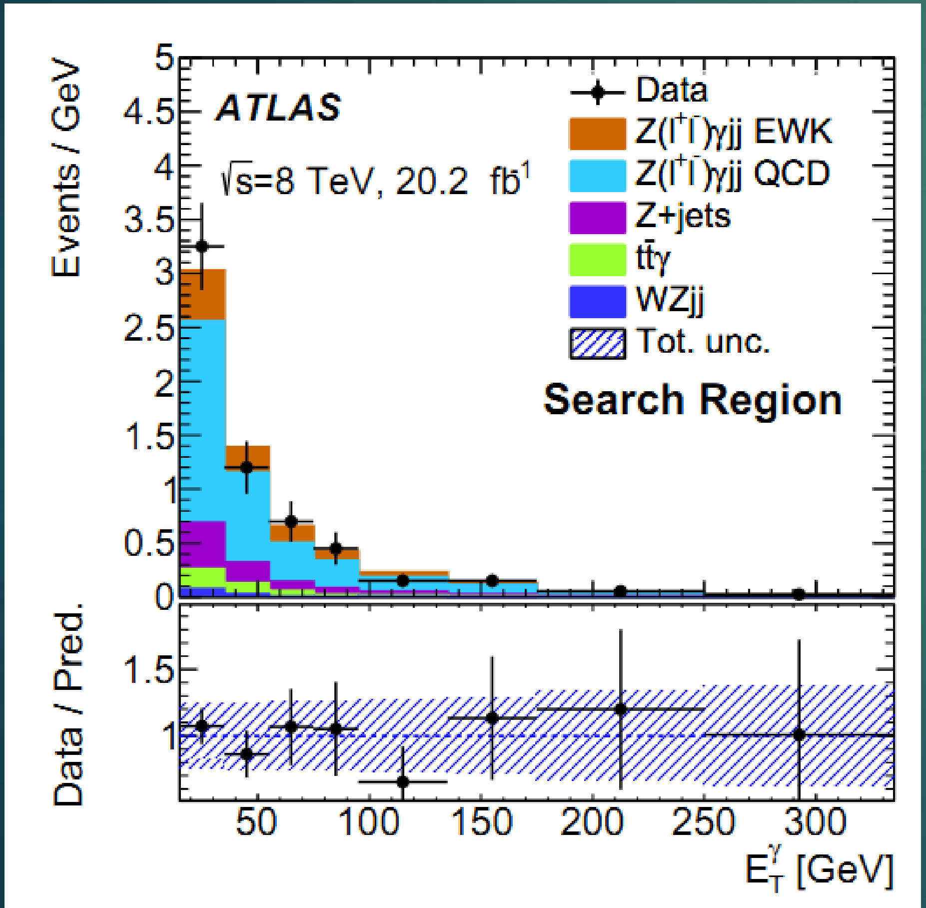
arXiv:1705.01966v1







- Test gauge boson interactions



Event selected with Mll > 40 GeV, Mllγ> 182 GeV, Mjj>500 GeV

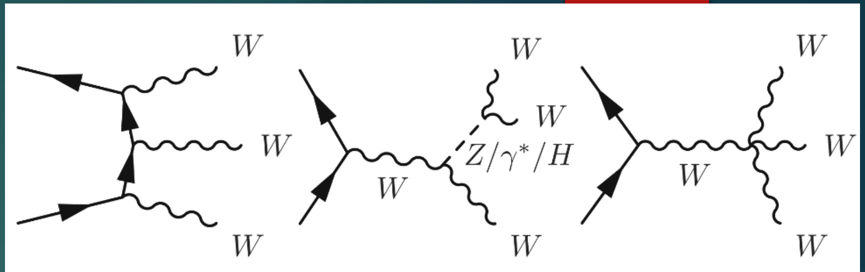
Process	Contribution (events)
$Z\gamma$jj EWK	11
$Z\gamma$jj QCD	37
Z+jets	9
Other	5.8

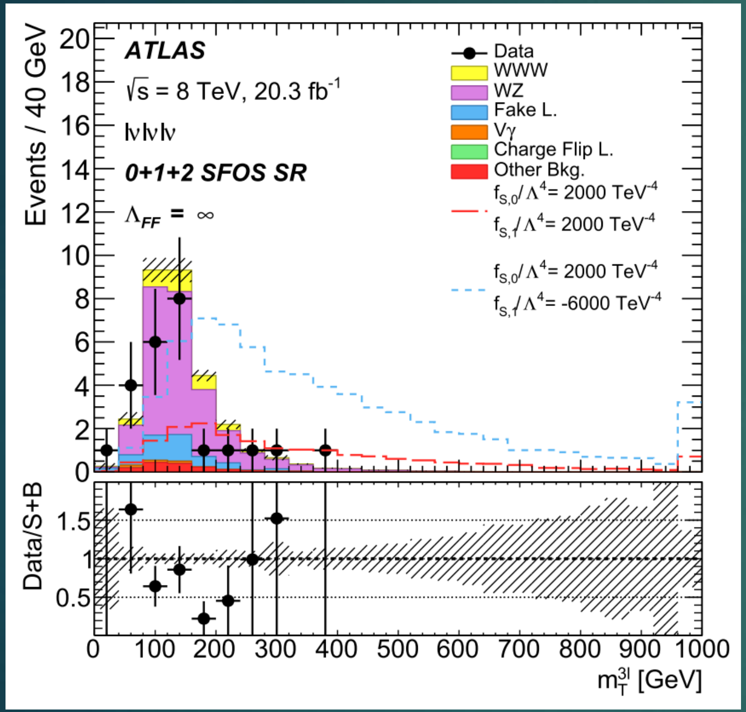
$$\sigma^{\text{EWK}}_{Z\gamma jj} = 1.1 \pm 0.6 \text{ fb}$$

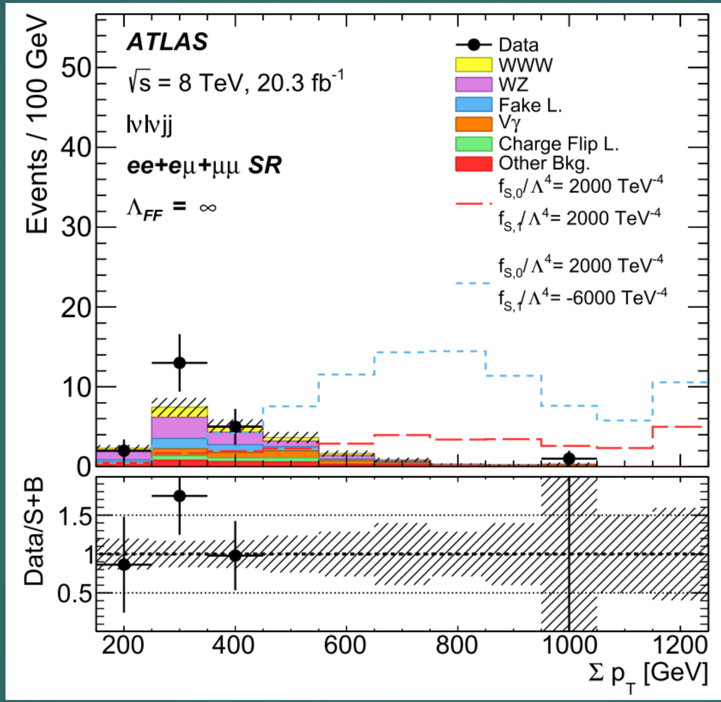
Significance: 2 sigma

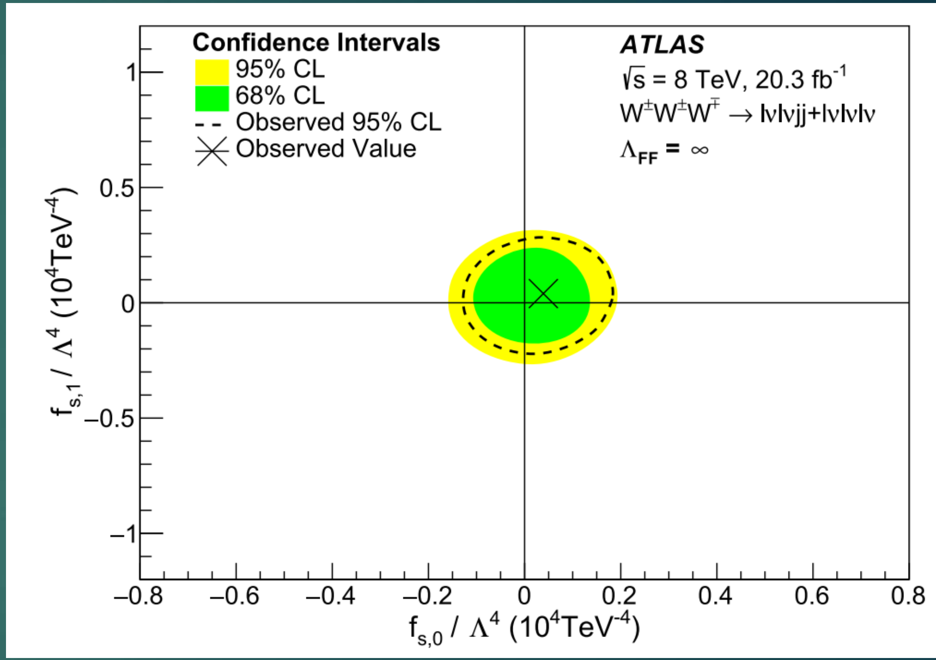
[Eur. Phys. J. C (2017) 77: 141]

WWW production









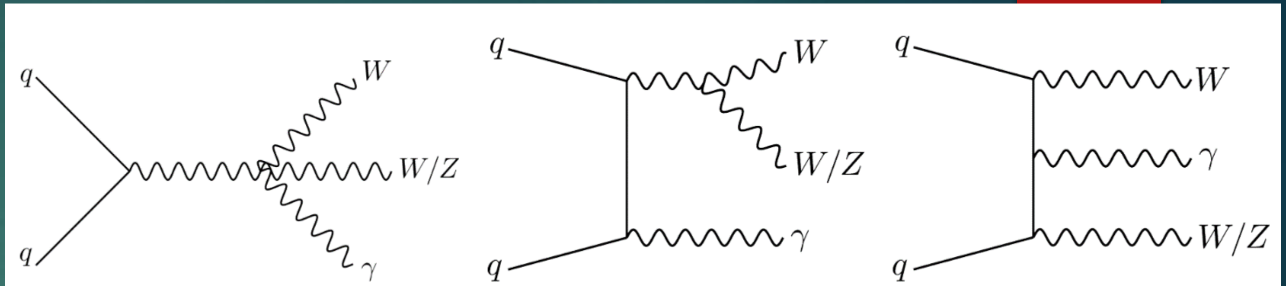
$$\mathcal{L}_{S,0} = \frac{f_{S,0}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

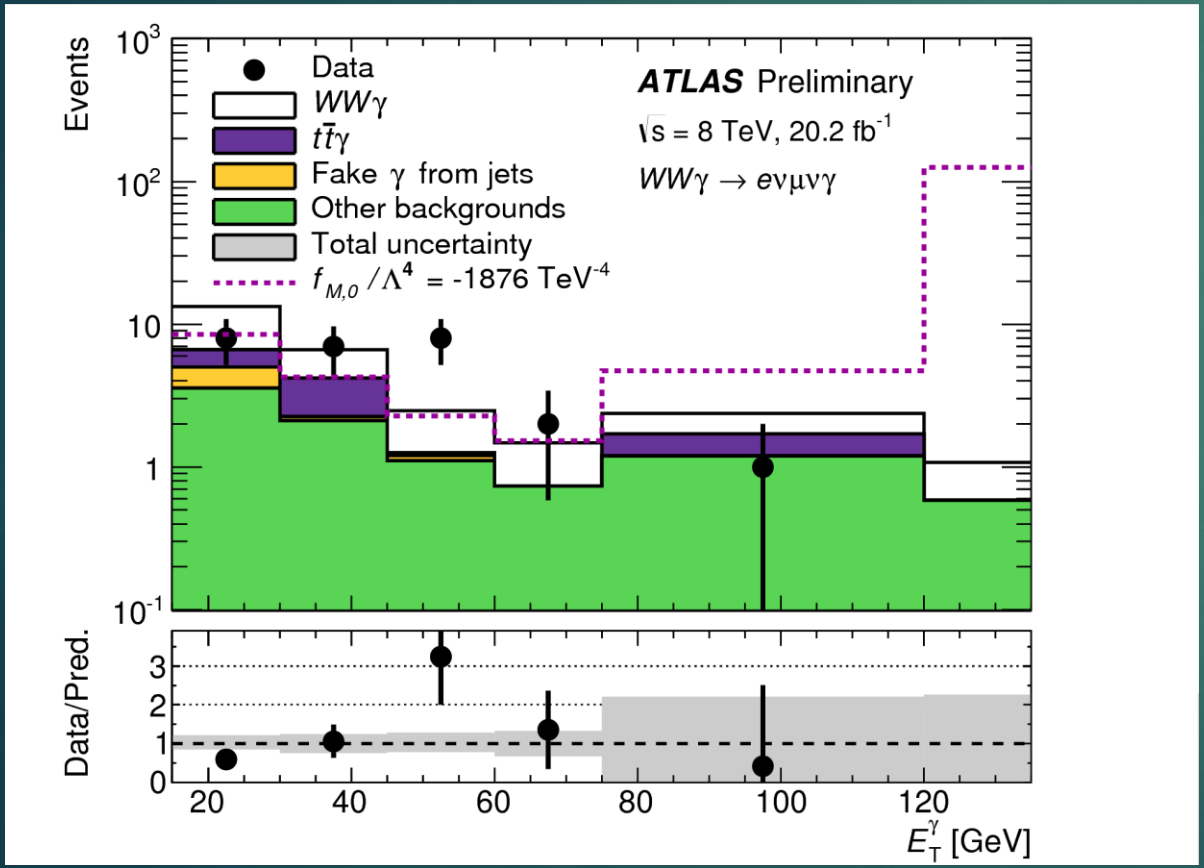
$$\mathcal{L}_{S,1} = \frac{f_{S,1}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

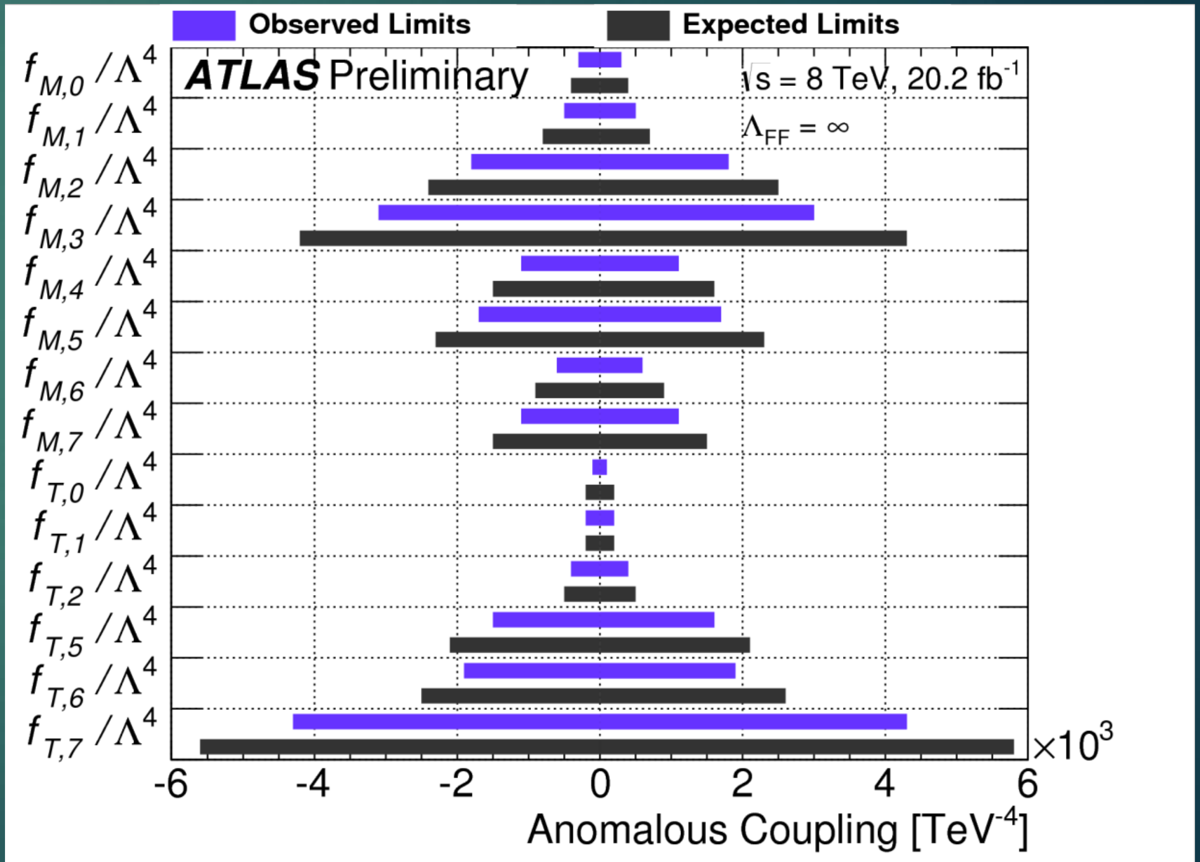
Signal significance : 1 sigma
Constraints on aQGC

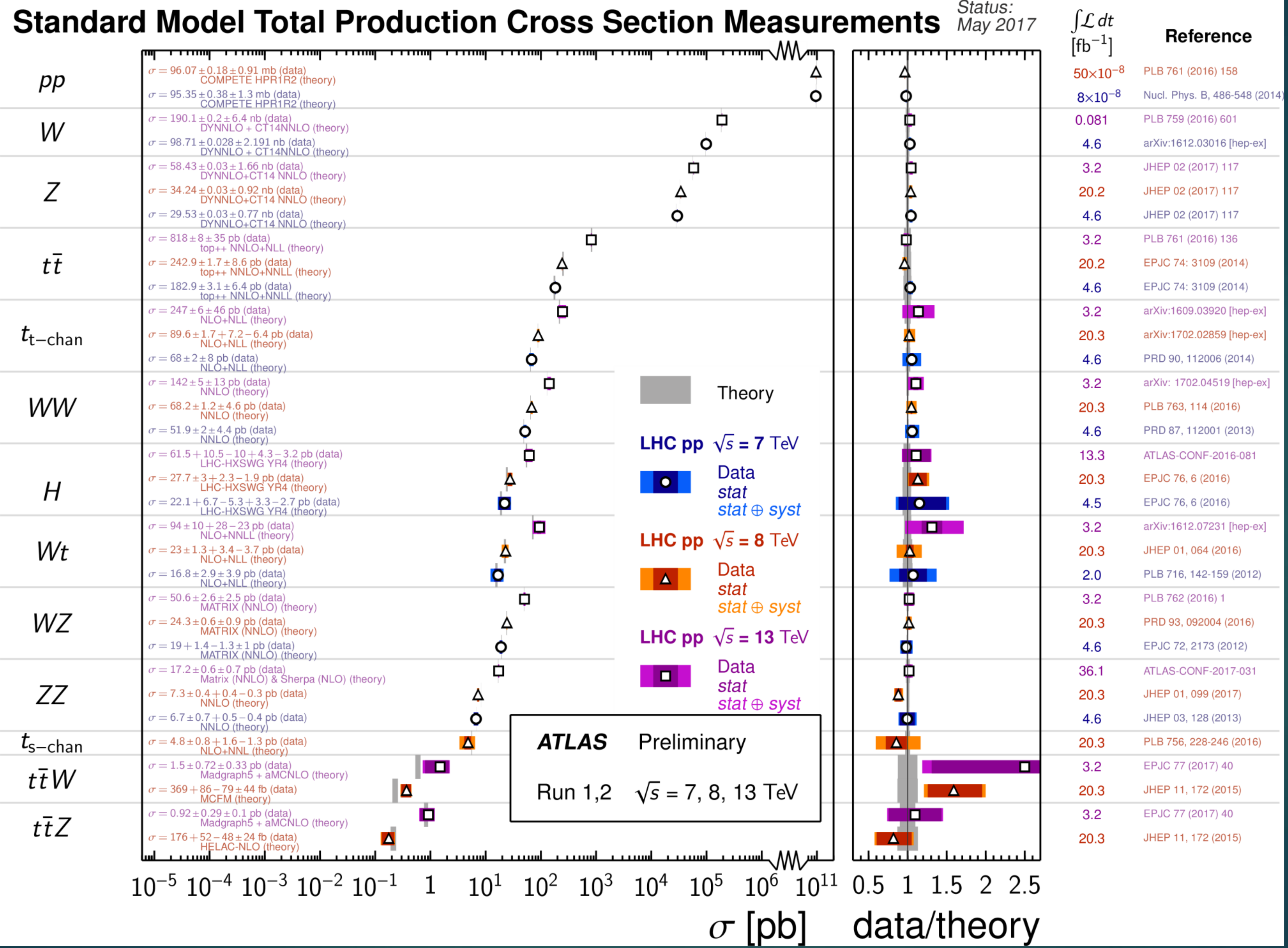
$WV\gamma$

STDM-2016-05



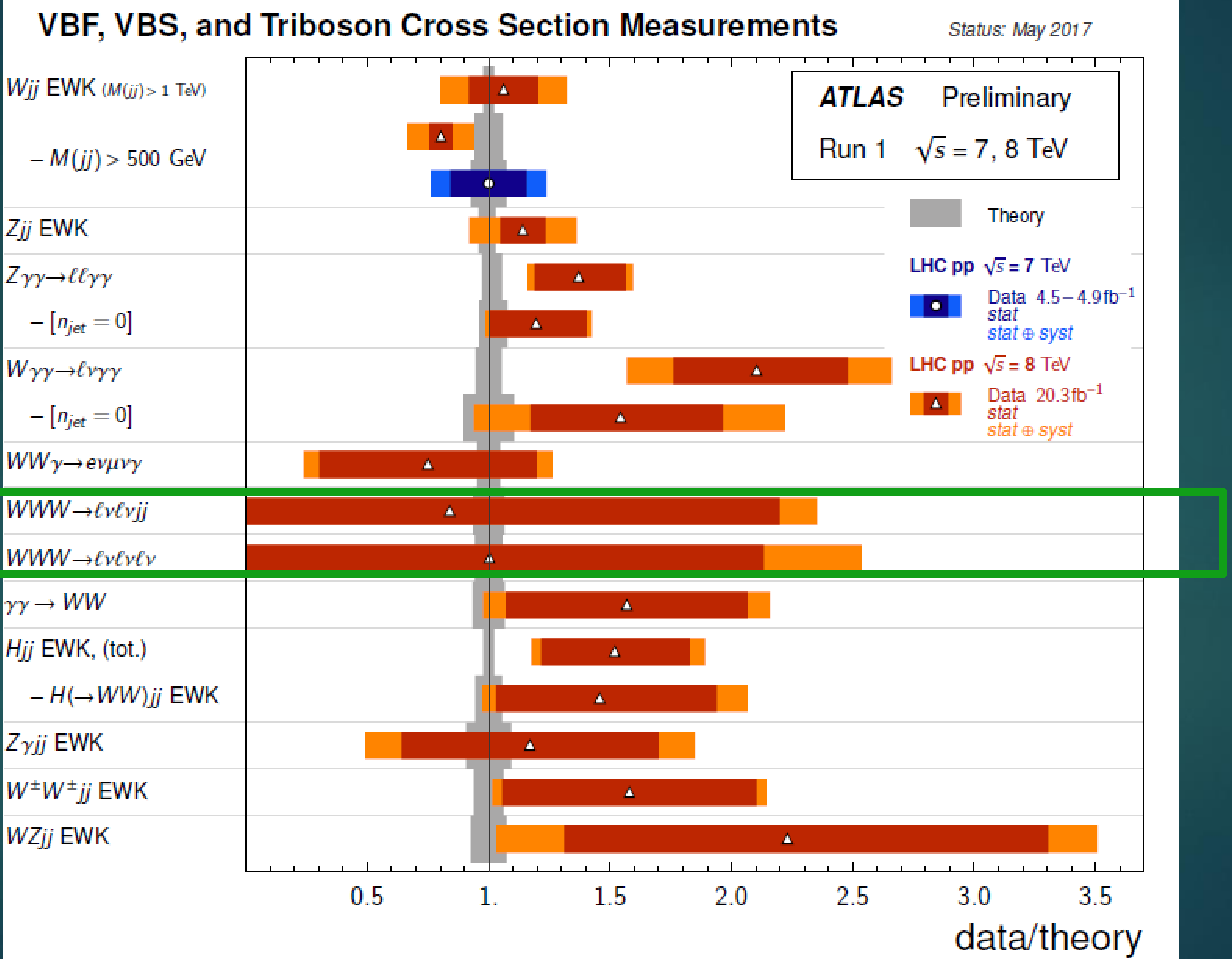






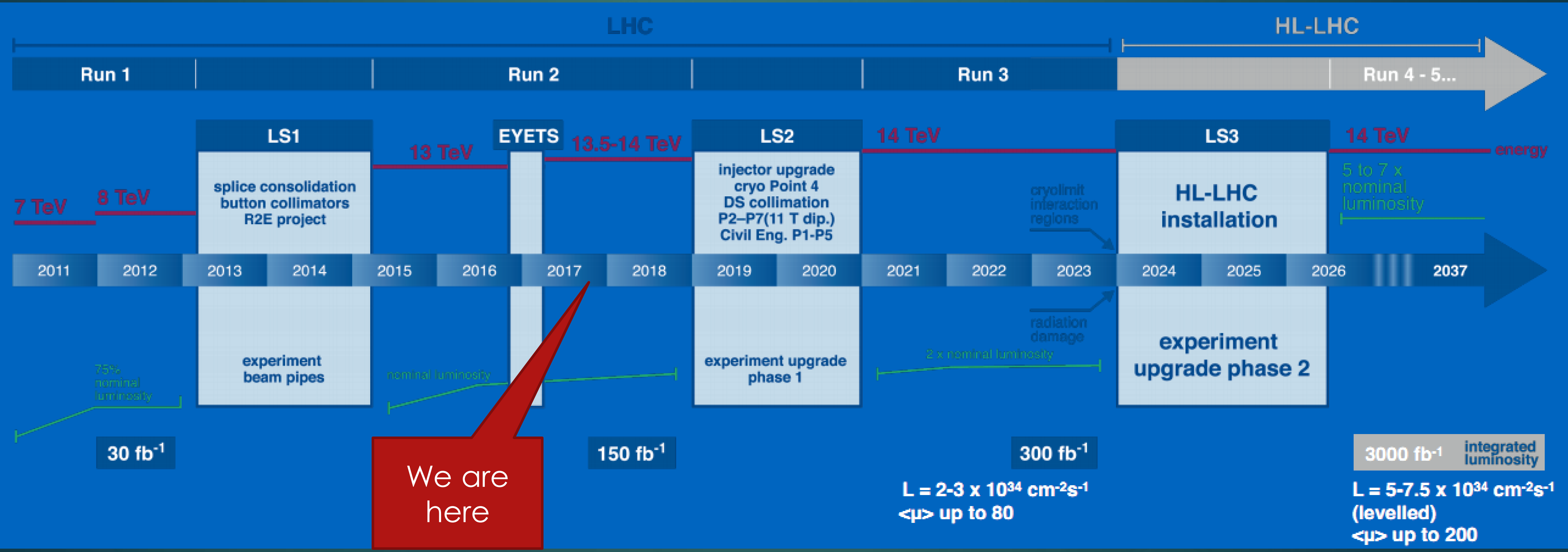
Consistencies in 12 orders of magnitudes!

Picture from ATLAS SM Summary



Picture from ATLAS SM Summary

Looking ahead



Conclusions

- SM spans 12 order of magnitudes in cross sections, no significant deviation seen
- On fundamental parameters in SM:
  - $m_W$measured to a precision of 19 MeV, modeling systematics dominate
  - $\sin\theta_W$, α_s measured
- Jet inclusive cross sections consistent with prediction
- Inclusive photon and photon pair: N(N)LO predictions challenged, SHERPA OK
- Failure to model the kT splitting scales in Z+jets
- W/Z data ➔ test of EWK(lepton universality), ATLAS-epWZ16(more strange), Vcs
- Di-boson, VBS, triboson: No suprises, constraints on anomalous couplings

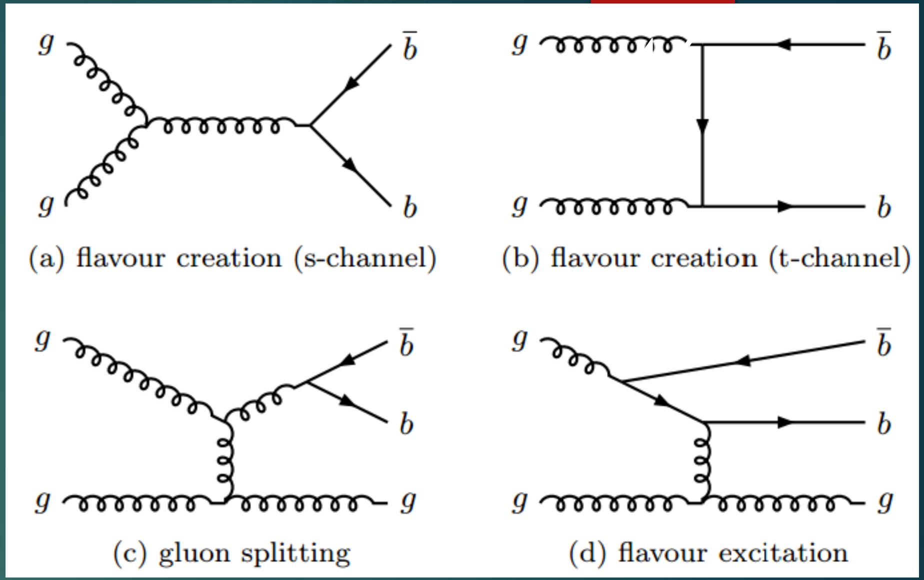
3000 fb^{-1} ahead, stay tuned for discoveries!

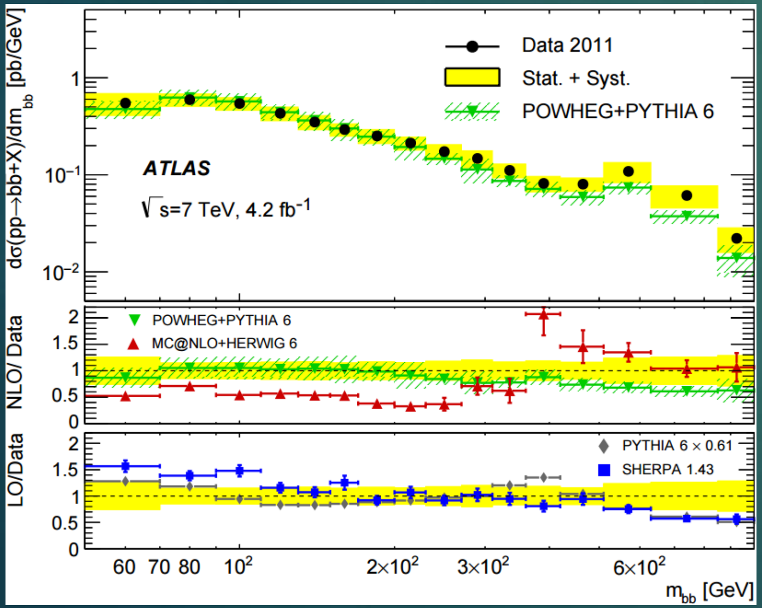
BACK UP SLIDES START

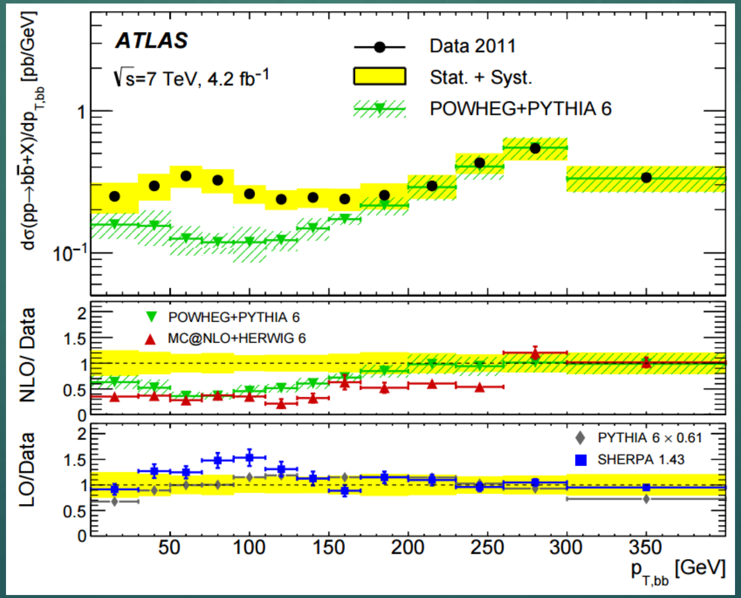
Eur. Phys. J. C 76 (2016) 670

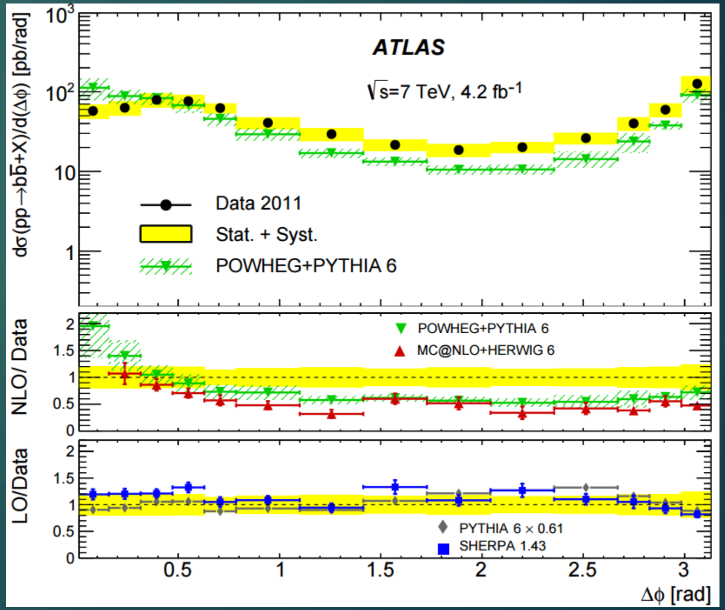
Measurement of $b\bar{b}$ dijet

- Test of pQCD
- Important background for Higgs and BSM physics
- Leading jet P_T > 270 GeV(trigger)



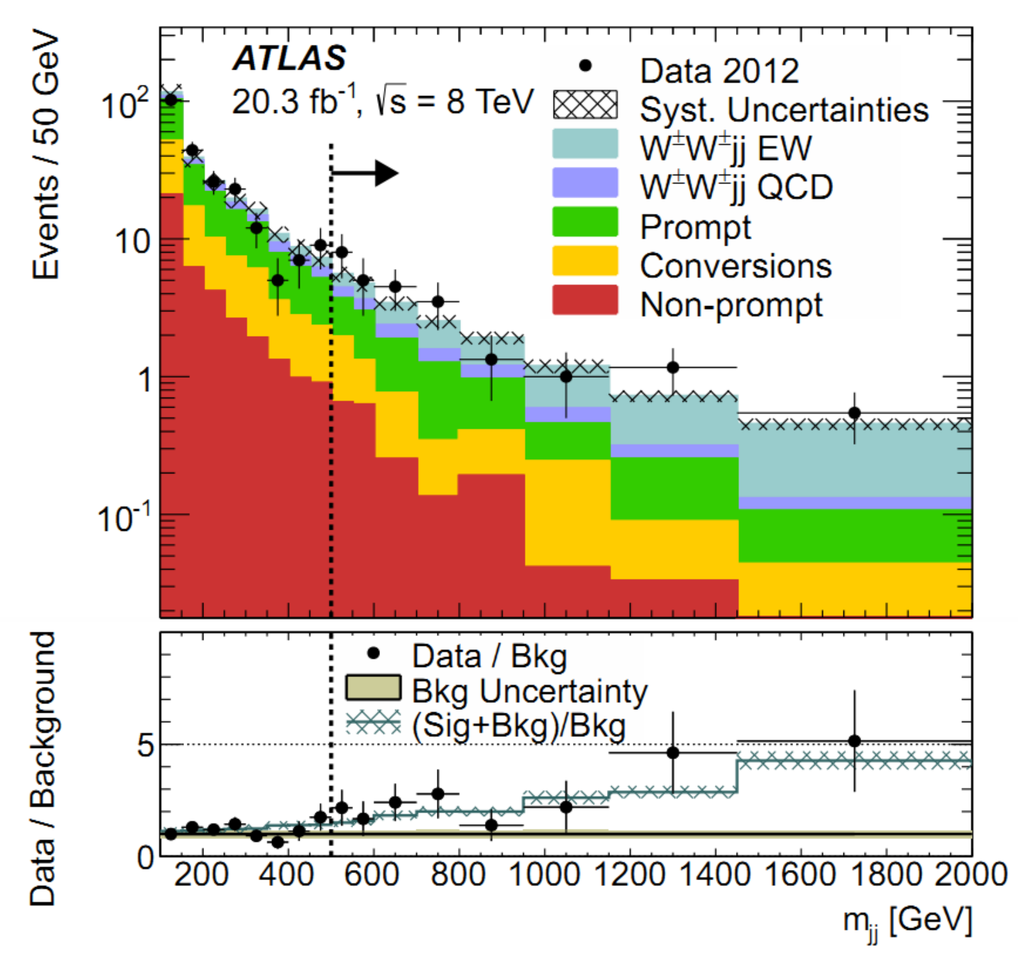


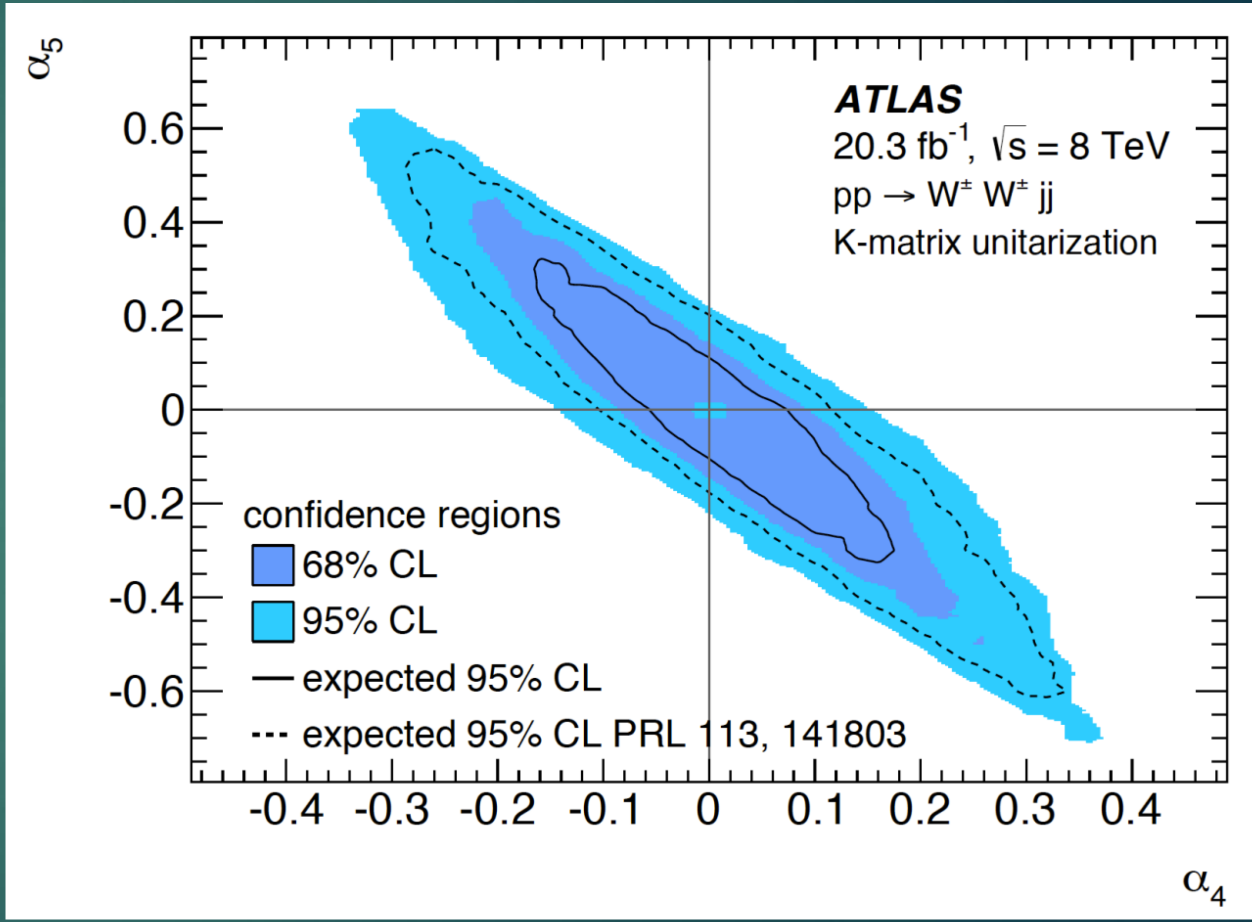




arXiv:1611.02428

VBS ssWW





Significance: 3.6 sigma
(VBS SR: ΔRjj > 2.4)

$$\alpha_4 \mathcal{L}_4 = \alpha_4 \left[\mathrm{tr}(V_\mu V_\nu)\right]^2$$

$$\alpha_5 \mathcal{L}_5 = \alpha_5 \left[\mathrm{tr}(V_\mu V^\mu)\right]^2$$

θ_W and AFB

JHEP09(2015)049

$$\bar{g}_V^f = \sqrt{\rho_f}\left(T_f^3 - 2Q_f \sin^2\theta_{\text{eff}}\right)$$

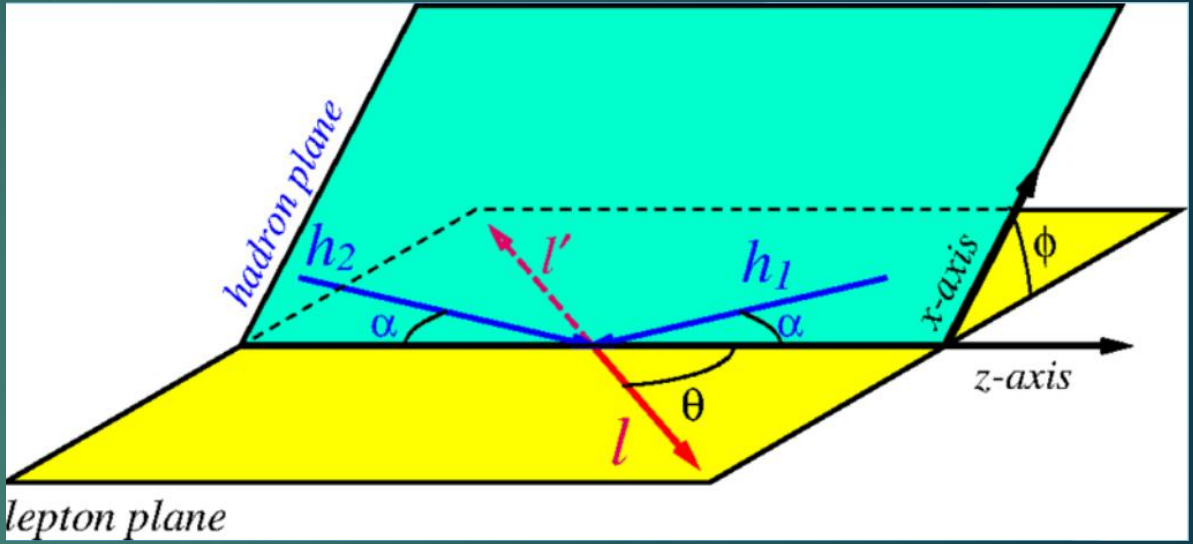
- EWK leads to AFB in $q\bar{q} \to Z/\gamma^* \to l^+l^-$events

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

- In Collins-Soper Frame:

$$A_{\text{FB}} = \frac{\sigma_{\text{F}} - \sigma_{\text{B}}}{\sigma_{\text{F}} + \sigma_{\text{B}}}$$

- At pp collider, direction of the quark not known: assume the direction of the boost of l^+l^- system

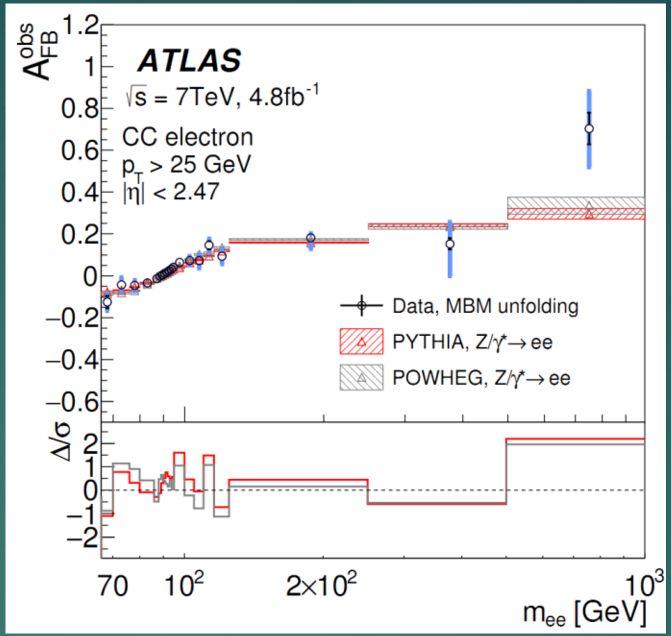


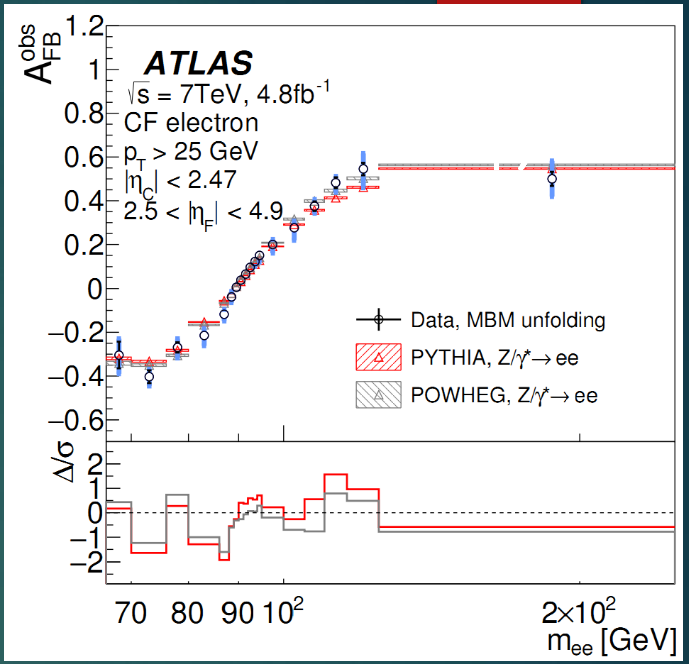
$$\cos\theta^*_{\text{CS}} = \frac{p_{z,\ell\ell}}{|p_{z,\ell\ell}|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m_{\ell\ell}\sqrt{m_{\ell\ell}^2 + p_{\text{T},\ell\ell}^2}}$$

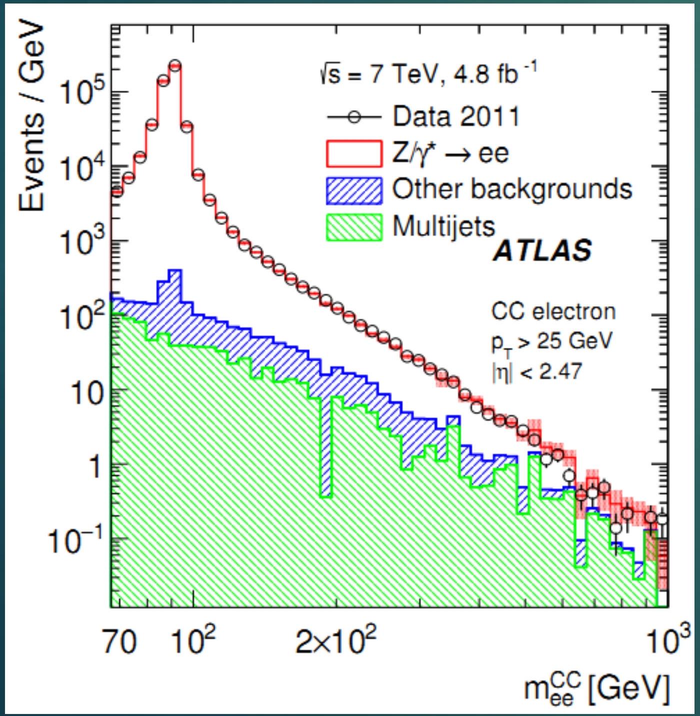
$$p_i^{\pm} = \frac{1}{\sqrt{2}}(E_i \pm p_{z,i})$$

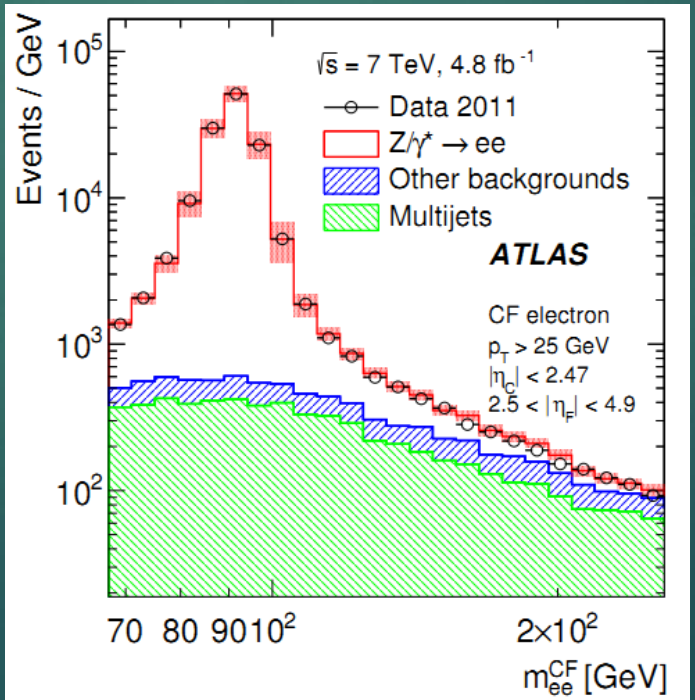
Measurement

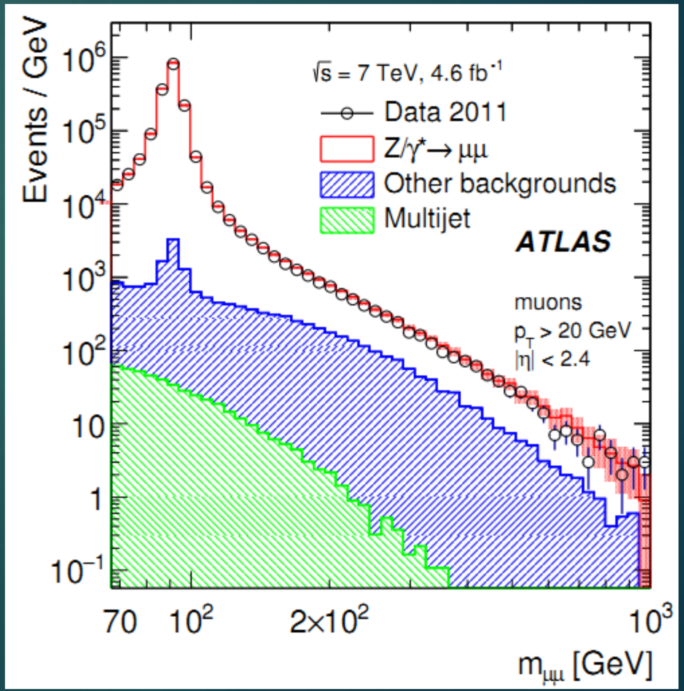
- $4.7\ pb^{-1}$ of pp collisions at 7 TeV
- Electrons up to $|\eta|$=**4.9**
- Muons up to $|\eta|$=2.4









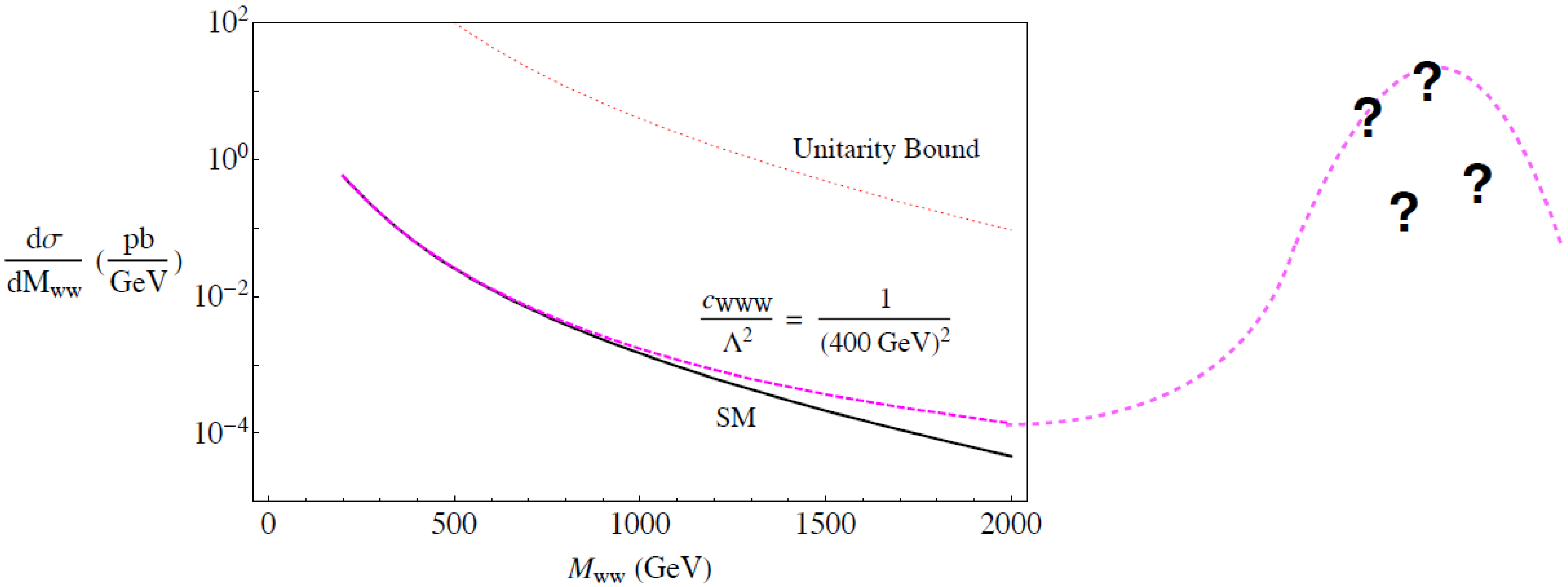


$$\mathcal{L}^{NP} = \mathcal{L}^{SM(4)} + \frac{1}{\Lambda}\mathcal{L}^{5} + \frac{1}{\Lambda^2}\mathcal{L}^{6} + \frac{1}{\Lambda^3}\mathcal{L}^{7} + \frac{1}{\Lambda^4}\mathcal{L}^{8} + \cdots$$

✗ Ignore lepton/baryon number violating terms

Dim-6, search for **aTGCs**

Dim-8, search for **aQGC** assuming no aTGC



C. Degrande et al arxiv:1205.4231

Unknown new physics at energy scale beyond the reach of the collider

CP conserving Operators

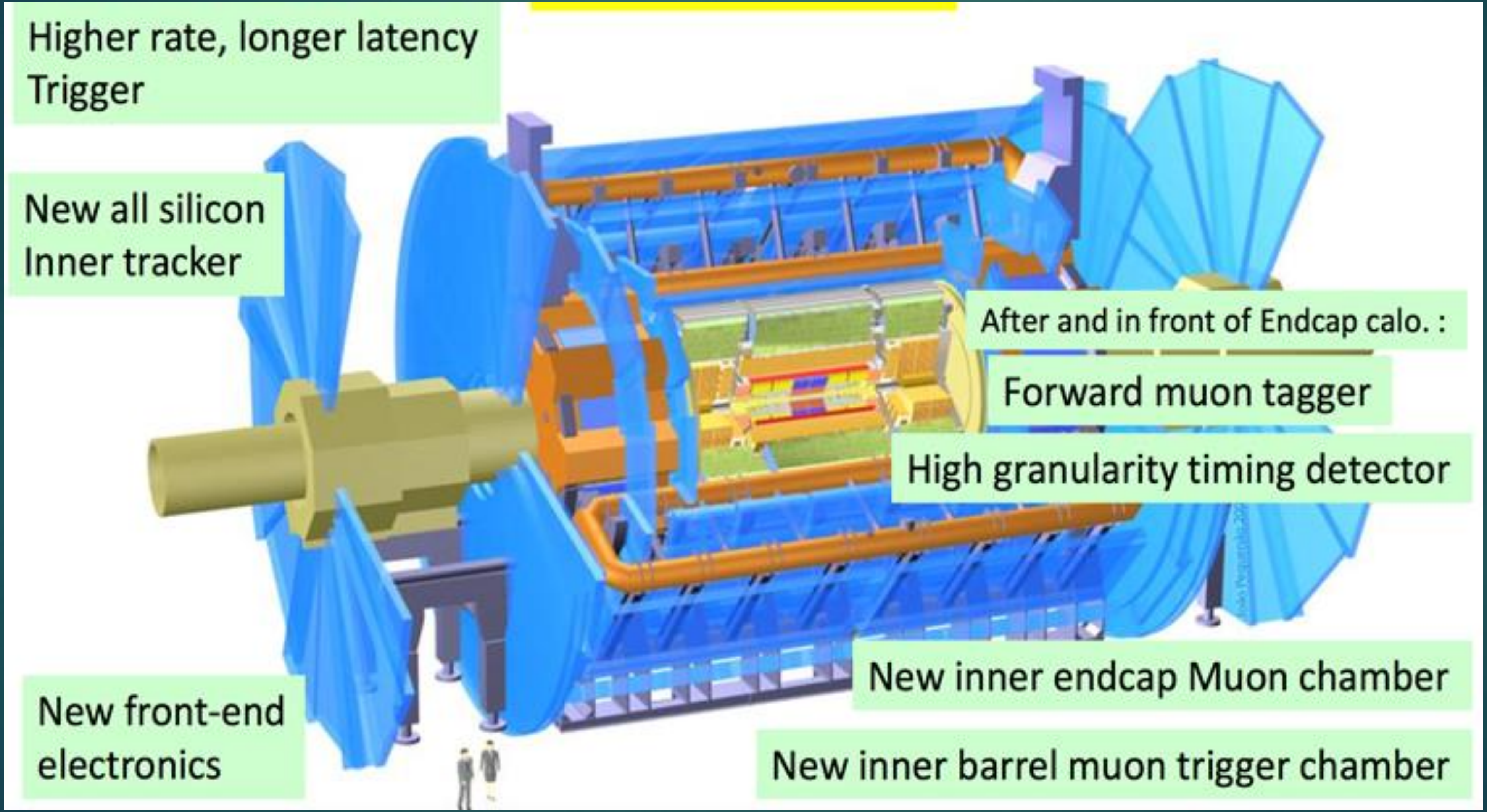
$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

Dim-6

$$L_{S,0} = \left[\left(D_\mu\Phi\right)^\dagger D_\nu\Phi\right] \times \left[\left(D_\mu\Phi\right)^\dagger D_\nu\Phi\right]$$
$$L_{S,1} = \left[\left(D_\mu\Phi\right)^\dagger D^\mu\Phi\right] \times \left[\left(D_\nu\Phi\right)^\dagger D_\nu\Phi\right]$$
$$L_{M,0} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right]$$
$$L_{M,1} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times \left[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\right]$$
$$L_{M,6} = \left[\left(D_\mu\Phi\right)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right]$$
$$L_{M,7} = \left[\left(D_\mu\Phi\right)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right]$$
$$L_{T,0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
$$L_{T,1} = Tr\left[W_{\alpha\nu}W^{\mu\beta}\right] \times Tr\left[W_{\mu\beta}W^{\alpha\nu}\right]$$
$$L_{T,2} = Tr\left[W_{\alpha\mu}W^{\mu\beta}\right] \times Tr\left[W_{\beta\nu}W^{\nu\alpha}\right]$$

Dim-8

Upgrades


Higher rate, longer latency
Trigger
New all silicon
Inner tracker
After and in front of Endcap calo. :
Forward muon tagger
High granularity timing detector
New inner endcap Muon chamber
New front-end
electronics
New inner barrel muon trigger chamber