Overview of precision measurements (angular coefficients, charge asymmetry, $\sin 2\Theta$, m_W, etc)

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for the CMS and ATLAS Collaborations

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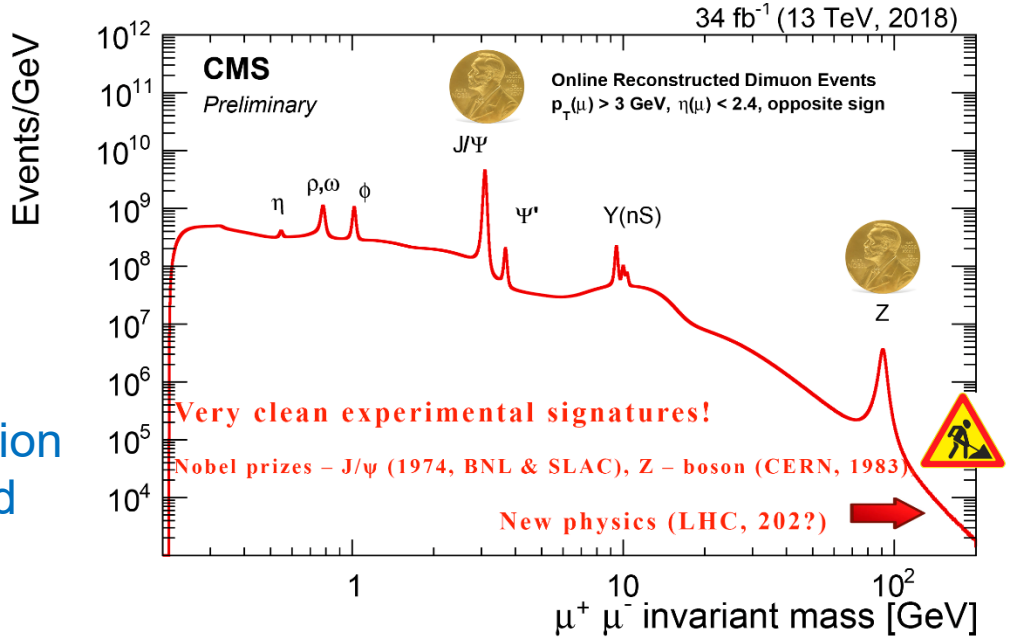
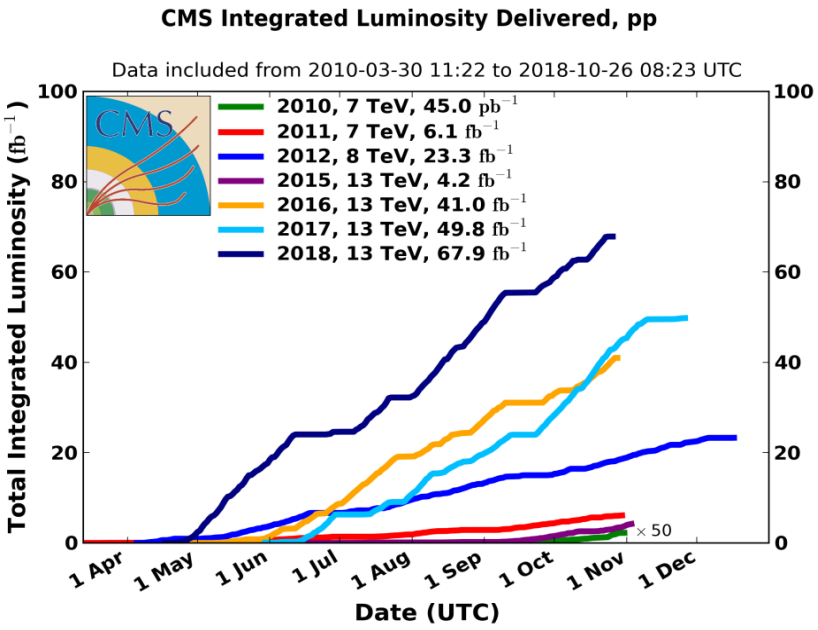
Outline

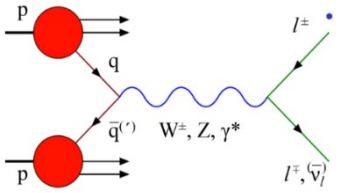
- Z/W production, Drell-Yan
  - ✓ total cross sections
  - ✓ differential cross sections
  - ✓ Branching
  - ✓ m_W measurements
- Asymmetries
  - ✓ charged asymmetry in W production
  - ✓ forward-backward asymmetry and angular coefficients for Drell-Yan
  - ✓ weak mixing angle
- V_{tb} measurements
- Rare decays





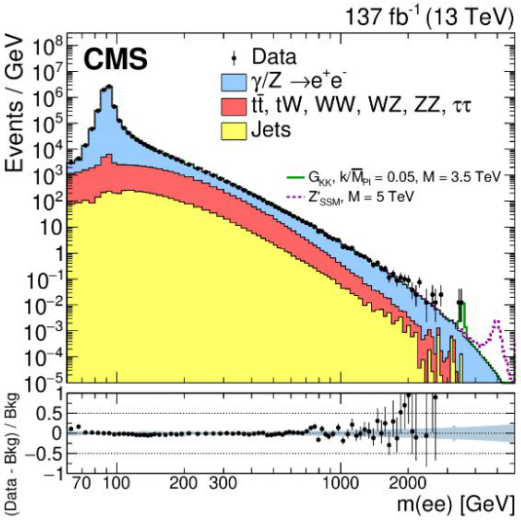
CMS Standard Models Physics Results
https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
CMS B Physics and Quarkonia Physics Results
https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html
ATLAS Standard Models Physics Results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

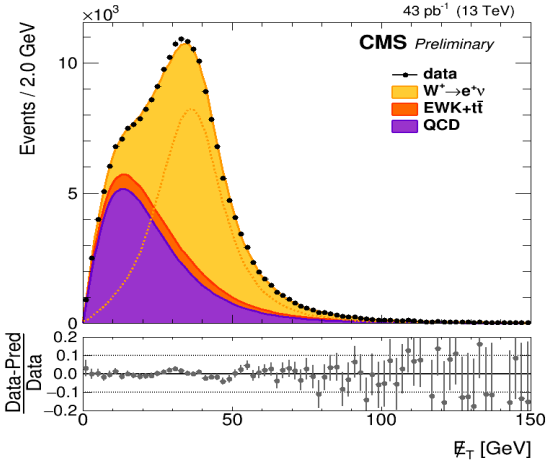
EWK Gauge Bosons: Z and W production

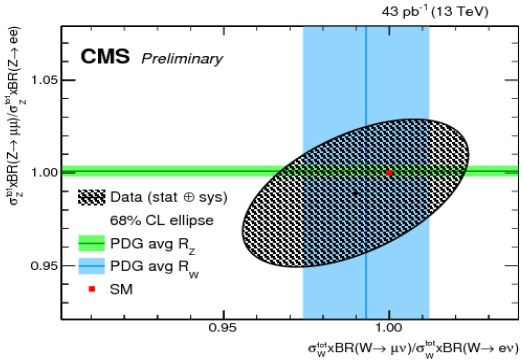


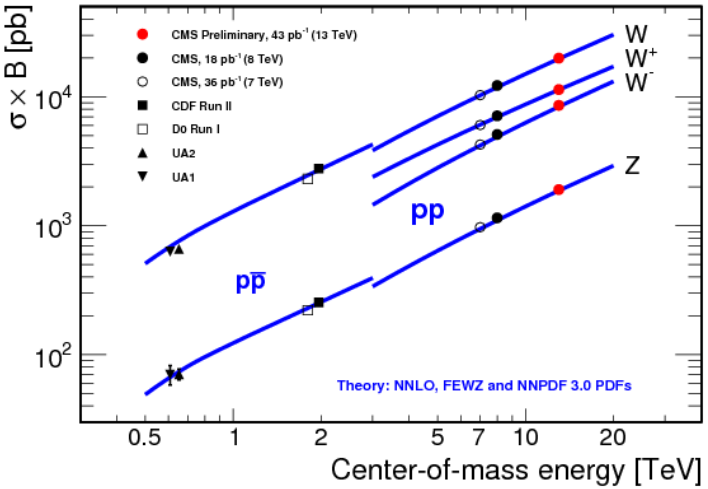
High rate at the LHC

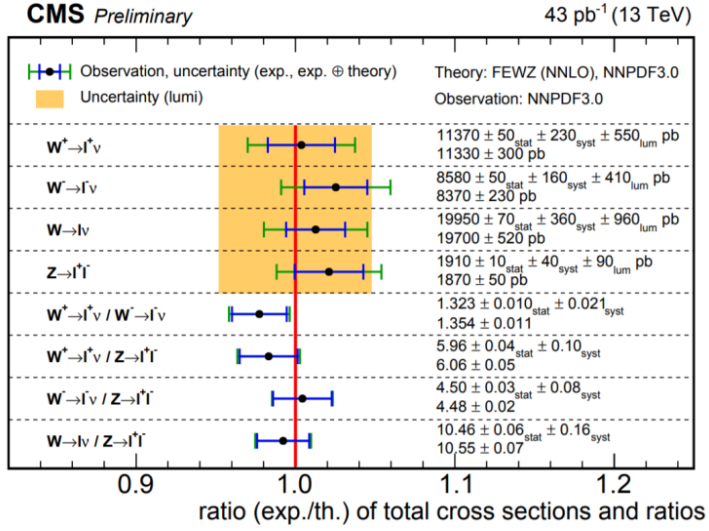
- ✓ Provides statistic to study inclusive and differential distributions
- ✓ Good understanding of the detectors allow for precision measurements
- ✓ Test p-QCD and PDF in different regimes
- ✓ Developments and testing of new MC generators and techniques











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Good agreement with NNLO SM predictions

CMS-PAS-SMP-15-004

EWK Gauge Bosons: Z and W production. Branching.

- ✓ W/Z production cross sections are measured at different $\sqrt{s}$
- ✓ Measured leptonic decay branching fractions of W and Z boson
- ✓ Precision is better than for the LEP results
- ✓ Results support the hypothesis of lepton universality for the weak interaction

$\sqrt{s} = 2.76$ TeV (ATLAS)

$$\sigma^{tot}_{W^+\to\ell\nu} = 2312 \pm 26\,(stat.) \pm 27\,(syst.) \pm 72\,(lumi.) \pm 30\,(extr.)\ pb,$$
$$\sigma^{tot}_{W^-\to\ell\nu} = 1399 \pm 21\,(stat.) \pm 17\,(syst.) \pm 43\,(lumi.) \pm 21\,(extr.)\ pb,$$
$$\sigma^{tot}_{Z\to\ell\ell} = 323.4 \pm 9.8\,(stat.) \pm 5.0\,(syst.) \pm 10.0\,(lumi.) \pm 5.5(extr.)\ pb$$

$$R_{W^-} = \frac{\sigma^{fid}_{W^-\to e^-\bar{\nu}}}{\sigma^{fid}_{W^-\to\mu^-\bar{\nu}}} = 0.988 \pm 0.030\,(stat.) \pm 0.028\,(syst.)$$

$$R_{W} = \frac{\sigma^{fid}_{W\to e\nu}}{\sigma^{fid}_{W\to\mu\nu}} = 0.986 \pm 0.018\,(stat.) \pm 0.028\,(syst.)$$

$$R_{Z} = \frac{\sigma^{fid}_{Z\to e^+e^-}}{\sigma^{fid}_{Z\to\mu^+\mu^-}} = 0.96 \pm 0.06\,(stat.) \pm 0.05\,(syst.)$$

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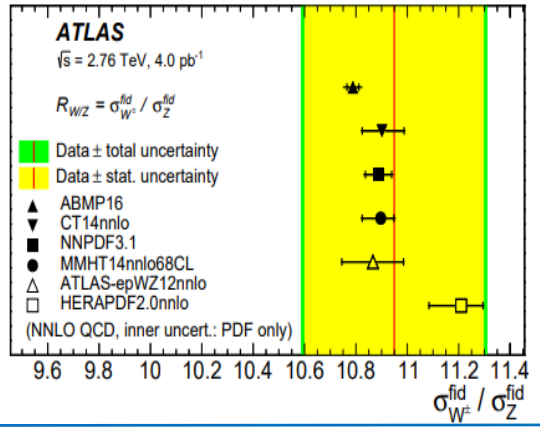
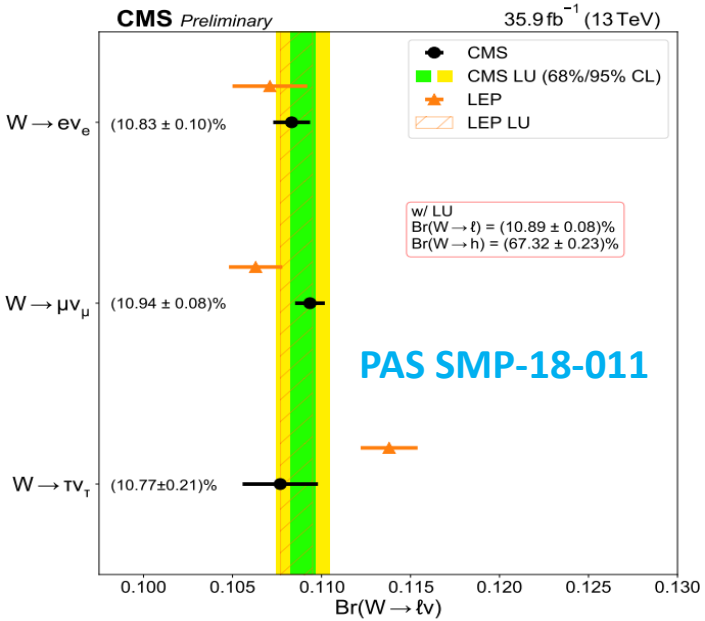
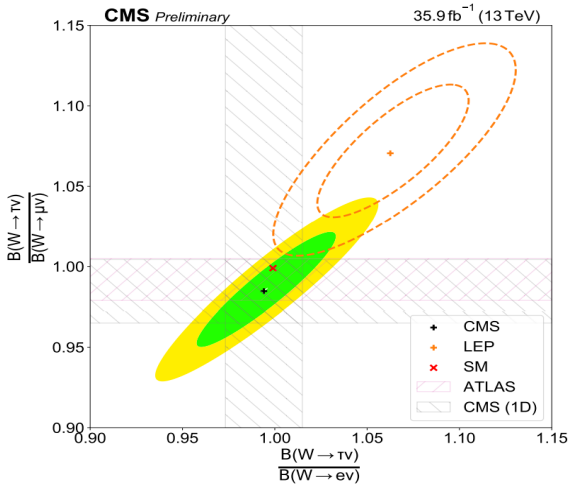


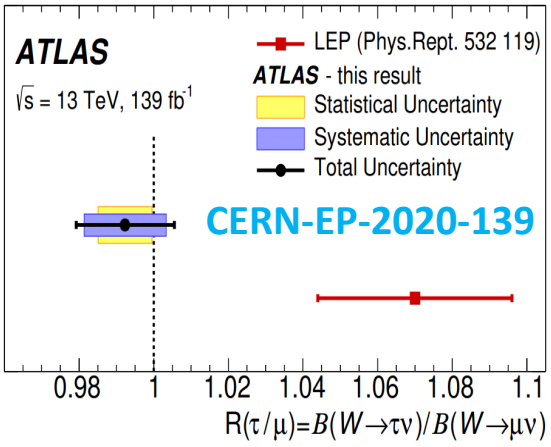
$\sqrt{s} = 13$ TeV (CMS & ATLAS)

	CMS	LEP	ATLAS
$R_{\mu/e} = \mathcal{B}(W\to\mu\bar{\nu}_\mu)/\mathcal{B}(W\to e\bar{\nu}_e)$	1.009 ± 0.009	0.993 ± 0.019	–
$R_{\tau/e} = \mathcal{B}(W\to\tau\bar{\nu}_\tau)/\mathcal{B}(W\to e\bar{\nu}_e)$	0.994 ± 0.021	1.063 ± 0.027	–
$R_{\tau/\mu} = \mathcal{B}(W\to\tau\bar{\nu}_\tau)/\mathcal{B}(W\to\mu\bar{\nu}_\mu)$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	–



PAS SMP-18-011



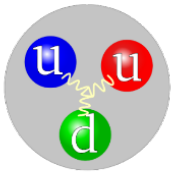


CERN-EP-2020-139

W Charge Asymmetry

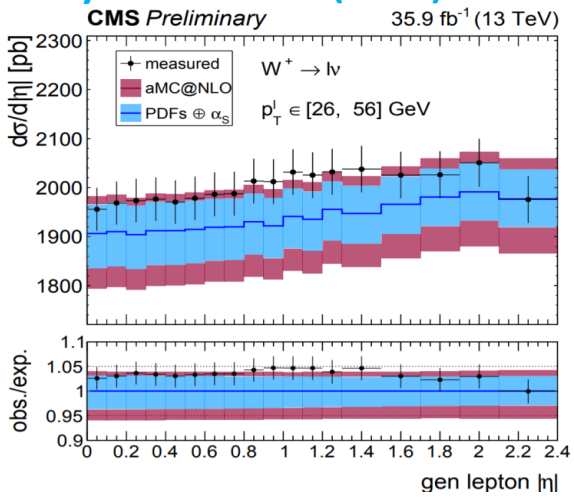
- ✓ Gives important constraints on the ratio of u and d quark distributions in the proton

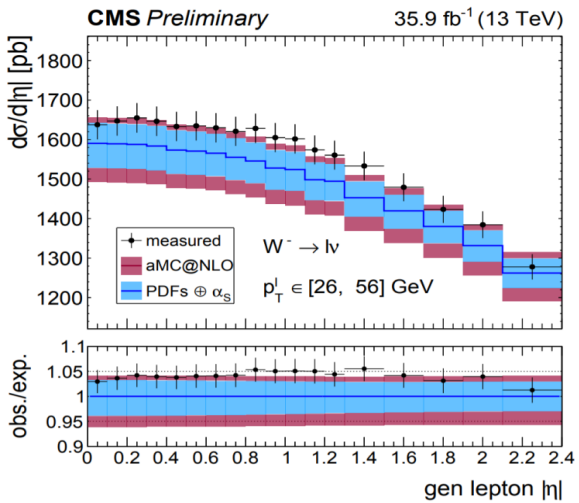
$$u\bar{d} \rightarrow W^+$$
$$d\bar{u} \rightarrow W^-$$
$$\mathcal{A}(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$$

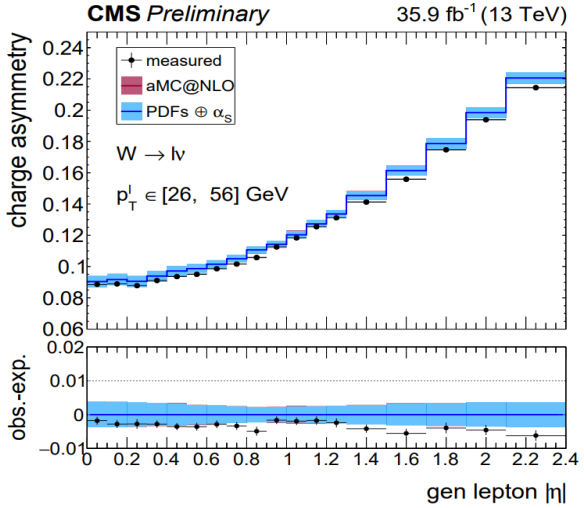


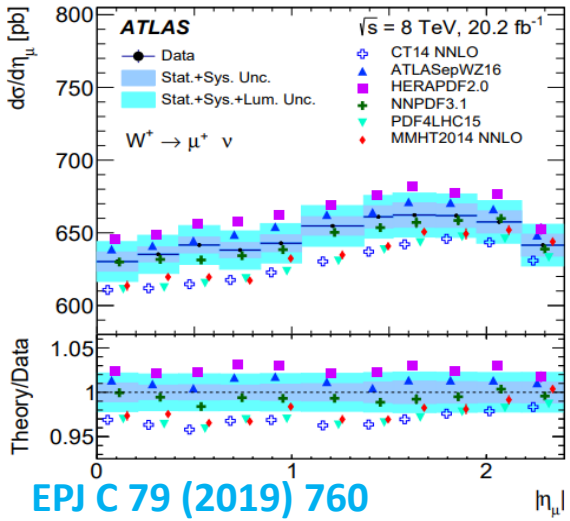
Done by ATLAS (8 TeV) and CMS (13 TeV, 2016). Good agreement between each other and MC predictions!

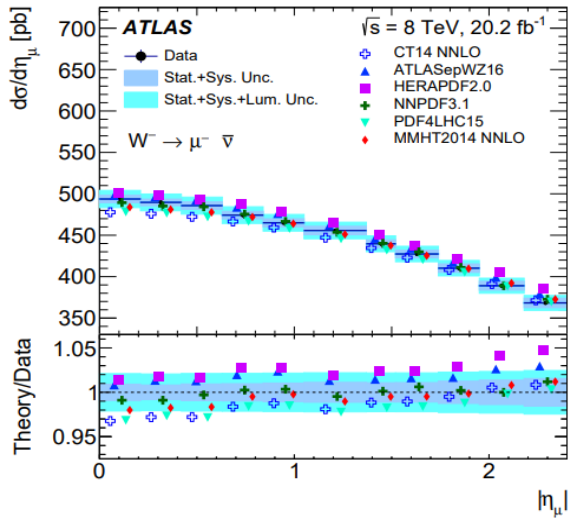
Phys. Rev. D 102 (2020) 092012

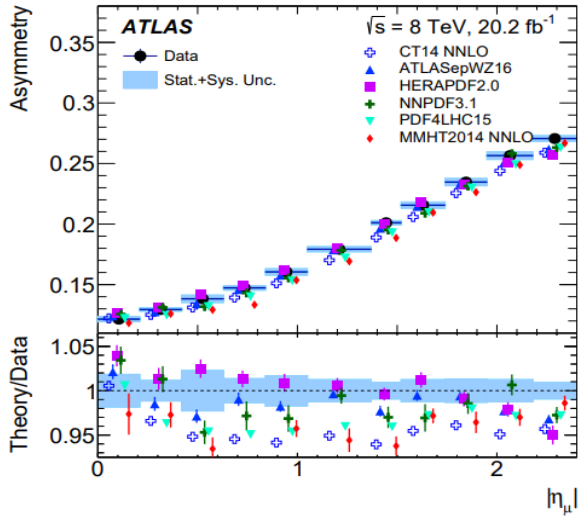












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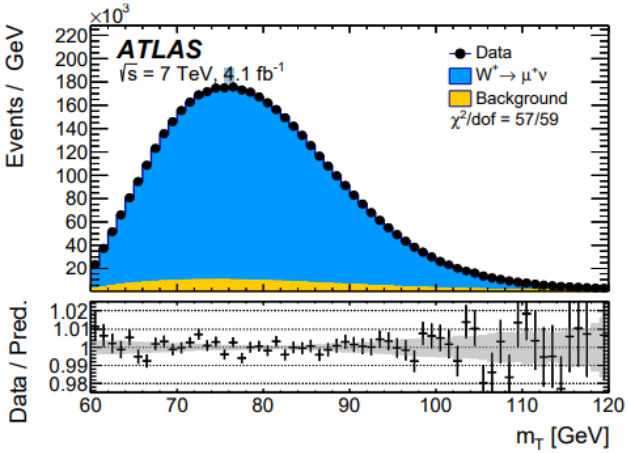
Measurement of the W-boson mass

- ✓ The W-boson mass is obtained from template fits to the reconstructed distributions of the charged lepton transverse momentum and of the W boson transverse mass by ATLAS collaboration at 7 TeV



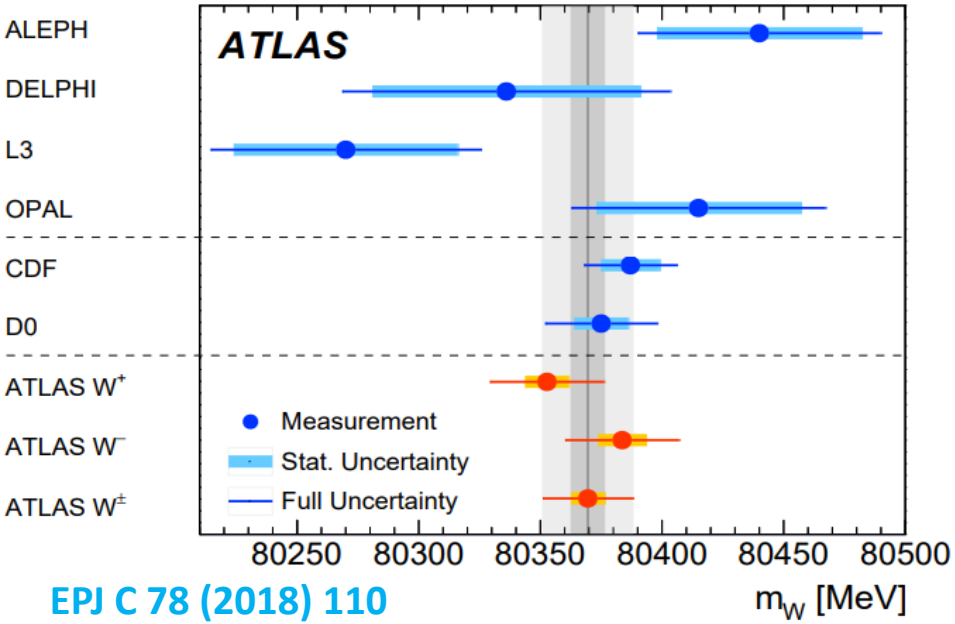
ATLAS:

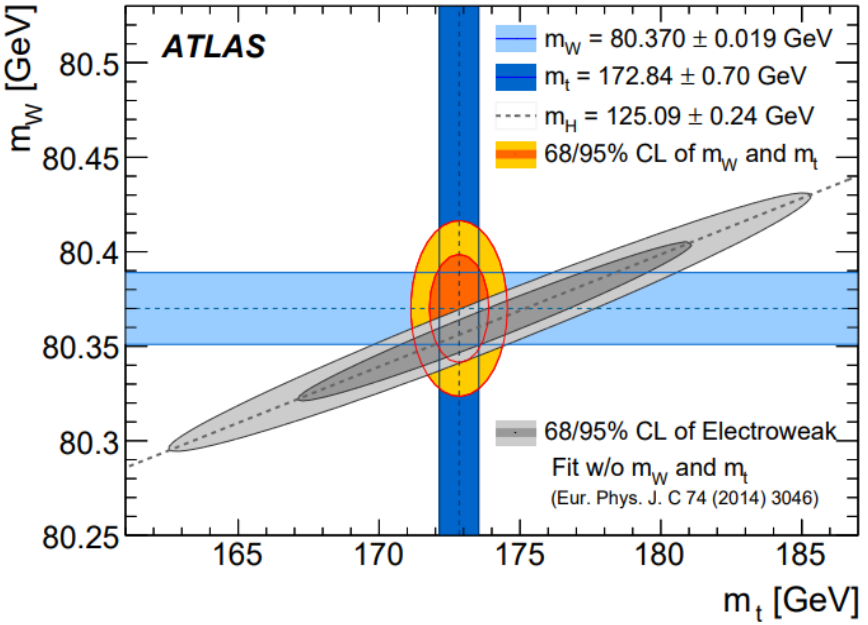
$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$

EWK Global Fit:

$$m_W = 80385 \pm 15\ \text{MeV}$$

- ✓ The W-boson mass measurement is compatible with the current world average of m_W





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Z (Differential) Cross Section (I)

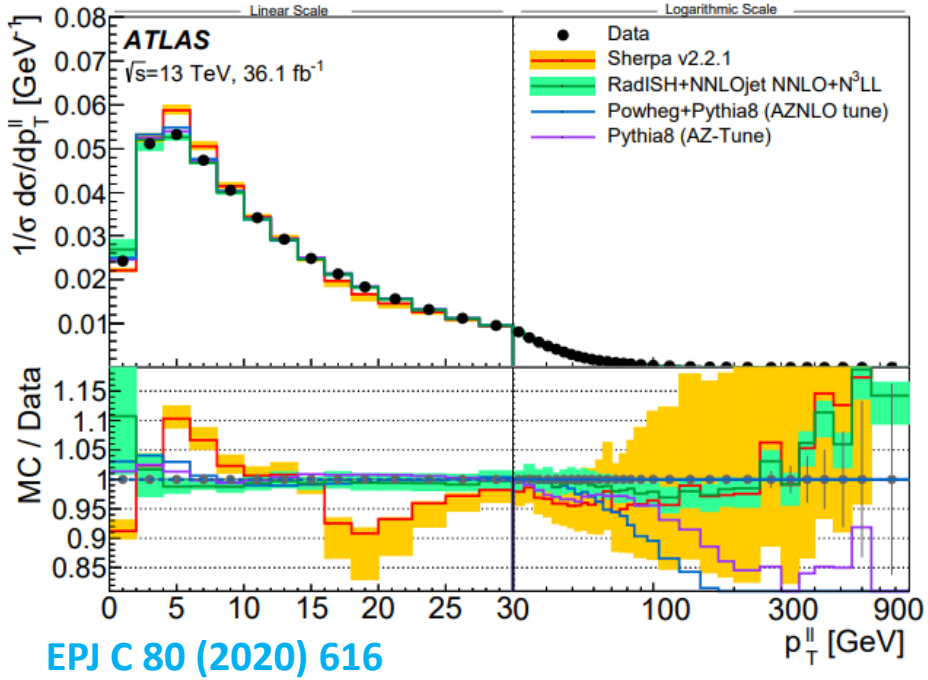
- Important information about BSM physics background
- W boson mass measurements relies on p_T^{ll} spectrum
- Different approaches to describe p_T^{ll} spectrum in different p_T^{ll} ranges

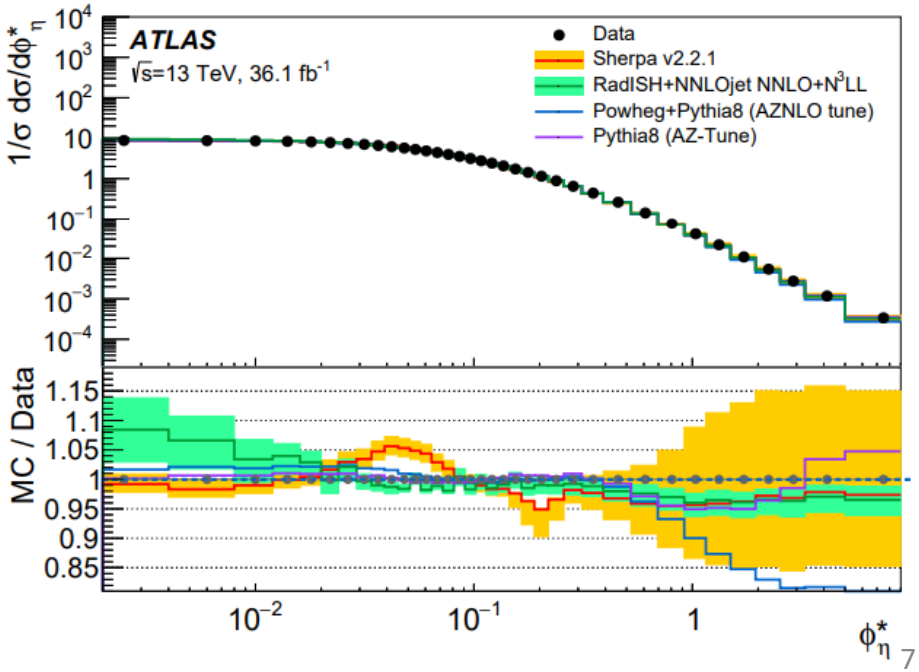
$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \times \sin(\theta_\eta^*)$$

$$\cos(\theta_\eta^*) = \tanh[(\eta^- - \eta^+)/2]$$

it is found that predictions based on resummation approaches can describe the full spectrum within uncertainties

Channel	Measured cross-section × $\mathcal{B}(Z/\gamma^* \to \ell\ell)$ (value ± stat. ± syst. ± lumi.)	Predicted cross-section × $\mathcal{B}(Z/\gamma^* \to \ell\ell)$ (value ± PDF ± α_S ± scale ± intrinsic)
$Z/\gamma^* \to ee$	$738.3 \pm 0.2 \pm 7.7 \pm 15.5$ pb	
$Z/\gamma^* \to \mu\mu$	$731.7 \pm 0.2 \pm 11.3 \pm 15.3$ pb	
$Z/\gamma^* \to \ell\ell$	$736.2 \pm 0.2 \pm 6.4 \pm 15.5$ pb	$703^{+19}_{-24}\ ^{+6}_{-8}\ ^{+4}_{-6}\ ^{+5}_{-5}$ pb [72]





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Z Differential Cross Section (II)

EPJ C 80 (2020) 616

Channel	Measured cross-section × $\mathcal{B}(Z/\gamma^* \to \ell\ell)$ (value ± stat. ± syst. ± lumi.)	Predicted cross-section × $\mathcal{B}(Z/\gamma^* \to \ell\ell)$ (value ± PDF ± α_S ± scale ± intrinsic)
$Z/\gamma^* \to ee$	$738.3 \pm 0.2 \pm 7.7 \pm 15.5$ pb	
$Z/\gamma^* \to \mu\mu$	$731.7 \pm 0.2 \pm 11.3 \pm 15.3$ pb	
$Z/\gamma^* \to \ell\ell$	$736.2 \pm 0.2 \pm 6.4 \pm 15.5$ pb	$703^{+19}_{-24}{}^{+6}_{-8}{}^{+4}_{-6}{}^{+5}_{-5}$ pb [72]

describe the full spectrum within uncertainties

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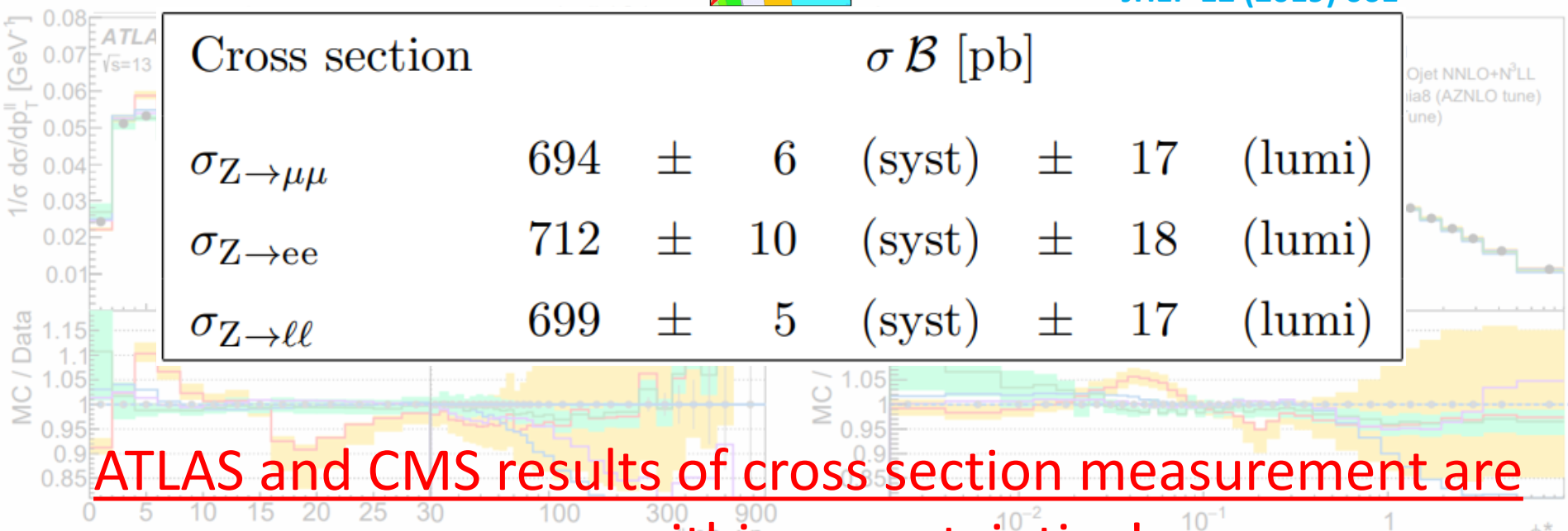
Cross section	$\sigma\,\mathcal{B}$ [pb]
$\sigma_{Z\to\mu\mu}$	694 ± 6 (syst) ± 17 (lumi)
$\sigma_{Z\to ee}$	712 ± 10 (syst) ± 18 (lumi)
$\sigma_{Z\to\ell\ell}$	699 ± 5 (syst) ± 17 (lumi)



ATLAS and CMS results of cross section measurement are agree within uncertainties!

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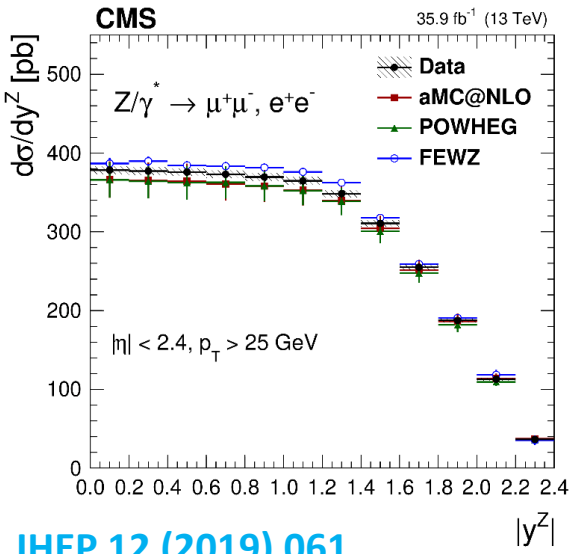
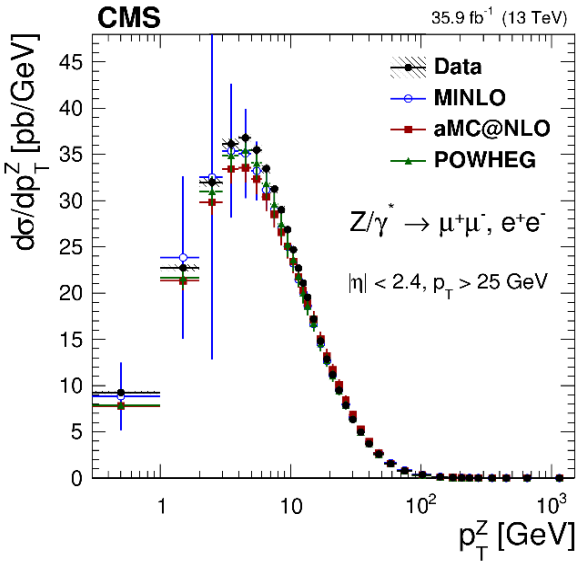
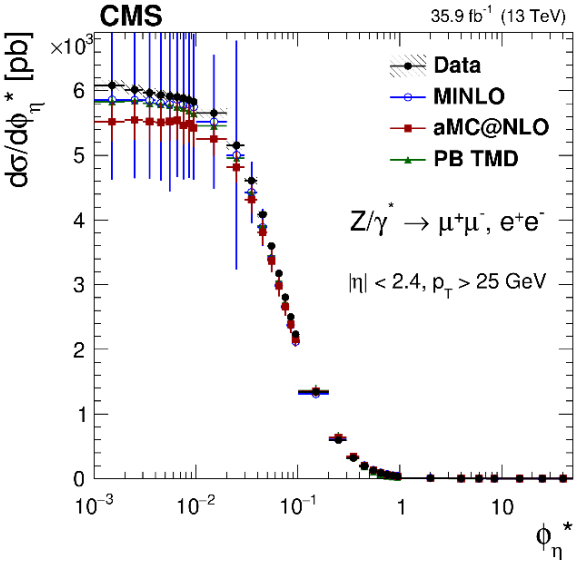
Z Differential Cross Section (II)

Differential cross sections of the transverse momentum p_T, the optimized angular variable φ*, η, and the rapidity of lepton pairs are measured by ATLAS and CMS at 13 TeV (2016)







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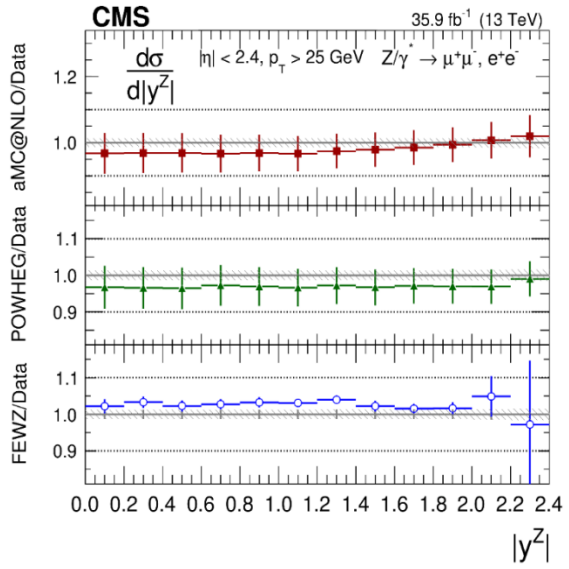

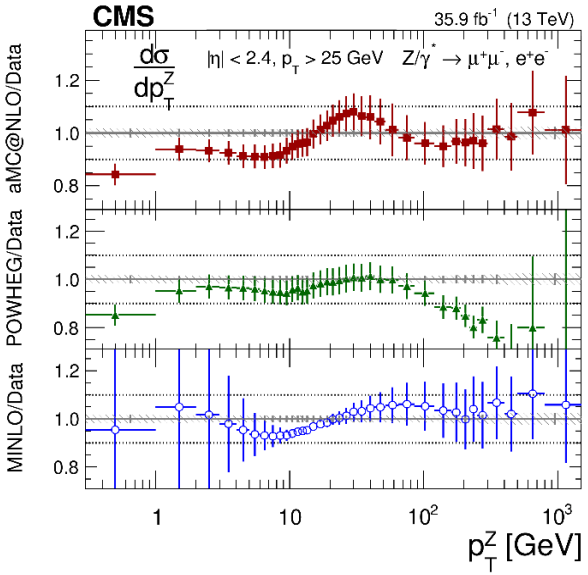

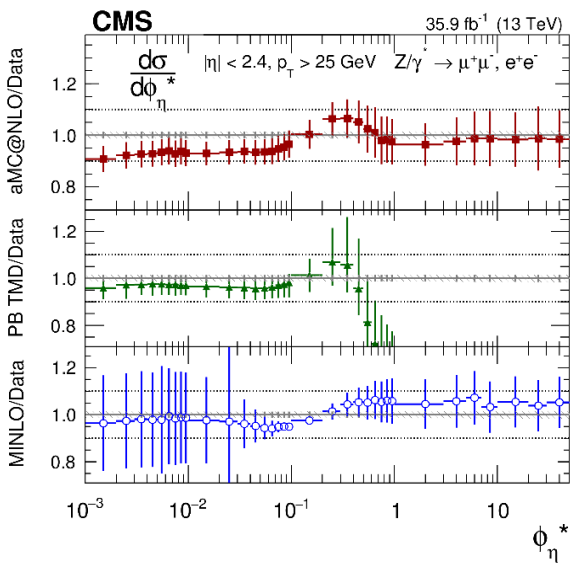

Drell-Yan Differential Cross Section

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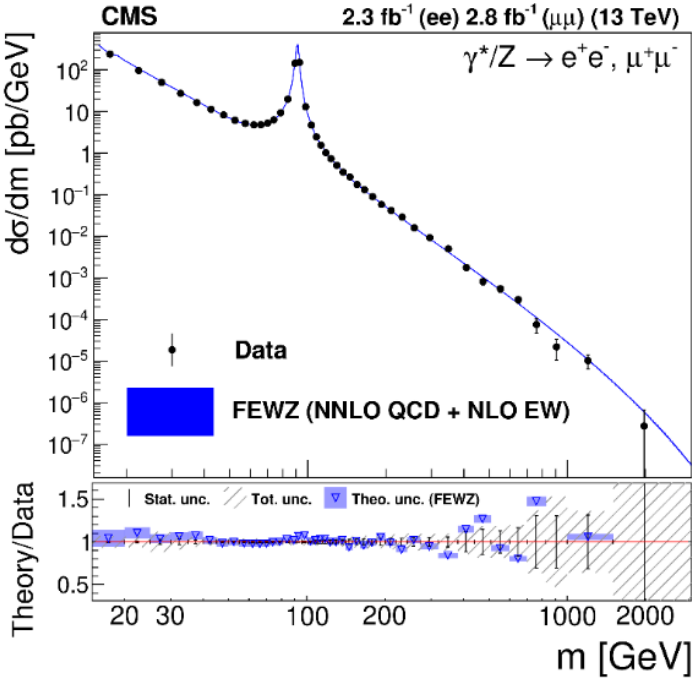
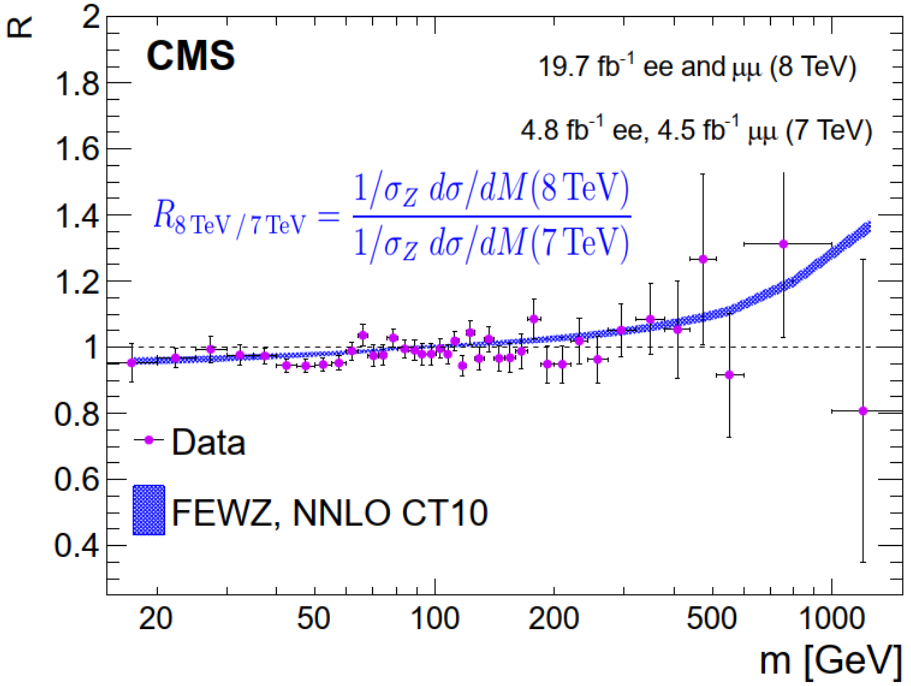


EPJ C 75 (2015) 147, arXiv:1412.1115



✓ The total cross section measurements are presented as a function of dilepton invariant mass in the range 15 to 3000 GeV

✓ The measured differential cross sections are in good agreement with the theoretical calculations (NNLO QCD + NLO EWK)

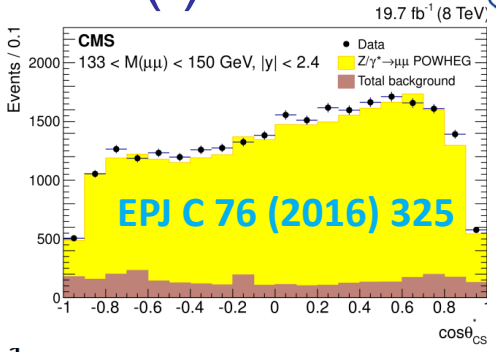
$3 \times 10^{-4} < x < 1.0$ and $6 \times 10^2 < Q^2 < 3 \times 10^6$ GeV^2

✓ The shape of the distribution is defined entirely by the √s and the Bjorken x dependencies of the PDFs, since the dependence on the hard scattering cross section is canceled out. In the Z peak region, the expected double ratio is close to 1 by definition.

We observe agreement of the cross section(s) and double ratio measurement with the theoretical prediction within uncertainties

Drell-Yan Angular Coefficients (I)

The lepton angular distribution in the Drell - Yan process in the γ^*/Z rest frame is expressed by both the CMS and ATLAS Collaborations (measured at 8 TeV) as:



$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta^*\mathrm{d}\phi^*} \propto \left[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)\right.$$
$$\left. + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\right].$$

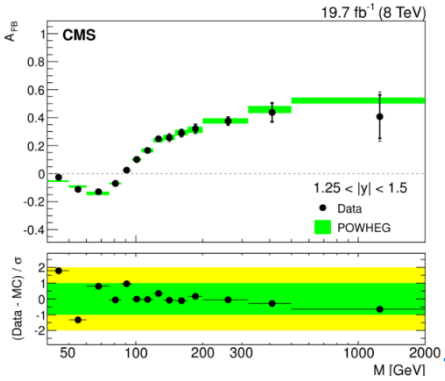
where θ and ϕ are the polar and azimuthal angles of l^- (e^- or μ^-) in the rest frame of γ^*/Z (Collins-Soper) and coefficients $A_0 - A_7$ are functions of p_T^Z, Y^Z, M^Z kinematic variables.

Integrated cross section by φ^*

$$\frac{d^2\sigma}{dcos\theta^*} = 1 + A_4 cos\theta^* + cos^2\theta^*$$

and

$$A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B},$$



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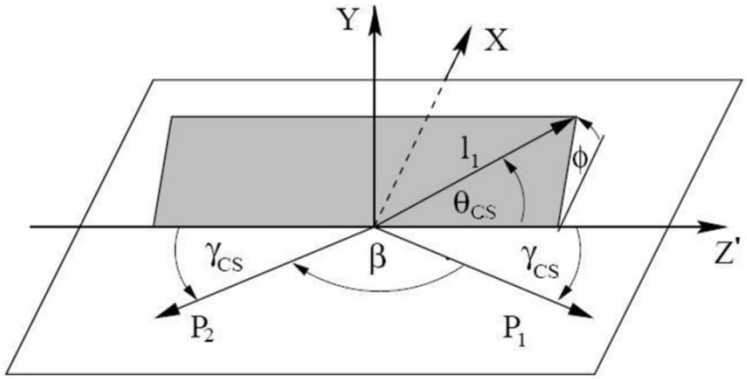
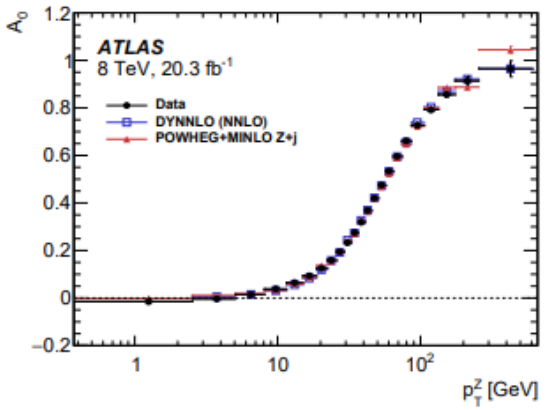
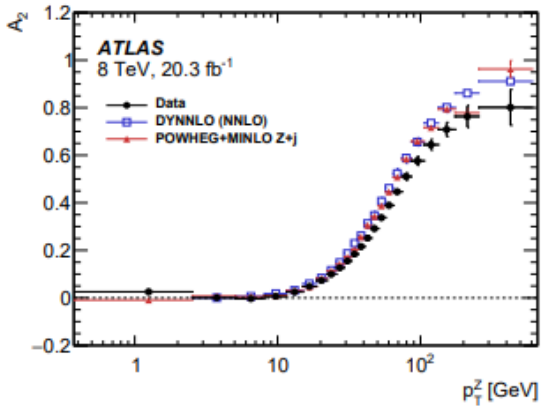
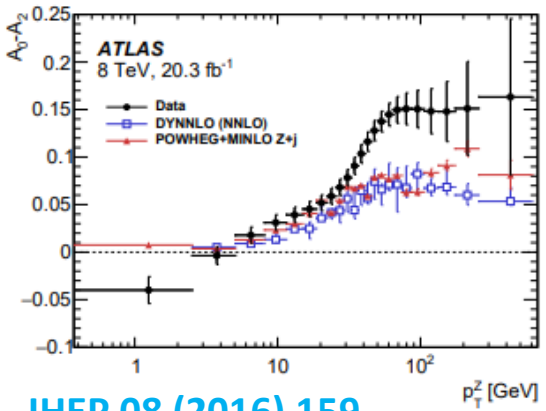


The Collins-Soper coordinate system is chosen in such a way that the Z-axis bisects the angle between the interacting quarks

Drell-Yan Angular Coefficients (II)







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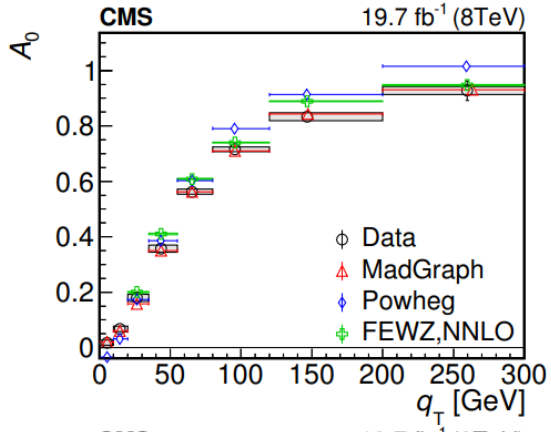
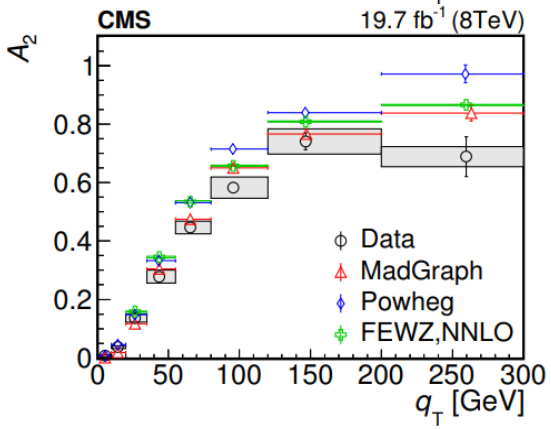
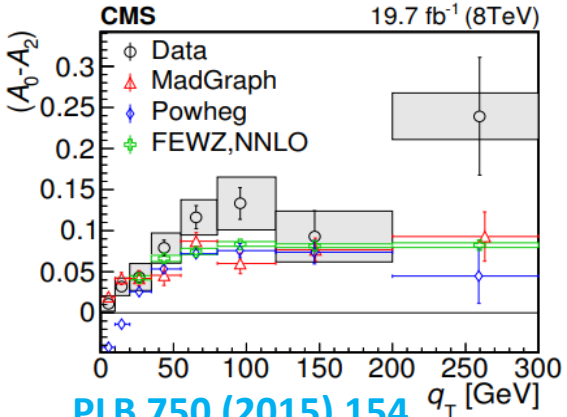






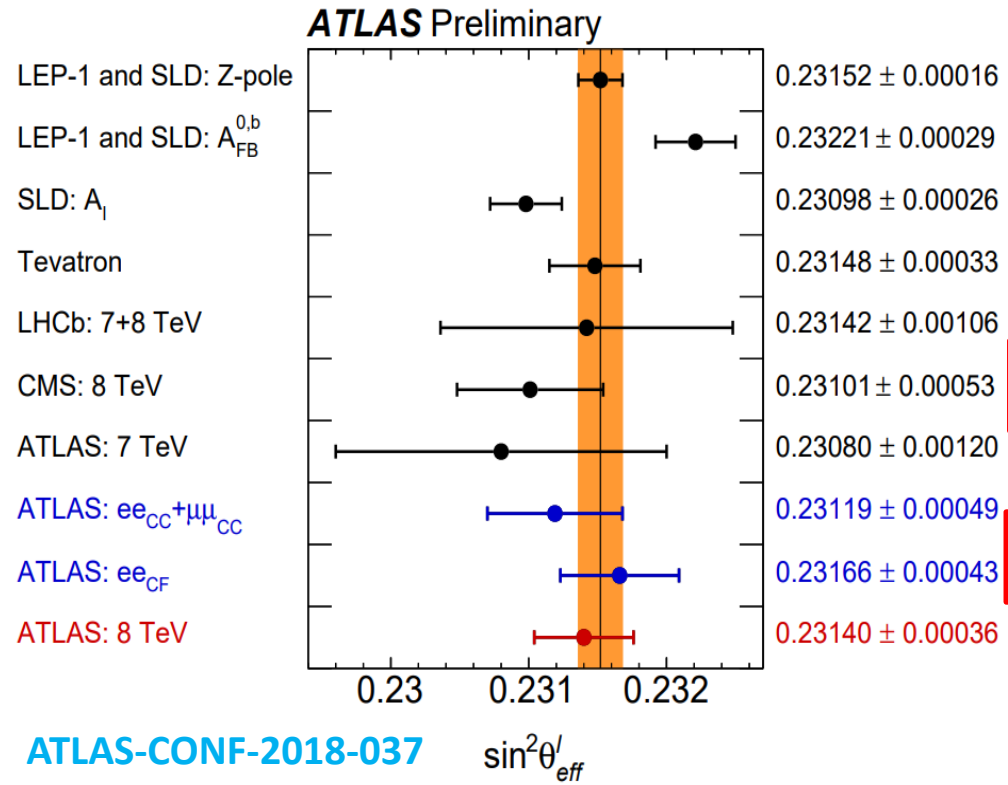
PLB 750 (2015) 154

Angular coefficients A_{0-7} (A_{0-4}) are obtained in bins of dilepton (dimuon) transverse momentum and rapidity $80 < M_{\mu^+\mu^-} < 100$ GeV by ATLAS (CMS) collaboration at 8 TeV

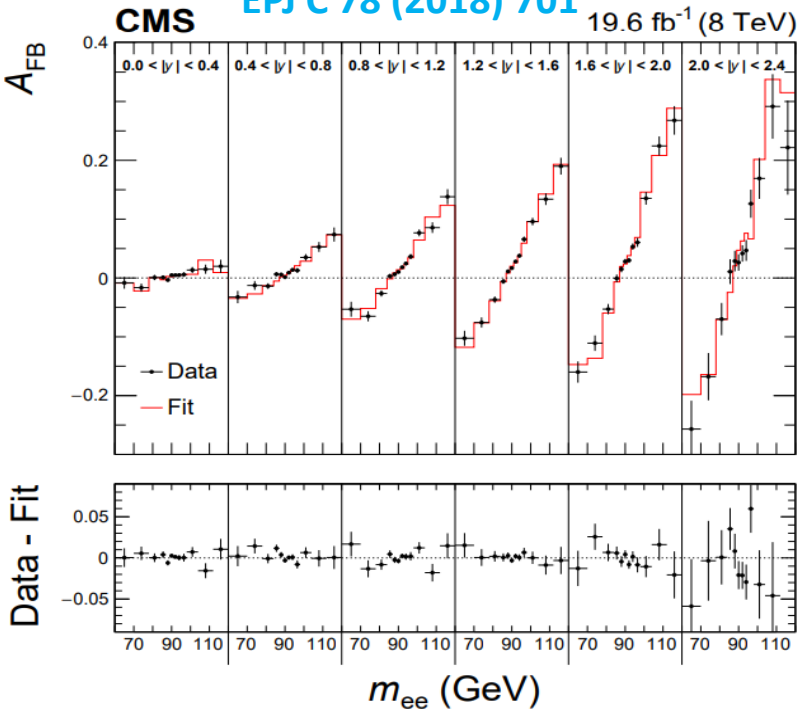
- ✓ Lam-Tung relation $A_0 = A_2$ (related with rotation invariance) violation was observed
- ✓ Non –zero coefficients A_{5-7} were measured by ATLAS collaboration
- ✓ Experimental data of CMS and ATLAS experiments are in agreement with each other and with SM NNLO predictions, but some deviations are exist at high p_T^Z
- ✓ A_{0-7} measurements at 13 TeV are in progress (CMS)

Weak Mixing Angle

- $A_4\left(\frac{3}{8}A_{FB}\right)$ sensetive to V-A structure of the couplings in parity violation terms
- Only $A_4\left(\frac{3}{8}A_{FB}\right)$ is non-zero at LO QCD at small p_T^Z
- A_{FB} was used to extracting $sin^2\theta_{eff}^l$ value by CMS and ATLAS collaborations



ATLAS-CONF-2018-037



EPJ C 78 (2018) 701

$sin^2\theta_{eff}^l$ (ATLAS):

$0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.})$

$sin^2\theta_{eff}^l$ (CMS):

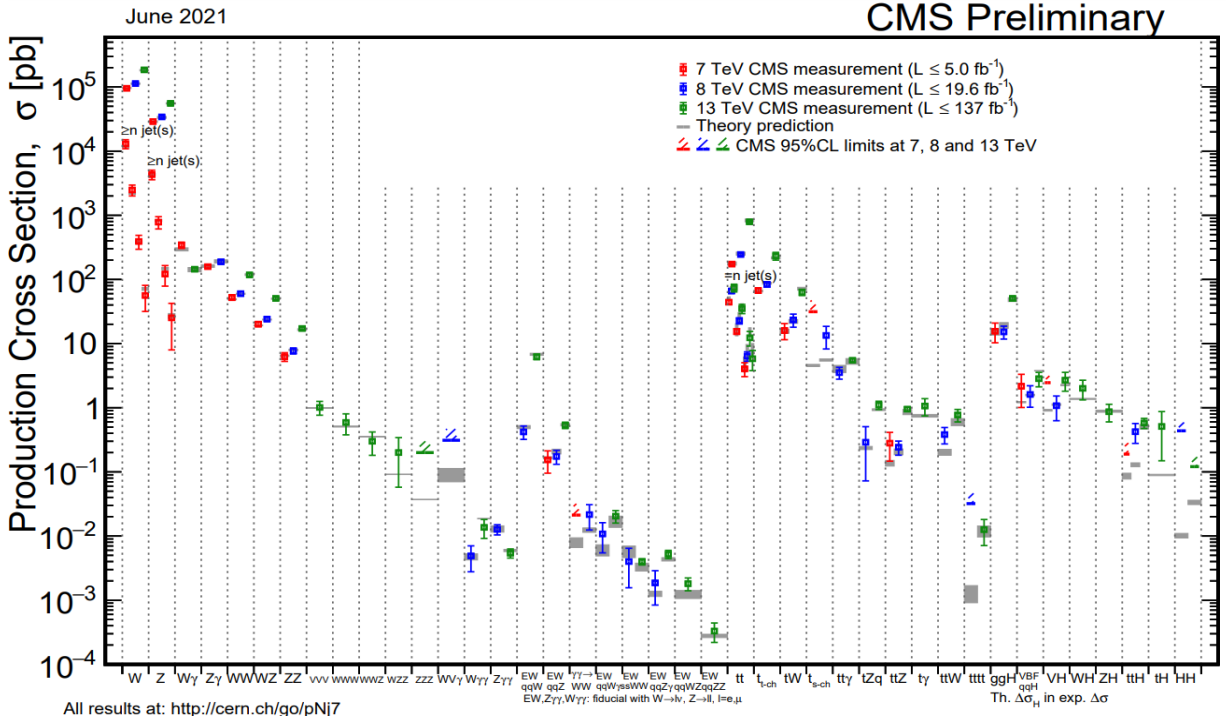
$0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00031\,(\text{PDF})$

$sin^2\theta_{eff}^l$ (Global EWK fit):

0.23150 ± 0.00006

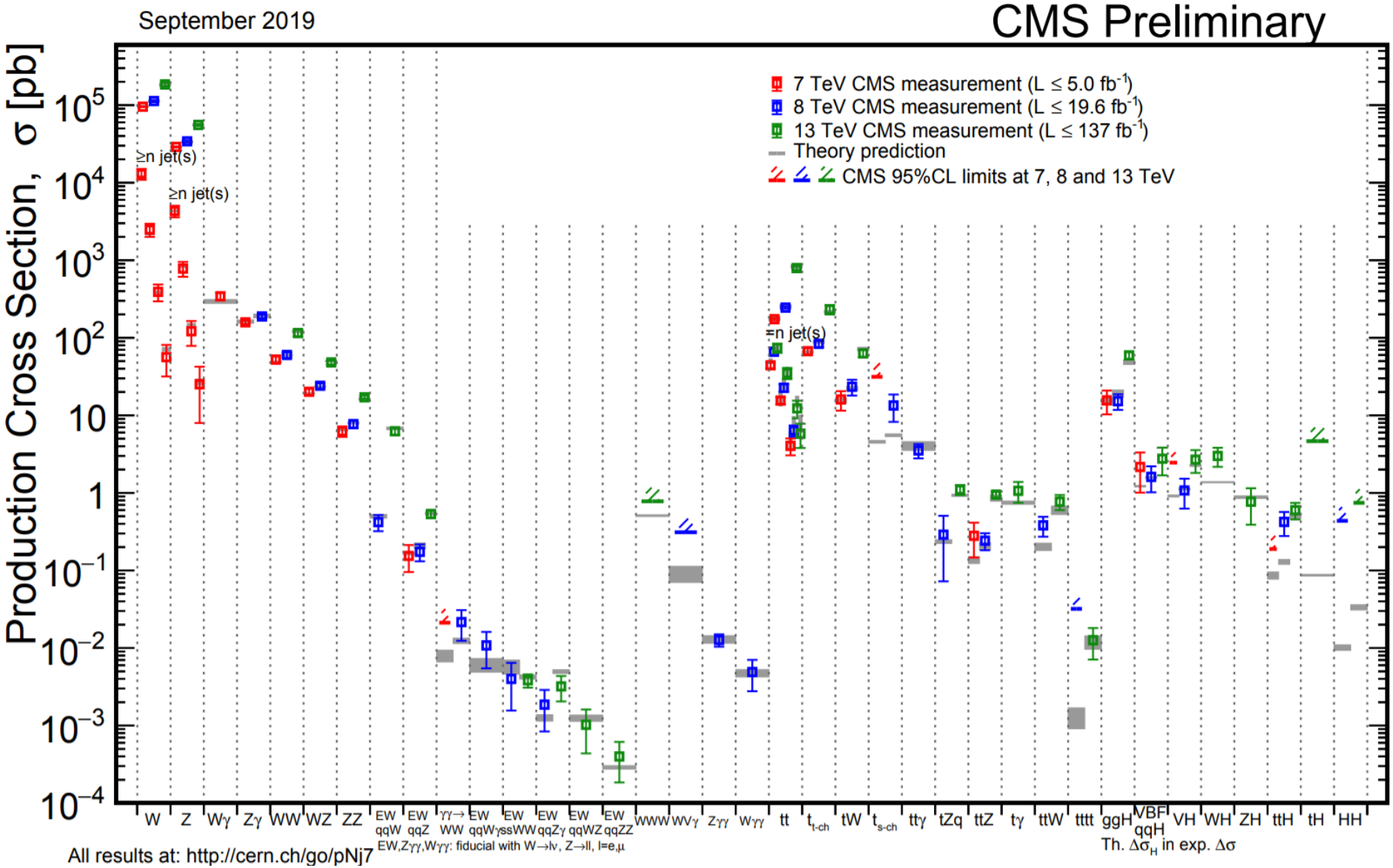
Conclusions

- ✓ CMS and ATLAS show an excellent performance to detect different signals and produced many EWK measurements at 7, 8 and 13 TeV
- ✓ Precision measurements of inclusive W and Z and di-boson production cross section with large statistic
- ✓ Detailed studies of differential cross sections and many observables, like asymmetries and angular coefficients
- ✓ W and Z production associated to jets, including Z plus b-jets, studied W polarisation in W+jets
- ✓ All ATLAS and CMS measurements are so far in agreement with theoretical predictions from the Standard model and each other. No new physic is observed



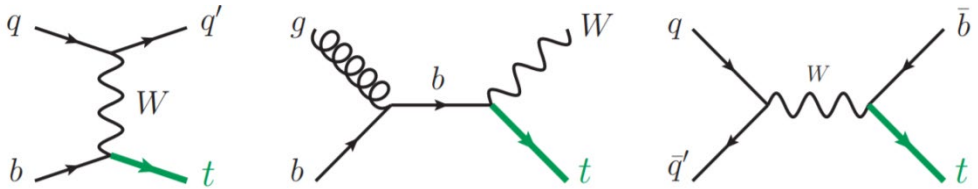

Thanks for
your
attention!

Summary


September 2019
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 137 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqW γssWW EW qqZγ EW qqWZ EW qqZZ WWW WVγ Zγγ Wγγ tt t t-ch tW t s-ch ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
All results at: http://cern.ch/go/pNj7
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ

t – physics. Vtb Measurements

$$|f_{LV}\cdot V_{tb}| = \sqrt{\frac{\sigma^{meas.}_{t-chan.}}{\sigma^{theo.}_{t-chan.}}}, with\ |V_{td}|, |V_{ts}| \ll V_{tb}$$



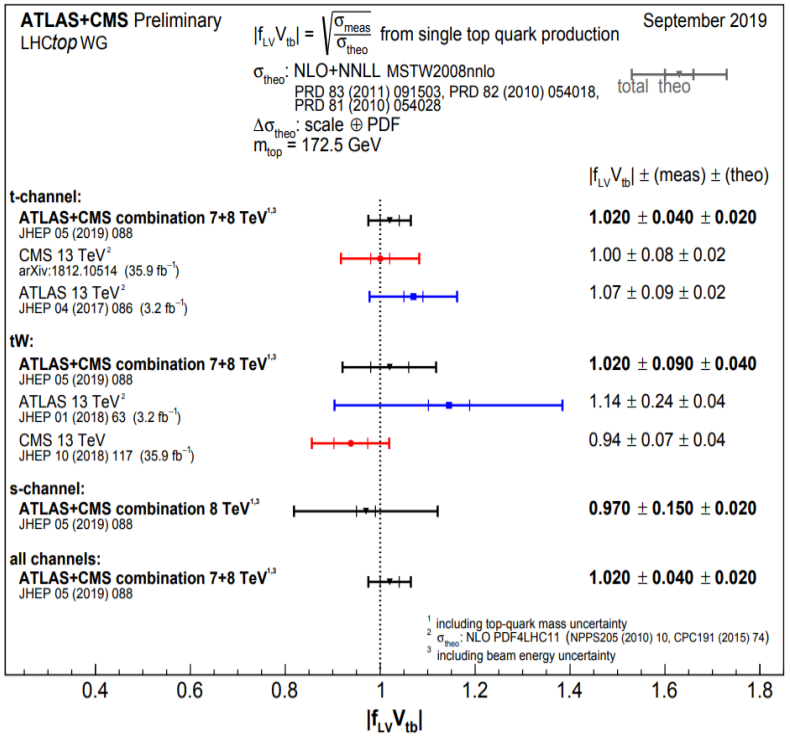
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures#tt_cross_section

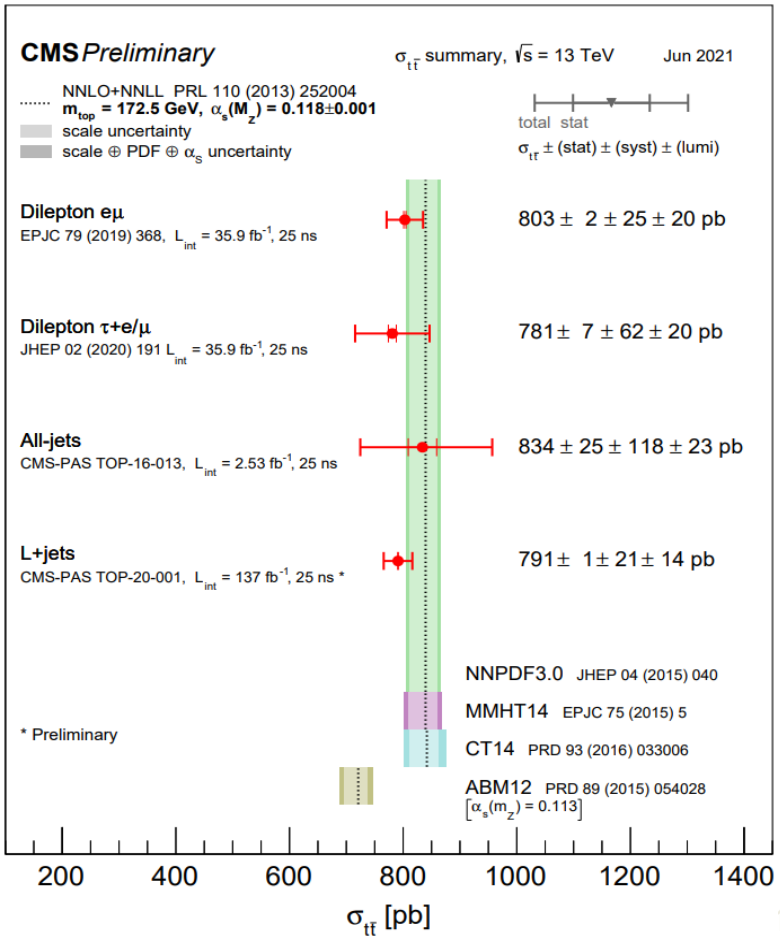
Single top quark productions has direct access to V_{tb} ($\sigma \sim V_{tb}^2$)

V_{tb} has been constrained in all t-channel and Wt-channel measurements

Assumptions:

- BR(t → Wb) ≈ 1
- $|V_{tb}| >> |V_{td}|, |V_{ts}|$
- $f_{LV} = 1$ for the SM





Rare decays: $B_S/B^0 \to \mu\mu$

SM predictions:

$Br(B_S \to \mu\mu)$: $(3.66 \pm 0.14) \times 10^{-9}$

$Br(B^0 \to \mu\mu)$: $(1.03 \pm 0.05) \times 10^{-10}$

$$\tau_{B_s^0} = 1.509 \pm 0.004\,\text{ps}$$

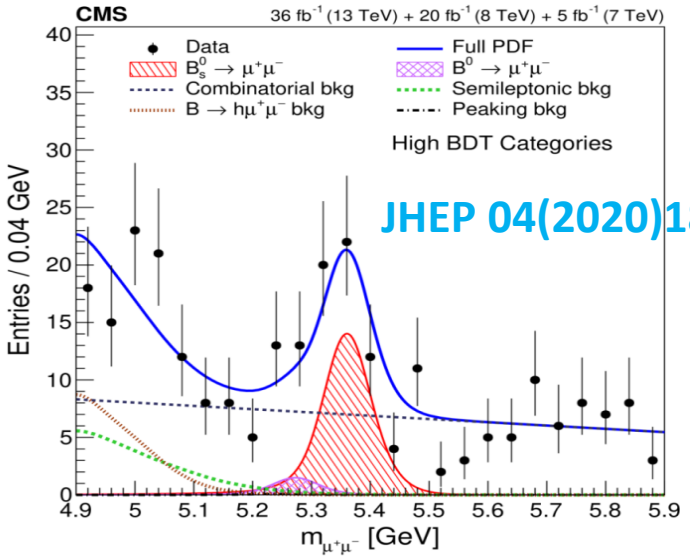
$$\mathcal{R} < 0.052$$

Measurements:

$Br(B_S \to \mu\mu)$: $(2.69 \pm 0.36) \times 10^{-9}$

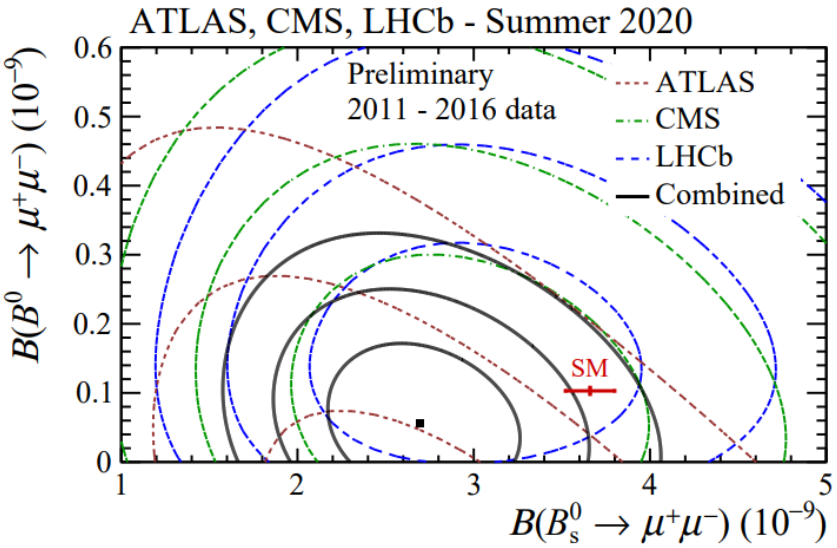
$Br(B^0 \to \mu\mu)$: $< 1.6 \times 10^{-10}$

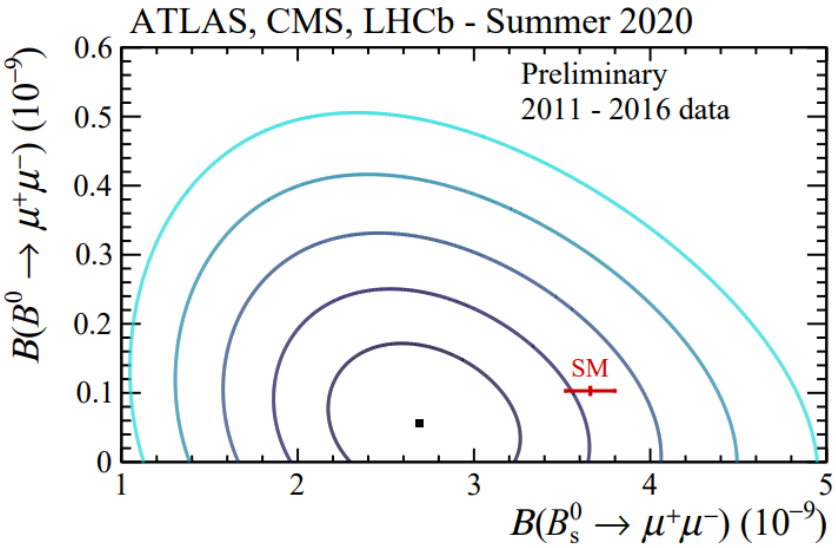
$$\tau_{B_s^0 \to \mu^+\mu^-} = 1.91^{+0.37}_{-0.35}\ \text{ps}$$



JHEP 04(2020)188

CMS-PAS-BPH-20-003 ; LHCb-CONF-2020-002 ; ATLAS-CONF-2020-049



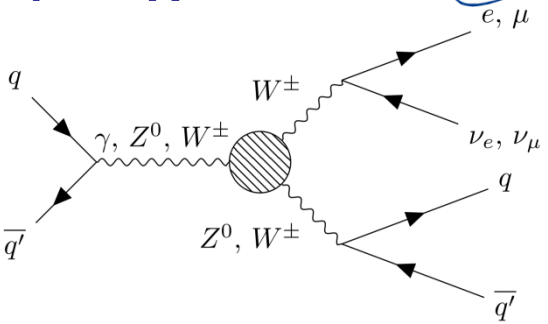


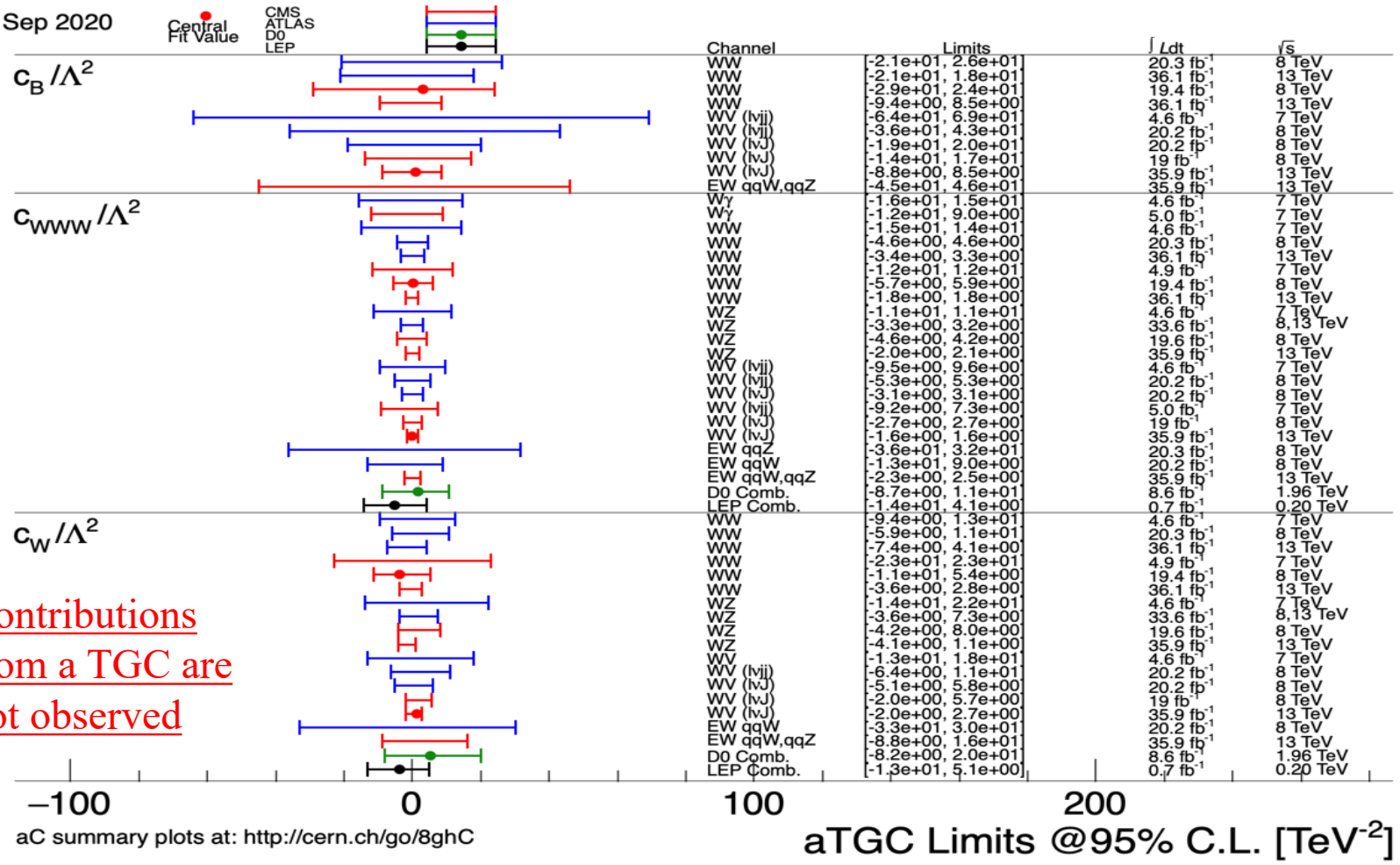
No significant excess from SM predictions are observed!

Anomalous Triple Gouge Couplings

Standard model predictions: $c_W = c_{WWW} = c_B = 0$

Non-zero c-coefficients could indicate a new physics!

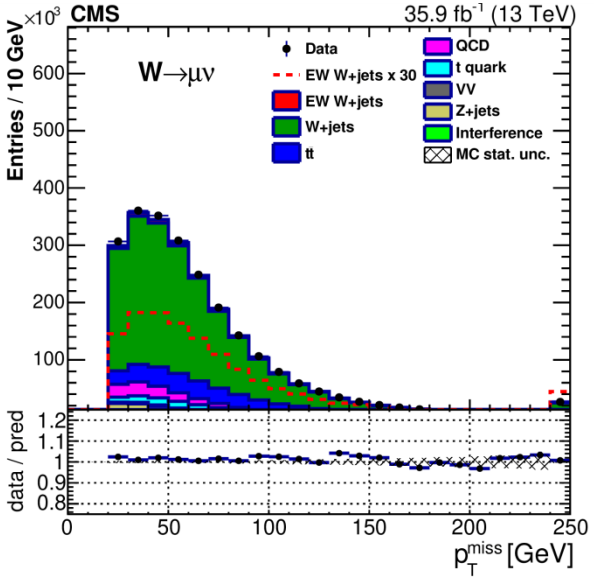


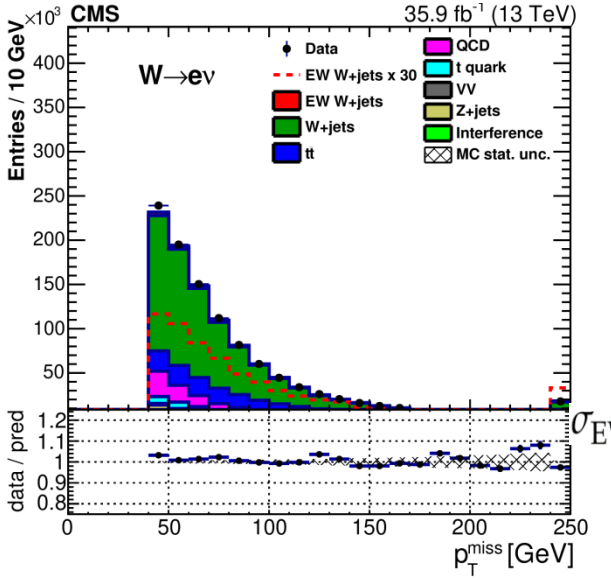


Contributions from a TGC are not observed

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

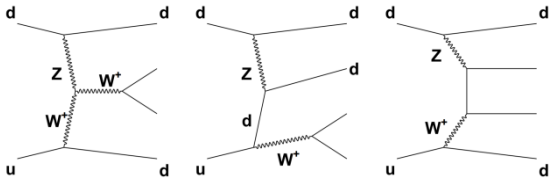
NLO pQCD Stringent Tests: V + jets, VV+jets





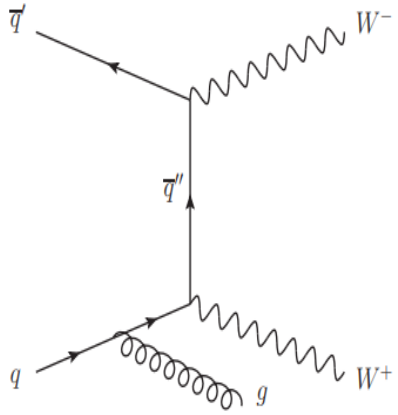
EPJ C 80 (2020) 43

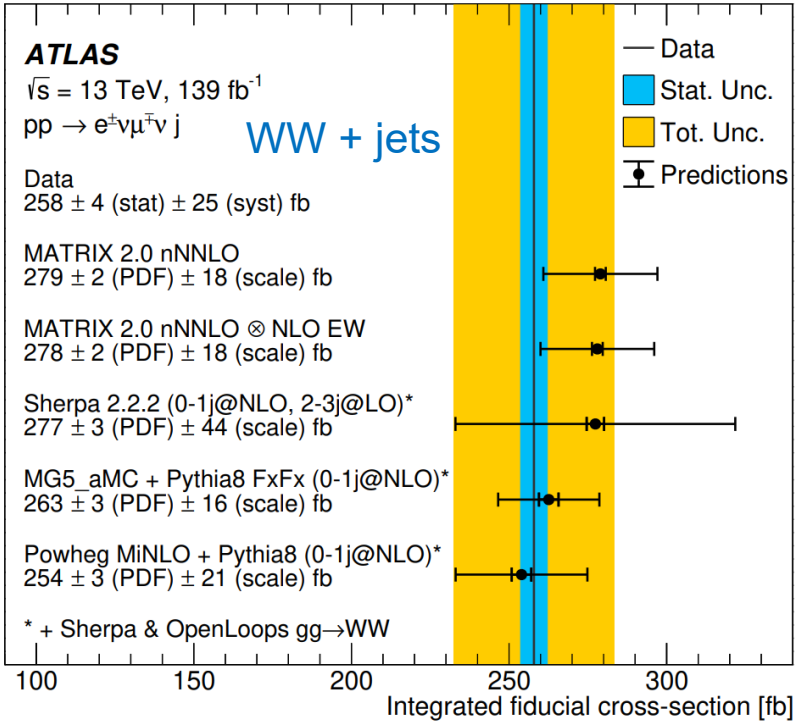
W + 2jets



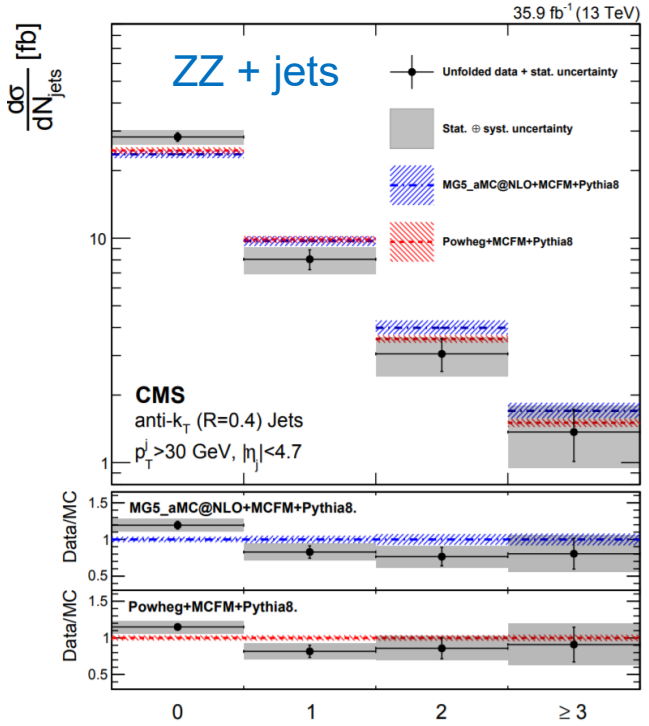
$$\sigma_{EW}(Wjj) = 6.23 \pm 0.12\,(stat) \pm 0.61\,(syst)$$

JHEP 06 (2021) 003





Agrees with the NLO and NNLO standard model prediction!

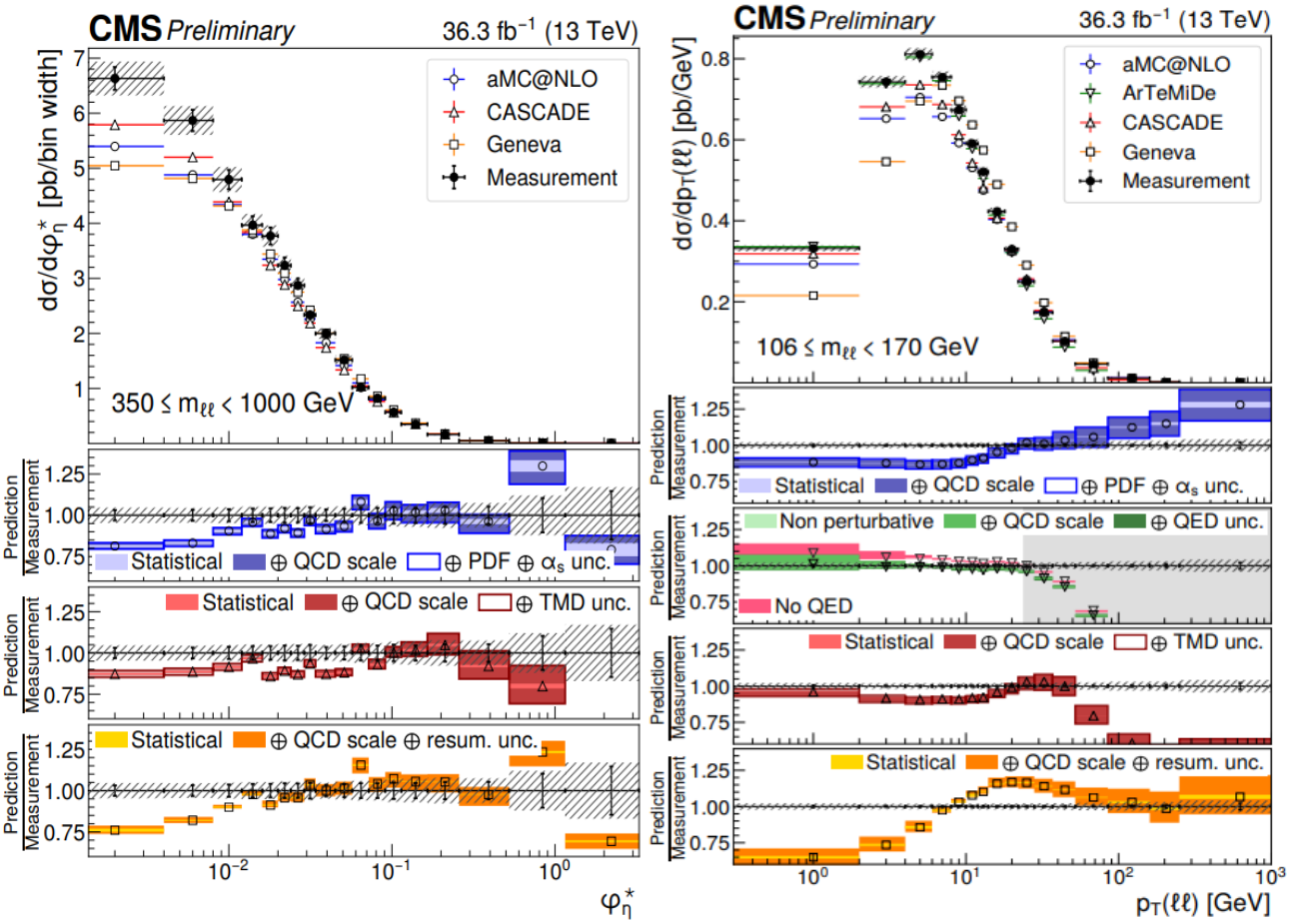


PLB 789 (2019) 19-44

Drell-Yan Differential Cross Sections vs M_{ll}

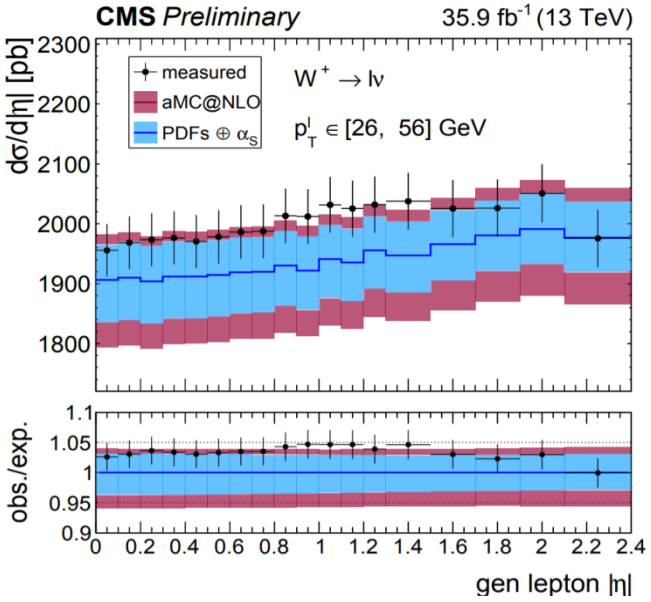
PAS-SMP-20-003

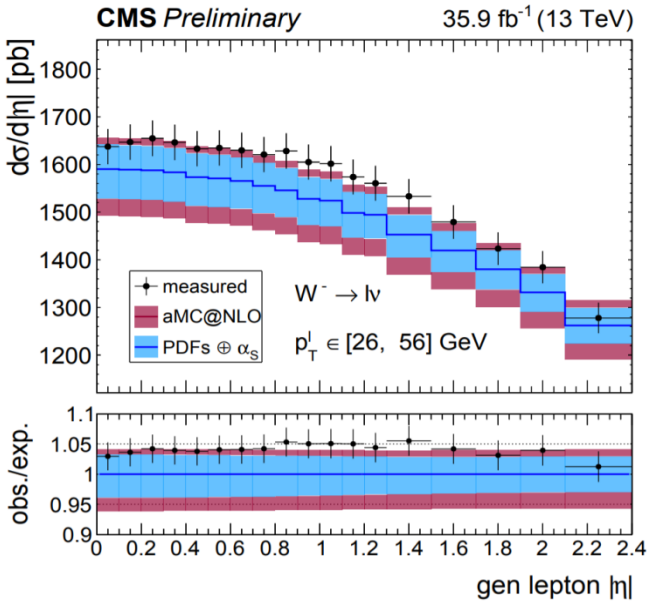
- ✓ The double differential cross sections of the Drell-Yan lepton pair production, as a function M_{ll}, p_T^{ll}, φ_η^* are measured up to M_{ll} = 1000 GeV
- ✓ Measurements are compared to state-of-the-art predictions based on perturbative quantum chromodynamics including soft gluon resummation



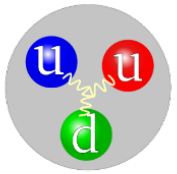
✓The DY double-differential cross sections and double ratio measurements presented here can be used to impose constraints on the quark and antiquark PDFs in a wide range of x

W Charge Asymmetry and Branching



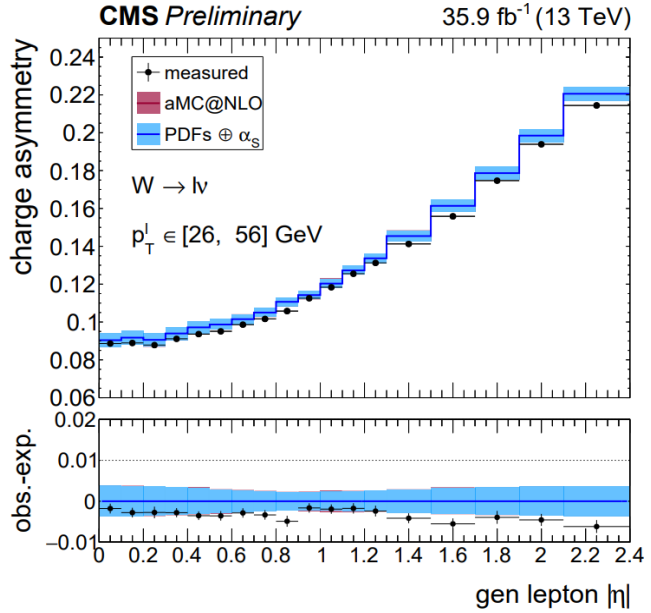


$$u\bar{d} \rightarrow W^+$$
$$d\bar{u} \rightarrow W^-$$

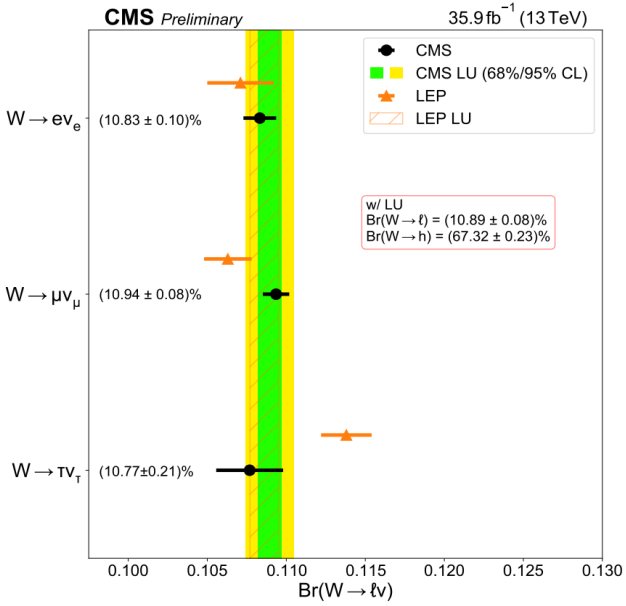


$$\mathcal{A}(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$$

- ✓ Gives important constraints on the ratio of u and d quark distributions in the proton
- ✓ Also done by ATLAS at 8 TeV in muon channel (EPJ. C 79 (2019) 760)



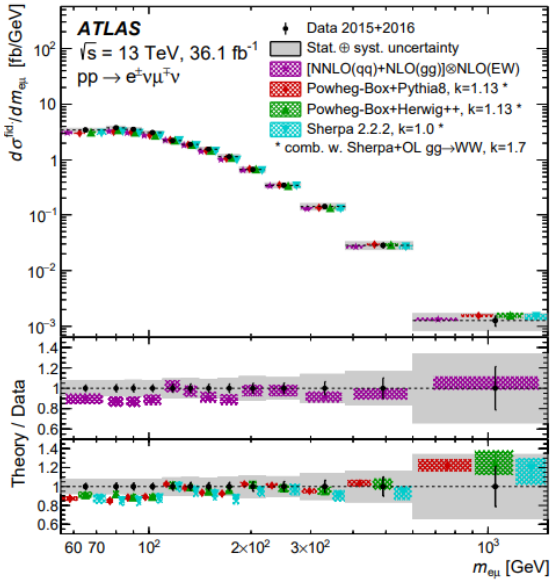
- ✓ Measured leptonic and inclusive hadronic decay branching fractions of W boson
- ✓ Precision is better than for the LEP results
- ✓ Results support the hypothesis of lepton universality for the weak interaction



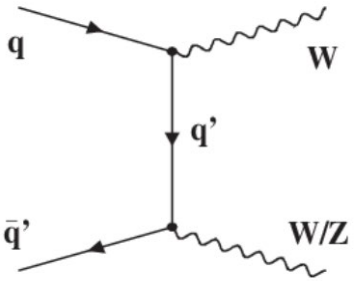
Phys. Rev. D 102 (2020) 092012

PAS SMP-18-011

Multi-boson production

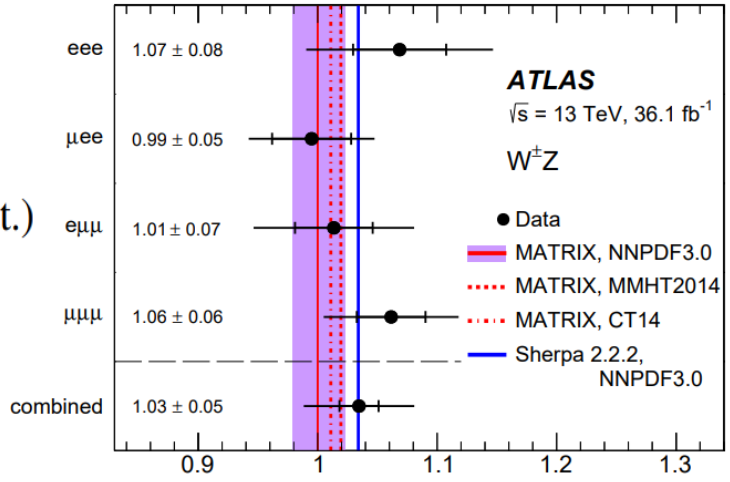


$\sigma_{\text{fid}} = (379.1 \pm 5.0\,(\text{stat}) \pm 25.4\,(\text{syst}) \pm 8.0\,(\text{lumi}))\,\text{fb}$

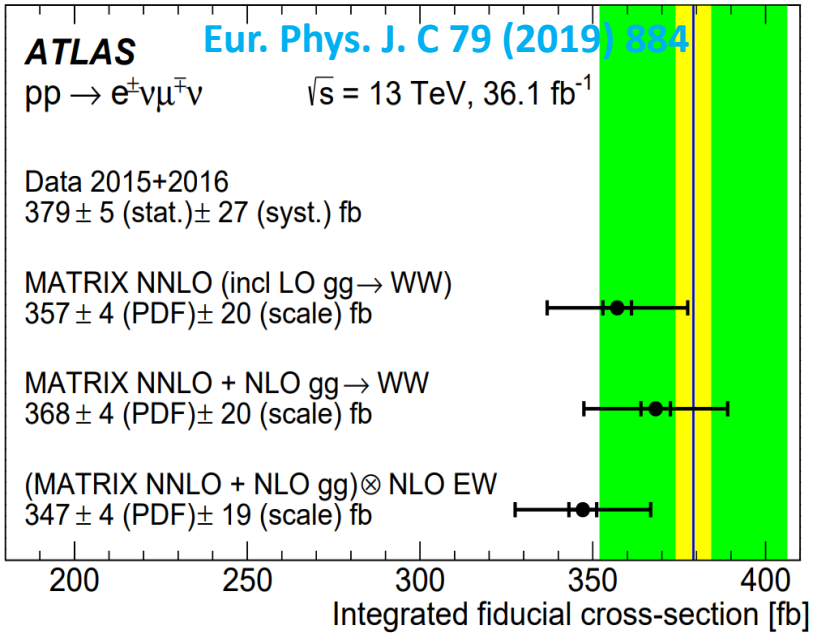


$$\frac{\sigma^{\text{fid.}}_{W^+Z\to\ell'\nu\ell\ell}}{\sigma^{\text{fid.}}_{W^-Z\to\ell'\nu\ell\ell}} = 1.47 \pm 0.05\,(\text{stat.}) \pm 0.02\,(\text{syst.}).$$

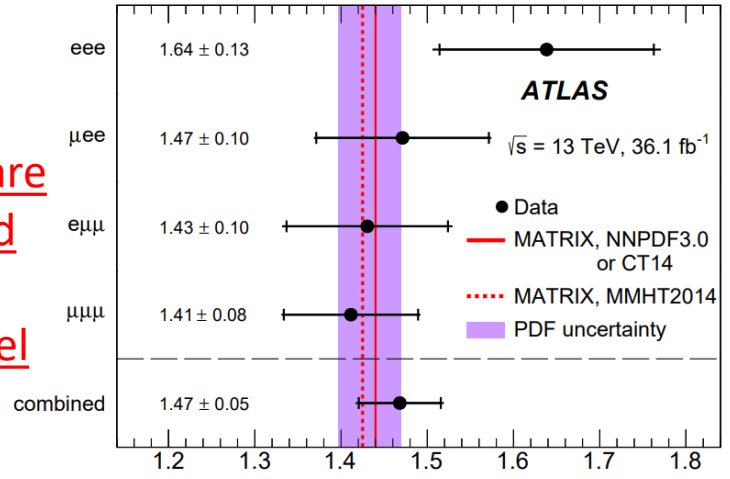
- Challenging analysis, benchmark for H→WW search
- Limits to anomalous WWγ and WWZ couplings set



Eur. Phys. J. C 79 (2019) 535 $\sigma^{\text{fid.}}_{W^\pm Z} / \sigma^{\text{theory}}_{W^\pm Z}$



Multiboson production measurments are well described with NNLO standard model prediction!

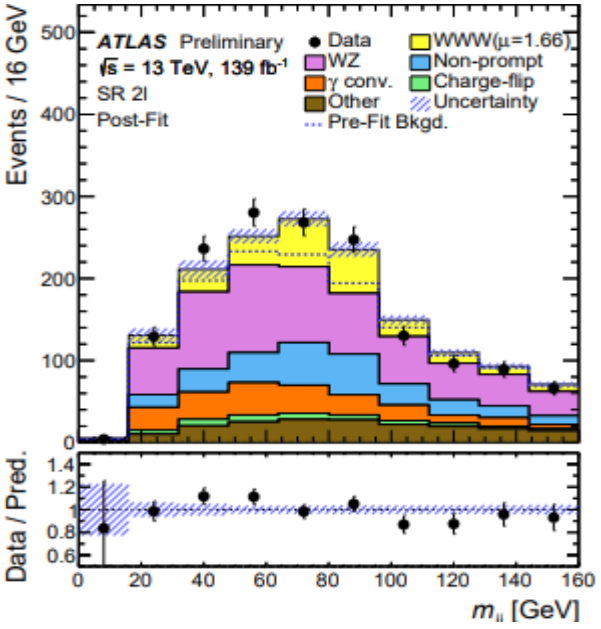


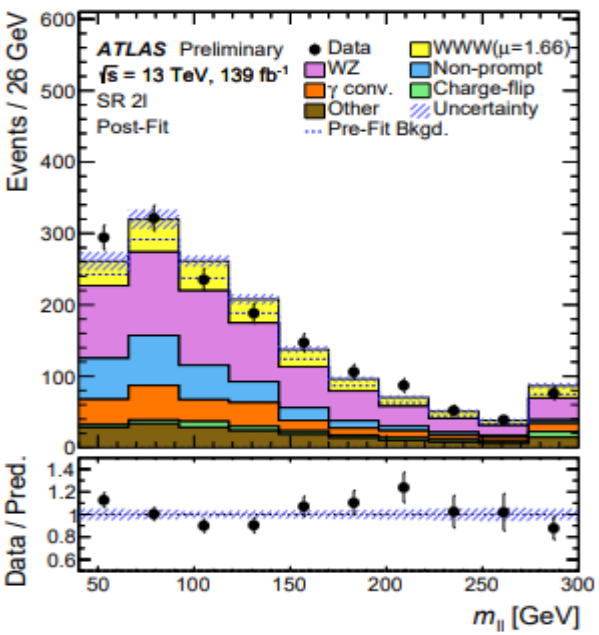
$\sigma^{\text{fid.}}_{W^+Z} / \sigma^{\text{fid.}}_{W^-Z}$

Production of Three Massive Gauge Bosons

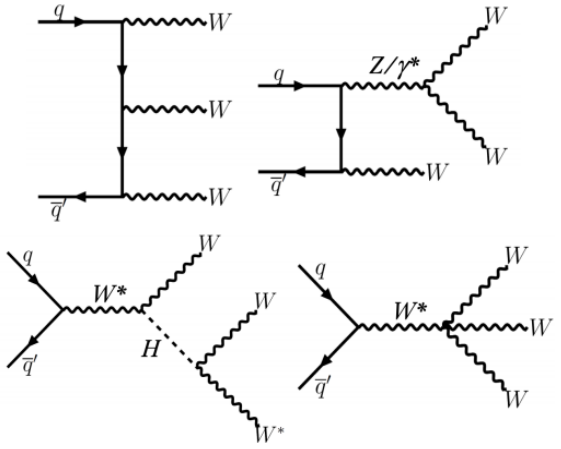
- Triboson final states are among the least-known SM processes due to their small production cross sections
- The presence of quadruple gauge boson interactions can be probed through VVV production
- First bservation by ATLAS with significance 4.1 standard deviations at 13 TeV!
- Observed by CMS as well (PRL 125 (202) 151802)

Decay channel	Significance Observed	Expected
WWW combined	3.2σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ



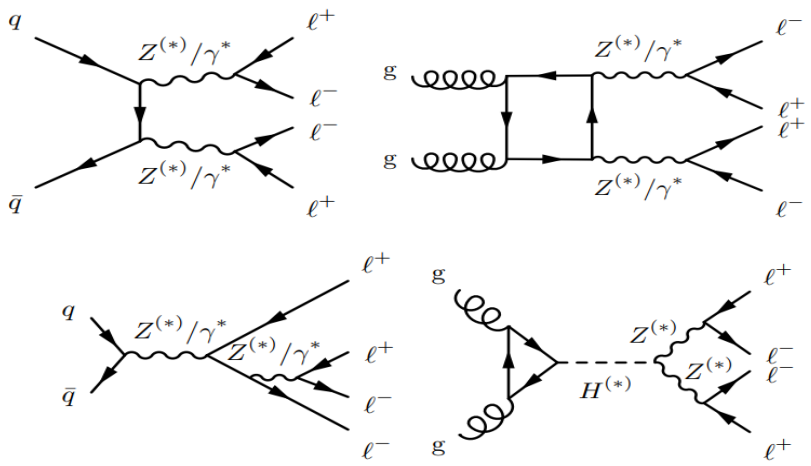


PLB 798 (2019) 134913



Contributions from a TGC and QGC are not observed!

4 Lepton Processes



	Region				
	Full	$Z \to 4\ell$	$H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured	88.9	22.1	4.76	12.4	49.3
fiducial	±1.1 (stat.)	±0.7 (stat.)	±0.29 (stat.)	±0.5 (stat.)	±0.8 (stat.)
cross-section	±2.3 (syst.)	±1.1 (syst.)	±0.18 (syst.)	±0.6 (syst.)	±0.8 (syst.)
[fb]	±1.5 (lumi.)	±0.4 (lumi.)	±0.08 (lumi.)	±0.2 (lumi.)	±0.8 (lumi.)
	±3.0 (total)	±1.3 (total)	±0.35 (total)	±0.8 (total)	±1.3 (total)
SHERPA	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
POWHEG + PYTHIA8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

Accepted by JHEP, arXiv:2103.01918

- Measurements can be used to set limits on variety of BSM models
- Measurements are performed as functions of kinematic variables primary (secondary) lepton pair $(m_{12(34)}, p_{T,12(34)})$, m_{4l}, $|\Delta Y_{pair}|$, $|\Delta\varphi_{pair}|$
- Measurements agree well with predictions from Sherpa and Powheg in all regions