Precise electroweak measurements at the LHC

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on behalf of the **ATLAS**, **CMS** and **LHCb** collaborations

QUARK - LEPTON

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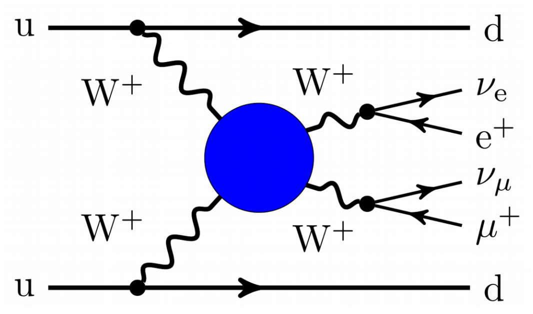
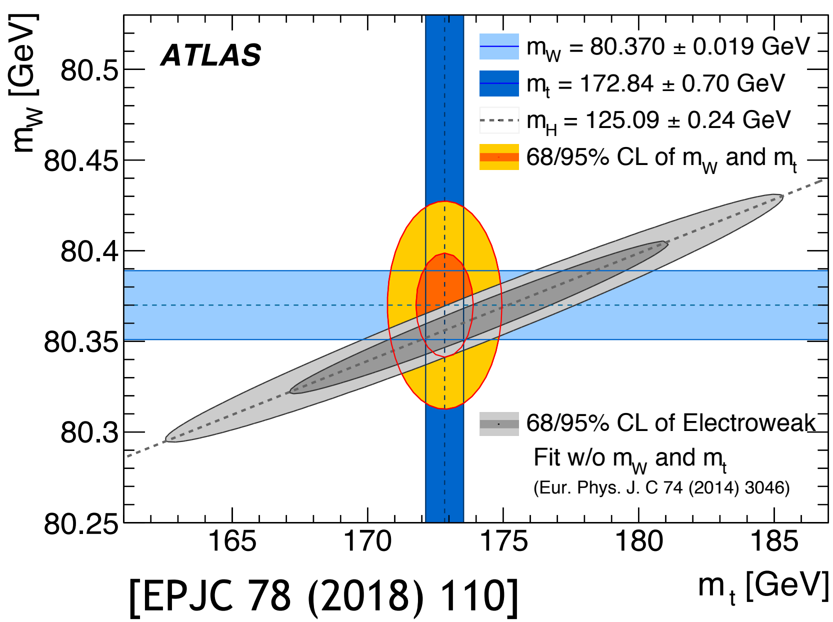
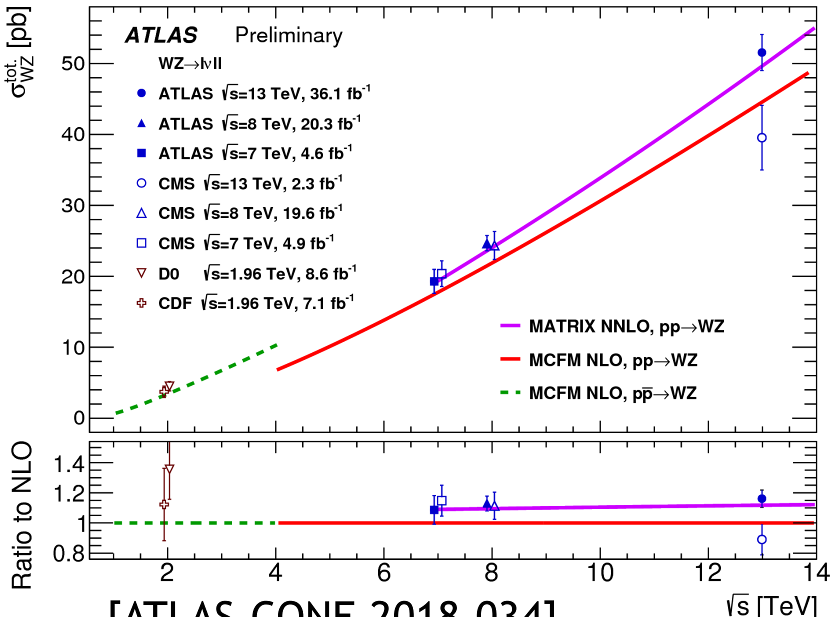
Introduction

- Production of **electroweak (EW) gauge bosons** at the LHC
- Precise tool to probe
  - **SM parameters (m_W, m_H, $\sin^2\theta_{eff}$, …)**
  - **Gauge structure of EW sector**
  - **QCD (NNLO corrections, …)**





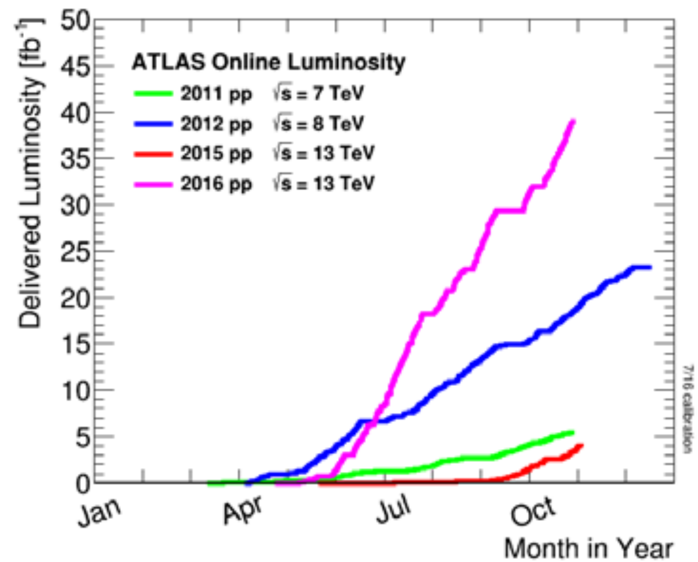
[EPJC 78 (2018) 110]



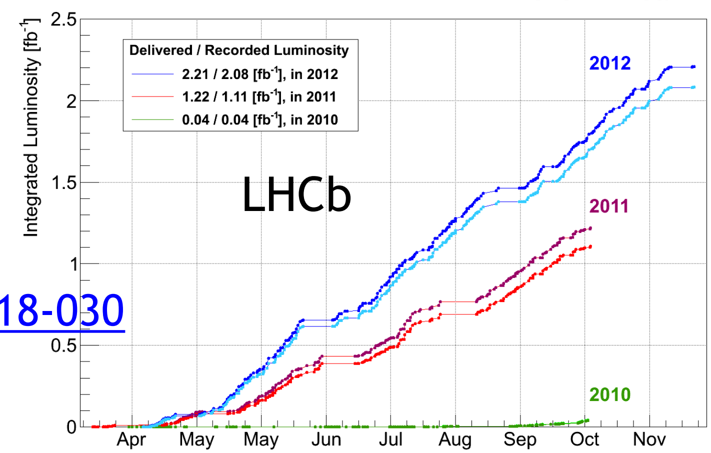
[ATLAS-CONF-2018-034]

Measurements discussed in this talk

- **Weak mixing angle extraction @8 TeV**
  - CMS EPJC 78 (2018) 701; ATLAS-CONF-2018-037
- **Triple-differential Drell-Yan @8 TeV**
  - ATLAS JHEP 12 (2017) 059
- **Forward Z → τ+τ− @ 8 TeV**
  - LHCb arXiv:1806.05008

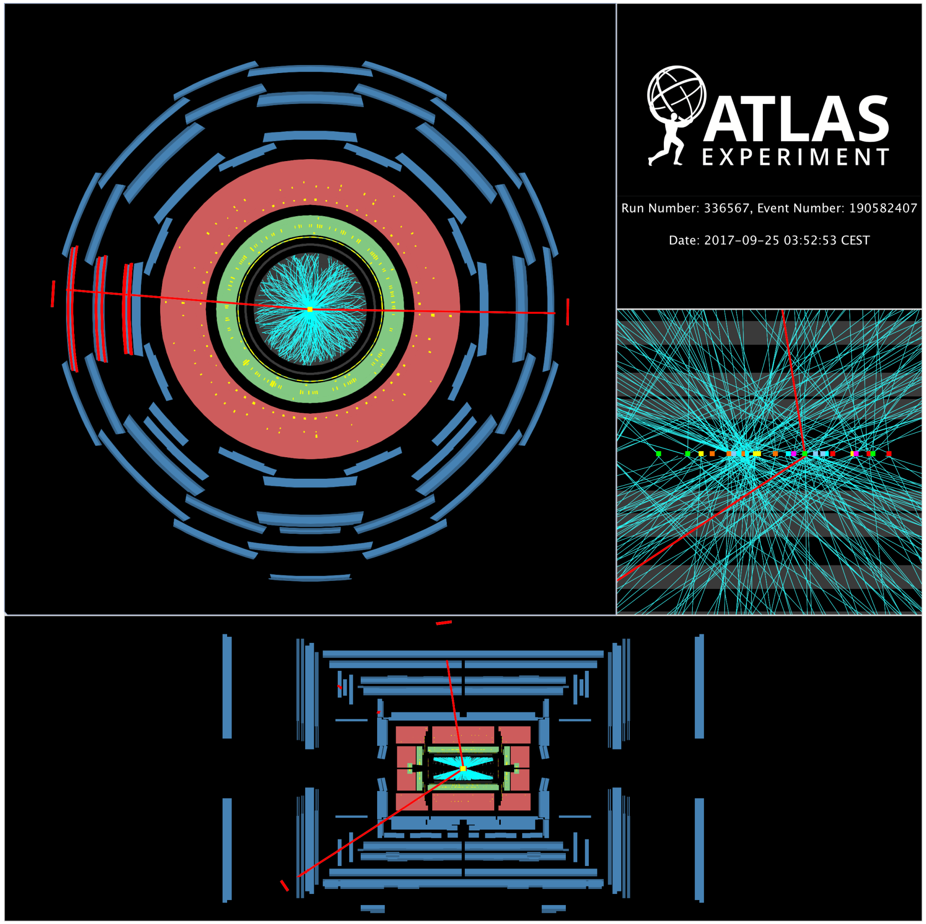


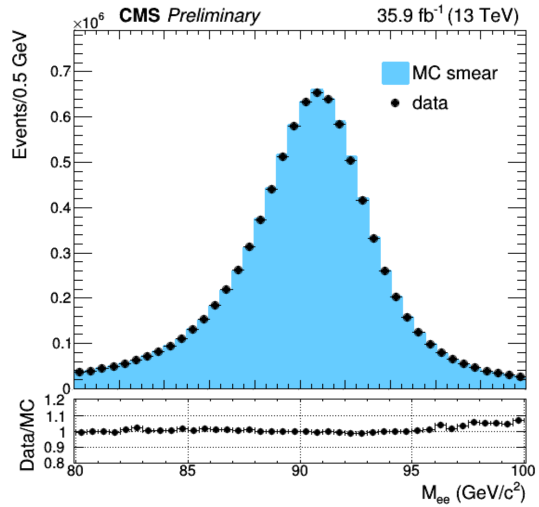
- **Inclusive WZ production @13 TeV**
  - ATLAS-CONF-2018-034, CMS-PAS-SMP-18-002
- **Electroweak diboson production @13 TeV**
  - WZ: ATLAS-CONF-2018-033, CMS-PAS-SMP-18-001
  - ZZ: CMS PLB 774 (2017) 682
  - WW: CMS PRL 120 (2018) 081801; ATLAS-CONF-2018-030
- **γγ → ll with proton-tagging @13 TeV**
  - CMS+TOTEM JHEP 1807 (2018) 153
- **Light-by-light scattering @5 TeV Pb+Pb**
  - ATLAS Nature Phys. 13 (2017) 852; CMS-PAS-FSQ-16-012

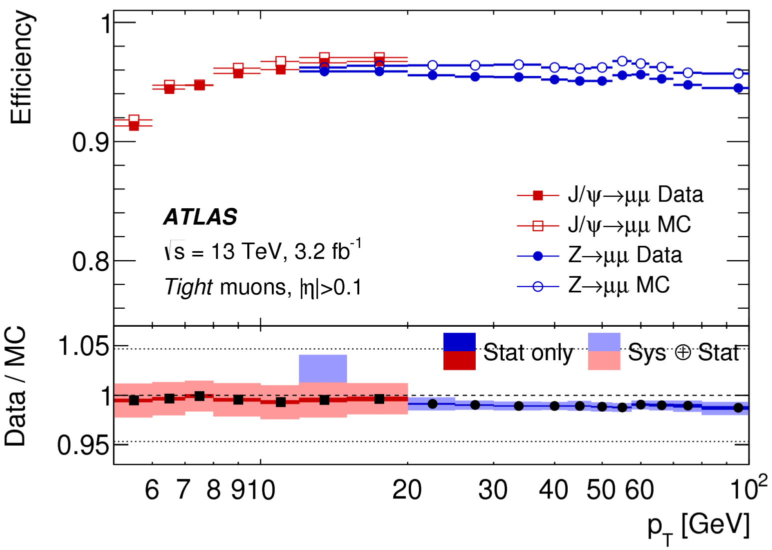


Detecting the objects

- For this type of measurements, **leptonic final states** are preferred (e.g. $Z \rightarrow ll$)
  - Clean to identify/calibrate in the detector







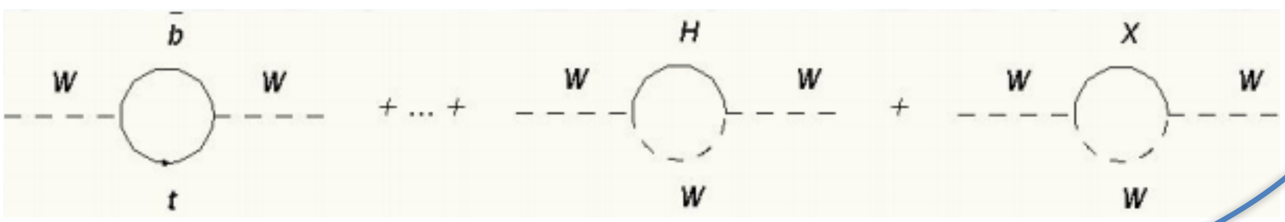
Standard Model parameters

- **α_{em}, G_F, m_Z** → known with high precision

- Other parameters can be constrained:

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \qquad m_W^2 \sin^2\theta_W = \frac{\pi\alpha_{em}}{\sqrt{2}G_F}$$

- BUT: modified by higher-order corrections



$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha_{em}}{\sqrt{2}G_F}\frac{1}{1-\mathbf{\Delta r}}$$

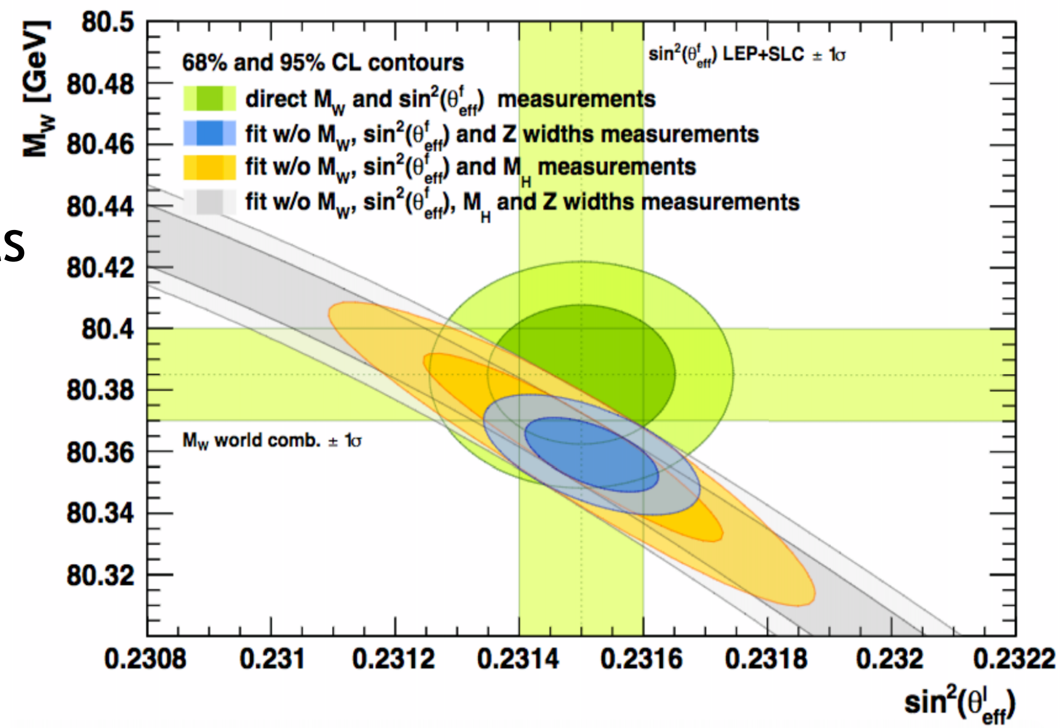
→ **radiative corrections**
~$f(m_{top}^2, \log m_H)$ ~3%

Direct measurement vs global fit

- **Gfitter**
  arXiv:1803.01853

Parameter	Measurement	Indirect determination from EW fit
m_H [GeV]	125.1 ± 0.2	90 ± 21
m_t [GeV]	172.47 ± 0.68	176.4 ± 2.1
m_W [GeV]	80.379 ± 0.013	80.354 ± **0.007**
$\sin^2\theta_{eff}$ (LEP+SLC)	0.23152 ± 0.00016	0.23149 ± **0.00007**

- **At the LHC:**
  Tests of the consistency of the EW sector through high-precision measurements of $\mathbf{\sin^2\theta_{eff}}$ and $\mathbf{m_W}$ possible



Weak mixing angle @ 8 TeV

- **Previous measurements** (LHC/Tevatron)
  - Based on forward-backward asymmetry (**A_{FB}**) in **DY ee/μμ**

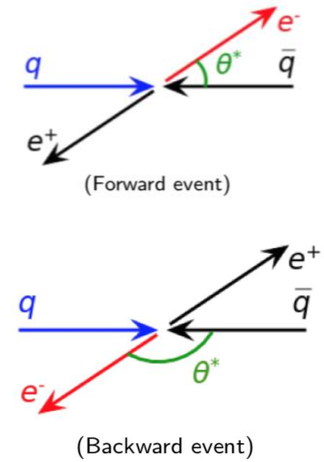
At LO SM:

$$\frac{d\sigma}{d\cos\theta^*} = A(1+\cos^2\theta^*) + B\cos\theta^*$$

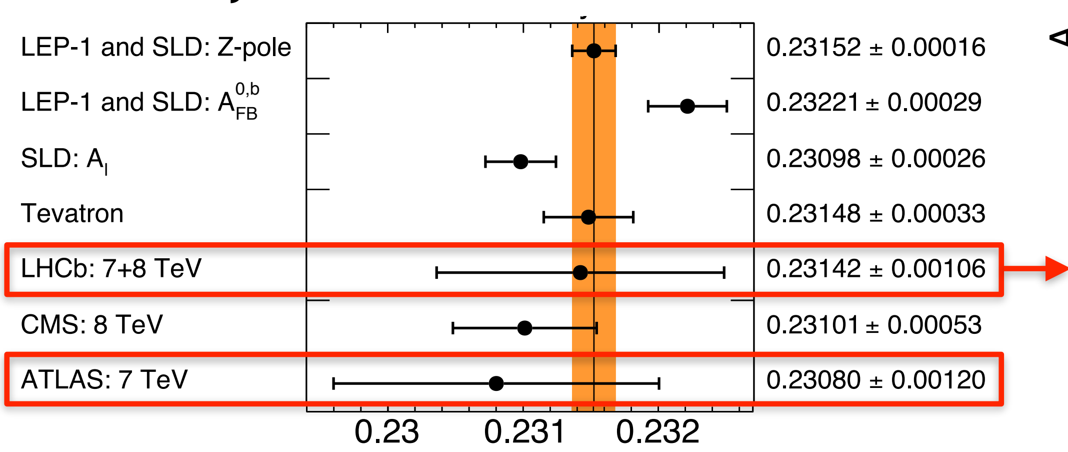
θ*: decay angle in Collins-Soper frame

Parity-violating term
B ~ A_{FB} and function of $\sin^2\theta_W$

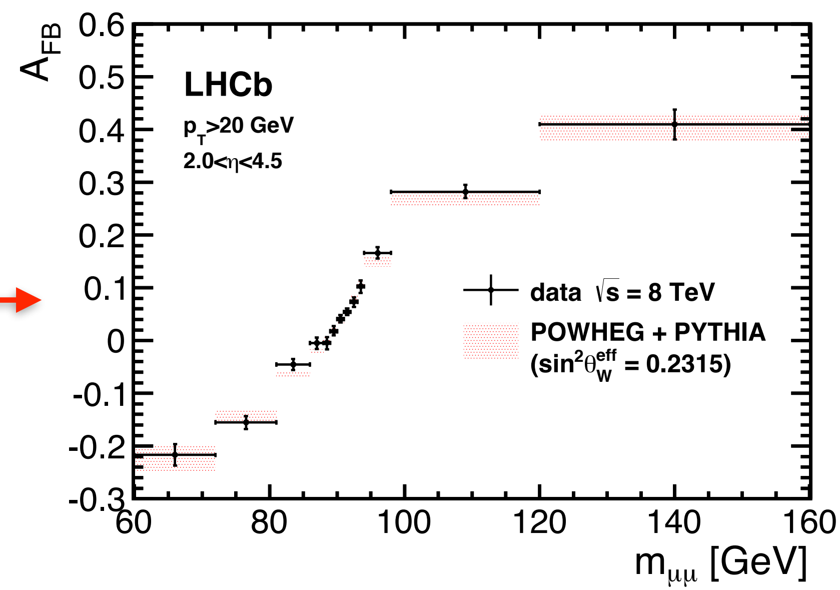
$$A_{FB} = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$$



  - ATLAS & LHCb measurements heavily limited by PDF uncertainties

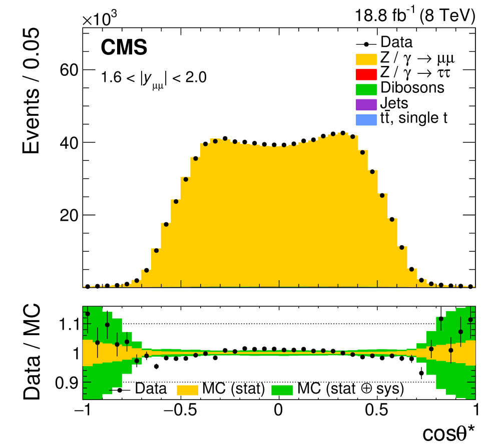


$$\sin^2\theta^\ell_{\text{eff}} = K^\ell_Z \cdot \sin^2\theta_W$$

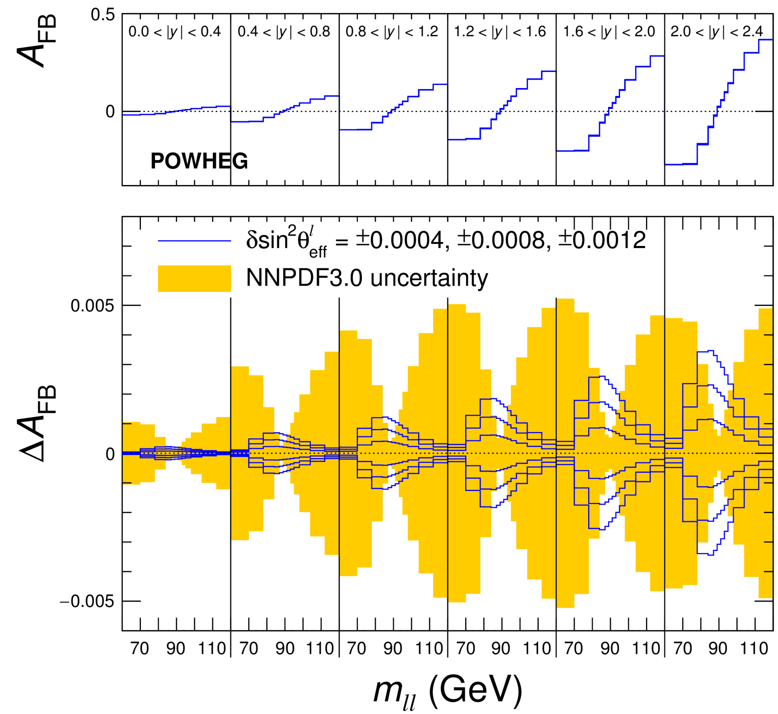


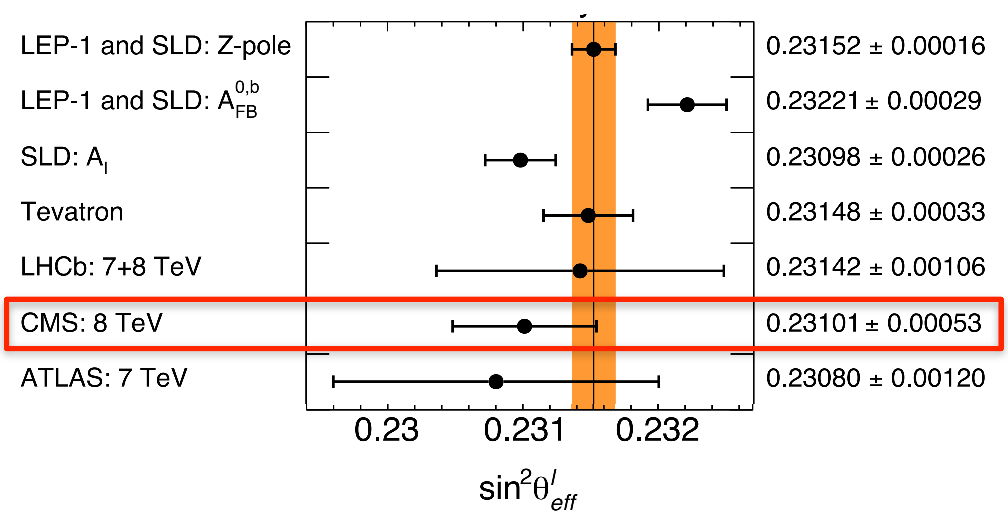
CMS weak mixing angle @ 8 TeV

- To reduce impact of PDFs
  - Fit **mass & rapidity** dependence of observed A_{FB} to SM predictions, as function of $\sin^2\theta_{eff}$
  - PDF reweighting using NNPDF3.0 replicas



$\sin^2\theta_{eff}$ = 0.23101 ±0.00036(stat) ±0.00018(sys) ±0.00016(theo) ±0.00031(PDF) **[0.00053 tot]**

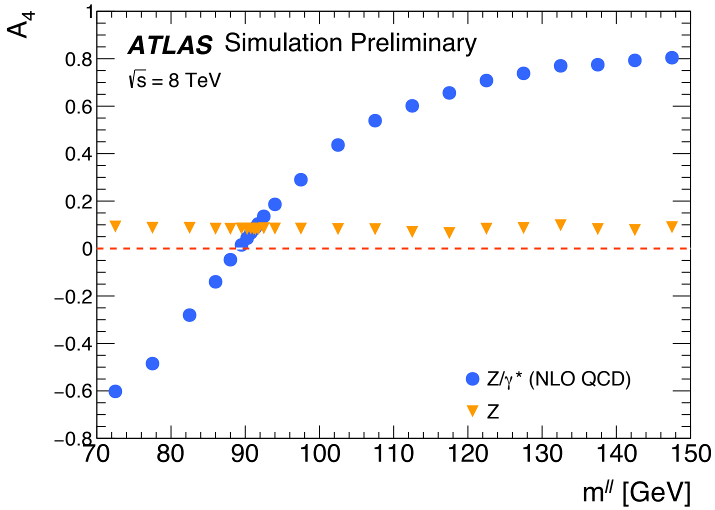




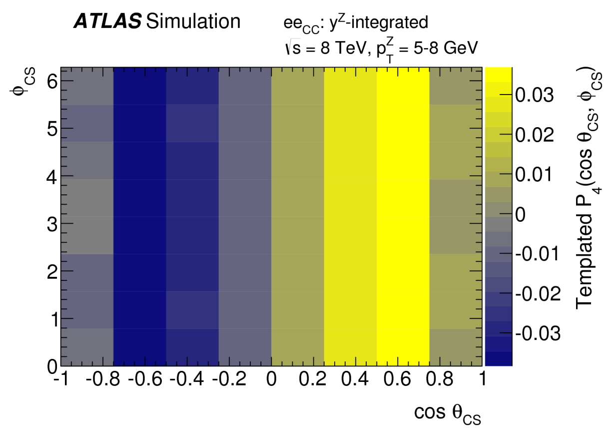
ATLAS weak mixing angle @ 8 TeV

- **Measurement strategy**
  - **5D** differential cross section $\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi}$ can be decomposed as 1+8 harmonic polynomials **P_i (cosθ*, φ*)**, multiplied by dimensionless angular coefficients **A_i (p_T^Z, y_Z, m_Z)**
  - Angular coefficients **A_i** describe full QCD production dynamics:

$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}} \Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}.$$



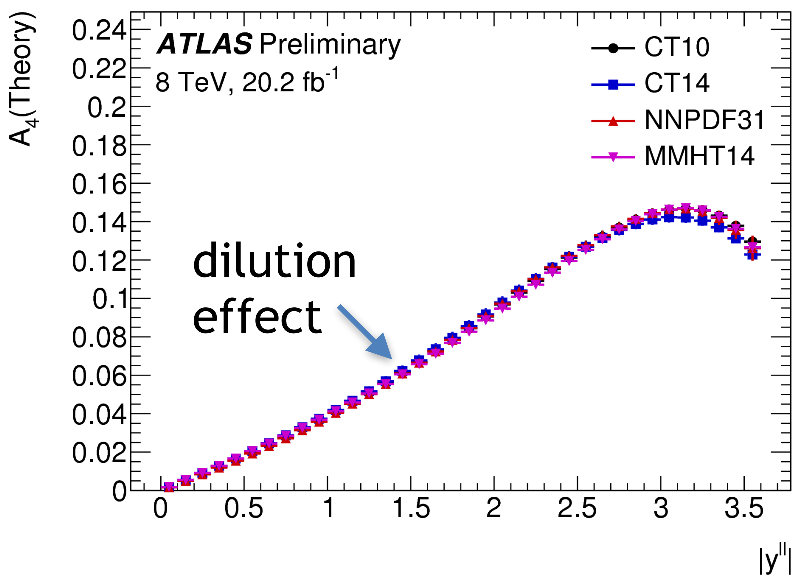
  - **A_{FB} = 3/8 A_4** (in full phase space → folding)
  - **A_i extraction:** fit templates of the P_i polynomials to reconstructed angular distributions; 8×8 bins in (cosθ*, φ*) for each **y_{ll}, m_{ll}** bin [see also JHEP 08 (2016) 159]

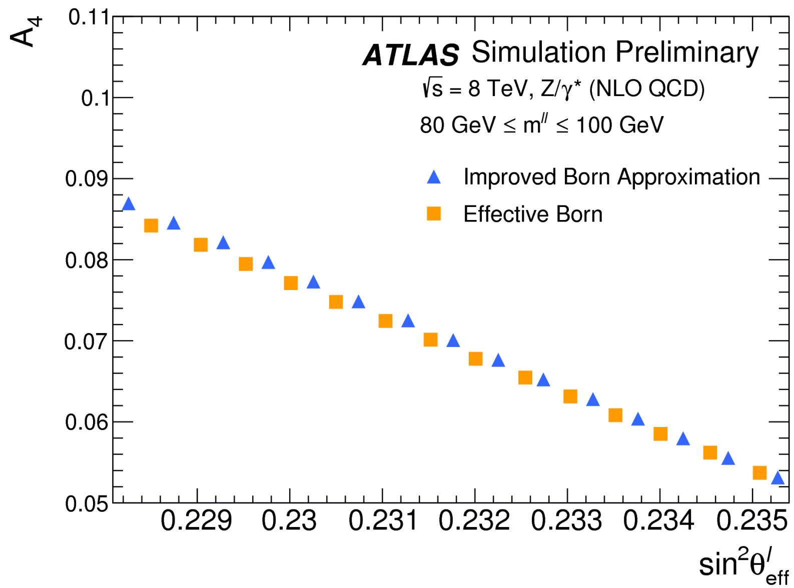


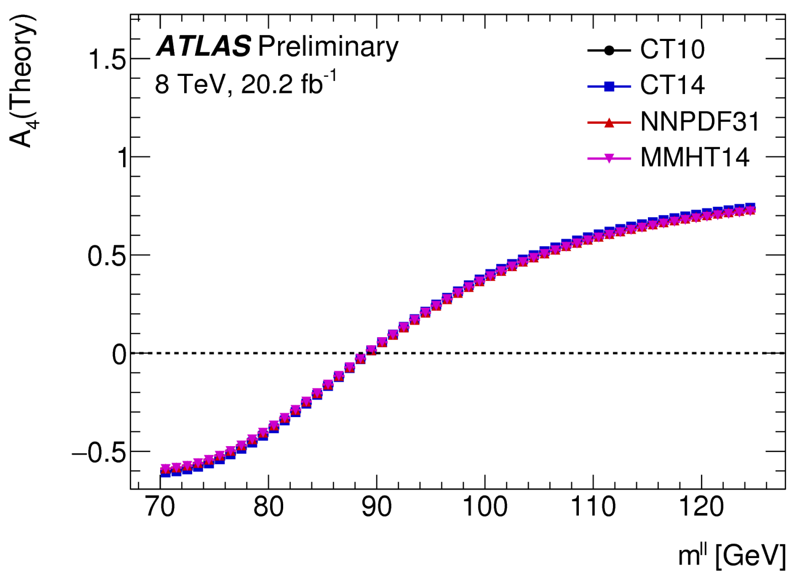
ATLAS weak mixing angle @ 8 TeV

- **Predictions**
  - A_4 largest at y_Z ~ 3

- $A_4 \rightarrow \sin^2\theta_{eff}$ mapping
  - Based on effective linear relation
    $A_4 = a \times \sin^2\theta_{eff} + b$ (in each bin)
    (EW corrections absorbed in (a,b))



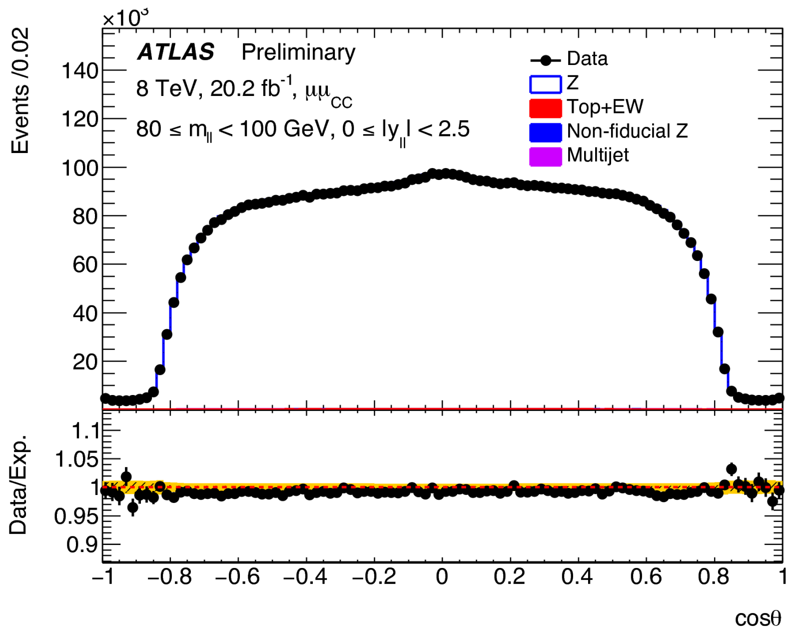


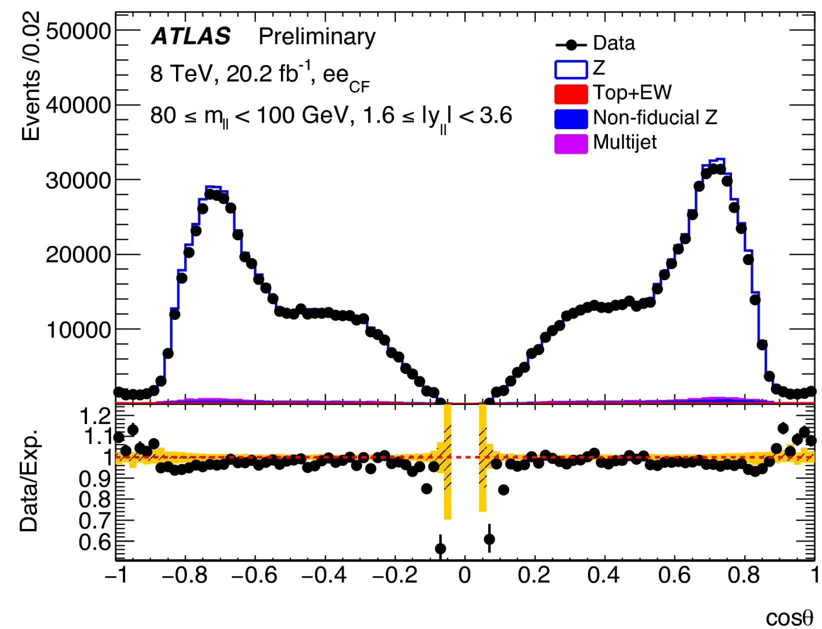


ATLAS weak mixing angle @ 8 TeV

- **Data analysis**
  - **~15M ee+μμ** pairs selected in data
  - **Central-forward Z→ee** (**ee_{CF}**) production: adds extra sensitivity (1.6< **y_Z** <3.6)

Central: $|\eta_e|<2.4$
Forward: $2.5<|\eta_e|<4.9$





	$80 < m_{ll} < 100$ GeV			
$\lvert y_{ll}\rvert$	Data	Top+EW	Multijets	Non-fiducial Z
0-0.8	2 866 016	0.002	0.001	< 0.001
0.8-1.6	2 948 371	0.002	0.001	< 0.001
1.6-2.5	1 314 890	0.002	0.001	< 0.001

	$80 < m_{ll} < 100$ GeV			
$\lvert y_{ll}\rvert$	Data	Top+EW	Multijets	Non-fiducial Z
1.6-2.5	702 142	0.001	0.010	0.017
2.5-3.6	441 104	0.001	0.011	0.013

ATLAS weak mixing angle @ 8 TeV

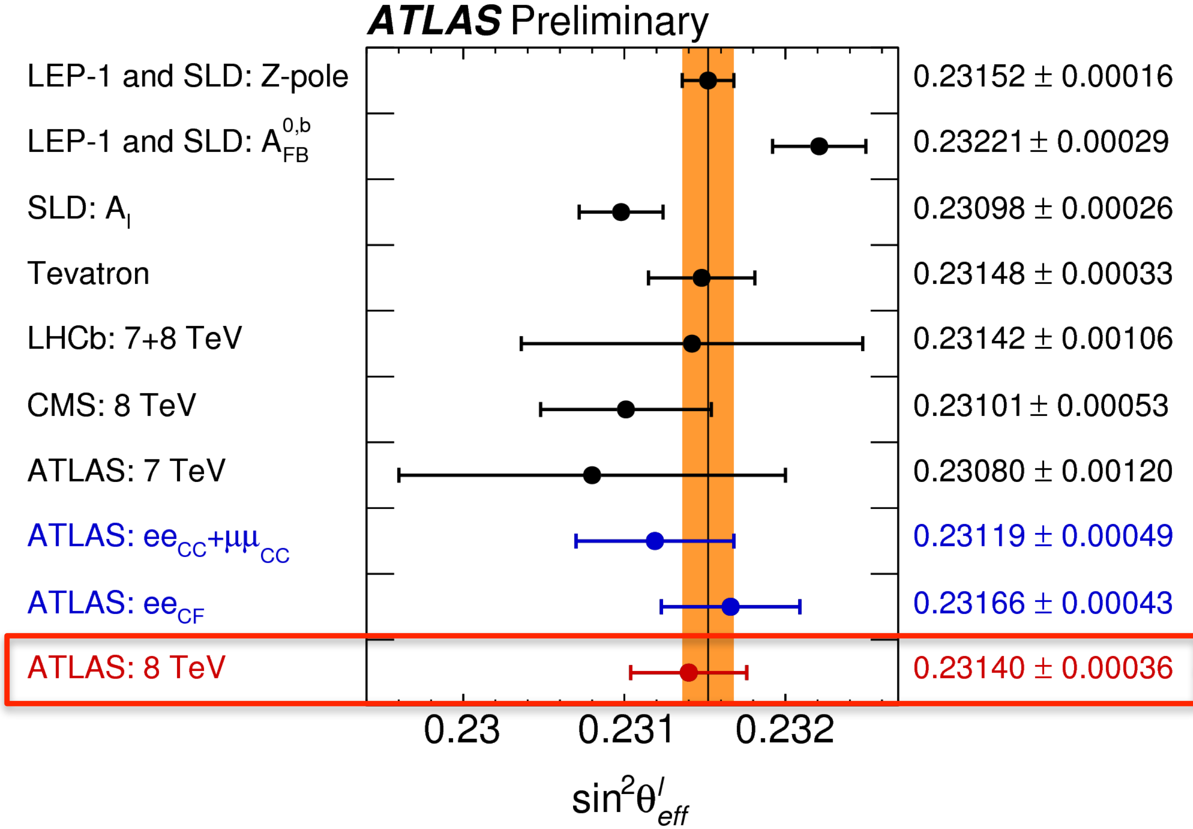
- **$\sin^2\theta_{eff}$ results** → based on reference PDF set (MMHT14)
  - **ee_{CF}** channel most precise (only 1.5M events, cf. 13.5M ee_{CC} + $\mu\mu_{CC}$)
  - **MC statistics** second largest systematic uncertainty

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_T^Z modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

$\times 10^{-5}$

ATLAS weak mixing angle @ 8 TeV

- **Compatibility with other measurements**
  - $\sin^2\theta_{eff}$ = **0.23140** ±0.00021(stat) ±0.00016(sys) ±0.00024(PDF) **[0.00036 tot]**
  - This measurement improves the overall consistency of the full set of measurements

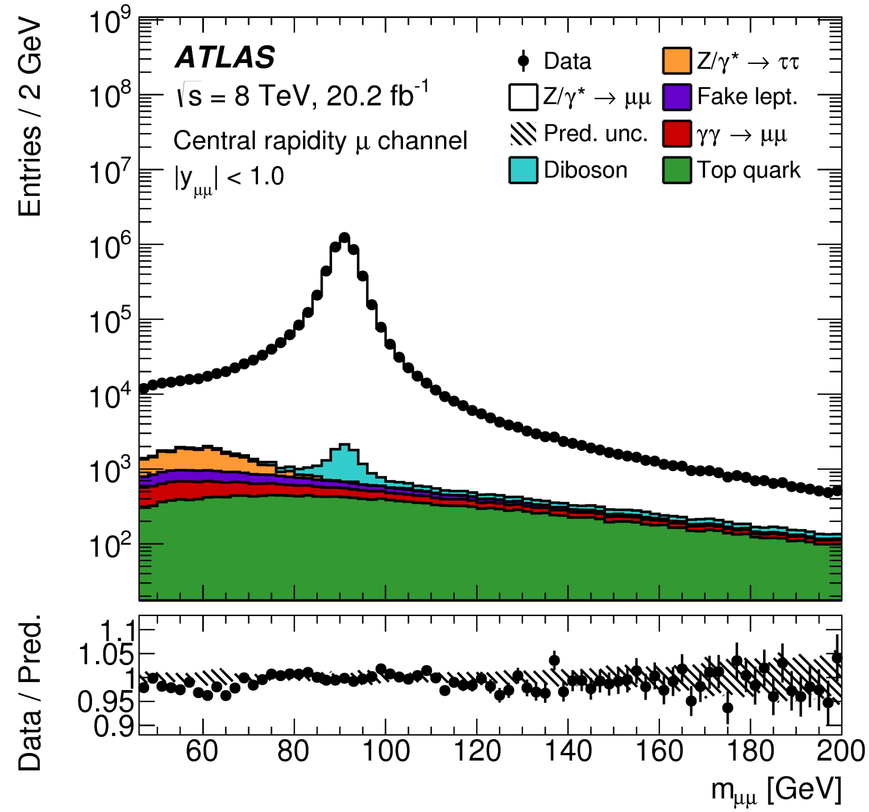


0.15% precision

ATLAS triple-differential Drell-Yan @ 8 TeV

- **$d^3\sigma/dy_{ll}\, dm_{ll}\, d\cos\theta^*$** measurement designed to be **simultaneously sensitive** to $\sin^2\theta_{eff}$ and PDFs
  - **y_{ll}** and **m_{ll}** → sensitive to PDFs
  - **$\cos\theta^*$** → sensitive to $\sin^2\theta_{eff}$ and PDFs

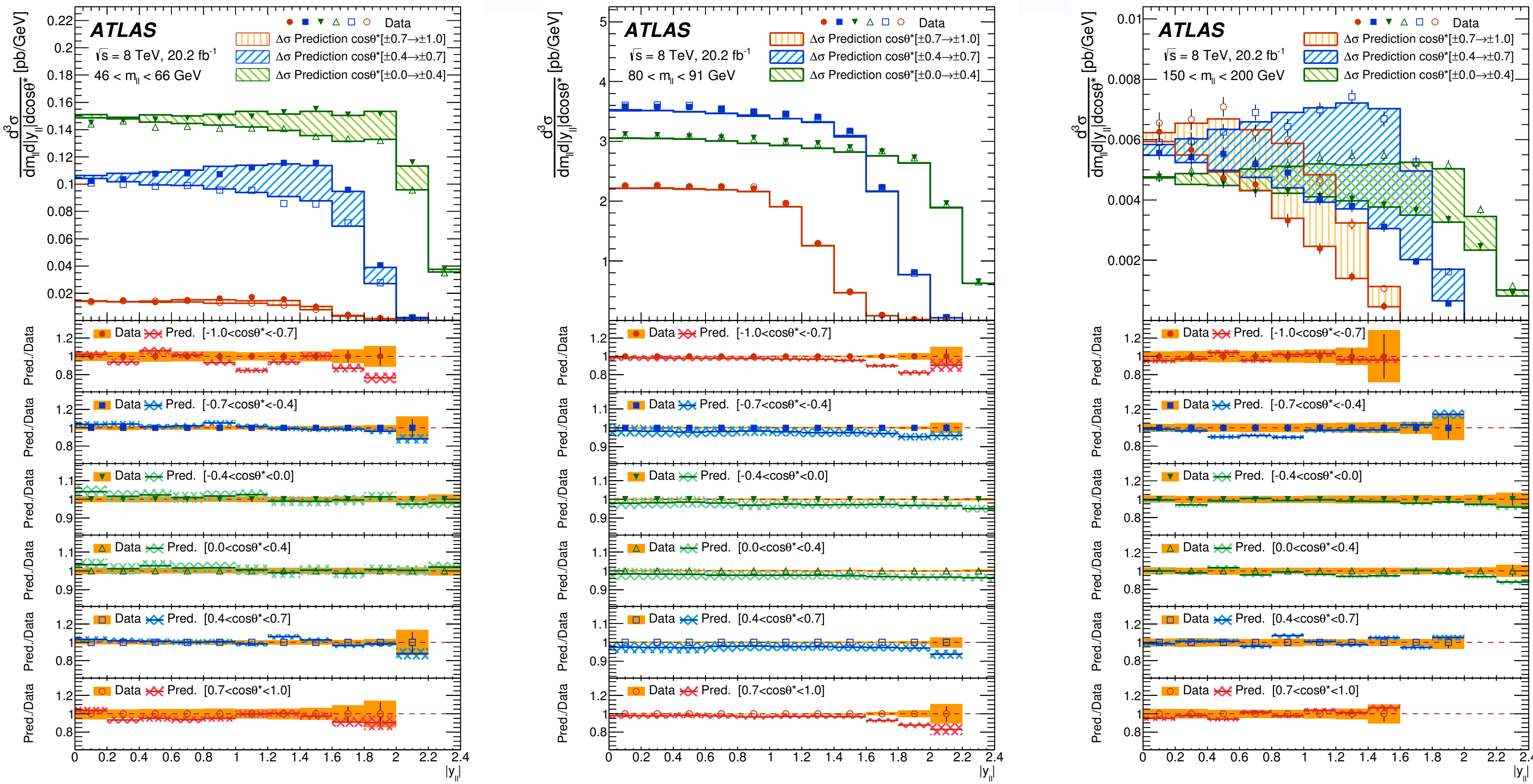
- Measurement
  - Wide kinematic range is covered: **$46 < m_{ll} < 200$ GeV** and **$|y_{ll}| < 3.6$**
  - **654** differential bins in total
  - **Accuracy: about 2%** [1.9% (lumi) + 0.5%(stat) + 0.5%(exp)]



ATLAS triple-differential Drell-Yan @ 8 TeV

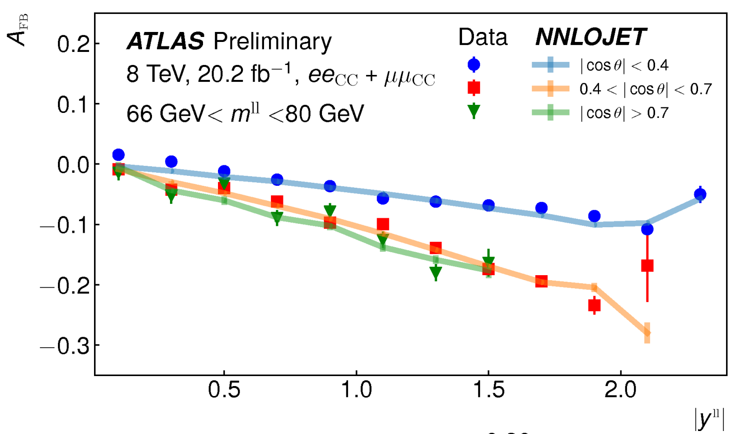
- Good agreement of triple-diff. measurements with predictions
- Asymmetry (A_{FB}) evolution clearly visible

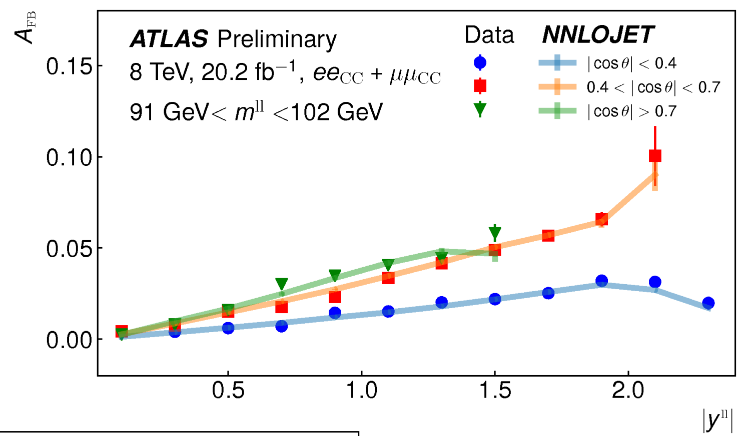
$$A_{\mathrm{FB}} = \frac{\mathrm{d}^3\sigma(\cos\theta^* > 0) - \mathrm{d}^3\sigma(\cos\theta^* < 0)}{\mathrm{d}^3\sigma(\cos\theta^* > 0) + \mathrm{d}^3\sigma(\cos\theta^* < 0)}$$

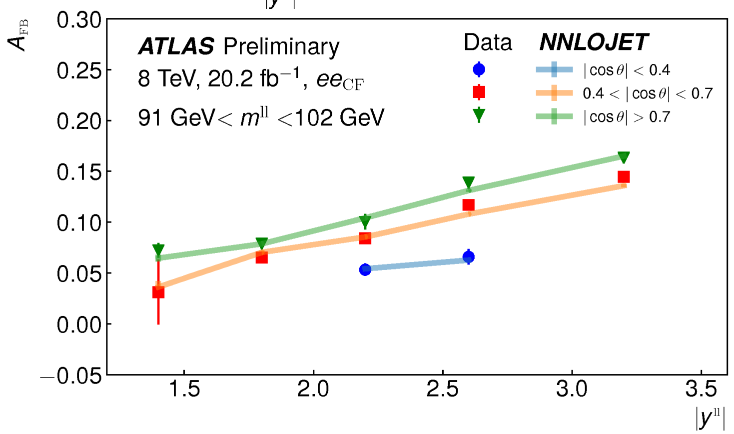


ATLAS triple-differential Drell-Yan @ 8 TeV

- **Measurement reinterpretation**
  - Cross-check of A_i-based $\sin^2\theta_{eff}$ measurement
  - Extracted triple-differential A_{FB} distributions are compared with NNLO calculations using MMHT14 PDF set for $\sin^2\theta_{eff} = 0.23148$

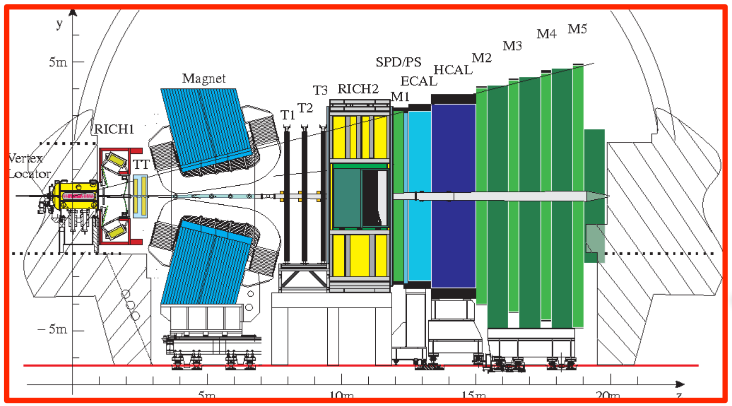


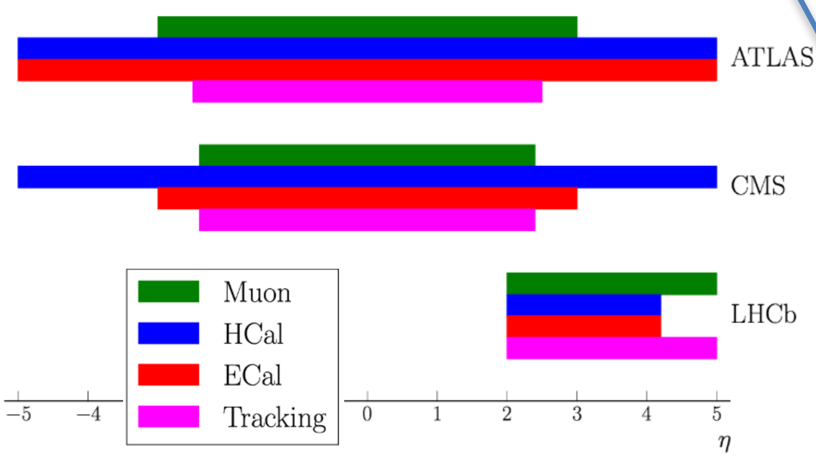


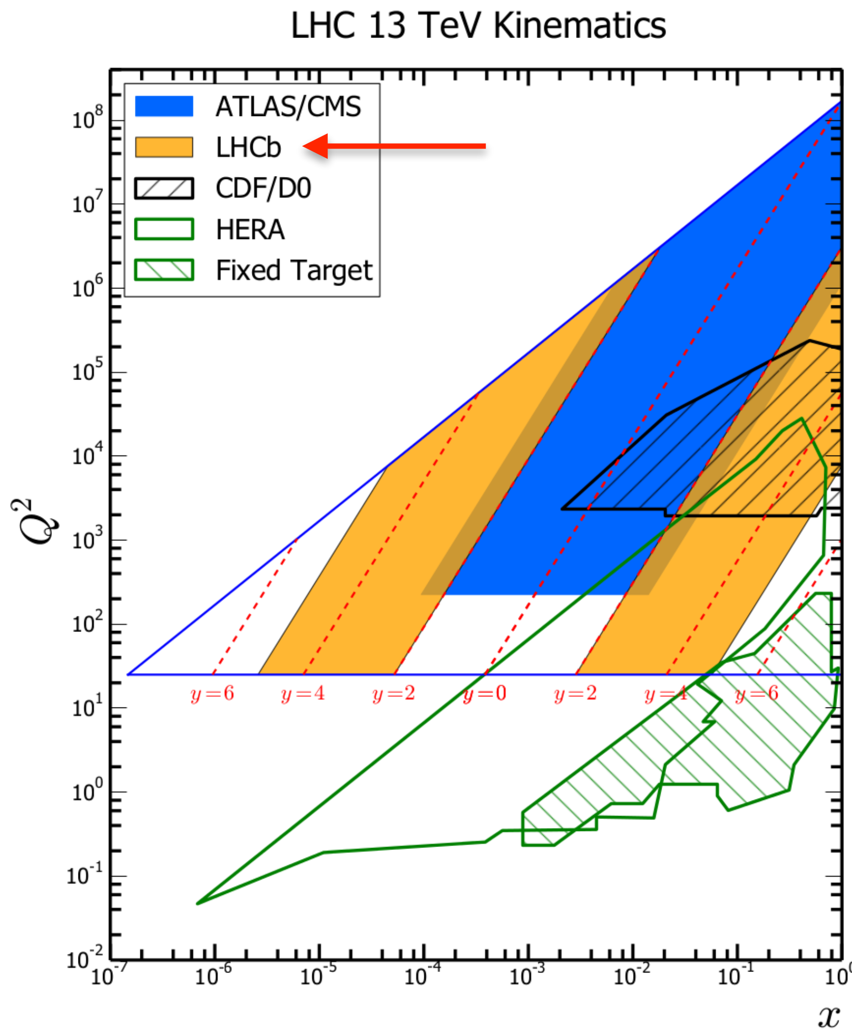


Z→τ+τ− production with LHCb

- **LHCb** provides a complementary phase-space region (wrt ATLAS and CMS) for EW measurements
  - **High** and/or **low** Bjorken-**x** values are probed

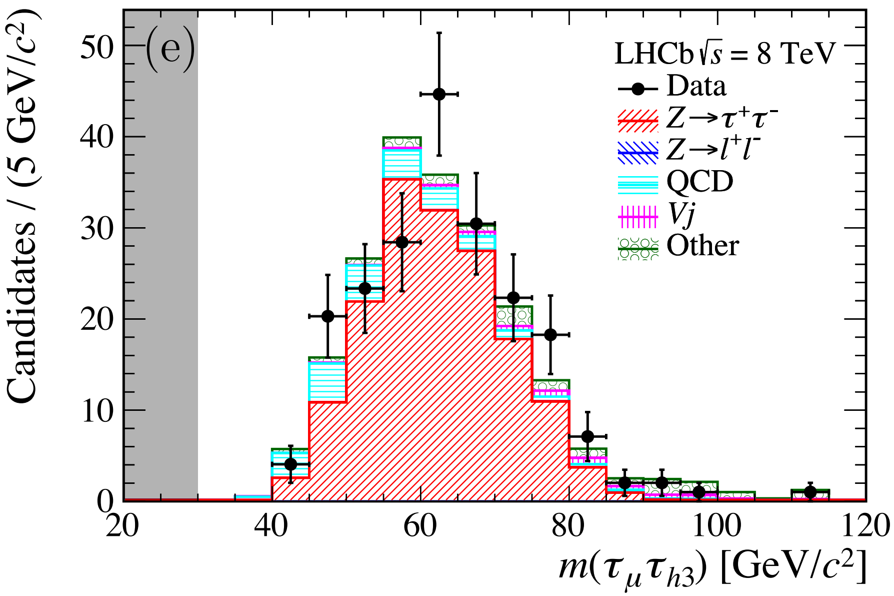


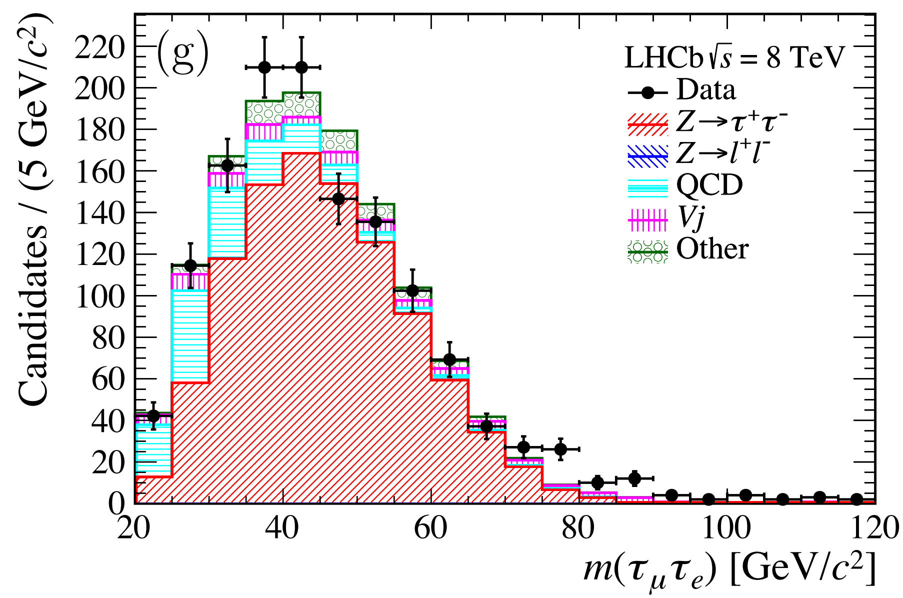




$Z\rightarrow\tau^+\tau^-$ production with LHCb

- Measurement of **Z-boson** production cross-section in **di-tau** final state @ 8 TeV
- Taus reconstructed in leptonic (muon or e) or hadronic (one or three hadrons) final states
  - Seven channels in total: $\tau_e\tau_e$, $\tau_\mu\tau_\mu$, $\tau_\mu\tau_{h1}$, $\tau_e\tau_{h1}$, $\tau_\mu\tau_{h3}$, $\tau_e\tau_{h3}$, $\tau_\mu\tau_e$

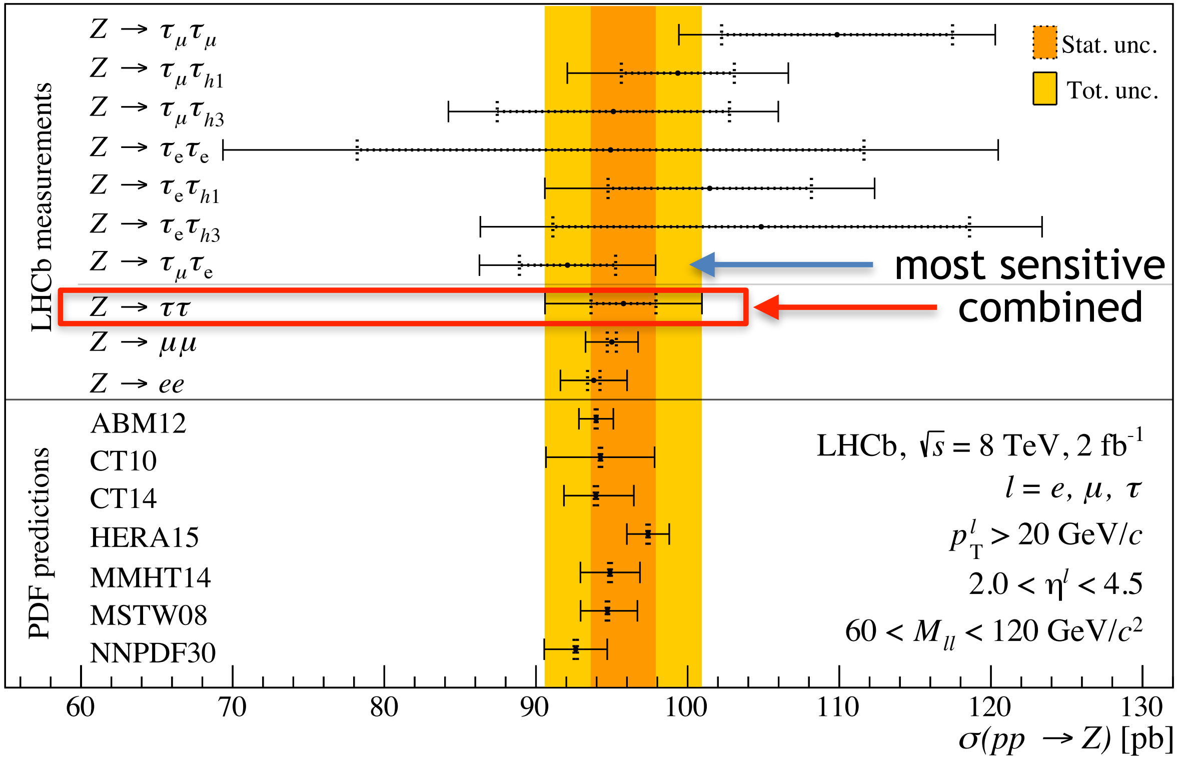




- Main background (multijet, W/Z) → data-driven techniques

Z→τ+τ− production with LHCb

- Measurements compatible with NNLO pQCD predictions (and different PDF sets)



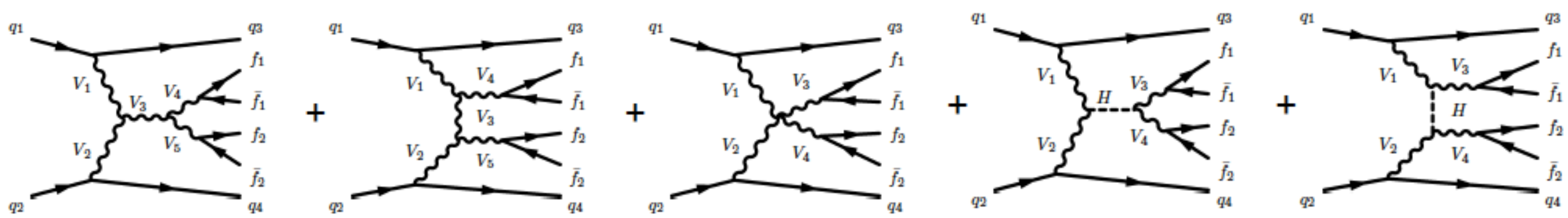
- Test of lepton flavour universality in Z decays:

$$\frac{\sigma^{8\,\text{TeV}}_{pp\to Z\to\tau^+\tau^-}}{\sigma^{8\,\text{TeV}}_{pp\to Z\to\mu^+\mu^-}} = 1.01 \pm 0.05 \quad , \quad \frac{\sigma^{8\,\text{TeV}}_{pp\to Z\to\tau^+\tau^-}}{\sigma^{8\,\text{TeV}}_{pp\to Z\to e^+e^-}} = 1.02 \pm 0.06$$

Diboson production

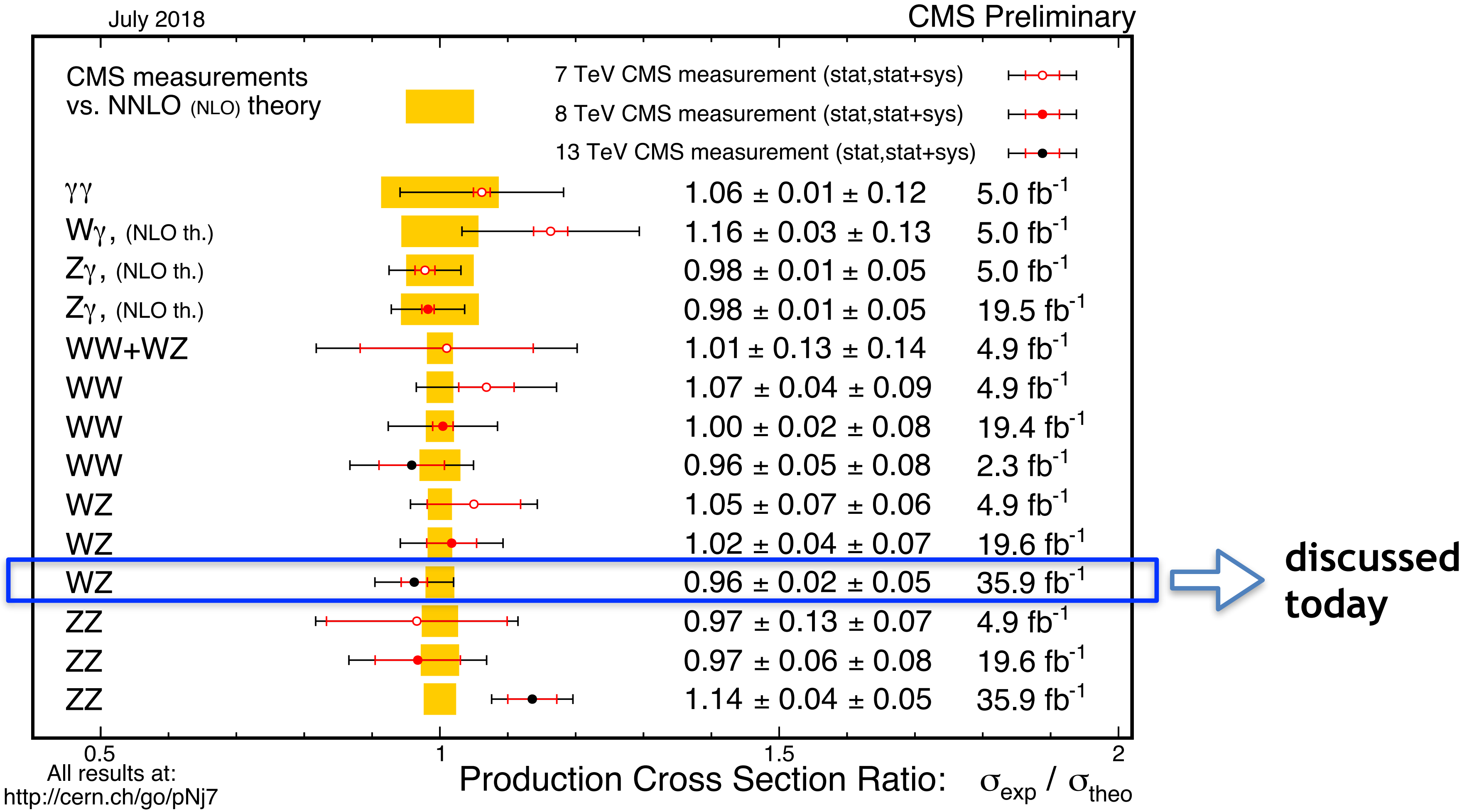
- Good way to test gauge structure of SM
- Look for signs of new physics (anomalous couplings)
- With more data at the LHC: precision test of NNLO pQCD

- Two types of measurements
  - **Inclusive → larger cross-sections**, less sensitive to 'pure' EW diagrams
  - **Vector boson scattering (VBS)** → smaller cross-sections, **more sensitive** to **QGC**, **EWSB**, …



Example diagrams for EW (VBS) VV production

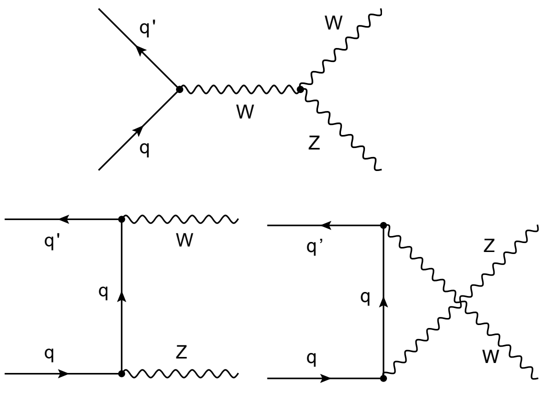
Diboson production

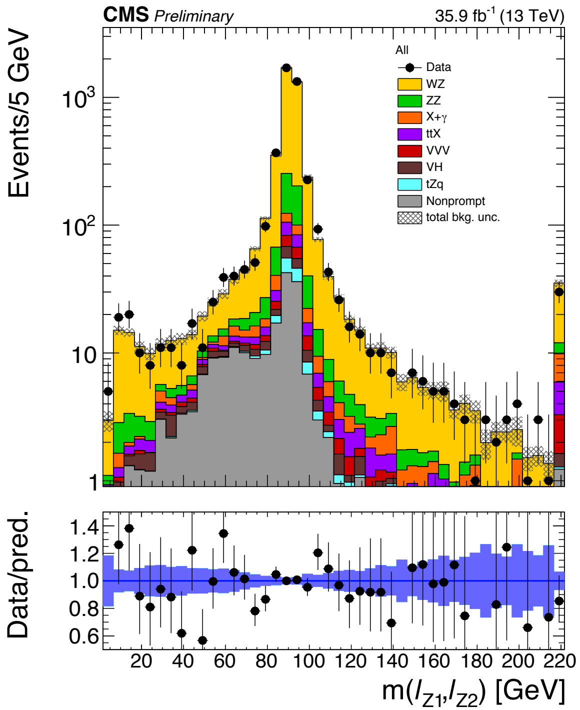


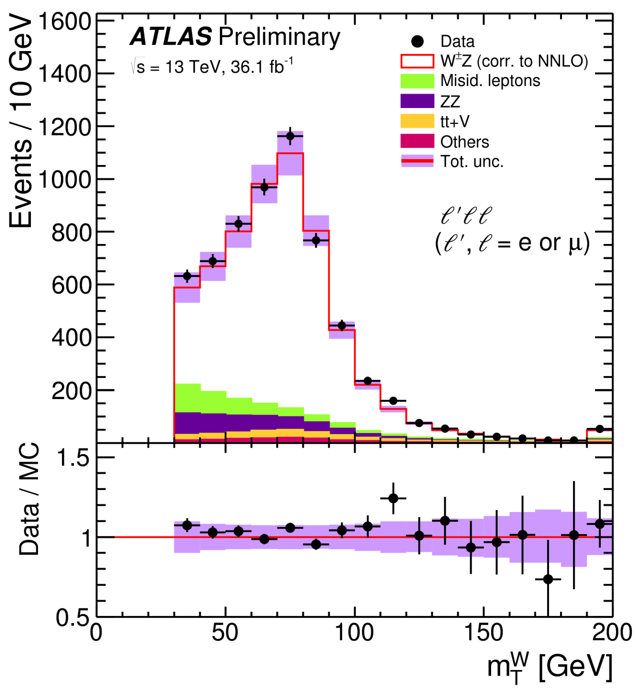
- Recent inclusive diboson measurements at the LHC can reach ~**5% precision**

Inclusive WZ production @ 13 TeV

- **WZ inclusive** + **differential** cross section measurements from both ATLAS & CMS
- **WZ → 3lν (3e, 3μ, eeμ, eμμ)**
  - Clean channel due to leptons
  - Z-boson is on-shell
  - 3rd lepton+E_T^{miss} consistent with W

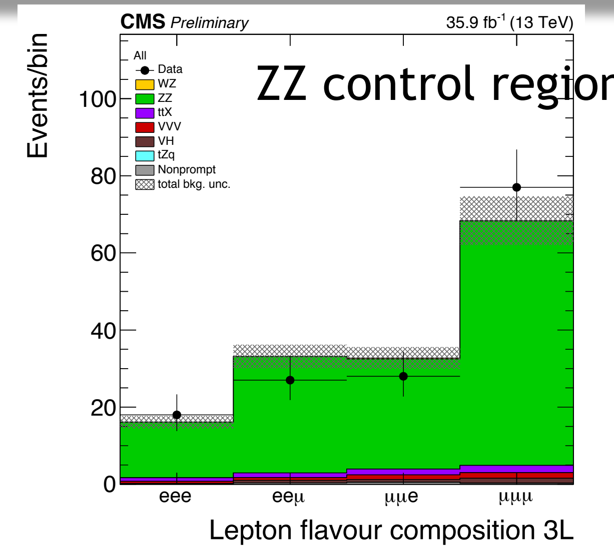






Inclusive WZ production @ 13 TeV

- Irreducible background:
  - ZZ, VVV, ttV, tZ with ≥3 prompt leptons
  - Estimated from MC
- Reducible background:
  - At least one fake/non-prompt lepton
  - Z+jets, Z+γ, W+γ, tt, WW
  - From data-driven methods
- Main systematic uncertainties:
  - Data-driven background
  - Luminosity



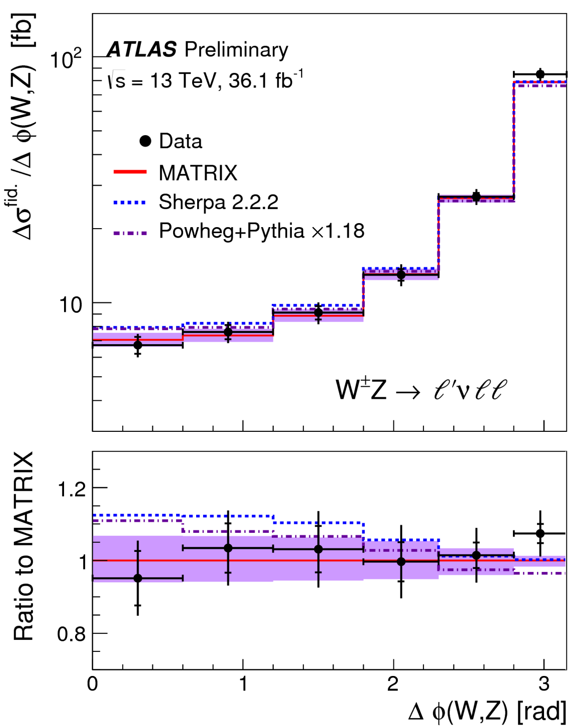
from ATLAS analysis

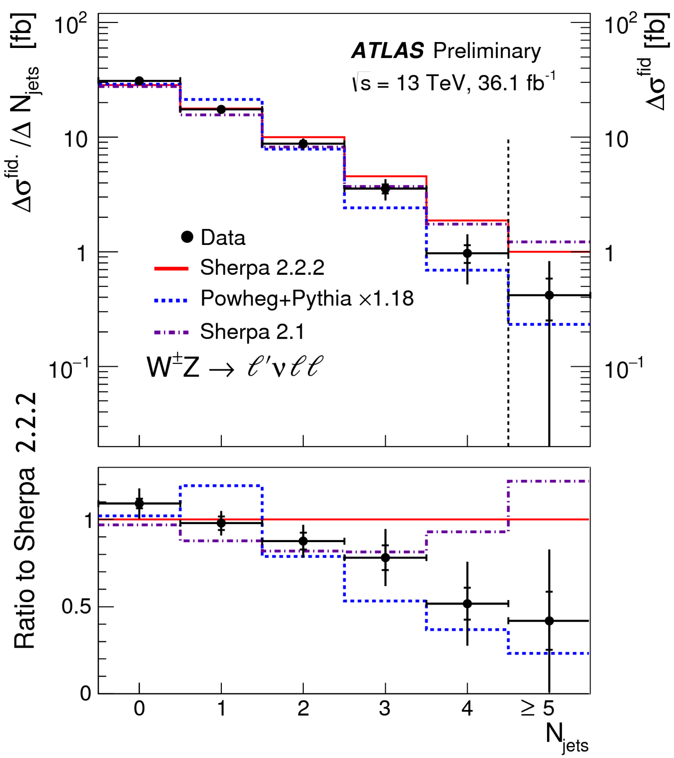
	eee	μee	$e\mu\mu$	$\mu\mu\mu$	combined
Relative uncertainties [%]					
e energy scale	0.2	0.1	0.1	< 0.1	0.1
e id. efficiency	2.8	1.8	1.0	< 0.1	1.1
μ momentum scale	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
μ id. efficiency	< 0.1	1.3	1.6	2.8	1.5
E_T^{miss} and jets	0.2	0.2	0.3	0.5	0.3
Trigger	< 0.1	< 0.1	0.2	0.3	0.2
Pileup	1.0	1.5	1.2	1.5	1.3
Misid. leptons background	4.7	1.1	4.5	1.6	1.9
ZZ background	1.0	1.0	1.1	1.0	1.0
Other backgrounds	1.6	1.5	1.4	1.2	1.4
Uncorrelated	0.7	0.6	0.7	0.5	0.3
Total systematics	6.0	3.5	5.4	4.1	3.6
Luminosity	2.4	2.4	2.4	2.4	2.4
Modelling	0.5	0.5	0.5	0.5	0.5
Statistics	3.6	3.3	3.2	2.7	1.6
Total	7.4	5.4	6.7	5.4	4.6

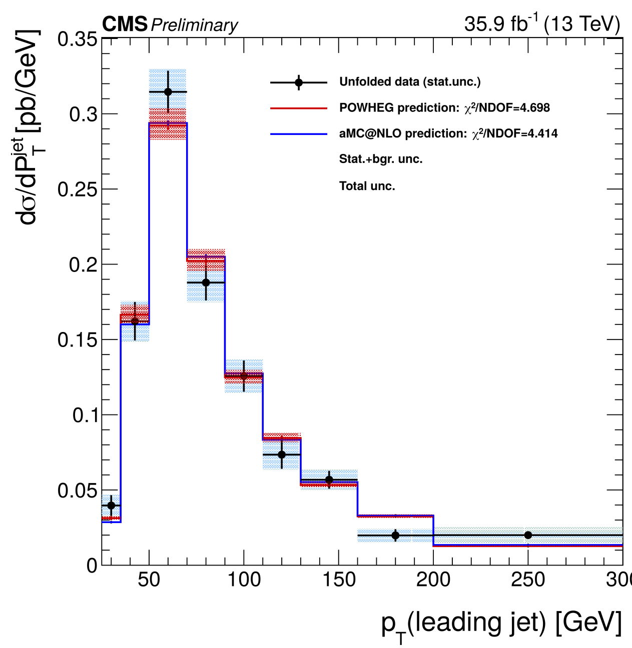
Inclusive WZ production @ 13 TeV

- **Cross section results**
  - **NNLO** calculations (in general) improve data/MC agreement
  - **NLO + parton shower** reasonably describe (extra) jet kinematics

$$\sigma^{\text{fid.}}_{W^\pm Z\to \ell'\nu\ell\ell} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L}\cdot C_{WZ}} \times \left(1 - \frac{N_\tau}{N_{\text{all}}}\right)$$

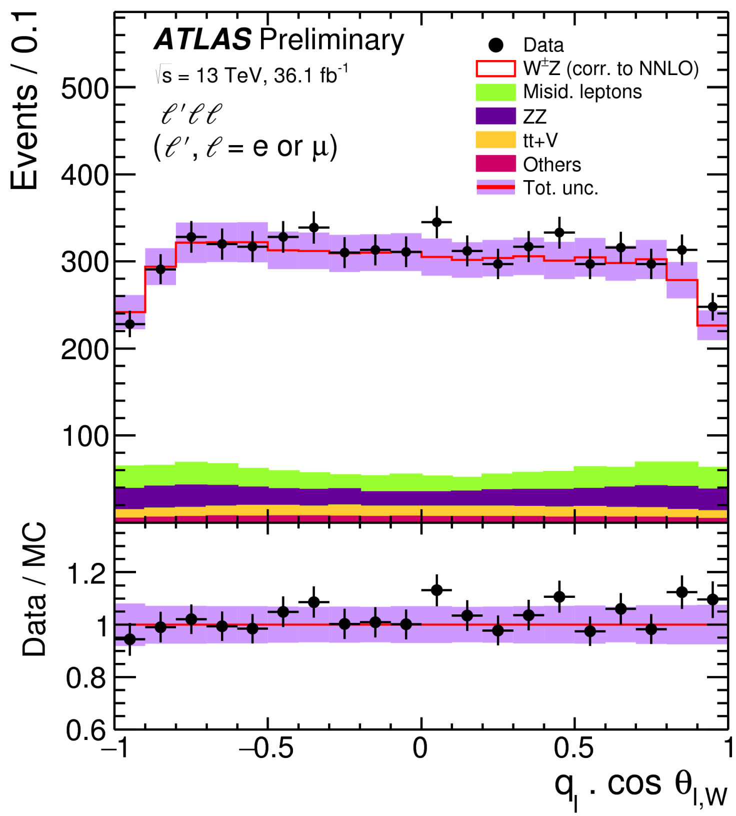




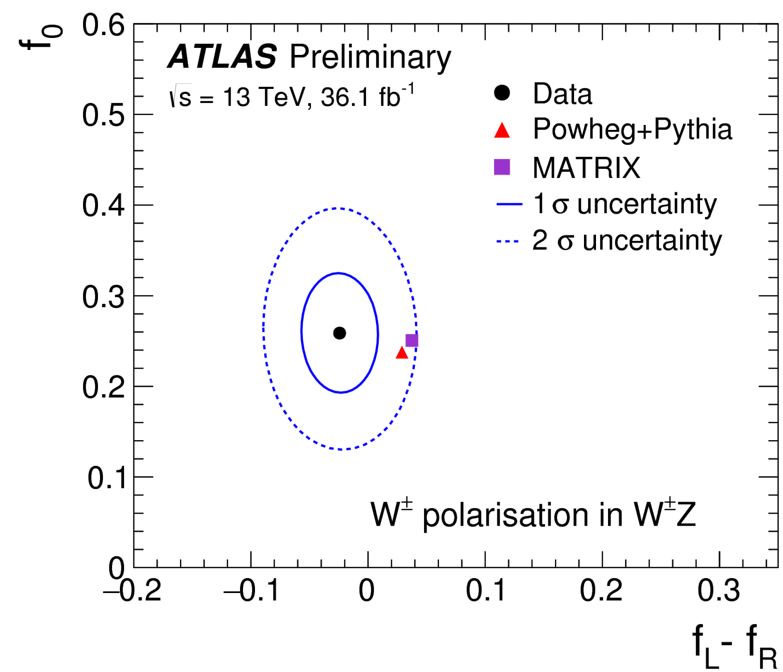


Inclusive WZ production @ 13 TeV

- **W(Z) polarisation** extracted by ATLAS
  - Helicity fractions **f_0** (longitudinal polarisation) and **f_L/f_R** (transverse)
  - Extraction via template fits to **lepton decay angle in W(Z) rest-frame**
  - Evidence for longitudinally polarised **Ws** at **4.2σ** (3.8σ expected)

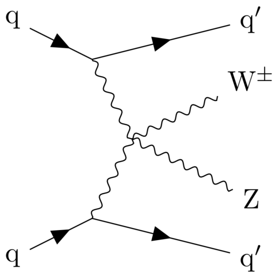


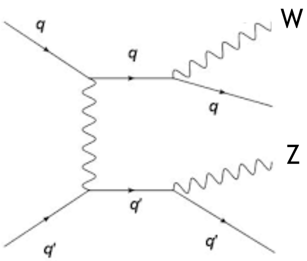
$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8}f_L(1\mp\cos\theta_{\ell,W})^2 + \frac{3}{8}f_R(1\pm\cos\theta_{\ell,W})^2 + \frac{3}{4}f_0\sin^2\theta_{\ell,W}$$

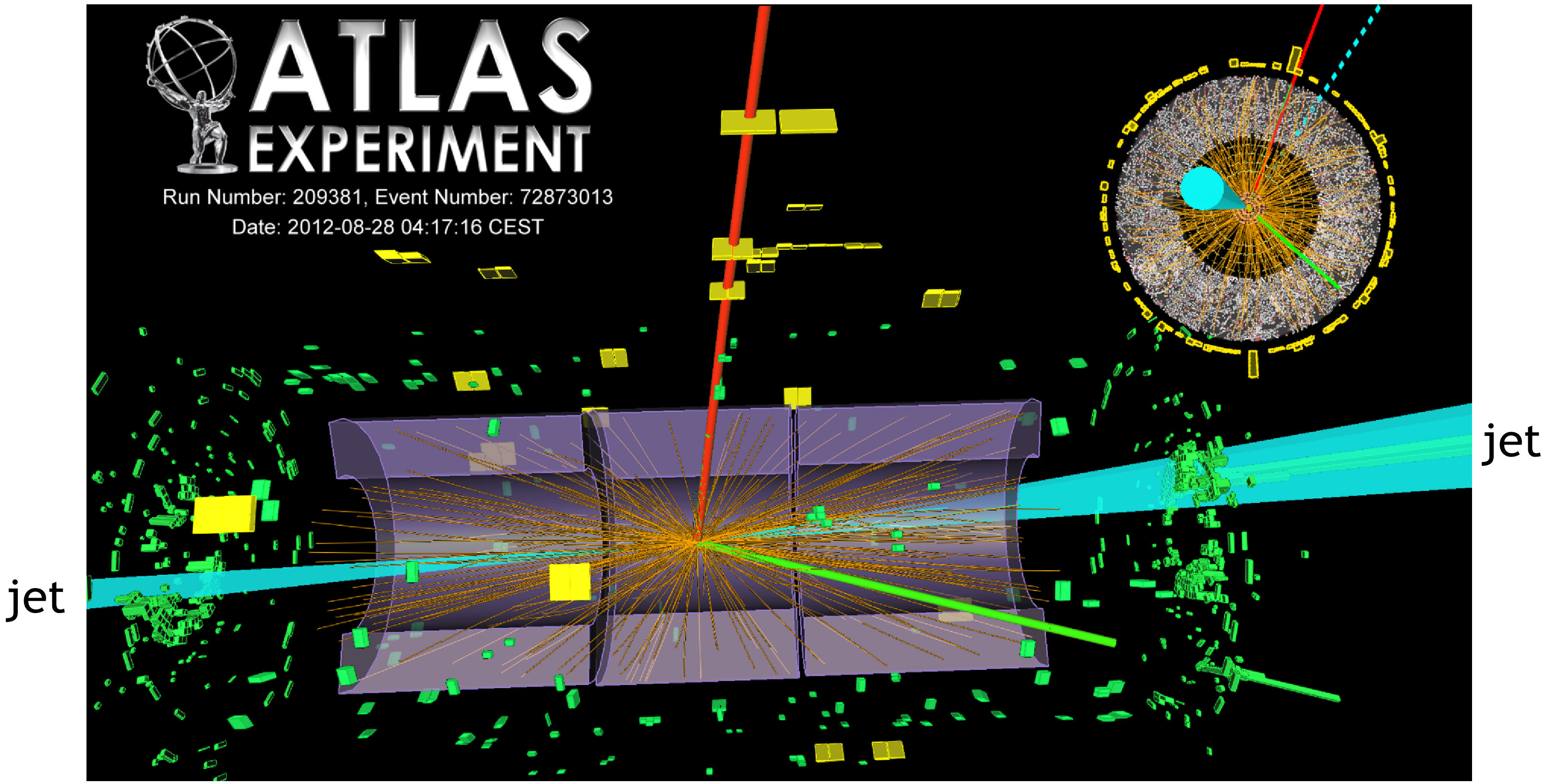


Electroweak WZ production @ 13 TeV

- Search by both ATLAS & CMS
- Relatively clean signature:
  - 3 leptons + E_T^{miss}
  - VBS **dijet** production topology (large $\mathbf{m_{jj}}$ + large jet **rapidity separation**)

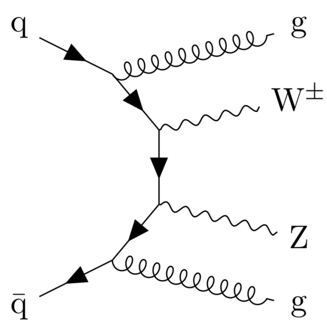


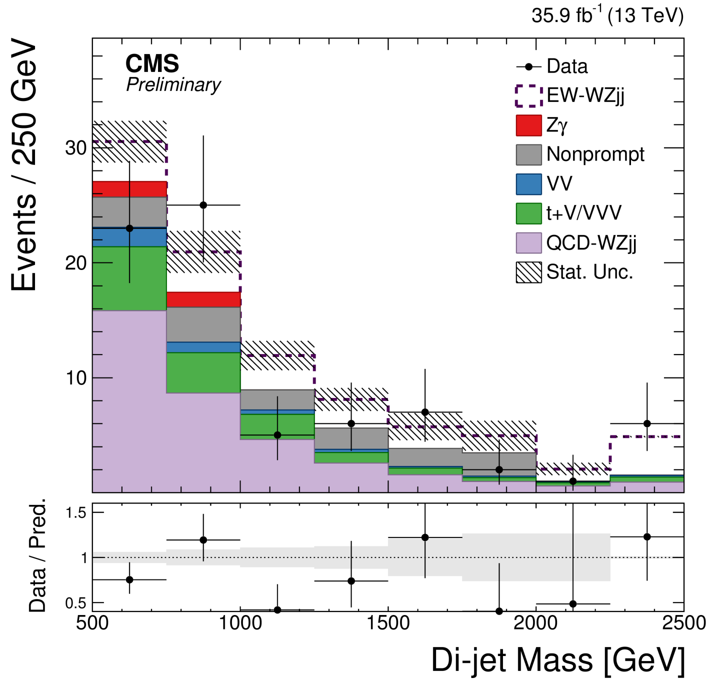


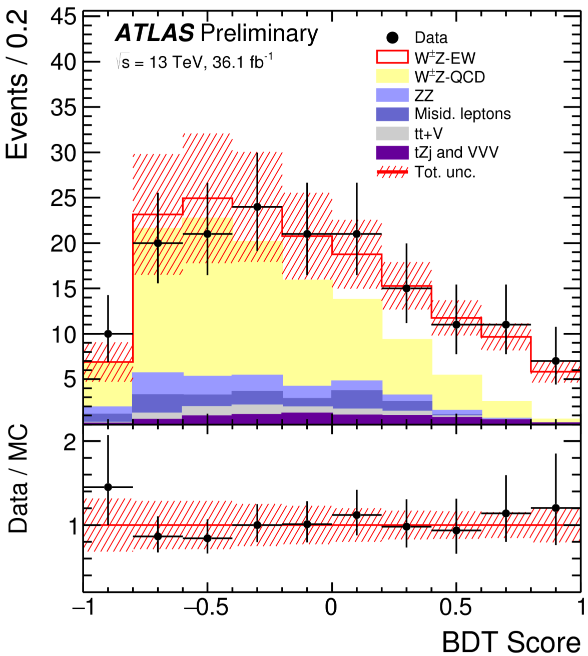


Electroweak WZ production @ 13 TeV

- Dominant background (dedicated control regions are used)
  - QCD WZjj
  - Misidentified leptons
- Signal extraction
  - Simultaneous fit of background event yields including various control regions
  - ATLAS: extra cut on BDT discriminant







Post-fit background normalisations

$\mu_{WZ\text{-}QCD}$ = 0.60 ± 0.25

μ_{ttV} = 1.18 ± 0.19

μ_{ZZ} = 1.34 ± 0.29

Electroweak WZ production @ 13 TeV

- **Observed (expected) signal significance:**
  - **5.6σ** (3.3σ) ATLAS → **first observation**
  - **1.9σ** (2.7σ) CMS

- Measured **cross sections** are also compared to theory predictions

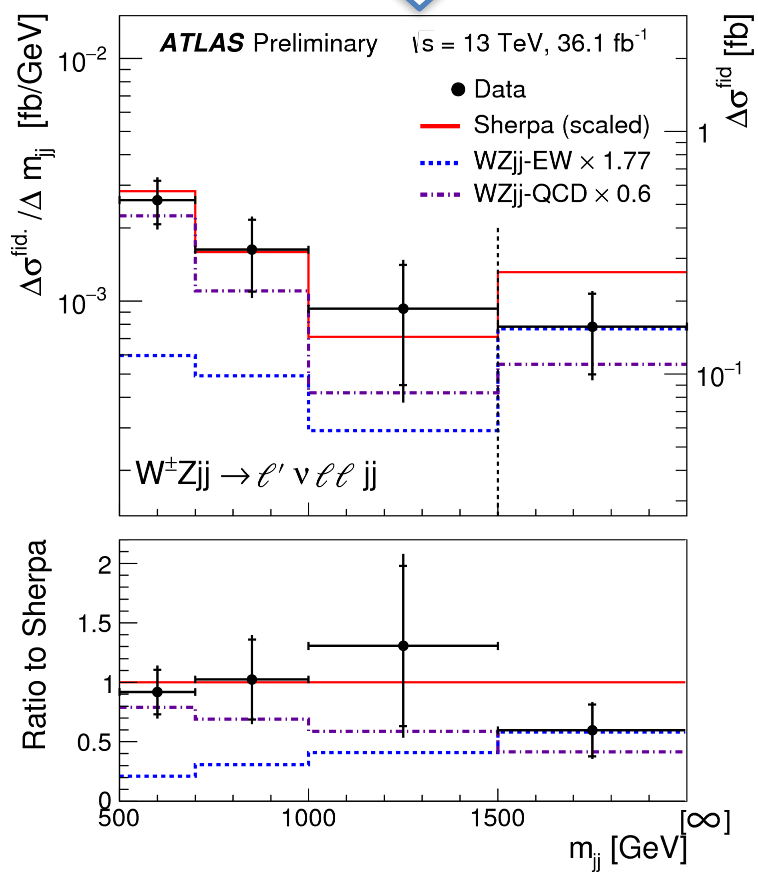
ATLAS

$$\mu_{\mathrm{EW}} = 1.77 \pm 0.41(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})$$

CMS

$$\mu_{EW} = 0.64^{+0.45}_{-0.37}$$

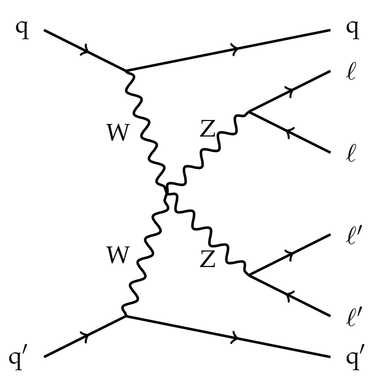
Differential cross sections in SR for WZjj production

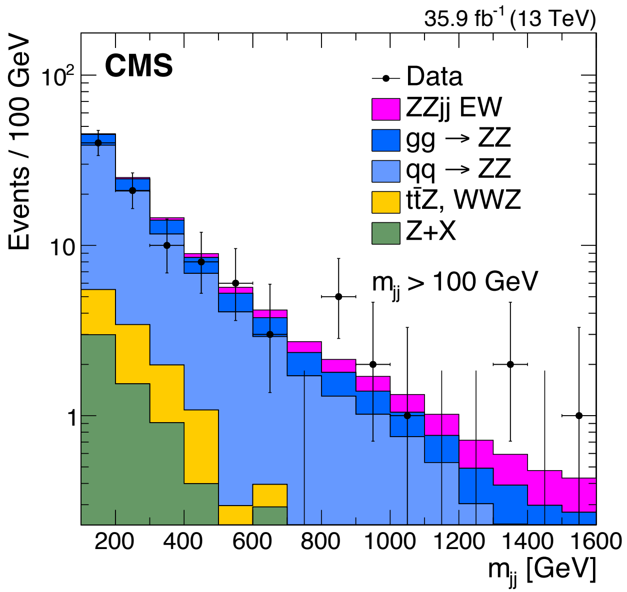


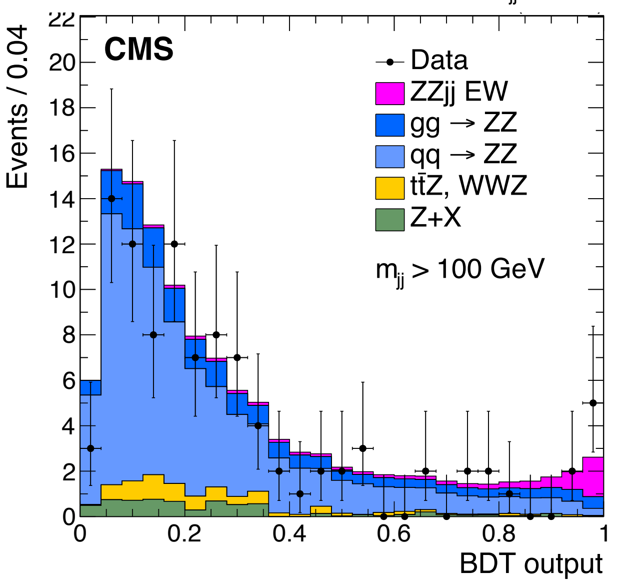
ZZjj electroweak production @ 13 TeV

- **Measurement by CMS**
  - Extremely clean 4 lepton signal
  - BUT: very low production cross-section → Limited statistics
- Use BDT for extra background discrimination
- Observed (expected) significance:
  - **2.7σ** (1.6σ) CMS

$$\mu = \sigma_{obs}/\sigma_{th.} = 1.39 \,^{+0.72}_{-0.57}\,(\text{stat}) \,^{+0.46}_{-0.31}\,(\text{syst.})$$

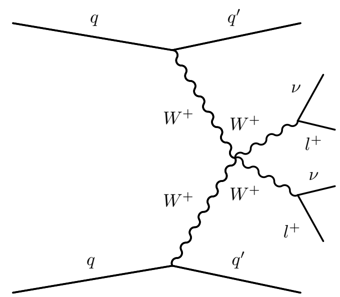


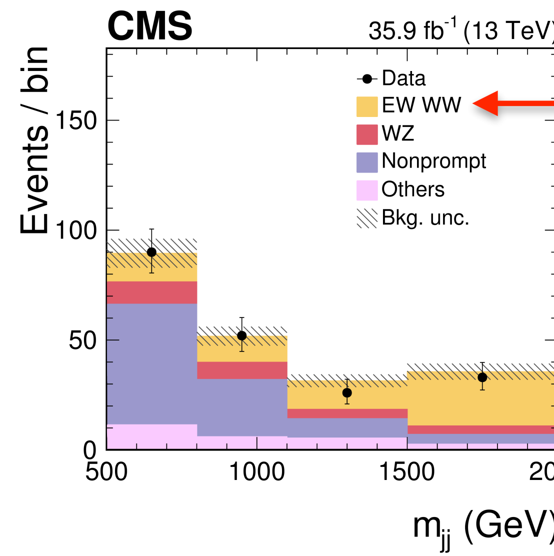




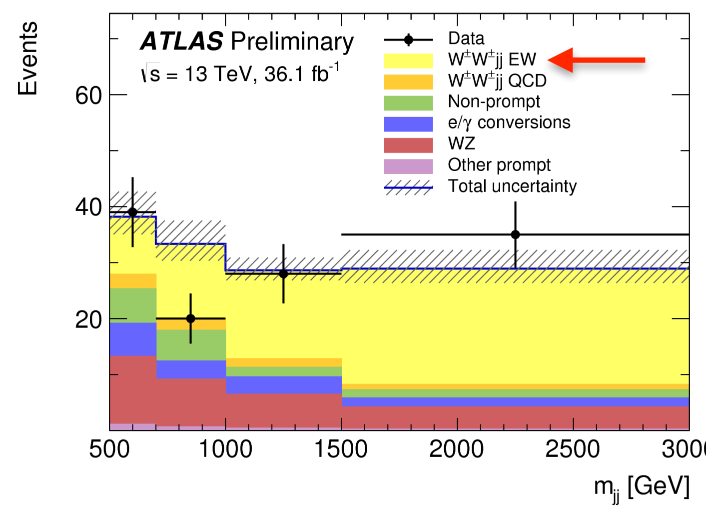
$W^{\pm}W^{\pm}jj$ electroweak production @ 13 TeV

- **Similar analysis strategy/selection** (ATLAS & CMS)
  - **Same-sign leptons:** QCD background suppression
  - Two jets, **m_{jj} > 500 GeV**; $\Delta\eta_{jj}$ > 2.0 (2.5)
- Observed (expected) significance:
  - **5.5σ** (5.7σ) CMS
  - **6.9σ** (4.6σ) ATLAS





- Fiducial cross sections in agreement with theory:
  - **σ_{CMS} = 3.83 ±0.66 (stat) ±0.35 (sys) fb**
  - σ_{LO}^{MG5} = 4.25 ± 0.27
  - **σ_{ATLAS} = 2.95 ±0.49 (stat) ± 0.23 (sys) fb**
  - σ_{LO}^{Powheg} = 3.08 ± 0.45

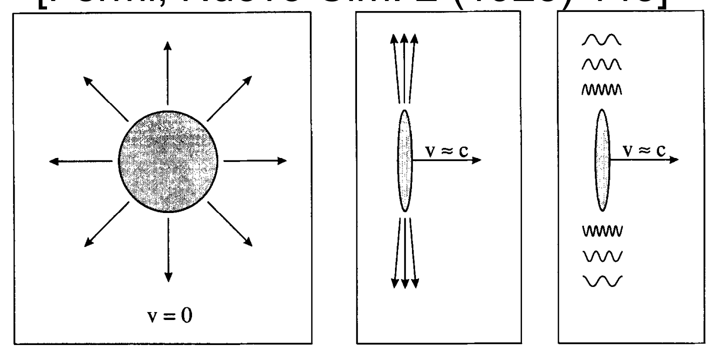


- **Precision VBS EW results expected with full Run-2 datasets**

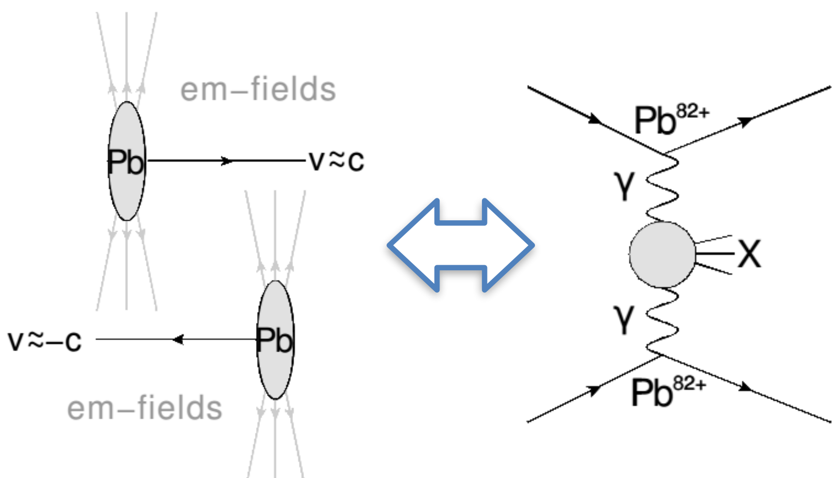
LHC as a photon-photon collider

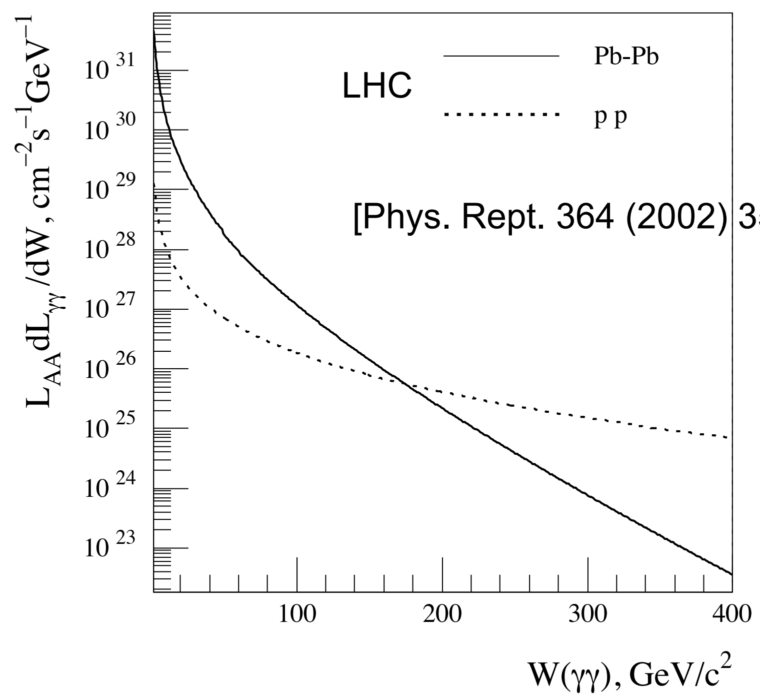
- **Boosted charged-particles** are intense source of photons
- **Quasi-real photon flux**
  - Q ~0.3 GeV (protons @LHC)
    ~0.06 GeV (Pb ions)
  - E_{max} **~2.5 TeV** (protons @LHC)
    ~80 GeV (Pb ions)

[Fermi, Nuovo Cim. 2 (1925) 143]



  - Clean access to high-energy EW interactions

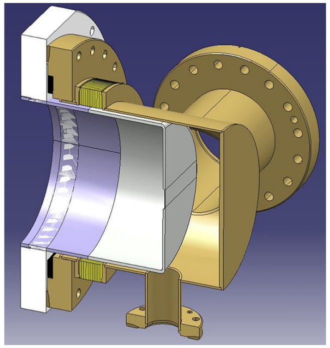


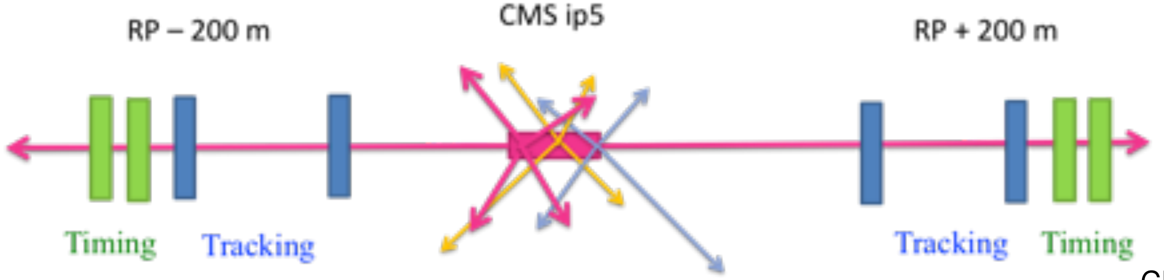


[Phys. Rept. 364 (2002) 359-450]

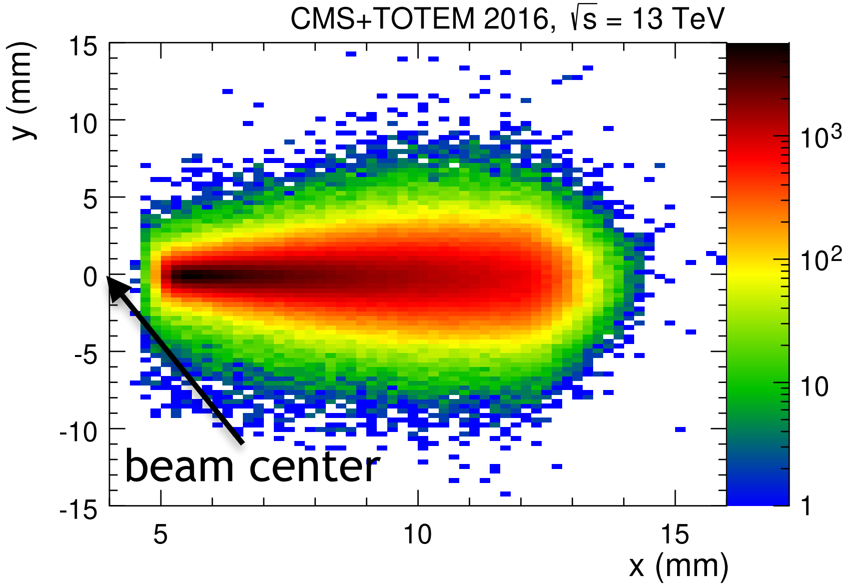
γγ → ll with proton-tagging @ 13 TeV

- **CT-PPS**: near-beam proton spectrometer at IP5 of the LHC **(CMS + TOTEM)**
  - **Tracking** (+**timing)** detectors in Roman Pots (RP), **210-220 m** from IP5
  - Designed to operate at the full LHC luminosity (pile-up!)



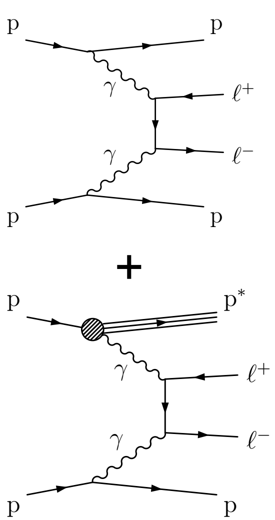


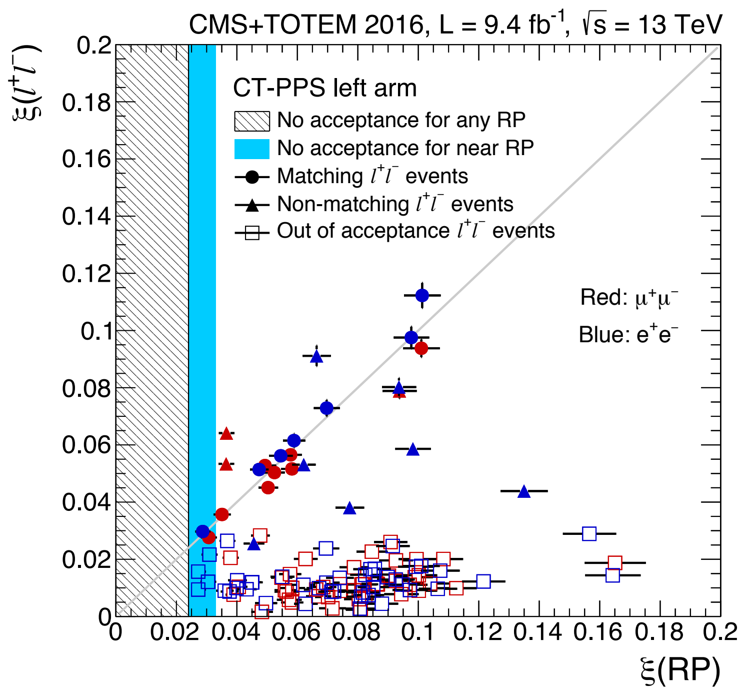
- Reconstruction of proton momentum loss -> **direct access to central-state kinematics**
- Requires good understanding of **LHC optics**

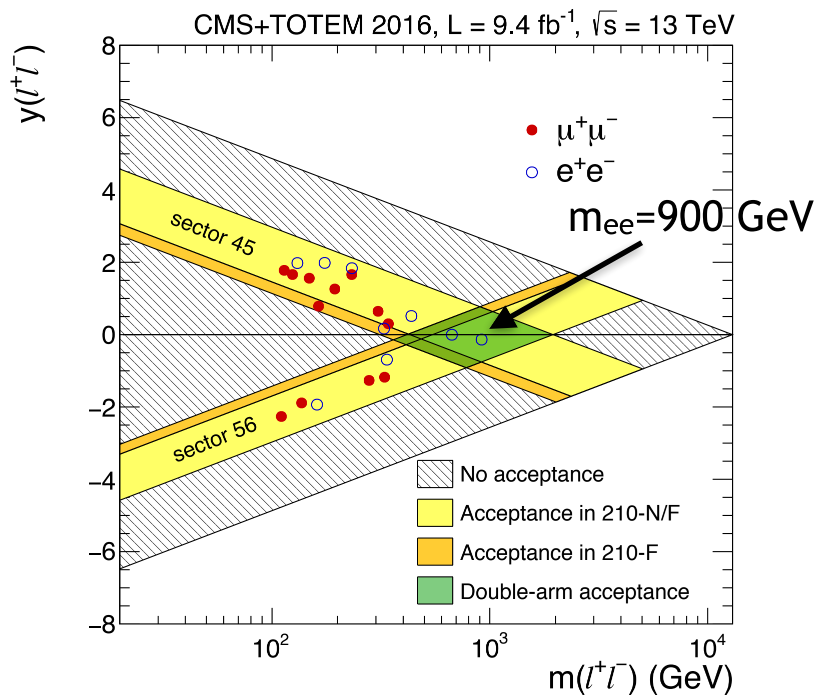


γγ → ll with proton-tagging @ 13 TeV

- Matching central-state kinematics (l+l-) with proton kinematics
  - Significant background reduction (mostly **DY + pile-up**)



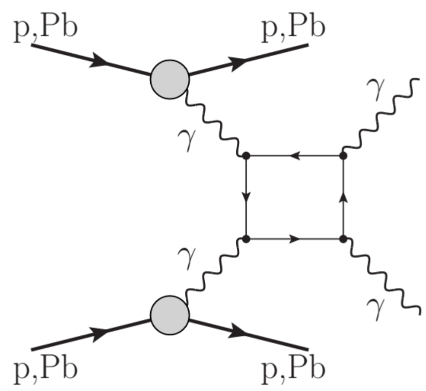




- **20 events** observed with matched kinematics (12 μ+μ- + 8 e+e-)
  - μ+μ- background estimate: 1.49 ± 0.07 (stat) ± 0.53 (sys)
  - e+e- background estimate: 2.36 ± 0.09 (stat) ± 0.47 (sys)
- **Excellent prospects for high-mass/low xs electroweak physics**

Light-by-light scattering at the LHC

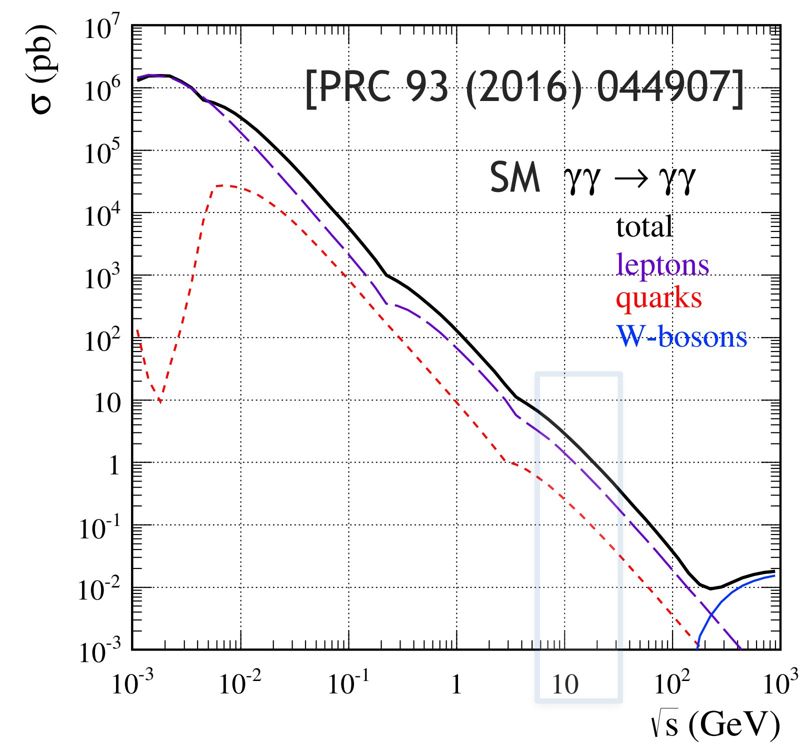
- **HI collisions**: each photon flux scales with $\mathbf{Z^2}$
  - γγ luminosities are extremely enhanced for ion beams ($\mathbf{Z^4 = 5x10^7}$ for Pb+Pb)
  - Excellent environment to test strong-field QED



Previous (related) measurements

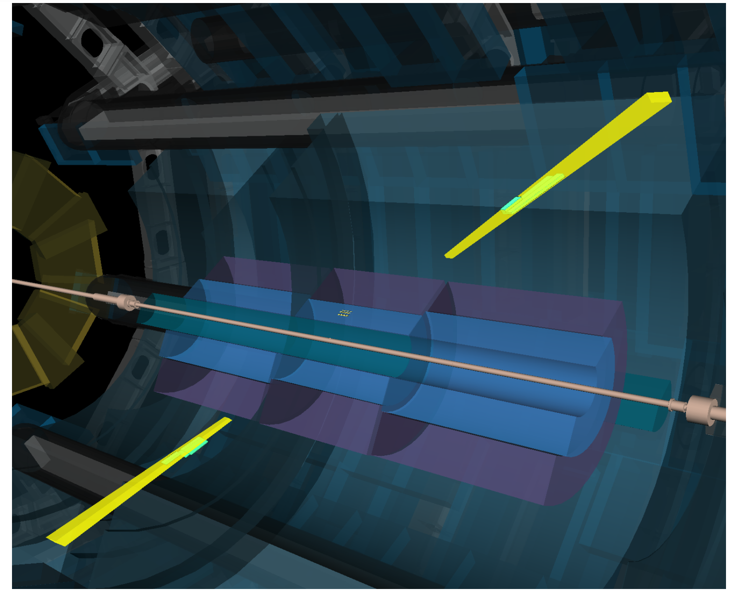
- Indirect test via **electron/muon g-2**
- **Delbruck scattering** and **photon splitting** process at low energies

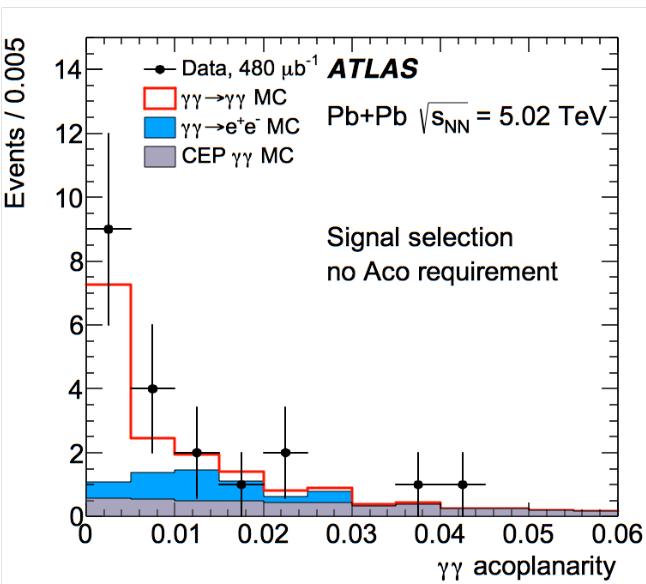
- At high-energy, proposed as a clean channel to study:
  - Anomalous gauge couplings
  - Contributions from BSM particles

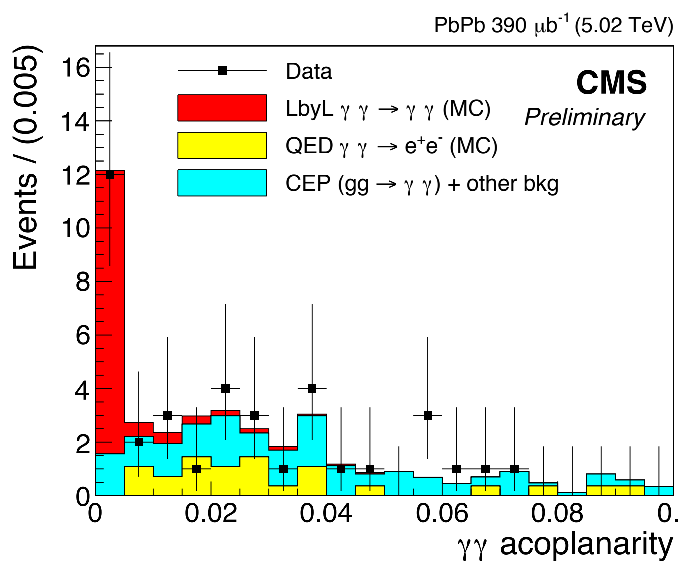


Light-by-light scattering at the LHC

- Event selection
  - Two back-to-back **low-E_T** photons and "**nothing else**" in the detector
- Fiducial cross-sections consistent with SM
- First **high-energy** evidence for **$\gamma\gamma \rightarrow \gamma\gamma$** interaction (formally also **VBS process**)
  - **4.4σ** (3.8σ expected) in ATLAS
  - **4.1σ** (4.4σ expected) in CMS



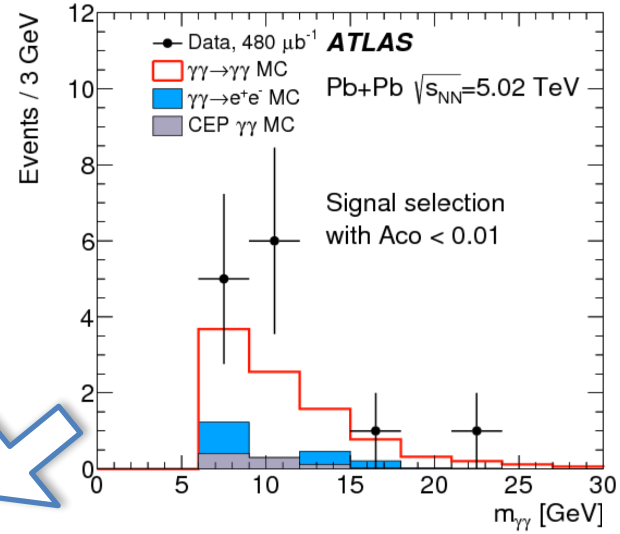




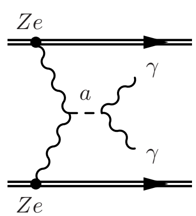
$$\text{Aco} = 1 - \Delta\phi_{\gamma\gamma}/\pi$$

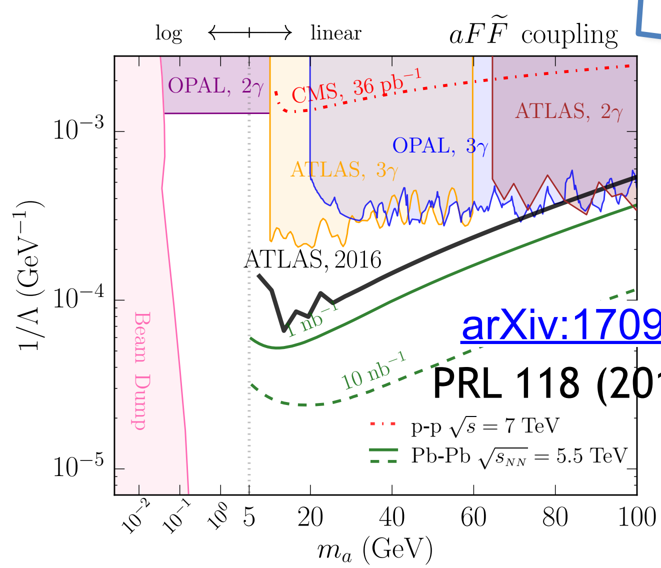
LbyL impact on specific BSM models

- ATLAS measurement already interpreted in terms of limits on specific **BSM models**



Axion-like particles





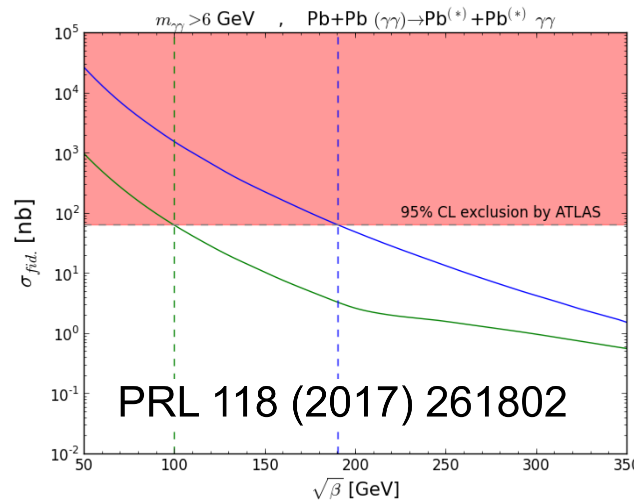
arXiv:1709.07110

PRL 118 (2017) 171801

Born-Infeld extension of QED

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \rightarrow$$

$$\mathcal{L}_{\rm BI} = \beta^2\Big(1 - \sqrt{1 + \frac{1}{2\beta^2}F_{\mu\nu}F^{\mu\nu} - \frac{1}{16\beta^4}(F_{\mu\nu}\tilde{F}^{\mu\nu})^2}\Big)$$



PRL 118 (2017) 261802

Summary & outlook

- This talk presents only some of the (most recent) EW measurements
  - **Single-bosons** → extraction of EW parameters (like $\mathbf{sin^2\theta_{eff}}$)
  - **Multi-bosons** → test of gauge structure of SM (first observation of electroweak **WZ** and **same-sign WW** production);
    → precision for some measurements sufficient to test NNLO pQCD

- **Alternative ideas** become interesting
  - EW interactions with forward protons
  - Heavy-ion UPC as a clean test of QED (LbyL)

- (Very) precise measurements require **time…**
  - Still finishing some of the LHC Run-1 (8 TeV) measurements

- Expecting **new measurements** (with full Run-2 datasets)
  - More statistics, special **low-pileup runs** taken
  - In some cases already restricted by systematic uncertainties
    → understanding of them is crucial

Backup

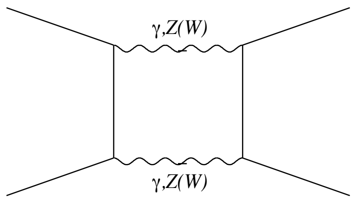
ATLAS weak mixing angle @ 8 TeV

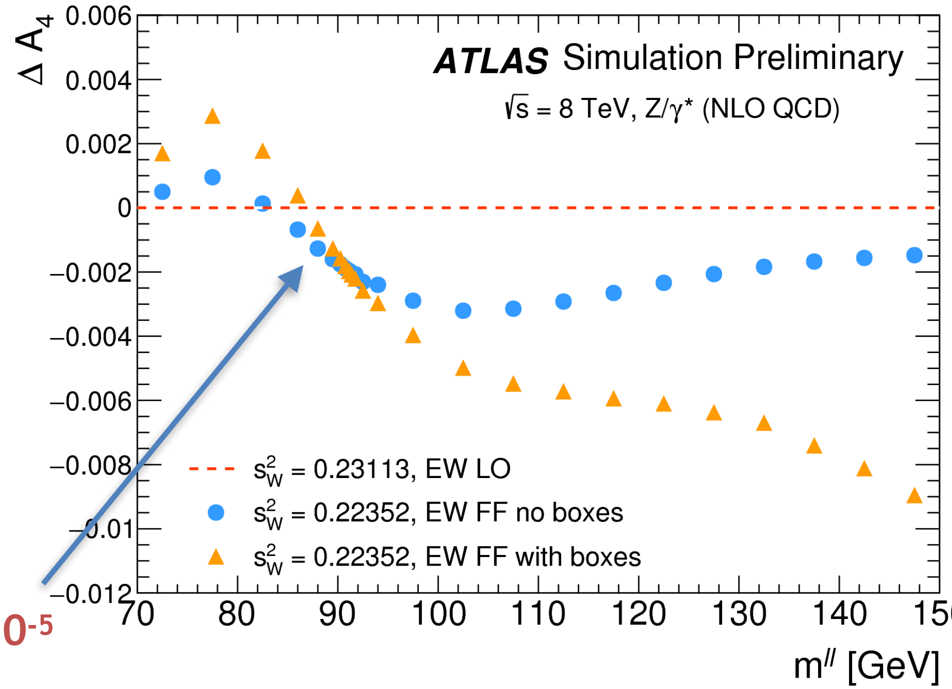
- **EW corrections**
  - Use **EW form factors** (Dizet library) to assess impact of EW corrections
  - Five complex (flavour-dependent) FFs

Ratio effective vector to axial-vector couplings:

$$\frac{v_l}{a_l} = 1 - 4 \cdot |q_f| \cdot \underbrace{K_Z^l \cdot \underbrace{\sin^2\theta_W}_{\text{on-mass shell}}}_{\sin^2\theta^\ell_{\text{eff}}}$$

- Improved Born Approximation
  - Similar methodology as at LEP
  - Per-event weights are defined
- Box diagrams
  - Potentially can break **cross-section factorisation**
  - **Impact is small near Z-pole →**



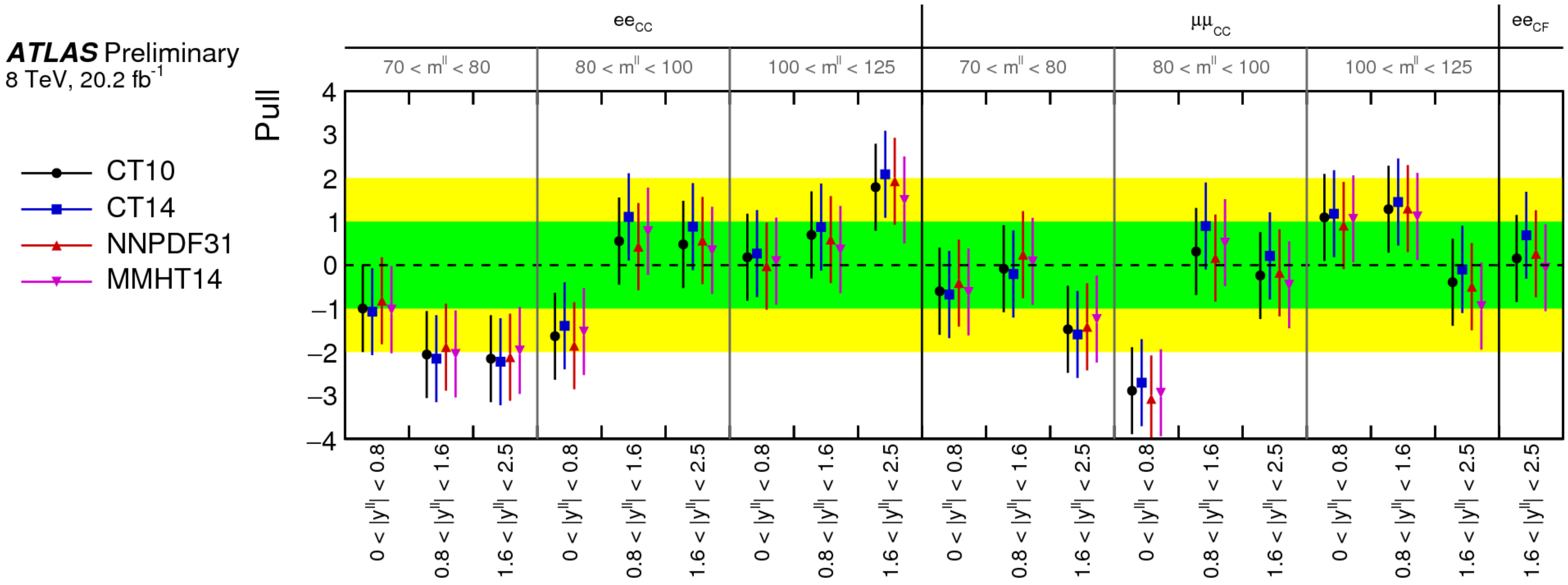


Shift of A_4 by **0.001** → shift of **$\sin^2\theta_{\text{eff}}$** by **$20\text{x}10^{-5}$**

=> **EW corrections are important!**

ATLAS weak mixing angle @ 8 TeV

- **Results**
  - Compatibility of $\sin^2\theta_{eff}$ in **20** measurement channels (9 ee_{CC}+9 $\mu\mu_{CC}$+2 ee_{CF})



Pulls of each measurement wrt most sensitive measurement (ee_{CF} in $2.5<|y_Z|<3.6$)

ATLAS weak mixing angle @ 8 TeV

- Results with other PDF sets

	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^{\ell}_{\rm eff}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

Electroweak WZ production @ 13 TeV

- Fiducial regions

CMS

	Electroweak Signal
$p_T(\ell_{Z,1})$ [GeV]	> 25
$p_T(\ell_{Z,2})$ [GeV]	> 15
$p_T(\ell_W)$ [GeV]	> 20
$\lvert\eta(\mu)\rvert$	< 2.4
$\lvert\eta(e)\rvert$	< 2.5
$\lvert m_Z - m_Z^{PDG}\rvert$ [GeV]	< 15
$m_{3\ell}$ [GeV]	> 100
$m_{\ell\ell}$ [GeV]	> 4
p_T^{miss} [GeV]	> 30
$\lvert\eta(j)\rvert$	< 4.7
$p_T(j)$ [GeV]	> 50
$\lvert\Delta R(j, \ell)\rvert$	> 0.4
n_j	≥ 2
$p_T(b)$ [GeV]	> 30
n_{b-jet}	$= 0$
m_{jj}	> 500
$\lvert\Delta\eta(j_1, j_2)\rvert$	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$	< 2.5

ATLAS

Leptons from Z: pT > 15GeV, |η|<2.5
Lepton from W: pT > 20GeV, |η|<2.5
mT > 30 GeV

Jets:
pT1,2 > 40 GeV
|η| < 4.5
b-jet veto
mjj > 500 GeV + high BDT score

Electroweak WZ production @ 13 TeV

- QCD WZjj control region