Precision W and Z physics at colliders

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W and Z boson production

Drell-Yan Z/γ^* and Drell-Yan-like W-boson production

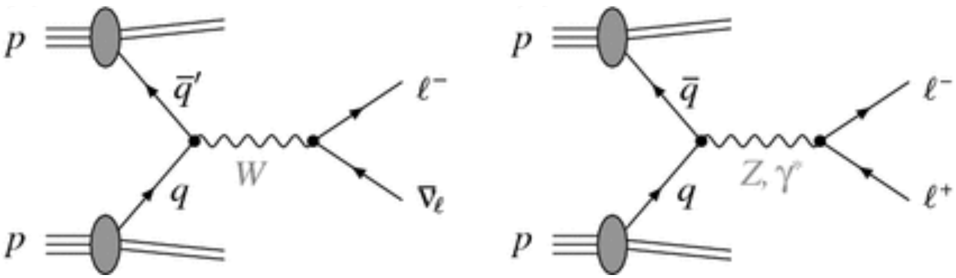


Image credit: doi 10.1007/978-3-319-15001-7_4

- very clean signature
- observables are sensitive both to QCD and EW sectors of the SM
- theoretically understood to NNLO QCD and NLO EW
- access to proton structure

EW production of W and Z bosons

- vector boson fusion and other diagrams
- handle on triple gauge coupling
- sensitivity to new physics

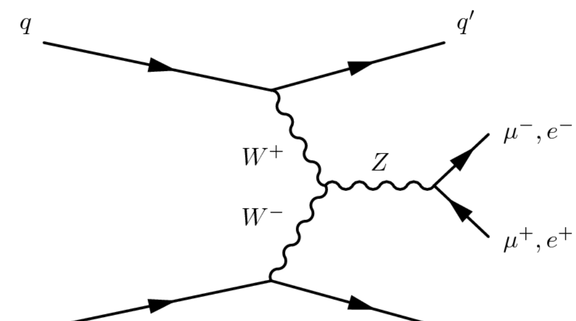


Image credit: ATLAS/CERN

Multiple W and Z boson production

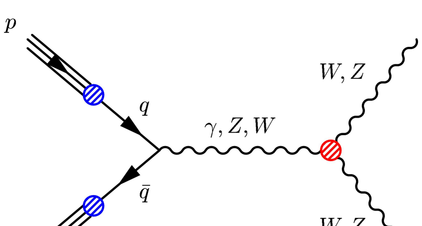


Image: CDF/FNAL

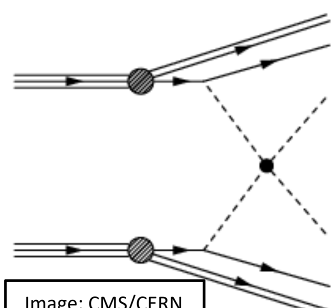
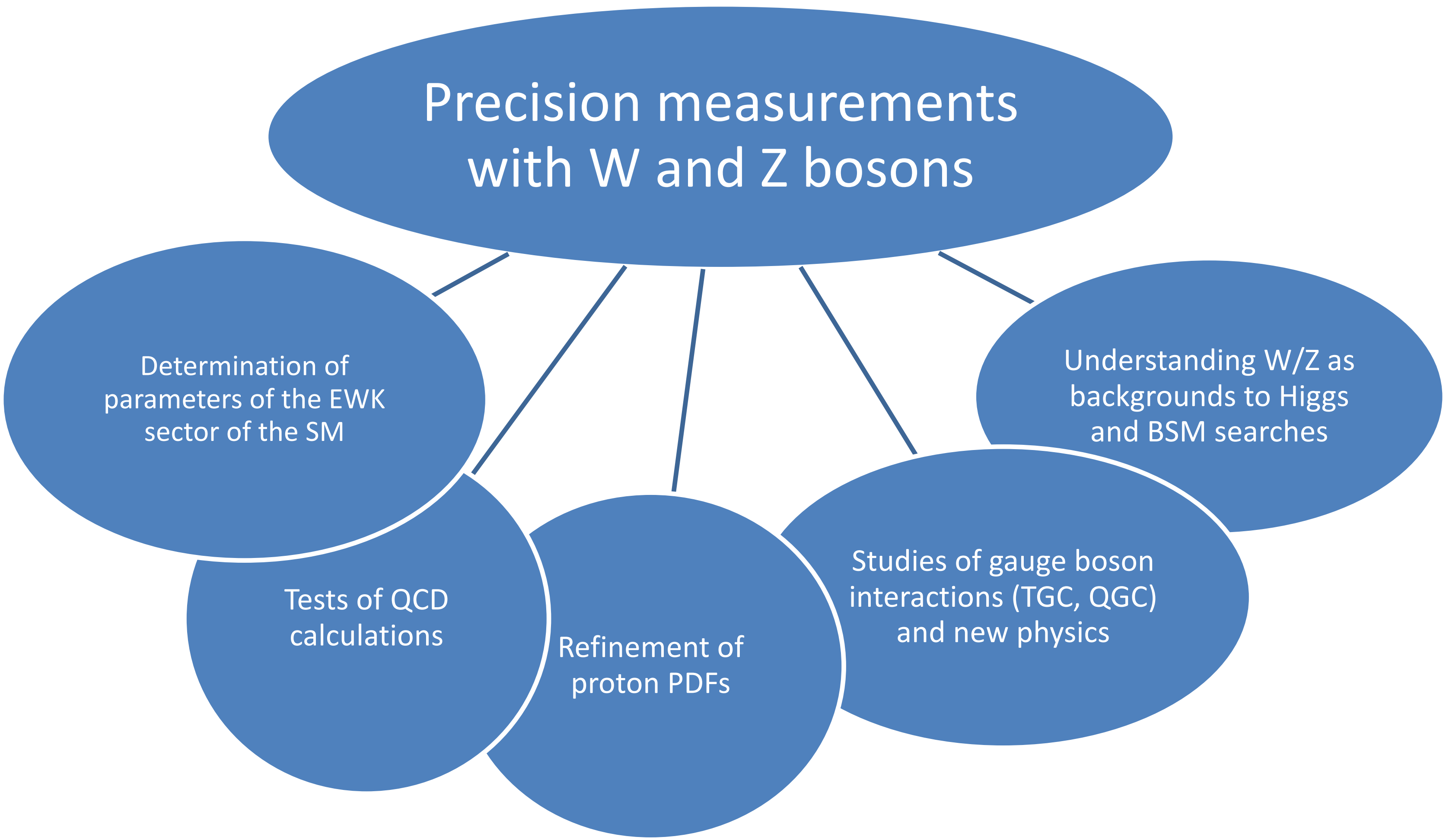


Image: CMS/CERN

- vector boson scattering, VV/VVV production, many diagrams
- handle on triple and quadruple gauge coupling
- sensitivity to new physics

Roles of W and Z measurements



Parameters of the SM: EW sector

Parameters of the SM (about 19 total, but 3 define EW):

- EW sector: U(1), SU(2) couplings and the vacuum expectation value (g, g', v) is a more fundamental choice
- other sets are better for various purposes, e.g. (α_{EM}, G_F, M_Z)
- at tree level, simple relations to EW observables:

$$M_W = \frac{v|g|}{2} \qquad M_Z = \frac{v\sqrt{g^2+g'^2}}{2} \qquad \cos\theta_W = \frac{M_W}{M_Z}$$ and others

Main EW observables at LHC and Tevatron:

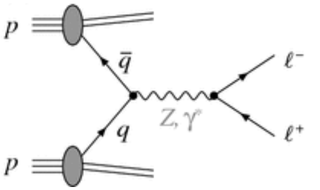
- mass of W boson (not this talk)
- weak mixing angle θ_W
- M_W and θ_W come from precision W and Z measurements
- same 3 EW parameters govern VVV and VVVV interactions, but in EW W/Z production, VBS, multiboson production the accuracy is lower (but can look for new physics)

Fundamental massless bosons W_3 and B mix and yield Z and γ:

$$Z = W_3 \cos\theta_W - B \sin\theta_W$$
$$\gamma = W_3 \sin\theta_W + B \cos\theta_W$$

QCD tests with W and Z

- Z and W productions are an excellent testing ground for high-order QCD calculations
  - DY process (almost) neatly factorizes with strong interaction affecting only the left side



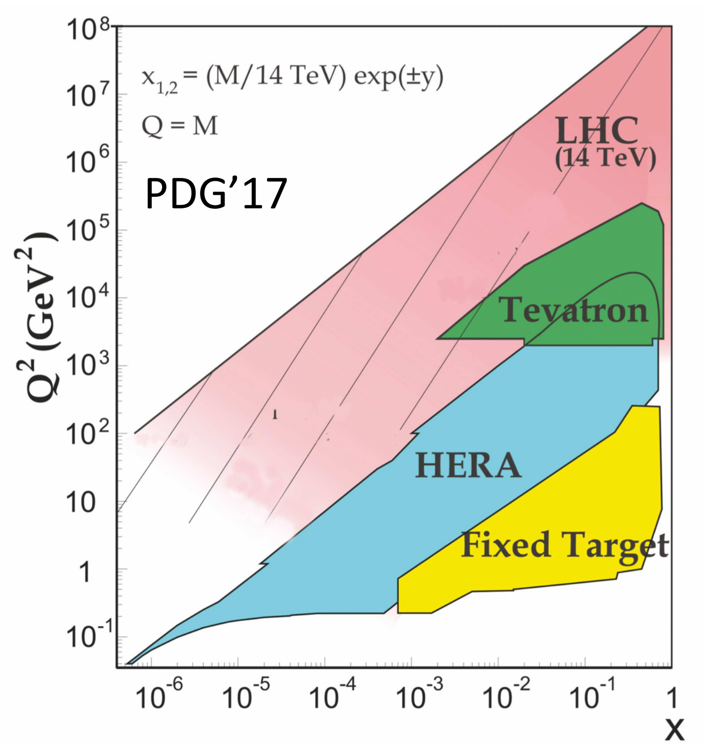
  - LO is easy, W and Z produced at rest
  - production with small p_T requires treatment of soft gluon emissions with resummation techniques, non-perturbative
  - production with higher p_T is handled with perturbative QCD
  - the state of the art is NNLO QCD and NLO EW calculations
    - this yields O(1%) precision, experiment is often at sub-% level
- Measurements are compared to a variety of theory tools: FEWZ & DYNNLO, ResBos, Powheg & Madgraph, Pythia & Herwig, Alpgen & Sherpa, and others

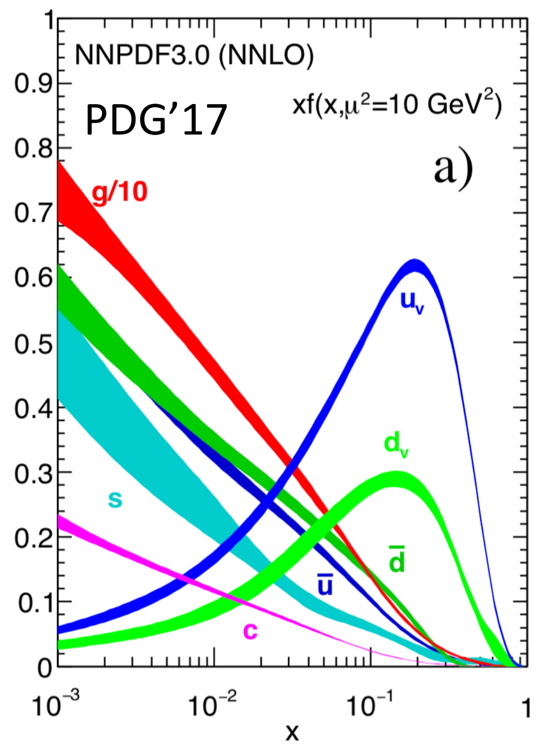
Proton structure

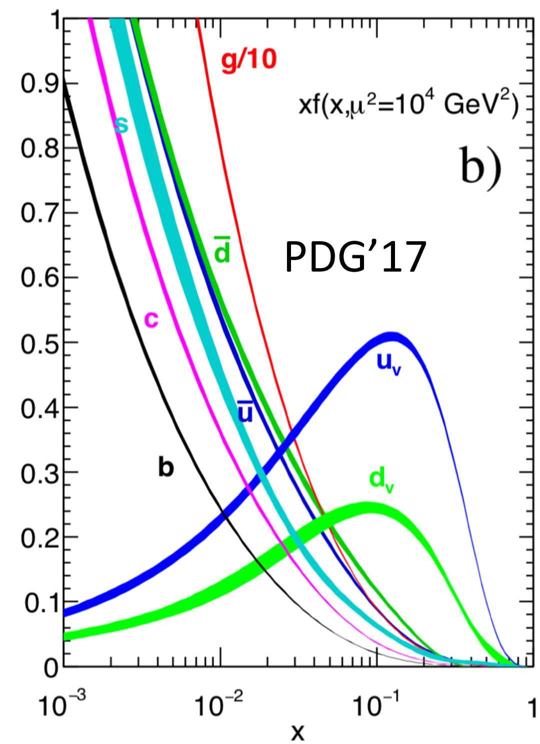
The knowledge of proton structure is of general interest and necessary for theoretical predictions of about anything studied at hadron colliders.

Proton PDFs: $f(x, Q^2)dx$ shows how many partons of given flavor carry fraction of proton's momentum between x and $x + dx$.

LHC data expand this knowledge to new kinematic domains and W/Z measurements are among the main inputs.







W/Z at colliders

Tevatron (CDF, D0):

- results still appear with the full dataset
- this talk: the ultimate weak mixing angle Tevatron result

LHC (ATLAS, CMS, LHCb):

- every year more measurements with 7, 8, 13 TeV
- V production diff. x-sections with respect to anything
- EW precision: W mass and weak mixing angle
- EW V production/VBF, multiboson production and VBS, studies of TGC and QGC
- V production with light and heavy jets

In this talk we review most recent precision measurements

Focus of this talk

Discuss recent Z production results from colliders

- differential and inclusive cross sections
- Drell-Yan angular analysis

Most recent W measurements are very interesting, but less related to the spin of this talk

For discussion of W production and a variety of multiboson results, see parallel talks by *Christian Gutschow, Andrew Pilkington, Gabriella Pasztor, Kenneth Long, and Valentina Cairo* from LHC

Studies of the Drell-Yan process

Full picture of DY process kinematics in QCD requires 5 kinematic variables (Born-level): $\sigma(m_{\ell\ell}, y_{\ell\ell}, p_{T,\ell\ell}, \theta, \varphi)$

- dilepton invariant mass $m_{\ell\ell}$
- dilepton rapidity $y_{\ell\ell}$

Sensitive to proton PDFs

- dilepton transverse momentum $p_{T,\ell\ell}$

Tests of QCD predictions

- lepton decay angles in dilepton rest frame θ and φ

Sensitive to the weak mixing angle θ_W

Ultimate experimental result: 5D differential x-section

- approach step by step with more data, better detector understanding, time for technically complex measurements
- inclusive W/Z to single differential to double differential
- new: the first triple differential result from ATLAS

Notable DY x-sections from LHC

Cross section type		7 TeV	8 TeV	13 TeV
Inclusive		ATLAS, CMS, LHCb	ATLAS, CMS, LHCb	ATLAS, CMS, LHCb
Single differential	$m_{\ell\ell}$	ATLAS, CMS	ATLAS, CMS	
	$y_{\ell\ell}$	ATLAS, CMS, LHCb	CMS, LHCb	LHCb
	$p_{T,\ell\ell}\,/\varphi^{*}$	ATLAS, CMS, LHCb	ATLAS, CMS, LHCb	CMS, LHCb
Double differential	$(m_{\ell\ell}, y_{\ell\ell})$	CMS	ATLAS, CMS	
	$(m_{\ell\ell}, p_{T,\ell\ell})$		ATLAS	
	$(p_{T,\ell\ell}, y_{\ell\ell})$		ATALS, CMS	
Triple differential	$(m_{\ell\ell}, y_{\ell\ell}, \theta)$		ATLAS	

more coming soon

New since Blois'17

- higher-D x-sections require more data (and time)
- multi-variable x-sections for 13 TeV are yet to come
- many of these discussed in detail at Blois'17
- not listed: x-sec w.r.t. N jets and jet quantities

Triple differential DY x-section

ATLAS measures DY production w.r.t. 3 kinematic variables

JHEP 12 (2017) 059

$$\frac{d^3\sigma}{dm_{\ell\ell}\, d|y_{\ell\ell}|\, d\cos\theta^*}$$

θ^*: neg. lepton decay angle in Collins-Soper frame (see backup)

- $dm_{\ell\ell}$: improves both θ_W and PDF sensitivities
- $d|y_{\ell\ell}|$: sensitivity to proton PDFs
- $d\cos\theta^*$: sensitivity to θ_W

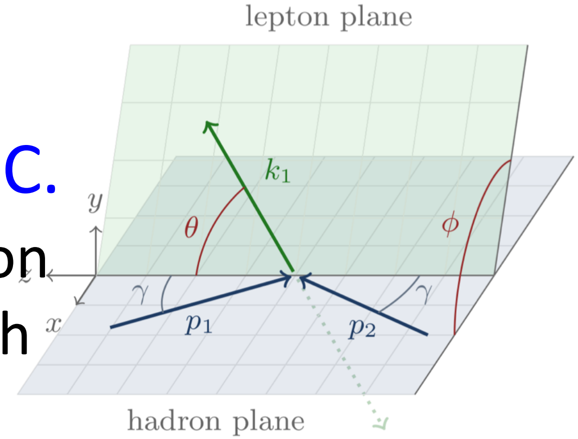


Image credit: hep-ph:1708.00008

Unique measurement, 1st of its kind at LHC.

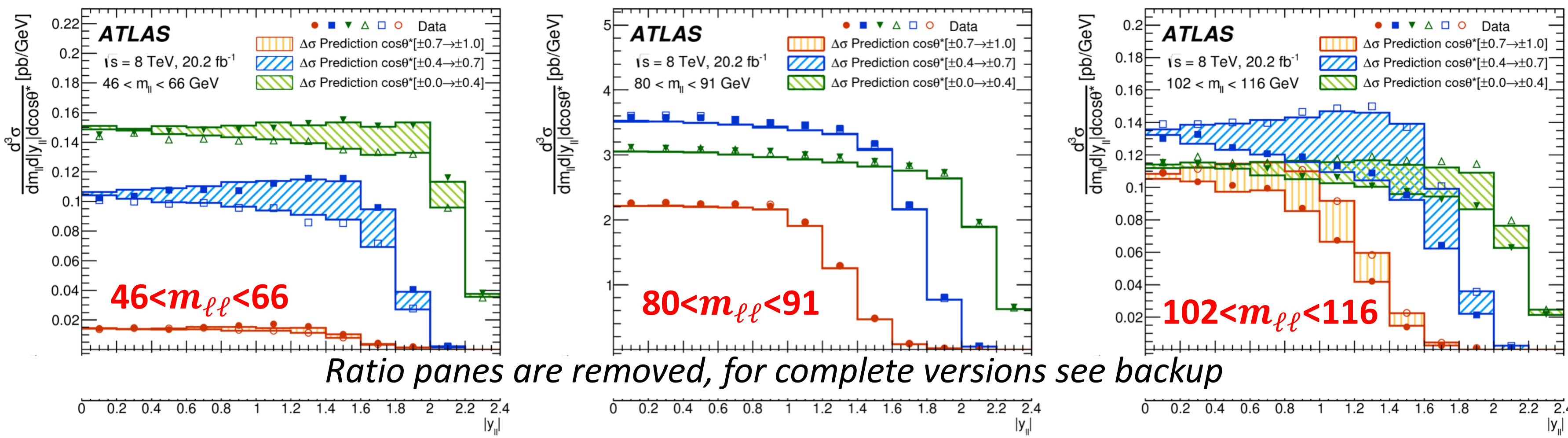
- weak mixing angle measurements at hadron colliders usually systematically limited, with leading systematics from PDFs
- this measurement can be used for simultaneous fit for θ_W and constraining PDFs, leading to reduced systematics on θ_W

3D DY: the primary result

$d^3\sigma$ measured in fiducial region, corrected to Born-level

- phase space defined by lepton p_T, η, and $m_{\ell\ell}$ ranges
- $d^3\sigma$ up to $|y_{\ell\ell}| < 2.4$ with $ee + \mu\mu$ and up to 3.6 with ee

See Chris Gutschow's talk for more!



- 3 of 7 mass ranges shown for $|y_{\ell\ell}| < 2.4$ region
- asymmetry between $\pm\cos\theta^*$ (open/closed markers): reflects parity violation in Z-boson decays
- asymmetry is zero and flips sign at $m_{\ell\ell} \sim M_Z$

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3D DY: derived results

The ATLAS paper also derives integrated results:

- over $y_{\ell\ell}$ and $\cos\theta^*$: $d\sigma/dm_{\ell\ell}$, over $\cos\theta^*$: $d^2\sigma/dm_{\ell\ell}d|y_{\ell\ell}|$
- forward-backward asymmetry in θ^*, which makes most clear the parity violation effects:

$$A_{FB}(m_{\ell\ell},|y_{\ell\ell}|) = \frac{\int d\sigma(\cos\theta^* > 0) - \int d\sigma(\cos\theta^* < 0)}{\int d\sigma(\cos\theta^* > 0) + \int d\sigma(\cos\theta^* < 0)}$$

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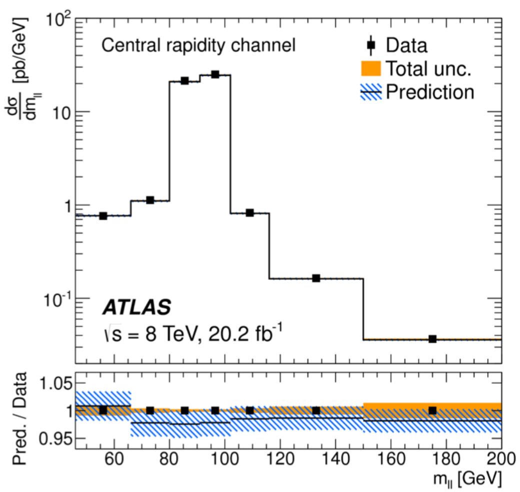
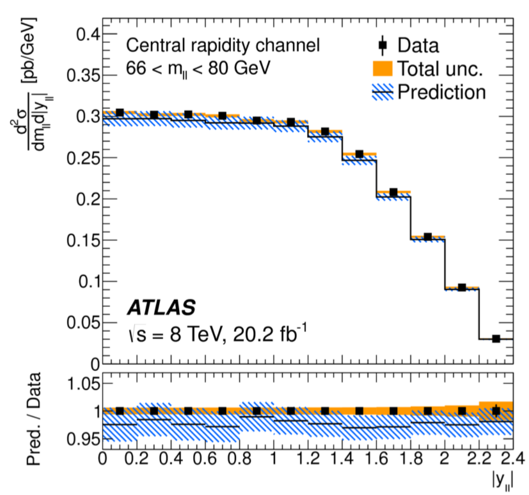
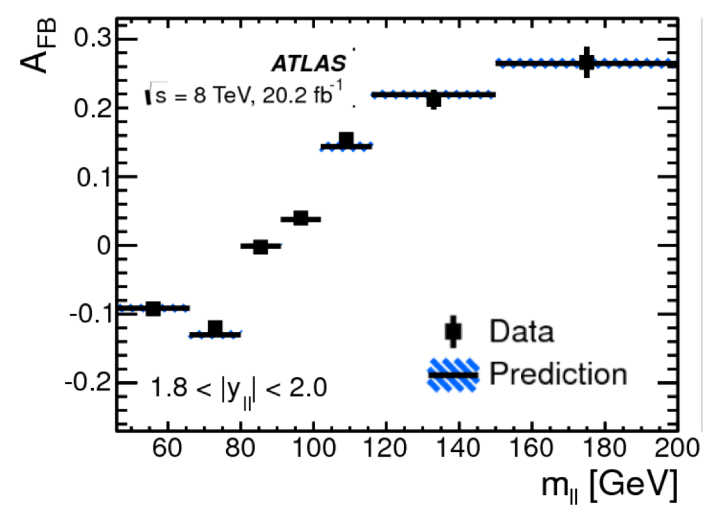
Sample results from a few regions of phase space:







3D DY: interpretation

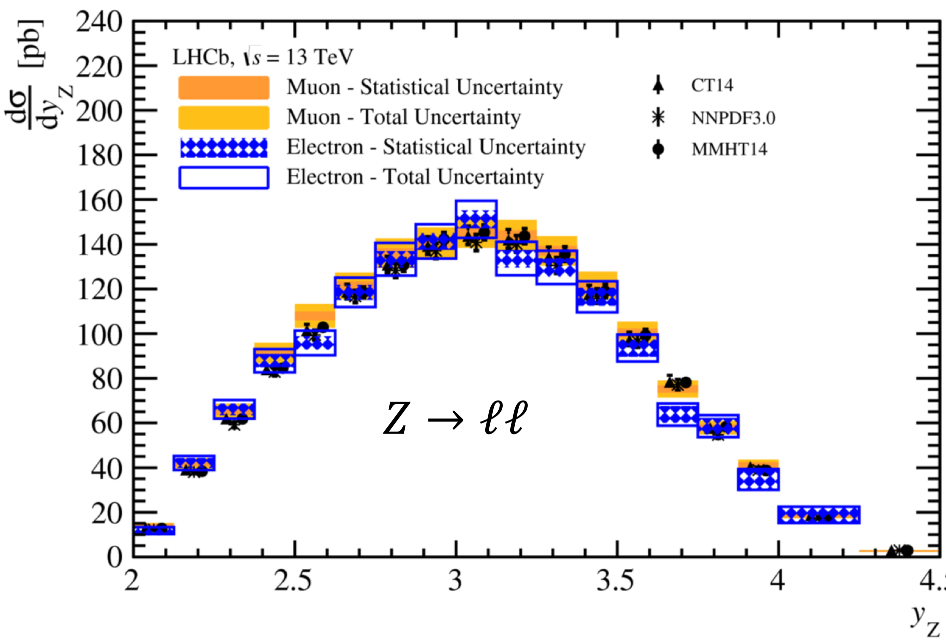
- $d^3\sigma$ from ATLAS can be used for proton PDF constraints, θ_W extraction, or both at the same time
- A_{FB} is convenient for θ_W extraction as used in many prior LHC and Tevatron measurements
- ATLAS is now working on inferences, meanwhile:
  - authors do include careful comparison to predictions of Powheg/CT10/Pythia8 boosted to NNLO QCD with FEWZ3.1/MSTW2008NNLO and to NLO EW with G_μ EW scheme, for a particular value of θ_W
  - agreement with measured $d^3\sigma$ is very good, except at some high-$y_{\ell\ell}$ and high-$\cos\theta^*$ cases (could be $p_T^{\ell\ell}$ modeling)
- Interpretation started, e.g. recent report by Duncan Walker & Col. at LHC EW working group with NNLOJET

Forward W and Z production at LHC

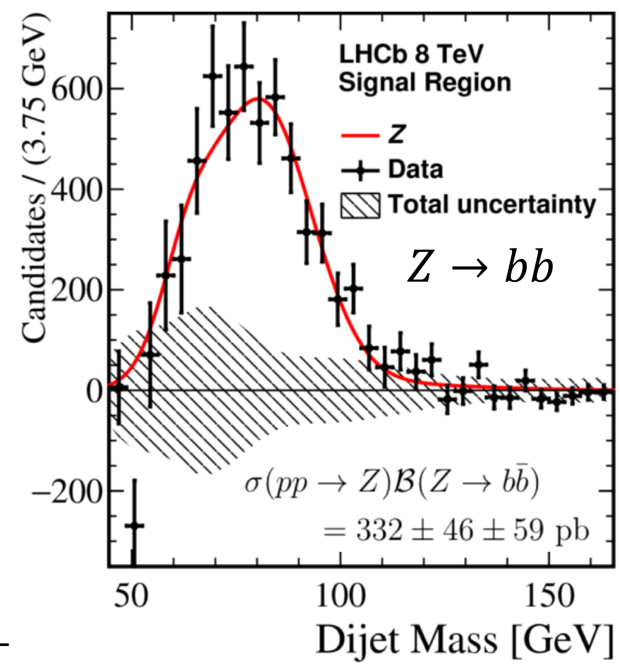
LHCb especially suited for high-y forward Drell-Yan studies

Among more recent, fiducial results (objects $|\eta| \gtrsim 2$):

- 13 TeV diff. x-sections of Z production ($y_{\ell\ell}, \varphi^*$) with $ee/\mu\mu$
  - sensitive to proton PDFs, good agreement with theory
- first observation of forward $Z \to b\bar{b}$ at 8 TeV
  - b-scale calibration, new physics, background to any $b\bar{b}X$ analysis



Phys. Lett. B776 (2017) 430–439



JHEP 09 (2016) 136

Diff x-section with respect to φ^*

ATLAS counterpart: EPJC 76(5), 1 (2016)

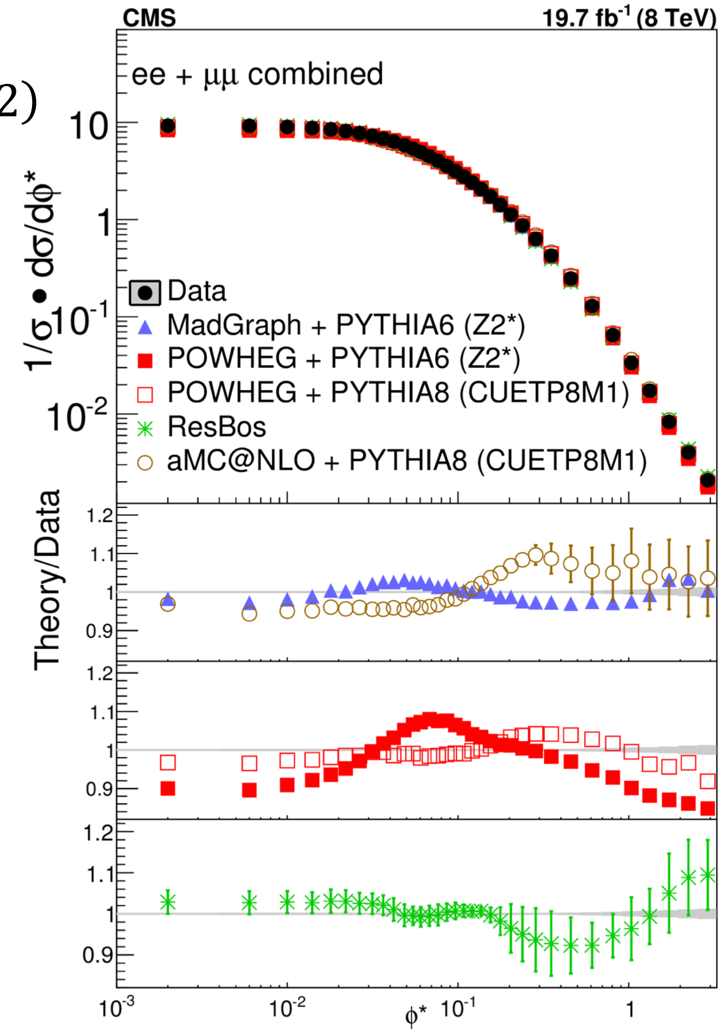
CMS studies DY production w.r.t. φ^* and y at 8 TeV

JHEP 03 (2018) 172

Definition and physics meaning:

$$\varphi^* = \tan\left(\frac{\pi - \Delta\varphi}{2}\right)\sin\theta^*_\eta \ \text{ where } \cos\theta^*_\eta = \tanh(\Delta\eta/2)$$

- φ^* is strongly correlated with $p_T^{\ell\ell}$
- lepton angles-only quantity has better resolution than with p_T^{ℓ}
- perturbative and non-pert. regimes, difficult for theory to describe



A few % disagreement at φ^* <0.1, order 10% above 0.1 for ResBos, Powheg+Py8, aMC@NLO+PY8. More advanced hard scattering description is needed, but underlying event also important.

Drell-Yan angular analysis and θ_W

Full DY description: $\sigma(m_{\ell\ell}, y_{\ell\ell}, p_{T,\ell\ell}, \theta^*, \phi^*)$

Angular behavior of leptons can be factored out as:

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

formula ref: arXiv:1606.00689

where A_i are functions of $m_{\ell\ell}, y_{\ell\ell}, p_{T,\ell\ell}$ only and correspond to cross sections for particular helicity amplitudes normalized to unpolarized cross section. All hadronic dynamics and EW fundamental parameters dependence is in A_i.

ATLAS experiment performed an impressive measurement of $A_0 - A_7$ reported in the 2016 paper JHEP 08 (2016) 159. CMS also reported $A_0 - A_4$ in PLB750 (2015) 154.

Parity violation, asymmetry, θ_W

Integrating over ϕ^* we obtain

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}\,\mathrm{d}\cos\theta} = \frac{3}{8}\frac{d\sigma^{U+L}}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}}\left\{(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_4\cos\theta\right\}$$

formula ref: arXiv:1606.00689

The term $A_4 \cos\theta^*$ is forward-backward asymmetric and violates parity. It comes from:

- $Z-\gamma^*$ axial-vector – vector interference
- Z axial-vector – vector self-interference (depends on θ_W)

Path to θ_W: measure A_4 or, more commonly, measure A_{FB}

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

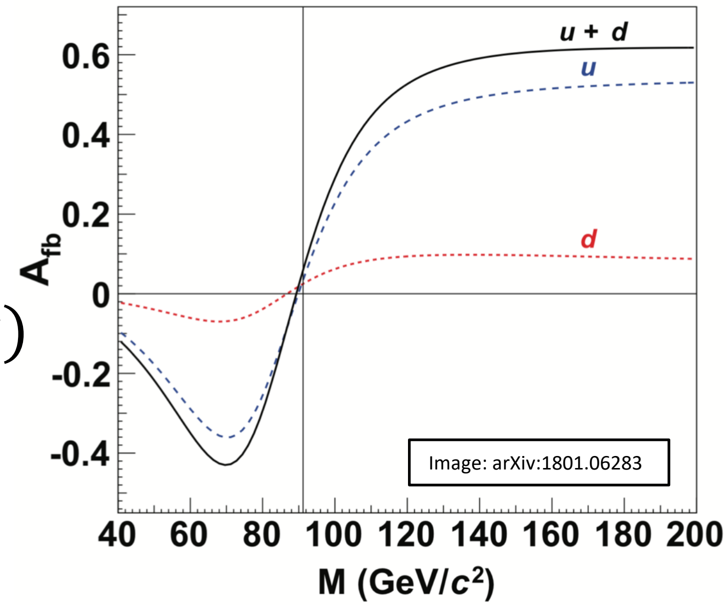
$\sin^2\theta_W$ measurements

Fine points in measurements at colliders:

- A_{FB} depends on $m_{\ell\ell}$, at m_Z solely due to Z self-interference
- A_{FB} depends on quark flavor => sensitivity to PDFs
- at LHC direction of incoming quark is unknown
  - analyses are done in $(m_{\ell\ell}, y_{\ell\ell})$ space
  - dilepton system direction on average reflects valence quark direction
- A_{FB} is enhanced by event weighting

Radiative corrections

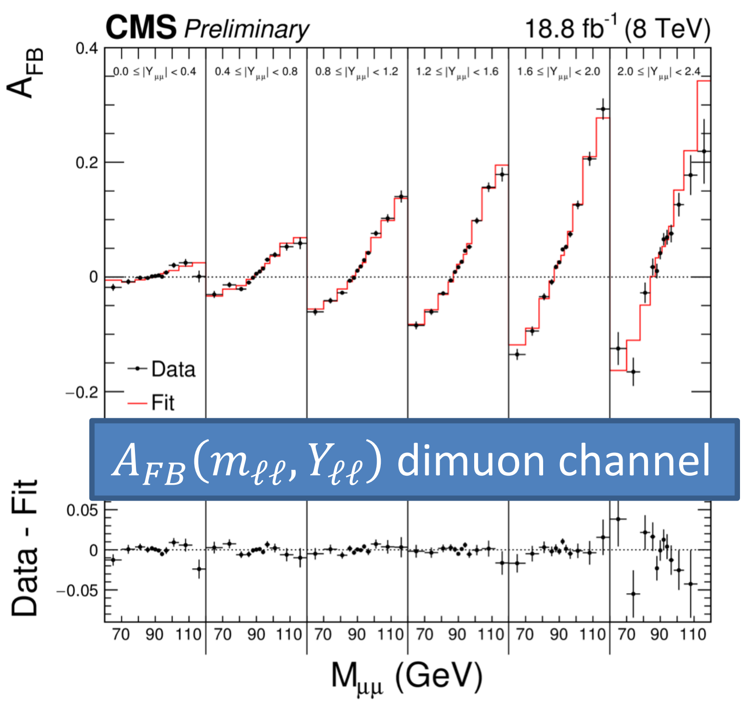
- at LO EW, $\sin^2\theta_W = 1 - M_W/M_Z$
- beyond: $\sin^2\theta_{eff} = \sin^2\theta_W(1+\Delta r)$
- Δr are flavor dependent
- at colliders, measure $\sin^2\theta_{eff}^{lep}$



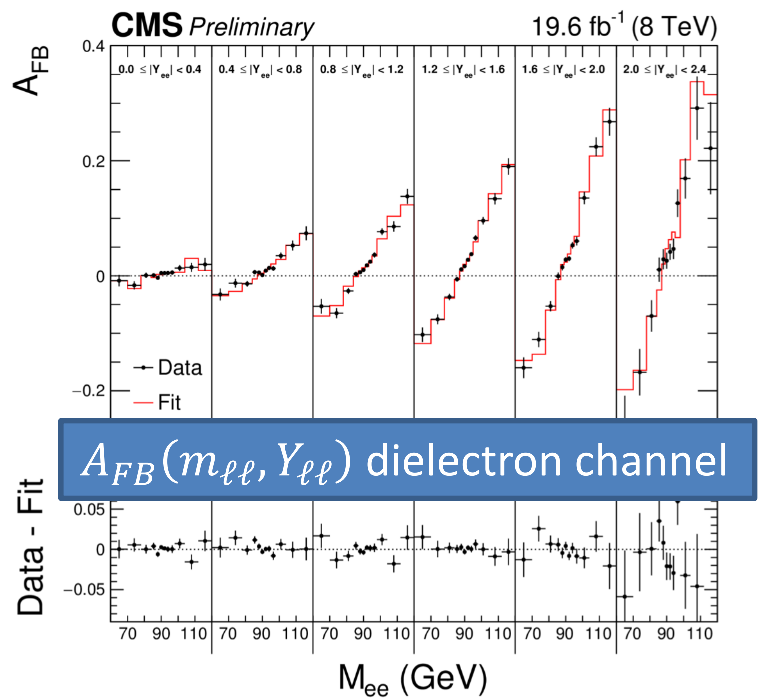
Recent $\sin^2\theta_{eff}^{lep}$ from CMS: A_{FB}

CMS measures $\sin^2\theta_{eff}^{lep}$ with 8 TeV dataset

- A_{FB} computed in 72 $(m_{\ell\ell}, Y_{\ell\ell})$ bins
- angular weighting is applied to candidates
- A_{FB} fit with templates generated with different $\sin^2\theta_{eff}^{lep}$



$A_{FB}(m_{\ell\ell}, Y_{\ell\ell})$ dimuon channel



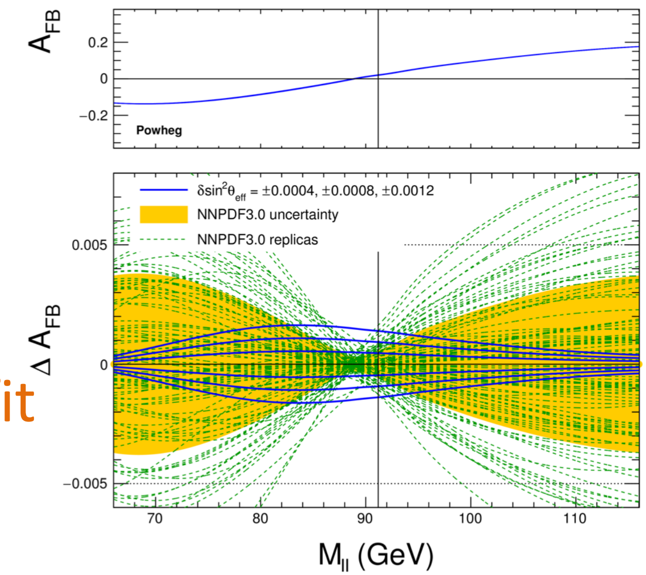
$A_{FB}(m_{\ell\ell}, Y_{\ell\ell})$ dielectron channel

CMS PAS SMP-16-007

$\sin^2\theta_{eff}^{lep}$ from CMS: systematics

Leading systematic uncertainty: PDF

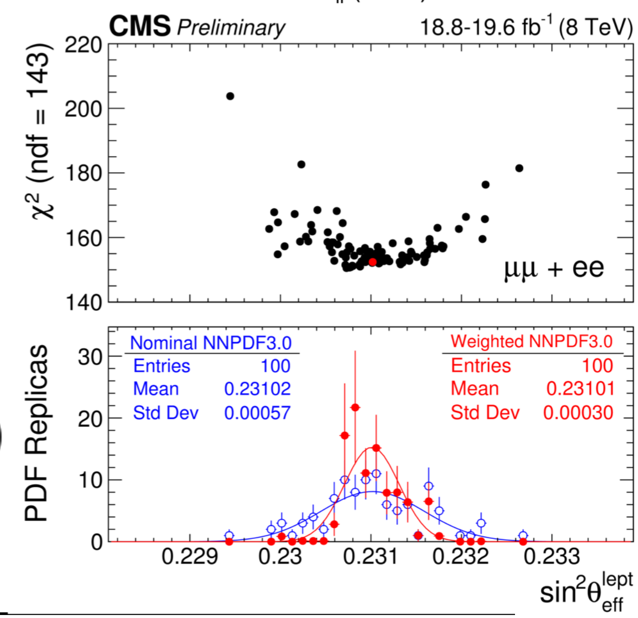
- $\sin^2\theta_{eff}^{lep}$ max sensitivity: $m_{\ell\ell}{\sim}m_Z$
- PDF uncertainty is max away from m_Z
- reweight PDF effect with χ^2_{min} of A_{FB} fit



Central value and PDF uncertainty:

Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

PDF uncertainty reduced by x2



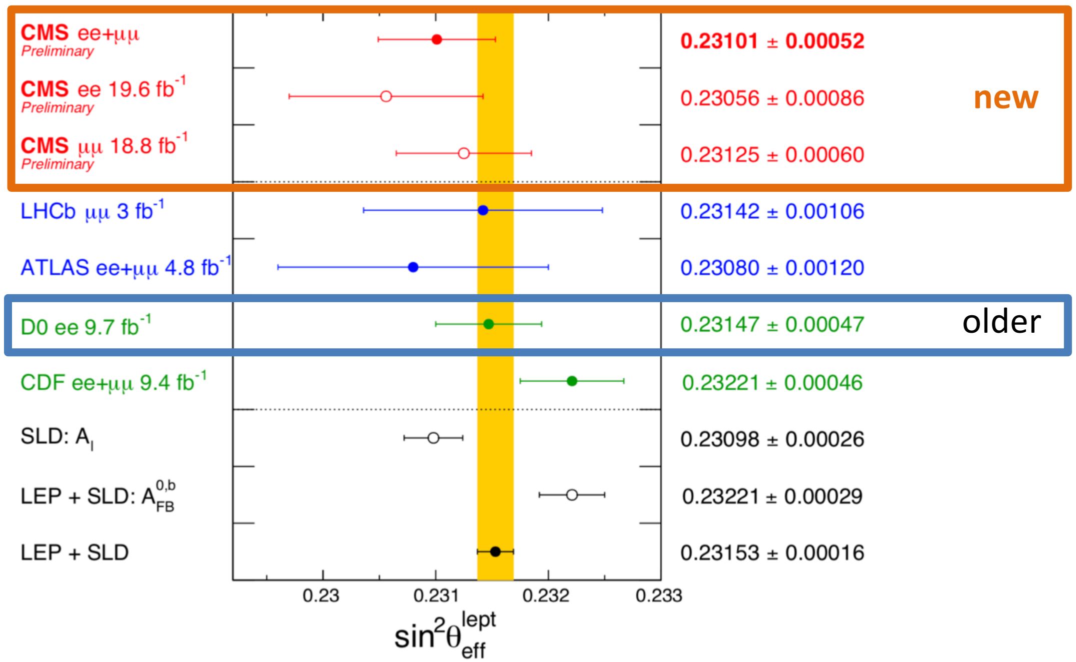
Final result:

$$\sin^2\theta_{eff}^{lept} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$

Recent $\sin^2\theta_{eff}^{lep}$ from colliders

Over last year, Tevatron released ultimate $\sin^2\theta_{eff}^{lep}$ from full data. CMS also had new result. *See Breese Quinn's talk for more!*

CMS PAS SMP-16-007



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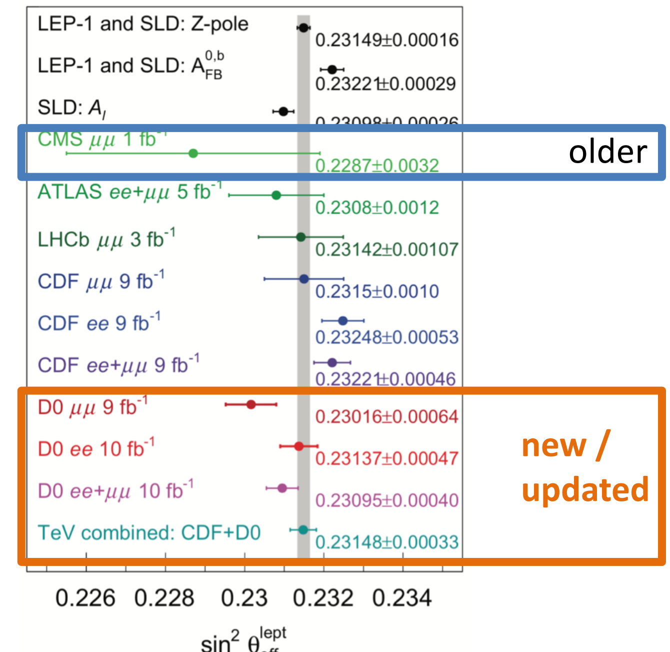


- hadron collider measurements approach e^+e^- level
- Tevatron also infers $\sin^2\theta_W$ and M_W (as a SM test)

Summary

- Precision W and Z studies at LHC are in full swing, with occasional Tevatron results appearing
- Primary focus areas remain:
  - precision measurements of EW parameters
  - SM tests at NNLO QCD, NLO EW level and beyond
  - differential x-sections for proton PDFs at high-Q^2 and low-x
- The 13 TeV LHC dataset is yet to be fully analyzed (LHC will keep running until end of this year), most 13 TeV precision measurements are yet to come
- Future LHC runs and HL-LHC era will take W/Z precision measurements to the next level with x100 in sample sizes.

EXTRA MATERIAL

Collins-Soper frame

Collins-Soper frame definition:

- in rest frame of $\ell\ell$
- Z axis bisects directions of incoming protons $\pm(\vec{p}_1 - \vec{p}_2)$
- Z direction is $(\vec{p}_1 - \vec{p}_2)$ at Tevatron, or of the $\ell\ell$ system in the lab (LHC)
- X axis is in the hadron plane
- X axis points to $-(\vec{p}_1 + \vec{p}_2)$
- Y axis complements to right-handed Cartesian system

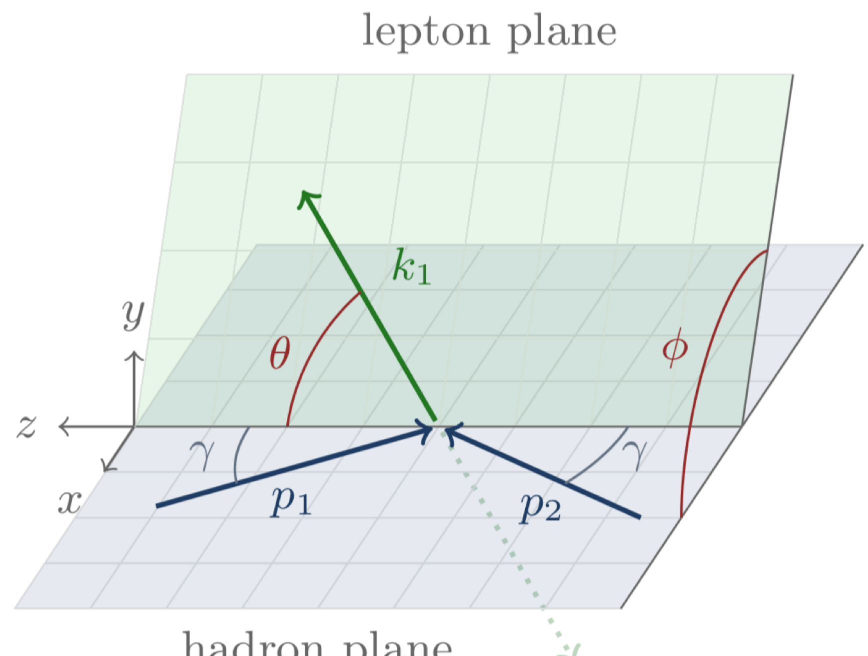


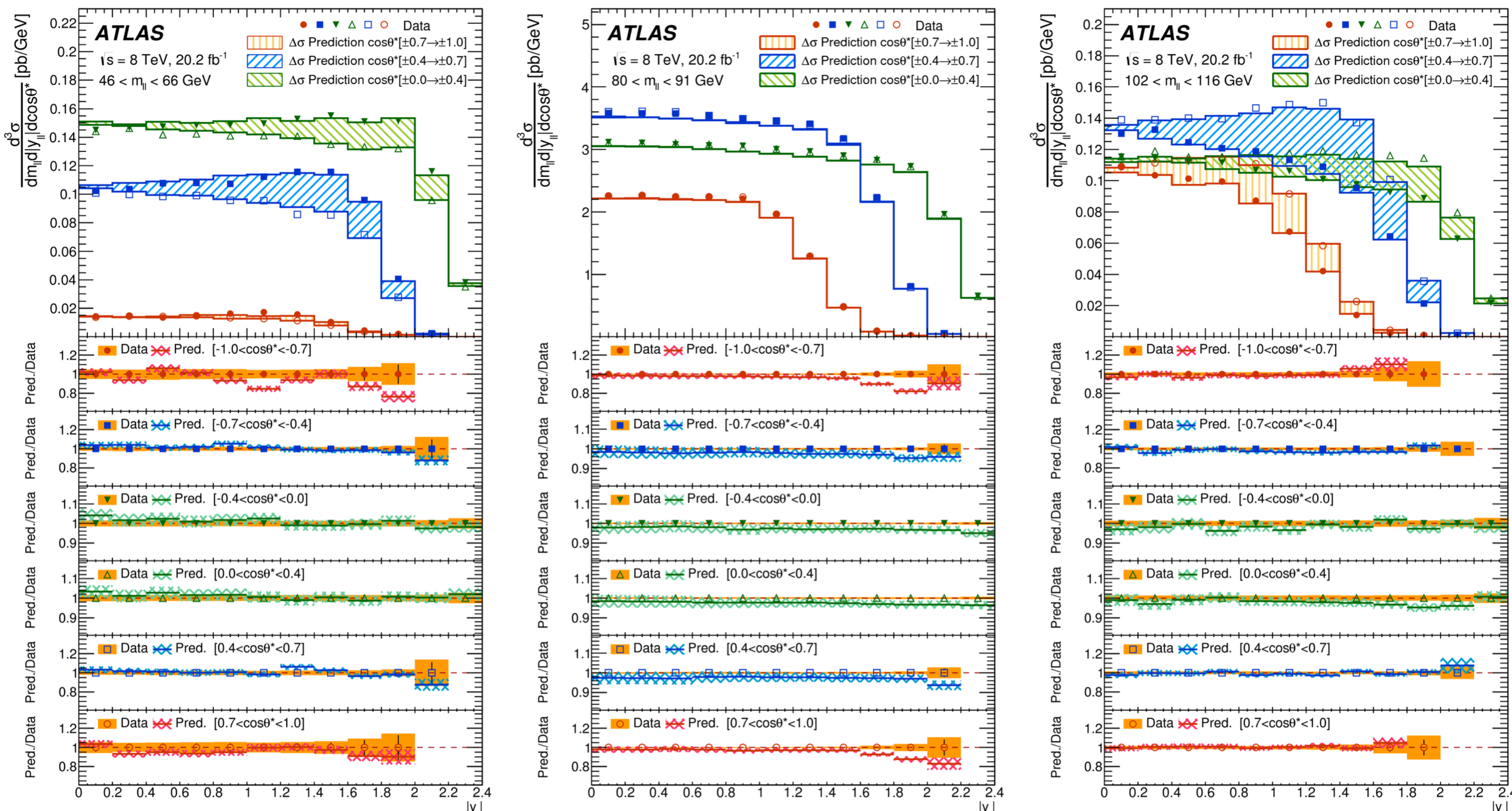
Image credit: hep-ph:1708.00008

C-S frame minimizes transverse motion of partons

For DY, $\theta^*$and $\varphi^*$are spherical system angles of negative lepton

3D DY cross section from ATLAS

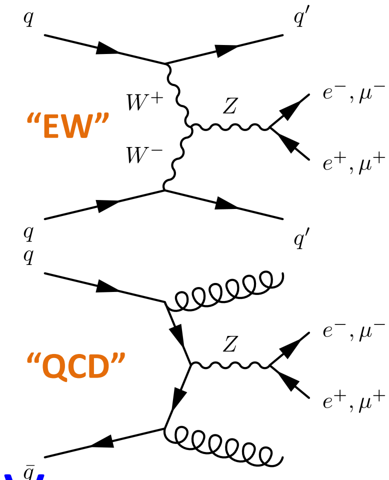
Complete plots, with ratio panes, mentioned earlier in the talk. From ATLAS's JHEP 12 (2017) 059.



EW Z production

Non-DY Z production: "EW" is one interesting mechanism

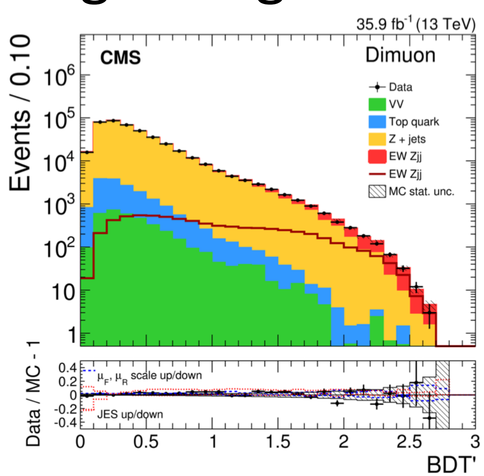
- VBF and VBS understanding important for Higgs measurements and new physics searches
- EW Z production is tiny, but can be disentangled from "QCD" kinematically
- handles: high dijet mass, large η separation

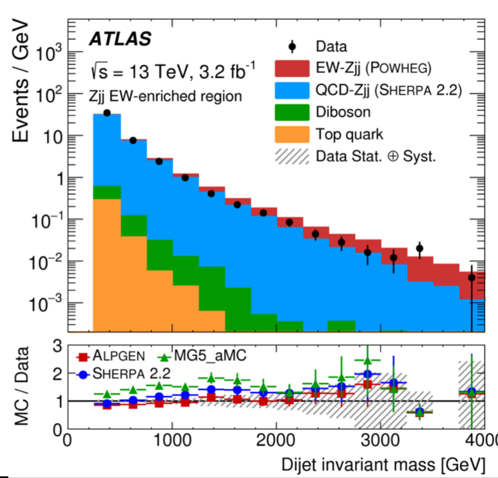


Images: ATLAS/CERN

ATLAS and CMS measure inclusive x-sec at 13 TeV

- good agreement with SM predictions





ATLAS: **Phys. Lett. B 775 (2017) 206**
CMS: **CMS-SMP-16-018 (sub to EPJ)**

See Andy Pilkington's talk for in-depth discussuion!

Both ATLAS and CMS published EW $pp \to Zjj$ 8 TeV x-sections a few years back.