Measurement of the Drell-Yan triple-differential cross section

$$\frac{d^3\sigma}{dy_{ll}\,dm_{ll}\,d\cos(\theta^*_{CS})}$$

in proton-proton collisions at $\sqrt{s}$=8 TeV

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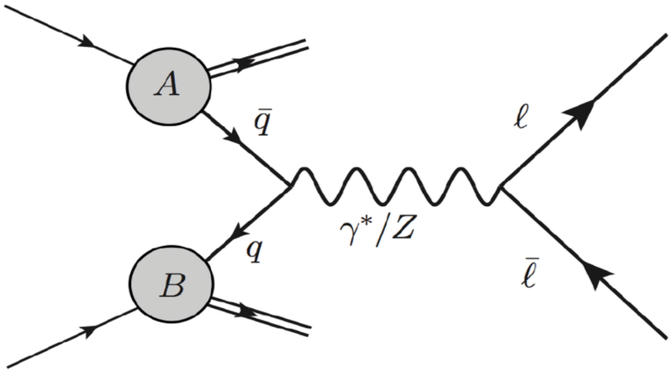
Published: JHEP 12 (2017) 059

Drell-Yan

Lepton pairs produced in hadron-hadron collisions.



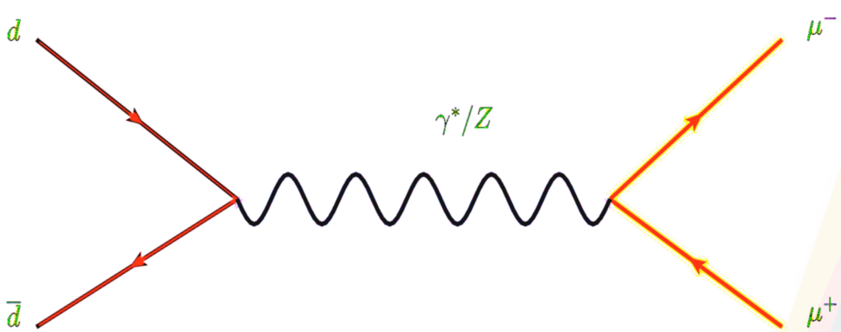
Phys. Rev. Lett. 25 (1970) 316.

Ann. Phys. 66 (1971) 578

Fundamental interpretation: quark—antiquark annihilation

$$q\bar{q} \rightarrow Z/\gamma^* \rightarrow l^+l^-$$

$l = e, \mu$ in this measurement



Motivation

- A triple-differential cross section measurement is sensitive to both:
  - The weak mixing angle through measurement of the **forward-backward asymmetry**.

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

    - $\cos\theta^*$ is the cosine of the decay angle in the Collins-Soper frame.

  - The parton distribution functions through measurement of the invariant mass of the leptons and their rapidity.

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$ where z is the beam axis.

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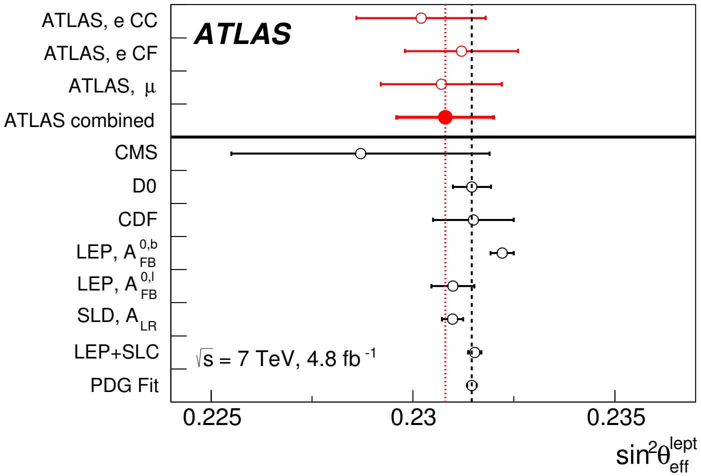
Motivation



Uncertainty source	CC electrons $[10^{-4}]$	CF electrons $[10^{-4}]$	Muons $[10^{-4}]$	Combined $[10^{-4}]$
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron energy resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2

- ATLAS measurement (JHEP09(2015)049) of $\sin^2\theta_W$ using 4.6 fb^{-1} of $\sqrt{s} = 7$ TeV data suffered from large PDF uncertainty.
- Large 20.2 fb^{-1} sample of well-understood $\sqrt{s} = 8$ TeV data.
- Design unfolded measurement to be sensitive to both PDFs and $\sin^2\theta_W$.

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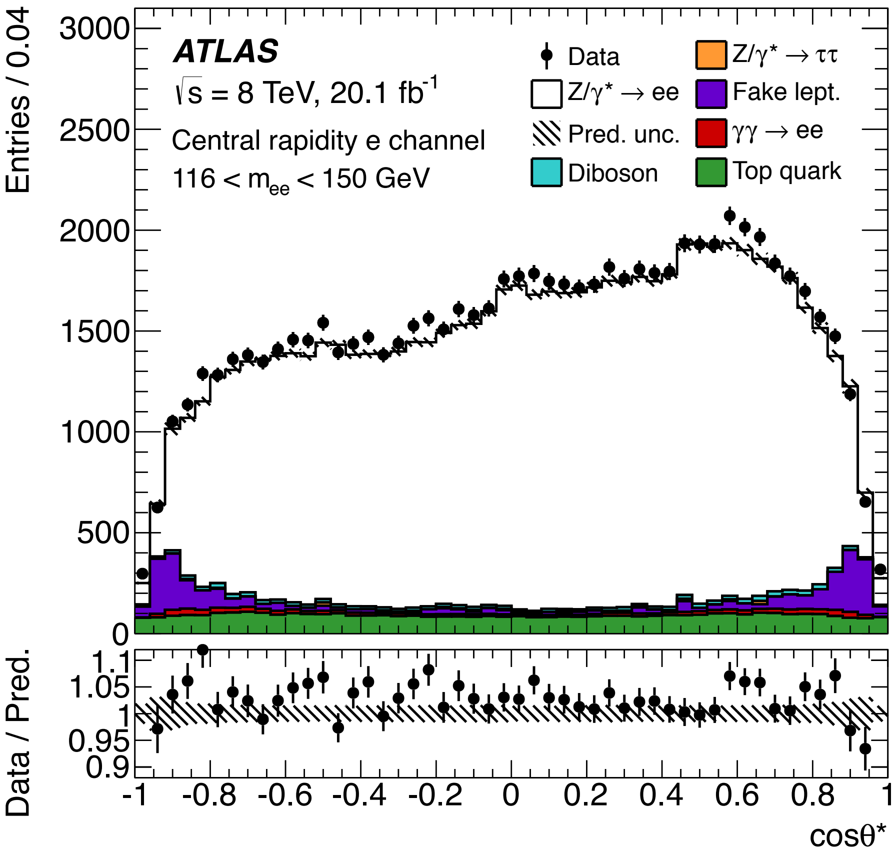
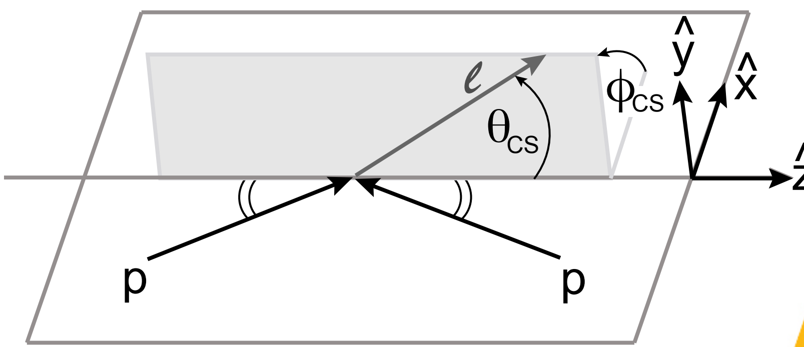
Collins-Soper Frame

- The decay angle is defined in the Collins-Soper Frame.
  - Phys. Rev. D 16 (1977) 2219
- Well defined using laboratory quantities.



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

$p_i^{\pm} = E_i \pm p_{z,i}$ where l^- is i=1



LO prediction

$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s}\sum_q P_q\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2) + (q \leftrightarrow \bar{q})\right]$$

- The parton distribution functions (PDF), $f(x,Q^2)$ describe the momentum fraction of the partons in the colliding protons (symmetric under quark—anti-quark exchange).
  - Asymmetry is rapidity dependent

$$x_{\pm} = \frac{M_{ll}}{\sqrt{s}}e^{\pm y}$$

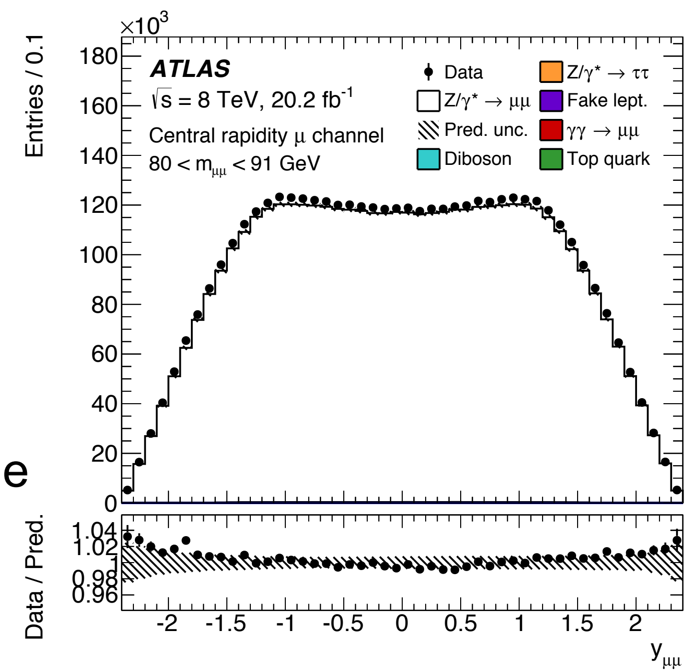
- The momentum transfer is given by the invariant mass of the lepton pair: $Q^2=m_{ll}^2$

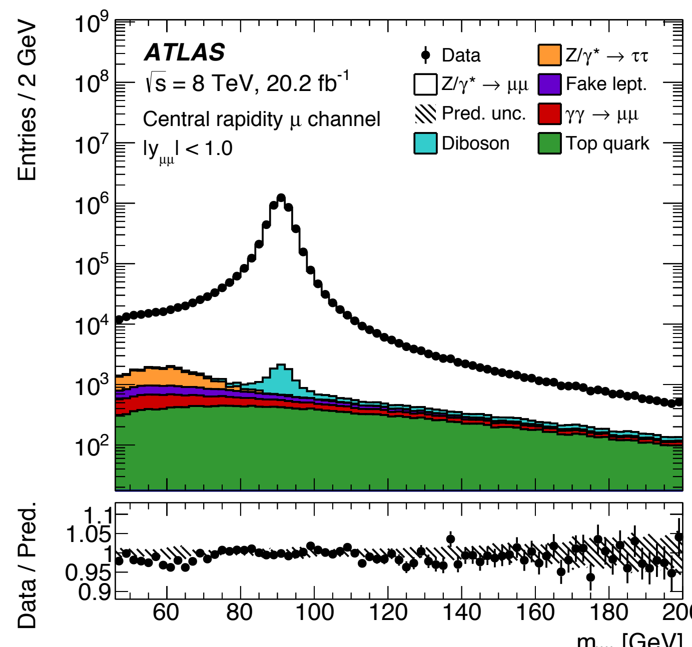
P_q is LO EW propagator

Di-muon rapidity left

Invariant mass right

Z peak is clearly visible





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Drell-Yan Measurement

Central

- Measurement: $|\eta^{l}|<2.4$ and $p_T>20$ GeV electrons and muons
- Total number bins:

504 bins each for e and μ

Variable	Bin boundaries
$y_{\ell\ell}$	0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4
$M_{\ell\ell}$/GeV	46, 66, 80, 91, 102, 116, 150, 200
$\cos\theta^*$	-1, -0.7, -0.4, 0., 0.4, 0.7 1.0

Extended forward electrons

- Measurement:
  - one central electron $|\eta^{e}|<2.4$ and $p^{e}_{T}>25$ GeV
  - And one forward electron $2.5<|\eta^{e}|<4.9$ and $p^{e}_{T}>20$ GeV
- Total number of bins: 150

Variable	Bin boundaries
$y_{\ell\ell}$	1.2, 1.6, 2.0, 2.4, 2.8, 3.6,
$M_{\ell\ell}$/GeV	66, 80, 91, 102, 116, 150
$\cos\theta^*$	-1, -0.7, -0.4, 0., 0.4, 0.7 1.0

Signal Monte Carlo

Powheg with CT10 PDF and mass-dependent NNLO/NLO k-factors calculated with FEWZ and p_T^{ll}-dependent polarization coefficients corrections calculated using DYNNLO.

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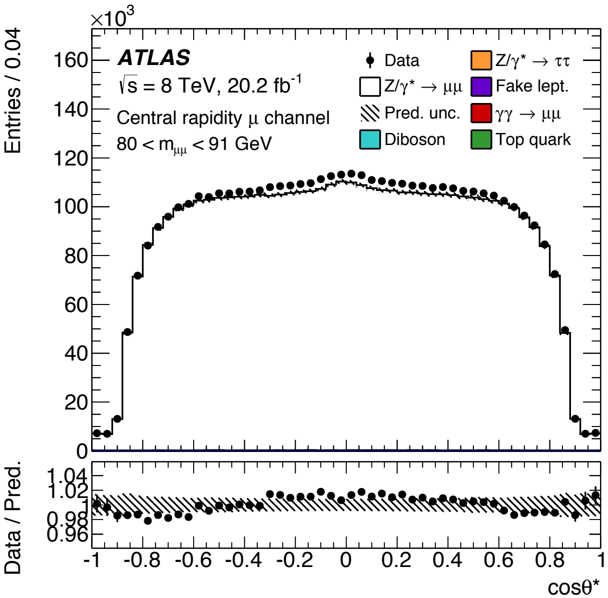
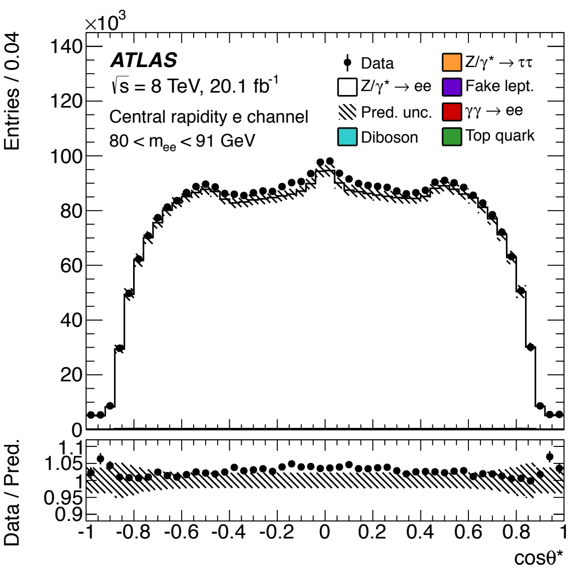
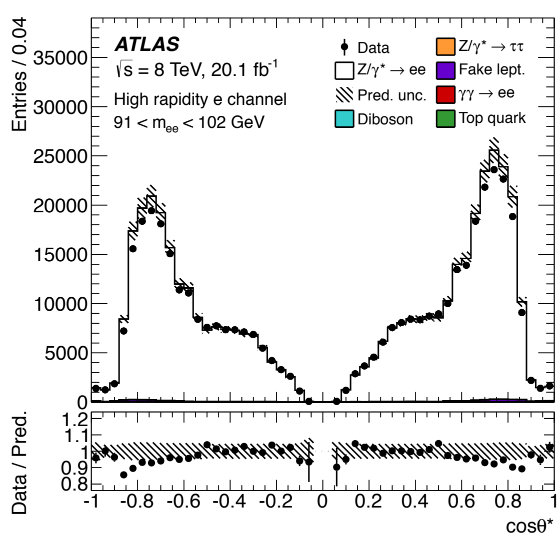
$\cos\theta^*_{\mathrm{CS}}$ near the Z-peak



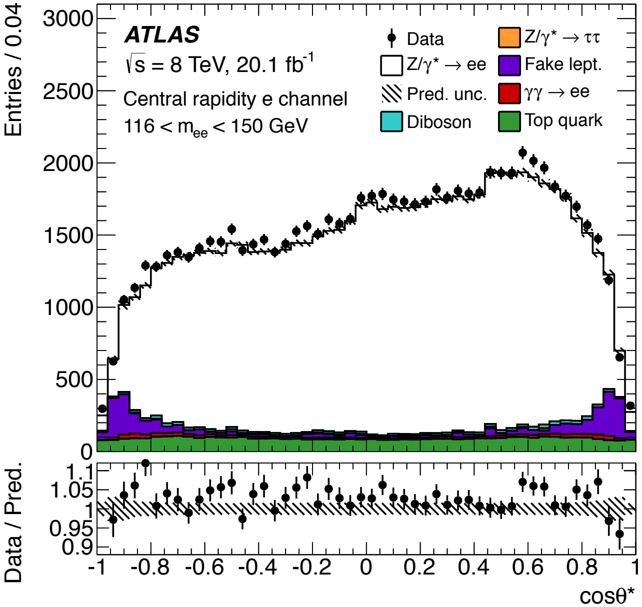
- Symmetric around zero
- Very low background
- Electron and muon results are consistent
- Extended analysis increases rapidity but also provides more data at large decay angle.
- Main systematic uncertainties are:



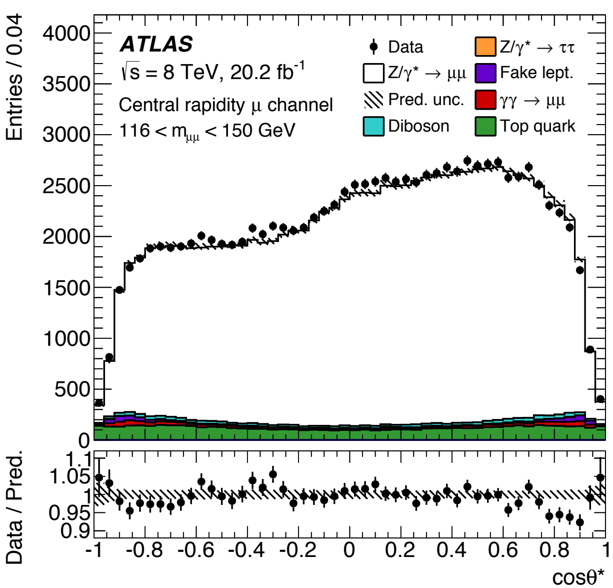


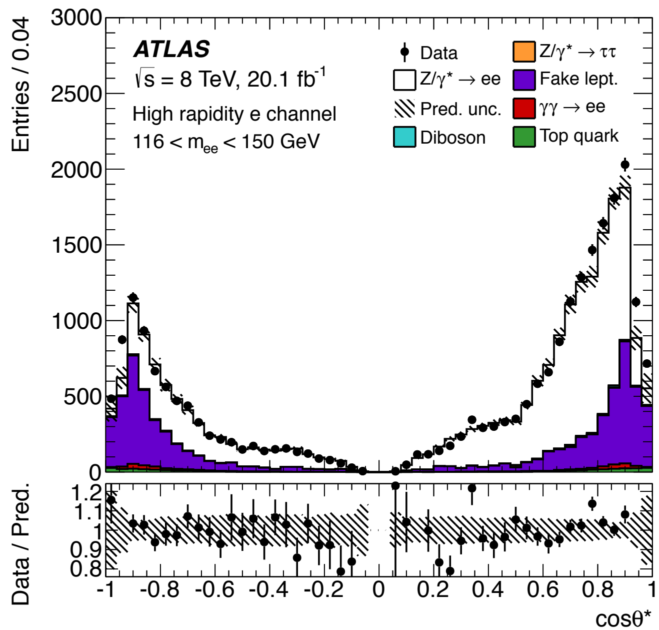
- Efficiencies <0.5%
- Energy scale and resolution ~1%
- Charge-dependent momentum reconstruction for muons ~1%

$\cos\theta^*_{\mathrm{CS}}$ above the Z-peak



- Forward-backward asymmetry becomes pronounced.
- Background from top quark and multi-jet production become significant
- Most backgrounds are FB symmetric (except W+jets)
- Largest systematic uncertainties are from background subtraction





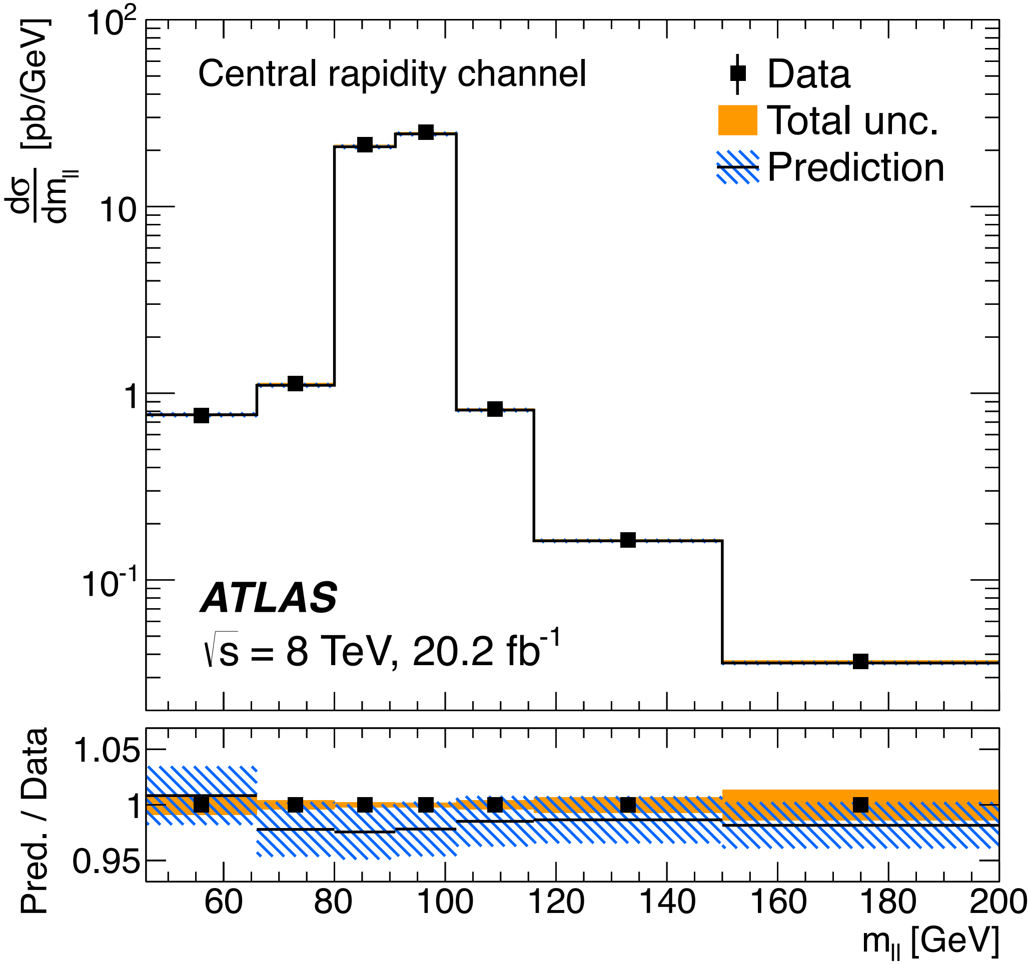
- For forward electrons, energy resolution becomes an important systematic uncertainty

Cross Sections: $\frac{d\sigma}{dm_{\ell\ell}}$

- All cross sections are unfolded and corrected to the Born level so that they can be directly compared with theory.
- Start with 3D cross sections and integrate to get 1D and 2D.
- The e and μ results are combined using a fit that takes into account systematic uncertainties using nuisance parameters

$$\frac{d\sigma}{dm_{\ell\ell}} \quad \chi^2/\mathrm{N_{DoF}} = 12.8/7$$

- Powheg-based predictions are in good agreement with the data



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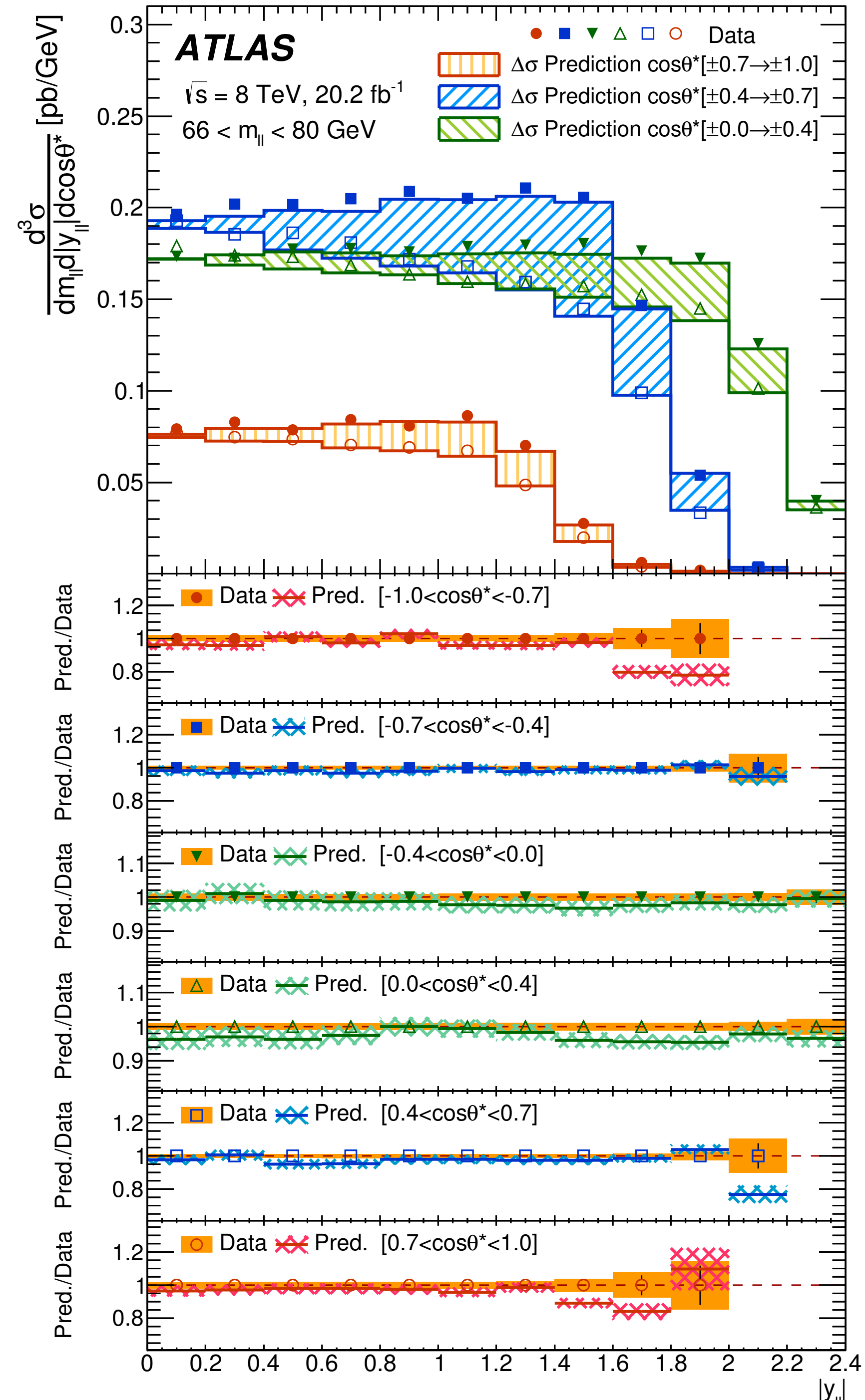
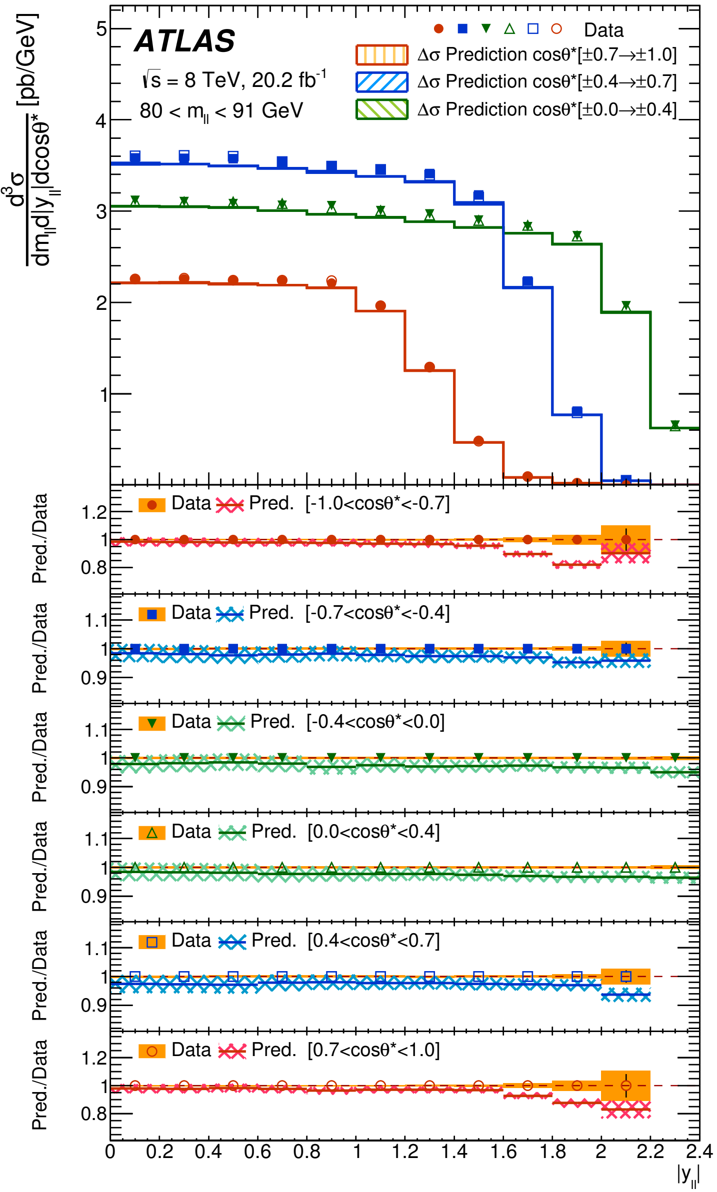
3D LOW MASS CENTRAL COMBINED

$$\frac{d^3\sigma}{dy_{ll}dm_{ll}d\cos(\theta^*_{CS})}$$

- Mass bin $66<m_{ll}<80$
- Central analysis
- For each color:
  - Solid marker is cosθ <0
  - Open marker is cosθ >0
  - Asymmetry is proportional to hashed colored area between the open and closed markers
- Negative asymmetry
- Prediction is the modified Powheg MC described earlier
- PDF uncertainty is included in the uncertainty band shown in the ratio plots



3D Z-PEAK Central Combined



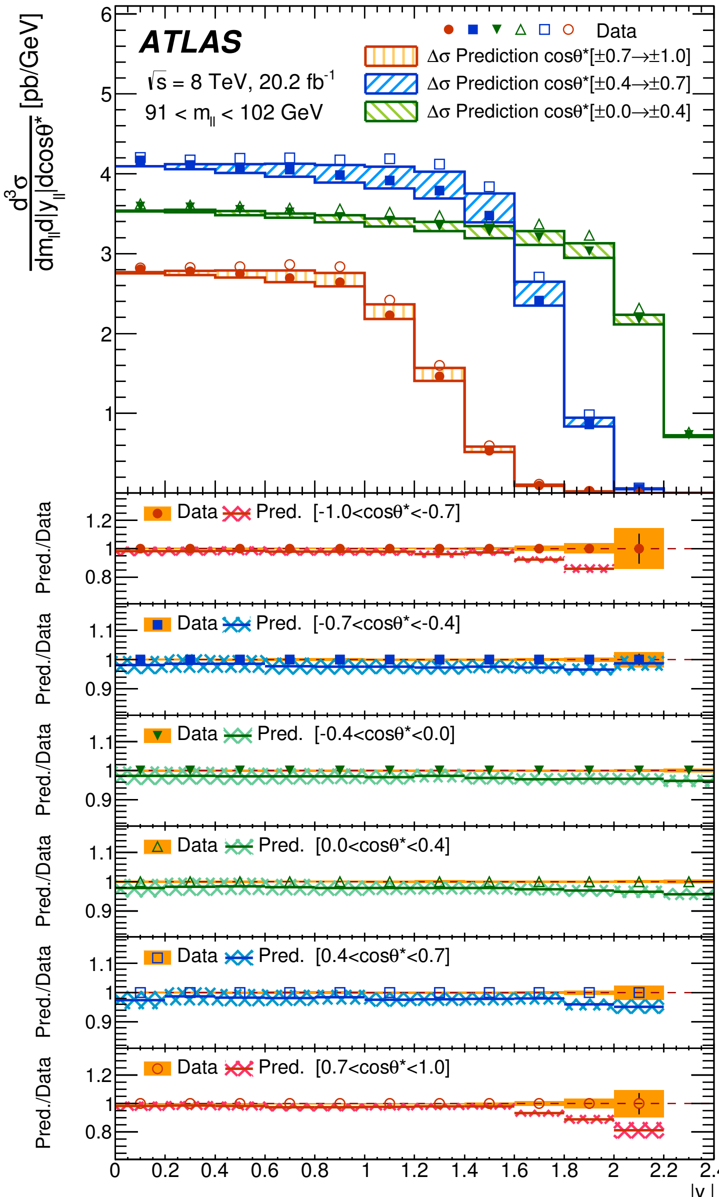
Mass:

80—91 GeV

91—102 GeV

Asymmetry ≅ 0

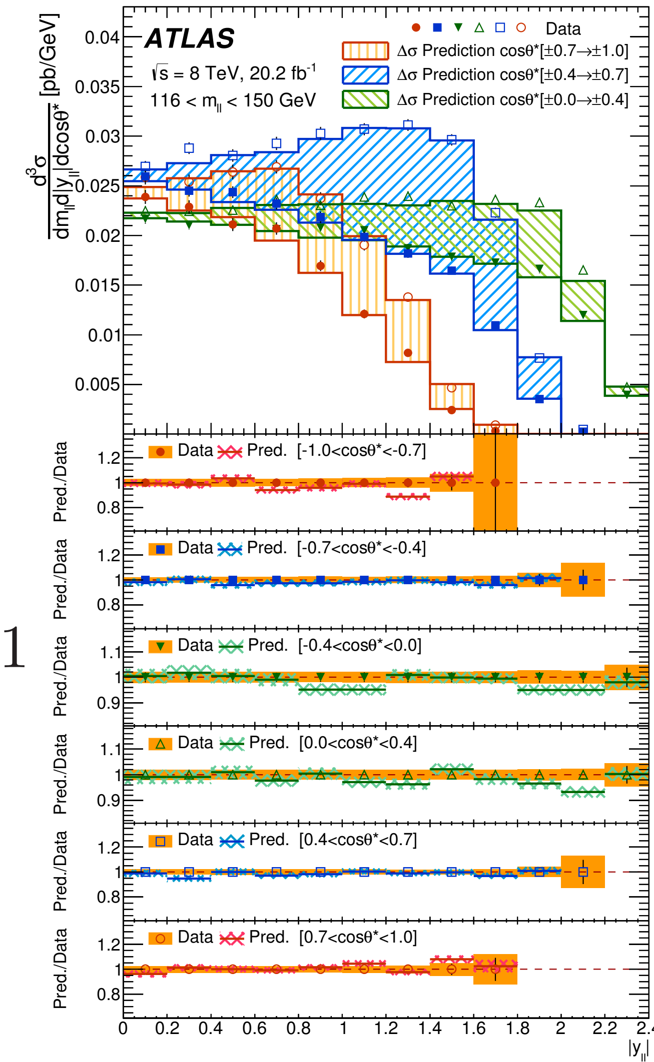
Cross section measurement precision at Z peak is better than 0.5% for $|y_{ll}|$<1.4

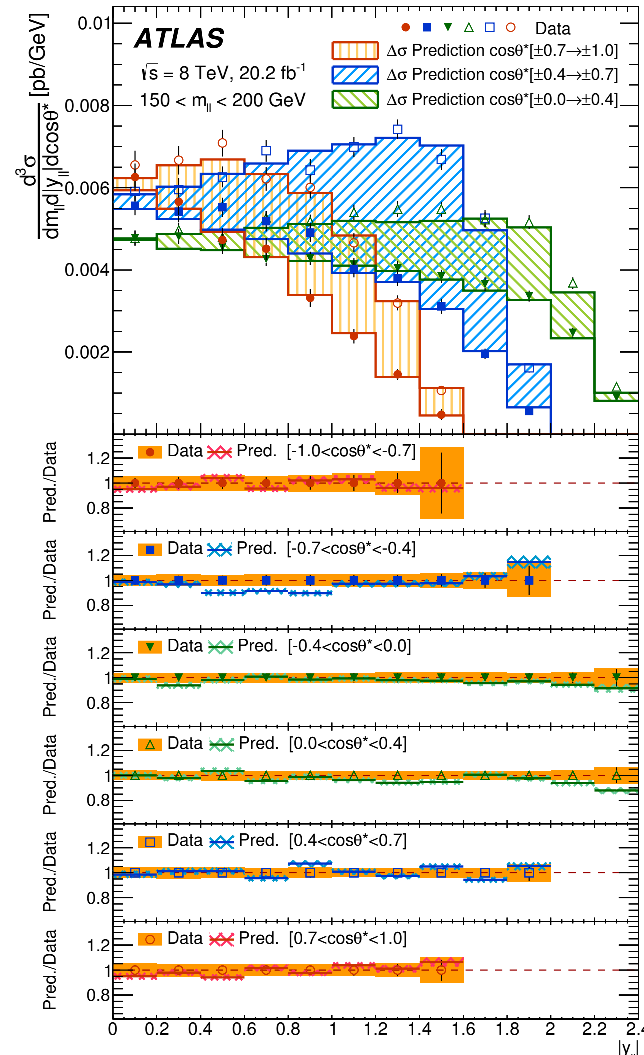


3D HIGH MASS Central Combined

- Positive asymmetry
- Overall goodness of fit for the e-μ central combinations is

$$\chi^2/\mathrm{N_{DoF}} = 489.4/451$$





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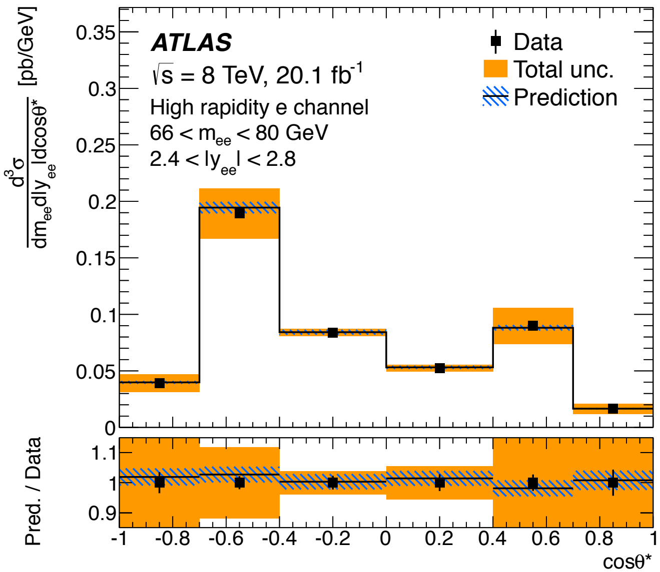
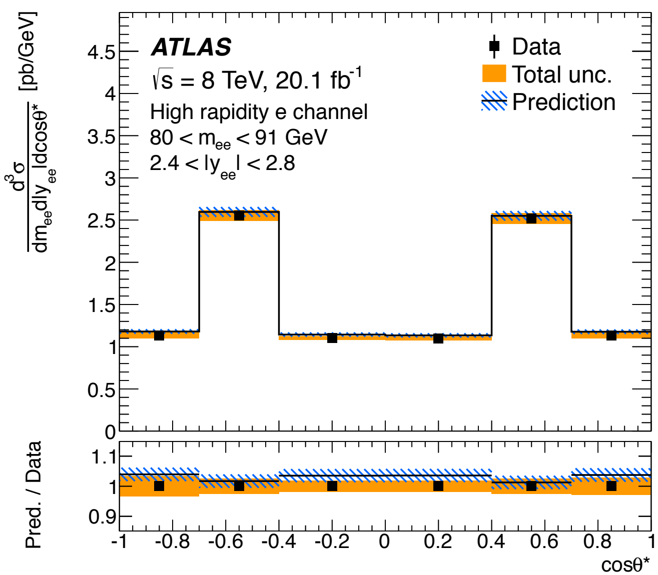
Selected Results from Extended Rapidity Electron Analysis

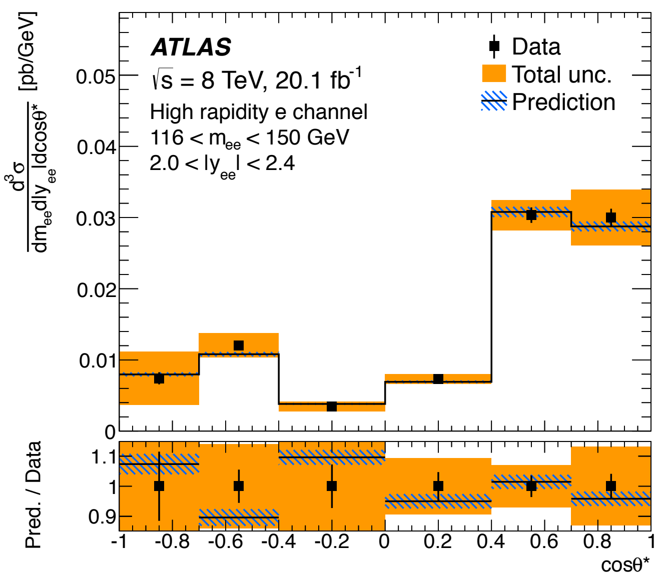


2.4<|y_{ll}|<2.8

Mass: 66-80, 80-91, 116-150

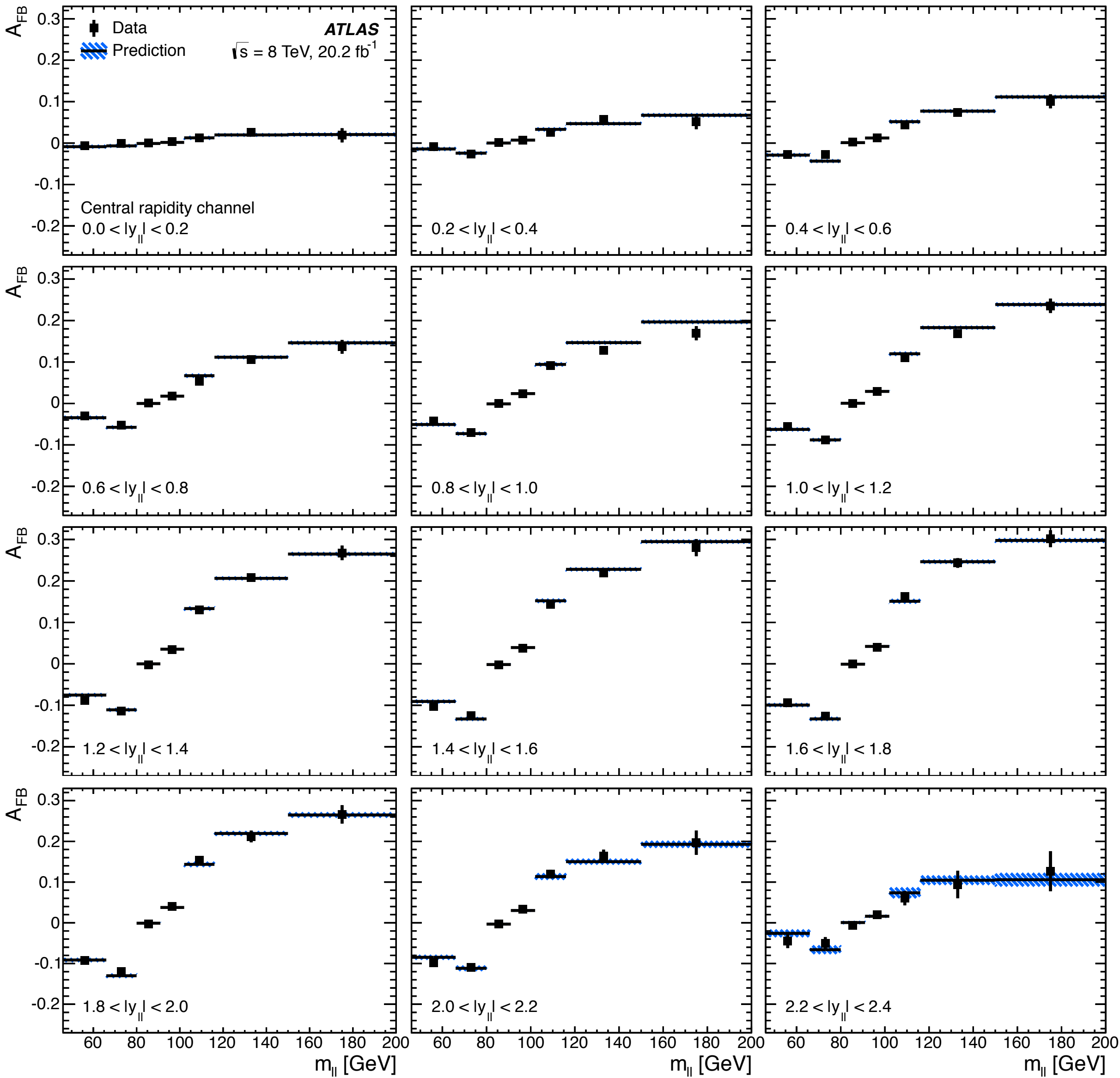
- Large asymmetry at low and high mass
- Precise measurement near Z peak





Forward—Backward Asymmetry for Central Combined

- Cancellation of uncertainties that are symmetric in the decay angle
- Asymmetry increases with y_{ll}
- Good agreement with Powheg-based predictions



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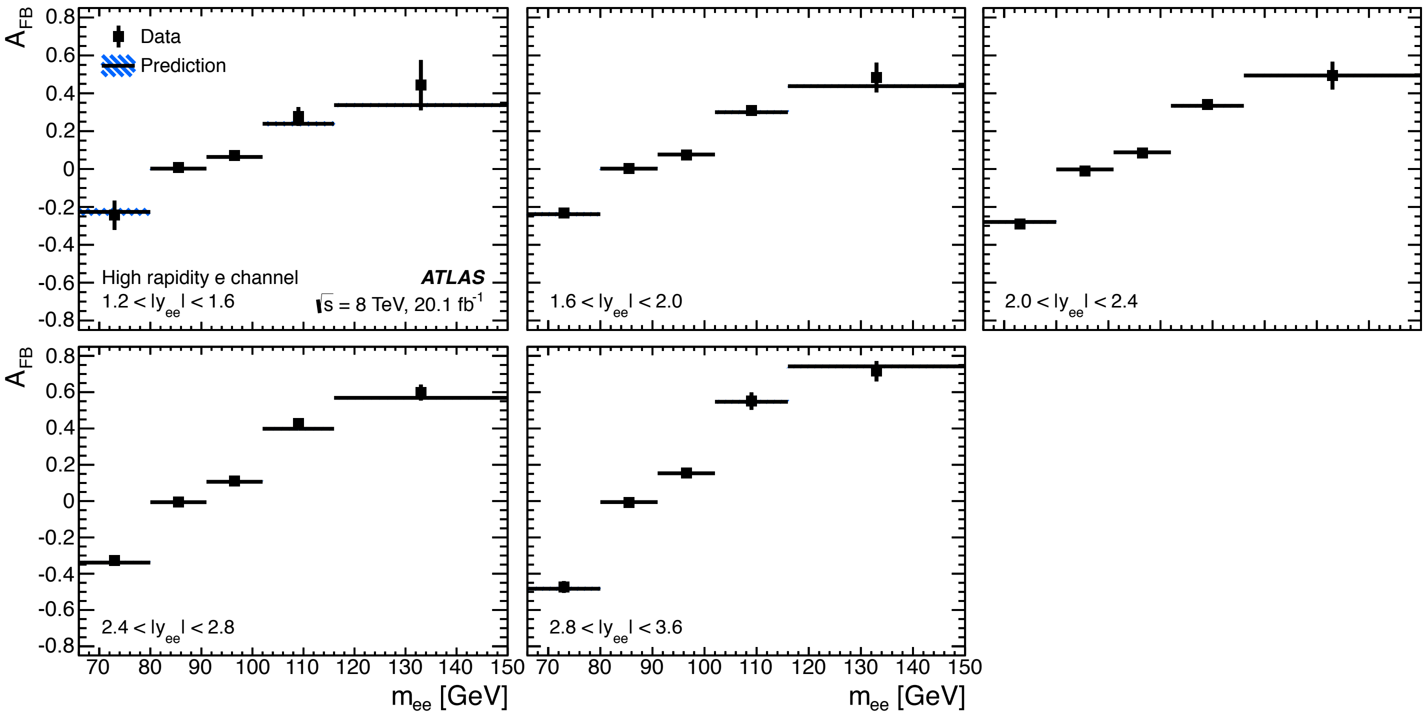
Forward—Backward Asymmetry for the Extended Rapidity Electrons



Measured asymmetries range from -0.2 to +0.7

Conclusions

- Unique triple differential measurement by the ATLAS Collaboration over
  - $46 < m_{ll} < 200$ Gev
  - $|y_{ll}| < 3.6$
  - $\sqrt{s} = 8$ TeV
- Precision better than 0.5% near the Z peak.
- Data is described well by the augmented Powheg predictions.
- Forward—backward asymmetry is measured
- Working on using this data and other measurements to extract the weak mixing angle

Backup Slides

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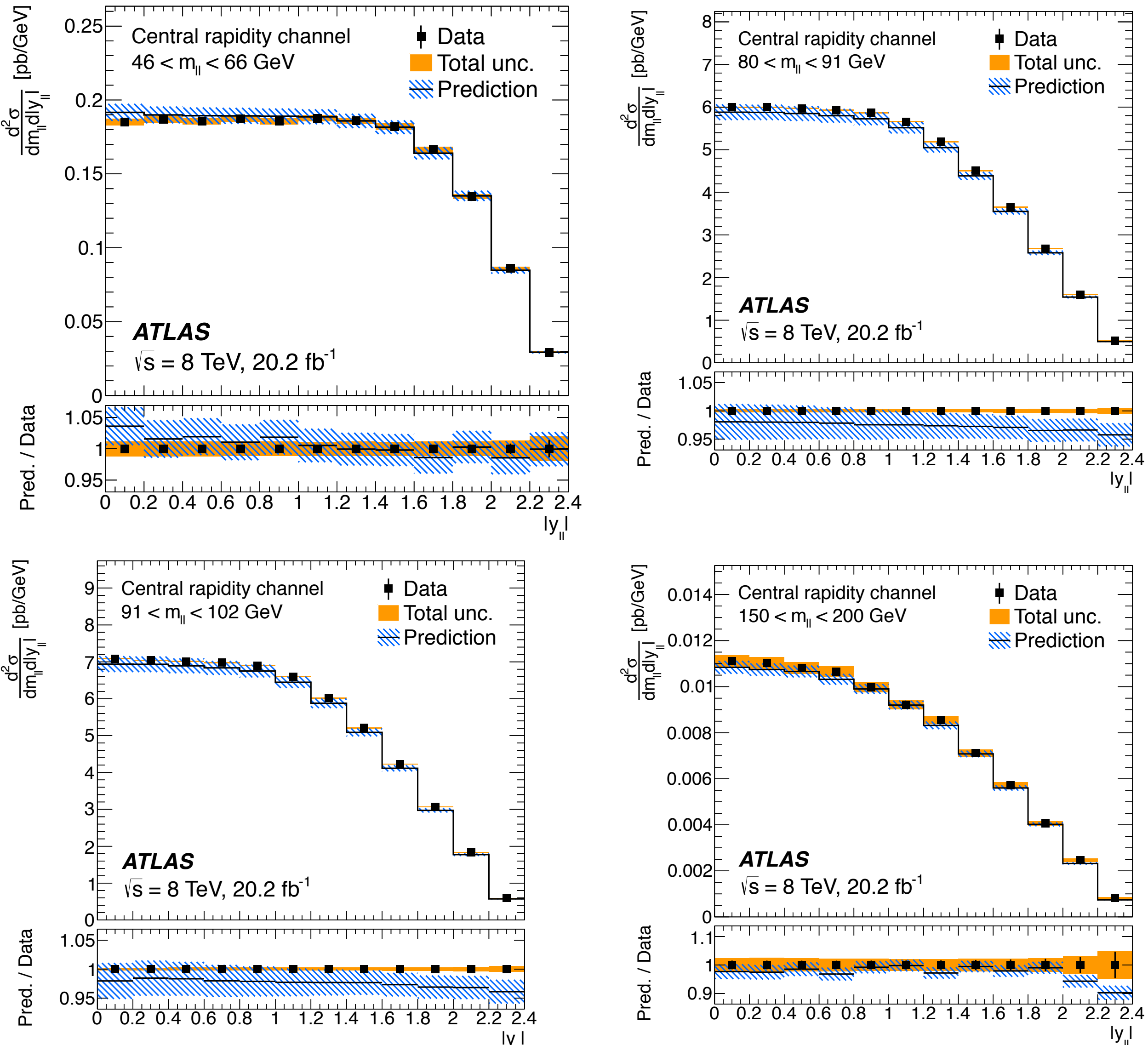
Cross Section $\frac{d^2\sigma}{dm_{\ell\ell}dy_{\ell\ell}}$



- Powheg-based predictions are in good agreement with the data
- Central Electron and muon results are consistent with each other and therefore can be combined.

$$\chi^2/\mathrm{N_{DoF}} = 103.4/84$$

LO Electroweak Propagator

$$P_q = e_\ell^2 e_q^2 (1+\cos^2\theta^*)$$ Photon exchange

$$+e_\ell e_q \frac{2m_{\ell\ell}^2(m_{\ell\ell}^2 - m_Z^2)}{\sin^2\theta_W \cos^2\theta_W \left[(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2\right]}\left[v_\ell v_q (1+\cos^2\theta^*) + 2a_\ell a_q \cos\theta^*\right]$$ Z/γ^* interference

$$+\frac{m_{\ell\ell}^4}{\sin^4\theta_W \cos^4\theta_W \left[(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2\right]}\left[(a_\ell^2 + v_\ell^2)(a_q^2 + v_q^2)(1+\cos^2\theta^*) + 8a_\ell v_\ell a_q v_q \cos\theta^*\right]$$ Z exchange

Difference in photon and Z coupling allows for PDF decomposition into u- and d-type quarks. Photon—Z contribution is mass dependent.

Rapidity selects x – high x favours valence quarks

Interference and Z terms have $\cos(\theta_{cs}^{*})$ terms that generate a forward-backward asymmetry, A_{FB}.

- Z term A_{FB} is very small because the small vector coupling to leptons.
- Interference term dominates except at $m_{ll} = m_Z$.
- Negative for $m_{ll} < m_Z$ and Positive for $m_{ll} > m_Z$..
- Z term A_{FB} makes zero crossing at slightly below the Z mass peak.

• A_{FB} is zero at $y_{ll}=0$ [symmetric proton-proton] and gets larger for large dilepton rapidity.

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Parton Distribution Functions and Forward-Backward Asymmetry

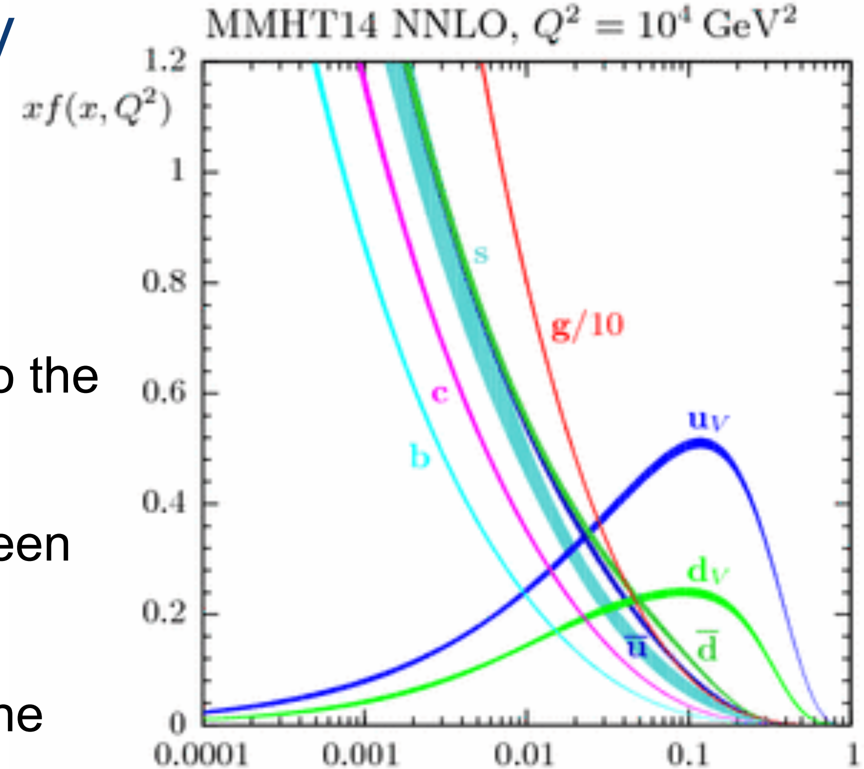
Anti-quark is from the sea

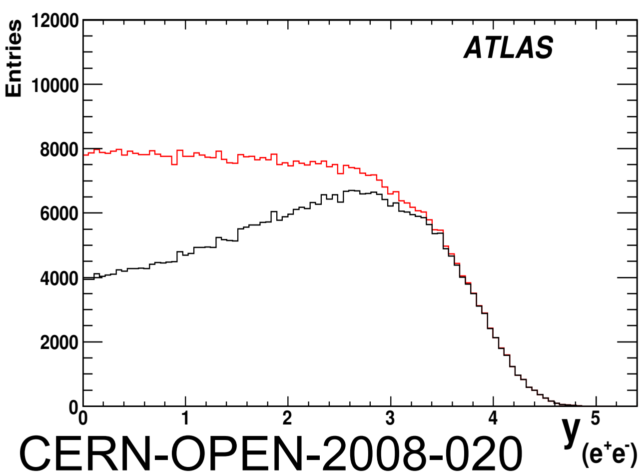
Quark is from valence + sea and has a larger value of x on average.

The rapidity of the lepton pair is proportional to the difference in x of the quark and anti-quark.

The decay angle is defined as the angle between the negative lepton and the quark direction.

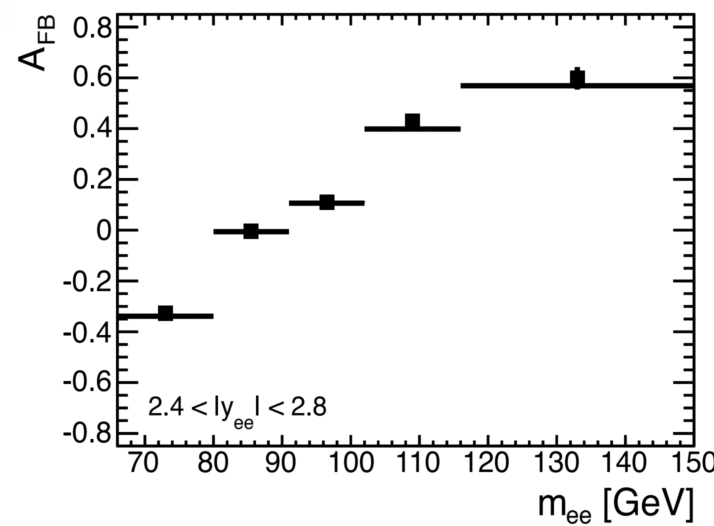
At small y_{ll}, this results in misidentification of the quark angle: “dilution”





← Red is all quarks
Black is correctly identified

Example asymmetry →



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ATLAS Detector

- Inner Detector tracks to ~ |η|<2.5
- Calorimeter clusters |η|<4.9
- Muon tracking |η|<2.7