ATLAS and CMS Drell-Yan measurements / weak mixing angle

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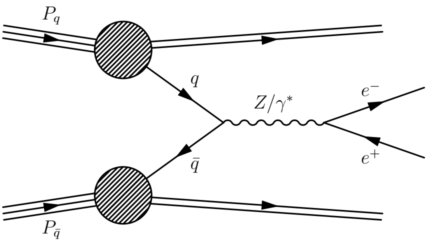
on behalf of the ATLAS and CMS Collaborations

SM@LHC 2021

April 26–30, 2021

The Drell-Yan Process

Neutral current Drell-Yan (DY) process: $q(P_1) + \bar{q}(P_2) \to Z/\gamma^* \to \ell^+\ell^-$



Measurement of the Drell-Yan process:

- Provides a tests of perturbative QCD;
- Constrains the parton distribution functions of the proton;
- Extraction of fundamental electroweak parameters like the weak mixing angle θ_{W}.

Presentation Outline:

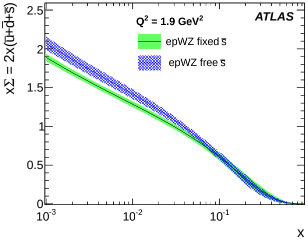
- ATLAS [1] and CMS [2] differential measurements of the Drell-Yan cross section at 13 TeV;
- ATLAS weak mixing angle measurement using polarization coefficients at 8 TeV [3];
- CMS weak mixing angle measurement using forward-backward asymmetry at 8 TeV [4];
- Prospects at the HL-LHC [5];
- ATLAS [6] and CMS [7] charged current Drell-Yan.

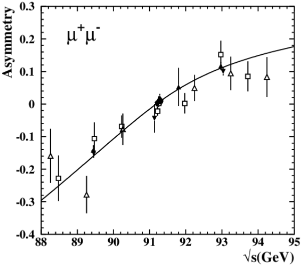
Differential Measurements

Differential measurements of the Drell-Yan cross section allow a wide variety of physics to be tested, constrained, and extracted.

- Measurement about $m_Z \longrightarrow$ calibrate the detector.
- Measurement in y and $m_{\ell\ell} \longrightarrow$ probe PDF space.
- Measurement in $\theta \longrightarrow A_{\mathrm{FB}}$.

- Dilepton transverse momentum, $p_{\mathrm{T}}^{\ell\ell}$, predictions:
  - At low $p_{\mathrm{T}}^{\ell\ell}$, soft-gluon resummation and non-perturbative models more accurately describe $p_{\mathrm{T}}^{\ell\ell}$.
  - At high $p_{\mathrm{T}}^{\ell\ell}$, fixed-order perturbative QCD predictions are better.
  - Matching the two prediction methods to measurements of $p_{\mathrm{T}}^{\ell\ell}$ gives the most reliable predictions of the dilepton transverse momentum.
- Knowledge of $p_{\mathrm{T}}^{\ell\ell}$ is important for SM measurements; e.g. the W boson mass.
- Constraints on the SM are beneficial to the searches for physics beyond the SM.



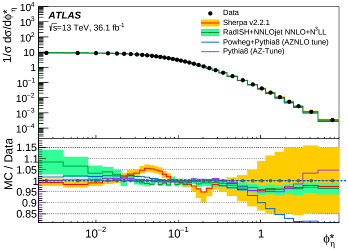


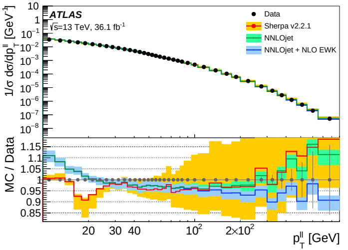
- $\mathcal{L}$ = 36.1 fb^{-1} of pp data from 2015 and 2016; $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ channels; unfolded to the Born and dressed levels **[see talk by Dennis Pudzha later today]**.
- Measurement in $p_T^{\ell\ell}$ and observable ϕ^*_η:

$$\phi^*_\eta = \tan\left(\frac{\pi - (\phi^- - \phi^+)}{2}\right)\sin\theta^*_\eta$$

$$\cos\theta^*_\eta = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

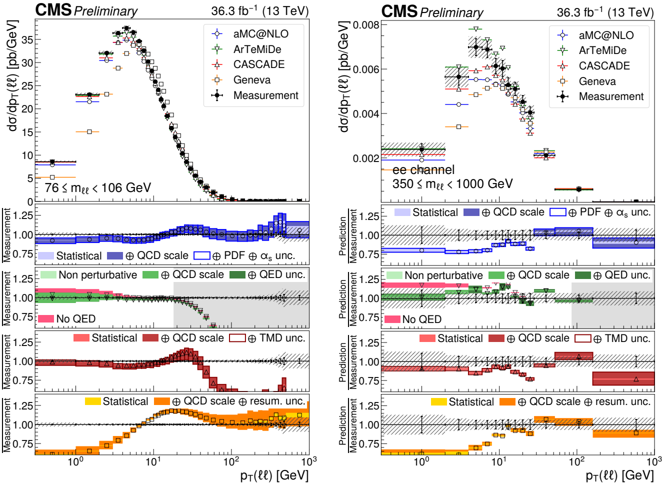
- $\phi^*_\eta \sim p_T^{\ell\ell}/m_{\ell\ell}$, ideal observable to probe p_T of the Z.
- Sherpa (merging of higher-order, high-multiplicity matrix elements) prediction gives a good description of data at high $p_T^{\ell\ell}$.
- RadISH (NNLO+N^{3}LL) prediction agrees with data for the full spectrum.
- Pythia8 (parton showering) predictions found to describe the 13 TeV data at low $p_T^{\ell\ell}$ and ϕ^*_η.
- Fixed-order NNLOjet prediction with and without NLO EW effects describes the data well for high $p_T^{\ell\ell}$.





CMS Differential DY Cross Section at 13 TeV (I) [2]

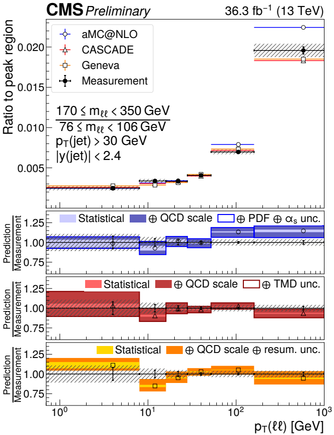
- $\mathcal{L} = 36.3\ \text{fb}^{-1}$ of *pp* data from 2016; $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ channels; unfolded to the dressed level.
- Additionally, a measurement is performed requiring at least one jet in the final state.
- Measurement in $p_T^{\ell\ell}$ and ϕ^*_η, in addition to $m_{\ell\ell}$.
- **Selection:**
  - $p_T^\ell > 25, 20$ GeV;
  - $|\eta^\ell| < 2.4$;
  - $p_T^{jet} > 30$ GeV and $|\eta^{jet}| < 2.4$;
  - $50 < m_{\ell\ell} < 1000$ GeV.

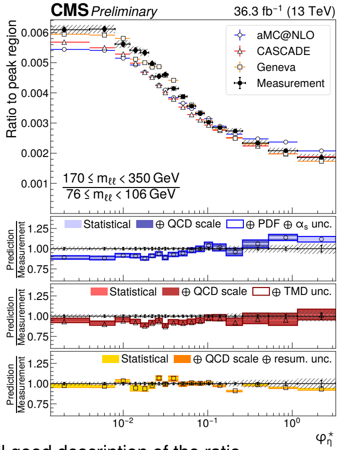


- Dominant uncertainties include the limited data and Monte Carlo statistics, especially in high $p_T^{\ell\ell}$ regions, and uncertainty from fakes background.

CMS Differential DY Cross Section at 13 TeV (II)

- To benefit from partial cancellation of the systematic uncertainties, cross section ratios are taken with respect to the measurement bin centred at the Z mass, $76 < m_{\ell\ell} < 106$ GeV.
- The aMC@NLO prediction (parton shower) describes the data well globally, under predicts at $p_T^{\ell\ell} < 30$ GeV in the inclusive case.





- CASCADE (soft gluon resummation) predictions give an overall good description of the ratio measurements.
- GENEVA (NNLO matrix element) at high $p_T^{\ell\ell}$ is the only prediction presented here in agreement with the measurement in all mass bins, showing the importance of higher order matrix element inclusion in this phase space region.

Drell-Yan and the Effective Weak Mixing Angle

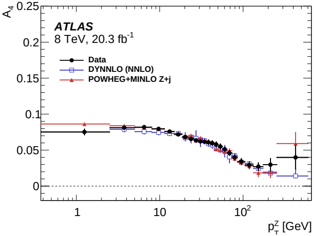
Effective weak mixing angle $\theta_{\rm eff}$: $\sin^2\theta_{\rm eff} = \kappa \sin^2\theta_{\rm W}$, where $\kappa = 1 + \delta\kappa$, and $\delta\kappa$ contains the higher-order corrections.

Polarization coefficients:

- 5D Drell-Yan differential cross section decomposed into 1 + 8 harmonic polynomials, $P_i\,(cos\theta, \phi)$, with coefficients $A_i\,(p_T^{\ell\ell}, y^{\ell\ell}, m^{\ell\ell})$:

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

- Electroweak parameters can be extracted from measurements of A_i, e.g. A_4 can be used to extract $\theta_{\rm eff}$.

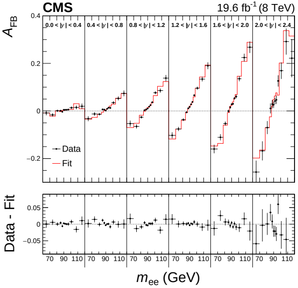


Forward-Backward Asymmetry:

- Collins-Soper frame polar angle θ^* can be computed using lab frame quantities.
- Imbalance between forward ($\cos\theta^* > 0$) and backward ($\cos\theta^* < 0$) events is the forward-backward asymmetry:

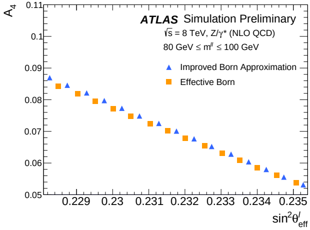
$$A_{\rm FB} = (N_{\rm fwd} - N_{\rm bwd})/(N_{\rm fwd} + N_{\rm bwd})$$

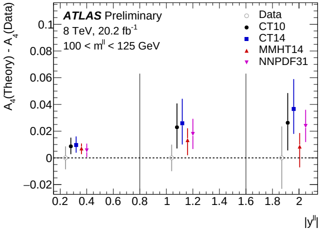
- $A_{\rm FB}$ is sensitive to $\theta_{\rm eff}$.



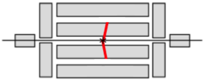
ATLAS Effective Weak Mixing Angle at 8 TeV [3]

- $\mathcal{L}$ = 20.2 fb^{-1} of *pp* data from 2012.
- Extraction of $\sin^2\theta^{\ell}_{\rm eff}$ is made using A_4 measurements from 3 analysis channels.
- $\mathrm{ee}_{\rm CF}$ most challenging but sensitive to $\theta^{\ell}_{\rm eff}$.
- LO in EW and NLO in QCD predictions of A_4 as a function of $\sin^2\theta^{\ell}_{\rm eff}$ are computed using DYTurbo, further enhanced with higher order EW and NNLO QCD corrections.
- The $\sin^2\theta^{\ell}_{\rm eff}$ that maximizes a likelihood function (or best describes the data) is taken as the measurement.
- Dominant uncertainties on the fully combined result include signal Monte Carlo statistics and the PDF uncertainty on the prediction.

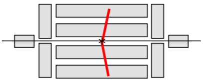




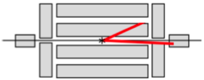
“$\mathrm{ee}_{\rm CC}$”: $q\bar{q} \to Z/\gamma^* \to e^+e^-$:



“$\mu\mu_{\rm CC}$”: $q\bar{q} \to Z/\gamma^* \to \mu^+\mu^-$:

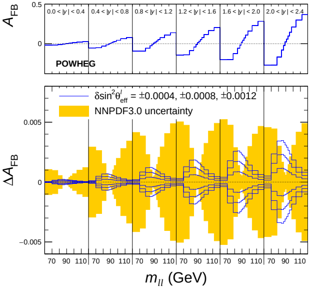


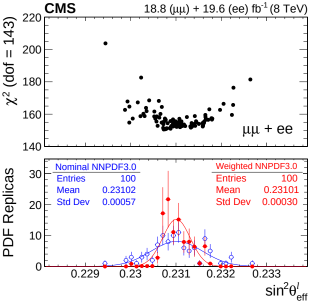
“$\mathrm{ee}_{\rm CF}$”: $q\bar{q} \to Z/\gamma^* \to e^+e^-$:



CMS Effective Weak Mixing Angle at 8 TeV [4]

- $\mathcal{L}$ = 19.6 (muon channel), 18.8 fb^{-1} (electron channel) of *pp* data from 2012.
- $\mathrm{ee}_{\mathrm{CC}}$ and $\mu\mu_{\mathrm{CC}}$ were used in the measurement of A_{FB}.
- An angular event weighting is used to compute A_{FB}, making it less sensitive to detector efficiency and acceptance effects while reducing the statistical uncertainty.
- Experimental uncertainty is dominated by the lepton momentum calibration and the limited size of the signal MC.
- $\sin^2\theta^{\ell}_{\mathrm{eff}}$ is extracted from the data by fitting it with predictions from POWHEG v2 event generator using the NNPDF3.0 PDFs and varying the input effective weak mixing angle.
- The PDF uncertainty, a dominant uncertainty in the A_{FB} analysis of $\theta^{\ell}_{\mathrm{eff}}$, is reduced by constraining the PDFs using a Bayesian χ^2 reweighting procedure.

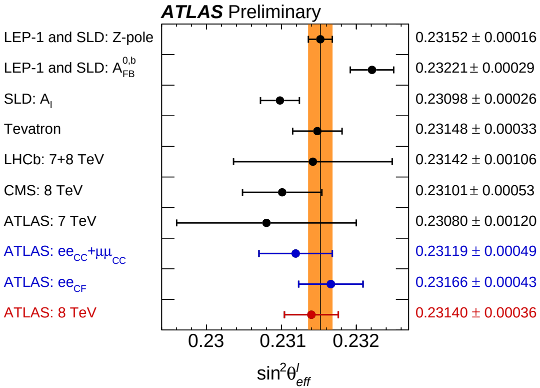




ATLAS and CMS Results [3, 4]

ATLAS: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.})$

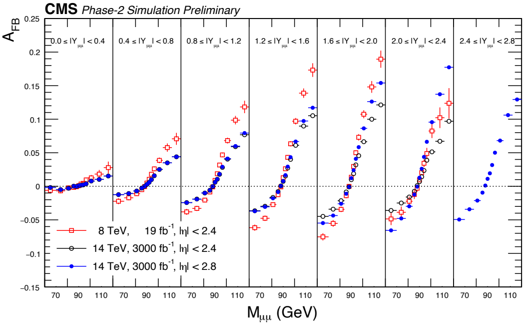
CMS: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036\,(\text{stat.}) \pm 0.00031\,(\text{PDF}) \pm 0.00018\,(\text{syst.}) \pm 0.00016\,(\text{theo.})$



- Uncertainties are significantly reduced relative to previous measurements, now approaching Tevatron precision:
  - **ATLAS:** 0.23080 ± 0.0012 (ATLAS 7 TeV) $\rightarrow$ 0.23140 ± 0.00036 (ATLAS 8 TeV)
  - **CMS:** 0.22870 ± 0.0032 (CMS 7 TeV) $\rightarrow$ 0.23101 ± 0.00053 (CMS 8 TeV)
- Not including ee_{CF}, ATLAS ee_{CC}+$\mu\mu_{\text{CC}}$ comparable to CMS result.

Prospects at the HL-LHC [5]

- Studies performed to assess the potential impact of the HL-LHC on future measurements of $\theta^{\ell}_{\text{eff}}$ at ATLAS and CMS (and LHCb).
- $\mathcal{L} = 3000\ \text{fb}^{-1}$ of data at $\sqrt{s} = 14$ TeV.
- $\theta^{\ell}_{\text{eff}}$ precision obtained from an A_{FB} analysis with expected to exceed the precision achieved in all previous single-experiment results to date.



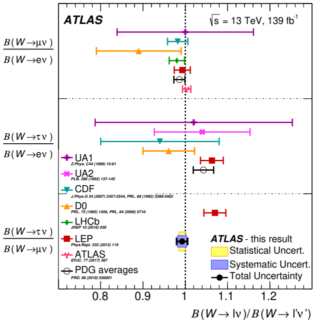
- The uncertainty on future measurements with HL-LHC are expected to be dominated by PDF uncertainty making it essential to reduce their effect as much as possible.

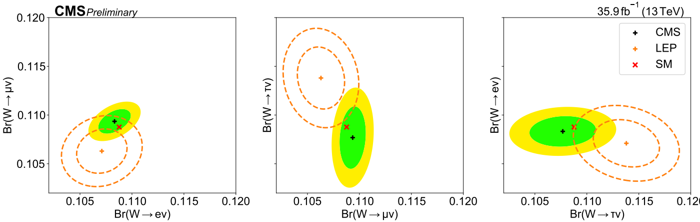
	ATLAS $\sqrt{s} = 8$ TeV	ATLAS $\sqrt{s} = 14$ TeV	ATLAS $\sqrt{s} = 14$ TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14	CT14	PDF4LHC15$_{HL-LHC}$
$\sin^2\theta^{\text{lept}}_{\text{eff}}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	$\pm$ 21	$\pm$ 4	$\pm$ 4
PDFs	$\pm$ 24	$\pm$ 16	$\pm$ 13
Experimental Syst.	$\pm$ 9	$\pm$ 8	$\pm$ 6
Other Syst.	$\pm$ 13	-	-
Total	$\pm$ 36	$\pm$ 18	$\pm$ 15

L_{int}	$\delta_{\text{stat}}[10^{-5}]$		$\delta^{\text{nominal}}_{\text{nnpdf3.0}}[10^{-5}]$		$\delta^{\text{constrained}}_{\text{nnpdf3.0}}[10^{-5}]$	
(fb^{-1})	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$
10	76	51	75	57	39	29
100	24	16	75	57	27	20
500	11	7	75	57	20	16
1000	8	5	75	57	18	14
3000	4	3	75	57	15	12
19	43		49		27	
19 (from [4])	44		54		32	

ATLAS and CMS Charged Current Drell-Yan [6, 7]

- Charged current Drell-Yan (mediated by the $W^{\pm}$) is also an important and physics rich process actively being studied by the two experiments.
- Recent ATLAS measurements include a test of the universality of τ and μ lepton couplings in W decays from $t\bar{t}$ events at 13 TeV.
  - $R(\tau/\mu) = B(W \to \tau\nu_\tau)/B(W \to \mu\nu_\mu) = 0.992 \pm 0.013$ (or $\pm 0.007(\mathrm{stat.}) \pm 0.011(\mathrm{syst.})$), which is in agreement with the hypothesis of universal lepton couplings.
- CMS has performed a similar measurement of the W branching fractions in pp collisions at 13 TeV.
  - $W \to e, \mu, \tau$: $(10.83 \pm 0.1)\%$, $(10.94 \pm 0.08)\%$, and $(10.77 \pm 0.21)\%$ in support of lepton universality.





Conclusions

- Both the ATLAS and CMS experiments have thoroughly studied the Drell-Yan process using their respective 8 TeV and 13 TeV datasets.
- Differential measurements of the production cross section have been used to further our understanding of QCD in a large energy range – greatly important for a wide variety of Standard Model measurements and searches being done by the two experiments.
- ATLAS and CMS have measured the effective weak mixing angle at 8 TeV using novel techniques, drastically improving on the precision of the 7 TeV measurements.
- As the community works towards the HL-LHC, the large dataset that will be collected will offer many new opportunities for exciting Drell-Yan measurements.
- Finally, extremely rich Standard Model physics can be studied from measurements of the charged current Drell-Yan process.