NNLO QCD predictions of charge asymmetry distributions for inclusive W-boson hadroproduction

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Outline of the talk

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- ✓ The master formula
- ✓ W boson & lepton charge asymmetry
- ✓ Computational setup & fiducial requirements
- ✓ Theoretical uncertainties
- ✓ Comparison with the data
- ✓ Forward distributions at higher energies
- ✓ Impact of p^l_T on charge asymmetries at 13 TeV
- ✓ Predictions in the p^W_T bins at 13 TeV
- ✓ Conclusion

✓Presented here the main phenomenological results from the charge asymmetry predictions acquired in perturbative QCD for W boson hadroproduction, based on the following original papers:

- ➢ *arXiv:2105.14265*, NNLO QCD predictions in the forward region
- ➢ *arXiv:2108.04570*, Impact of lepton p_T threshold on charge asymmetry predictions

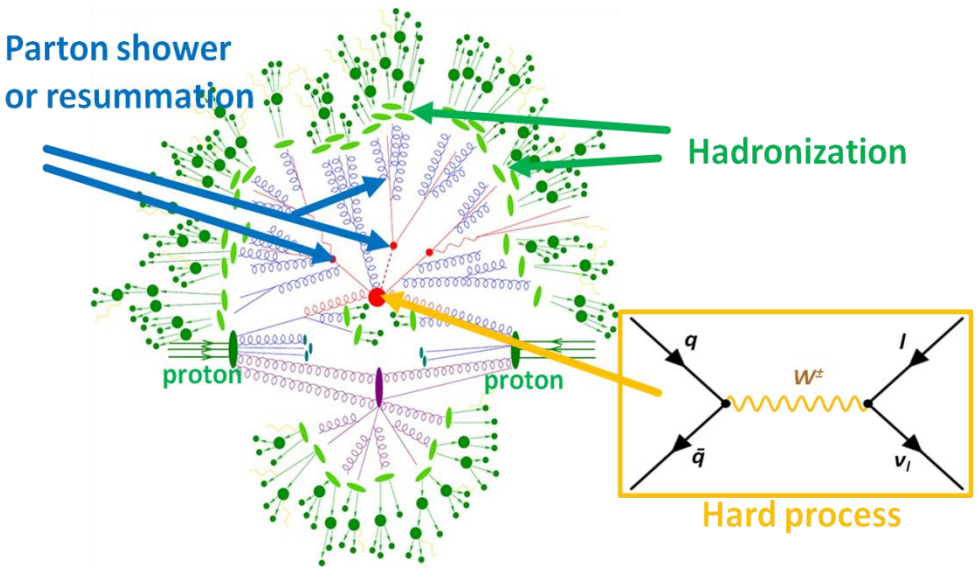
Motivation

- **Weak vector boson (W and Z boson) production at hadron colliders including the CERN LHC constitutes prominent benchmark processes:**
  - **precision tests of QCD and EW sectors of the SM**
  - **valuable inputs for parton distribution functions (PDFs) in the proton**
  - **improved background modeling for some SM processes and in BSM searches**
  - **calibrating detector responses for leptons, jets, and missing energy signatures**

➢ **Notably enabling stringent tests of MC generators and (non)perturbative QCD calculations**

➢ **Produced in abundance in leptonic final states *$W \to l\nu$ and $Z/\gamma^* \to l^+l^-$ (l=e, μ)*, offering clean experimental signatures such as in pp collisions at the LHC**

➢ **A typical W boson event is characterized by one isolated charged lepton with high transverse momentum and large missing transverse energy due to the neutrino**



The master formula

- We consider the pp collision as hadronic process $p_1(P_1) + p_2(P_2) \to W + X \to l\nu + X$ where P_1 and P_2 are the momenta of the colliding protons p_1 and p_2, respectively
- The differential hadronic cross section $d\sigma$ is expressed by the generic formula:

$$d\sigma(p_1 p_2 \to W + X) = \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 f_{i,p_1}(x_1, \mu_F^2) f_{j,p_2}(x_2, \mu_F^2) d\hat{\sigma}_{ij}(x_1 P_1, x_2 P_2; \mu_F^2)(1 + \mathcal{O}(\Lambda_{QCD}/Q))$$

- $f_{ip_1,jp_2}(x, \mu_F^2)(i,j = q, \bar{q}, g$ stand for parton distribution functions of the proton, μ_F is the corresponding factorization scale
- The partonic cross section $d\hat{\sigma}_{ij}$ is calculated in QCD perturbation theory:

$$d\hat{\sigma}_{ij}(P_1, P_2; \mu_F^2) = d\hat{\sigma}^{(0)}(P_1, P_2) + \alpha_S(\mu_R^2) d\hat{\sigma}^{(1)}(P_1, P_2; \mu_F^2) + \alpha_S^2(\mu_R^2) d\hat{\sigma}^{(2)}(P_1, P_2; \mu_F^2, \mu_R^2) + \mathcal{O}(\alpha_S^3)$$

- with α_S is the QCD running coupling, and μ_R is the renormalization scale. The leading order (LO) partonic cross section is $d\hat{\sigma}^{(0)}$, $d\hat{\sigma}^{(1)}$ and $d\hat{\sigma}^{(2)}$ are the included next-to-LO (NLO) and next-to-NLO (NNLO) corrections , respectively
- Here NNLO and beyond refer to precise prediction and robust uncertainty:

$$d\hat{\sigma}_{ij} \sim d\hat{\sigma}_{LO} \cdot (1 + \alpha_S + \alpha_S^2 + \alpha_S^3 + \ldots)$$

fixed order: LO NLO NNLO N^3LO + …

Uncertainties: (for α_S=0.118)
LO ~ $\mathcal{O}$(100%)
NLO ~ $\mathcal{O}$(10%)
NNLO ~ $\mathcal{O}$(1%)

W boson & lepton charge asymmetry

- W bosons produced primarily through the annihilation mechanisms as $u\bar{d} \rightarrow W^+$ and $d\bar{u} \rightarrow W^-$
- W^+ bosons are produced more often than W^- bosons due to excess of two valence u quarks over one valence d quark in the proton
- Leading to a production asymmetry between W^+ and W^- bosons, referred to as the W boson charge asymmetry A_{yW}, expressed differentially by $\sigma(W^+)$ and $\sigma(W^-)$ in rapidity y_W

$$A_{y_W} = \frac{d\sigma(W^+ \rightarrow l^+\nu)/dy_W - d\sigma(W^- \rightarrow l^-\bar{\nu})/dy_W}{d\sigma(W^+ \rightarrow l^+\nu)/dy_W + d\sigma(W^- \rightarrow l^-\bar{\nu})/dy_W}$$

- Limitation: W boson momentum p^W_T and its rapidity y_W cannot be directly reconstructed owing to the neutrino leaving detector unobserved
- Alternatively in experiments, charge asymmetry from the decay letpon $A_{\eta l}$ is measured as a function of its pseudorapidity η_l (which is strongly correlated with y_W)

$$A_{\eta_l} = \frac{d\sigma(W^+ \rightarrow l^+\nu)/d\eta_l - d\sigma(W^- \rightarrow l^-\bar{\nu})/d\eta_l}{d\sigma(W^+ \rightarrow l^+\nu)/d\eta_l + d\sigma(W^- \rightarrow l^-\bar{\nu})/d\eta_l}$$

- $A_{\eta l}$ can provide significant constraints on the ratio of u and d quark densities as a function of parton Bjorken-x values, help discriminate among different PDFs, and be measured more precisely as some systematic uncertainties cancel in its ratio

Computational setup & fiducial requirements

- *MATRIX* framework *[arXiv: 0903.2120, 1711.06631]* used for fixed-order calculations
- Resummation of logarithmic terms achieved by the *MATRIX+RadISH [arXiv:2004.07720]*
  - *q_T-subtraction* method *for* the cancellation of IR divergences using a fixed cut-off as r_{cut}=0.0015 (0.15%)
  - various PDF models as NNPDF3.1, CT14, MMHT2014, and PDF4LHC15 exploited, all based on α_S=0.118
- The Fermi constant EW input scheme used including m_W=80.385 GeV and G_F=1.16639x10^{-5} GeV^{-2}
- Central values for the scales $\mu_R=\mu_F=x_Q=m_W$=80.385 GeV with x_Q as resummation scale

- Fiducial phase space requirements adopted from actual LHC experiments

i. Calculations in the forward acceptance region $2.0<\eta_l<4.25$:
   - the decay electron mode considered at center-of-mass energies 8 TeV, 13 TeV, and 14 TeV, where p^e_T>20 GeV required in line with the LHCb measurement *[arXiv: 1608.01484]*

ii. Calculations in the full acceptance region $0<\eta_l<4.5$:
   - the muon decay mode considered at 8 TeV, p^μ_T>25 GeV (p^μ_T>20 GeV) required in the region $0<\eta_\mu<2.4$ ($2.0<\eta_\mu<4.5$) in line with the CMS *[arXiv: 1603.01803]* and LHCb *[arXiv: 1511.08039]* measurements
   - the lepton (both e and μ) decay mode used at 13 TeV, p^l_T>20, 25, 30, and 40 GeV required

Theoretical uncertainties

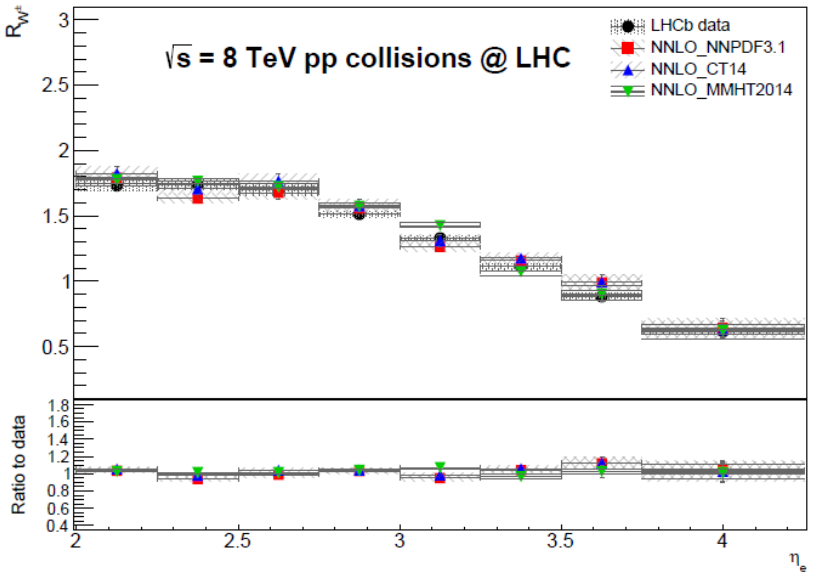
- **Estimate of theoretical uncertainties from *scale variation*, *PDFs*, and α_S *variation***
- **Scale uncertainties based on μ_R and μ_F variation up and down around their central values excluding $0.5 \leqslant \mu_R/\mu_F \leqslant 2.0$, customarily as 7-point scale variation scheme**
- **9-point variation scheme considered (an additional 2-point variation with μ_R and μ_R fixed at the central value while resummation scale x_Q is varied up and down) in matching of fixed-order calculations to resummation**

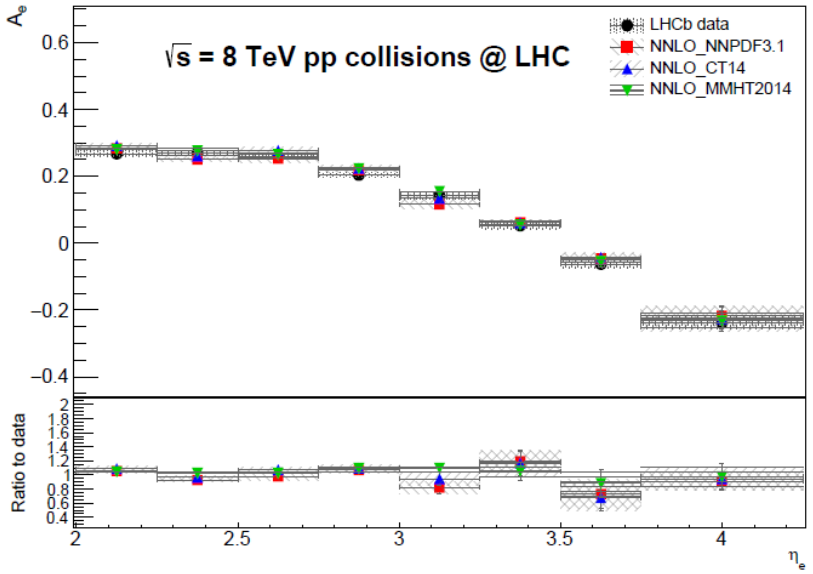
Uncertainty	NNPDF3.1	CT14	MMHT2014
	Values for $W^+ \to e^+\nu$ process		
Scale (%)	0.74	0.76	0.78
PDF (%)	1.96	2.40	1.64
α_s (%)	1.06	1.04	1.10
Total (%)	2.35	2.72	2.12
	Values for $W^- \to e^-\nu$ process		
Scale (%)	0.72	0.64	0.80
PDF (%)	2.22	2.90	1.50
α_s (%)	1.16	1.00	1.14
Total (%)	2.61	3.13	2.05

Estimated sizes of uncertainties for W boson inclusive cross section at NNLO

Comparison with the data - I

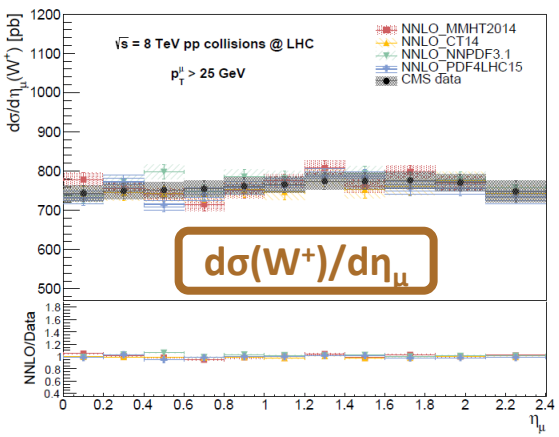
- $W^{\pm}$ decay processes in the *e* decay channel in the forward region $2.0<\eta_e<4.25$
- Compared with the 8 TeV LHCb data in the fiducial region for the ratio $R_{W^{\pm}}$ and A_{η_e} variables
- Predicted distributions at NNLO using different PDF sets are in agreement with the data
- Predictions using MMHT2014 PDF set describe data slightly better in the range ~5% over other PDF sets

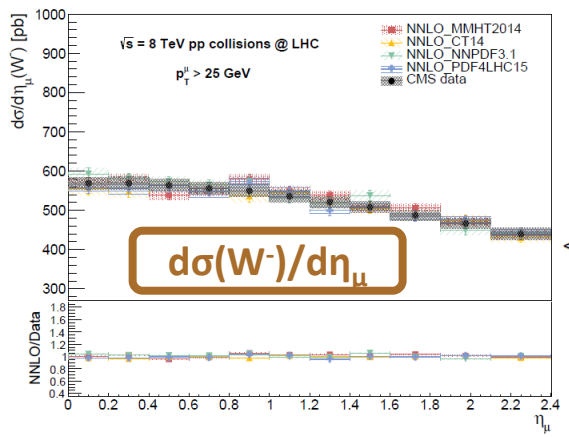


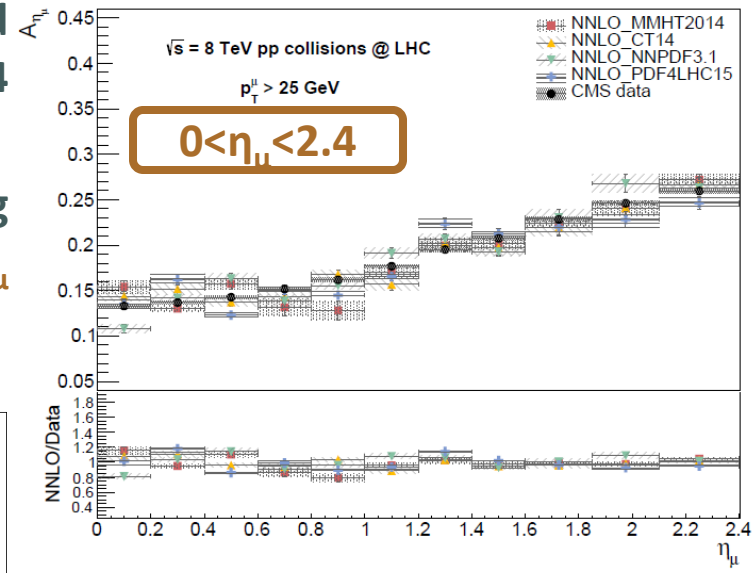


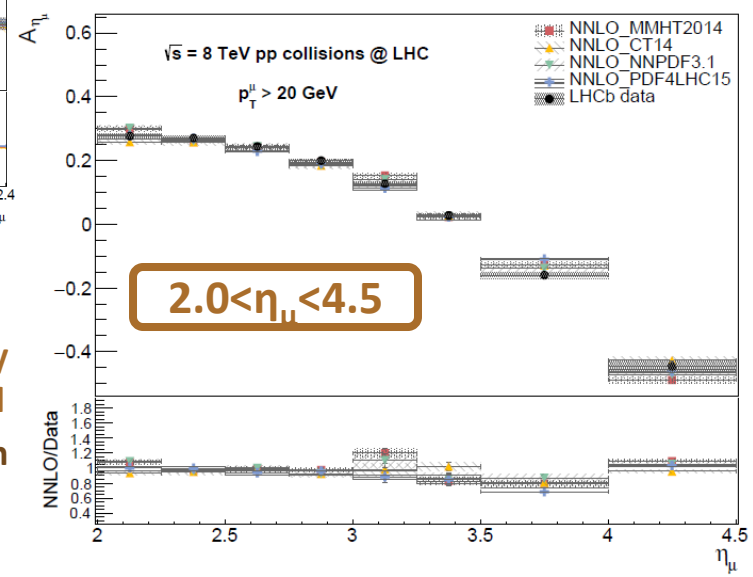
Comparison with the data - II

- Predicted distributions at NNLO accuracy compared with the CMS (LHCb) data in the central $0<\eta_\mu<2.4$ (forward $2.0<\eta_\mu<4.5$) region separately
- Predictions in the μ decay channel at 8 TeV using differential cross sections $d\sigma(W^+)/d\eta_\mu$, $d\sigma(W^-)/d\eta_\mu$ (bottom), and A_{η_μ} variable (right)









- Good agreement with the data in the entire region $0<\eta_\mu<4.5$ probed
- The predicted distribution from CT14 describes the data slightly better over the predictions using the other PDF sets in the μ channel
- Sensitivity to discriminate among various PDF sets is enhanced in the A_{η_μ} variable in comparison to the differential cross sections

Forward distributions at higher energies

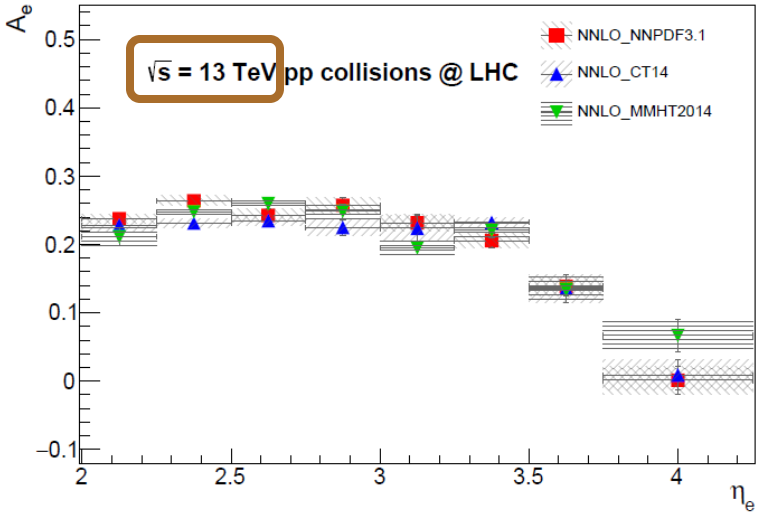
- Predicted A_{η_e} distributions at 13 TeV and 14 TeV represent important probe for u and d quark densities in the proton
- The forward region $2.0<\eta_l<4.5$ opens up unique opportunities for more accurate PDF determination at very small and large Bjorken-x vlues within $10^{-4}<x<10^{-1}$

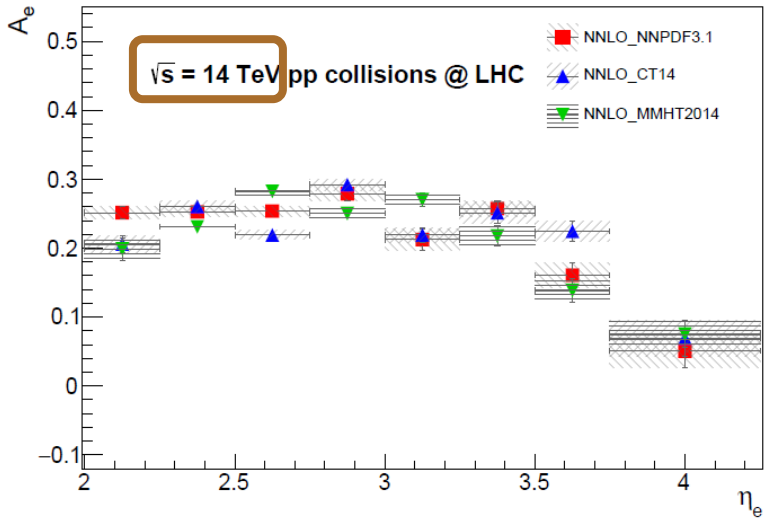
A_{η_e}@13 TeV

η_e	NNPDF3.1	CT14	MMHT2014
2.00–2.25	23.78±0.6	22.84±0.9	21.11±1.3
2.25–2.50	26.40±0.7	23.13±0.7	24.77±0.6
2.50–2.75	24.27±1.0	23.47±0.7	26.00±1.6
2.75–3.00	25.75±1.2	22.51±1.1	24.85±1.1
3.00–3.25	23.18±1.2	22.38±1.9	19.50±1.0
3.25–3.50	20.57±1.1	23.23±0.8	22.07±1.1
3.50–3.75	13.86±1.7	13.57±1.9	13.41±1.9
3.75–4.25	0.15±2.0	0.91±2.2	6.67±2.3

A_{η_e}@14 TeV

η_e	NNPDF3.1	CT14	MMHT2014
2.00–2.25	25.15±0.9	20.60±1.3	19.90±1.6
2.25–2.50	25.26±0.7	26.05±0.8	23.09±0.5
2.50–2.75	25.38±0.7	21.91±0.7	28.24±0.6
2.75–3.00	27.90±1.0	29.22±0.8	25.04±0.8
3.00–3.25	21.24±1.5	21.93±1.1	27.04±1.1
3.25–3.50	25.74±1.1	25.13±1.6	21.76±1.5
3.50–3.75	16.06±1.8	22.46±1.4	13.87±1.7
3.75–4.25	5.08±2.4	6.97±2.6	7.53±2.0

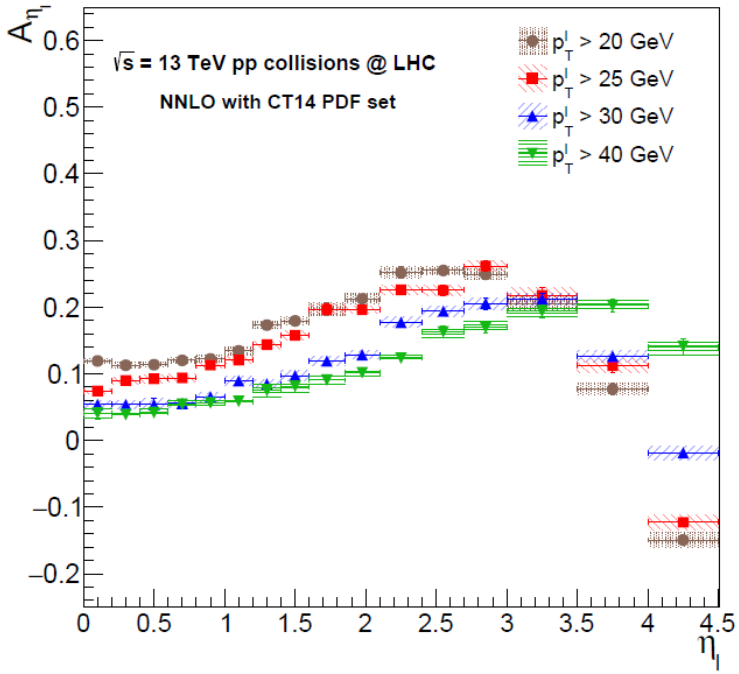


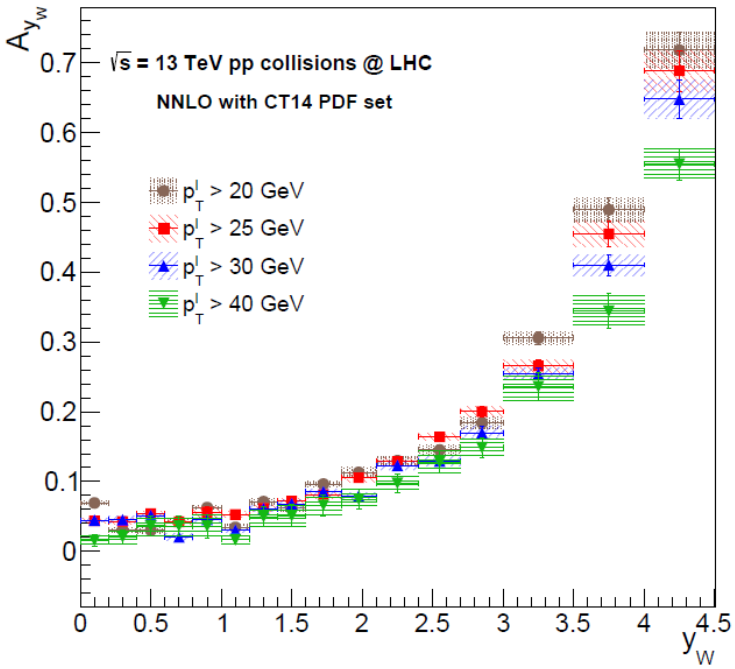


Predicted $A_{\eta l}$ distributions tend to distinguish among numerous PDF sets increasingly from 8 TeV onwards 13 TeV and 14 TeV

Impact of p^l_T on charge asymmetries at 13 TeV

- Assess the impact of low-p^l_T thresholds at NNLO QCD in the entire region $0<\eta_l<4.5$
- Thresholds p^l_T>20, 25, 30, and 40 GeV examined in the combined lepton (e and μ) channel
- Represents a finer probe in constraining PDFs in the range $10^{-4}<x<1$
- Profit from both charge asymmetry definitions $A_{\eta l}$ and A_{yW}





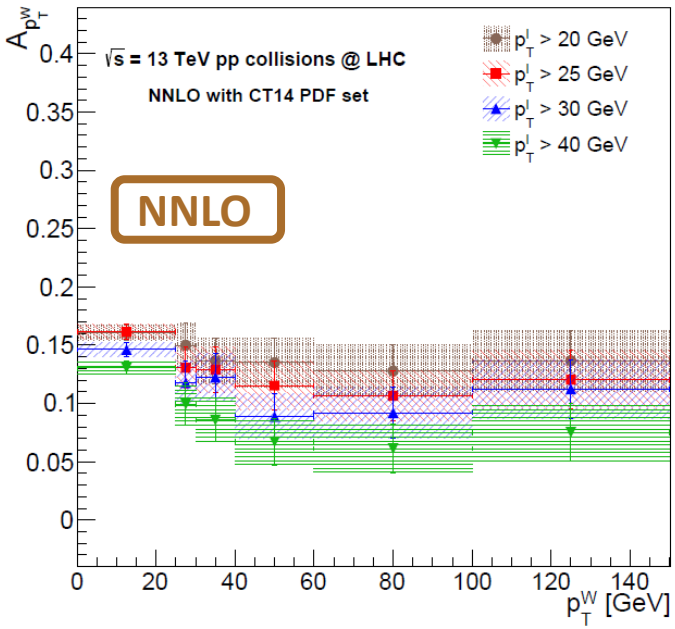
- Minimum p^l_T values clearly exhibit dependence on the $A_{\eta l}$ and A_{yW} distributions
- The correlation between $A_{\eta l}$ and A_{yW} variables become more apparent in the forward region when the distribution shapes approach each other with increasing values of the p^l_T

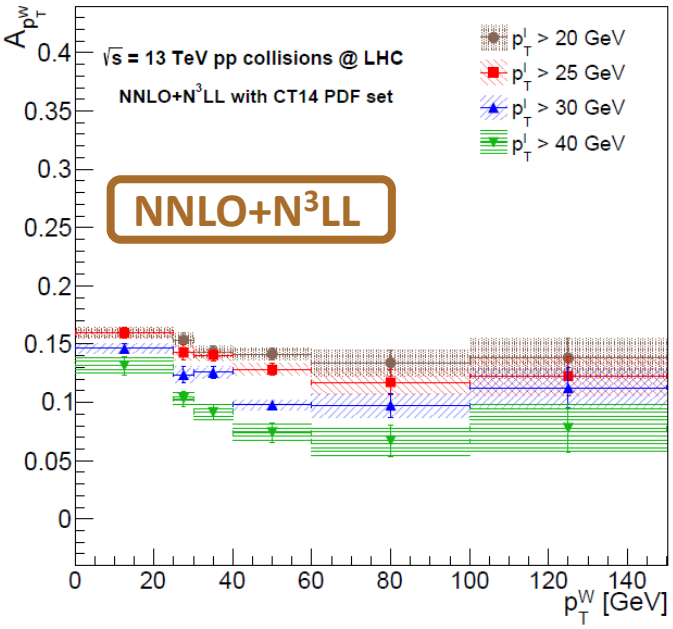
Predictions in the p^W_T bins at 13 TeV

- **The state-of-the-art predictions for $A_{p^W_T}$, based on an analogous definition in bins of p^W_T**

$$A_{p_T^W} = \frac{d\sigma(W^+ \to l^+\nu)/dp_T^W - d\sigma(W^- \to l^-\bar{\nu})/dp_T^W}{d\sigma(W^+ \to l^+\nu)/dp_T^W + d\sigma(W^- \to l^-\bar{\nu})/dp_T^W}$$

- **Fixed-order calculations are unable to sufficiently account for soft and collinear gluon radiation at low p^W_T values → exploit resummed calculations (up to N³LL accuracy) matched to fixed-order NNLO to have higher-accuracy**





- **Increasing p^l_T threshold yields lower values in both the central and forward regions**
- **Flatter distributions throughout almost the entire region, contrary to A_{η_l} and A_{y_W}**

Conclusion

- ✓ We have presented precise predictions for W boson and lepton charge asymmetry, with the inclusion of NNLO corrections in perturbative QCD based on existing PDF models, which were justified with the LHC data at 8 TeV
- ✓ Sensitivity to relative u and d quark densities in the proton and also in more constrained phase space with higher p^l_T thresholds provide unique set of input for better determination of PDFs
- ✓ Charge asymmetry distributions are shown to be prominent for discriminating among various PDF models
- ✓ W boson and lepton charge asymmetries are predicted to be more correlated with increasing p^l_T thresholds in the forward region
- ✓ Charge asymmetry in bins of p^W_T can offer an alternate probe for theoretical predictions
- ✓ Overall, the predicted results represent a substantial contribution to the context of the high-precision phenomenological studies.

Thank you!

Back-up slides