Parton distribution functions and Monte Carlo simulations of photon-photon collisions

ATP seminar

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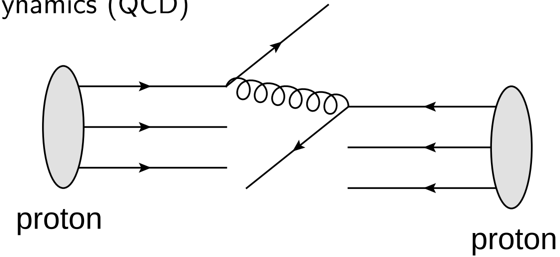
13.5.2015

Outline

Introduction

- In high-energy proton-proton collisions interactions happens between the quarks and gluons (=partons), described by Quantum Chromodynamics (QCD)



Collinear Factorization

Factorize long and short distance physics:

$$d\sigma^{p+p\to k+X} = \sum_{i,j,X'} f_i(x_1, Q^2) \otimes f_j(x_2, Q^2) \otimes d\hat{\sigma}^{ij\to k+X'} + \mathcal{O}(1/Q^2)$$

- $d\hat{\sigma}^{ij\to k+X'}$ calculated using perturbative QCD
- $f_i(x, Q^2)$ non-perturbative but universal functions
- x fraction of proton momentum carried by the parton ($\hat{p} = xp$)

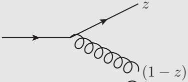
Parton distribution functions (PDFs)

- PDFs can not be calculated from first principles of QCD
- However, the Q^2 depedence is given by DGLAP evolution equations:

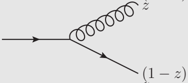
$$\frac{\partial f_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{\mathrm{d}z}{z} P_{ij}(z)\, f_j(x/z,Q^2)$$

where j runs over the parton flavours

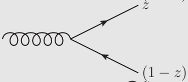
The leading order (LO) splitting functions



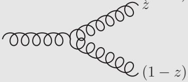
$$P_{qq}(z) = \frac{4}{3}\left[\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\right]$$



$$P_{qg}(z) = \frac{4}{3}\left[\frac{1+(1-z)^2}{z}\right]$$



$$P_{gq}(z) = \frac{1}{2}\left[z^2 + (1-z)^2\right]$$



$$P_{gg}(z) = 6\left[\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z) + \frac{11-\frac{2}{3}n_f}{12}\delta(1-z)\right]$$

Parton distribution functions (PDFs)

- Problem: The x-depedence not given by QCD
- Solution: Use experimental data to fix the non-perturbative input

Global DGLAP analysis

1. Parametrize $f_i(x, Q^2)$ at chosen initial scale Q_0 $(\sim 1\,\mathrm{GeV})$

$$f_i(x, Q_0^2) = N_i x^{a_i}(1-x)^{b_i} F(x, c_i, \ldots)$$

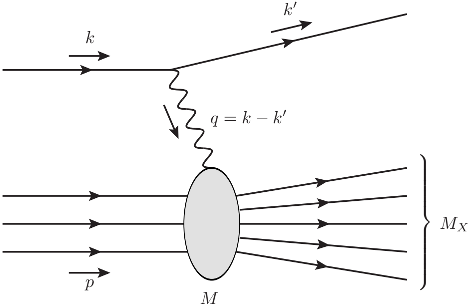
2. Use DGLAP equations to calculate $f_i(x, Q^2)$ at $Q > Q_0$

$$\frac{\partial f_i(x, Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{\mathrm{d}z}{z} P_{ij}(z)\, f_j(x/z, Q^2)$$

3. Calculate cross section with the evolved PDFs
4. Fit to data to obtain the values for parameters $\{a_i\}$

Deep inelastic scattering

- Probe hadron with a lepton beam



Invariant variables

$$Q^2 = -q^2$$
$$x = \frac{Q^2}{2\,p\cdot q}$$
$$y = \frac{p\cdot q}{p\cdot k}$$

- Provided by the scattered lepton

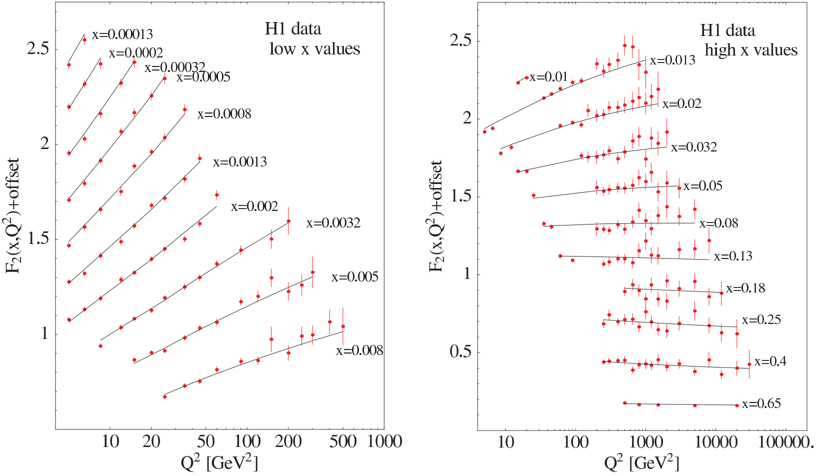
Cross section

$$\frac{\mathrm{d}\sigma^{\mathrm{DIS}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha_{\mathrm{EM}}^2}{Q^4}\frac{1}{x}\left[xy^2 F_1(x,Q^2) + (1-y)\,F_2(x,Q^2)\right]$$

- Structure functions $F_i(x,Q^2)$ can be directly related to PDFs
- At LO: $2xF_1(x,Q^2) = F_2(x,Q^2) = \sum_q e_q^2 f_q(x,Q^2)$

DGLAP evolution

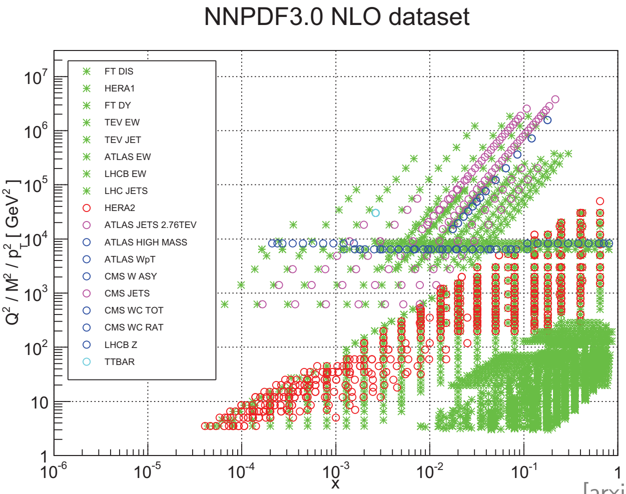
The scale evolution of $F_2(x, Q^2)$ (HERA data, CTEQ6NLO fit)



[JHEP 0207 (2002) 012]

- DGLAP evolution describes the data very well
  $\Rightarrow$ With higher scales more partonic substructure observed

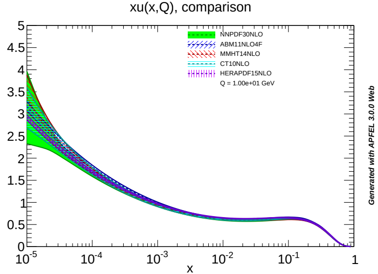
Current kinematical coverage

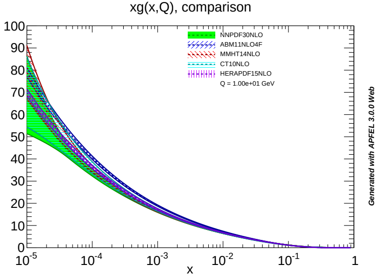


[arxiv:1410.8849]

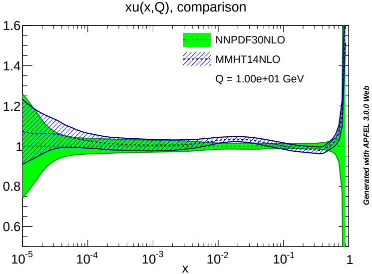
- Also other data available for the fits (from LHC and Tevatron)
- For proton PDFs ~ 4000 data points available (~ 3000 from DIS)
- Precise data constraints at $x \gtrsim 10^{-4}$

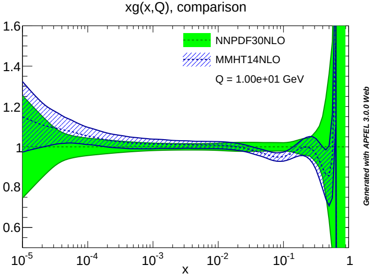
PDF comparison





Relative uncertainties

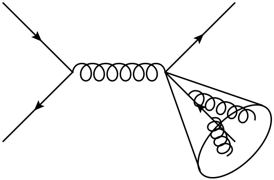


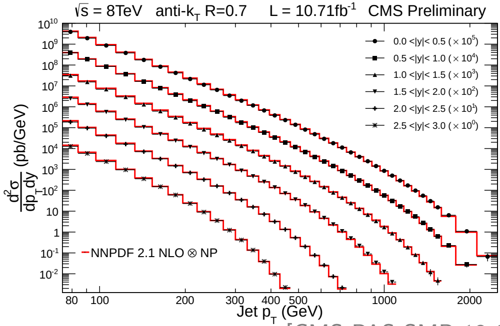


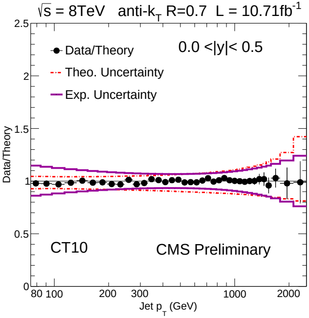
- Good agreement between different analyses
- Uncertainties $< 5\,\%$ where there are data

Inclusive jet production in p+p

$$\frac{\mathrm{d}\sigma^{\mathrm{jet}}}{\mathrm{d}p_T\mathrm{d}y} = \sum_{i,j} \int \mathrm{d}x_1\,\mathrm{d}x_2\, x_1 f_i(x_1,Q^2)\, x_2 f_j(x_2,Q^2) \frac{\mathrm{d}\hat{\sigma}^{ij\to\mathrm{jet}}}{\mathrm{d}p_T\mathrm{d}y}$$





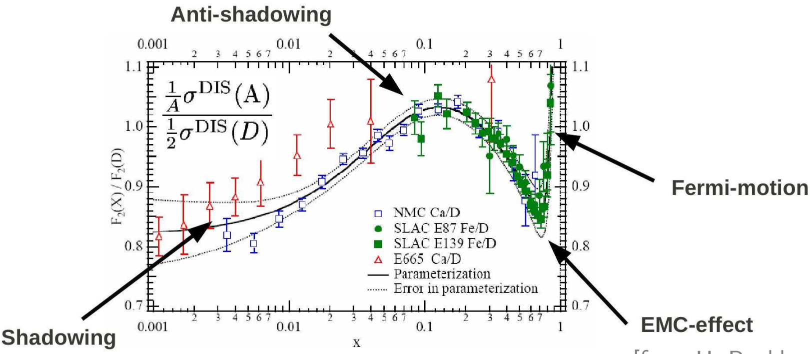


[CMS-PAS-SMP-12-012]

- Very good describtion of the data for jet production
  $\Rightarrow$ Factorization works well at the LHC
- Small PDF uncertainties

Nuclear PDFs

- In addition to p+p, also p+Pb and Pb+Pb collisions at the LHC
- Structure functions modified in nuclear DIS:



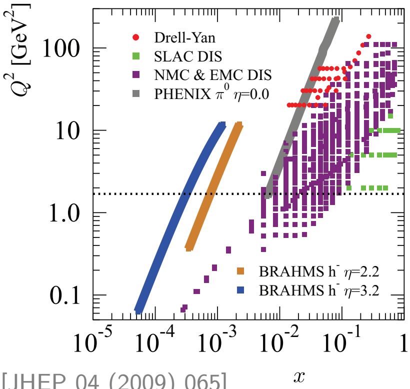
[from H. Paukkunen]

- Modifications absorbed into *process independent* nuclear PDFs:

$$f_i^A(x, Q^2) = R_i^A(x, Q^2) f_i(x, Q^2)$$

- Global DGLAP analyses
  - Provide the nuclear modifications $R_i^A(x, Q^2)$
  - Test factorization of nuclear effects

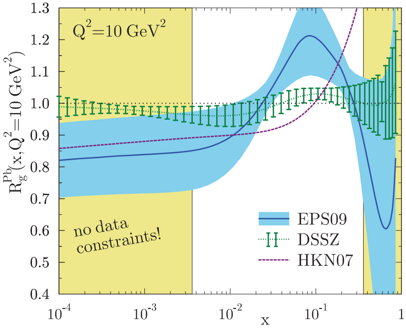
Kinematic coverage of nuclear data:



[JHEP 04 (2009) 065]

- Much less data than for proton

Gluon nuclear modification:



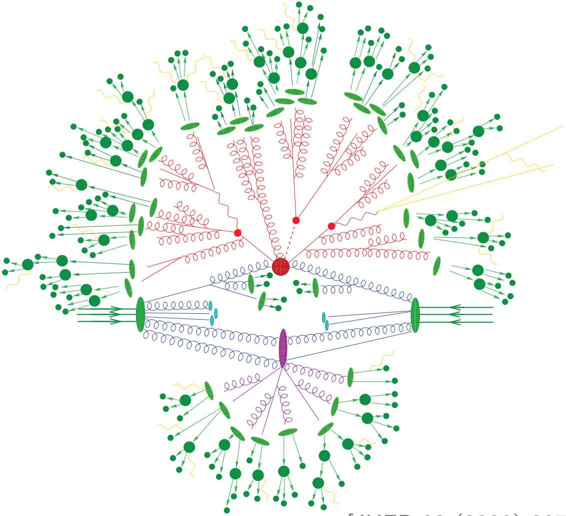
[Nucl.Phys.A926 (2014) 24-33]

- Sizeable uncertainties in the fits
- Discrepancies between analyses

- Fits not at the same level of accuracy as for protons
- Recent data from p+Pb collisions consistent with the predictions
  $\Rightarrow$ Factorization of nuclear effects holds also at LHC energies

Monte Carlo event generators

- Hadronic collisions are complex events



[JHEP 02 (2009) 007]

Need to simulate:

1. Hard process
2. Parton shower
3. Multiple interactions
4. Beam remnants
5. Hadronization
6. Decays

...

MC generators

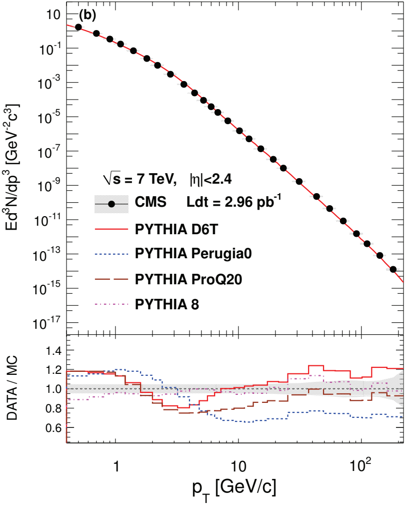
- Herwig
- Sherpa
- Pythia

PYTHIA8

Typical simulation pattern

1. Generate hard process using
   - PDFs
   - perturbative QCD
2. Generate parton shower using DGLAP equations
   - Initial state radiation (ISR)
   - Final state radiation (FSR)
3. Construct beam remnants
4. Hadronize event
   - String model

[JHEP 09 (2011) 086]



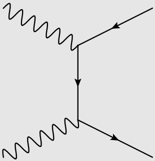
- Very good description of charged particle yield

Photon-photon collisions

Photon-photon collisions

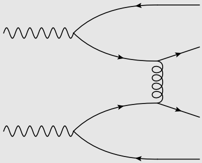
- Next large collider project most likely a electron-positron collider
  - Linear collider
  - Circular collider (FCC-ee)
- Clean environment to make precision measurements
- However, high-energy $e^{\pm}$ radiate photons
  $\Rightarrow$ background from photon-photon interactions
- High-energy photons can fluctuate to hadronic state

Direct processes



- Can be directly calculated

Resolved processes



- Need photon PDFs!

Photon PDFs

- Determined via global DGLAP analysis

Photon scale evolution

- Inhomogeneous DGLAP equations for photons

$$\frac{\partial f_i^{\gamma}(x,Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{\mathrm{EM}}}{2\pi} e_i^2 k_i(x) + \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{\mathrm{d}z}{z} P_{ij}(z)\, f_j(x/z, Q^2)$$

where $k_i(x) = 3(x^2 + (1-x)^2)$ arise from the $\gamma \rightarrow \mathrm{q\bar{q}}$ splitting

- Solution has two components:

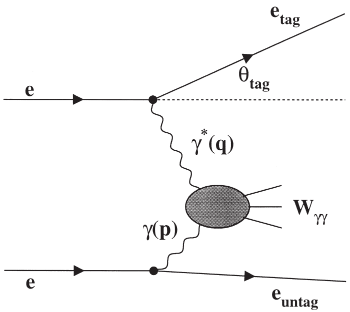
$$f_i^{\gamma}(x,Q^2) = f_i^{\gamma,\mathrm{pl}}(x,Q^2) + f_i^{\gamma,\mathrm{had}}(x,Q^2)$$

  - Point-like part, special solution of full equation
  - Hadron-like part, general solution of homogeneous part
    $\Rightarrow$ Need non-perturbative input which is fixed by the data

$$f_i^{\gamma,\mathrm{had}}(x,Q_0^2) = N_i x^{a_i}(1-x)^{b_i}$$

Data for photon PDFs

- Photon structure functions can be measured in $\mathrm{e}^{-}+\mathrm{e}^{+}$ collisions



[Phys.Lett.B436 (1998) 403-416]

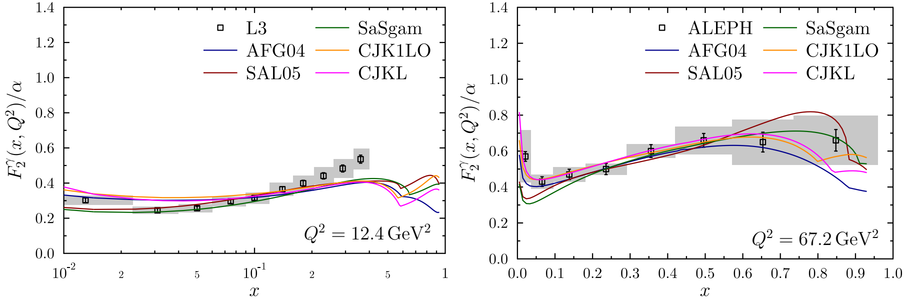
"Photon DIS"

- Other electron emits a virtual photon (γ^{*})
  - $\Rightarrow$ This electron is measured
- Other electron is not detected as the scattering angle is small
  - $\Rightarrow$ Photon from this electron has small virtuality
- Also $W_{\gamma\gamma}$ need to be measured to construct kinematics

- Data available mainly from different LEP experiments ($\mathcal{O}(200)$ points)
- Precision and kinematic coverage more limited than for proton PDFs

Photon PDF fits

- Several groups have performed photon PDF analyses



- Reasonable agreement between the data and the fits
- Some differences between different analyses
- Due to the point-like component $F_2^\gamma(x,Q^2)$ rises with Q^2 for all values of x ($\neq F_2(x,Q^2)$ of protons)

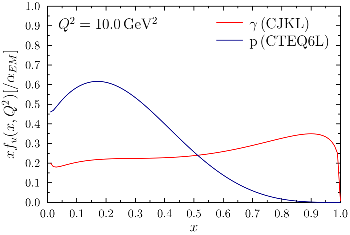
Comparison to p+p collisions

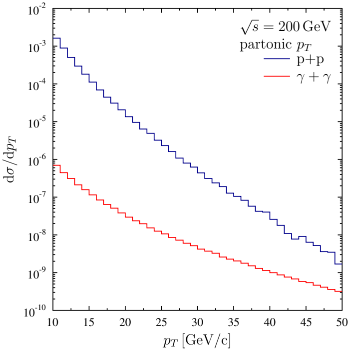
Comparison to proton PDFs

- Photon DGLAP evolution
$$\frac{\partial f_i(Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{\mathrm{EM}}}{2\pi} k_i + \frac{\alpha_s(Q^2)}{2\pi} P_{ij} \otimes f_j(Q^2)$$
has the $\gamma \rightarrow \mathrm{q\bar{q}}$ splitting
- Partons take larger fraction of momenta

Partonic cross section

- Cross section lower due to small coupling constant ($\alpha_{\mathrm{EM}}^2 \sim 10^{-4}$)
- The slope of the cross section less steep
$\Rightarrow$ More high-p_T partons



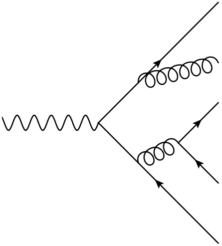


Monte Carlo simulations

- Goal: Simulate photon-photon collisions with `PYTHIA8`

Requires

- Implement photon PDFs into code
- Modify the beam remnant handling
- Modify the initial state radiation
  - Add possibility to the end up to a photon
- Include multiple partonic interactions
  - Add parametrization for total cross section



Further developments

- Consider also virtual photons (currently only real photons)
- Modelling of soft interactions (so far only hard interactions)

Summary & Outlook

Parton distribution functions

- Proton PDFs can be accurately determined with global DGLAP-based analysis
- Also fits for nuclear PDFs but precision still quite limited
- Energetic photons can fluctuate into hadronic state
  $\Rightarrow$ Also photons have partonic structure
- Photon PDFs can be determined using $\mathrm{e}^+ + \mathrm{e}^-$ data

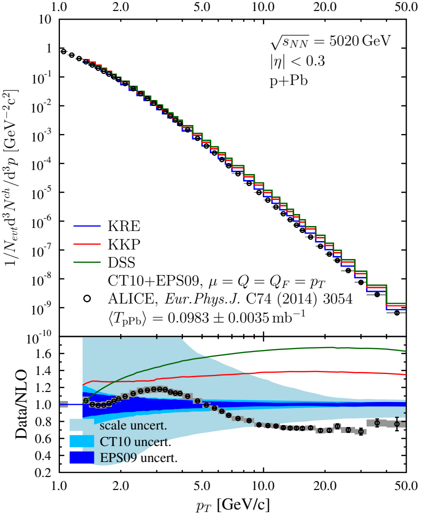
Monte Carlo simulations

- Provide very good description of proton-proton collisions
- Simulations of photon-photon collisions important for future $\mathrm{e}^+ + \mathrm{e}^-$ colliders
- Work ongoing to implement photon-photon collisions into `PYTHIA8`

Backup

Inclusive hadron production

Charged hadron spectra in p+Pb:

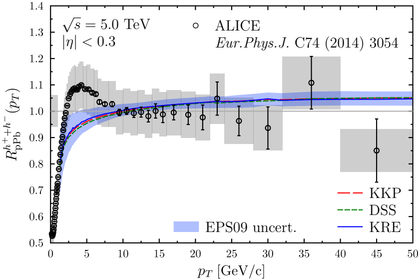


- NLO calculations overshoot the data at $p_T > 10\,\mathrm{GeV/c}$

p+p: [Nucl.Phys. B883 (2014) 615-628]

Nuclear modification ratio

$$R^h_{\mathrm{pPb}}(p_T, \eta) = \frac{1}{208} \frac{\mathrm{d}^2\sigma^h_{\mathrm{pPb}}}{\mathrm{d}p_T \mathrm{d}\eta} \Big/ \frac{\mathrm{d}^2\sigma^h_{\mathrm{pp}}}{\mathrm{d}p_T \mathrm{d}\eta}$$



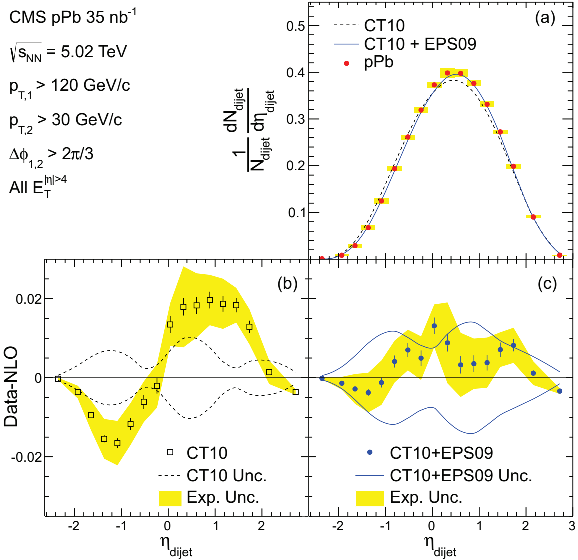
- FF differences cancel in ratio $\Rightarrow R_{\mathrm{pPb}}$ not sensitive to FFs
- Enhacement in the data at $p_T \sim 3\,\mathrm{GeV/c}$

Dijets in p+Pb

Dijet pseudorapidity

$$\eta_{\text{dijet}} = \frac{\eta_1 + \eta_2}{2}$$

- at $\eta_{\text{dijet}} < 0$ data sensitive to antishadowing region
- at $\eta_{\text{dijet}} > 0$ data sensitive to EMC effect
- Good description with EPS09



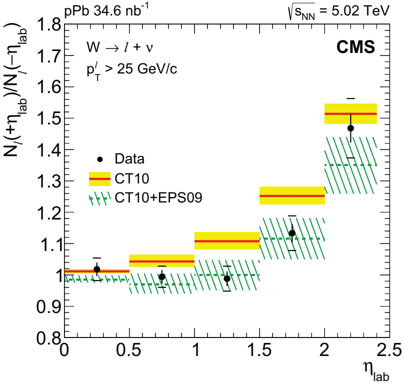
[*Eur.Phys.J.* C74 (2014) 2951]
[*JHEP* 1310 (2013) 213]

$\mathrm{W}^{\pm}$ production

Forward-backward asymmetry

$$N(+\eta_{\rm lab})/N(-\eta_{\rm lab})$$

- Sum over W^{+} and W^{-}
- $\eta_{\rm lab} = \eta + 0.465$
  where η pseudorapidity in nucleon-nucleon CMS frame
- Dominating processes:
  $\mathrm{u}\bar{\mathrm{d}} \rightarrow \mathrm{W}^{+}$ and $\mathrm{d}\bar{\mathrm{u}} \rightarrow \mathrm{W}^{-}$
- Sensitive to
  - $\eta_{\rm lab} > 0$: $0.002 < x < 0.02$
  - $\eta_{\rm lab} < 0$: $0.02 < x < 0.2$
- Good agreement with EPS09



[arXiv:1503.05825]
[*JHEP* 03 (2011) 071]

The gluon nPDFs at small-x remain badly constrained!