Nuclear Parton Distribution Functions

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Motivation

Jets in collinear factorization

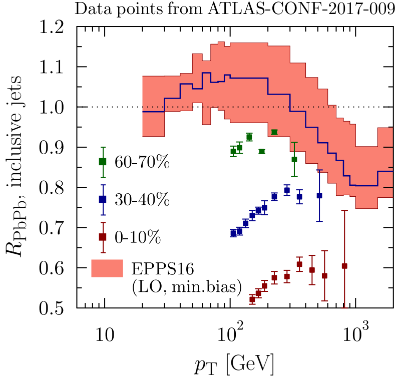
$$\mathrm{d}\sigma^{AB\to jet+X} = \sum_{ij} f_i^A \otimes f_j^B \otimes \mathrm{d}\sigma^{ij\to jet+X}$$

- $\mathrm{d}\sigma^{ij\to jet+X}$: partonic cross section
- f_i^A: Parton distribution functions (PDFs) describing the partonic structure of the beam particle

Nuclear PDFs

- $f_i^A \neq f_i^p$
- Determined from exp. data
- Provides pQCD baseline for jet quenching effects

$$R_{\mathrm{PbPb}} = \frac{\mathrm{d}\sigma^{\mathrm{PbPb}}}{208^2 \mathrm{d}\sigma^{\mathrm{pp}}}$$



[Figure: H. Paukkunen]

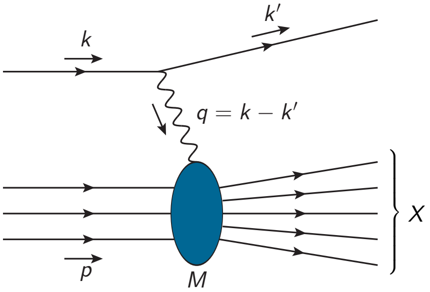
Outline for the lecture

1. Theoretical framework for PDF analyses
   - Deep Inelastic scattering
   - DGLAP evolution
   - Uncertainty analysis
2. Nuclear PDF analyses
   - Data types
   - Current status and uncertainties
3. New constraints from
   - LHC experiments
   - Future facilities
4. Loose ends

Theoretical framework for PDF analyses

How to probe nucleon structure?

Deep Inelastic Scattering (DIS)



- Lepton scatters from a nucleon via a virtual photon with $Q^2 = -q^2$
- High $Q^2 \Rightarrow$ Small length scales

  $\Rightarrow$ Sensitive to nucleon structure
- Invariant variables:

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

- Cross section in terms of structure functions $F_{1,2}(x, Q^2)$

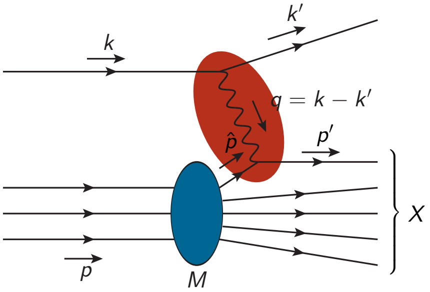
$$\frac{d\sigma^{\text{DIS}}}{dx dQ^2} = \frac{4\pi\alpha_{EM}^2}{Q^4}\frac{1}{x}\left[xy^2 F_1(x, Q^2) + \left(1 - y - \frac{xyM^2}{s - M^2}\right) F_2(x, Q^2)\right]$$

$\Rightarrow$ Scattered lepton provides information on $F_{1,2}(x, Q^2)$

Parton model in leading order

Assume that nucleon consists of partons

- Each parton carries a certain fraction x of the nucleon momentum ($\hat{p} = x\,p$)
- Lepton scatters off from a parton



$$\mathrm{d}\sigma^{\mathrm{DIS}} = \sum_i \int_0^1 \mathrm{d}x\, \mathrm{d}\hat{\sigma}\, f_i(x)$$

where

- $\mathrm{d}\hat{\sigma}$: Partonic cross section of $2 \to 2$ scattering
- $f_i(x)$: Number density of partons i inside nucleon (=PDF)
  - Leading-order parton model: $2xF_1(x, Q^2) = F_2(x, Q^2) = \sum_i e_i^2 f_i(x)$
  - Process-independent (unlike $F_{1,2}$)

Scale dependence

- At higher orders in α_s the PDFs become scale dependent
  $\Rightarrow$ The partonic structure depends on the scale at which the nucleon is probed

Scale evolution from DGLAP equations [Dokshitzer-Gribov-Lipatov-Altarelli-Parisi]

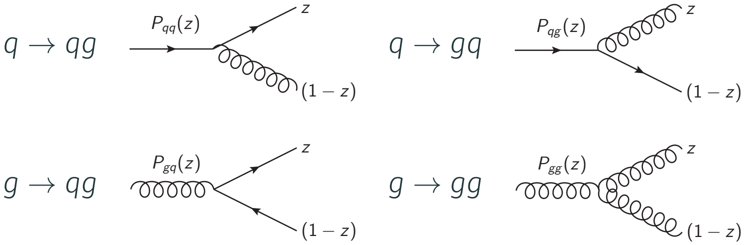
- Derived by resumming logarithmically divergent terms from collinear emissions to all orders

$$\frac{\partial f_{q_i}(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[P_{q_iq_j}\otimes f_{q_j}(Q^2) + P_{q_ig}\otimes f_g(Q^2)\right]$$
$$\frac{\partial f_g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[P_{gg}\otimes f_g(Q^2) + P_{gq_j}\otimes f_{q_j}(Q^2)\right]$$

- Convolution defined as

$$P_{ij}\otimes f_j = \int_x^1 \frac{\mathrm{d}z}{z} P_{ij}(x/z)\, f_j(z)$$

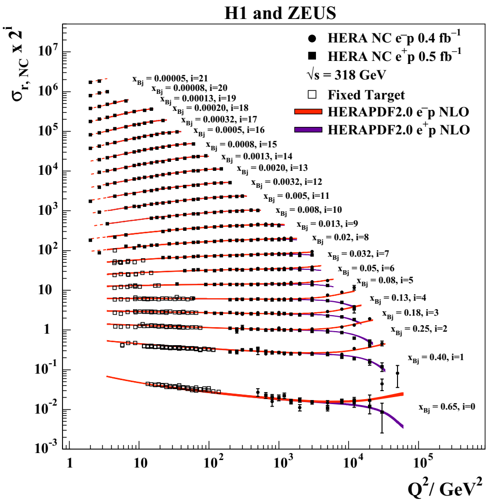
Splitting function can be interpreted as probabilities for partonic splittings



- Splitting functions P_{ij} calculable within pQCD, currently know up to α_s^2 (NNLL)
- PDFs for different partons mix during evolution

DGLAP evolution

Scale evolution of $d\sigma^{DIS}_{reduced} (\propto F_2 \approx \sum_i e_i^2 f_i)$ from HERA [Eur. Phys. J. C (2015) 75]



- Small x:
  F_2 increase with Q^2
- Intermediate-x:
  Weak dependence on Q^2
- Large x:
  F_2 decrease with Q^2

$\Rightarrow$ DGLAP evolution shifts partons from high x to low x

$\Rightarrow$ Very good description of the data in broad range of x and Q^2

PDF determination

Problem:

- PDFs cannot be calculated from perturbative QCD

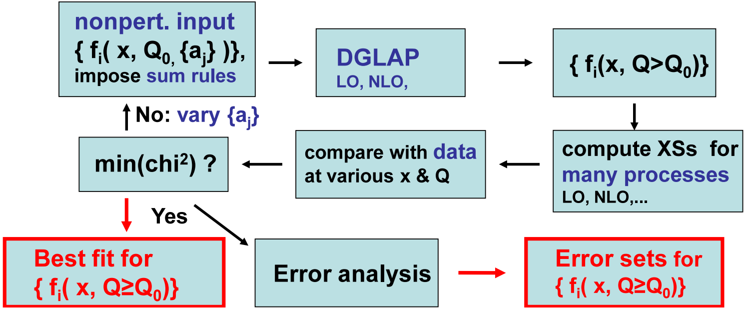
Solution:

- Parametrize the x dependence of PDFs at an initial scale Q_0^2 ($\mathcal{O}(1\,\mathrm{GeV}^2)$)

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

- Use DGLAP equations to evolve PDFs and use data to fix the parameters
- Parametrization should be flexible enough to accommodate the physical features of the data
- PDF analyses also test the universality of the PDFs and QCD factorization

Fitting procedure



[from K.J.Eskola]

PDF fitting requires

- Effective DGLAP solving
- Fast evaluation of the cross sections
- Robust minimization algorithm
- Data with broad reach in x and Q^2 and flavour sensitivity

PDF properties

A few parameters may be fixed by sum rules

- Number of valence quarks

$$\int_0^1 \mathrm{d}x[f_q(x,Q^2) - f_{\bar{q}}(x,Q^2)] = N_q,$$

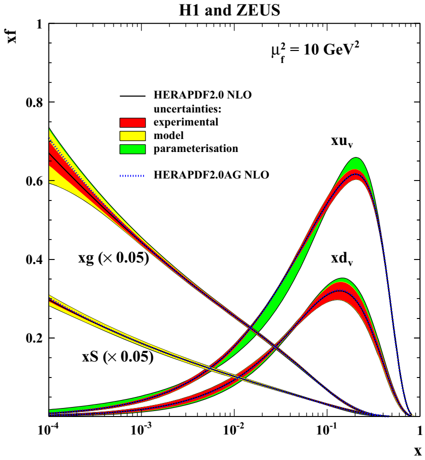
where $N_\mathrm{u} = 2$, $N_\mathrm{d} = 1$ for protons

- Momentum sum rule

$$\sum_{i=q,\bar{q},g} \int_0^1 \mathrm{d}x\, x f_i(x,Q^2) = 1$$

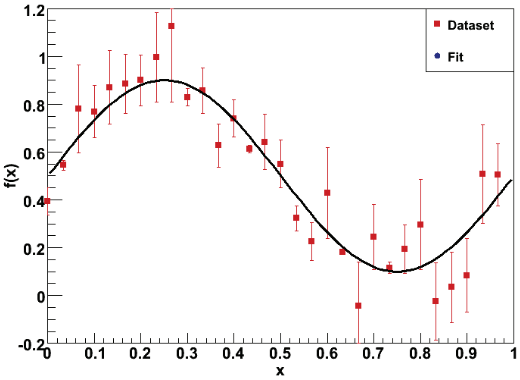
$\Rightarrow$ The total momentum of all partons equals the momentum of the nucleon

Example of a proton PDF analysis



[Eur. Phys. J. C (2015) 75]

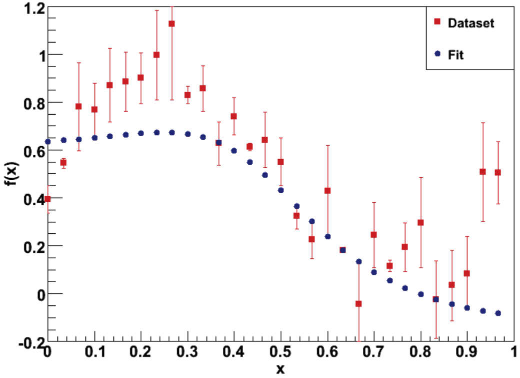
PDF uncertainties



[Figures: A. Guffanti]

The PDFs are fitted to finite number of points with some experimental uncertainty

PDF uncertainties



[Figures: A. Guffanti]

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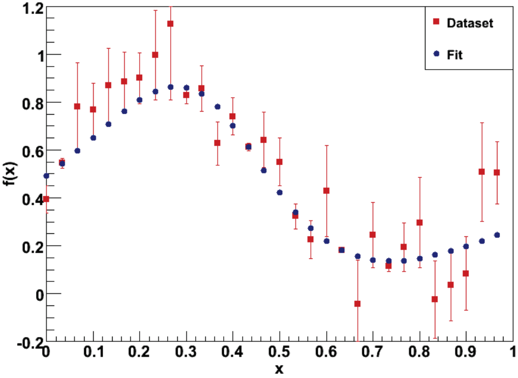

[Figures: A. Guffanti]

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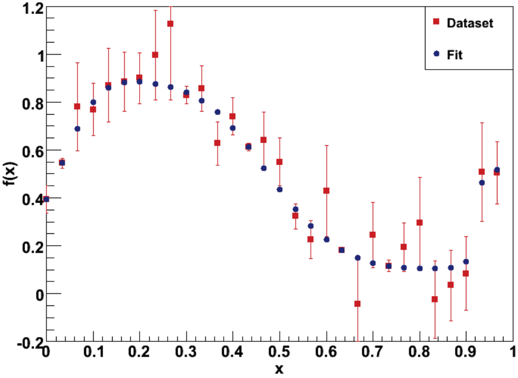
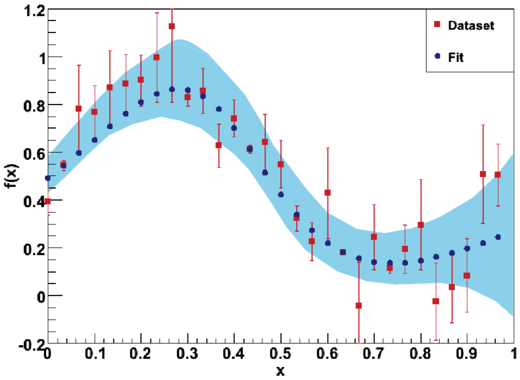


[Figures: A. Guffanti]

The PDFs are fitted to finite number of points with some experimental uncertainty

- Acceptable agreement with different parameters and parametrizations

PDF uncertainties



[Figures: A. Guffanti]

The PDFs are fitted to finite number of points with some experimental uncertainty

- Acceptable agreement with different parameters and parametrizations
- Fits comprise some amount of uncertainty

$\Rightarrow$ How to quantify this uncertainty and how it propagates to observables?

PDF uncertainties: The Hessian method

[Phys. Rev. D65 (2001) 014013]

- The fit minimizes χ^2 defined as

$$\chi^2 = \sum_i^N \left[\frac{D_i - T_i(\{a_j\})}{\delta_i} \right]^2$$

where D_i are data points, δ_i their (statistical) uncertainty and T_i corresponding theory points with given set of parameters $\{a_j\}$

- Expand in terms of parameters a_i around minimum χ_0^2

$$\chi^2 \approx \chi_0^2 + \sum_{ij} \frac{1}{2}(a_i - a_i^0)(a_j - a_j^0) \left. \frac{\partial^2 \chi^2}{\partial a_i \partial a_j} \right|_{a=a^0}$$

where parameter set $\{a^0\}$ gives the χ_0^2

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where parameter set $\{a^0\}$ gives the χ_0^2

- Diagonalize to find an orthonormal basis $\{z_i\}$
- Define error sets $S_k^{\pm}$ by allowing certain $\Delta\chi^2 = \chi^2 - \chi_0^2$ when moving along z_k in positive and negative directions ($\Delta\chi^2 \sim 1 - 100$)

PDF uncertainties: The Monte-Carlo method

- Generate replicas of the data as

$$D_i \to D_i(1 + \delta_i R_i)$$

where δ_i is the experimental uncertainty and R_i a random number from a gaussian distribution
- Perform a refit to each prepared replica data
- The uncertainty of an observable is estimated from the variance of replica sets
- Requires $\mathcal{O}(1000)$ replicas for sufficient statistics

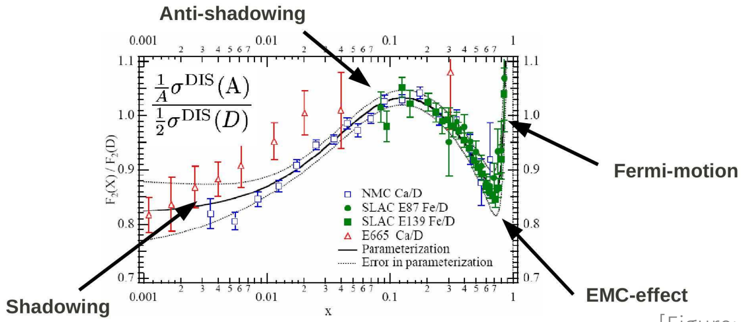
Further uncertainties

- These methods quantify only the uncertainty originating from the data
- Also some theoretical uncertainties due to parametrization etc.

Nuclear PDFs

Motivation for nPDFs

Observation: Differences in structure functions between different nuclei



[Figure: H. Paukkunen]

Factorization of nuclear modifications:

- Absorb the observed modifications into universal nuclear PDFs, $f_i^A(x, Q^2)$
- Perform a global QCD analysis with the same framework as for proton PDFs

Nuclear PDFs

- Nuclear PDFs (nPDFs) are the sum of proton and neutron PDFs:

$$f_i^A(x,Q^2) = Z\,f_i^{\mathrm{p}/A}(x,Q^2) + (A-Z)\,f_i^{\mathrm{n}/A}(x,Q^2)$$

  for nucleus with a mass number A and Z protons
- The PDFs for neutrons can be obtained from proton PDFs using *isospin symmetry*:

$$f_{\mathrm{u}}^{\mathrm{n}/A}(x,Q^2) = f_{\mathrm{d}}^{\mathrm{p}/A}(x,Q^2) \quad \text{and} \quad f_{\mathrm{d}}^{\mathrm{n}/A}(x,Q^2) = f_{\mathrm{u}}^{\mathrm{p}/A}(x,Q^2)$$

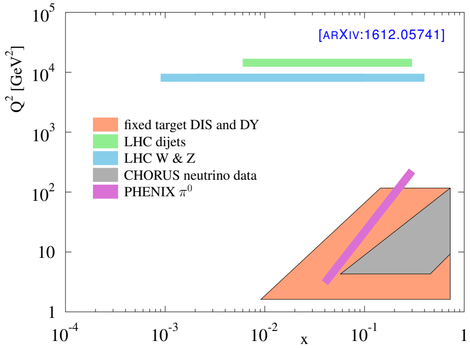
- Often one considers the nuclear modification of the PDFs defined as

$$R_i^A(x,Q^2) = \frac{f_i^{\mathrm{p}/A}(x,Q^2)}{f_i^{\mathrm{p}}(x,Q^2)}$$

Overview on applied data sets

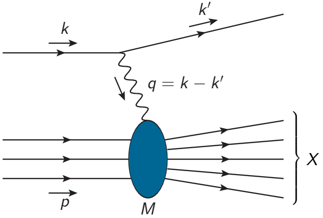
- Should include only data where factorization of nuclear effects valid and no final state energy loss expected
- Measurements with several different *A* required to constrain *A* dependence

Kinematic reach in x and Q^2 of applied data



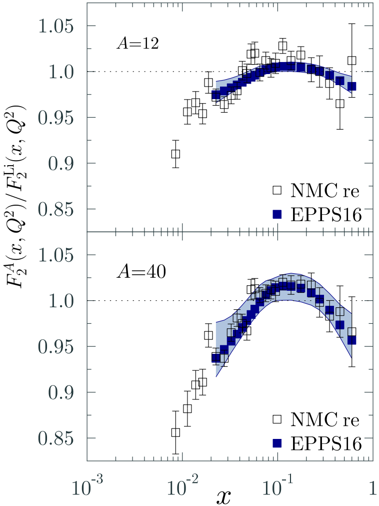
- (neutrino) DIS with nuclear target (fixed target only)
- Drell-Yan (DY) dilepton production in p+*A* (fixed target)
- Inclusive π^0 production in d+Au
- Dijets in p+Pb at the LHC
- $W^{\pm}$ and Z production in p+Pb

Nuclear DIS data



Kinematics from k'

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



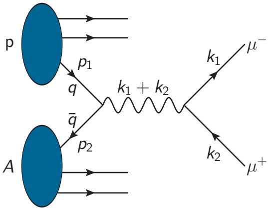
[EPJC 77 (2017) 163]

LO cross section

$$\frac{d\sigma^{\mathrm{DIS}}}{dx dQ^2} \approx \frac{\pi\alpha_{\mathrm{em}}^2}{xQ^4}\left[1+(1-y)^2\right]\sum_q e_q^2\left(f_q^A(x,Q^2)+f_{\bar{q}}^A(x,Q^2)\right)$$

- x and Q^2 can be directly related to observable
- Probes gluons only at NLO (and via scale evolution)
- Only fixed-target experiments with nuclear targets
  $\Rightarrow$ Limited reach in x and Q^2

Nuclear DY data



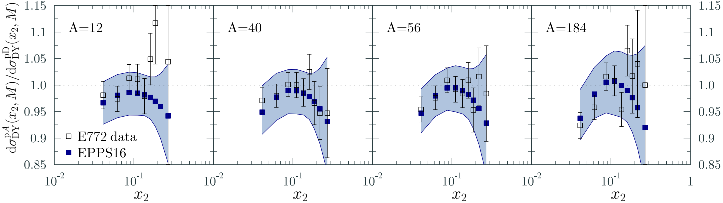
LO cross section

$$\frac{d\sigma^{DY}}{dM^2 dy_R} = \frac{4\pi\alpha_{EM}^2}{9sM^2} \sum_q e_q^2 \left[f_q^p(x_1, Q^2) f_{\bar{q}}^A(x_2, Q^2) + f_q^A(x_2, Q^2) f_{\bar{q}}^p(x_1, Q^2) \right]$$

- x_1 and x_2 can be related to measured quantities
- Enhanced sensitive to sea quark PDFs
- Gluons appear only at NLO (and DGLAP)
- Fixed-target pA for nuclear targets, LHC soon

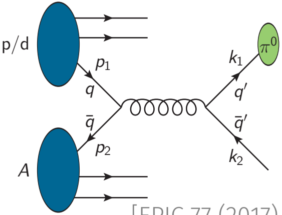
Kinematics from k_1, k_2

- $M^2 \equiv (k_1 + k_2)^2$
- $y_R = \frac{1}{2} \log \frac{E_{k_1+k_2} + p^z_{k_1+k_2}}{E_{k_1+k_2} - p^z_{k_1+k_2}}$
- $x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y_R}$

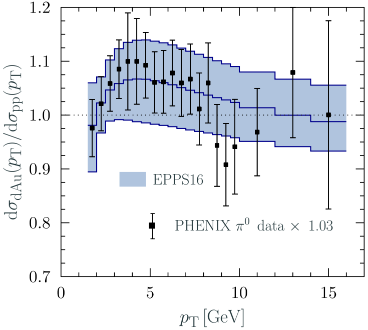


[EPJC 77 (2017) 163]

Inclusive hadron production



[EPJC 77 (2017) 163]



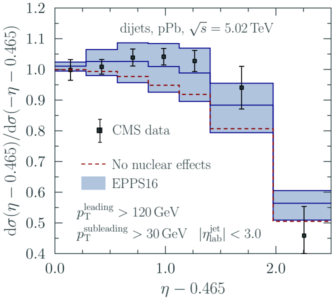
Partonic spectra convoluted with fragmentation functions (FFs)

$$\frac{d\sigma^{\pi^0}}{dP_T dY} = \sum_{i,j,k} f_i^p(x_1, Q^2) \otimes f_j^A(x_2, Q^2) \otimes \frac{d\hat{\sigma}^{ij\to k+X}}{dp_T dy} \otimes D_k^{\pi^0}(x_2, Q^2)$$

- Directly sensitive to gluon PDFs
- Convolutions smear the kinematics
  $\Rightarrow$ Contribution from broad x_2 range
- Fragmentation not completely independent even in pA (baryon production, strangeness enhancement, ...)
- Now data also from LHC

Further data from LHC

[EPJC 77 (2017) 163]

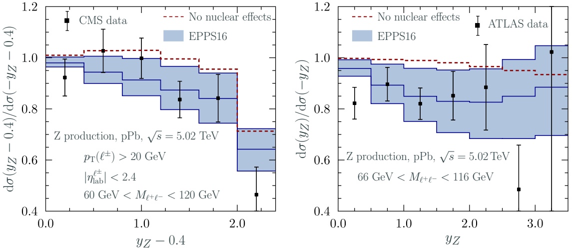


Dijets in pPb

- Sensitivity to gluons PDFs
- Theoretically well known and only small effects from hadronization
- Requires high-p_T $\Rightarrow$ difficult to study small-x

Z bosons in pPb

- Very clean process
- Does not couple to gluons
- High-Q^2 process



[EPJC 77 (2017) 163]

Recent nPDF analyses

	EPS09	DSSZ12	KA15	NCTEQ15	EPPS16
Order in α_s	NLO	NLO	NNLO	NLO	NLO
DIS in ℓ^-+A	✓	✓	✓	✓	✓
Drell-Yan in p+A	✓	✓	✓	✓	✓
RHIC pions d+Au	✓	✓		✓	✓
Neutrino-nucleus DIS		✓			✓
Drell-Yan in π+A					✓
LHC p+Pb dijets					✓
LHC p+Pb W, Z					✓
Q cut in DIS	$1.3\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$2\,\mathrm{GeV}$	$1.3\,\mathrm{GeV}$
datapoints	929	1579	1479	708	1811
free parameters	15	25	16	16	20
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	N.N	35	52
proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like	CT14NLO
Heavy-quark effects		✓		✓	✓
Flavour separation				partial	full
Reference	JHEP 0904 065	PR D85 074028	PR D93, 014026	PR D93 085037	EPJ C77 163

[Table: H. Paukkunen]

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[Table: H. Paukkunen]

EPPS16 vs nCTEQ15

Parametrizations

- EPPS16: piece-wise function for R_i^A

$$R_i^{\text{EPPS16}}(x,Q_0^2) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a < x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x) & x_e < x \le 1 \end{cases}$$

with A dependence on three parameters

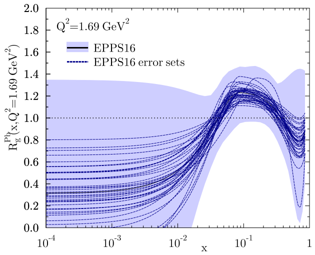
$\Rightarrow$ In total 20 parameters to fit

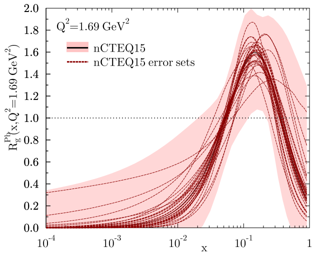
- nCTEQ15: CTEQ-like parametrization for $f_i^{p/A}$:

$$f_i^{\text{NCTEQ15}}(x,Q_0^2) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4} x)^{c_5},$$

with $c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$

16 free parameters, $R_i^A = f_i^{p/A}/f_i^p$



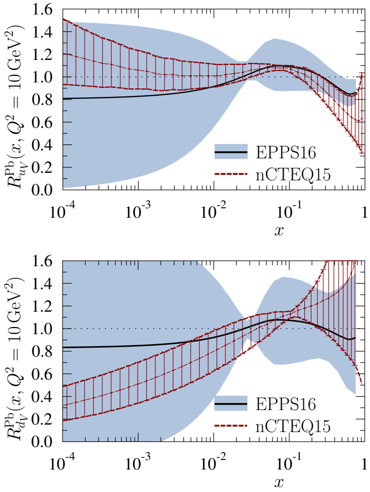


Valence quarks

Nuclear modification

- In both analyses u_V and d_V parameters independent
- However, nCTEQ15 finds large differences whereas in EPPS16 behaviour similar
  - EPPS16 use also neutrino-DIS data sensitive to flavour separation
- Remember: $f_i^{p/A} \neq f_i^A$

$\Rightarrow$ Total uncertainty reduced compared to individual ones as uncertainties correlated

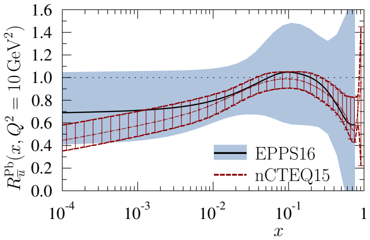


Sea quarks

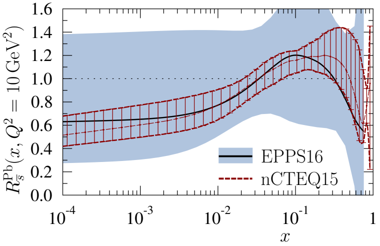
Nuclear modification

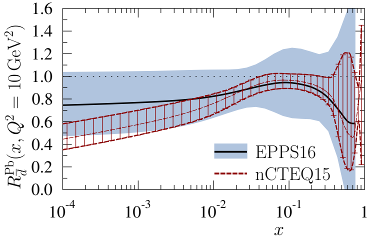
- In nCTEQ15 the sea quark parametrization flavor independent
- In EPPS16 $R_{\bar{u}}$, $R_{\bar{d}}$, $R_{\bar{s}}$ free

⇒ Larger uncertainties in EPPS16 but less biased



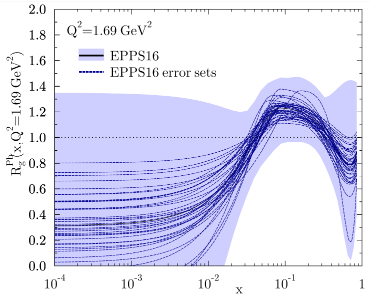
- Uncertainties in s-quark nPDFs large due to lack of data

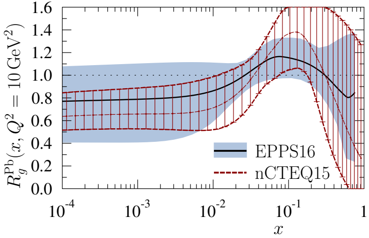




Nuclear modification

- Data constrain gluons only around $x \sim 0.1$
  $\Rightarrow$ Large uncertainties at small-x
- However, scale evolution rapidly shrinks the uncertainties at small-x as these originate from well-constrained quarks at higher x
- Reasonable agreement between the analyses
  - Intermediate x: Smaller uncertainty in EPPS16 due to dijet data
  - Small x: Smaller uncertainty in nCTEQ15 probably due to more restrictive parametrization

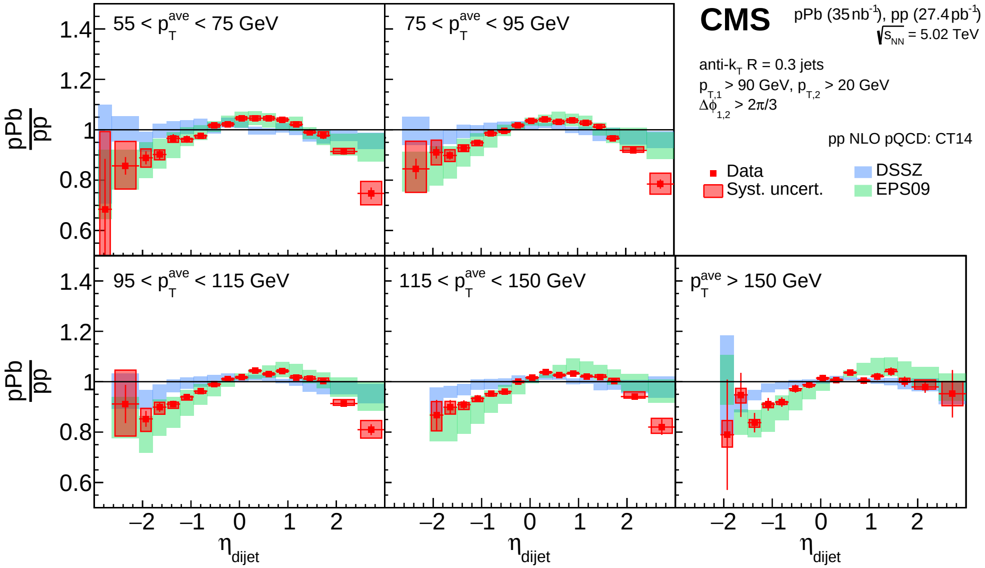




New constraints from LHC

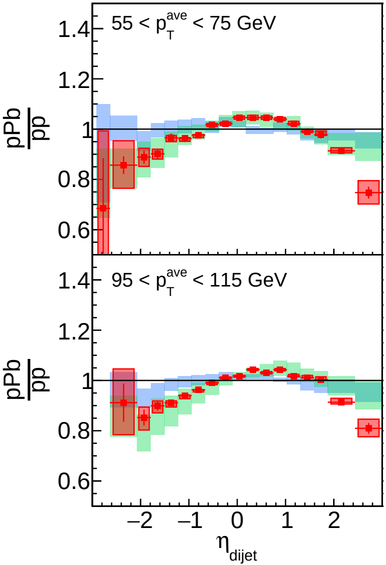
New dijet from pPb at the LHC from CMS

[PRL 121 (2018) no.6, 062002]

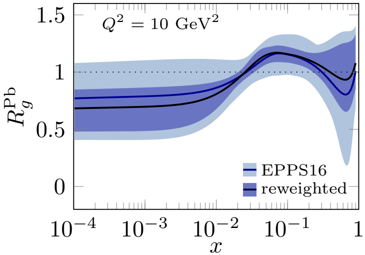


New dijet from pPb at the LHC from CMS

[PRL 121 (2018) no.6, 062002]



- Increased statistics, More data points
- Impact quantified with reweighting method
- Reduces gluon uncertainty
- Favours enhanced shadowing



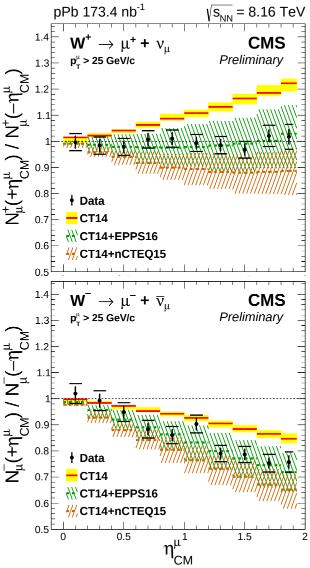
[K.J. Eskola, P. Paakkinen, H. Paukkunen, arXiv:1812.05438]

New data for $W^{\pm}$ and Z production

[CMS-PAS-HIN-17-007]

New data from CMS

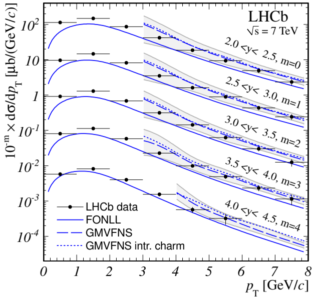
- Old 5 TeV data on $W^{\pm}$ had only little impact due to small statistical weight
- Now data at 8 TeV with higher precision
- Strong preference for nPDFs
- Very good agreement with EPPS16
- Will provide further constraints for flavor decomposition

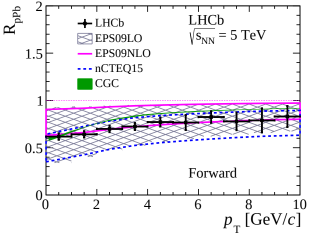


- Recent interest to constrain gluon PDFs in proton with *D* (and *B*) mesons
  [Gauld, Rojo, PRL 118, 072001; PROSA, EPJ C75, 396]
- Now also data from pPb collisions

D-meson production

- Contains a c-quark
  $\Rightarrow$ Always produced perturbatively
- Can probe very low *x* and Q^2, especially with LHCb acceptance
- Some challenge in theoretical treatment





Heavy-flavour R_{pPb} impact on nPDFs

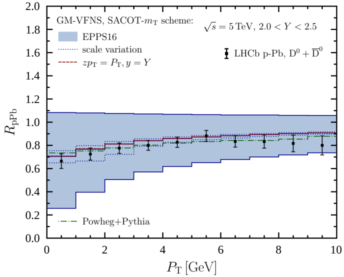
Strong constraints for gluons

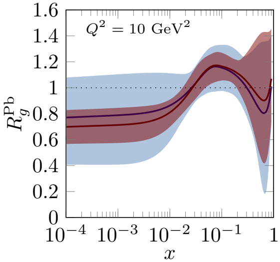
- LHCb data up to $Y = 4$ [JHEP 1710 (2017) 090]
- Sensitivity down to $x \sim 10^{-5}$
- Impact studied with reweighting method
  - Assuming simplified kinematics

    [Kusina et al., PRL 121, 052004]
  - With full GM-VFNS NLO calculation

    [Paukkunen et al., *to appear*]

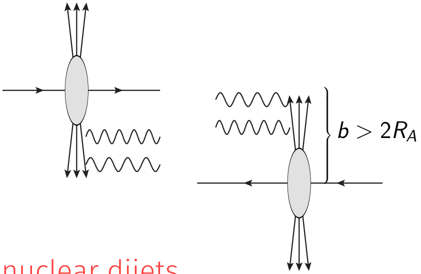
- Good agreement with collinear factorization
- Provides significant reduction of the small-x gluon uncertainty
- Shadowing consistent with the dijet R_{pPb}





Ultra-peripheral collisions

[See next lecture by W. Schafer]



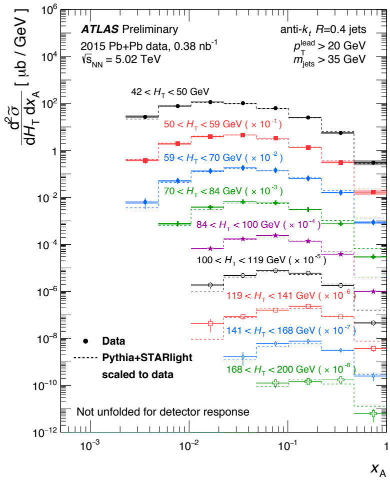


Photo-nuclear dijets

- Nuclei pass without strong interaction
- EM-field, described with quasi-real photons, interacts with another nucleus
  $\Rightarrow \gamma A$ collision that can produce jets
- First preliminary data by ATLAS

[ATLAS-CONF-2017-011]

Future facilities

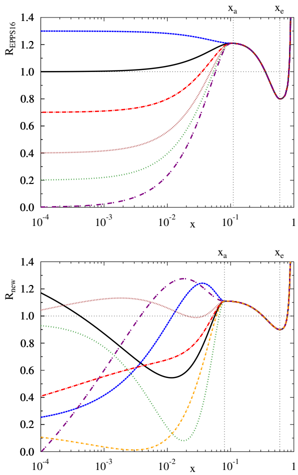
Electron-Ion collider (EIC)

Proposed ep/eA collider projects

- JLEIC@JLAB ($\sqrt{s} \sim 20 - 60$ GeV) [arXiv:1504.07961]
- eRHIC@BNL ($\sqrt{s} \sim 80 - 140$ GeV) [arXiv:1409.1633]

nPDF constraints

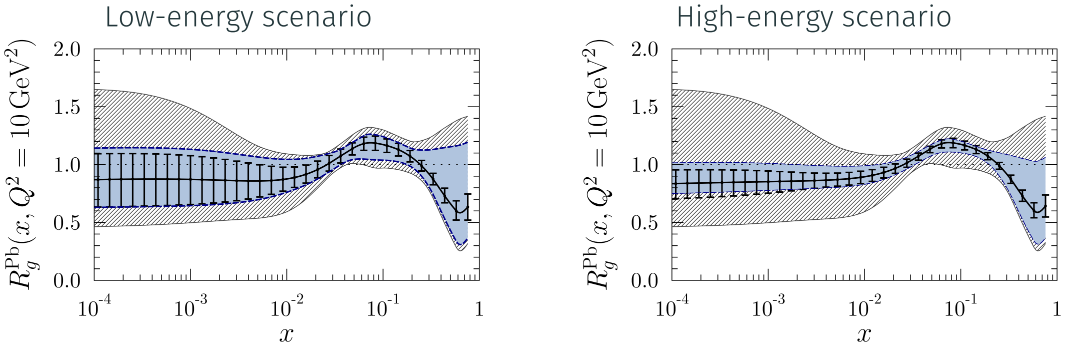
- DIS still the cleanest probe of (n)PDFs
- Need more flexible parametrization for unbiased studies
  - $R^A_{\mathrm{EPPS16}}(x < x_a) = a_0 + a_1(x - x_a)^2$
  - $R^A_{\mathrm{NEW}}(x < x_a) = a_0 + a_1(x - x_a)^2 + (x - x_a)^2 \sum_{k=1}^{2} a_{k+2} x^{k/4}]$



[E.C. Aschenauer, S. Fazio, M.A.C. Lamont, H. Paukkunen, P. Zurita, PRD96 (2017) no.11, 114005]

EIC impact on gluon nPDFs

- Increased freedom at small-*x* yields larger uncertainty (gray) than in EPPS16
- Estimated EIC potential provides significant constraints (blue)
- Some further effect when including also inclusive charm (bars)



[E.C. Aschenauer, S. Fazio, M.A.C. Lamont, H. Paukkunen, P. Zurita, PRD 96 (2017) no.11, 114005]

Large hadron-electron collider

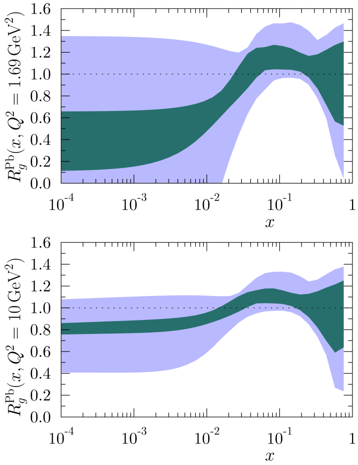
- Use the proton/ion beam from LHC
- Construct a new lepton accelerator

  $\Rightarrow$ Provides e+p/A collider with $\sqrt{s} \sim 1$ TeV

Estimated impact on nPDF precision

- Baseline: EPPS16 (blue)

  (Recall parameter-bias at small-x)
- After simulated LHeC data (green)
- A drastic reduction of gluon nPDF uncertainties

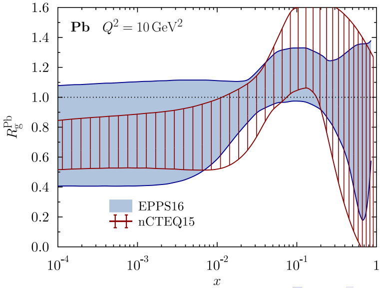


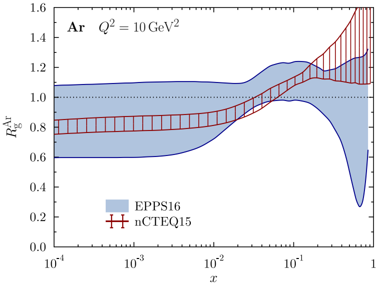
[arXiv:1709.08342]

Loose ends

nPDFs for smaller nuclei

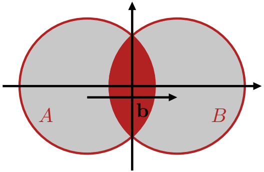
- Only fixed-target data for lighter than ^{197}Au, LHC data only for ^{208}Pb
- *A*-dependence not well in control (parametrization-bias)
- Relevant for astrophysical applications (^{16}O, ^{14}N)





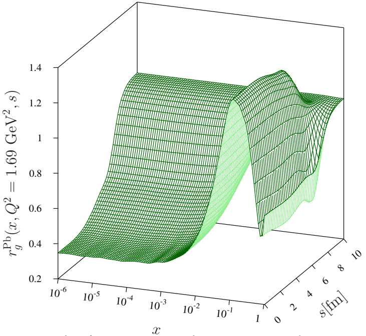
- Very different large-*x* *A* dependence in EPPS16 and nCTEQ15

Impact parameter dependence



- Different centralities probes different parts of nuclei
- Currently only min. bias (integrated over impact parameters) data in global analyses

- Only few studies on impact-parameter dependence
- Need more data for further studies



[I.H., K.J. Eskola, H. Honkanen and C.A Salgado, JHEP 1207 (2012) 073]

Summary

Nuclear PDFs

- Based on the well-established DGLAP framework
- Essential input for factorization-based cross-section calculations in nuclear collisions
- Currently well-constrained only at $x \gtrsim 0.01$

LHC impact

- Already some LHC data in nPDF analysis
- Further constraints will be provided by
  - $W^{\pm}$ and Z boson production in pPb (maybe also PbPb)
  - Dijets in pPb collisions, possibly also UPCs
  - Inclusive D-meson production in pPb by LHCb
- So far no observation of factorization breaking at the LHC

Outlook

Nuclear PDFs

- Add more data from LHC for improved constraints
- Current state-of-the art NLO in pQCD $\Rightarrow$ first NNLO fits to come
- Need also more data for different nuclei, only Pb at the LHC
- Reduce parametrization bias by releasing some assumptions
- Impact-parameter dependence?

New experimental facilities

- Projected electron-ion colliders can provide clean nPDF constraints (EIC, LHeC, also other proposals)
- Further possibilities with Future Circular Collider (FCC) at CERN ($\sqrt{s} \sim 40 - 100$ TeV)