Constraining the EPPS nPDFs with W-bosons at 8.16 TeV pPb

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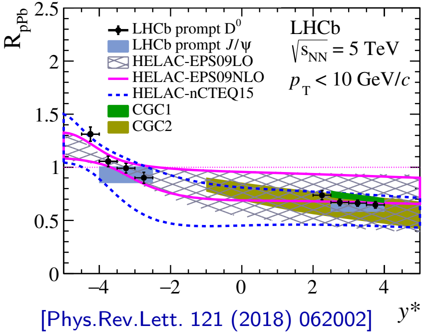
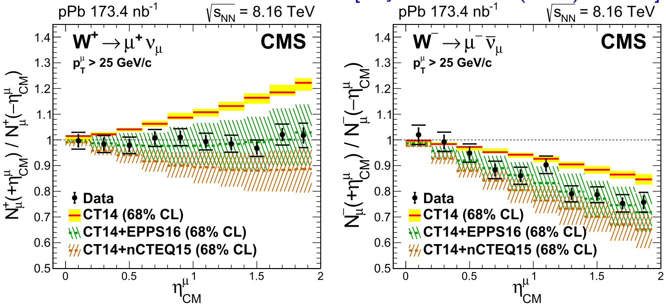
SnowMass2021 EF07 meeting: EW and nPDF in HIC
23 Nov 2020

LHC is currently the driving force of nPDF analyses

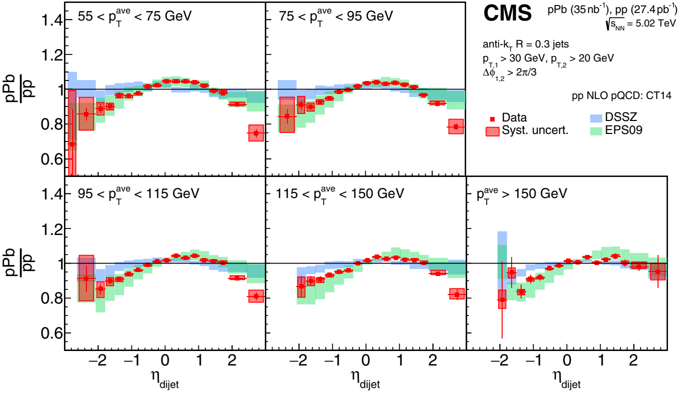
[JHEP 10 (2017) 090]



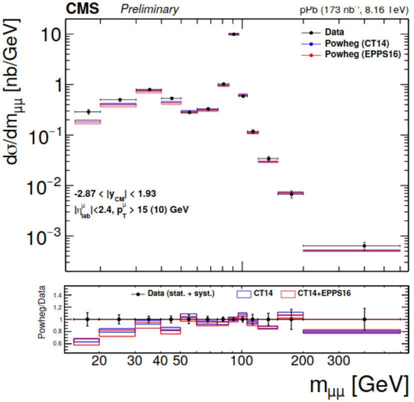
[Phys.Lett.B 800 (2020) 135048]



[Phys.Rev.Lett. 121 (2018) 062002]



[CMS-PAS-HIN-18-003]



Dijets and D^0s – strong constraints for gluons

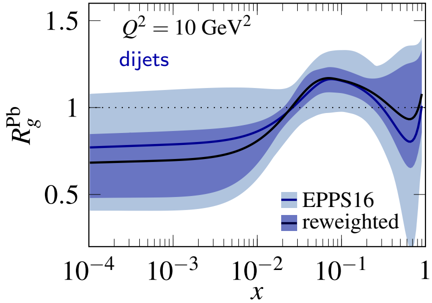
We have performed **Hessian PDF reweighting** studies to see the impact of dijets and D^0s

- Drastic reduction in EPPS16 gluon uncertainties
- Support for mid-x antishadowing and small-x shadowing
- Constraints from dijet and D-meson data mutually consistent!

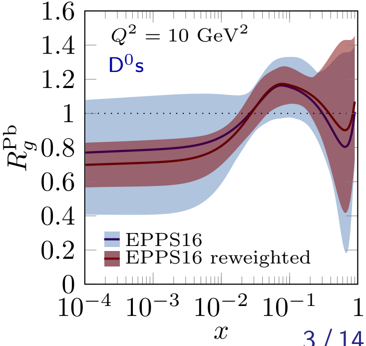
Work in progress:

- Include these and the CMS 8.16 TeV W bosons into a **global analysis**
- Studies in more relaxed parametrization ongoing
- Unfortunately, cannot show the results yet ☹

[Eur.Phys.J. C79 (2019) 511]



[JHEP 05 (2020) 037]



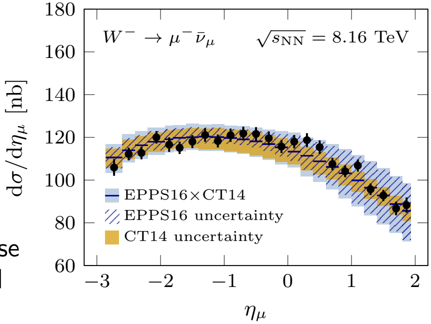
More detailed look into the W data

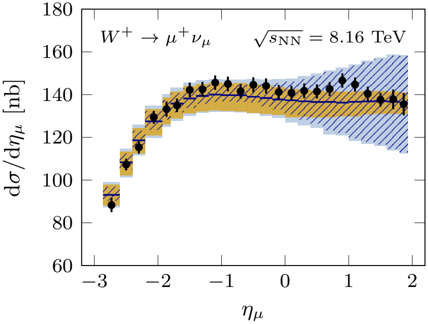
Work in progress

Absolute cross sections carry large proton-PDF uncertainty!

Cannot be neglected when fitting the nPDFs

No *obvious* best way to use these data, but we should test different options:





- **Use the absolute cross sections** **as in nNNPDF2.0, nCTEQ15WZ**
  - ➔ susceptible to the proton-PDF uncertainties, need to be accounted in the fit
- **Use self-normalized cross sections**
  - ➔ cancel overall-normalization uncertainty, some proton-PDF uncertainties bound to remain
- **Use forward-to-backward ratios** **as in EPPS16**
  - ➔ more direct cancellation of the proton-PDF uncertainties, lose statistical significance
- **Use nuclear modification ratios** **the current plan for EPPS2x**
  - ➔ expect good cancellation of the proton-PDF uncertainties, additional experimental uncertainties from the proton–proton measurement

How to include proton-PDF uncertainties in nPDF reweighting?

Work in progress

Construct a total figure-of-merit function of the CT14 and EPPS16 parameters:

$$\chi^2_{\text{total}}(z_{\text{CT14}}, z_{\text{EPPS16}}) = \chi^2_{\text{CT14}}(z_{\text{CT14}}) + \chi^2_{\text{EPPS16}}(z_{\text{EPPS16}}) \\ + \left(y(z_{\text{CT14}}, z_{\text{EPPS16}}) - y^{\text{data}}\right)^T C^{-1} \left(y(z_{\text{CT14}}, z_{\text{EPPS16}}) - y^{\text{data}}\right)$$

Take the quadratic–linear approximation:

$$\chi^2_{\text{CT14}}(z_{\text{CT14}}) = \chi^2_{\text{CT14,min}} + z^2_{\text{CT14}}, \qquad \chi^2_{\text{EPPS16}}(z_{\text{EPPS16}}) = \chi^2_{\text{EPPS16,min}} + z^2_{\text{EPPS16}},$$

$$y(z_{\text{CT14}}, z_{\text{EPPS16}}) = y_0 + D_{\text{CT14}} z_{\text{CT14}} + D_{\text{EPPS16}} z_{\text{EPPS16}}$$

Marginalizing (i.e. integrating out) the CT14 parameters then gives:

$$\chi^2_{\text{marginal}}(z_{\text{EPPS16}}) = \chi^2_{\text{CT14,min}} + \chi^2_{\text{EPPS16,min}} + z^2_{\text{EPPS16}} \\ + \left(y_0 + D_{\text{EPPS16}} z_{\text{EPPS16}} - y^{\text{data}}\right)^T \left(C + S_{\text{CT14}}\right)^{-1} \left(y_0 + D_{\text{EPPS16}} z_{\text{EPPS16}} - y^{\text{data}}\right),$$

where

$$S_{\text{CT14}} = D_{\text{CT14}} D^T_{\text{CT14}}$$

c.f. [Abdul Khalek *et al.*, Eur.Phys.J. C79 (2019) 931]

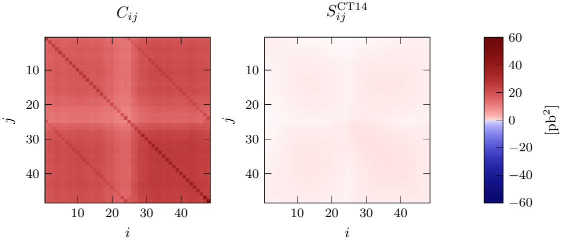
How to set error tolerance in theoretical covariance matrix?

Work in progress

The simple derivation above gives:

$$S_{ij}^{\mathsf{CT14}} = \frac{1}{\Delta\chi^2} \sum_k \frac{y_i[S_k^+] - y_i[S_k^-]}{2} \frac{y_j[S_k^+] - y_j[S_k^-]}{2}$$

Too small, does not reproduce the CT14 variances!

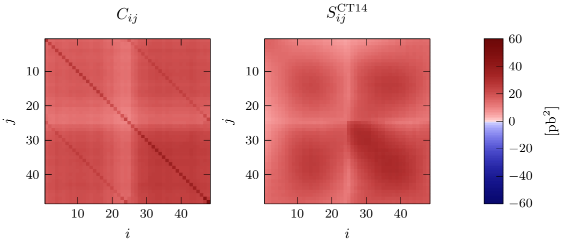


The problem is in normalizing with the error tolerance $\Delta\chi^2$: effectively, this leads to setting $\Delta\chi^2 \to 1$, which is *not* consistent with the CT14 error analysis

Using instead the CT14 (co)variances directly

$$S_{ij}^{\mathsf{CT14}} = \sum_k \frac{y_i[S_k^+] - y_i[S_k^-]}{2} \frac{y_j[S_k^+] - y_j[S_k^-]}{2}$$

is consistent with the CT14 definition of $\Delta\chi^2 = 100$

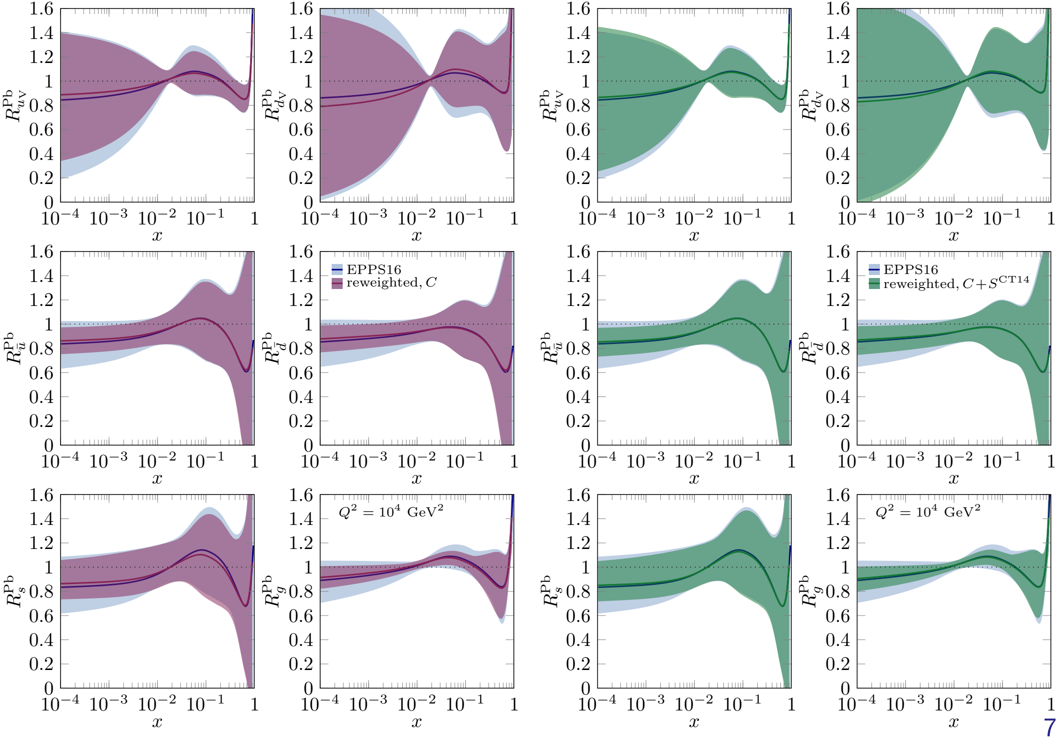


Obviously, the results will depend heavily on the chosen error tolerance

Note: It is the strong *positive* correlations which make the uncertainty reduction with ratios possible

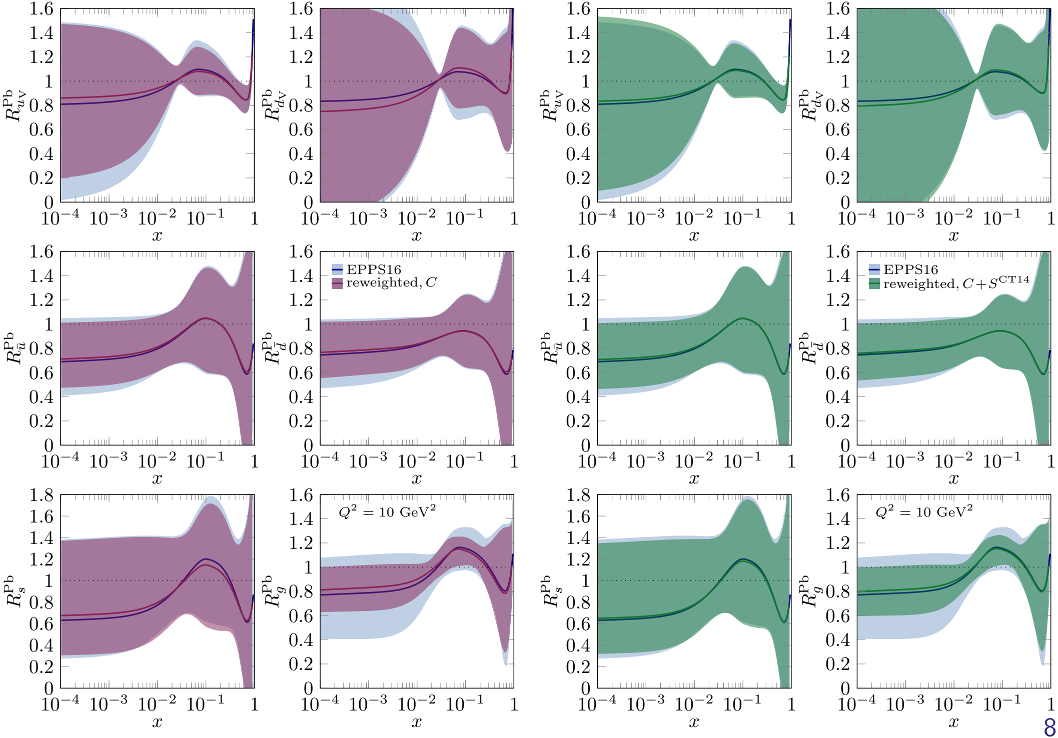
Reweighting results with absolute cross sections

Work in progress



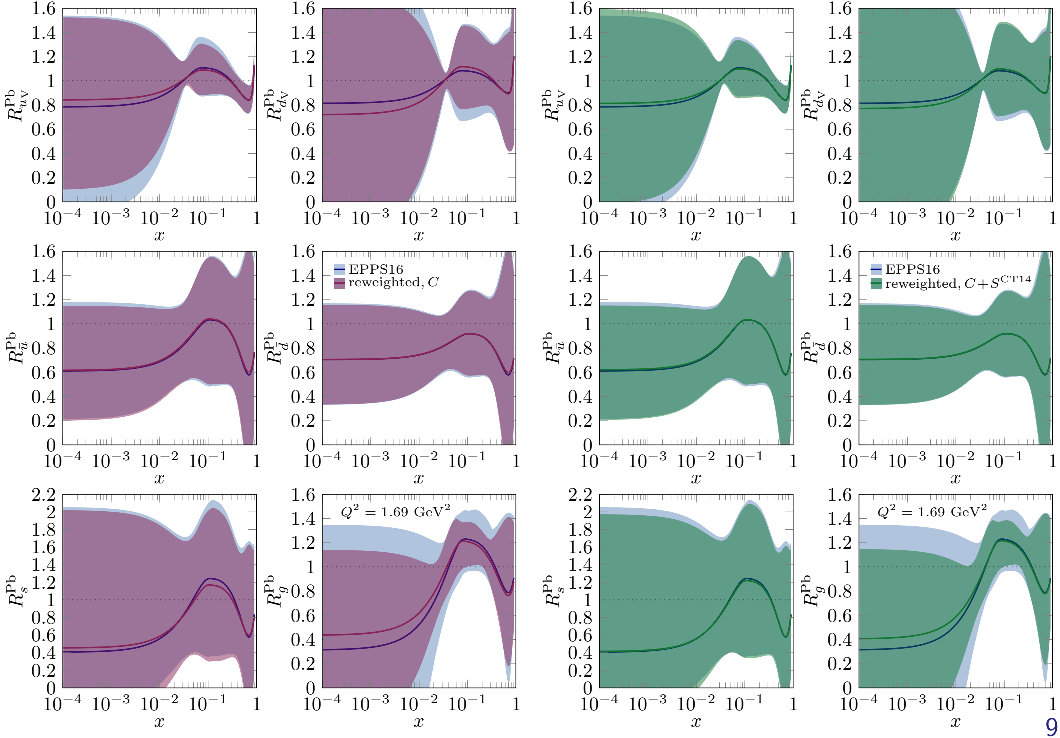
Reweighting results with absolute cross sections

Work in progress



Reweighting results with absolute cross sections

Work in progress



Why is it so hard to constrain the flavour separation?

There is a subtle interplay with isospin

For example, we can write

$$f_{u_\mathrm{V}}^{A} = \left(R_{u_\mathrm{V}+d_\mathrm{V}}^{A} - \frac{A-2Z}{A} R_{u_\mathrm{V}-d_\mathrm{V}}^{A} \right) \frac{f_{u_\mathrm{V}}^{p} + f_{d_\mathrm{V}}^{p}}{2}$$

$$f_{d_\mathrm{V}}^{A} = \left(R_{u_\mathrm{V}+d_\mathrm{V}}^{A} + \frac{A-2Z}{A} R_{u_\mathrm{V}-d_\mathrm{V}}^{A} \right) \frac{f_{u_\mathrm{V}}^{p} + f_{d_\mathrm{V}}^{p}}{2}$$

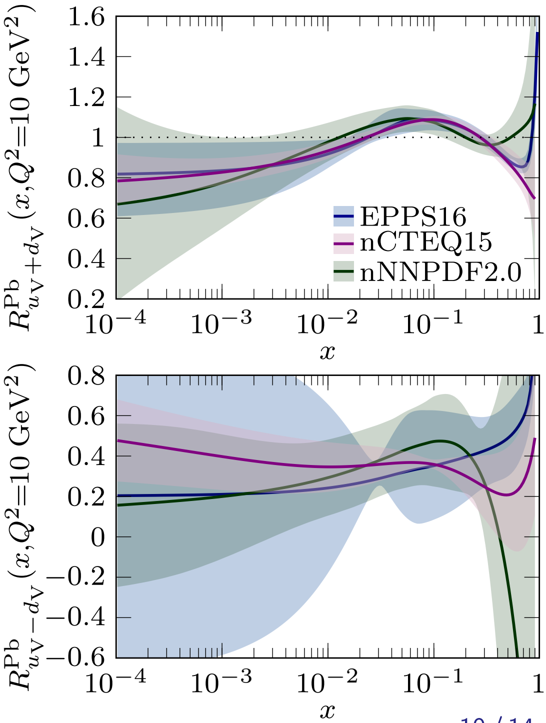
where

$$R_{u_\mathrm{V}+d_\mathrm{V}}^{A} = \frac{f_{u_\mathrm{V}}^{p/A} + f_{d_\mathrm{V}}^{p/A}}{f_{u_\mathrm{V}}^{p} + f_{d_\mathrm{V}}^{p}}$$

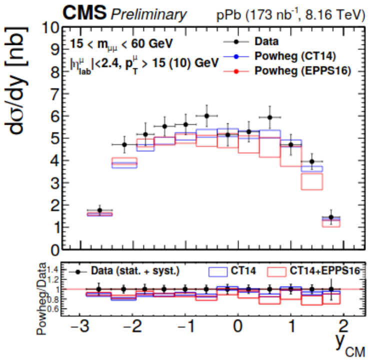
$$R_{u_\mathrm{V}-d_\mathrm{V}}^{A} = \frac{f_{u_\mathrm{V}}^{p/A} - f_{d_\mathrm{V}}^{p/A}}{f_{u_\mathrm{V}}^{p} + f_{d_\mathrm{V}}^{p}}$$

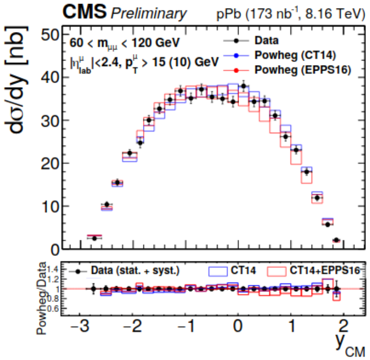
and neutron excess $\frac{A-2Z}{A} \approx 0.2$ for Pb

- ➔ Need high-precision data on non-isoscalar nuclei to constrain the difference



Future prospects: DY at 8.16 TeV





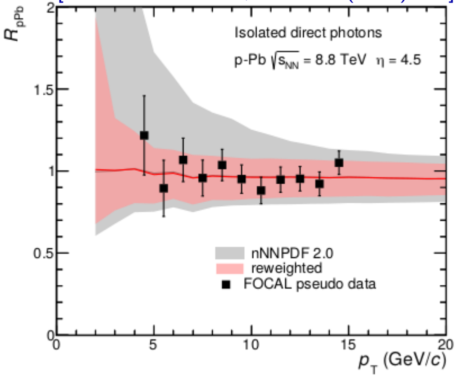
CMS 8.16 TeV DY measurement extends to lower scales than what is accessible with the Ws

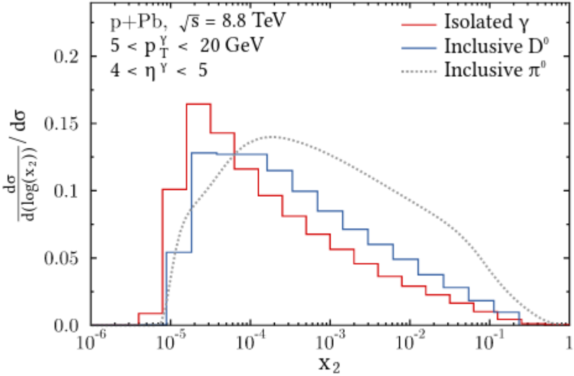
- Do we get a better handle on the sea quarks at the parametrization scale?
- DGLAP evolution effects are large already between the parametrization scale and 15 to 60 GeV, which can again hinder the constraints for sea quarks

As with the Ws, proton-PDF uncertainties can become as large as the data uncertainties, particularly in the high-mass region

- Need to find a way to mitigate these, or take them into account in the fit
- Do we get better results with R_{FB}, R_{pPb}?

Future prospects: Forward photons with FoCal


[Abdul Khalek *et al.*, JHEP 09 (2020) 183]

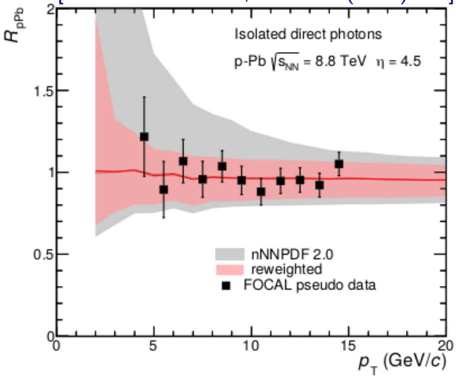

[fig. from CERN-LHCC-2020-009]

Isolated photons at forward rapidities are a good probe of the nuclear small-x gluons

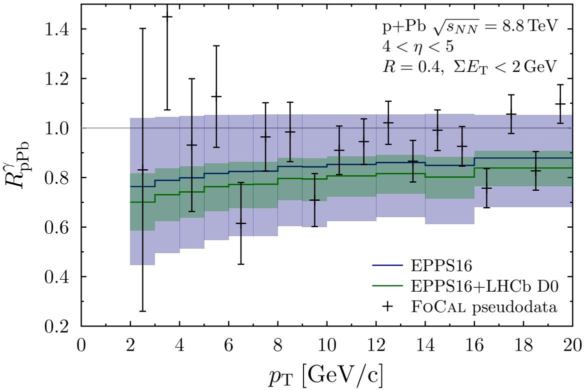
- Isolation cut reduces the fragmentation component
  - enhanced small-x sensitivity [Helenius *et al.*, JHEP 09 (2014) 138]
- Test for the possible onset of non-linear QCD effects
- Complementary to the forward D^0s and DY [cf. CERN Yellow Rep.Monogr. 7 (2019), pp. 1312-1313]

Future prospects: Forward photons with FoCal (versus D^0 constraints)

[Abdul Khalek *et al.*, JHEP 09 (2020) 183]



[collab. with Eskola, Helenius & Paukkunen]



Constraints from D^0s already more stringent than what we can expect from FoCal

Still, there is important complementarity between forward photons and D^0s

- "Cleaner" probe of the nPDFs in the small-p_T region, where theoretical uncertainties in D^0 production can become significant
  - The good π^0 reconstruction in FoCal becomes important
- Test for the factorization & process independence (universality) of nPDFs

Some concluding remarks

- LHC dijet, D-meson and W-boson data are all capable of setting constraints on gluon nPDF
  - New global analysis on its way
- With increasingly precise data, uncertainties from free-proton PDFs become important
  - PDF reweighting offers an easy and effective way to test different ways to cancel these uncertainties or how to eventually account for them in a global analysis
  - PDF error tolerance needs to be treated correctly (not totally unambiguous)
- Flavour separation remains difficult to constrain
  - Constraints from Ws currently hindered by free-proton uncertainties, can improve in the future
  - Some additional constraints could be expected from the proposed COMPASS++/AMBER pion–nucleus DY experiment
  - CC DIS at EIC/LHeC might help?
- Interesting future prospects with DY and isolated photons

Backup

Short intro to EPPS16

[Eur.Phys.J. C77 (2017) 163]

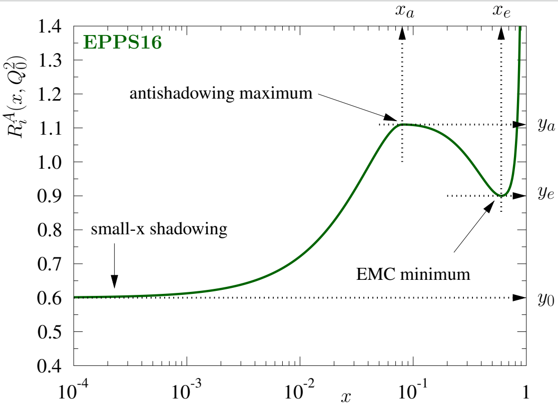
- Define nPDFs in terms of

$$\underbrace{f_i^{p/A}(x,Q^2)}_{\text{bound-proton PDF}} = \overbrace{R_i^A(x,Q^2)}^{\text{nuclear modification}}\,\underbrace{f_i^p(x,Q^2)}_{\text{free-proton PDF}}$$

- Parametrize the x and A dependence of $R_i^A(x,Q_0^2)$ at $Q_0^2 = m^2_{\text{charm}}$
- PDFs of the full nucleus are then constructed with

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

where the neutron content is obtained via isospin symmetry



- Allow full flavour separation and include heavy-quark mass effects with a general-mass variable flavour number scheme (GM-VFNS)
- Most extensive data set to date, with νA DIS, πA DY, LHC pPb dijets and EW bosons

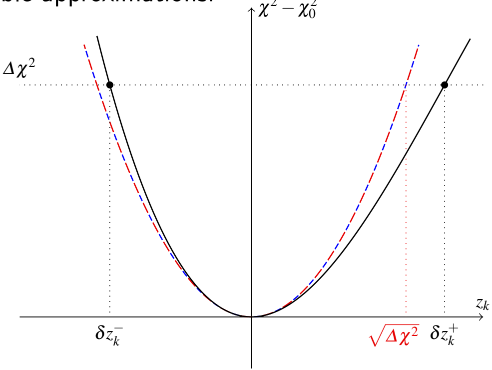
PDF reweighting: different approximations

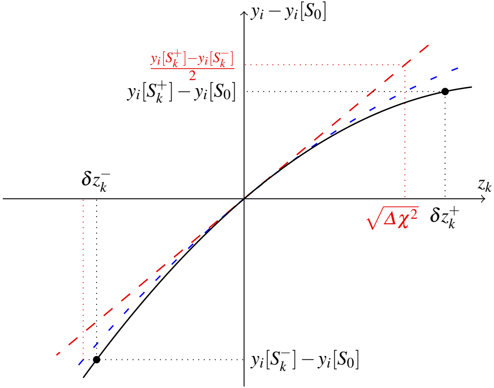
[Eur.Phys.J. C79 (2019) 511]

The Hessian reweighting is a method to study the impact of a new set of data on the PDFs without performing a full global fit

$$\chi^2_{\mathsf{new}}(\mathbf{z}) = \chi^2_{\mathsf{old}}(\mathbf{z}) + \sum_{ij} \left(y_i(\mathbf{z}) - y_i^{\mathsf{data}}\right) C_{ij}^{-1} \left(y_j(\mathbf{z}) - y_j^{\mathsf{data}}\right)$$

Possible approximations:





quadratic–linear: $\chi^2_{\mathsf{old}} \approx \chi^2_0 + \sum_k z_k^2,$ $\quad y_i \approx y_i[S_0] + \sum_k d_{ik} z_k$

quadratic–quadratic: $\chi^2_{\mathsf{old}} \approx \chi^2_0 + \sum_k z_k^2,$ $\quad y_i \approx y_i[S_0] + \sum_k (d_{ik} z_k + e_{ik} z_k^2)$

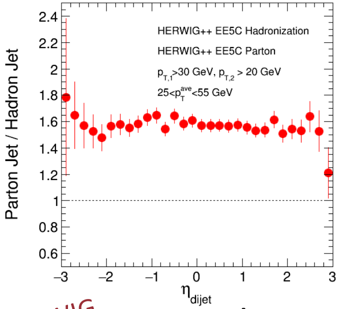
cubic–quadratic: $\chi^2_{\mathsf{old}} \approx \chi^2_0 + \sum_k (a_k z_k^2 + b_k z_k^3),$ $\quad y_i \approx y_i[S_0] + \sum_k (d_{ik} z_k + e_{ik} z_k^2)$

Cancellation of hadronization effects

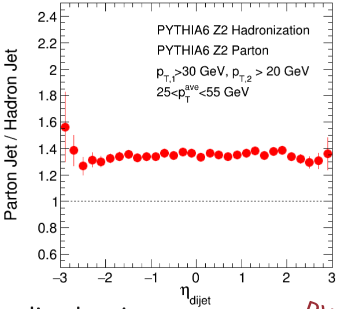
slide from: Doga Gulhan, HI Jet Workshop, July 2016

Cross-section ratios

HERWIG

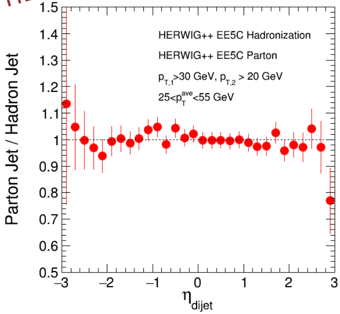


PYTHIA



Area normalized ratios

HERWIG



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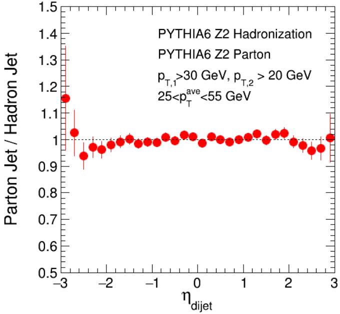


Hadronization uncertainty

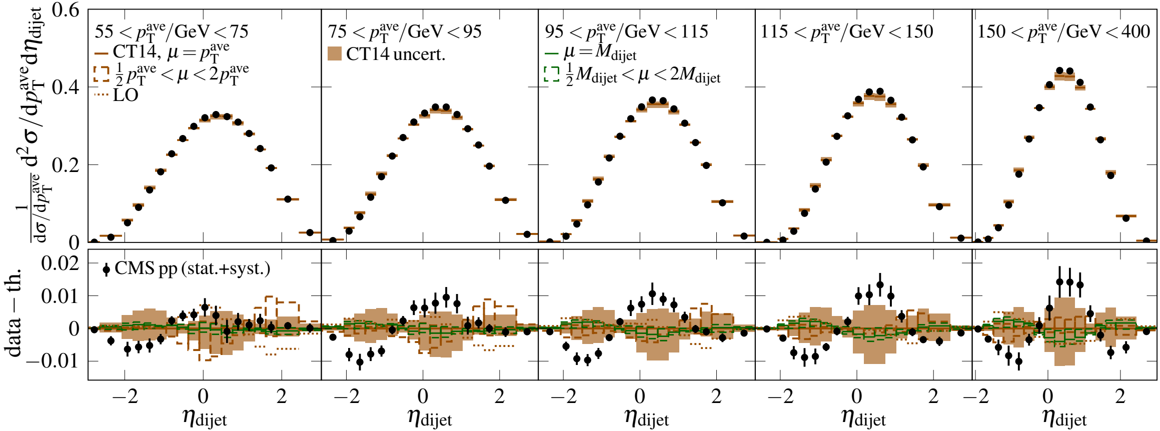
Parton jets have higher cross section for R = 0.3 jets with same kinematic selections compared to hadron jets

Parton jets are harder fragmenting

After self normalization effect of hadronization is negligible

CMS dijets at pp

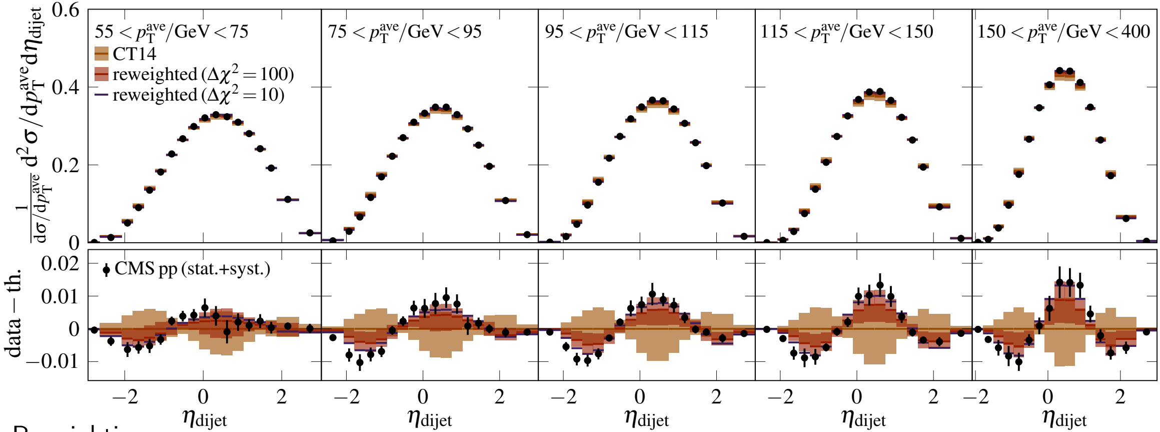
[Eur.Phys.J. C79 (2019) 511]



- Predicted NLO distributions somewhat wider than the measured spectra
- High-p_T^{ave} midrapidity robust against scale variations and LO-to-NLO effects
  - ➔ can expect NNLO corrections to be small in this region
  - ➔ observed discrepancy seems to be a PDF related issue
- Refitting might be needed to improve agreement with data
  - ➔ study the impact with the reweighting method

CMS dijets at **pp** – CT14 reweighted

[Eur.Phys.J. C79 (2019) 511]

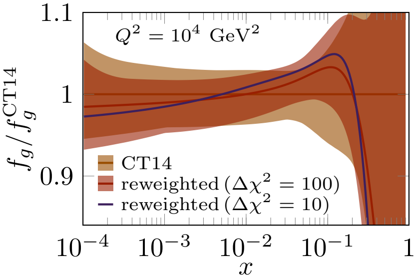


Reweighting:

- improves midrapidity description
- is not able to fully reproduce data at large rapidities even when applied with additional weight ($\Delta\chi^2 = 10$) (high-x parametrization issue? NNLO? data systematics?)

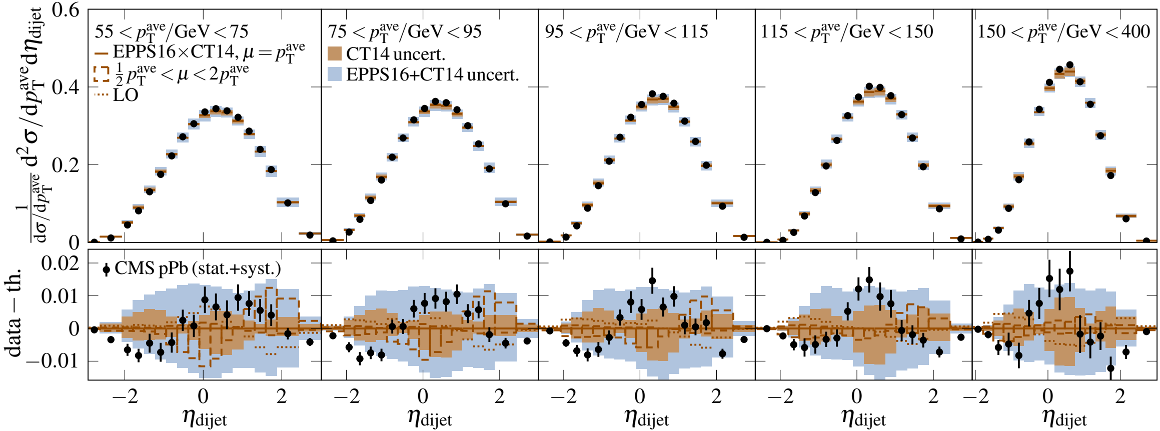
Significant gluon modifications needed especially at large x

- also valence quarks get modified



CMS dijets at **pPb**

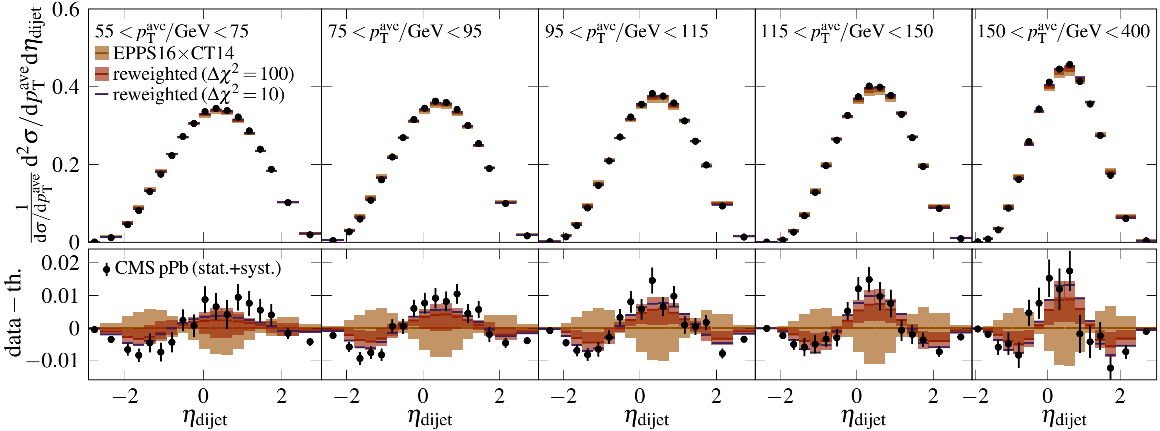
[Eur.Phys.J. C79 (2019) 511]



- pPb data deviates from NLO calculations *almost the same way* as the pp data
  - ➔ had we not seen the same deviations in pp, we might have interpreted this as a fault in our nuclear PDFs
- Compared to pp case we have additional suppression in data compared to theory at forward rapidities
  - ➔ implication of deeper gluon shadowing

CMS dijets at **pPb** – impact of CT14 reweighting

[Eur.Phys.J. C79 (2019) 511]

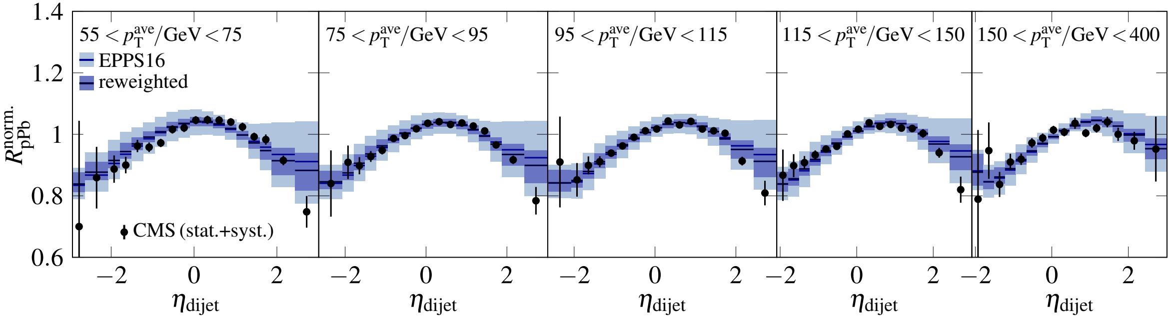


- Modifications needed in CT14 to describe pp data have large impact on pPb predictions
  - ➔ it is imperative to understand the pp baseline before making far-reaching conclusions from pPb data
- Using these data directly in nuclear PDF analysis with CT14 proton PDFs would lead to
  - ▶ overestimating nuclear effects
  - ▶ large scale-choice bias

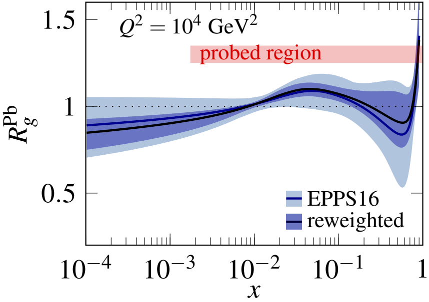
➔ Consider nuclear modification factor instead

CMS dijet $R_{\text{pPb}}^{\text{norm.}}$ – EPPS16 reweighted

[Eur.Phys.J. C79 (2019) 511]

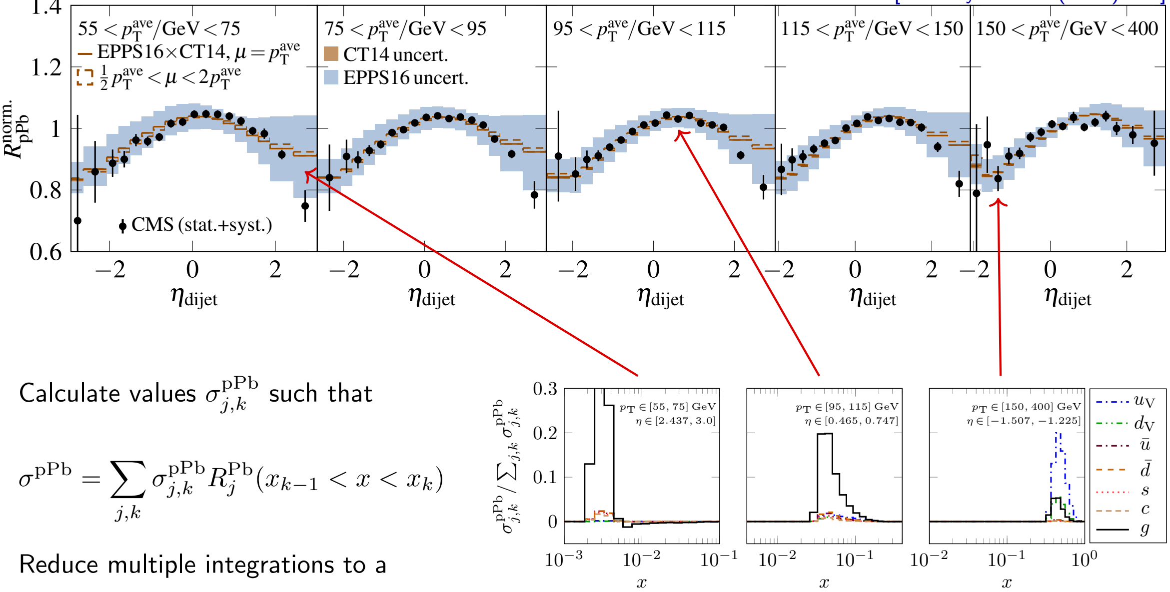


- Drastic reduction in EPPS16 uncertainties!
- Downward pull in the forward region
- The most forward data points lie systematically below the reweighted uncertainty band – could be due to
  - inflexibility in EPPS16 parametrization at small x
  - systematics of the measurement – would be helpful to have correlations of uncertainties available to us



Constructing fast-calculation grids for the next EPPS analysis

[Eur.Phys.J. C79 (2019) 511]



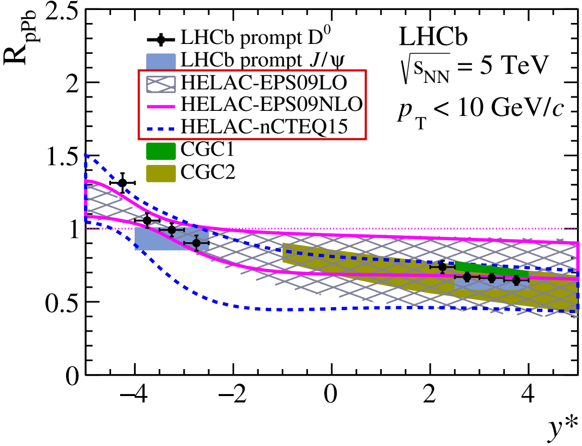
Calculate values $\sigma_{j,k}^{\text{pPb}}$ such that

$$\sigma^{\text{pPb}} = \sum_{j,k} \sigma_{j,k}^{\text{pPb}} R_j^{\text{Pb}}(x_{k-1} < x < x_k)$$

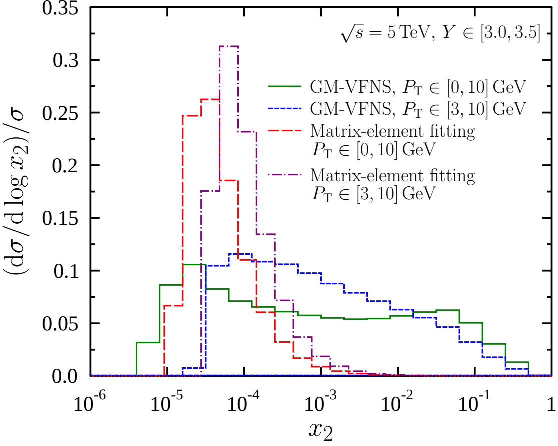
Reduce multiple integrations to a mere sum

D-mesons at 5.02 TeV – differences in theoretical descriptions

[JHEP 10 (2017) 090]



[JHEP 05 (2020) 037]



- The matrix-element fitting method [Lansberg & Shao, EPJ C77 (2017) 1], uses $2 \to 2$ kinematics producing a narrow distribution in x
- The SACOT-m_T scheme [Helenius & Paukkunen, JHEP 1805 (2018) 196] of GM-VFNS gives a much wider x-distribution due to taking into account the gluon-to-HQ fragmentation
- Still, the data can probe nPDFs down to $x \sim 10^{-5}$

Heavy-flavour production mass schemes

FFNS

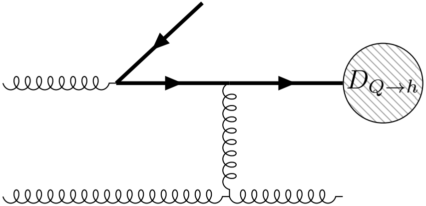
In *fixed flavour number scheme*, valid at small p_{T}, heavy quarks are produced only at the matrix element level

Contains $\log(p_{\mathrm{T}}/m)$ and m/p_{T} terms

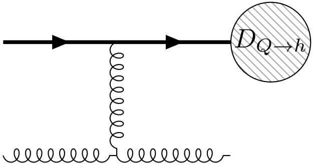
ZM-VFNS

In *zero-mass variable flavour number scheme*, valid at large p_{T}, heavy quarks are treated as massless particles produced also in ISR/FSR

Resums $\log(p_{\mathrm{T}}/m)$ but ignores m/p_{T} terms



$-$ subtraction term $+$



GM-VFNS

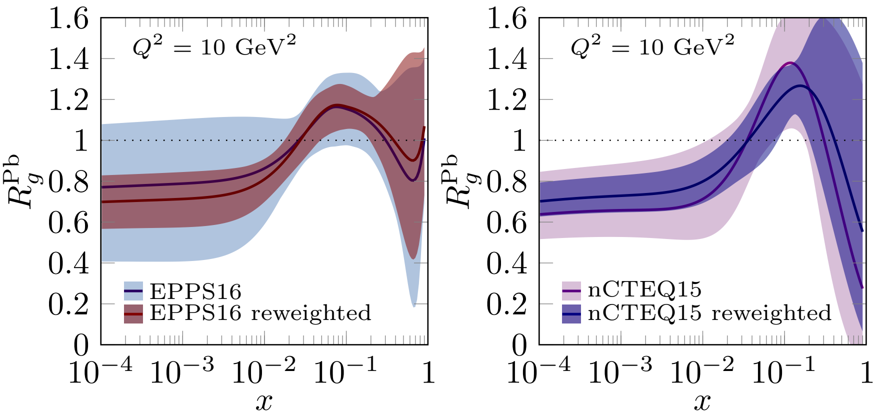
A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, valid at all p_{T}

Resums $\log(p_{\mathrm{T}}/m)$ and includes m/p_{T} terms in the FFNS matrix elements

Important: includes also gluon-to-HF fragmentation – large contribution to the cross section!

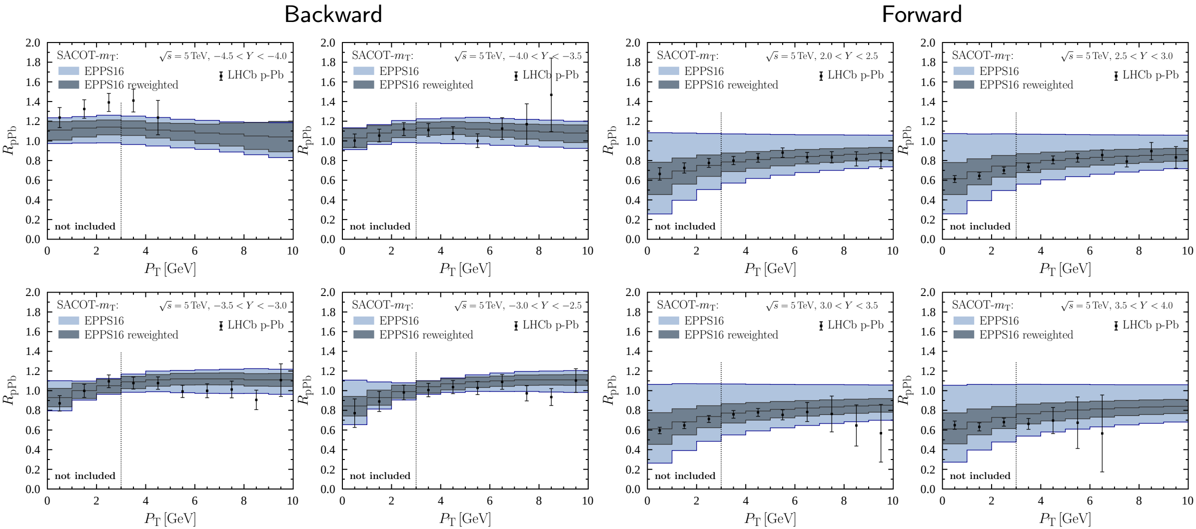
nPDFs reweighted with LHCb D-meson R_{pPb} at 5.02 TeV

[JHEP 05 (2020) 037]



- Large reduction in small-x uncertainties, probed down to $x \sim 10^{-5}$
- Support for stronger (weaker) shadowing than in the EPPS16 (nCTEQ15) central set
- EPPS16 and nCTEQ15 brought to a closer mutual agreement
- Striking similarity with the results with dijets → Supports the validity of collinear factorization in pPb and the universality of nPDFs

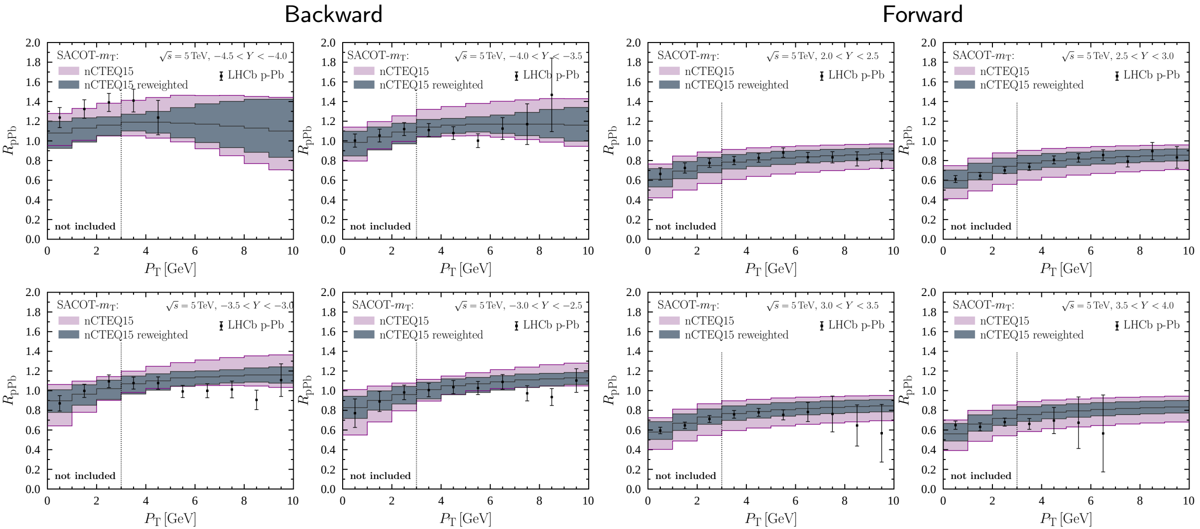
EPPS16 reweighted with LHCb D-meson R_{pPb} at 5.02 TeV [JHEP 05 (2020) 037]



- Data well reproduced with the reweighted results
- Significant reduction in EPPS16 uncertainties especially in forward bins
- Good agreement with data below cut – no physics beyond collinear factorization needed

nCTEQ15 reweighted with LHCb D-meson R_{pPb} at 5.02 TeV

[JHEP 05 (2020) 037]

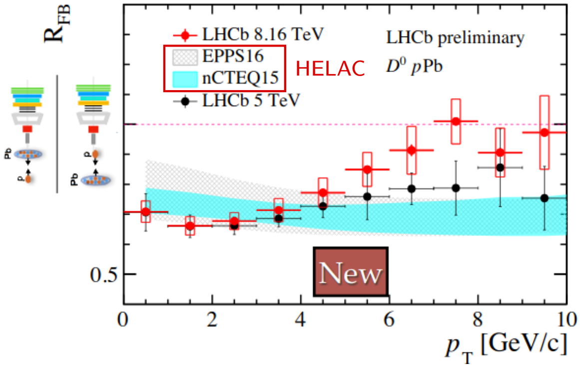


Backward

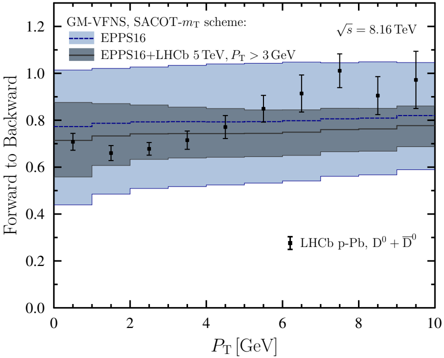
Forward

- Uncertainties smaller to begin with in the forward direction (less flexible small-x parametrization) while larger in backward – almost identical results
- Data well reproduced

Future prospects: D-mesons at 8.16 TeV – do we have tension?



➔



QM2019 LHCb summary talk:

> ~~*"Tension between data and nPDFs predictions. Additional effects required."*~~
>
> ➔ *Theoretical description matters, HELAC underestimates the nPDF uncertainties*

The slope of the 8.16 TeV data still differs from that in EPPS16

- ➔ might hint a preference for a slightly different parametric form
- ➔ can we explain the different behaviour in 8.16 TeV vs. 5.02 TeV data?

Constraining the valence flavour separation with pion–nucleus DY Work in progress

To constrain the flavour separation, we can use neutrino DIS [Paukkunen & Salgado, JHEP 07 (2010) 032] or **pion–nucleus Drell–Yan** [Phys.Lett.B 768 (2017) 7-11]

To cancel pion-PDF uncertainties, we can use either ratios of the cross sections directly,

$$\frac{\frac{1}{A_1}\mathrm{d}\sigma^{\pi^-+A_1}/\mathrm{d}x_\mathrm{N}}{\frac{1}{A_2}\mathrm{d}\sigma^{\pi^-+A_2}/\mathrm{d}x_\mathrm{N}} \approx \frac{4u^{A_1}+\bar{d}^{A_1}}{4u^{A_2}+\bar{d}^{A_2}}$$ ➔ probes *mostly* u valence

$$\frac{\mathrm{d}\sigma^{\pi^++A}/\mathrm{d}x_\mathrm{N}}{\mathrm{d}\sigma^{\pi^-+A}/\mathrm{d}x_\mathrm{N}} \approx \frac{4\bar{u}^A+d^A}{4u^A+\bar{d}^A}$$ ➔ probes *mostly* u/d valence ratio, but more sensitive to sea quarks

or through the linear combinations

$$\Sigma^A_\mathrm{val} = -\sigma^{\pi^++A}+\sigma^{\pi^-+A}, \qquad \Sigma^A_\mathrm{sea} = 4\sigma^{\pi^++A}-\sigma^{\pi^-+A},$$

which give

$$\frac{\frac{1}{A_1}\mathrm{d}\Sigma^{A_1}_\mathrm{val}/\mathrm{d}x_\mathrm{N}}{\frac{1}{A_2}\mathrm{d}\Sigma^{A_2}_\mathrm{val}/\mathrm{d}x_\mathrm{N}} \approx \frac{4u_\mathrm{V}^{A_1}-d_\mathrm{V}^{A_1}}{4u_\mathrm{V}^{A_2}-d_\mathrm{V}^{A_2}}$$ ➔ probes *only* valence quarks

$$\frac{\frac{1}{A_1}\mathrm{d}\Sigma^{A_1}_\mathrm{sea}/\mathrm{d}x_\mathrm{N}}{\frac{1}{A_2}\mathrm{d}\Sigma^{A_2}_\mathrm{sea}/\mathrm{d}x_\mathrm{N}} \approx \frac{3(4\bar{u}^{A_1}+\bar{d}^{A_1})+4(d_\mathrm{V}^{A_1}-u_\mathrm{V}^{A_1})}{3(4\bar{u}^{A_2}+\bar{d}^{A_2})+4(d_\mathrm{V}^{A_2}-u_\mathrm{V}^{A_2})}$$ ➔ probes sea quarks + *valence-quark difference*

Pion–nucleus DY at COMPASS++/AMBER

Work in progress

For

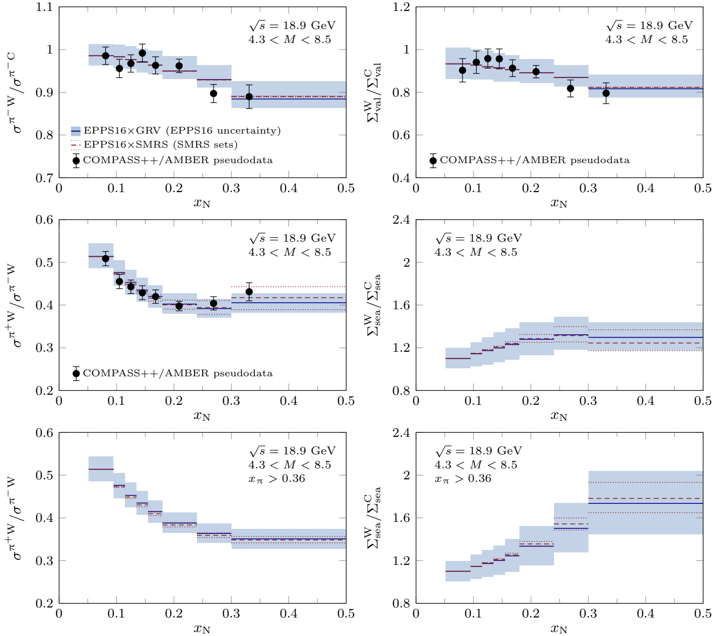
$$\frac{\frac{1}{A_1}\mathrm{d}\sigma^{\pi^-+A_1}/\mathrm{d}x_\mathrm{N}}{\frac{1}{A_2}\mathrm{d}\sigma^{\pi^-+A_2}/\mathrm{d}x_\mathrm{N}}, \qquad \frac{\frac{1}{A_1}\mathrm{d}\Sigma^{A_1}_\mathrm{val}/\mathrm{d}x_\mathrm{N}}{\frac{1}{A_2}\mathrm{d}\Sigma^{A_2}_\mathrm{val}/\mathrm{d}x_\mathrm{N}}$$

the pion-PDF cancellation is extremely good straight out of the box, but for

$$\frac{\mathrm{d}\sigma^{\pi^++A}/\mathrm{d}x_\mathrm{N}}{\mathrm{d}\sigma^{\pi^-+A}/\mathrm{d}x_\mathrm{N}}, \qquad \frac{\frac{1}{A_1}\mathrm{d}\Sigma^{A_1}_\mathrm{sea}/\mathrm{d}x_\mathrm{N}}{\frac{1}{A_2}\mathrm{d}\Sigma^{A_2}_\mathrm{sea}/\mathrm{d}x_\mathrm{N}}$$

it is better to use additional x_π cut

NLO predictions compared here with the expected statistics from 213 days (π^+ beam) + 67 days (π^- beam) run at the COMPASS++/AMBER facility



COMPASS++/AMBER projections provided by Vincent Andrieux (University of Illinois)

Pion–nucleus DY at COMPASS++/AMBER

Work in progress

Reweighting EPPS16 with projected data shows that we can expect some, but not very strong, additional constraints on flavour separation

However:

- The flavour-separation constraints in EPPS16 come mostly from $\nu + \mathrm{Pb}$ DIS, for lighter nuclei the dependence is strongly influenced by the used parametrization
- Still an important check for the universality of the nPDFs and test for the existence of CNM energy loss [Arleo *et al.*, JHEP 01 (2019) 129]

TODO:

- Check the expected impact with $\Sigma^{\mathrm{W}}_{\mathrm{sea}}/\Sigma^{\mathrm{C}}_{\mathrm{sea}}$