Status of nPDF, constraints from HF/onia

A. Kusina

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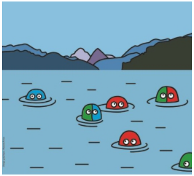

HF2022: Heavy Flavours from small to large systems

Institute Pascal

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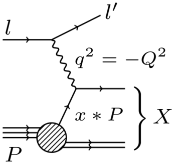
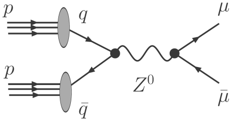
PDFs and QCD Factorization

- **Factorization** in case of **Deep Inelastic Scattering** (DIS)



$$\frac{d^2\sigma}{dx dQ^2} = \sum_{i=q,\bar{q},g} \int_x^1 \frac{dz}{z} f_i(z,\mu) d\hat{\sigma}_{il\to l'X}\left(\frac{x}{z}, \frac{Q}{\mu}\right) + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\right)$$

- **Factorization** in case of **Drell-Yan lepton pair production** (DY)



$$\sigma_{pp\to l\bar{l}X} = \sum_{i,j=q,\bar{q},g} \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2$$

$$\times f_i(z_1,\mu) f_j(z_2,\mu) \hat{\sigma}_{ij\to l\bar{l}X}\left(\frac{x_1}{z_1}, \frac{x_2}{z_2}, \frac{Q}{\mu}\right) + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\right)$$

- $f_i(z,\mu)$ – proton PDFs of parton i (**non-perturbative**).

PDFs are **UNIVERSAL** – do not depend on the process!!!

- $\hat{\sigma}$ – parton level matrix element (**calculable in pQCD**).
- $\mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\right)$ – non-leading terms defining accuracy of factorization formula.

Properties of PDFs

- **Sum rules**
  - **Number sum rules** – connect partons to quarks from SU(3) flavour symmetry of hadrons; proton (uud), neutron (udd). For protons:

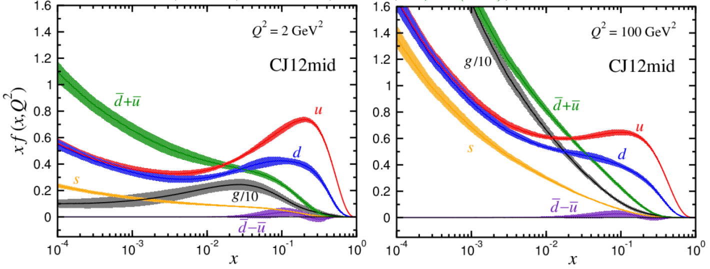
$$\int_0^1 dx[\underbrace{f_u(x) - f_{\bar{u}}(x)}_{u-\text{valence distr.}}] = 2 \qquad \int_0^1 dx[\underbrace{f_d(x) - f_{\bar{d}}(x)}_{d-\text{valence distr.}}] = 1$$

  - **Momentum sum rule** – momentum conservation connecting all flavours

$$\sum_{i=q,\bar{q},g} \int_0^1 dx\, x f_i(x) = 1$$

- **Scale dependence**
  - x-**dependence** of PDFs is NOT calculable in pQCD
  - μ^2-**dependence** is calculable in pQCD – given by **DGLAP** equations

Owens, Accardi, Melnitchouk, PRD 87, 094012 (2013), `arXiv:1212.1702`



Schematics of Global Analysis

1. Choose experimental data (e.g. DIS, DY, inclusive jet prod., etc.)
2. Parametrize PDFs at low initial scale $\mu = Q_0 = 1.3\text{GeV}$:

$$f_i(x, Q_0) = f_i(x; a_0, a_1, \dots) = a_0 x^{a_1} (1-x)^{a_2} P(x; a_3, \dots)$$

3. Use DGLAP equation to evolve $f_i(x, \mu)$ from $\mu = Q_0$ to $\mu = Q_{\text{max}}$.
4. Calculate theory predictions corresponding to the data (σ_{DIS}, σ_{DIS}, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

$$\chi^2(\{a_i\}) = \sum_{\text{experiments}} w_n \chi_n^2(\{a_i\})$$

$$\chi_n^2(\{a_i\}) = \sum_{\text{data points}} \left(\frac{\text{data} - \text{theory}(\{a_i\})}{\text{uncertainty}} \right)^2$$

(by default $w_n = 1$)

6. Minimize χ^2 function with respect to parameters $a_0, a_1, \dots$

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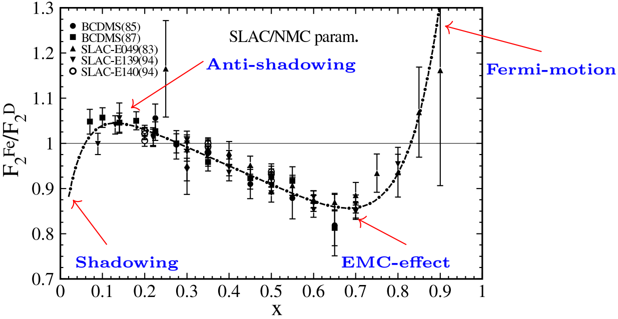
- Cross-sections in nuclear collisions are modified

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$



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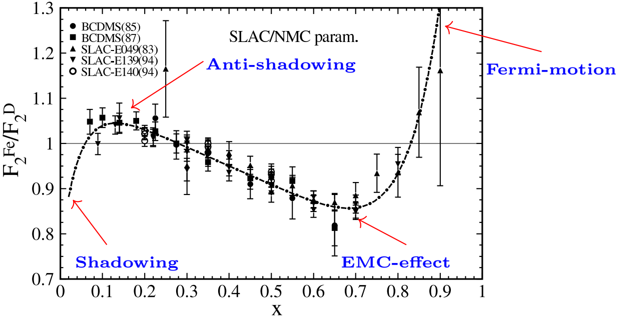
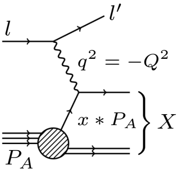


- Working assumption: **factorization** = *universal* **nPDFs**



$$\frac{d^2\sigma}{dx dQ^2} = \sum_i f_i^A(x, Q^2) \otimes d\hat{\sigma}_{il \to l' X}$$

- Do not consider any cold nuclear matter effects (e.g. energy loss).

Assumptions entering nuclear PDF analyses

1. **Factorization** & DGLAP evolution
   - allow for definition of **universal PDFs**
   - make the formalism **predictive**
   - needed even if it is broken

2. Isospin symmetry $\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases}$ $\qquad f_i^{(A,Z)} = \frac{Z}{A} f_i^{p/A} + \frac{A-Z}{A} f_i^{n/A}$

3. The *bound proton* PDFs have the *same evolution equations* and sum rules as the free proton PDFs *provided we neglect any contributions from the region* $x > 1$ (which is expected to have negligible contribution [PRC 73, 045206 (2006)])

Then observables $\mathcal{O}^A$ can be calculated as:

$$\mathcal{O}^A = Z\,\mathcal{O}^{p/A} + (A-Z)\,\mathcal{O}^{n/A}$$

With the above assumptions we can use the free proton framework to analyze nuclear data

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   with $a_j = a_j(A)$ depending on the nuclei.
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Differences with the free-proton PDFs

- Theoretical status of Factorization
- Parametrization – more parameters to model A-dependence
- Different data sets – much less data:

  - Less data → less constraining power → more assumptions (fixing) about a_i parameters
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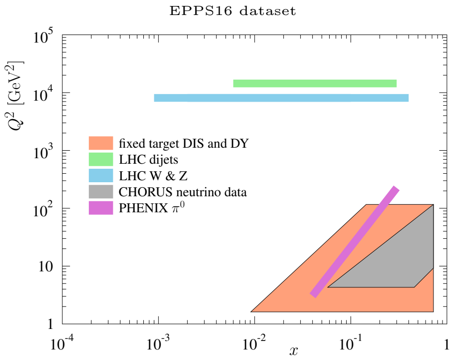

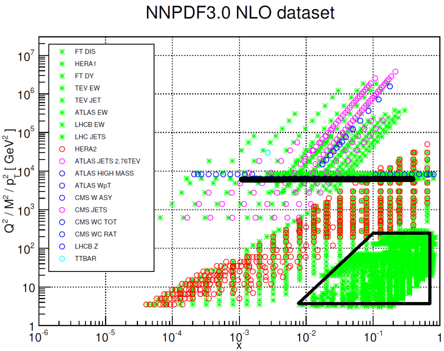

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- more process give access to more flavour combination - better flavour separation
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For nPDFs we generally lack good constraints on **gluon**:

- 😐 **DIS** (from Q^2 evolution): not large enough lever arm
- 🙂 W/Z from pPb in LHC: good for $x \geq 10^{-3}$
- 🙁 **Dijets** from pPb in LHC: problematic NLO doesn't work
- 😐 **Direct photon** from pPb in LHC: not very precise
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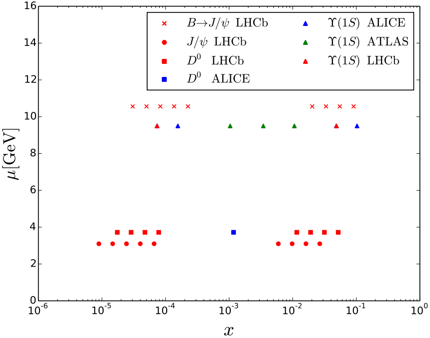
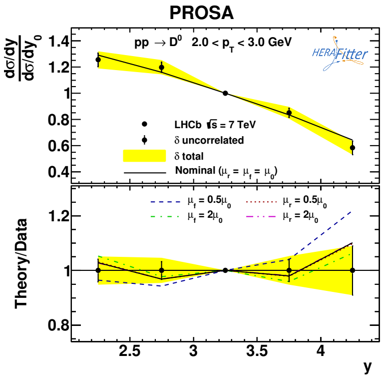
- **SIH** (Single Inclusive Hadron) from LHC & RHIC: FF-dependent + $x \geq 10^{-2}$

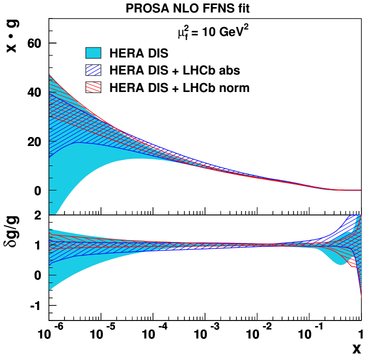
? **Heavy quark(onia)**: precise + access to very small $x \leq 10^{-5}$ but...



First use of HF data to constrain (n)PDFs

- PROSA [EPJC 75, 396 (2015)] first use of D and B data to constrain proton PDFs
  - use ratio to central bin to reduce scale uncertainty





First use of HF data to constrain (n)PDFs

- First use in nPDFs [PRL 121 (2018) 052004; PRD 104 (2021) 014010]: pPb data for D, B, J/ψ, Υ

- Use PDF reweighting
- Data-driven approach for theory calculations [PRL107, 082002 (2011); EPJC77, 1 (2017)]

$$\overline{\left|\mathcal{A}_{gg\to Q+X}\right|^2} = \frac{\lambda^2\kappa\hat{s}}{M_{\mathcal{Q}}^2}\begin{cases} e^{-\kappa\frac{p_T^2}{M_Q^2}} & \text{if } p_T \leq \langle p_T\rangle \\ e^{-\kappa\frac{\langle p_T\rangle^2}{M_Q^2}}\left(1+\frac{\kappa}{n}\frac{p_T^2-\langle p_T\rangle^2}{M_Q^2}\right)^{-n} & \text{if } p_T > \langle p_T\rangle \end{cases}$$

✓ removes model dependence
✓ fast to generate events
✗ currently limited to probes produced in $2\to 2$ partonic processes dominated by single partonic channel (gg, $q\bar{q}$, ...)
$\to$ In our case (D^0, J/ψ, $B\to J/\psi$, $\Upsilon(1S)$ production) gg dominated.
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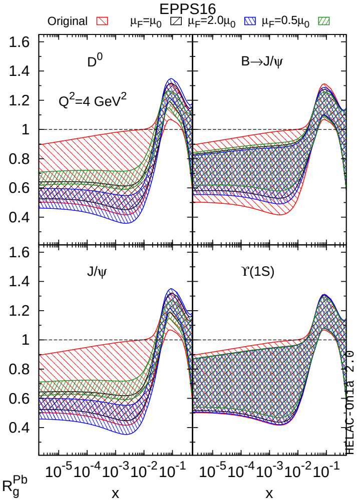

- Use PDF reweighting
- Data-driven approach for theory calculations [PRL107, 082002 (2011); EPJC77, 1 (2017)]
- Predictions for D and B validated against available pQCD calculations (FONLL, GMVFNS).
- Additional features:
  - ✓ large available data sets from multiple LHC experiments
  - ✓ uncertainty in pp collision is well controlled by the data
  - ✓ removes model dependence
  - ✓ fast to generate events
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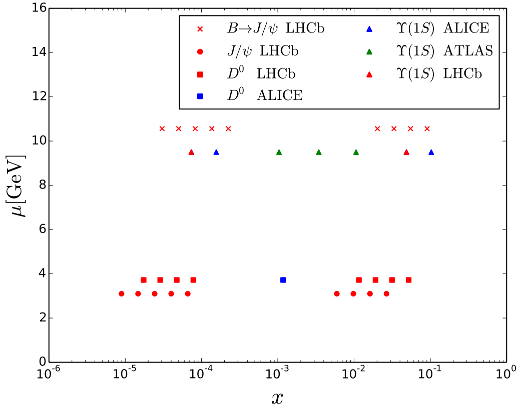
	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$
μ_0	$\sqrt{4M_{D^0}^2 + P_{T,D^0}^2}$	$\sqrt{M_{J/\psi}^2 + P_{T,J/\psi}^2}$	$\sqrt{4M_B^2 + \left(\frac{M_B}{M_{J/\psi}} P_{T,J/\psi}\right)^2}$	$\sqrt{M_{\Upsilon(1S)}^2 + P_{T,\Upsilon(1S)}^2}$
p+p data	LHCb [1]	LHCb [2,3]	LHCb [2,3]	ALICE [4], ATLAS [5], CMS [6], LHCb [7,8]
R_{pPb} data	ALICE [9], LHCb [15]	ALICE [10,11], LHCb [16,12]	LHCb [12]	ALICE [13], ATLAS [14], LHCb [17]

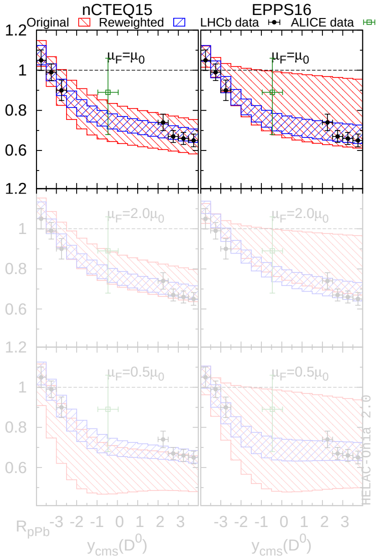


Expected nuclear effects on heavy quark(onium) production in pA collisions

- Nuclear modification of PDFs: initial-state effect
- Energy loss (w.r.t. pp collisions): initial-state or final-state effect
- Break up of the quarkonium in the nuclear matter: final-state effect
- Break up by comoving particles: final-state effect
- Colour filtering of intrinsic QQ pairs: initial-state effect
- ...

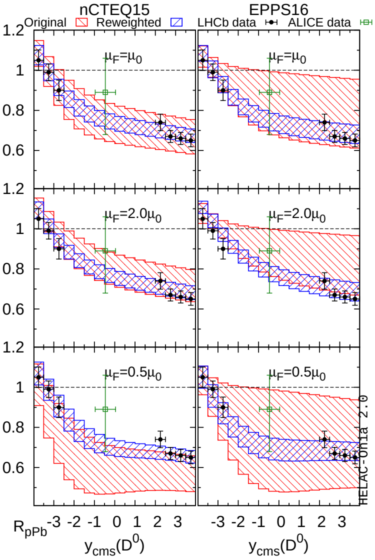
> - We assume leading twist factorization is valid – ONLY modifications of PDFs are present → “shadowing-only” hypothesis.

Reweighting with D^0 data



LHCb [JHEP 1710 (2017) 090, 1707.02750]
ALICE [PRL113, 232301 (2014), 1405.3452]

- Initial description of data is good for both nCTEQ15 and EPPS16.
- Substantial reduction of uncertainty especially for EPPS16.



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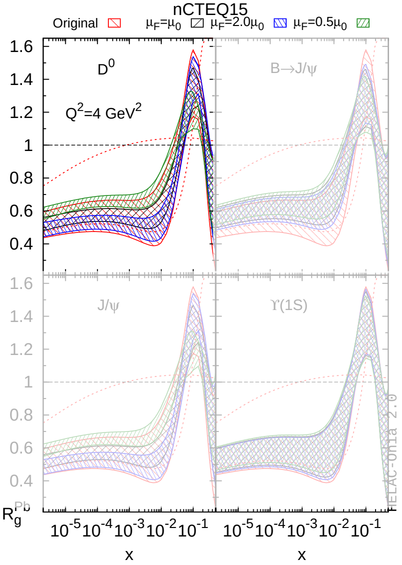
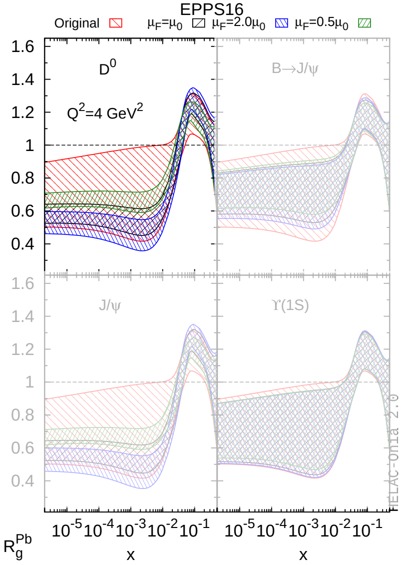
- If we include factorization scale uncertainty errors increase and it can become the dominant uncertainty.

Reweighting results: $R_g^{\mathrm{Pb}} = f_g^{\mathrm{Pb}} / f_g^p$





Consistency with other data

We checked the consistency of the reweighted (**nCTEQ15**) nPDFs with other data sets entering global analysis:

- DIS data (the most precise set NMC Sn/C [NPB 481 (1996) 23]).
- LHC W/Z boson production data [EPJC 77, (2017) 488].
- PHENIX J/ψ $R_{d\mathrm{Au}}$ data [PRL 107 (2011) 142301; PRC 87, (2013) 034904].

This is very non-trivial and further confirms the “shadowing-only” hypothesis of leading twist factorization is valid within the current data precision!

Consistency with other data

- The results of the [PRL 121 (2018), 052004] study were successfully used e.g. to describe data at RHIC.

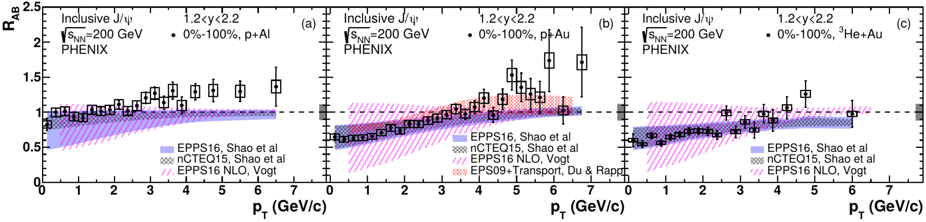


FIG. 10. Nuclear modification factor of inclusive J/ψ as a function of p_T at forward rapidity ($p/^3$He-going direction) for 0%–100% p+Al, p+Au, and ^{3}He+Au collisions. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties. The theory bands are discussed in the text.

arXiv:1910.14487

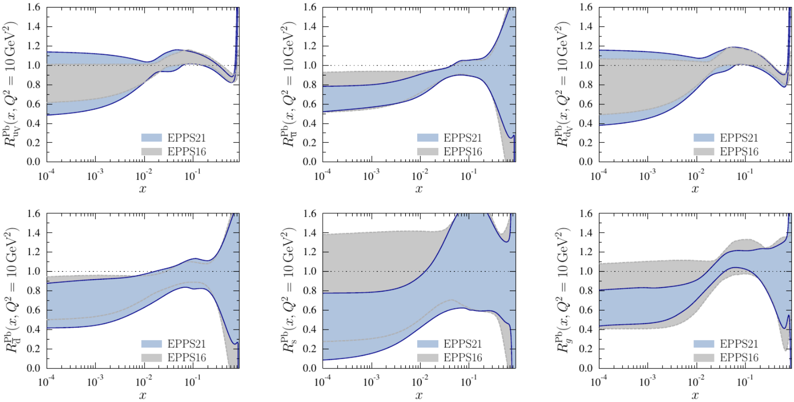
see also: K. Smith, Quark Matter 2019

Available nPDFs including heavy quark(onium) data

	N_{data}	N_{params}	Observables
EPPS21	2029+48	24	(ν)DIS, DY, SIH, W/Z, dijet, D
nNNPDF3.0	2151+37	256	(ν)DIS, DY, W/Z, dijet, γ, D
nCTEQ15HQ	936+548	19	DIS, DY, SIH, W/Z D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$

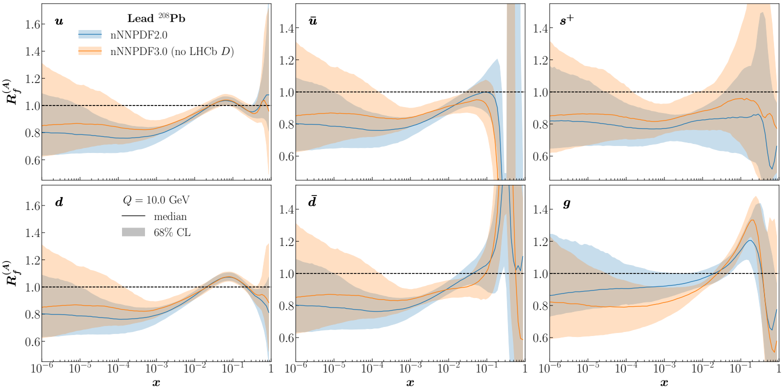
EPPS21 [EPJC 82 (2022) 5, 413]

- New data compared to EPPS16:
  JLAB DIS, CMS W from pPb @8TeV, CMS dijet, LHCb D^0
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson (double differential in p_T and y) calculated in version of GM-VFNS scheme [JHEP 05 (2018) 196]



nNNPDF3.0 [EPJC 82 (2022) 6, 507]

- New data compared to nNNPDF2.0:
  pPb data from LHC: ALICE W @5TeV, LHCb Z @5TeV, ALICE Z @8TeV, CMS Z @8TeV, CMS dijet, prompt photon ATLAS @8TeV, LHCb D^0
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson in FFNS done in POWHEG+PYTHIA included using **PDF reweighting**



nNNPDF3.0 [EPJC 82 (2022) 6, 507]

- New data compared to nNNPDF2.0:
  pPb data from LHC: ALICE W @5TeV, LHCb Z @5TeV, ALICE Z @8TeV, CMS Z @8TeV, CMS dijet, prompt photon ATLAS @8TeV, LHCb D^0
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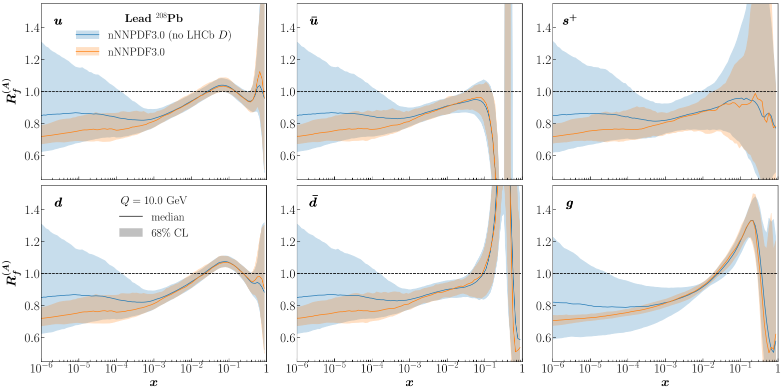
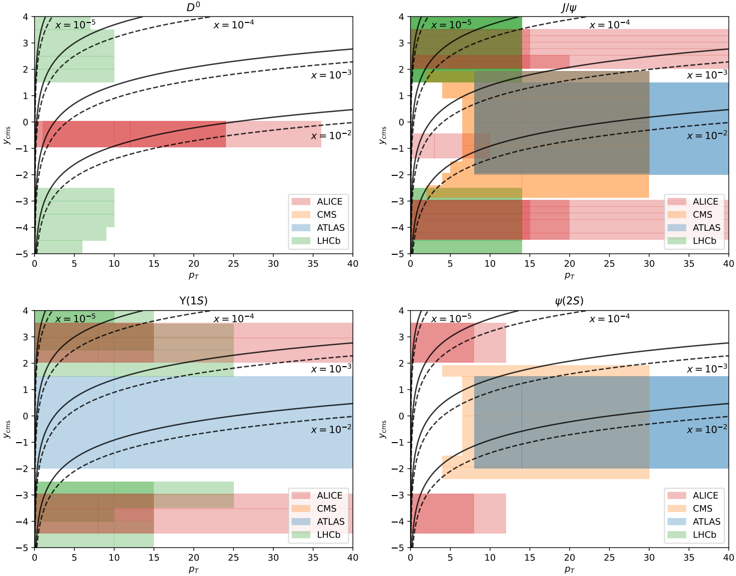
- Predictions for D meson in FFNS done in POWHEG+PYTHIA included using **PDF reweighting**



- New data compared to nCTEQ15WZ+SIH ($p_T > 3$ GeV): D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$



Different schemes for the calculation of open **heavy quark** production (D, B mesons):

- **FFNS**: heavy quarks present only in final state. Valid for small p_T.
- **ZM-VFNS**: heavy quarks treated as massless, but included in PDFs for $\mu_f > \mu_T$. Valid at large p_T.
- Schemes interpolating between the two:
  - **FONLL**:

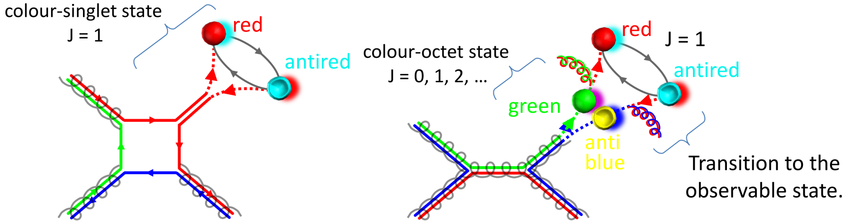
$$d\sigma_{\text{FONLL}} = d\sigma_{\text{FFNS}} + (d\sigma_{\text{ZMVFNS}} - d\sigma_{\text{FFNS},0}) \times G(m_Q, p_T),$$

  - **GM-VFNS**: Massive heavy quarks included in the PDFs for $\mu_f > \mu_T$.

All schemes introduce dependence on non-perturbative final-state fragmentation functions

Different schemes for the calculation of **quarkonium** production:

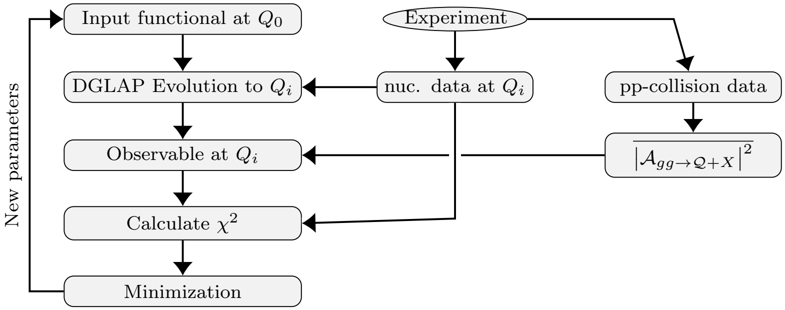
- **Color-evaporation model**: hard scattering creates $Q\bar{Q}$-pair, which radiates gluons until it hadronizes
- **Color-singlet model**: Intermediate state is a color neutral $Q\bar{Q}$-pair
- **Non-relativistic QCD**: separation of short and long distance physics through expansion in velocity



Illustrations by Pietro Faccioli (https://idpasc.lip.pt/uploads/talk/file/530/LIP_curso_polarization.pdf)

Data-driven Approach

$$\sigma(AB \to \mathcal{Q} + X) = \int \mathrm{d}x_1 \; \mathrm{d}x_2 f_{1,g}(x_1) \, f_{2,g}(x_2) \, \frac{1}{2\hat{s}} \overline{\left|\mathcal{A}_{gg\to Q} + X\right|^2} \mathrm{dLIPS}$$



- Crystal-Ball parametrization extended to include rapidity dependence (a param.)

$$\overline{\left|\mathcal{A}_{gg\to Q+X}\right|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \begin{cases} e^{-\kappa \frac{p_T^2}{M_Q^2} + a|y|} & \text{if } p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{\langle p_T \rangle^2}{M_Q^2} + a|y|} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_Q^2}\right)^{-n} & \text{if } p_T > \langle p_T \rangle \end{cases}$$

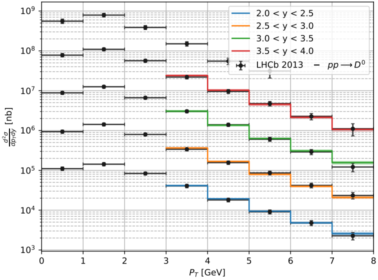
Data-driven Approach: Proton-proton baseline

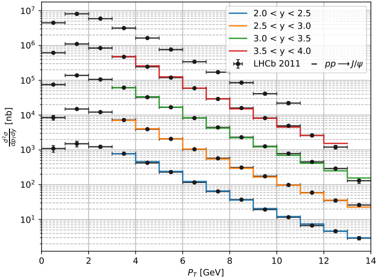
$$\overline{\left|\mathcal{A}_{gg\to Q+X}\right|^2} = \frac{\lambda^2\kappa\hat{s}}{M_Q^2}\begin{cases} e^{-\kappa\frac{p_T^2}{M_Q^2}+a|y|} & \text{if } p_T \le \langle p_T\rangle \\ e^{-\kappa\frac{\langle p_T\rangle^2}{M_Q^2}+a|y|}\left(1+\frac{\kappa}{n}\frac{p_T^2-\langle p_T\rangle^2}{M_Q^2}\right)^{-n} & \text{if } p_T > \langle p_T\rangle \end{cases}$$

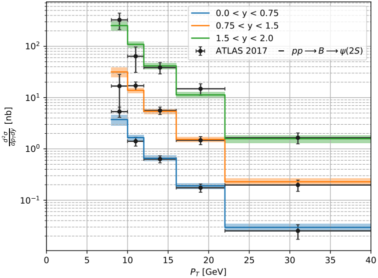
- Impose cuts to remove data with $p_T < 3\,\text{GeV}$ and outside of $-4 \le y_{cms} \le 4$

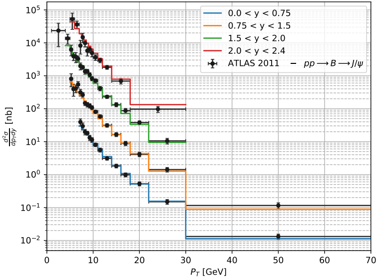
	D^0	J/ψ	$B\to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B\to\psi(2S)$
κ	0.3345	0.4789	0.1548	0.9452	0.2158	0.4527
λ	1.8259	0.3037	0.1213	0.0656	0.0752	0.1385
$\langle p_T\rangle$	2.4009	5.2931	-7.6502	8.6378	8.9881	7.8052
n	2.0007	2.1736	1.5553	1.9323	1.0720	1.6479
a	-0.0329	0.0281	-0.0808	0.2238	-0.1061	0.0617
N_{points}	34	501		375	55	
χ^2/N_{dof}	0.25	0.88		0.92	0.77	

- Very good agreement between data and fitted theory


2.0 < y < 2.5
2.5 < y < 3.0
3.0 < y < 3.5
3.5 < y < 4.0
LHCb 2013 – $pp \longrightarrow D^0$
$\frac{d^2\sigma}{dp_T dy}$ [nb]
P_T [GeV]

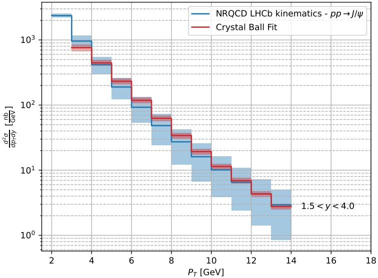

2.0 < y < 2.5
2.5 < y < 3.0
3.0 < y < 3.5
3.5 < y < 4.0
LHCb 2011 – $pp \longrightarrow J/\psi$
$\frac{d^2\sigma}{dp_T dy}$ [nb]
P_T [GeV]

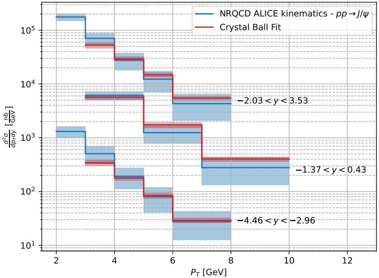

0.0 < y < 0.75
0.75 < y < 1.5
1.5 < y < 2.0
ATLAS 2017 – $pp \longrightarrow B \longrightarrow \psi(2S)$
$\frac{d^2\sigma}{dp_T dy}$ [nb]
P_T [GeV]


0.0 < y < 0.75
0.75 < y < 1.5
1.5 < y < 2.0
2.0 < y < 2.4
ATLAS 2011 – $pp \longrightarrow B \longrightarrow J/\psi$
$\frac{d^2\sigma}{dp_T dy}$ [nb]
P_T [GeV]

Baseline - comparison with NRQCD for J/ψ

Calculations by Mathias Butenschoen, Bernd Kniehl [M. Butenschoen et al., Nucl.Phys.B Proc.Suppl. 222-224 (2012) 151-161]

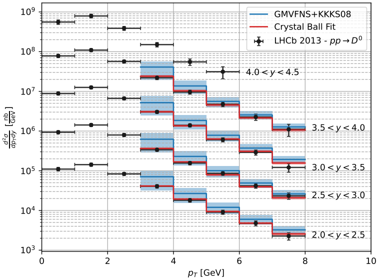


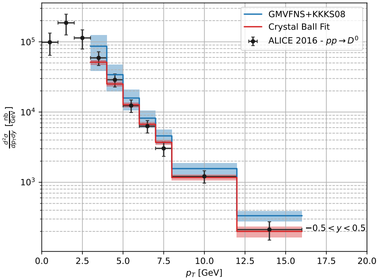


- NRQCD Uncertainties due to scale variations: $1/2 < \mu_r/\mu_{r,0} = \mu_i/\mu_{i,0} = \mu_{\mathrm{NRQCD}}/\mu_{\mathrm{NRQCD},0} < 2$
- Base scale $\mu_{r,0} = \mu_{i,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_{\mathrm{NRQCD},0} = m_c$

Baseline - comparison with GMVFNS for D^0

Calculations in the GMVFNS using KKKS08 fragmentation functions





- GMVFNS Uncertainties due to scale variations: $1/2 < \mu_r/\mu_{r,0}, \mu_i/\mu_{i,0}, \mu_f/\mu_{f,0} < 2$
- Base scale $\mu_{r,0} = \mu_{i,0} = \mu_{f,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_c = 1.3$ GeV

nCTEQ15HQ fit setup [PRD 105 (2022) 11, 114043]

- Include all data from nCTEQ15WZ+SIH (936 points) [PRD 104 (2021) 094005] + 548 Heavy Quark(onia) data points

- Use the same open parameters and settings as nCTEQ15WZ+SIH

PDF of nucleus:

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

bound proton PDFs:

$$x f_i^{p/A}(x,Q_0) = x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4} x)^{c_5}$$

A-dependence:

$$c_k \to c_k(A) \equiv p_k + a_k \left(1 - A^{-b_k}\right)$$

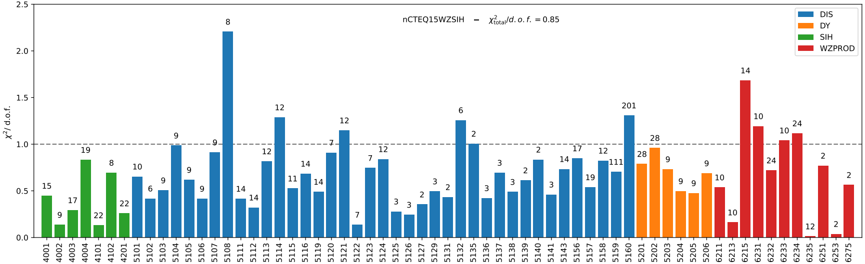
Open parameters: $\{a_1^{u_v},\ a_2^{u_v},\ a_4^{u_v},\ a_5^{u_v},\ a_1^{d_v},\ a_2^{d_v},\ a_5^{d_v},\ a_1^{\bar{u}+\bar{d}},\ a_5^{\bar{u}+\bar{d}},$
$a_1^g,\ a_4^g,\ a_5^g,\ b_0^g,\ b_1^g,\ b_4^g,\ b_5^g,\ a_0^{s+\bar{s}},\ a_1^{s+\bar{s}},\ a_2^{s+\bar{s}}\}$

- Add uncertainties of the CB fit to data systematic uncertainties

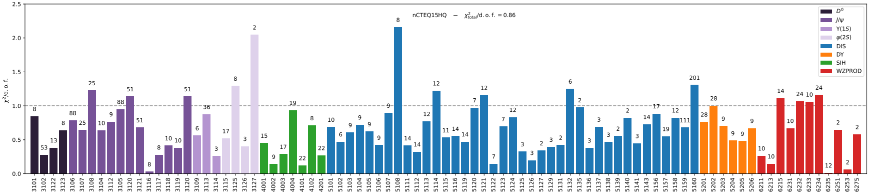
- Repeat full procedure with different scale choices $\mu_f/\mu_{f,0} = \{\frac{1}{2}, 1, 2\}$

nCTEQ15HQ data description χ^2 [PRD 105 (2022) 11, 114043]

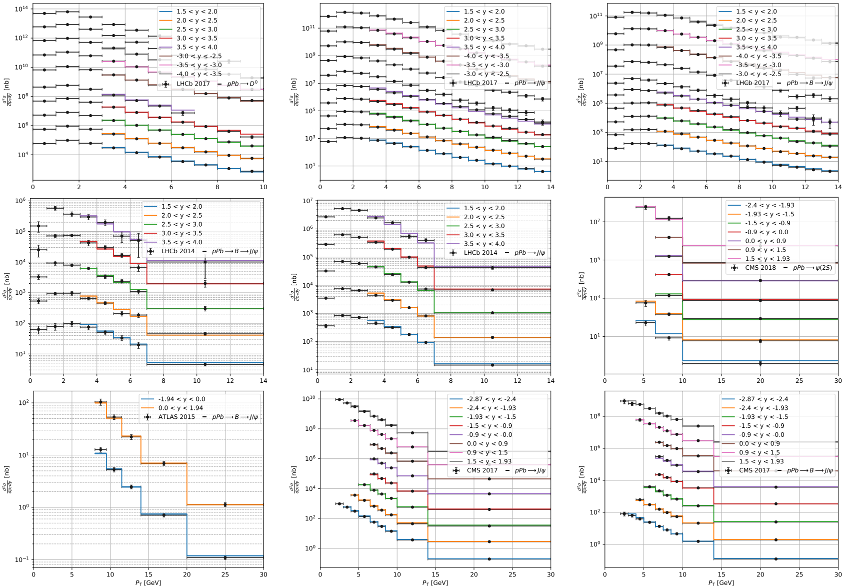
Earlier nCTEQ15WZ+SIH fit:



Now with 548 new HF data points nCTEQ15HQ:

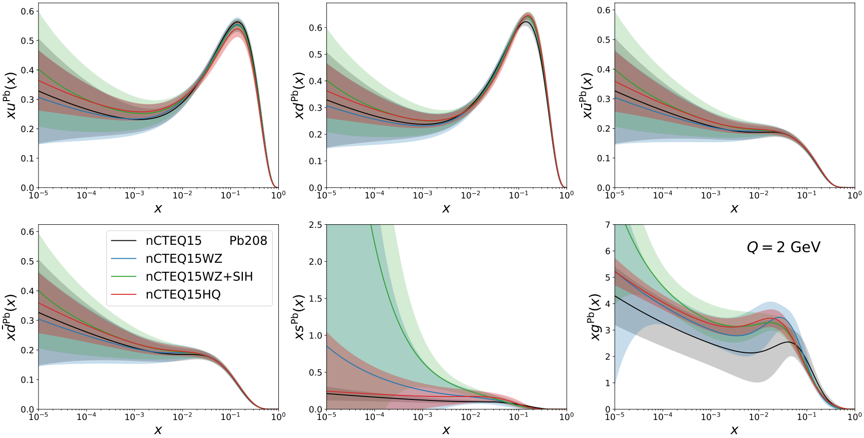


nCTEQ15HQ data description [PRD 105 (2022) 11, 114043]

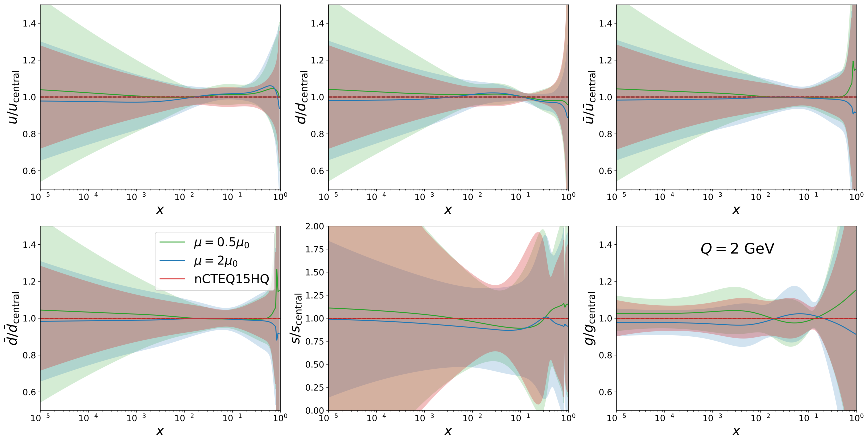


nCTEQ15HQ nPDFs [PRD 105 (2022) 11, 114043]

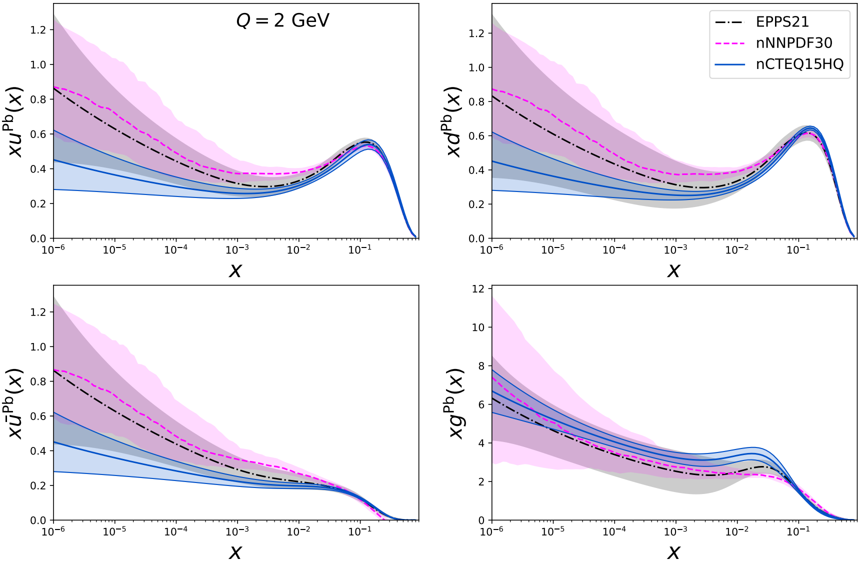
- New data compared to nCTEQ15WZ+SIH:
  D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$
- Predictions for heavy quark(onium) data done with data-driven method [PRL 121 (2018) 052004; PRL107, 082002 (2011); EPJC77, 1 (2017)]



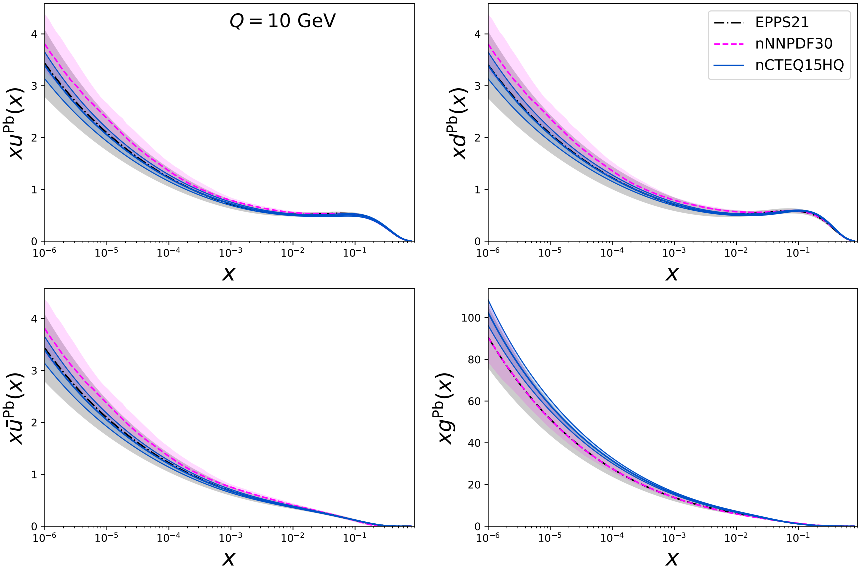
nCTEQ15HQ nPDFs scale dependence [PRD 105 (2022) 11, 114043]



Comparison of nPDFs using HF data



Comparison of nPDFs using HF data



Summary

- **Heavy Quark(onia)** data can constrain low-x gluon nPDFs in a region unconstrained by any other data but should we use them???
  - ✓ data-driven approach reduces uncertainties
  - ✓ compatible with data of other processes
  - ✗ but does it mean the collinear factorization is work?
  - ✗ possible other effects like energy loss
  - ✗ large scale uncertainties for charm
  - ✗ very low-x possible saturation region
  - ✗ dependence on fragmentation functions
- Maybe better to restrict to open heavy flavour especially B meson?
  - ✓ pQCD calculations should be reliable
  - ✓ scale uncertainties reduced compared to charm
  - ✗ there still can be other effects [JHEP 01 (2022) 164] (could be removed by cuts?)
  - ✗ removes a lot of data

Nuclear CTEQ parto

ncteq.hepforge.org

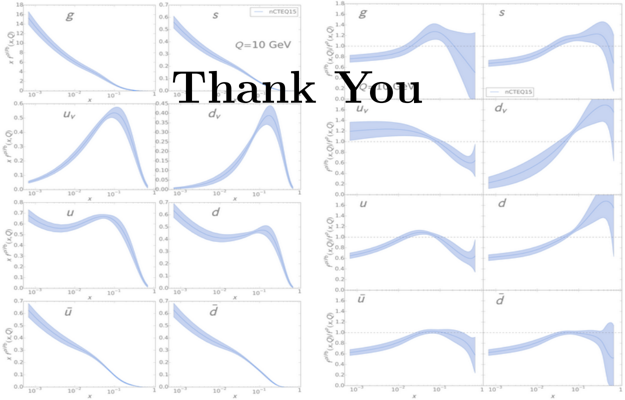
nCTEQ is hosted by Hepforge, IPPP Durham

nCTEQ

nuclear parton distribution functions

- Home
- PDF grids & code
  - nCTEQ15
  - previous PDF grids
- Papers & Talks
- Subversion
- Tracker
- Wiki

nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). All details on the framework and the first complete results can be found in arXiv:15????? [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities or nuclear correction factors (for example for lead as shown below)



Thank You