Constraining the nuclear gluon PDF with quarkonium production data

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nCTEQ
nuclear parton distribution functions

isoQuant SFB1225

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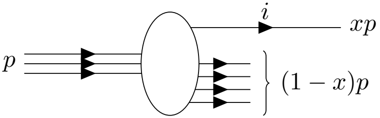
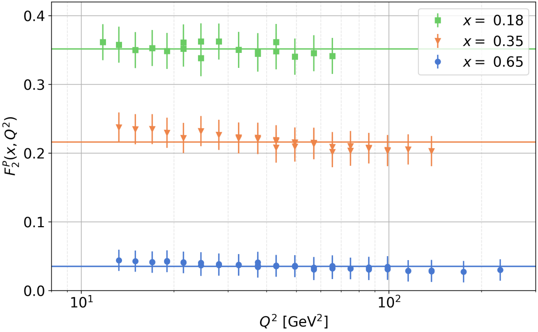
Introduction - What are PDFs?

- Probability densities of finding a parton (i.e. quark, gluon) with momentum fraction x in a hadron.

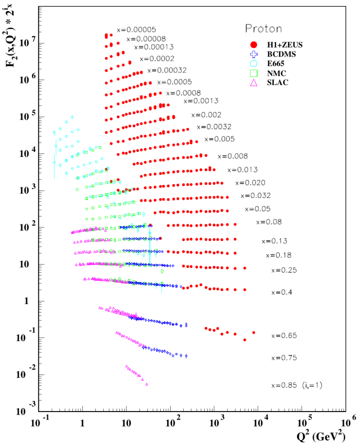
$$f_i(x) \equiv \frac{dP_i}{dx} =$$



- Non-perturbative quantity
- At leading order: Proton structure function F_2 only depends on x



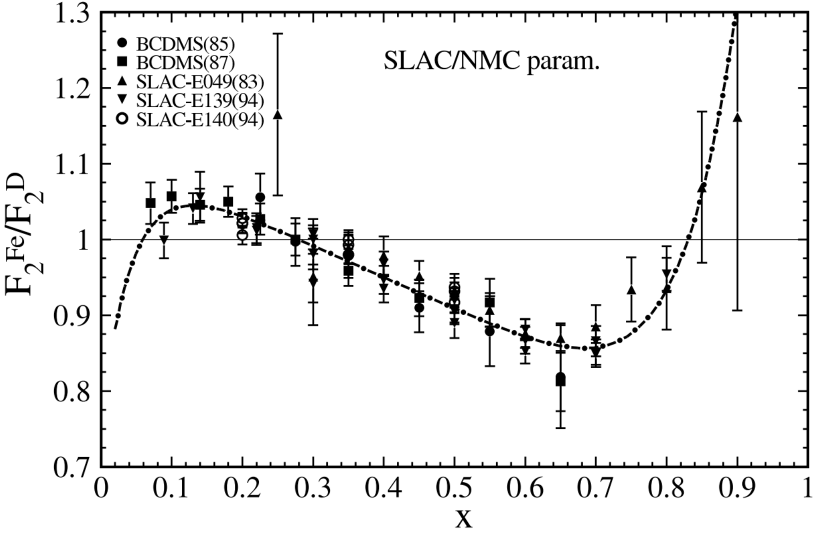
Introduction - DGLAP evolution



$$Q^2 \frac{d}{dQ^2} \begin{pmatrix} f_i(x,Q^2) \\ f_g(x,Q^2) \end{pmatrix} = \sum_j \frac{\alpha_s}{2\pi} \int_x^1 \frac{d\xi}{\xi} \begin{pmatrix} P_{q_i q_j}\left(\frac{x}{\xi}\right) & P_{q_i g}\left(\frac{x}{\xi}\right) \\ P_{g q_j}\left(\frac{x}{\xi}\right) & P_{gg}\left(\frac{x}{\xi}\right) \end{pmatrix} \begin{pmatrix} f_j(\xi,Q^2) \\ f_g(\xi,Q^2) \end{pmatrix}$$

Introduction - nuclear PDFs

Nuclear PDFs are more than the sum of their parts, i.e. not just the sum of Z proton PDFs and $(A - Z)$ neutron PDFs.



Introduction - Nuclear PDF fitting

PDF parameterization:

$$f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}$$

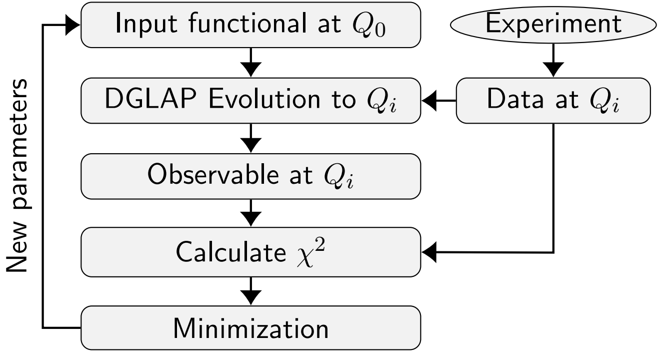
Nuclear A dependence:

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

Total Nucleus:

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

Introduction - Nuclear PDF fitting

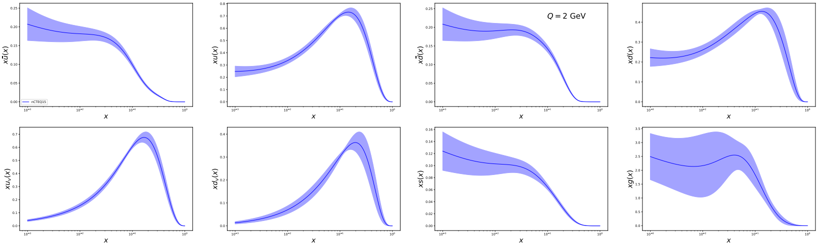


Current status of nPDFs

PDFs enter any calculation involving hadrons in the initial state

- More precise PDFs mean more precise predictions for observables measured at the LHC and "soon" the EIC

Current main release: nCTEQ15



- Large uncertainties on the gluon, especially at low x

Recent updates to nCTEQ15

nCTEQ15: 740 data points

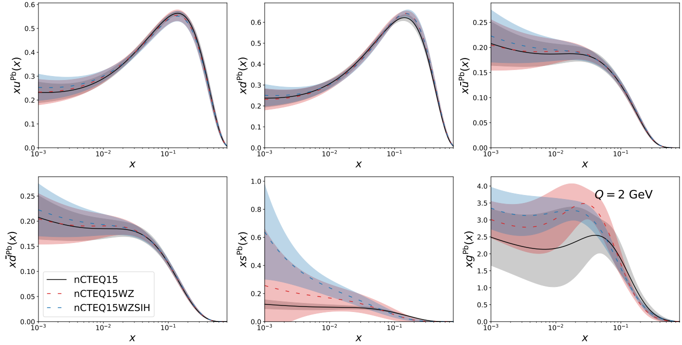
- Mainly DIS and DY data

nCTEQ15WZ: 860 data points

- Added W and Z boson production data to nCTEQ15
- Opened up strange quark parameters

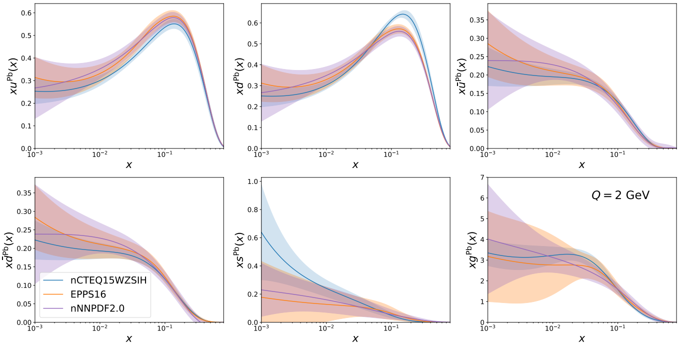
nCTEQ15WZSIH: 948 data points

- Added $\pi^0, \pi^\pm, K^\pm$ production data to nCTEQ15WZ



Current status of other nPDF fits

	N_{data}	N_{params}	Observables
nCTEQ15WZSIH	948	19	DIS, DY, SIH, WZ
EPPS16	1811	20	(ν)DIS, DY, SIH, WZ, dijet
nNNPDF2.0	1467	256	(ν)DIS, DY, WZ



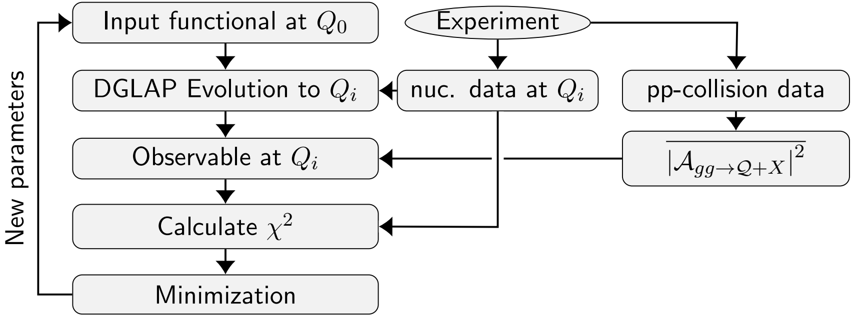
Heavy Quarks - Motivation

Why are we interested in quarkonium (and open heavy-flavour meson) production data?

- Sensitivity to gluon PDFs down to very low x values ($x \approx 10^{-4.5}$)
- Large available data sets from multiple LHC experiments
- Interesting data-driven approach [A. Kusina et al., PRL 121 (2018) 052004; PRD 104 (2021) 014010]
  - Understanding of quarkonium production in pQCD is limited
  - Fast calculation
  - Can quantify theory uncertainties
  - Potentially applicable for many single-inclusive particle production processes

Data-driven Approach

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



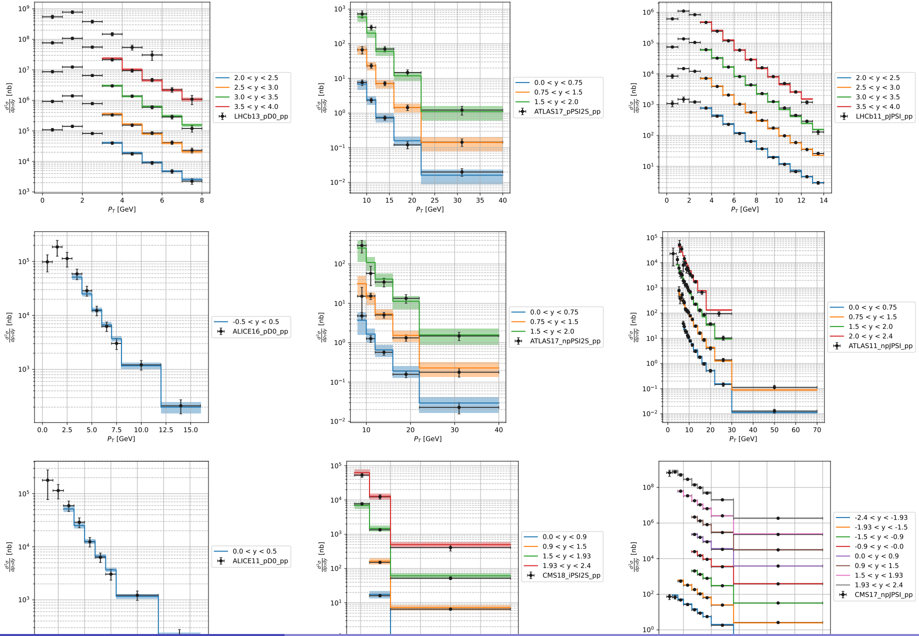
$$\overline{|\mathcal{A}_{gg\to Q+X}|^2} = \begin{cases} \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \exp\left(-\kappa \frac{p_T^2}{M_Q^2}\right) & \text{if } p_T \leq \langle p_T \rangle \\ \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \exp\left(-\kappa \frac{\langle p_T \rangle^2}{M_Q^2}\right)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

Proton-proton baseline

- But we impose cuts to remove data with $p_T < 3$ GeV and outside of $-4 \leq y_{cms} \leq 4$

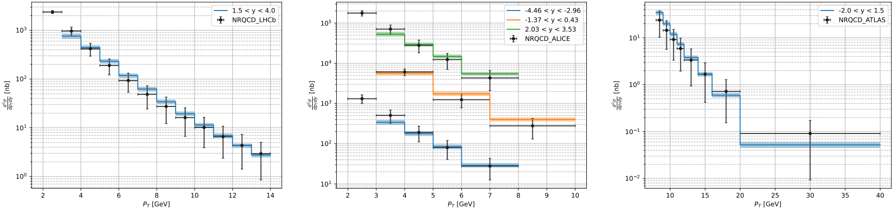
	D^0	J/ψ	$\Psi(2S)$	$\Upsilon(1S)$
κ	0.962±0.109	1.140±0.017	0.443±0.011	0.948±0.005
λ	1.869±0.070	0.271±0.002	0.127±0.002	0.084±0.003
$\langle p_T \rangle$	-0.007±0.392	-0.643±0.185	-0.356±0.360	8.415±0.155
n	1.861±0.162	2.199±0.033	1.540±0.046	2.025±0.067
N_{points}	34	501	55	306
$\frac{\chi^2}{N_{\text{points}}}$	0.31	0.94	0.93	1.63

Proton-proton baseline



Baseline - comparison with NRQCD

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

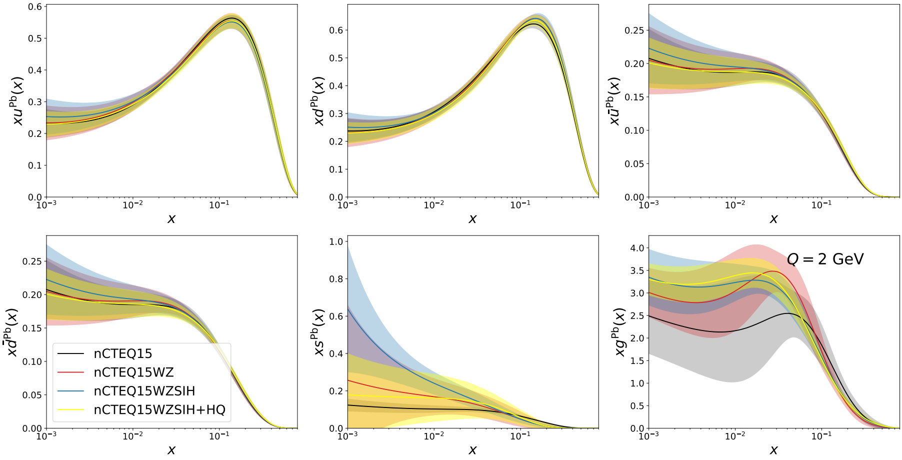


- NRQCD Uncertainties due to scale variations: $1/2 < \mu_r/\mu_{r,0} = \mu_f/\mu_{f,0} = \mu_{\mathrm{NRQCD}}/\mu_{\mathrm{NRQCD},0} < 2$
- Base scale $\mu_{r,0} = \mu_{f,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_{\mathrm{NRQCD},0} = m_c$

PDF Fits - Data selection and settings

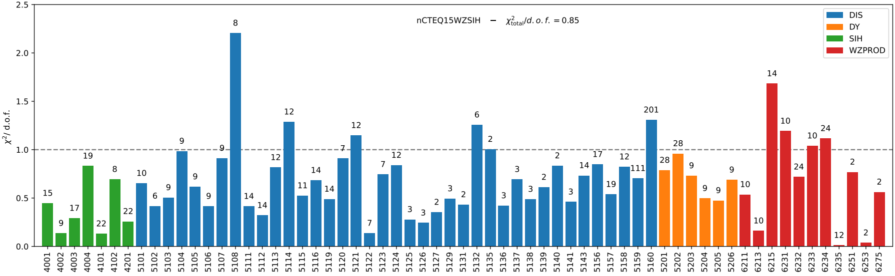
- Include all data from nCTEQ15WZ+SIH
- Use the same open parameters as nCTEQ15WZ+SIH
- Cut data below $p_T < 3.0$ GeV and outside $-4 \leq y_{cms} \leq 4$
  - No good fit with less restrictive cuts.
- Exclude $Y(1S)$ data
  - No good fit can be obtained for this particle.
- Include 499 new data points

New nuclear PDF fit

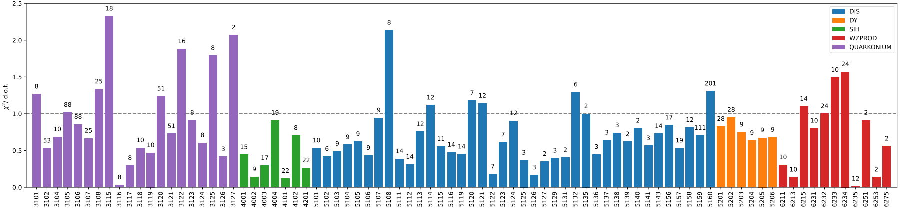


New nuclear PDF fit - χ^2

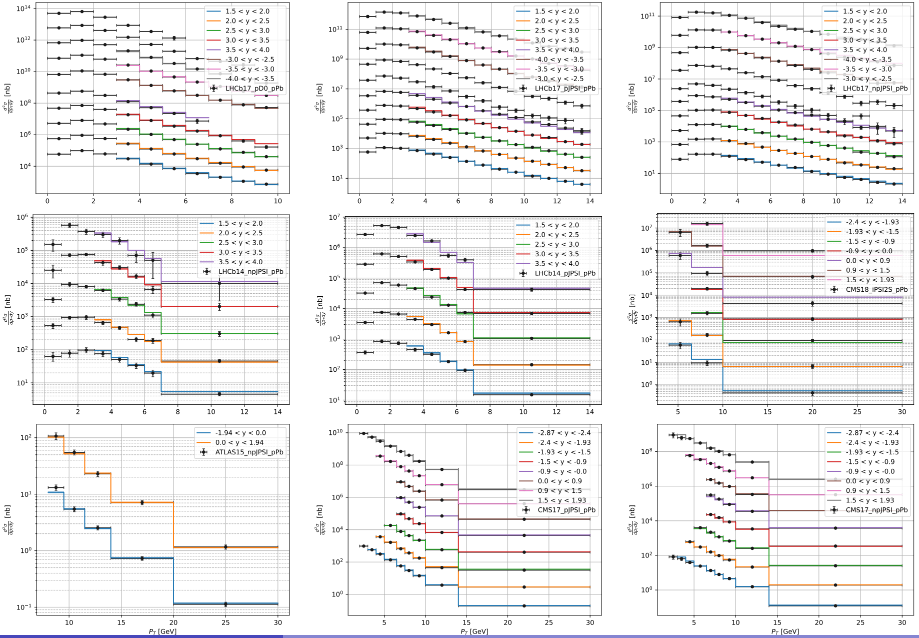
Before:



With 499 new Heavy Quark data points:



New nuclear PDF fit - data



Recap and Outlook

Conclusions:

- New data driven approach
- Heavy Quark data helps constrain the low-x gluon PDF and is compatible with data of other processes

Outlook for the future:

- Try different parameterizations of the matrix element to reach a wider kinematic range and possibly include $Y(1S)$ data
- Take fit uncertainty from the proton-proton baseline into account

Thanks for listening !