Impact of inclusive light and heavy meson production on nuclear PDFs

Intersections 2022 – Lake Buena Vista

Peter Risse

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nCTEQ nuclear PDFs parametrization

- define nuclear PDFs by extending the proton PDF parametrization to account for A-dependence.
- PDF of nucleus (A - mass, Z - charge, N - number of neutrons)

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

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

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- A - dependence

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

Recent updates on nCTEQ15

- **nCTEQ15**: 740 data points
  - mainly DIS and DY data

16 open parameters:

$$\underbrace{a_1^{u_v},\ a_2^{u_v},\ a_4^{u_v},\ a_5^{u_v},\ a_1^{d_v},\ a_2^{d_v},\ a_5^{d_v},\ a_1^{\bar{u}+\bar{d}},\ a_5^{\bar{u}+\bar{d}}}_{\text{up, down}},\ \underbrace{a_1^{g},\ a_4^{g},\ a_5^{g},\ b_0^{g},\ b_1^{g},\ b_4^{g},\ b_5^{g}}_{\text{gluon}},$$

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16 + 3 open parameters:

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  - added π^0, $\pi^\pm$, $K^\pm$ production data to nCTEQ15WZ
- nCTEQ15HQ: 1,488 data points
  - added J/Ψ, $\Upsilon(1S)$, $\psi(2S)$ and D^0 meson production data to nCTEQ15WZ+SIH

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Motivation – Light meson production

Why are we interested in Singe Inclusive Hadron production (SIH) data?

- precise **new data from ALICE**
- sensitivity to nuclear gluon PDF $\rightarrow$ **dominates cross section** at high CMS-energy (or low p_T)

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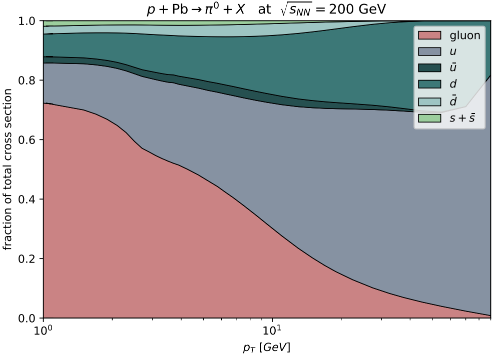

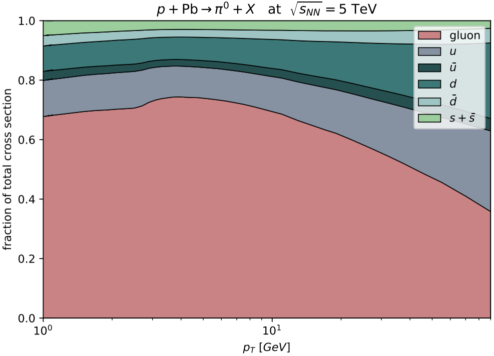

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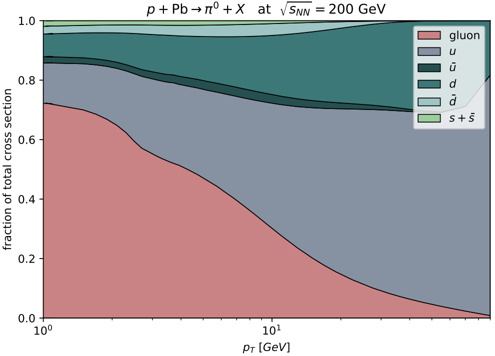

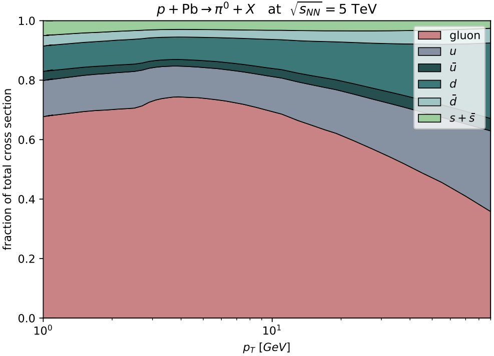

Problems? Fragmentation Function dependence and most precise data at low p_T (non-perturbative!)

Fragmentation Functions

FF	Year	Available particles
BKK	1994	$\pi_0, \pi^\pm, K^\pm$
KKP	2000	$\pi_0, \pi^\pm, K^\pm$
KRETZER	2000	$\pi_0, \pi^\pm, K^\pm$
HKNS07	2007	$\pi_0, \pi^\pm, K^\pm$
AKK	2008	$\pi_0, \pi^\pm, K^\pm$
NNFF	2017	$\pi_0, \pi^\pm, K^\pm$
JAM20	2021	$\pi_0, \pi^\pm, K^\pm$
DSS14	2014	$\pi_0, \pi^\pm$
DSS17	2017	$K^\pm$
AESSS	2011	η

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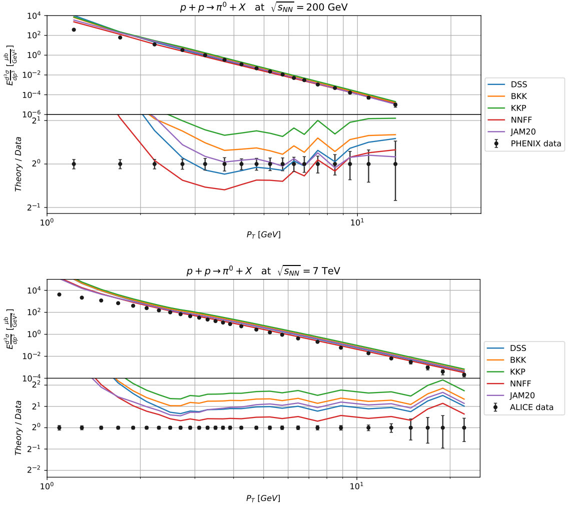
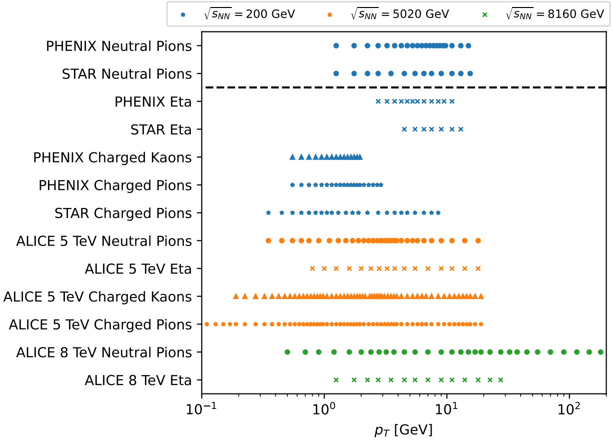
- FF dependence mitigated by taking **ratios of cross sections**



Available data and fit settings



- DSS fragmentation
- add **DSS uncertainty to syst. errors** of the data
  - compensate for choice of FF

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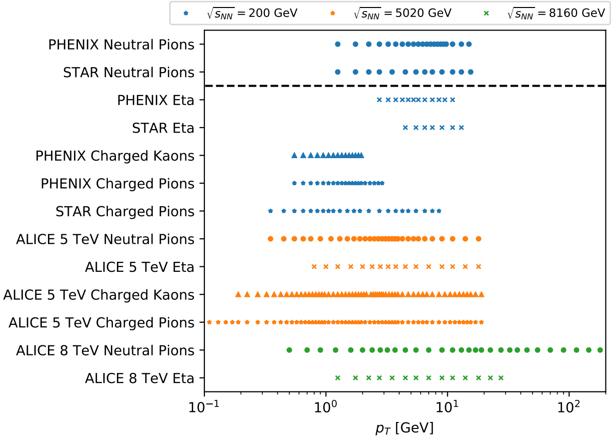

- DSS fragmentation
- add **DSS uncertainty to syst. errors** of the data
  - compensate for choice of FF
- cut data below $\mathbf{p_T < 3.0}$**GeV**
- **removed η-meson** production data

Main nCTEQ15WZ+SIH fit – Comparison

$\chi^2/N_{d.o.f.}$ for individual processes					
	DIS	DY	WZ	SIH	**Total**
nCTEQ15	0.86	0.78	(2.19)	(0.78)*	**1.03**
nCTEQ15WZ	0.91	0.77	0.63	(0.47)*	**0.83**
nCTEQ15WZ+SIH	0.91	0.77	0.72	0.40	**0.83**

***nCTEQ15** and nCTEQ15WZ include STAR and PHENIX neutral pions

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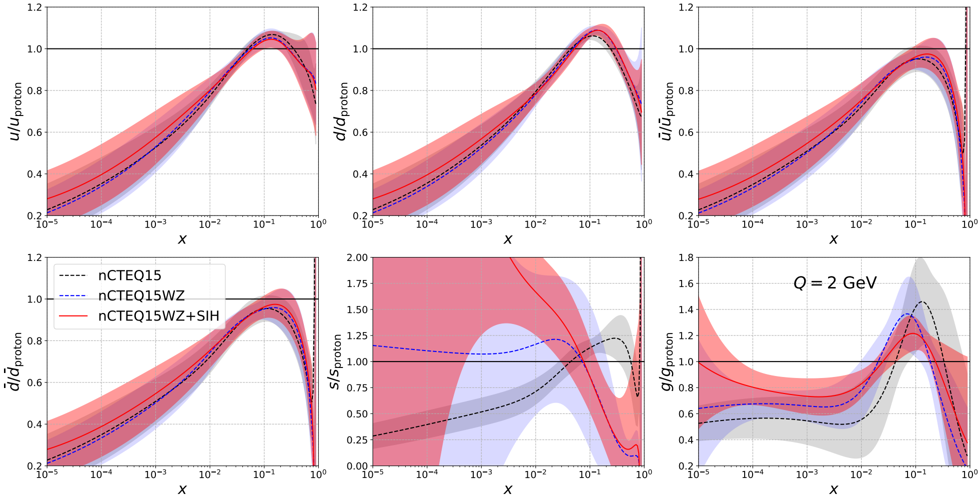
χ^2 values of the light meson production data obtained by **using different fragmentation functions**

DSS	DSS (errors not added)	KKP	BKK	NNFF	JAM20
0.402	0.461	0.401	0.420	0.456	0.553

***nCTEQ15** and nCTEQ15WZ include STAR and PHENIX neutral pions

Main nCTEQ15WZ+SIH fit – Extending the nCTEQ15WZ result



Conclusion (part 1 out of 2)

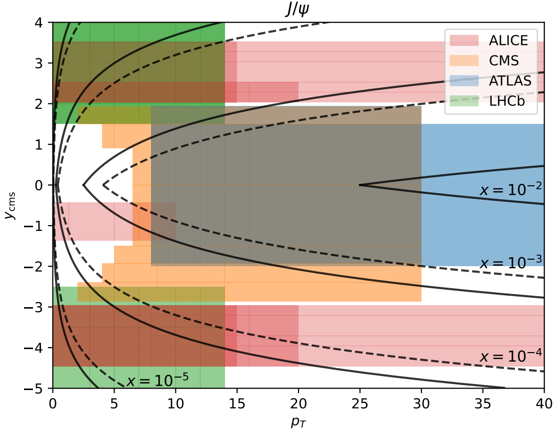
Light meson production data

- important to **account for fragmentation function uncertainty**
- data needs to be **cut below $\mathbf{p_T = 3GeV}$** to ensure validity of theoretical predictions
- Single Inclusive Hadron data **still helps to constrain gluons**
  - new release: nCTEQ15WZ+SIH supersedes nCTEQ15WZ

Motivation – Heavy meson production

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

- large available data sets from multiple LHC experiments
- sensitivity to gluon pdf down to **very low** $\mathbf{x \approx 10^{-5}}$ values



Analysis also includes $\Upsilon(1S)$, $\psi(2S)$ and D^0 meson production.

Motivation – Heavy meson production

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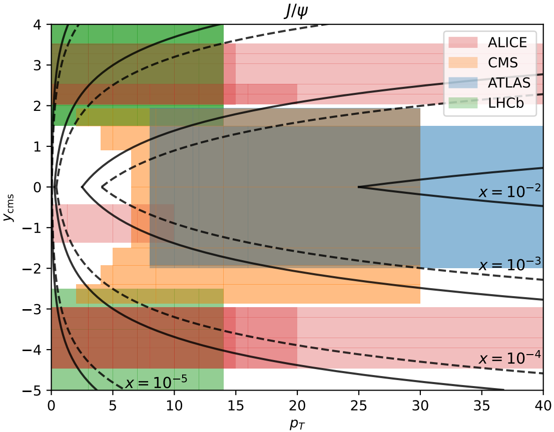
- large available data sets from multiple LHC experiments
- sensitivity to gluon pdf down to **very low** $\mathbf{x \approx 10^{-5}}$ values
- interesting data-driven approach
  - understanding of quarkonium production is limited in pQCD
  - fast calculation
  - provides an **estimate for theory uncertainties**
  - potentially applicable for many singe-inclusive particle production processes

[A. Kusina et al., PRL 121 (2018) 052004; PRD 104 (2021) 014010]



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Data-driven approach – the crystal ball function

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

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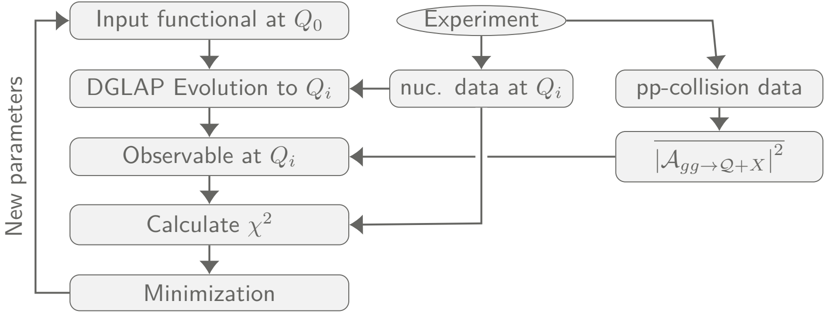

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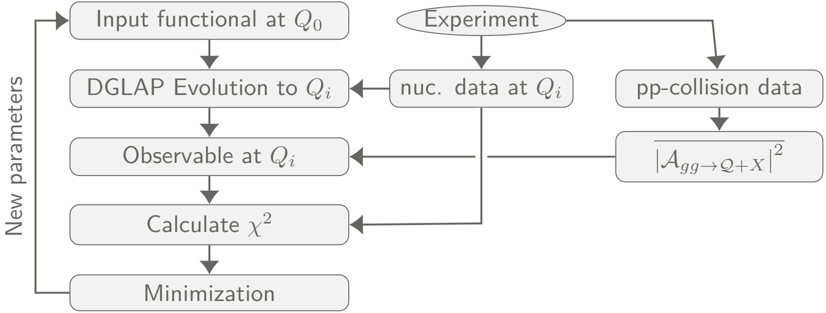

$$\overline{|\mathcal{A}_{gg\to\mathcal{Q}+X}|^2} = \begin{cases} \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \exp\left(-\kappa \frac{p_T^2}{M_{\mathcal{Q}}^2} + a|y|\right) & \text{if } p_T \leq \langle p_T \rangle \\ \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \exp\left(-\kappa \frac{\langle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

Fitting the crystal ball parameters from proton data

- Impose cuts to **remove proton data** with $p_T < 3\,\text{GeV}$ and outside of $-4 \leq y_{\text{c.m.s.}} \leq 4$

	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B \to \psi(2S)$
N_{points}	34	501		375	55	
χ^2/N_{dof}	0.25	0.88		0.92	0.77	

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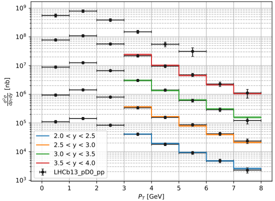
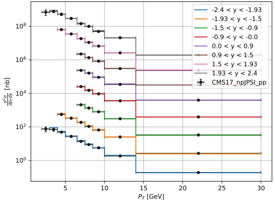
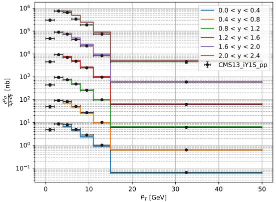
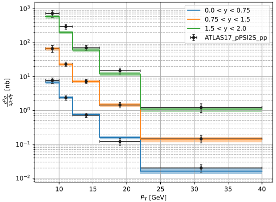
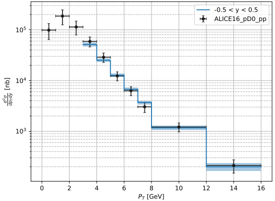
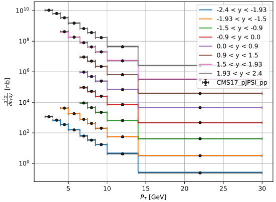


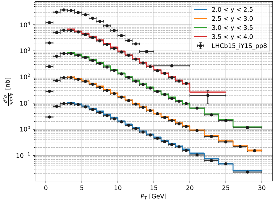


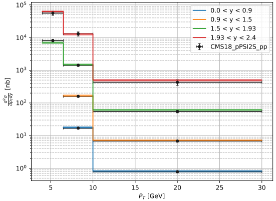




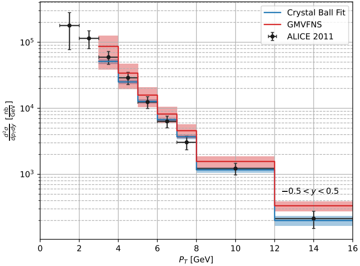


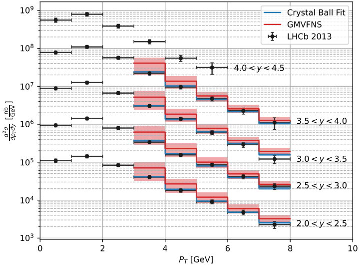


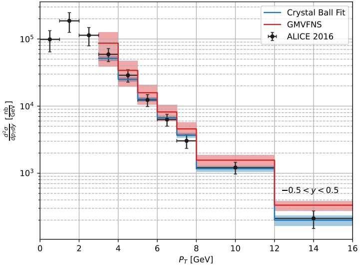




Proton baseline – comparison with GMVFNS







- **KKKS08 fragmentation functions**
- Base scale $\mu_r = \mu_i = \mu_f = \sqrt{p_T^2 + 4m_c^2}$
- Uncertainties due to individual scale variations by factor 2 or $\frac{1}{2}$

nCTEQ15HQ Fit – Data selection and settings

- include all data from nCTEQ15WZ+SIH
- use the same open parameters as nCTEQ15WZ+SIH

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nCTEQ15HQ	0.93	0.77	0.78	0.40	0.77	**0.86**

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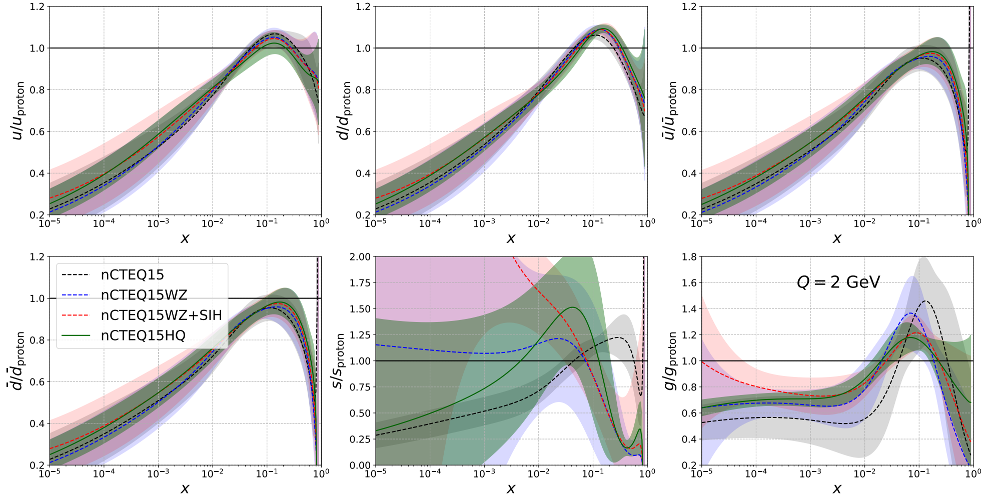
nCTEQ15HQ Fit – Ratio to Proton



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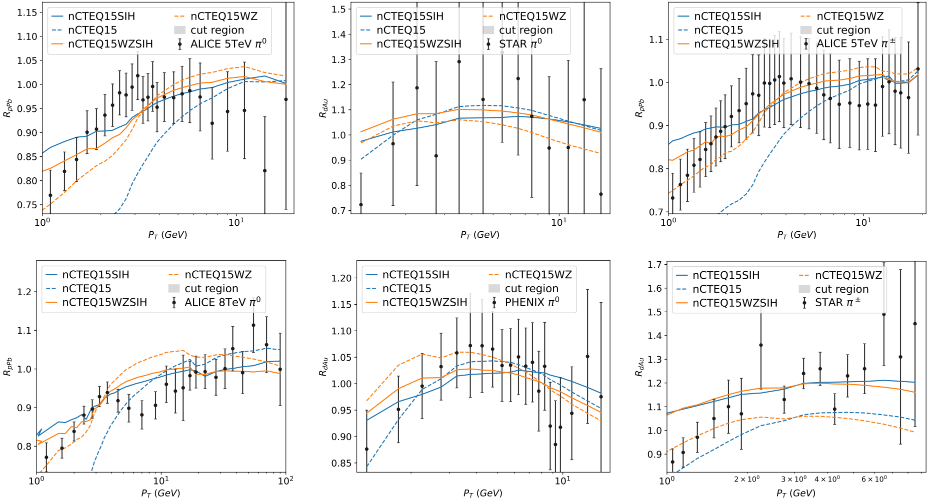
Heavy meson production data

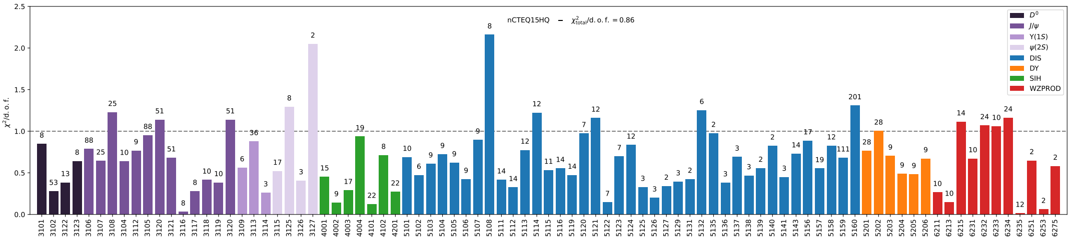
- new data driven approach
  - **compatible predictions** from NRQCD and GMVFNS, **excellent description** of proton data
  - controlled uncertainties
- strong new constraints on the gluon PDF, particularly **at low $\mathbf{x}$**
  - new release: nCTEQ15HQ supersedes nCTEQ15WZ+SIH

backup

Main nCTEQ15WZ+SIH fit – Theory Predictions

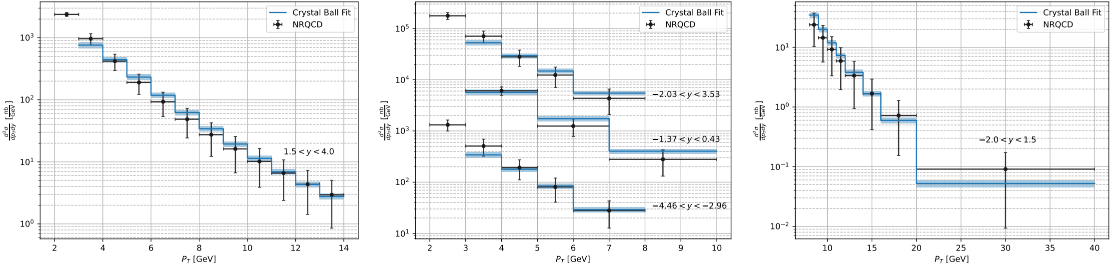


nCTEQ15HQ Fit – Data selection and settings



Proton baseline – comparison with NRQCD

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



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