WWU MÜNSTER

isoQuant SFB1225

nCTEQ
nuclear parton distribution functions

Nuclear parton distribution functions with nCTEQ

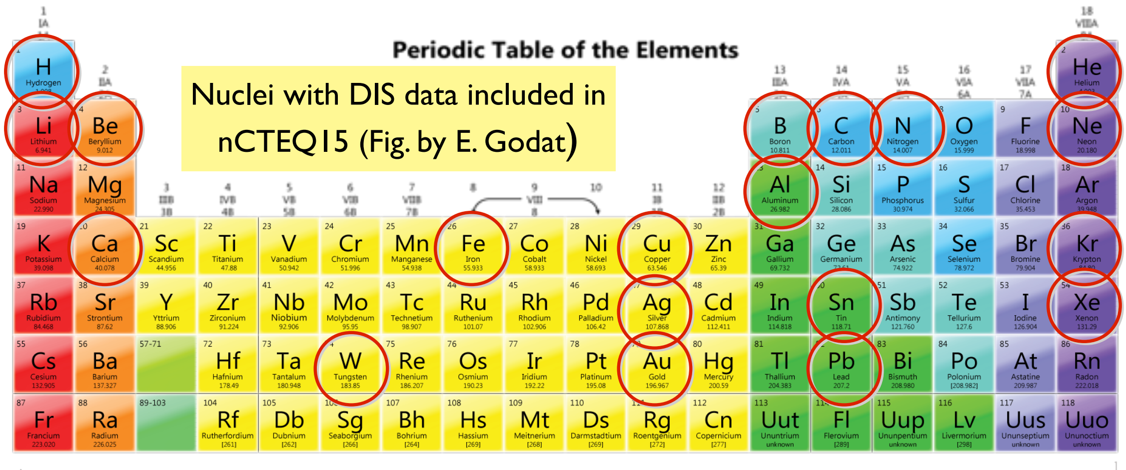
Tomáš Ježo

nCTEQ collaboration

ITP, WWU

SFB 1225 isoQuant

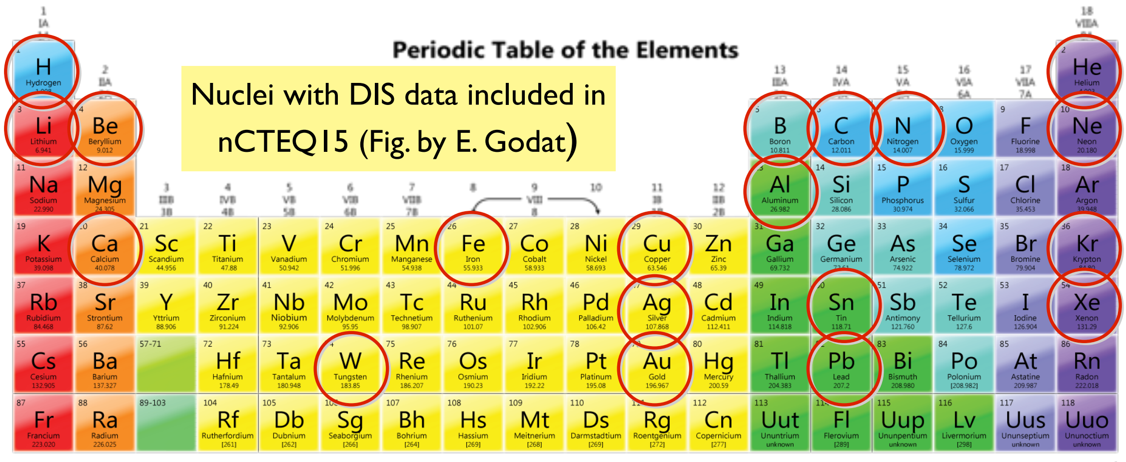
Nuclear structure with nCTEQ



- nCTEQ's fundamental quest: study structure of nuclei from high energy perspective
- Highlights for today:
  - Nuclear structure from heavy quark production [*a*]
  - Short-range–correlation inspired atomic number dependence [*b*]

[*a*] Düwentester, **TJ**, Klasen et al., '22
[*b*] Deniston, **TJ**, Kusina et al., '22/23

Nuclear structure with nCTEQ



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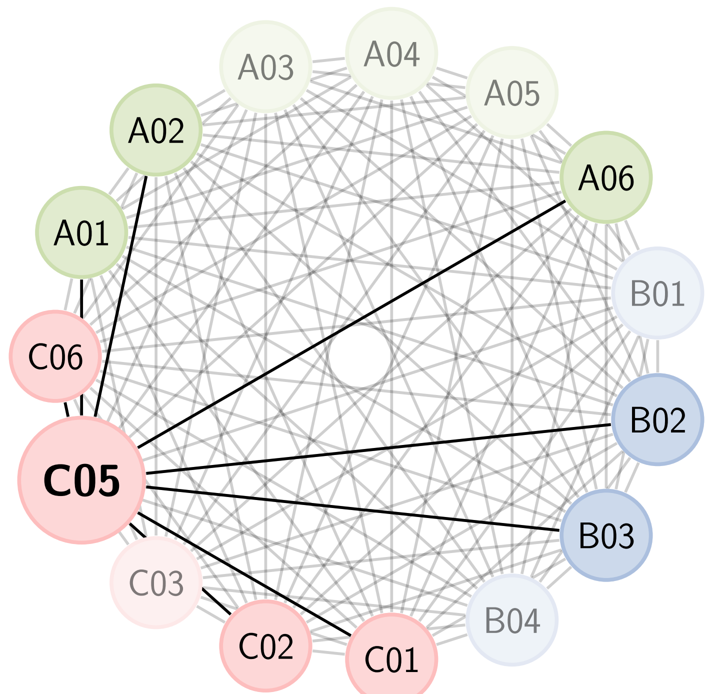
Nuclear structure with nPDFs in isoQuqant

- C05: Probing the QCD phase structure with heavy quarks



Nuclear structure with nPDFs in isoQuqant

- C05: Probing the QCD phase structure with heavy quarks
- Connections to other projects:

A01: Initial state and thermalisation in HI collisions [Berges, Reygers, Stachel]
- Jet quenching: T_I dependence vs. nPDF uncertainty
- Low-p_T photons: Subtraction of direct/fragmentation photons

A02: From QCD transport to particle yields [Masciocchi, Pawlowski, Stachel]
- Low-p_T π, K, p, D: Transport coefficient vs. nPDF uncertainty

B02: NP QED theory in strong EM fields [Harman, Keitel, Di Piazza]
- J/ψ in UPCs: Photoproduction, diffraction and shadowing

B03: Quantum dynamics of strong gauge fields and condensates [Berges, Pawlowski, Wienhard]
- Test BE enhan. in BFKL with J/ψ's [Gotsman, Levin, 1804.02561, 1808.04982]

C02: From few to many – ultracold atoms in recuded dimensions [Enss, Jochim]
- Fermi gas correlations at large x (EMC eff.) [Arrington et al., 1206.06343]

C06: Flow and fluctuations in relativ. HI collisions [Flörchinger, Masciocchi]
- Small-x region of nPDFs determines initial state fluctuations

From a slide of M. Klasen

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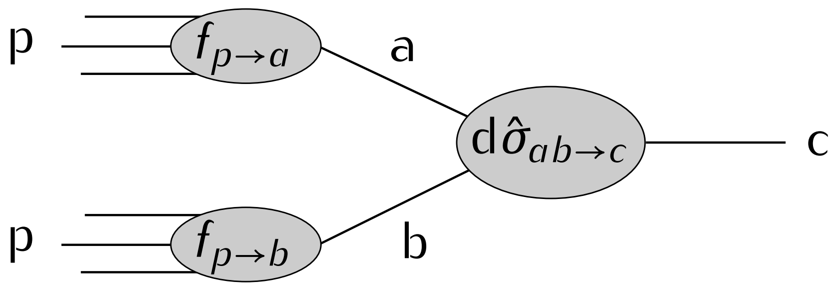
From a slide of M. Klasen

High energy particle collisions

- Take for example proton-proton (pp) collisions in picture:



- Or in formula, in the collinear factorization framework:

$$d\sigma_{pp\to c} = \sum_{a,b} f_{p\to a}(x_a, \mu) \otimes f_{p\to b}(x_b, \mu) \otimes d\hat{\sigma}_{ab\to c}(\mu)$$
$$\mu \gtrsim 1 \text{ GeV}, x \in (0,1)$$

- With μ: factorization scale, x: fraction of parton $a(b)$ momentum in proton p

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- With μ: factorization scale, x: fraction of parton $a(b)$ momentum in proton p
- Parton Distribution Functions (PDFs) $f_{p\to a}(x,\mu)$
  - Universal
  - Not calculable from first principles (not yet)
- Hard cross section $\mathrm{d}\hat{\sigma}_{ab\to c}(\mu)$
  - Process specific
  - Calculable in perturbative QCD (pQCD)
- Similarly for lp, νp and one-particle inclusive[a] processes

[a] Which involve second factorization scale and convolution with fragmentation functions.

High energy particle collisions

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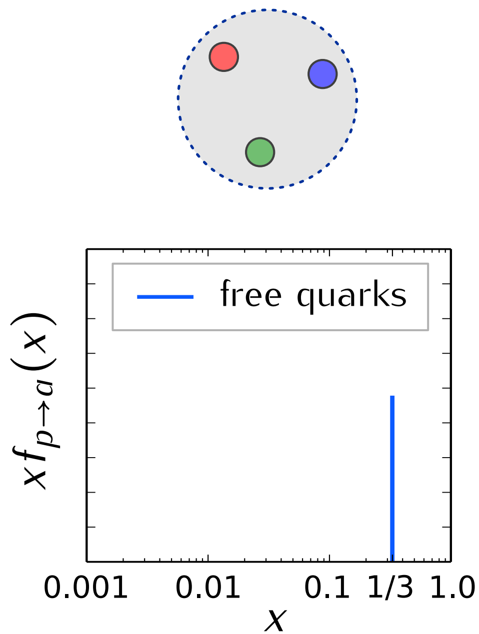
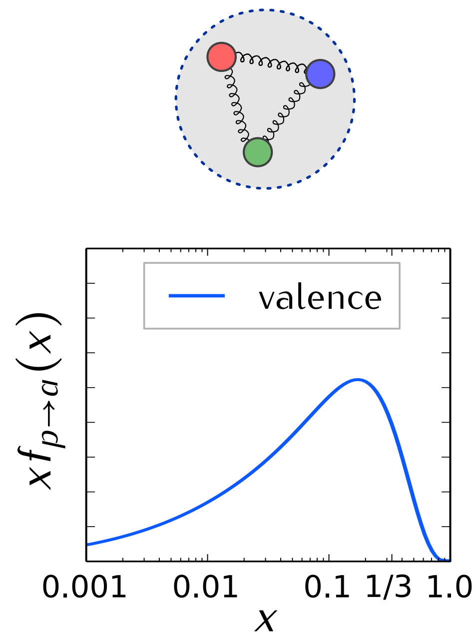
Parton Distribution Functions (PDFs)

- PDF$[f_{p\to a}(x,\mu)]$: probability that parton a carries fraction[a] x of proton p momentum

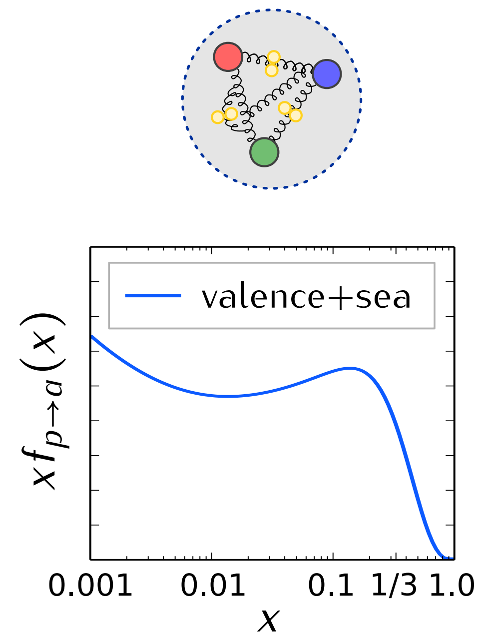
Free partons



Bound partons



Bound partons
& QCD effects



[a] Longitudinal.

Inspired by a slide from P. Risse

Parton Distribution Functions (PDFs)

- Universal: same PDF enters different processes (DIS, DY, SIH, HQ, ...)
- x dependence not calculable in pQCD
- μ dependence governed by DGLAP evolution equations

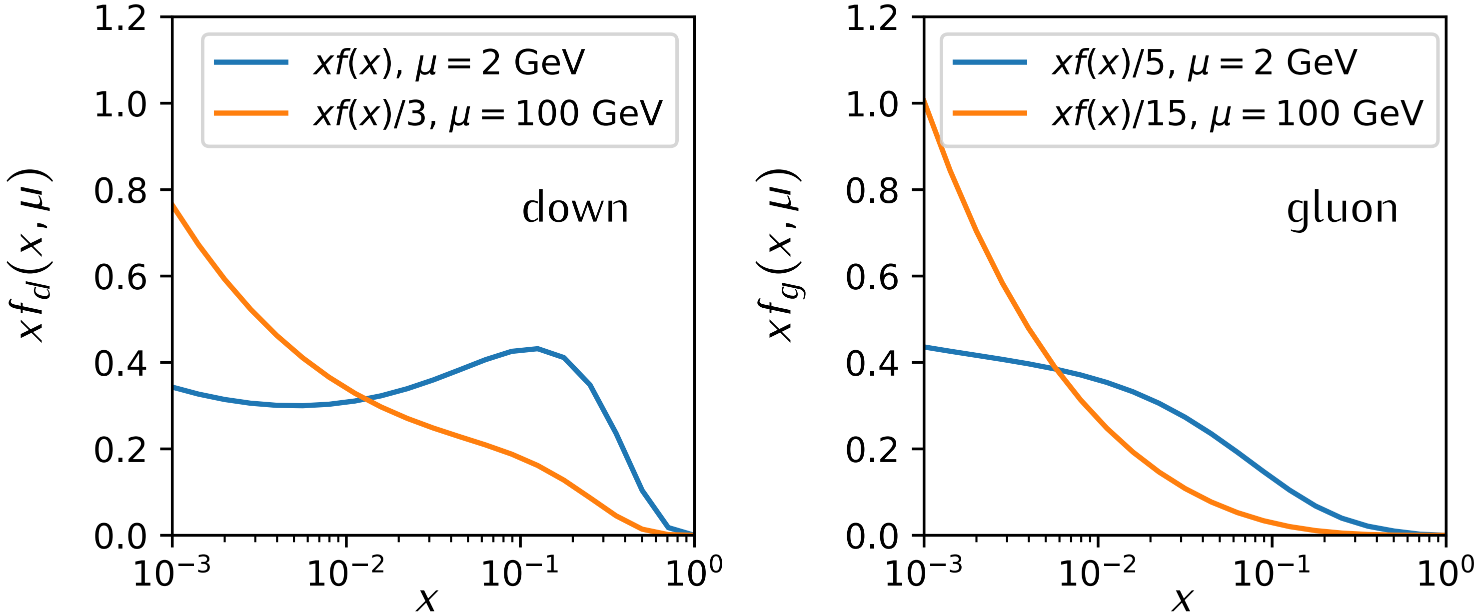
$$\frac{df_q(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)f_q(y,\mu^2) + P_{qg}\left(\frac{x}{y}\right)f_g(y,\mu^2)\right]$$

$$\frac{df_g(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gg}\left(\frac{x}{y}\right)f_g(y,\mu^2) + P_{gq}\left(\frac{x}{y}\right)f_q(y,\mu^2)\right]$$

- Describe violations of Bjorken x scaling
- Different PDFs mix: set of $(2n_f + 1)$ coupled integro-differential equations.

Parton Distribution Functions (PDFs)

- μ dependence governed by DGLAP evolution equations:



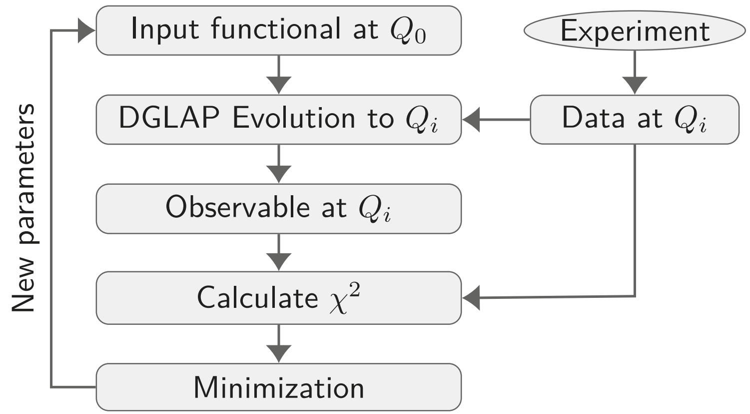
  - Reduces valence and increases sea
  - Mixes flavours

Parton Distribution Functions (PDFs)

- x dependence not calculable in pQCD[a]:
  - assume parametrization in x[b] at a chosen input scale Q_0:

$$x f_i(x, Q_0) = N(1-x)^{p_{i,1}} P(x, p_{i,2}, \ldots)$$

  - set $p_{i,j}$, calculate theoretical predictions, compare to data, iterate:

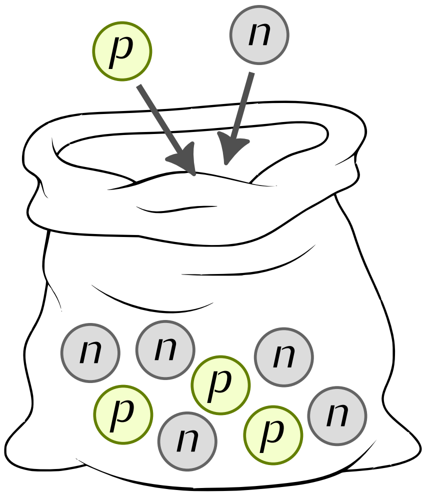


$$\chi^2 = \sum_{ij}^{N} (D_i - T_i)\,(C^{-1})_{ij}\,(D_j - T_j)$$

[a] Calculable in lattice QCD in near future?
[b] NNPDF collaboration use NN to avoid parametrization bias.

Nuclear Parton Distribution Functions (nPDFs)

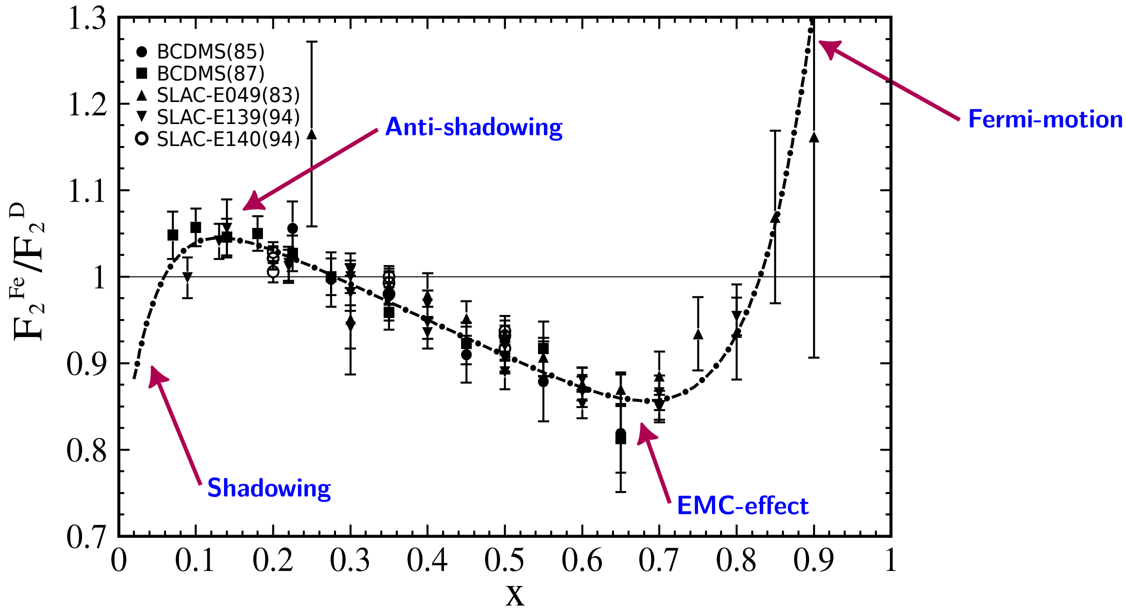
- Free nucleon approximation:



$$Af^A(x,\mu) = Zf^p(x,\mu) + Nf^n(x,\mu)$$

Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification:



$$Af^A(x,\mu) \neq Zf^p(x,\mu) + Nf^n(x,\mu)$$

Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification can be incorporated into the PDF framework[a]:
  1. nucleon PDF × A-dependent nuclear modification: $f_i^{p/A} = f_i^p(x,\mu) \times R_i(x,\mu,A)$
  2. A-dependent bound nucleon PDF: $f_i^{p/A} = f_i(x,\mu,A), f_i(x,\mu,A=1) = f_i^p(x,\mu)$

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

  - bound proton PDF fulfils the usual evolution equations and sum rules
  - bound neutron PDF from isospin symmetry, i.e. $f_{d,u}^{p/A} = f_{u,d}^{p/A}$
  - nPDFs replace PDFs in the factorization formula[b]
  - momentum fraction now $x \in (0,A)$ but $x > 1$ region negligible

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[a] Underlying dynamics of nuclear modifications remains to be theoretically understood.

[b] Proof of factorization for collisions of nuclei not yet available.

nCTEQ nPDFs

- nCTEQ nPDFs:

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}$$
$$c_k \to c_k(A) \equiv p_k + a_k \left(1 - A^{-b_k}\right)$$

  - NLO QCD; $Q_0 = 1.3$ GeV; $f_i^{p/A}(x, Q, A = 1) \equiv$ CTEQ6 w/o nuclear data
  - A dependence: not from first principles; constraint for A's with few data pts
  - data: DIS NC (1472) & CC (974/4644), DY (92), LHC W/Z (86), SIH (112), HQ (965); no jet or direct photon yet
  - NEW!: High-x vs. JLAB DIS data [a], Impact of HQ data [b], Compatibility of ν-DIS data [c]

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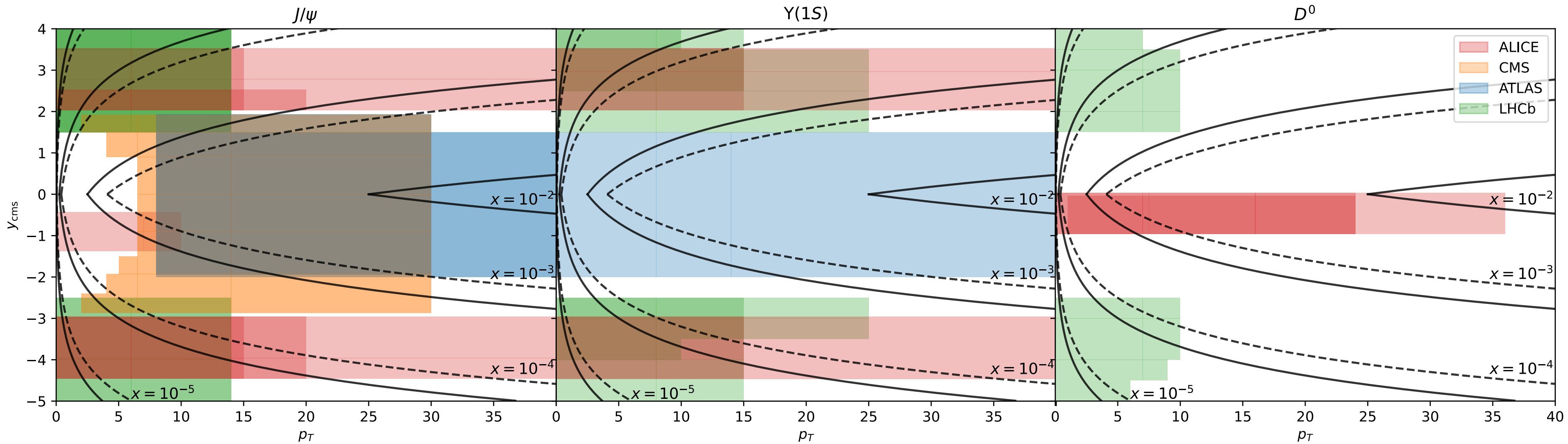
[a] Segarra, **TJ**, Klasen et al., '21
[b] Düwentester, **TJ**, Klasen et al., '22
[c] Muzakka, **TJ**, Kovařík, Klasen et al., '22

Impact of heavy quark(-onia) production

[Düwentester, TJ, Klasen et al., ’22]

- Heavy Quarks reach down to $x \simeq 10^{-5}$ ($x \approx 2 p_T e^{-|y|}/\sqrt{s}$):



Impact of heavy quark(-onia) production

[Düwentester, TJ, Klasen et al., '22]

- Heavy quarks and quarkonia production modelled using a data driven approach:
  - dominated by gg channel

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

  - effective amplitude parametrized by CB-like model

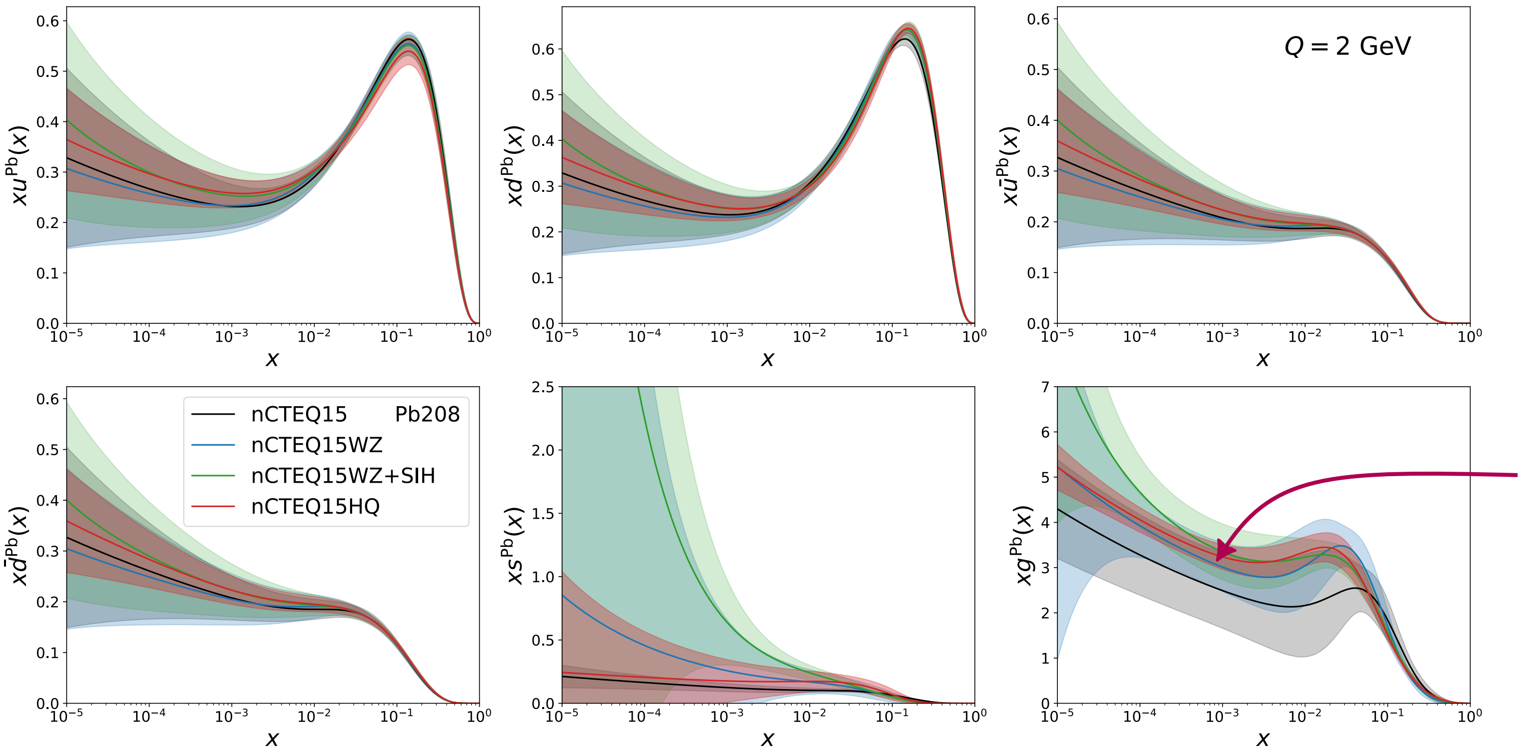
$$\overline{\left|\mathcal{A}_{gg \to \mathcal{Q}+X}\right|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} e^{a|y|} \begin{cases} e^{-\kappa \frac{p_T^2}{M_{\mathcal{Q}}^2}} & \text{if } p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{\langle p_T \rangle^2}{M_{\mathcal{Q}}^2}} \left(1 + \frac{\kappa}{n}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

  - κ, λ, $< p_T >$, n and a fitted to pp data for each final state separately and fixed in an nuclear PDF fit

Impact of heavy quark(-onia) production

[Düwentester, TJ, Klasen et al., '22]

- Pb^{208} results compared to our previous results

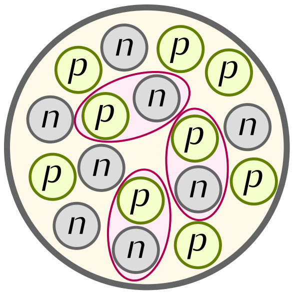


Impressive reduction of gluon PDF uncertainty

Short-Range–Correlation inspired A dependence

[Deniston, **TJ**, Kusina et al., '22/23]

- Short-Range–Correlation (SRC) model of the nuclear structure:



$$f_i^{p/A}(x,\mu,A) = z(A)(f_i^p)^{\text{src}}(x,Q) + [1-z(A)]f_i^p(x,Q)$$
$$f_i^{n/A}(x,\mu,A) = n(A)(f_i^n)^{\text{src}}(x,Q) + [1-n(A)]f_i^n(x,Q)$$

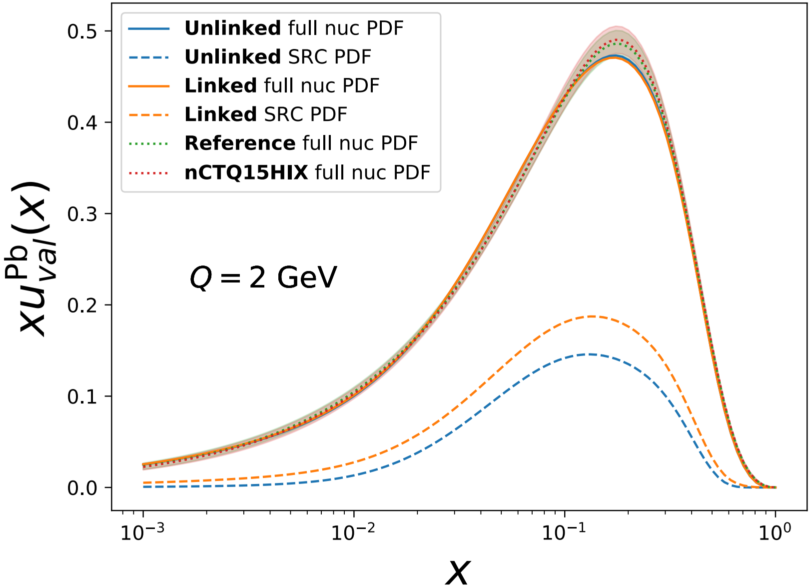
$$f_i(x,\mu,A) = \frac{Z}{A} f_i^{p/A}(x,\mu,A) + \frac{N}{A} f_i^{n/A}(x,\mu,A)$$

  - $f^{p(n)}$: proton (neutron) PDF (fixed)
  - $(f^{p(n)})^{\text{src}}$: SRC pair PDF and its isopartner (p fitted, n tied)
  - $z(A)$ and $n(A)$ fractions of SRC pairs (fitted independently or tied)
  - There is only one and universal $(f^p)^{\text{src}}$ PDF (x dep., no A dep.)
  - One z (and opt. one n) fraction per nucleus (A dep., no x dep.)
  - In the original nCTEQ parametrization x and A dependences do not factorize

Short-Range–Correlation inspired A dependence

[Deniston, TJ, Kusina et al., '22/23]

- Fit with the new parametrization obtains a very good description of data:

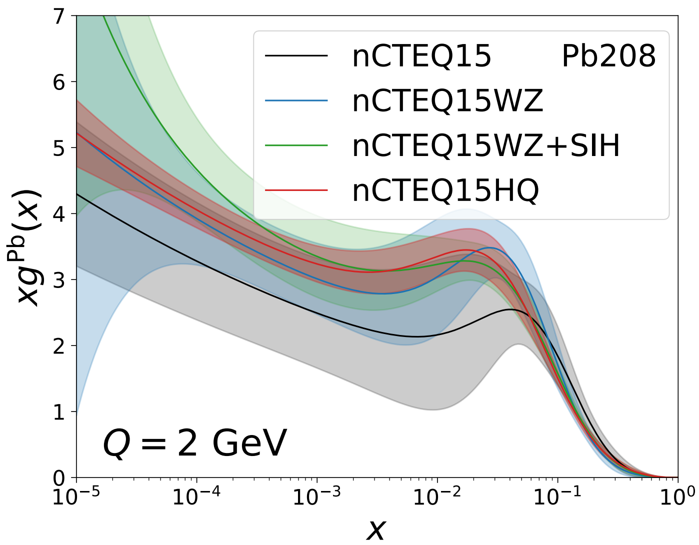


- Same nuclear PDFs as before, but ...
- Now we also extract z fractions and compare them to quasi elastic scattering data
- How does this affect low x?

Summary

- Introduced collinear factorization & PDFs as measure of proton structure
- Discussed some basic properties of PDFs
- Shown the nuclear modification fractions & how to incorporate it into nPDFs
- Selection of recent global nPDF analyses:

[Düwentester, **TJ**, Klasen et al., '22]



[Deniston, **TJ**, Kusina et al., '2X]

preliminary

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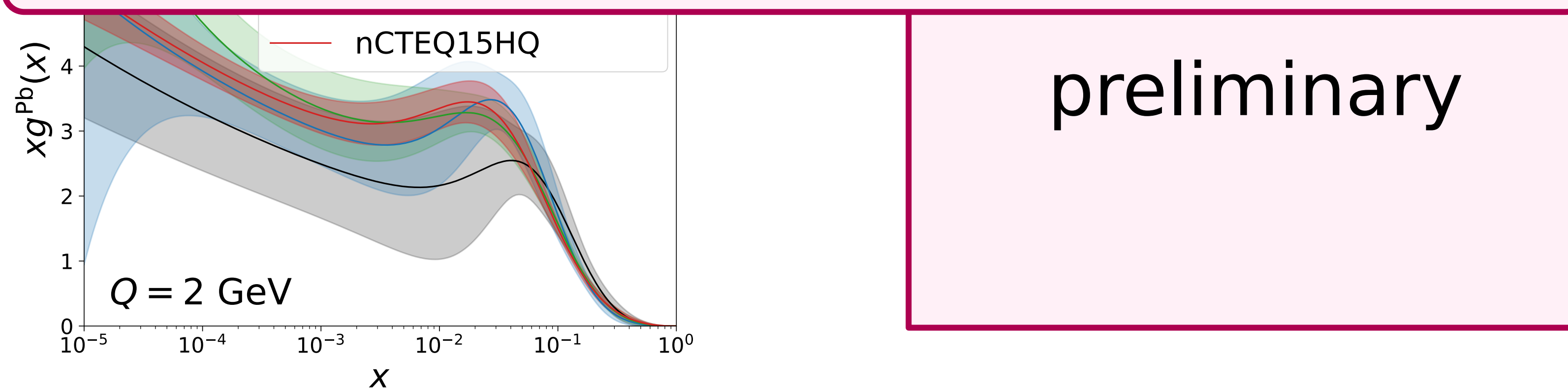
- S



THANK YOU!