Nuclear PDFs

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Atelier "Physique Théorique des deux infinis"
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nCTEQ collaboration

- **nCTEQ** is part of **CTEQ** (The Coordinated Theoretical-Experimental Project on QCD)

- Devoted to understanding **QCD** at the **interface between nuclear and particle physics**:

  - Understand **nuclei** in terms of **quark and gluon degrees of freedom**

  - Understand **nuclear corrections** needed to use nuclear data in **studies of nucleon structure**

- Webpage: https://ncteq.hepforge.org/

nCTEQ
nuclear parton distribution functions

nCTEQ collaboration

- **Initiated in 2006** by **Fred Olness**, **IS** and **Ji-Young Yu** (**SMU Dallas**) joined by the CTEQ members **C. Keppel** (**Hampton Univ./JLAB**), **J. G. Morfin** (**FNAL**), and **J. Owens** (**Florida State Univ.**)

- **Members in 2021 [3rd generation! underlined: (former) LPSC]**:

  - **SMU Dallas**: F. Olness (CTEQ), T. Hobbs (Post-Doc), J.-Y. Yu

  - **FNAL**: J. G. Morfin (CTEQ)

  - **LPSC Grenoble:** I. Schienbein (CTEQ), C. Léger (PhD)

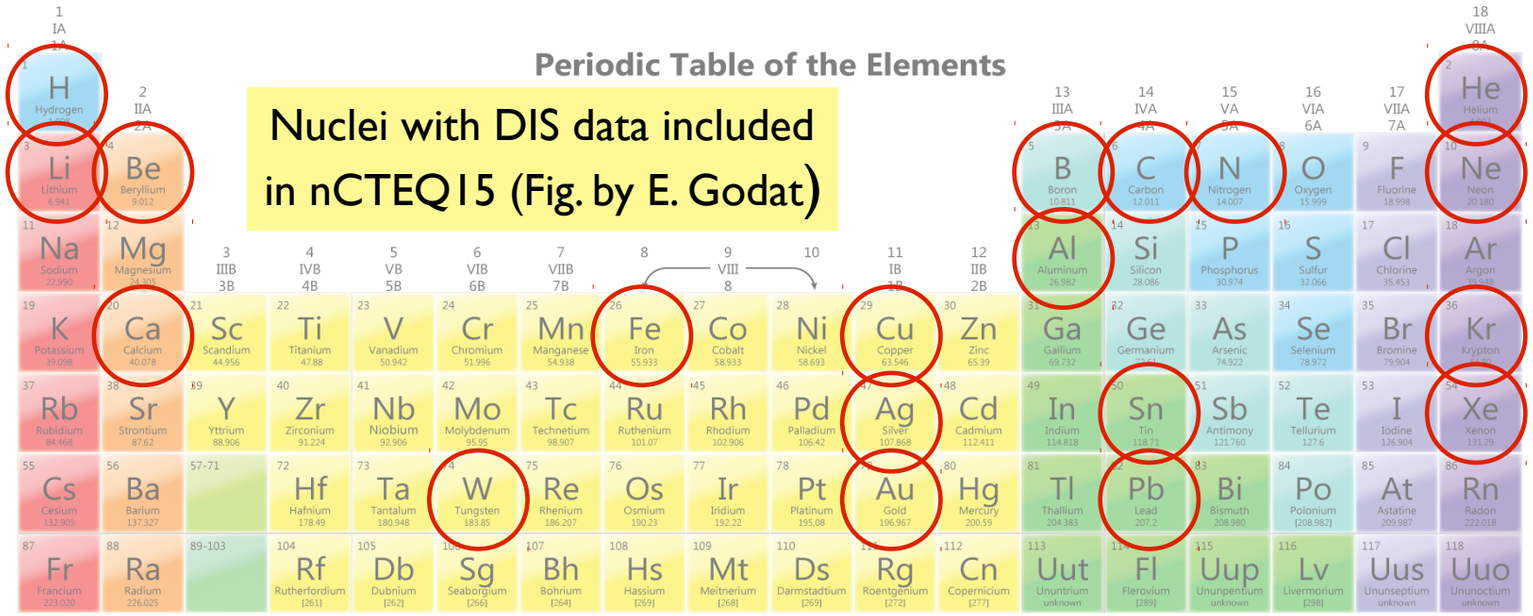
  - **JLAB**: C. Keppel (CTEQ)

  - **INP Krakow**: A. Kusina, R. Ruiz (Post-Doc)

  - **Univ. Münster**: M. Klasen (CTEQ), K. Kovarik (CTEQ), F. Muzakka (PhD), P. Duwentäster (PhD), P. Risse (PhD)

  - **Univ. Karlsruhe**: T. Jezo (senior Post-Doc)

Partonic structure of nuclei

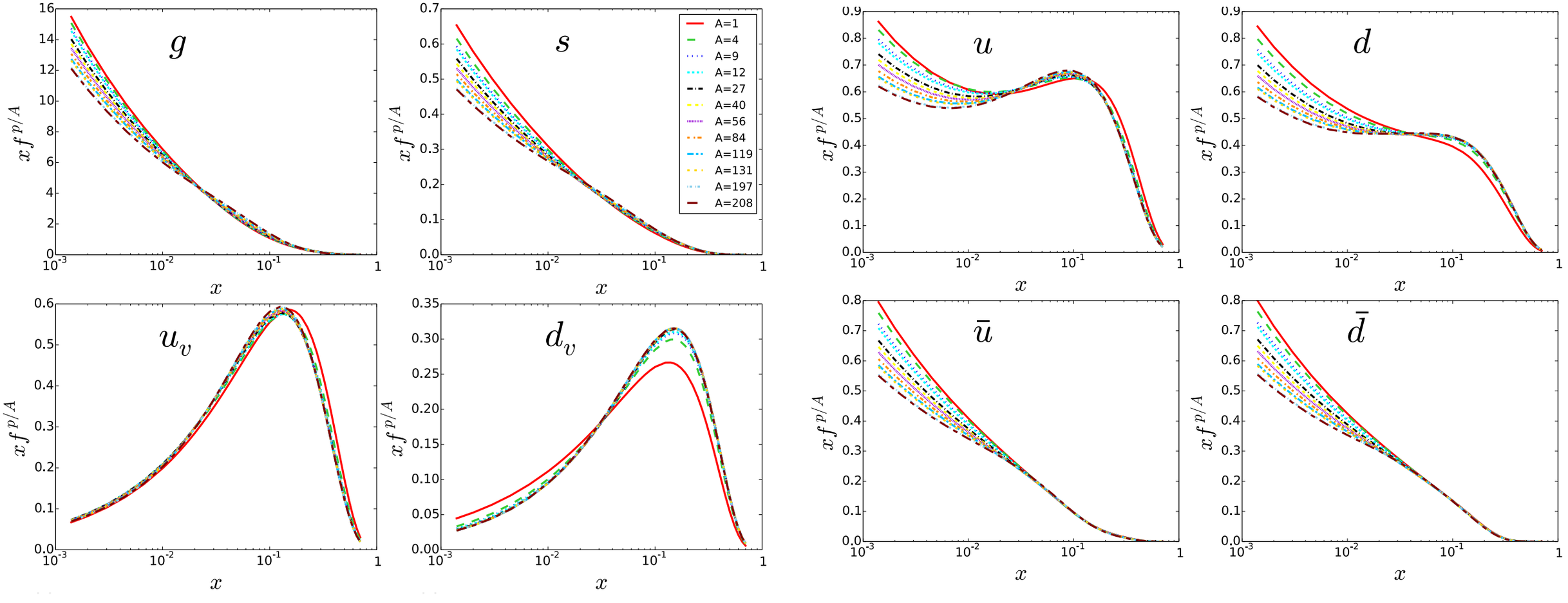


- Fundamental quest
- New data from LHC, EIC, LHeC, etc. will allow for a refined parametrization; zoom in on high-x region
- Ultimately, fits to lead only (or other targets); no need to combine different A in one analysis

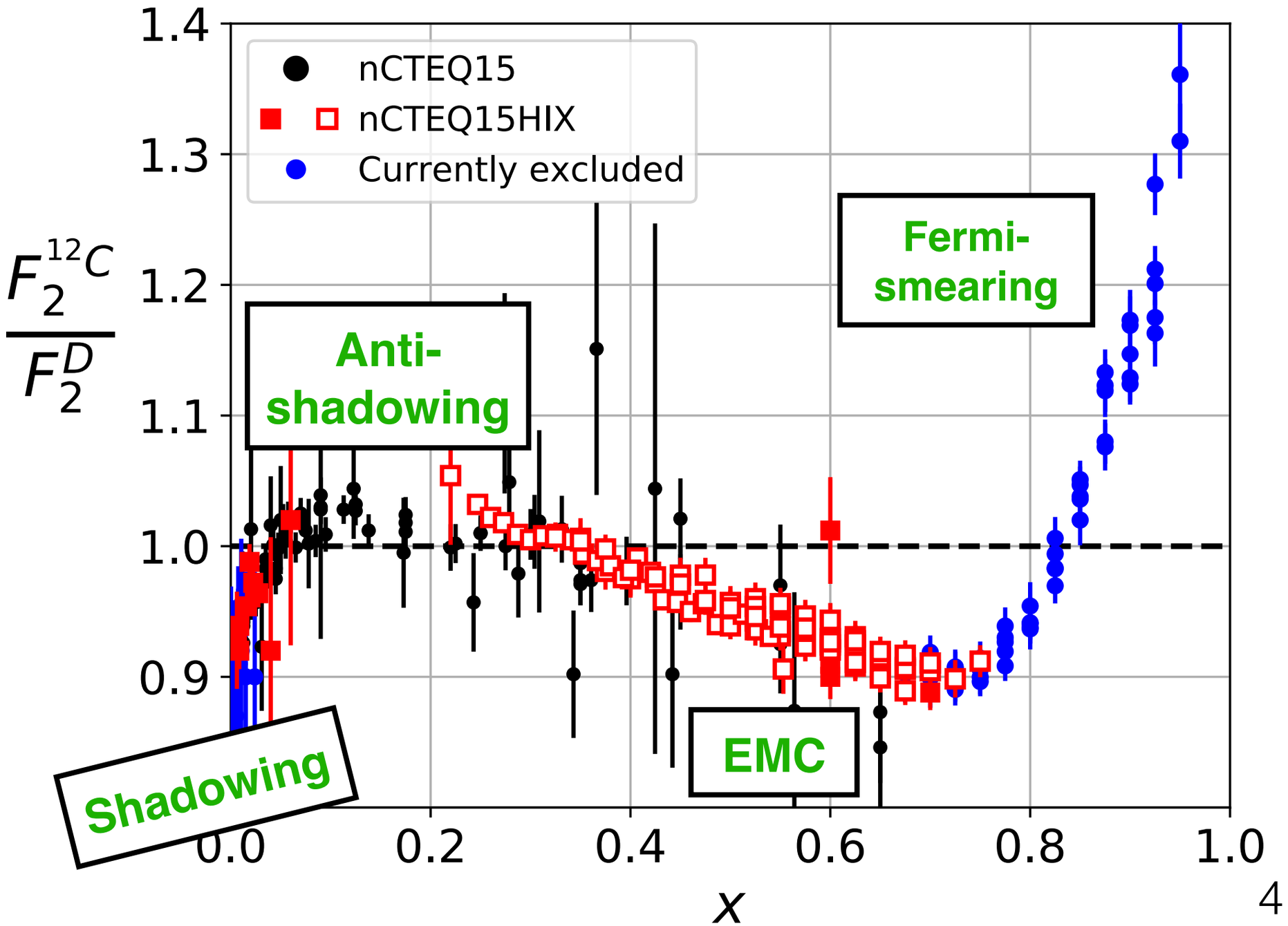
nCTEQ15, arXiv:1509.00792

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

$$c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$



A nucleus is not a collection of free nucleons



Theoretical Framework (pQCD formalism)

Factorization Theorems:

- Provide (field theoretical) **definitions** of the **universal** PDFs
- Make the formalism **predictive**!
- Make a statement about the **error** of the factorization formula

PDFs and predictions for **observables+uncertainties** **refer to this standard pQCD framework**

Need a solid understanding of the standard framework!

- For pp and ep collisions there a **rigorous factorization proofs**
- For pA and AA factorization is a **working assumption** to be tested phenomenologically

  There might be breaking of QCD factorization, deviations from DGLAP evolution, other nuclear matter effects to be included

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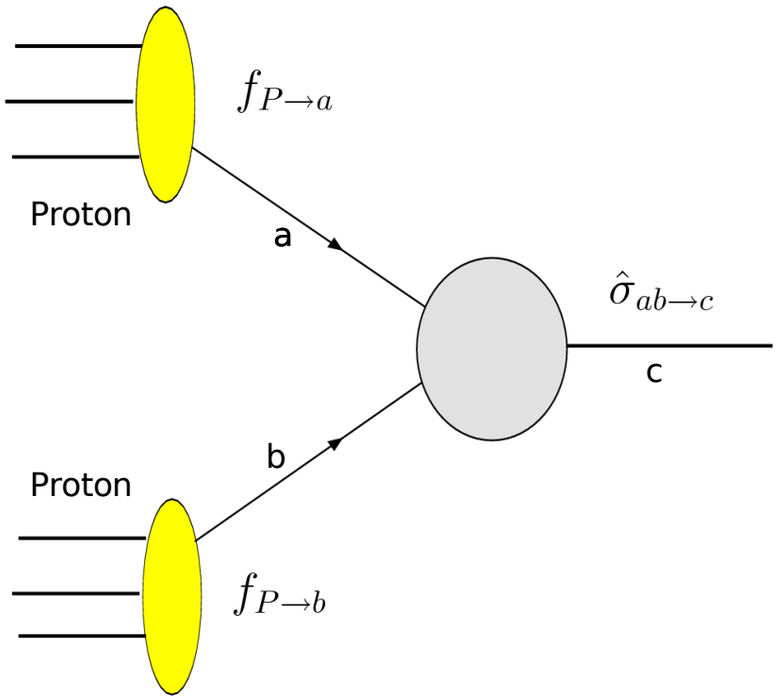
Talk by C. Marquet

Talk by F. Arleo

Factorization for pp collisions



$$\sigma = f_{P\to a} \otimes f_{P\to b} \otimes \hat{\sigma}_{ab\to c}$$

From experiment

Calculable from theoretical model

Parton Distribution Functions (PDFs)

$f_{P\to a,b}(x,\mu^2)$

- Universal
- Describe the structure of hadrons
- Obey DGLAP evolution equations

The hard part $\hat{\sigma}_{ab\to c}(\mu^2)$

- Free of short distance scales
- Calculable in perturbation theory
- Depends on the process

Predictive Power

Universality: same PDFs/FFs enter different processes:

- DIS: $$F_2^A(x,Q^2) = \sum_i \left[f_i^A \otimes C_{2,i}\right](x,Q^2)$$

- DY: $$\sigma_{A+B\to\ell^+ +\ell^- +X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to\ell^+ +\ell^- +X}$$

- A+B -> H + X: $$\sigma_{A+B\to H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to k+X} \otimes D_k^H$$

- Predictions for unexplored kinematic regions and for your favorite new physics process

Scale dependence predicted by QCD

- x-**dependence** of PDFs is NOT calculable in pQCD
- μ^2-**dependence** is calculable in pQCD – given by **DGLAP** (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations

DGLAP evolution equations

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

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

- Need to fix boundary conditions $\mathbf{f_i(x,Q_0)}$ at some perturbative initial scale $\mathbf{Q_0 \gtrsim 1\ GeV}$
- Perform **global analysis** of wide range of experimental data
- Progress on the lattice: interplay between global fits and lattice calculations see PDFLattice white papers arXiv:1711.07916, arXiv:2006.08636 [see talk by S. Zafeiropoulos]

Global analysis of nuclear PDFs

Same approach as for proton PDF determinations

1. Boundary conditions:
   Parameterize x-dependence of PDFs at initial scale Q_0

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2} P(x;A_3,...); f=u_v, d_v, g, \bar{u}, \bar{d}, s, \bar{s}$$

2. Evolve from Q_0 to Q solving the DGLAP evolution equations: f(x,Q)

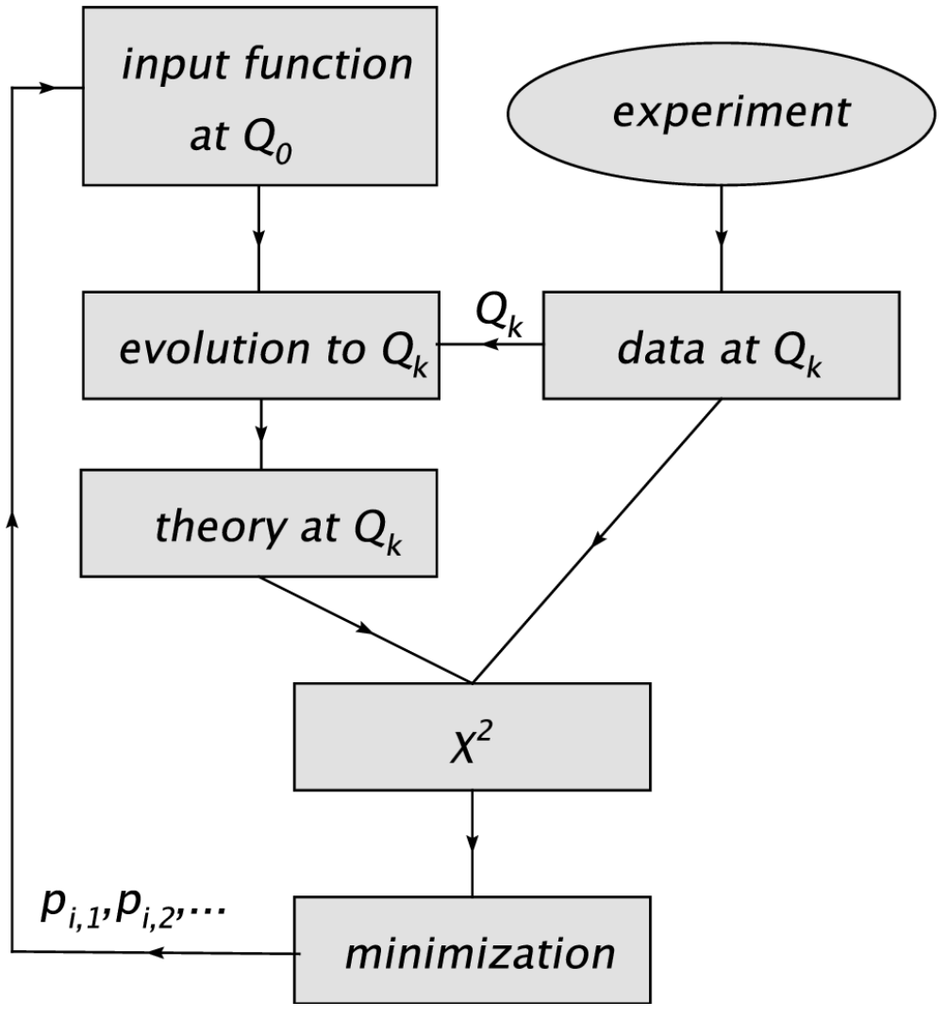
3. Define suitable χ^2 function and minimize w.r.t. fit parameters

$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n; \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

weights: default=1, allows to emphasize certain data sets



Complex code, entirely rewritten in C++ by my former PhD students F. Lyonnet, T. Jezo

Current nPDFs

	nNNPDF1.0 EPJC79(2019471	EPPS16 EPJC77(2017)163	nCTEQ15 PRD93(2016)085037	KA15 PRD93(2016)014036	DSSZ12 PRD85(2012)074028	EPS09 JHEP0904(2009)065
IA DIS	✔	✔	✔	✔	✔	✔
DY in p+A	✘	✔	✔	✔	✔	✔
RHIC π d+Au	✘	✔	✔	✘	✔	✔
νA DIS	✘	✔	✘	✘	✔	✘
DY in π+A	✘	✔	✘	✘	✘	✘
LHC p+Pb dijets	✘	✔	✘	✘	✘	✘
LHC p+Pb W,Z	✘	✔	✘	✘	✘	✘

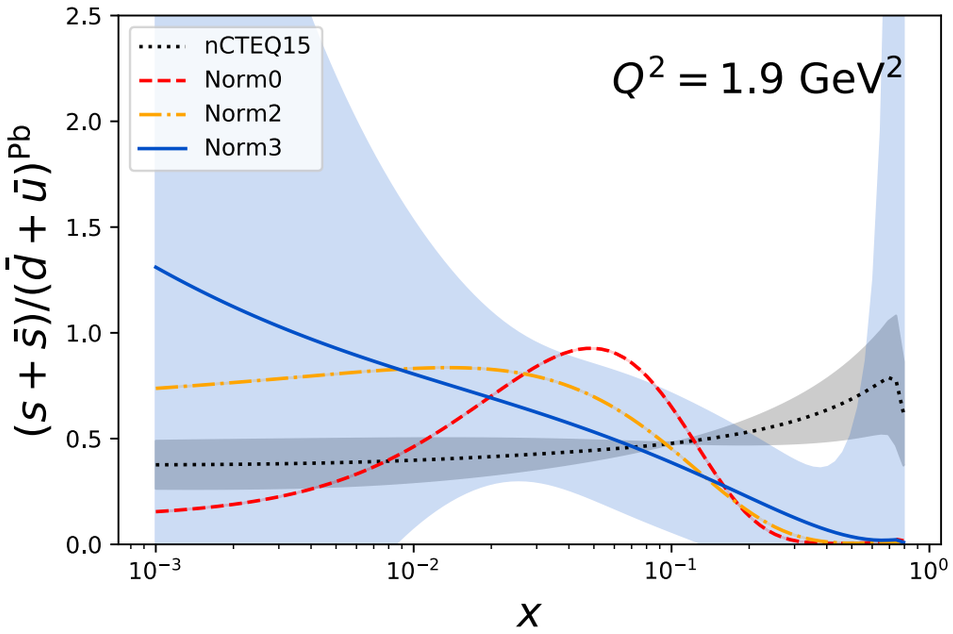
Order in α_s	NNLO	NLO	NLO	NNLO	NLO	NLO
Q-cut in DIS	**1.87 GeV**	1.3 GeV	**2 GeV**	1 GeV	1 GeV	1.3 GeV
W-cut	**3.53 GeV**	-	**3.5 GeV**	-	-	-
Data points	451	1811	708	1479	1579	929
Free parameters	Neural Net	20	16	16	25	15
Error tolerance	MC replica	52	35	N.N.	30	50
Proton baseline	NNPDF3.1	CT14NLO	~CTEQ6.1	JR09	MSTW08	CTEQ6.1
Mass scheme	FONLL-B	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS	ZM-VFNS
Flavour sep.	-	val.+sea	valence	-	-	-

Recent and ongoing work

- Global Analysis including LHC W/Z data: **nCTEQ15WZ** [2007.09100]

- Global Analysis including high-x, low-Q^2 data from JLAB: **nCTEQ15HIx** [2012.11566]

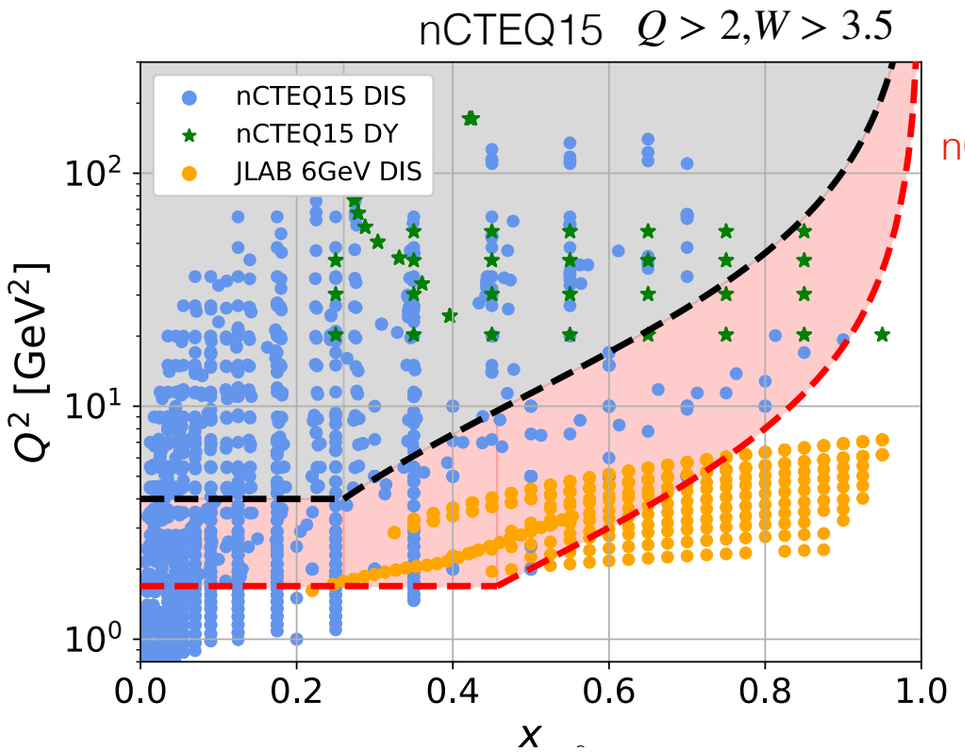
- Global Analysis including new single inclusive hadron (SIH) data from ALICE and RHIC: **nCTEQ15SIH** [2105.09873]



- Global Analysis including **neutrino-nucleus DIS** data: soon to appear

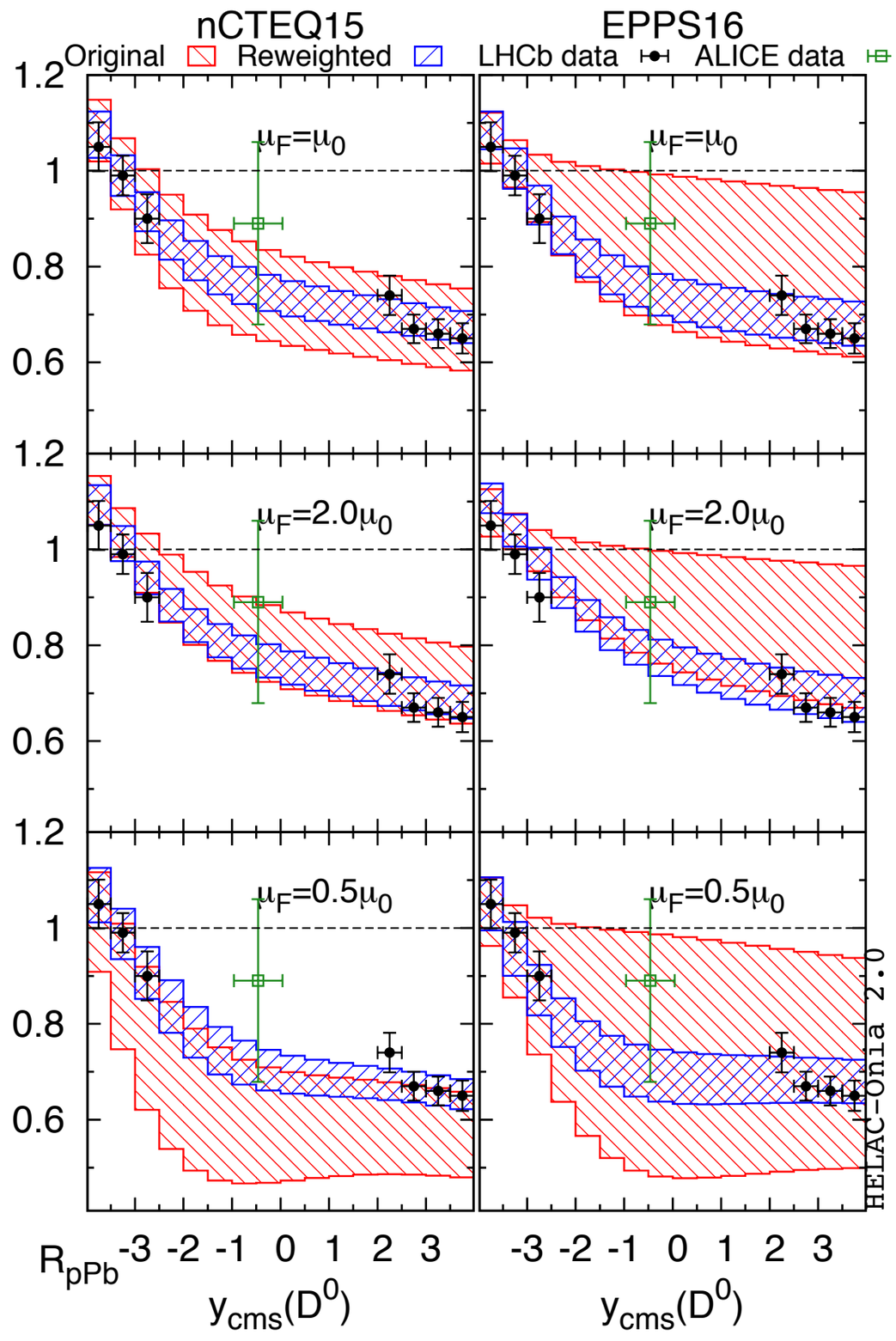
- Paper on nuclear DIS in terms of quarks and gluons **without** describing the nucleus in terms of nucleons; clearer and more solid basis for defining nuclear PDFs

- Heavy flavour production at the LHC and the nuclear gluon distribution: Kusina, Lansberg, Shao, IS, [2103.00876,PRL121(2018)052004]



The small-x gluon content (GLUE@NLO)

- First analysis of LHC heavy quark(-onium) data in the standard pQCD approach: PRL121(2018)052004
  - Consistent with a strongly shadowed gluon at small-x (alternative explanations: energy loss, saturation, …)
    - Reweighting analysis of nCTEQ15 and EPPS16 performed [2012.11462]
- Need to include heavy quark data in global analysis
- Include also prompt photon data (gluon sensitive, other systematics): FOCAL to cover small-x



(a) Prompt D^0

Summary

What: nuclear Parton Distribution Functions

Why:

- Information on hadron structure
- Needed to calculate cross sections involving initial state hadrons (RHIC, LHC, EIC, high-energy interactions in the atmosphere, long-baseline neutrino-int.)
- Precise knowledge needed to disentangle initial state effects (nuclear PDFs) from final state and medium effects

How:

- Global QCD Analyses
- Ab initio lattice calculations

Who:

- nCTEQ collaboration [with many (former) LPSC members]
- Master project GLUE@NLO: Lansberg, Wallon (IJCLab), Shao (LPTHE)

Plans:

- Include more LHC data in global analysis framework (prompt photons, heavy quarks, jets)
- Prepare next big release of nCTEQ nPDFs: nCTEQ22 or nCTEQ23
- Improve A-dependence, switch to NNLO, MCMC approaches, Machine Learning
- Future: data from HL-LHC, EIC, LHeC, …

Summary

Links:

- Global analysis of proton PDFs
  - simultaneous fits of proton PDFs and nuclear PDFs
  - Proton fits use data taken on nuclei! Need to understand nuclear corrections
- There are other collinear PDFs: helicity dependent PDFs, transversity PDFs
- Generalized PDFs: H. Moutarde (CEA Saclay), C. Mezrag (CEA Saclay), C. Lorce (Palaiseau), S. Wallon (IJCLab)
- Transverse Mass Dependent PDFs (TMD): J.-P. Lansberg, S. Wallon (IJCLAb)
- PDFs inside nucleons, nuclei but also pions, kaons, even photons
  pion structure: COMPASS experiment (S. Platchkov (CEA Saclay, …)
- Fragmentation Functions
- Ab initio lattice calculations: S. Zafeiropoulos (Marseille), M. Mangin-Brinet (LPSC), …

Goal: Understanding the 3D-structure of hadrons

Collaborators in France

- Long term collaboration with J.-P. Lansberg (IJCLab), H. S. Shao (LPTHE) [Common Master projects *GLUE@NLO*, *PDFs and Hard processes* and joint Theorie-LHC-France projects]

- How to include energy loss effects in nPDF determinations? F. Arleo (LLR/Subatech), S. Peigne (Subatech) [see talk by F. Arleo]

- Prompt photon production and heavy quark production with the FOCAL detector: R. Guernane (ALICE, LPSC)

- Interactions with S. Zafeiropoulos on PDF determinations on the lattice [see his talk]

- Work on photon+heavy quark production in pp, pA and AA collisions: J.-P. Guillet (LAPTH), F. Arleo, P.-B. Gossiaux (Subatech) [see talk by J.-P. Guillet]

- Many interactions with experimentalists from ALICE, ATLAS, CMS and LHCb

Thank you!