Nuclear PDFs after 10 years of LHC data[1]

Michael Klasen

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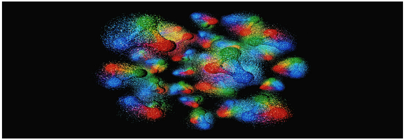
CTEQ Fall Meeting, MSU, November 9, 2023

GEFÖRDERT VOM

[1]MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]

Nuclear structure at high energies



Important current research topic:

- Understand fundamental q, g dynamics of p, n bound in nuclei
- Determine initial conditions in creation of new state of matter: Color-glass condensate (CGC) $\rightarrow$ Quark-gluon plasma (QGP)

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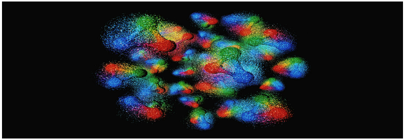

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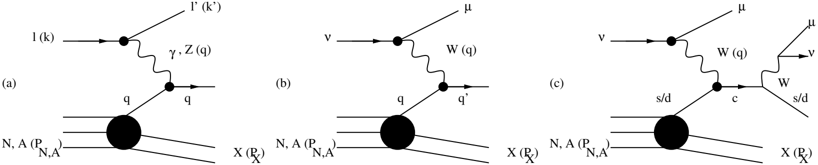
Knowns and (known) unknowns:

- Evolution of PDFs $f_{q,g}(x, Q^2)$ with squared energy Q^2: Calculable at NLO and beyond through DGLAP equations
- Dependence on longitudinal momentum fraction x: QCD factorization theorem $\rightarrow$ global fits to experimental data
- Fundamental dynamics of nuclear modifications: Parameterized, but remain to be fully understood

Key processes and open questions

Deep-inelastic scattering (NC, CC, dimuon production):



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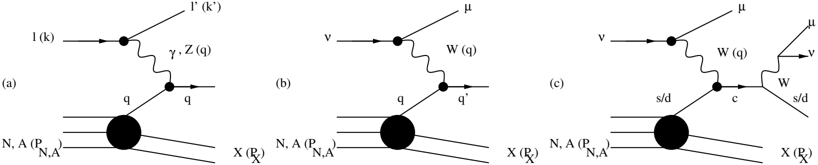
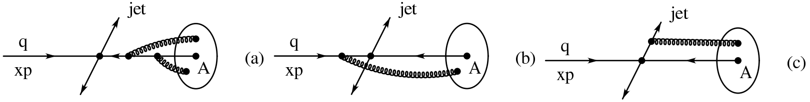


Hadronic collisions: Leading twist, higher-twist [J.w. Qiu, 0305161]

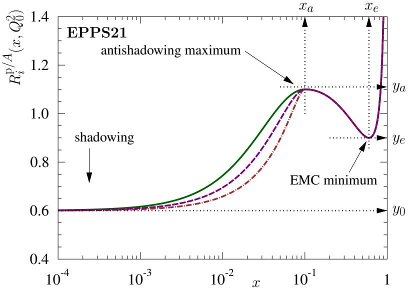


- Transv. size, jet mass, rescattering: $\mathcal{O}\left(r_T^2 \sim \frac{1}{p_T^2}, \frac{m_J^2}{p_T^2}, \frac{\alpha_s(Q^2)\Lambda^2}{Q^2}\right)$
- Enhanced in nuclear collisions by $A^{1/3}$

Nuclear modification factor

Definition:

$$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q)$$



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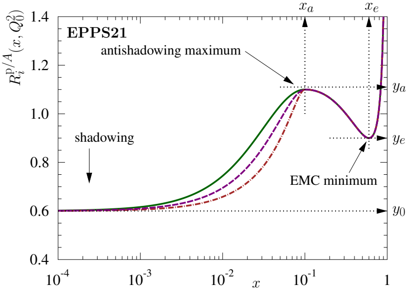

Regions:

- Shadowing: Surface nucleons absorb $q\bar{q}$ dipole, cast shadow
- Antishadowing: Imposed by momentum sum rule
- EMC effect: q_v suppression due to nuclear binding, pions, quark clusters, Nachtmann scaling, short-range correlations, ...
- Fermi motion: Nucleons move, $F_2^A = \int_x^A dz\ f_N(z)\ F_2^N(\frac{x}{z})$

(Perturbative) Quantum Chromodynamics

Nuclear structure function(s) in deep-inelastic scattering (DIS):

$$F_2^A(x, Q^2) = \sum_i f_i^{(A,Z)}(x, Q^2) \otimes C_{2,i}(x, Q^2)$$

QCD factorization theorem, Wilson coefficients $C_{2,i}$ at (N)NLO

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$$f_i^{(A,Z)}(x, Q^2) \;=\; \frac{Z}{A} f_i^{p/A}(x, Q^2) + \frac{A-Z}{A} f_i^{n/A}(x, Q^2)$$

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DGLAP evolution equations:

$$\frac{\partial f_i(x,Q^2)}{\partial \log Q^2} = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z},\alpha_s(Q^2)\right) f_j(z,Q^2)$$

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Sum rules, but also isospin symmetry:

$$f_{d,u}^{n/A}(x,Q^2) \;=\; f_{u,d}^{p/A}(x,Q^2)$$

Theoretical input and experimental data

Analysis	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KSASG20
Theoretical input:					
Perturbative order	NLO	NLO	NLO	NNLO	NNLO
Heavy-quark scheme	SACOT$-\chi$	SACOT$-\chi$	FONLL	FONLL	FONLL
Data points	1484	2077	2188	2410	4353
Independent flavors	5	6	6	4	3
Free parameters	19	24	256	16	18
Error analysis	Hessian	Hessian	Monte Carlo	Hessian	Hessian
Tolerance	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 33$	N/A	$\Delta\chi^2 = 50$	$\Delta\chi^2 = 20$
Proton PDF	∼CTEQ6.1	CT18A	∼NNPDF4.0	∼HERAPDF2.0	CT18
Deuteron corrections	(✓)[a,b]	✓[c]	✓	✓	✓
Fixed-target data:					
SLAC/EMC/NMC NC DIS	✓	✓	✓	✓	✓
– Cut on Q^2	4 GeV^2	1.69 GeV^2	3.5 GeV^2	3.5 GeV^2	1.2 GeV^2
– Cut on W^2	12.25 GeV^2	3.24 GeV^2	12.5 GeV^2	12.0 GeV^2	
JLab NC DIS	(✓)[a]	✓			✓
CHORUS/CDHSW CC DIS	(✓/-)[b]	✓/-	✓/-	✓/✓	✓/✓
NuTeV/CCFR 2μ CC DIS	(✓/✓)[b]		✓/-		
pA DY	✓	✓	✓		✓
Collider data:					
Z bosons	✓	✓	✓	✓	
$W^\pm$ bosons	✓	✓	✓	✓	
Light hadrons	✓	✓[d]			
Jets		✓	✓		
Prompt photons			✓		
Prompt D^0	✓	✓	✓[e]		
Quarkonia (J/ψ, ψ', Υ)	✓				

Perturbative order

Required precision:

- Protons: Wealth of HERA, LHC pp data → 1% accuracy, NNLO
- Nuclei: Mostly FT, some LHC pA, no EIC → 10% accuracy, NLO ok

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Available precision:

- Fast NNLO for DIS: APFEL(++), QCDNUM → xFitter
- Slow NNLO for pA: V (FEWZ, MCFM, Vrap, DYNNLO→Matrix), jets (NNLOjet), t (top++, Matrix) [, b (top++, Matrix)]
- Bottleneck: Grids (fastNLO, APPLgrid, PineAPPL → Ploughshare)

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Open heavy quarks (important for pA):

- FFNS → FONLL
- VFNS ZM → GM (ACOT, RT)

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Heavy quarkonia (important for pA):

- CEM [R. Vogt et al., PRC 105 (2022) 055202: J.P. Lansberg et al., PLB 807 (2020) 135559]
- NRQCD [K.T. Chao et al., JHEP 08 (2021) 111; M. Butenschön, B. Kniehl, PRL 130 (2023) 041901]

Compatibility of neutrino DIS data

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]

Are CC DIS data compatible with NC DIS and DY data?

- No (in particular high-precision NuTeV data)

  [nCTEQ Coll., PRD 77 (2008) 054013, PRL 106 (2011) 122301, PRD 106 (2022) 074004; also prel. HKN]

- Yes (if taken without correlations, normalized)

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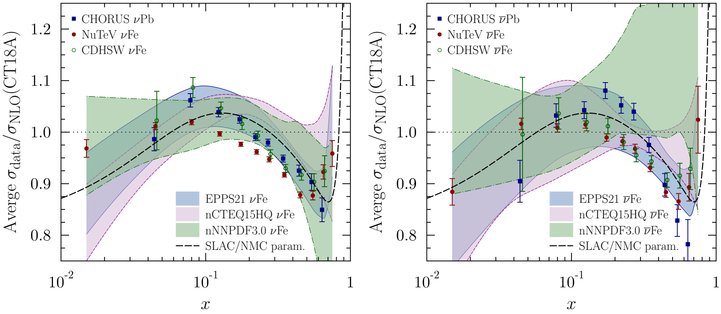
Consolidated perspective:



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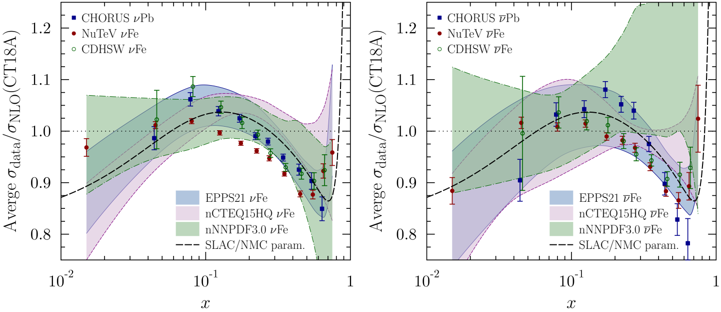
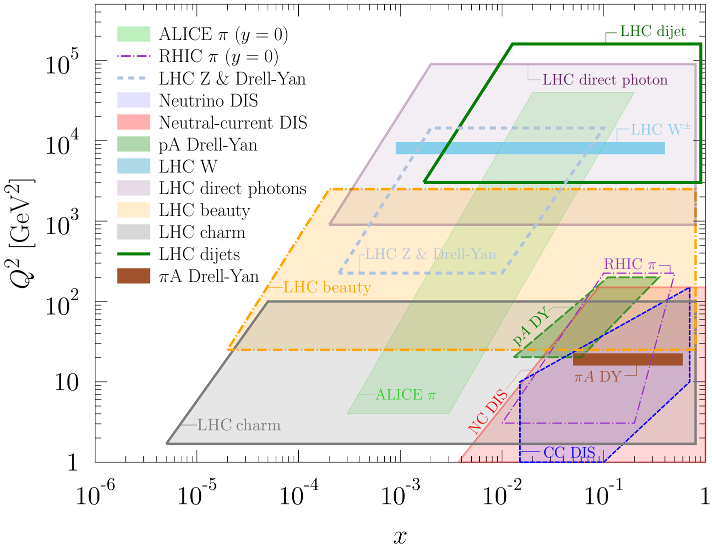


NB: Proton is CT18A, EW corr. in CDHSW. Impact on s quark!

Kinematic coverage in x and Q^2



Experimental data on W/Z bosons

Analysis	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KP16
Run-I:					
ATLAS Z	✓	✓	✓	✓	✓
CMS Z	✓	✓	✓	✓	✓
ALICE Z			✓[b]		
LHCb Z	✓		✓[b]		
ATLAS $W^{\pm}$	✓				✓
CMS $W^{\pm}$	✓	✓	✓		
ALICE $W^{\pm}$	✓		✓[b]		
Run-II:					
CMS Z			✓[b]		
ALICE Z			✓[b]		
LHCb Z					
CMS $W^{\pm}$	✓	✓[a]	✓	✓	
ALICE $W^{\pm}$					

[a] added in EPPS21; [b] added in nNNPDF3.0.

Electroweak boson production in pPb with CMS

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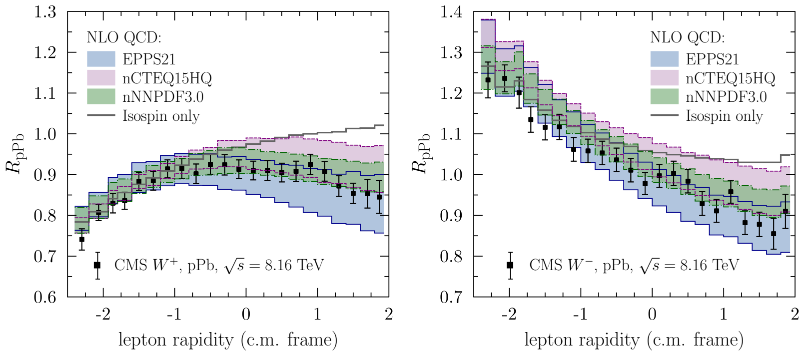

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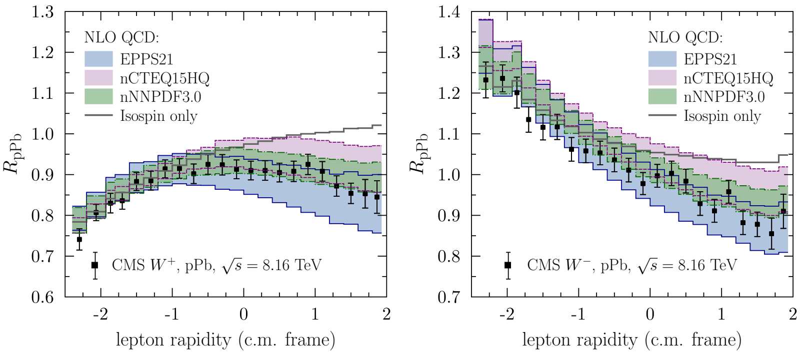
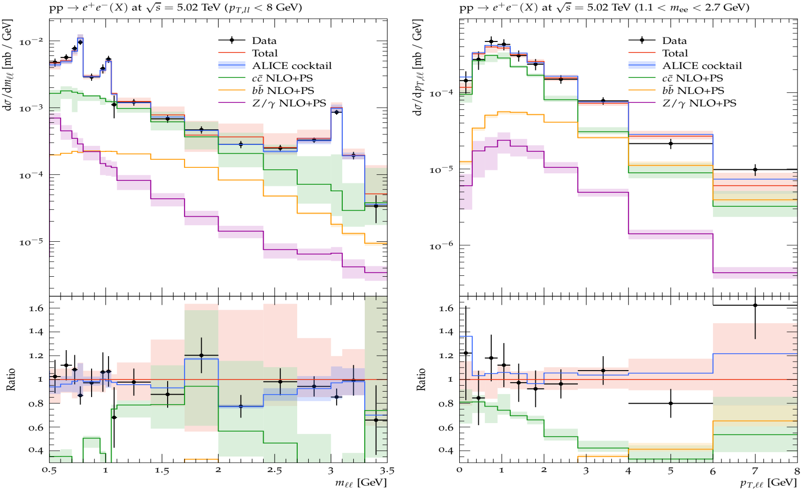


- nCTEQ/nNNPDF fit absolute cross sections, EPPS ratios
- Limited impact on s quark, since mostly evolved from gluon
- CMS Run-II NC in tension with NLO → NNLO? (cf. TUJU21)

Virtual photon contribution in POWHEG

A. Andronic, T. Jezo, MK, C. Klein-Bösing, A. Neuwirth, in preparation



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ATLAS Coll., PLB 796 (2019) 230; nNNPDF Coll., EPJC 82 (2022) 507

Pre-LHC data: E706 (pBe); PHENIX, STAR (DAu)

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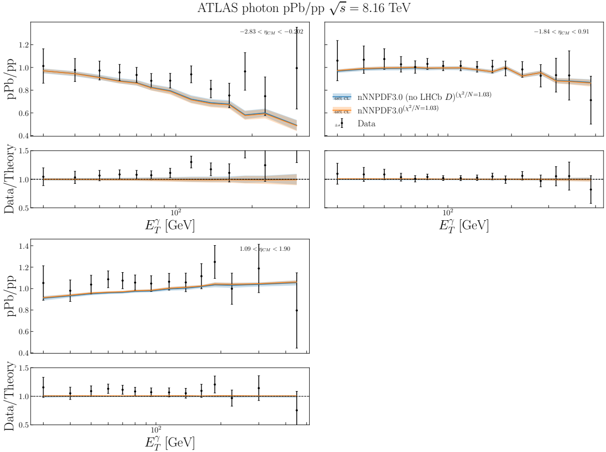

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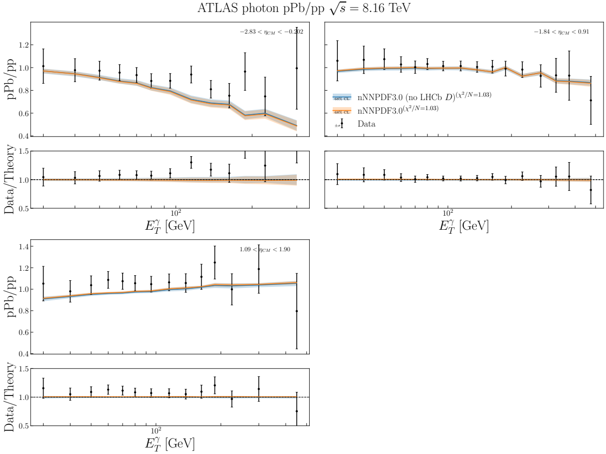
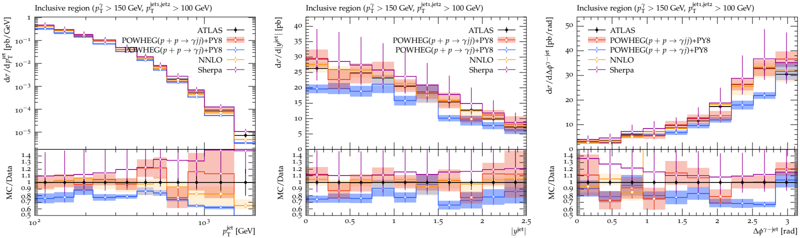


NB: Absolute cross sections underestimated at NLO → NNLO?

Photon+jet production in pp with ATLAS

T. Jezo, MK, A. Neuwirth, in preparation



Single inclusive hadrons

P. Duwentäster, MK et al. [nCTEQ Coll.], PRD 104 (2021) 094005

(In-)sensitivity to fragmentation functions:

DSS unmodified data	DSS modified data	KKP	BKK	NNFF	JAM20
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Impact of (RHIC+) LHC (ALICE) data:

χ^2/N_{dof} for selected experiments and processes												
	STAR		PHENIX	ALICE				DIS	DY	WZ	SIH	**Total**
	π^0	$\pi^\pm$	π^0	5 TeV π^0	5 TeV $\pi^\pm$	5 TeV $K^\pm$	8 TeV π^0					
nCTEQ15	0.13	2.68	0.30	2.53	0.62	0.71	1.96	0.86	0.78	(3.74)	(1.23)	**1.28**
nCTEQ15SIH	0.16	0.69	0.41	0.48	0.13	0.29	0.58	0.87	0.72	(2.32)	0.38	**1.00**
nCTEQ15WZ	0.17	3.24	0.23	0.67	0.21	0.41	1.58	0.90	0.78	0.90	(0.81)	**0.90**
nCTEQ15WZ+SIH	0.14	0.75	0.30	0.47	0.13	0.26	0.79	0.91	0.77	1.02	0.41	**0.85**

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Little impact of η data, also no FF uncertainty available.

Jets

CMS Coll., PRL 21 (2018) 062002; K. Eskola et al., EPJC 82 (2022) 413

Specific to nuclear collisions:

- Large background from Underlying Event
- 7 ± 5 pN interactions (Glauber) [Loizides, Kamin, d'Enterria, PRC 97 (2018) 054910]
- Requires subtraction of MPIs and sufficiently large p_T/small R

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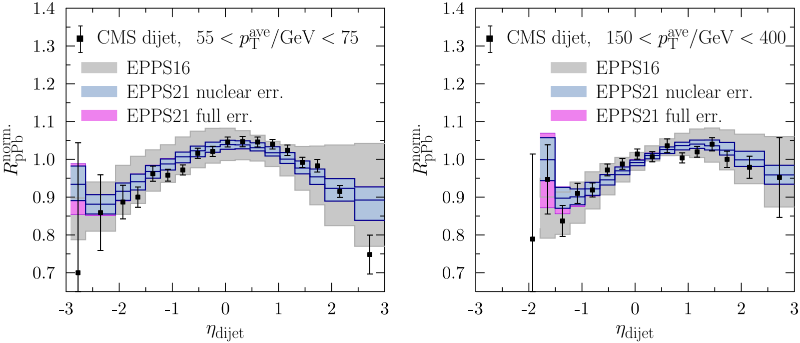

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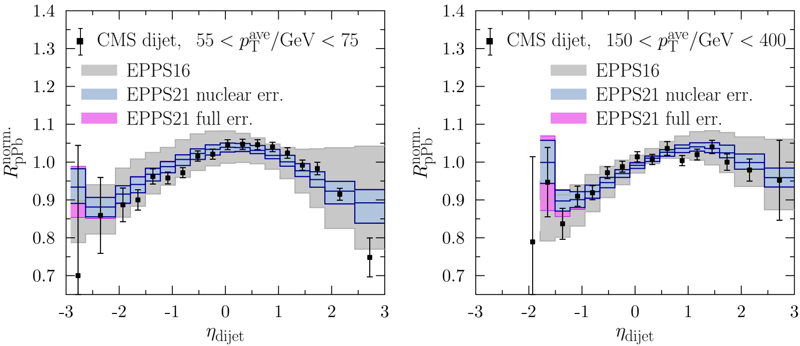

NB: CMS Run-I *pp* rapidity ratios in tension with NLO $\to$ NNLO?

Methodology for heavy quark/quarkonium production

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]

Data-driven approach (Crystal Ball function):

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

- Originally proposed for J/Ψ pairs and double parton scattering

  [C.H. Kom, A. Kulesza, J. Stirling, PRL 107 (2011) 082002]

- Impact on nPDFs demonstrated with reweighting studies

  [A. Kusina, J.P. Lansberg, I. Schienbein, H.S. Shao, PRL 121 (2018) 052004 and PRD 104 (2021) 014010]

- New rapidity dependence allows to cover also LHCb data

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Choice of proton PDF (nCTEQ15) and factorization scales:

	D^0	J/ψ	$B\to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B\to\psi(2S)$
μ_0^2	$4M_D^2+p_{T,D}^2$	$M_{J/\psi}^2+p_{T,J/\psi}^2$	$4M_B^2+\frac{M_B^2}{M_{J/\psi}^2}p_{T,J/\psi}^2$	$M_{\Upsilon(1S)}^2+p_{T,\Upsilon(1S)}^2$	$M_{\psi(2S)}^2+p_{T,\psi(2S)}^2$	$4M_B^2+\frac{M_B^2}{M_{\psi(2S)}^2}p_{T,\psi(2S)}^2$

Fit to *pp* data and validation with NLO predictions

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]

Crystal Ball fit parameters: Cut data with $p_T < 3$ GeV and $|y| > 4$

	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B \to \psi(2S)$
κ	0.33457	0.47892	0.15488	0.94524	0.21589	0.45273
λ	1.82596	0.30379	0.12137	0.06562	0.07528	0.13852
$\langle p_T \rangle$	2.40097	5.29310	-7.65026	8.63780	8.98819	7.80526
n	2.00076	2.17366	1.55538	1.93239	1.07203	1.64797
a	-0.03295	0.02816	-0.08083	0.22389	-0.10614	0.06179
N_{points}	34	501		375	55	
χ^2/N_{dof}	0.25	0.88		0.92	0.77	

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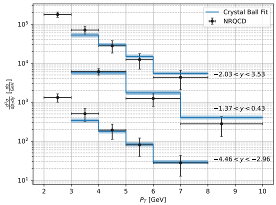
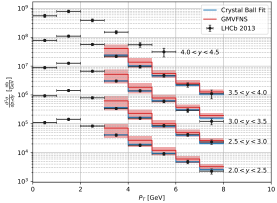
Heavy quarkonia in NRQCD:

[M. Butenschön, B. Kniehl, PRL 106 (2011) 022003]



Open heavy quarks in GM-VFNS:

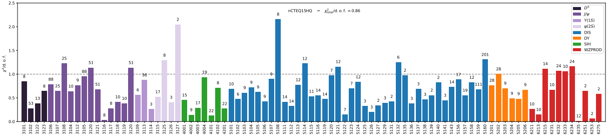
[B. Kniehl et al., PRD 71 (2005) 014018]



Impact of heavy quark and quarkonium data

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]

Cut D^0 data with $p_T > 15$ GeV (no p), 2 high-p_T LHCb Υ points



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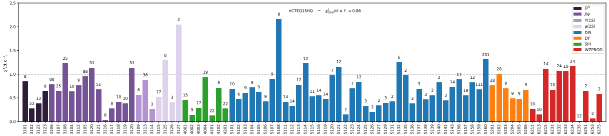
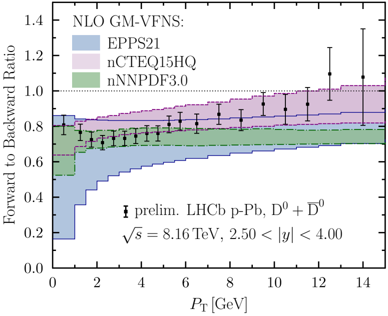
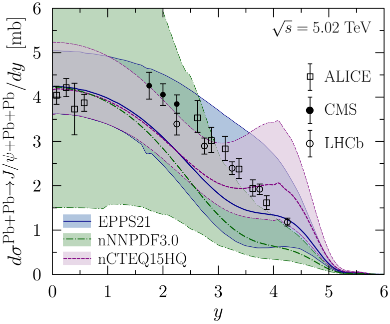


Comparison with incl. D^0 (LHCb Run-II) and excl. J/ψ data:





Heavy-quark and quarkonium data

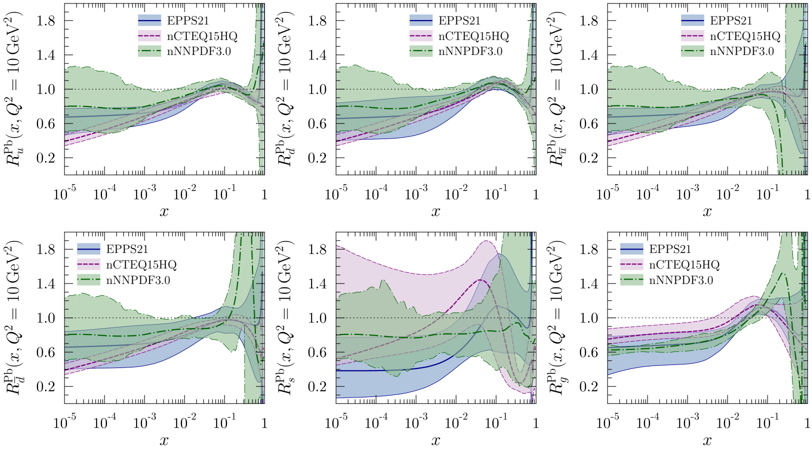
MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]

Observable $\mathcal{O}$	D^0	J/ψ	$\Upsilon(1S)$	$\psi(2S)$	B^0, $B^\pm$	c jet	b jet
Run-I:							
ATLAS		(240, 241)[a]	(241)[a]	(241)[a]			
CMS		(242)[a]	(243)	(244)[a]		(245)	(246)
ALICE	(247, 248, 249)[a]	(250, 251)[a], (252)	(253)	(254)[a]			(255)
LHCb	(256)[a,b,c]	(257)[a]	(258)				
Run-II:							
ALICE		(259)[a], (260)	(261)[a]	(262)[a]			
LHCb	(263)	(264)[a]	(265)[a]		(266)		
Fixed target:							
LHCb	(267, 268)	(267, 269)		(269)			

[a] included in nCTEQ15HQ (50); [b] included in EPPS21 (51); [c] included in nNNPDF3.0 (52).

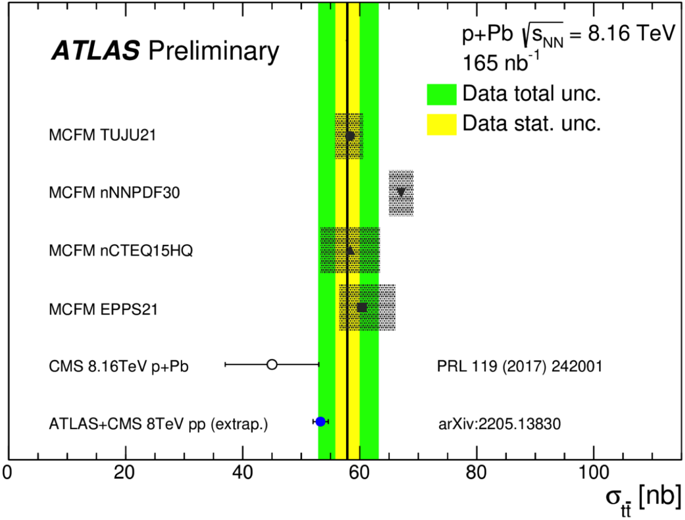
Nuclear PDFs after 10 years of LHC data

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]



Top pair production in pPb with ATLAS

ATLAS-CONF-2023-063



Conclusion

Nuclear PDFs:

- QCD factorization, DGLAP evolution, HT enhancement
- Shadowing (LTA?), antishadowing, EMC effect, Fermi motion
- Dynamics: Partonic, hadronic, duality?
- Non-linear effects, initial-state phase transition to QGP

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Recent developments in fixed-target experiments:

- NC DIS: JLab at high $x \rightarrow$ TMC, HT, deuteron
- CC DIS: CHORUS (CDHSW, dimuon) ((CCFR/NuTeV))
- Neutrino data constrain in particular the strange quark

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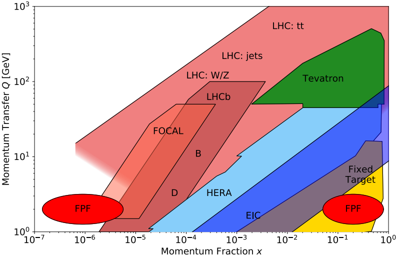
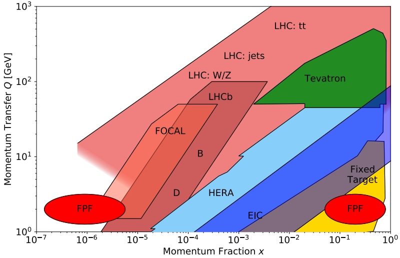
Lattice QCD: [LP3 Coll., NPLQCD Coll.]

- Large x, low A, m_π, quasi-/pseudo-PDFs etc., R_{u-d}, p_g/p_A

Outlook


LHC: tt
LHC: jets
LHC: W/Z
LHCb
Tevatron
FOCAL
B
D
HERA
EIC
Fixed Target
FPF
FPF
Momentum Transfer Q [GeV]
Momentum Fraction x

Outlook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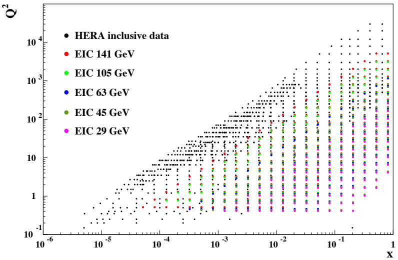
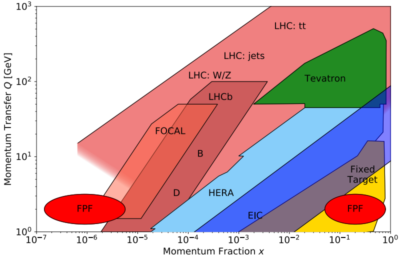

HERA inclusive data
EIC 141 GeV
EIC 105 GeV
EIC 63 GeV
EIC 45 GeV
EIC 29 GeV
Q²
x

Outlook



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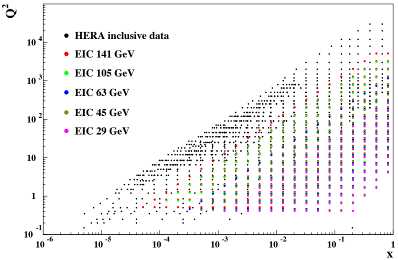

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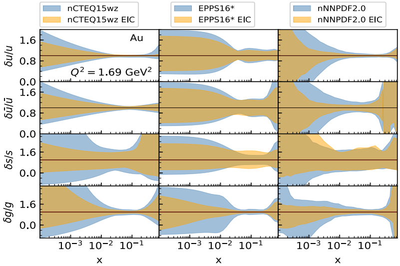
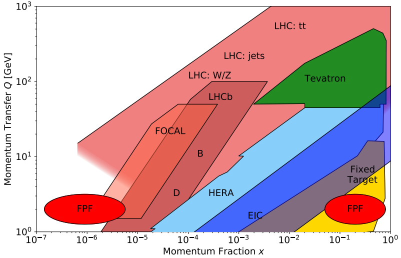


nCTEQ15wz
nCTEQ15wz EIC
EPPS16*
EPPS16* EIC
nNNPDF2.0
nNNPDF2.0 EIC
Au
$Q^2 = 1.69$ GeV²
δu/u
δū/ū
δs/s
δg/g
x

Outlook



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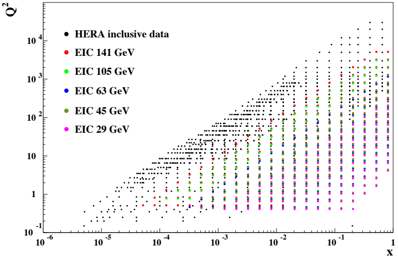

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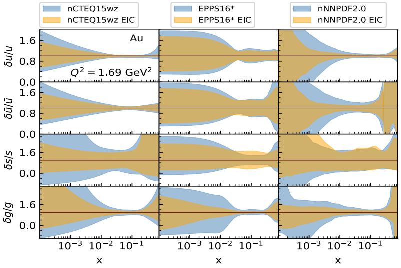

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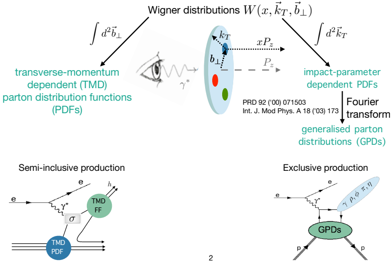
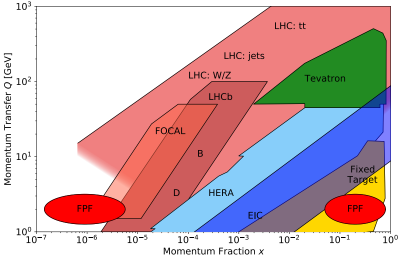


Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$
$\int d^2\vec{b}_\perp$
$\int d^2\vec{k}_T$
transverse-momentum dependent (TMD) parton distribution functions (PDFs)
impact-parameter dependent PDFs
PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173
Fourier transform
generalised parton distributions (GPDs)
Semi-inclusive production
Exclusive production
TMD FF
TMD PDF
GPDs

Outlook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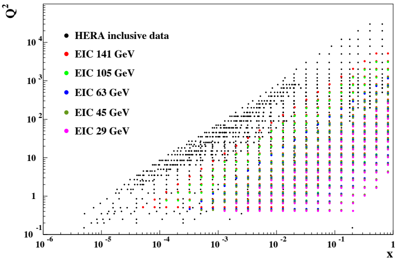
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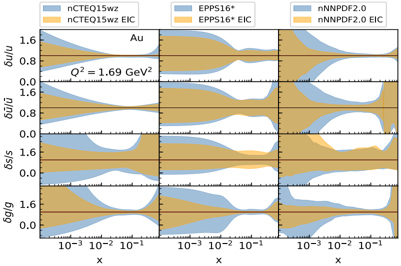
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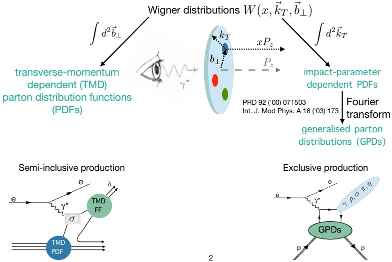
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