Executive Summary

WELCOME to All Pa

Joint ECFA-NuPECC-APPEC Workshop
"Synergies between the EIC and the LHC"
DESY, Hamburg, December 14-15, 2023

Initiative Coordinators:

Daniël Boer (Univ. Groeningen), Pasquale di Nezza (INFN-LNF & CERN),
Maria Vittoria Garzelli (Universitaet Hamburg)

Local Organizing Committee:

Markus Diehl (DESY-TH), Isabell Melzer Pellmann (DESY-EXP),
Achim Geiser (DESY-EXP), Sven-Olaf Moch (Universitaet Hamburg)

Workshop on Synergies ep/eA – pp/pA/AA, CERN, February 29 - March 1, 2024

Workshop roots

2022: Expression of Interest for a Joint Activity focused on understanding and strenghtening the synergies between the Electron Ion Collider and the Large Hadron Collider, with the involvement of three communities (particle, nuclear and astroparticle physics, represented by ECFA, NuPECC and APPEC, respectively).
Available at:

https://indico.ph.tum.de/event/7004/

~ 129 scientists, various of whom are present here today, endorsed it.
Still open for signatures, in the case you wish to endorse it.

June 2022: kick-off meeting “Synergies between the EIC and the LHC”, took place for two days at CERN:

https://indico.ph.tum.de/event/7014

Last Workshop (DESY, December 2023)

Follow up of the previous one, with the intention of bringing out new/different aspects of the EIC-LHC synergy in theory, phenomenology and experiment.

Topics of last edition included, but were not restricted to:

- **EIC and LHC synergies in physics:**
  - **nucleon and nuclear structure**
  - **forward physics, diffractive processes**
  - **small x**
  - **exclusive processes**
  - **fragmentation and jets**
  - **event generators, computing and ML**
- **Connections with cosmic-ray physics**
- **EIC and LHC detectors**
- **Complementary projects**

Workshop Program: talks

https://indico.desy.de/event/41404

- 22 Plenary Talks
- 16 Parallel Talks in 4 parallel sessions

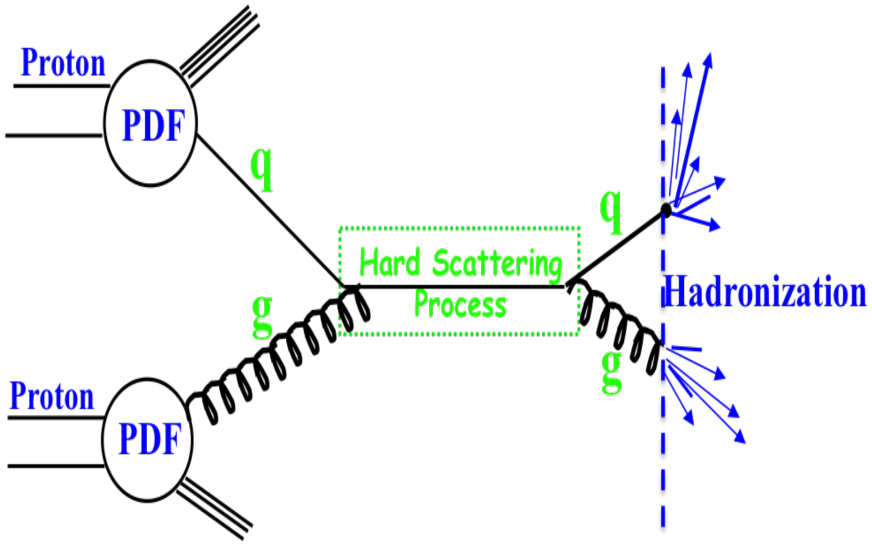
It is impossible to summarize all of them in short time,
in the following personally biased and limited choice, limited to some phenomenology aspects: apologies for all what is missing (the majority)

Need for multiple colliders

We need multiple colliders (ee, eh, hh) to test

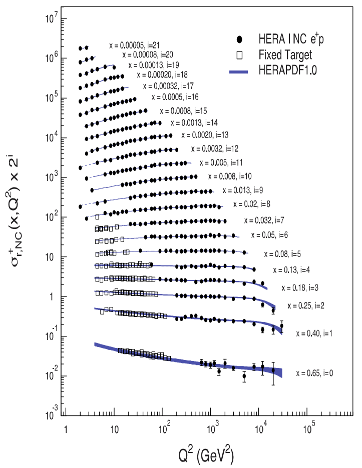
E. Aschenauer

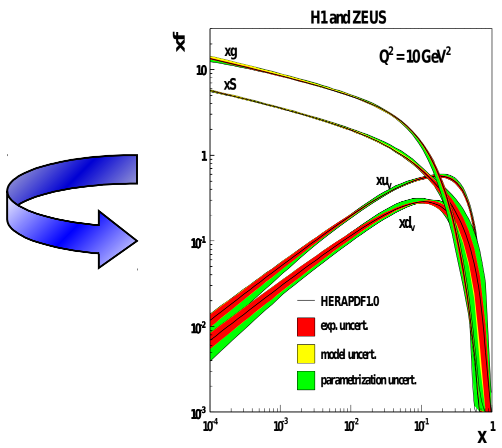
Factorization



Universality

Example: Measure PDFs at HERA at √s=0.3 TeV:





Predict pp and compare to measurements at √s=0.2, 1.96 & 7 TeV

p-p

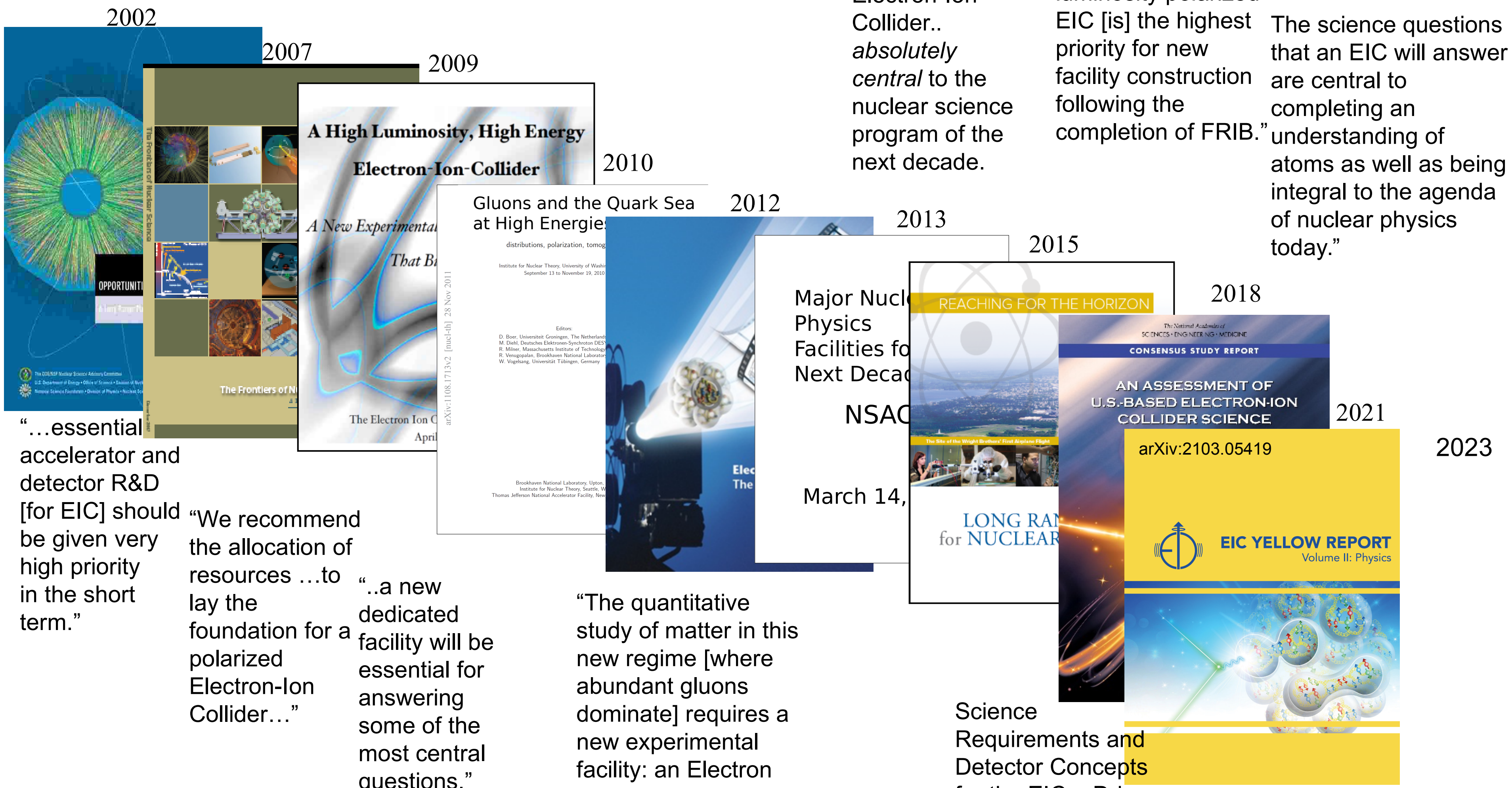
- probe has complex structure
- no simple access to parton kinematics
- Gluons can be accessed directly via qg &gg

e-h

- Point-like probe gives good resolution
- High precision & access to partonic kinematics through scattered lepton
  - initial and final state effects can be cleanly disentangled
    - inclusive measurements of structure functions only sensitive to initial state

EIC over two decades

E. Aschenauer



"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

"..a new dedicated facility will be essential for answering some of the most central questions."

"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

Electron-Ion Collider.. *absolutely central* to the nuclear science program of the next decade.

"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors

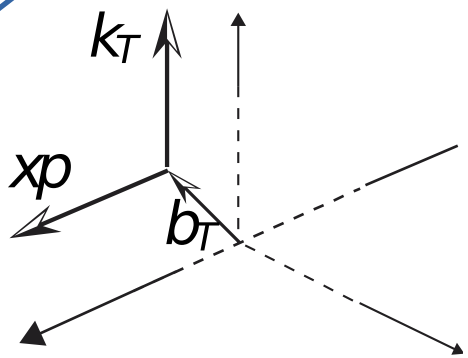
Timeline EIC: possible start of data taking ~2034:
EIC will co-exist with Run5 and 6 HL-LHC (up to 2041)

Multidimensional imaging of quarks and gluons

Wigner function $W(x,b_T,k_T)$ QCD genetic map

Momentum space

$\int d^2b_T$



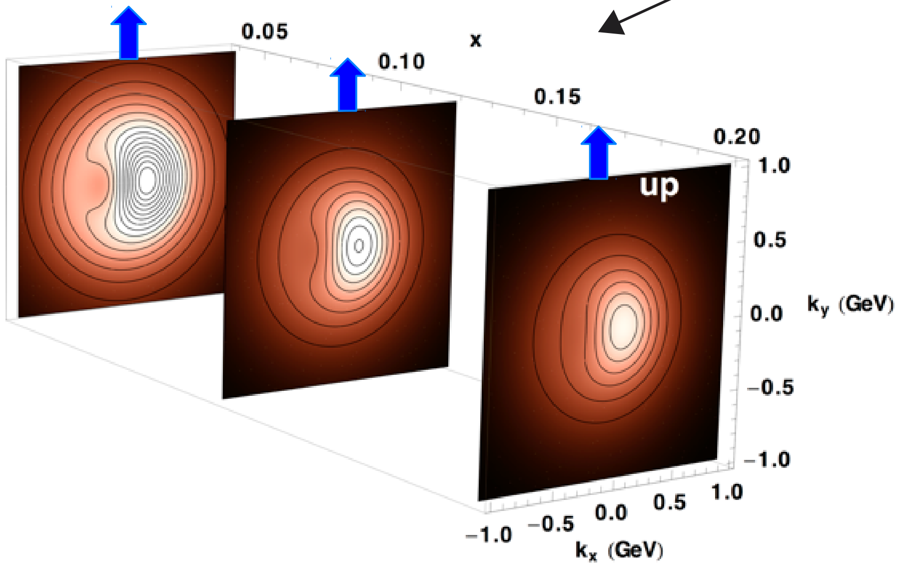
$\int d^2k_T$

Coordinate space

$f(x,k_T)$

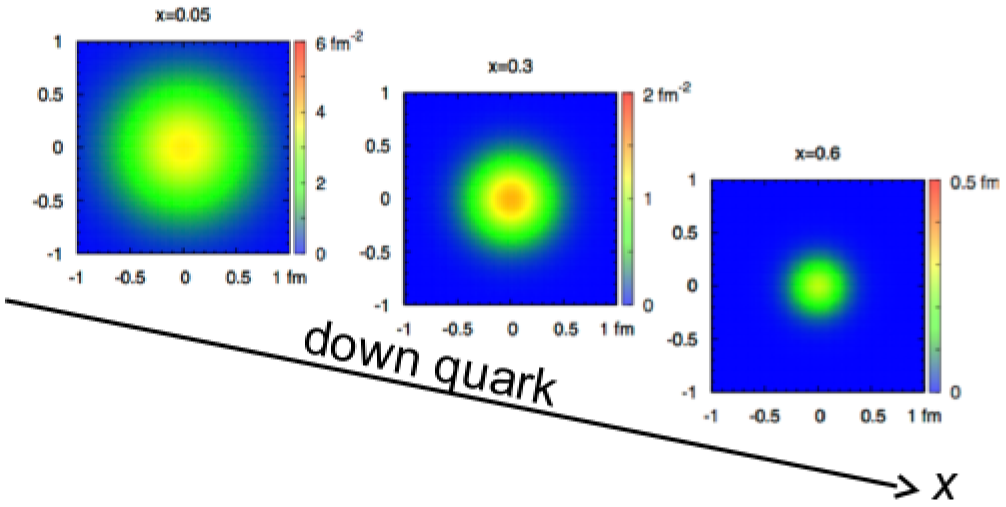
$f(x,b_T)$

Quarks



From semi-inclusive scattering

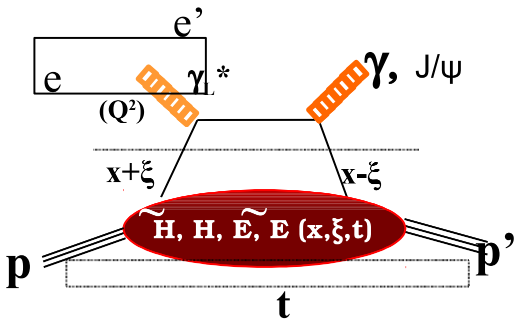
Quarks



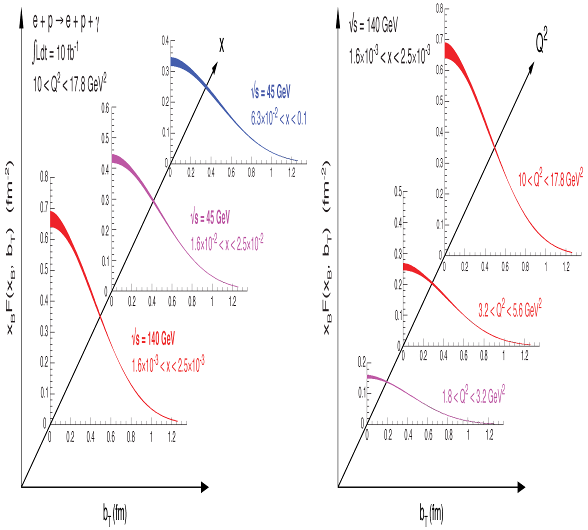
From exclusive scattering

E. Aschenauer

Spatial distribution of quarks and gluons

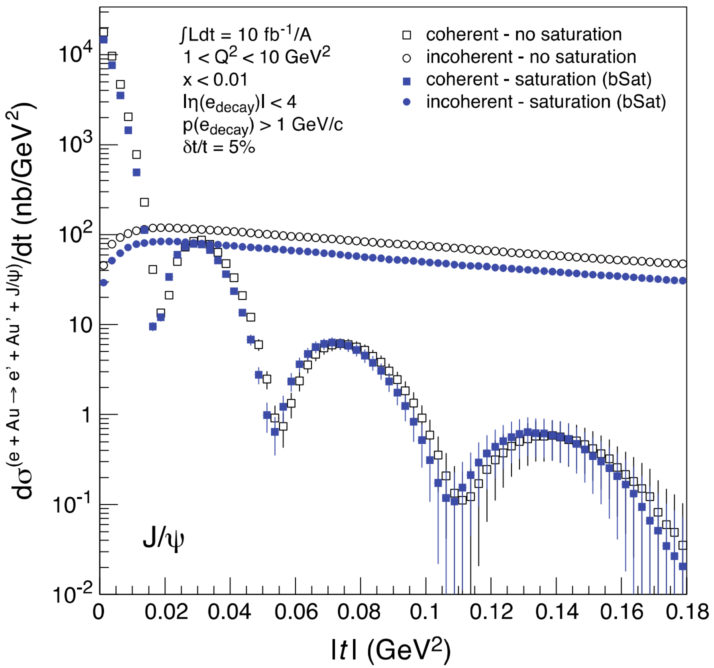


DVCS, J/ψ

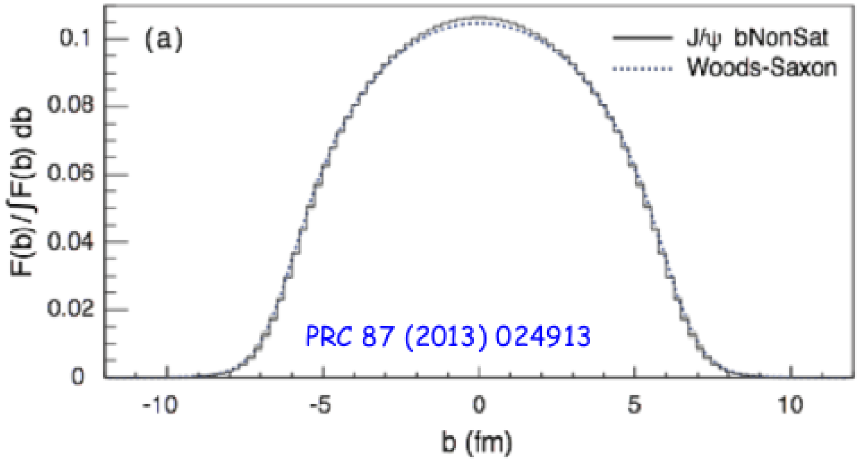


Diffractive vector meson production: e + Au → e′ + Au′ + J/ψ, φ, ρ

Momentum transfer $t = |\mathbf{p}_{Au}-\mathbf{p}_{Au'}|^2$ conjugate to b_T



➡ *Fourier Transform*



Coherent cross-section sensitive to average geometry

- Steepness and the position of first dip depends on density profile, non-linear effects and correlations

H.Mantysaari,B.Schenke PRC 101 (2020) 015203

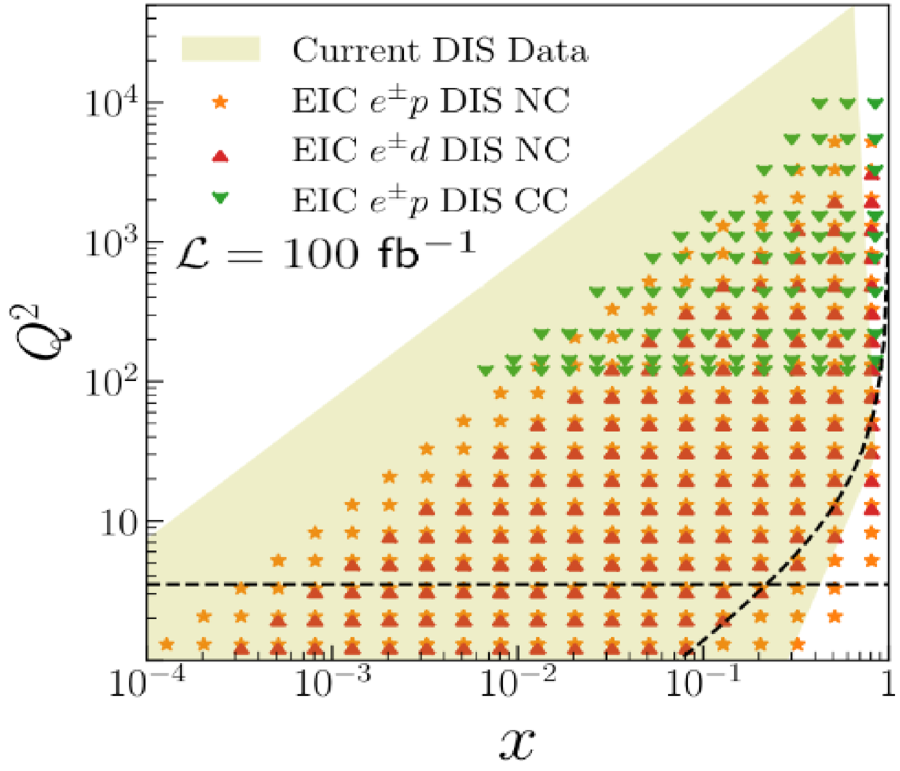
Incoherent cross-section

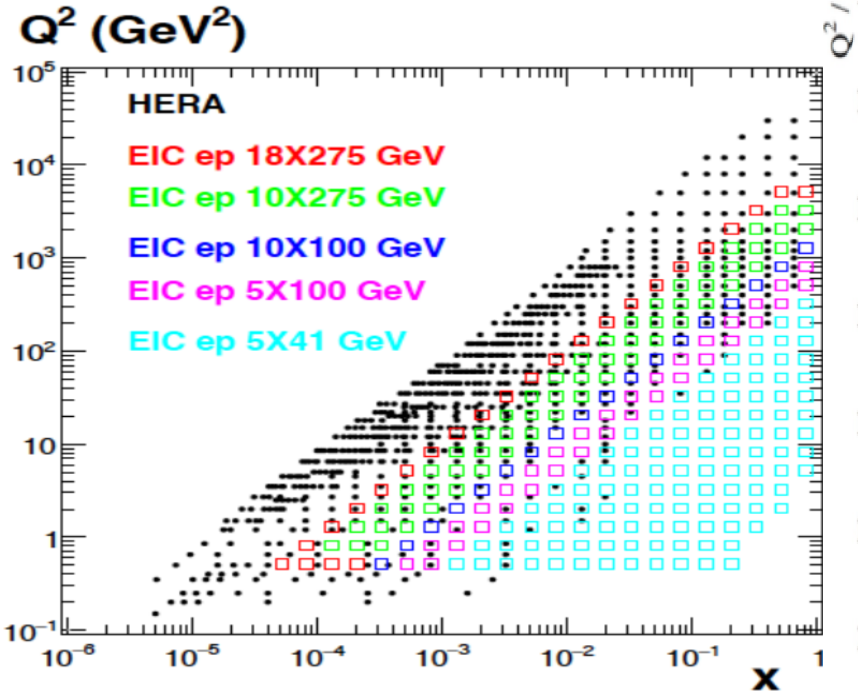
- Shaps in different |t| regions sensitive to deformation of the nucleus

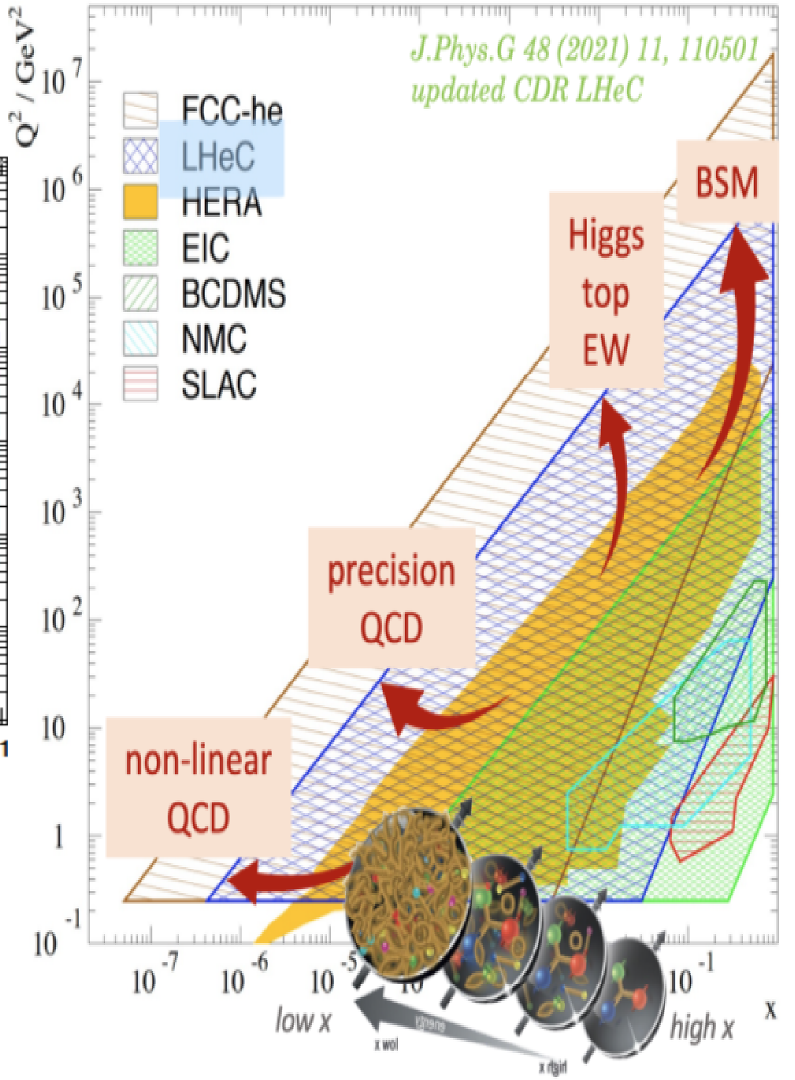
H.Mantysaari et al. 2023

E. Aschenauer

EIC ep, ed coverage in (x, Q^2)







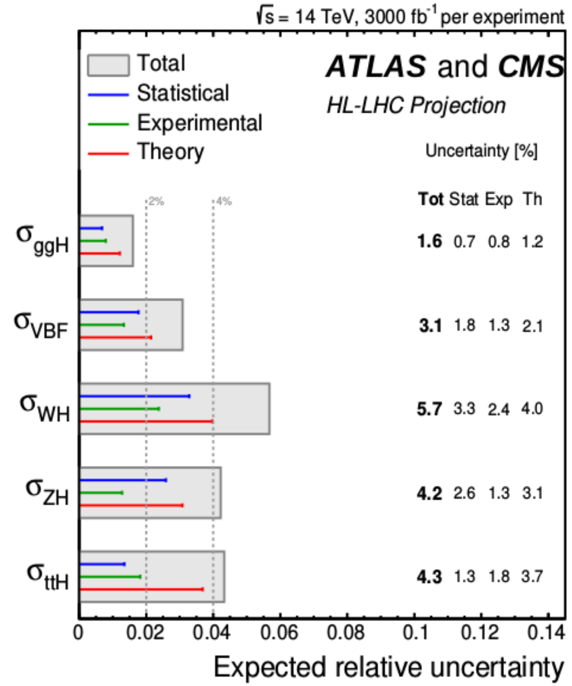
EIC: large x, with precision

LHeC/FCC-he: increased coverage towards smaller x and larger Q^2

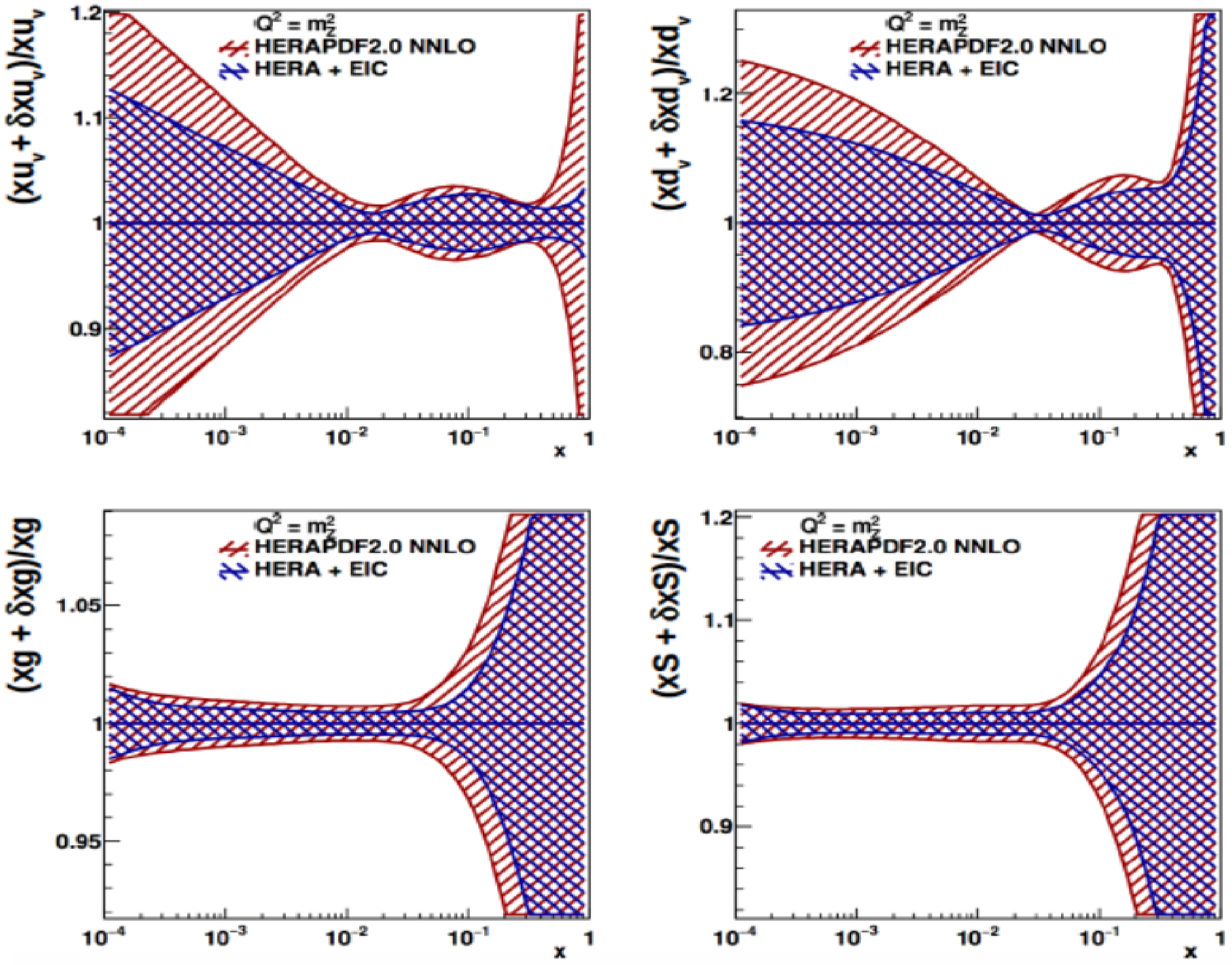
N. Armesto, E. Nocera,
C. Schwanenberger

EIC impact on NNLO pPDFs

For fundamental processes at HL-LHC, currently theory unc. (and in particular PDFs/alphas) dominates the error badget



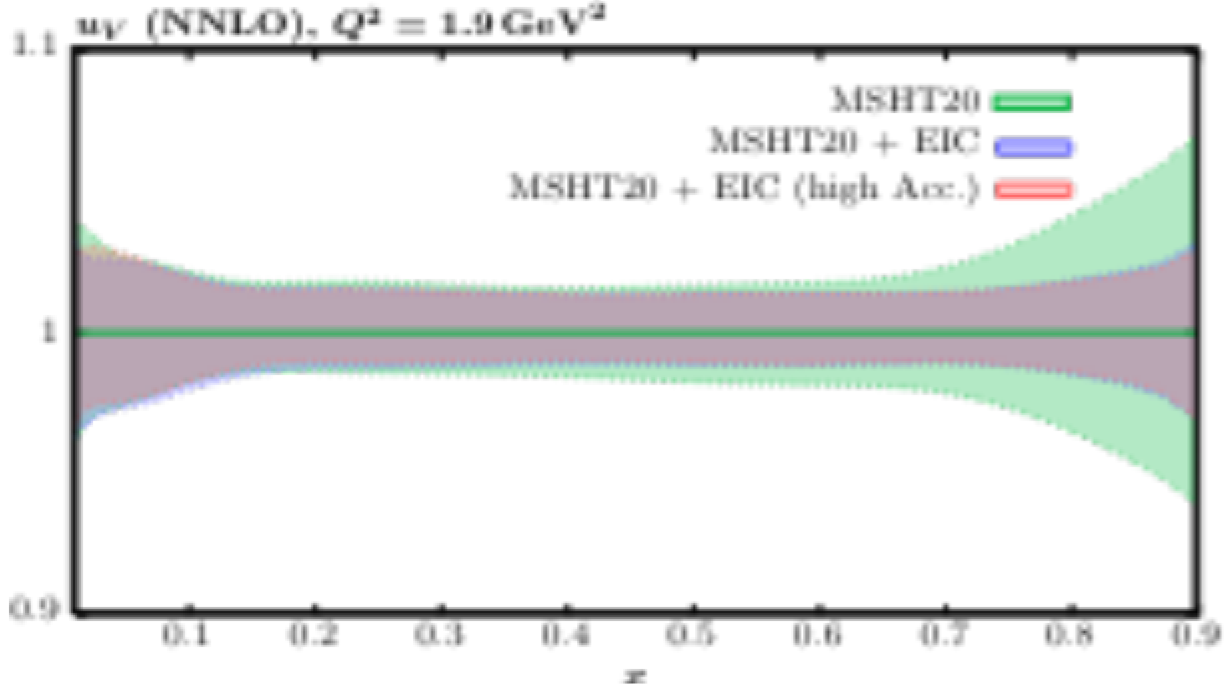
→ PDFs needs better constraints

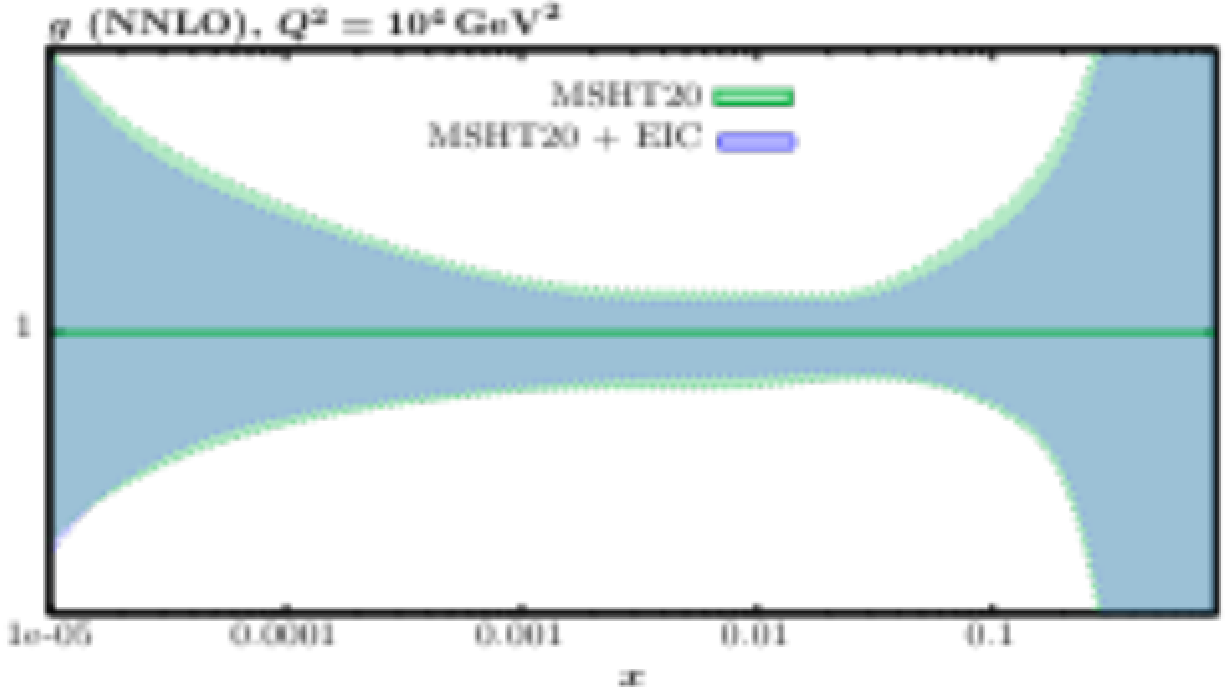


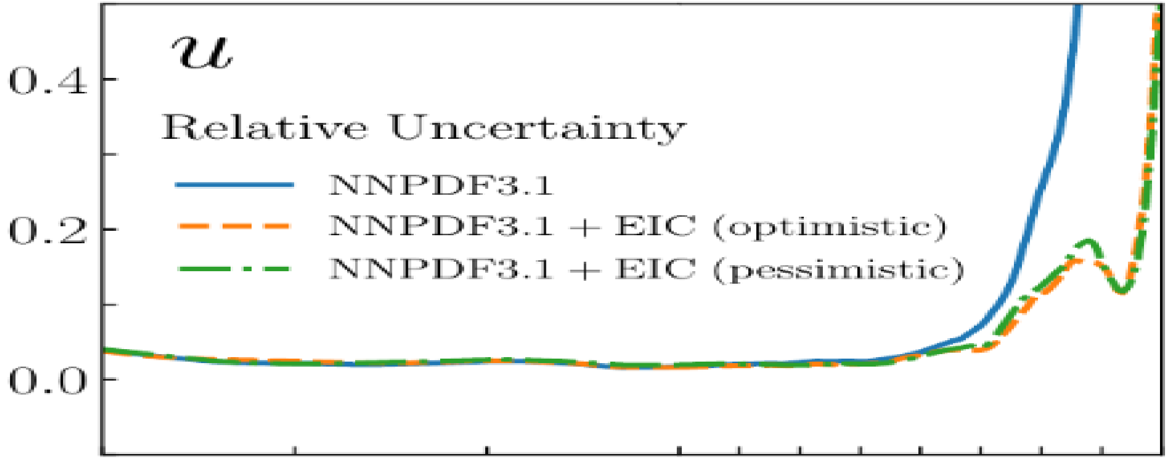
EIC pseudodata: larger impact on quarks than on gluons, but still at all x's

N. Armesto, G. Falcioni, K. Wichmann

EIC impact on NNLO pPDFs



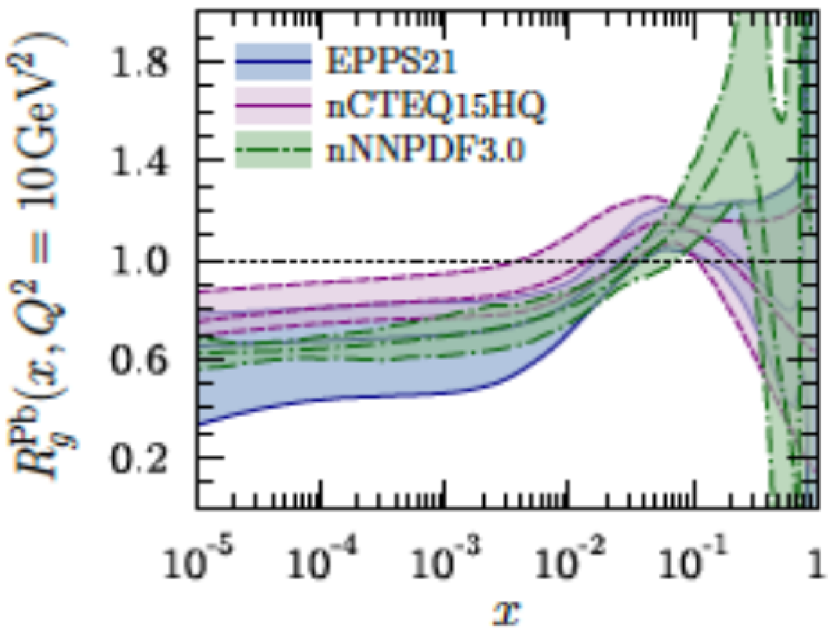


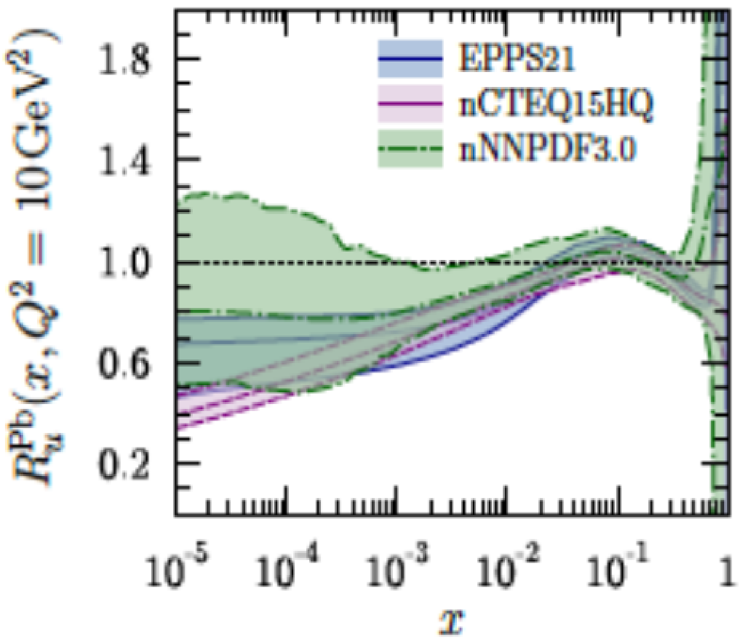


EIC pseudodata: larger impact on quarks than on gluons, but still at all x's

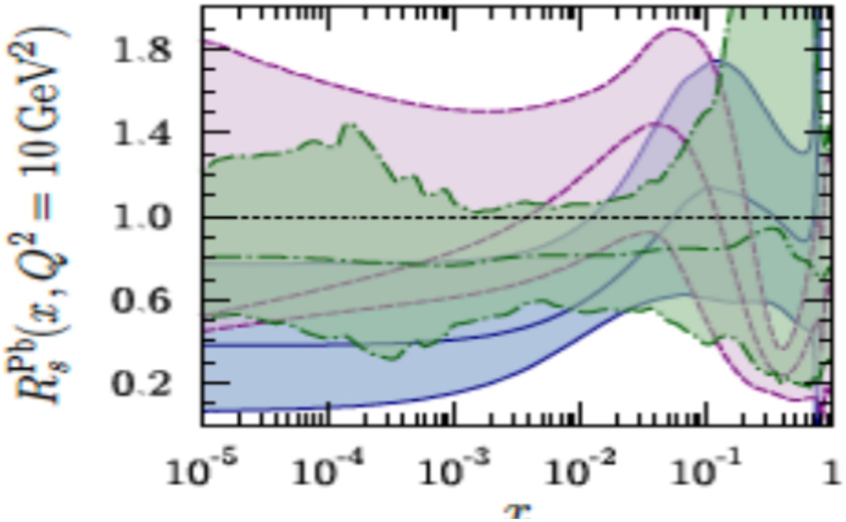
T. Cridge, E. Nocera

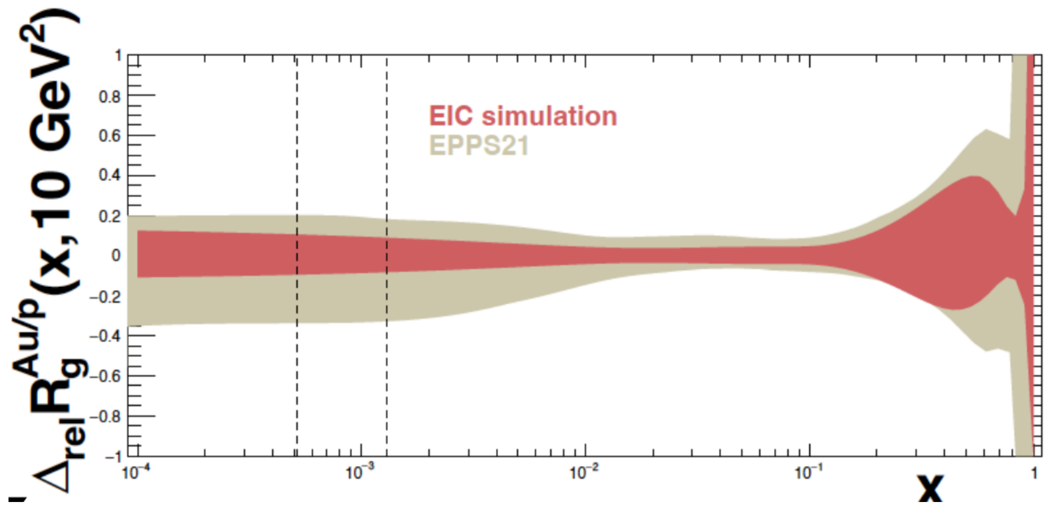
EIC impact on NLO nuclear PDFs





current status nuclear PDFs





EIC pseudodata: larger impact for nuclear PDFs than for pPDF, especially as for gluons

N. Armesto

Open issues towards improved precision/accuracy

How to account for **missing higher-order uncertainty** (theory) ?

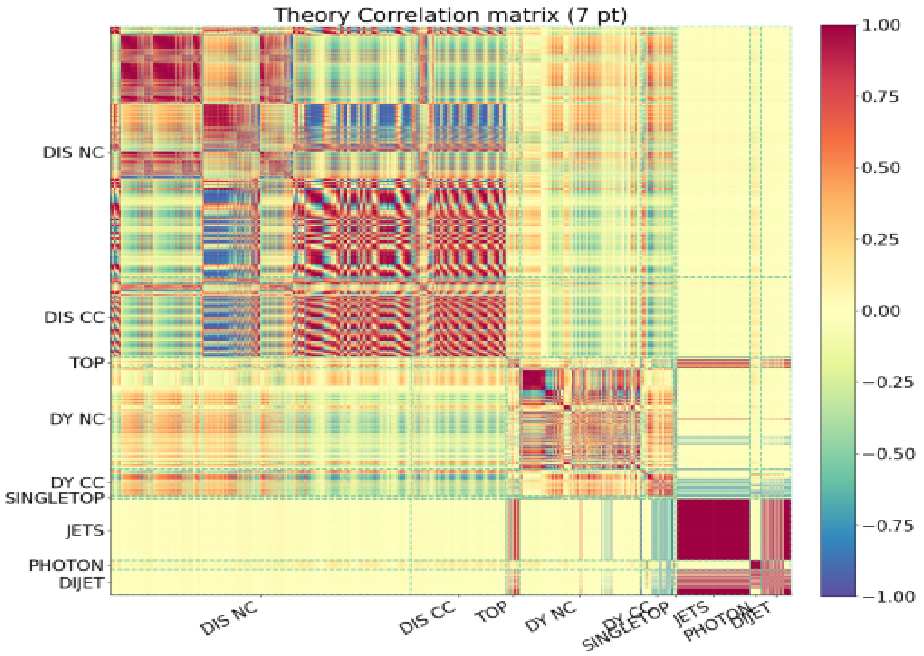
E. Nocera

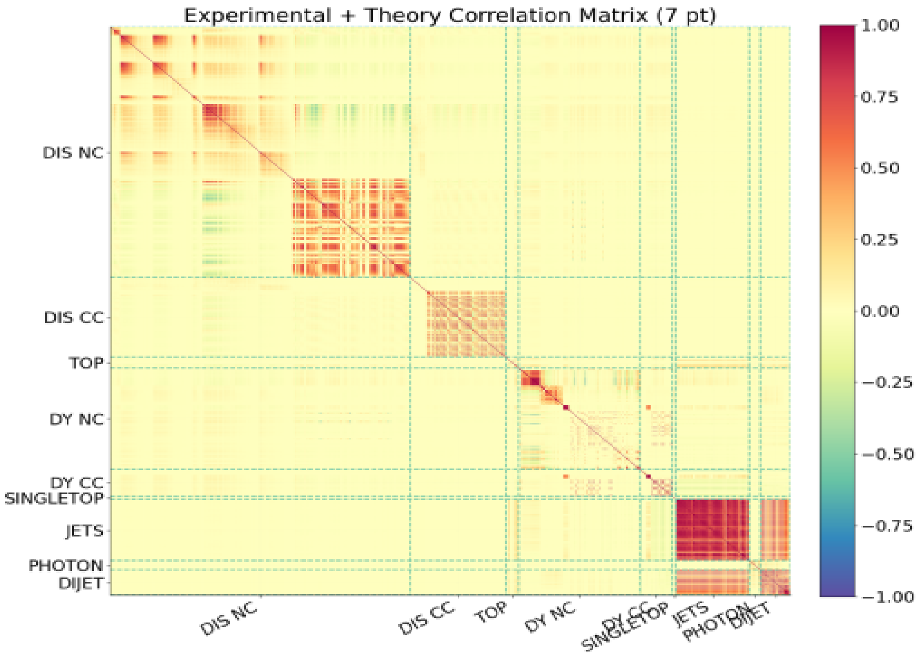
Assuming that theory uncertainties are (a) Gaussian and (b) independent from experimental uncertainties, modify the figure of merit to account for theory errors

$$\chi^2 = \sum_{i,j}^{N_{\rm dat}} (D_i - T_i)(\mathrm{cov}_{\rm exp} + \mathrm{cov}_{\rm th})^{-1}_{ij}(D_j - T_j); \; (\mathrm{cov}_{\rm th})_{ij} = \frac{1}{N}\sum_k^N \Delta_i^{(k)}\Delta_j^{(k)}; \; \Delta_i^{(k)} \equiv T_i^{(k)} - T_i$$

Problem reduced to estimate the th. cov. matrix, *e.g.* in terms of nuisance parameters

$$\Delta_i^{(k)} = T_i(\mu_R, \mu_F) - T_i(\mu_{R,0}, \mu_{F,0}); \text{ vary scales in } \frac{1}{2} \le \frac{\mu_F}{\mu_{F,0}}, \frac{\mu_R}{\mu_{R,0}} \le 2$$





Open issues towards improved precision/accuracy

E. Nocera

*** Missing higher-order uncertainties (at LO, NLO, NNLO,etc......)**

N^3LO QCD corrections in PDF determination

NNLO is the precision frontier for PDF determination

N3LO is the precision frontier for partonic cross sections

Mismatch between perturbative order of partonic cross sections and accuracy of PDFs is becoming a significant source of uncertainty

*** Incomplete higher-order uncertainties**

(from imperfect knowledge of theory at N3LO)

Towards N3LO PDFs

Ingredients: what's needed vs. what's known:

Theory	Utility	Order required	What's known?
1. **Splitting functions** $P_{ab}^{(3)}(x)$	PDF evolution	4-loop	Mellin moments[3–5], leading small-x behaviour[3,6–11], plus some leading large-x in places[3]. *Plus new* [12–15].
2. **Transition matrix elements** $A_{ab,H}^{(3)}(x)$	Transitions between number of flavours in PDFs at mass thresholds	3-loop	Mellin moments[16,17], leading small-x behaviour[18–19], plus some leading large-x in places[19,20]. *Plus new* [21–23].
3. **DIS Coefficient functions** (NC DIS) $C_{H,a}^{VF,(3)}$	Combine with PDFs and Transition Matrix Elements to form Structure Functions (NC DIS)	N3LO	Some approximations to FFNS (low Q^2) coefficient functions at α_S^3 (with exact LL pieces at low x, NLL unknown)[24–26], ZM-VFNS (high Q^2) N3LO coefficient functions known exactly[27]. Therefore GM-VFNS not completely known.
4. **Hadronic Coefficients (K-factors)**	Determine cross-sections at N3LO	N3LO	Very little (none in usable form for PDFs)

T. Cridge, E. Nocera, G.Falcioni, G. Magni

inclusive DIS at 3-loops: diagrams with two masses contribute.
Work in progress on 3-loop calculation of OME entering heavy-flavour part of Wilson coefficients

J. Bluemlein

Towards N3LO PDFs

N^3LO QCD corrections in PDF determination [See also G. Falcioni's talk]

Splitting Functions

Singlet $(P_{qq},\ P_{gg},\ P_{gq},\ P_{qg})$

– large-n_f limit [NPB 915 (2017) 335; arXiv:2308.07958]

– small-x limit [JHEP 06 (2018) 145]

– large-x limit [NPB 832 (2010) 152; JHEP 04 (2020) 018; JHEP 09 (2022) 155]

– 5 (10) lowest Mellin moments [PLB 825 (2022) 136853; ibid. 842 (2023) 137944; ibid. 846 (2023) 138215]

Non-singlet $(P_{NS,v},\ P_{NS,+},\ P_{NS,-})$

– large-n_f limit [NPB 915 (2017) 335; arXiv:2308.07958]

– small-x limit [JHEP 08 (2022) 135]

– large-x limit [JHEP 10 (2017) 041]

– 8 lowest Mellin moments [JHEP 06 (2018) 073]

DIS structure functions $(F_L,\ F_2,\ F_3)$

– DIS NC (massless) [NPB 492 (1997) 338; PLB 606 (2005) 123; NPB 724 (2005) 3]

– DIS CC (massless) [Nucl.Phys.B 813 (2009) 220]

– massive from parametrisation combining known limits and damping functions [NPB 864 (2012) 399]

PDF matching conditions

– all known except for $a^3_{H,g}$ [NPB 820 (2009) 417; NPB 886 (2014) 733; JHEP 12 (2022) 134]

Coefficient functions for other processes

– DY (inclusive) [JHEP 11 (2020) 143]; DY (y differential) [PRL 128 (2022) 052001]

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Towards N3LO PDFs: first N3LO fits

N3LO g(x) vs. NNLO one:

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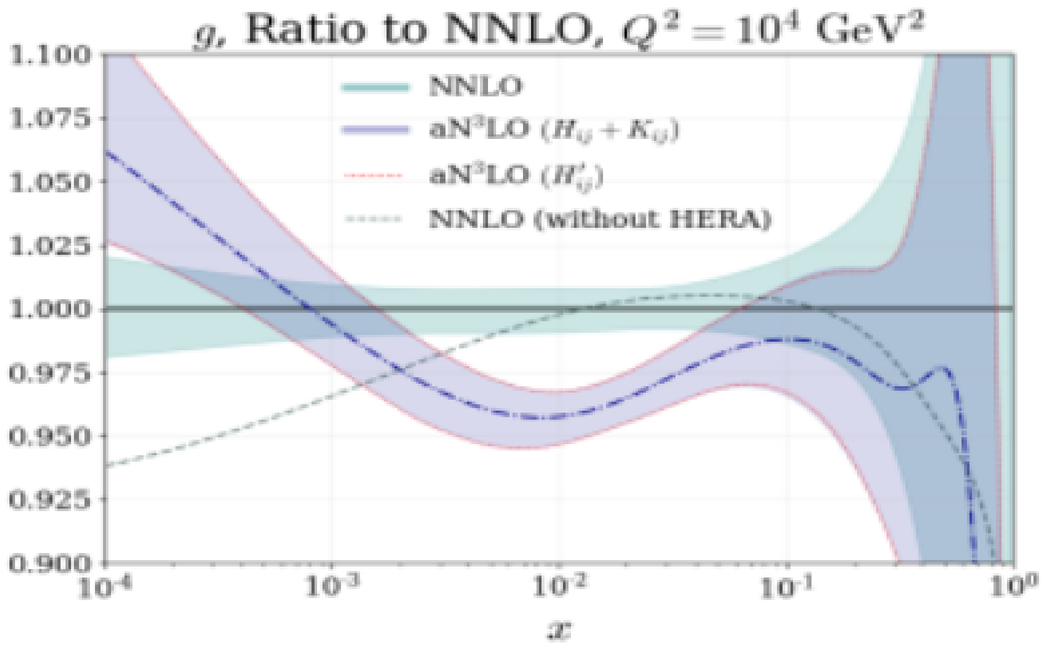

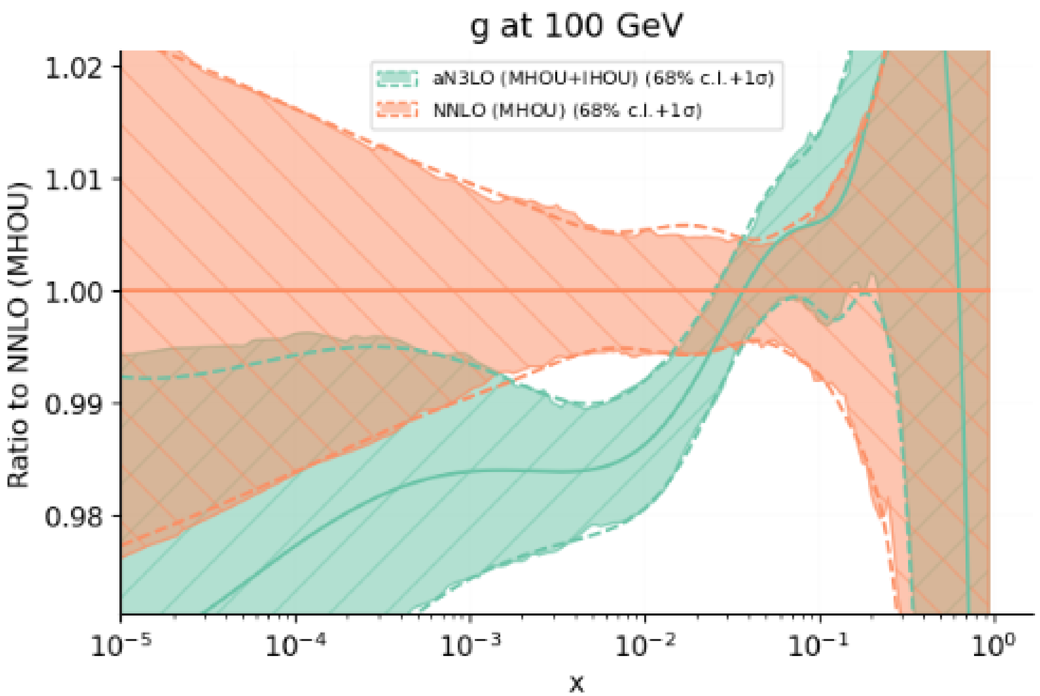

Large urcentainties at low *x* and shape change due to MHOU/IHOW

Towards N3LO PDFs

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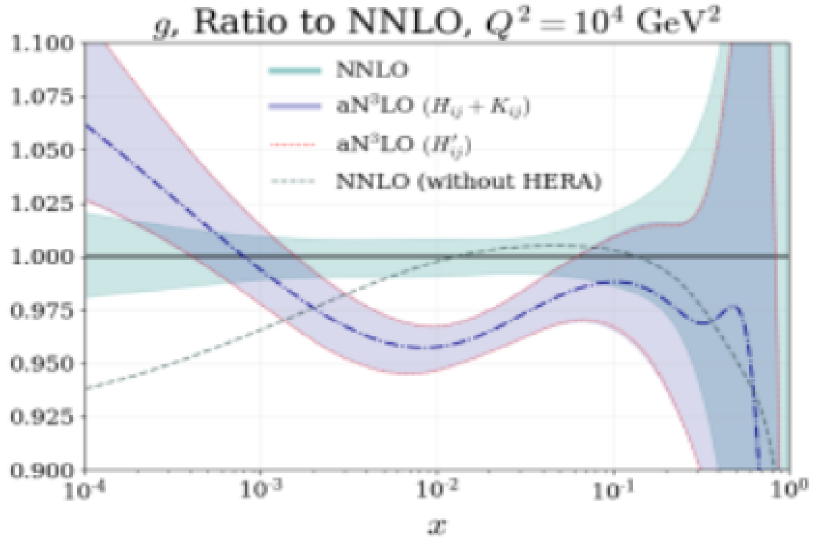
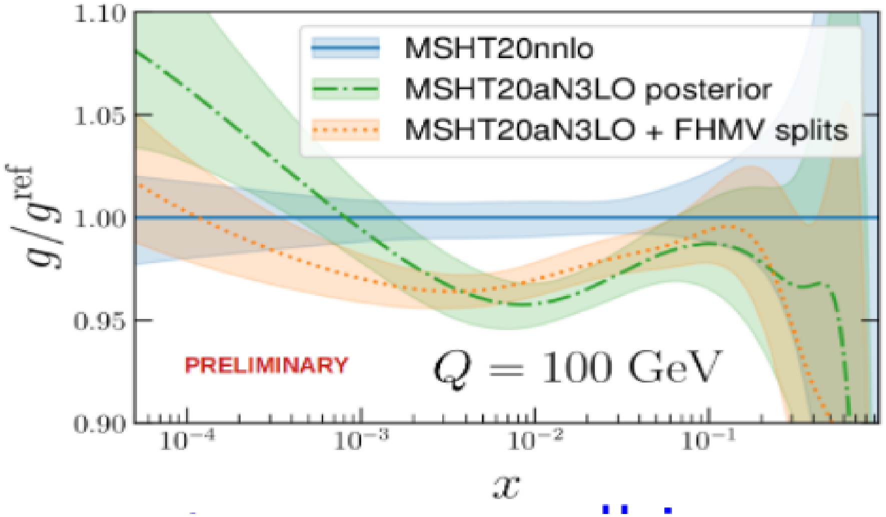
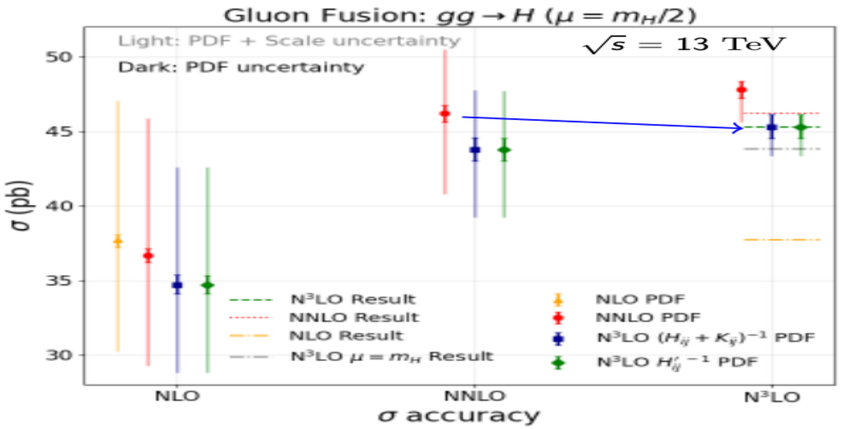
N3LO g vs.
NN



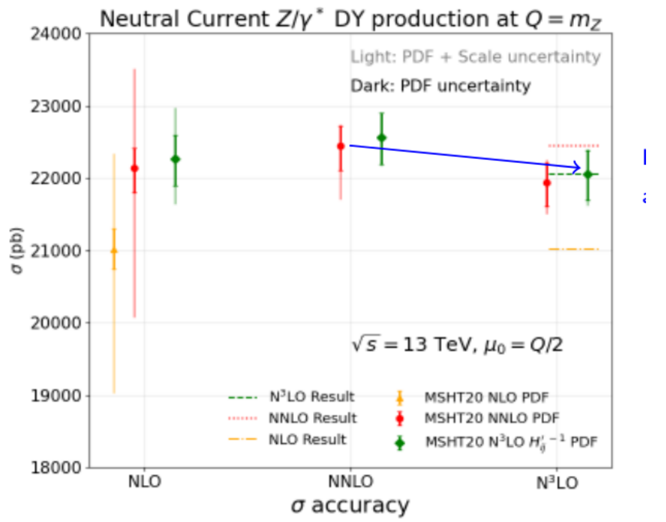
After improved knowledge
of moments of
splitting functions



Impact on phenomenology at the LHC:



Consistent use of
N3LO PDFS with N3LO
partonic cross-section
improves perturbative
stability



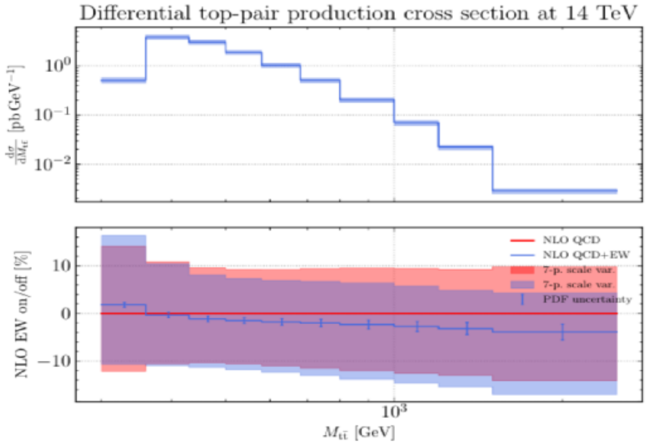
Towards N3LO PDFs: photons & EW effects

$\alpha_{\text{QED}}(M_Z) \sim \alpha_S^2(M_Z)$

Precision studies require the inclusion of photons in the PDFs

NLO K-factors(MSHT20) vs. automated NLO EW corrections (NNPDF)

Need to combine aN3LO QCD evolution and $\mathcal{O}(\alpha, \alpha\alpha_S, \alpha^2)$:



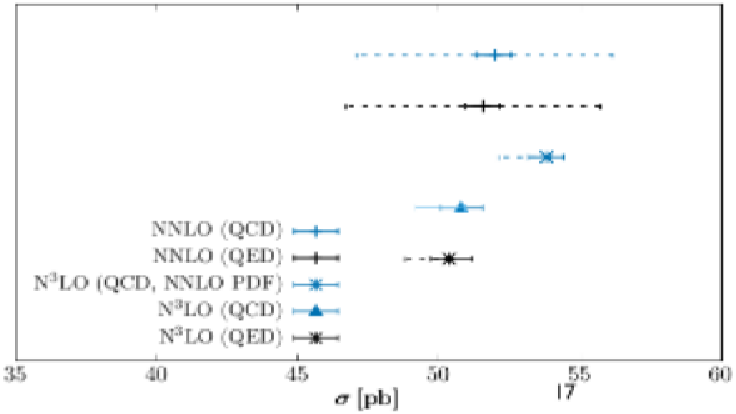
QED $$P_{ij} = \frac{\alpha}{2\pi} P_{ij}^{(0,1)} + \frac{\alpha\alpha_S}{(2\pi)^2} P_{ij}^{(1,1)} + \left(\frac{\alpha}{2\pi}\right)^2 P_{ij}^{(0,2)}$$

NNLO QCD $$+ \frac{\alpha_S}{2\pi} P_{ij}^{(1,0)} + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ij}^{(2,0)} + \left(\frac{\alpha_S}{2\pi}\right)^3 P_{ij}^{(3,0)}$$

aN3LO QCD $$+ \left(\frac{\alpha_S}{2\pi}\right)^4 P_{ij}^{(4,0)} .$$

N3LO and NNLO fit quality improvement after adding QED

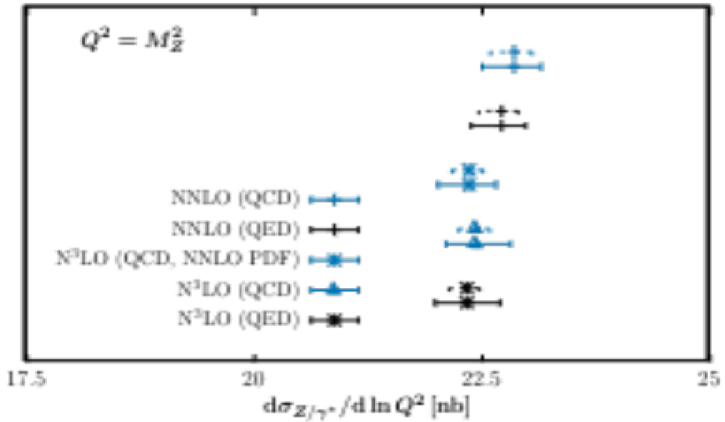
Knock-on impact on cross-sections, ggF Higgs (left), Z (right):



N3LO QCD + NNLO PDFS

N3LO QCD + aN3LO PDFS

N3LO QCD + aN3LO/QED PDFS



T. Cridge, E. Nocera

Summary key-concepts PDFs

Summary

A precise and accurate determination of PDFs is key to do precision phenomenology.

LHC measurements are being instrumental to reduce PDF uncertainties to few percent.

This is not enough. Good complementarity with other planned facilities.

The goal of achieving PDF determinations accurate to 1% opens up some challenges.

Understand the interplay between data, theory, and methodology into PDF uncertainties.

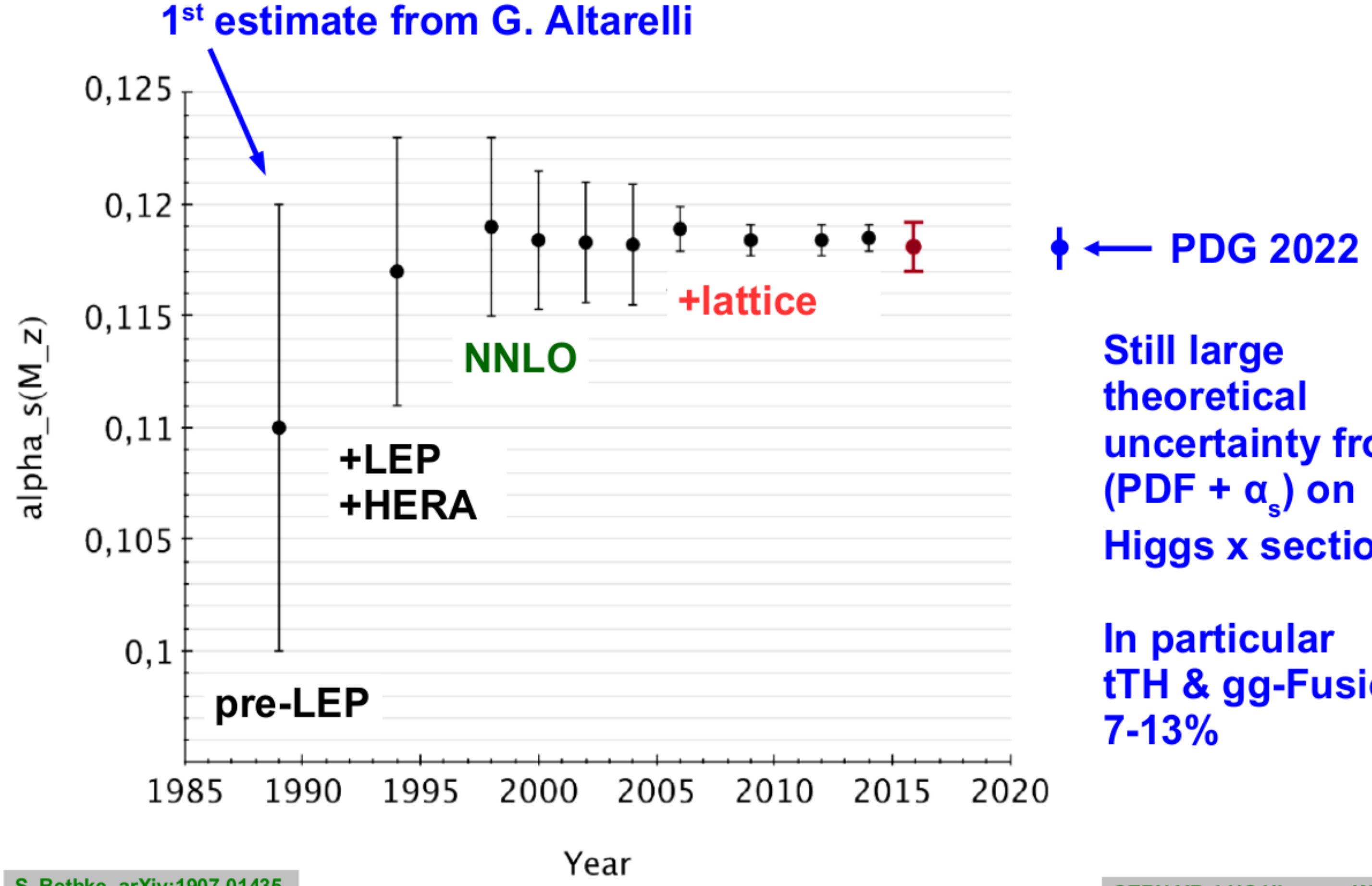
Refine the theoretical accuracy of a PDF determination.

Represent theory uncertainties into PDF uncertainties.

Deploy a robust fitting methodology and good statistical tests of it.

Benchmark efforts may benefit from public releases of PDF codes and inputs.

alpha_s

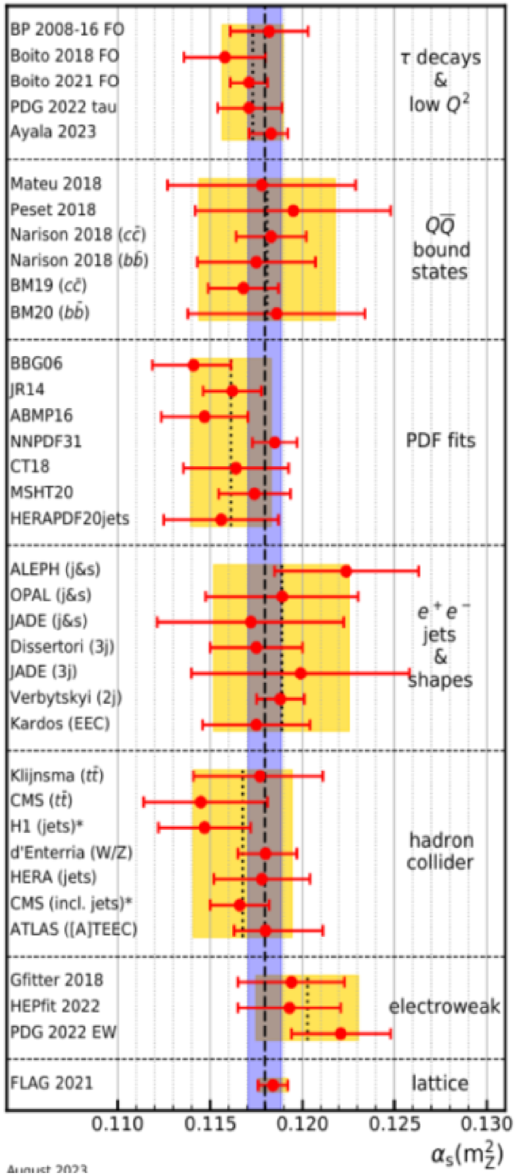


S. Bethke, arXiv:1907.01435.

Still large theoretical uncertainty from (PDF + α_s) on Higgs x sections

In particular tTH & gg-Fusion: 7-13%

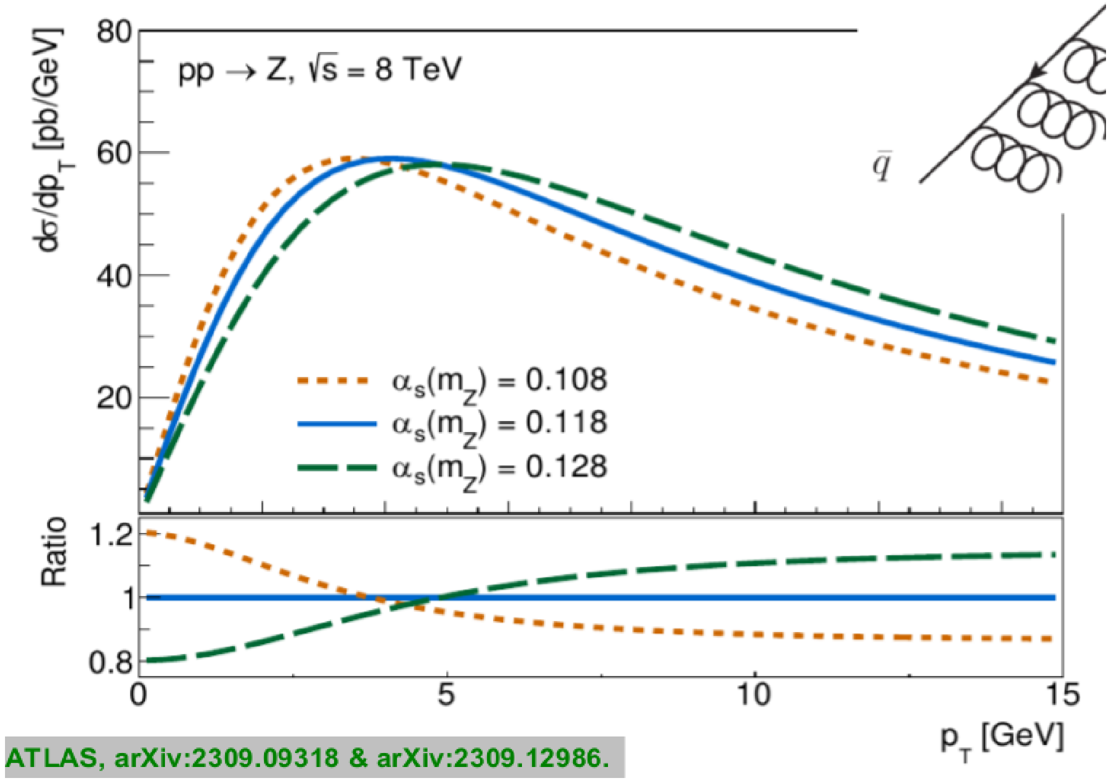
CERN YR, LHC Higgs xs WG.



alpha_s average PDG 2023

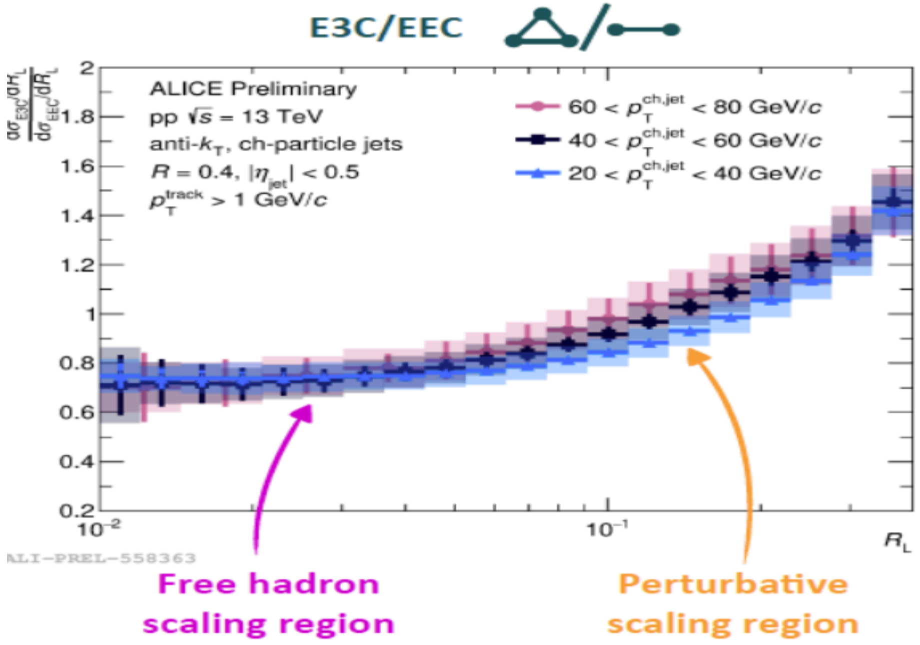
K. Rabbertz, K. Wichmann

New observables with sensitivity to alphas



ATLAS, arXiv:2309.09318 & arXiv:2309.12986.

3-point vs. 2-point energy-energy correlator



Flatter ratio in perturbative region corresponds to smaller alphas

→ **Ratio of E3C/E2C**

$$\propto \alpha_s(Q)\ln R + \mathcal{O}(\alpha_s^2)$$

Peak of the pT distribution of inclusive Z production, due to multiple initial state soft gluon emissions (treated by resummation).

$$\alpha_s(M_Z) = 0.1229^{+0.0040}_{-0.0050}$$

NLO

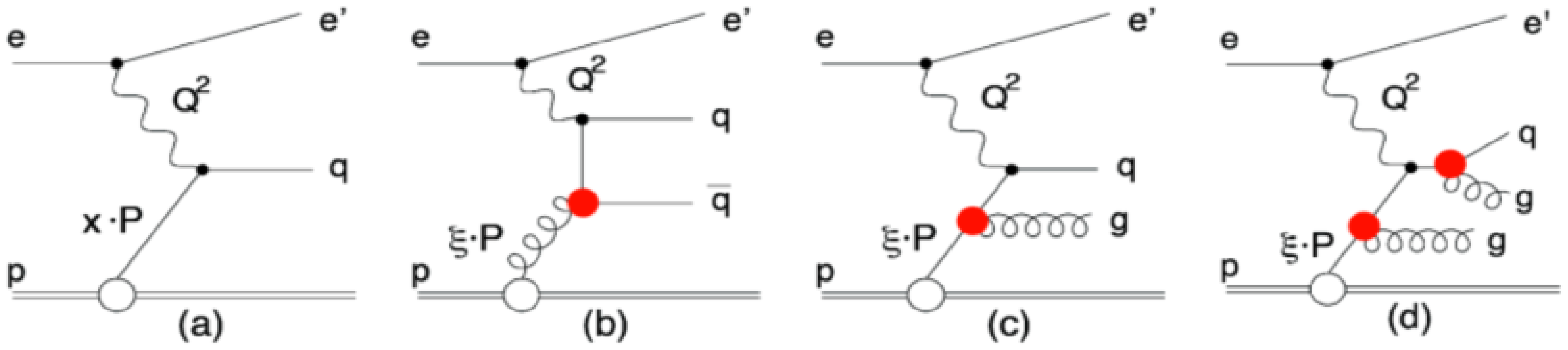
K. Rabbertz, B. Jacak

alpha_s at HERA

At HERA direct information on gluon and $\alpha_s(M_Z)$ comes from jet production

→ Possible simultaneous determination of parton densities and $\alpha_s(M_Z)$

Jets at HERA

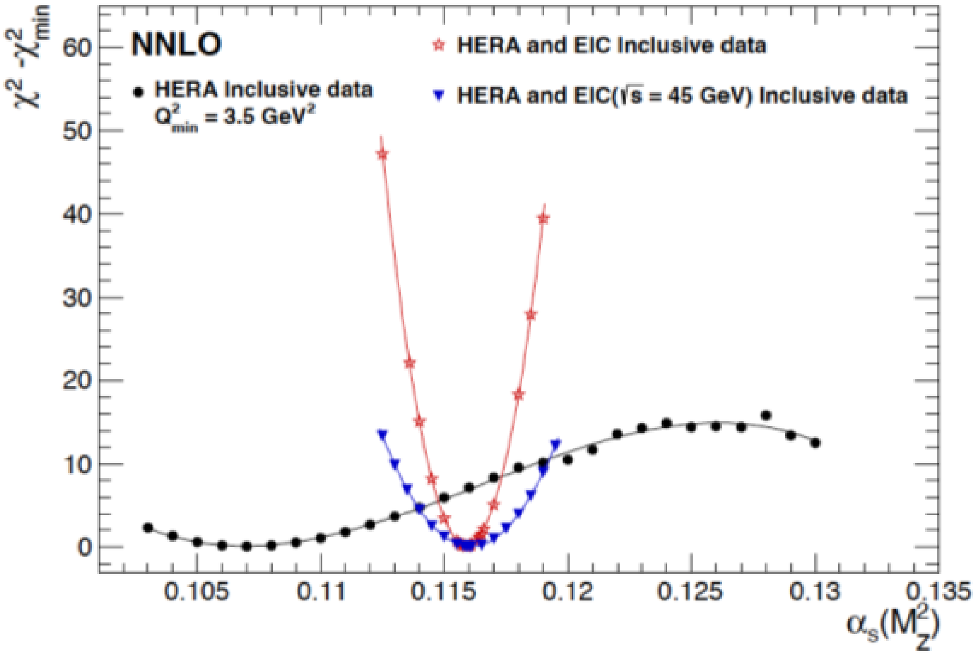


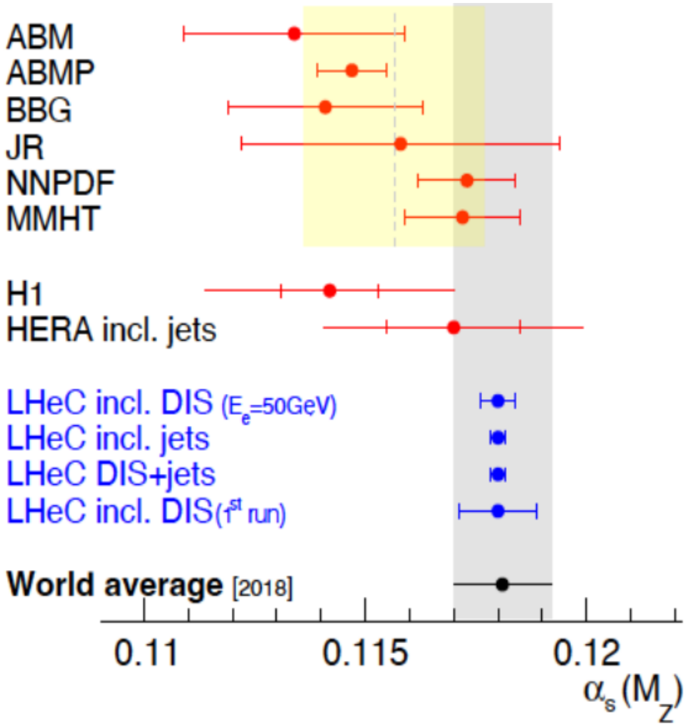
elweak coupling $\propto \alpha_S$ $\propto \alpha_S$ $\propto \alpha_S^2$

dijets trijets

K. Wichmann

alpha_s in ep experiments



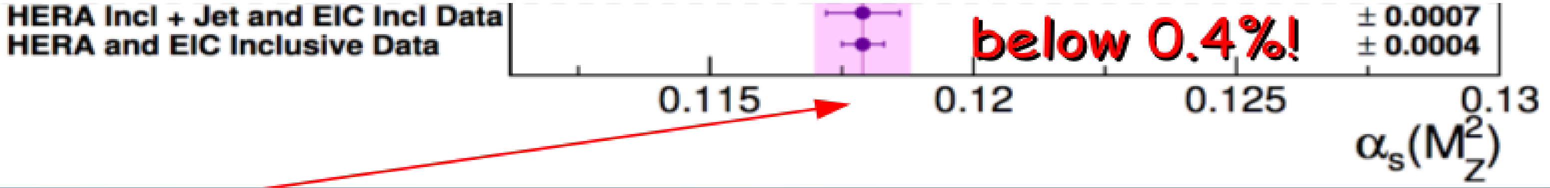


Simultaneous PDF and alphas fit with only inclusive data from HERA and EIC.

HERAPDF inclusive DIS data do not play a big role on alpha_S (jet production works much better). However, combining with EIC can decrease the present uncertainties on alphas by a factor ~5.

LheC can do comparably or even better

K. Rabbertz, N. Armesto,
C. Schwanenberger, K. Wichmann



alpha_s: summary

(4) DIS & PDF fits	1.7% $N^{2,(3)}$LO PDF (SF) fits Span of PDF-based results	$\approx$ 1% (0.2%) N^3LO fits. Add new SF fits: $F_2^{p,d}$, g_i (EIC) Better corr. matrices. More PDF data (LHeC/FCC-eh)

- LHC results reached $\Delta\alpha_s(M_Z)$ ~ 0.5% experimentally
- LHC theory uncertainty still leads to $\Delta\alpha_s(M_Z)$ ~ 1.5% in total (except one)
- Theory at full N3LO desperately needed
- Lattice gauge reached $\Delta\alpha_s(M_Z)$ ~ 0.6%, has potential for permille level
- With N3LO great potential for $\Delta\alpha_s(M_Z)$ < 0.5% from DIS, structure functions and jets at EIC (& LHeC)

K. Rabbertz, K. Wichmann

Energy-energy correlators

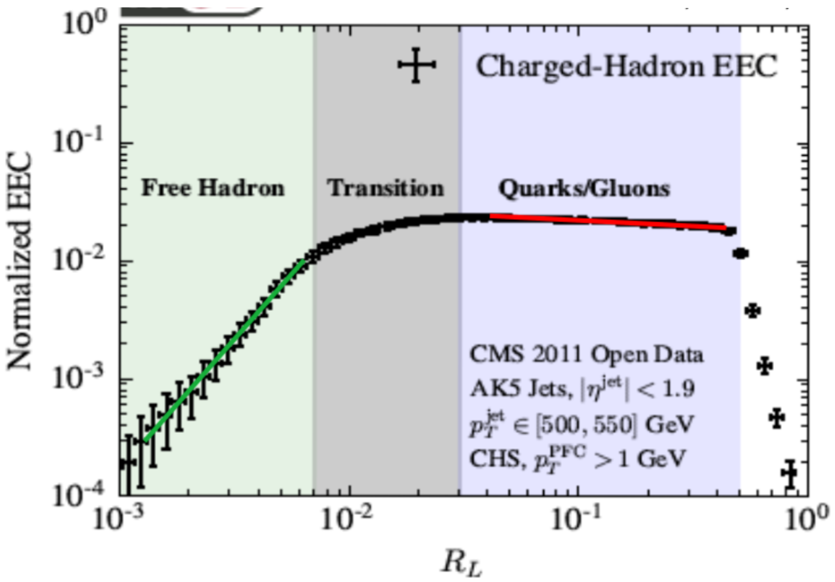
$$EEC(R_L) = \sum_{pairs} \frac{p_{T1}\, p_{T2}}{p_{T,jet}^2} \text{ with } R_L = \sqrt[2]{\Delta\varphi^2 + \Delta\eta^2}$$

experimental definition

Energy-Energy correlators considering **all particles** of an event have first been proposed in 1978

They have been studied at LEP

More recently, EEC for **particles in jets**



$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j}),$$

$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k})).$$

EEC allow to separate scales
(hadron interactions/hadronization/parton splitting
and probe hadronization

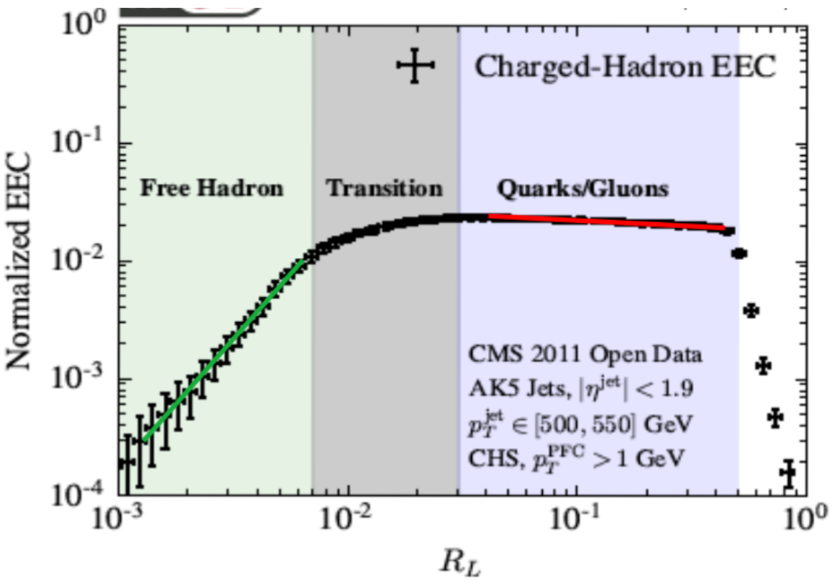
Deviation data from pQCD predictions (NLL):
onset on non-perturbative regime

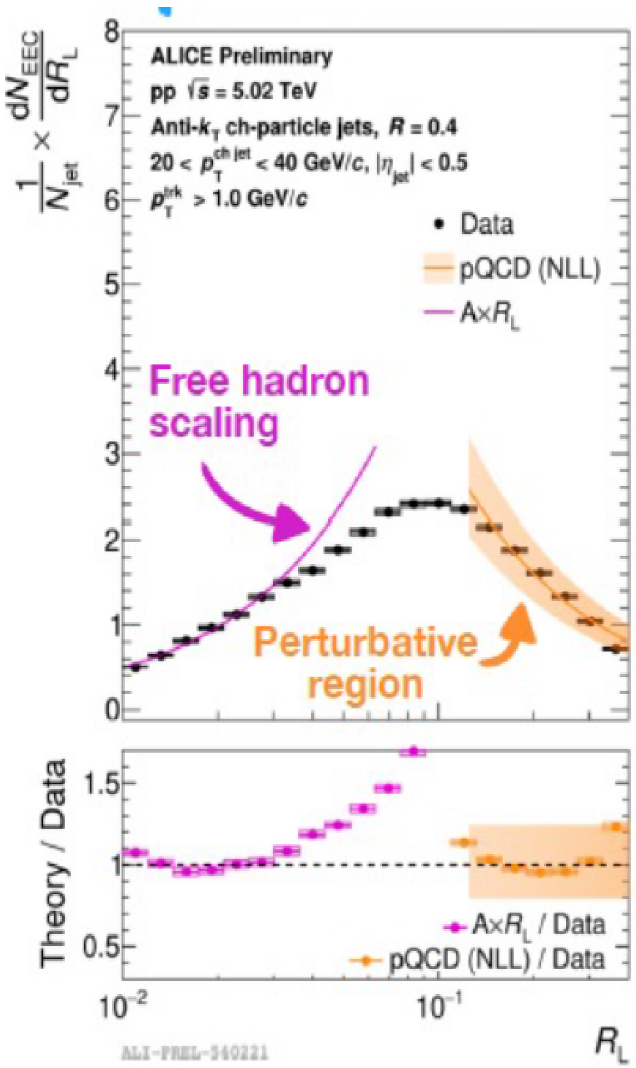
B. Jacak, L. Cunqueiro

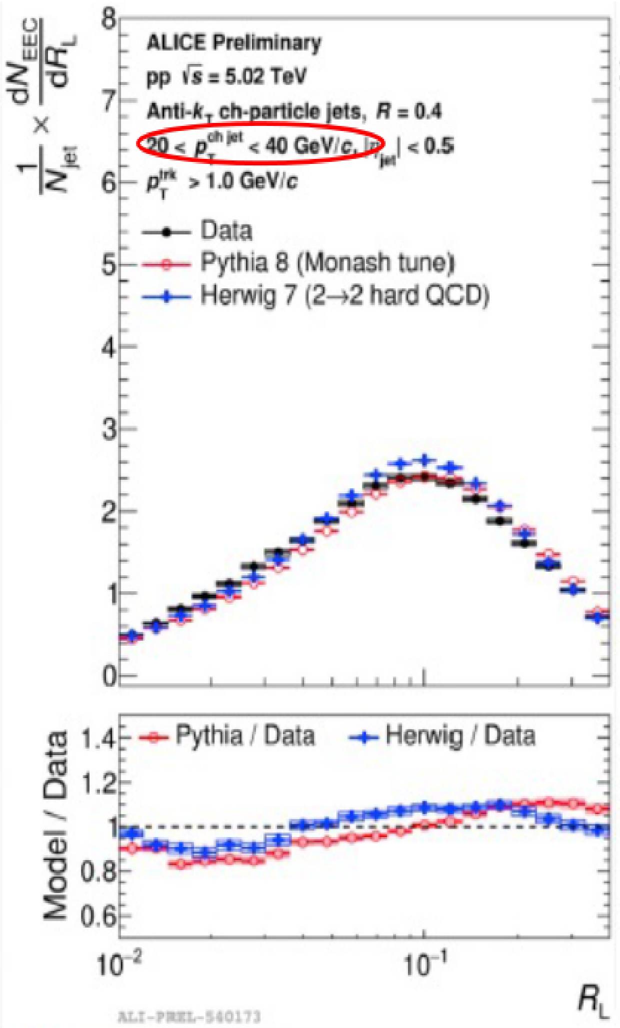
Energy-energy correlators

B. Jacak

EEC for **particles in jets**







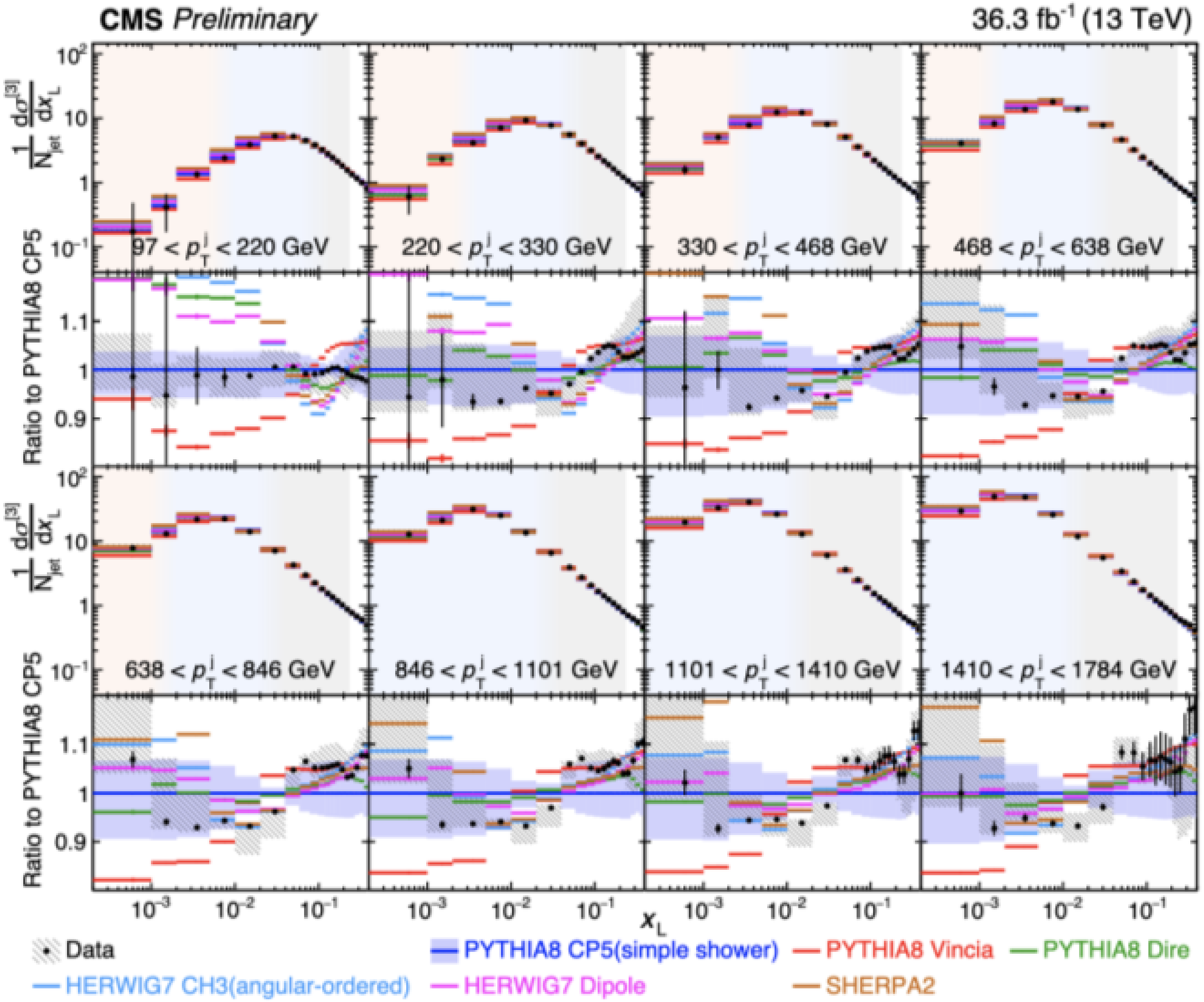
EEC allow to separate scales (hadron interactions/hadronization/parton splitting and probe hadronization

Deviation data from pQCD predictions (NLL): onset on non-perturbative regime

HERWIG vs. PYTHIA

Three-point energy-energy correlator (E3C)

L. Cunqueiro

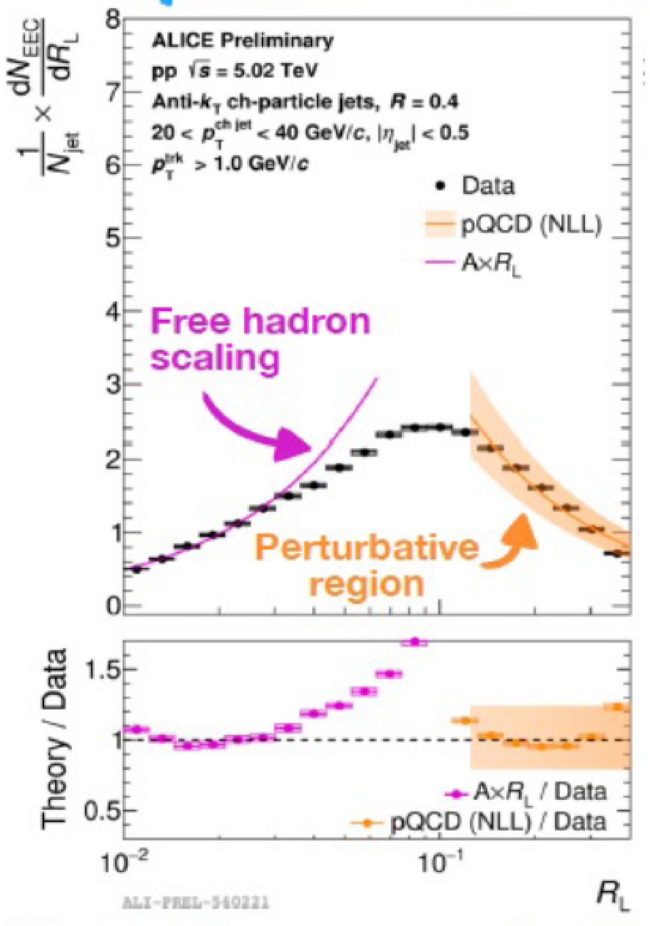


Measurement is not reproduced by any Monte Carlo,
discrepancies especially
in the non-perturbative region

HERWIG vs. PYTHIA vs. SHERPA

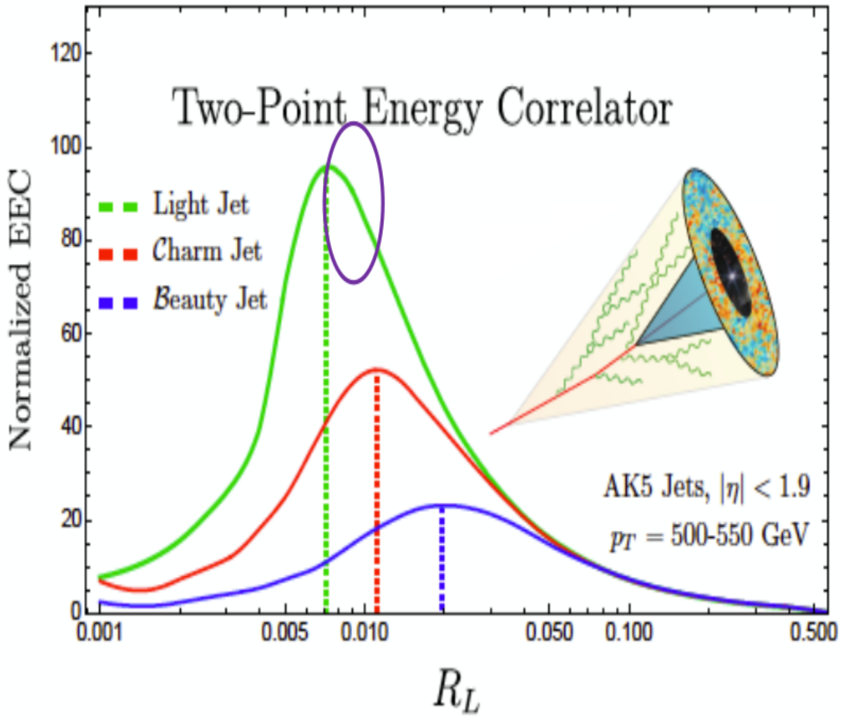
EEC in jets: heavy-flavoured jets (vacuum)

EEC for **light jets**

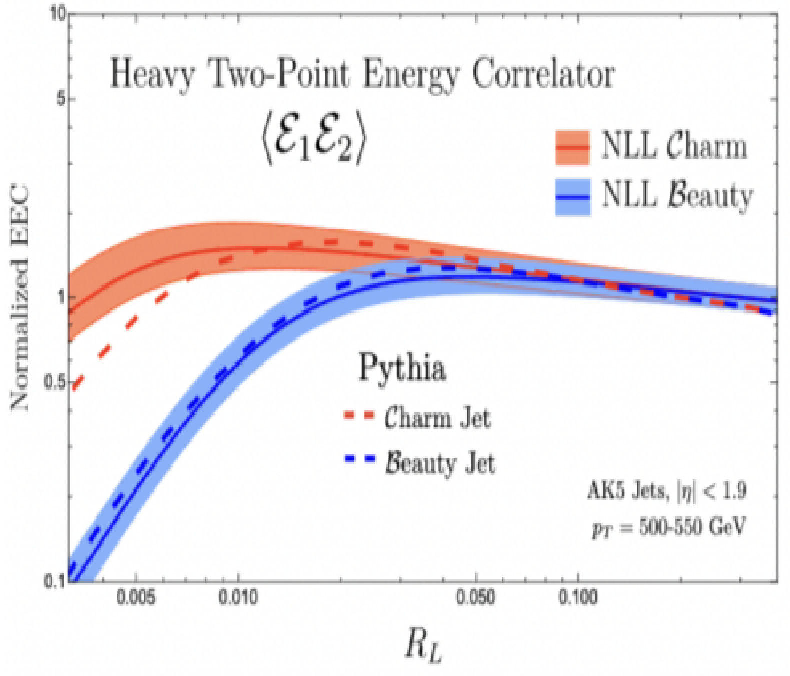


EEC for **heavy-flavoured** vs. light jets

Craft, Lee, Mecaj, Moult arXiv:2210.09311



Dead-cone effect for heavy flavoured jets



Calculations of EEC for heavy-flavoured jets: NLL vs. PYTHIA

Deviation data from pQCD predictions (NLL): onset on non-perturbative regime

B. Jacak, L. Cunqueiro

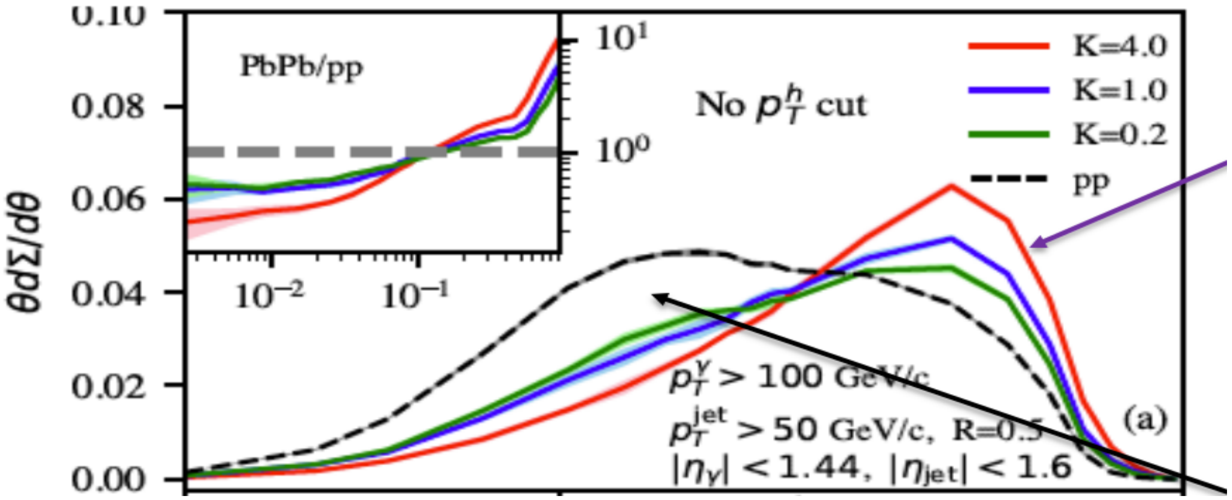
EEC in jets: medium modifications

During jet propagation in QGP matter:

- **Collisions in plasma induce more gluon splitting**
- **Jet deposits some energy into the QGP**

Early studies showed that medium-induced gluon radiation is expected to fill the dead cone
Armesto, Salgado, Wiedemann, Phys.Rev.D 69 (2004) 114003

Yang, He, Moult, Wang arXiv:2310.01500



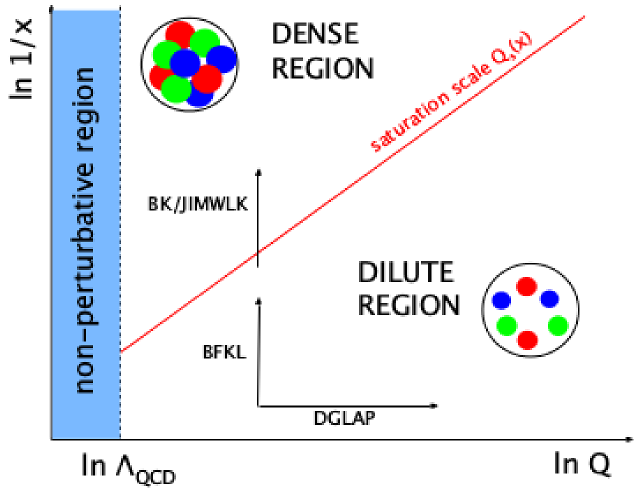
Medium induced splittings
pT broadening of Jet
Energy loess

Besides LHC, EEC can be studied for *eA* DIS at EIC and even saturation effects might lead to imprints on them: suppression at small angle.

B. Jacak, L. Cunqueiro

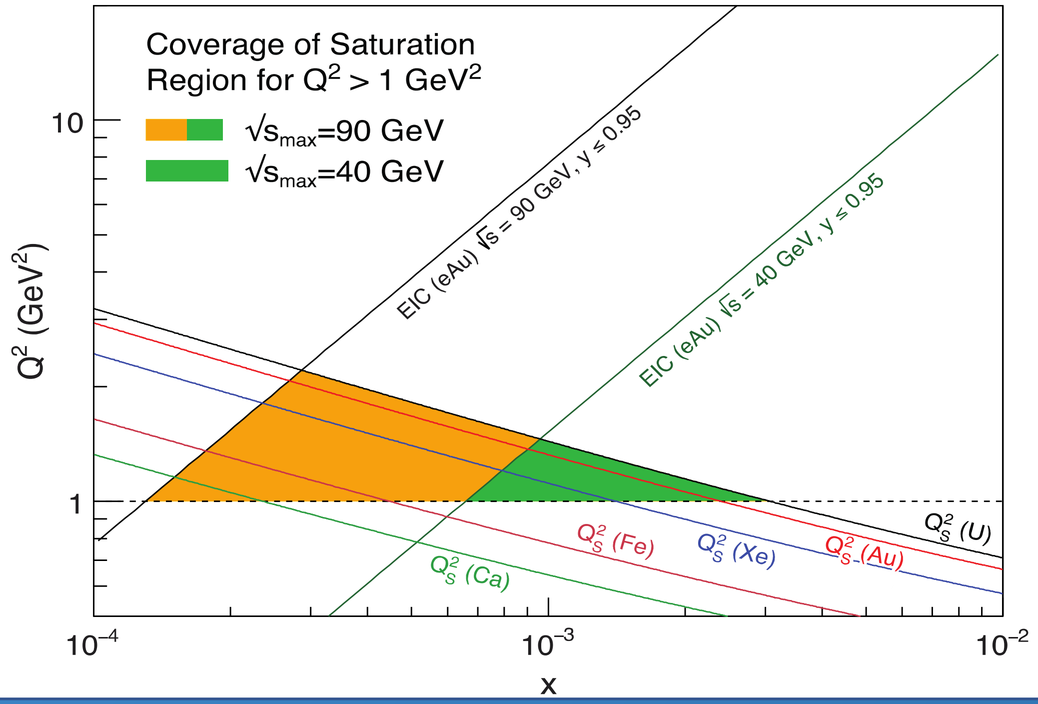
Non-linear effects in nuclei

Enhancement of Q_S with A ⇒ non-linear QCD regime reached
at significantly lower √s in nuclei than in proton



EIC can map the transition
from a linear to a non-linear QCD regime:
evolution of Q_s with x

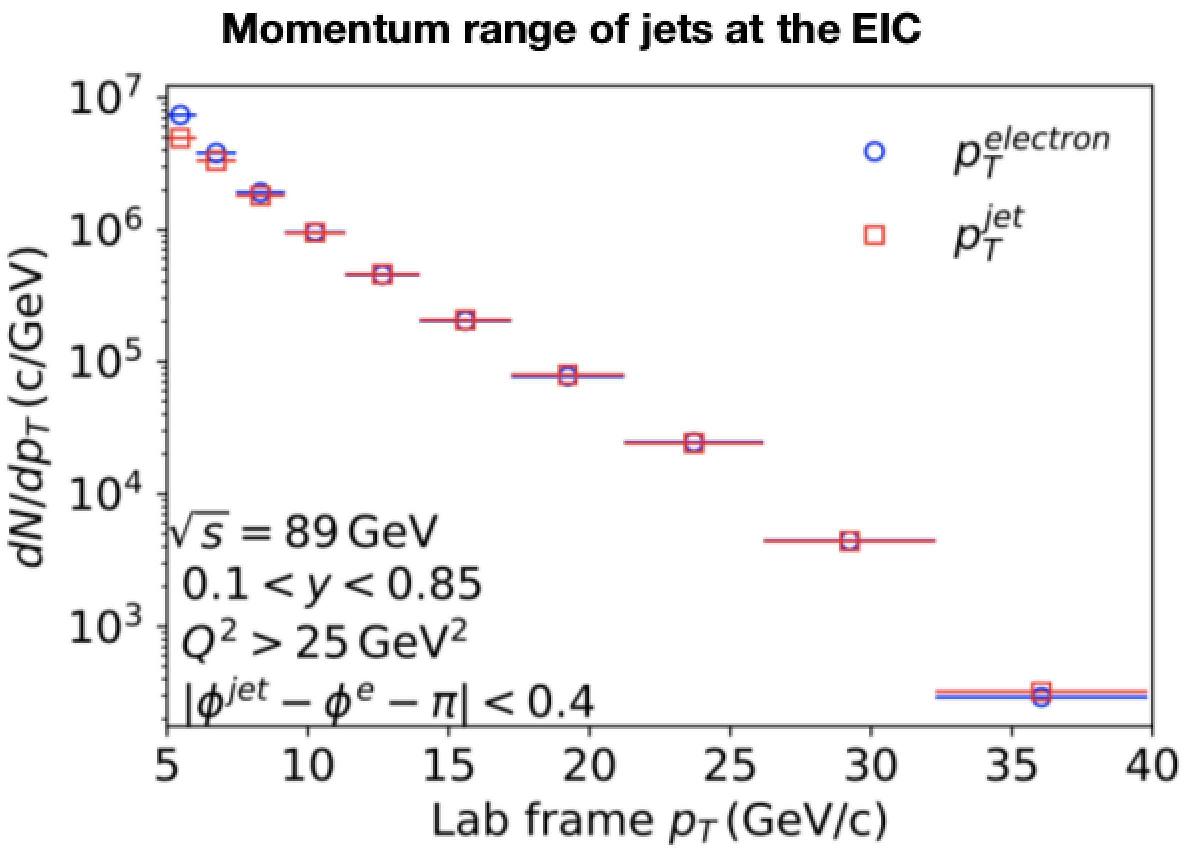
Study of dihadron/dijet production in eA



E. Aschenauer,
K. Kutak

Jets at the EIC: medium modifications

Small pT for jets, of the order of 10-20 GeV

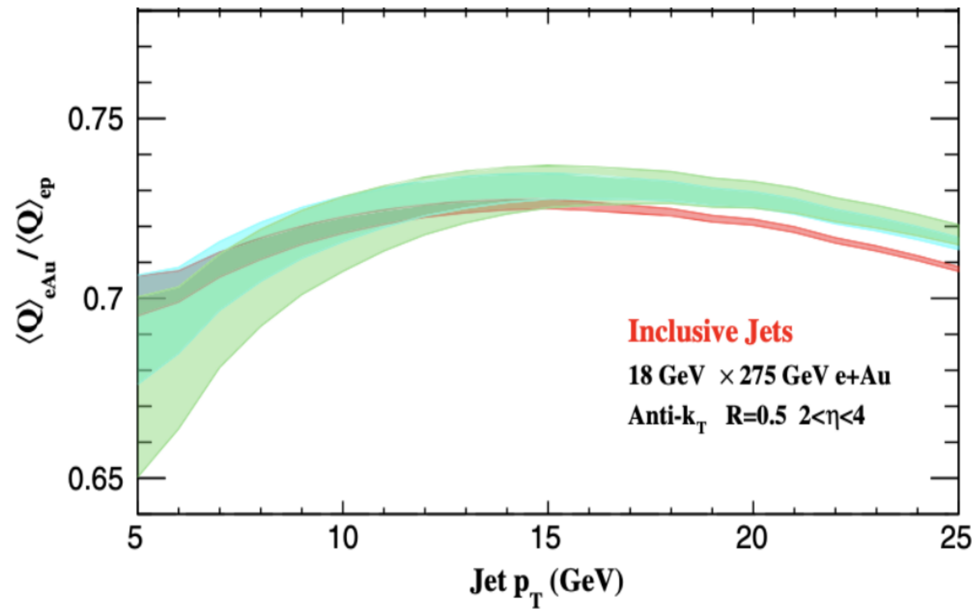


Jet Charge

(p_T weighted sum of the charges of the jet constituents)

$$Q_{\kappa,\text{jet}} = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_{i \in \text{jet}} Q_i (p_T^i)^\kappa$$

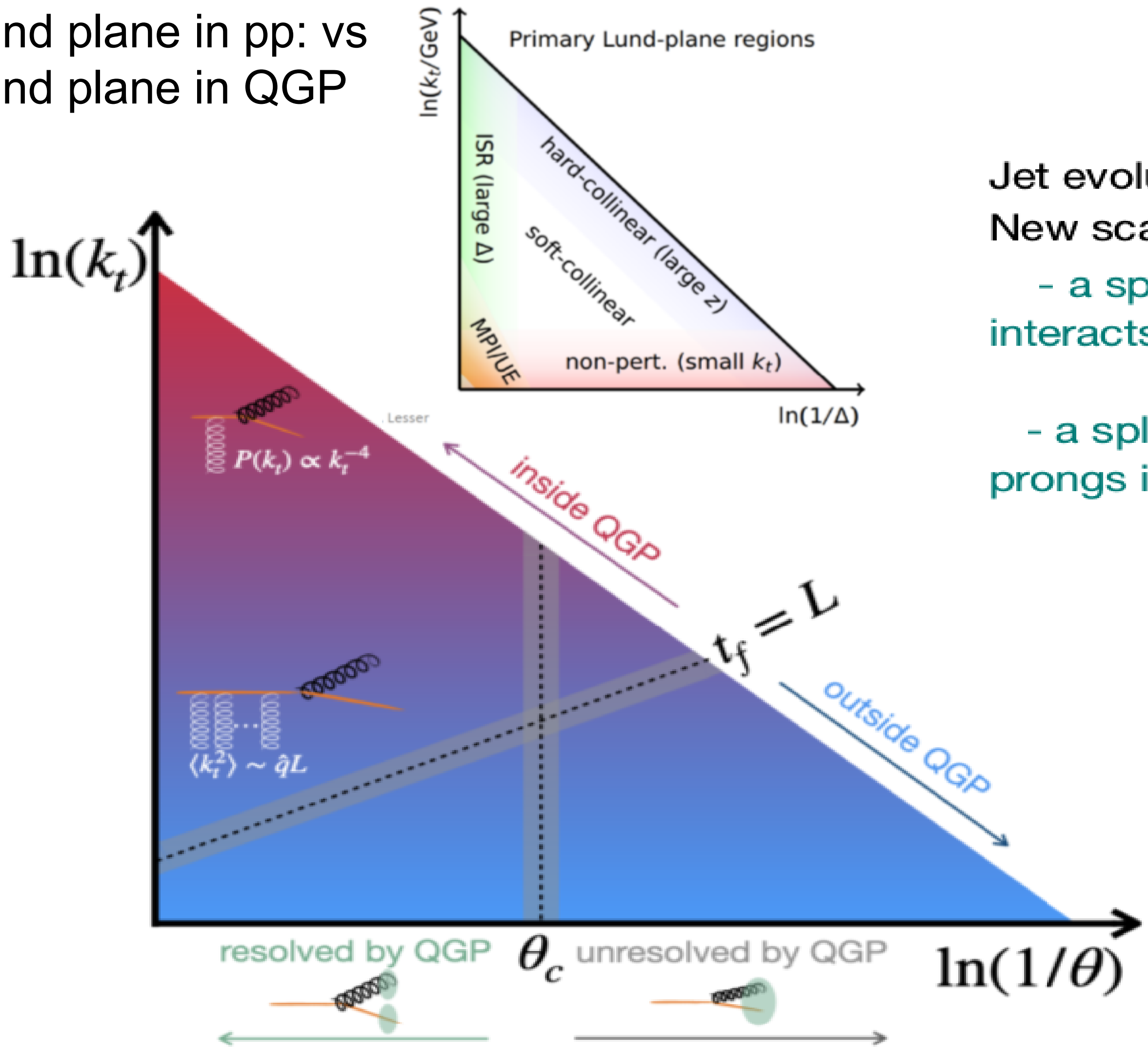
≈10% suppression of the jet charge for large K values in eAu relative to ep due to final state interaction



L. Cunqueiro

jet evolution/interaction (branching) in medium: Lund plane

Lund plane in pp: vs Lund plane in QGP



Jet evolution is embedded in a hot and dense medium of length L

New scale: decoherence angle θ_C

- a splitting with angle $\theta < \theta_C$ is not resolved by the QGP and interacts with it as a single color charge

- a splitting with angle $\theta > \theta_C$ is resolved by the QGP and the prongs interact with it incoherently

→ the way a jet interacts with the QGP depends on its substructure

At LO the Lund plane is not filled uniformly as in vacuum

Strategies to isolate and characterize QGP-induced signal and map it to the microscopic properties of the QGP

L. Cunqueiro

Summary: jet physics at EIC

Jets have several properties which will make them important tools for realizing the EIC physics program

The importance of jet probes was reflected in the EIC Yellow Report where they touched on nearly every major physics topic (Nucl. Phys. A, Vol 1026, 122447)

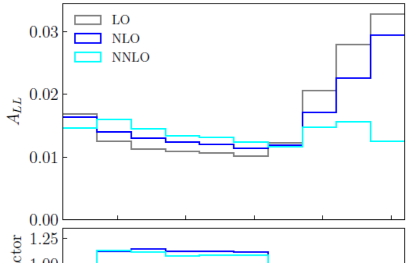
- Well understood theoretically and experimentally
- Excellent proxies for the underlying parton kinematics
- Showers probe QCD from hard interaction to hadronization scale within the same event – can explore dynamics at different time (angular) scales
- Precision tools exist to probe these shower properties - substructure

Global properties and parton structure of hadrons

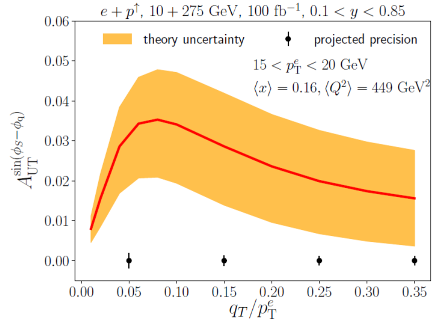
Multi-dimensional imaging of nucleons, nuclei and mesons

The nucleus: a laboratory for QCD

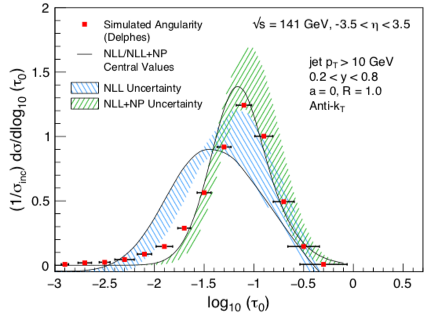
Understanding hadronization



Borsa, de Florian, Pedron '20



Arratia, Kang, Prokudin, Ringer '20



J. Adam *et al* 2022 *JINST* 17 P10019

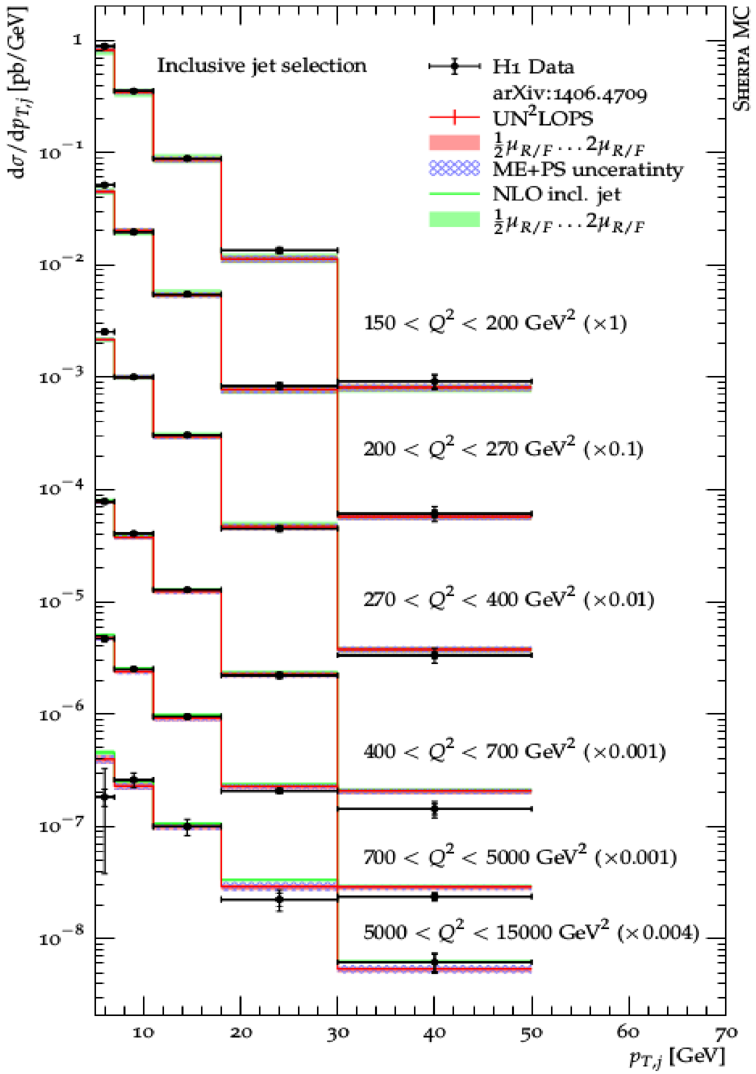
E. Aschenhauer

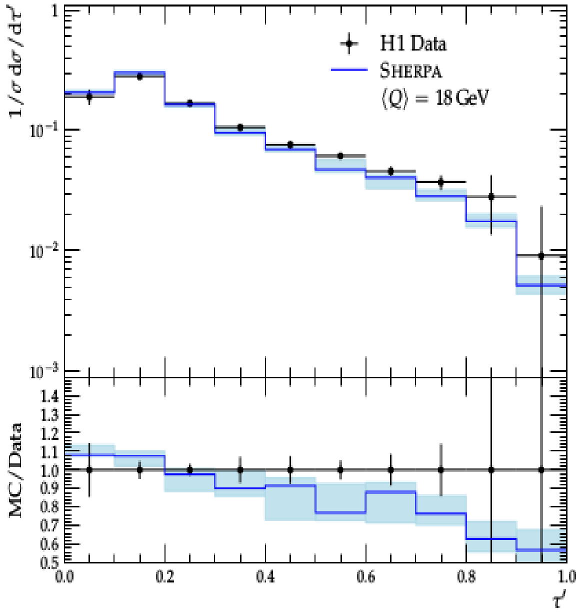
34

Event generators: NLO matching and merging

NLO matching to PS

- matching to NLO QCD, 2 main schemes: Powheg [Nason '04] and MC@NLO [Frixione, Webber '02]
- concepts in general not collider dependent, but some recent DIS specific studies [Banfi, Ravasio, Jäger, Karlberg, Reichenbach '23], [Knobbe, DR, Schumann '23]





Towards NNLO matching

Matching to NNLO (inclusive for some processes) in principle available

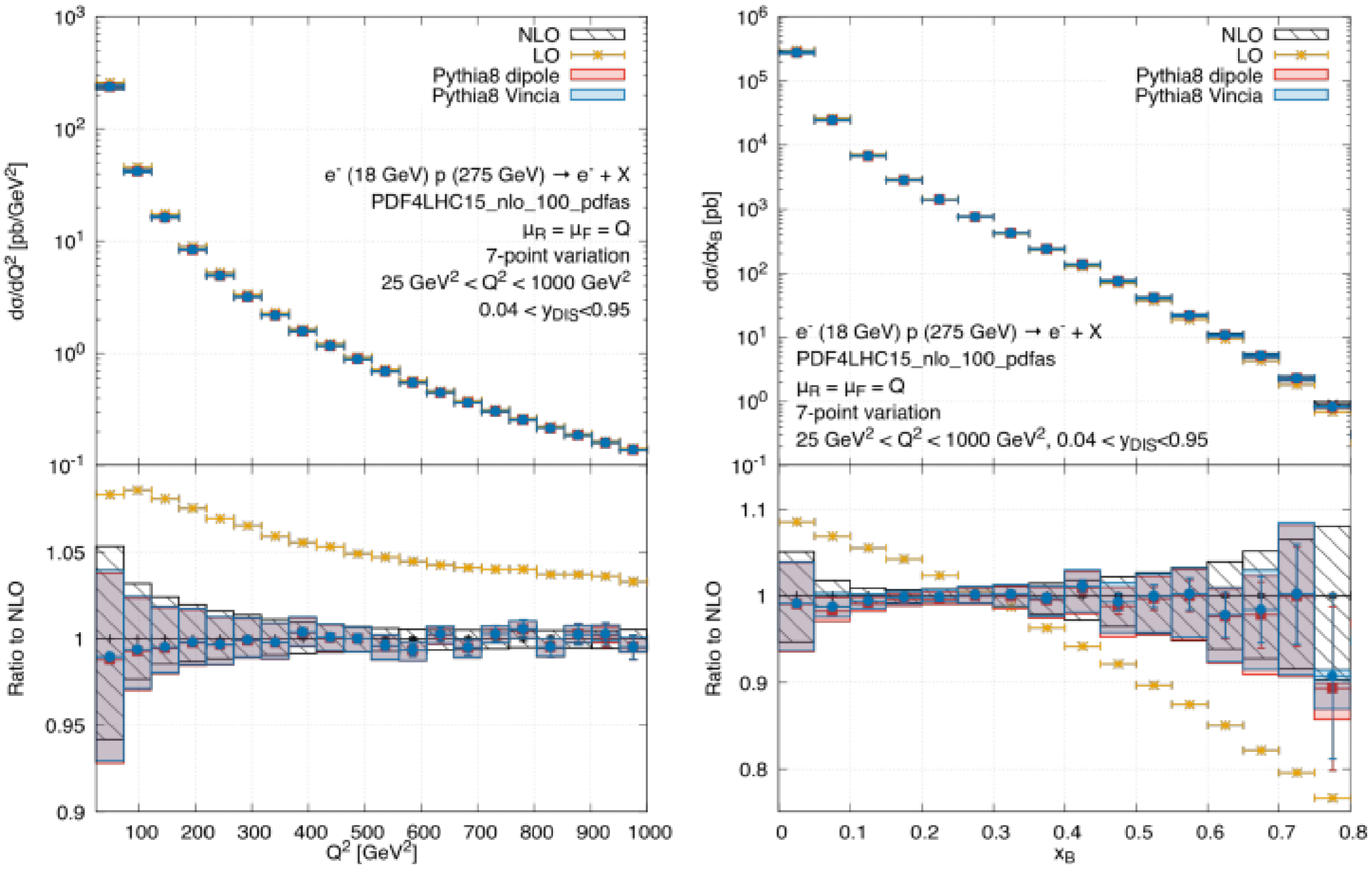
NLO matching to PS and merging

Technology fully applicable in DIS, with some care

D. Reichelt

NLO matching: applications to EIC

- EIC at lower energy, but predictions still highly relevant (for ep runs)
- for example [Banfi, Ravasio, Jäger, Karlberg, Reichenbach '23], NLO predictions at $\sqrt{s} = 140$ GeV matched in the Powheg scheme



progress both in matching and parton shower accuracy, NNLO+NNLL likely on EIC timescales (vs. todays standard NLO+NLL)

work needed to progress improvements to specific DIS/EIC cases like photo production of jets

D. Reichelt

General Purpose Event Generators at EIC

Are the *general purpose* event generators ready for nuclei at the EIC?

Can they handle

- *eA*?
- DIS?
- Photo-production?
- Nuclei in general?
- Saturation? Polarisation? Lower energy? Diffraction? . . .

Todo: EVERYTHING

We see collective effects in all (?) collision systems

- Flow
- Strangeness enhancement
- Jet quenching (?)

Is there Quark-Gluon Plasma everywhere?

Or are the mechanisms in play in *AA* different from those in pp?

Which ones could become important at the EIC?

- The generator programs are not ready for the EIC (yet)

Collective effects implemented differently in different event generators (e.g. core-corona, color reconnections, string shoving, rope hadronization, hadron rescattering
jet quenching)

L. Lonnblad

General Purpose Event Generators: tuning

Tuning to different processes:

e^+e^-	$\Rightarrow$	Hadronisation and FSR
ep	$\Rightarrow$	ISR and remnant jets.
pp	$\Rightarrow$	UE and MPI
pA	$\Rightarrow$	small dense systems, flow
AA	$\Rightarrow$	large dense systems, jet quenching
eA	$\Rightarrow$	?

To facilitate the work: develop tools to compare predictions to data

Already at HERA it was realised that comparing measured data with models was difficult.

- HZTool

For the LHC this was generalised and improved in

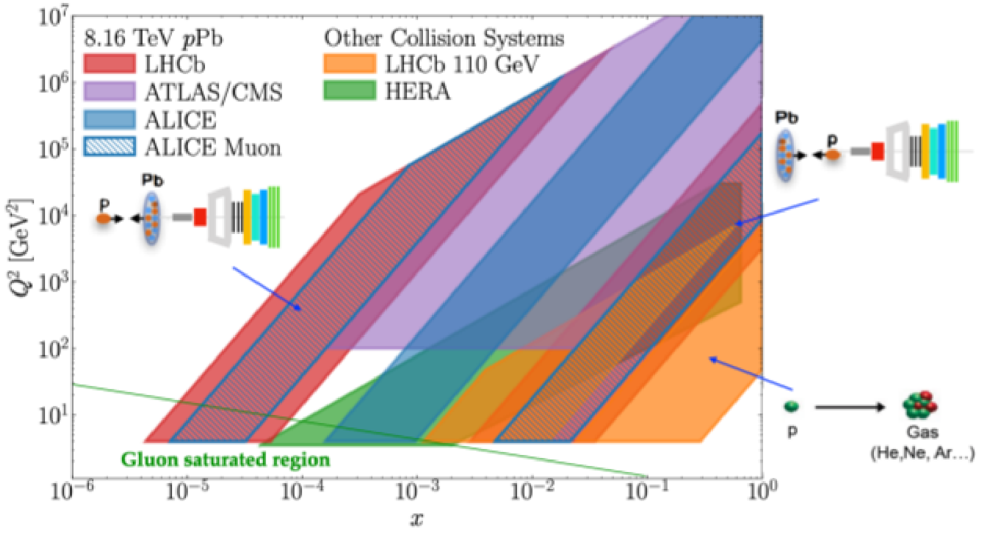
- Rivet

And at EIC ?

L. Lonnblad

Synergies between LHCb fixed-target and EIC

Similarities:



- Similar **centre of mass energies**

  EIC : $\sqrt{s}$ ~ 20-100, possibly 140 GeV

  SMOG: $\sqrt{s}$ ~ 41-115 GeV

- **Similar/identical nuclear species**, including both light and heavy
- Emphasis on forward region due to **kinematic boost** provided by asymmetric beams or fixed-target kinematics, respectively
- Overlap and **complementarity in x-Q^2 coverage**
- With a polarised target, LHCb SMOG2 could even be used to study **spin physics** which will also be a big focus of the EIC

With LHCb SMOG data and the EIC, we can compare *p*A and *e*A collisions at similar energies and in similar regions of phase space

The question becomes, what do we learn by comparing *p*A and *e*A?

K. Mattioli,
G. Graziani,
M. Santimaria

Nuclear Matter Effects: LHCb fixed-target vs. EIC

- Can we use these three systems, measured at the same $\sqrt{s}$, to (predominantly) isolate and study specific CNM effects?
- *e*A is useful, but not sufficient, to constrain all CNM effects in a strongly interacting medium

System		Measure at	Advantages
e ⟶	A	EIC	• Separate current vs target fragmentation regions • Precisely measure CNM effects due to the nucleus (nPDF, absorption, etc.)
p ⟶	A	SMOG/ SMOG2	• Measure CNM effects arising from the nucleus *and* additional QCD interactions in the initial state
Pb ⟶	A	SMOG/ SMOG2	• Probe onset of QGP effects by varying A • Probe CNM effects arising from large system size/density (Comovers, etc.)

K. Mattioli,
G. Graziani,
M. Santimaria

Measurements from LHCb fixed-target relevant for EIC

From *pA* to *eA*

Other measurements we can do with SMOG that are possibly relevant for the EIC:

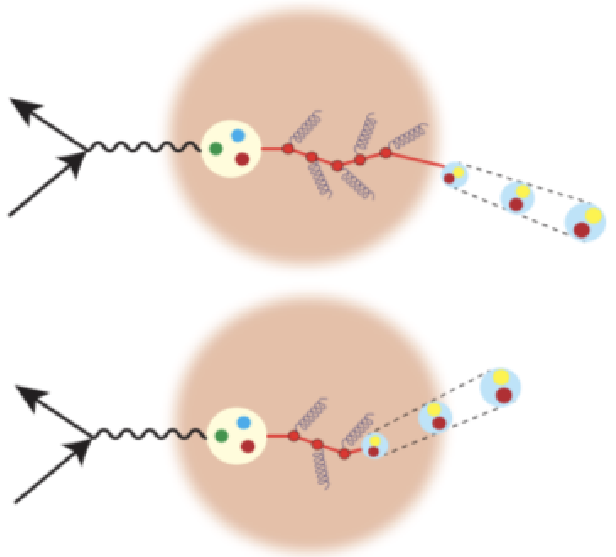
- Measurements of open charm and beauty hadrons - proposed as promising probes for studying hadronization and nuclear absorption at the EIC PLB 816 (2021) 136261
- Jet measurements with similar jet kinematics to those expected at the EIC
- Exclusive physics
- Flow
- Multiplicity-dependent production measurements

We can do all of these measurements at the same $\sqrt{s}$ planned for the EIC!

Not all observables proposed for *eA* are possible to measure in *pA* and vice versa... but we should still be able to learn a lot from comparing these processes in *pA* and *eA* collisions at the same $\sqrt{s}$

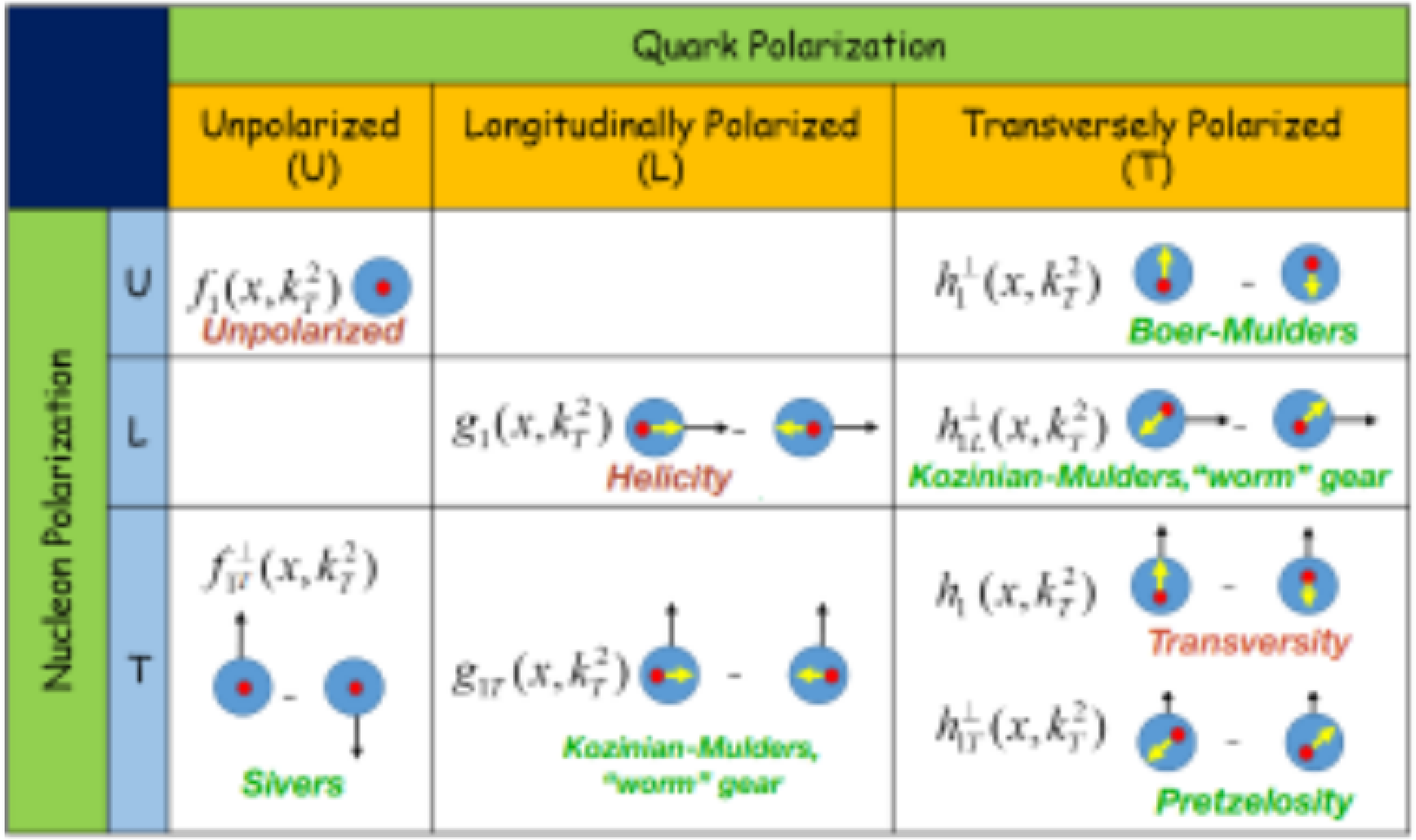
Nucl. Phys. A 1026 (2022) 122447 EPJA 52 (2016) 268

Hadronization "inside" or "outside" the medium - probe with varying A



K. Mattioli,
G. Graziani,
M. Santimaria

TMDPDFs



Different quark TMDPDFs:
current fit attempts focused on
the unpolarized case

Analogous scheme for
gluon TMDPDFs, that however are
nowadays much more uncertain (even
the unpolarized ones)

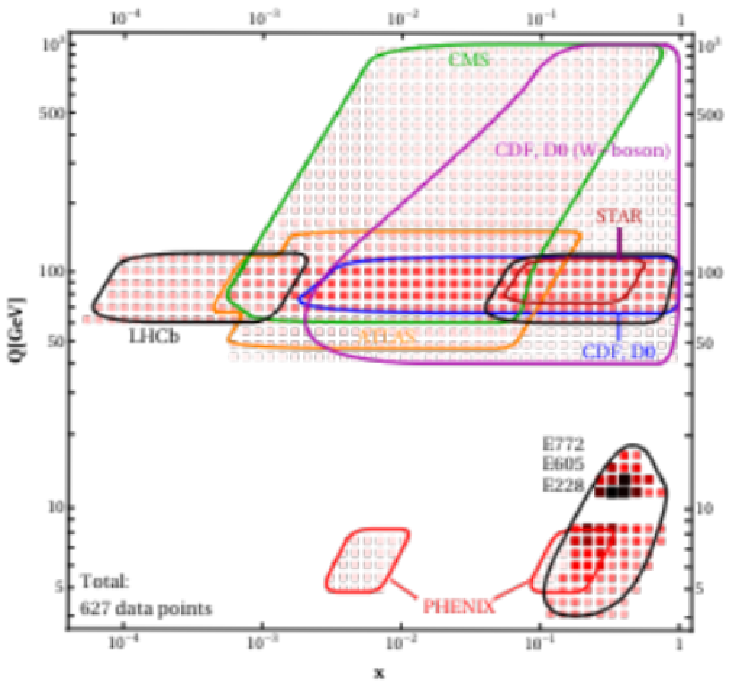
Y. Liang, A. Vladimirov

unpolarized TMDPDFs: recent fits

ART23

[V.Moos, I.Scimemi, AV, P.Zurita, 2305.07473]

First extraction at
N^{4}LL



* **data included for the first time**

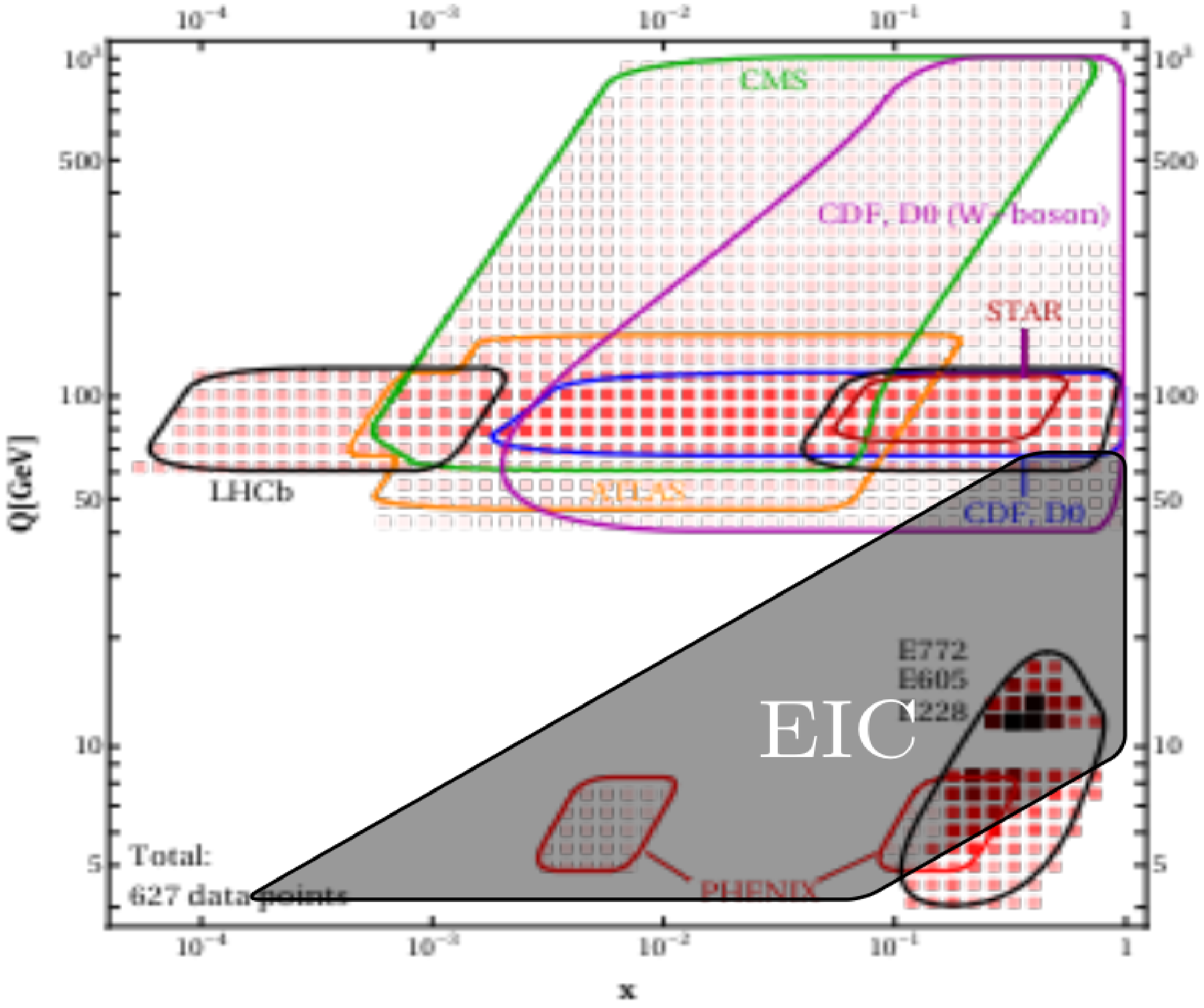
- ATLAS
  - Z-boson at 8 (y-diff.)
  - **Z-boson at 13 TeV (0.1% prec.!)**
- CMS
  - Z-boson at 7 and 8 TeV
  - Z-boson at 13 TeV (y-diff.)
  - **Z/γ up to $Q = 1000$GeV**
- LHCb
  - Z-boson at 7 and 8 TeV
  - **Z-boson at 13 TeV (y-diff.)**
- **Further more:**
  - Z-boson at Tevatron
  - **W-boson at Tevatron**
  - **Z-boson at RHIC**
  - DY at PHENIX
  - DY at FERMILAB (fix target)

627 data points

vs. 457 in SV19
vs. 484 in MAP22

A. Vladimirov

(x, Q^2) coverage of data for unpolarized TMDPDF fits

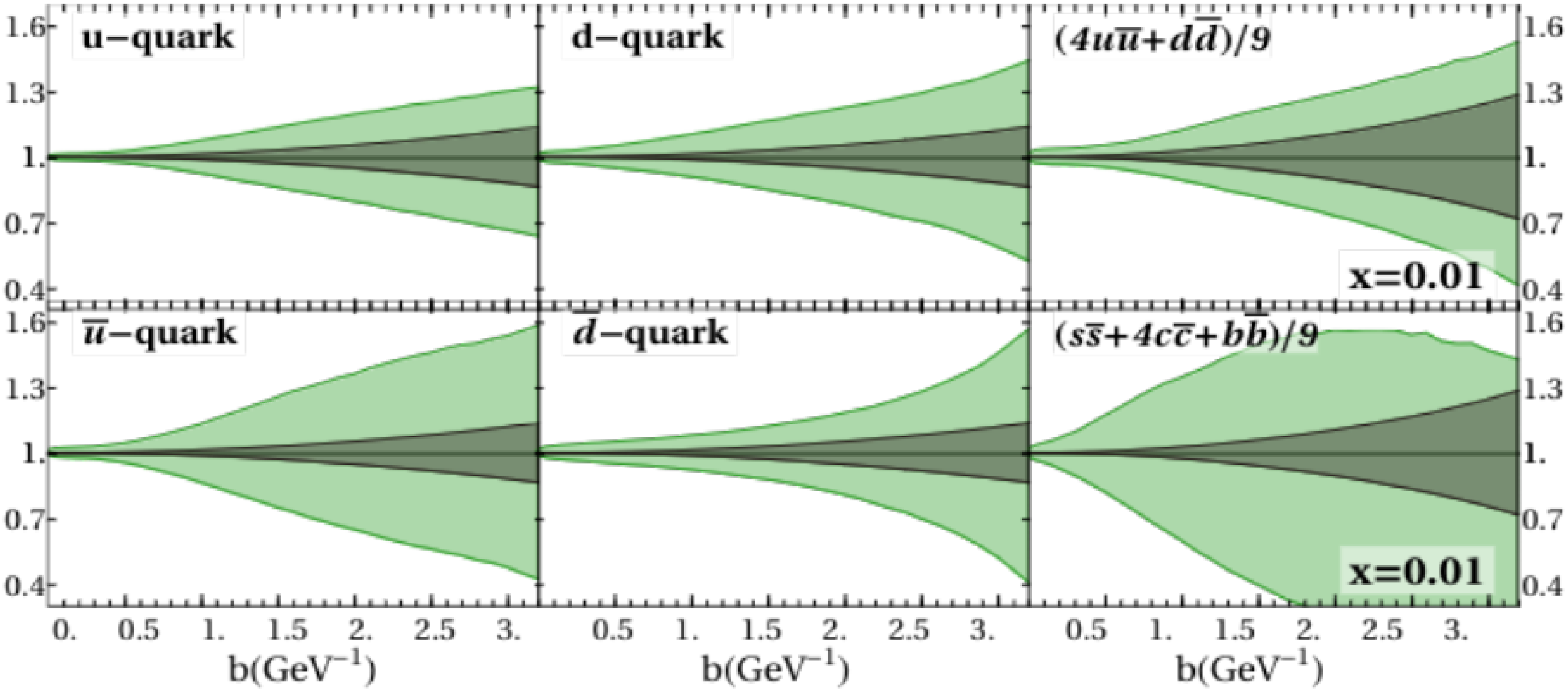


The EIC will cover a large range of (x,Q^2) region not yet covered and it will also allow to use polarized beams

A. Vladimirov

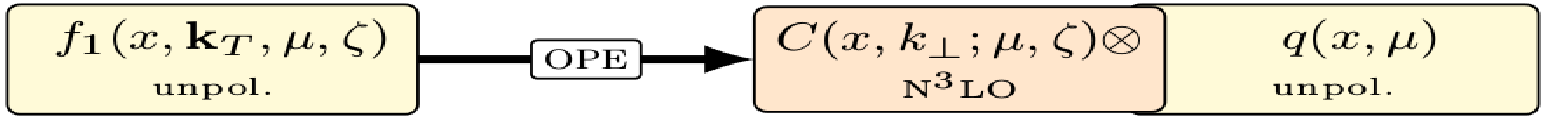
Towards simultaneous fits of PDFs and TMDPDFs

Propagation of PDF uncertainty into TMD uncertainty



Large uncertainty on TMDPDFs derive from the PDFs (and FFs) used as a basis for their fit!

Relation between TMDs and PDFs is more than an integral:



A. Vladimirov

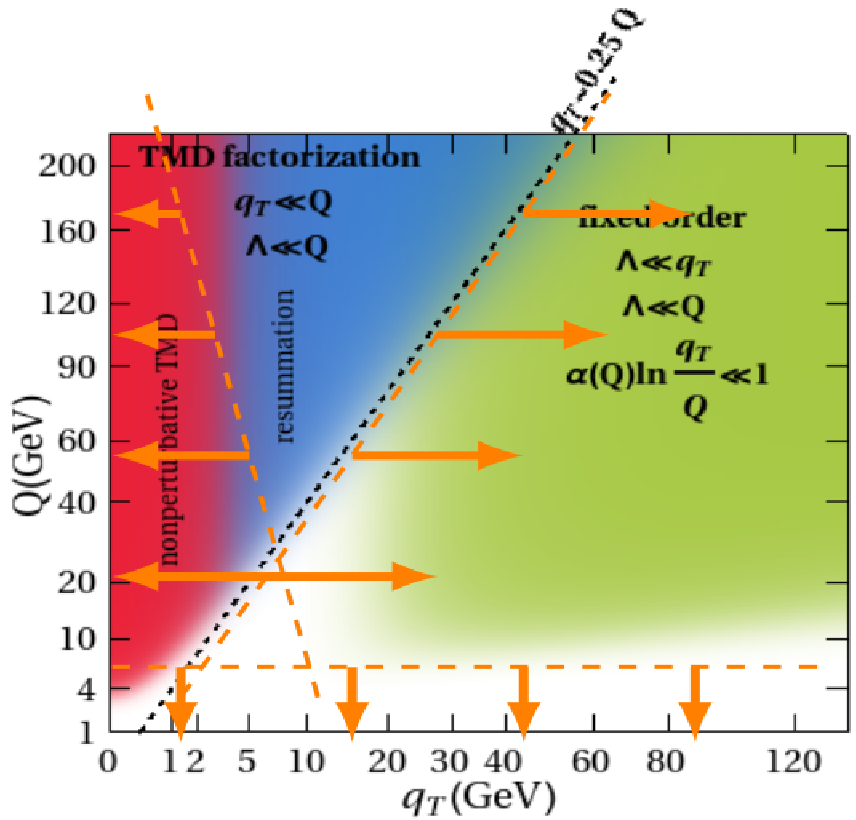
Issues with normalization and power corrections

Multiple observations of normalization problems at $Q < 10 - 15\text{GeV}$

- $\sim 30\%$ at $Q \sim 10 - 15\text{GeV}$ (πDY, DY)
- $\sim 100 - 150\%$ at $Q \sim 3 - 5\text{GeV}$ (πDY, DY, SIDIS)

Possible source is **power corrections!**

However some data in old fixed-target experiments are already not very accurate by themselves....with normalization uncertainties ~30%



NLP TMD factorization

Power corrections:

1. q_T/Q-corrections
   Y-term

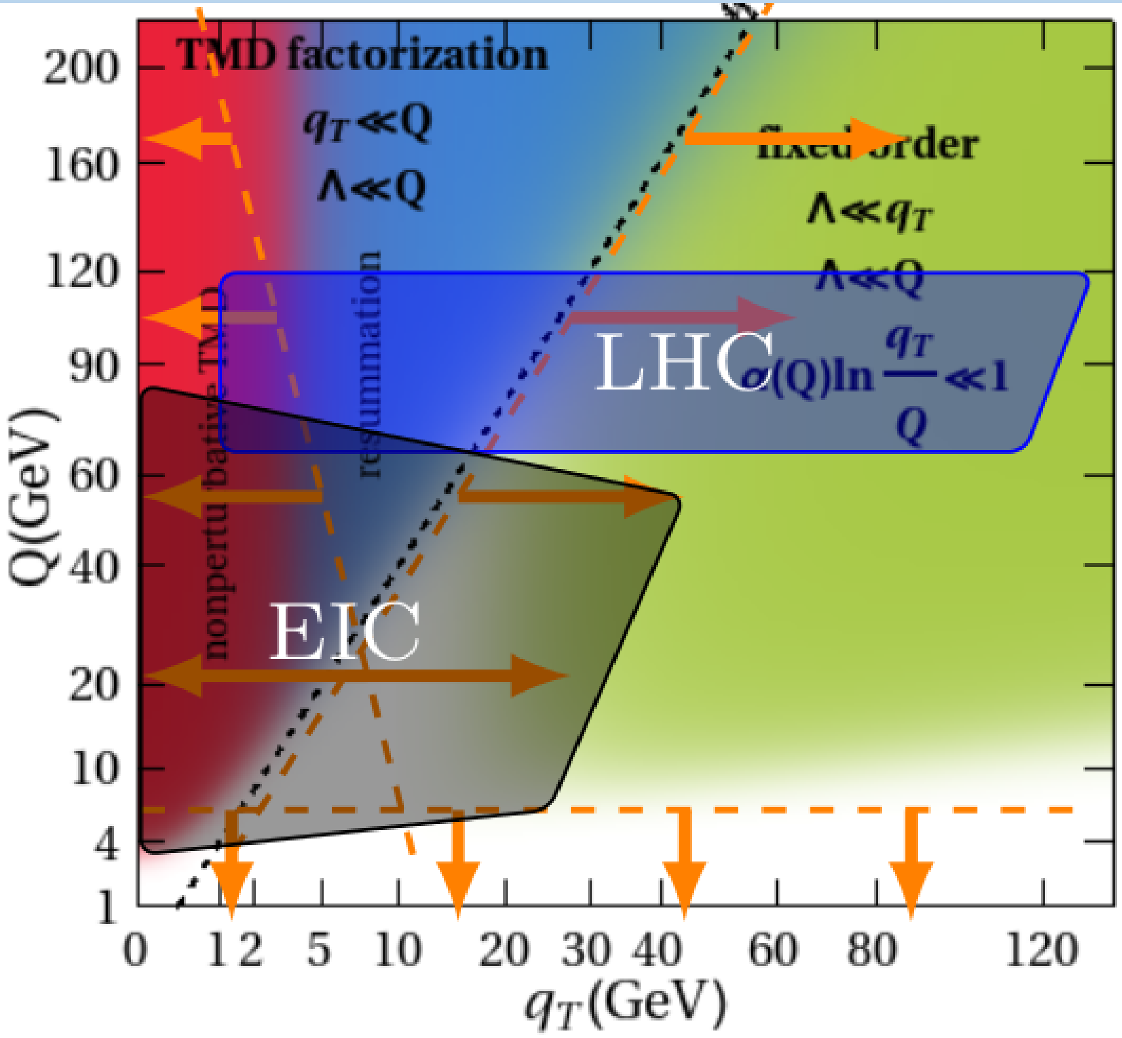
2. Λ/Q & M/Q-corrections
   higher-twist
   target-mass

3. k_T/Q-corrections
   kinematic

[AV,2307.13054]

A. Vladimirov

Power corrections for TMDPDF fit: EIC vs. LHC



NLP TMD factorization
is very important for data analysis at EIC:
power corrections there will be much more relevant than at LHC, considering the EIC exploration of lower qT and lower Q

Nowadays, extractions of TMDs are **mainly** driven by LHC, despite it has not perfect low-q_T resolution and no polarization.

LHC is perturbation-theory dominated, and thus we can polish our codes and prepare them for future.

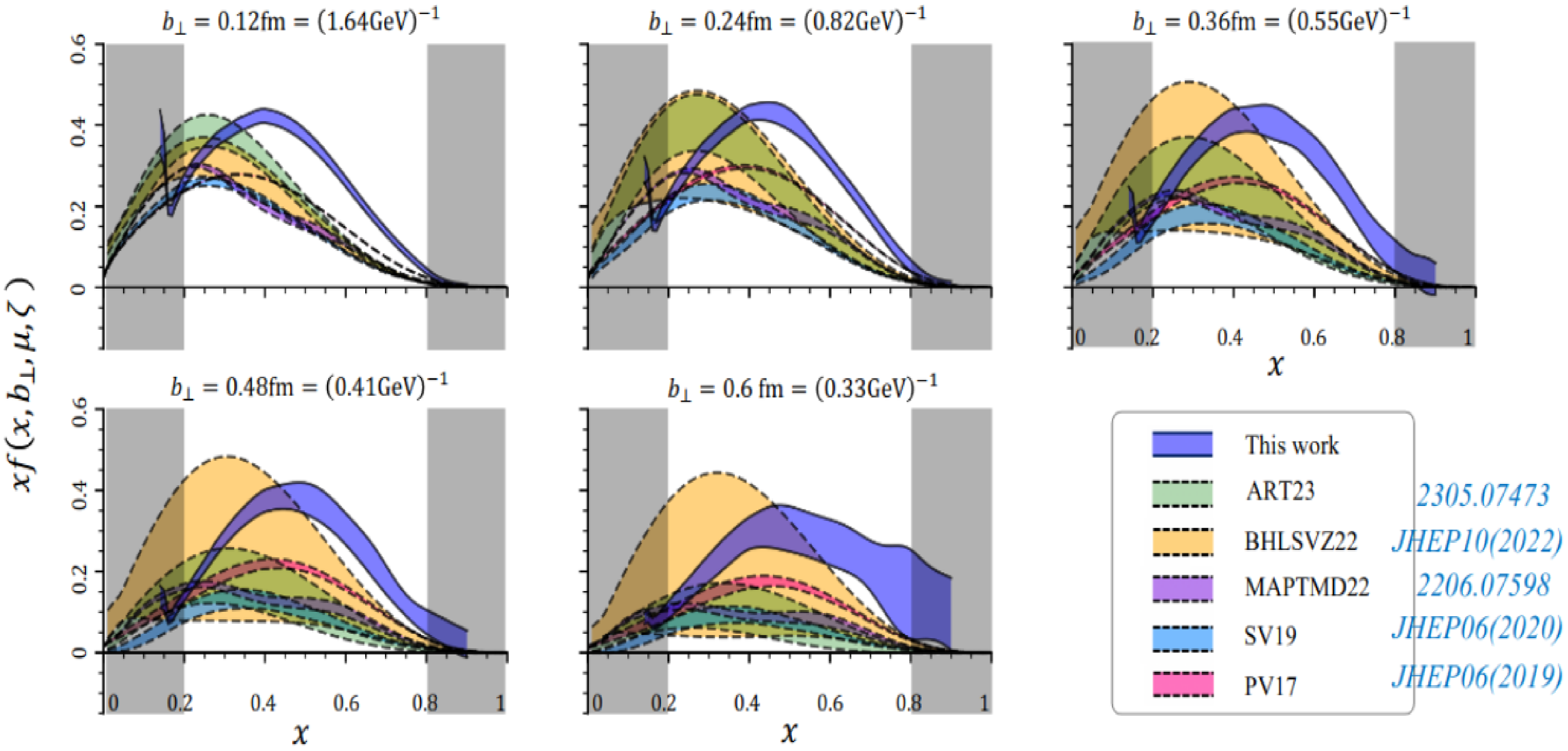
Future is for EIC, which will be perfect machine for TMDs.

A. Vladimirov

TMDPDFs from lattice QCD

First determination of the TMDPDF from the lattice

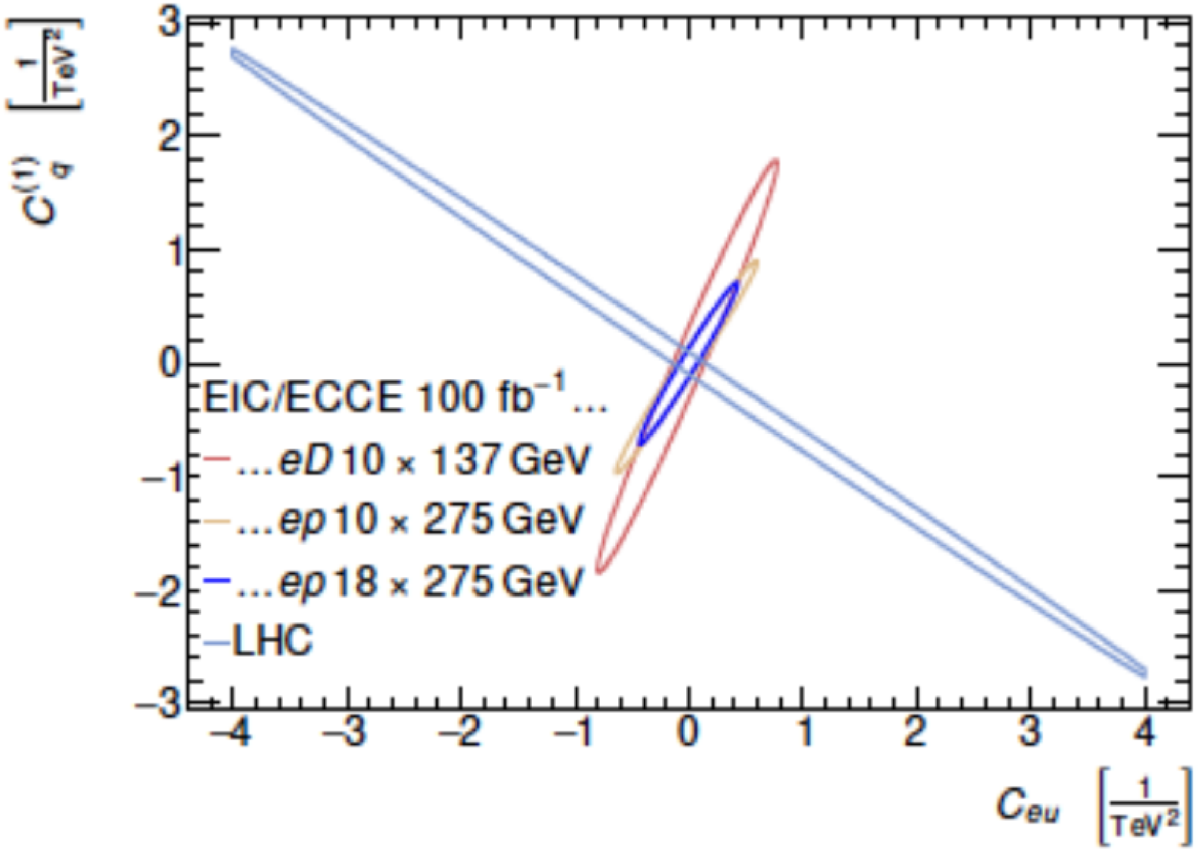
[LPC, hep-lat/2211.02340]

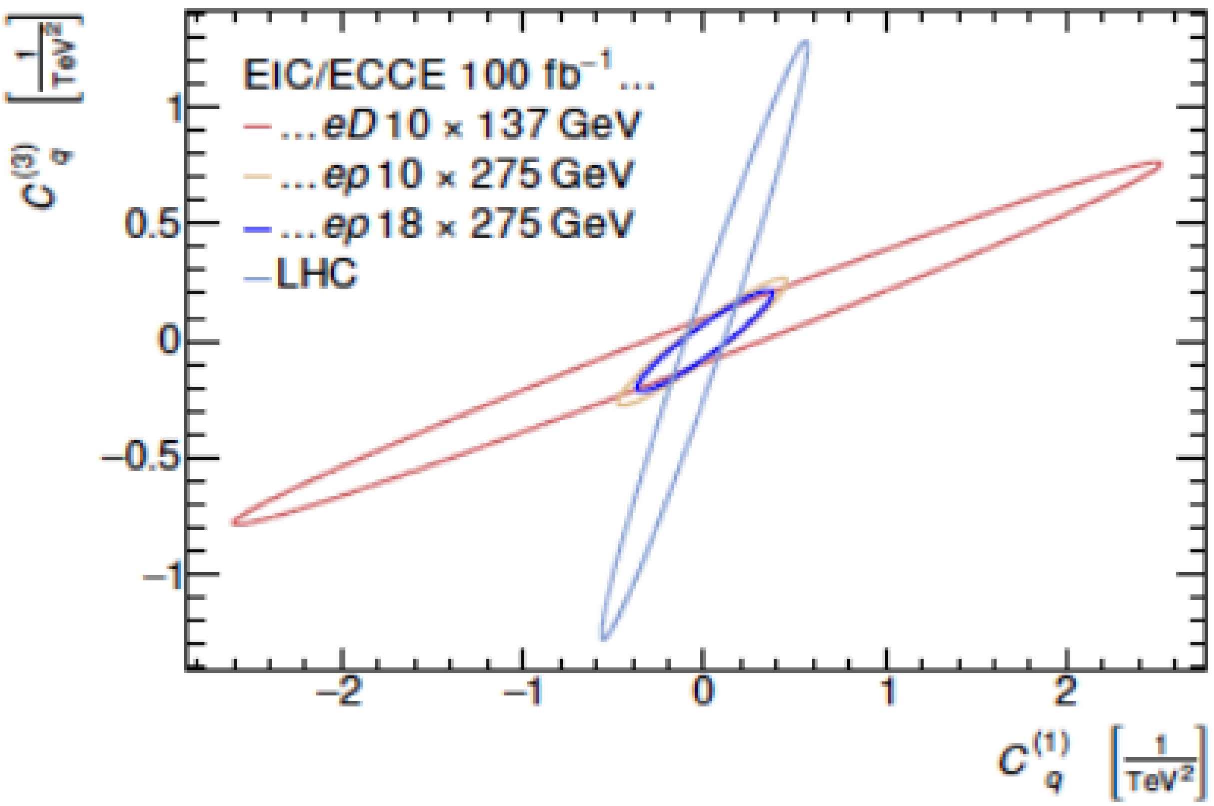


A. Vladimirov

Systematic uncertainty still unknown...

SMEFT fits





2203.13199

EIC can help to solve the degeneracies from LHC when fitting SMEFT parameters

N. Armesto

Conclusions

EIC		LHC
Improved PDFs at large x and values of α_s	→	Improved determination of SM parameters
Improved PDFs at large x and values of α_s	→	Enlarged reach for BSM searches
Additional determinations of SM parameters	↔	Solution of degeneracies in global fits
Improved PDFs and 3D structure of protons and nuclei	→	Improved initial conditions for hadronic collisions for extraction of QGP parameters and clarification of the small system problem
Precision in the extraction of a variety of TMDs/GPDs	↔	Small x evolution of such distributions
Precision in the clarification of the new dynamics through different observables and nuclei	↔	Lever arm for discovery (e.g. new dynamics at small x with implications on SM and BSM)
…		…

N. Armesto

Multiple colliders fundamental for probing pillars of QCD: factorization, universality, evolution
LHeC adds on top of that: extended (x,Q^2) coverage, Higgs physics, Wtb coupling, etc....

Workshop Sponsors and Supporters

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Forschungsgruppe FOR 2926/2
Next Generation Perturbative QCD for Hadron Structure:
Preparing for the Electron-Ion Collider
HRT

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We are grateful to all of them for material and/or financial support (not only for our Workshop, but even for coming CERN today)!

Your abstracts for ICHEP2024 are welcome!

Deadline for abstract Submission:
this evening !!!!