Synergy between Electron-Ion collider & the LHC

Physics

Michael Winn

10.10.2024

EIC France workshop

Idea of this talk

Timeline

Comparison between electron-hadron encounters at EIC & hadron-hadron encounters at the LHC

- available processes and their kinematics
- experimental conditions
- luminosities

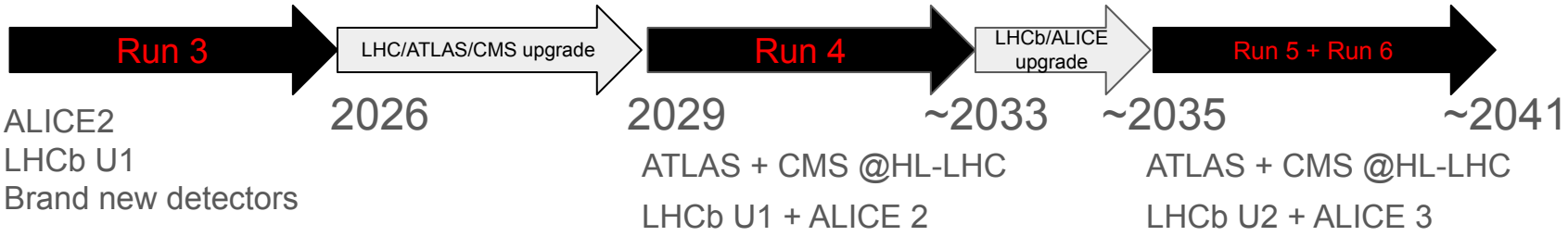
Selected physics synergies between the EIC & the HL-LHC QCD

- Initial state of hadron-hadron collisions
- Parton distribution function of nuclei
- Search for gluon saturation

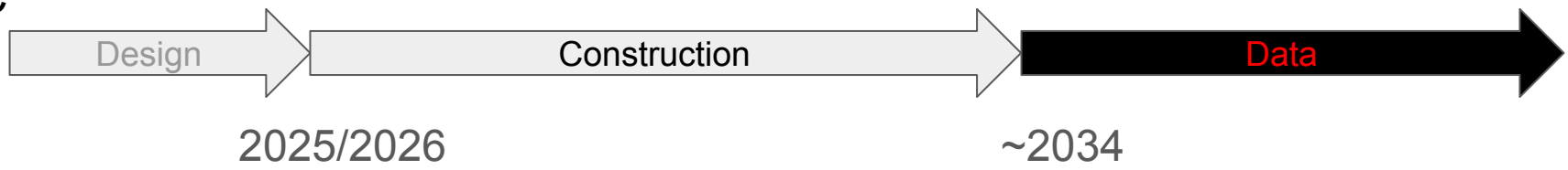
Focus on (semi)-hard processes: perturbative QCD

Time schedule

LHC



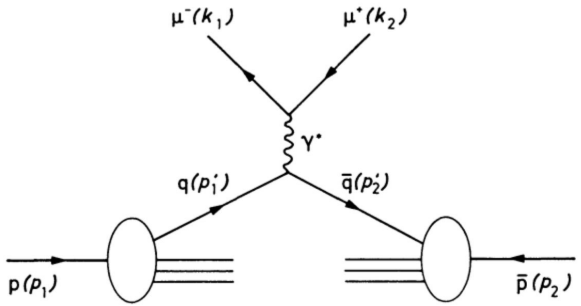
EIC



LHC and EIC will be running in parallel for 5-10 years

Inclusive hard processes

Hadron-hadron



Processes

Drell-Yan, (Di-)Jet production

Single & Two-hadron production

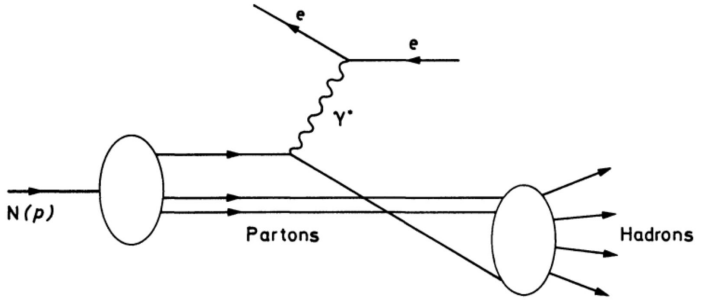
Heavy-quark hadro-production

Quarkonium hadro-production

Theoretical objects

PDFs, TMDs, Fragmentation functions and more

Electron-hadron



Processes

inclusive deep-inelastic scattering, (Di)Jet photo and electroproduction

Semi-inclusive deep-inelastic scattering: Single & two-hadron production

Heavy-quark photo and electro-production

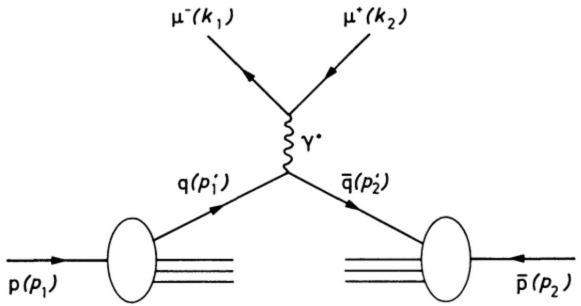
Quarkonium photo and electro production

Theoretical objects

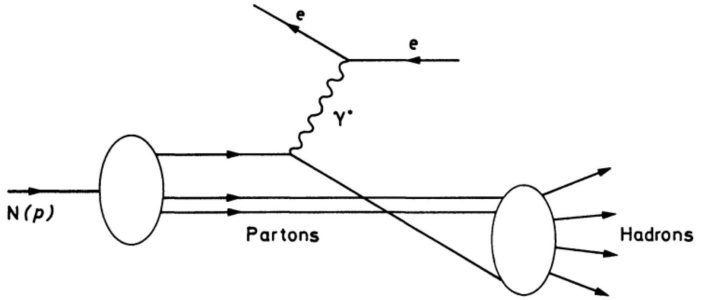
PDFs, TMDs, Fragmentation functions and more

Inclusive hard processes

Hadron-hadron



Electron-hadron



Processes

Drell-Yan, (Di-)Jet production

Single & Two-hadron production

Heavy-quark hadro-production

Quarkonium hadro-production

Close correspondence

Processes

inclusive deep-inelastic scattering, (Di)Jet photo and electroproduction

Semi-inclusive deep-inelastic scattering: Single & two-hadron production

Heavy-quark photo and electro-production

Quarkonium photo and electro production

Theoretical objects

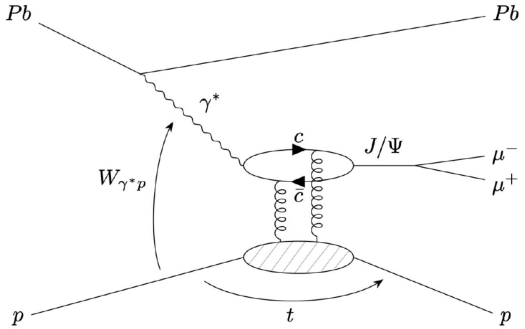
PDFs, TMDs, Fragmentation functions and more

Theoretical objects

PDFs, TMDs, Fragmentation functions and more

Exclusive hard particle production

Hadron-hadron collision

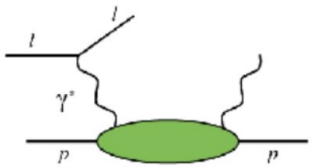


Processes

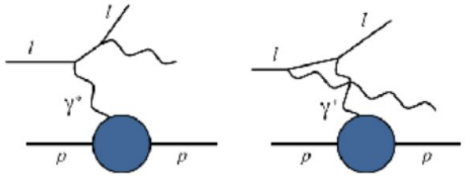
- Photoproduction: Vector mesons
- Photoproduction of dijets

- Continuum dilepton production in Photoproduction

Electron-hadron collision



DVCS



Bethe-Heitler

Processes

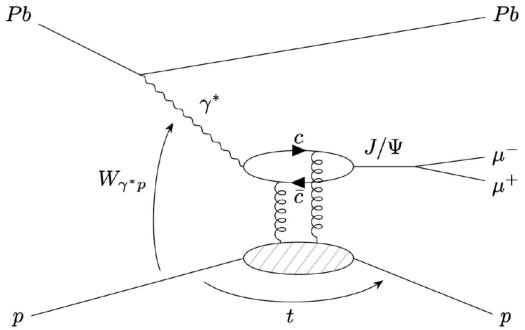
- Photo and electroproduction: Vector mesons,
- Photo and electropdoction of dijets
- photon emission

- Continuum dilepton production

In addition: Hadron-hadron: depending on process, photon replaced by other colour neutral propagator (e.g. pomeron)
+ dissociative/incoherent processes with rapidity-gaps

Exclusive hard particle production

Hadron-hadron collision



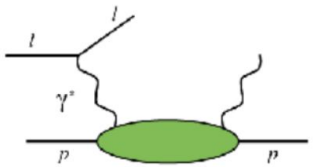
Processes

- Photoproduction: Vector mesons
- Photoproduction of dijets

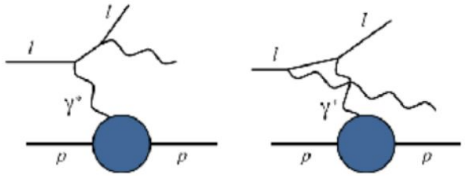
- Continuum dilepton production in Photoproduction

Close correspondence

Electron-hadron collision



DVCS



Bethe-Heitler

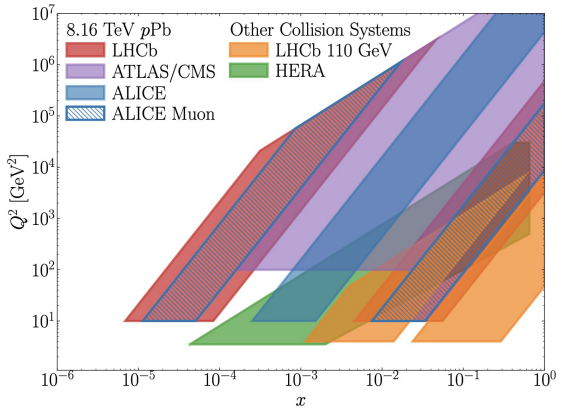
Processes

- Photo and electroproduction: Vector mesons,
- Photo and electropdoction of dijets
- photon emission

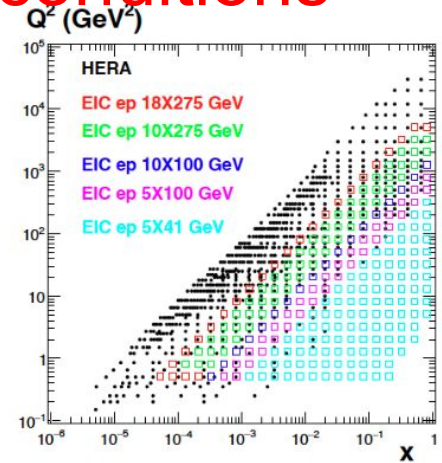
- Continuum dilepton production

In addition: Hadron-hadron: depending on process, photon replaced by other colour neutral propagator (e.g. pomeron)
+ dissociative/incoherent processes with rapidity-gaps

Kinematics and experimental conditions



Courtesy T. Boettcher



arXiv:2309.11269,
example proton-PDF

Scales

hadroproduction: mass or transverse momentum:

QCD radiation for both incoming particles

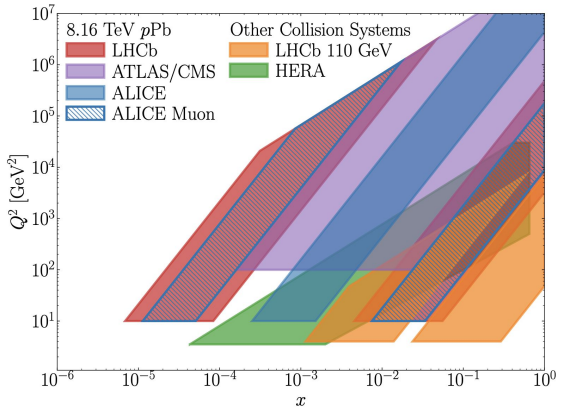
Photoproduction like in e-p/A, but lower rates and only selected observables

Scales

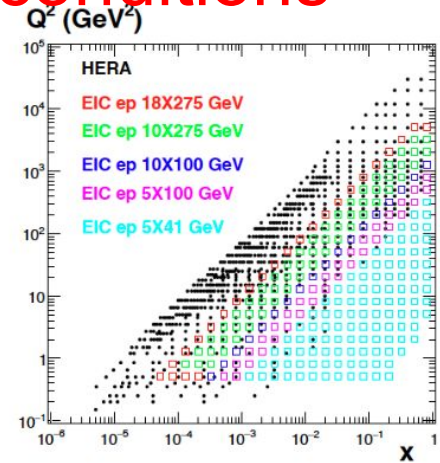
Q2 in DIS: scale experimentally accessible

up to radiative QED corrections

Kinematics and experimental conditions



Courtesy T. Boettcher



arXiv:2309.11269,
example proton-PDF

Kinematic reach

Very large in particular down to low-x and high Q2, but S/B and/or instrumentation does not allow to access equally full plane

Kinematic reach

Kinematic reach smaller, detector designed to cover as much as possible of kinematic plane for inclusive DIS and to provide also instrumentation for exclusive measurements

Kinematics and experimental conditions

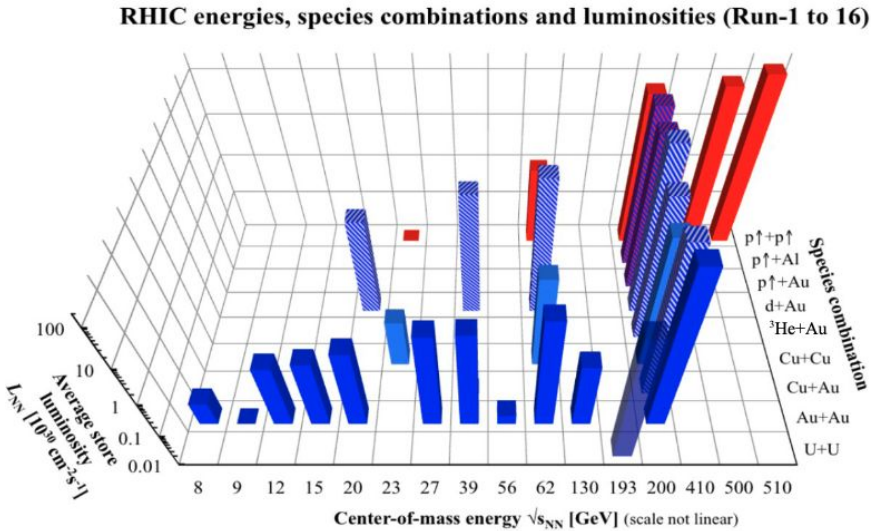
Targets

Ion-running about 1 month per year

So far proton, Lead, Xenon, next year Oxygen

Fixed-target programme of LHCb adding much more flexibility and high-luminosity at about 100 times lower sqrts

Discussions ongoing for other ions in the future including injector upgrades, see workshop

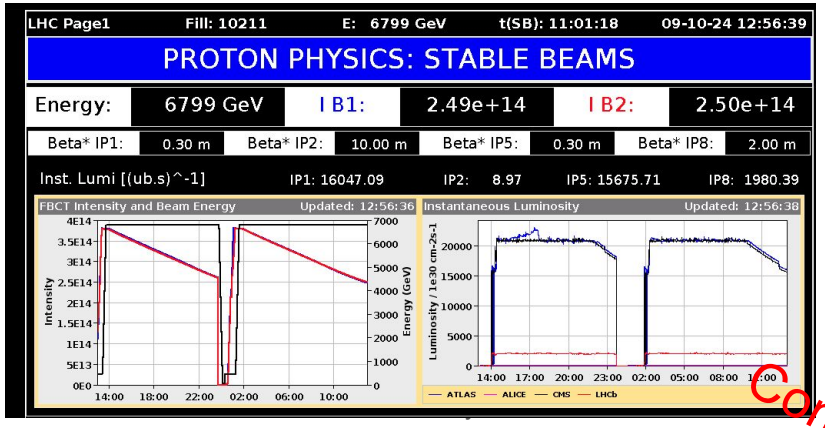


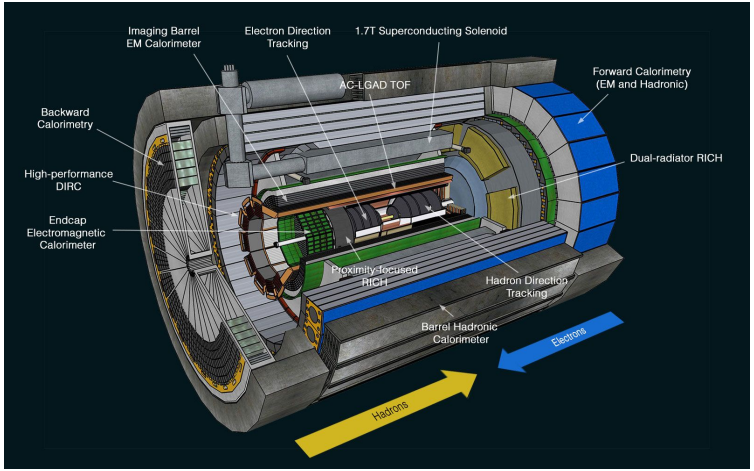
Targets

Large flexibility from RHIC preserved for EIC

Plot from QM 2023, isobar run and Oxygen data not shown

Kinematics and experimental conditions





Complementary

Instrumentation

ALICE, ATLAS, CMS, LHCb

Four complementary detectors in terms of acceptance, resolutions, particle identification

Instantaneous luminosity in proton-proton collisions more than 3 orders of magnitude different between experiments:

Allows for measurements from very soft to very hard

Instrumentation

EPIC as multi-purpose detector:

large acceptance, particle identification, extended forward instrumentation

Wish for a second detector

Discuss three independent
but strongly related long-standing questions

EIC & HL-LHC will contribute to both
It is our responsibility to get the most out of it

What is the initial state of hadron-hadron collisions?

Modelling of energy-momentum flow in heavy-ion collisions

- Many free parameters for initial state
- Can be seen two-fold
  - Infer information on initial state from soft heavy-ion data
  - Information accessible also from other sources: precision limitation

Energy deposition dominated by partonic interactions:

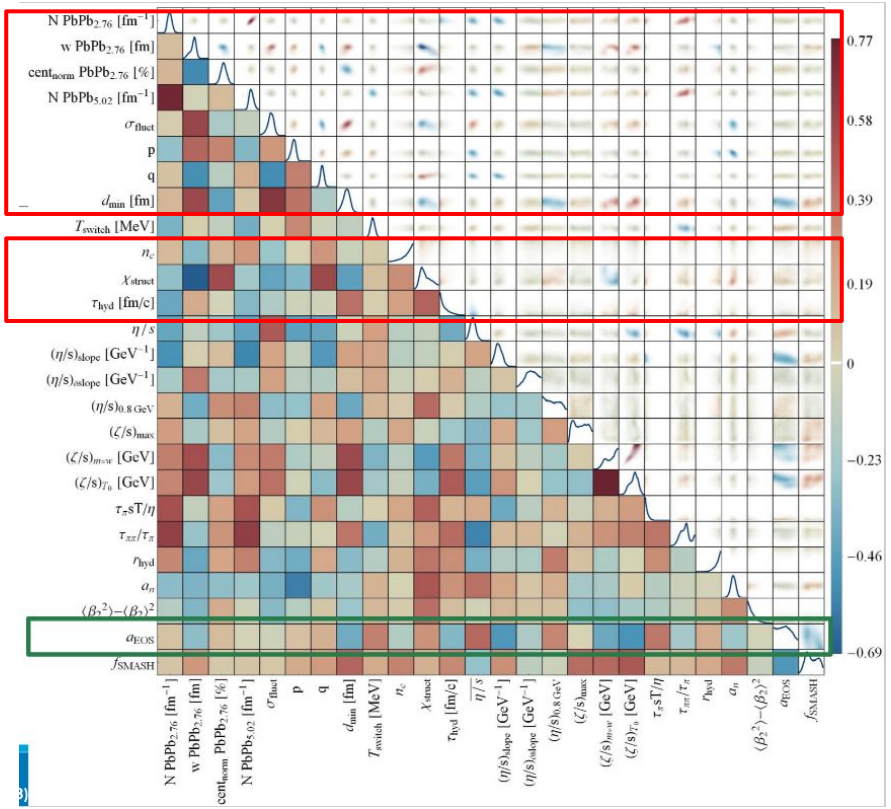
- In principle accessible information via hard particle production

Uncertainties large:

- Scale uncertainties: small typical scales
- PDF uncertainties: nuclear partons not well known

EIC can provide precision for RHIC kinematics

- Unfortunately not down to as low-x as relevant for most of energy deposition at the LHC
- However can check reliability of knowledge transfer



Taken from slide by W. van der Schee:
https://indico.cern.ch/event/1341120/contributions/5867064/attachments/2884693/5055513/Talk_Qingdao.pdf

What are the effects present in nuclear PDFs

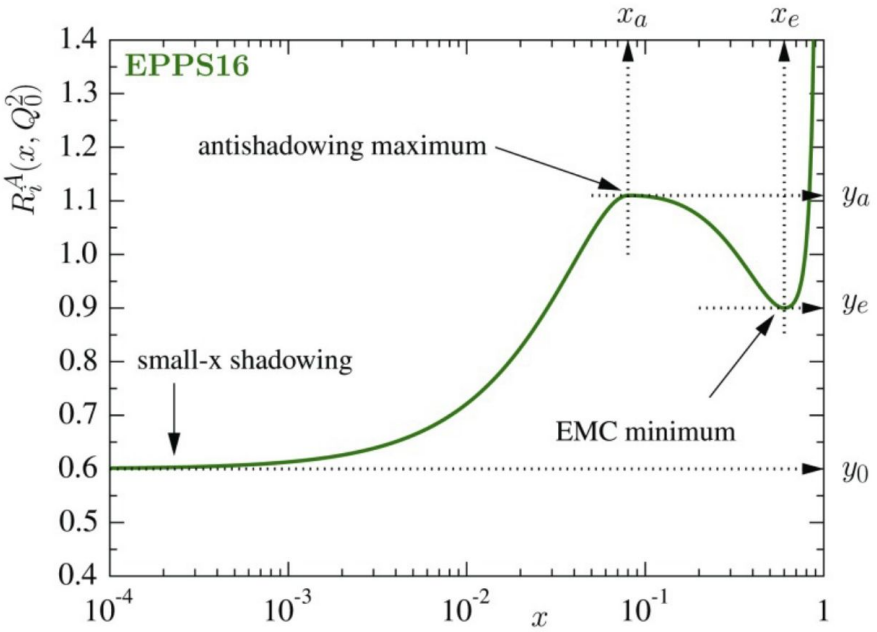
Various physical phenomena at play

application of collinear parton distribution functions: a conjecture

not tested to the same level of precision as for the proton

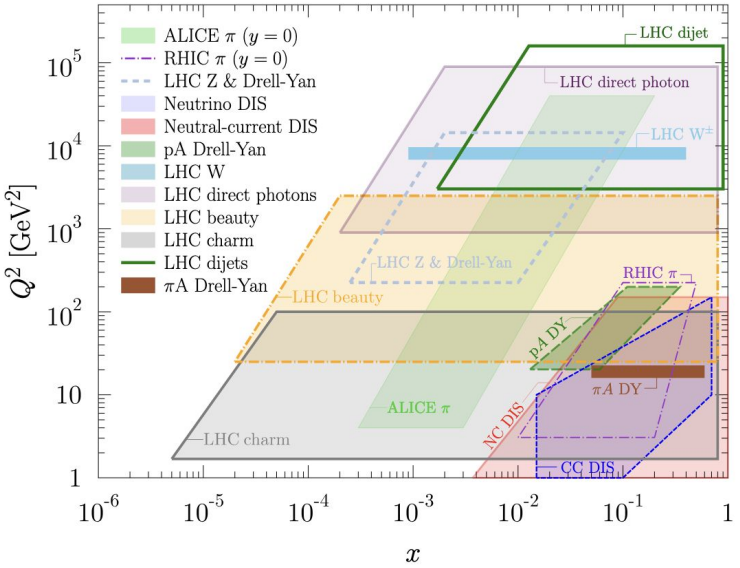
- Need to check DGLAP-applicability with precision

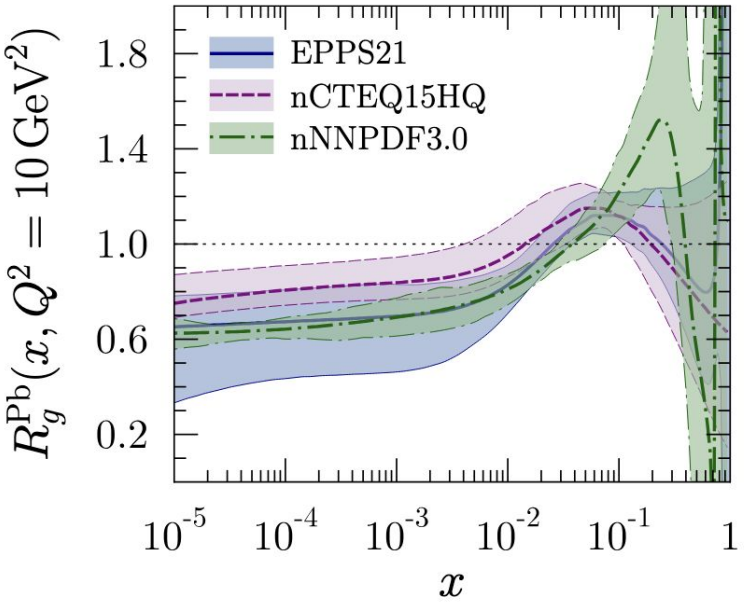
- Need to establish baseline for saturation searches for nuclei



A possible way for knowledge transfer from nuclear structure to heavy-ion collisions

What are the effects present in nuclear PDFs





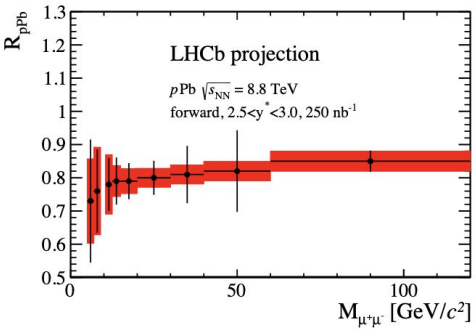
https://arxiv.org/abs/2311.00450

LHC: strong contributor to nuclear PDF precision down to low Bjorken-x

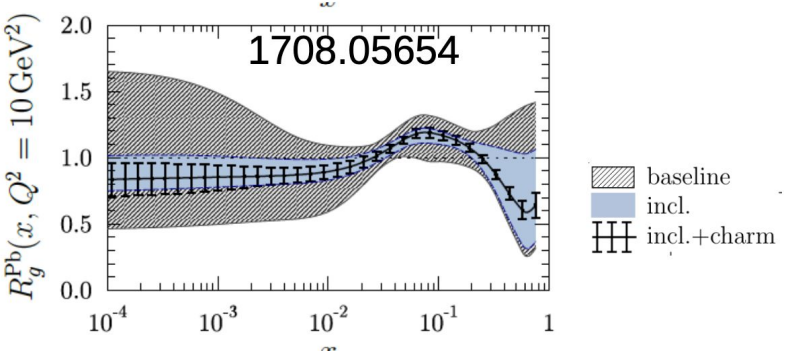
One highlight: sizeable gluon shadowing consistently observed by 3 different global fits

Important to confirm with cleaner measurement (photon/DY/DIS) to exclude confounding effects

What are the effects present in nuclear PDFs



Low-x Low-mass DY: clean constraints



EIC impact on gluons

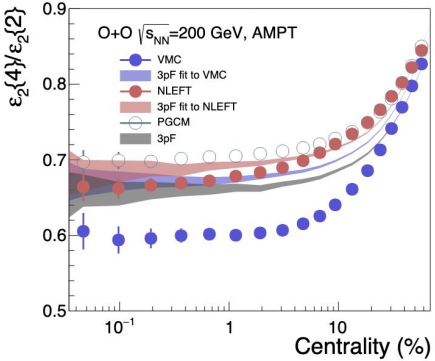
LHC: larger luminosity and new channels, see HL-LHC Yellow report WG5

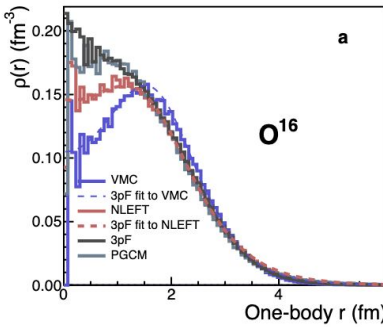
- improve statistically limited channels: Z, W production, beauty production
- Exploitation of new kinematics and/or theoretically cleaner channels: Dijet photoproduction, prompt forward photons (Focal, LHCb), Drell-Yan forward (LHCb, ALICE muon)

EIC will be able to sample with high precision nuclear PDFs in the provided kinematic range

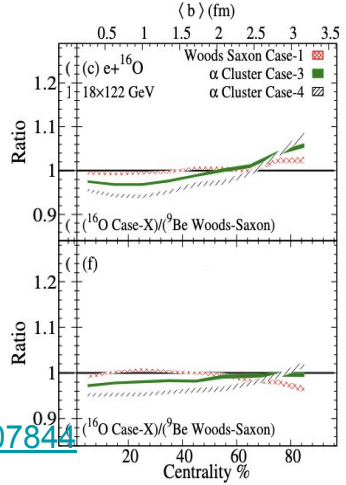
- **check DGLAP evolution within the EIC data and with LHC: very crucial**
- **Constrain mass dependence**

Nuclear structure on large length scales from high-energy





https://arxiv.org/pdf/2404.08385v1



https://arxiv.org/pdf/2405.07844

LHC and RHIC: pioneer to explore nuclear structure via correlation measurements

Small nuclei collisions: new access to nuclear structure

EIC: measurements of <E> in fragmentation region sensitive to clustering

- New access to nuclear structure at high-energy

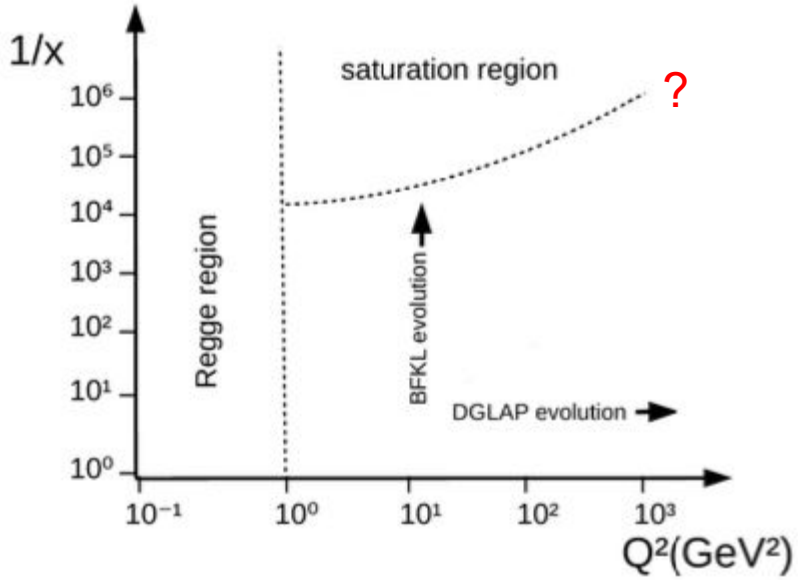
Saturation

Saturation:

- A theoretical prediction since the 8(

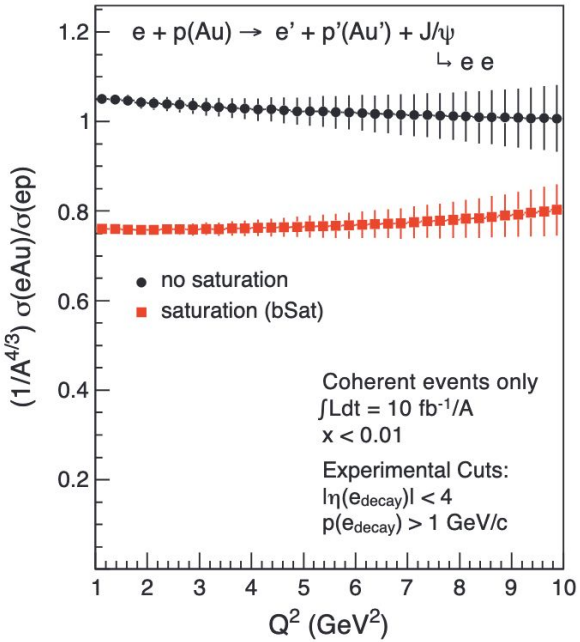
Conjectured, but not unambiguously identified in HERA/LHC data yet

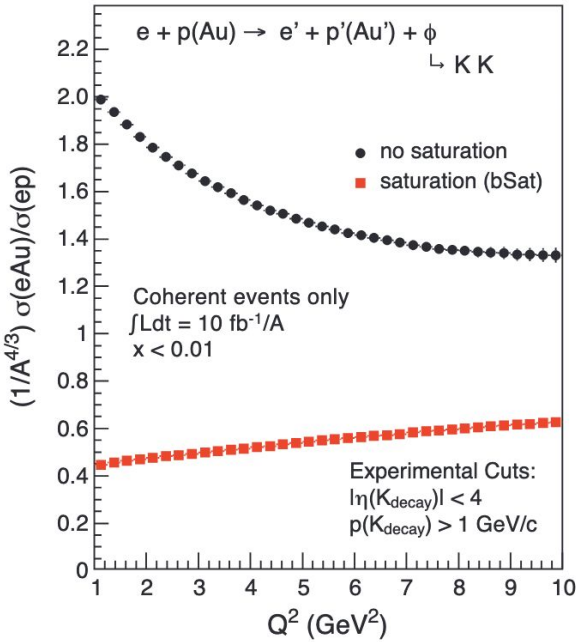
- One of the science drivers of the EI



modified version of graphic in “QCD and collider physics”, Ellis, Stirling, Webber

Saturation

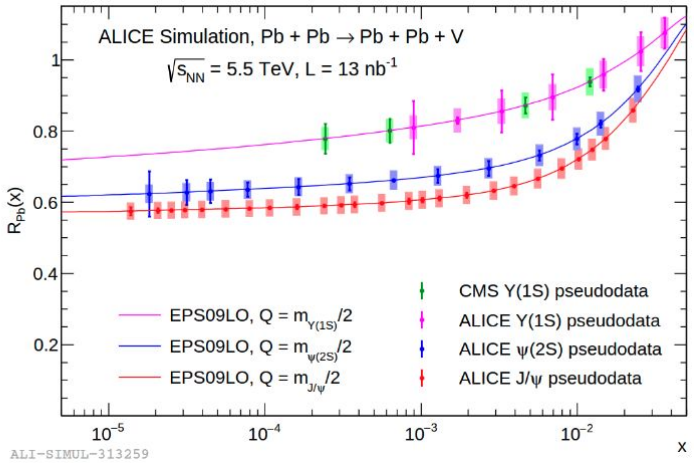




Lower energy@EIC: use nuclear collisions to access saturation regime

- Example for dissociative over coherent vector meson production
- Precision longitudinal structure function: see e.g. https://arxiv.org/abs/2203.05846

Saturation



Future measurements at the LHC down to Bjorken-x to 10^{-6} in pPb, gamma-p &gamma-Pb

Conclusive measurements from both facilities should allow to have a final word for the kinematics accessible

LHC proved to be capable to go beyond past projections (here from the YR WG5 report):

- t - dependence, incoherent production & dissociative production shown to be feasible in UPC
- Important for LHC & EIC: develop theory with uncertainty bars as for structure functions
  - steps ongoing for exclusive quarkonium production using GPDs and low-x resummation: https://arxiv.org/pdf/2409.05738

An uncomplete discussion

High precision proton PDF and TMD constraints

- LHC Drell-Yan, high-pt Jet and top production measurements already now contributing: precise will improve and will contribute
- arxiv:1902.04070
- EIC will push precision at x with low-Q2, see e.g. at: arxiv:2309.11269

TMD physics with spin

- vast programme with observables only available with polarised beams at EIC
- LHC spin as a possible complement with polarized target project for late 2020ies for LHCb fixed-target

Generalised Parton distribution functions

- GPD physics at the core of the EIC programme: gravitational form factors and spin decomposition
- LHC UPC programme only starts to be seen as GPD playground

An uncomplete discussion

Energy loss

- Cold energy loss programme at EIC and at LHC

Collectivity: the limits of the hydrodynamic regime

- EIC allows to have a point-like initial state with a finite Q2: not available easily in UPC at the LHC

Important to note that QCD research so far largely data-driven:

Very lucky that LHC and EIC will run at the same time !

A tentative summary

Correspondence

- Same formalism
  - Use same event-generator
  - Use same type of calculations

Complementary

- Test factorisation as function of Q^2
- Extend kinematics substantially by combining both facilities
- Different observables

Redundancy

- Importance of phenomena & systematic uncertainties largely different
- Support or falsify strong claims

Conclusion

QCD programe at EIC and at HL-LHC

Both stand on their own right and with their stand-alone questions

However: their respective potential enlarged by each other

Correspondence

Complementarity

Redundancy

Mutual empowerment

We should reach out to each other to learn more about nature

- often exchange/combinations/collaboration existing, starting in other cases
- We should make an effort for consensus building on common topics: priorities, falsification strategies, conclusions