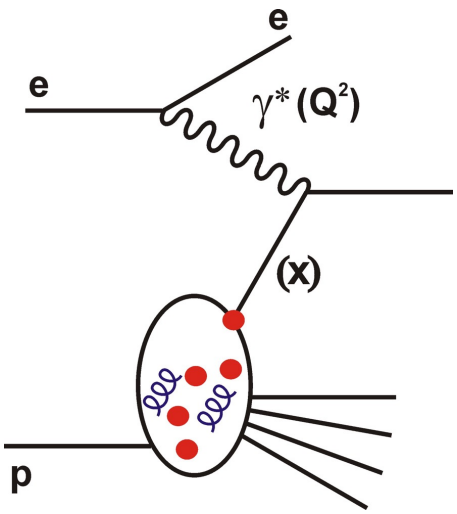
Deep Inelastic Scattering and Hadronic Structure

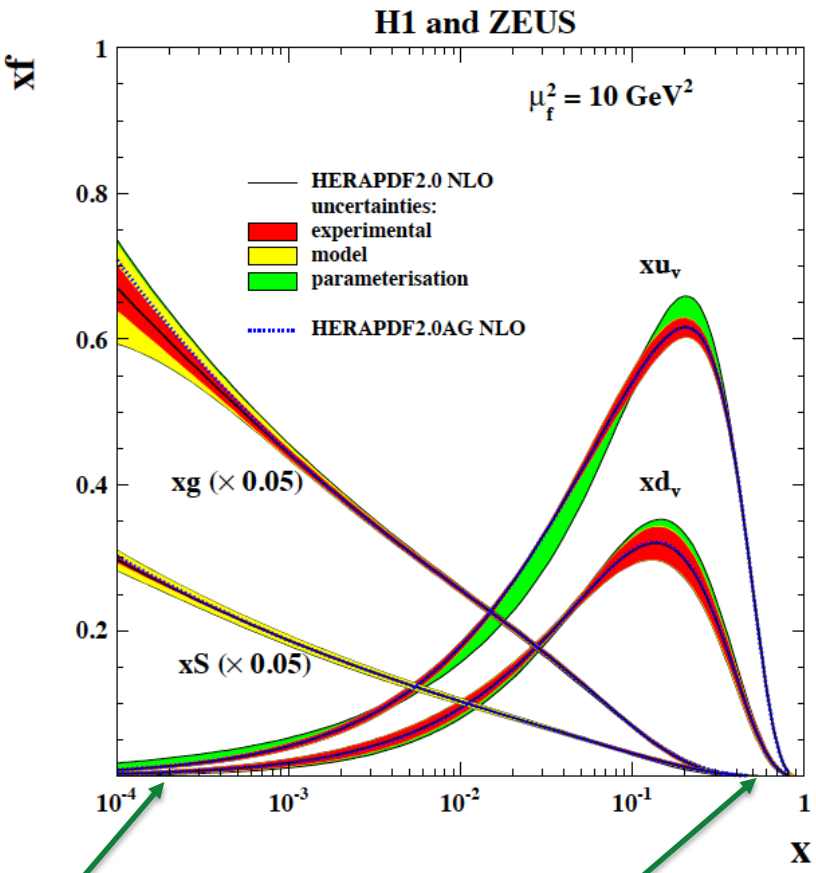


Paul Newman

UNIVERSITY OF BIRMINGHAM

1) Collinear Proton PDFs from HERA and LHC
2) Extension to Nuclei
3) Future Prospects at LHC / CERN
4) Future DIS and the Electron Ion Collider

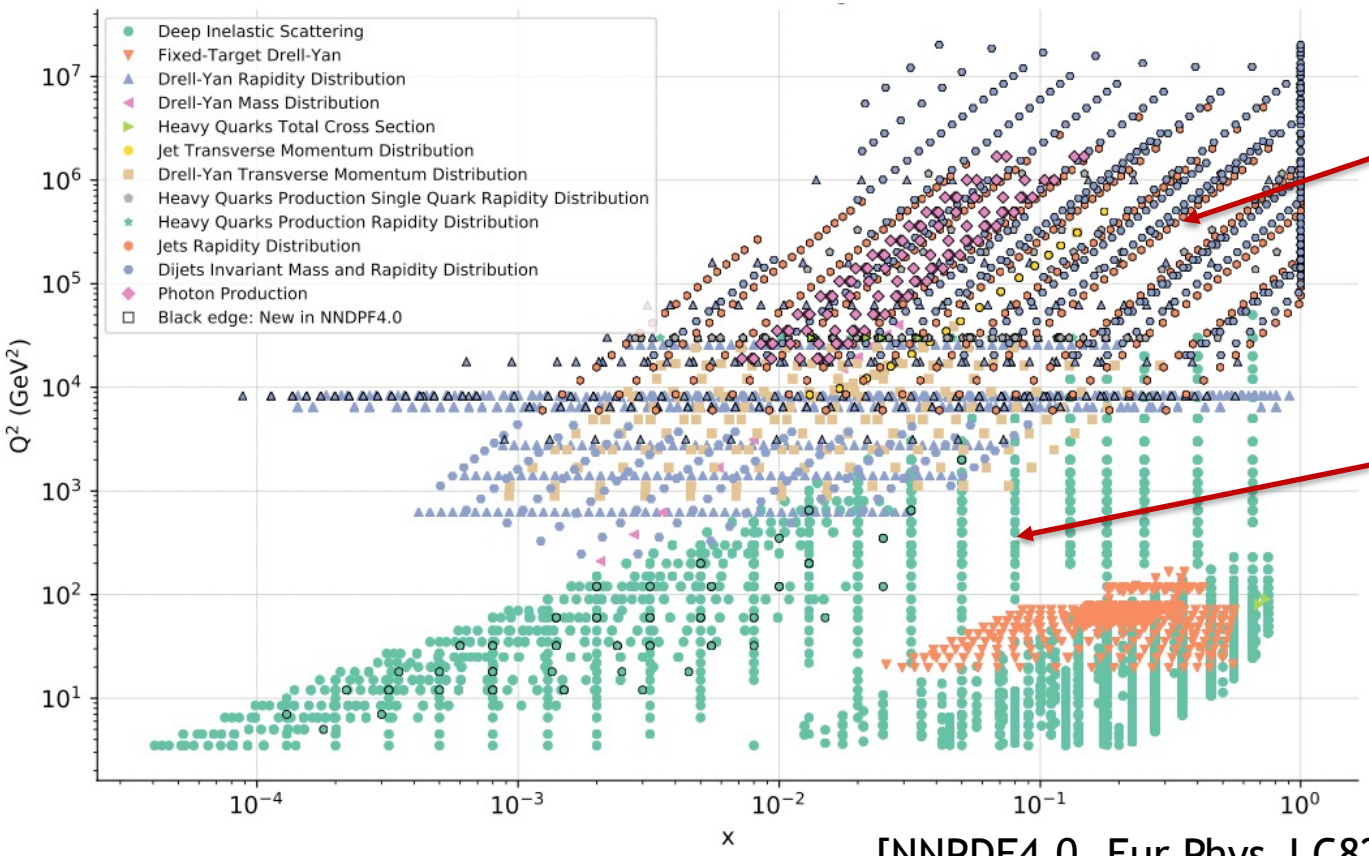
HERA at DESY: Still the Backbone of Proton Parton Density Functions (PDFs)



Strong interaction dragons?

Input to energy frontier discovery?

Data used in current PDF fits



Lots of PDF-sensitive observables at LHC

HERA limited at low x by kinematic range and high x by luminosity

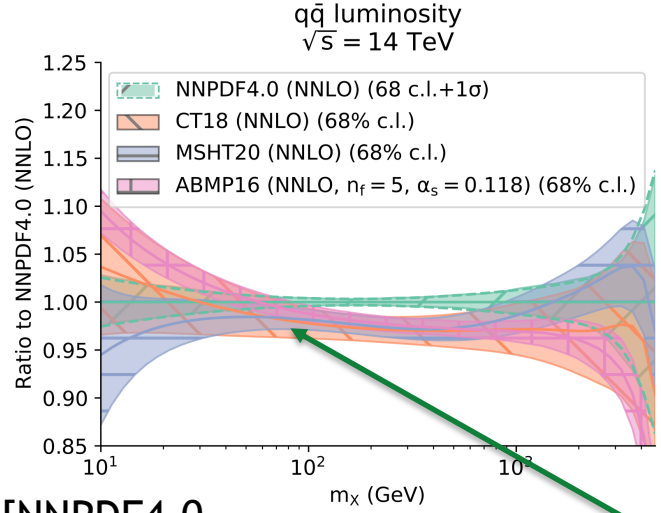
[NNPDF4.0, Eur Phys J C82 (2022) 428]

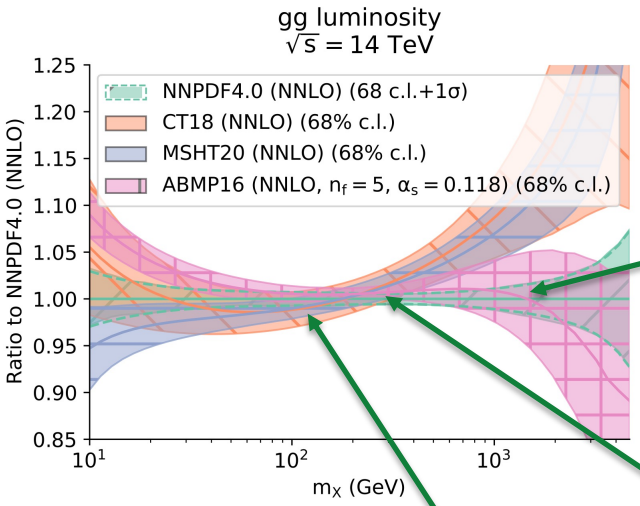
Including LHC data brings:
Advantages: improve precision, exploit all available inputs

Caveats: use of data that may contain BSM effects, theoretical complexity (eg non-perturbative input), some incompatibilities between data sets

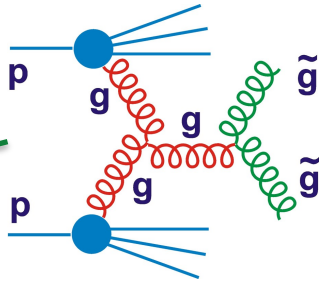
Current State of the Art / Motivation

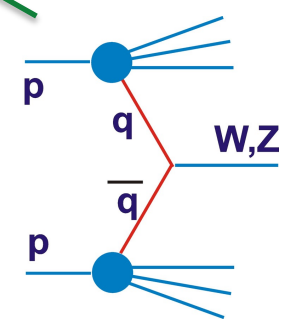
e.g. Comparisons between current global fits on LHC $q\bar{q}$ and gg luminosities

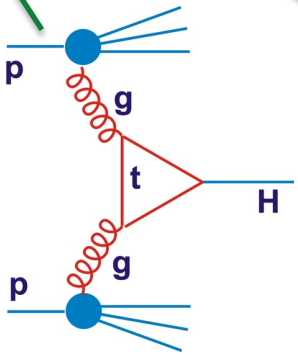


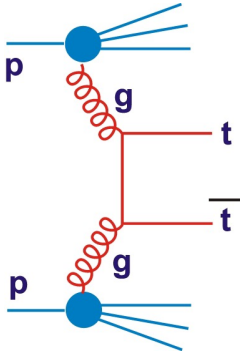


[NNPDF4.0 ,
Eur Phys J C82 (2022) 428]







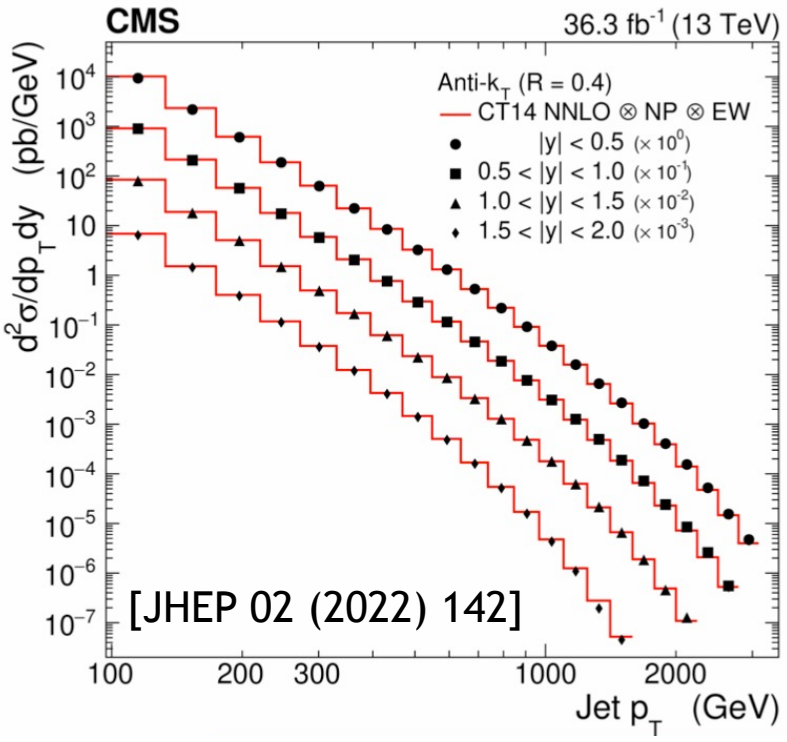


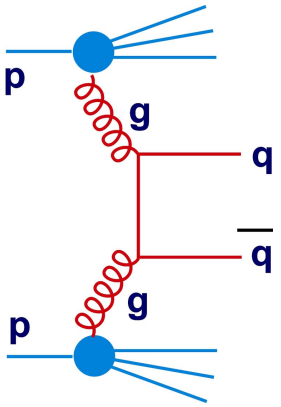
- Knowing initial state often limits precision measurements & searches

Many more reasons to improve PDF precision:

- Cosmic ray air showers
- Neutrino interactions with matter
- Understanding strong interaction dynamics …

e.g. Jets & the Gluon Density



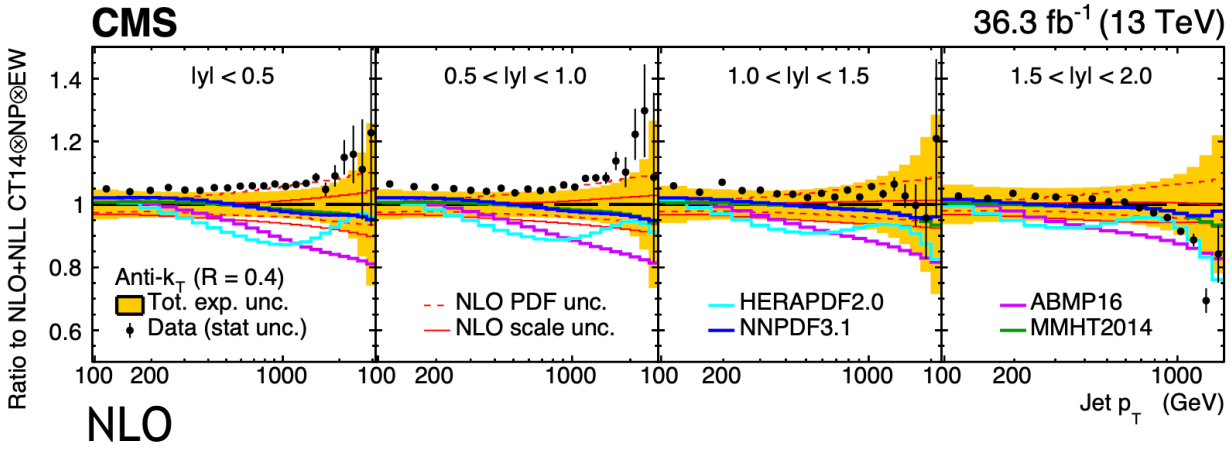


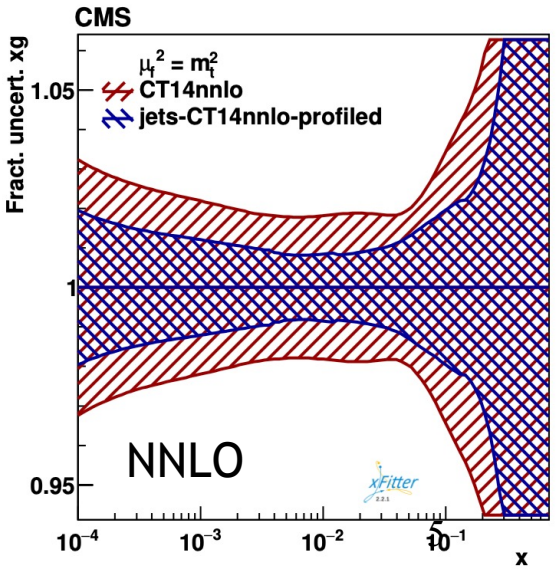
CMS 13 TeV inclusive jets versus PDF sets that include LHC run 1 data

Deviations at typically 5% level, getting worse at largest p_T (highest x)

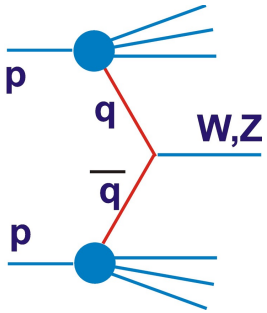
… improved constraints on gluon density

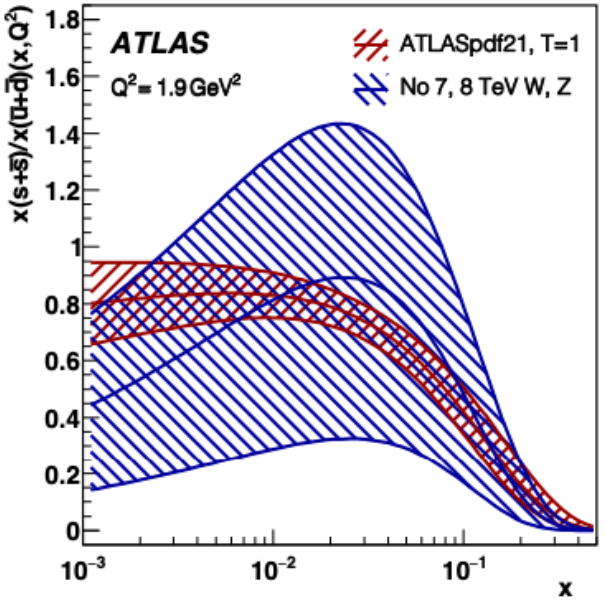
$$x_{1,2} = \frac{p_T}{\sqrt{s}} e^{\pm y}$$





e.g. W, Z, Drell-Yan & Quark Densities





[EPJ C82 (2022) 438]

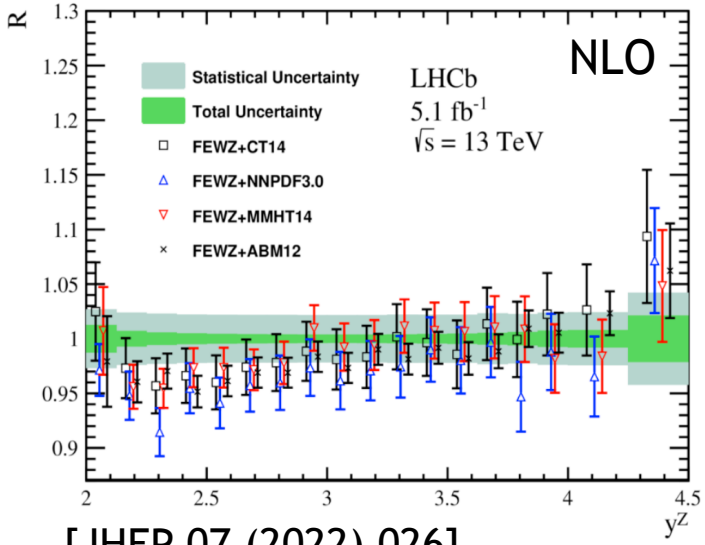
e.g. In ATLAS 'global fit', W & Z data provide flavour decomposition

→ At low x, strange only slightly suppressed compared with up and down

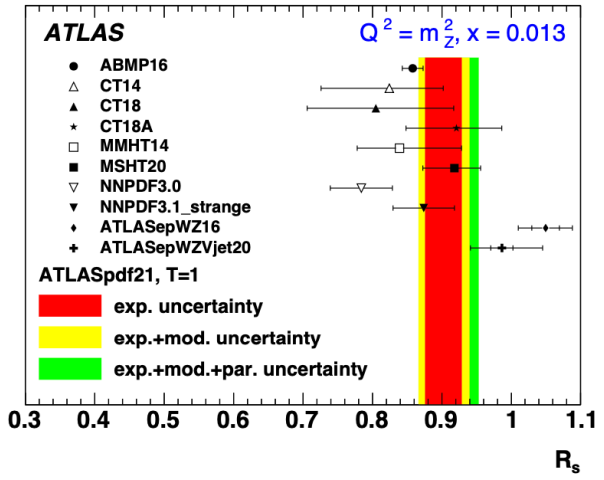
$$x_{1,2} = \frac{M_{W/Z}}{\sqrt{s}} e^{\pm y}$$

e.g. Favourable LHCb kinematics

→ Improved u,d constraints at low and (mostly) high x



[JHEP 07 (2022) 026]

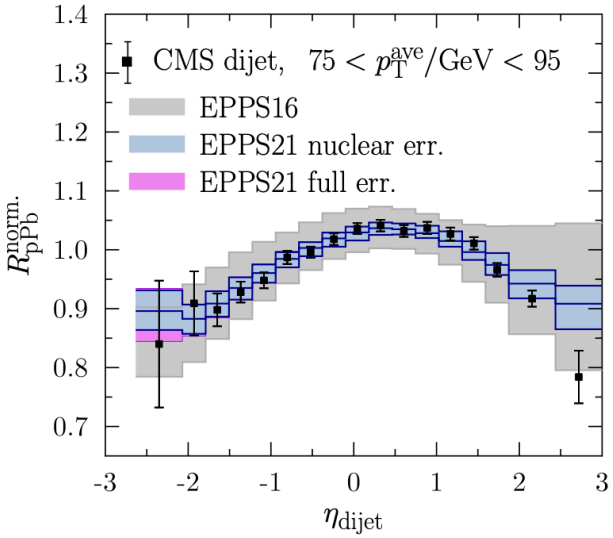


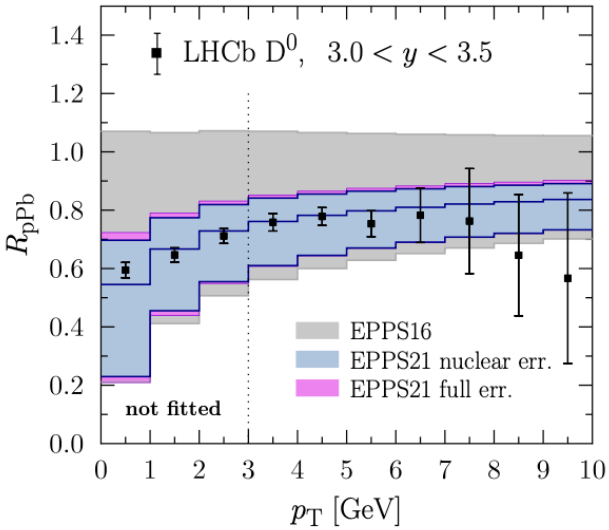
- Some further progress expected at HL-LHC [eg EPJ C78 (2018) 962]

Nuclear Parton Densities

- Nuclear effects in PDFs still not fully understood.
- Important e.g. for initial State in QGP studies

- Progress with Jlab, RHIC and LHC pPb → **Examples from EPPS21**





[EPJ C82 (2022) 413]

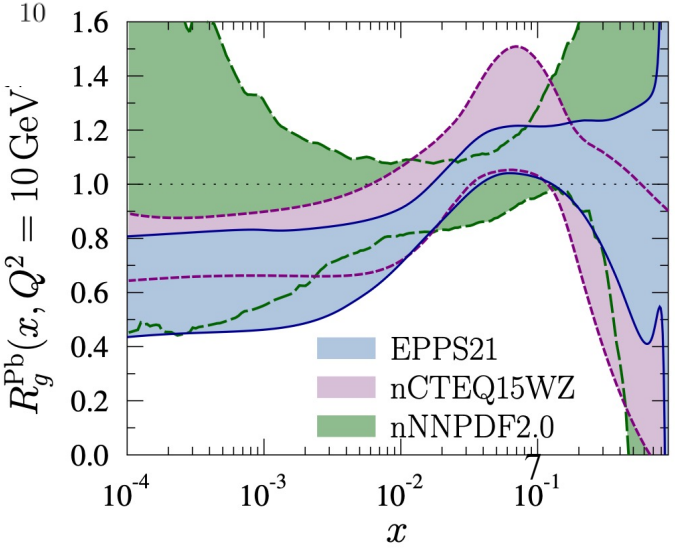
- CMS central jets
- LHCb forward D^0

expressed through:

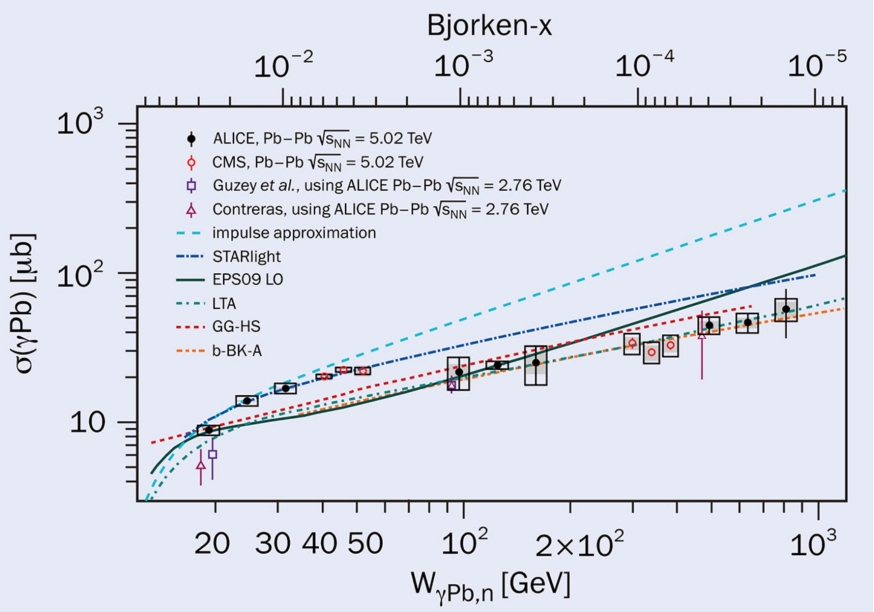
$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

- Still large uncertainties at low x, where there may be new density-driven dynamics

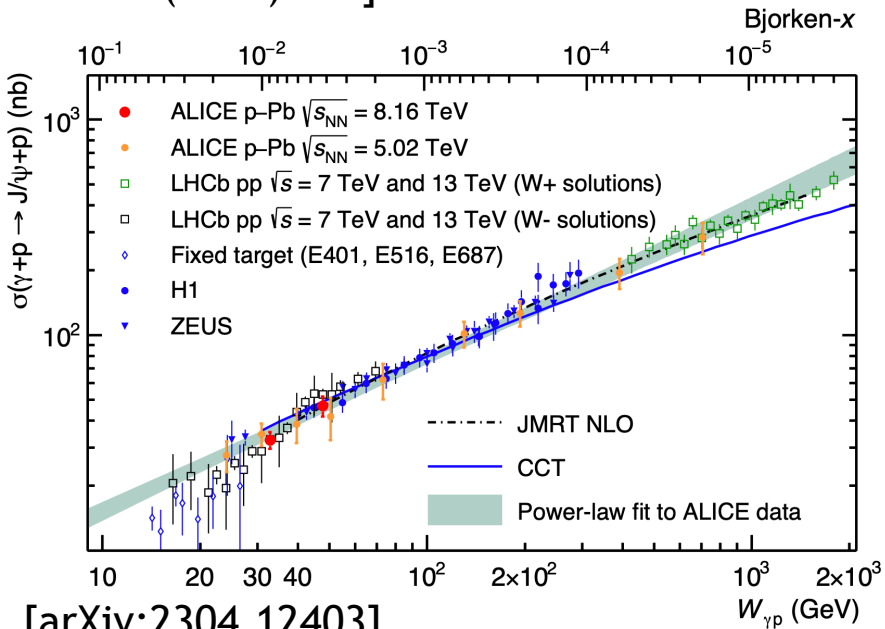
- Future LHC prospects e.g. with ALICE FOCAL



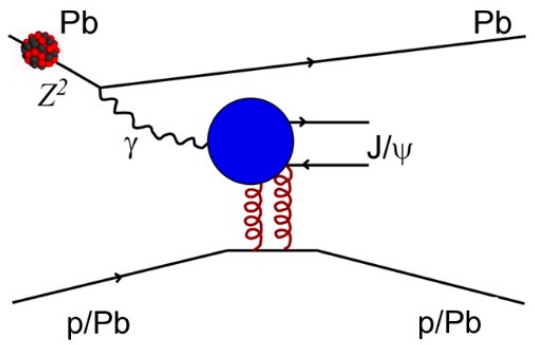
Ultra-peripheral Collisions and the Gluon



[JHEP 10 (2023) 119]



[arXiv:2304.12403]



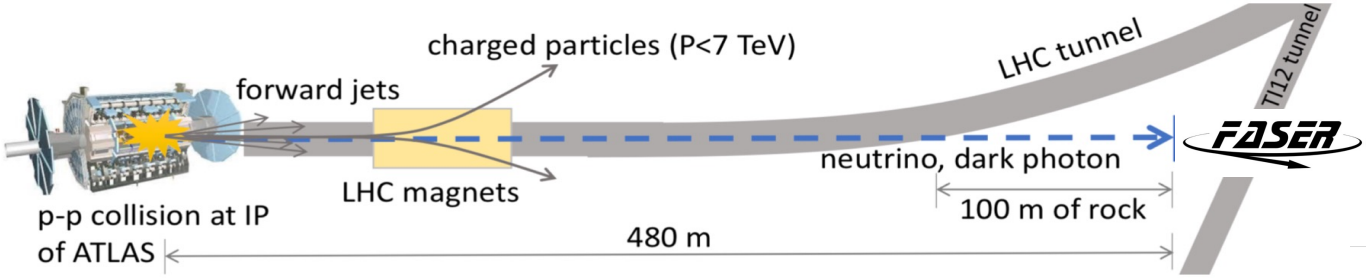
Ultra-peripheral collisions being studied in AA at RHIC and LHC: e.g. J/Ψ

→ γA → J/Ψ A cross-sections
→ Clear suppressions relative to simply scaled protons, extending to $x \sim 10^{-5}$.

Corresponding pp, pPb data:
→ γp → J/Ψ Pb
→ Sensitivity to gluons in the proton

Excellent data, limitations are in partonic interpretation

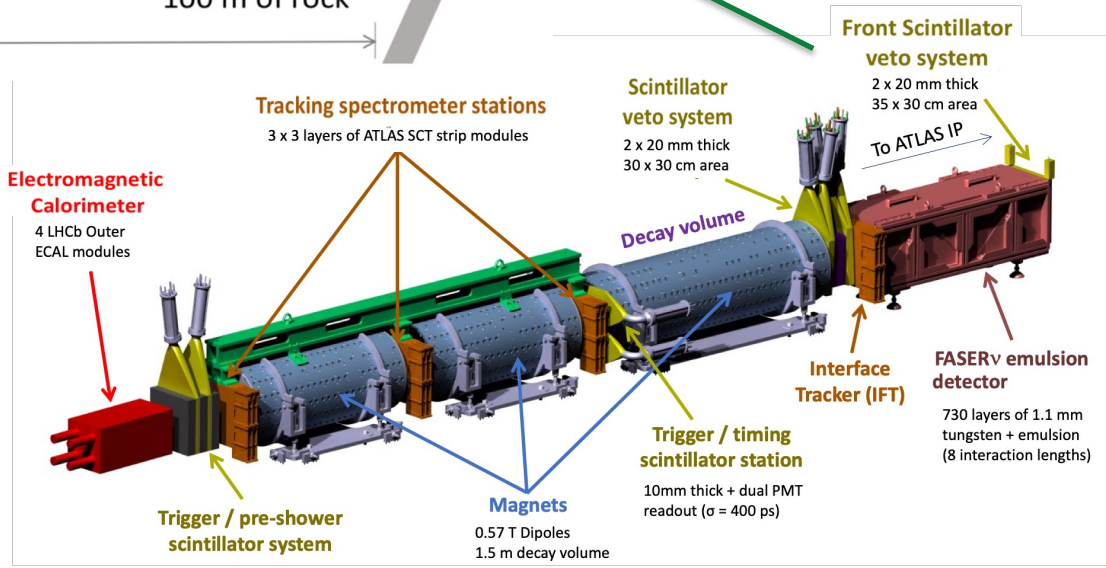
FASER: Neutrinos from the LHC

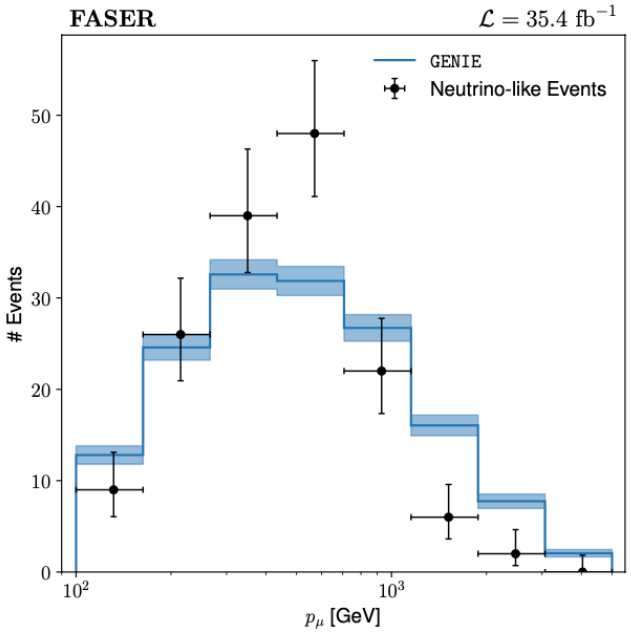


As part of a much wider programme:

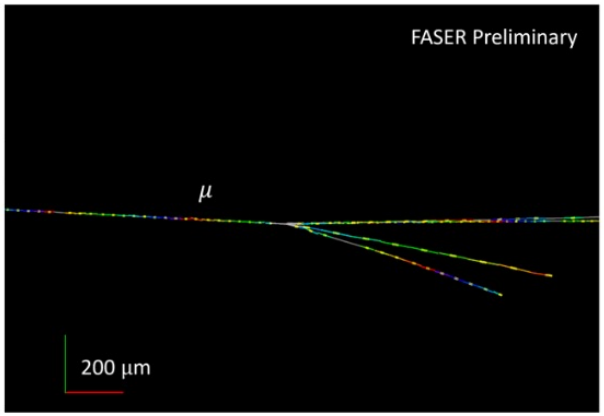
First observation of collider neutrinos (TeV scale)

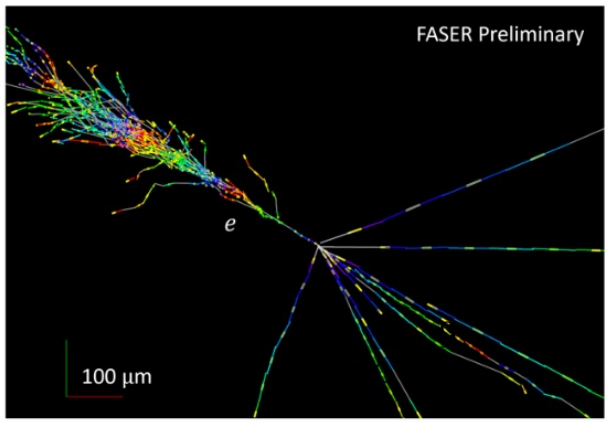
- 153 $\mu^{\pm}$ appearance (16σ)
- 3 e appearance (5σ)



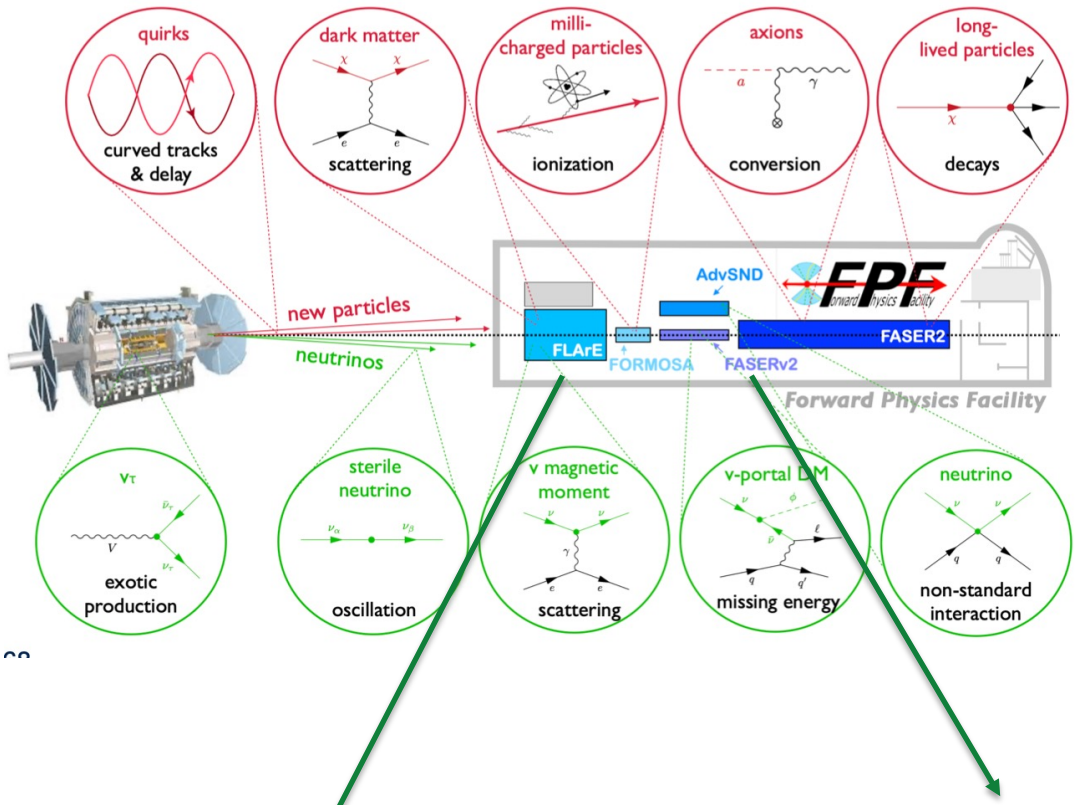


[Phys. Rev. Lett. 131 (2023) 031801]

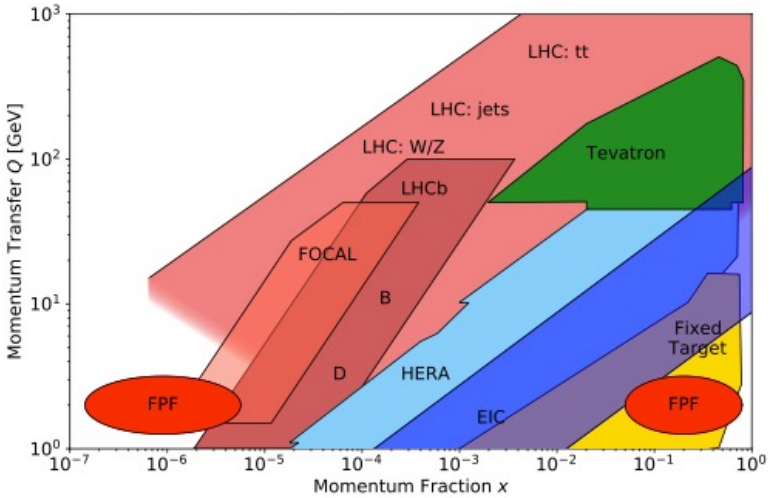




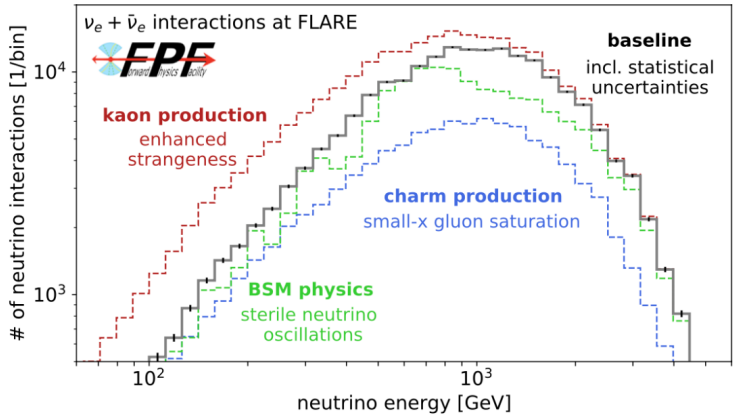
Forward Proton Facility for the HL-LHC

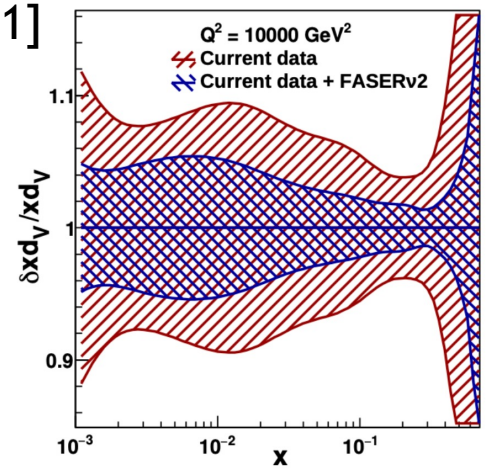


Proposal to create a forward multi-experiment facility



[arXiv:2309.09581]





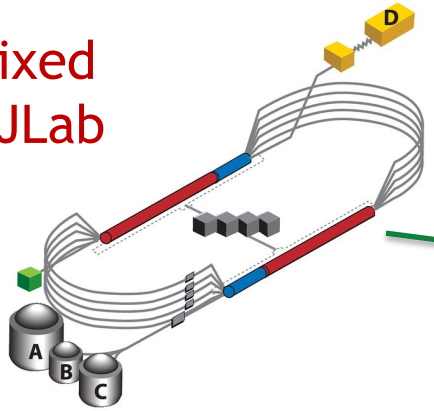
… very forward fixed target neutrino scattering

… ~10^6 observable ν_μ interactions

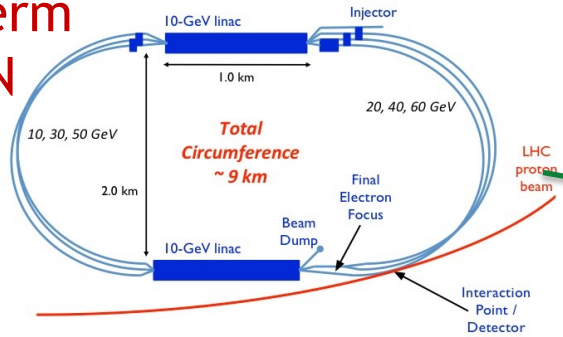
→ PDF constraints on valence densities and flavour decomposition

Current and Future ep Colliders

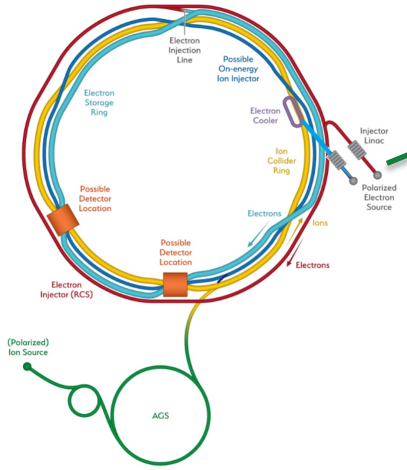
Ongoing fixed target @ JLab

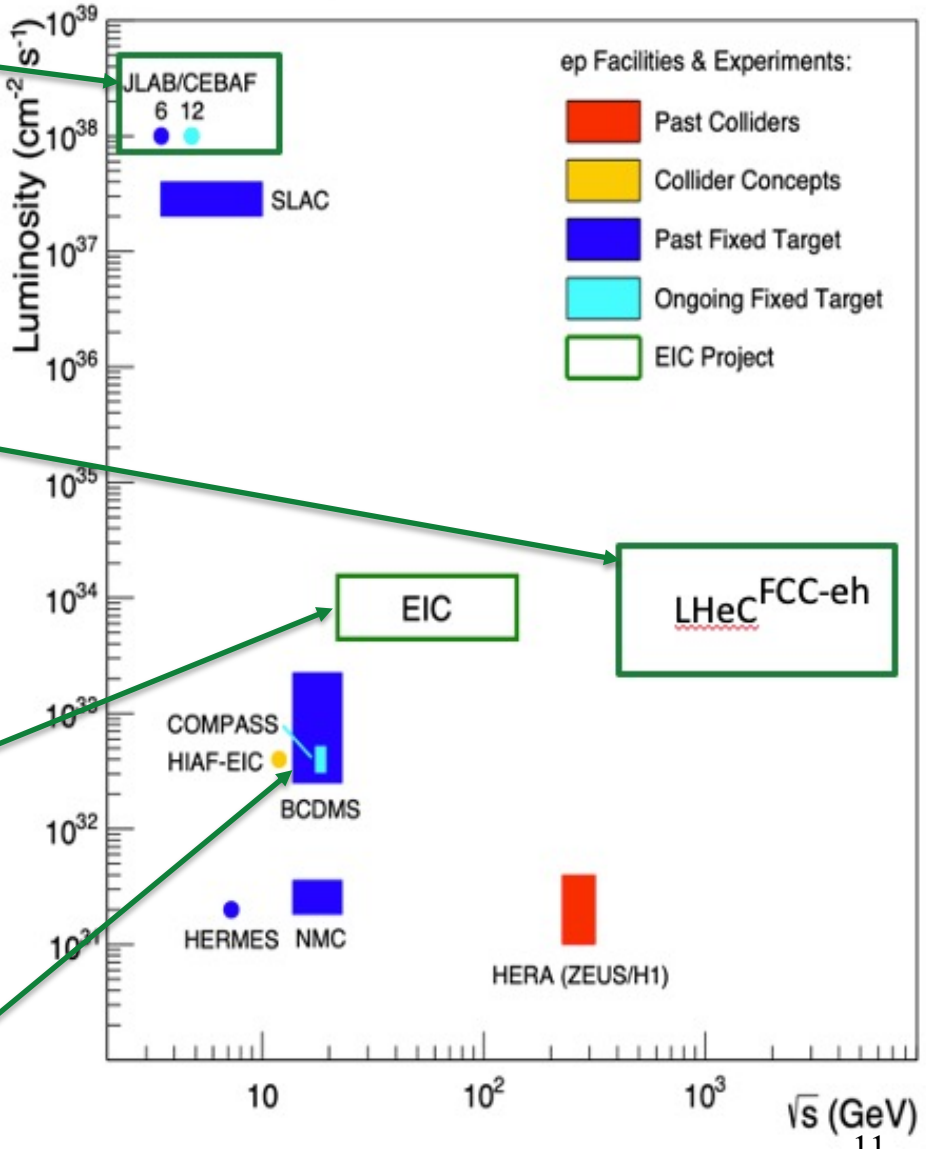


Longer-term @ CERN



On-target for early 2030s @ BNL





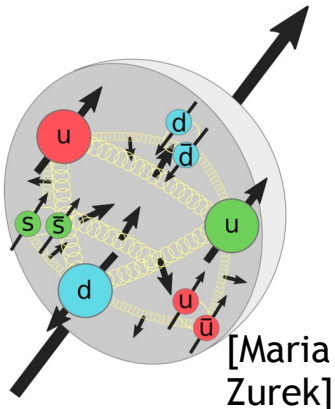
[COMPASS @ CERN also took muon data on polarised deuterons in 2021-22]

Physics at JLab CEBAF 12 GeV

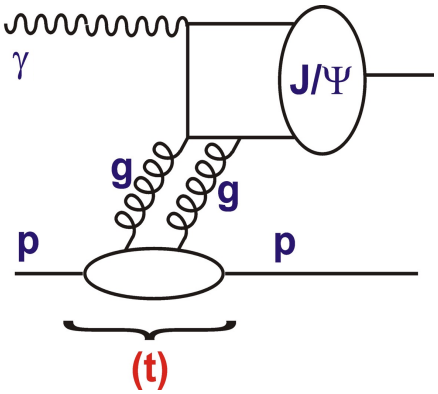
Extensive programme emphasizing 3D tomography, including:

- High x longitudinal structure
- Unravelling the spin puzzle
- Precision nuclear effects in valence region

[much of which is mirrored in EIC context]

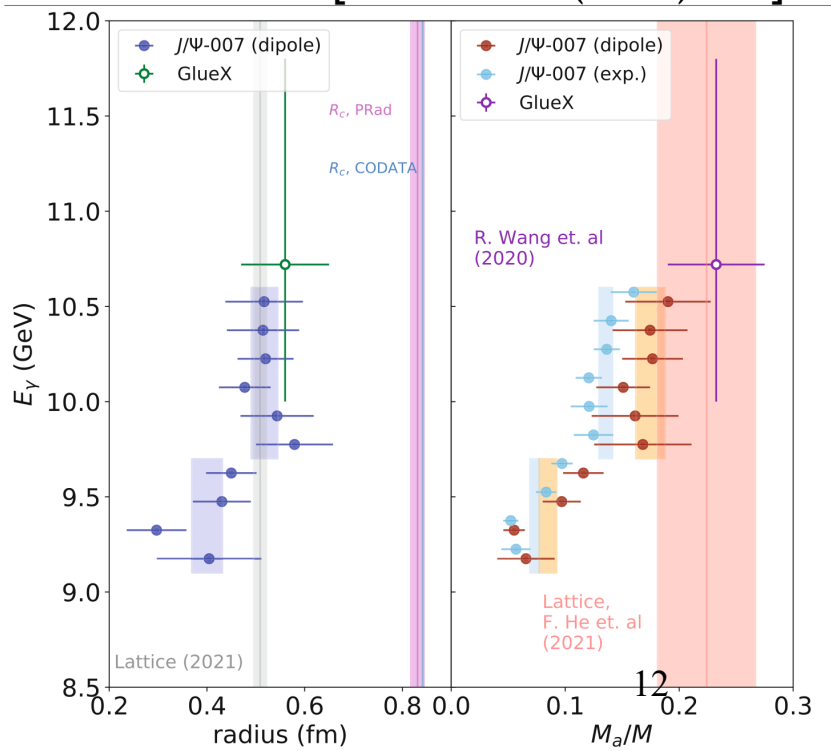


[Maria Zurek]



e.g. Recent data on t dependences of J/Ψ photoproduction near threshold

[Nature 615 (2023) 813]



Interpreted in terms of proton gravitational form factors:

- Mass radius notably smaller than charge radius
- Extraction of QCD trace anomaly (contribution to proton mass)

The Electron-Ion Collider (BNL)

See Ferdi Willeke, Thursday

New electron ring, to collide with RHIC p, A

- **Construction scheduled from 2025**
- **Operations / science from early 2030s**

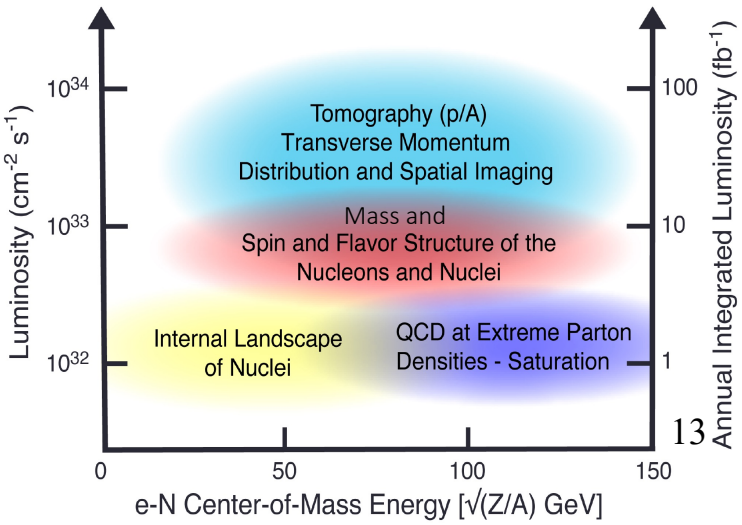
- Energy range **28 < $\sqrt{s}$ < 140 GeV**, accessing moderate / large x values compared with HERA

World's first …

- High lumi ep Collider **(~ 10^{34} cm^{-2} s^{-1})**
- Double-polarised DIS collider
  (~70% for leptons and light hadrons)
- eA collider **(Ions ranging from H to U)**

Specifications driven by science goals:

- 3D proton structure
- Proton mass
- Proton spin
- Dense partonic systems in nuclei



A Detector for the EIC

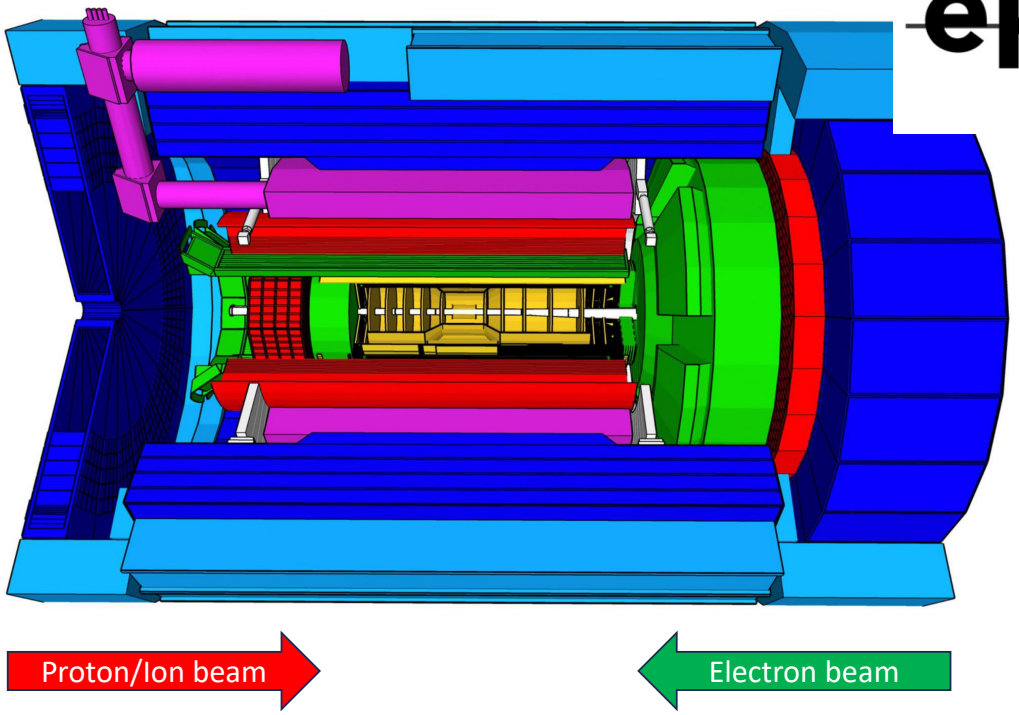
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

PID
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

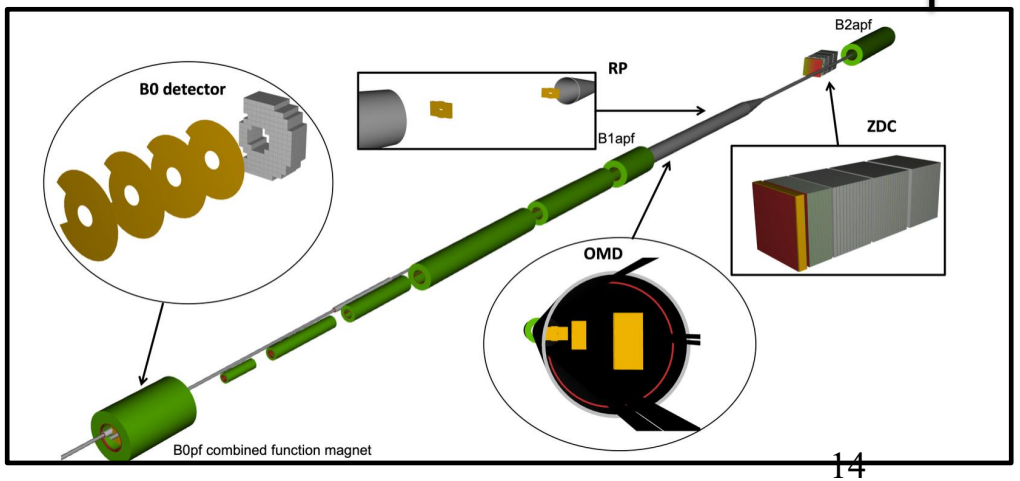
Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



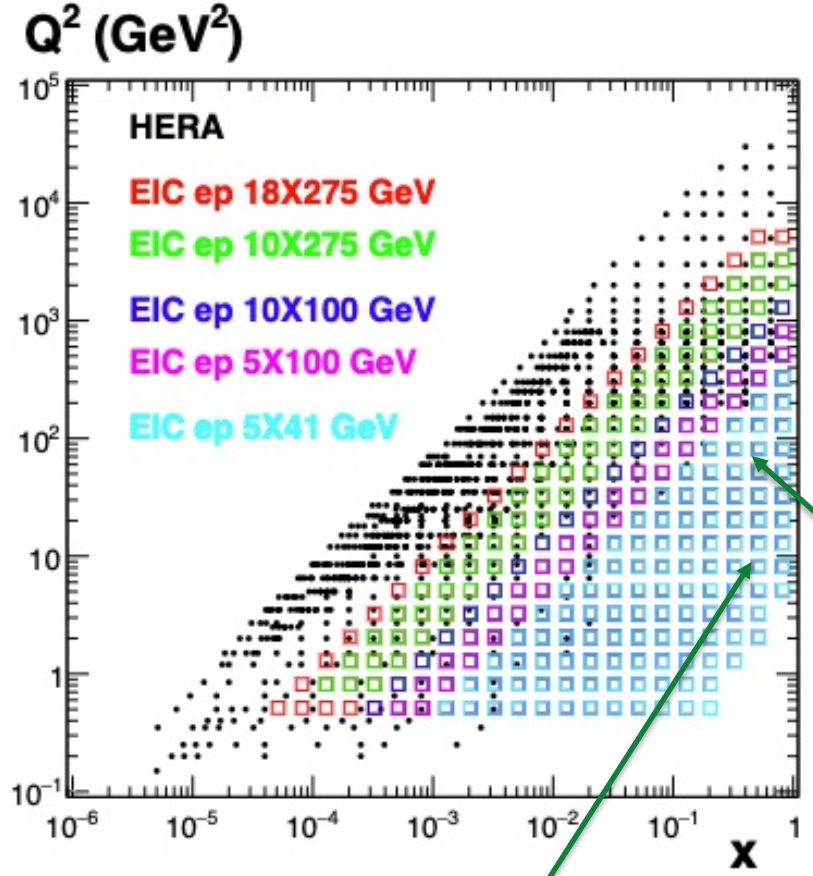
- Optimised for inclusive, semi-inclusive and exclusive DIS

- Emphasis on forward & backward instrumentation, integrated in interaction region design

- Ongoing work towards a second, complementary detector



EIC Physics Motivation: Inclusive DIS on Proton



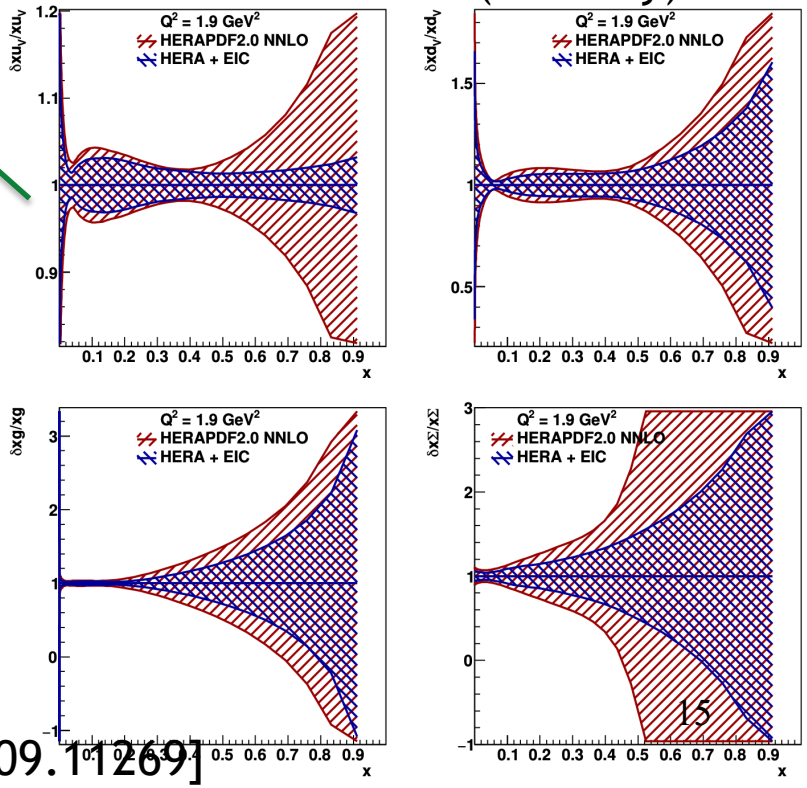
Precision at large x, intermediate Q^2, complementing HERA and fixed target

Newly accessed region ideally suited to constrain high x PDFs and offers potentially world-beating α_s precision

$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004\ (\text{exp})\ {}^{+0.0002}_{-0.0001}\ (\text{model} + \text{parameterisation})$$

[Eur Phys J C83 (2023), 1011]

Improvement relative to HERAPDF2.0 (DIS only) PDFs



[arXiv:2309.11269]

EIC Physics Motivation: Proton Spin

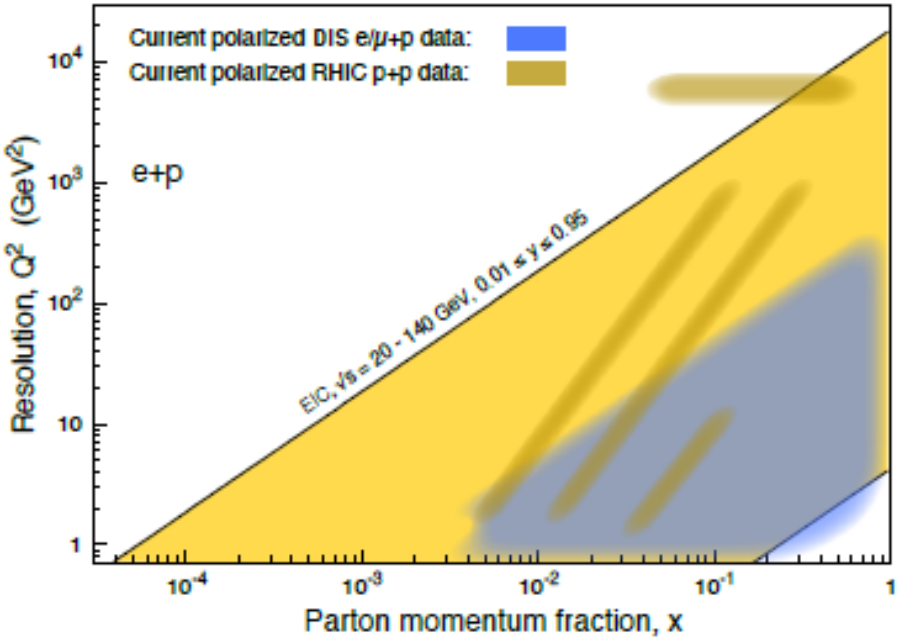
EMC ‘spin crisis’ (1987) - quarks carry only ~10% of proton spin …

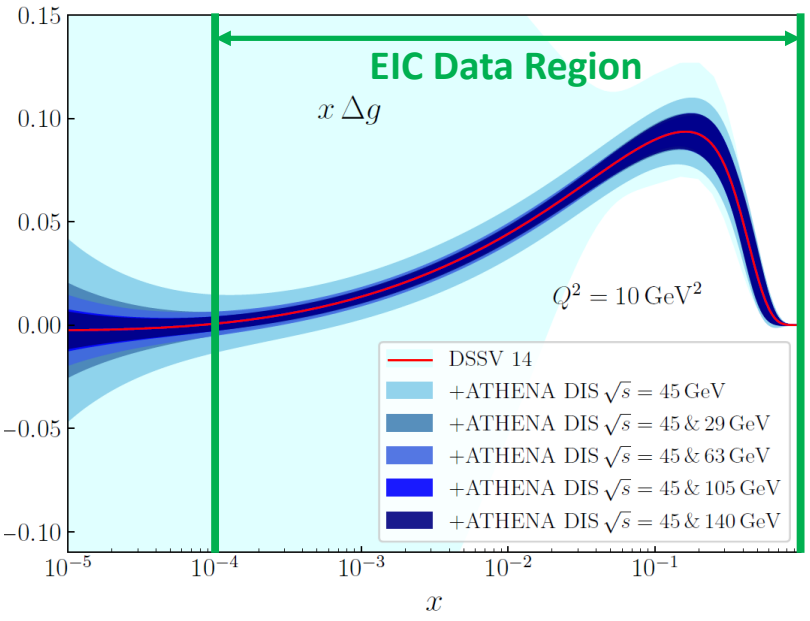
Viewed at the parton level:

Jaffe-Manohar sum rule:

$$\frac{\Delta\Sigma}{2} + \Delta G + \ell_q + \ell_g = \frac{\hbar}{2}$$

Quark helicity | Gluon helicity | Quark canonical orbital angular momentum | Gluon canonical orbital angular momentum





Can be resolved in full with EIC inclusive, semi-inclusive and exclusive data

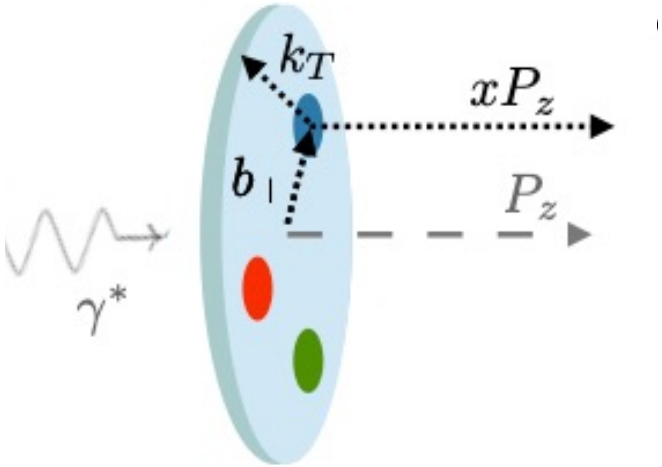
e.g. impact relative to recent global fit (DSSV14) of inclusive EIC data (double spin asymmetries 15fb^{-1} and 70% e,p polarization)

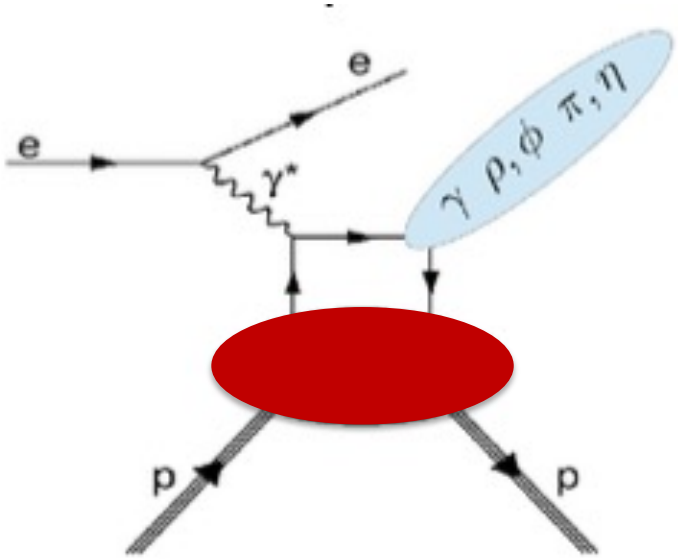
EIC Physics Motivation: 3D Structure

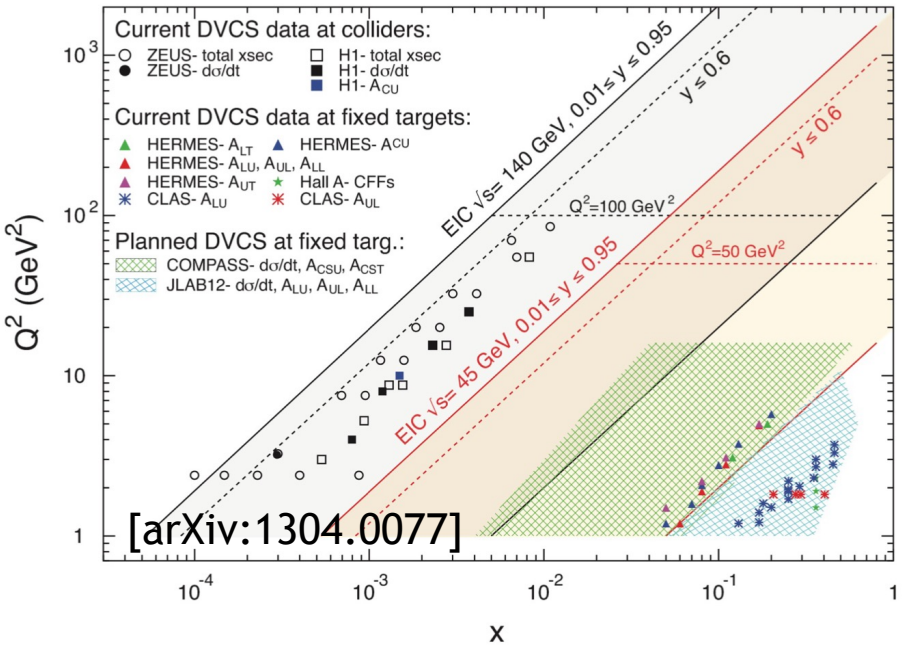
Exclusive processes, yielding intact protons, require (minimum) 2 partons exchanged

→ Sensitivity to correlations between partons in longitudinal / transverse momentum and spatial coordinates

→ access to 3D tomography







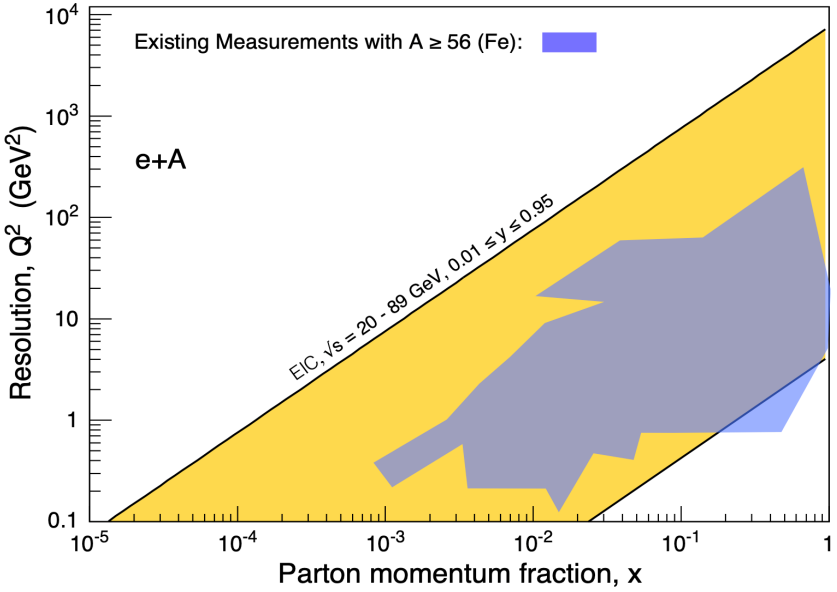
e.g. **Deeply Virtual Compton Scattering, ep → eγp**:

EIC fills gap between (high stats) fixed target & (low stats) HERA data

EIC Physics Motivation: Dense Gluonic Systems

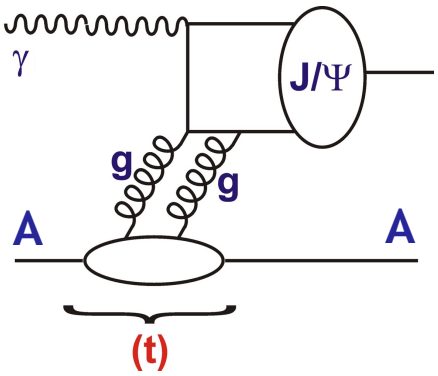
Nuclei enhance density of partons (“ $A^{1/3}$ ” factor)

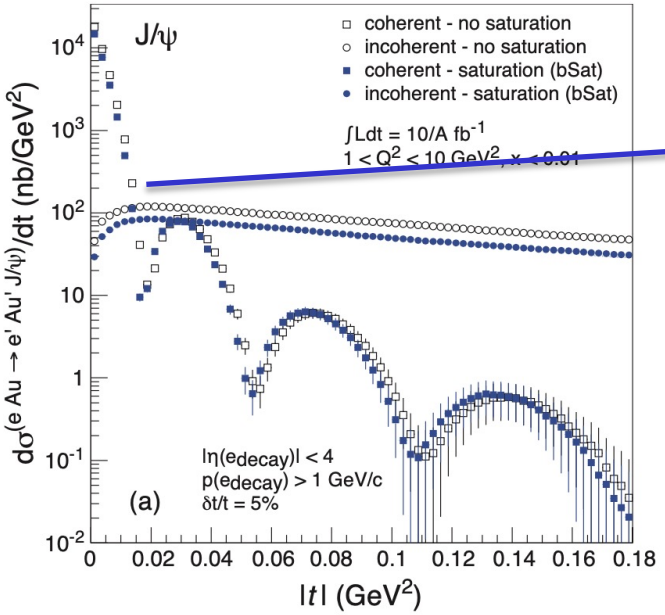
→ Very large impact on eA phase space, extending into expected region of density effects

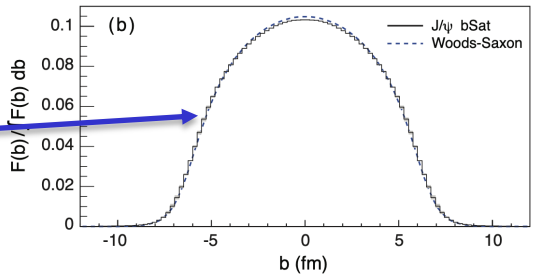


Mandelstam t in exclusive processes conjugate to transverse spatial distributions

→ Fourier transform the target



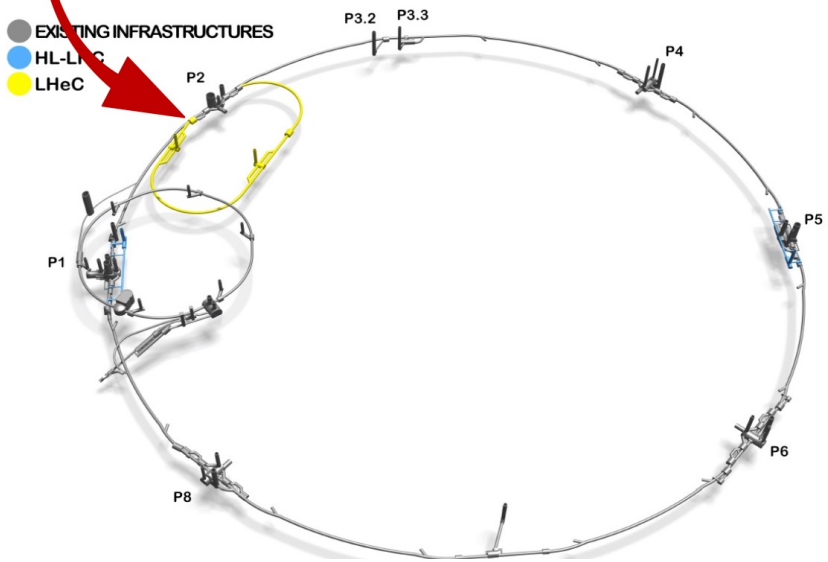




e.g. Coherent J/Ψ in eAu: dips sensitive to saturation

Future ep and eA Options at CERN

LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)

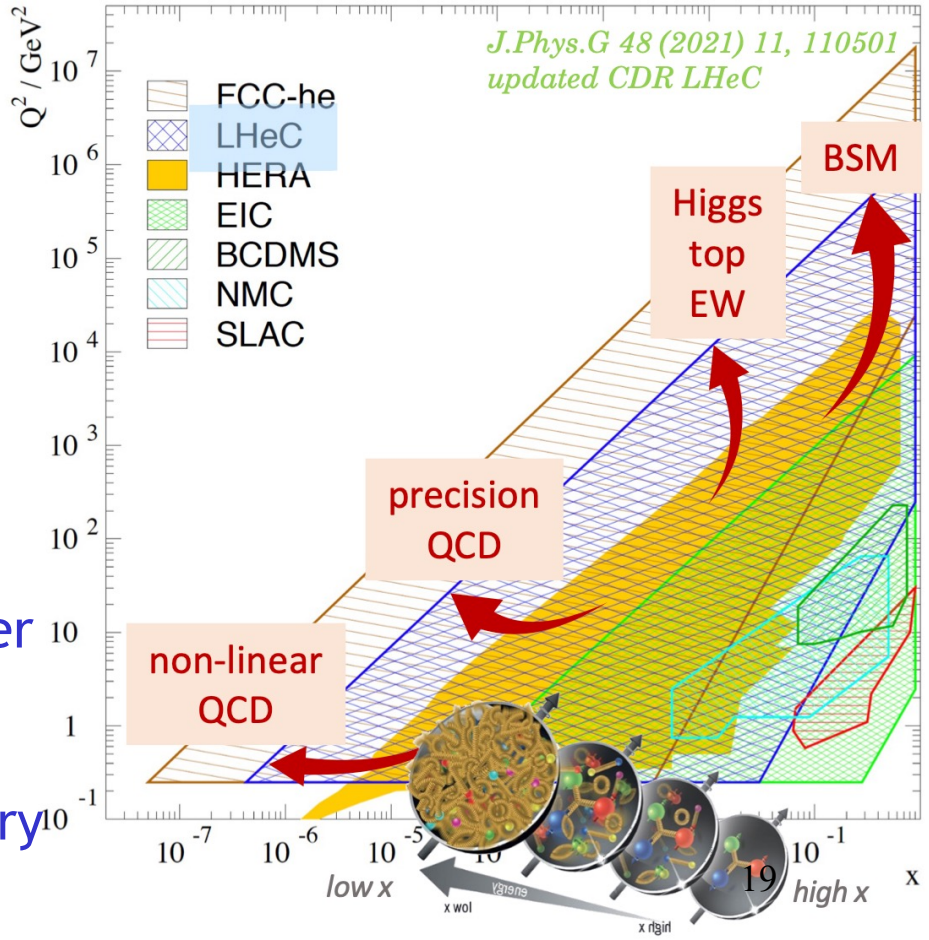


FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh

- Extending lepton-proton energy frontier by up to 2 orders of magnitude

- Crucial technical step: Energy Recovery Linac prototype (PERLE @ Orsay)

Renewed mandate, structure and coordination (J d'Hondt)
See https://indico.cern.ch/event/1335332/



Example LHeC and FCC-eh Physics

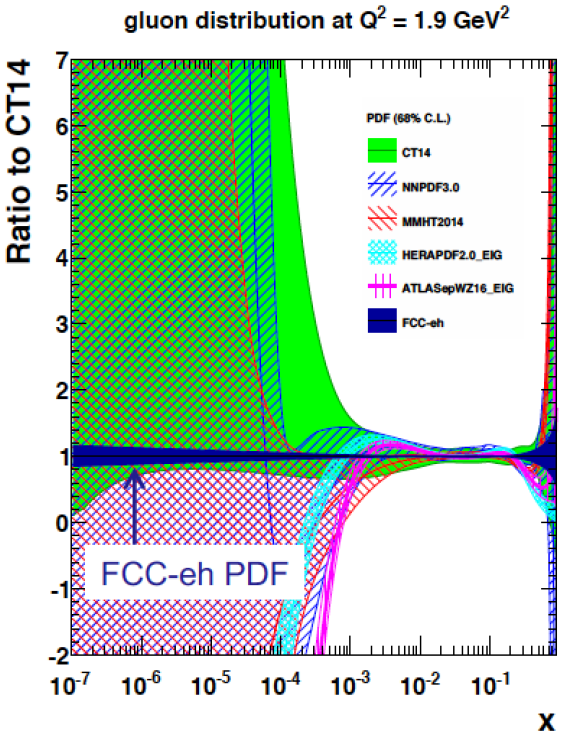
Revolutionary proton PDF precision

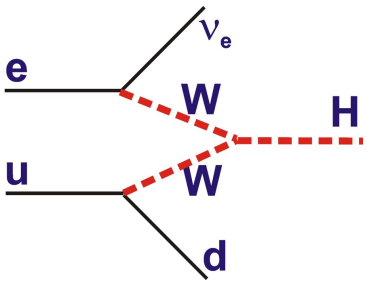
→ Facilitates LHC / FCC-hh precision measurements and BSM searches

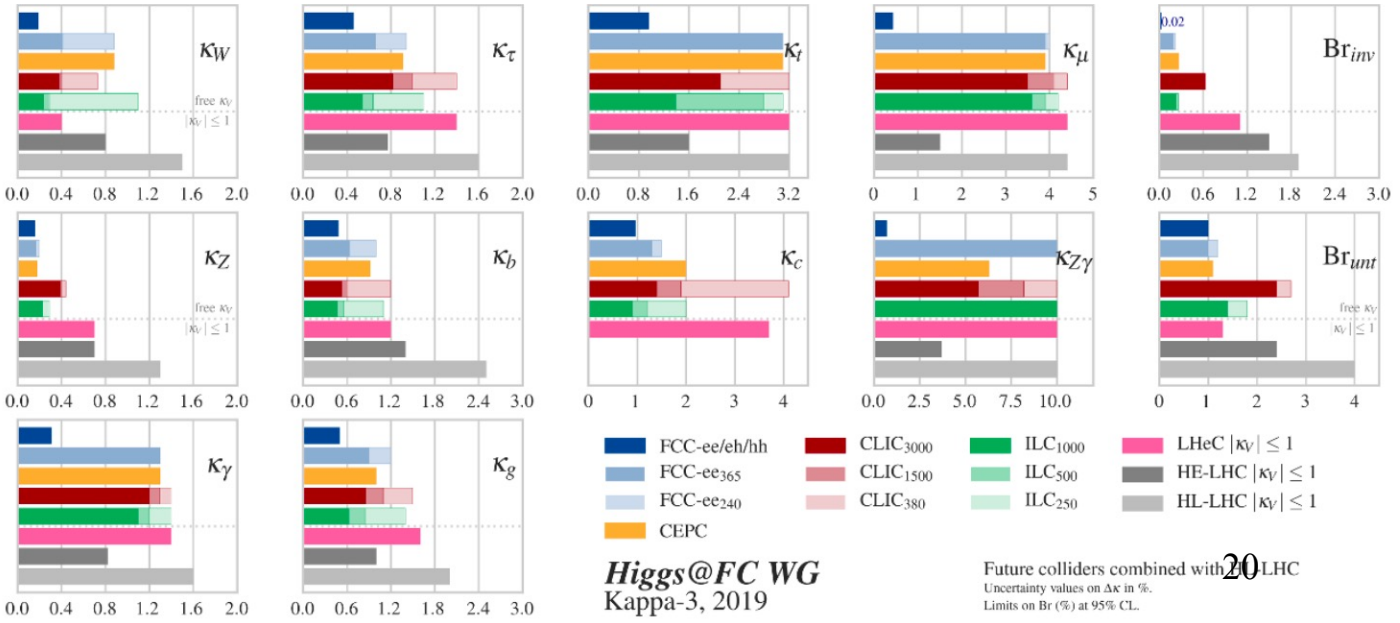
→ Elucidates very low x dynamics in ep / eA

Impactful Higgs programme

→ Complements HL-LHC (and FCC-ee / FCC-hh)







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following Sarah Heim]

SUMMARY

Progress continues on proton and nuclear longitudinal (and spin) structure

→ Better understanding may yet be needed for full exploitation of LHC

Current / future facilities are revealing the 3D structure and dynamics of strongly interacting matter in new ways

→ Electron-Ion Collider on course to transform the picture from early 2030s

Apologies for the many uncovered topics

Thanks to J d'Hondt, S Dalla Torre, R Ent, K Wichmann, & many other colleagues

"Circles in a circle"
Wassily Kandinsky (1923)
Philadelphia Museum of Art