CERN Council Open Symposium on the Update of the European Strategy for Particle Physics
Granada, Spain, May 15th 2019

Strong interaction physics at future eA colliders

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Unión Europea
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"
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GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Contents:

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Main contributions: 159 (LHeC/FCC-eh), 99 (US-based EIC) and 103 (DIS).

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Nuclear structure functions:

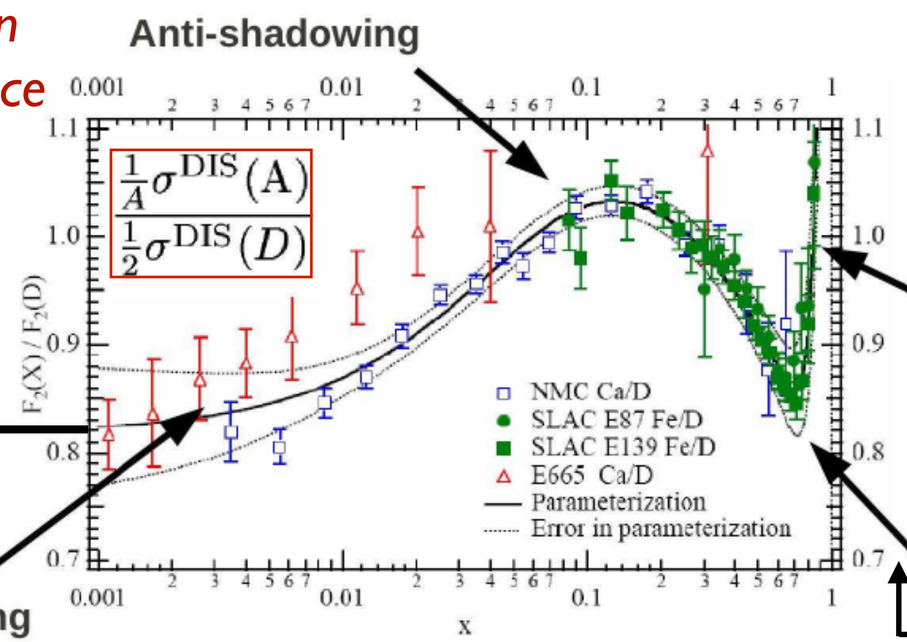
How much does the structure of a hadron change when it is immersed in a nuclear medium?

Flavour dependence?; relation with shadowing and coherence

ePb at LHeC/ FCC-eh

eAu at EIC

Multiple scattering, saturation,…; high-energy QCD



Short versus long range correlations, pion cloud, intrinsic charm,…

Superfast quarks

- Bound nucleon $\neq$ free nucleon: search for process independent nPDFs that realise this condition, within collinear factorisation.

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} \underbrace{f_i^A(\mu^2)}_{\text{Nuclear PDFs, obeying the standard DGLAP}} \otimes \underbrace{\hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)}_{\text{Usual perturbative coefficient functions}}$$

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

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

Small-x physics:

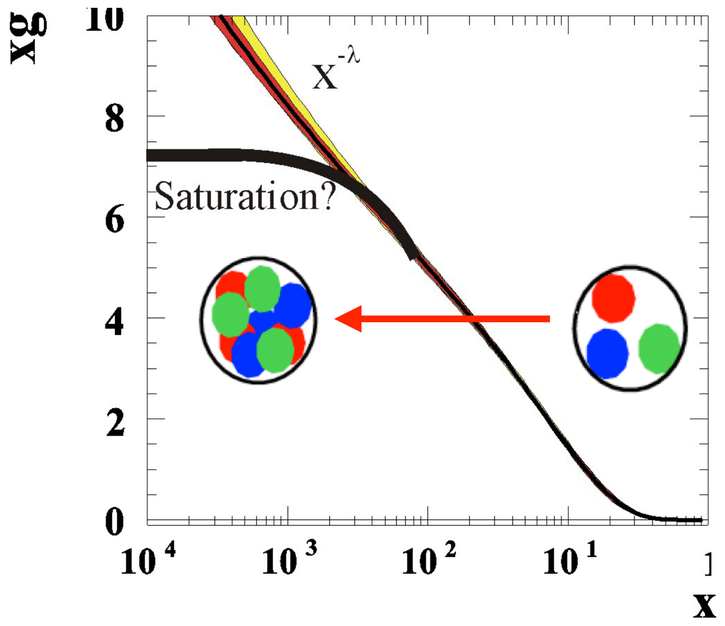
- HERA found xg α $x^{-0.3}$.
- Present data can be described by:
  - ➜ Linear evolution approaches, either DGLAP or resummation at low x.
  - ➜ Non-linear approaches - weak coupling but high density: saturation.

- Theory: at high energies (i.e. small x), non-linear dynamics must be present.

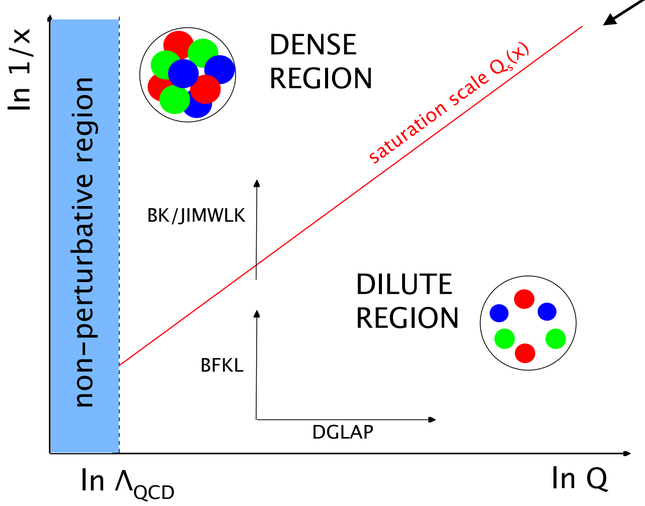
Where is it? At HERA:
  - ➜ Hints of failure of DGLAP at small x, Q^2, resummation?
  - ➜ No ridge azimuthal structures yet found.

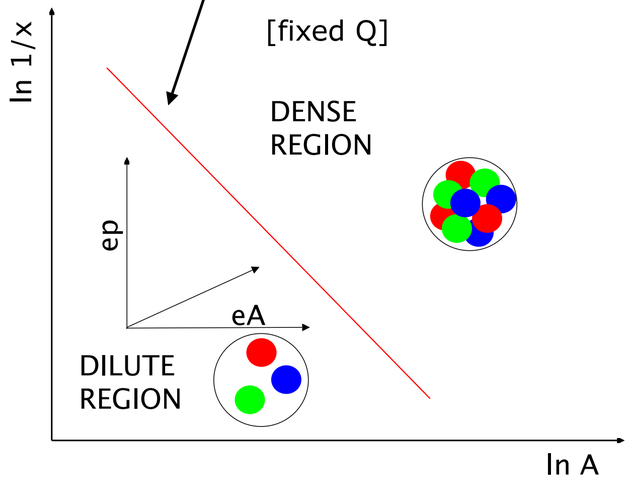
- Saturation is density-driven: ↓x/↑A ⇒

ep&eA + large range in 1/x & Q^2 essential for full understanding.



$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$





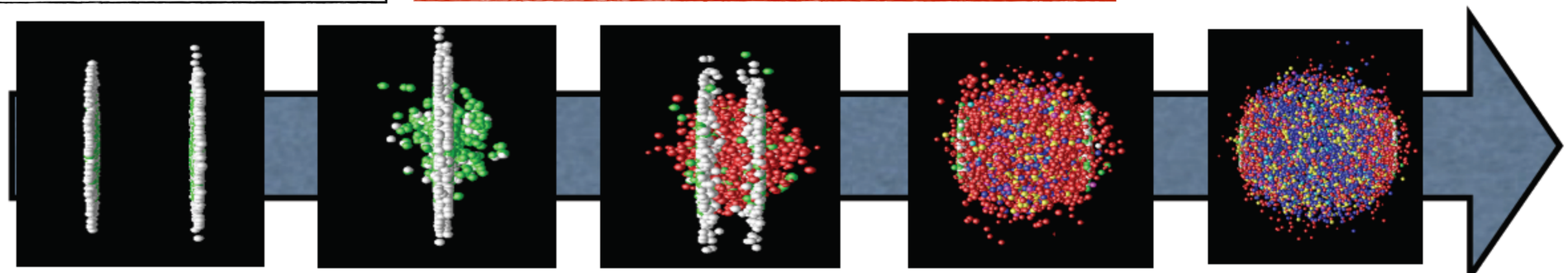
Implications on pA/AA:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).

- Medium behaves very early like a low viscosity liquid: macroscopic description.

- Medium is very opaque to coloured particles traversing it.

[B. Cole]



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

- How isotropised the system becomes?
- Why is hydro effective so fast, which dynamics?

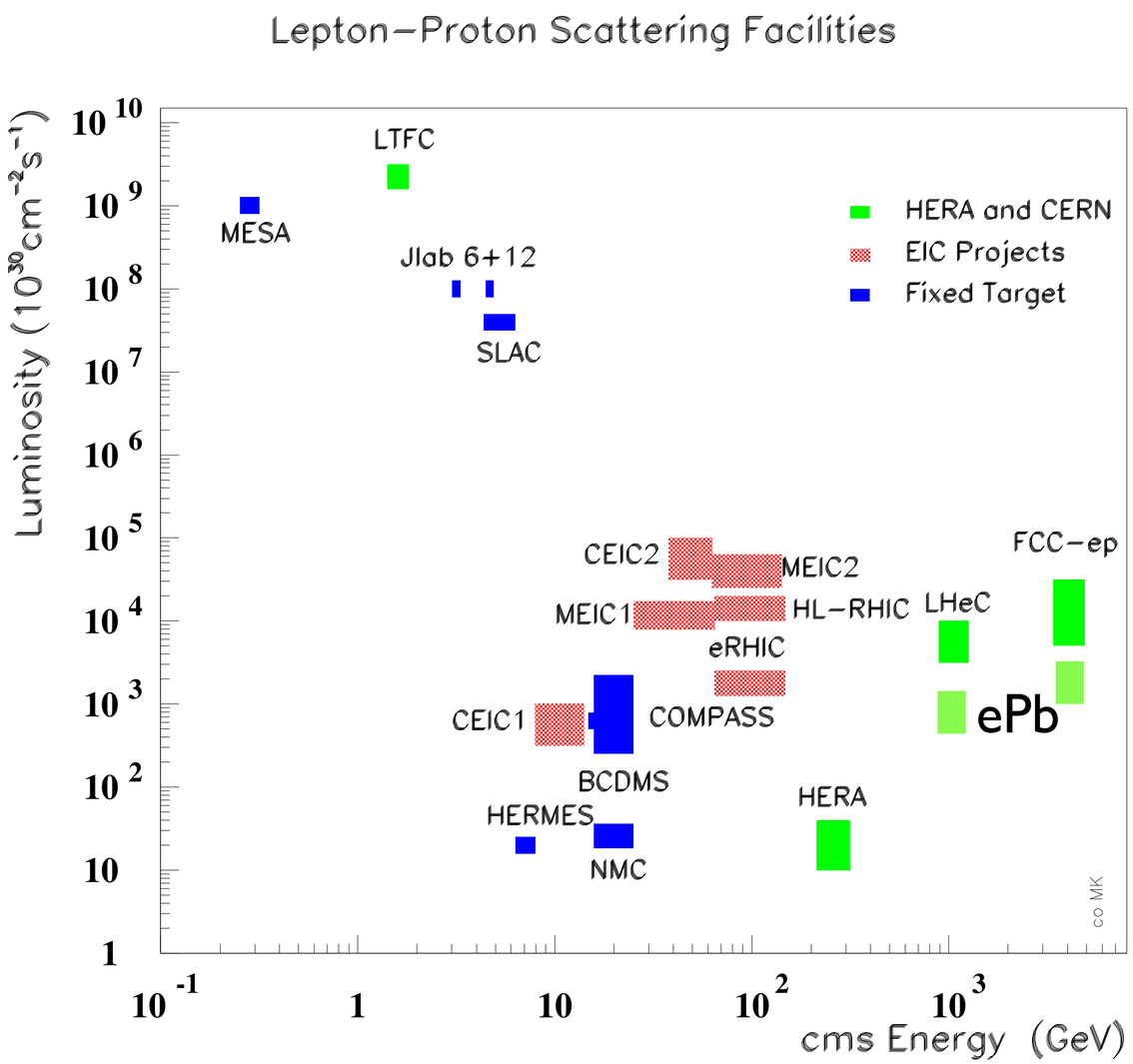
- Dynamical mechanisms for such opacity? Weak or strong coupling?
- How to extract accurately medium parameters?

➜ eA: nuclear WF and mechanism of particle production.

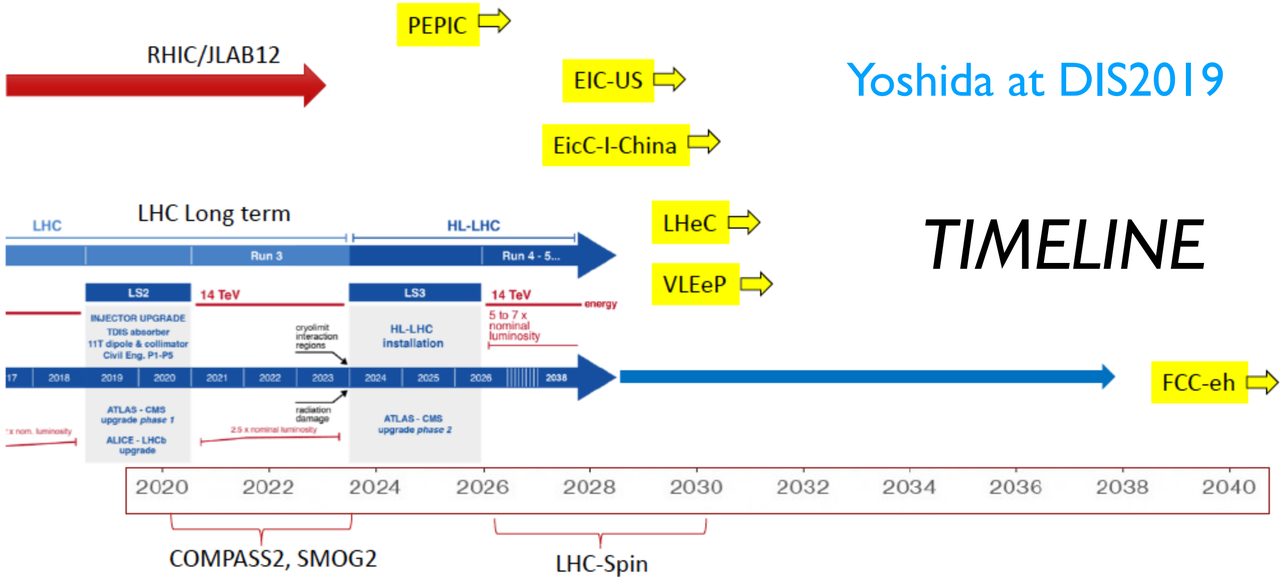
➜ eA: initial conditions; how small can a system become and still show 'collectivity'?

➜ eA: in-medium QCD radiation, cold nuclear effects on hard probes.

Machines:



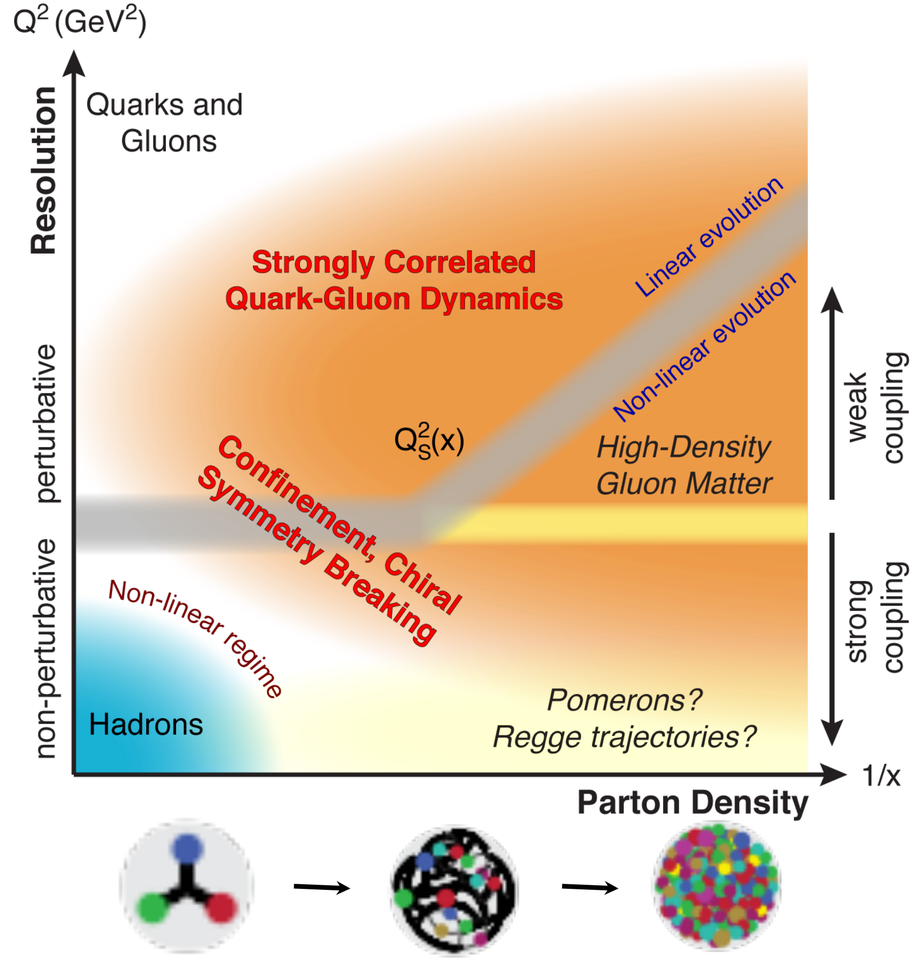
- ***Projects of eA colliders with E_{cm} ~ $\mathcal{O}$(0.1) TeV/A (EICs at US and China) and $\mathcal{O}$(1) TeV/A (LHeC and FCC-eh at CERN) addressing different physics.***



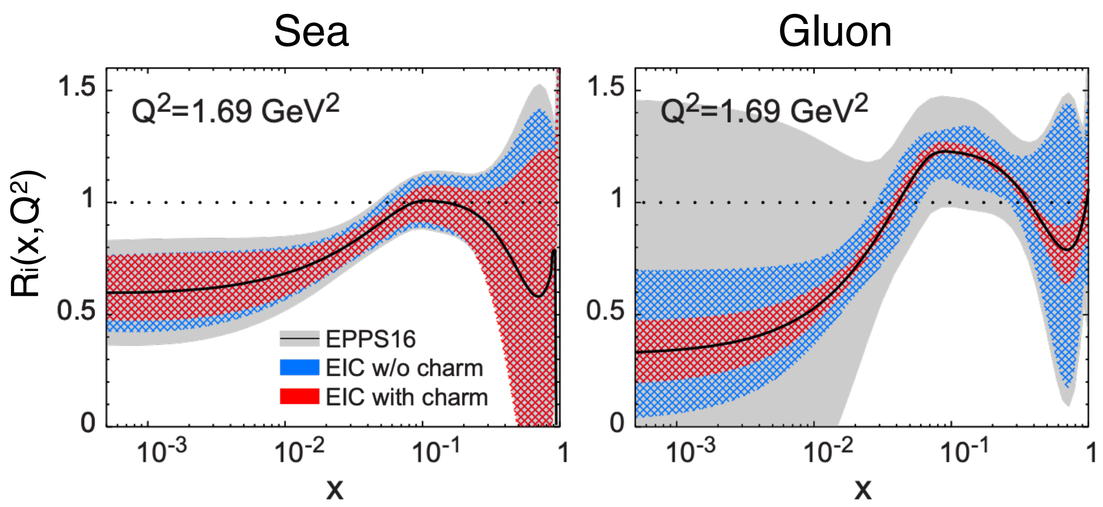
Physics cases:

The EIC Physics Pillars

QCD dynamics / Parton distributions in nuclei



arXiv:1212.1701

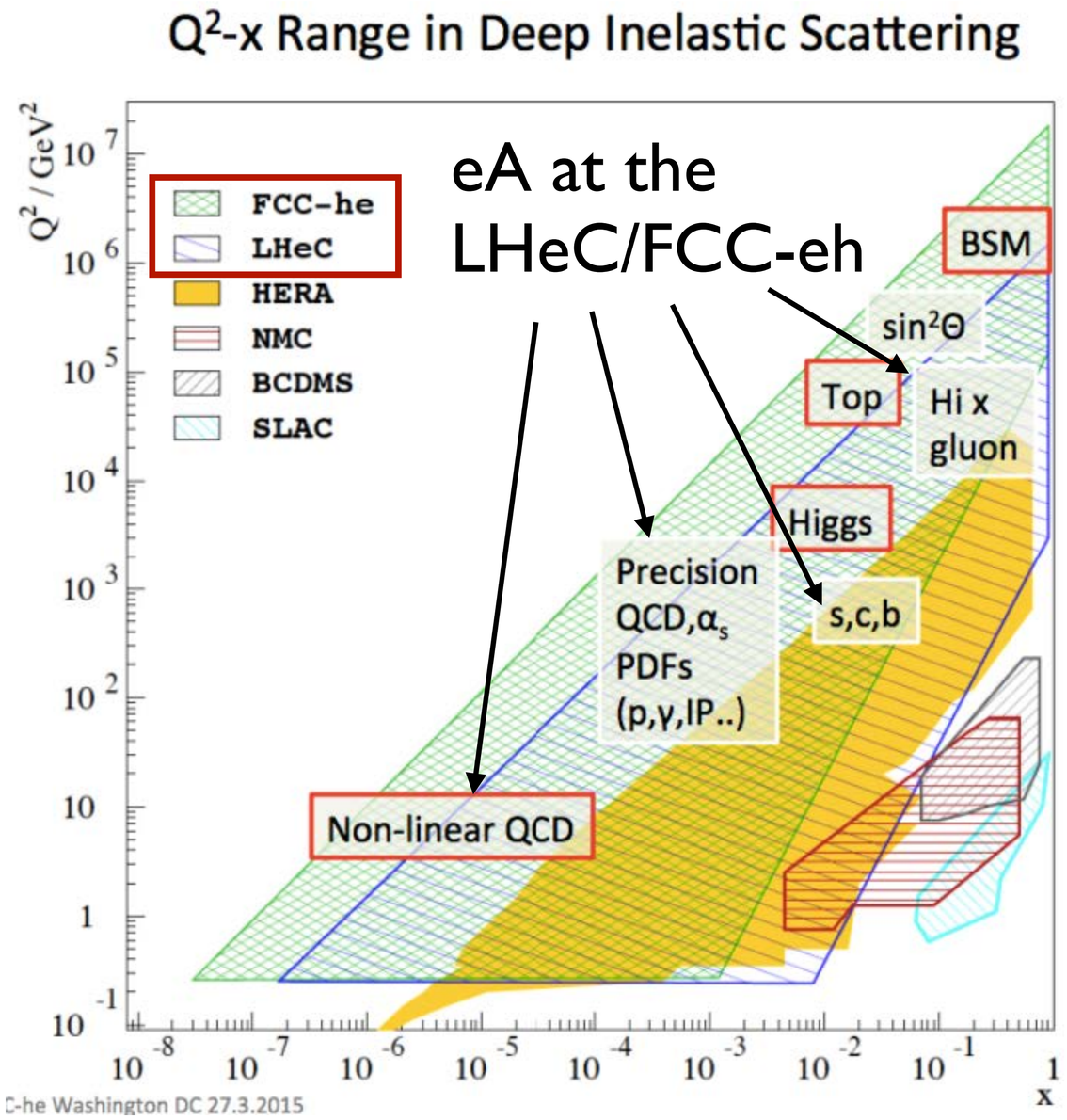


- Ratio $R_i(x,Q^2)$ of PDF's of Pb/p - Significant reduction of uncertainties of nuclear sea quarks / gluons with EIC
- Explore QCD landscape in various aspects over a wide range in x and Q^2 - Heavy nuclei at high energy critical to explore high-density gluon matter!

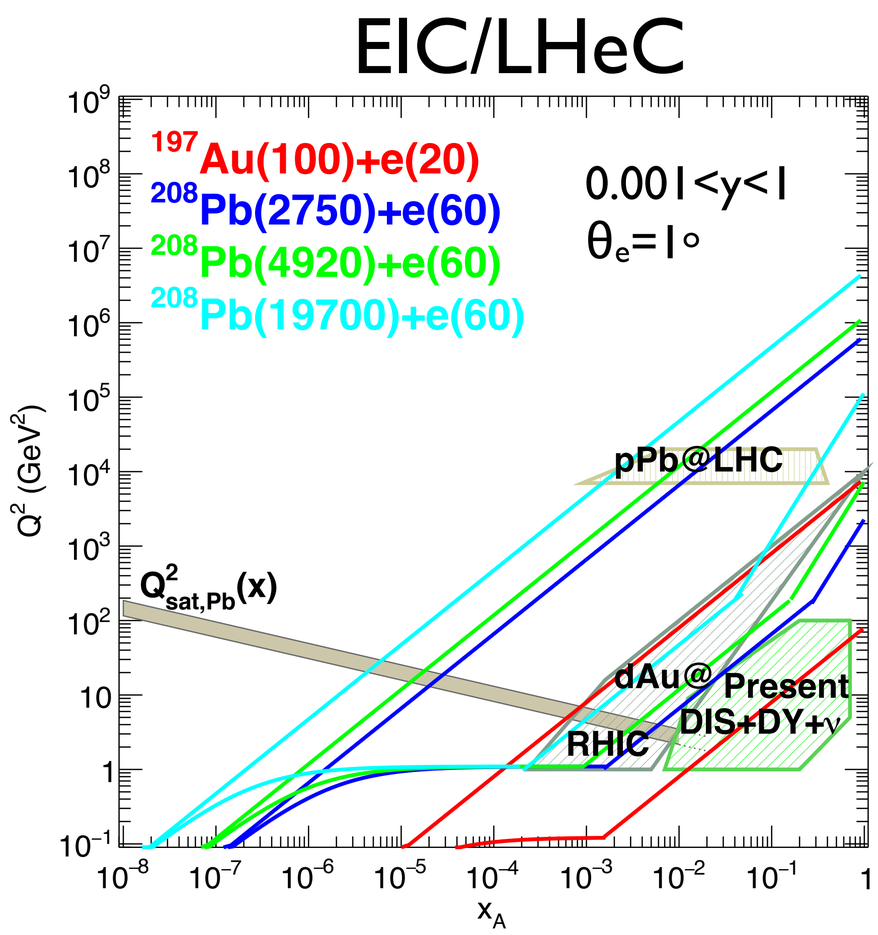
EICUG Steering Committee

European Strategy for Particle Physics
Granada, Spain, May 13-16, 2019

Physics cases:



Kinematics:



- **LHeC-FCC-eh**: extension of 4-5 orders of magnitude in x and Q^2 w.r.t. existing DIS data.

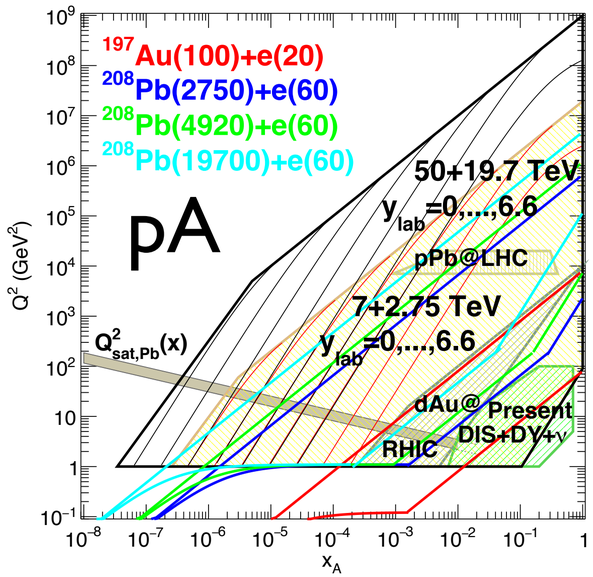
- **DIS versus hh**:

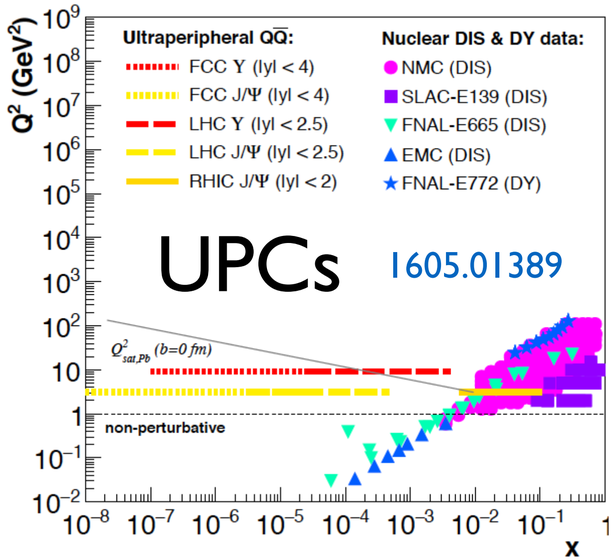
➜ pA/AA covers largest range in kinematics.

➜ **DIS offers**:

➢ A clean experimental environment - low multiplicity, no pileup, fully constrained kinematics x,Q^2 reconstructing the outgoing lepton;

➢ A more controlled theoretical setup - many first-principles calculations, factorisation tests.





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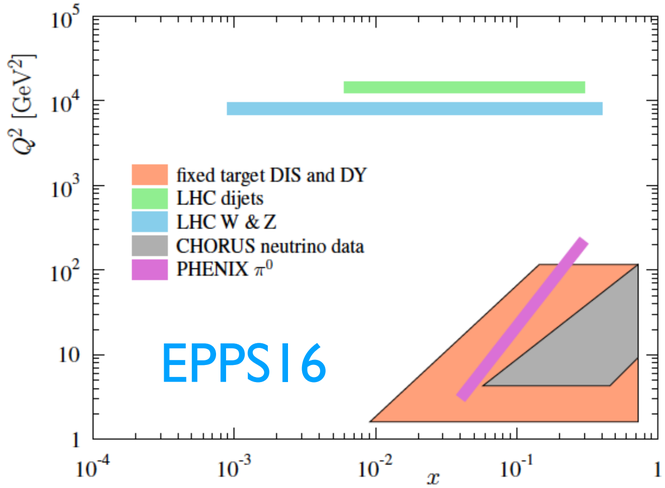
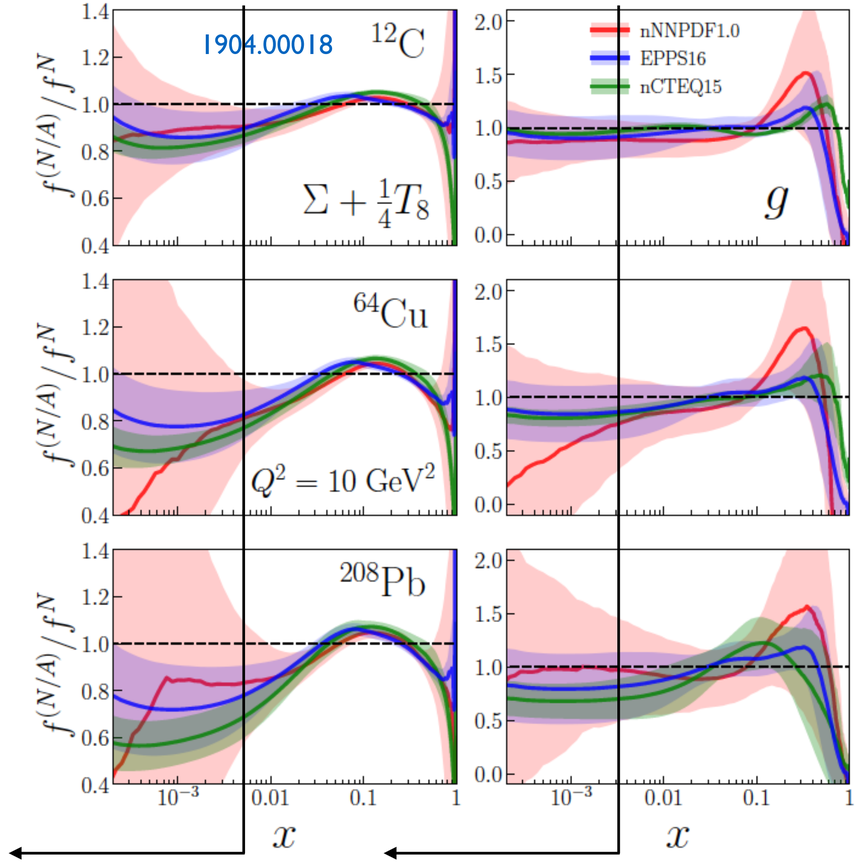
nPDFs: status

- Large uncertainties for x<0.01 and for large x glue (parametrisation biases, weakly constrained flavour decomposition and impact parameter dependence); small impact of present LHC data.
- Few data for any single A e.g. Pb (15 DIS+30 pPb+νA): A-dependence of initial conditions.
- Sizeable impact on precision in hard probes of the QGP.

$$R_{i/A}(x,Q^2) = \frac{f_{i/A}(x,Q^2)}{A f_{i/p}(x,Q^2)}$$





unconstrained unconstrained

- HL-LHC to provide additional constrains, see 1812.06772: W/Z, jets, heavy quarks (including top) and quarkonium (inclusive, and exclusive in UPCs) under study; FT@LHC for large x.
- **eA will provide precise nPDFs to be contrasted with pA/AA**: checks of factorisation in the nuclear environment required for hard probes of the QGP.

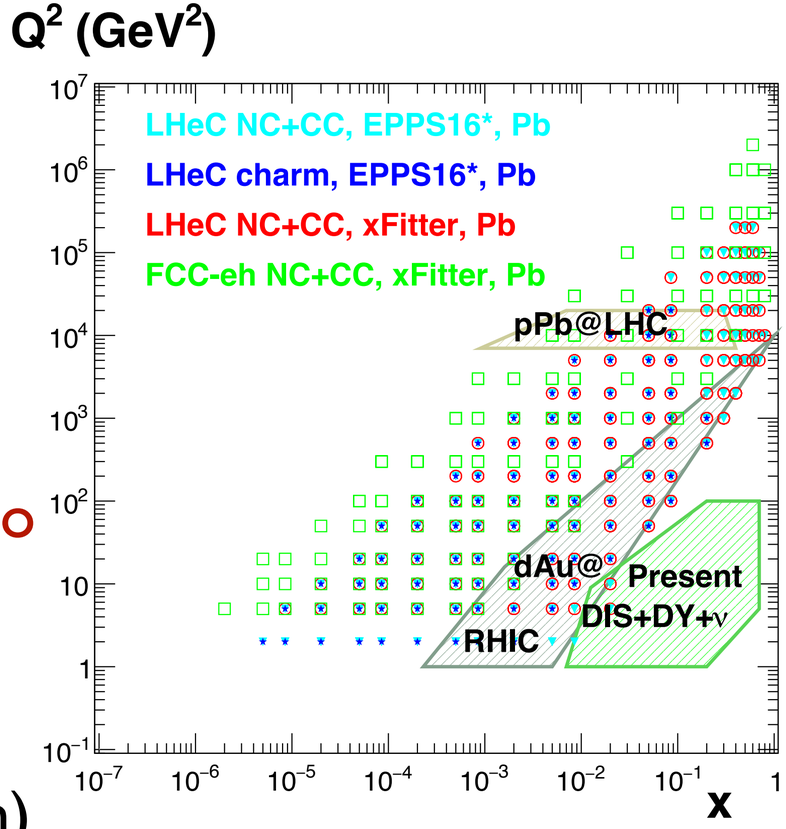
nPDFs: fits to a single nucleus

- LHeC/FCC-eh ePb included in EPPS16-like global fits and HERAPDF DIS-only fits: **large reduction of uncertainties in a completely new kinematical region.**

- Fit to a single nucleus: no A-dependence modelling.

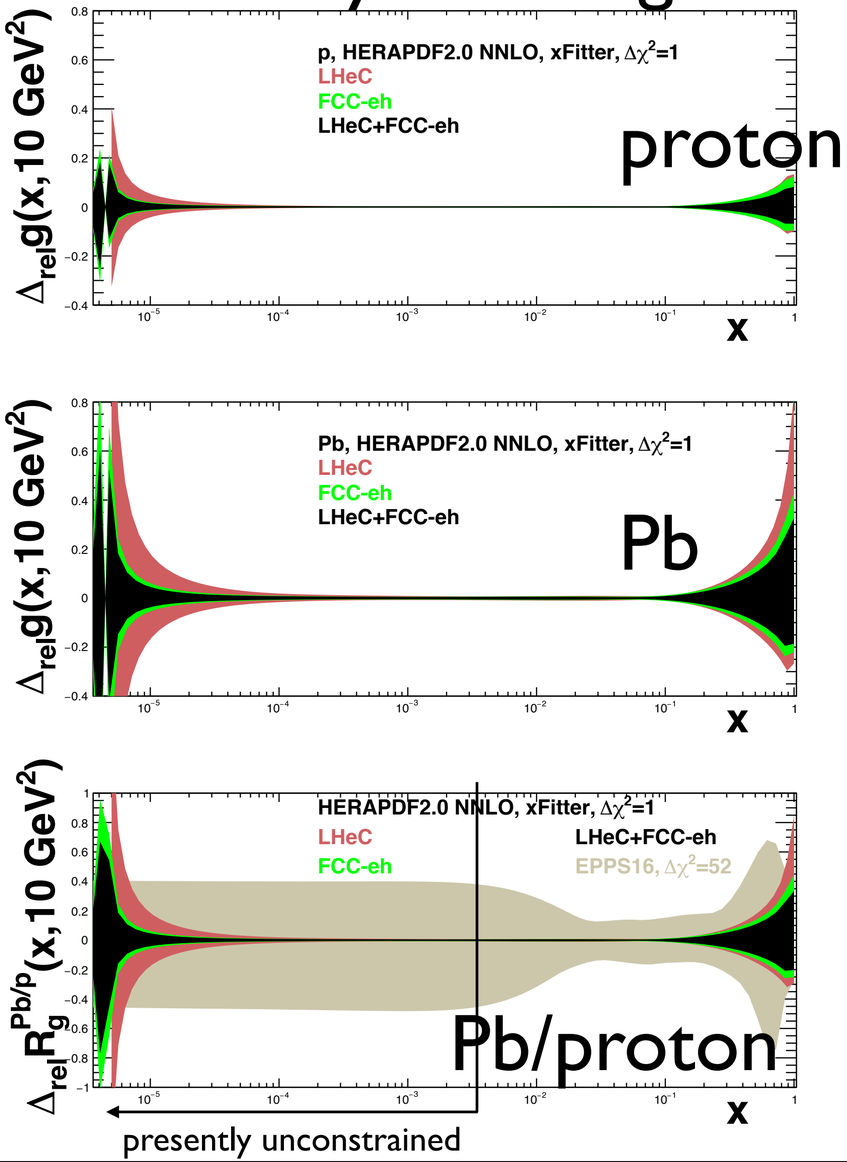
- Charm, beauty, c-tagged CC for strange (not yet in) ⇒ complete unfolding of different parton species.

LHeC/FCC-eh



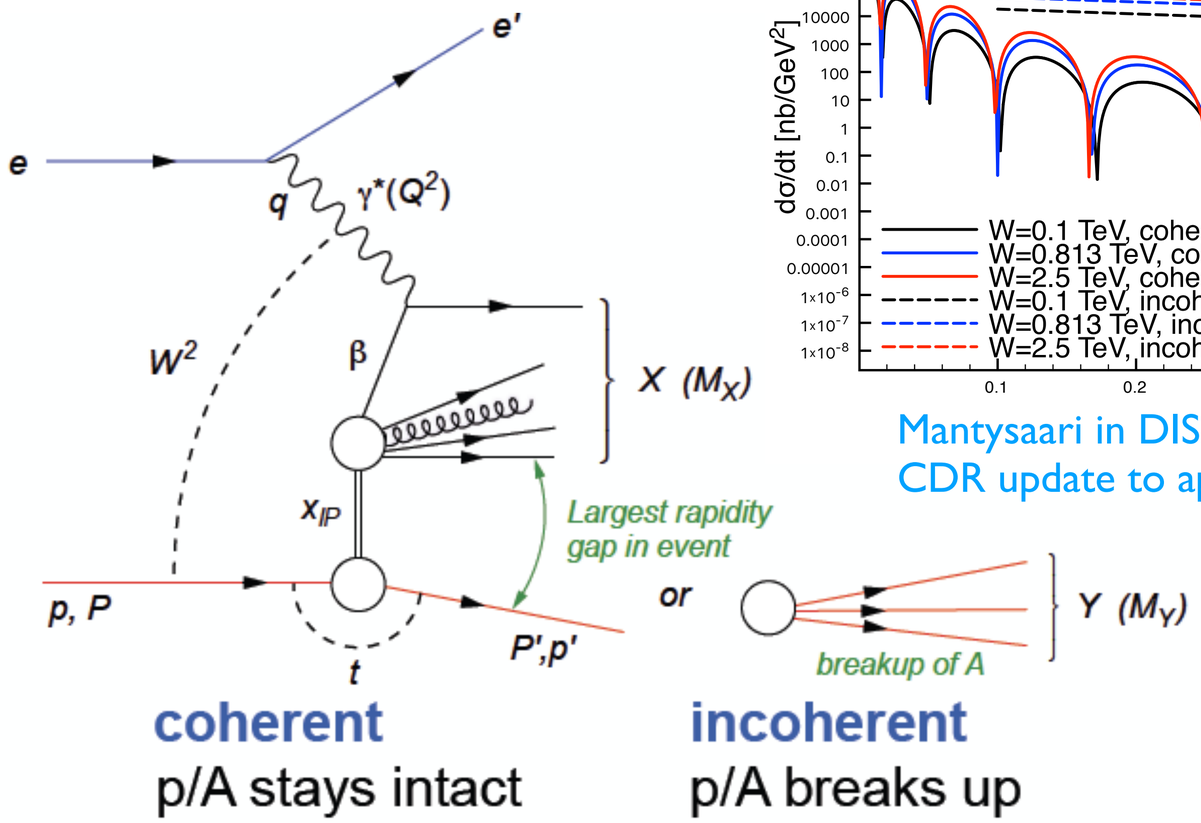
NA at DIS2019, LHeC CDR update to appear

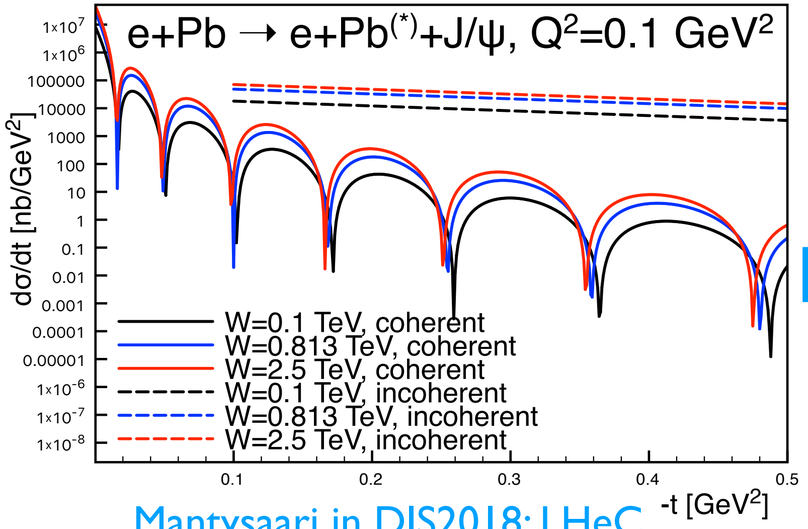
uncertainty on the gluon



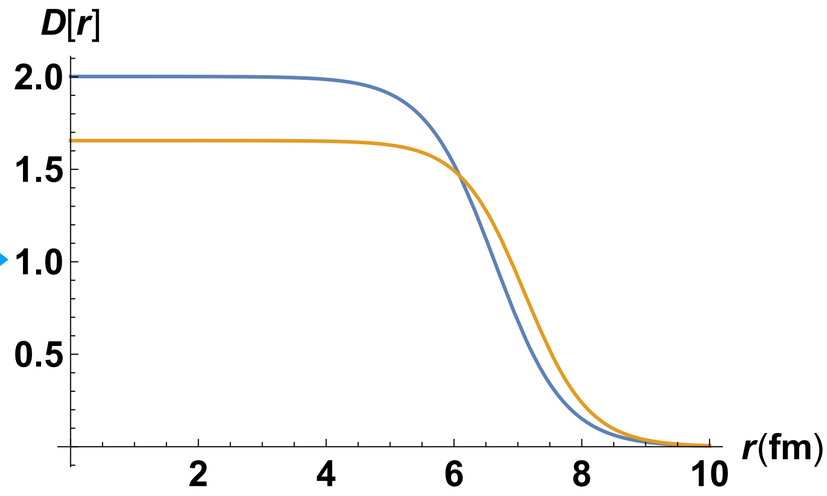
3D - GPDs and TMDs:

- The extraction of 3D-structure (GPDs and TMDs and their evolution equations) is a huge undergoing program: scarcely known in the proton, **mostly unknown in nuclei**.





Mantysaari in DIS2018; LHeC CDR update to appear



- Coherent exclusive production (γ/VM) ⇒ q/g GPDs, transverse profile.
- Incoherent exclusive production yields information about fluctuations: hot spots ⇒ MPIs.

- It can be done at the LHeC/FCC-eh in a large range of x and Q^2 ⇒ evolution.

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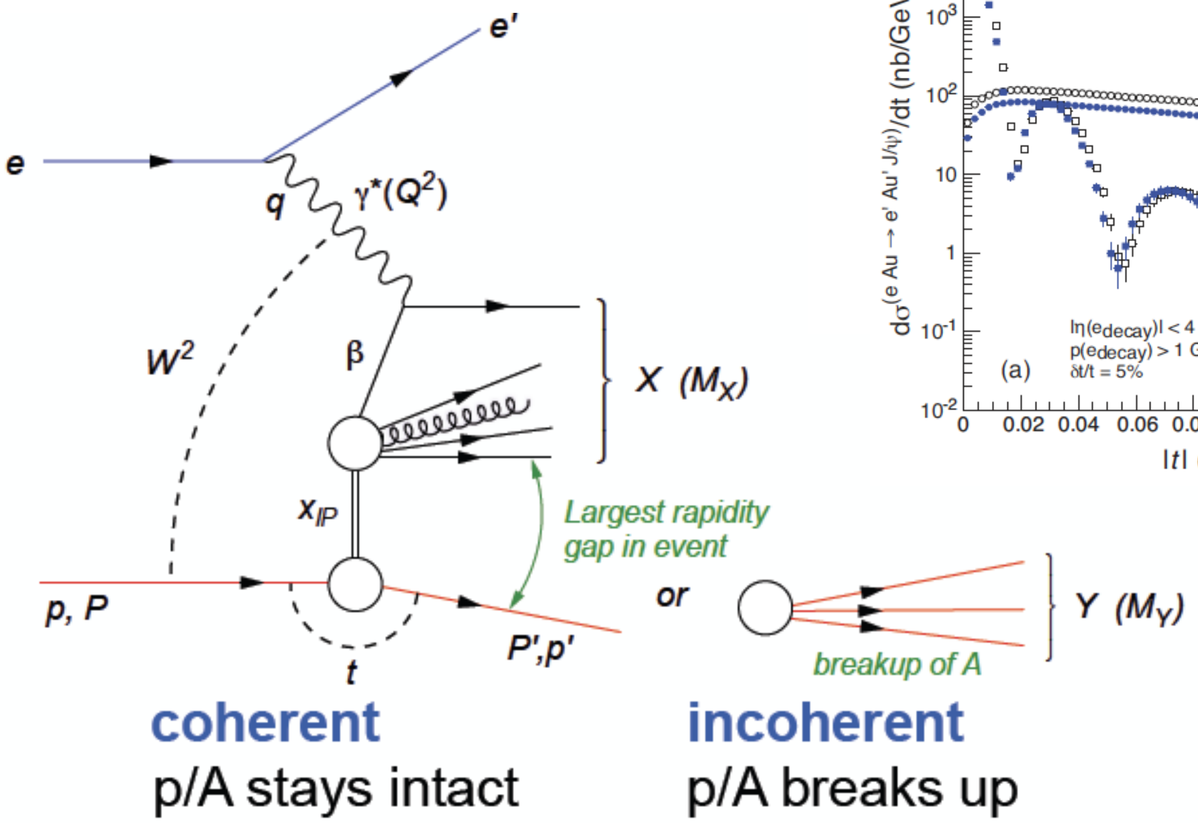
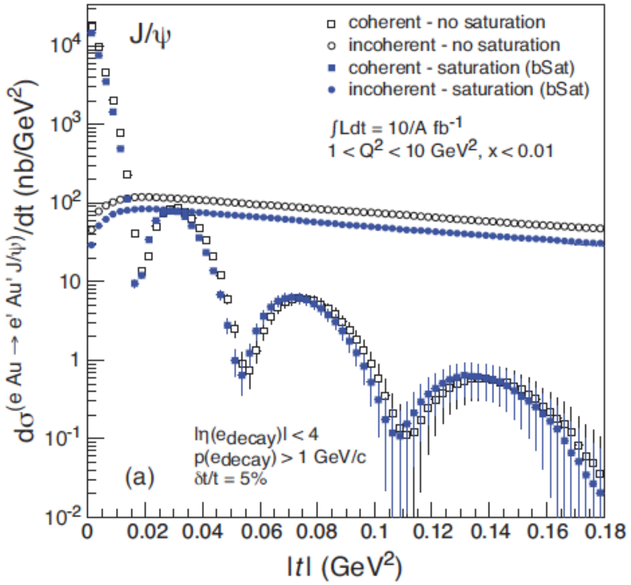
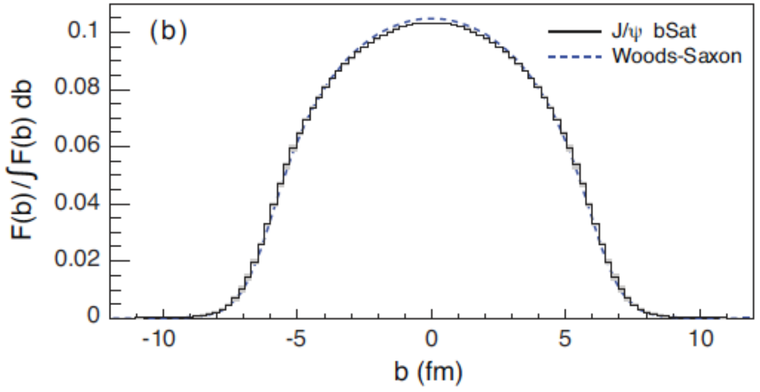




eAu at EIC, 1211.3048



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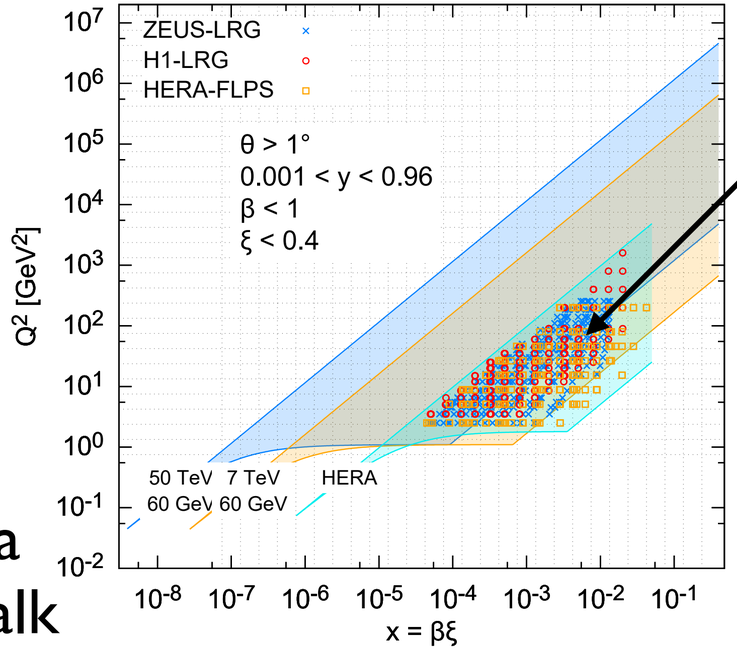
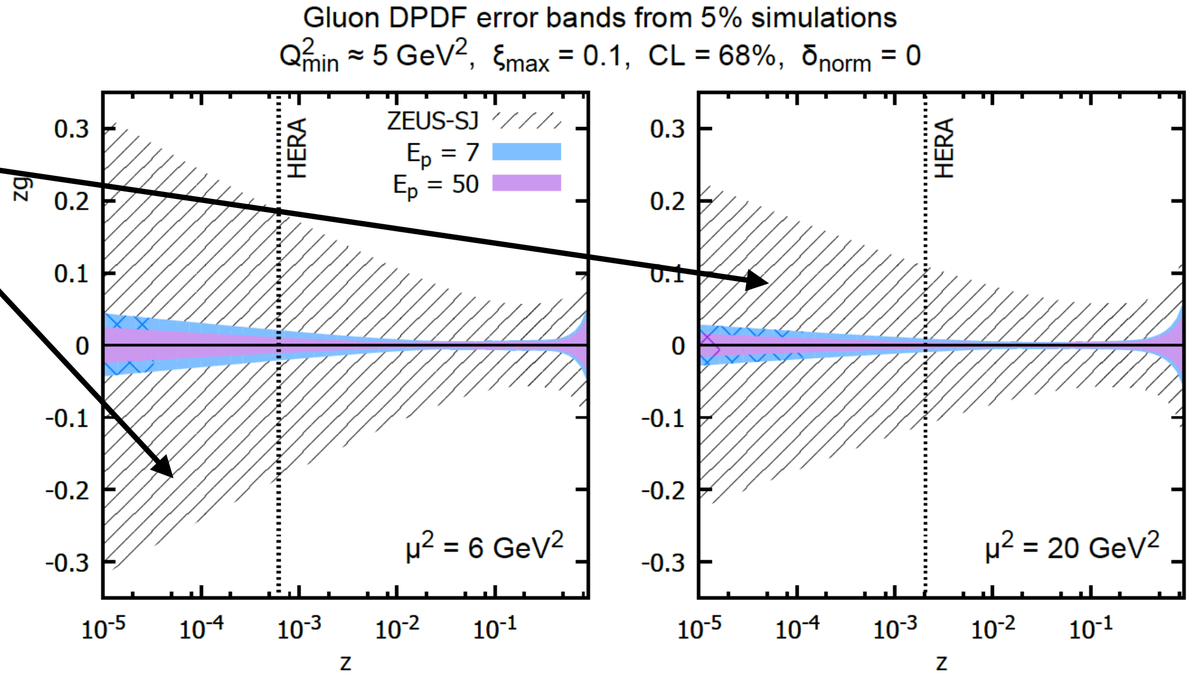
Nuclear diffractive PDFs:

- Diffractive PDFs give the conditional probability of measuring a parton in the hadron with the hadron remaining intact: ~10 % events at HERA are diffractive!
- Never measured in nuclei, incoherent diffraction dominant above relatively small -t: interplay between multiple scattering and survival probability of the colourless exchange (rapidity gap), relation between diffraction in ep and nuclear shadowing ⇒ MPIs, CEP.
- At the LHeC/FCC-eh, **extractable in nuclei with the same accuracy as in proton**.

LHeC/FCC-eh, coherent diffraction 1901.09076



Not existing in eA



See Uta Klein's talk

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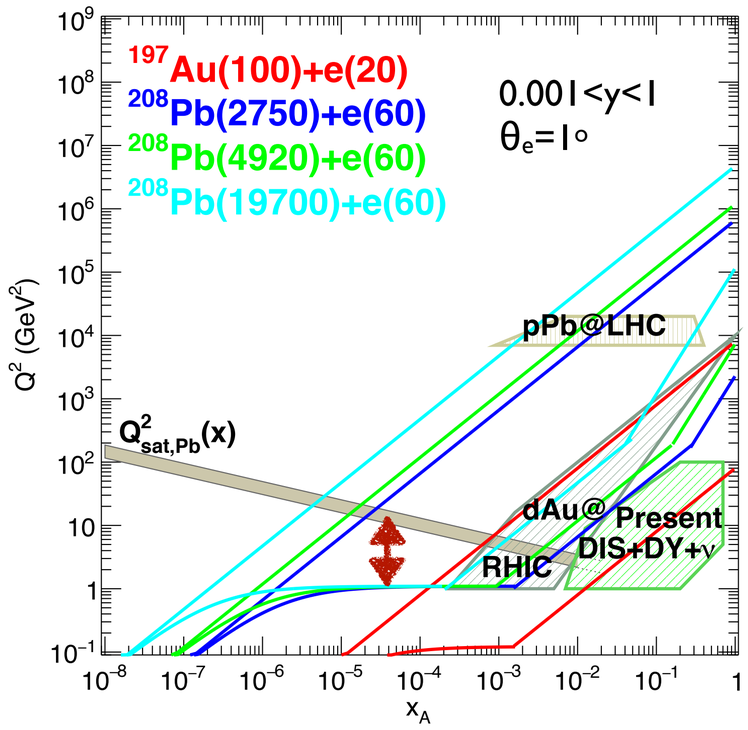
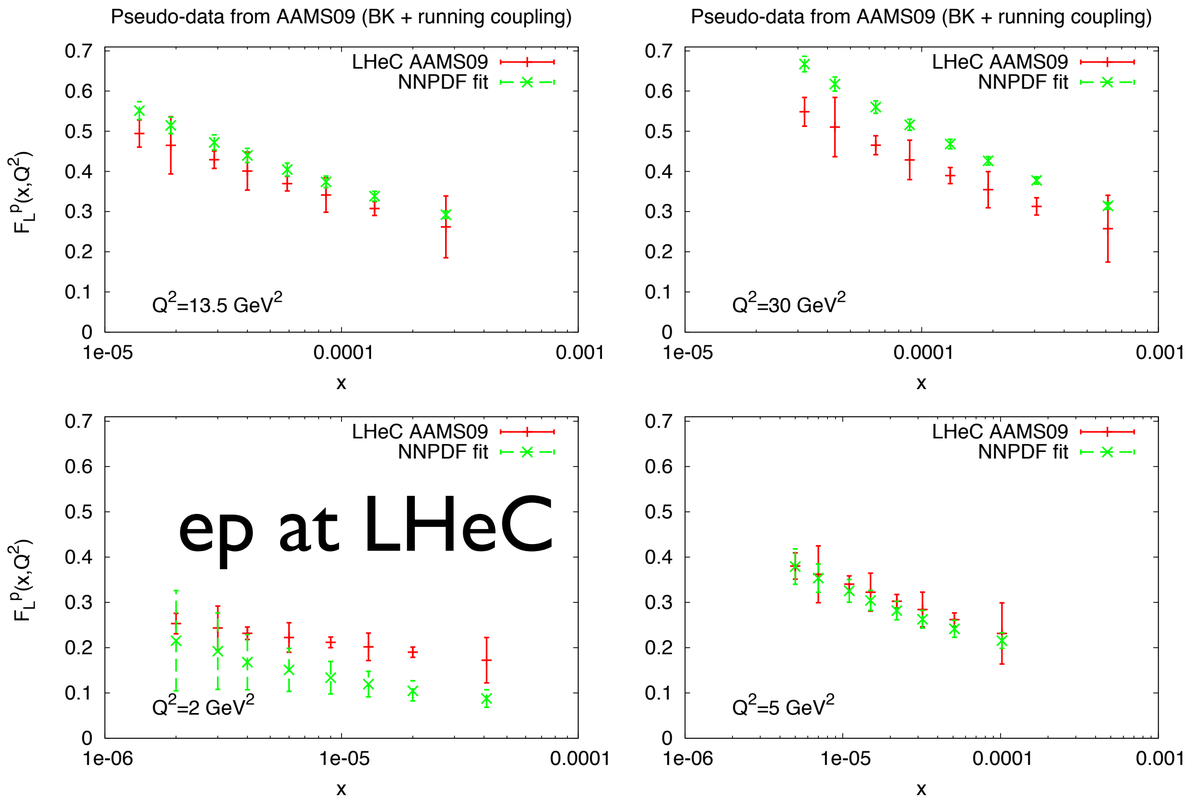
Search for new parton dynamics at small x:

- **Saturation modifies evolution**: tension between the description in DGLAP analyses of different inclusive observables (with different sensitivities to glue and sea, e.g. F_2 and F_L or σ_r^{HQ}), **if enough lever arm in Q^2 at small x available**.

See LHeC CDR 1206.2913 and 1203.1043

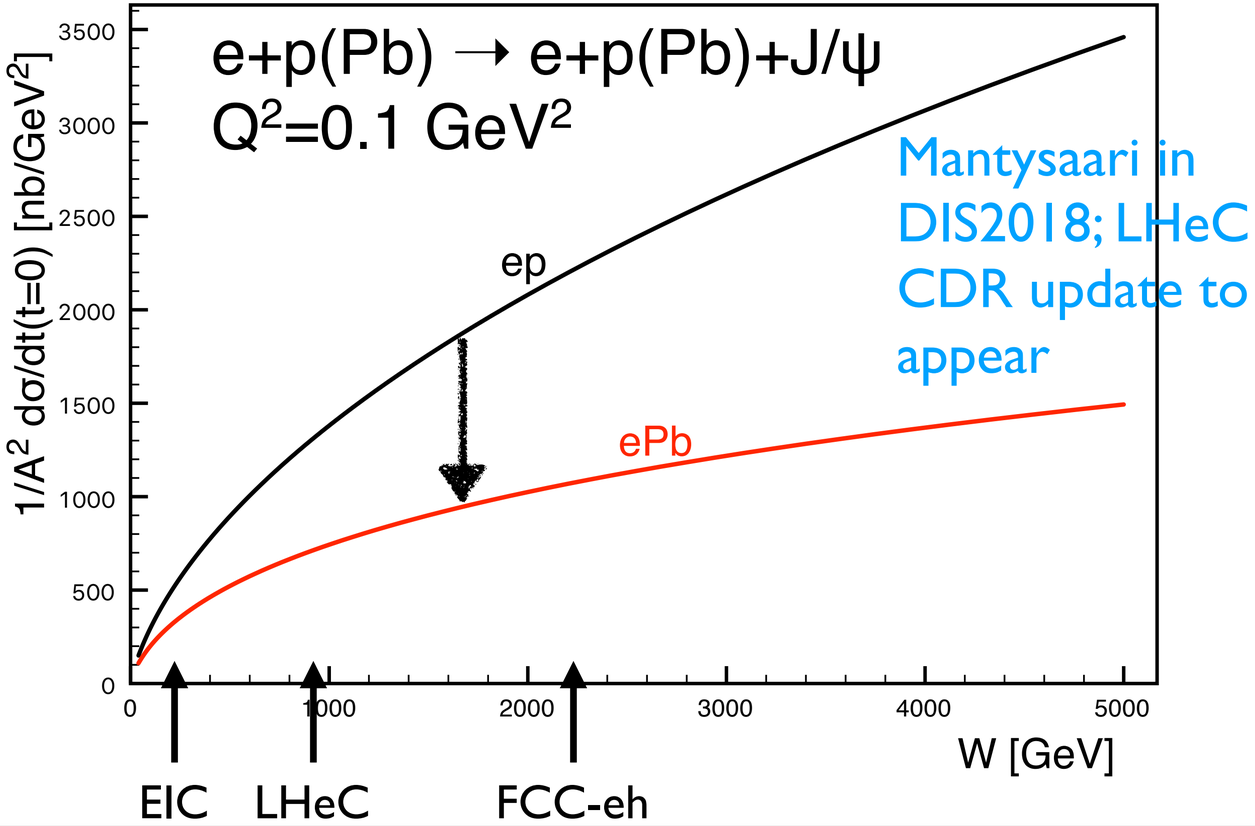


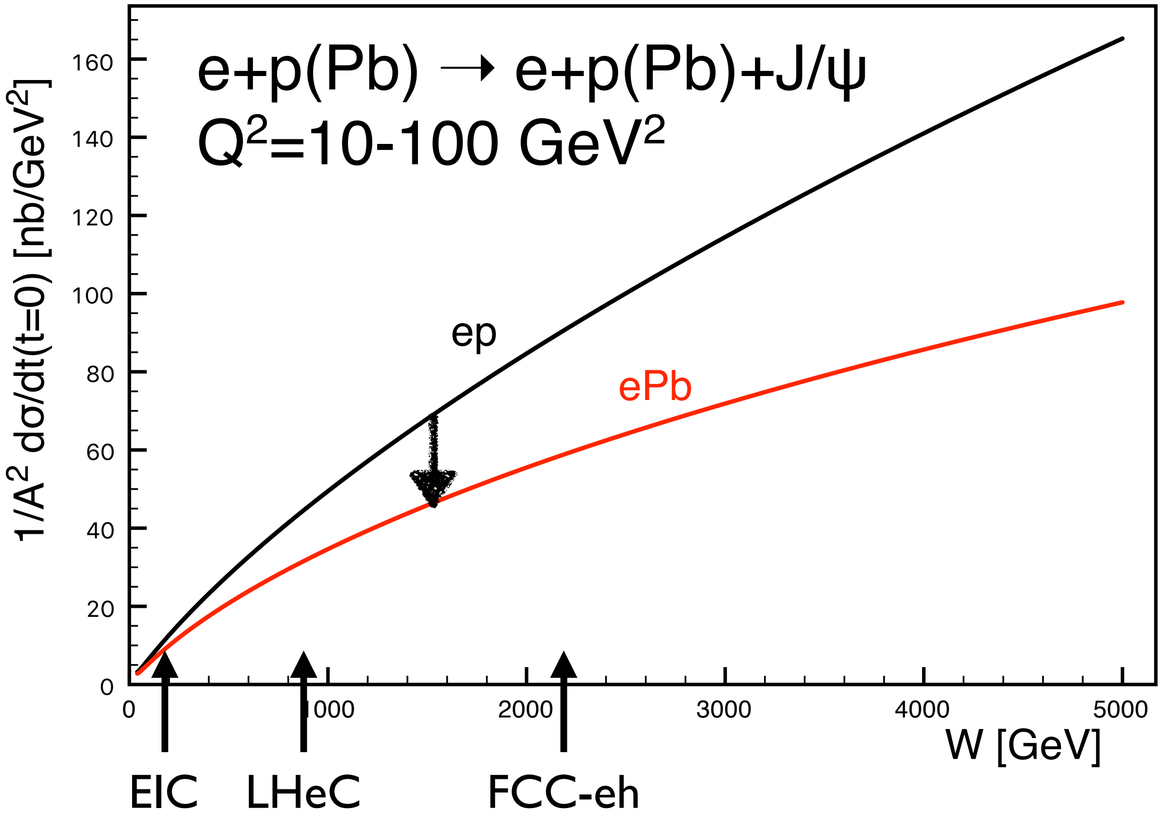


- High scales are small x at the FCC-AA: e.g. top production in pPb sensitive to x ~ 0.02-0.2 at HL-LHC and 0.0002-0.2 at the FCC-hh (1501.05879).

Diffractive observables:

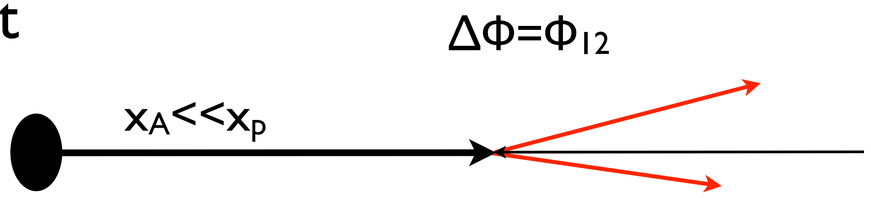
- Saturation (the approach to the black disk limit) affects both the energy and the t (impact parameter)-dependence of coherent exclusive VM production: smaller energy dependence, shrinking of the diffractive peak.
- Saturation results in a larger diffractive over inclusive cross section (Nikolaev et al., Z.Phys. A351 (1995) 435): interplay between non-linear phenomena and survival probability.



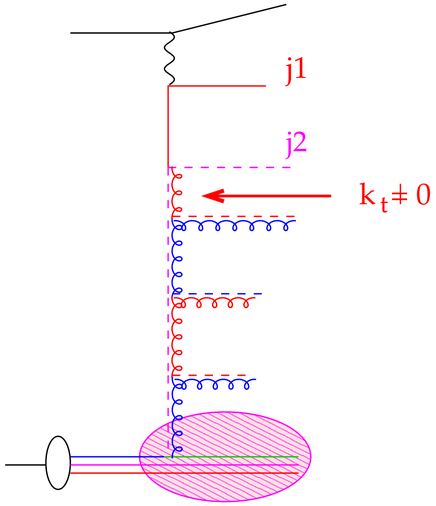


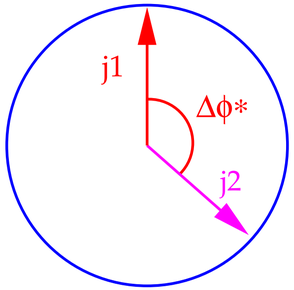
Correlations:

- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- To be studied at LHeC/FCC-eh far from kinematical limits.



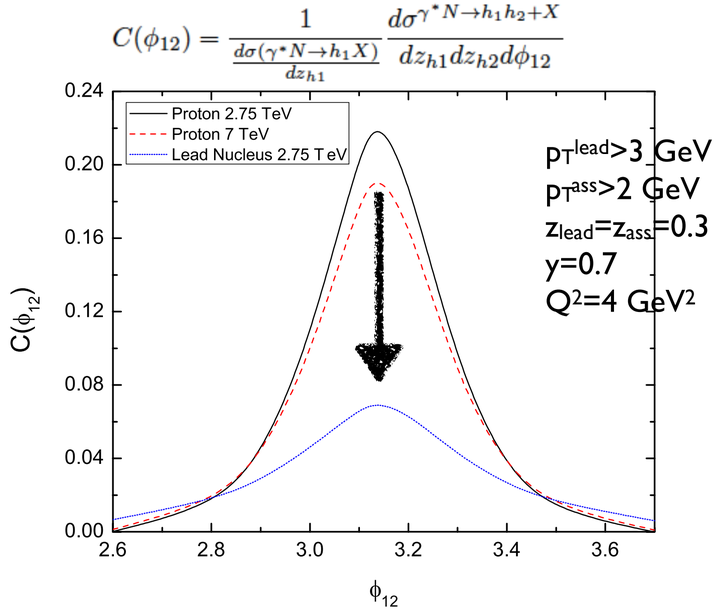
- **Nuclear and saturation effects on usual BFKL signals** (e.g. dijet azimuthal decorrelation, Mueller-Navelet jets) has not been extensively addressed: A-dependence contrary to linear resummation?





$\Delta\phi^* < 120^o$

LHeC CDR 1206.2913



- HL-LHC and higher energy hh/AA colliders: many of these signals can be considered (nuclear modification factors at small-x, exclusive vector meson production in UPCs, particle and jet decorrelation), but larger uncertainties will remain: collectivity, factorisation,… **DIS would be decisive to set the existence of a new regime of QCD**.

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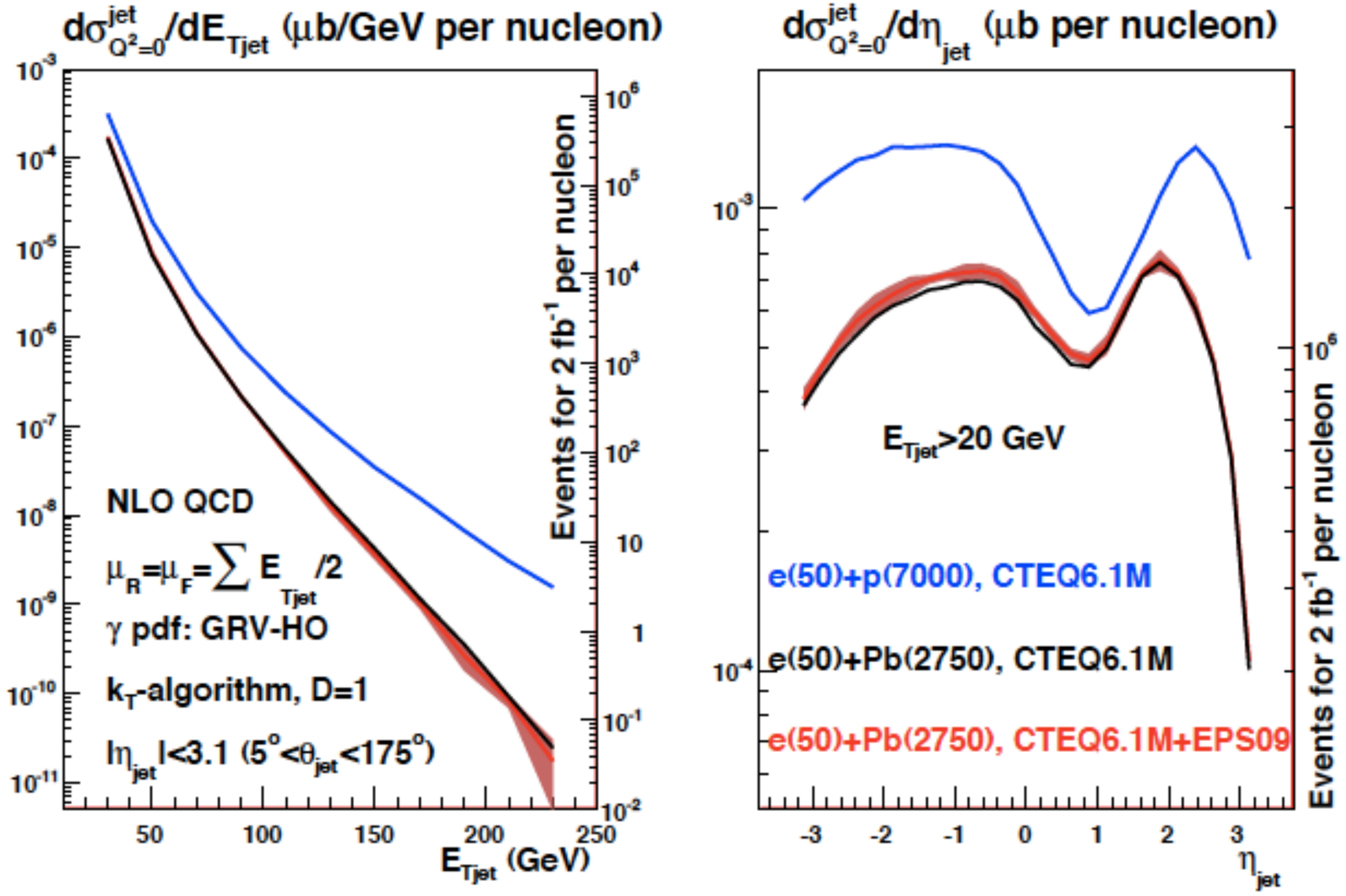
Jets:

- Jet observables in AA: energy loss + response of the medium must be disentangled for characterisation of the medium.
- Jets not suppressed in pPb @ LHC: compatibility with softer observables? → **small systems**.
- Jets (inclusive and diffractive) abundantly produced in eA up to sizeable E_T, they can be used to **test factorisation and for precision studies of changes of QCD radiation in the nuclear environment ⇒ hard probes of the QGP.**

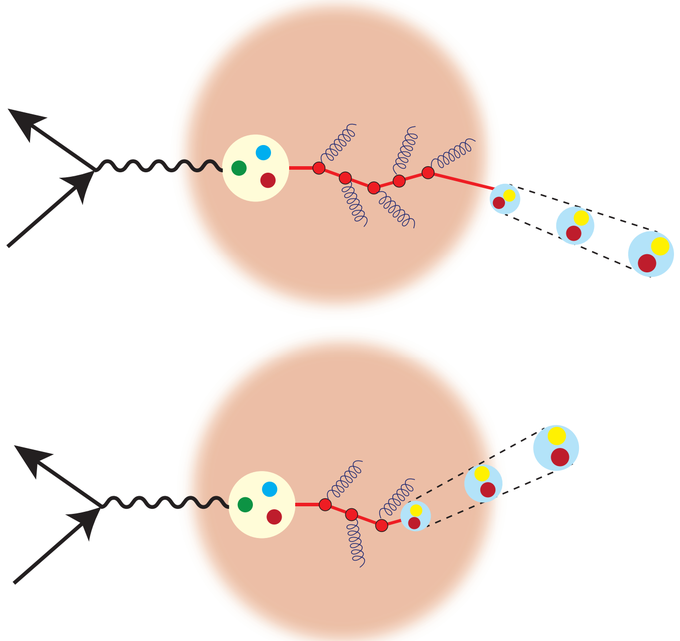
LHeC CDR 1206.2913



Fragmentation functions:

- eA: dynamics of QCD radiation and hadronization for light and heavy particles (energy loss of light and heavy, and quarkonium production and suppression), **relevant for particle production off nuclei** (nPDF determination in pA) **and for QGP analysis in AA.**

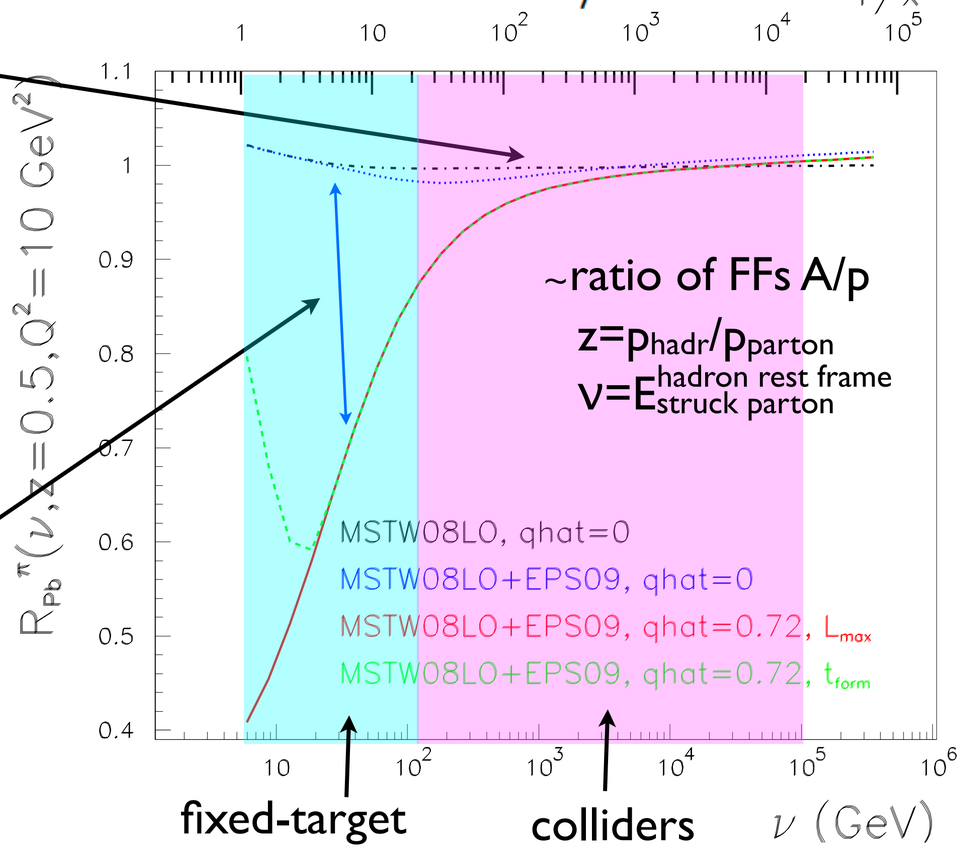
➜ High energy: partonic evolution altered in the nuclear medium.



➜ Low energy: hadronization inside → formation time, (pre-)hadronic absorption,...

LHeC CDR
1206.2913

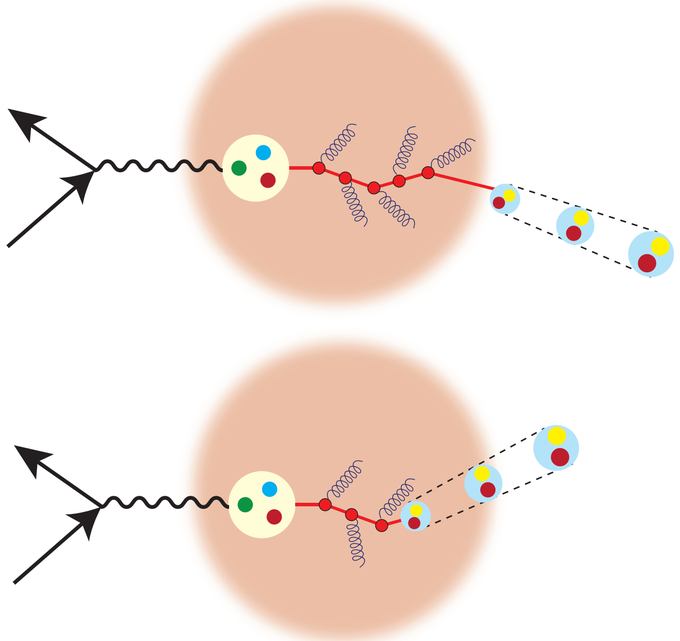
$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Big/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$



Fragmentation functions:

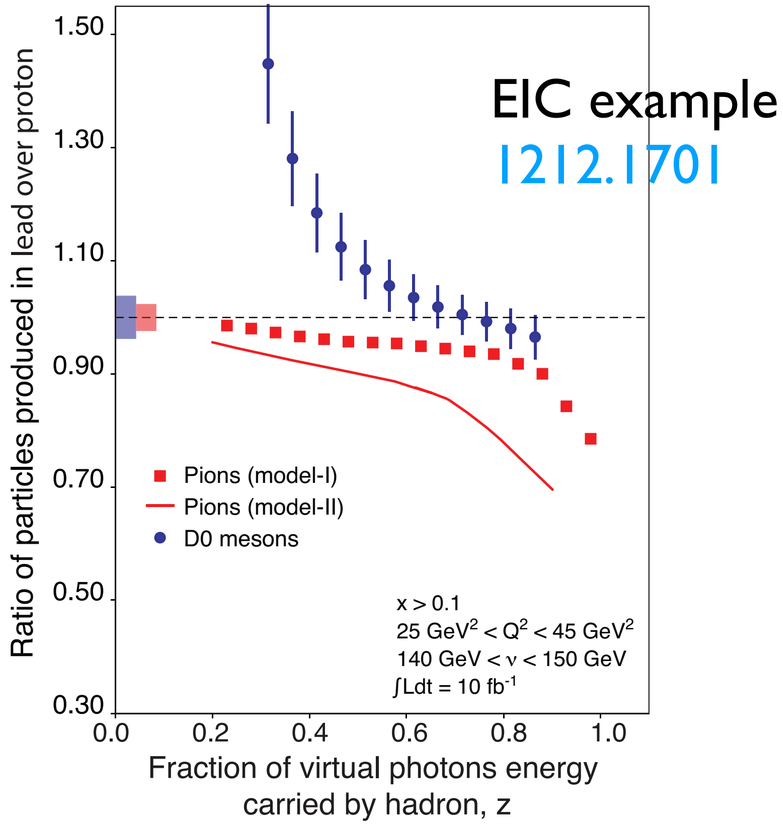
- eA: dynamics of QCD radiation and hadronization for light and heavy particles (energy loss of light and heavy, and quarkonium production and suppression), **relevant for particle production off nuclei** (nPDF determination in pA) **and for QGP analysis in AA.**

➜ High energy: partonic evolution altered in the nuclear medium.



➜ Low energy: hadronization inside → formation time, (pre-)hadronic absorption,...

$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{\mathrm{d}N_A^h(z,\nu)}{\mathrm{d}\nu\,\mathrm{d}z} \Big/ \frac{1}{N_D^e}\frac{\mathrm{d}N_D^h(z,\nu)}{\mathrm{d}\nu\,\mathrm{d}z}$$



Summary / recommendations:

- eA colliders offer huge possibilities for QCD physics in new kinematic and dynamics domains:
  - ➜ Determination of nuclear partonic structure with high precision: collinear nuclear PDFs, nuclear GPDs/ TMDs (3D-structure), diffractive nuclear PDFs, to be contrasted with those in pA and AA.
  - ➜ Searches of signals of a new regime of QCD - saturation - in inclusive and diffractive observables, and through correlations; both ep & eA are required to discover it and understand the underlying dynamics.
  - ➜ Modifications of particle production, hadronisation and QCD radiation in the nuclear environment.

Support further studies of the eA physics case at the largest possible energy and its implications on pp/ pA/AA.

- The EIC and the LHeC are complementary:
  - ➜ PDFs for future AA colliders and the study of saturation demand the highest possible energy.
  - ➜ 3D-structure and hadronisation/QCD radiation will be studied in complementary domains.
  - ➜ The EIC will have a unique role in spin.

Support the exploitation of synergies and complementarities between the EIC and the LHeC/FCC-eh.

- All these aspects are relevant for the heavy-ion program:
  - ➜ Benchmarking of hard probes.
  - ➜ Initial conditions for collective behaviour.
  - ➜ Understanding of the onset of collectivity: small systems, MPIs, …

Encourage the development of a broad QCD program for the 2030's comprising pp/pA/AA and ep/eA.

Backup

Purpose:

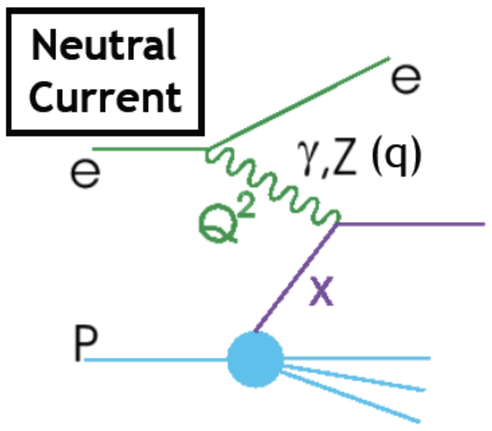
- To cover: Prospects and Challenges for Electron-Ion Collider, also from the perspectives of the US-EIC, to trigger our understanding of the rich variety of structures at the subatomic scale.

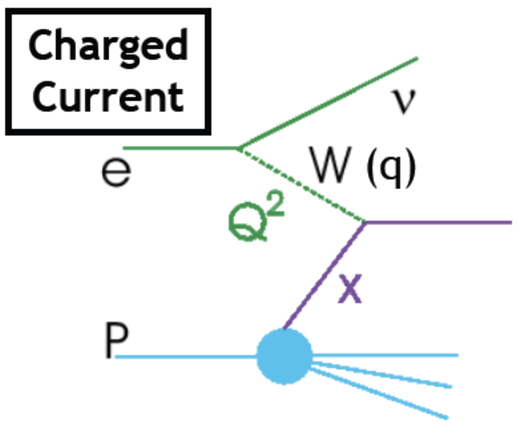
- Related contributions submitted to the ESPPU:

ID	Title
159	LHeC/PERLE
99	US-based EIC
103	DIS
152	QCD/HI at HL-LHC
135	QCD/HI at FCC-hh and FCC-eh
163	QCD theory
148	NuPECC
21	INFN hadron
114	MC generators
33	Germany HEP

DIS:

- Consider the process of lepton (e, μ, ν) scattering on a proton (or neutron or nucleus).





Standard DIS variables:

electron-proton cms energy squared:

$$s = (k+p)^2$$

photon-proton cms energy squared:

$$W^2 = (q+p)^2$$

inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

Bjorken x

$$x = \frac{-q^2}{2p \cdot q}$$

(minus) photon virtuality

$$Q^2 = -q^2$$

- For charged lepton scattering and neglecting Z exchange,

$$\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \sigma_{r,NC}$$

$$\sigma_{r,NC} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_+}\mathbf{F_L},$$

$$\sigma^{\pm}_{r,CC} = W_2^{\pm} \mp \frac{Y_-}{Y_+} x W_3^{\pm} - \frac{y^2}{Y_+} W_L^{\pm}$$

$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{1 \pm P}{2} \cdot \frac{G_F^2}{2\pi x} \cdot \left[\frac{M_W^2}{M_W^2 + Q^2}\right]^2 Y_+ \cdot \sigma_{r,CC}$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

$$\begin{aligned} \mathbf{F_2^{\pm}} &= F_2 + \kappa_Z(-v_e \mp P a_e) \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e) \cdot F_2^Z \\ \mathbf{xF_3^{\pm}} &= \kappa_Z(\pm a_e + P v_e) \cdot x F_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2)) \cdot x F_3^Z \end{aligned}$$

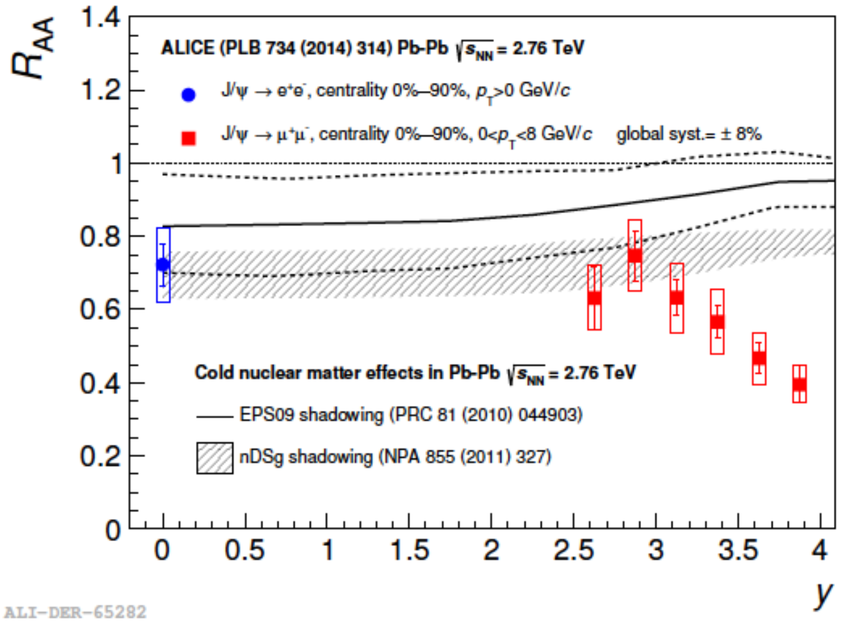
nPDFs: status

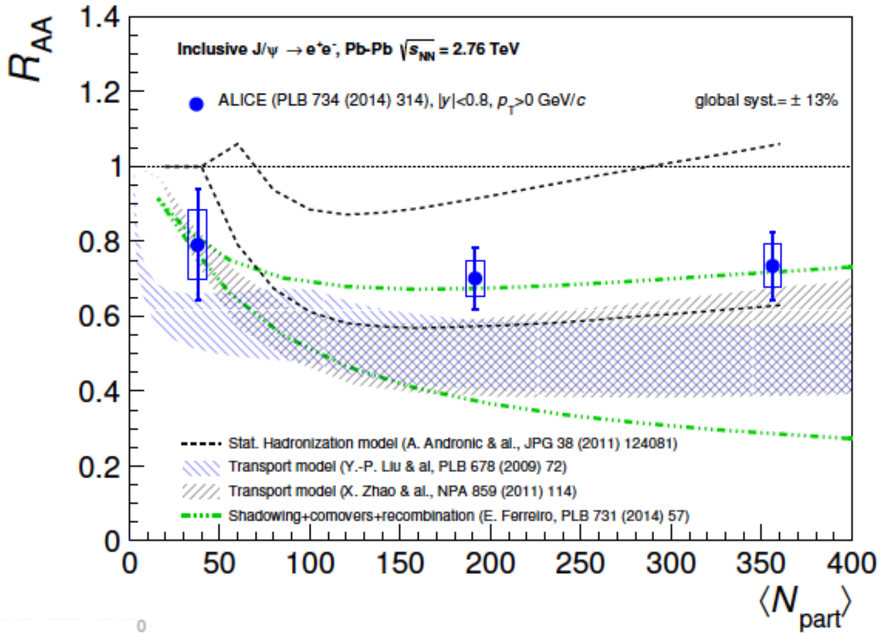
SET		EPS09 JHEP 0904 (2009) 065	DSSZ PRD85 (2012) 074028	nCTEQ15 PRD93 (2016) 085037	KA15 PRD93 (2016) 014036	EPPS16 EPJC C77 (2017)163	nNNPDF1.0 1904.00018
data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✘
	π^0	✔	✔	✔	✘	✔	✘
	νDIS	✘	✔	✘	✘	✔	✘
	pPb	✘	✘	✘	✘	✔	✘
# data		929	1579	740	1479	1811	451
order		NLO	NLO	NLO	NNLO	NLO	NNLO
proton PDF		CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO	NNPDF3.1
mass scheme		ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS	FONLL-B
comments		$\Delta\chi^2$=50, ratios, huge shadowing-antishadowing	$\Delta\chi^2$=30, ratios, medium-modified FFs for π^0	$\Delta\chi^2$=35, PDFs, valence flavour sep., not enough sensitivity	PDFs, deuteron data included	$\Delta\chi^2$=52, flavour sep., ratios, LHC pPb data	NNPDF methodology, isoscalarity assumed

nPDFs: status

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

- Lack of data ⇒ large uncertainties for the nuclear glue at small scales and x: problem for benchmarking in HIC in order to extract medium parameters.

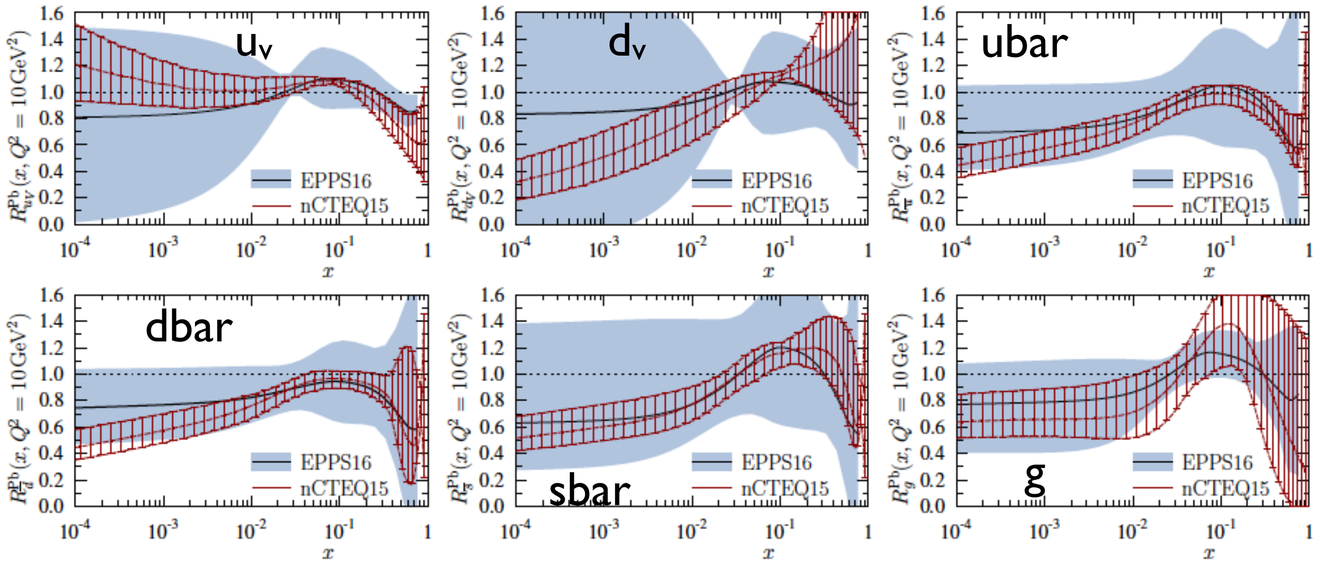




1506.03981

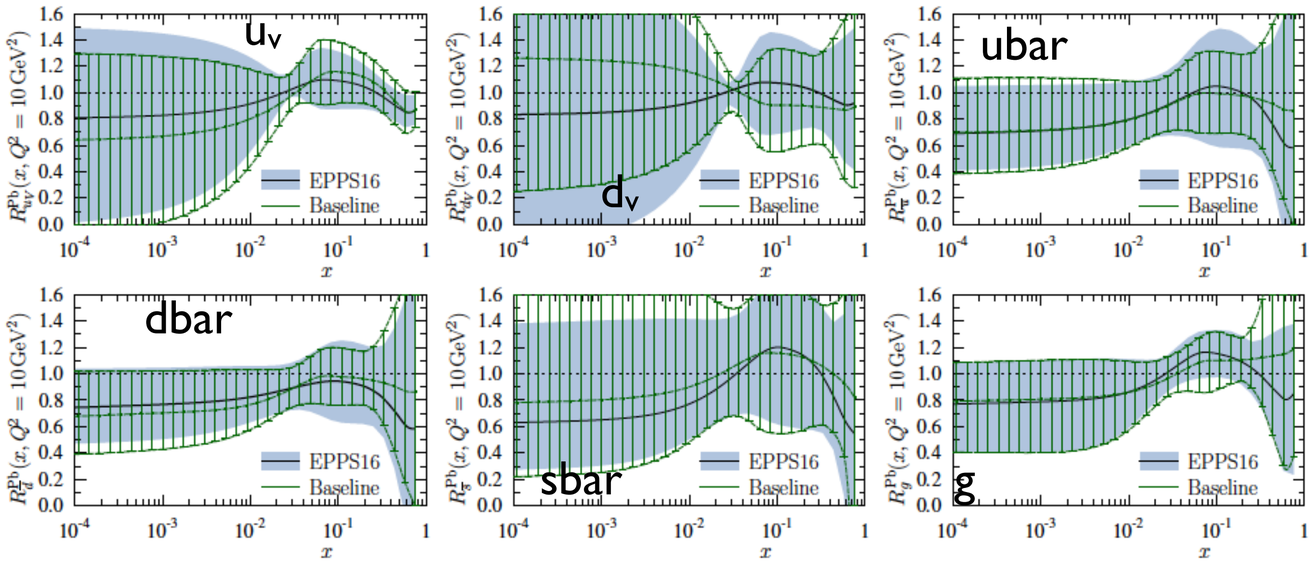
nPDFs: status

- nCTEQ15 vs. EPPS16: note the parametrisation bias.



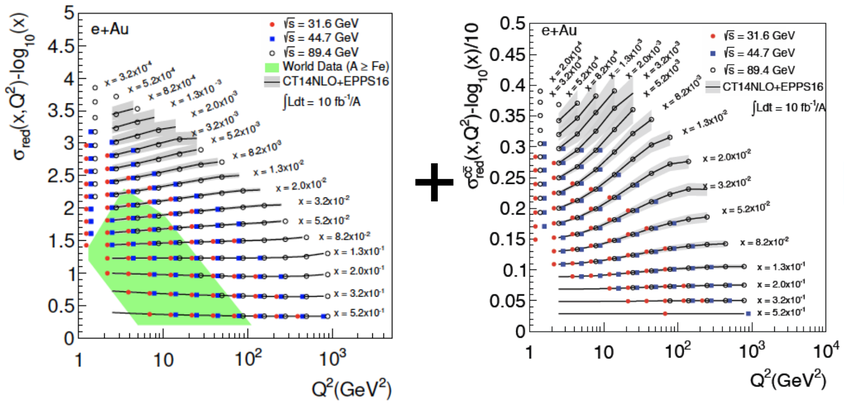
1612.05741

- Presently available LHC data seem not to have a large effect: large-x glue (baseline=no ν, no LHC data).



nPDFs: fits

- LHeC/FCC-eh ePb and EIC eAu pseudodata included in EPPS16-like global fits: large impact.



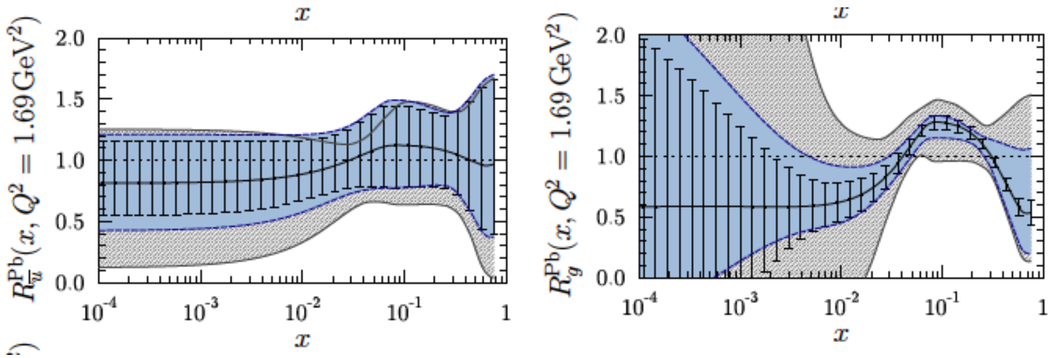
+

1708.05654

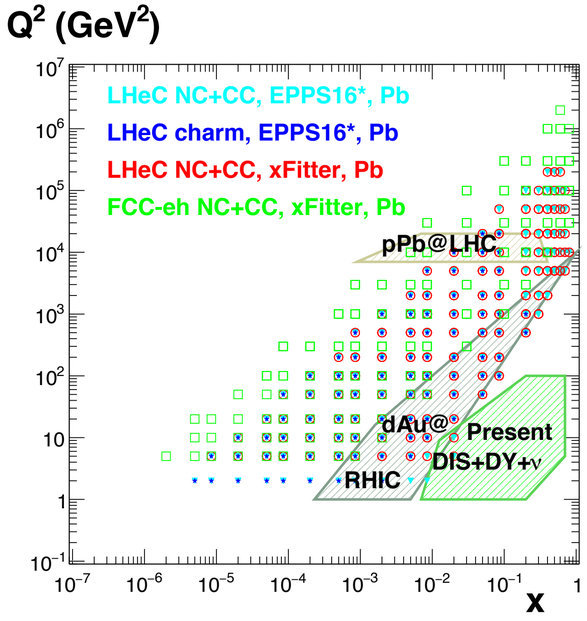
EIC

sea

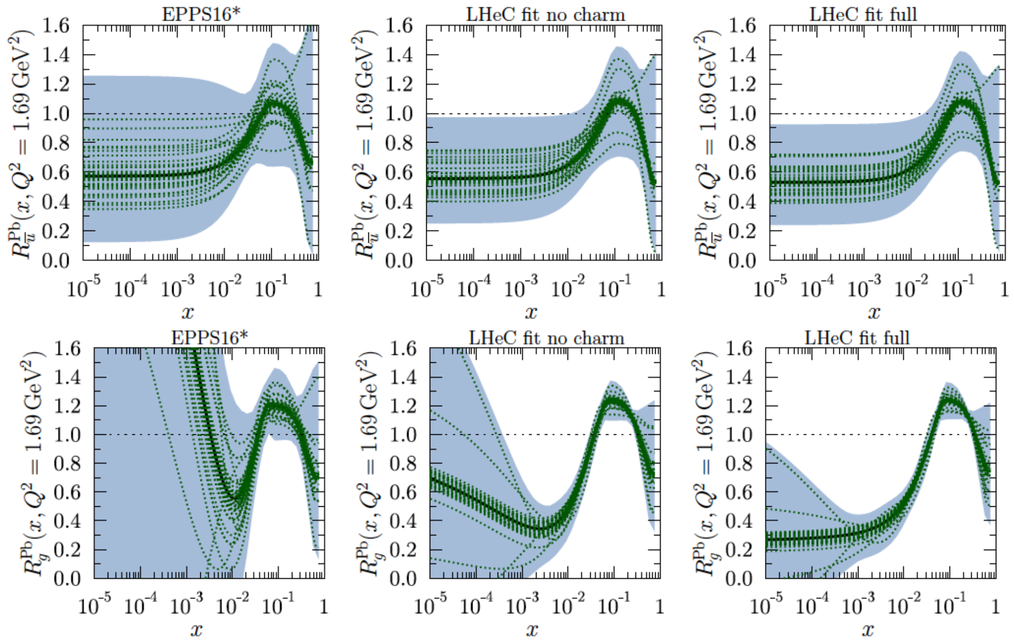
glue



- Inclusion of charm has sizeable impact (on glue).
- Not yet included: beauty, c-tagged CC for strange.



LHeC



sea

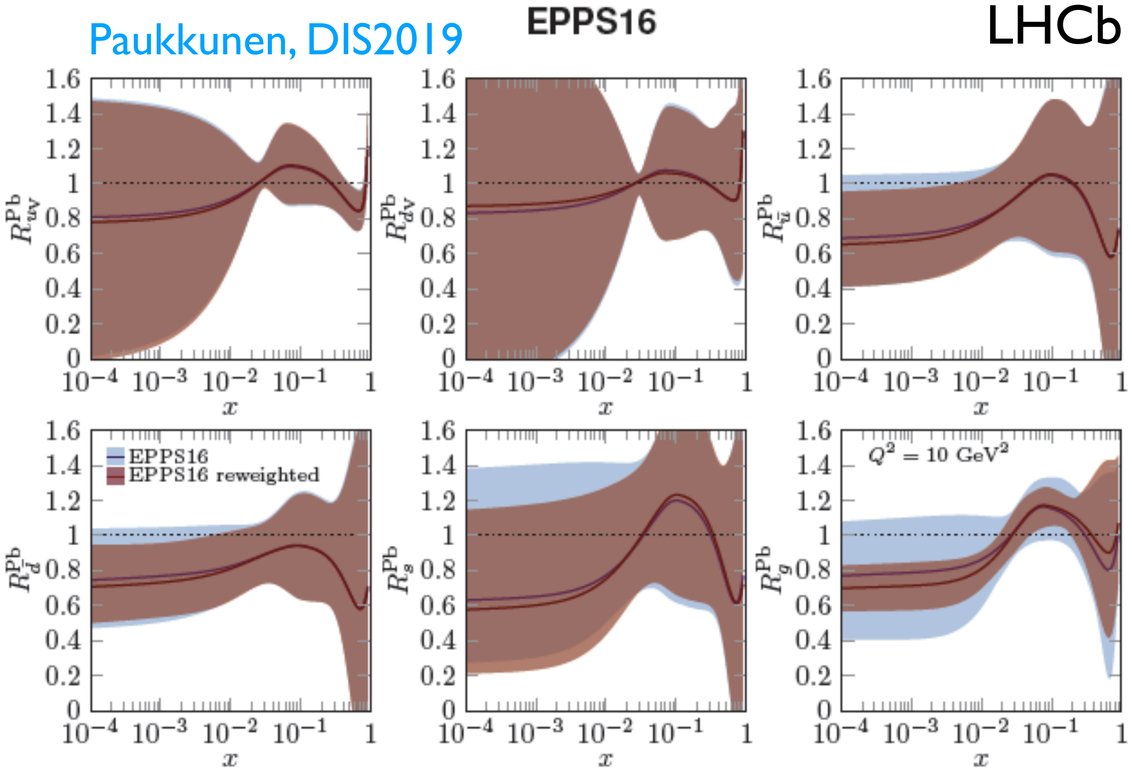
glue

Paukkunen at DIS2018

nPDFs: HL-LHC

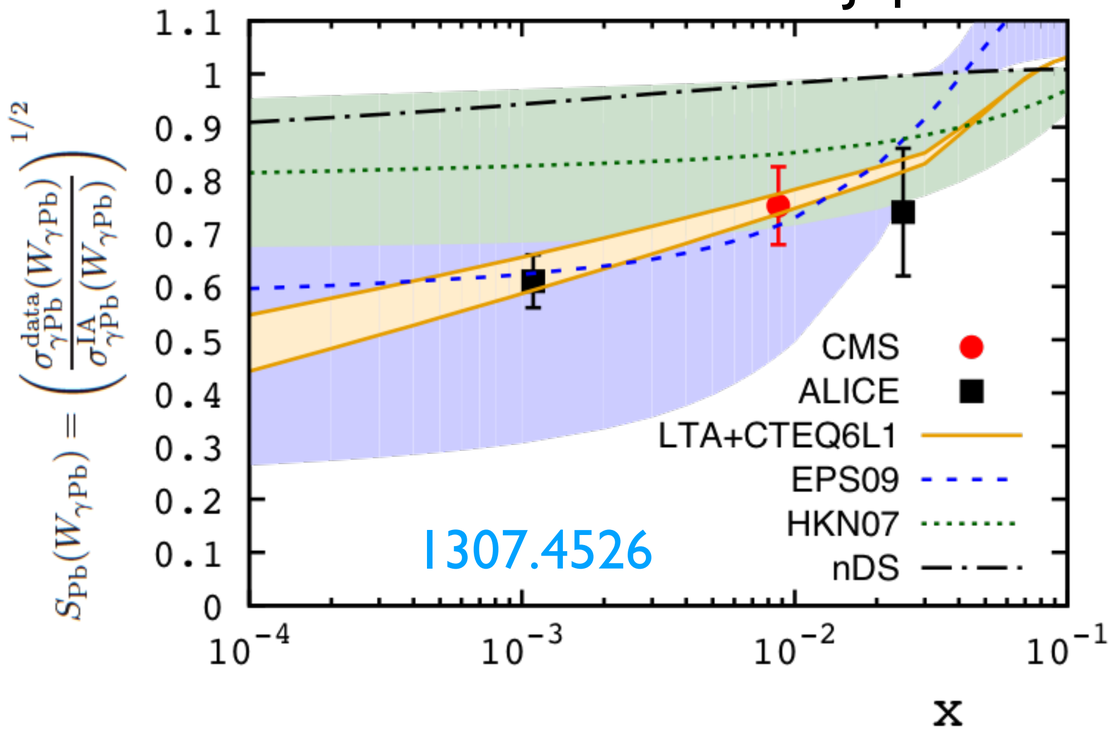
- Presently, only dijet and W/Z data from pPb at the LHC are used in global fits.
- Use of heavy quarks (including top) and quarkonium under study. See 1812.06772

Paukkunen, DIS2019



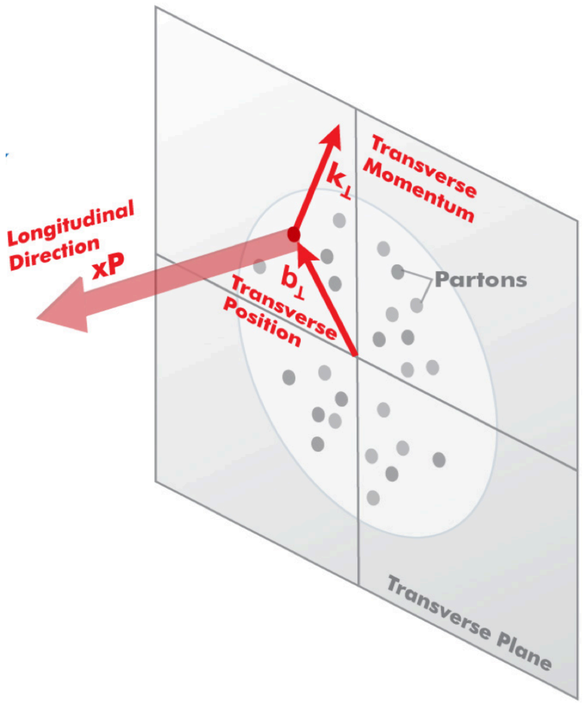
LHCb D-mesons

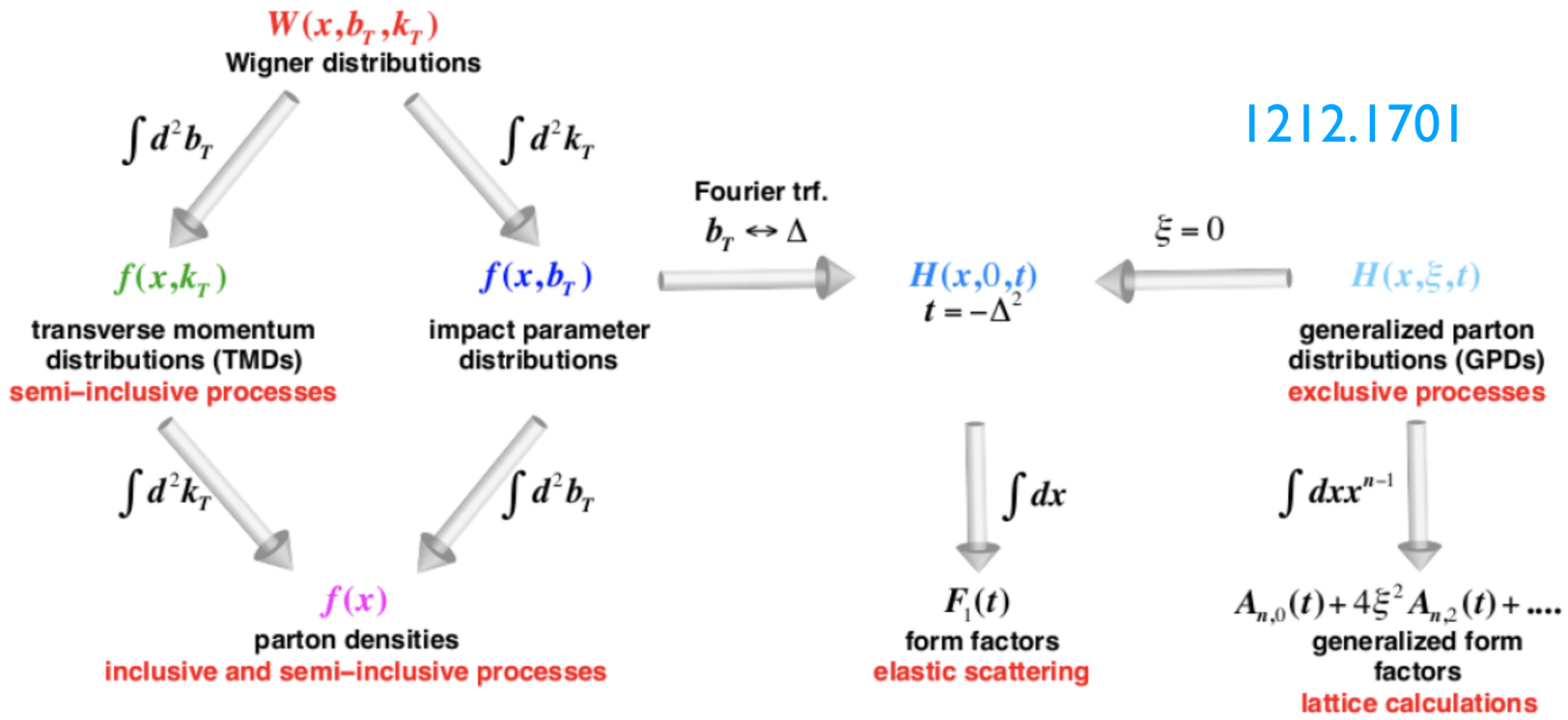
Exclusive J/ψ in UPCs



- Also exclusive vector meson production in UPCs - additional assumptions are required.
- **nPDFs from eA to be contrasted with pA/AA**: precise checks of factorisation in the nuclear environment.

3D-structure of hadrons and nuclei:





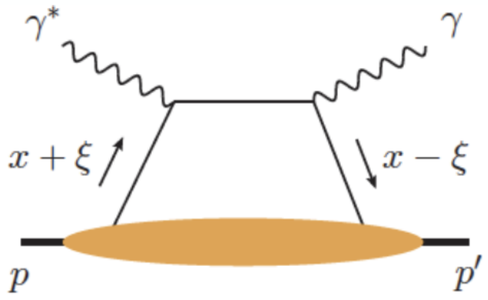
1212.1701

Two-scale processes

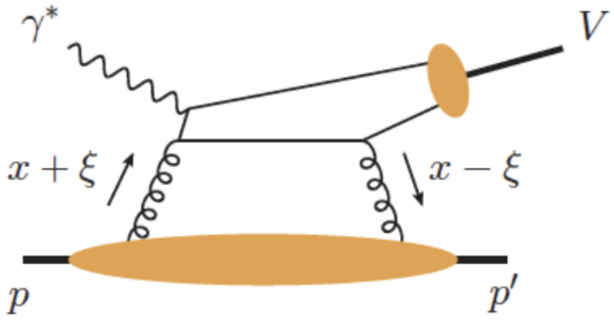
One-scale processes

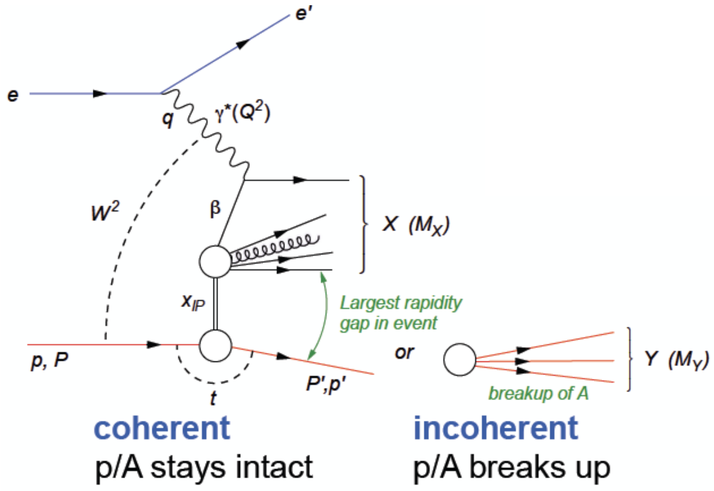
- New kinds of factorisation (or lack of it), new evolution equations.
- Directly related with spin.
- Most of these quantities can be ideally explored in the EIC and the LHeC; they also can be explored in fixed target programs (talks by Lansberg and Schnell) and UPCs (at Q=0).

Quark and gluon GPDs:



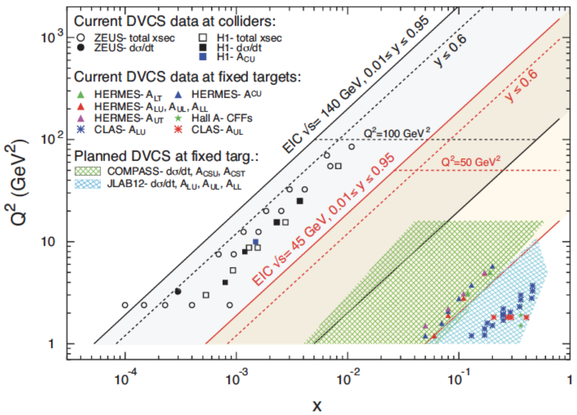
$$\int \frac{dw^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \left| T\overline{\psi}_j\left(0, \frac{1}{2}w^-, \mathbf{0}_T\right) \frac{\gamma^+}{2} \psi_j\left(0, -\frac{1}{2}w^-, \mathbf{0}_T\right) \right| P \right\rangle_c$$



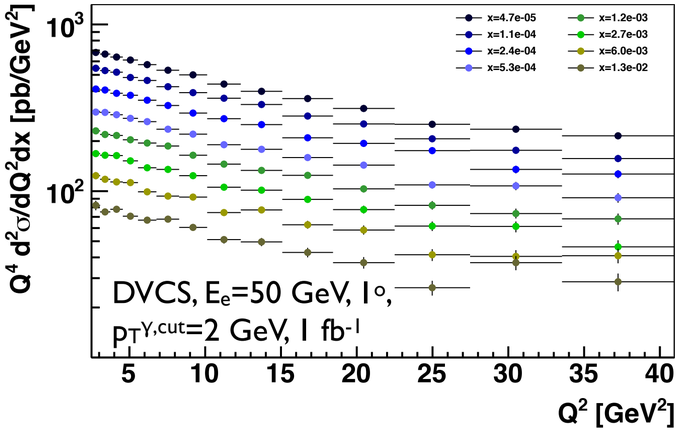


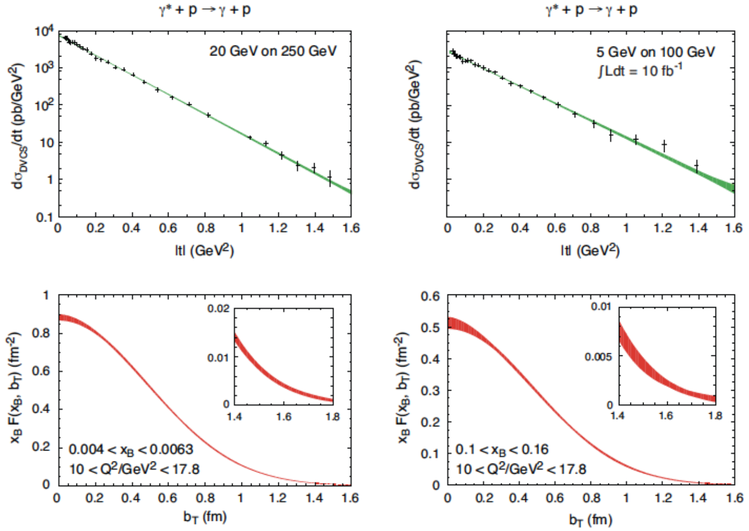
- Coherent exclusive production of γ and VM yields information about q and g GPDs.

EIC, 1212.1701

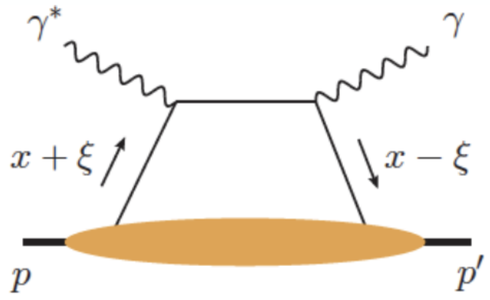


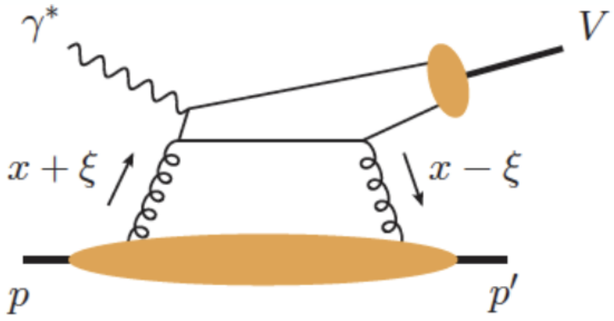
LHeC 1206.2913

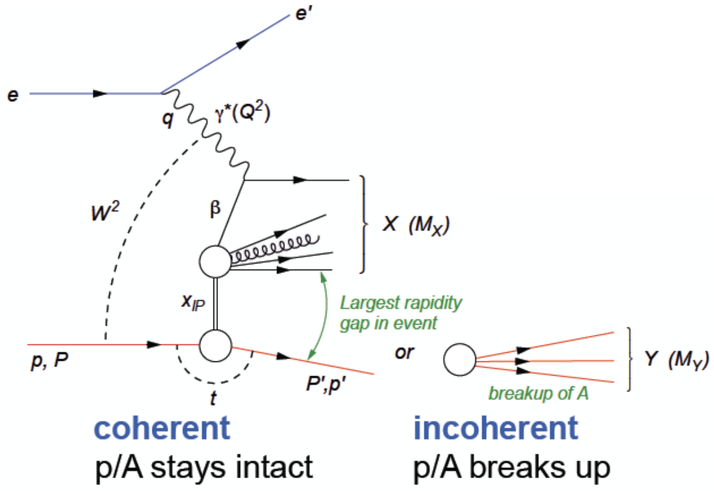




Quark and gluon GPDs:



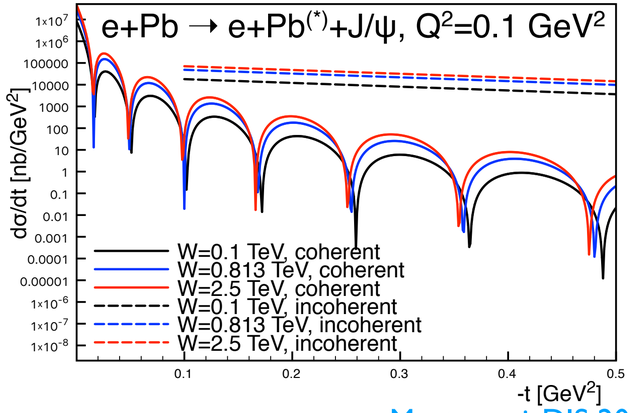


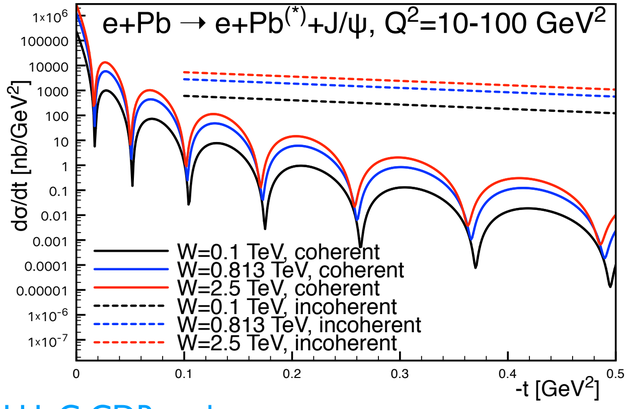


$$\int \frac{\mathrm{d}w^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \middle| T\overline{\psi}_j\left(0, \frac{1}{2}w^-, \mathbf{0}_\mathrm{T}\right) \frac{\gamma^+}{2} \psi_j\left(0, -\frac{1}{2}w^-, \mathbf{0}_\mathrm{T}\right) \middle| P \right\rangle_c$$

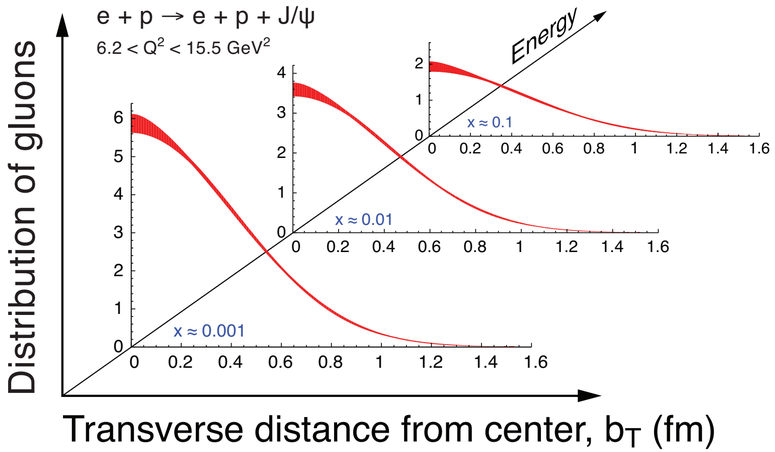
- Coherent exclusive production of γ and VM yields information about q and g GPDs.

1212.1701

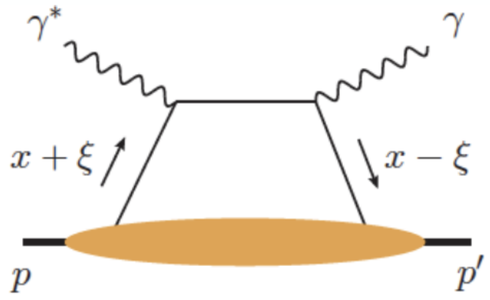




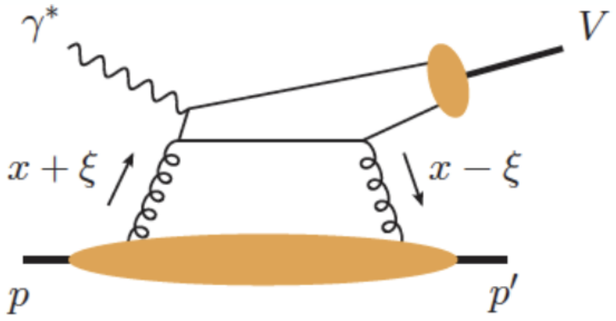
Mantysaari, DIS 2018, LHeC CDR update to appear

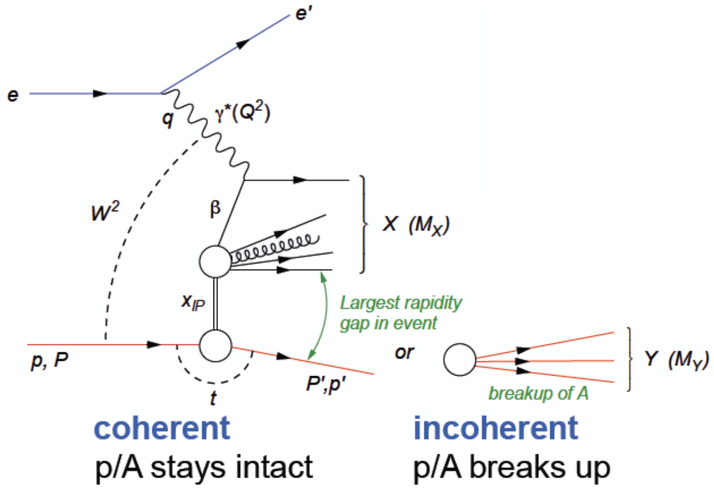


Quark and gluon GPDs:

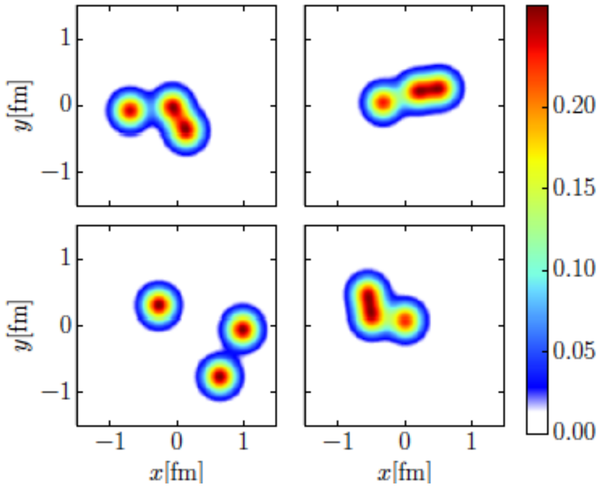


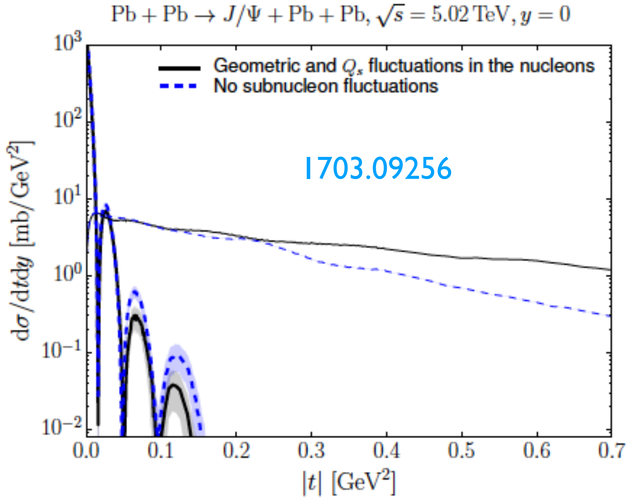
$$\int \frac{\mathrm{d}w^-}{2\pi} e^{-i\xi P^+ w^-} \left\langle P' \middle| T\overline{\psi}_j\left(0, \frac{1}{2}w^-, \mathbf{0}_\mathrm{T}\right) \frac{\gamma^+}{2} \psi_j\left(0, -\frac{1}{2}w^-, \mathbf{0}_\mathrm{T}\right) \middle| P \right\rangle_c$$



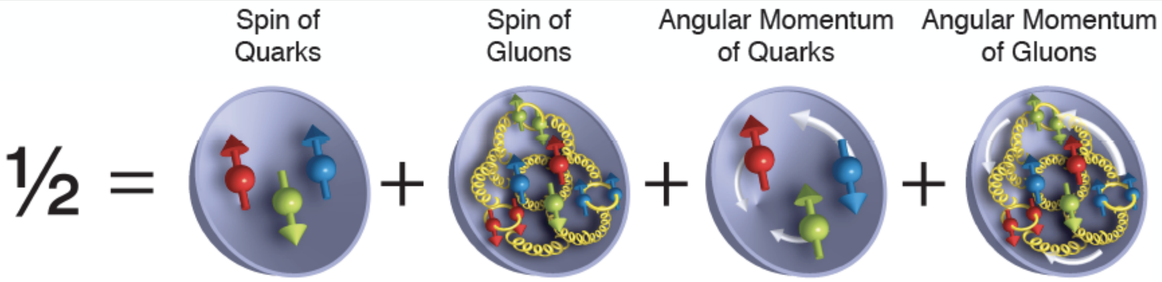


- Coherent exclusive production of γ and VM yields information about q and g GPDs.
- Incoherent exclusive production yields information about fluctuations: hot spots.





Spin:



Inclusive Measurement: e+p → e′+X

$$\frac{1}{2}\left[\frac{d^2\sigma^{\rightleftarrows}}{dx\,dQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dx\,dQ^2}\right] \simeq \frac{4\pi\alpha^2}{Q^4} y\,(2-y)\,g_1(x,Q^2)$$

Leading Order:

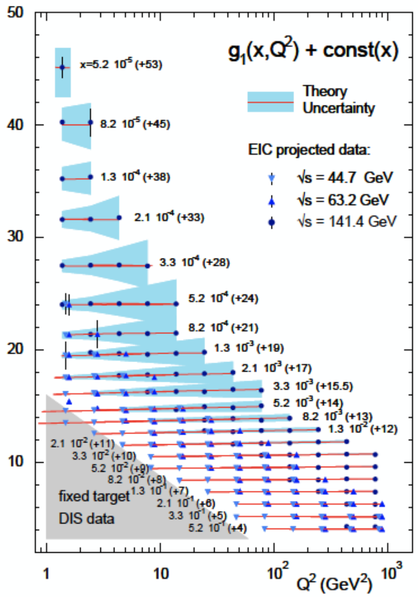
$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\,\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

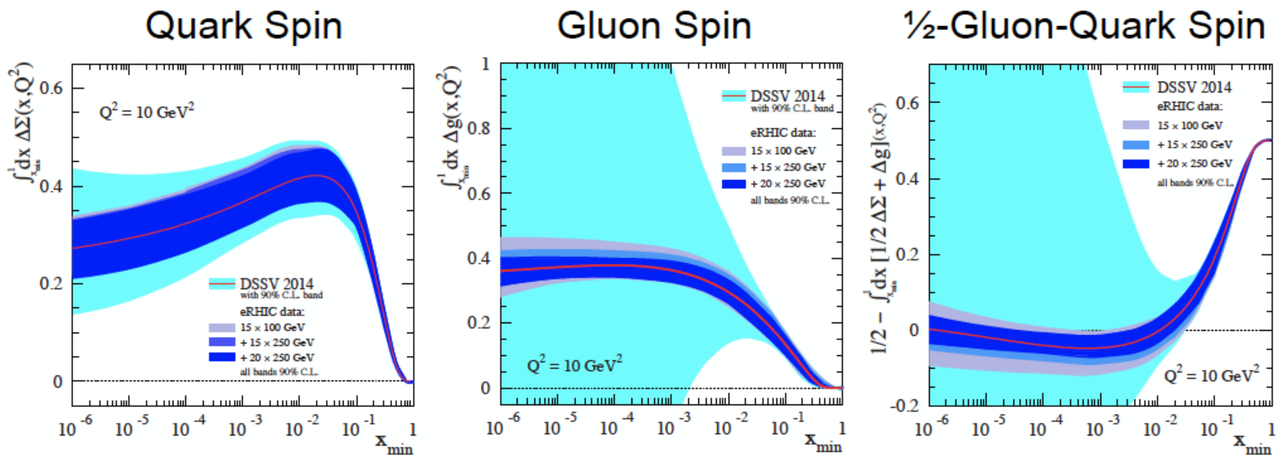
$$\Delta\Sigma(Q^2) = \int_0^1 dx\; g_1(x,Q^2) \quad \text{(Quark Spin)}$$

Higher Order:

$$\frac{dg_1}{d\log Q^2} \propto \Delta g(x,Q^2) \quad \text{(Gluon Spin)}$$

- The origin of proton spin has been an open issue for several decades: schematically speaking, quarks account for ~30 %, gluons for ~ 20 % (known in a limited x-range), the rest?





- Inclusive measurements with both e and p polarised (**EIC**): huge improvement at low x.

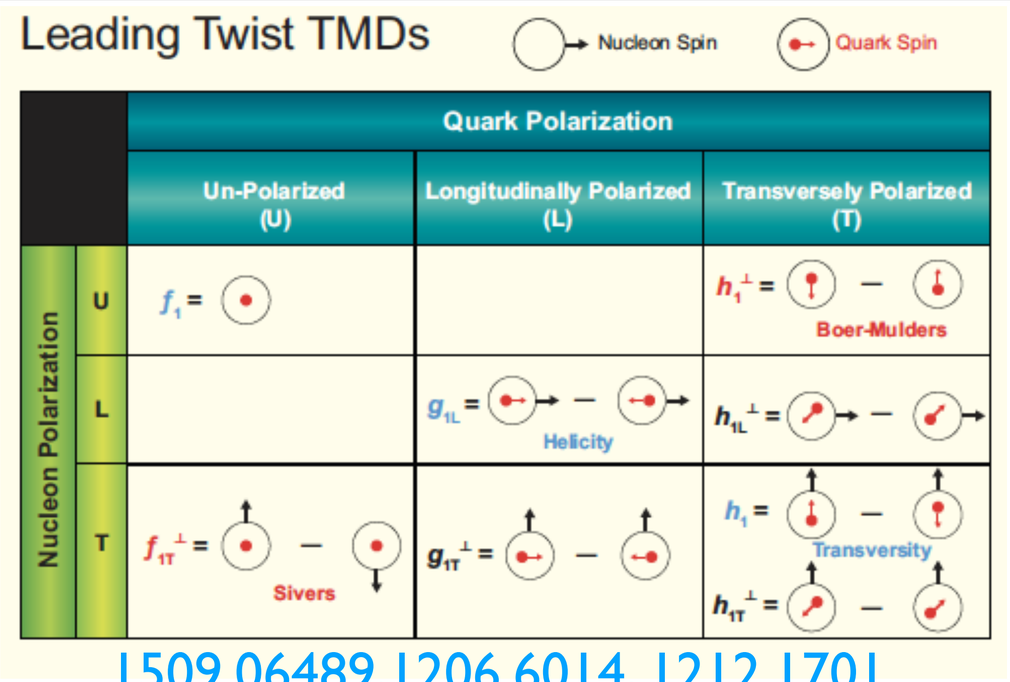
1509.06489, 1206.6014, 1212.1701

TMDs and spin:

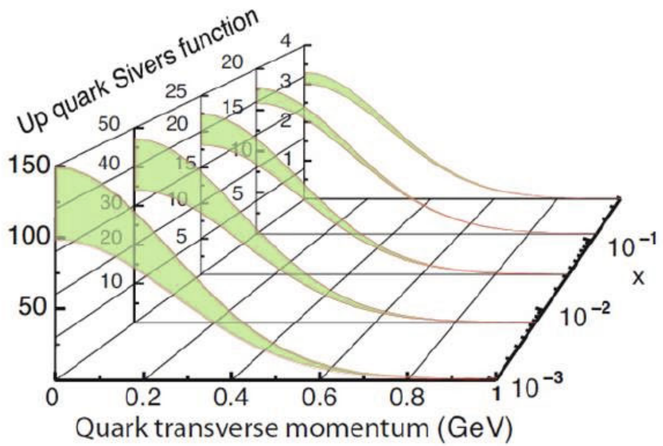
- Several TMDs to be determined by different observables: beyond inclusive DIS, further possibilities are SIDIS (FFs required), CC,…

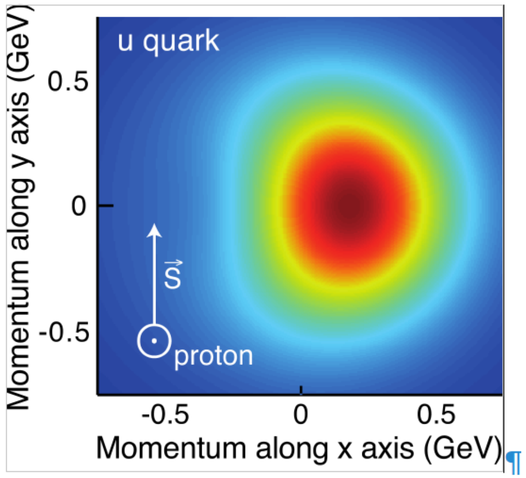
- Besides, polarised light nuclei, diffraction,…

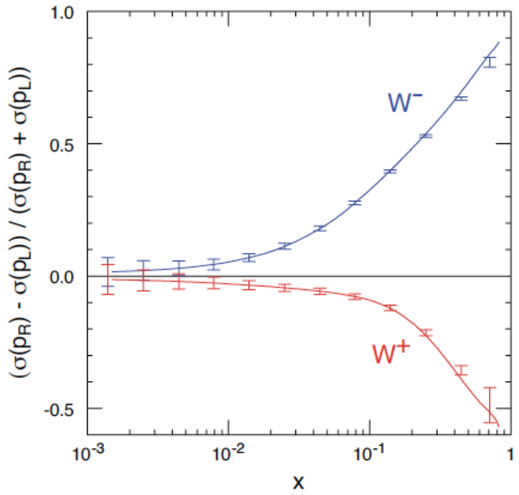
- TMD factorisation can be tested in non-polarised collisions: dijets, charm,… Relation at small x with CGC.



1509.06489,1206.6014, 1212.1701



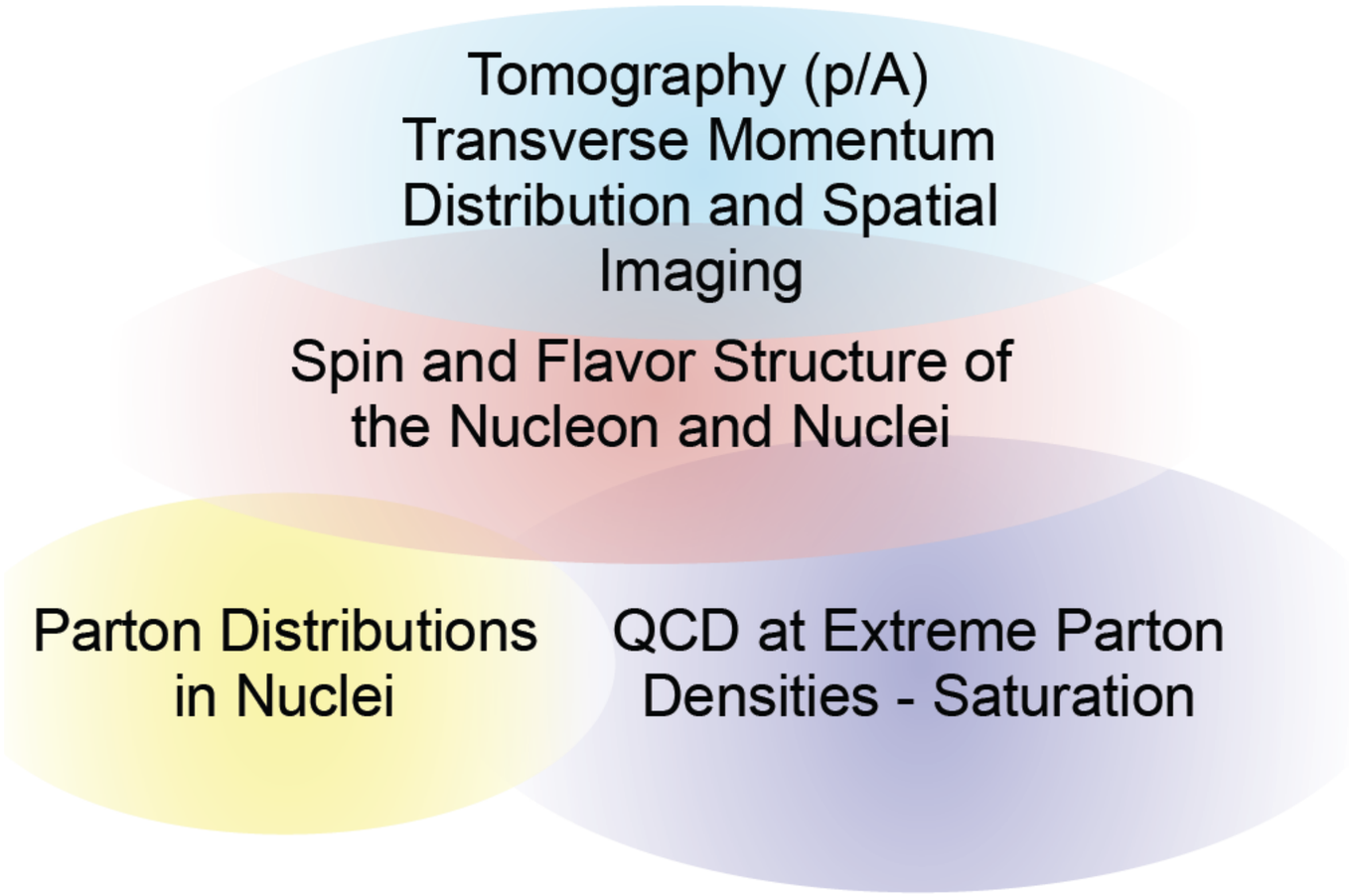




EIC:

The EIC Physics Pillars

1212.1701



EICUG: ~ 860 people (1/3 from Europe)

EIC:

The EIC Physics Pillars

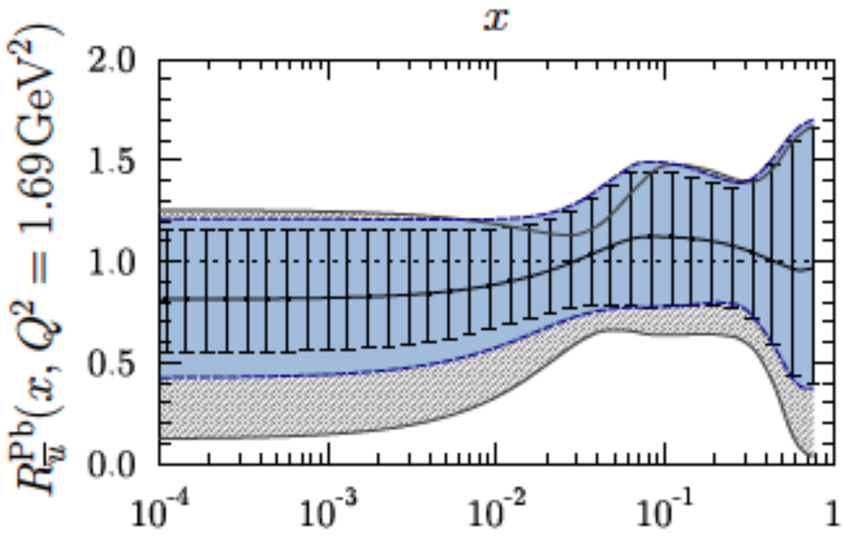
1212.1701

Tomography (p/A)
Transverse Momentum
Distribution and Spatial
Imaging

Spin and Flavor Structure of
the Nucleon and Nuclei

Parton Distributions
in Nuclei

QCD at Extreme Parton
Densities - Saturation



sea

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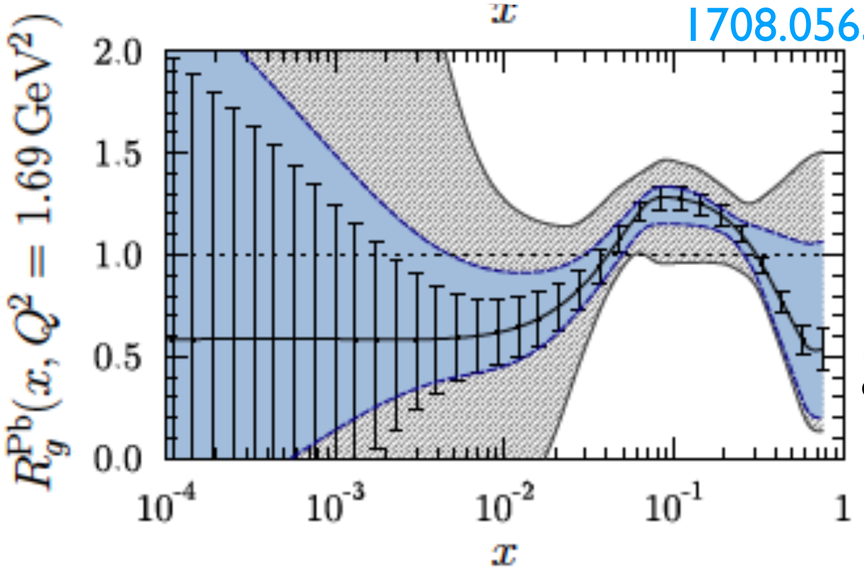

glue

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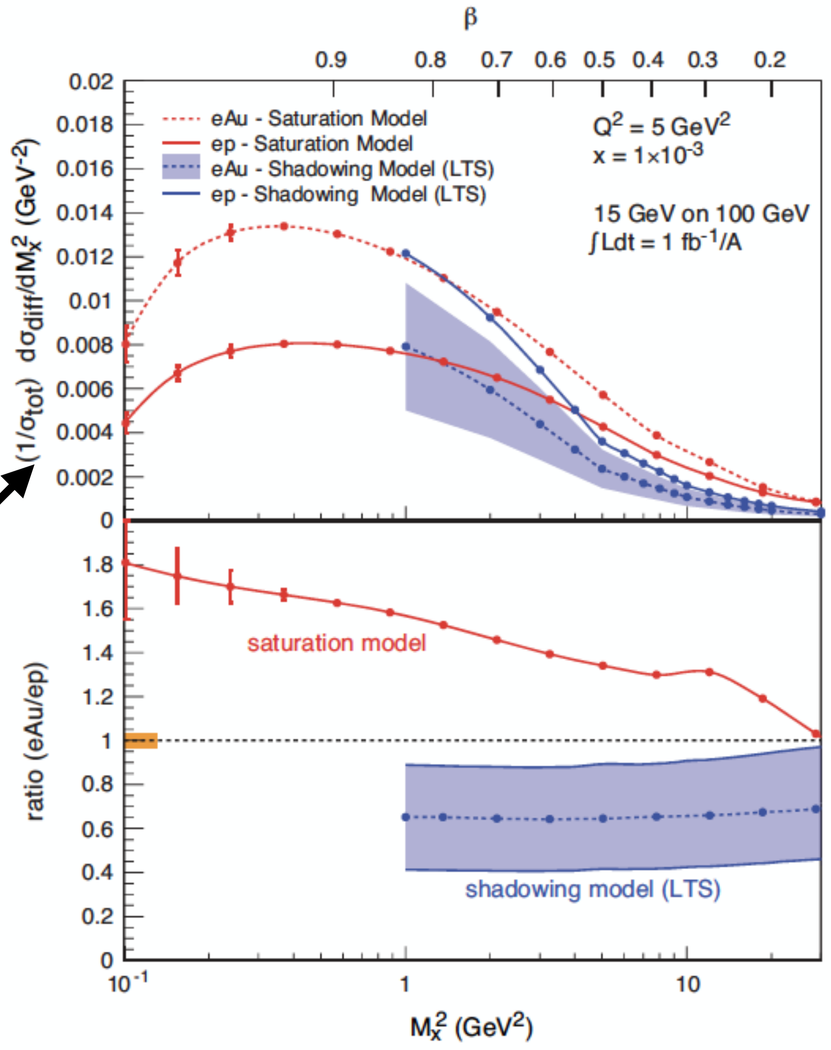
Diffraction



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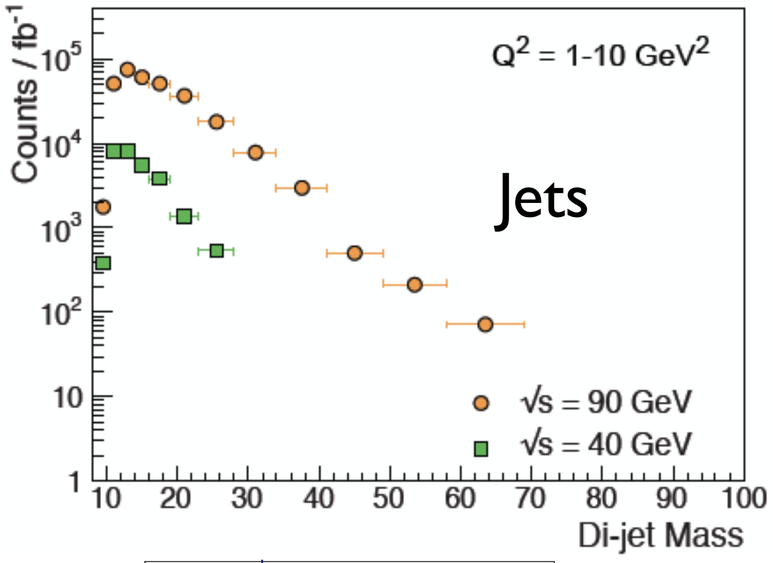
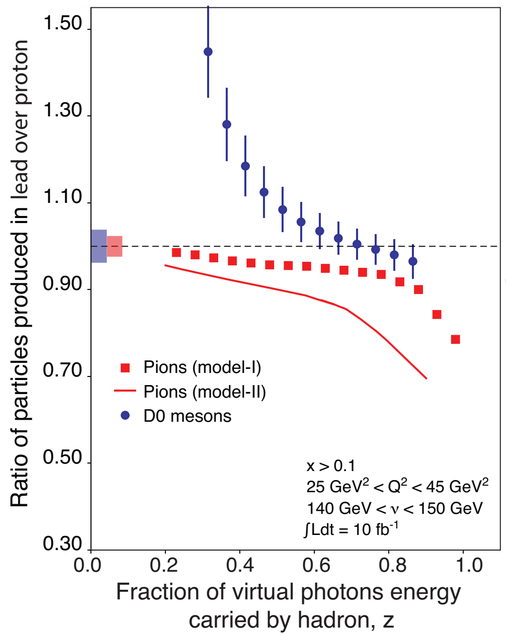
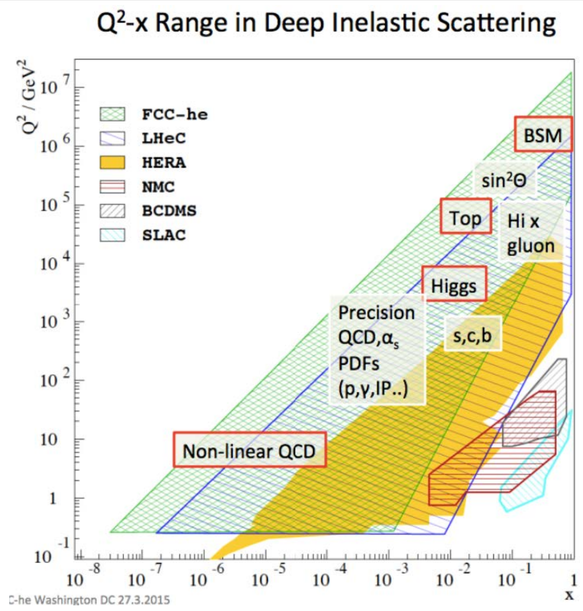




Fragmentation functions

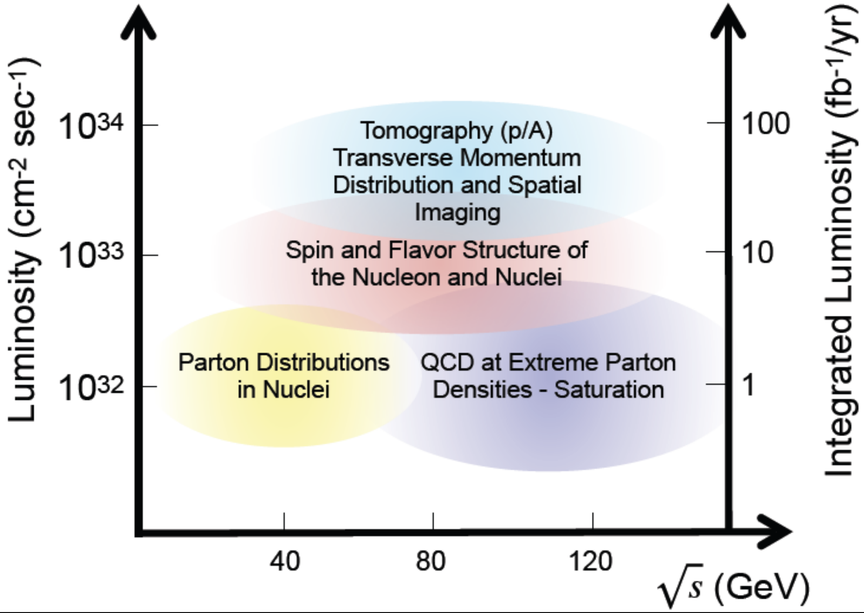
LHeC & EIC: synergies and complementarities

- **EIC versus LHeC/FCC-eh: different kinematics and different focus of the physics programs - even on the QCD side.**



- Synergies:
  - ➜ Detector studies: forward instrumentation for diffraction?
  - ➜ QCD Monte Carlo simulators.
  - ➜ Analysis frameworks?
  - ➜ Theoretical developments: higher orders e.g. N³LO DGLAP.

- Complementarities:
  - ➜ Kinematics: $Q^2 < 1$ GeV² and large x and not so large Q^2 to be studied at the EIC; evolution to be obtained at the LHeC/FCC-eh.
  - ➜ Detector optimisation: EIC more focused to PID and low transverse momentum.
  - ➜ Nuclear species: in principle, more flexibility at the EIC, but proposals for lighter ions at the LHC in the 2030's have been done in the context of the HL/HE-LHC studies (see 1812.06772).



Relation with other fields:

- String theory (AdS/CFT correspondence): models for QCD at strong coupling at zero and finite temperature, applied to model DIS at low Q^2.

- Cosmic ray physics, see Tanguy Pierog's talk.

- Information theory: how to reconcile the parton picture with the the proton/nucleus as a pure quantum state? Relation with:
  - ➜ The physics of open quantum systems.
  - ➜ Entropy produced in hadronic and nuclear collisions.
  - ➜ Wigner distributions: TMDs, GPDs.
  - ➜ Entropy in QCD radiation: jets.