Mining for gluon saturation at the Electron Ion Collider

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ePIC/EIC Early Science Workshop
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Outline

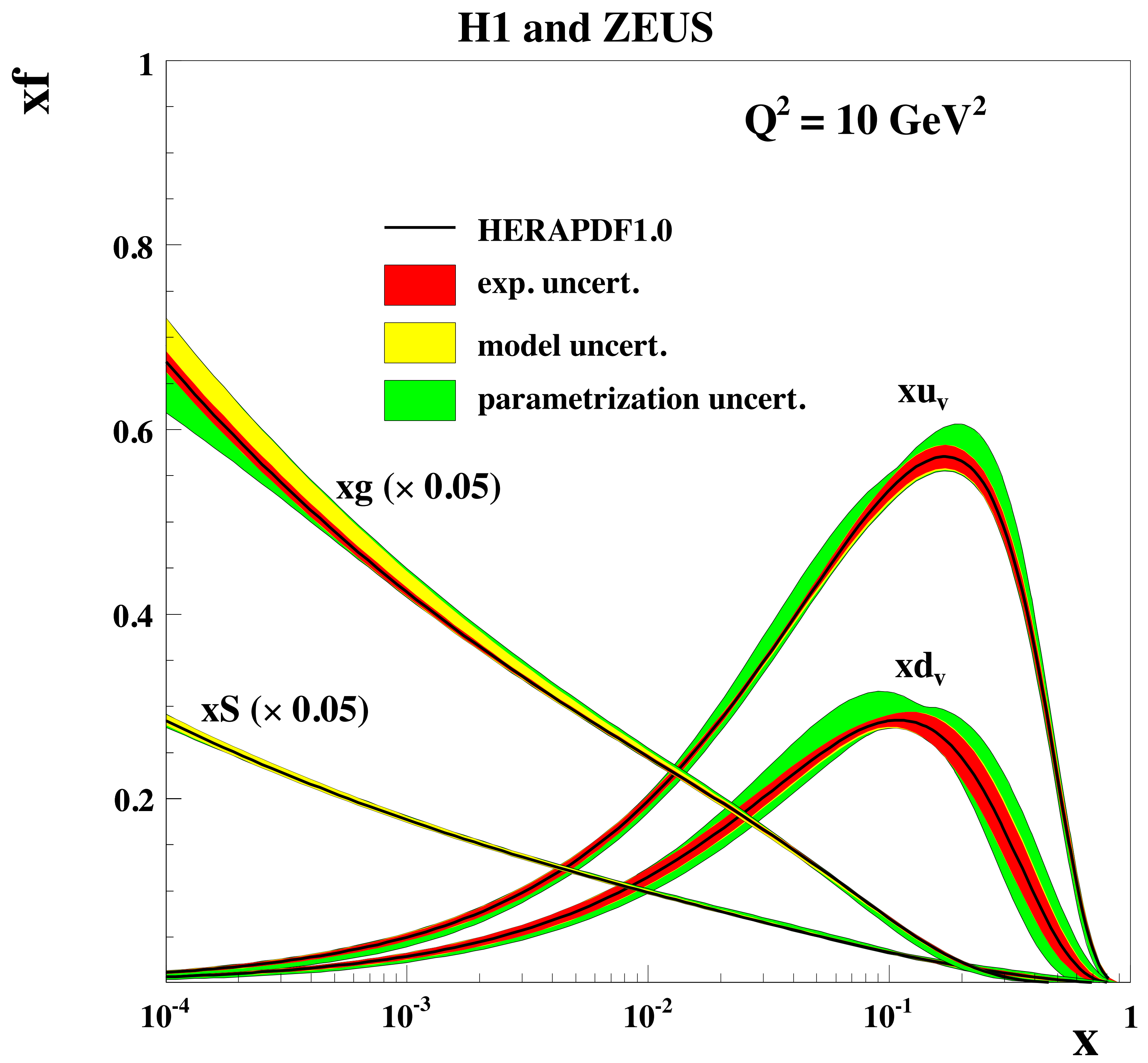
- CGC in a nutshell

- Observables at the EIC

  Inclusive: structure functions
  Semi-inclusive: two-particle correlations
  Exclusive: vector meson production

- Summary

Anatomy of high-energy QCD



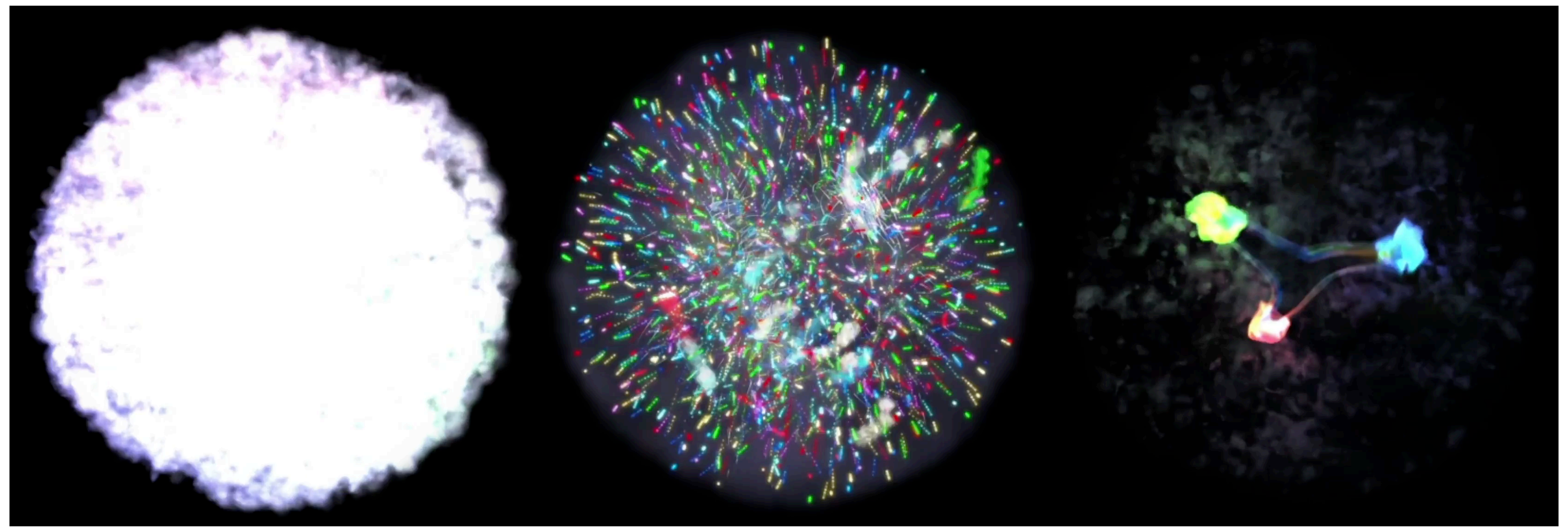
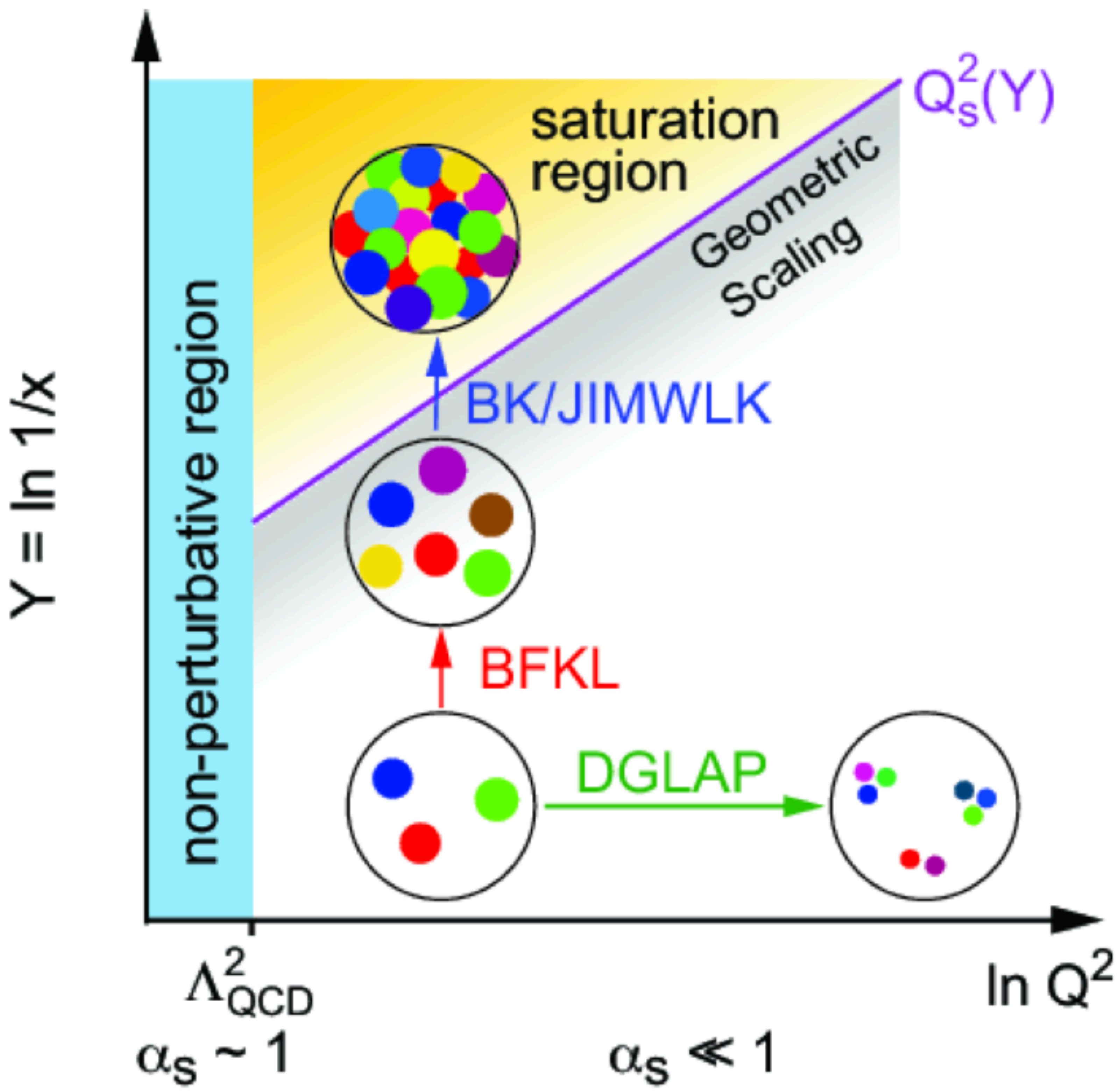


Figure from MIT/Jefferson Lab/Sputnik

Hadronic matter a vibrant
QCD environment

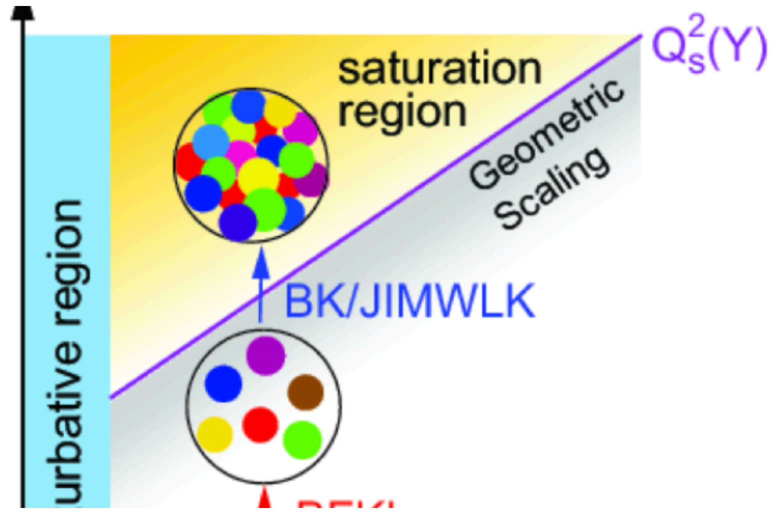


Partonic picture superseded by **strong color fields**

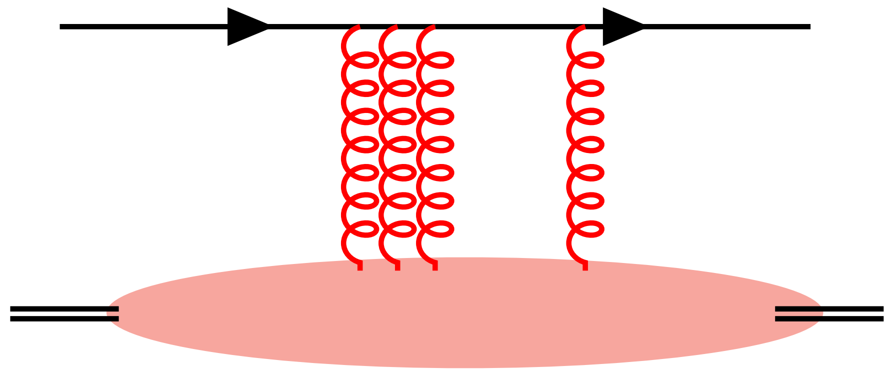
Emergence of x-dependent momentum scale $Q_s^2(x)$
allow for weakly coupled methods

Universality: unified description of QCD at high-energies

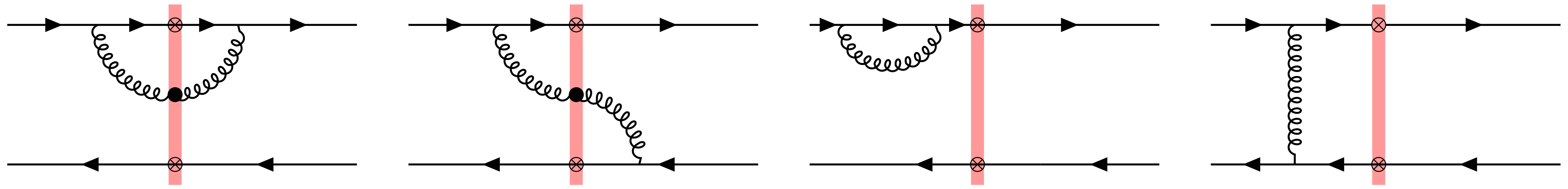
The Color Glass Condensate in a nutshell



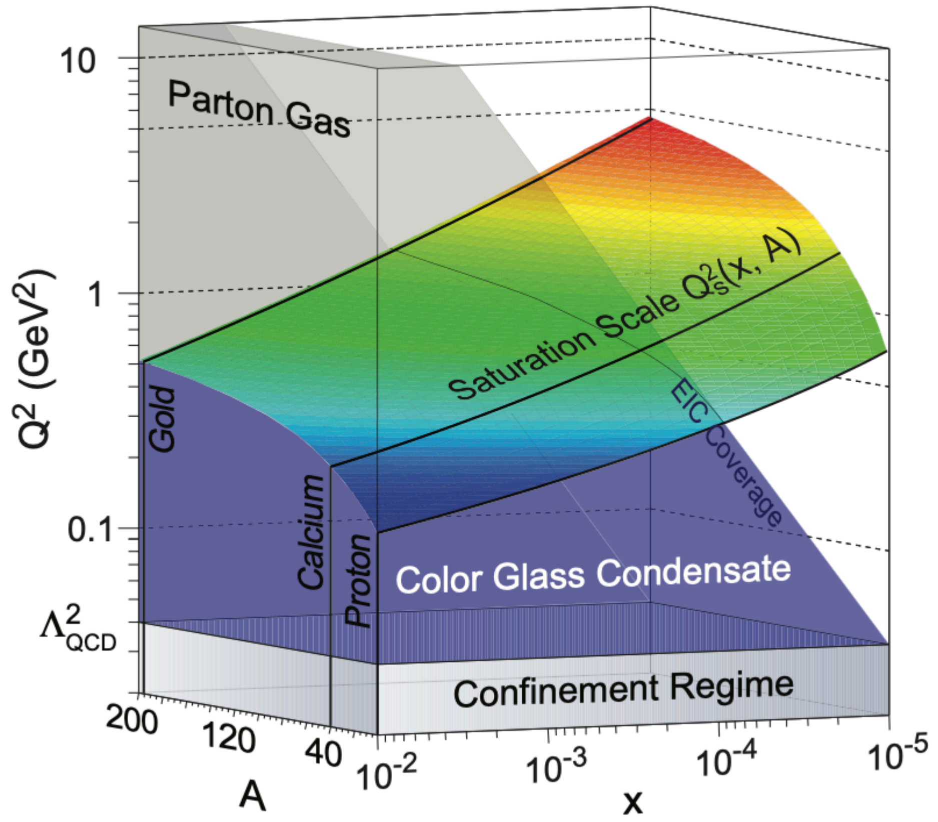
- CGC is an EFT of QCD providing a weak coupling approach for unitarization of cross-section



- Strong classical field -> multiple scattering -> broadening (Glauber)



- Small-x radiation -> quantum (non-linear) evolution-> suppression (Gribov)

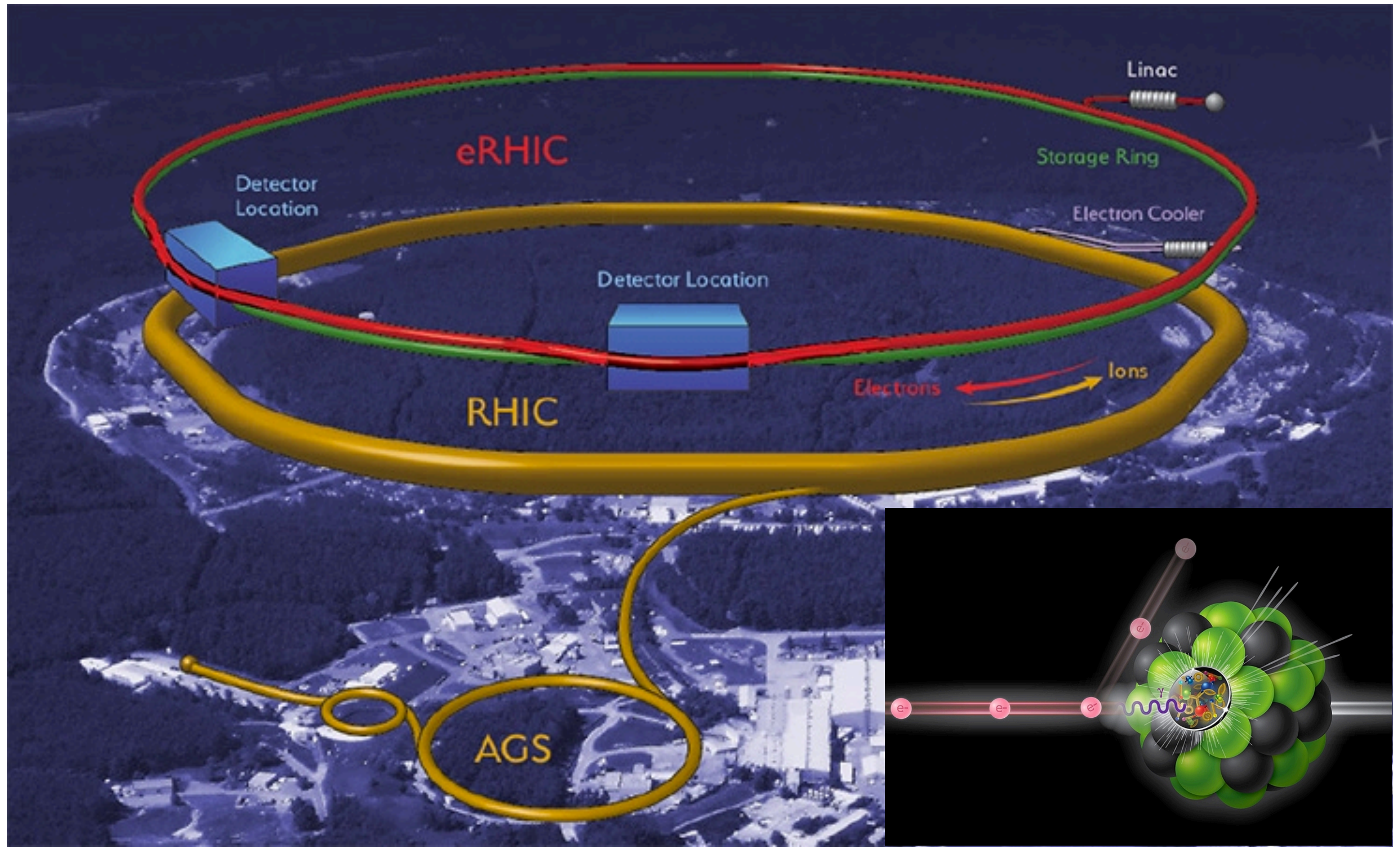


- Emergence of an x-dependent and A-dependent momentum scale: $Q_s^2(x) \approx \Lambda_{QCD}^2 A^{1/3}(x_0/x)^\lambda$

- Saturation phenomena manifests in particle production of invariant mass $M^2 \lesssim Q_s^2(x)$

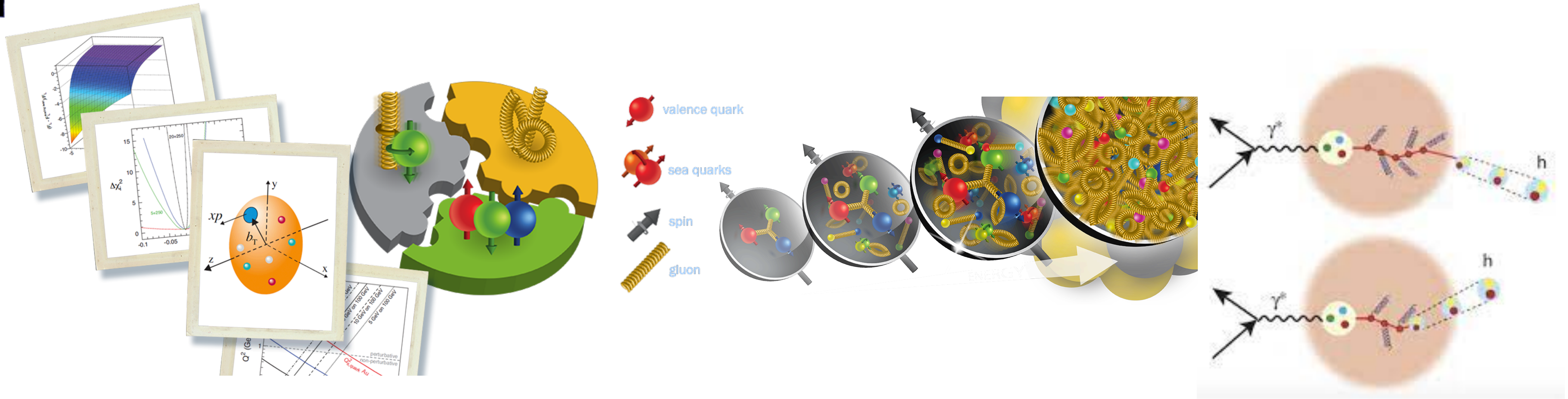
Electron-Ion Collider Era

Capabilities and scientific case



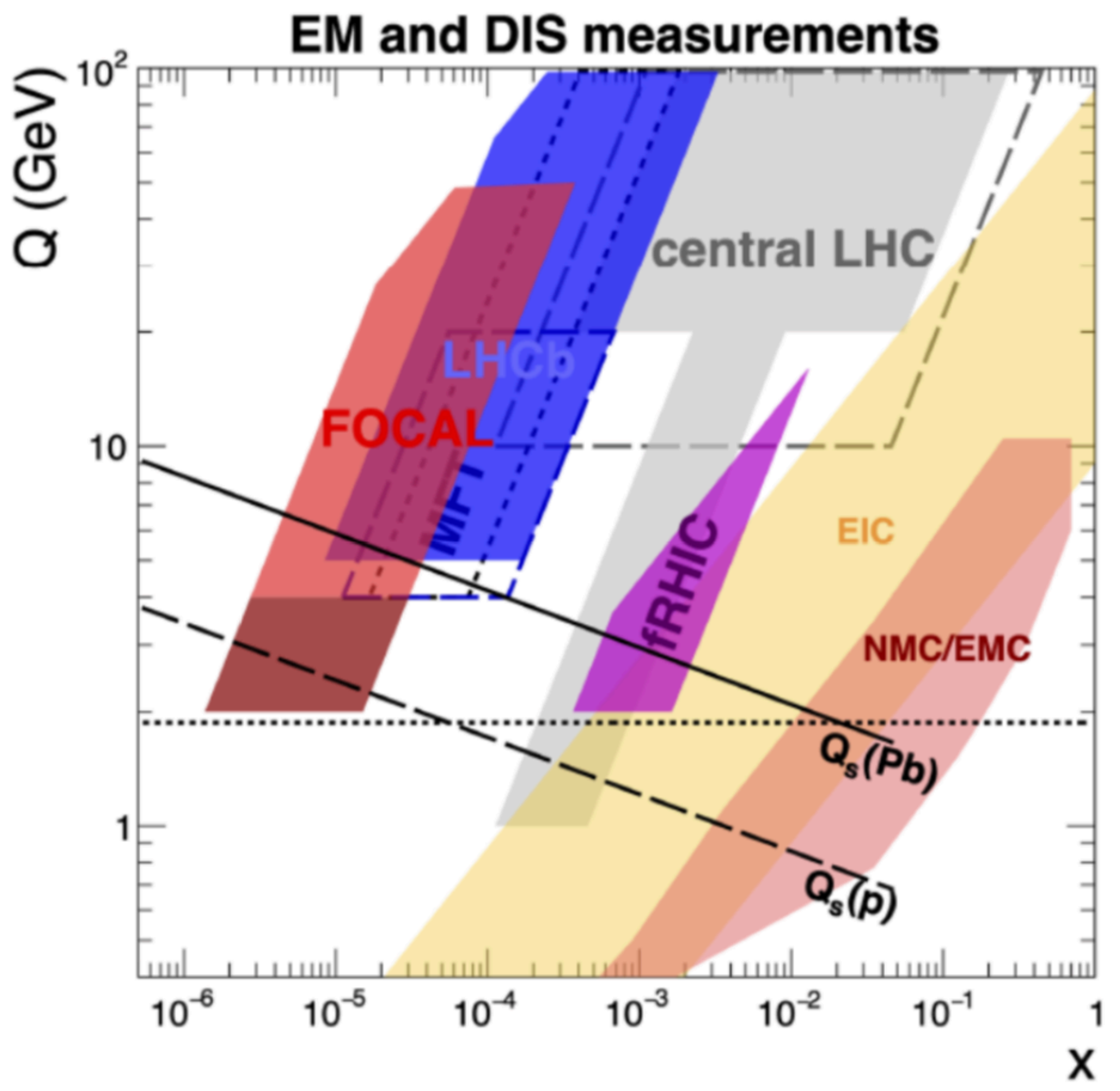
- High luminosity (high rate of collisions)
- Up to ~ 140 GeV center of mass energy
- Polarized beams of (light) ions and electrons
- Large ion species (from proton to gold)

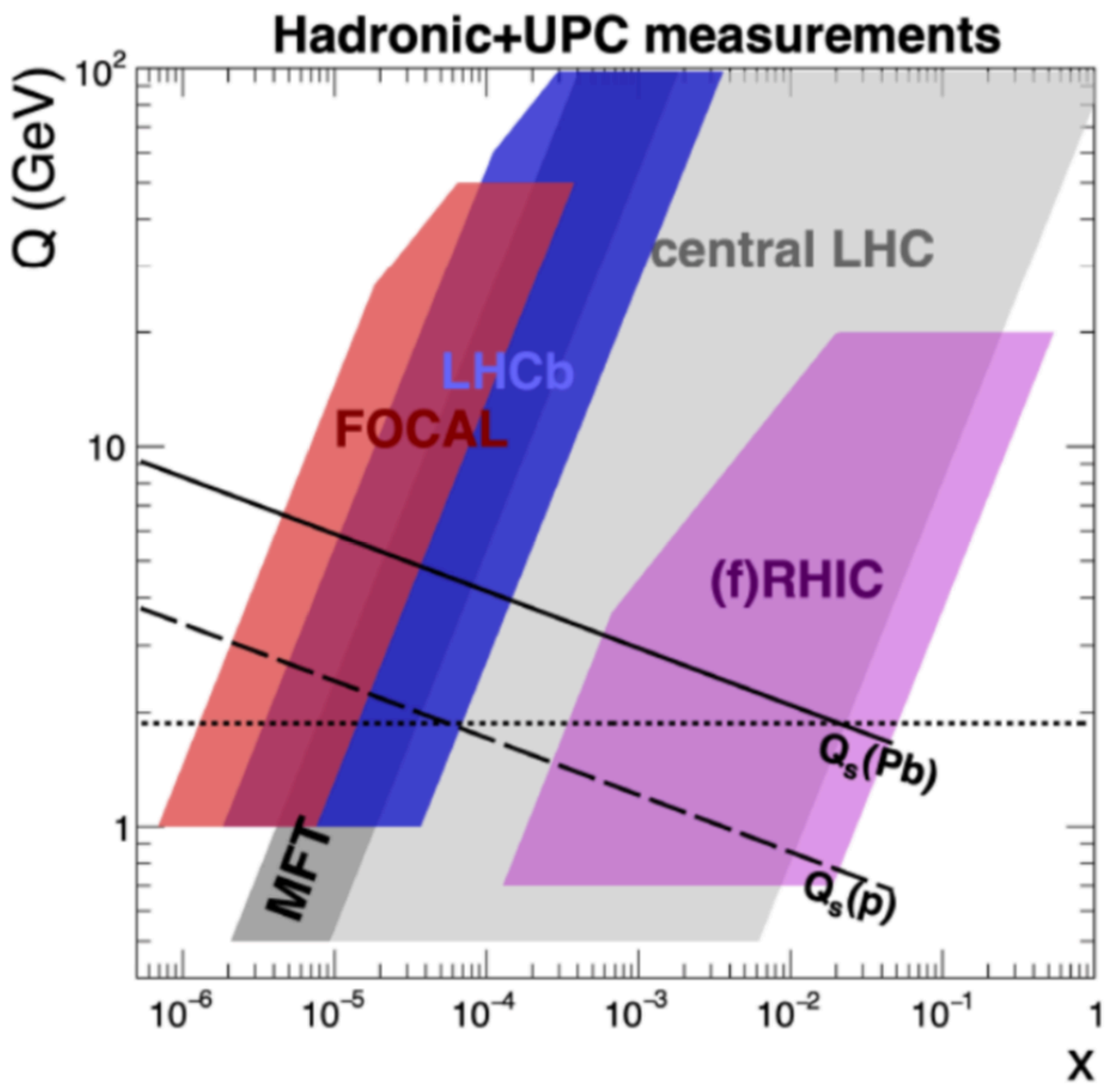
EIC goals: tomography, spin, gluon saturation, hadronization

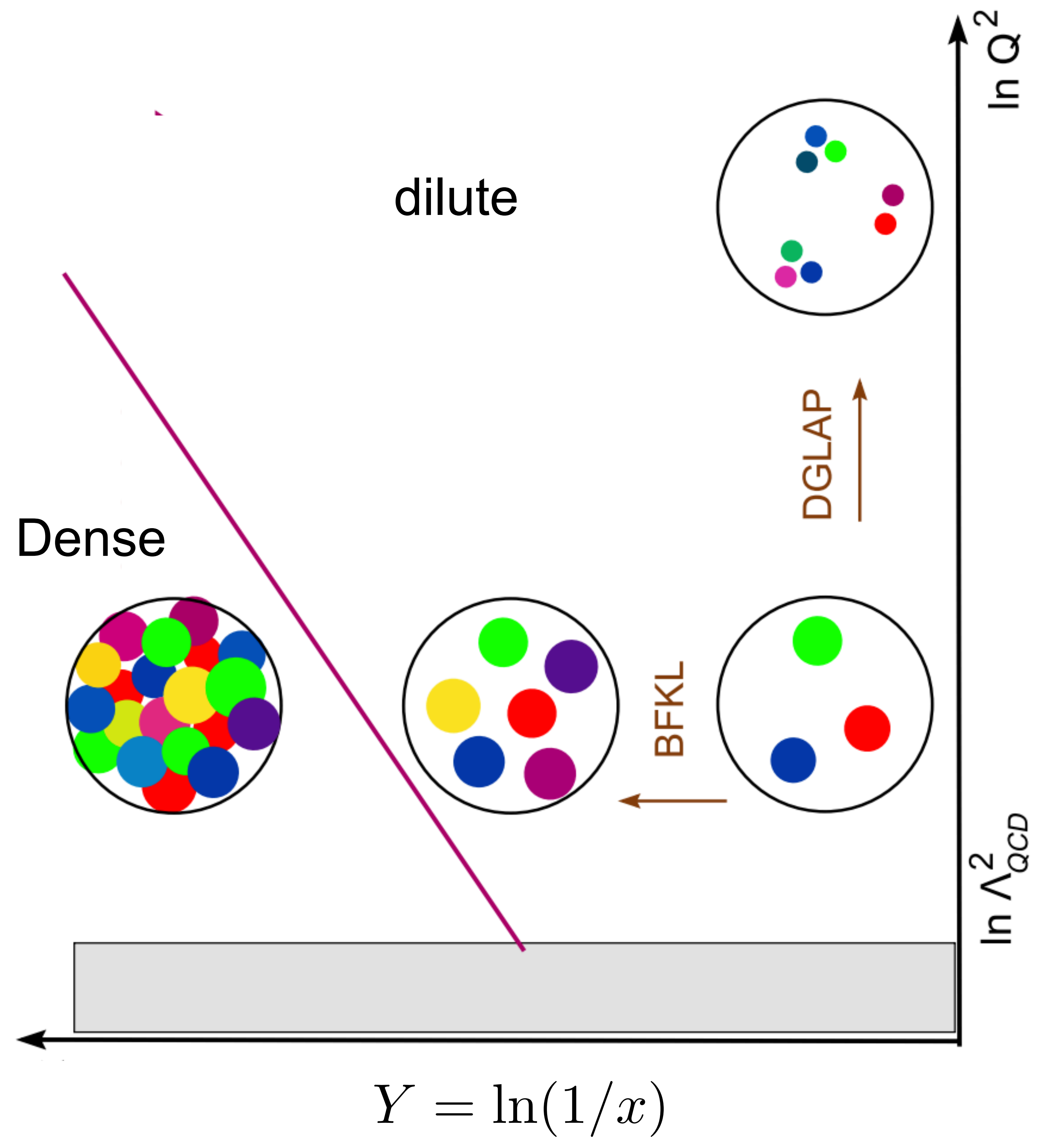


Figures from https://www.bnl.gov/eic/science.php

Experimental prospects: LHC and EIC



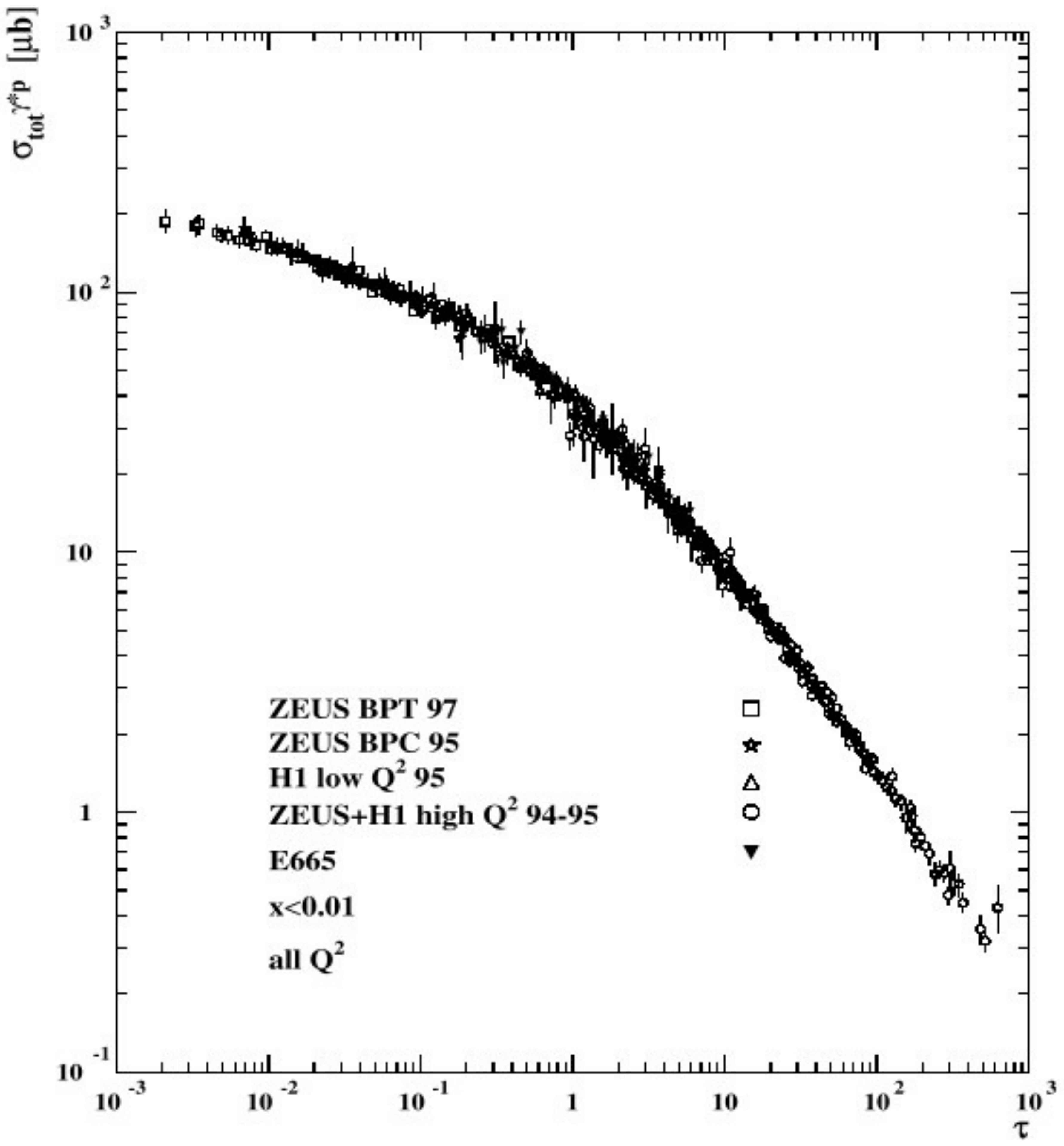




Complementarity between LHC and EIC

Inclusive

Structure functions: geometric scaling



$$\sigma_r(x, y, Q^2) = F_2(x, Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x, Q^2)$$

- DIS cross-section generically depends on Q^2 and x
- HERA data shows signs of scaling: $\tau = Q^2/Q_s^2(x)$

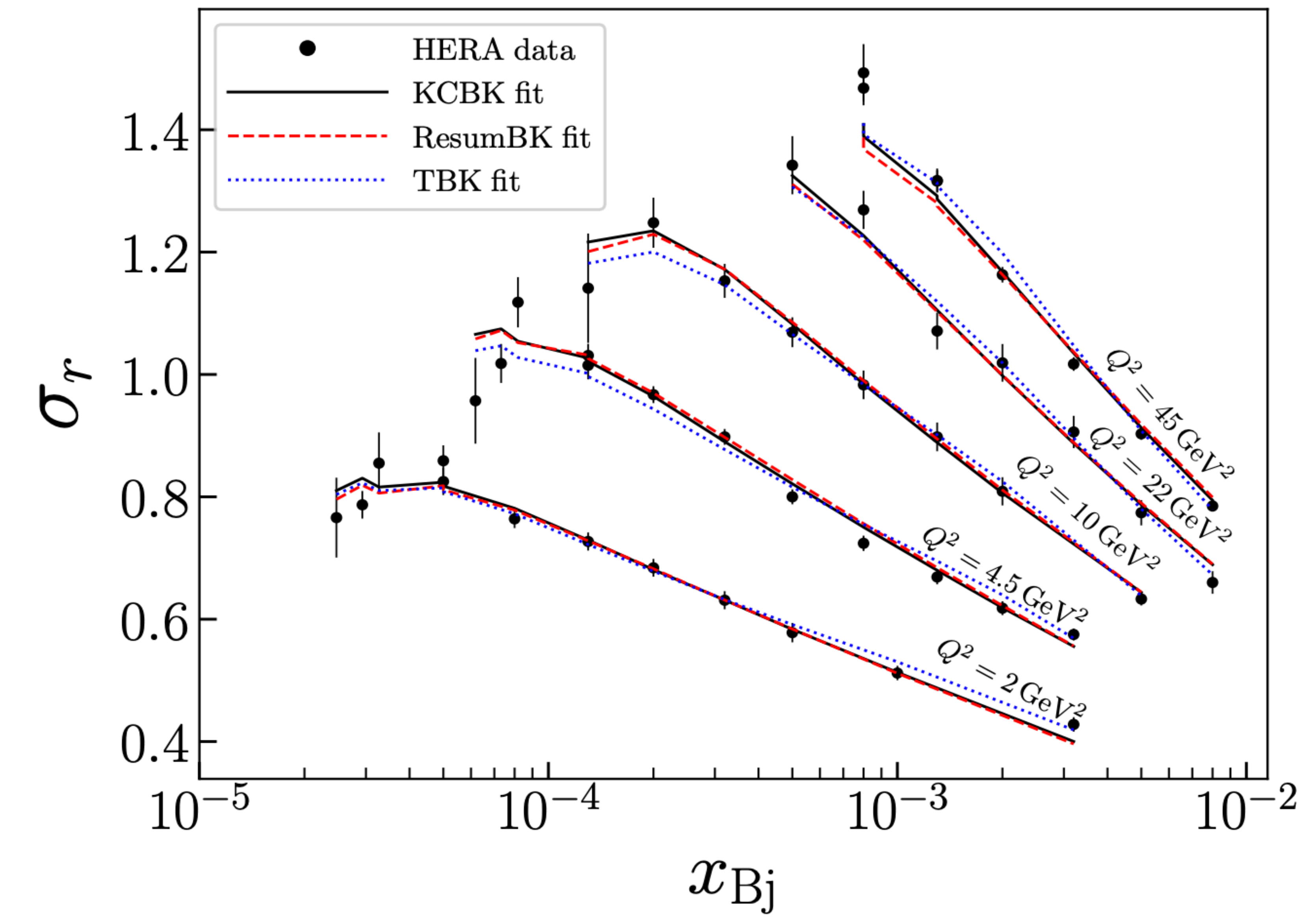
$$Q_s^2(x) = Q_{s,0}^2 (x_0/x)^\lambda$$

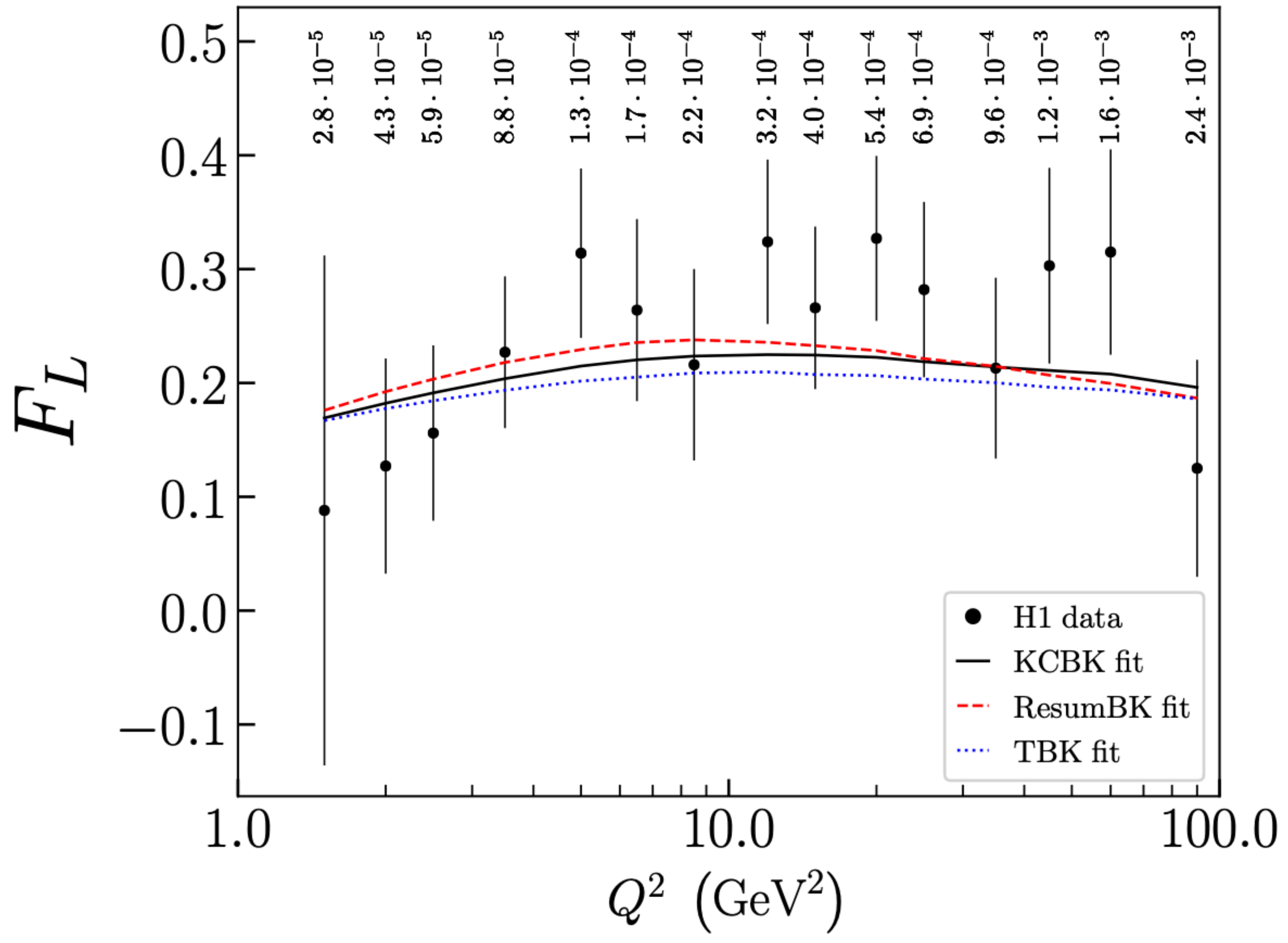
- Can we observe geometric scaling for different nuclear species?
- Will we observe the nuclear size dependence of the saturation scale?

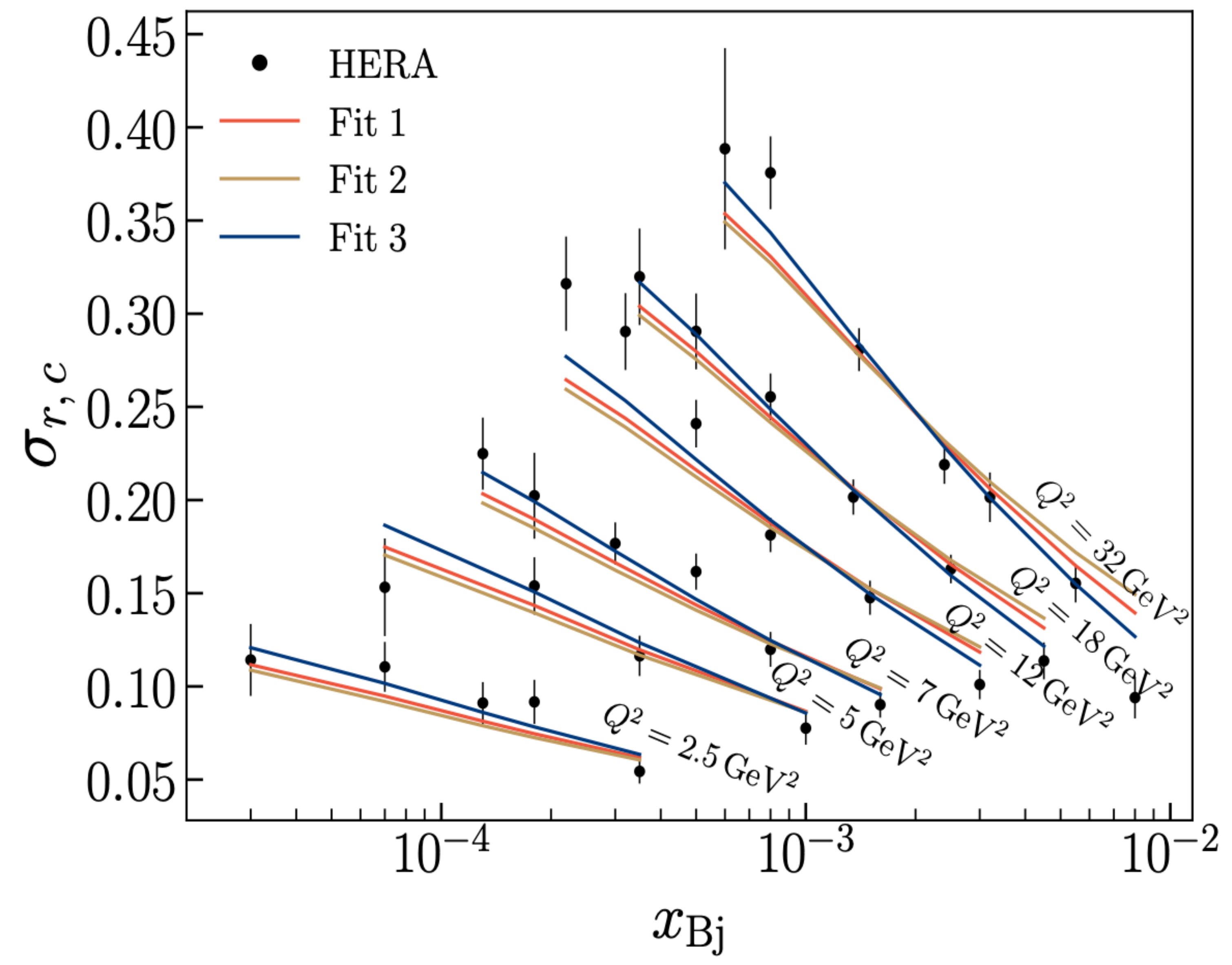
$$Q_s^2(x, A) = Q_{s,0}^2 (x_0/x)^\lambda A^{1/3}$$

Structure functions: F_2 and F_L

- CGC at NLO provides a good simultaneous description of structure functions including charm







Beuf, Lappi, Hänninen, Mäntysaari (2020)

- However, F_2 has large non-perturbative contributions. It would be best to focus on F_L or $F_{2,c}$

- Confront CGC to nuclear structrure functions at the EIC

Structure functions: linear vs non-linear evolution

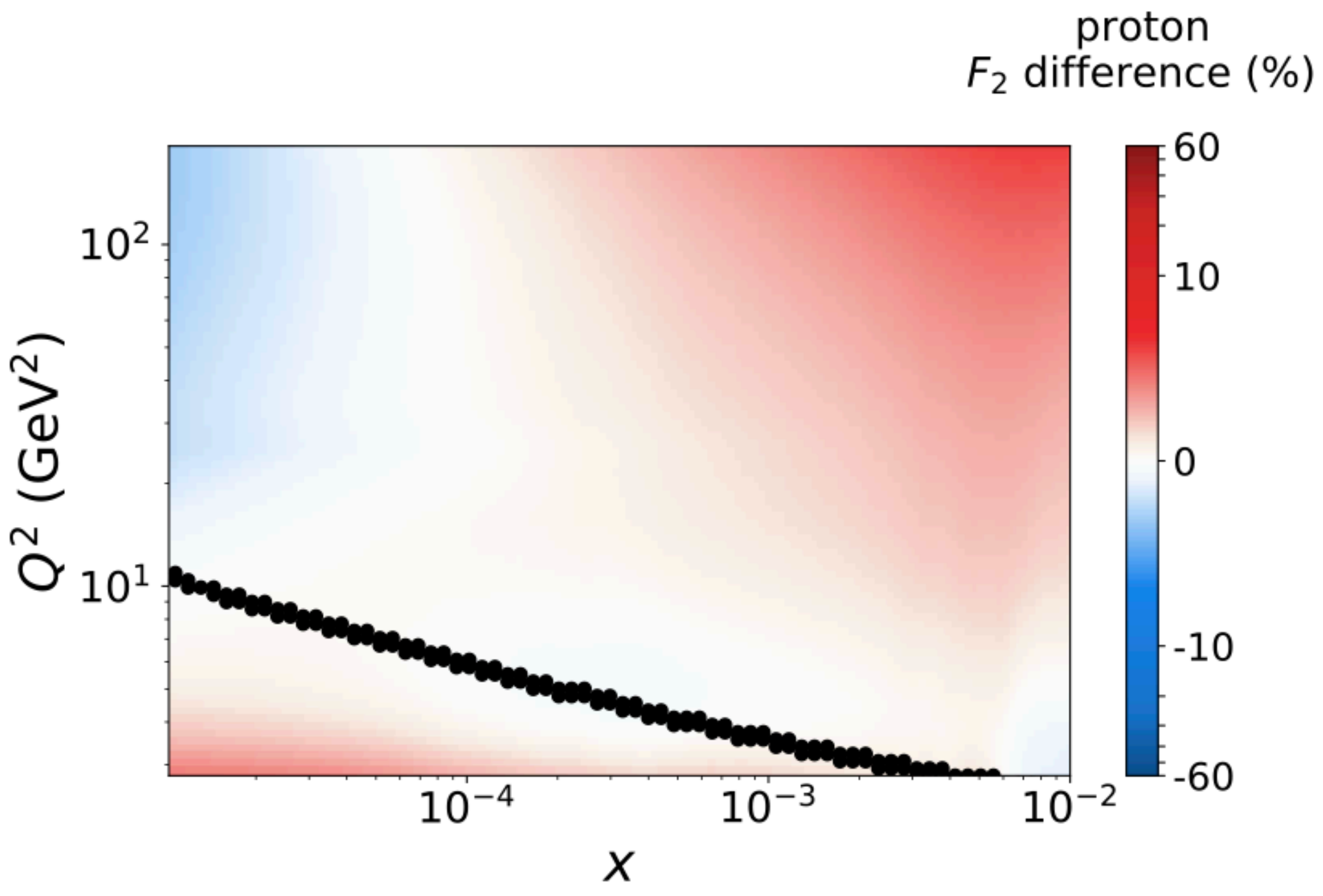
- Difference in predictions for $F_{2,L}$:
  linear (collinear/DGLAP)
  non-linear (dipole/Balitsky-Kovchegov)

$$(F_{2/L}^{\mathrm{BK}} - F_{2/L}^{\mathrm{DGLAP,Rew}})/F_{2/L}^{\mathrm{BK}}$$

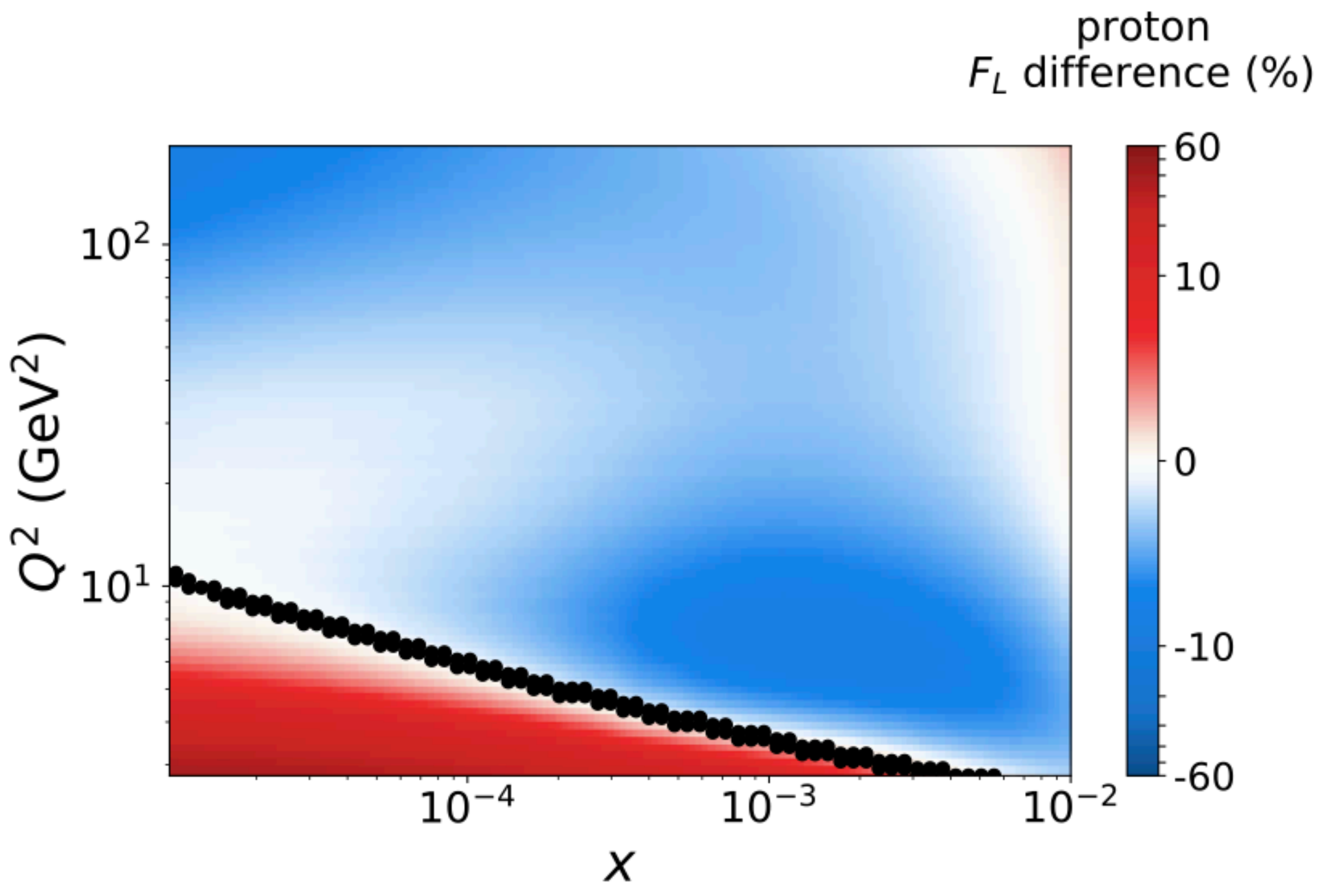
- Stronger effects for F_L than F_2

- Stronger effects for γAu than γp

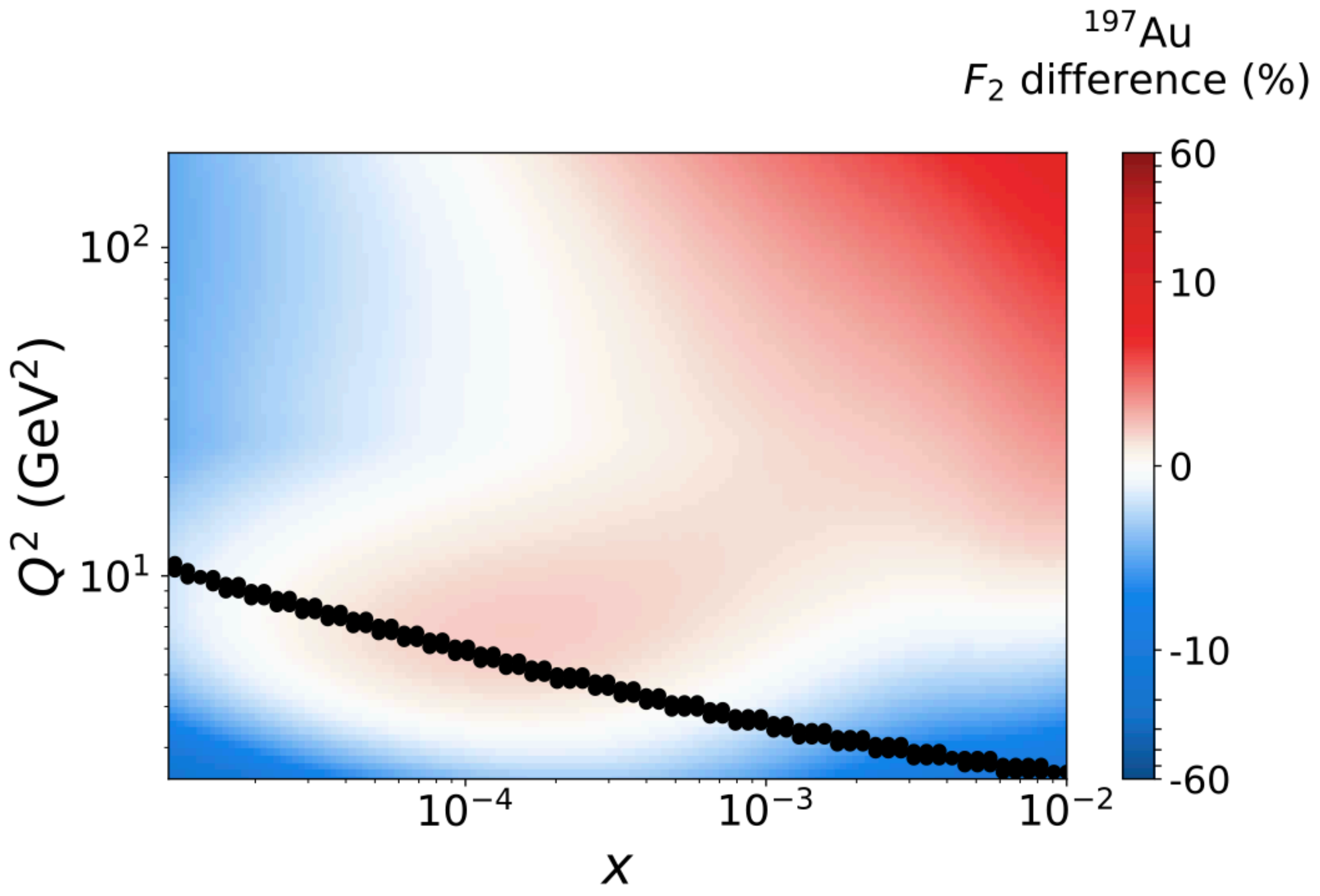
- It would be interesting to incorporate small-x evolution into DGLAP via BFKL (à la) and compare with non-linear BK



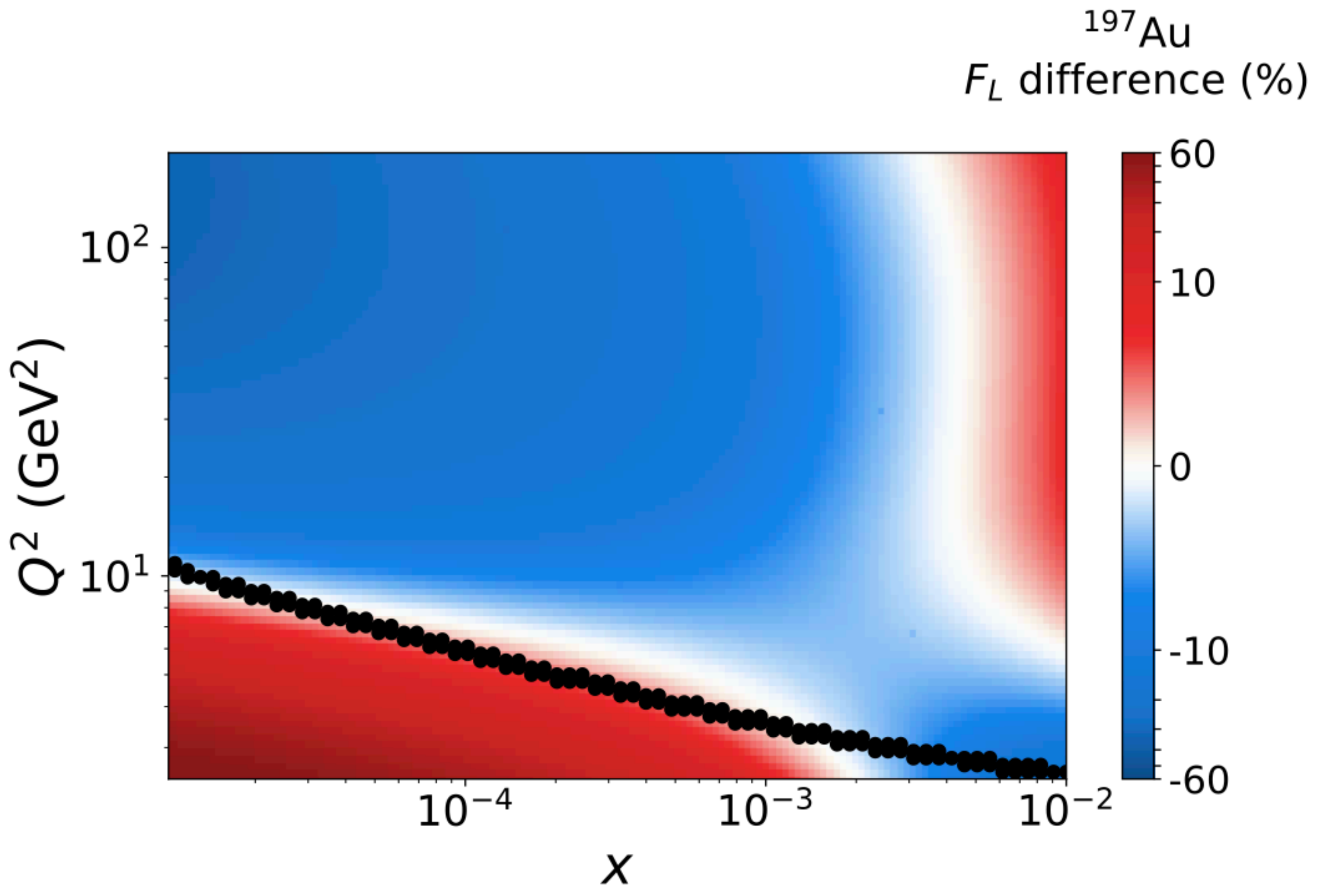
(a) F_2



(b) F_L



(a) F_2

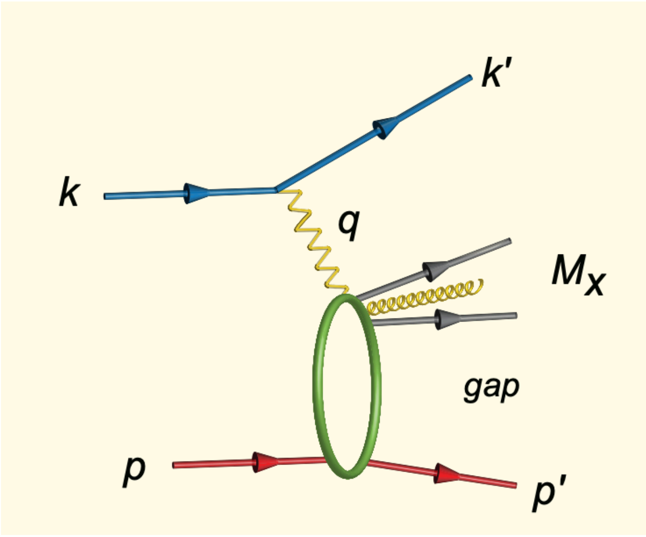


(b) F_L

Armesto, Lappi, Mäntysaari, Paukkunen, Tevio (2022)

See also Marquet, Moldes, Zurita (2017)

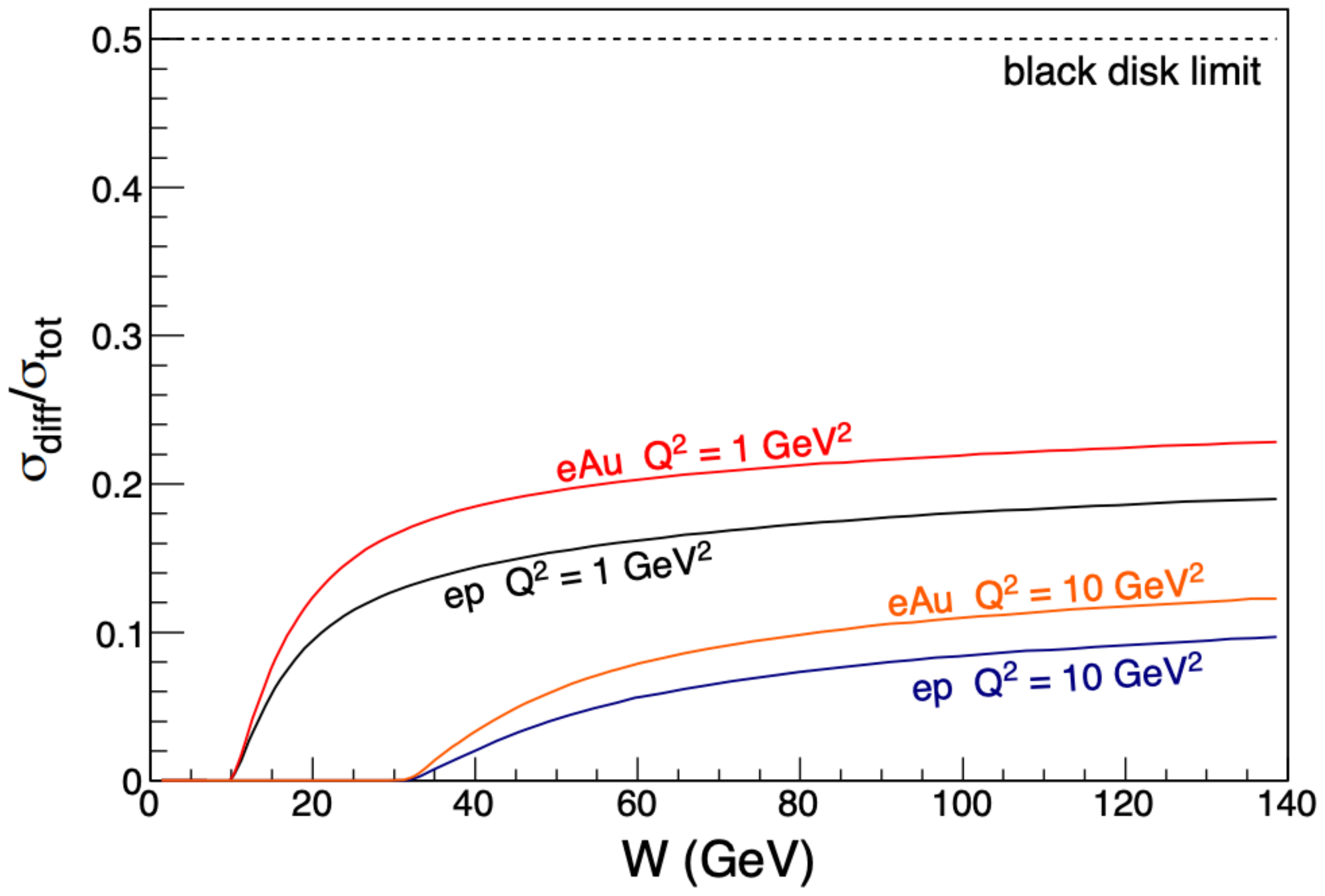
Diffractive structure functions



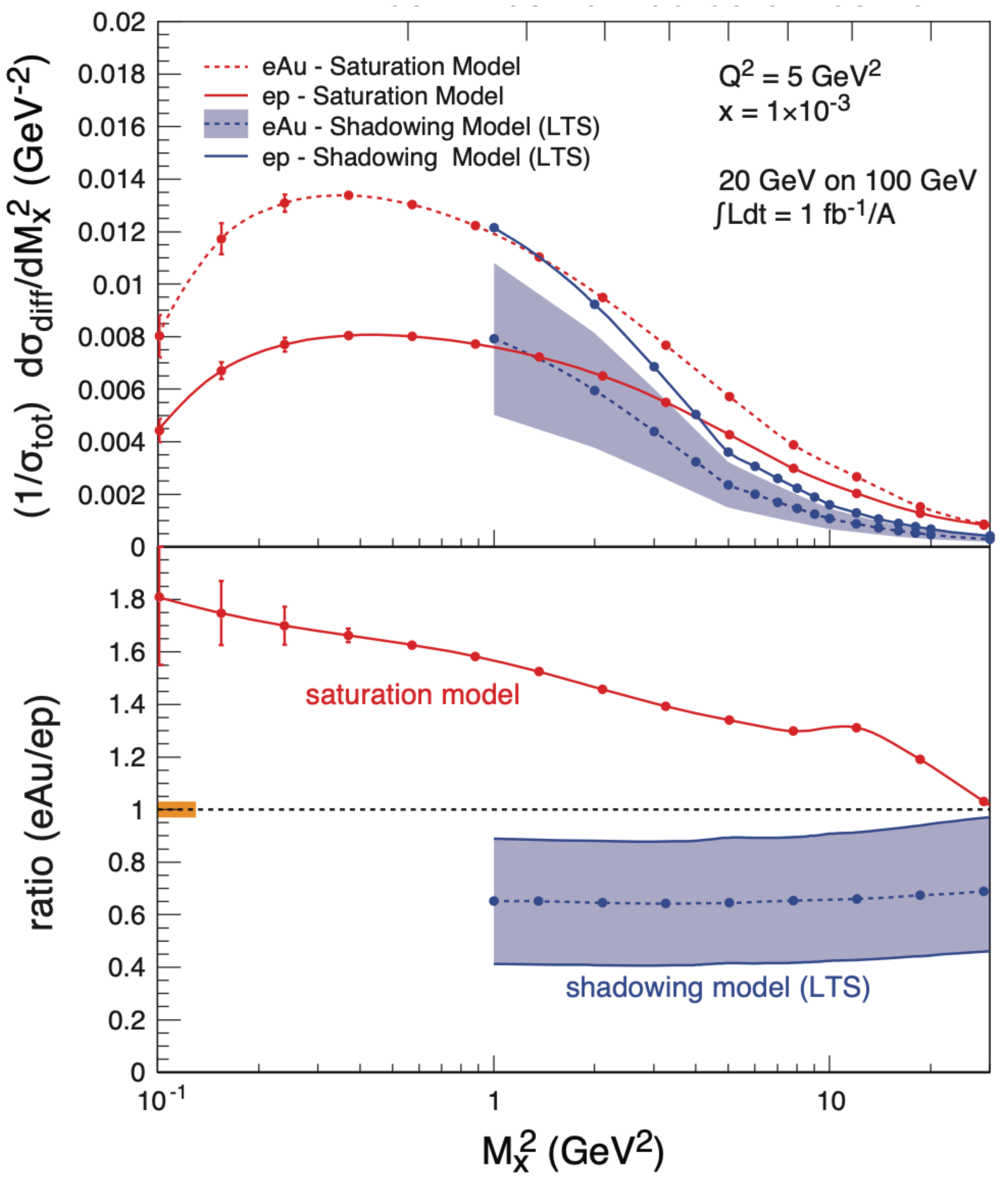
Diffractive events are characterized by rapidity gap

Neutral color exchange requires at least two-gluons (enhanced sensitivity to gluon sat)

Ratio of diffractive and total cross-section in ep and eAu collisions



Diffractive events enhanced at lower Q^2 and have weak dependence on energy



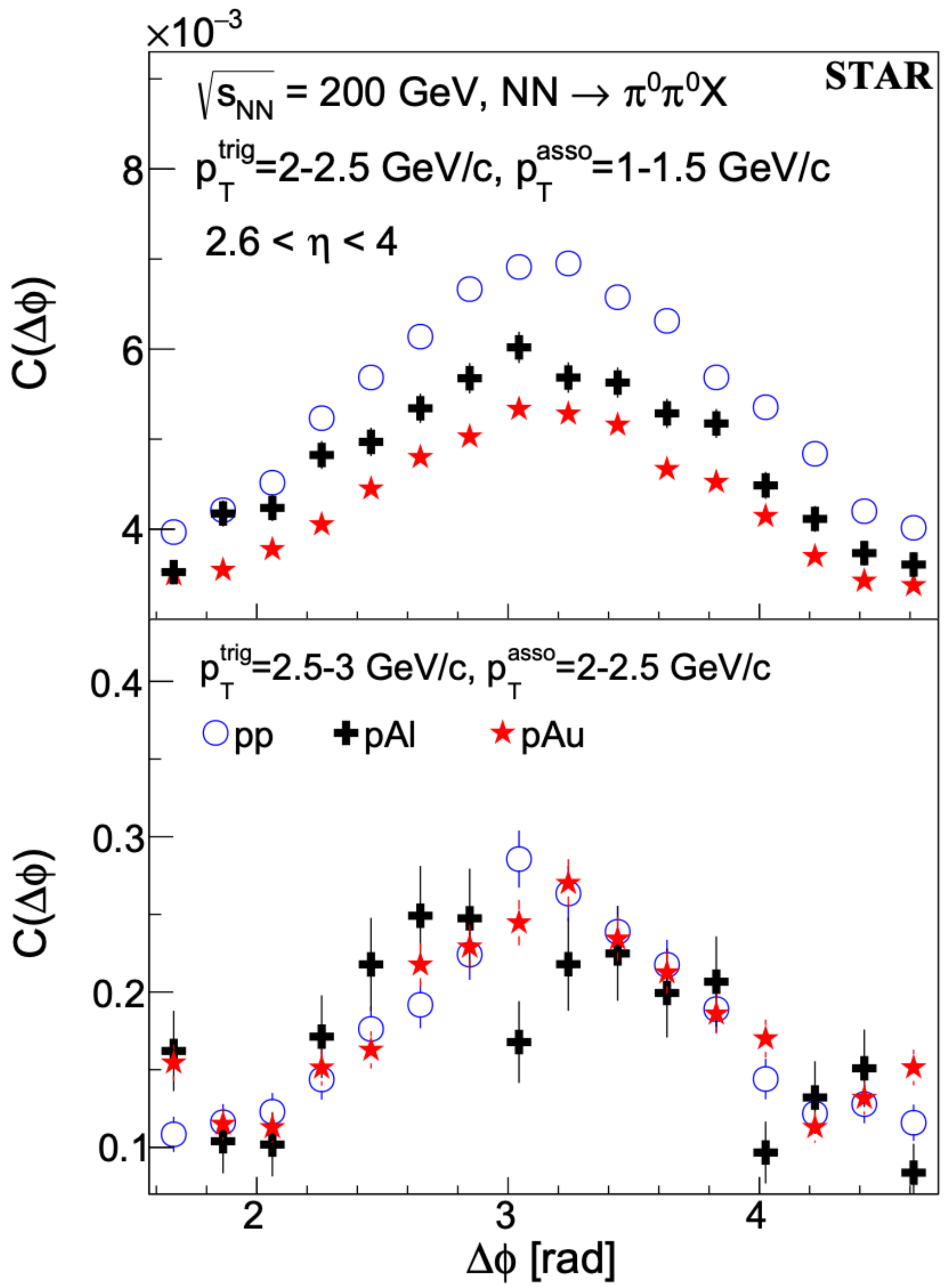
Clear difference between saturation models and leading twist shadowing (LTS)

EIC White paper (2012)

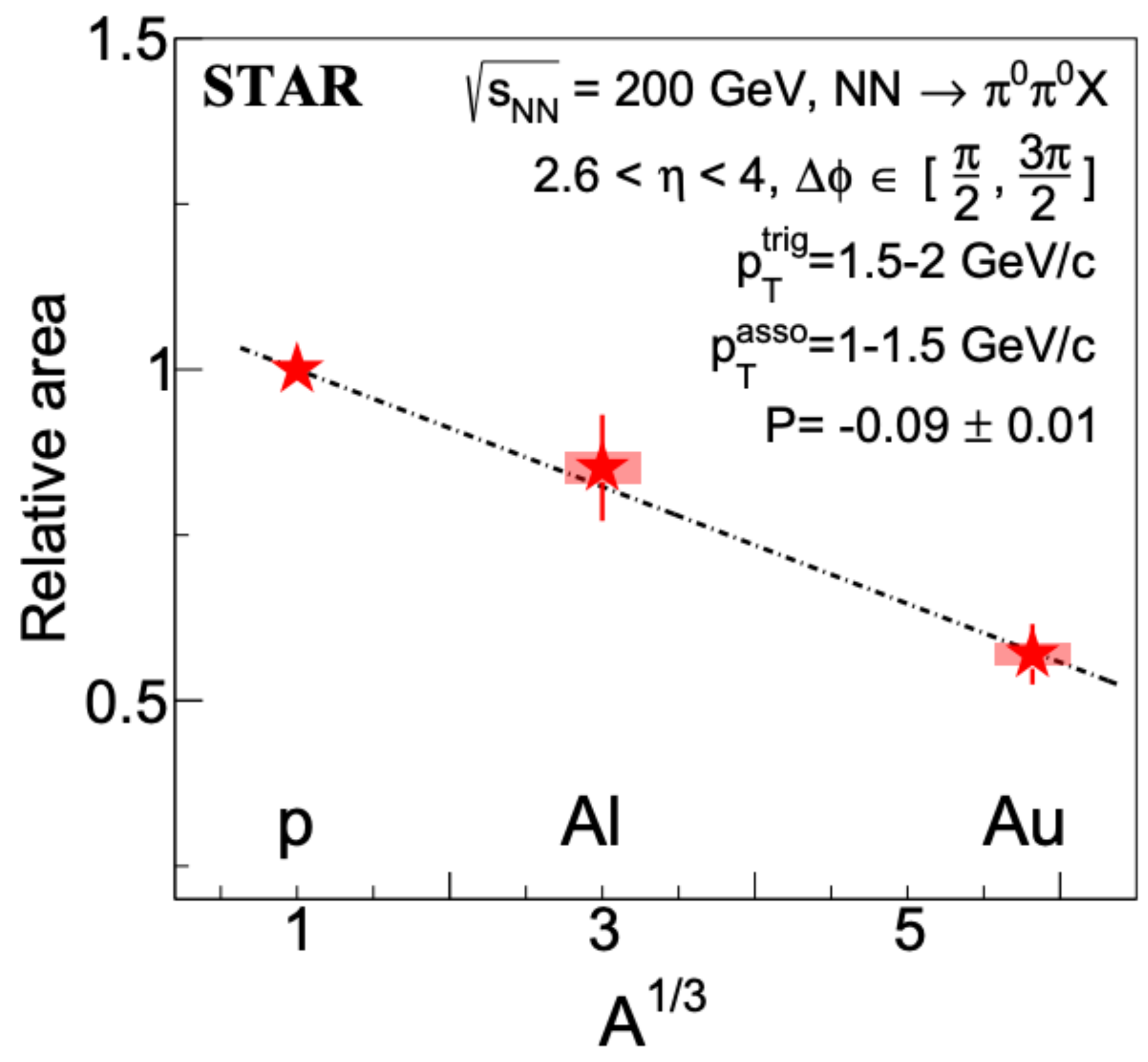
Semi-inclusive

Two particle correlations at RHIC

Evidence for Nonlinear Gluon Effects in QCD and Their Mass Number Dependence at STAR

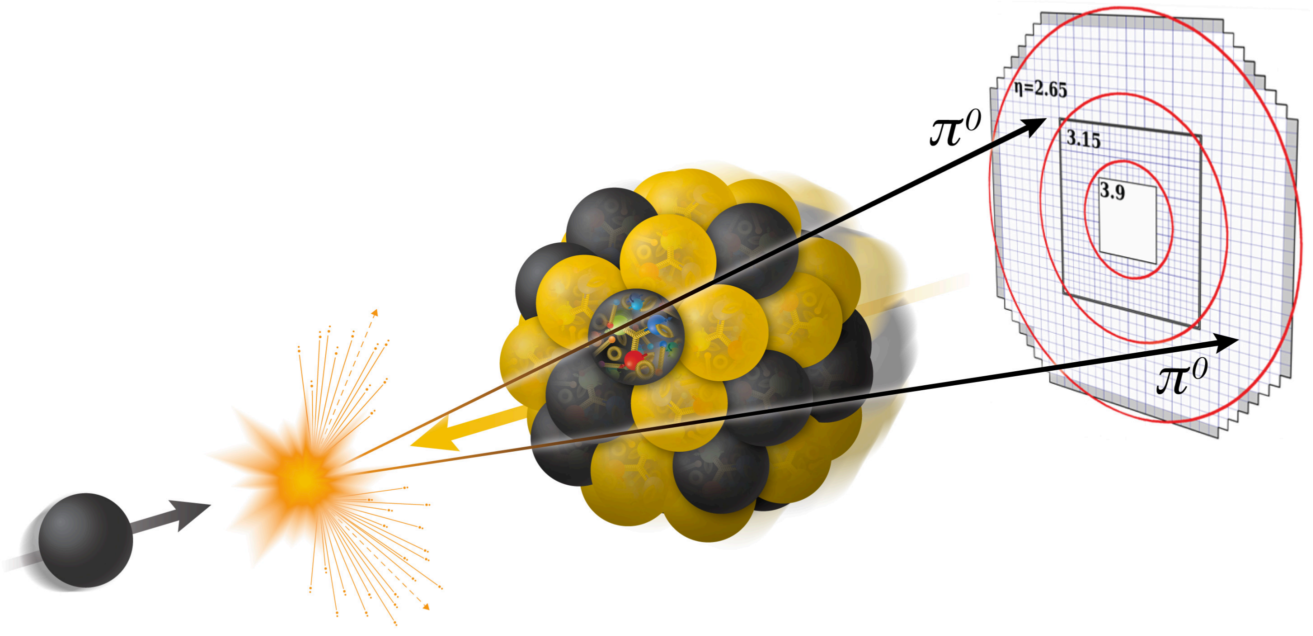


STAR Collaboration
Phys. Rev. Lett. 129, 092501 (2022)



Suppression characteristic of saturation

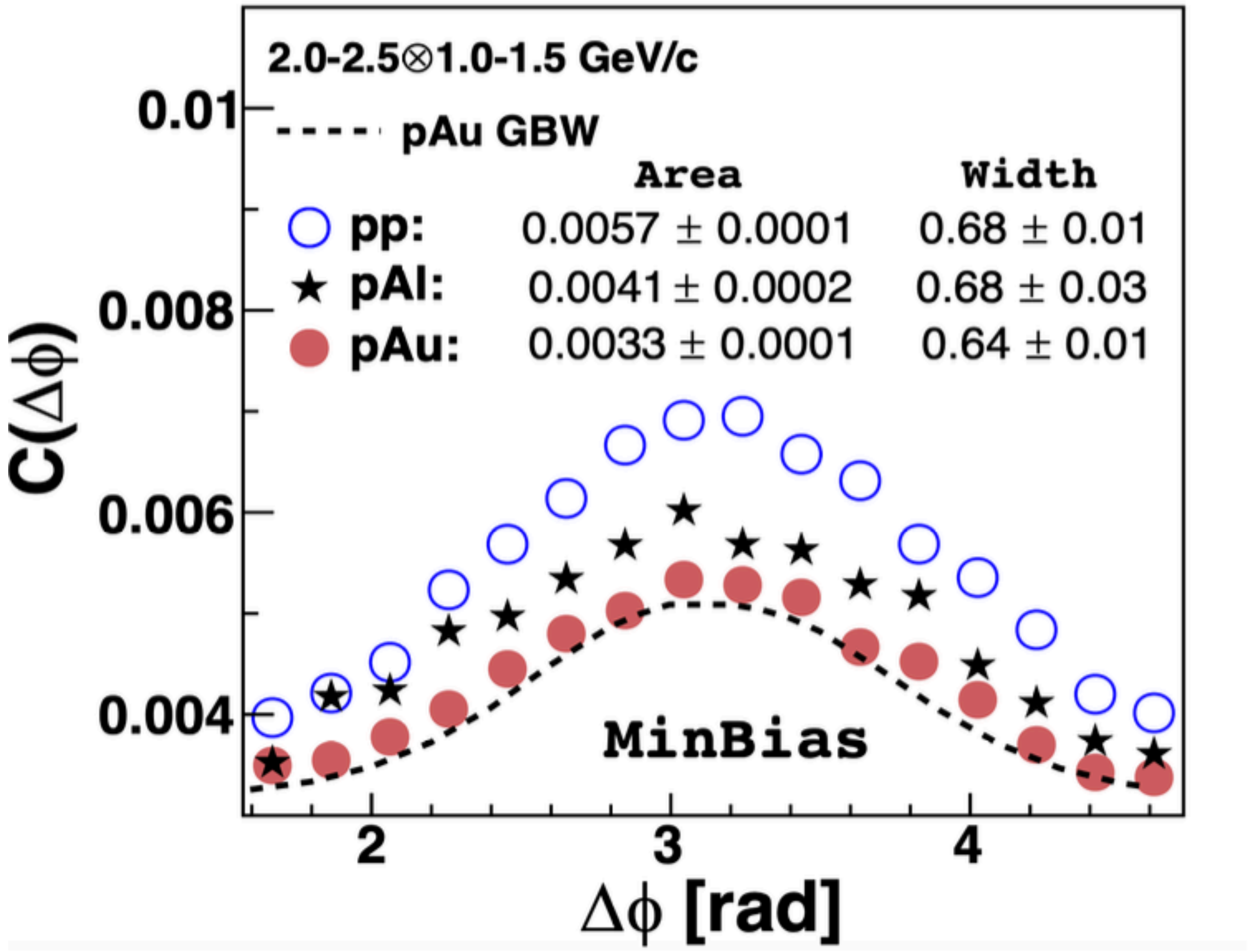
$$Q_s^2 \propto A^{1/3}$$



Xiaoxuan Chu and Elke Aschenauer

Two particle correlations at RHIC

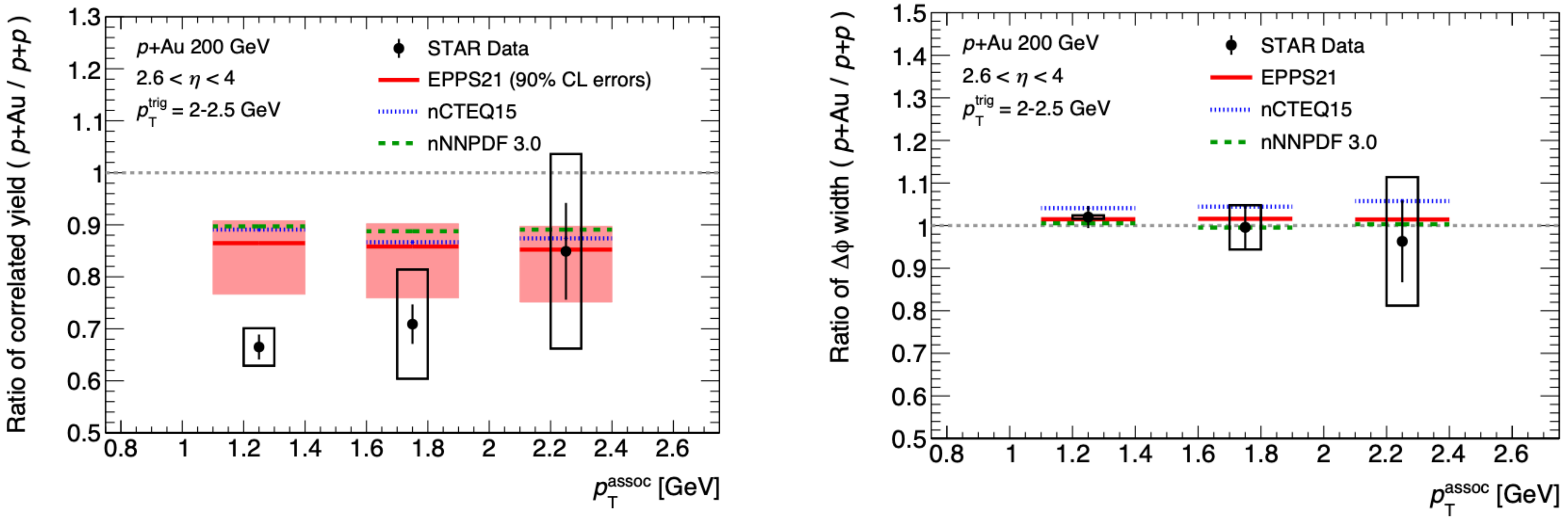
nPDF or saturation?

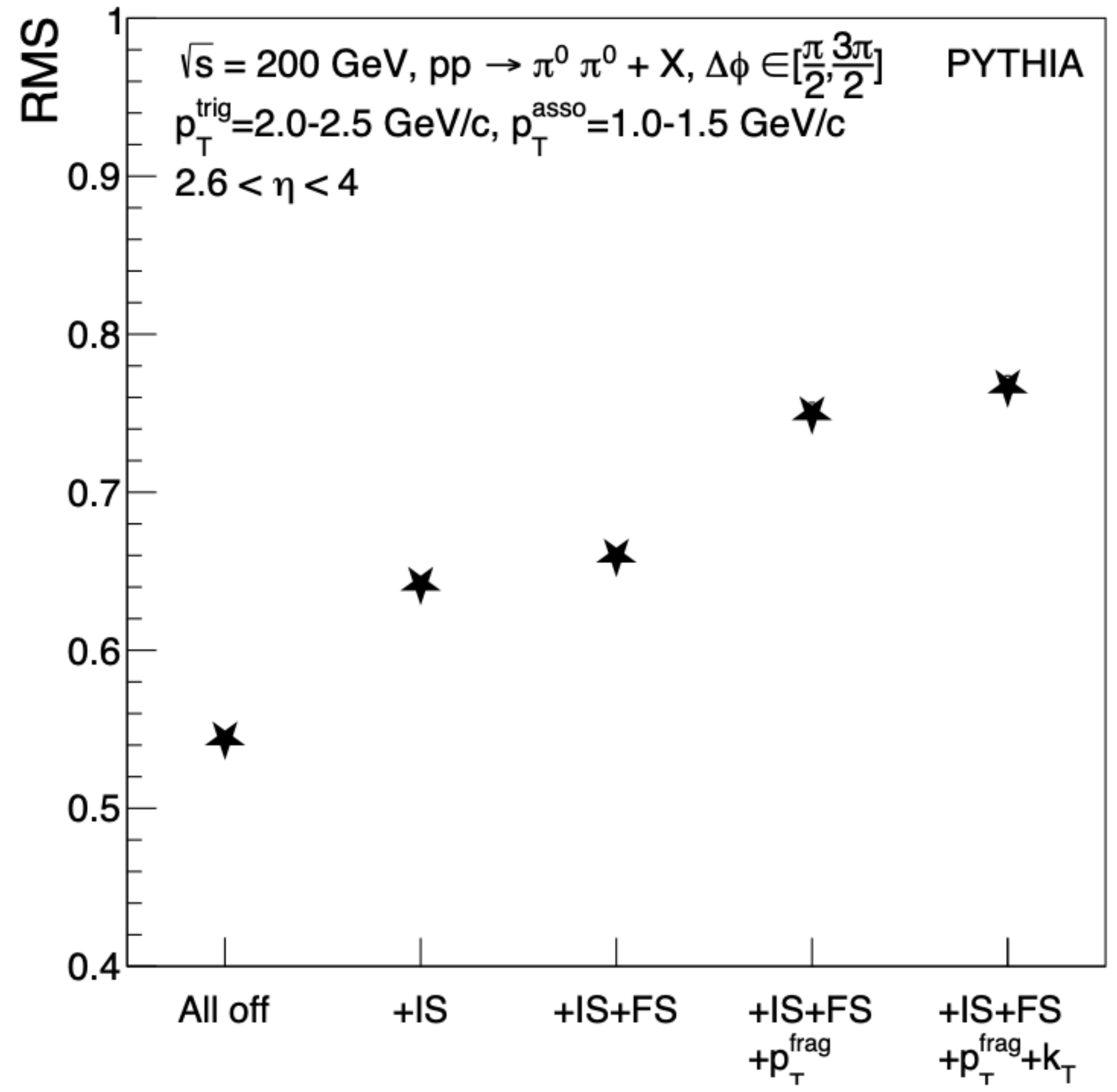


STAR (2021)

- CGC approach (work in progress Zhao et al)
  -Small-x evolution -> $p_\perp$**-dependent suppression** (more suppression for $p_\perp \lesssim Q_s(x)$)
  -Soft gluon radiation -> **similar width of correlation in pp and pA** (i.e. not much broadening) hints of this in full NLO calculation in DIS Caucal, Salazar, Schenke, Stebel, Venugopalan (2024)

- nPDFs approach: Perepelitsa (2025)
  di-hadron RHIC data shows **nuclear size dependent suppression** but **no significant broadening**



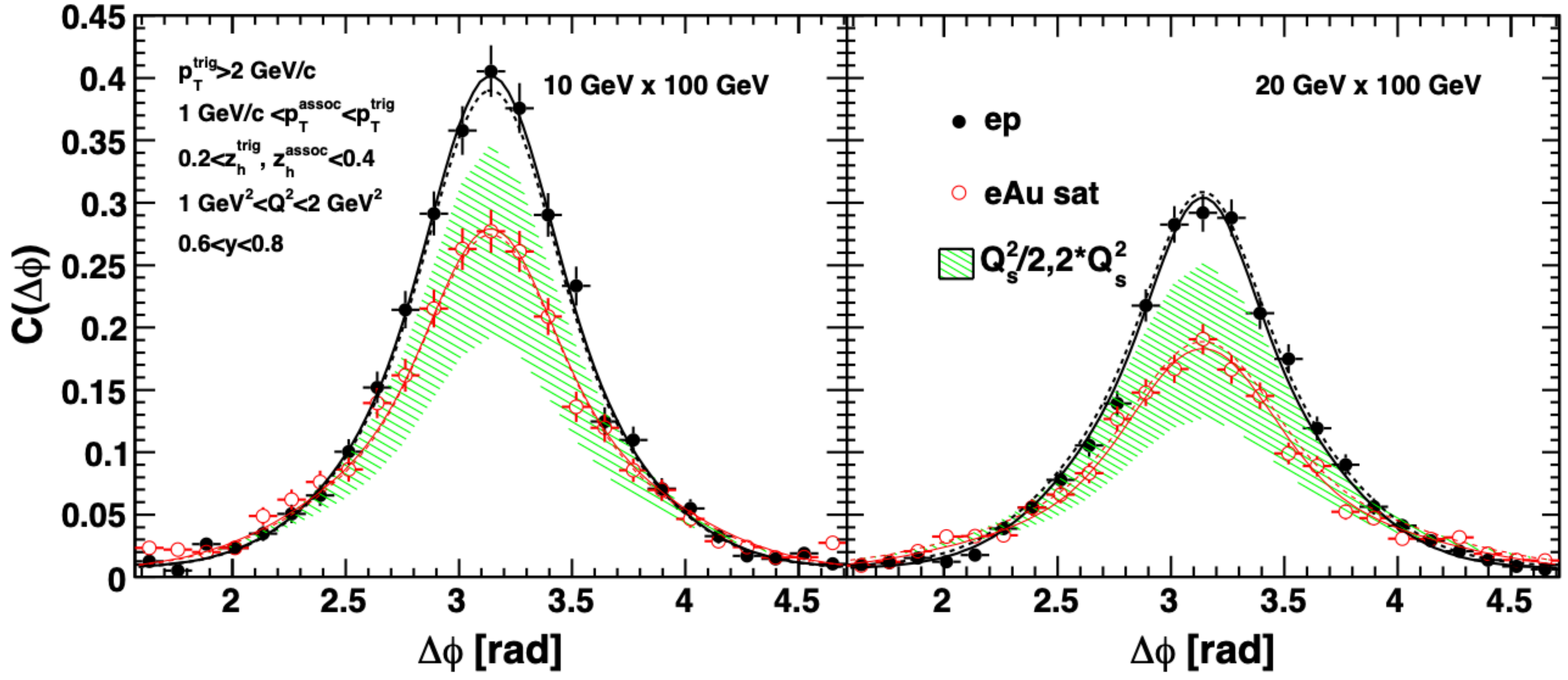


- Cassar, Wang, Chu, Aschenauer (2025)
  Parton shower + hadron fragmentation control width of correlation

  Absence of broadening is not necessarily challenge to the saturation paradigm

Two particle correlations at EIC

Dihadron suppression
back-to-back peak at EIC

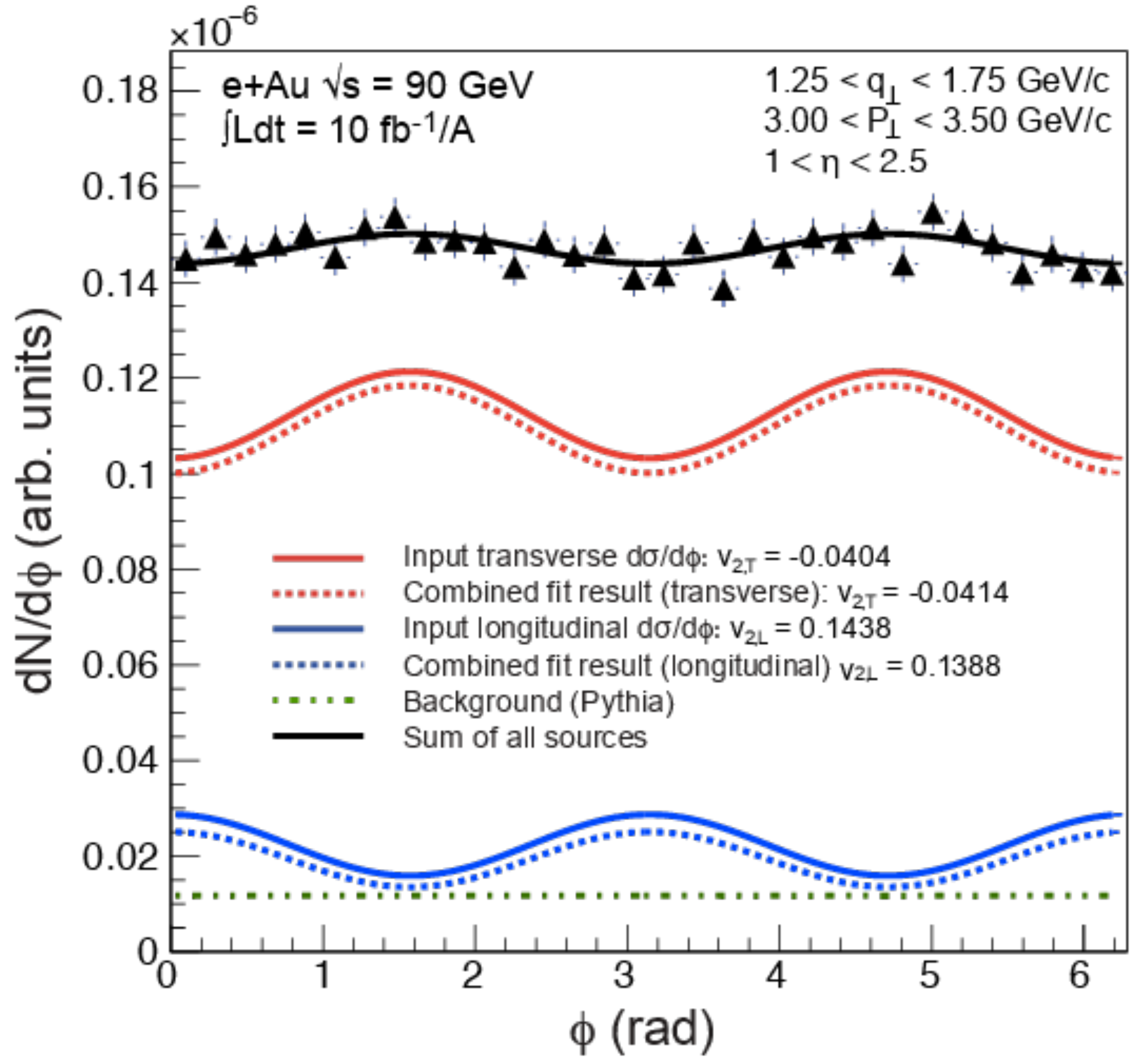


Zheng, Aschenauer, Lee, Xiao (2014)

Typical momentum transfer from proton/ nucleus to dihadron pair is $\sim Q_s$

Momentum imbalance → $k_\perp \sim Q_s$ ← Saturation scale

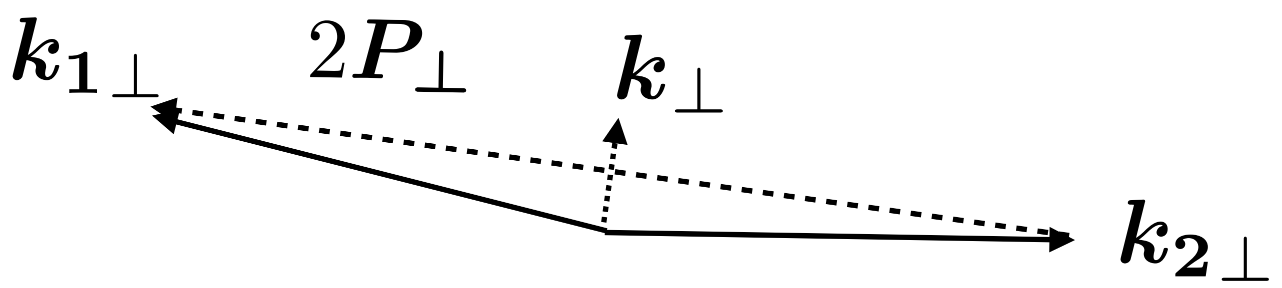
Dijet momentum imbalance
azimuthal correlations



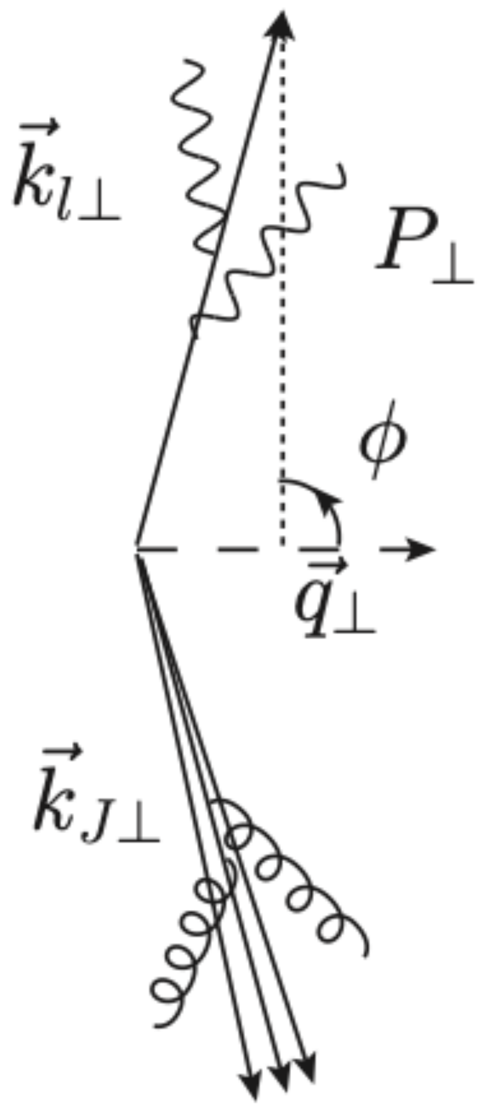
Dumitru, Skokov, Ullrich (2018)

Sensitivity to linearly polarized gluons

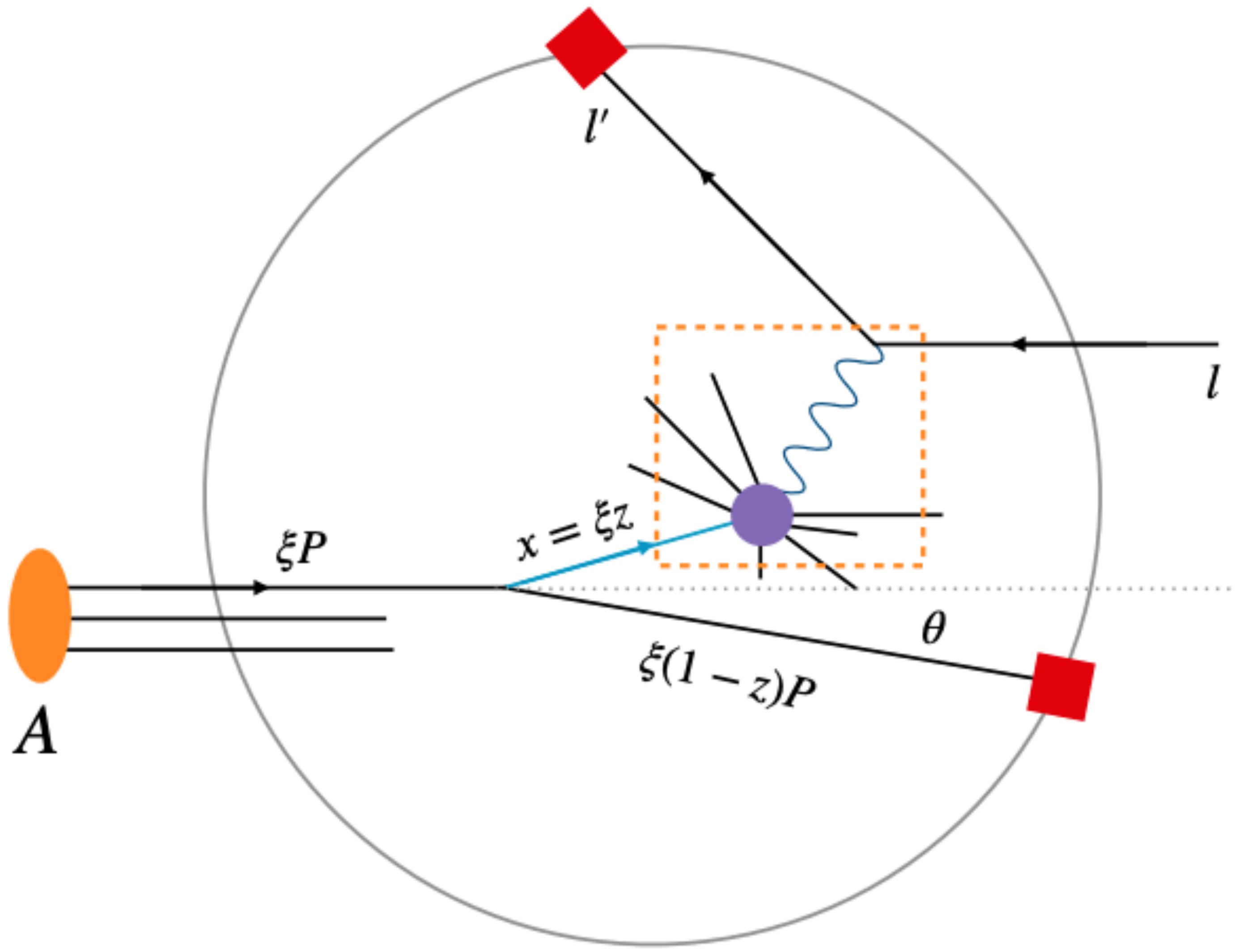
ϕ angle between $P_\perp$ and $k_\perp$



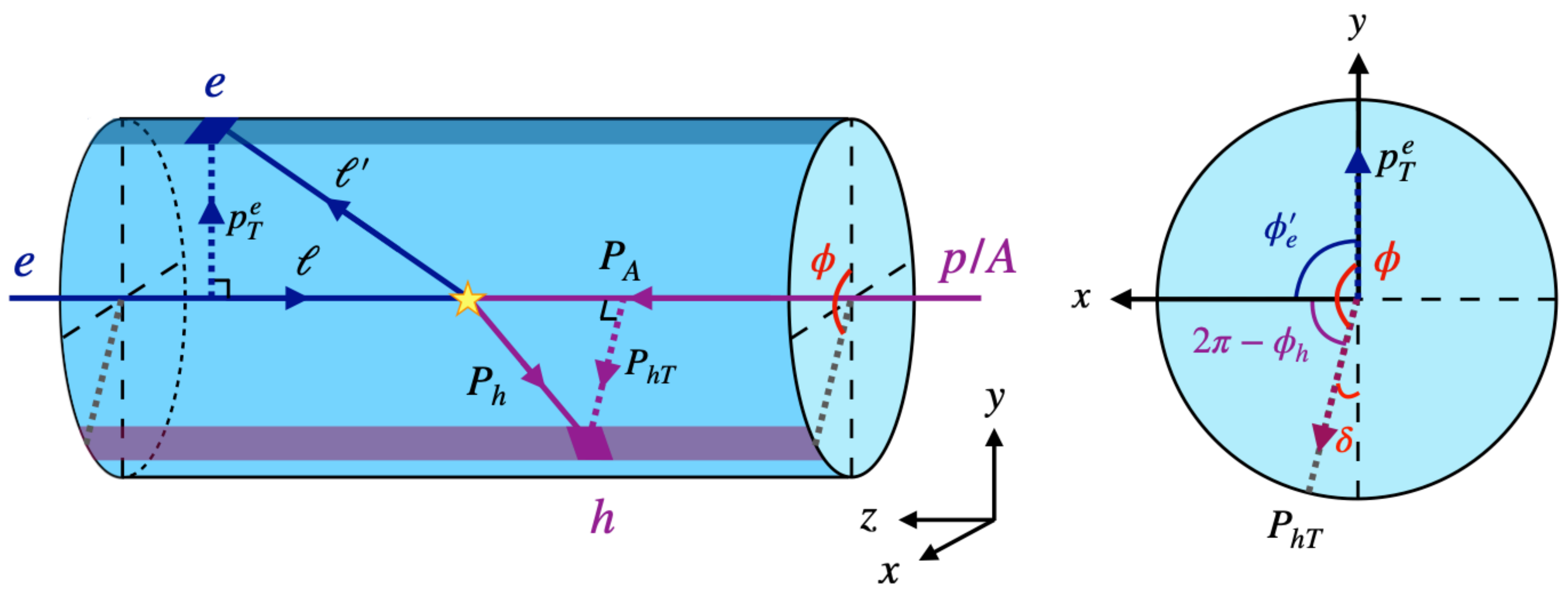
Other two-particle correlations: lepton-jet and nucleon-energy energy correlators



Lepton-jet correlations
Tong, Xiao, Zhang (2022)



Nucleon energy correlator
Liu, Pan, Yuan, Zhu (2023)

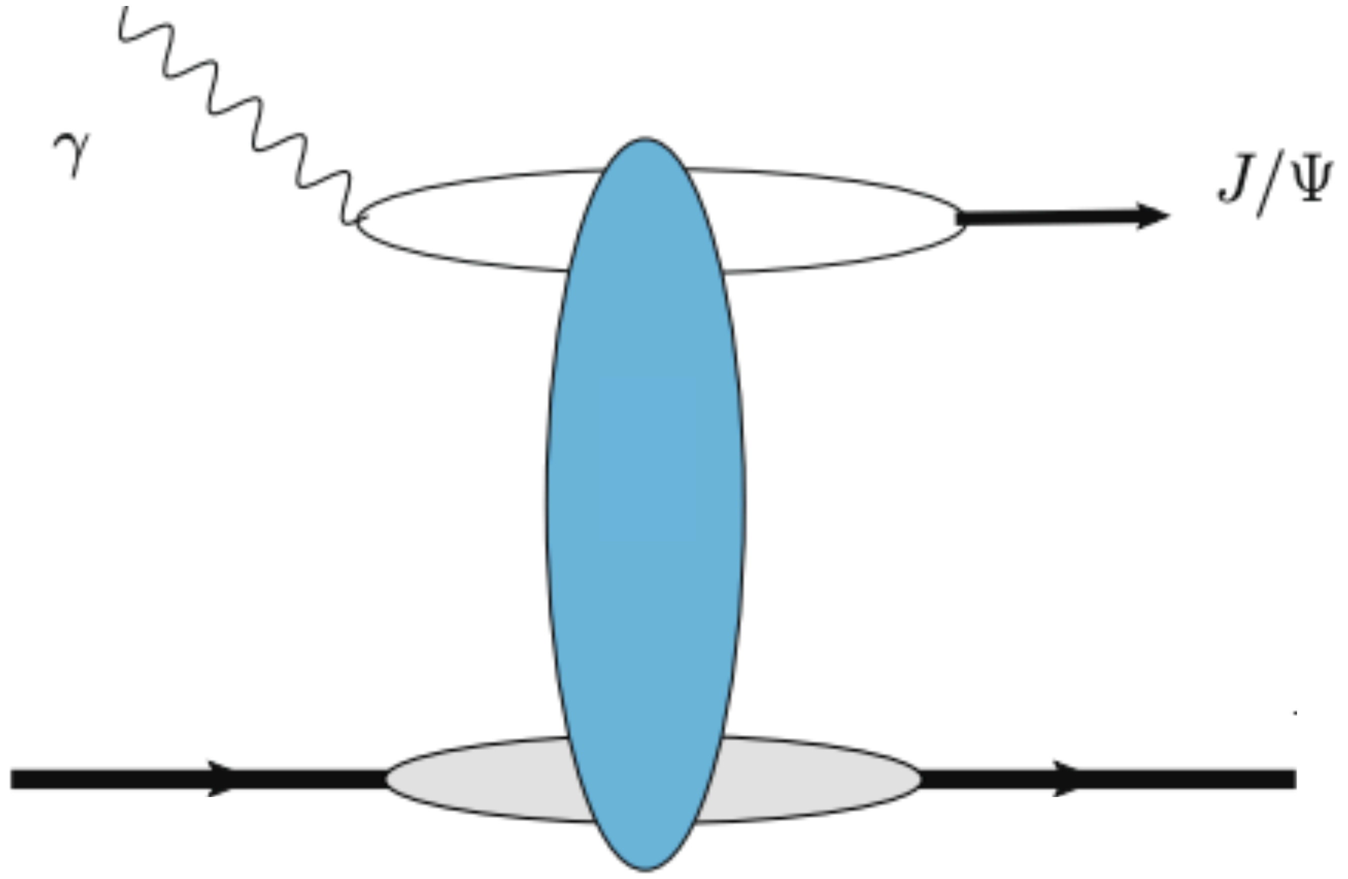


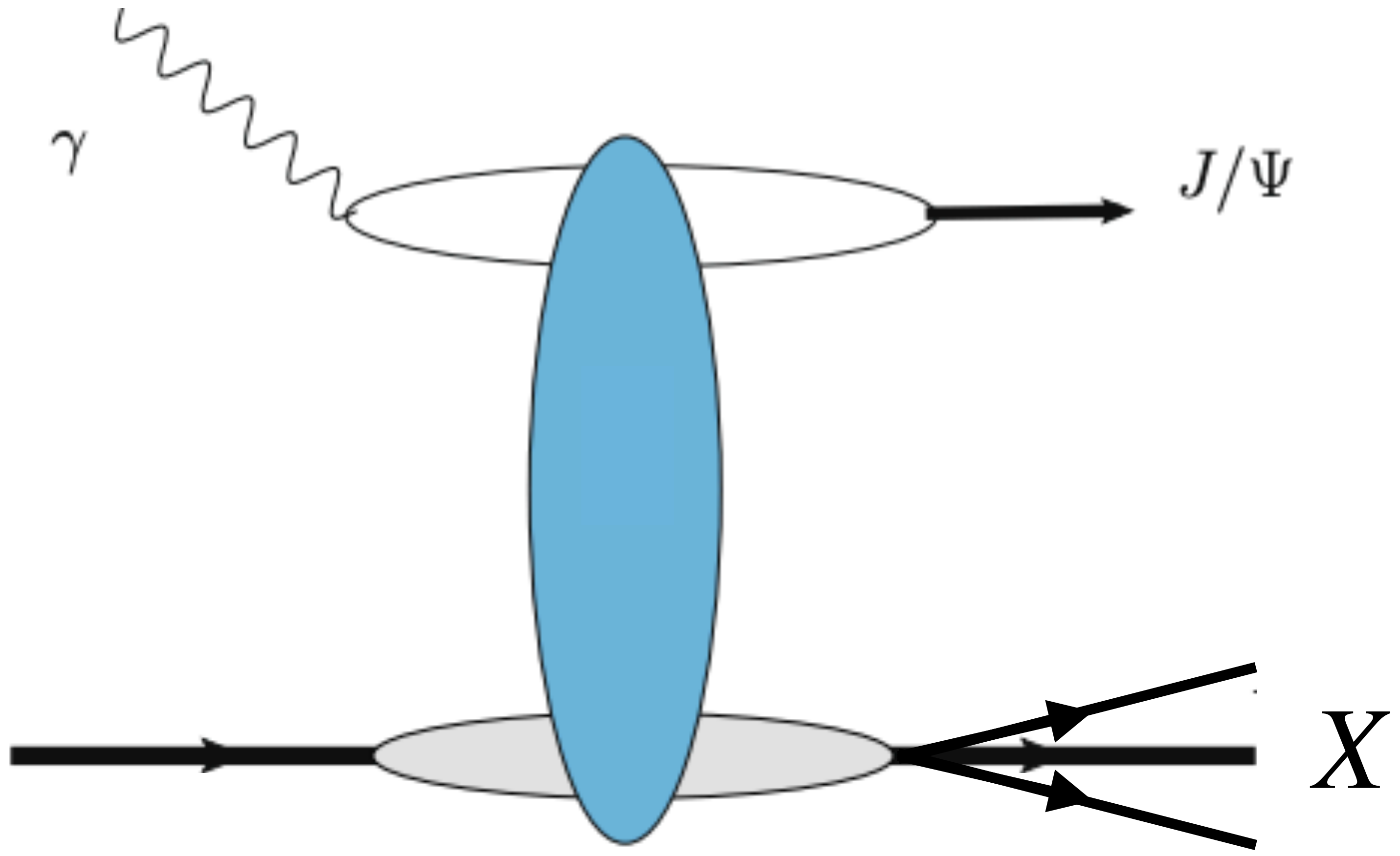
Transverse energy-energy correlators
Kang, Penttala, Zhao, Zhou (2024)

Exclusive

Exclusive vector meson production

Coherent and incoherent reactions





$$\mathrm{d}\sigma_{\mathrm{coh}} \propto \langle \mathcal{A}^\dagger(\mathbf{\Delta}_\perp)\rangle\langle\mathcal{A}(\mathbf{\Delta}_\perp)\rangle$$

- Nuclear target remains intact
- t-dependence gives information on spatial distribution gluons in transverse plane (to the beam)
- Connection to GPDs

$$\mathrm{d}\sigma_{\mathrm{incoh}} \propto \langle \mathcal{A}^\dagger(\mathbf{\Delta}_\perp)\mathcal{A}(\mathbf{\Delta}_\perp)\rangle - \langle\mathcal{A}^\dagger(\mathbf{\Delta}_\perp)\rangle\langle\mathcal{A}(\mathbf{\Delta}_\perp)\rangle$$

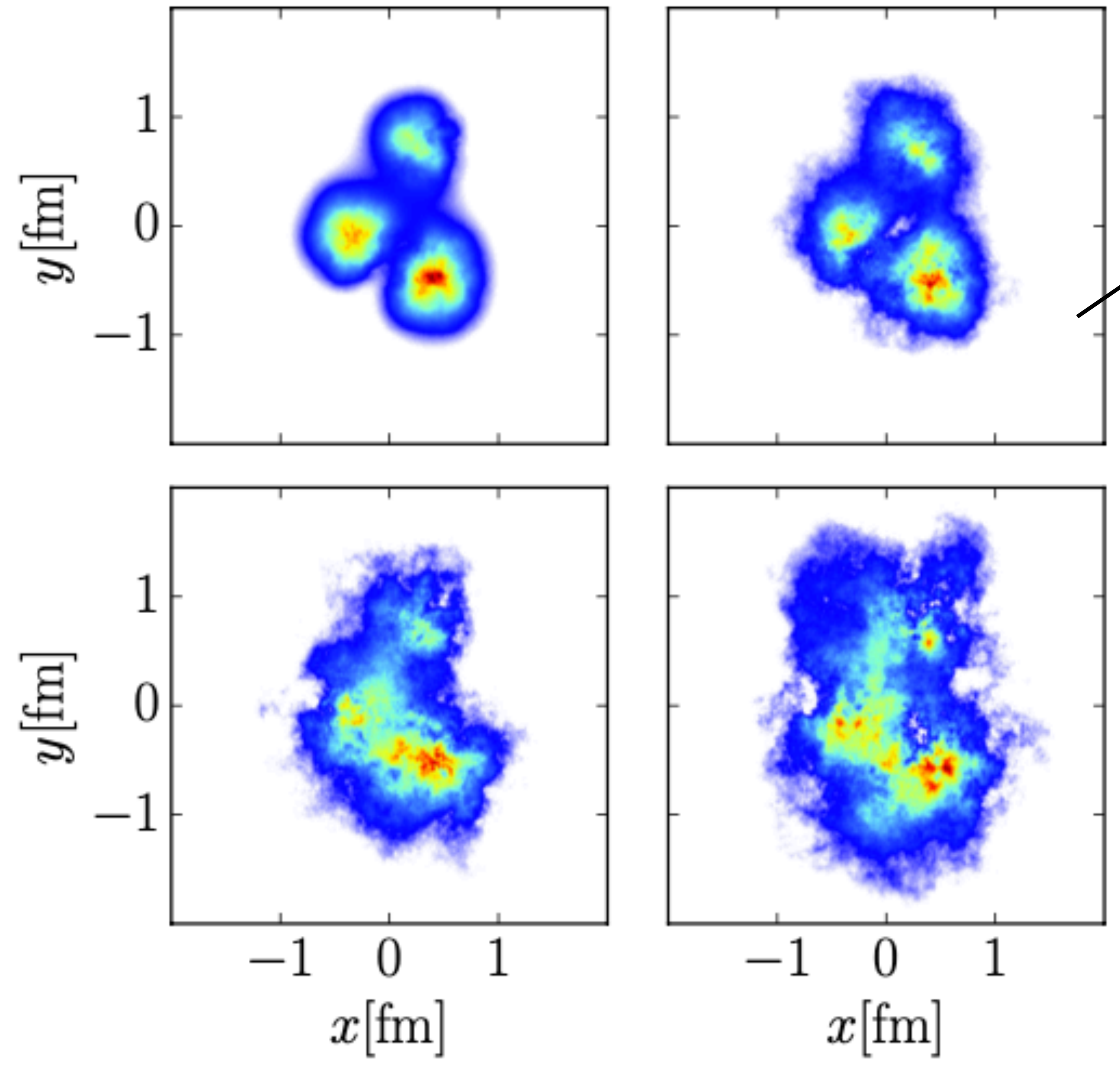
- Target breaks up, but one has a rapidity gap
- Sensitive to fluctuations: color charge, sub-nucleon, nucleon

Exclusive vector meson production

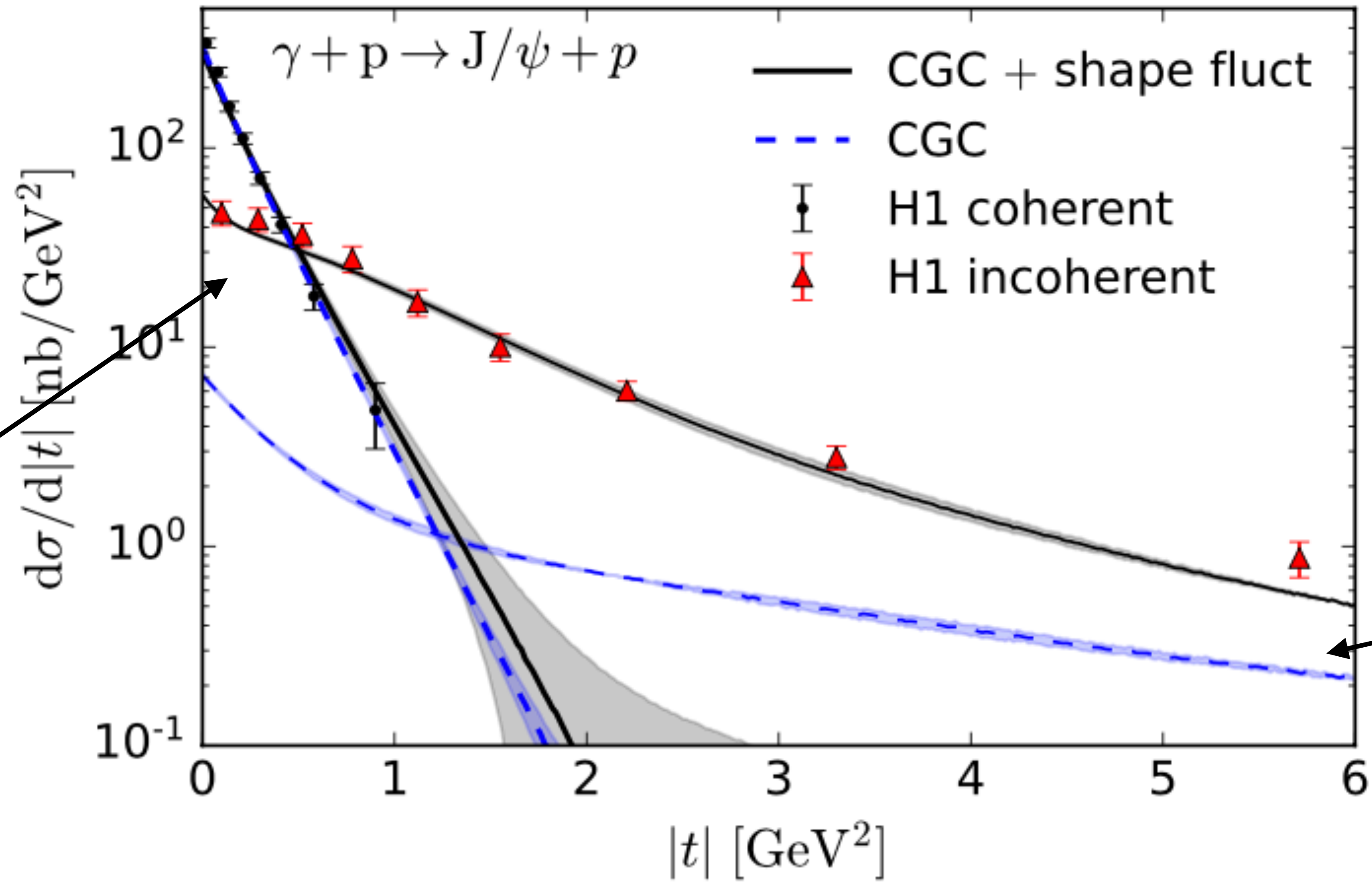
Event-by-event sub-nuclear fluctuations

Introduce sub-nucleon structure

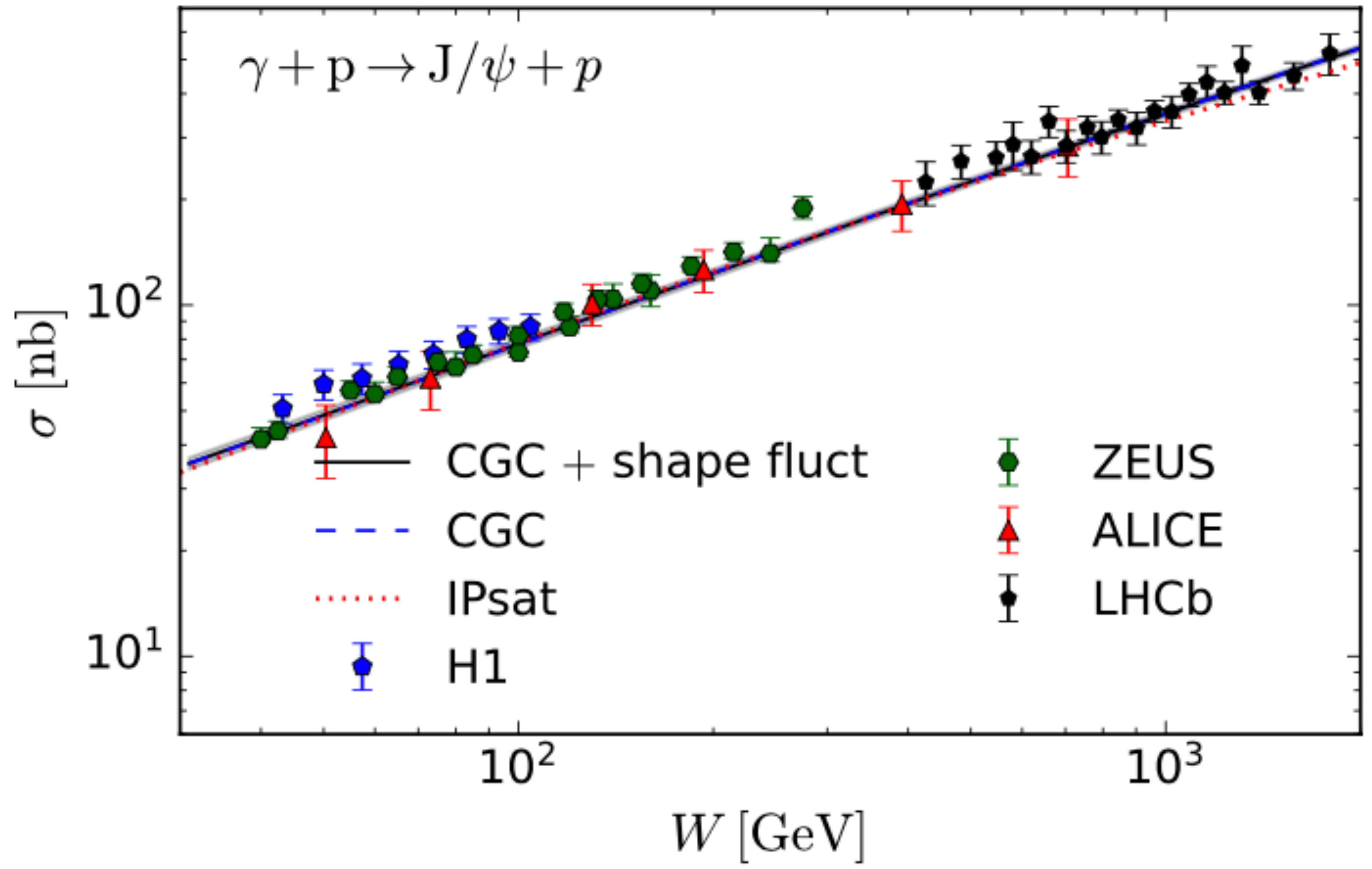
Mäntysaari, Schenke (2016)



Mäntysaari, Schenke (2018)
Mäntysaari, Salazar, Schenke (2022)

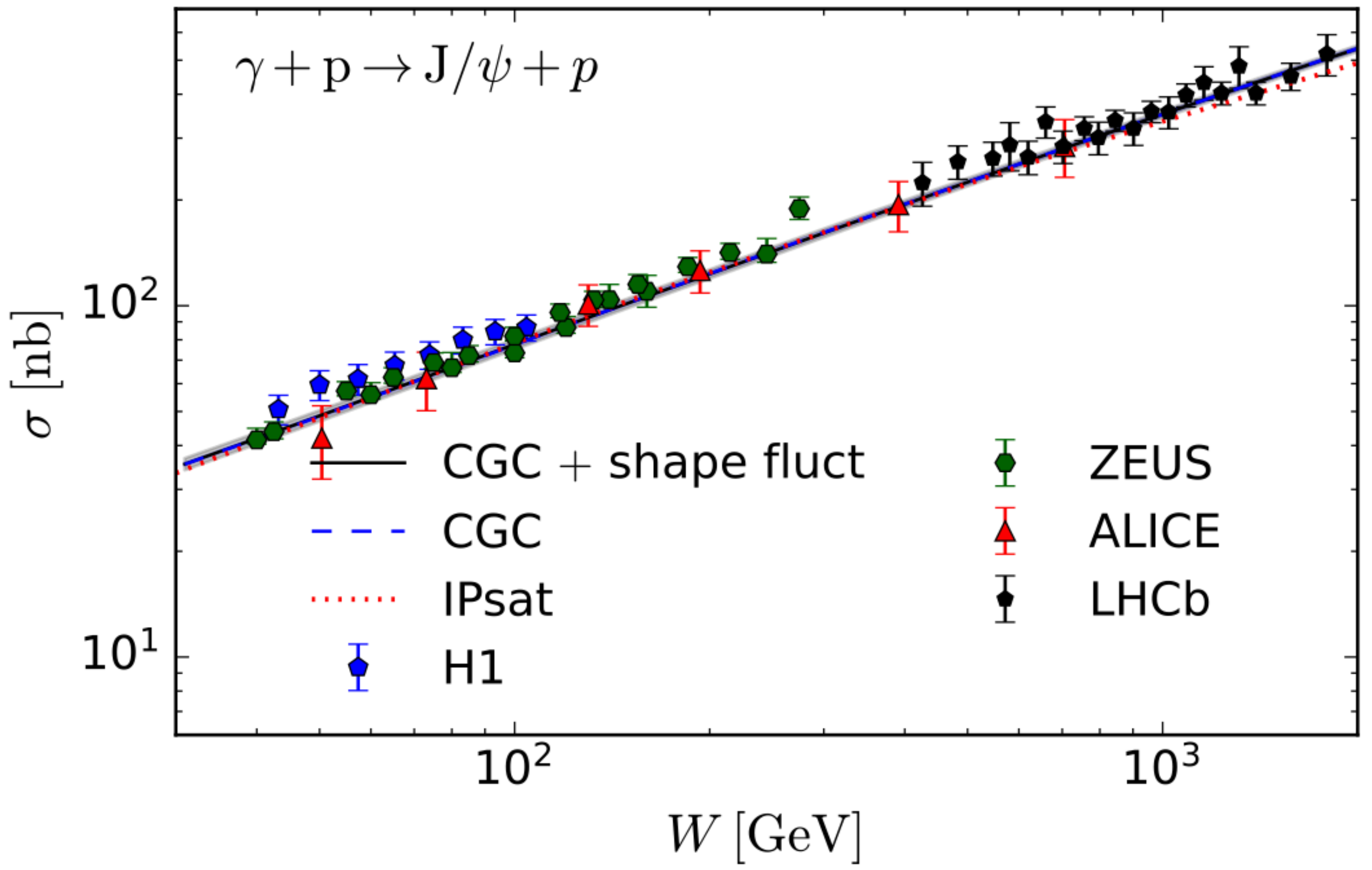


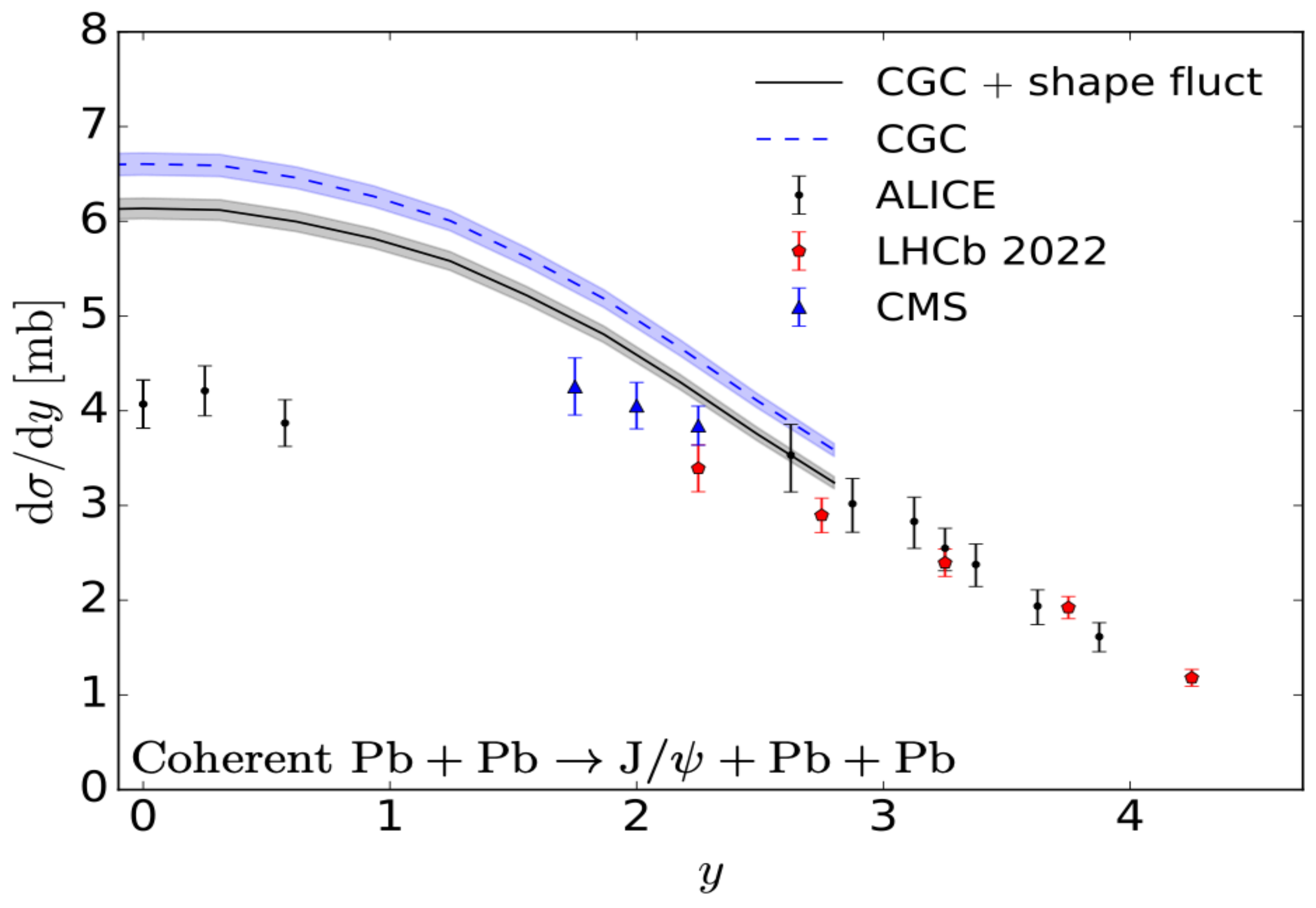
No subnucleon fluctuations



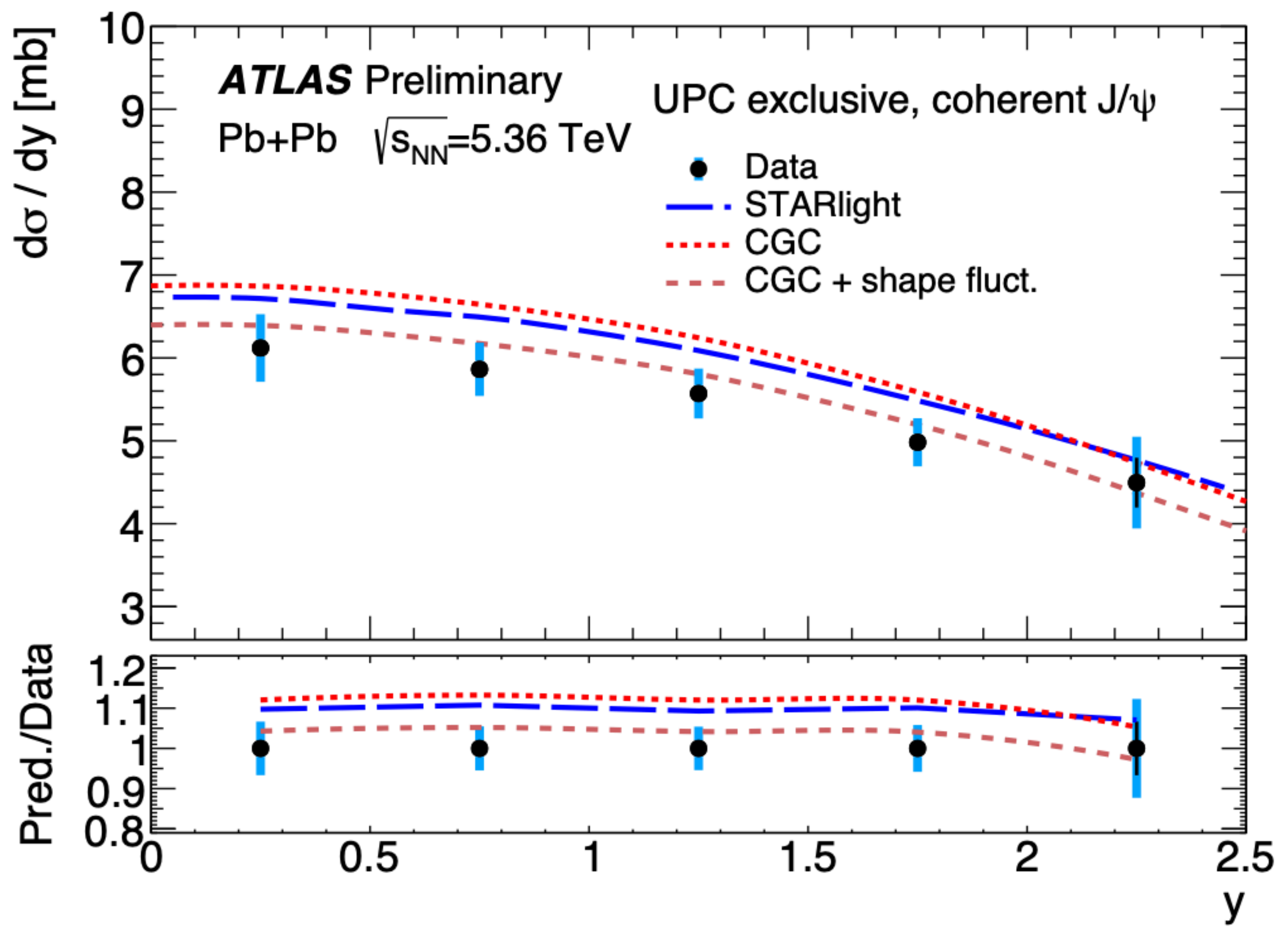
Exclusive vector meson production in UPCs

Coherent production γp and γA



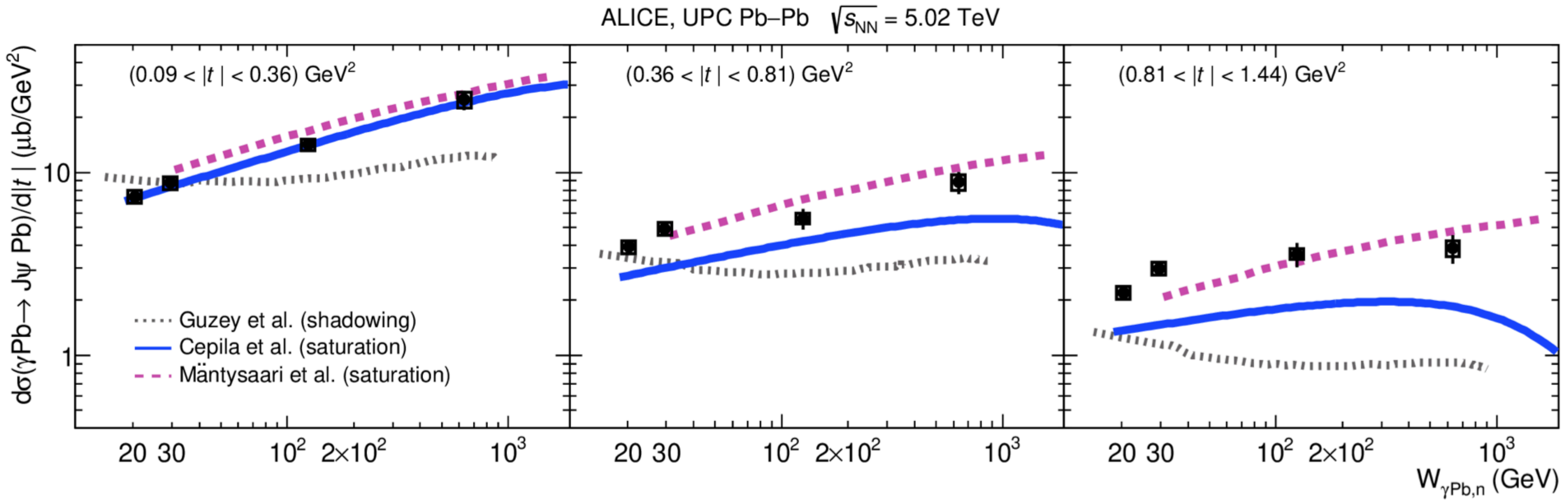


Mäntysaari, Salazar, Schenke (2022, 2024)



[ATLAS (preliminary)]

Double-differential incoherent γA



← [ALICE]

[CGC-based Bayesian analysis for J/ψ data γp and γA work in progress]

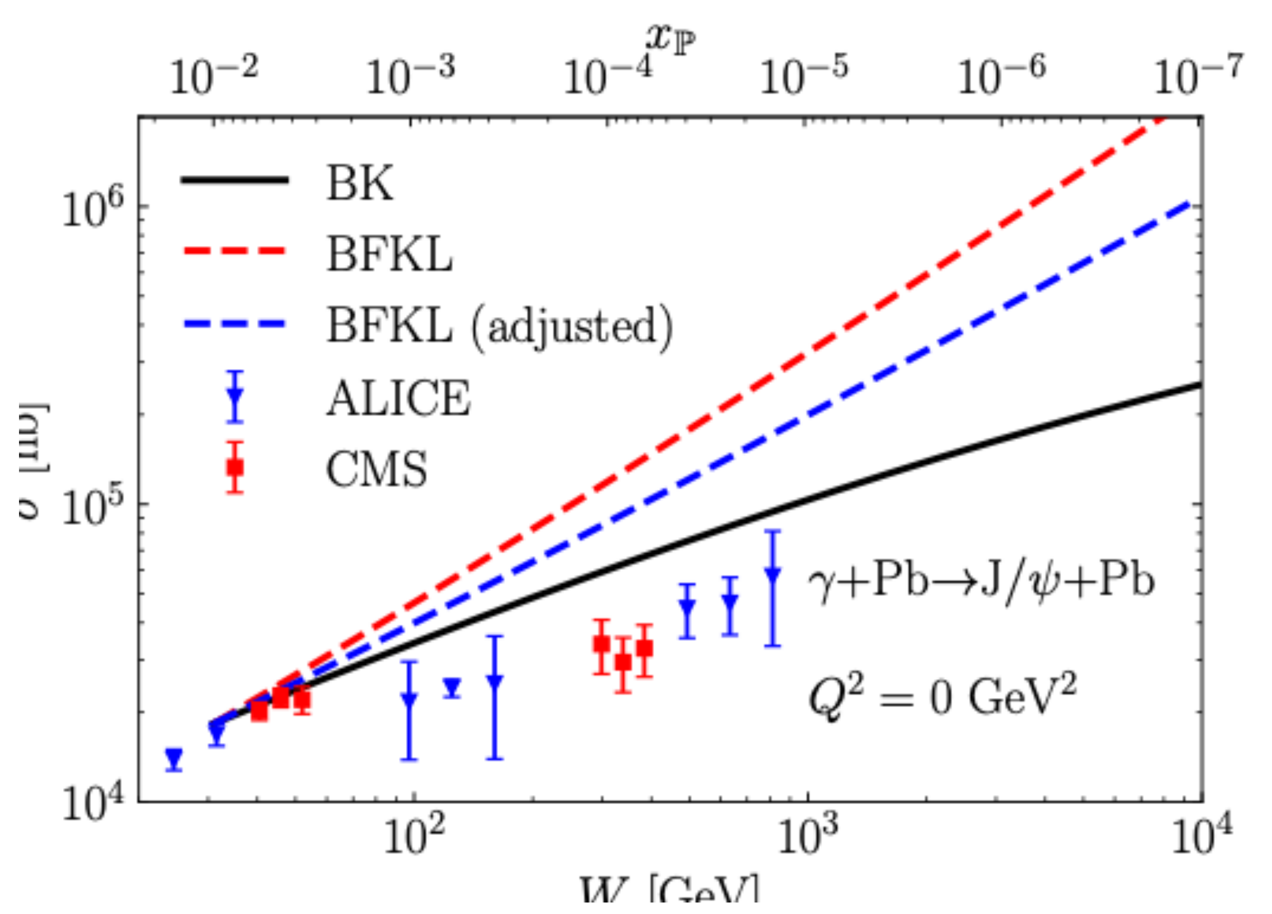
Exclusive vector meson production in UPCs

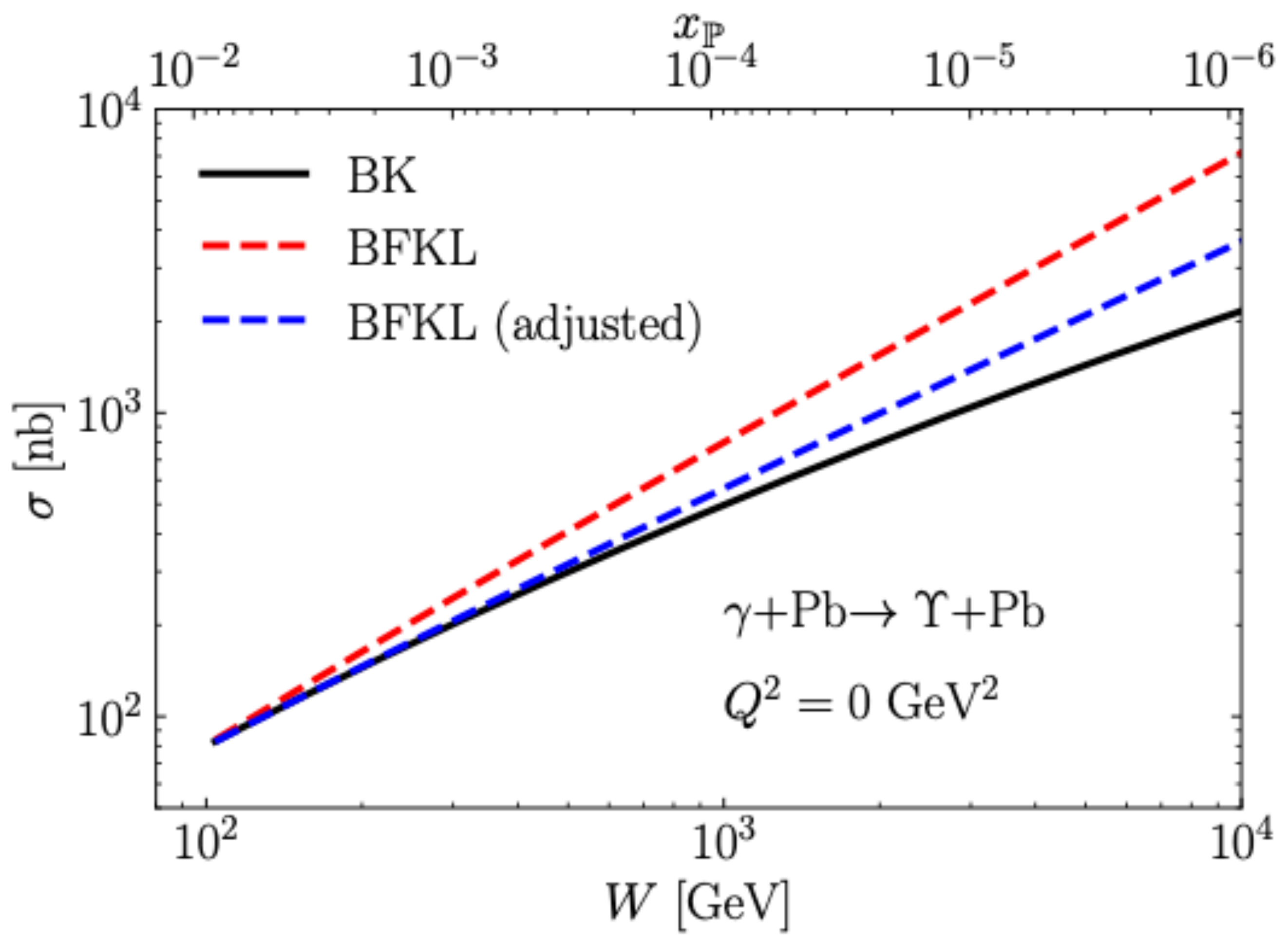
- Stronger saturation effects(more nuclear suppression) :

  -for larger nuclei and larger energy (smaller-x)

$$Q_s^2(x) \approx \Lambda_{QCD}^2 A^{1/3}(x_0/x)^\lambda$$

  -for less massive vector meson $M_V^2 \lesssim Q_s^2(x)$





Penttala, Royon (2024)

Map Q² varying VM mass

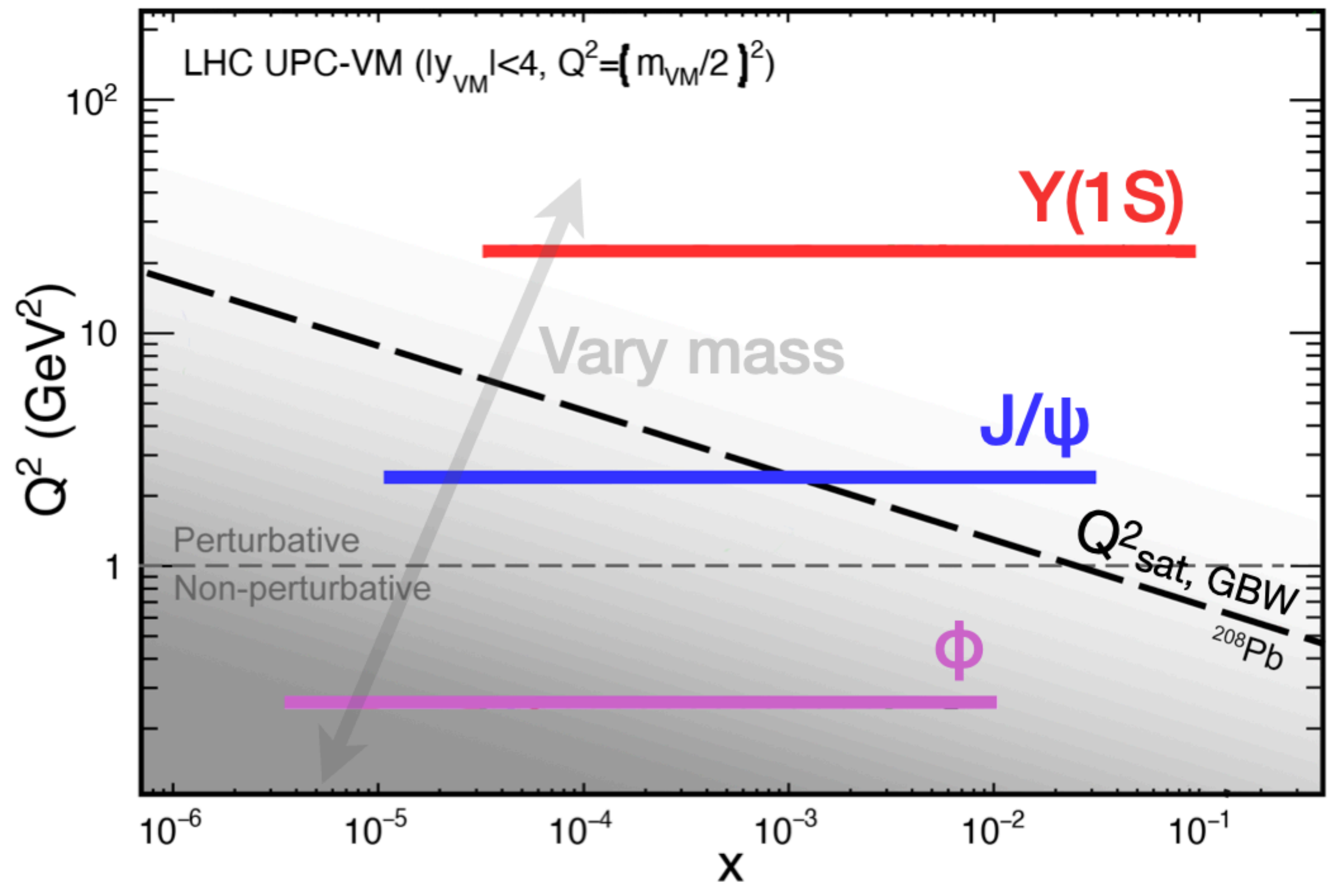
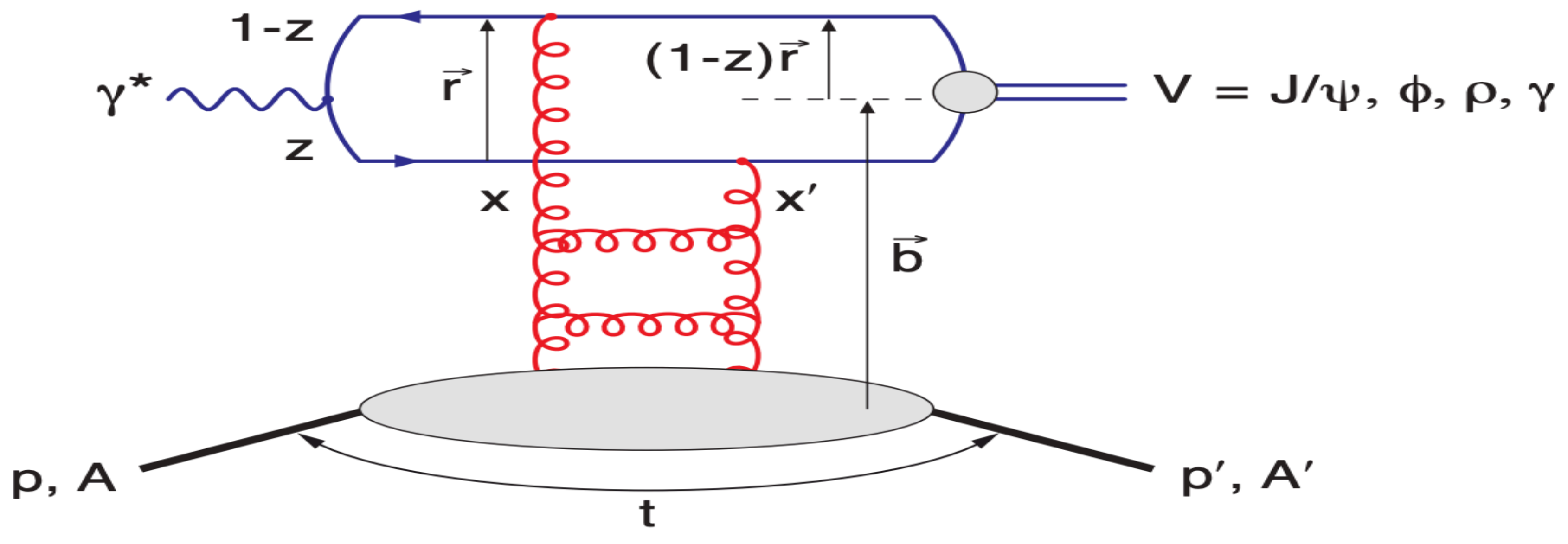


Figure from CMS (preliminary talk at QM)

- Also results for ϕ from CMS (and upcoming from STAR). CGC predictions for ϕ in UPC not very reliable due to non-perturbative effects.
  - Preliminary CMS data shows more suppression for Υ than expected from CGC

- At EIC we can perform a scan on the virtuality of the photon Q^2, low Q^2 saturation regime, high Q^2 dilute regime

Exclusive vector meson production in UPCs



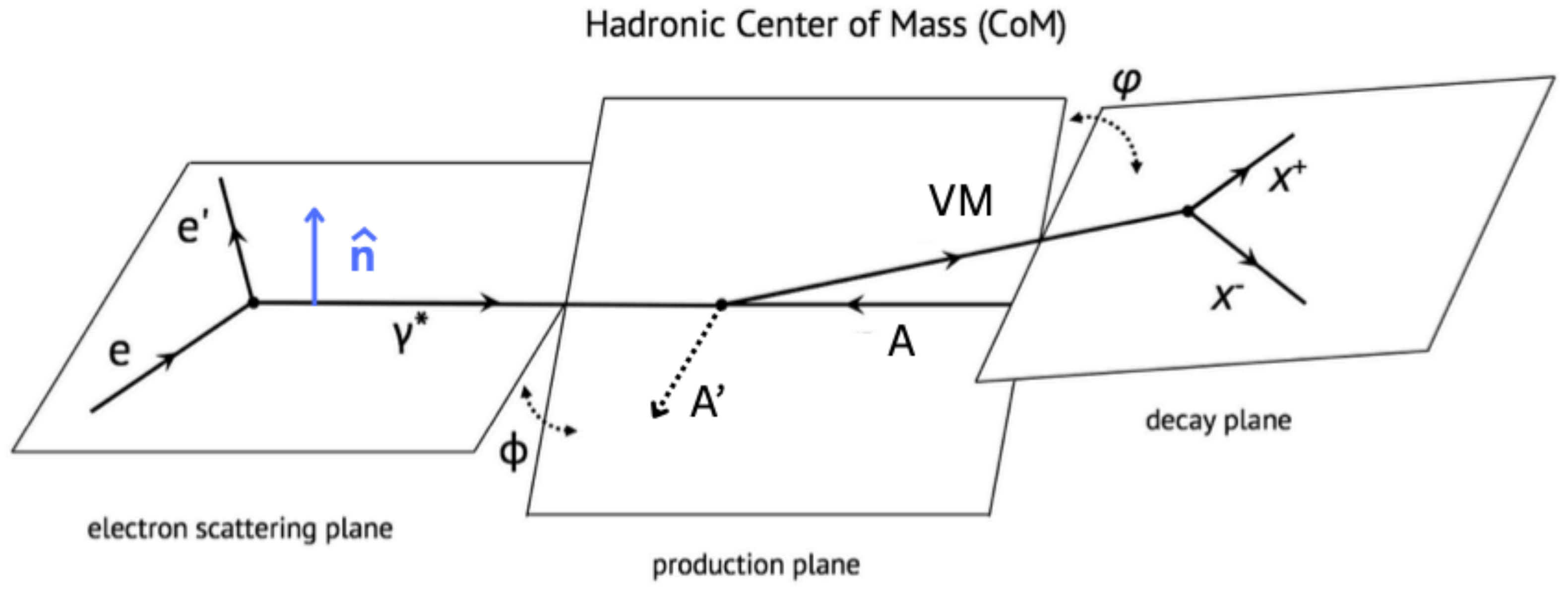
Sensitive to spatial distribution (tomography)

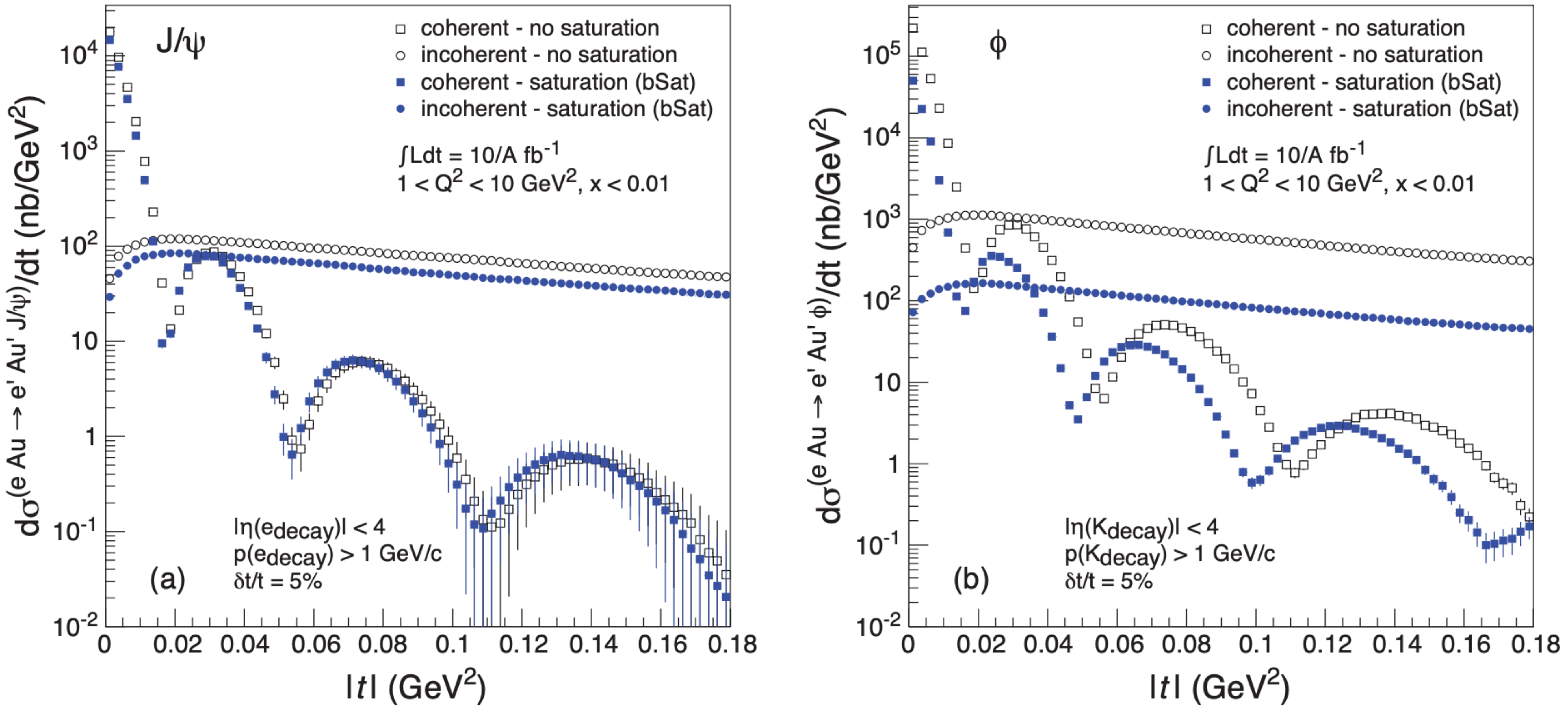
$$t = -\boldsymbol{\Delta}_\perp^2$$

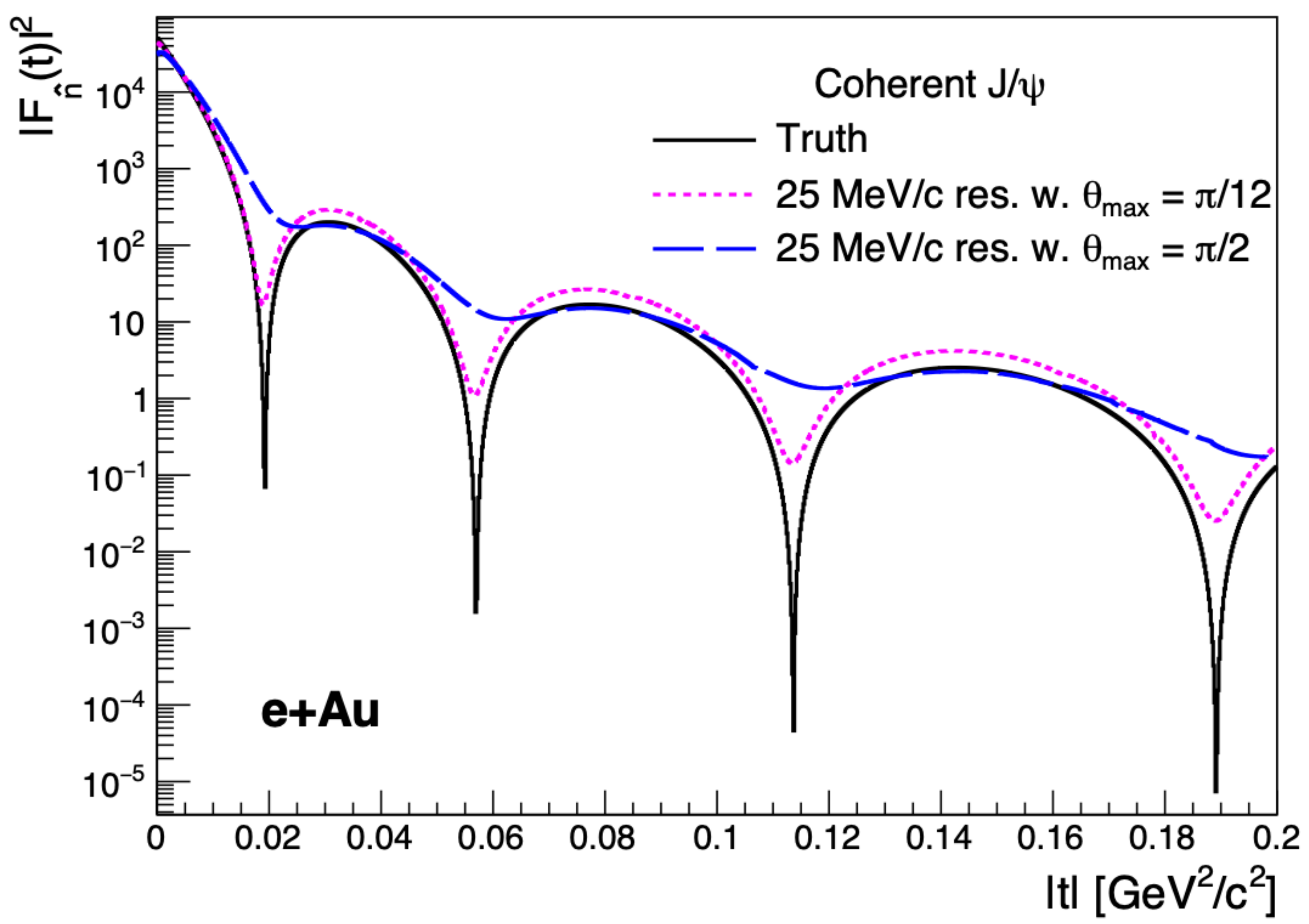
$$\boldsymbol{\Delta}_\perp \leftrightarrow \boldsymbol{b}_\perp$$

- Disentangle coherent from incoherent with polarized electron

Kesler, Ikbal Sheikh, Ma, Tu, Ullrich, Xu (2025)







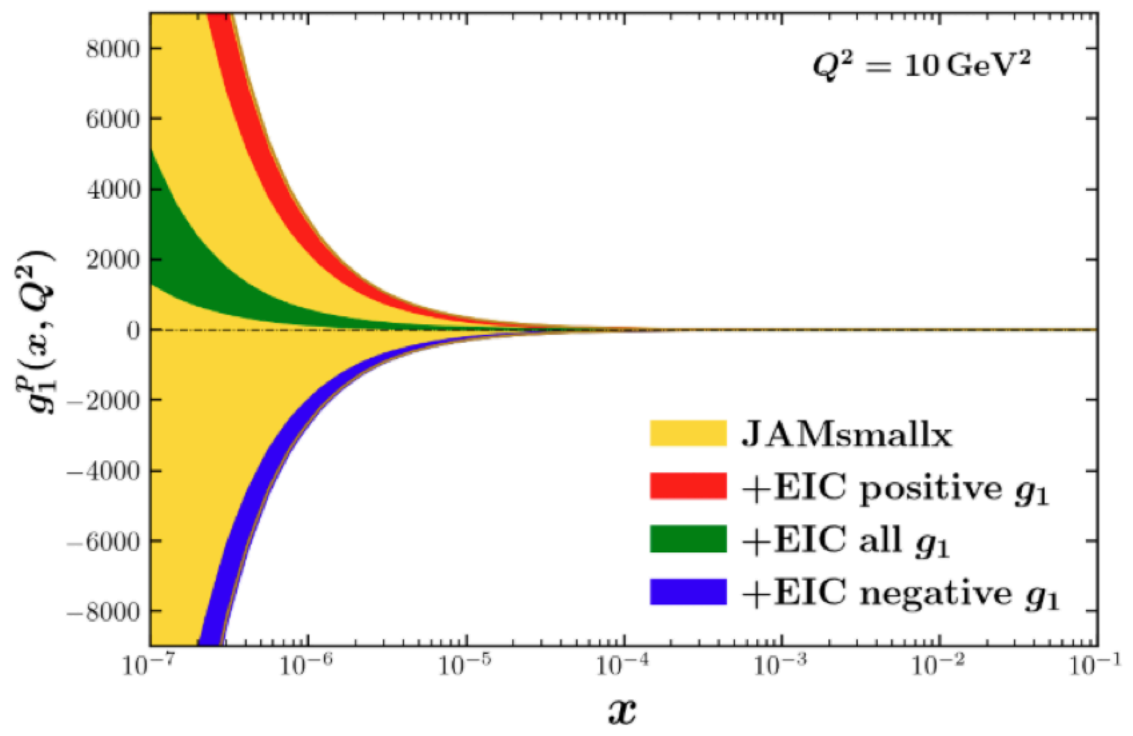
- Sartre event generator (bSat & bNonSat = linearized bSat)
- Saturation has an imprint on the spectrum. Large difference for φ less so for J/ψ

T. Toll, T. Ullrich (2012)

Other interesting avenues

- Spin and small-x physics

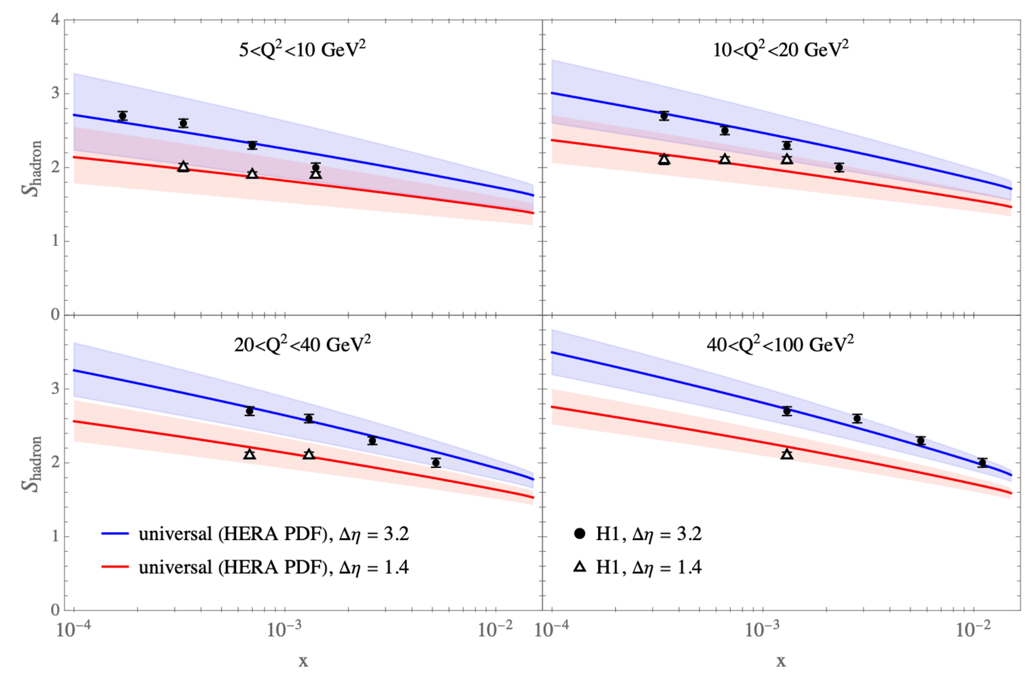
  Kovchegov, Sievert, Pitonyak, …(2012-present)



2503.21006

- Entanglement at small-x

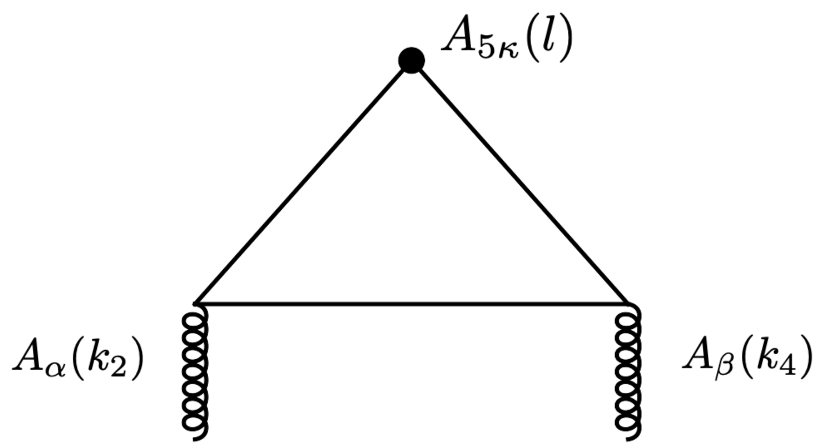
  Kharzeev, Levin, Kutak, Hentschinski, Tu (2012-present)



Rept.Prog.Phys. 87 (2024) 12, 120501

- Sphalerons at the EIC and interplay with chiral anomaly

  Tarasov, Venugopalan (2020-present)



- Tomography at small-x: Wigner distribution, angular momentum…

See Shohini's talk

Summary

- Search for gluon saturation is one of major goals of the EIC, and future upgrades to the LHC (e.g. ALICE FoCal)
- The Color Glass Condensate is one framework that provides a potential unifying description of different observables and across different colliding systems
- Saturation leaves its signatures in inclusive, semi-inclusive and exclusive processes
- A unified picture provides an opportunity for a Bayesian framework across different colliding systems

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