TEMPLE UNIVERSITY

Brookhaven National Laboratory

The physics of gluon saturation

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Temple University and RIKEN BNL

Outline

- CGC in a nutshell
- Observables at the EIC (highlights)

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

- Theoretical challenges and interdisciplinary connections
- Summary

Hadronic and nuclear matter

Deep inelastic scattering (DIS)

microscope to the subatomic world

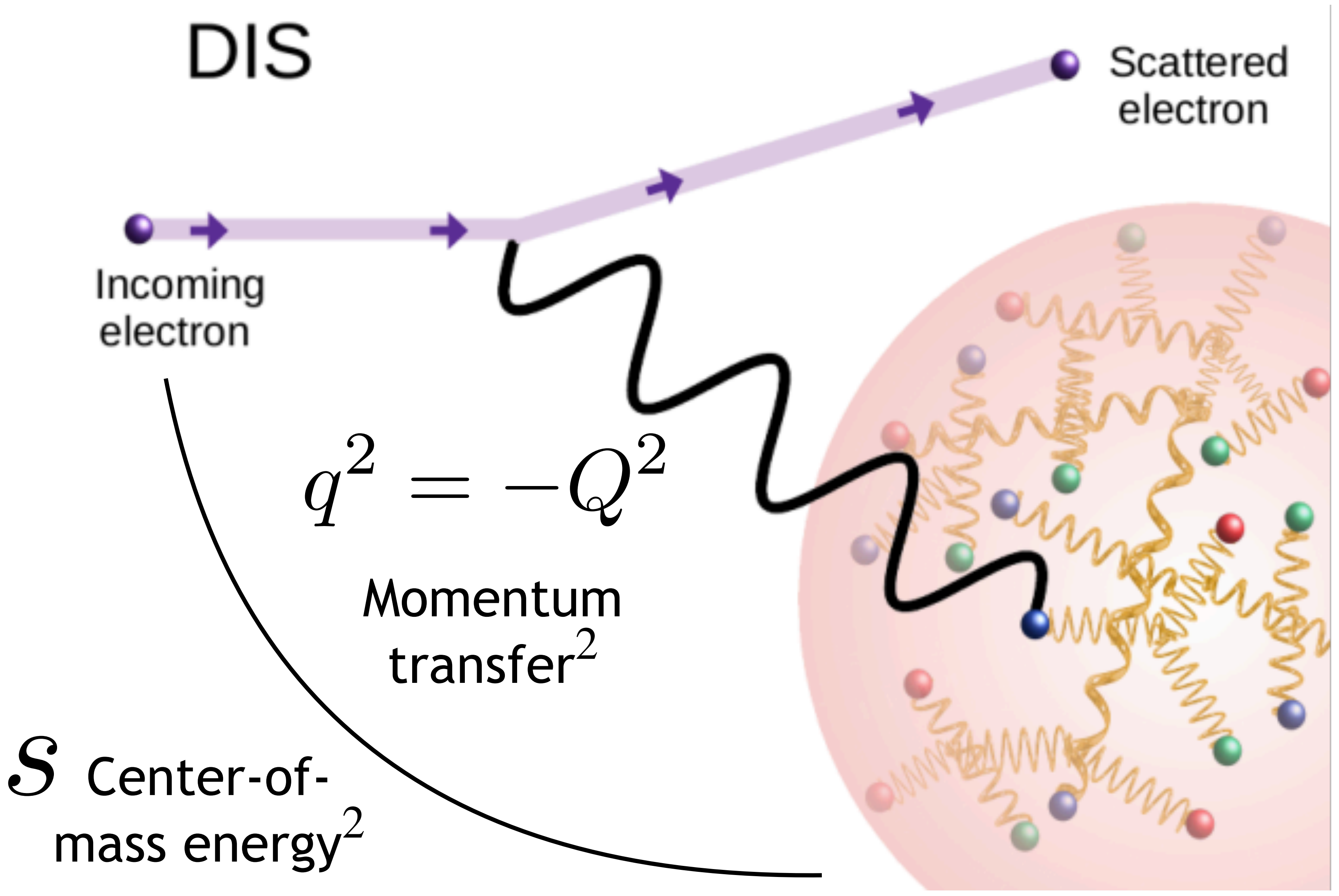


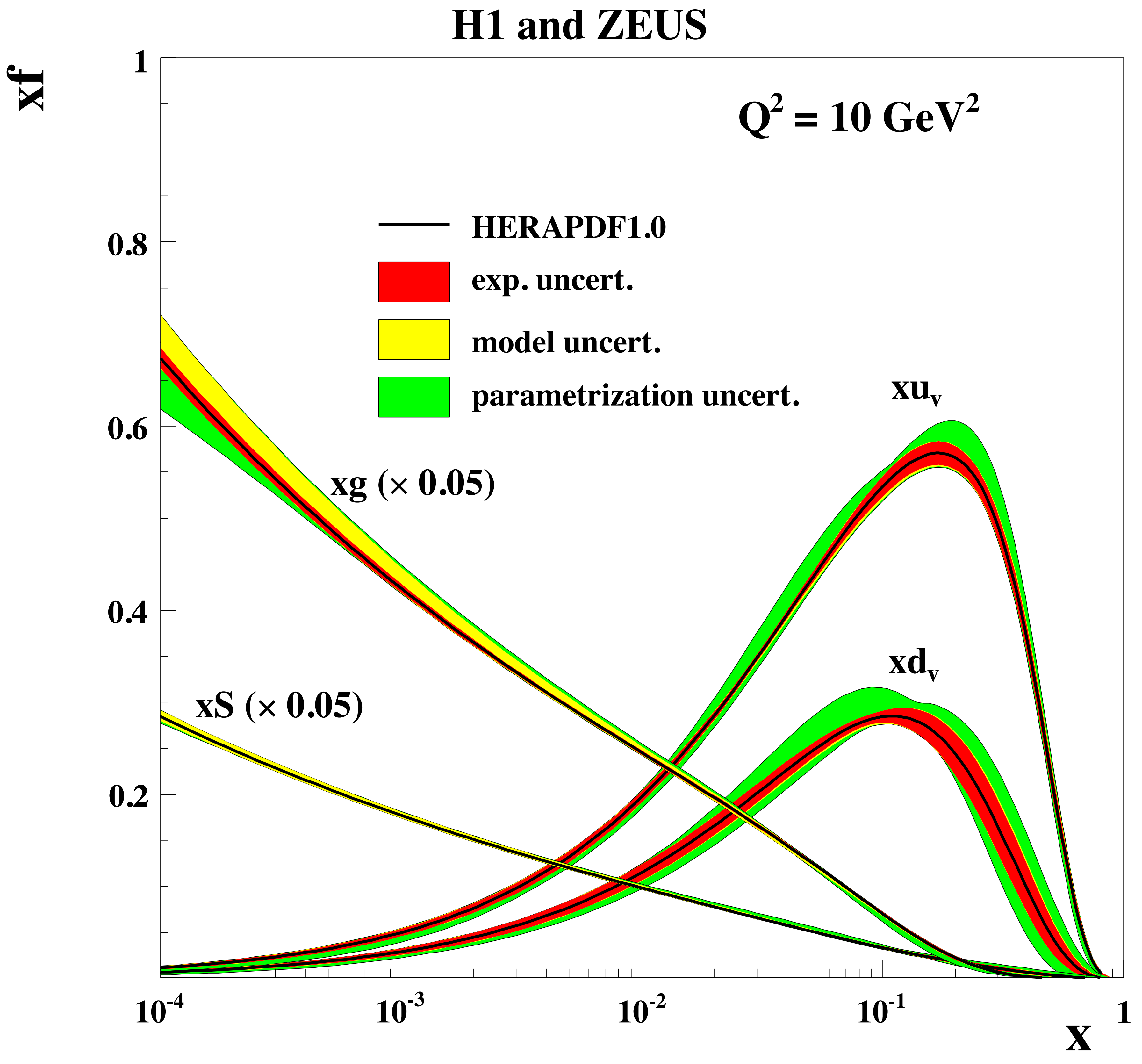
Figure (edited) from ZEUS collaboration

Q^2 Virtuality

$x_{\mathrm{Bj}} \sim Q^2/s$ Bjorken-x

pixel

shutter time



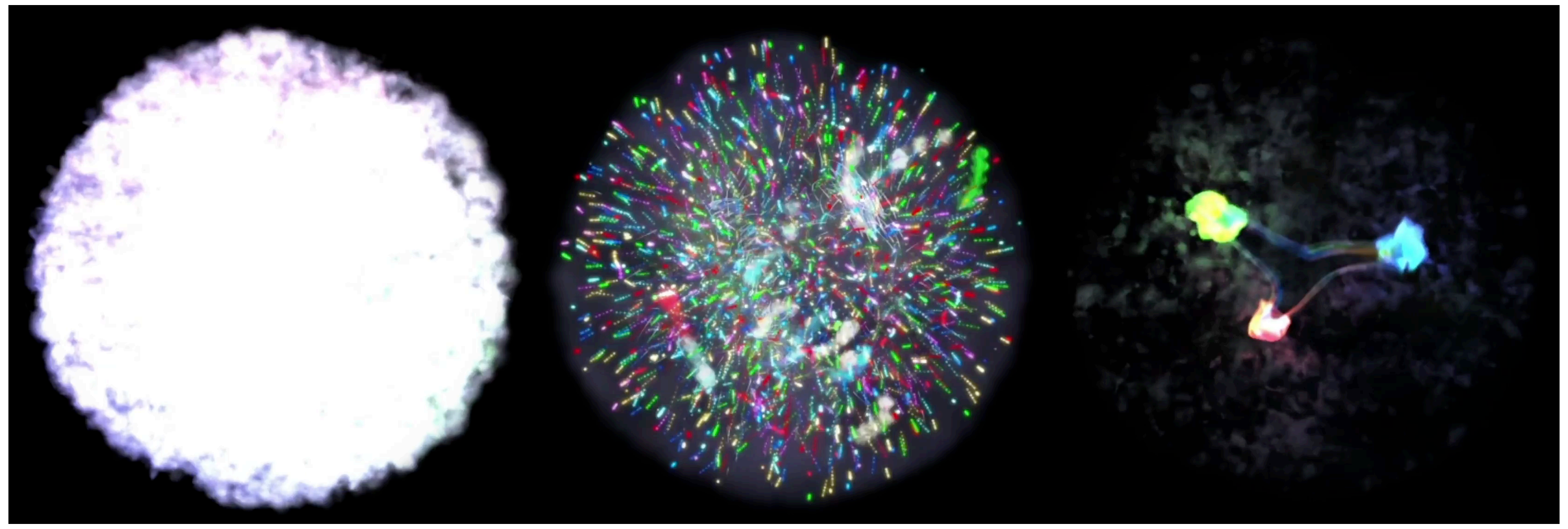
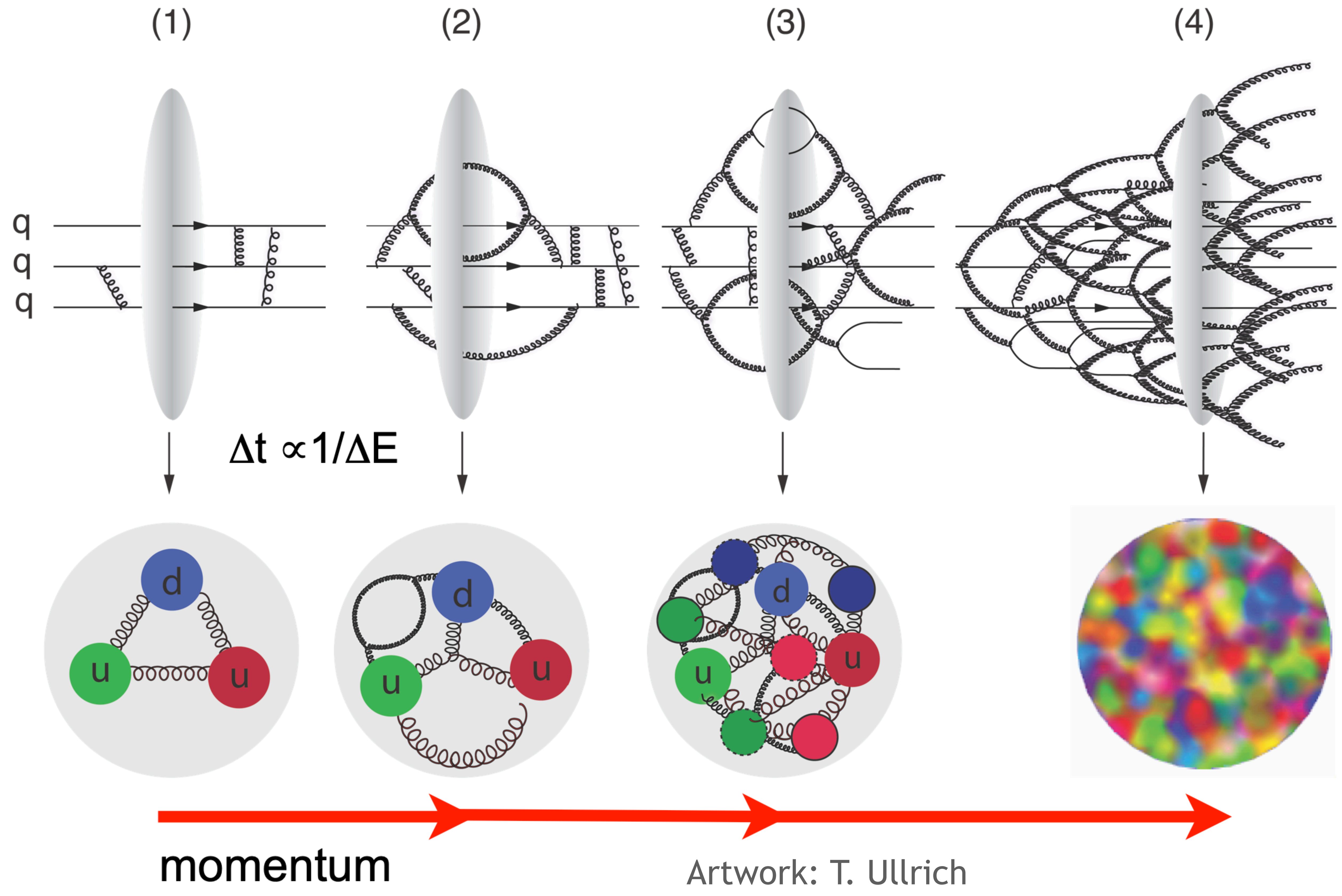


Figure from MIT/Jefferson Lab/Sputnik

Hadronic matter a vibrant QCD environment

Anatomy of nuclear matter at high-energies



Artwork: T. Ullrich

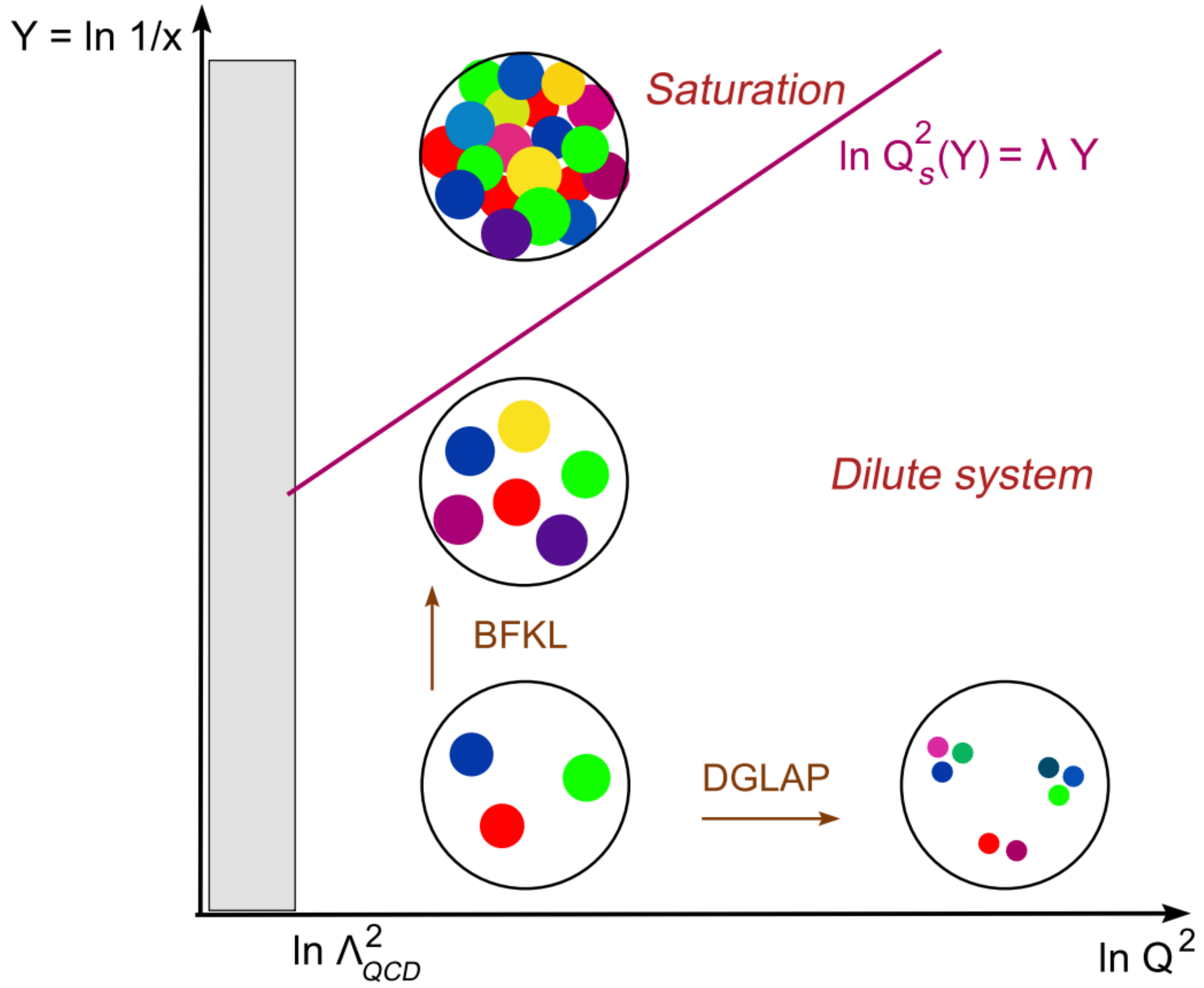
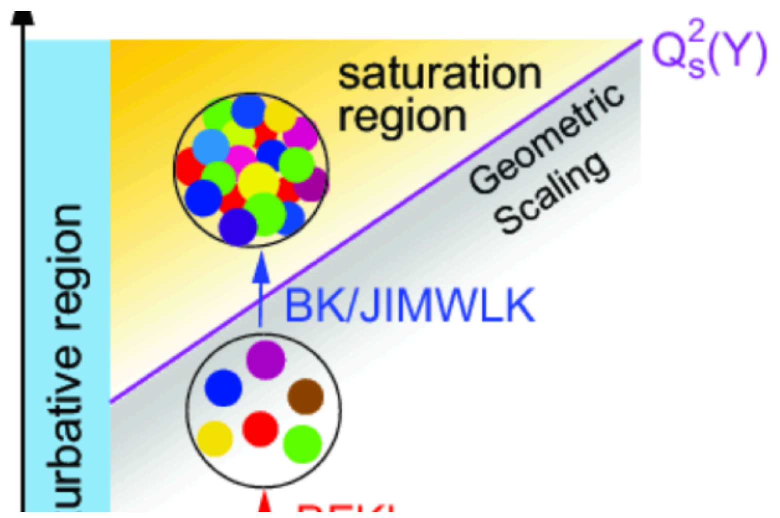


Figure from EIC White paper (2012)

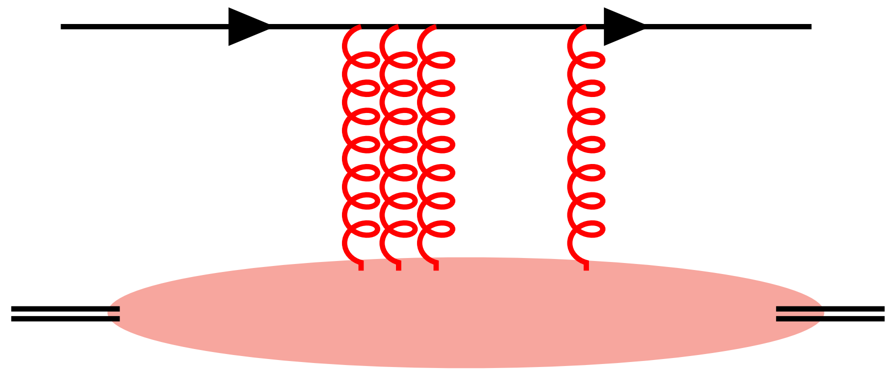
Partonic picture superseded by **strong color fields**

Universality: unified description of QCD at high-energies

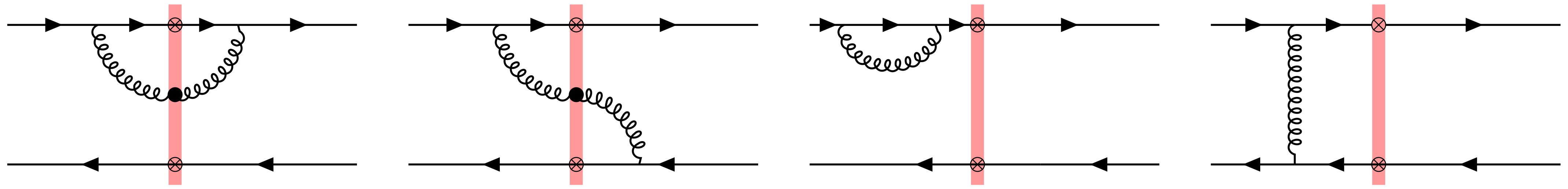
The Color Glass Condensate in a nutshell



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

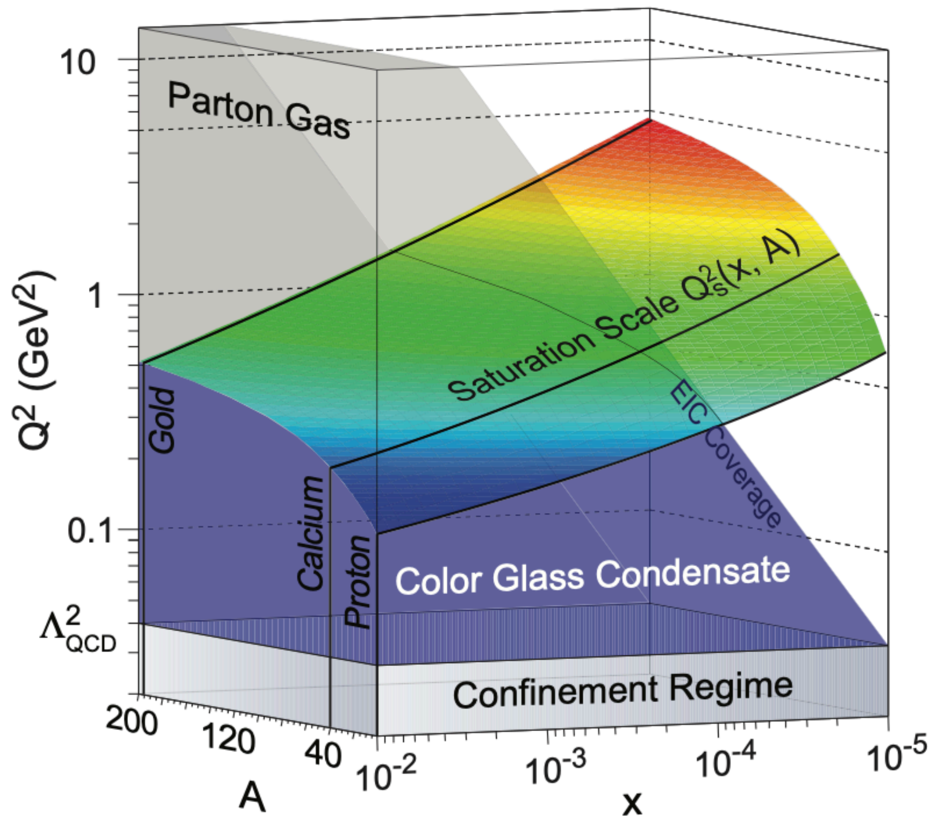


- Strong classical field -> multiple scattering -> broadening (Glauber)



- 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/virtualities $Q^2 \lesssim Q_s^2(x)$

Power-counting in the CGC

Dilute-dilute: $Q_{sA}^2/k_{A\perp}^2 \ll 1$ and $Q_{sB}^2/k_{B\perp}^2 \ll 1$

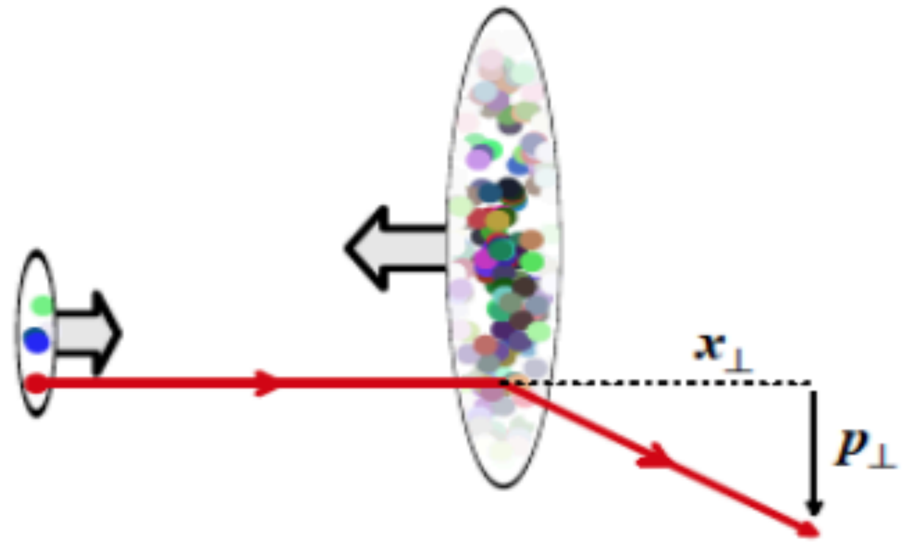
Match to pQCD computation of hard processes at small x

Hard production in hadron collisions

Dilute-dense: $Q_{sA}^2/k_{A\perp}^2 \ll 1$ and $Q_{sB}^2/k_{B\perp}^2 \sim 1$

Hybrid approach pQCD/CGC, advances at NLO and relation to TMD and GPDs

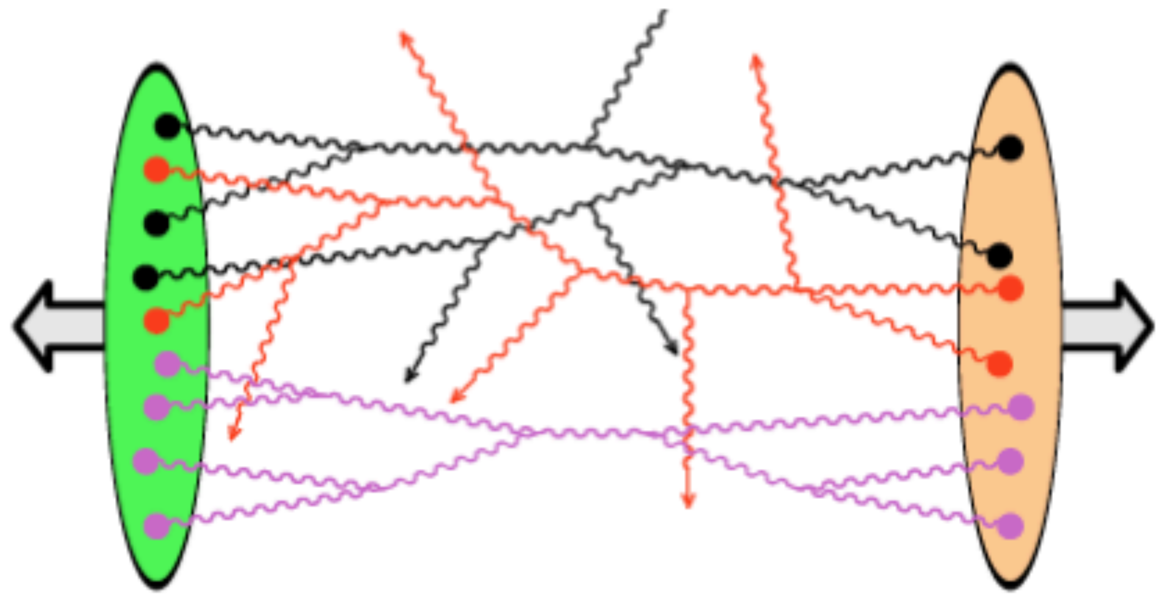
Semi-hard and forward particle production in proton-nucleus, electron-nucleus collisions



Dense-dense: $Q_{sA}^2/k_{A\perp}^2 \sim 1$ and $Q_{sB}^2/k_{B\perp}^2 \sim 1$

Solve classical YM equations numerically in 2+1 D (boost-invariant) /3+1 D

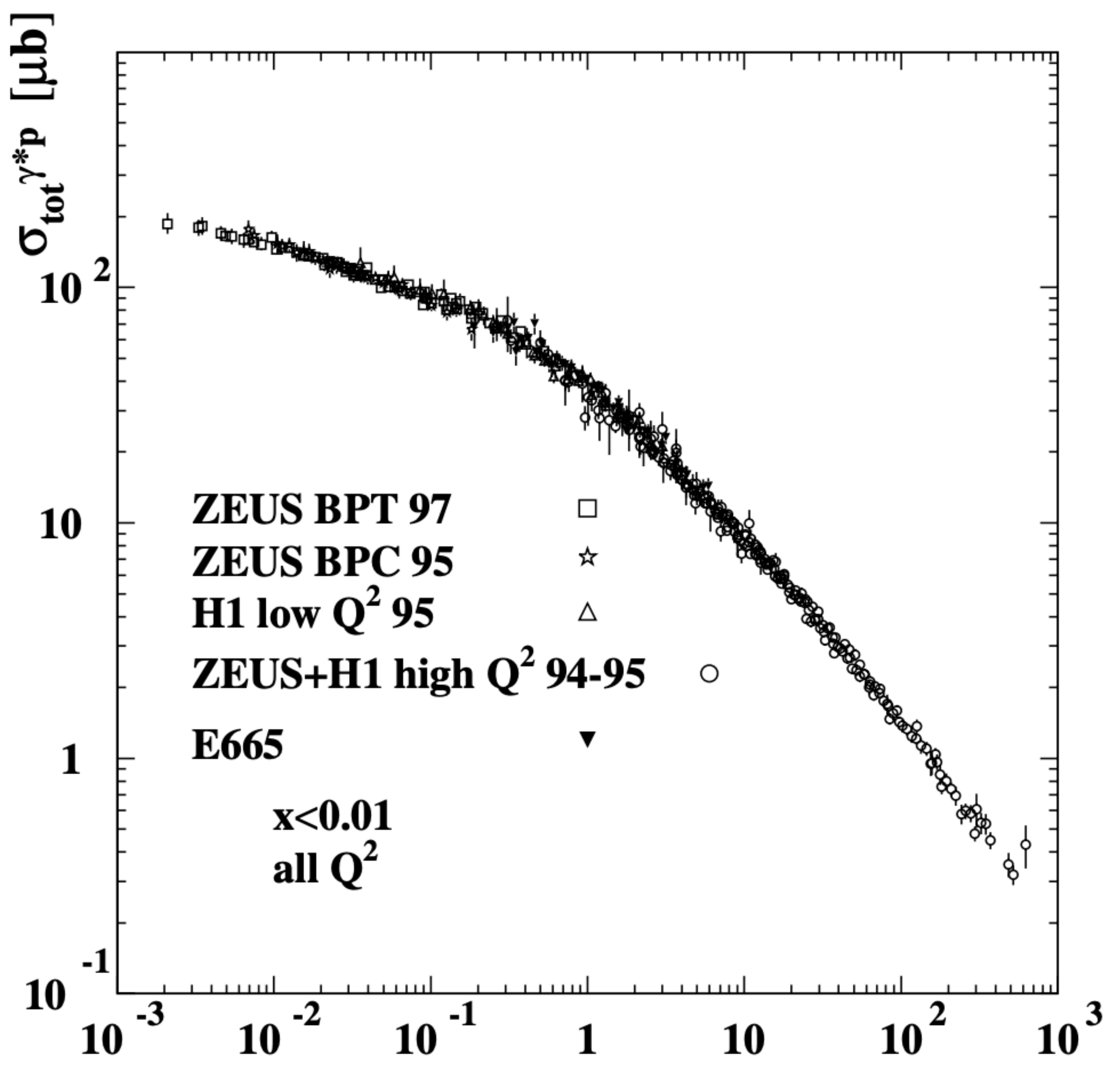
Semi-hard particle production in heavy-ion collisions



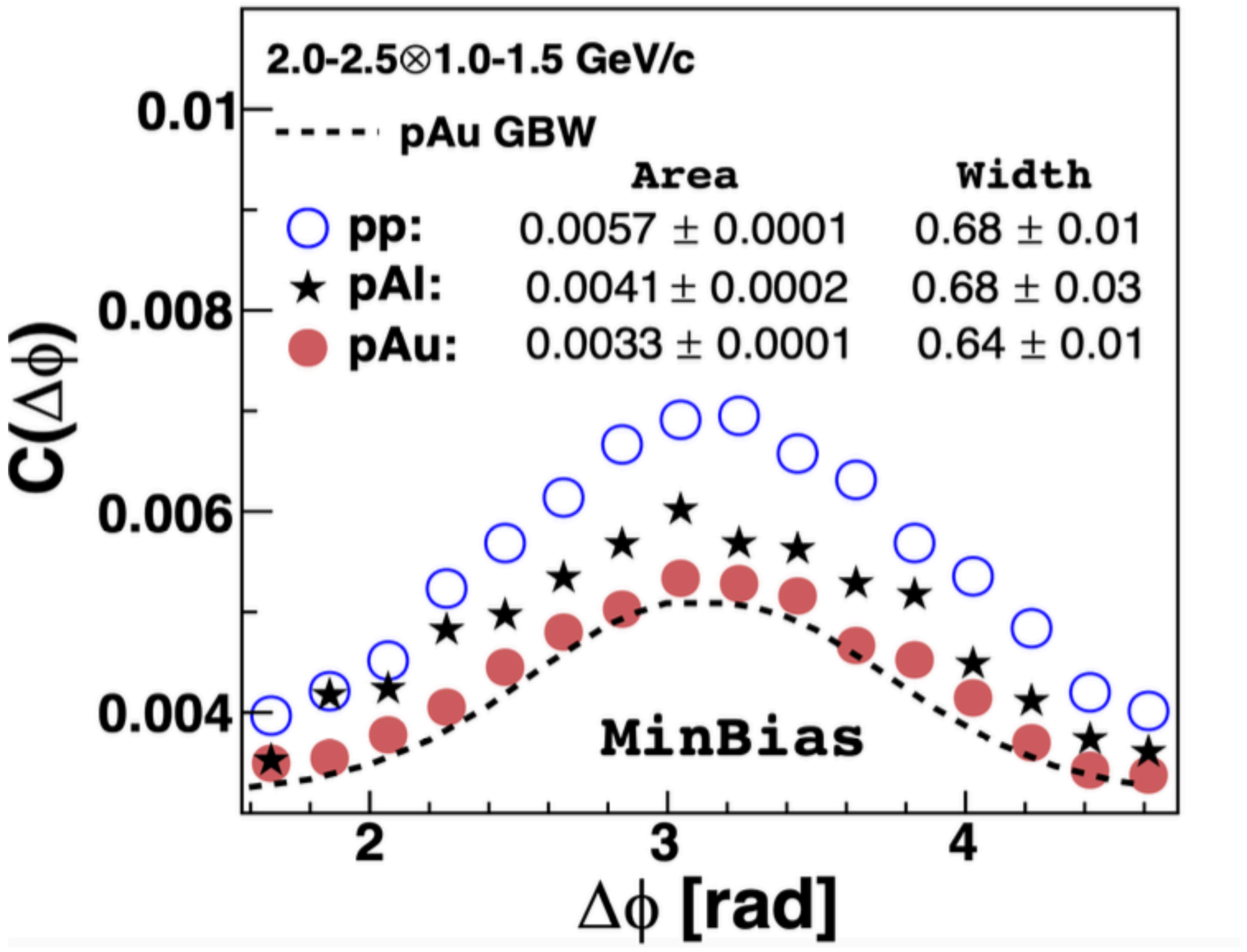
Regime is dictated by the colliding system, energy, centrality, rapidity, and transverse momentum of observed particles

Phenomenology at HERA, RHIC and LHC

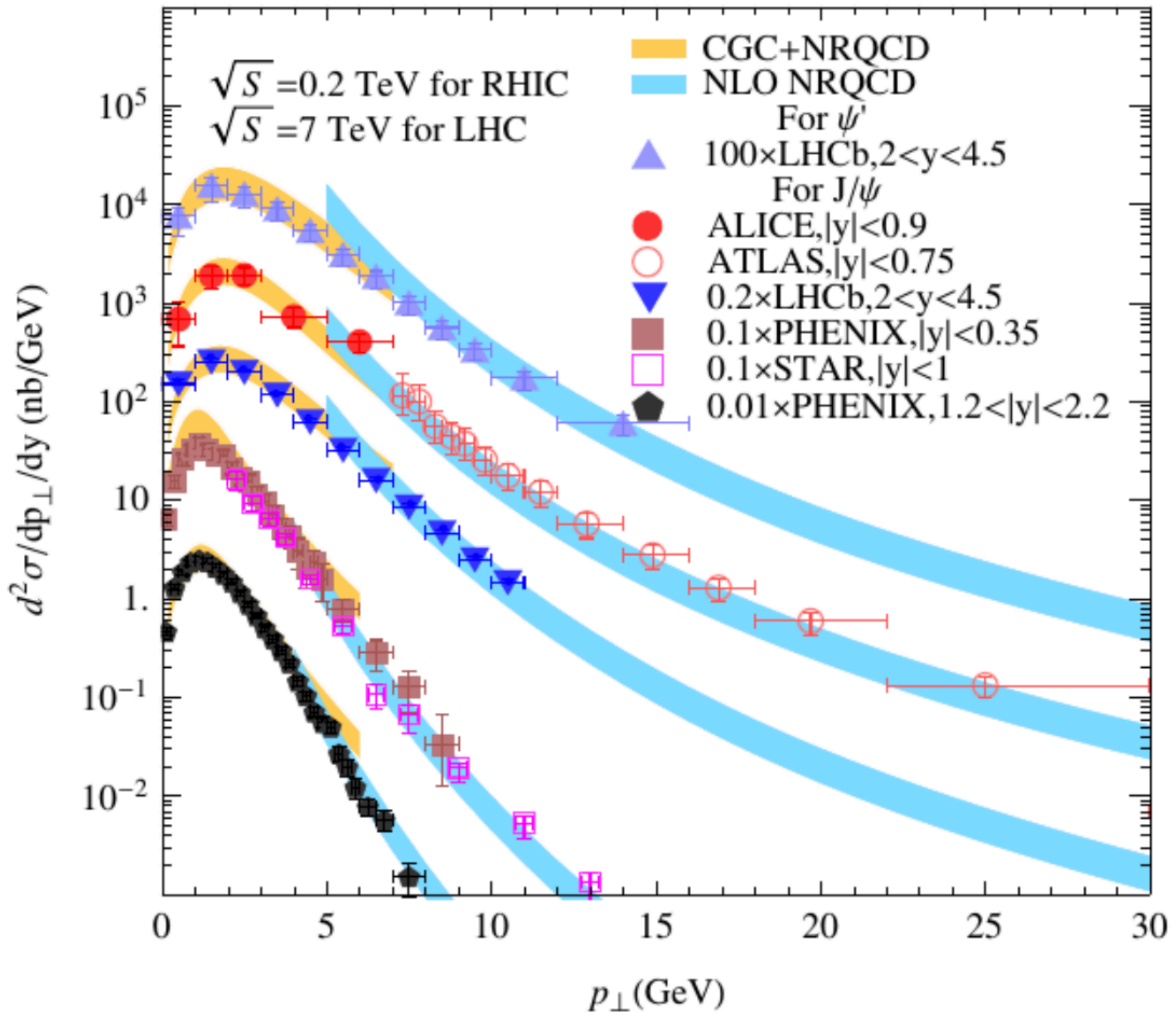
- Hadronic collisions, UPCs (e.g. RHIC and LHC)
- Deep-inelastic scattering (at HERA and future EIC)
- Inclusive, semi-inclusive, diffractive processes



Geometric scaling at HERA



Dihadron suppression at RHIC

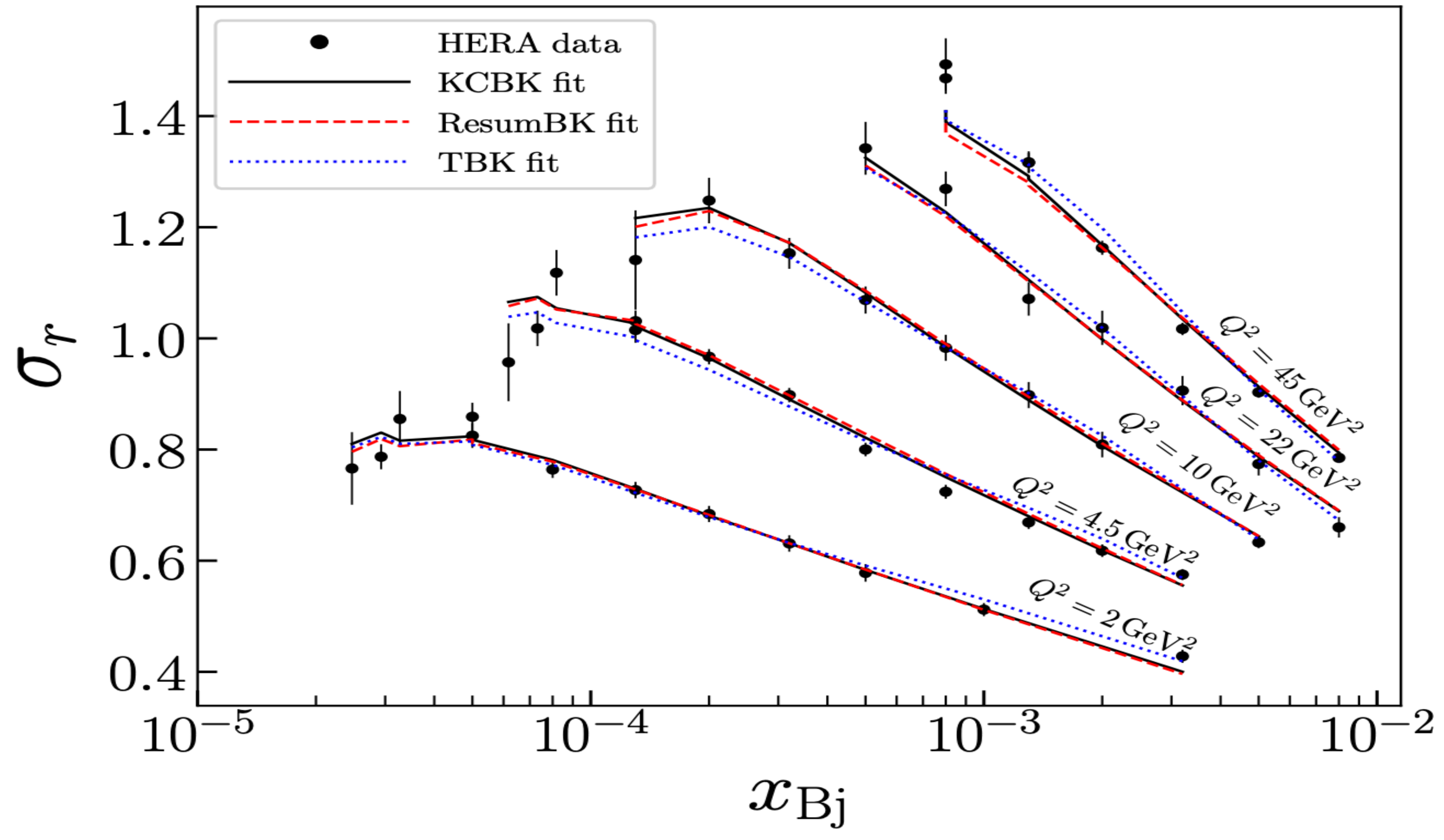


Quarkonium production at RHIC and LHC

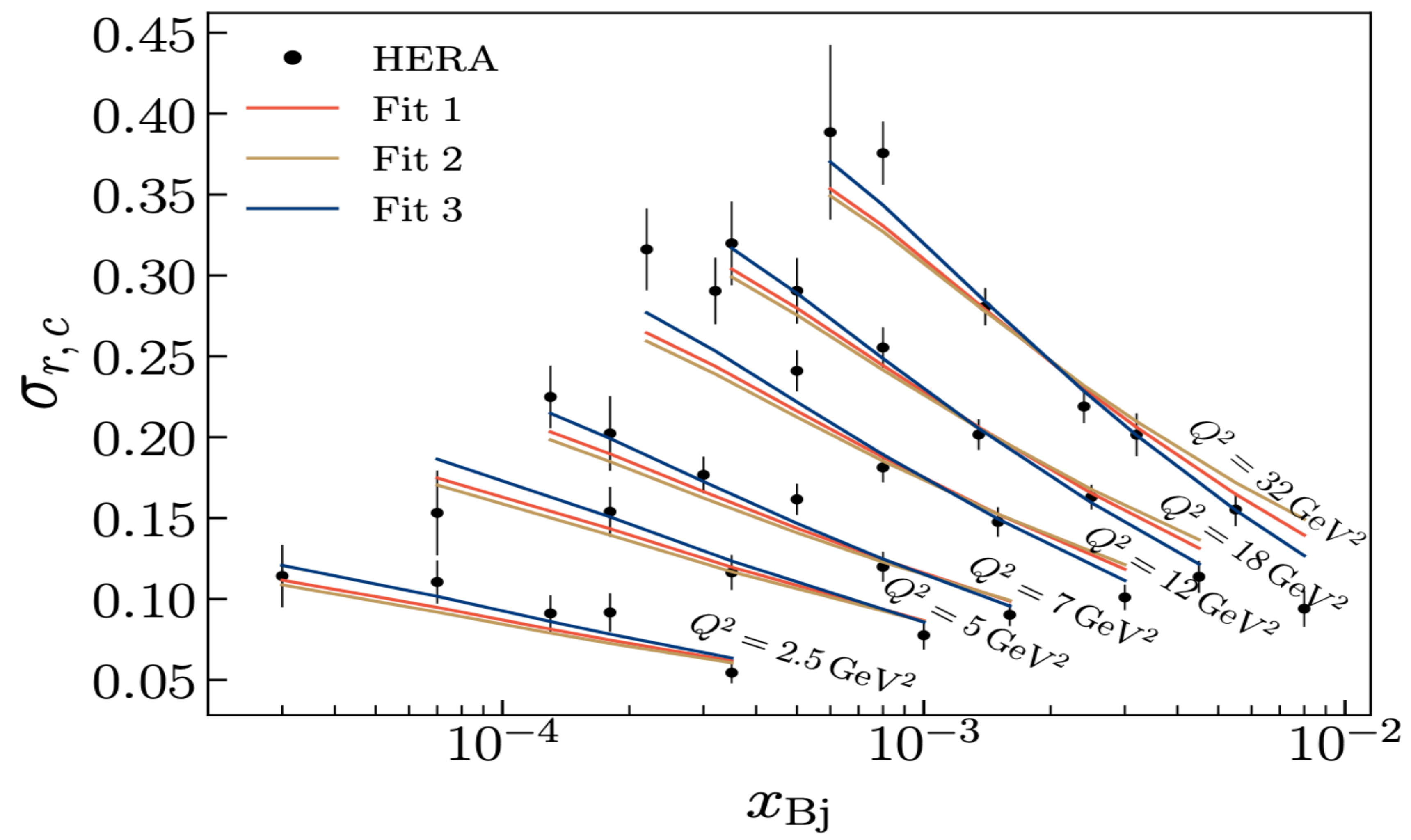
For a recent review see: Morreale, Salazar (2021) Garcia-Montero, Schlichting (2025)

Phenomenology at HERA, RHIC and LHC

Reduced structure functions HERA

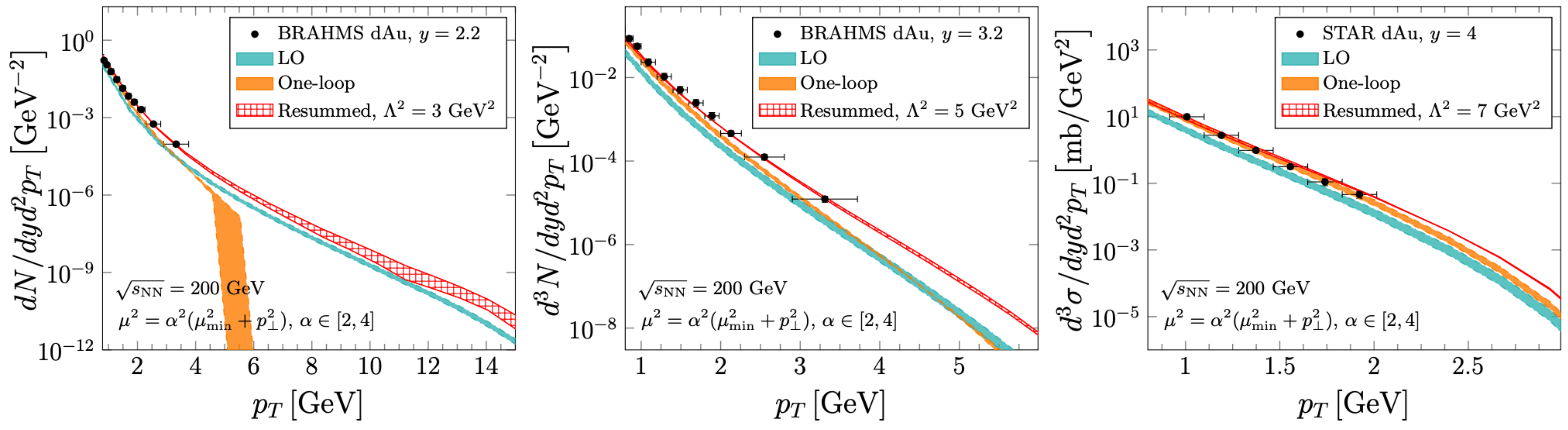


Beuf, Lappi, Hänninen, Mäntysaari (2020)

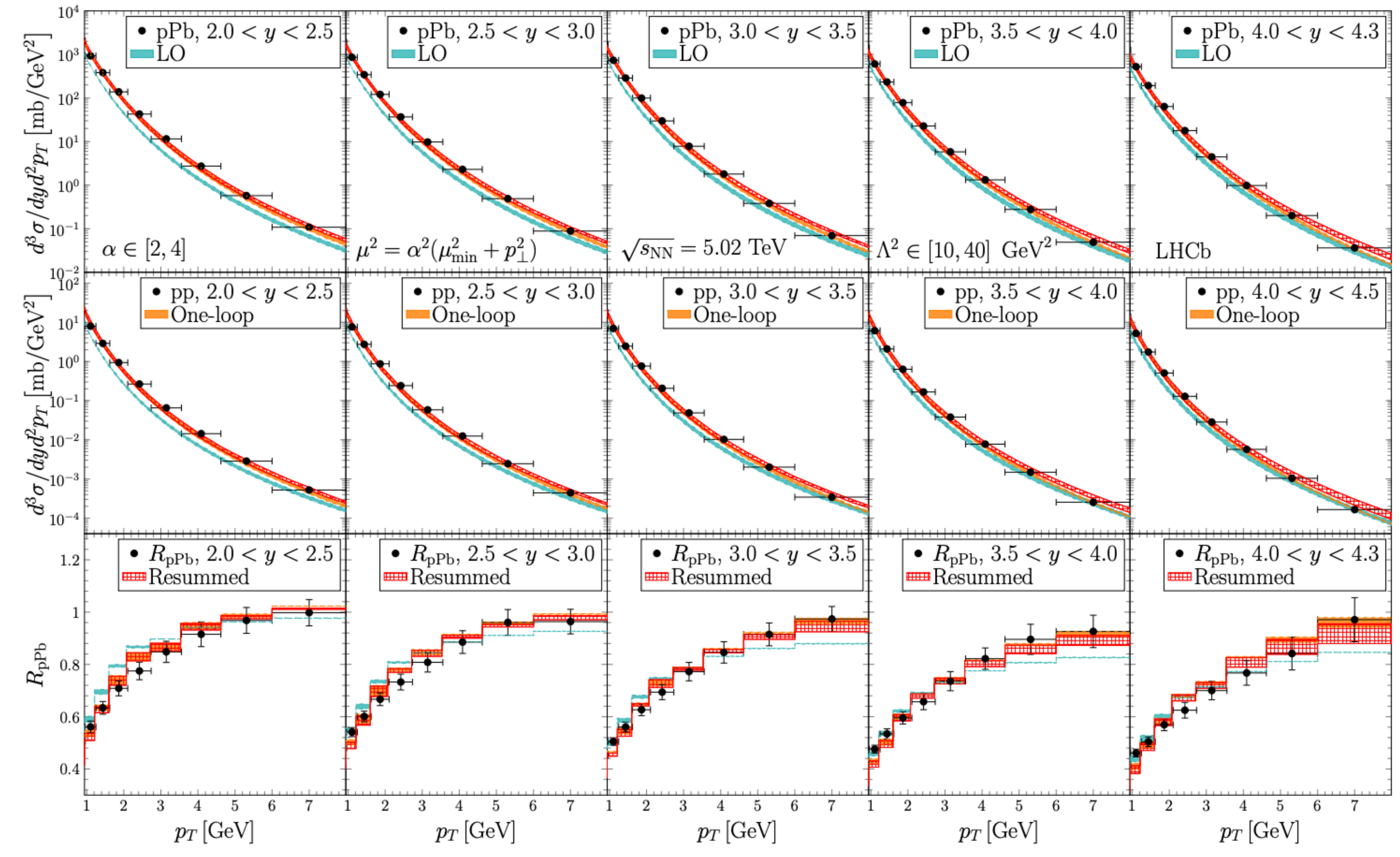


Hänninen, Mäntysaari, Paatelainen, Penttala (2023)

Single-inclusive hadron production in proton-nucleus at RHIC



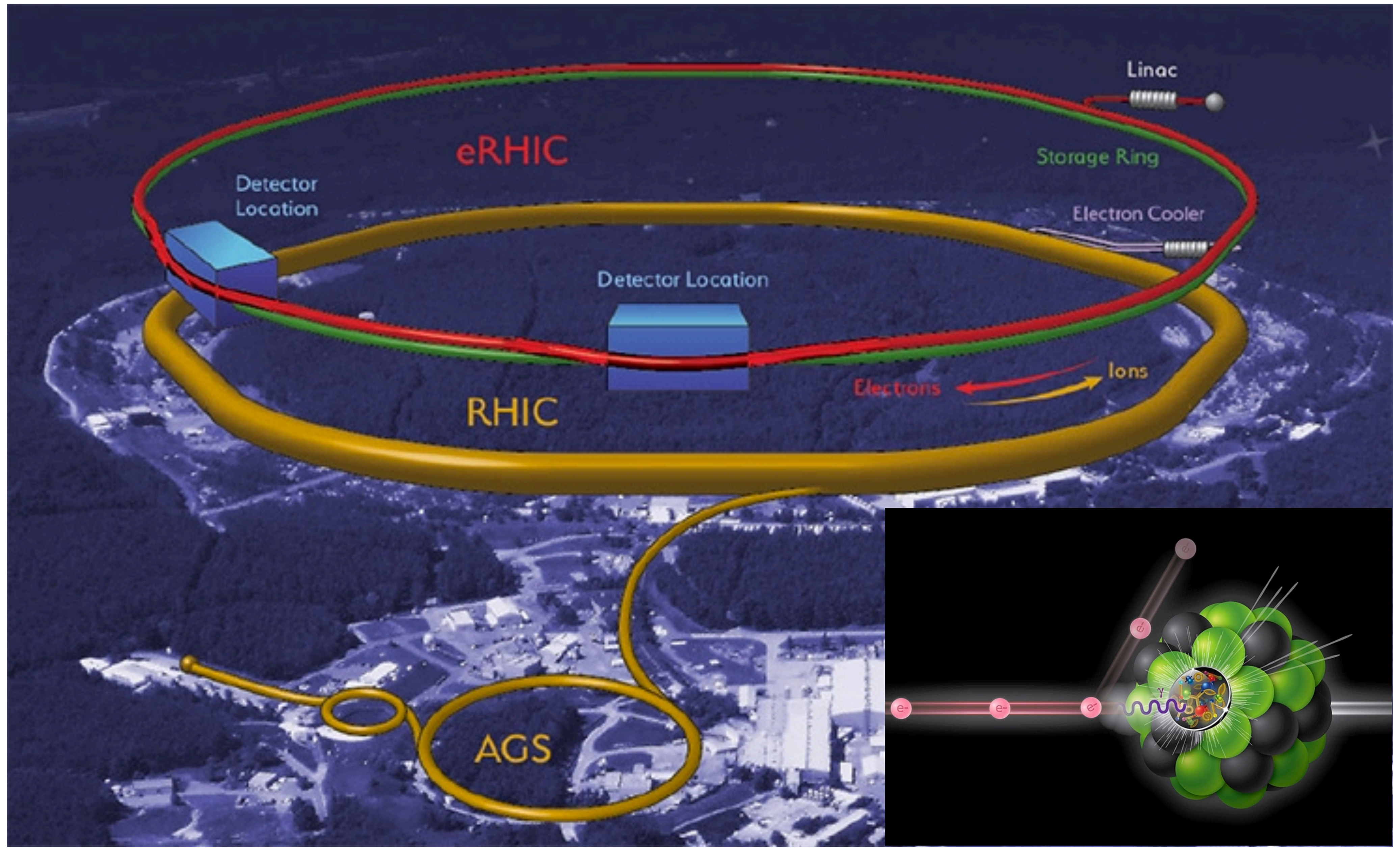
LHC



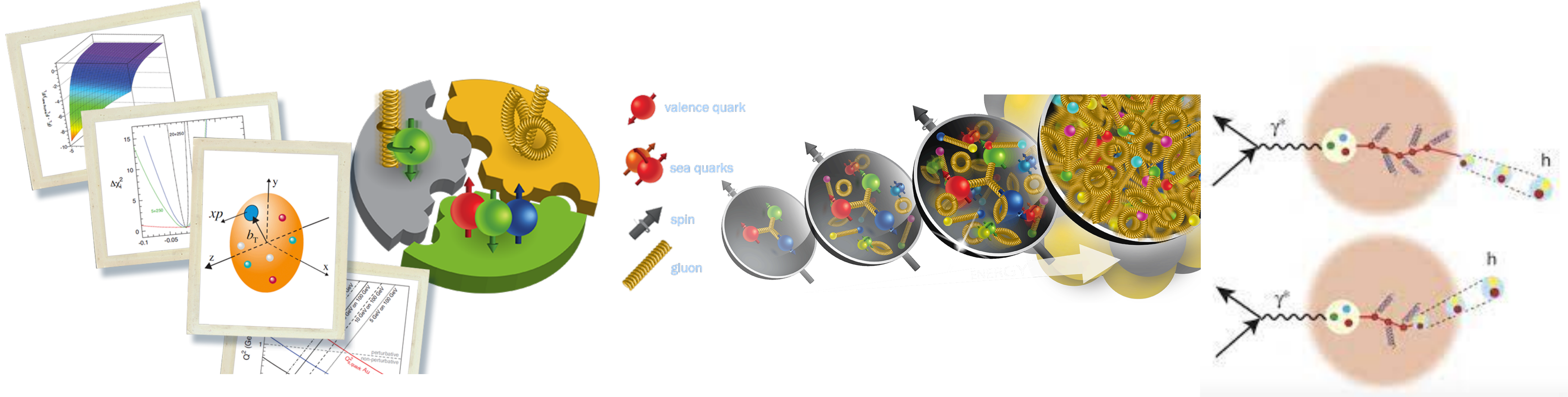
Shi, Wang, Wei, Xiao (2021)

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

More on EIC opportunities: Abhay Deshpande and John Lajoie talks

Structure functions: linear vs non-linear evolution

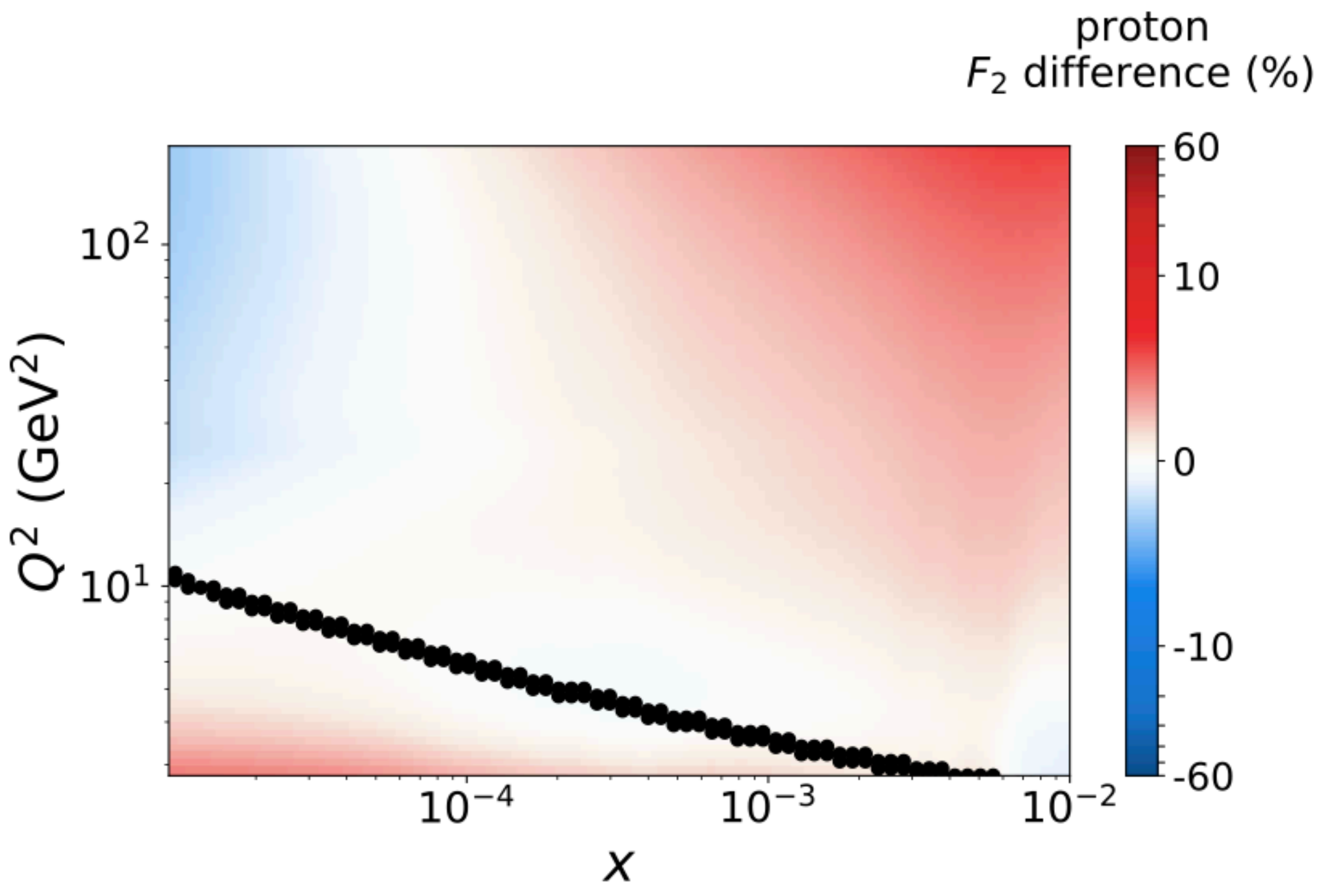
- Difference in predictions for $F_{2,L}$:
  linear (collinear/DGLAP)
  non-linear (dipole/Balitsky-Kovchegov)

$$(F^{\text{BK}}_{2/L} - F^{\text{DGLAP,Rew}}_{2/L})/F^{\text{BK}}_{2/L}$$

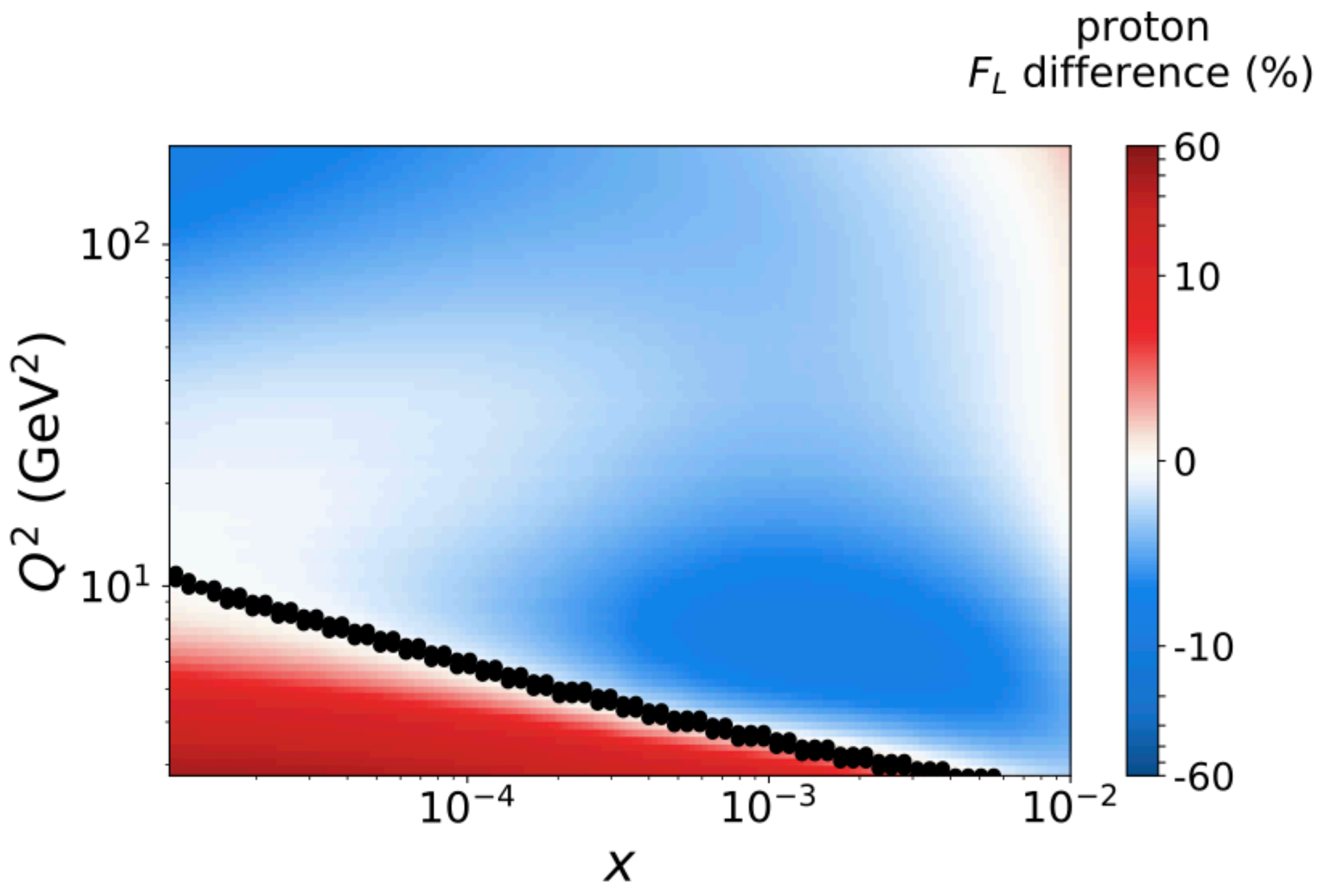
- Stronger effects for F_L than F_2

- Stronger effects for γAu than γp

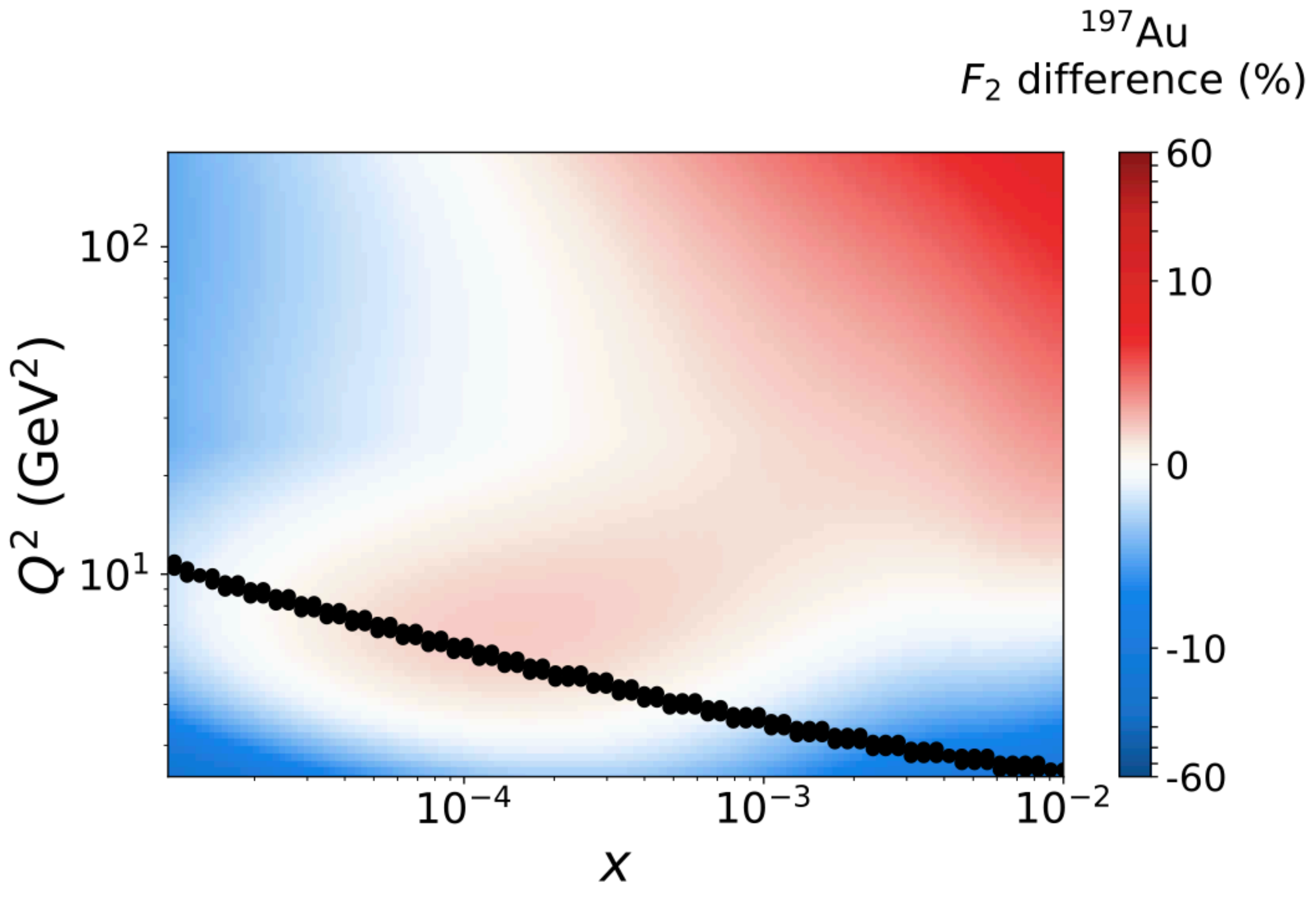
- It would be interesting to incorporate small-x evolution into DGLAP via BFKL, à la Ball, Bertone, Bonvini, Marazani, Rojo, Rottoli (2017), and compare with non-linear BK



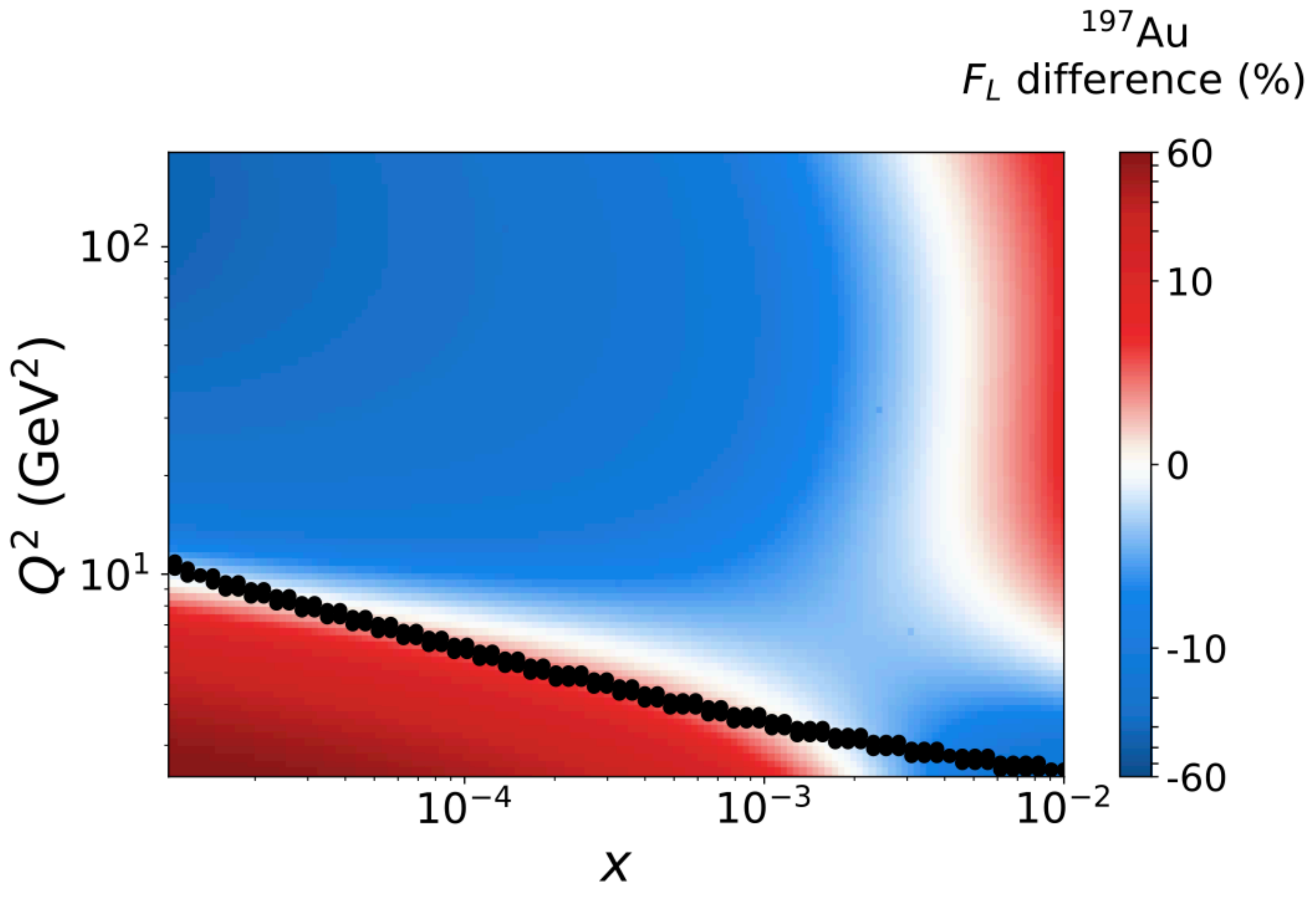
(a) F_2



(b) F_L



(a) F_2



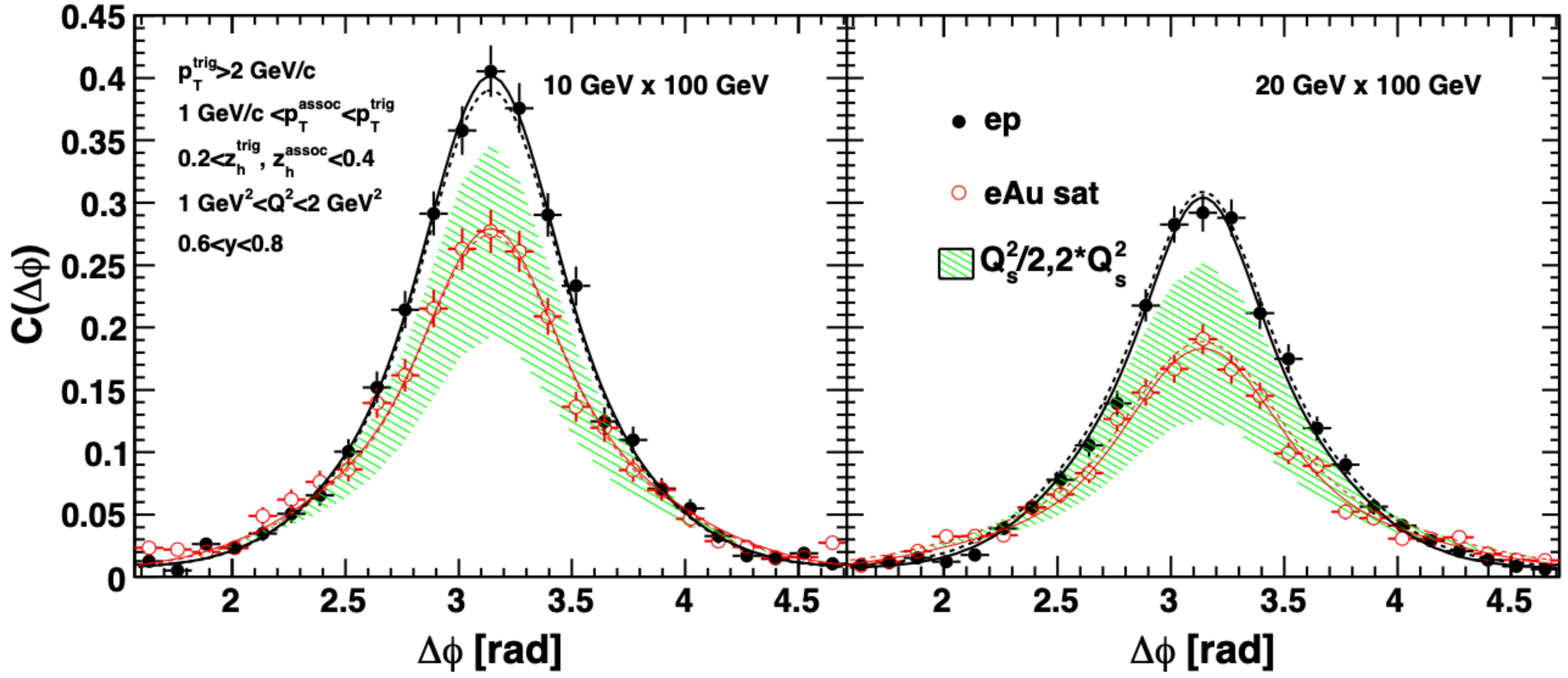
(b) F_L

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

See also Marquet, Moldes, Zurita (2017)

Two particle correlations at EIC

Dihadron suppression
back-to-back peak at EIC



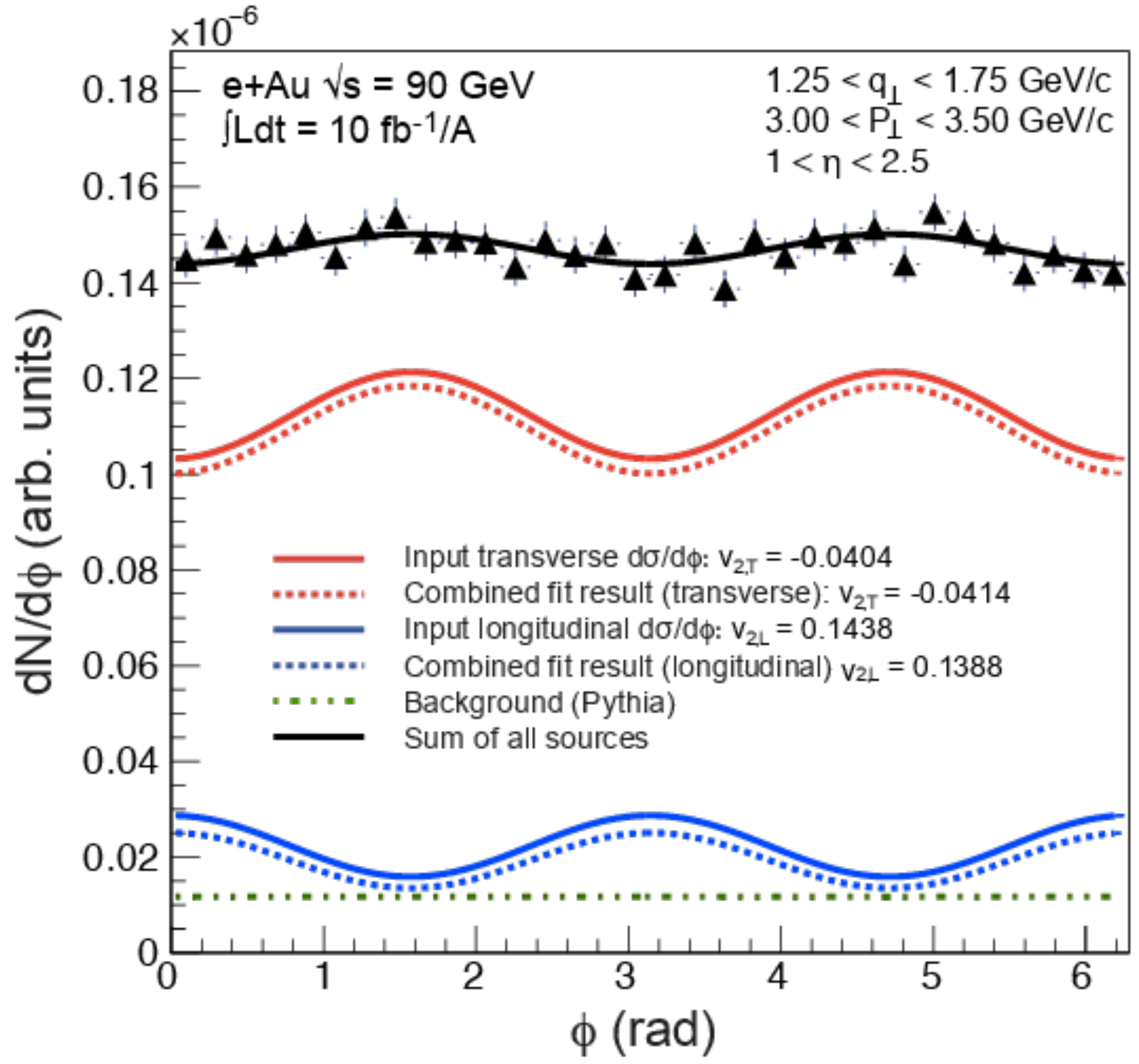
Zheng, Aschenauer, Lee, Xiao (2014)

Suppression of particle production for momentum imbalance $\lesssim Q_s$

Further suppression in eAu than ep due to larger sat scale

NLO calculation
Caucal, Salazar, Schenke, Stebel, Venugopalan (2024)
Caucal, Salazar (2025)

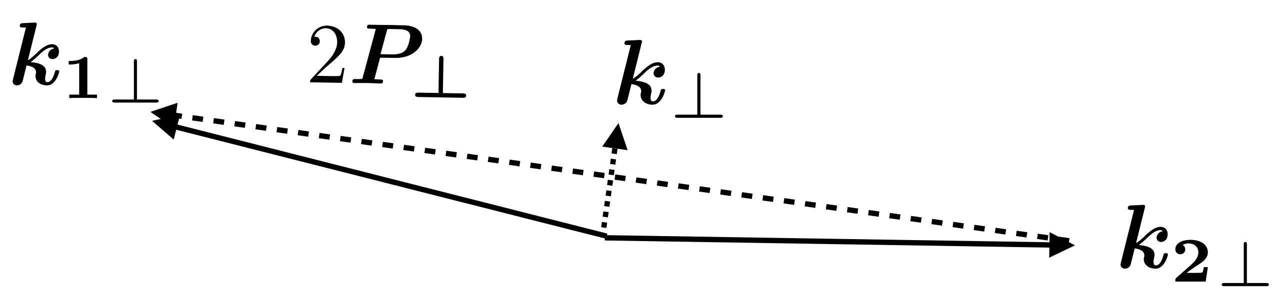
Dijet momentum imbalance
azimuthal correlations



Dumitru, Skokov, Ullrich (2018)

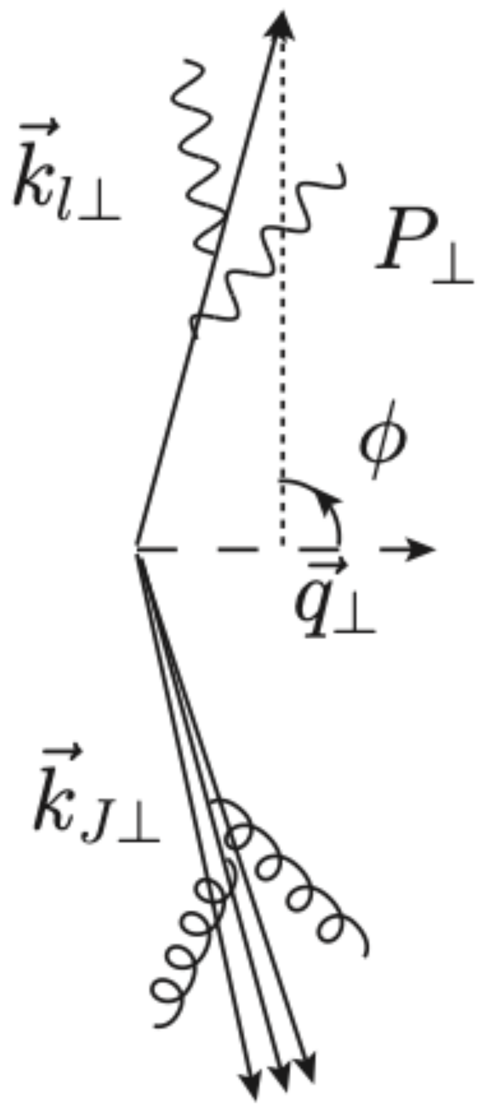
Sensitivity to linearly polarized gluons

ϕ angle between $\boldsymbol{P}_\perp$ and $\boldsymbol{k}_\perp$

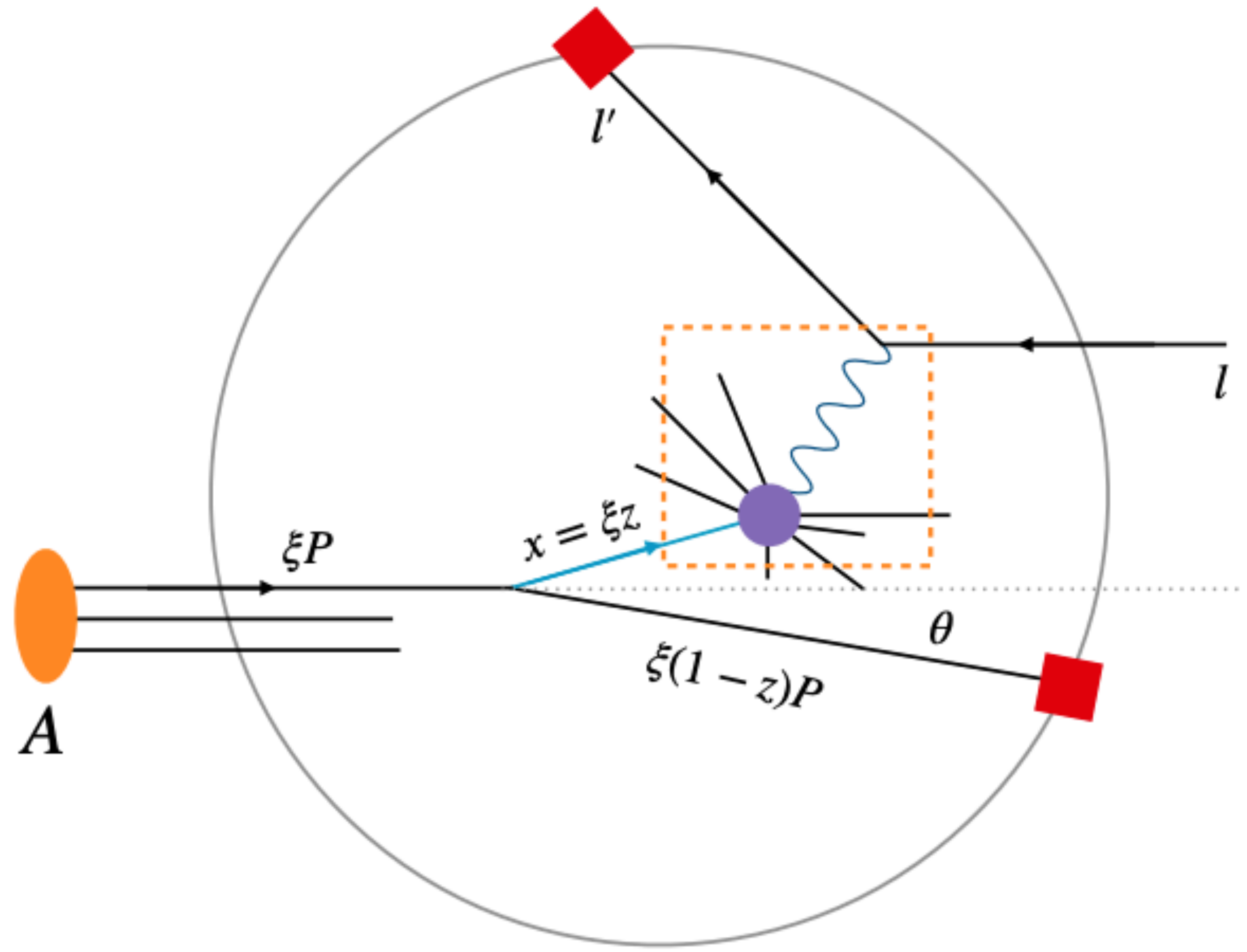


Can also be measured with direct J/ψ production in DIS
Cheung, Kang, Salazar, Vogt (2024)

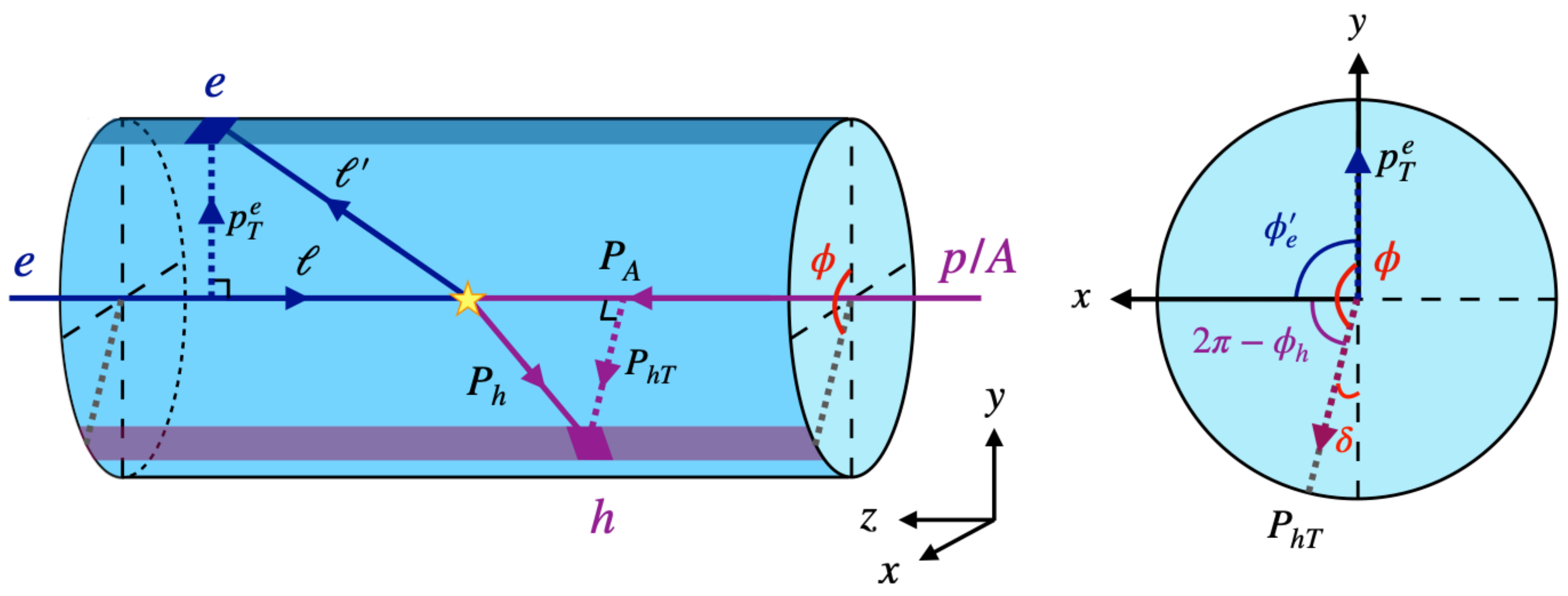
Other two-particle correlations: lepton-jet and nucleon-energy energy correlators



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



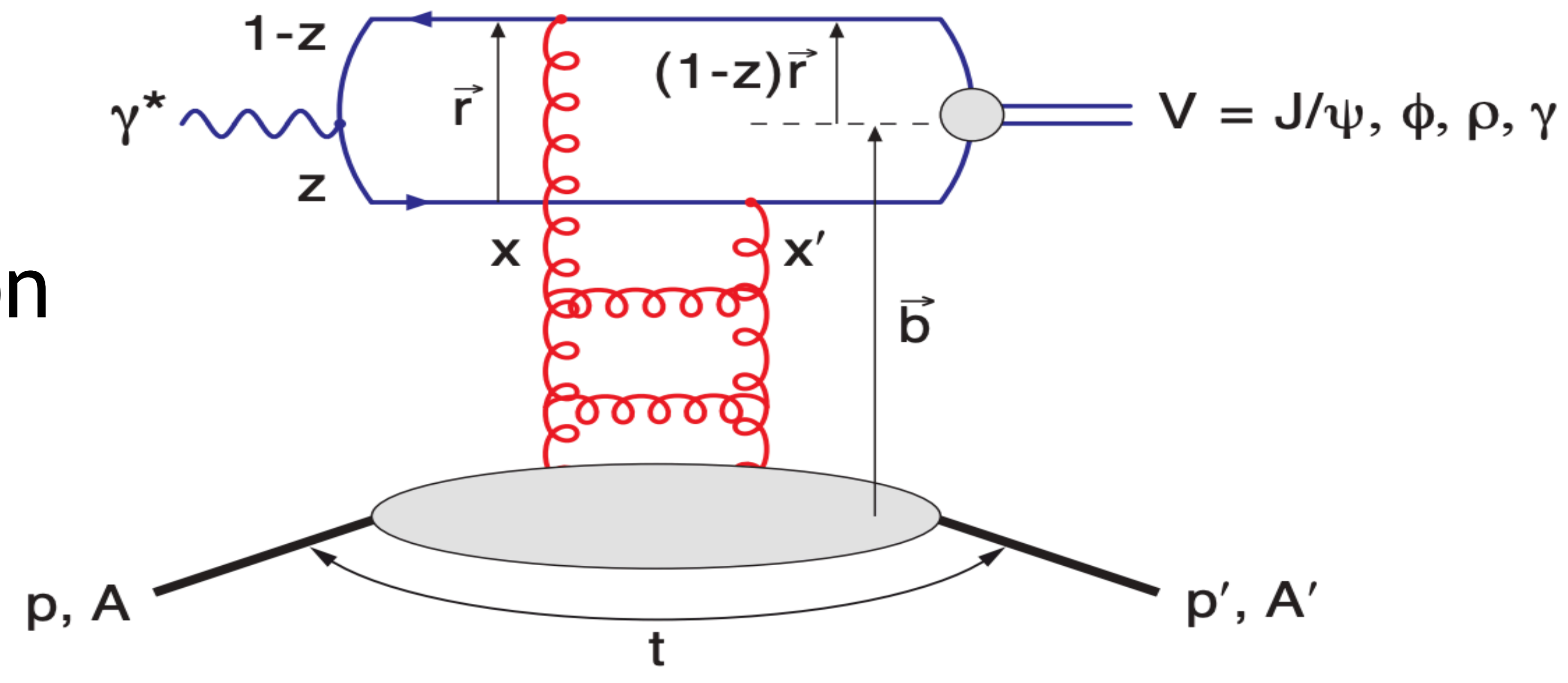
Nucleon energy correlator
Liu, Pan, Yuan, Zhu (2023)

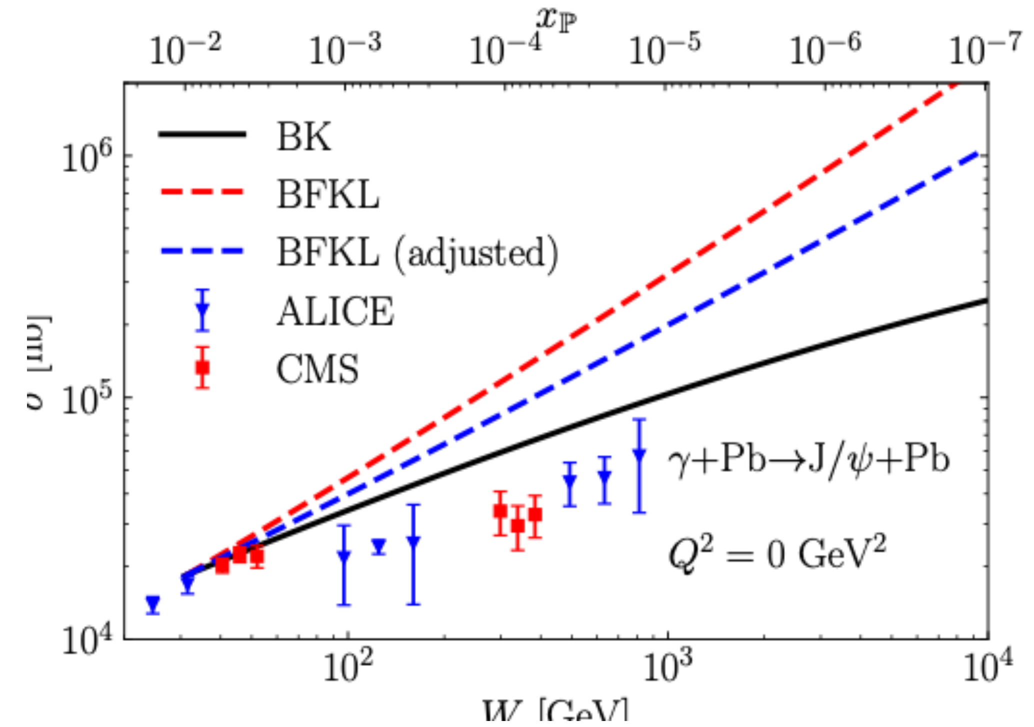


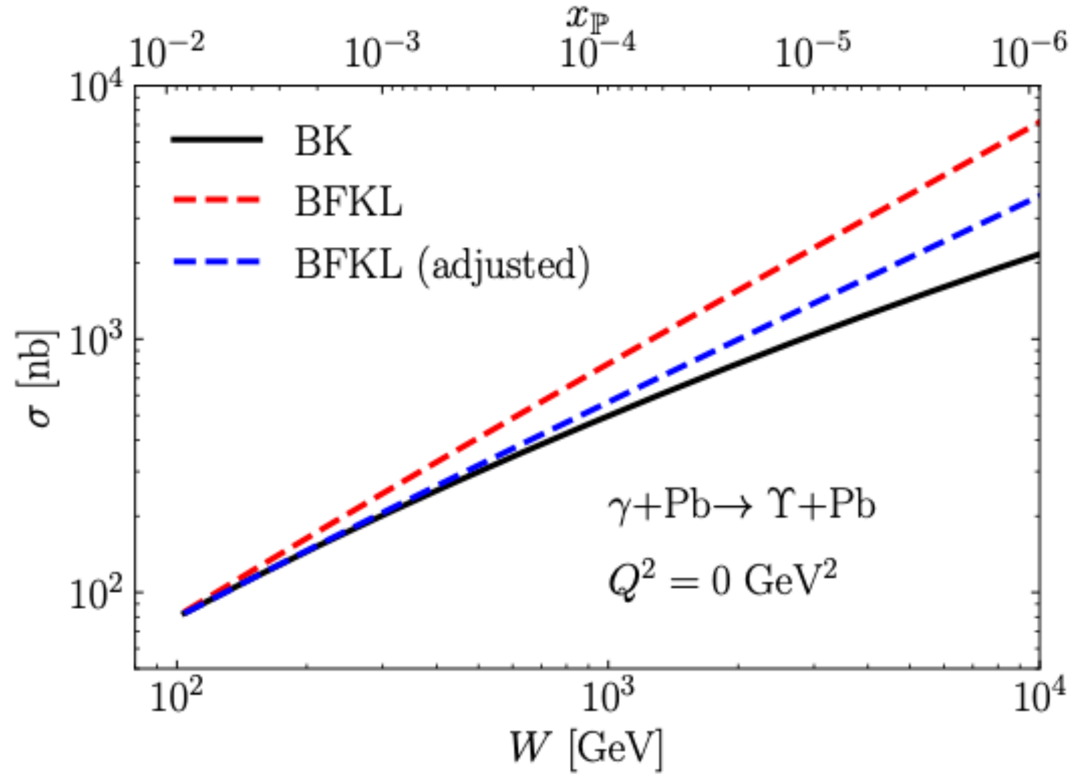
Transverse energy-energy correlators
Kang, Penttala, Zhao, Zhou (2024)

Exclusive vector meson production

- Diffractive process: rapidity gap = color neutral exchange
- Needs at least two-gluon exchange -> enhanced sensitivity to gluon
- Extensively studied at LHC and RHIC in UPCs $(\gamma p/\gamma A)$
- 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 $M_V^2 \lesssim Q_s^2(x)$







Royon, Penttala (2024)

Map Q² varying VM mass

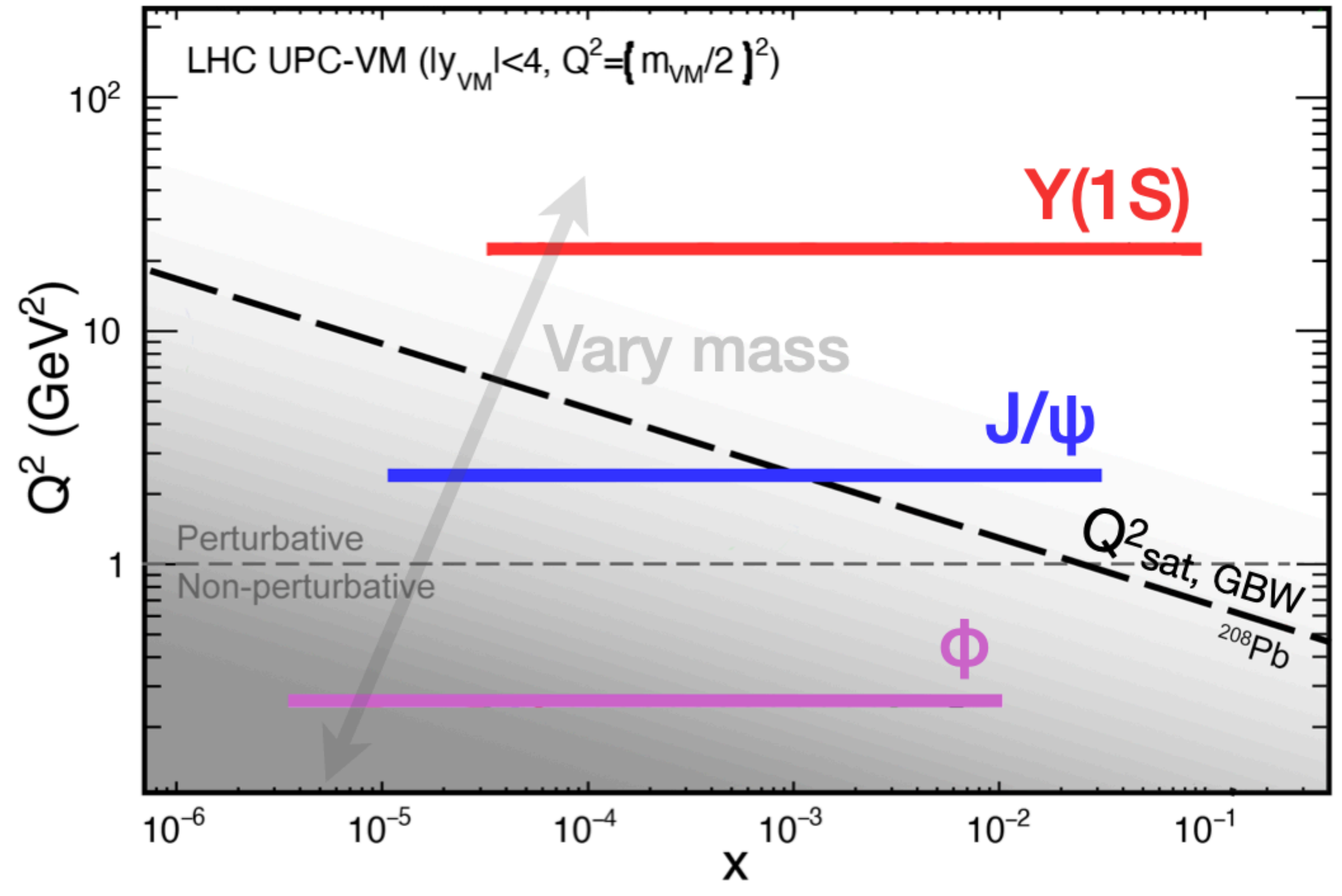


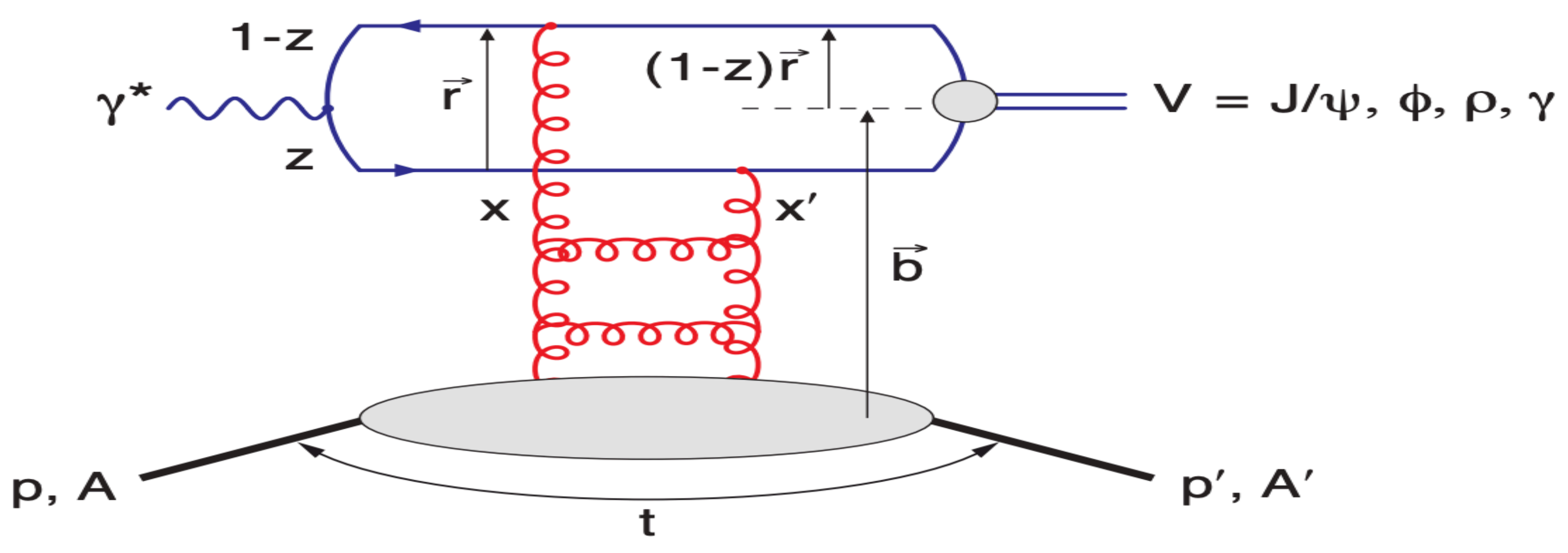
Figure from CMS

- At EIC one can also scan virtuality Q^2 to transition between dense and dilute regimes

See also Padrón Molina, Hentschinski (2020)
Alcazar Peredo, Hentschinski (2023)

More on UPCs by Michael Murray

Exclusive vector meson production t-spectra

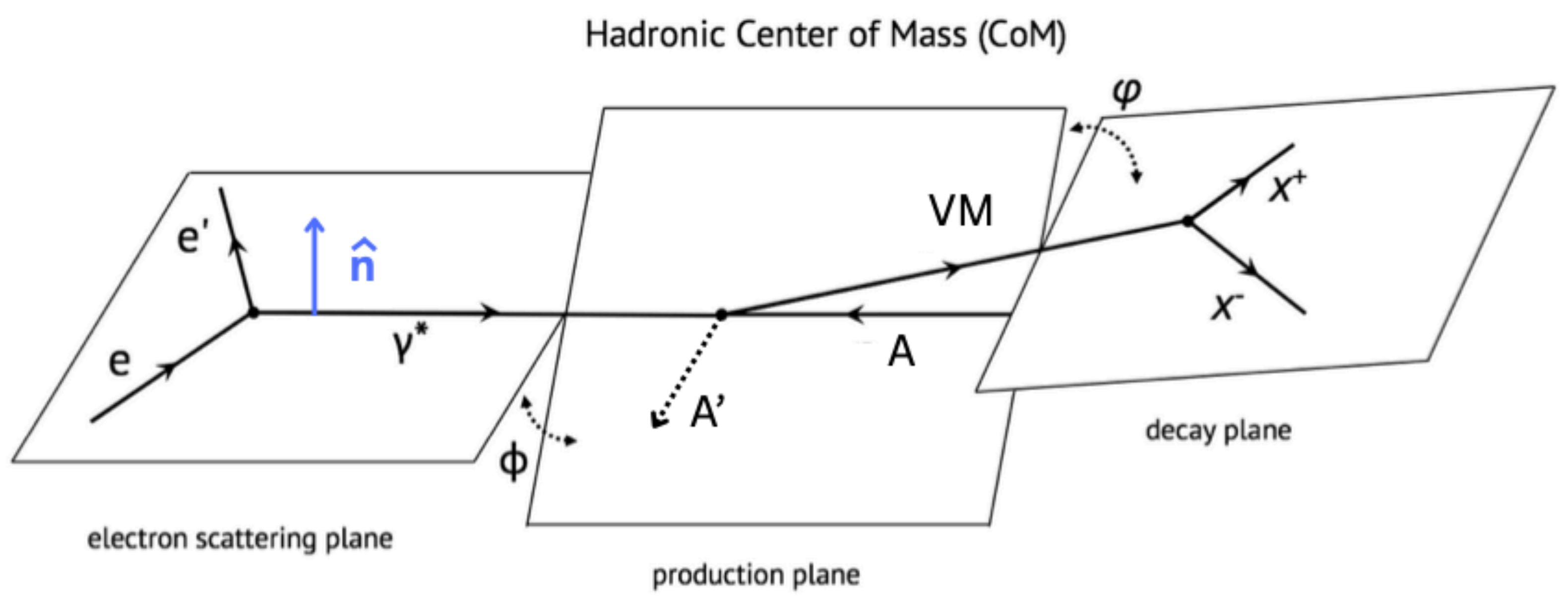


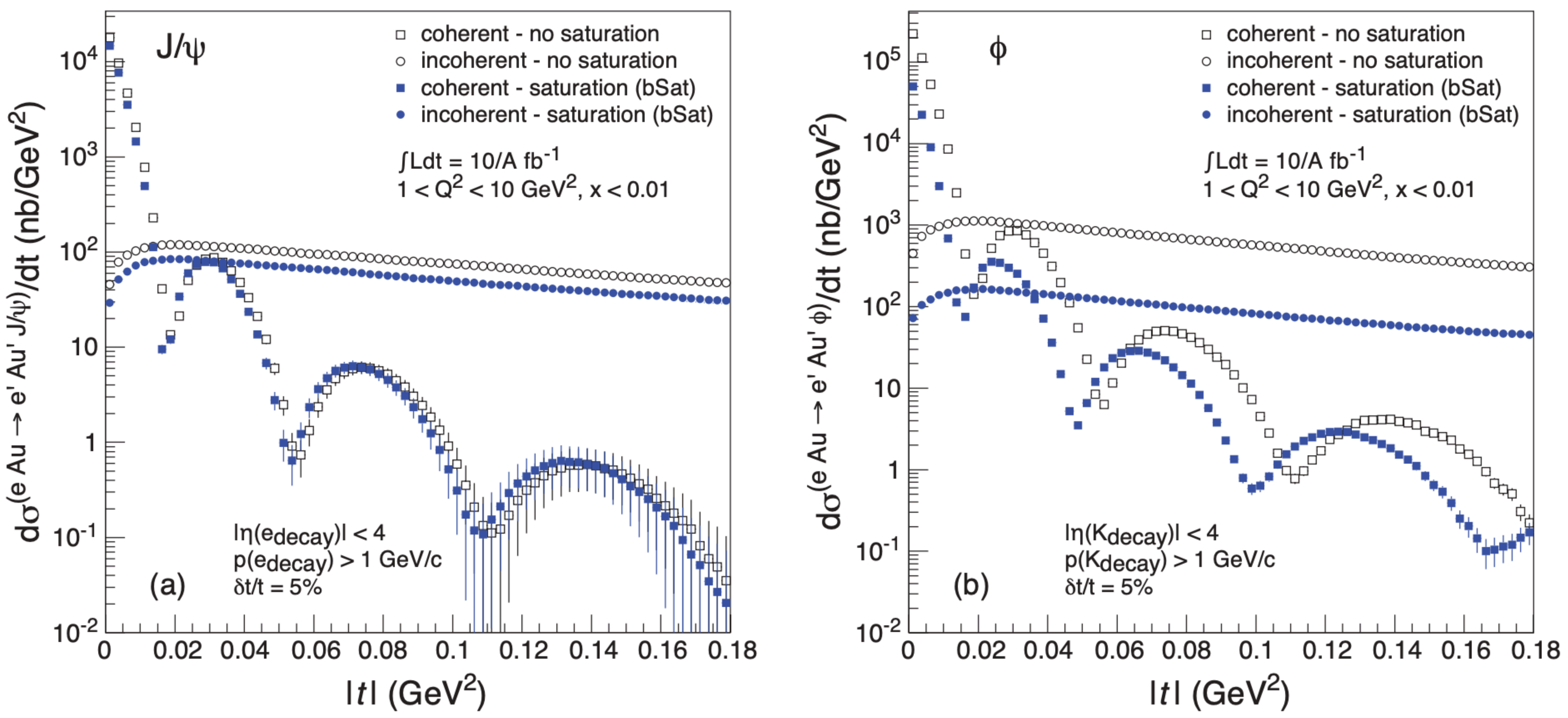
Sensitive to spatial distribution (tomography)

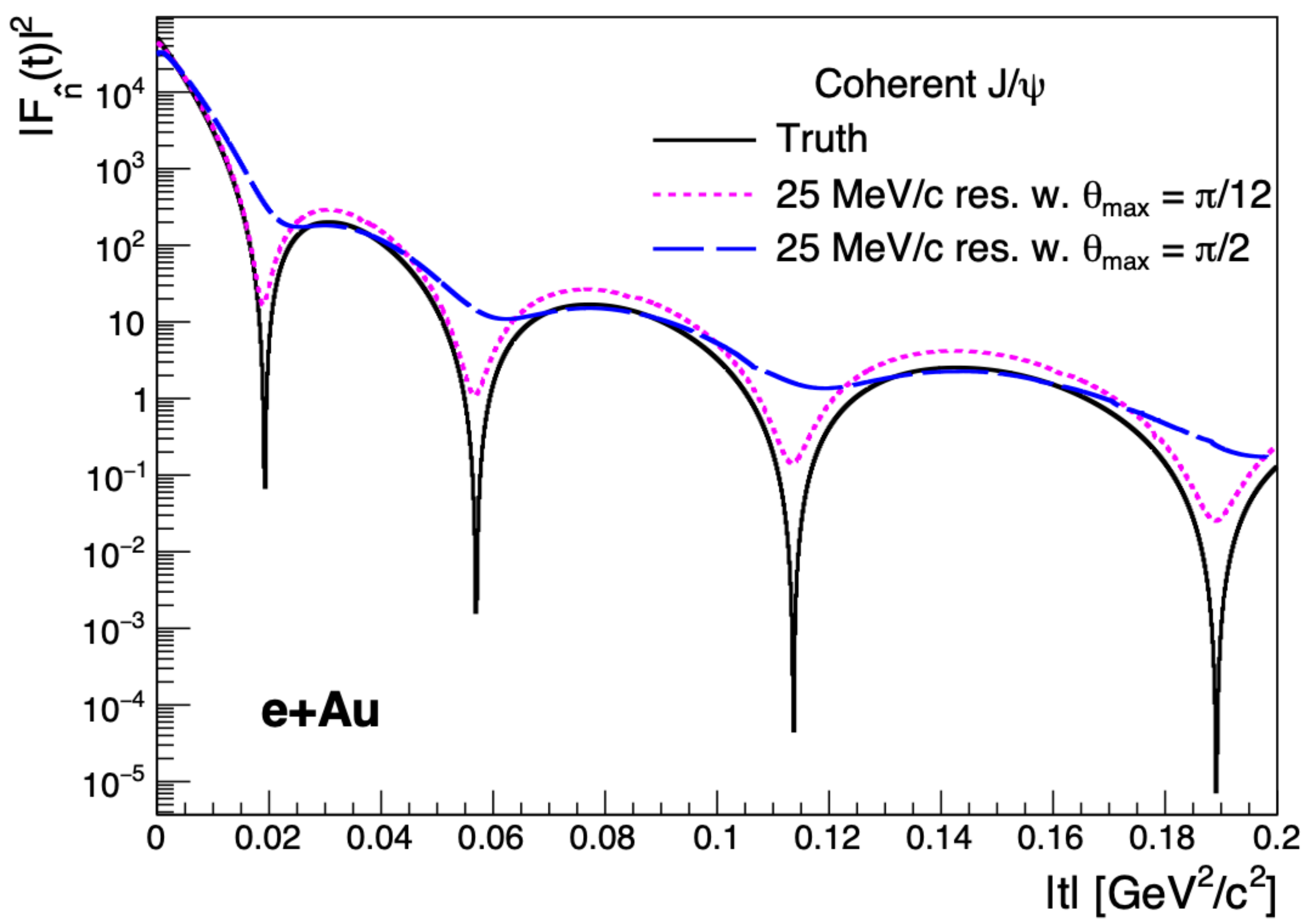
$$t = -\boldsymbol{\Delta}_\perp^2$$
$$\boldsymbol{\Delta}_\perp \leftrightarrow \boldsymbol{b}_\perp$$

- Disentangle coherent from incoherent with polarized electron

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







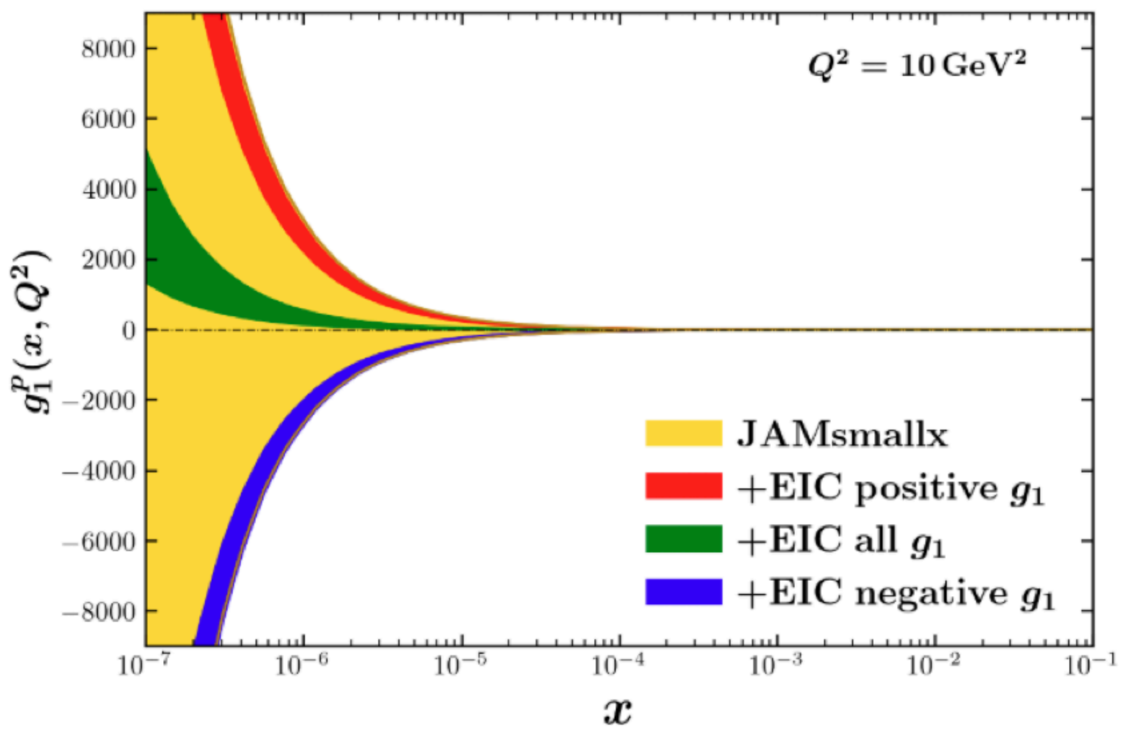
- Sartre event generator (bSat & bNonSat = linearized bSat)
- Saturation has an imprint on the spectrum. Large difference for φ less so for J/ψ

T. Toll, T. Ullrich (2012)

Other interesting avenues

- Spin and small-x physics

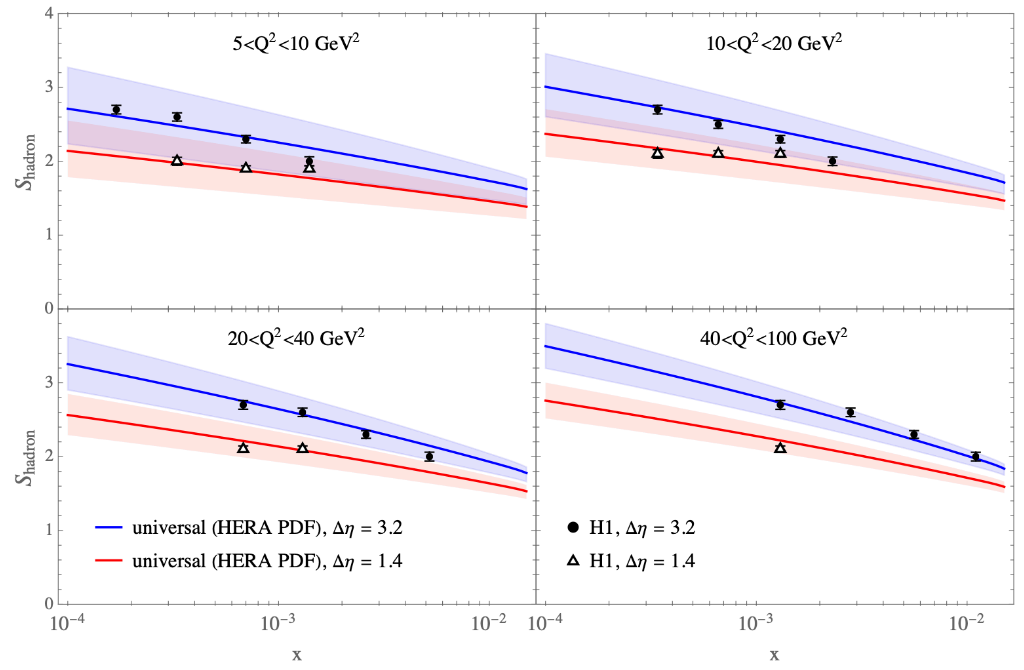
  Kovchegov, Sievert, Pitonyak, …(2012-present)



2503.21006

- Entanglement at small-x

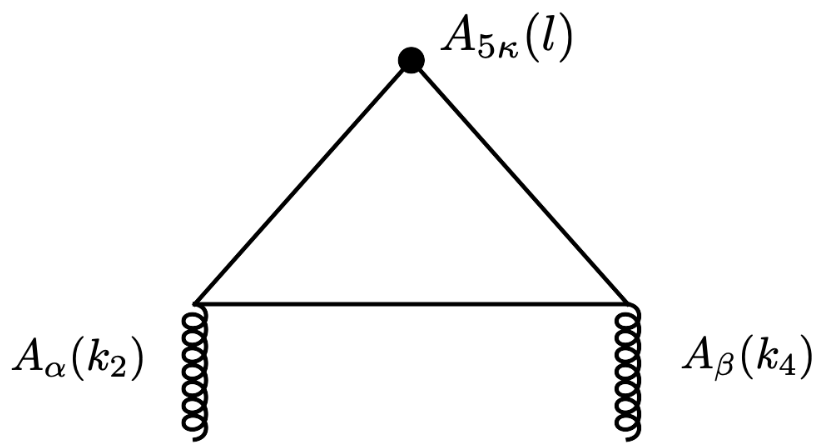
  Kharzeev, Levin, Kutak, Hentschinski, Tu (2012-present)



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…

Latin American contributions to QCD theory at small-x

- Brazil:
  -**Maria Beatriz Gay Ducati (Rio Grande do Sul U.)**
  -heavy flavor, shadowing, high-density QCD, linear and non-linear evolution equations
  -**Victor Gonçalves (Pelotas U.), Magno Machado (Rio Grande do Sul U.)**
  numerous efforts on saturation phenomenology: vector meson production, diffraction, structure functions
- Chile:
  -**Benjamín Guiot (Santa Maria U.)**
  high-energy kT factorization for heavy-flavor
  -**Eugene Levin (Santa Maria U.)**
  pioneering studies of entropy at small-x, unitarity, Pomeron loops

  -**Ivan Schmidt and Boris Kopeliovich (Santa Maria U.)**
  color dipole approach to DIS, diffraction, heavy flavor production
- Mexico:
  -**Irais Bautista (BUAP)**
  phenomenology of heavy-ions, vector meson production
  -**Martin Hentschinski (U. Americas Puebla)** + students/collaborators:
  entanglement, vector meson production, higher-order computations, CGC-Lipatov effective action, BFKL
  also with **A. Ayala (UNAM) and M.E. Tejeda-Yeomans (Colima U.)**:
  helicity methods in the CGC

- Work by students at this conference:

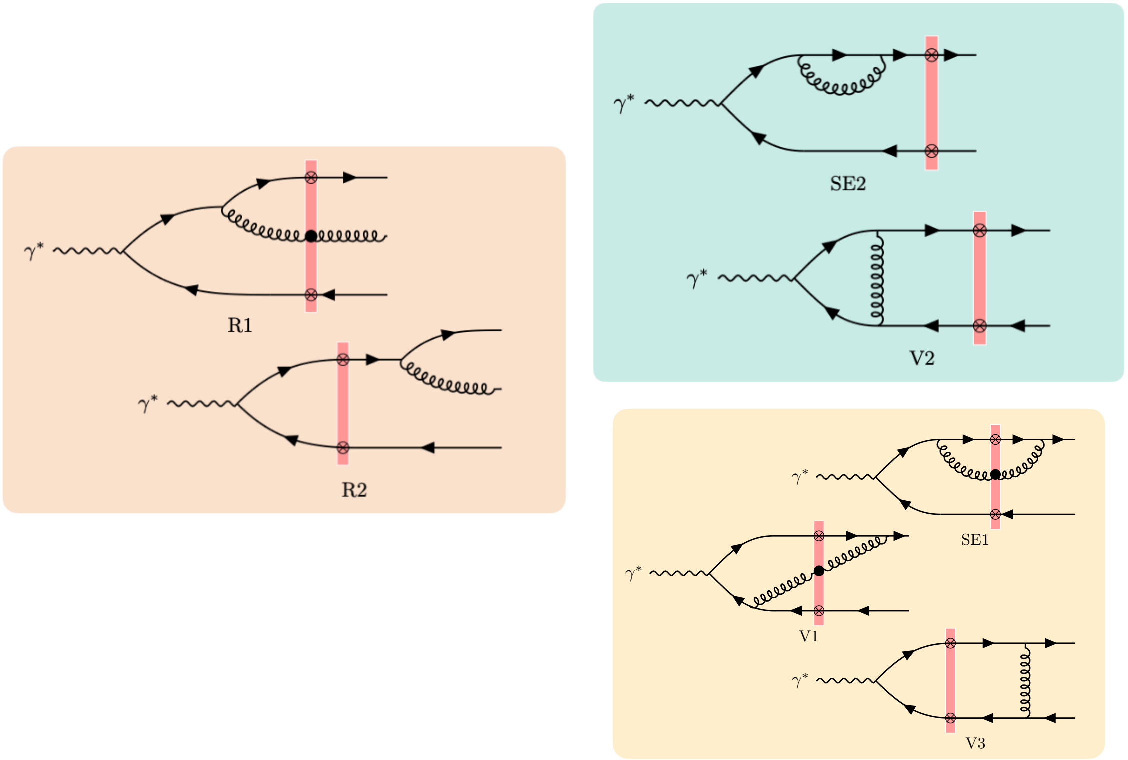
  Ricardo Rangel Ramirez (UAP): vector meson production in UPC and BFKL (linear regime)

  Sergio Delgadillo Fuentes (UAP): dijet production with large rapidity gaps and BFKL (linear regime)

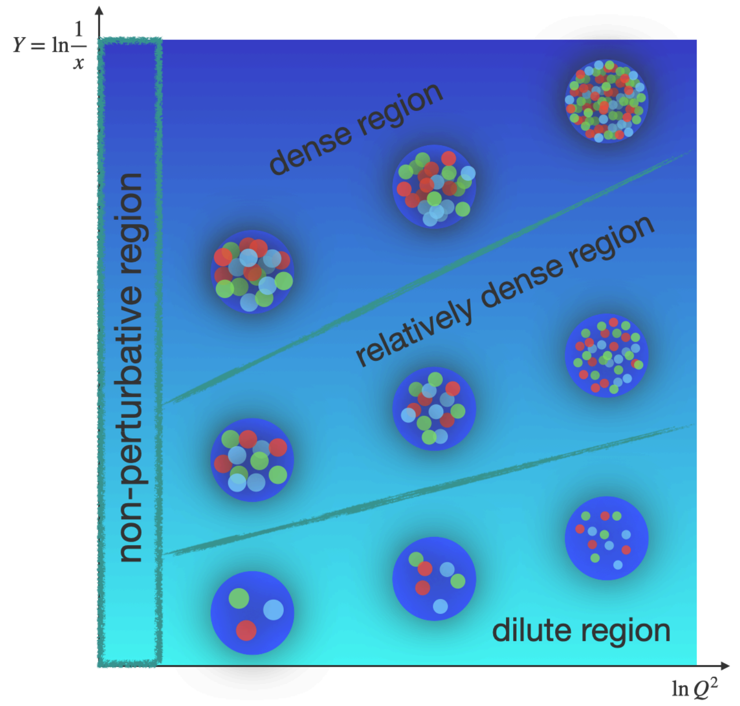
- Abroad:
  -**Guillermo Contreras Nuno (Prague Tech U., Czech Republic)**
  phenomenology vector meson production, impact parameter dependent small-x evolution
  -**Farid Salazar (Temple U., USA)**
  higher order computations, factorization, resummation, phenomenology of two-particle correlations and vector meson production. Recent project: role of sea-quarks in the CGC with PhD student **Marcos Guerrero Morales**.
  -**Pia Zurita (U. Complutense de Madrid, Spain)**
  phenomenological studies of saturation at HERA and EIC

Outstanding theoretical challenges

- Higher-order calculations for precision



- Unification of dilute and dense QCD (beyond CGC)



- Event generators and global analysis

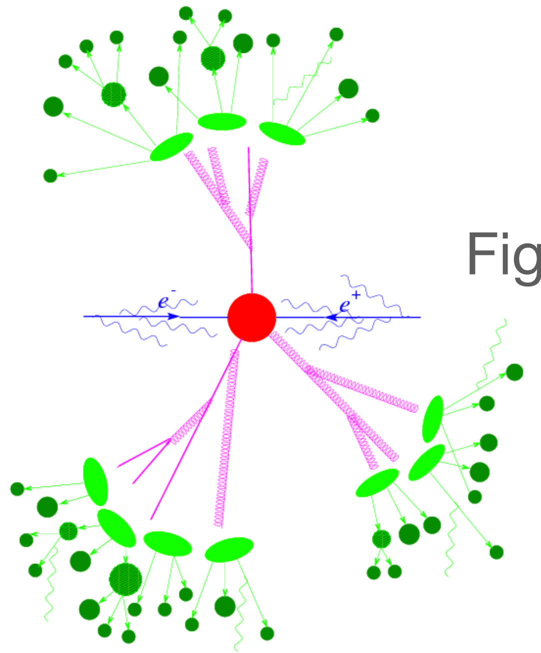


Figure from ATLAS collaboration

- Spin Physics and saturation

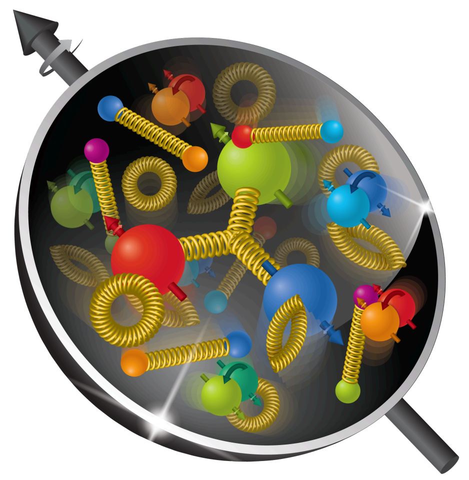


Figure from BNL newsroom

- Identification of novel observables

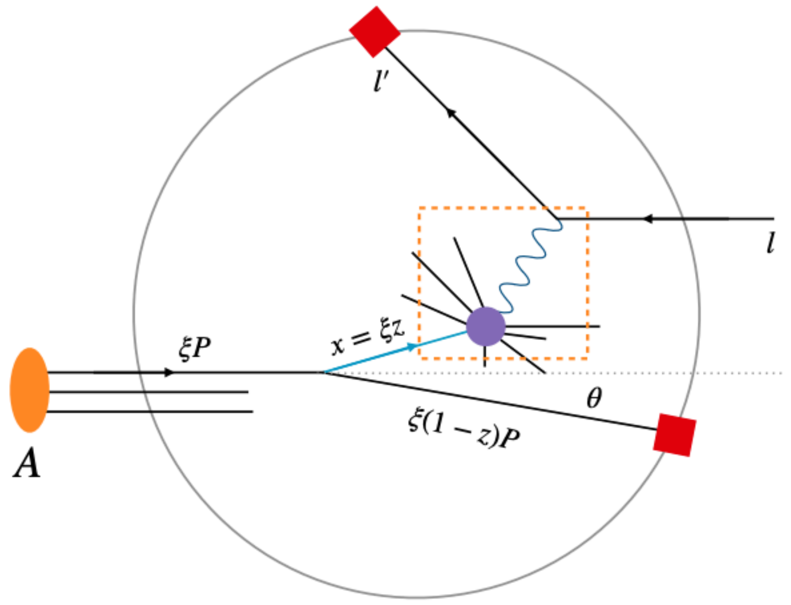


Figure from Liu, Liu, Pan, Yuan, Zhu (PRL 2023)

- Modeling of initial conditions

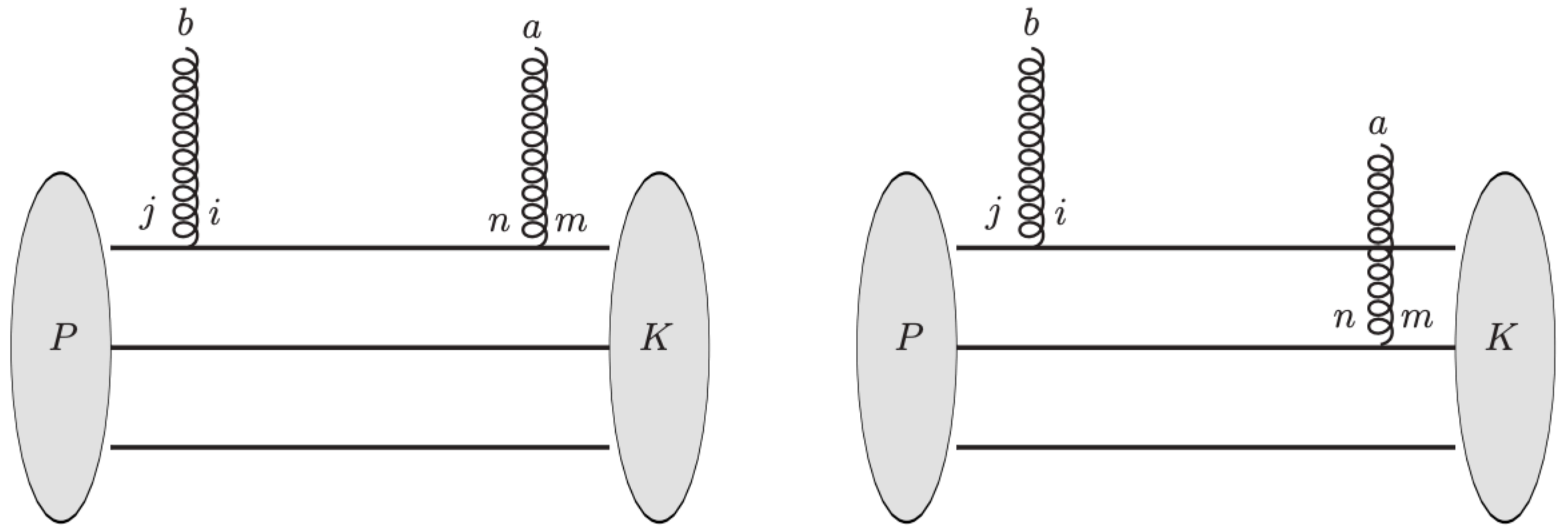


Figure from Dumitru, Miller, Venugopalan (PRD 2018)

Interdisciplinary connections

- High-energy theory:

Scattering amplitudes in the Regge limit in N=4 SYM/ integrability

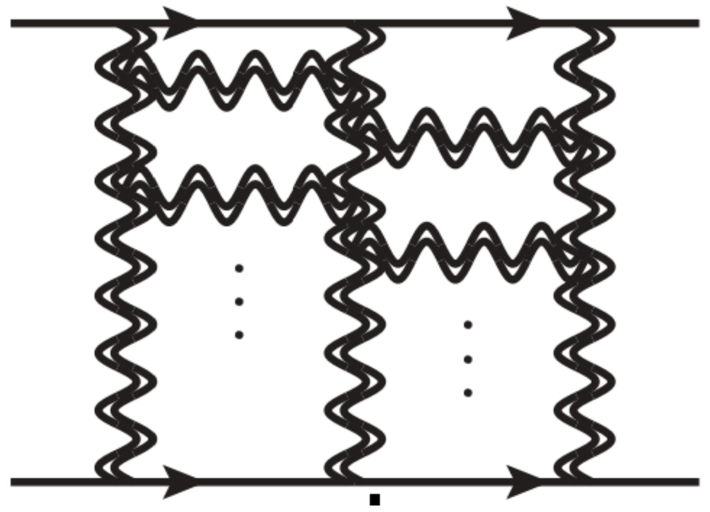


Figure from Simon Caron-Huot

- Condensed matter:

Correspondence between CGC and spin glass system

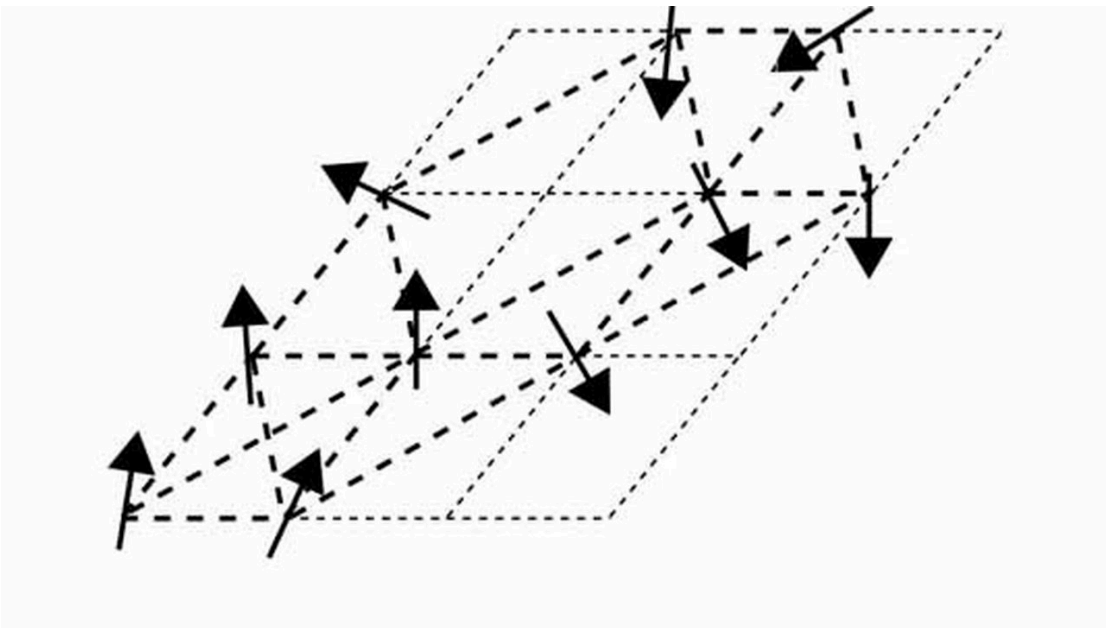
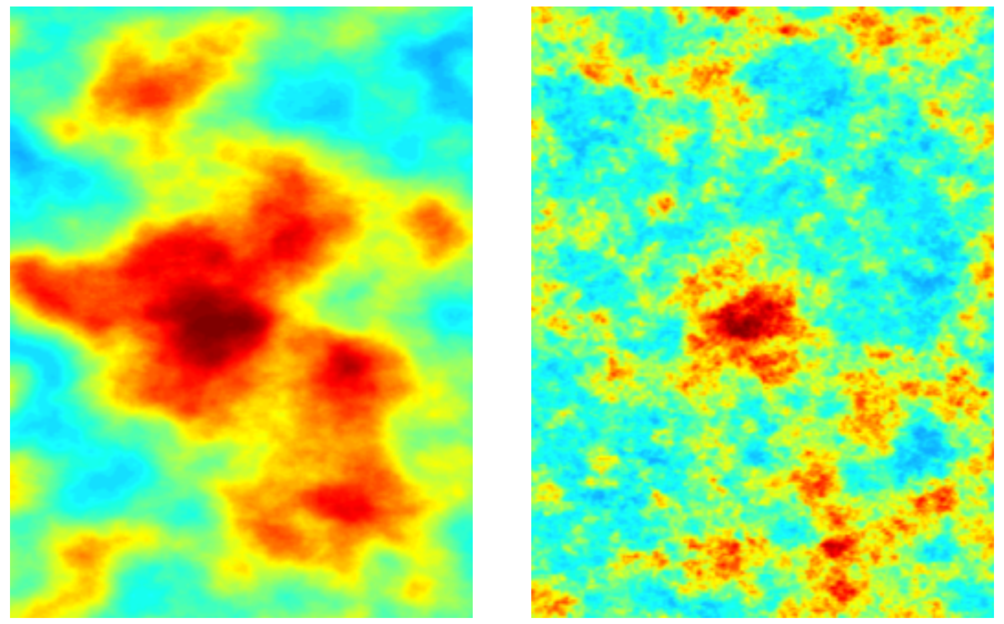


Figure from Santa Fe institute

- Statistical mechanics:

RGE evolution can be mapped to Langevin equation



- High-energy pheno:

High-energy neutrinos in cosmic rays

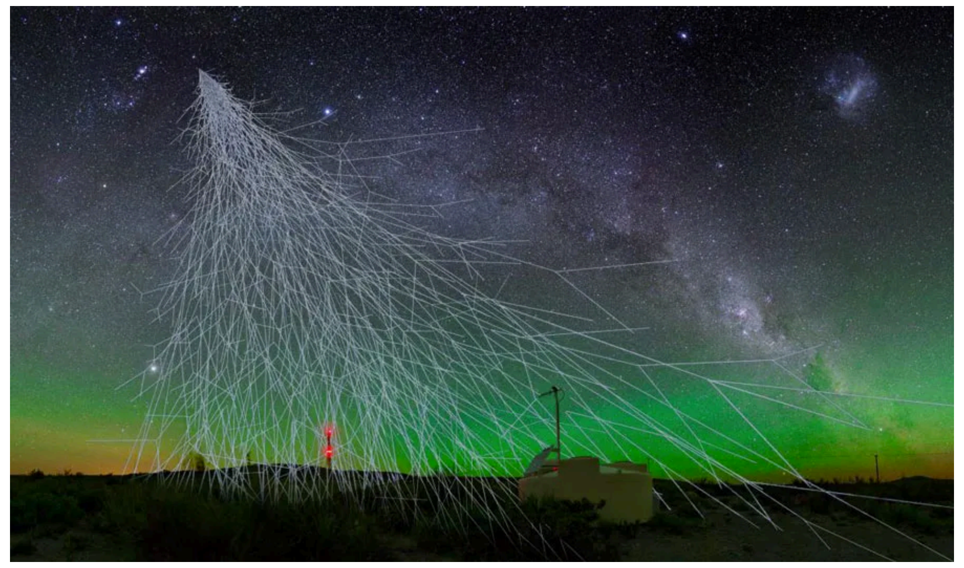


Figure from Astronomy Magazine

- Cosmology:

Gravitons also saturate, possible implications in the physics of black holes

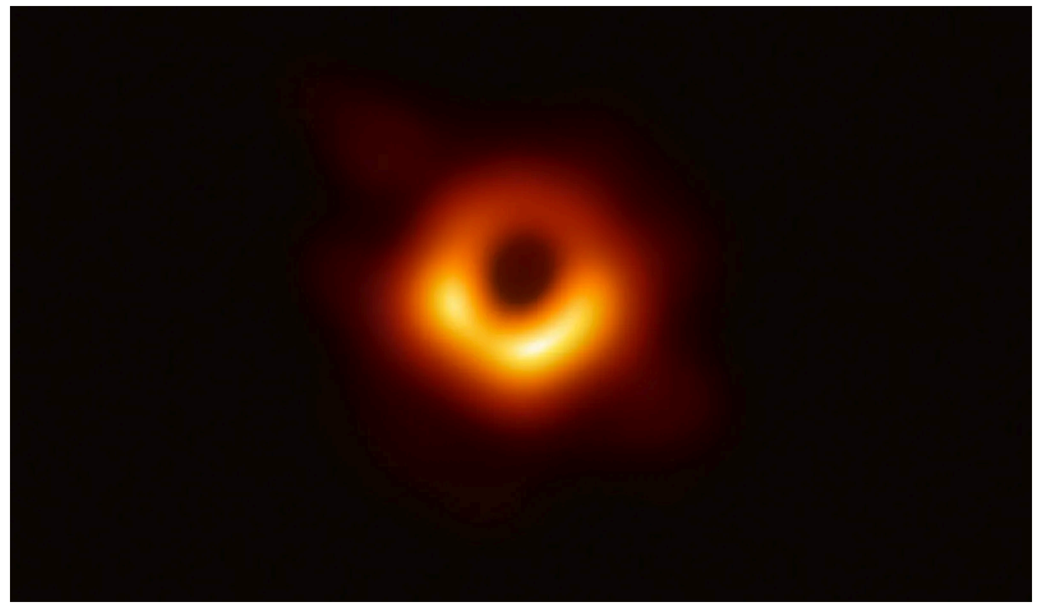


Figure from ETH collaboration

Summary

- Search for gluon saturation is one of major goals of the EIC
- The Color Glass Condensate is one framework that provides a potential unifying description of different observables across different colliding systems
- Saturation leaves imprint in inclusive, semi-inclusive and exclusive processes
- Several outstanding challenges and interdisciplinary connections to be explored
- Continuous efforts from Latin American community

Questions/comments:

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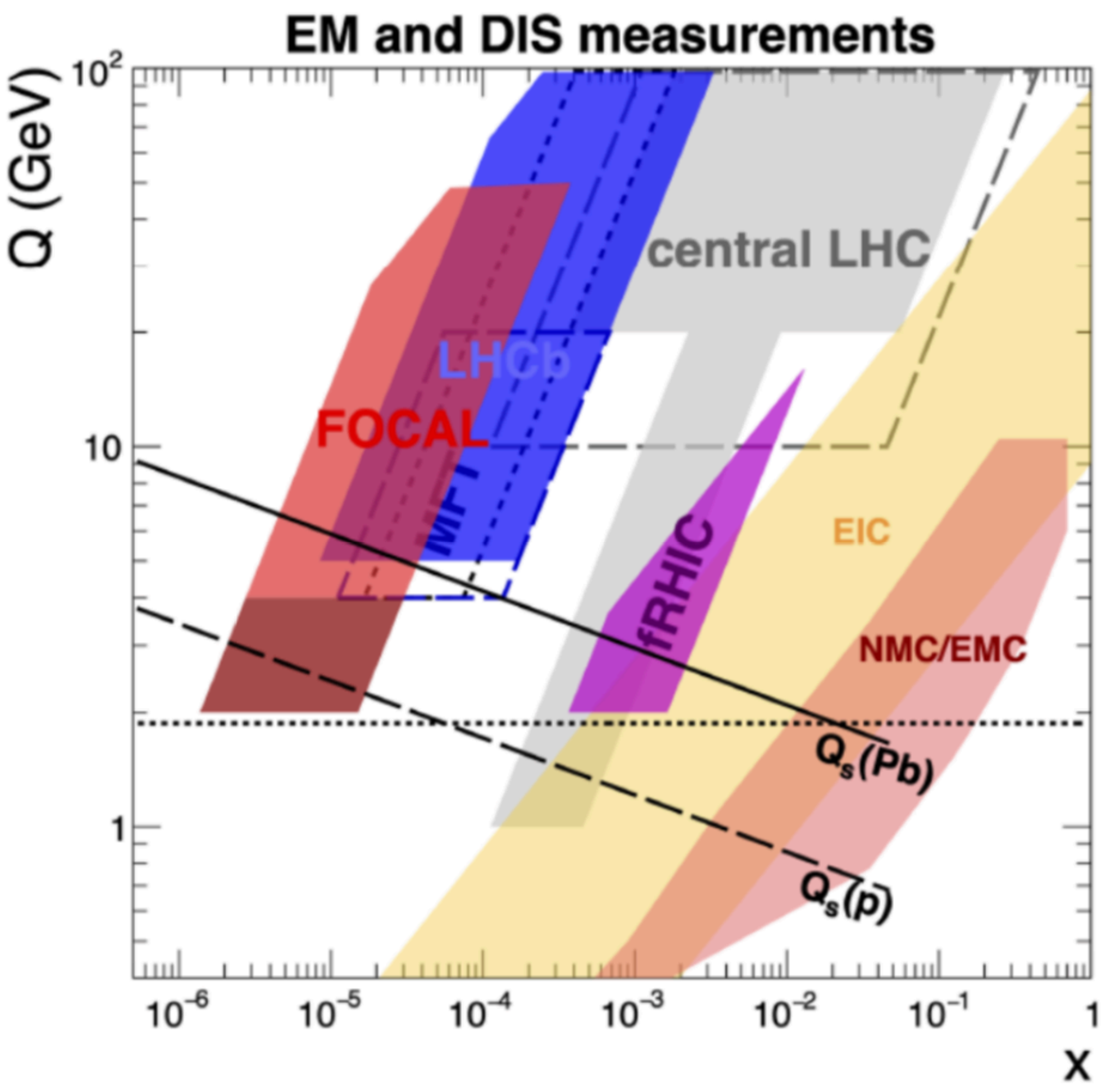
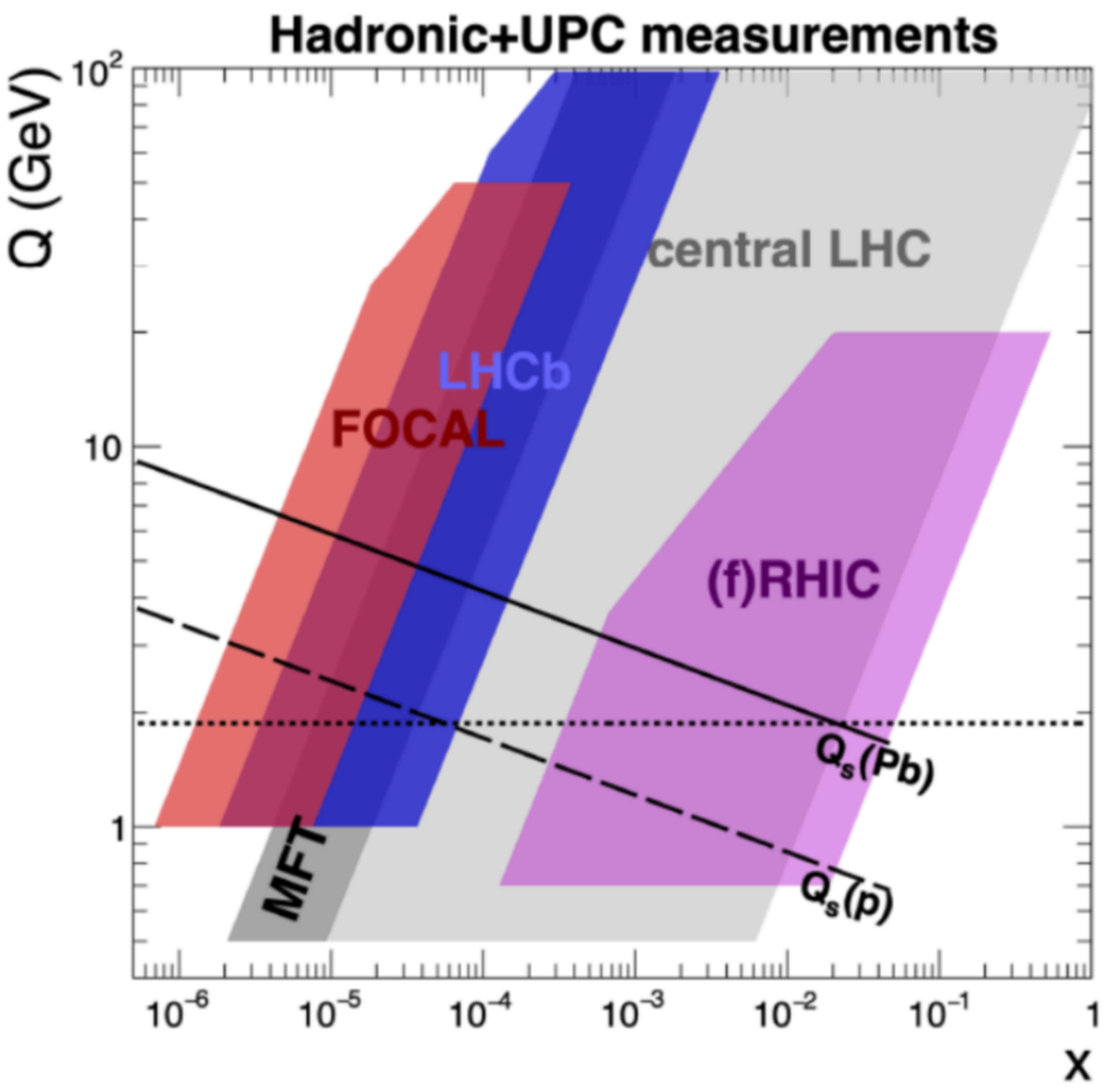
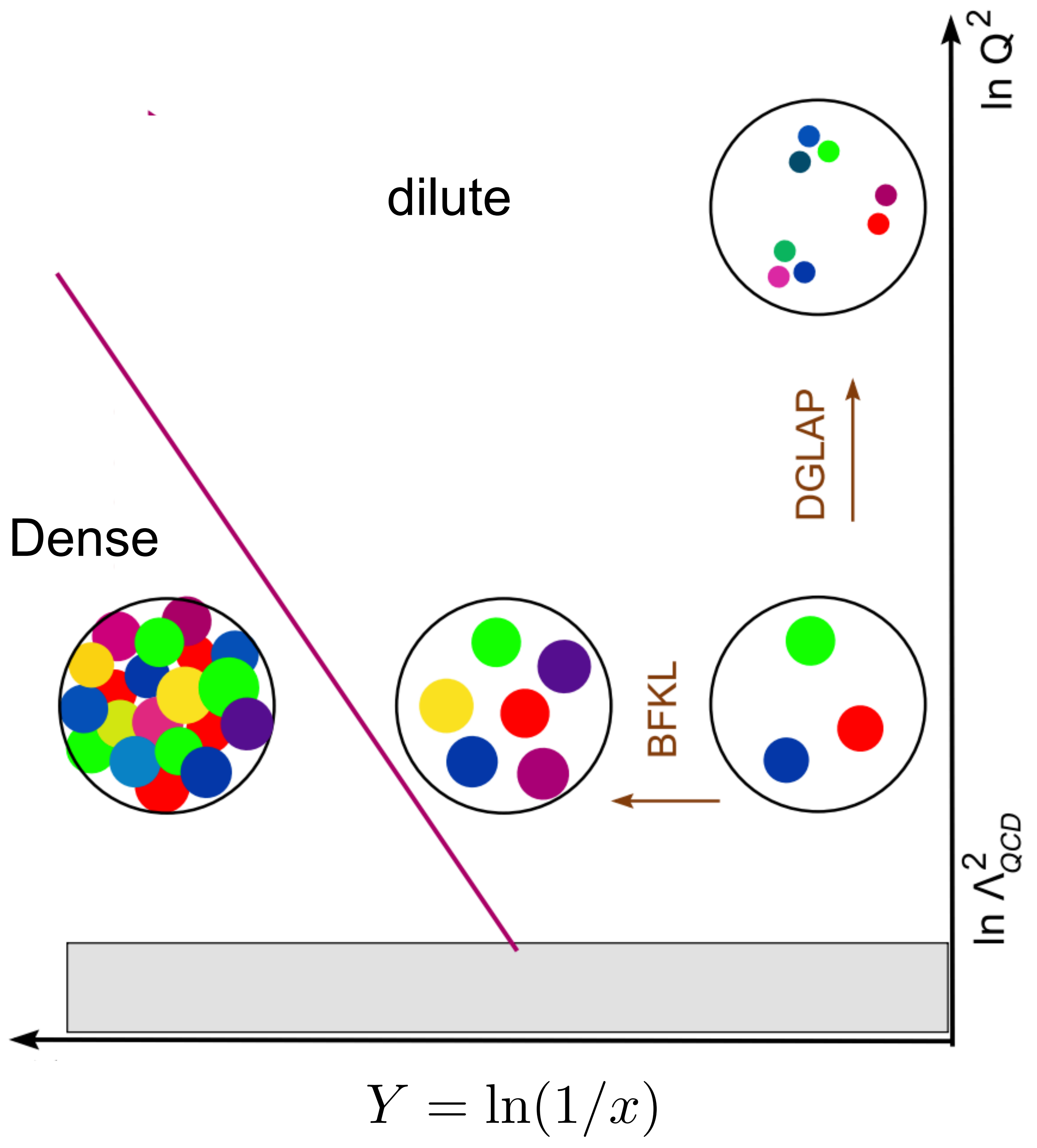
fsalazarw@bnl.gov

Back-up slides

Experimental prospects: LHC and EIC







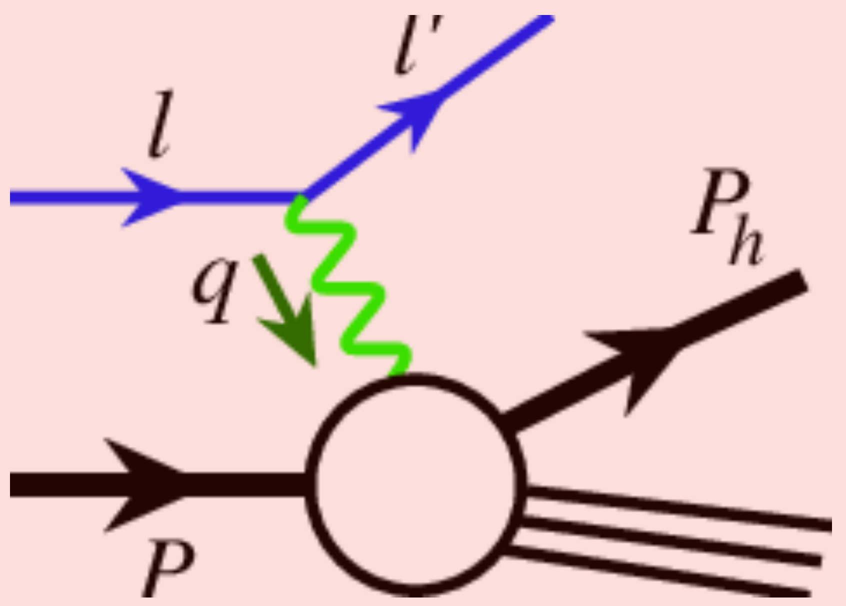
Complementarity between LHC and EIC

Hadronic and nuclear matter

Tomography of nuclear matter

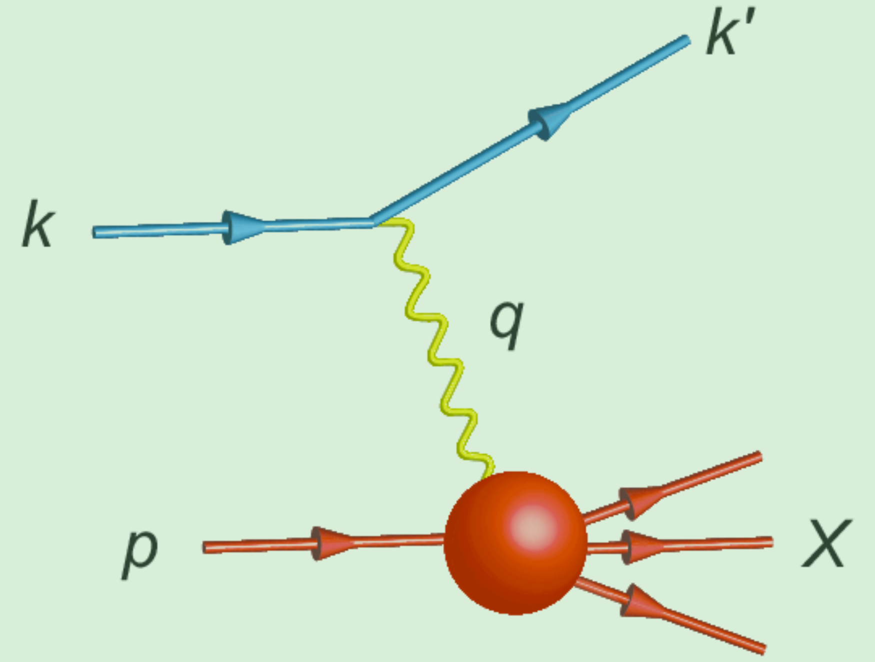
Semi-inclusive production

e.g. $e + p \rightarrow h + X$



Inclusive cross-section

e.g. $e + p \rightarrow X$



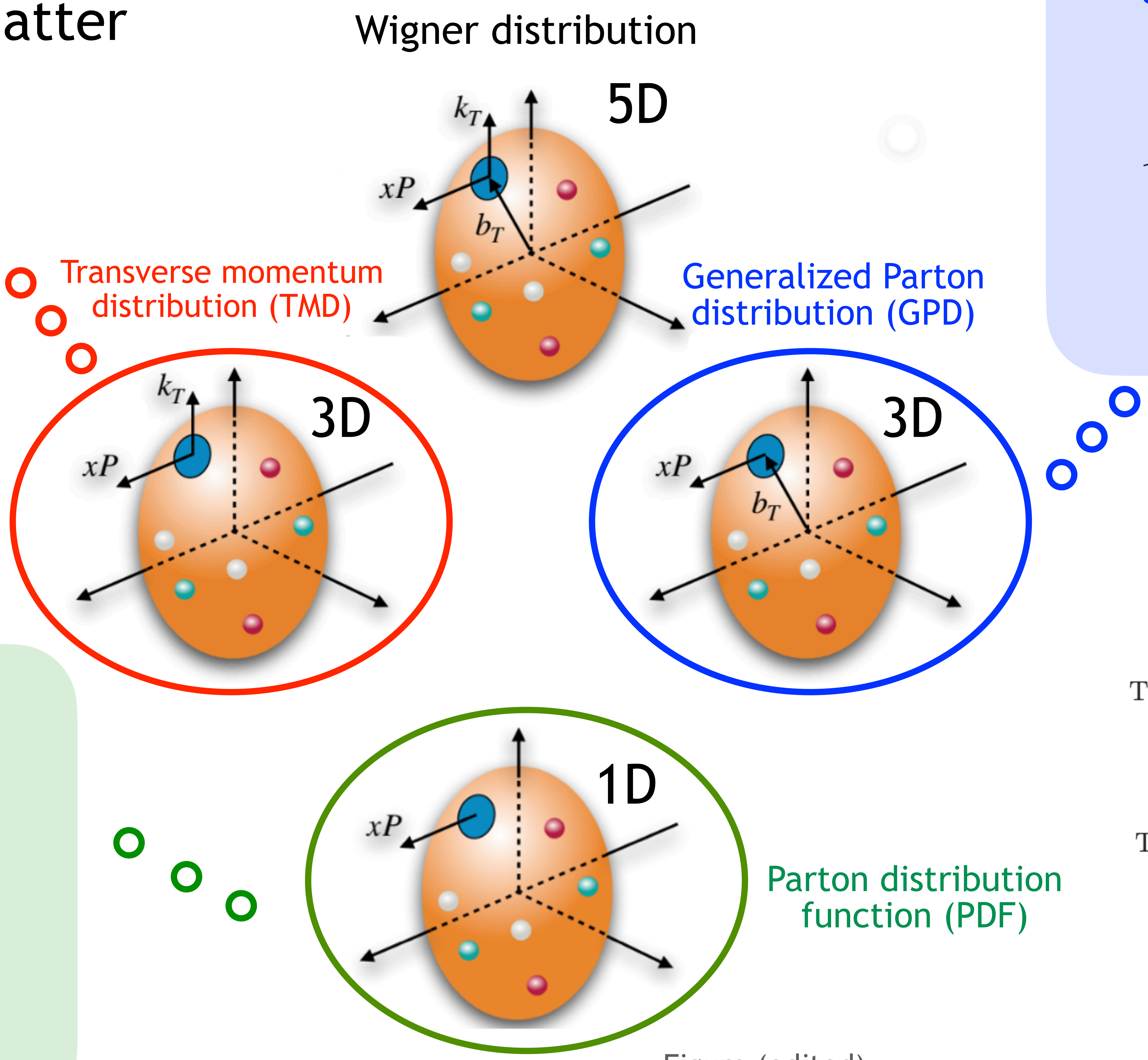
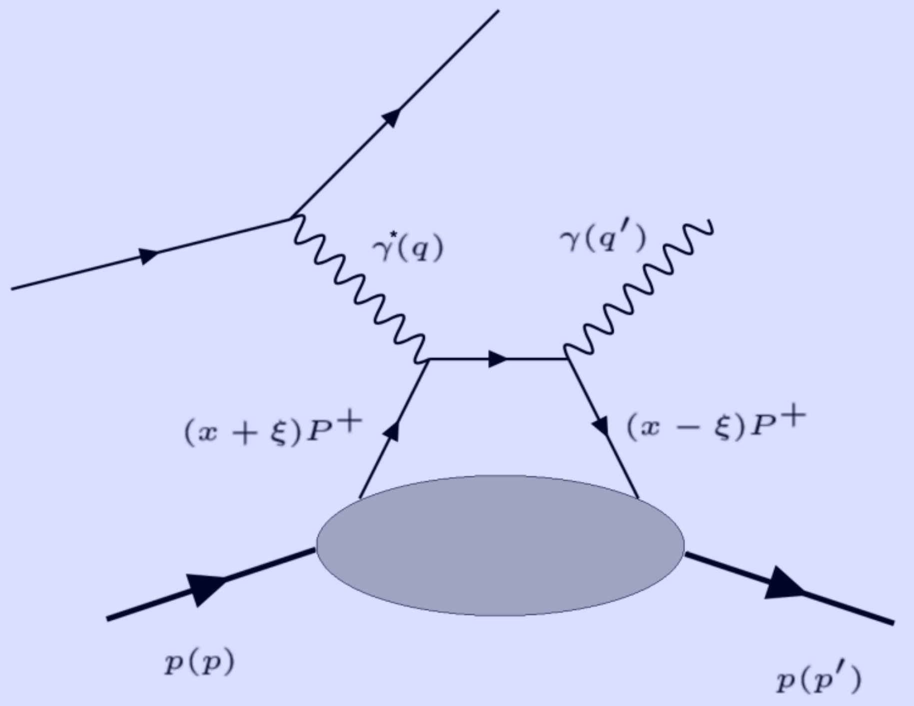


Figure (edited) from A. Prokudin

Exclusive production

e.g. $e + p \rightarrow \gamma + p' + e'$



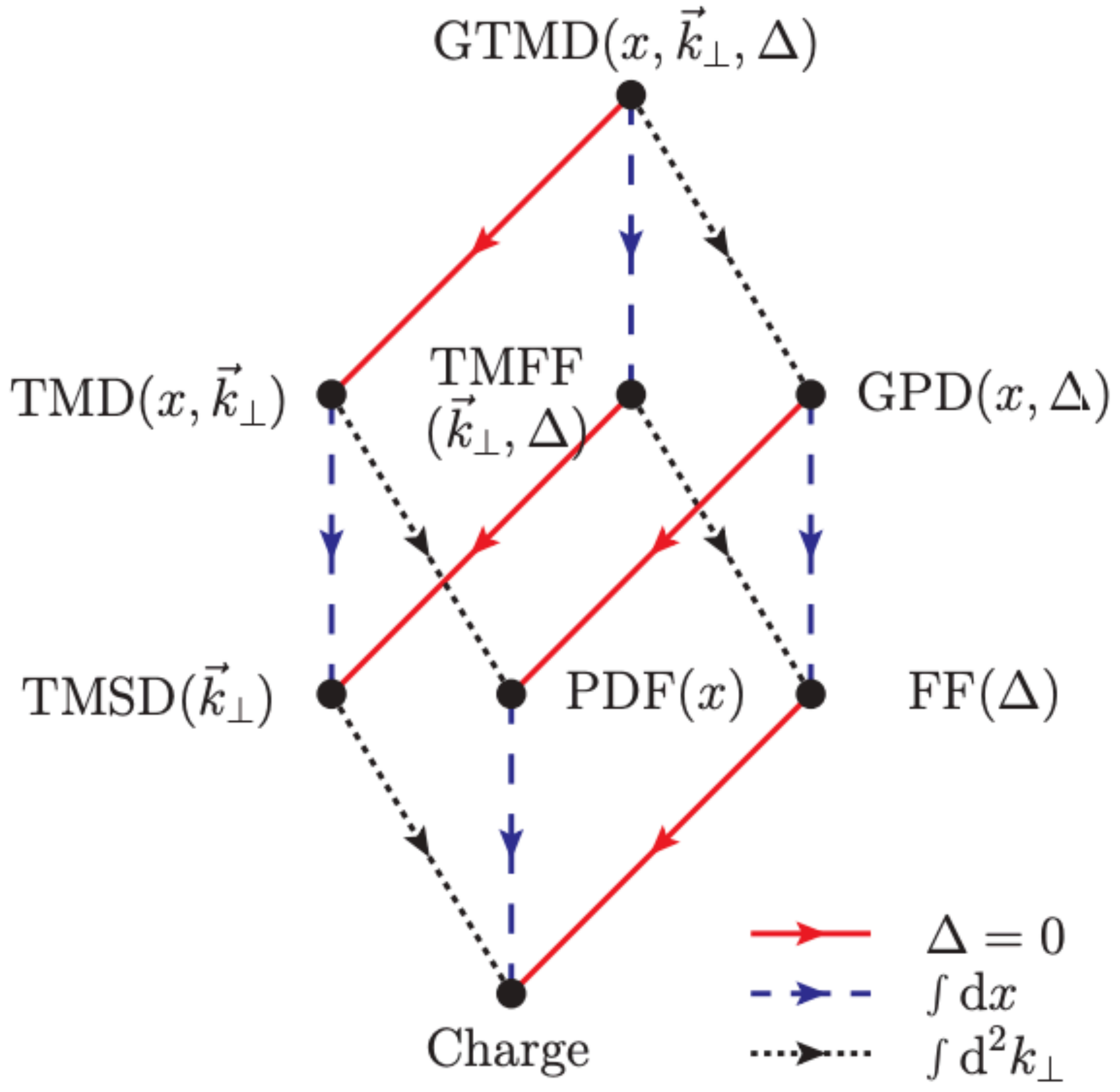
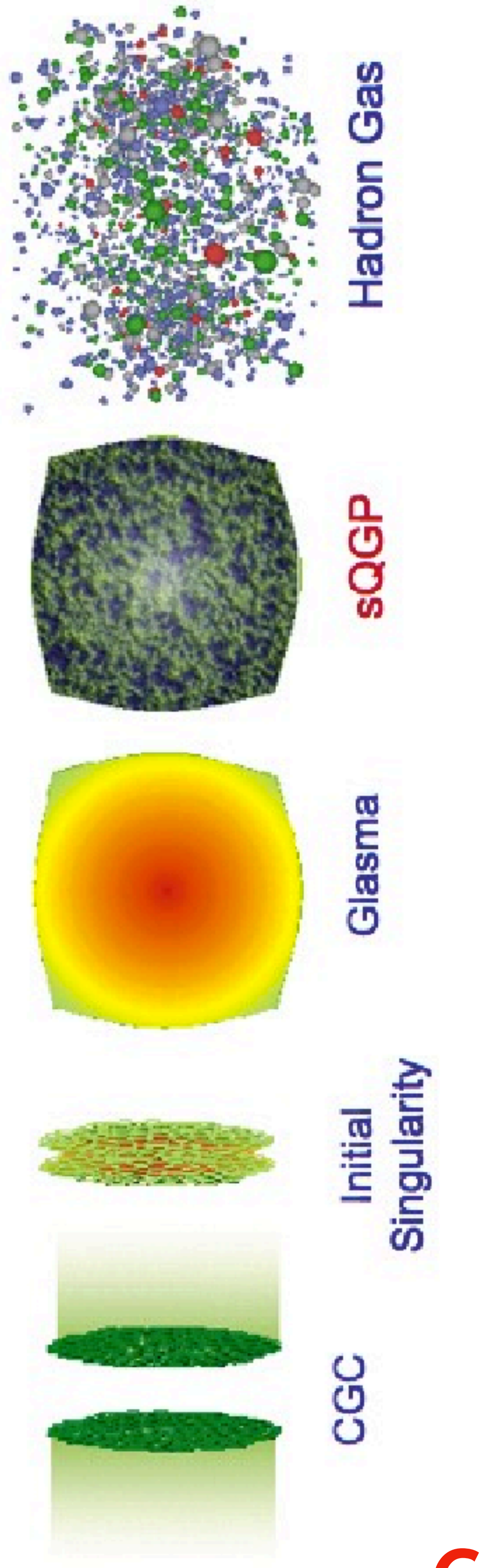
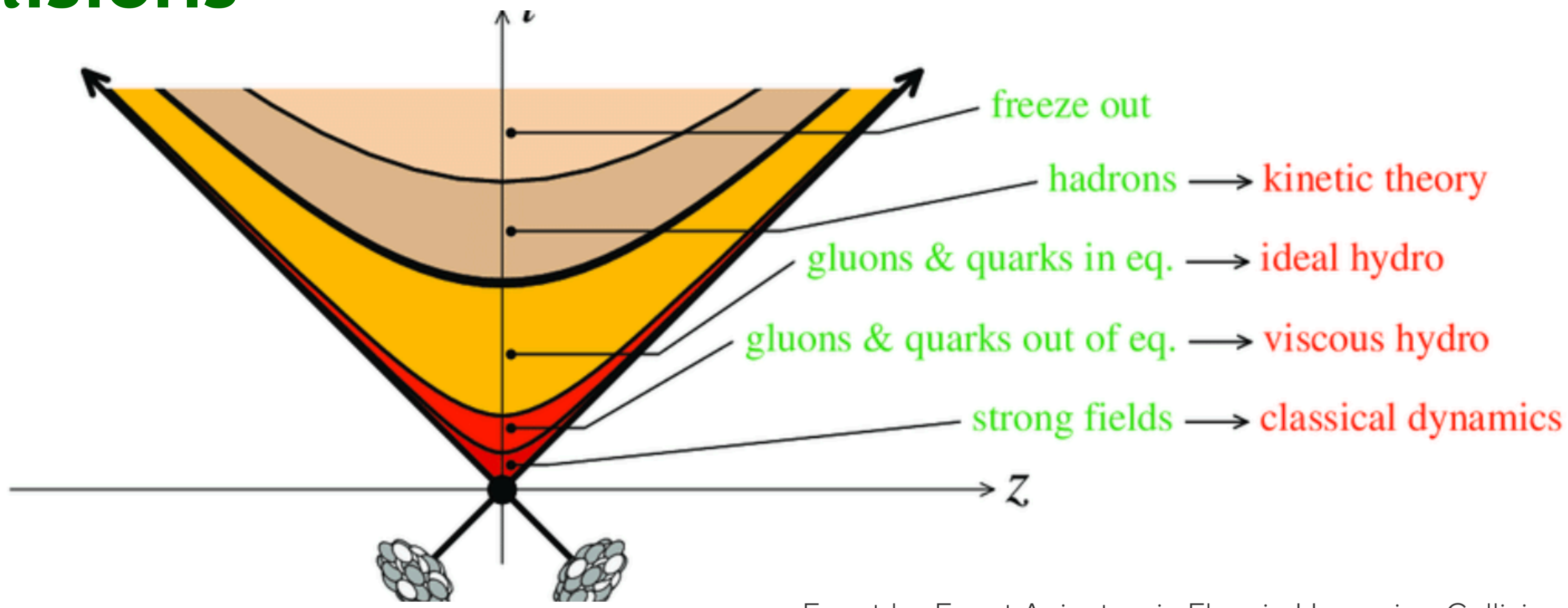


Figure from Lorcé, Pasquini, Vanderhaeghen (JHEP 2011)

Heavy-ion collisions





IP-GLASMA (CGC) + MUSIC
(Hydrodynamic evolution)

Event-by-Event Anisotropic Flow in Heavy-ion Collisions from Combined Yang-Mills and Viscous Fluid Dynamics

Charles Gale, Sangyong Jeon, Björn Schenke, Prithwish Tribedy, and Raju Venugopalan
Phys. Rev. Lett. **110**, 012302 – Published 2 January 2013

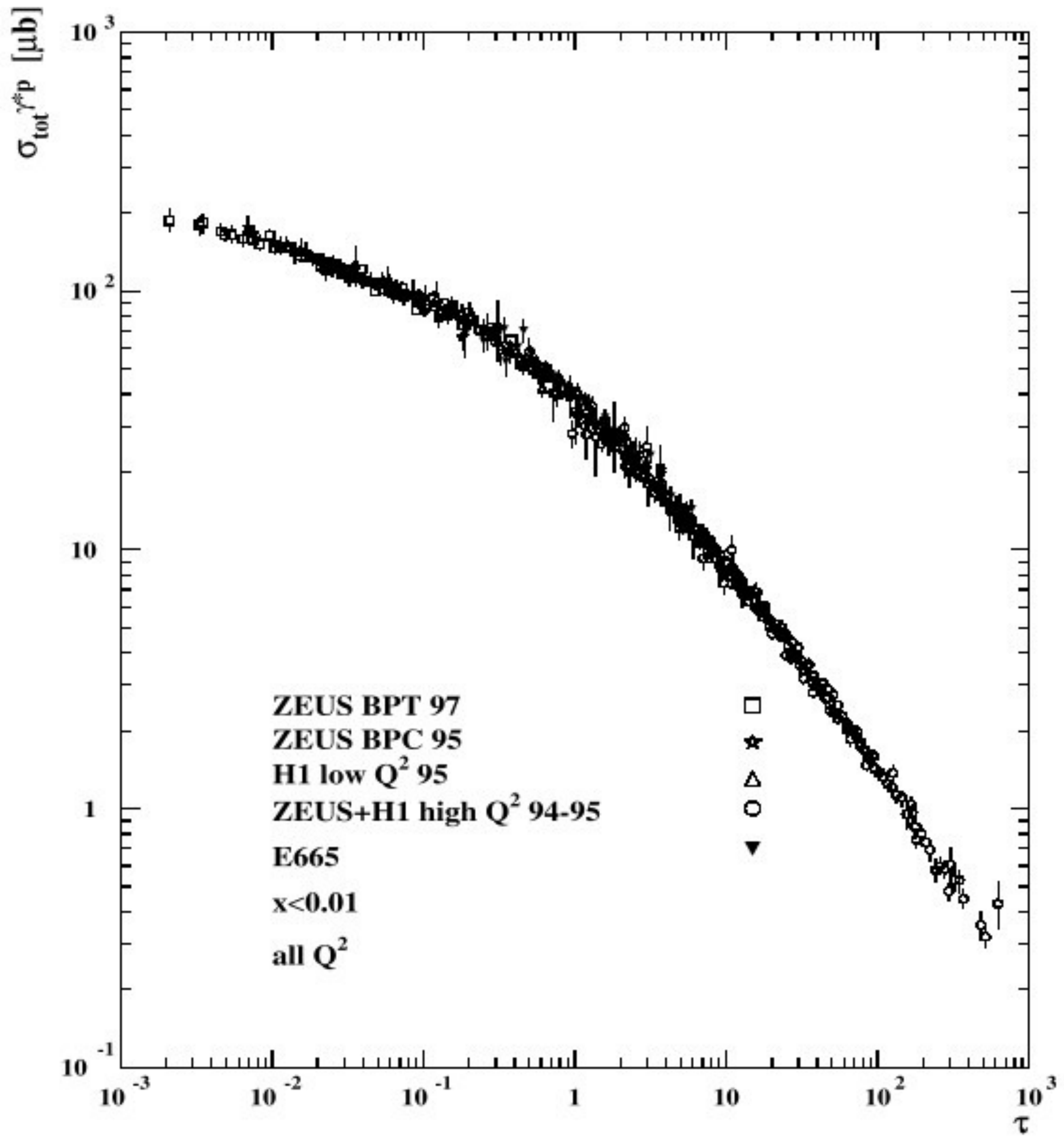
Challenge: distinguish CGC initial state momentum anisotropies from final state interactions (couple to initial geometry) in observables

Novel proposals:
Giacalone, Schenke, Shen (PRL 2020)

For a comprehensive review see
Schenke Rept.Prog.Phys. 84 (2021)

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: $\tau = Q^2/Q_s^2(x)$

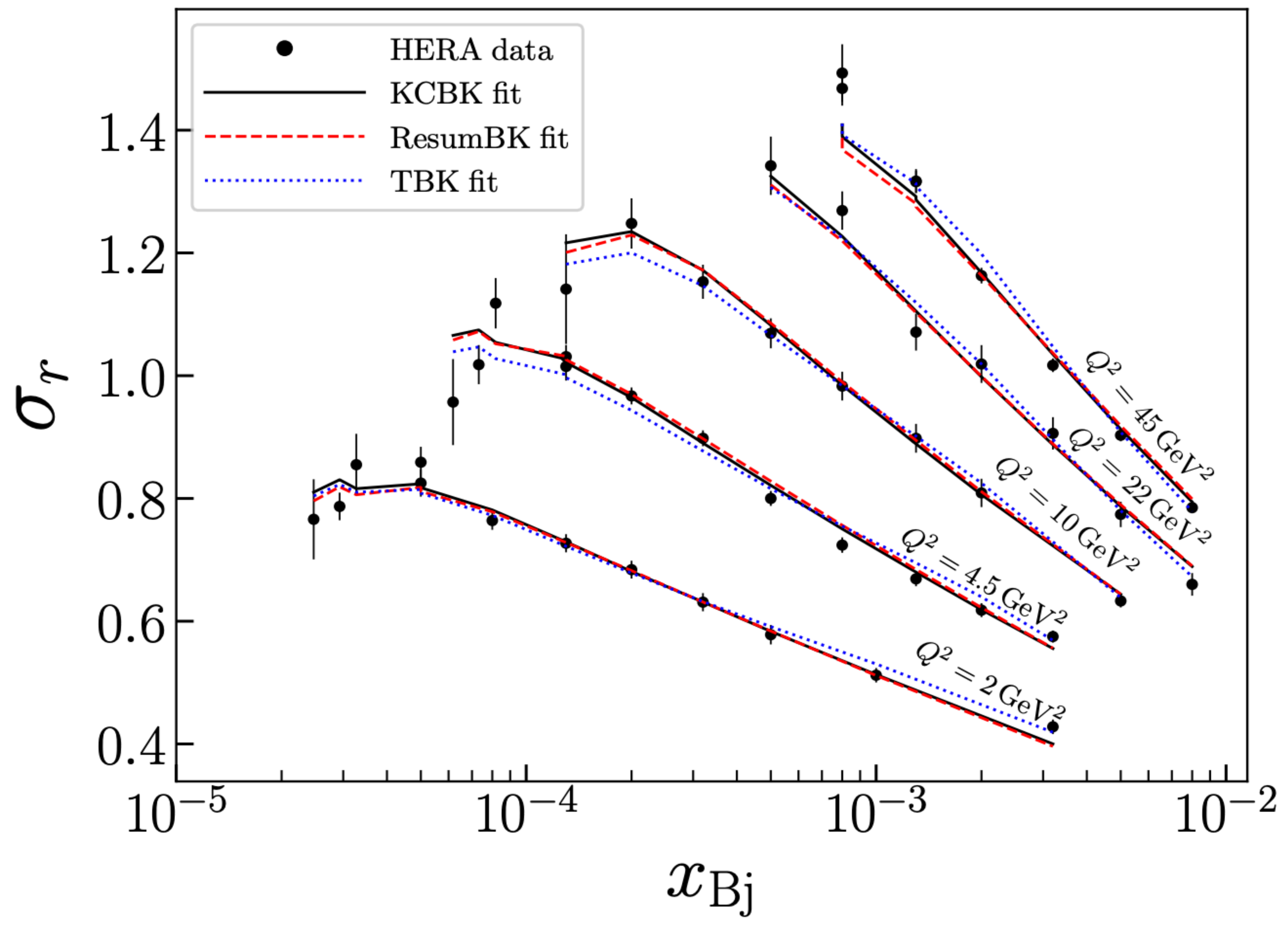
$$Q_s^2(x) = Q_{s,0}^2(x_0/x)^\lambda$$

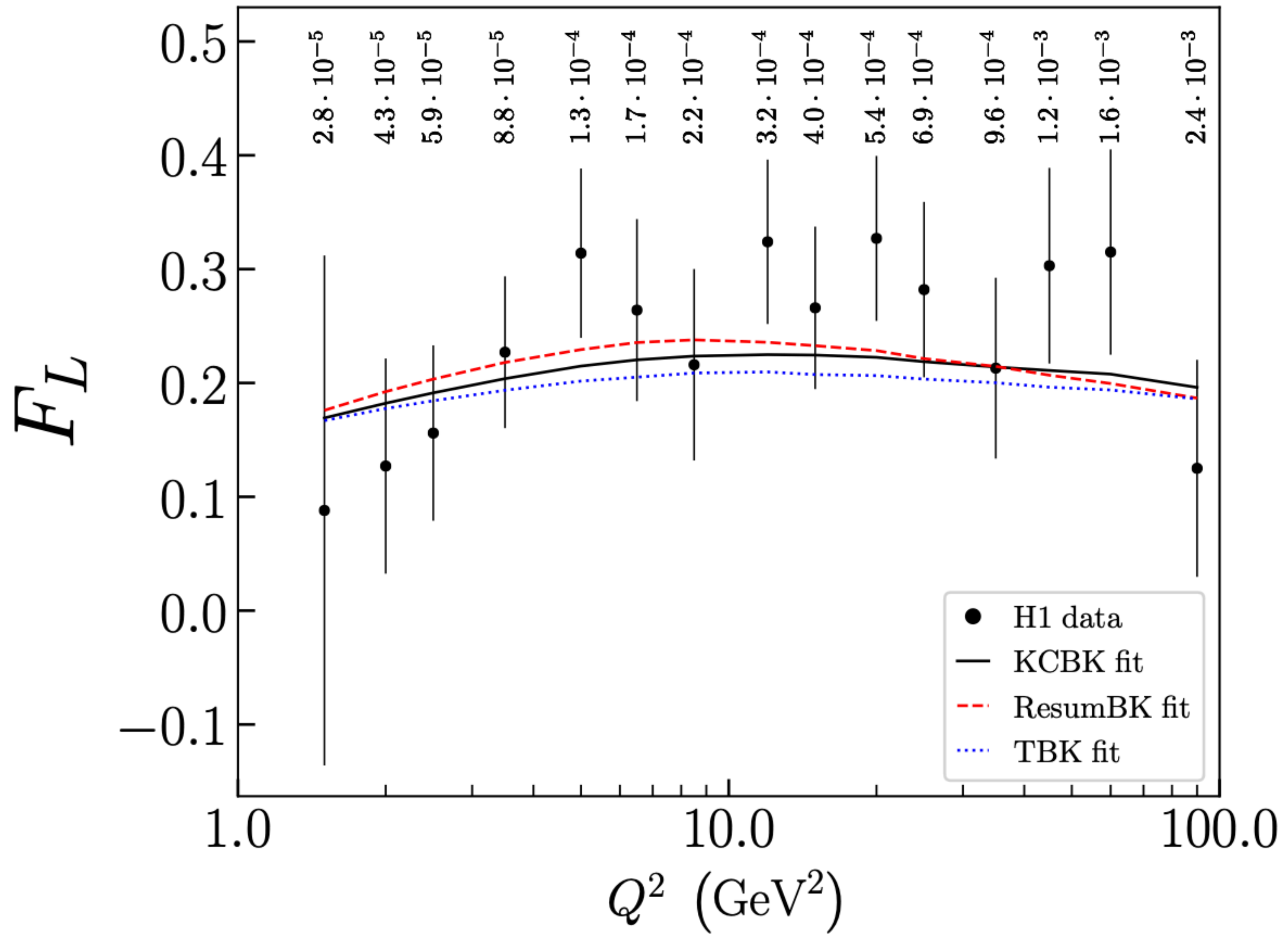
- Can we observe geometric scaling for different nuclear species?
- Will we observe the nuclear size dependence of the saturation scale?

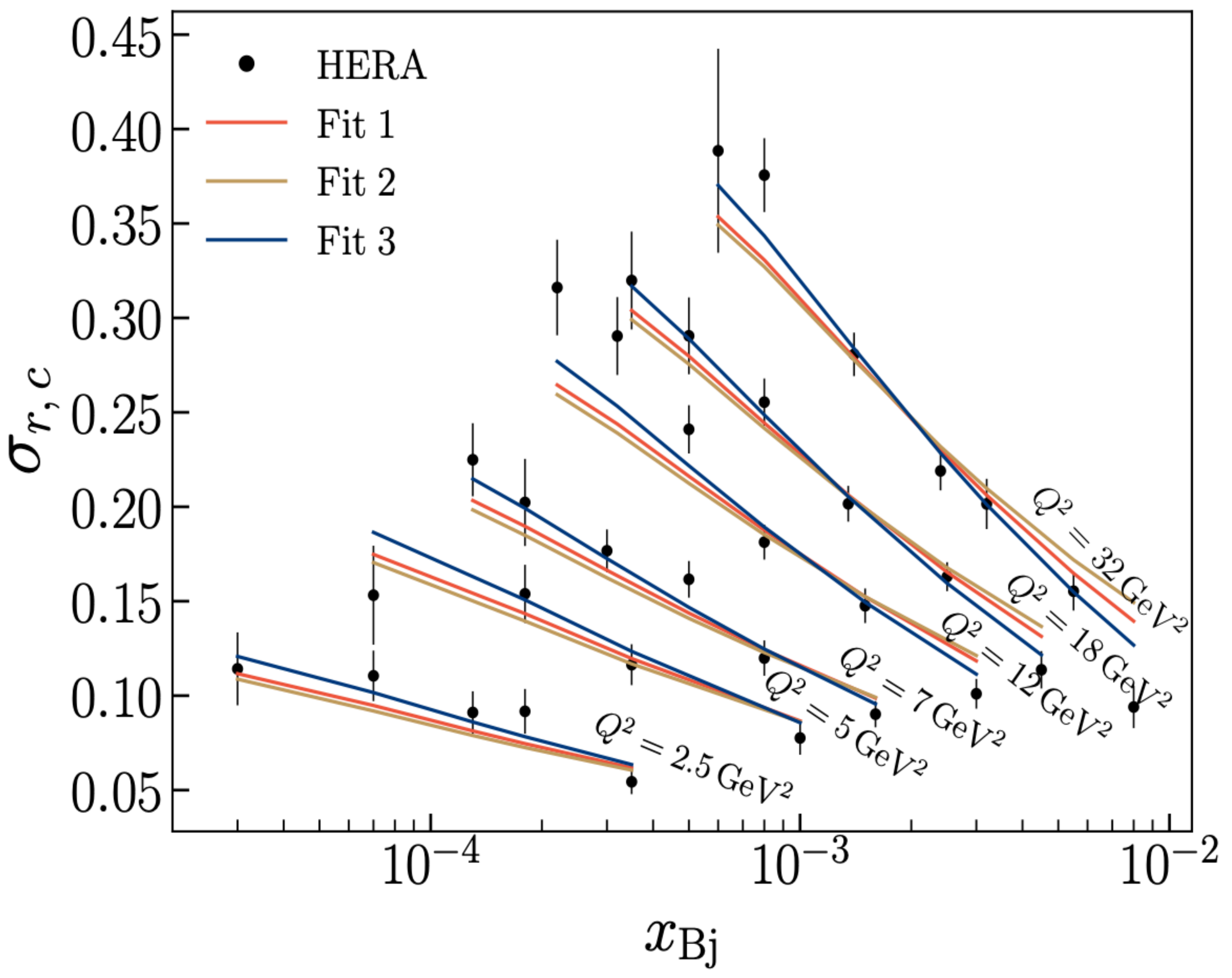
$$Q_s^2(x,A) = Q_{s,0}^2(x_0/x)^\lambda A^{1/3}$$

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

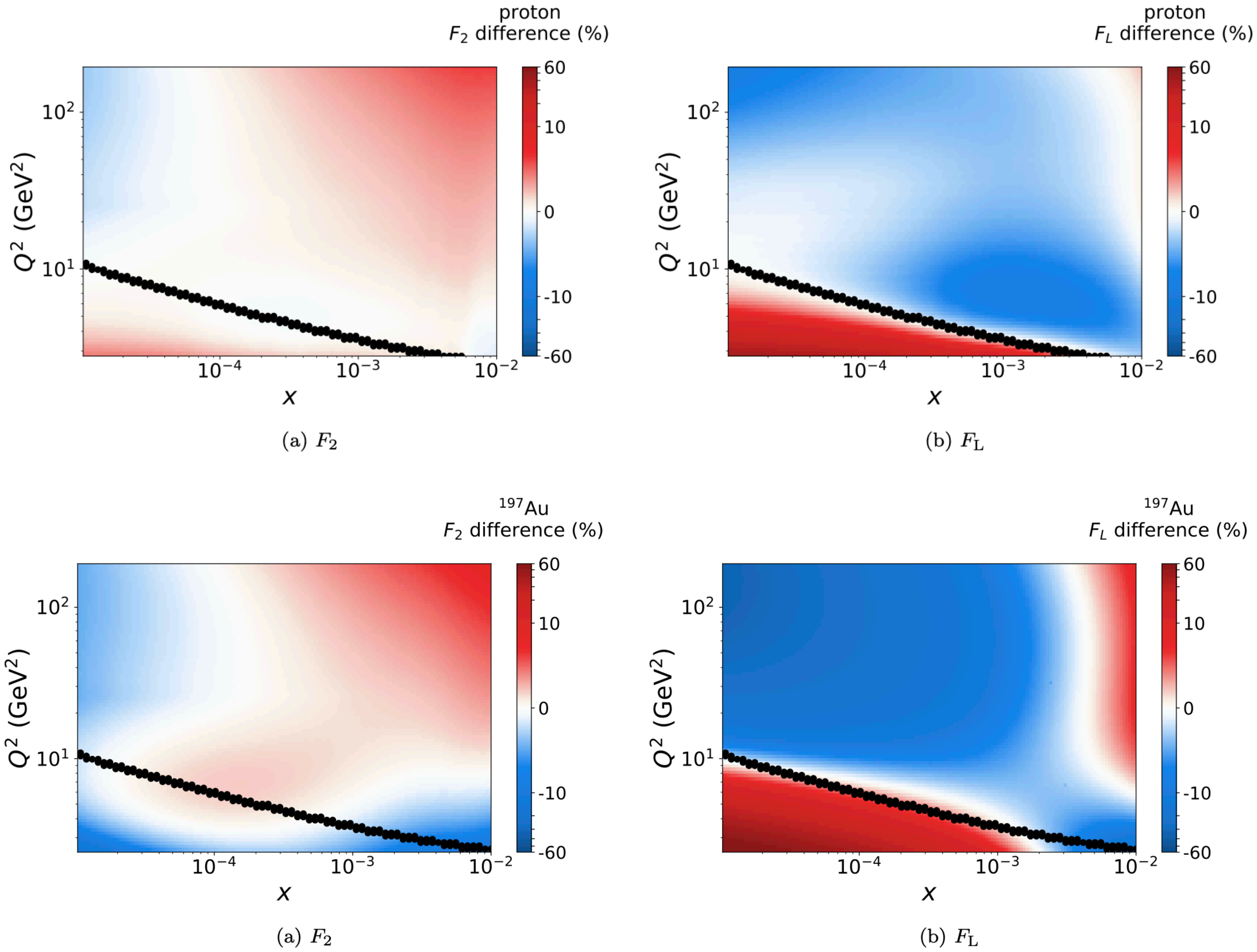
- Difference in predictions for $F_{2,L}$:
  linear (collinear/DGLAP)
  non-linear (dipole/Balitsky-Kovchegov)

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

- Stronger effects for F_L than F_2

- Stronger effects for γAu than γp

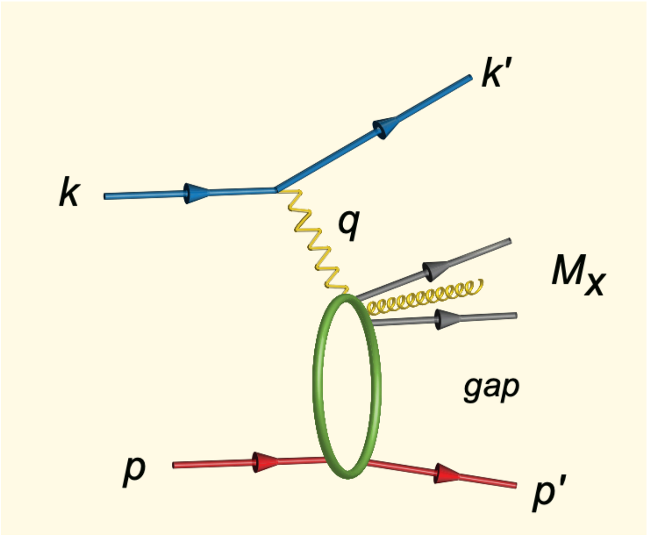
- It would be interesting to incorporate small-x evolution into DGLAP via BFKL, à la Ball, Bertone, Bonvini, Marazani, Rojo, Rottoli (2017), and compare with non-linear BK



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

See also Marquet, Moldes, Zurita (2017)

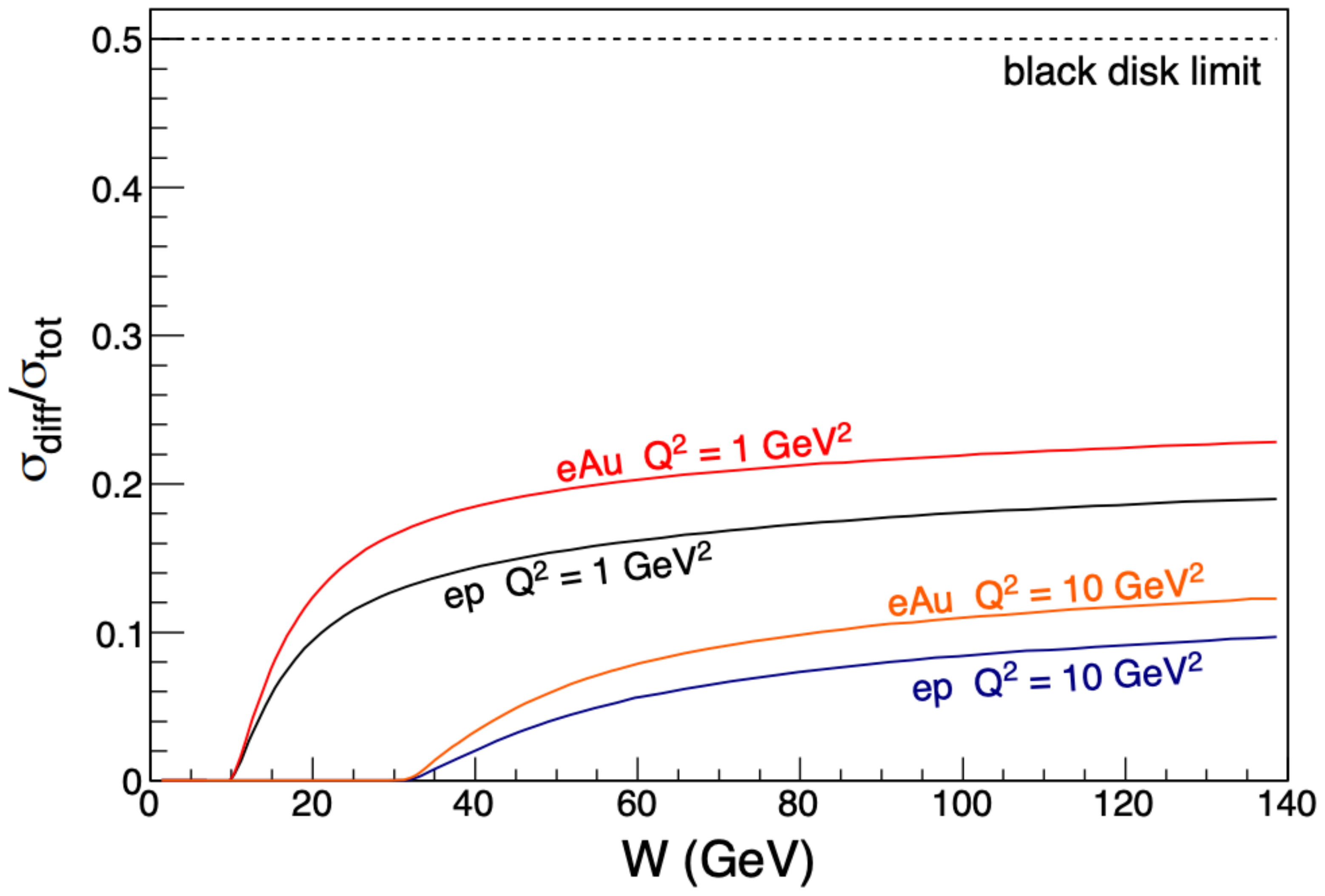
Diffractive structure functions



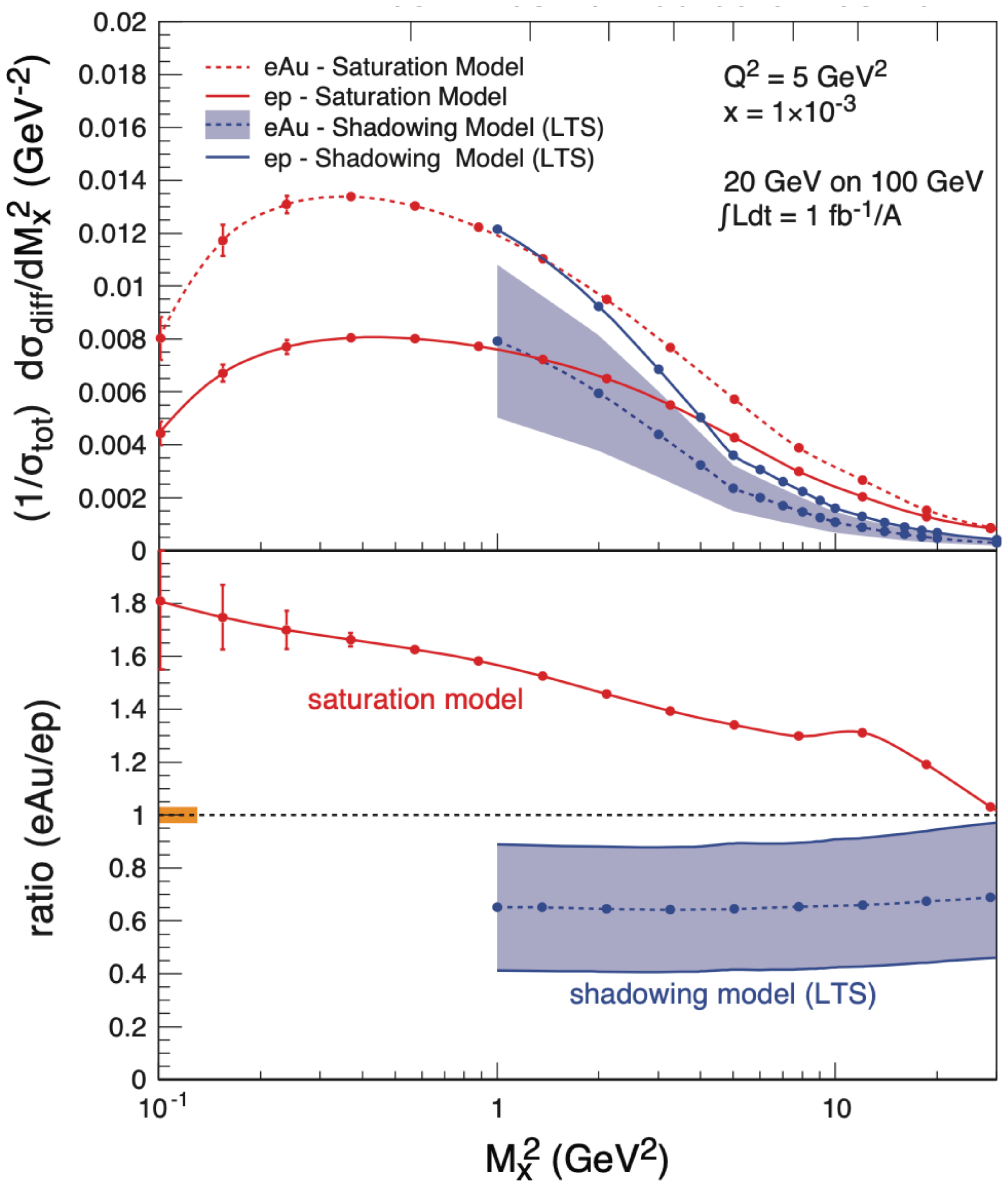
Diffractive events are characterized by rapidity gap

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



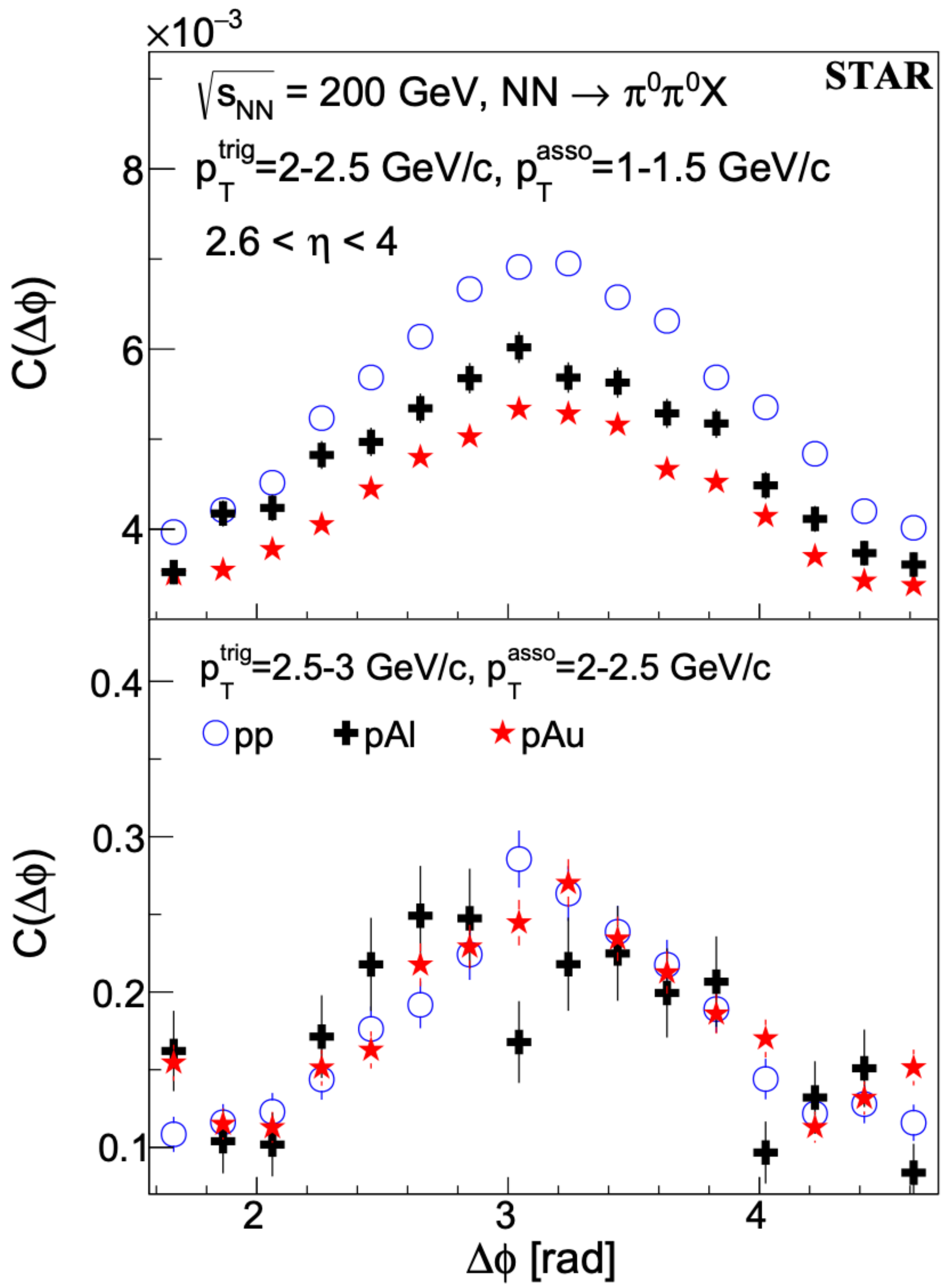
Clear difference between saturation models and leading twist shadowing (LTS)

EIC White paper (2012)

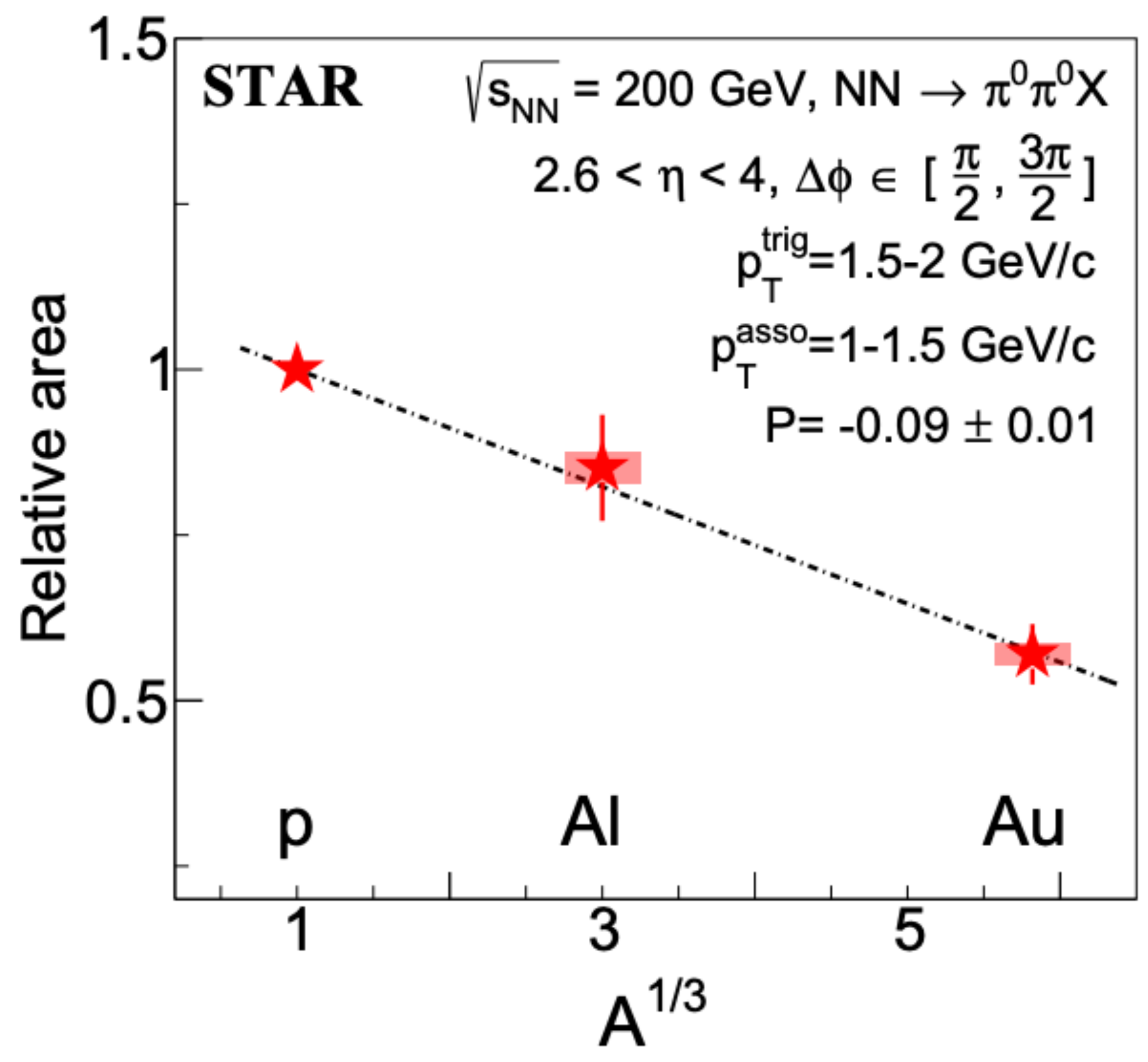
Semi-inclusive

Two particle correlations at RHIC

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

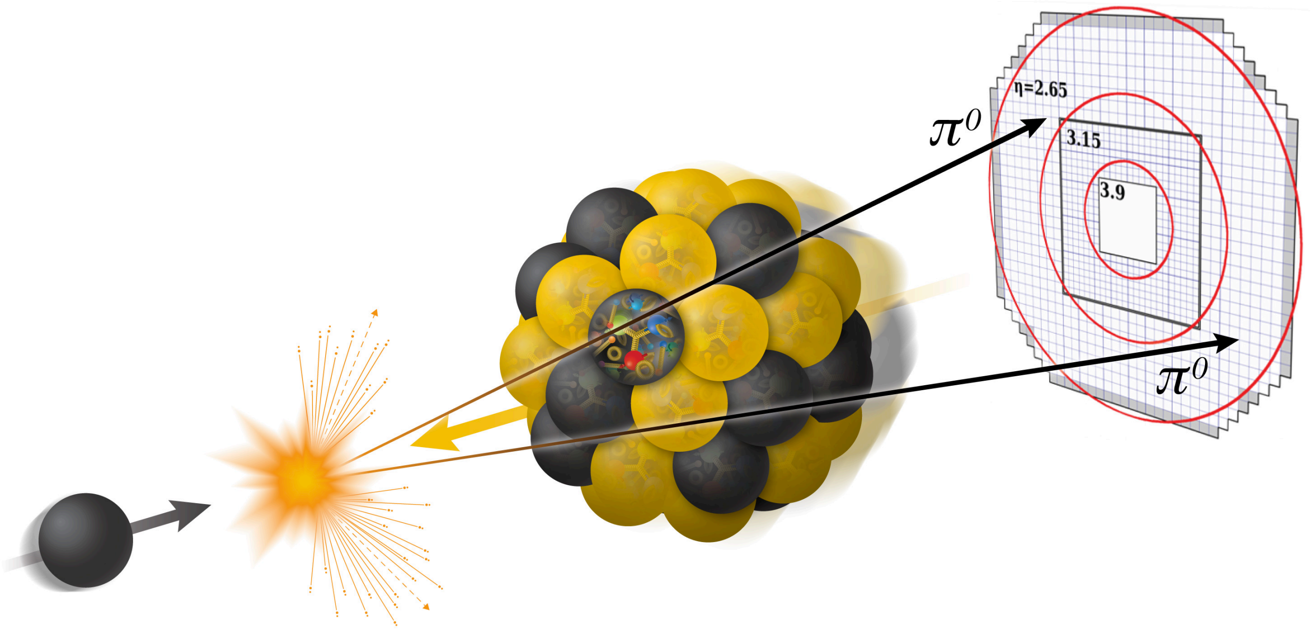


STAR Collaboration
Phys. Rev. Lett. 129, 092501 (2022)



Suppression characteristic of saturation

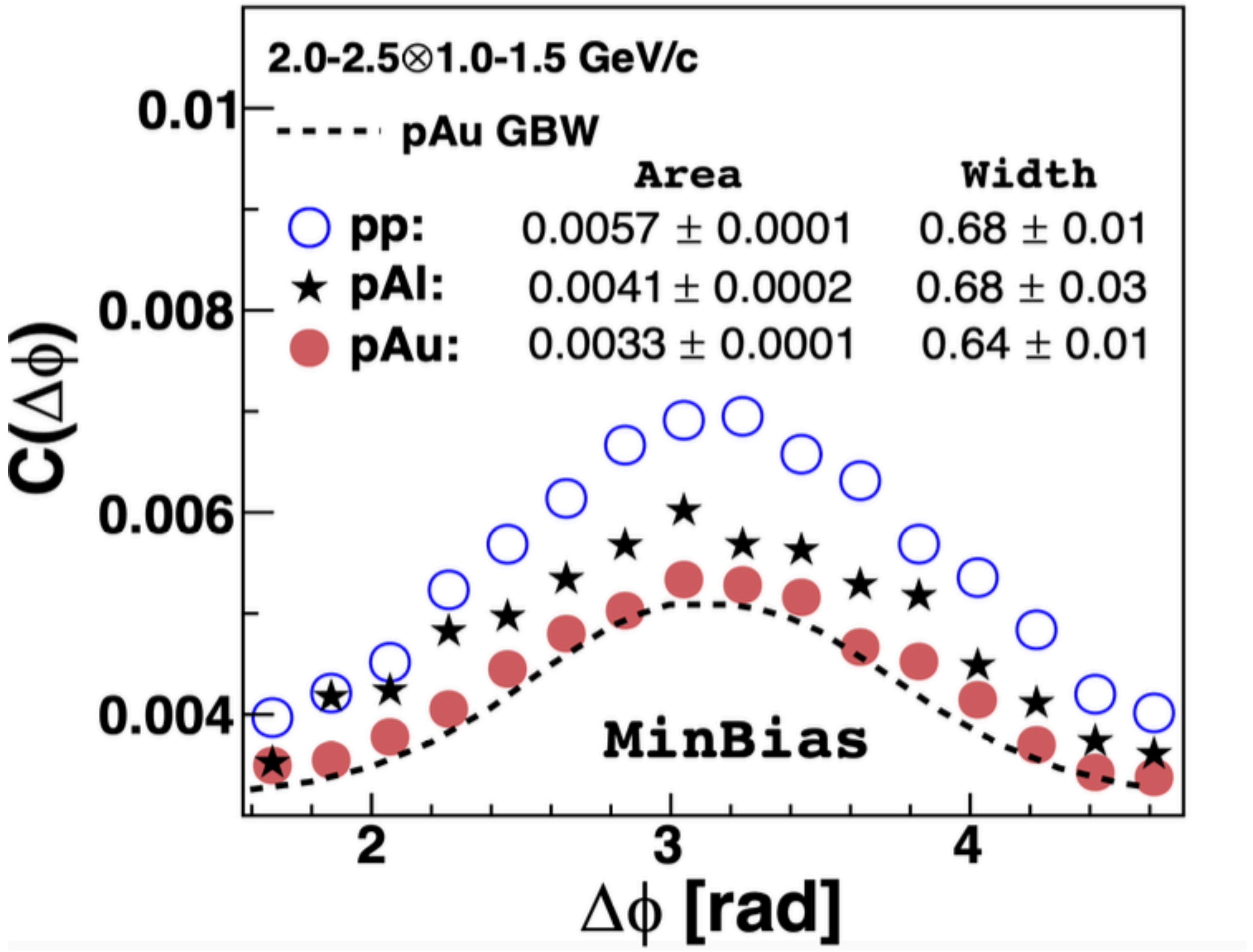
$$Q_s^2 \propto A^{1/3}$$



Xiaoxuan Chu and Elke Aschenauer

Two particle correlations at RHIC

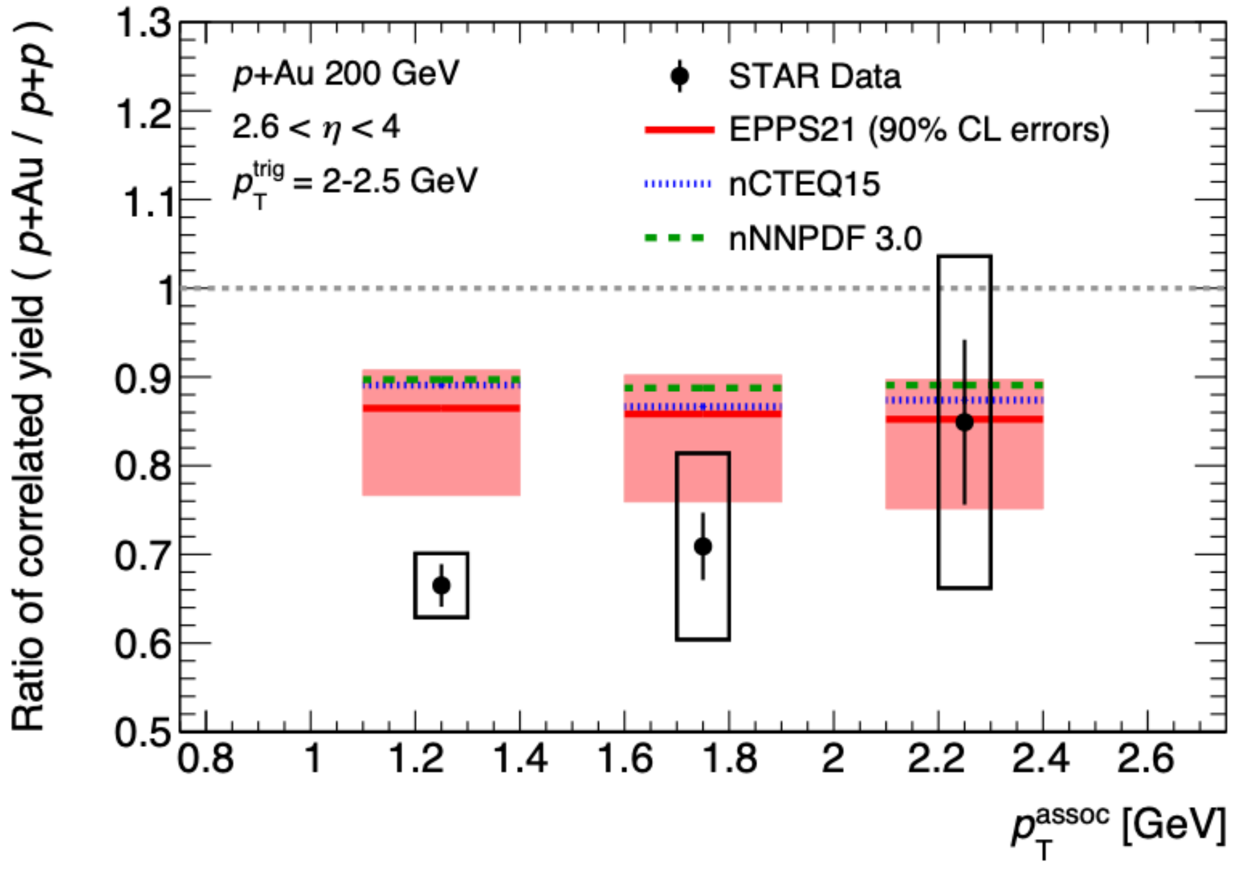
nPDF or saturation?

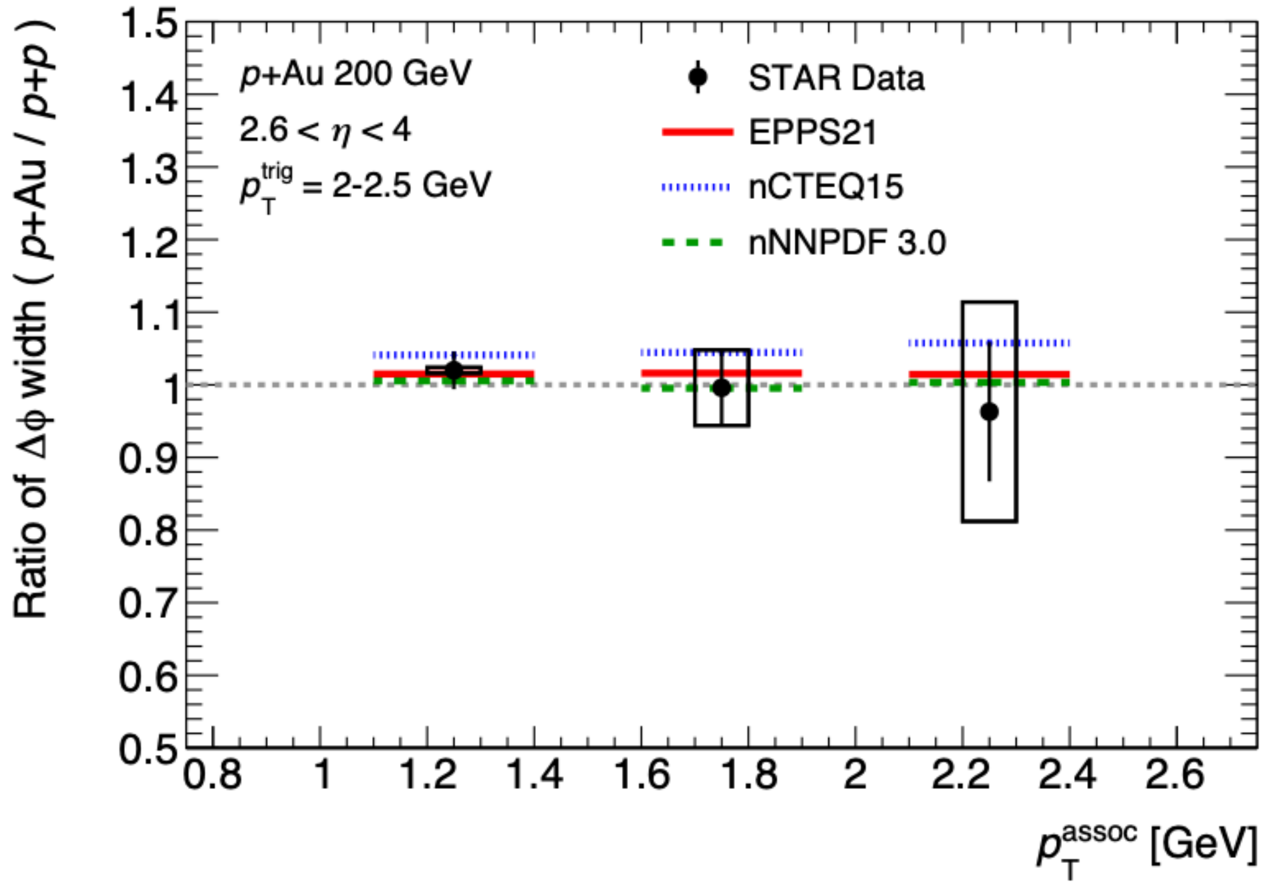


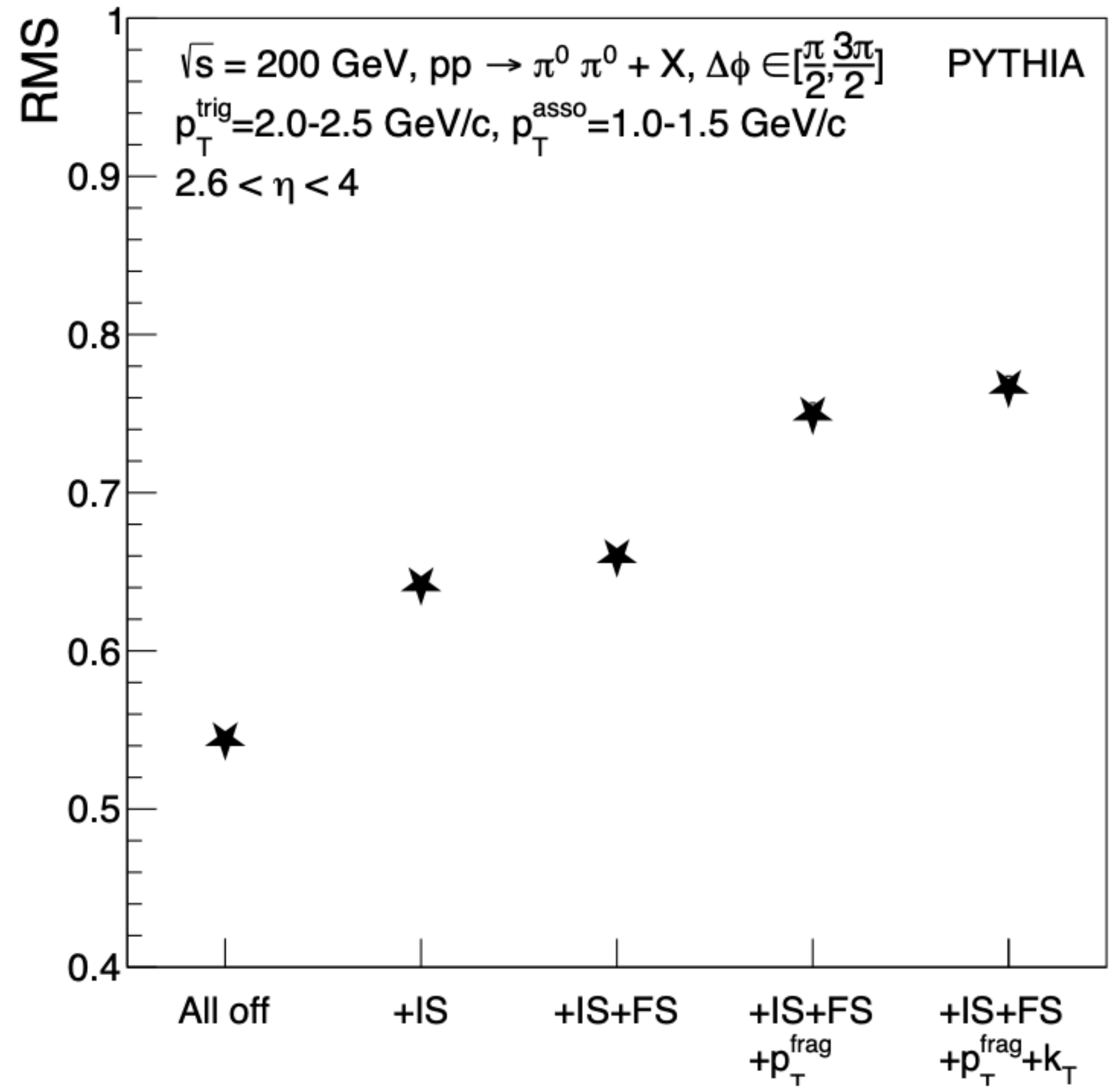
STAR (2021)

- 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**





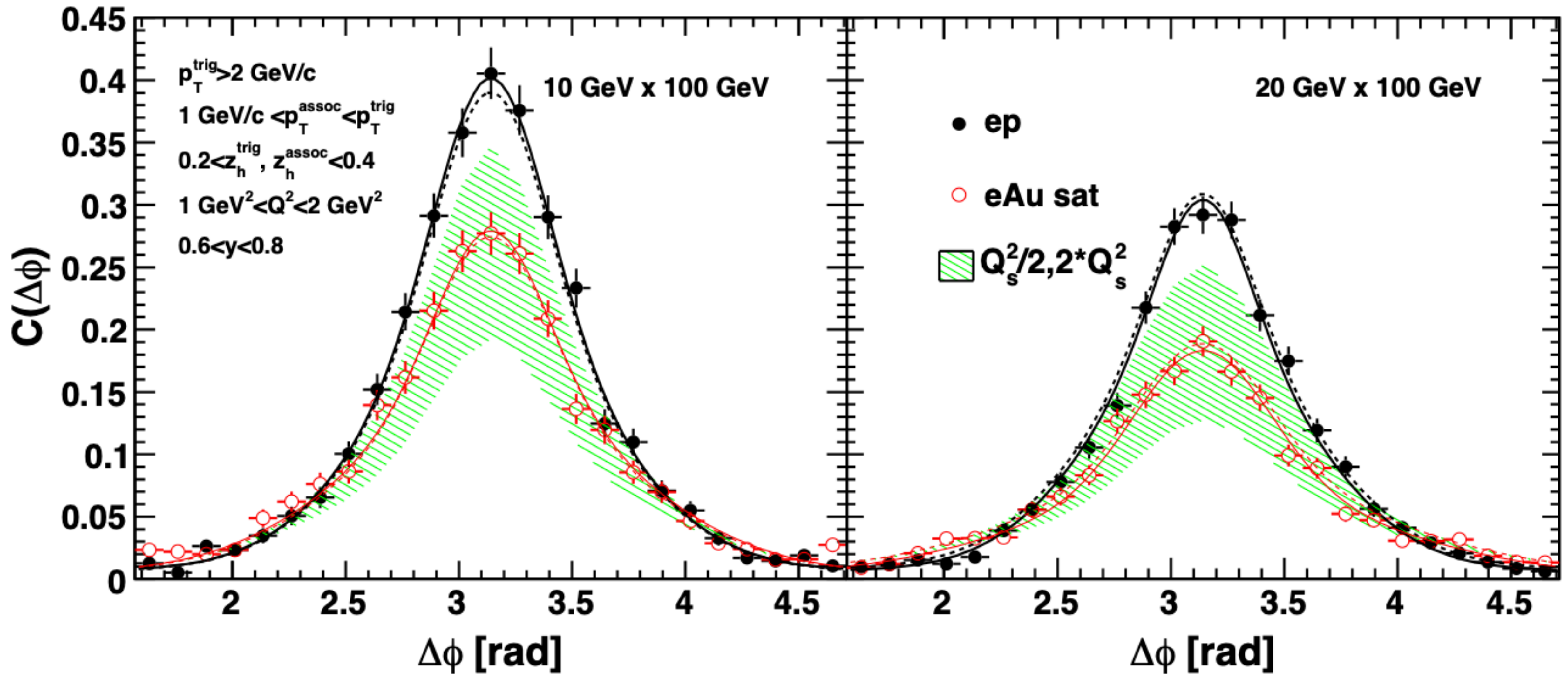


- Cassar, Wang, Chu, Aschenauer (2025)
  Parton shower + hadron fragmentation control width of correlation

  Absence of broadening is not necessarily challenge to the saturation paradigm

Two particle correlations at EIC

Dihadron suppression
back-to-back peak at EIC

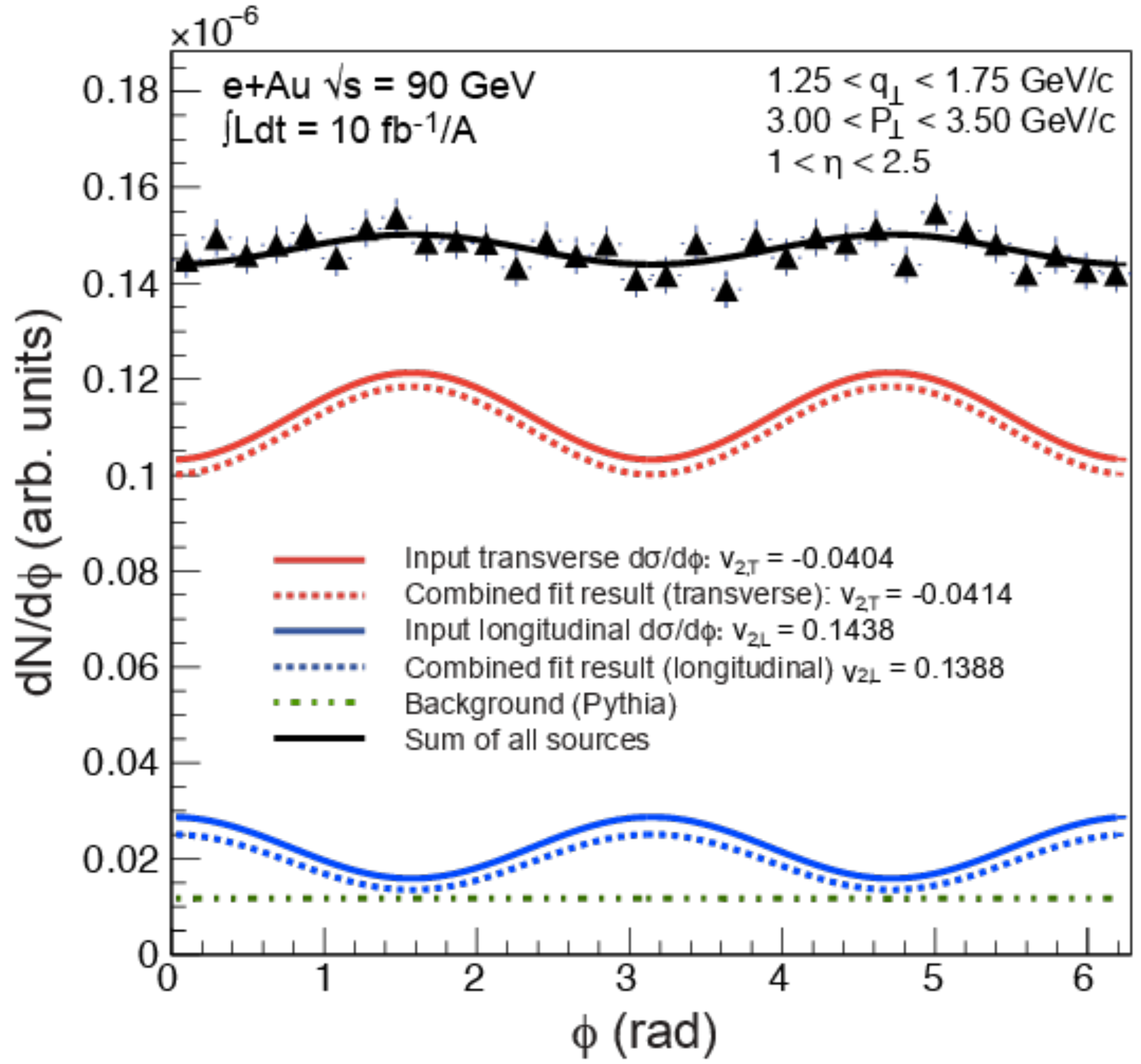


Zheng, Aschenauer, Lee, Xiao (2014)

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

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

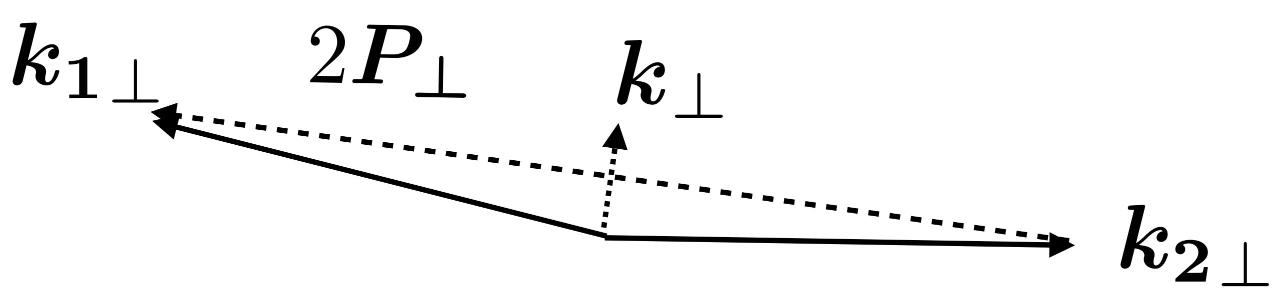
Dijet momentum imbalance
azimuthal correlations



Dumitru, Skokov, Ullrich (2018)

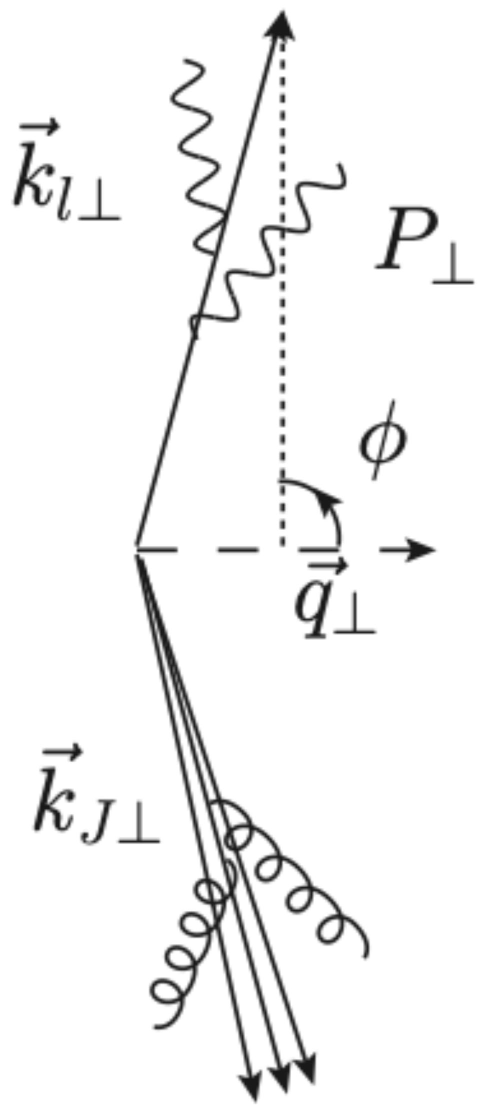
Sensitivity to linearly polarized gluons

ϕ angle between $\boldsymbol{P}_\perp$ and $\boldsymbol{k}_\perp$

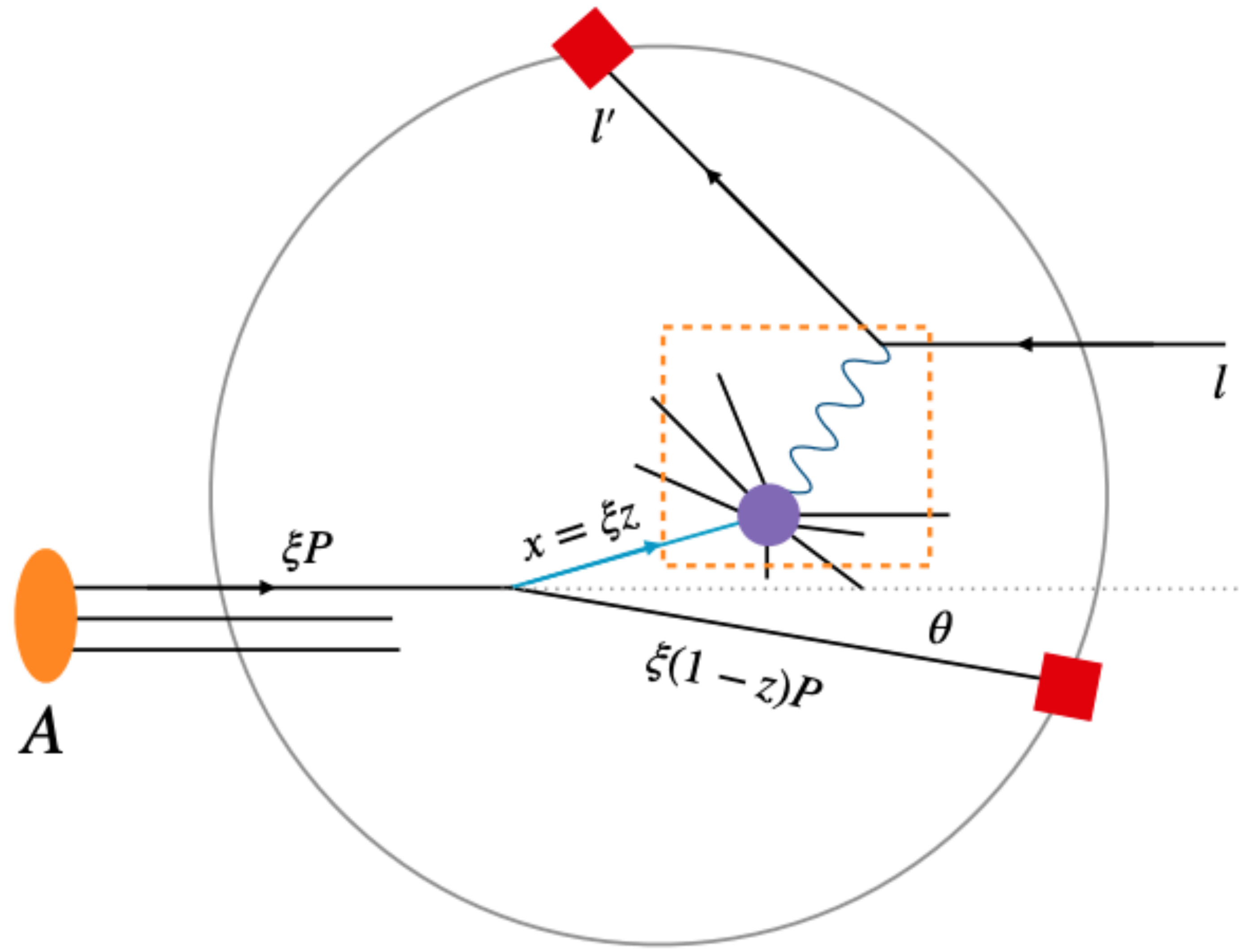


Can also be measured with direct J/ψ production in DIS
Cheung, Kang, Salazar, Vogt (2024)

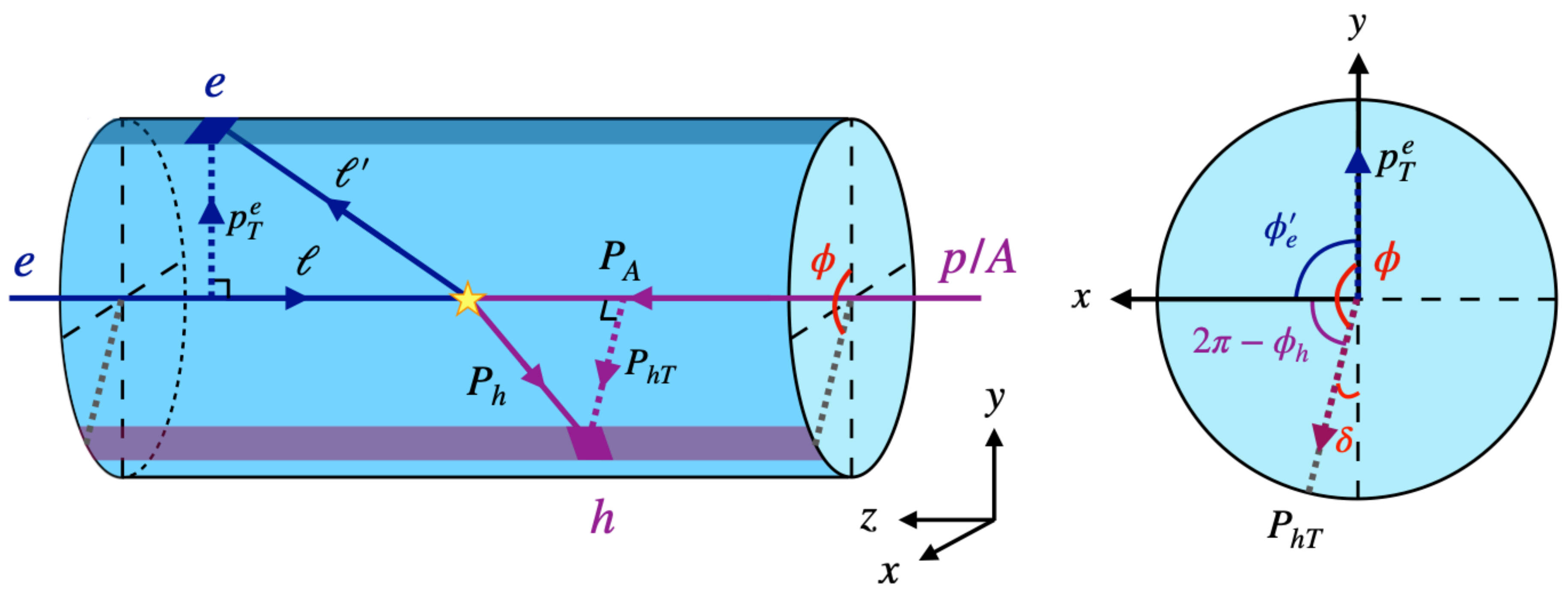
Other two-particle correlations: lepton-jet and nucleon-energy energy correlators



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



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

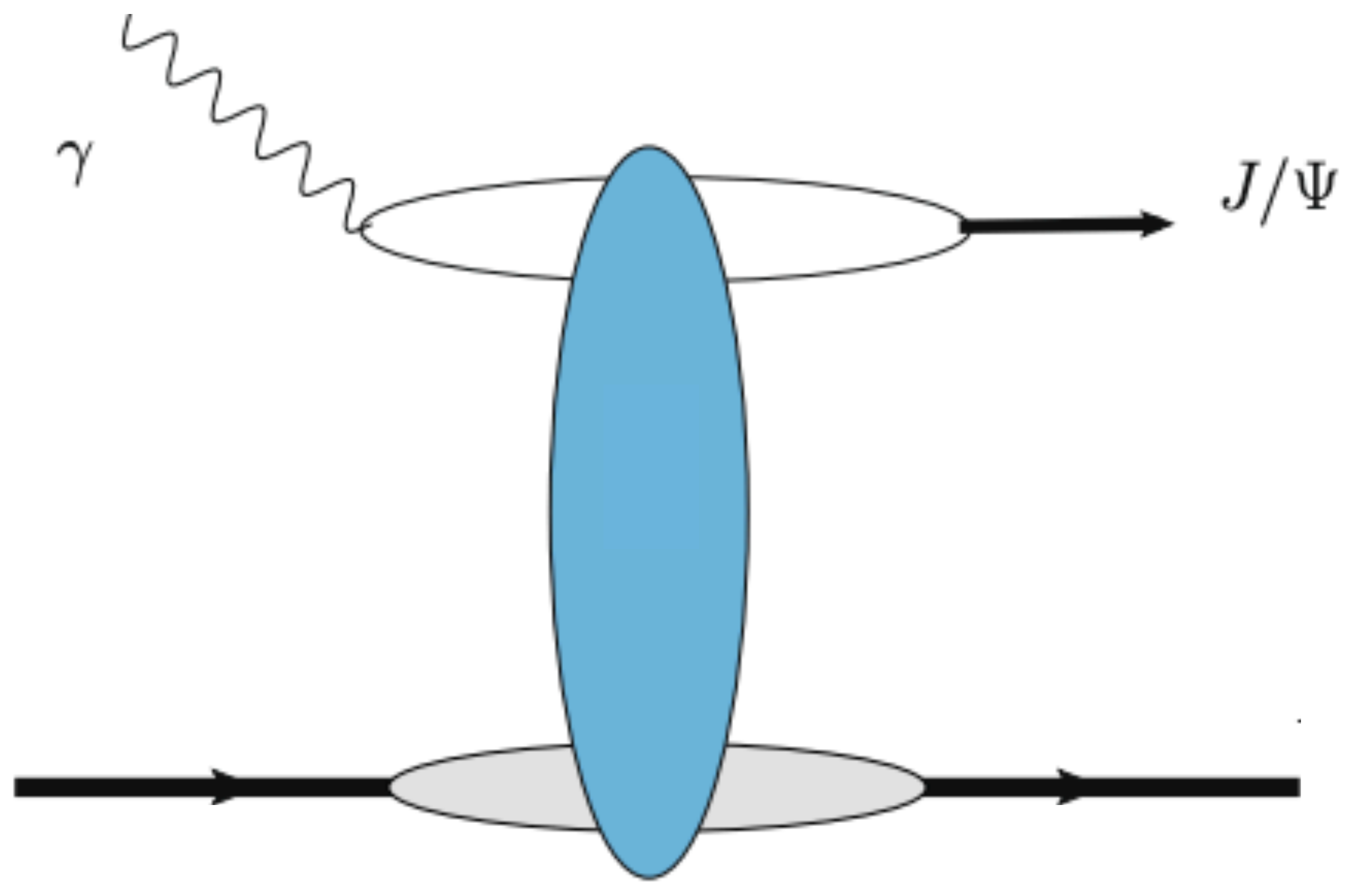


Transverse energy-energy correlators
Kang, Penttala, Zhao, Zhou (2024)

Exclusive

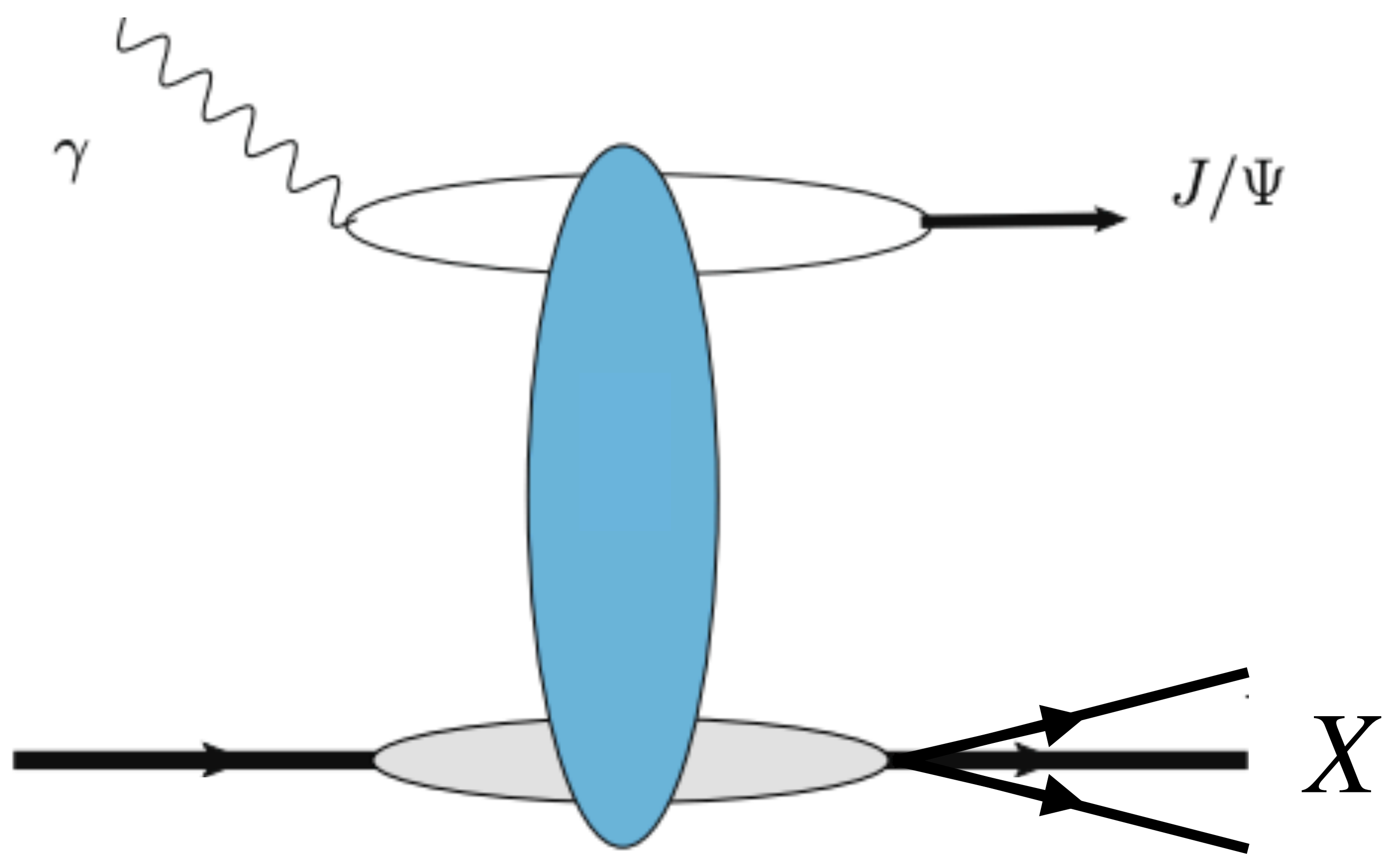
Exclusive vector meson production

Coherent and incoherent reactions



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

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



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

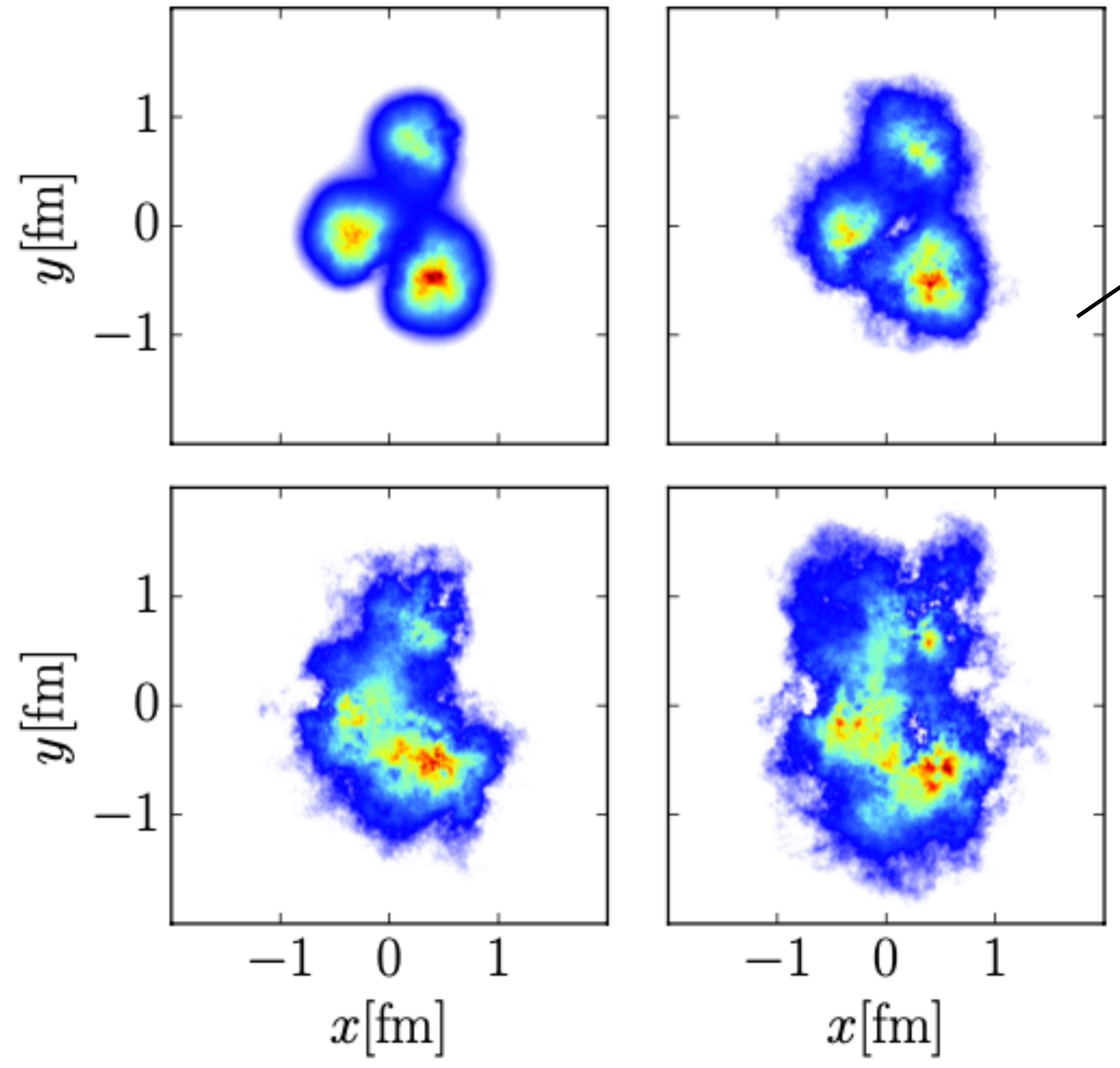
- Target breaks up, but one has a rapidity gap
- Sensitive to fluctuations: color charge, sub-nucleon, nucleon

Exclusive vector meson production

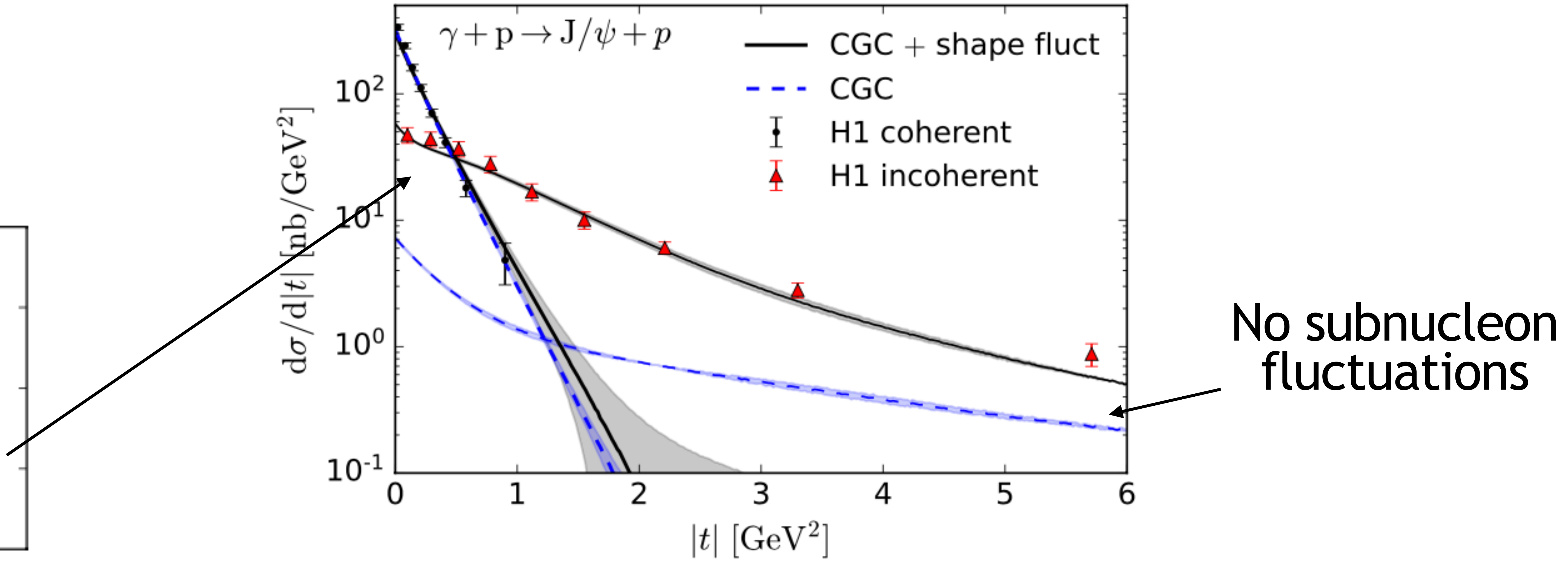
Event-by-event sub-nuclear fluctuations

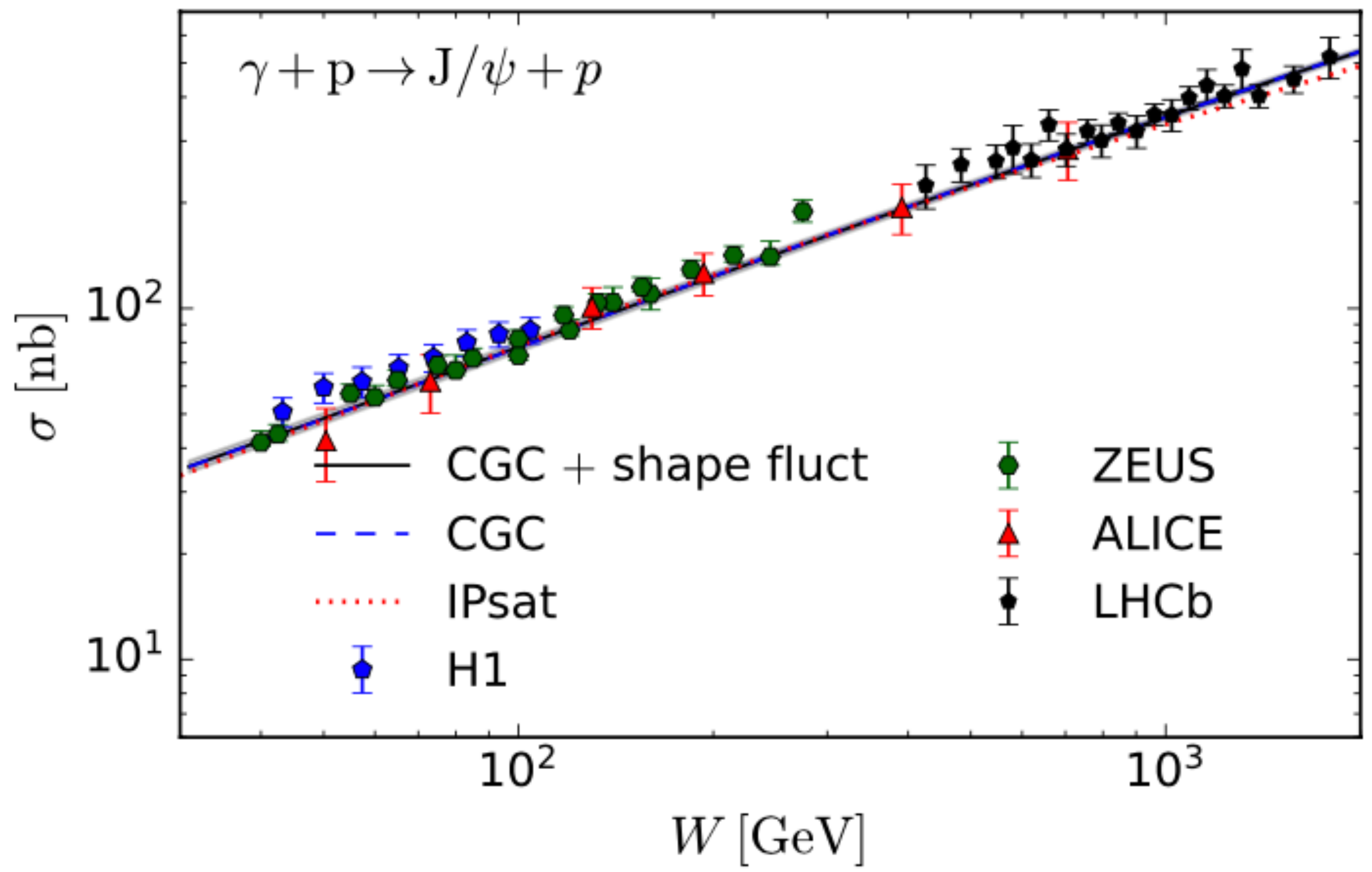
Introduce sub-nucleon structure

Mäntysaari, Schenke (2016)



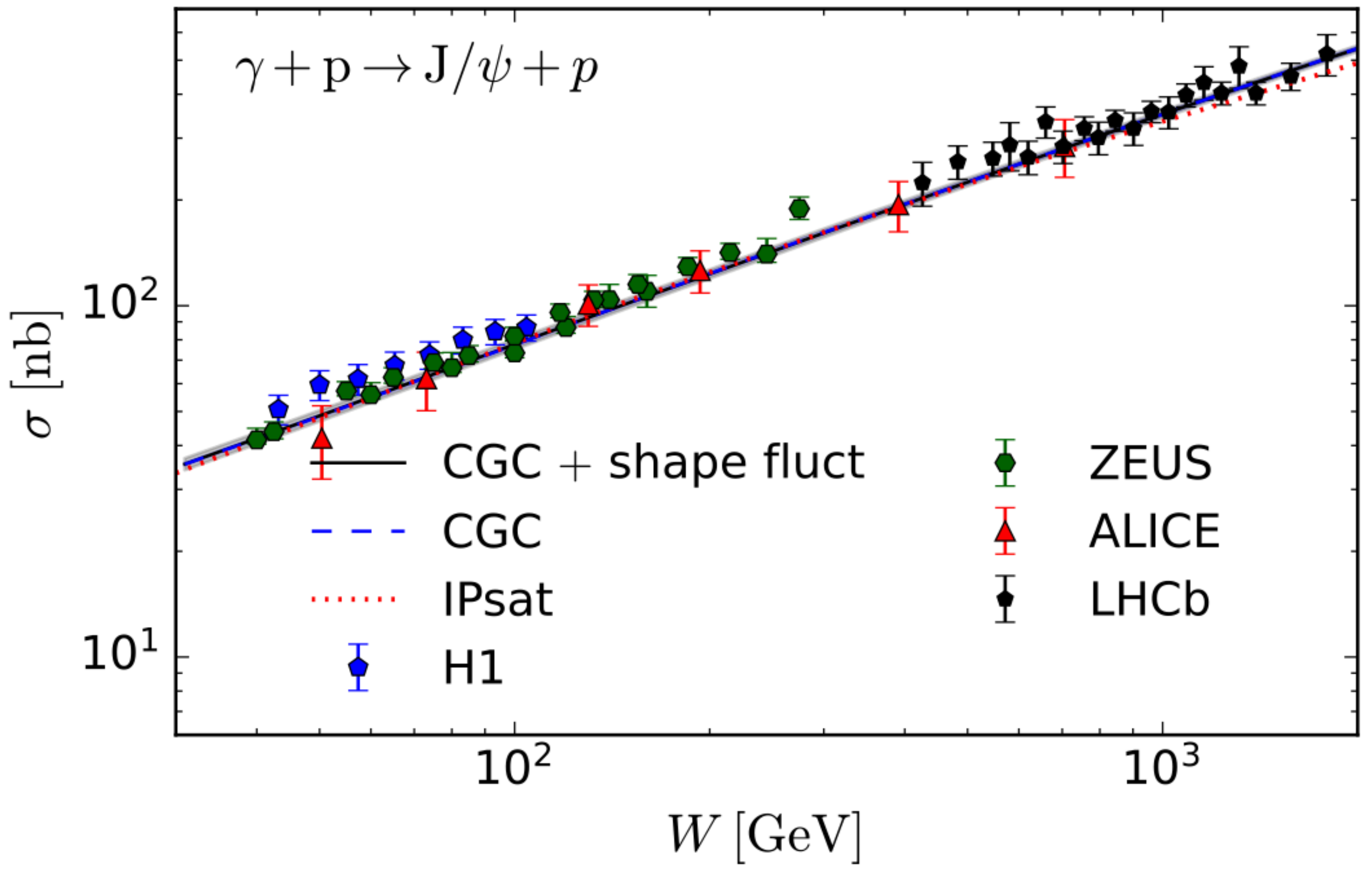
Mäntysaari, Schenke (2018)
Mäntysaari, Salazar, Schenke (2022)

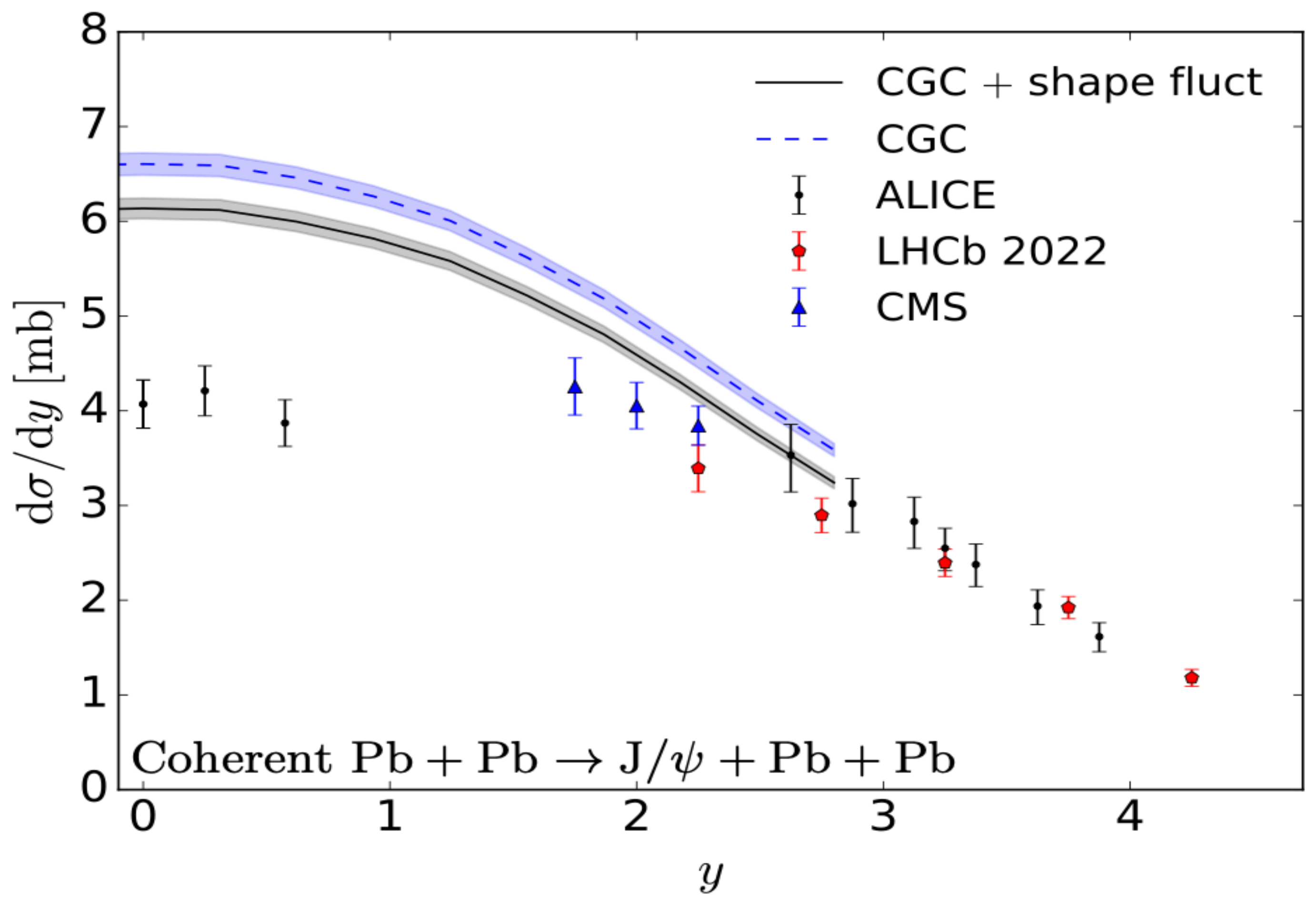




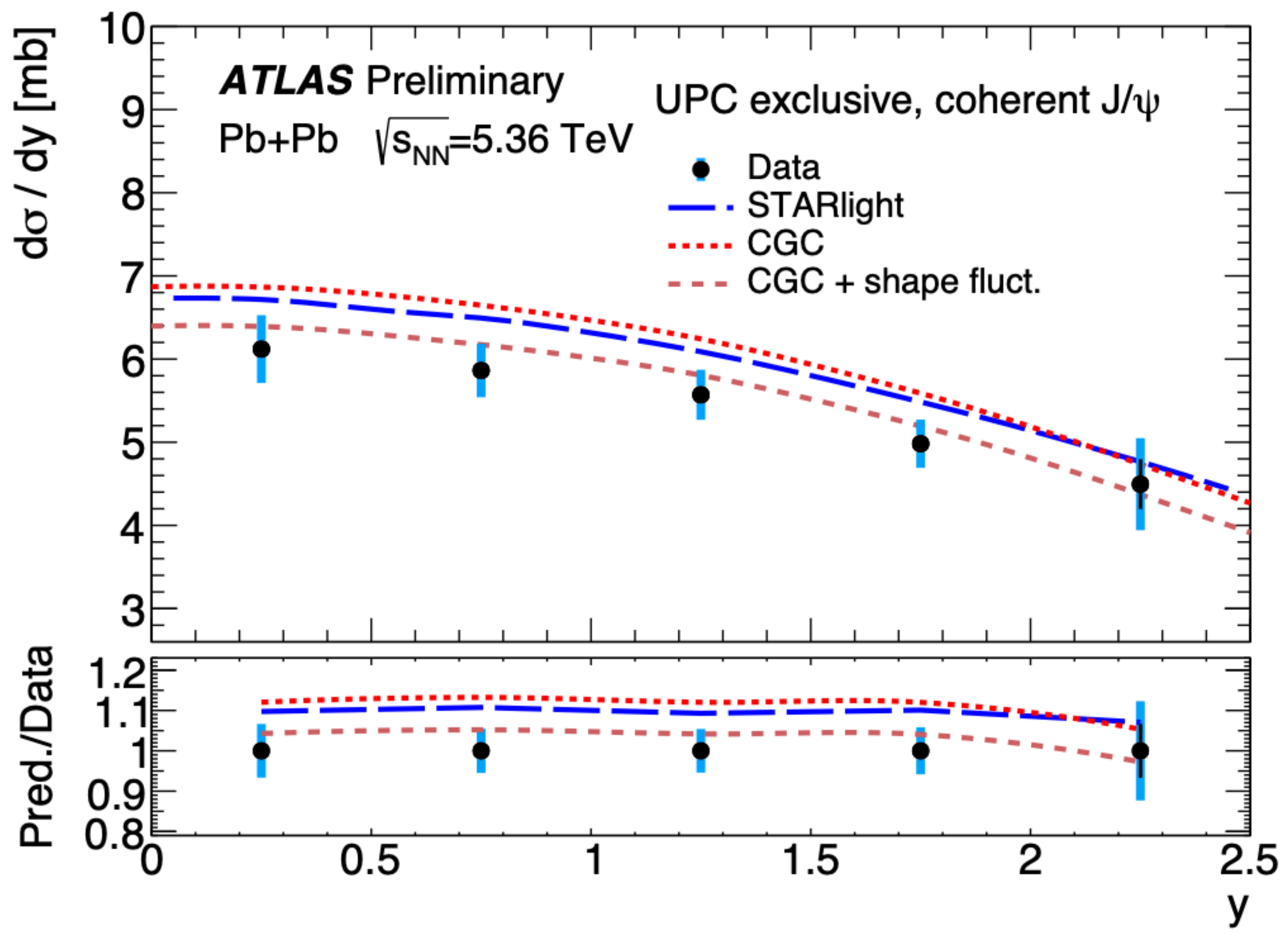
Exclusive vector meson production in UPCs

Coherent production γp and γA



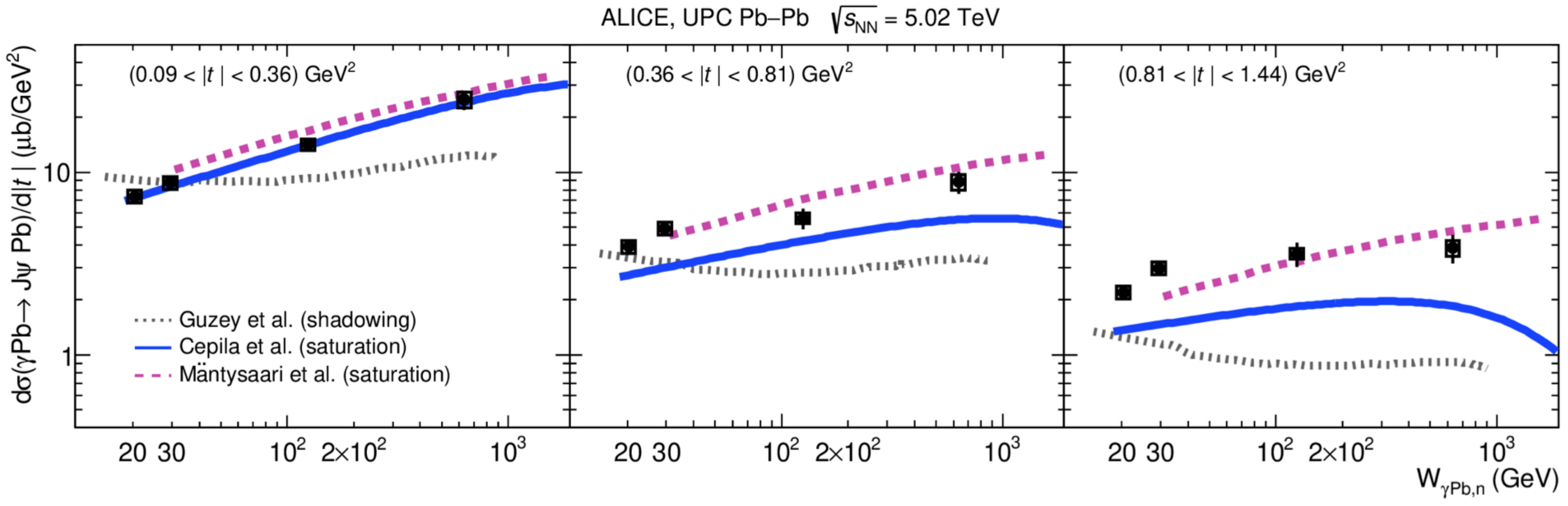


Mäntysaari, Salazar, Schenke (2022, 2024)



ATLAS (preliminary)

Double-differential incoherent γA



← ALICE

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

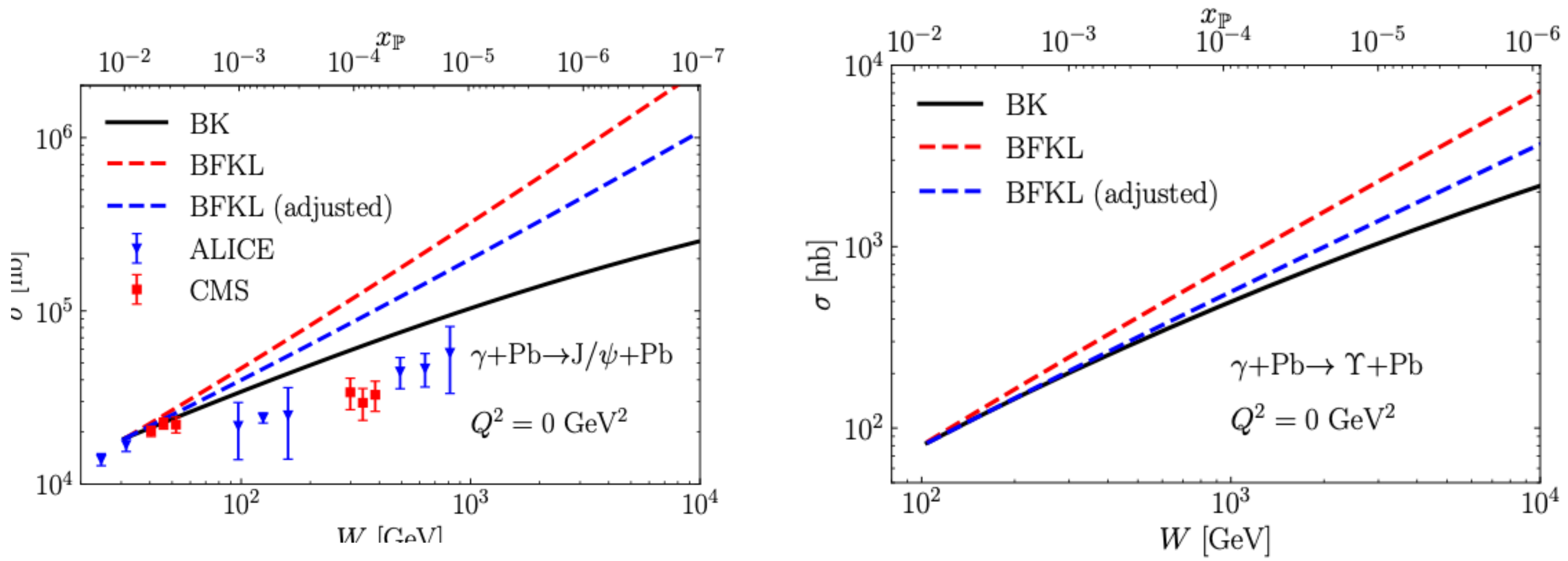
Exclusive vector meson production

- 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 Q^2 varying VM mass

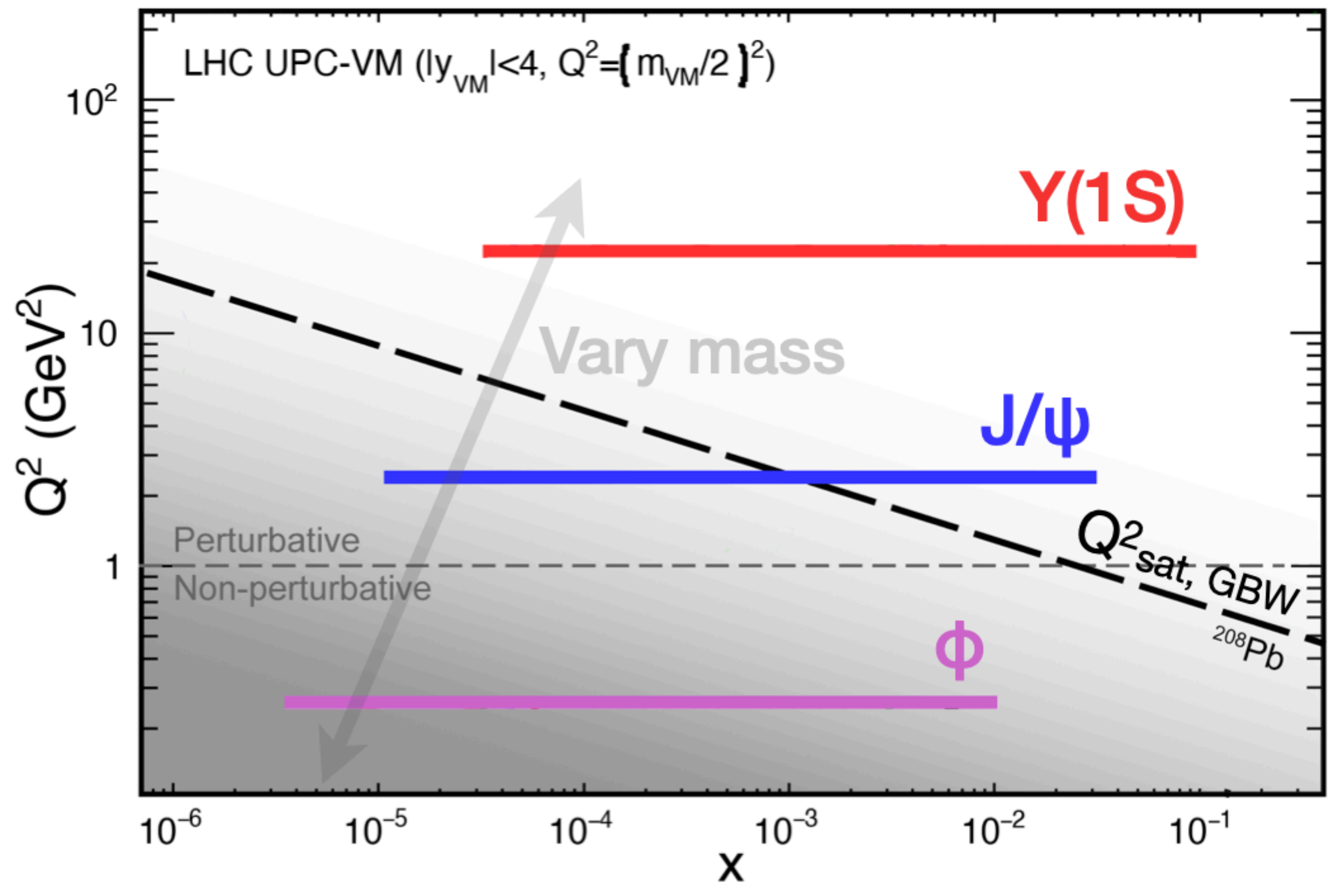


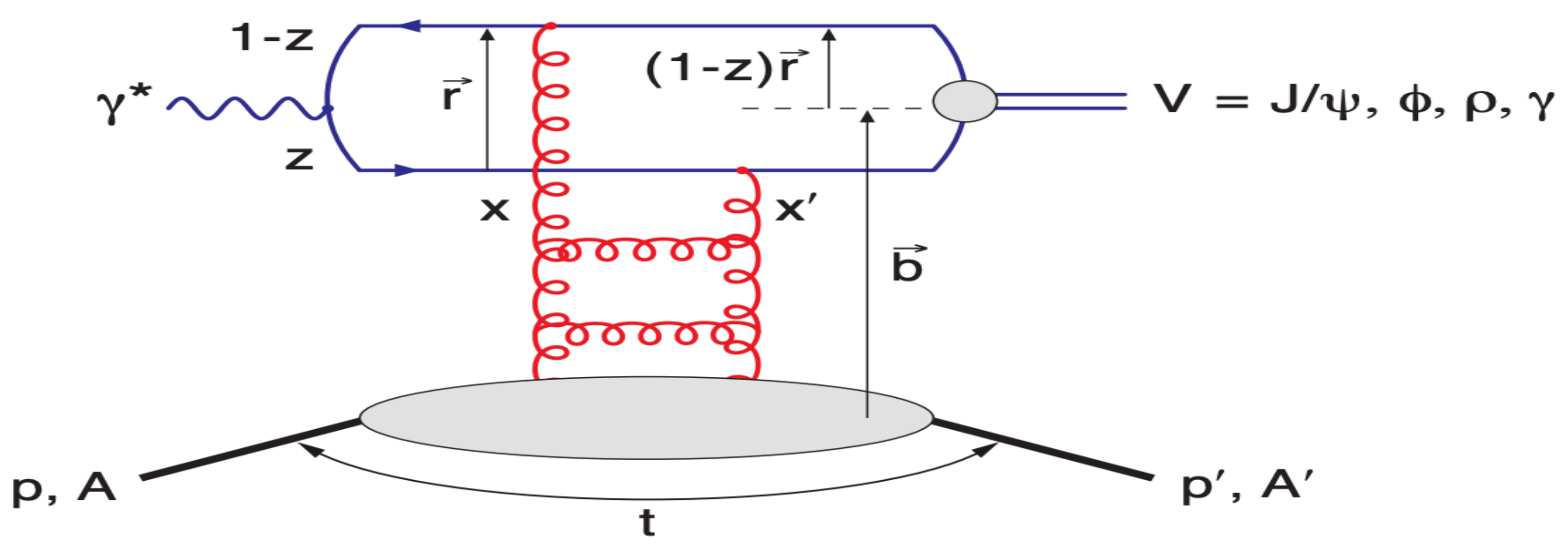
Figure from CMS (preliminary talk at QM)

- 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



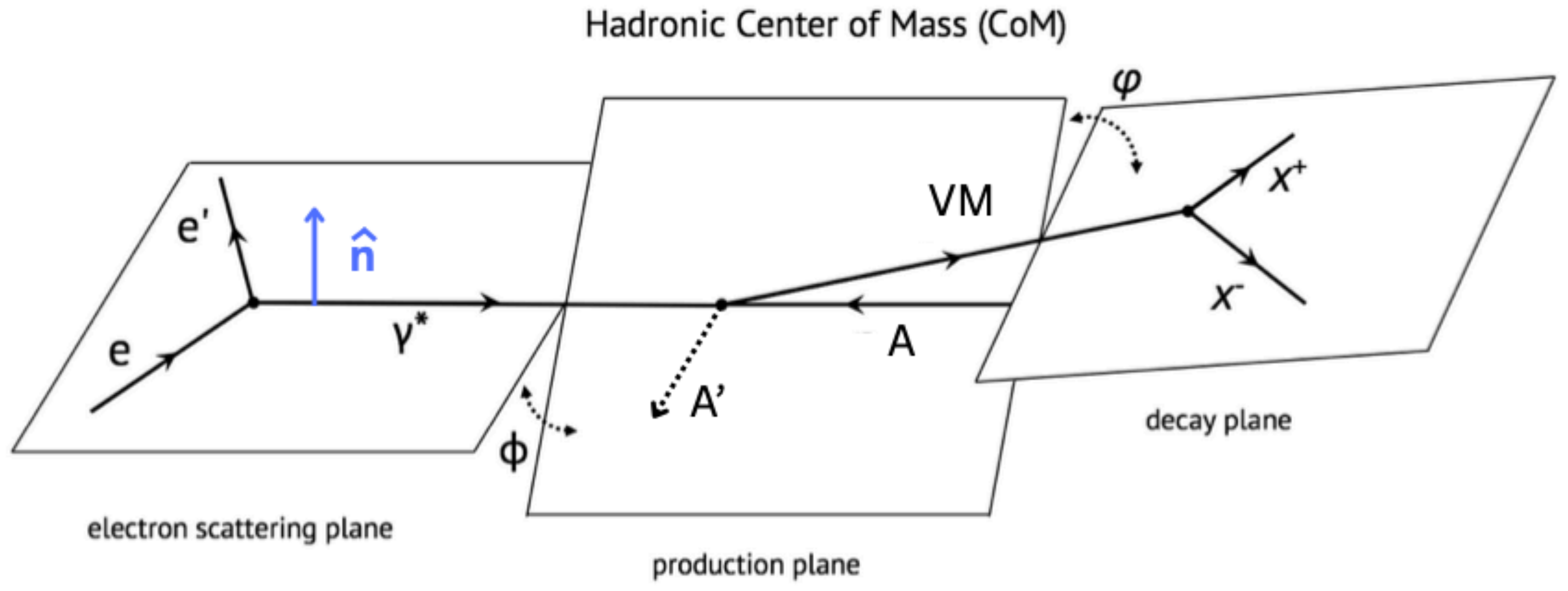
Sensitive to spatial distribution (tomography)

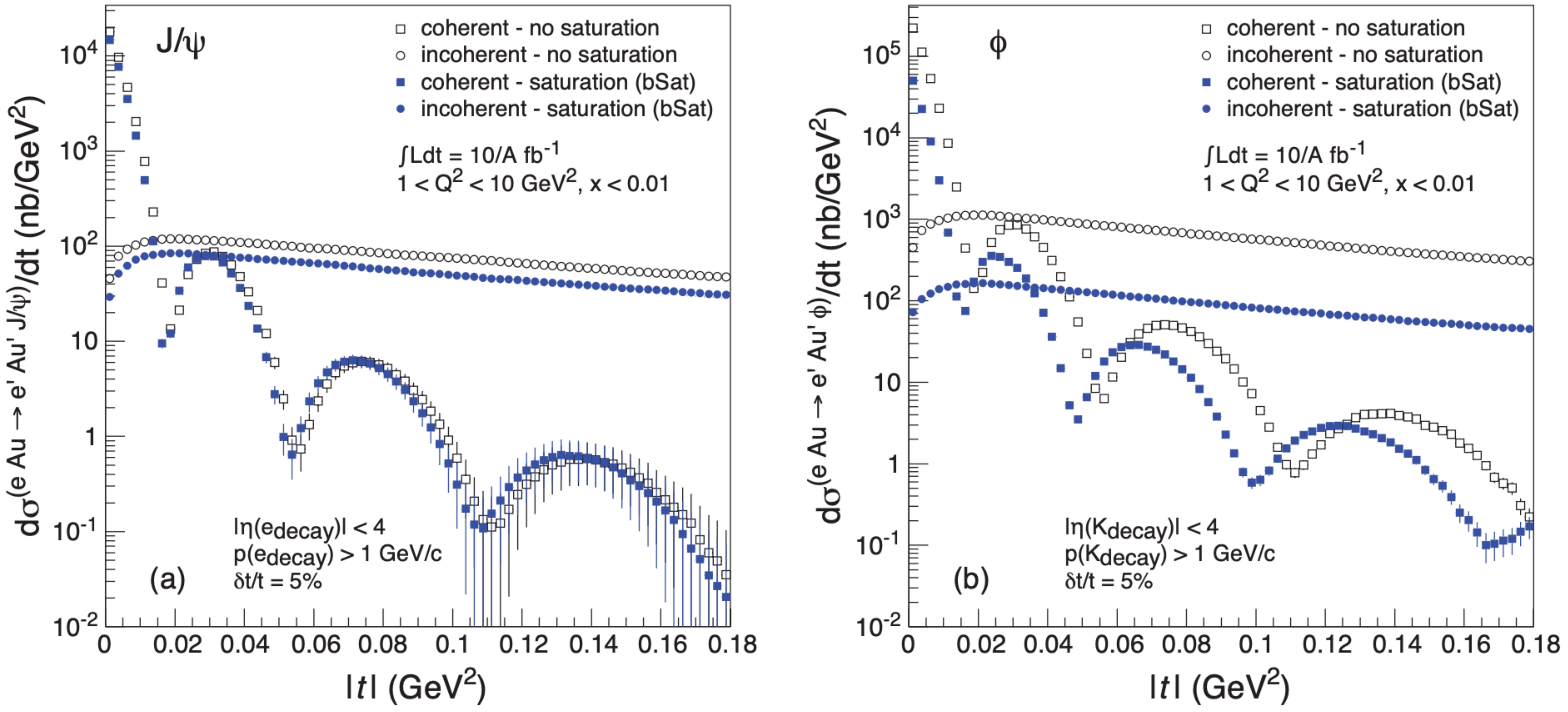
$t = -\boldsymbol{\Delta}_\perp^2$

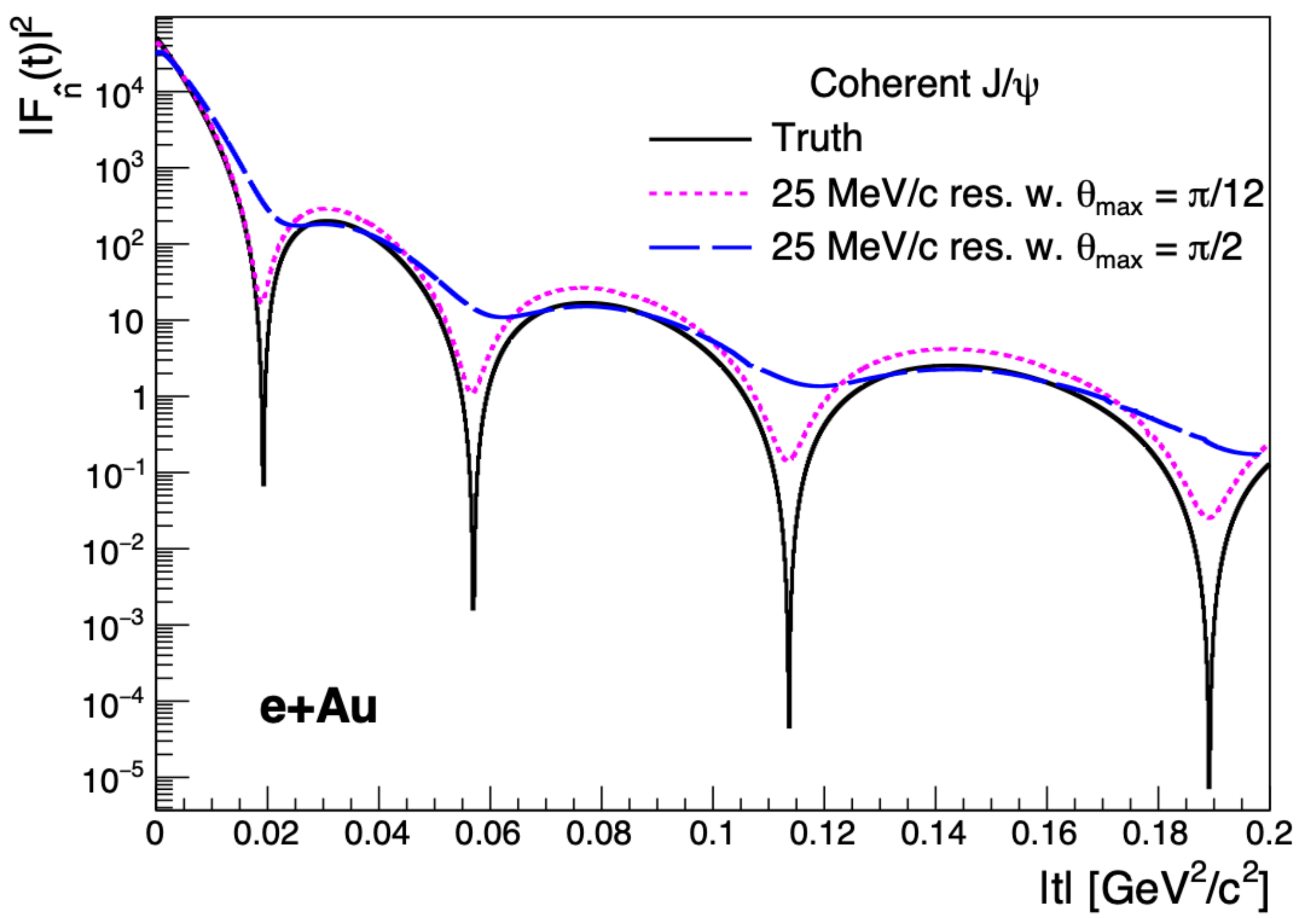
$\boldsymbol{\Delta}_\perp \leftrightarrow \boldsymbol{b}_\perp$

- 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)