Saturation probes: semi-inclusive particle correlations

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Open detector-II Meeting & Discussions
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Outline

- High-energy QCD/CGC in a nutshell
- Two-particle correlations in pA (RHIC and LHC)
- Two-particle correlations in DIS (EIC)
- Experimental requirements

Hadronic and nuclear matter

Deep inelastic scattering (DIS)

microscope to the subatomic world

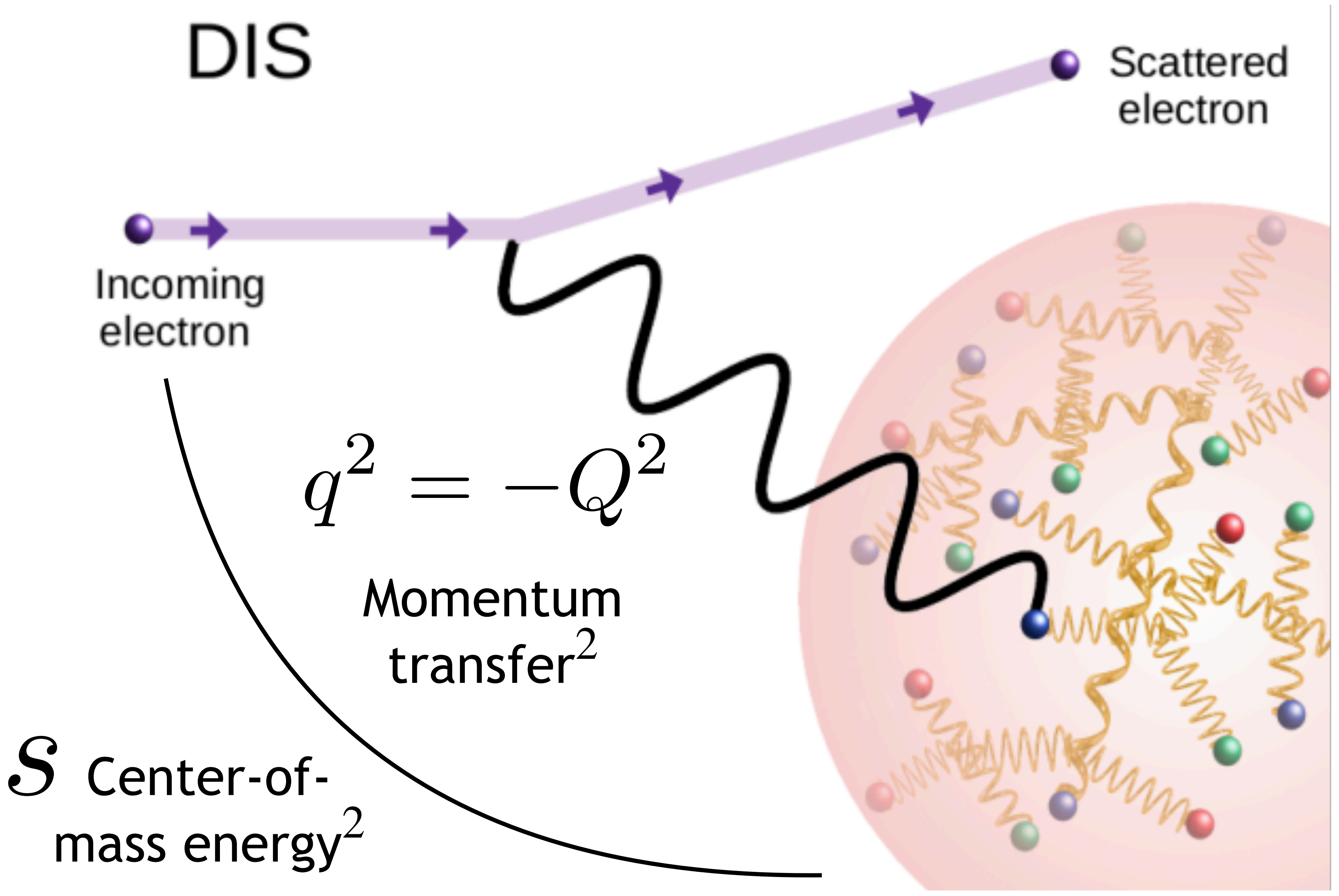
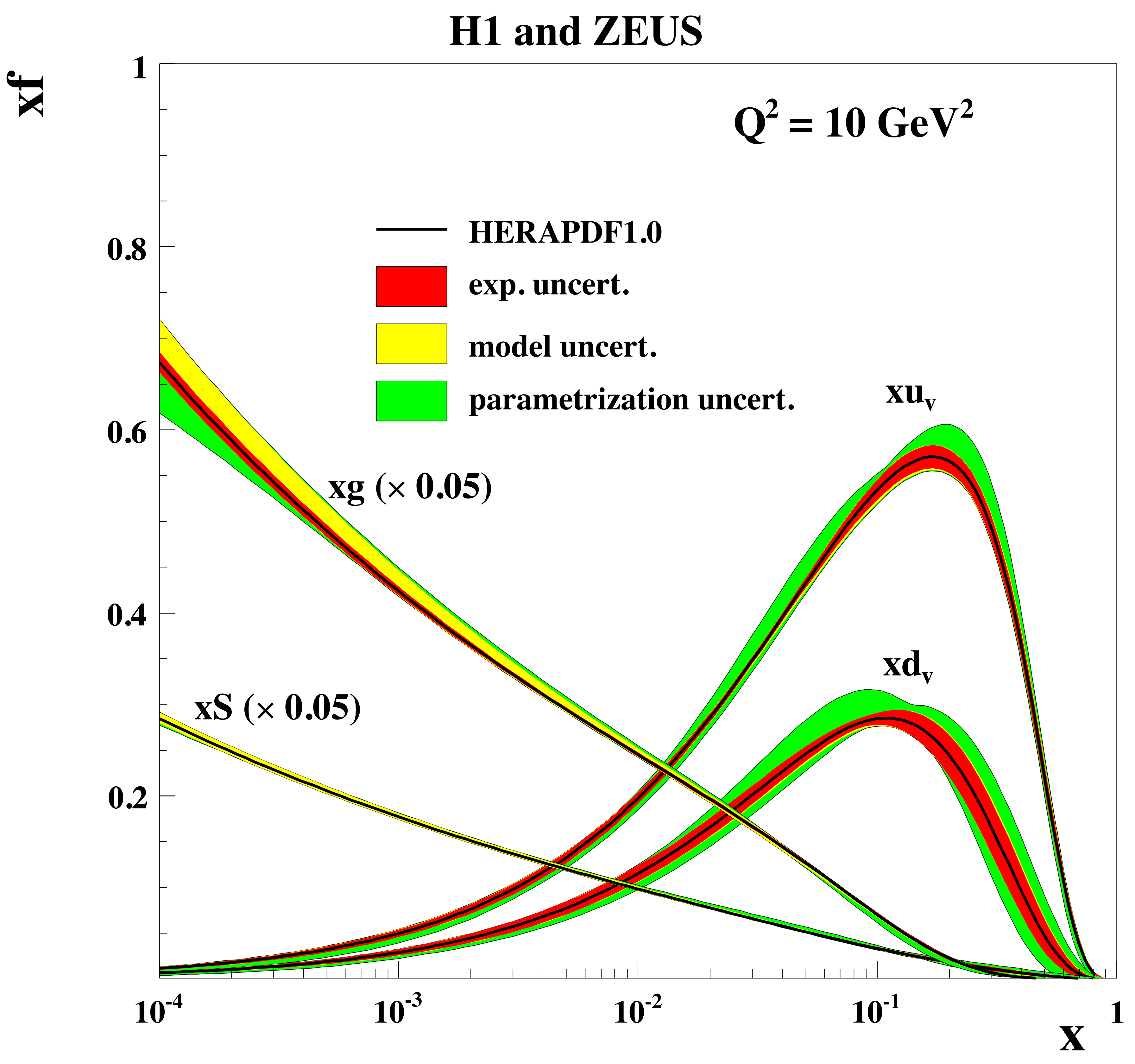


Figure (edited) from ZEUS collaboration



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

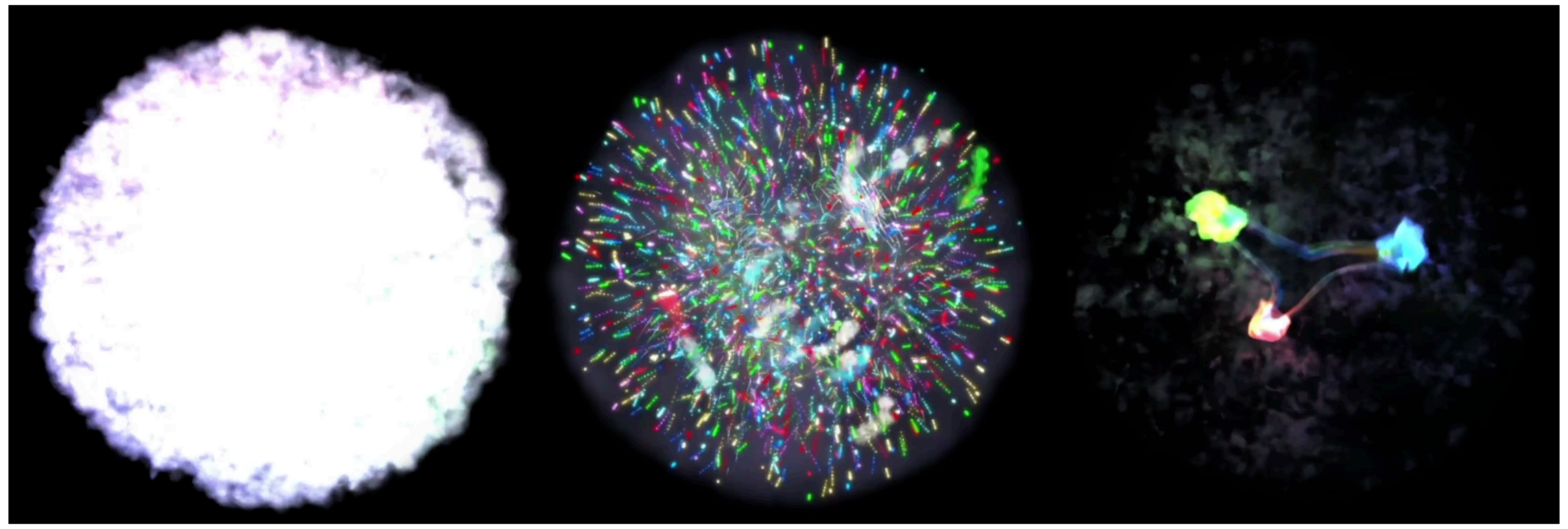
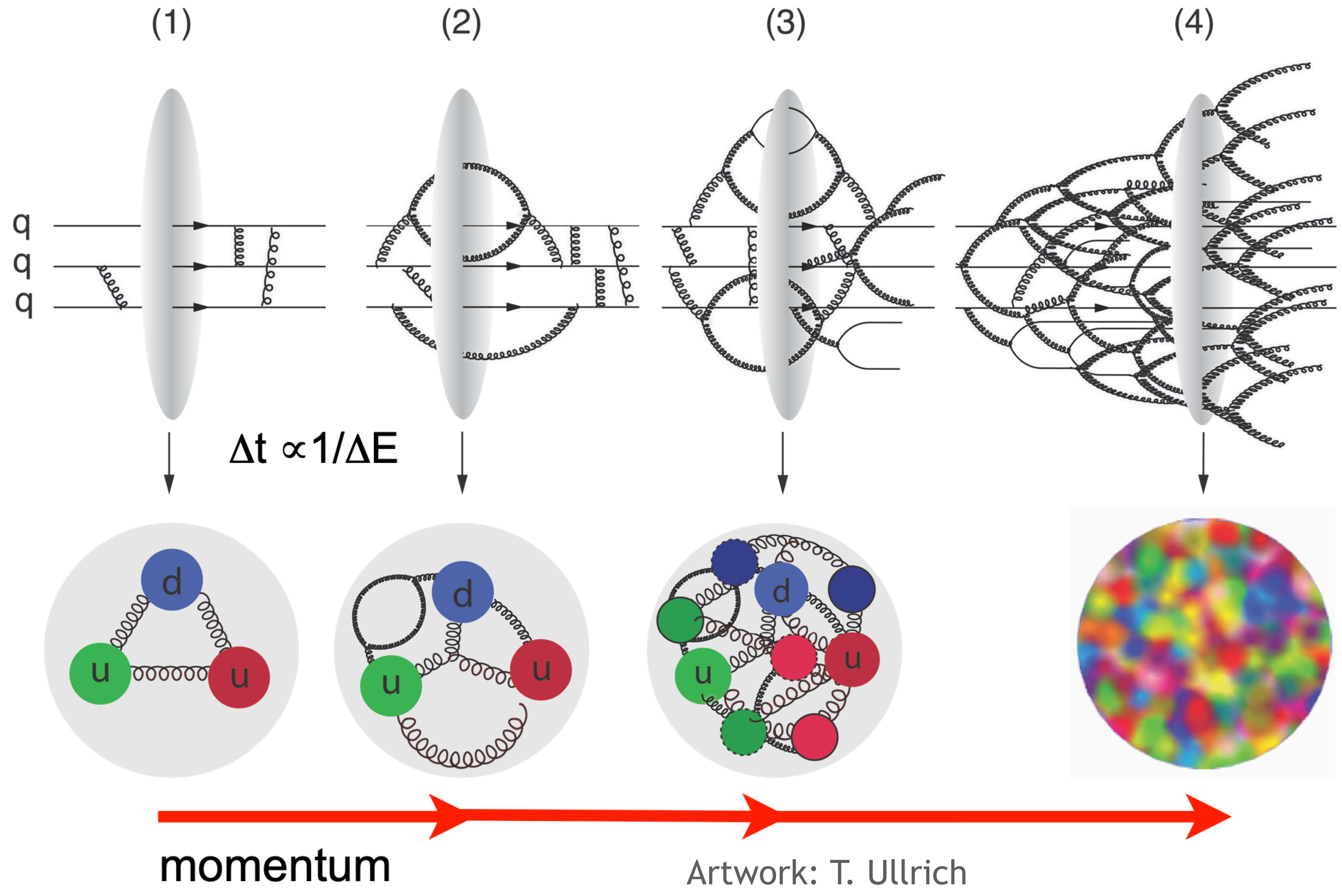


Figure from MIT/Jefferson Lab/Sputnik

Hadronic matter a vibrant QCD environment

Anatomy of nuclear matter at high-energies



Artwork: T. Ullrich

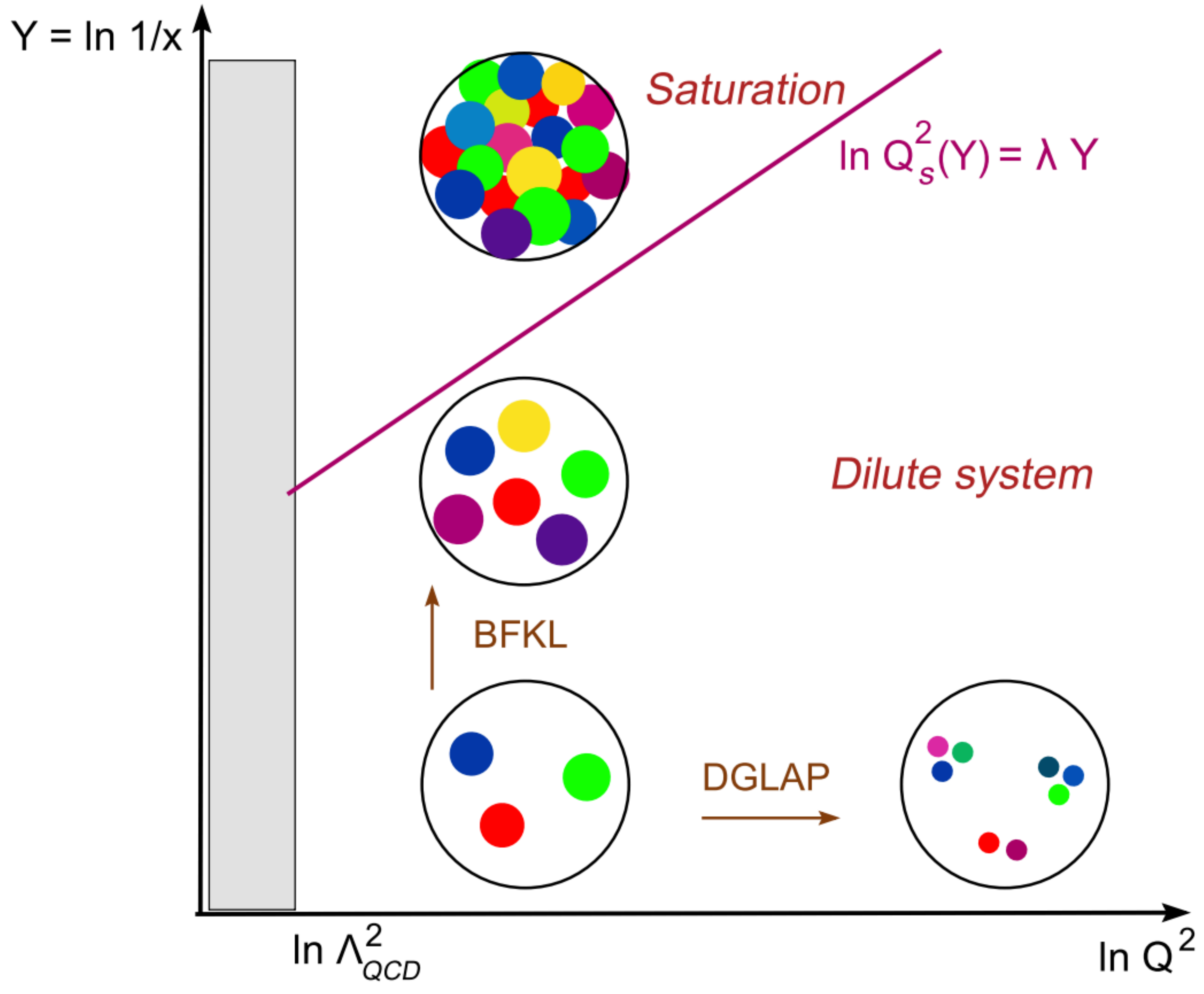


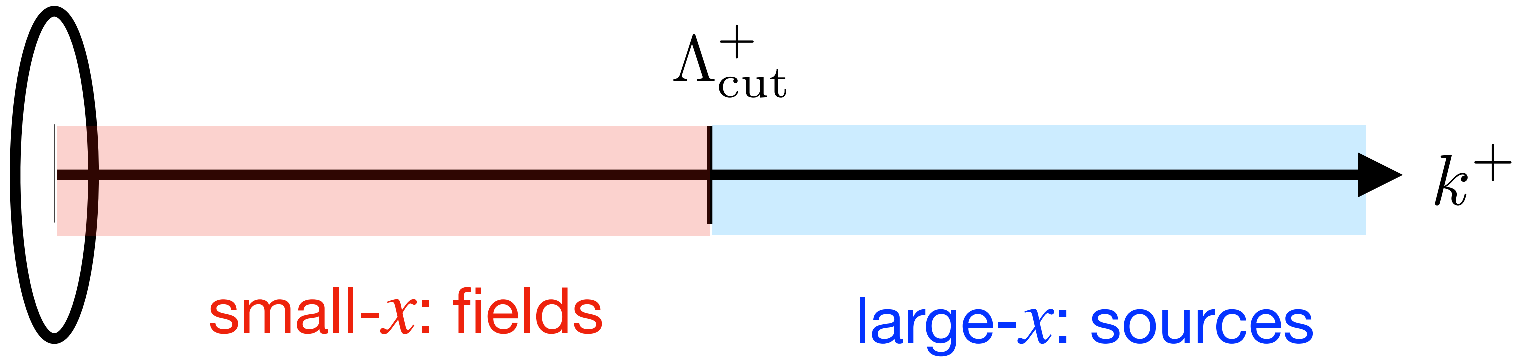
Figure from EIC White paper (2012)

Partonic picture superseded by **strong color fields**

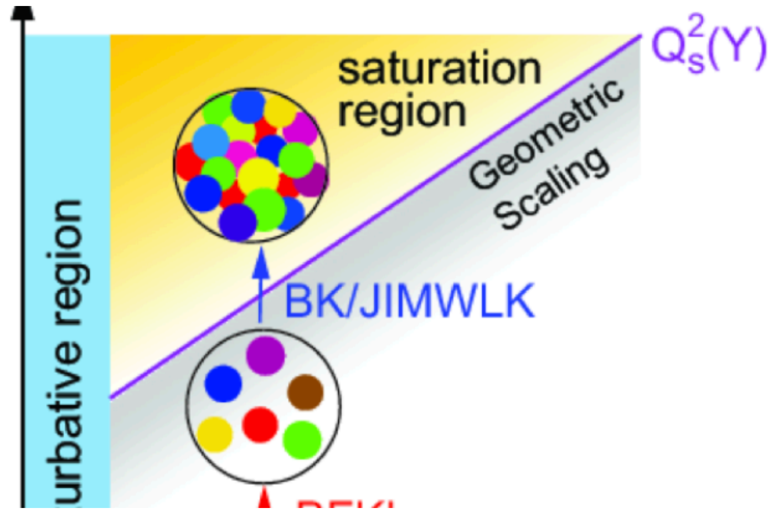
Universality: unified description of QCD at high-energies

The Color Glass Condensate in a nutshell

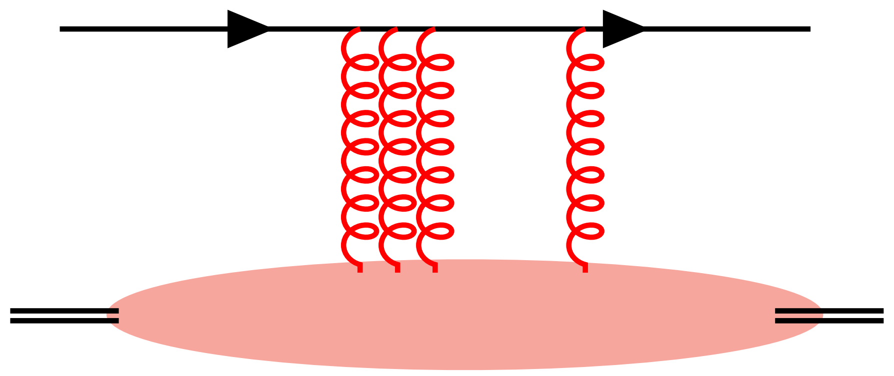
- Separation of degrees of freedom into sources and fields



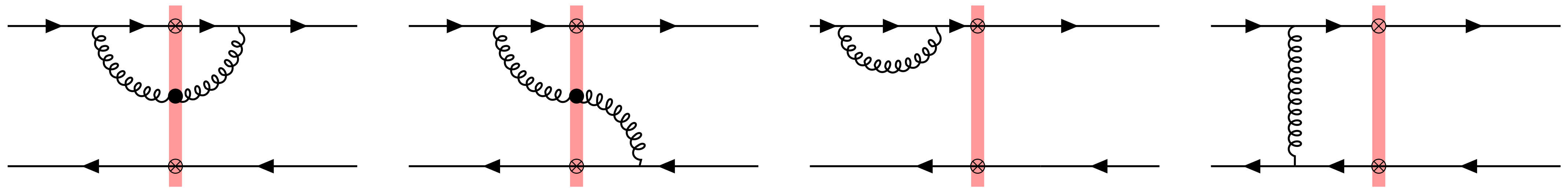
- CGC is an EFT of QCD providing a weak coupling approach for unitarization of cross-section



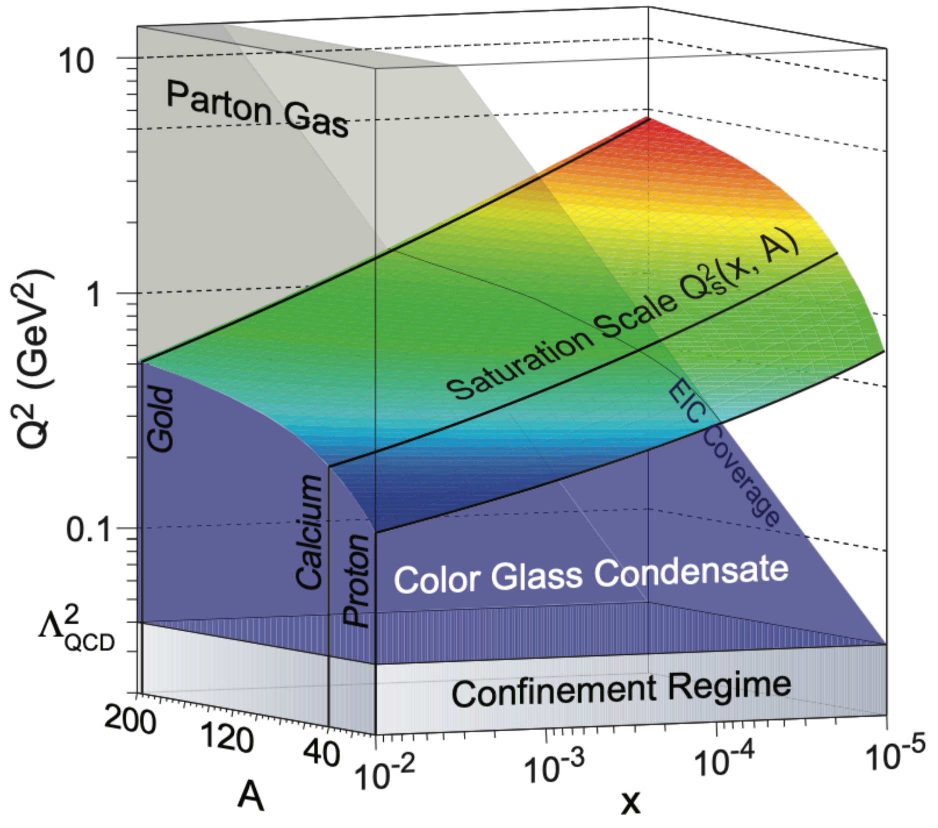
- Strong classical field -> multiple scattering via light-like Wilson lines -> broadening (Glauber)



- Small-x radiation -> quantum (non-linear) evolution of Wilson line correlators-> 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 $M^2 \lesssim Q_s^2(x)$

Power-counting in the CGC

Dilute-dilute: $Q^2_{sA}/k^2_{A\perp} \ll 1$ and $Q^2_{sB}/k^2_{B\perp} \ll 1$

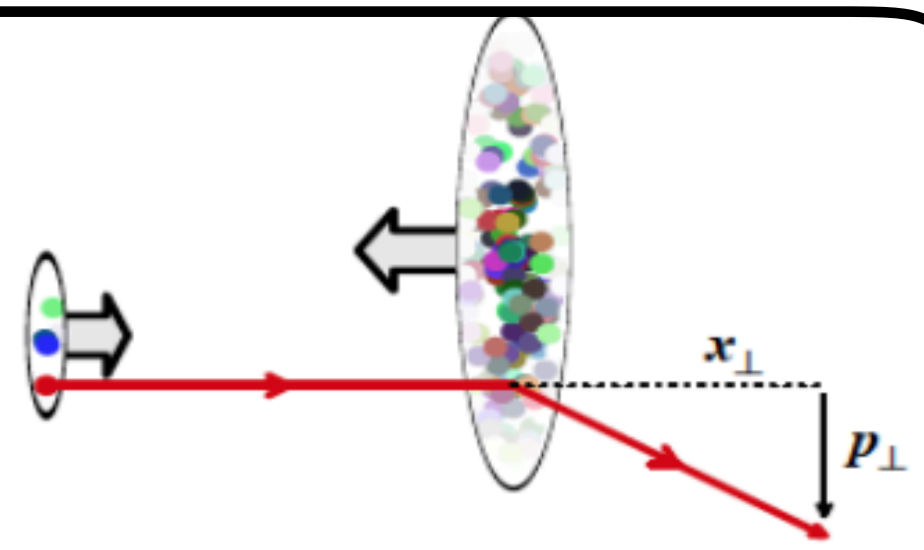
Match to pQCD computation of hard processes at small x

Hard production in hadron collisions

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

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

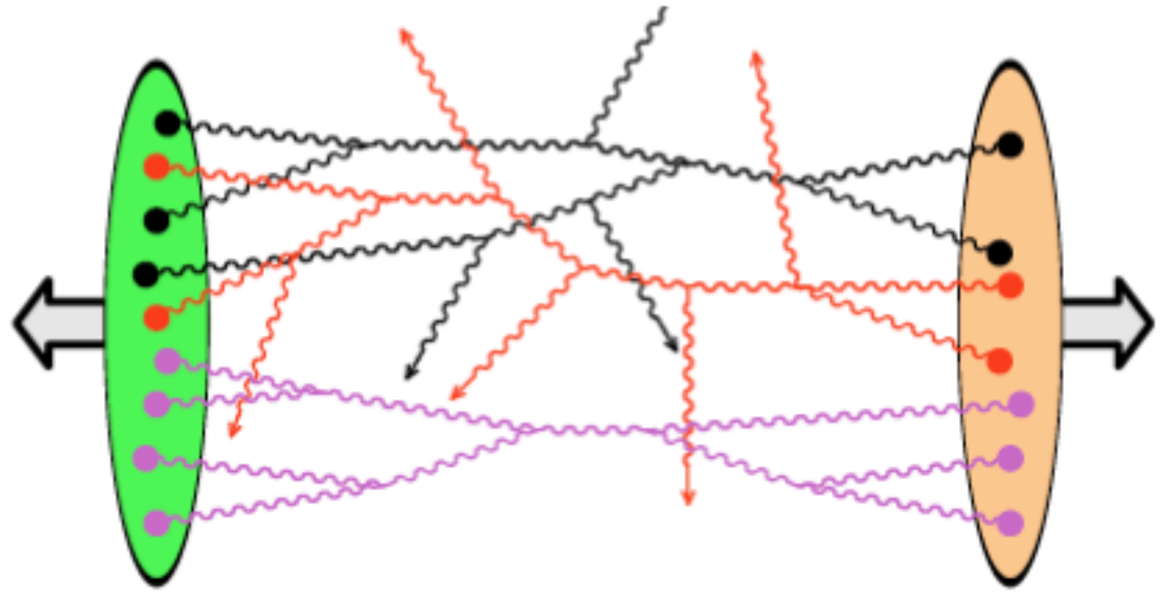
Semi-hard and forward particle production in proton-nucleus, electron-nucleus collisions



Dense-dense: $Q^2_{sA}/k^2_{A\perp} \sim 1$ and $Q^2_{sB}/k^2_{B\perp} \sim 1$

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

Semi-hard particle production in heavy-ion collisions



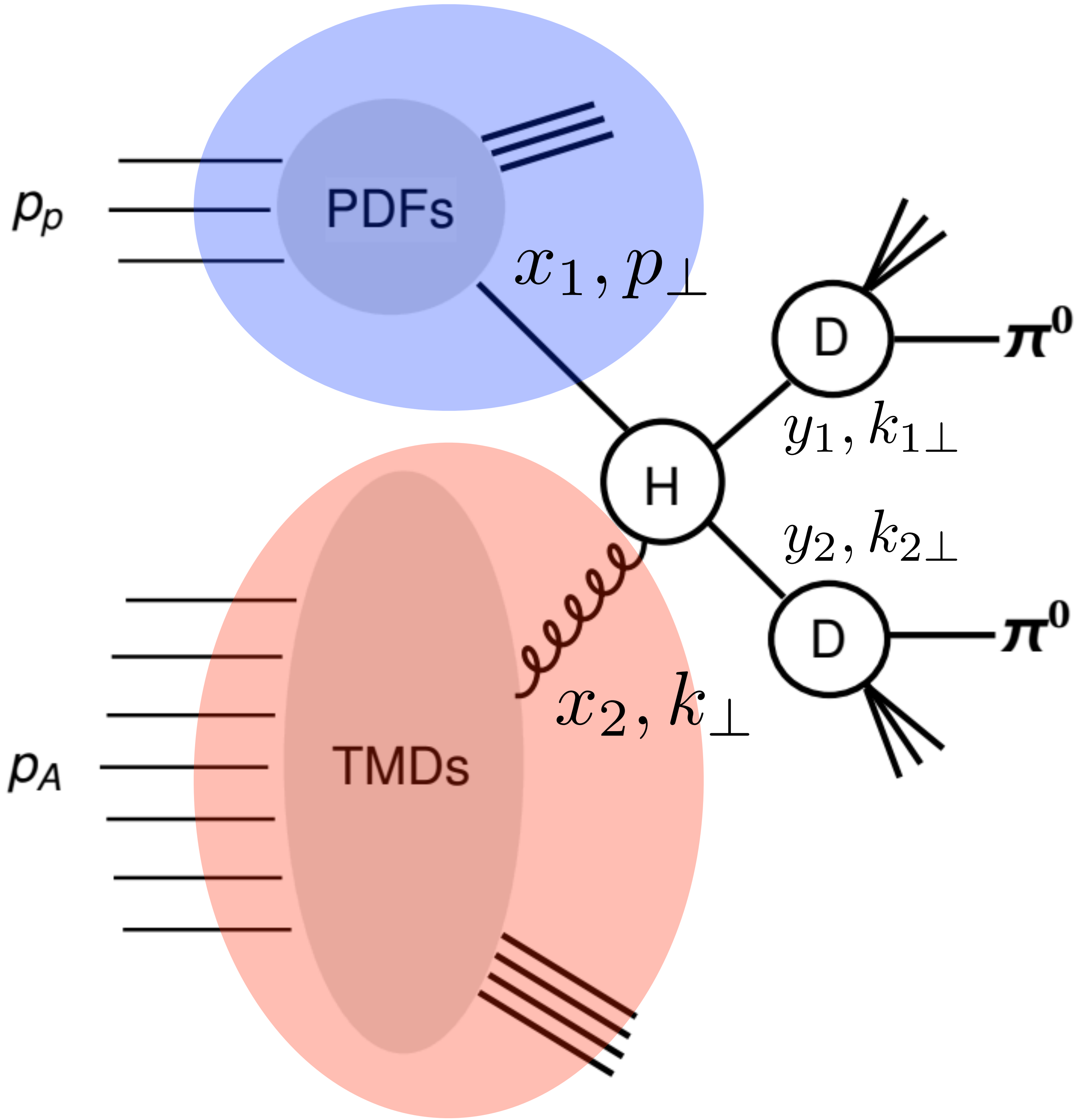
Regime is dictated by the colliding system, energy, centrality, rapidity, and transverse momentum of observed particles

Two particle correlations in pA

Saturation imprint into correlations

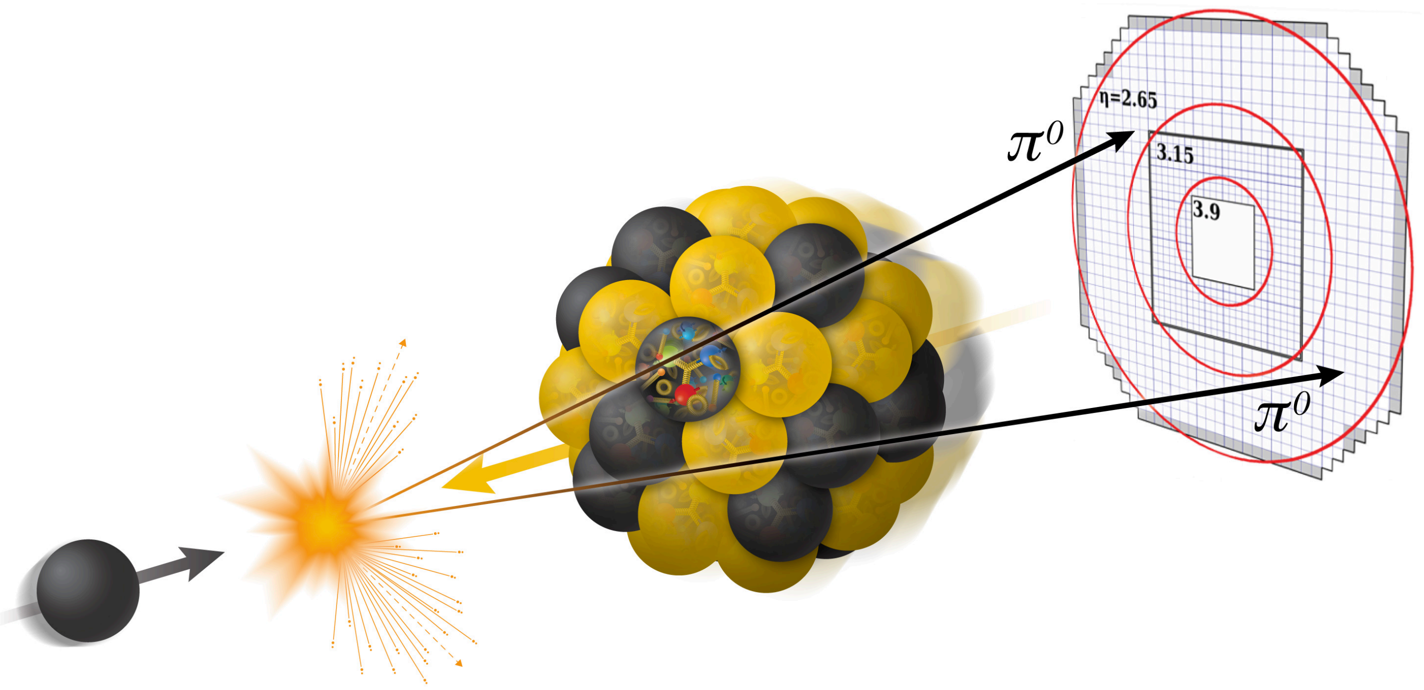
Azimuthal correlations as a probe for gluon saturation proposed
by D. Kharzeev, E. Levin, L. McLerran *(2005)*

TMD formalism at small-x was established
by F. Dominguez, C. Marquet, B.W. Xiao, F. Yuan (2011)



$$x_1 = \frac{1}{\sqrt{s}}(k_{1\perp}e^{y_1} + k_{2\perp}e^{y_2}) \sim 1$$

$$x_2 = \frac{1}{\sqrt{s}}(k_{1\perp}e^{-y_1} + k_{2\perp}e^{-y_2}) \ll 1$$

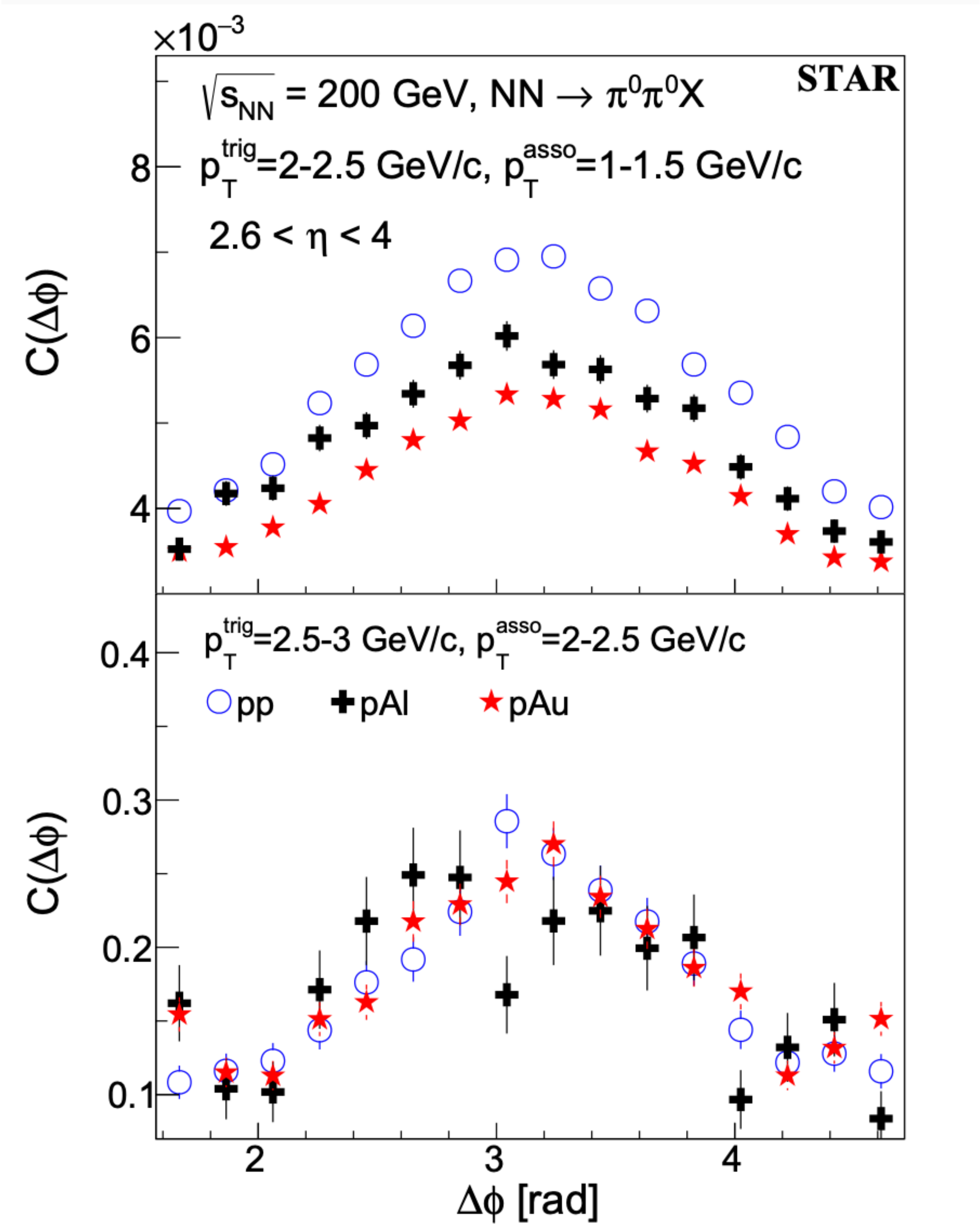


$p_\perp \sim \Lambda_{\mathrm{QCD}}$ $\quad$ $k_\perp \sim Q_s(x_2)$ $\quad$ $Q_s(x_2) \gg \Lambda_{\mathrm{QCD}}$

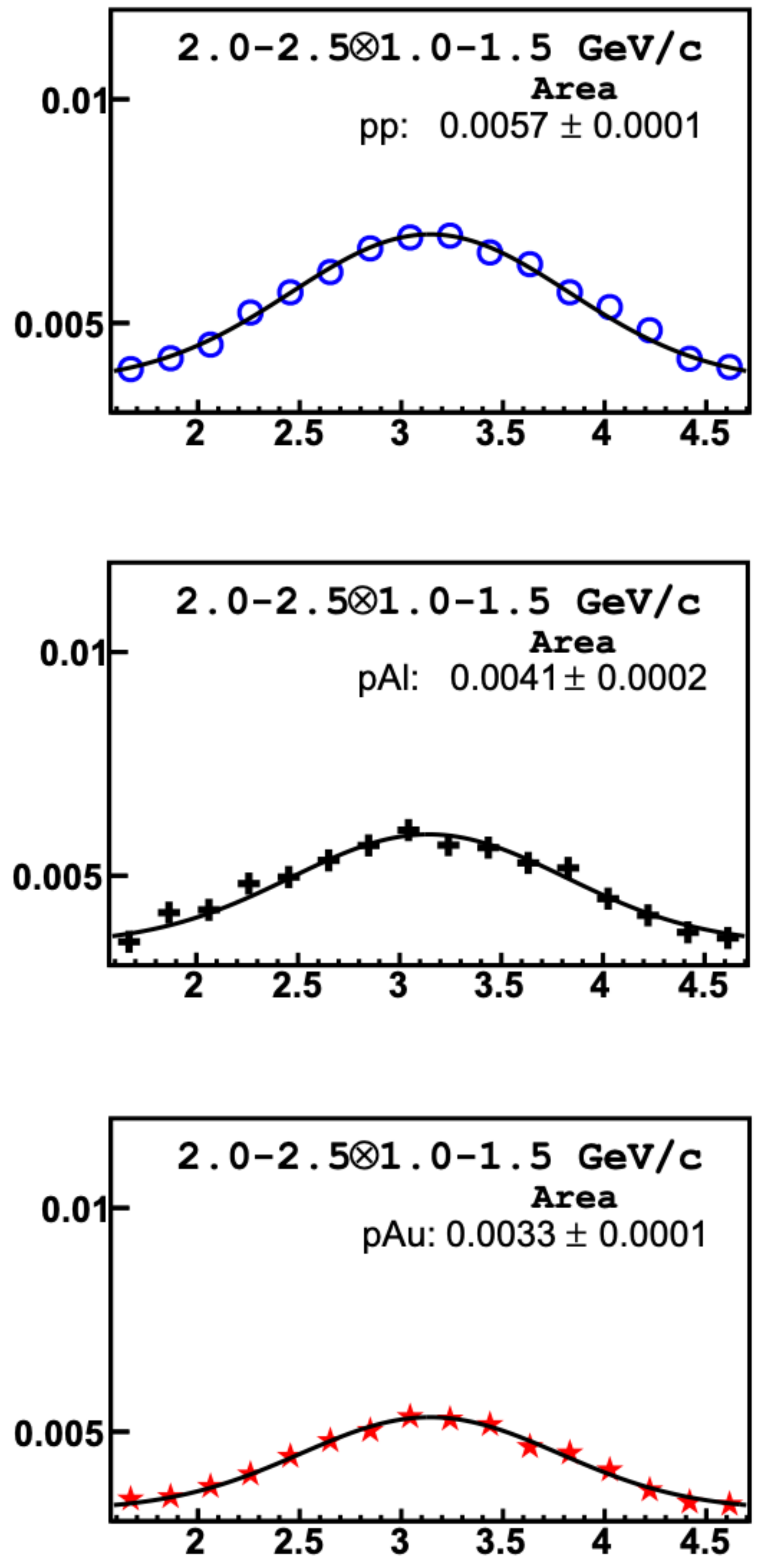
Figure from Albacete et al (*Phys.Rev.D 99 (2019) 1, 014002)*

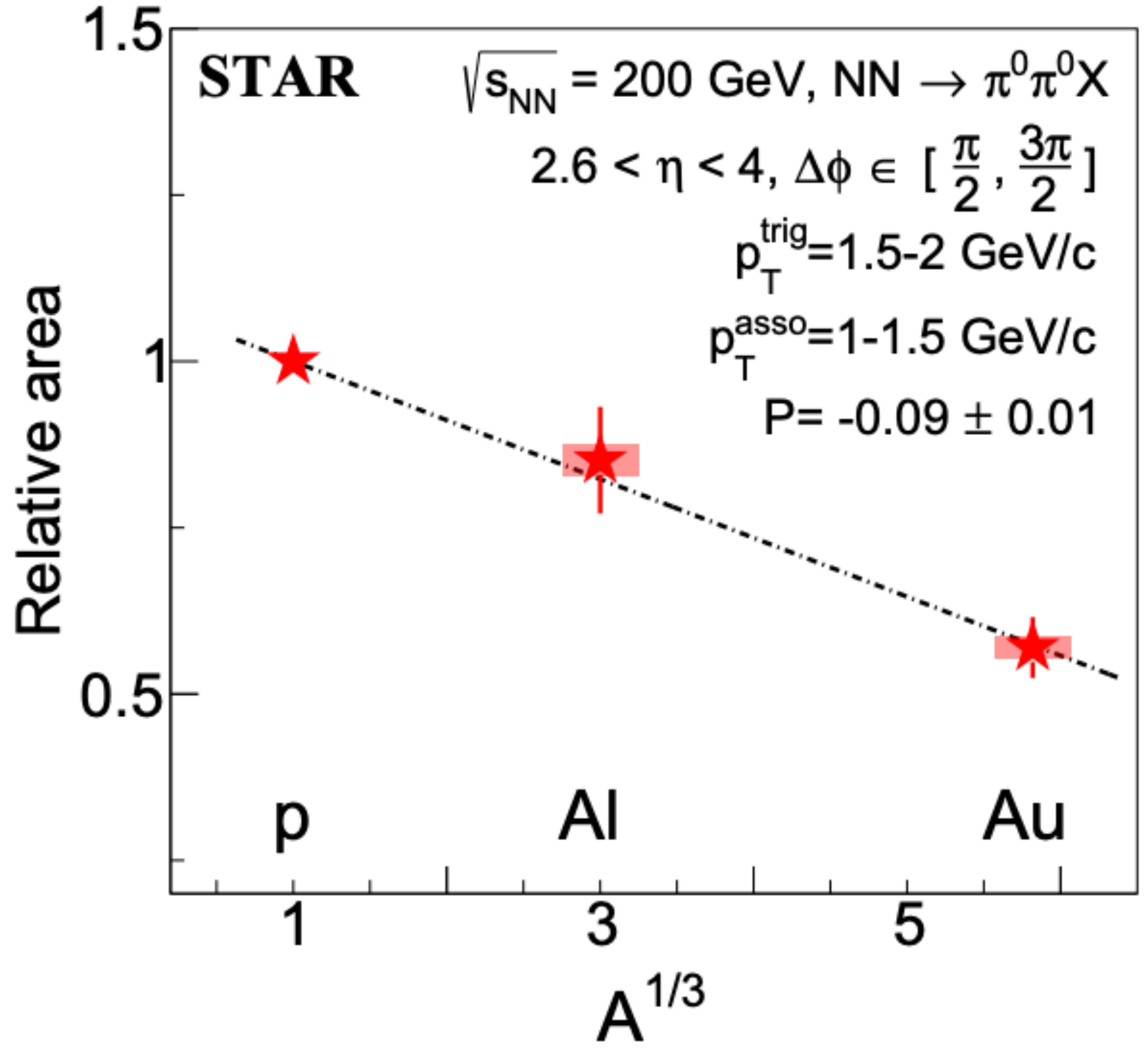
Two particle correlations at RHIC

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



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



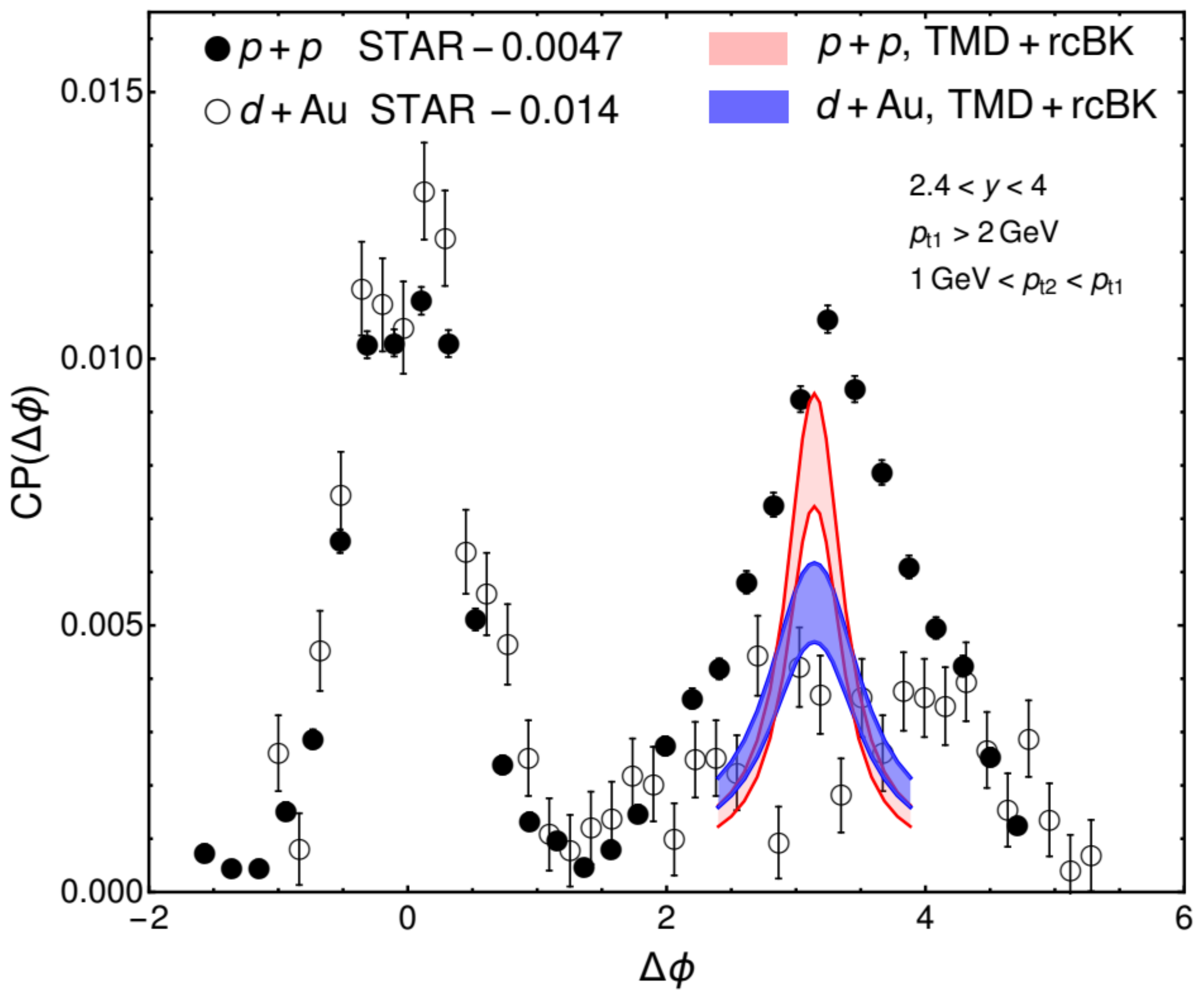


Suppression characteristic of saturation

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

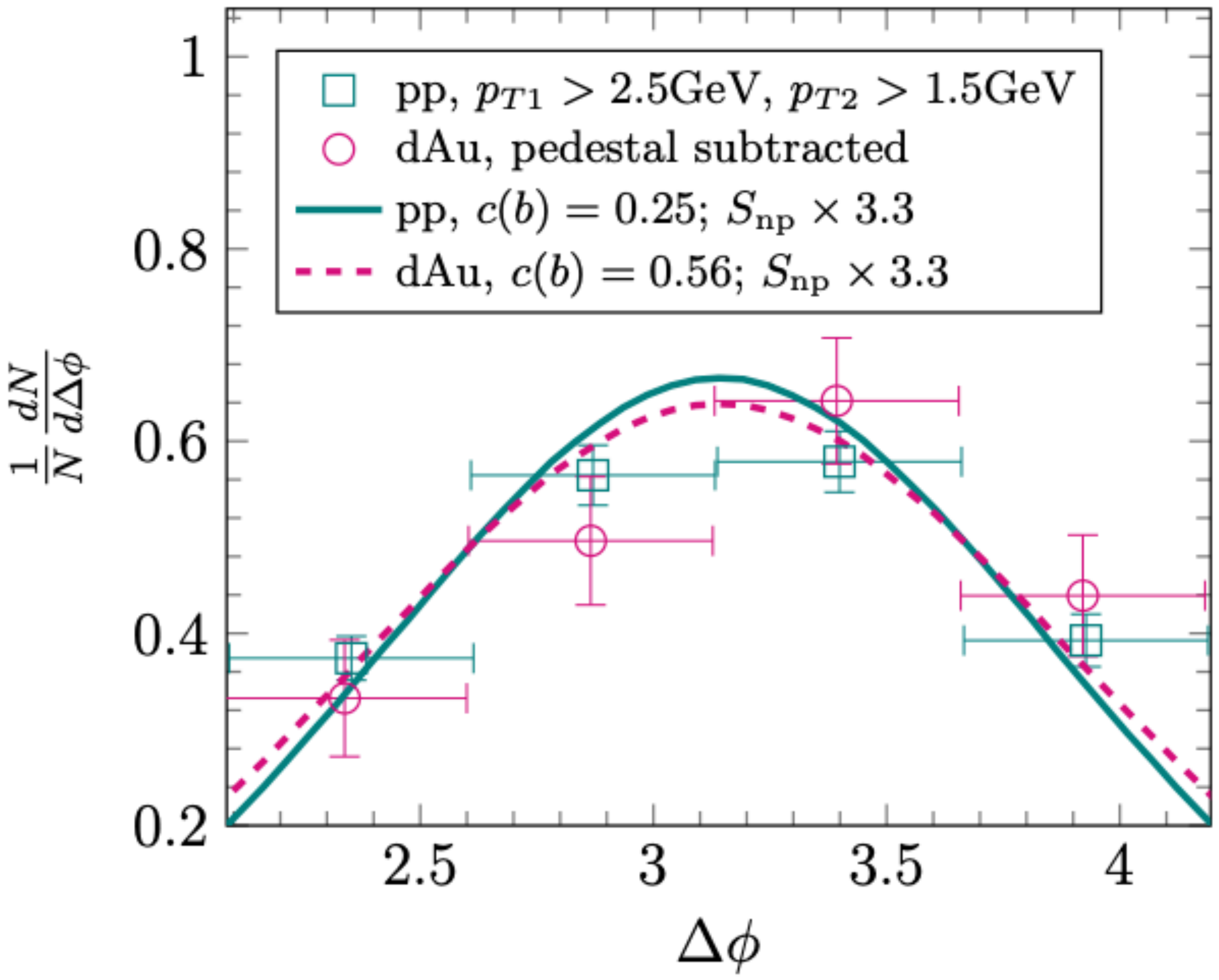
Two particle correlations at RHIC

Existing CGC-based predictions



CGC based calculation including small-x evolution
Albacete et al (2019)

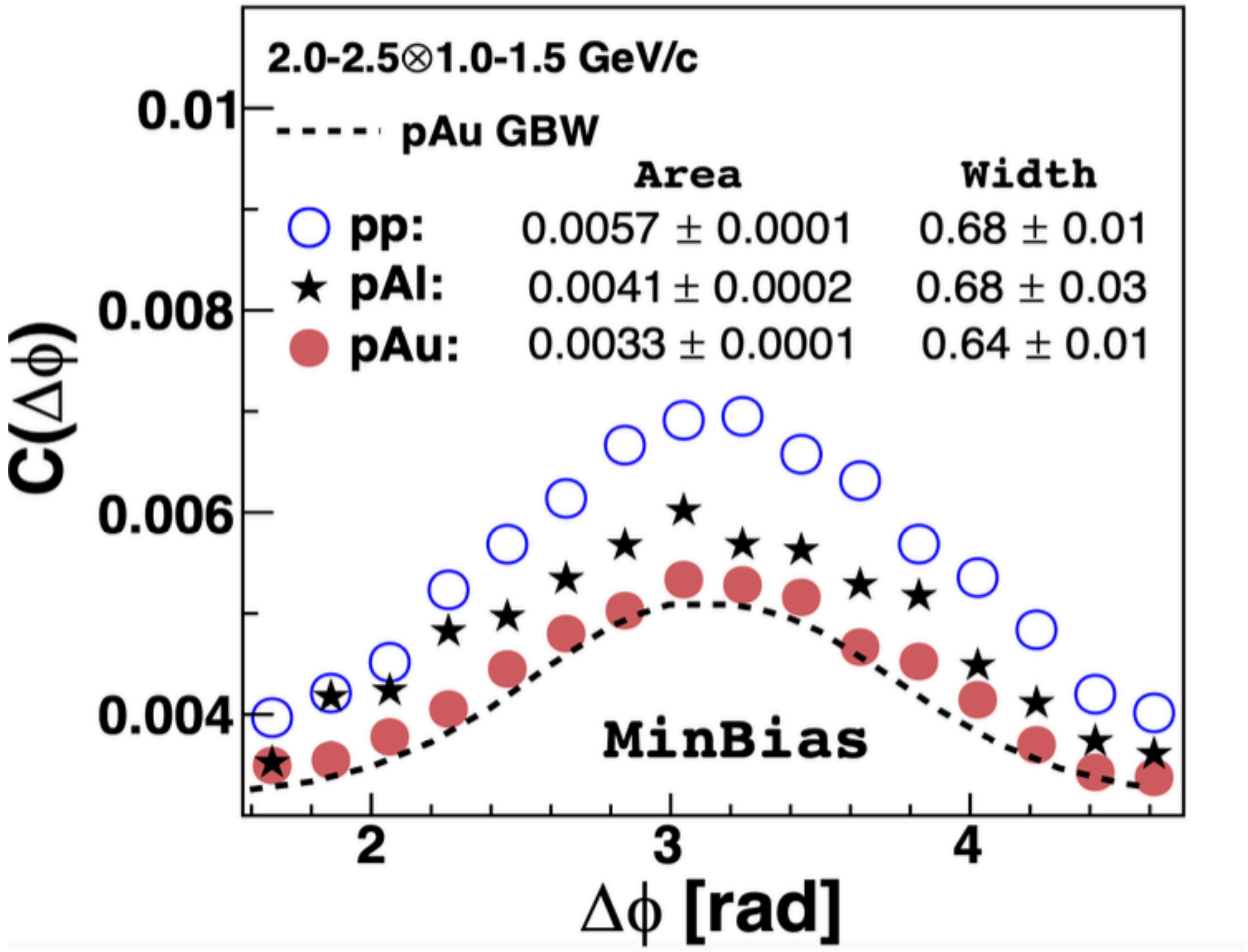
Suppression reasonably well-described
but width largely underestimated



Saturation-model (GBW) + Sudakov
Stasto, Wei, Xiao, Yuan (2019)
Adding Sudakov results good description of the width
Comparison only done for self-normalized cross-section
Not possible to see the suppression

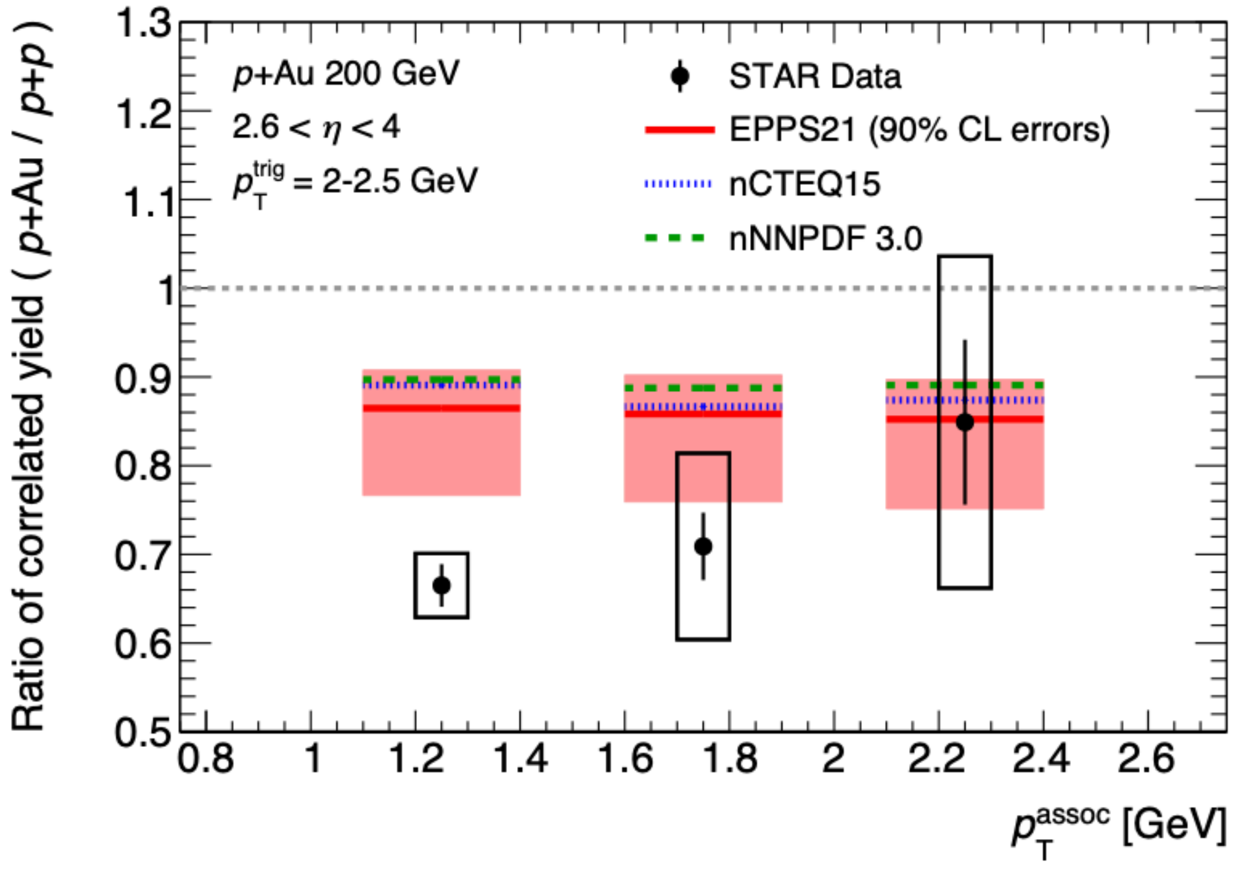
Two particle correlations at RHIC

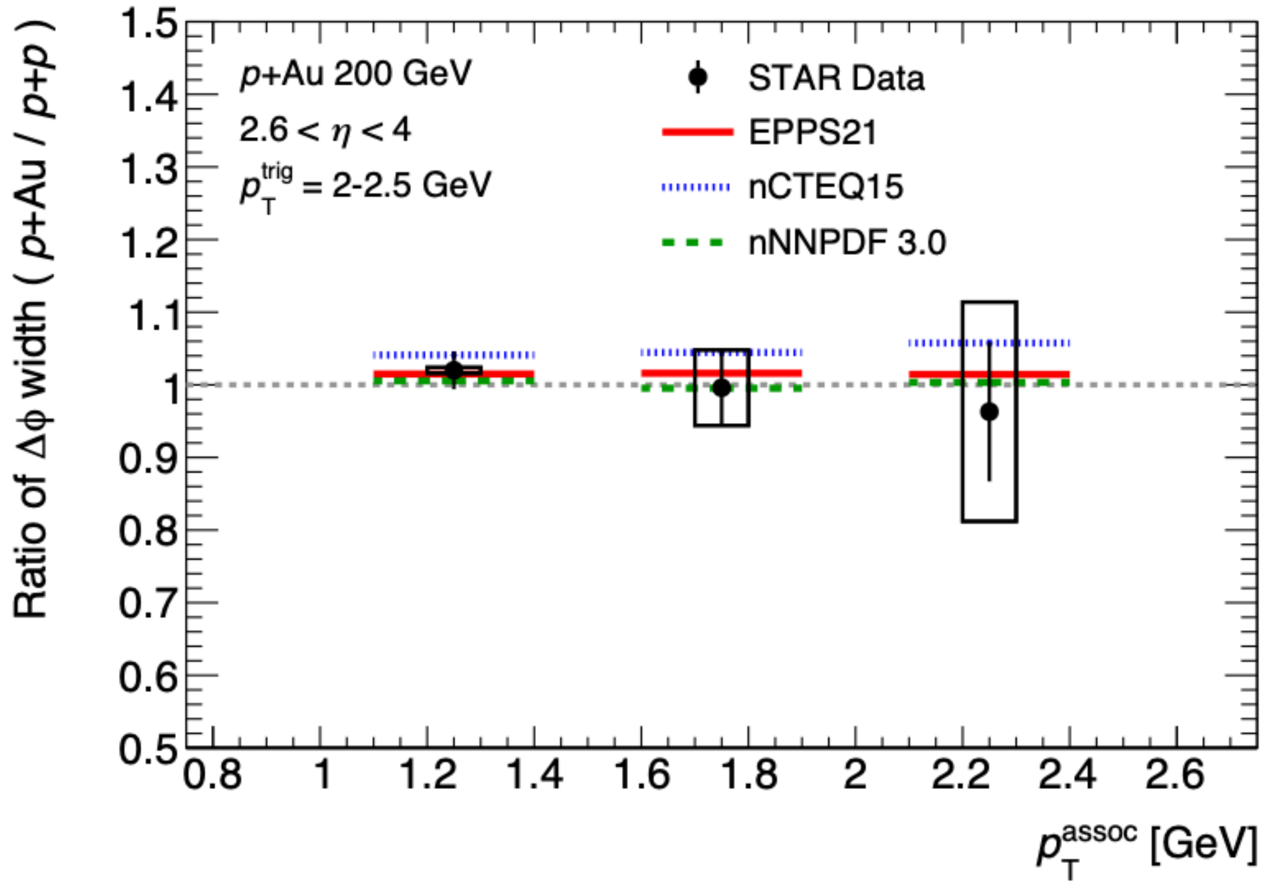
nPDF or saturation?

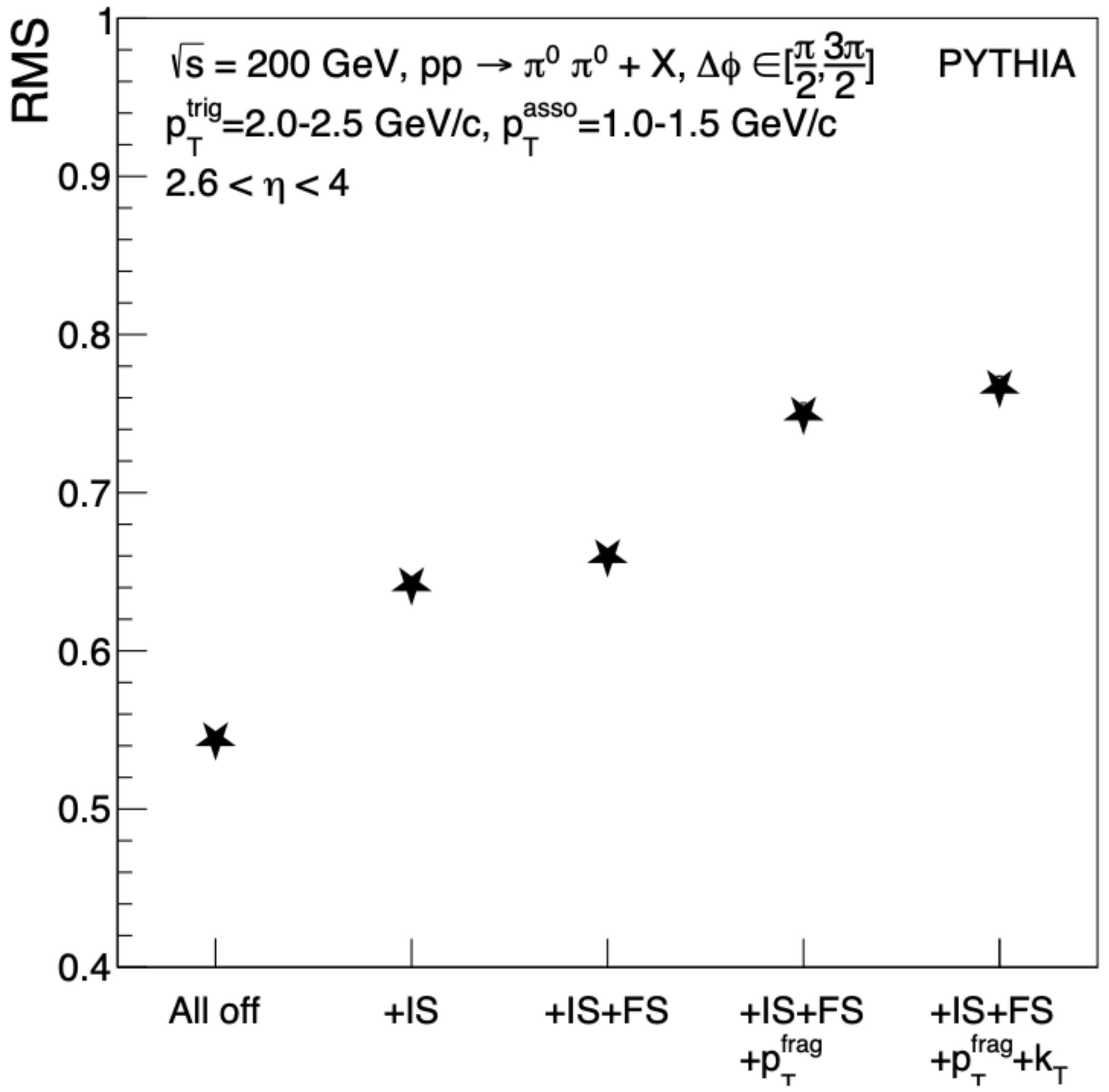


STAR (2021)

- 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

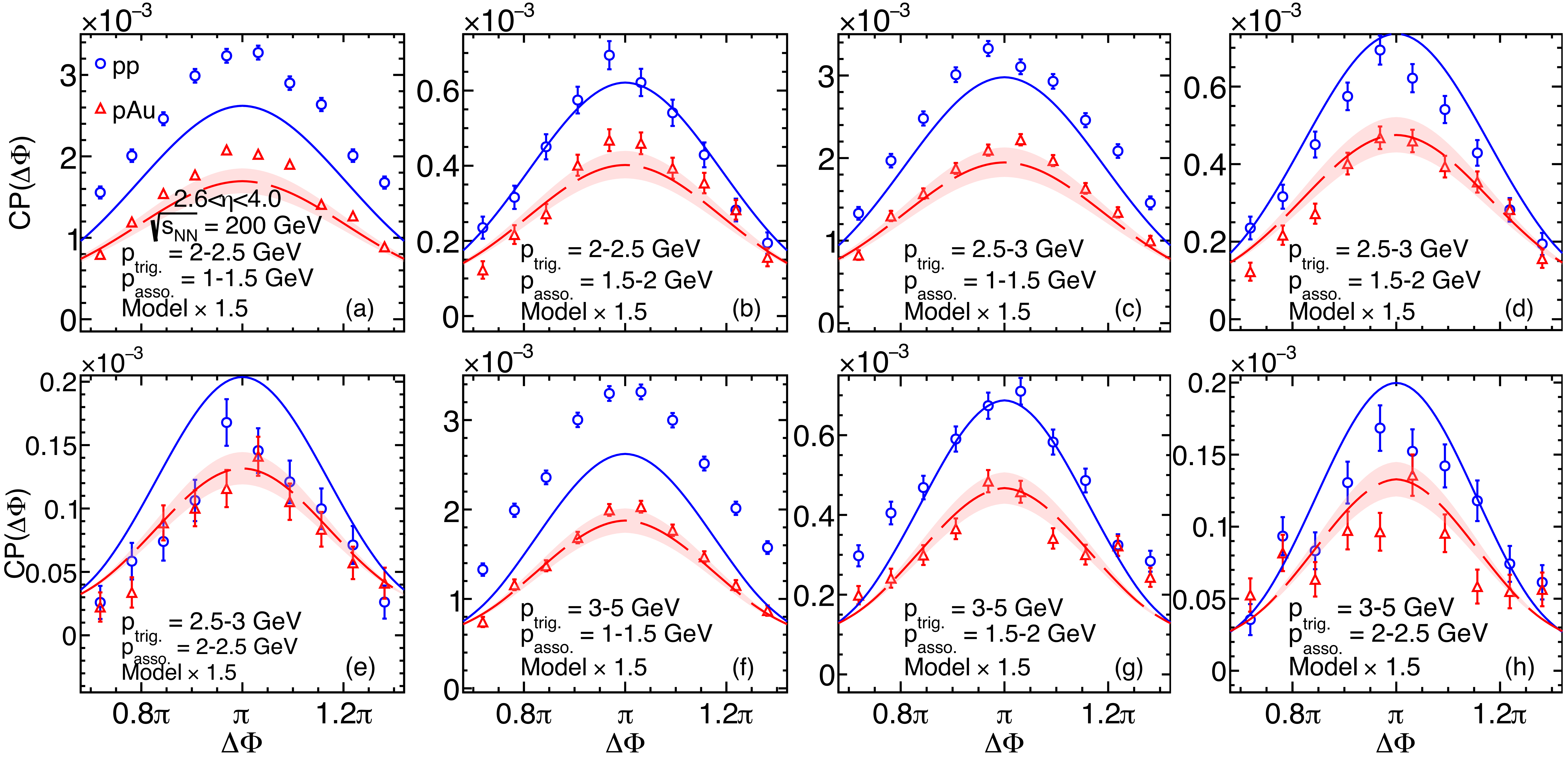
Two particle correlations at RHIC

Our setup

- First numerical results for di-hadron based on CGC with small-x evolution and Sudakov (both perturbative and non-perturbative part)
- Initial conditions of small-x gluon TMD constrained by fits to HERA data (proton), and nucleus constructed via Glauber at $x = 0.01$ and minimum bias events account for realistic impact parameter-dependent density of nucleus (Woods-Saxon)
- PDF and FF functions from JAM collaboration (comparable results to DSS)
- Non-perturbative Sudakov following SIYY parametrization. Compared to DY and SIDIS NP Sudakov for di-hadrons requires to be larger (factor of 2). Non-universality?

Caucal, Kang, Korcyl, Salazar, Schenke, Stebel, Venugopalan, Zhao
(in progress)

Two particle correlations at RHIC

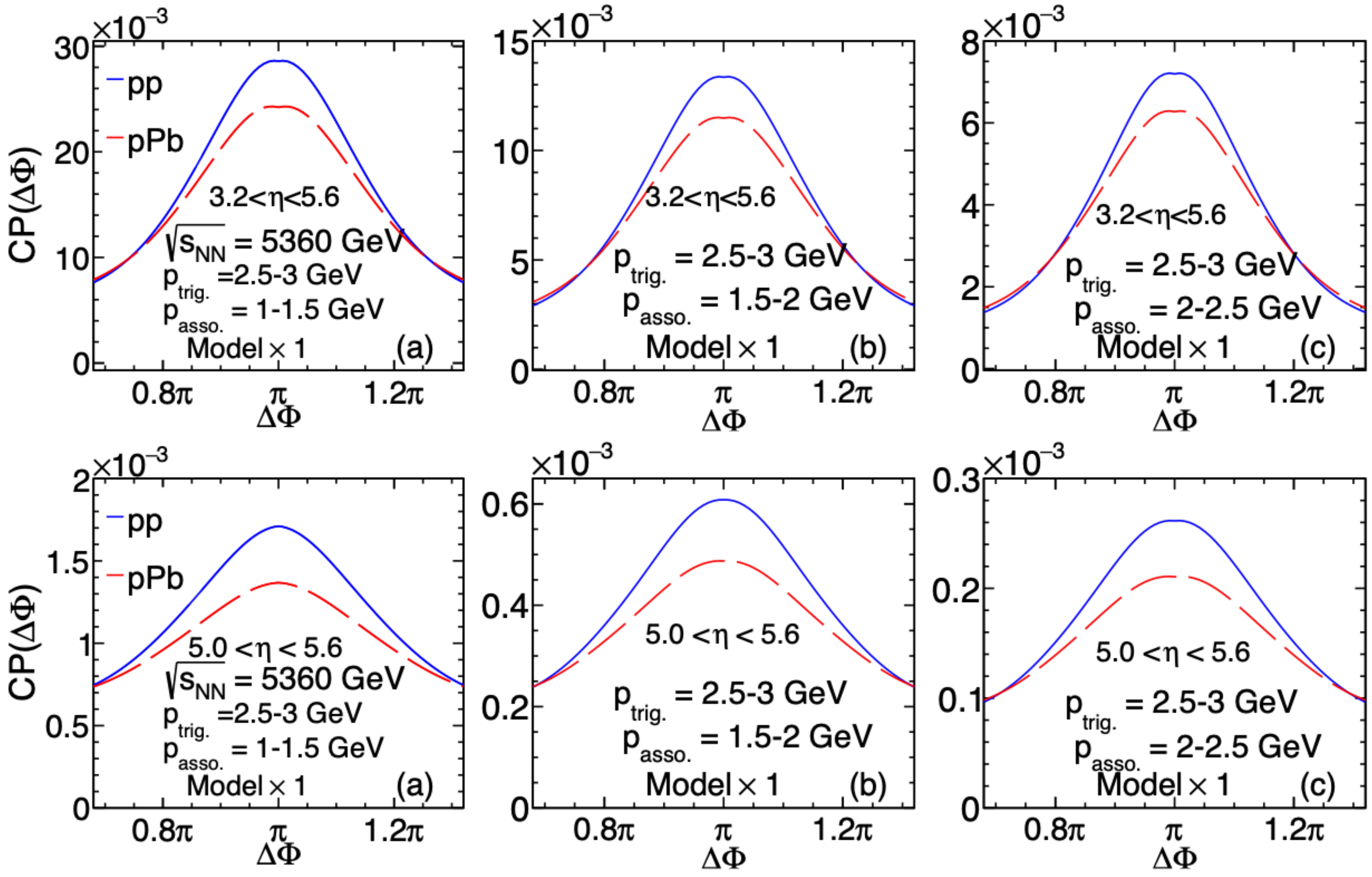


Reasonable description of suppression

Challenging to describe the overall normalization for all pT bins. Fragmentation functions are poorly constrained at low pTs.

Caucal, Kang, Korcyl, Salazar, Schenke, Stebel, Venugopalan, Zhao (in progress)

Two particle correlations at LHC FoCal



Less suppression at LHC energies despite the smaller values of x, since at these energies hadrons are produced by partons at larger transverse momenta (enhanced phase space)

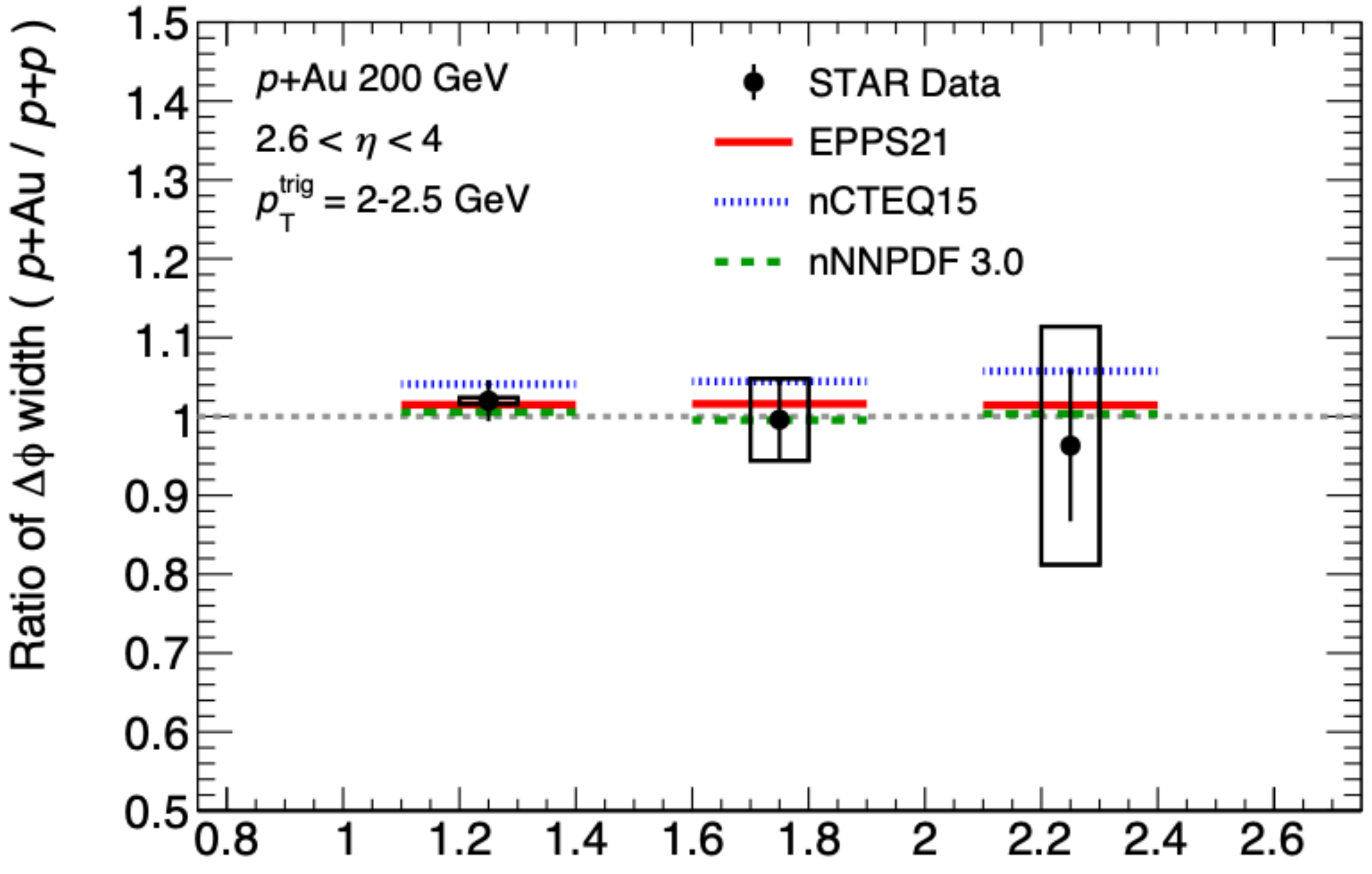
Caucal, Kang, Korcyl, Salazar, Schenke, Stebel, Venugopalan, Zhao (in progress)

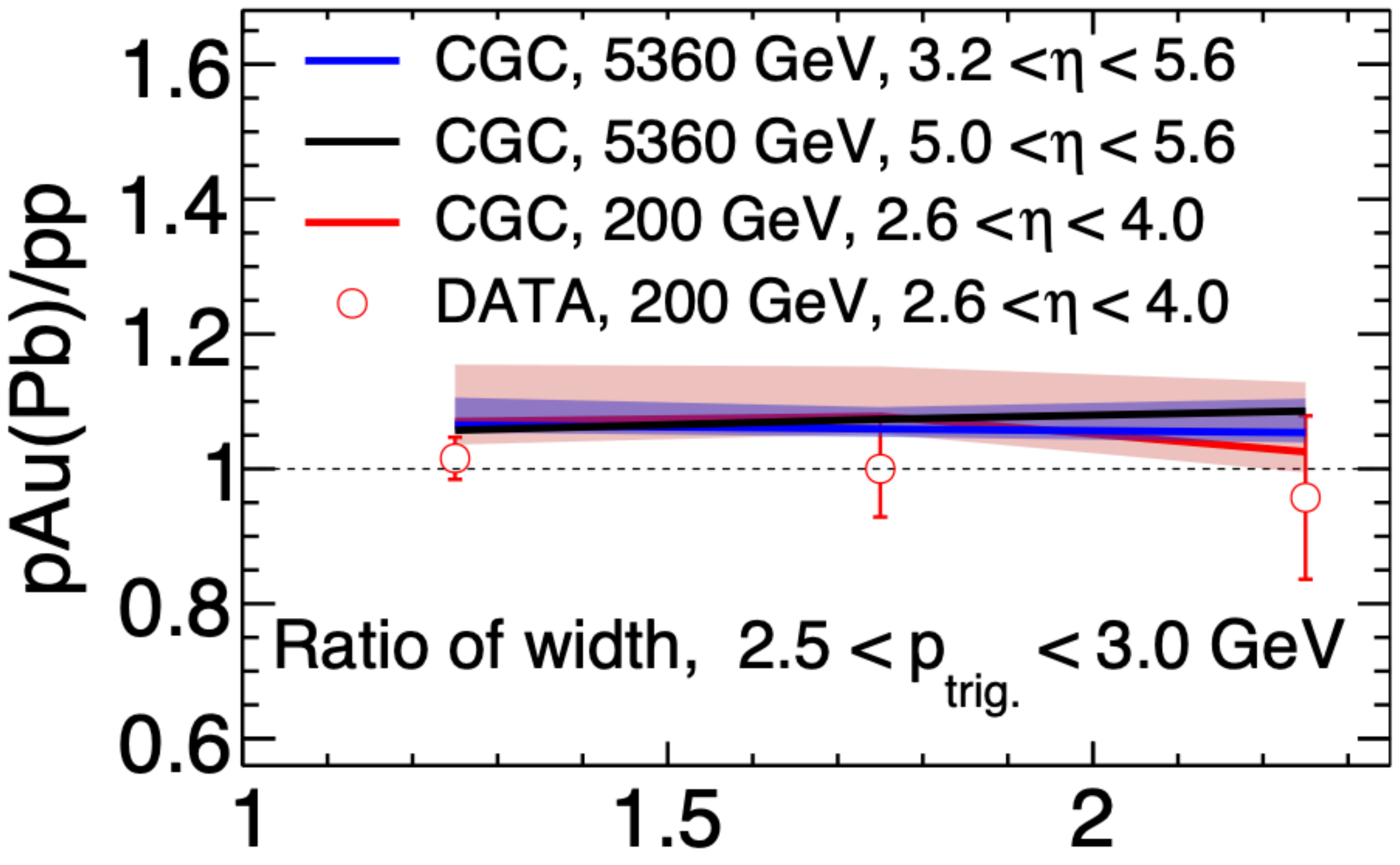
Suppression and broadening

nPDF based

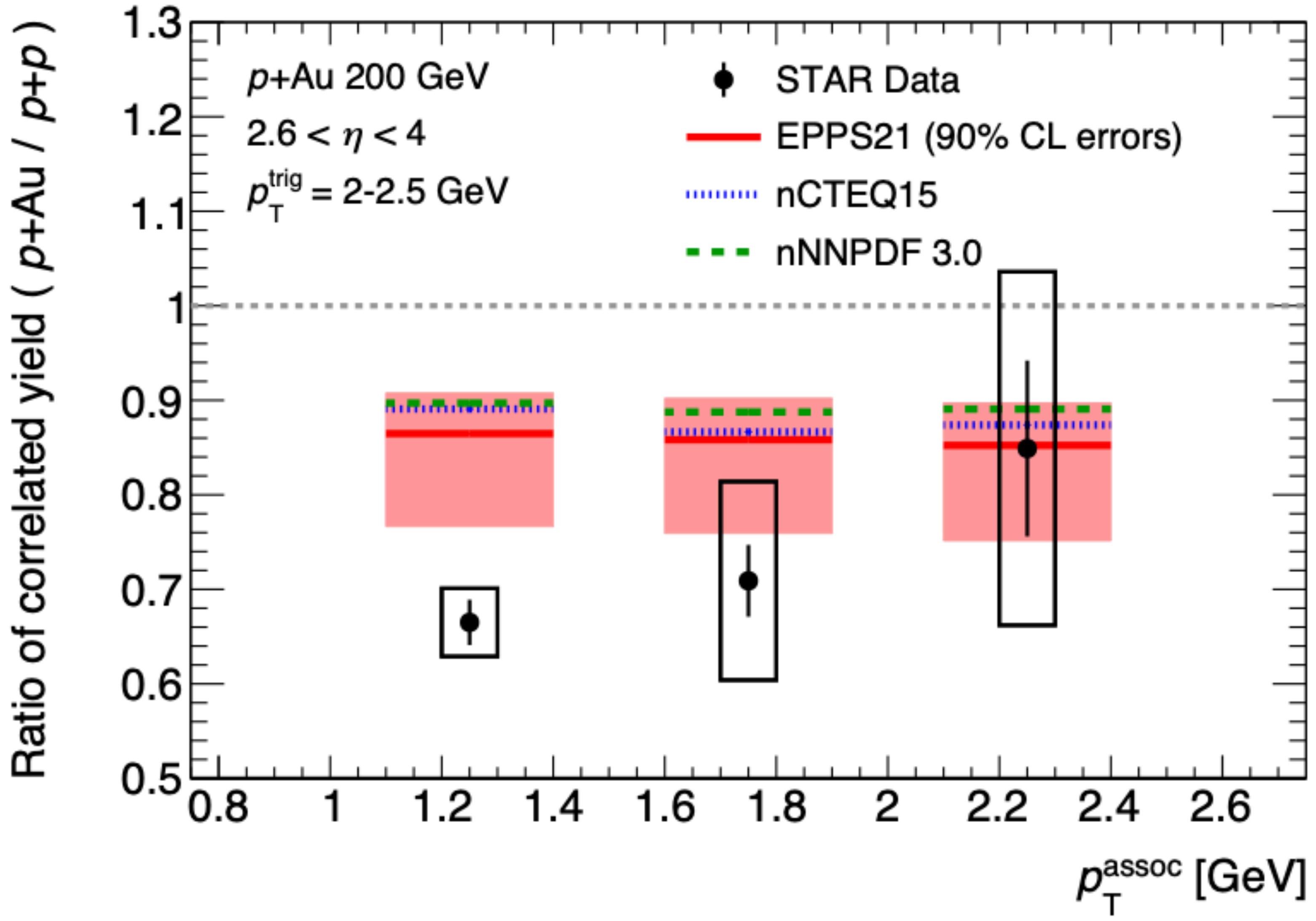
CGC based

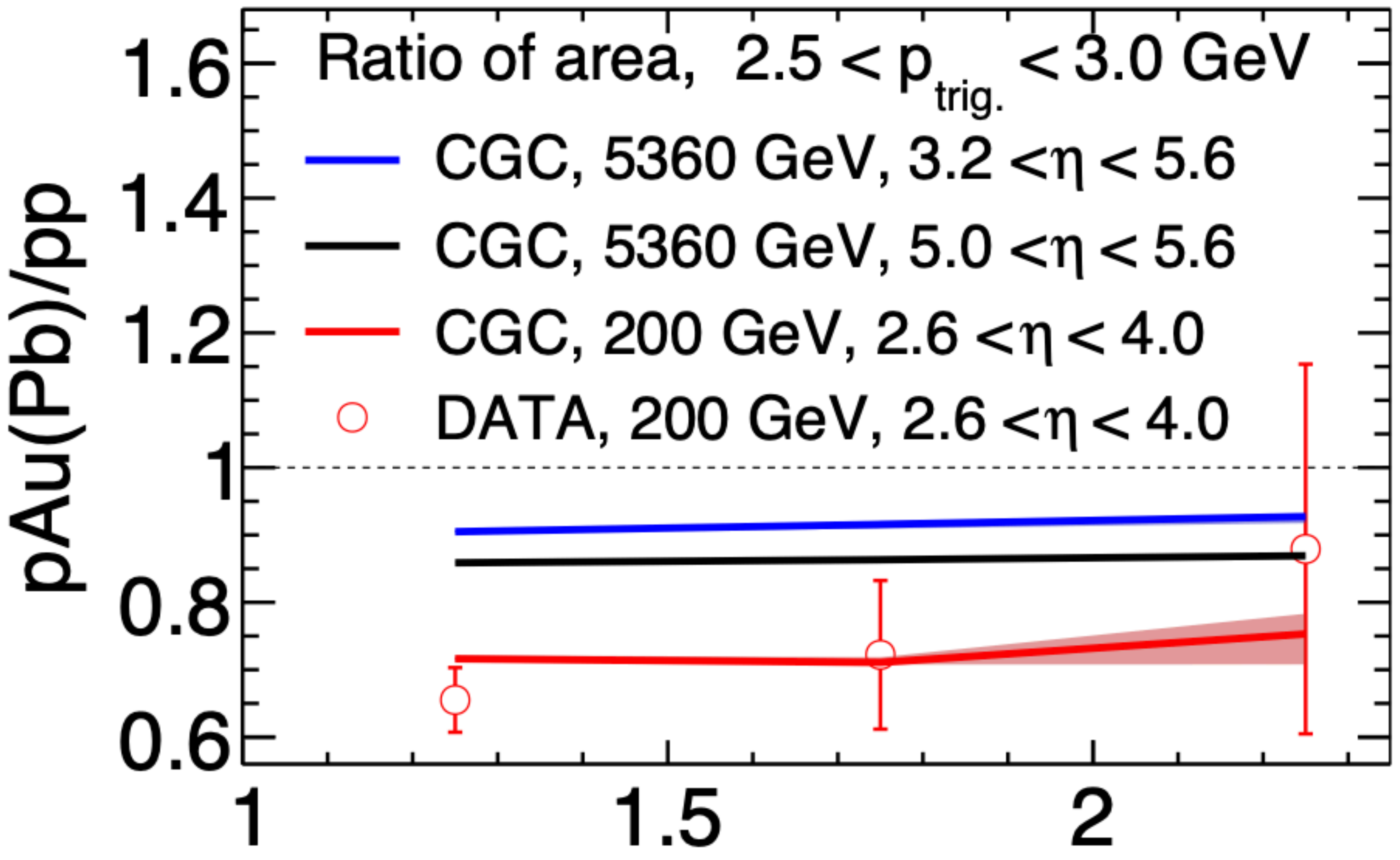
Broadening





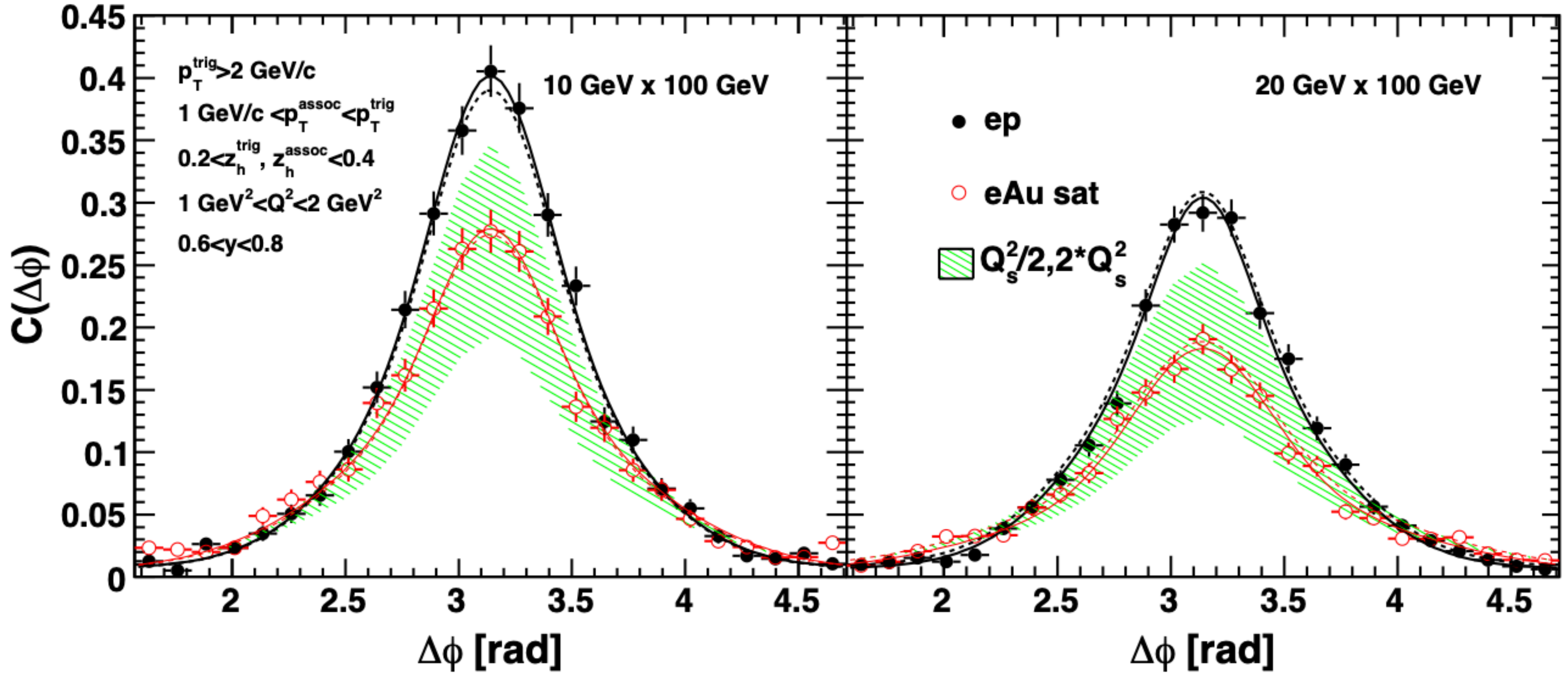
Suppression





Two particle correlations at EIC

Dihadron suppression
back-to-back peak at EIC



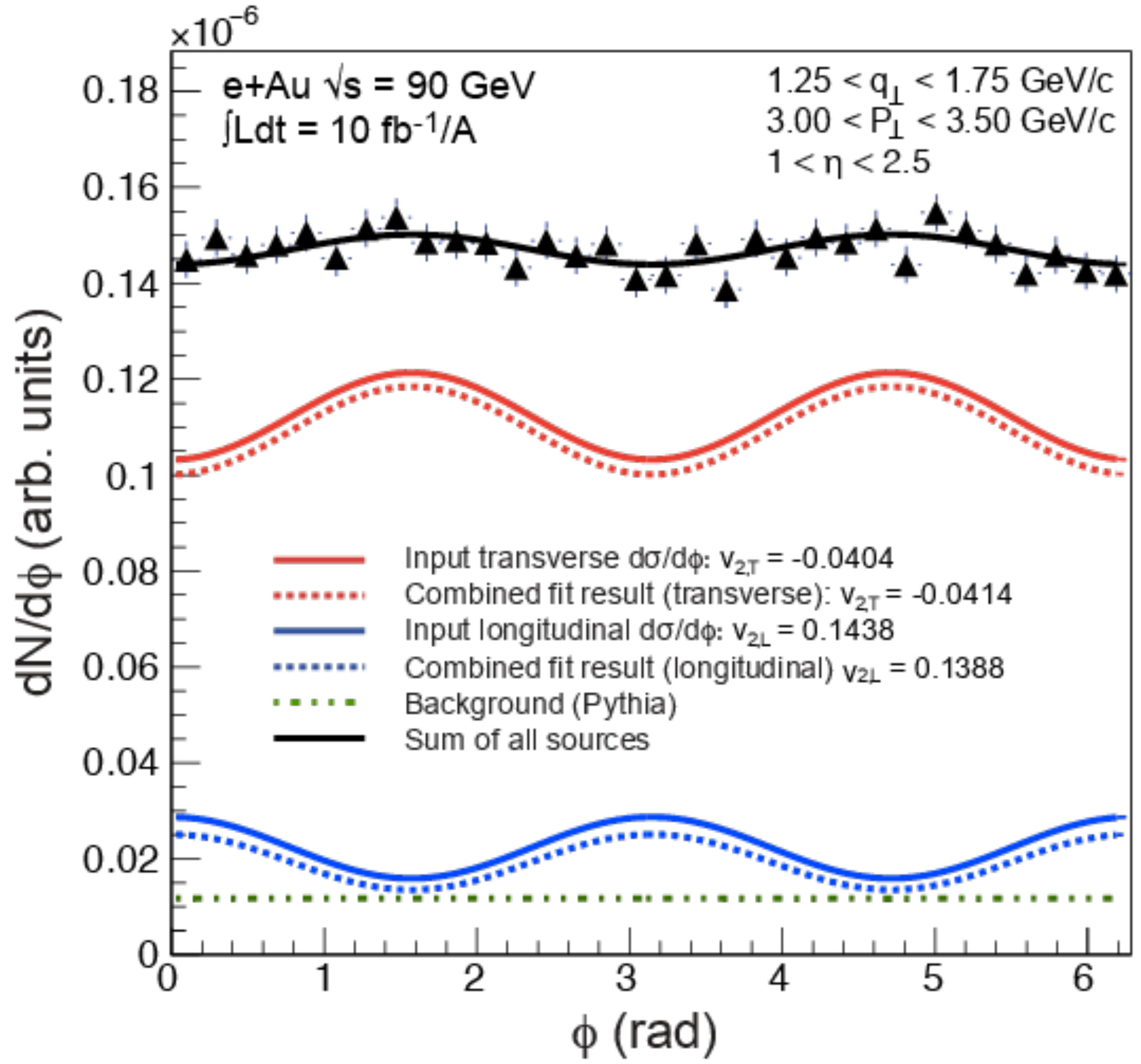
Zheng, Aschenauer, Lee, Xiao (2014)

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)

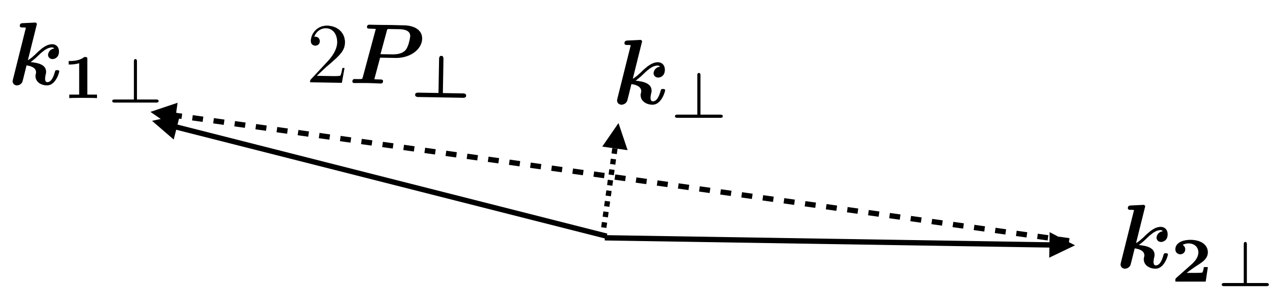
Dijet momentum imbalance
azimuthal correlations



Dumitru, Skokov, Ullrich (2018)

Sensitivity to linearly polarized gluons

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



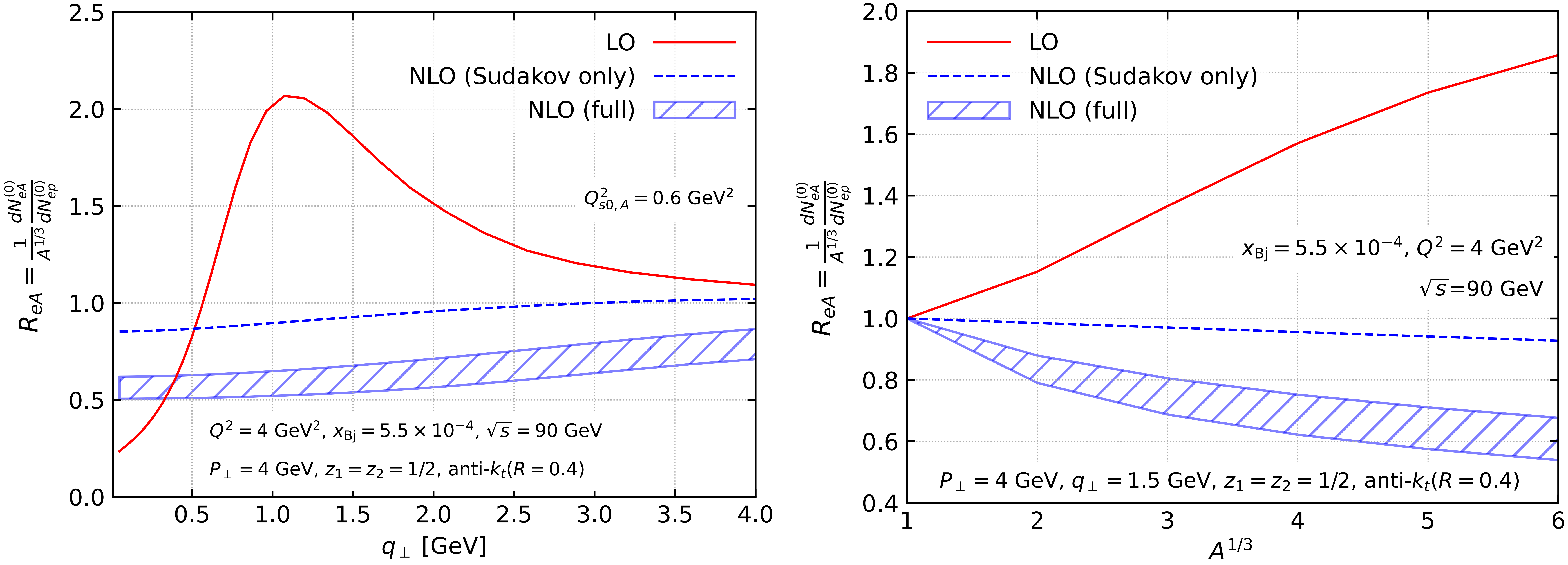
Can also be measured with direct J/ψ production in DIS
Cheung, Kang, Salazar, Vogt (2024)

Two particle correlations at EIC: dijets

Predictions for nuclear modification at the Electron-Ion Collider

$\mathrm{d}N$ min-bias differential yield $\quad R_{\mathrm{eA}} = \frac{1}{A^{1/3}} \frac{\mathrm{d}N_{eA}}{\mathrm{d}N_{ep}}$

Caucal, Salazar, Schenke, Venugopalan, Stebel (PRL 2024)



Full NLO (Sudakov + small-x evolution) shows a significant A-dependent suppression

Enhance saturation effects

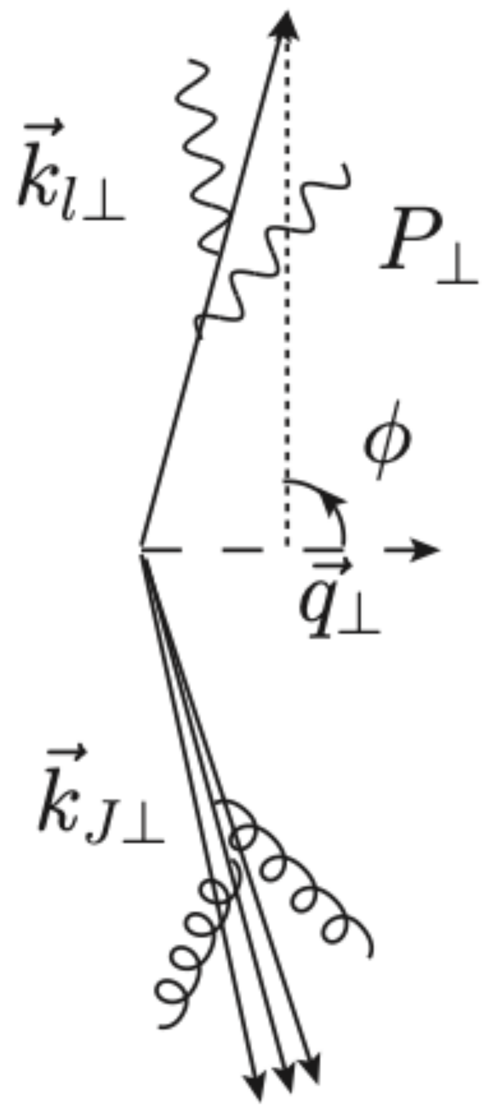
- Emergence of an x-dependent and A-dependent momentum scale: $Q_s^2(x,b) \approx \Lambda_{QCD}^2 A^{1/3} (x_0/x)^\lambda T(b)$
- Saturation phenomena manifests in particle production of invariant mass $M^2 \lesssim Q_s^2(x)$

- Saturation effects enhanced for **larger nuclei**, **central collisions**, collisions along **long axis of deformed nuclei**

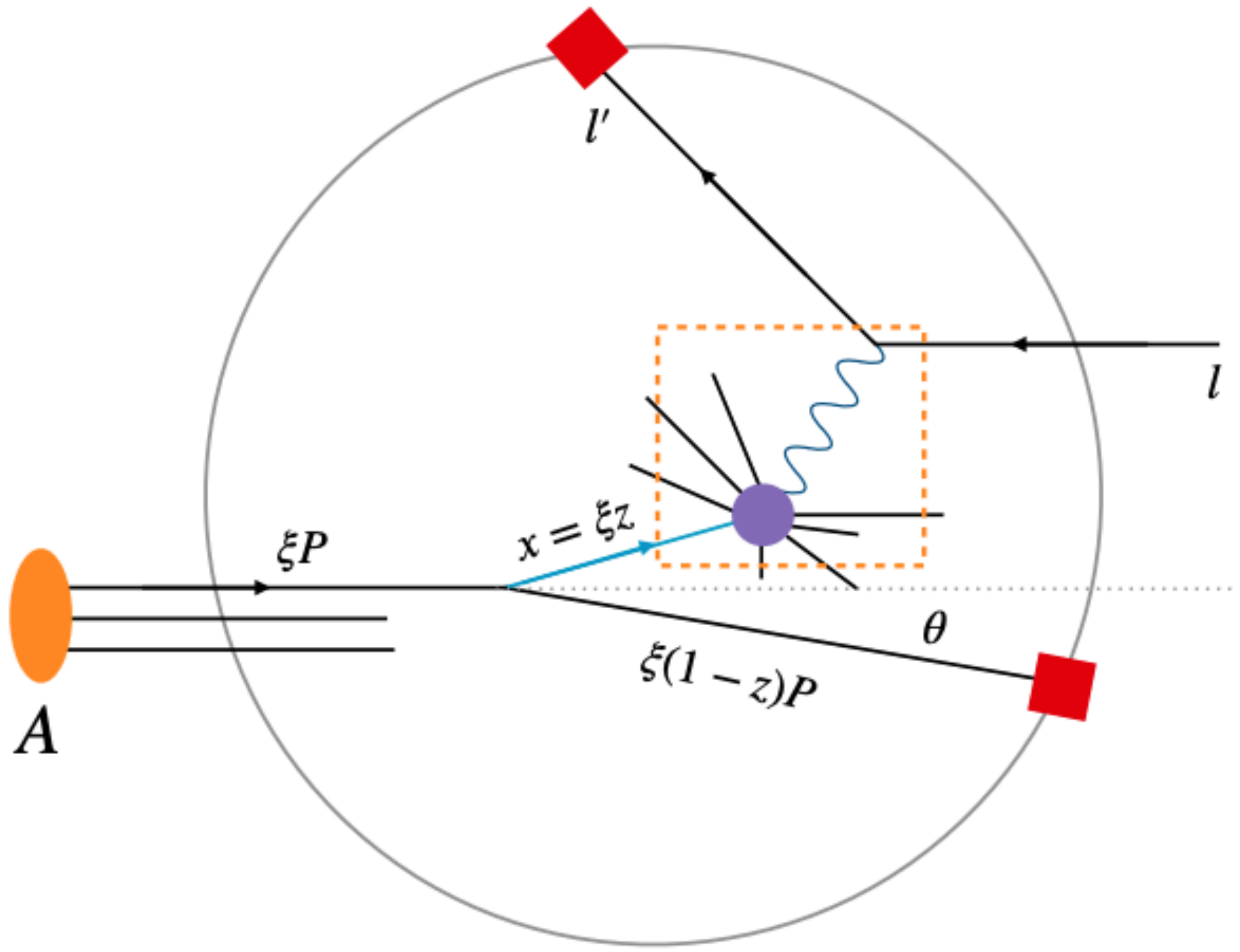
- Diff cross-section for low pT hadron production suffers from large theoretical uncertainties (although ratio proton to nucleus seems to be more or less robust) and hadrons come from partons with larger pT. Consider **heavy flavor** instead (closer to parton kinematics).

- Other possibilities to minimize hadronization effects: **energy correlators**?

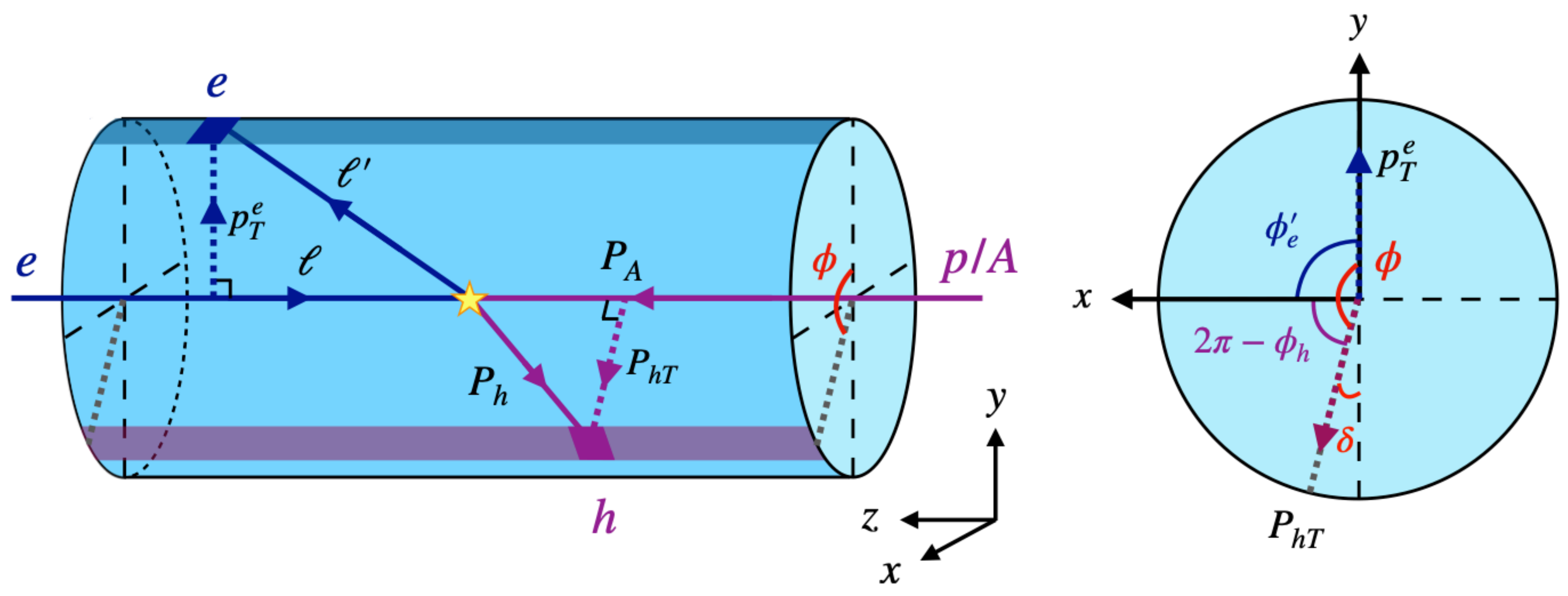
Other two-particle correlations: lepton-jet and nucleon-energy energy correlators



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



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



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

Experimental requirements

- Good reconstruction of scattered electron (at small-x) to pin down DIS kinematics
- Inelasticity close to 1, in order to maximize the center of mass energy of the photon-nucleus system (thus maximal sensitivity to small-x gluons)
- Reconstruct small pT hadrons/jets/heavy flavor in the mid-rapidity/backward region with the ability to resolve their azimuthal angle distribution
- Larger nuclei more favorable to see enhanced saturation effects. Is it possible to distinguish impact parameter of collisions in eA? Or orientation of deformed nuclei?