BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

INITIAL CONDITIONS AND GLUON DISTRIBUTIONS

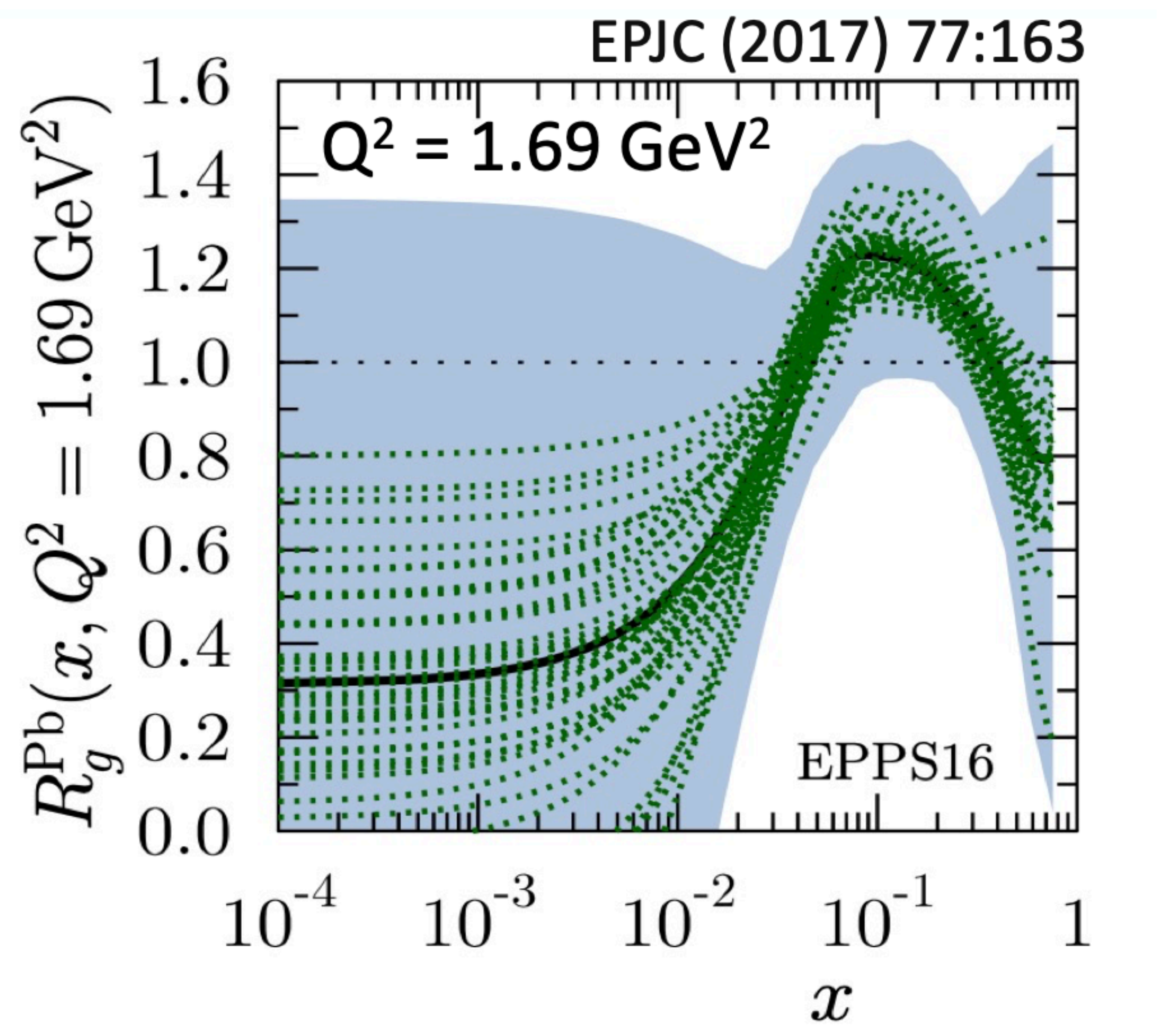
Workshop: RHIC Science Programs Informative Toward EIC in the Coming Years
CFNS
5/26/2021

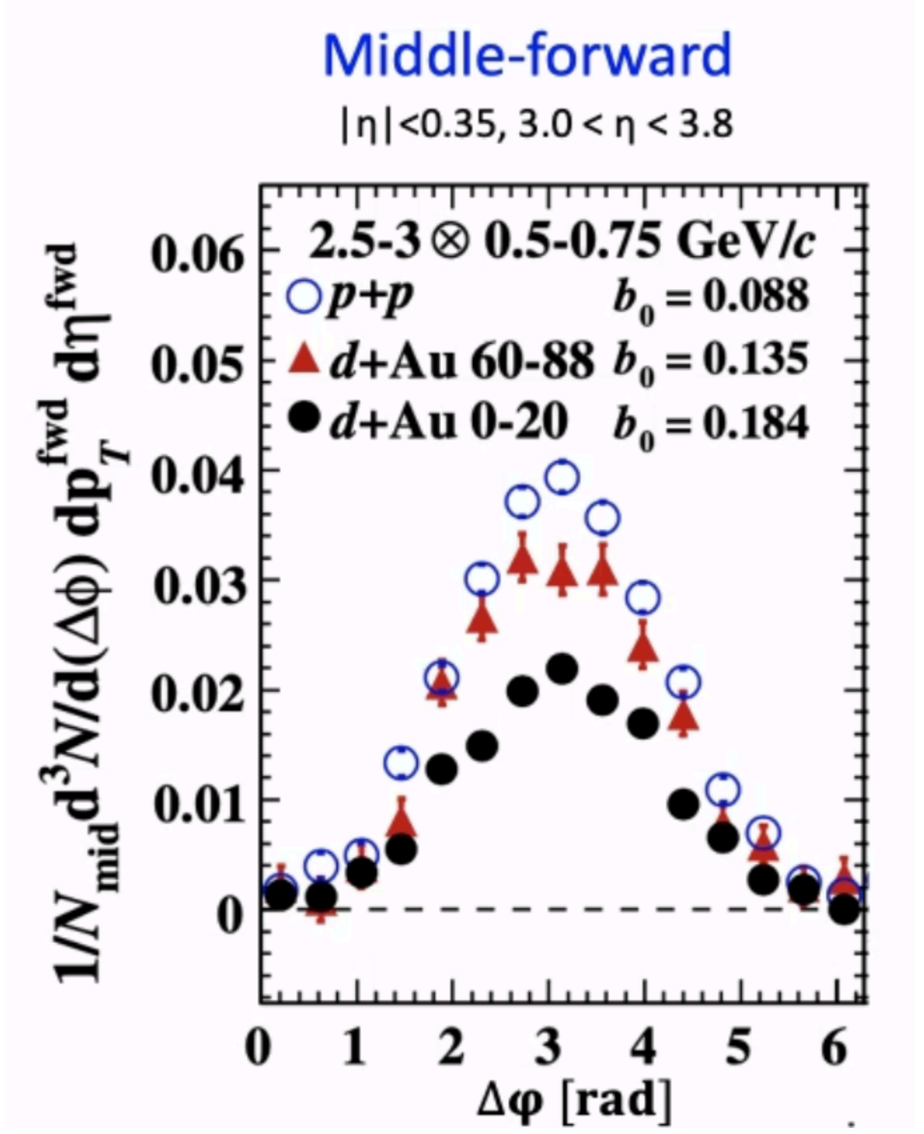
WORKSHOP GOALS

- Our goal is to identify and write up a summary of the RHIC science programs that can be leveraged toward the EIC in the remaining years of RHIC operation.
  - Gluon momentum density
  - Spatial gluon distribution: Coherent and incoherent diffractive VM production
  - Properties of nuclei
  - Collectivity in UPCs - what to expect at EIC
  - Entanglement - what can RHIC contribute?

GLUON DENSITY

- RHIC data can probe small *x*, small and moderate Q^2 region
  - Inclusive measurement: yields suppressed in forward direction, low pT
  - Two-particle correlations: suppression in back-to-back (forward) correlation
- Future:
  - Direct photon with STAR forward upgrade
  - Direct photon-jet/charged hadron correlations with STAR forward upgrade
  - Charged hadron correlations at future EIC
- Saturation vs. energy loss (cold nuclear matter effects)? Shouldn't both be present?





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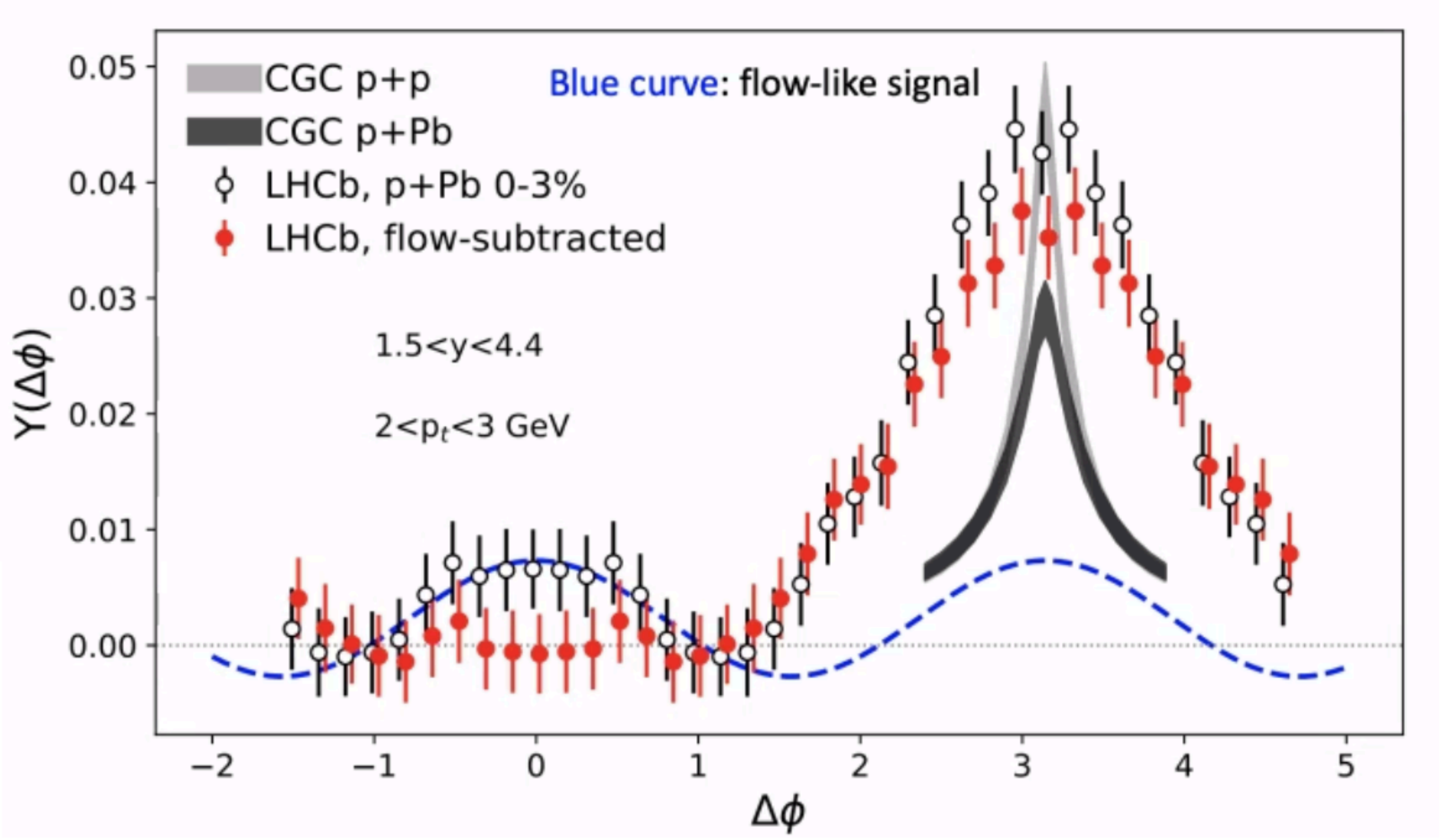
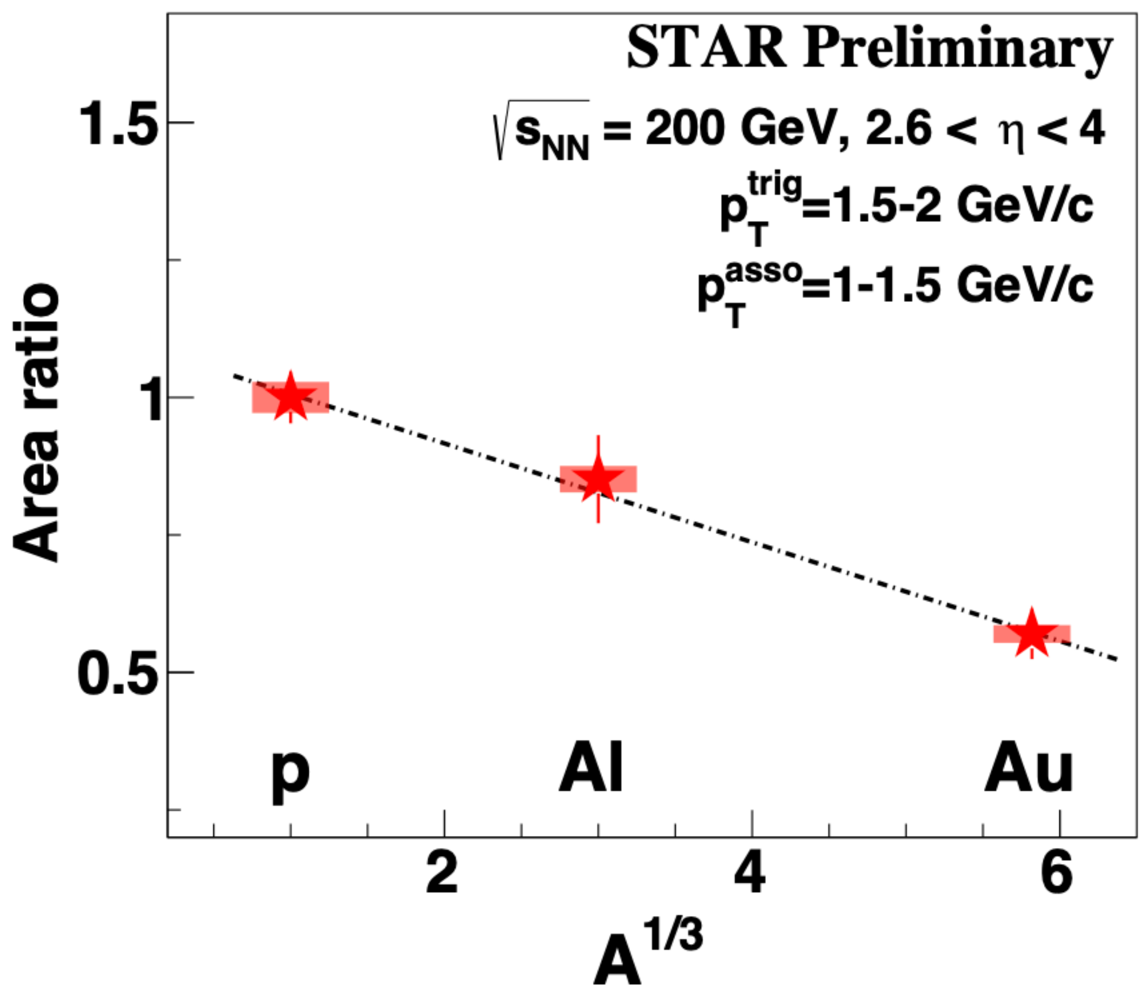


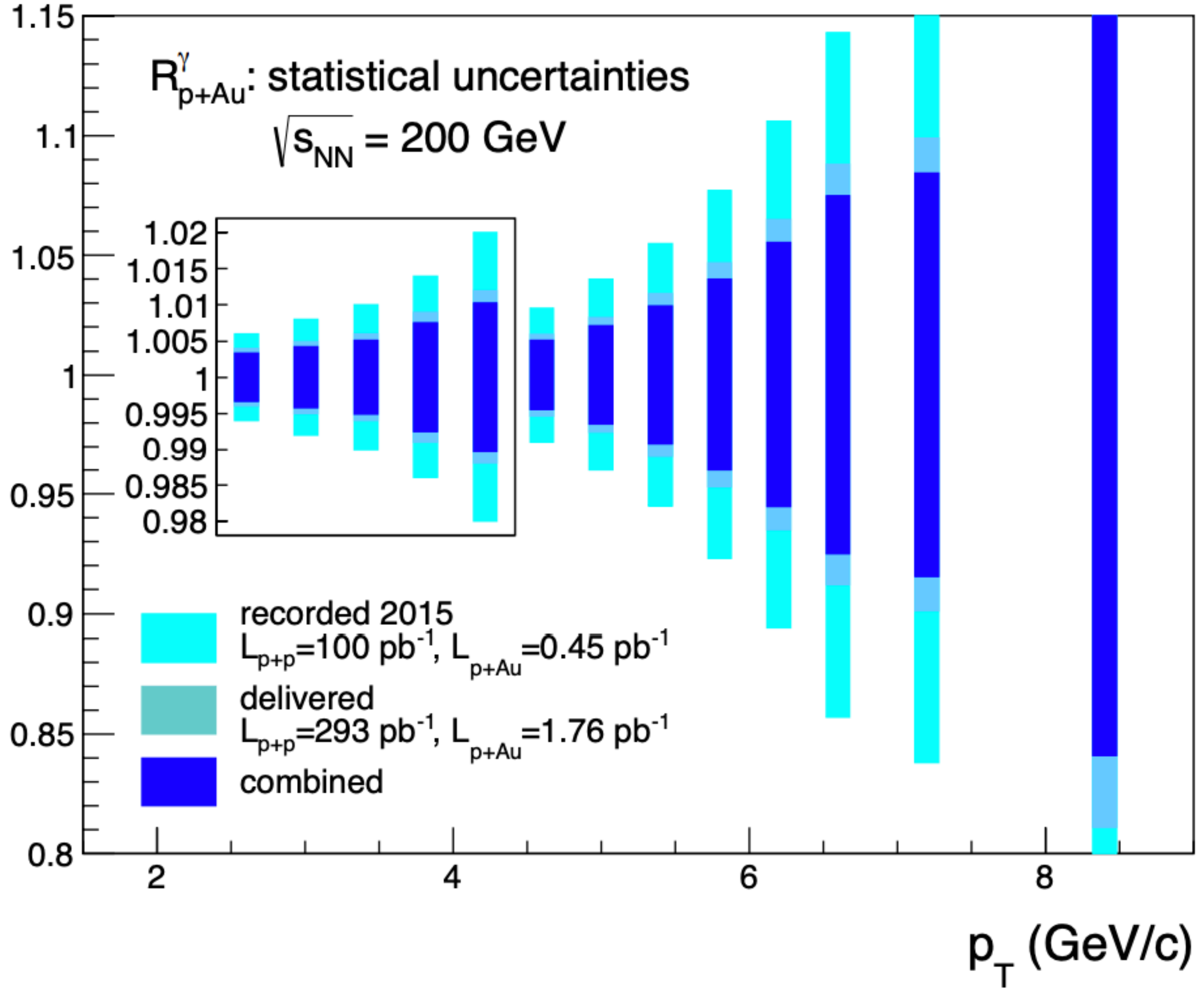


Suppression measure: area under the curve

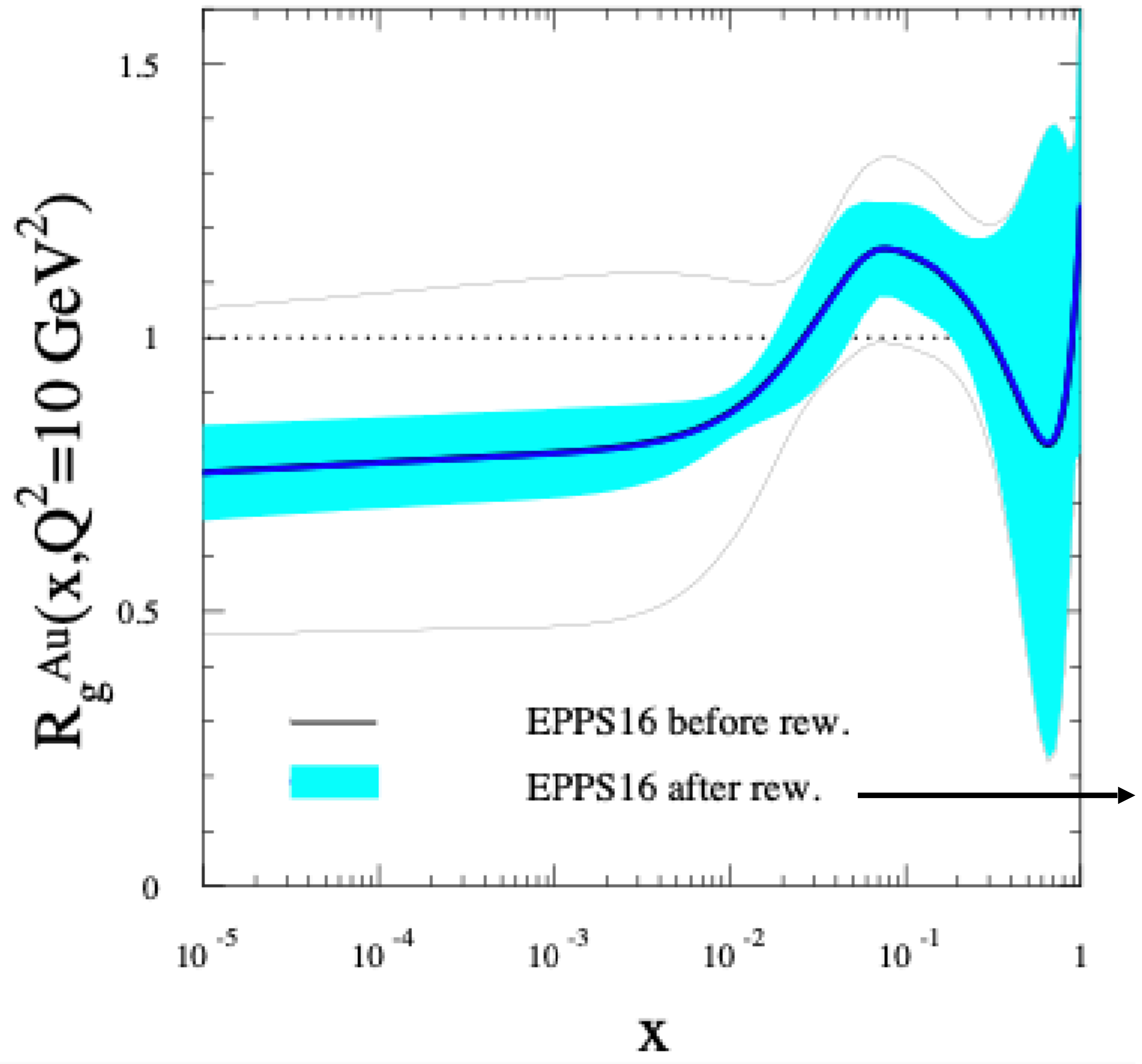
- RHIC's versatility helps here

Inclusive direct photon measurement with STAR forward upgrade

RHIC Cold QCD Plan, arxiv:1602.03922



STAR BUR 2022



After adding direct photon R_{pA} data in 2015 and future 2024.

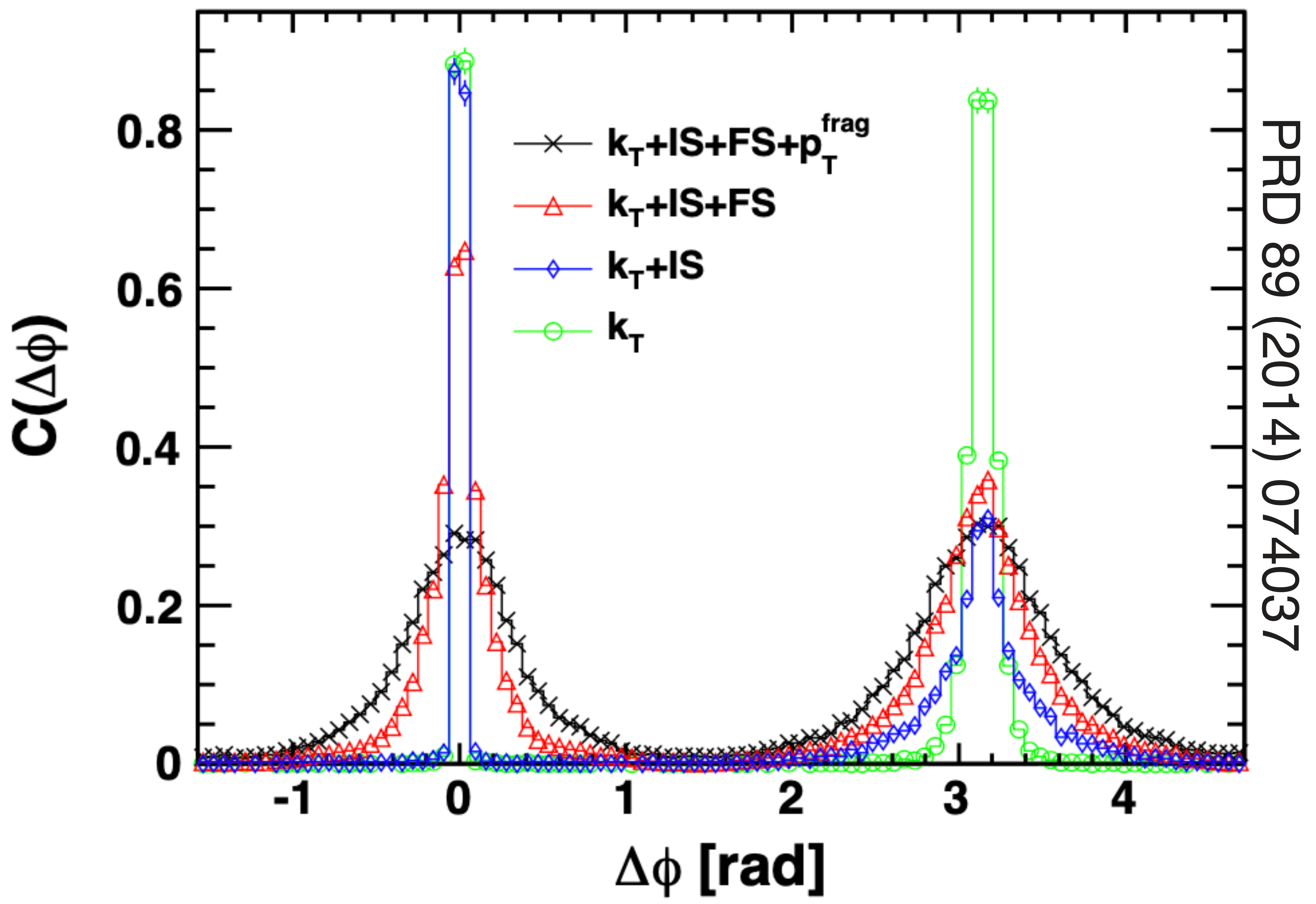
2024 pAu with STAR forward upgrade + 2015 pAu:

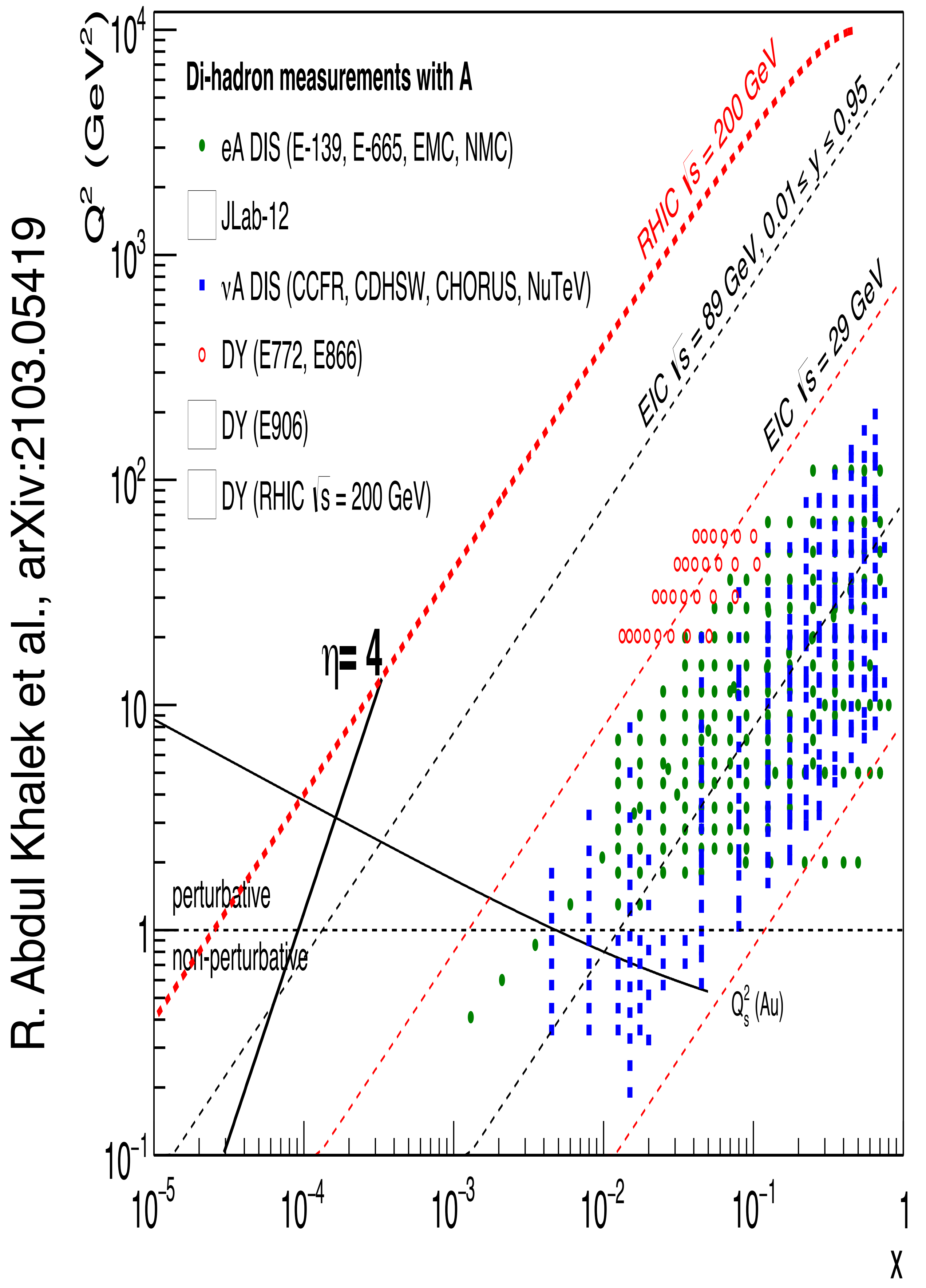
- R^{γ}_{pAu} of direct photons from q+g→q+γ: sensitive to gluon from Au
- Direct photon: free from the final state effects
- Higher delivered integrated luminosity data: significantly improve the constrain on gluon distributions
- Challenge: remove photons from fragmentation or hadron decay; small cross section at forward rapidity

Xiaoxuan Chu

Di-jet correlations with STAR forward upgrade

EIC simulations: e+p 20 GeV × 100 GeV

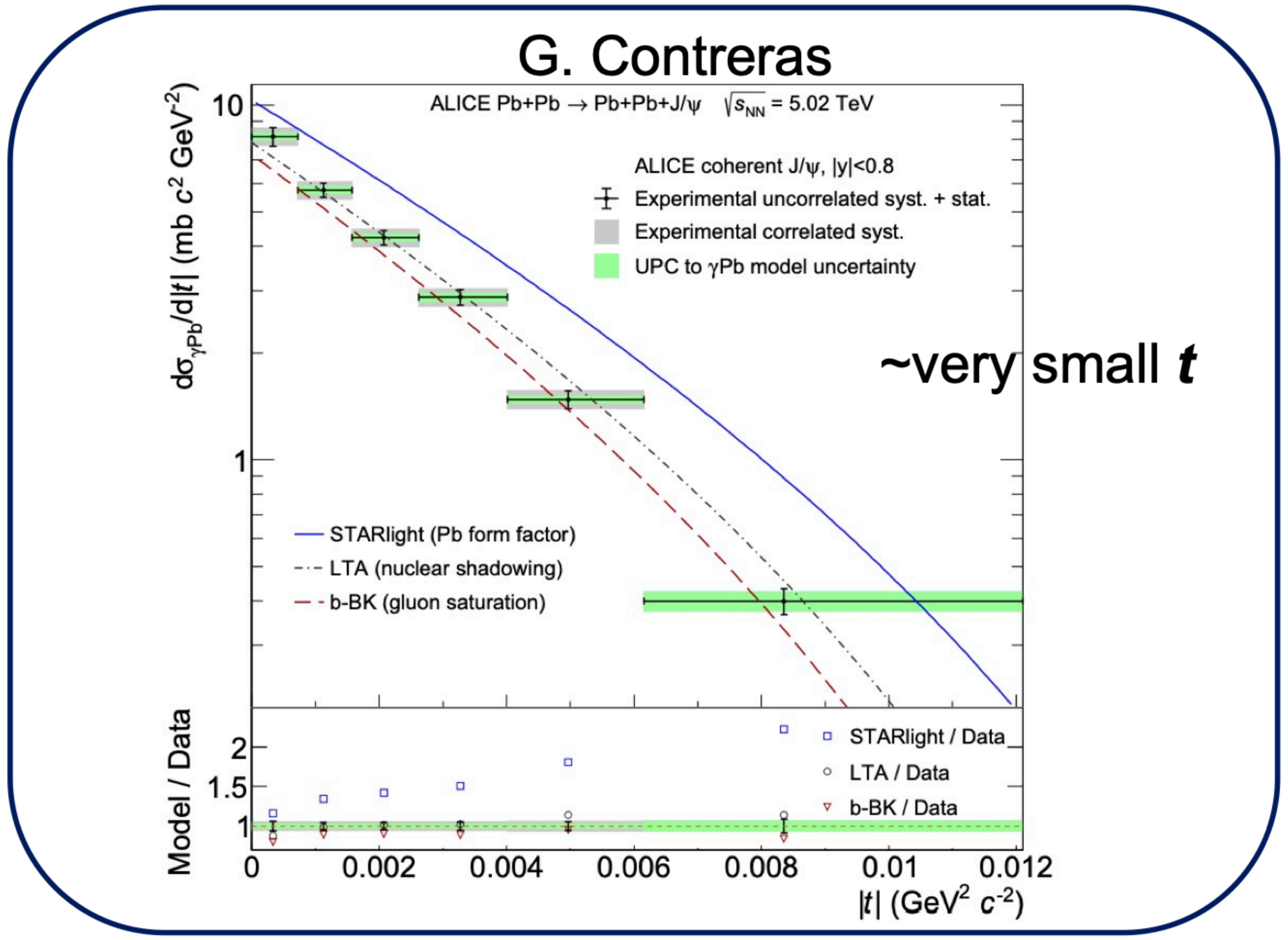


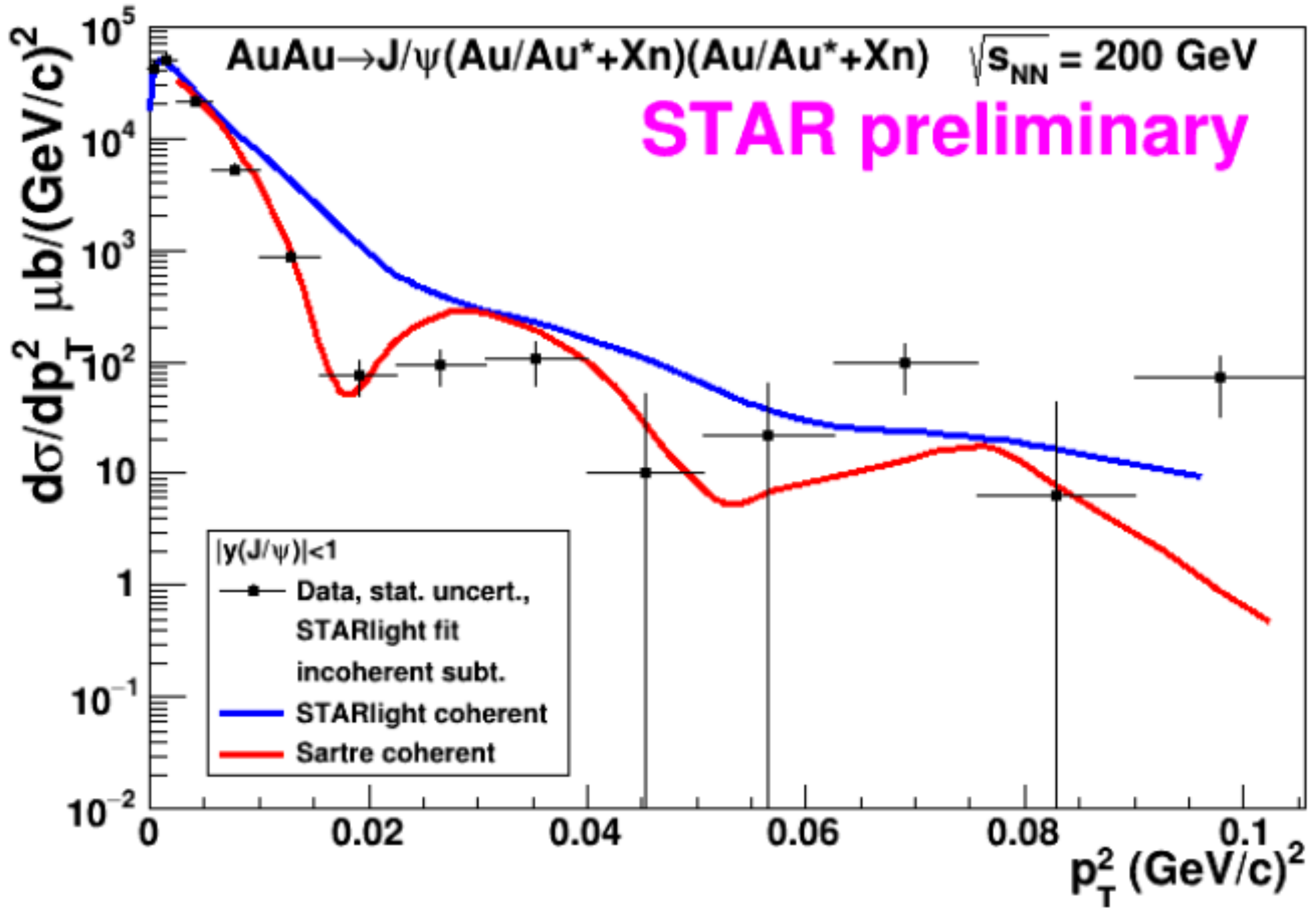


- Away side peak is smeared by k_T, initial/final-state parton shower and fragmentation apart from gluon saturation
- STAR forward upgrade includes EMCal + HCal + tracking:
  - Expand observables to di-charged hadron, di-jet and γ-hadron/jet than di-π^0
  - Can probe similar saturation region as highest energy of eA collisions at EIC
  - Better resolution to improve the measurement of broadening
- Di-jet correlations with STAR forward upgrade:
  - Jet matches parton better than leading hadron, can construct initial kinematics more accurately than hadron
  - Final-state parton shower and fragmentation would be suppressed by jets
  - However, jet has lower p_T limit, cannot probe as small p_T as hadron

VECTOR MESON PRODUCTION

- Diffractive pattern in coherent cross section is sensitive to spatial structure





VM productions off heavy nucleus

- Differential cross section –*t* → spatial distributions

Open questions:

- Initial-state photon smearing (lessons learned from photon-photon physics?)
- **Diffractive pattern →** b_T
- Veto on nuclear breakups – protons, neutrons, photons. (bottleneck – beam pipe, photons, etc…)
- Forward detections are absolutely critical

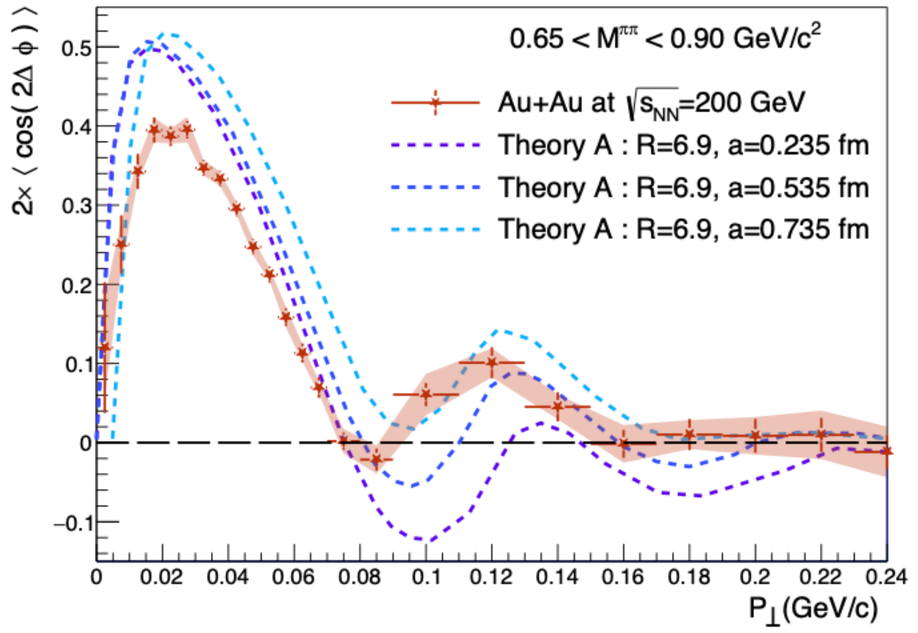
- Saturation describes shadowing. How do the leading twist nuclear shadowing model and saturation models (and CGC) compare? What are the differences between the models, what is equivalent?

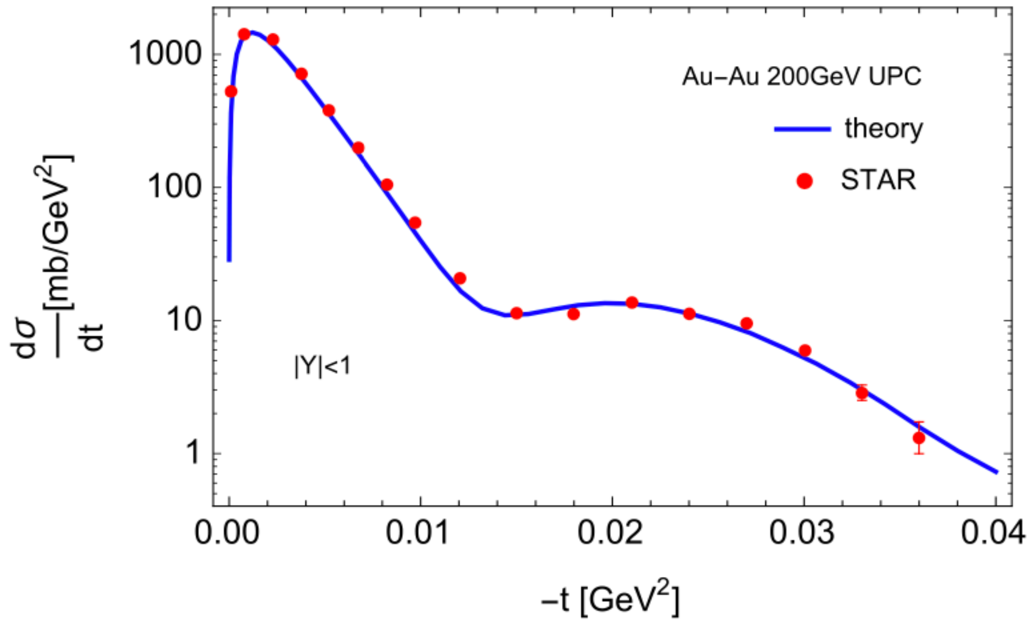
VECTOR MESON PRODUCTION - ANISOTROPIES

- Separating coherent vs. incoherent spectra experimentally would be great
- Could be possible with anisotropy from two-source interference, which only appears in coherent case

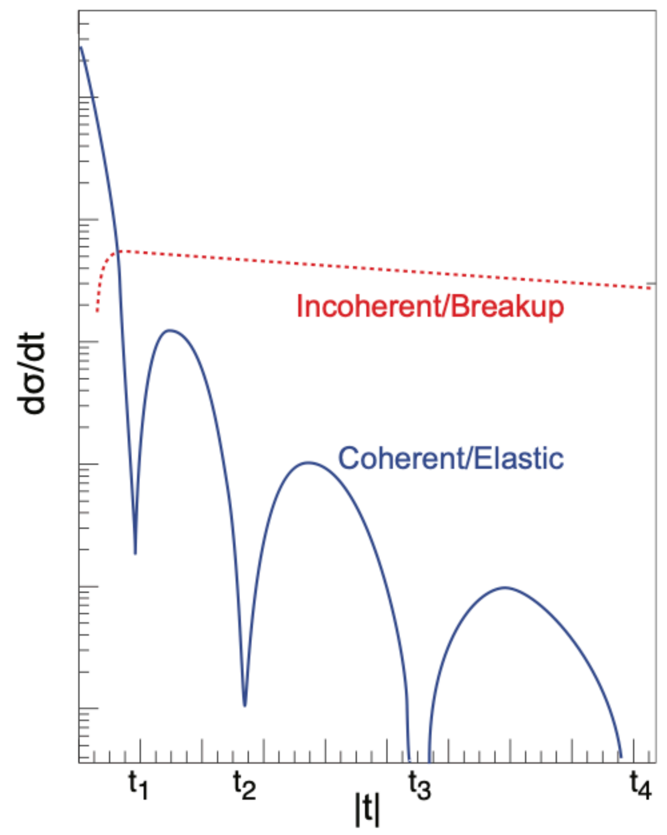
Use interference to separate Coherent/Incoherent

- Experimentally, we observe that incoherent does not contribute to interference pattern (Zero above pT > 160 MeV/c)
- Once quantitative agreement is reached between data & theory for $\Delta\phi$
  - → Use interference effect to help disentangle coherent vs. incoherent
  - Simultaneous fit measured spectra (coherent + incoherent) with $\cos 2\Delta\phi$



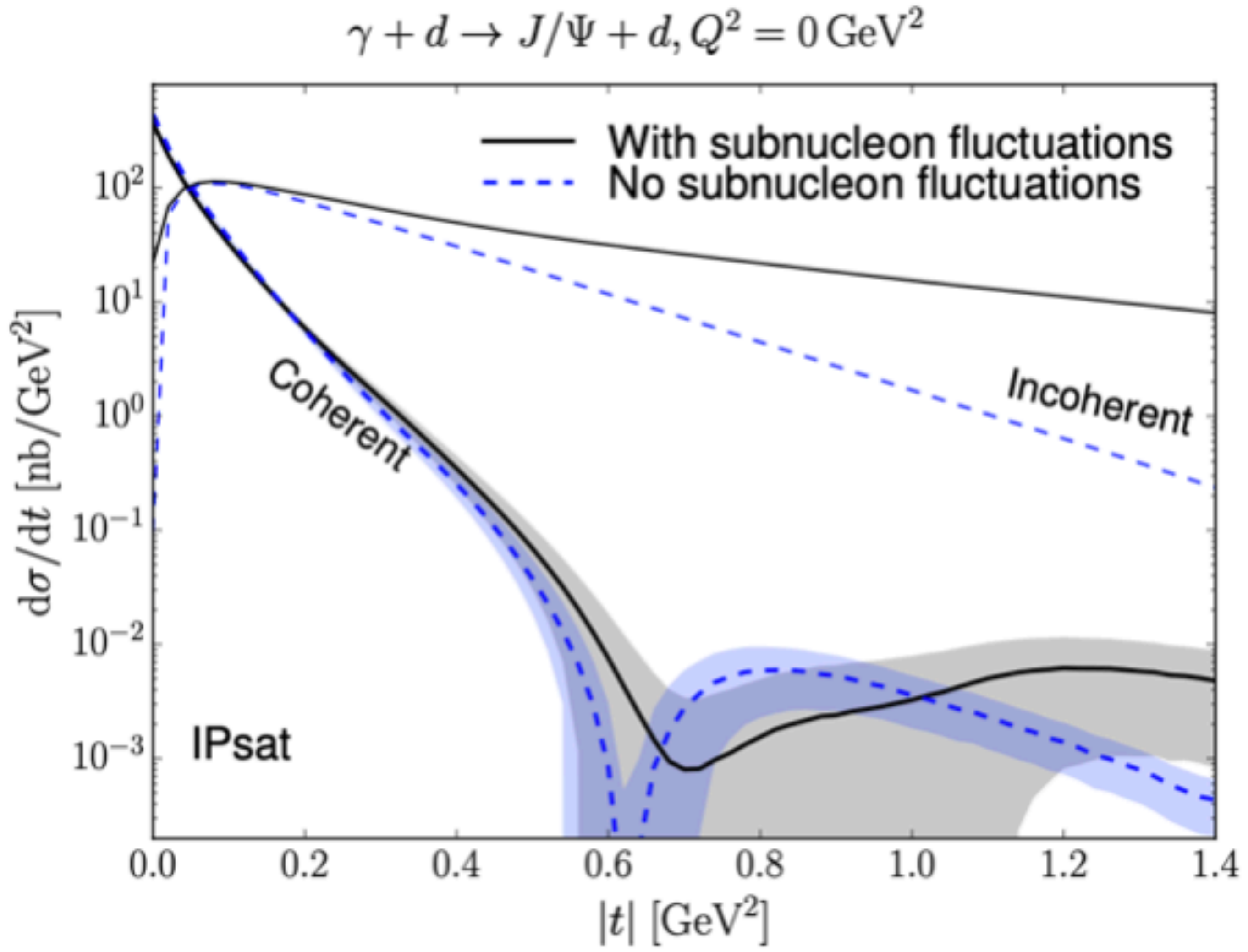


Separation of coherent vs. incoherent is the essential experimental challenge for EIC measurements



- Proof of concept already carried out in [1], however STAR t spectra had incoherent pre-subtracted using a dipole form factor.

[1] Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020).



- Can we do these measurements in p+Au or d+Au?
- Probably no interference as basically just one source

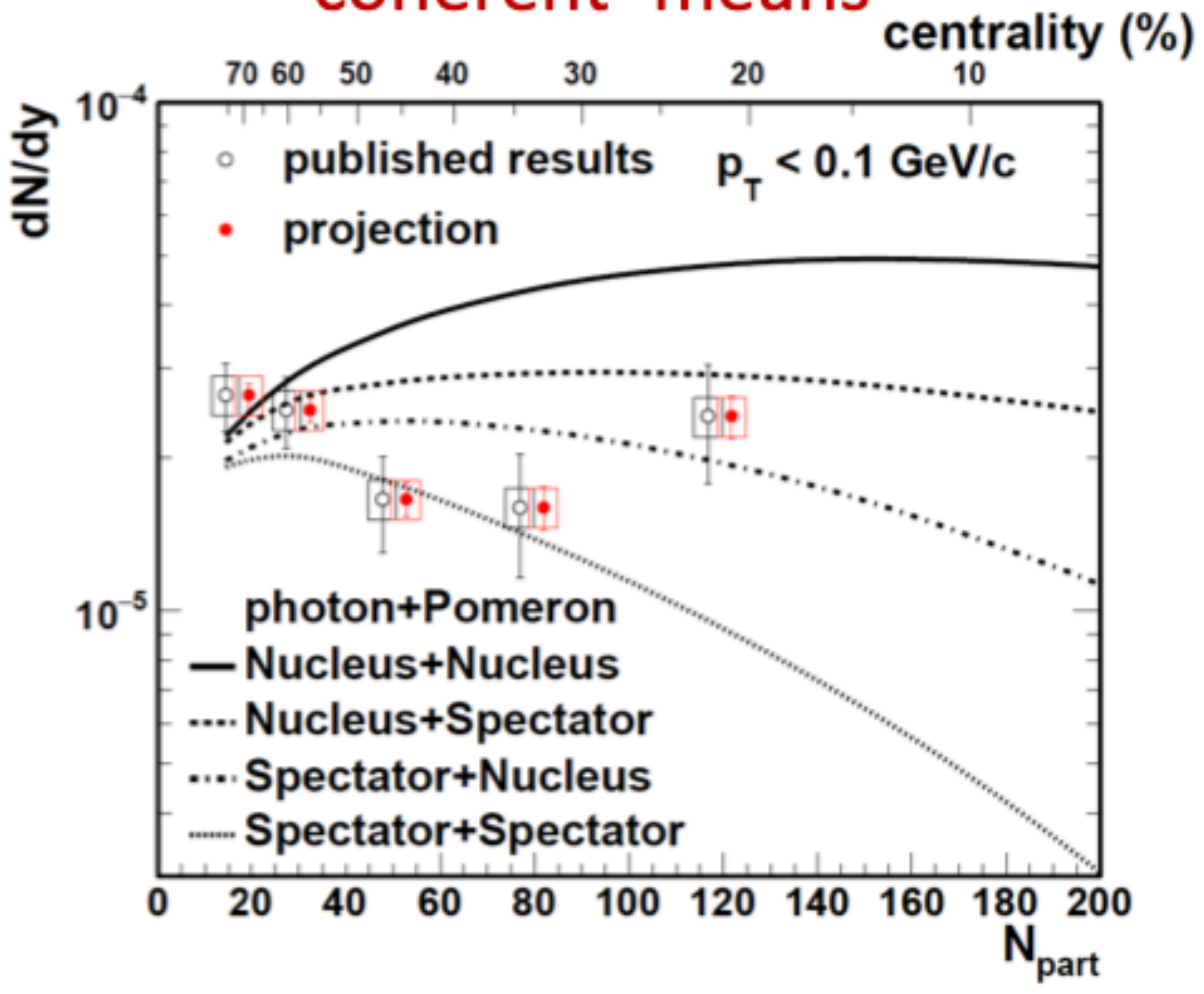
- Medium effects in non-UPCs?

Highlights II : Theory Questions and EIC

Theory Wish List:

- Full calculations for J/ψ etc.
- Predictions for U+U considering deformation
- Rapidity and mass dependence
- Pursue calculations for EIC case – do correlations exist and if so, what can we learn?
- Quantify effects of saturation/ modified gluon distribution?

Gain a deeper understanding of what 'coherent' means



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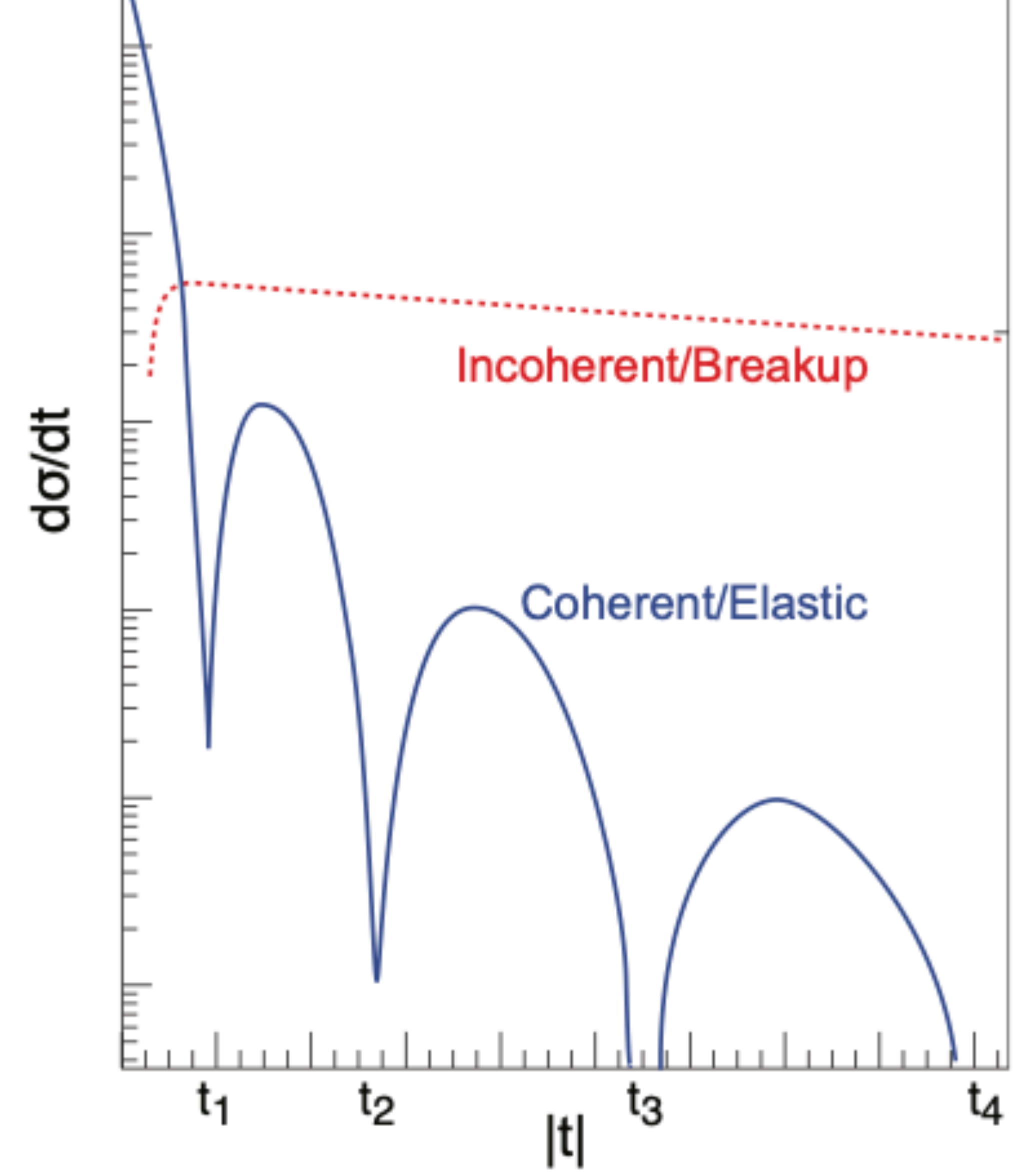
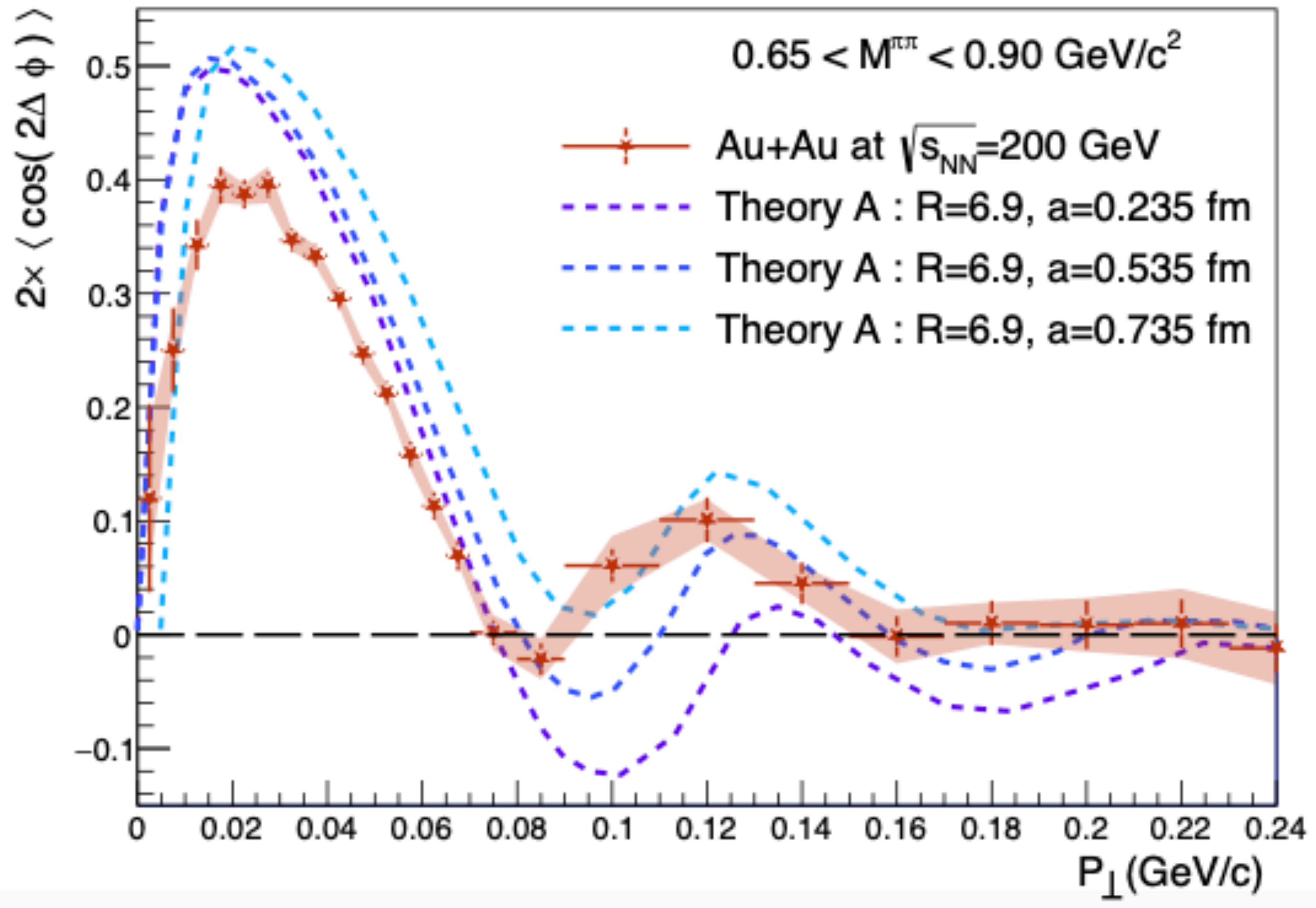
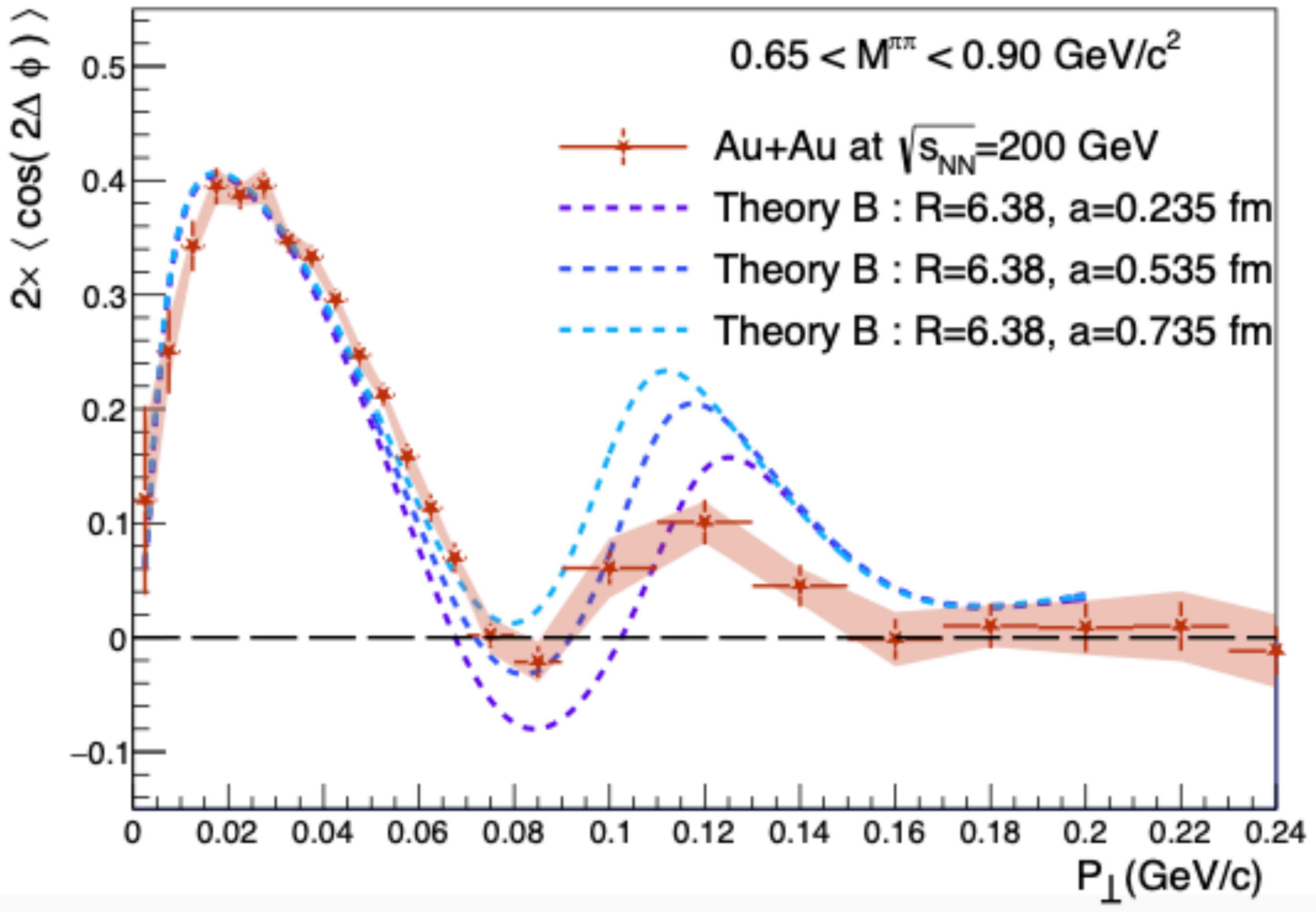
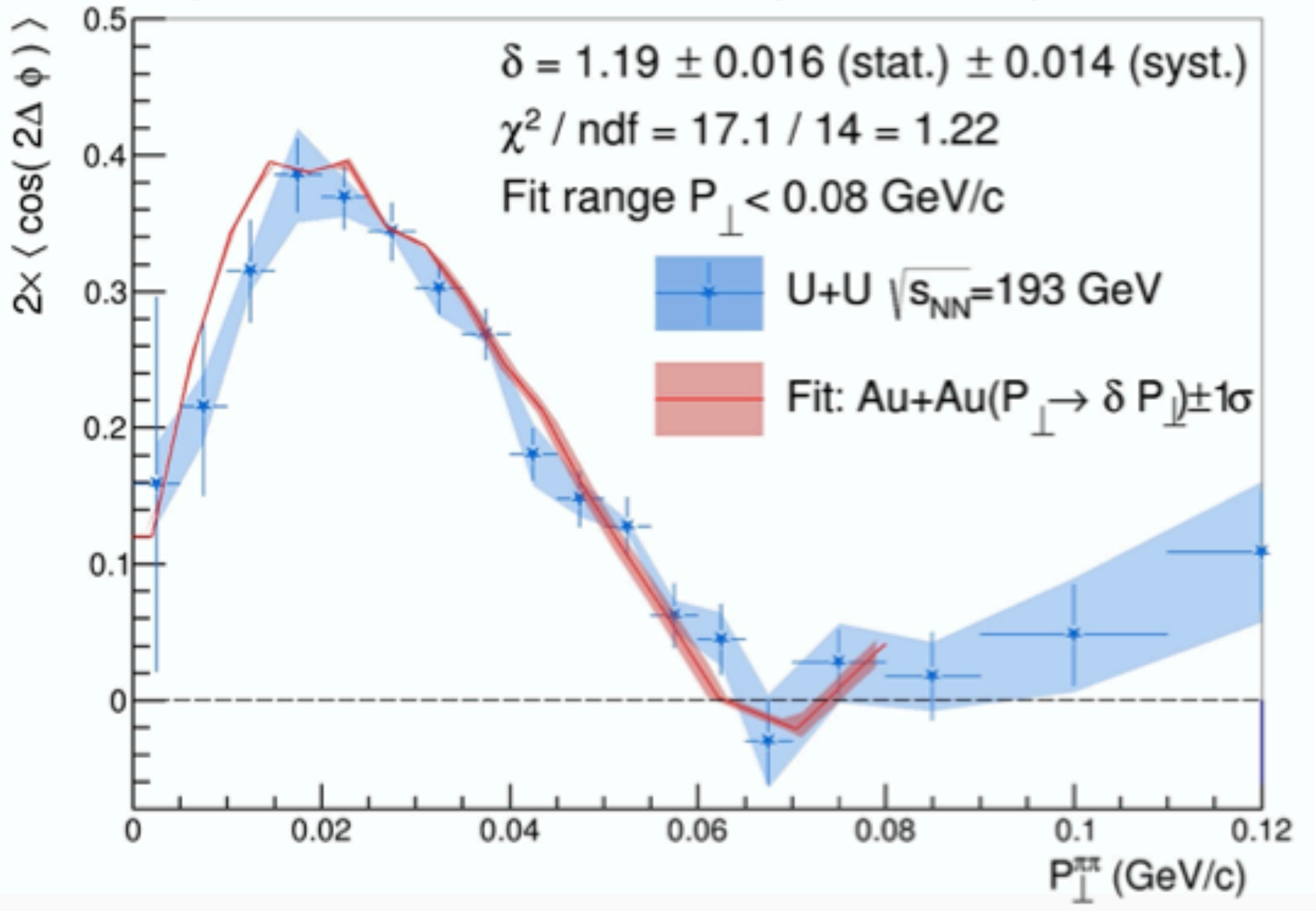


- Continue to pursue theory – gain quantitative agreement



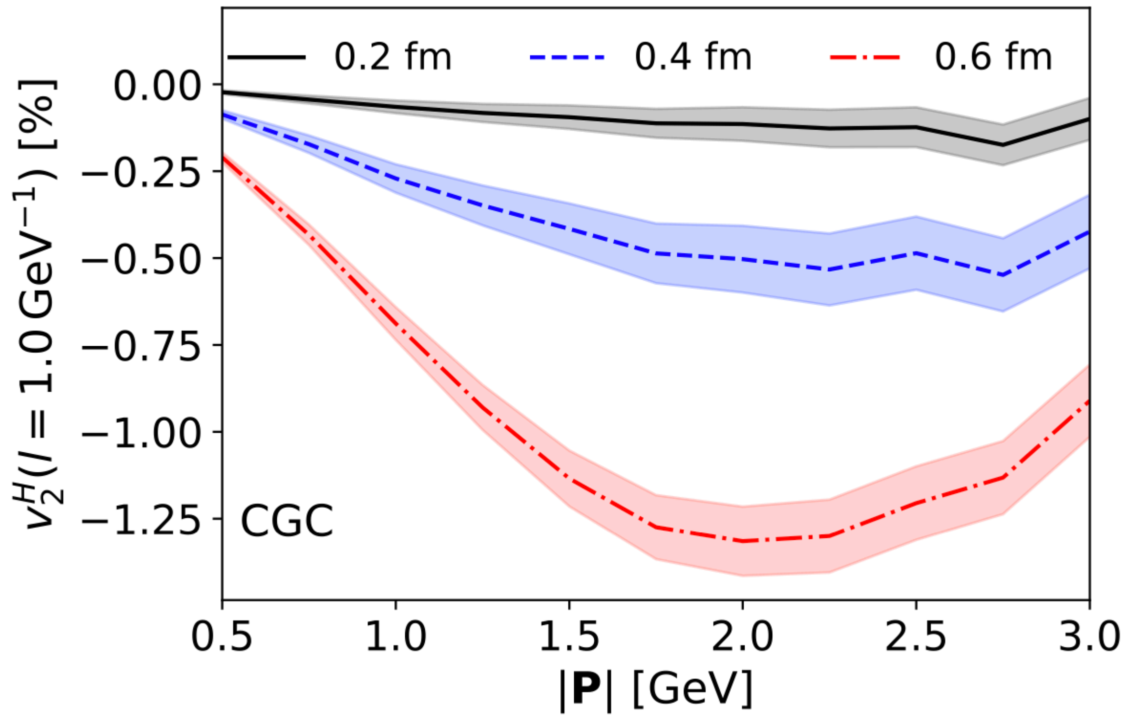


Why are we sensitive primarily to the 'long'-axis

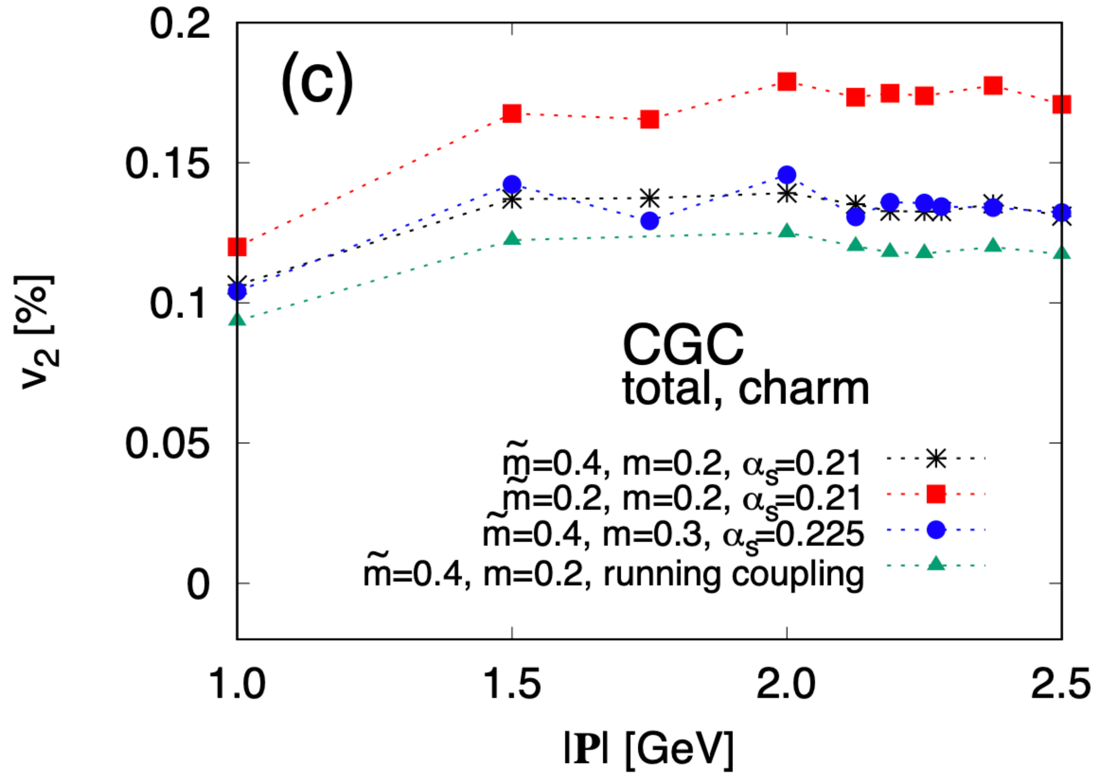


UPC DIJET PRODUCTION

- Exclusive dijet azimuthal correlations
- Dijet anisotropy in $$\boldsymbol{P} = \frac{1}{2}(\boldsymbol{p}_0 - \boldsymbol{p}_1) \; , \quad \boldsymbol{\Delta} = \boldsymbol{p}_0 + \boldsymbol{p}_1 \; ,$$ is sensitive to the spatial and momentum correlations of gluons
- Second Fourier harmonic ⟨cos (2φ)⟩ in exclusive dijet photoproduction is expected to provide insights into “elliptic gluon” dynamics - non-trivial angular correlations of the gluon Wigner distribution in the nucleus, that depend on impact parameter and gluon transverse momentum
- CGC calculation limited to small p_T in order not to go to too large *x*



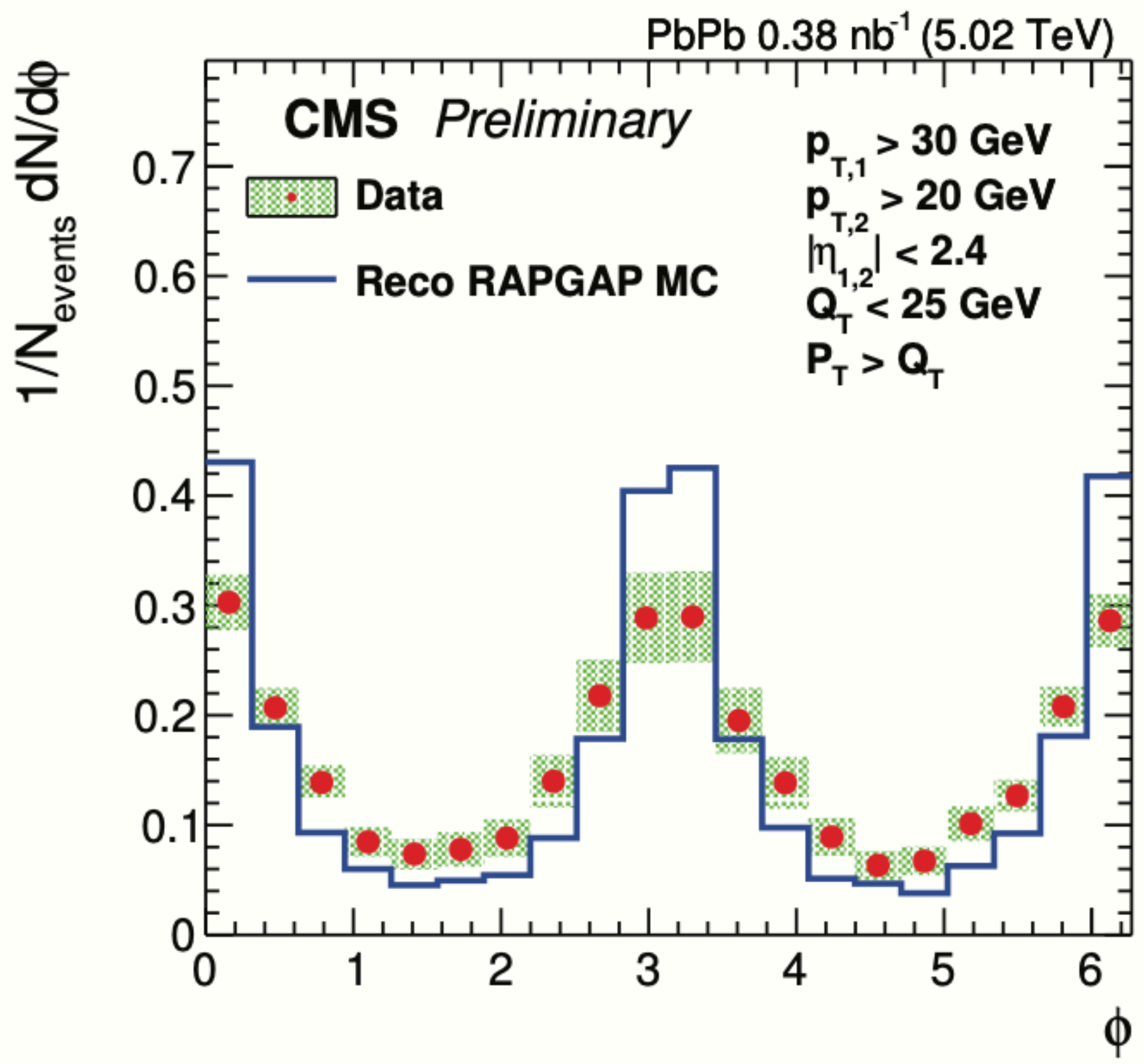
Anisotropy (between momentum and impact parameter) in the gluon Husimi distribution

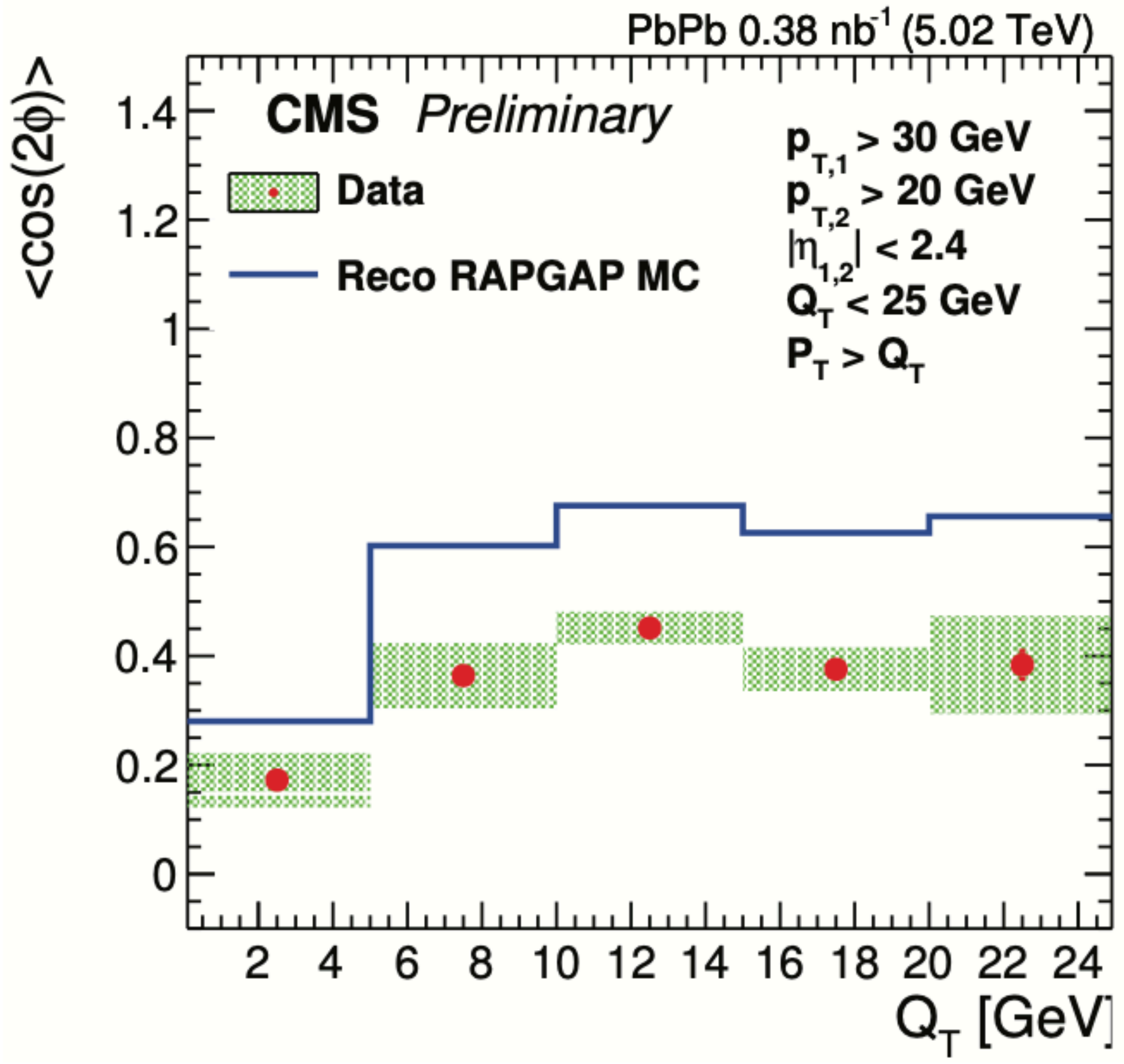


Phys. Rev. D99, 074004, (2019)

Anisotropy in charm dijet for $|\Delta| = 0.1\,\mathrm{GeV}$

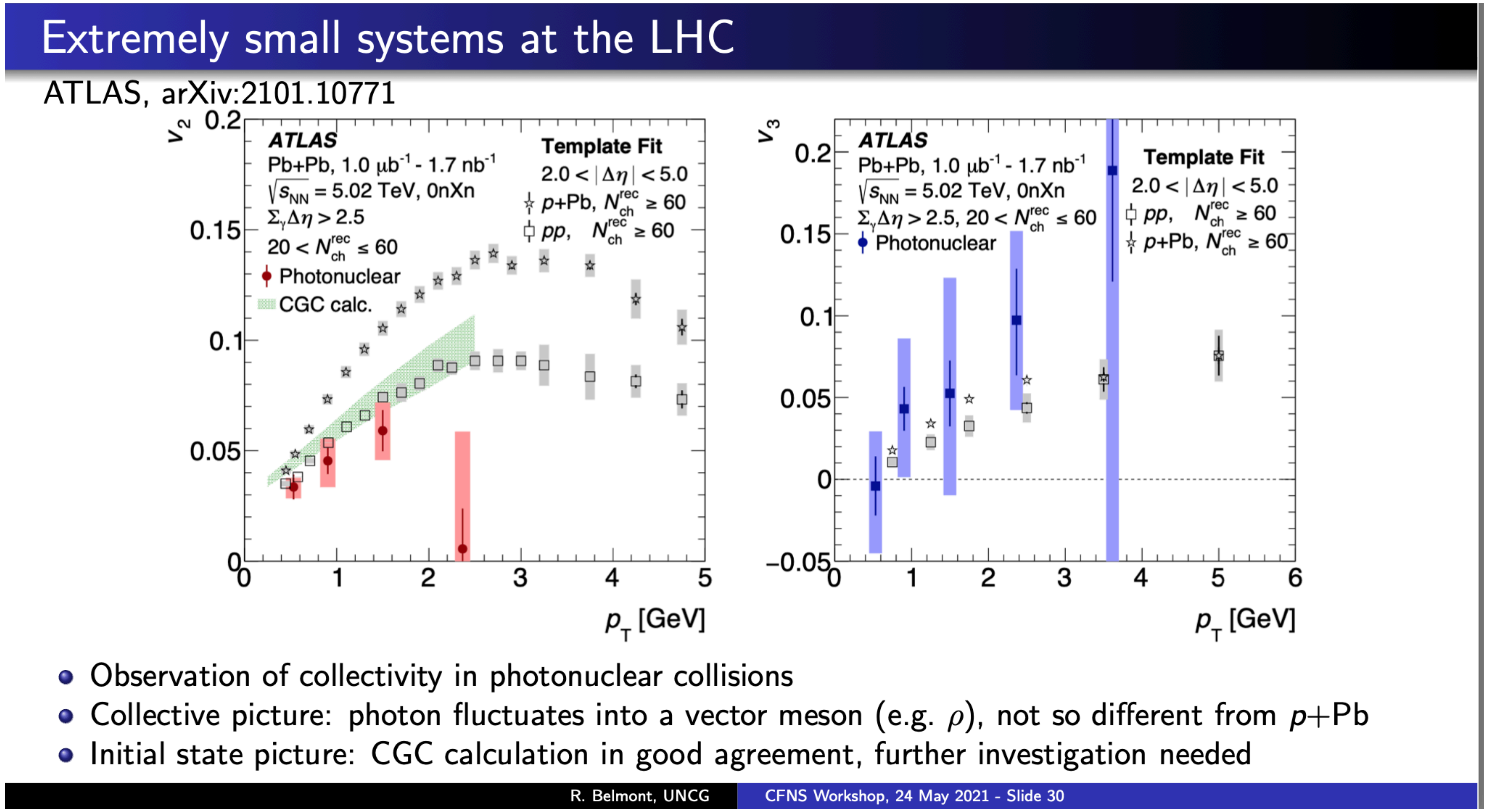
CMS-PAS-HIN-18-011





UPC in sPHENIX?

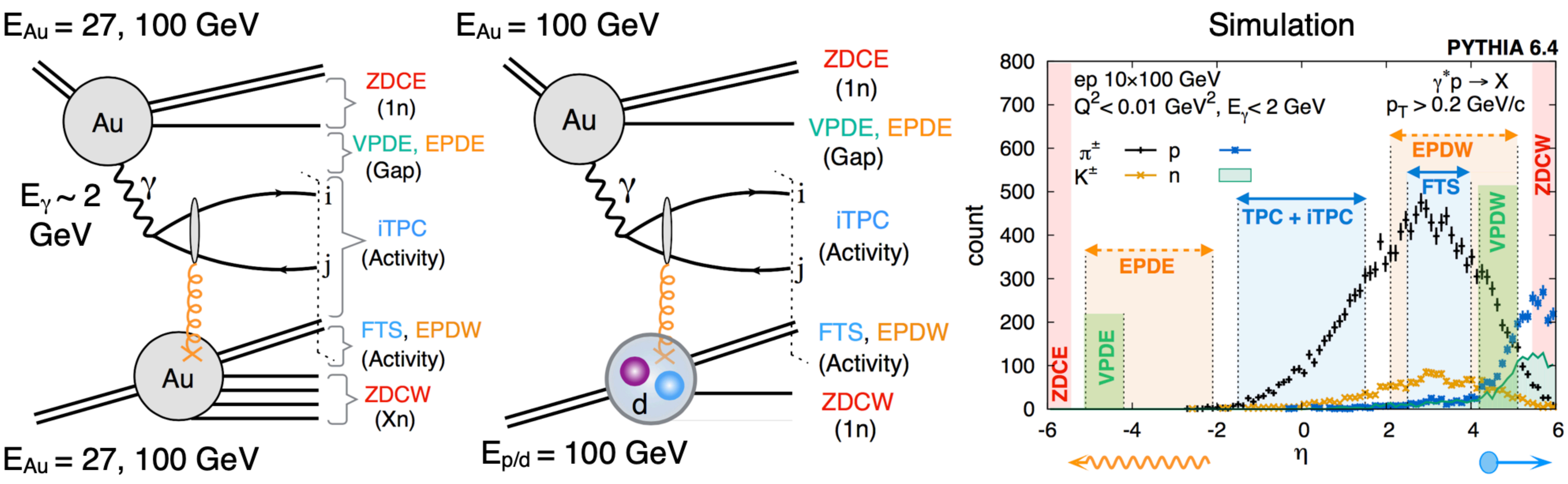
ANISOTROPY IN PHOTONUCLEAR COLLISIONS



- Rapidity dependence of the CGC signal? Note $\Delta\eta > 2.5$.
- Final state calcluations? Hydro? What is the initial geometry? ρ-meson + A collision

Prithwish Tribedy

Photonuclear processes in UPC from STAR



Opportunities and scope:

1. STAR with enhanced pseodorapidity acceptance (iTPC + EPD + FTS/FCS)
2. Anticipated Au+Au 200 GeV run of RHIC (2023, 2025)
3. Data on tape: Au+Au 54 GeV (2017), Au+Au 200 GeV (2019)
4. Opportunistic p+Au or d+Au run at RHIC (2021, 2024)

Measurements:

1. Ridge, 2. change of chemistry (pi/k/p yield) & compare to hadronic events

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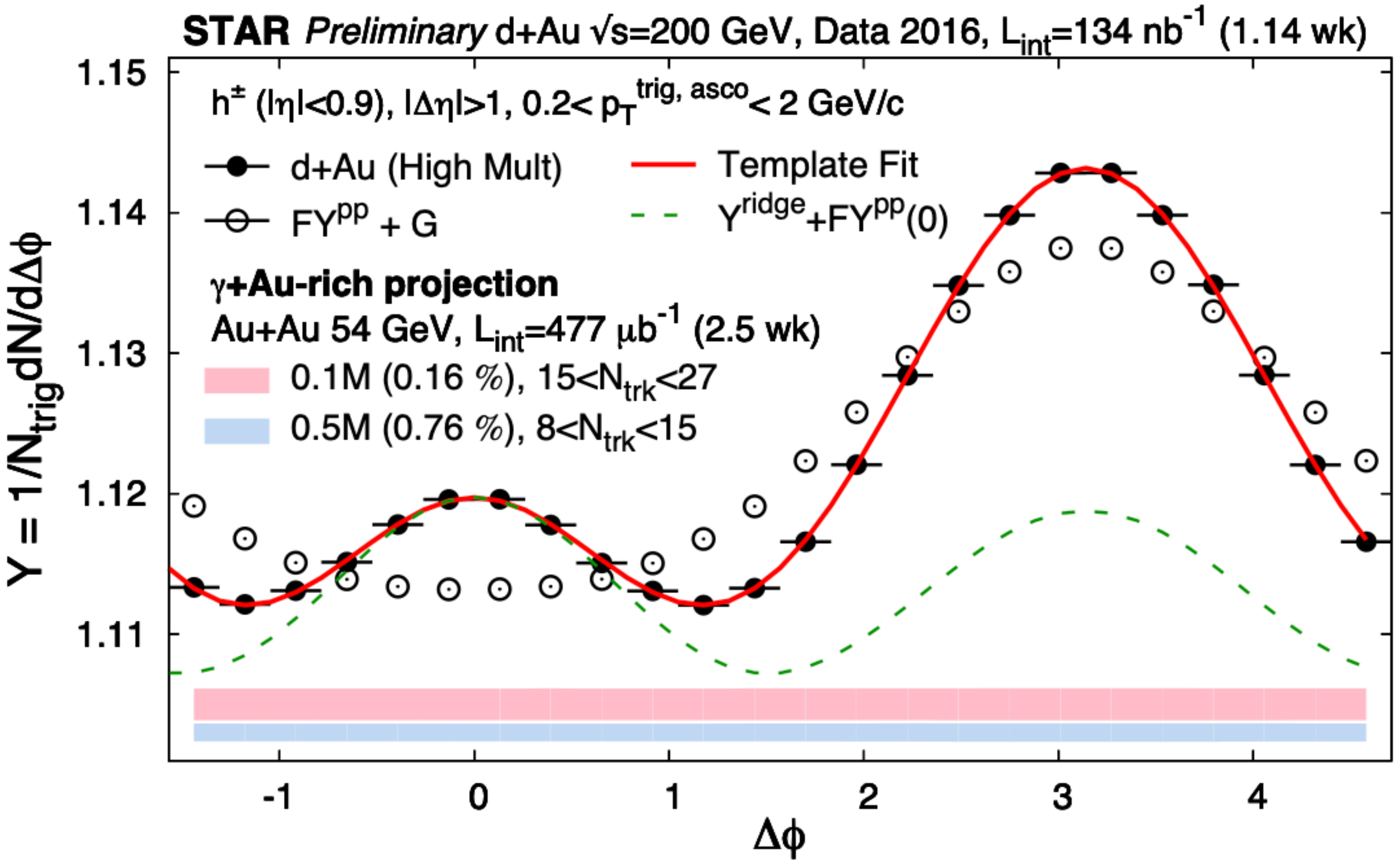
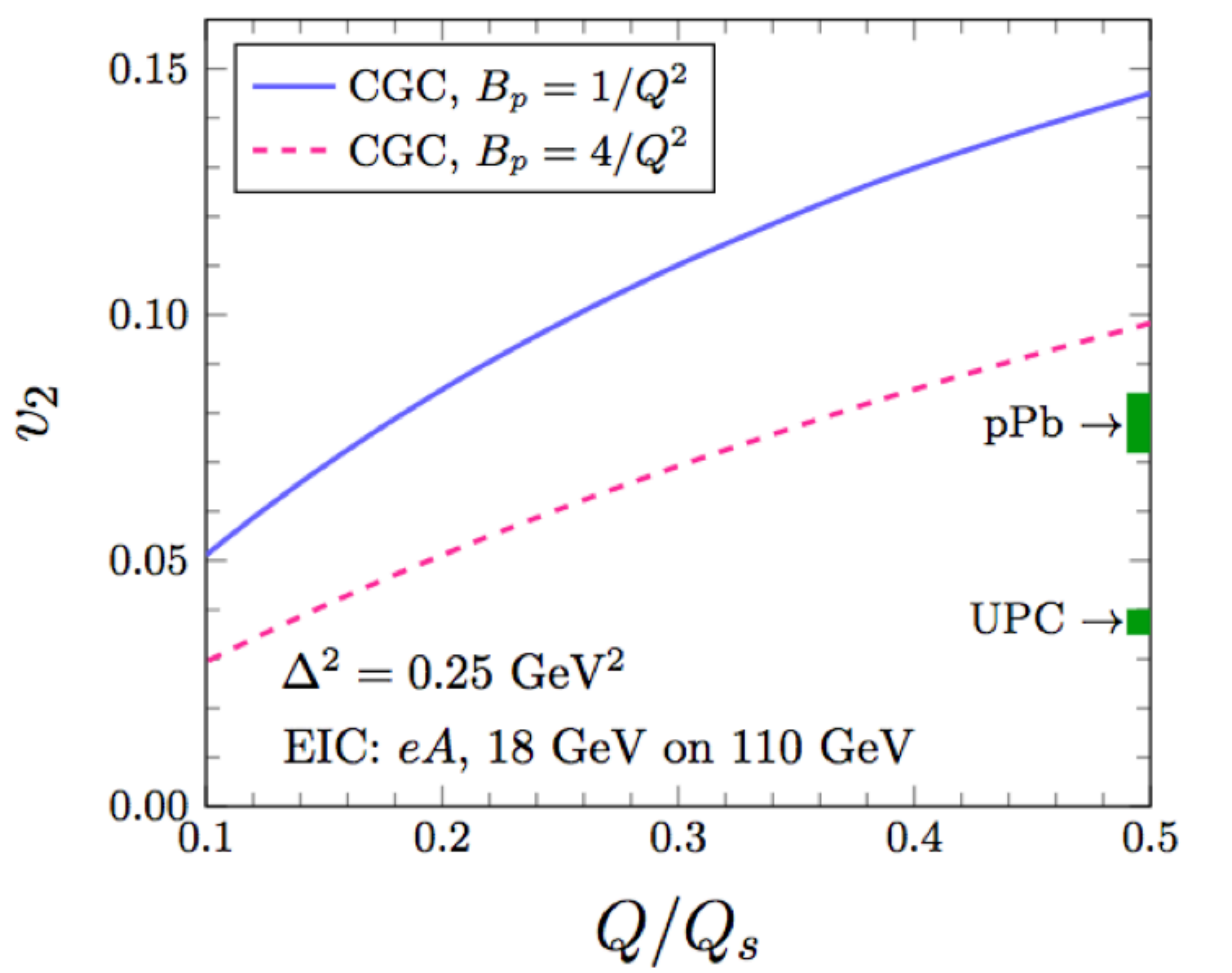


CGC calculation arXiv: 2008.03569



Significant difference between correlation in HM (red) & LM (blue) γ+p/Au will be interesting

Understanding anisotropy from CGC:

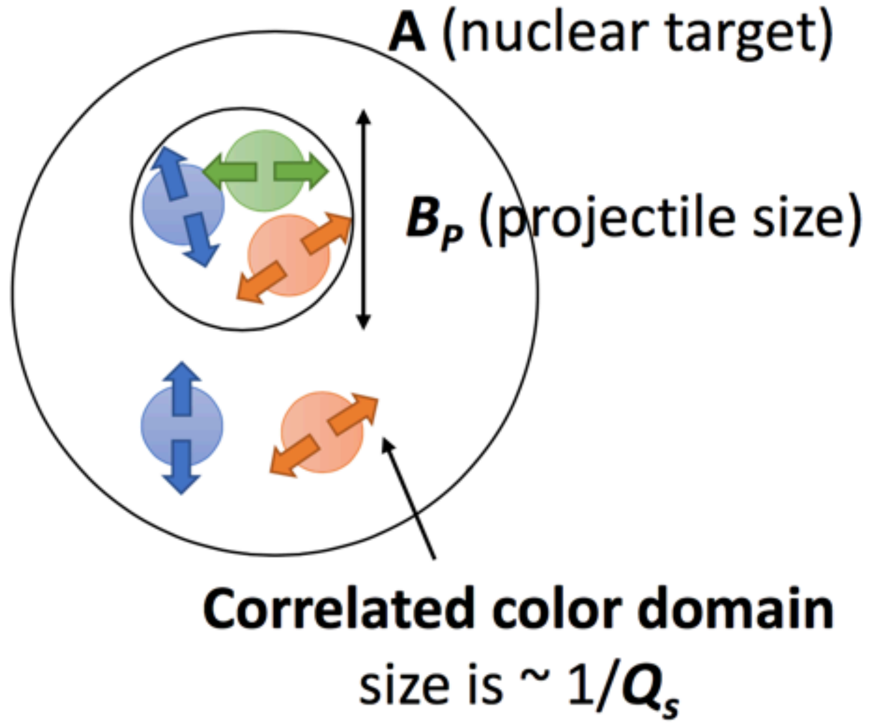
x — Q_s and domain size in Target

Q^2 — Size of the probe #domains

Best opportunity:

Controlled scan of x-Q^2 at EIC

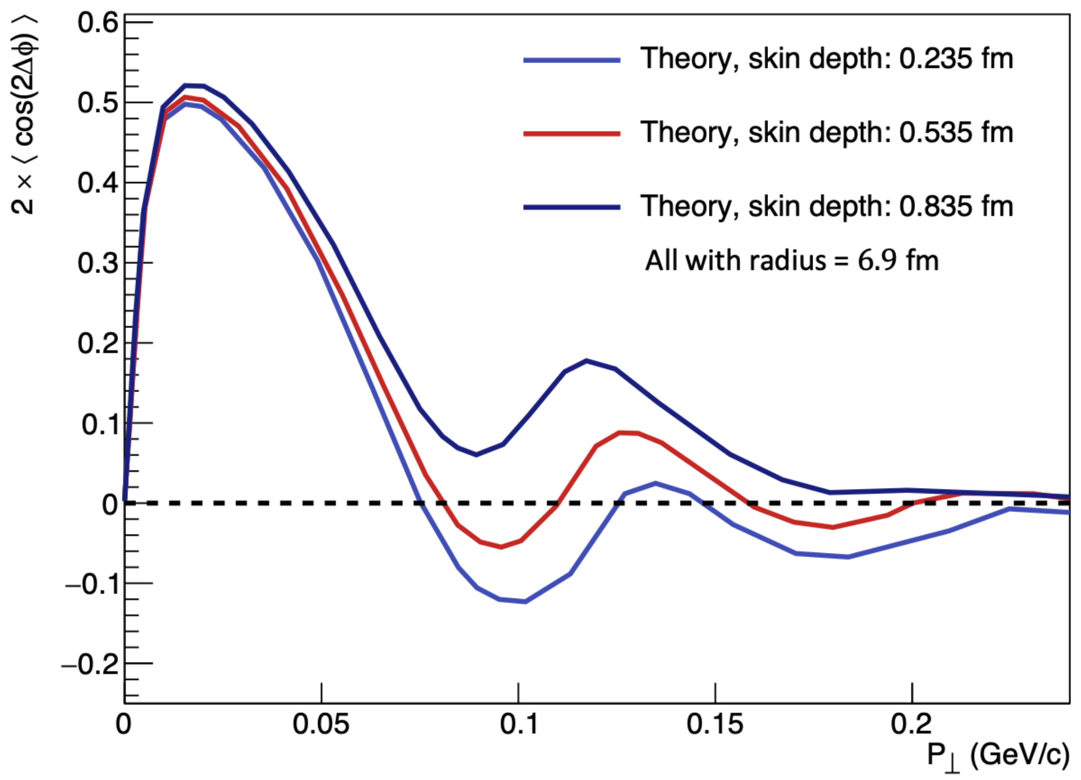
How anisotropy in p+p/Au compare to γ+p/Au @RHIC ?

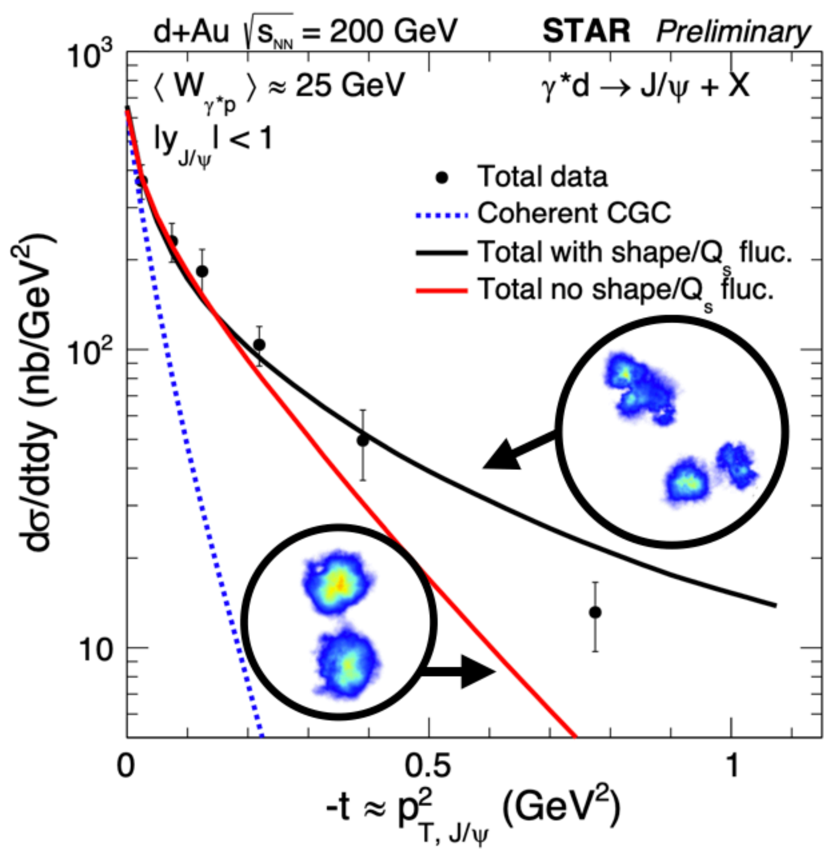


Cartoon: Blair Seidlitz, IS2021

CONSTRAINING THE HIC INITIAL STATE

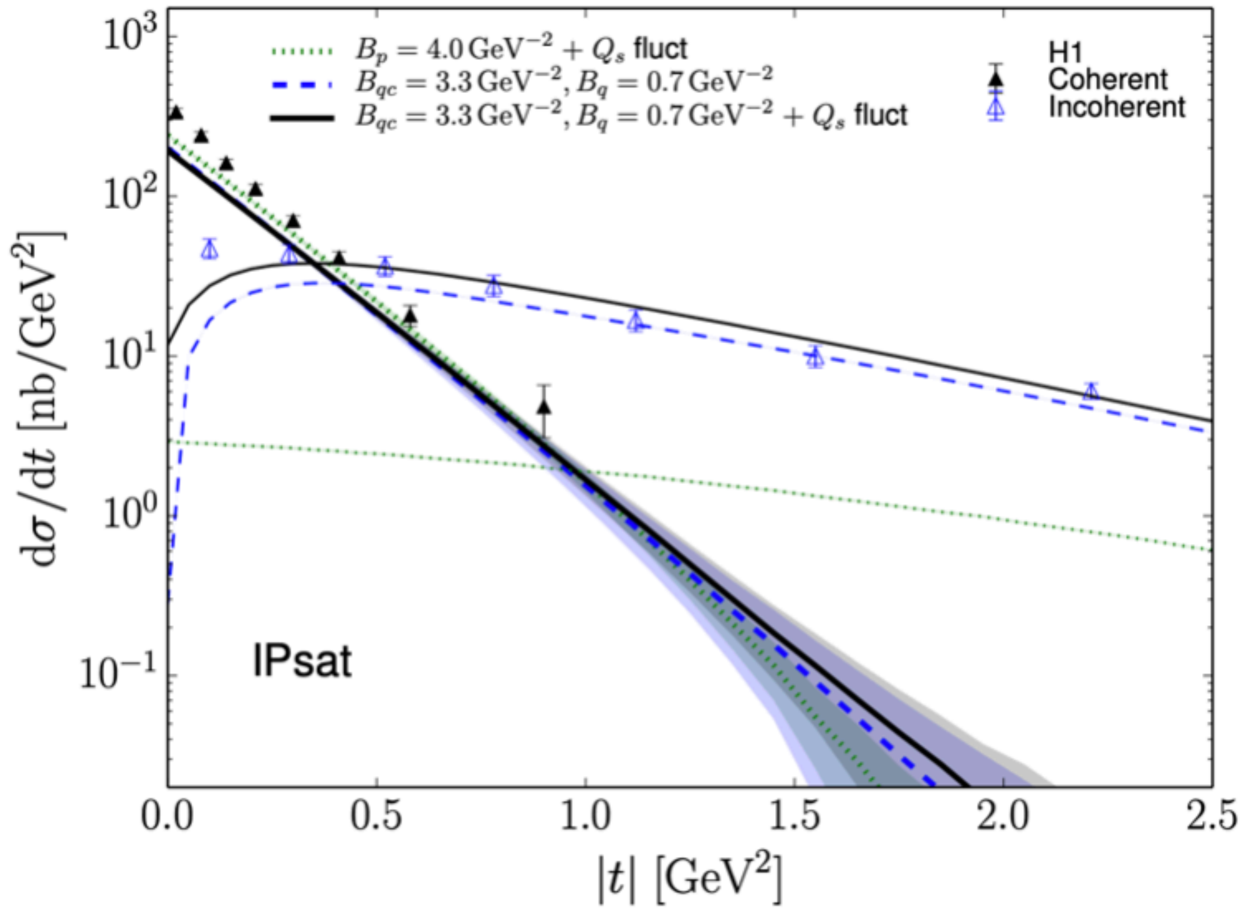
- Can use UPCs
  to constrain nuclear properties

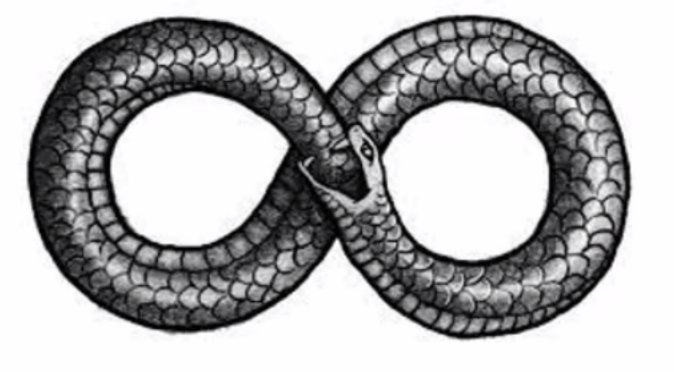




STAR Collaboration at Hard Probes 2020
arXiv:2009.04860

- Can use diffractive production at EIC to constrain spatial gluon distribution in protons and nuclei (and fluctuations)





Quantum mechanics of partons and entanglement

Dima Kharzeev

Proton is a pure state with zero entropy; a collection of quasi-free partons is not.
The key to solving this apparent paradox may be quantum entanglement:

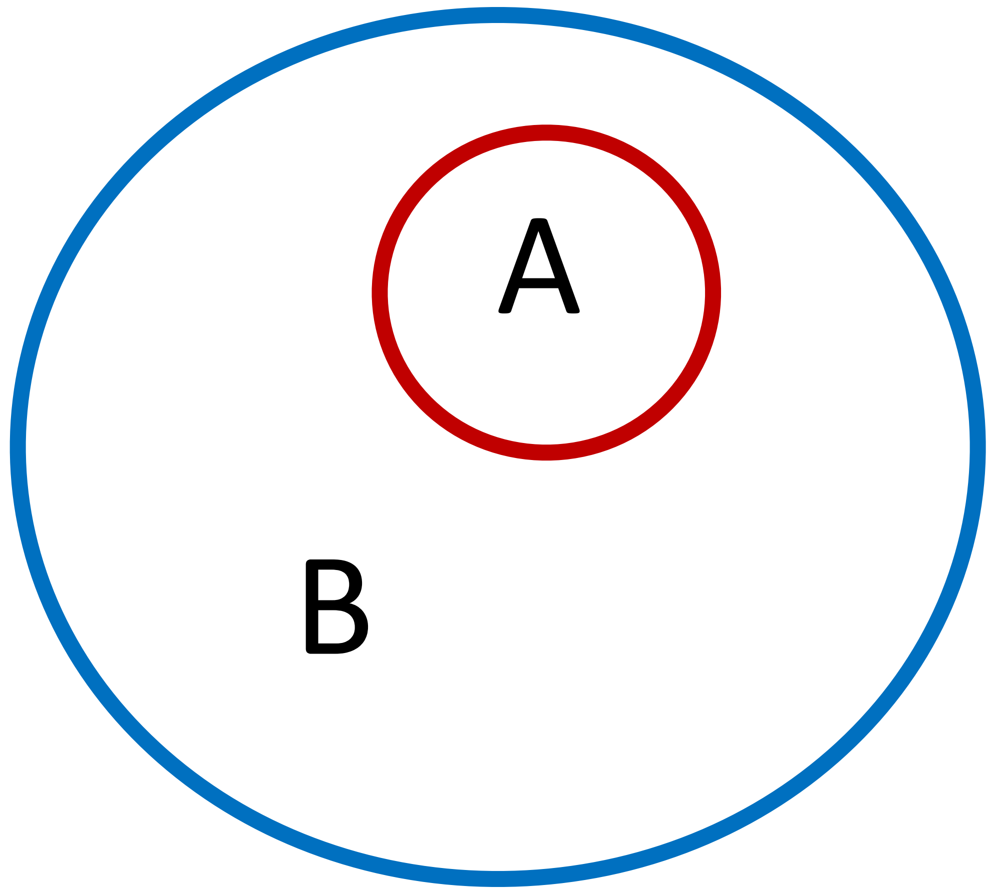
D. Kharzeev, E. Levin, arXiv:1702.03489; PRD (2017)

DIS probes only a part of the proton's wave function (region A). We sum over all hadronic final states; in quantum mechanics, this corresponds to accessing the density matrix of a mixed state

$$\hat{\rho}_A = \mathrm{tr}_{\mathrm{B}}\hat{\rho}$$

with a non-zero entanglement entropy

$$S_A = -\mathrm{tr}\left[\hat{\rho}_{\mathrm{A}} \ln \hat{\rho}_{\mathrm{A}}\right]$$



Dima Kharzeev

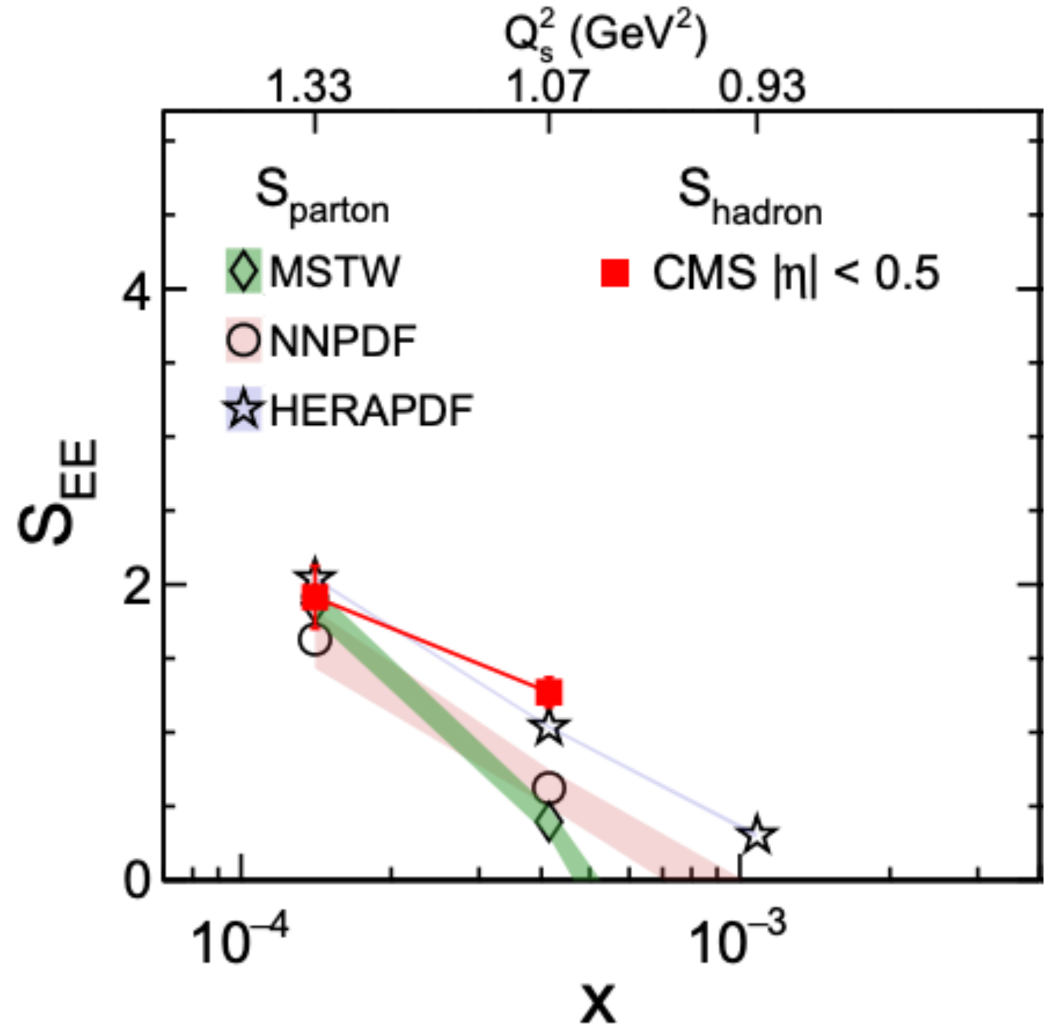
Tests of the entanglement and the EIC

LHC data (CMS Coll.):

$$S = \ln[xG(x)]$$

is satisfied at small x

(**maximal entanglement?!)**



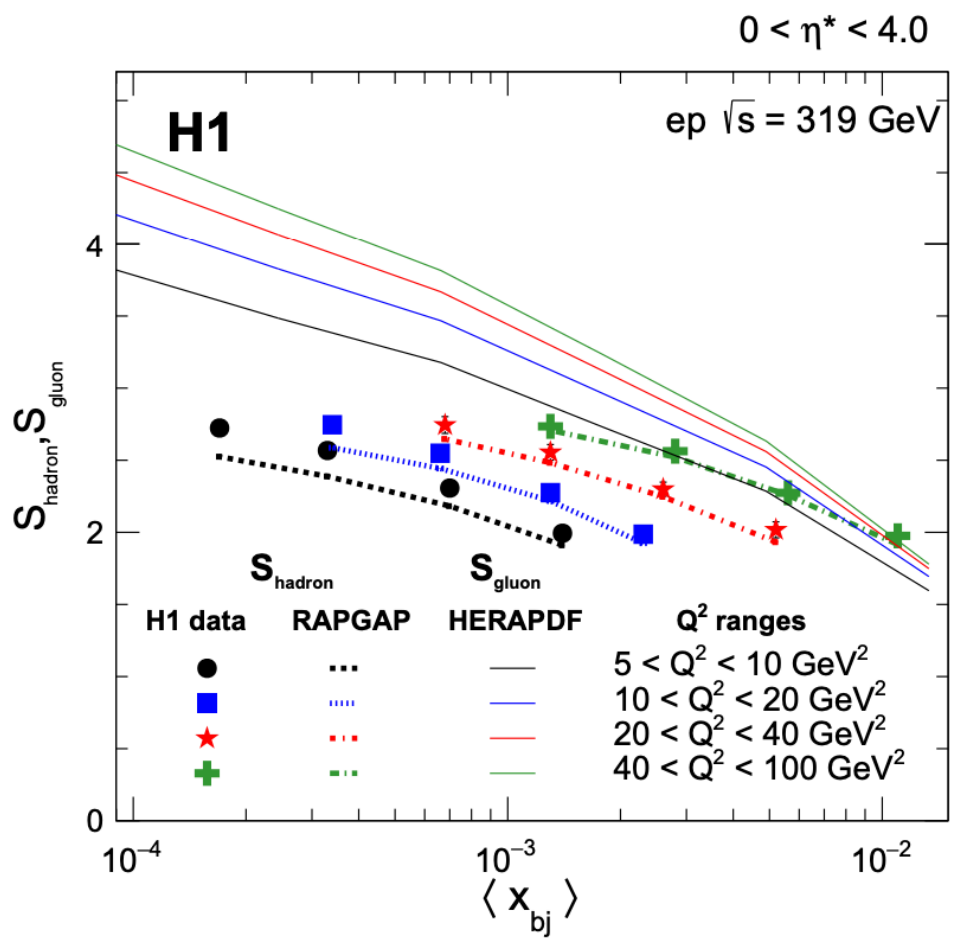
Z. Tu, D. Kharzeev, T. Ullrich, arXiv:1904.11974; PRL(2020)

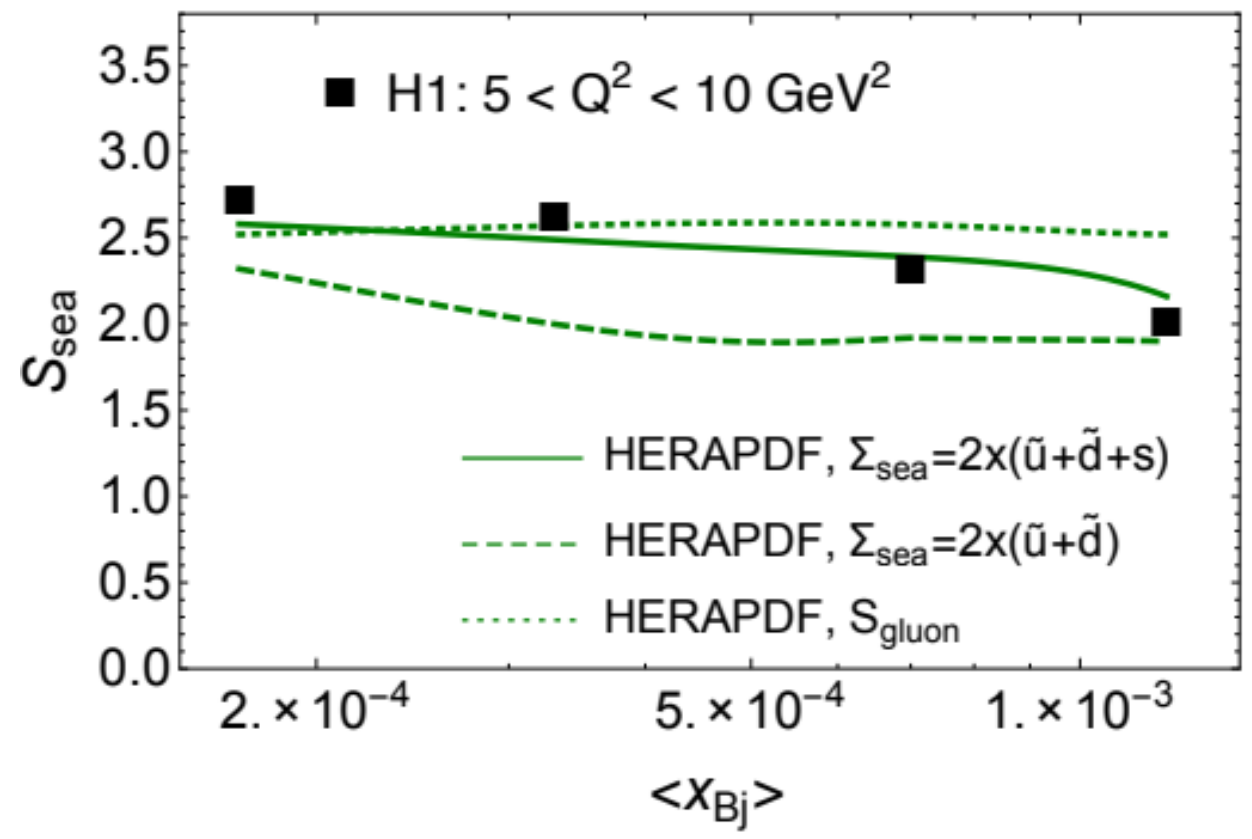
HERA DIS data (H1 Coll.):

Agreement with the data once the current fragmentation region is accounted for:

sea quark distribution

H1 Collaboration (Z. Tu et al) arXiv:2011.01812; EPJC(2021)





D. Kharzeev, E. Levin, arXiv:2102.09773

EIC can perform pioneering measurements in the target fragmentation region (maximally entangled state); Real discovery potential!

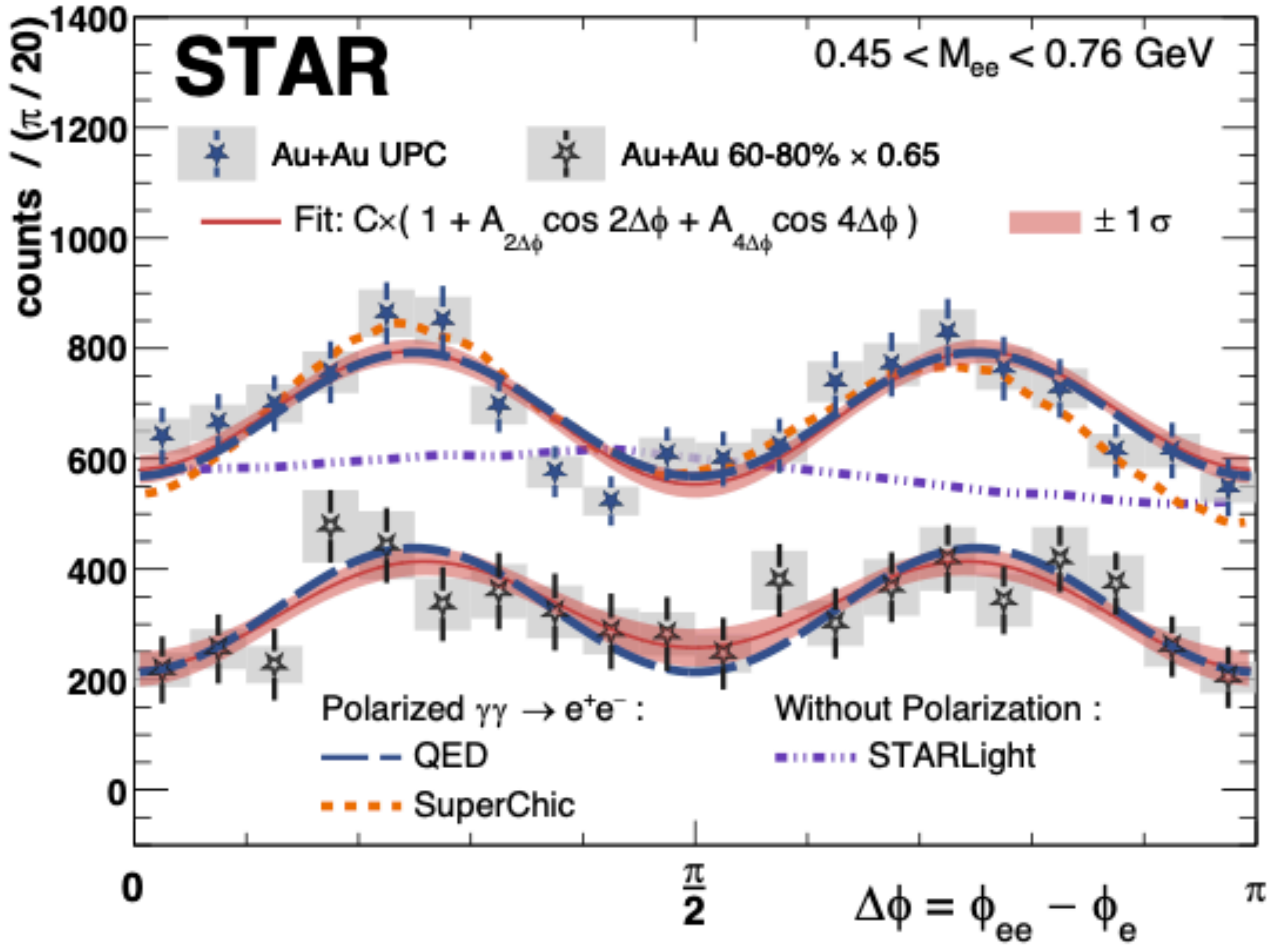
ENTANGLEMENT

- Anything RHIC can/should do?

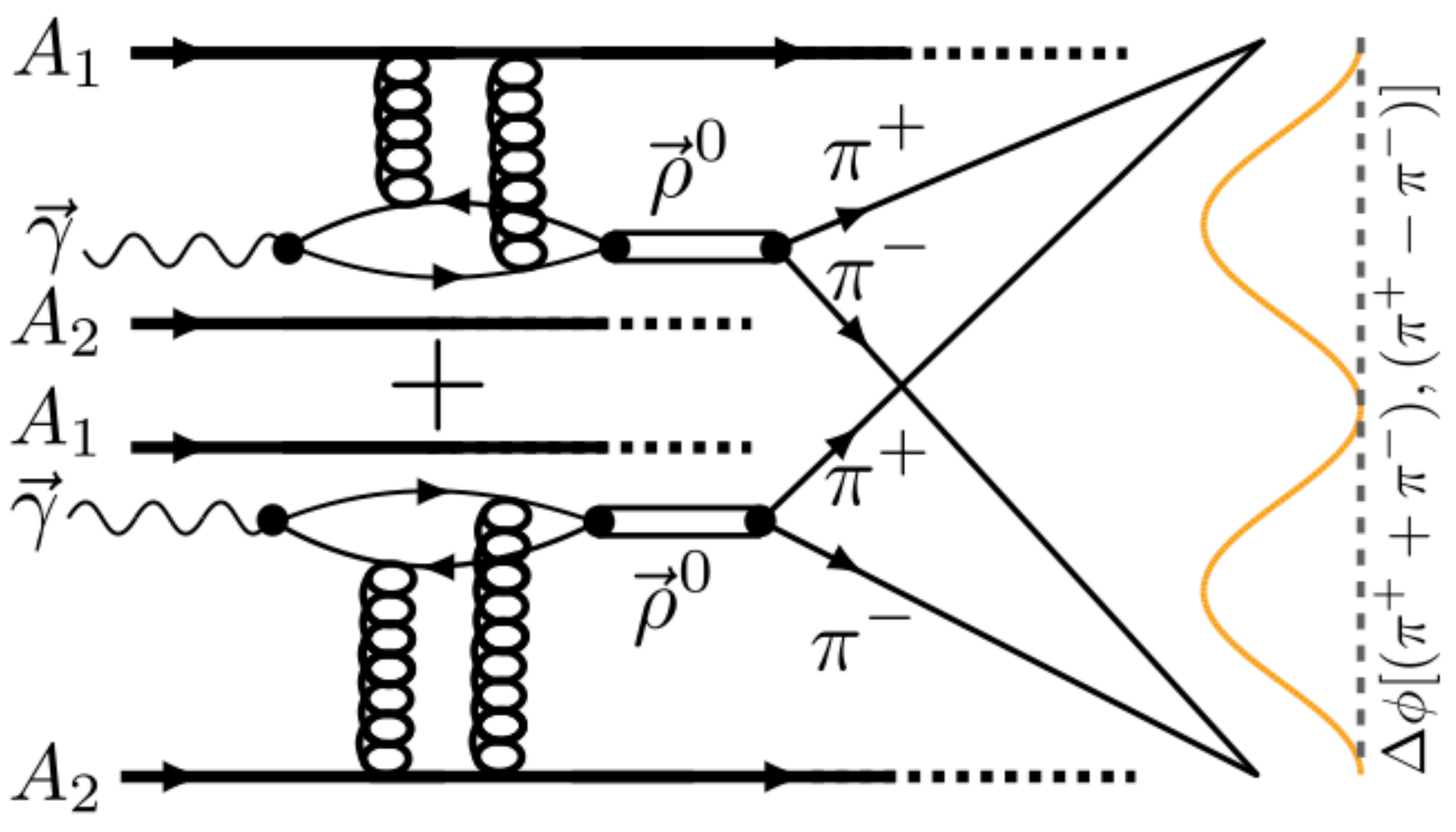
SOME MORE SLIDES

Highlights I : Polarized Photon-Gluon Collisions

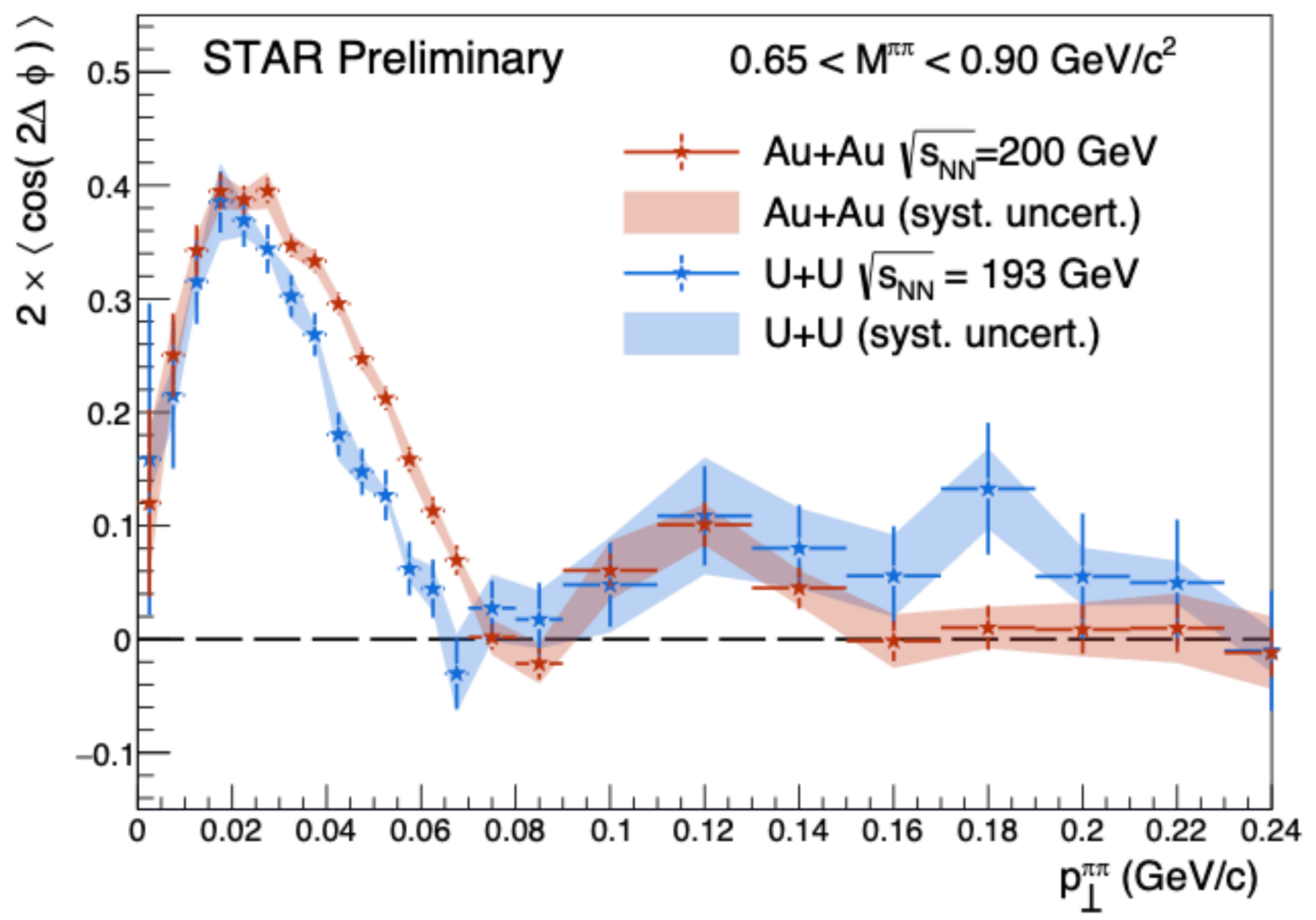
Significant $\cos 4\Delta\phi$ modulation in $\gamma\gamma \rightarrow e^+e^-$ process: Experimental demonstration of linear polarization of quasi-real photons



Two source interference in VM production → $\cos 2\Delta\phi$ modulation in $\rho^0 \rightarrow \pi^+\pi^-$



Interference shows rich structure vs. P_T



New Interference pattern observed in diffractive photo-nuclear interactions

- Experimental demonstration of <u>sensitivity to gluon distribution</u> and that <u>incoherent does not contribute to interference pattern</u>
- New measurement possibilities:
  - J/ψ, which provides hard scale for theoretical calculations,
  - Measurements in non-UPC, comparison of $\rho^0 \rightarrow \pi^+\pi^-$ vs. $J/\psi \rightarrow l^+l^-$ to see if interference exists in both
  - Differential measurements w.r.t. mass, rapidity to test interference characteristics
  - Observation of Coulomb-Nuclear Interference

Coulomb-Nuclear Interference