Nuclear imaging with diffractive vector meson production in UPCs

SPIN Symposium

Joint GPD/Nuclear Session
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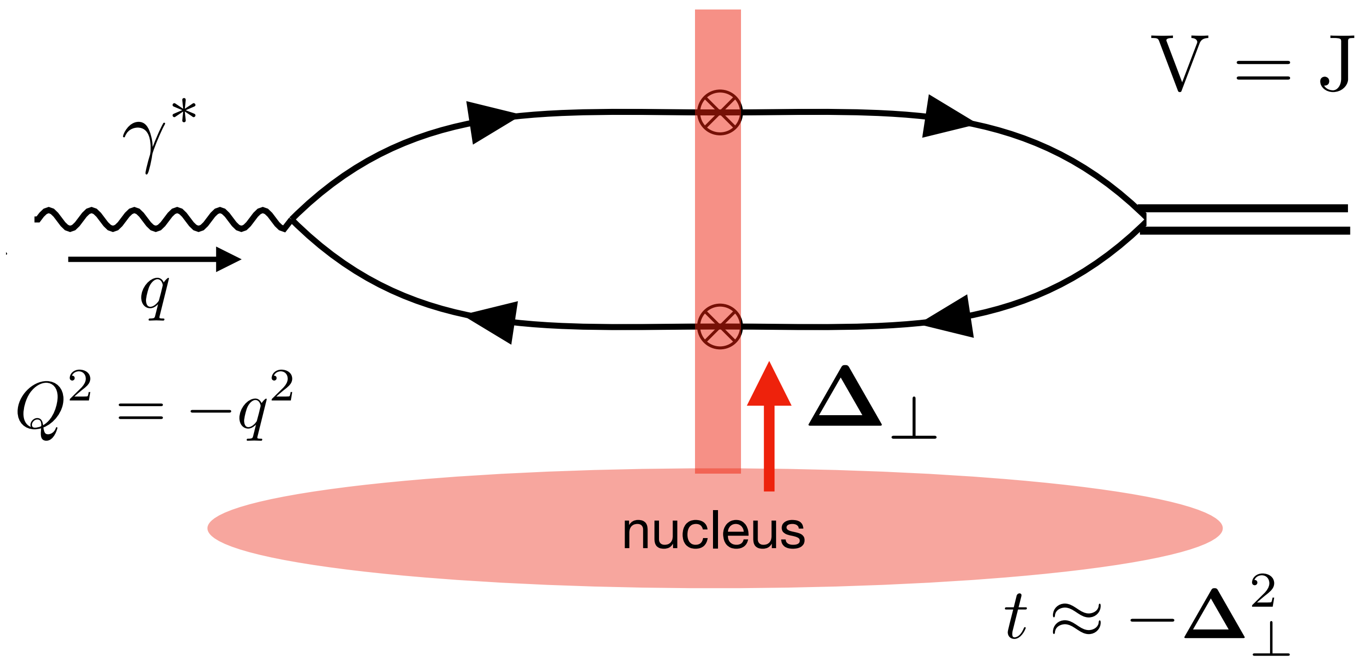
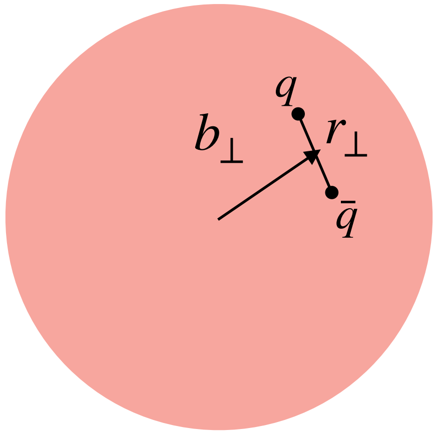
Phys.Rev.D 106 (2022) 7, 074019. arXiv: 2207.03712. H. Mäntysaari, FS, B. Schenke.
Work in progress 2310.XXXX. HM, FS, BS, Chun Shen, Wenbin Zhao

Diffraction, Saturation and Vector Meson Production

The dipole picture



$\mathrm{V} = \mathrm{J}/\psi, \rho, \omega, \ldots$



Diffraction = no net color exchange
rapidity gap

$\Psi_{\gamma*}$ computed in QED, Ψ_V needs a non-perturbative modeling

$$\mathcal{A}(Q, \boldsymbol{\Delta}_\perp) = \int_{\boldsymbol{b}_\perp, \boldsymbol{r}_\perp, z} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \Psi_\gamma^*(Q, \boldsymbol{r}_\perp, z) D(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \Psi_V(\boldsymbol{r}_\perp, z)$$

Interaction of the dipole with small-x background field, aka CGC, shock-wave…

Diffraction, Saturation and Vector Meson Production

Coherent and nuclear imaging

- Coherent (aka exclusive): Target remains intact

$$\mathrm{d}\sigma_{coh}/\mathrm{d}|t| \propto \langle \mathcal{A}^{\dagger}(\boldsymbol{\Delta}_{\perp})\rangle_x \langle \mathcal{A}(\boldsymbol{\Delta}_{\perp})\rangle_x$$

Simplest model

$$\langle D(\boldsymbol{r}_{\perp}, \boldsymbol{b}_{\perp})\rangle_x \propto T(\boldsymbol{b}_{\perp}) \qquad \mathrm{d}\sigma_{coh} \propto \left| \int \mathrm{d}^2\boldsymbol{b}_{\perp} e^{-i\boldsymbol{\Delta}_{\perp}\cdot\boldsymbol{b}_{\perp}} T(\boldsymbol{b}_{\perp}) \right|^2$$

Study $\boldsymbol{\Delta}_{\perp}$-dependence -> form factor of nuclei (Nuclear imaging)

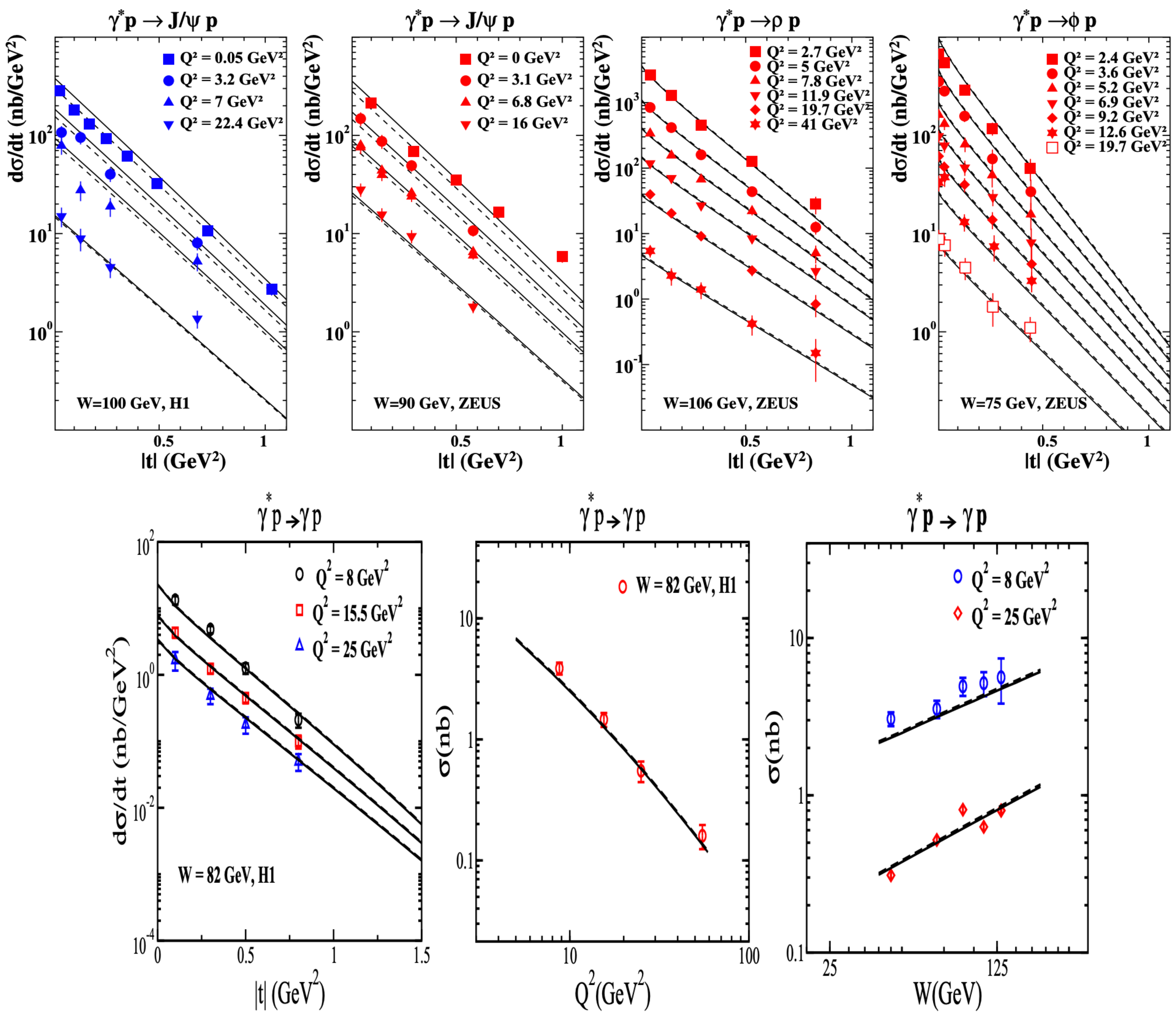
Saturation model (e.g. GBW or IPSAT) modify the profile

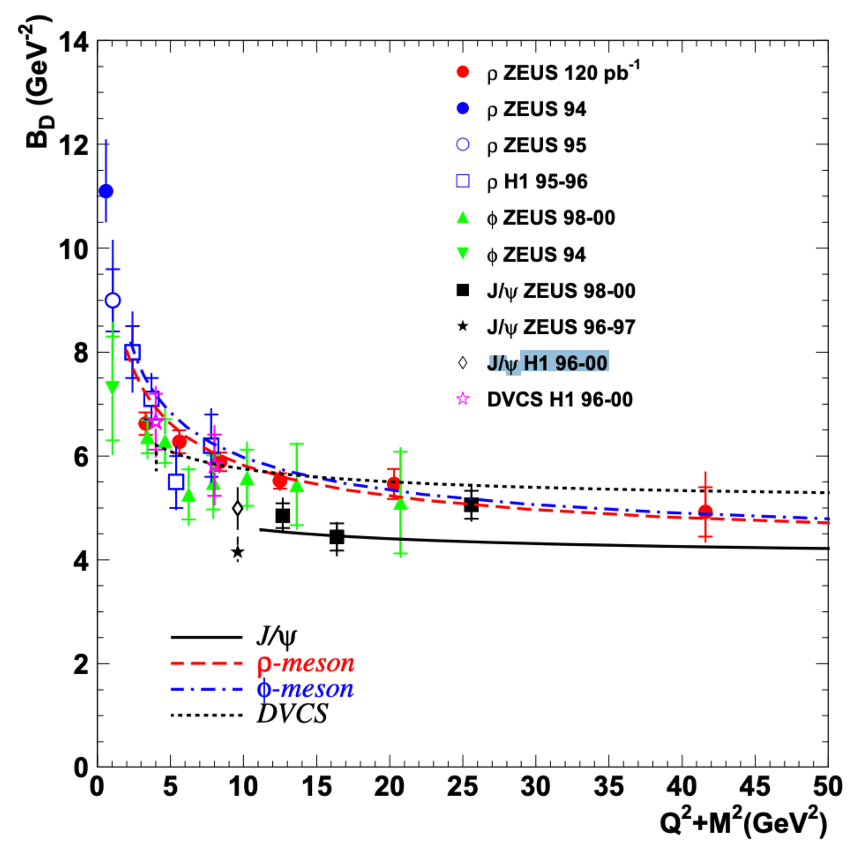
$$\langle D(\boldsymbol{r}_{\perp}, \boldsymbol{b}_{\perp})\rangle_x = 1 - e^{-g(x, 1/\boldsymbol{r}_{\perp}^2) T(\boldsymbol{b}_{\perp})}$$

Teaney and Kowalski (PRD 2003)

Diffraction, Saturation and Vector Meson Production

Comparison of HERA to saturation





Extract proton size from slope of exclusive spectra

Saturation model = IPSAT

Rezaeian, Siddikov, Klundert, Venugopalan (PRD 2013)

Diffraction, Saturation and Vector Meson Production

Incoherent and fluctuations

- Incoherent: Target breaks-up

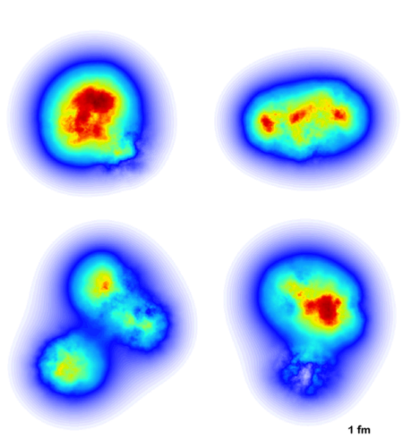
$$\mathrm{d}\sigma_{incoh} \propto \langle \mathcal{A}^\dagger(\mathbf{\Delta}_\perp)\mathcal{A}(\mathbf{\Delta}_\perp)\rangle_x - \langle \mathcal{A}^\dagger(\mathbf{\Delta}_\perp)\rangle_x \langle \mathcal{A}(\mathbf{\Delta}_\perp)\rangle_x$$

Origin of fluctuations in proton:

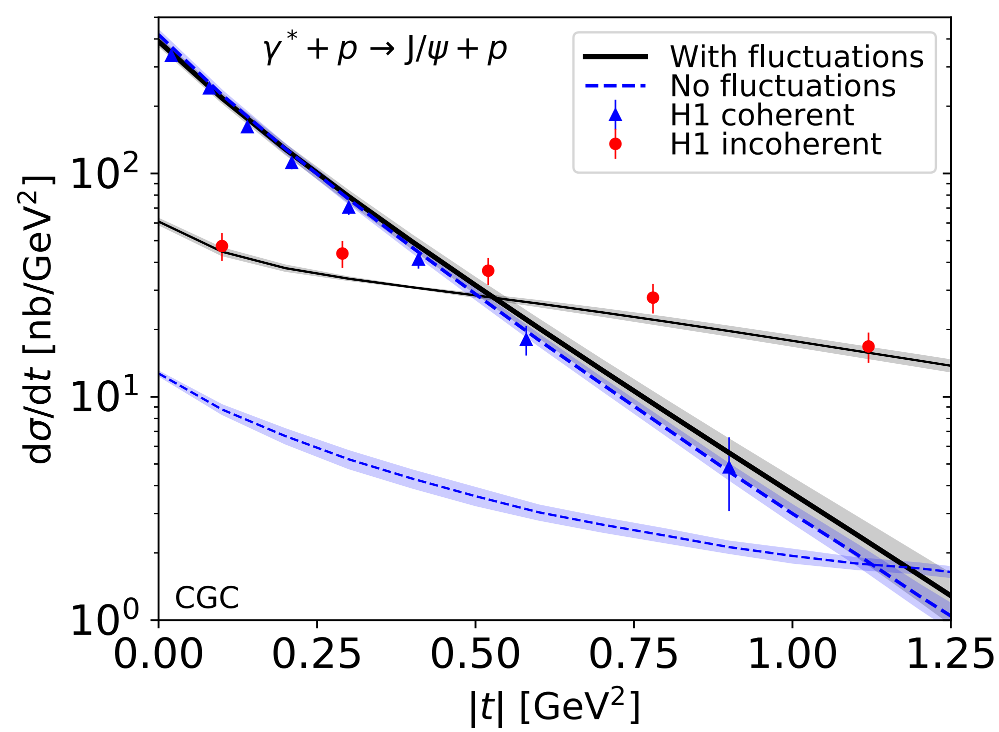
Color charge correlations in CGC (beyond IPSAT or GBW)

$$\langle D^\dagger(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) D(\boldsymbol{r}'_\perp, \boldsymbol{b}'_\perp)\rangle_x - \langle D^\dagger(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\rangle_x \langle D(\boldsymbol{r}'_\perp, \boldsymbol{b}'_\perp)\rangle_x \sim \mathcal{O}(1/N_c^2)$$

Sub-nucleon fluctuations (hotspots)

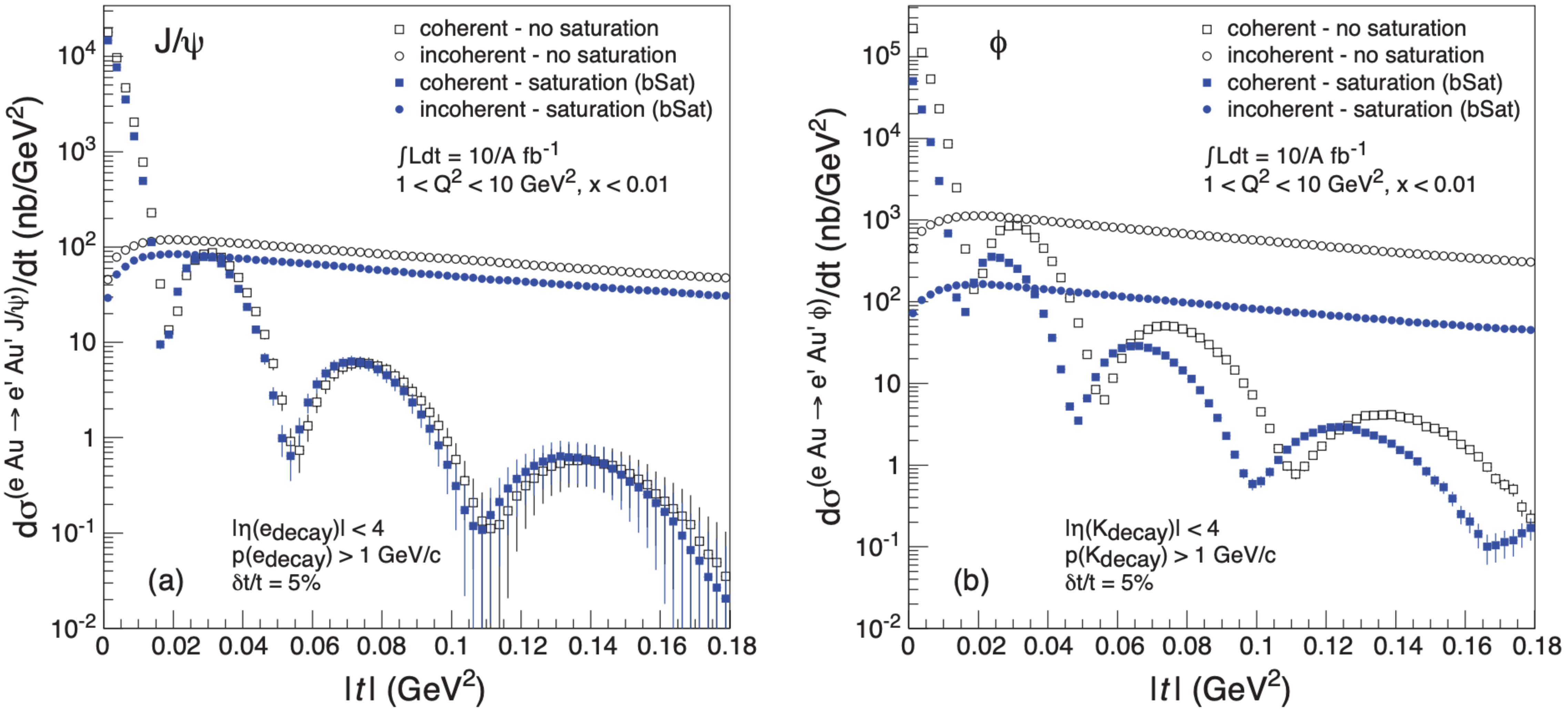


Mantysaari and Schenke (PRL 2016)



Diffraction, Saturation and Vector Meson Production

Expectations for the future EIC



Toll, Ullrich (PRC 2013)

Characteristic dips at ~ multiples of nuclear size (linearized model)

Saturation modifies |t| spectrum, large modifications for φ less so for J/ψ

Incoherent production dominates $|t| > 0.02\ \mathrm{GeV}^2$

Diffraction, Saturation and Vector Meson Production

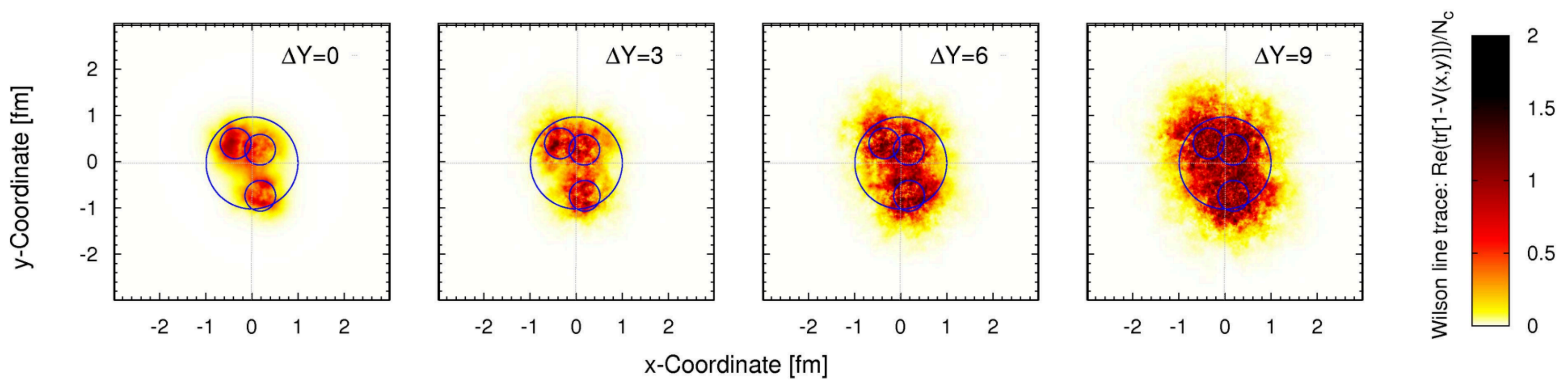
Our setup

- Initial condition: McLerran-Venugopalan model with nucleon substructure

$$\langle \rho^a(\boldsymbol{x}_\perp)\rho^b(\boldsymbol{y}_\perp)\rangle \propto \delta^{ab}\delta^{(2)}(\boldsymbol{x}_\perp - \boldsymbol{y}_\perp)T_p(\boldsymbol{x}_\perp) \qquad T_p(\boldsymbol{b}_\perp) = \frac{1}{2\pi B_q N_q}\sum_{i=1}^{N_q} p_i e^{-(\boldsymbol{b}_\perp - \boldsymbol{b}_{\boldsymbol{i}\perp})^2/(2B_q)}$$

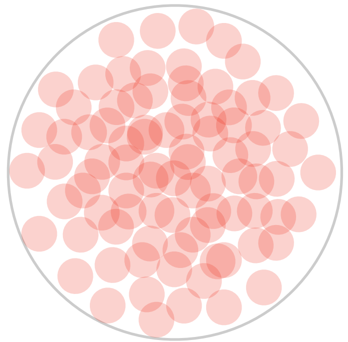
Parameters constrained by HERA data

- Small-x evolution (gluon emissions/recombinations) via JIMWLK



Growth of the target with increasing energy/rapidity

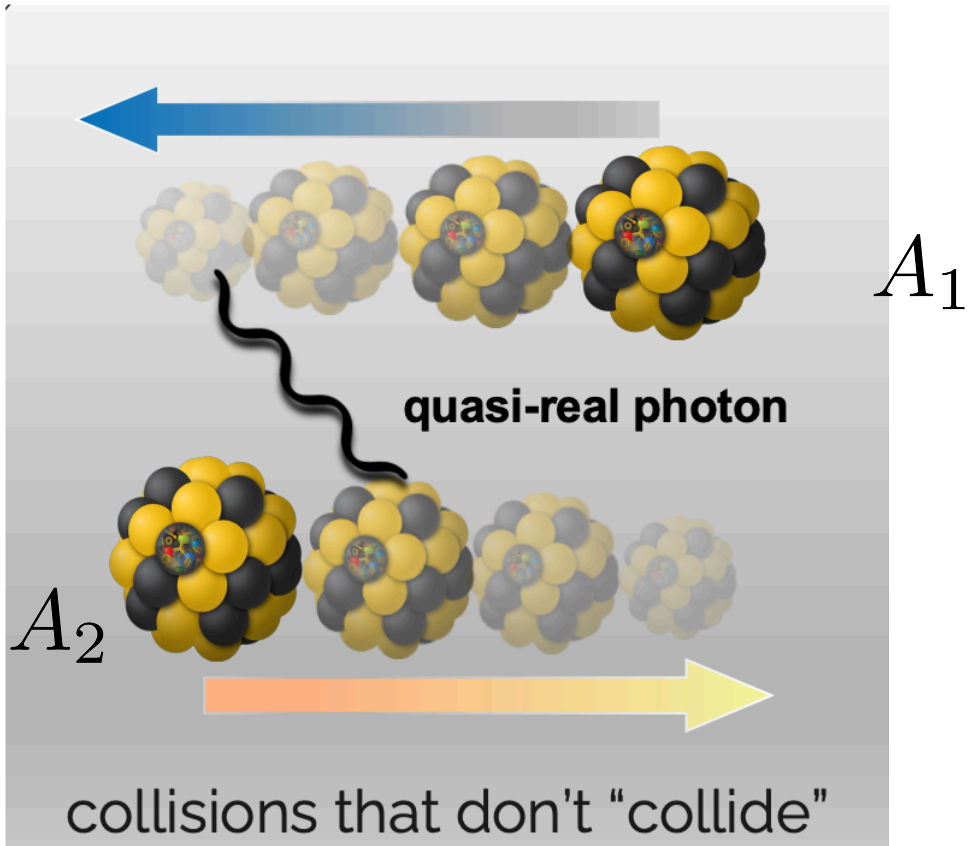
- For collisions with nuclei: we sample nucleons according to Woods-Saxon distribution



Connection to heavy ions see Mäntysaari, Schenke, Shen and Tribedy (PLB 2017)

Ultra-peripheral collisions

Photon-nucleus collisions with heavy-ions



Credit: Kong Tu DIS 2023

Ion (electrically charged) serves as a photon source, the other ion serves as the nuclear target

Minimum distance between ions:

$$B_{min} \geq R_{A_1} + R_{A_2}$$

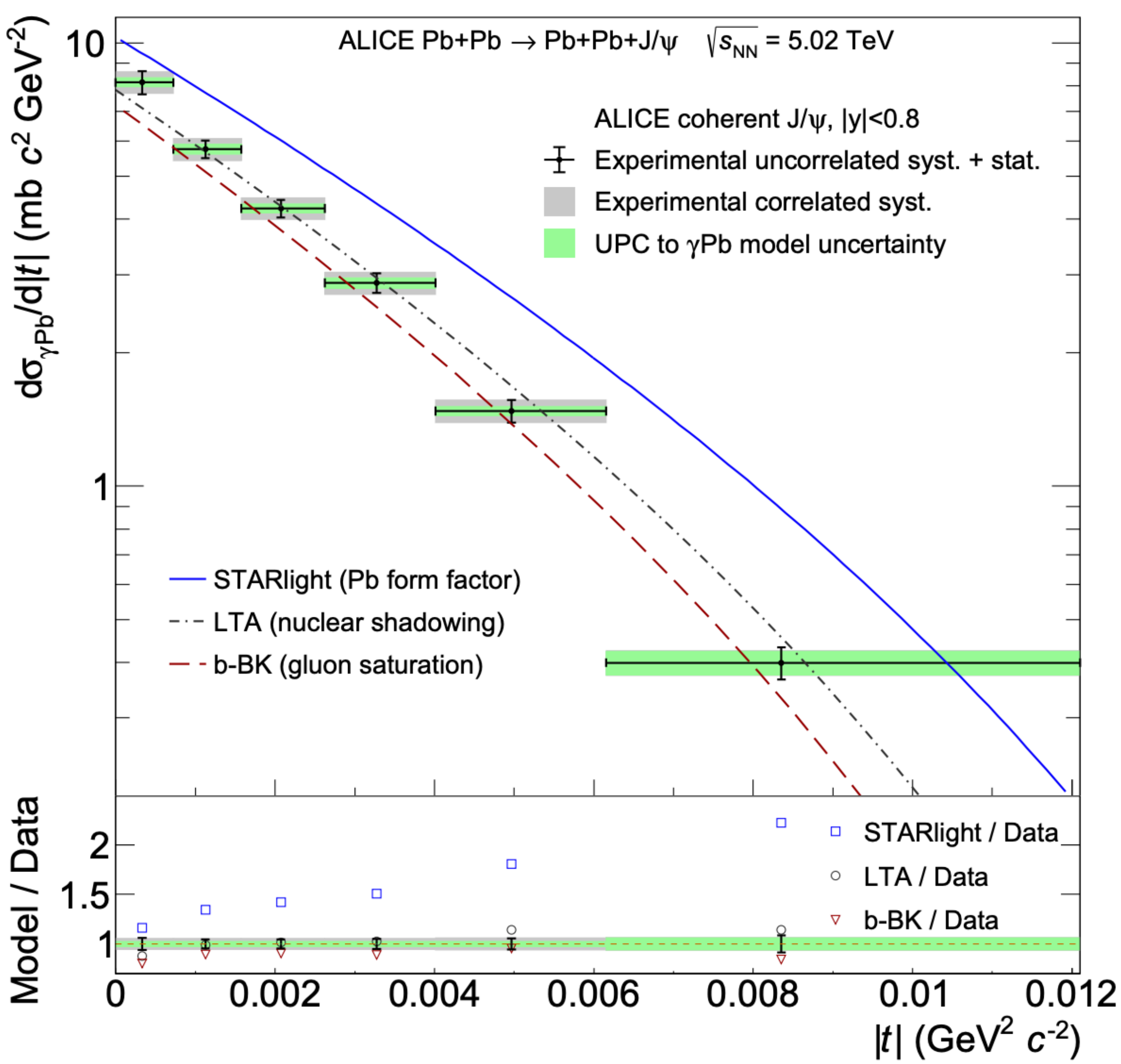
Photon fluxes

$$\frac{\mathrm{d}\sigma^{A_1+A_2\to A_1+A_2+V}}{\mathrm{d}|t|\mathrm{d}y} = N(x_1)\left.\frac{\mathrm{d}\sigma^{\gamma+A_2\to A_2+V}}{\mathrm{d}|t|\mathrm{d}y}\right|_{x_2} + N(x_2)\left.\frac{\mathrm{d}\sigma^{\gamma+A_1\to A_1+V}}{\mathrm{d}|t|\mathrm{d}y}\right|_{x_1}$$

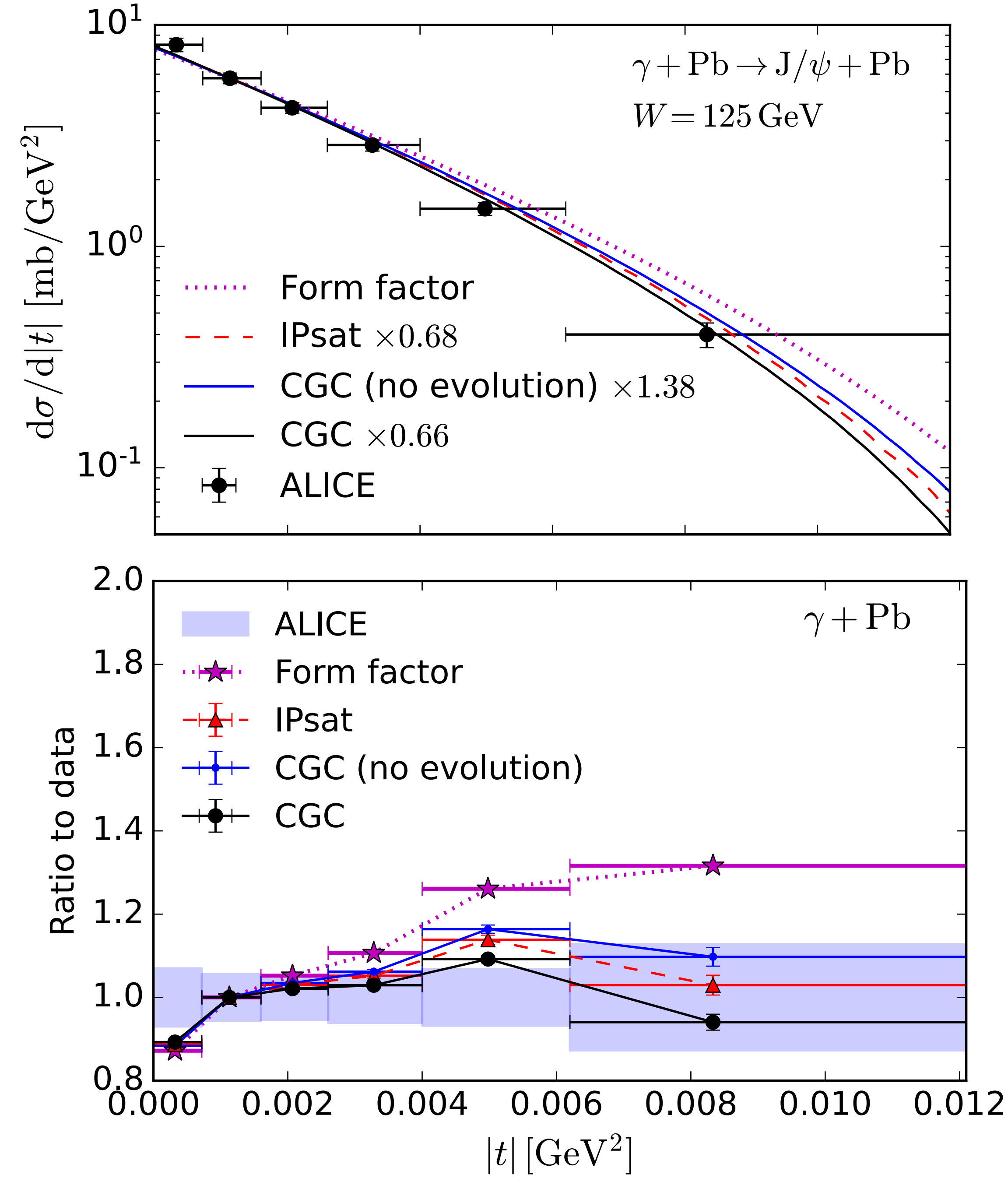
$$x_1 = \frac{M_V e^{-y}}{\sqrt{s}} \qquad x_2 = \frac{M_V e^{y}}{\sqrt{s}}$$

Ultra-peripheral collisions

Results from LHC for J/Ψ in γPb



ALICE extracts (via unfolding) $\gamma^{*}Pb$ collision from UPC (PLB 2021)



STARlight = FT of form factor (FT of Woods-Saxon)

H. Mäntysaari, FS, B. Schenke (PRD 2022)

LTA = Leading Twist Shadowing

b-BK= saturation framework

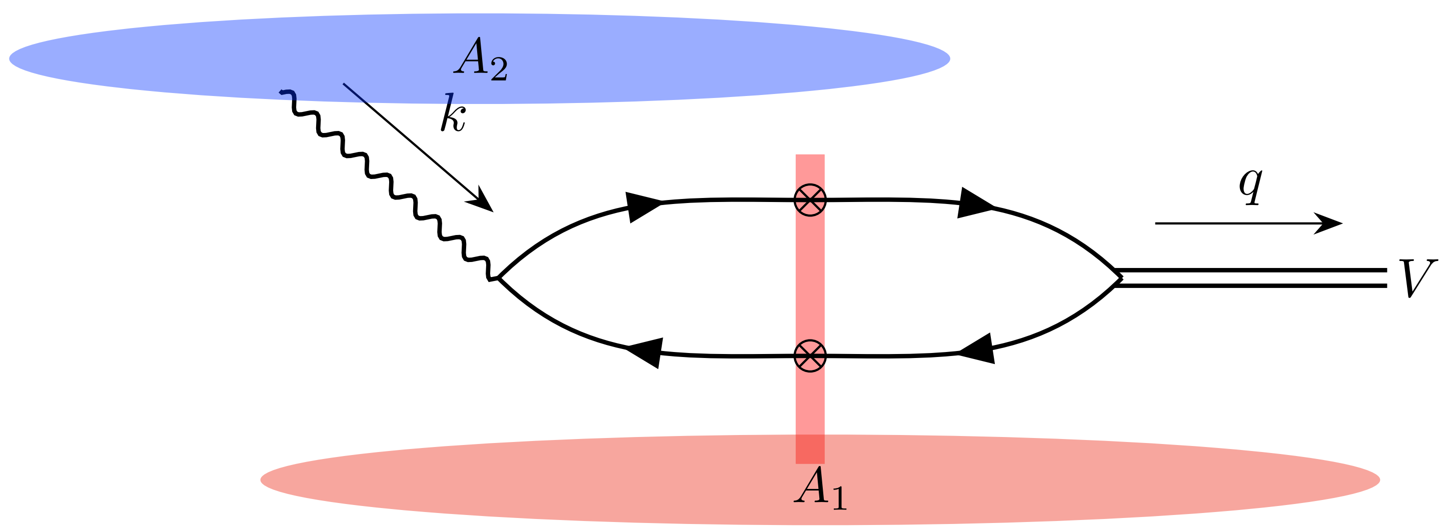
Ultra-peripheral collisions

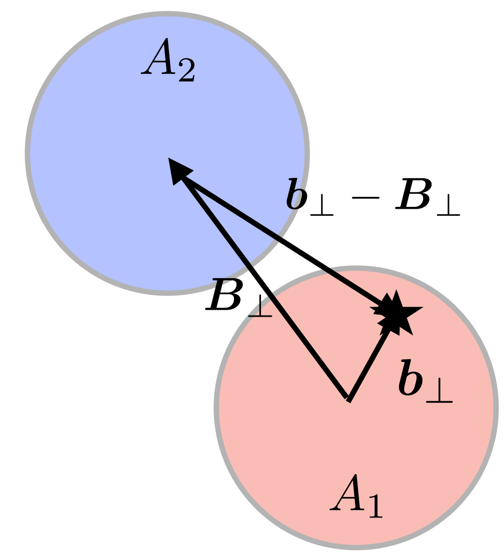
Quantum interference and finite photon kT

"The emitters and targets can switch roles, and the two possibilities are indistinguishable, so [quantum] interference may occur" Klein, Nystrand (PRL 2000)

Photon carries small but non-zero transverse momentum kT

Joint impact parameter-TMD framework proposed by Xing, Zhang, Zhou, Zhou (JHEP 2020)





$+A_1 \leftrightarrow A_2$

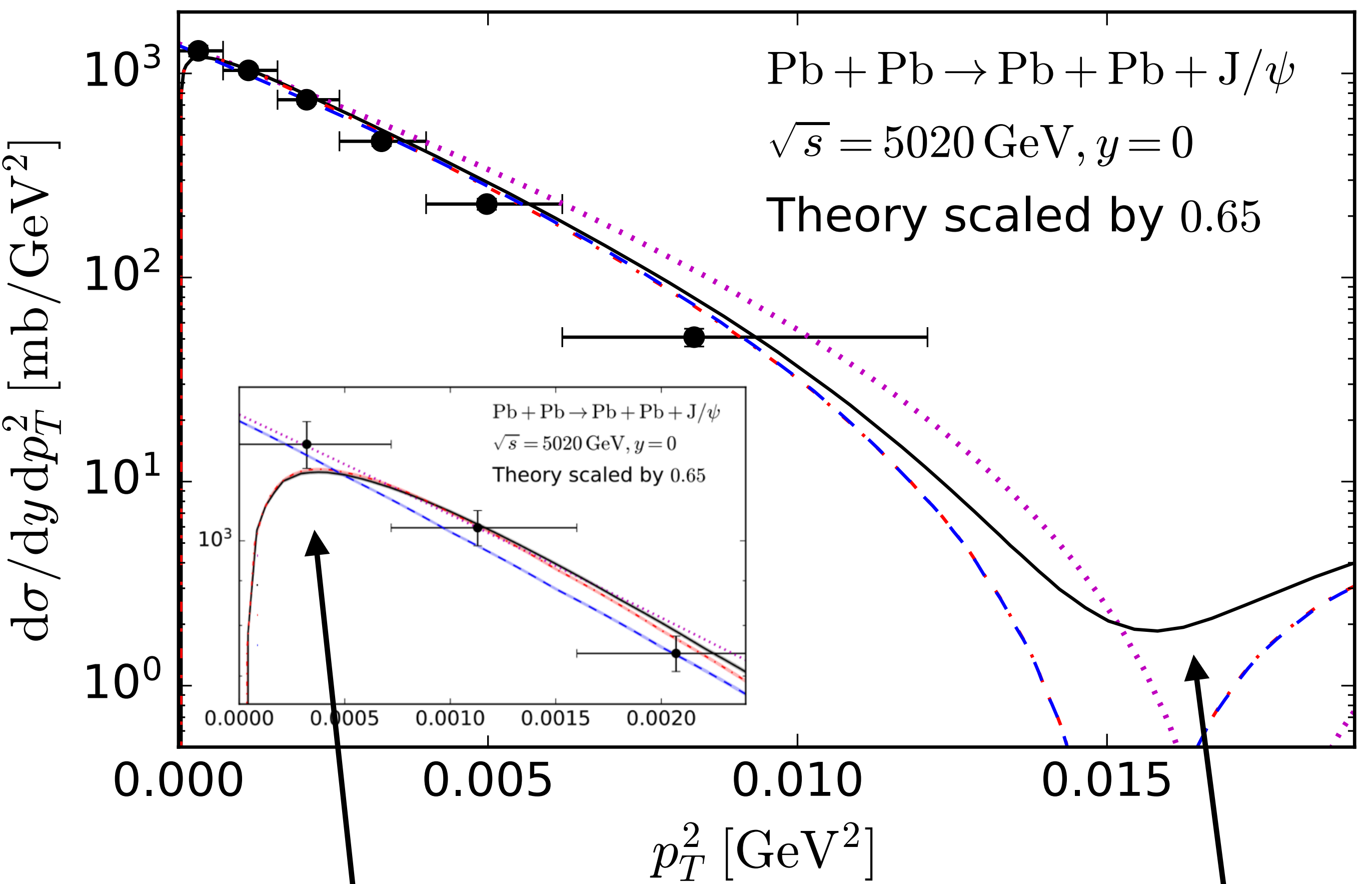
$$\frac{\mathrm{d}\sigma^{A_1+A_2\to V+A_1+A_2}}{\mathrm{d}\boldsymbol{p}_\perp^2\,\mathrm{d}y} = \frac{1}{4\pi}\int_{|\boldsymbol{B}_\perp|>B_{\min}} \mathrm{d}^2\boldsymbol{B}_\perp \langle \mathcal{M}_\lambda^\dagger(y,\boldsymbol{p}_\perp,\boldsymbol{B}_\perp)\rangle\langle \mathcal{M}_\lambda(y,\boldsymbol{p}_\perp,\boldsymbol{B}_\perp)\rangle$$

$$\mathcal{M}^\lambda(y,\boldsymbol{p}_\perp,\boldsymbol{B}_\perp) = \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{p}_\perp\cdot\boldsymbol{b}_\perp}\left[\langle\widetilde{\mathcal{A}}(\boldsymbol{b}_\perp)\rangle_{x_1}\widetilde{\mathcal{F}}_\perp^\alpha(x_2,\boldsymbol{b}_\perp-\boldsymbol{B}_\perp) + \langle\widetilde{\mathcal{A}}(\boldsymbol{b}_\perp-\boldsymbol{B}_\perp)\rangle_{x_2}\widetilde{\mathcal{F}}_\perp^\alpha(x_1,\boldsymbol{b}_\perp)\right]\epsilon_\alpha^{V\lambda,*}$$

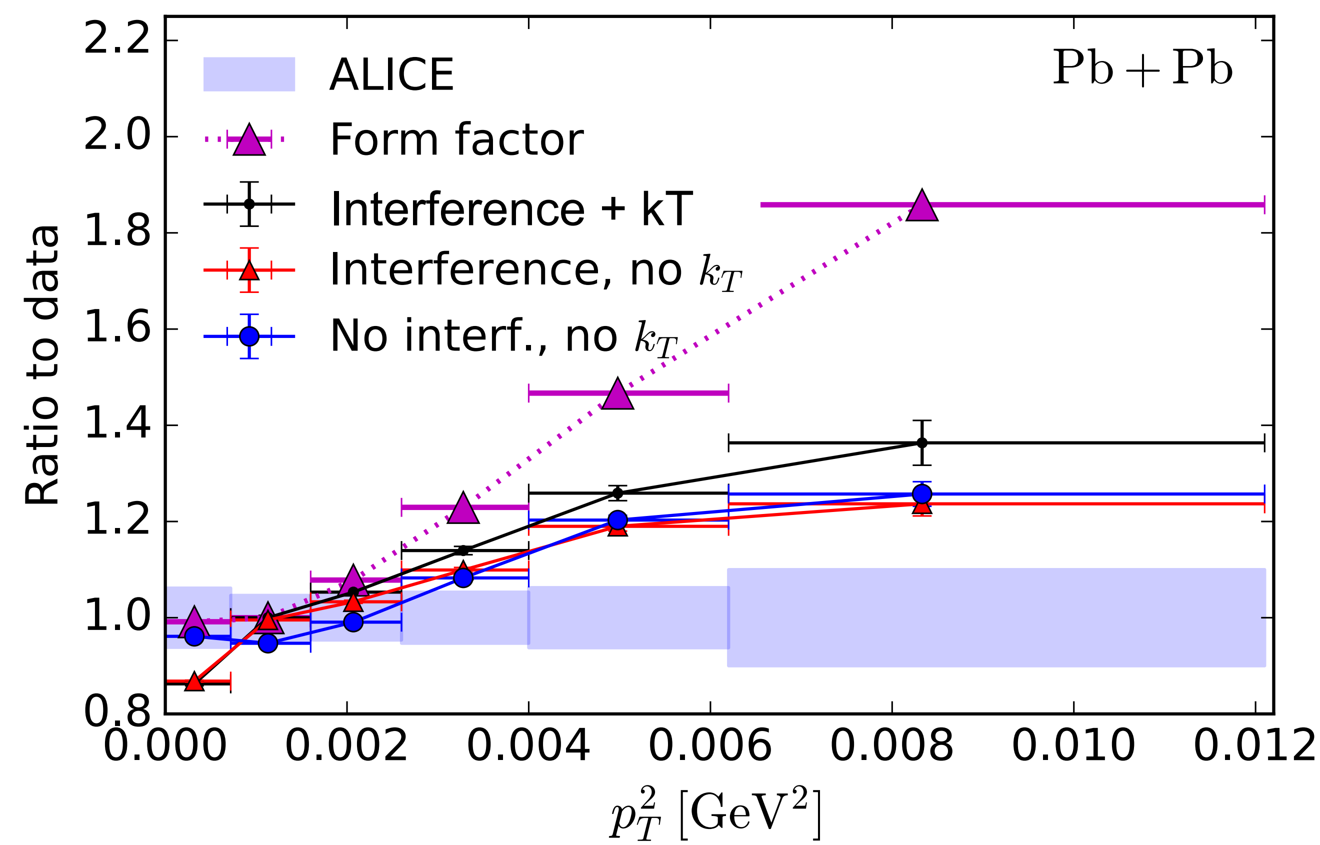
Incorporates both quantum interference and non-zero photon kT

Ultra-peripheral collisions

Results from LHC for J/Ψ in $PbPb$



All results computed with CGC



Photon kT washes away the diffractive dip

Interference at play
Cross-section vanishes at low $p_\perp$

Theory: Photon kT makes pT spectrum wider

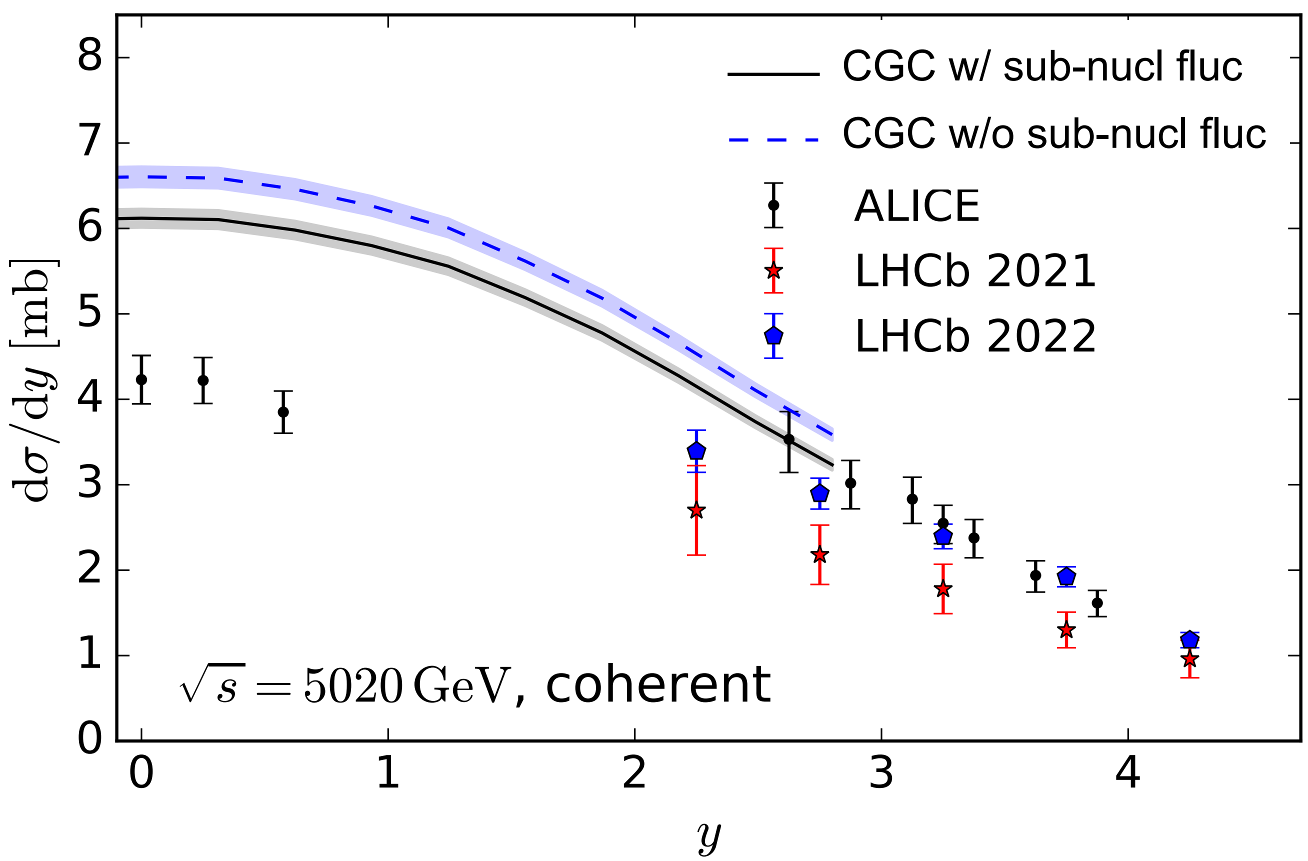
Data: Photon kT makes pT spectrum steeper. Counterintuitive!

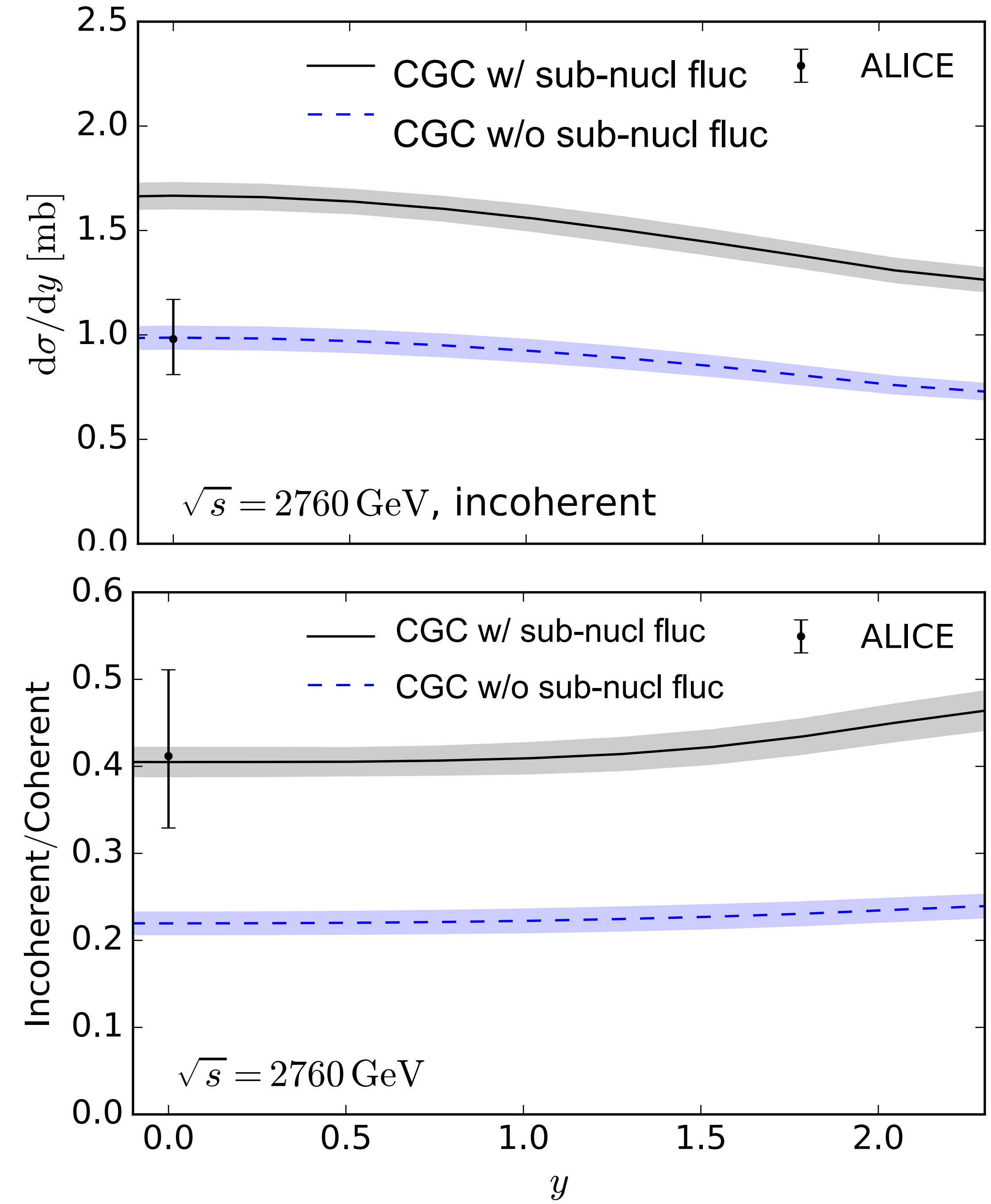
Larger discrepancy between theory and data for $PbPb$ than in γPb.
Unfolding seems to be inconsistent with the joint-impact parameter TMD framework

H. Mäntysaari, FS, B. Schenke (PRD 2022)

Ultra-peripheral collisions

Rapidity dependence and incoherent production





Normalization fixed by HERA ep data
Current setup has too little nuclear suppression

H. Mäntysaari, FS, B. Schenke (PRD 2022)

Normalization should cancel in ratio coherent-to-incoherent. Data seems to favor sub-nucleon fluctuations

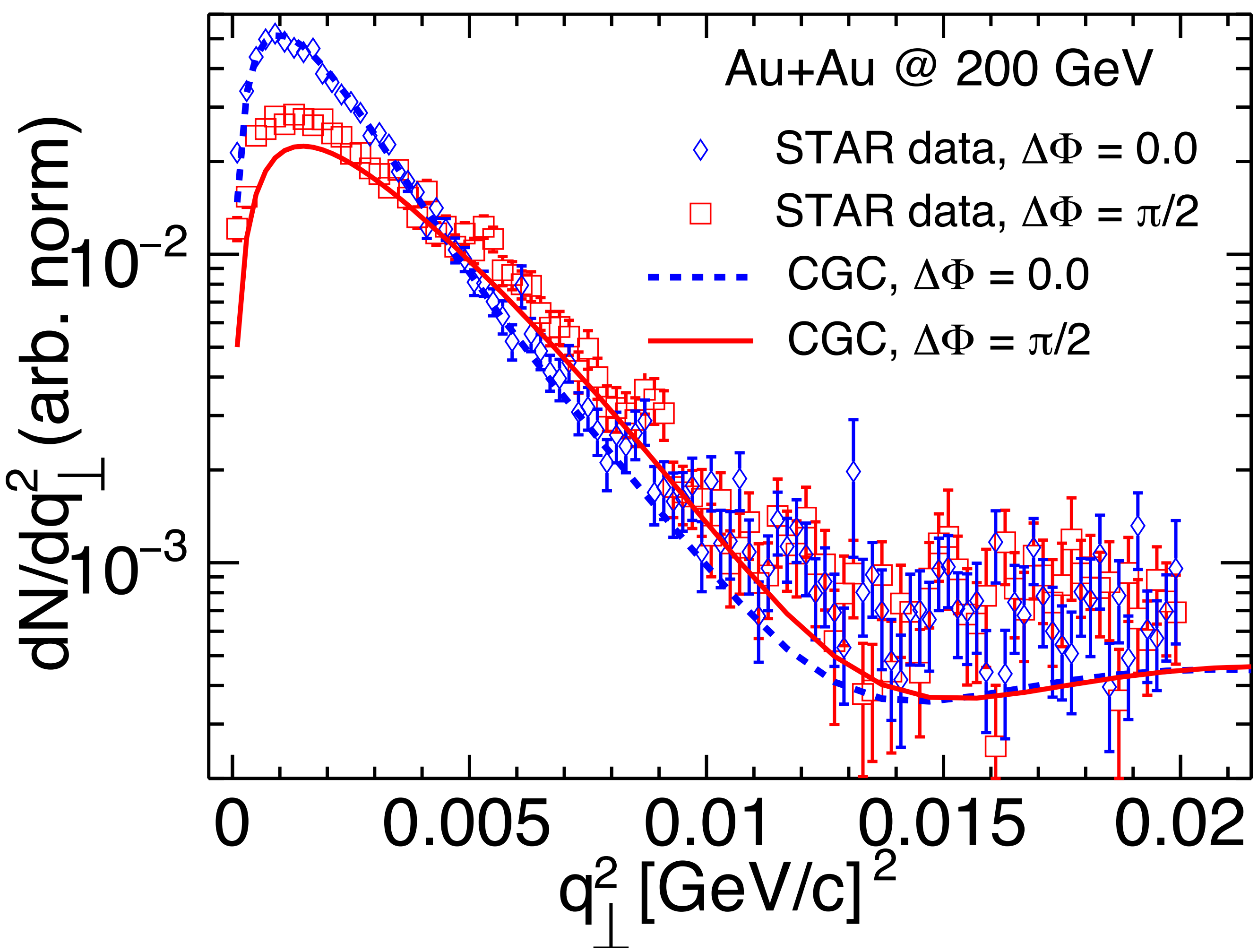
Ultra-peripheral collisions

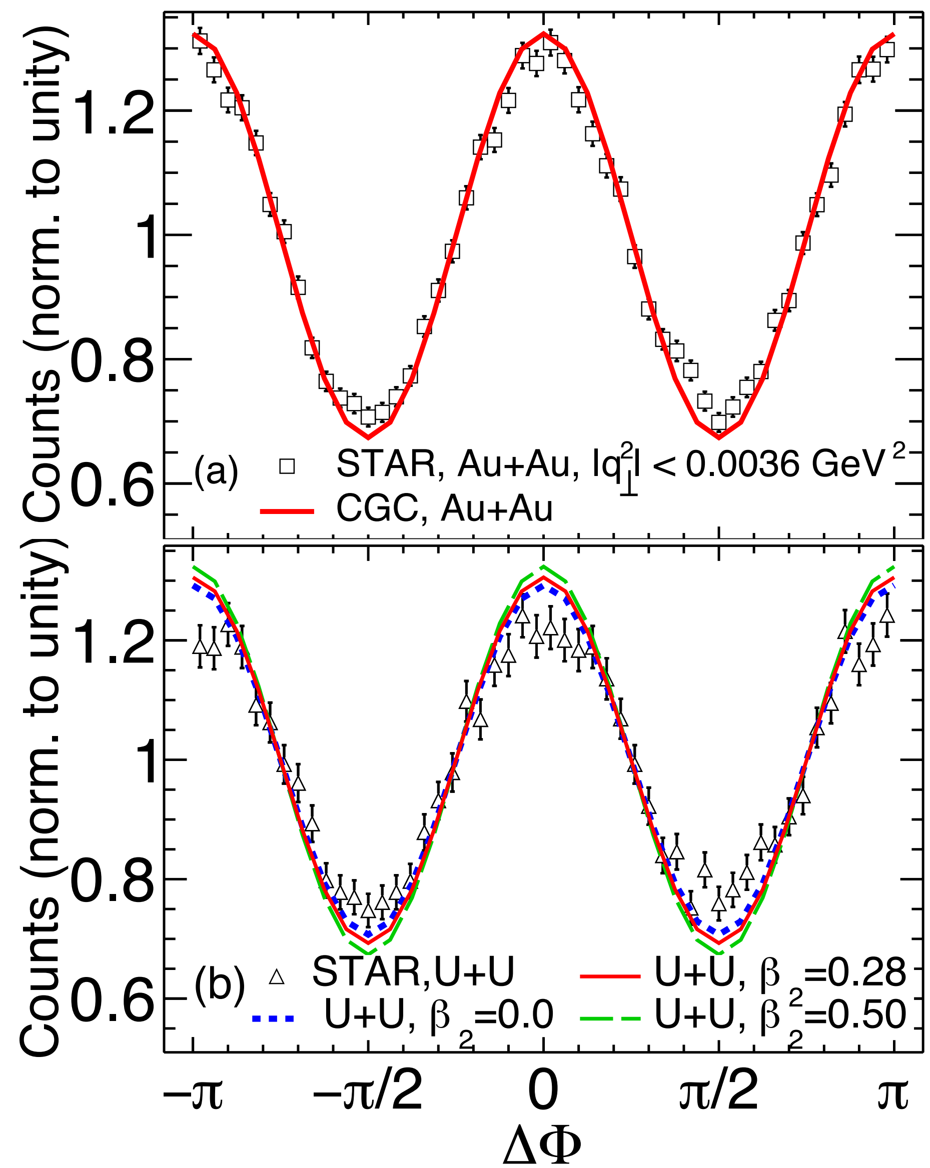
Azimuthal correlations at RHIC

Correlations in daughter particles $\rho \to \pi^+\pi^-$

$$\boldsymbol{P}_\perp = \frac{1}{2}(\boldsymbol{p}_\perp^{\pi^+} - \boldsymbol{p}_\perp^{\pi^-}) \quad \boldsymbol{q}_\perp = \boldsymbol{p}_\perp^{\pi^+} + \boldsymbol{p}_\perp^{\pi^-}$$

$\Delta\Phi$ angle between $\boldsymbol{P}_\perp$ and $\boldsymbol{q}_\perp$





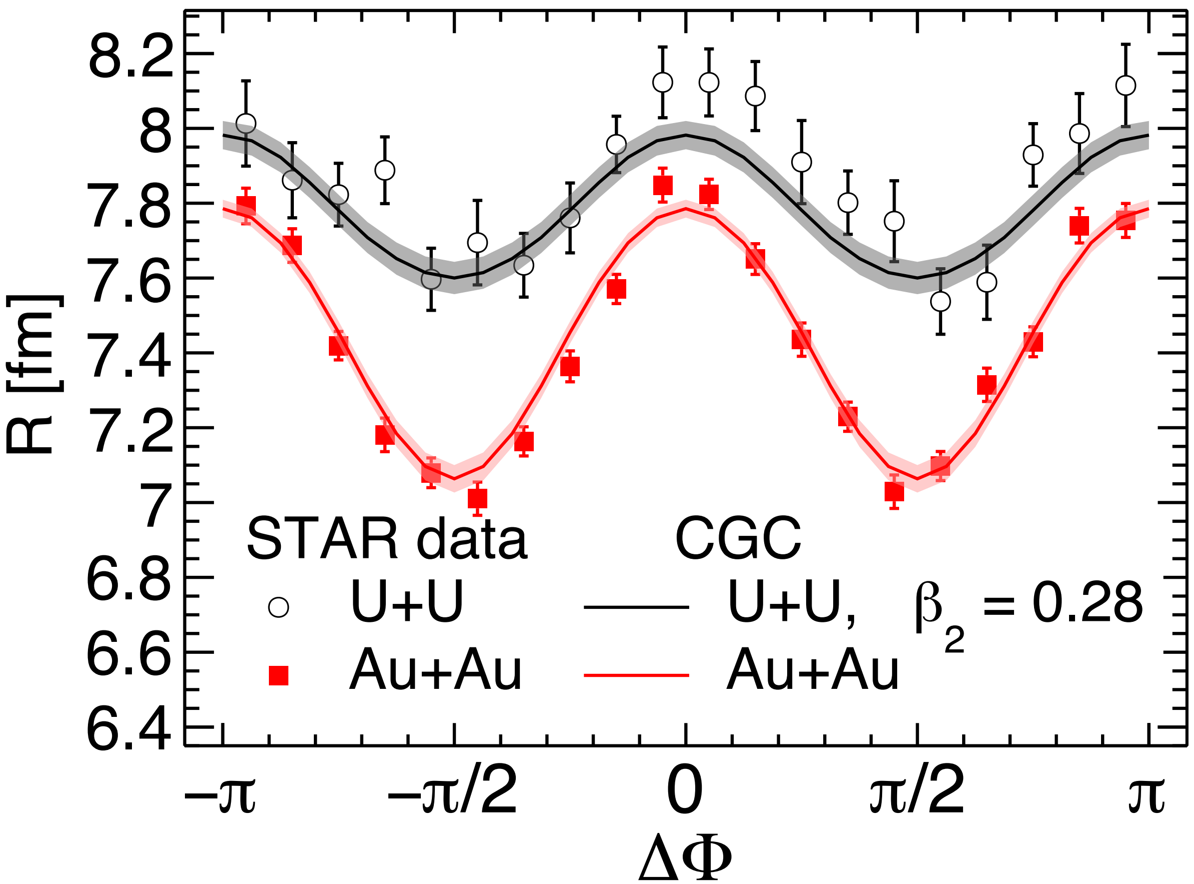
Correlations induced by interference and finite photon kT

Work in progress 2310.XXXX. HM, FS, BS, Chun Shen, Wenbin Zhao

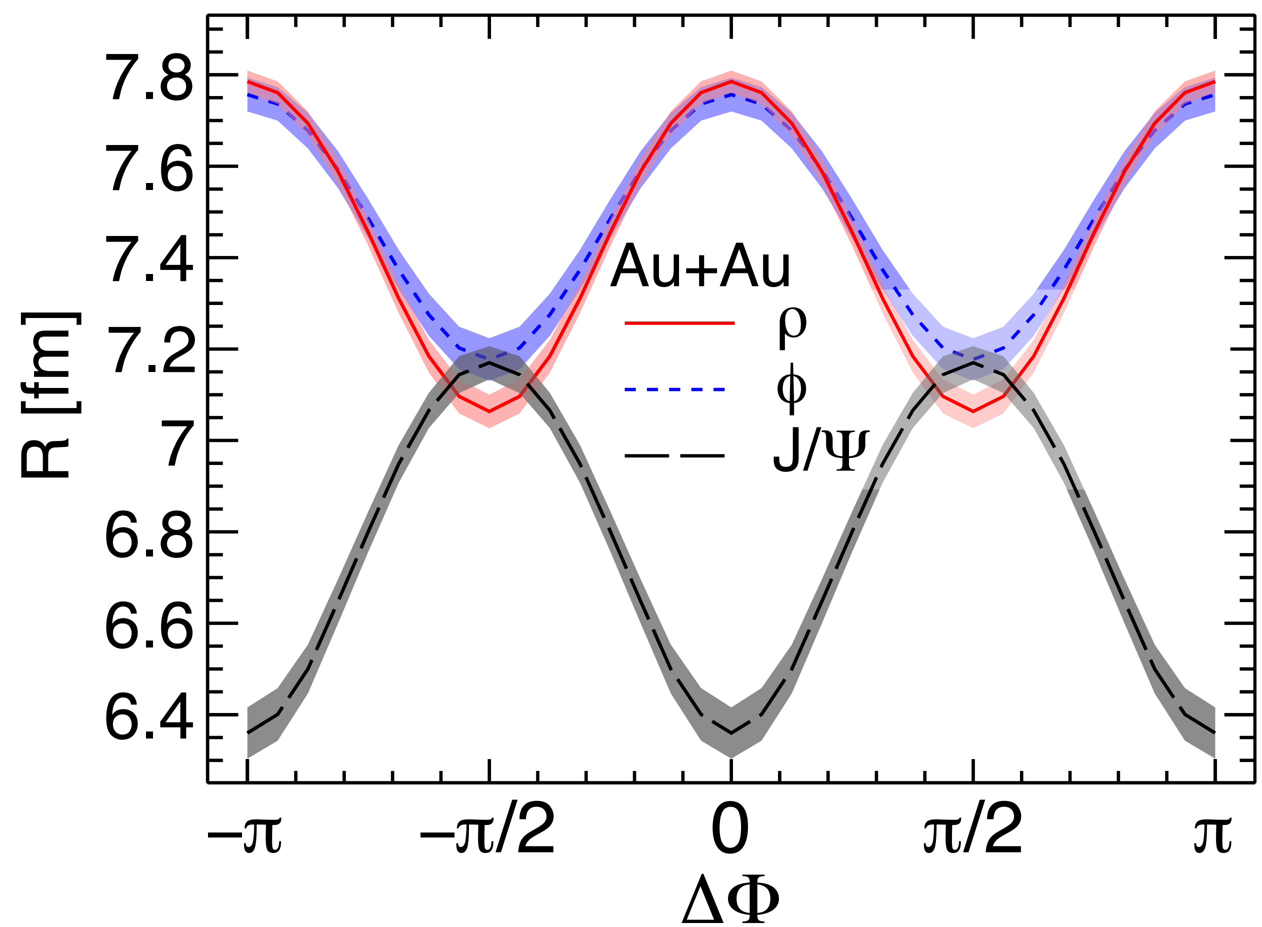
See more at Yajin's talk

Ultra-peripheral collisions

Angle dependent nuclear radius



Nuclear radius (size) extracted from qT spectrum is angle-dependent!



Sign of correlation depends on spin of particle in the final state (spin 0 vs spin 1/2)

Work in progress 2310.XXXX. HM, FS, BS, Chun Shen, Wenbin Zhao

Summary

- Diffractive vector meson production in photon-nucleus collisions allows imaging of nuclei at HERA, EIC, and UPCs
- The saturation framework provides a reasonable description of the data (steeper spectrum than the form factor)
- In UPCs, one must take into account interference effects and non-zero photon kT
- Interference leads to interesting azimuthal correlations on the daughter particles