Probing parton distributions in ep and ultra-peripheral collisions

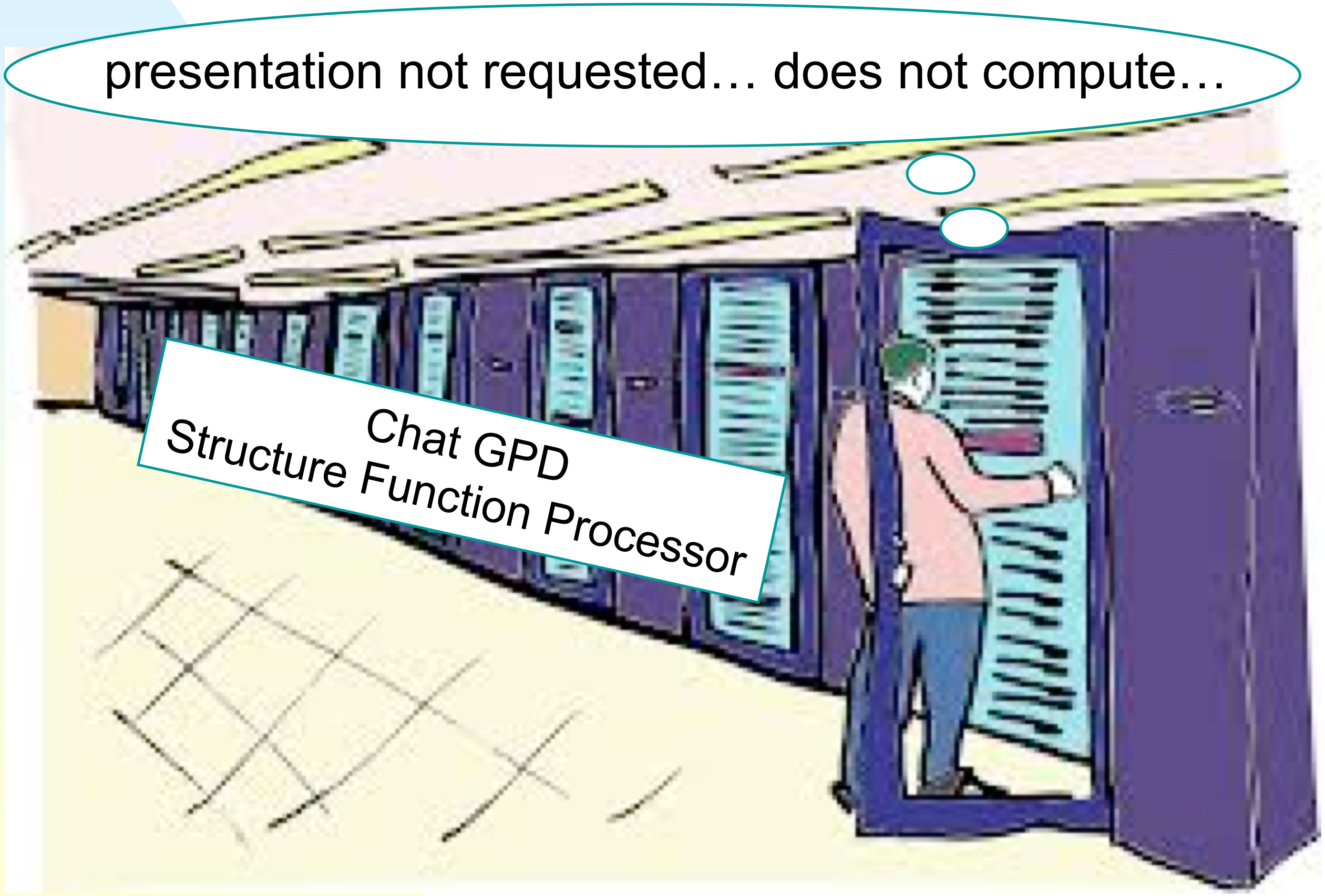
Spencer R. Klein, LBNL

Spin 2023, Sept. 24-29, 2023
Durham, NC

- UPCs and (briefly) the EIC
- Dijets & Open Charm to probe gluons
- Vector Mesons in γA and γ^*A collisions
  - Structure Functions and GPDs
- Accessing the Wigner distribution with dijets
- Studying partonic fluctuations
- Conclusions

With some Experimental emphasis

Thanks to the organizers for asking me and not ChatGPD



Ultra-peripheral collisions (UPCs)

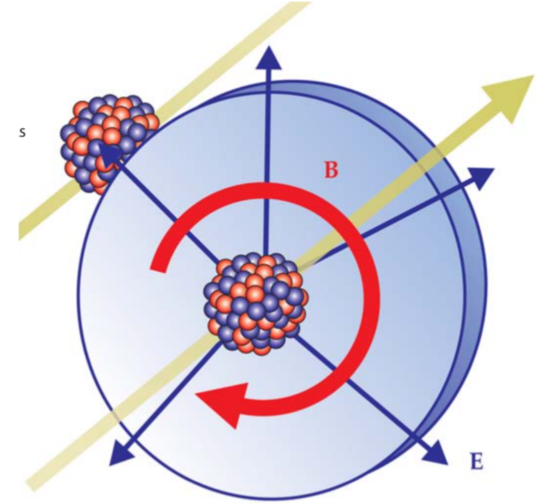
- Heavy nuclei carry strong electric and magnetic fields
  - Fields are perpendicular -> nearly-real virtual photon field
    - $E_{max} = \gamma hc/b$
  - Photonuclear interactions
    - Two-photon interactions also occur, but less relevant here
- Most visible when $b>\sim 2R_A$, so there are no hadronic interactions;
  - STAR & ALICE also see coherent J/ψ photoproduction in peripheral nuclear collisions

Energy	AuAu RHIC	pp RHIC	PbPb LHC	pp LHC
Photon energy (target frame)	0.6 TeV	~12 TeV	500 TeV	~5,000 TeV
CM Energy $W_{\gamma p}$	24 GeV	~80 GeV	700 GeV	~3000 GeV
Max $\gamma\gamma$ Energy	6 GeV	~100 GeV	200 GeV	~1400 GeV

*LHC at full energy $\sqrt{s}$=14 TeV/5.6 TeV

The energy frontier for photon physics!

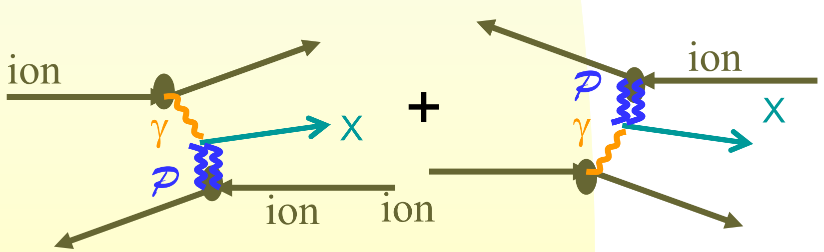
UPCs – good and bad



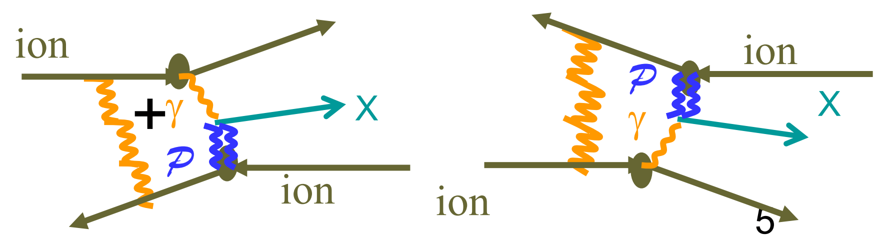
- The energy frontier for electromagnetic probes
  - Maximum CM energy $W_{\gamma p}$ ~ 3 TeV for pp at the LHC
    - ~ 10 times higher than HERA
  - Probe parton distributions in proton and heavy-ions down to
    - Bjorken-x down to a few 10^{-6} at moderate Q^2
- Electromagnetic probes have α_{EM} ~ 1/137, so are less affected by multiple interactions than hadronic interactions
  - Exclusive interactions
- Bidirectional photon beams
- $Z\alpha$ ~ 0.6 for lead -> multiple interactions with a single ion pair.
  - E. g. vector meson production + nuclear excitation or 2 vector mesons
  - Useful for tagging the impact parameter vector, but we cannot select pure single-photon exchange events

Bidirectional photon beams

- In pp/AA collisions, either nucleus can emit the photon
  - In pA, photon usually comes from the heavy nucleus
- In coherent reactions, the 2 possibilities are indistinguishable, so amplitudes add, and interfere destructively
  - σ->0 as p_T -> 0 at y=0
- 2 directions have different photon energies and Bjorken-x:
  - $k = M_V/2\exp(\pm y)$ and $xm_p = M_V/2\gamma_{beam} m_p \exp(\mp y)$
- To find $\sigma(k)$ requires selecting events with different photon spectra
  - Additional photons -> Different impact-parameter distributions
  - Events with and w/o nuclear excitation
  - Systems of linear equations -> solvable, at a cost in uncertainty

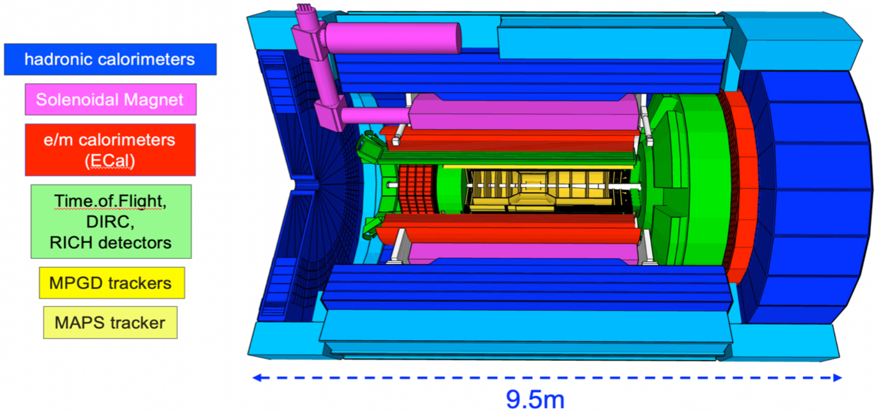


vs.



The electron-ion collider & ePIC

- High luminosity ep/eA collisions
- Photons with a wide range of virtuality
  - Observe scattered electron to determine photon energy and Q^2
- Detector optimized for $\gamma^* p/\gamma^* A$ collisions
  - Near 4 π acceptance
  - Good forward instrumentation to determine if nucleus dissociated or not
- Precision measurements down to Bjorken-x ~ 10^{-4}
  - Less energy reach than UPCs at the EIC, but more precision



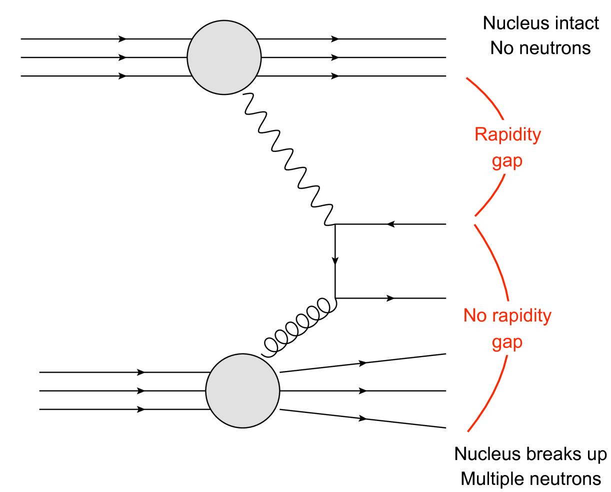
See talks by Christoph Montag (EIC), Barak Schnooker (ePIC) and Maria Zurek (proton spin @ the EIC)

Experimental Probes

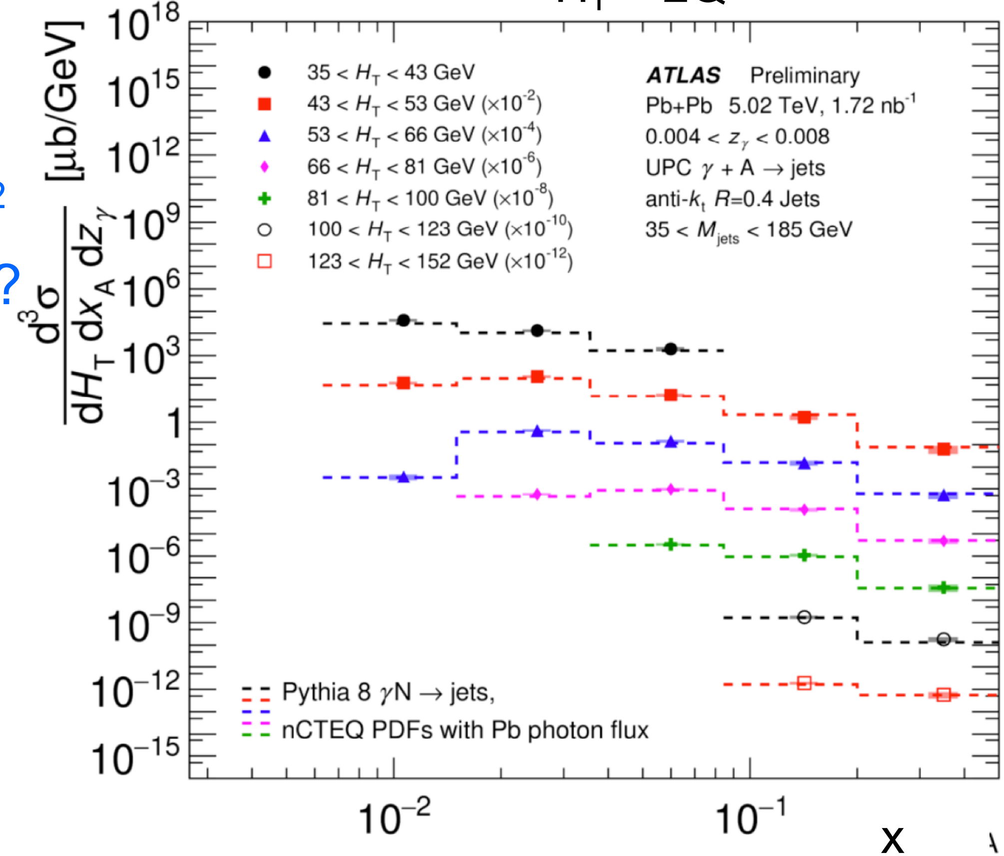
- Dijets and open charm/bottom
  - To lowest order, single gluon exchange
  - Target nucleus breaks up
  - Exclusive reconstruction almost not possible
- Vector mesons
  - At lowest order, two-gluon exchange
  - Exclusive reactions – coherent photoproduction possible
    - Access to transverse distributions of gluons in target
    - Incoherent interactions probe partonic fluctuations
  - Easy to fully reconstruct, e. g. $J/\psi \to e^+e^-$
    - Bulk of experimental UPC studies to date
    - Many possible light and heavy mesons: ρ, ϕ, ω, ρ', J/ψ, ψ', Υ
- Deeply Virtual Compton Scattering
  - Similar to vector meson production, but with a lower σ
  - Timelike Compton scattering also possible at the EIC

Dijets and open charm

- Single gluon exchange
  - theoretically clean
  - One rapidity gap
- x depends on dijet mass & rapidity
- Jet masses give Q^2
- ATLAS studied dijets at LHC
  - $10^{-2} < x < 1$
  - $1600\ \mathrm{GeV}^2 < Q^2 < 40{,}000\ \mathrm{GeV}^2$
  - Consistent with nCTEQ PDFs?
- 1st open charm studies soon
  - LHC Run 3 data
  - Probe lower x,Q^2 region than dijets



$H_T \sim 2Q$



B. Gilbert [ATLAS], Quark Matter 2023

Coherent and incoherent production: transverse distributions and fluctuations

- The Good-Walker formalism links coherent and incoherent production to the average nuclear configuration and event-by-event fluctuations respectively
  - Configuration = position of nucleons, gluonic hot spots etc.
- Coherent: Sum the amplitudes, then square -> average over different configurations
- Incoherent = Total – coherent; total: square, then sum cross-sections for different configurations
  - Fluctuations could be included in parton distributions

$$\frac{\mathrm{d}\sigma_{\mathrm{tot}}}{\mathrm{d}t} = \frac{1}{16\pi}\left\langle \left|A(K,\Omega)\right|^2 \right\rangle$$

Average cross-sections (Ω)

$$\frac{\mathrm{d}\sigma_{\mathrm{coh}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$

Average amplitudes (Ω)

$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle \left|A(K,\Omega)\right|^2 \right\rangle - \left| \langle A(K,\Omega)\rangle \right|^2 \right)$$

Incoherent is difference

Mantysaari and Schenk, PRD **94**, 034042 (2016)

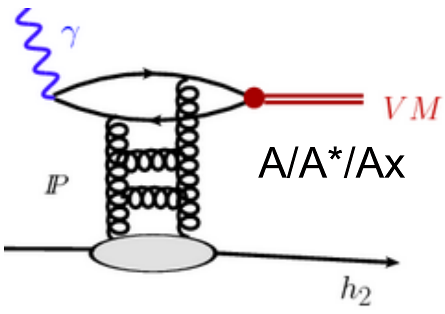
The Good-Walker paradox

- Per Good-Walker, in coherent interactions the nucleus remains in the ground state, while incoherent interactions leave the target excited.
- However, we have clearly observed coherent summing of amplitudes in cases where the target is excited
  - Photoproduction accompanied by nuclear excitation
  - J/ψ photoproduction in peripheral nuclear collisions
    - With 100's of final state particles
  - This conflicts with Good-Walker
- A semi-classical model, where the amplitudes for indistinguishable final states are added works well
  - $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
  - Similar phenomenology for coherent interactions, but very different predictions for incoherent.
- This paradox underpins most exclusive-reactions physics; we need to understand it!

SK, Phys. Rev. C **107**, 055203 (2023)

Exclusive vector meson photoproduction

- Photons fluctuate to q-qbar pairs (dipoles) which scatter elastically from target nuclei
  - Strong force, but colorless exchange
  - 'Pomeron exchange'
    - >=2 gluon exchange for color neutrality
      - Gluon ladder

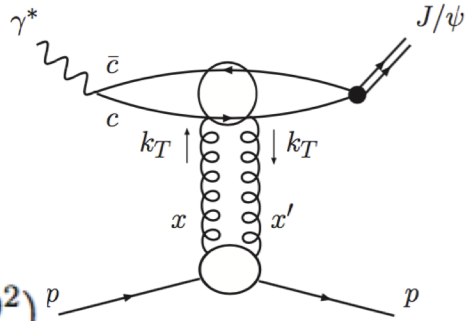


- Momentum transfer (mostly p_T) depends on coherence scale
  - 3 coherence length scales -> 3 p_T scales
  - Coherent: nucleus remains intact. $p_T < \sim$ hbar/R_A & $\sigma \sim A^2$
  - Incoherent: nucleus breaks up; protons remain intact. $p_T <\sim$ hbar/R_p
  - Nucleon dissociation: struck proton breaks up. $p_T \sim \Lambda_{QCD} \sim 300$ MeV
- Vector meson inherits photon polarization due to s-channel helicity conservation (vector meson dominance).
- Calculations possible with pQCD or dipole formalism
  - Dipole approach is more commonly used because it can probe spatial variations in nuclear composition

VM photoproduction in pQCD - LO

- Leading order pQCD (2 gluons)

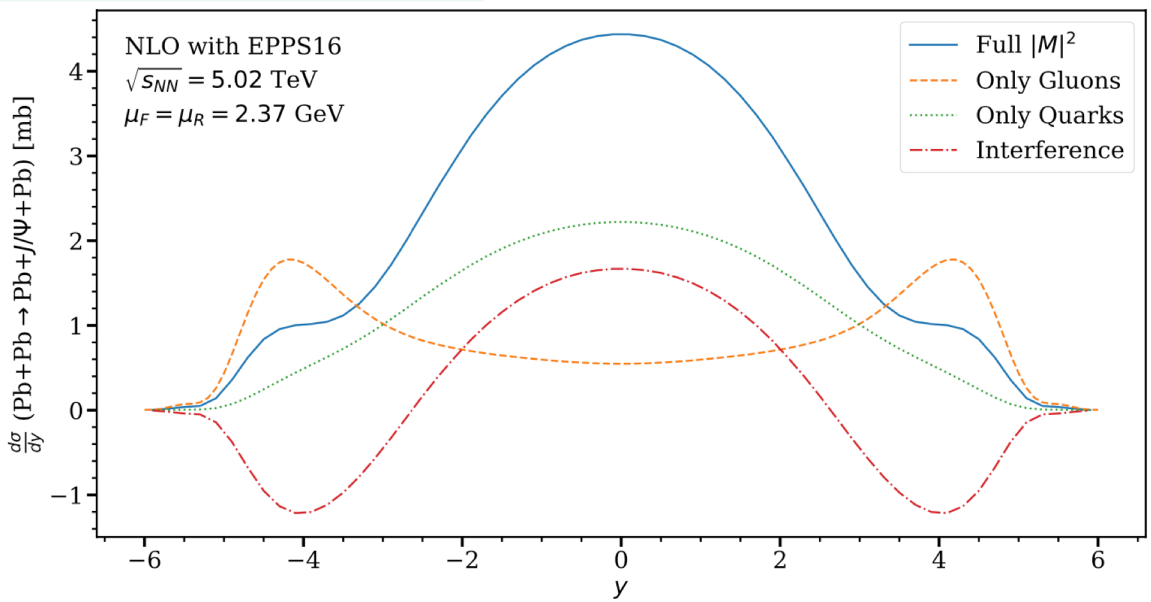
$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right).$$

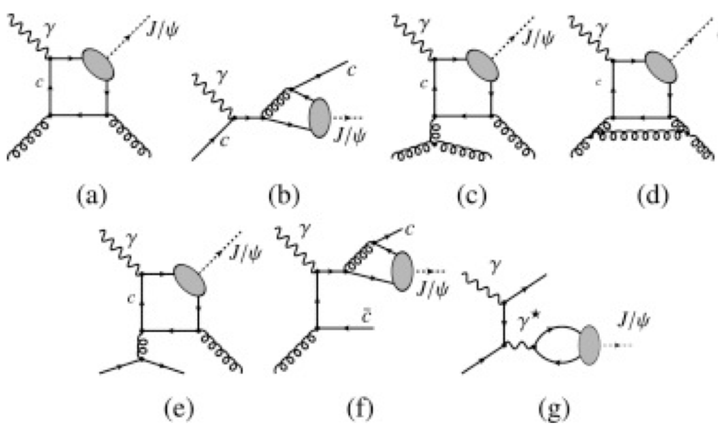


- With $\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4, \qquad x = (Q^2 + M_{J/\psi}^2)/(W^2+Q^2)$
  - Vector meson mass provides hard scale even in photoproduction
- Gluons have different x values (x' ≪ x ≪ 1)
  - Generalized (skewed) gluon distributions.
  - Can do exactly with Shuvaev transform
- More natural with GPDs, but (in UPCs) Δ unknown

VM photoproduction in pQCD - NLO

- NLO calculations look very different from LO
  - Quark contribution is significant, some gluonic cancellation
  - Still usable in NLO fits by including quarks
- Large NLO scale uncertainty
  - Can mostly evade by comparing p and heavy A
- GPD analyses of these reactions should face the same NLO issues

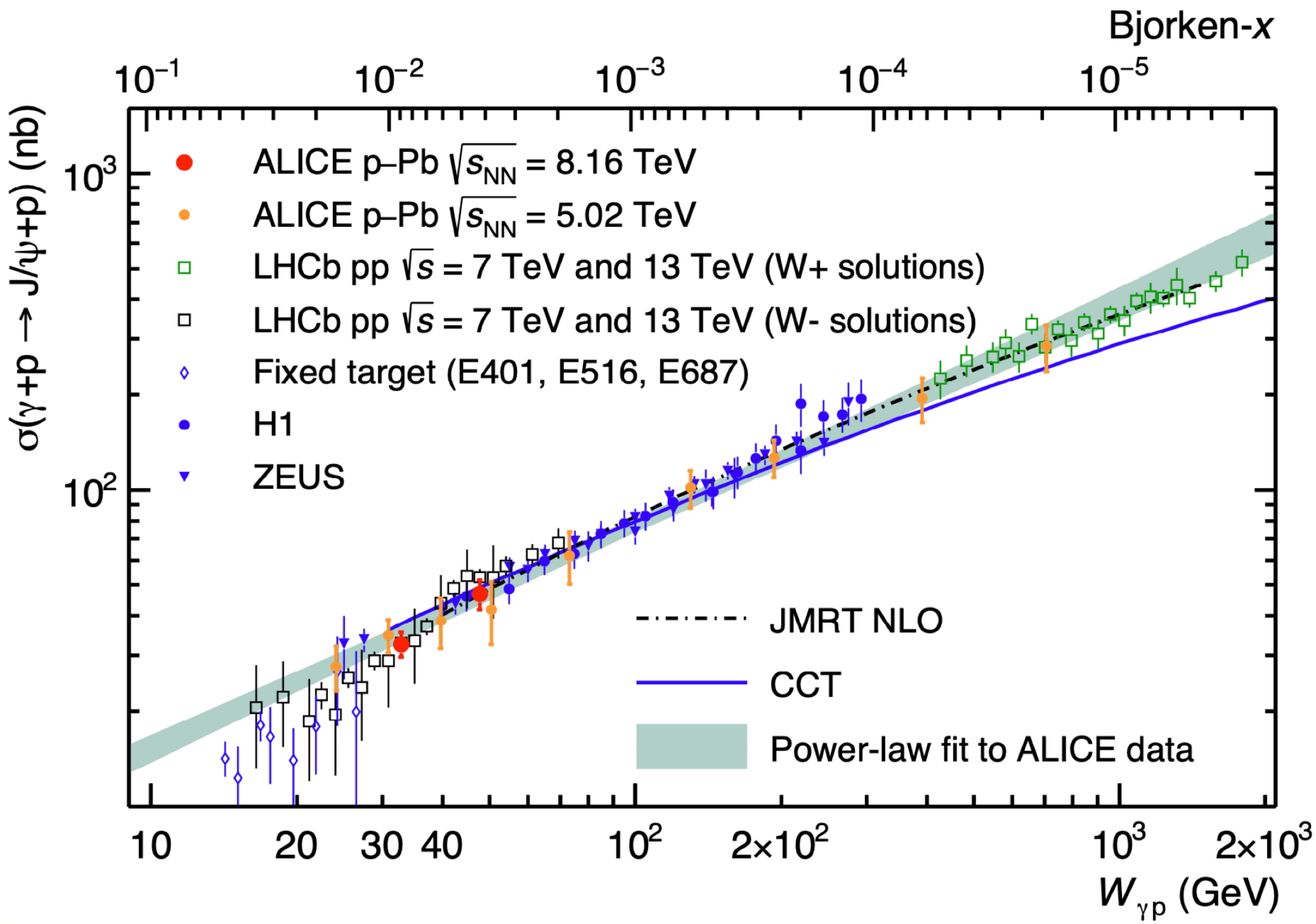




K. Eskola et al., Phys. Rev. C **106**, 035202 (2022); diagrams from C. Flore et al., PLB **811**, 135926 (2020)

σ(γp->J/ψp) on proton targets

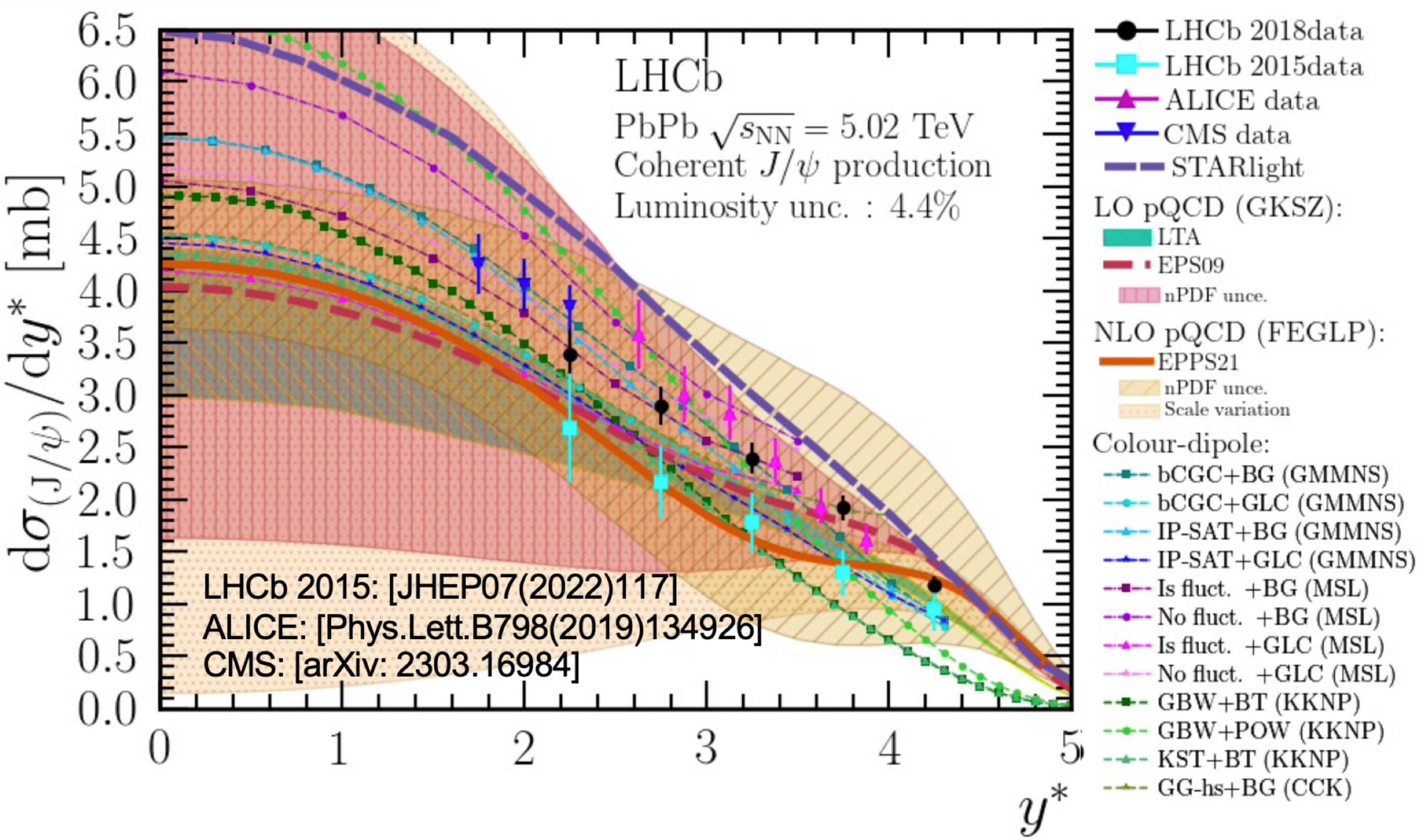
- Measurements in pA collisions and pp w/ bootstrapping
- $\sigma(W_{\gamma p}) \sim W_{\gamma p}^{0.70\pm0.04}$ up to $W_{\gamma p}$=2 TeV, corresponding to $x_g \sim 2*10^{-6}$
- In 2- gluon (LO) picture, gluons also follow a power law
  - Power law -> no saturation (or a more complex picture)



ALICE, arXiv:2304.12403

Nuclear shadowing: γPb-> J/ψ Pb

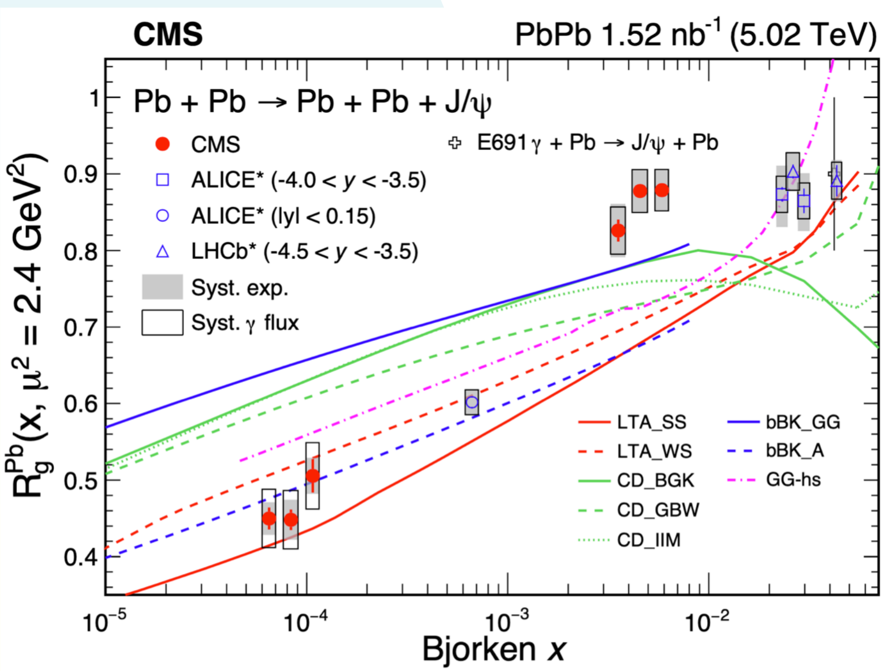
- Mostly via comparison of dσ/dy with different models or γp data
- J/ψ data has high precision, ψ' data is getting there
- Data clearly favors 'moderate' shadowing.
  - Good agreement with central values of EPS09, EPPS16, EPPS21
  - Error on data << uncertainty on EPS… fits

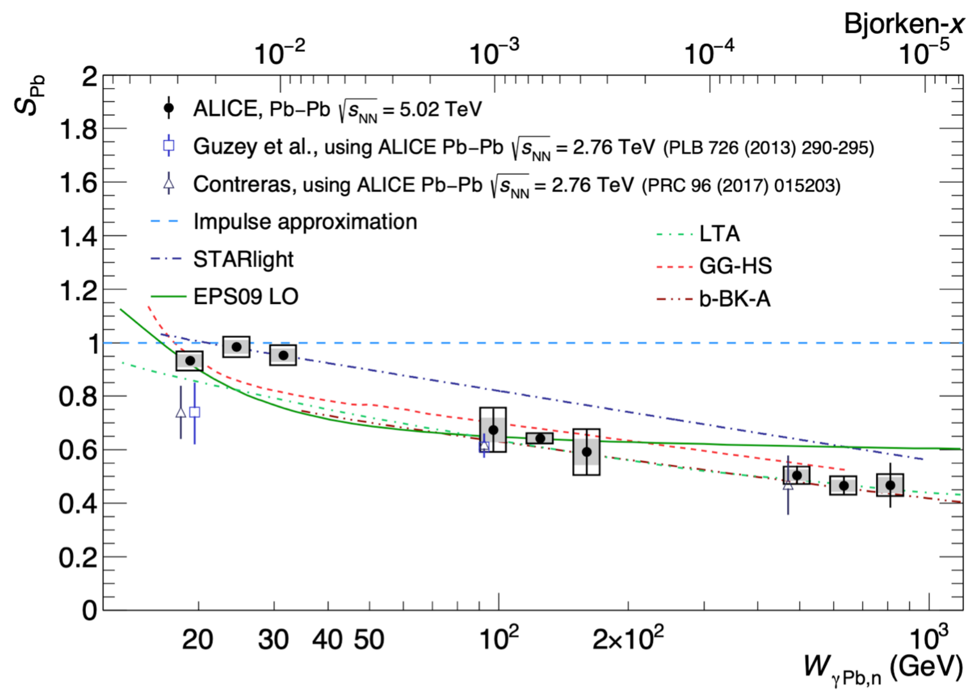


X. Wang (LHCb)
Quark Matter 2023

Measurements of σ(k)

- Use neutrons in ZDC to ‘solve’ bidirectional ambiguity
- Suppression compared to pp reference
- Some tension between CMS and ALICE
- Reasonable agreement with EPS09, except at low energies

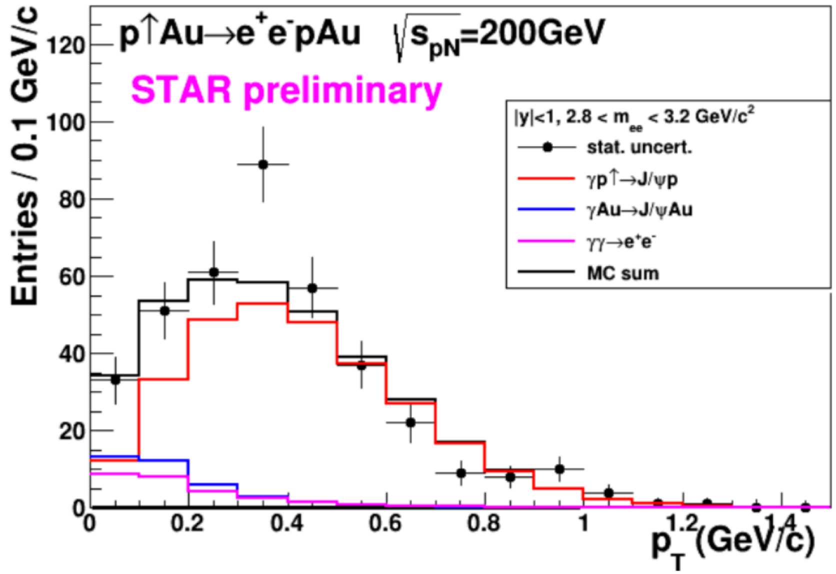


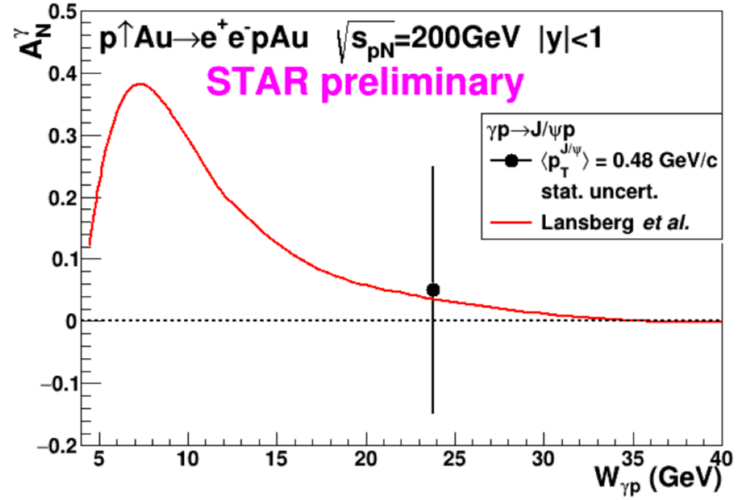


ALICE arXiv:2305.19060; CMS arXiv:2303.16984

Polarized J/ψ photoproduction at STAR

- Sensitive to polarized GPDs
  - Is gluon polarization dependent on position within nucleus?
- Polarized p on Au collisions
  - Dominated by photon-from-gold
    - p_T cut improves separation
  - Polarized proton target
- Measure scattering asymmetries, which depends on $W_{\gamma p}$ and p_T
- 1st measurement; proof of principle

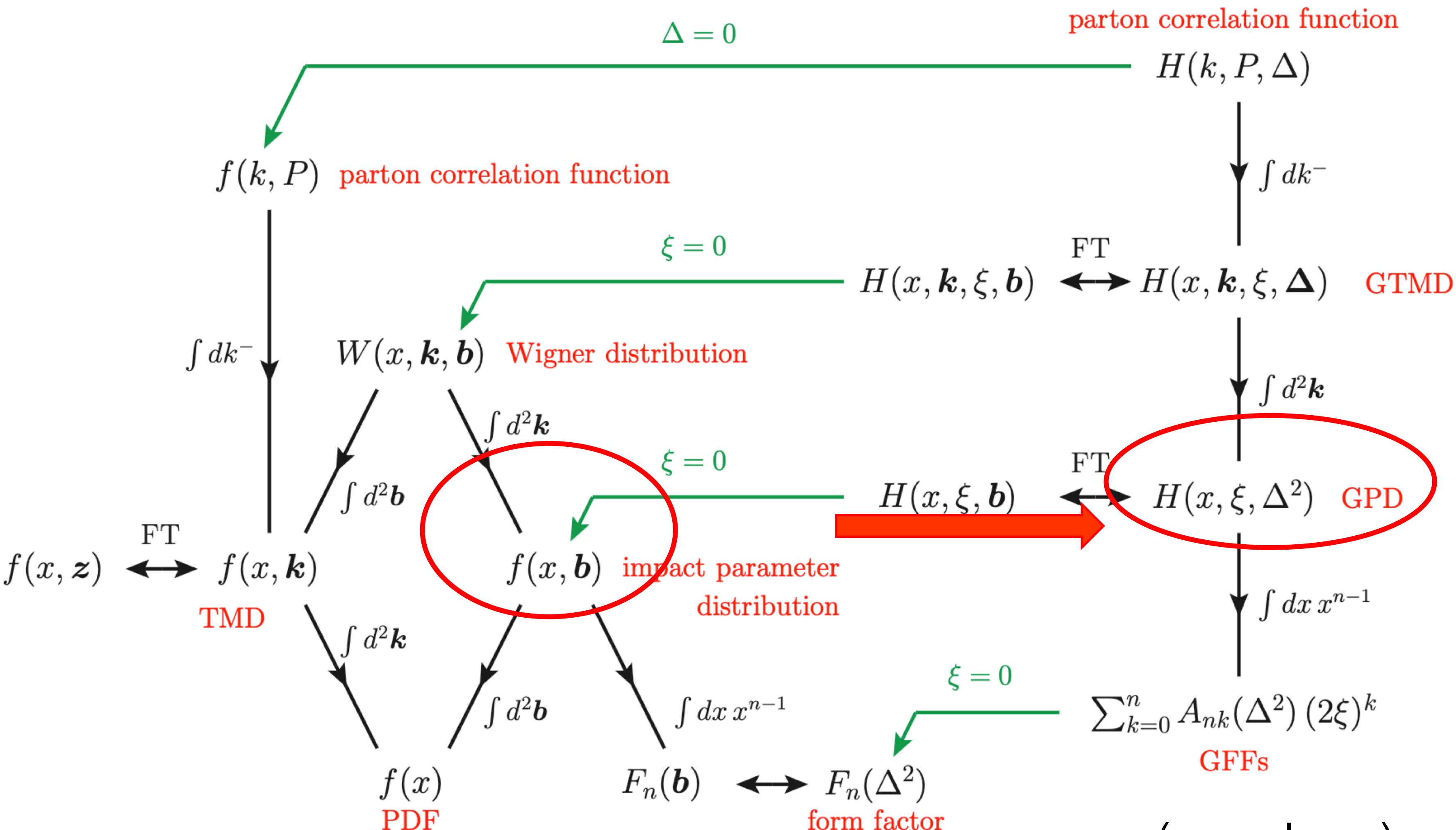




Carl Gagliardi (yesterday); W. Schmidke [STAR], DPF 2019

GPDs via the Wigner distribution

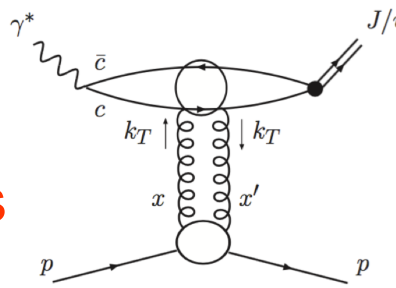
No direct access to GPDs but…



(a roadmap)

M. Diehl, Eur. Phys. J. A52, 149 (2016); see also Silvia Niccolai's talk

GPDs and tomography



- 2-gluon exchange – natural for GPDs
- Unfortunately, in UPCs Δ is poorly known
- Current studies have focused on spatial distributions
  - Not tied to specific calculations (LO/NLO/dipole…)
  - Tests of dipole-model (& other) calculations of $d\sigma/dt$
- Measure $d\sigma/dt$ for coherent photoproduction
- Fourier transform to get transverse interaction density F(b)

$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T p_T J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$

* = flips sign after each minimum

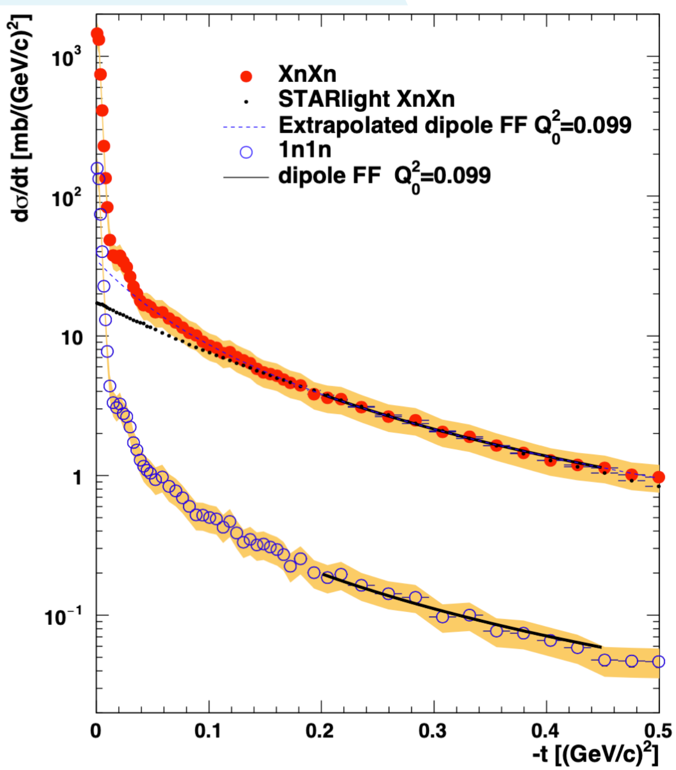
- For 'low-density targets' (small dipoles/high Q^2/…) single interactions are common, so F(b) is related to f(x,b)

$$q(x, b_T) = \int \frac{d^2\vec{q}_T}{(2\pi)^2} H_q(x, \xi = 0, q_T^2)\, e^{i\,\vec{q}_T \cdot \vec{b}_T}$$

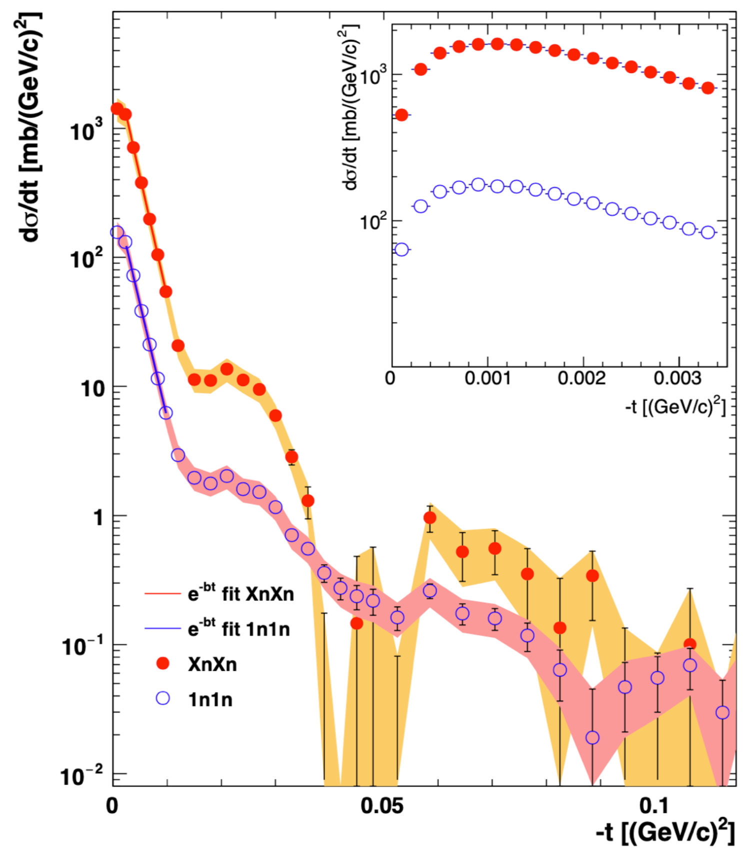
- Experimentally tractable, but some touchy issues
  - Few other low-x probes; other probes are also theoretically complex

First measurement of F(b)

- 394,000 $\pi^+\pi^-$ pairs from ρ^0, direct $\pi\pi$, and $\omega\text{->}\pi^+\pi^-$
  - Far from small-dipole limit, but good statistics
- Coherent + incoherent production
  - Fit $d\sigma/dt$ at large t to dipole form factor, subtract coherent
    - Exponential does not fit large-t data



Subtract fit



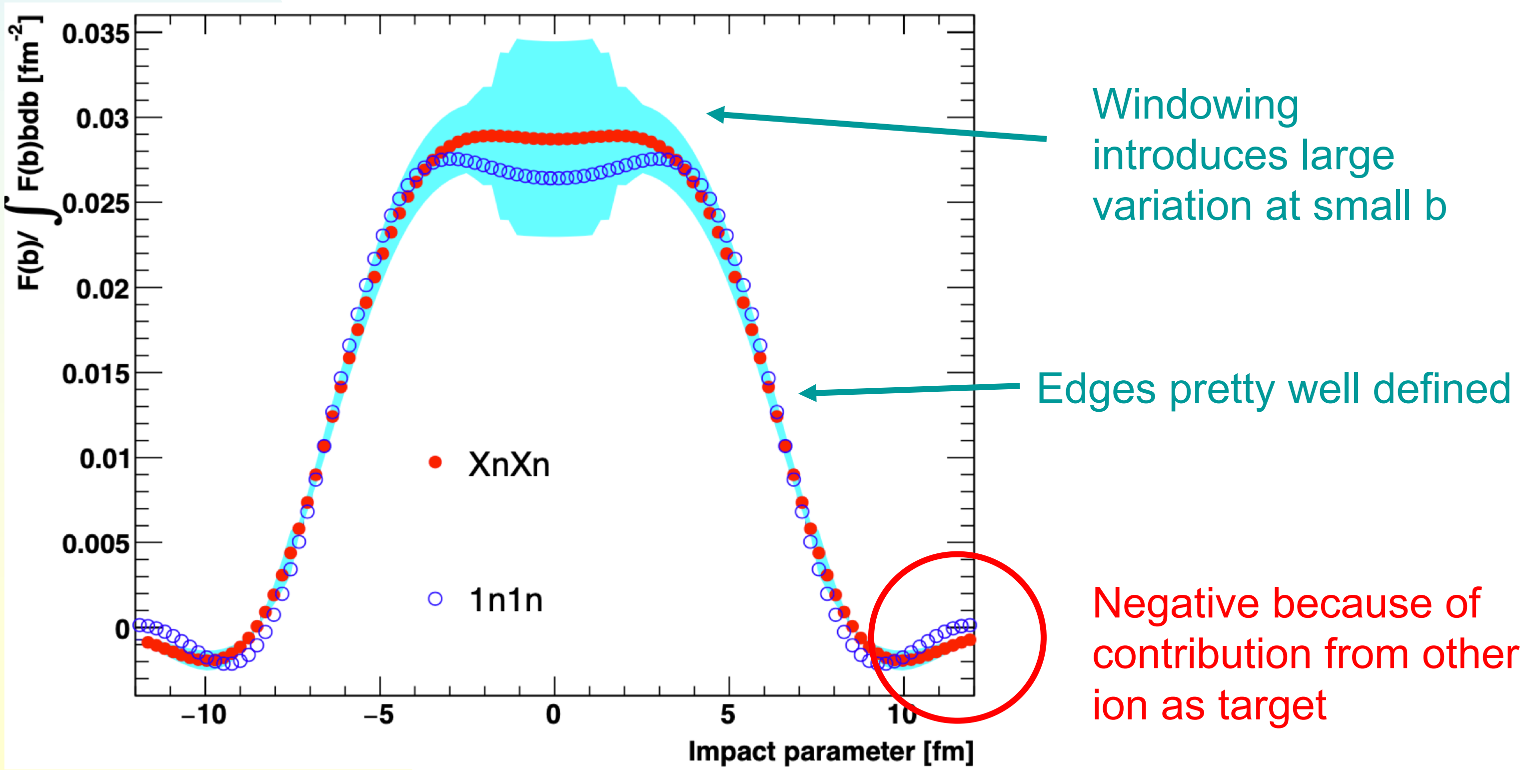
STAR, Phys. Rev. C**96**, 054904 (2017)

Fourier Transform to get F(b)

$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T p_T J_0(bp_T) \sqrt{\frac{d\sigma}{dt}}$$

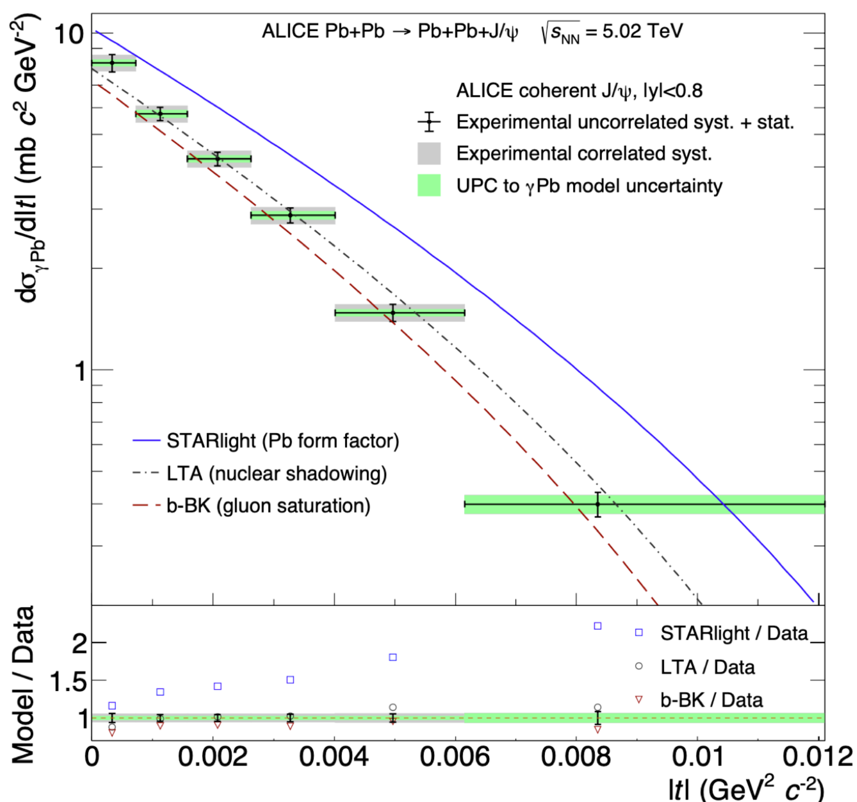
* = flips sign after each minimum

- dp_T integral goes to infinity, but data does not
  - Choose t_{max}=0.06 GeV^2, vary t_{max} to estimate syst. uncertainty
    - Windowing artifacts vary with t_{max}
- Position of diffractive minima are not precisely measurable



From F(b) to a nuclear profile

- F(b) includes contributions from the Pomeron p_T (nuclear structure function), photon p_T and resolution
  - The latter two must be removed by deconvolution to see the nucleus alone
- ALICE has performed that deconvolution for $d\sigma/dt$, and measured the effective shape of lead nuclei
- |t| spectrum is steeper than lead form factor-> nucleus is effectively larger



ALICE, Phys. Lett. B **817**, 136280 (2021)

Can we access the Wigner distribution?

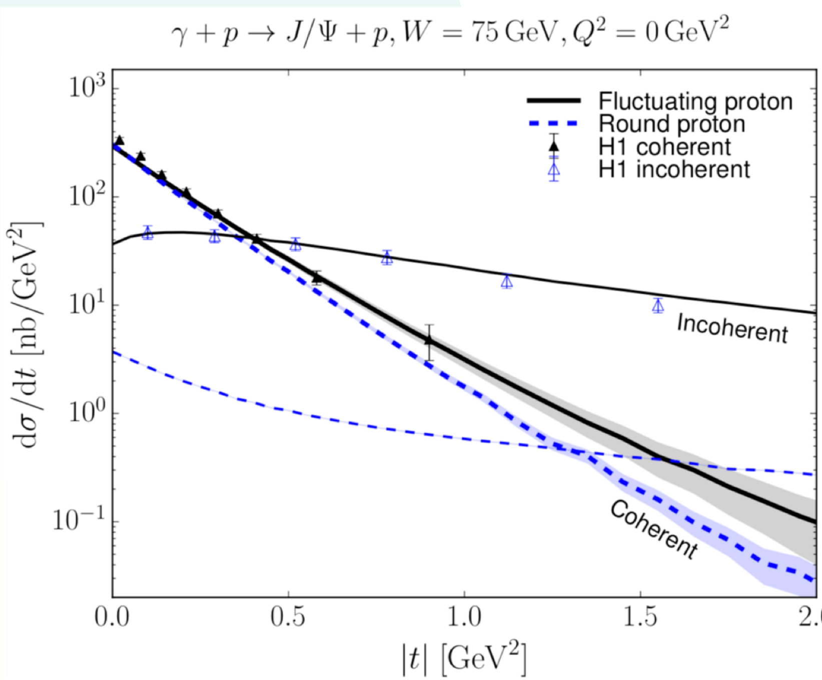
- The Wigner distribution is a function of conjugate variables x_T and p_T so is problematic to observe
- Can evade uncertainty by looking at event types with two different momentum scales.
  - Only at small-x
- Studied for photoproduction of dijets
  - Relies on dipole approach, where the dipole orientation is correlated with the impact-parameter within the target.
    - The dipole cross-section is sensitive to the orientation of the dipole with respect to spatial gradients of parton density
  - Correlations between parton p_T and transverse position causes an azimuthal correlation between the pair p_T ($p_{T1}+p_{T2}$) and the difference p_T ($p_{T1}-p_{T2}$)

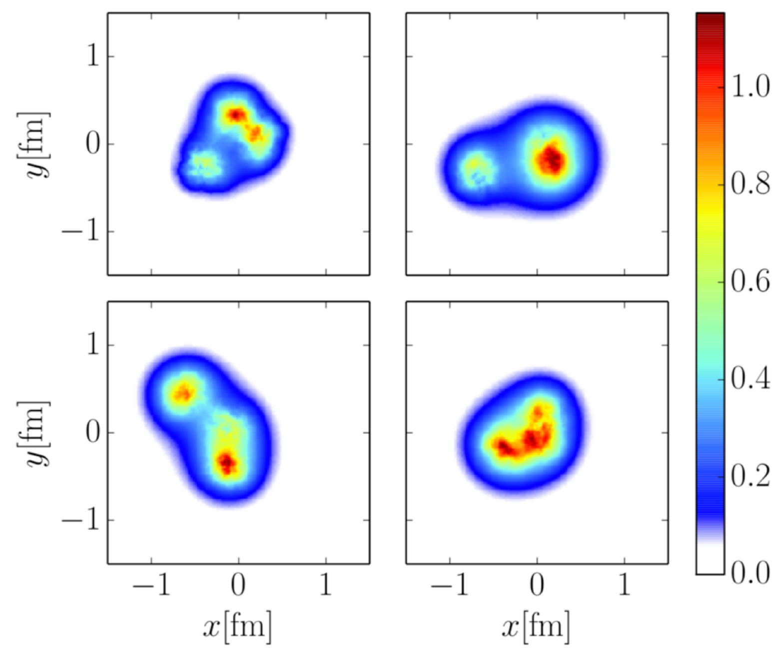
$$\frac{d\sigma^{\gamma^*+A\to j_1+j_2+A}}{d\theta} = v_0[1 + 2v_2\cos(2\Delta\theta)].$$

Hatta, Xiao and Yuan, PRL **116**, 202301 (2016)

Bonus topic – parton fluctuations

- Thanks to the Good-Walker paradigm, we can go beyond average parton distributions, and probe partonic fluctuations.
- Proton fluctuations studied using coherent & incoherent J/ψ photoproduction.
- Data prefers a fluctuating proton over a smooth proton

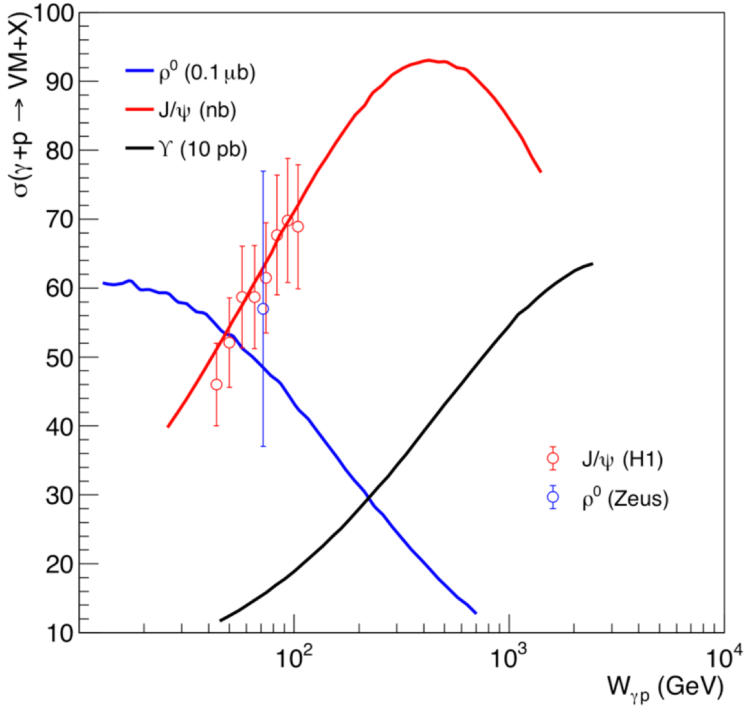




Mantysaari and Schenk, PRD **94**, 034042 (2016)

Partonic fluctuations of ions

- Fluctuations in nucleon positions plus partonic fluctuations
- As cross-section increases (as photon energy increases and target Bjorken-x decreases), we expect a progression
  - small absorption -> hotspots -> black disk
  - The ratio of incoherent cross-section will rise, reach a maximum, and then decrease to zero in the black disk limit
    - Black disks don't fluctuate
  - The turn-over energy depends on the cross-section
    - Higher for heavier/smaller dipoles



J. Cepila et al., Nucl. Phys. B934, 330 (2018)

Conclusions

- Ultra-peripheral collisions at the LHC are the energy frontier for photon interactions at moderate Q^2
- J/ψ photoproduction on proton targets follows a near power law up to $W_{\gamma p}$ ~ 2 TeV, probing Bjorken-x down to $2*10^{-6}$ at Q^2~ 2.25 GeV^2. No clear sign of a turn-over or other structure is seen.
- J/ψ photoproduction on lead targets is suppressed compared to a proton-target reference, consistent with the midpoint of nuclear PDF fits.
- GPDs can be probed (for z~0) by using measuring $d\sigma/dt$ for coherent photoproduction and transforming it to F(b).
- Incoherent photoproduction can probe partonic fluctuations.
  - PDF-like structures might be used to quantify fluctuations.
- Looking ahead, the EIC will provide very high luminosity γ^*p/γ^*A collisions which can be studied in detail with an optimized detector – ePIC.