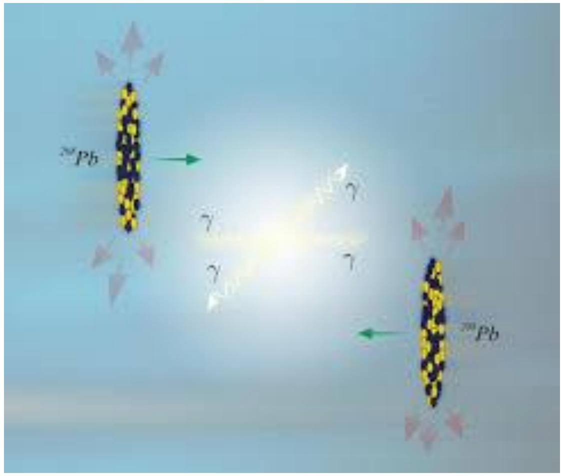
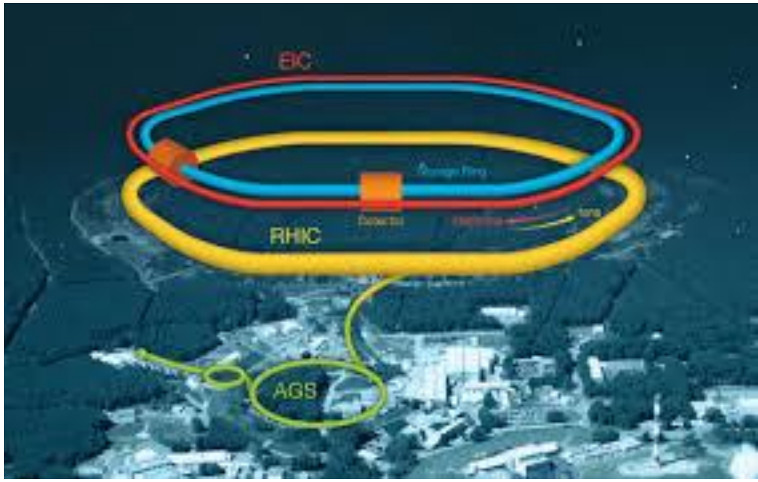
Connections between an exclusive program at EIC and UPCs

Spencer Klein, LBNL for
the ePIC Collaboration

- Ultra-peripheral collisions
- Exclusive interactions at the EIC
  - The ePIC detector (forward)
  - Exclusive interactions in ePIC
- Cross-sections
- dσ/dt and gluon spatial distributions
- Reggeons and exotica
- Backward production
- UPCs in the EIC era
- Conclusions





Ultra-peripheral collisions (UPCs)

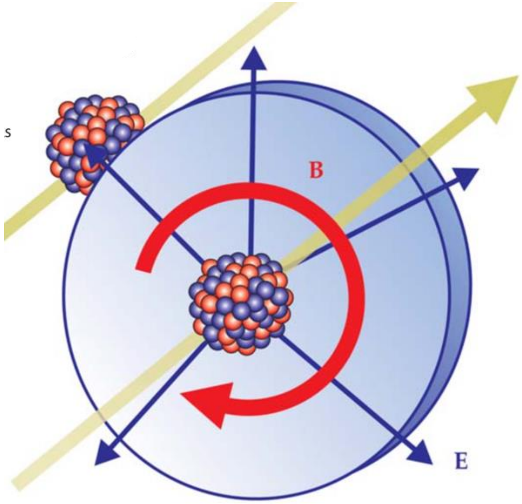
- Heavy nuclei carry strong electric and magnetic fields
  - Fields are perpendicular -> nearly-real virtual photon field
    - $E_{max} = \gamma hc/b$
  - Photonuclear interactions
    - Two-photon interactions also occur, but less relevant here
- Most visible when b>~2R_A, so there are no hadronic interactions;
  - We 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!

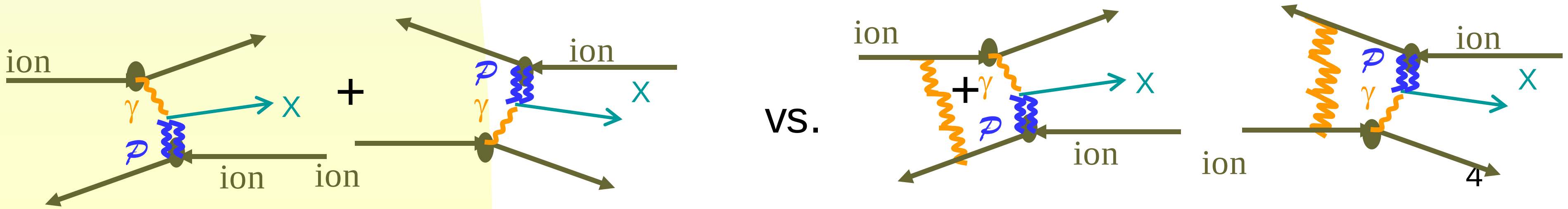
UPCs – good and bad



- 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

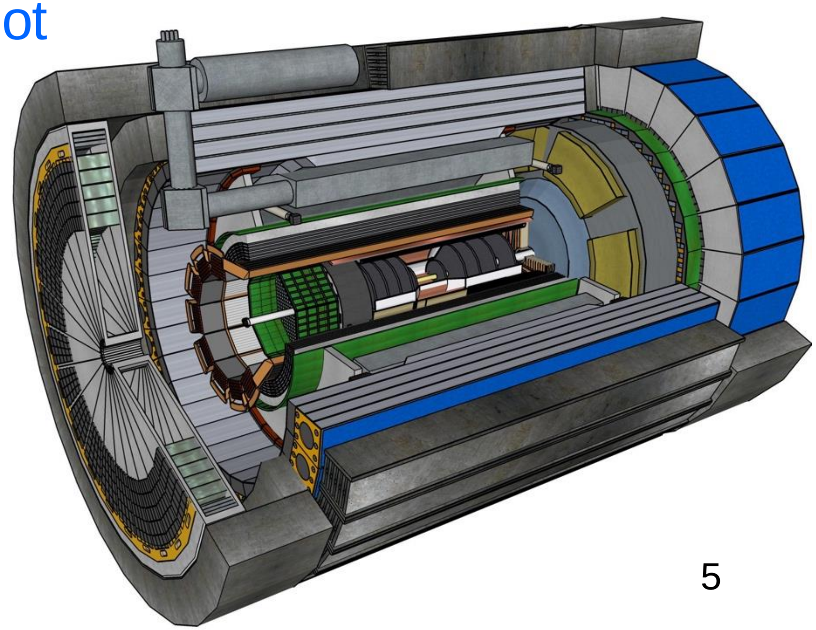
Bidirectional photon beams

- 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



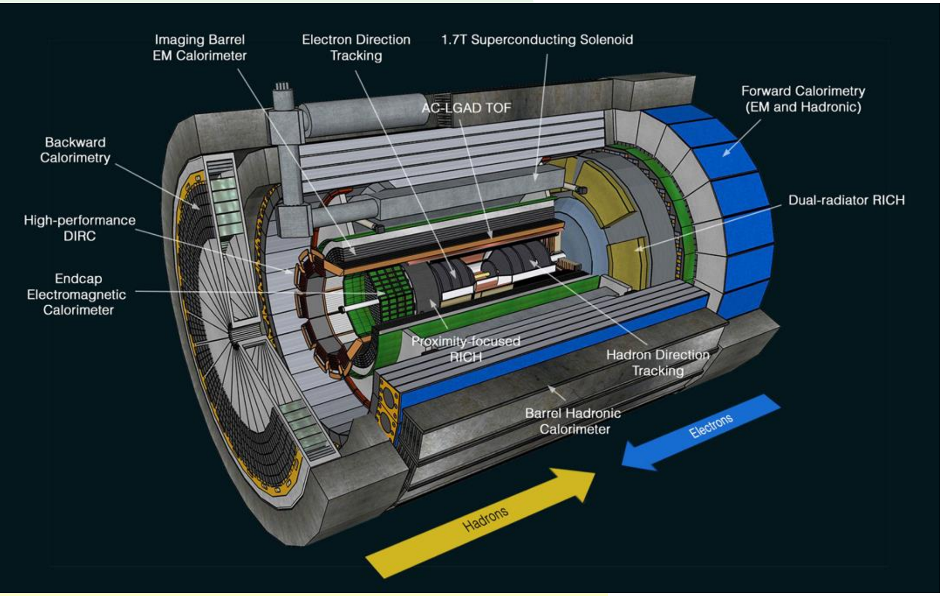
The electron-ion collider & ePIC

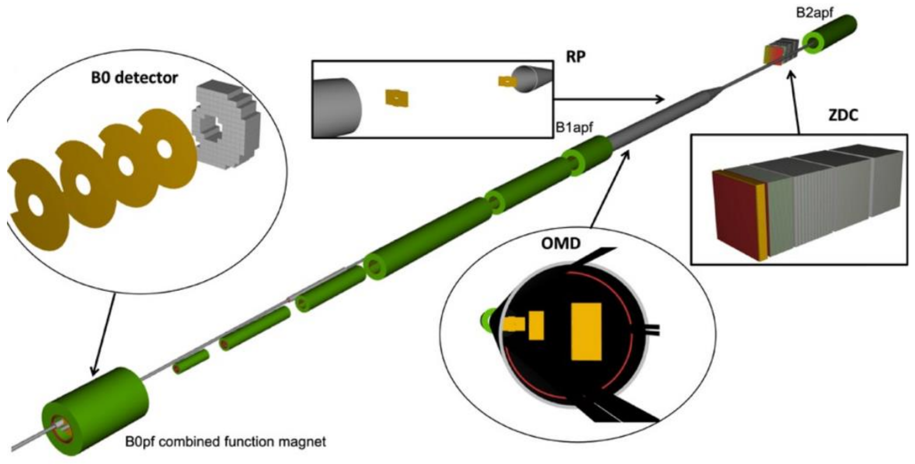
- High luminosity ep/eA collisions
- Photons with a wide range of virtuality
  - Observe scattered electron to determine photon energy and Q^2
- Detector optimized for γ^*p/γ^*A collisions
  - Near 4π acceptance
  - Good forward instrumentation to determine if nucleus dissociated or not
- Precision measurements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



The ePIC detector

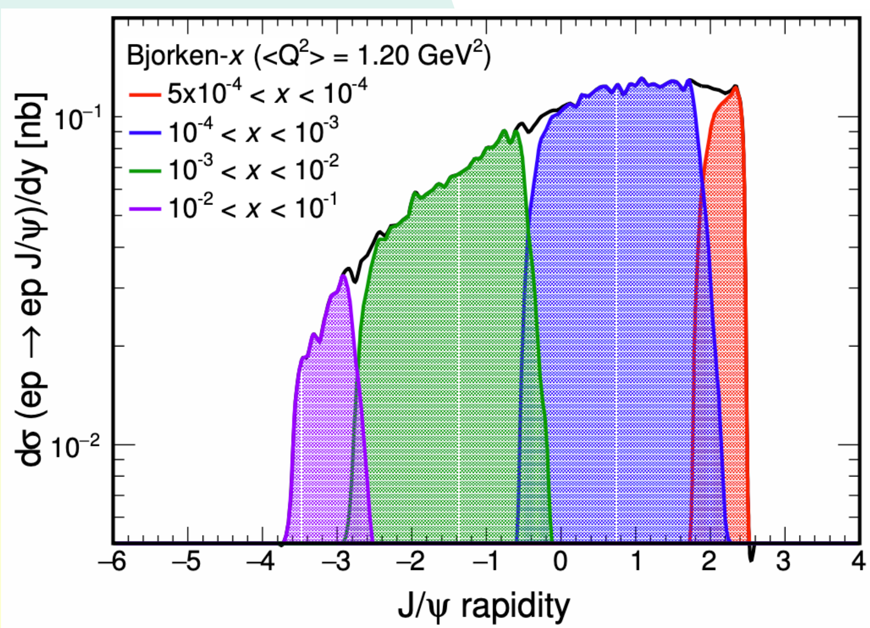
- The central region (|y|<4) See Olga Evdokimov's talk
- Low Q^2 electron tagger determine photon E, Q^2
- Forward detectors
  - B0 tracker & calorimeter ($4.6 < \eta < 5.9$)
  - Roman pots and Off-Momentum Detector detect scattered protons
  - Zero Degree Calorimeter for photons and neutrons
- Big forward question: did the nucleus break up, or not?

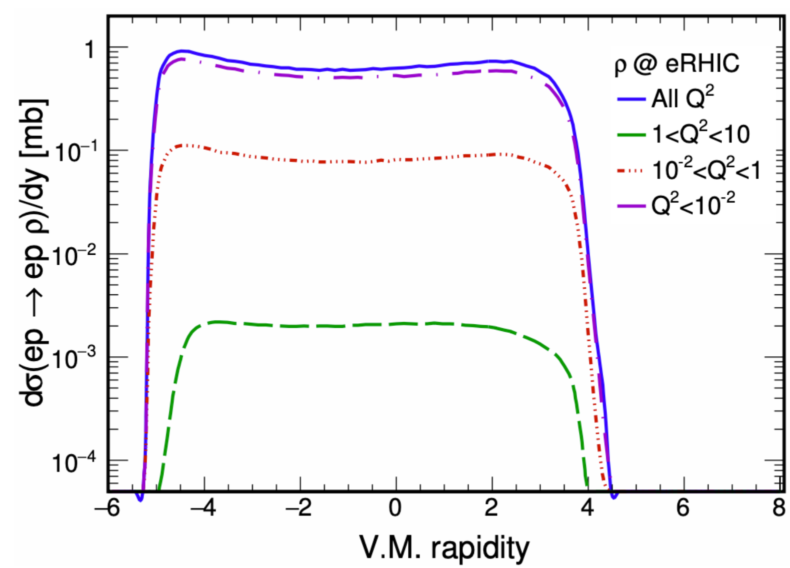




Energy and rapidity

- For exclusive interactions, energy and rapidity are related
  - Photon energy $K=M_X/2 \exp(y)$
  - Bjorken-x: $x=M_X/\gamma M_p \exp(-y)$
- Wide energy coverage requires a wide rapidity range
  - For vector mesons, need ~ +1 unit of pseudorapidity coverage to cover a given rapidity range.





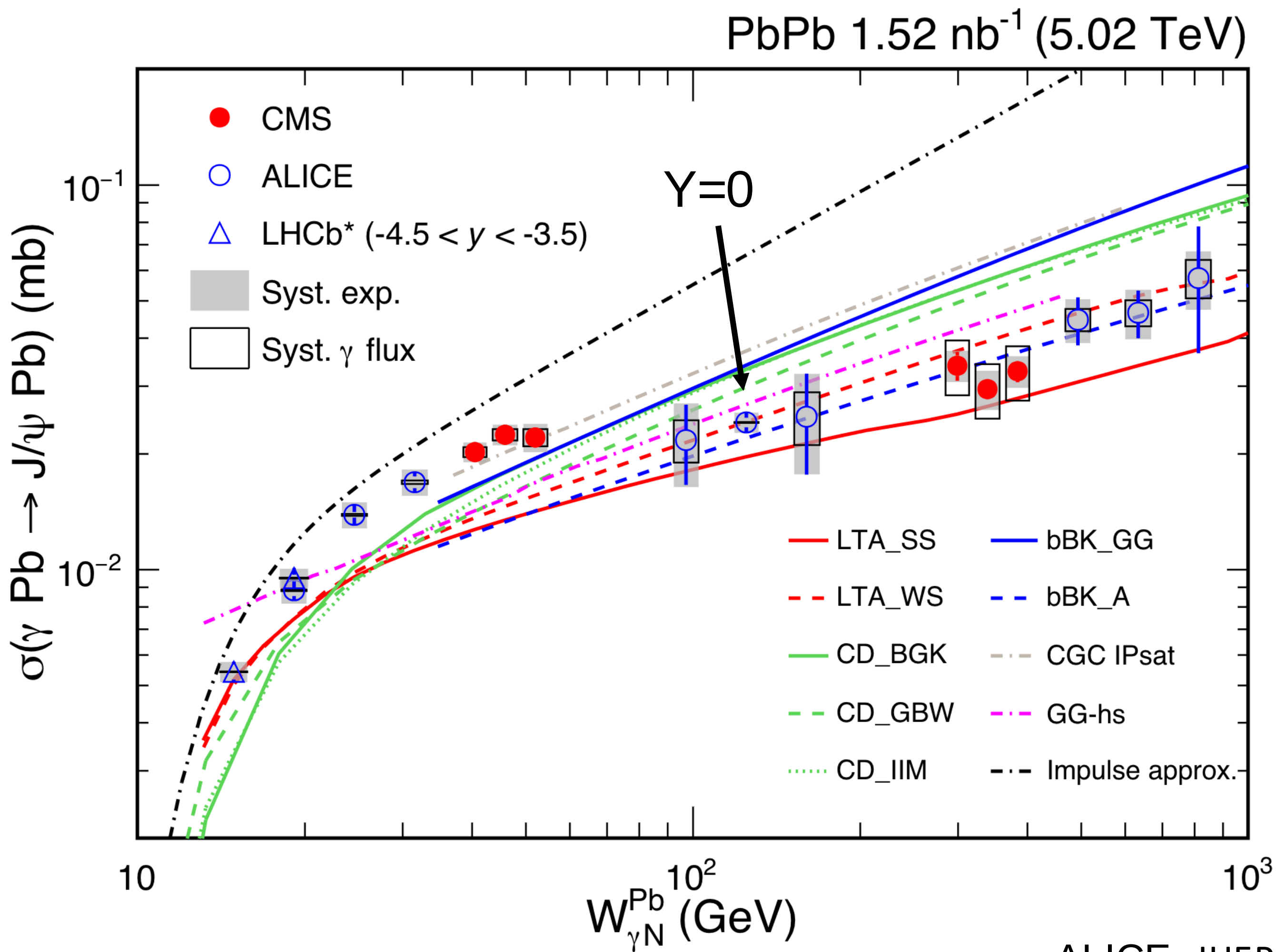
SK & M. Lomnitz, Phys. Rev. C **99**, 105203 (2019): n. b. flipped rapidity convention

Energy and Rapidity in UPCs

- AuAu/PbPb collisions are symmetric -> either nucleus can emit the photon -> bidirectional ambiguity
  - Photon energy $K=M_X/2 \exp(\pm y)$
  - Bjorken-x: $x=M_X/\gamma M_p \exp(\mp y)$
- Total amplitude is sum of both directions. Away from y=0, $p_T=0$, interference is small -> can directly use cross-sections.
- The cross-section at a given $y\neq 0$ is the sum of two directional cross-sections, with different energies.
- The solution is to use measurements with two different photon spectra, so different energies, i. e. with two different cross-section ratios
  - Two different impact parameter distributions

J/ψ cross-sections vs. energy

- $\sigma \sim W^{\delta}$ continues up to $W_{\gamma p} \sim 1$ TeV
  - Some wiggles -> tension between analyses?



ALICE, JHEP 10 (2023) 119

Coherent and Incoherent Photoproduction: a quantum view

- 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: Nucleus remains in ground state, so sum the amplitudes, then square -> average over different configurations
- Incoherent = Total – coherent; total: square, then sum cross-sections for different configurations

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

Good and Walker, Phys. Rev. D **120**, 1857 (1960); Miettinen and Pumplin, Phys. Rev. D **18**, 1696 (1978)

Coherence in Good-Walker

- Coherent production ⇔ Target remains in the ground state
  - -> $d\sigma/dt$ probes transverse distribution of scatterers
- Incoherent production ⇔ Target is excited/dissociated
  - Cross-section probes event-by-event target fluctuations
- But… we observe coherent production accompanied by mutual Coulomb excitation, and in peripheral heavy ion collisions
  - Here, coherent ⇔ the amplitudes from the nuclei add in-phase
    - $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
  - Something is missing/problematic from Good-Walker
    - How coherent is coherent enough?
      - A soft bremsstrahlung photon can be added to any reaction
- Use caution in interpretation, especially in relating incoherent production to target fluctuations

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

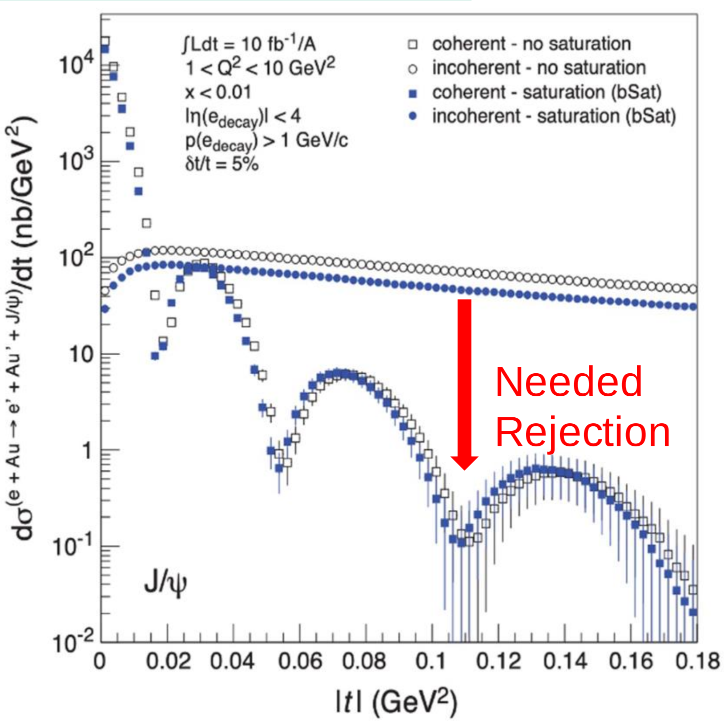
dσ/dt and the transverse distribution of gluons in protons/nuclei from coherent production

- Position (within nucleus) and p_T are conjugate variables
  - F(b), the transverse distribution of scatterers in a target, is the 2-d Fourier transform of ds/dp_T

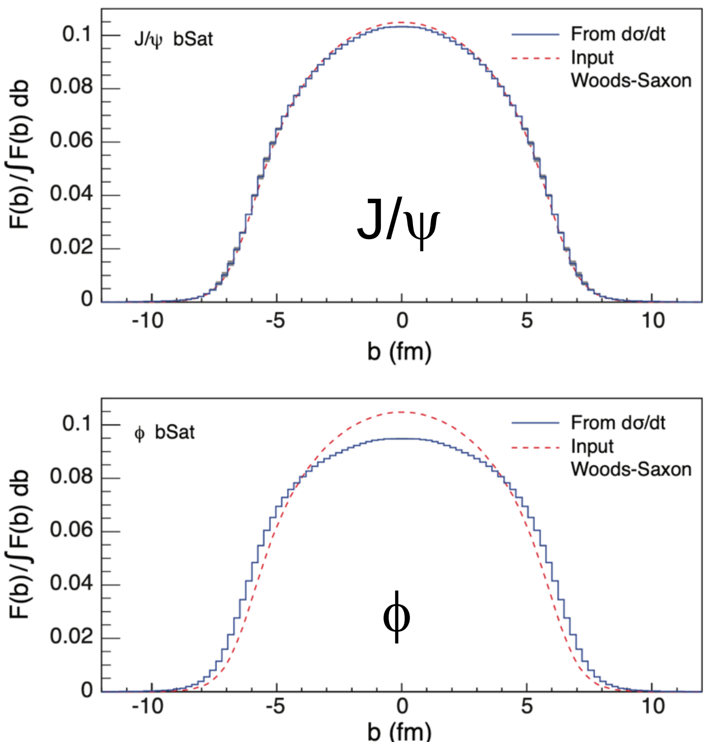
$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$

*must flip sign at each diffractive minimum

- Sensitive to shadowing; major focus of EIC White Paper



Fourier Transform

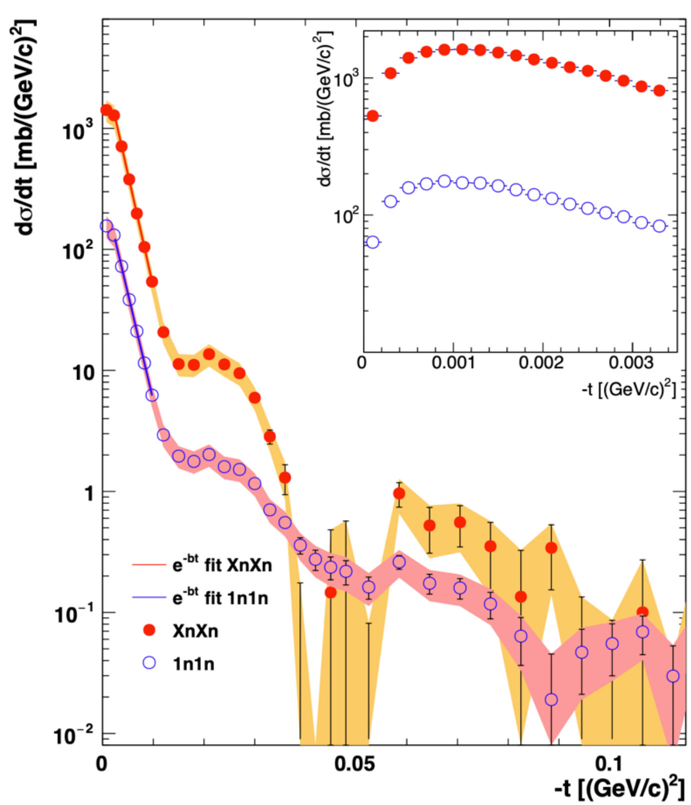


Difficulties in measuring $d\sigma/dt$

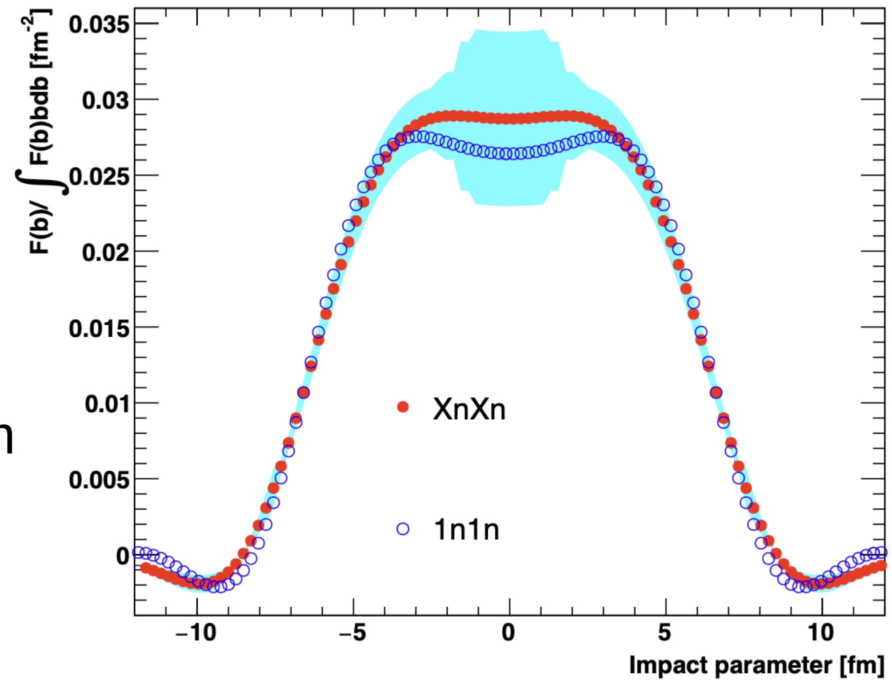
- Resolution fills in the diffractive dips
- In UPCs
  - The photon flux must be removed by deconvolution
  - Limited p_T reach creates windowing artifacts
    - May be alleviated with ALICE Run 3 data
- At the EIC
  - Resolution is an issue, especially for the electron.
  - Momentum transfer is << electron energy
  - Beam energy spread must be considered
- If the diffractive dips are filled in, they cannot be so well localized, and F(b) becomes less precise

STAR transverse distribution measurements

- Fit incoherent contribution at large |t| and subtract
  - Use a dipole form factor for scattering off a single nucleon
    - Not related to event-by-event fluctuations
- Vector sum of 'Pomeron' p_T, photon p_T and resolution
- L



Fourier Transform



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

Low-x VM production in eA in ePIC

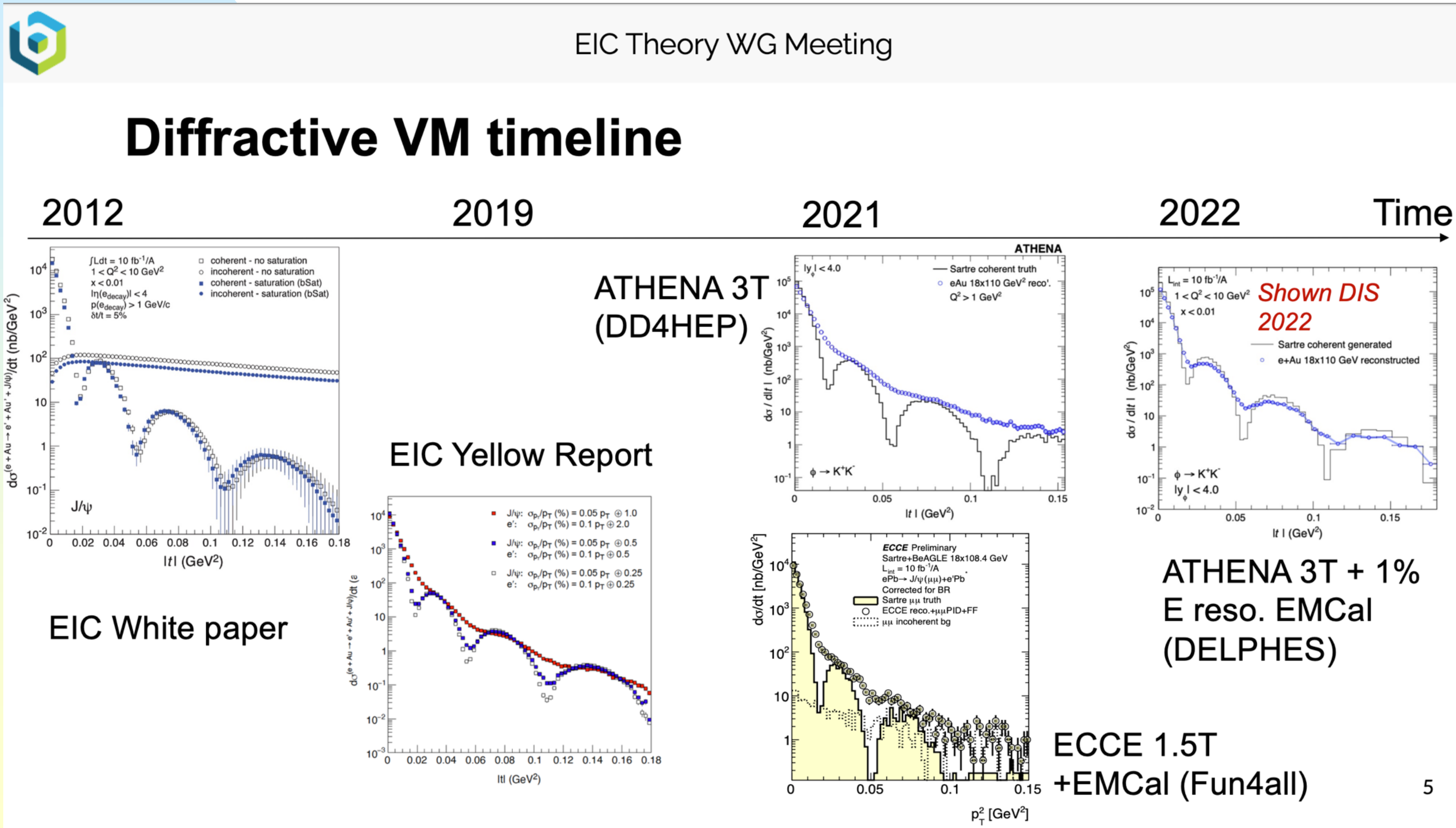
- More saturation expected for light mesons
  - ϕ (light) and J/ψ (heavy) are featured in EIC studies
    - ϕ is particular problem because the $K^{\pm}$ daughters are so soft
      - p=135 MeV/c in ϕ rest frame; $\beta \sim 0.2$ so dE/dx is large
  - Consider ρ as a replacement
- Usually cannot see outgoing ion
    - Some protons observable in Roman pot detectors, etc.
- Even if ion is observed, t is difference of large numbers
    - Beam spread, measurement errors
- Multiple t-measurement methods considered

- Method Exact (E): $-t = -(\boldsymbol{p}_{e} - \boldsymbol{p}_{e'} - \boldsymbol{p}_{VM})^2 = -(\boldsymbol{p}_{A'} - \boldsymbol{p}_{A})^2$
- Method Approximate (A) (UPCs) $-t = (p_{T,e'} + p_{T,VM})^2$
- Method with **exclusivity corrected** (L): $-t = -(\boldsymbol{p}_{A',corr} - \boldsymbol{p}_{A})^2$,

where $\boldsymbol{p}_{A',corr}$ is constrained by exclusive reaction.

History of EIC t-measurements

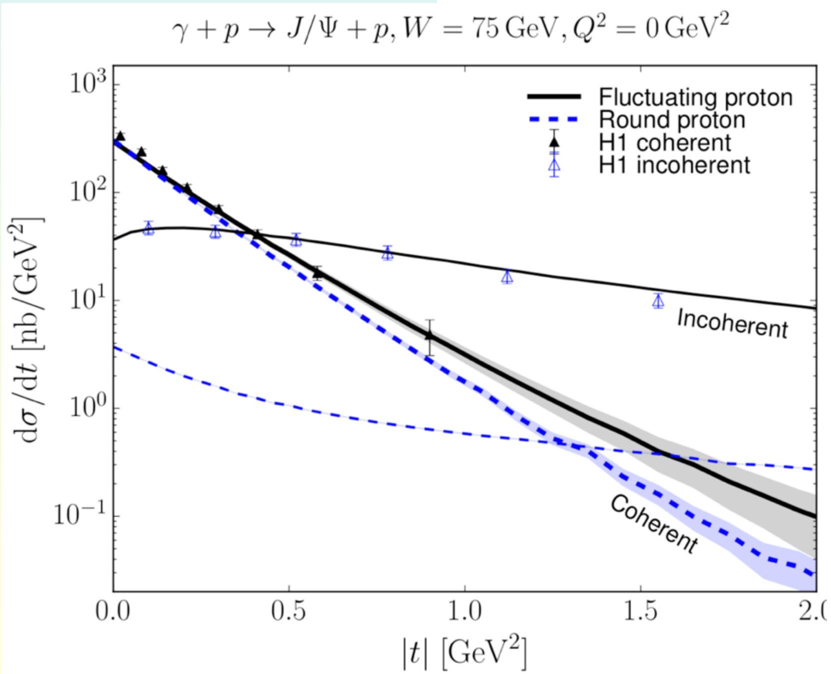
- Diffractive dips are likely to be (barely) visible
  - Implications for Fourier transform

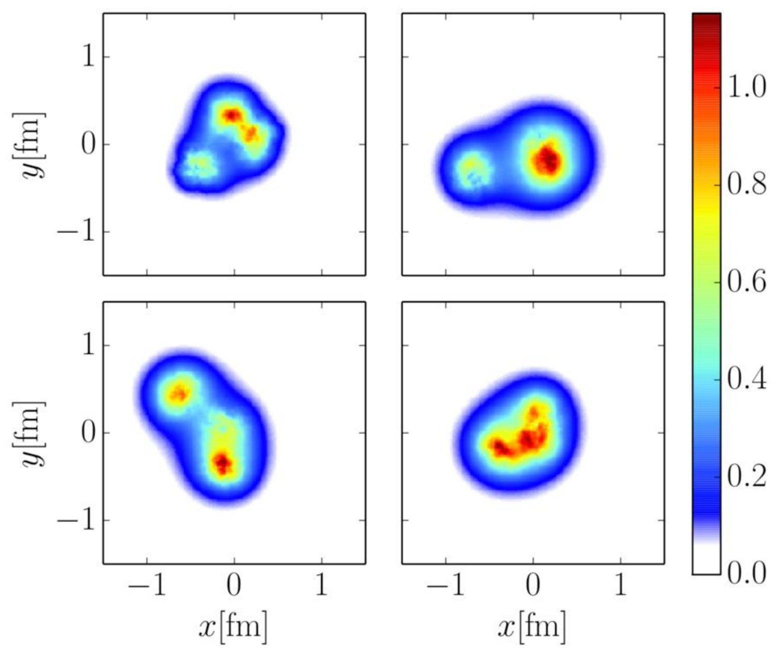


Slide from Kong Tu, presented at an EIC Theory Group meeting

Incoherent production on protons

- H1 at HERA data on J/ψ production on protons
- Fluctuations from coherent & incoherent J/ψ photoproduction.
  - Proton excitations (Δ^+) -> incoherent
- Two models/calculations of dσ/dt compared
  - Data prefers a fluctuating proton over a smooth proton
- EIC can make precision measurements like this

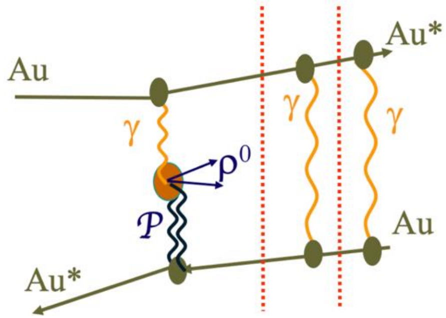


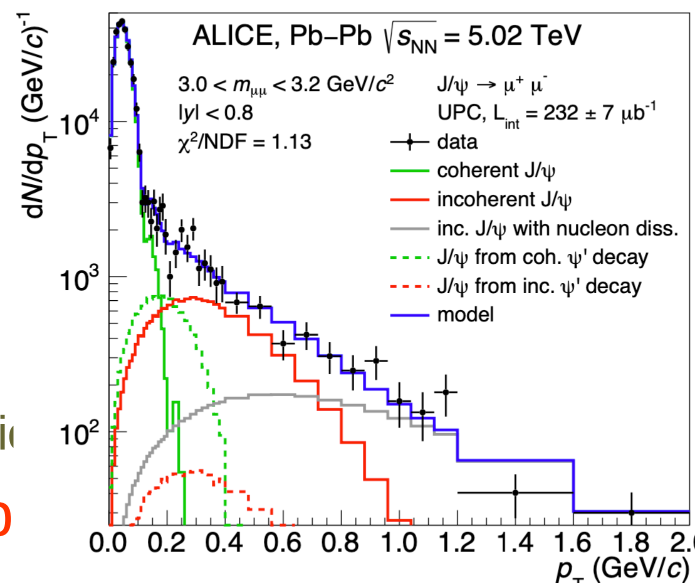


Mantysaari and Schenk, PRD **94**, 034042 (2016)

Separating coherent & incoherent production on ions

- In UPCs, $Z\alpha$ is large enough so that the nuclei may exchange additional photons
  - Nuclear breakup complicates separation
  - Photon exchange factorizes
- Coherent dominates at low p_T
  - Incoherent dominates at high p_T
  - Subtract one component to get the other
    - Need assumptions re. shape of $d\sigma/dp_T$
      - Shape is based on paradigm
        - $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
      - Somewhat inconsistent to use this paradigm + Good-Walker to find fluctuati
- Presence/absence of neutrons could help separation

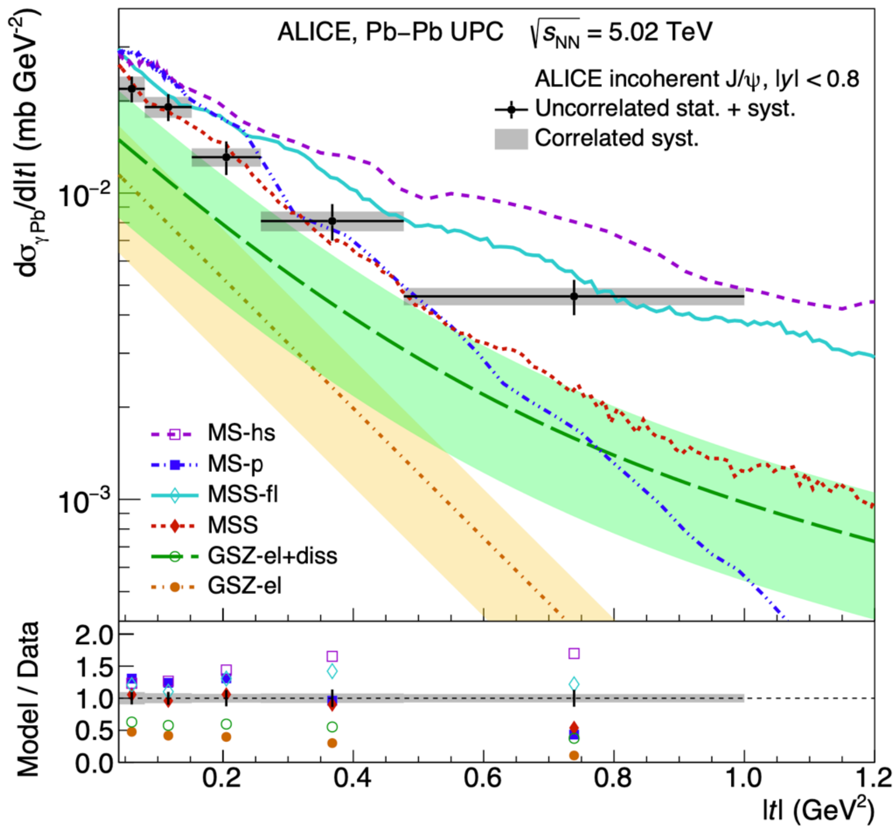




ALICE, PRL **132**, 162302 (2024)

Incoherent J/ψ photoproduction on Pb

- p_T>200 MeV/c
- Better agreement with models that include subnucleonic fluctuations
  - Large high |t| tail above expectations from proton form factor



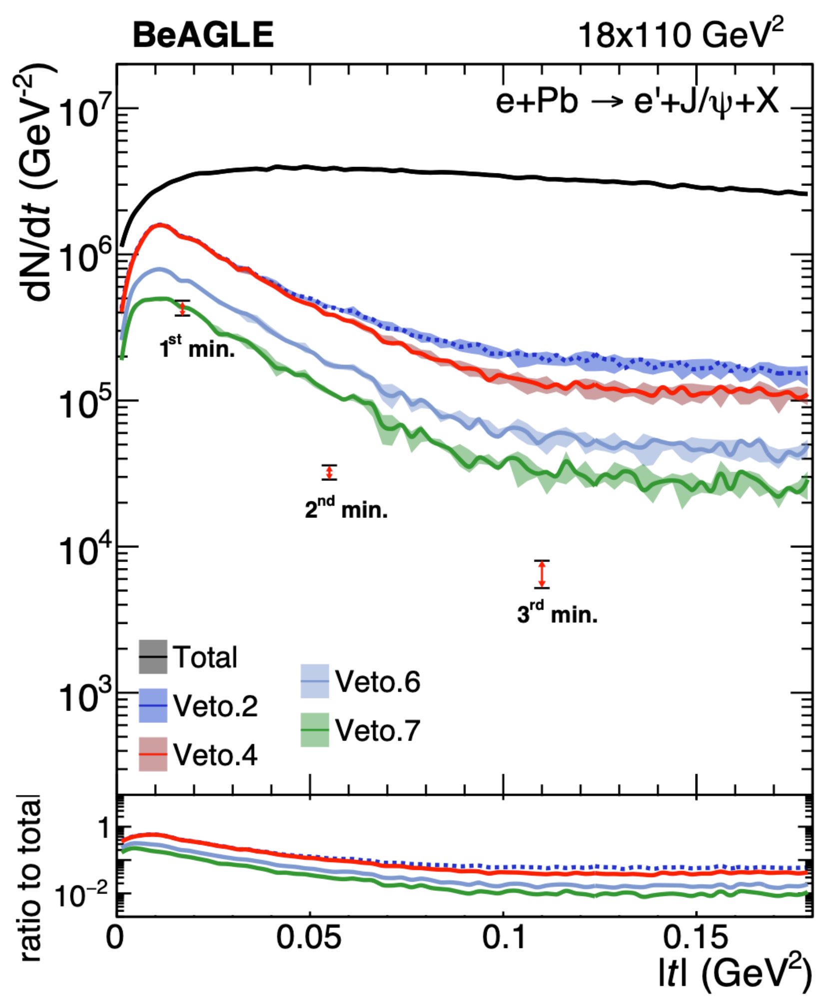
ALICE, PRL **132**, 162302 (2024)

Theoretical uncertainties in ion breakup

- ePIC can detect nuclear breakup by the presence of neutrons or protons (with near-beam momentum), or of photons in the ZDC from nuclear excitations
  - Typical photon energies are ~ few MeV in emitter frame
    - Lorentz boosted in lab frame
- ^{197}Au has a first excited state at 77 keV (with ct~ 60 cm))
  - Not visible in ZDC
  - 2nd excited state at 269 keV; boosted to 63 MeV max
- Other low-energy photon lines may be missed, or detected with low efficiency
  - ZDC threshold matters, but background from synch. radiation
- To determine the excitation efficiency accurately, we need a good model of the products of nuclear breakup.
  - Currently use BeAGLE
    - DPMJET + FLUKA for intranuclear cascade
      - Uncertainties are acknowledged to be large

ePIC veto projected performance

- How well can ePIC veto incoherent J/ψ production to study coherent?
  - Requires ~ 500:1 to 1,000:1 to study coherent production



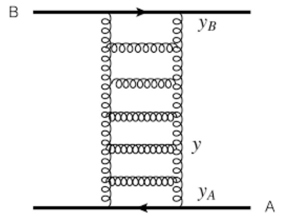
- Veto.1: no activity other than e^- and J/ψ in the main detector ($|\eta| < 4.0$ and $p_T > 100$ MeV$/c$) ;
- Veto.2: Veto.1 and no neutron in ZDC;
- Veto.3: Veto.2 and no proton in RP;
- Veto.4: Veto.3 and no proton in OMDs;
- Veto.5: Veto.4 and no proton in B0;
- Veto.6: Veto.5 and no photon in B0;
- Veto.7: Veto.6 and no photon with $E > 50$ MeV in ZDC.

Does not reach 500:1
Modelling will be critical!

W. Chang *et al.*, Phys. Rev. D **104**, 114030 (2021)

Beyond Pomerons: Reggeons

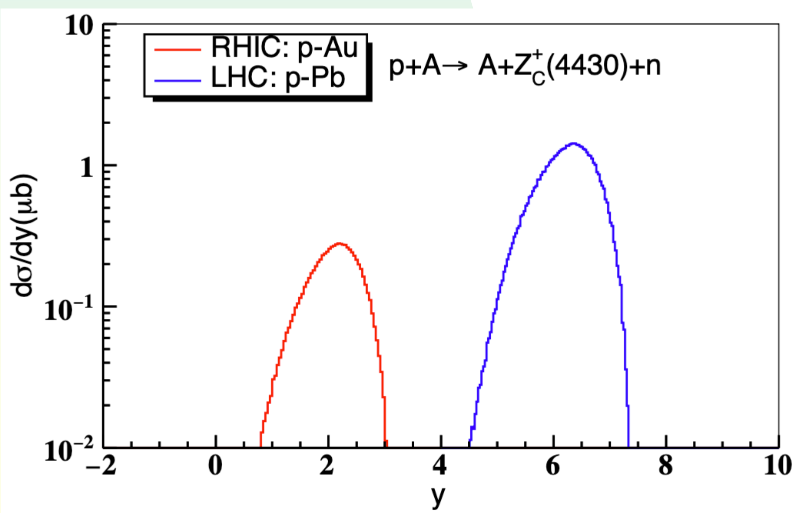
- Pomerons carry the quantum numbers of the vacuum
  - s-channel helicity conservation means that photon + Pomeron interactions lead to $J^{PC}=1^{-}$ states
    - Experimentally well tested
  - Mostly gluons
  - Cross-section rises with energy ($\sigma \sim W_{\gamma p}^{0.22}$)

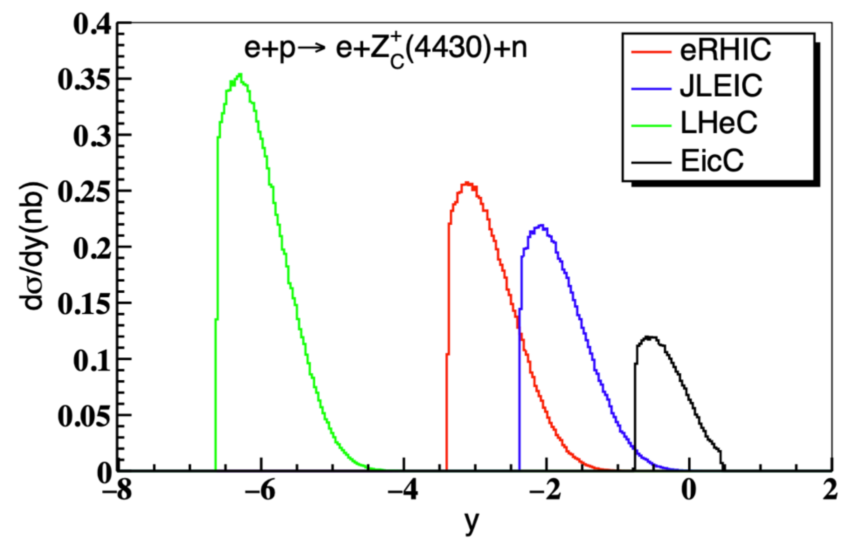


- Reggeons are summed meson Regge trajectories
  - Mostly quark-antiquark pairs+
  - Can accommodate a wider range of quantum numbers
    - Broad range of physics!
  - Cross-section drops with energy, ($\sigma \sim W_{\gamma p}^{-1}$) so Reggeon interactions are close-ish to threshold
    - Optimum EIC data collection may occur below maximum energy

Production of exotica in UPCs and the EIC

- Exotica with $J^{PC}=1^{--}$ can come from γ-Pomeron interaction.
- Other J^{PC} can only (if at all) come from γ-Reggeon interactions
- In UPCs, γ-Reggeon fusion products are forward, mostly beyond the reach of current detectors.
- γ-Reggeon final states are visible at the EIC.
- Predicted rates at the EIC are high enough for characterization
  - γ-exotica coupling sensitive to internal structure

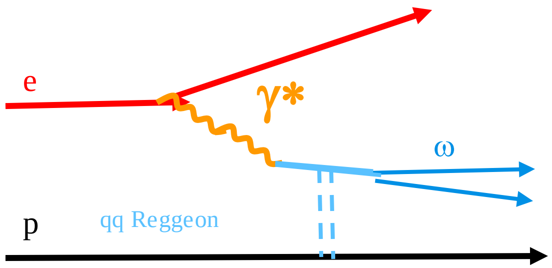




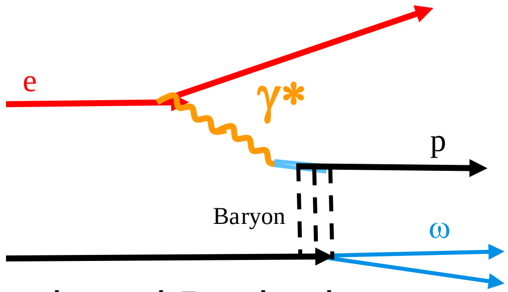
SK & Y. Xie, Phys. Rev. C 100, 024620 (2019)

Backward (u-channel) production

- Reggeons reactions that carry baryon number like $\gamma p \to \rho/\omega/\pi^0/\gamma\ p$
  - $d\sigma/dt$ is large $d\sigma/du$ is small
- Seen by many fixed-target experiments, including at JLab
  - Parameterize using Regge trajectories
  - Rate ~~ 1/1000 of forward producgtion
  - Similar to baryon stopping in heavy-ion collisions baryon junction models
- The γ/meson takes most of the proton momentum (so is far forward), while t
  - The proton ~ stops -> at mid-rapidity
- γ/meson rapidity depends on its mass
  - $\rho \to \pi\pi$, $\omega \to \gamma\pi^0$ in B0 detector at lower beam energies
  - π^0 and γ in ZDC - best at higher beam energies



Forward Production

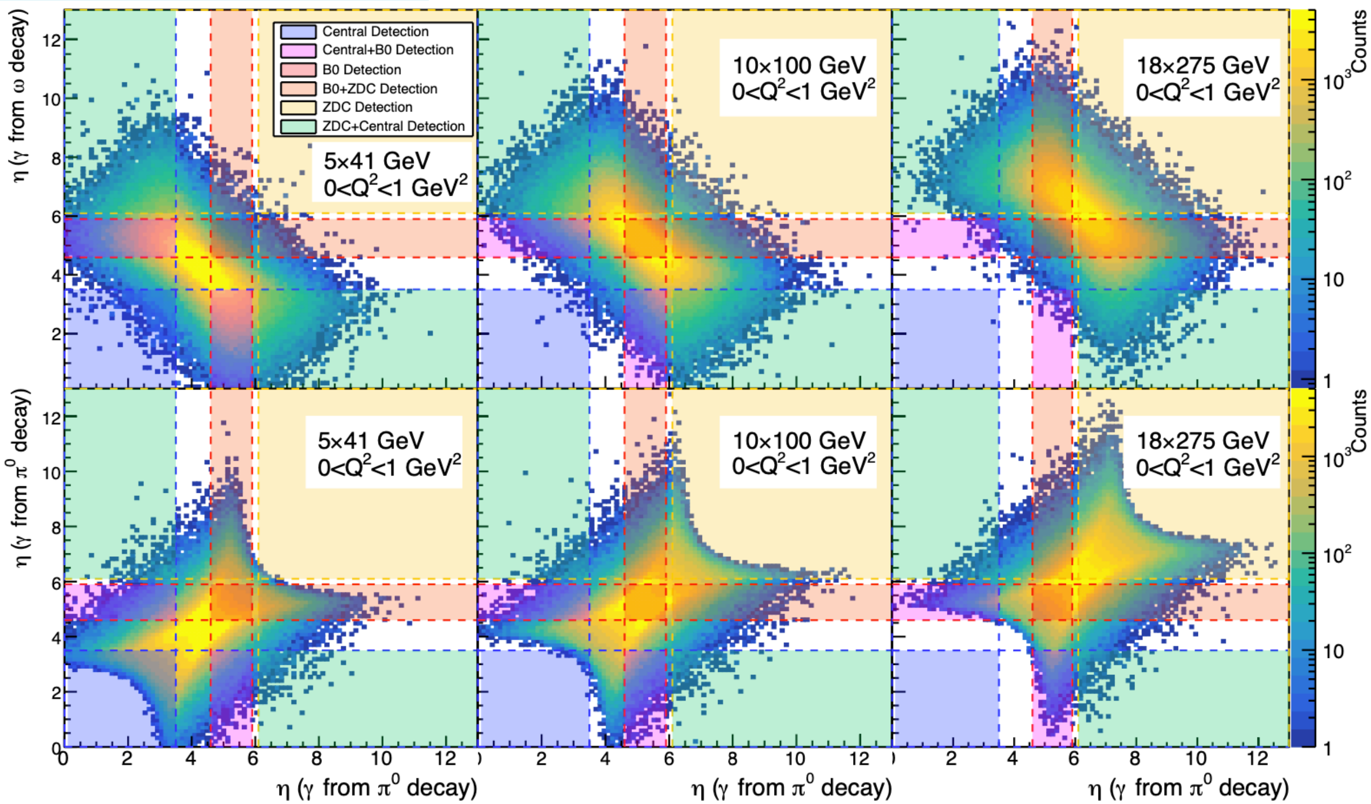


Backward Production

D. Cebra *et al.,* PRC **106**, 015204 (2022); Z. Sweger *et al.,* PRC **108**, 055205 (2023)

ω->γπ⁰ backward production kinematics

- ρ-> ππ kinematics are similar
- B0 is the key detector
- Best detection for 10 GeV e on 100 GeV p
  - Q^2 doesn't change kinematics a lot



D. Cebra *et al.*,
PRC **106**, 015204 (2022);
Z. Sweger *et al.*,
PRC **108**, 055205 (2023)

How do UPCs and the EIC compare?

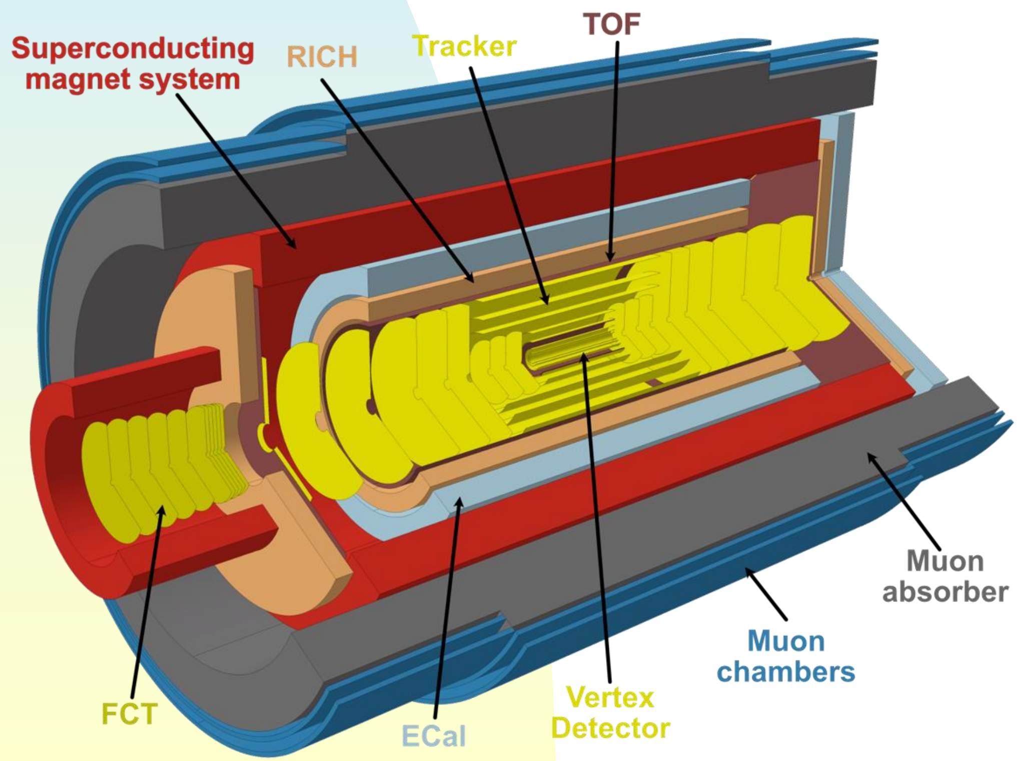
- UPCs reach higher energy, so lower Bjorken-x
  - Photons are nearly real, but Q^2 comes from the hard scale of the final state
- The EIC photons cover a wide range of Q^2, and ePIC can detect the scattered electron, and so tag the photon
- Between the scattered electron and the nearly-hermetic detector, ePIC has very strong power to completely reconstruct exclusive interactions with low backgrounds.
  - The proposed ALICE 3 has coverage out to $|y|<4$, so will partially compete.

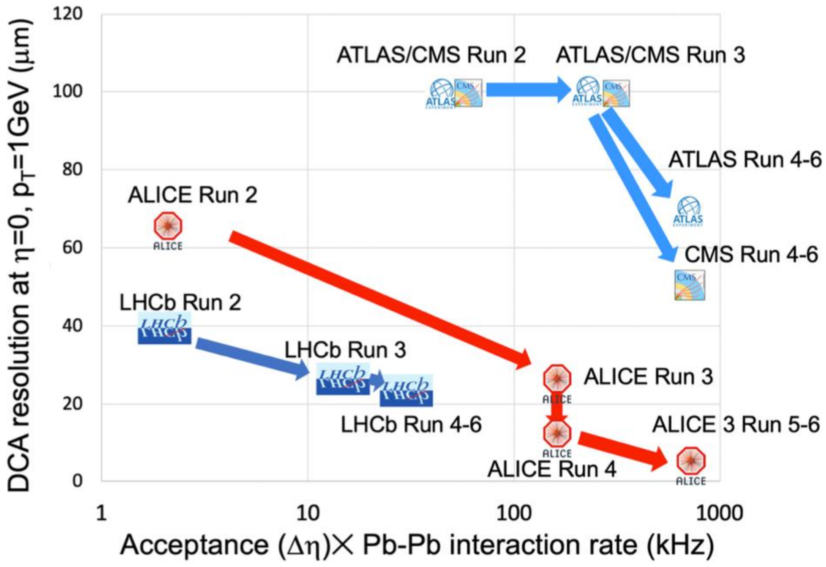
UPCs in the EIC era

- CMS, ATLAS and LHCb will continue to take data with improved vertexing and other smaller upgrades
  - More mass reach than the EIC
- ALICE 3 is a proposed completely-new detector
- A broad UPC program in $\gamma\gamma$ and γp interactions is on-going, and will continue
- What can UPCs do that the EIC can't? <- Key question for US
  - Higher collision-energy $\gamma\gamma$ and γp interactions
    - Lower Bjorken-x values (but only at large |y|)
  - Physics in a strong (EM) field environment
    - UPCs act as a 2-source interferometer
      - Interference seen with single mesons
    - The LHC can extend this to interferometers with two or more mesons

ALICE 3

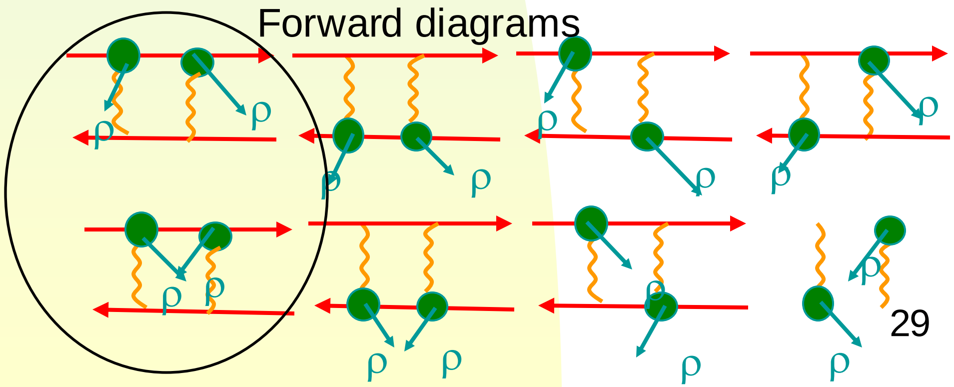
- Proposed detector for LHC Runs 5 and 6 (starting ~ 2035)
- Tracking and calorimetry for $|\eta|<4$
- Particle identification
- Vertex detector inside beampipe (~ 4 μm resolution @ 1 GeV/c)

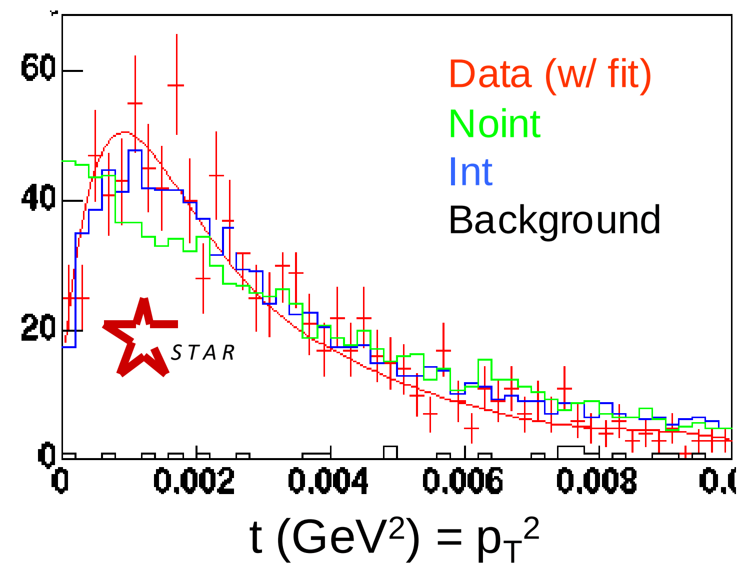




Two-meson interferometry

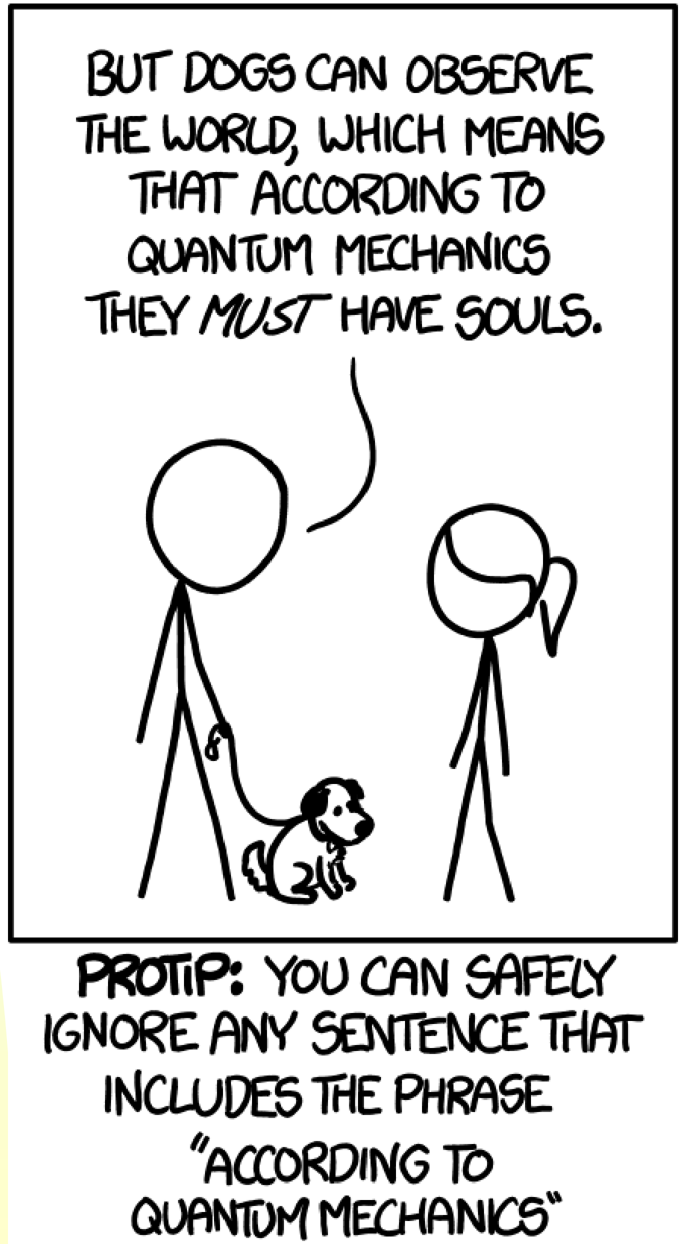
- For 1 meson, : $\sigma \sim |A_1 - A_2 e^{ip \cdot b}|^2$
  - At midrapidity $A_1 = A_2$ and , $\sigma \rightarrow 0$ as $p_T \rightarrow 0$
- With 2 identical mesons, the possibilities multiply.
  - Like an interferometer containing two photons.
- For |y|>>0, the two photons are from the same nucleus
  - Superradiant emission: N meson probability is enhanced by N!
    - Like a laser
    - $\langle p_T \rangle \sim \langle p_{T1} \rangle / N$
- Stimulated decay?
  - e. g. π^+ from ρ decay close in phase





STAR, 2008

Quantum interferometry – an alternate view



xkcd.com

Conclusions

- Exclusive interactions can probe many interesting physics topics, including the low-x structure of matter, including its spatial distribution
- The nearly-hermetic ePIC detector at the EIC is well suited to pursue high-statistics measurements with small systematic errors, over a wide range of Q^2.
  - Precise measurements of gluon saturation.
  - Transverse distribution of gluons in nucleus
  - Event-by-event fluctuations in gluon content (hot spots)
    - Measurements of $d\sigma/dt$ are limited by the limited t resolution.
- ePIC will also study backward production, exotica, etc.
- UPCs at the LHC will retain their interest during the EIC era, providing unique data on multi-meson production in high fields, and of nuclear structure at lower Bjorken-x than the EIC can reach.