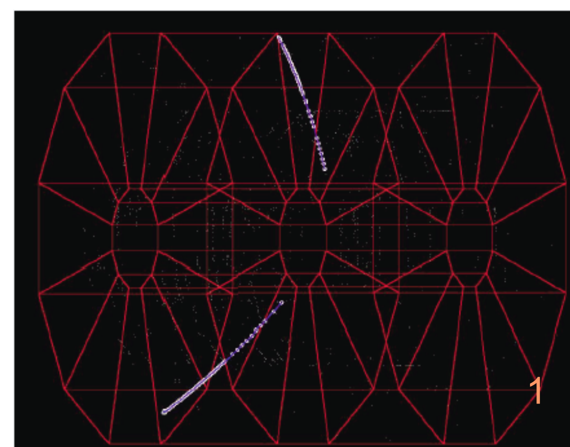
Diffractive Physics at the EIC: physics and detectors

Spencer Klein, LBNL

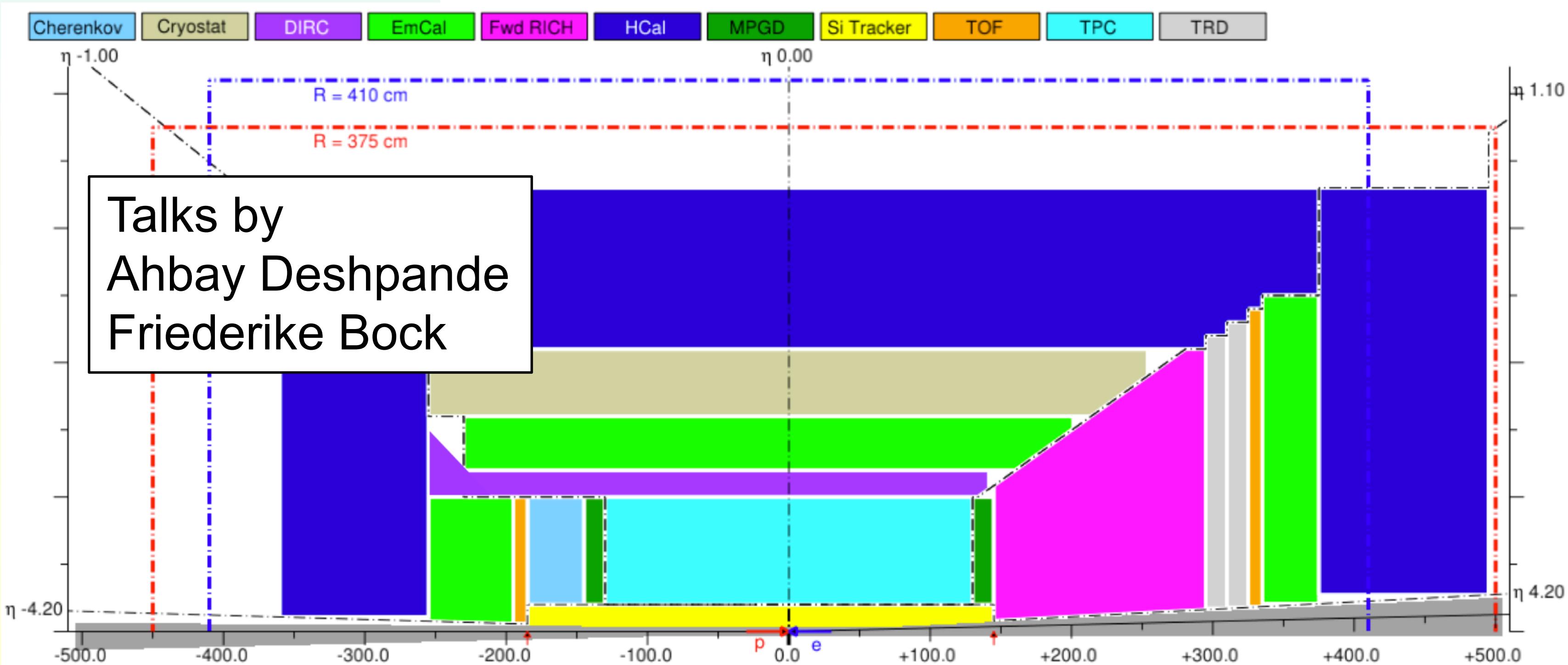
Presented at the Workshop on Forward QCD: open questions and future directions

- Diffraction at the EIC: parton distributions and imaging
- Differences between EIC collisions and UPCs
- The planned EIC detector(s): response to diffraction
- Distinguishing coherent & incoherent production
- Regge-mediated interactions
- Backward production
- Conclusions



Reference Detector

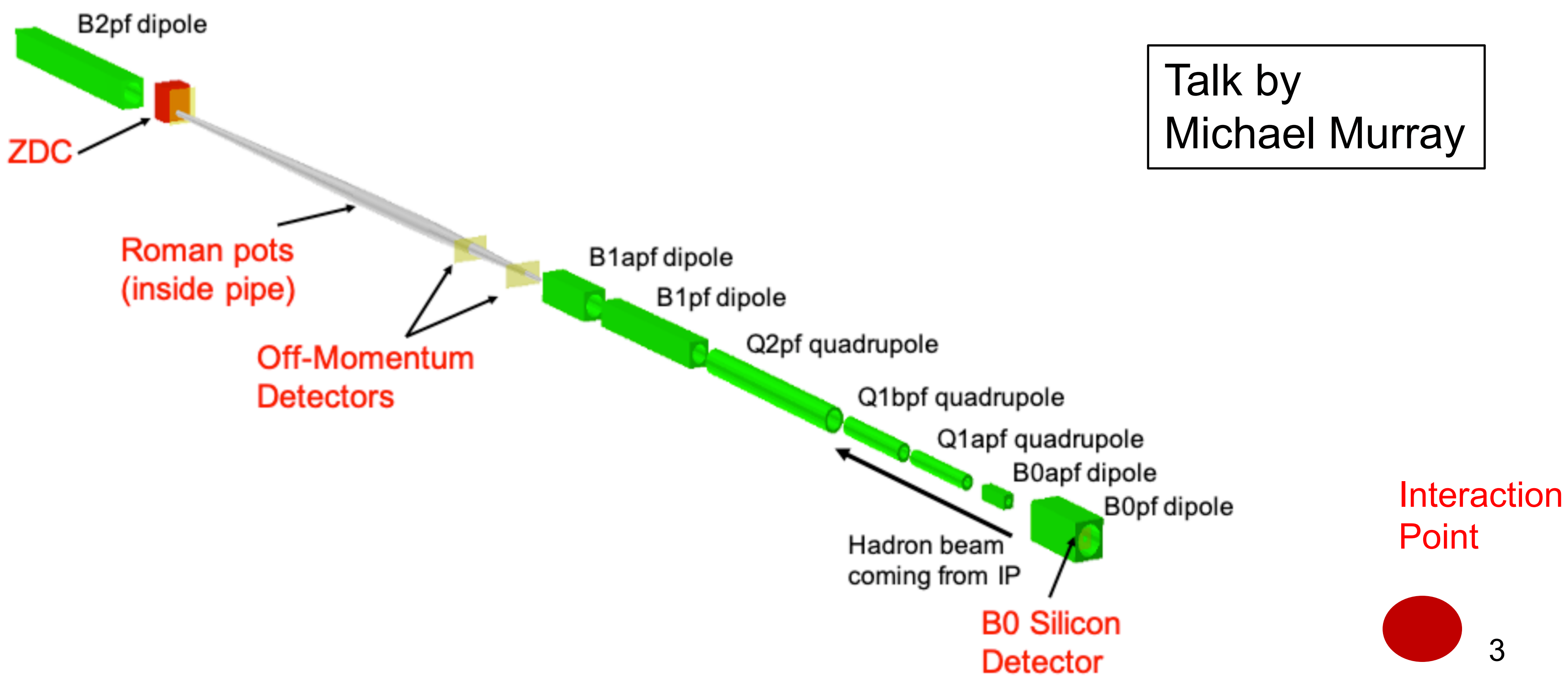
- Central barrel + endcaps cover ~3.5 < η < ~3.5
  - Vertexer, tracking, PID, electromagnetic and hadronic calorimetry
  - Non-zero crossing angle complicates acceptance in η
    - Acceptance limited by beampipe/machine constraints
- Forward detectors for scattered or dissociated nuclei
- Backward detector for scattered electron
  - Effort to go to the smallest possible energy loss, Q^2



Talks by
Ahbay Deshpande
Friederike Bock

The forward region

- Detectors well integrated with accelerator magnets, pumps etc.
- Must detect nuclear breakup with high efficiency, to separate coherent and incoherent production
- Probe diffractive excitations of nuclear target
- Study pion, kaon structure functions

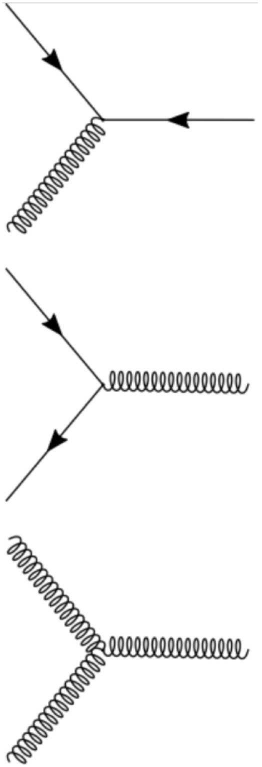


Talk by
Michael Murray

Goals of diffractive/exclusive studies at the EIC

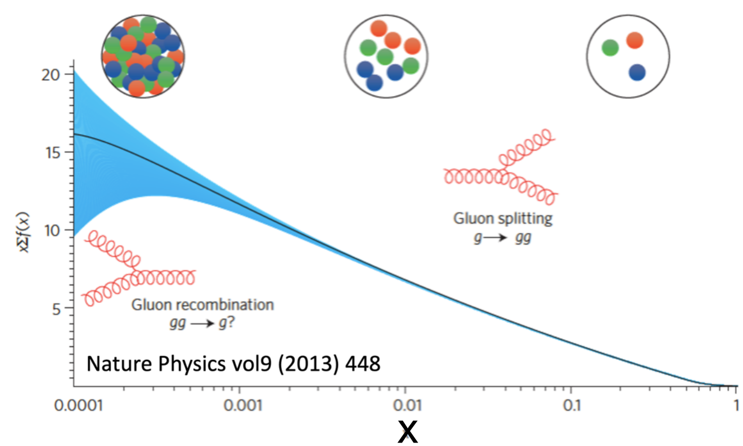
- Measurement of parton distributions especially gluons
  - In protons and (especially) ions
  - Searching for new phenomena at high gluon densities
    - Saturation/the colored glass condensate
- Measurement of the transverse distribution of partons, especially gluons
- Studies of event-by-event parton fluctuations (gluonic hotspots)
- Studies of exclusive photoproduction, for hadron spectroscopy
  - XYZ charmonium states
  - γ-exotic coupling sheds light on their nature
  - γ+Reggeon reactions allow a wide range of final states
- Studies of near-threshold photoproduction of heavy quarkonium
- Studies of backward production
  - Reactions like $\gamma^* p \to \rho/\omega/\pi^0\, p$, where |t| is large but |u| is small
    - Responsible for baryon stopping in heavy ion collisions?

Quarks and gluons at high densities



- Parton densities rise due to splitting
- At high densities, parton recombination also occurs
- At very high densities, the splitting & recombination rates are equal
  - Equilibrium - saturation
  - Describable as a colored glass condensate
    - A classical gluon field
      - Originally predicted new phenomena, such as monojets in heavy-ion collisions
      - Now is mostly considered a calculational tool
- With the higher density, nuclei are more likely to exhibit high-density phenomena, like saturation
  - Phenomena emerge at larger Bjorken-x
  - Increase is by "Oomph factor" ~
    - $A^{1/3}$ ~ 6 for gold/lead

Talk by
Martin Hentschinski

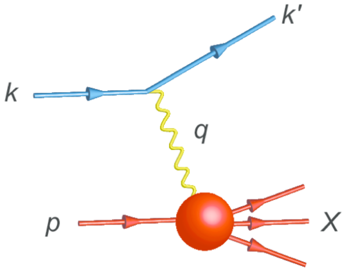


How does the EIC compare to UPCs?

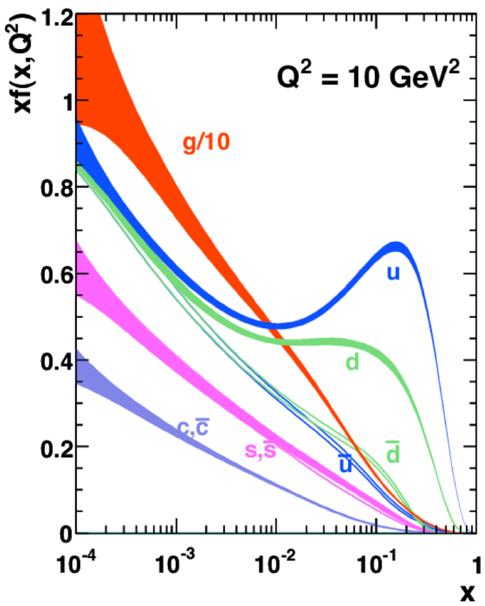
- Virtual photons covering the full range of Q^2
  - Measure parton distribution studies over Q^2
    The EIC can directly probe partons via deep inelastic scattering
- Polarized protons & light ions, wide range of unpolarized ions
  - Polarized protons/ions give access to polarized parton distributions and GPDs
- High luminosity
- A detector that covers almost the full solid angle with charged particle tracking, particle identification and calorimetry
  - Down to low momentum (p_T < 100 MeV/c)
  - Reconstruct the full event
    - Missing mass techniques*
- But… lower energies than the LHC (comparable to RHIC), so less reach in Bjorken-x
  - Maximum 18 GeV electrons on 275 GeV p/110 GeV/n nuclei

*some limitations apply

Measuring gluon distributions

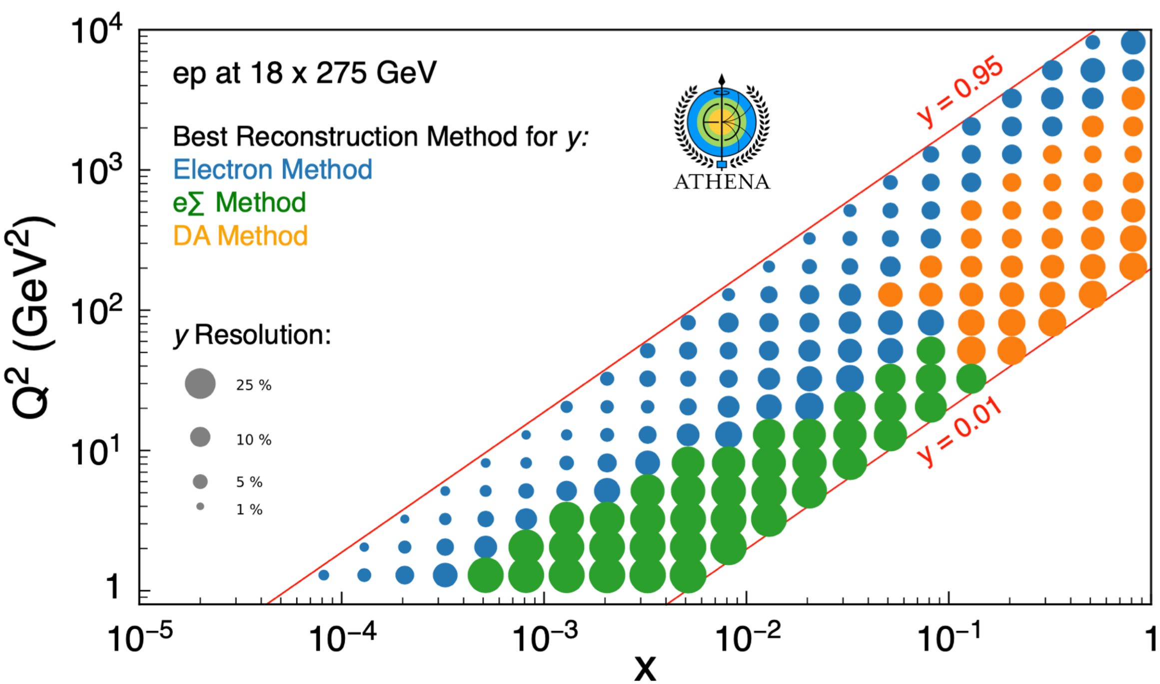


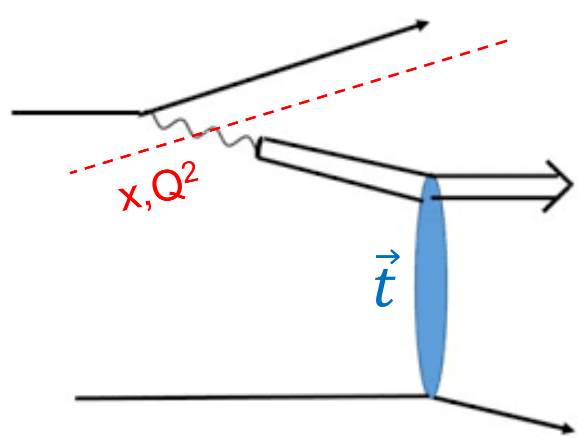
- In Deep Inelastic Scattering, an emits a virtual photon which interacts with quarks in the nucleus
  - x and Q^2 determined from scattered electron
  - y = inelasticity=fraction of electron energy transferred to hadrons
    - $Q^2 \sim sxy$
- Gluons may be inferred from evolution of quark distributions
  - How does the quark density change with x or Q^2?
- Direct measurements are highly desirable
  - Reactions that proceed via gluons
  - Photoproduction of dijets, open charm, or vector mesons
    - Single gluon exchange, but experimentally harder
  - Photoproduction of vector mesons
    - Experimentally simple, but theoretical complications



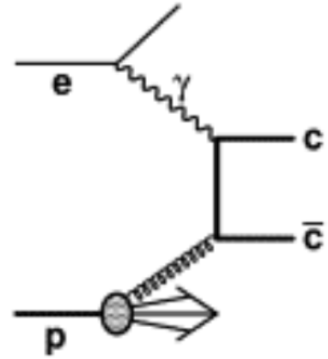
Kinematic Range and reconstruction

- Key variables: x, Q^2
  - y=inelasticity; $Q^2 \sim sxy$
- x,Q^2 determinable by observing scattered electron
  - Best over most of kinematic range, except at low y
  - Alternately, reconstruct x,Q^2 from hadronic final state
    - Double-angle method uses hadronic system + electron angles
    - Σ method uses hadronic final state

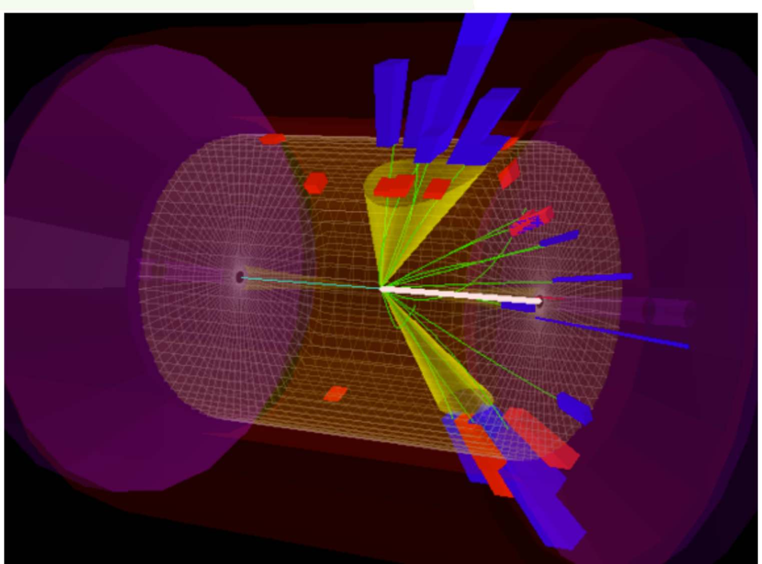


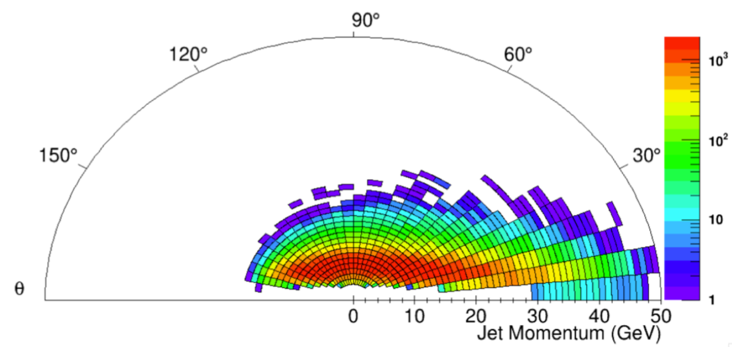


Dijets and open charm



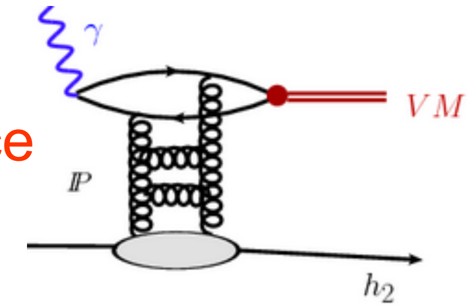
- Theoretically relatively clean
- Rates are high (γ-charm coupling is large)
- Low Bjorken x corresponds to high photon energies, so the jet goes in the backward region
  - For photoproduction $y = \ln(2k/M_{final})$ and $x = M_{final}/M_{proton} \exp(-y)$
    - Electroproduction only affects this a little
- Diffractive dijets/charm also expected
  - Proton/ion stays intact. Probe of Pomeron, test of Odderon





Exclusive vector meson photoproduction

- Occurs via colorless 'Pomeron exchange'
  - Require >=2 gluon exchange for color neutrality
    - Gluon ladder
- Light meson production via vector meson dominance
  - ρ, direct $\pi^+\pi^-$, ω, ρ'
- Heavy meson production treated with pQCD
  - J/ψ, ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$
- 3 targets, 3 coherence lengths and 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. $p_T <\sim \hbar/R_p$
  - Proton dissociation: struck proton breaks up. $p_T \sim \Lambda_{QCD} \sim 300$ MeV
  - Forward detectors can separate these three classes of events
- γ + Odderon (3+-gluon state) could lead to tensor mesons
- At low energy, photon+Reggeon contributes significantly
  - Reggeon = quark + antiquark ladder
    - Meson exchange trajectories
  - Allows a much wider range of quantum number, including charge

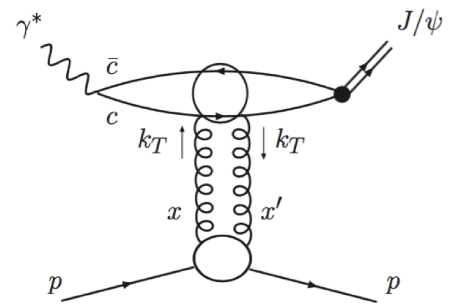


A/A*/Ax

VM photoproduction in LO pQCD

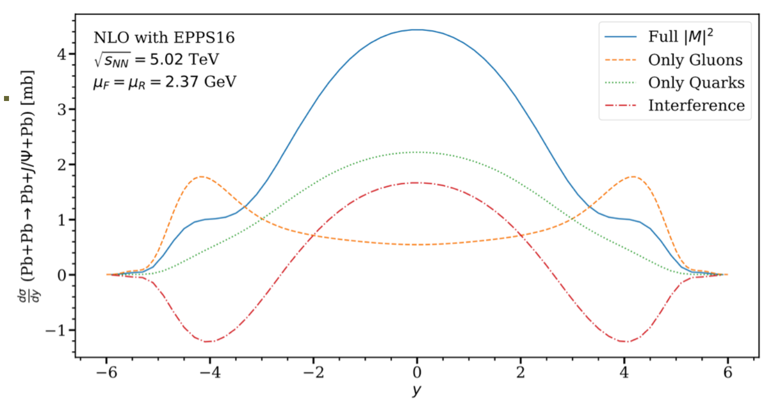
- In 2-gluon model, leading order pQCD

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



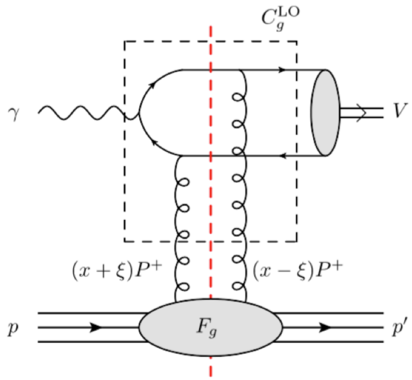
- With $\bar{Q}^2 = (Q^2 + M^2_{J/\psi})/4, \qquad x = (Q^2 + M^2_{J/\psi})/(W^2 + Q^2)$
  - Vector meson mass provides hard scale
- Some caveats
  - NLO calculations look very different
    - Less problematic as Q^2 rises
  - pQCD factorization is imperfect
    - Gluons have different x values (x' ≪ x ≪ 1)
      - Generalized (skewed) gluon distributions.
      - Can do exactly with Shuvaev transform
      - More natural to treat as GPD
  - Photon is not pure $q\bar{q}$ dipole
  - Choice of scale μ (especially in NLO)

Talk by
Chris Flett et al.



Jones, Martin, Ryskin and Teubner ("JMRT"), JHEP 1311, 085 (2013); K. Eskola et al., arXiv:2203.11613

The dipole approach



- Needed to incorporate transverse size into calculation
  - Important for nuclei
- Start with basics: $\sigma = |\langle\Psi_\gamma|M|\Psi_V\rangle|^2$
- Treat the $\bar{q}q$ pair as a dipole with size r
  - Need VM and photon wave functions, matrix element as f(r)
  - $\sigma \sim r^2$; r scales with 1/Q, but relationship is not simple
  - Different matrix elements for different nuclear models
    - pQCD, shadowing, colored glass condensate, etc.

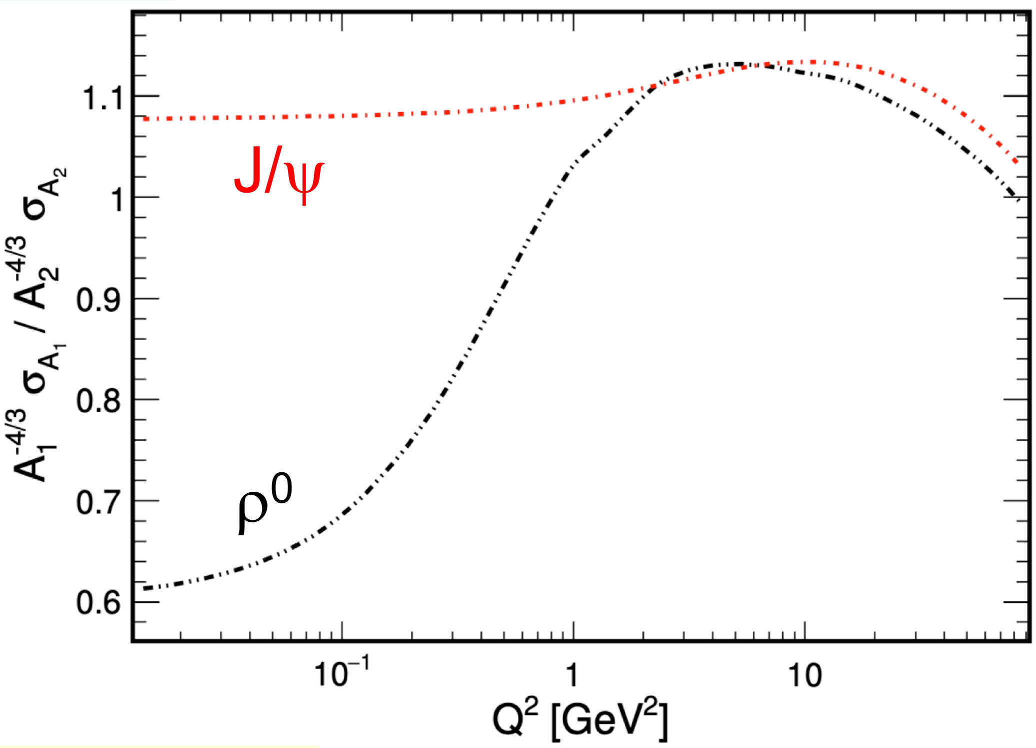
$$A(K,\Omega) = 2\mathrm{i}\int \mathrm{d}^2\mathbf{r}_T \frac{\mathrm{d}z}{4\pi}\mathrm{d}^2\mathbf{b}_T e^{-i\mathbf{b}_T\cdot\mathbf{k}_T/\hbar} \times \Psi^*(\mathbf{r}_T,z,Q^2)\Psi_V(\mathbf{r}_T,z,Q^2)N_\Omega(\mathbf{r}_T,\mathbf{b}_T)$$

- Dipole approach allows impact-parameter dependent calculations
  - Can calculate $d\sigma/dt$ for different nuclear conditions
    - Different effective target shapes at different x,Q^2

Exclusive production, gluon shadowing & hotspots

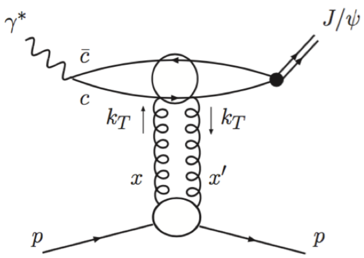
- The EIC will study γ^*p, A -> V p,A over full range of
  - Bjorken-x
  - Q^2 - saturation is most visible at low Q^2 region!
  - Transverse and longitudinal polarization
  - A wide range of vector mesons, and photons for DVCS

Scaled cross-section wrt no shadowing

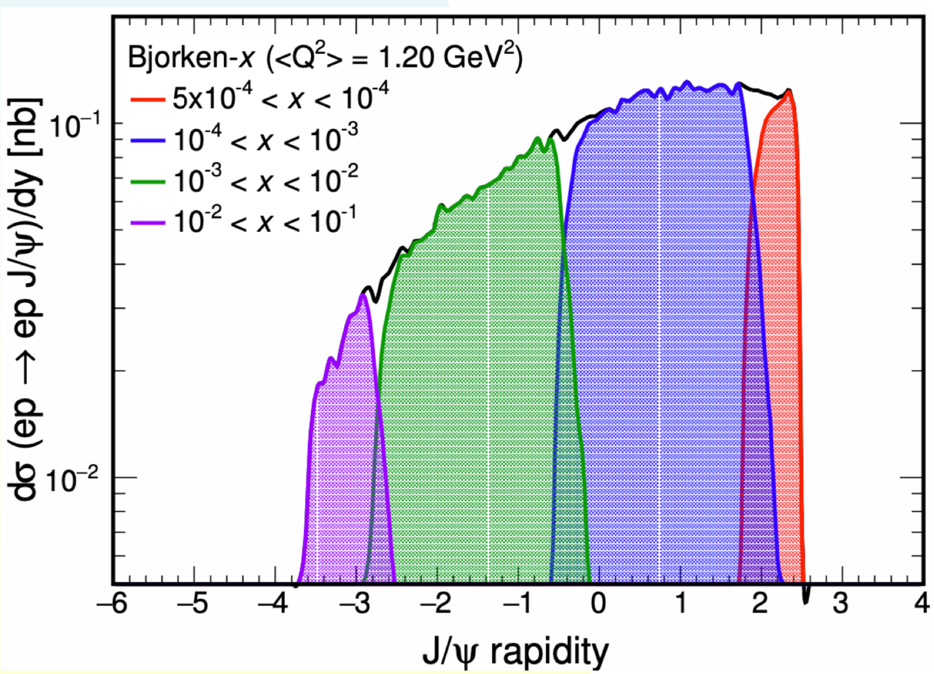


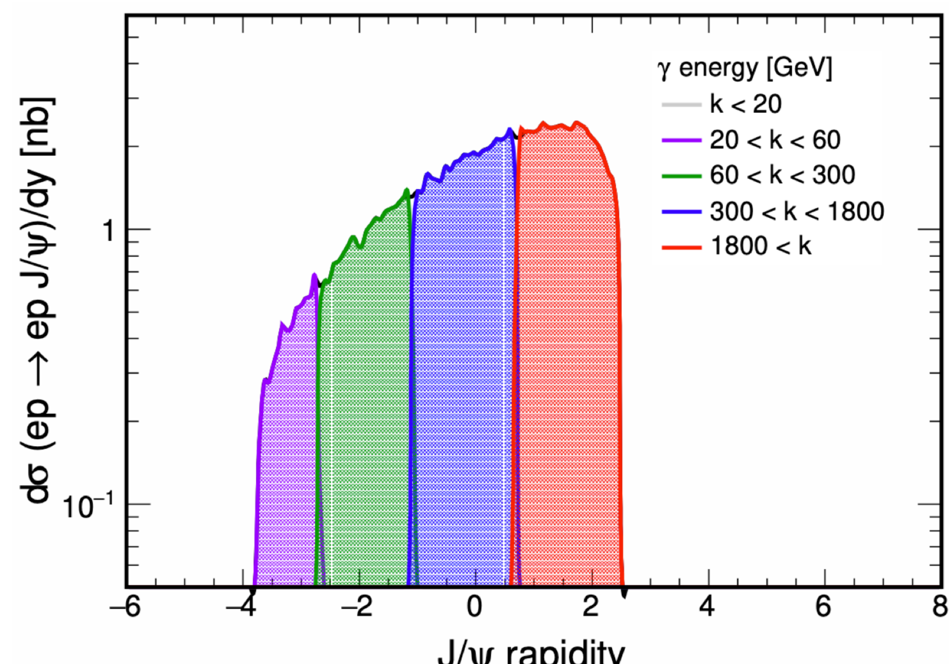
SK and M. Lomnitz, Phys. Rev. C99, 015203 (2018)

Coherent production – practical aspects



- Bjorken-x is mapped from rapidity:
  - $x = M_F/2\gamma_P Mp \exp(y)$
    - M_F = final state mass, γ_p = ion Lorentz boost, and M_p = proton mass
    - Modified for photons with high Q^2
- Broad coverage in Bjorken-x requires broad coverage in rapidity





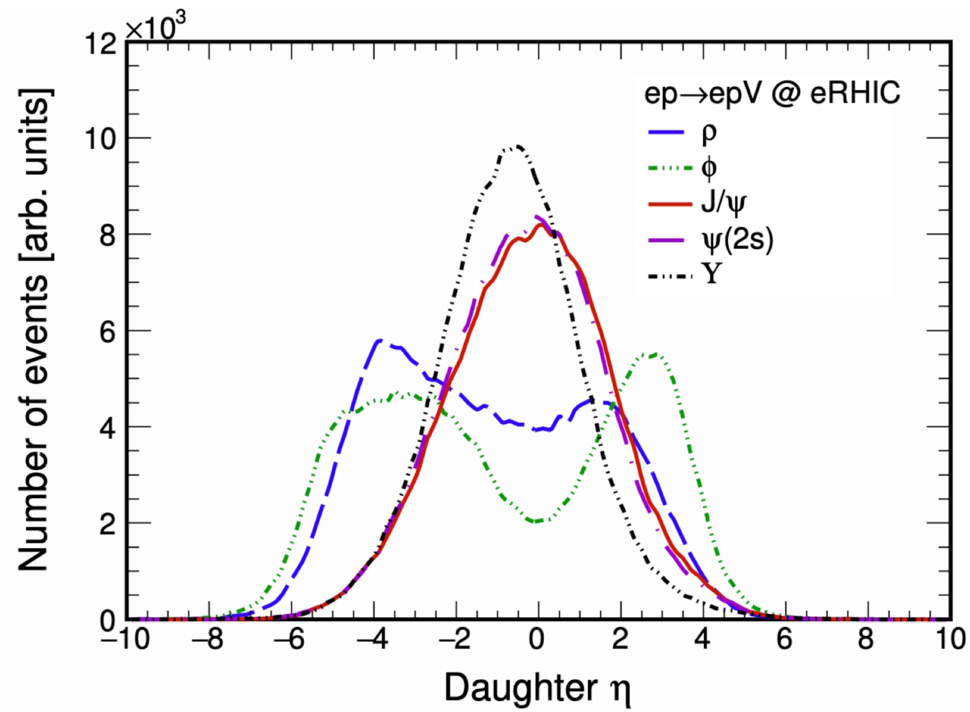
(Flipped Rapidity Convention)

M. Lomnitz & SK, eSTARlight, Phys. Rev. C**99**, 015203 (2019)

Coherent VM production in ATHENA: x, Q^2 range

- x depends on rapidity range of central tracker
- Roughly, tracking a vector meson out to rapidity $|y_{max}|$ with good efficiency requires tracking daughters out to $|\eta_{max}| = |y_{max}| + 1$
  - Not fully satisfied in any EIC detector
  - Loss of efficiency for x~1 or $x \sim x_{minimum}$
- Rapidity distribution depends on decay Clebsch-Gordon coefficients

M. Lomnitz & SK, eSTARlight, Phys. Rev. C**99**, 015203 (2019)



Beyond gluon densities: to spatial distribution 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

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

Good-Walker and transverse interaction profiles

- The coherent cross-section gives us access to the transverse spatial distribution of individual targets within the nucleus

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

Average amplitudes (Ω)

- We can also write $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
  - Usually work with $t = p_T^2 + p_z^2 \sim p_T^2$
- Because of exponential $d\sigma/dp_T$ encodes information about the transverse locations of the interactions
  - without shadowing, this is the shape of the nucleus
- The two-dimensional Fourier transform of $d\sigma/dt$ gives F(b), the transverse distribution of targets

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

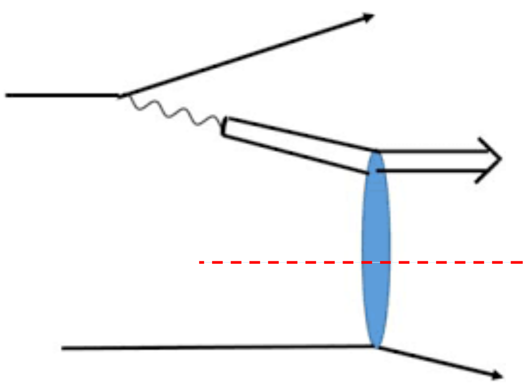
*flips sign after each diffractive minimum

- Multiple serious caveats – range of integration/ windowing finding diffractive minima, subtracting out photon p_T etc.

Experimental aspects of imaging

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

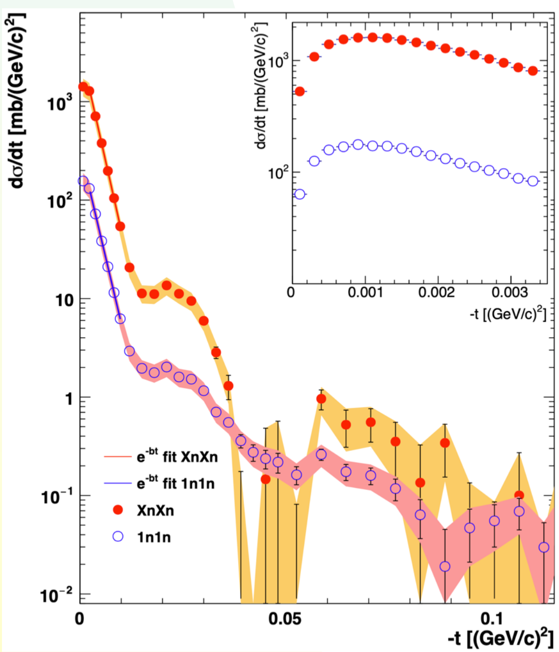
- This integral goes from 0 to infinity, but data has a maximum p_T
  - This introduces a 'window' (box) from 0 to p_{Tmax}, which is unavoidable convoluted with the signal
  - Need to go to large p_T to minimize windowing
    - ~ to the third minimum
- Find t via scattered p/ion, or e + hadrons
  - Scattered ion only visible for protons/light ions



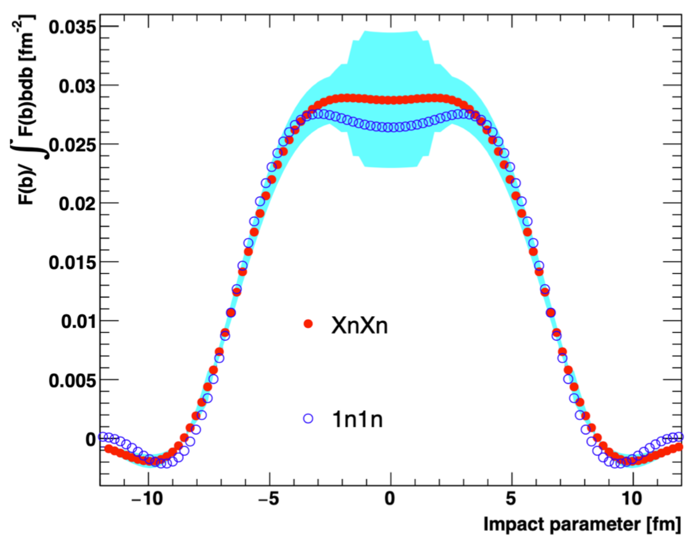
- Need to remove resolution via deconvolution
  - Including beam energy & momentum spreads
    - Most important when electron energy loss is small
- Need to account for photon polarization as function of Q^2, and correlation between photon p_T and decay product p_T
  - s-channel helicity conservation: vector meson retains γ polarization

The STAR ρ^0 analysis

- 384,000 dipion events
- Fit $d\sigma_{incoherent}/dt$ in region of large |t| with a dipole form factor, extrapolate and subtract, leaving $d\sigma_{coherent}/dt$
  - Diffractive minima are visible
- 2-d Fourier tranform
- Blue band shows effect of varying $|t|_{max}$ from 0.05 - 0.09 GeV^2
  - Variation at small |b| may be due to windowing (finite t range)
  - Negative wings at large |b| are likely from interference



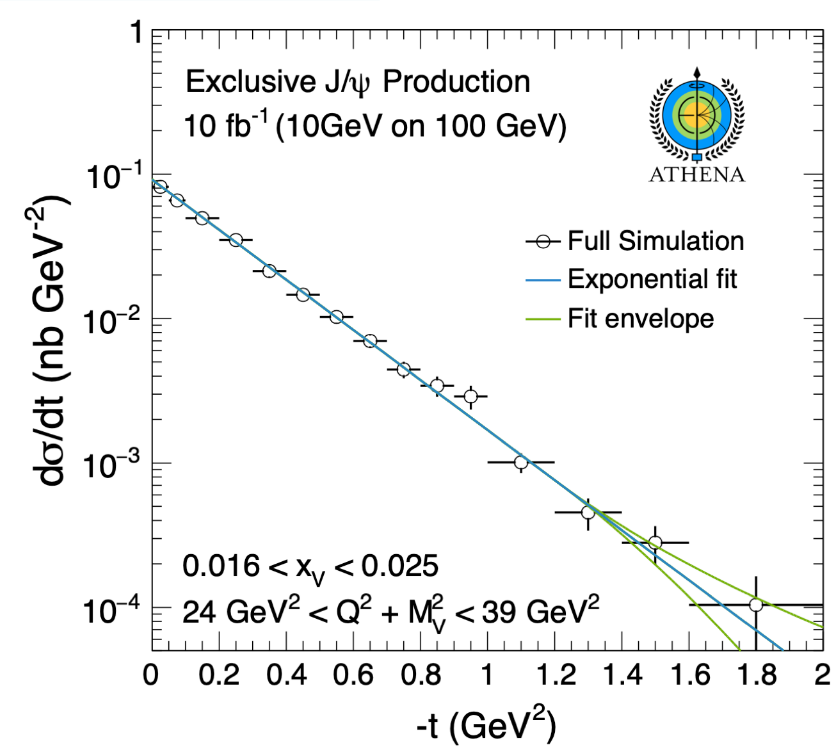
Fourier Transform

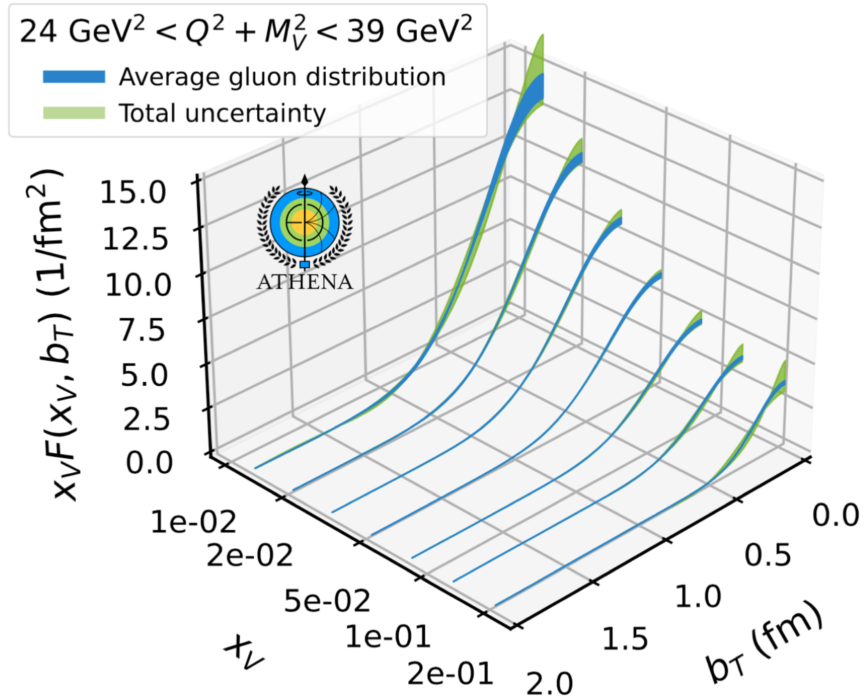


STAR, Phys. Rev. C**96**, 054904 (2017)

ATHENA gluon tomography of the proton using coherent J/ψ production

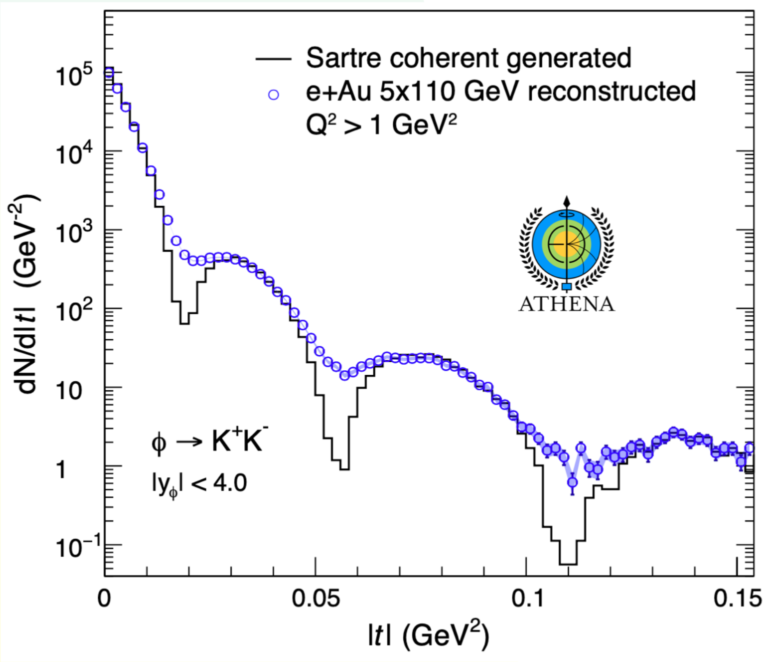
- In ep, so t comes from scattered proton
- Gluon distribution is Fourier transform of $d\sigma/dt$

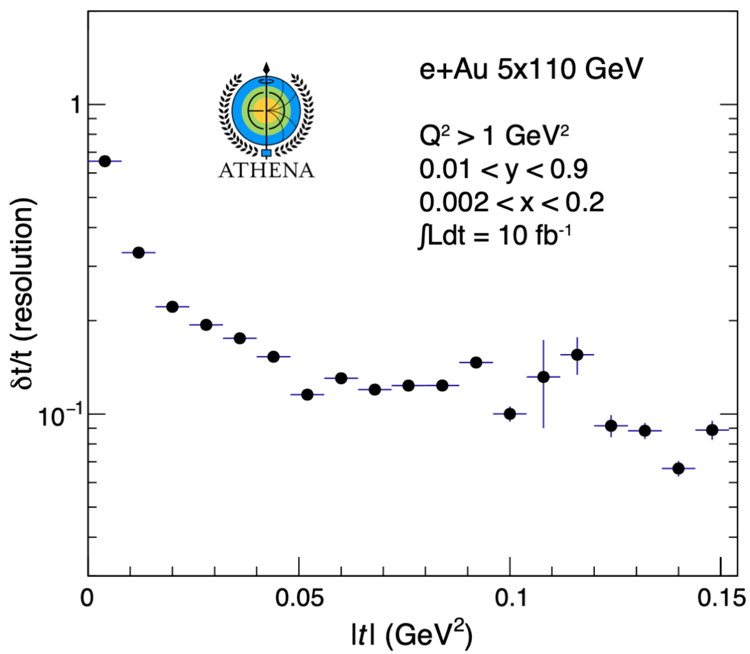




Low-x ϕ production in eA

- Must reconstruct t using scattered electron + ϕ
  - Difference between two large numbers
    - Initial electron momentum, with beam spread
    - Scattered electron momentum
- Good resolution at lower electron energy
- Tradeoff between narrower x range and good t resolution
  - Large Q^2 helps, so electron is at smaller |y|





Incoherent production and event-by-event fluctuations

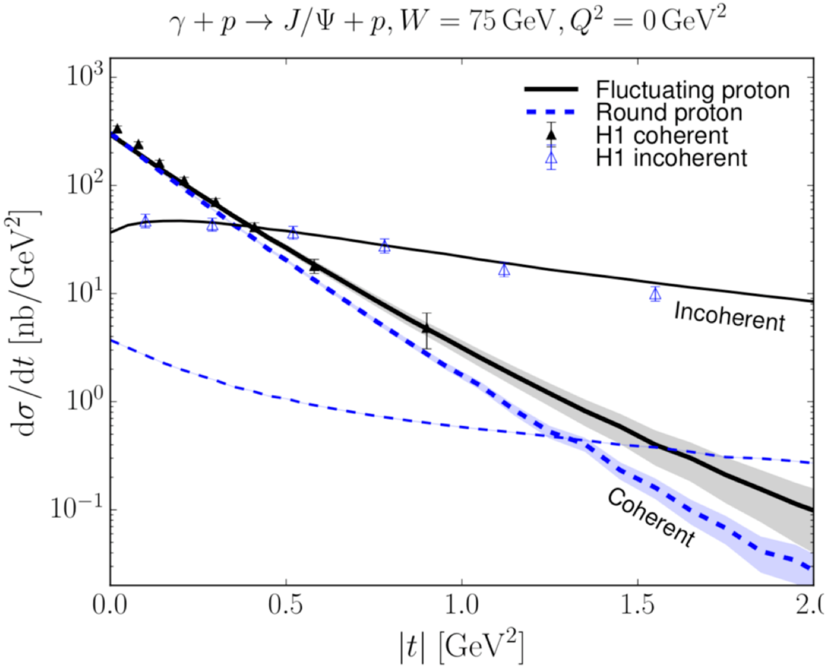
- The incoherent cross-section lets us measure the event-by-event fluctuations in the nuclear configuration, including the positions of individual nucleons, gluonic hot spots, etc.

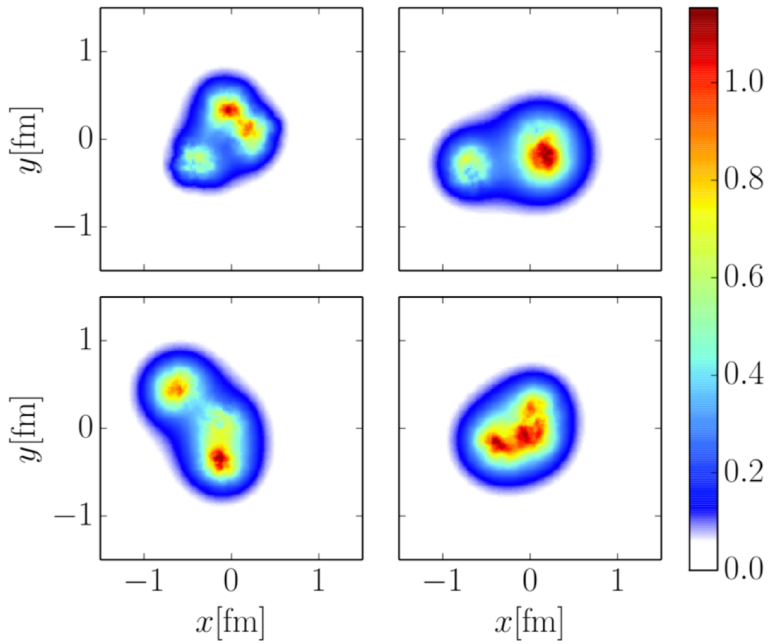
$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle \left| A(K,\Omega) \right|^2 \right\rangle - \left| \left\langle A(K,\Omega) \right\rangle \right|^2 \right)$$

- Probes the deviations from the mean.
- The connection between t and impact parameter is weaker than with coherent production, but this can be used to test models.

$\gamma^*p \to J/\psi$ at HERA and gluonic hot spots

- HERA data provides an application of the Good-Walker formalism



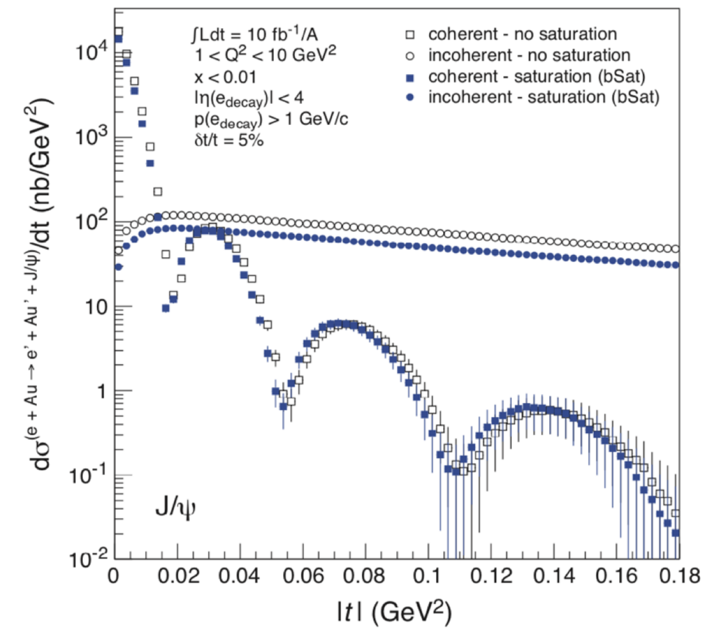


- The proton is far from smooth. It contains gluonic hot spots (or other fluctuations)
- The EIC will map this behavior in x, Q^2, and should apply it to nuclei

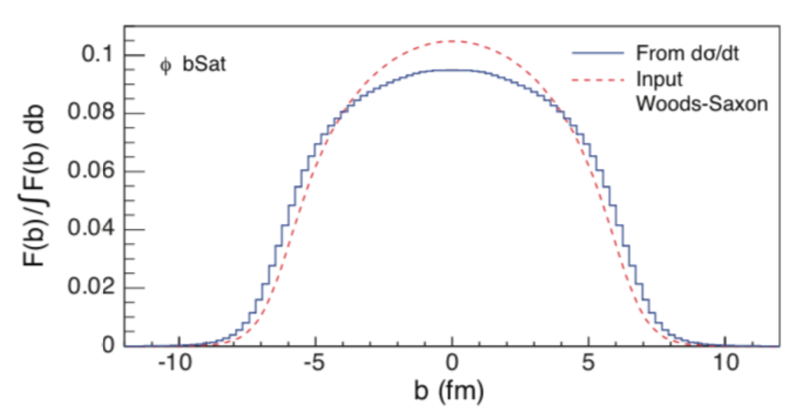
Mantysaari and Schenk, PRD **94**, 034042 (2016)

How good a coherent/incoherent separation is needed?

- Wide |t| range required for coherent photoproduction to measure GPDs
  - Parton distributions as a function of transverse position within the nucleus
  - Fourier transform $d\sigma/dt$ to F(b)
  - Accurate Fourier transform requires $0 < |t| < \sim 0.18$ GeV^2 range for eAu
- Need ~500:1 rejection of incoherent production to observe coherent production with $|t| > \sim 0.1$ GeV^2
- Need 100:1 rejection of coherent production to observe incoherent production at small |t|



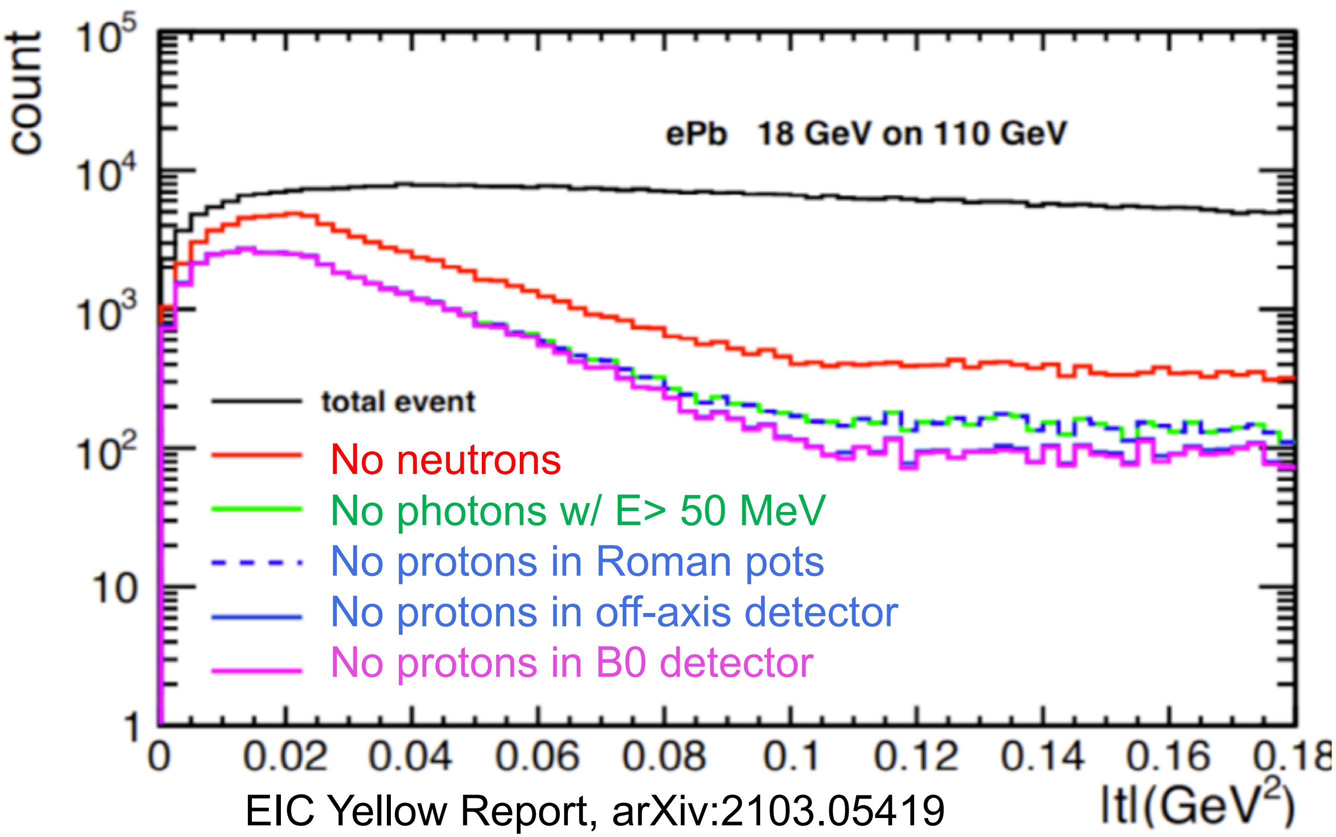
Fourier Transform



Discussed in Yellow Report; Plots from EIC White Paper

Separating coherent and incoherent production with heavy ion targets

- Nuclear breakup via neutron, proton or photon emission
  - Mixture depends on t, since nucleon emission reactions are exothermic
  - Significant theoretical uncertainties in branching ratios



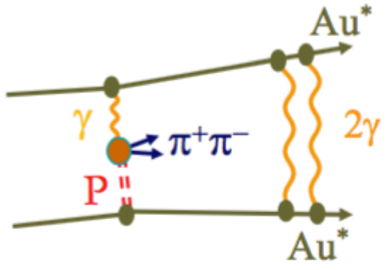
EIC Yellow Report, arXiv:2103.05419

Detecting photonic deexcitation

- For excitation energy < 1-5 MeV, the final state is well defined
  - Shell model state with fixed energy, spin, parity
- Relationship between E and t depends on mass of recoiling state
  - STAR ρ^0 photoproduction data supports single-nucleon recoil fits
    - Fit is in range 0.45 $GeV^2 > t > 0.2$ GeV^2
- Lab-frame energy depends on Lorentz boost & angle
- For ^{208}Pb, the lowest lying excited state is at 2.6 MeV
  - Incoherent production impossible below this threshold
  - $J^\pi=3^-$, so production is marginal, due to angular momentum
  - In the single nucleon paradigm (questionable here), with maximum boost, p_{min} ~ 70 MeV/c, t_{min} ~ 0.005 GeV^2
- For ^{197}Au, the lowest lying excited state is at 77 keV
  - τ=1.9 nsec, so the excited nucleus escapes the detector
  - Next lowest states are at 269 keV and 279 keV
- Lead is preferred for coherent production studies

Cautions, questions and caveats

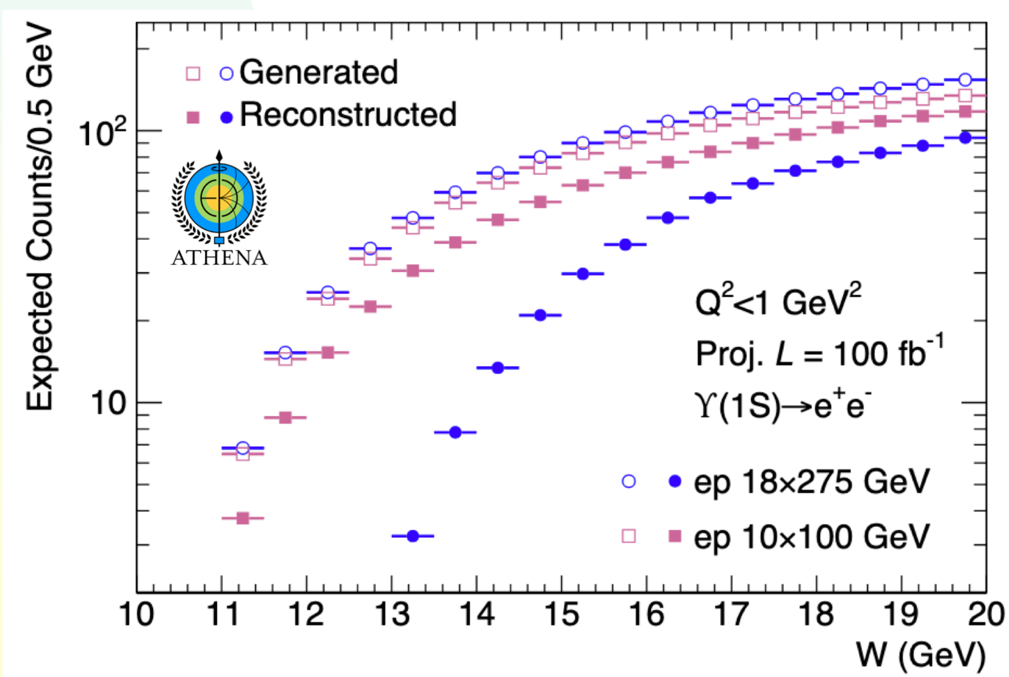
- Breakup into A>1 fragments is possible, but probably unlikely
- Can a recoiling nucleon emit bremsstrahlung γ w/o breakup?
  - eA->eVγA
    - Rate is probably low
- What are the real requirements for coherence?
  - Same initial and final state, per Good-Walker
  - $\sigma = | \Sigma_i A_i \exp(ikx)|^2$
    - AA->A*A* V (ρ, ρ', J/ψ) still exhibits coherence
    - There must be more to the Good-Walker coherence requirements
- Strictly speaking, Good-Walker applies only for stable final states.



Miettinen and Pumplin, Phys. Rev. Lett. 42, 204 (1979).
Caneschi and Schwimmer, Nucl. Phys. **B133**, 408 (1978).

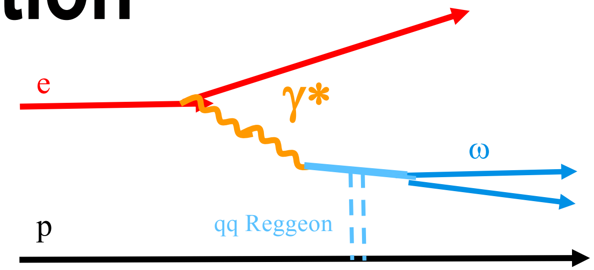
Example: near-threshold Υ

- At full beam energy (18 x 275 GeV^2), near-threshold U production is at/beyond the edge of the detector acceptance
- Solution: run at lower beam energy (10 x100 GeV^2), which shifts the threshold to near mid-rapidity
  - Total Υ rate is much lower, but the near-threshold rates are the same
  - Unfortunately, this does not work at low x

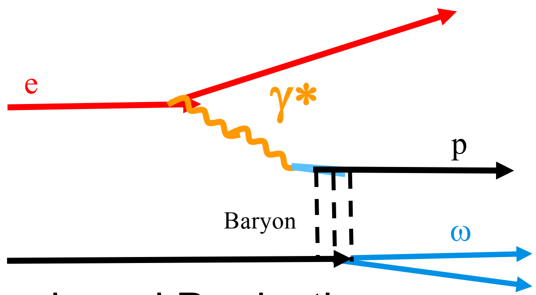


Backward (u-channel) J/ψ production

- t is large and u is small
  - In γp center-of-mass frame, meson and proton switch places
  - The meson is far-forward, while the proton is at mid-rapidity
- Studied at fixed target accelerators
  - Only light mesons
    - Proton and meson share quark flavors
- Production models using Transition Distribution Amplitudes (TDA, like GPDs) or Regge trajectories involving baryons
  - Regge model like models of baryon stopping in heavy-ion collisions
- Cross-section parameterized for the ω
  - For ω, $d\sigma/du \sim 4.4\ \mu b/GeV^2\ (s/1GeV)^{-2.7} \exp(-21\ GeV^{-2}u)$
  - At EIC, backward ω rate is ~ 1/300 of forward ω rate
    - J/ψ rate 1,000-10,000 times lower????
      - If so, backward J/ψ are accessible



Forward Production



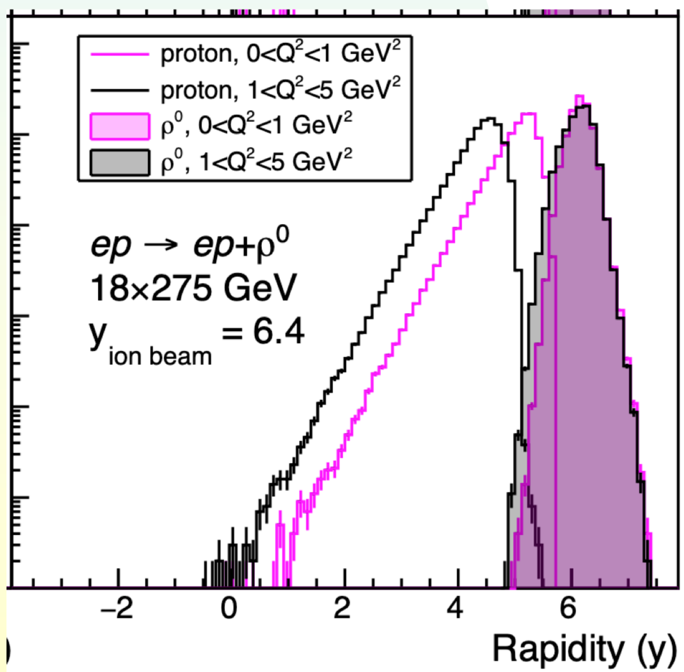
Backward Production

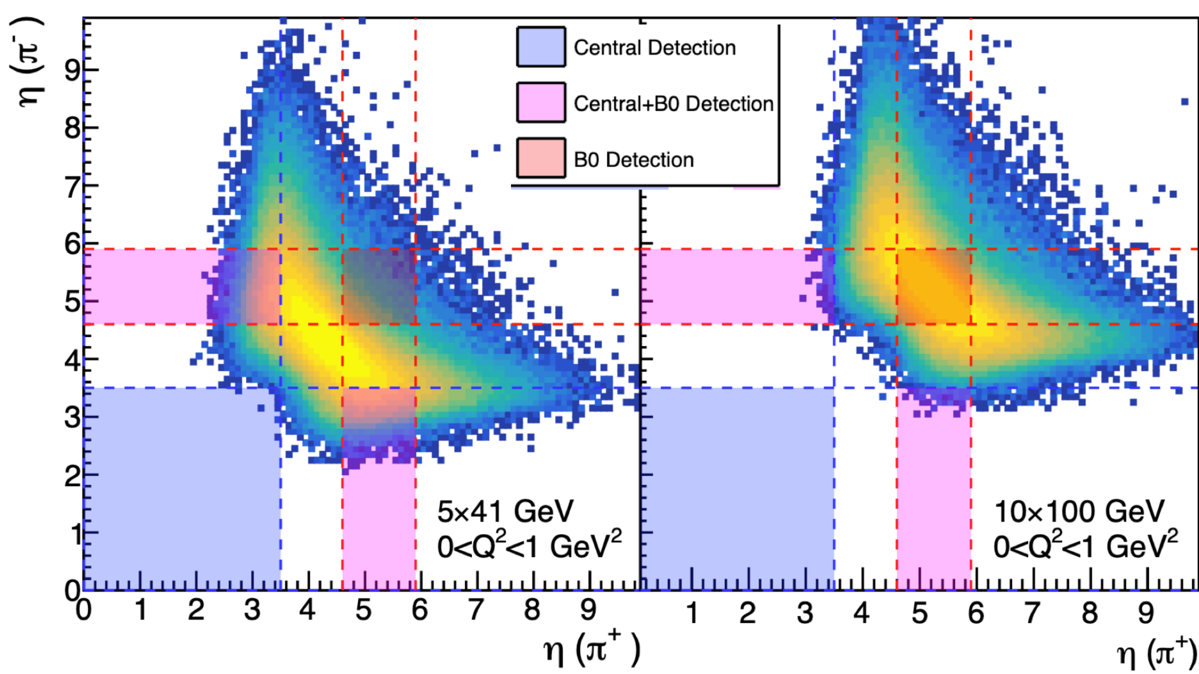
C. Ayerbe Gayoso et al., arXiv:2107.06748; D. Cebra et al. . arXiv:2204.07915

Kinematics of backward production at the EIC

- Forward vector meson + mid-rapidity proton (+ electron for $Q^2>0$)
- Proton near mid-rapidity (baryon stopping)
- Meson decay products in forward region
  - Shifts to lower y by reducing beam energy
    - For some final states, optimal detection at lower energies
    - Shifts to lower y for heavier final state mesons (e. g. ϕ, J/ψ)
  - Detection in combination of central detector, B0 magnet spectrometer and zero degree calorimeter
  - B0 and central detector

D. Cebra et al. arXiv:2204.07915





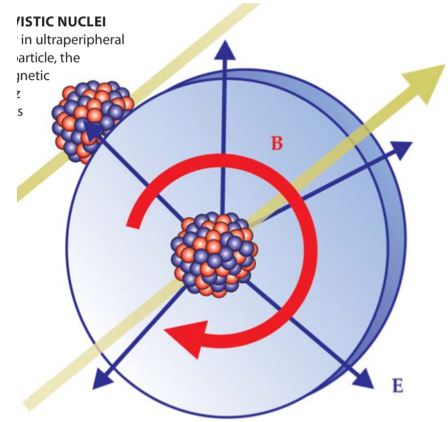
Conclusions

- Photoproduction is a key tool to study partons in dense nuclear environments
- The EIC will open an era of systematic, precision measurements on a variety of ion targets
- Photoproduction of open charm and dijets are theoretically fairly clean, but messy experimentally.
- Photoproduction of light and heavy quarkonium is mostly experimentally straightforward
  - low Q^2 ϕ phi are exceptions
- By measuring $d\sigma/dt$ for coherent production, we can image the targets in protons and nuclei
- By studying $d\sigma/dt$ for incoherent production, we can study gluonic hot-spots and other event-by-event variations
- Measuring t with good enough resolution will be a challenge
- More work is needed on separation of coherent and incoherent interactions

Backup

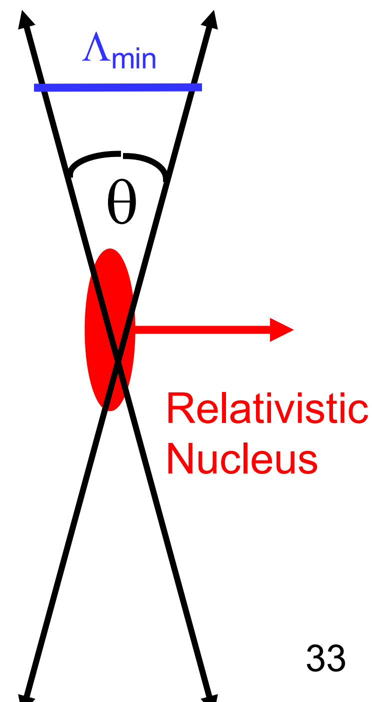
Photons from relativistic nuclei

- Perpendicular E and B fields -> just like a photon field
  - Fourier transform E(x,b)-> E(k,b) and quantize
  - Equivalent photon approximation
- Pancaked E & M fields: opening angle $\theta=1/\gamma$
- $k_{max} = c/\lambda_{max} = \gamma$ hbar c/b



$$N(k,b) = \frac{Z^2 \alpha k^2}{\pi^2 \gamma^2 \hbar^2 \beta^2} \left(K_1^2(x) + \frac{K_0^2(x)}{\gamma^2} \right)$$

  - $x=kb/\gamma$ hbar c
    - $x<1$: $N \sim K_1^2(x) \sim 1/x^2$
    - $x > 1$: N is exponentially suppressed
    - Note: $1/b^2$ dependence
- Integrate over d^2b: with $b>2R_A$ (no nuclear collision)



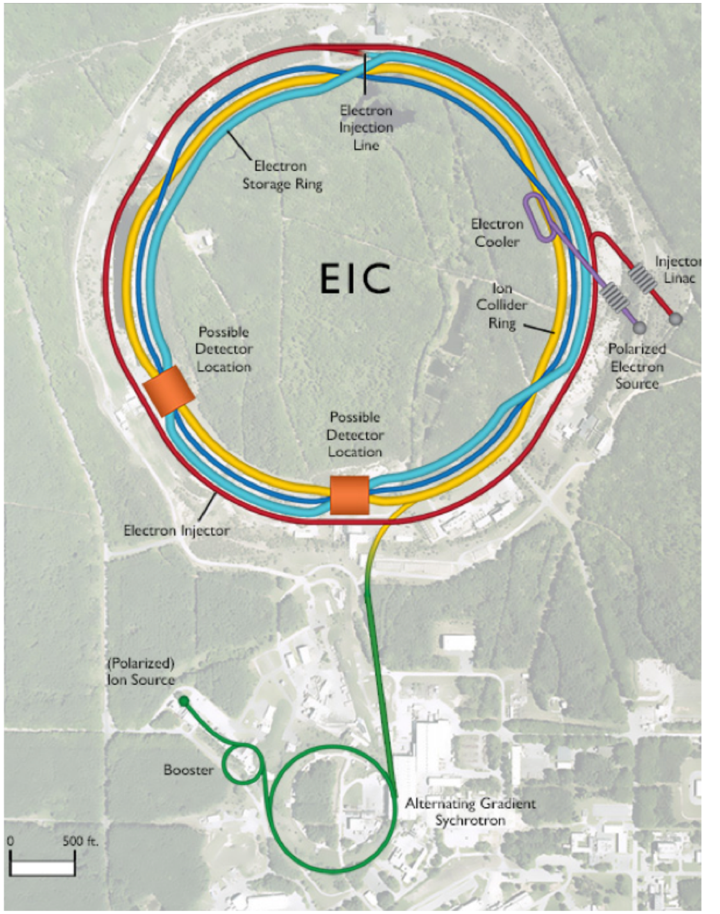
$$N(k) = \frac{Z^2 \alpha k^2}{\pi^2 \gamma^2 \hbar^2 \beta^2} \left(K_1^2(u) + \frac{K_0^2(u)}{\gamma^2} \right)$$

  - $u= \gamma$ hbar $c/2R_A$

Fermi, Weizsacker, Williams…

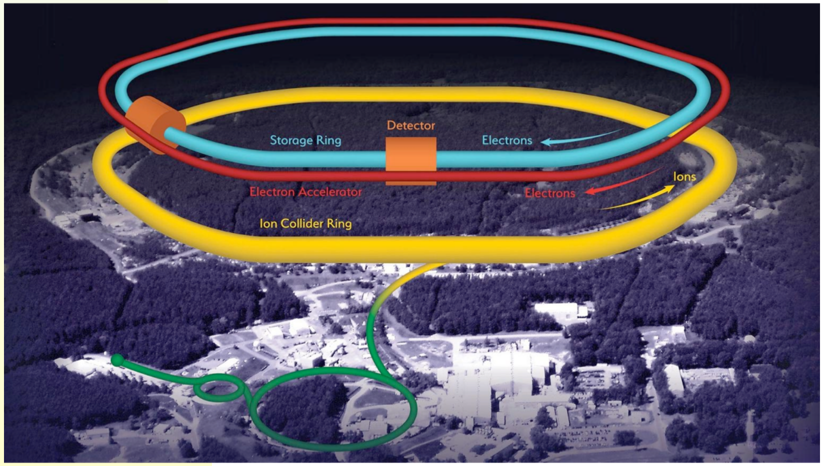
The electron-ion collider

- Add an 18 GeV electron ring to the RHIC complex
- Augmented ion ring
  - 275 GeV p, 110 GeV/n ions
  - Improve polarized source
- Coherent electron cooling to reduce emittance
- Very high luminosity ~ $10^{34}/cm^2/s$
  - Precision physics
- At least one detector
  - Full acceptance, with excellent forward and backward coverage
  - Collaboration forming now
- Completion in early 2030s



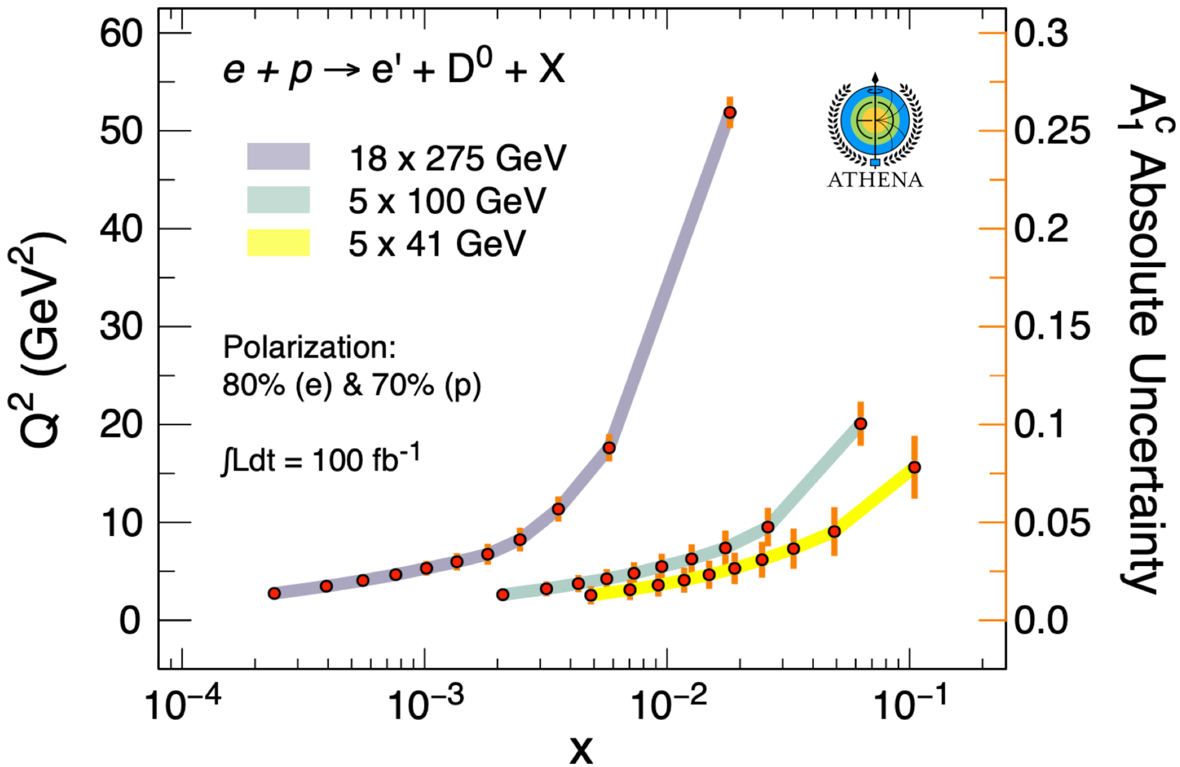
EIC detectors

- "Reference detector" developed in the EIC Yellow Report
- Three responses to 'Call for proposals' from EIC Project
  - ATHENA: all-new detector with a 3 T solenoid magnet
  - ECCE: reuse components where possible.
    - 1.5 T solenoid, from sPHENIX, or new
  - CORE: compact detector
- ECCE was preferred by review committee
- Currently forming a new 'Detector One' collaboration
  - ECCE is base design, but it will be optimized, and may incorporate elements from ATHENA or CORE



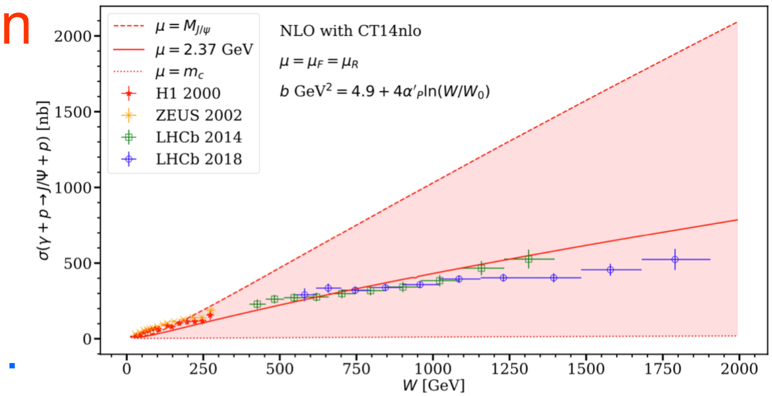
More direct access to the gluons

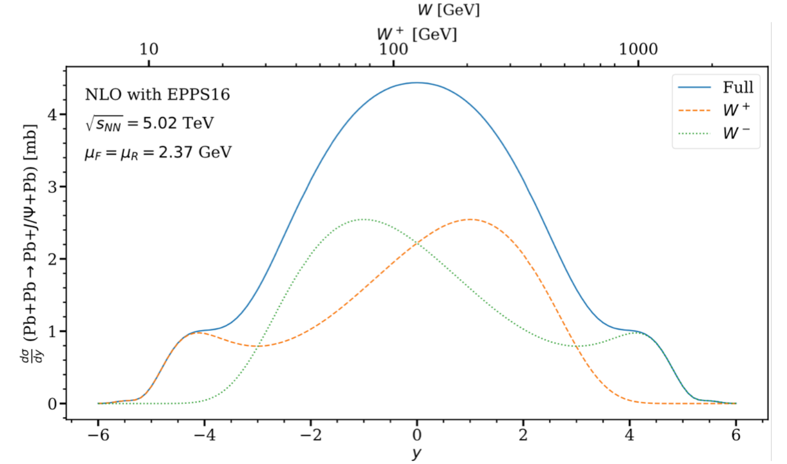
- Photoproduction of open charm and dijets
  - γ + g -> ccbar (or qqbar-> dijets)
    - Jets are tricky at low energy (i. e. low x)
- $Q^2 = Q^2_{photon} + Q^2_{pair} = Q^2_{photon} + (M_{finalstate}/2)^2$
- Polarized and unpolarized measurements in ep

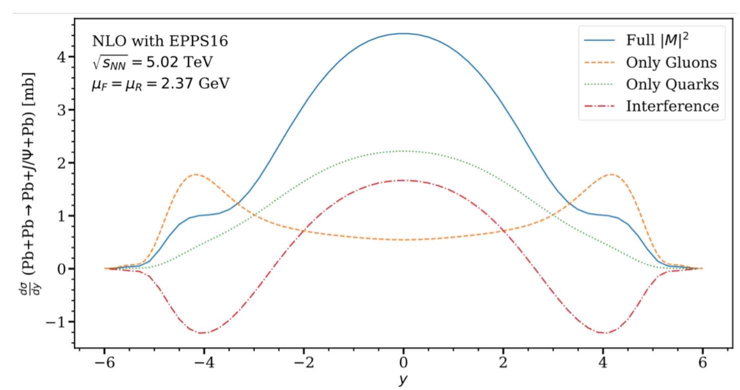


J/ψ photoproduction in NLO

- Some surprises in a new NLO calculation
- Very large scale uncertainty
  - Hope for reduction using some tricks
- σ_{NLO} ~55-70% below σ_{LO}
  - Previous LO calculations matched data…
- Multiple peaks in dσ/dy for UPCs
  - Note photon directional ambiguity
- NLO gluon contribution partly cancels LO gluon contribution
  - Quark contribution is important
- Different parton distribution fits give different results
  - Real part of gluon amplitude
- How well do uncertainties cancel when comparing proton and ion data?



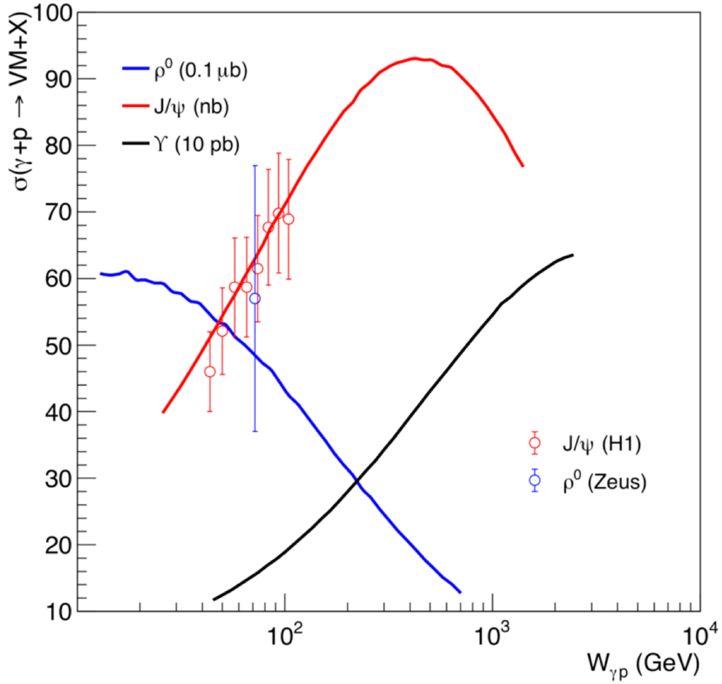




K. Eskola et al., arXiv:2203.11613

Strong saturation and the black disk limit

- Higher photon energies probe lower Bjorken-x values
  - Lower x values -> more gluons, more hotspots
  - The fraction of the proton or ion surface covered with hot spots rises
- Eventually, the whole surface is covered. This is the ‘black disk limit,’ when the nucleus acts like a totally absorptive disk
- Black disks don’t fluctuate, so incoherent photoproduction should disappear.
- High-mass final states require more energetic (larger x) gluons, so they will be slower to disappear
- Extension to nuclei model dependent



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

Vector meson rates in 10 fb^{-1}/A

Accelerator	σ					Number of events				
	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$
eRHIC - *ep*	5.0 μb	230.0 nb	8.5 nb	1.4 nb	14.0 pb	50 giga	2.3 giga	85 mega	14 mega	140 kilo
eRHIC - *eA*	870.0 μb	55.0 μb	1.9 μb	320.0 nb	1.2 nb	44 giga	2.8 giga	100 mega	16 mega	60 kilo
JLEIC - *ep*	3.7 μb	160.0 nb	3.9 nb	600.0 pb	4.3 pb	37 giga	1.6 giga	39 mega	6.0 mega	43 kilo
JLEIC - *eA*	580.0 μb	33.0 μb	590.0 nb	82.0 nb	-	28 giga	1.6 giga	28 mega	3.9 mega	-
LHeC - *ep*	10.0 μb	560.0 nb	47.0 nb	7.8 nb	120.0 pb	100 giga	5.6 giga	470 mega	78 mega	1.2 mega
LHeC - *eA*	2.3 mb	170.0 μb	15.0 μb	2.9 μb	41.0 nb	110 giga	8.2 giga	720 mega	140 mega	2.0 mega
HERA - *ep*	7.9 μb	450.0 nb	40.0 nb	6.4 nb	85.0 pb	-	-	-	-	-

TABLE III. The cross-sections and rates for VM photoproduction ($Q^2 < 1$ GeV^2) at the proposed EICs, and at HERA.

Accelerator	σ					Number of events				
	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$
eRHIC - *ep*	14.0 nb	1.7 nb	570.0 pb	120.0 pb	2.4 pb	140 mega	17 mega	5.7 mega	1.2 mega	24 kilo
eRHIC - *eA*	730.0 nb	110.0 nb	77.0 nb	19.0 nb	200.0 pb	37 mega	5.6 mega	3.9 mega	960 kilo	10 kilo
JLEIC - *ep*	10.0 nb	1.2 nb	270.0 pb	55.0 pb	790.0 fb	100.0 mega	12 mega	2.7 mega	550 kilo	7.9 kilo
JLEIC - *eA*	450.0 nb	67.0 nb	25.0 nb	5.1 nb	-	22 mega	3.2 mega	1.2 mega	250 kilo	-
LHeC - *ep*	26.0 nb	3.7 nb	2.9 nb	630.0 pb	18.0 pb	260 mega	37 mega	29 mega	6.3 mega	180 kilo
LHeC - *eA*	2.0 μb	340.0 nb	560.0 nb	150.0 nb	5.3 nb	100 mega	16 mega	27 mega	7.2 mega	250 kilo
HERA - *ep*	44.0 nb	6.4 nb	17.0 nb	3.6 nb	120.0 pb	-	-	-	-	-

TABLE IV. The cross-sections and rates for VM electroproduction ($Q^2 > 1$ GeV^2) at the proposed EICs and at HERA.

$\Upsilon(2S)$ $\Upsilon(3S)$ somewhat lower than $\Upsilon(1S)$

From eSTARlight; M. Lomnitz and SK, Phys. Rev. C99, 015203 (2019)

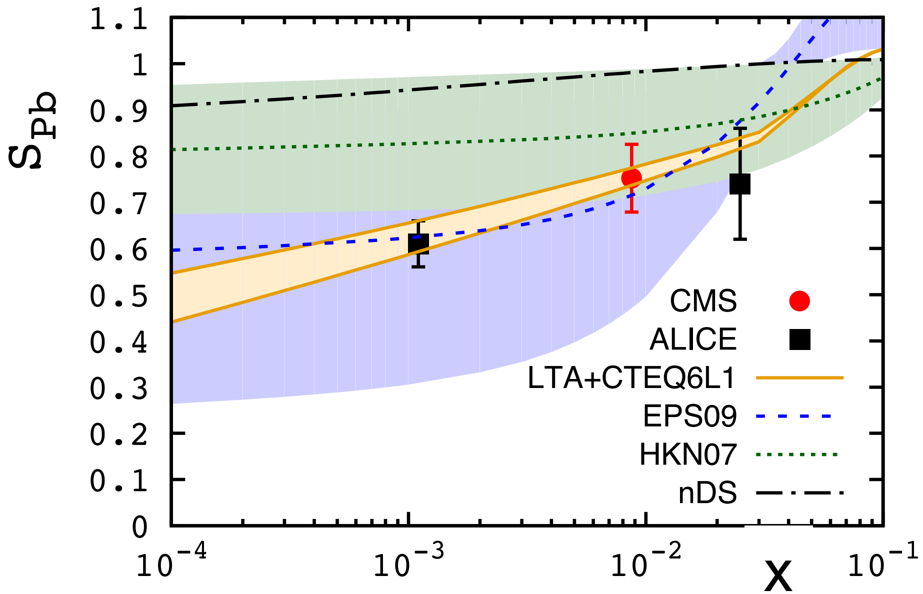
Models of Incoherent production

- BEAGLE
  - qqbar dipole scatters from a single nucleon, which recoils
  - Recoil causes an intra-nuclear cascade, leading to dissociation.
    - Microscopic model.
  - At low energies, photonic excitations may appear
  - nucleon-free fraction depends on |t|
    - Expected – nuclear breakup depends on available energy
  - Rejection < ~ 1/50 at large |t|
- Sartre
  - Similar dipole to BEAGLE
  - Nucleus diffractively dissociates, with fragments ~ $1/M^2$
  - Nuclear breakup is from the GEMINI++ intranuclear cascade code
- Large theoretical uncertainties from intranuclear cascades

M. D. Baker, https://wiki.bnl.gov/conferences/images/f/f7/ERD17-2020-06-plus.pdf
T. Toll and T. Ullrich, *Comput.Phys.Commun.* **185** (2014) 1835-1853

Nuclear Shadowing

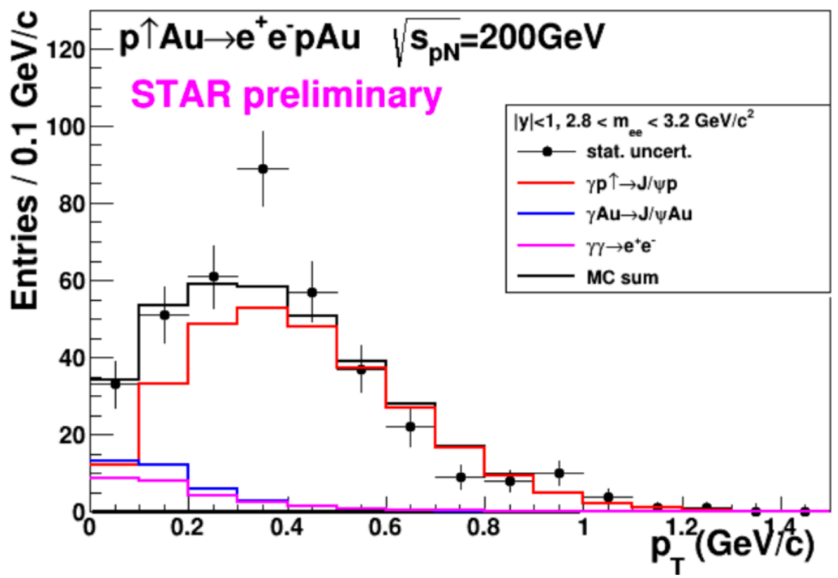
- Compare ALICE & CMS data with PDF shadowing models
  - Use impulse approximation for proton reference
    - Normalize to HERA data to correct for higher order terms
    - 6 different parton distributions
- Consistent w/ 2012 leading twist approximation calculation
  - Except for MNRT07 parameterization
- More shadowing than HKN07 parameterization
- EPS09 parameterization fits data well
  - Error bars should shrink
    - Also true w/ EPPS'16
- No need for exotica e. g.
  - Colored glass condensate
  - Hard saturation cutoff

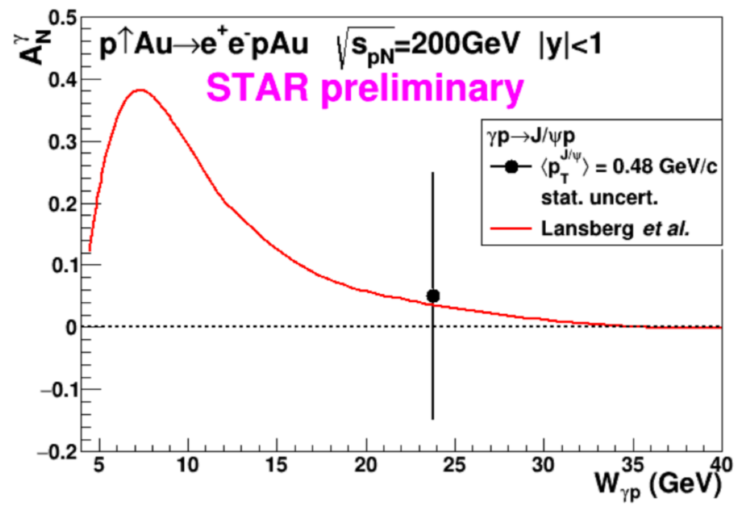


V. Guzey & M. Zhalov, JHEP 1310, 207 (2013)
Frankfurt Guzey & Strikman, Phys. Rept. 512, 255 (2012) updated by V. Guzey & M. Strikman.

Polarized J/ψ photoproduction at STAR

- Sensitive to polarized GPDs (generalized parton distributions), which probe the transverse position of partons with the nucleus
  - Is gluon polarization dependent on position within nucleus?
- From polarized p on Au collisions
  - Dominated by photon-from-gold
    - p_T cut improves separation
  - Polarized proton target
- Look at scattering asymmetries, which depends on $W_{\gamma p}$ and p_T
- 1st measurement; proof of principle

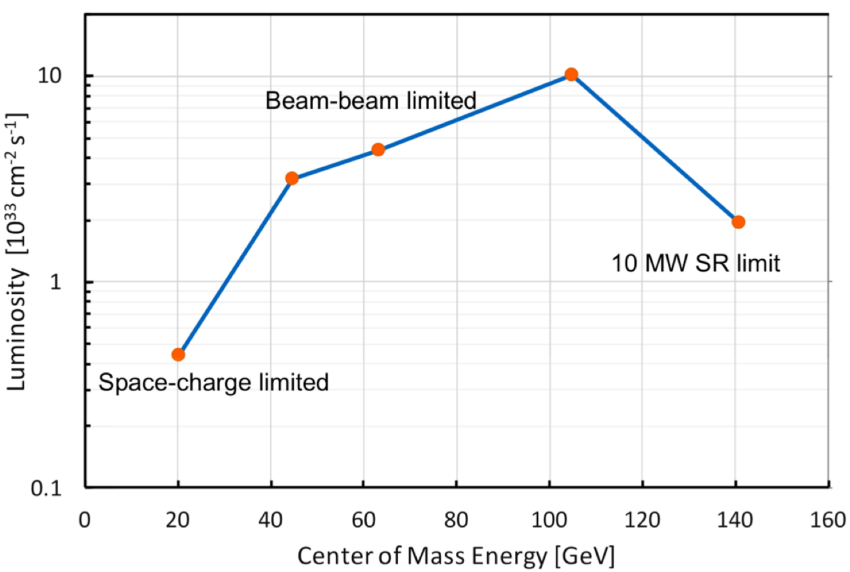


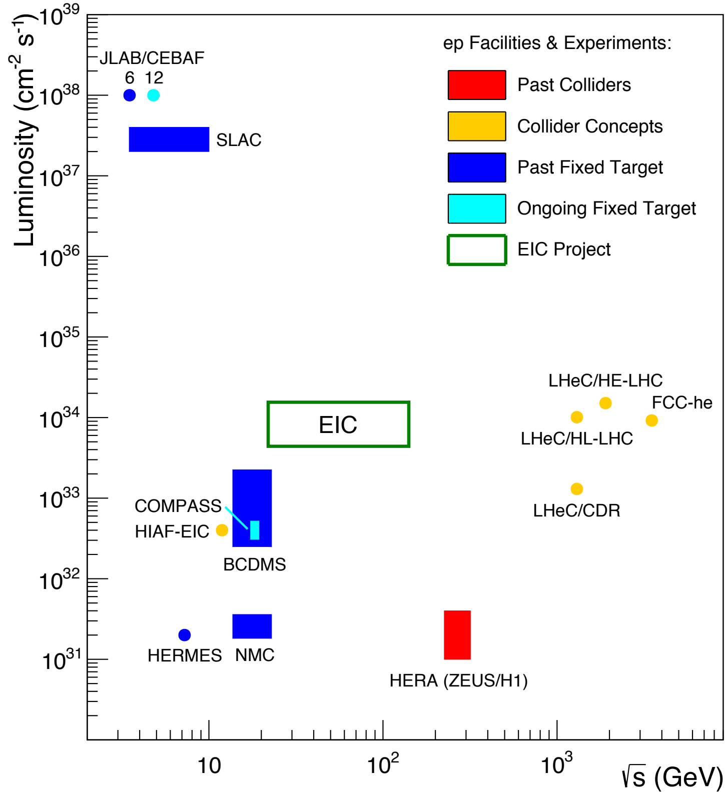


W. Schmidke [STAR], DPF 2019

EIC luminosity

- Luminosity 1000 times HERA
  - High currents required
  - $I_{electron}$=2.5 A
    - Max. 9 (or 10) MW synchrotron radiation limits $I_{electron}$ at high energies
      - Cost of cooling
  - I_{hadron} =1.0 A
- For ion beams, luminosity/nucleon is roughly constant

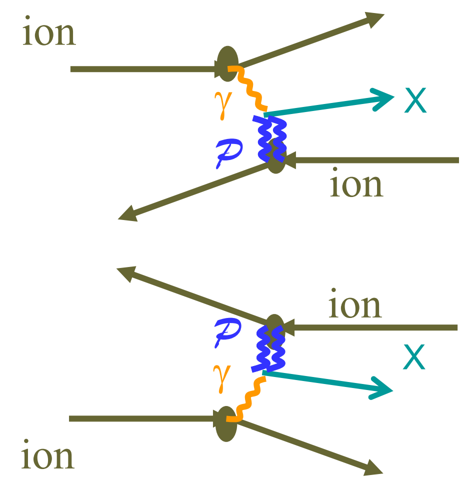




Trade energy for luminosity?

Different physics topics may hav different optimal energies

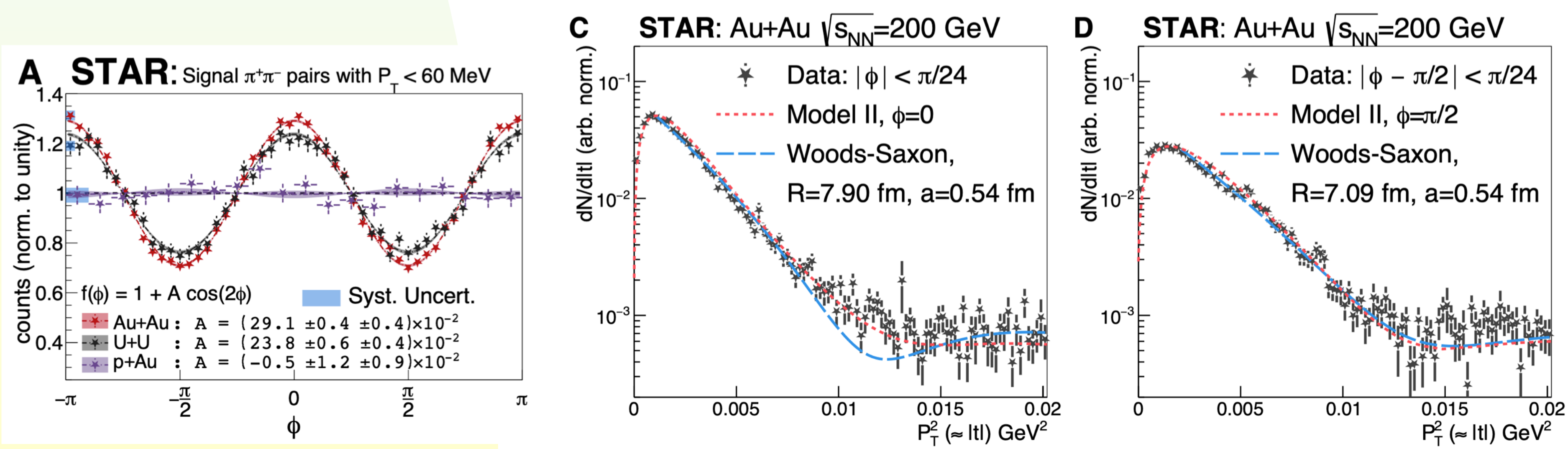
STAR fit to ρ^0 data



- Model includes photon p_T, ρ^0 scattering on target, and interference between the two γ directions
- Cross-section $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$
  - The vector meson is linearly polarized along b
    - π^+ and π^- p_T preferentially follow b
  - $e^{ip\cdot b}$ gives a correlation between the ρ^0 p_T & pion p_T
    - -> an angular modulation in p_T
- Model fits data well
  - Hadronic radii (w/ neutron skin) R_{Au}= 6.62±0.03 fm & R_U = 7.29±0.08 fm

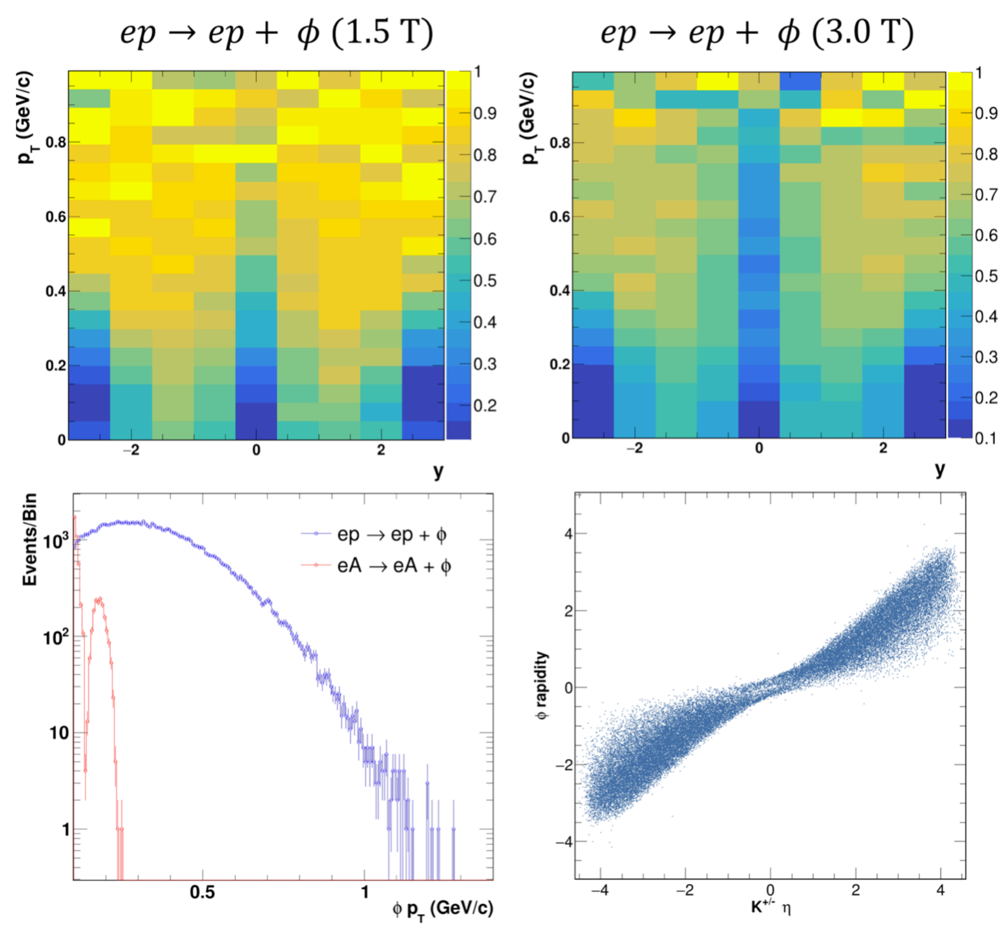
Precision UPC physics!

STAR, arXiv:2204.01625



Challenges in exclusive ϕ production

- ϕ was highlighted in EIC White Paper
- $K^{\pm}$ from ϕ decay have 135 MeV/c in ϕ rest frame
  - Other decay channels are impractical
- ϕ w/o longitudinal ($|y|>0$) or transverse (large Q^2) boost are hard to reconstruct
  - Limited range in x,Q^2 space
- Background from $\rho \to \pi^+\pi^-$
- The ρ is much easier
  - Usable for theory?



J. Arrington et al.
arXiv:2102.08337

An ATHENA-like silicon detector