Exclusive Quarkonium at the EIC – experimental aspects

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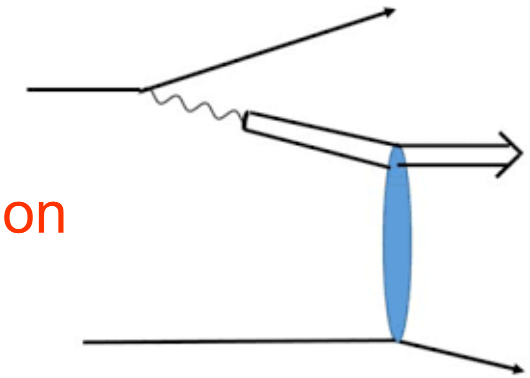
Presented at the Workshop on Physics Opportunities with Heavy Quarkonia at the EIC, CFNS, Oct. 25-27, 2021

- Introduction
- Exclusive vector mesons
- Going beyond vector mesons
- Separating coherent and incoherent production
- Conclusions



Physics from vector meson quarkonia

- Probes of nucleon/nuclear gluons
  - Shadowing, saturation colored glass condensate…
- Transverse distribution of gluons (GPDs)
  - The same, but with transverse information
- Event-by-event fluctuations (gluonic hot spots)
- Near-threshold production in ep
  - Gravitational form factor of proton?
  - Highest twist contributions to cross-section
  - Vp scattering length
- Near-threshold and sub-threshold production in eA
  - High Bjorken-x gluons
  - Nucleon correlations in nuclei

Cross-sections and shadowing measurements

- Measure cross-section for p, A over full range of
  - Bjorken-x
  - Q^2 - the low Q^2 region is also important!
  - Transverse and longitudinal polarization
  - Different mesons

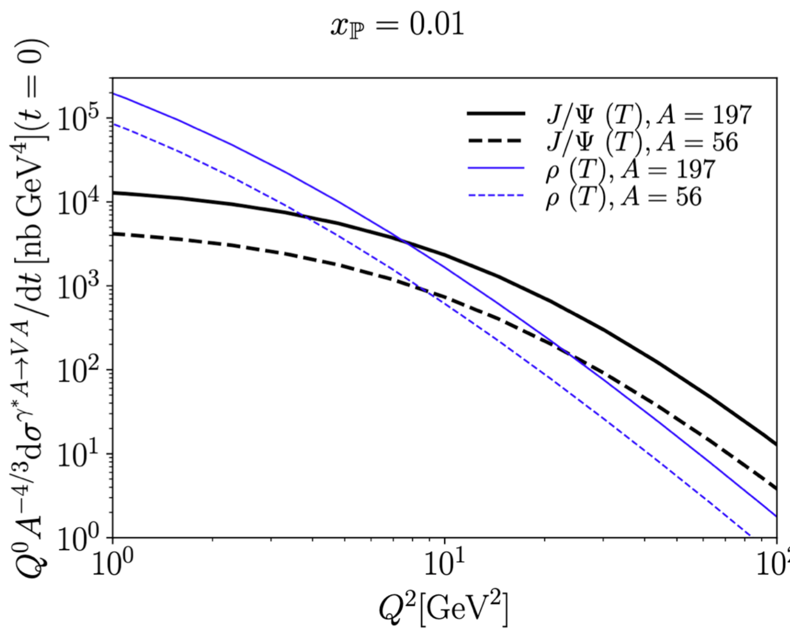


FIG. 6: The cross-section for coherent transverse vector meson production production at $t = 0$. It is Q^2 independent at low Q^2. The cross-section is scaled in A by the asymptotic analytical expectation $\approx A^{4/3}$.

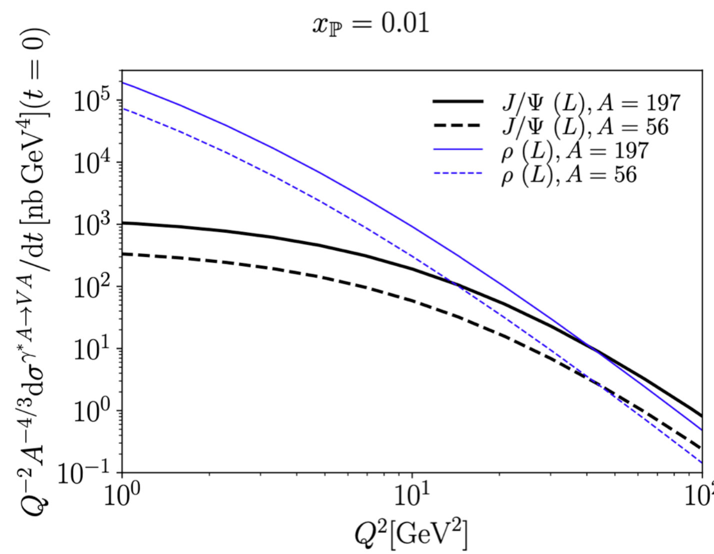


FIG. 5: The cross-section for coherent longitudinal vector meson production at $t = 0$. At low Q, the cross-section is flat at low Q^2 when scaled by Q^{-2}. For ρ, this behavior is only obtained at asymptotically small Q^2 values where our model is not applicable.The cross-section is scaled in A by the analytical asymptotical expectation $\approx A^{4/3}$. Our result here shows that the scaling is not exact for realistic kinematics.

H. Mantysaari and R. Venugopalan, Phys. Lett. B781, 664 (2018)

Experimental requirements for ep/A-> ep/AVX

- Most studied VM are 2-prong decays:
  - J/ψ, $\psi(2S)$, $\Upsilon(1S)\to l^+l^-$, $\Upsilon(2S)\to l^+l^-$, $\Upsilon(3S)\to l^+l^-$
  - $\rho\to\pi^+\pi^-$, $\Phi\to K^+K^-$
  - Higher Ψ and Υ are of interest, but have had much less attention
- Reconstruct full final state?
  - Can get by without electron at low Q^2
    - HERA shows this works
    - Scattered protons somewhat accessible; scatter heavy ions are not
      - Detection of light ions highly desirable, but difficult
- Acceptance to cover full Bjorken-x range
  - For photoproduction, photon energy $k = M_V/2 \exp(-y)$
  - $x_{BJ} = M_V/(2\gamma m_p) \exp(y)$; γ is ion Lorentz boost
    - For Υ, rapidity range is roughly $-3 < y < 3$
      - Threshold corresponds to $y \sim 3.1$
- Need to determine if the target nucleon/nucleus broke up

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	-	-	-	-	-

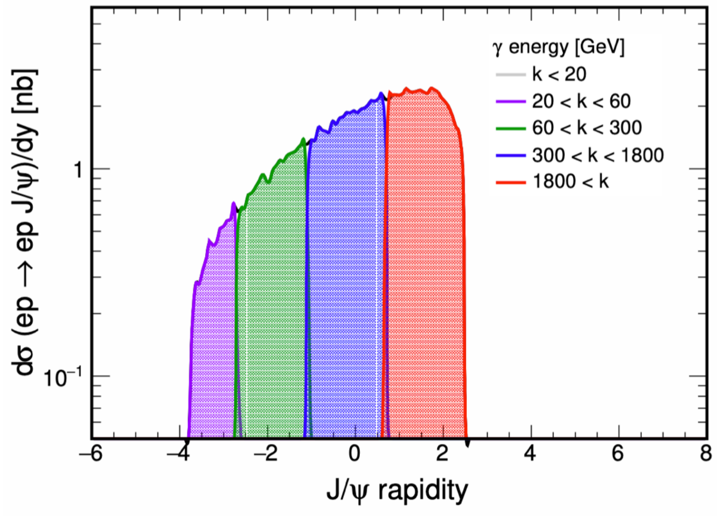
TABLE IV. The cross-sections and rates for VM electroproduction ($Q^2 > 1$ GeV^2) at the proposed EICs and at HERA.

Υ(2S) Υ(3S) somewhat lower than Υ(1S)

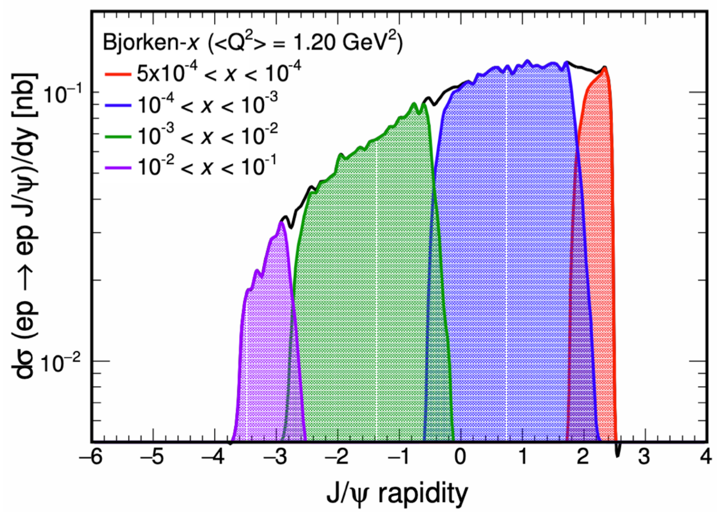
From eSTARlight; M. Lomnitz and SK, Phys. Rev. C99, 015203 (2019)

J/ψ rapidities

- Threshold: y ~ 4
- Full beam energy: y ~ -2.5



(a)



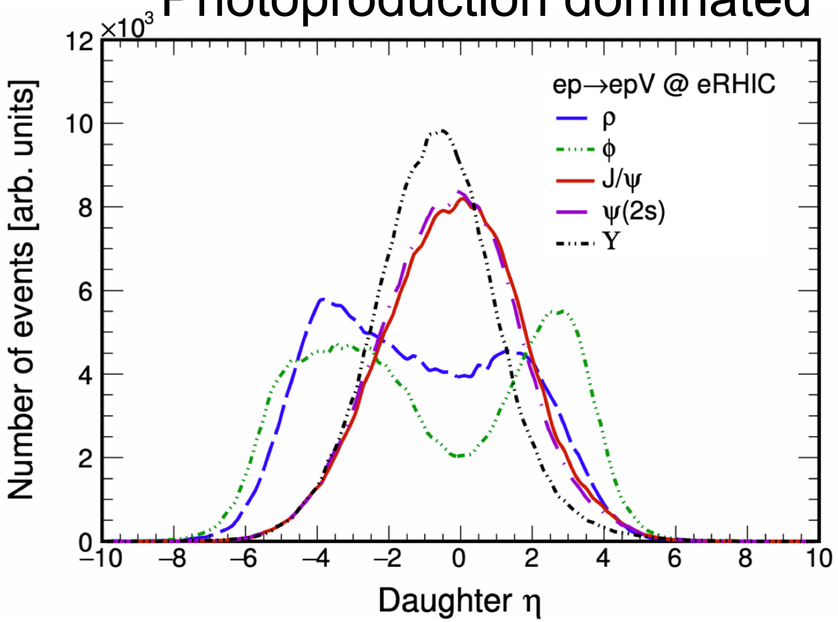
Flipped Rapidity

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

Parent rapidity and daughter pseudorapidity

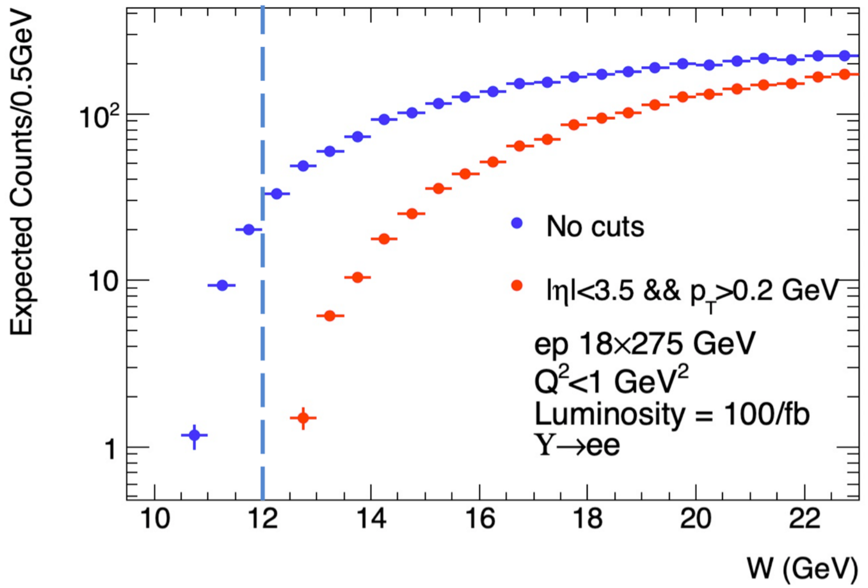
- Depends on Clebsch-Gordon Coefficients
  - VM-> 2 spin 0 mesons
  - VM -> 2 spin ½ leptons
    - Range of daughter leptons in η ~ range of parent y +1
- For J/ψ need to cover $|\eta|< \sim 4$
  - Beyond reach of proposed EIC detectors
- Detectors covering $|\eta|<3.5$
  - Cannot see lowest-x region
  - Cannot see threshold region at full beam energy
    - Accessible at lower energy

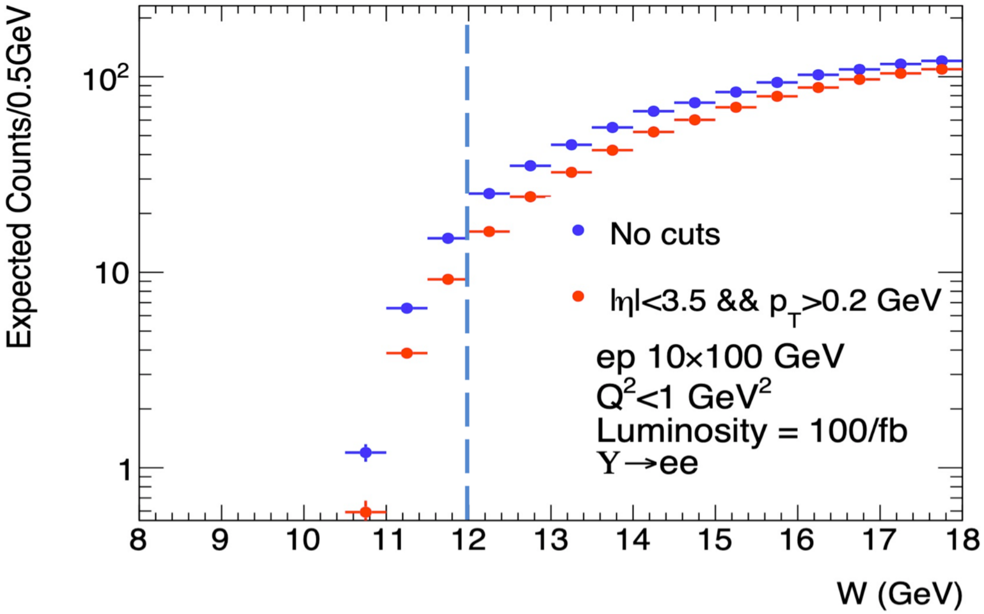
Photoproduction dominated



The Υ at threshold

- A detector covering |h|<3.5 is not fully efficient for the Υ in 18 x 275 GeV ep collisions
- We can 'shift' the threshold toward mid-rapidity by running at lower beam energies.
  - Nearly fully efficient for 10 x 100 GeV ep collisions
    - No similar trick for the low-x region

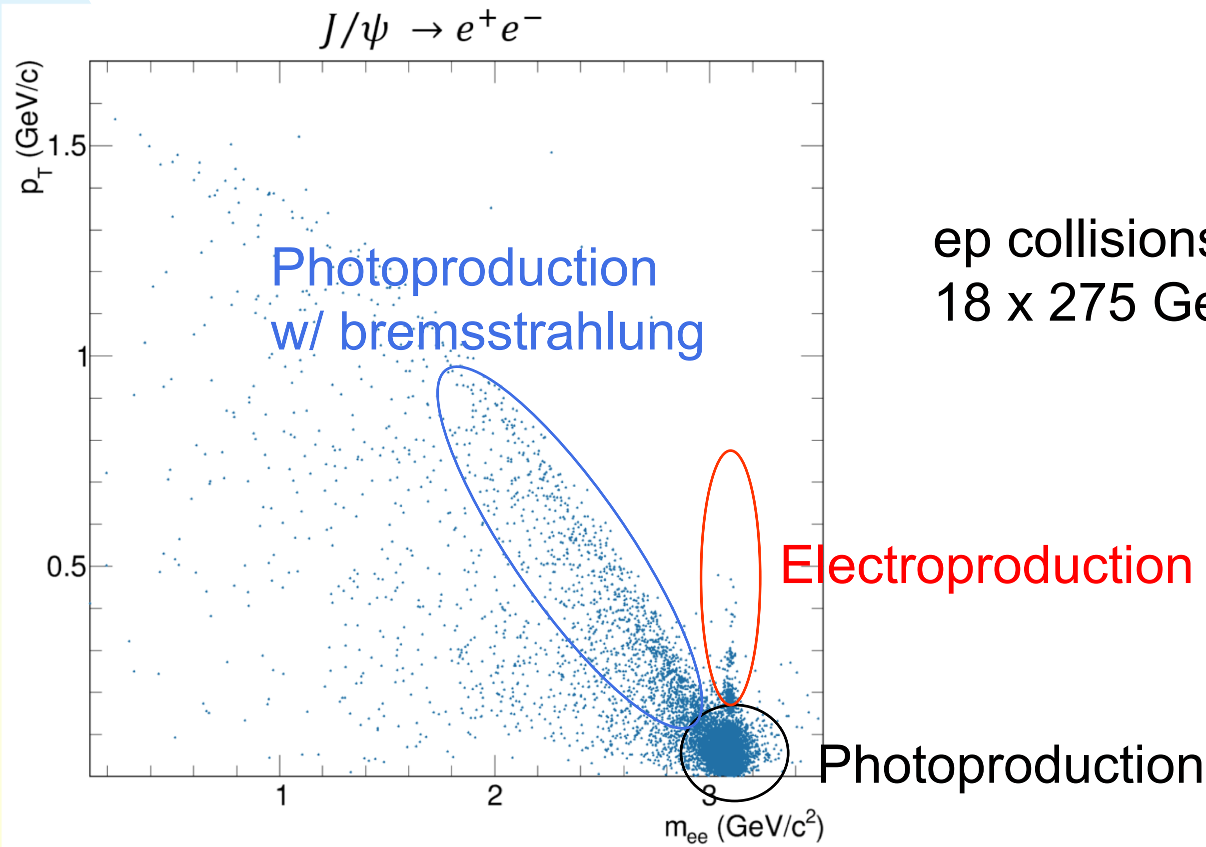




Plots by Yuanjing Ji (LBNL)

Thin detectors required for J/ψ etc. ->e^+e^-

- Bremsstrahlung causes signal confusion
- There is also a background from $\gamma\gamma$->e^+e^-
  - OK @ HERA, but larger in eA collisions

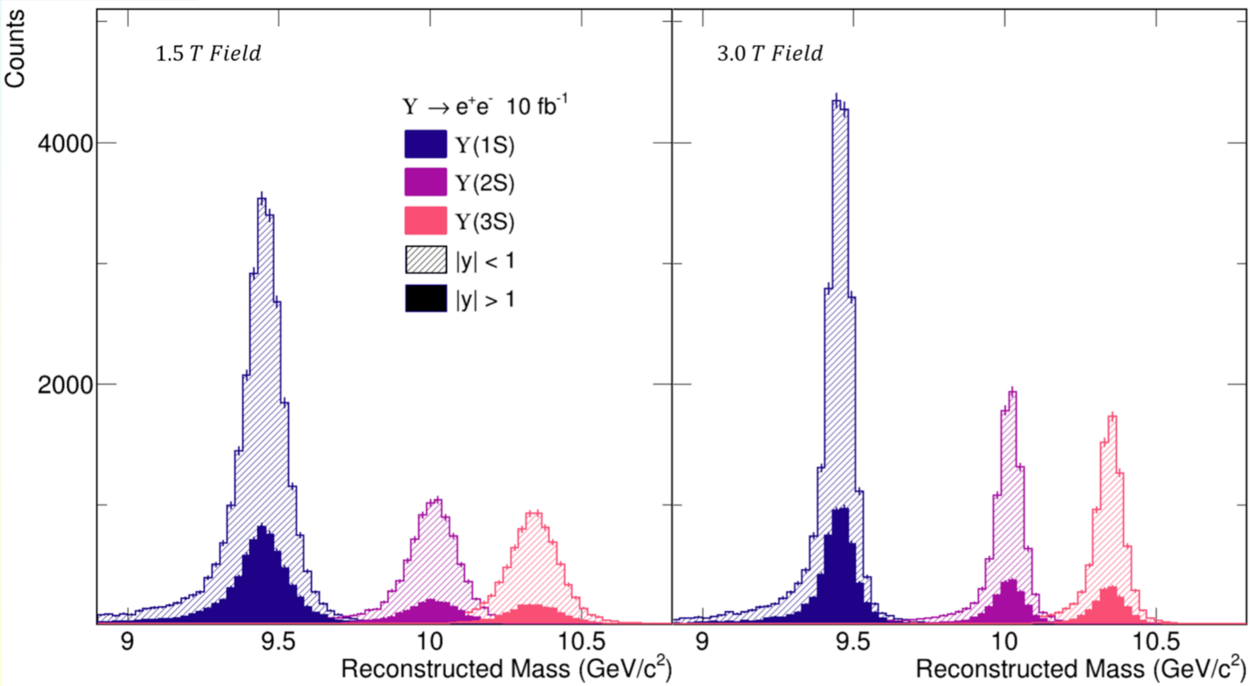


ep collisions
18 x 275 GeV

J. Arrington et al., arXiv:2103.08337 & YR

Υ challenge II- separating the Υ(1S), Υ(2S) & Υ(3S)

- Requires $\sigma(M_{ll}) < \sim 100$ MeV
- $\sigma(p) \sim < 1\%$ for 5 GeV/c tracks
- Less stringent than other momentum resolution requirements
- Resolution degrades at large |y|
- Good resolution is also important for $\gamma\gamma \to e^+e^-$ backgrounds



Separation in the all-silicon reference design, in 1.5 & 3.0 T fields

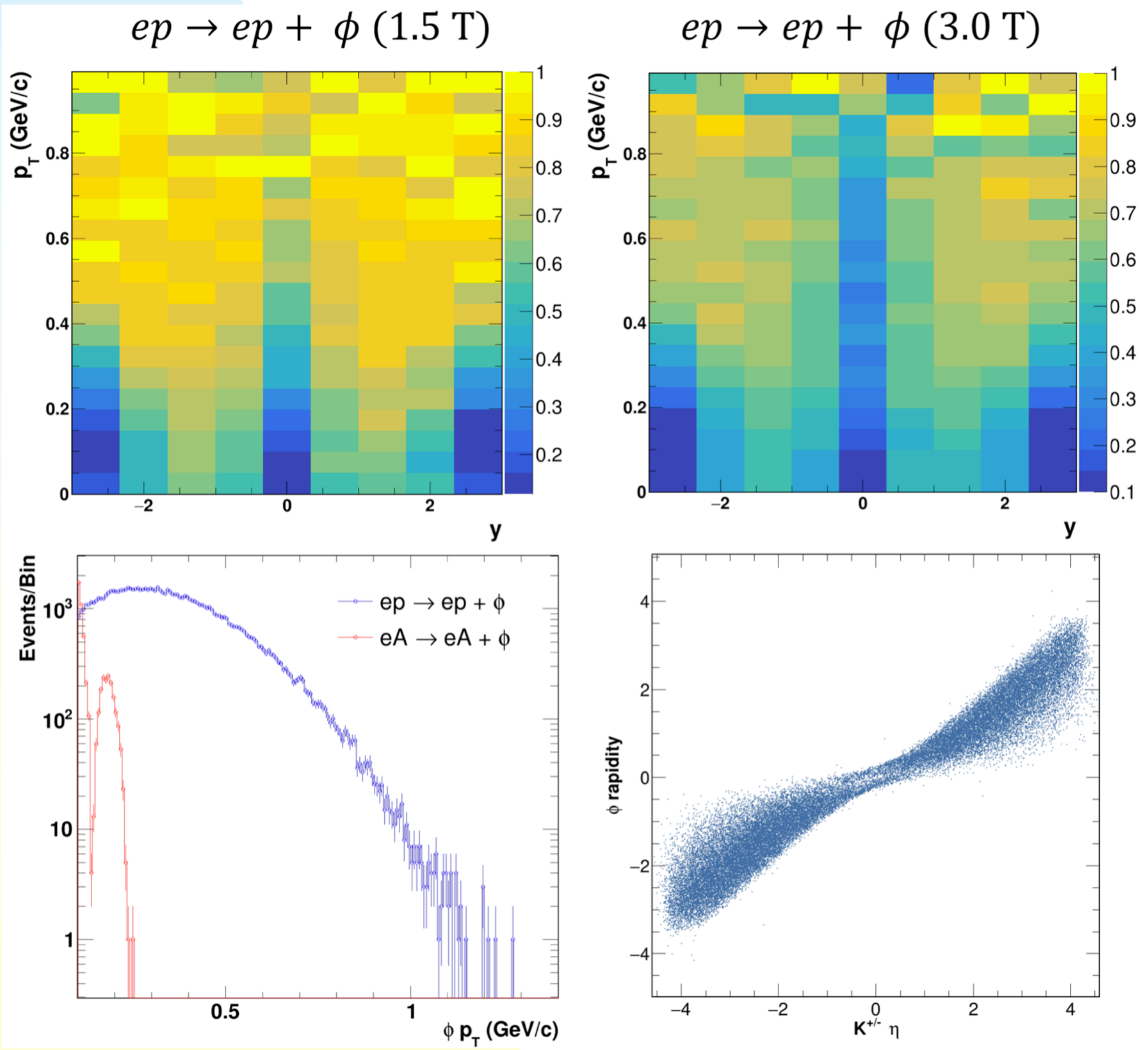
J. Arrington et al., arXiv:2103.08337

The ϕ is a unique challenge

- In Φ->K^+K^- the kaons have momenta of 135 MeV/c in ϕ frame
  - β ~ 0.2 -> non-relativistic, heavily ionizing
- For photoproduction near y=0, the kaons are slow in the lab frame
- In Φ->K_SK_L, the K_L is only detectable in a hadronic calorimeter
  - Very low energy K_L are iffy
- Φ->l^+l^- and other modes have very small branching ratio

Φ efficiency vs. y and p_T

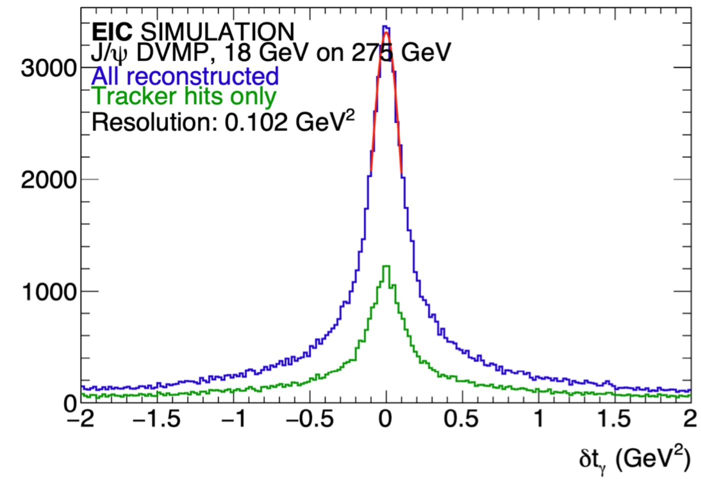
- Poor acceptance @ low p_T for y~0 & |y|> ~3
  - Worse in a 3 T field
  - Problematic for eA collisions



J. Arrington et al., arXiv:2103.08337

Resolution

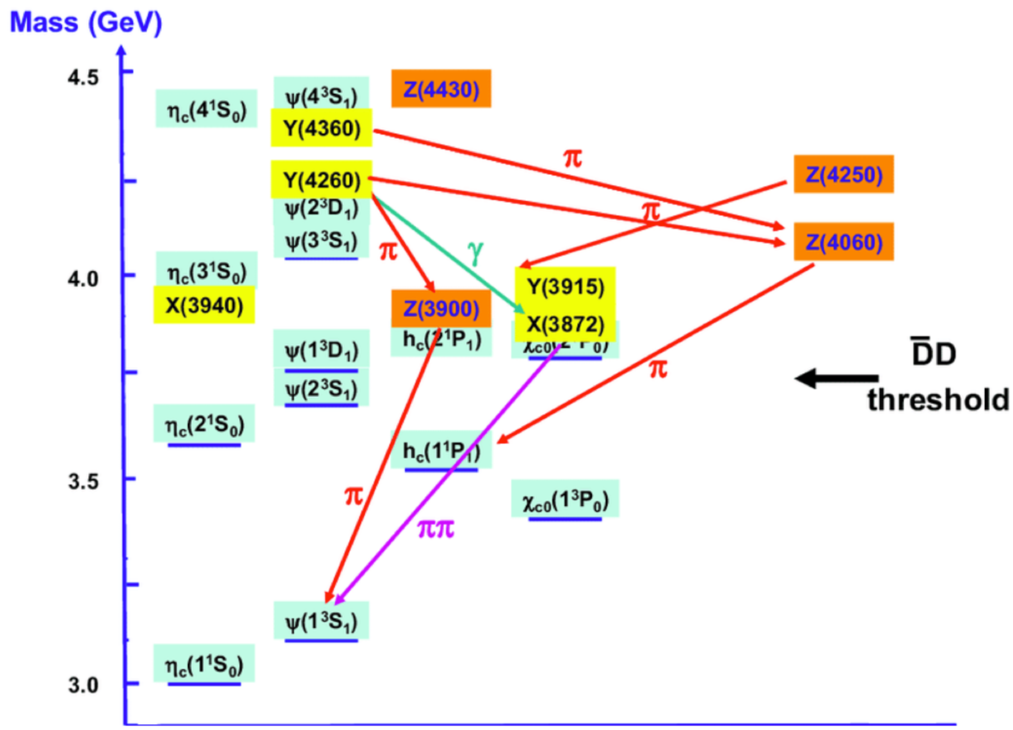
e⁻ + VM method



- Q^2
  - From scattered electron.
- Bjorken-x
  - From vector meson rapidity & Q^2
- Two approaches to t
  - Measure outgoing electron and vector meson
    - Account for electron beam energy/momentum spread
      - Electroproduction only
  - Measure outgoing proton in forward spectrometer
    - Only workable for protons & some light ions
    - Proton beam energy/momentum spread
    - Limited Acceptance

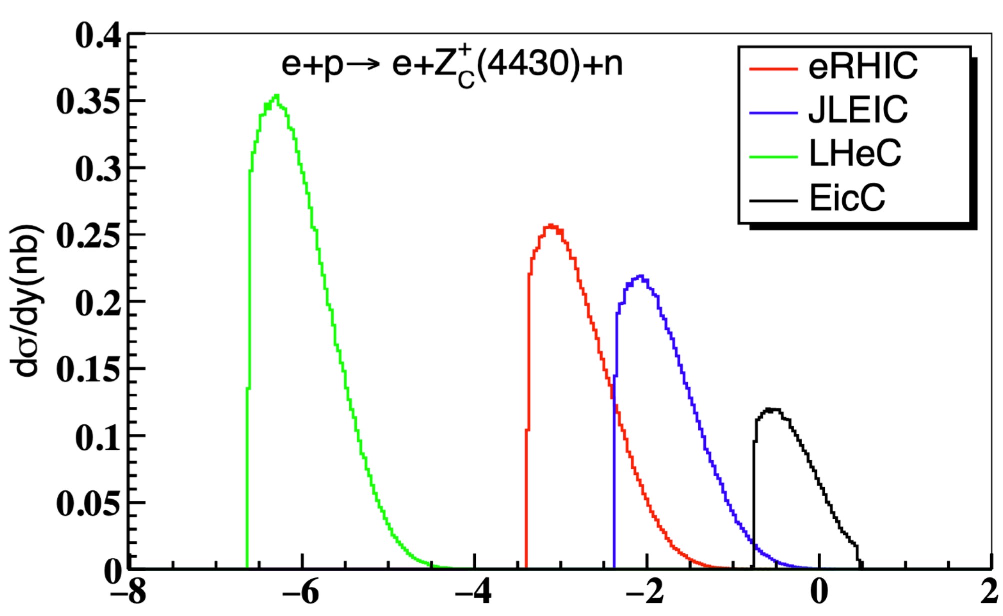
Going beyond vector mesons

- The EIC integrated luminosity should be high enough to probe other quarkonia, at least in ep
- Production by photon + Reggeon
  - Wide range of quantum numbers exchange
  - Cross-section decreases with increasing $W_{\gamma p}$
    - Forward production…
    - Run at lower energy
- Soft photons are important
- We should work through the physics case & practicalities



Going further – exotic quarkonia

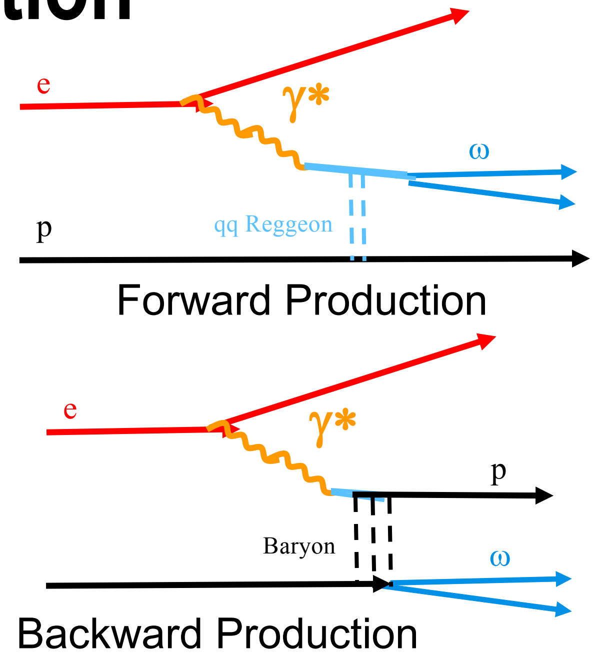
- Example: the Z_c^+ (4430)
- Using a model where the Z_c is a spin-1 tetraquark
  - Rate sensitive to Z_c structure and spin
- $Z_c^+ \rightarrow J/\psi\ \pi^+$ is experimentally straightforward
  - Z_c is in EIC detector acceptance
  - Neutron tags charge-exchange reaction
- σ (photoproduction) = 0.26 nb -> 2.6 M events/10^7 s
- σ (electroproduction, $Q^2 > 1$ GeV^2) = 12 pb -> 120K events/10^7 s



SK & Ya-Ping Xie,
Phys. Rev. C **100**, 024620 (2019)

Backward (u-channel) J/ψ production

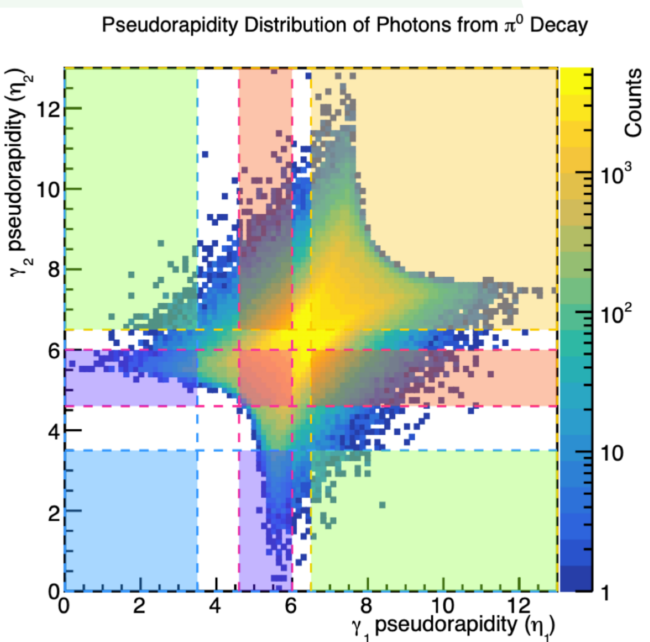
- t is large and u is small
  - In γp center-of-mass frame, meson and proton switch places
  - The meson is far-forward, while the proton is at mid-rapidity
- Studied at fixed target accelerators
  - Only light mesons
    - Proton and meson share quark flavors
    - Production models using Transition Distribution Amplitudes (TDA, like GPDs) or Regge trajectories involving baryons
- 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 ~~~ few percent of forward ω rate
    - J/ψ rate 1,000-10,000 times lower????
      - If so, backward J/ψ are accessible

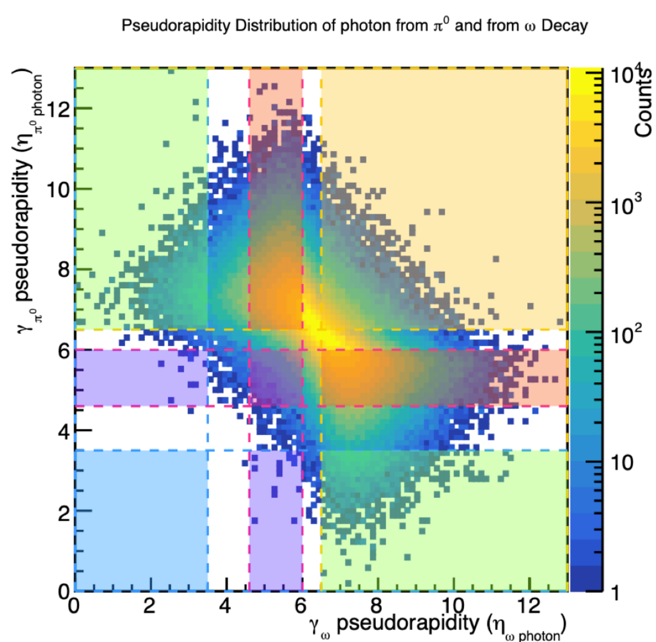


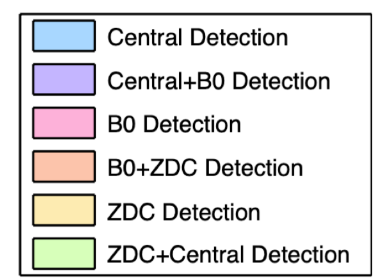
SK, Aaron Stanek, Sam Heppelman, Zach Sweger, et al., to appear
C. Ayerbe Gayoso et al., arXiv:2107.06748

Kinematics of backward production at the EIC

- Forward vector meson + mid-rapidity proton (+ electron for Q^2>0)
- Meson detection in central detector ($|\eta|$<3.5), B0 detector ($4.6 < \eta < 6.0$) and ZDC (η>6.5)
  - Different sensitive regions for charged and neutral products
- For light mesons:
  - 18 x 275 GeV beams -> some products in ZDC
  - 10 x 100 GeV beams -> products in B0
- Heavier mesons (like J/ψ) have smaller <η>
  - B0 and central detector







$\omega \to \pi^0\gamma$

Plots by Zach Sweger

Separating Coherent and Incoherent production

- Absolutely critical for physics!!!
- The Good-Walker paradigm relates the coherent and incoherent $d\sigma/dt$ to the average nuclear structure and event-by-event fluctuations respectively.

$$\frac{d\sigma_{tot}}{dt} = \frac{1}{16\pi}\left\langle \left|A(K,\Omega)\right|^2 \right\rangle$$ Average cross-sections (Ω)

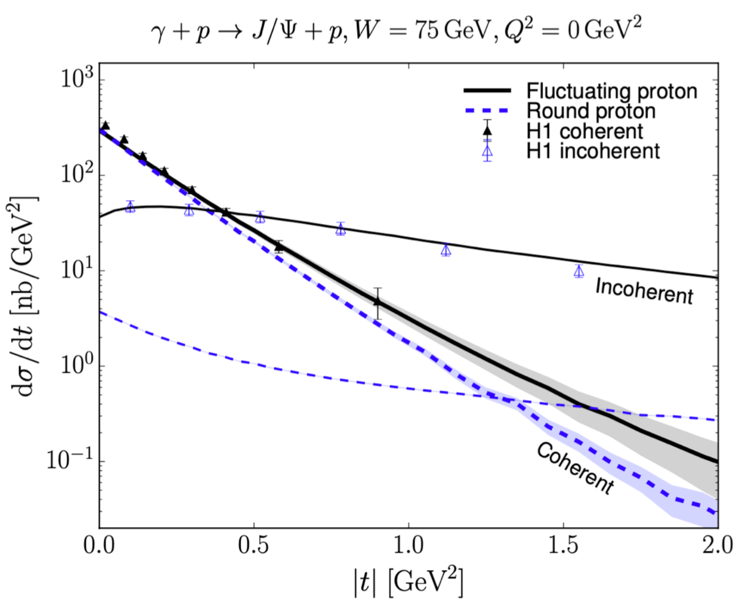
$$\frac{d\sigma_{coh}}{dt} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$ Average amplitudes (Ω)

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

  - K is the kinematic factors of the reaction (s,t,…)
  - Ω is nuclear configuration –nucleon positions, gluonic hot spots….
    - Assumed to be fixed throughout the interaction
- $d\sigma_{coherent}/dt$ can be used to image the nucleus
- $d\sigma_{incoherent}/dt$ probes event-by-event fluctuations in nuclear config.

J/ψ photoproduction on protons and ions

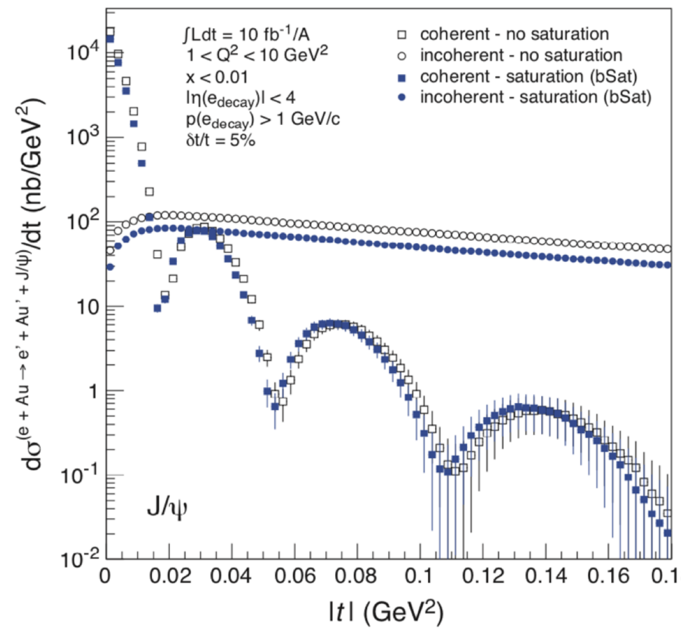
- Fit coherent and incoherent production together
  - Fluctuating protons greatly preferred!
- Fluctuations are energy dependent
  - As energy rises there are more hotspots-> $\sigma_{incoherent}$ rises
  - At very high energies, there is a black disk -> > $\sigma_{incoherent}$ -> 0
- For ions, there are more targets -> saturation at lower energy



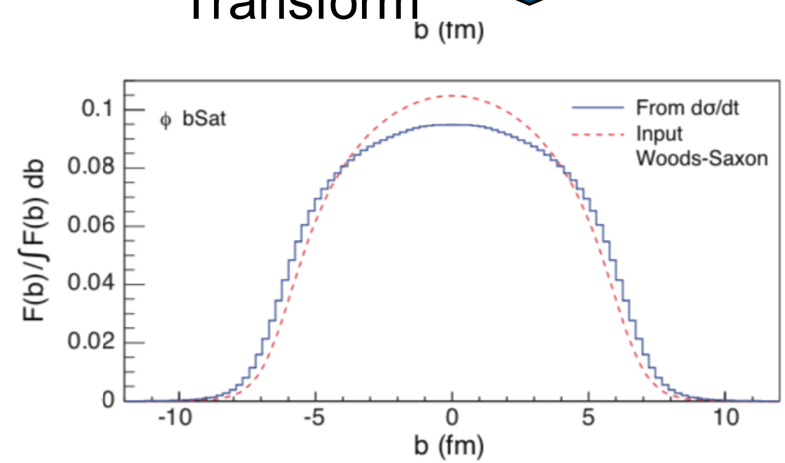
Mantysaari and Schenke, Phys. Rev. D94, 034042 (2016)

How good a 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 dσ/dt to F(b)
  - Accurate Fourier transform requires $0 < |t| < \sim 0.18\ \mathrm{GeV}^2$ range
- Need ~500:1 rejection of incoherent production to observe coherent production with $|t| > \sim 0.1\ \mathrm{GeV}^2$
- Need 100:1 rejection of coherent production to observe incoherent production at small |t|



Fourier Transform



Plots from EIC White Paper

Dissociation products

- For protons, p->Δ^+ -> $n\pi^+$, $p\pi^0$ is fairly easy to see
    - Pion carries substantial energy
- Heavy nuclei can emit, in order of decreasing likelihood
    - Neutrons
        - In LHC UPC production of J/ψ on lead, 7% of incoherent production does not include neutrons
        - Seen by Zero Degree Calorimeters, except at large p_T
    - Protons
        - Seen by off-axis spectrometer, B0 detector etc.
    - Photons
        - Seen in ZDC and B0 converter or calorimeter

M. Strikman et al, Phys. Lett. **B626**, 72 (2005)

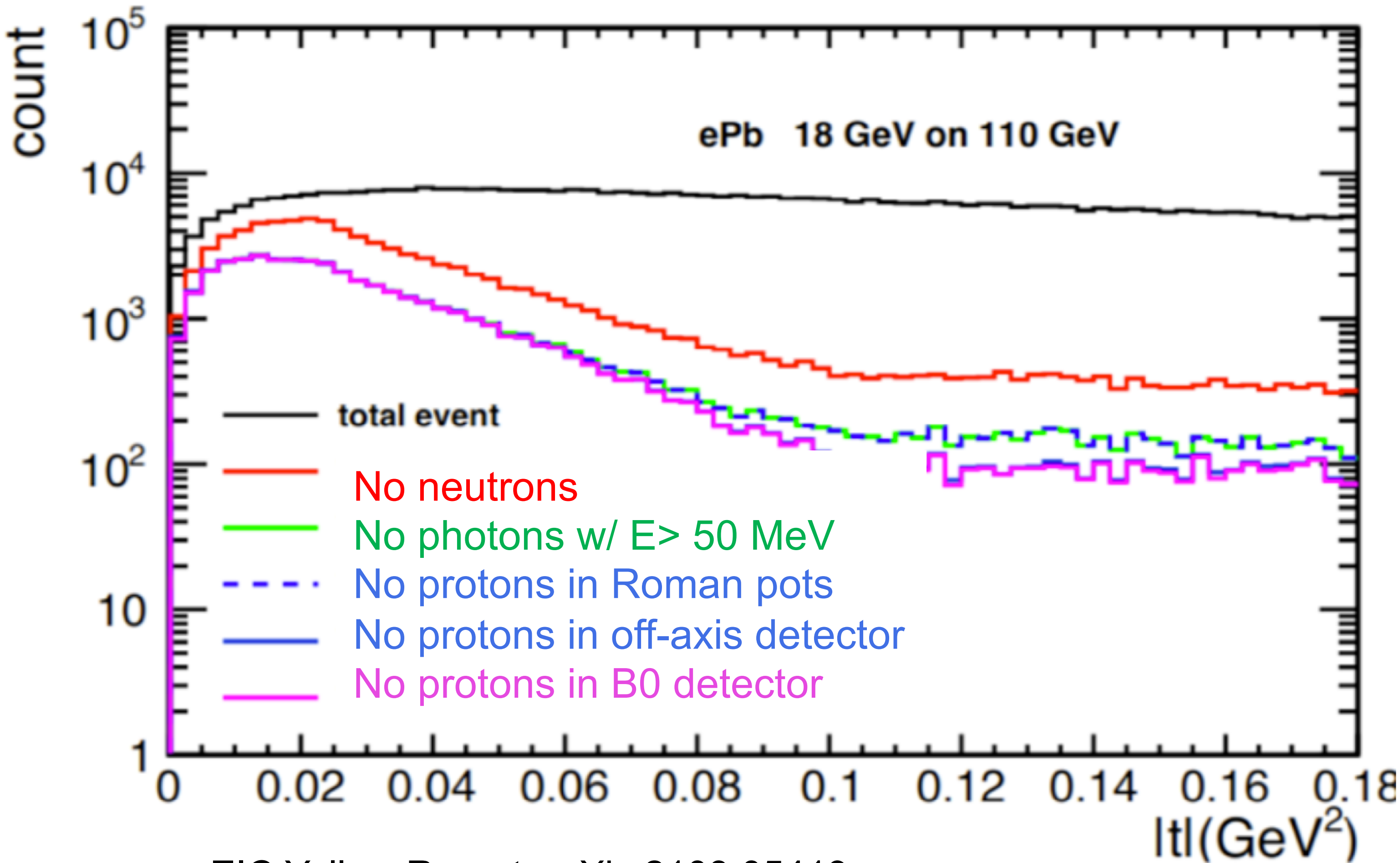
Models of Incoherent production

- 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

Detecting incoherent excitations at an EIC reference detector, with Beagle simulations

- Slow, partial dropoff in nucleon emission below t=0.1 GeV^2
- Rejection <~ 1/100, even at large |t|



EIC Yellow Report, arXiv:2103.05419

Energy conservation and dσ/dt

- Nucleon emission from heavy nuclei is endothermic
  - Neutron emission requires 8.07 / 7.38 MeV for ^{197}Au/^{208}Pb
  - Proton emission requires 5.27 / 7.5 MeV for ^{197}Au/^{208}Pb
- Without this energy, nucleon emission is impossible
  - Nucleon emission disappears as t -> 0
- IF the Pomeron exchange leads to single nucleon recoil in the target (as in the Beagle model), then we can find the required momentum transfer
  - Single nucleon supported by STAR UPC ρ^0 photoproduction data
  - p_{min} ~ 100 MeV/c, so t_{min}~0.01 GeV^2
  - Nucleon emission is not possible at smaller t
- The nuclear final state must depend on t
  - We cannot measure at large t, and expect it to hold as t drops

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

Final states for photonic de-excitation

- For E< 1-5 MeV, the final state is a well defined shell-model state
  - Fixed energy, spin, parity
    - Better described with nuclear shells than using nucleon positions and momentum, which are known only probabilistically
  - At higher energies, multiple photons are emitted
- For photonic excitation, energy loss is quantized
- For ^{208}Pb, the lowest lying excited state is at 2.6 MeV
  - $J^{\pi}=3^{-}$, so production is marginal, due to angular momentum
  - In the single nucleon paradigm (questionable here), this corresponds to 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
    - These excitations are not detectable
  - Next lowest states are at 269 keV and 279 keV
- Lead is preferred for vector meson studies

Detecting excitation photons

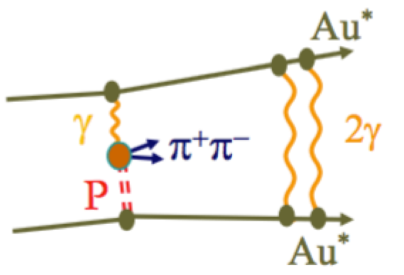
- The photons are Lorentz boosted
- Most hit the ZDC or B0 detector
- Maximum Lorentz boost is $2\gamma \sim 234$ at full EIC ion energy
  - 600 MeV for 2.6 MeV lead photons
  - ~ 65 MeV for 270 keV gold photons
- Typical Lorentz boost is lower, and some photons are downshifted.
  - Lead is much easier than gold, even neglecting the long-lived 77 keV state

New approaches to calculation and experiment?

- An intranuclear cascade model could be used to find the final state in terms of nucleon positions, etc., and then the overlap with different final states, but this is not the natural approach
- It may be better to consider the final state directly from the matrix elements
  - $\sigma \sim |\langle A^*| \mathcal{P} |A\rangle|^2$, where $\mathcal{P}$ is the Pomeron excitation
- Relevant data would help!
  - Small downstream high-resolution EM calorimeter at RHIC/ LHC
    - E_γ ~ 1 MeV*Lorentz boost: 100 MeV (RHIC) 3 GeV (LHC)
      - Good resolution is required to resolve lines.
    - Also of interest to study Lows theorem & low-energy bremsstrahlung
  - HPGe detector at Jlab for vector meson photoproduction
    - Excitation γ-rays coincident with vector meson production
    - Caveat: t_{min} is pretty high since the beam energy is low
      - Study lighter mesons?

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?
  - $\sigma = | \Sigma_i A_i \exp(ikx)|^2$
    - AA->A*A* V (ρ, ρ',J/ψ) still exhibits coherence
- 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).

Conclusions

- Exclusive quarkonium production is an important probe of light and heavy nuclei
  - Rates are high and many states are easy to reconstruct
  - Coherent production probes the transverse distribution of gluons
  - Incoherent production probes event-by-event gluon fluctuations
  - It will be challenging to adequately separate coherent and incoherent production
    - Both experimental and theoretical work are needed
- The EIC's high energy and luminosity will offer opportunities to study new quarkonium states, including non-vector mesons.
  - Theoretical and experimental work is required to understand the opportunities and any limitations.