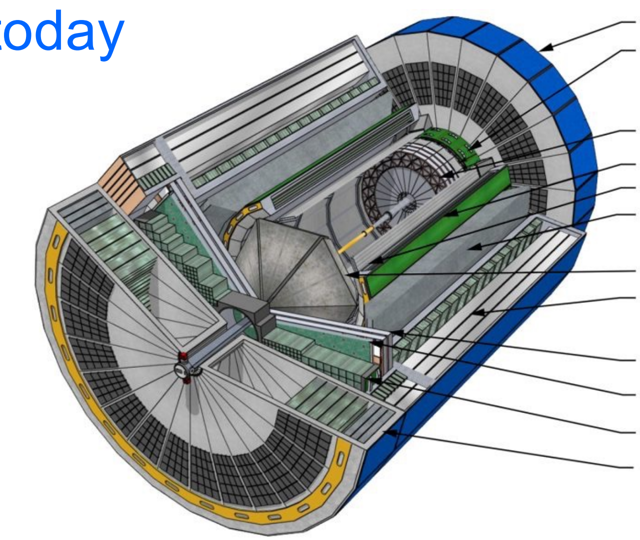
Heavy Quarkonium reconstruction and challenges with ePIC

Spencer Klein, LBNL

Presented at the Workshop on Exotic heavy meson spectroscopy and structure with EIC: Next-level physics and detector simulations, CFNS, April 14-17, 2025

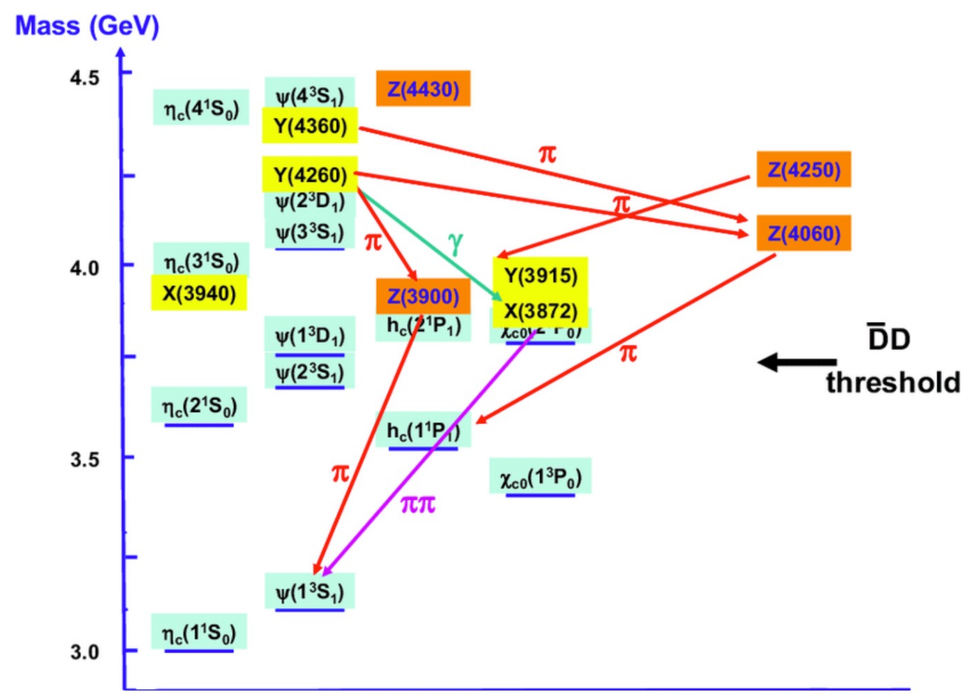
- Introduction – ePIC and exotics
  - 2nd detector interesting, but not today
- Physics goals
- Production characteristics
- Thoughts on ion targets
- Conclusions



It's all about rapidity

Quarkonium

- Exotic quarkonia has a rich spectroscopy
- EIC integrated luminosity should be high enough to probe many exotic quarkonium states
  - Rates depend on σ, which is very model-dependent
    - 10^{-2} to 10^{-4} of corresponding non-exotic cross sections
- States have a wide range of quantum numbers
  - Different quantum numbers -> different production mechanisms
- Complex decays, often with high multiplicity
  - Good acceptance is needed
- Radiative decays show relationships between different states

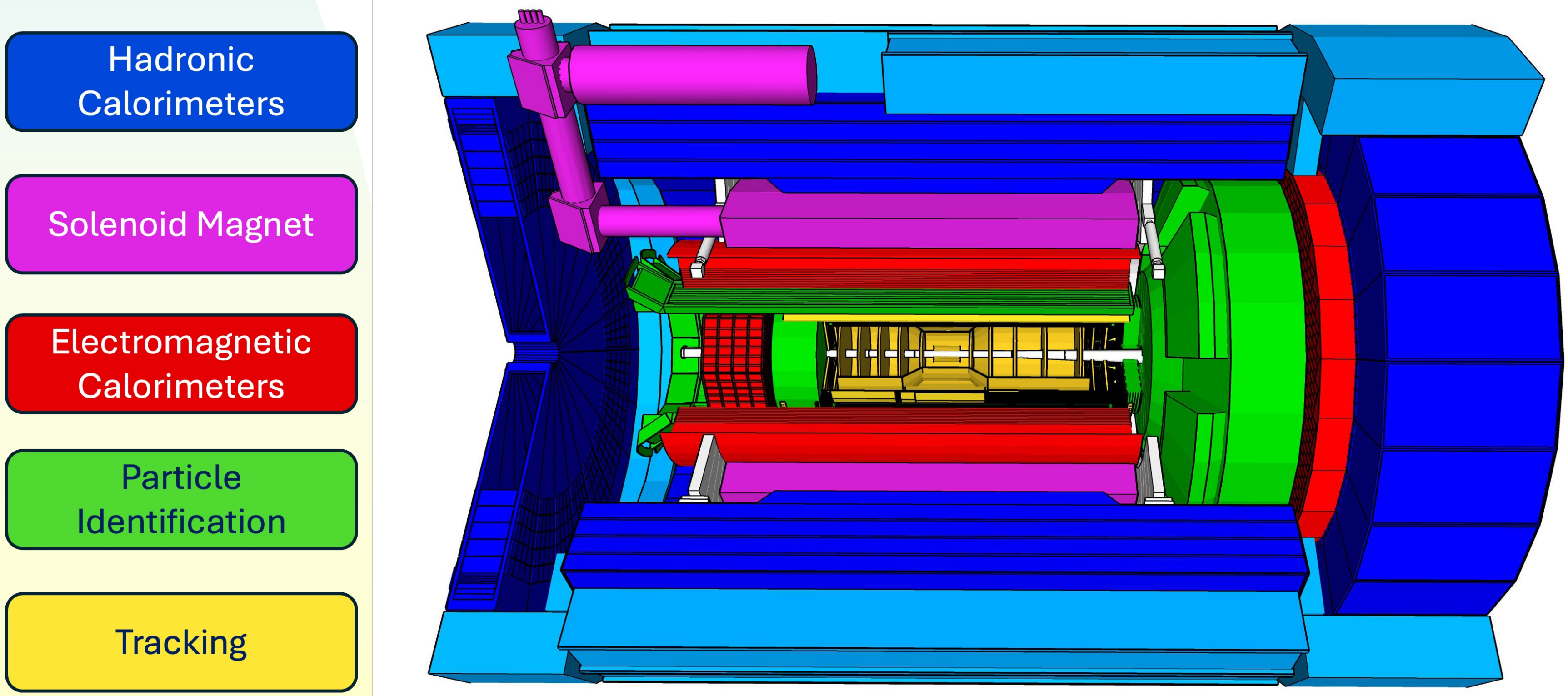


Physics goals for EIC studies

- Photoproduction cross-section is a probe of structure
- Measure JPC
  - Decay angles (especially 2-prong decays)
  - Rapidity distribution -> production mechanism -> info on J^{PC}
- Branching ratios for many final states
  - Relative branching ratios
  - Absolute branching ratios by comparing ep/eA?
    - Caveats apply
- Relationships between mesons, from radiative decays
- Q^2 dependence may also be sensitive to internal structure
  - σ_T and σ_L
- Topics that benefit from higher energies
  - Heavier (beyond the reach of Jlab) pentaquarks
    - Polarized production?
  - b-quark containing exotics

A spectro-centric view of the ePIC detector

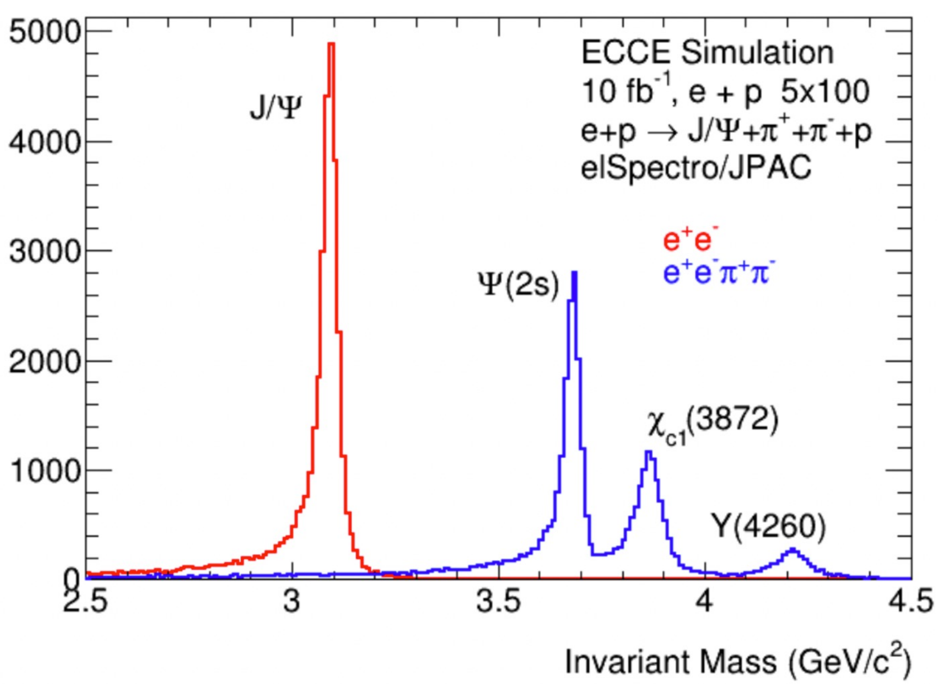
- Central Barrel $|\eta|<3.5$, with good vertexing tracking, PID and electromagnetic & hadronic calorimetry.
  - Good acceptance for mid-rapidity final states
  - Good acceptance & resolution for ~ 100-300 MeV photons
- B0 detector $4.6 < \eta < 5.9$, with tracking and EM calorimetry
- Forward detectors (ZDC++) to detect nuclear breakup
- Consider 10 fb^{-1}/A and 100 fb^{-1}/A



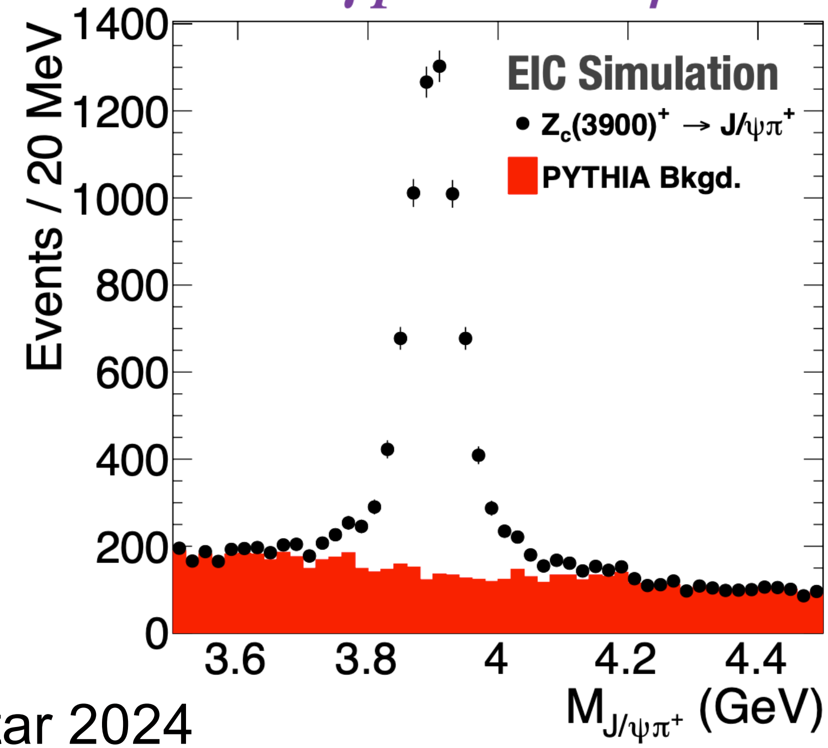
Exotic reconstruction at the EIC

- Multiple channels studied
- Resolutions are good enough
  - Caveat – simulations needed with real ePIC configuration
- Relative rates are model dependent

EIC: $\gamma p \rightarrow pJ/\psi\pi^+\pi^-$



EIC: $\gamma p \rightarrow nJ/\psi\pi^+$



J. Stevens, at Nstar 2024

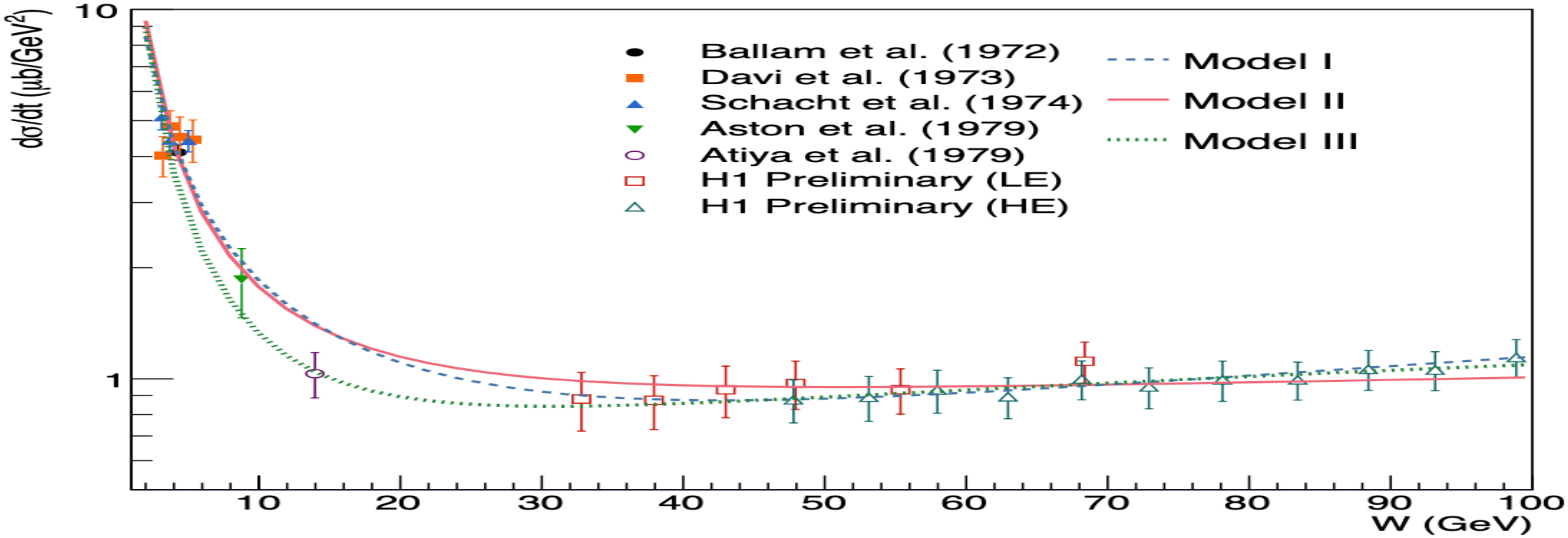
Fully reconstructing high-multiplicity states

- High efficiency is critical
  - Charged particles and photons
    - Soft photons are critical for radiative decays
- PID is important to reduce combinatorics
- Vertexing is important to reduce combinatorics for D^0,$D^{+/-}$ etc.
- ePIC does well for these factors. But, there are some small holes
  - No acceptance for η < -3.5,
  - Poor acceptance for η>3.5
    - Hole between central detector and B0
  - Limited resolution for neutrons and (most) K_L
    - Hadronic calorimetery resolution is limited for soft(er) particles
    - K_L usually do not decay in the tracking volume

Exotics are a broad category

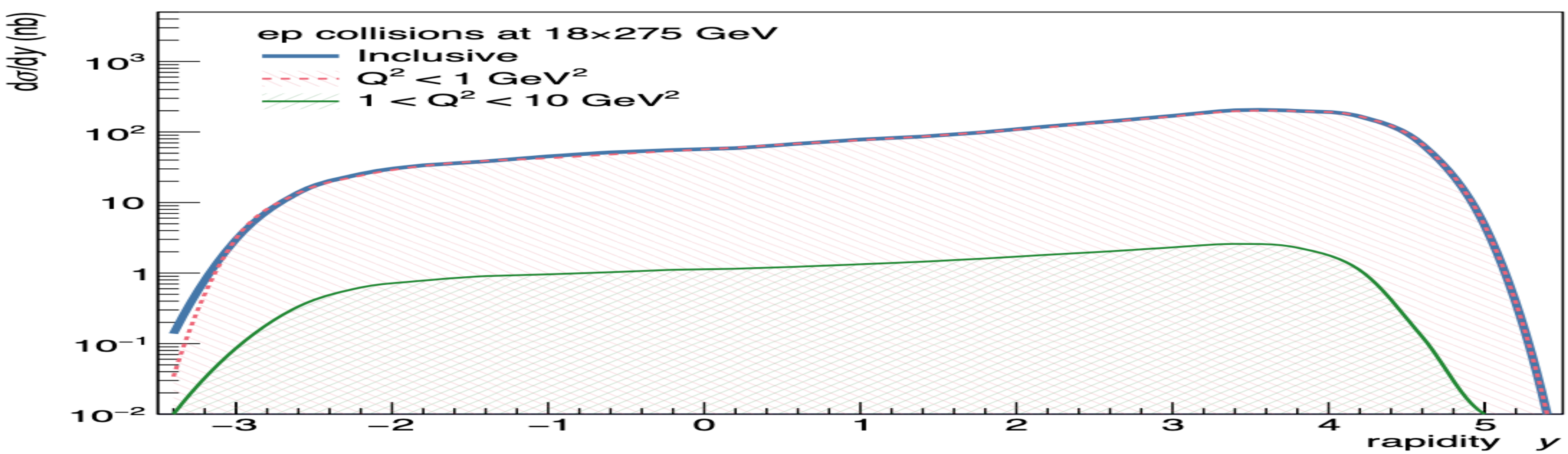
- Different production mechanisms for different states
- Non-exclusive production
  - Energetically challenging -> not today
- Different exclusive production channels have different rapidity distributions
- Four quark states (or meson molecules, etc.)
  - Produced by photon + Reggeon
  - Four-quark states with $J^{PC}=1^{-}$ can also be produced via Pomeron exchange
- Pentaquarks
  - Produced by photon-baryon fusion
- Most states can also be produced via two-photon fusion
  - Cross-section depends on charge content
  - Low cross-section, but the EIC is a high-luminosity machine
- Photon + Odderon production might also be possible

Production mechanisms & rapidity



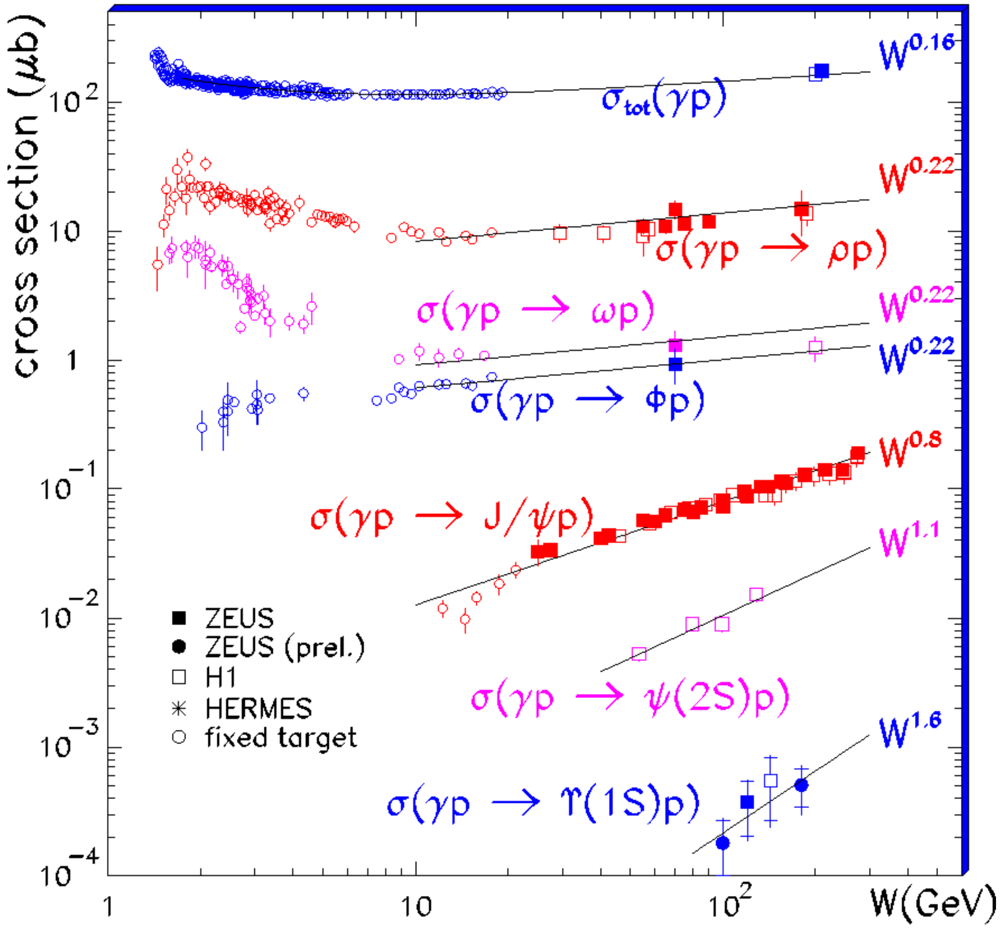
Low photon energy->
Reggeon dominated

High photon nergy->
Pomeron dominated



Charmonium rapidity distributions

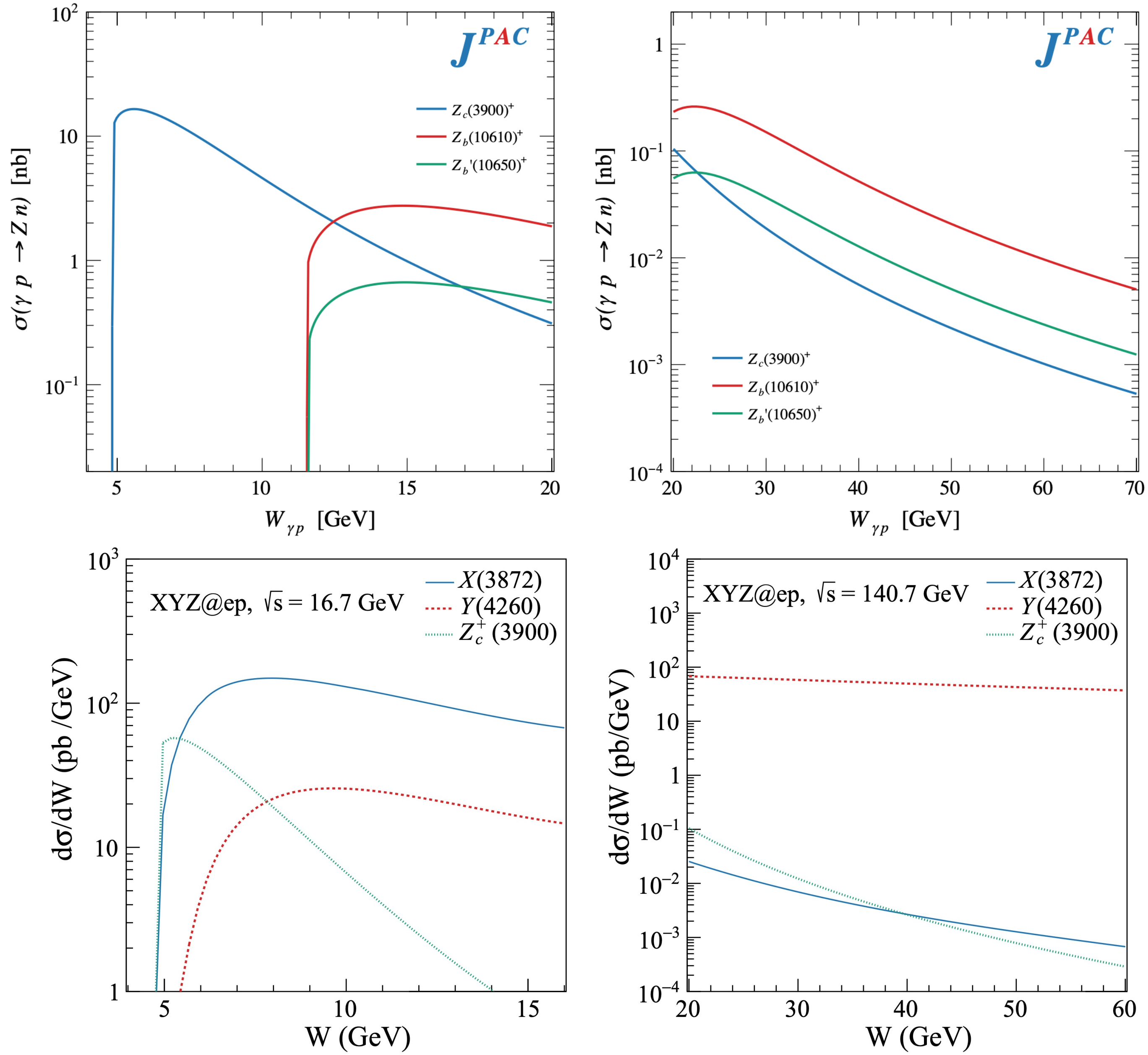
- Photon + Pomeron
  - σ(γp)~W$^{\delta}$, δ ~0.2 for light mesons, higher (0.8) for charm
- Photon + Reggeon
  - (γp)~W$^{\delta}$, δ ~~ -1 to -2 for light mesons
  - Production is concentrated fairly near threshold
    - Low-energy photons
  - Negative rapidity



Plot from A. Levy, arXiv:0711.0737

Exotica production characteristics

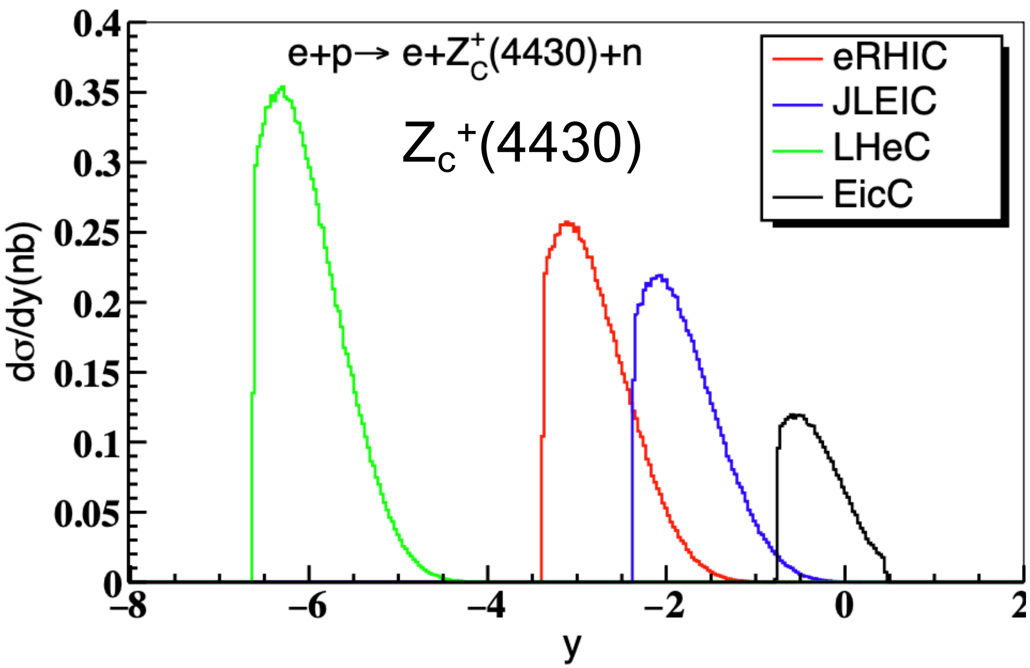
- Similar pattern as non-exotics
- In these models, some difference in fall-off with increasing energy
- Rates OK for charmonium exotica.
  - Marginal for bottom exotica

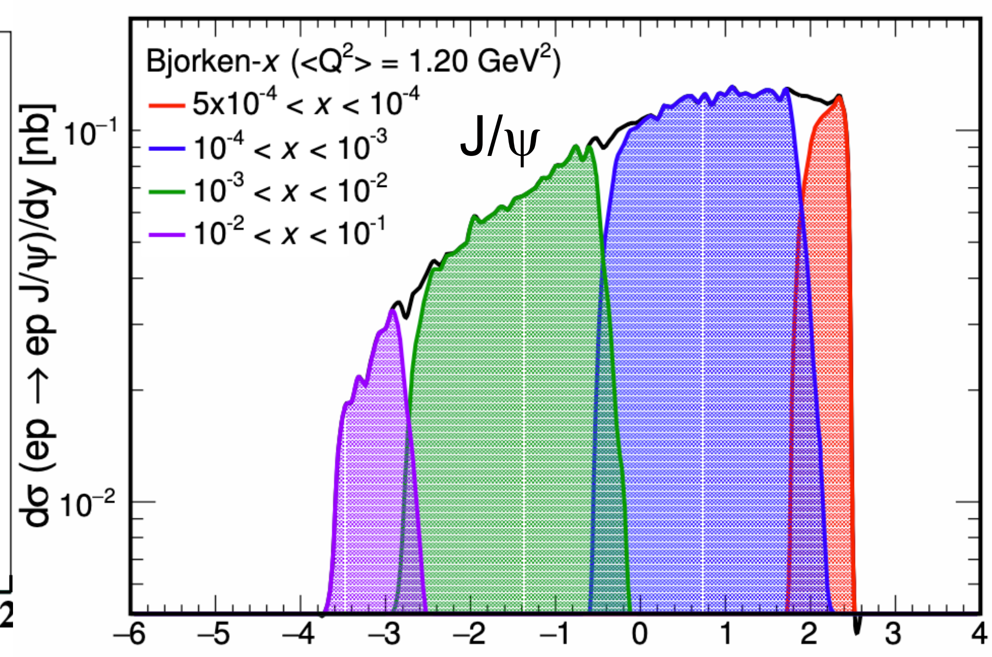


M. Albaladejo et al.,, Phys. Rev. D **102**, 114010 (2020);
J. P. Xie et al., EPJ C **81**, 710 (2021)

Rapidity comparison

- J/ψ vs. $Z_c^+(4430)$ exotic
  - Tetraquark, hadronic molecule or hadro-quarkonium state
  - $Z_c^+(4430)$ is produced via photon+Reggeon





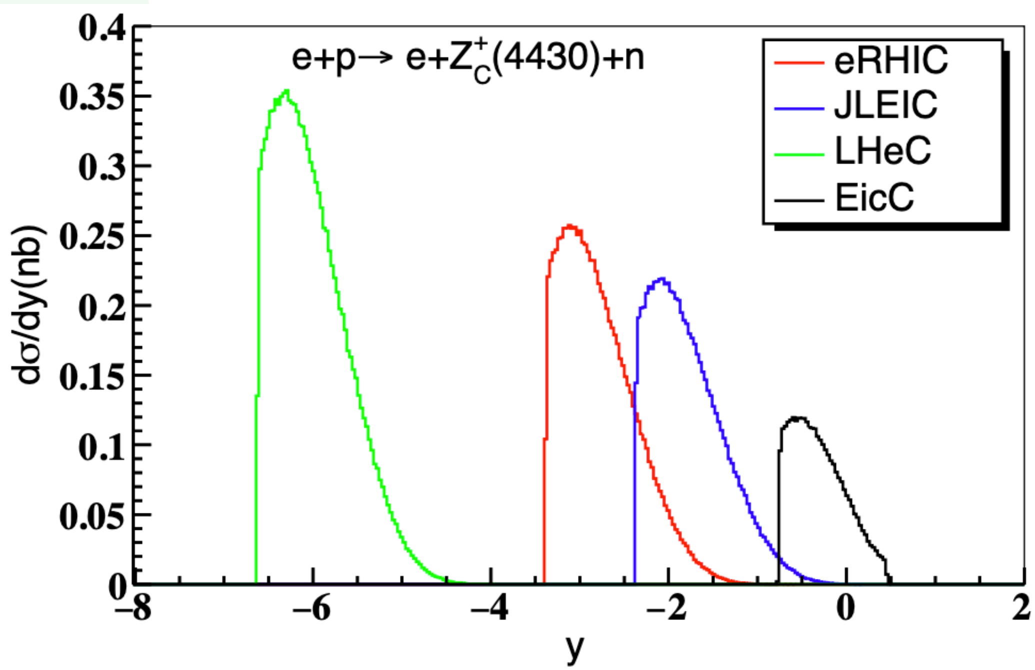
Flipped

The Z_c^+ is produced mostly at negative rapidity.
Most production is outside the central barrel acceptance
Shift toward mid-rapidity for lower proton beam energies

SK and Ya-Ping Xie, Phys. Rev. C **100**, 024620 (2019);
SK & M. Lomnitz, Phys. Rev. C **99**, 015203 (2019)

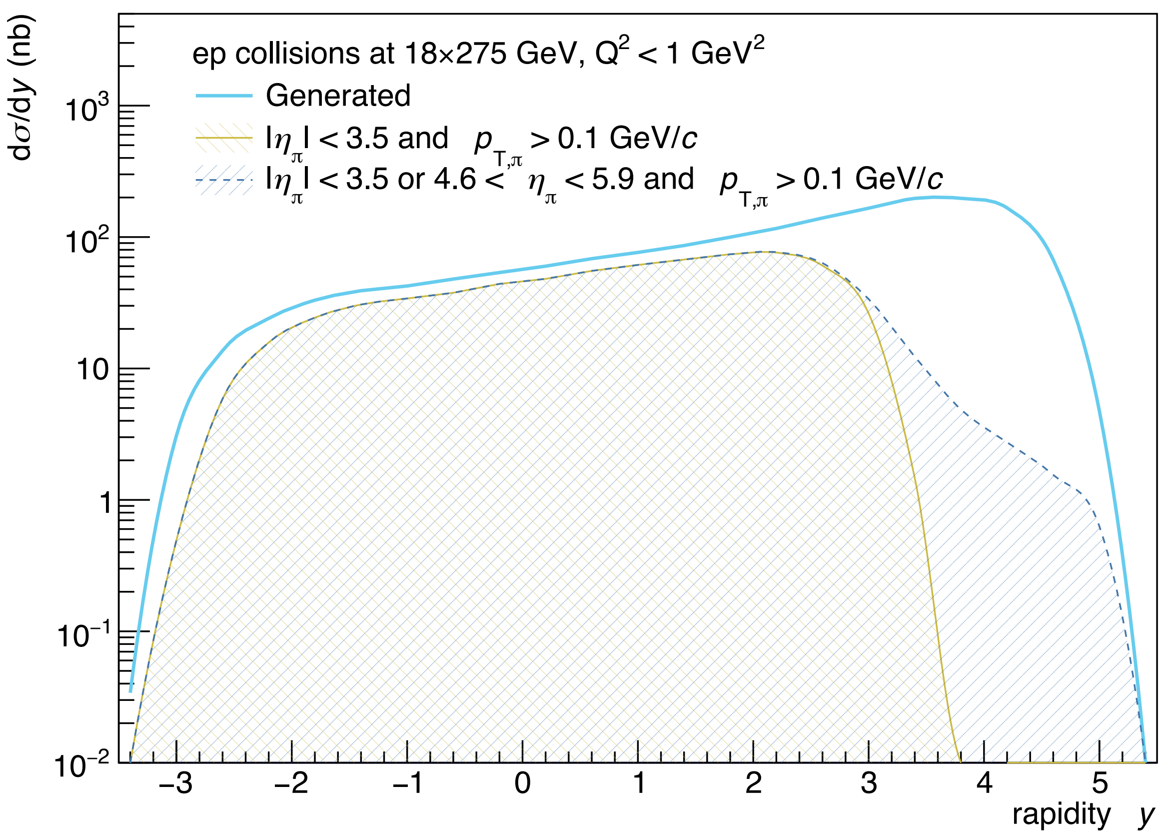
Rapidity and proton energy

- For photoproduction ($Q^2 \sim 0$) $y = \ln(2k/M_E)$
- Define near threshold as $W_{\gamma p} \sim 3\, M_E$
  - Photon + Reggeon production
- $W_{\gamma p}^2 = 4k\gamma m_p$, where γ is the ion Lorentz boost
  - $k=9M_E/4\gamma m_p$ so $y=\ln(9M_E/2\gamma m_p)$
- If $M_E/m_p \sim 3$ then $y=\ln(27/2\gamma) \sim -3$ for 275 GeV protons
  - Good acceptance requires charged particle acceptance to $|\eta|\sim 4$
  - The situation improves greatly at lower beam energies



Rapidity – the importance of the B0 detector

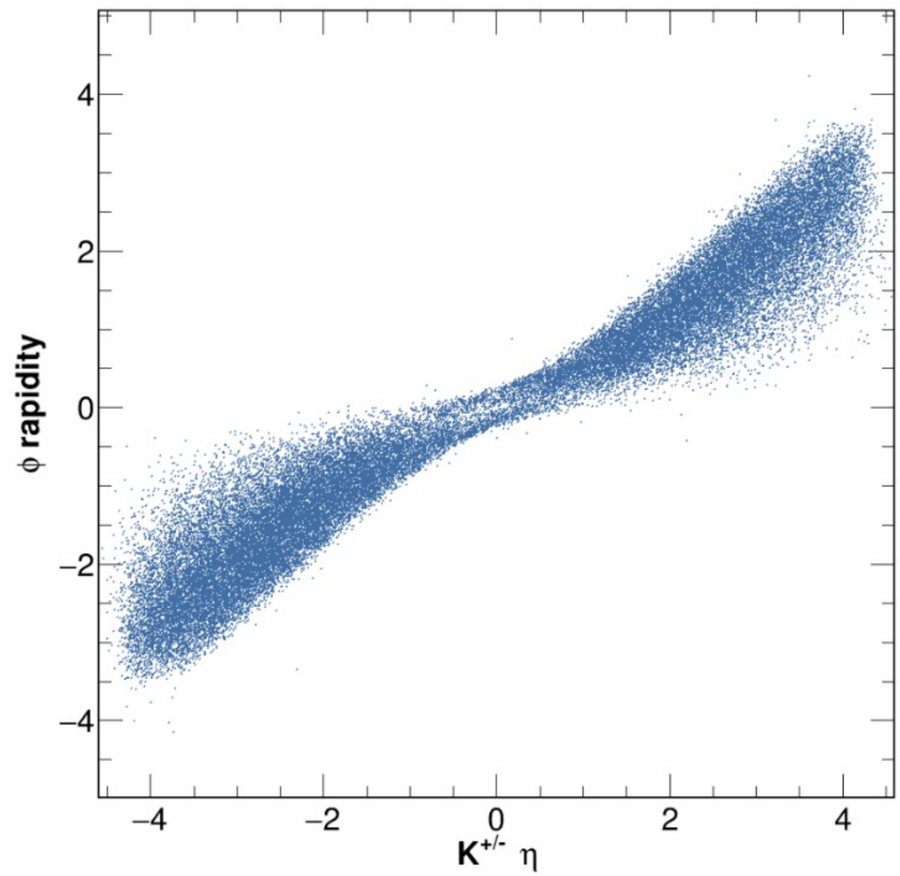
- $y = \ln(2k/M_X) = \ln(k/2x\gamma m_p)$
- Large y corresponds to the lowest Bjorken-x region
- Vector meson example: $\rho'(1450/1540/1700) \to \pi^+\pi^-\pi^+\pi^-$
- Central detector cannot cover the full range of Bjorken-x
  - The B0 detector is needed to probe the full x/y range!
    - Efficiency could be better, but still an improvement



SK + Minjung Kim,
to appear shortly

Exotic rapidity and daughter pseudorapidity

- Roughly, good acceptance for a decaying particle at rapidity y requires acceptance in pseudorapidity out to y+1
  - $y-1 < \eta < y+1$
- Range widens at large |y|
- Example: $\phi \to K^+K^-$
  - This decay has a low Q value.
  - Decays with a higher Q value may require a wider acceptance.



Plot from J. Arrington et al., arXiv:2102.08337

Absolute branching ratios (and cross-sections)?

- A Glauber calculation relates σ(Vp) to σ(VA)

$$\underbrace{\sigma(\gamma p \to \rho' p \to \pi^+\pi^-\pi^+\pi^- p)}_{\text{From data}} = (XW^\epsilon + YW^{-\eta}) \cdot \mathrm{Br}(\rho' \to \pi^+\pi^-\pi^+\pi^-).$$

(…) is σ(γp->Vp))

$$\frac{d\sigma(\gamma p \to Vp)}{dt}\bigg|_{t=0} = \frac{4\pi\alpha}{f_V^2} \frac{d\sigma(Vp \to Vp)}{dt}\bigg|_{t=0}$$

$$\frac{f_V^2}{4\pi} = \frac{M_V \alpha^2}{3\Gamma_{V\to ee}},$$

Need to know Γ_{ee}

$$\sigma_{tot}^2(Vp) = 16\pi \frac{d\sigma(Vp \to Vp)}{dt}\bigg|_{t=0}$$

Optical theorem

$$\sigma_{Tot}(VA) = \int d^3\vec{r}\,(1 - 2e^{-\sigma_{Tot}(Vp)T_A(\vec{r})/2})$$

Nonlinear in σ(Vp)
Any corrections?

$$\sigma(\gamma A \to \rho' A \to \pi^+\pi^-\pi^+\pi^- A) = \frac{\sigma(\gamma A \to \rho' A)}{dt}\bigg|_{t=0} \int_{t_{\min}}^{\infty} dt |F(t)|^2 \cdot \mathrm{Br}(\rho' \to \pi^+\pi^-\pi^+\pi^-).$$

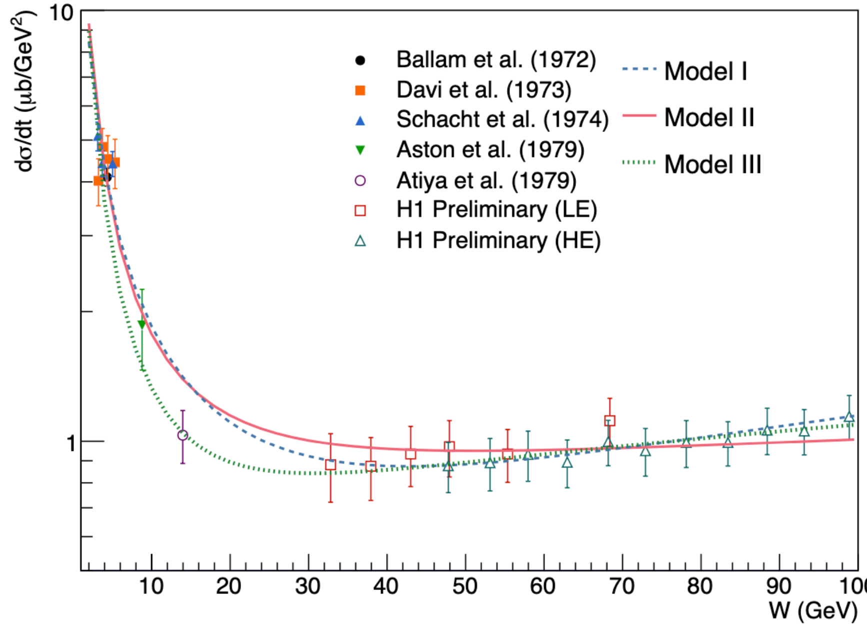
Reverse the process

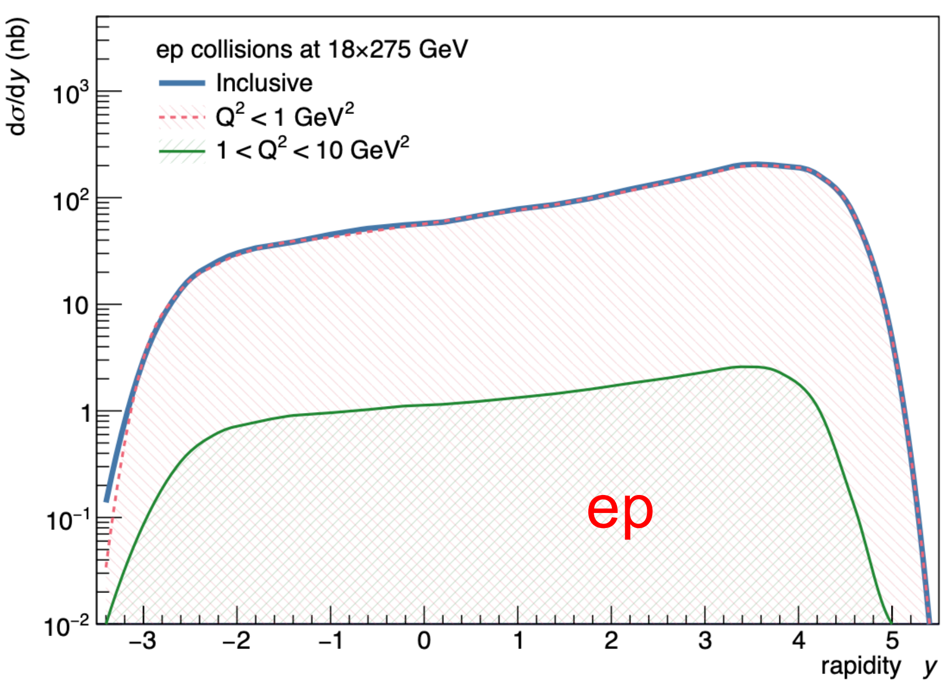
Smaller Br -> Larger σ(Vp->Xp)-> smaller σ(VA->XA)/σ(Vp->Xp)->
Smaller σ(γA->VA)

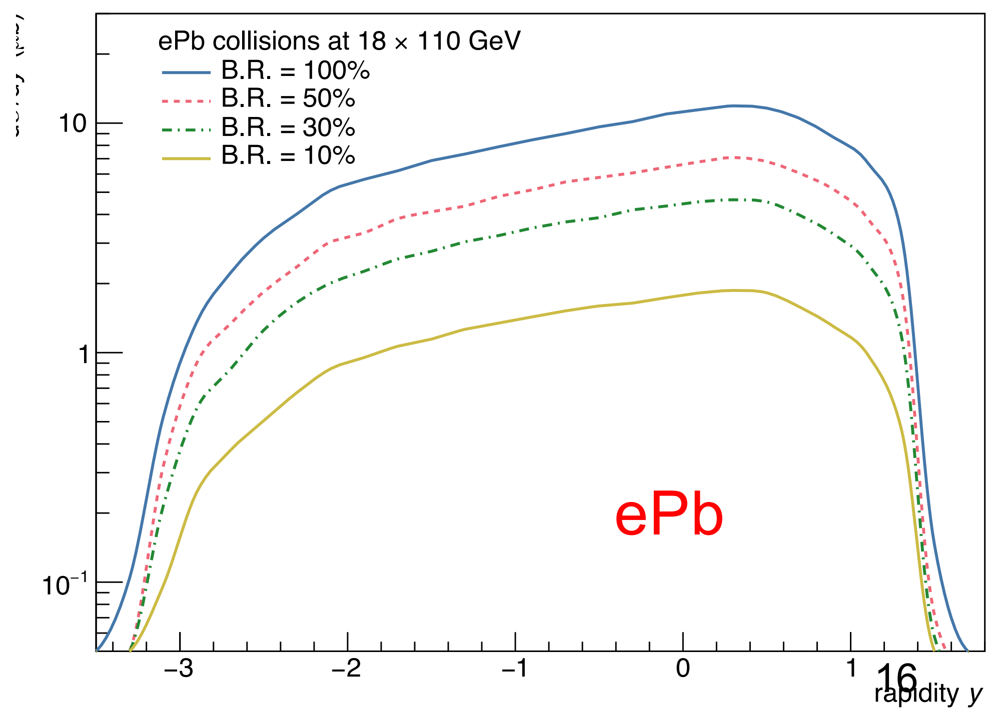
SK + Minjung Kim, to appear soon

Example: $\rho' \to \pi^+\pi^- \pi^+\pi^-$

- Parameterized HERA + fixed target data
- eSTARlight photon flux
- Consider 10% < Br < 100%
  - Cancels in ratio, except for Glaube
- Here Γ_{ee} is not well known

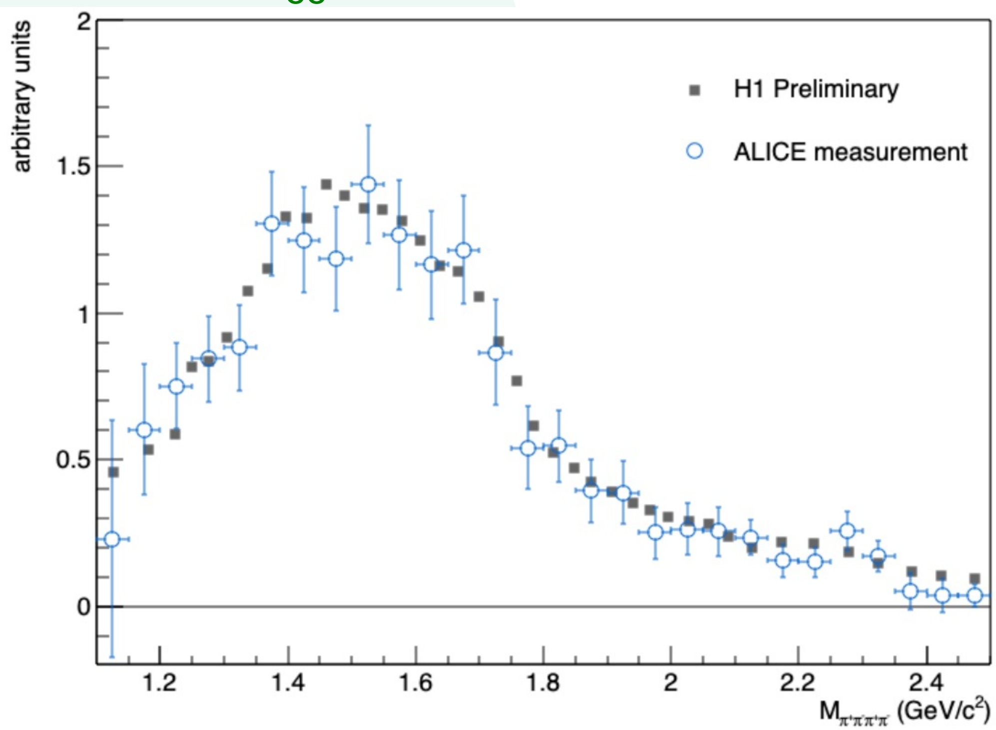






Separating overlapping resonances

- One resonance -> one $\sigma(Vp)$->$\sigma(VA)$
  - Resonance shape is preserved
- Two resonances -> likely different $\sigma(Vp)$
  - The resonance shape will differ for proton vs. heavy-ion targets
- The "ρ'" is though to be 2 resonances: $\rho(1450)$ and $\rho(1700)$
  - But the shapes look similar in γp and γA collisions
    - $\Gamma_{ee}*Br$ is similar for the two resonances



HERA ep vs.
ALICE UPC γA

Pentaquark production

- γ+p -> P_c
  - Narrow range of k -> narrow range of rapidity (?)

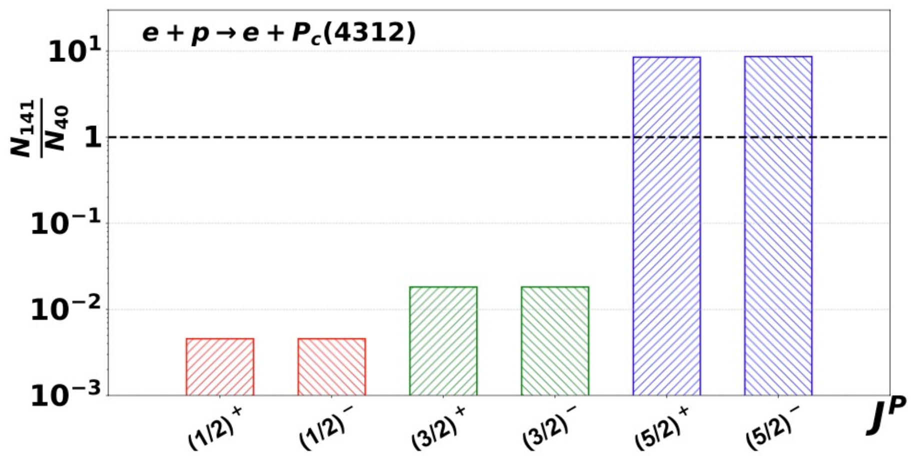


FIG. 3. Ratio of the integrated $P_c(4312)$ yields in $e+p$ collisions at $\sqrt{s}$=141 GeV and $\sqrt{s}$=40 GeV for six spin-parity assignments. The pseudorapidity range is restricted to $|\eta|$<4 to account for detector geometry.

See also talk Wednesday by Jihee Kim

TABLE III. Expected $P_c(4312)$ yields to be measured by the ePIC experiment at $\sqrt{s}$=141 GeV (N_{141}) and $\sqrt{s}$=40 GeV (N_{40}), assuming an integrated luminosity of 100 fb^{-1}.

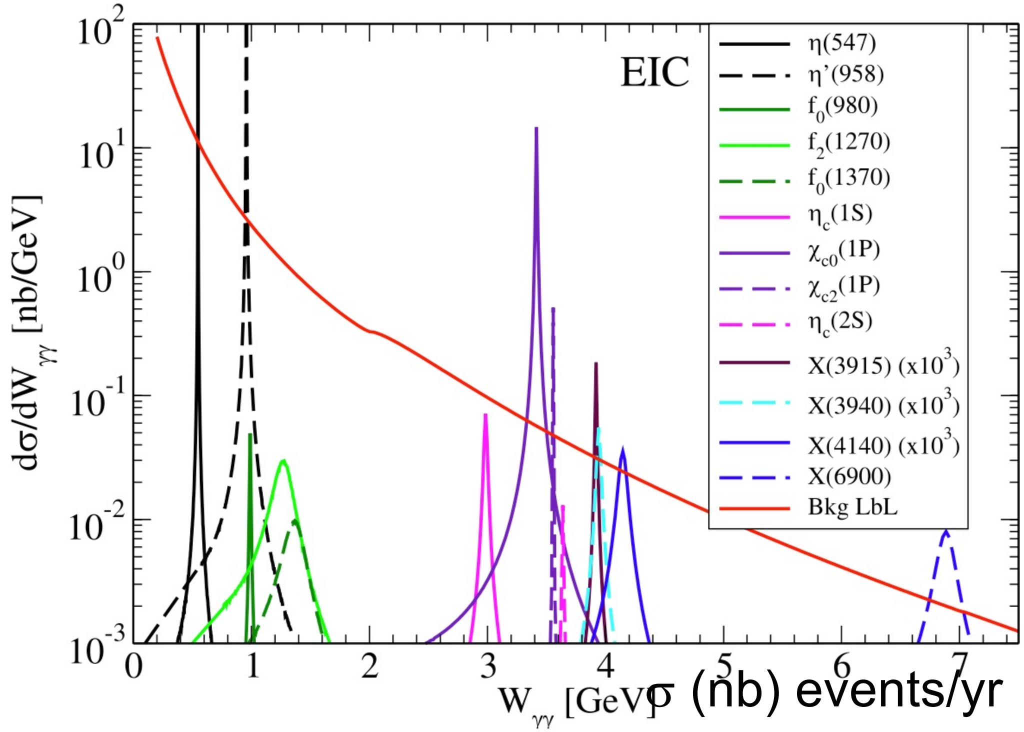
J^P	$(1/2)^+$	$(1/2)^-$	$(3/2)^+$	$(3/2)^-$	$(5/2)^+$	$(5/2)^-$
N_{141}	790	350	5.1×10^3	2.0×10^3	4.1×10^7	1.0×10^8
N_{40}	1.7×10^5	7.7×10^4	2.8×10^5	1.1×10^5	4.8×10^6	1.2×10^7

I. W. Park et al., arXiv:2503.02676

Two-photon production

- Heavy-ion targets
- Sensitive probe of charge content
- Rate estimates using $\Gamma_{\gamma\gamma}$ determined with coupled channel approach
  - Dynamically generated resonances
- Rates are for 1 year at $\mathcal{L}=10^{33}/\text{cm}^2\text{-s}$
- Observable!
  - Subdominant to other processes

C. Bertulani et al., Phys. Rev. C **111**, 025201 (2025)



σ (nb) events/yr

	eAu (EicC)	eAu (EIC)
$\eta(547)$	$253.51\ (12.67 \times 10^9)$	$2126.88\ (2.13 \times 10^{11})$
$\eta'(958)$	$125.50\ (6.28 \times 10^9)$	$2126.32\ (2.13 \times 10^{11})$
$f_0(980)$	$7.25\ (0.36 \times 10^9)$	$125.59\ (12.56 \times 10^9)$
$f_2(1270)$	$76.90\ (3.85 \times 10^9)$	$2096.30\ (2.10 \times 10^{11})$
$\eta_c(1S)$	$17.53 \times 10^{-3}\ (0.88 \times 10^6)$	$23.41\ (2.34 \times 10^9)$
$\chi_{c0}(1P)$	$19.15 \times 10^{-3}\ (0.96 \times 10^6)$	$85.20\ (8.52 \times 10^9)$
$\chi_{c2}(1P)$	$0.68 \times 10^{-3}\ (34.00 \times 10^3)$	$6.16\ (0.62 \times 10^9)$
$\eta_c(2S)$	$0.25 \times 10^{-3}\ (12.55 \times 10^3)$	$2.44\ (0.24 \times 10^9)$
$X(3915)$	$1.40 \times 10^{-5}\ (0.70 \times 10^3)$	$0.27\ (27.00 \times 10^6)$
$X(3940)$	$2.22 \times 10^{-5}\ (1.11 \times 10^3)$	$0.44\ (44.00 \times 10^6)$
$X(4140)$	$2.87 \times 10^{-5}\ (1.44 \times 10^3)$	$0.65\ (65.00 \times 10^6)$
$X(6900)$	$2.28 \times 10^{-6}\ (114.15)$	$5.37\ (0.54 \times 10^9)$

Photoproduction and electroproduction

- Exotic searches/studies are luminosity hungry
  - 10 fb^{-1}/A will allow some studies, but a more systematic approach requires 100 fb^{-1}/A
- Need to study photoproduction
  - Probably need to study untagged interactions, where the outgoing electron is not observed
    - Need to reconstruct full final state
- In a few channels, may have enough luminosity to study Q^2 evolution of final state

b-containing exotica

- ep: Expect 140,000 Υ(1S) in 10 fb^{-1} integrated luminosity
  - eA: Expect 60,000 Υ(1S) in 10 fb^{-1}/A
    - Lower $\sqrt{s_{eN}}$ hits harder here
- If exotic rates are 1% of Υ(1S) rates, and individual branching ratios are a few % we should be able to see signals in 10 fb^{-1}
  - May need to stack multiple final states
- If they are 0.1% of Υ(1S) rates, we need 100 fb^{-1}
- Even photon + Reggeon interactions should be fairly near mid-rapidity

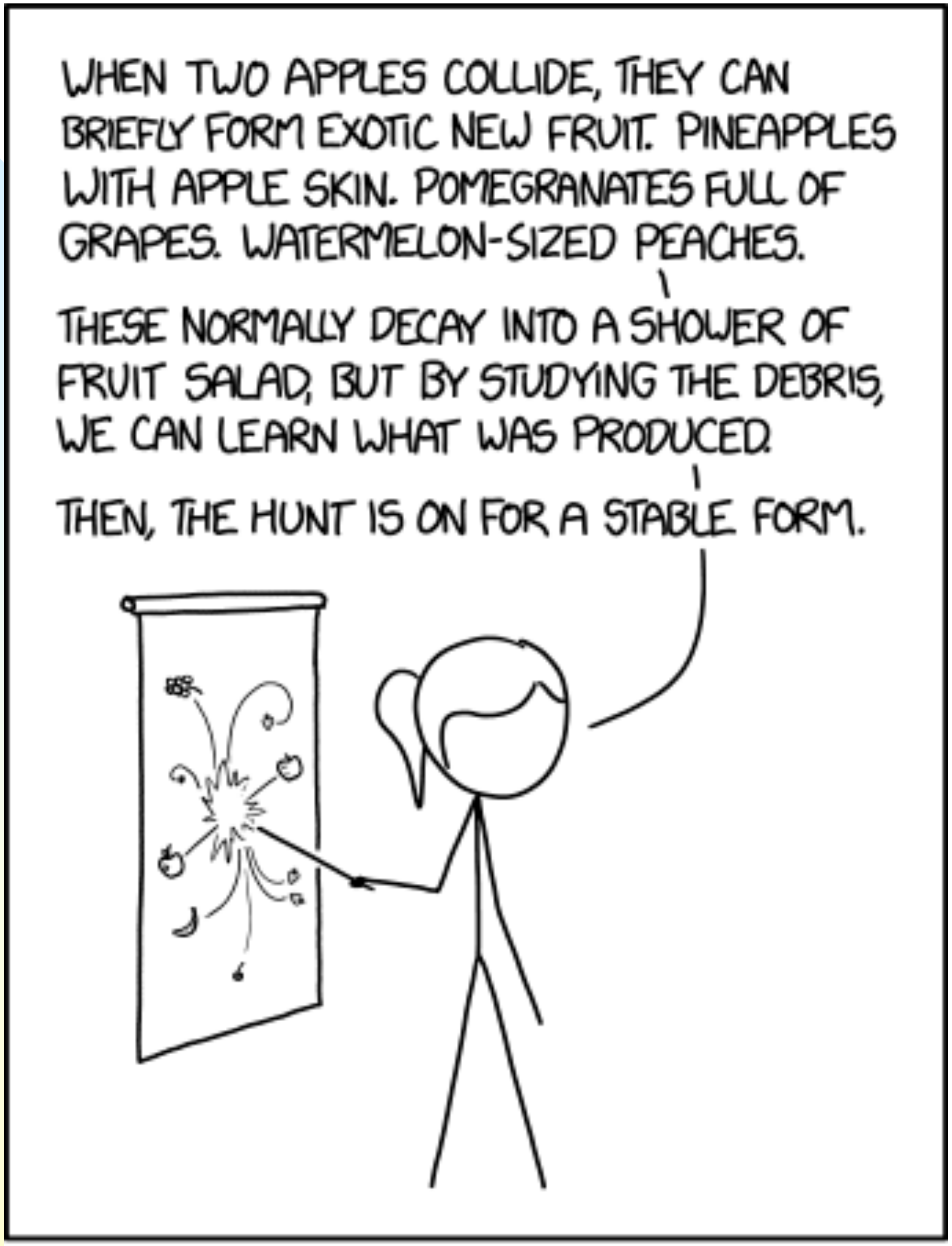
Exotica production on ion targets

- Lower per-nucleon energy -> somewhat lower cross section
  - Smallish effect for photon+Reggeon production, since most of the action is near threshold
  - Rapidity shifted toward y=0 -> higher detection efficiency
- Important for photon+ Pomeron production, and for (hypothetical) photon-Odderon
- Targets include neutrons – important for charged exotica.
  - Only exclusive route to negatively charged exotica
- Possibility of coherent production
  - Enhanced cross sections
- Two-photon production rate scales as Z^2
  - Probably only observable with heavy-ion beams
  - Spin 0, 2, etc.

What is required for coherent exotic production?

- Standard thinking: Nucleus must remain in its ground state. Only possible for the exchange of vacuum quantum numbers.
  - Photon + Pomeron only
- But: we observe coherent enhancement to the cross-section for $p_T < hbar/R_A$ even when the nucleus breaks up
  - Vector meson photoproduction + single/mutual Coulomb excitation of the targets
  - Peripheral heavy-ion collisions, where the nucleus fragments and produces > 100 particles
- The nucleus does not need to stay intact
- Explainable in a semi-classical approach $\sigma=|\Sigma_i A_i \exp(ikx_i)|^2$
  - Add the amplitudes for indistinguishable final states, then square
    - We cannot tell which nucleon contributed to the scatter
    - This would allow coherence for a broader range of reactions, including those with charge exchange

Other heavy exotica at colliders



HOW NEW TYPES OF FRUIT ARE DEVELOPED

https://xkcd.com/1949/

Conclusions

- ”Exotic charmonium” is a broad field, encompassing many hadrons, with different production mechanisms and characteristics
  - Most general exclusive channel is via γ + Reggeon interactions
    - Near threshold -> negative rapidity
      - Near edge of detector acceptance
  - $J^{PC}=1^{-}$ mesons can be produced via γ + Pomeron interactions
    - Over a wide rapidity range
  - $\gamma\gamma$ production expected, albeit at lower rates
- Most rates should be high enough for moderate-precision studies of charm-containing resonances
  - Exotic b-containing hadrons may eventually be within reach
- Production mechanisms, J^{PC}, relationships, branching ratios, etc.
  - If Γ_{ee} can be measured, can measure absolute branching ratios by comparing γp and γA rates

Backup…

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

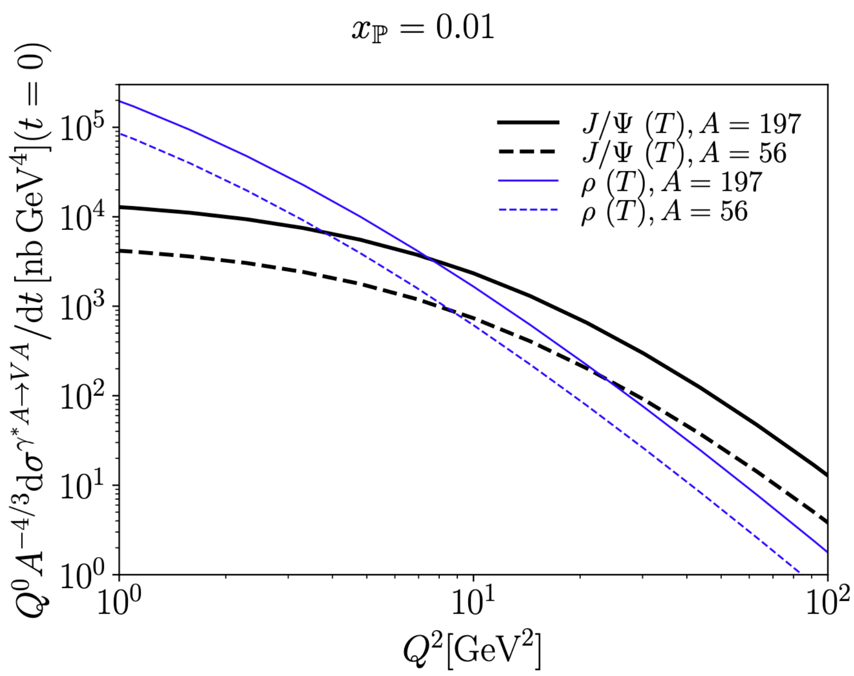


FIG. 6: The cross-section for coherent transverse vector meson production production at $t = 0$. It is Q^2 independent at low Q^2. The cross-section is scaled in A by the asymptotic analytical expectation $\approx A^{4/3}$.

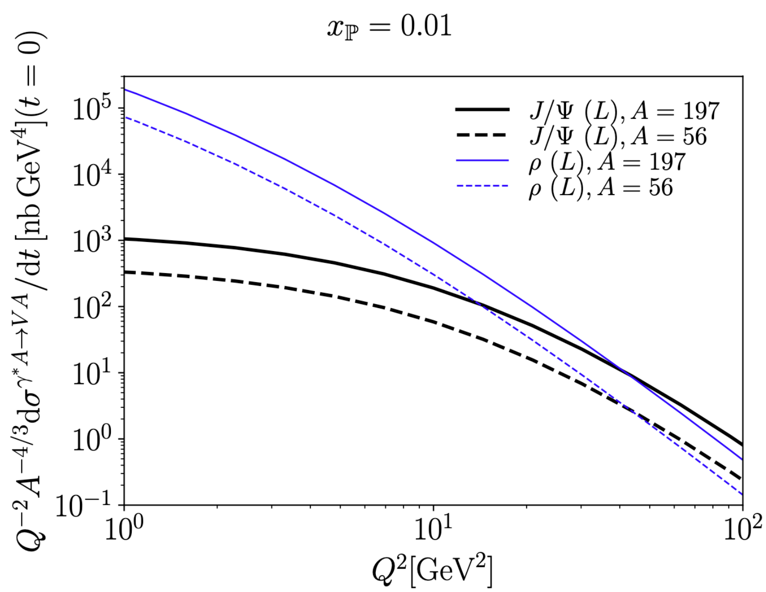


FIG. 5: The cross-section for coherent longitudinal vector meson production at $t = 0$. At low Q, the cross-section is flat at low Q^2 when scaled by Q^{-2}. For ρ, this behavior is only obtained at asymptotically small Q^2 values where our model is not applicable.The cross-section is scaled in A by 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.

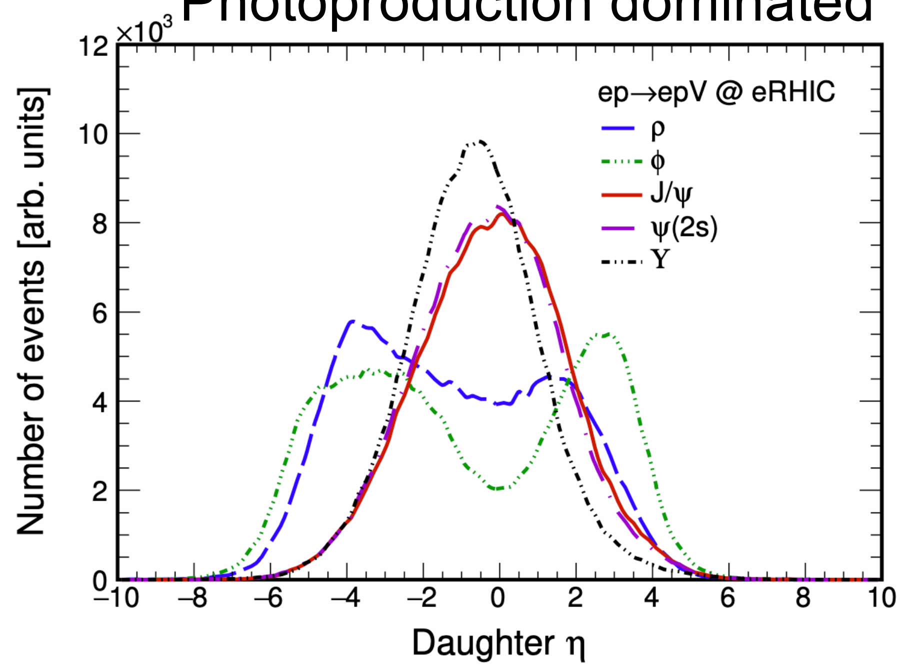
Υ(2S) Υ(3S) somewhat lower than Υ(1S)

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

Parent rapidity and daughter pseudorapidity

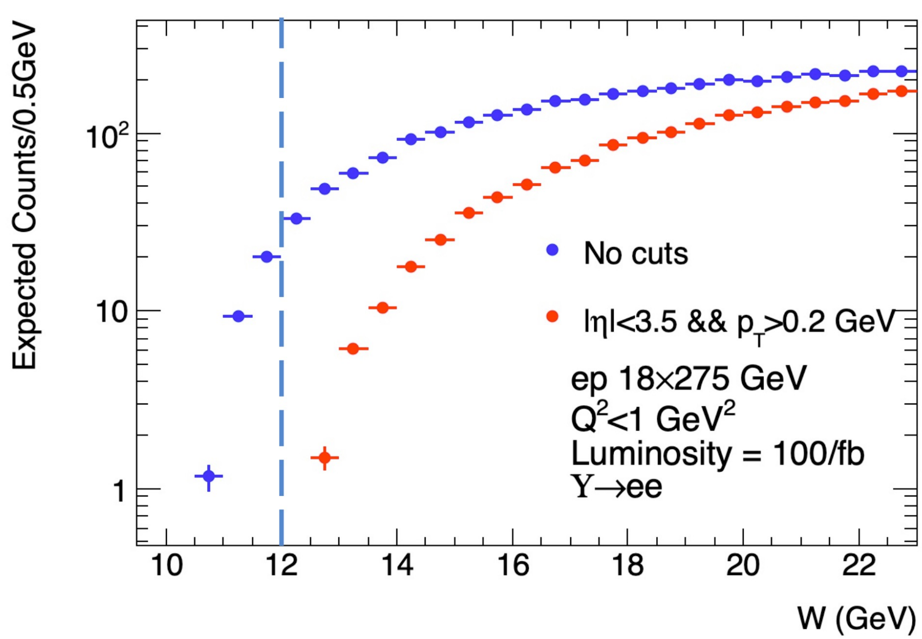
- Depends on Clebsch-Gordon Coefficients
  - VM-> 2 spin 0 mesons
  - VM -> 2 spin ½ leptons
    - Range of daughter leptons in η ~ range of parent y +1
- For J/ψ need to cover $|\eta|< \sim 4$
  - Beyond reach of proposed EIC detectors
- Detectors covering $|\eta|<3.5$
  - Cannot see lowest-x region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

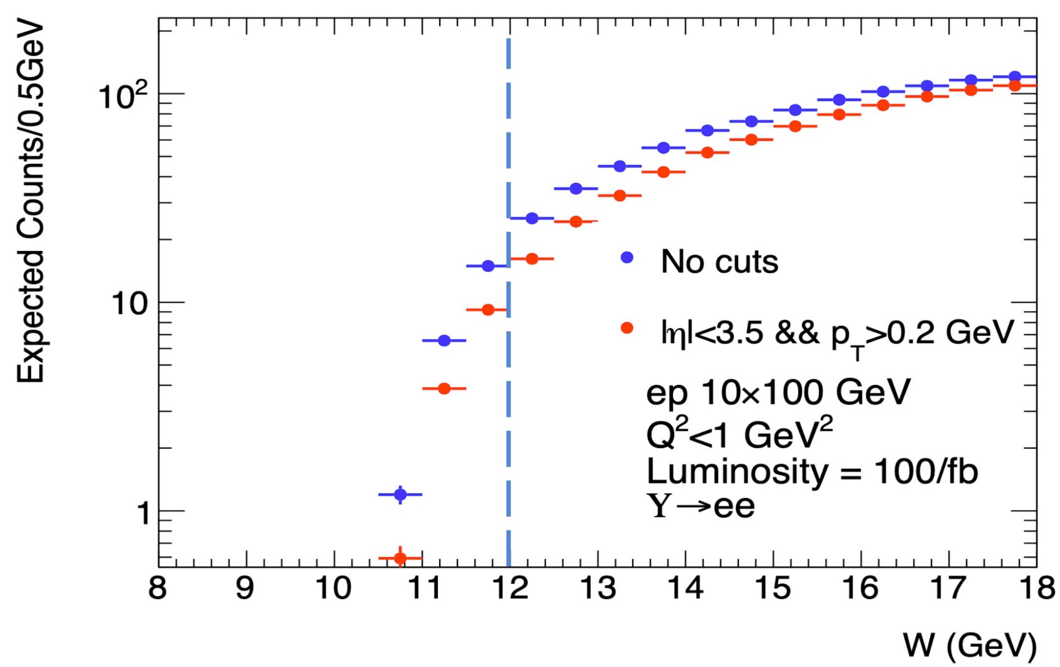
Photoproduction dominated



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

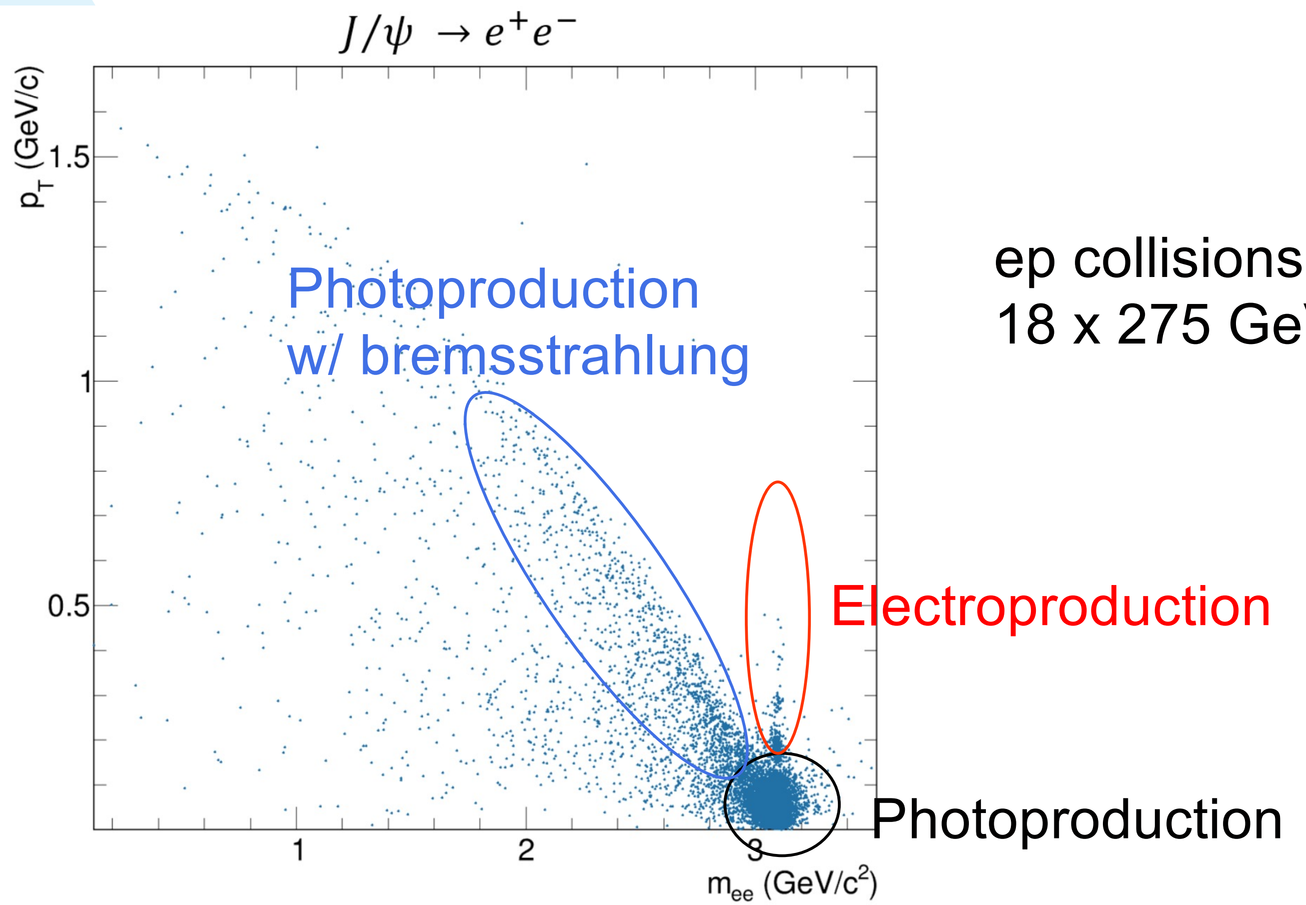




Plots by Yuanjing Ji (LBNL)

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

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

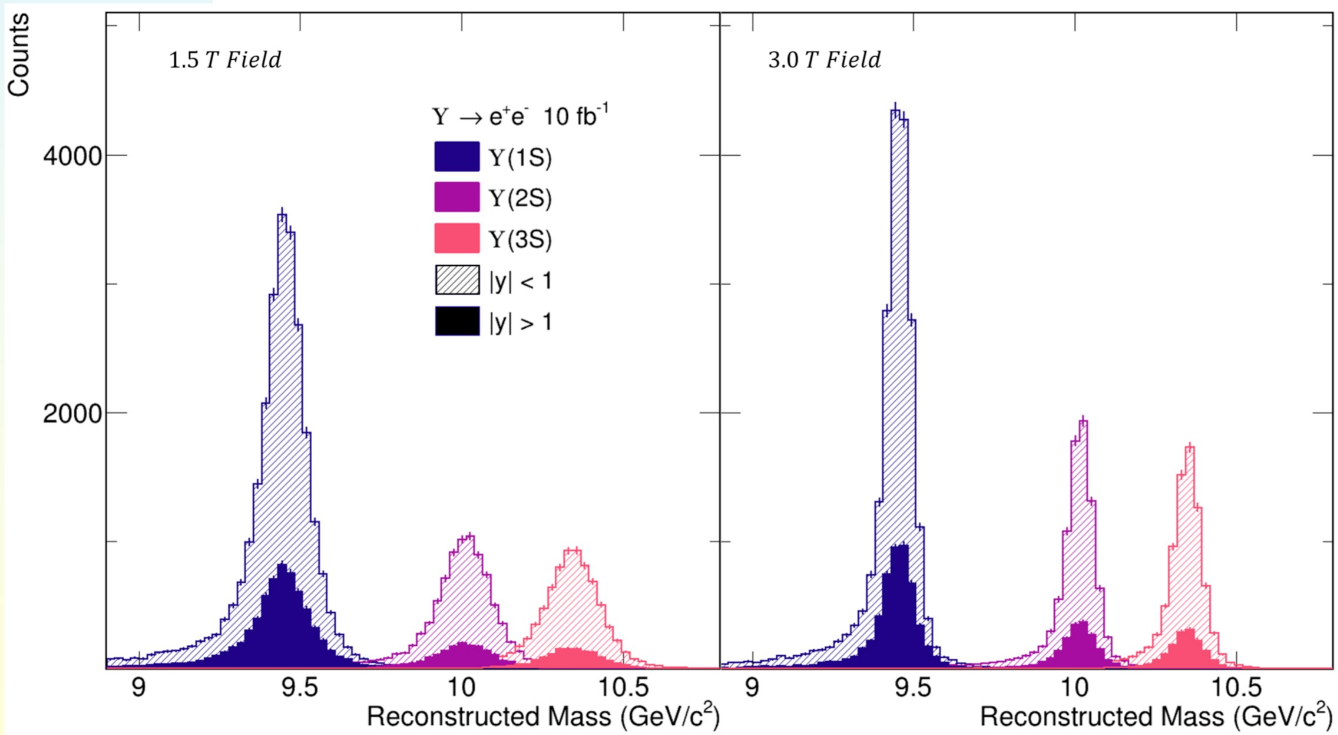


ep collisions
18 x 275 GeV

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

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

- Requires $\sigma(M_{ll})$ < ~ 100 MeV
- $\sigma(p)$ ~ < 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

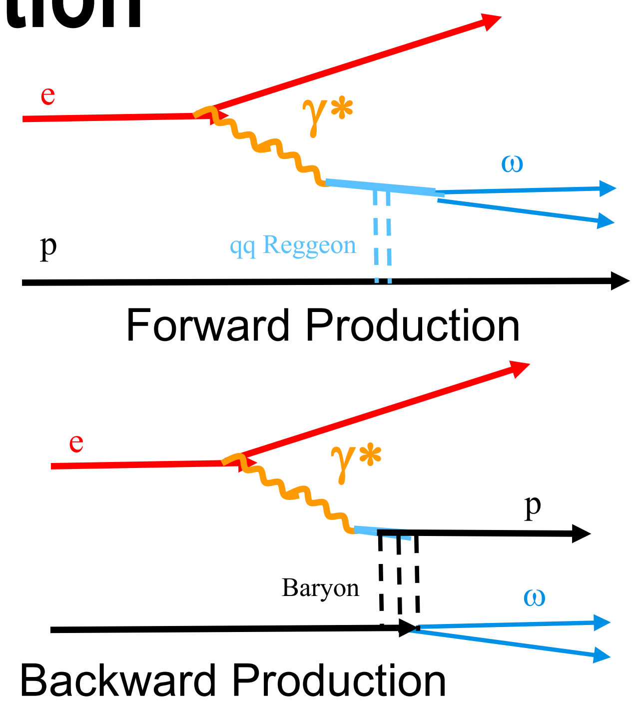


Separation in the all-silicon reference design, in 1.5 & 3.0 T fields

J. Arrington et al., arXiv:2103.08337

Backward (u-channel) J/ψ production

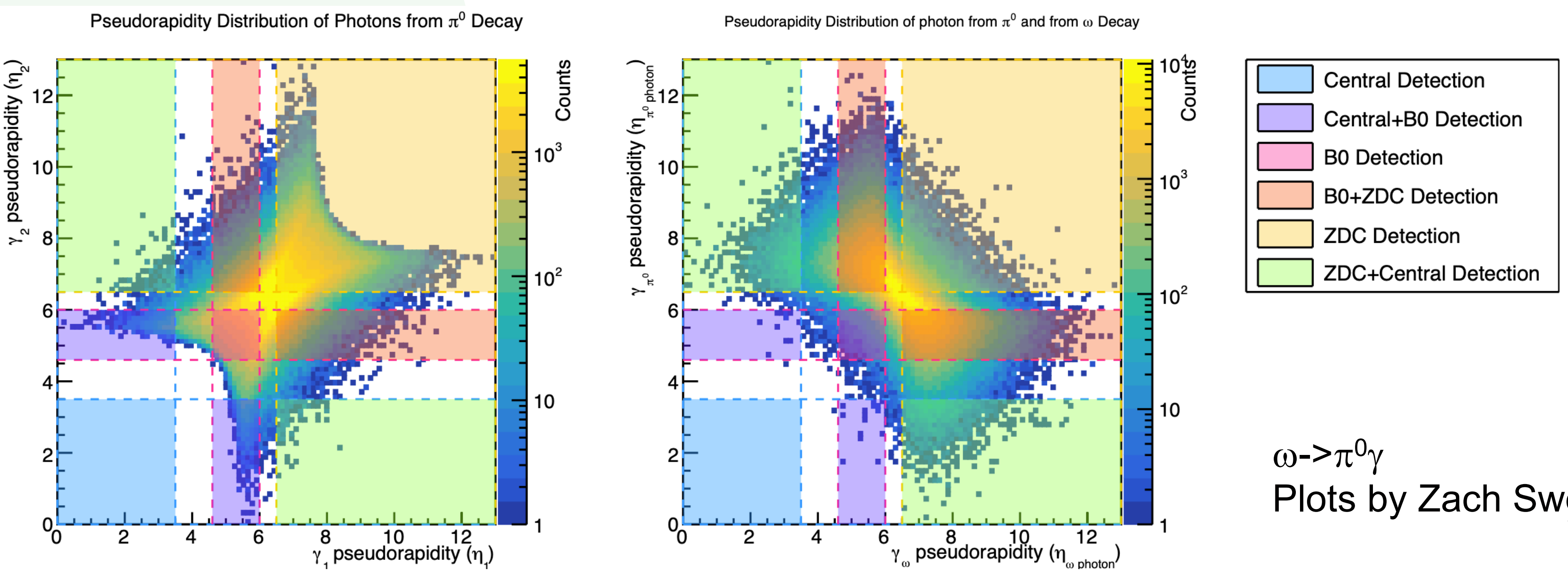
- t is large and u is small
  - In γp center-of-mass frame, meson and proton switch places
  - The meson is far-forward, while the proton is at mid-rapidity
- Studied at fixed target accelerators
  - Only light mesons
    - Proton and meson share quark flavors
    - Production models using Transition 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 ($\eta>6.5$)
  - 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 $<\eta>$
  - B0 and central detector



$\omega\text{->}\pi^0\gamma$

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.

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

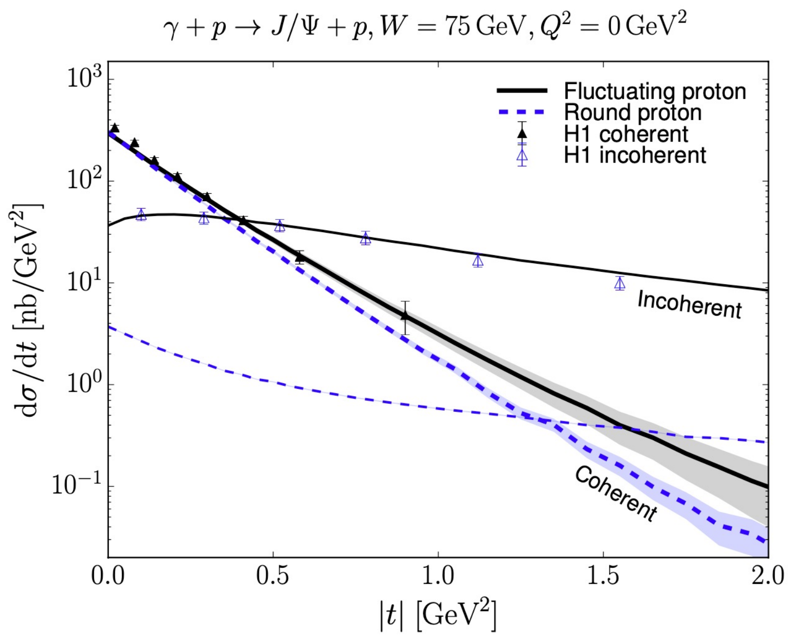
$$\frac{d\sigma_{\mathrm{coh}}}{dt} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$ Average amplitudes (Ω)

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

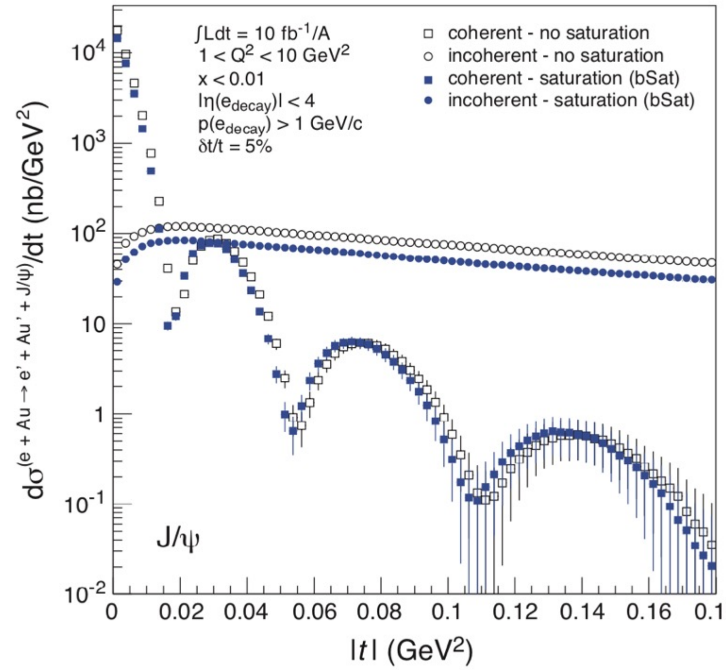
- Fit coherent and incoherent production together
  - Fluctuating protons greatly preferred!
- Fluctuations are energy dependent
  - As energy rises there are more hotspots-> $\sigma_{incoherent}$ rises
  - At very high energies, there is a black disk -> > $\sigma_{incoherent}$ -> 0
- For ions, there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



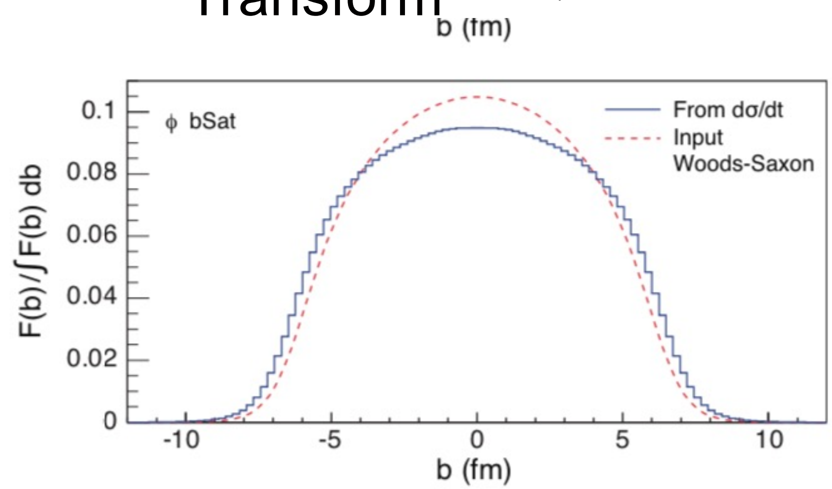
Mantysaari and Schenke, Phys. Rev. D94, 034042 (2016)

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

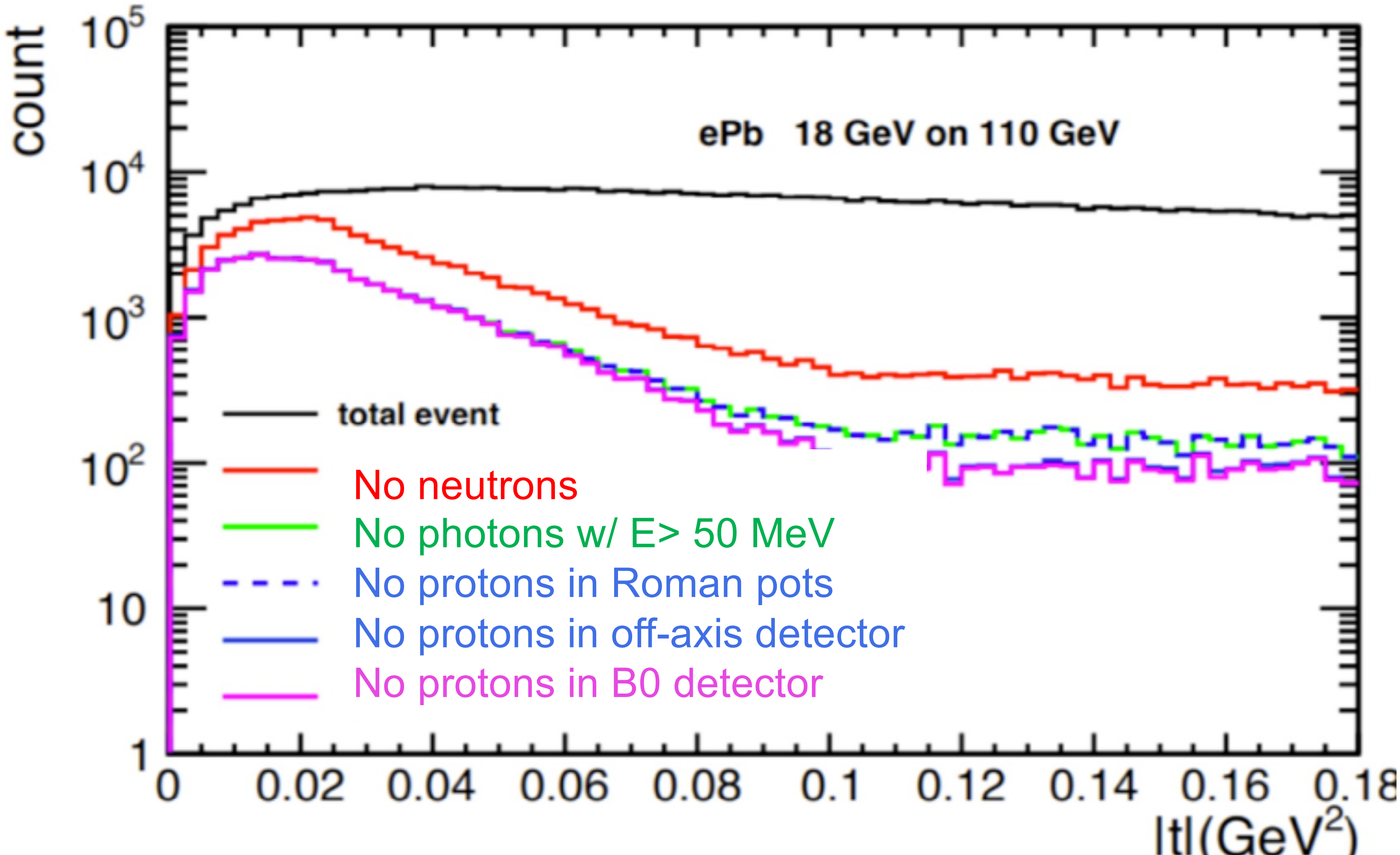
Models of Incoherent production

- 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 $d\sigma/dt$

- 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 $t \to 0$
- 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

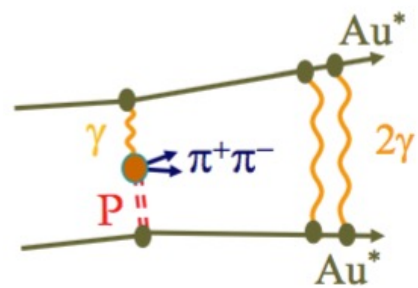
- The photons are Lorentz boosted
- Most hit the ZDC or B0 detector
- Maximum Lorentz boost is 2γ ~ 234 at full EIC ion energy
  - 600 MeV for 2.6 MeV lead photons
  - ~ 65 MeV for 270 keV gold photons
- Typical Lorentz boost is lower, and some photons are downshifted.
  - Lead is much easier than gold, 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).