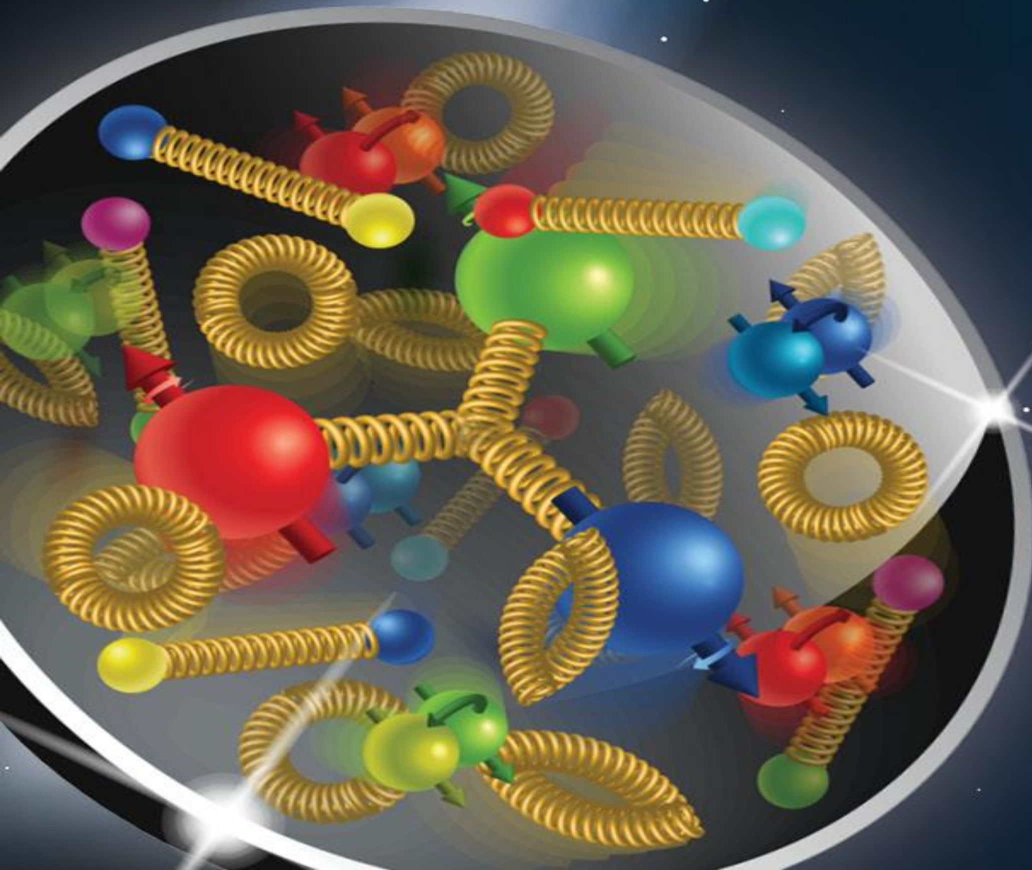
Exclusive quarkonia photoproduction simulation and physics at EICs



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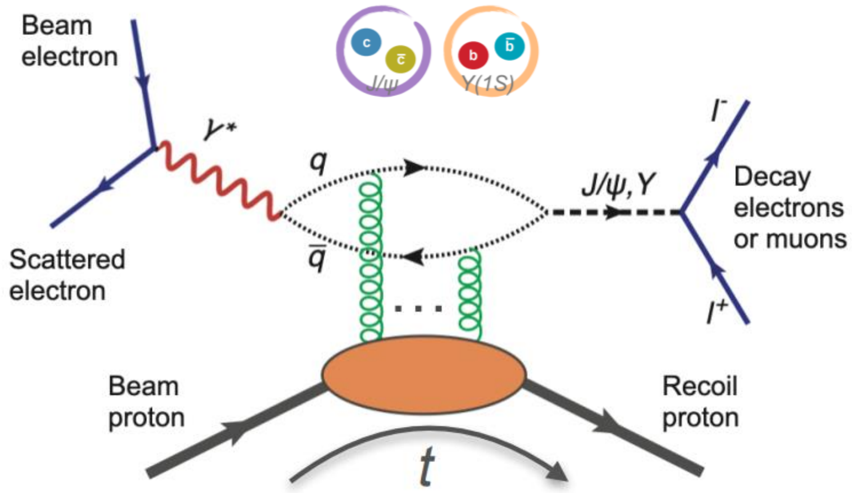
X. Li et al., NIMA 1048 (2023) 167956

ePIC Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY Office of Science

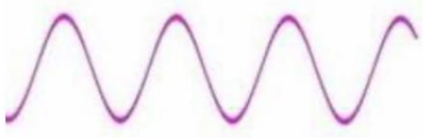
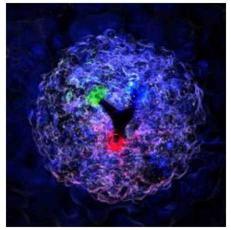
Process of interest



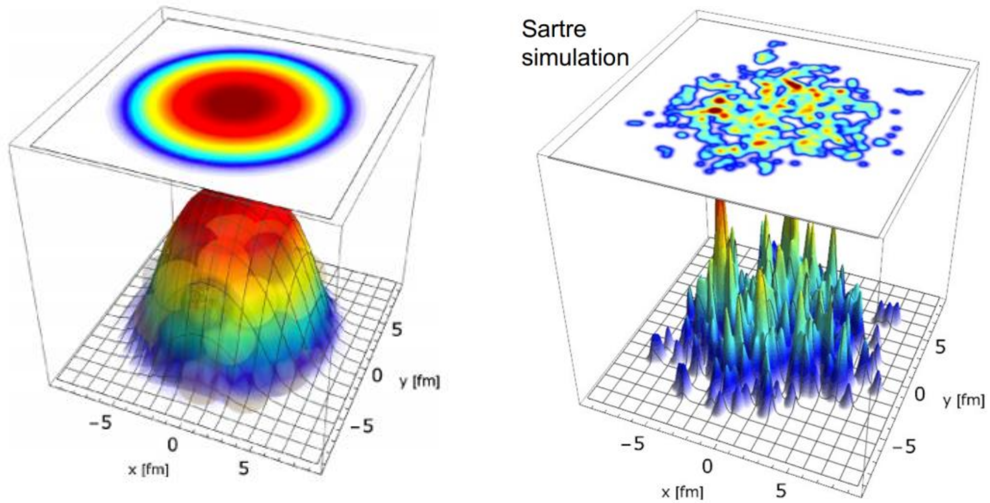
- The energy of photon decided the wave length and is related to the momentum fraction x of the detected partons (down to 5×10^{-4}).
- EIC will benefit from the large detector rapidity acceptance (-3.5-3.5) so that the maximum energy of photon could be close to the electron beam energy (5-18 GeV).

$$E_\gamma = \frac{M_v}{2} e^{-y}$$

between RHIC ~4GeV and LHC ~ 75-100 GeV

Diffraction pattern is like a CT scan for spatial and momentum distributions of gluons in nucleon/nuclei.

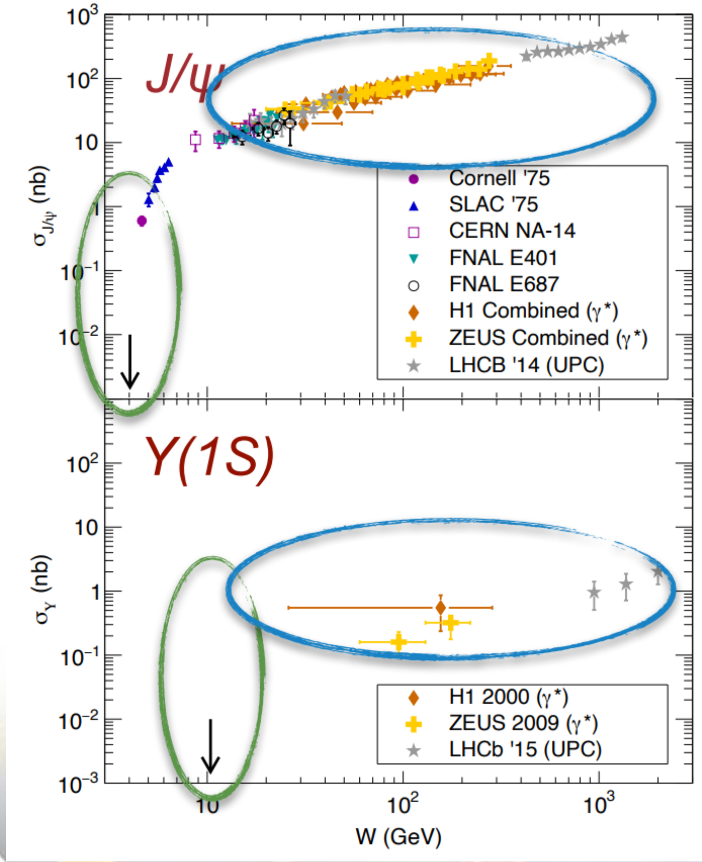


Gold nuclear gluon density profile (from Kong's slide) [made by A. Kumar (IIT, Delhi)]

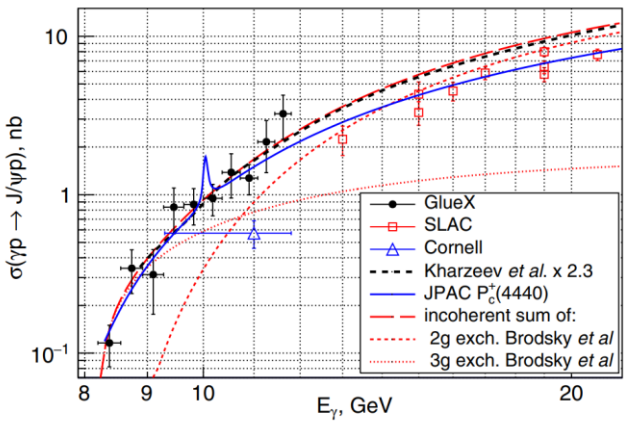
Coherent: photons interact with the whole nucleon/nucleus.
Incoherent: vector meson production with nucleon/nucleus excited.

What do we know?

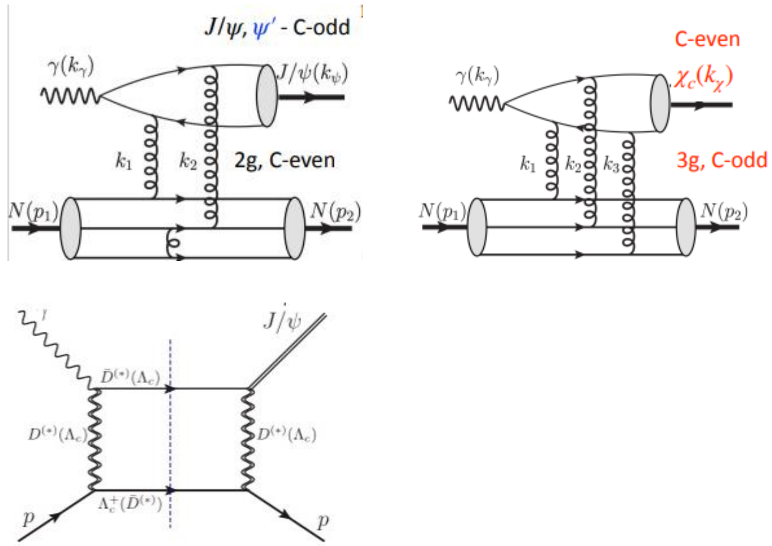
- Low momentum transfer ($t=P_T^2$) is dominated by coherent photoproduction.
- Strong proton shape fluctuations in incoherent diffraction… *H. Mantysaari and B. Schenke PRL 117 (2016) 052301*
- The ratio of the incoherent to coherent cross-section drops with increasing photon energy.
- …… *H. Mantysaari and B. Schenke PRD 98 (2018) 034013*



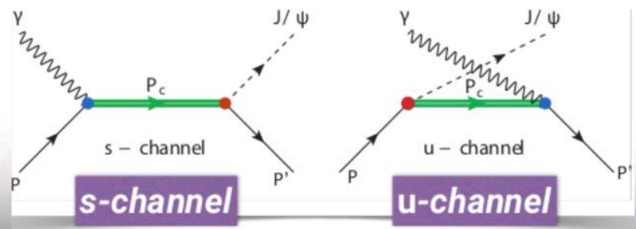
Near threshold production at JLab



Ali et al., PRL 123 (2019) 072001;
Brodsky et al., PLB 498 (2001) 23



- Set upper limits for P_c^+ channels



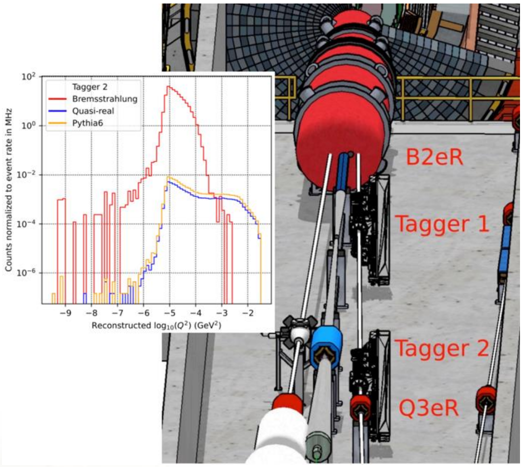
- Recent GlueX measurements have observed the higher mass C-even χ_c and possible evidence for production from open charm channel. (DIS 2023)

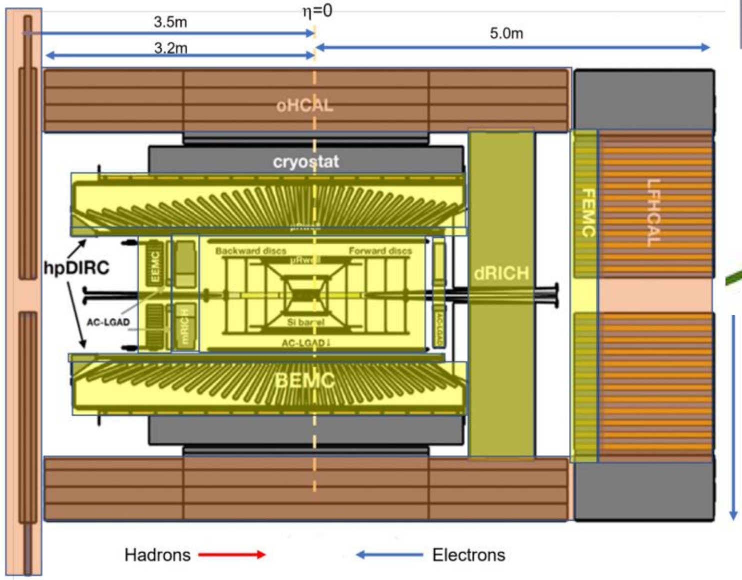
EIC detector overview

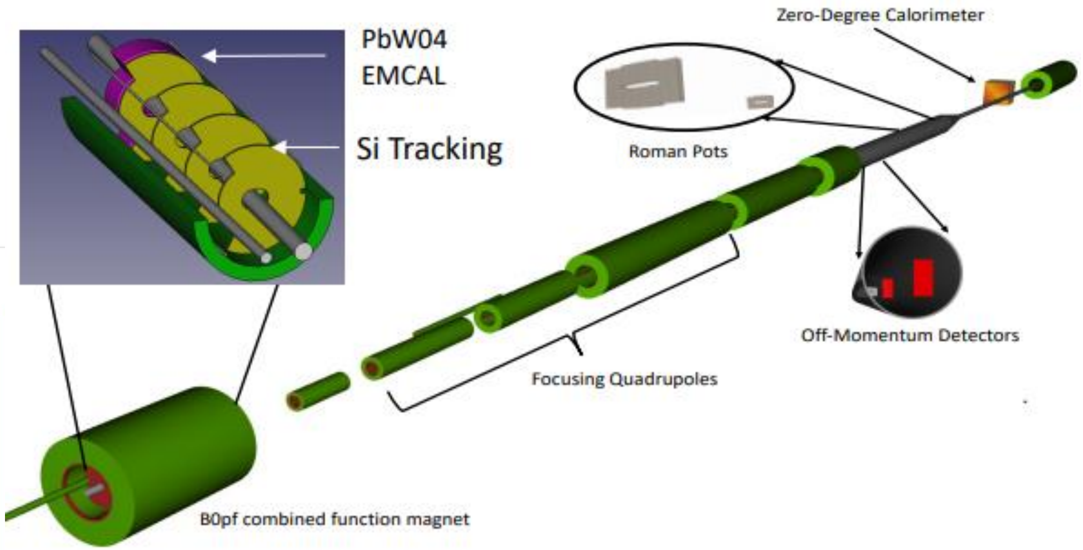
Exclusive measurements —— all final state particles could be detected (e', daughters of V, (p'))
[better t resolution; large Q^2 lever arm to reduce model dependence; allow to analyze photon flux and gluon density separately.]

ePIC Detector Design (Current)

Far-Backward Detectors
- Luminosity monitor
- Low-Q^2 Tagging Detectors







Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0* <θ< 5.0 mrad (η> 6)
Off-Momentum Detectors (2 stations)	0.0* <θ< 5.0 mrad (η> 6)
B0 Detector	5.5 <θ< 20.0 mrad (4.6 <η< 5.9)

Clean photoproduction signal for $10^{-3} < Q^2 < 10^{-1}$

Reference: ePIC wiki page: Electron-Proton/Ion Collider Experiment

Theoretical framework to estimate the yield

Equivalent photon approximation vector meson dominate model (EPA-VPD) with several modifications.

$$\sigma(eA \to eAV) = \int \frac{dW}{W} \int dk \int dQ^2 \frac{d^2N_\gamma}{dkdQ^2} \sigma_{\gamma^* A \to VA}\left(W, Q^2\right),$$

$$\frac{d^2N_\gamma}{dkdQ^2} = \frac{\alpha}{\pi k Q^2}\left[1 - \frac{k}{Ee} + \frac{k^2}{2E_e^2} - \left(1 - \frac{k}{Ee}\right)\left|\frac{Q^2_{\min}}{Q^2}\right|\right].$$

$$\sigma_{\gamma^* A \to VA}\left(W, Q^2\right) = f\left(M_V\right)\sigma\left(W, Q^2 = 0\right)\left(\frac{M_V^2}{M_V^2 + Q^2}\right)^n$$

$$n = c_1 + c_2\left(Q^2 + M_V^2\right),$$

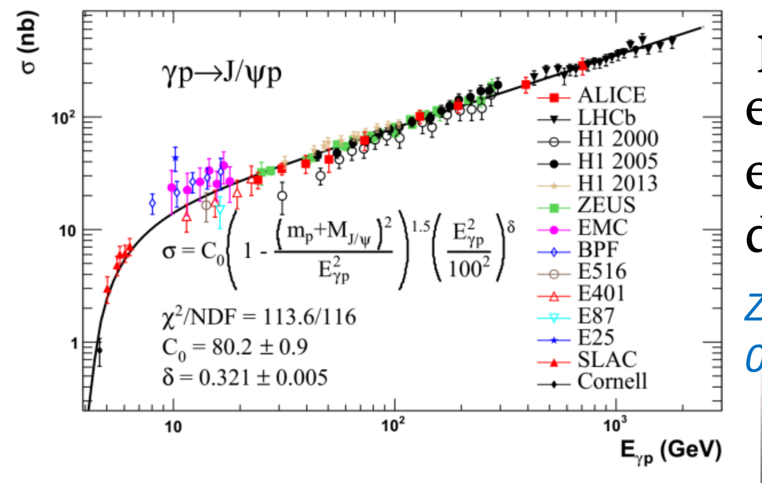
$$\sigma\left(W, Q^2 = 0\right) = \int_{t_{\min}}^{\infty} dt \frac{d\sigma(\gamma A \to VA)}{dt}\bigg|_{t=0} |F(t)|^2,$$

<u>event observable reconstruction</u>

$$W_{\gamma p} = \sqrt{m_p^2 + 2m_p E_\gamma}, \quad E_\gamma = \frac{M_v}{2} e^{-y}, \quad x = \frac{M_V e^y}{2E_N},$$

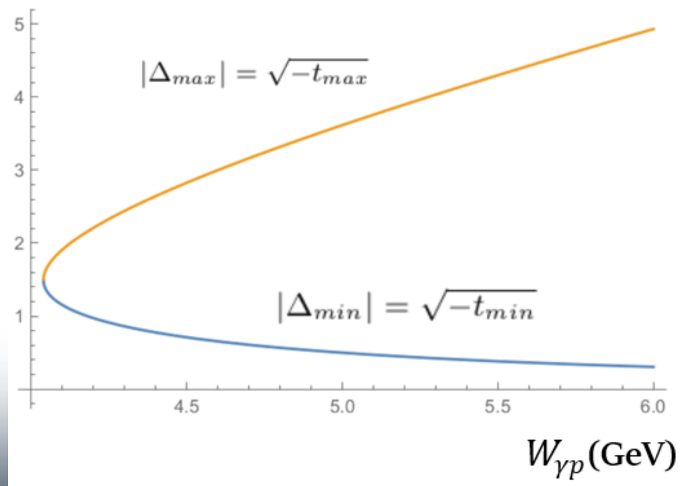
$$Q^2 = -q^2 = -(l - l')^2, \quad t = -(p' - p)^2$$

<u>All of them could be precisely measured!</u>



pQCD motivated expression fitting of exist experimental data for $\sigma_{\gamma p \to J/\psi p}$

Z. Cao et al., CPC 43 (2019) 064103

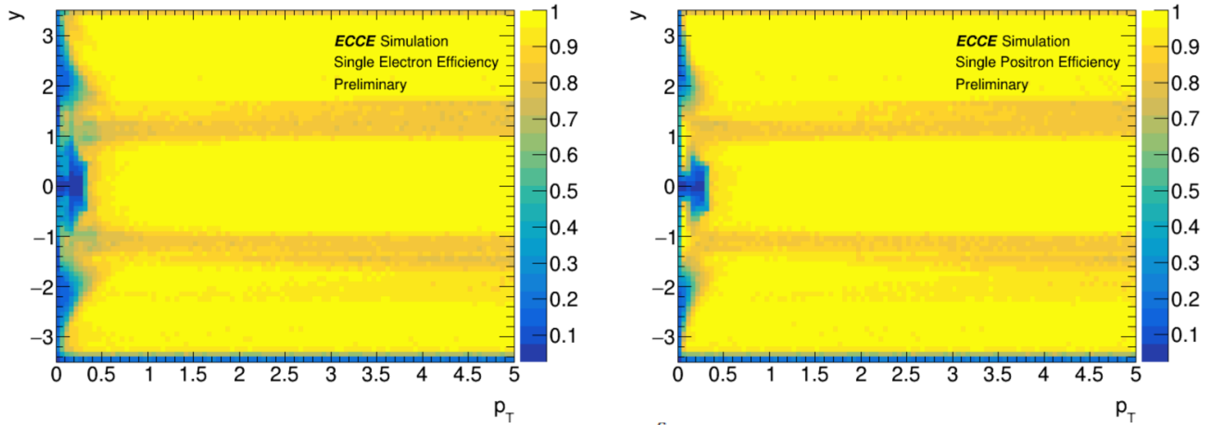


t limitation when center of γp mass is close to J/ψ threshold

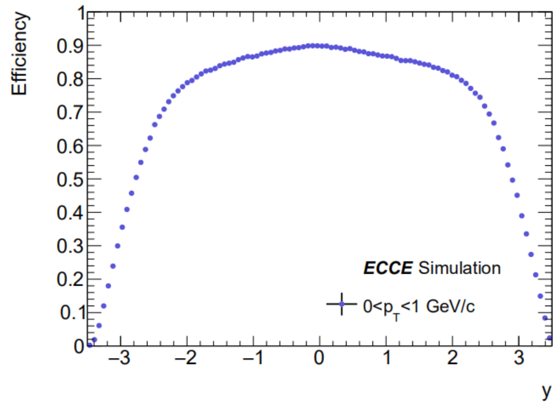
Differential yield prediction

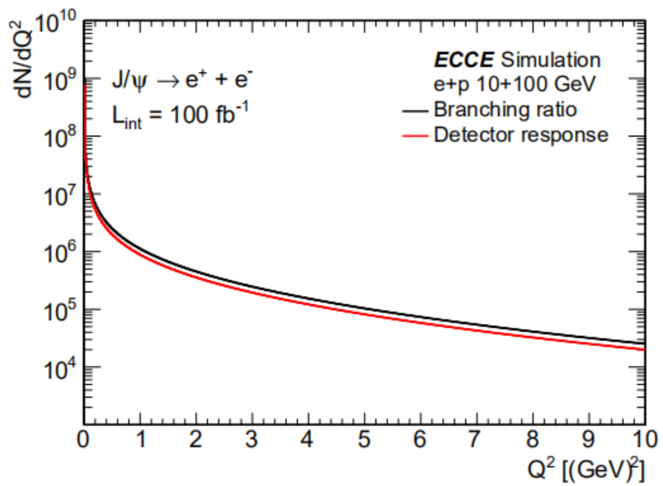
A prediction for the yield of J/ψ photoproduction at EIC (EicC) with fast efficiency correction.

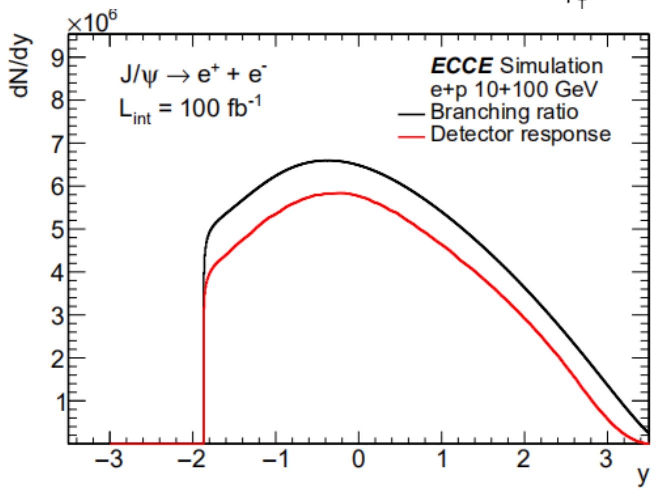
Single track efficiency. Left Panel: e^- efficiency. Right Panel: e^+ efficiency

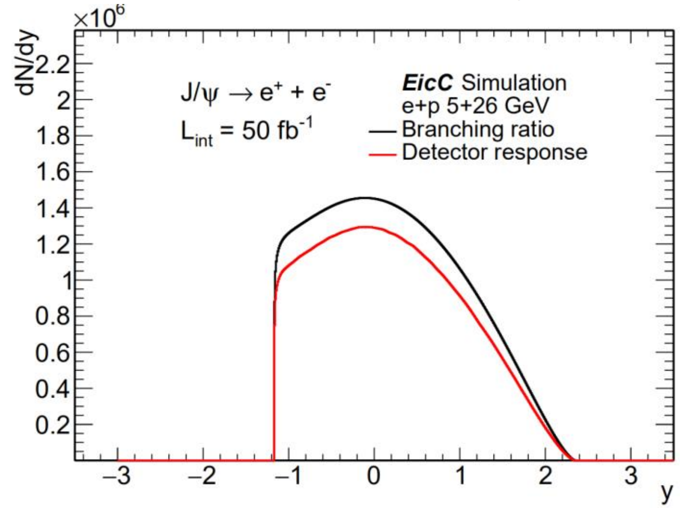


J/ψ tagging efficiency









- Results for more beam energy sets could be found in Backup.
- Amounts of photo-produced J/ψ would be measured at EIC and EicC.
- Anticipated 10^{34} $cm^{-2}s^{-1}$ luminosity on HIAF.

X. Li et al., NIMA 1048 (2023) 167956

Probe nuclear gluon profile

The powerful probe of nuclear gluon multi-dimensional distributions:

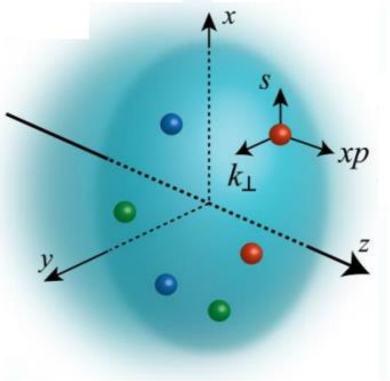
Generalized transverse momentum dependent parton distributions (GTMDs) / Wigner Function

$w_p^u(x, k_T, r_T)$

5D Dist.

$d^2 r_T$ $d^2 k_T$

Transverse Momentum Dep. Dist. (TMDs)

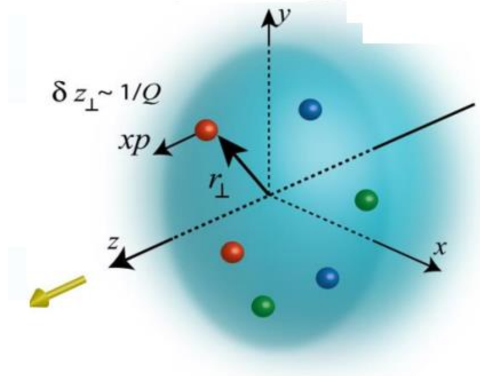


$f_1^u(x, k_T)$
$h_1^u(x, k_T)$

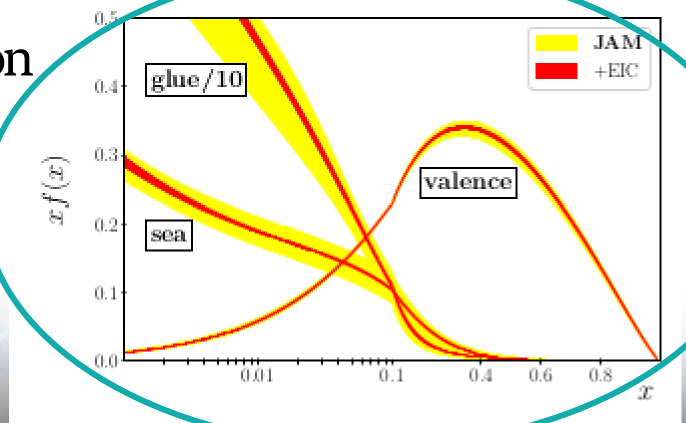
"3D" imagining

Generalized Parton Dist. (GPDs)

GPD



Parton Distribution Functions (PDFs)
x is available.



Fourier transform

$$f(x, b, Q^2) \equiv \int \frac{d^2\Delta}{(2\pi)^2} e^{-i(\boldsymbol{\Delta b})} \, \mathrm{GPD}(x, t = -\boldsymbol{\Delta}^2, Q^2)$$

Imaging in position space

Probe nuclear gluon profile — PDF

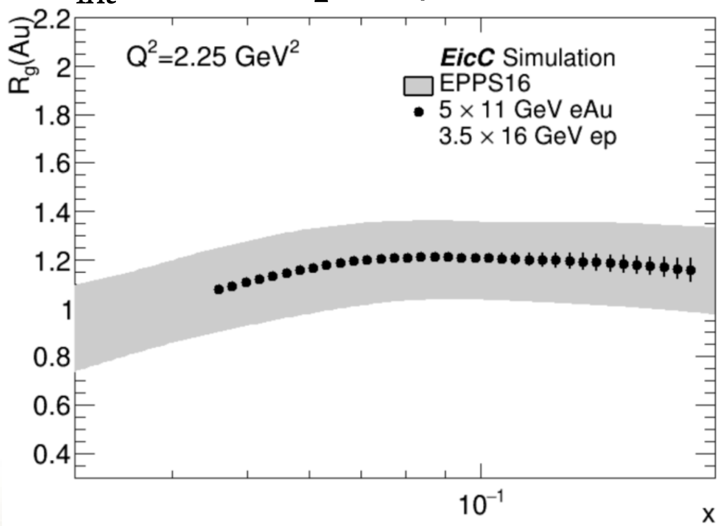
Nuclear parton distribution functions (nPDF) describe the behavior of bound partons in the nucleus. (Recently gluon shadowing exhibited by J/ψ photoproduction data from LHC have little impact on it.)

B. Abelev, et al., PLB 718 (4) (2013) 355 1273–1283. *V. Khachatryan, et al., PLB 772 (2017) 489–511*

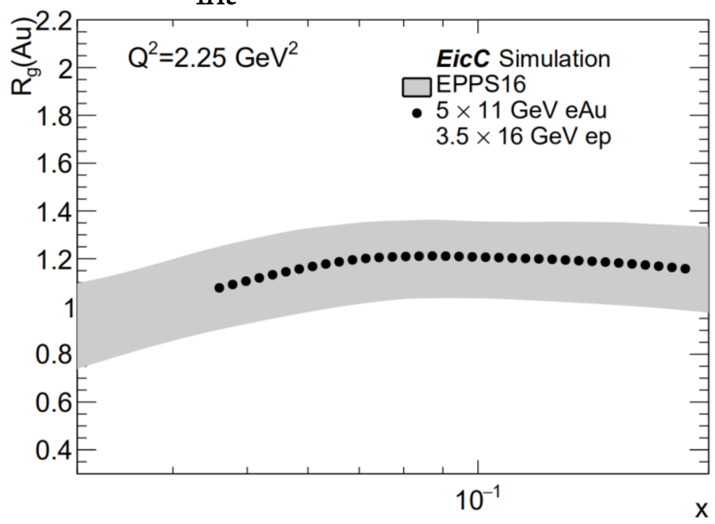
$$\left.\frac{d\sigma(\gamma A\rightarrow VA)}{dt}\right|_{t=0}=\frac{\alpha_s^2\Gamma_{ee}}{3\alpha M_V^{\xi}}16\pi^3\left[xg_A(x,\mu^2)\right]^2$$

$$R_g=\sqrt{\frac{\left.\frac{d\sigma(\gamma A\rightarrow VA)}{dt}\right|_{t=0}}{\left.\frac{d\sigma(\gamma p\rightarrow Vp)}{dt}\right|_{t=0}}}$$

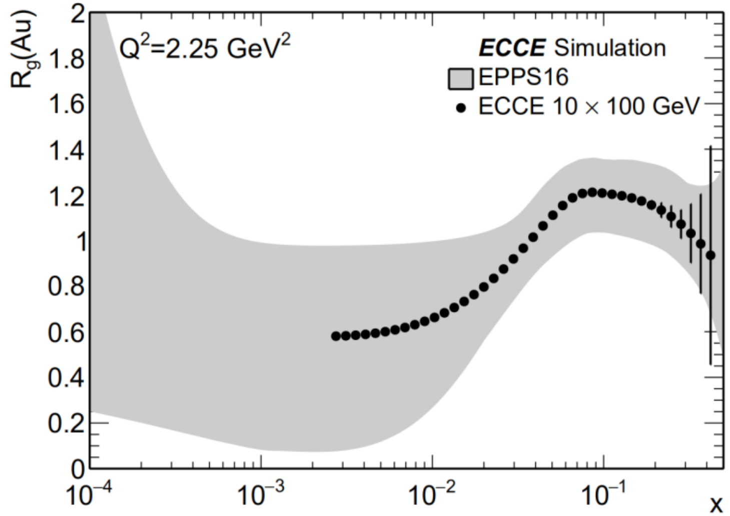
L_{int}=50 fb^{-1} ep; 50/197 fb^{-1} eAu



L_{int}=20 fb^{-1} eAu



L_{int}=100 fb^{-1} ep; 10/197 fb^{-1} eAu



- ➢ One of the advantages of photon gluon fusion to extract PDF is that low x is dominated by gluons (significant constrain power)

X. Li et al., NIMA 1048 (2023) 167956

- ➢ Little is known about anti-shadowing at x ~ 0.1. x could down to 5×10^{-4} for ep 18+275

Electron-Ion Collider

Probe nuclear gluon profile — GPD

unpolarized gluon GPD

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

$$F(b) \;=\; \frac{1}{2\pi}\int_0^\infty d\Delta\cdot\Delta J_0(\Delta b)\sqrt{\frac{d\sigma_{\text{coherent}}}{d|t|}(\Delta)}\,\Bigg|_{\text{mod}}$$

***t*-spectra**

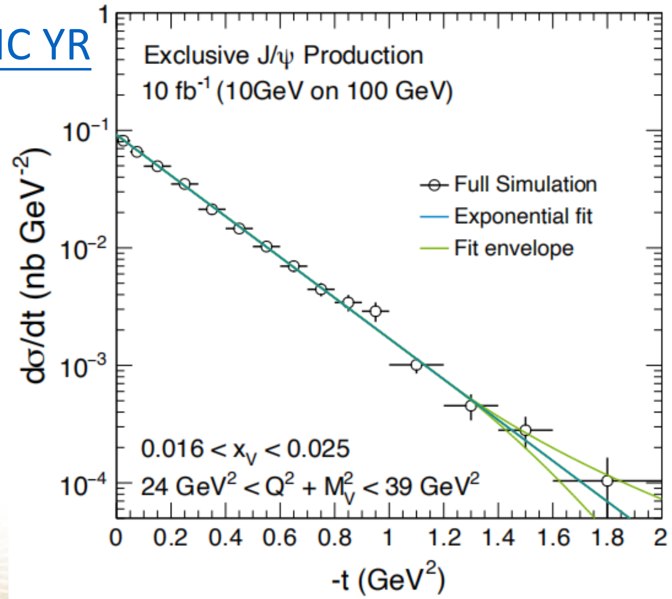
Only possible at an EIC:
from the valence region
deep into the sea!

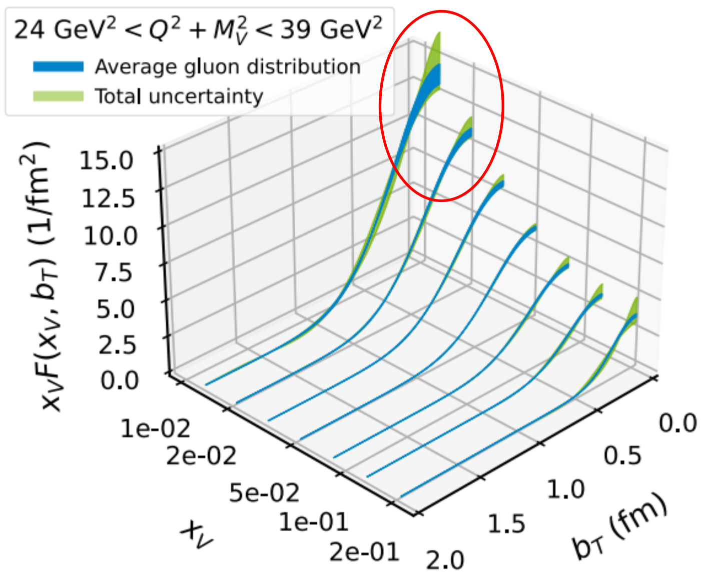
Normalized average gluon density

Hard scale: $Q^2 + M_V^2$

Modified Bjorken-x: $x_V = \dfrac{Q^2 + M_V^2}{2p\cdot q}$

From EIC YR





- **Remarks:**
  - **Simplest** possible GPD extraction
  - Intrinsic systematic uncertainty due to **extrapolation** outside of measured *t*-range
  - **NLO effects** could be significant
    - Corrections expected to be smaller for *Y(1s)* than for *J/ψ*

Slide from S. Joosten

High suppression ratio of coherent to incoherent should be guaranteed for measurements of coherent process to probe nuclear shape or structure! (coherent/incoherent > 500)

Probe nuclear gluon profile — t distribution

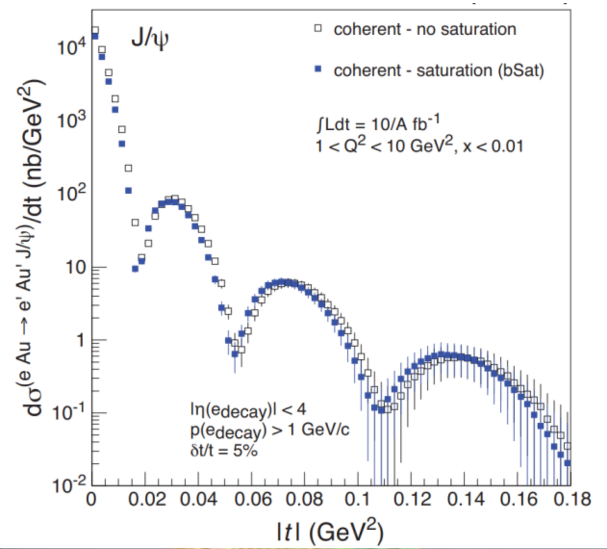
- Exclusive and diffractive vector meson production as a golden channel to precisely probe t
- Several methods have been investigated to reconstruct t when scattered ion beam is invisible

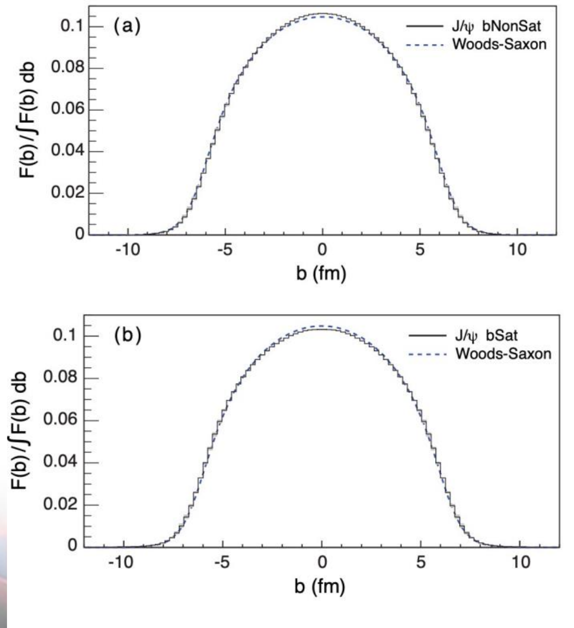
Exact (E):	$-t = -(\boldsymbol{p}_{e}-\boldsymbol{p}_{e'}-\boldsymbol{p}_{VM})^2 = -(\boldsymbol{p}_{A'} - \boldsymbol{p}_{A})^2$
Approximate (A):	$-t = (p_{T,e'}+p_{T,VM})^2$
Exclusivity corrected (L):	$-t = -(\boldsymbol{p}_{A',corr} - \boldsymbol{p}_{A})^2$,

where $p_{A',corr}$ is constrained by exclusive reaction.

Besides the slope for t distributions, the shape is also sensitive to gluon spatial distributions.

EIC YR, Toll & Ullrich (2012)





From EIC Yellow Report (YR), the best method is method L:

- t resolution is sensitive to momentum spread beam effect at low t close to t_{min}.
- More precise than Method A for electroproduction.

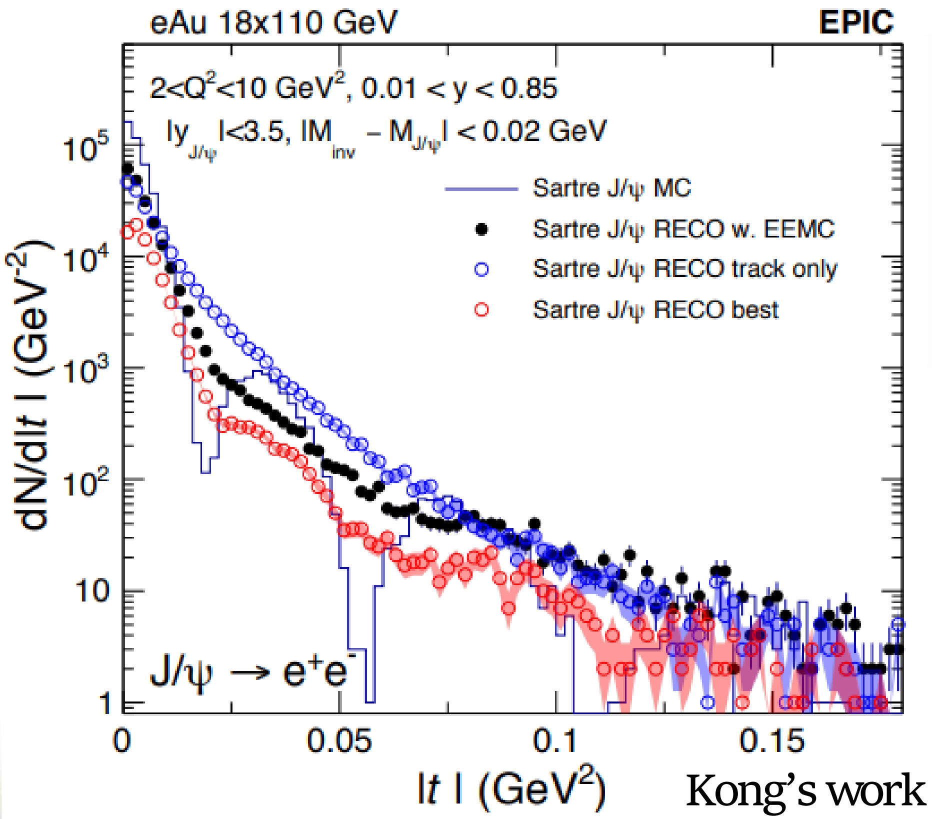
EIC YR

From Kong's slide in DIS 2023

Probe nuclear gluon profile — t distribution

- First full ePIC simulation (current ePIC detector) in an unified and modern software framework (2023).
- Bottle neck is scattered electron detection.
- State of the art theoretical study from EIC theory group for the smearing of the dips (Coulomb interaction).

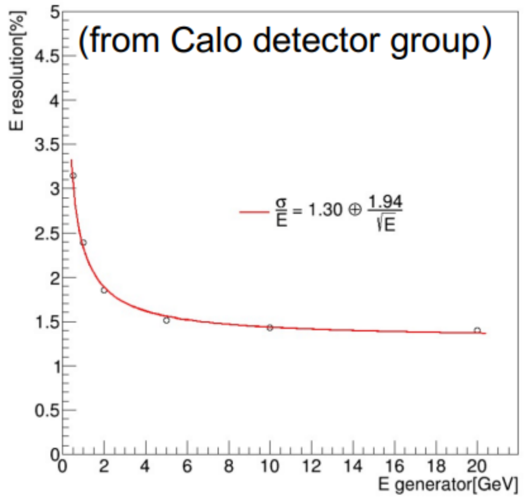
X. Roca-Maza et al., PRC 78 (2018) 044332



Kong's work

Legend details:
- w. EEMC, electron energy from EEMC, angle from tracking
- Track only: all from tracking
- Best: average of the above 2 E-by-E

~ 1.5% energy resolution for EEMC

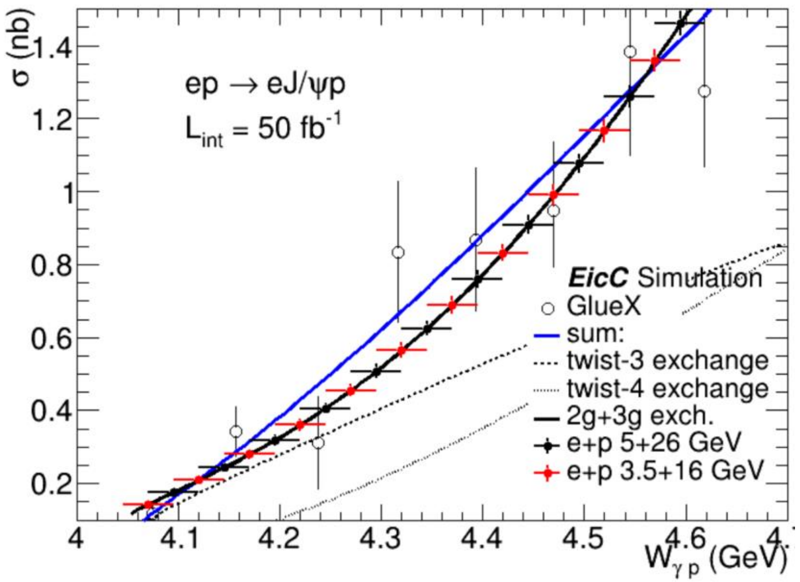


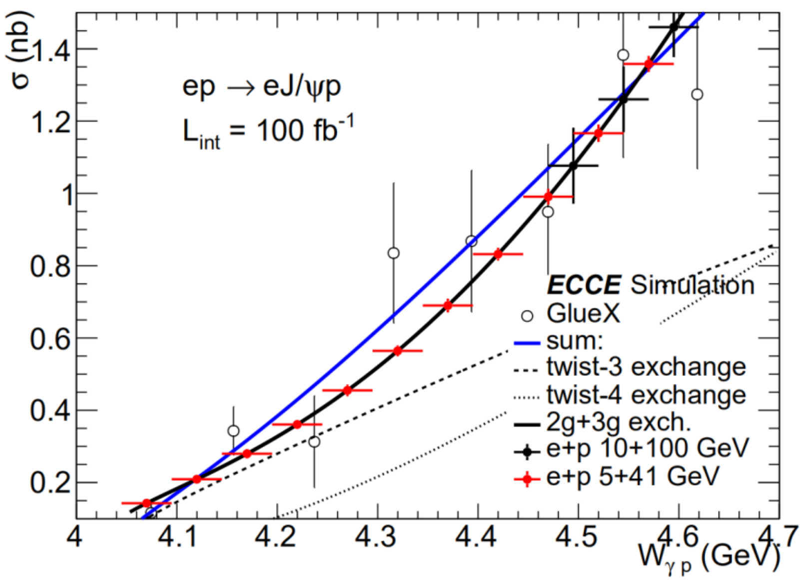
- For lower electron energy, there will be longer transit time through the nucleus for the coulomb interaction.
- Generally we thought the lifetime of the dipole is longer than the transit time (fixed configuration).

Near-Threshold Production Mechanism

- 2g+3g is still used to describe the GlueX data in YR.
- Higher-mass charmonium states C-even χ_c with 3g exchange.
- EIC, EicC and (JLab) can dramatically improve the statistics near threshold to optimize models

X. Li et al., NIMA 1048 (2023) 167956





- The uncertainty of the prediction (red and black points) is obviously smaller than the discrepancy between models. (more beam configuration choices for EicC)
- Further study should focus on the problem: find a kinematic region to separate the gluon exchange, open-charm exchange, or any other contribution.

New power law twist 3+4 form factor, 5?

$$\frac{d\sigma}{dt}\Big|_{(-t)\gg\Lambda^2_{QCD}} = \frac{1}{16\pi(W^2_{\gamma p} - M^2_p)^2}\left(|\overline{\mathcal{A}_3}|^2 + |\overline{\mathcal{A}_4}|^2\right)$$
$$\approx \frac{1}{(-t)^4}\left[(1-\chi)\mathcal{N}_3 + \widetilde{m}^2_t\mathcal{N}_4\right],$$

P. Sun et al., PLB 822 (2021) 136655

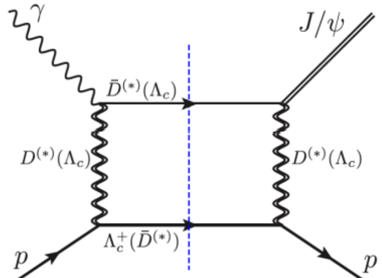
2g+3g C-odd and C-even

$$\frac{d\sigma}{dt} = \mathcal{N}_{2g}v\frac{(1-x)^2}{R^2\mathcal{M}^2}F^2_{2g}(t)\left(W^2_{\gamma p} - m^2_p\right)^2$$

$$\frac{d\sigma}{dt} = \mathcal{N}_{3g}v\frac{(1-x)^0}{R^4\mathcal{M}^4}F^2_{3g}(t)\left(W^2_{\gamma p} - m^2_p\right)^2$$

S.J. Brodsky, et al., PLB 498 (2001) 23–28

alternative production mechanism!



Open charm exchanges.
Possible pentaquark state?

Proton shape and mass structure

- The latest measurements of this process carried out by JLab to answer the fundamental questions of proton mass radius and mass structure. *Z.-E. Meziani et al., Nature 615 (2023) 813–816*
- EIC, EicC and JLab (CLAS 12 with upgrade and SoLID) are promising to further address on them.
- Although no direct relationship with gravitational form factor (GFF), theorists insist the forward amplitude is an important observable to understand mass decomposition.

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s}\frac{1}{|p_{\gamma cm}|^2}(Q_e c_2)^2\left(\frac{16\pi^2 M}{b}\right)^2 G(t)^2, \qquad \langle r_m^2\rangle = \frac{6}{M}\frac{dG}{dt}|_{t=0} = \frac{12}{m_s^2}$$

$$M_N = M_m + M_q + M_g + M_a$$

Ji, PRD 52 (1995) 271; Hatta and Yang, PRD 98 (2018) 074003

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b\, m_p$$

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) m_p$$

$$M_g = \frac{3}{4}(1-a)\, m_p$$

$$M_a = \frac{1}{4}(1-b)\, m_p$$

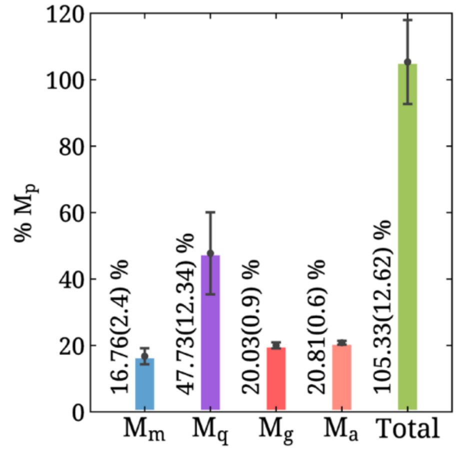
$$T^\mu_\mu = \frac{\tilde{\beta}(g)}{2g} G^2 + \sum_{q=u,d,s} m_q(1+\gamma_m)\bar{\psi}_q\psi_q$$

Trace Anomaly — Light Quark Mass

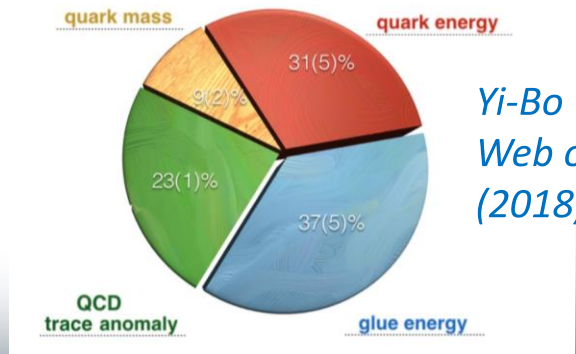
$$\left.\frac{d\sigma_{\gamma N\to J/\psi N}}{dt}\right|_{t=0} = \frac{3\Gamma(J/\psi\to e^+e^-)}{\alpha m_{J/\psi}}\left(\frac{k_{J/\psi N}}{k_{\gamma N}}\right)^2 \left.\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}\right|_{t=0}$$

$$F_{J/\psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - \left\langle N\left|\sum_{i=u,d,s} m_i \bar{q}_i q_i\right|N\right\rangle\right)$$
$$\simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - 2bM_N^2\right)$$
$$\simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2 \boxed{(1-b),}$$

$$\left.\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}\right|_{t=0} = \frac{1}{64\pi}\frac{1}{m_{J/\psi}^2(\lambda^2 - m_N^2)}|F_{J/\psi N}|^2.$$



C. Alexandrou et al., (ETMC), PRL 116, 252001 (2016)



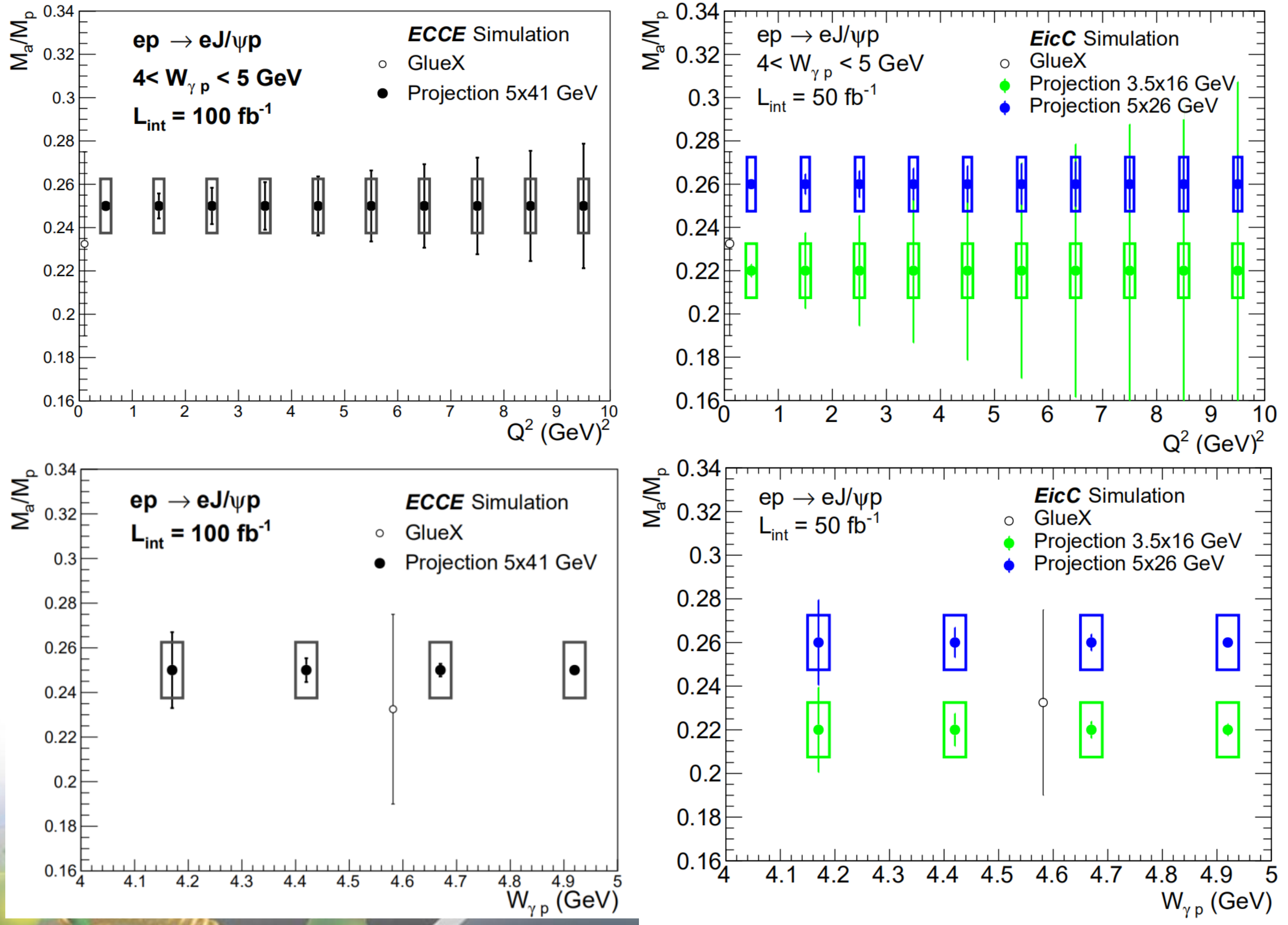
Yi-Bo Yang et al, EPJ Web of Conferences 175, (2018) 14002

Trace anomaly prediction at EIC/EicC

New HMS+SHMS results with dipole GFF fit at JLab (W in 4.36-4.55 GeV) have comparable uncertainty with prediction at W in 4.04-4.29 GeV. *Z.-E. Meziani et al., Nature 615 (2023) 813–816*

Q^2 distribution

W distribution



GlueX data from R. Wang et al., EPJC 80 (2020) 507

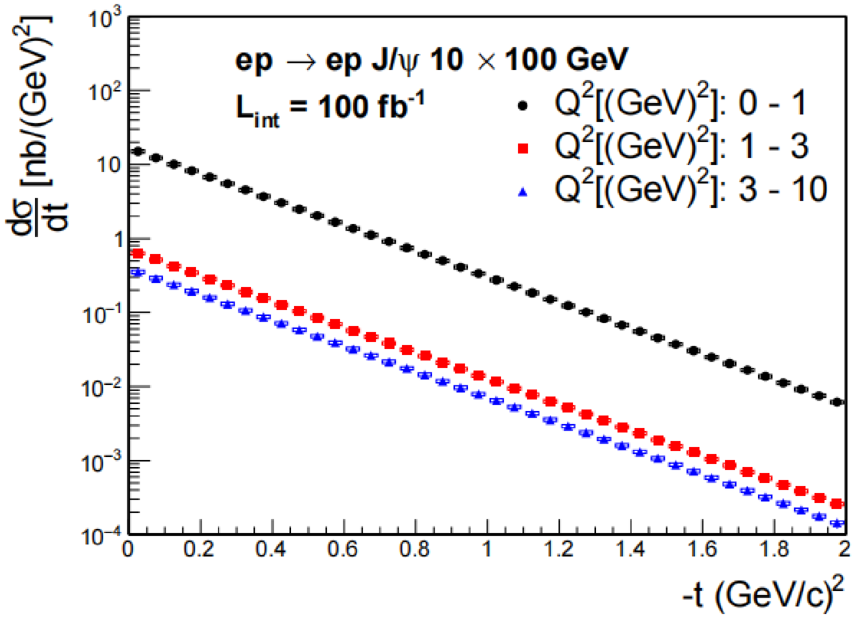
Colliders will cover a wider kinematic region (Q^2 and W) to reduce the model dependence compared with fixed target experiments.

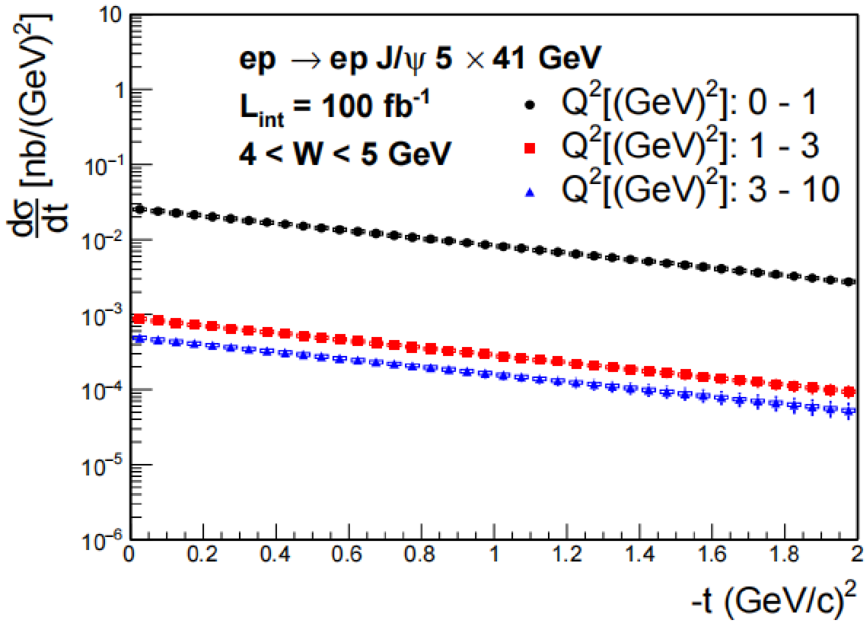
——see next slide

X. Li et al., NIMA 1048 (2023) 167956

Trace anomaly prediction at EIC/EicC

- JLab took advantage of two dimensional (t-W) near threshold J/ψ photoproduction measurements.
- It is possible to do for another two dimensional distribution (t-Q^2) at EIC. (parameter a and b in P12 are sensitive to Q^2!)
- Three dimensions ? (W in 4-5 GeV)



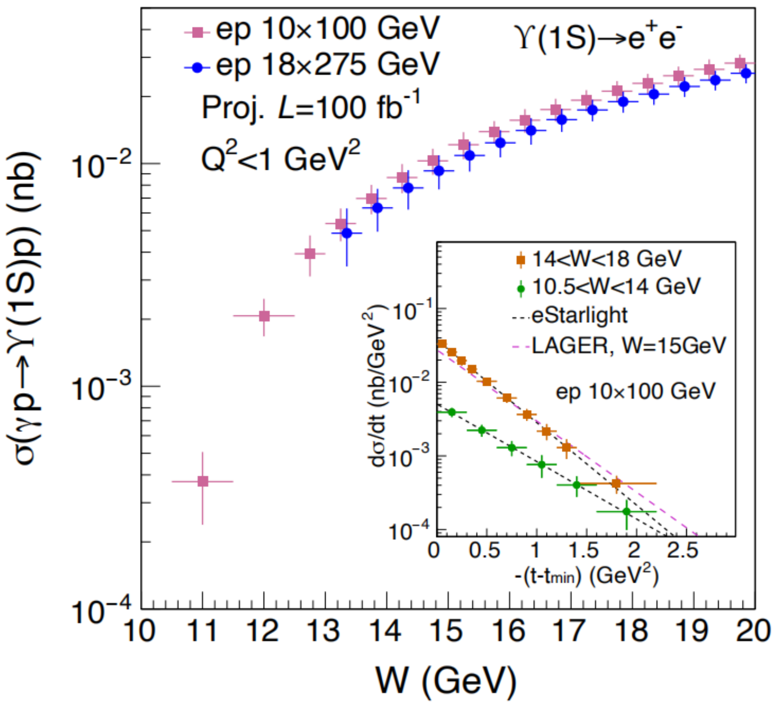


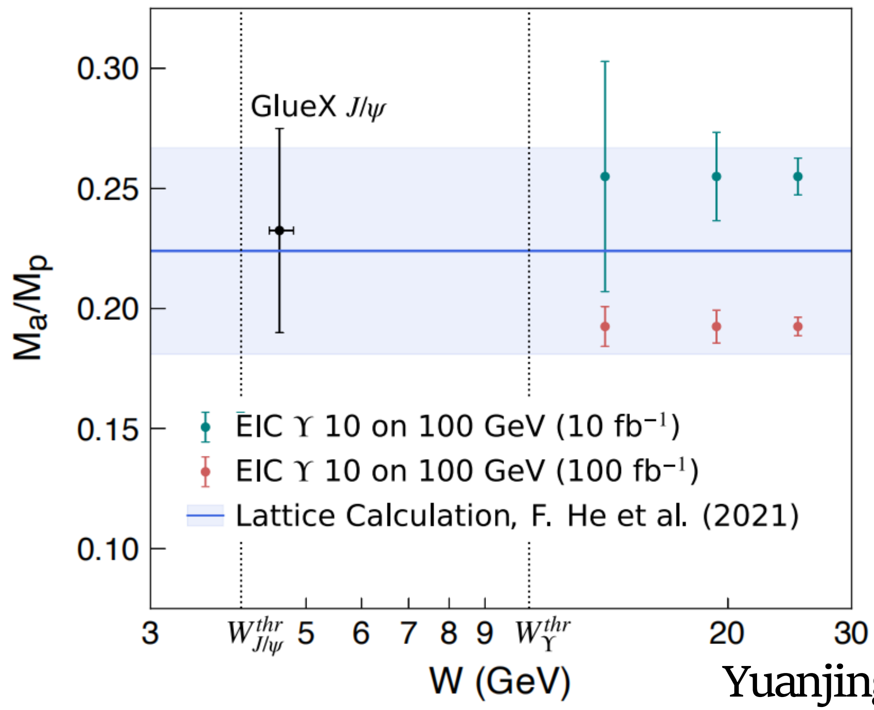
X. Li et al., NIMA 1048 (2023) 167956

Additional Q^2 lever arm could help further check the models.

Trace anomaly prediction at EIC/EicC

- The measurements of Υ threshold photoproduction will be a strong complementarity for J/ψ programs.
- The larger bottomonium mass leads to negligible uncertainty from higher order corrections.





Yuanjing's work

Uncertainty from Υ near threshold one-year yield at EIC seems comparable to GlueX J/ψ.

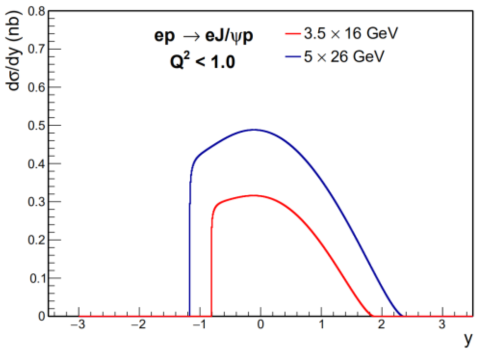
Summary

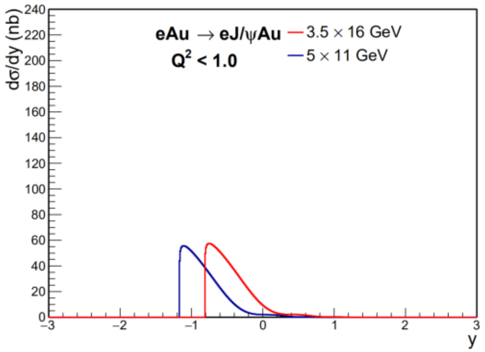
- Quarkonia photoproduction is a powerful probe for the gluonic physics.
- ePIC detector at EIC will cover a wide kinematic region to detect this process with precise measurements of event variables.
- The measurements of this process at EIC have the ability to significantly reduce the model uncertainty on nuclear gluon PDF, GPD, spatial distributions and near-threshold production mechanism and nuclear mass structure.
- EIC will be a bridge between physics related to photoproduction at RHIC/LHC and JLab.

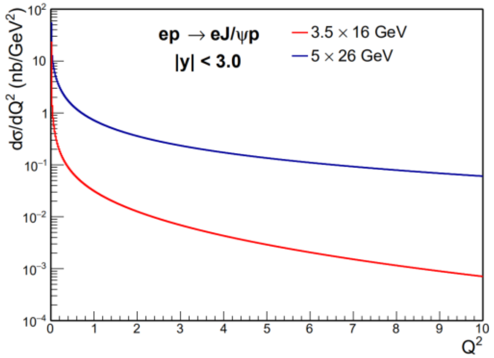

QUESTIONS?

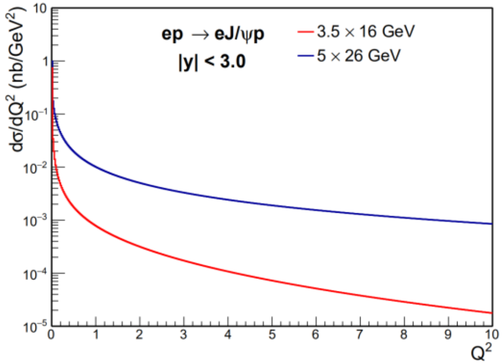
BACK UP

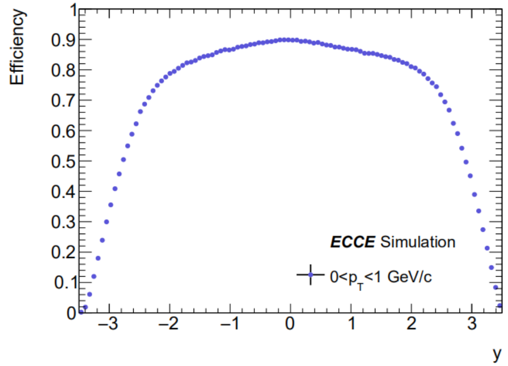
y and Q2 dependence

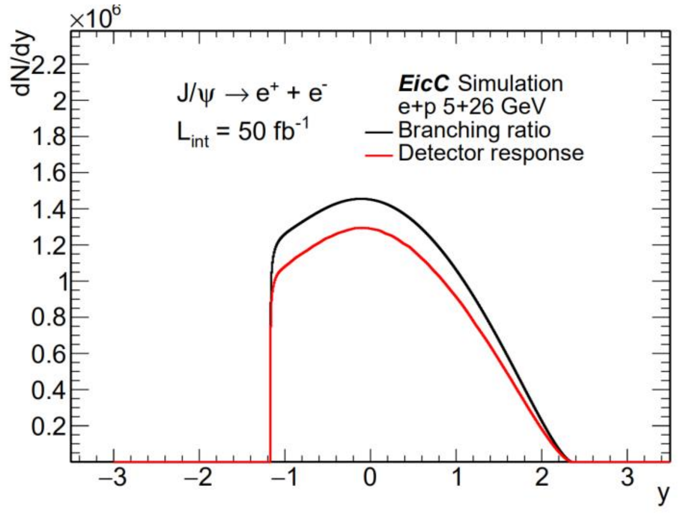


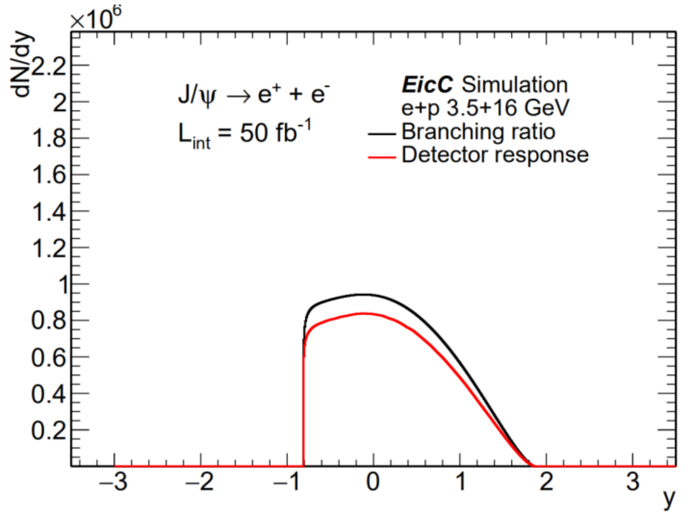


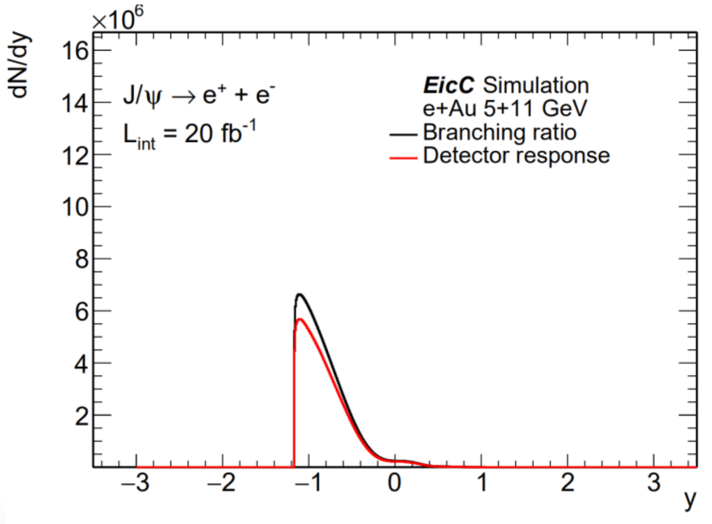










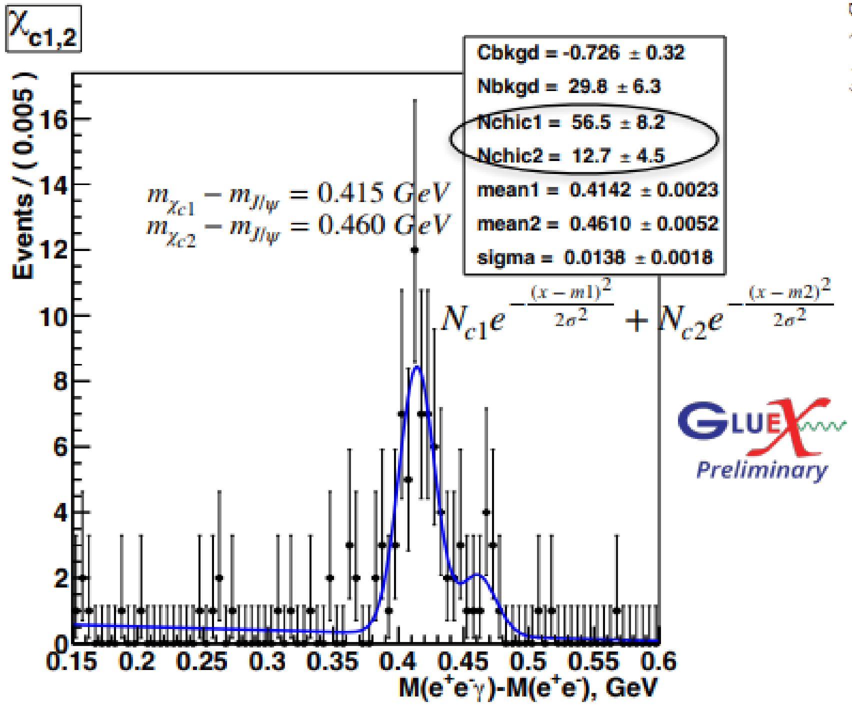


Odderon

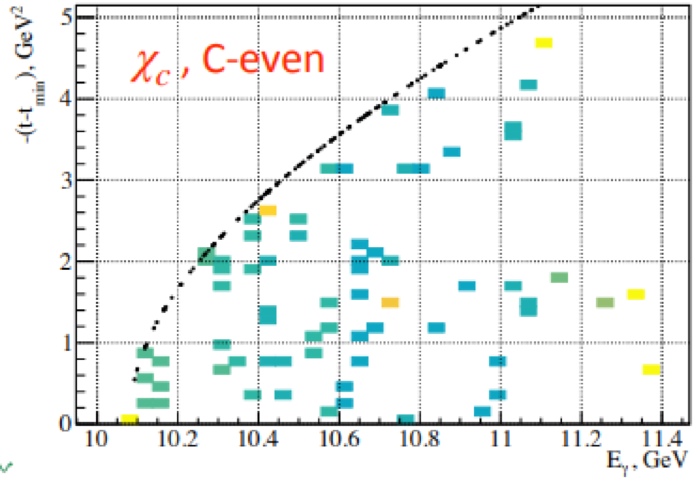
Higher-mass charmonium states with GlueX

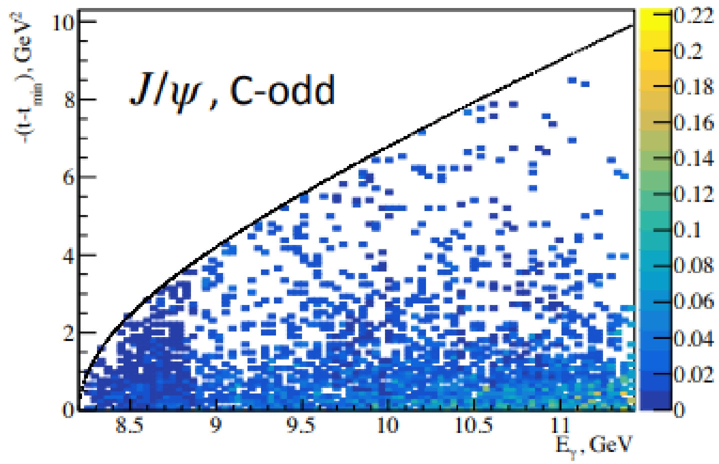
C-odd (J/ψ, ψ') vs C-even (χ_c) production

$$\gamma p \to \chi_c p \to (J/\psi\gamma) p \to (e^+e^-\gamma) p$$



GlueX Preliminary

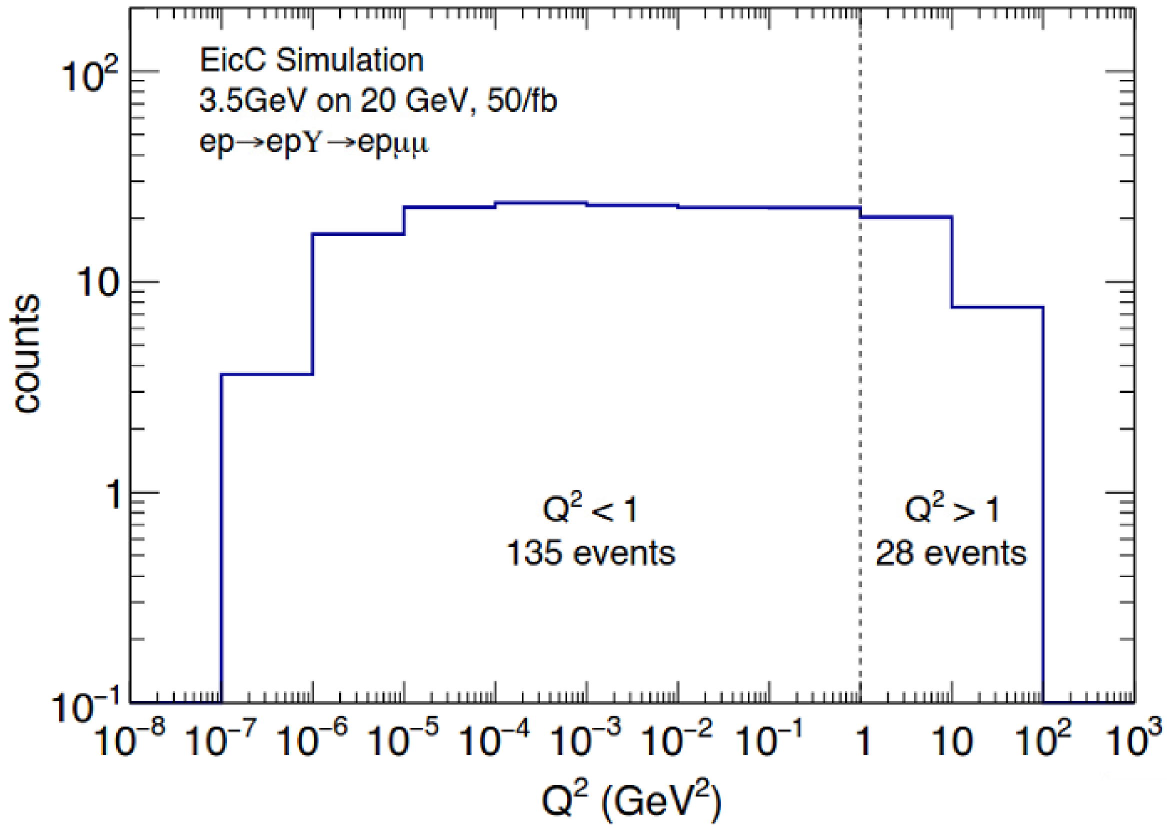




$weight = \frac{1}{L(E_\gamma)}$

- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} $(1P)$, $E_\gamma^{thr} = 10.1$ GeV
- C-even charmonium states require 3g-exchange
- Dramatic difference in (E_γ, t) distribution w.r.t J/ψ

Υ experiments at EicC compared



ep 3.5+20 GeV seems perfect for Y(1S) near threshold due to the center of mass.

Photo-production dominants.

Low statistics.

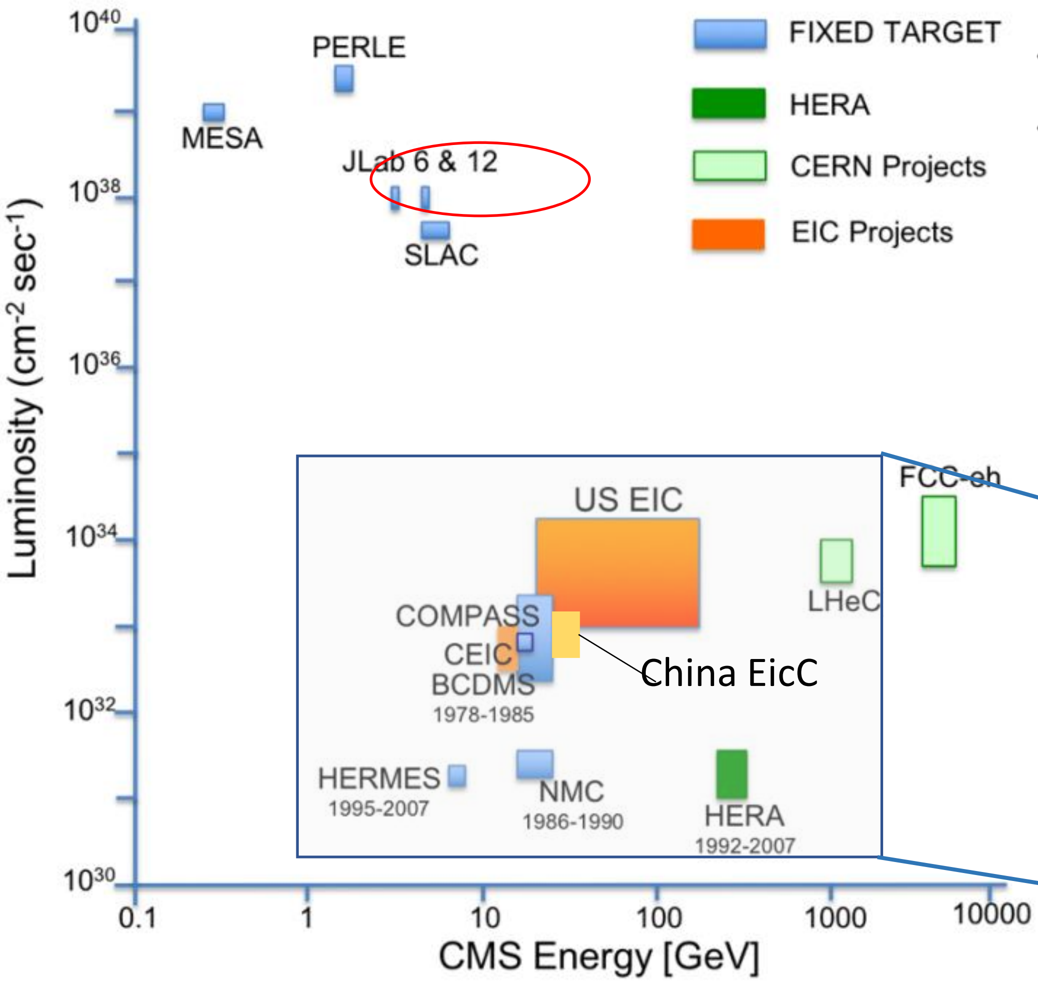
Allow to search beautiful pentaquark!

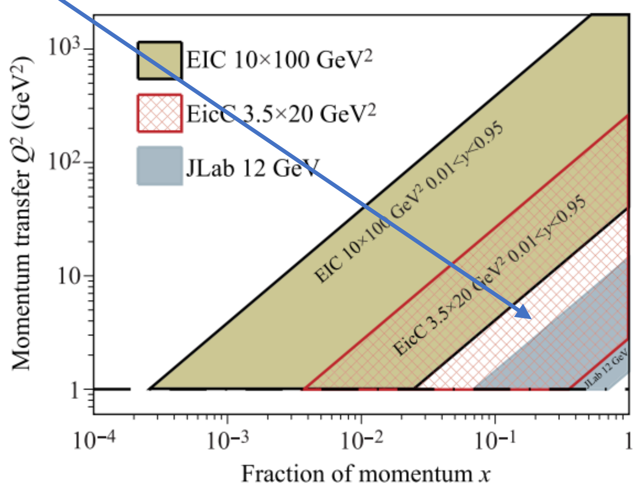
Figure from S. Jooster's slide (meeting)

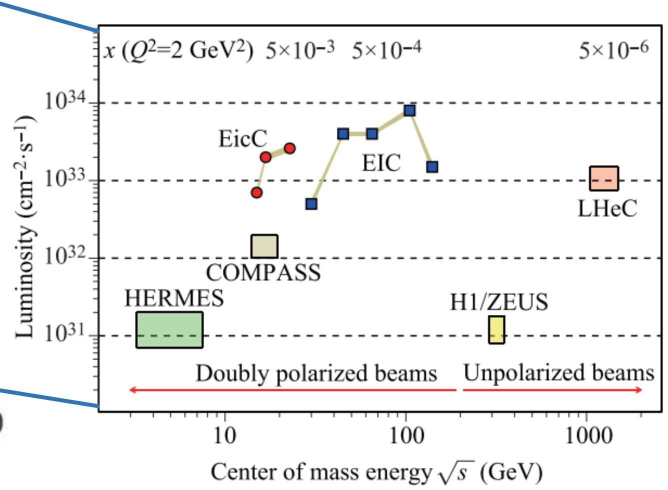
Kinematic coverage and nucleon's partonic structure

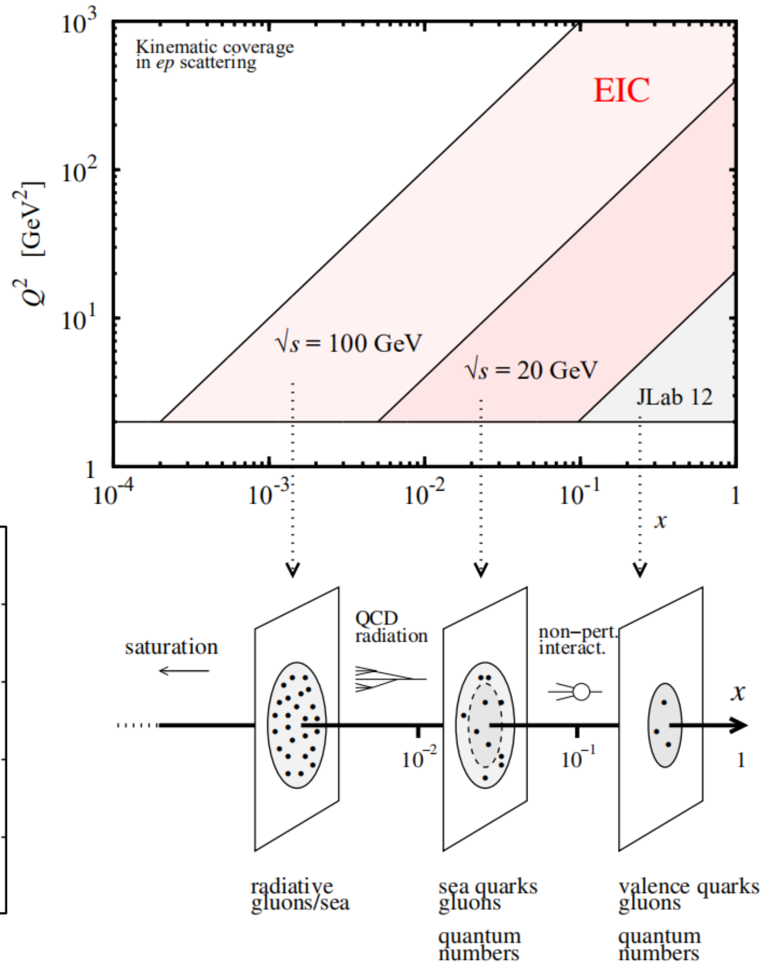
What physics should be important here?

$\sqrt{s_{ep}}$ = 28 – 140 GeV at EIC 15-20 GeV at EicC







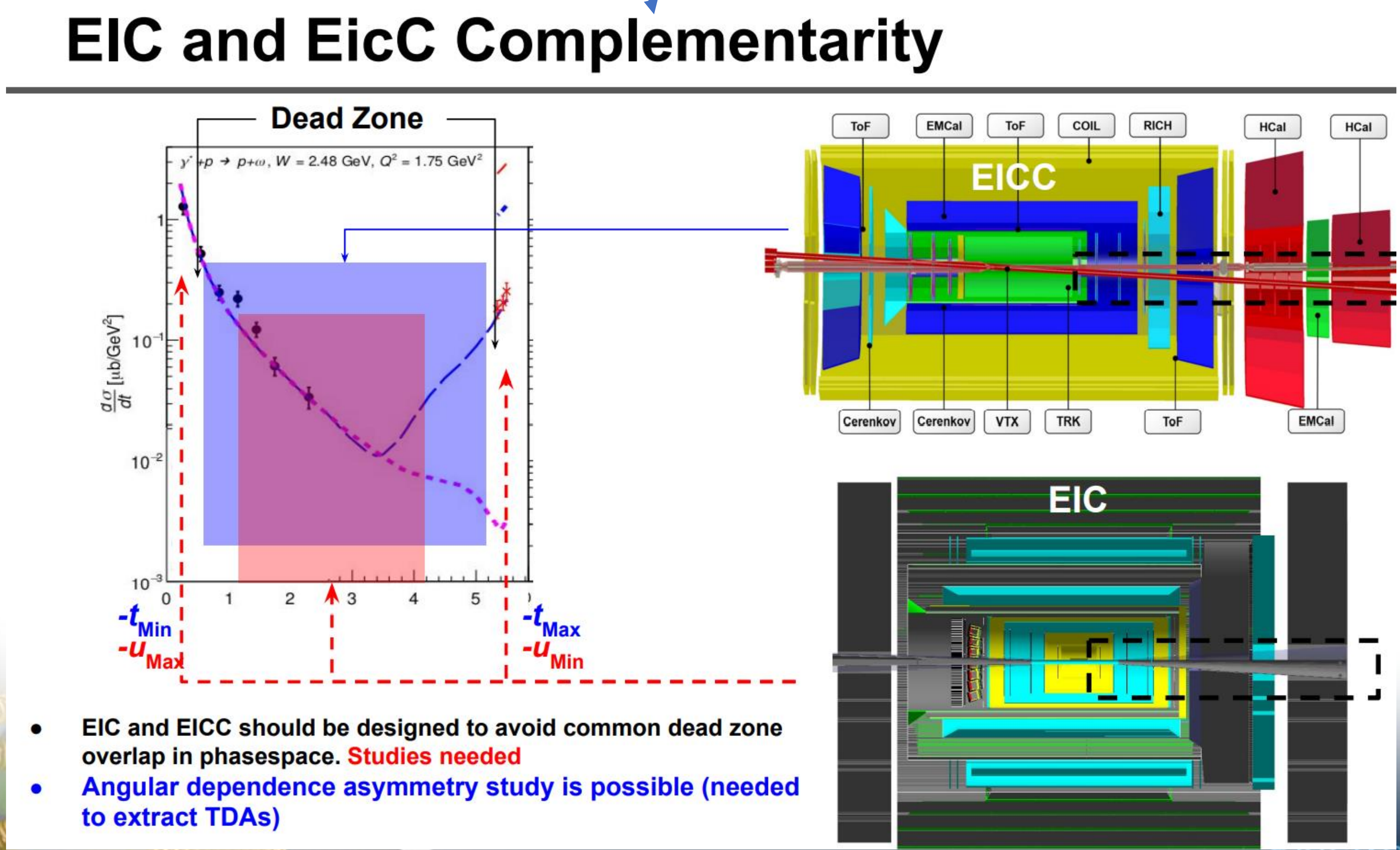


Special physics – Backup angle u-channel

See in Bill Li's presentation: link

History and physics of this channel: link

Adv: Larger acceptance of ZDC: 15mrad and kinematic coverage

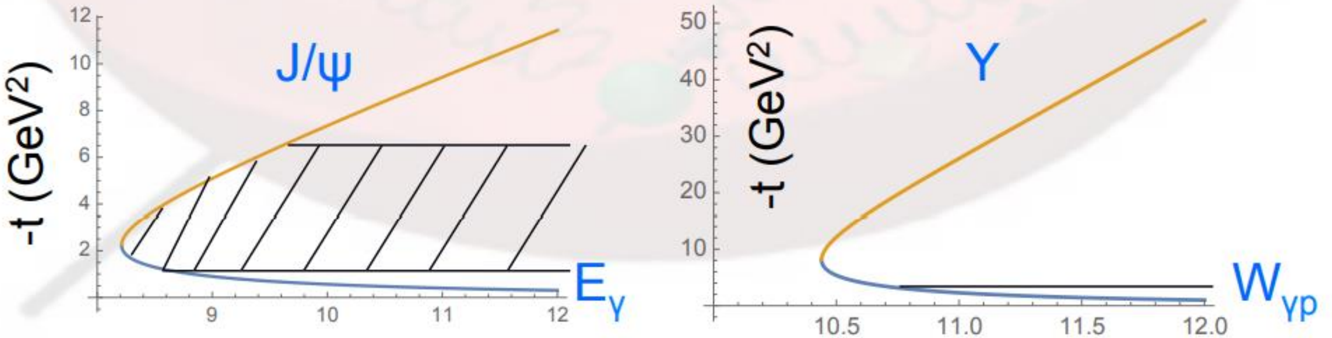


Slide from Bill

Materials – gravitational FF (form factor)

This talk focuses on the special kinematics: large momentum transfer

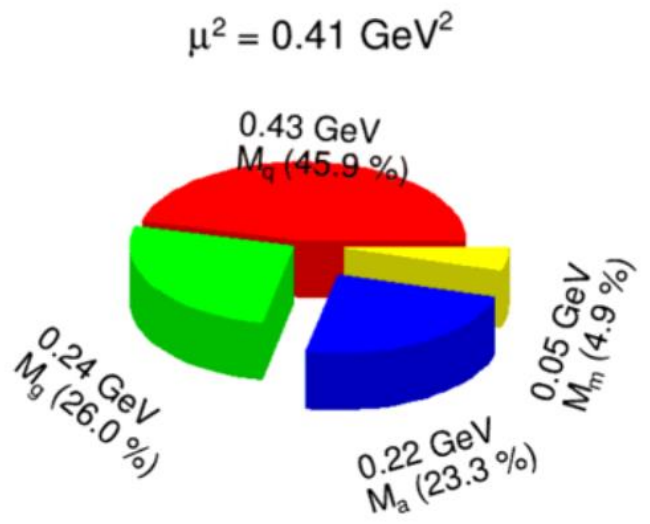
- We can compute both the cross section and the form factors separately in perturbative QCD, then we can check that if there is/not direct connection between the near threshold production and the gluonic gravitational form factors

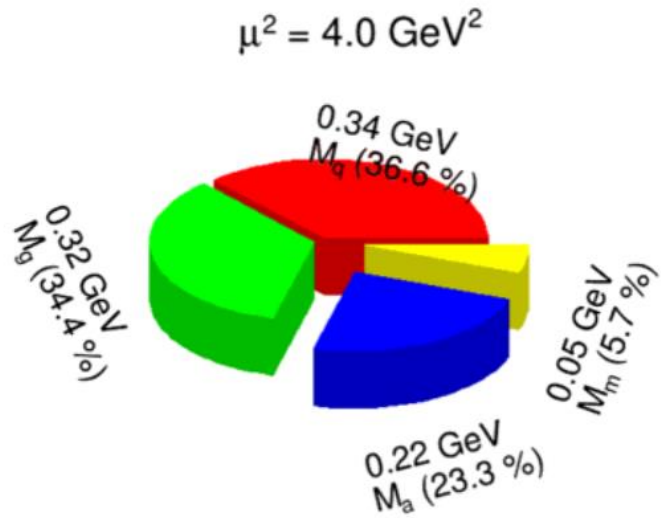


Direct connection?

Slide from Feng Yuan

Materials – mass decom. & Q2 limitation





Input interpretation

solve

$$\sqrt{(w+26)^2 - ((5-w)\sin(t))^2 - (26 - ((5-w)\cos(t)+5))^2} = 4.04$$

$$2\times 5\,w - 2\times 5^2 + Q = 2\times 5\,(5-w)\cos(t)$$

$Q \geq 0$

$w \geq 0$

$t \geq 0$

$t \leq \pi$

for w

Results — Approximate form

$w = \frac{10201}{65000}$ and $Q = 0$ and $t = \pi$

$w = \frac{10201 - 2625\,Q}{65000}$ and $0 < Q \leq \frac{10201}{2625}$ and $t = \cos^{-1}\left(\frac{3875\,Q - 314799}{2625\,Q + 314799}\right)$

$\cos^{-1}(x)$ is the inverse cosine function

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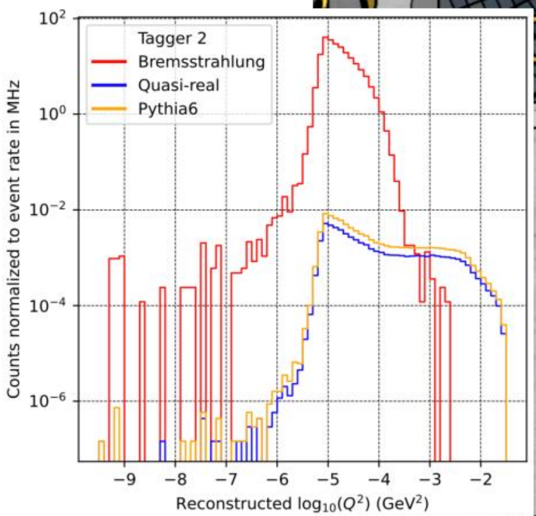
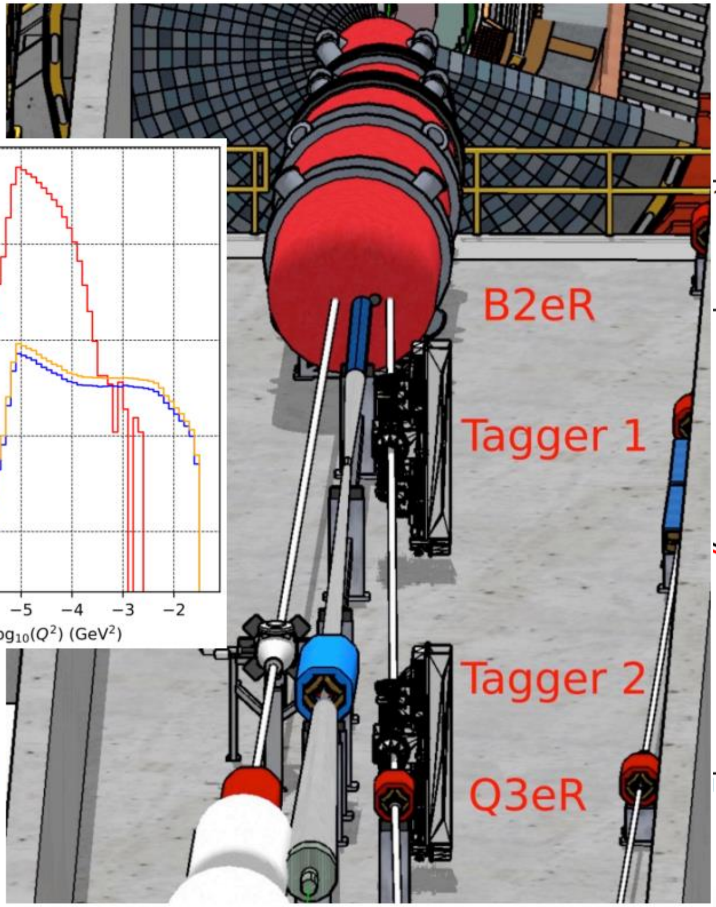
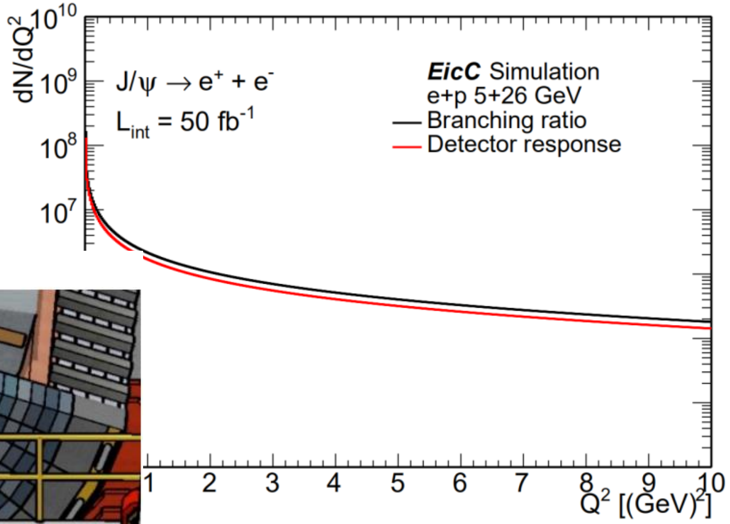
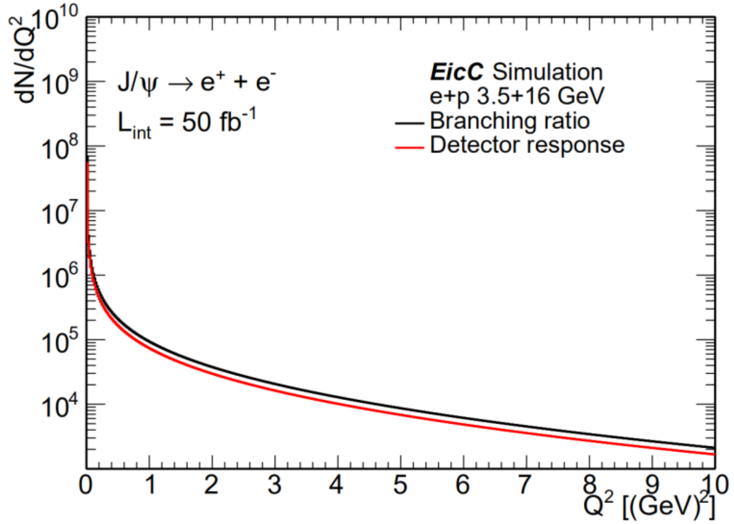
POWERED BY THE **WOLFRAM LANGUAGE**

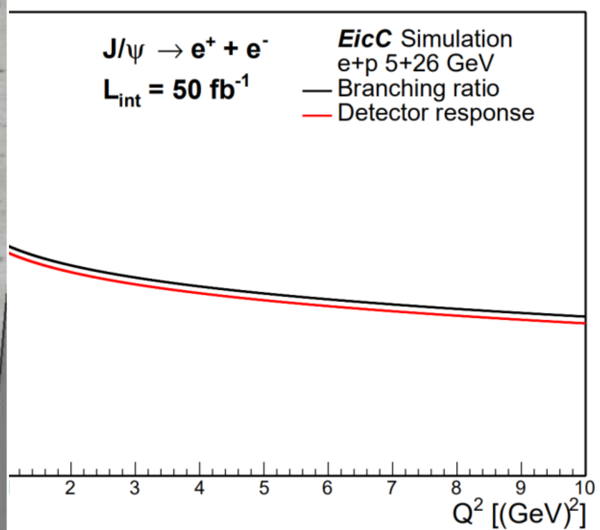
Materials


Tagger 2
Bremsstrahlung
Quasi-real
Pythia6
Counts normalized to event rate in MHz
Reconstructed $\log_{10}(Q^2)$ (GeV^2)


B2eR
Tagger 1
Tagger 2
Q3eR


$J/\psi \to e^+ + e^-$
L_{int} = 50 fb^{-1}
EicC Simulation
e+p 5+26 GeV
Branching ratio
Detector response
dN/dQ^2
Q^2 [(GeV)^2]


$J/\psi \to e^+ + e^-$
L_{int} = 50 fb^{-1}
EicC Simulation
e+p 3.5+16 GeV
Branching ratio
Detector response
dN/dQ^2
Q^2 [(GeV)^2]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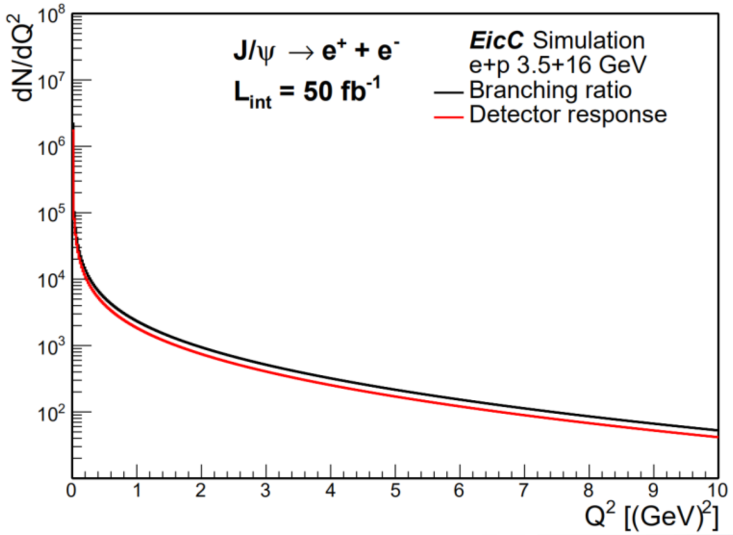
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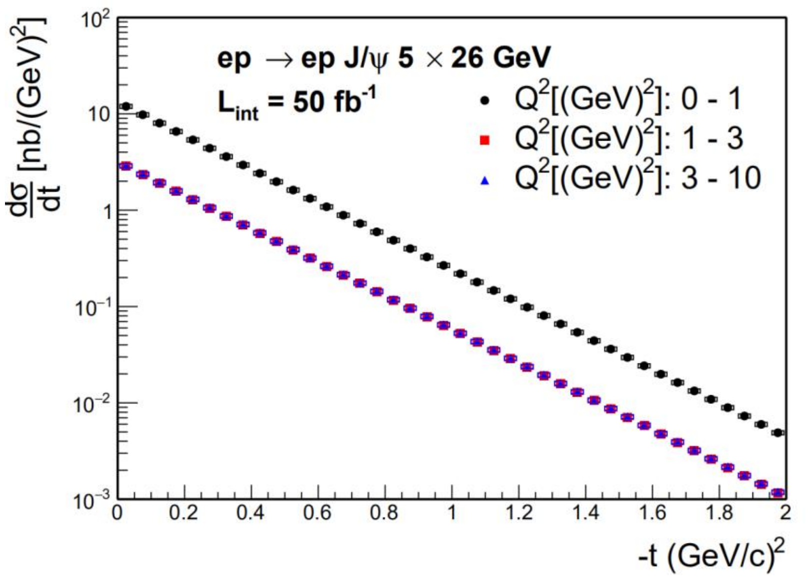
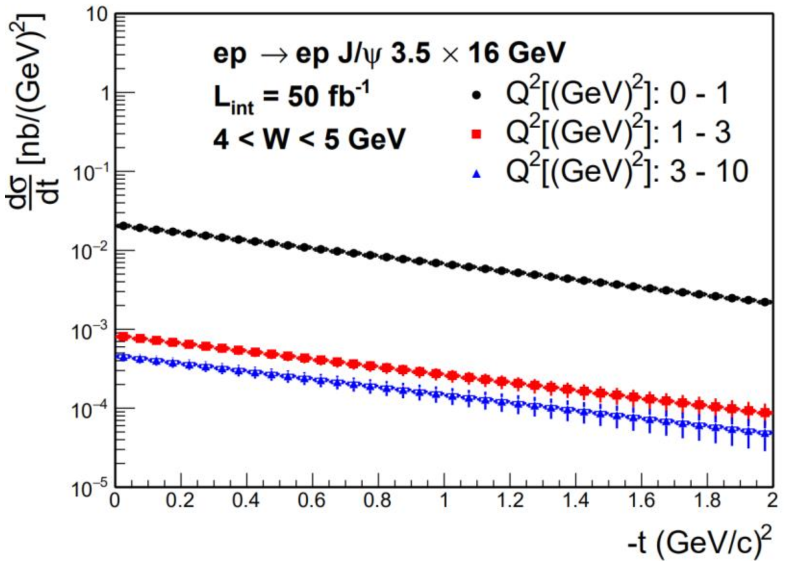
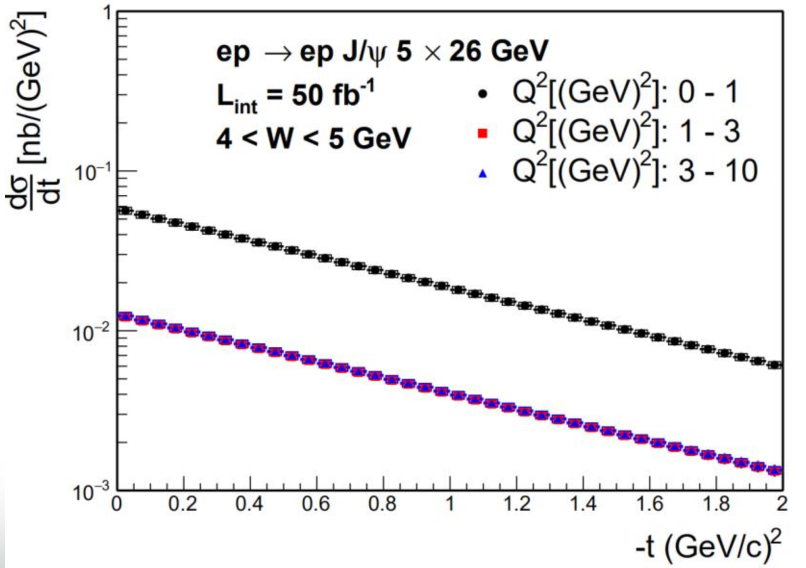
Q^2 [(GeV)^2]

Materials


ep → ep J/ψ 5 × 26 GeV
L_int = 50 fb^-1
Q^2[(GeV)^2]: 0 - 1
Q^2[(GeV)^2]: 1 - 3
Q^2[(GeV)^2]: 3 - 10
dσ/dt [nb/(GeV)^2]
-t (GeV/c)^2


ep → ep J/ψ 3.5 × 16 GeV
L_int = 50 fb^-1
4 < W < 5 GeV
Q^2[(GeV)^2]: 0 - 1
Q^2[(GeV)^2]: 1 - 3
Q^2[(GeV)^2]: 3 - 10
dσ/dt [nb/(GeV)^2]
-t (GeV/c)^2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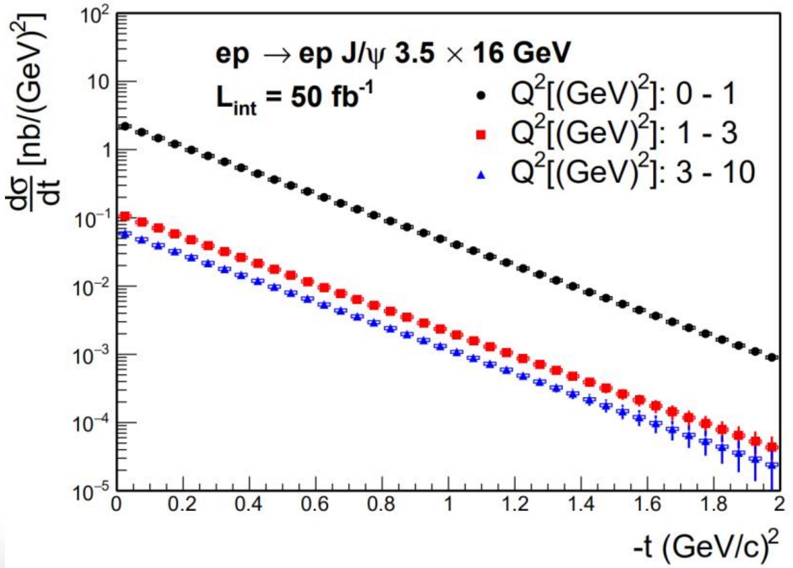
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Q^2[(GeV)^2]: 3 - 10
dσ/dt [nb/(GeV)^2]
-t (GeV/c)^2

Materials – EPIC (EIC)

News: voted logo!; New simulation framework (in process - EICrecon)

At EIC: Asymmetric system: no two photon sources interference [more statistics at low t, baseline]
Coulomb dissociation should be suppressed due to the limited EM field by electron side.
Low momentum fraction x “Gluon sea” will enhance the cross section.