The Theoretical Calculation for Exclusive Vector Meson Production at Future EIC

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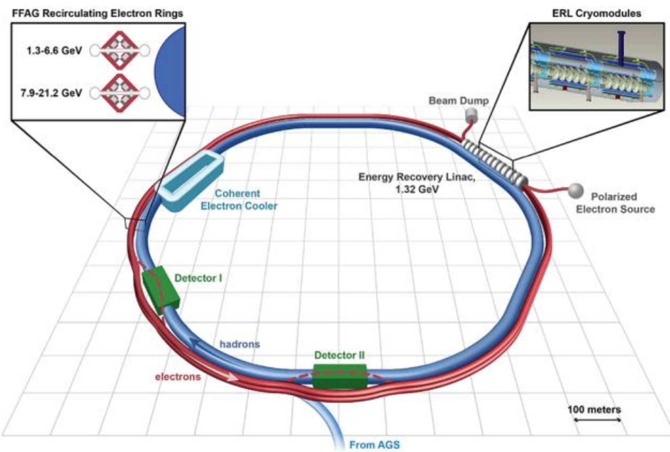
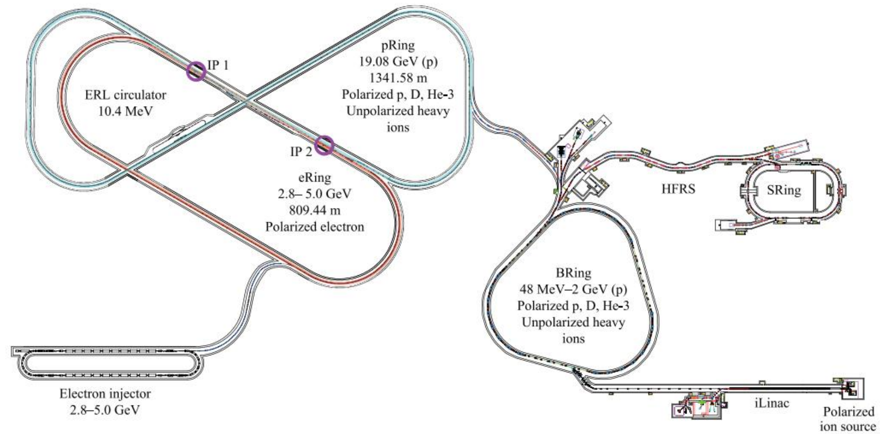
EIC and exclusive process

- EIC: study the properties and dynamics of quarks and gluons



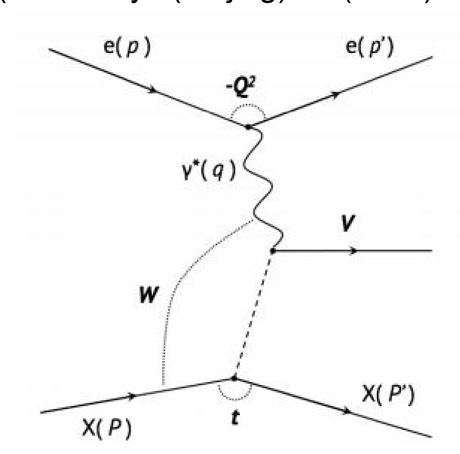
eRHIC (Eur.Phys.J.A 52 (2016) 9, 268)



EIcC (Front.Phys.(Beijing) 16 (2021) 6, 64701)

- Exclusive process: important channels for investigating the composition of protons and nuclear targets

- Simulate the detection of exclusive products at EIC is essetial at the present stage



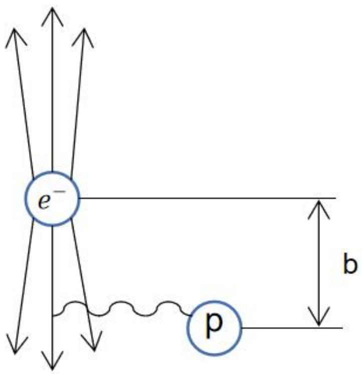
The cross section for exclusive process

- $ep \rightarrow epV$ Cross section:

$$\sigma(ep \rightarrow epV) = \int dW \int d\omega \int dQ^2 \frac{d^2 n}{d\omega dQ^2} \sigma_{\gamma * p \rightarrow Vp}(W, Q^2)$$

- Classical Weizsacker–Williams Equivalent Photon Approximation (EPA):

  The electromagnetic field of a fast moving charged particle can be regarded as a swarm of photons



$$n(\omega, \vec{x}_\perp) = \frac{Z^2 \alpha_{QED}}{\pi^2 \omega} \left| \int_0^\infty dk_\perp k_\perp^2 \frac{F(k_\perp^2 + (\frac{\omega}{\gamma})^2)}{k_\perp^2 + (\frac{\omega}{\gamma})^2} J_1(x_\perp k_\perp) \right|^2$$

Prog.Part.Nucl.Phys. 39 (1997) 503-564

- The issues in classical EPA:
- ➢ Charged particle keep moving on a straight trajectory (?)
- ➢ Photon energy ω can be larger than charged particle energy E (?)

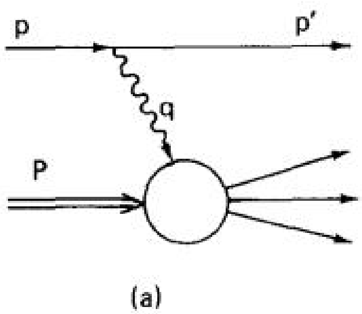
Photon flux used in eSTARlight

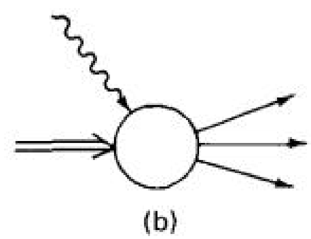
- The photon flux used in eSTARlight is (Phys.Rev.C 99 (2019) 1, 015203)

$$\frac{d^2n}{d\omega dQ^2} = \frac{\alpha}{\pi\omega Q^2}\left[1 - \frac{\omega}{E} + \frac{\omega^2}{2E^2} - (1 - \frac{\omega}{E})\left|\frac{Q^2_{min}}{Q^2}\right|)\right]$$

with $Q^2_{min} = \dfrac{m_e^2\omega^2}{E(E-\omega)}$ and $Q^2_{max} = 4E(E-\omega)$ require $\omega < E - 10m_e$

- Feynman diagram for electroproduction





Cross section: $d\sigma_{ep} = \sigma_\gamma(\omega)dn$ absorption cross section $\sigma_\gamma(\omega)$

QED EPA method

- Express the cross section in terms of photon density matrix $\rho^{\mu\nu}$ and photo-absorption amplitude M^{μ}:

$$d\sigma_{ep} = \frac{4\pi\alpha}{(-q^2)} M^{*\nu} M^{\mu} \rho^{\mu\nu} \frac{(2\pi)^4 \delta(p + P - p' - k) d\Gamma}{4\sqrt{(pP)^2 - p^2 P^2}} \frac{d^3 p'}{2E'(2\pi)^3}$$

$$\rho^{\mu\nu} = \frac{1}{2(-q^2)} Tr[(\hat{p} + m_e)\gamma^{\mu}(\widehat{p'} + m_e)\gamma^{\nu}] =- (g^{\mu\nu} - \frac{q^{\mu}q^{\nu}}{q^2}) - \frac{(2p-q)^{\mu}(2p-q)^{\nu}}{q^2}$$

- Expand the cross section using the transverse and scalar photon absorption cross section:

$$d\sigma = \frac{\alpha}{4\pi^2 |q^2|} \left[\frac{(qP)^2 - q^2 P^2}{(pP)^2 - p^2 P^2}\right]^{1/2} (2\rho^{++}\sigma_T + \rho^{00}\sigma_S) \frac{d^3 p'}{E'}$$

- The equivalent photon flux:

$$dn = \frac{\alpha}{2\pi E^2} \rho^{++} \omega d\omega \frac{d(-q^2)}{|q^2|} = \frac{\alpha}{4\pi E^2} \left[\frac{(2E-\omega)^2}{\omega^2 - q^2} + 1 + \frac{4m_e^2}{q^2}\right] \frac{\sqrt{\omega^2 - q^2} d\omega d(-q^2)}{|q^2|}$$

Correction for eSTARlight

- The equivalent photon flux:

$$dn = \frac{\alpha}{4\pi E^2}\left[\frac{(2E-\omega)^2}{\omega^2-q^2}+1+\frac{4m_e^2}{q^2}\right]\frac{\sqrt{\omega^2-q^2}\,d\omega d(-q^2)}{|q^2|}$$

- For $Q^2(=-q^2) \ll \omega^2$ (eSTARlight)

$$\frac{d^2n}{d\omega dQ^2} = \frac{\alpha}{\pi\omega Q^2}\left[1-\frac{\omega}{E}+\frac{\omega^2}{2E^2}-(1-\frac{\omega}{E})\left|\frac{Q^2_{min}}{Q^2}\right|)\right]$$

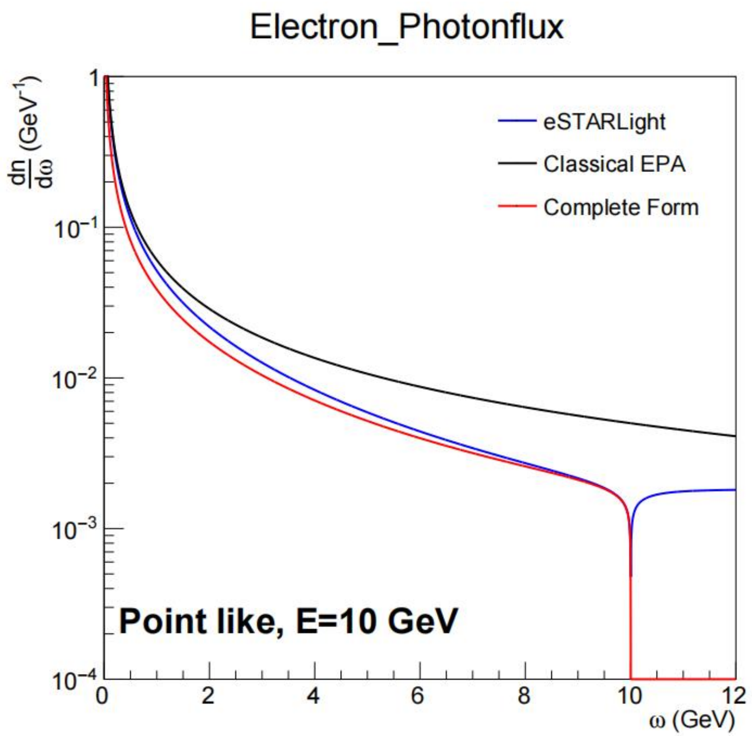
with $Q^2_{min} = \frac{m_e^2\omega^2}{E(E-\omega)}$ and $Q^2_{max} = 4E(E-\omega)$ require $\omega < E - 10m_e$

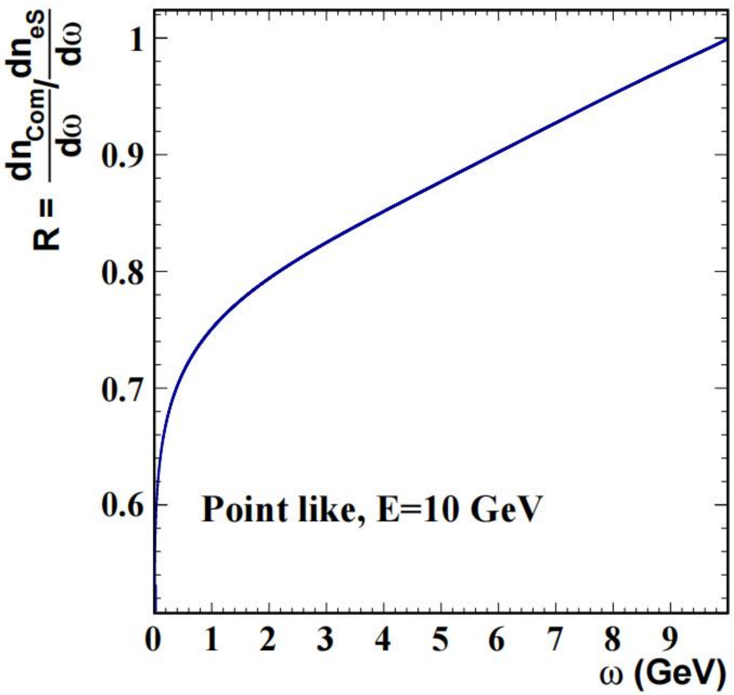
- The complete form of the Q^2_{min} and Q^2_{max}

$$Q^2_{min} =-\left(2E\omega-2E^2+2m_e^2+2\sqrt{(E^2-m_e^2)[(E-\omega)^2-m_e^2]}\right)$$

$$Q^2_{max} = \left[\sqrt{E^2-m_e^2}+\sqrt{(E-\omega)^2-m_e^2}\right]^2-\omega^2$$

The ω distribution of the photon flux





- Classical EPA fails at large ω
- Q^2 term causes a significant difference at low ω

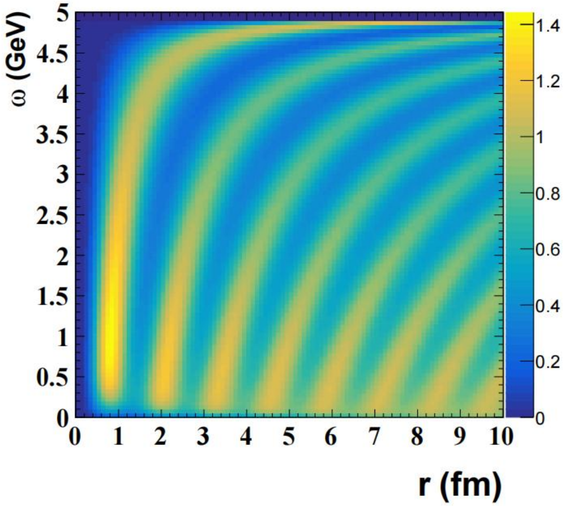
Photonflux in coordinate space

- Convert $\frac{d^2n}{dQ^2d\omega}$ to $\frac{d^2n}{dp_t d\omega}$ by performing a variable change:

$$dQ^2 d\omega = \begin{vmatrix} \frac{\partial Q^2}{\partial p_t} & \frac{\partial Q^2}{\partial \omega} \\ \frac{\partial \omega}{\partial p_t} & \frac{\partial \omega}{\partial \omega} \end{vmatrix} dp_t d\omega \quad \rightarrow \quad \begin{aligned} dQ^2 d\omega &= \frac{\partial Q^2}{\partial p_t} dp_t d\omega \\ &= \left(\frac{2p_z p_t}{\sqrt{(E_e-\omega)^2 - p_t^2 - m_e^2}}\right) dp_t d\omega \end{aligned}$$

- Transform to coordinate space:

$$\frac{d^3n}{d^2r d\omega} = \frac{\alpha}{\omega\pi^2}\left(\int_0^{p_{tmax}} \sqrt{\frac{p_t \pi\omega}{2\alpha}\frac{d^2n}{d\omega dp_t}} J_1(p_t \cdot r)\right)^2 \quad \rightarrow$$



R=complete/classical EPA
electron energy E = 5 GeV

Photonnuclear cross section for virtual photon

- The Q^2 dependence of the photonnuclear cross section following

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

$f(M_V)$ is the mass distribution of the vector meson and $\sigma(W,Q^2=0)$ is the cross-section for VM photoproduction with real photons, n ~ 2

- The term $\frac{M_V^2}{M_V^2+Q^2}$ represents the amplitude of a virtual photon fluctuates to a given hadronic component, thus the vector meson flux can be written as

$$\frac{d^3n_V}{d^2r d\omega} = \frac{\alpha}{\omega\pi^2}\frac{e^2}{f_V^2}\left(\int_0^{p_{tmax}}\sqrt{\frac{p_t\pi\omega}{2\alpha}\left(\frac{M_V^2}{M_V^2+Q^2}\right)^2\frac{d^2n}{d\omega dp_t}}J_1(p_t\cdot r)dp_t\right)^2$$

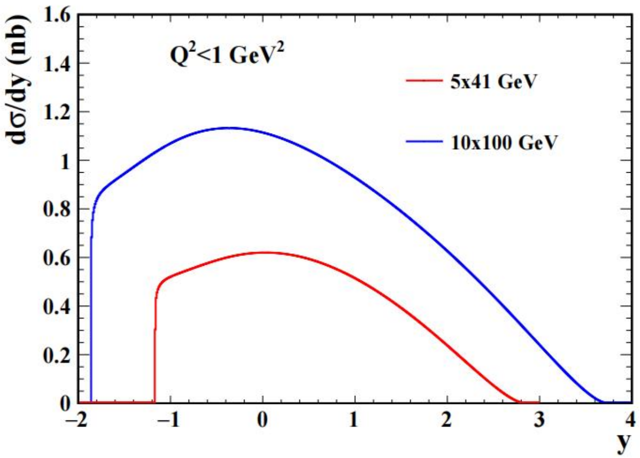
$$Q^2 = p_t^2 + p_{\gamma_z}^2 - \omega^2 \qquad p_{\gamma_z}^2 = \left(p_z - p_z^{'}\right)^2 = \left(\sqrt{E^2-m_e^2} - \sqrt{(E-\omega)^2-m_e^2}\right)^2$$

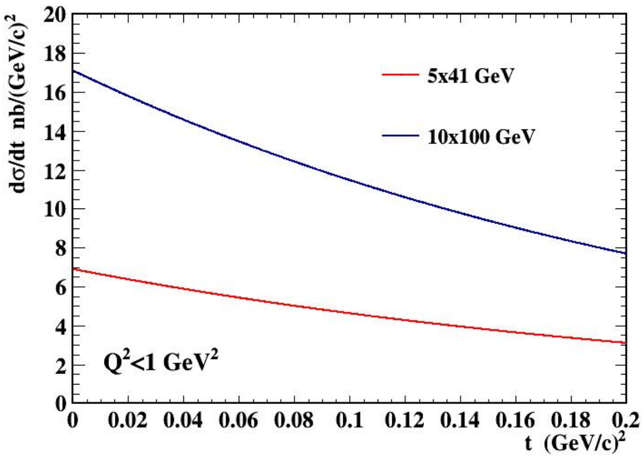
The ep→epV cross section

- The cross section

$$\sigma(ep \to epV) = \int dW \int d\omega \int dQ^2 \frac{d^2n}{d\omega dQ^2} \sigma_{\gamma * p \to Vp}(W, Q^2)$$

- For ep 5×41 GeV and 10×100 GeV scattering, the rapidity distribution of the J/Ψ electroproduction cross section are calculated as





The eA→eAV cross section

- The scattering amplitude (Phys.Rev.C 99 (2019) 6, 061901):

$$\Gamma_{\gamma A\to VA}(\vec{r}) = \frac{f_{\gamma A\to VA}(0)}{\sigma_{VN}} 2\left[1 - \exp\left(-\frac{\sigma_{VN}}{2}T'(\vec{r})\right)\right]$$

$f_{\gamma A\to VA}(0)$: forward-scattering amplitude, $T'(\vec{r})$: modified thickness function

- Set the electron at origin, the production amplitude:

$$A(\vec{r}) = a(\omega,\vec{r})\Gamma_{\gamma A\to VA}(\vec{r} - \vec{b})$$

$a(\omega,\vec{x}_\perp) = \sqrt{n(\omega,\vec{r})}$ is the photonflux amplitude

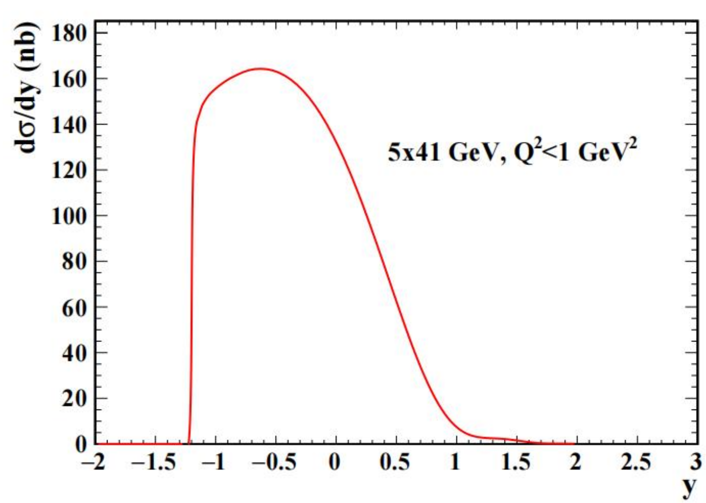
- The production amplitude in momentum space:

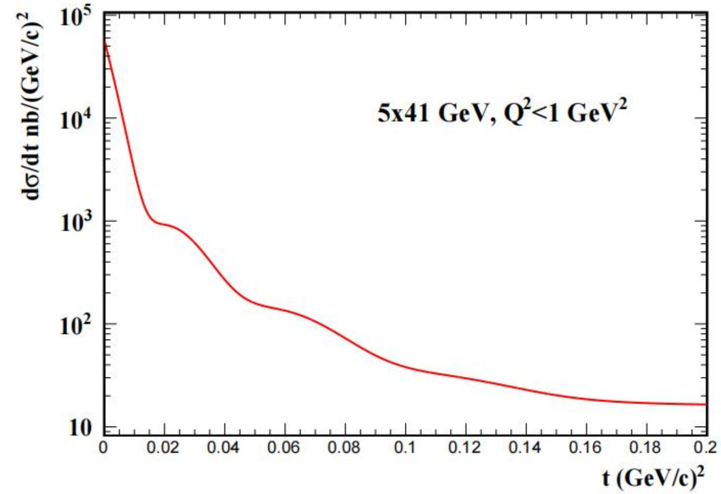
$$A(\vec{p}_\perp) = \frac{1}{2\pi}\int d^2\vec{r}\, A(\vec{r})e^{i\vec{p}_\perp\cdot\vec{r}}$$

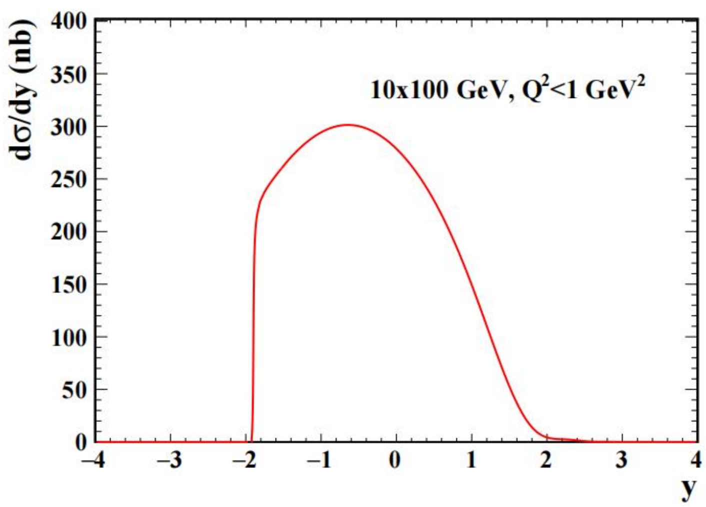
- The cross section:

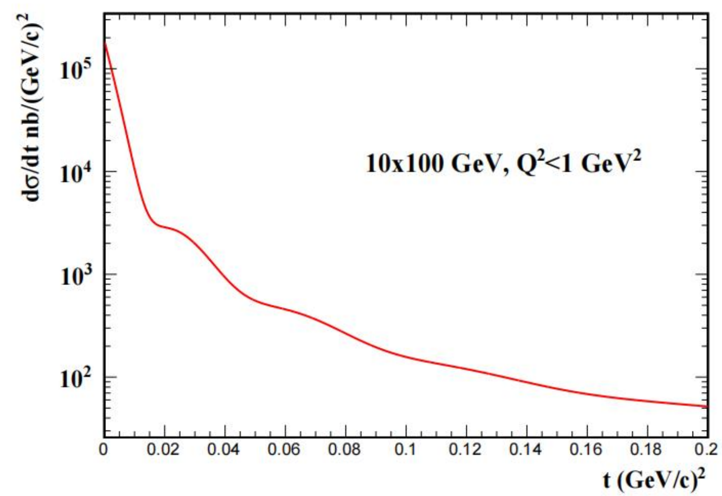
$$\sigma_{eA\to eAV} = \int 2\pi b db \int d^2\vec{p}_\perp\, |A(\vec{p}_\perp)|^2$$

eAu→eAu+J/ψ cross section









Summary

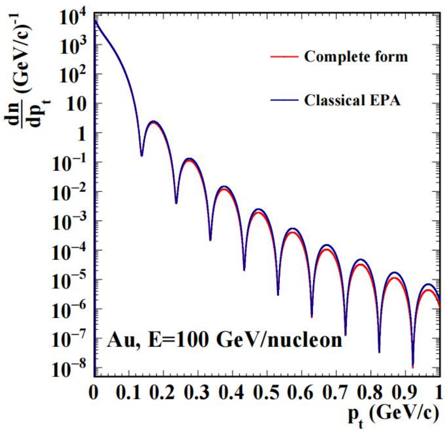
- An improved equivalent approximate photon distribution based on QED was derived, overcomes the weakness of traditional EPA at large photon energy
- The Q_{min}^2 and Q_{max}^2 were corrected and the Q^2 term in the denominator is considered.
- The J/ψ photoproduction cross section of ep and eAu was shown, the formula in coordinate space includes the impact parameter.

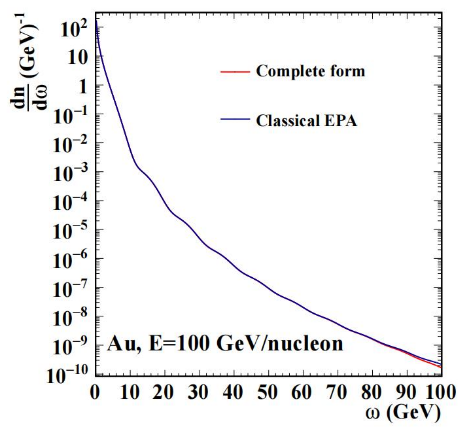
Outlook: correction for large Q^2 calculation

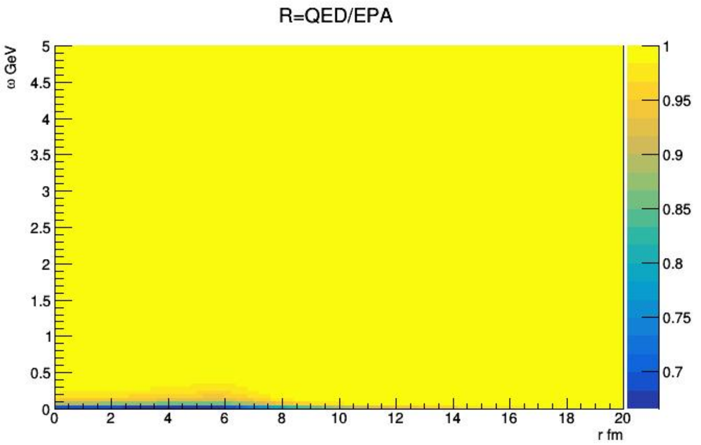
Thank you!

Back up

- For Au with E = 100 GeV/nucleon:







- Classical EPA can be safely used in heavy-ion collisions

Back up

- Photon flux induced by a proton: