Exclusive production of charmonia, bottomonia and $B_c^+ B_c^-$ meson pairs

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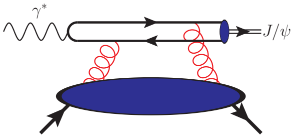
Exclusive quarkonia photoproduction

(see QWG review, Eur.Phys.J. C71 (2011) 1534)

Single quarkonia photoproduction



- Clean probe of gluonic structure, complements inclusive data in phenomenological fits
  Color Dipole framework:
  – probe dipole amplitude (b-dependence)
  Collinear factorization approach:
  – probe (gluon) GPDs of the protons
- Heavy mass $m_Q \gg \Lambda_{\rm QCD}$ is "natural" hard scale, wide region of applicability of perturbative treatment (up to photoproduction, $Q^2 \approx 0$)
  –Accessible both in ep colliders and pA, AA colliders in ultraperipheral kinematics

Photoproduction of quarkonia *pairs*

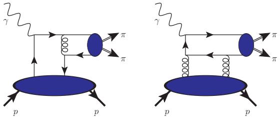
$$\gamma^{(*)} + p \to M_1 + M_2 + p, \quad M_1, M_2 = J/\psi,\, \eta_c,\, \chi_c, \ldots$$

- Can vary quantum numbers and kinematics of produced quarkonia in order to disentangle effects due to wave function from target-related effects
  $\Rightarrow$ much more detailed information about the target (parton distributions, dipole amplitudes at $x \ll 1$)
- Cross-sections within reach of **EIC**, JLab@24 GeV, UPC@LHC, LHeC, FCC

Previous studies of meson *pair* production

▶ **Studies in Bjorken regime:** [PLB 475, 147; PRD 63, 114001; NPA 679, 185 ...]

$$\gamma^{(*)} + p \to M_1 + M_2 + p, \quad M_1, M_2 = \pi^{\pm}, \pi^0 \ldots$$



Focused on light mesons

▷ mass $M \ll Q$, twist expansion

▷ If $(p_{M_1} + p_{M_2})^2$ is small, contributions from feed-down channels ($\rho \to \pi\pi$, ...)

▷Depend on 2-pion distribution amplitudes (poorly known as of now)

Not applicable when $M \sim Q \gg \Lambda_{\rm QCD}$

▶ **Photoproduction of heavy quarkonia:**

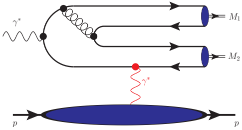
[PRD **101**, 034025; EPJC **49**, 675; **73**, 2335; **76**, 103; **80**, 806.]

▷ Focused on $J/\psi\, J/\psi$ channel

▷ Is dominated by photon-photon fusion (C-parity)

▷ Extra photon⇒additional $\mathcal{O}\left(\alpha_{\rm em}^2\right)$-suppression in cross-sections

▷ Might get contributions from diagrams with odderon in t-channel



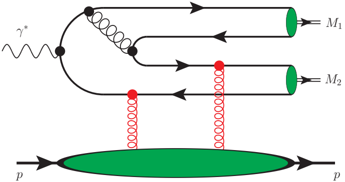
Our suggestion: quarkonia pairs with *opposite* C-parity

- Wide range of possible quarkonia choices: $J/\psi\,\eta_c$, $J/\psi\,\chi_c$, $\Upsilon\,\eta_c$...
- Hard part is dominated by 2-gluon exchange in t-channel,

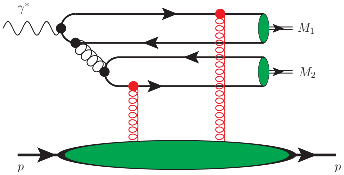
$\Rightarrow$significantly larger cross-section than for $J/\psi\,J/\psi$

▷ Two main production mechanisms, depending on heavy flavour content:

(A)



(B)



Final state	**Mechanism**	
	(A)	(B)
2 charmonia or 2 bottomonia $\left(J/\psi\,\eta_c,\ \Upsilon\,\eta_b,\ \ldots\right)$	✓	✓
B_c meson pairs $\left(B_c^+\,B_c^-\right),\ \left(B_c^{*+}\,B_c^-\right)$	✓	✗
Charmonium+bottomonium $\left(J/\psi\,\eta_b,\ \Upsilon\,\eta_c,\ \ldots\right)$	✗	✓

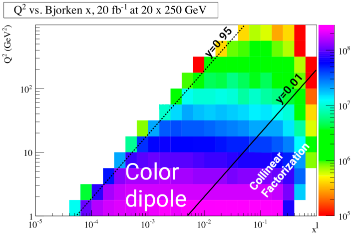
Kinematics and choice of framework

Our main focus: Electron Ion Collider

- Typical values of variables ξ, x_B

$$x_B \approx \frac{Q^2 + M_{12}^2}{Q^2 + W^2}, \qquad \xi = \frac{x_B}{2 - x_B}.$$

- ▷ In EIC kinematics, accessible x_B, Q^2 might vary significantly, depending on choice of electron-proton energy E_e, E_p (see left)
  —Values of $x_B, \xi \in \left(10^{-4}, 1\right)$
- ▷ Dominant contribution (from spectrum of equivalent photons): $Q^2 \approx 0$ ($Q^2 \ll M_Q^2$)



Choice of framework:

- For $x_B, \xi \ll 1$ saturation effects are important, color dipole description is a natural choice.
  —Collinear factorization (and similar) unreliable due to large NLO corrections ($\sim \ln x_B$), lack of saturation effects
- For $x_B, \xi \gtrsim 0.01 \ldots 0.1$ collinear factorization is a natural choice
  —eikonal-based description used in small-x approaches might be unreliable

Evaluations in collinear factorization framework

- **Bjorken regime** $(Q^2, p \cdot q \gg M_i^2, |t|)$

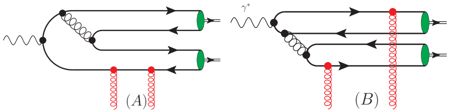
  Evaluation straightforward, amplitude:

$$\mathcal{A} \sim \int dx\, F_g^{(a)}(x, \xi, t)\, C^{(a)}(x, \xi),$$

$$F_g^{(a)} = \left\{ H_g, E_g, \tilde{H}_g, \tilde{E}_g \right\}$$

- Full expression for $C(x, \xi)$ is too lengthy, has a structure

$$C(x, \xi) = \sum_{\pm} \frac{N_{\pm}(x, \xi)}{(x \mp \xi \pm i0)^n}, \quad n \lesssim 3$$



where functions $N_{\pm}(x, \xi)$ remain finite for $x \to \pm\xi$

▷ Behaviour near points $x = \pm\xi$ signals potential breakdown of collinear factorization

– Similar singularities observed for dijet production [PRL 128 (2022), 182002]

– need to take into account transverse momenta [EPJC 74, 2725 (2014)]

*Effective regularization: $\left| k_\perp^2 / Q^2 \right|$

- **Caution:** ▷ Presence of large scale $M_{12}^2 \gtrsim \left(M_{J/\psi} + M_{\eta_c}\right)^2 \sim 36\,\mathrm{GeV}^2$

  ▷ Cross-section is small, and decreases at least as $\sim 1/Q^6$

  $\Rightarrow$ For $Q^2 \gg M_{12}^2$ get extremely tiny numbers, "pure" Bjorken regime is difficult to achieve from experimental point of view

Evaluations in collinear factorization framework (II)

- **Beyond Bjorken limit**
- **Hierarchy of scales:**

$$\underbrace{m_N,\ \sqrt{|t|},\ |p_\perp|}_{\sim\Lambda^{-1}\approx 0} \ll \underbrace{Q,\ M_{J/\psi},\ M_{\eta_c}}_{\sim\Lambda^{0}} \ll \underbrace{p^+,\ q^-,\ W_{\gamma p}}_{\sim\Lambda^{1}}$$

$$\alpha_s(m_c),\ \alpha_s(Q) \ll 1$$

where $\Lambda \to \infty$ is some hard scale. Keep only the leading order in Λ for simplicity

- Reasonable for EIC, LHeC, FCC-he kinematics
- ***Subtle point***: in back-to-back kinematics no suppression if $\boldsymbol{p}_\perp^{J/\psi} \approx -\boldsymbol{p}_\perp^{\eta_c}$:
  - * GPD is sensitive only to $|t| \approx \left(\boldsymbol{p}_\perp^{J/\psi} + \boldsymbol{p}_\perp^{\eta_c}\right)^2$
  - * $p_\perp$ is disregarded in coef. functions in collinear factorization

  $\Rightarrow$Should be careful with observables which might get contributions from this region

- Structure function $C(x,\xi)$:

$$C(x,\xi) = \sum_{\pm} \frac{\tilde{N}_\pm(x,\ \xi)}{x \mp \xi \pm i0}$$

where $\tilde{N}_\pm(x,\ \xi)$ are finite for $|x| < 1$

Caution: Evaluation done at LO.

- ▷ At higher orders (NLO, ...) large contributions due to BFKL logs.
  - Important if $x_B \sim M_{12}^2/W^2 \ll 1$,
  - Explicit evaluation of all those corrections is not feasible.

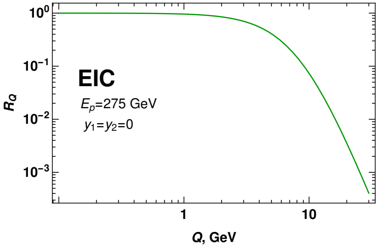
– ***Photoproduction @very high energy***: $\xi \approx M_{J/\psi}^2/W_{\gamma p}^2 \approx 0$, probe GPD moments (form factors) $R_n(t) = \int dx\, x^n H_g(x,0,t)$, $\quad n \gtrsim -1$

Results in collinear factorization

- Use Kroll-Goloskokov GPD for gluons
  - In $ep \to ep\,\eta_c\,J/\psi$ cross-section there is $\sim 1/Q^2$ from leptonic part, so cross-section is dominated by small-Q photons
    - Consider instead cross-section of $\gamma^* p \to p\,\eta_c\,J/\psi$ subprocess:
    - Consider normalized ratio

$$R_Q \equiv \frac{d\sigma(Q,\,...)/d\Omega}{d\sigma(Q=0,\,...)/d\Omega}$$

–values of $d\sigma$ depends on $y_a, \boldsymbol{p}_{a\perp}$
–for R_Q dependence largely cancels



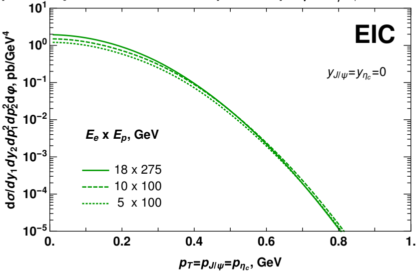
- The Q^2-dependence is controlled by

$$M_{12} = \sqrt{\left(p_{J/\psi} + p_{\eta_c}\right)^2} \gtrsim \left(M_{J/\psi} + M_{\eta_c}\right)$$

–very mild dependence for $Q^2 \lesssim M_{12}^2$
– $R_Q(Q) \sim 1/Q^6$ for $Q^2 \gg M_{12}^2$

Results in collinear factorization (II)

p_T dependence for $ep \to ep\,\eta_c\,J/\psi$:

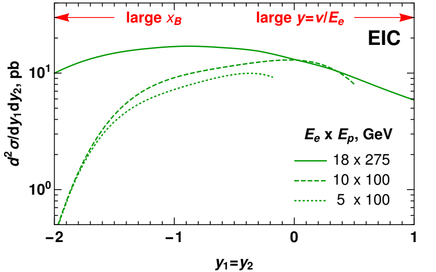


- Exponential suppression at large-p_T
  - ▷ due to implemented t-dependence in gluon GPD $H_g(x,\xi,t)$

$$H_g(x,\xi,t) \sim e^{B(x)\,t}$$

– recall that $t \sim -4p_\perp^2 + \ldots$

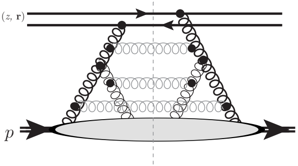
Rapidity dependence for $ep \to ep\,\eta_c\,J/\psi$:



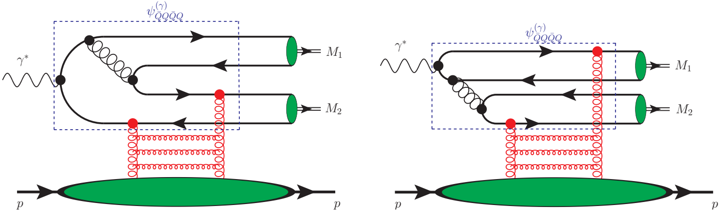
- Peaked at central rapidities $(y_1, y_2 \sim (-1,\,0))$
  - ▷ At negative rapidities x_B, ξ increase; so gluon GPD decreases
  - ▷ At positive rapidities suppression due to leptonic factor, elasticity $y = q\cdot p/k\cdot p = \nu/E_e$ approaches unity

Framework for evaluations (II)

- **Color Dipole approach**
  - ▷Valid at high energies (small-$x, \xi \ll 1$)
  - ▷ Based on eikonal picture in the target rest frame
  - ▷Replaces individual partons $\Rightarrow$ parton showers
  - ▷Interaction with target is described by (universal) dipole amplitude, which:
    - – satisfies Balitsky-Kovchegov equation
    - – effectively resums the fan-like diagrams as shown in the Figure



- Interactions of shower with heavy quarks is still suppressed by $\alpha_s(m_Q)$:

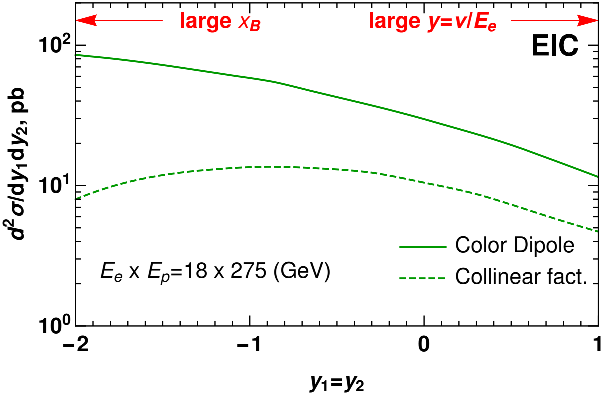


Eikonal picture: factorize amplitude into WFs and dipole amplitudes in config. space

–WFs from potential models

Color dipole vs. collinear factorization approach

► Use Kroll-Goloskokov GPD for gluons, b-CGC for color dipole amplitude



► At positive $y_1, y_2 > 0$:

– the shape of rapidity dependence is similar

– numerically predictions for cross-section differ by a factor of 2.

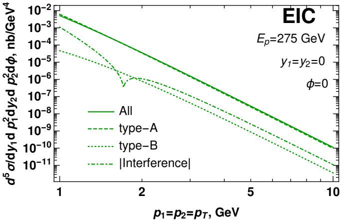
► At negative $y_1, y_2 < 0$:

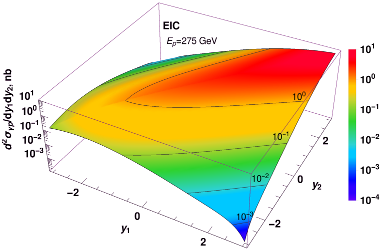
– the shape of rapidity dependence is completely different

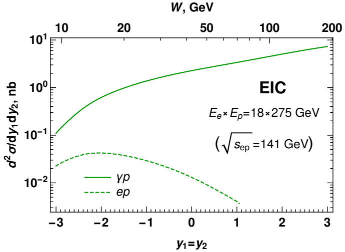
– approach the kinematics $x_B \gtrsim 10^{-2}$, where dipole model is less reliable.

Analysis of cross-sections

- ► $J/\psi\,\eta_c$ has the largest cross-section, dominated by contributions of "type-A" diagrams, "type-B" is strongly suppressed
  $\Rightarrow$ Important for understanding processes, which get contributions only from "type-B".
- ▷ Strong p_T-dependence $\sim 1/p_T^n$. Dominant contribution from $p_T \lesssim 1\,\mathrm{GeV}$.







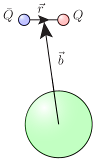
Rapidity sign:

- ▷ positive in direction of $e/\gamma^{(*)}$
- ▷ negative in direction of proton

- ▷ For ep suppression at very forward direction due to leptonic prefactor
- ▷ For other colliders (FCC-he, LHeC) predictions are similar

Azimuthal dependence

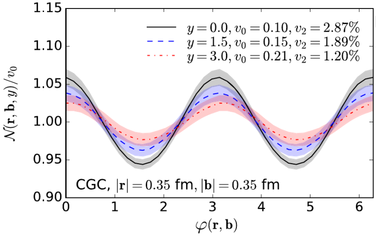
- Can study dependence on azimuthal angle ϕ between $\boldsymbol{p}_\perp^{J/\psi}$ and $\boldsymbol{p}_\perp^{\eta_c}$
- **Motivation**:



—might be used to study dependence on angle φ between color dipole orientation and impact parameter

- Early phenomenological parametrizations (b-CGC, b-Sat): no φ-dep., $N = N(x, |\boldsymbol{r}|, |\boldsymbol{b}|)$

—Might be incompatible with JIMWLK [PRD 99 (2019) 7, 074004]



[PRD 99 (2019) 7, 074004]

- Modern expectations:

— Dependence is mild:

$$N(x, |\boldsymbol{r}|, |\boldsymbol{b}|) = v_0(1 + v_2 \cos 2\varphi)$$

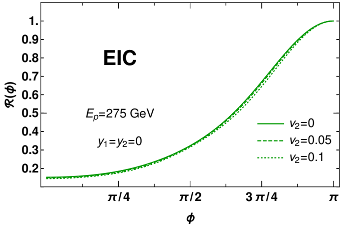
—v_0 is taken from coventional parametrizations

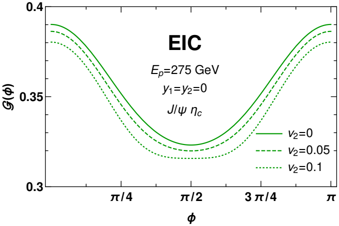
—$v_2 \ll 1$ is a small phenomenological parameter

— v_2 might be accessed in dijet production

Azimuthal dependence

- The dependence on ϕ has a peak at $\phi = \pi$ (back-to-back kinematics):





▷ Minimizes momentum transfer to proton at fixed $|p_\perp^{J/\psi}|$ and $|p_\perp^{\eta_c}|$:

$$|t| \approx |p_\perp^{J/\psi}|^2 + |p_\perp^{\eta_c}|^2 - 2|p_\perp^{J/\psi}||p_\perp^{\eta_c}|\cos\phi$$

▷ $\mathcal{R}(\phi)$ is cross-section normalized to 1 at peak ($\phi = \pi$) to eliminate rapidity dependent factors, integrated over $\left|p_\perp^{J/\psi}\right|$, $|p_\perp^{\eta_c}|$ to improve sensitivity
−changes $\gtrsim$ an order of magnitude, whereas v_2 is just a few % effect

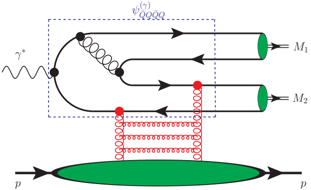
▷ **Suggestion**: study $\mathcal{G}(\phi) = \sqrt{\mathcal{R}(\phi)\mathcal{R}(\pi - \phi)}$ instead of $\mathcal{R}(\phi)$
− At small $|t|$ cross-section $d\sigma \sim e^{Bt}$, so ϕ-dependence due to $t(\phi)$ (almost) cancels.
$\Rightarrow$ Sensitivity to v_2 is much stronger

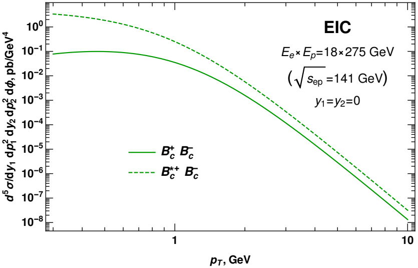
Predictions for quarkonia with b-mesons

- Bottomonia-bottomonia pairs (e.g. $\Upsilon(1S)\,\eta_b$) are similar to all-charm; numerically have much smaller cross-section

- Mixed pairs are more interesting, probe subsets of diagrams:

  ▷ $B_c^+ B_c^-$ might be produced only via mechanism (A):

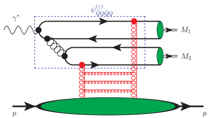




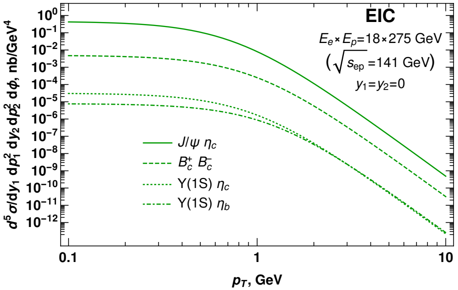
  ▷ C-parity does NOT give restrictions for internal quantum numbers, so can study both scalar (B_c) and vector (B_c^*) quarkonia in different combinations

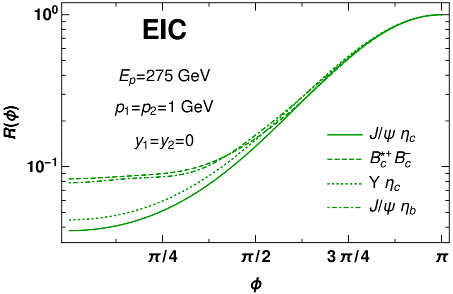
Predictions for quarkonia with b-mesons (II)

- Charmonia-Bottomonia pairs are produced only via mechanism (B):



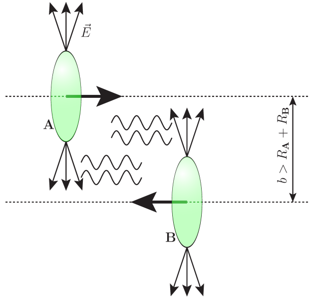
- Results for cross-sections:





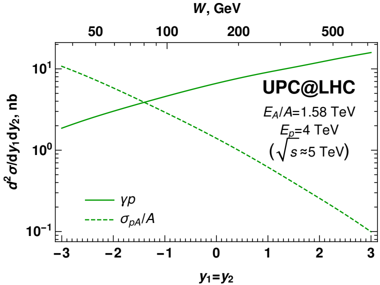
- Qualitatively similar behaviour for p_T, ϕ, y-dependence.
- Suppression with mass $\sim (\Lambda/\mu_1)^{2n}(\Lambda/\mu_2)^{2n}$, where μ_i is the reduced mass of the $\bar{Q}Q$ pair in mesons M_1, M_2
  - ▷For $\Upsilon(1S)\eta_c$ cross-section is much smaller than for $B_c^+B_c^-$ since it gets contribution only from "small" type-B diagrams

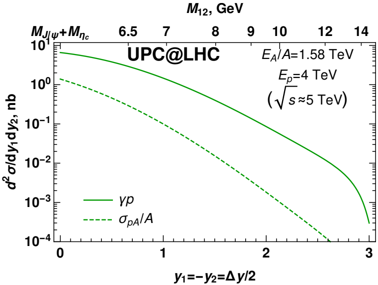
Studies in ultraperipheral *pp* and *pA* collisions @LHC



Ultraperipheral collisions:

- Impact parameter $b > R_A + R_B$
- Proceed via exchange of quasireal photon ($Q^2 < 1\,\mathrm{GeV}^2$)
- Nuclear targets:
  - ▷ Enhancement by $\sim Z$(atomic number) in amplitude, $\sim Z^2$ in cross-section
  - ▷ Due to nuclear form factor $Q^2 \lesssim 1/R_A^2 \lesssim 0.1\,\mathrm{GeV}^2$
- Feasibility demonstrated at RHIC, LHC

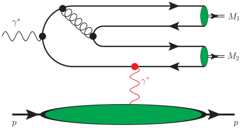




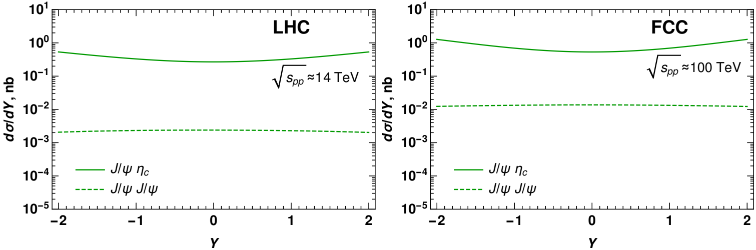
- Qualitatively the same behavior as for *ep* (see our publication for more details)

Our mechanism ($J/\psi\,\eta_c$) vs. $J/\psi\,J/\psi$ production

- $J/\psi\,J/\psi$ proceeds via $\gamma\gamma \to J/\psi\,J/\psi$ subprocess, extra suppression $\sim \mathcal{O}\left(\alpha_{\rm em}^2\right)$
  ▷ Extra photon⇒additional $\mathcal{O}\left(\alpha_{\rm em}^2\right)$-suppression in cross-sections



- Comparison with predictions from [PRD 101 (2020) no.3, 034025] :



- Cross-section of suggested mechanism is larger by 2 orders of magnitude (not by factor $\sim \mathcal{O}\left(\alpha_{\rm em}^{-2}\right) \sim 10^4$ as naively expected)

Summary

- We suggest to study exclusive production of opposite C-parity quarkonia ($J/\psi\,\eta_c$, $J/\psi\,\chi_c$...) as a complementary source of information about the gluonic field of the target
  - Access to GPD H_g in collinear factorization approach
  - Access to dipole amplitude in color dipole approach

- The cross-section are large enough for experimental studies, at least for charmonia pairs
  - Bottomonia and $B_c^+ B_c^-$ pairs have smaller cross-sections, but are also theoretically interesting
  - The quarkonia pairs are produced predominantly with small and oppositely directed transverse momenta ($|p_\perp| \lesssim 1\,\mathrm{GeV}$) , small rapidity difference

Summary

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Thank You for your attention!

Appendix I: Amplitude in color dipole picture

Eikonal picture:

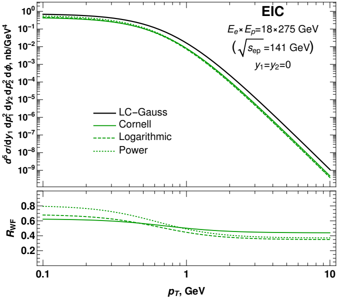
- t-channel interactions$\Rightarrow$multiplicative factors in config. space

$\Rightarrow$The amplitude factorizes into wave functions with a linear combination of color singlet dipole amplitudes

$$\mathcal{A} \sim \prod_{s=1}^{4} \left(\int d\alpha_s d^2 r_s \right) \sum_{ijklm} \psi_{M_1} \left(\alpha_{ij}, \boldsymbol{r}_i - \boldsymbol{r}_j \right) \psi_{M_2} \left(\alpha_{kl}, \boldsymbol{r}_k - \boldsymbol{r}_\ell \right) \otimes$$

$$\otimes c_m N \left(x, \mathfrak{r}_m, \mathfrak{b}_m \right) \psi^{(\gamma)}_{QQQQ} \left(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3, \boldsymbol{r}_4 \right) e^{i \left(\boldsymbol{p}_T^{(1)} \cdot \boldsymbol{r}_{ij} + \boldsymbol{p}_T^{(2)} \cdot \boldsymbol{r}_{k\ell} \right)}$$

where $\mathfrak{r}_m$, $\mathfrak{b}_m$ are some linear combinations of $\boldsymbol{r}_1 ... \boldsymbol{r}_4$, and c_m are color factors



- The wave function $\psi^{(\gamma)}_{QQQQ}$ is evaluated perturbatively, since $\alpha_s (m_c) \ll 1$
- The quarkonia WFs ψ_{M_1}, ψ_{M_2} are evaluated in potential models; comparable with LC-Gauss for J/ψ wave function

  - ▷ In general results are close to each other, discrepancy $\sim \alpha_s (m_c) \sim 1/3$ (see left)