Exclusive photoproduction of heavy quarkonia pairs

Marat Siddikov

In collaboration with Ivan Schmidt, Sebastian Andradé

UNIVERSIDAD TECNICA
FEDERICO SANTA MARIA

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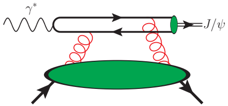
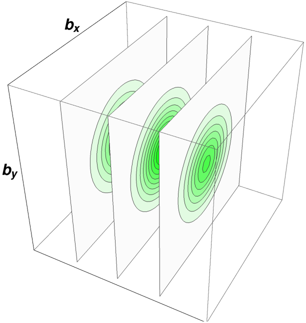
Why exclusive photoproduction of quarkonia?

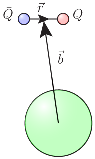
(see QWG review, Eur.Phys.J. C71 (2011) 1534)

Single quarkonia photoproduction

- Clean probe of the hadronic structure
- Collinear factorization approach:
  - ▷ probe (gluon) GPDs of the protons
- Color dipole approach:
  - ▷ fix b-dependence of dipole amplitudes
- Advantages:
  - ▷ Heavy mass $m_Q \gg \Lambda_{\rm QCD}$, "natural" hard scale, wide region of applicability of perturbative treatment
- Disadvantage: this process alone provides limited information, dependence on some variables is either "integrated out" or difficult to measure:
  - ▷ E.g. in dipole picture can't study dependence on orientation of dipole: angle between $\bar{Q}Q$ separation vector $\boldsymbol{r}$ ($\sim$dipole moment) and transverse CM position $\boldsymbol{b}$ (see right)



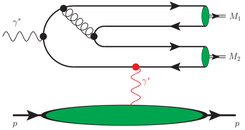




Exclusive photoproduction of quarkonia *pairs*

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

- **Advantages:**
  - ▷ Can study meson pairs with different J^P ⇒ should help to disentangle effects due to wave function from target-related effects
  - ▷ Can vary independently $(y, \boldsymbol{p}_\perp)$ of each quarkonium, form various new observables ⇒ much more detailed information about the target (parton distributions, dipole amplitudes at $x \ll 1$)
- **Disadvantage:**
  - ▷ Cross-sections are small
    - –Measurable at high-luminosity UPC@LHC, EIC, LHeC, FCC-he
    - –Focus on charmonia sector (larger cross-sections than for bottomonia).
- **Previous studies:** [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
  - ▷ At smaller energies might get contributions from diagrams with odderon in t-channel



Our suggestion:

► Production of quarkonia pairs with *opposite* C-parity:

$$J/\psi\,\eta_c,\ \ J/\psi\,\chi_c,\ J/\psi\,\eta_b,\ B_c^+B_c^-\ldots$$

▷ All possible diagrams fall into two main classes (see right)

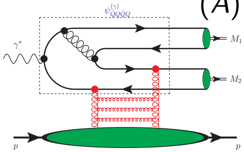
– Heavy flavour content of quarkonia determines if (A) or (B) contributes (same flavour or mixed)

	type-A	type-B
$(J/\psi\,\eta_c)$, $(\Upsilon\,\eta_b)$, ...	✓	✓
$(B_c^+B_c^-)$, $(B_c^{*+}B_c^-)$	✓	✗
$(J/\psi\,\eta_b)$, $(\Upsilon\,\eta_c)$, ...	✗	✓

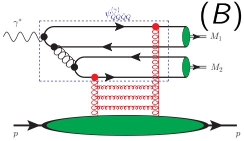
▷ Hard part is dominated by pomeron exchange,

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

(A)



(B)



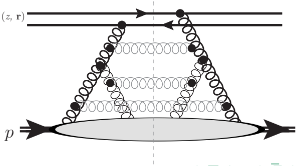
Summation over all possible connections of gluons to quark lines is implied

▷ We used color dipole approach, based on eikonal in the target rest frame

Dipole amplitude (b-CGC):

▷ Satisfies Balitsky-Kovchegov equation

▷ ... effectively resums the fan-like diagrams as shown in the Figure



Amplitude of the process

Eikonal picture:

▶Interactions with t-channel gluons are multiplicative in config. space

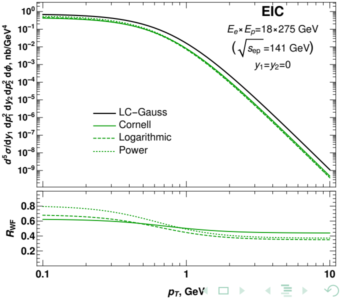
⇒The amplitude reduces to a convolutions of wave functions with a linear combination of color singlet dipole amplitudes

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

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

where $\mathfrak{r}_m$, $\mathfrak{b}_m$ are some linear combinations of $\boldsymbol{r}_1 \ldots \boldsymbol{r}_4$, and c_m are color factors (exact structure of $\mathfrak{r}_m$, $\mathfrak{b}_m$, c_m) depends on diagram

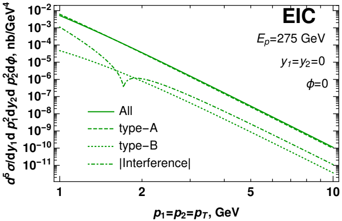
- ▶The wave function $\psi_{QQQQ}^{(\gamma)}$ is evaluated perturbatively, since $\alpha_s\left(m_c\right) \ll 1$
- ▶ The quarkonia WFs $\psi_{M_1}, \psi_{M_2}$are evaluated in potential models; comparable with LC-Gauss for J/ψ wave function



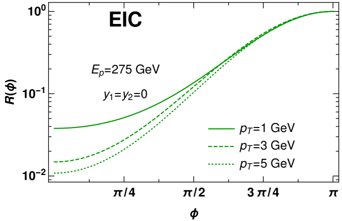
- ▷ In general results are close to each other, discrepancy $\sim \alpha_s\left(m_c\right) \sim 1/3$ (see right)

Cross-sections

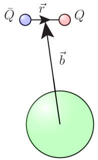
- $J/\psi\,\eta_c$ has the largest cross-section, dominated by contributions of "type-A" diagrams, "type-B" is strongly suppressed
  - $\Rightarrow$ Important for understanding processes, which get contributions only from "type-B".
  - ▷ Strong p_T-dependence $\sim 1/p_T^n$. Dominant contribution from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



- The dependence on azimuthal angle ϕ between $\boldsymbol{p}_\perp^{J/\psi}$ and $\boldsymbol{p}_\perp^{\eta_c}$ has a peak at $\phi = \pi$ (back-to-back)
  - ▷ Minimizes momentum transfer to proton at fixed $|p_\perp^{J/\psi}|$ and $|p_\perp^{\eta_c}|$
  - ▷ $R(\phi)$ is cross-sections normalized to 1 at $\phi = \pi$ (eliminate $\sim 1/p_T^n$ suppression factor)

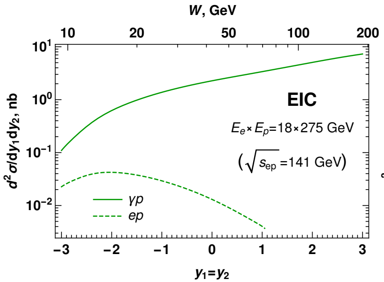


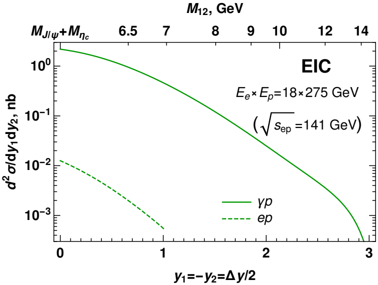
  - ▷ Sensitive probe of implemented dependence on dipole orientation in dipole amplitude (angle between $\vec{\boldsymbol{r}}, \vec{\boldsymbol{b}}$)

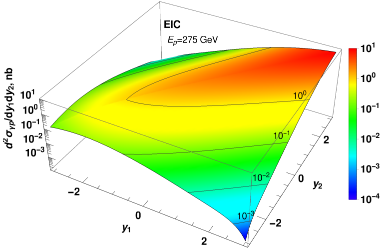


Phen. parametrizations (b-CGC, b-Sat): no φ-dependence $N = N(x, |\boldsymbol{r}|, |\boldsymbol{b}|)$

Rapidity dependence







Rapidity sign:

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

▷ negative in direction of proton

- The variable $W \equiv \sqrt{s_{\gamma p}}$ and

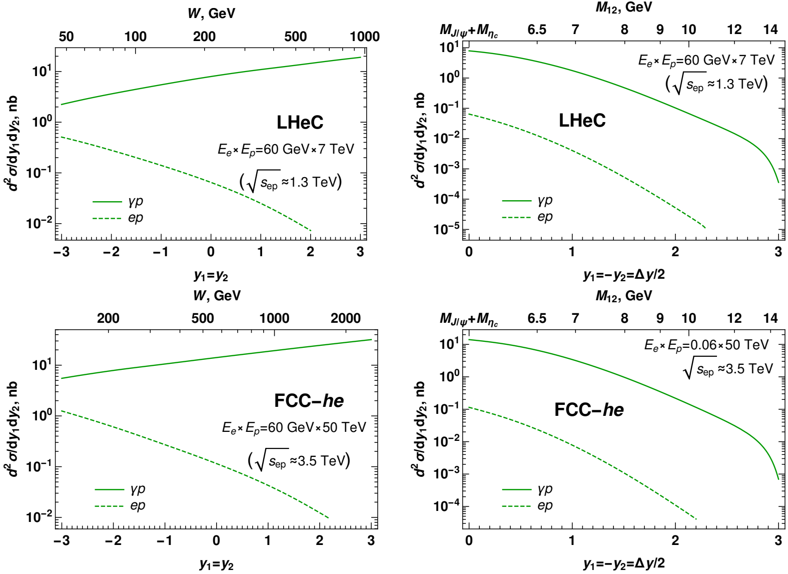
$$M_{12} = \sqrt{\left(p_{J/\psi} + p_{\eta_c}\right)^2}$$

is the invariant mass

▷ In collider kinematics quarkonia pair are produced with small rapidity separation in forward $(e/\gamma^{(*)})$ direction

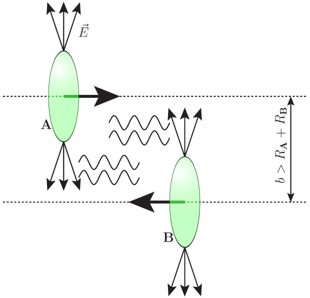
▷ For *ep* suppression at very forward direction due to leptonic prefactor

Predictions for other future *ep* colliders



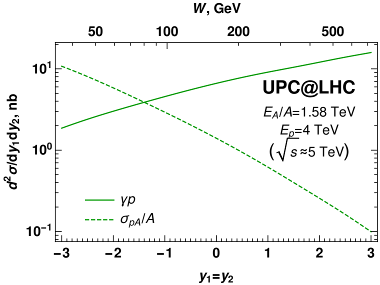
- Qualitatively the same behaviour as for EIC
- Cross-section grows mildly with energy as $(W_{\gamma p})^{\lambda}$

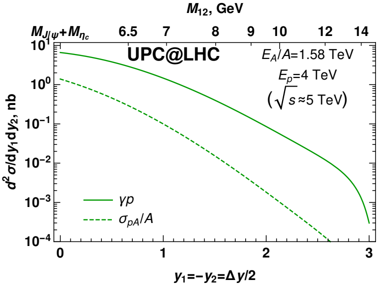
Studies in ultraperipheral *pp* and *pA* collisions @LHC



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

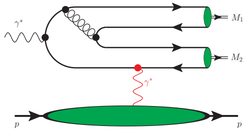




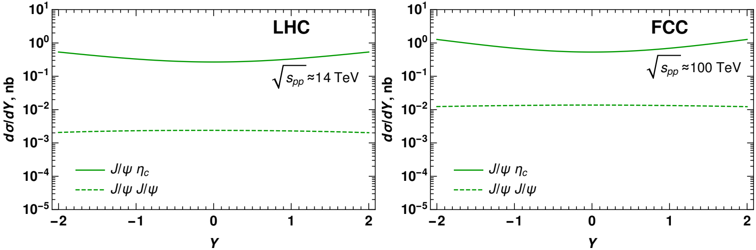
- Qualitatively the same behaviour as for *ep* (see our publication for more details)

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

- $J/\psi\,J/\psi$ proceeds via $\gamma\gamma \to J/\psi\,J/\psi$ sub-process, 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] :



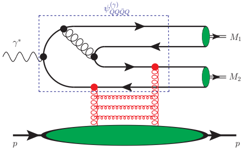
- Cross-section of suggested mechanism is larger by 2 orders of magnitude (not by factor $\sim \mathcal{O}\left(\alpha_{\rm em}^{-2}\right) \sim 10^4$ as naively expected)

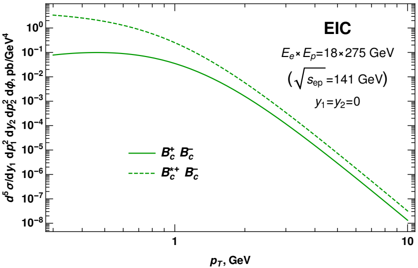
Predictions for quarkonia with b-mesons

- All-bottom meson 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:

  - $B_c^+ B_c^-$ are sensitive only to type-A diagrams

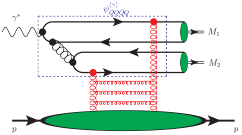




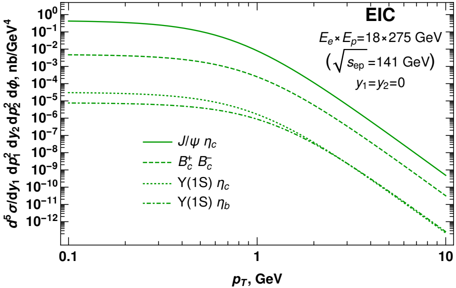
  - No restrictions from C-parity on internal quantum numbers, so can study both B_c and B_c^* in different combinations (probe of spin structure)
  - As of now, PDG2021 includes only $B_c^\pm$ with $J^P = 0^-$. Our mechanism could be used for clean (low-background) studies of possible $B_c^{*\pm}$ states.

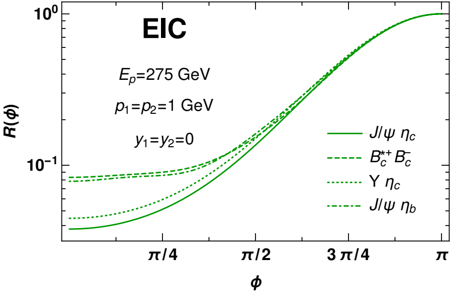
Predictions for quarkonia with b-mesons (II)

- Mixed hidden-charm hidden-bottom pairs get contributions only from type-B subsets of diagrams (see right)



- 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

Summary

- We suggest that exclusive production of opposite C-parity quarkonia ($J/\psi\,\eta_c$, $J/\psi\,\chi_c$...) might be used as complementary source of information about the partonic structure of the target.
- We analyzed the cross-section in EIC, LHeC and UPC@LHC kinematics and found that numerically it is reasonably large for experimental studies
  - ► The quarkonia pairs are produced predominantly with small and oppositely directed transverse momenta ($|p_\perp| \lesssim 1\,\mathrm{GeV}$) , small rapidity difference
- Interesting extensions:
  - ► bottomonia pairs ($\Upsilon\eta_b$, $\Upsilon\chi_b$) and mixed charmonia-bottomonia pairs ($\Upsilon\eta_c$, $\Upsilon\chi_b$, $J/\psi\,\eta_b$, $J/\psi\,\chi_b$)
    - ▷ Get contributions only from subset of diagrams, better theoretical control
  - ► $B_c^+ B_c^-$ pairs
    - ▷ No restrictions on quantum numbers of quarkonia due to C-parity

Thank You for your attention!