Heavy quarkonium coherent photoproduction on nuclei

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Based on [Phys.Rev.D 105 (2022) 5, 054023]()

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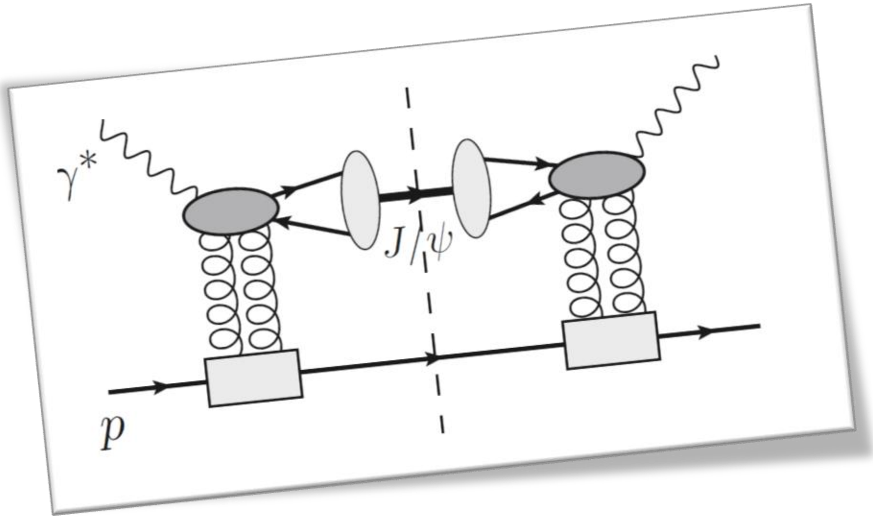
Outline

- Motivation & introduction
- Color dipole framework
- Dipole cross section
- $\vec{b}$-$\vec{r}$ correlation
- Nuclear cross section
- Gluon shadowing
- Numerical results
- Conclusions



Based on:

- Phys.Rev.D 105 (2022) 5, 054023

Why to be interested in VM and UPC?

- **Vector Mesons (VM)** are used as a probe, for example, in heavy-ion collisions or saturation phenomena in ep, eA
- In particular, we can study, e.g., **gluon distribution in hadrons**
- Photoproduction is well phenomenologically understood
- Heavy quarkonia with a small size minimize uncertainties inherited from the non-perturbative region

- Natural way of calculation:
  color dipole formalism

- Experimental data: LHC, RHIC
  - Recently also t-dep data

1^3S_1	1^{--}	$I=0,\ c\bar{c}$	0	$J/\psi(1S)$	3.0969
1^3S_1	1^{--}	$I=0,\ b\bar{b}$	0	$\Upsilon(1S)$	9.46030
1^3S_1	1^{--}	$I=1/2,\ u\bar{c}, \bar{u}c$	0	D^*	2.00685
1^3S_1	1^{--}	$I=1/2,\ d\bar{c}, \bar{d}c$	±1	D^*	2.01026
1^3S_1	1^{--}	$I=0,\ c\bar{s}, \bar{c}s$	±1	$D_s^{*\pm}$	??
1^3S_1	1^{--}	$I=1/2,\ d\bar{b}, \bar{d}b$	0	B^*	5.32465
1^3S_1	1^{--}	$I=1/2,\ u\bar{b}, \bar{u}b$	±1	B^*	??
1^3S_1	1^{--}	$I=0,\ b\bar{s}, \bar{b}s$	0	B_s^*	5.4154
1^3D_1	1^{--}	$I=0,\ c\bar{c}$	0	$\psi(3770)$	3.77313
1^3D_1	1^{--}	$I=0,\ c\bar{s}, \bar{c}s$	±1	$D^*_{s1}(2700)^{\pm}$	2.7083
2^3S_1	1^{--}	$I=0,\ c\bar{c}$	0	$\psi(2S)$	3.686097
2^3S_1	1^{--}	$I=0,\ b\bar{b}$	0	$\Upsilon(2S)$	10.02326
3^3S_1	1^{--}	$I=0,\ b\bar{b}$	0	$\Upsilon(3S)$	10.3552
4^3S_1	1^{--}	$I=0,\ b\bar{b}$	0	$\Upsilon(4S)$	10.5794

Minimize theoretical uncertainties

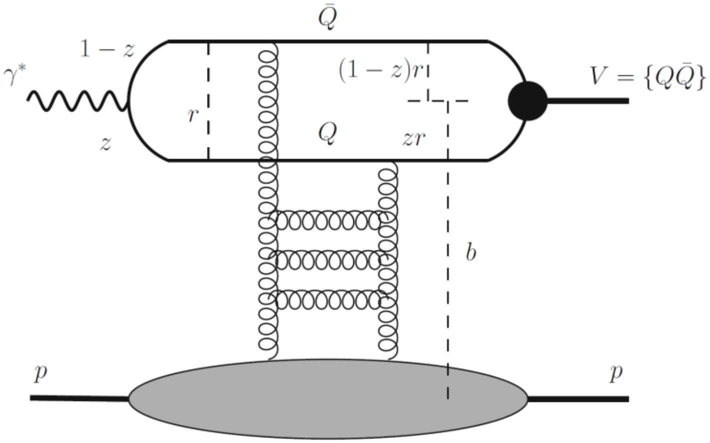
- A lot of various theoretical descriptions of coherent production of heavy quarkonia in UPC

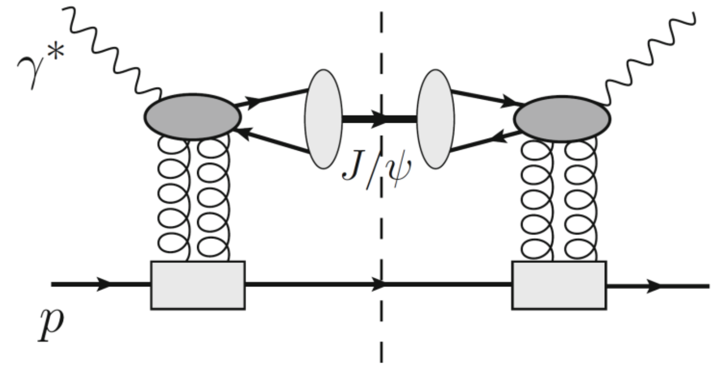
- **Earlier, we studied quarkonia uncertainties, for example:**
  - Quarkonium vertex
  - Wave function vs $Q\bar{Q}$ potential
  - $\vec{b}$-$\vec{r}$ correlation

B.Kopeliovich, MK, J.Nemchik, Phys.Rev.D 103 (2021) 9, 094027
MK, J.Nemchik, Phys.Rev.D 102 (2020) 11, 114033
MK, J.Nemchik, R.Pasechnik, Eur.Phys.J.C 80 (2020) 2, 92
J.Cepila, MK, J.Nemchik, R.Pasechnik, Eur.Phys.J.C 79 (2019) 6, 495
J.Cepila, MK, J.Nemchik, R.Pasechnik, Eur.Phys.J.C 79 (2019) 2, 154

- **Now, we focus on nuclear effects**
  - Higher twist shadowing
  - Gluon shadowing and higher Fock states

Color dipole formalism for VM





Amplitude:

$$\mathcal{A}^{\gamma^* p \to V p}(x, Q^2, \vec{q}) = \langle V | \tilde{A} | \gamma^* \rangle = \int d^2 r \int_0^1 d\alpha \, \Psi_V^*(\vec{r}, \alpha) \, \mathcal{A}_{Q\bar{Q}}(\vec{r}, x, \alpha, \vec{q}) \, \Psi_{\gamma^*}(\vec{r}, \alpha, Q^2)$$

t-dependent differential cross section:

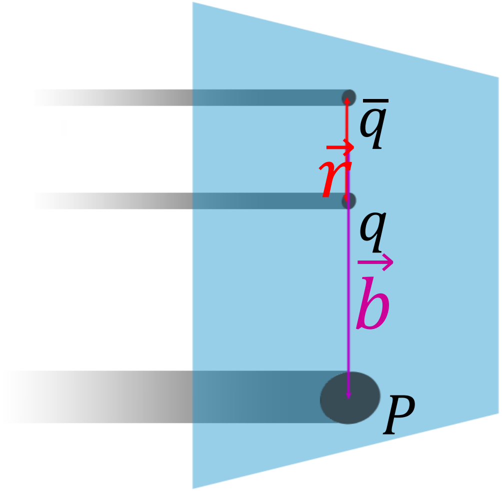
$$\frac{d\sigma^{\gamma^* p \to V p}(s, Q^2, t = -q^2)}{dt} = \frac{1}{16\,\pi} \left| \mathcal{A}^{\gamma^* p \to V p}(s, Q^2, \vec{q}) \right|^2$$

Dipole cross section

- Describes the interaction of $Q\bar{Q}$ with a proton
- Nonperturbative effects, **no theoretically calculable**
- Just models
  - Nevertheless, qualitatively, we have ideas, what is going inside
  - In the perturbative area described by the gluon distribution function
- Various models on the market: GBW, KST, IP-Sat, BGBK, BK, …
- Usually, they are fitted from DIS data, mostly from HERA
- However, such a fit is integrated over impact parameter $\vec{b}$
- For *t*-dependence, **we need a *b*-dependent dipole cross section (amplitude)**

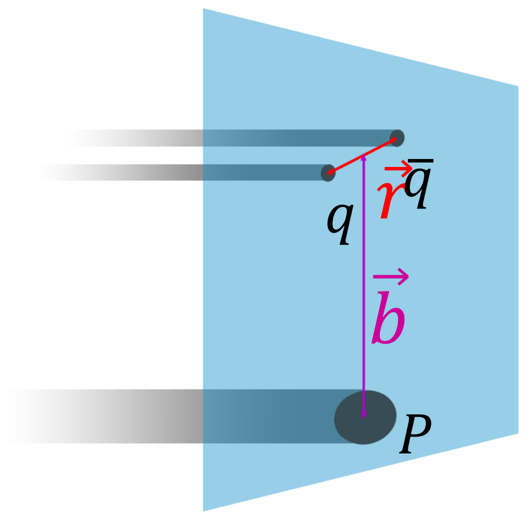
More in B.Kopeliovich, MK, J.Nemchik, Phys.Rev.D 103 (2021) 9, 094027

$\vec{b}$-$\vec{r}$ correlation



This is the case of maximal contribution.

$\vec{b} \parallel \vec{r}$ is simpler to calculate, no angle dependence.



Solution: Inspired by the Born approximation with two-gluon exchange

In reality, the angle between $\vec{b}$-$\vec{r}$ can be arbitrary.

One should integrate over all possibilities.

This is a challenge e.g. for BK. So far, only the $\vec{b} \parallel \vec{r}$ approximation was used.

More in B.Kopeliovich, MK, J.Nemchik, Phys.Rev.D 103 (2021) 9, 094027 & DIS2021

Photoproduction off nuclei I.

- $\gamma^* A$ coherent *amplitude* and *cross section*

$$\mathcal{A}^{\gamma^* A \to V A}(x, Q^2, \vec{q}) = \int d^2 b_A \, e^{i\vec{q}\cdot\vec{b}_A} \int d^2 r \int_0^1 d\alpha \, \Psi_V^*(\vec{r}, \alpha) \, \mathcal{A}_{\bar{Q}Q}^A(\vec{r}, x, \alpha, \vec{b}_A) \, \Psi_{\gamma^*}(\vec{r}, \alpha, Q^2)$$

$$\left. \frac{d\sigma^{\gamma^* A \to V A}(x, Q^2, t = -q^2)}{dt} \right|_{l_c \gg R_A} = \frac{1}{16\,\pi} \left| \mathcal{A}^{\gamma^* A \to V A}(x, Q^2, \vec{q}) \right|^2$$

- If coherence length $\gg R_A$
  - This is ok for LHC at midrapidity
  - Otherwise Green function should be used

$$\left. \mathrm{Im} \mathcal{A}_{\bar{Q}Q}^A(\vec{r}, x, \alpha, \vec{b}_A) \right|_{l_c \gg R_A} = 1 - \left[1 - \frac{1}{A} \int d^2 b \, \mathrm{Im} \mathcal{A}_{\bar{Q}Q}^N(\vec{r}, x, \alpha, \vec{b}) \, T_A(\vec{b}_A + \vec{b}) \right]^A$$

Glauber-Gribov form
Aka “frozen” approximation

$$\sigma_{q\bar{q}}(r, s) \quad \to \quad \sigma_{q\bar{q}}^{A,coh}(r, s, b) = 1 - \exp\left[-\frac{1}{2} \sigma_{q\bar{q}}(r, s) T_A(b) \right]$$

Photoproduction off nuclei II.

- We can apply other modifications:
  - **Real part**

$$\mathrm{Im}\mathcal{A}^{N}_{\bar{Q}Q}(\vec{r},x,\alpha,\vec{b}) \Rightarrow \mathrm{Im}\mathcal{A}^{N}_{\bar{Q}Q}(\vec{r},x,\alpha,\vec{b}) \cdot \left(1 - i\,\frac{\pi\,\Lambda}{2}\right)$$

  - **Skewness correction**

$$\mathrm{Im}\mathcal{A}^{N}_{\bar{Q}Q}(\vec{r},x,\alpha,\vec{b}) \Rightarrow \mathrm{Im}\mathcal{A}^{N}_{\bar{Q}Q}(\vec{r},x,\alpha,\vec{b}) \cdot R_S(\Lambda)$$

  - **Gluon shadowing**

$$\mathrm{Im}\mathcal{A}^{N}_{\bar{Q}Q}(\vec{r},x,\alpha,\vec{b}) \Rightarrow \mathrm{Im}\mathcal{A}^{N}_{\bar{Q}Q}(\vec{r},x,\alpha,\vec{b}) \cdot R_G(x,|\vec{b}_A+\vec{b}|)$$

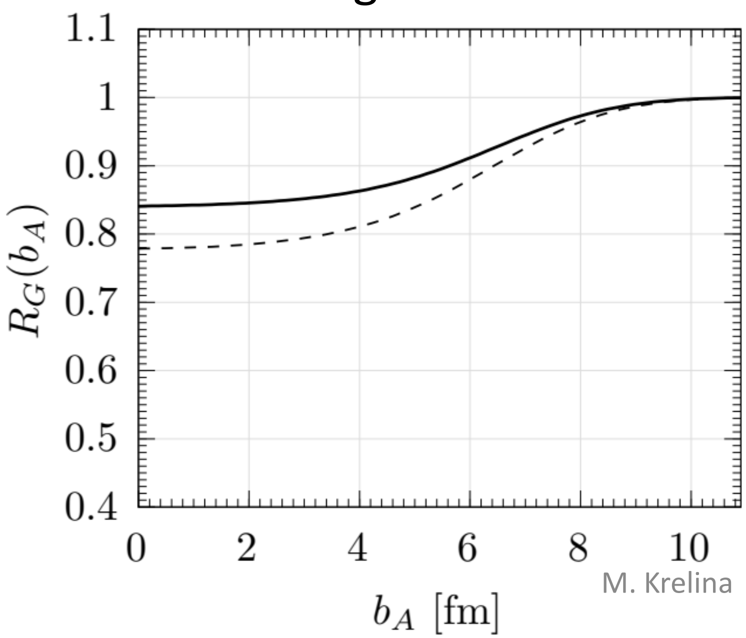
Gluon shadowing

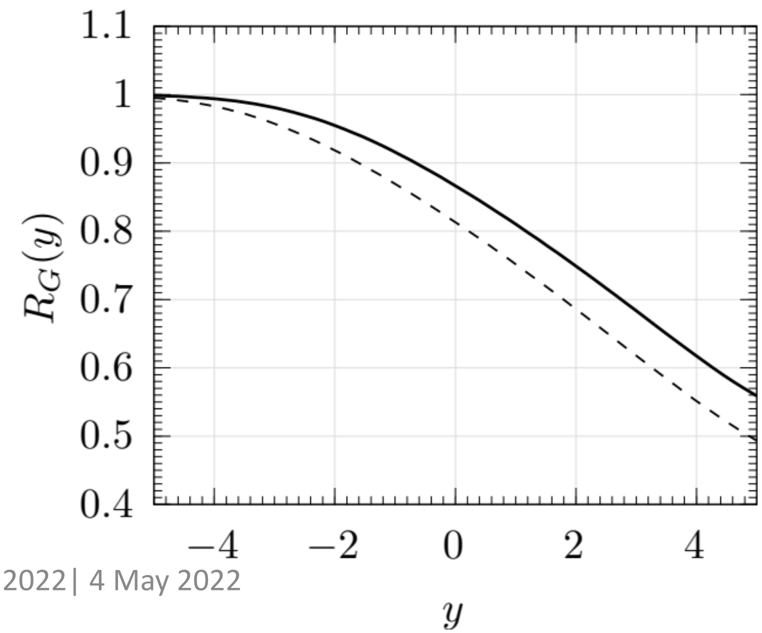
- Lowest Fock component: $|Q\bar{Q}\rangle$ More in MK, J.Nemchik, *Eur.Phys.J.Plus* 135 (2020) 6, 444.
- Higher Fock components: $|Q\bar{Q}g\rangle$, $|Q\bar{Q}2g\rangle$, ...
  - correspond to gluon radiation processes

  → higher-order corrections to the gluonic exchange
- **Complications:** higher Fock states are heavier

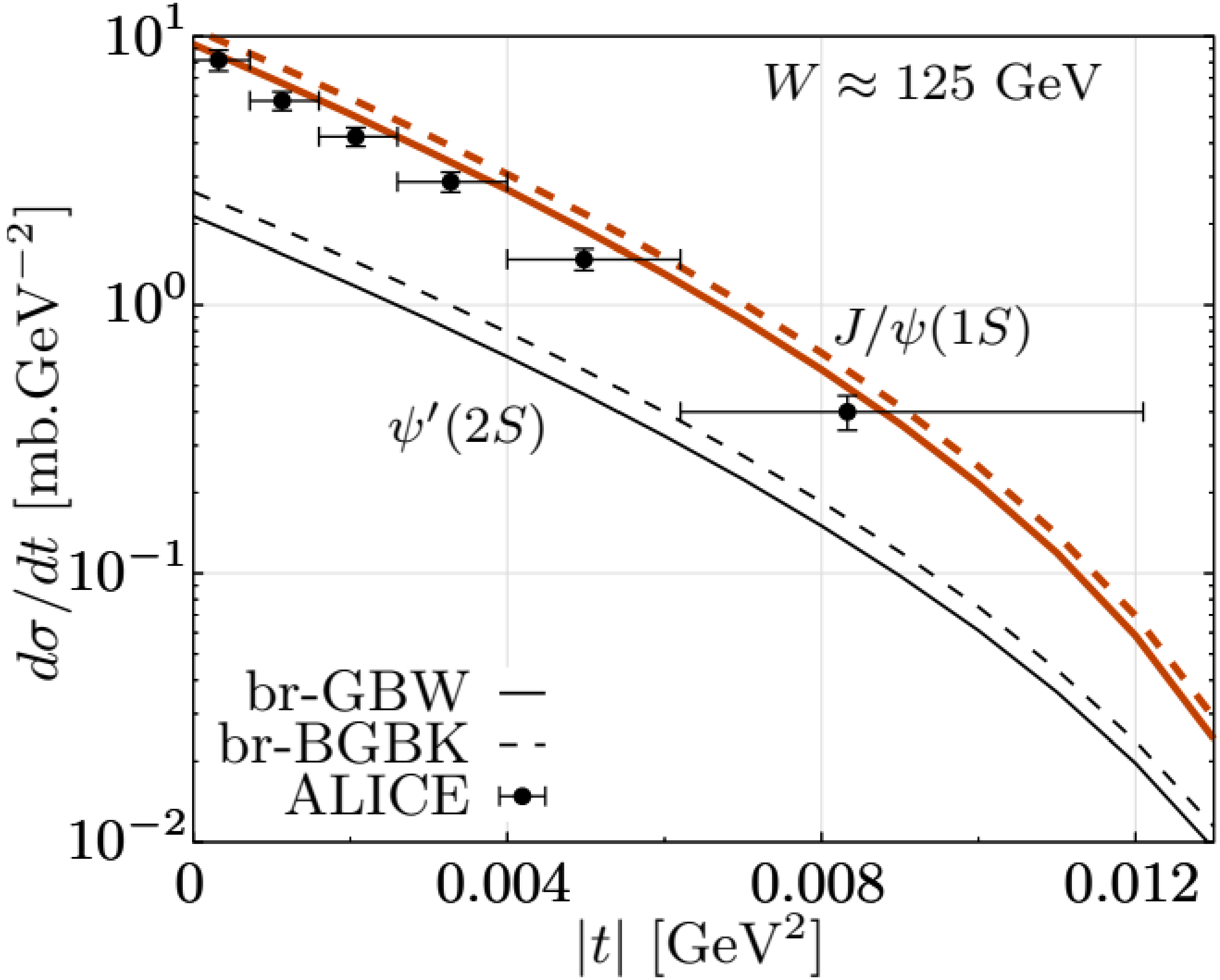
  → we cannot treat them as frozen – not a long coherence length limit

  → **we need to use the Green function**
- *n*-gluon Fock component *n* times shorter than the single-gluon coherence length



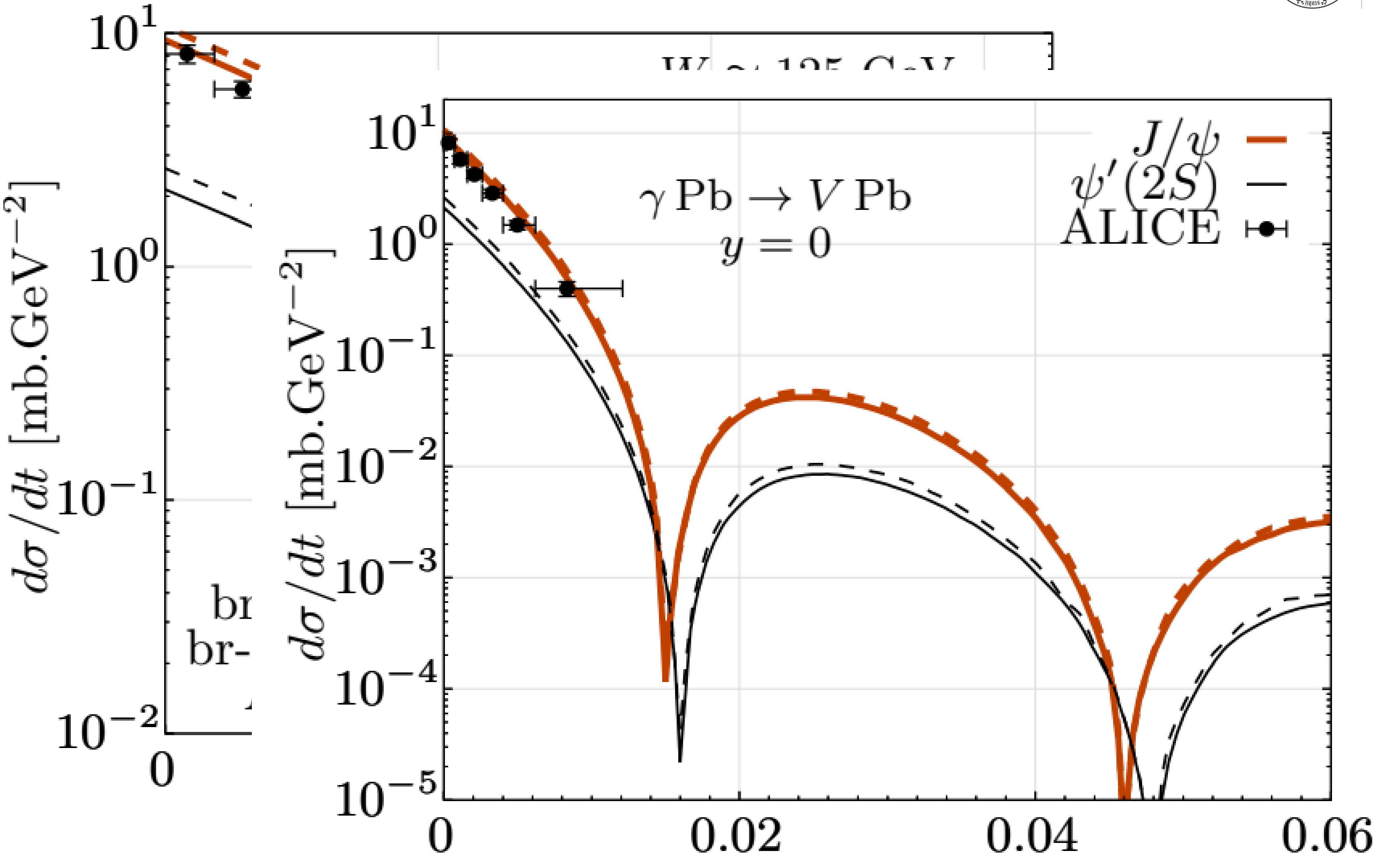


Results



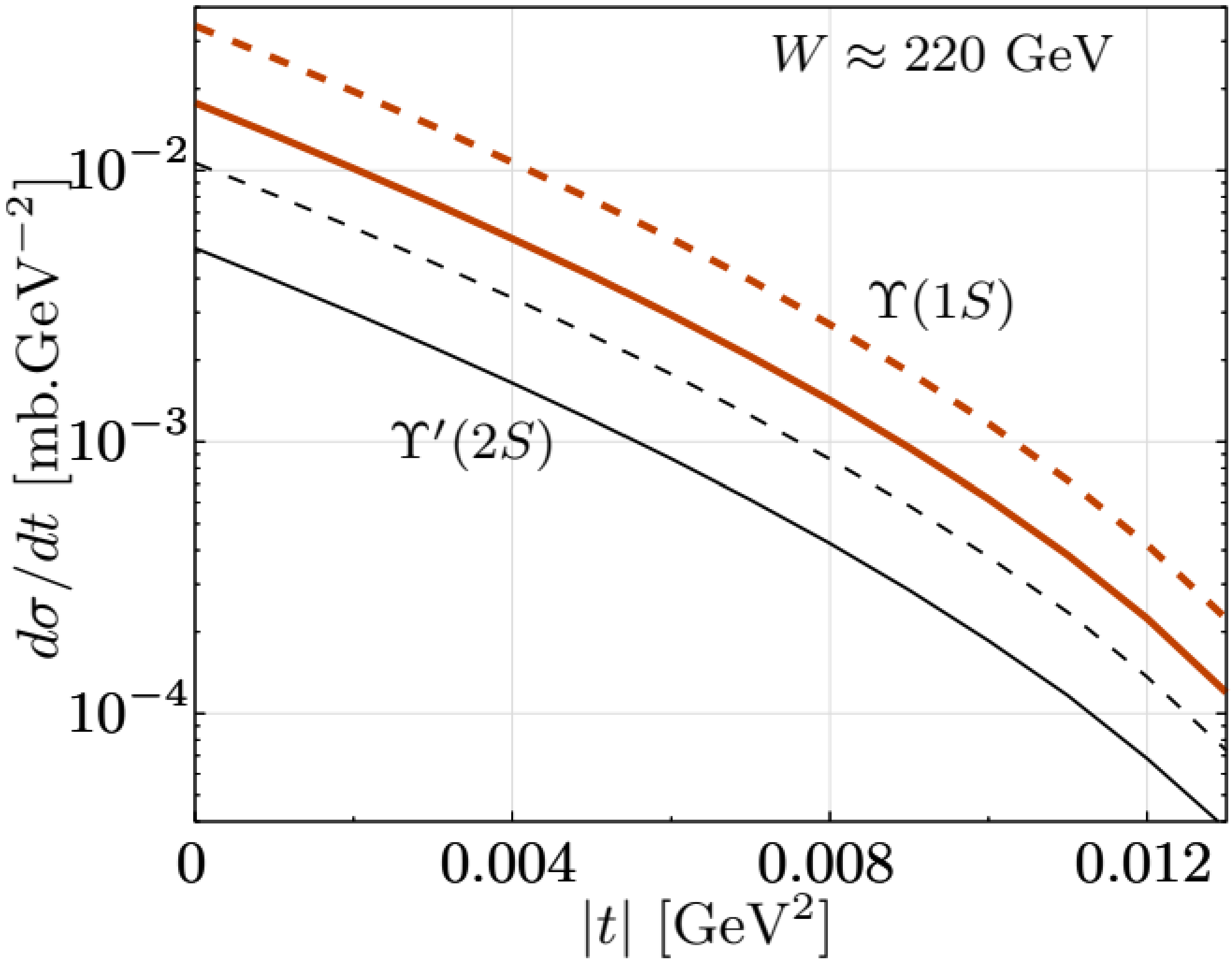
10^1
10^0
10^{-1}
10^{-2}
$d\sigma/dt$ [mb.GeV^{-2}]
0
0.004
0.008
0.012
$|t|$ [GeV^2]
$W \approx 125$ GeV
$J/\psi(1S)$
$\psi'(2S)$
br-GBW
br-BGBK
ALICE

Results



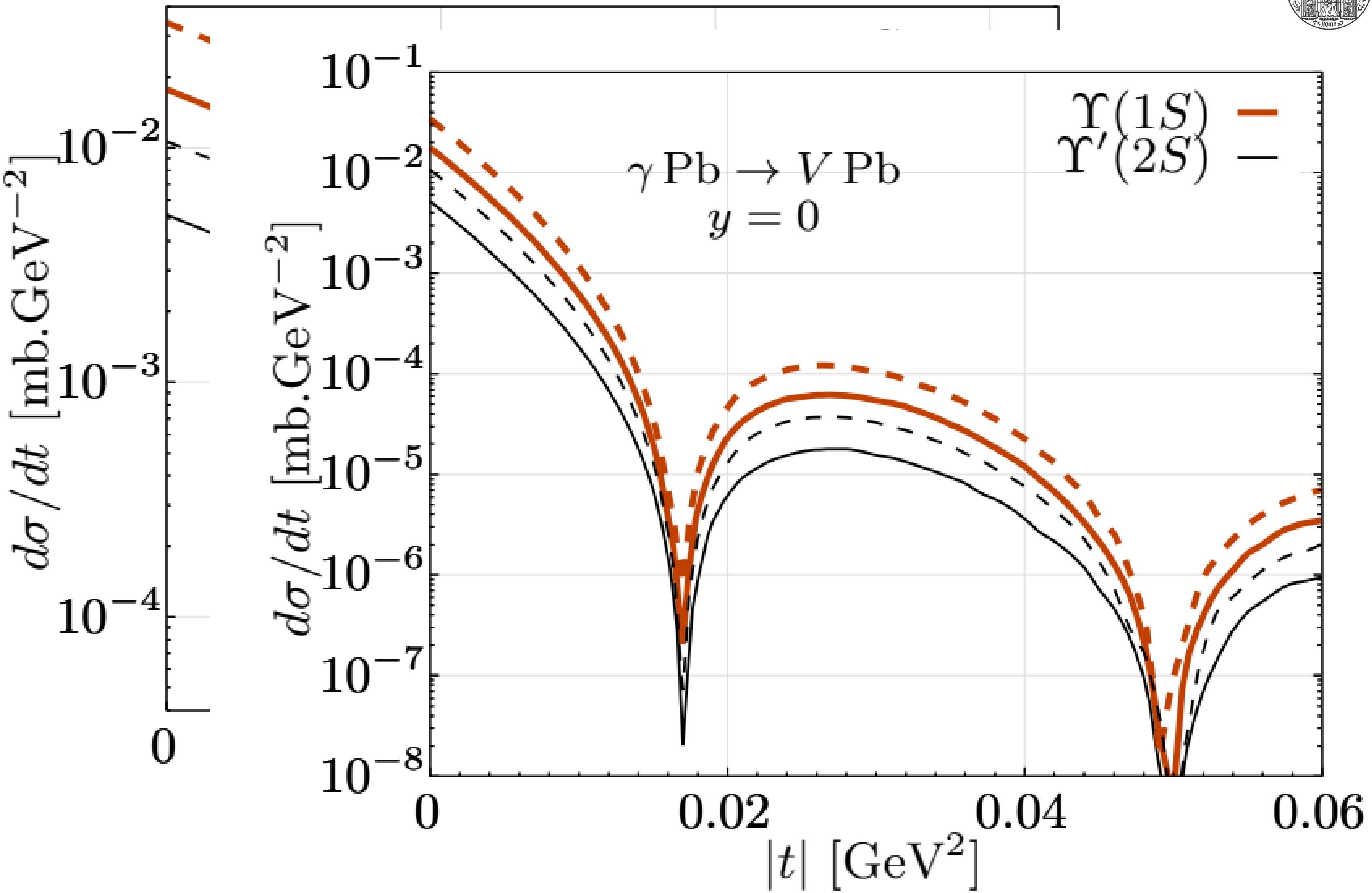
$\gamma\,\mathrm{Pb} \to V\,\mathrm{Pb}$
$y = 0$
J/ψ
$\psi'(2S)$
ALICE
$d\sigma/dt$ [mb.GeV^{-2}]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.02
0.04
0.06

Results



$W \approx 220$ GeV
$\Upsilon(1S)$
$\Upsilon'(2S)$
10^{-2}
10^{-3}
10^{-4}
$d\sigma/dt$ [mb.GeV^{-2}]
0
0.004
0.008
0.012
$|t|$ [GeV^2]

Results



$d\sigma/dt$ [mb.GeV^{-2}]
10^{-2}
10^{-3}
10^{-4}
0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$\gamma\,\mathrm{Pb} \to V\,\mathrm{Pb}$
$y = 0$
$\Upsilon(1S)$
$\Upsilon'(2S)$
0
0.02
0.04
0.06
$|t|$ [GeV^2]

Conclusions

- We studied the momentum transfer dependence of differential cross sections for coherent photoproduction of heavy quarkonia on nuclei, in the framework of the **dipole description**.
- We employ various corrections and precise calculations:
    - **Realistic $Q\bar{Q}$, $\vec{b}$-$\vec{r}$ correlation, gluon shadowing**
- Our calculations of dσ/dt for the coherent process are **in a good accord with recent ALICE data at the LHC**
- We also provided predictions for other quarkonium states that can be verified in the current experiments at the LHC.

Thank you for your attention!