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MINISTRY OF EDUCATION, YOUTH AND SPORTS

CZECH TECHNICAL UNIVERSITY IN PRAGUE

How can the photon-like heavy quarkonium $V \to Q\bar{Q}$ transition falsify our predictions ?

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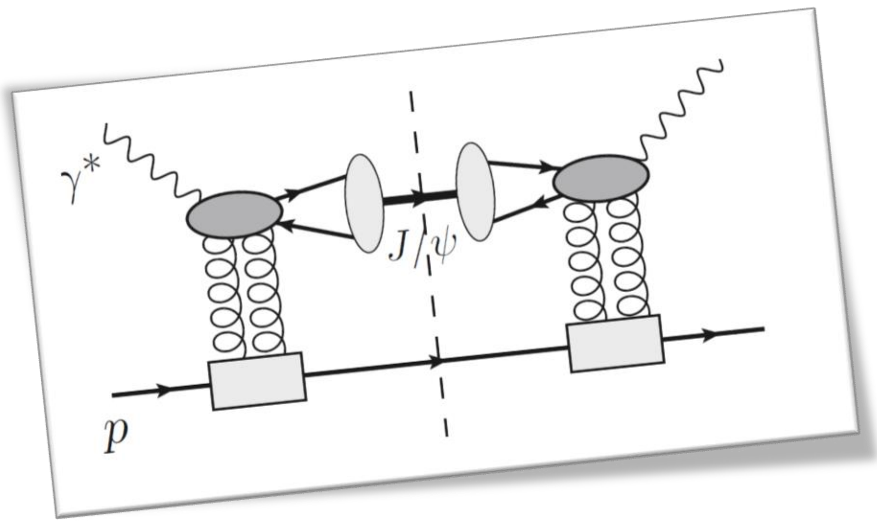
Outline

- Motivation & introduction
- VM Wave function
- VM production
- Vertex problem
- Various scenarios
- Numerical results
- Conclusions



Based on:

- Eur.Phys.J.C 80 (2020) 2, 92; arXiv:1909.12770

Why to be interested in VM?

- **Vector Mesons (VM)** are used as a probe for example in heavy-ion collisions
- Mostly 1S states of heavy quarkonia are used J/ψ and Υ
- The size of heavy quarkonia is relatively small

But do we use the correct wave functions?

- Many publication uses the so called boosted-Gaussian light cone wave function
  - Uses photon-like vertex
  - Consider the HO $Q\bar{Q}$ potential

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

- Vector Mesons (VM) are used as a probe for example in heavy-ion collisions
- Mostly 1S states of heavy quarkonia are used J/ψ and Υ
- The size of heavy quarkonia is relatively small

We can use the pQCD calculation, that can be verified by the scanning phenomenon

But do we use the correct wave functions?

VM wave function cookbook I

1) Go to the rest frame of the quark-antiquark $Q\bar{Q}$ system

2) Solve the Schrödinger equation (SE)

   The potential in SE corresponds to the potential between both quark and antiquark

3) Boost it to the light cone (LC) frame

4) Use it for example within the color dipole framework

But how is it with the radial and spin-orbital part?

VM wave function cookbook II

- In case of VM, we can factorize the radial and spin-orbital part
- In most cases, the spin-orbital part is omitted (only effect in normalization)

- If we use the potential of the harmonic oscillator (HO), we can solve it analytically, and we get commonly used Gaussian LC wave function (assuming the same spin and polarization structure as the photon)

  H. G. Dosch, T. Gousset, G. Kulzinger and H. J. Pirner, Phys. Rev. D 55 (1997) 2602.
  J. R. Forshaw, R. Sandapen and G. Shaw, Phys. Rev. D 69 (2004) 094013.
  J. Nemchik, N. N. Nikolaev and B. G. Zakharov, Phys. Lett. B 341 (1994) 228.
  J. Nemchik, N. N. Nikolaev, E. Predazzi and B. G. Zakharov, Z. Phys. C 75 (1997) 71.

VM wave function - radial part

- The $Q\bar{Q}$ rest frame => Schrödinger equation

$$\left(-\frac{\Delta}{2\mu}+V(\tilde{r})\right)\Psi_{nlm}(\vec{\tilde{r}})=E_{nl}\Psi_{nlm}(\vec{\tilde{r}}),\quad \mu=\frac{m_Q}{2},$$

$$\Psi_{nlm}(\vec{\tilde{r}})=\psi_{nl}(\tilde{r})\,Y_{lm}(\theta,\varphi)$$

- $V_{Q\bar{Q}}(r)$ - potentials:

$$\int|\psi(\tilde{r})|^2\mathrm{d}^3\tilde{r}=1.$$

  - Harmonic oscillator (HO)
  - Cornell potential (COR)
  - Logarithmic potential (LOG)
  - Buchmüller–Tye (BT)
  - Power-law (POW)

For references and more details see *Eur.Phys.J. C79 (2019) no.6, 495; arXiv:1901.02664*

Melosh spin rotation

- H.J. Melosh found a relation between of the spin-orbital part in the $Q\bar{Q}$ rest frame and the LC frame

  H.J. Melosh, Phys. Rev. D 9, 1095 (1974)

  J. Hufner, Y.P. Ivanov, B.Z. Kopeliovich, A.V. Tarasov, Phys. Rev. D 62, 094022 (2000)

$$\Psi_V^{(\mu,\bar{\mu})}(z,\vec{p}_T) = U^{(\mu,\bar{\mu})}(z,\vec{p}_T)\Psi_V(z,p_T)$$

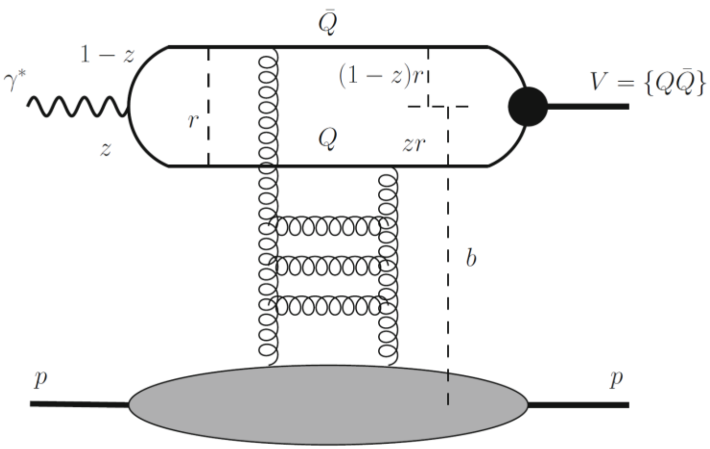
$$U^{(\mu,\bar{\mu})}(z,\vec{p}_T) = \frac{1}{\sqrt{2}}\xi_Q^{\mu\dagger}\vec{\sigma}\vec{e}_V\tilde{\xi}_{\bar{Q}}^{\bar{\mu}}, \qquad \tilde{\xi}_{\bar{Q}}^{\bar{\mu}} = i\sigma_y\xi_{\bar{Q}}^{\bar{\mu}*},$$

$$\xi_Q^{\mu} = R(z,\vec{p}_T)\chi_Q^{\mu}, \qquad \xi_{\bar{Q}}^{\bar{\mu}} = R(1-z,-\vec{p}_T)\chi_{\bar{Q}}^{\bar{\mu}},$$

$$R(z,\vec{p}_T) = \frac{m_Q + zM_V - i(\vec{\sigma}\times\vec{n})\vec{p}_T}{\sqrt{(m_Q + zM_V)^2 + p_T^2}}$$

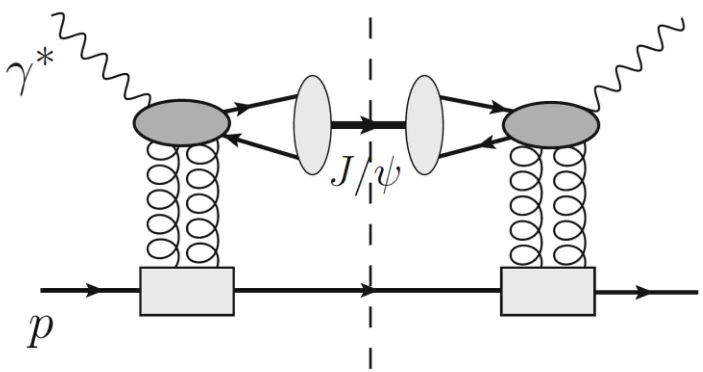
Exclusive quarkonia electroproduction

- We study the effects of the Melosh spin rotation in diffractive electroproduction



$$\mathrm{Im}\mathcal{A}_{T,L}^{\gamma^* p\to Vp}(x,\,Q^2)=\int_0^1 \mathrm{d}z\int \mathrm{d}^2r\,\Sigma_{T,L}\times(z,\vec{r};\,Q^2)\,\sigma_{q\bar{q}}(x,r),$$

$$\Sigma_{T,L}(z,\vec{r};\,Q^2)=\int\frac{\mathrm{d}^2p_T}{2\pi}e^{-i\vec{p}_T\vec{r}}\Psi_V(z,\,p_T)\times\sum_{\mu,\bar{\mu}}U^{\dagger(\mu,\bar{\mu})}(z,\,\vec{p}_T)\Psi_{\gamma^*_{T,L}}^{(\mu,\bar{\mu})}(r,\,z;\,Q^2).$$



$$\sigma^{\gamma^* p\to Vp}(x,\,Q^2)=\sigma_T^{\gamma^* p\to Vp}+\tilde{\varepsilon}\,\sigma_L^{\gamma^* p\to Vp}=\frac{1}{16\pi B}\left(\left|\mathcal{A}_T^{\gamma^* p\to Vp}\right|^2+\tilde{\varepsilon}\left|\mathcal{A}_L^{\gamma^* p\to Vp}\right|^2\right)$$

VM LC Wave function

Melosh spin rotation

- $\Phi_V \approx N \quad \chi_Q^\dagger R^\dagger(z, p_T) \hat{O}_{T,L} R^*(1-z, -p_T) \chi_Q \quad \psi_V(p_T, z)$

Some constants $\qquad Q\bar{Q} \to V$ vertex $\qquad$ radial wave function

Vertex option:

- *Massive photon-like:*

$$\hat{O}_T = m_q \vec{\sigma} \cdot \vec{e} + i(1-2z)(\vec{\sigma} \cdot \vec{n})\left(\vec{e} \cdot \vec{\nabla}_r\right) + (\vec{n} \times \vec{e}) \cdot \vec{\nabla}_r$$

- *S-wave-only-like:* $\hat{O}_T = \vec{\sigma} \cdot \vec{e}$

Spin rotation matrix

- *No rotation:* $R = \hat{1}$
- *Melosh spin rotation:* $R = \frac{m_q + zM_V - i(\vec{\sigma} \times \vec{n}) \cdot \vec{p}_T}{\sqrt{\left(m_q + zM_V\right)^2 + p_T^2}}$

Massive phon-like vertex

- Vertex: $m_q \vec{\sigma} \cdot \vec{e} + i(1-2z)(\vec{\sigma} \cdot \vec{n})\left(\vec{e} \cdot \vec{\nabla}_r\right) + (\vec{n} \times \vec{e}) \cdot \vec{\nabla}_r$

- Performed in light-front (LF) frame
- Is rather postulated than computed from the first principles
- The results is *D*-wave admixture in the $Q\bar{Q}$ rest frame (the derivative terms represent *D*-Wave)
  - the relative weight of these contributions cannot be justified by any reasonable nonrelativistic $Q\bar{Q}$ potential model

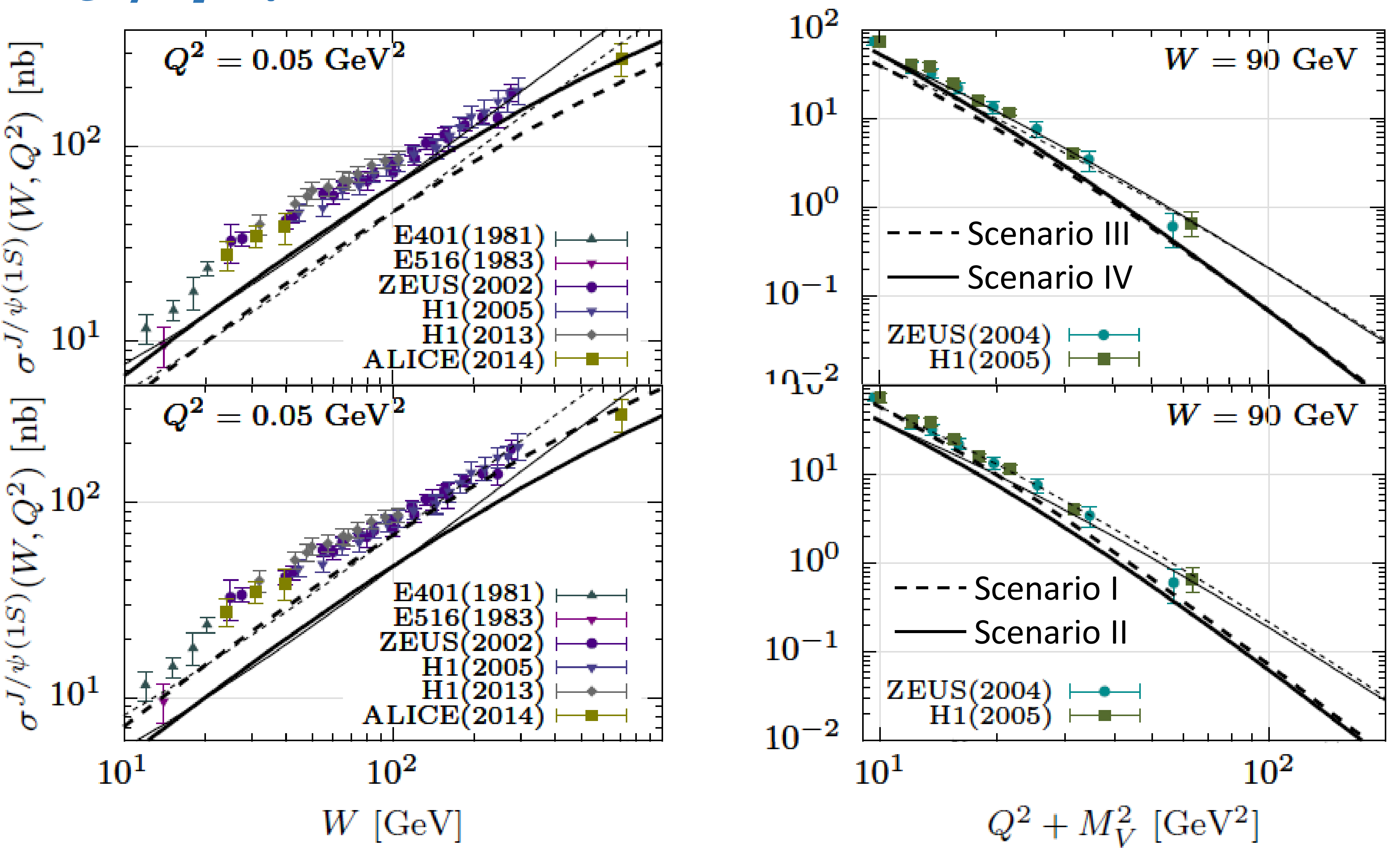
Scenarios

- We study several scenarios because n
- Scenario I:
  - Photon-like $\mathrm{V} \to Q\bar{Q}$
- Scenario II:
  - Photon-like $\mathrm{V} \to Q\bar{Q}$ + Melosh spin rotation
- Scenario III:
  - Pure *S*-wave $\mathrm{V} \to Q\bar{Q}$
- Scenario IV:
  - Pure *S*-wave $\mathrm{V} \to Q\bar{Q}$ + Melosh spin rotation

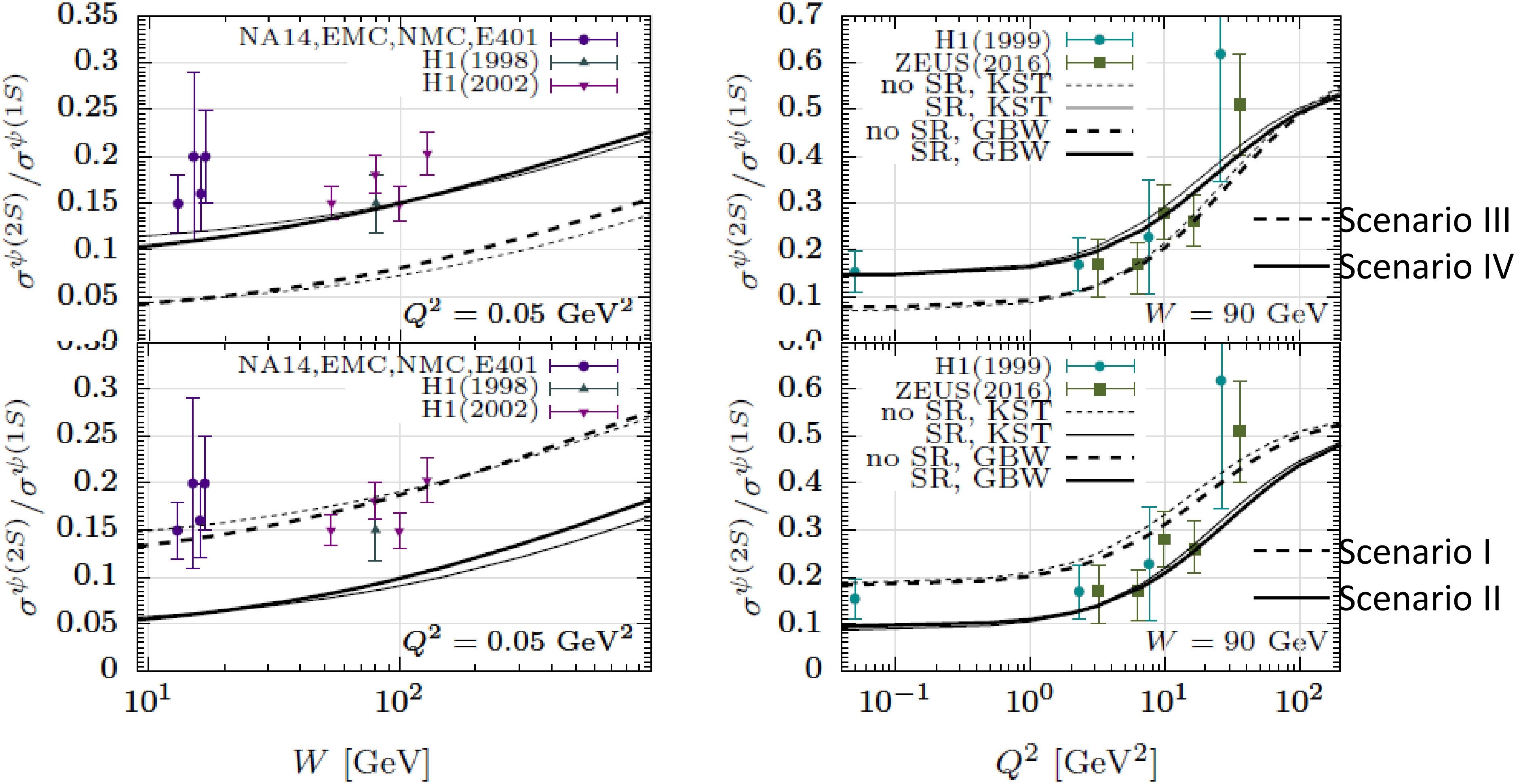
- Scenarios III+IV in details:

  Eur.Phys.J. C79 (2019) no.2, 154; arXiv:1812.03001
  Eur.Phys.J. C79 (2019) no.6, 495; arXiv:1901.02664

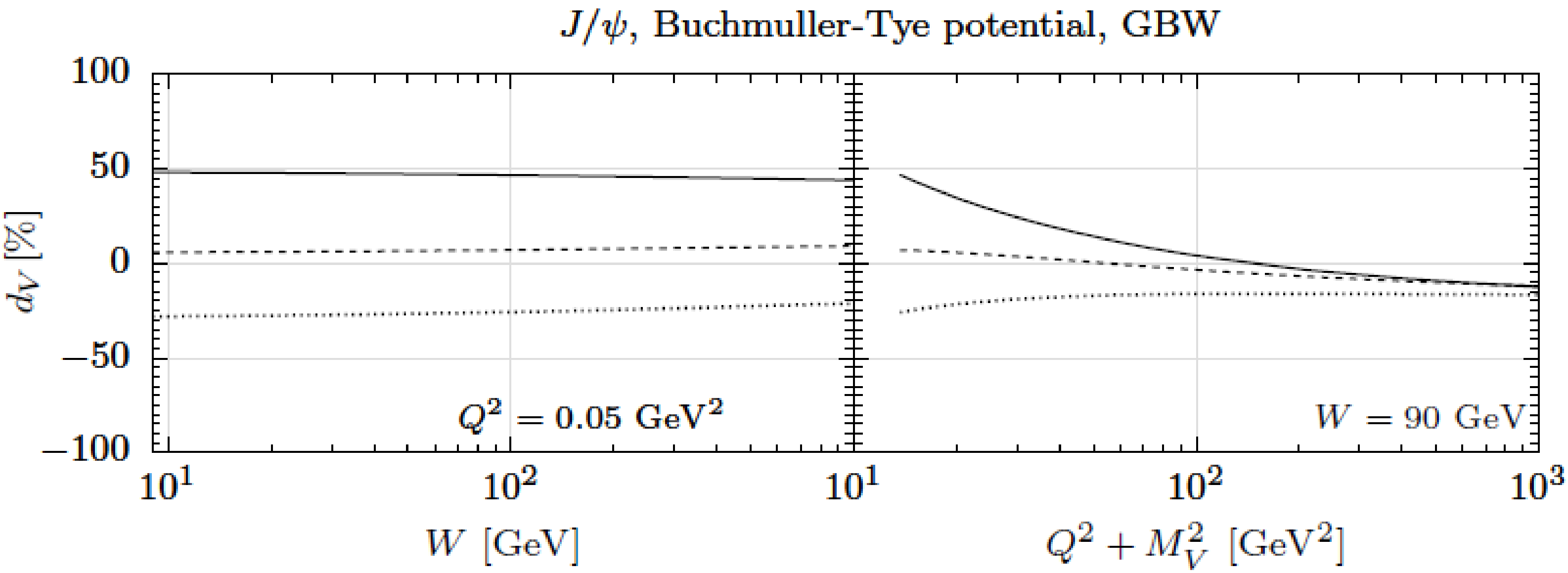
J/ψ production

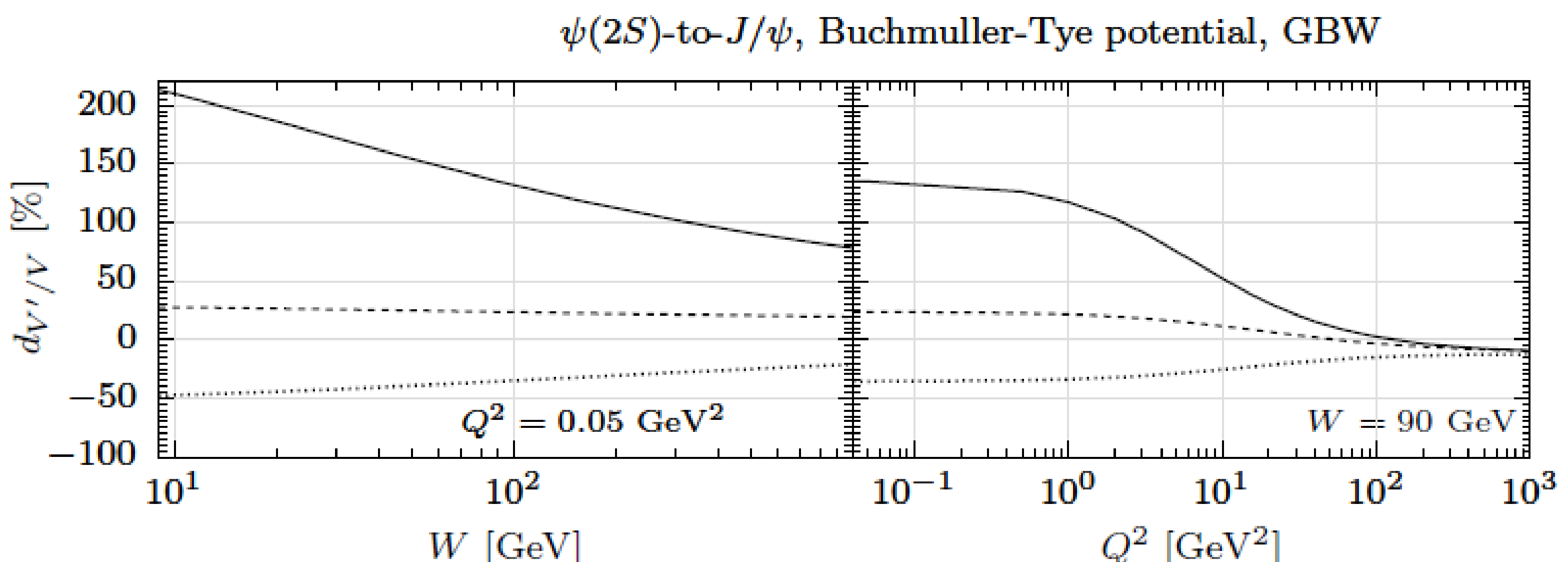


ψ' / J/ψ production



Relative impact





Scenarios:

$\frac{I-III}{III}$

$\frac{I-IV}{IV}$

$\frac{II-IV}{IV}$

Conclusions

- **Photon-like vertex** more difficult to justify
  - Besides *S*-Wave contains also *D*-Wave
- The interplaying *D*-wave and spin rotation effects is strongly correlated with a structure of the quarkonium vertex
- The correlation *D*-wave and spin effects is stronger for the **radially-excited states** than in production of **ground state *1S*** quarkonia due to a nodal structure of corresponding radial wave functions
- We are awaiting more precise data on VM production especially from EIC where the photoproduction is a very clear probe

Thank you for your attention!

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