Exclusive photoproduction of excited vector mesons in the dipole picture

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Challenges in VM production studies

✓ **Quarkonia production in pp/pA, as well as high pT forward particle production in pA, traditionally are very important probes for QCD dynamics**
e.g. QCD factorisation, gluon resummations, higher order PT and non-PT effects, medium, CGC etc

★ *probe for QCD in heavy quark production*

heavy quarks provide a naturally hard enough scale to study the production mechanisms in perturbative QCD (factorisation breaking, CS vs CO etc)

★ *probe for large-distance evolution and formation*

Quarkonia are suppressed in a deconfined medium which is believed to be due to a Debye screening of the heavy quark potential (Matsui-Satz'86)

★ *Quarkonia are sensitive to all the stages, from early heavy quark production to late time evolution and bound states' formation*

✓ **Charmonia are very special!**

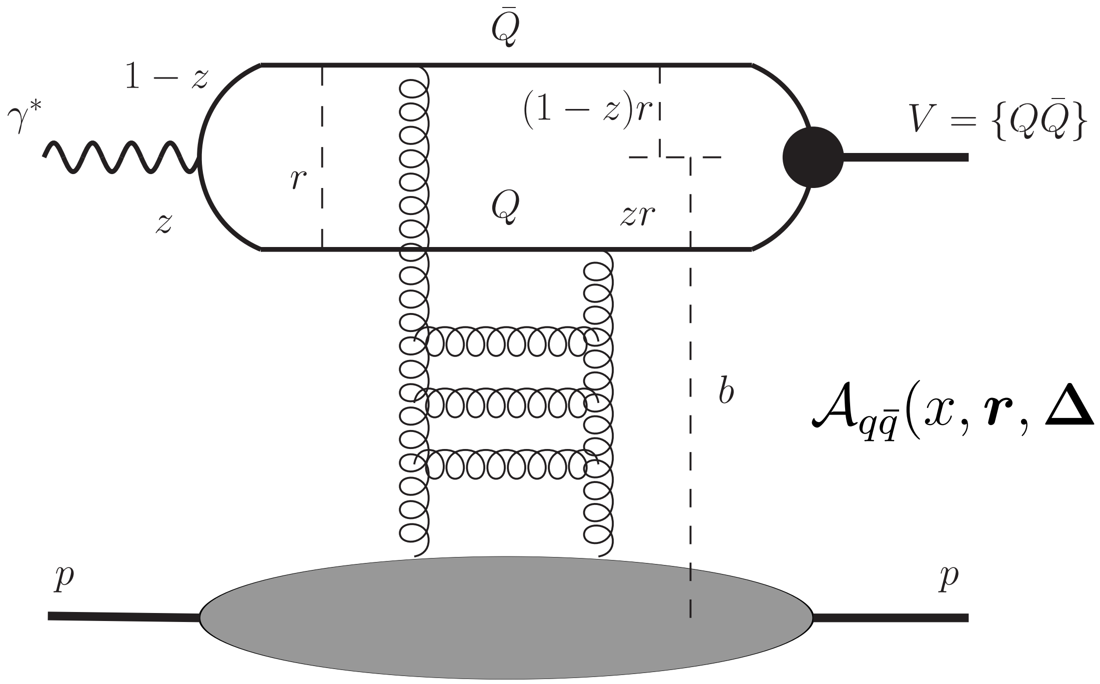
★ *Charm quark mass scale is at the boundary between pQCD and soft QCD*
★ *Specific for production and destruction mechanisms in HIC*

✓ **J/psi puzzle: highly uncertain production and evolution in hot environment**
What is the dominate QCD mechanism and role of the medium? why R_{pA} is close to one?

Quantitative understanding of VMs in pp/pA/AA at different energies remains a challenge

VM exclusive photo production: an overview

$$\frac{d\sigma^{\gamma p \to Vp}}{dt} = \frac{1}{16\pi} \left|\mathcal{A}^{\gamma p}(x, \Delta_T)\right|^2 \qquad x = \frac{M_V^2 + Q^2}{s}$$



$$\mathcal{A}^{\gamma p}(x, \Delta_T) = \int d^2\boldsymbol{r} \int_0^1 dz \; (\Psi_V^* \Psi_\gamma) \; \mathcal{A}_{q\bar{q}}(x, \boldsymbol{r}, \boldsymbol{\Delta})$$

$$\mathcal{A}_{q\bar{q}}(x, \boldsymbol{r}, \boldsymbol{\Delta}) = \int d^2\boldsymbol{b}\, e^{-i\boldsymbol{b}\cdot\boldsymbol{\Delta}} \mathcal{A}_{q\bar{q}}(x, \boldsymbol{r}, \boldsymbol{b}) = i \int d^2\boldsymbol{b}\, e^{-i\boldsymbol{b}\cdot\boldsymbol{\Delta}}\, 2[1 - S(x, \boldsymbol{r}, \boldsymbol{b})]$$

$$\mathcal{A}^{\gamma p}(x, \Delta_T) = 2i \int d^2\boldsymbol{r} \int_0^1 dz \int d^2\boldsymbol{b}\, (\Psi_V^* \Psi)\, e^{-i[\boldsymbol{b} - (1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}} N(x, \boldsymbol{r}, \boldsymbol{b})$$

$$N(x, \boldsymbol{r}, \boldsymbol{b}) \equiv \mathrm{Im}\mathcal{A}_{q\bar{q}}(x, \boldsymbol{r}, \boldsymbol{b}) = 2[1 - \mathrm{Re}S(x, \boldsymbol{r}, \boldsymbol{b})] \qquad \sigma_{q\bar{q}}(x, r) = 2 \int d^2\boldsymbol{b}\, N(x, \boldsymbol{r}, \boldsymbol{b})$$

H. Kowalski, L. Motyka, and G. Watt, Phys. Rev. **D74**, 074016 (2006)

J. Hufner, Yu. P. Ivanov, B. Z. Kopeliovich, and A. V. Tarasov, Phys. Rev. **D62**, 094022 (2000), arXiv:hep-ph/0007111 [hep-ph].

J. Nemchik, N. N. Nikolaev, and B. G. Zakharov, Phys. Lett. **B341**, 228 (1994)

VM wave functions in the Light-Front approach

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

In case of VM, we can factorize the radial and spin-orbital part

In most cases, the spin-orbital part is omitted **Absorbed into normalisation!**

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)

HO doesn't include the Coulomb repulsion

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.

Quarkonia wave functions: radial part

The $Q\bar{Q}$ rest frame

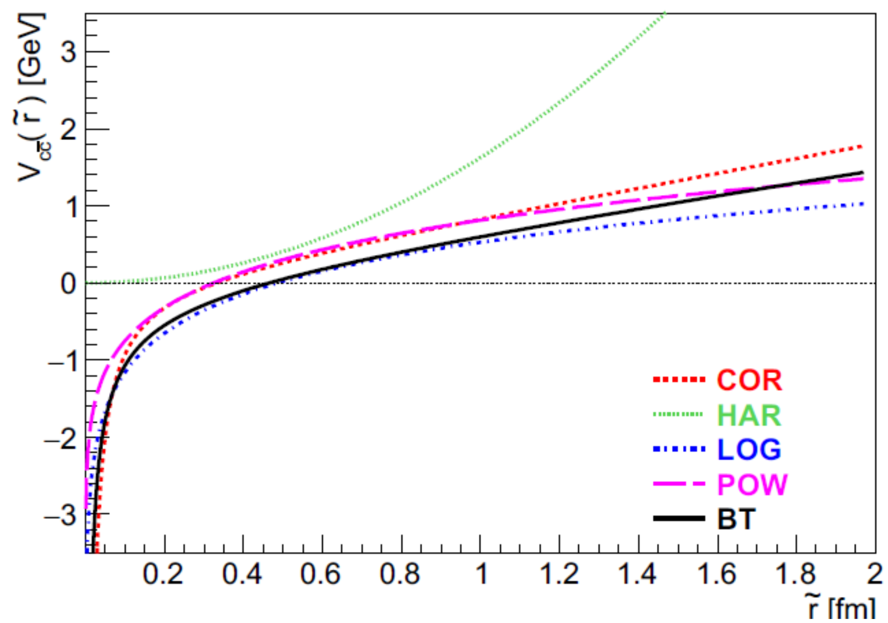
Schrodinger equation for spatial $Q\bar{Q}$ wave function

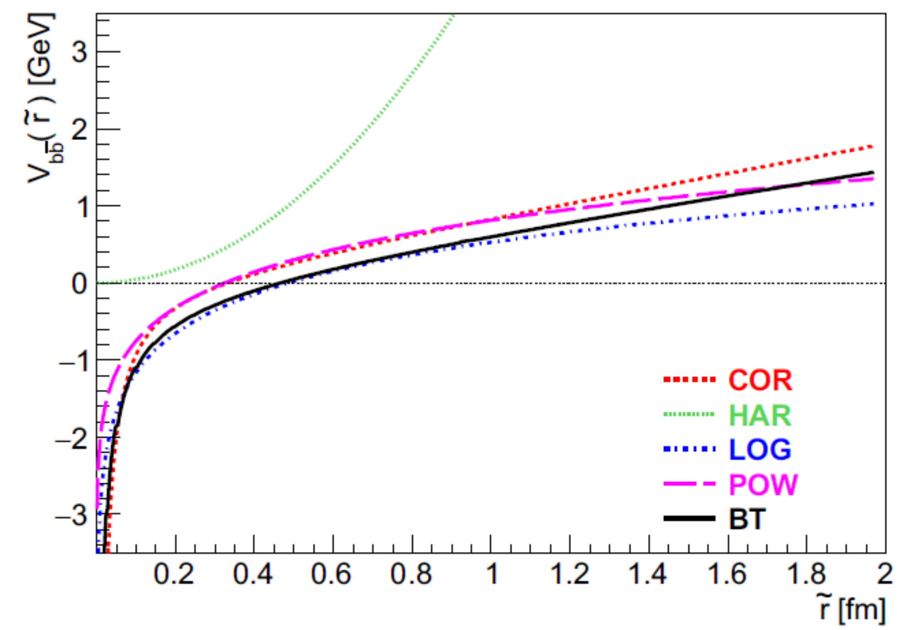
$$\left(-\frac{\Delta}{m_c} + V(r)\right)\,\Psi_{nlm}(\vec{r}) = E_{nl}\,\Psi_{nlm}(\vec{r}) \qquad \Psi(\vec{r}) = \Psi_{nl}(r)\cdot Y_{lm}(\theta,\varphi)$$

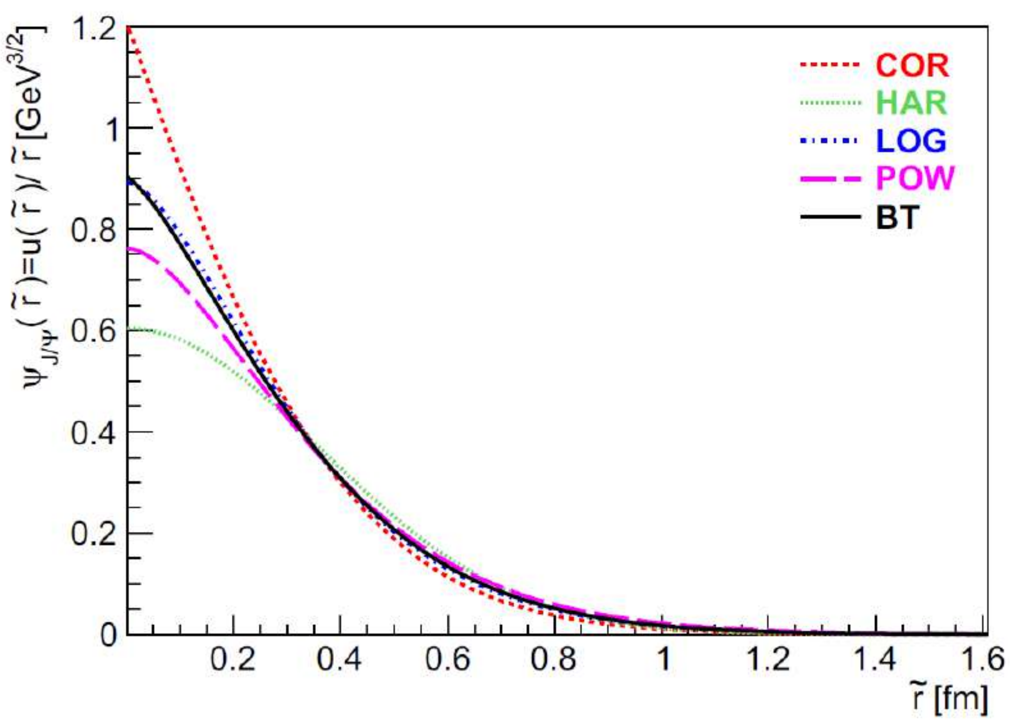
For references and more details see *Eur.Phys.J. C79 (2019) no.6, 495; arXiv:1901.02664*

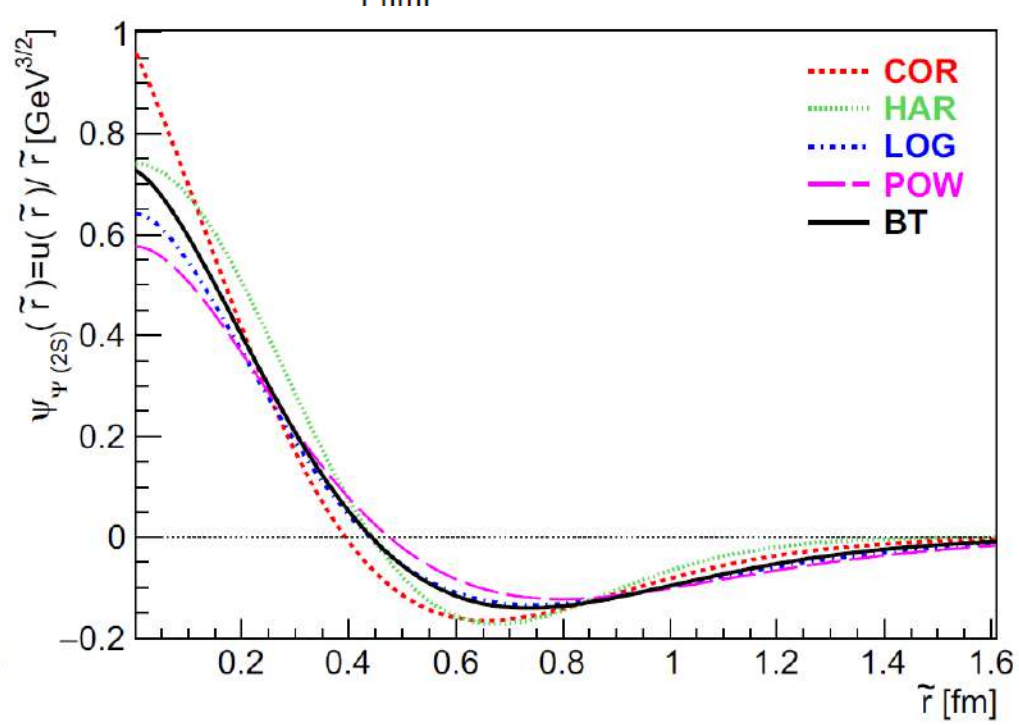
$V_{Q\bar{Q}}(r)$ - potentials:

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









Boosting and Melosh spin rotation

Boosting the radial part!

..from the rest frame to the LC frame

$$\Psi(\vec{r}) \Rightarrow \Psi(\vec{p})$$

$$M^2 = 4(p^2 + m_c^2) = \frac{p_T^2 + m_c^2}{\alpha(1-\alpha)}$$

$$p_L = (\alpha - 1/2) M(p_T, \alpha)$$

"Terentiev trick"

$$\Psi(\vec{p}) \Rightarrow \sqrt{2}\,\frac{(p^2+m_c^2)^{3/4}}{(p_T^2+m_c^2)^{1/2}} \cdot \Psi(\alpha, \vec{p}_T) \equiv \Phi_\psi(\alpha, \vec{p}_T)$$

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)

Melosh spin rotation

$$\overline{\chi}_{\mathbf{c}} = \widehat{R}(\alpha, \vec{p}_T)\,\chi_c\ , \quad \overline{\chi}_{\bar{\mathbf{c}}} = \widehat{R}(1-\alpha, -\vec{p}_T)\,\chi_{\bar{c}}\ ,$$

$$\widehat{R}(\alpha, \vec{p}_T) = \frac{m_c + \alpha\, M - i\,[\vec{\sigma} \times \vec{n}]\,\vec{p}_T}{\sqrt{(m_c + \alpha\, M)^2 + p_T^2}}$$

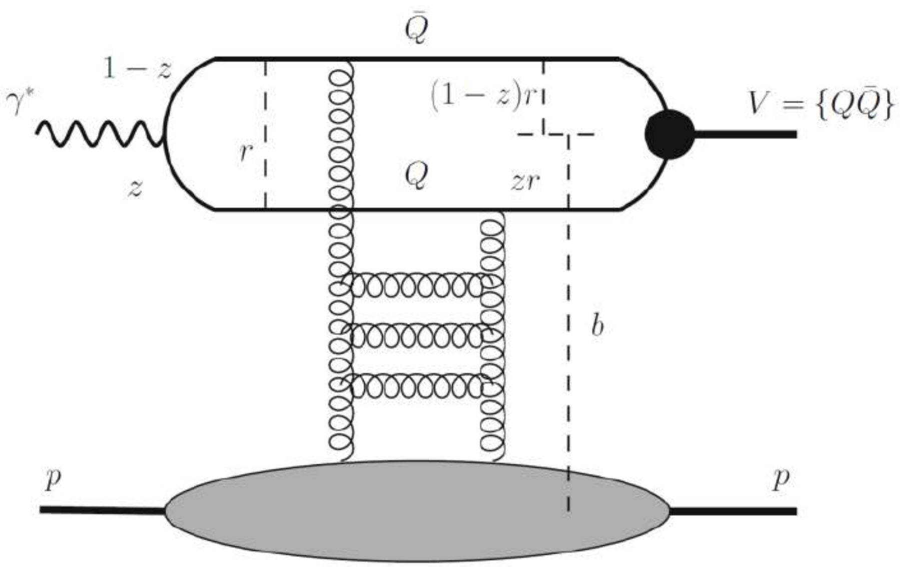
$$U^{(\mu,\bar{\mu})}(\alpha, \vec{p}_T) = \chi_c^{\mu\dagger}\,\widehat{R}^\dagger(\alpha, \vec{p}_T)\,\vec{\sigma}\cdot\vec{e}_\psi\,\sigma_y\,\widehat{R}^*(1-\alpha, -\vec{p}_T)\,\sigma_y^{-1}\,\widetilde{\chi}_{\bar{c}}^{\bar{\mu}}$$

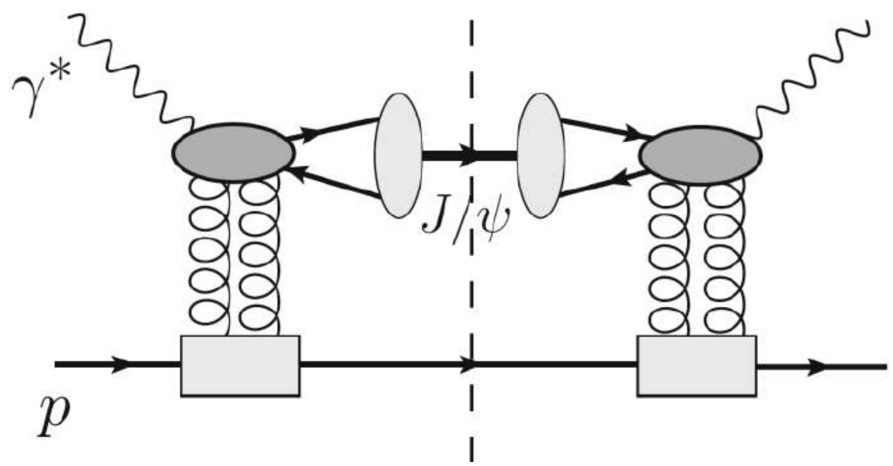
$$\Phi_\psi^{(\mu,\bar{\mu})}(\alpha, \vec{p}_T) = U^{(\mu,\bar{\mu})}(\alpha, \vec{p}_T) \cdot \Phi_\psi(\alpha, \vec{p}_T)$$

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

Exclusive electroproduction of heavy vector mesons

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





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

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

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

As part of the project we published the VM wave functions grid at https://hep.fjfi.cvut.cz/vm.php for

- $J/\psi, \psi(2S), \Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$
- 5 different potentials

We also published grids for electro-production cross sections with and with out spin rotation for

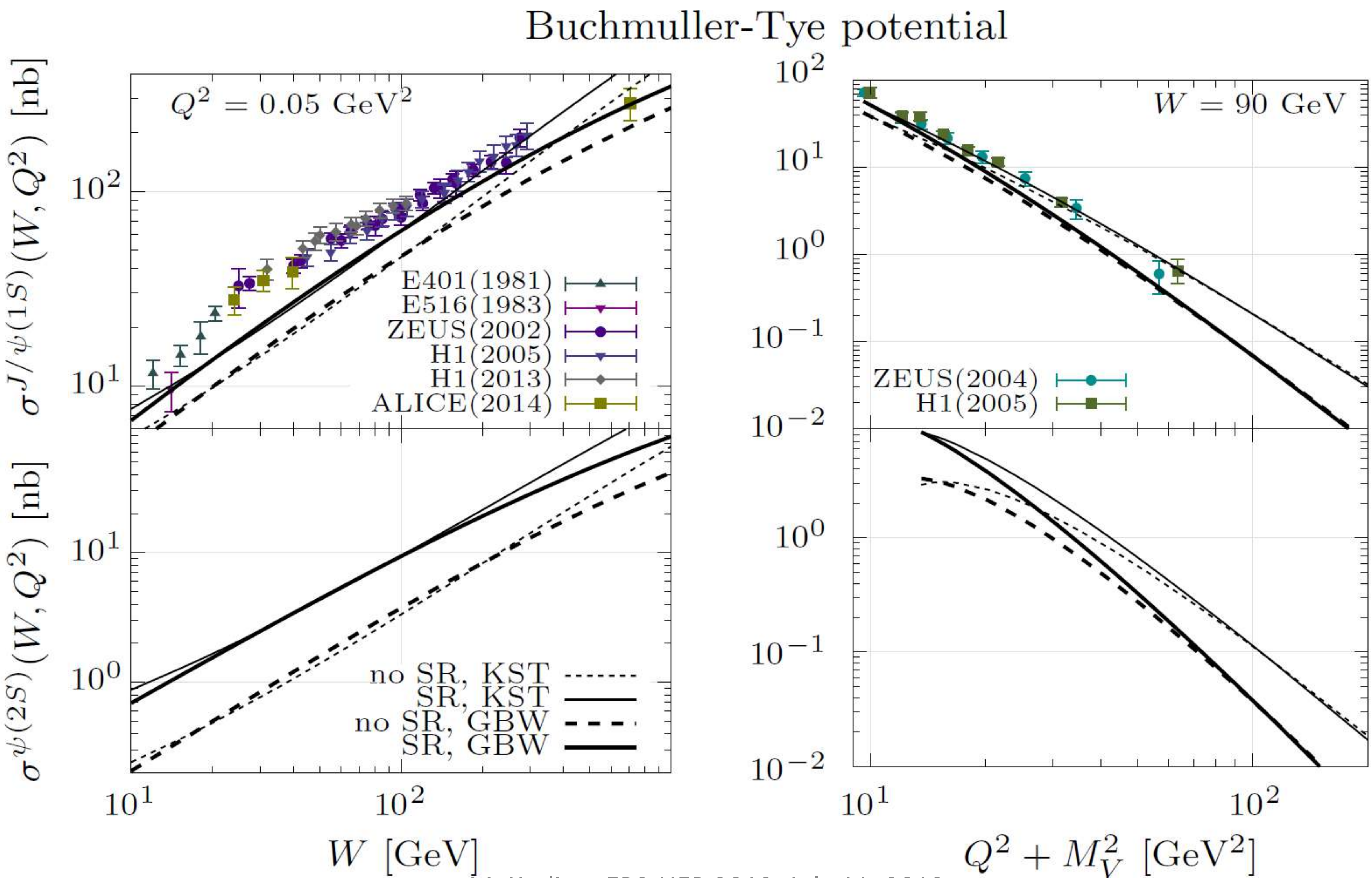
- 5 different dipole cross sections

Highlights of spin rotation: 1S and 2S charmonia cross sections

- BT potential + KST/GBW dipole cross section
- Stronger effect of the spin rotation for $\psi(2S)$

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

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



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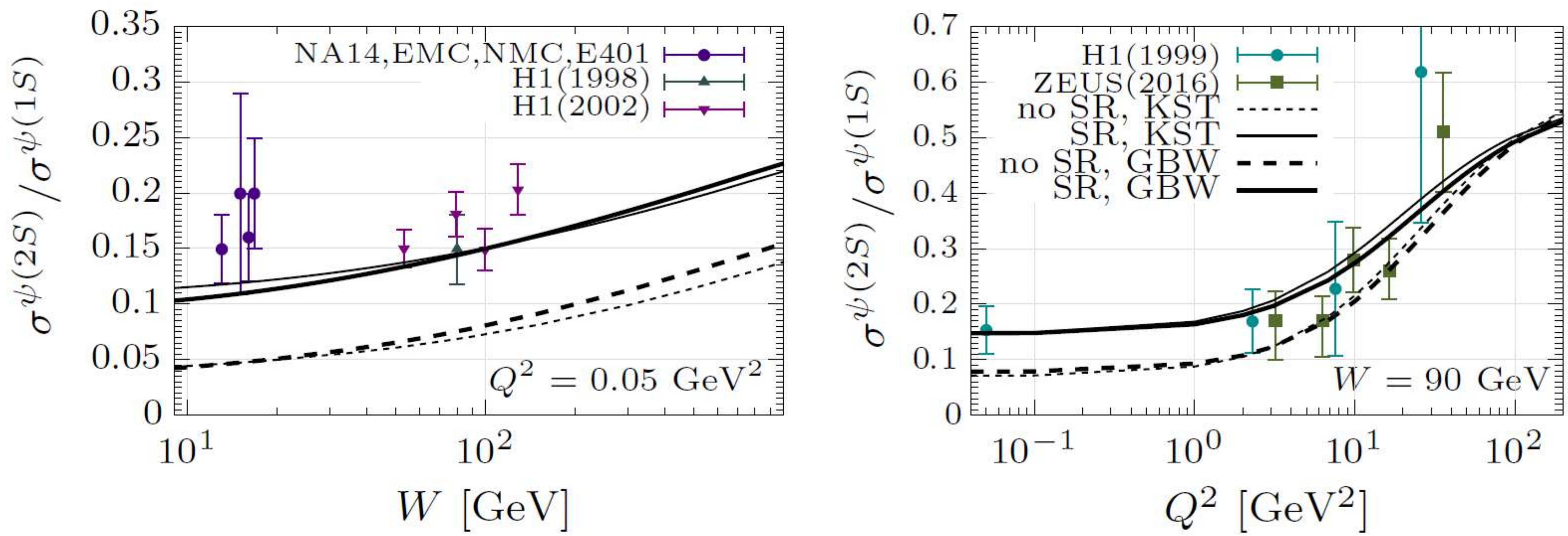
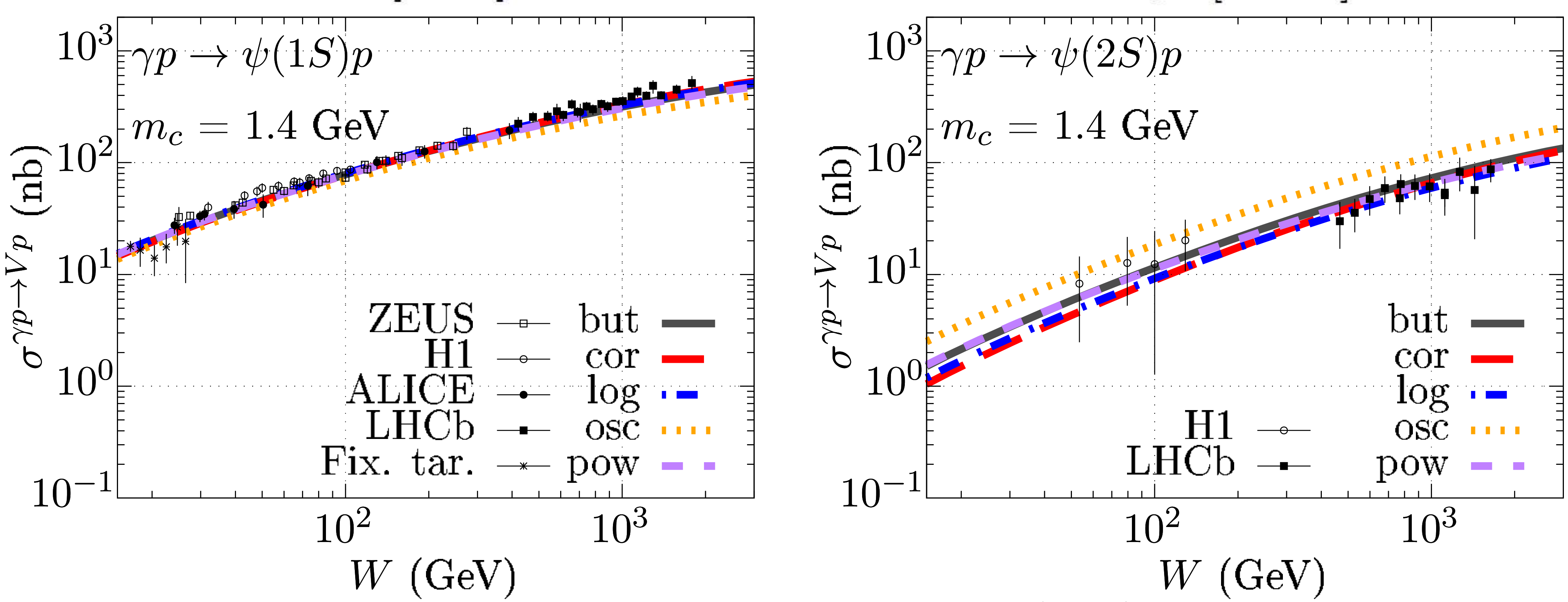
Eur.Phys.J. C79 (2019) no.2, 154; arXiv:1812.03001

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

Buchmuller-Tye potential



GBW model

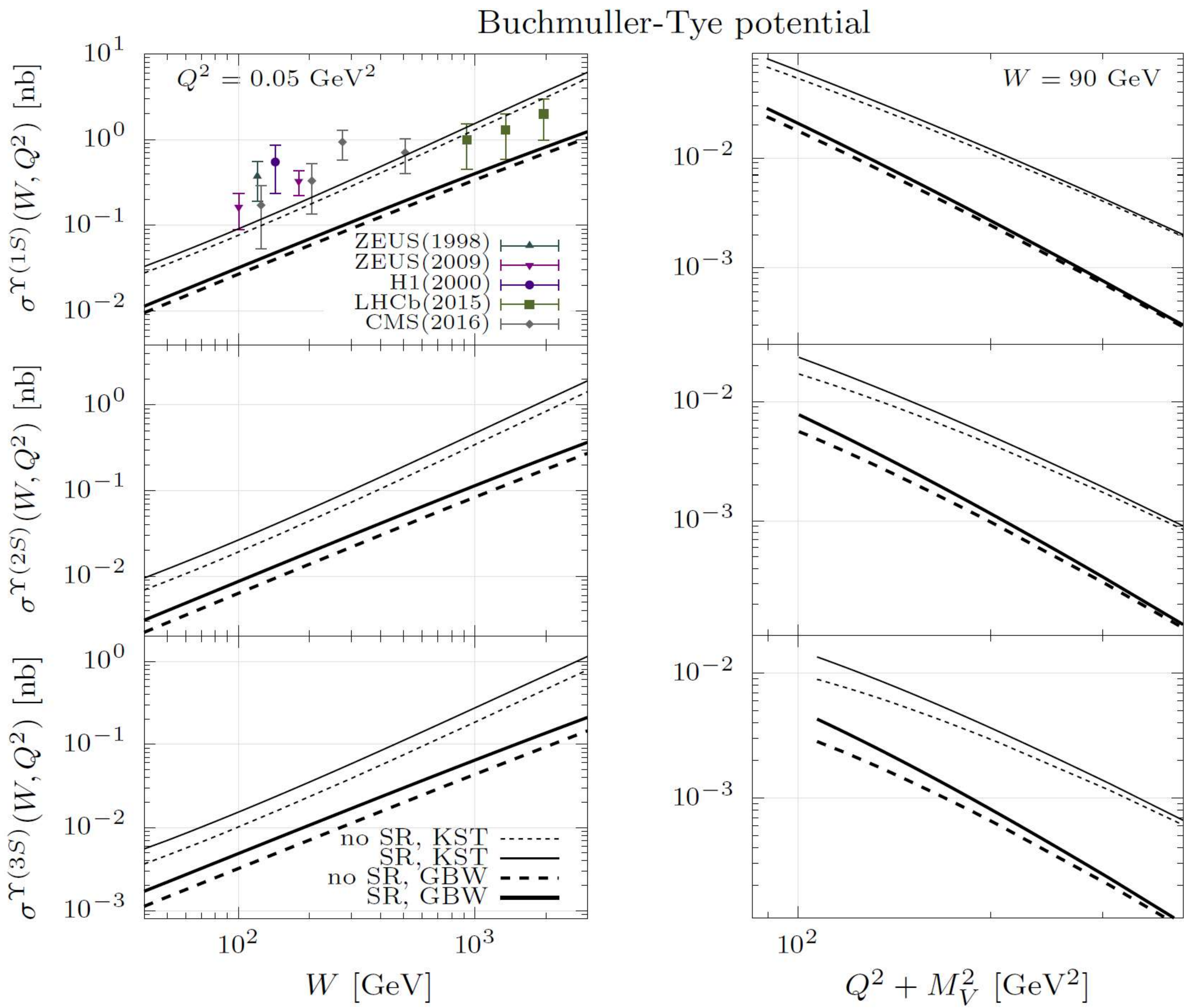


C.Henkels, E.G.de Oliveira, RP and H.Trebien, Phys. Rev. D102, no.1, 014024 (2020)

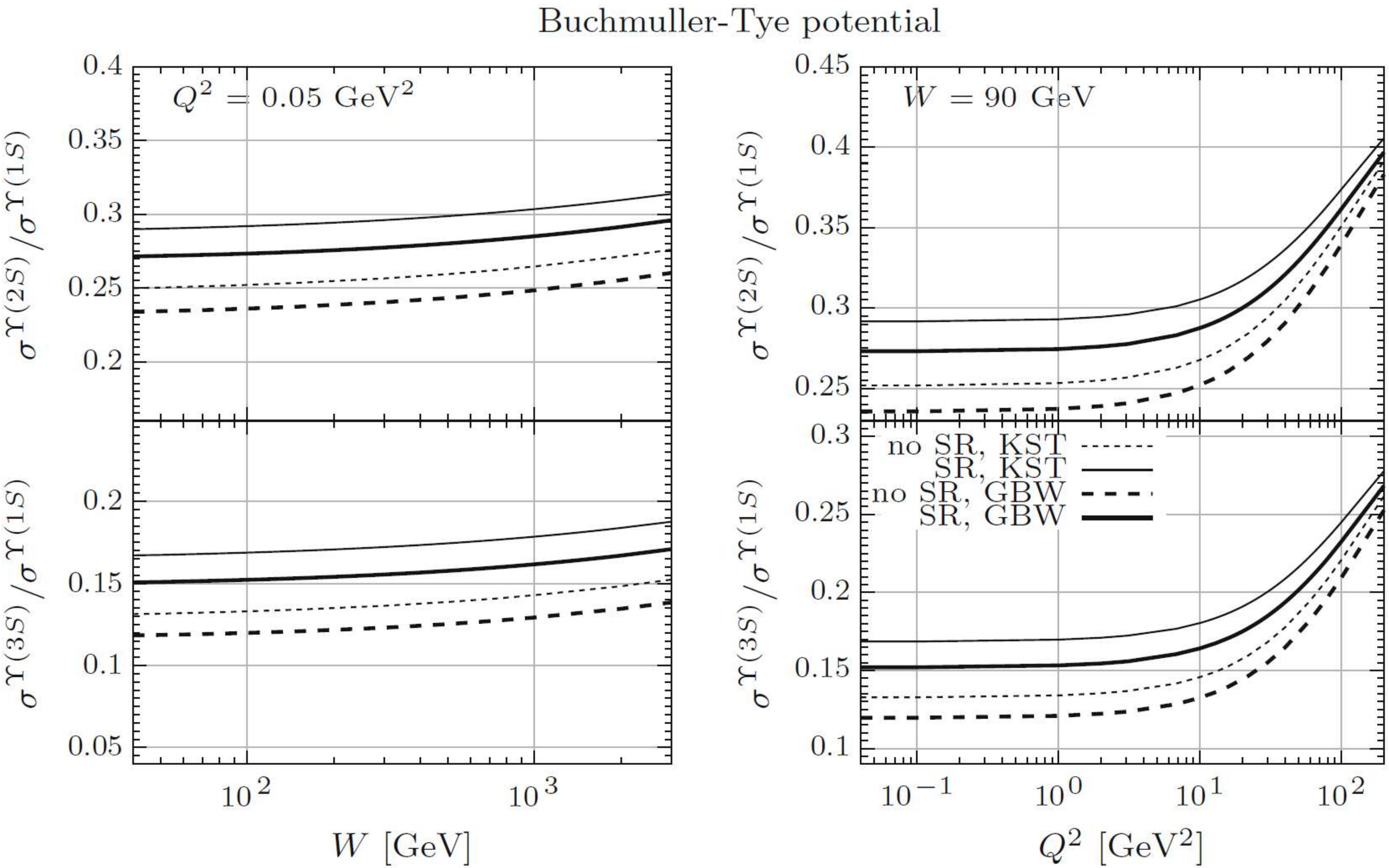
Highlights of spin rotation: 1S,2S,3S bottomonia

BT potential + KST/GBW dipole cross section

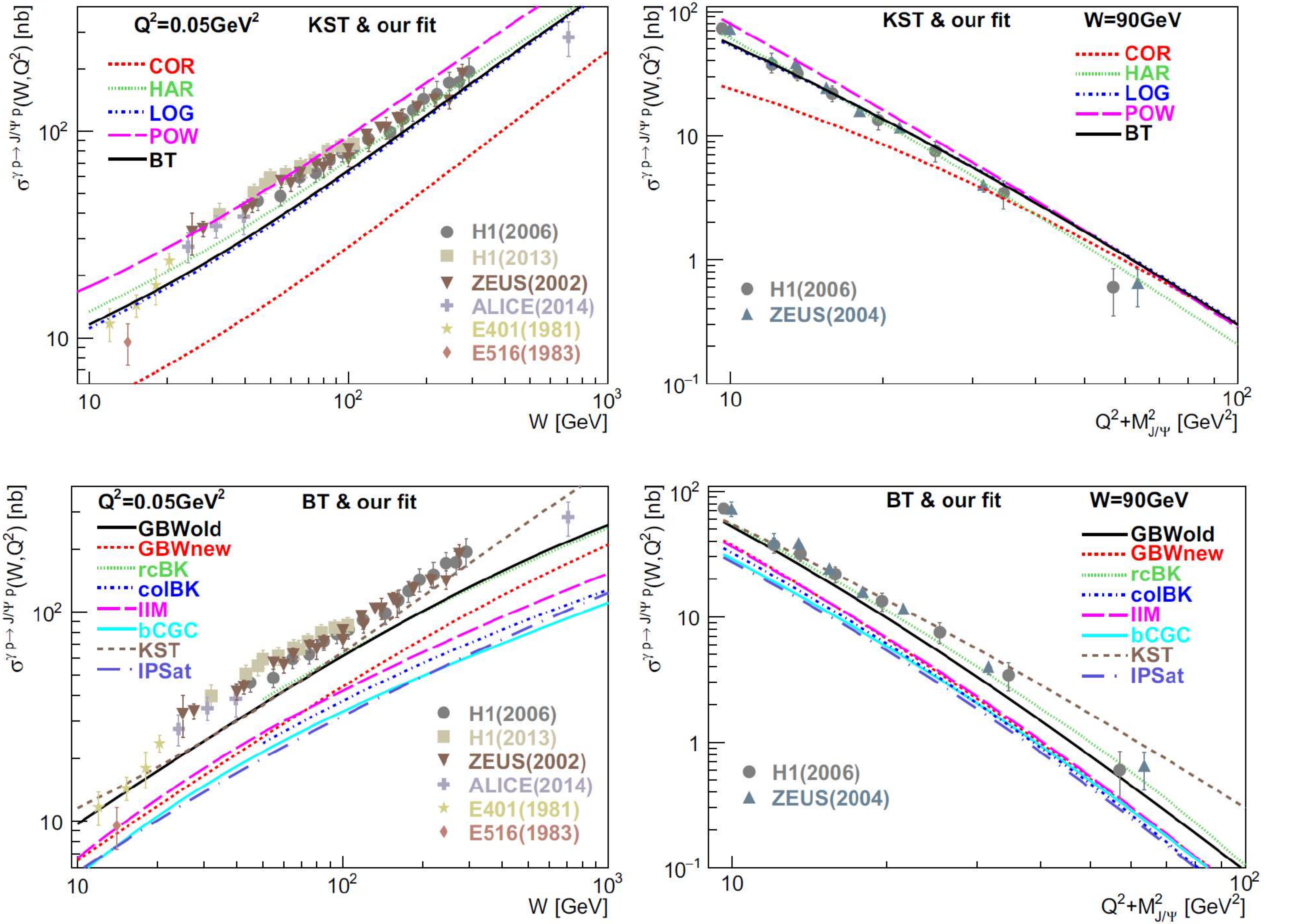
With increasing Q^2 the spin rot. effect disappearing



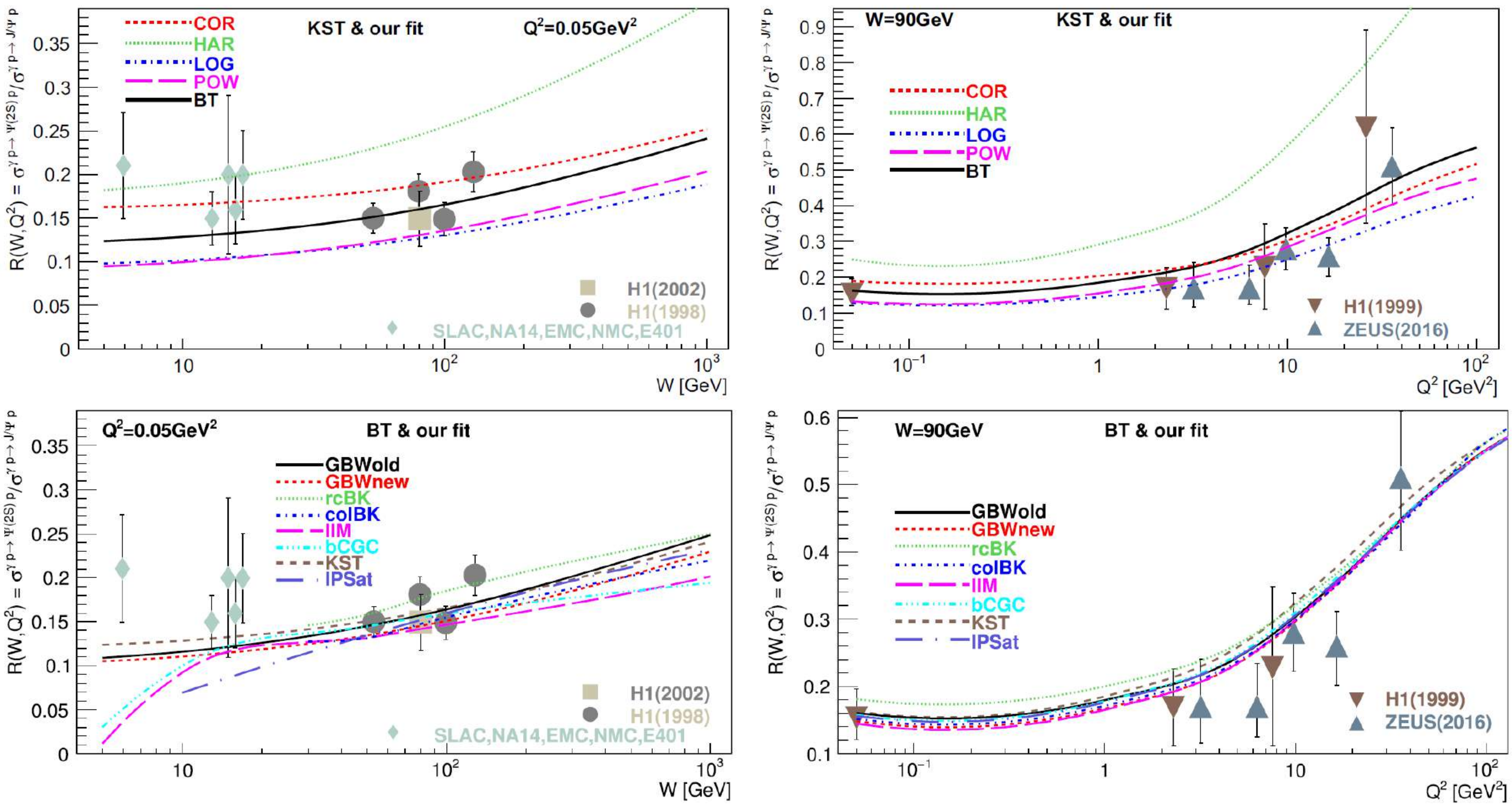
Highlights of spin rotation: 2S/1S and 3S/1S bottomonia ratio



1S and 2S electro/photo production: uncertainties



1S and 2S electro/photo production: uncertainties



b-dependent partial dipole amplitude: two saturation models

b-Sat model

$$N(x, \boldsymbol{r}, \boldsymbol{b}) = 1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2)\, xg(x,\mu^2) T(b)\right)$$

$$\mu^2 = 4/r^2 + \mu_0^2 \qquad T(b) = \frac{1}{2\pi B_G} \mathrm{e}^{-b^2/2B_G} \qquad B_G = 4.25\,\mathrm{GeV}^{-2}$$

H. Kowalski and D. Teaney, Phys. Rev. D **68**, 114005 (2003)

BK model

$$N(x, \boldsymbol{r}, \boldsymbol{b}) = \mathcal{N}(r, b, \ln(0.008/x))$$

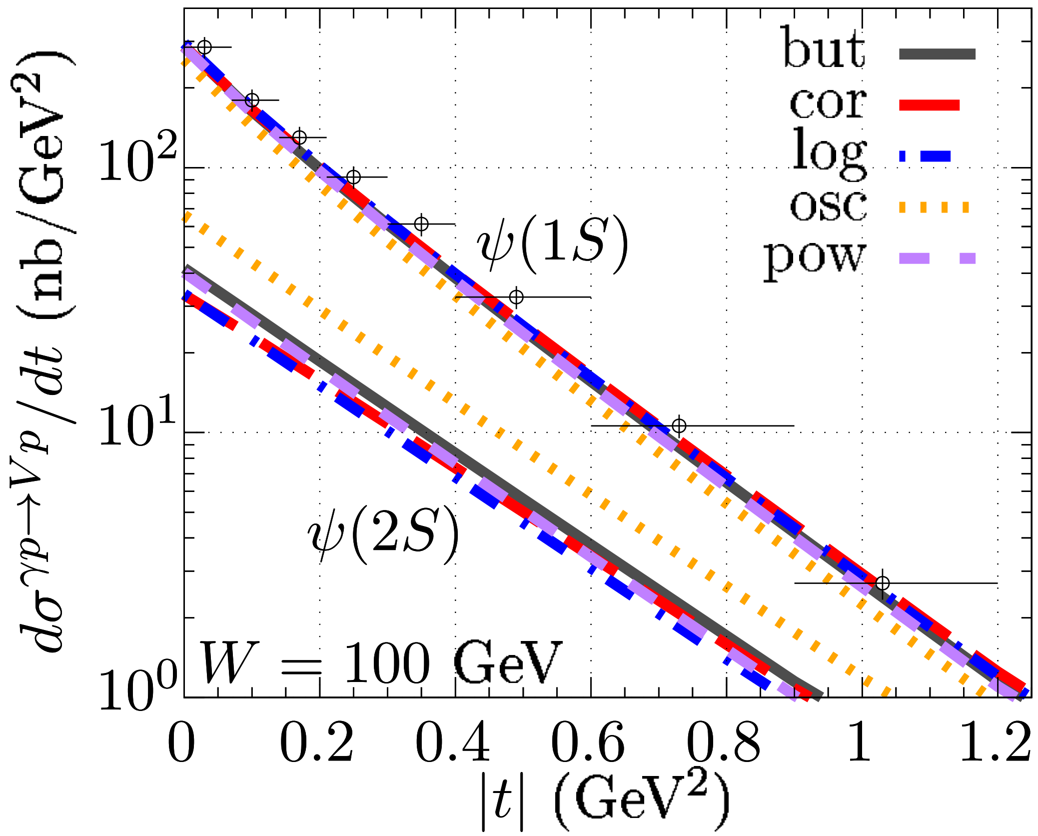
$$\frac{\partial \mathcal{N}(r,b,Y)}{\partial Y} = \int d^2\boldsymbol{r}_1 K(r, r_1, r_2)\Big(\mathcal{N}(r_1, b_1, Y) + \mathcal{N}(r_2, b_2, Y) - \mathcal{N}(r, b, Y) - \mathcal{N}(r_1, b_1, Y)\mathcal{N}(r_2, b_2, Y)\Big)$$

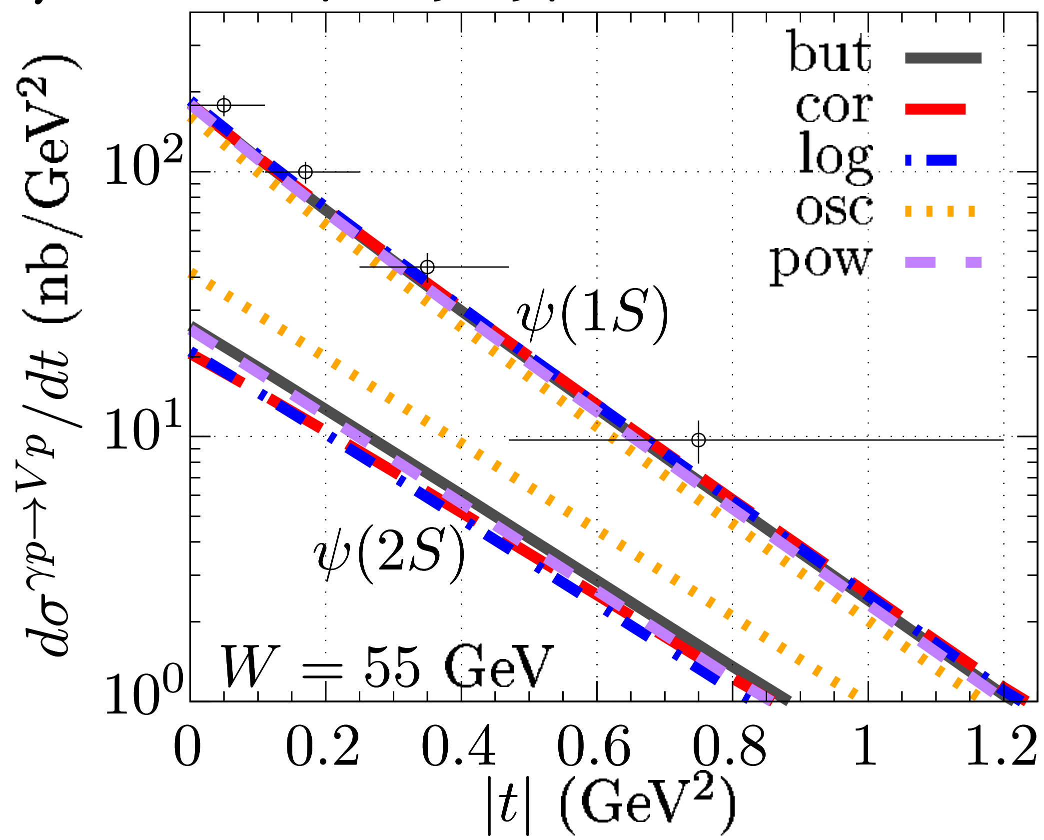
D. Bendova, J. Cepila, J. G. Contreras, and M. Matas, Phys. Rev. **D100**, 054015 (2019)

Differential cross sections: charmonia

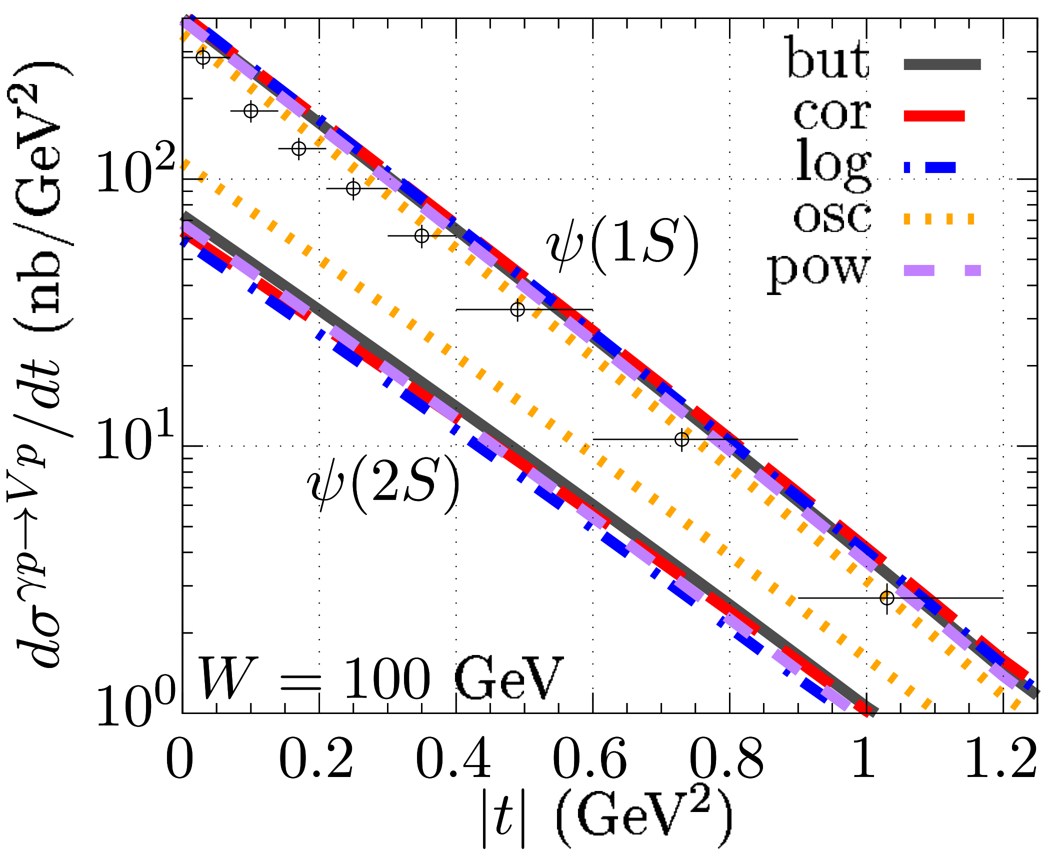
C.Henkels, E.G.de Oliveira, RP and H.Trebien, Phys. Rev. D104, no.5, 054008 (2021)

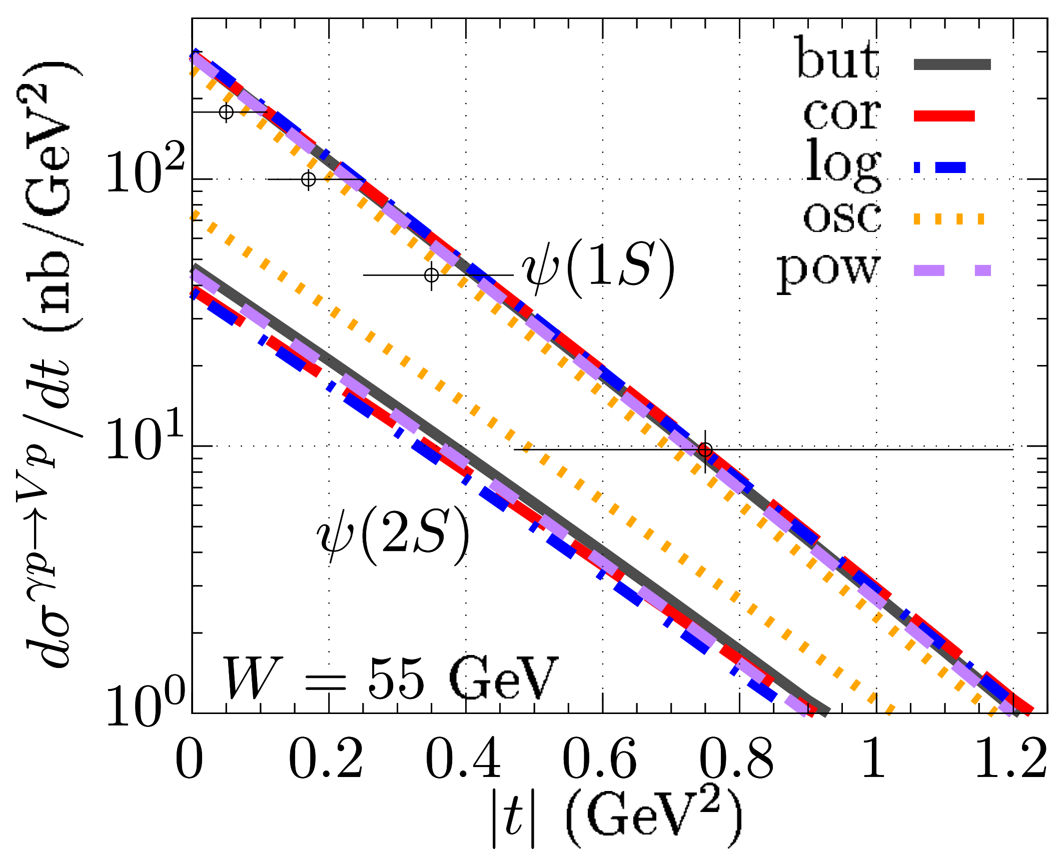
BK model





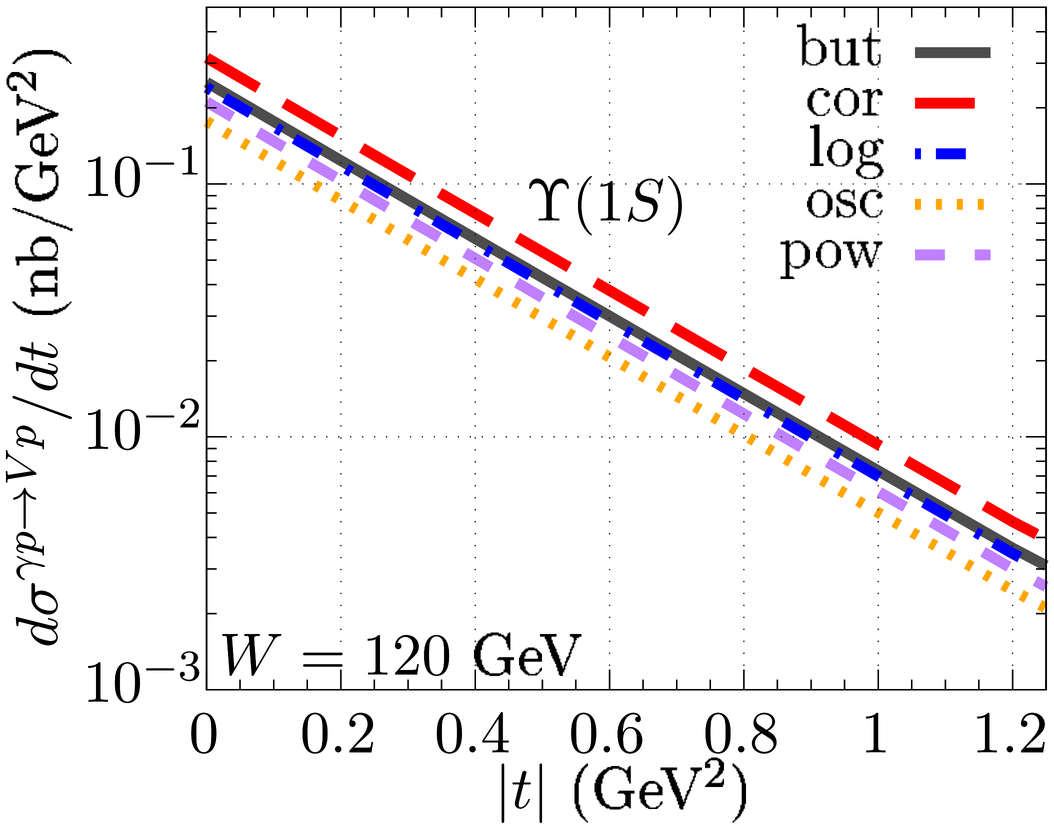
b-Sat model

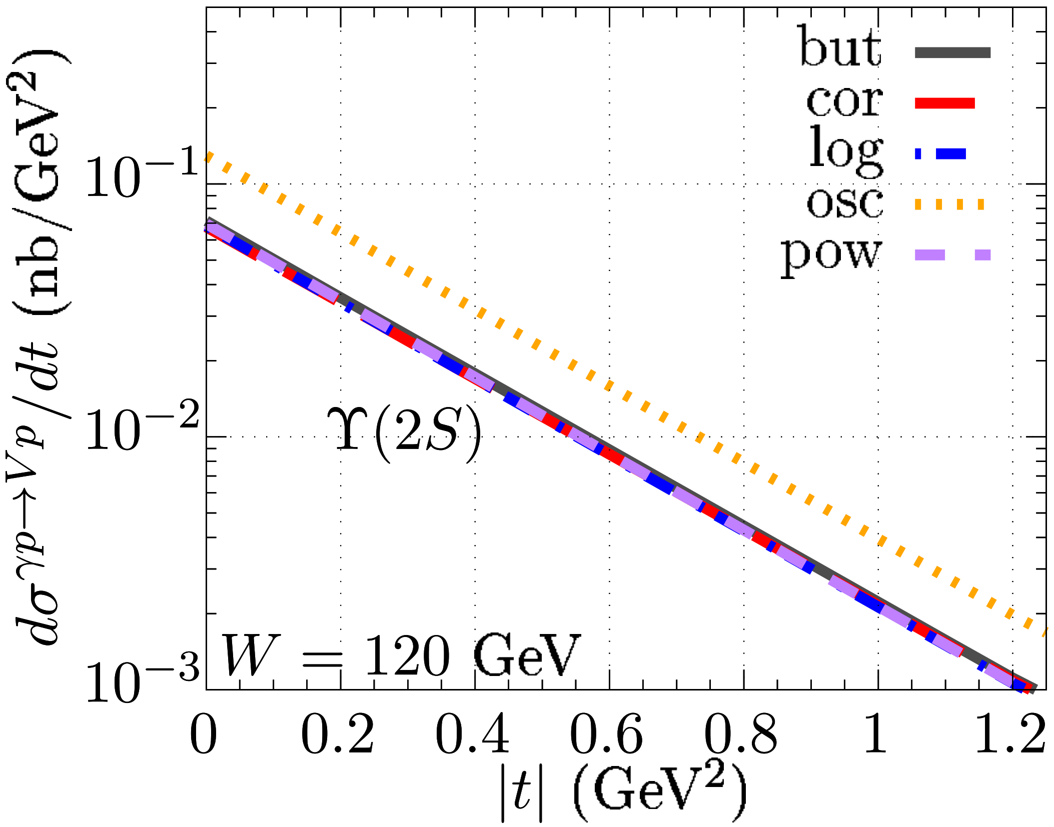




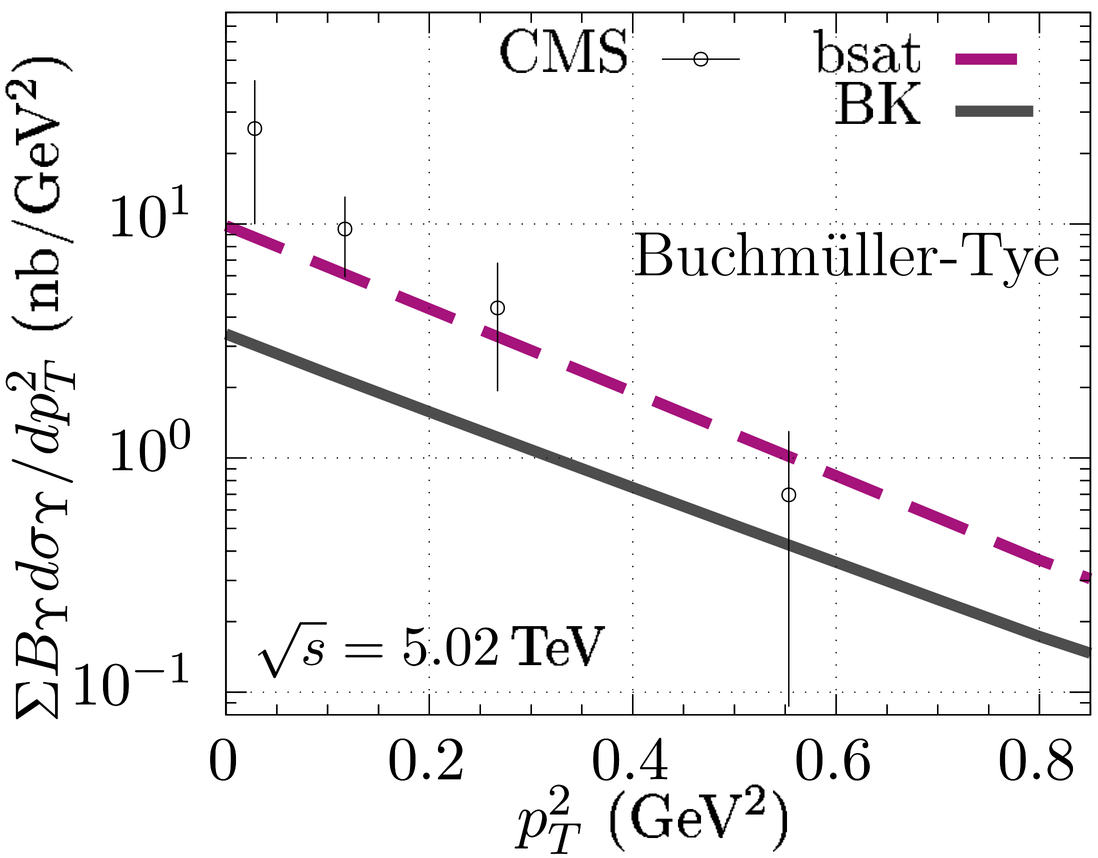
Differential cross sections: bottomonia

BK model



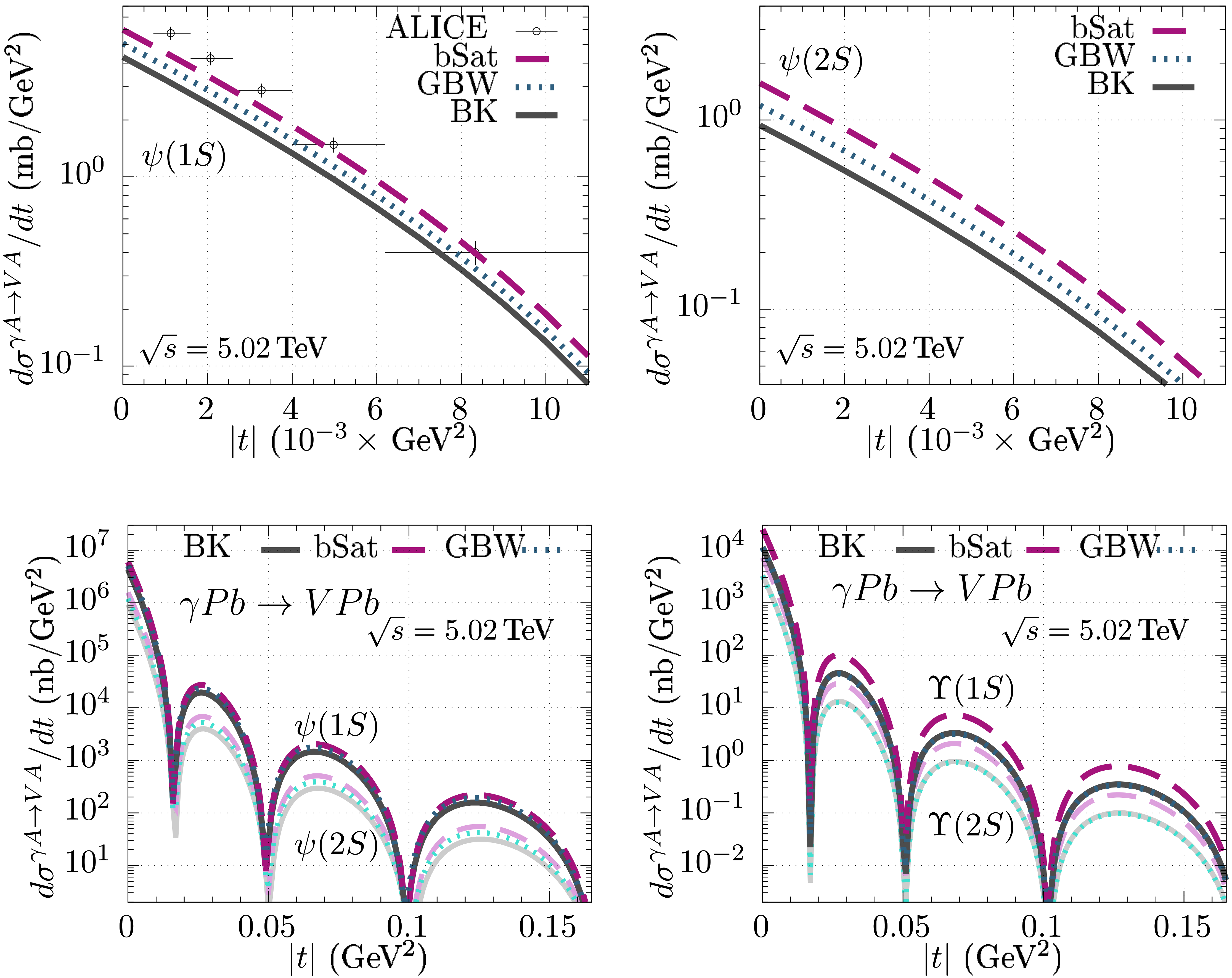


$pPb \to \Upsilon(nS)pPb$

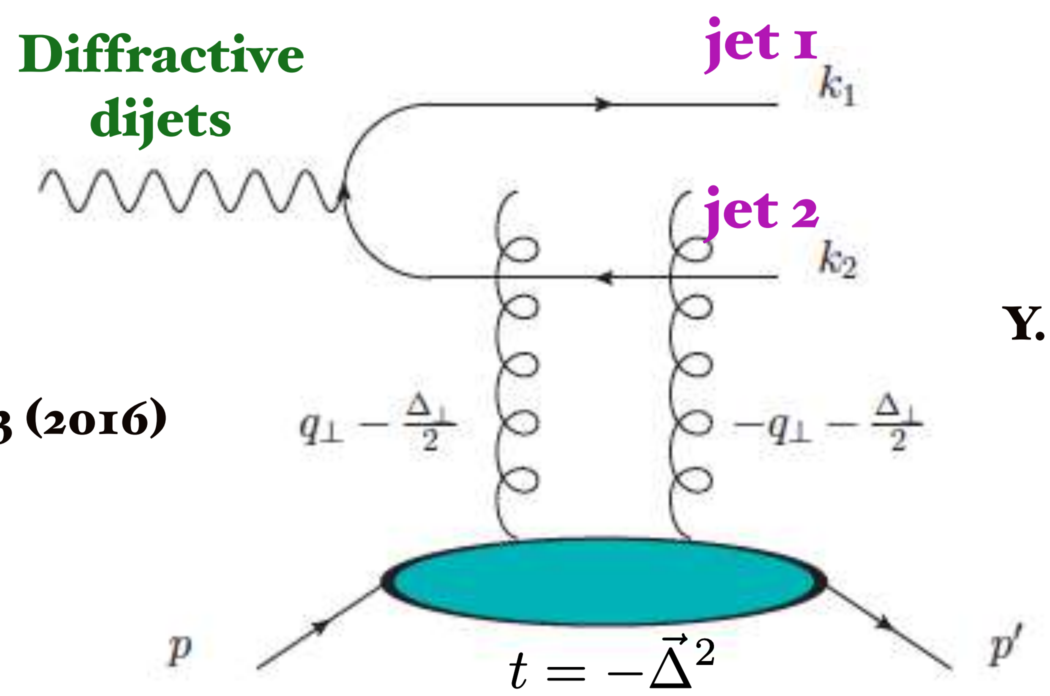


Coherent photoproduction off nuclear targets

C.Henkels, E.G.de Oliveira, RP and H.Trebien, Phys. Rev. D104, no.5, 054008 (2021)



Gluon Wigner distribution from exclusive photoproduction



T. Altinoluk et al, PLB758, 373 (2016)

Y. Hatta, B. W. Xiao, F. Yuan, PRL 116, 202301 (2016)

Y. Hagiwara, Y. Hatta, RP, M. Tasevsky, O. Teryaev, PRD 96, 034009 (2017)

Dijet observables:

Proton recoil momentum: $\vec{k}_{1\perp} + \vec{k}_{2\perp} = -\vec{\Delta}_\perp$

Dijet relative momentum: $\vec{P}_\perp = \frac{1}{2}(\vec{k}_{2\perp} - \vec{k}_{1\perp})$

Fourier transform of the dipole S-matrix!

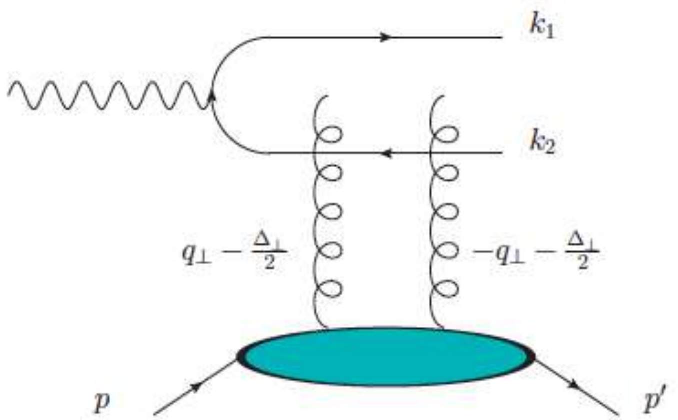
$$\frac{d\sigma}{d\vec{P}_\perp d\vec{\Delta}_\perp} \propto |\vec{M}|^2, \qquad \vec{M}(\vec{P}_\perp, \vec{\Delta}_\perp) = \int \frac{d^2\vec{q}_\perp}{2\pi} \frac{\vec{P}_\perp - \vec{q}_\perp}{(\vec{P}_\perp - \vec{q}_\perp)^2 + \epsilon_f^2} S_Y(\vec{q}_\perp, \vec{\Delta}_\perp)$$

for small-Q^2 $\quad \vec{q}_\perp \sim \vec{P}_\perp$

$$\frac{d\sigma}{d\vec{P}_\perp d\vec{\Delta}_\perp} \propto \Big(S_Y(\vec{P}_\perp, \vec{\Delta}_\perp)\Big)^2$$

Advantage!

Elliptic Wigner distribution and dipole orientation



Y. Hatta, B. W. Xiao, F. Yuan, PRL 116, 202301 (2016)

Y. Hagiwara, Y. Hatta, T. Ueda, PRD 94, 094036 (2016)

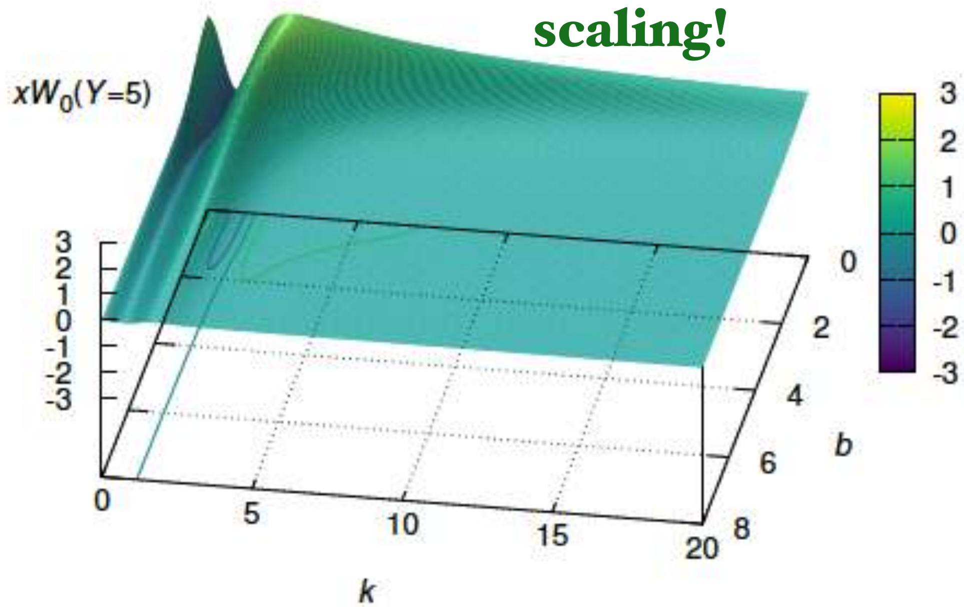
$$W(x,\boldsymbol{b},\boldsymbol{k}) = W_0(x,b,k) + 2\cos 2(\phi_k - \phi_b) W_1(x,b,k) + \cdots$$

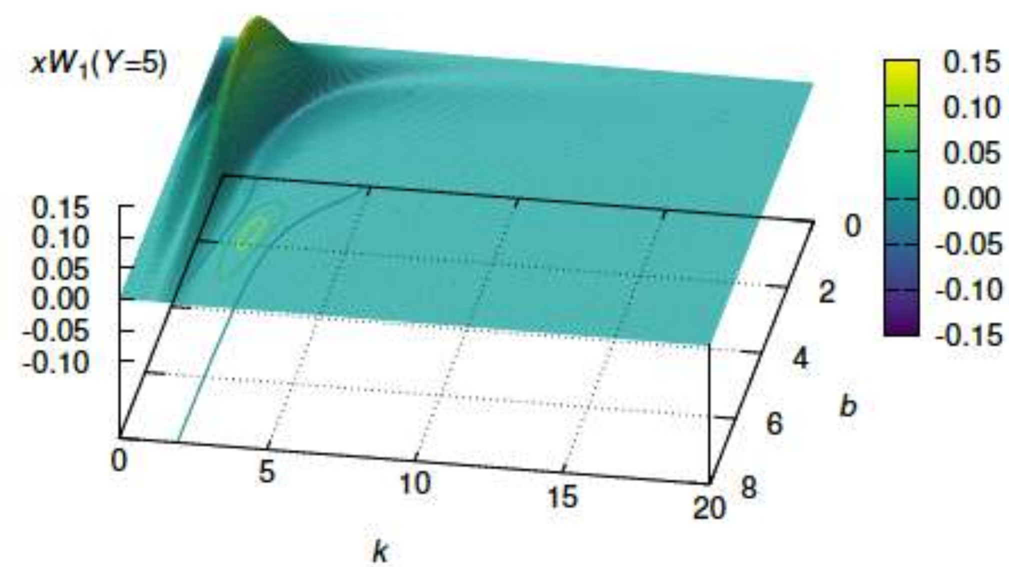
"Elliptic" gluon Wigner

Geometric scaling!

BK equation with SO(3) symmetry (CGC)

Gubser (2011)



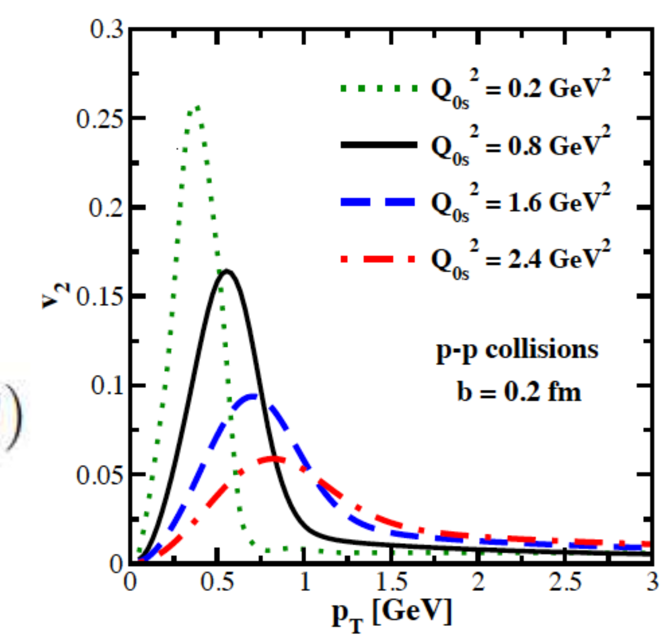


E. Iancu and A. Rezaeian, PRD95, 094003 (2017)

McLerran-Venugopalan model for the dipole S-matrix

$$S(\boldsymbol{b},\boldsymbol{r}) = \exp\{-N_{2g}(\boldsymbol{b},\boldsymbol{r})\}$$

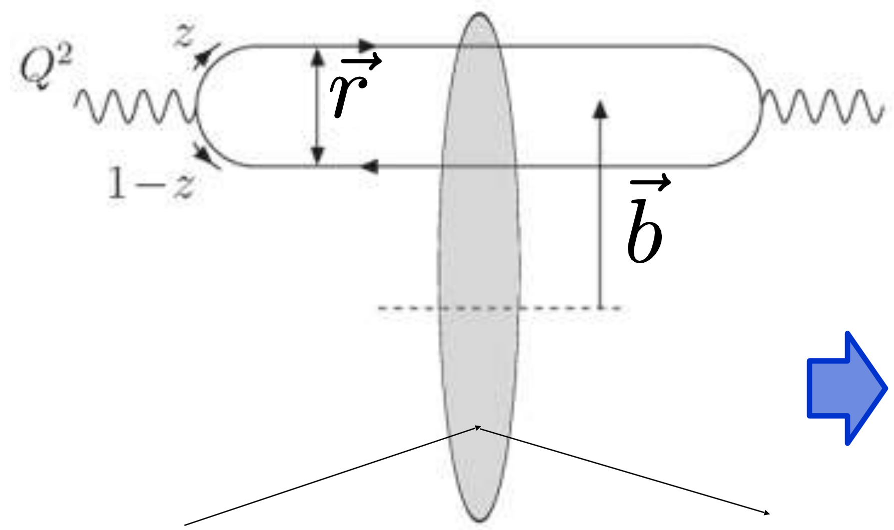
$$N_{2g}(b,r,\theta) = \mathcal{N}_0(b,r) + \mathcal{N}_\theta(b,r)\cos(2\theta)$$



<u>**Dipole orientation effects**</u> → **Elliptic flow, gluon transversity, angular correlation in DVCS etc**

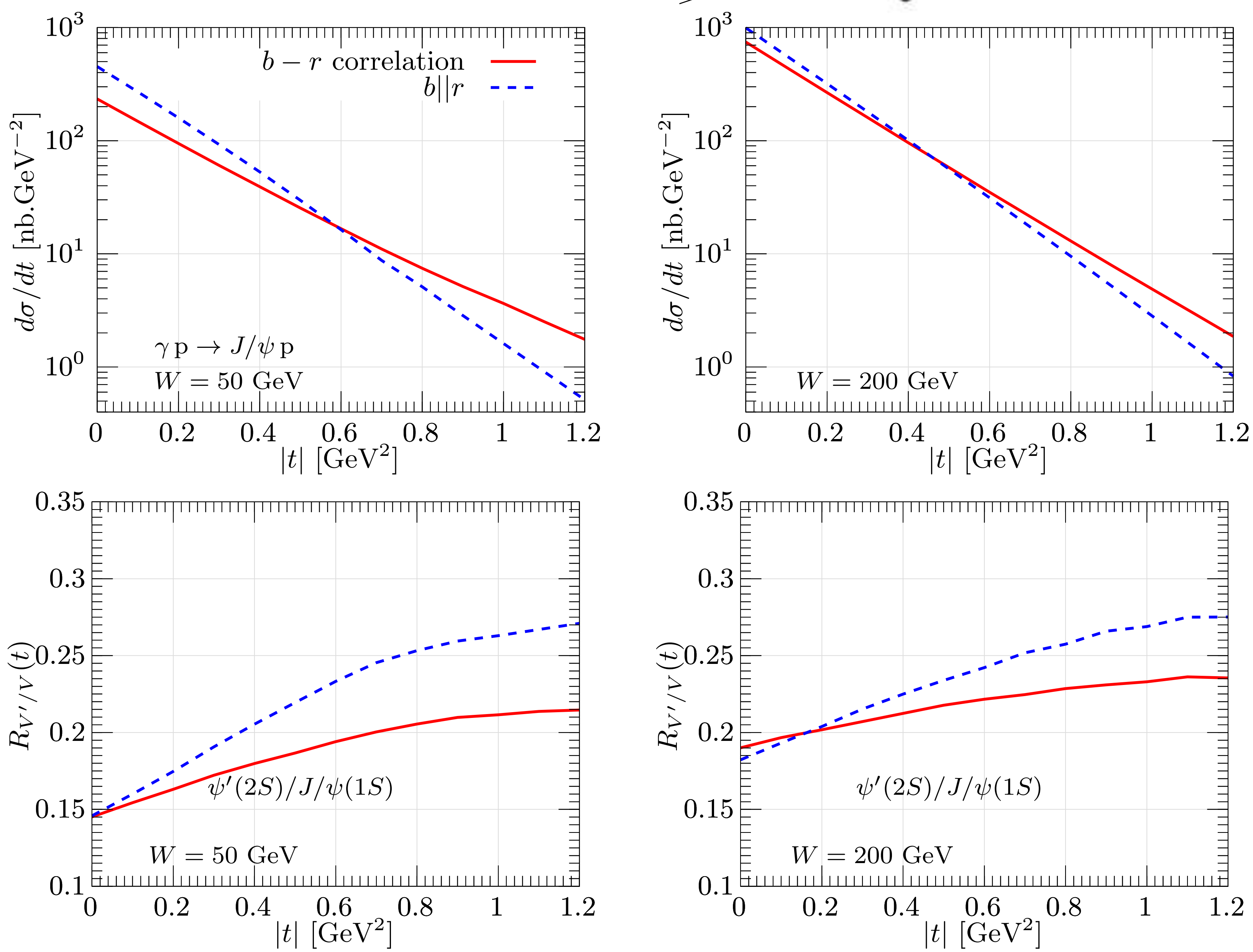
Dipole orientation effects VM production

Diffractive photon/VM



Y. Hatta, B. W. Xiao, F. Yuan, PRD95, 114026 (2017)

Can only access b-profile but not kT-dependence of the gluon Wigner!



B.Z.Kopeliovich, M.Krelina and J.Nemchik, Phys. Rev. D103, no.9, 094027 (2021)

A controversy?

Summary

- ✓ The dipole picture enables to universally explore VM photo production off proton and nuclear targets
- ✓ Proper treatment of the radial wave function and spin effects contribute to a reasonable agreement with available data on VM photo production without any adjustable parameters
- ✓ Predictions for differential cross sections off both nuclear and proton targets are obtained for excited (charmonia and bottomonia) states
- ✓ A controversy in the impact of dipole orientation effects on t-dependence has been spotted in the literature, and more investigations are needed