Probing the proton structure with exclusive vector meson photoproduction

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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 suppression in a deconfined medium

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

✓ **Charmonia are very special!**

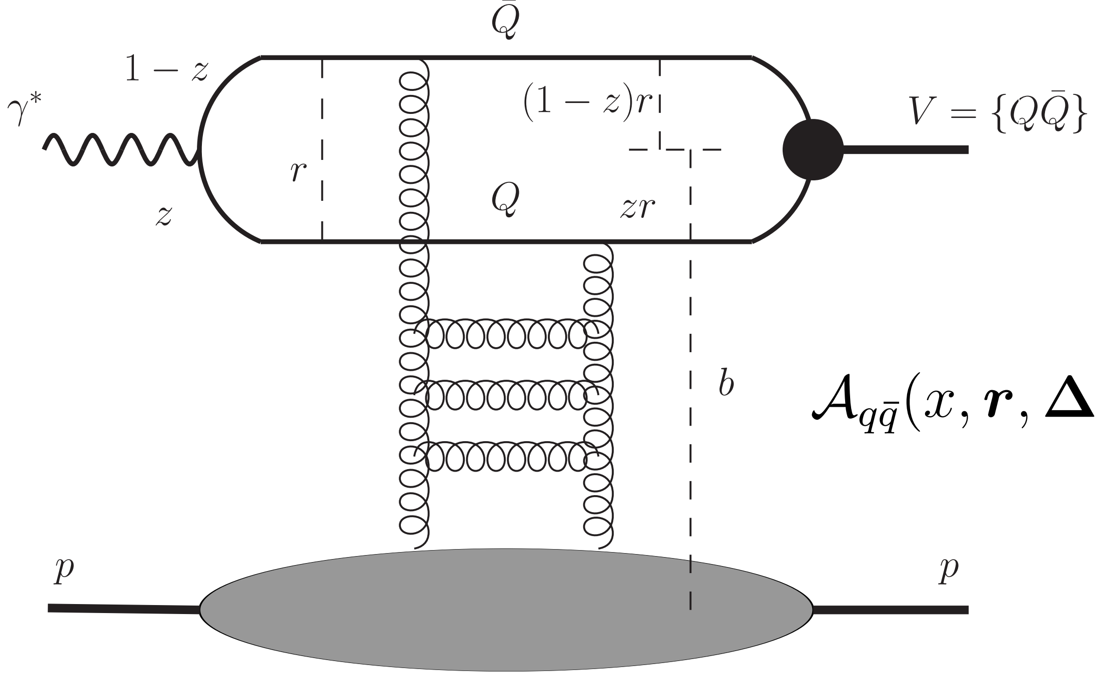
★ *Charm quark mass scale is at the boundary between pQCD and soft QCD*
★ *Specific for production and destruction mechanisms in HIC*

✓ **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

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



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

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

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

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

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)

Good-Walker picture of QCD scattering: basis for LF approach

R. J. Glauber, Phys. Rev. 100, 242 (1955).
E. Feinberg and I. Ya. Pomeranchuk, Nuovo. Cimento. Suppl. 3 (1956) 652.
M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857.

Projectile has a substructure!

Hadron can be excited:
not an eigenstate of interaction!

$$|h\rangle = \sum_{\alpha=1} C^h_\alpha |\alpha\rangle \qquad \hat{f}_{el}|\alpha\rangle = f_\alpha |\alpha\rangle$$

Completeness and orthogonality

$$\langle h'|h\rangle = \sum_{\alpha=1} (C^{h'}_\alpha)^* C^h_\alpha = \delta_{hh'}$$
$$\langle \beta|\alpha\rangle = \sum_{h'} (C^{h'}_\beta)^* C^{h'}_\alpha = \delta_{\alpha\beta}$$

semi-hard/ semi-soft — soft

	$\|C_\alpha\|^2$	σ_α	$\sigma_{tot} = \sum_{\alpha=soft}^{hard} \|C_\alpha\|^2 \sigma_\alpha$	$\sigma_{sd} = \sum_{\alpha=soft}^{hard} \|C_\alpha\|^2 \sigma^2_\alpha$
Hard	~ 1	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^4}$
Soft	$\sim \frac{m_q^2}{Q^2}$	$\sim \frac{1}{m_q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{m_q^2 Q^2}$

Elastic and single diffractive amplitudes

$$f^{h\to h}_{el} = \sum_{\alpha=1} |C^h_\alpha|^2 f_\alpha$$
$$f^{h\to h'}_{sd} = \sum_{\alpha=1} (C^{h'}_\alpha)^* C^h_\alpha f_\alpha$$

Single diffractive cross section

$$\sum_{h'\neq h} \frac{d\sigma^{h\to h'}_{sd}}{dt}\bigg|_{t=0} = \frac{1}{4\pi}\left[\sum_{h'} |f^{hh'}_{sd}|^2 - |f^{hh}_{el}|^2\right]$$
$$= \frac{1}{4\pi}\left[\sum_\alpha |C^h_\alpha|^2 |f_\alpha|^2 - \left(\sum_\alpha |C^h_\alpha| f_\alpha\right)^2\right] = \boxed{\frac{\langle f^2_\alpha\rangle - \langle f_\alpha\rangle^2}{4\pi}}$$

Dispersion of the eigenvalues distribution

Important basis for the dipole picture!

Phenomenological dipole approach

Eigenvalue of the total cross section is
the universal dipole cross section

see e.g. B. Kopeliovich et al, since 1981

Dipole:
- cannot be excited
- experience only elastic scattering
- have no definite mass, but only separation
- universal – elastic amplitude can be extracted in one process and used in another

Eigenstates of interaction in QCD:
color dipoles

$$\sum_{h'} \frac{d\sigma_{sd}^{h\to h'}}{dt}\Bigg|_{t=0} = \sum_{\alpha=1} |C_\alpha^h|^2 \frac{\sigma_\alpha^2}{16\pi} =$$ **SD cross section**

$$\int d^2 r_T |\Psi_h(r_T)|^2 \frac{\sigma^2(r_T)}{16\pi} = \frac{\langle\sigma^2(r_T)\rangle}{16\pi}$$

wave function of
a given Fock state

partonic interpretation of a scattering does depend on frame of reference!

total DIS cross section

$$\sigma_{tot}^{\gamma^* p}(Q^2, x_{Bj}) = \int d^2 r_T \int_0^1 dx \left|\Psi_{\gamma^*}(r_T, Q^2)\right|^2 \sigma_{\bar{q}q,}(r_T, x_{Bj})$$

Theoretical calculation of
the dipole CS is a challenge

BUT! *Can be extracted from data and used in ANY process!*

Example: Naive GBW parameterization
of HERA data

$$\sigma_{\bar{q}q}(r_T, x) = \sigma_0 \left[1 - e^{-\frac{1}{4} r_T^2 Q_s^2(x)}\right]$$

saturates at
large separations

$$r_T^2 \gg 1/Q_s^2$$

color transparency $\sigma_{\bar{q}q}(r_T) \propto r_T^2 \qquad r_T \to 0$

QCD factorisation $\sigma_{q\bar{q}}(r, x) \propto r^2 x g(x)$

A point-like colorless object
does not interact with
external color field!

ANY inclusive/diffractive scattering is due to an interference of dipole scatterings!

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

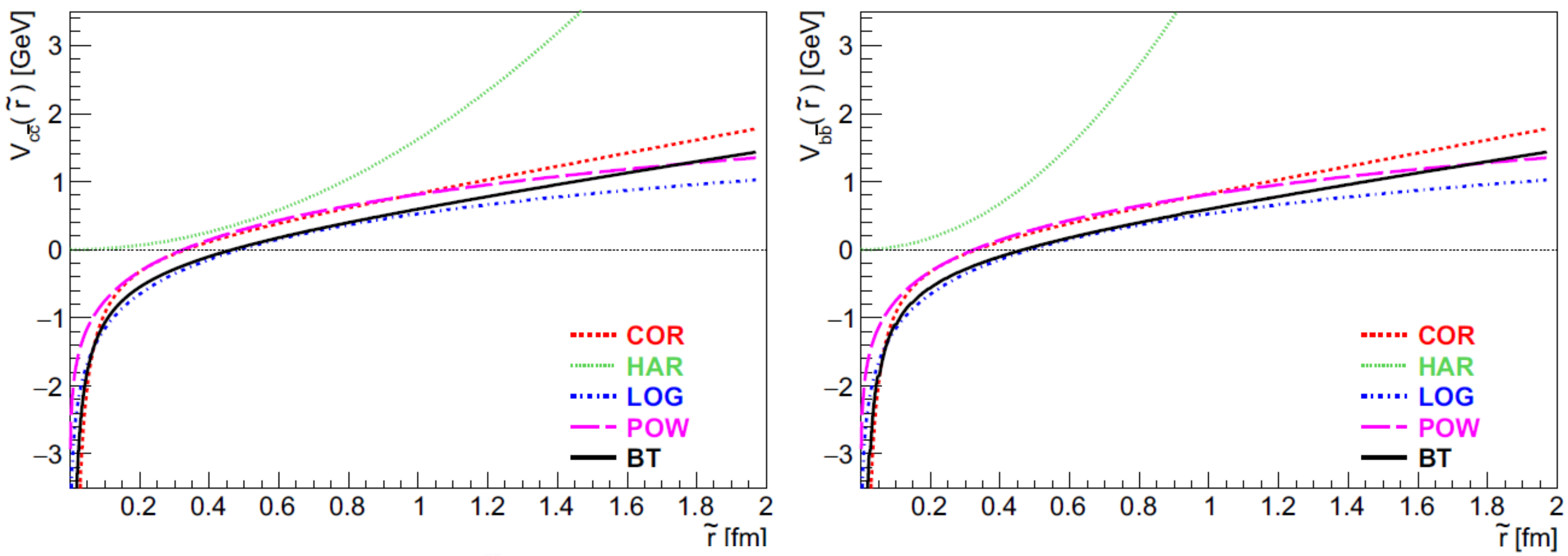
Schrodinger equation for spatial $Q\bar{Q}$ wave function

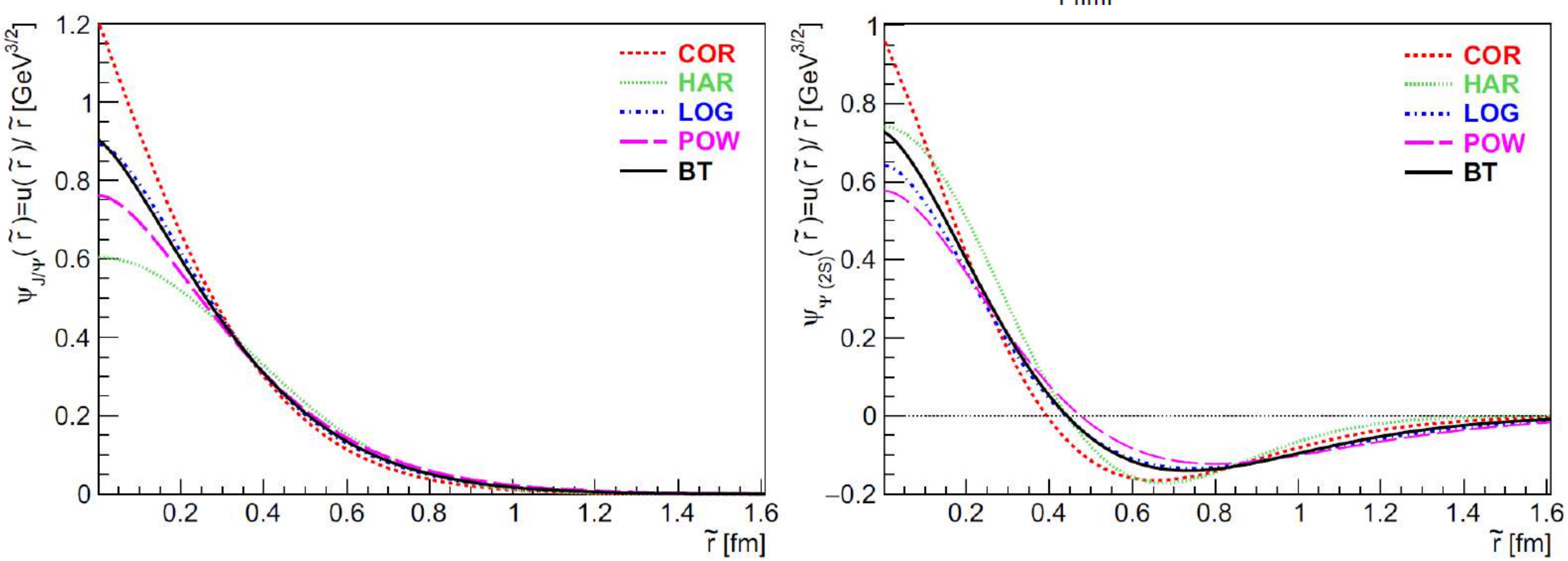
$$\left(-\frac{\Delta}{m_c} + V(r)\right) \Psi_{nlm}(\vec{r}) = E_{nl}\, \Psi_{nlm}(\vec{r}) \qquad \Psi(\vec{r}) = \Psi_{nl}(r) \cdot Y_{lm}(\theta, \varphi)$$

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

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

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

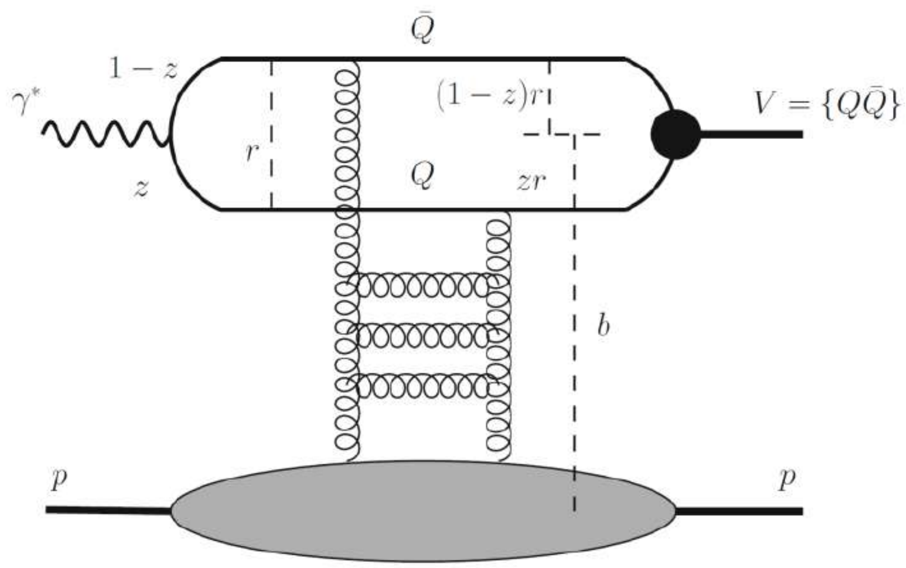
$$U^{(\mu,\bar{\mu})}(\alpha, \vec{p}_T) = \chi_c^{\mu\dagger}\,\widehat{R}^\dagger(\alpha, \vec{p}_T)\,\vec{\sigma}\cdot\vec{e}_\psi\,\sigma_y\,\widehat{R}^*(1-\alpha, -\vec{p}_T)\,\sigma_y^{-1}\,\widetilde{\chi}_{\bar{c}}^{\bar{\mu}}$$

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

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

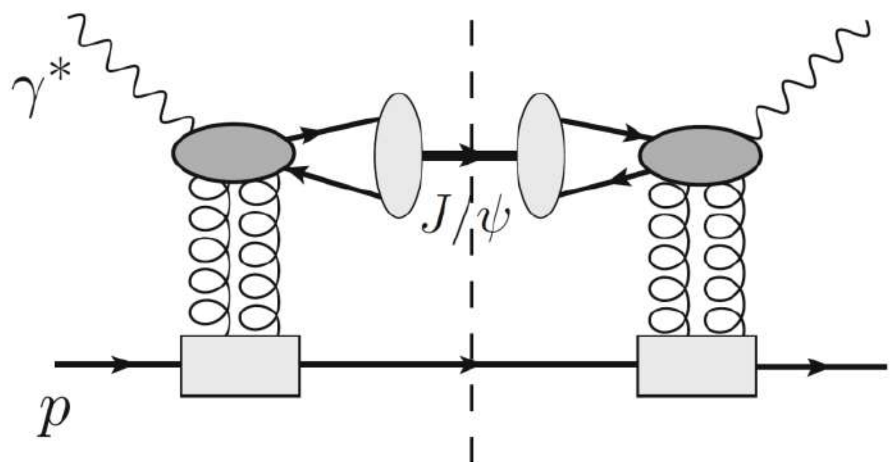
Exclusive electroproduction of heavy vector mesons

- 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

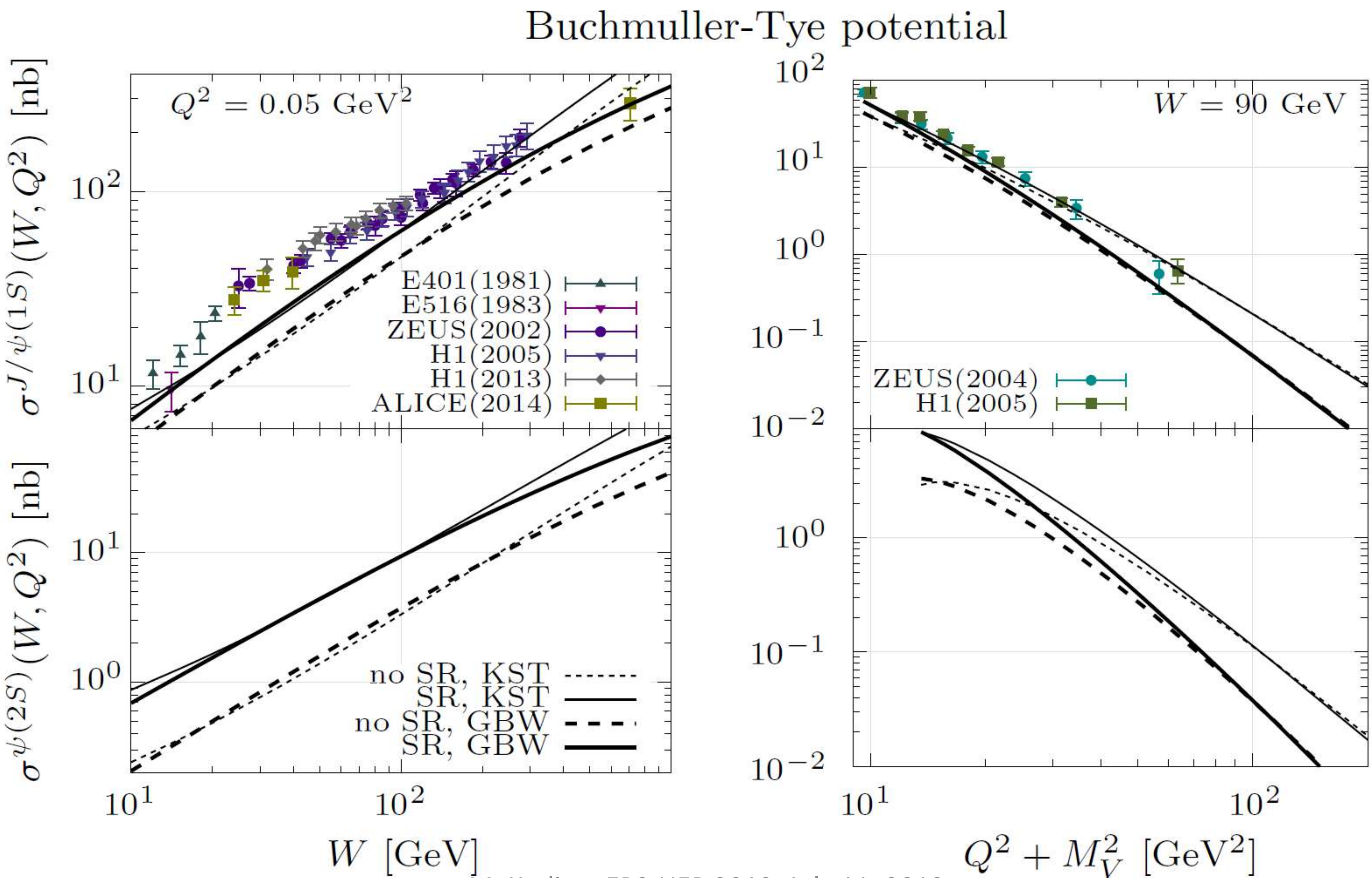
- 5 different dipole cross sections

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



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

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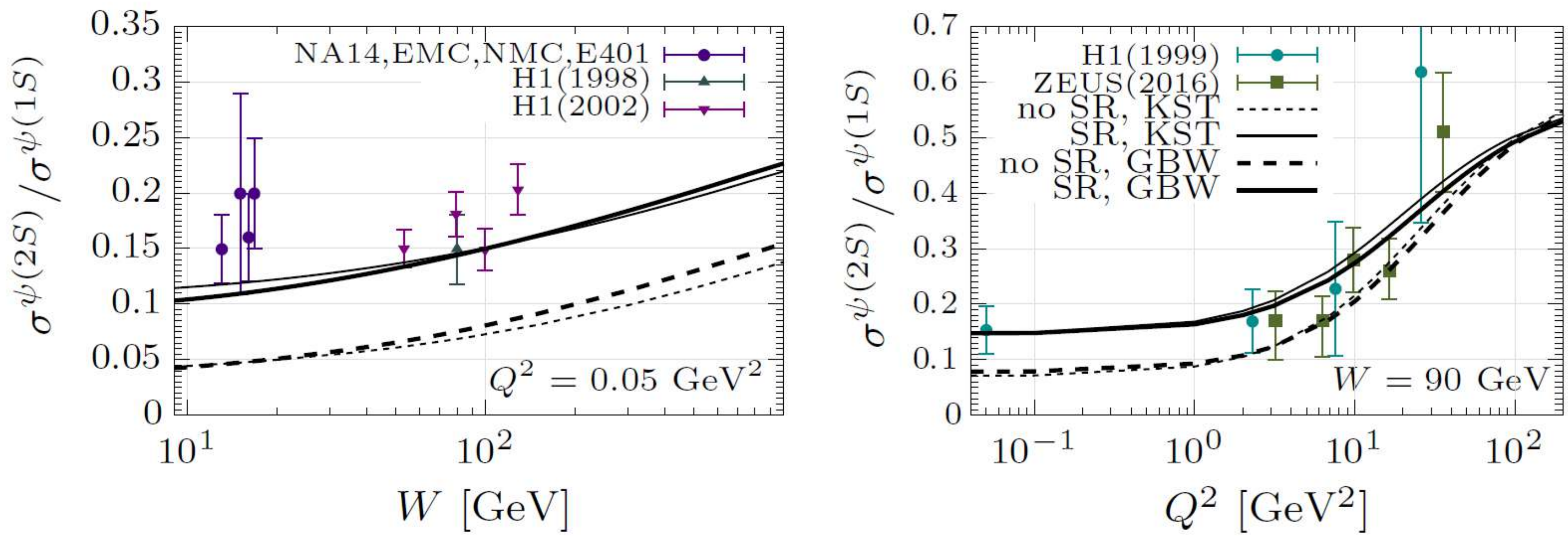
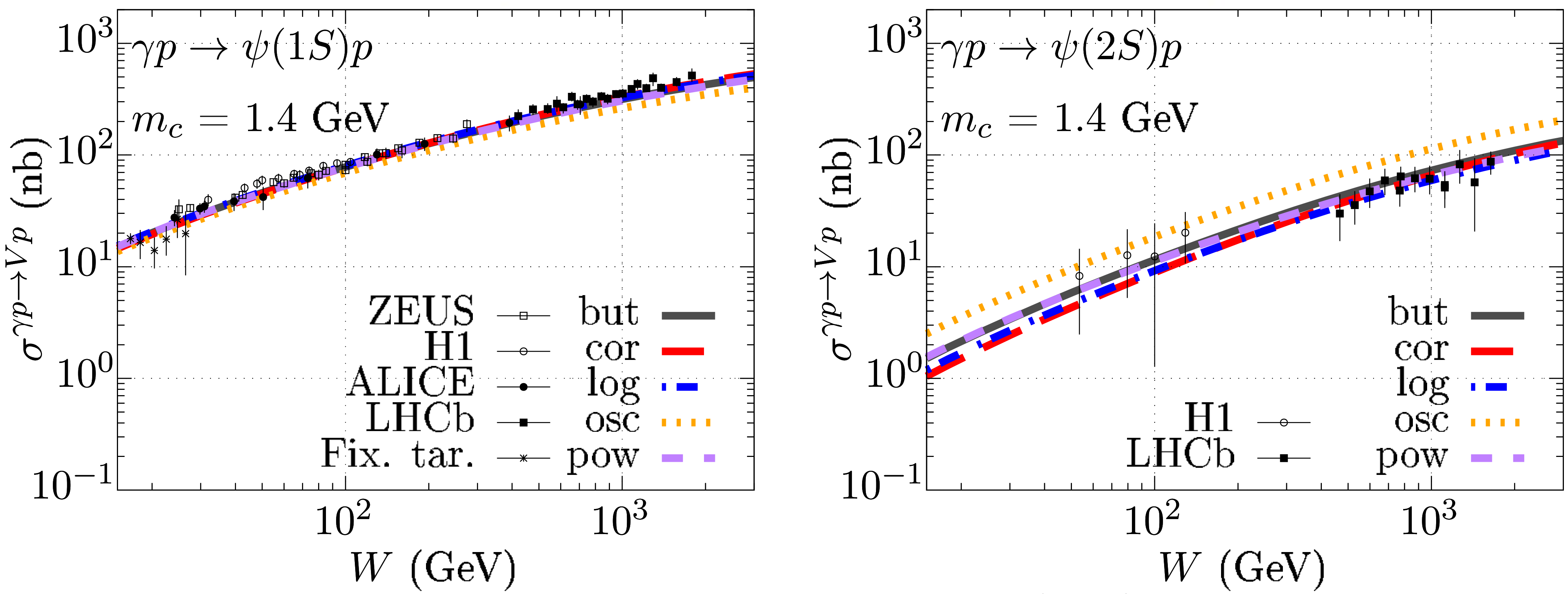
Eur.Phys.J. C79 (2019) no.2, 154; arXiv:1812.03001

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

Buchmuller-Tye potential



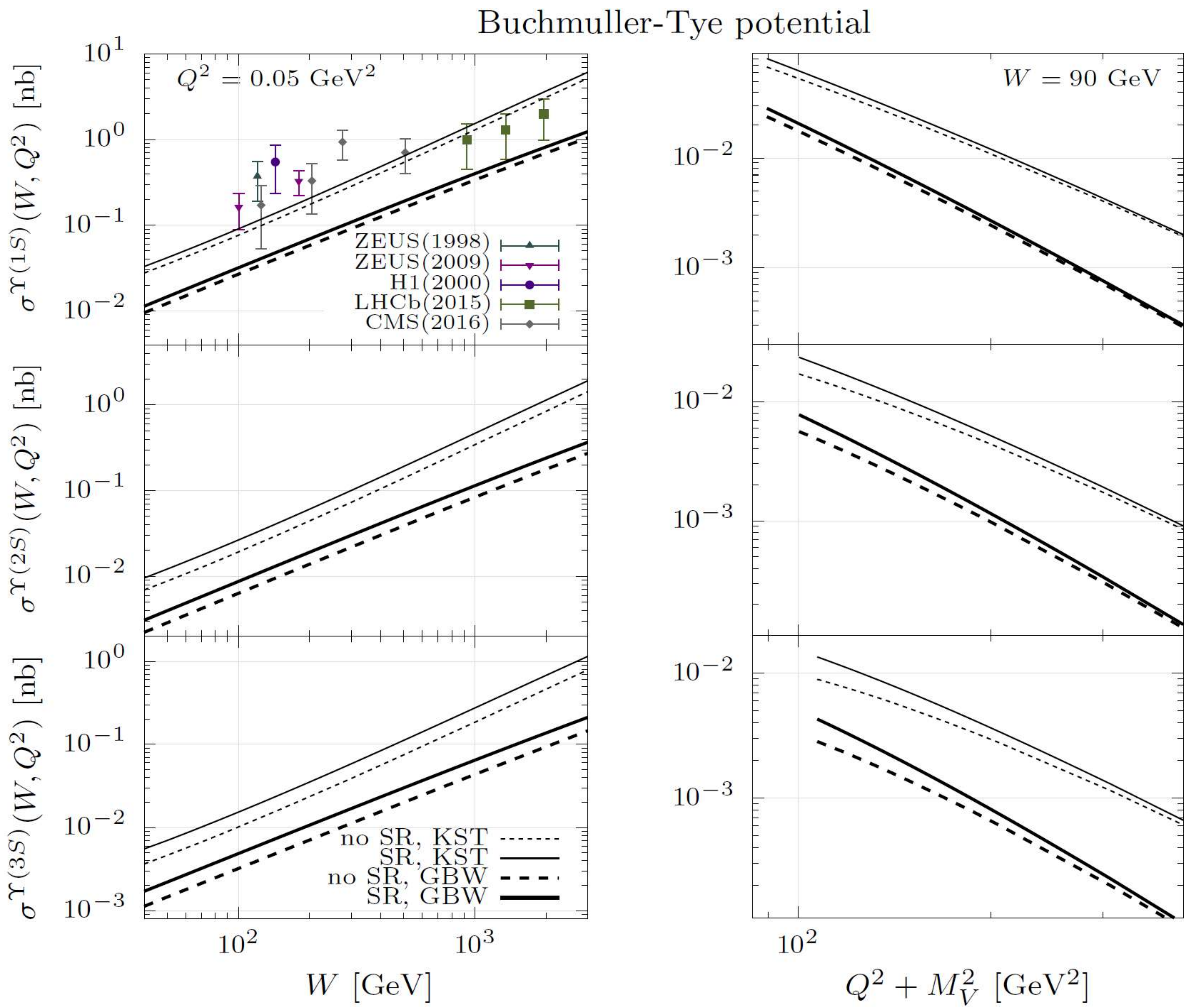
GBW model



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

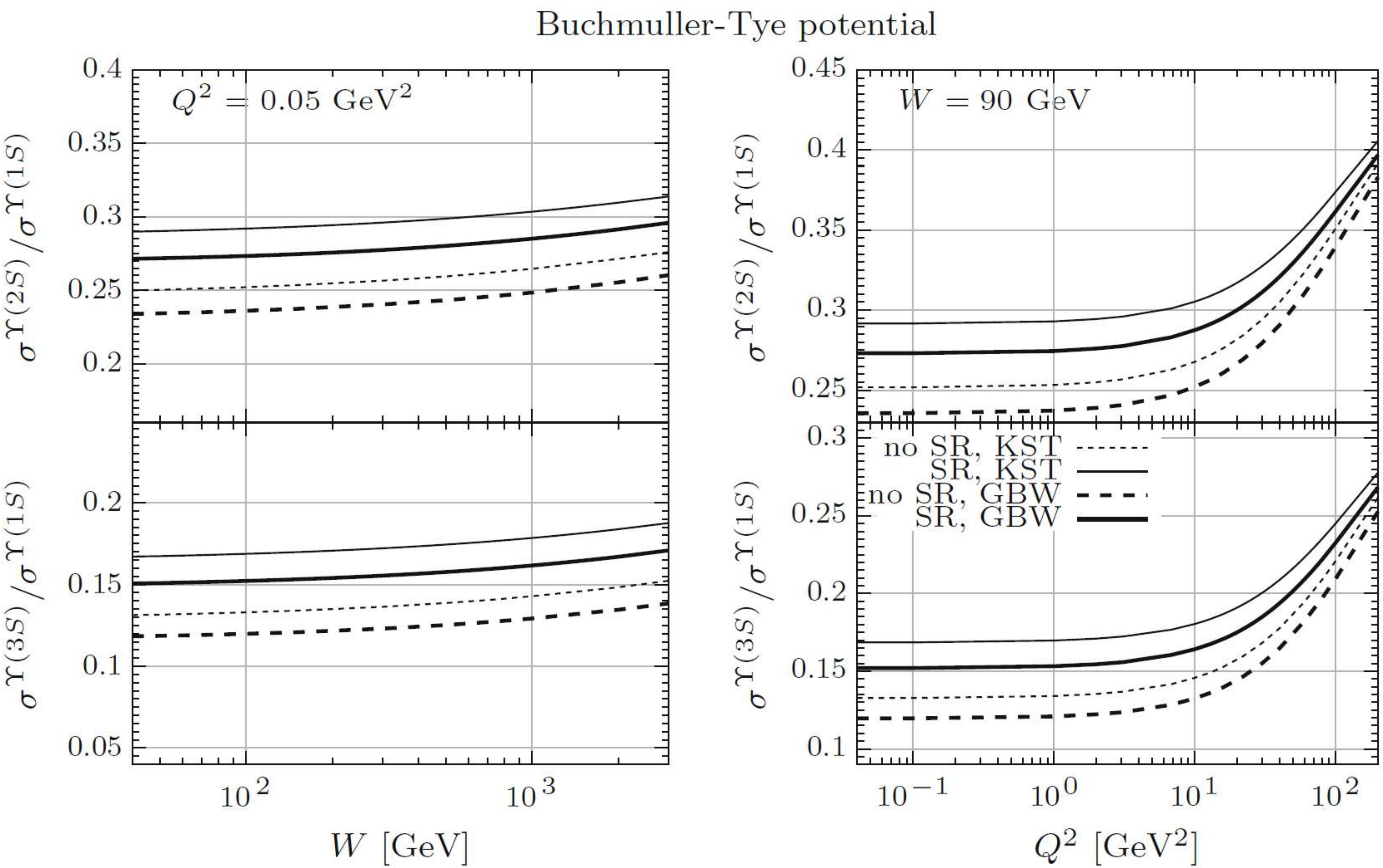
Highlights of spin rotation: 1S,2S,3S bottomonia

BT potential + KST/GBW dipole cross section

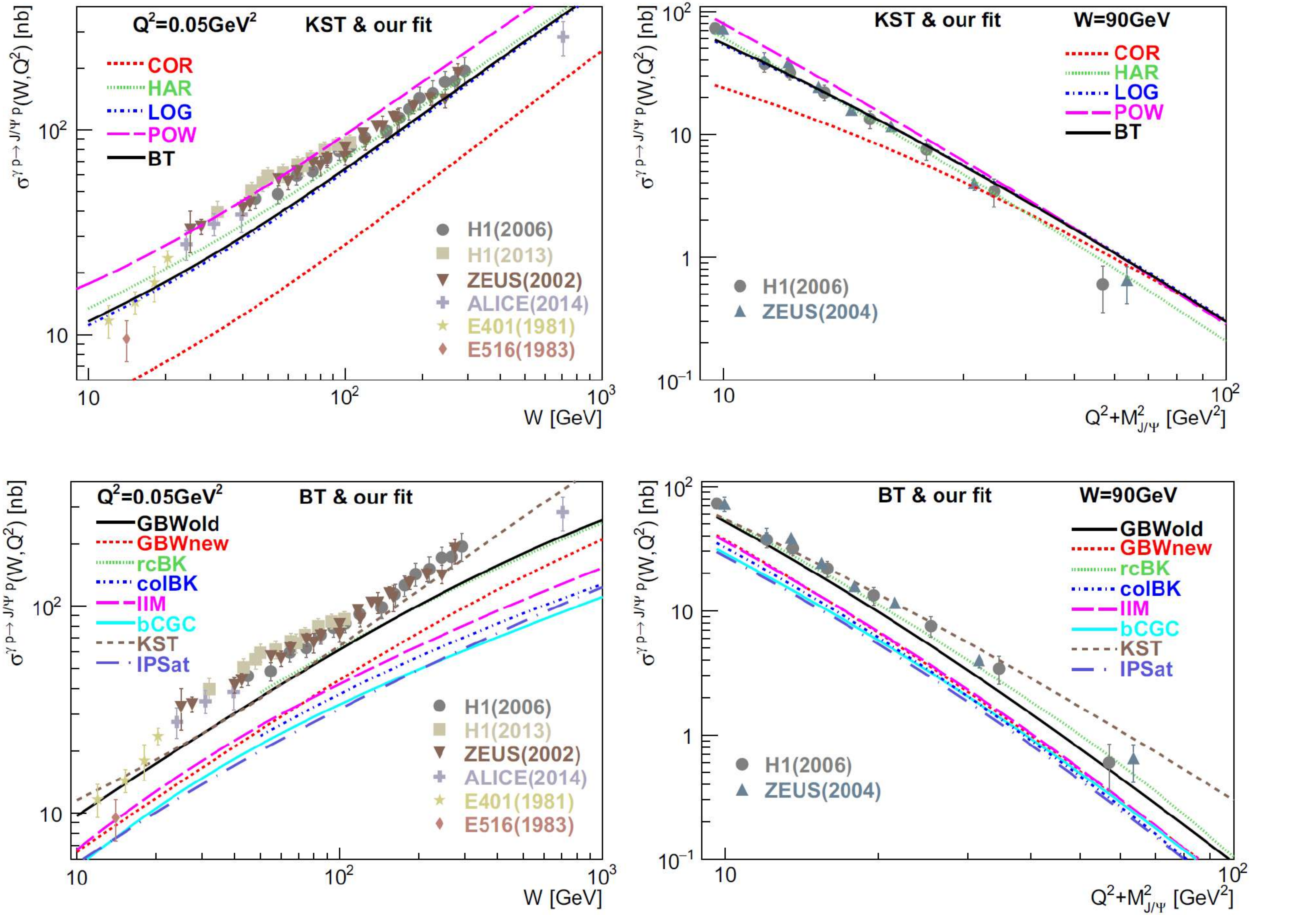


With increasing Q^2 the spin rot. effect disappearing

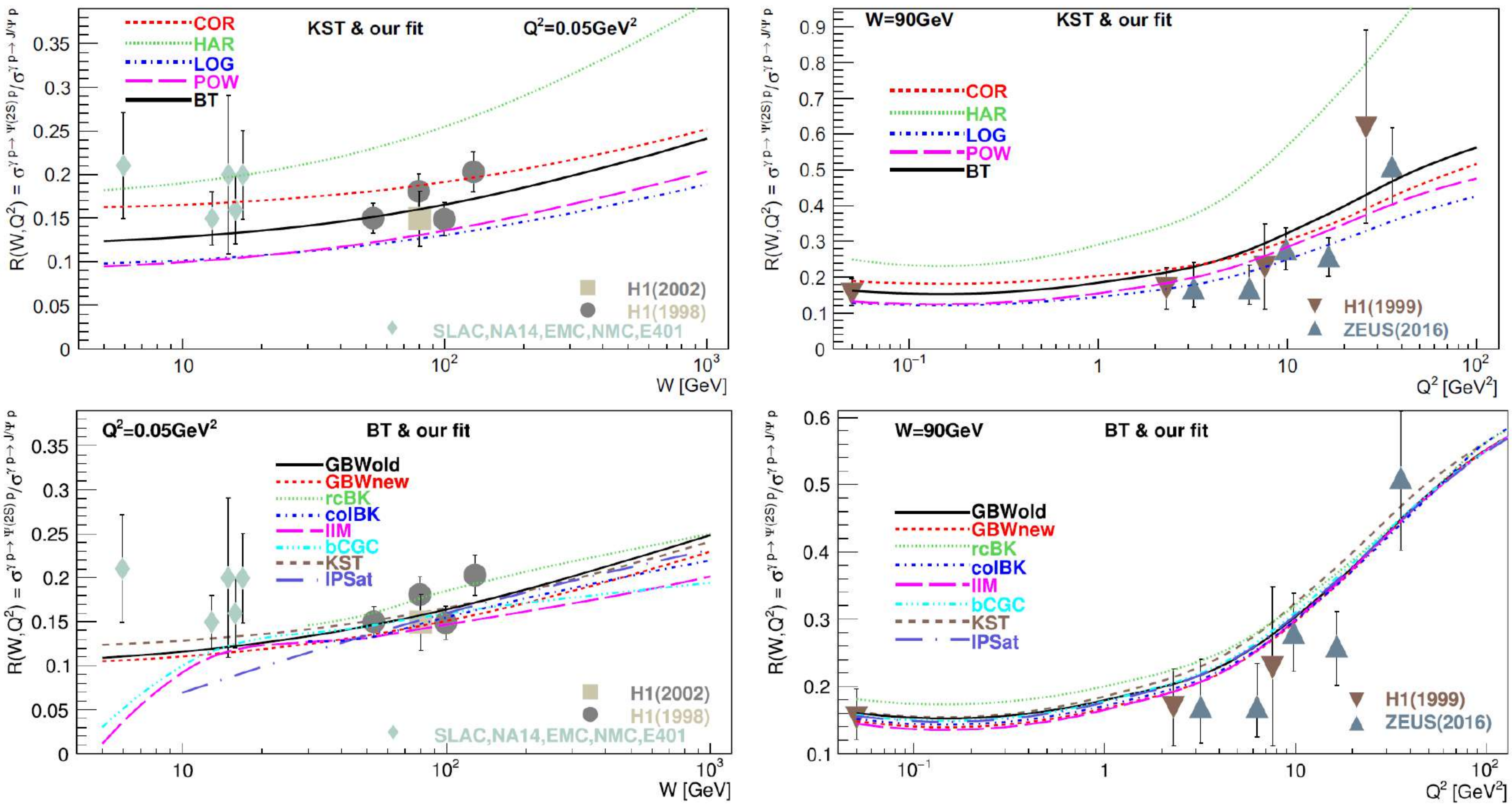
Highlights of spin rotation: 2S/1S and 3S/1S bottomonia ratio



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

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

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

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

BK model

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

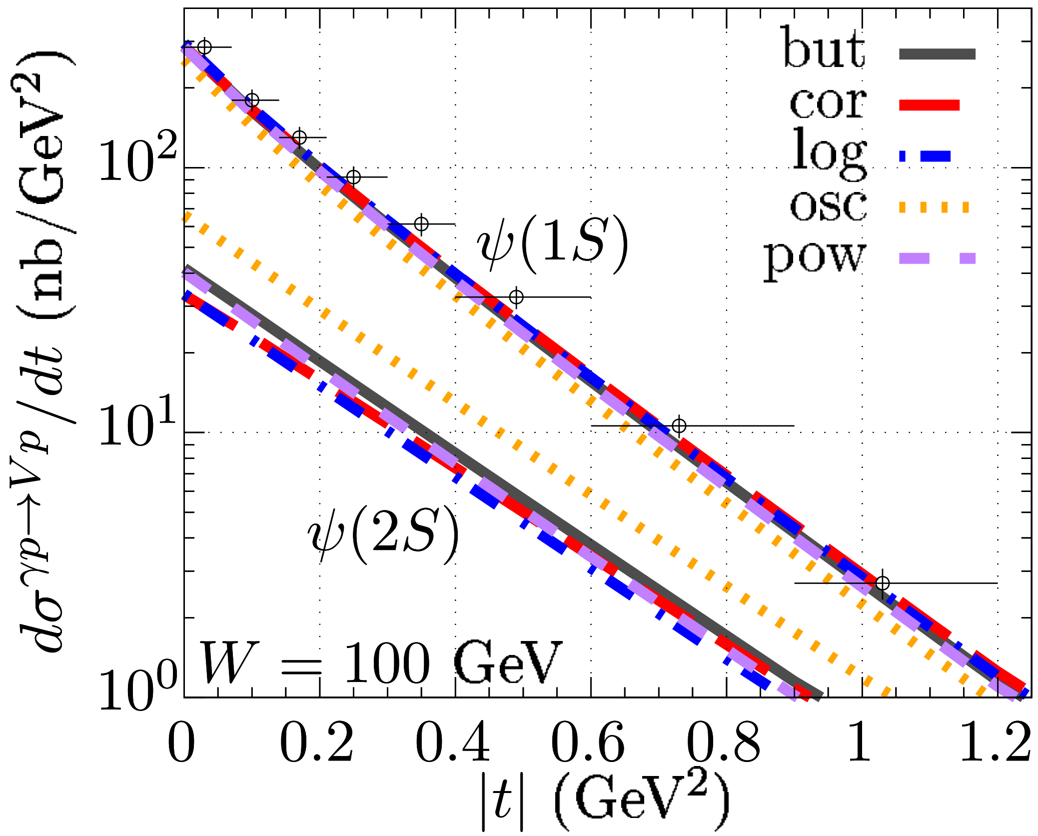
$$\frac{\partial \mathcal{N}(r,b,Y)}{\partial Y} = \int d^2\boldsymbol{r}_1 K(r,r_1,r_2)\Big(\mathcal{N}(r_1,b_1,Y) + \mathcal{N}(r_2,b_2,Y) - \mathcal{N}(r,b,Y) - \mathcal{N}(r_1,b_1,Y)\mathcal{N}(r_2,b_2,Y)\Big)$$

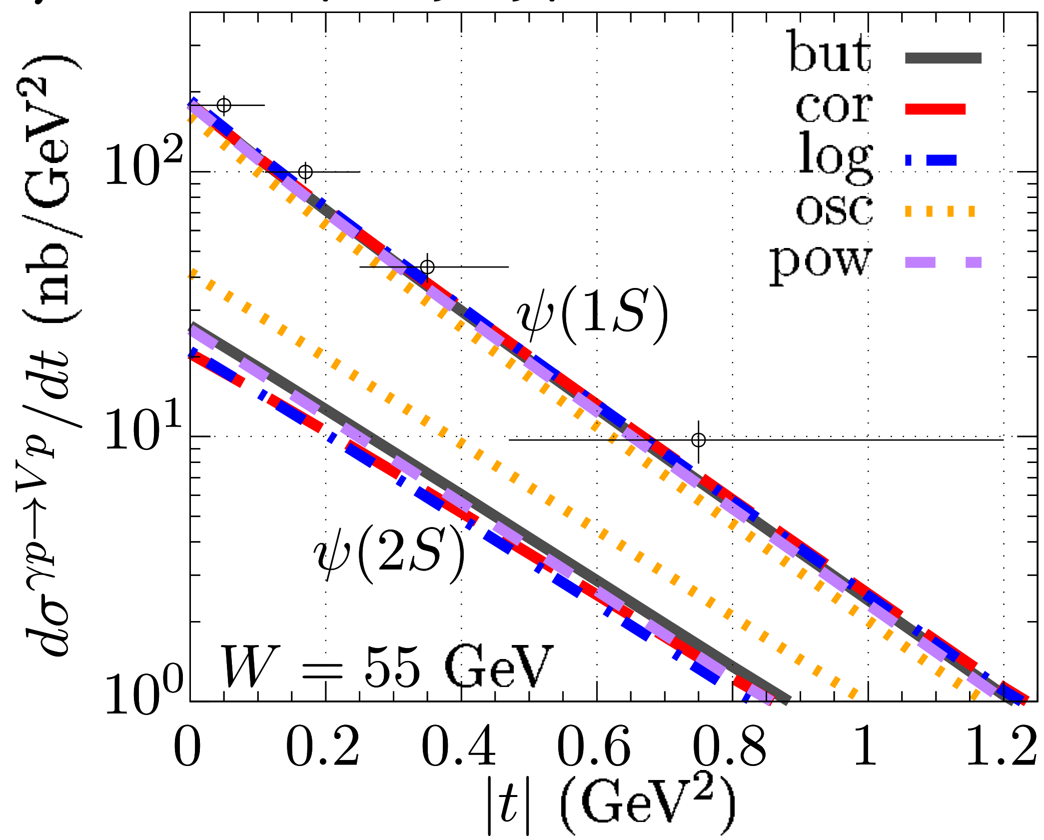
D. Bendova, J. Cepila, J. G. Contreras, and M. Matas, Phys. Rev. **D100**, 054015 (2019)

Differential cross sections: charmonia

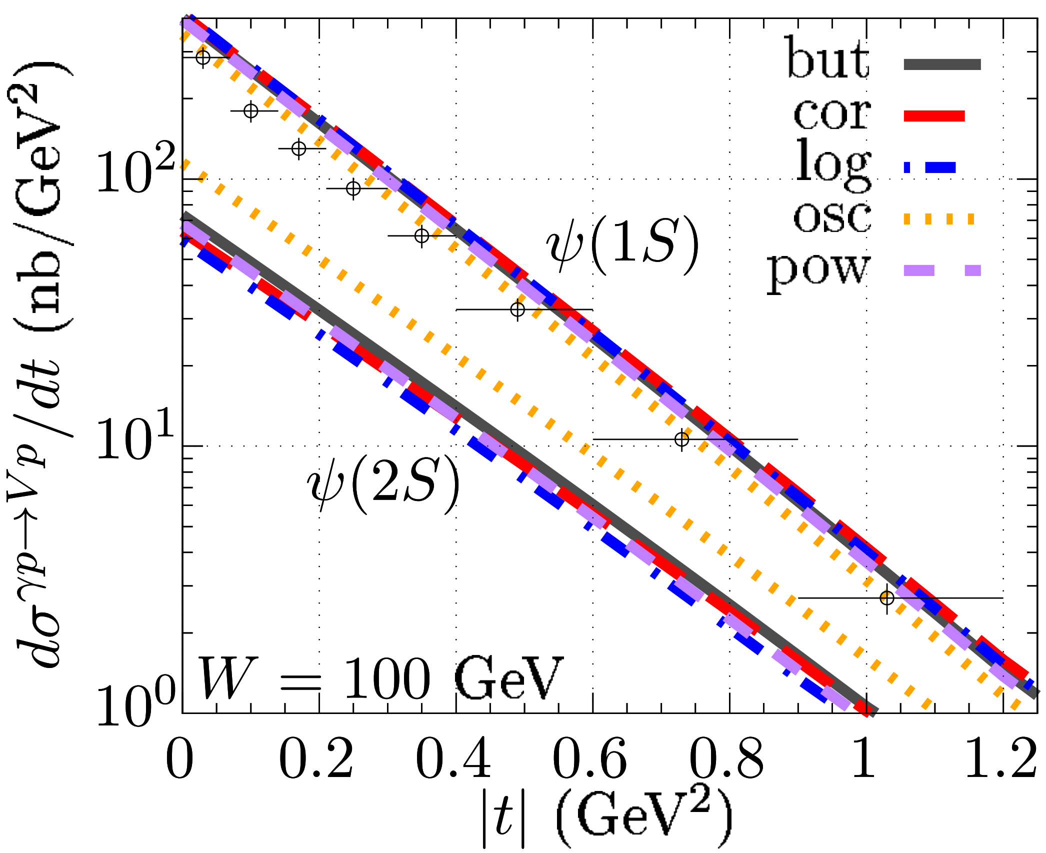
C.Henkels, E.G.de Oliveira, RP and H.Trebien, Phys. Rev. D104, no.5, 054008 (2021)

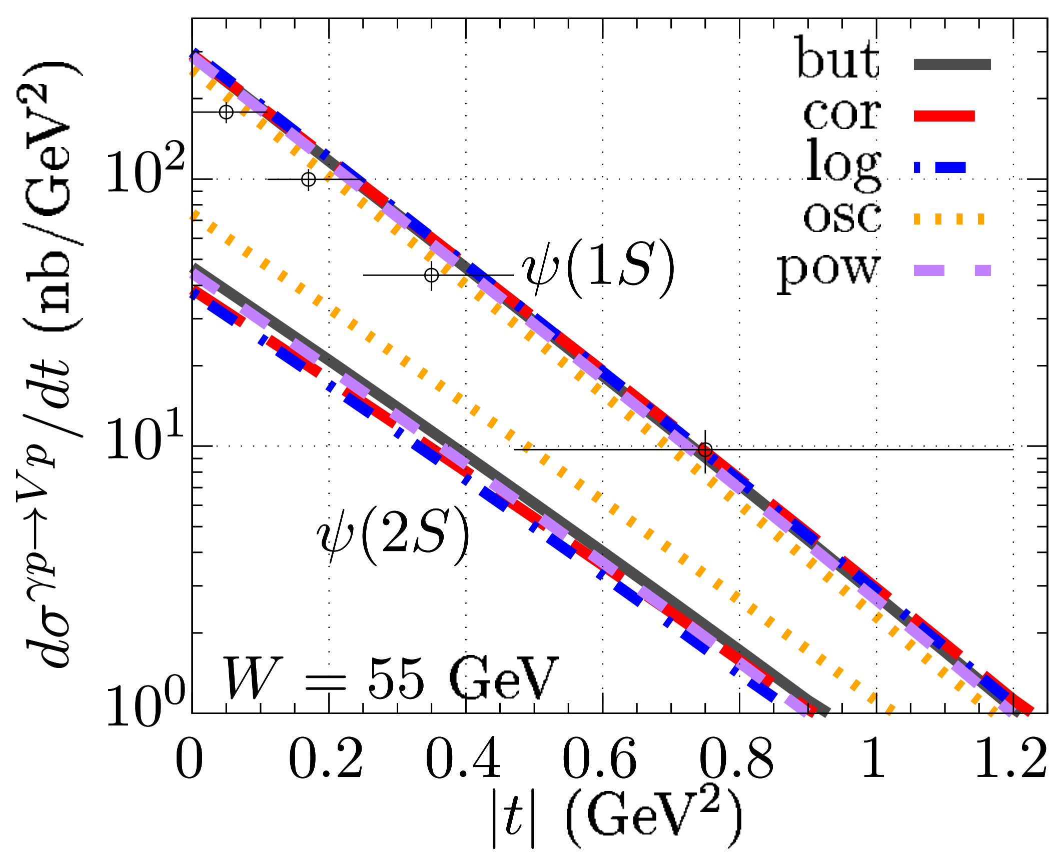
BK model





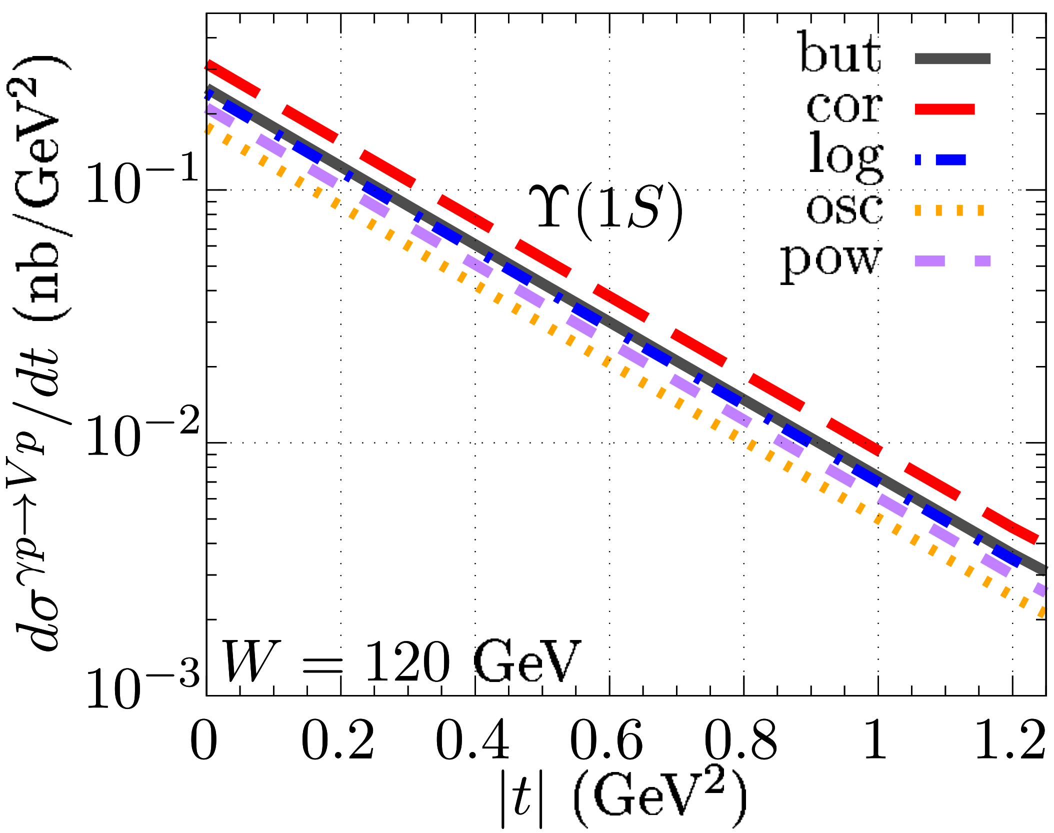
b-Sat model

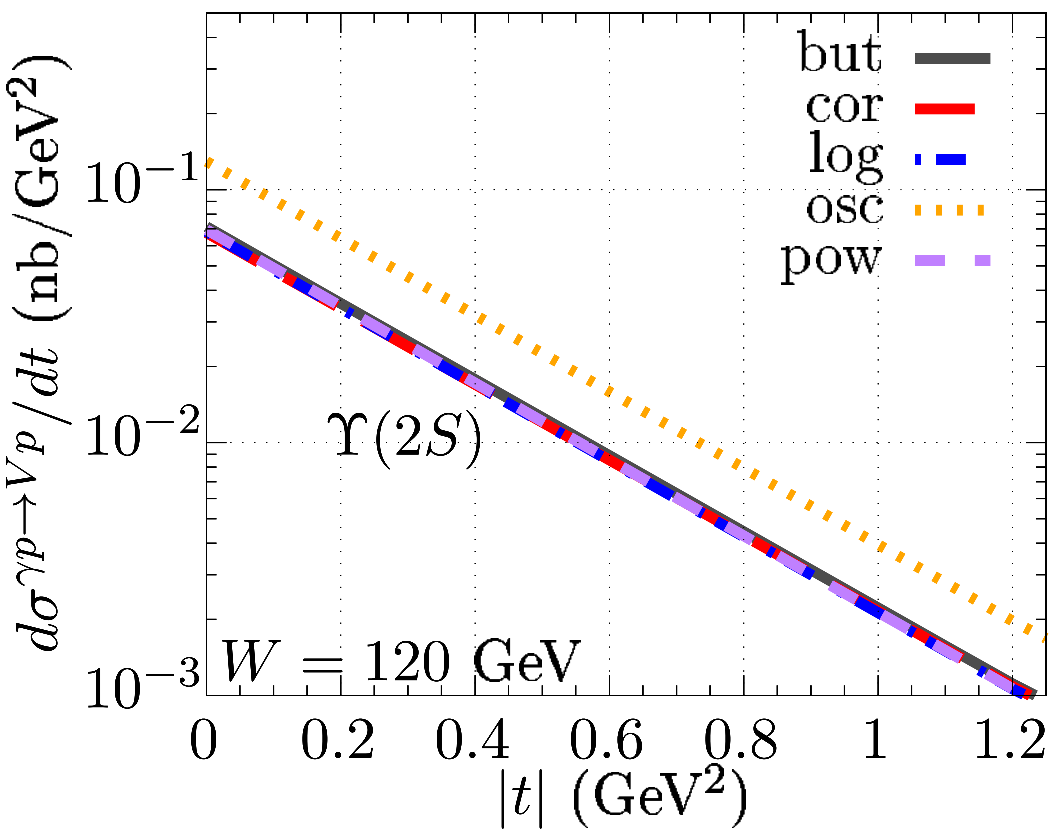




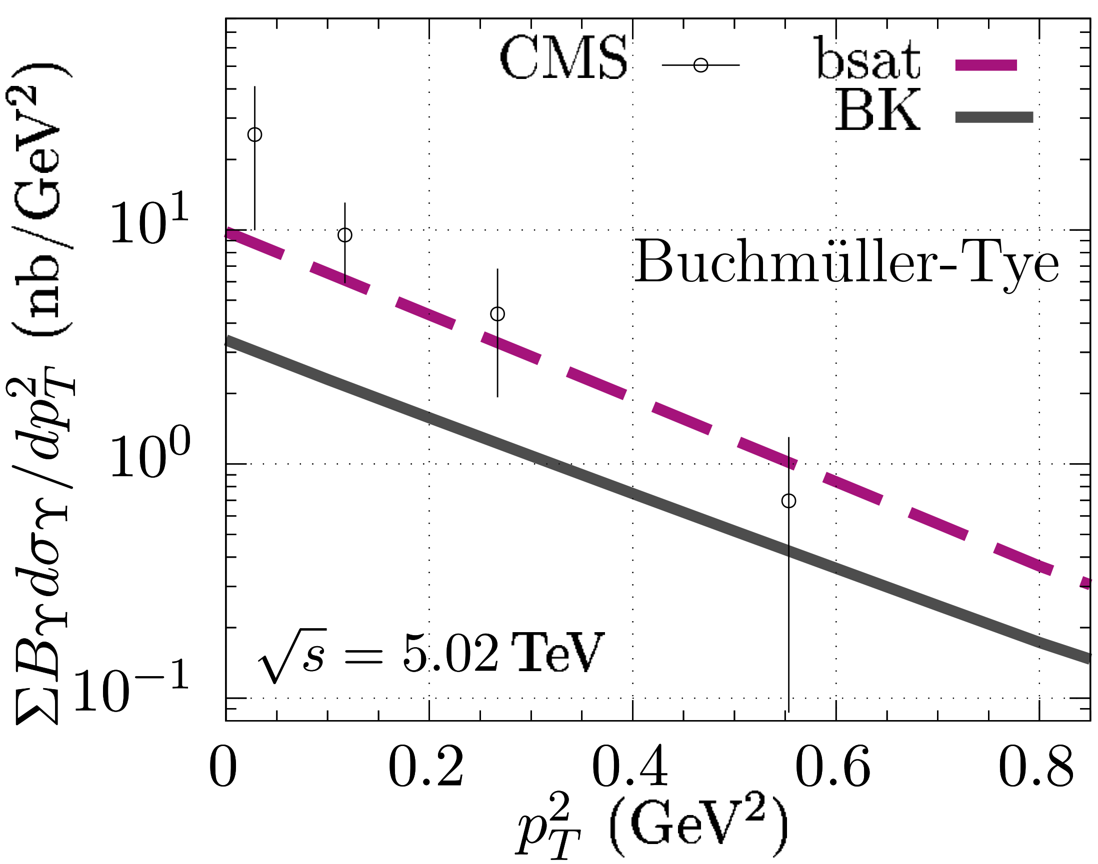
Differential cross sections: bottomonia

BK model



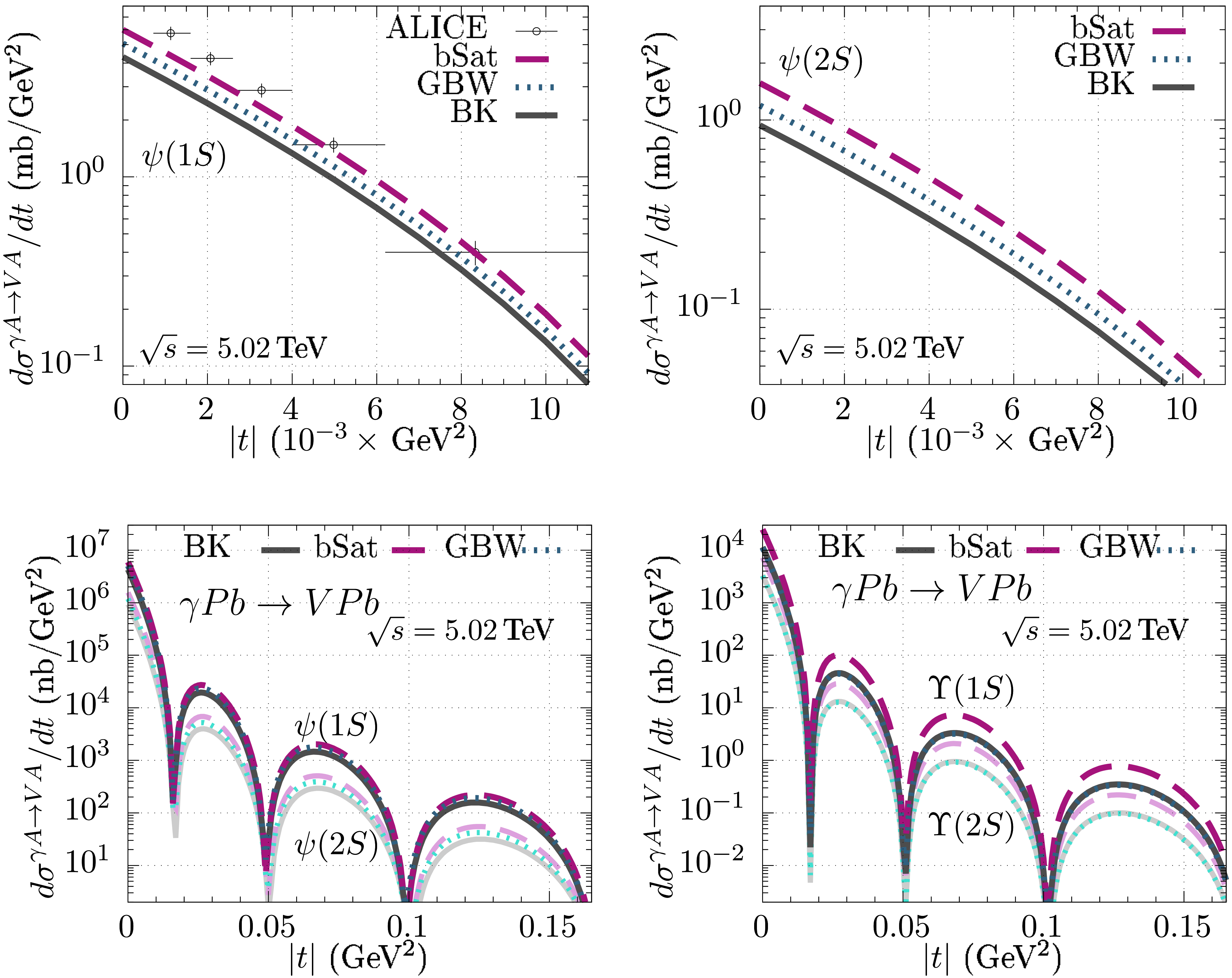


$pPb \to \Upsilon(nS)pPb$



Coherent photoproduction off nuclear targets

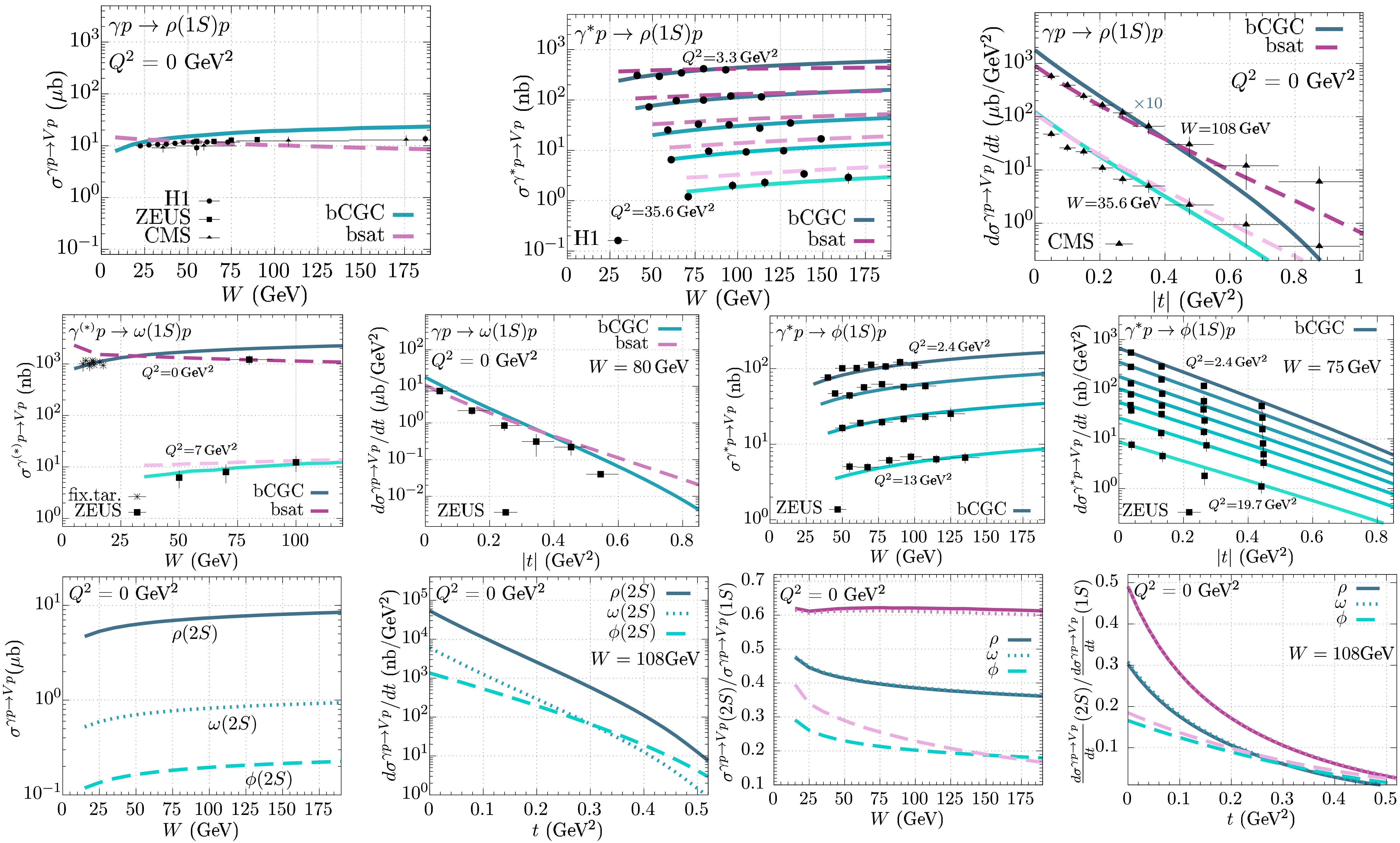
C.Henkels, E.G.de Oliveira, RP and H.Trebien, Phys. Rev. D104, no.5, 054008 (2021)



Light VM photoproduction with holographic wave functions

S. J. Brodsky, G. F. de Teramond, H. G. Dosch, and J. Erlich, Phys. Rept. **584**, 1 (2015)

J. R. Forshaw and R. Sandapen, Phys. Rev. Lett. **109**, 081601 (2012)



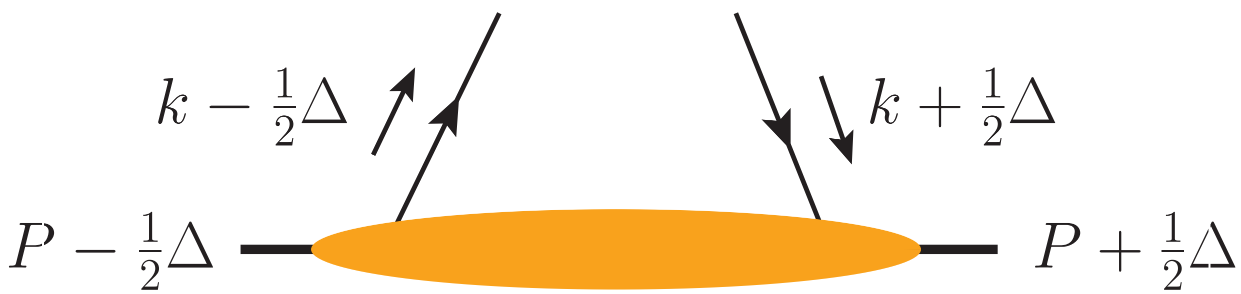
C.Henkels, E.G.de Oliveira, RP and H.Trebien, arXiv:2207.13756

Nucleon tomography: phase space distributions

What do we know about the nucleon?

It is a complicated object!

$$H(k, P, \Delta) = (2\pi)^{-4} \int d^4z \, e^{izk} \times \langle p(P + \tfrac{1}{2}\Delta) | \bar{q}(-\tfrac{1}{2}z) \, \Gamma \, q(\tfrac{1}{2}z) | p(P - \tfrac{1}{2}\Delta) \rangle$$



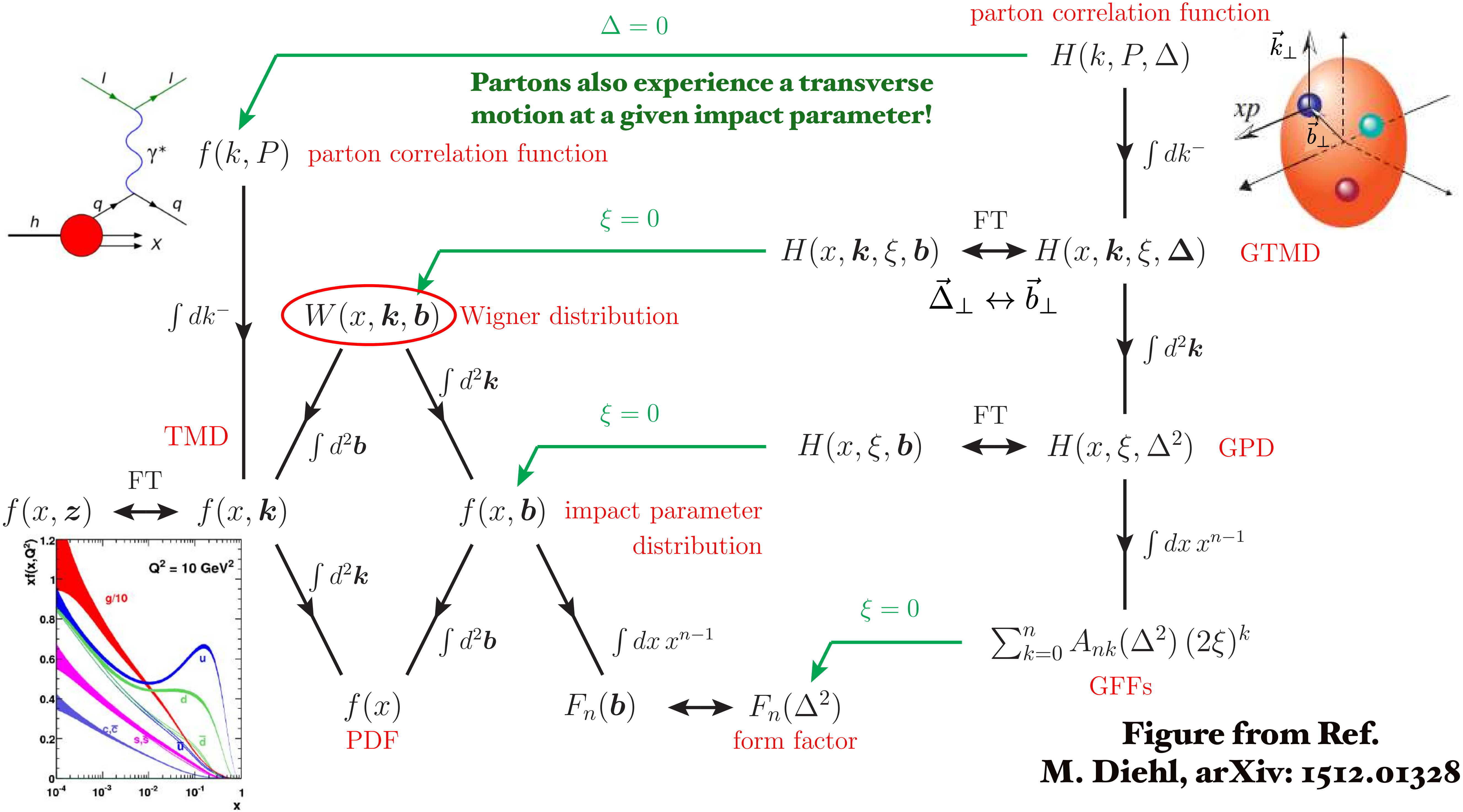


Figure from Ref.
M. Diehl, arXiv: 1512.01328

Nucleon 5D tomography: the "mother distribution"

✓ ***5D tomography:*** ***Generalised TMD (GTMD)*** — **Meissner, Metz, Schlegel (2009)...**

Husimi distribution — **Y. Hagiwara, Y. Hatta (2015)...**

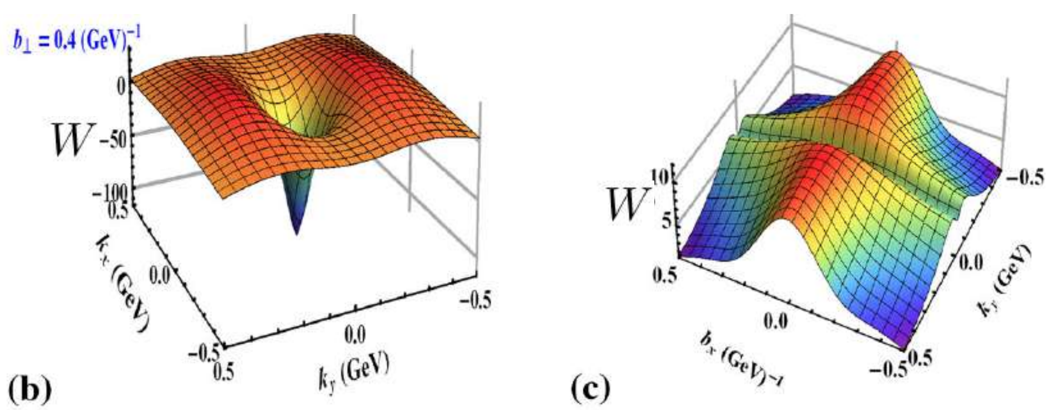
Wigner'1932 — ***Wigner distribution*** — **Belitsky, Ji, Yuan (2004); Ji (2003); Lorce, Pasquini (2011); Y. Hatta (2011)...**

+ many more studies...

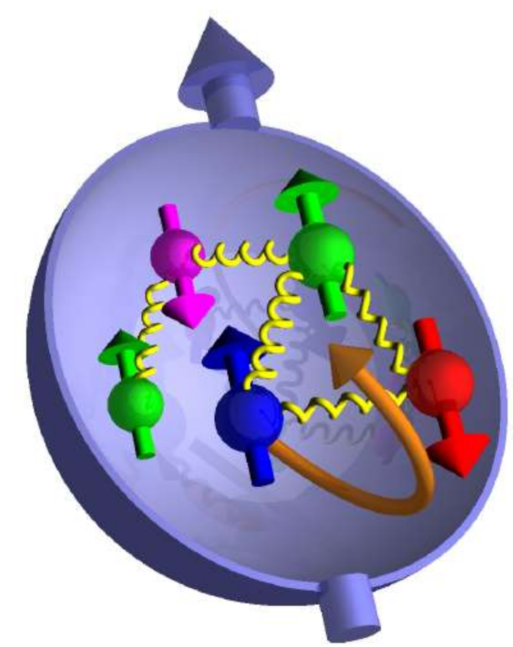
Example: leading-twist quark Wigner distribution

$$W(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \int \frac{dz^- d^2z_\perp}{16\pi^3} e^{ixP^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp} \langle P-\frac{\Delta}{2}|\bar{q}(-z/2)\gamma^+ q(z/2)|P+\frac{\Delta}{2}\rangle$$

J. More et al, PRD'17



Non-trivial correlation between the transverse momentum and the impact parameter due to orbital angular momentum!



Spin decomposition of the nucleon:

$$\frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g \equiv \frac{1}{2}$$

$$L = \int dx d^2b_\perp d^2k_\perp\, (\vec{b}_\perp \times \vec{k}_\perp)_z \cdot W(x,\vec{k}_\perp,\vec{b}_\perp)$$

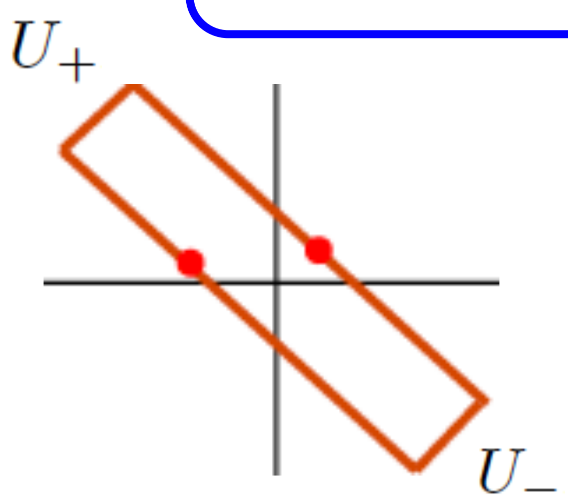
canonical orbital angular momentum

Wigner/GTMD distributions provide the most complete information on partonic "image" of the nucleon!

The gluon Wigner distribution at small x: dipole picture

From quark to gluon: $\bar{\Psi}(\vec{r}-\xi/2)\Gamma\Psi(\vec{r}+\xi/2) \rightarrow F^{+\nu}(\vec{r}-\xi/2)F^{+}_{\nu}(\vec{r}+\xi/2)$

$$xW(x,\vec{q}_\perp,\vec{b}_\perp) = \frac{2}{P^+(2\pi)^3}\int dz^+ d^2\vec{z}_\perp \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{i\vec{q}_\perp\cdot\vec{z}_\perp - ixP^-z^+} \times \left\langle P+\frac{\vec{\Delta}_\perp}{2}\right| \mathrm{Tr}\left[U_+ F_a^{+i}\left(\vec{b}_\perp+\frac{z}{2}\right)U_- F_a^{+i}\left(\vec{b}_\perp-\frac{z}{2}\right)\right]\left| P-\frac{\vec{\Delta}_\perp}{2}\right\rangle$$



Staple-shaped Wilson lines: $U_\pm \equiv U[0,\pm\infty;0]U[\pm\infty,z^+;\vec{z}_\perp]$

$$U[z_1^+,z_2^+;\vec{z}_\perp] \equiv \mathcal{P}\exp\left(ig\int_{z_1^+}^{z_2^+} dz^+ \hat{A}^-(z^+,\vec{z}_\perp)\right)$$

$x \ll 1$ $\quad e^{-ixP^-z^+} \approx 1$

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

$$xW_g(x,\mathbf{k},\mathbf{b}_\perp) = \frac{2N_c}{\alpha_S}\int \frac{d^2\mathbf{r}}{(2\pi)^2} e^{i\mathbf{k}\cdot\mathbf{r}}\left(\frac{1}{4}\nabla^2_{\mathbf{b}_\perp} - \nabla^2_{\mathbf{r}}\right) S_Y(\mathbf{r},\mathbf{b}_\perp) \qquad Y = \ln\frac{1}{x}$$

Dipole S-matrix: $S_Y(\vec{q}_\perp,\vec{\Delta}_\perp) = \int \frac{d^2\vec{r}_\perp d^2\vec{b}_\perp}{(2\pi)^4} e^{i\vec{\Delta}_\perp\cdot\vec{b}_\perp + i\vec{q}_\perp\cdot\vec{r}_\perp}\left\langle \frac{1}{N_c}\mathrm{Tr}\, U\left(\vec{b}_\perp+\frac{\vec{r}_\perp}{2}\right)U^\dagger\left(\vec{b}_\perp-\frac{\vec{r}_\perp}{2}\right)\right\rangle_Y$

Nucleon tomography: relevant processes

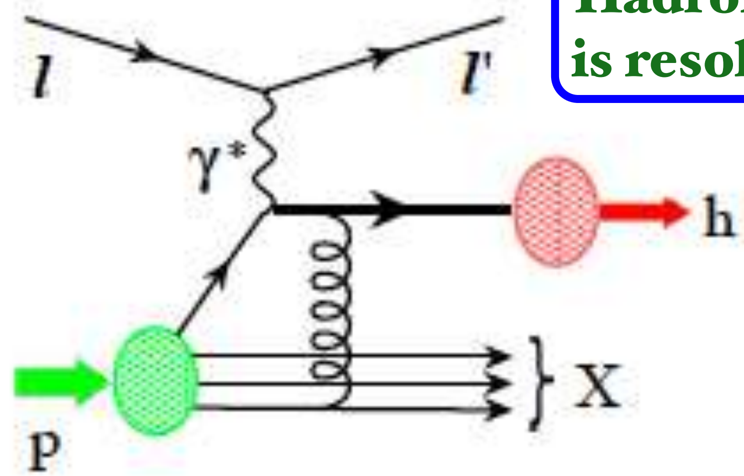
Combination of TMD and GPD provide a deep 3D picture of the quark and gluon content of the nucleon

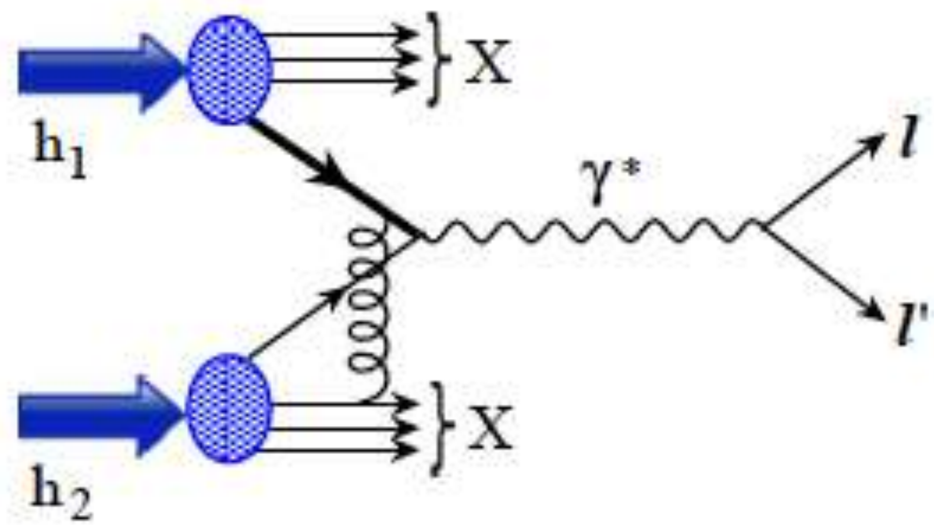
Semi-Inclusive DIS

Hadron pT is resolved!

Drell-Yan

TMD

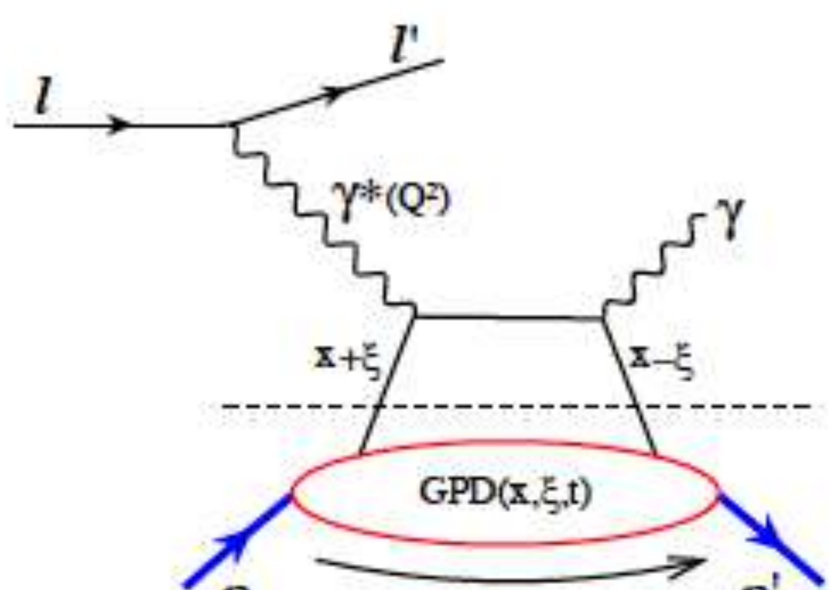




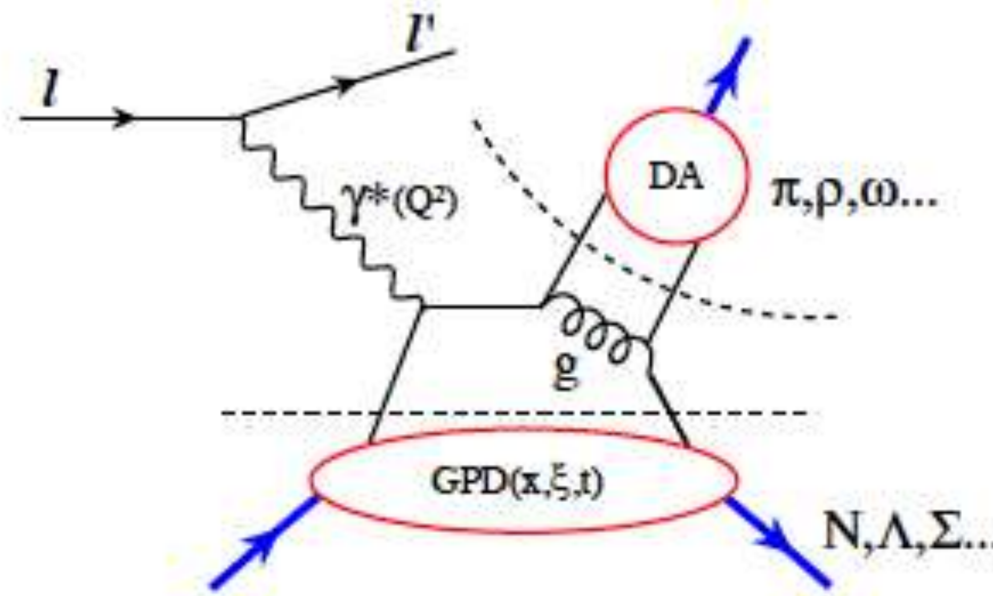
Review: e.g. N. Stefanis et al. arXiv: 1612.03077

Deeply-Virtual Compton Scattering

GPD



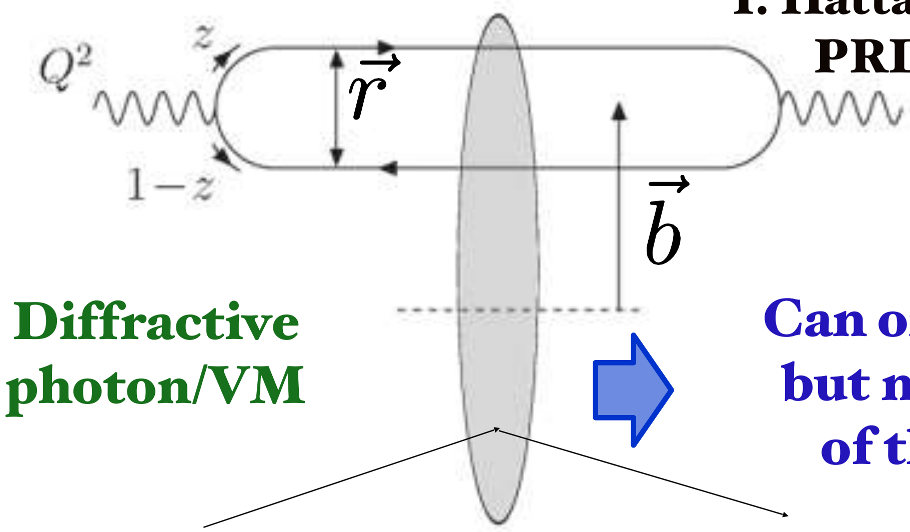
$t = -\vec{\Delta}_{\perp}^2$



What about accessing the 5D Wigner/GTMD distributions?

Gluon Wigner from diffractive DIS processes

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

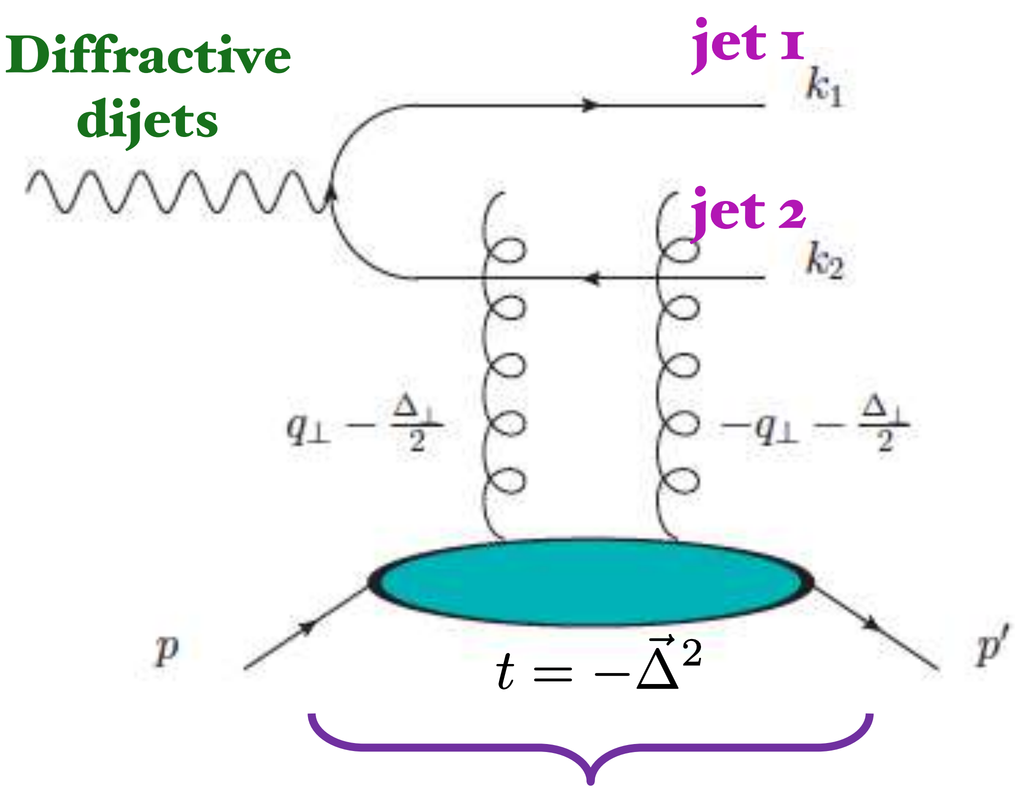


Diffractive photon/VM

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

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

Diffractive dijets



Dijet observables:

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

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

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

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

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

Advantage!

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

Fourier transform of the dipole S-matrix!

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)

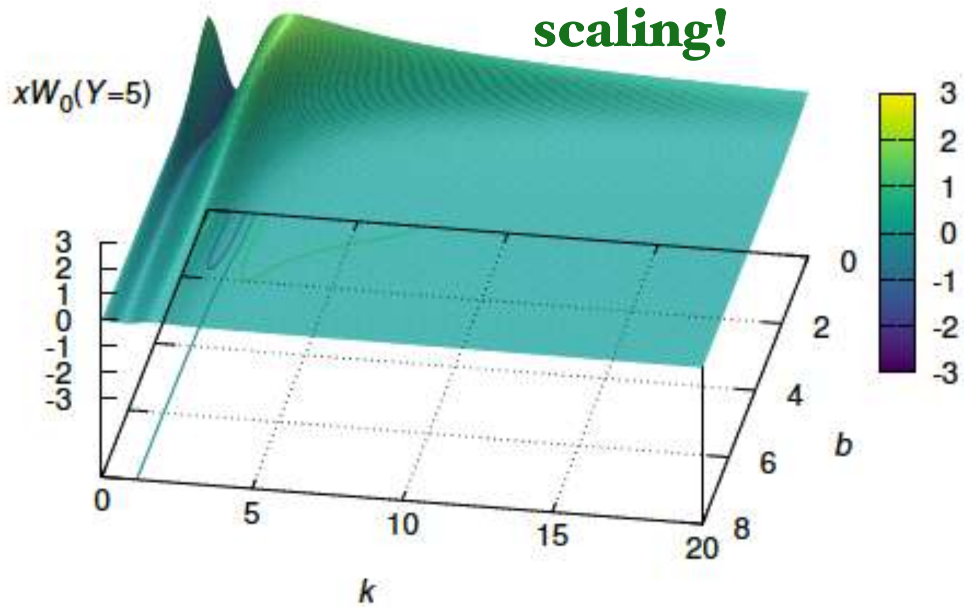
$$W(x,\boldsymbol{b},\boldsymbol{k}) = W_0(x,b,k) + 2\cos 2(\phi_k - \phi_b) W_1(x,b,k) + \cdots$$

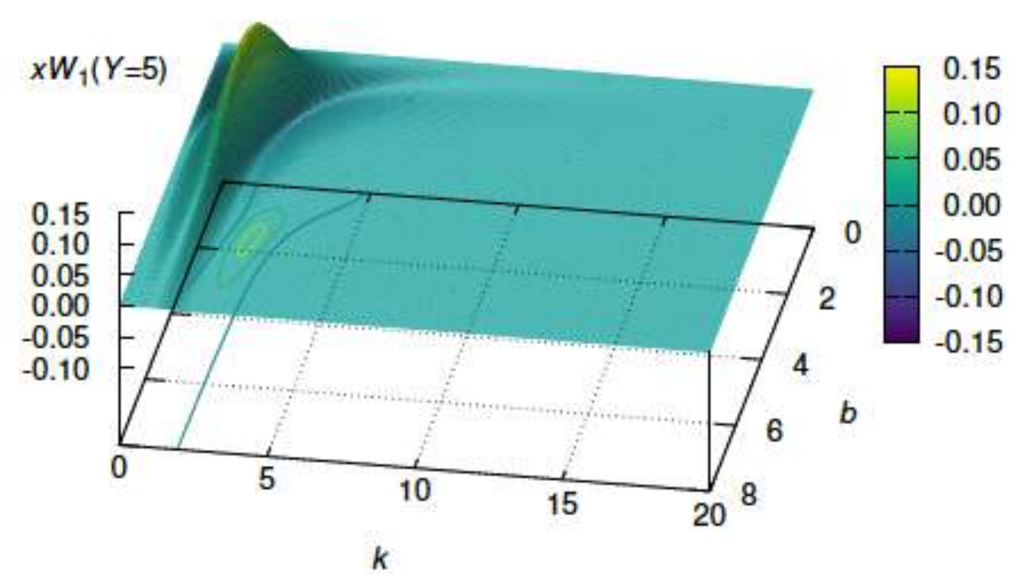
Geometric scaling!

"Elliptic" gluon Wigner

BK equation with SO(3) symmetry (CGC)

Gubser (2011)



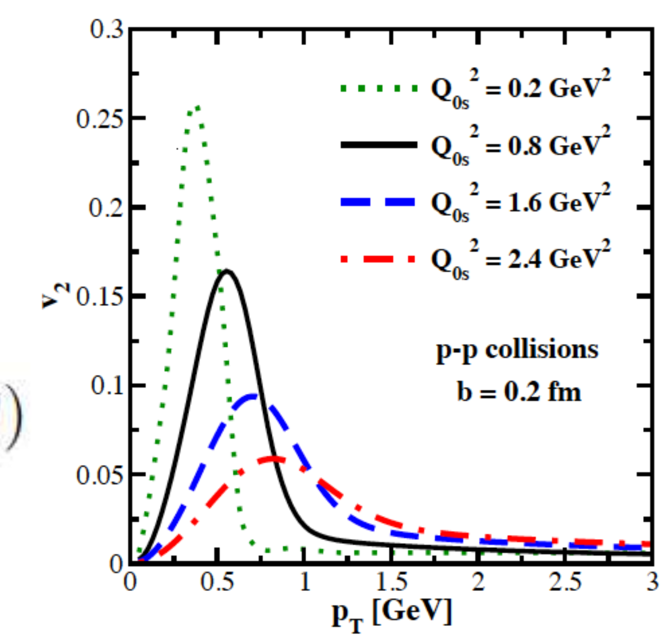


E. Iancu and A. Rezaeian, PRD95, 094003 (2017)

McLerran-Venugopalan model for the dipole S-matrix

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

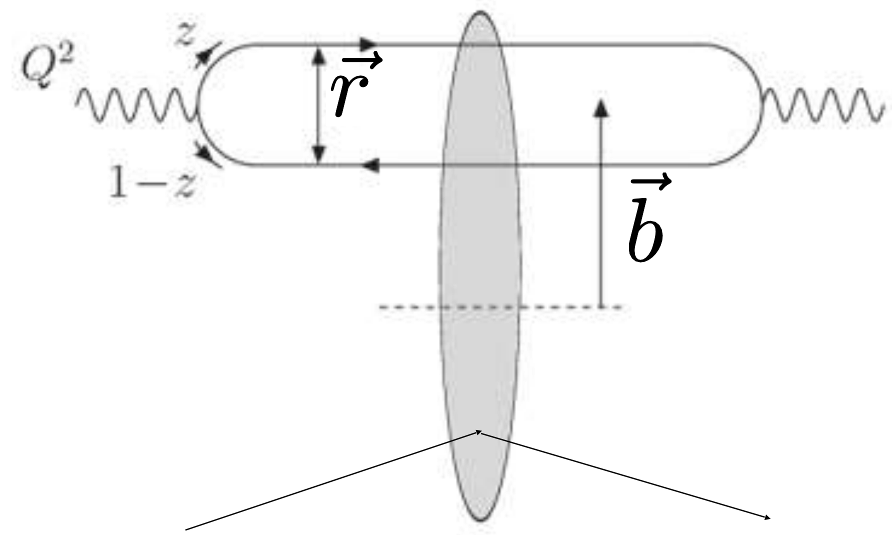
$$N_{2g}(b,r,\theta) = \mathcal{N}_0(b,r) + \mathcal{N}_\theta(b,r)\cos(2\theta)$$



Dipole orientation effects ⇨ **Elliptic flow, gluon transversity, angular correlation in DVCS etc**

Dipole orientation effects VM production

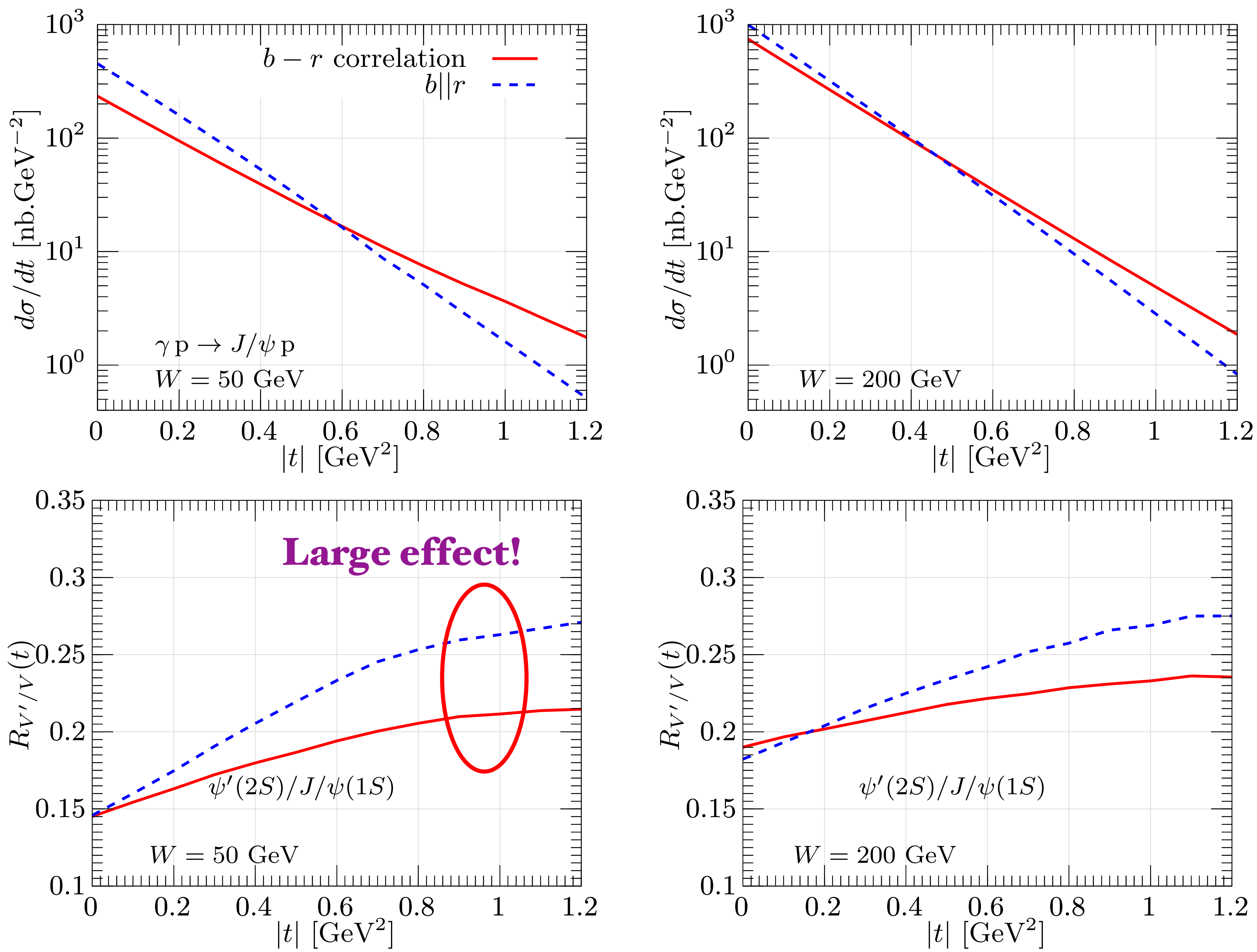
Diffractive photon/VM



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

Y. Hatta, B.W. Xiao and F. Yuan, Phys. Rev. Lett. 116, no.20, 202301 (2016)

Helicity-flip and L-polarisation generate cos ϕ and cos 2ϕ correlations in DVCS related to the dipole orientation effects!



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

The possibility to constrain elliptic gluon density through helicity-flip VM photoproduction!

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

✓ The dipole orientation effects cause azimuthal angle correlations in the helicity-flip VM photoproduction, while the size of their impact is model-dependent and is subject for further explorations.