Heavy quarkonium diffractive production using holographic wavefunctions

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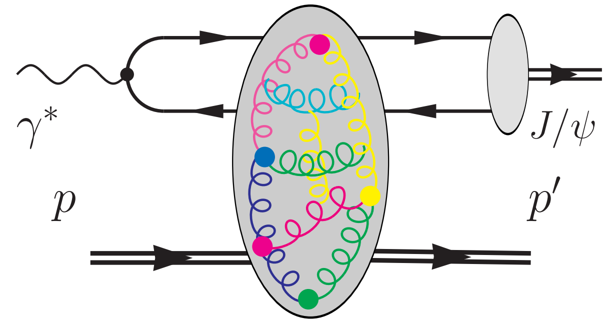
Y. Li et al., PLB 758,118, 2016
G. Chen et al., arXiv:1610.04945

VM production in the dipole picture

Talks by A. Rezaeian, H. Mantysaari

- ❑ Photon LFWF: pQED
- ❑ Dipole cross section
- ❑ Vector meson LFWFs



- ❑ $$\mathcal{A}_{T,L}^{\gamma^* p \to Ep}(x, Q, \Delta) = \mathrm{i} \int d^2\vec{r} \int_0^1 \frac{dz}{4\pi} \int d^2\vec{b}\, (\Psi_E{}^* \Psi)_{T,L} \times \mathrm{e}^{-\mathrm{i}[\vec{b}-(1-z)\vec{r}]\cdot\vec{\Delta}} \frac{d\sigma_{q\bar{q}}}{d^2\vec{b}}$$

- ❑ Probing gluon density at small-x

$$\sigma \sim [xg(x_{IP}, Q^2)]^2$$

A. Mueller, '90
N. Nikolaev, '91
K. Golec-Biernat et al., '99

Phenomenological VM LFWFs

- Photon wavefunction

$$\Psi_{h\bar{h},\lambda=0}(r,z,Q) = e_f e\,\sqrt{N_c}\,\delta_{h,-\bar{h}}\,2Qz(1-z)\,\frac{K_0(\epsilon r)}{2\pi}$$

$$\Psi_{h\bar{h},\lambda=\pm1}(r,z,Q) = \pm e_f e\,\sqrt{2N_c}\,\{\mathrm{i}e^{\pm\mathrm{i}\theta_r}[z\delta_{h,\pm}\delta_{\bar{h},\mp} - (1-z)\delta_{h,\mp}\delta_{\bar{h},\pm}]\partial_r + m_f\delta_{h,\pm}\delta_{\bar{h},\pm}\}\,\frac{K_0(\epsilon r)}{2\pi}$$

- Popular VM LFWFs assumptions

a. Spin structure same as photon LFWF

b. Replacement: $e_f e\, z(1-z)\,\frac{K_0(\epsilon r)}{2\pi} \longrightarrow \phi_{T,L}(r,z)$

- Successful models: boosted Gaussian, holographic AdS/QCD, etc.

Boosted Gaussian

- Gaussian in VM Rest Frame, boosted to IMF

Brodsky, Huang and Lepage, 1980

$$\phi_{T,L}(r,z) = \mathcal{N}_{T,L}\, z(1-z)\exp\left(-\frac{m_f^2\mathcal{R}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}^2} + \frac{m_f^2\mathcal{R}^2}{2}\right)$$

- Constraints Nemchik, Nikolaev, Predazzi and Zakharov, 1997

1. Normalization: $1 = \sum_{h,\bar{h}} \int d^2\vec{r} \int_0^1 \frac{dz}{4\pi} \left|\Psi^V_{h\bar{h},\lambda}(\vec{r},z)\right|^2$.
2. Decay constants, related to: $\phi_{T,L}(r,z)|_{r=0}$.

- Strength: same width for L&T, boost invariant, proper short-distance limit in the massless limit, successful in explaining diffractive processes.

Holographic AdS/QCD VM LFWF

- Semi-classical QCD on the light-front

$$\psi(x,\zeta,\varphi) = e^{iL\varphi} X(x) \frac{\phi(\zeta)}{\sqrt{2\pi\zeta}} \;, \zeta = \sqrt{x(1-x)\mathbf{b}_\perp^2}$$

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right)\phi(\zeta) = M^2\phi(\zeta)$$

Brodsky, Teramond, Dosch and Erlich, 2015

- $\phi(\zeta)$: probability amplitude, determines the hadronic mass spectrum.
- $U(\zeta)$: encodes all QCD interactions beyond valence Fock sector.
- AdS/QCD: quadratic dilaton $U(\zeta) = \kappa^4 \zeta^2$.

Holographic AdS/QCD VM LFWF

- Strength: contains no free parameters, predicts spectrum on Reggie trajectory, explains light meson diffractive production. Forshaw and R. Sandapen, 2012
  Ahmady, R. Sandapen and Sharma, 2016
- Limitations:

a. Works in massless (small mass) limit,

b. Difficult to describe higher excited states,

c. Spin-structure relies on photon LFWF.

Longitudinal Confinement $\Longrightarrow$ Heavy

- Generalizing the holographic AdS/QCD to 3D

$$U(\zeta) = \kappa^4\zeta^2 + \frac{\kappa^4}{4m_q^2}\partial_z\big(z(1-z)\partial_z\big)$$

- Strength:

Li, Maris, Zhao and Vary, PLB 758, 118, 2016

a. Works for both heavy and light system,

b. Consistent with pQCD asymptotic $\phi^{\mathrm{DA}}(z) \sim z^{\alpha}(1-z)^{\beta}$,

c. Analytically solvable,

d. Proper massless and NR limits.

- Weakness: higher excited states not well-determined.

One-gluon exchange $\Longrightarrow$ excited

- Finding spectrum using light-front Hamiltonian

$$H_{LF}|\psi_h\rangle = M_h^2|\psi_h\rangle, \quad (H_{LF} \equiv P^+\hat{P}^-_{LF} - \vec{P}_\perp^2)$$

- Effective Light-front Hamiltonian

$$H_{\text{eff}} = \underbrace{\frac{\vec{k}_\perp^2 + m_q^2}{z(1-z)}}_{\text{LF kinetic energy}} + \underbrace{\kappa^4\zeta_\perp^2 - \frac{\kappa^4}{4m_q^2}\partial_z\left[z(1-z)\partial_z\right]}_{\text{confinement}} - \underbrace{\frac{C_F 4\pi\alpha_s}{Q^2}\bar{u}_{s'}(k')\gamma_\mu u_s(k)\bar{v}_{\bar{s}}(\bar{k})\gamma^\mu v_{\bar{s}'}(\bar{k}')}_{\text{one-gluon exchange}}$$

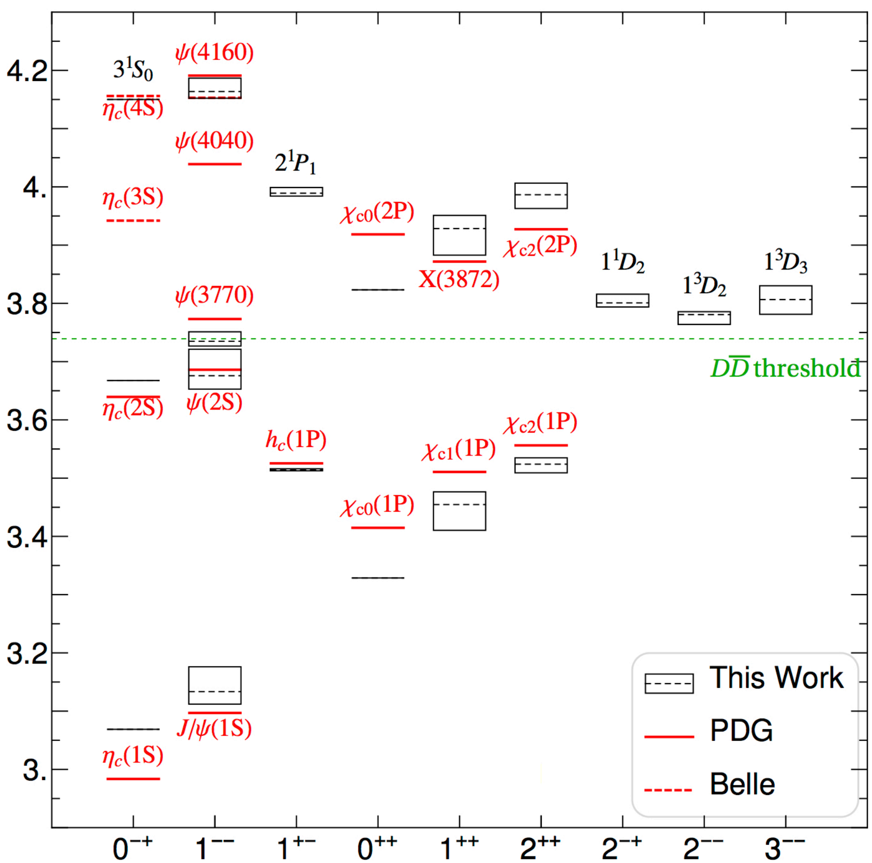
Li, Maris, Zhao and Vary, PLB 758, 118, 2016

- Parameter m_q and κ fixed by quarkonia spectra in the BLFQ framework.

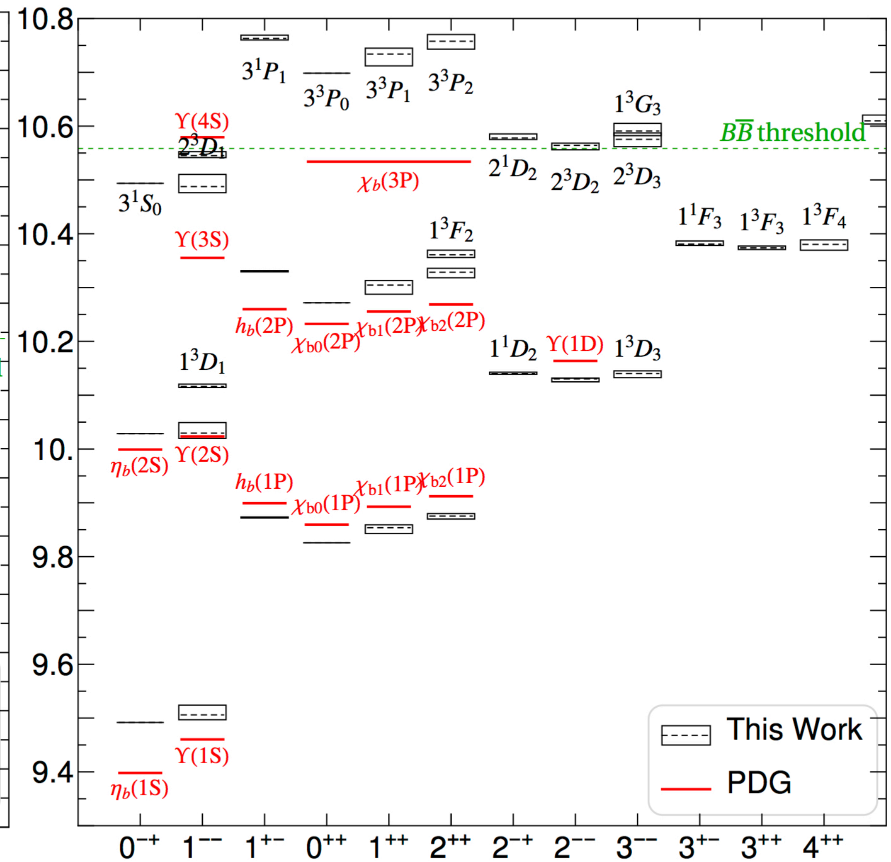
Vary et al ‘10, Honkanen et al ‘11
X. Zhao et al. , ‘14
P. Wiecki et al., ‘15

Heavy Quarkonium Spectroscopy

Li, Maris, Zhao and Vary, PLB 758, 118, 2016



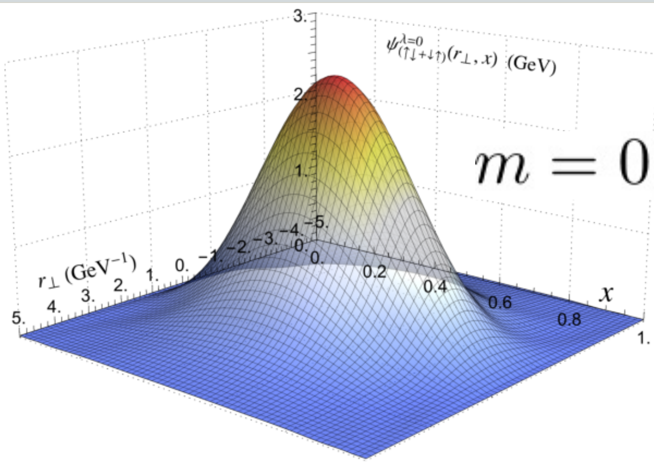
$$\delta\overline{M} = 52 \text{ MeV}$$



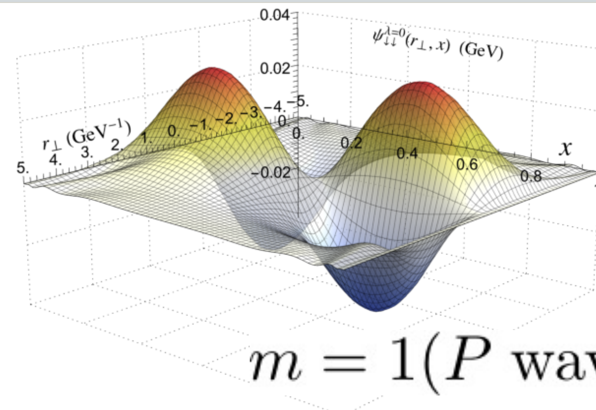
$$\delta\overline{M} = 50 \text{ MeV}$$

Visualizing LFWF: J/Ψ

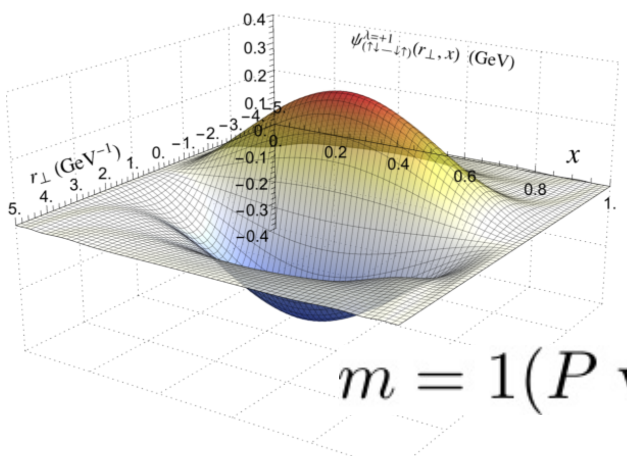
Y. Li, arXiv:1612.01295



$m = 0(S \text{ wave})$

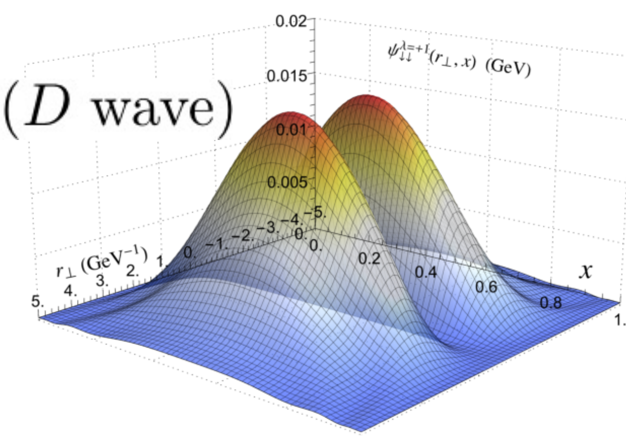


$m = 1(P \text{ wave})$



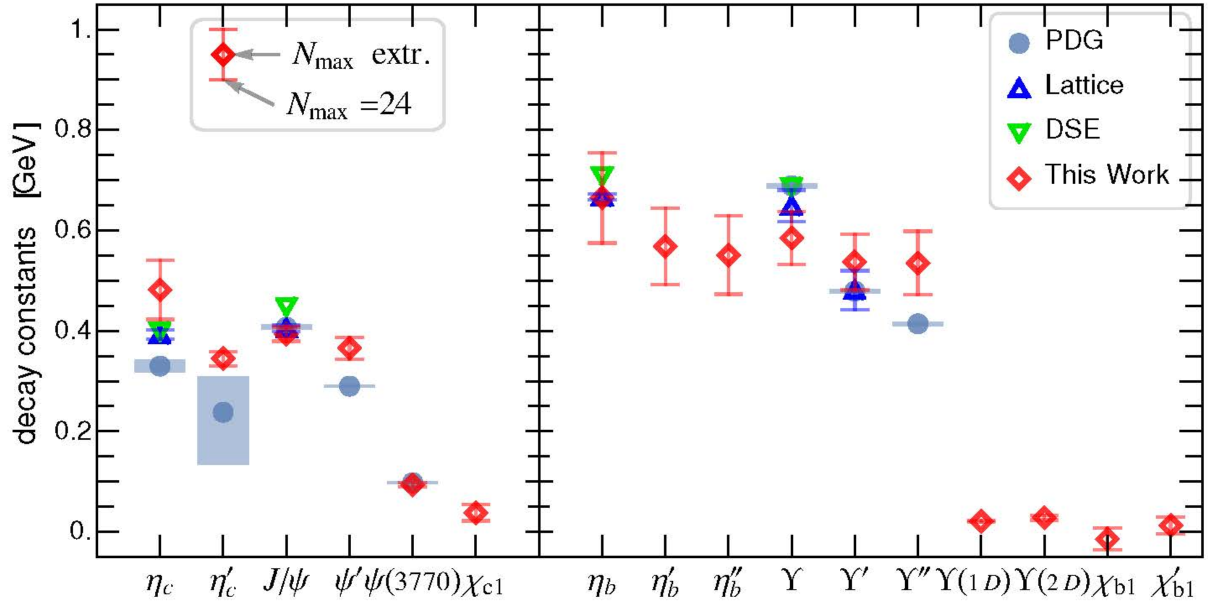
$m = 1(P \text{ wave})$

$m = 2(D \text{ wave})$



BLFQ LFWF predictions

- Decay constants Li, Maris, Zhao and Vary, PLB 758, 118, 2016



- Also predict radii and charge form factor!

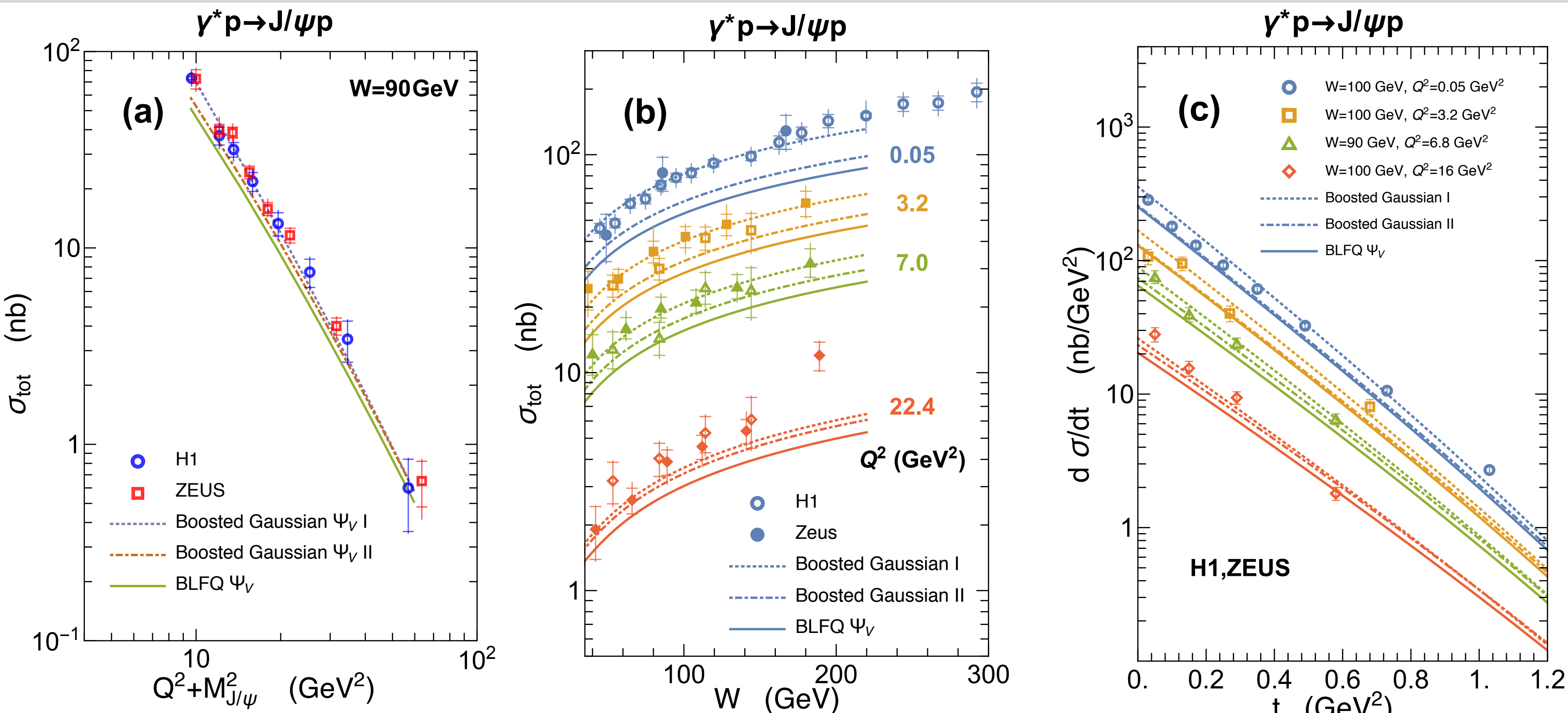
Mini sum: BLFQ LFWF

- Effective Hamiltonian: confinement + one-gluon exchange,
- Parameters fitted by spectrum, r.m.s. deviation ~ 50 MeV,
- Could describe both heavy and light system,
- Generate spin-structure through one-gluon exchange, including S, P, D waves,
- Excited states without any additional assumptions,
- Predict various physics observables.
- Q: compatible with diffractive VM production? Yes!

HERA: cross section

ZEUS, 2004.
H1, 2006.

GC, Li, Maris, Tuchin and Vary, arXiv:1610.04945

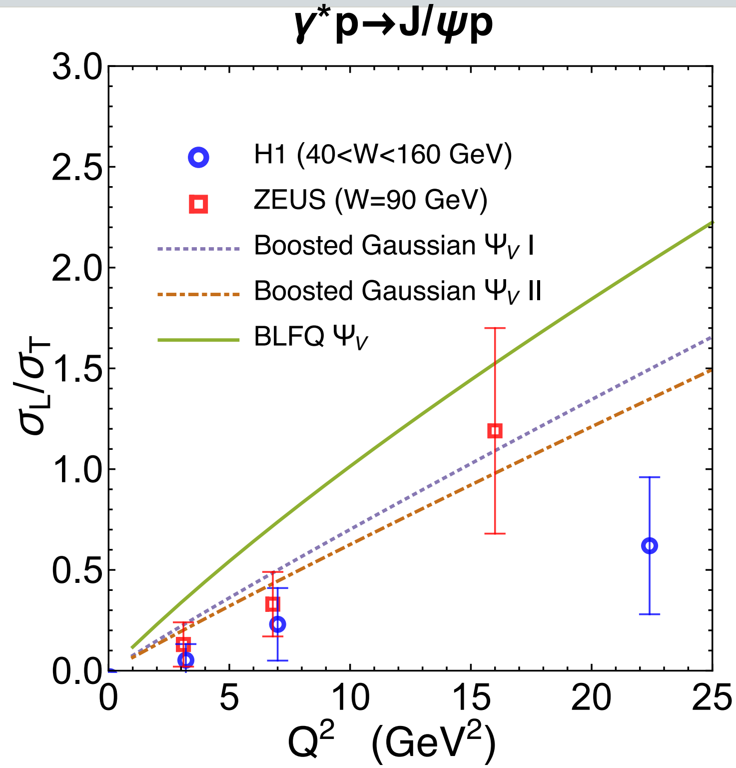


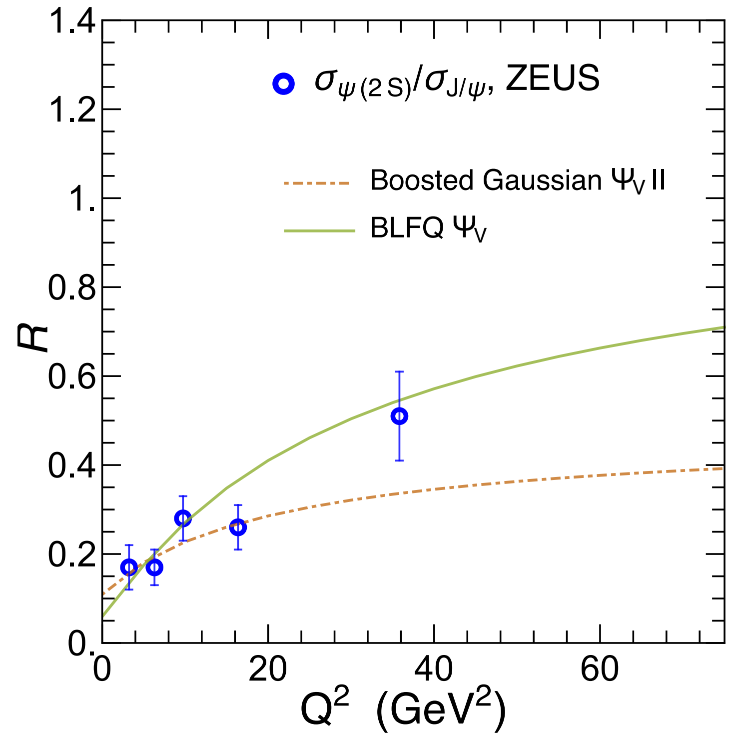
bCGC, Rezaeian and Schmidt, PRD88, 074016 (2013).
Boosted Gaussian I, Armesto and Rezaeian, PRD90, 054003 (2014).
Boosted Gaussian II, Kowalski et al., PRD74, 074016 (2006).

HERA: cross-section ratio

ZEUS, 2016.
H1, 2006.

GC, Li, Maris, Tuchin and Vary, arXiv:1610.04945





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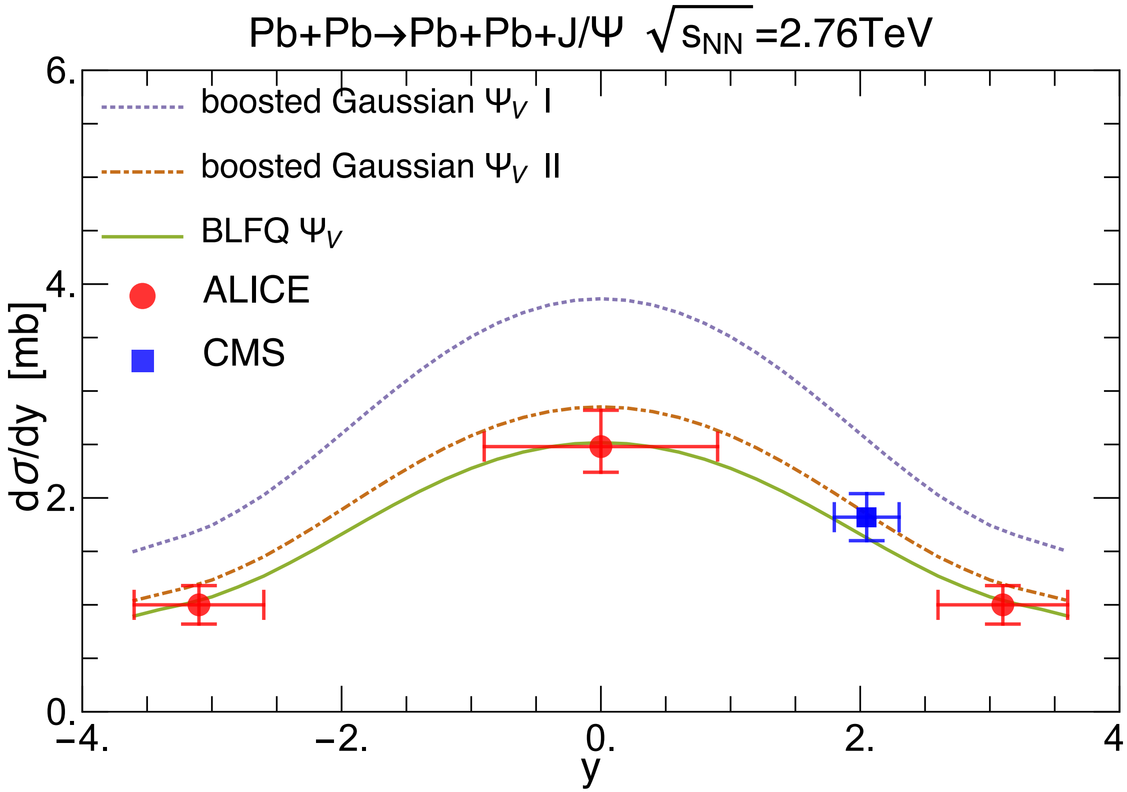
Boosted Gaussian II, Kowalski et al., PRD74, 074016 (2006).

Pb-Pb UPC at LHC

GC, Li, Maris, Tuchin and Vary, arXiv:1610.04945

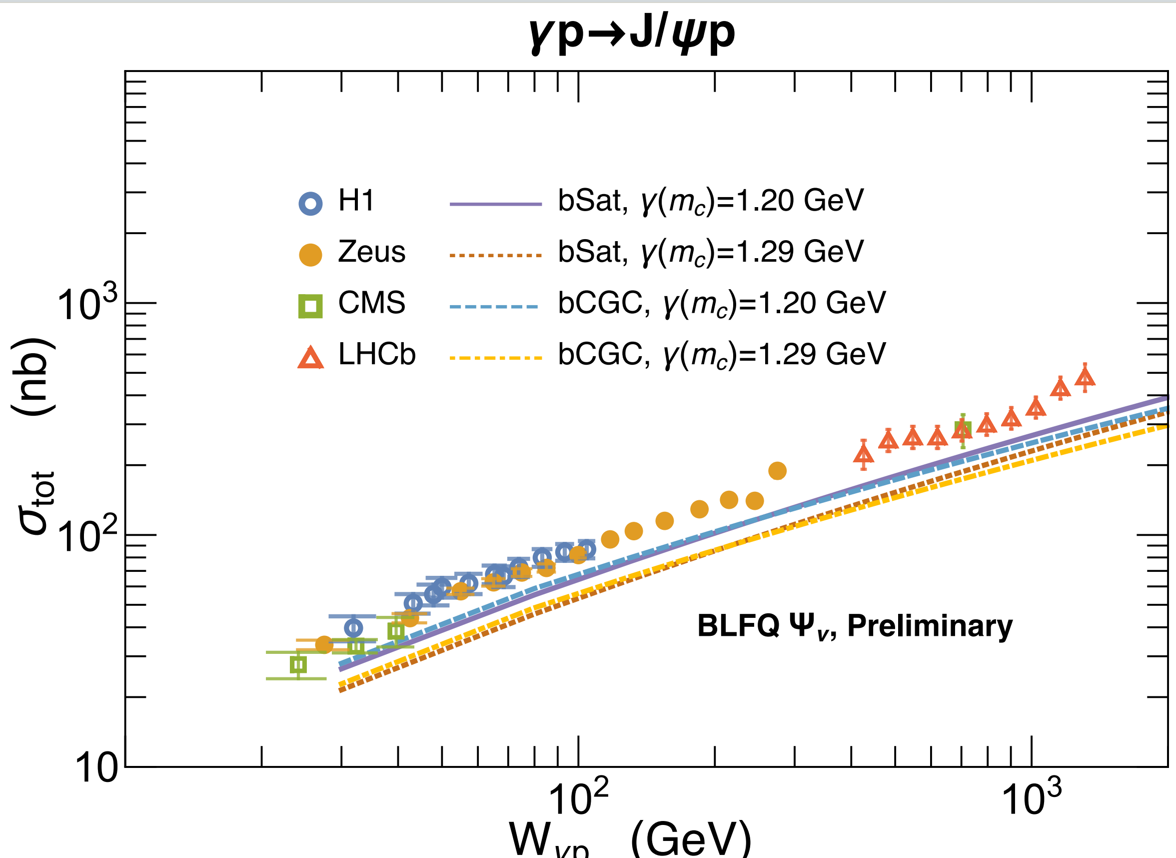
ALICE, 2013.
CMS, 2016.



bCGC, Rezaeian and Schmidt, PRD88, 074016 (2013).
Boosted Gaussian I, Armesto and Rezaeian, PRD90, 054003 (2014).
Boosted Gaussian II, Kowalski et al., PRD74, 074016 (2006).

J/Ψ in γp at LHC

GC, Li, Maris, Tuchin and Vary, in preparation

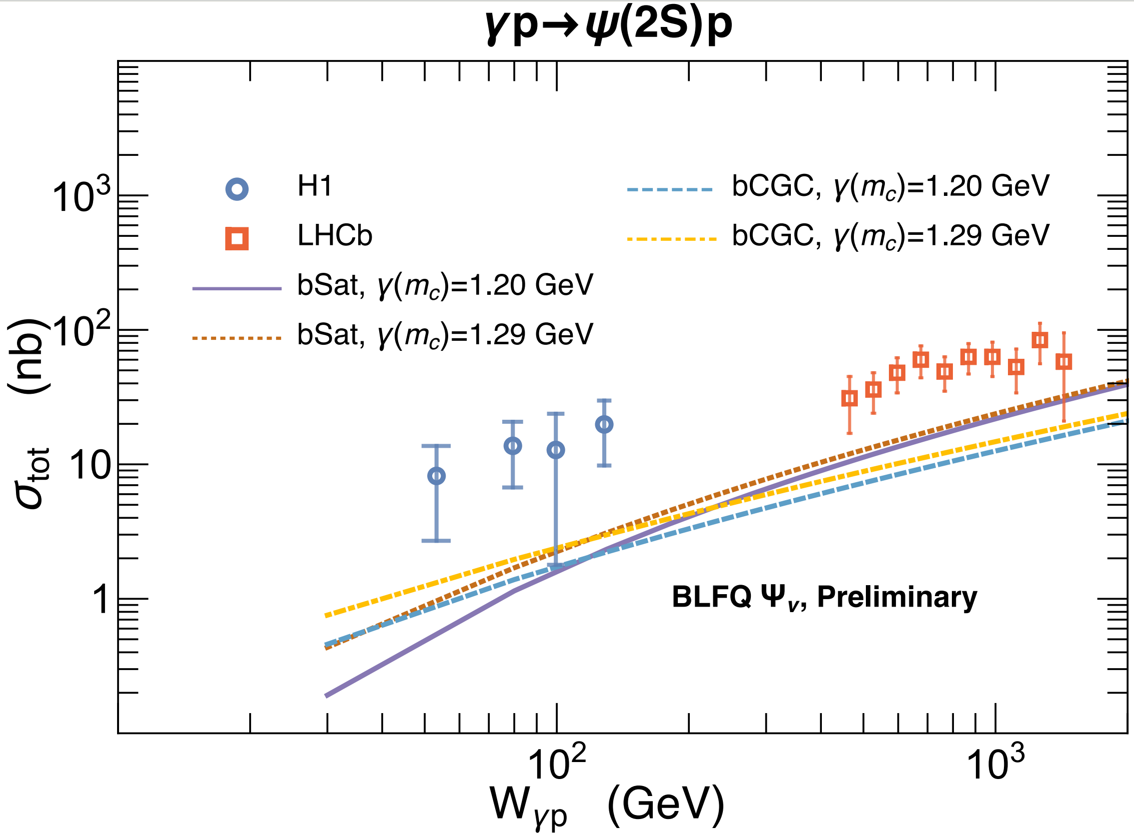


ZEUS, 2004.
H1, 2006.
CMS, 2015.
LHCb, 2016.

bSat, Rezaeian et al., Phys. Rev. D 87, 034002 (2013).
bCGC, Rezaeian and Schmidt, PRD88, 074016 (2013).

$\Psi(2s)$ in γp at LHC

GC, Li, Maris, Tuchin and Vary, in preparation

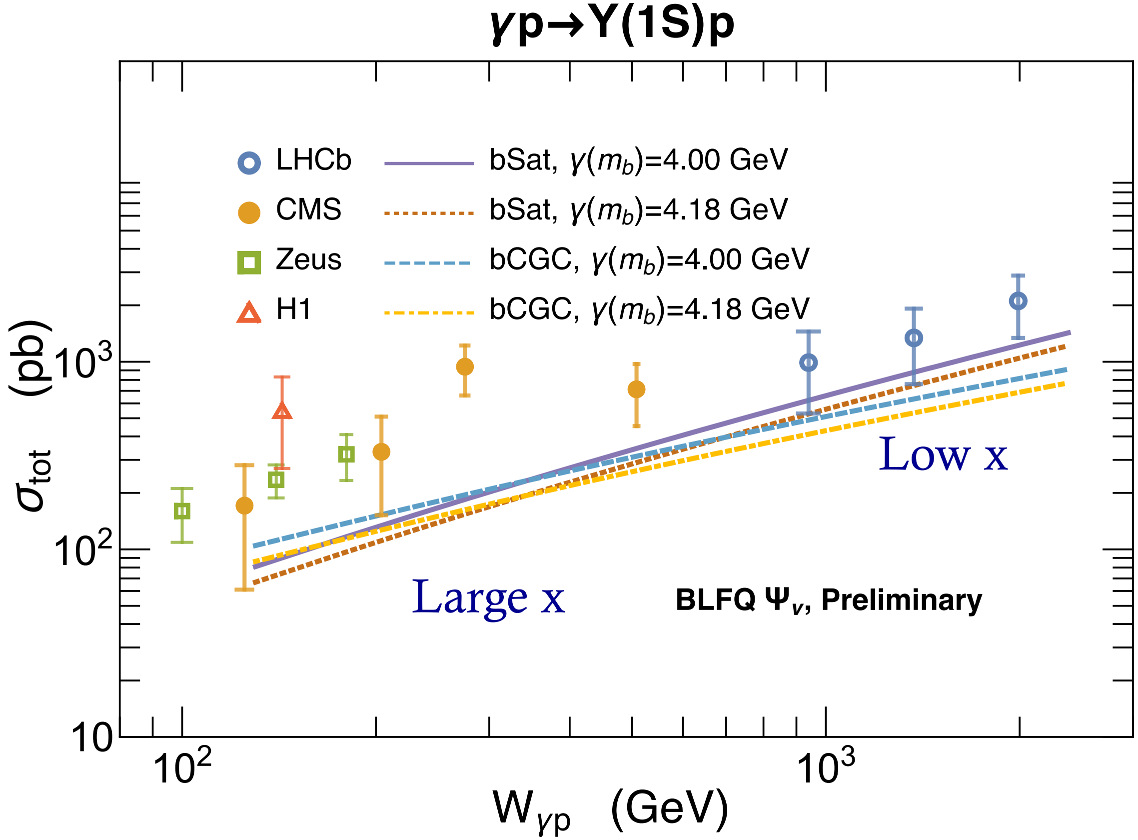


H1, 2002.
LHCb, 2016.

bSat, Rezaeian et al., Phys. Rev. D 87, 034002 (2013).
bCGC, Rezaeian and Schmidt, PRD88, 074016 (2013).

$\Upsilon(1s)$ in γp at LHC

GC, Li, Maris, Tuchin and Vary, in preparation



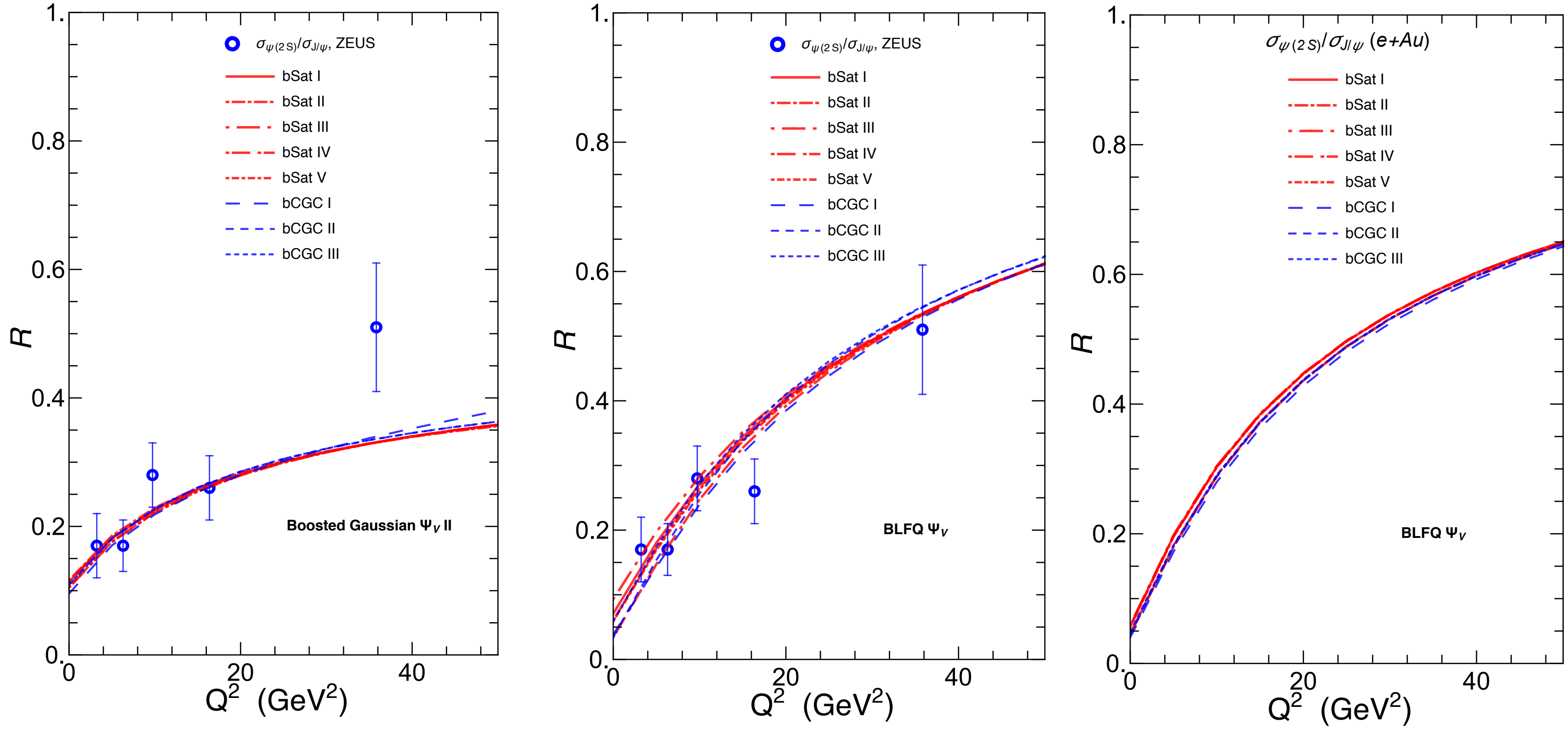
ZEUS, 2009.
H1, 2012.
CMS, 2016.
LHCb, 2016.

$$x \sim \frac{M_V^2}{W_{\gamma p}^2}$$

bSat, Rezaeian et al., Phys. Rev. D 87, 034002 (2013).
bCGC, Rezaeian and Schmidt, PRD88, 074016 (2013).

Cross section ratio, revisit ZEUS, 2016.

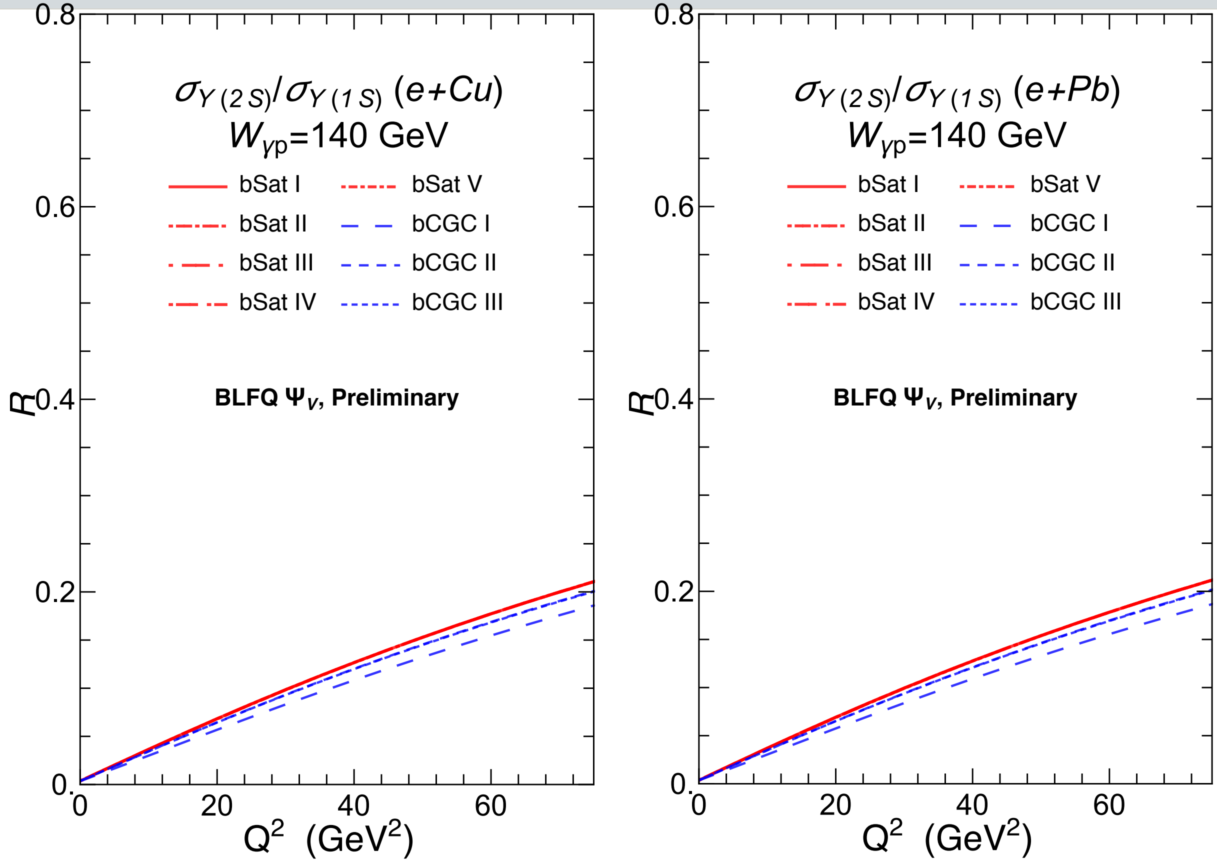
GC, Li, Maris, Tuchin and Vary, arXiv:1610.04945



bCGC, Rezaeian and Schmidt (2013), Soyez (2006).
bSat, Rezaeian et al. (2013), Kowalski et al. (2006).
Boosted Gaussian II, Kowalski et al., PRD74, 074016 (2006).

Cross section ratio, Upsilons

GC, Li, Maris, Tuchin and Vary, in preparation



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Cross section ratio, Upsilons

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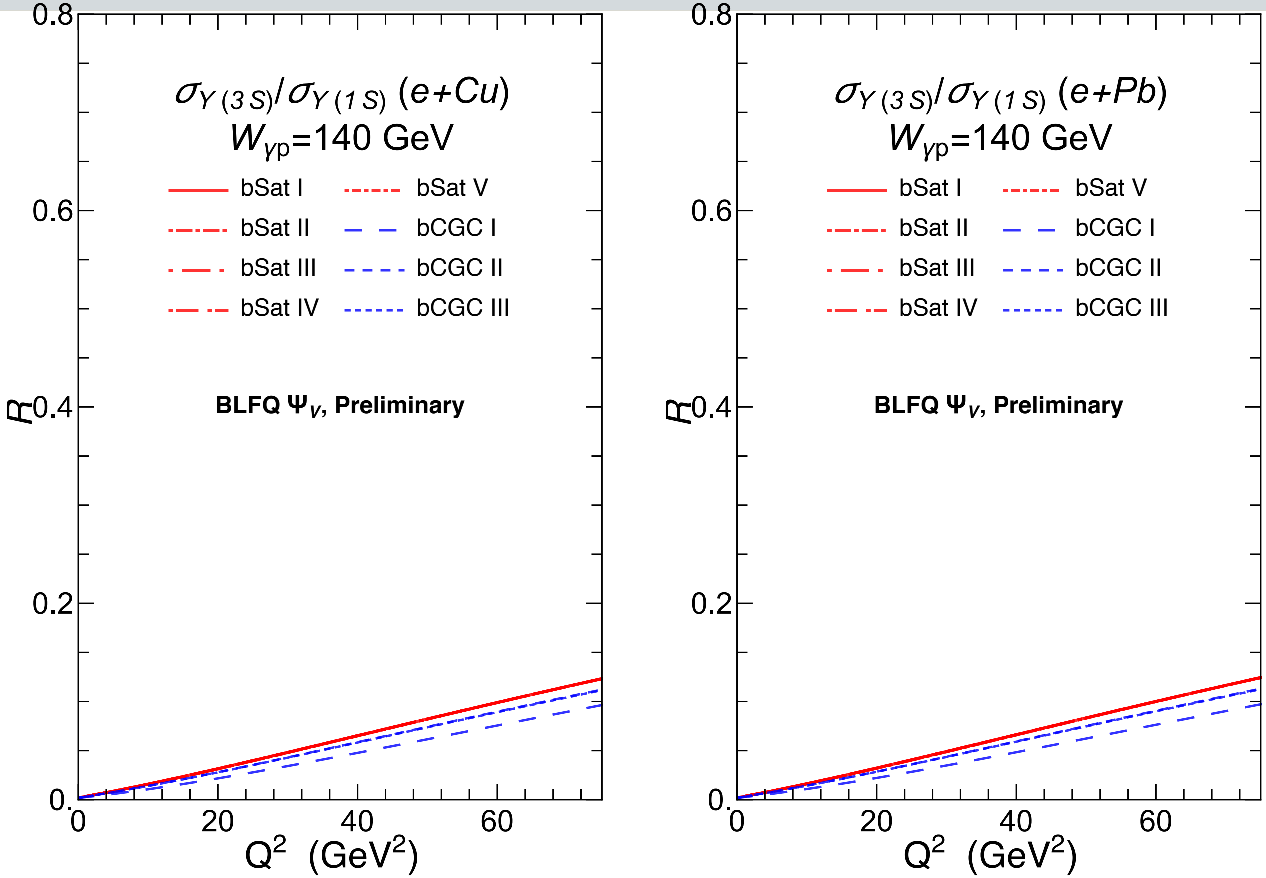

bCGC, Rezaeian and Schmidt (2013), Soyez (2006).
bSat, Rezaeian et al. (2013), Kowalski et al. (2006).

Summary

- ❑ The BLFQ LFWFs give reasonable fit to the diffractive heavy quarkonium production data at HERA, RHIC and LHC, including higher excited states!

- ❑ The cross-section ratios of higher excited states over ground states reveal significant independence of model parameters $\Longrightarrow$ useful for understanding heavy quarkonium LFWFs,

- ❑ Future work: charmonium and bottomonium production at EIC, both coherently and incoherently.

Thank you!

- Acknowledgement: Xingbo Zhao, Nataliia Kovalchuk, Amir Rezaeian, Ronan Mcnulty, Daniel Johnson

- Support by Department of Energy, USA

Dipole Models

- The GBW model — Golec-Biernat and Wusthoff , 1999

$$\sigma_{q\bar{q}}^{\mathrm{GBW}}(x,r) = \sigma_0 \left(1 - \mathrm{e}^{-r^2 Q_s^2(x)/4}\right)$$

- The b-Sat Model — Kowalski and Teaney , 2001
- The b-CGC Model — Iancu, Itakura and Munier, 2003

  An approximate solution of Balitsky-Kovchegov equation

- The rcBK Model — Albacete, Armesto, Milhano, Salgado , 2009

  A numerical solution of BK equation with running coupling

Photon-nucleus Dipole Model

- For coherent production, Kowalski and Teaney , 2001

$$\left\langle \frac{d\sigma_{q\bar{q}}}{d^2b} \right\rangle_\Omega = 2\left[1 - \left(1 - \frac{T_A(b)}{2}\sigma^p_{q\bar{q}}\right)^A\right]$$

- Profile needed, e.g., Woods-Saxon.
- No nuclear shadowing, anti-shadowing was considered. See talk by V. Guzey.

General Procedures of BLFQ

- Derive LF-Hamiltonian from Lagrangian
- Construct basis states $|\alpha\rangle$, and truncation scheme
- Evaluate Hamiltonian in the basis
- Diagonalize Hamiltonian and obtain its eigen states and their LF-amplitudes
- Evaluate observables using LF-amplitudes
- Extrapolate to continuum limit

Vary et al ‘10, Honkanen et al ‘11
X. Zhao et al. , ‘14
P. Wiecki et al., ‘15
Y. Li et al., ‘15

J/ψ production at RHIC

- $x_{IP} \approx 0.015$, dipole model barely works at midrapidity
- PHENIX measurement PHENIX, 2009, Takahara, thesis 2013

2010: $$\frac{d\sigma}{dy}|_{y=0} = 45.6 \pm 13.2(stat) \pm 6.0(sys)\mu b$$

2004+2007: $$\frac{d\sigma}{dy}|_{y=0} = 55.9 \pm 13.2(stat) \pm 7.6(sys)\mu b$$

- BLFQ calculation: $60.4\ \mu b$
- Boosted Gaussian prediction: $109\mu b$ Lappi et. al, 2013

Equivalent Photon Approximation

- Proton M. Drees and Zeppenfeld, '89

$$\frac{dN_\gamma^p}{d\omega} = \frac{\alpha_{\rm em}}{2\pi}\left[1+(1-\frac{2\omega}{\sqrt{s}})^2\right] \times \left[\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}\right] \qquad \Omega = 1 + \frac{0.71\mathrm{GeV}^2}{Q^2_{min}}$$

- Nuclei

$$\frac{dN_\gamma^A}{d\omega} = \frac{2Z^2\alpha_{em}}{\pi\beta}\left[\xi K_0(\xi)K_1(\xi) - \frac{\xi^2}{2}(K_1^2(\xi) - K_0^2(\xi))\right]$$

$$\xi = \omega(R_{A1} + R_{A2})/(\gamma_L\beta)$$

Klein and Nystrand, '99

Excited States in boosted Gaussian

- Introduce an additional term

Cox, Forshaw and R. Sandapen, 2009

$$\phi^{2s}_{T,L}(r,z) = \mathcal{N}^{2s}_{T,L} z(1-z) \exp\left(-\frac{m_q^2 \mathcal{R}_{2s}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}_{2s}^2} + \frac{m_q^2 \mathcal{R}_{2s}^2}{2}\right) \times \left[1 + \alpha_{2s}\left(2 + \frac{m_q^2 \mathcal{R}_{2s}^2}{4z(1-z)} - \frac{4z(1-z)r^2}{\mathcal{R}_{2s}^2} - m_q^2 \mathcal{R}_{2s}^2\right)\right]$$

- One more parameter, one more constraint—orthogonality.