Probing small-x gluons in high energy nucleus collisions

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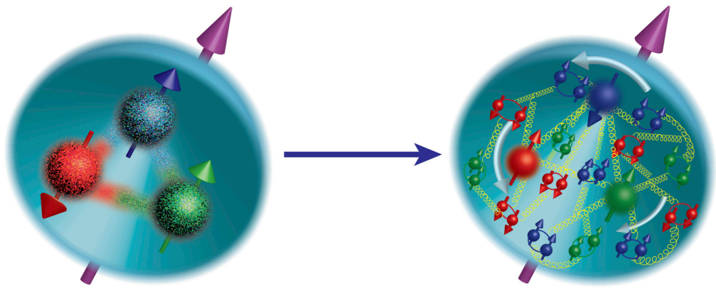
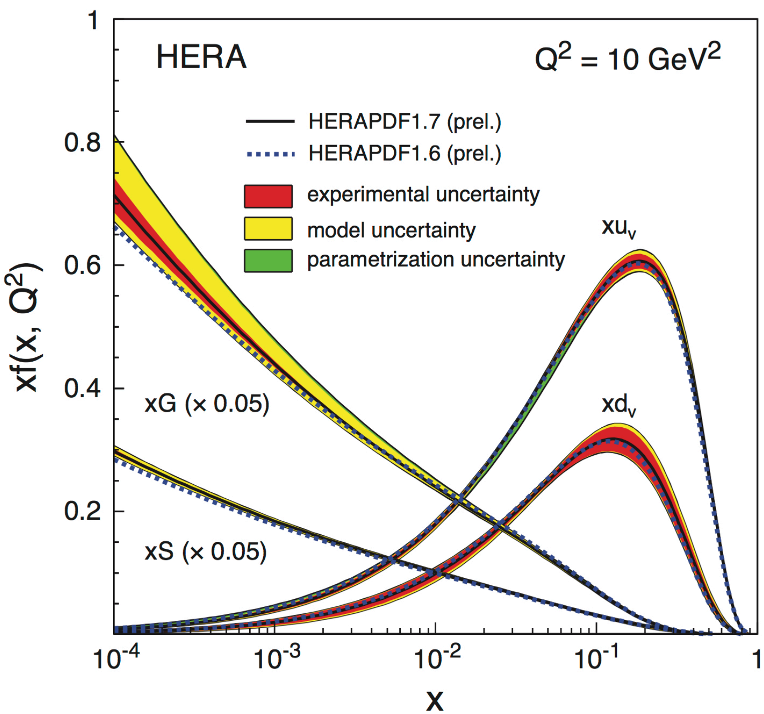
Proton at High Energy

- ❑Our knowledge of proton is rapidly evolving

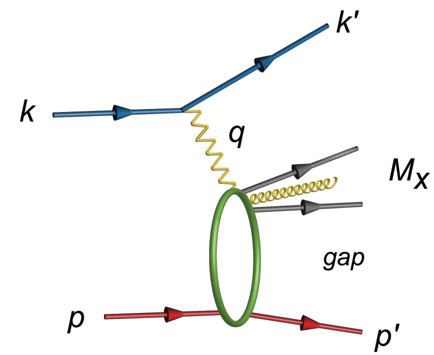


- ❑Proton at high energy?
  - 3D tomography
  - Saturation
  - Spin

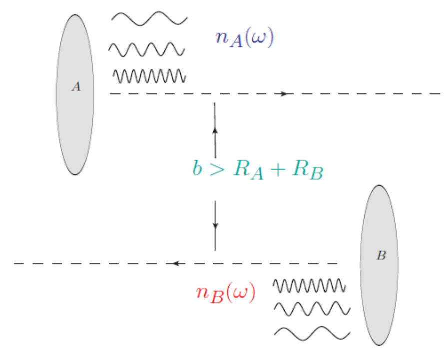


Exclusive Diffractive Processes

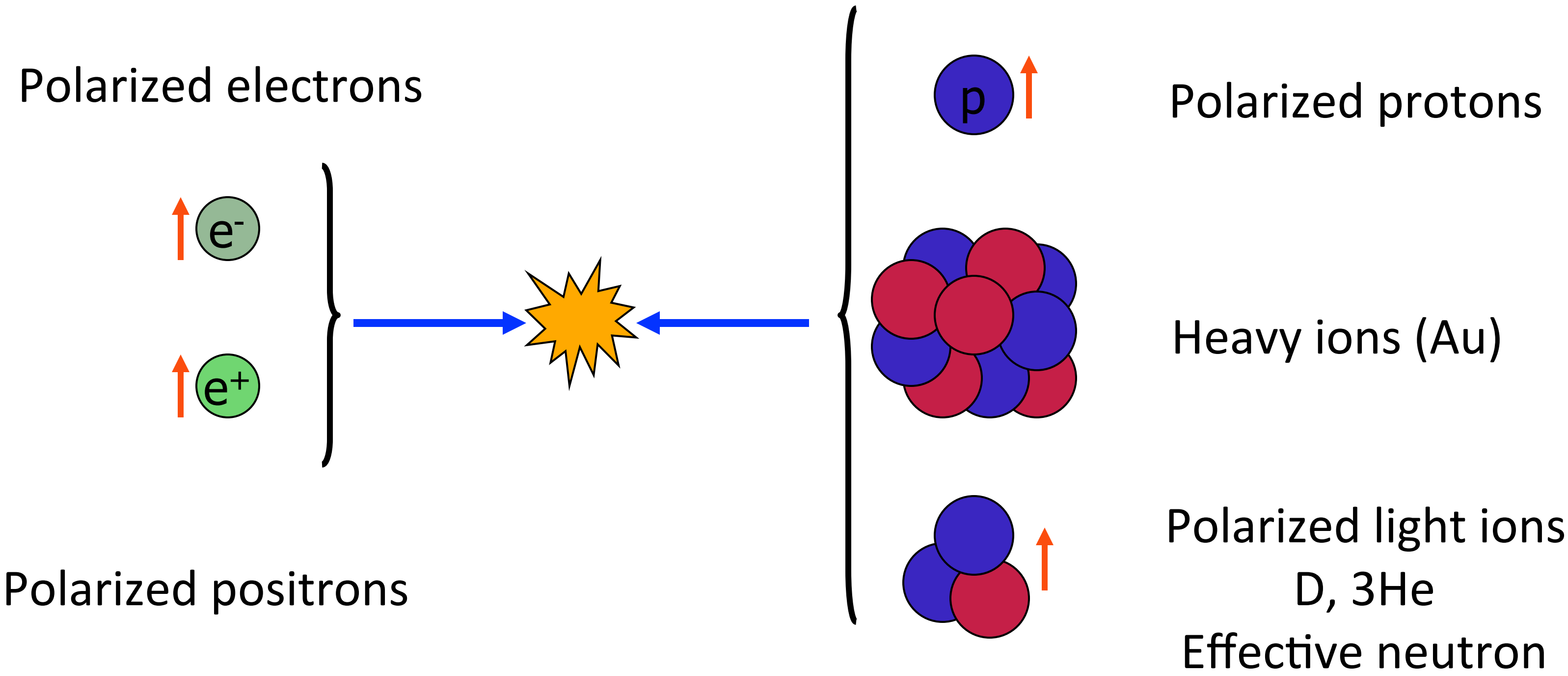
- **First observed at HERA**
  - 15% events are diffractive
  - Characterized by rapidity gap
  - $x_{\text{probed}} \sim (Q^2 + M_X^2)/W^2$



- **Ultra-Peripheral Collisions**
  - Photon-nuclear interaction
  - WW formalism for
    Photon flux ~ Z^2
  - x_{probed} up to 10^{-5} at LHC



Electron-Ion Collider



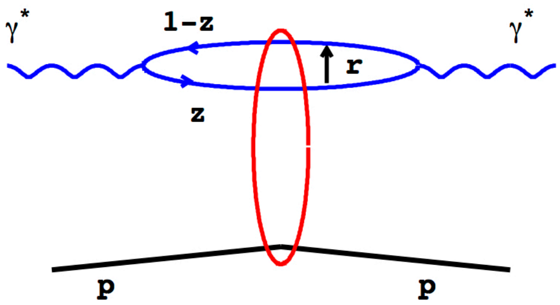
A collider with versatile range of kinematics and beam polarizations, as well as beam species, wide energy variability and high luminosity, the next QCD frontier:
3D tomography of proton, spin, saturation, etc.

EIC White Paper

Dipole picture of DIS

- ❑In the LRF of proton, photon is on LC.
- ❑The photon fluctuates.
  - Fock sector expansion:

$$\left|\gamma^*\right\rangle = \left|q\bar{q}\right\rangle + \left|q\bar{q}g\right\rangle + \cdots$$



- ❑The dipole interacts with the proton.
- ❑The dipole recombines.

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

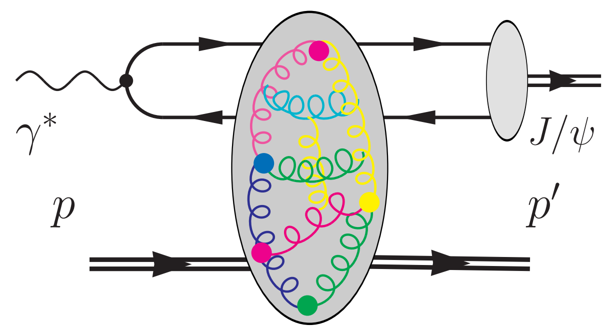
- ❑Dipole model: fitted to proton F_2.
  - bCGC (Color Glass Condensate). Iancu, Itakura and Munier, 2003
  - bSat (Glauber–Mueller). Kowalski and Teaney , 2001

Dipole picture of diffractive processes

- The exclusive VM production amplitude:

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

- Ψ_E : LFWF of vector meson
- Ψ : Photon LFWF
- $\frac{d\sigma_{q\bar{q}}}{d^2\vec{b}}$: dipole cross section



- Description of vector meson on the Light-front is the KEY!

Golec-Biernat and Wusthoff , 1999
Kowalski and Teaney , 2001

Heavy Quarkonium in BLFQ

- Talks on BLFQ: J. Vary (Mon), X. Zhao, C. Mondal, M. Li and S. Jia (Later today).
- Spectrum from light-front Hamiltonian

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

- Effective Hamiltonian Li et al., PLB 758, 118 (2016)

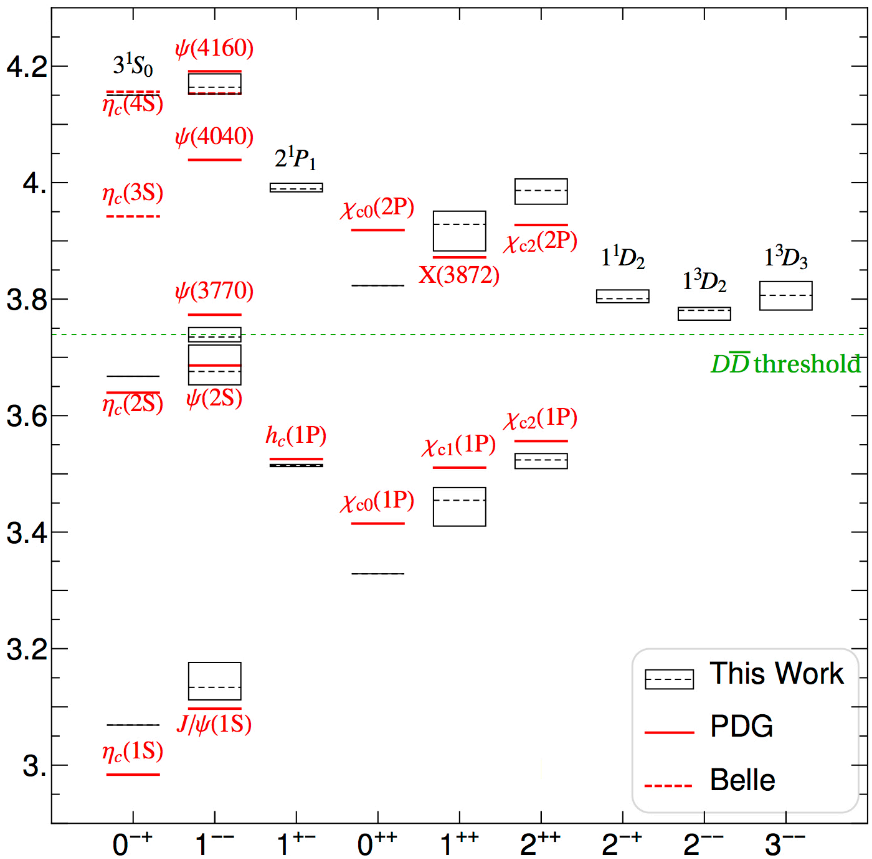
$$H_{\rm eff} = \underbrace{\frac{\vec{k}_\perp^2 + m_q^2}{z(1-z)}}_{\rm LF\ kinetic\ energy} + \underbrace{\kappa^4\zeta_\perp^2 - \frac{\kappa^4}{4m_q^2}\partial_z\left[z(1-z)\partial_z\right]}_{\rm confinement} - \underbrace{\frac{C_F 4\pi\alpha_s}{Q^2}\bar{u}_{s'}(k')\gamma_\mu u_s(k)\bar{v}_{\bar{s}}(\bar{k})\gamma^\mu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

- Based on holographic AdS/QCD. Teramond and Brodsky, '09
- Two parameters fitted to spectra.
- Recent improvement: running coupling.

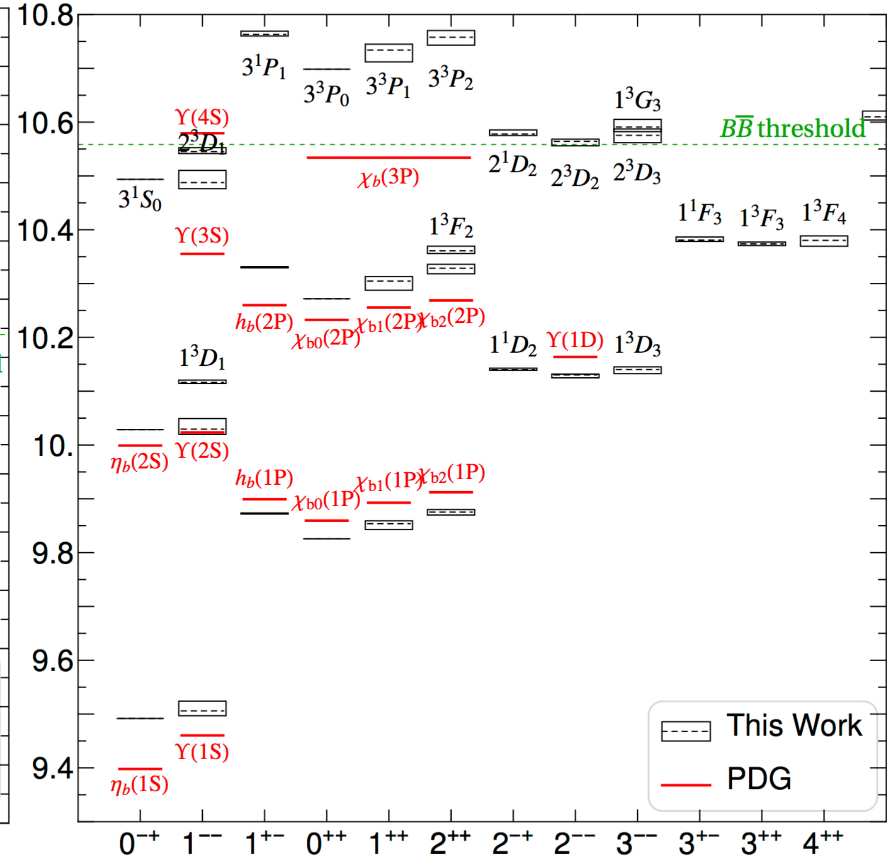
Li et al., PRD96, 016022, (2017)

Heavy Quarkonia Spectra

Li et al., PLB 758, 118 (2016)



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



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

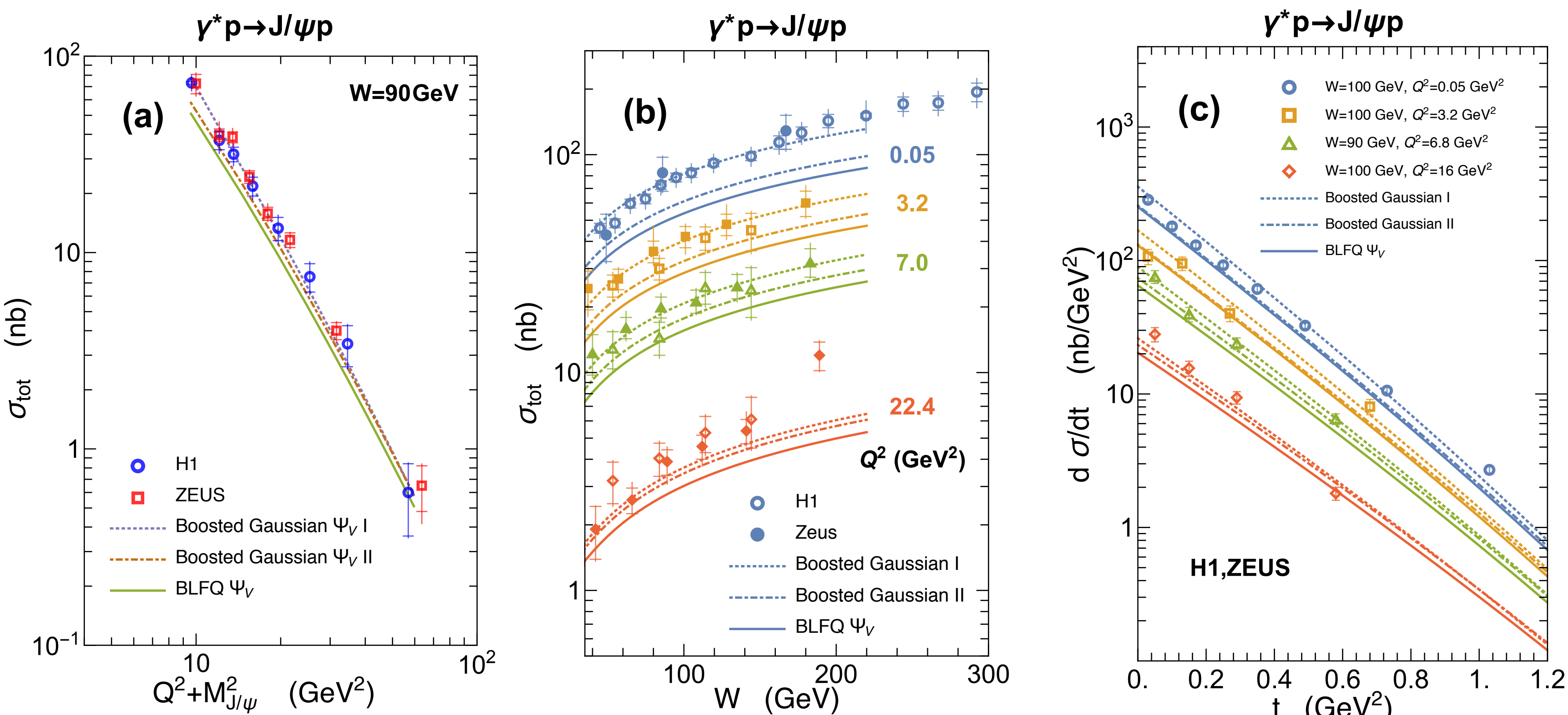
Heavy Quarkonia LFWF

- Theoretical foundation: QCD one-gluon exchange + holographic AdS/QCD.
- Heavy quarkonia LFWF on the light-front, including excited states without any additional assumptions.
- Two parameters fitted by spectrum, posterior r.m.s. deviation ~ 50 MeV (most up to date, ~30 MeV).
- Meson spin-structure emerge automatically!
- Predictive: decay constant, charge radii (J. Vary), radioactive decay (M. Li).
- Unified description of heavy and light system (S. Jia), and baryon (C. Mondal).
- Focus of this talk: diffractive VM production at various nuclear collision with the obtained LFWF.

HERA: cross section

GC et al., PLB 769, 477, 2017

ZEUS, 2004.
H1, 2006.



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

GC et al., PLB 769, 477, 2017

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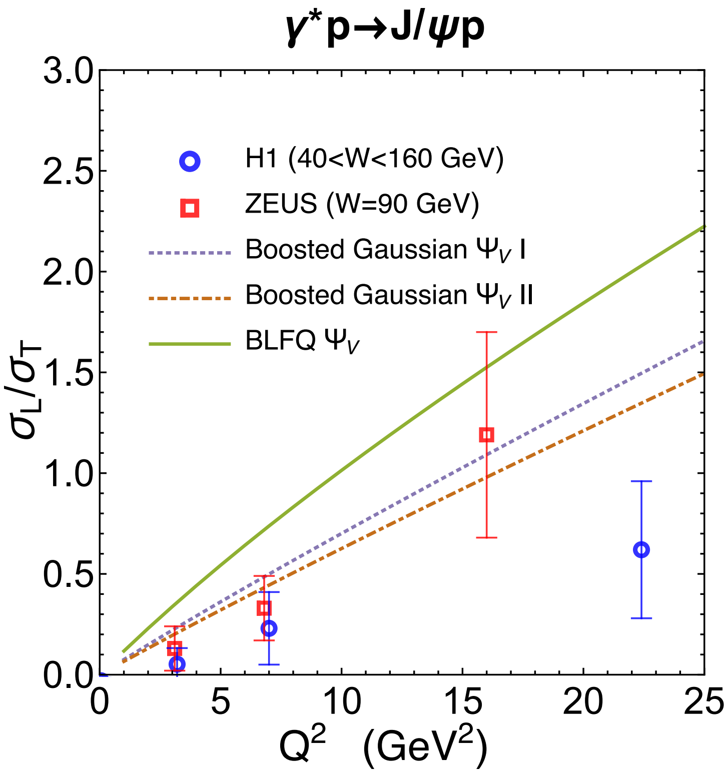
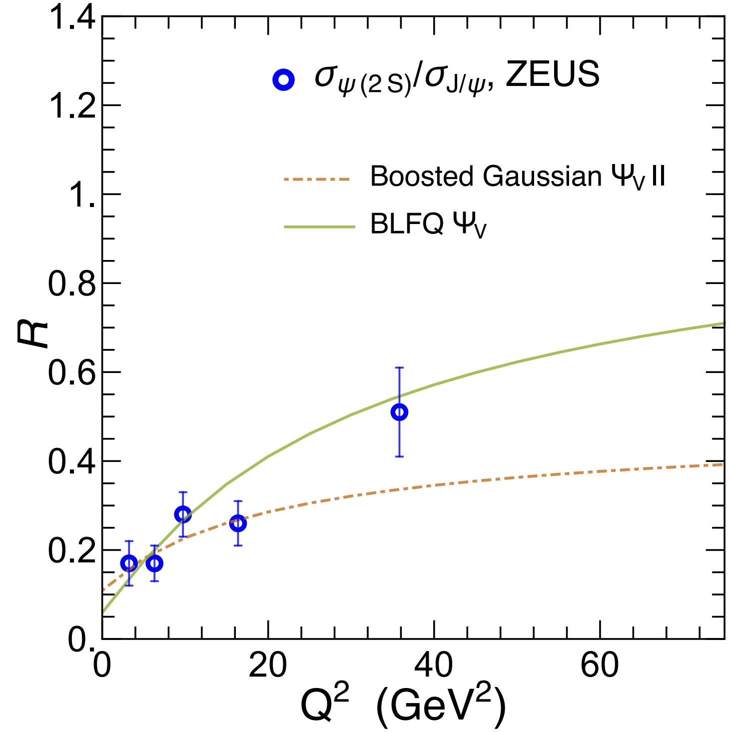
H1, 2006.





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J/Ψ production at RHIC

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

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

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

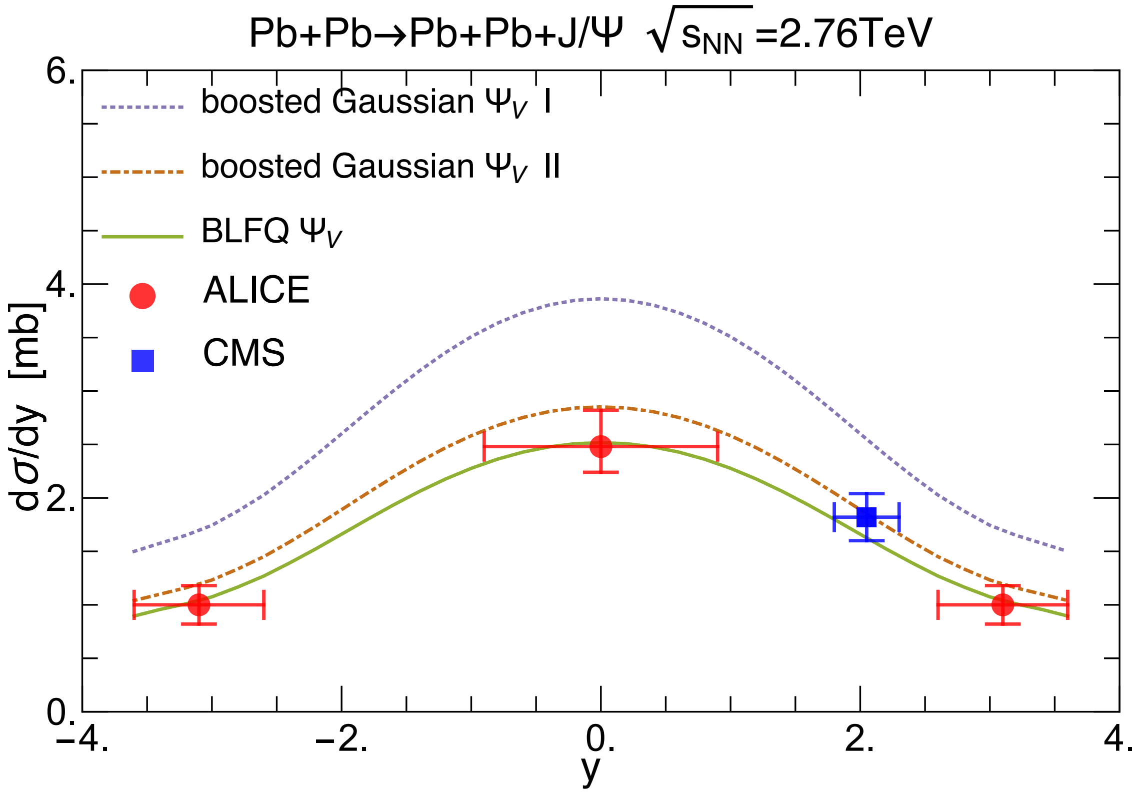
- BLFQ calculation: $60.4\ \mu b$
- Boosted Gaussian prediction: $109 \mu b$

Lappi et. al, 2013

J/Ψ from Pb-Pb UPC at LHC

GC et al., PLB 769, 477, 2017

ALICE, 2013.
CMS, 2016.



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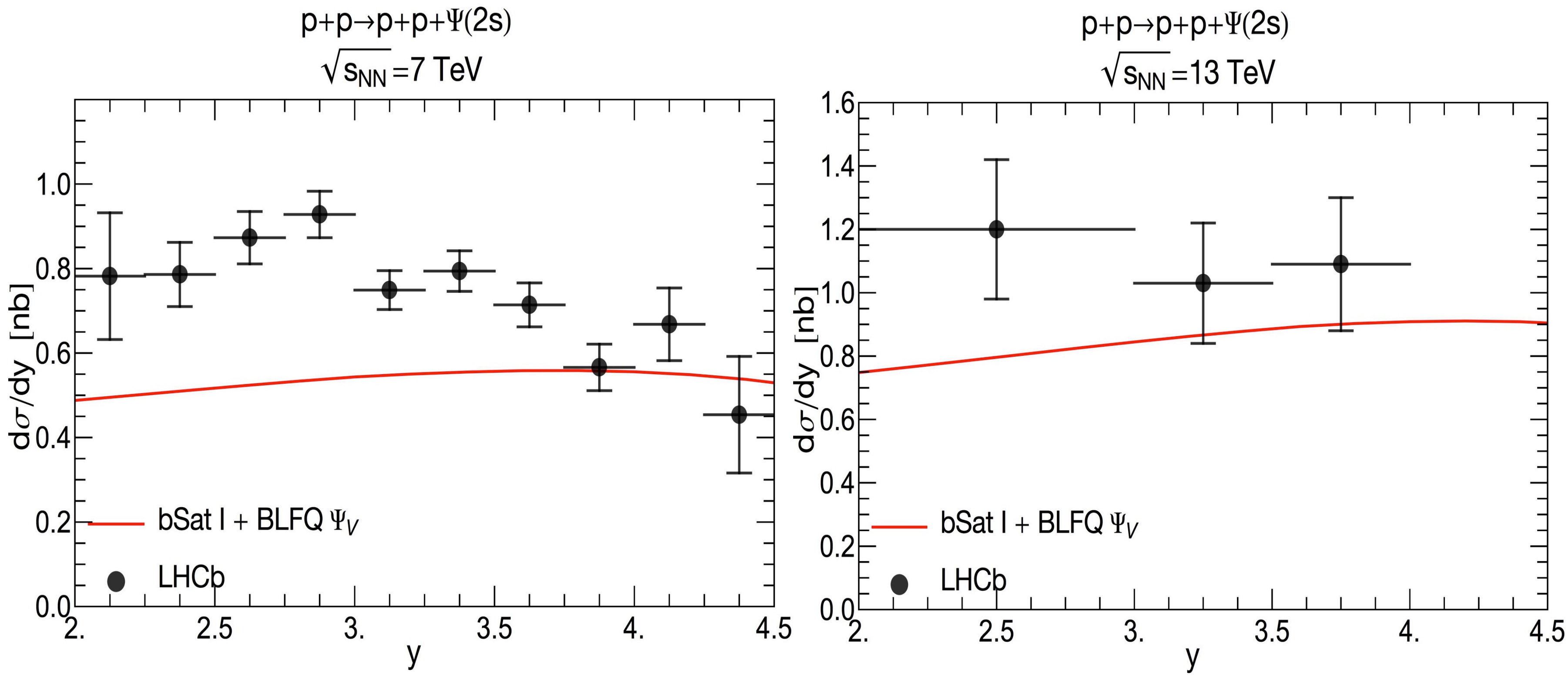
Boosted Gaussian I, Armesto and Rezaeian, PRD90, 054003 (2014).

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

$\Psi(2s)$ from pp UPC at LHC

GC et al., in preparation

LHCb, 2014, 2016

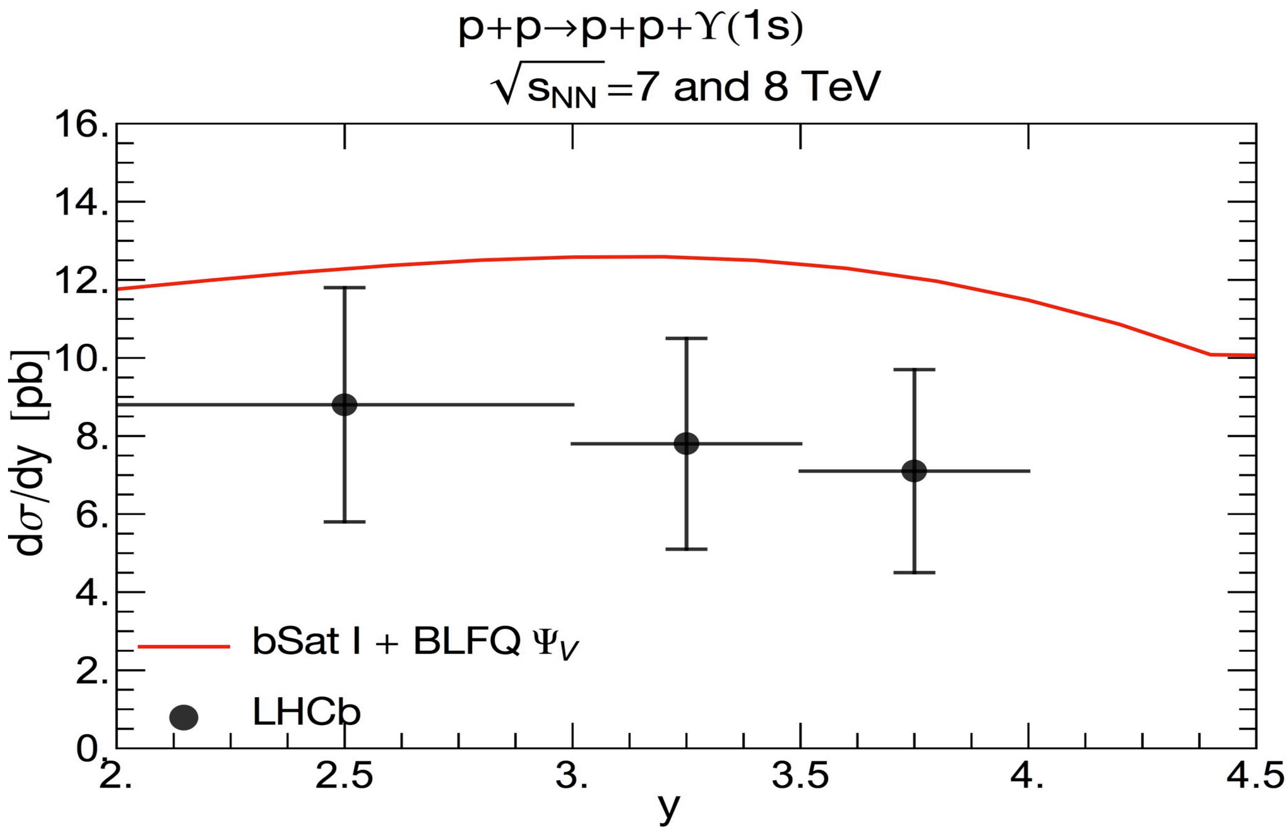


bCGC, Rezaeian and Schmidt, PRD88, 074016 (2013).

$\Upsilon(1s)$ from pp UPC at LHC

GC et al., in preparation

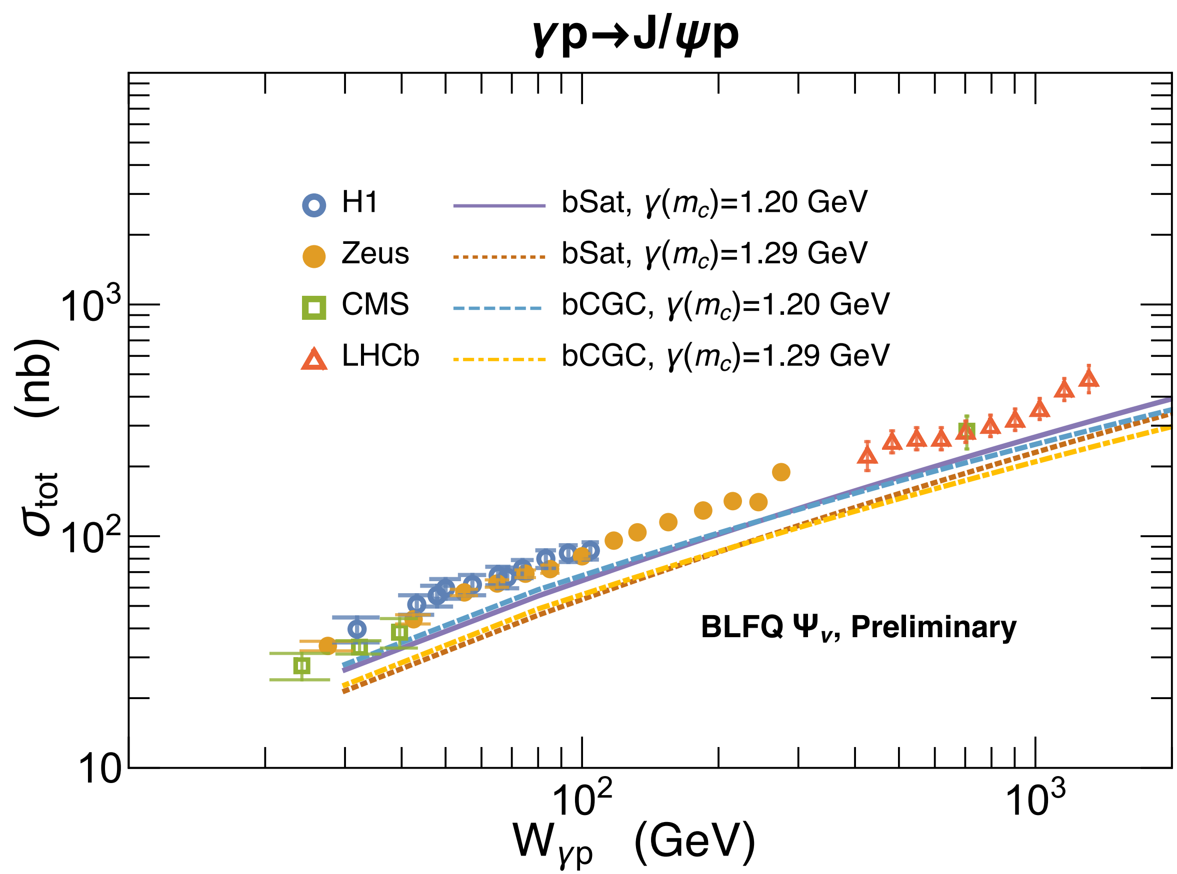
LHCb, 2015



bCGC, Rezaeian and Schmidt, PRD88, 074016 (2013).

J/Ψ in γp at LHC

GC et al, in preparation

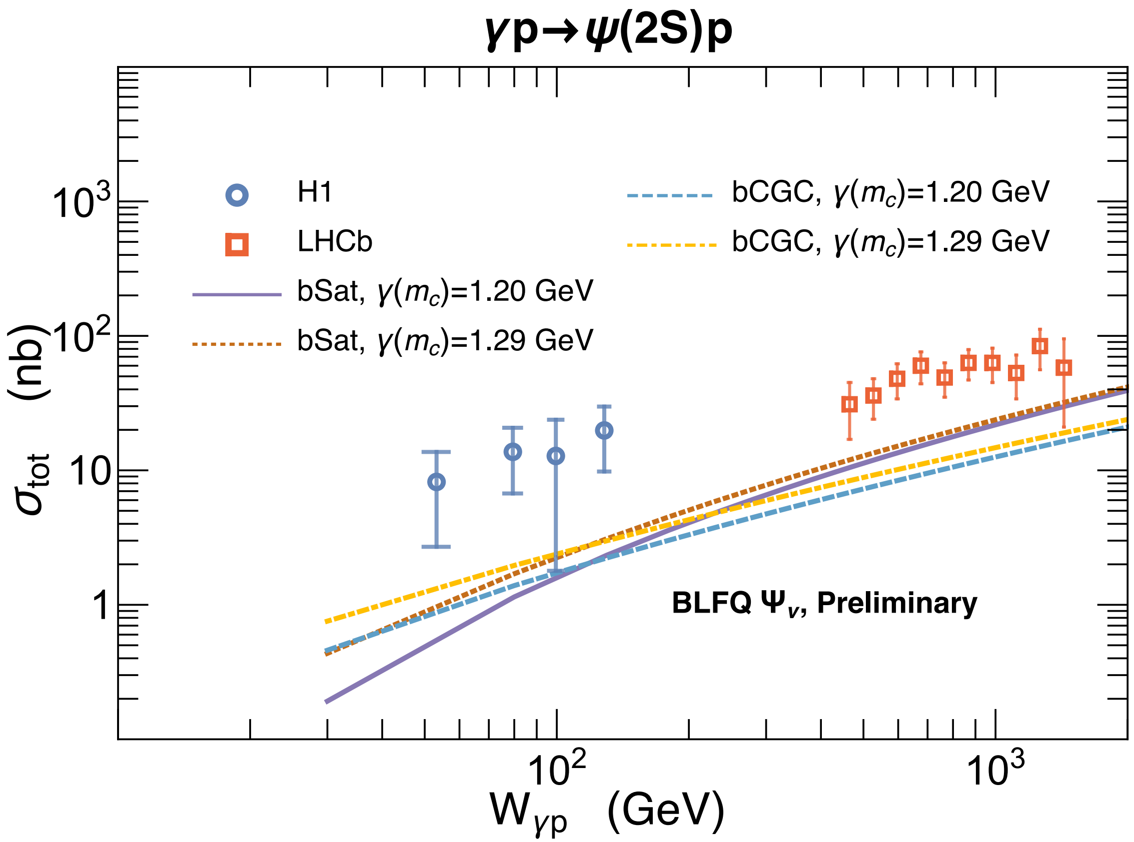


ZEUS, 2004.
H1, 2006.
CMS, 2015.
LHCb, 2016.

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

$\Psi(2s)$ in γp at LHC

GC et al., in preparation



H1, 2002.
LHCb, 2016.

bSat, Rezaeian et al., Phys. Rev. D 87, 034002 (2013).
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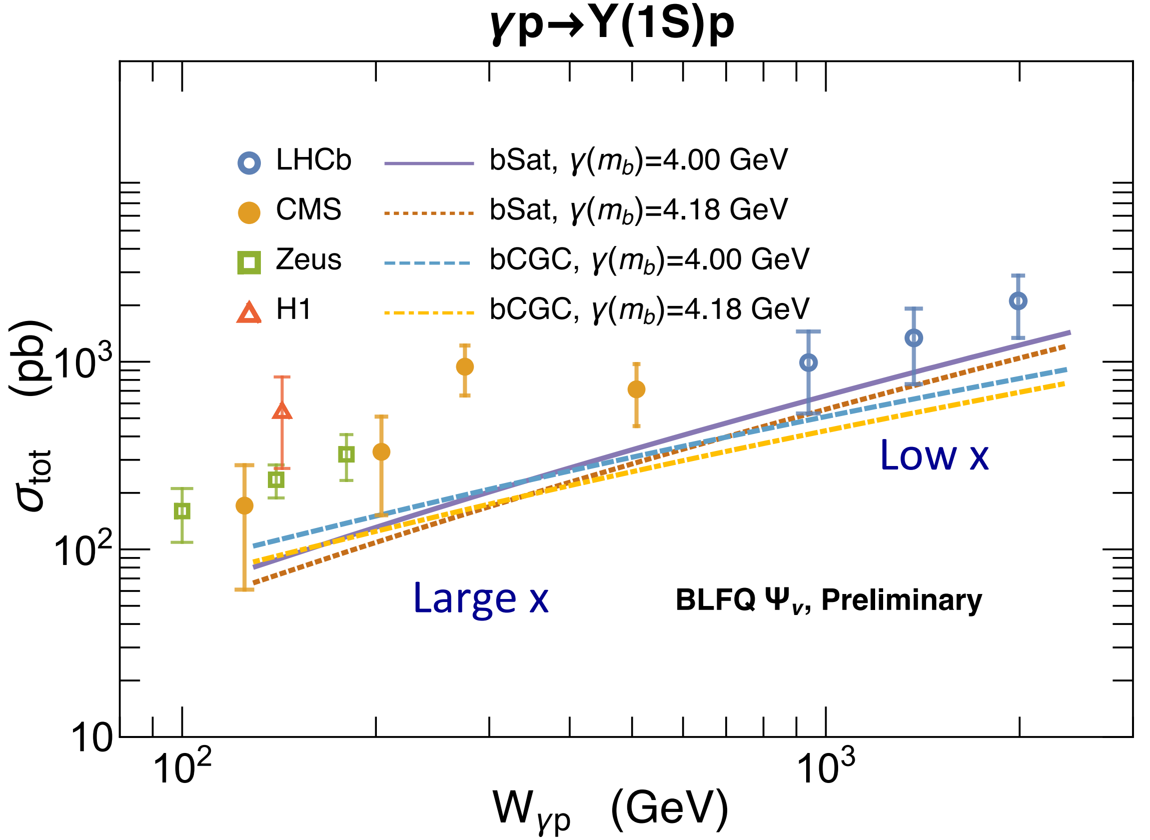
$\Upsilon(1s)$ in γp at LHC

GC et al., in preparation



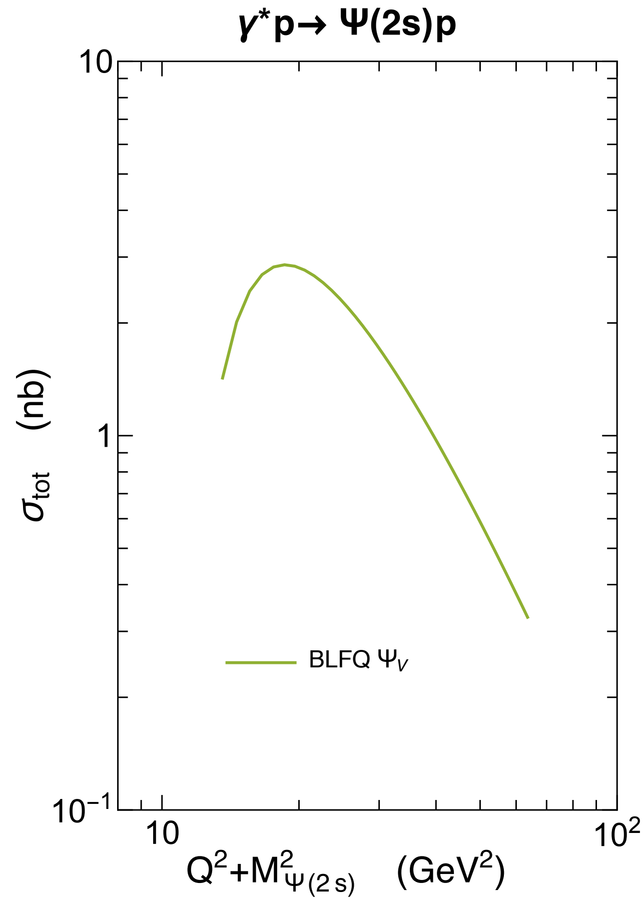
ZEUS, 2009.
H1, 2012.
CMS, 2016.
LHCb, 2016.

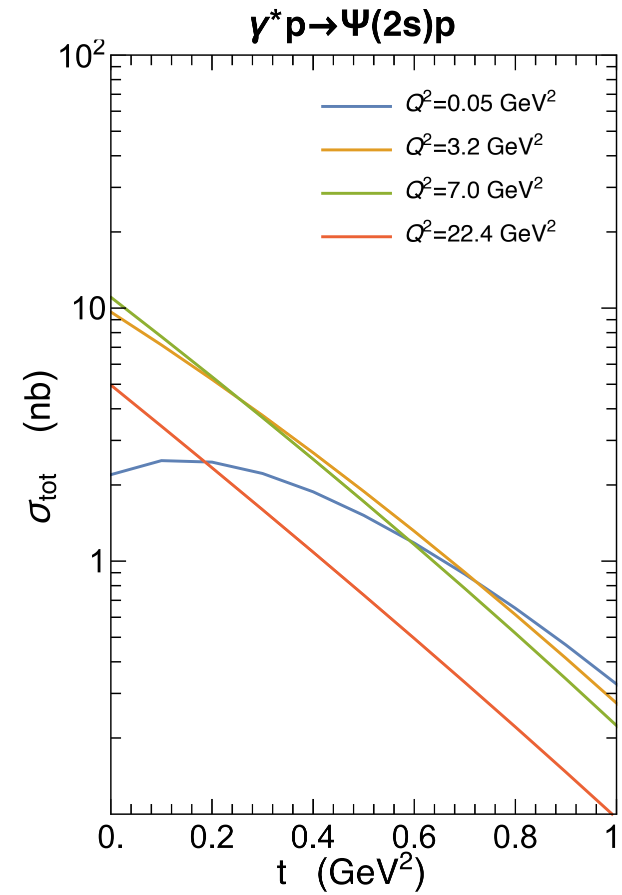
$$x \sim \frac{M_V^2}{W_{\gamma p}^2}$$

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

$\Psi(2s)$ production at EIC

GC et al., in preparation



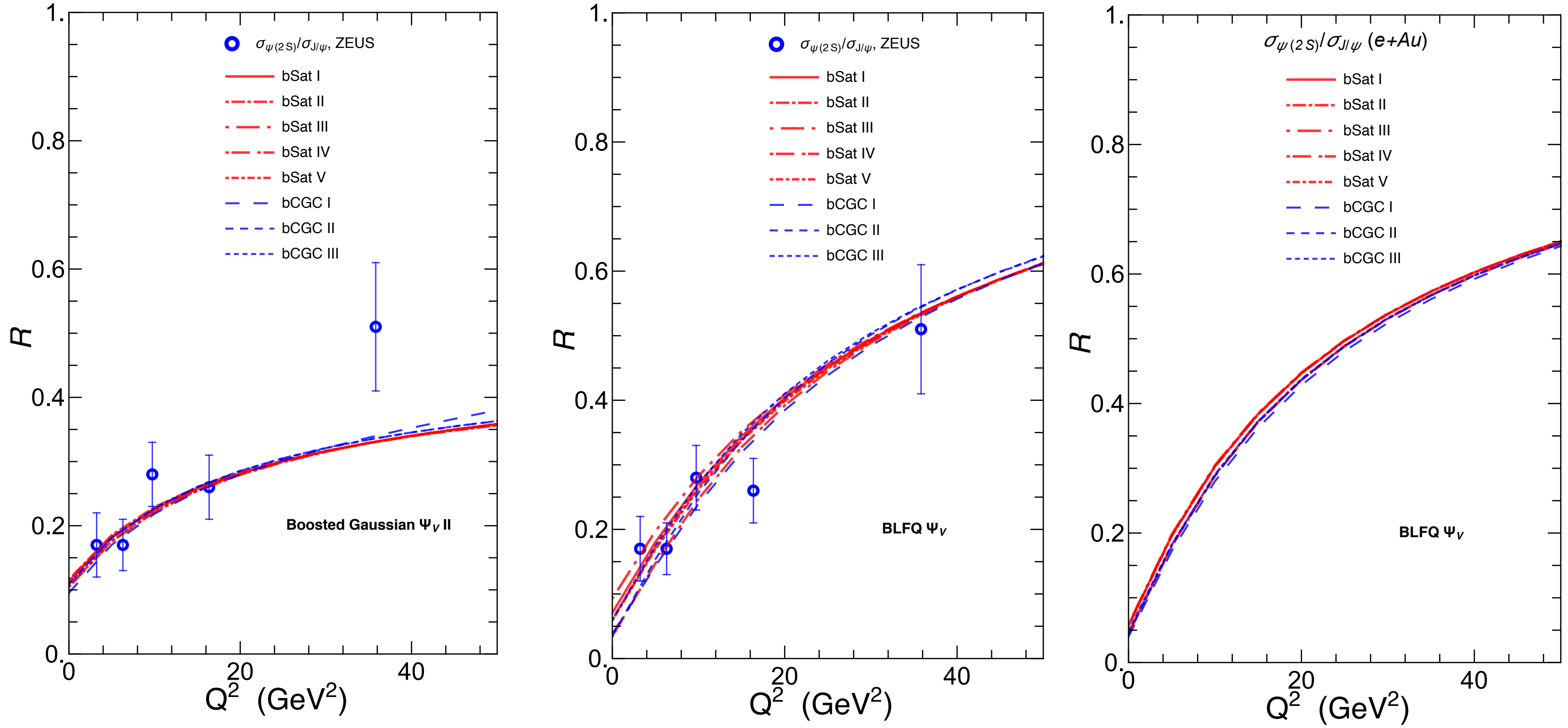


bCGC, Rezaeian and Schmidt, PRD88, 074016 (2013).

Cross section ratio, revisit

ZEUS, 2016.

GC et al., PLB 769, 477, 2017



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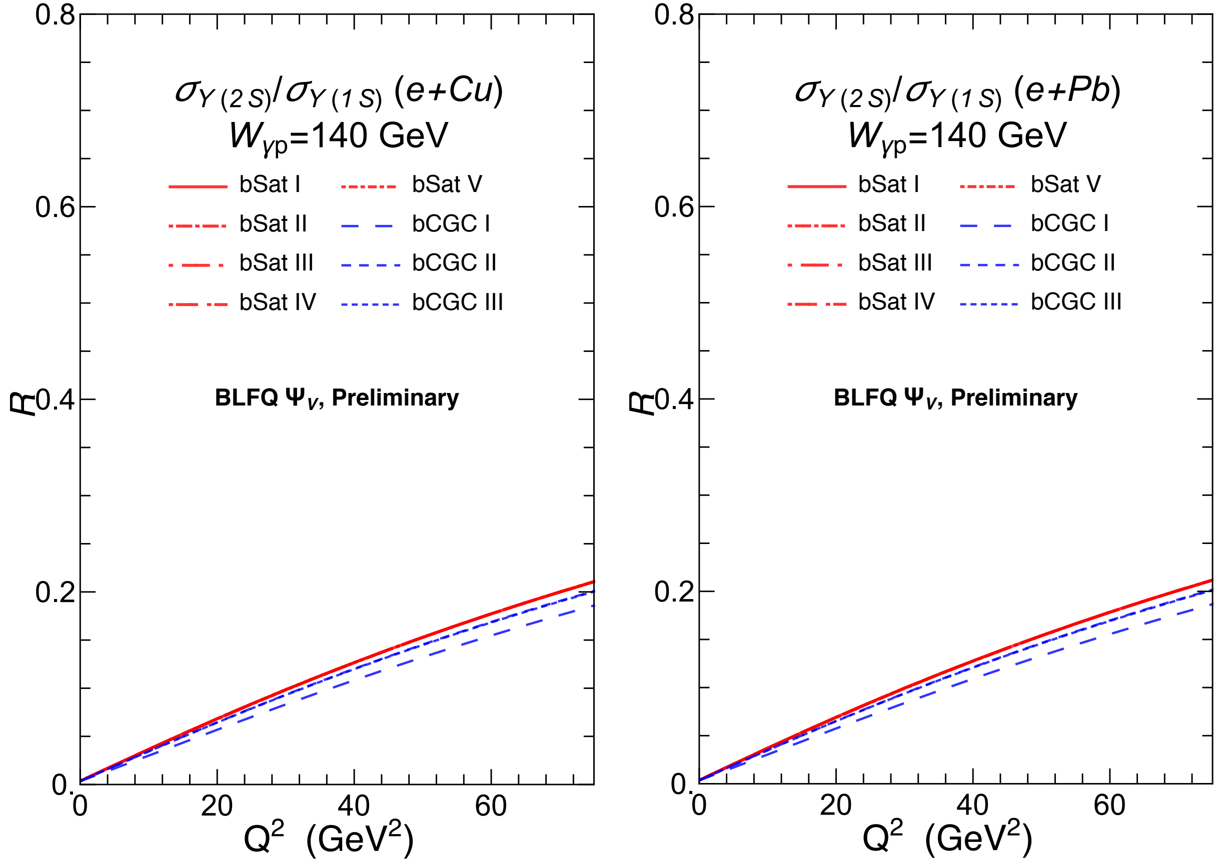
bSat, Rezaeian et al. (2013), Kowalski et al. (2006).
Boosted Gaussian II, Kowalski et al., PRD74, 074016 (2006).

Cross section ratio, Upsilons

GC et al., in preparation



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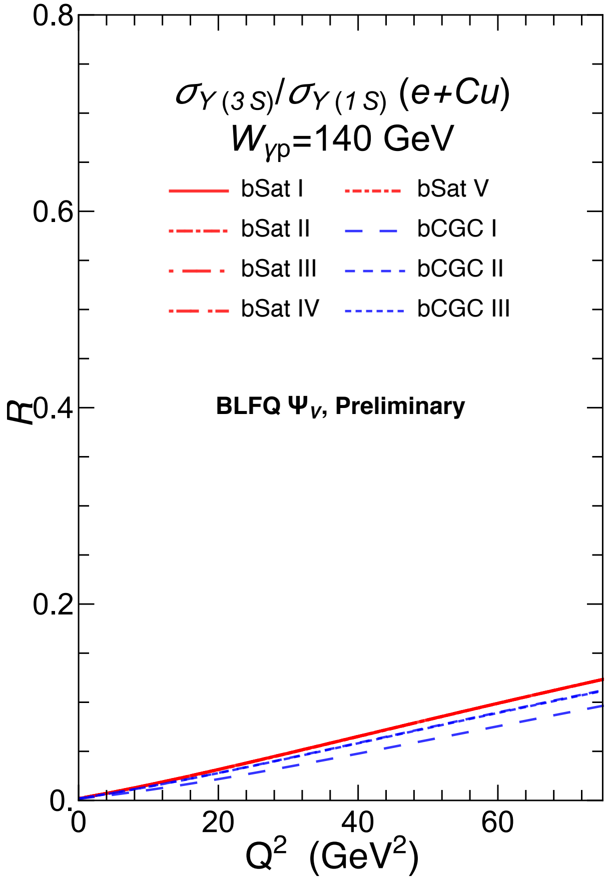
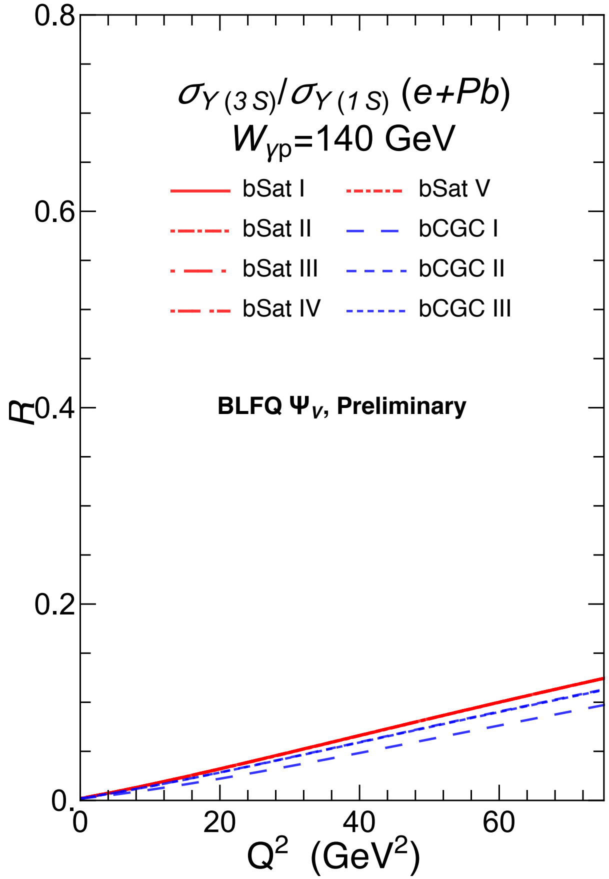
Cross section ratio, Upsilons

GC et al., in preparation





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

Summary

- A description of vector meson on the light-front in the BLFQ framework.
- Confronted 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: measuring meson LFWF at EIC.
- Outlook: higher Fock sector! (X. Zhao)

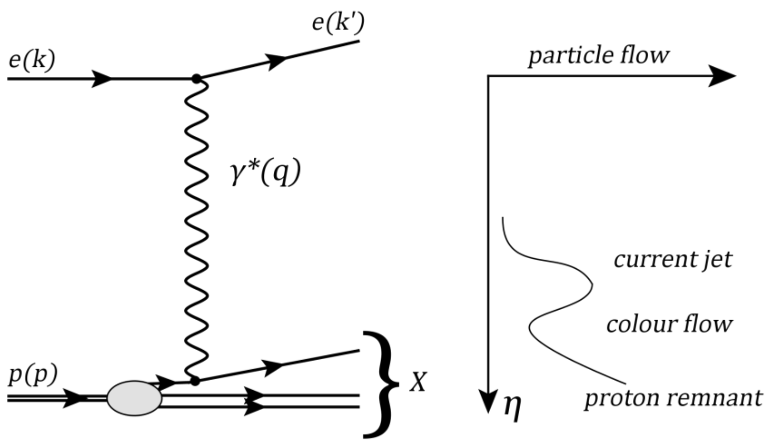
Thank you!

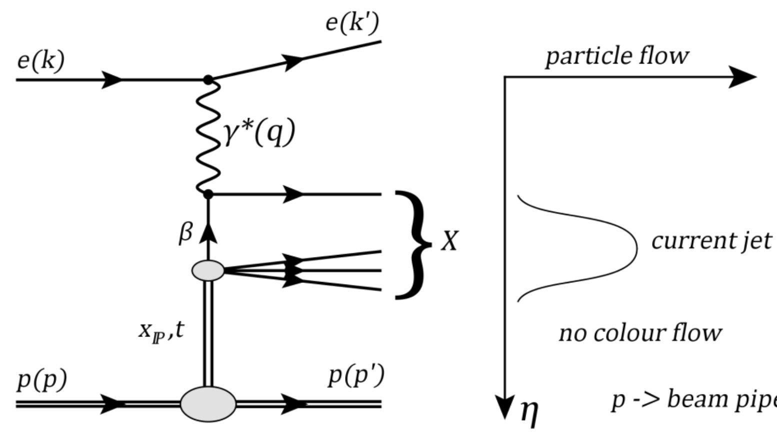
- Collaborators: James Vary, Kirill Tuchin, Pieter Maris, Yang Li, Xingbo Zhao
- Support by Department of Energy, USA
- Acknowledgement: ILCAC

Backup Slides

VM production in Diffractive DIS

- ❑ Deep Inelastic Scattering (DIS)   Diffractive Scattering(DDIS)

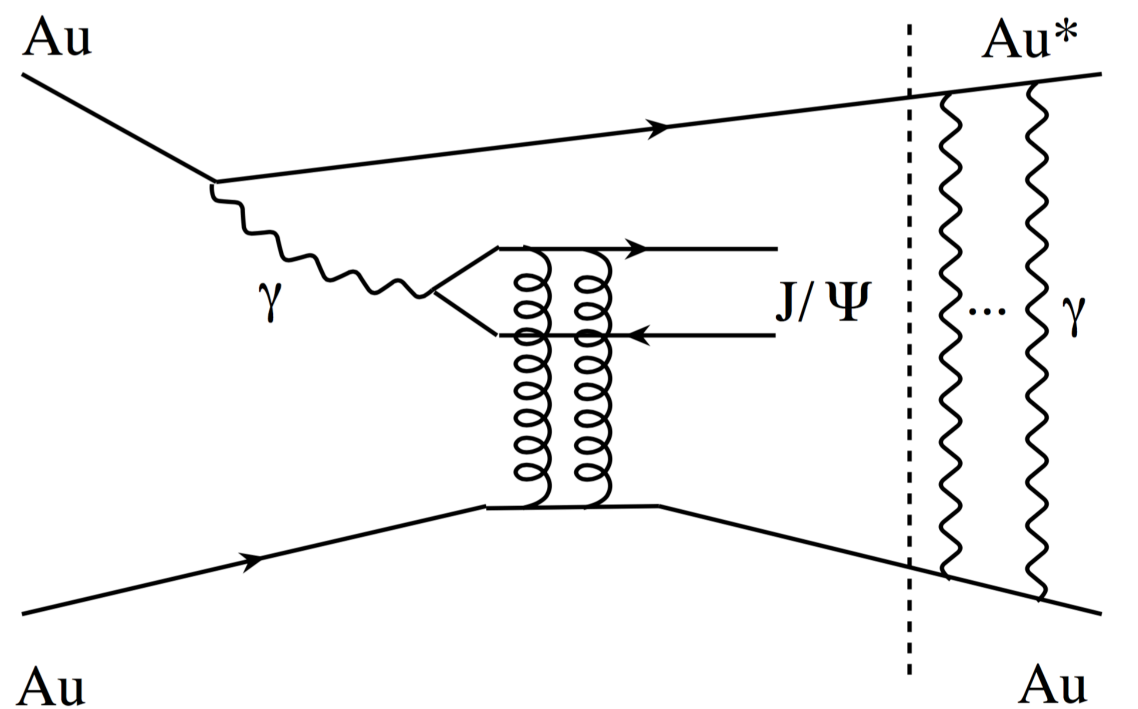




- ❑ Q^2 Virtuality of the photon, W photon-proton CME
- ❑ Bjorken-x, longitudinal momentum fraction of parton
- ❑ t 4-momentum transfer squared

VM production in UPC

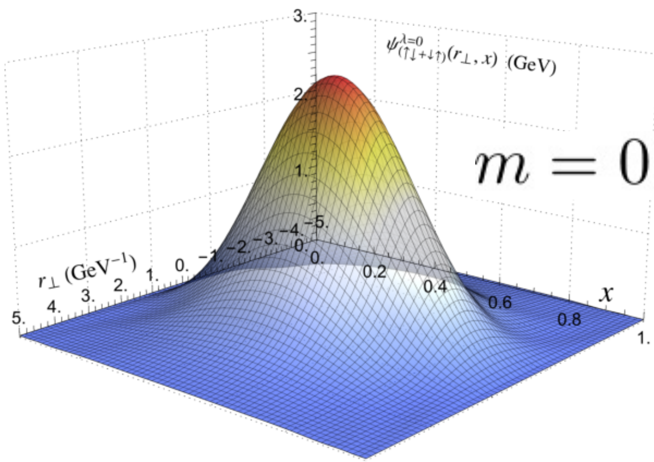
- J/Psi Production at Ultra-Peripheral Collisions (RHIC)



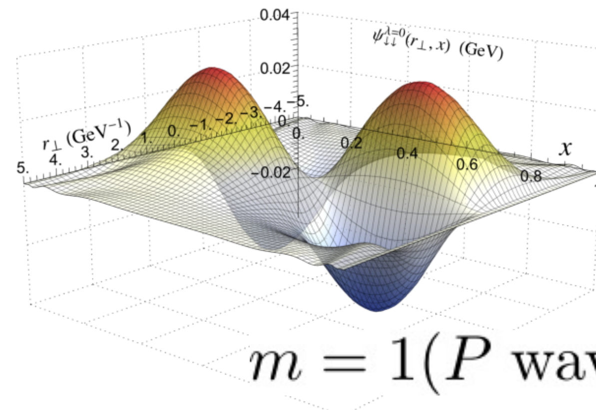
PHENIX, 2009

Visualizing LFWF

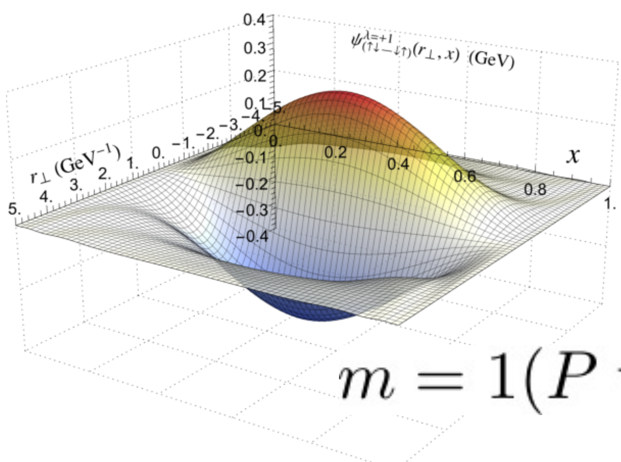
Li et al., PRD96, 016022, (2017)



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

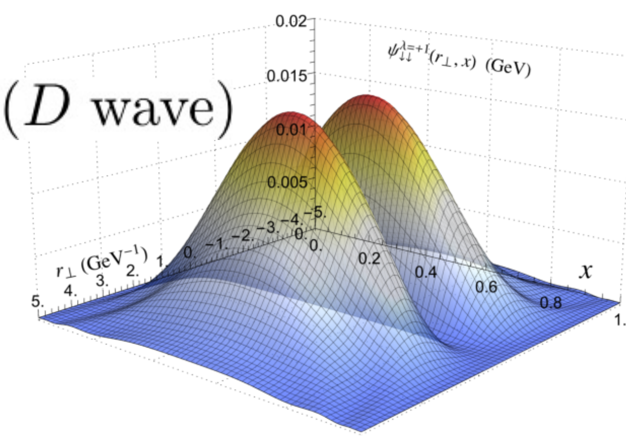


$m = 1(P \text{ wave})$



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

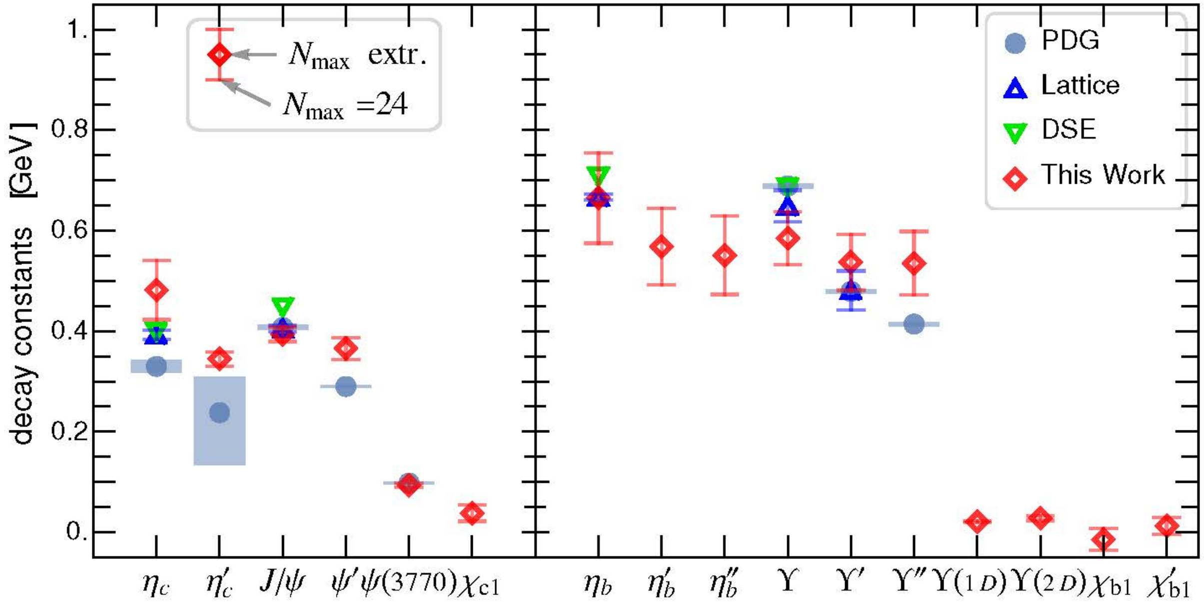
$m = 2(D \text{ wave})$



BLFQ LFWF predictions

Li et al., PLB 758, 118, (2016)

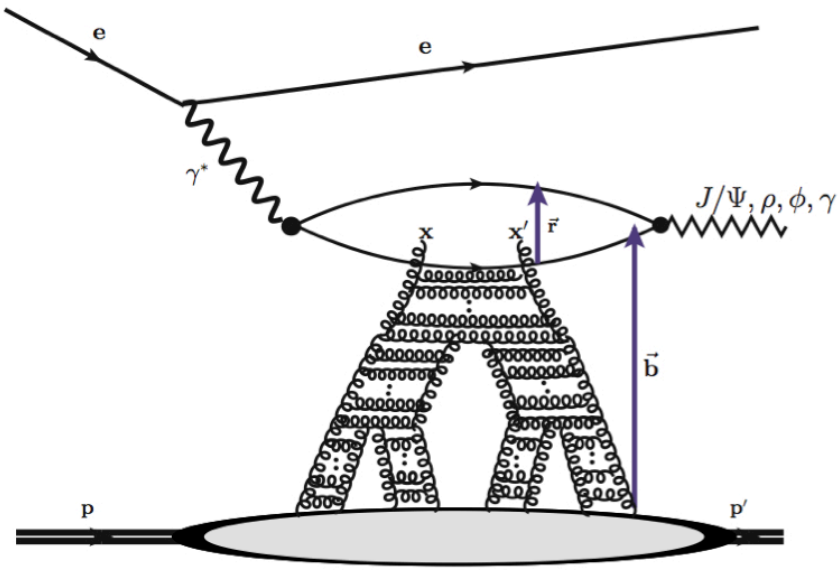
- Decay constants

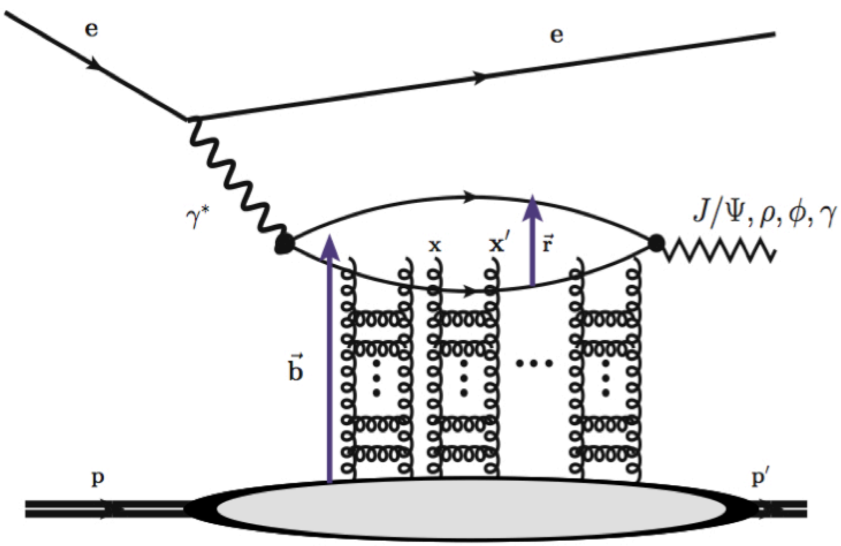


- Also predict radii and charge form factor!

Dipole Model

bCGC v.s. bSat





Rezaeian and Schmidt, PRD88, 074016 (2013).

Equivalent Photon Approximation

- Proton M. Drees and Zeppenfeld, '89

$$\frac{\mathrm{d}N_\gamma^p}{\mathrm{d}\omega} = \frac{\alpha_{\mathrm{em}}}{2\pi}\left[1 + (1 - \frac{2\omega}{\sqrt{s}})^2\right] \times \left[\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}\right]$$

$$\Omega = 1 + \frac{0.71\mathrm{GeV}^2}{Q^2_{min}}$$

- Nuclei

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

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

Klein and Nystrand, '99

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