

Heavy quarkonium spectrum and diffractive production -A light-front Hamiltonian approach

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Y. Li et al., PLB 758,118, 2016
G. Chen et al., in preparation

Basis Light-Front Quantization

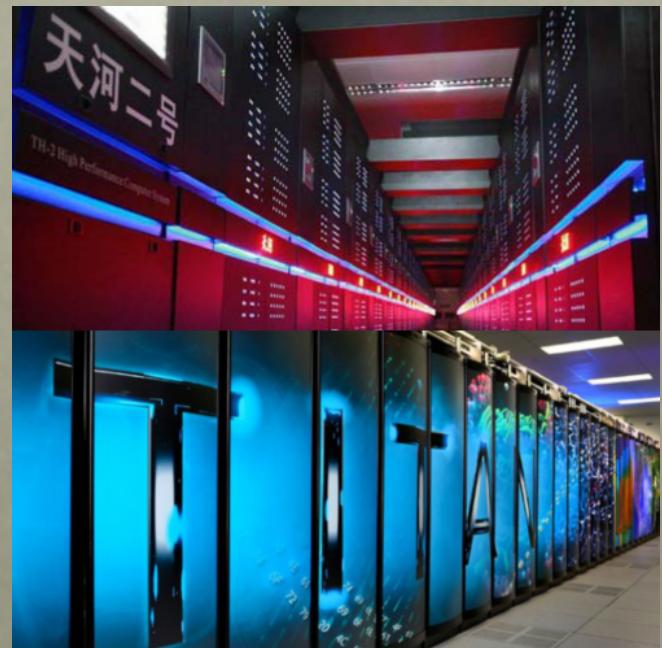
- Finding spectrum using light-front Hamiltonian

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

- Adopting basis according to the symmetry of system

- Advantages:

- Boost Invariant Amplitude
- Parton Interpretation
- Fully relativistic
- Moore's Law



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

Effective Hamiltonian

□ Effective Hamiltonian for heavy quarkonium system

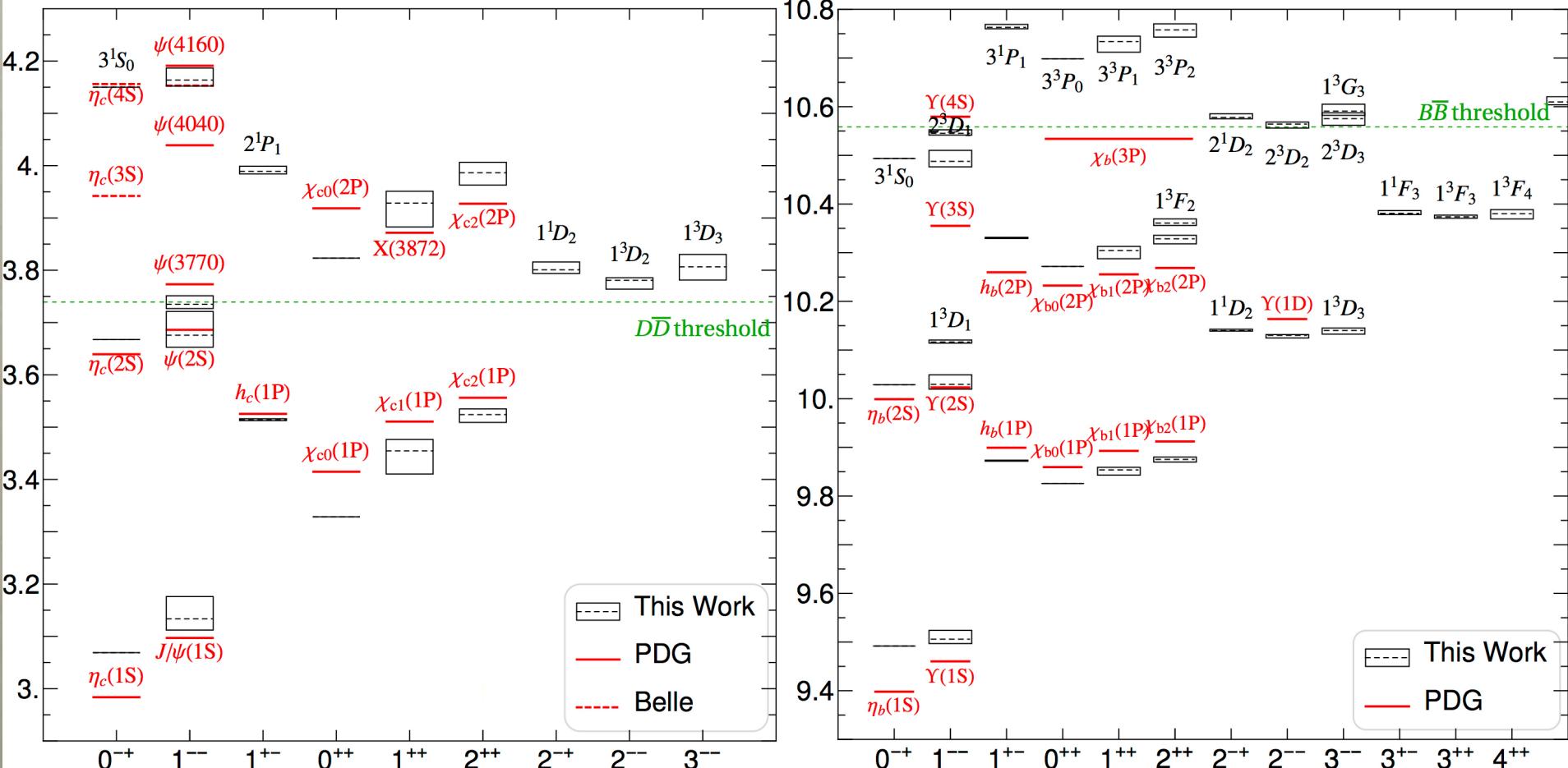
$$H_{\text{eff}} = \underbrace{\frac{\vec{k}_\perp^2 + m_q^2}{z(1-z)}}_{\text{LF kinetic energy}} + \underbrace{\kappa^4 \zeta_\perp^2 - \frac{\kappa^4}{4m_q^2} \partial_z [z(1-z)\partial_z]}_{\text{confinement}} - \underbrace{\frac{C_F 4\pi \alpha_s}{Q^2} \bar{u}_{s'}(k') \gamma_\mu u_s(k) \bar{v}_{\bar{s}}(\bar{k})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

S. Brodsky, '08

- Generalize the soft-wall confinement to 3D
- Consistent with pQCD asymptotics $\phi^{\text{DA}}(z) \sim z^\alpha (1-z)^\beta$
- Basis: analytical solution of KE + confinement
- Proper massless and NR limits

Y. Li et al., PLB 758,118, 2016

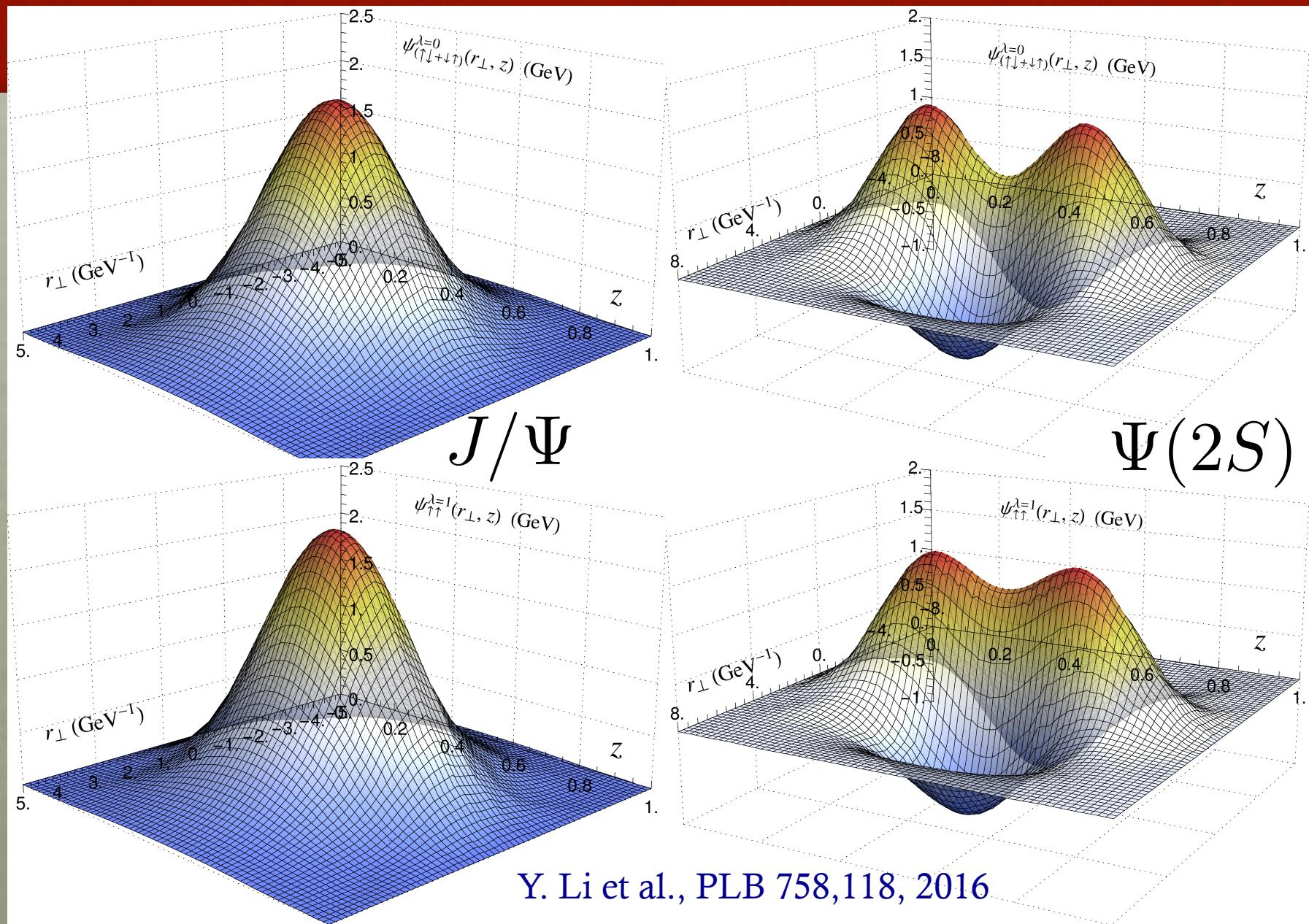
Mass Spectroscopy



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

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Charmonium Light-front Wavefunction



Exclusive process in the dipole picture

□ Photon LFWF: pQED

□ Dipole cross section

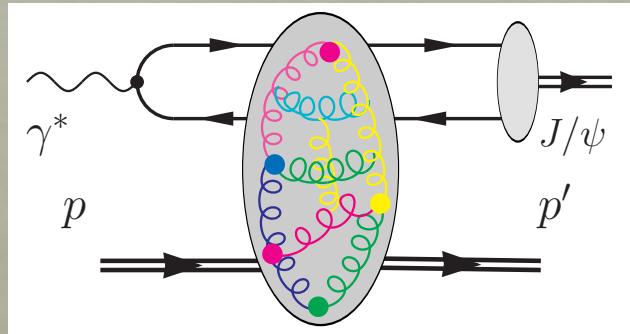
□ Vector meson LFWFs

$$\square \quad \mathcal{A}_{T,L}^{\gamma^* p \rightarrow E p}(x, Q, \Delta) = i \int d^2 \vec{r} \int_0^1 \frac{dz}{4\pi} \int d^2 \vec{b} (\Psi_E^* \Psi)_{T,L}$$

$$\times e^{-i[\vec{b} - (1-z)\vec{r}] \cdot \vec{\Delta}} \frac{d\sigma_{q\bar{q}}}{d^2 \vec{b}}$$

□ Probing gluon density at small-x

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



A. Mueller, '90

N. Nikolaev, '91

K. Golec-Biernat et al., '99

Dipole cross-section parameterizations

□ b-Saturation model

H. Kowalski and D. Teaney , '01

Model	m_c/GeV	μ_0^2/GeV^2	A_g	λ_g	$\chi^2/\text{d.o.f.}$	Ref.
bSat I	1.4	1.17	2.55	0.020	1.21	PRD 74 , 074016
bSat II	1.35	1.20	2.51	0.024	1.19	PRD 74 , 074016
bSat III	1.5	1.11	2.64	0.011	1.24	PRD 74 , 074016
bSat IV	1.27	1.51	2.308	0.058	1.15	PRD 87 , 034002
bSat V	1.4	1.11	2.373	0.052	1.22	PRD 87 , 034002

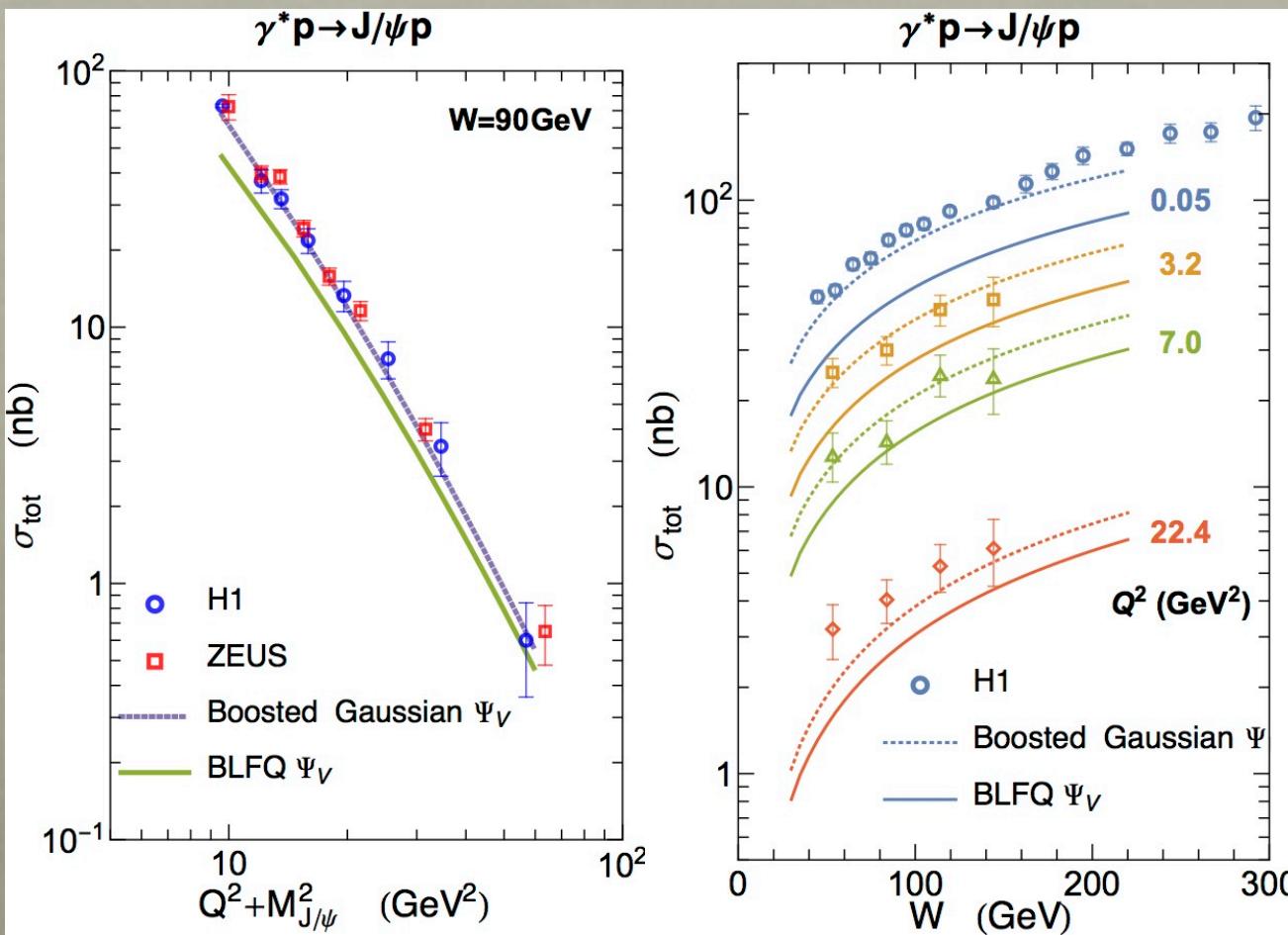
□ b-CGC

E. Iancu, K. Itakura and S. Munier, '04

Model	m_c/GeV	γ_s	N_0	x_0	λ	$\chi^2/\text{d.o.f.}$	Ref.
bCGC I	1.4	0.7376	0.7	1.632×10^{-5}	0.2197	0.900	PLB 655 , 32
bCGC II	1.27	0.6599	0.3358	0.00105	0.2063	1.241	PRD 88 , 074016
bCGC III	1.4	0.7376	0.3658	0.00069	0.2023	1.249	PRD 88 , 074016

J/ ψ production at HERA

bSat I + BLFQ v.s. bSat I + boosted Gaussian

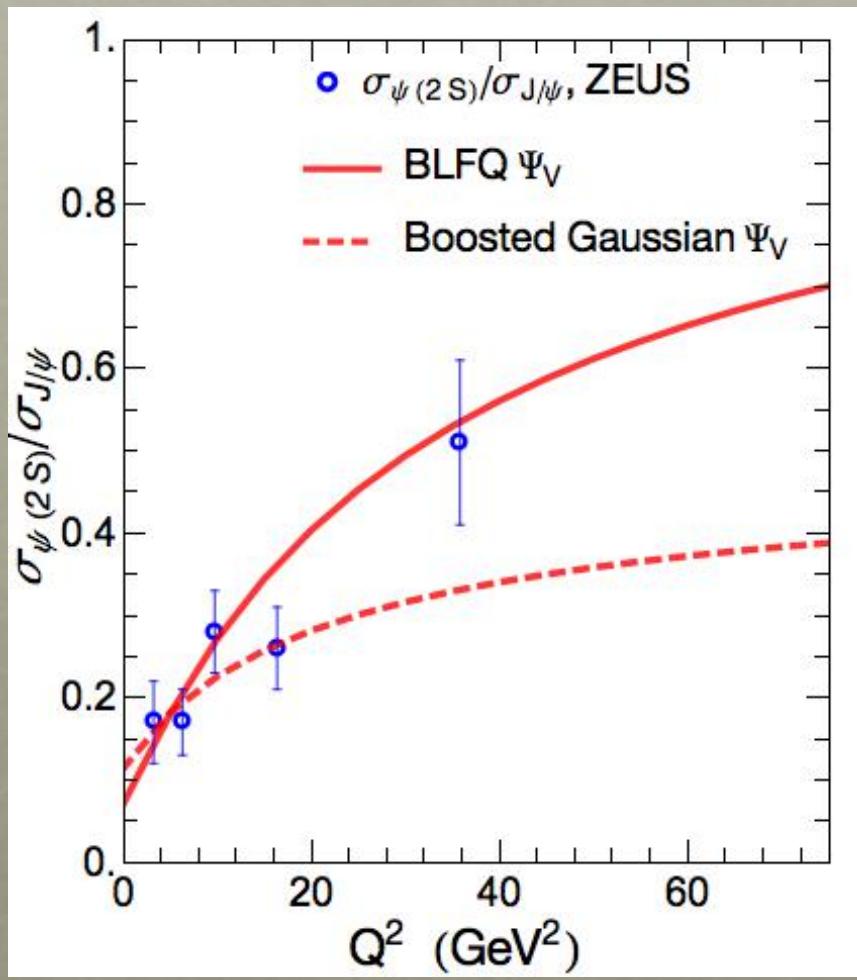


ZEUS, NPB, '04
H1, EPJC, '06

bSat I
boosted Gaussian
H. Kowaski et al.,
'06

$\Psi(2\text{s})$ production at HERA

bSat I + BLFQ v.s. bSat I + boosted Gaussian



ZEUS, '16

bSat I
boosted Gaussian
H. Kowaski et al., '06

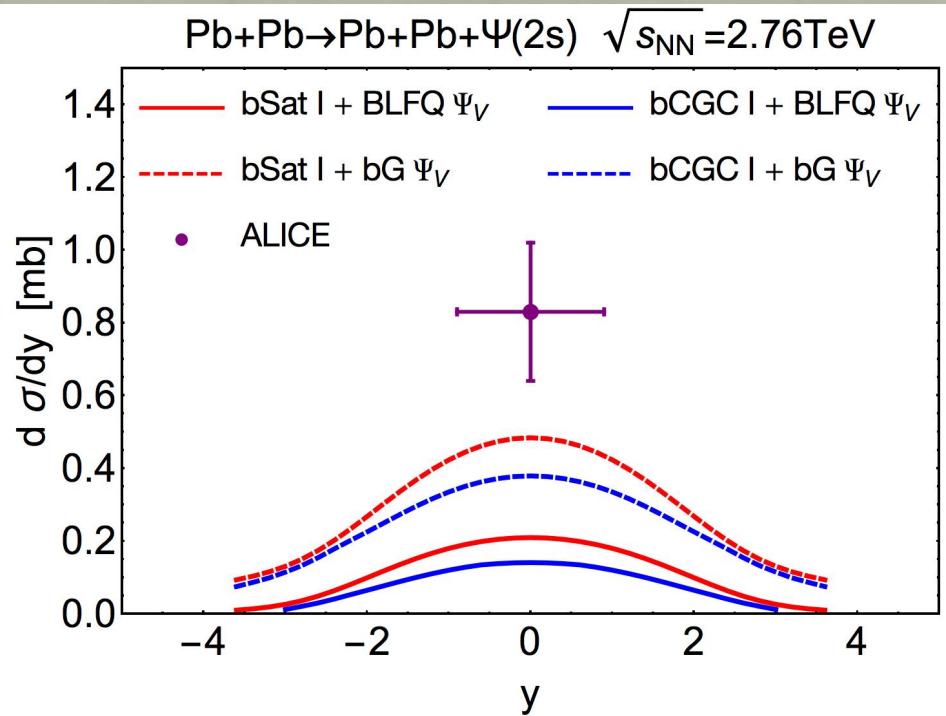
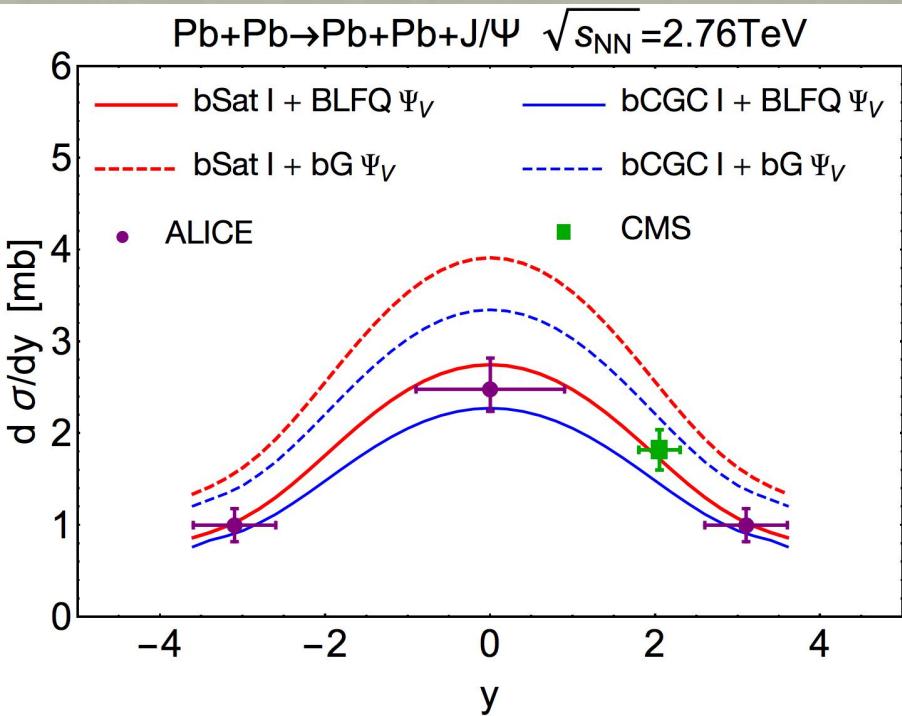
T. Lappi et al., '14

J/ ψ production at RHIC

- $x_{IP} \approx 0.015$, dipole model marginally works at mid-rapidity
- PHENIX measurement [PHENIX, PLB, '09, A. Takahara, '13](#)
- 2010:
$$\frac{d\sigma}{dy} \Big|_{y=0} = 45.6 \pm 13.2(stat) \pm 6.0(sys) \mu b$$
- 2004+2007:
$$\frac{d\sigma}{dy} \Big|_{y=0} = 55.9 \pm 13.2(stat) \pm 7.6(sys) \mu b$$
- BLFQ+bSat I calculation: $65 \mu b$
- Boosted Gaussian + bSat I prediction: $109 \mu b$

[T. Lappi et. al, '13](#)

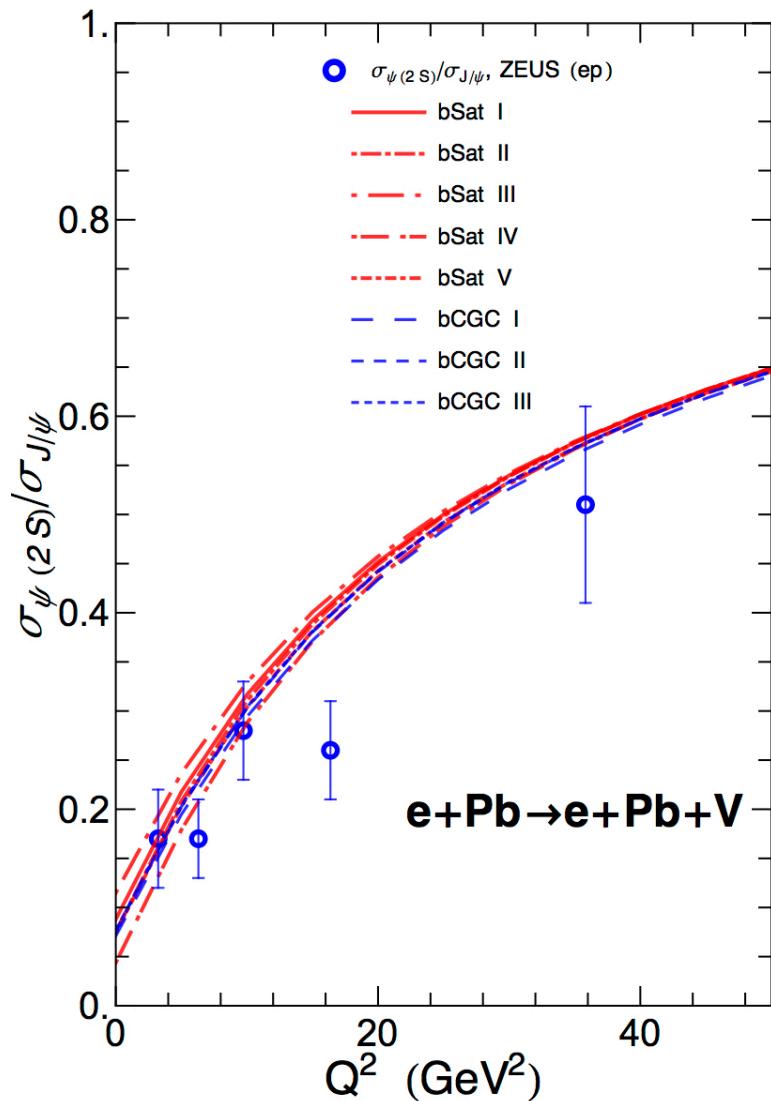
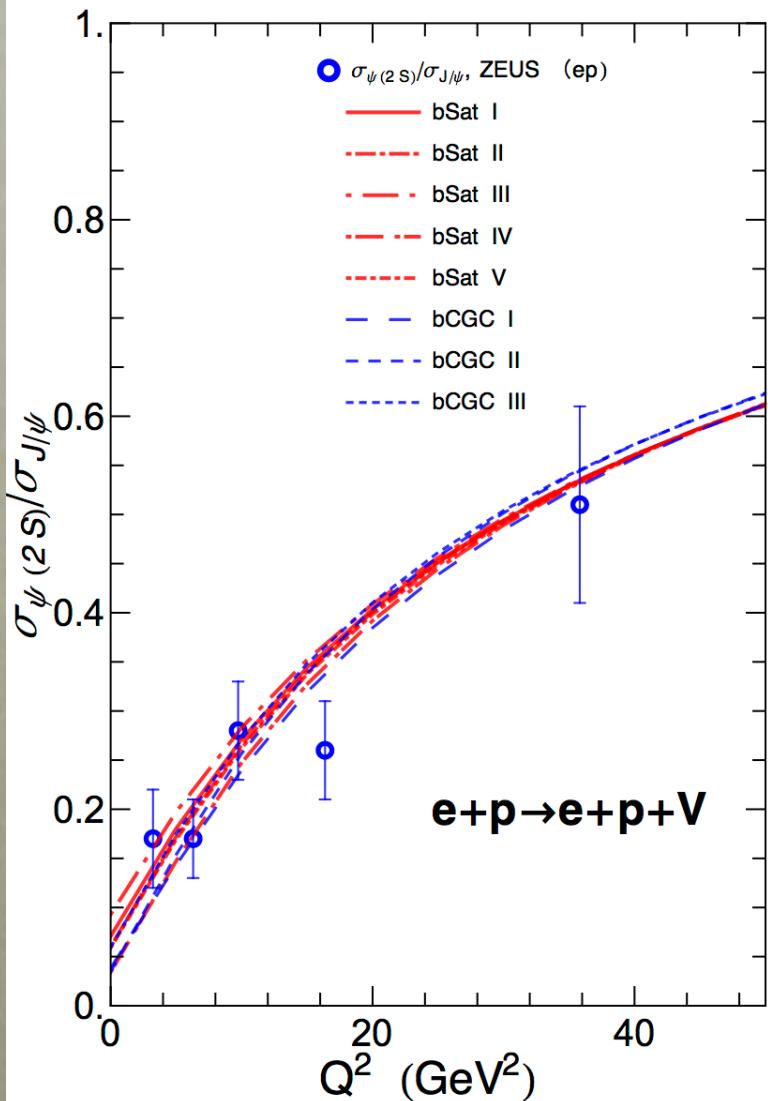
Charmonium Production at LHC



ALICE, EPJC, '13
CMS, '16

ALICE, PLB, '15

Dipole model dependence



Conclusions and Outlook

- Reproduce the heavy quarkonia spectrum in the basis light-front quantization formalism,
- The obtained LFWFs give reasonable predictions to the exclusive charmonium production process at HERA, RHIC and LHC, along with other observables, e.g., decay constant, radii,
- The cross-section ratio of $\sigma_{\Psi(2s)} / \sigma_{J/\Psi}$ reveals significant independence of model parameters,
- Uncertainty of charmonium LFWFs can be reduced through measuring cross-section ratio at EIC,
- Future work: charmonium and bottomonium production at EIC, both coherently and incoherently.

Thank you!

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❑ Supports

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Backup slides

Boosted Gaussian

- Gaussian in VM Rest Frame S. Brodsky, T. Huang and G. Lepage, '80

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

- Constraints

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

- Free parameters > Constraints

- Possible to generalized to higher excited states B. Cox et al., '09

H. Kowaski et al., '06

T. Lappi et al., '14

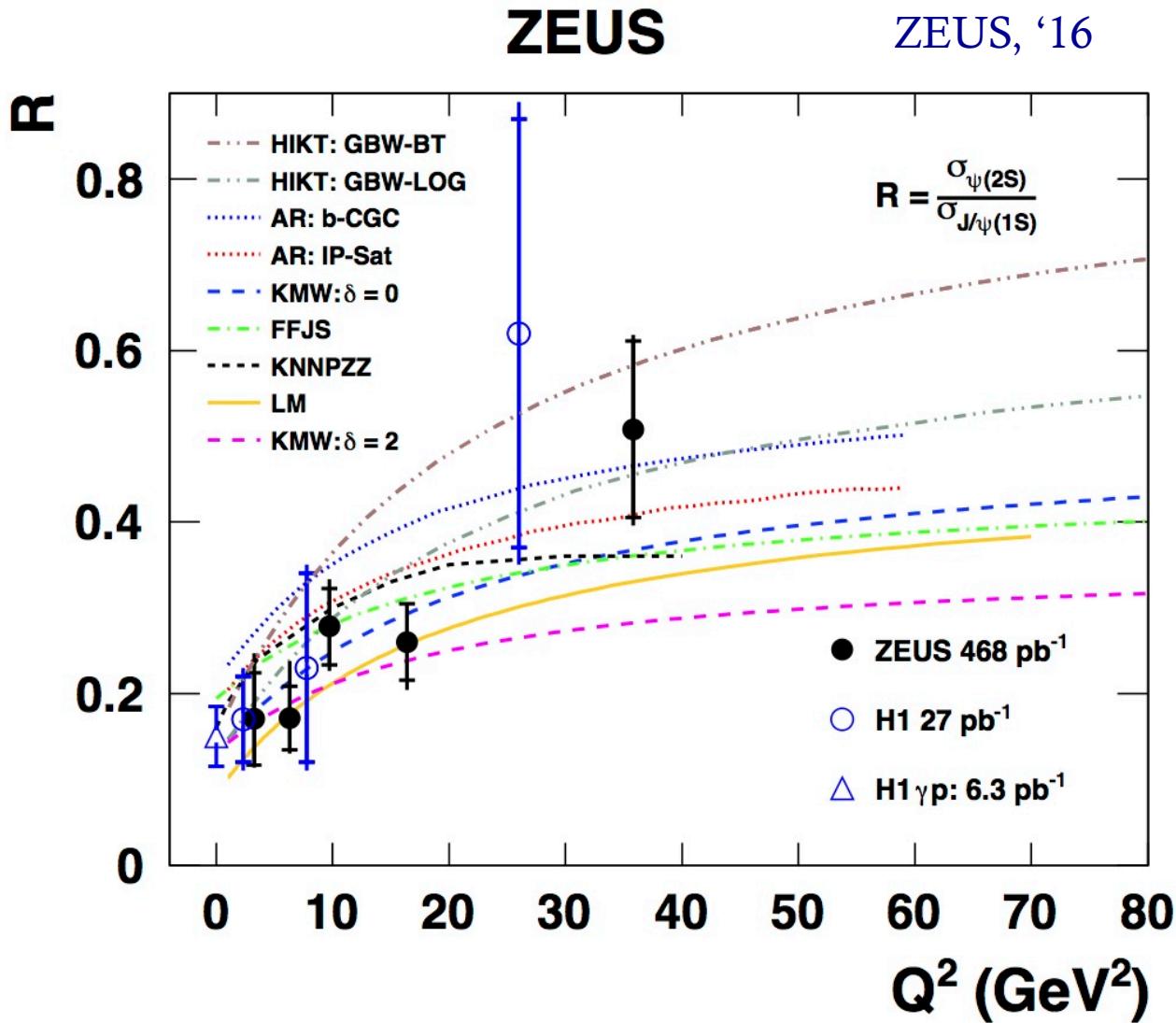
Ultra-Peripheral Collisions

- ❑ Exclusive vector meson production exists in UPC.
 - ❑ Related to photon-nucleus collision—Weizsacker-Williams fields
 - ❑ Glauber model for nucleon positions
Good and Walker, 1960
 - ❑ Coherent v.s incoherent—Good-Walker picture

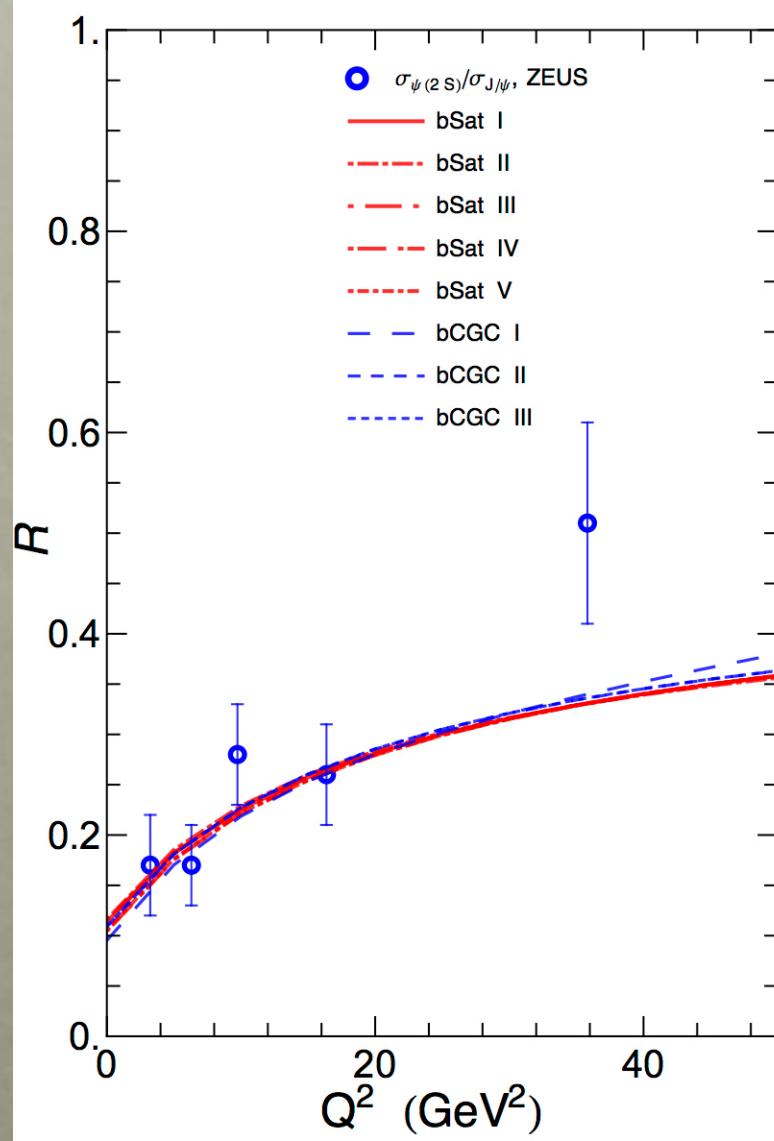
$$\frac{d\sigma_{\text{incoh}}}{dt} \sim \left\langle \left| \mathcal{A}(x, Q^2, t, \Omega) \right|^2 \right\rangle_{\Omega} - \left| \left\langle \mathcal{A}(x, Q^2, t, \Omega) \right\rangle_{\Omega} \right|^2$$

- Access to gluon distribution and “lumpiness” of nucleus

$\Psi(2S)/J/\psi$ ratio at HERA



$\Psi(2\text{s})$ production at HERA with BG

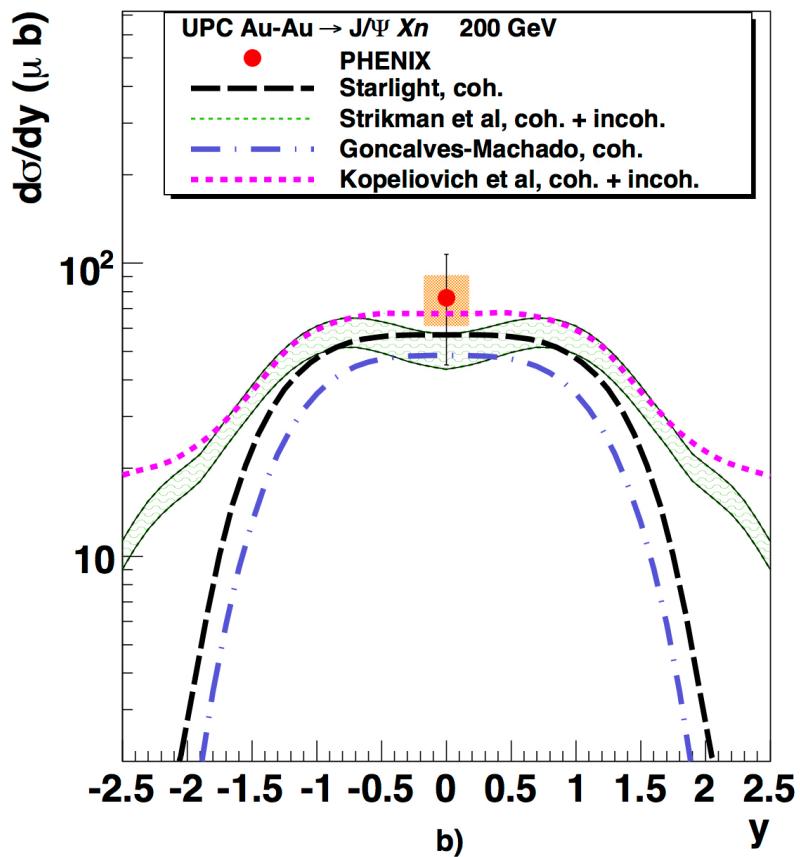
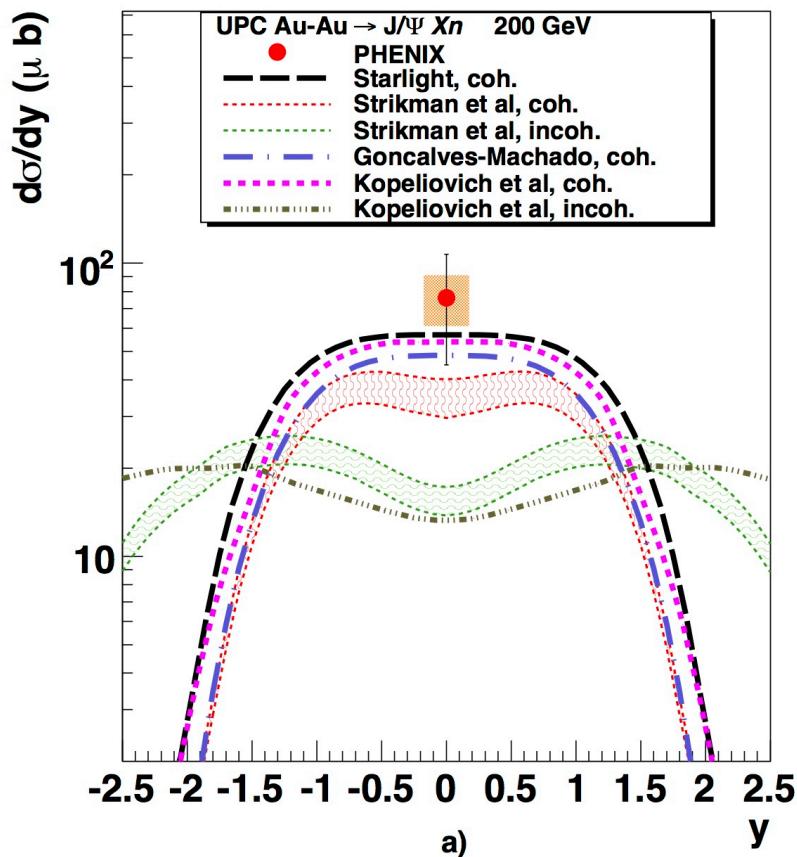


ZEUS, '16

H. Kowaski et al., '06
T. Lappi et al., '14

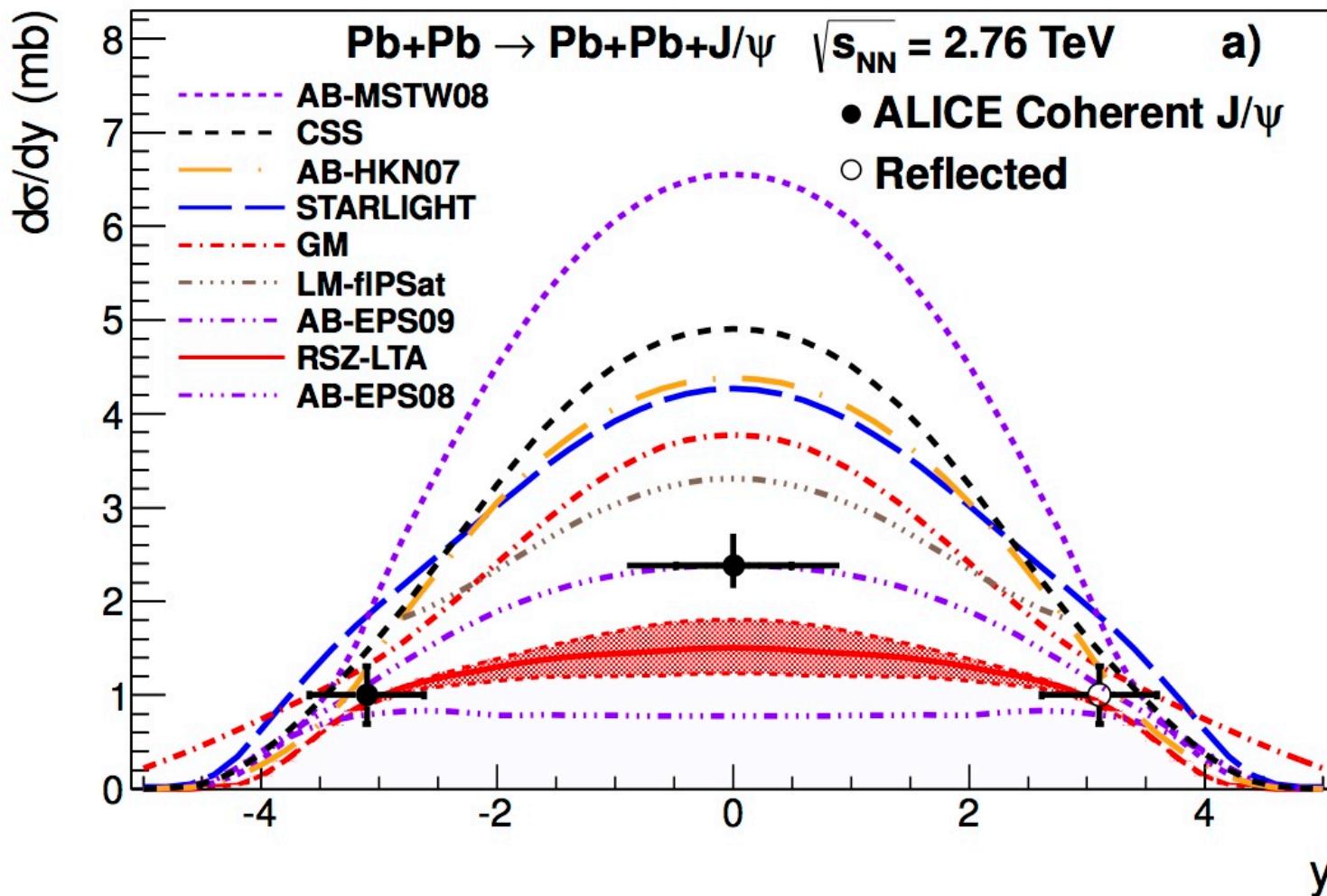
J/ ψ production at RHIC

PHENIX, PLB, '09

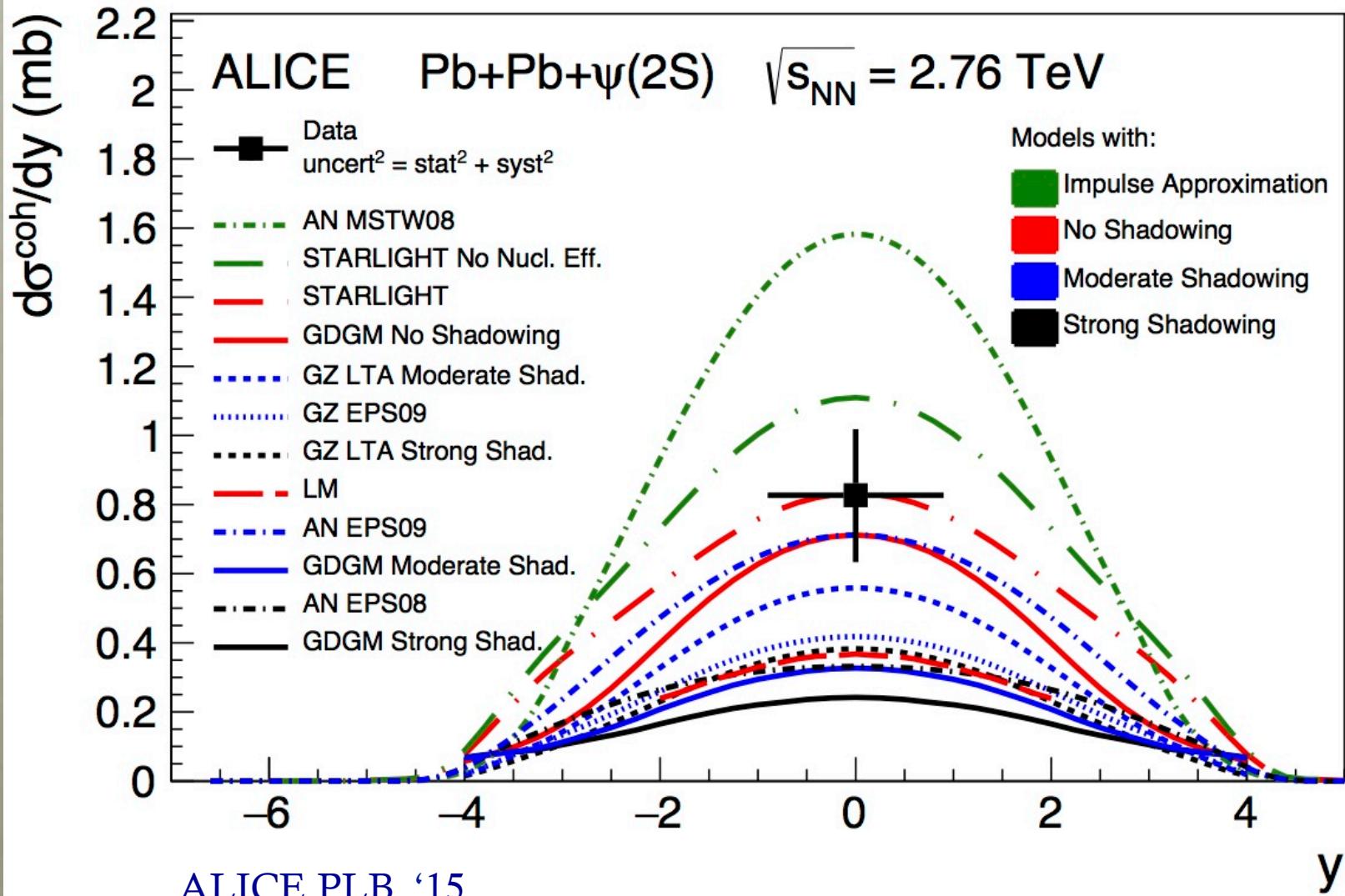


J/ ψ production at LHC

ALICE, EPJC, '13



$\Psi(2S)$ production at LHC



$\Psi(2S)$, proton v.s. nucleus

ALICE,PLB, '15

