Exclusive and diffractive production of quarkonia at High Energy

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Towards improved hadron femtography with hard exclusive reactions

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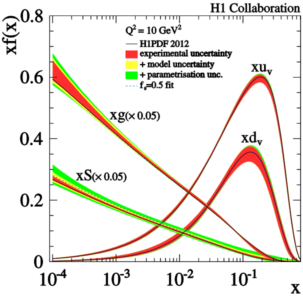
Outlook

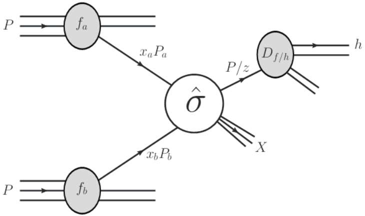
- Theoretical Framework
  - $\rightarrow$ The Exclusive Photoproduction.
  - $\rightarrow$ The Colour Dipole Models.
- Ultraperipheral Collisions (UPC)
  - $\rightarrow$ Rapidity Distribution in pp, pA and AA Collisions
- Peripheral Collisions
  - $\rightarrow$ Rapidity Distribution
  - $\rightarrow$ Nuclear Modification Factor
- New attempts (NLO...)

Hadronic Interactions

- The production cross section can be written as

$$\sigma_{hh\to hx} \propto f_{a/h}(x_1, Q^2) \otimes f_{b/h}(x_2, Q^2) \otimes \hat{\sigma}(ab \to cd) \otimes D_{h/c}(z_c, \hat{Q}^2)$$





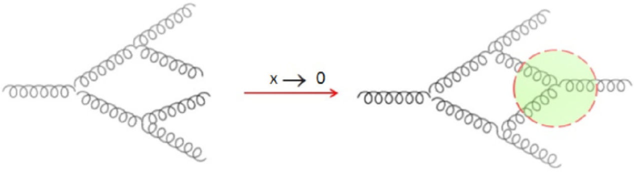
$f_p(x, Q^2) \to$ Parton Distribution Functions (PDF's): CTEQ, MRST, GRV, ...

$\hat{\sigma}(ab \to cd) \to$ partonic subprocess $ab \to cd$: $qq \to qq$, $q\bar{q} \to gg$, $gg \to gg$, ...

$D_{h/c}(z_c, \hat{Q}^2) \to$ fragmentations functions of hadron h from a parton c.

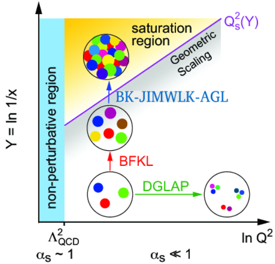
Saturation Phenomena

- In small-x, the gluon recombination process is important



Gluon splitting — Corrections of gluon recombination

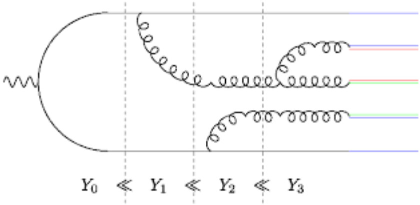
- Some evolution equations:



- Linear equations
  - DGLAP
  - BFKL
- Non-Linear equations
  - AGL
  - JIMWLK
  - BK

Balitsky-Kovchegov

- The photon splitting in the $q\bar{q}$ pair with z and $1-z$ fraction of light cone momentum.
- The quark or antiquark can emit soft gluons ($z_2 \ll z_1$), which can also emit softer gluons.
- In the limit $N_c \to \infty$, these soft gluons can be considered as quark-antiquark pairs.



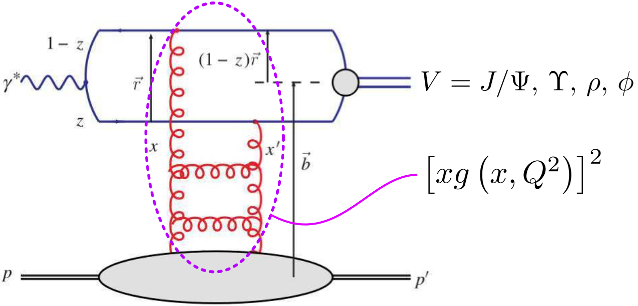
The Balitsky-Kovchegov Equation

$$\partial_Y \langle T(x,z)\rangle = \frac{\bar{\alpha}}{2\pi}\int d^2z \mathscr{M}(x,y,z)[\langle T(x,z)\rangle + \langle T(z,y)\rangle - \langle T(x,y)\rangle - \langle T(x,z)\rangle\langle T(z,y)\rangle]$$

- This equation evolves $\langle T(x,y)\rangle$.
- The evolution quantity is the rapidity $Y \approx \ln 1/x$.
- $\bar{\alpha}_s = \alpha_s N_c/\pi$ and $\mathscr{M}(x,y,z) = \frac{(x-y)^2}{(x-z)^2(z-y)^2}$.

Colour Dipole Formalism

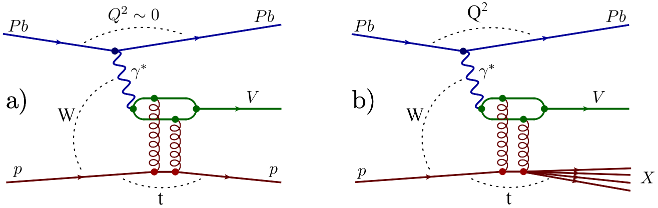
- Complementary information on gluons distribution can be obtained



r is the dipole separation.
z(1-z) is the quark(antiquark) momentum fraction.
b is the dipole-target impact parameter.

Photo-Induced Interactions

- Diffractive production of vector mesons in hadron-hadron collisions.
- The process is characterized by large rapidity gaps in the final state.



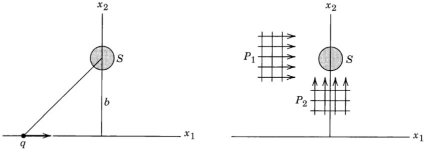
$Q^2 \rightarrow$ photon virtuality.
$W^2 \rightarrow \gamma * p$ center of mass energy.
$t \rightarrow$ squared momentum transfer.

- We are interested in the first case: **Exclusive Photoproduction ($Q^2 \sim 0$),**

$$p \otimes Pb \rightarrow Pb \otimes V \otimes p$$

Weizsäcker-Williams Method

- Hadron-Hadron interaction $\rightarrow$ photon-hadron interaction



- Thus, the hadron process can be written in a simpler way

$$\sigma_X = \frac{dN(\omega)}{d\omega} \otimes {\sigma_X}^{\gamma}(\omega)$$

where the equivalent photon flux is written as

$$\frac{dI(\omega)}{d\omega} = \frac{2q^2}{\pi}\left[\chi_{min} K_0(\chi_{min}) K_1(\chi_{min}) - \frac{1}{2}\chi^2_{min}\left[K_1^2(\chi_{min}) - K_0^2(\chi_{min})\right]\right]$$

and σ_X^{γ} is the photoproduction cross section.

The Photoproduction Cross Section

- For $\gamma - p$ interaction, the forward scattering amplitude is given by

$$\mathrm{Im}\, A_{\mathrm{proton}}(x, t=0) = \int\int \frac{d^2 r dz}{4\pi} \left(\psi_V^* \psi_\gamma\right)_T \sigma_{\mathrm{dip}}^{\mathrm{proton}}(x, r)$$

  - $\left(\psi_V^* \psi_\gamma\right)_T$ - photon-meson wave function → Boosted Gaussian;
  - $\sigma_{dip}^{proton}(x, r)$ - dipole cross section → GBW and CGC models;;

- Then, the photoproduction cross section will be

$$\sigma(\gamma p \to Vp) = \frac{\left|\mathrm{Im}\, A_{\mathrm{proton}}(x, t=0)\right|^2}{16\pi B_V} \left(1 + \beta(\lambda_{eff})^2\right) R_g^2(\lambda_{eff})$$

  - $x = \left(M_V^2 + Q^2\right) / \left(Q^2 + 2\omega\sqrt{s_{NN}}\right)$ and B_V is the slope parameter;
  - $\beta(\lambda_{eff}) = \frac{\mathrm{Re}\, A_{proton}(x,t=0)}{\mathrm{Im}\, A_{proton}(x,t=0)}$ restores the real contribution of the $A_{proton}(x, t=0)$;
  - $R_g^2(\lambda_{eff})$ - skewedness effect.

The Photoproduction Cross Section

- For $\gamma - A$ interaction, the forward scattering amplitude is given by

$$\mathrm{Im}\, A_{\mathrm{nuc}}(x, t=0) = \int\int \frac{d^2 r dz}{4\pi} \left(\psi_V^* \psi_\gamma\right)_T \sigma_{\mathrm{dip}}^{\mathrm{nuc}}(x, r)$$

where

$$\sigma_{\mathrm{dip}}^{\mathrm{nuc}}(x, r) = 2\int d^2 b' \left\{1 - \exp\left[-\frac{1}{2} T_A(b') \sigma_{\mathrm{dip}}^{\mathrm{proton}}(x, r)\right]\right\}$$

b' is the photon-nuclei impact parameter.

$T_A(b')$ is the nuclear profile function;

- Then, the photoproduction cross section will be

$$\sigma(\gamma A \to VA) = \frac{|\mathrm{Im}\, A_{nuc}(x, t=0)|^2}{16\pi} \left(1 + \beta(\lambda_{eff})^2\right) R_g^2(\lambda_{eff}) \int_{t_{min}}^{\infty} |F(t)|^2\, dt$$

$F(t)$ - electromagnetic form factor and $t_{min} = \left(M_V^2 / 2\omega\gamma\right)^2$;

Introduction

UPC Collisions

pp Collisions

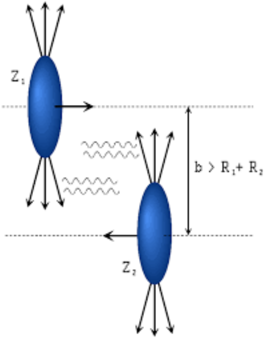
pA Collisions

AA Collisions

Peripheral Collisions

Summary

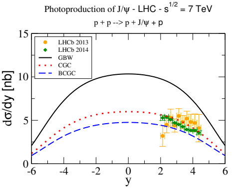
Ultraperipheral Collisions

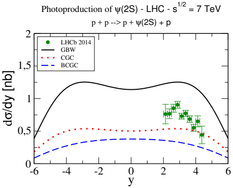


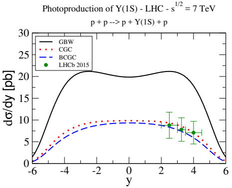
Results for $\sqrt{s} = 7$ TeV in pp collisions

- Comparison of the rapidity distribution for pp collisions with the LHCb data[1]

$$\frac{d\sigma}{dy}(pp \to p \otimes V \otimes p) = \omega \frac{dN_\gamma}{d\omega}\sigma(\gamma p \to Vp) + (y \to -y)$$







- *GBW* model overestimates the data.

Parametrization: M. Kozlov, A. Shoshi and W. Xiang - JHEP 0710 (2007) 020.

- The other models are consistent with the data of J/ψ and $Y(1S)$.

M. B. Gay Ducati, F. Kopp, M. V. T. Machado and S. Martins, PRD94, 094023 (2016).

[1] **R. Aaij *et al.*, J. Phys. G40, 045001 (2013); J. Phys. G41, 055002 (2014); JHEP 1509, 084 (2015).**

Results for $\sqrt{s} = 7$ TeV in pp collisions

- Total cross section corrected by acceptance and branching ratio ($BR_{V\to\mu^+\mu^-}$).

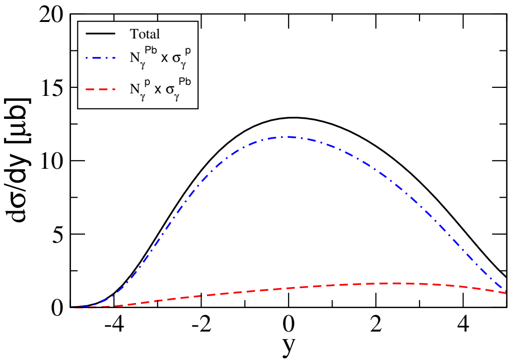
$\sqrt{s} = 7$ TeV	GBW	CGC	b-CGC	LHCb
J/ψ [pb]	553.87	316.82	246.29	291±20 pb
$\psi(2S)$ [pb]	10.80	4.64	2.76	6.5±1.0 pb
$Y(1S)$ [pb]	22.05	9.25	8.05	9.0±2.7 pb
$Y(2S)$ [pb]	4.16	1.71	1.59	1.3±0.85 pb
$Y(3S)$ [pb]	2.07	0.87	0.83	$<$3.4 pb

Results for $\sqrt{s} = 5.02$ TeV in pA collisions

$$\frac{d\sigma}{dy}(pPb \to p \otimes V \otimes Pb) = \omega(y) N_{\gamma}^{p}(\omega(y)) \sigma_V^{\gamma Pb}(\omega(y)) + \omega(-y) N_{\gamma}^{Pb}(\omega(-y)) \sigma_V^{\gamma p}(\omega(-y))$$

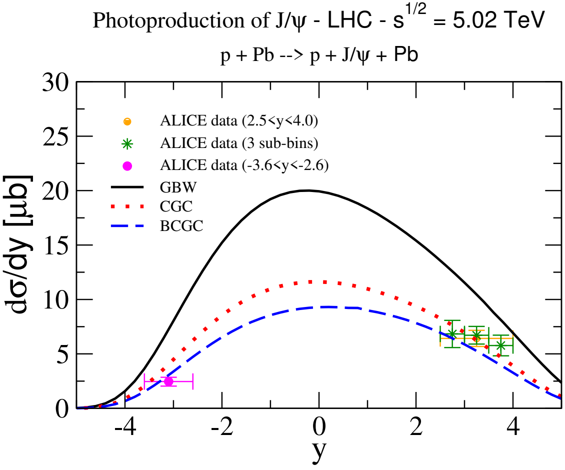
Photoproduction of J/ψ - LHC - $s^{1/2}$ = 5.02 TeV

p + Pb --> p + J/ψ + Pb



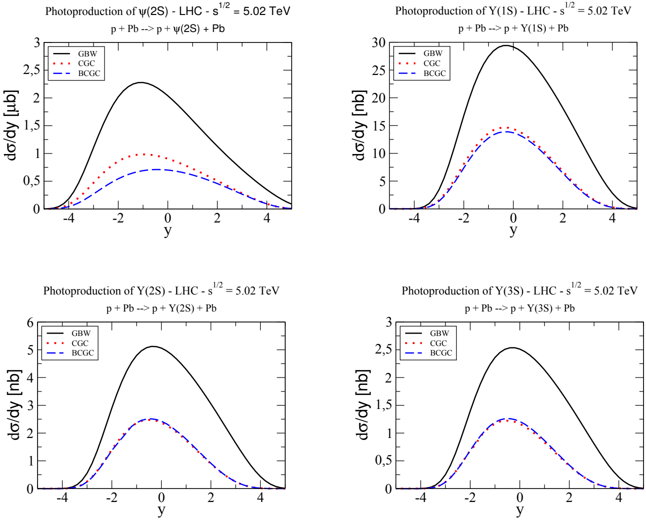
Results for $\sqrt{s} = 5.02$ TeV in pA collisions

- Comparison of the rapidity distribution for pA collisions with the ALICE data[2]



[2] B. B. Abelev et al. Phys. Rev. Lett. 113, (2014) 232504

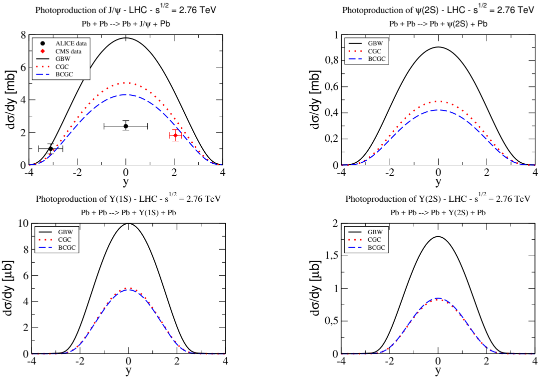
Results for $\sqrt{s} = 5.02$ TeV in pA collisions



Results for $\sqrt{s} = 2.76$ TeV in AA collisions

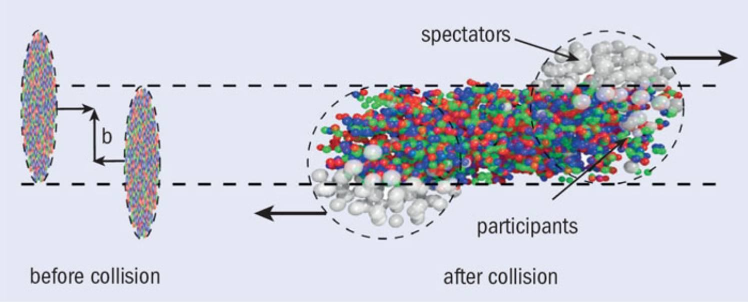
- Comparison of the rapidity distribution for AA collisions with the ALICE data[3]

$$\frac{d\sigma}{dy}(AA \to A \otimes V \otimes A) = \omega \frac{dN(\omega)}{d\omega}\sigma(\gamma A \to VA) + (y \to -y)$$



[3] B. Abelev *et al.*, Phys. Lett. B718, 1273 (2013); E. Abbas *et al.*, Eur. Phys. J. C73, 2617 (2013).

Peripheral Collisions



Introduction

UPC Collisions

Peripheral Collisions

Experimental Data

b-Dependence

The eff. Photon Flux

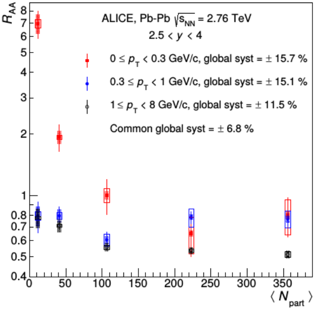
The eff. Photonuclear Cross Section

Summary

ALICE Measurements - J/ψ

- The nuclear modification factor (R_{AA}) is given by [4]

$$R_{AA}^{hJ/\psi} = \frac{N_{AA}^{J/\psi}}{BR_{J/\psi\to l^+l^-} \cdot N_{events} \cdot (A\times\varepsilon)_{AA}^{J/\psi} \cdot \langle T_{AA}\rangle \cdot \sigma_{pp}^{hJ/\psi}}$$



- $N_{AA}^{J/\psi} \to$ raw number of J/ψ
- $BR_{J/\psi\to l^+l^-} = 5.96\%$
- $N_{events}{}^{a} \simeq 10.6\times 10^7$
- $(A\times\varepsilon)_{AA}^{J/\psi} \sim 11.31\%$
- $\langle T_{AA}\rangle^{b} = \begin{cases} 3.84\ \mathrm{mb}^{-1}, & 30\% - 50\% \\ 0.954\ \mathrm{mb}^{-1}, & 50\% - 70\% \\ 0.17\ \mathrm{mb}^{-1}, & 70\% - 90\% \end{cases}$
- $\sigma_{pp}^{hJ/\psi} = 0.0514\mu b$

[a] ALICE Coll., B. Abelev et al., PLB734, 314, (2014)

[b] ALICE Coll., B. Abelev et al., PRC88, 044909, (2013)

[4] ALICE Collaboration, J. Adam et al., Phys. Rev. Lett. 116, 222301, (2016)

GFPAE

ALICE Measurements - J/ψ

- The Average Rapidity Distribution

$$\left.\frac{d\sigma}{dy}\right|_{2.5<y<4.0} = \frac{1}{\Delta y}\int_{2.5}^{4.0}\frac{d\sigma}{dy}dy$$

- ALICE measurements [5]

$p_T < 0.3$ GeV/c and $\sqrt{s_{NN}} = 2.76$ TeV

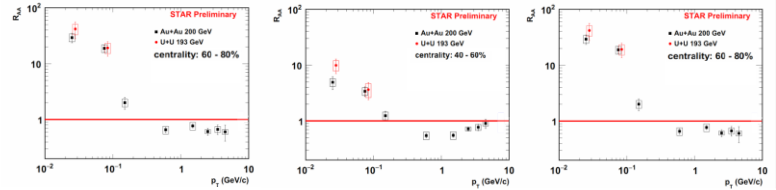
Cent.%	$N_{AA}^{J/\psi}$	$N_{AA}^{hJ/\psi}$	$N_{AA}^{\mathrm{excess}J/\psi}$	$d\sigma^{\mathrm{coh}}_{J/\psi}/dy$ [μb]
0-10	339±85±78	406±14±55	<251	<318
10-30	373±87±75	397±10±61	<237	<290
30-50	187±37±15	126±4±15	62±2±5	$73\pm44^{+26}_{-27}\pm10$
50-70	89±13±2	39±2±5	50±14±5	$58\pm16^{+8}_{-10}\pm8$
70-90	59±9±3	8±1±1	51±9±3	$59\pm11^{+7}_{-10}\pm8$

- $N_{AA}^{J/\psi} \rightarrow$ raw number of J/ψ.
- $N_{AA}^{\mathrm{excess}J/\psi} \rightarrow$ excess of J/ψ.
- $N_{AA}^{hJ/\psi} \rightarrow$ raw hadronic number of J/ψ.

[5] ALICE Collaboration, J. Adam et al., Phys. Rev. Lett. 116, 222301, (2016)

STAR Measurements - J/ψ

- R_{AA} as a function of p_T for mid-rapidity ($|y| < 1$) [6].
- $\sqrt{s} = 200$ GeV for Au-Au and $\sqrt{s} = 193$ GeV for U-U.
- More intense excess for **60%-80%** centrality bin.
- The J/ψ excess is still present for **40%-60%** centrality class.



[6] W. Zha (STAR Collaboration), Journal of Physics: Conference Series 779, 012039 (2017).

b-Dependence Photon Flux

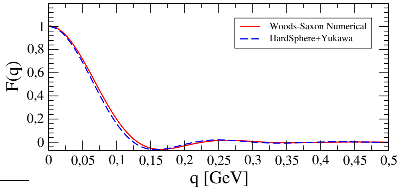
- For peripheral collisions $\rightarrow N(\omega, b)$ with b-dependence [7],

$$\frac{dN(\omega,b)}{d\omega db^2} = \frac{Z^2\alpha_{qed}}{\pi^2\omega}\left|\int d^2k_T k_T^2 \frac{F(k)}{k^2} J_1(k_T b)\right|^2$$

- Yukawa potential+hard sphere (more realistic for lead) [8],

$$F(k) = \frac{4\pi\rho_0}{Ak^3}\left[\sin\,(kR_A) - kR_A\cos\,(kR_A)\right]\left[\frac{1}{1+a^2k^2}\right]$$

- $k^2 = (\omega/\gamma)^2 + k_\perp^2$.
- $\rho_0 = 0.1385$ fm and $a = 0.7$ fm
- A=208 and $R_A = 1.2A^{1/3}$ fm



[7] F. Krauss, M. Greiner and G. Soff, Prog. Part. Nucl. Phys. 39, 503, (1997)

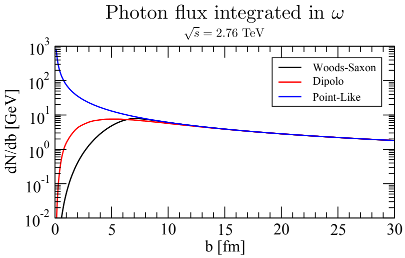
[8] K. T. R. Davies and J. R. Nix, Phys. Rev. C14, 1977 (1976).

Comparing the Form Factors

- Centrality classes and related impact parameters range:

Centrality Classes	Glauber Model		ALICE	
	b_{min} (fm)	b_{max} (fm)	b_{min}^{exp} (fm)	b_{max}^{exp} (fm)
30%-50%	7.77	10	8.55	11.04
50%-70%	10	11.87	11.04	13.05
70%-90%	11.87	13.47	13.05	14.96

- Analysis of the different form factors



Point Like (used in UPC)

- $F(k^2) = 1$.

Dipole Form Factor

- $F_{dip}(k^2) = \frac{\Lambda^2}{\Lambda^2+k^2}$.

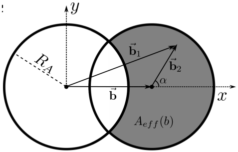
Woods-Saxon+Yukawa

- $F_{WSY}(k^2) = \frac{4\pi\rho_0}{Ak^3}\left[\sin(kR_{Pb}) - kR_{Pb}\cos(kR_{Pb})\right]\left[\frac{1}{1+a^2k^2}\right]$.

The Effective Photon Flux

- Considering an effective photon flux [9]:

$$\sigma_X = \int \omega \frac{dN^{eff}(\omega)}{d\omega} \sigma_X(\omega)$$



- **Hypothesis:** Only spectators interact coherently with the photon.

- In this scenario, $\frac{dN^{eff}(\omega,b)}{d\omega}$ can be described as [10]

$$N^{eff}(\omega,b) = \frac{1}{A_{eff}(b)} \int N^{usual}(\omega,b_1)\theta(b_1 - R_A)\theta(R_A - b_2)d^2 b_2$$

- $A_{eff} = R_A^2\left[\pi - 2\cos^{-1}(b/2R_A)\right] + (b/2)\sqrt{4R_A^2 - b^2}$ and $b_1^2 = b^2 + b_2^2 + 2bb_2\cos(\alpha)$

[9] M. K. Gawenda and A. Szczurek, Phys. Rev. C93, 044912, (2016).

[10] M. B. Gay Ducati and S. Martins, Phys. Rev. D97, 116013, (2018).

The Effective Photonuclear Cross Section

- The forward scattering amplitude is given by

$$\mathrm{Im}\,\mathscr{A}_{nuc}(x,t=0)=\int\frac{d^2r dz}{4\pi}\left(\psi_V^*\psi_\gamma\right)_T\sigma_{\mathrm{dip}}^{\mathrm{nucleus}}(x,r)$$

where

$$\sigma_{\mathrm{dip}}^{\mathrm{nucleus}}(x,r)=2\int d^2b'\left\{1-\exp\left[-\frac{1}{2}T_A(b')\sigma_{\mathrm{dip}}^{\mathrm{proton}}(x,r)\right]\right\}$$

- For consistency with the construction of $N^{eff}(\omega,b)$, restrict $\sigma_{dip}^{nucleus}(x,r)$:

$$\sigma_{\mathrm{dip}}^{\mathrm{nucleus}}(x,r)=2\int d^2b_2\Theta(b_1-R_A)\left\{1-\exp\left[-\frac{1}{2}T_A(b_2)\sigma_{\mathrm{dip}}^{\mathrm{proton}}(x,r)\right]\right\}$$

- $b_1^2=b^2+b_2^2+2bb_2\cos(\alpha)$.

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Our results for dσ/dy

- Essencially, three modification were considered

  - b-dependence.
  - Effective photon flux.
  - Effective Photonuclear cross section.

- Comparing with ALICE data,

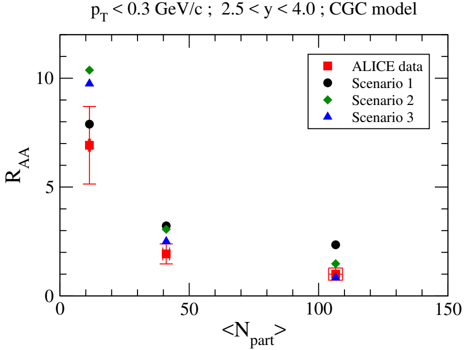
Average Rapidity Distribution: $2.5 < y < 4.0$

GBW / CGC	$d\sigma^{\text{theo}}_{J/\psi}/dy$ [μb]	$d\sigma^{\text{exp}}_{J/\psi}/dy$ [μb]
30%-50%	134 / 85	$73 \pm 44^{+26}_{-27} \pm 10$
50%-70%	145 / 91	$58 \pm 16^{+8}_{-10} \pm 8$
70%-90%	138 / 87	$59 \pm 11^{+7}_{-10} \pm 8$

- Better agreement for CGC model.

Our results for R_{AA}

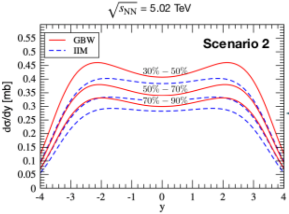
- Black circles: only the b-dependence
  - Best agrees with the data only in the more peripheral region;
- Green losangle: b-dependence + effective photon flux
  - Better results were achieved for the more central classes;
- Blue triangle: All the three modifications was applyed
  - A slight correction in direction to data in relation to last case;



Our results: Quark Matter 2022

J/ψ photoproduction in peripheral collisions

- **Transition from ultra-peripheral to peripheral collisions:**
  - Need to account for the geometrical constraints of a given impact parameter
  - Modification of the photon flux / photonuclear cross section



Scenario 1: UPC like
Scenario 2: effective photon flux
Scenario 3: effective photon flux + photonuclear cross section

IIM: Color Glass Condensate approach
GBW: light cone dipole formalism

M. B. Gay Ducati et al., PRD 97 (2018) 11

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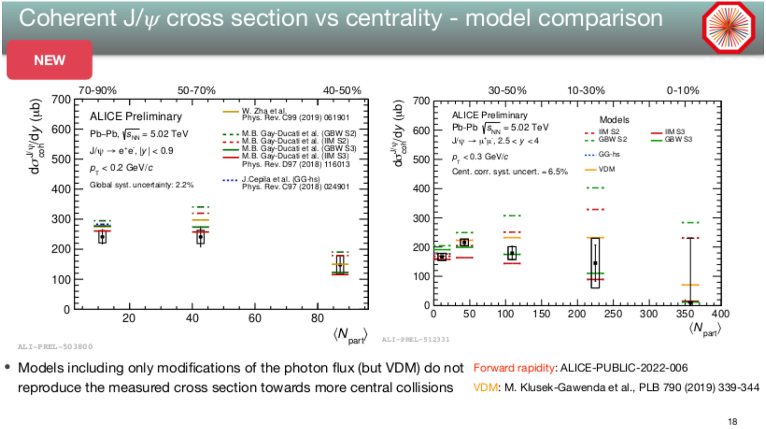
Quark Matter 2022 - A. Neagu

Our results: Quark Matter 2022



Quark Matter 2022 - A. Neagu

Our results: Quark Matter 2022

Coherent J/ψ cross section at forward rapidity

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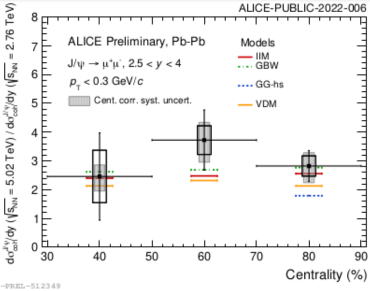

- Ratio of the measurements at $\sqrt{s_{NN}}$ = 5.02 TeV and $\sqrt{s_{NN}}$ = 2.76 TeV shows no centrality dependence within uncertainties
- Fair agreement of the measured ratio to models (except GG-hs) within uncertainties

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Quark Matter 2022 - A. Neagu

UPC vs Peripheral

The Effective Photon Flow

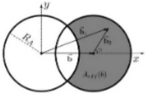


Fig. 1: Scheme of the interaction according to scenario 2.

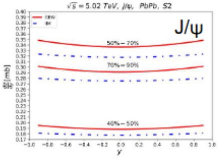
- From the standard photon flux (N^{usual}) emitted by the projectile nucleus, only the photons that reach the geometric region of the target nucleus will be considered;
- Photons that reach the nuclear superposition region will be discarded (dominated by the strong interaction).

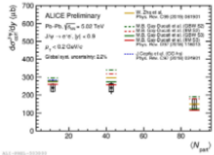
effective photon flow:

$$N^{eff}(\omega, b) = \int N^{usual}(\omega, b_1)\frac{\theta(b_1 - R_A)\theta(R_A - b_2)}{A_{eff}(b)}d^2b_2$$

spectators area:

$$A_{eff}(b) = R_A^2\left[\pi - 2\cos^{-1}\left(\frac{b}{2R_A}\right)\right] + \frac{b}{2}\sqrt{4R_A^2 - b^2}$$





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UPC vs Peripheral

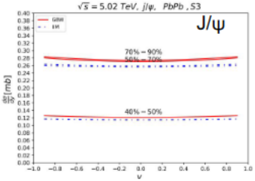
The effective photonuclear cross section

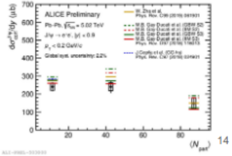
- Applying the same geometric constraint on the photonuclear cross section.
    - The dipole-core interaction will be restricted to only the dipole interaction with the part of the core that forms the spectator region

$$\sigma_{\rm dip}^{\rm nucleus}(x,r) = 2\int d^2b_2\Theta(b_1 - R_A)\left\{1 - \exp\left[-\frac{1}{2}T_A(b)\sigma_{\rm dip}^{\rm proton}(x,r)\right]\right\}$$

$$b_1^2 = b^2 + b_2^2 + 2bb_2\cos(\alpha)$$

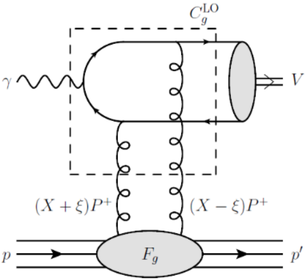
➢ Effective photon flux and an effective photonuclear cross section

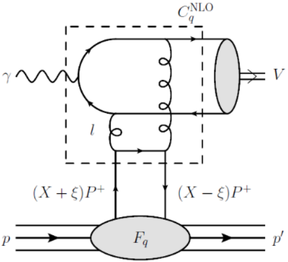




NLO study in pQCD

- Scale dependence
- Gluons and quarks contributions (!)
- Nuclear effects





- only gluons GPD's

- Gluons + quarks GPD's

[Ivanov et al., Eur. Phys. J. C 34 (2004) no. 3, 297]

How about data (LHC)?

Figures from C. Flett, PhD thesis [Flett:2021xsl]

NLO study in pQCD: amplitude

K. Eskola et al., arXiv:2203.11613 [hep-ph]

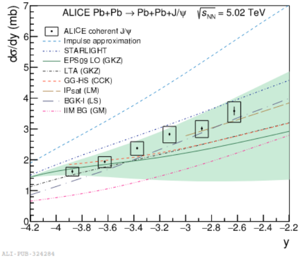
$$\mathcal{M}^{\gamma N \to VN} \propto \langle O_1 \rangle_V^{1/2} \int_{-1}^{1} dx [T_g(x,\xi) F^g(x,\xi,t) + T_q(x,\xi) F^{q,S}(x,\xi,t)],$$

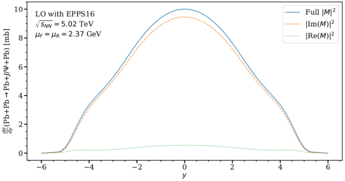
- $\langle O_1 \rangle_V^{1/2}$ NRQCD element
- T_g *and* T_q hard scattering functions from pQCD[1], scale dependent (μ_F, μ_R)
- F^g *and* $F^{q,S}$ GPDs[2], nonperturbative (μ_F)

$$|\mathcal{M}|^2 = |\mathcal{M}_G^{\text{LO}} + \mathcal{M}_G^{\text{NLO}}|^2 + |\mathcal{M}_Q^{\text{NLO}}|^2 + 2\Big[\text{Re}(\mathcal{M}_G^{\text{LO}} + \mathcal{M}_G^{\text{NLO}})\text{Re}(\mathcal{M}_Q^{\text{NLO}}) + \text{Im}(\mathcal{M}_G^{\text{LO}} + \mathcal{M}_G^{\text{NLO}})\text{Im}(\mathcal{M}_Q^{\text{NLO}})\Big].$$

[1] D. Y. Ivanov, A. Schafer, L. Szymanowski, G. Krasnikov, Eur. Phys. J. C 34 (2004) no. 3, 297 [Erratum: Eur.Phys.J.C 75, 75 (2015)]
[2] J. C. Collins, L. Frankfurt and M. Strikman, Phys. Rev. D 56 (1997) 2982

Comparison of LO for exclusive J/ψ photoproduction in PbPb





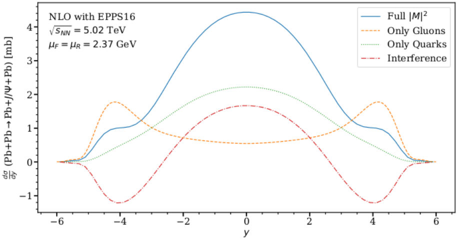
- In pQCD and QCD models
- Linear and non-linear evolution equations

ALI-PUB-324284

- In pQCD
- The $|Re(M)|^2$ in LO is almost irrelevant.

K. Eskola et al., arXiv:2203.11613 [hep-ph]

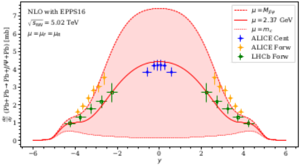
NLO for exclusive J/ψ photoproduction in PbPb (pQCD): contributions of quark, gluons and interference term

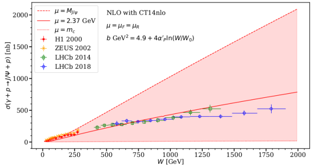


- How the quark, gluons and interference terms contribute to final amplitude.

K. Eskola et al., arXiv:2203.11613 [hep-ph]

NLO for exclusive J/ψ photoproduction in PbPb (pQCD)





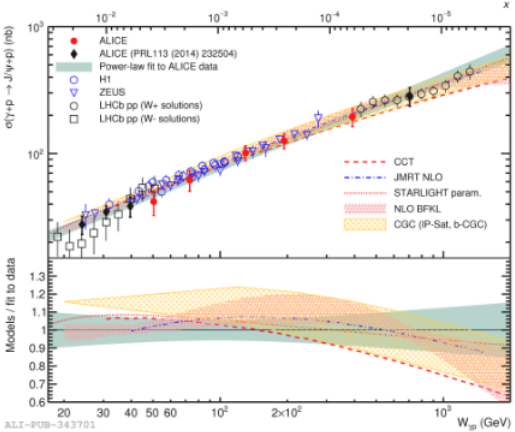
- Considerable difference at forward direction for ALICE and LHCb

- "The best value" for the μ scale is in agreement with data. However, there is a large uncertainty on μ scale.

$$M_{j/\psi}/2 < \mu < M_{j/\psi}$$

K. Eskola et al., arXiv:2203.11613 [hep-ph]

Energy depence for J/ψ photoproduction: CGC, NLO BFKL and others



- These models consider only gluons: NLO BFKL (K-factor), JMNRT NLO (K-factor).

Conclusions and a Look Ahead

- Exclusive quarkonium photoproduction off protons in p-Pb UPC
  - Probe the gluon density at low x
  - Search for gluon saturation effects
- Light vector mesons photoproduction in UPC provides
  - Test theoretical models
  - Study shadowing effects in the nonperturbative regime
- Photoproduction in peripheral collisions
  - Complements the knowledge on hadroproduction
  - Learning on nuclear medium and quark gluon plasma
- LO calculations require comparison to NLO
  - Role of quark contribution in heavy vector meson production
  - Confrontation data on different energies, y's, centralities...