New Vistas in Photon Physics in Heavy-Ion Collisions

Kraków, September 2022

László Jenkovszky

Ultra-peripheral physics at the LHC

Based on papers written in collaboration with

Slava Libov and Magno Machado,

Physics Letters, B v. 824 (2022) 136836 &

ibid: v. 827 (2022) 137004 .

Abstract

Coherent photoproduction of charmonium in peripheral heavy-ion collisions at the Large Hadron Collider (LHC) is studied. The centrality dependence is investigated and compared to the experimental results for coherent J/ψ production in lead-lead LHC runs at the energies of 2.76 and 5.02 TeV.

Outline

- 1. UPC and Difffractive dissociation
- 2. The photon and pomeron
- 3. The UPC formalism
- 4. Vector meson production (VMP)
- 5. From nucleons to nuclei (Glaber)
- *Items 4 and 5 are interchangeable (“factorization”)*
- 6. Results and discussion

UPC & Central Diffractioon Dissociation

Figure: Feynman diagram of vector meson production in ultra-peripheral collision of hadronic/muclei

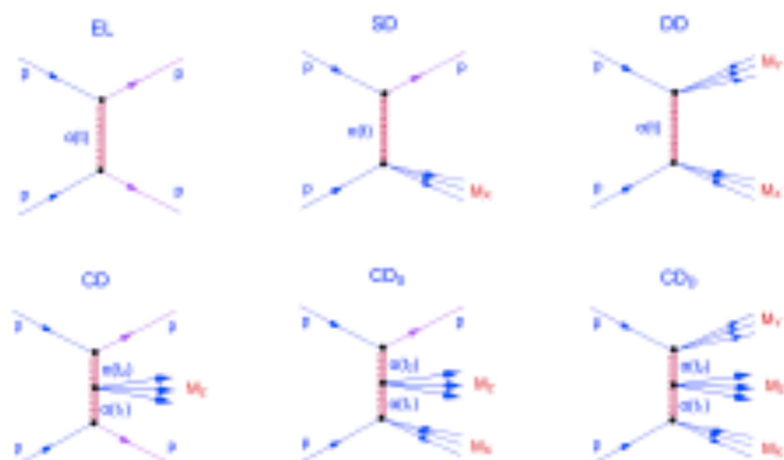


Figure: Single, double and central diffractive dissociation of protons

The pomeron-proton vertices as:

$$\tilde{W_2}^{Pp}(M_X^2, t) \equiv \frac{W_2^{Pp}(M_X^2, t)}{2m_p}, \tag{7}$$

where

$$W_2^{Pp}(M_X^2, t) = \frac{F_2^p(M_X^2, t)}{\nu(M_X^2, t)}, \quad F_2^p(M_X^2, t) = \frac{-t(1-x)}{4\pi\alpha(1-4m_p^2x^2/t)}\sigma_t^{Pp}(M_X^2, \tag{8}$$

σ_t^{Pp} is the total pomeron-proton cross section, m_p is the mass of the proton, α being the fine structure constant

$$x \equiv x(M_X^2, t) = \frac{-t}{M_X^2 - t - m_p^2}, \tag{9}$$

$$\nu(M_X^2, t) = \frac{-t}{2m_p x(M_X^2, t)}. \tag{10}$$

From VPP to UPC

We use a simple parametrization of the $\sigma_{\gamma p \to Vp}(W)$ cross section, suggested by Donnachie and Landshoff:
$\sigma_{\gamma p \to Vp}(W) \sim W^{\delta},\ \delta \approx 0.8.$
The differential cross section as function of the rapidity Y reads

$$\frac{d\sigma(h_1 + h_2 \to h_1 + V + h_2)}{dY} = \omega_+ \frac{dN_{\gamma/h_1}(\omega_+)}{d\omega} \sigma_{\gamma h_2 \to V h_2}(\omega_+) + \omega_- \frac{dN_{\gamma/h_2}(\omega_-)}{d\omega} \sigma_{\gamma h_1 \to V h_1}(\omega_-), \quad (4)$$

where

$\frac{dN_{\gamma/h}(\omega)}{d\omega}$ is the "equivalent" photon flux, defined as

$$\frac{dN_{\gamma/h}(\omega)}{d\omega} = \frac{\alpha_{em}}{2\pi\omega}[1+(1-\frac{2\omega}{\sqrt{s}})^2](\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}), \quad (2)$$

and $\sigma_{\gamma p \to Vp}(\omega)$ is the total cross section of the vector meson photoproduction subprocess. ω is the photon energy, $\omega = W_{\gamma p}^2/2\sqrt{s}$, where $\sqrt{s}$ denotes now the c.m.s. energy of the proton-proton system; $\omega_{min} = M_V^2/(4\gamma_L m_p)$, where $\gamma_L = \sqrt{s}/(2m_p)$ is the Lorentz factor (Lorentz boost of a single beam); e.g., for pp at the LHC for $\sqrt{s} = 7$ TeV, $\gamma_L = 3731$. Furthermore, $\Omega = 1 + Q_0^2/Q_{min}^2$, with $Q_{min}^2 = (\omega/\gamma_L)^2$ and $Q_0^2 = 0.71\, GeV^2$, $Y \sim \ln(2\omega/M_V)$. The differential cross section in W can be calculated as $d\sigma/dW = (d\sigma/dY)/W$.

From hadrons to nuclei (Glauber)

Using the classical mechanics Glauber formula for multiple scattering, the differential cross section becomes:

$$\left.\frac{\mathrm{d}\sigma\left(\gamma A \rightarrow J/\psi A\right)}{\mathrm{d}t}\right|_{t=0} = \frac{\alpha_{em}}{4f_{J/\psi}^2}\left\{\int \mathrm{d}^2\mathbf{b}\left[1-\exp\left(-\sigma_{tot}\left(J/\psi p\right) T_A\left(\mathbf{b}\right)\right)\right]\right\}$$

where $T_A(b)$ is the nuclear thickness function and $f_{J/\Psi}$ is the vector-meson coupling, $f_{J/\Psi}^2/4\pi = 10.4$. The input for the Glauber model calculation is the cross section for the process $J/\psi + p \rightarrow J/\psi + p$, given by:

$$\sigma_{tot}\left(J/\psi p\right) = \sqrt{\frac{4f_{J/\psi}^2}{\alpha_{em}} \left.\frac{\mathrm{d}\sigma\left(\gamma + p \rightarrow J/\psi + p\right)}{\mathrm{d}t}\right|_{t=0}}. \tag{9}$$

Vector meson production (VMP) cross section in hadronic collisions can be written in a factorized form. The distribution in rapidity Y of the production of a vector meson V in the reaction $h_1 + h_2 \to h_1 V h_2$, (where h may be a hadron, e.g. proton, or a nucleus, pPb, PbPb,...) is calculated according to a standard prescription based on the factorization of the photon flux and photon-proton cross section.
The γp differential cross section depends on three variables: the total energy of the γp system, W, the squared momentum transfer at the proton vertex, t, and $\widetilde{Q}^2 = Q^2 + M_V^2$, where Q^2 is the photon virtuality and M_V is the mass of the produced vector meson. Since, by definition, in ultra-peripheral collisions we have $b >> R_1 + R_2$, where b is the impact parameter, i.e. the closest distance between the centres of the colliding particles/nuclei with radii R_i (i $= 1,2$), photons are nearly real, $Q^2 \simeq 0$, and M_V^2 remains the only measure of "hardness". Notice that this might not be true for peripheral collisions, where $b \sim R_1 + R_2$, and in the Pomeron or Odderon exchange instead of the photon.

VMP & Reggeometry

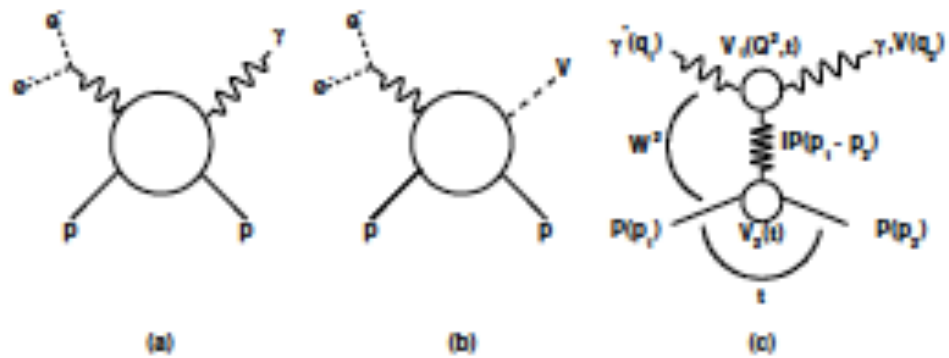


Figure: Diagrams of Deeply Virtual Compton scattering (DVCS) (a) and vector meson production (VPM) (b) in $e^{\pm}p$ scattering; (c) DVCS (VMP) amplitude in a Regge-factorized form.

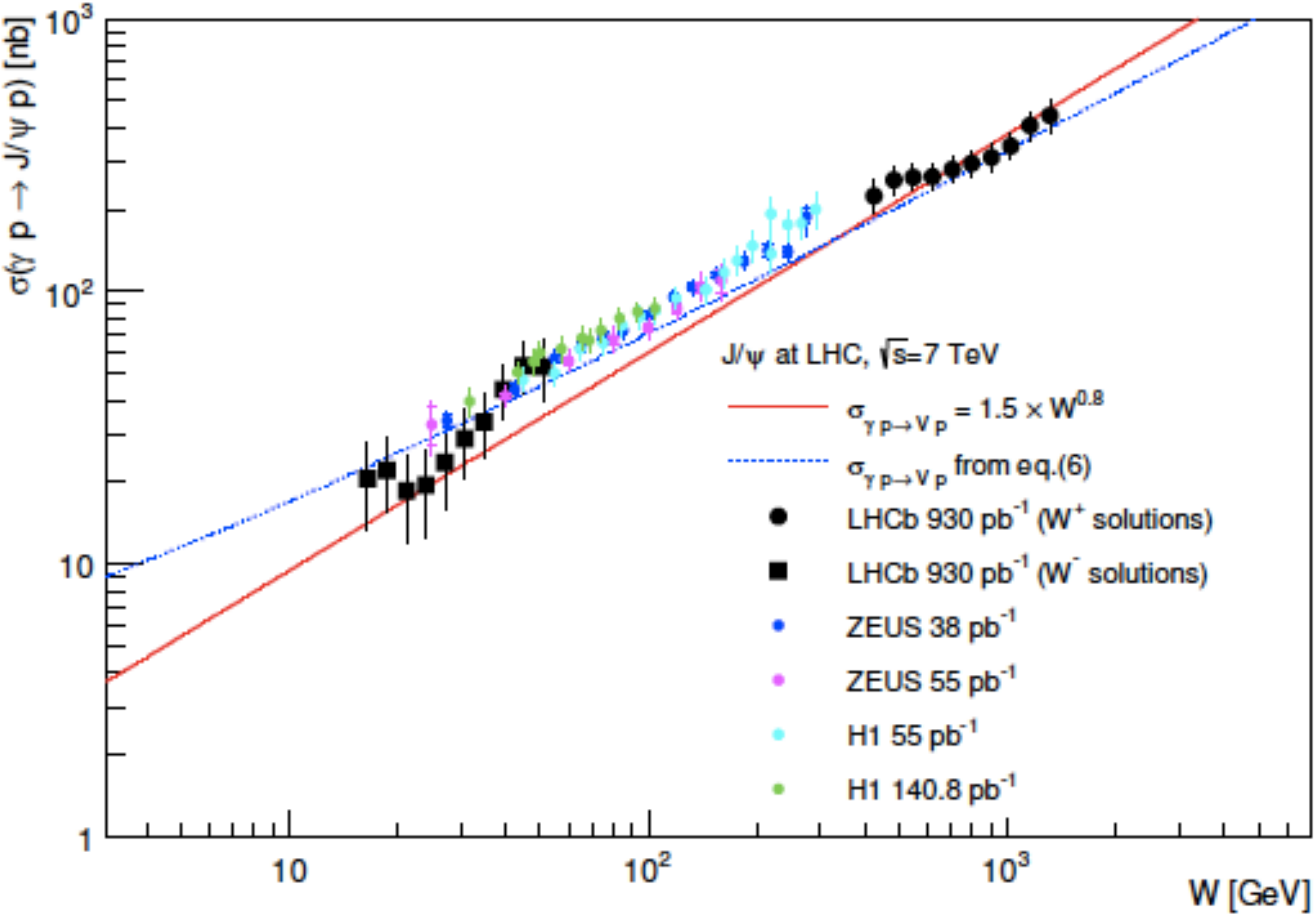
The scattering amplitude in the (single-component) Reggeometric Pomeron (RP) is :

$$\mathcal{A}_{\rm RP}(Q^2,s,t)=\frac{\widetilde{A_0}}{\left(1+\frac{\widetilde{Q^2}}{Q_0^2}\right)^n}e^{-\frac{i\pi\alpha(t)}{2}}\left(\frac{s}{s_0}\right)^{\alpha(t)}e^{(B_0/2)t}, \tag{3}$$

$$B_0(\widetilde{Q^2})=4\left(\frac{a}{\widetilde{Q^2}}+\frac{b}{2m_N^2}\right), \tag{4}$$

where the exponential factor in Eq. (4) reflects its geometrical nature. The center-of-mass energy of photon-nucleon system is $\sqrt{s}=W_{\gamma p}$ and the quantities $a/\widetilde{Q}^2$ and $b/2m_N^2$ in (4) correspond to the effective sizes of upper and lower vertices in Fig. 3-c.
The elastic differential cross section is:

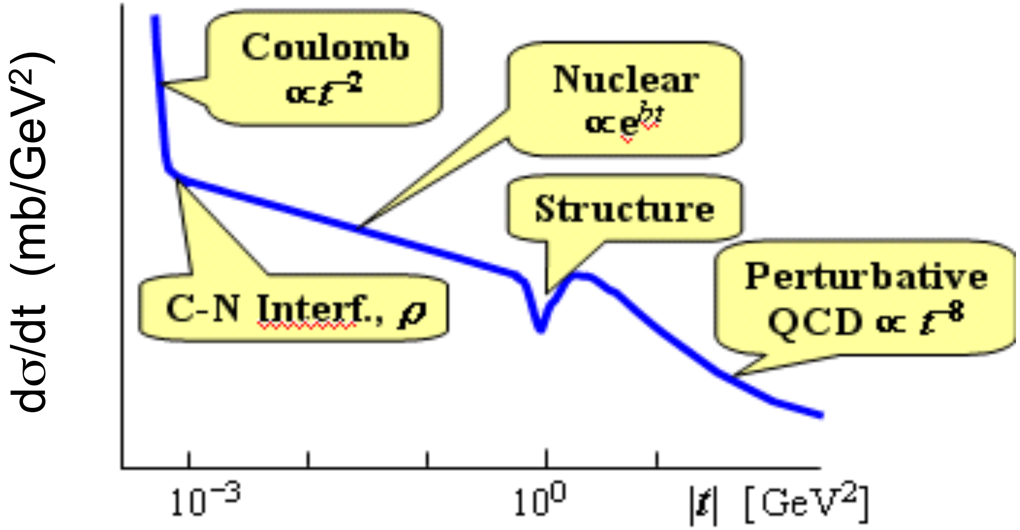
$$\frac{d\sigma_{el}}{dt}=\frac{A_0^2}{\left(1+\frac{\widetilde{Q^2}}{Q_0^2}\right)^{2n}}\left(\frac{s}{s_0}\right)^{2(\alpha(t)-1)}\exp\left[B_0(\widetilde{Q^2})\,t\right]. \tag{5}$$



$\sigma(\gamma\, p \to J/\psi\, p)$ [nb]
10^3
10^2
10
1
10
10^2
10^3
W [GeV]
J/ψ at LHC, $\sqrt{s}$=7 TeV
$\sigma_{\gamma\, p \to V\, p} = 1.5 \times W^{0.8}$
$\sigma_{\gamma\, p \to V\, p}$ from eq.(6)
LHCb 930 pb^{-1} (W^+ solutions)
LHCb 930 pb^{-1} (W^- solutions)
ZEUS 38 pb^{-1}
ZEUS 55 pb^{-1}
H1 55 pb^{-1}
H1 140.8 pb^{-1}

Elastic Scattering

$\sqrt{s}$ = 14 TeV prediction of BSW model



momentum transfer $-t \sim (p\theta)^2$

θ = beam scattering angle

p = beam momentum

$$\rho = \left. \frac{\mathrm{Re}(f_{el}(t))}{\mathrm{Im}(f_{el}(t))} \right|_{t \to 0}$$

$$\left. \frac{dN}{dt} \right|_{t=CNI} = L\pi |f_C + f_N|^2 \approx L\pi \left| -\frac{2\alpha_{\mathrm{EM}}}{|t|} + \frac{\sigma_{\mathrm{tot}}}{4\pi}(i+\rho)e^{-\frac{b|t|}{2}} \right|^2$$

L, σ_{tot}, b, and ρ from FIT in CNI region (UA4)

CNI region: $|f_C| \sim |f_N|$ → @ LHC: $-t \sim 6.5\ 10^{-4}$ GeV²; $\theta_{min} \sim 3.4$ μrad

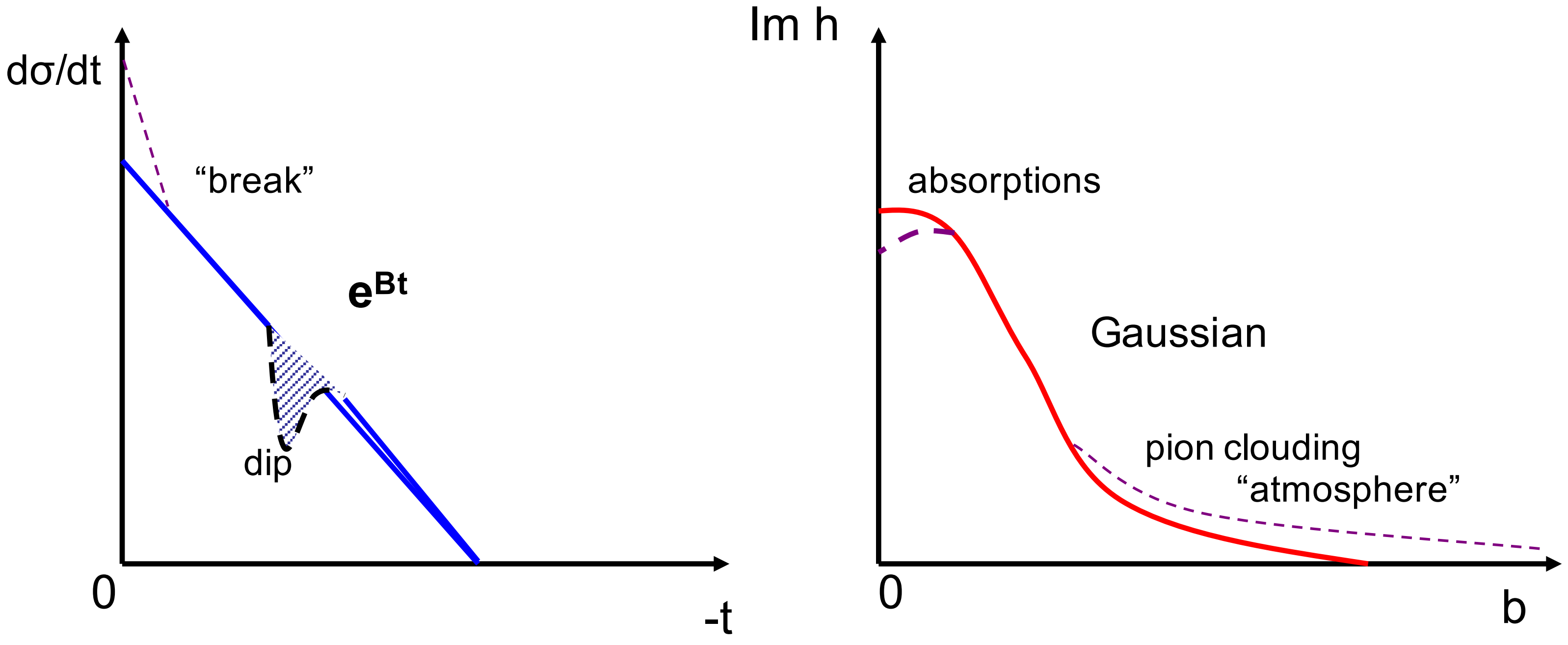
($\theta_{min} \sim 120$ μrad @ SPS)

Geometrical scaling (GS), saturation and unitarity

1. On-shell (hadronic) reactions (s,t, Q^2=m^2);

$t \leftrightarrow b$ **transformation:** $h(s,b) = \int_0^\infty d\sqrt{-t}\sqrt{-t}A(s,t)$

and dictionary:



Results (and important earlier references)

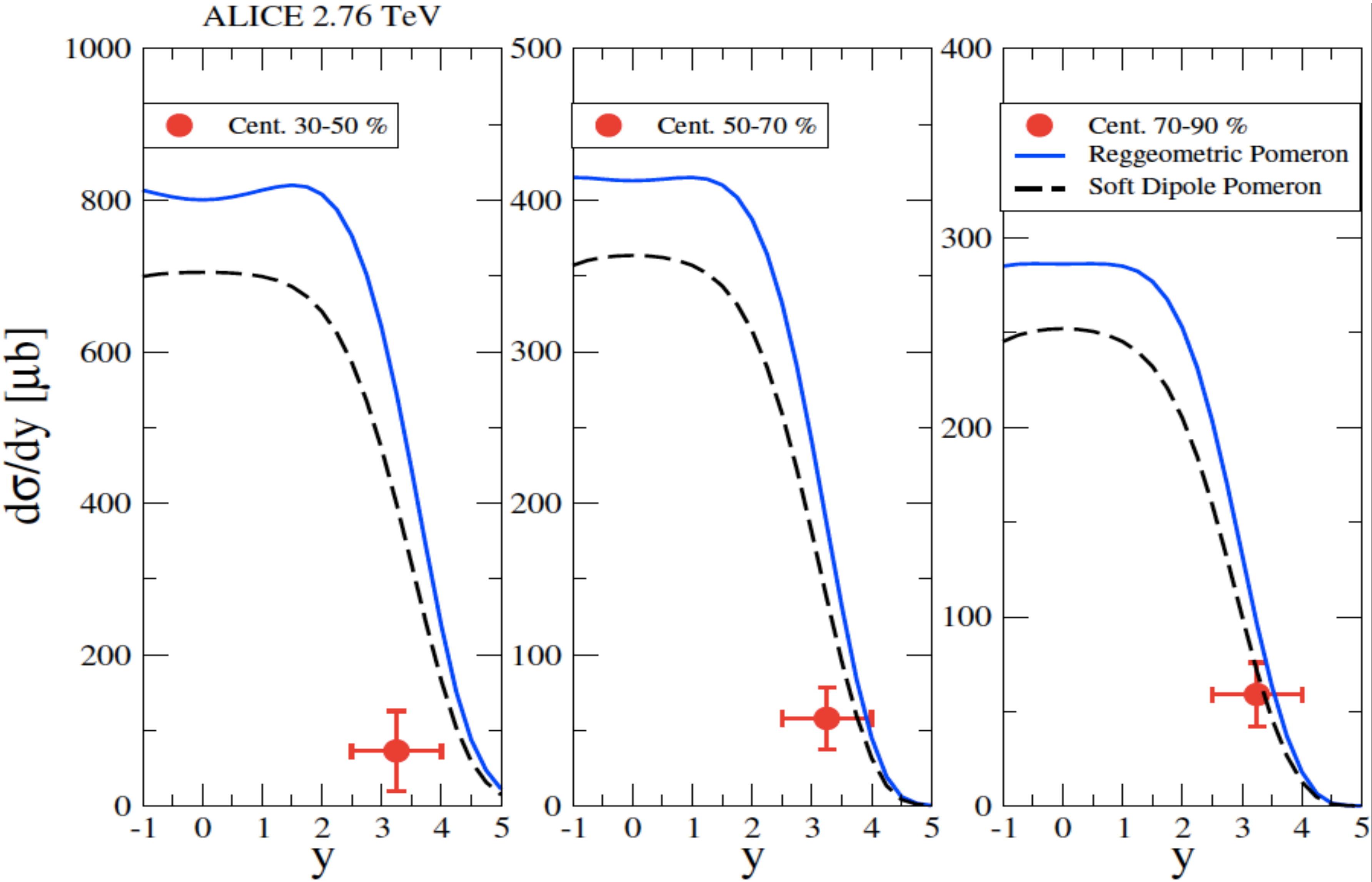
T.H. Baur, R.D. Spital, D.R. Yennie, and F.M. Pipkin, Rev. Mod. Phys. **50** (1978) 261.

S. Klein and J. Nystrand, Phys. Rev. **C60** (1999) 014903.

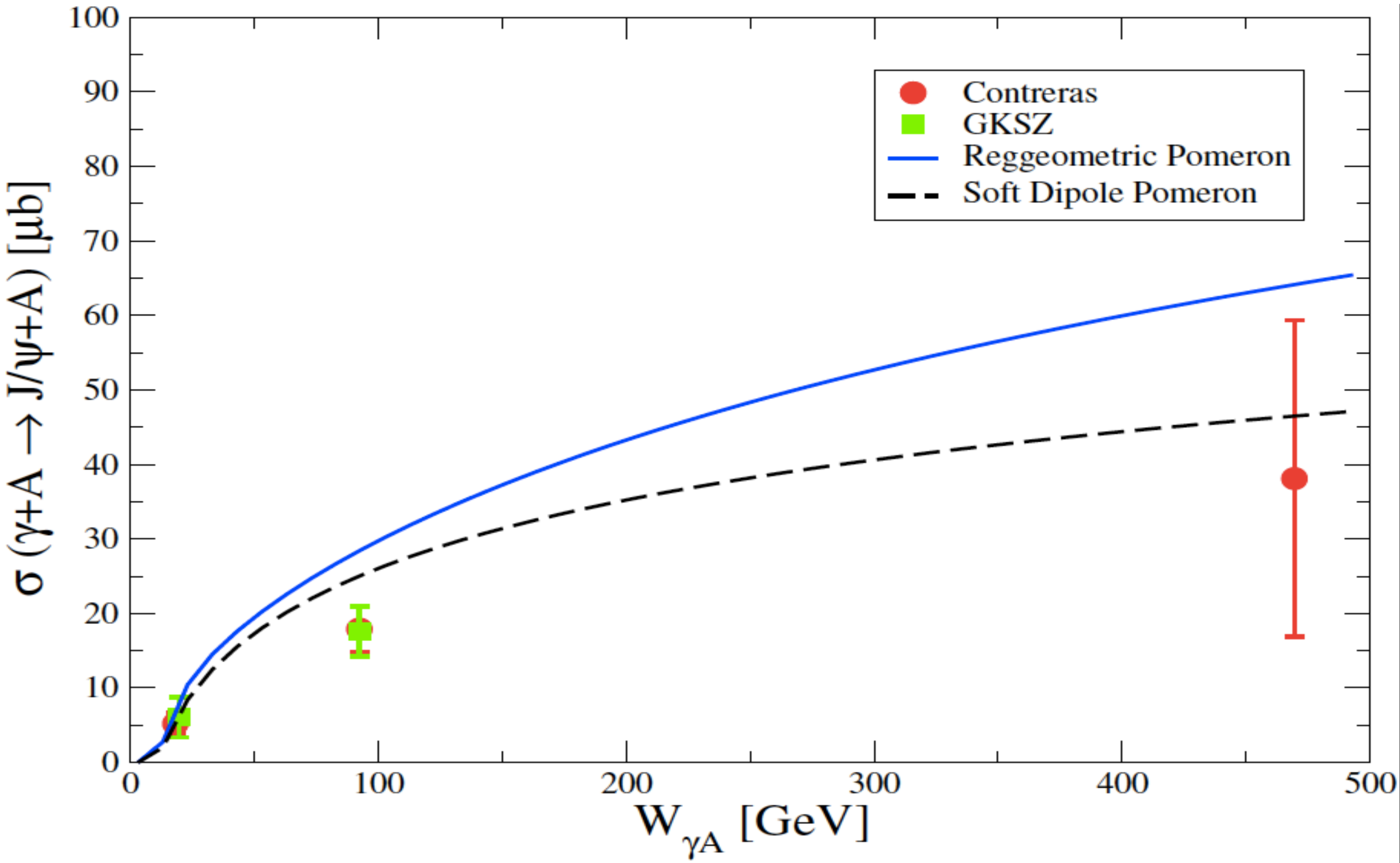
Mariola Klusek-Gawenda and Antoni Szczurek, Phys. Rev. **C93** (2016) 044912.

V.P. Gonçalves and M.V.T. Machado, Phys. Rev. **C84** (2011) 011902.

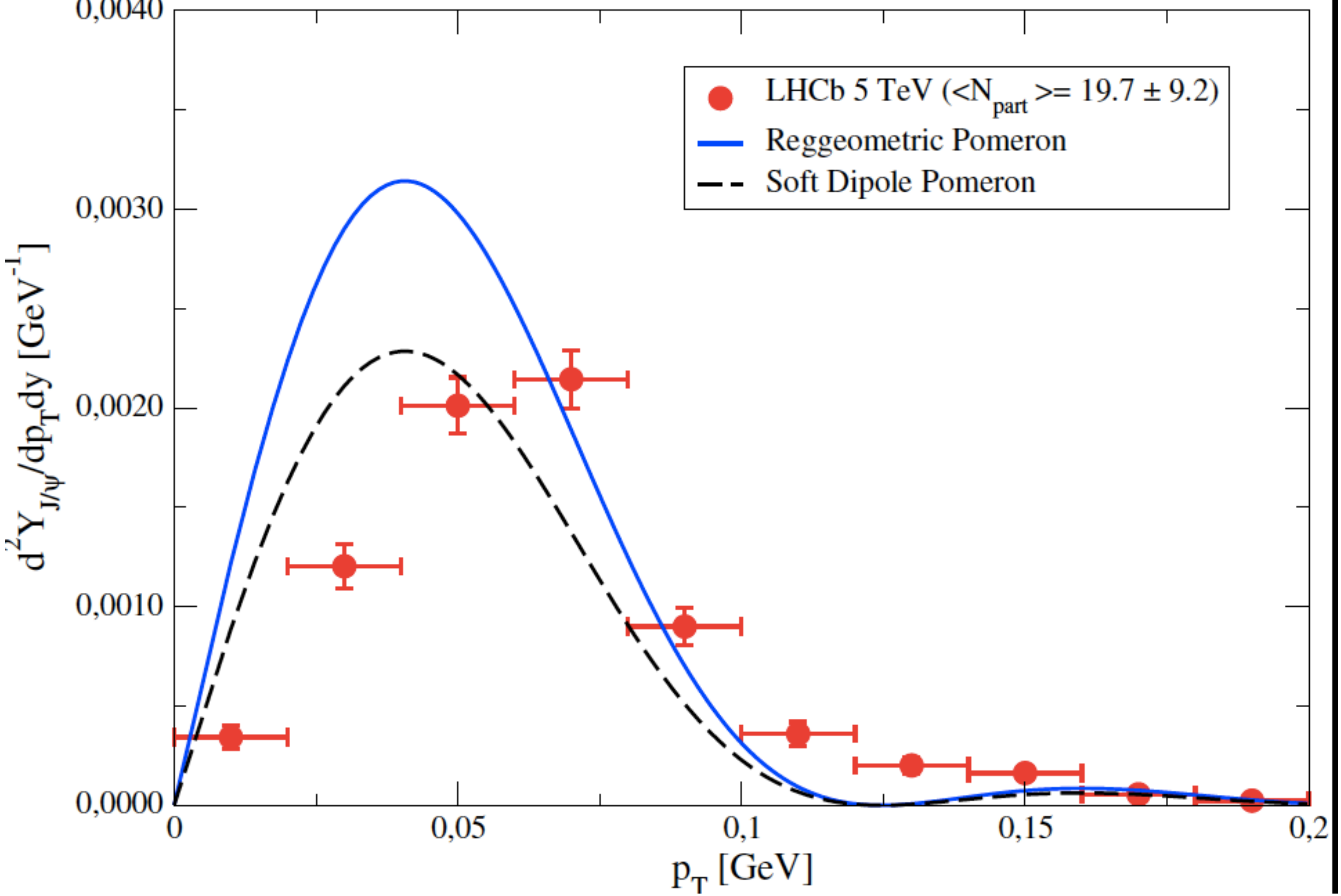
Reggeometry: S. Fazio *et al., Phys. Rev.* ***D90*** *(2014) 016007.*



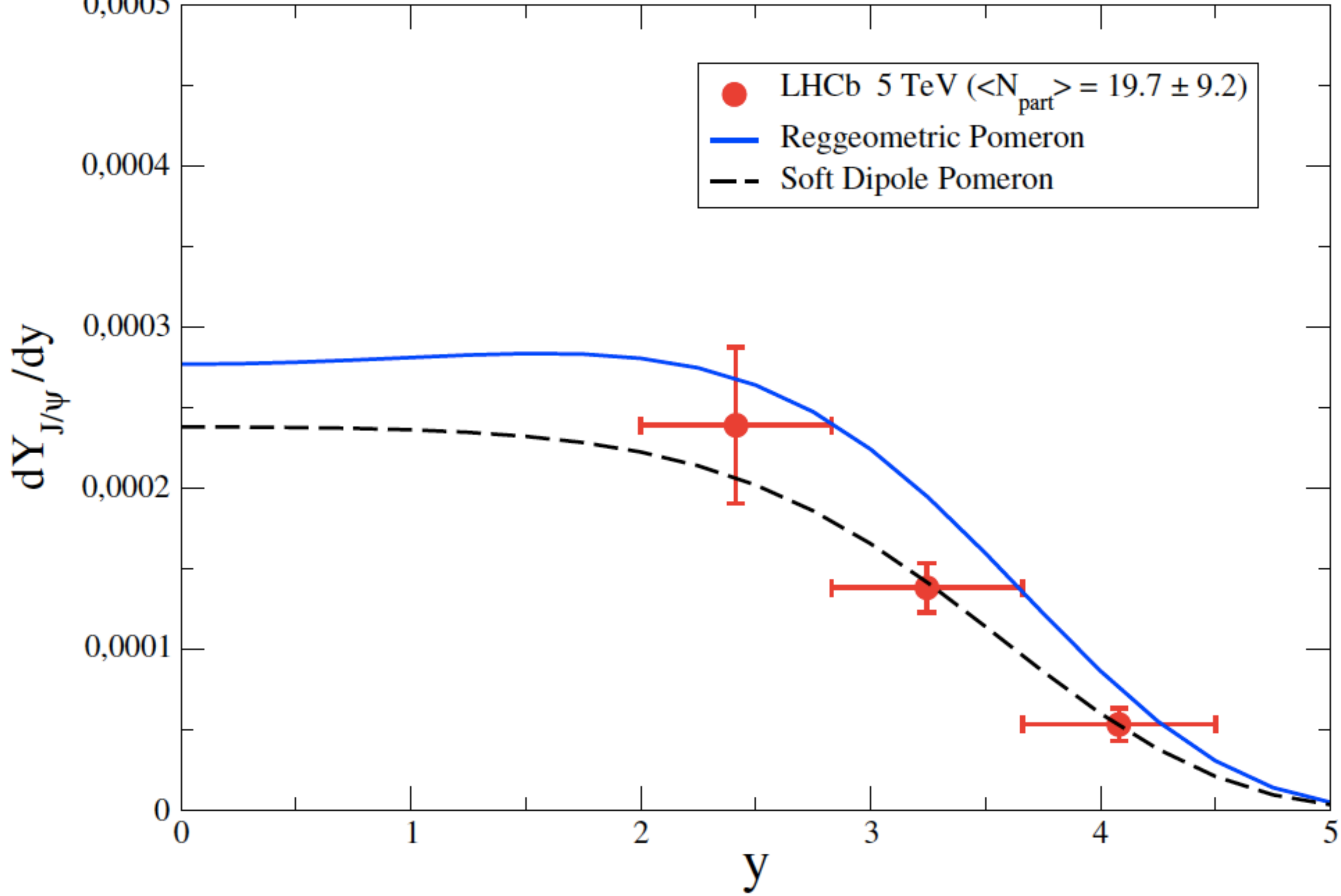
Rapidity distribution of coherently photoproduced J/Psi at forward rapidities in Pb-Pb collisions at 2.76 TeV compared with the ALICE data.



The coherent nuclear cross section as function of the corresponding photon-nucleus energy



The double differential J/Psi photoproduction yields as function of the transverse momentum for 5.02 TeV in the rapidity range 2.0<y<4.5.



Differential J/Psi photoproduction yields as funcion of the rapidity in peripheral PbPb collisions fof <N>=19.7+/-9.2. The data are from LHCb collaboration at 5 TeV.

I thank the Organizers of this Meeting, above all

Mariola Kłusek-Gawenda

for taking care of us

and EMMI for its support