

Gluon shadowing in nuclei and the role of the $c\bar{c}g$ state in the coherent photoproduction of J/ψ

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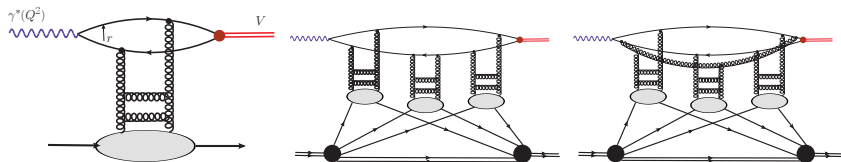


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Introduction

- We discuss the role of $c\bar{c}g$ -Fock states in the diffractive photoproduction of J/ψ -mesons. We build on our earlier description of the process in the color-dipole approach, where we took into account the rescattering of $c\bar{c}$ pairs using a Glauber-Gribov form of the dipole-nucleus amplitude.
- The color dipole approach to coherent photoproduction on the nucleus, is a variant of Glauber-Gribov multiple scattering theory. It sums up multiple scatterings of a color-dipole within the nucleus, as on a typical diagram:



- We test a number of dipole cross sections fitted to inclusive F_2 -data against the total cross section of exclusive J/ψ -production on the free nucleon and calculate the diffractive amplitude on the nuclear target.
- We compare our results to recent data on exclusive J/ψ production in ultraperipheral lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV.

Formalism: Nucleon Target

- The coherent diffractive amplitude on the free nucleon then takes a form:

$$\begin{aligned}\mathcal{A}(\gamma N \rightarrow V N; W, \mathbf{q}) &= 2(i + \rho_N) \int d^2\mathbf{b} \exp[i\mathbf{b}\mathbf{q}] \langle V | \exp[i(1 - 2z)\mathbf{r}\mathbf{q}/2] \\ &\quad * \Gamma_N(x, \mathbf{b}, \mathbf{r}) | \gamma \rangle \\ &= (i + \rho_N) \int d^2\mathbf{r} \rho_{V \leftarrow \gamma}(\mathbf{r}, \mathbf{q}) \sigma(x, \mathbf{r}, \mathbf{q}) \\ &\approx (i + \rho_N) \int d^2\mathbf{r} \rho_{V \leftarrow \gamma}(\mathbf{r}, 0) \sigma(x, r) \exp[-B\mathbf{q}^2/2]\end{aligned}$$

Here $x = M_V^2/W^2$, where W is the γp -cms energy. The amplitude is normalized such that the differential cross section is obtained from:

$$\frac{d\sigma(\gamma N \rightarrow V N; W)}{dt} = \frac{d\sigma(\gamma N \rightarrow V N; W)}{d\mathbf{q}^2} = \frac{1}{16\pi} \left| \mathcal{A}(\gamma^* N \rightarrow V N; W, \mathbf{q}) \right|^2$$

The overlap of light-front wave functions of photon and the vector meson is:

$$\rho_{V \leftarrow \gamma}(\mathbf{r}, \mathbf{q}) = \int_0^1 dz \Psi_V(z, \mathbf{r}) \Psi_\gamma(z, \mathbf{r}) \exp[i(1 - 2z)\mathbf{r}\mathbf{q}/2]$$

Formalism: Nucleon Target

- For the dipole cross section we assume a factorized form:

$$\sigma(x, \mathbf{r}, \mathbf{q}) = \sigma(x, r) \exp[-B\mathbf{q}^2/2]$$

- The overlap of vector meson and photon light-cone wave function, obtained from the γ_μ -vertex for the $Q\bar{Q} \rightarrow V$ vertex is given by:

$$\begin{aligned} \Psi_V^*(z, \mathbf{r}) \Psi_\gamma(z, \mathbf{r}) = & \frac{e_Q \sqrt{4\pi\alpha_{\text{em}}} N_c}{4\pi^2 z(1-z)} \left\{ m_Q^2 K_0(m_Q r) \psi(z, r) \right. \\ & \left. - [z^2 + (1-z)^2] m_Q K_1(m_Q r) \frac{\partial \psi(z, r)}{\partial r} \right\} \end{aligned}$$

- Parameters of **wave function** are taken from *Kowalski, Motyka, Watt, Phys. Rev. D74, 2006*.

Formalism: Nuclear target

- For the nuclear targets color dipoles can be regarded as eigenstates of the interaction and we can apply the standard rules of Glauber theory.
- The Glauber form of the dipole scattering amplitude for $l_c \gg R_A$ (the coherence length is much larger than the nuclear size) is:

$$\Gamma_A(x, \mathbf{b}, \mathbf{r}) = 1 - \exp[-\tfrac{1}{2}\sigma(x, r)T_A(\mathbf{b})]$$

- The dipole amplitude corresponds to a rescattering of the dipole in a purely absorptive medium. The real part of the dipole-nucleon amplitude is often neglected. It induces the refractive effects and instead of first eq. we should take:

$$\Gamma_A(x, \mathbf{b}, \mathbf{r}) = 1 - \exp[-\tfrac{1}{2}\sigma(x, r)(1 - i\rho_N)T_A(\mathbf{b})]$$

- The optical thickness $T_A(\mathbf{b})$ is calculated from a Wood-Saxon distribution $n_A(\vec{r})$:

$$T_A(\mathbf{b}) = \int_{-\infty}^{\infty} dz n_A(\vec{r}); \vec{r} = (\mathbf{b}, z), \int d^2\mathbf{b} T_A(\mathbf{b}) = A$$

Formalism: Nuclear target

- The diffractive amplitude in \mathbf{b} -space is:

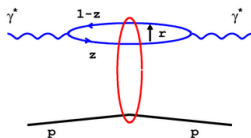
$$\mathcal{A}(\gamma A \rightarrow VA; W, \mathbf{b}) = 2i \langle V | \Gamma_A(x, \mathbf{b}, \mathbf{r}) | \gamma \rangle \mathcal{F}_A(q_z)$$

- The nuclear form factor $\mathcal{F}_A(q) = \exp[-R_{\text{ch}}^2 q^2/6]$ depends on the finite longitudinal momentum transfer $q_z = xm_N$.
- The total cross section for the $\gamma A \rightarrow VA$ reaction is obtained as:

$$\sigma(\gamma A \rightarrow VA; W) = \frac{1}{4} \int d^2\mathbf{b} \left| \mathcal{A}(\gamma A \rightarrow VA; W, \mathbf{b}) \right|^2$$

Dipole model of DIS

- Dipole picture of DIS at small x in the proton rest frame



r - dipole size

z - longitudinal momentum fraction of the quark/antiquark

- Factorization: dipole formation + dipole interaction

$$\sigma^{\gamma p} = \frac{4\pi^2 \alpha_{em}}{Q^2} F_2 = \sum_f \int d^2 r \int_0^1 dz |\Psi^\gamma(r, z, Q^2, m_f)|^2 \hat{\sigma}(r, x)$$

- Dipole-proton interaction

$$\hat{\sigma}(r, x) = \sigma_0 (1 - \exp\{-\hat{r}^2\})$$

$$\hat{r} = r/R_s(x)$$

Dipole cross section: GBW(Golec-Biernat-Wüsthoff)

- GBW parametrization with heavy quarks:

$$f = u, d, s, c$$

$$\hat{\sigma}(r, x) = \sigma_0 \left(1 - \exp(-r^2/R_s^2)\right), \quad R_s^2 = Q_0^2 \cdot (x/x_0)^\lambda \text{ GeV}^2$$

- The dipole scattering amplitude in such a case reads:

$$\hat{N}(\mathbf{r}, \mathbf{b}, x) = \theta(b_0 - b) \left(1 - \exp(-r^2/R_s^2)\right)$$

where

$$\hat{\sigma}(r, x) = 2 \int d^2b \hat{N}(\mathbf{r}, \mathbf{b}, x)$$

- Parameters b_0 , x_0 and λ from fits of \hat{N} to F_2 data

$$\lambda = 0.288 \quad x_0 = 4 \cdot 10^{-5} \quad 2\pi b_0^2 = \sigma_0 = 29 \text{ mb}$$

Dipole cross section: BGK (Bartels-Golec-Kowalski)

- BGK parametrization

$$\hat{\sigma}(r, x) = \sigma_0 \left\{ 1 - \exp \left[-\pi^2 r^2 \alpha_s(\mu^2) x g(x, \mu^2) / (3\sigma_0) \right] \right\}$$

from the xFitter QCD fit framework: <https://gitlab.cern.ch/fitters/xfitter>

- $\mu^2 = C/r^2 + \mu_0^2$ is the scale of the gluon density
- μ_0^2 is a starting scale of the QCD evolution. $\mu_0^2 = Q_0^2$
- gluon density is evolved according to the LO or NLO DGLAP eq.
- soft gluon:

$$xg(x, \mu_0^2) = A_g x^{\lambda_g} (1-x)^{C_g}$$

- soft + hard gluon:

$$xg(x, \mu^2) = A_g x^{\lambda_g} (1-x)^{C_g} (1 + D_g x + E_g x^2)$$

- A slightly different choice of the scale μ : (Golec-Biernat, Sapeta, JHEP 03, 2018)

$$\mu^2 = \frac{\mu_0^2}{1 - \exp(-\mu_0^2 r^2 / C)}$$

- which interpolates smoothly between the C/r^2 behaviour for small r and the constant behaviour, $\mu^2 = \mu_0^2$ for $r \rightarrow \infty$

Dipole cross section: IIM (Iancu, Itakura, Munier)

- The GBW and BGK models use for saturation the eikonal approximation, the IIM model uses a simplified version of the Balitsky-Kovchegov equation
- The dipole cross section is parametrized as:

$$\sigma(r, x) = 2\pi R_p^2 \begin{cases} N_0 \exp[-2\gamma L - \frac{L^2}{\kappa\lambda Y}] & \text{if } L \geq 0, \\ 1 - \exp[-a(L - L_0)^2] & \text{else,} \end{cases}$$

where

$$L = \log\left(\frac{2}{rQ_s}\right), Q_s^2 = \left(\frac{x_0}{x}\right)^\lambda \text{GeV}^2, Y = \log\left(\frac{1}{x}\right)$$

and

$$L_0 = \frac{1 - N_0}{\gamma N_0} \log\left(\frac{1}{1 - N_0}\right), a = \frac{1}{L_0^2} \log\left(\frac{1}{1 - N_0}\right)$$

We take the numerical values found in the xFitter code:

$$N_0 = 0.7, R_p = 3.44 \text{ GeV}^{-1}, \gamma = 0.737, \kappa = 9.9, \lambda = 0.219, x_0 = 1.632 \cdot 10^{-5}$$

Predictions for J/ψ production on the proton target

- For the GBW and IIM dipole cross sections, we calculate the total cross section from:

$$\sigma(\gamma p \rightarrow J/\psi p; W) = \frac{1 + \rho_N^2}{16\pi B} R_{\text{skewed}}^2 |\langle V | \sigma(x, r) | \gamma \rangle|^2$$

- The diffraction slope: $B = B_0 + 4\alpha' \log(W/W_0)$, with $B_0 = 4.88 \text{ GeV}^{-2}$, $\alpha' = 0.164 \text{ GeV}^{-2}$, and $W_0 = 90 \text{ GeV}$.
- For the BGK type of parametrizations, it proves to be more stable numerically to substitute the “skewed glue” in the exponent:

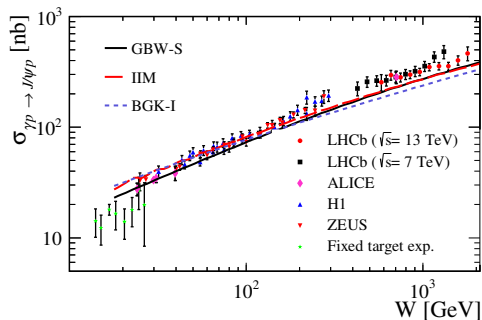
$$\sigma(x, r) = \sigma_0 \left(1 - \exp \left[-\frac{\pi^2 r^2 \alpha_s(\mu^2) R_{\text{skewed}} x g(x, \mu^2)}{3\sigma_0} \right] \right),$$

- For gluons exchanged in the amplitude carry different longitudinal momenta, at small $x = M_V^2/W^2$ we have typically, say $x_1 \sim x, x_2 \ll x_1$. In such a situation, the corresponding correction which multiplies the amplitude is Shuvaev's factor:

$$R_{\text{skewed}} = \frac{2^{2\Delta_{\mathbf{P}}+3}}{\sqrt{\pi}} \cdot \frac{\Gamma(\Delta_{\mathbf{P}} + 5/2)}{\Gamma(\Delta_{\mathbf{P}} + 4)}$$

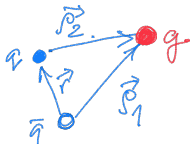
Predictions for J/ψ production on the proton target

A. Łuszczak, W. Schäfer, *Phys. Rev. C* **99**, no.4, 044905 (2019)



- Total cross section for the exclusive photoproduction $\gamma p \rightarrow J/\psi p$ as a function of γp -cms energy W
- We observe that the range of $30 \lesssim W \lesssim 300 \text{ GeV}$ is reasonably well described by all dipole cross sections. The very high-energy domain is covered by data extracted from the $pp \rightarrow ppJ/\psi$ reaction by the LHCb, the models do a good job.

Contribution of $q\bar{q}g$ Fock-state



- at high energies/small- x ($x \ll x_A \sim 0.01$) we need to take into account also the contribution of the $q\bar{q}g$ -Fock state, and possibly higher $q\bar{q}g_1g_2 \dots g_n$ states. This gives rise to the color dipole form of BFKL.

- The dipole cross section for the $q\bar{q}g$ state on the nucleon is [Nikolaev, Zakharov, Zoller '93](#)

$$\sigma_{q\bar{q}g}(x, \boldsymbol{\rho}_1, \boldsymbol{\rho}_2, \mathbf{r}) = \frac{C_A}{2C_F} \left(\sigma(x, \boldsymbol{\rho}_1) + \sigma(x, \boldsymbol{\rho}_2) - \sigma(x, \mathbf{r}) \right) + \sigma(x, \mathbf{r})$$

- integrating over dz_g/z_g spectrum of the gluon, the dipole cross section changes as

$$\sigma(x, \mathbf{r}) = \sigma(x_0, \mathbf{r}) + \log\left(\frac{x_0}{x}\right) \int d^2\boldsymbol{\rho}_1 |\psi(\boldsymbol{\rho}_1) - \psi(\boldsymbol{\rho}_2)|^2 \left\{ \sigma_{q\bar{q}g}(x_0, \boldsymbol{\rho}_1, \boldsymbol{\rho}_2, \mathbf{r}) - \sigma(x_0, \mathbf{r}) \right\}$$

- infrared “regularization” for large dipoles

$$\psi(\boldsymbol{\rho}) = \frac{\sqrt{C_F\alpha_s(\min(\rho, r))}}{\pi} \frac{\boldsymbol{\rho}}{\rho R_c} K_1\left(\frac{\rho}{R_c}\right), \quad \text{with} \quad R_c \sim 0.2 \div 0.3 \text{ fm.}$$

- freezing of $\alpha_s(r)$ for $r > R_c$.

Contribution of $c\bar{c}g$ Fock-state to the nuclear amplitude

- Integrating over all variables but the dipole size \mathbf{r} , the effect of the gluon is a change of the $q\bar{q}$ dipole amplitude ($x_A \sim 0.01$):

$$\Gamma_A(x, \mathbf{r}, \mathbf{b}) = \Gamma_A(x_A, \mathbf{r}, \mathbf{b}) + \log\left(\frac{x_A}{x}\right) \Delta\Gamma(x_A, \mathbf{r}, \mathbf{b})$$

$q\bar{q}g$ -contribution:

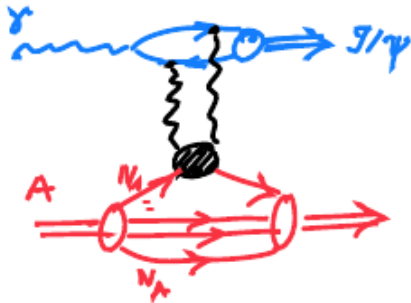
$$\begin{aligned} \Delta\Gamma(x_A, \mathbf{r}, \mathbf{b}) = & \int d^2\rho_1 |\psi(\rho_1) - \psi(\rho_2)|^2 \left\{ \Gamma_A(x_A, \rho_1, \mathbf{b} + \frac{\rho_2}{2}) + \Gamma_A(x_A, \rho_2, \mathbf{b} + \frac{\rho_1}{2}) \right. \\ & \left. - \Gamma_A(x_A, \mathbf{r}, \mathbf{b}) - \Gamma_A(x_A, \rho_1, \mathbf{b} + \frac{\rho_2}{2}) \Gamma_A(x_A, \rho_2, \mathbf{b} + \frac{\rho_1}{2}) \right\} \end{aligned}$$

- This is, up to our treatment of large dipoles, one iteration of the Balitsky-Kovchegov equation, including the *nonlinear term*.

$c\bar{c}g$ contribution to the diffractive amplitude

- The nuclear effect is best quantified by the ratio of the cross section including all nuclear modification effects to the impulse approximation.

$$\sigma_{IA}(\gamma A \rightarrow J/\psi A; W) = 4\pi \frac{d\sigma(\gamma p \rightarrow J/\psi p)}{dt} \Big|_{t=0} \int d^2\mathbf{b} T_A^2(\mathbf{b}) F^2(q_z^2).$$



- We calculate the ratio

$$R_{\text{coh}} = \frac{\sigma(\gamma A \rightarrow J/\psi A; W)}{\sigma_{IA}(\gamma A \rightarrow J/\psi A; W)}$$

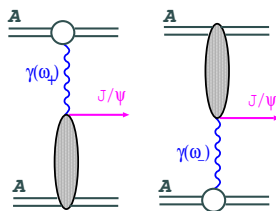
including $c\bar{c}$ and $c\bar{c}g$ contributions, but in the IA we switch off the nonlinear piece in the $c\bar{c}g$ amplitude.

cross section:

$$\sigma(\gamma A \rightarrow J/\psi A) = R_{\text{coh}} 4\pi B(W) \sigma(\gamma p \rightarrow J/\psi p) \int d^2\mathbf{b} T_A^2(\mathbf{b}) F_A(q_z^2).$$

Photoproduction in ultraperipheral collisions

- Exclusive photoproduction in ultraperipheral heavy-ion collisions: the left-moving ion serves as the photon source, and the right-moving one serves as the target.



- The rapidity-dependent cross section for exclusive J/ψ production from the Weizsäcker-Williams fluxes of quasi-real photons $n(\omega)$ as:

$$\frac{d\sigma(AA \rightarrow AAJ/\psi; \sqrt{s_{NN}})}{dy} = n(\omega_+) \sigma(\gamma A \rightarrow J/\psi A) + n(\omega_-) \sigma(\gamma A \rightarrow J/\psi A)$$

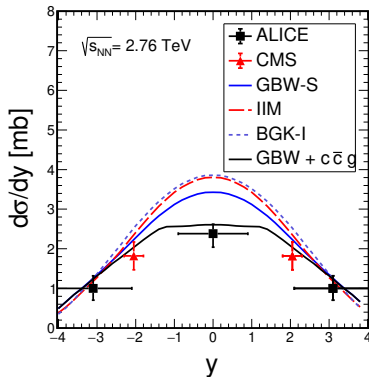
- We use the standard form of the Weizsäcker-Williams flux for the ion moving with boost γ :

$$n(\omega) = \frac{2Z^2\alpha_{\text{em}}}{\pi} \left[\xi K_0(\xi) K_1(\xi) - \frac{\xi^2}{2} (K_1^2(\xi) - K_0^2(\xi)) \right]$$

- ω is the photon energy, and $\xi = 2R_A\omega/\gamma$

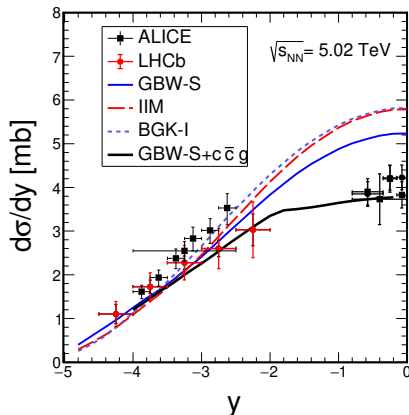
Results for photoproduction in ultraperipheral collisions

A. Łuszczak, W Schäfer, *Phys. Rev. C* **99**, no.4, 044905 (2019), and work in progress



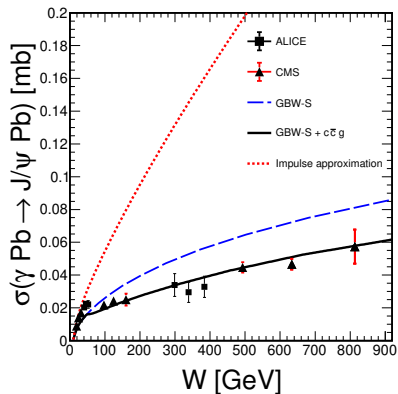
- Rapidity-dependent cross sections $d\sigma/dy$ for **exclusive production of J/ψ** in $^{208}\text{Pb}^{208}\text{Pb}$ collisions at per-nucleon c.m. system energy $\sqrt{s_{NN}} = 2.76$ TeV.
- For the $c\bar{c}g$ state we used the np. parameter $R_c = 0.28$ fm.

Results for photoproduction with $c\bar{c}g$ contribution



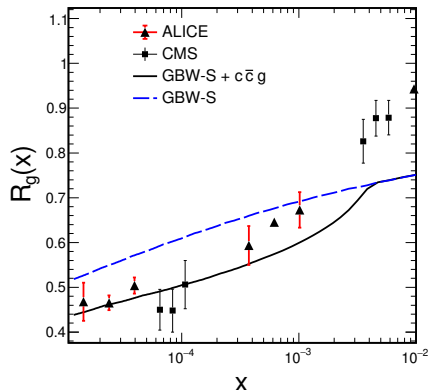
- Rapidity-dependent cross sections $d\sigma/dy$ for **exclusive production of J/ψ** in $^{208}\text{Pb}^{208}\text{Pb}$ collisions at per-nucleon c.m system energy $\sqrt{s_{NN}} = 5.02$ TeV.

Results for photoproduction with $c\bar{c}g$ contribution



- The total cross section $\sigma(\gamma A \rightarrow J/\psi A)$ for the ^{208}Pb nucleus as a function of γA -cm energy W .
- The impulse approximation fails dramatically, which illustrates the scale of nuclear effects. A large part of the nuclear suppression can be explained by Glauber-Gribov rescattering of the $c\bar{c}$ state alone.
- The calculations including the effect of the $c\bar{c}g$ state show an additional suppression of the nuclear cross section, as required by experimental data.

The putative “gluon shadowing”



$$R_g(x) = \sqrt{\frac{\sigma(\gamma Pb \rightarrow J/\psi Pb)}{\sigma_{IA}(\gamma Pb \rightarrow J/\psi Pb)}}$$

$$= \frac{g_A(x, m_c^2)}{Ag_N(x, m_c^2)}$$

- $R_g(x)$: is supposed to quantify the suppression (shadowing) of the per-nucleon glue in the nucleus at small- x .
- Impulse approximation baseline from a parametrization of Guzey et al. (2013) as this was also done in the analysis of the CMS collaboration (2023).
- CMS, [arXiv:2303.16984 [nucl-ex]]; ALICE, JHEP **10** (2023), 119.

Summary

- We calculated the total elastic photoproduction of J/ψ on the free nucleon and compared to the data available from fixed-target experiments, as well as to data extracted from pp or pA collisions by the LHCb and ALICE
- We have applied our results to the exclusive J/ψ production in heavy-ion (lead-lead) collisions at the energies $\sqrt{s_{NN}} = 2.76 \text{ GeV}$ and $\sqrt{s_{NN}} = 5.02 \text{ GeV}$, the description of data can be regarded satisfactory.
- Glauber-Gribov theory including only rescattering of the $c\bar{c}$ dipole works well in the forward region (large rapidities).
- In the central rapidity region inclusion of the $c\bar{c}g$ state introduces additional shadowing which is needed to describe the data.
- Shadowing due to the $c\bar{c}g$ state can be (roughly) identified with gluon shadowing of the nuclear pdf. It depends on the infrared regulator, the gluon propagation radius R_c , and is not a prediction of perturbation theory alone.
- It will be very interesting to investigate photoproduction in ultraperipheral collisions at the electron-ion collider where we will have a large Q^2 and a studies of the Q^2 evolution of the gluon shadowing are possible.

Energies available for photoproduction

$\sqrt{s_{NN}} = 2.76 \text{ TeV}$						
y	$W_+ [\text{GeV}]$	$W_- [\text{GeV}]$	x_+	x_-	$n(\omega_+)$	$n(\omega_-)$
0.0	92.5	92.5	$1.12 \cdot 10^{-3}$	$1.12 \cdot 10^{-3}$	69.4	69.4
1.0	152	56.1	$4.13 \cdot 10^{-4}$	$3.05 \cdot 10^{-3}$	39.5	100
2.0	251	34.0	$1.52 \cdot 10^{-4}$	$8.29 \cdot 10^{-3}$	14.5	132
3.0	414	20.6	$5.59 \cdot 10^{-5}$	$2.25 \cdot 10^{-2}$	1.68	163
3.8	618	13.8	$2.51 \cdot 10^{-5}$	$5.02 \cdot 10^{-2}$	0.03	188

Table: Subenergies W_{\pm} and Bjorken- x values x_{\pm} for $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ for a given rapidity y . Also shown are photon fluxes $n(\omega_{\pm})$.

$\sqrt{s_{NN}} = 5.02 \text{ TeV}$						
y	$W_+ [\text{GeV}]$	$W_- [\text{GeV}]$	x_+	x_-	$n(\omega_+)$	$n(\omega_-)$
0.0	125	125	$6.17 \cdot 10^{-4}$	$6.17 \cdot 10^{-4}$	87.9	87.9
1.0	206	75.6	$2.27 \cdot 10^{-4}$	$1.68 \cdot 10^{-3}$	57.2	119
2.0	339	45.9	$8.35 \cdot 10^{-5}$	$4.56 \cdot 10^{-3}$	28.5	150
3.0	559	27.8	$3.07 \cdot 10^{-5}$	$1.24 \cdot 10^{-2}$	7.5	181
4.0	921	16.9	$1.13 \cdot 10^{-5}$	$3.37 \cdot 10^{-2}$	0.35	213
4.8	1370	11.3	$5.08 \cdot 10^{-6}$	$7.50 \cdot 10^{-2}$	0.001	238

Table: Subenergies W_{\pm} and Bjorken- x values x_{\pm} for $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ for a given rapidity y .