# Probing double parton scattering via associated open charm and bottom production in ultraperipheral $pA$ collisions

**Emmanuel G. de Oliveira**

Federal University of Santa Catarina
Florianópolis – Brazil

*in collaboration with:* Edgar Huayra P. & Roman S. Pasechnik

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# Summary


1. Motivation
2. Ultra-Peripheral Collisions (UPCs) and Single Parton Scattering (SPS)
3. Double Parton Scattering (DPS)
4. Results and Conclusions

# Double Parton Scattering in *pp* collisions

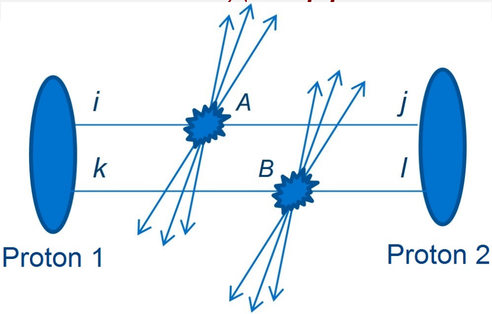



Figure: Double Parton Scattering process (DPS).

Pocket formula (simplest approximation):

$$\sigma^{DPS}_{p_1 p_2} = \frac{N}{2} \frac{\sigma^{SPS}_{A} \sigma^{SPS}_{B}}{\sigma_{\text{eff}}}$$

# Measurements of the effective cross section

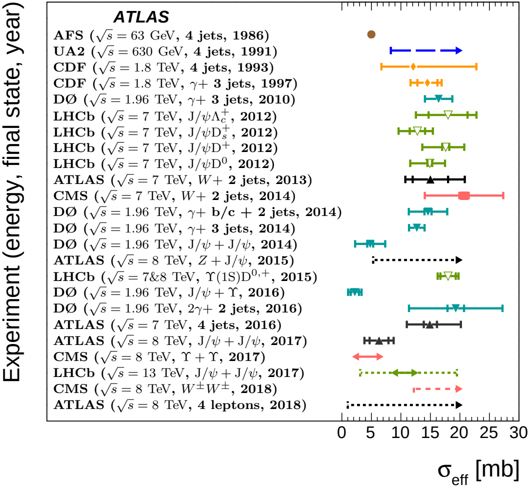
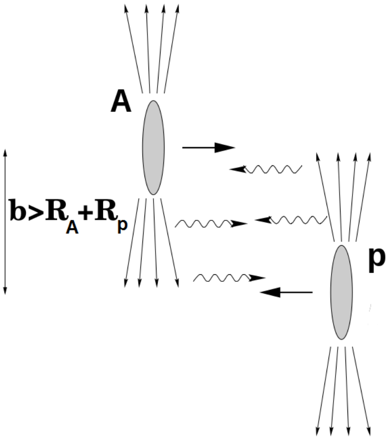
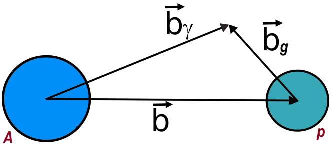



Figure: Compiled by the ATLAS Collaboration; PLB, 790, 595.

# Ultra-Peripheral Collisions (UPCs)

- Ultra-peripheral: impact parameter $b$ is greater that sum of the radii of the nuclei.
- Therefore, the interaction is mostly electromagnetic.
- The interacting photon is approximated as a real one ($Q^2 = 0$).



# Equivalent photon flux

Weizsäcker-Willians photon flux is given by:

$$\frac{d^3N_\gamma(\omega,\vec{b})}{d\omega d^2\vec{b}} = \frac{Z^2\alpha k^2}{\pi^2\omega b^2}\left[K_1^2(k) + \frac{1}{\gamma^2}K_0^2(k)\right], \qquad k = \frac{b\,\omega}{\gamma},$$

- $Z$: nuclear charge (lead: 82);
- $\omega$: photon energy;
- Lorentz factor: $\gamma = \sqrt{s}/2m_p$.

Now, we work with the photon momentum fraction $\xi$:

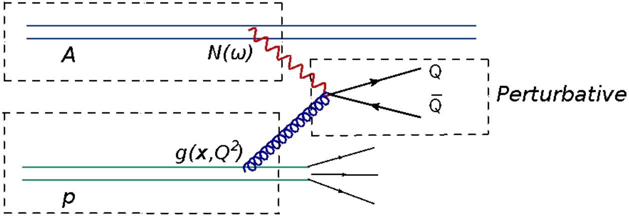
$$\xi = \frac{2\omega}{\sqrt{s}}.$$

We define the following distribution:

$$\frac{d^3N_\gamma(\xi,\vec{b})}{d\xi d^2\vec{b}} = \frac{\sqrt{s}}{2}\frac{d^3N_\gamma(\omega,\vec{b})}{d\omega d^2\vec{b}}$$

# Single Parton Scattering (SPS) in UPCs

- In the photon-gluon interaction we consider that the nucleus ($A$) survives intact and that the proton breaks.




We would like to have the factorized formula (after integral over the impact parameter outside the nucleus).

$$d\sigma_{pA\to Q\bar{Q}AX} = \int d\xi\, dx N(\xi) g(x,Q^2)\, d\hat{\sigma}_{\gamma g\to Q\bar{Q}}(\omega,x)$$

# Single Parton Scattering (SPS) in UPCs

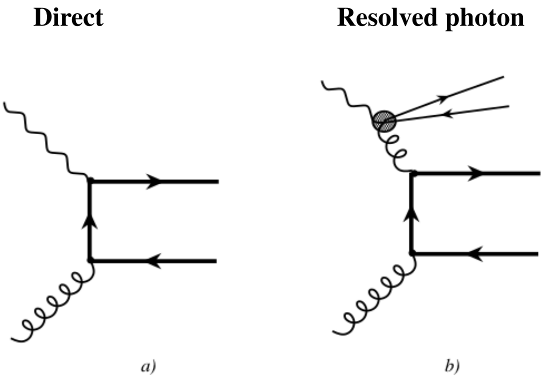



Figure: Feynman diagrams for: (a) direct contribution and (b) resolved photon contribution

# Direct contribution of the SPS in UPCs

- Direct contribution for the production of $c\bar{c}$

$$\frac{d\sigma^{\text{Direct},\gamma g}_{pA\to XA+c\bar{c}}}{dy_c dy_{\bar{c}} dp_\perp^2} = \int d^2\vec{b}\,\Theta(b-R_A-R_p)\frac{dP_{pA\to XA+c\bar{c}}(b)}{dy_c dy_{\bar{c}} dp_\perp^2},$$

$$\frac{dP_{pA\to XA+c\bar{c}}(b)}{dy_c dy_{\bar{c}} dp_\perp^2} = \int d^2\vec{b}_\gamma d^2\vec{b}_g\,\delta^{(2)}(\vec{b}+\vec{b}_g-\vec{b}_\gamma)\int d\xi\, dx\, N_\gamma(\xi,\vec{b}_\gamma) G_g(x,\vec{b}_g) \times \frac{d\hat{\sigma}_{\gamma g\to c\bar{c}}}{dy_c dy_{\bar{c}} dp_\perp^2}$$

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# Direct contribution of the SPS in UPCs

Suppose the factorization with narrow $b$ dependence:

$$\boxed{G_g(x,\vec{b}) = g(x) f_g(\vec{b})}$$

Then all the impact parameter dependence is a factor very close to 1:

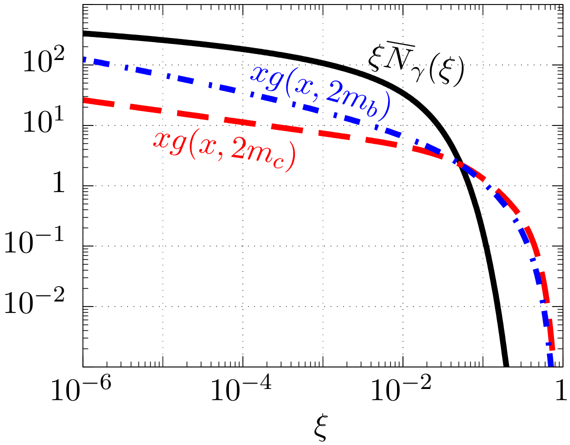
$$\frac{d\sigma^{\text{Direct},\,\gamma g}_{pA\to XA+c\bar{c}}}{dy_c dy_{\bar{c}}} = \int d\xi\, dx\, \overline{N}_\gamma(\xi) g(x) \frac{d\hat{\sigma}_{\gamma g\to c\bar{c}}}{dy_c dy_{\bar{c}}} \int d^2\vec{b}\, \Theta(b - R_A - R_p) T_{g\gamma}(\xi,\vec{b})$$

Where we define:

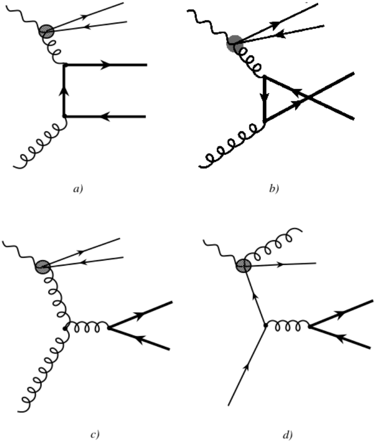
$$T_{g\gamma}(\xi,\vec{b}) = \frac{1}{\overline{N}_\gamma(\xi)} \int d^2\vec{b}_\gamma \Theta(b_\gamma - R_A) N_\gamma(\xi,\vec{b}_\gamma) f_g(\vec{b} - \vec{b}_\gamma)\,,$$

$$\overline{N}_\gamma(\xi) = \int d^2 b\, \Theta(b - R_A) N_\gamma(\xi,\vec{b})\,.$$

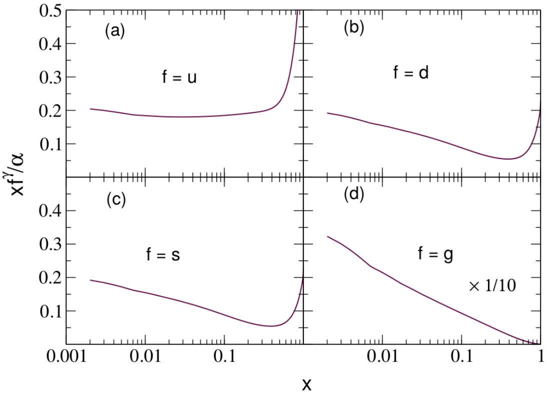
# Parton distributions



# Resolved photon contribution in UPCs



# Partons inside the photons




Distributions at next-to-leading order provided by Aurenche, Fontannaz, and Guillet (AFG04)

# Resolved contribution of the SPS in UPCs

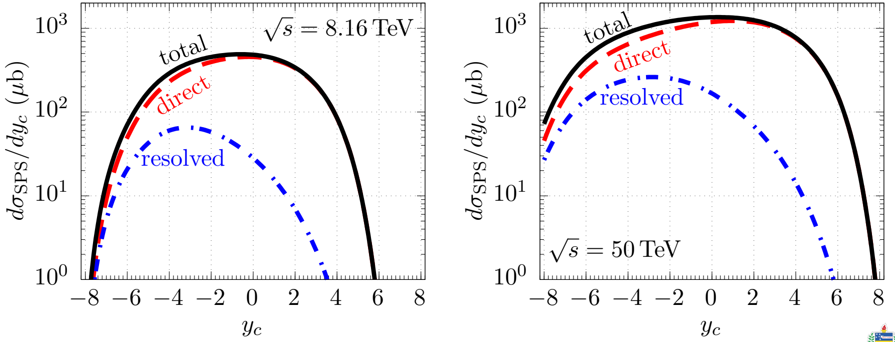
We have one more convolution:

$$\frac{d^2\sigma^{\text{Resolved, } gg}_{pA\to XA+c\bar{c}}}{dy_c dy_{\bar{c}}} = \int d\xi\, dx\, \overline{N}_\gamma(\xi)\, g(x) \int dz\, g^\gamma(z)\, \frac{d^2\hat{\sigma}_{gg\to Q\bar{Q}}}{dy_c dy_{\bar{c}}} \times \int d^2\vec{b}\, \Theta(b - R_A - R_p) T_{g\gamma}(\xi, \vec{b})$$

$$\frac{d^2\sigma^{\text{Resolved, } q\bar{q}}_{pA\to XA+c\bar{c}}}{dy_c dy_{\bar{c}}} = \sum_{q=u,d,s} \int d\xi\, dx\, \overline{N}_\gamma(\xi)\, \bar{q}(x) \int dz\, q^\gamma(z)\, \frac{d^2\hat{\sigma}_{qq\to Q\bar{Q}}}{dy_c dy_{\bar{c}}} \times \int d^2\vec{b}\, \Theta(b - R_A - R_p) T_{g\gamma}(\xi, \vec{b})$$

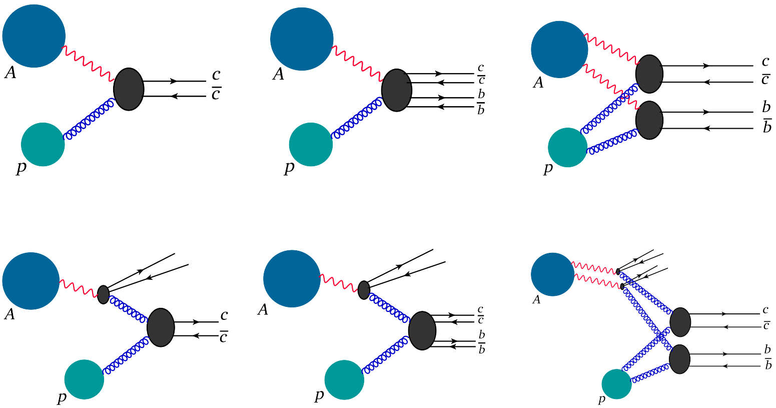
# SPS Results

- In this calculation we considered that the $A$(Pb) comes from the left and the $p$ comes from the right.



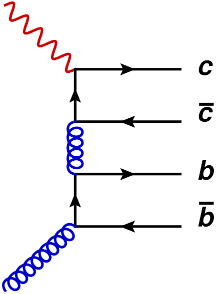
# SPS vs. DPS processes in UPCs

SPS ($c\bar{c}$) SPS ($c\bar{c}b\bar{b}$) DPS ($c\bar{c}b\bar{b}$)

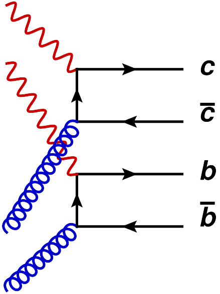


# SPS vs. DPS in UPCs

SPS




DPS




$$\sigma^{SPS} \approx \alpha_{\rm em}\alpha_s^3 g(x)\overline{N}_\gamma(\xi)$$

$$\sigma^{DPS} \approx \alpha_{\rm em}^2\alpha_s^2 g^2(x)\overline{N}_\gamma^2(\xi)$$

Enforce large $c\bar{c}b\bar{b}$ mass to suppress the SPS contribution.

E.g., large $y_c - y_b$.

# DPS in UPCs

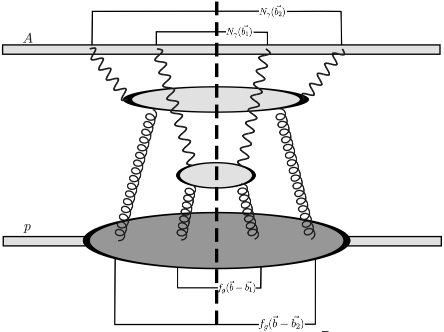



Figure: A schematic illustration of the $A+p\to A+(c\bar{c}b\bar{b})+X$ cross section in $pA$ UPCs.

$$\frac{d\sigma_{pA\to XA+c\bar{c}+b\bar{b}}}{dy_c dy_{\bar{c}} dy_b dy_{\bar{b}}} = \int d^2\vec{b}\,\Theta(b-R_A-R_p)\frac{dP_{pA\to XA+c\bar{c}}(b)}{dy_c dy_{\bar{c}}} \times \frac{dP_{pA\to XA+b\bar{b}}(b)}{dy_b dy_{\bar{b}}}$$

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# DPS in UPCs

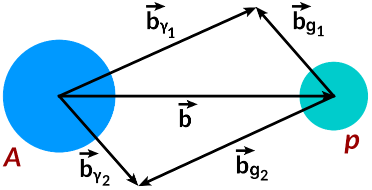


Figure: Schematic illustration of the geometry of a collision $pA$-UPCs.

$$\frac{d\sigma_{pA\to XA+c\bar{c}+b\bar{b}}}{dy_c dy_{\bar{c}} dy_b dy_{\bar{b}}} = \int d^2b\,\Theta(b-R_A-R_p)\int d^2\vec{b}_{\gamma,1}\,\Theta(b_{\gamma,1}-R_A)\int d^2\vec{b}_{\gamma,2}\,\Theta(b_{\gamma,2}-R_A)$$

$$\times\int d\xi_1 d\xi_2 dx_1 dx_2 N_{\gamma\gamma}(\xi_1,\vec{b}_{\gamma,1};\xi_2,\vec{b}_{\gamma,2})G_{gg}(x_1,\vec{b}_{g,1};x_2,\vec{b}_{g,2})\frac{d\hat{\sigma}_{\gamma g\to c\bar{c}}}{dy_c dy_{\bar{c}}}\frac{d\hat{\sigma}_{\gamma g\to b\bar{b}}}{dy_b dy_{\bar{b}}}$$

# DPS in UPCs

Neglecting correlations:

$$
\begin{aligned}
N_{\gamma\gamma}(\xi_1,\vec{b}_1;\xi_2,\vec{b}_2) &= N_\gamma(\xi_1,\vec{b}_1)N_\gamma(\xi_2,\vec{b}_2)\,, \\
G_{gg}(x_1,\vec{b}_1;x_2,\vec{b}_2) &= G_g(x_1,\vec{b}_1)G_g(x_2,\vec{b}_2)
\end{aligned}
$$

$$
\frac{d\sigma_{pA\to XA+c\bar{c}+b\bar{b}}}{dy_c dy_{\bar{c}} dy_b dy_{\bar{b}}} = \int d\xi_1 dx_1 d\xi_2 dx_2 \, \frac{1}{\sigma_{\rm eff}(\xi_1,\xi_2)} \boxed{\overline{N}_\gamma(\xi_1)g(x_1)\,\frac{d\hat{\sigma}_{\gamma g\to c\bar{c}}}{dy_c dy_{\bar{c}}}} \times \boxed{\overline{N}_\gamma(\xi_2)g(x_2)\,\frac{d\hat{\sigma}_{\gamma g\to b\bar{b}}}{dy_b dy_{\bar{b}}}}
$$

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# Effective cross section in UPCs

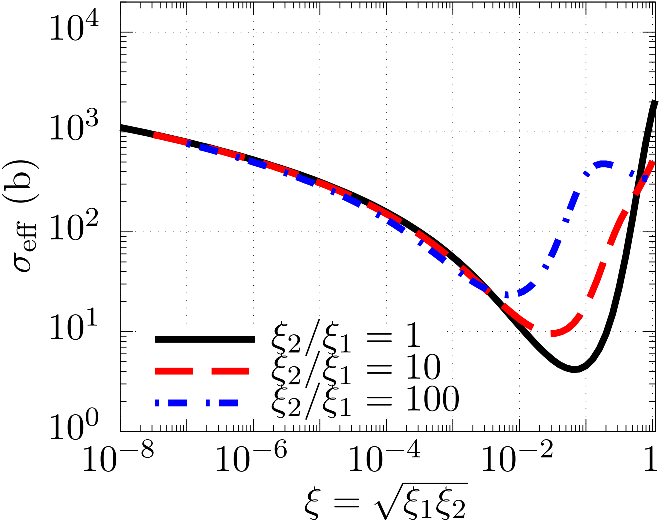
## $\sigma_{\text{eff}}$ in UPCs

$$\sigma_{\text{eff}}(\xi_1,\xi_2) \equiv \left[\int d^2b\,\Theta(b-R_A-R_p)T_{g\gamma}(\xi_1,b)T_{g\gamma}(\xi_2,b)\right]^{-1}$$

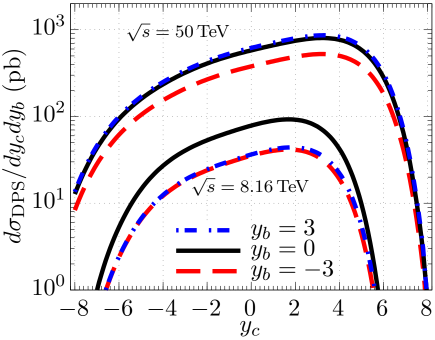
where the overlap is given by:

$$T_{g\gamma}(\xi,\vec{b}) = \frac{1}{\overline{N}_\gamma(\xi)}\int d^2\vec{b}_\gamma\Theta(b_\gamma-R_A)N_\gamma(\xi,\vec{b}_\gamma)f_g(\vec{b}-\vec{b}_\gamma)\,.$$

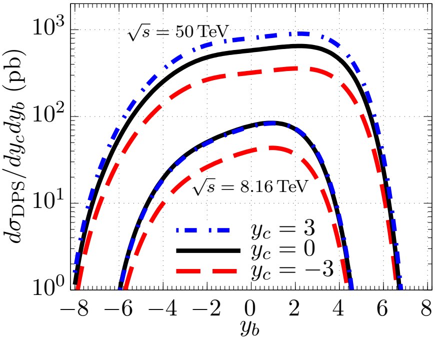
# Effective cross section in UPCs



# DPS results



$d\sigma_{\mathrm{DPS}}/dy_c dy_b$ (pb)
$\sqrt{s} = 50$ TeV
$\sqrt{s} = 8.16$ TeV
$y_b = 3$
$y_b = 0$
$y_b = -3$
$y_c$

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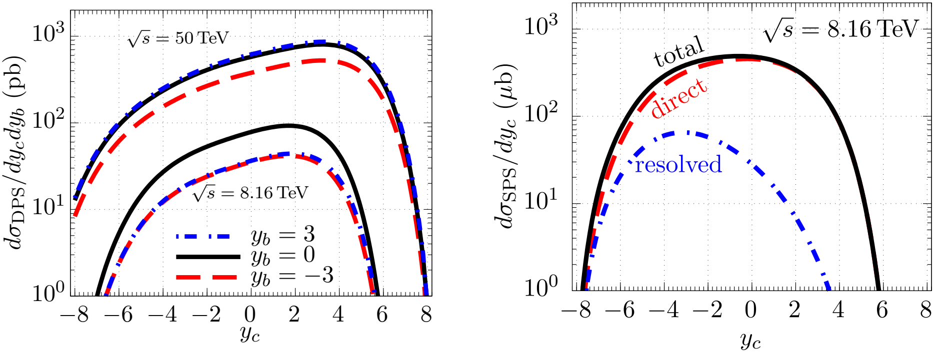
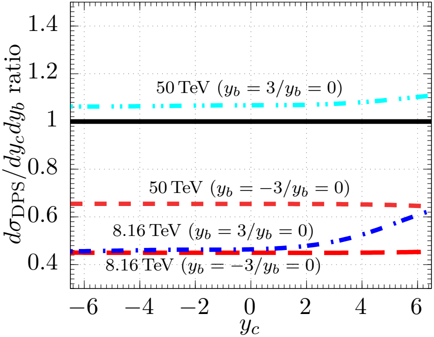
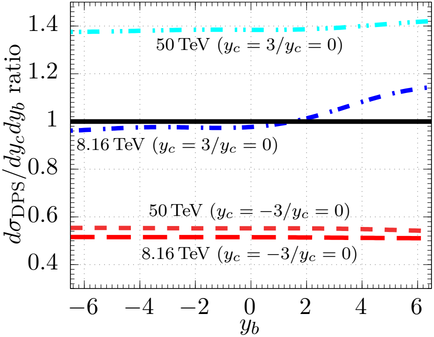
$\sqrt{s} = 50$ TeV
$\sqrt{s} = 8.16$ TeV
$y_c = 3$
$y_c = 0$
$y_c = -3$
$y_b$

# DPS vs SPS comparison

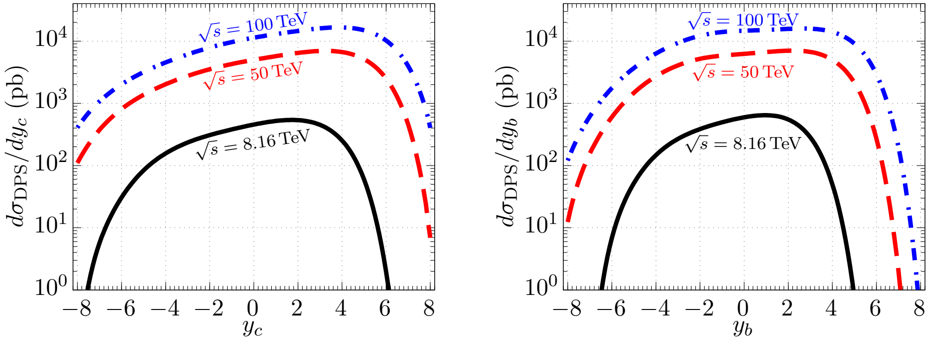


# DPS ratio results



# Single rapidity distributions



# Integrated cross sections

| $\sqrt{s}$ (TeV) | 8.16 | 50 | 100 |
|---|---|---|---|
| SPS UPC $c\bar{c}$ production in mb | | | |
| Direct | 3.10 | 10.46 | 15.75 |
| Resolved | 0.35 | 1.81 | 3.03 |
| Total | 3.45 | 12.27 | 18.78 |
| DPS UPC $c\bar{c}b\bar{b}$ production in nb | | | |
| Total | 3.55 | 54.1 | 136 |

Table: Table with the integrated cross sections for DPS and SPS production processes.

# Conclusion

- Ultra-peripheral collisions provide a new approach to study of double parton scattering.
- We derived the effective cross section in UPCs.
- The main difference is that it is strongly dependent on the the photon fraction of longitudinal moment. (Not a constant.)
- The naïve pocket formula would not work.
- The effective cross section is quite large.
- We are working now on the *AA* case.

# Than you very much!

Special thank to the MITP and the organizers for the invitation and support.

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