Exclusive heavy quark production in ultrarelativistic heavy ion collisions*

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Outline

- Short motivation (heavy quarks + exclusive)
- Heavy quark production in two-gamma process
- Comparison to other production channels
- Summary and conclusions

Short Motivation

- Production of heavy quarks is reasonably understood in perturbative QCD (hard scale - m_Q).
- Exclusive production presents smaller cross sections but a better balance signal/background.
- In heavy ion collisions, 3 channels of production have similar final state configurations (two large rapidity gaps): the processes $\gamma - \gamma$, $\gamma - I\!P$ and $I\!P - I\!P$.
- Here, we will focus on two-photon channel in PbPb collisions at LHC.

Heavy quark production in $\gamma\gamma$ process

- We use Equivalent Photon Approximation (EPA).
- Cross section for $PbPb \to PbPbQ\bar{Q}$ process can be factorized into the equivalent photon spectra, $N(\omega, b)$, and $\gamma\gamma \to Q\bar{Q}$ subprocess cross section:

$$\sigma\left(PbPb \to PbPbQ\bar{Q}\right) = \int \hat{\sigma}\left(\gamma\gamma \to Q\bar{Q}; W_{\gamma\gamma}\right)\,\theta\left(|\mathbf{b}_1 - \mathbf{b}_2| - 2\right.$$
$$\times\; N(\omega_1, \mathbf{b}_1)\, N(\omega_2, \mathbf{b}_2)\, \mathrm{d}^2\mathbf{b}_1 \mathrm{d}^2\mathbf{b}_2 \mathrm{d}\omega_1 \mathrm{d}\omega_2$$

- Photon flux can be expressed in terms of the charge form factors $F(Q^2)$:

$$N(\omega, b) = \frac{Z^2\alpha_{em}}{\pi^2}\frac{1}{b^2\omega}\left(\int_0^\infty u^2 J_1(u)\,\frac{F\left(Q^2\right)}{Q^2}\,du\right)^2,$$

$$Q^2 = \frac{\left(\frac{b\omega}{\gamma}\right)^2 + u^2}{b^2}$$

Subprocesses: Born direct contribution

- Leading–order elementary cross section for $\gamma\gamma \to Q\bar{Q}$ at 2-photon energy $W_{\gamma\gamma}$:

$$\sigma^{direct}_{\gamma\gamma\to Q\bar{Q}}(W_{\gamma\gamma}) = N_c e_Q^4 \frac{4\pi\alpha_{em}^2}{W_{\gamma\gamma}^2} \times$$

$$\left\{ 2\ln\left[\frac{W_{\gamma\gamma}}{2m_Q}(1+v)\right]\left(1+\frac{4m_Q^2 W_{\gamma\gamma}^2 - 8m_Q^4}{W_{\gamma\gamma}^4}\right) - \left(1+\frac{4m_Q^2 W_{\gamma\gamma}^2}{W_{\gamma\gamma}^4}\right)\right.$$

- $N_c = 3$ is the number of quark colors, $v = \sqrt{1 - \frac{4m_Q^2}{W_{\gamma\gamma}^2}}$ and e_Q is the fractional charge of the heavy quark.
- Here, heavy quark masses are taken to be: $m_c = 1.5$ GeV, $m_b = 4.75$ GeV.

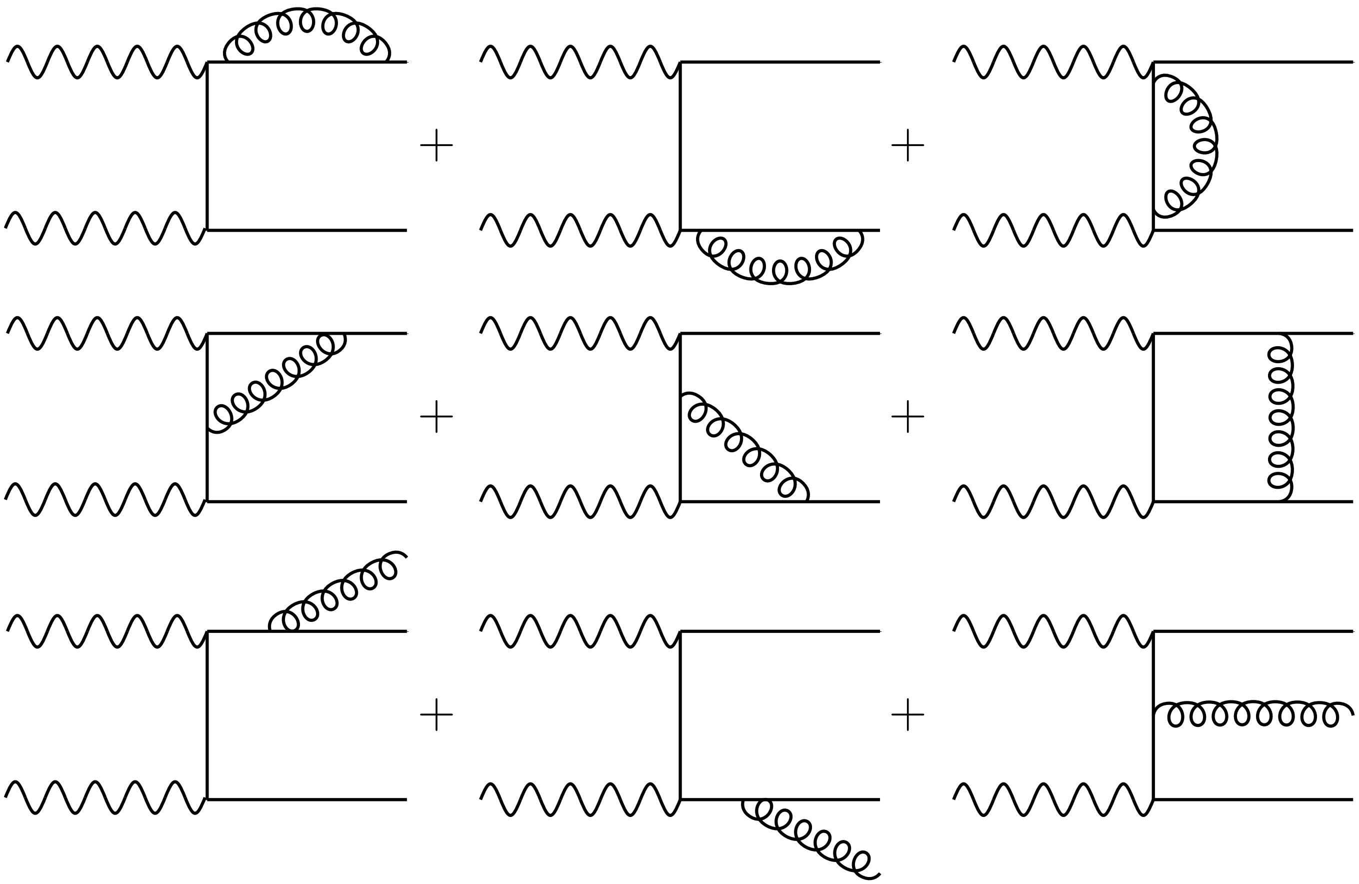
Subprocesses: LO QCD corrections

- For $Q\bar{Q}$ production one needs to include also higher-order QCD processes. Here, we include leading–order corrections only for direct contribution.
- In α_s-order there are one-gluon bremsstrahlung diagrams ($\gamma\gamma \to Q\bar{Q}g$) and interferences of the Born diagram with self-energy diagrams and vertex-correction diagrams (in $\gamma\gamma \to Q\bar{Q}$).

$$\sigma^{QCD}_{\gamma\gamma\to Q\bar{Q}(g)}(W_{\gamma\gamma}) = N_c e_Q^4 \frac{2\pi\alpha_{em}^2}{W_{\gamma\gamma}^2}\left[C_F \frac{\alpha_s}{\pi} c^{(1)}(m_Q/W_{\gamma\gamma})\right]$$

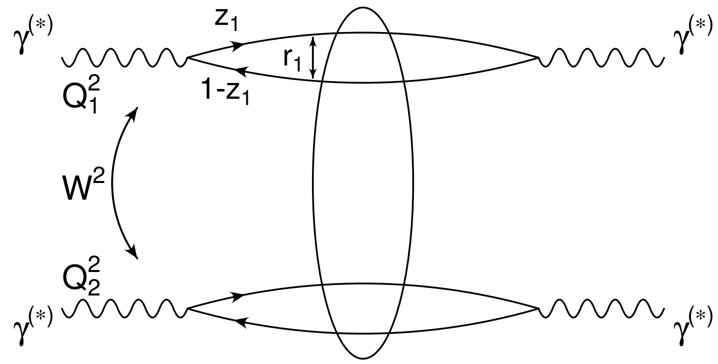
- The function $c^{(1)}$ is taken from B.A. Kniehl et al., Phys. Rev. D79 (2009) 114032.
- Scale of α_s is fixed at $\mu^2 = 4m_Q^2$.

Subprocesses: sample diagrams



- Representative diagrams for the leading–order QCD corrections.

Subprocesses: $Q\bar{Q}q\bar{q}$ contribution



- At high energies, contribution of dipole-dipole scattering can be computed in color dipole approach.

$$\sigma = \sum_{q_1 \neq Q} \int |\Psi_{q_1\bar{q}_1}(\boldsymbol{r}_1, z_1)|^2 \, |\Psi_{Q\bar{Q}}(\boldsymbol{r}_2, z_2)|^2 \sigma_{\rm dd}\left(\tilde{x}_{ab}\right) d^2\boldsymbol{r}_1 \, d^2\boldsymbol{r}_2 \, dz_1$$

$$+ \sum_{q_2 \neq Q} \int |\Psi_{Q\bar{Q}}(\boldsymbol{r}_1, z_1)|^2 \, |\Psi_{q_2\bar{q}_2}(\boldsymbol{r}_2, z_2)|^2 \sigma_{\rm dd}\left(\tilde{x}_{ab}\right) d^2\boldsymbol{r}_1 \, d^2\boldsymbol{r}_2 \, dz_1$$

- $\Psi_{q\bar{q},\,(Q\bar{Q})}$ are the wavefunctions for light (heavy) quarks in the mixed representation.

Color dipole model

- Process $\gamma\gamma \to Q\bar{Q}X$ can be computed using saturation model for the dipole-dipole cross section.

$$\sigma_{\rm dd}^{\rm sat}(\boldsymbol{r}_1, \boldsymbol{r}_2, \tilde{x}_{ab}) = \tilde{\sigma}_0 \left[1 - \exp\left(-\frac{\bar{r}^2}{4\,R_0^2(\tilde{x}_{ab})}\right)\right]$$

$$R_0^2(\tilde{x}_{ab}) = \left(\frac{\tilde{x}_{ab}}{x_0}\right)^{\lambda} \,{\rm GeV}^{-2}, \quad \tilde{x}_{ab} = \frac{4\,m_a^2 + 4\,m_b^2}{W_{\gamma\gamma}^2}$$

- Normalization is given by $\tilde{\sigma}_0 = 19.41$ mb and effective radius $\bar{r}$ is defined in such way that it reproduces the GBW model for dipole-proton cross section, that is $\bar{\boldsymbol{r}}^2 \sim \boldsymbol{r}_1^2\,(\sim \boldsymbol{r}_2^2)$ for dipoles size configurations $\boldsymbol{r}_2^2 \gg \boldsymbol{r}_1^2\,(\boldsymbol{r}_1^2 \gg \boldsymbol{r}_2^2)$.

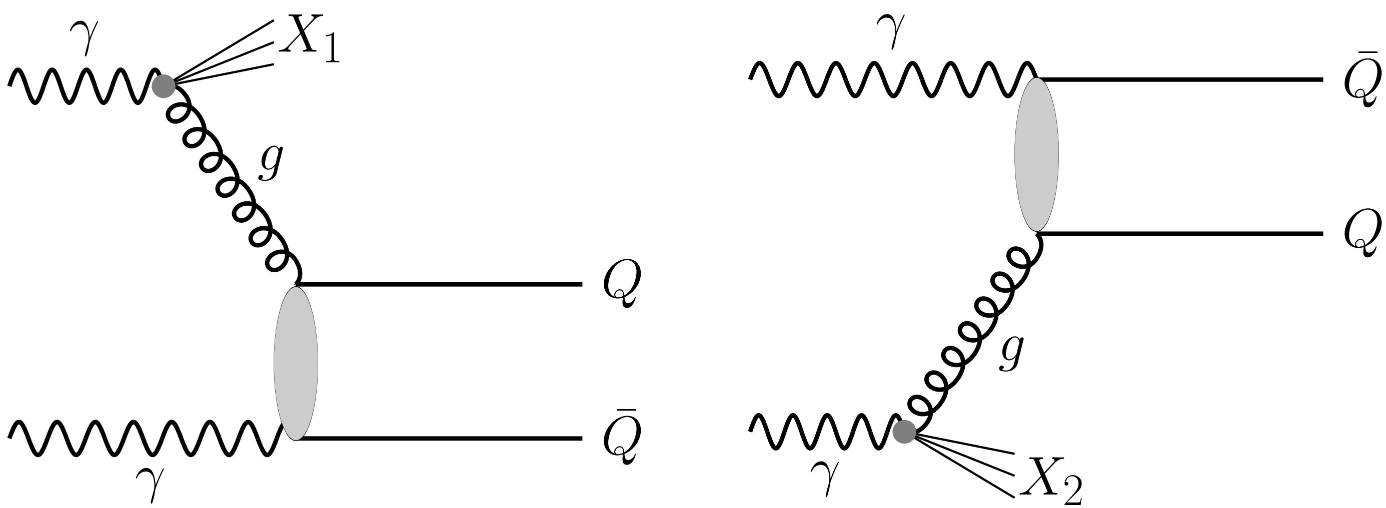
Subprocesses: single resolved contributi

- The $Q\bar{Q}q\bar{q}$ component have very small overlap with the single-resolved component (SR) because of quite different final state, so adding them together does not lead to double counting.
- Cross section for the single-resolved contribution can be written as:

$$\sigma_{SR}(s) = \int dx_1 \left[g_1\left(x_1, \mu^2\right) \hat{\sigma}_{g\gamma}\left(\hat{s} = x_1 s\right) \right] + \int dx_2 \left[g_2\left(x_2, \mu^2\right) \hat{\sigma}_{\gamma g}\left(\hat{s} = x_2 s\right) \right]$$

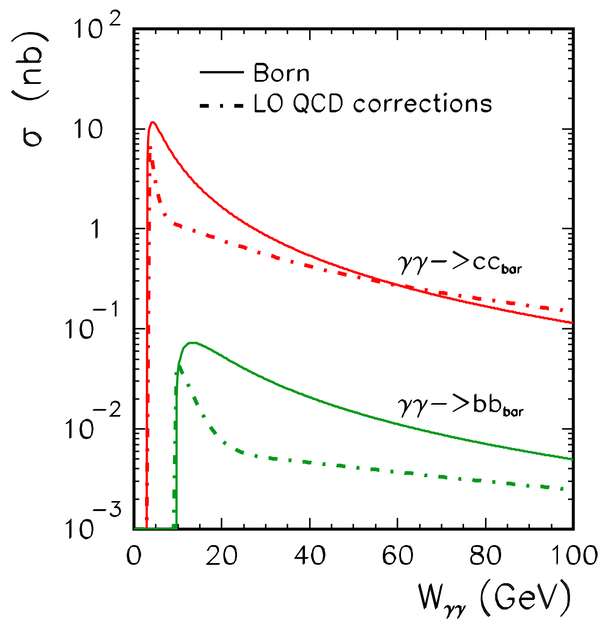
- The g_1 and g_2 are gluon distributions in photon 1 or photon 2 and $\hat{\sigma}_{q\gamma}$ and $\hat{\sigma}_{\gamma g}$ are elementary cross sections.

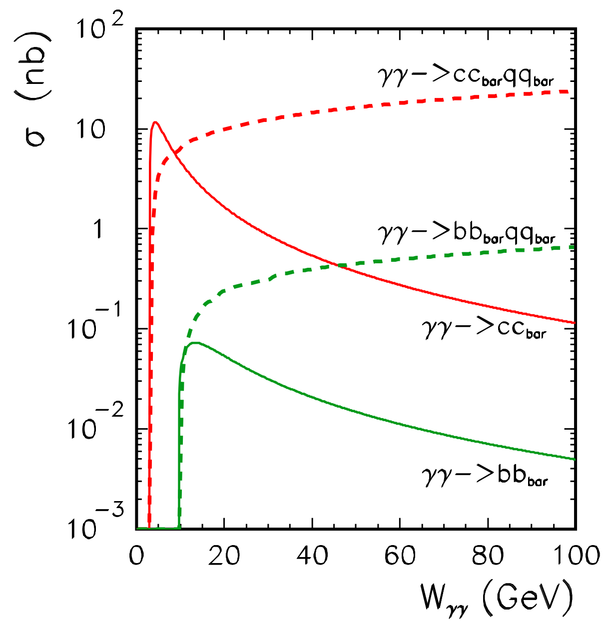
Subprocesses: diagrams for single resolv

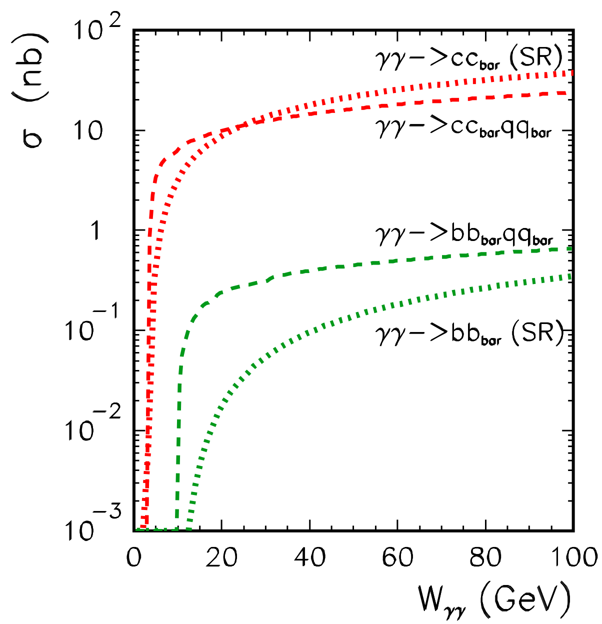


- Representative diagrams for the single-resolved mechanism.

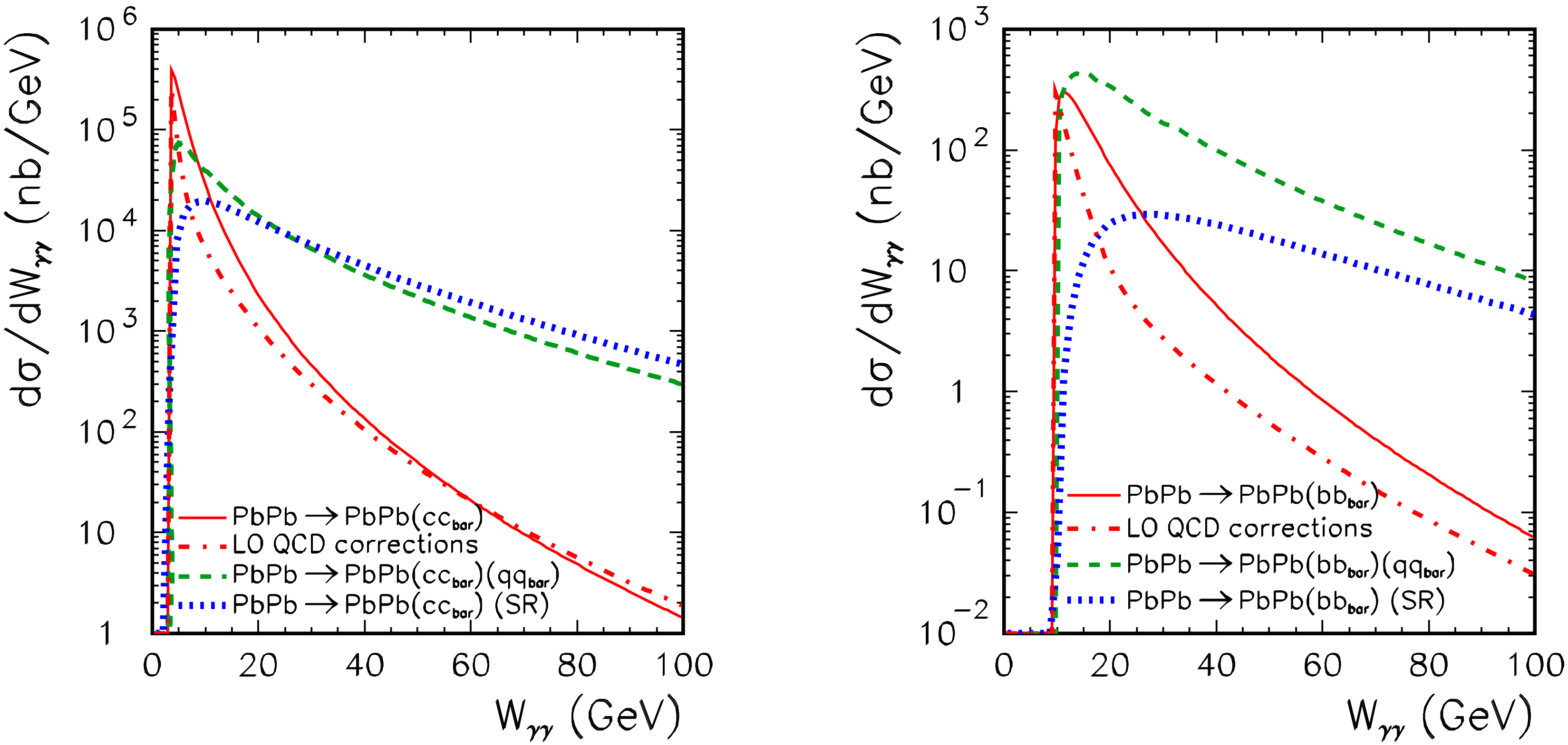
Numerics: elementary cross sections





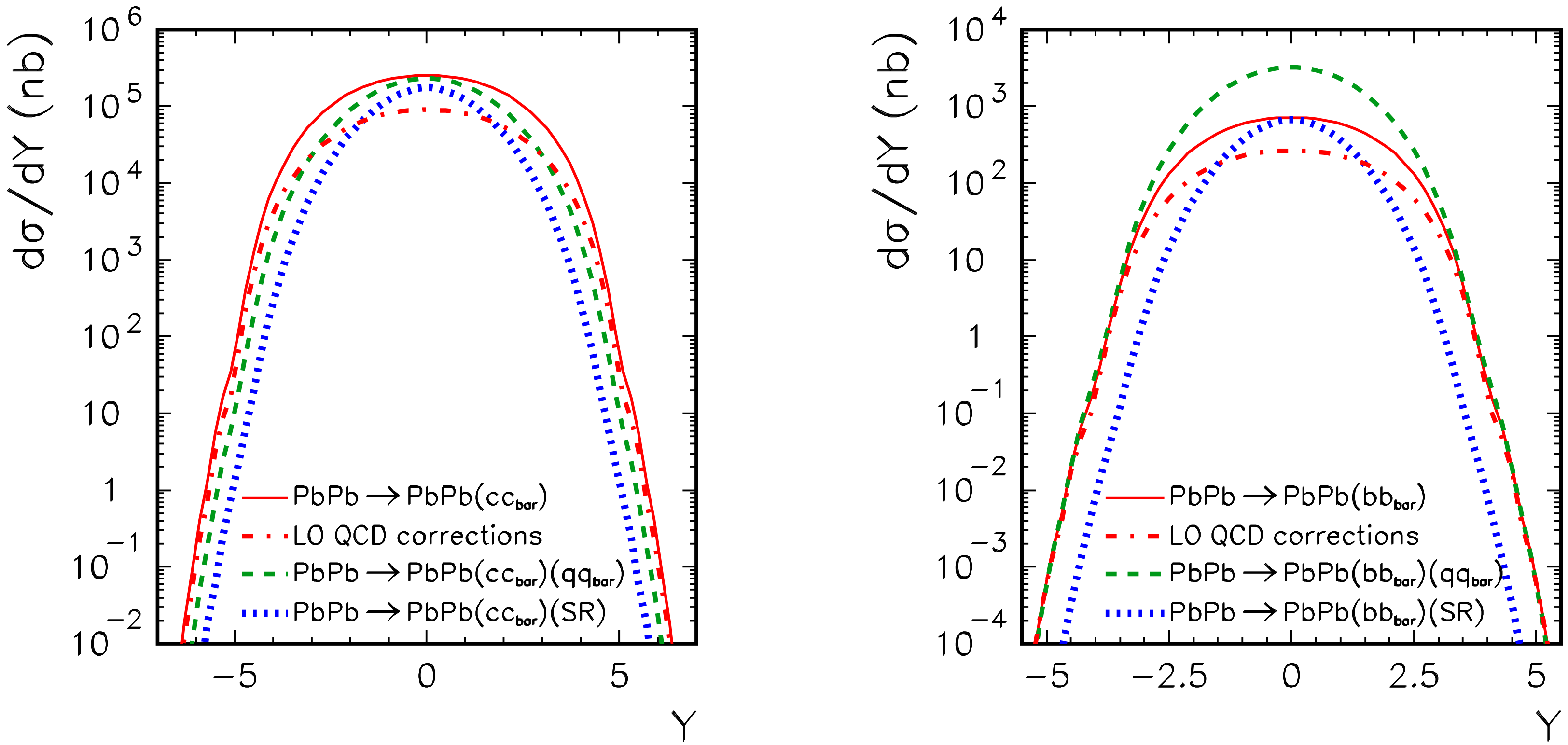


Numerics: invariant mass distribution



- The nuclear cross section as a function of photon–photon subsystem energy $W_{\gamma\gamma}$ in EPA.

Numerics: rapidity distribution



- The rapidity distribution, $\frac{d\sigma}{dY}$, in the b-space EPA.

Numerics: integrated cross sections

- Integrated cross sections for each contribution.

Process	DIRECT	LO QCD	$Q\bar{Q}q\bar{q}$	SR
$PbPb \to PbPb\, c\bar{c}$	1.05 mb	0.36 mb	0.67 mb	0.39 mb
$PbPb \to PbPb\, b\bar{b}$	2.05 μb	0.83 μb	6.98 μb	0.97 μb

- Partial contributions of different mechanisms.

	σ_{tot}	Born	QCD-corrections	4-quark	Single-resolve
$c\bar{c}$	2.47 mb	42.5 %	14.6 %	27.1 %	15.8 %
$b\bar{b}$	10.83 μb	18.9 %	7.7 %	64.5 %	8.9 %

Background: $\gamma I\!\!P$ process

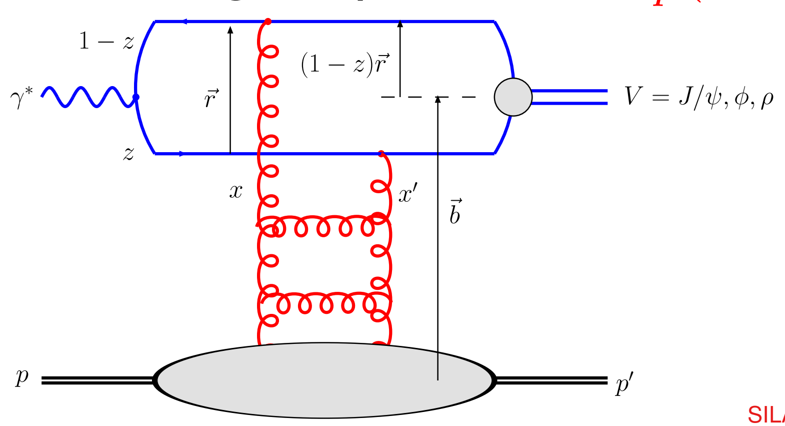
- Cross section for exclusive production of heavy flavours, $A + A \to A + (\gamma I\!\!P \to Q\bar{Q}) + A$ is given by:

$$\sigma(A + A \to A + A + Q\bar{Q}) = 2 \int \sigma^{\gamma I\!\!P}_{\gamma + A \to Q\bar{Q} + A}(k)\, \frac{dn_\gamma}{dk}\, dk$$

- Considering the color dipole approach (at $x \lesssim 10^{-2}$).

$$\sigma^{\gamma I\!\!P}_{\gamma + A \to Q\bar{Q} + A} \propto \int dz\, d^2r d^2b\, \Psi^*_\gamma(z, r, Q^2)\, N^2_{dip}(x, r; b)\, \Psi_\gamma(z, r, Q^2)$$

- Basic quantities: photon wavefunctions (Ψ_γ and the dipole-target scattering amplitude, $N_{dip}(x, r;\, b)$.



Dipole-target amplitude

- Amplitude can be computed using Glauber approach:

$$N_{dip}(x,\, r;\, b) = 2\left\{1 - \exp\left[-\frac{1}{2}\, A\, T_A(b)\, \sigma_{dip}(x,\, \boldsymbol{r})\right]\right\}$$

- The nuclear profile function is denoted by $T_A(b)$ (Wood-Saxon), where b is the impact parameter of scattering dipole-nucleus.

- This approach describes data for nuclear rations for structure functions F_2^A/F_2^p in the region $x \leq 10^{-2}$.

- As input we use GBW dipole cross section (based on saturation physics):

$$\sigma_{dip}^{\mathrm{GBW}}(x, \boldsymbol{r}) = \sigma_0\left[1 - \exp\left(-\frac{Q_{\mathrm{sat}}^2 r^2}{4}\right)\right]$$

- Saturation scale is denoted by $Q_{\mathrm{sat}}(x) = (x_0/x)^{\lambda/2}$.

Background: $I\!P I\!P$ process

- Here, we consider the Bialas-Landshoff model for exclusive production of heavy quarks.

$$\sigma_{I\!P I\!P}(pp \to p + Q\bar{Q} + p) = \frac{S^2_{\text{gap}}}{2s\,(2\pi)^8} \int \overline{|M_{fi}|^2}\, [F\,(t_1)\,F\,(t_2)]^2\, dPH$$

where $F\,(t) \approx \exp\,(b\,t)$, with $b = 2$ GeV^{-2}, is the nucleon form factor and the phase space factor dPH is given by,

$$\begin{aligned} dPH &= d^4k_1\delta\left(k_1^2\right) d^4k_2\,\delta\left(k_2^2\right) d^4r_1\,\delta\left(r_1^2 - m_Q^2\right) \\ &\times\; d^4r_2\,\delta\left(r_2^2 - m_Q^2\right)\Theta\left(k_1^0\right)\Theta\left(k_2^0\right)\Theta\left(r_1^0\right)\Theta\left(r_2^0\right) \\ &\times\; \delta^{(4)}\left(p_1 + p_2 - k_1 - k_2 - r_1 - r_2\right) \end{aligned}$$

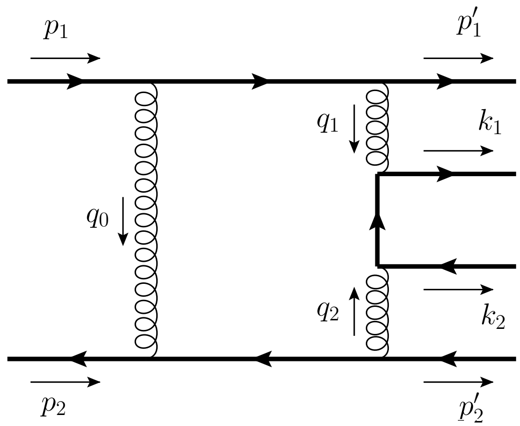
- $S^2_{\text{gap}}(\sqrt{s})$ is the gap survival probability factor.
- Extrapolation to AA collisions is made using approach from C. Pajares and V.A. Ramallo, Phys. Lett. B107 (1981).

Bialas-Landshoff model

- Squared matrix element is given by:

$$\overline{|M_{fi}|^2} = \frac{x_1 y_2 \, H \, \exp\left[2\beta\left(t_1 + t_2\right)\right]}{\left(s x_Q y_Q\right)^2 \left(\delta_1 \delta_2\right)^{1+2\epsilon} \, \delta_1^{2\alpha' t_1} \delta_2^{2\alpha' t_2}} \left(1 - \frac{4\, m_Q^2}{s \delta_1 \delta_2}\right)$$

- Overall normalization is $H = 2s\left[\frac{4\pi m_Q \left(G^2 D_0\right)^3 \mu^4}{9\left(2\pi\right)^2}\right]^2 \left(\frac{\alpha_s}{\alpha_0}\right)^2$.
- Here, $\alpha_s = \alpha_s(\mu_F^2)$ is the strong coupling constant and α_0 is the non-perturbative coupling and model parameters are $\epsilon = 0.08$, $\alpha' = 0.25$ GeV^{-2}, $\mu = 1.1$ GeV and $G^2 D_0 = 30$ GeV$^{-1}\mu^{-1}$.



Results and summary

- Comparison shows that a important process in AA collisions is due the photon-Pomeron channel.
- Experimental separation between the channels photon-photon and Pomeron-Pomeron has to be refined (e.g., p_T cuts for produced particles).

HEAVY QUARK	CHANNEL $\gamma\gamma$	CHANNEL $\gamma I\!P$	CHANNEL $I\!P I\!P$
$c\bar{c}$	2.47 mb	59 mb	9.67 ± 5.47 μb
$b\bar{b}$	10.83 μb	10 μb	0.4 ± 0.2 μb

- Error bands represent the model dependence.
- QCD inspitred models for $I\!P I\!P$ interaction give larger cross sections than Bialas-Landshoff (soft Pomeron) model.
- Notice that impact parameter cut was not imposed to photon-Pomeron and Pomeron-Pomeron contributions.