Exclusive production of heavy quarks in AA collisions at the LHC*

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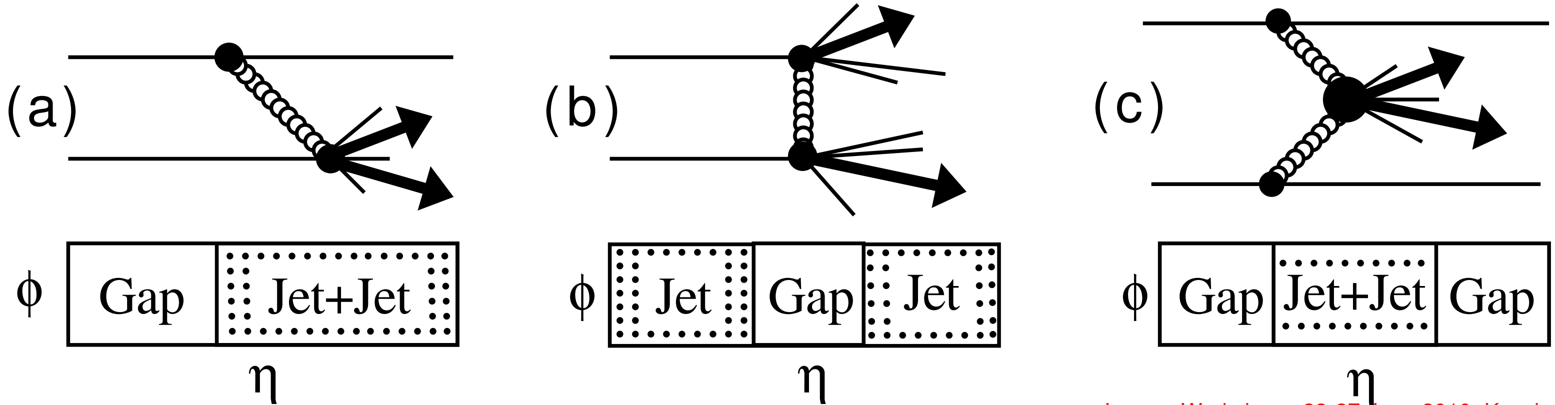
Motivation

- Production of heavy quarks is reasonably understood in perturbative QCD (hard scale - m_Q).
- Theoretical uncertainty among pQCD formalisms at high energies generate quite distinct predictions.
- Exclusive production presents smaller cross sections but a better balance signal/background.
- In heavy ion collisions at the LHC, 3 channels [Figure (c)] have similar final state configurations (two large rapidity gaps): processes $\gamma - \gamma$, $\gamma - I\!\!P$ and $I\!\!P - I\!\!P$.

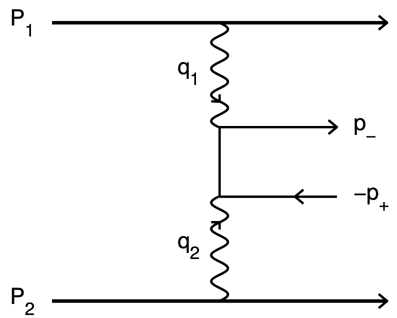


Heavy quark production in $\gamma\gamma$ process

- In equivalent photon approximation (EPA), the cross section for the process $A + A \to A + (\gamma\gamma \to Q\bar{Q}) + A$ is factorized:

$$\sigma(A + A \to A + A + Q\bar{Q}) \propto \int \sigma_{\gamma+\gamma\to Q\bar{Q}}(W_{\gamma\gamma}) \frac{dn_\gamma}{dk_1} \frac{dn_\gamma}{dk_2} dk_1\, dk_2$$

- Number of equivalent photons having energy k in nucleus is denoted by $\frac{dn_\gamma(k)}{dk}$.
- Cross section for 2-photon scattering at center of mass energy $W_{\gamma\gamma}$ is given by $\sigma_{\gamma+\gamma\to Q\bar{Q}}$.
- Production cross section is well known in Born level in QED.



Process $\gamma\gamma$ at LO

- As example, a simplified exppression is obtained using non-realistic form factor for nuclei, $F(Q^2) = 1/1 + (Q^2/\Lambda^2)$.

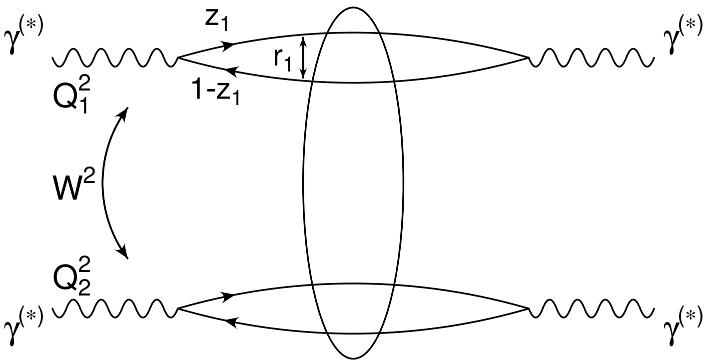
$$\sigma^{LLA}(A + A \to A + A + Q\bar{Q}) = \frac{28}{9\pi}\frac{(e_Q Z\alpha)^4}{m_Q^2}\ln^3\left[\left(\frac{\Lambda\gamma_L}{4m_Q}\right)^2\right]$$

- Calculation can be refined using a realistic form factor.
- Refs.: K. Hencken, E.A. Kuraev, V.G. Serbo, PRC75, 034903 (2007); U.D. Jentschura, V.G. Serbo, EPJC64, 309 (2009).

$$F(q^2) = \frac{\int \rho(r)\, e^{-i\vec{q}\cdot\vec{r}}\, d^3r}{\int \rho(r)\, d^3r}, \quad \rho(r) = \frac{\rho_0}{1 + \exp\left[(r - R_A)/a\right]}$$

- This gives $\sigma_{c\bar{c}} = 2.12$ mb and $\sigma_{b\bar{b}} = 3.84\ \mu$b.
- At high energy, QCD processes could be important . . .

Process $\gamma\gamma$ at high energy



- 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.

Process $\gamma\gamma$ at high energy

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

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

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

- 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 $\boldsymbol{r}_2^2 \gg \boldsymbol{r}_1^2\,(\boldsymbol{r}_1^2 \gg \boldsymbol{r}_2^2)$.
- In order to estimate the model dependence, cross section dipole-dipole can be computed using BFKL approach. See, e.g. V.P. Gonçalves, MVTM, EPJC29, 37 (2003).

Heavy quark production in $\gamma I\!\!P$ process

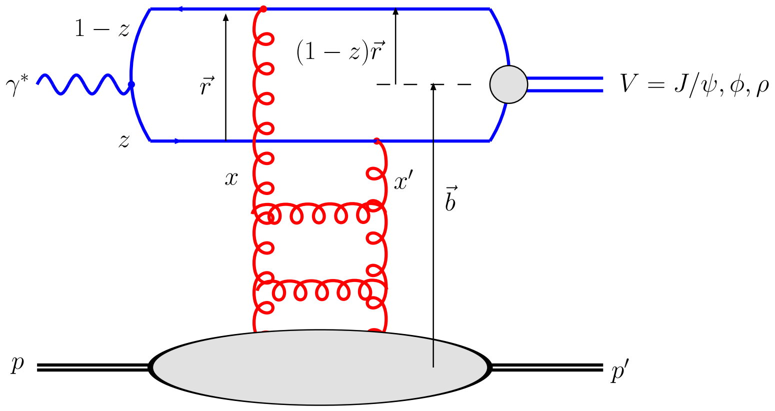
- Cross section for exclusive production of heavy flavours, $A + A \to A + (\gamma I\!\!P \to Q\bar{Q}) + A$ is given by:

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

- 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):

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

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

Heavy quark production in $I\!P I\!P$ 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,

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

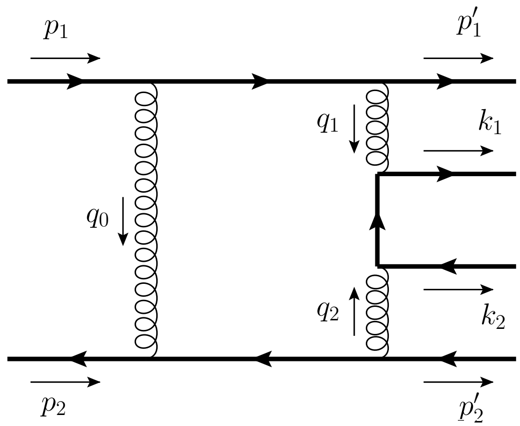
- $S^2_{\text{gap}}(\sqrt{s})$ is the gap survival probability factor.
- Extrapolation to AA collisions is made using Glauber aproach.

Bialas-Landshoff model

- Squared matrix element is given by:

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

- Overall normalization is $H = 2s\left[\frac{4\pi m_Q\,(G^2 D_0)^3 \mu^4}{9\,(2\pi)^2}\right]^2 \left(\frac{\alpha_s}{\alpha_0}\right)^2$.
- Here, $\alpha_s = \alpha_s(\mu_F^2)$ is the strong coupling constant and α_0 is the non-perturbative coupling (unknown) 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 the dominant 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 $I\!P I\!P$
$c\bar{c}$	1.88 ± 0.071 mb	107.7 ± 48.7 mb	9.67 ± 5.47 μb
$b\bar{b}$	2.1 ± 0.1 μb	13.7 ± 3.7 μb	0.4 ± 0.2 μb

- Error bands represent the model dependence.
- QCD models for $I\!P I\!P$ interaction give larger cross sections than Bialas-Landshoff (soft Pomeron) model.
- Work in progress: detailed study on $\gamma\gamma$ production (in collaboration with M. Klusek-Gawenda, A. Szczurek, V.G. Serbo).