Production of fully - heavy tetraquark states through the Double Parton Scattering mechanism in pp and pA collisions.

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Hadron spectroscopy and the new unexpected resonances.
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Our goal

- To estimate the production cross section of these tetraquark states (T_{4c}, T_{4b} and T_{2b2c}).

- for (pp) and (pA) collisions

- at the LHC and FCC energies

- considering double parton scattering (DPS).

Motivations

- Recents experimental results from the LHCb, ATLAS and CMS Collaborations: A peak in the di - J/ψ channel -> resonance at M = 6.9 GeV -> good candidate for a fully-charm tetraquark state.

- Several Studies: large number of exotic states.

- Mass spectra ✅
- Decay properties ✅
- Production Mechanism of these states are still on debate

➢ Single Parton Scattering (SPS):

Is a correction to the leading order gluon-gluon scattering, in which an extra $Q\bar{Q}$ pair is produced: $gg -> Q\bar{Q}Q\bar{Q}$.

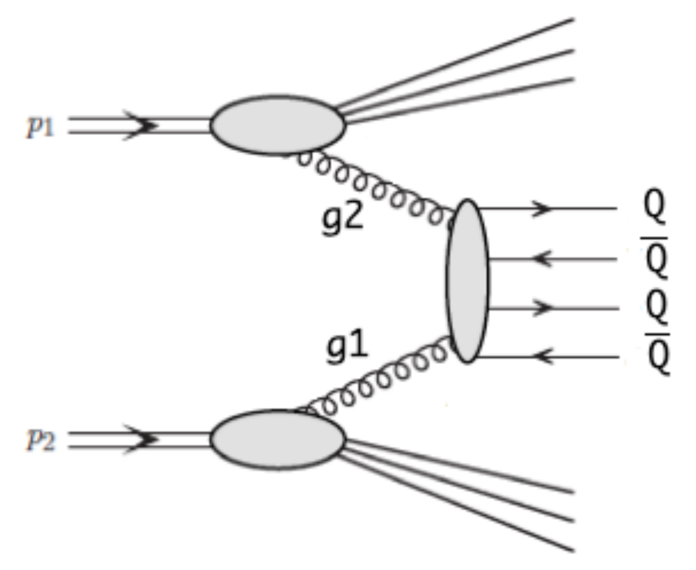


Fig.1 - SPS

- Double Parton Parton Scattering (DPS):

two independent leading order gluon-gluon scatterings, i.e., two times the reaction $gg -> Q\bar{Q}$.

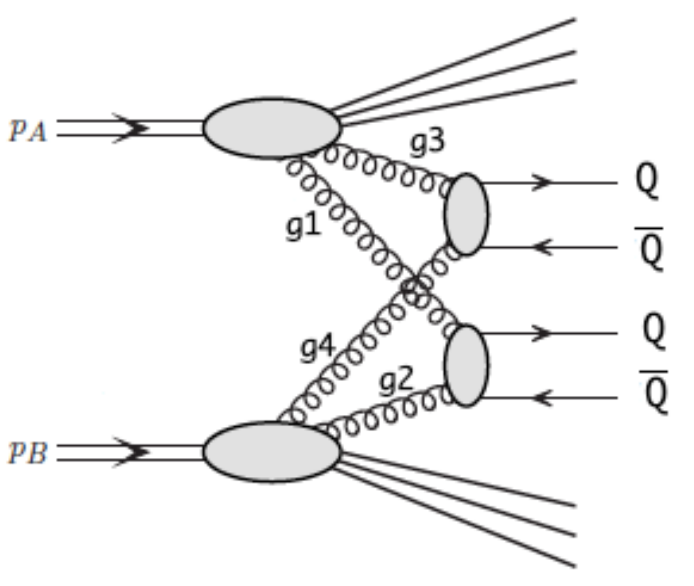


Fig.2 - DPS

SPS x DPS

- Gluon density grows with the increasing energy.
- SPS and DPS are sensitive to this density:

SPS -> convolution of the gluon densities $g(x, \mu^2)$ with the partonic cross sections:

$$\sigma_{SPS} \propto g(x_1, \mu^2) \times g(x_2, \mu^2) \times \sigma_{g_1 g_2 \to Q_i \bar{Q}_j Q_i \bar{Q}_j}$$

$\boldsymbol{\sigma_{SPS} \propto g^2}$!!

DPS: twice the convolution of the gluon densities with the partonic cross sections.

$$\sigma_{DPS} \propto g(x_1, \mu^2) \times g(x_2, \mu^2) \times \sigma_{g_1 g_2 \to Q_i \bar{Q}_j} \\ \times g(x_3, \mu^2) \times g(x_4, \mu^2) \times \sigma_{g_3 g_4 \to Q_i \bar{Q}_j}$$

$\boldsymbol{\sigma_{DPS} \propto g^4}$!!

Tetraquark states from DPS

- The two $Q\bar{Q}$ pairs are produced by DPS events.
- We have to bind them together to form the T_{4Q} state.

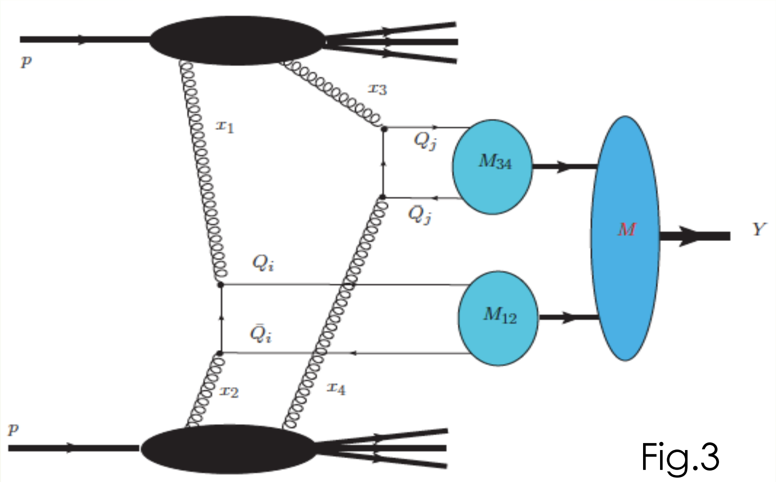


Fig.3

The kinematical constraints:

- invariant masses: M_{12} and M_{34}
- Rapidities: y_{12} and y_{34}
- They will form a system with mass $M = M_{12} + M_{34}$ **if**:
  - ➢ $y_{12} = y_{34}$ and
  - ➢ M is about the mass of the tetraquark (M_{T4Q}).

❖ Color Neutral State:

Color Evaporation Model: The T4Q becomes color neutral by the exchange of a soft gluon

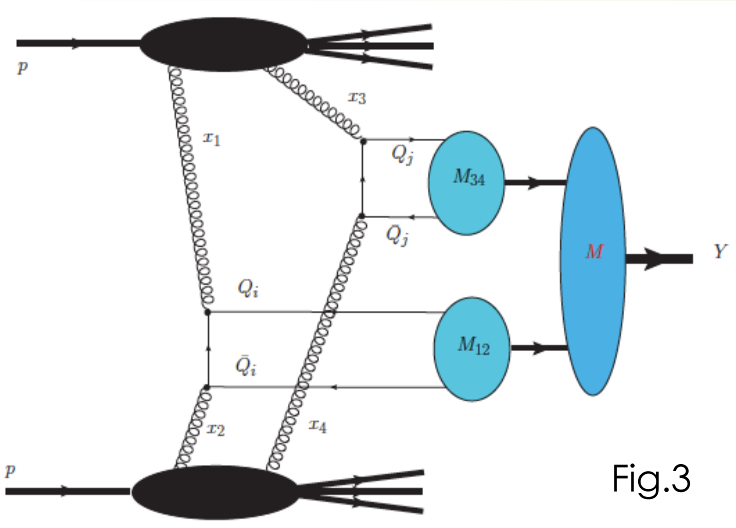


Fig.3

The calculations

Cross section of the Fig.3: **DPS “pocket” formula:**

$$\sigma^{DPS} \propto \frac{\sigma_{SPS}^{12} \times \sigma_{SPS}^{34}}{\sigma_{eff}}$$

Where

- $\sigma_{eff} = 15\, nb$ is a constant extracted from data
- σ_{SPS} is the standard QCD parton model formula.

$$
\begin{aligned}
\sigma_{DPS} = \frac{F_T}{\sigma_{eff}} & \left[\int dx_1 \;\; \int dx_2 \;\; g(x_1, \mu^2) \; g(x_2, \mu^2) \;\; \sigma_{g_1 g_2 \to Q_i \bar{Q}_j} \right] \\
& \times \left[\int dx_2 \;\; \int dx_4 \;\; g(x_3, \mu^2) \; g(x_4, \mu^2) \;\; \sigma_{g_3 g_4 \to Q_i \bar{Q}_j} \right] \\
& \times \; \Theta(1 - x_1 - x_3) \times \Theta(1 - x_2 - x_4) \times \Theta\left(M_{12}^2 - 4m_{Q_i}^2\right) \\
& \times \; \Theta\left(M_{34}^2 - 4m_{Q_j}^2\right) \times \delta(y_{34} - y_{12})
\end{aligned}
$$

Where:

- $g(x, \mu^2)$ is the gluon distribution function in the proton
- $\sigma_{gg \to QQ}$ is the elementary cross section for the $gg \to QQ$;
- The step functions $\Theta(1 - x_1 - x_3)$ and $\Theta(1 - x_2 - x_4)$ enforce momentum conservation;

$$\sigma_{DPS} = \frac{F_T}{\sigma_{eff}} \left[\int dx_1 \ \int dx_2 \ \ g(x_1,\mu^2) \ g(x_2,\mu^2) \ \ \sigma_{g_1 g_2 \rightarrow Q_i \bar{Q}_j} \right]$$

$$\times \left[\int dx_2 \ \int dx_4 \ \ g(x_3,\mu^2) \ g(x_4,\mu^2) \ \ \sigma_{g_3 g_4 \rightarrow Q_i \bar{Q}_j} \right]$$

$$\times \ \Theta(1 - x_1 - x_3) \times \Theta(1 - x_2 - x_4) \times \Theta\left(M_{12}^2 - 4m_{Q_i}^2\right)$$

$$\times \ \Theta\left(M_{34}^2 - 4m_{Q_j}^2\right) \times \ \delta(y_{34} - y_{12})$$

- The step functions $\Theta(M_{12}^2 - 4m_{Q_i}^2)$ and $\Theta(M_{34}^2 - 4m_{Q_j}^2)$ ➡ the invariant masses M_{12} and M_{34} are large enough to produce heavy quarks;
- The delta function $\delta(y_{34} - y_{12})$ ➡ two pairs are in the same rapidity.
- F_T is a constant to be determined.

Remembering that:

$$y_{12} = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right) \qquad y_{34} = \frac{1}{2}\ln\left(\frac{x_3}{4}\right) \qquad M_{12} = \sqrt{x_1 x_2 s} \qquad M_{34} = \sqrt{x_3 x_4 s}$$

we change the variables from x_1, x_2, x_3, and x_4 to y_{12}, y_{34}, M_{12}, and M_{34}:

$$\begin{aligned}
\sigma_{T_{4Q}}(\sqrt{s}) = \frac{F_T}{\sigma_{eff}} & \left[\frac{1}{s} \int dy_{12} \int dM_{12}^2 \; g(\bar{x}_1, \mu^2)\; g(\bar{x}_2, \mu^2) \; \sigma_{g_1 g_2 \to Q_i \bar{Q}_j}\right] \\
& \times \left[\frac{1}{s} \int dy_{34} \int dM_{34}^2 \; g(\bar{x}_3, \mu^2)\; g(\bar{x}_4, \mu^2) \; \sigma_{g_3 g_4 \to Q_i \bar{Q}_j}\right] \\
& \times \Theta(1 - \bar{x}_1 - \bar{x}_3) \times \Theta(1 - \bar{x}_2 - \bar{x}_4) \times \Theta\left(M_{12}^2 - 4m_{Q_i}^2\right) \\
& \times \Theta\left(M_{34}^2 - 4m_{Q_j}^2\right) \times \delta(y_{34} - y_{12})
\end{aligned}$$

Where $\bar{x}_1 = \frac{M_{12}}{\sqrt{s}}\, e^{y_{12}}$ $\quad \bar{x}_2 = \frac{M_{12}}{\sqrt{s}}\, e^{-y_{12}}$ $\quad \bar{x}_3 = \frac{M_{34}}{\sqrt{s}}\, e^{y_{34}}$ $\quad \bar{x}_4 = \frac{M_{34}}{\sqrt{s}}\, e^{-y_{34}}$

Ingredients to the calculation

- $g(x,\mu^2)$: ***CT14*** parametrization [PRD 89, nº.3, 033009 (2014)]
- $\sigma_{gg\to Q\bar{Q}}$: the standard leading order QCD result:

$$\sigma_{gg\to Q\bar{Q}} = \frac{\pi\alpha_s^2(M_{ij}^2)}{3M_{ij}^2}\left\{\left(1+\frac{4m_Q^2}{M_{ij}^2}+\frac{m_Q^4}{M_{ij}^4}\right) ln\left[\frac{1+\beta}{1-\beta}\right]-\frac{1}{4}\left(7+\frac{31m_Q^2}{M_{ij}^2}\right)\beta\right\}$$

where $\beta = \left[1-\frac{4m_Q^2}{M_{ij}^2}\right]^{1/2}$

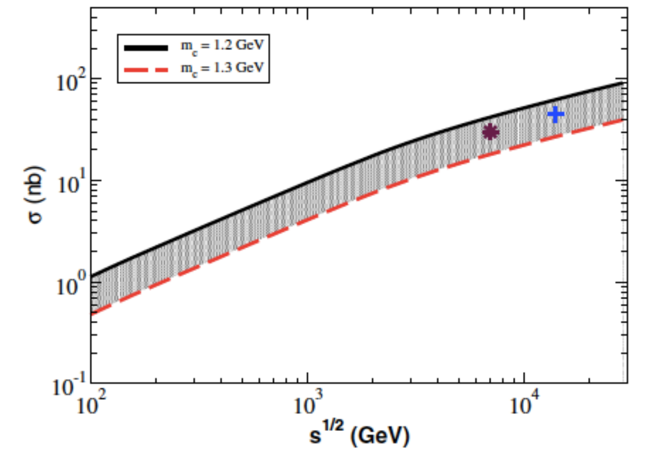
- F_T for the $T_{4c,}\, T_{4b}$ and T_{2c2b} states.

In the Ref. PRD 93, nº.3, 034004 (2016),

we have estimated $F_{T_{4c}}$ in terms of the cross section for the X(3872) production:

$$F_X \approx 0.01 \quad \rightarrow \quad \sigma_X\,(\sqrt{s} = 7.0\,TeV) \approx 30\,nb$$

(CMS collaboration in *pp* collisions)



We imposed a ”penalty” factor:

$$\sigma_{T_{4c}} = \frac{\sigma_{c\bar{c}c\bar{c}}}{\sigma_{c\bar{c}q\bar{q}}}\,\sigma_X \approx \frac{\sigma_{c\bar{c}} * \sigma_{c\bar{c}}}{\sigma_{c\bar{c}} * \sigma_{q\bar{q}}}\sigma_X \approx \frac{\sigma_{c\bar{c}}}{\sigma_{inel}}\sigma_X \approx 0.12\,\sigma_X$$

➡ $F_T \approx 0.12\,F_X \approx 0.0012$

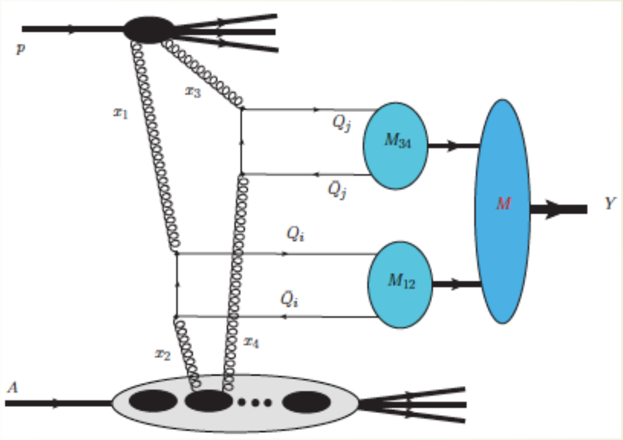
Ref. PRD D 65, 037503 (2002) has indicated that the value of this factor is similar for different quarkonium states.

We assumed the same value in the calculation of the T4b and T2b2c production cross sections.

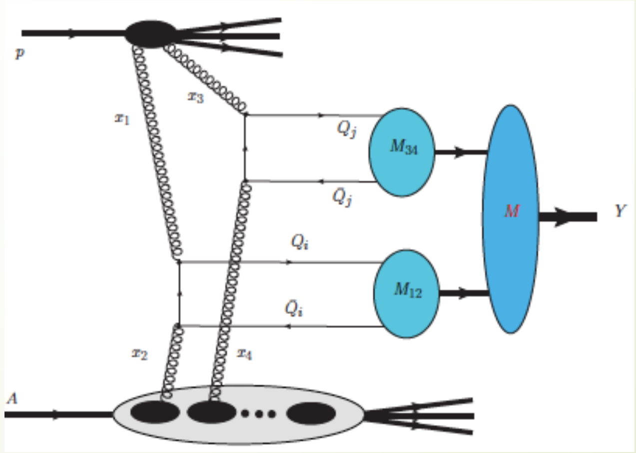
Generalization to pA collisions

Important things:

- the parton flux is enhanced by a factor ∝ atomic number A
- two contributions:
  - DPS1: gluons from the same nucleon
  - DPS2: gluons from diffent nucleons

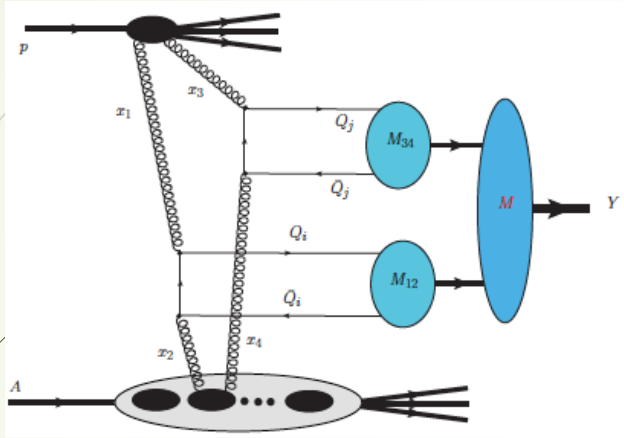


DPS1

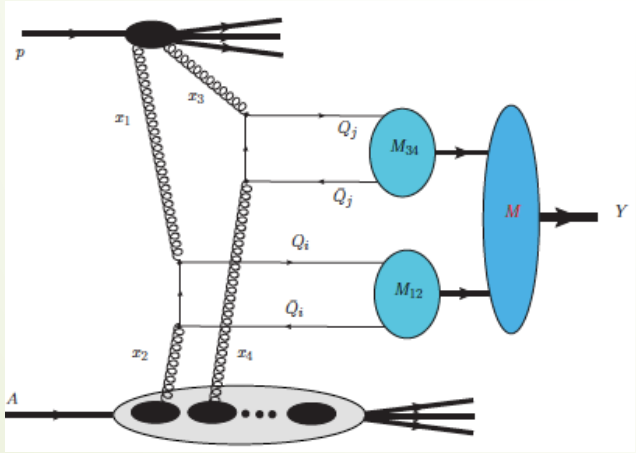


DPS2

Following Refs. PRL. 88, 031801 (2002) and PLB 718, 1395 (2013) we have:



$$\sigma^{pA}_{DPS1} = A \cdot \sigma^{pp}_{DPS}$$



$$\sigma^{pA}_{DPS2} = \sigma^{pp}_{DPS} \cdot \sigma_{eff} \cdot F_{pA}$$

Where $F_{pA} = [(A-1)/A] \int T_{pA}^2(r) d^2 r$

r is impact parameter

T_{pA} is the nuclear thickness function.

Assuming: $R_A = r_0 A^{1/3}$ (spherical nucleus, uniform nucleon density):

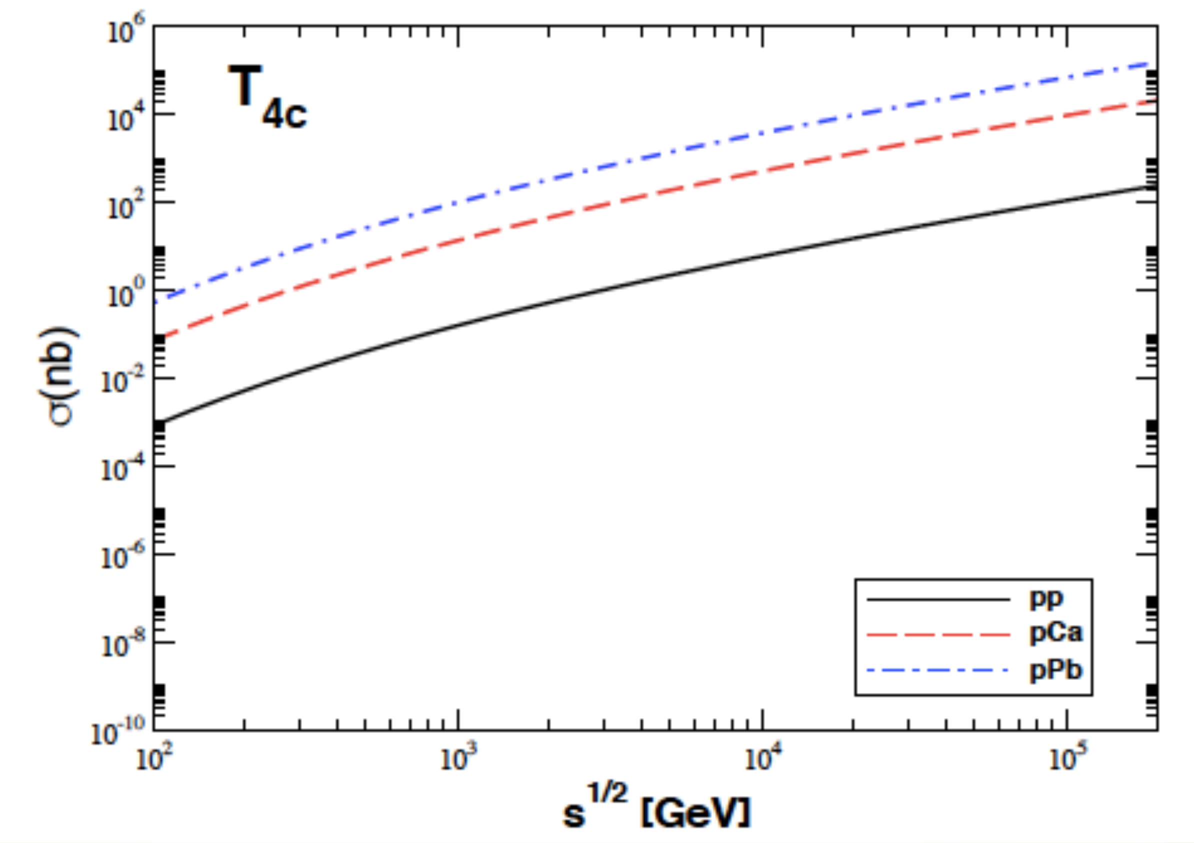
$$F_{pA} = 9A(A-1)/(8\pi R_A^2)$$

And then:

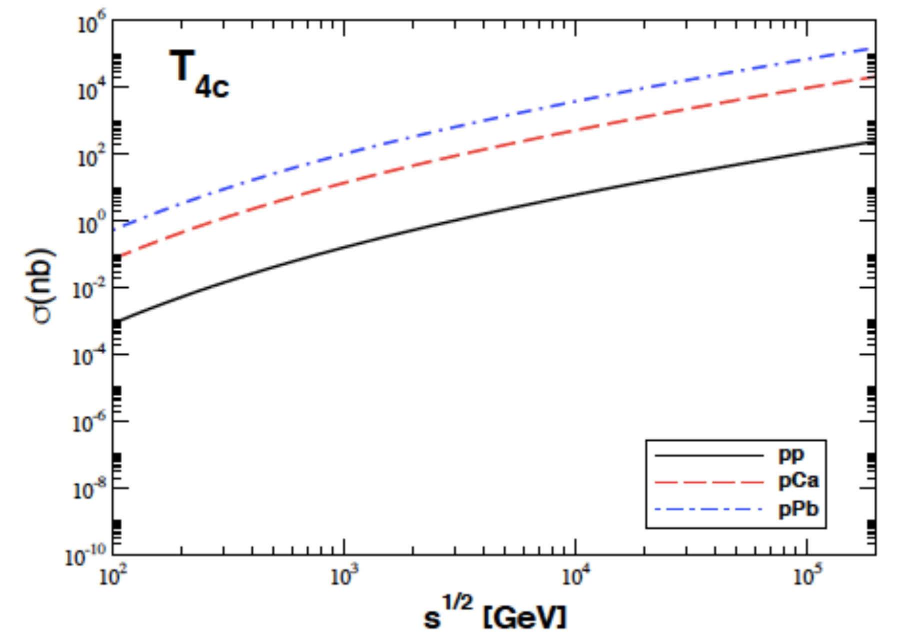
$$\sigma_{pA\to T_{4Q}}^{DPS} = \sigma_{pA\to T_{4Q}}^{DPS1} + \sigma_{pA\to T_{4Q}}^{DPS2} = A \cdot \sigma_{pp\to T_{4Q}}^{DPS} \cdot \left[1 + \frac{1}{A}\,\sigma_{eff} \cdot F_{pA}\right]$$

(A = 40 and A = 208)

Results



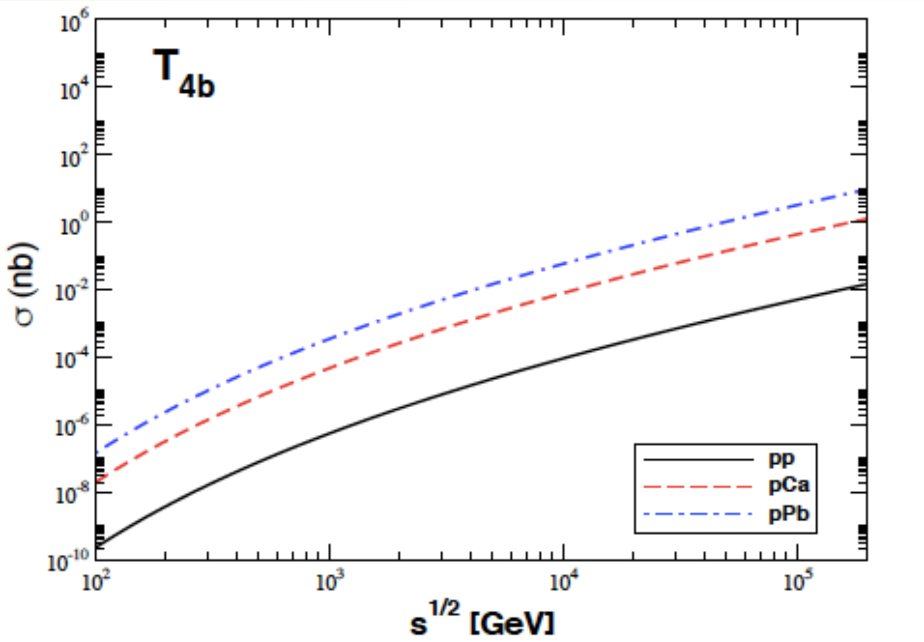
1) A strong increasing with the energy ➡ $\sigma_{DPS} \propto g(x)^4$

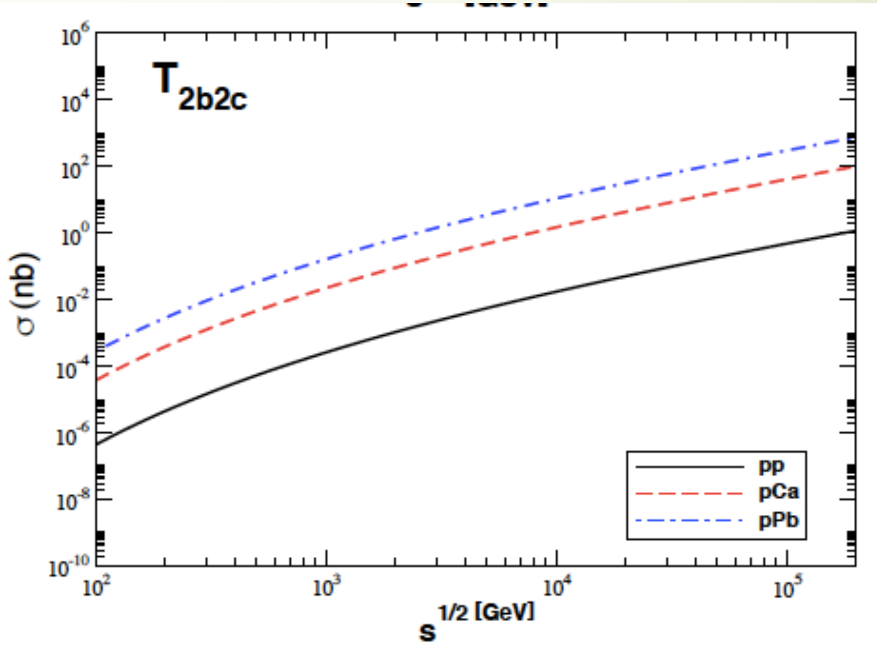


2) not a simple A scaling of the pp prediction:

- $\sigma_{pCa} \approx 85 \times \sigma_{pp}$
- $\sigma_{pPb} \approx 630 \times \sigma_{pp}$ → In agreement with MPLA 33, nº.25, 1850141(2018) – first results for heavy quark pair production in pA collisions

Predictions for the T_{4b} and T_{2b2c} production





- The energy behaviour is similar
- The pA cross sections are enhanced by a similar factor in comparison to the pp predictions.

The main difference: magnitude

LHC	$pp\ (\sqrt{s} = 14\ TeV)$		$pCa\ (\sqrt{s} = 8.1\ TeV)$		$pPb\ (\sqrt{s} = 8.1\ TeV)$	
	Central	**Forward**	**Central**	**Forward**	**Central**	**Forward**
$\sigma_{T4c}(nb)$	6	2	520	160	3820	1170
$\sigma_{T2b2c}(nb)$	0.02	0.006	1.8	0.5	13	3.5
$\sigma_{T4b}(nb)$	0.0003	0.00008	0.03	0.007	0.21	0.05

FCC	$pp\ (\sqrt{s} = 100TeV)$		$pCa\ (\sqrt{s} = 63\ TeV)$		$pPb\ (\sqrt{s} = 63\ TeV)$	
	Central	**Forward**	**Central**	**Forward**	**Central**	**Forward**
$\sigma_{T4c}(nb)$	57	22	4920	1870	36000	13700
$\sigma_{T2b2c}(nb)$	0.27	0.09	23	8	170	60
$\sigma_{T4b}(nb)$	0.008	0.003	0.7	0.22	5	1.6

- T_{2b2c} and T_{4b} are two and four orders of magnitude smaller than T_{4c}

- *The cross sections grow* with the energy.

- cross sections:

  few nb in pp -> become ~10 to 100 times larger in pA collisions

↓

Good place to looking for tetraquark states!

Summary

- We have investigated the production of fully – heavy tetraquark states through the double parton scattering (DPS) in pp and pA collisions at the LHC and FCC energies.
- We have calculated the cross section for the T_{4c}, T_{4b} and T_{2b2c} states.
- We found that T_{4b} and T_{2b2c} cross sections are smaller than the T_{4c} productions, but we predict an increasing in the cross sections at the higher energies, which makes possible to search for these states in the forthcoming years.

- We have demonstrated that in pA collisions, the DPS cross sections are enhanced by a factor larger than the A scaling.

- Such result indicates that a future experimental analysis of the T_{4Q} production in pA collisions can be useful to probe the existence of these states, as well to improve our understanding of the double parton scattering mechanism.

Thank You!