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Antiproton production with fixed target and search for superheavy particles in the ALICE

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OUTLINE

1. Introduction.
2. Large Extra Dimensions and the concept of Fundamental mass
3. Parton model of nucleus-nucleus collisions
4. Subthreshold antiproton production
5. Kinematically forbidden antiproton production with a fixed target
6. Estimation of the yield of superheavy particles
7. Conclusion

Introduction

- In the Grand Unified Theory it is assumed that the first massive particles responsible for the symmetry breaking up to the symmetry of the Standard Model have masses 10^{12} TeV.

- Next masses connected to the breaking of electroweak symmetry, Higgs scalar bosons, have masses 10^{2} GeV.

- Therefore rather artificial hypothesis was proposed on the existence of the “gauge desert” i.e. no particles between 0.2 - 10^{12} TeV

Main Problem of Particle Physics – the Hierarchy Problem

- Why gravity is so weak , compared to the other forces
- Strong force – the scale 1 GeV/ fm
- Electroweak force – mass of W and Z bosons – the scale 100 GeV/fm
- Scale of gravity – Plank mass 1.22 x10^{19} GeV/c^2

Three possible solutions of the Hierarchy Problem

1. Supersymmetry unifies the strong and electroweak forces below the Plank scale

2. High dimensional String Theory – theory of quantum gravity to be valid up to the Plank scale

3. Large Extra Dimensions – space time has higher dimension : 3 + 1 + n. Our world is a 4 – dimensional " brane " in the LED.

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429 (1998) 263
V.A. Rubakov, Physics-Uspekhi, 46 (2003) 211

Plank mass M_{Pl} and Fundamental mass M

The Value of the Plank mass is obtained from the Newtonian Gravitational constant G:

$$G = 6.67408 \text{ x } 10^{-11}\, m^3 s^{-2} kg^{-1} = 6.70861 \text{ x } 10^{-3}\ \text{hc}\ (\text{GeV}/c^2),^{-2}$$

$$M_{Pl} = \sqrt{\frac{\hbar c}{G}} = 1.224 \text{ x} 10^{19}\ \text{GeV}/c^2 \quad , \qquad G = \frac{\hbar c}{M_{Pl}^2}$$

Gravitational potential energy for masses $m_{1=} m_2 = 1\ \text{TeV}/c^2$

$$V = -\frac{6.70861 \text{ x1}\ \ ^{-33}}{r} \hbar \text{ c}$$

So it is strong as the electroweak force at $r = 10^{-33}\ m$

Plank mass M_{Pl} and Fundamental mass M (cont. 1)

The Newtonian gravitational law is confirmed only up to 0.02 cm

C.D.Hoyle et al. Phys.Rev.Lett 86 (2001) 1418

In the Large Extra Dimensions theory

$$V_n = - \frac{G_n \, m_1 m_2}{r^{n+1}} \quad \text{for} \quad r \leq r_c$$

r_c – compactification radius is the scale, when the gravity becomes as strong as electroweak,

for $r \gg r_c$ we have 4 – dimensional gravitation law

T. Kaluza, Acad. Wiss. Berlin. Math.-Phys.1 (1921) 966

O. Klein, Zeit. Phys. 37 (1926) 895

Plank mass M_{Pl} and Fundamental mass M (cont. 2)

Compactification radius

At $r \sim r_c$ $V = V_n$

$$\frac{G_n}{{r_c}^n} \sim G$$

$$G_n = \frac{(\hbar c)^n}{M^{2+n}}$$

$$G_n \, M^n = \frac{(\hbar c)^n}{M^2}$$

$$(r_c \; M)^{\,n} = \frac{M_{Pl}^2}{M^2} \qquad (\hbar c) = 1$$

Plank mass M_{Pl} and Fundamental mass M (cont. 3)

- Let us make new Fundamental Gravitational scale equal to the electroweak scale 1 TeV

M TeV	1	1	1	250
n	1	2	3	3
r_c cm	10^{15}	0.2	10^{-6}	$10^{-13} = 1\, fm$

- If the Fundamental mass is of the order of 250 TeV, we can expect the existence of superheavy particles of several tens of TeV

- Superheavy particles could be produced in “ subthreshold “ lead – lead collisions at the LHC (Pb – Pb with 2.76 ATeV beam).

$$\sqrt{s}_{max} = 1150 \text{ TeV}$$

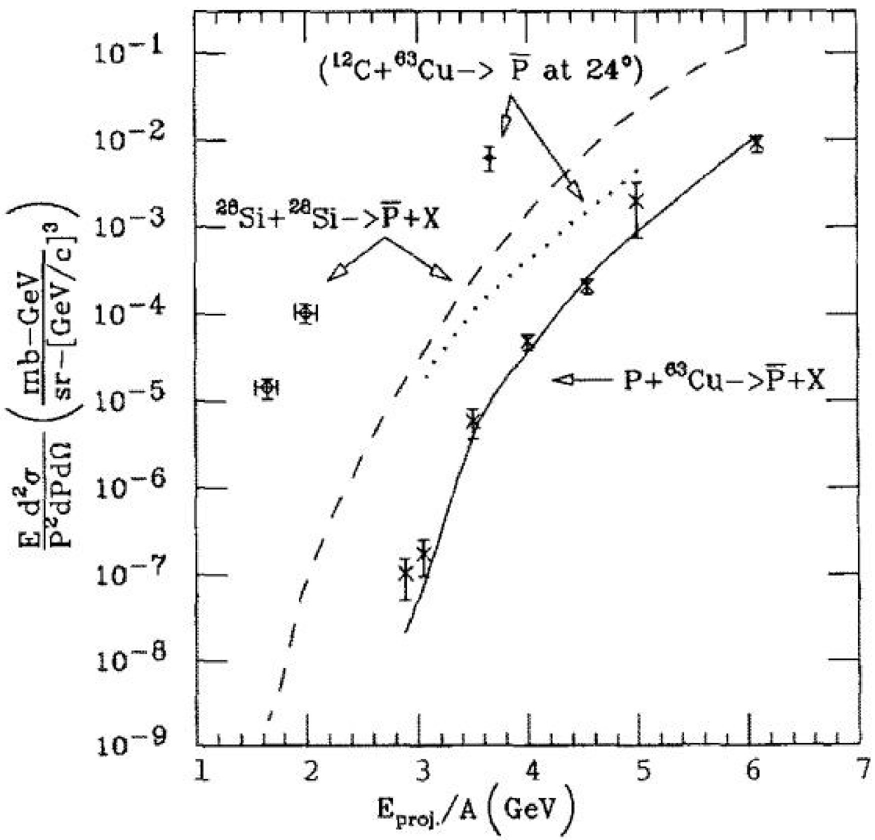
It is clear that the production cross section will be very small.

- However, detection of superheavy particles with mass of several TeV can solve the hierarchy problem

- We can try to make some estimates assuming that this process is similar to the “subthreshold” antiproton production at intermediate energies of several GeV.

Subthreshold production of antiprotons at intermediate energies at JINR, BNL, GSI and KEK

1. Baldin, A. A. et al. (1988) Antiproton yield in the collision of carbon nuclei with copper nuclei at energy of 3.65 GeV/nucleon. JETP Lett. **48**, 137-140.
2. Baldin, A. A. et al. (1990) Subthreshold anti-proton production in nucleon nucleus and nucleus-nucleus collisions. Nucl. Phys. A. **519**, 407-411.
3. Carroll, J. B. et al. (1989) Subthreshold antiproton production in 28Si collisions at 2.1 GeV/nucleon. Phys. Rev. Lett. **62**, 1829-1832.
4. Chiba, J. et al. (1993) Enhancement of subthreshold antiproton productions in deuteron induced reactions. Nucl. Phys. A. **553**, 771-774.
5. Schroeter, A. et al. (1993) Subthreshold antiproton production in heavy ion collisions at SIS-energies Nucl. Phys. A. **553**, 775-778.



Subthreshold anti-proton production in p-nucleus and nucleus-nucleus collisions. Calculations with internal nuclear momentum for target nucleons and projectile nucleons (when relevant). (a) $p+{}^{63}Cu\to\bar{p}+X$ (mostly at 0°) experimental data (symbol ×) calculation (solid line). (b) ${}^{28}Si+{}^{28}Si\to\bar{p}+X$ (at 0°) experimental data (symbol ◇) calculation (dashed line). (c) ${}^{12}C+{}^{63}Cu\to\bar{p}+X$ (at 24°) experimental data (symbol ⸸) calculation (dotted line).

A.Shor rt al. Nucl. Phys. A, 514 (1990) 717

- The significant increase in the subthreshold antiproton production cross section in nucleus-nucleus collisions in comparison with proton-nucleus collisions cannot be explained by the Fermi motion in nuclei.
- The method for the analysis of cumulative phenomena, developed in JINR by V.S.Stavinski, was used to generalize the Bjorken parton model and search for the scaling dependence on the parton parameter $X \geq 1$.

V.S.Stavinski, JINR Rapid Comm.№ 18-86 p.5

A.Kurepin., K.A. Shileev, N.S.Topilskaya, Genshiryoku Kenkyu, Tokyo, 41 (1997) 177

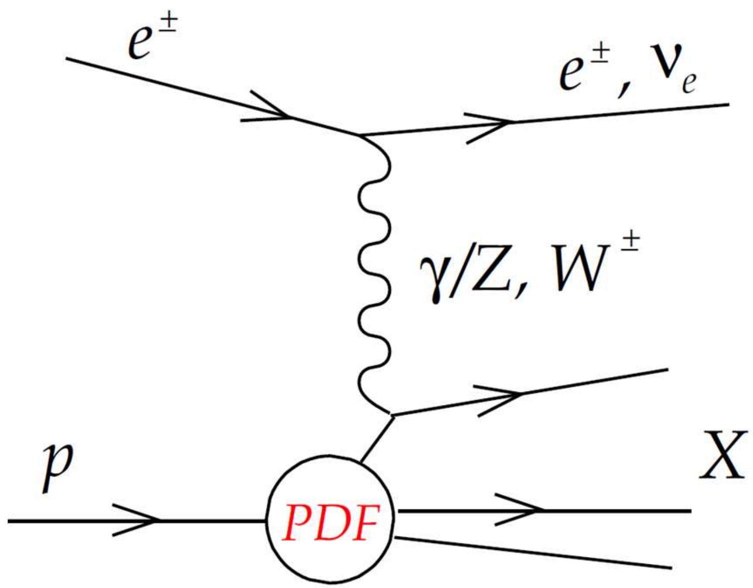
Scaling

We drop of some physical properties and introduce some scaled invariant parameters to find the similar behavior of physical events.

Empirical scaling of transverse momentum

1) m_T - scaling $\quad m_T = \sqrt{P_T^2 + m^2}$ at low P_T

2) x_T - scaling $\quad x_T = \frac{2\,Pt}{\sqrt{s}}$ at high P_T



Diagrams of neutral NC and charged CC current deep inelastic scattering processes

Derivation of the Bjorken scaling parameter

$p = [\varepsilon, \vec{p}\,] \qquad p' = \left[\varepsilon', \overrightarrow{p'}\right]$

x P = [xM, 0] $\qquad$ (xP)' = [E', x$\vec{P}$']

q = [ω, $\overrightarrow{p'} - \vec{p}$] $\qquad$ ω = ε' – ε

p + xP = p' + xP'

$(p-p' + xP)^2 = (xP')^2$

$(xP - q)^2 = (x M)^2$

$(xP)^2 - 2\, qxP + q^2 = (xM)^2$

$$x = \frac{q^2}{2M\,\omega}$$

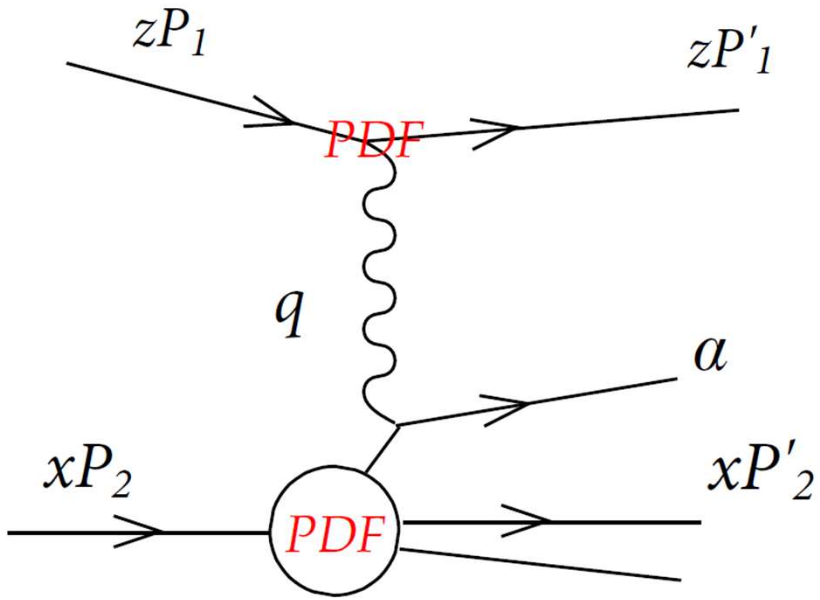


Diagram of parton-parton interaction

$1 + 2 \rightarrow 1 + 2 + m_i + \alpha$

Pion $m_i = 0$

Kaon + $m_i = 0$ $m_\Lambda \sim m_n$

Kaon - $m_i = m_k$

Antiproton $m_i = m_n$

Derivation of the generalized scaling parameters

$$(zP_1 + x P_2 - P_d)^2 = (z P'_1 + x P'_2 + P_i)^2$$

- For a maximum momentum value of the produced particle d :

$$\overrightarrow{p'}_1 = \overrightarrow{p'}_2 = \overrightarrow{p'}_i = 0$$

$$(P'_1)^2 = m^2 \qquad (P'_2)^2 = m^2$$

$$X = \frac{Z\,(P_a P_d) + Z\, m_a m_n + \frac{1}{2}\,(m_n^2 - m_d^2)}{Z\,(P_a P_b) - Z\, m_a m_b - (P_b P_d) - m_b m_n}$$

- It turns out that all data on subthreshold antiproton production can be described by one universal curve on the parameter x

$$(A_1 A_2)^{-0.43} \cdot E_1 \frac{d^3\sigma}{dp^3} \;[\text{ mb GeV}^{-2}\ c^3\ \text{sr}^{-1}] = 0.57 \exp(-X/0.158)$$

Figure 1. Systematics of Lorentz invariant antiproton subthreshold production cross section dependence on the scaling parameter X with $Z = 1$ for incident protons, $Z = 1.3$ for deuterons, $Z = 2$ for carbon ions, $Z = 3$ for heavy nuclei. Points p + C, open circles d + C, crosses C + C and C + Cu [2-3] , triangles p + C and d + C [5], squares p + Cu [7], rhombs Si + Si [4], stares Ne + Sn and Ni + Ni [6]. Only some statistical errors are presented to show the order of uncertainty for the measurements of subthreshold production.

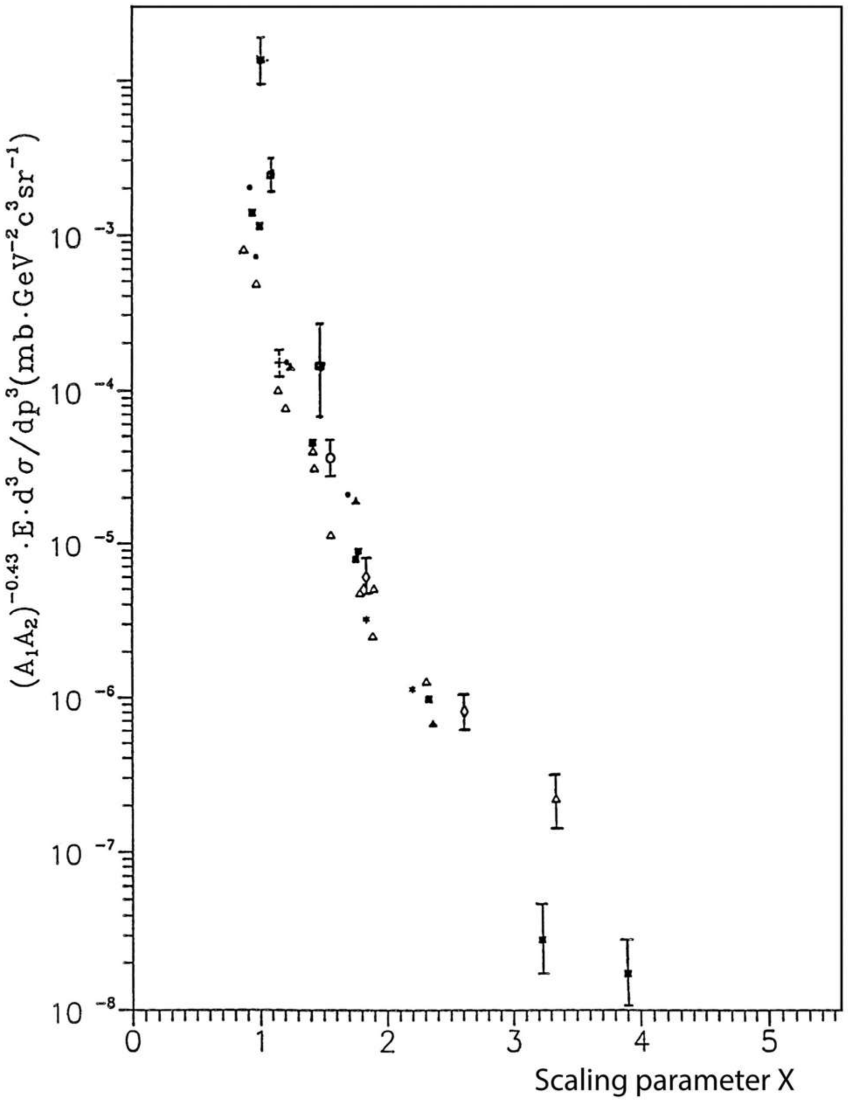
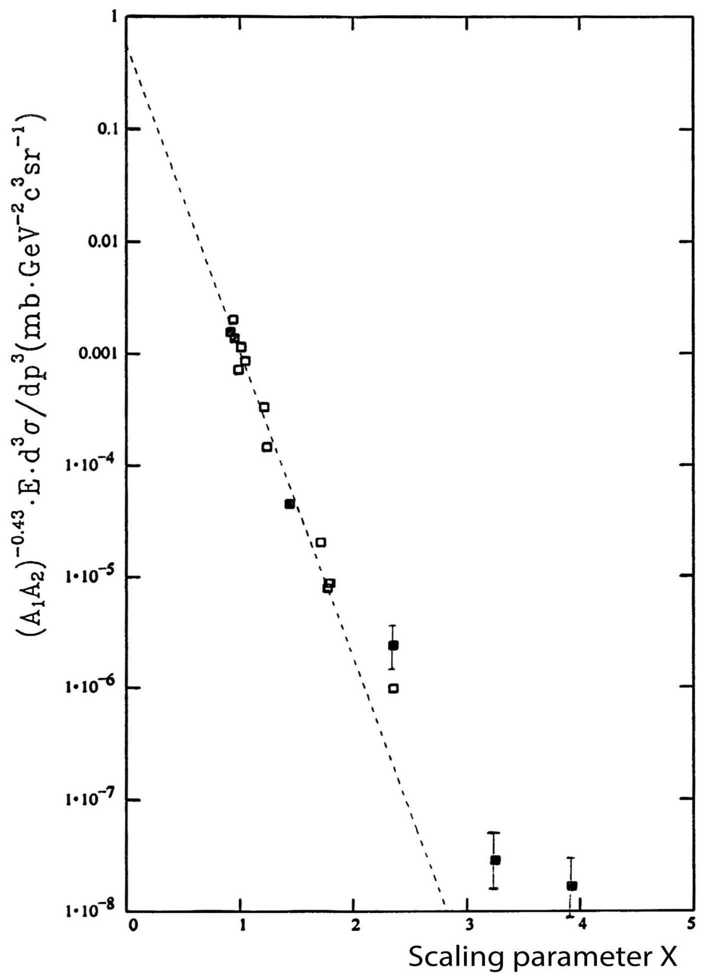


Figure 2. χ^2 – fit to the invariant antiproton production cross section dependence on the *X*- scaling parameter. Only data for the interaction of protons with carbon (open marks) and with copper (filled marks) are shown



$$X = \frac{2Z(\,E \cdot E_1 - E \cdot P \cdot \cos(\theta)\,) - M^2}{4Z \cdot E^2 - 2\,(\,E \cdot E_1 + E \cdot P \cdot \cos(\theta)\,)}$$

Collider:

$P_1 = \{E,\mathbf{p}\}$ $P_2 = \{E,\mathbf{p}\}$ $P_d = \{E_d,\mathbf{p}_d\}$

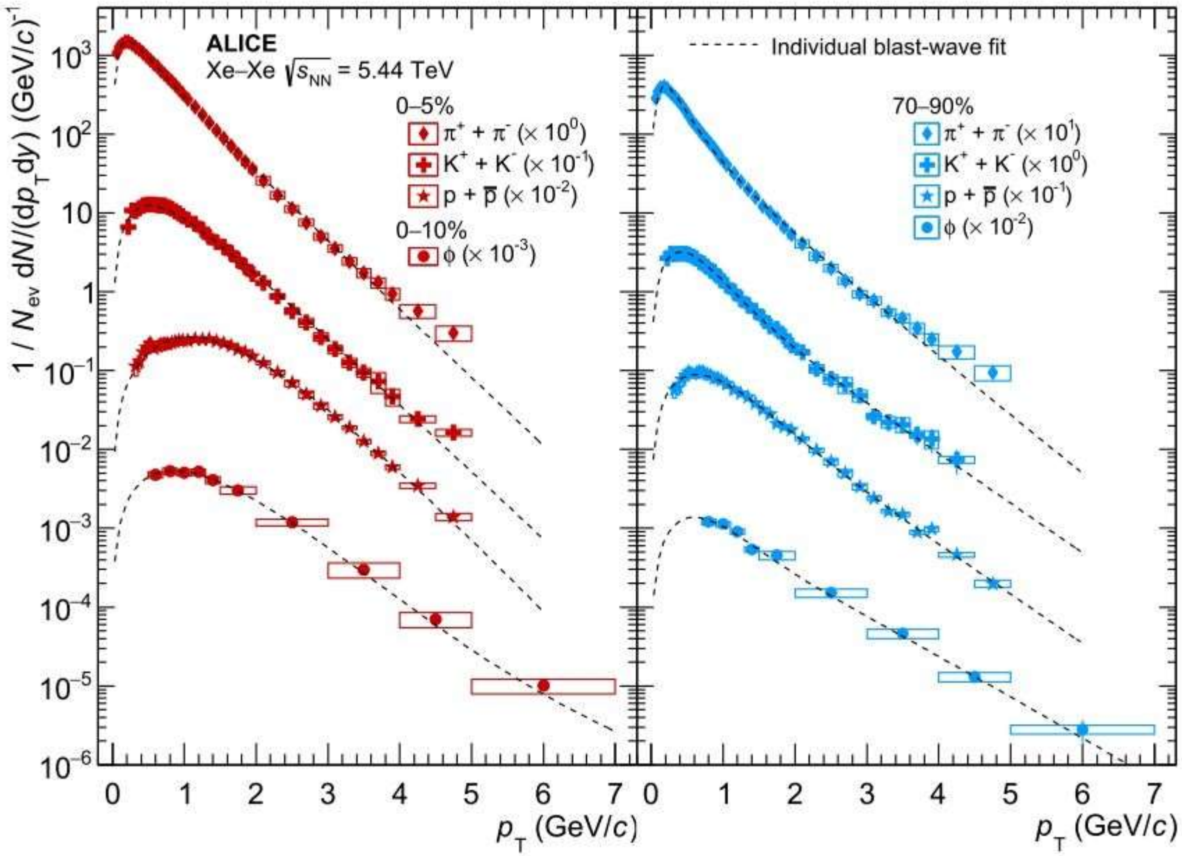
$E = 7$ TeV $E_d = 5$ GeV $\eta = 0$

$$X = \frac{Z\,E \cdot E_d - M^2}{2Z \cdot E^2 - E \cdot E_d} \approx 4 \cdot 10^{-4}$$

Fixed target:

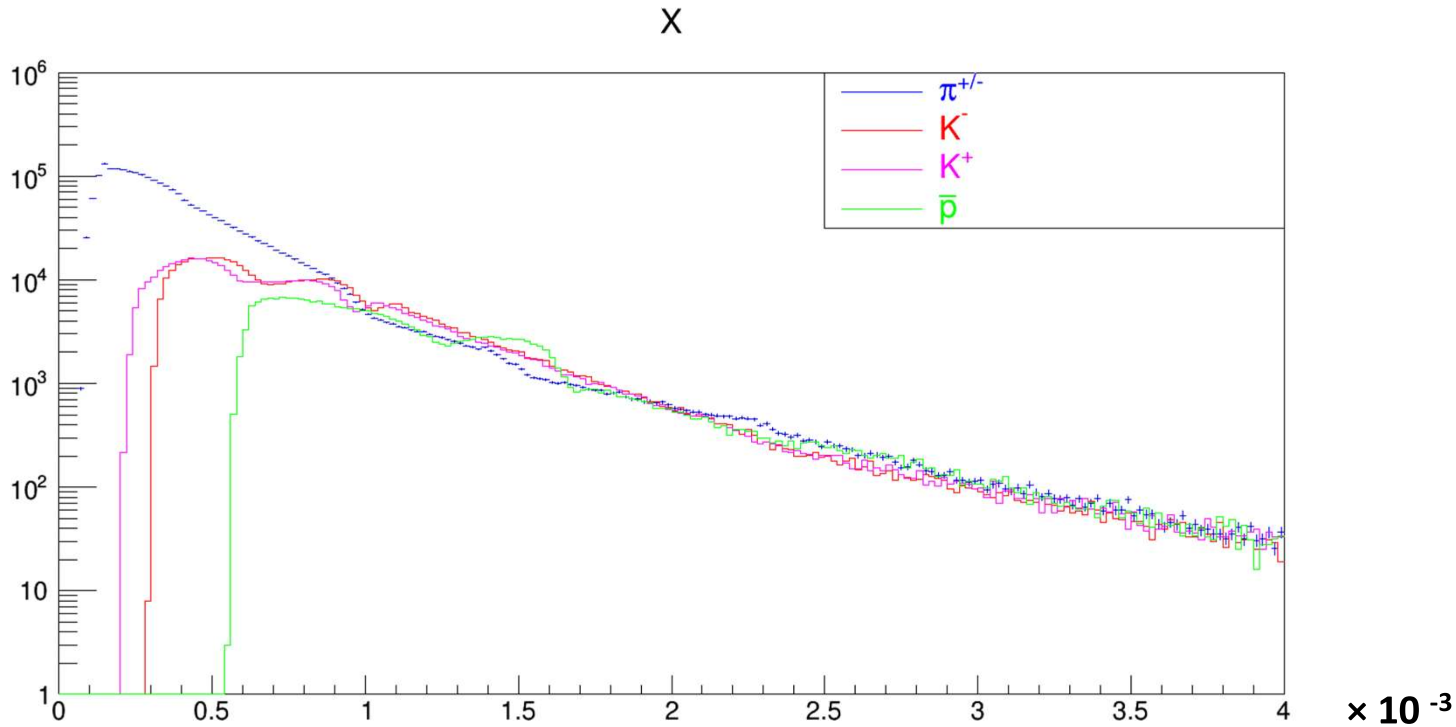
- At high energy almost no dependence of X on beam energy and on Z parameter

$$X = \frac{Z\,E \cdot E_d\,(\,1 - \cos(\theta)\,) - M^2}{(\,Z \cdot E\,' - E_d)m} \approx \frac{E_d\ (\,1 - \cos\theta)}{m}$$



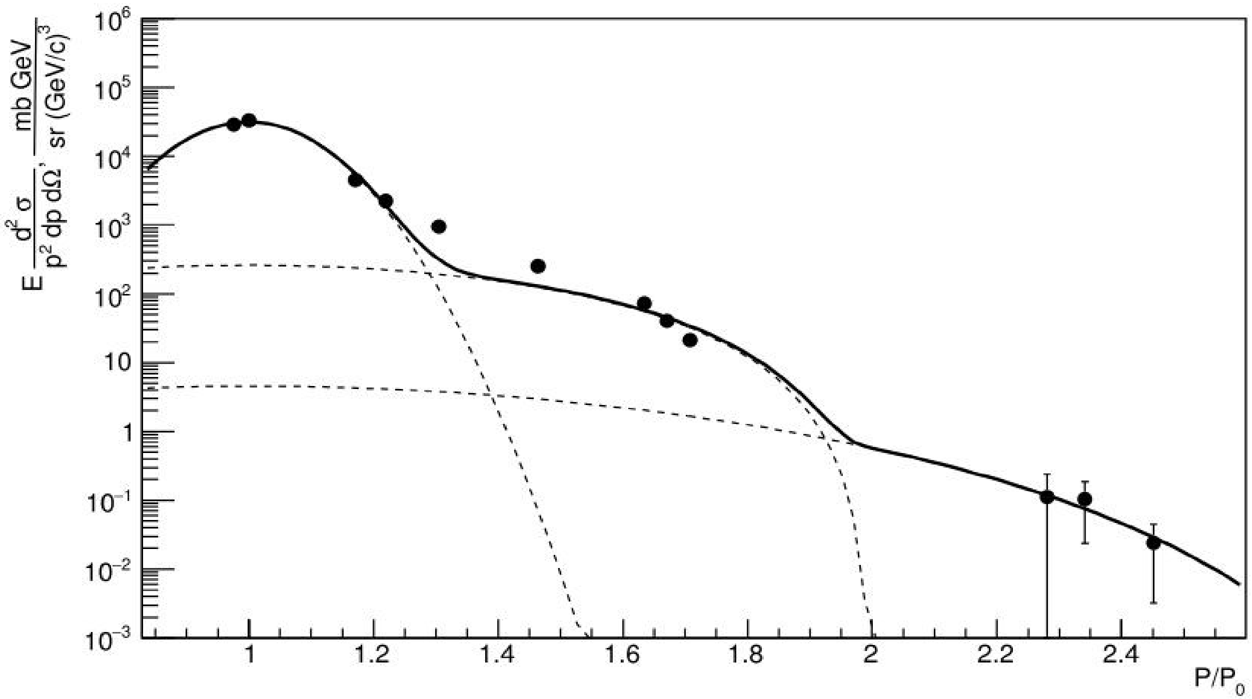
p_T distributions of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, ϕ as measured in central (left) and peripheral (right) Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The statistical and systematic uncertainties are shown as error bars and boxes around the data points.

ALICE Collaboration, arXiv: 2101.03100 [nucl-ex]



Parton distribution of X parameter

E. Karpechev, A. Kurepin, ALICE Physics week (2019)



Invariant cross section for proton production in carbon-carbon collisions at 19.6 GeV per nucleon and 3 mrad angle as a function of the ratio of proton momentum to the nucleon momentum in the beam nuclei. The dotted lines show the contribution of one-, two-, and three-nucleon clusters, the solid line shows the sum of all contributions.

A.G.Afonin et al. Physics of Atomic Nuclei, 83 (2020) 140

Fixed target antiproton production proton-lead at 7 TeV beam energy

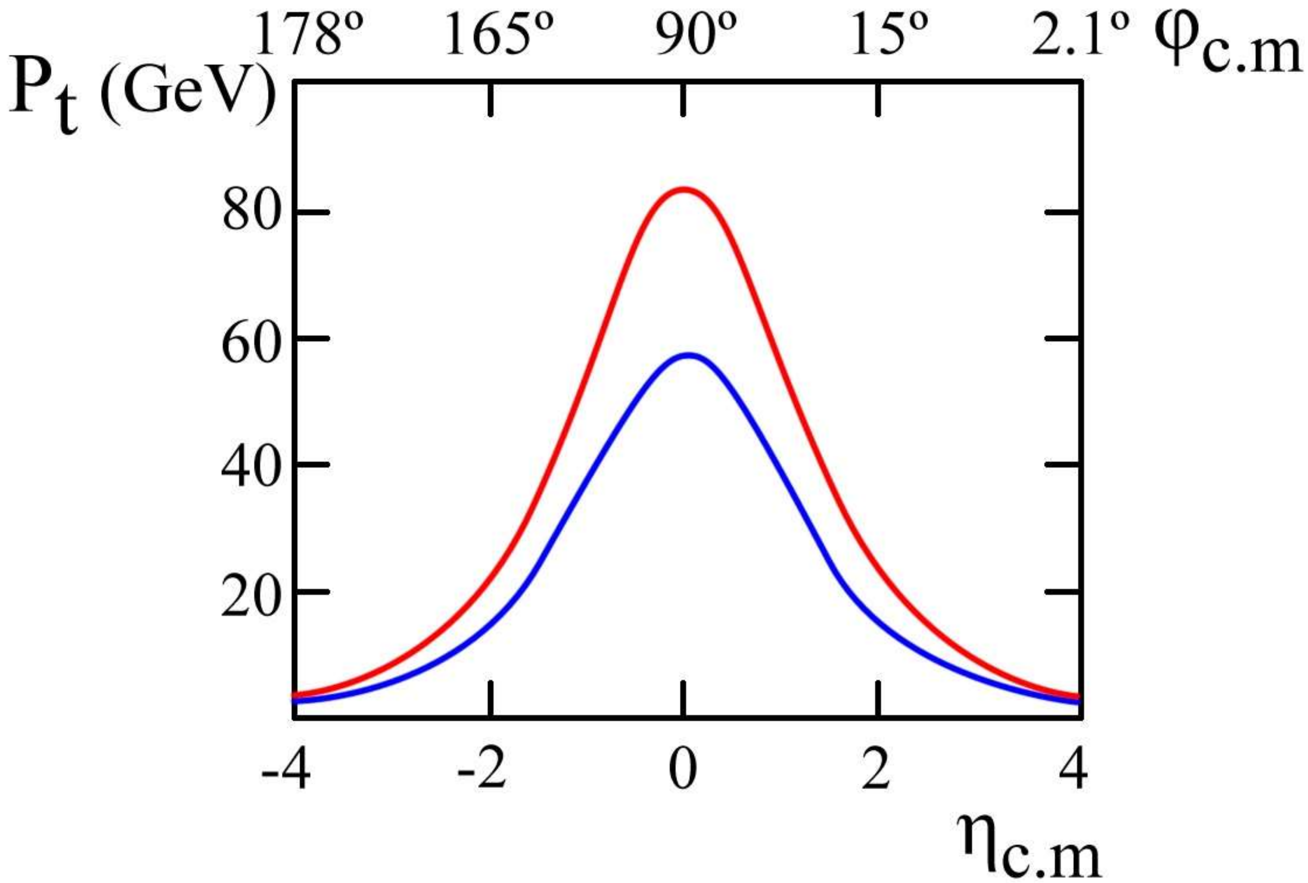
$$X = \frac{Z\,E \cdot E_{d} \cdot (1 - \cos(\theta)) - M^2}{(Z \cdot E\,' - E_d)m} \approx \frac{E_d \cdot (1 - \cos\theta)}{m}$$

$P_1 = \{E, \mathbf{p}\}$ $P_2 = \{m, \mathbf{0}\}$ $P_d = \{E_d, \mathbf{p}_d\}$

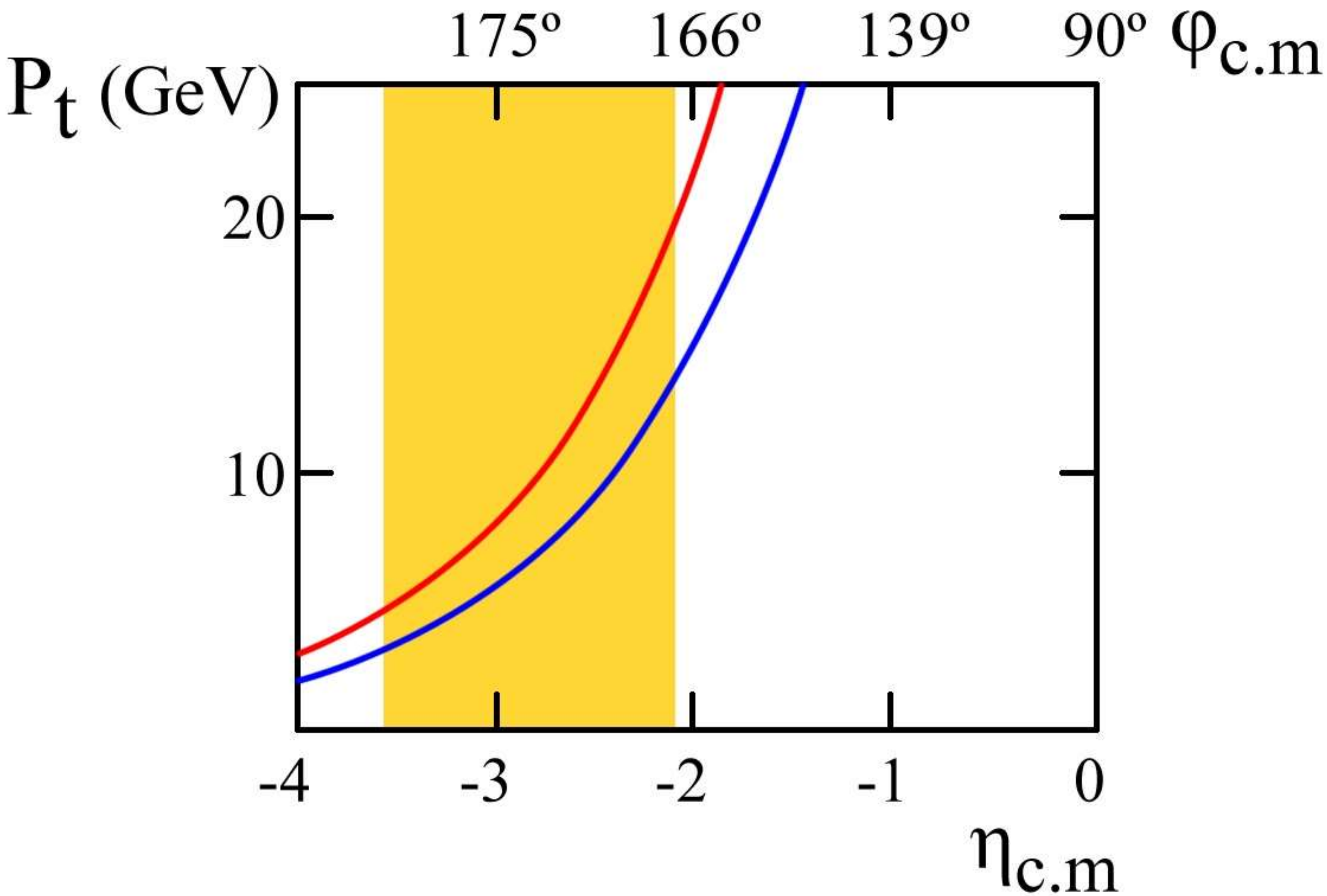
$E = 7$ TeV , $E_d = 5$ GeV, $M = 0.938272$ GeV

$\theta = 28$ degree, $\Delta p = 1$ GeV, $\Delta\Omega = 0.1$ sr

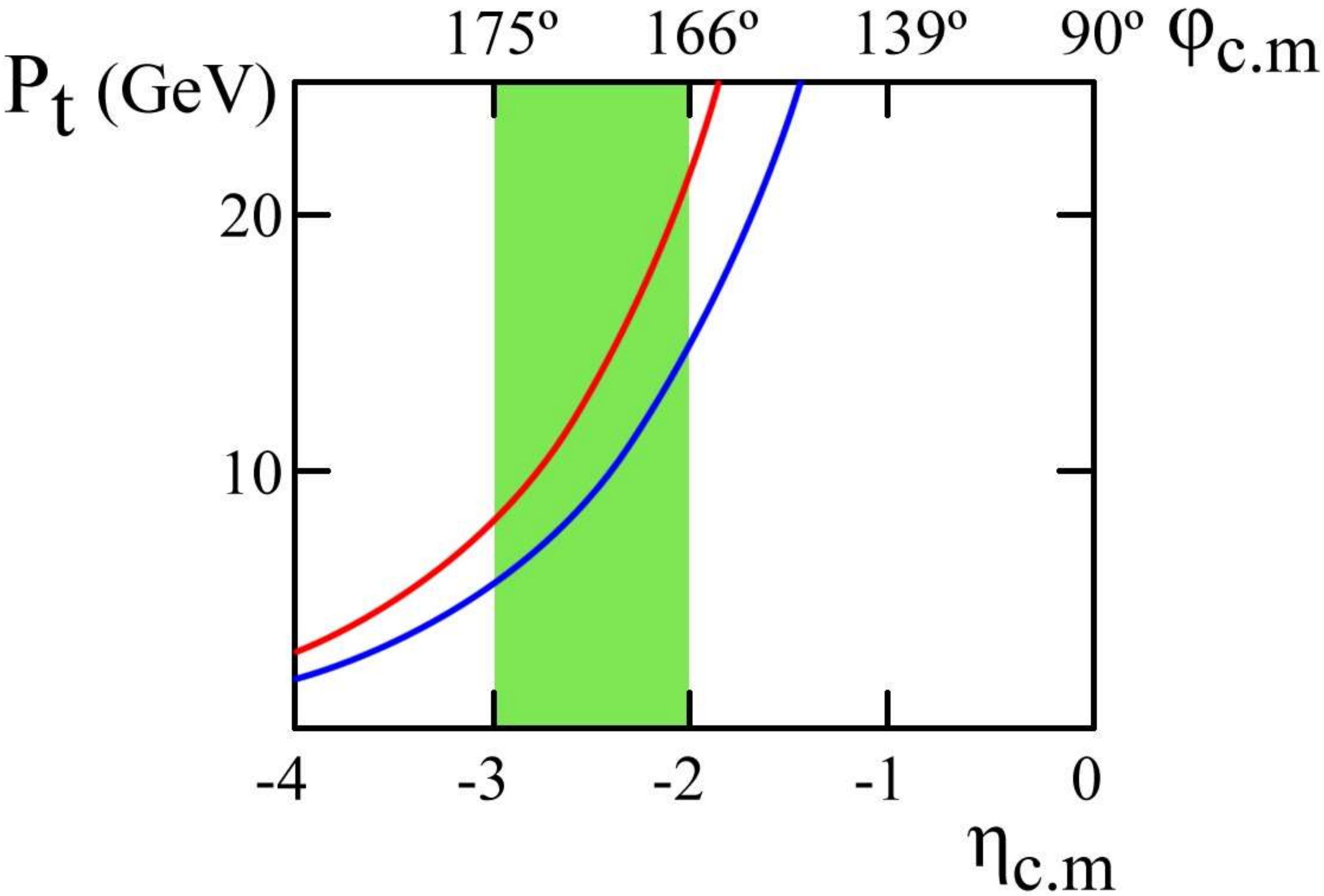
P_t	4	6	8	GeV
E_d	8.5	12.8	17	GeV
X	1.1	1.6	2.18	-
σ_{inv}	$8 \cdot 10^{-3}$	$6 \cdot 10^{-4}$	$8 \cdot 10^{-6}$	$mb\ GeV^{-2} c^3 sr^{-1}$
N_d	$25 \cdot 10^{3}$	$3 \cdot 10^{3}$	50	1/hour



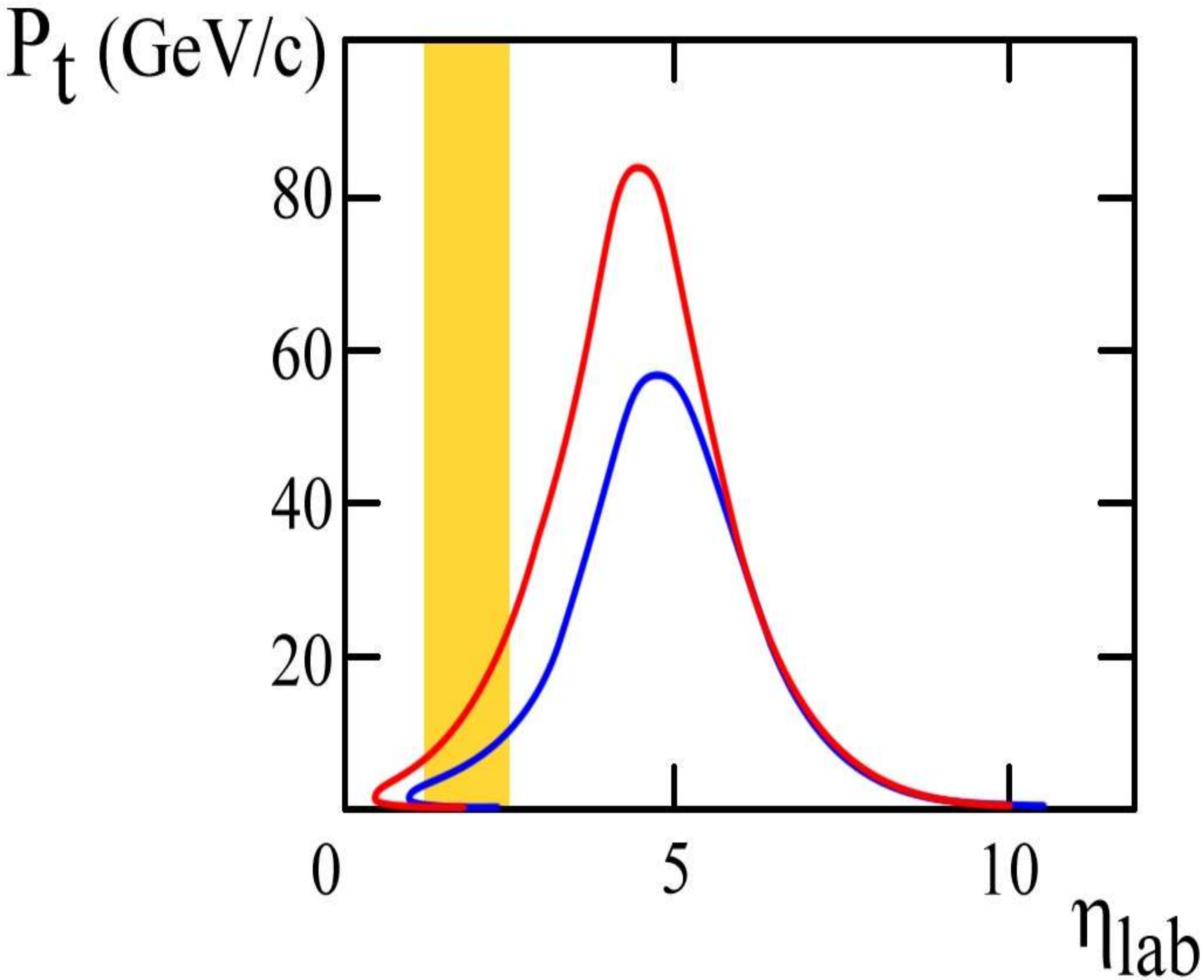
Dependence of the transverse momentum of antiprotons on the rapidity in the center of mass. Blue line with X=1, red line with X=2.



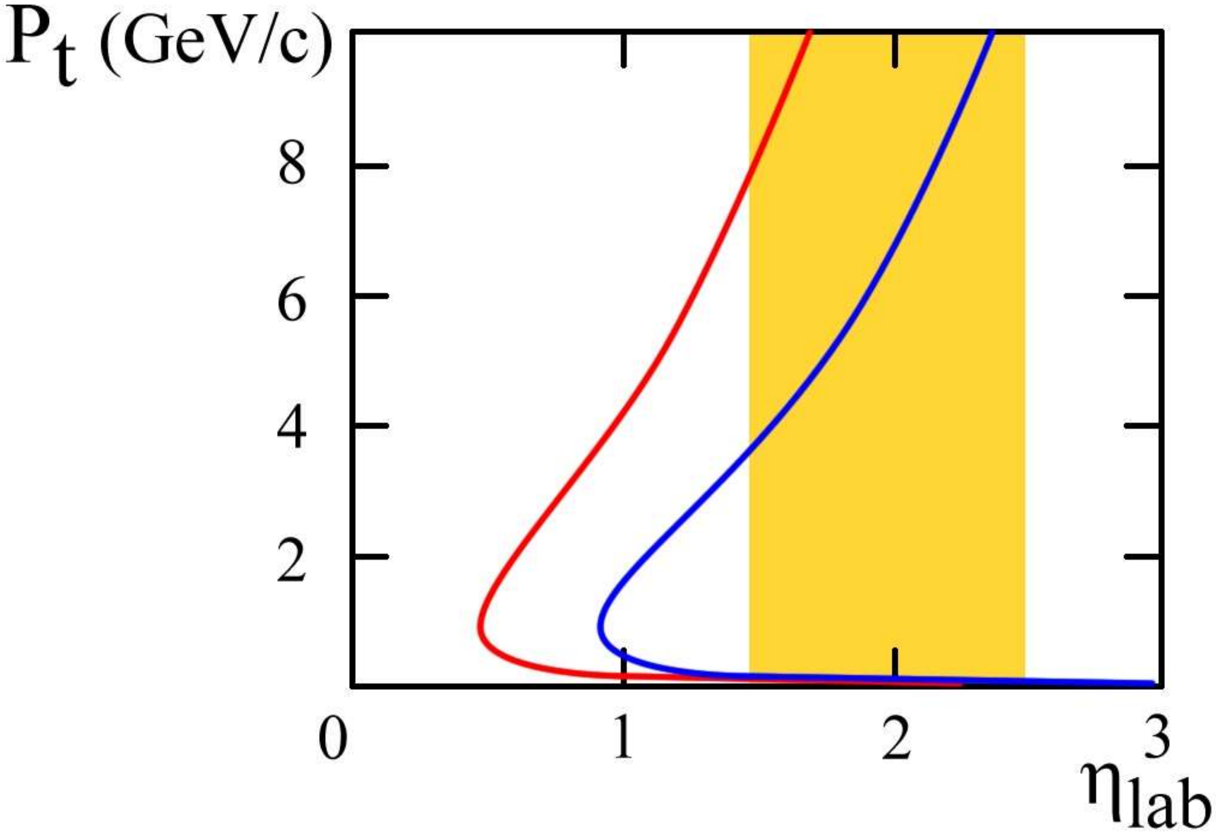
Dependence of the transverse momentum of antiprotons on the rapidity in the center of mass. Blue line with X=1, red line with X=2. The area available with a fixed target and X=1 is marked in yellow.



Dependence of the transverse momentum of antiprotons on the rapidity in the center of mass. Blue line with X=1, red line with X=2. The area available with a fixed target and X=2 is marked in green



Dependence of the transverse momentum of antiprotons on the rapidity in a laboratory system. Blue line with X=1, red line with X=2.
The area available with a fixed target is marked in yellow.



Dependence of the transverse momentum of antiprotons on the rapidity in a laboratory system. Blue line with X=1, red line with X=2.
The area available with a fixed target is marked in yellow.

Fixed target antiproton production by proton-lead at 7 TeV beam energy

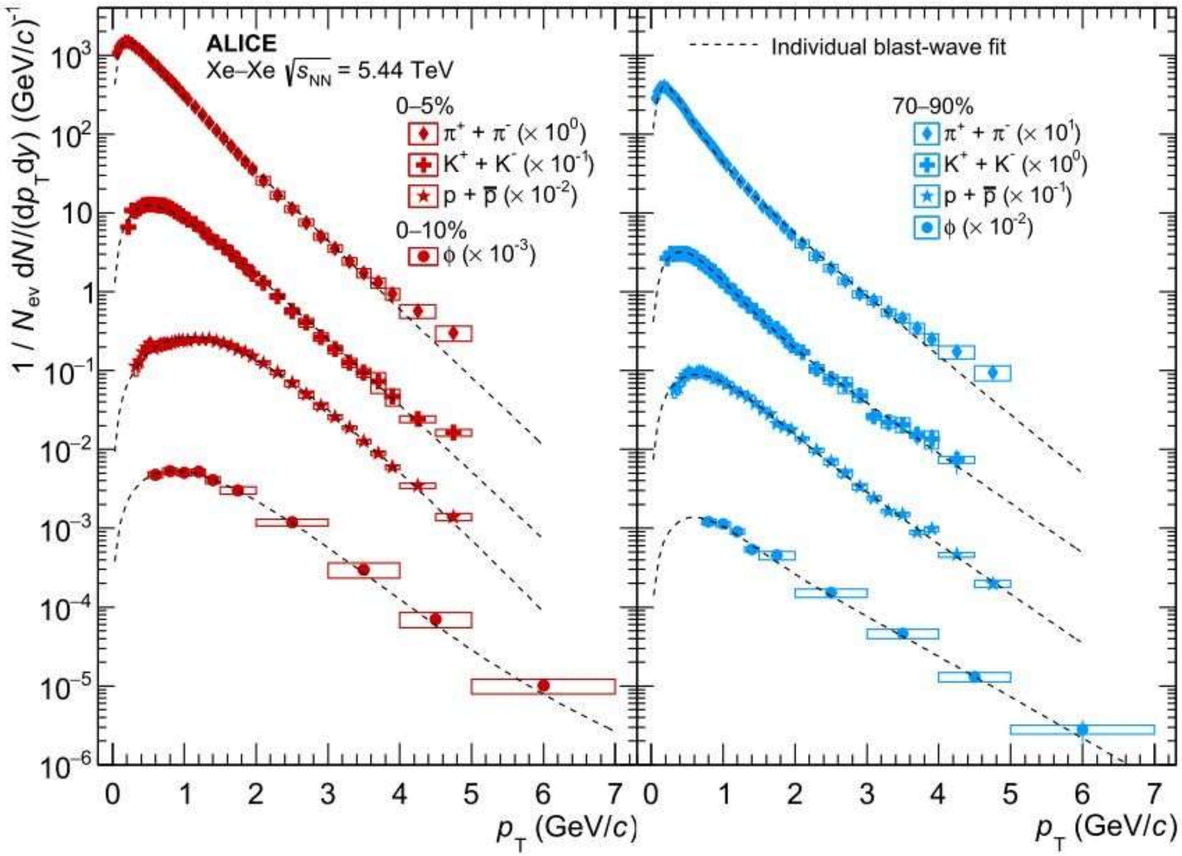
$$X = \frac{Z\,E \cdot E_{d}\cdot(1-\cos(\theta)) - M^2}{(Z \cdot E - E_d)m} \approx \frac{E_{d}\cdot(1-\cos\theta)}{m}$$

$P_1 = \{E,\mathbf{p}\}$ $P_2 = \{m,\mathbf{0}\}$ $P_d = \{E_d,\mathbf{p}_d\}$

$E = 7$ TeV , $M = 0.938272$ GeV

$\theta = 28$ degree, $\Delta p = 1$ GeV, $\Delta\Omega = 0.1$ sr

P_t	4	6	8	GeV
E_d	8.5	12.8	17	GeV
X	1.1	1.6	2.18	-
σ_{inv}	$8 \cdot 10^{-3}$	$6 \cdot 10^{-4}$	$8 \cdot 10^{-6}$	$mb\ GeV^{-2}c^3sr^{-1}$
N_d	$25 \cdot 10^{3}$	$3 \cdot 10^{3}$	50	1/hour



p_T distributions of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, ϕ as measured in central (left) and peripheral (right) Xe–Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV. The statistical and systematic uncertainties are shown as error bars and boxes around the data points.

ALICE Collaboration, arXiv: 2101.03100 [nucl-ex]

Superheavy particle production in lead-lead collisions at 2.76 TeV beam energy

$\mathrm{E} = 2.76\ \mathrm{TeV}, \quad \mathrm{E}_1 = 16\ \mathrm{TeV},$

$\Delta\, \mathrm{p} = 1\ \mathrm{TeV}, \quad \Delta\, \Omega = 0.1\ \mathrm{sr}, \ \theta = 0\ \mathrm{degree}$

$$\sqrt{S} = 2E\sqrt{X \cdot Z} \approx M$$

$$Z = 3, \ X = 3.54$$

$$(A_1 A_2)^{-0.43} \cdot E_1 \frac{d^3\sigma}{dp^3} \ [\mathrm{mb\ GeV}^{-2}\ \mathrm{c}^3\ \mathrm{sr}^{-1}] = 0.57 \exp(-X/0.158)$$

$$\sigma_{inv} \approx 10^{-8}$$

$$X = \frac{2Z(E \cdot E_1 - E \cdot P \cdot \cos(\theta)) - M^2}{4Z \cdot E^2 - 2(E \cdot E_1 + E \cdot P \cdot \cos(\theta))}$$

The yield of 16 TeV particles is of the order of 100 per month

A.Kurepin, *Journal of Modern Physics*, **12** (2021) 433

Conclusions

- Superheavy particles of the order of several tens of TeV could exist if gravity has additional dimensions at small distances

- Scaling observed for subthreshold antiproton production at intermediate energies can be investigated at ALICE-FT for kinematically forbidden antiproton production

- The estimate of the yield of superheavy particles with a mass of 16 TeV is about 100 per month

Thanks for your attentions

Back-up

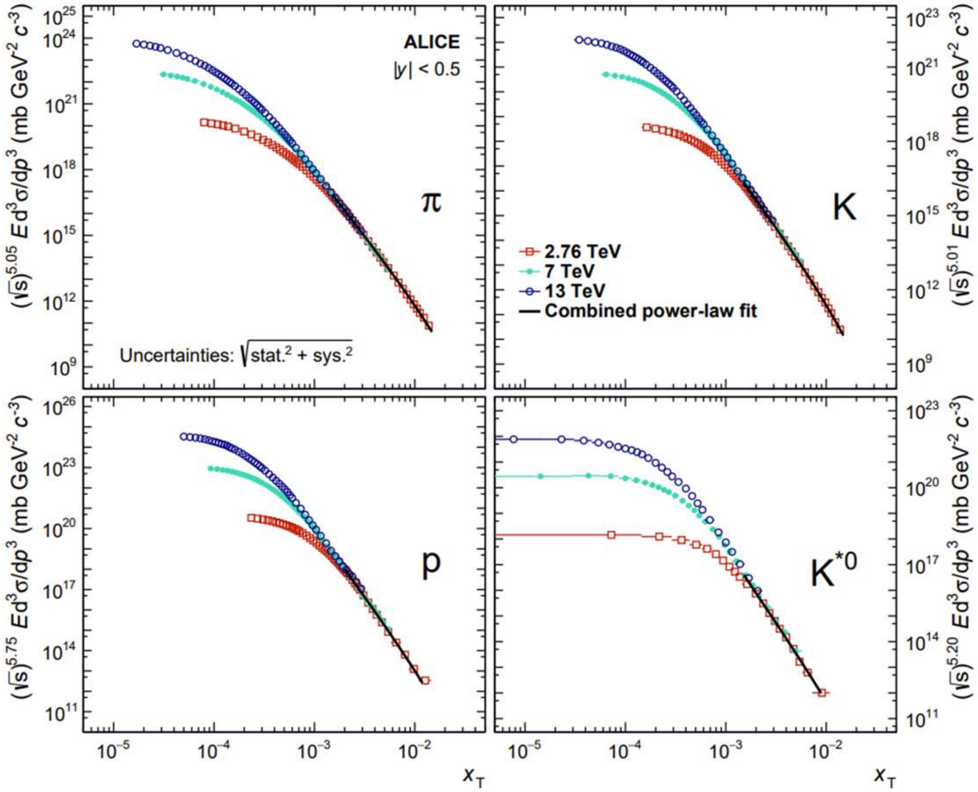
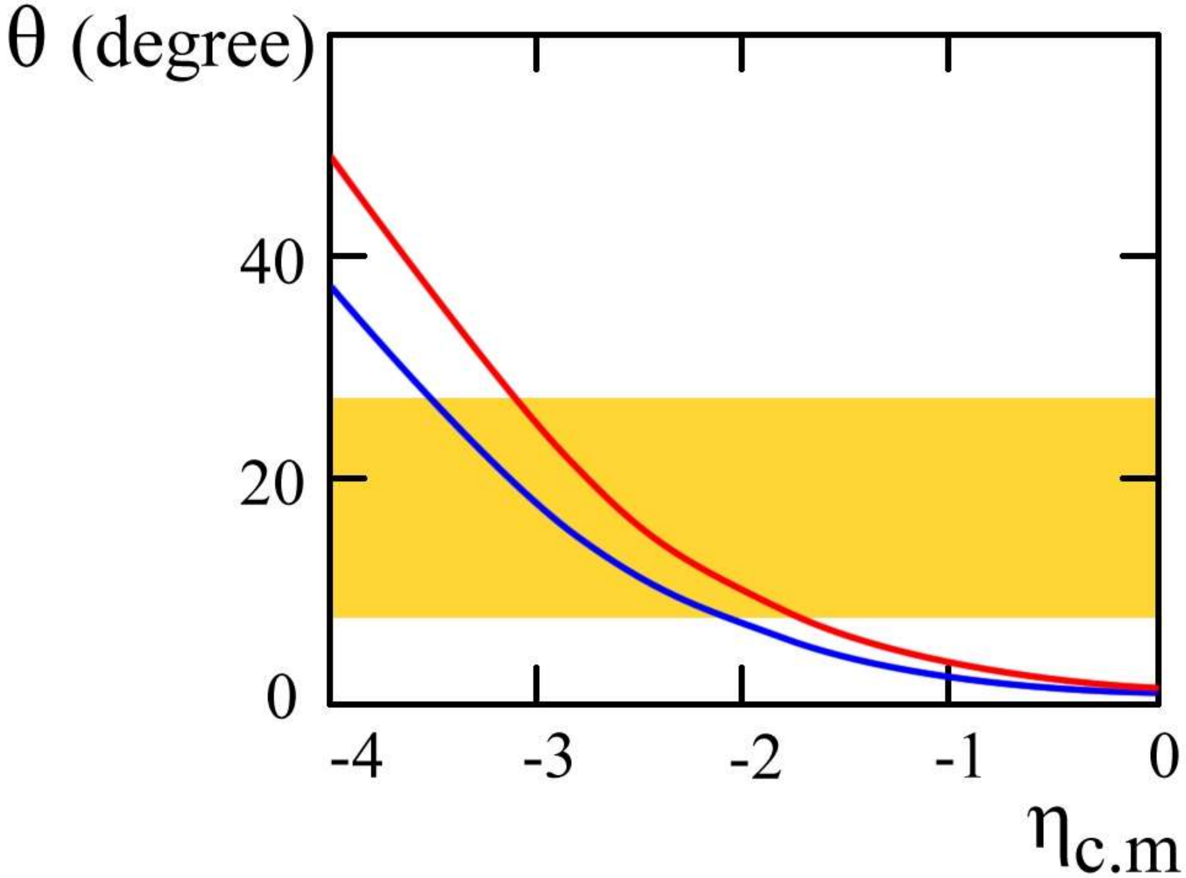


Fig. 1: Scaled invariant yields of π ±, K±, p(p), and K∗0 as a function of xT = 2pT/ √ s at different collision energies of √ s = 2.76 TeV, √ s = 7 TeV, and √ s = 13 TeV.



Dependence of the angle in a laboratory system of antiprotons on the rapidity in the center of mass. Blue line with X=1, red line with X=2. The area available with a fixed target is marked in yellow.