Cumulative production of pions by heavy baryonic resonances in proton-nucleus collisions

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Plan

- General overview
- Nucleon-nucleon collision
- Successive (N+A) collisions with nuclear nucleons
- UrQMD simulations
- Summary

Cumulative effect

Cumulative effect — creation of secondary particles in proton-nucleus (p+A) collisions outside of the kinematical boundary of proton-nucleon (p+N) collisions.

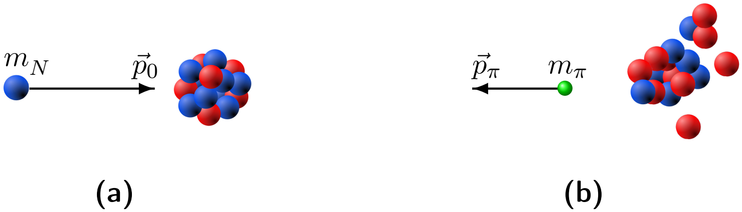


Figure: (a): initial stage, (b): final stage.

Experimental data

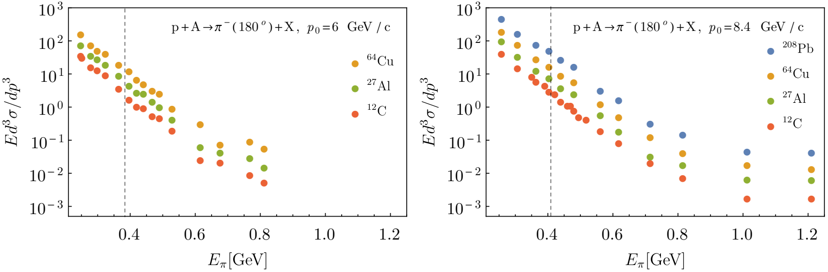


Figure: A. M. Baldin *et al.* Yad. Fiz. **20**, 1201 (1974). Dashed – kinematical boundary of proton-nucleon collision.

$$E_{max}^{exp}(6\ \text{GeV/c}) = 0.81\ \text{GeV}$$
$$E_{max}^{exp}(8.4\ \text{GeV/c}) = 1.21\ \text{GeV}$$

Fireball model

- M. I. Gorenstein and G. M. Zinovjev, Phys. Lett. B **67**, 100 (1977).

Collision with nucleus → ***Massive fireball formation*** → ***Successive collisions with nuclear nucleons*** → ***Decay with cumulative particle emission***

↓

Increase of M_R, decrease of v_R

Further development:

- I.G. Bogatskaya, C.B. Chiu, M.I. Gorenstein, G.M. Zinovjev, Phys.Rev. C **22** (1980).
- D.V. Anchishkin, M.I. Gorenstein, G.M. Zinovjev, Phys.Lett. B **108** (1982).

- Fireballs
- Massive resonances
- Quark-gluon bags
- Strings

N+N collision

As we need to maximize E_π:

- no additional particles;
- no p_T for all particles.

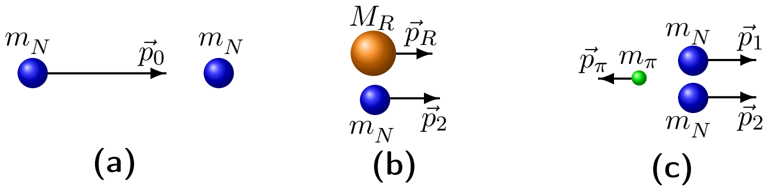


Figure: (a): initial stage, (b): intermediate stage, (c): final stage.

N+N collision: **Energy-momentum conservation**

$$\sqrt{p_0^2 + m_N^2} + m_N = E_\pi + \sqrt{p_1^2 + m_N^2} + p_0 = p_1 + p_2 - p_\pi$$

Maximal value for E_π denoted as E_π^* is when:

$$\partial E_\pi / \partial p_1 = 0 \quad \Rightarrow \quad p_1^* \equiv p_1 = p_2 = \frac{p_0 + p_\pi^*}{2}$$

So both nucleons should move with the same momenta.

$$E_\pi^* = m_N + \sqrt{m_N^2 + p_0^2} - 2\sqrt{m_N^2 + (p_1^*)^2}$$

Pion-nucleon invariant mass:

$$M_1^* = \left[\left(\sqrt{m_N^2 + (p_1^*)^2} + E_\pi^* \right)^2 - \left(p_1^* - p_\pi^*\right)^2 \right]^{1/2}$$

N+N collision: $\mathbf{E}^*_\pi$, $\mathbf{M}^*_1$

- At $p_0 = 6$ GeV/c and 8.4 GeV/c $E^*_\pi \cong 0.38$ GeV and 0.41 GeV respectively.
- At $p_0 \geq 20$ GeV/c one finds $M^*_1 \geq 4.3$ GeV/c^2 !

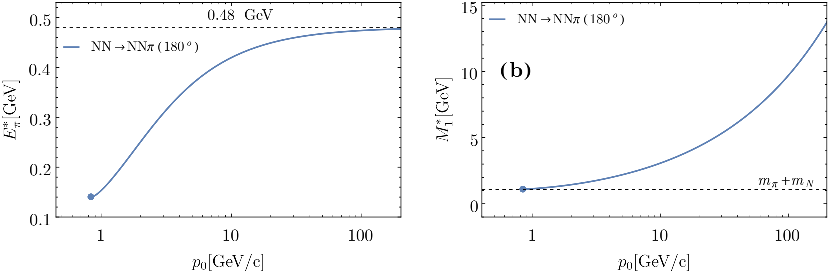


Figure: The maximal energy of $\pi(180°)$ (a) and invariant mass (b) as functions of p_0.

N+N collision: $\mathbf{M_R}$, $\mathbf{v_R}$

$$\mathrm{NN} \rightarrow \mathrm{NR}$$

$$\sqrt{m_N^2 + p_0} + m_N = \sqrt{M_R^2 + p_R^2} + \sqrt{m_N^2 + p_N^2}\ , \qquad p_0 = p_R + p_N$$

$$v_R = \frac{p_R}{E_R} = \left[1 - \frac{M_R^2}{M_R^2 + (p_0 - p_N)^2}\right]^{1/2}$$

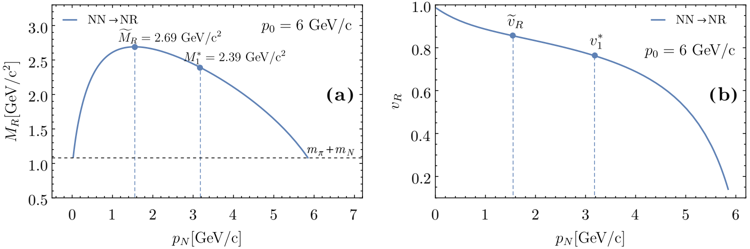


Figure: The resonance mass M_R (a) and its velocity v_R (b) as functions of p_N at fixed $p_0 = 6$ GeV/c.

N+N collision: **Role of $\mathbf{M_R}$, $\mathbf{v_R}$**

Baryonic resonance decay

$$\mathrm{R} \rightarrow \mathrm{N} + \pi(180^\circ)$$

In resonance rest frame:

$$E_\pi^0 = \frac{M_R^2 - m_N^2 + m_\pi^2}{2M_R}$$

In lab frame:

$$E_\pi = \frac{E_\pi^0 - v_R p_\pi^0}{\sqrt{1 - v_R^2}} \cong E_\pi^0 \sqrt{\frac{1 - v_R}{1 + v_R}}$$

Increase of M_R and decrease of v_R provide E_π growth.

Successive collisions with nuclear nucleons:

Assumptions

- projectile resonance propagates through nucleus and collides with nucleons;
- while propagating resonance may both enlarge its M_R and reduce v_R;
- after n-th collision resonance may decay with emission of $\pi(180^\circ)$.

Successive collisions with nuclear nucleons: $\mathbf{E}^*_{\pi,\mathbf{n}}$

At high energies growth is approximately linear $E^*_{\pi,n} \cong n \cdot 0.48$ GeV.

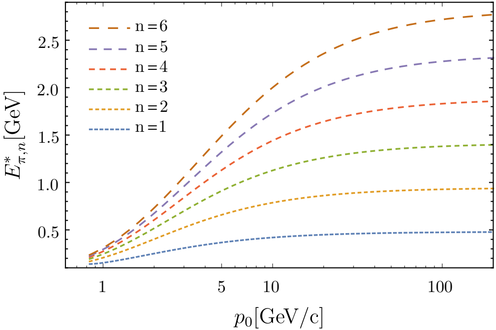


Figure: The maximum energies $E^*_{\pi,n}$ of π-meson emitted to 180° after the collisions with n nuclear nucleons ($n = 1, \ldots, 6$) as functions of projectile proton momentum p_0.

Successive collisions with nuclear nucleons: $\mathbf{M_n^*, v_n^*}$

As n grows:

- small growth of resonance mass M_n^*;
- decrease of velocity v_n^* is significant. **Even negative values!**

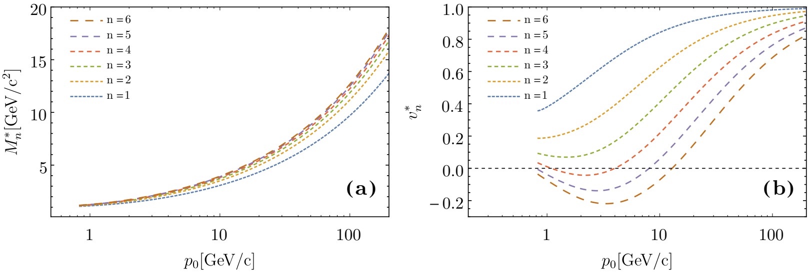


Figure: Invariant masses M_n^* (a) and velocities v_n^* (b) of the baryonic resonance after n successive collisions with nuclear nucleons.

Successive collisions with nuclear nucleons: $\mathbf{M^*_{n,k}}, \mathbf{v^*_{n,k}}$

At $k \approx n/2$ collision resonance gains its maximal mass ($> M^*_n$) and then **lose its mass and decreases velocity**!

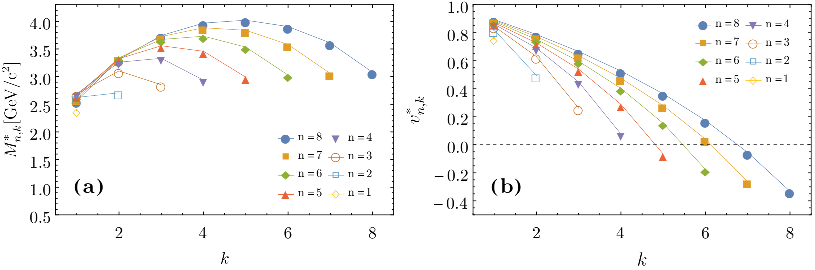


Figure: Mass of resonance $M^*_{n,k}$ (a) and its velocity $v^*_{n,k}$ (b) for $k = 1, \ldots, n$ and different $n = 1, \ldots, 8$ at fixed $p_0 = 6$ GeV/c.

UrQMD simulations

Is a microscopic transport
model used to simulate relativistic heavy
ion collisions in a wide range of collision energies.

Includes:

- All known hadrons and some unknown resonances;
- Strings.

References:

S.A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255 (1998); M. Bleicher *et al.*, J. Phys. G **25**, 1859 (1999);
H. Petersen, M. Bleicher, S.A. Bass, and H. Stöcker, arXiv:0805.0567 [hep-ph].

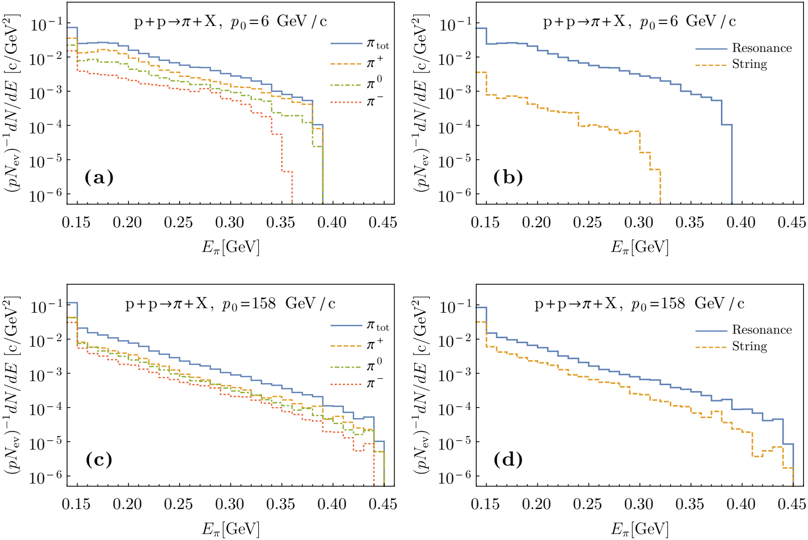
UrQMD simulations **Properties:**

- $\sim 10^8 \div 10^7$ events for every reaction;
- at $p_{lab} = 6$ and 158 GeV/c;
- impact parameter $b = 0$;
- p+p, p+C, p+Cu, p+Pb reactions;
- includes full history of collisions;
- provides information about origin/sources of final particles.

As $\pi(180^\circ)$ we select pions with $p_z < 0$ and $\frac{p_T}{|p_z|} < 0.1$ which corresponds to $\theta = 180^\circ \pm 6^\circ$.

UrQMD simulations p+p collisions

Proton-proton collisions at 6 GeV/c (up) and 158 GeV/c (down).



UrQMD simulations p+p collisions

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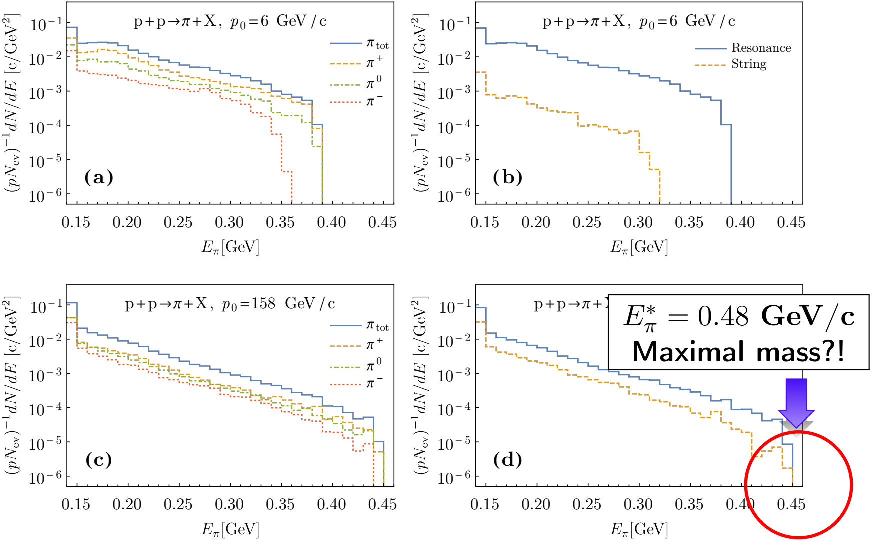

UrQMD simulations

Intermediate resonance mass restriction.

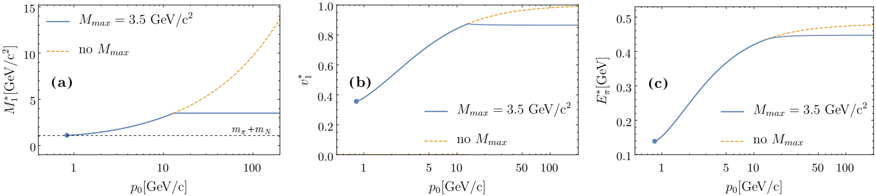

Figure: Mass of intermediate resonance M_R (a), its longitudinal velocity v_R (b), and maximal energy $E_\pi^{\max}$ of $\pi(180^\circ)$ (c) as functions of p_0. The upper limit for resonance mass is fixed as $M_{\max}$=3.5 GeV. The dashed lines correspond to M_1^*, v_1^*, and E_π^*.

UrQMD simulations

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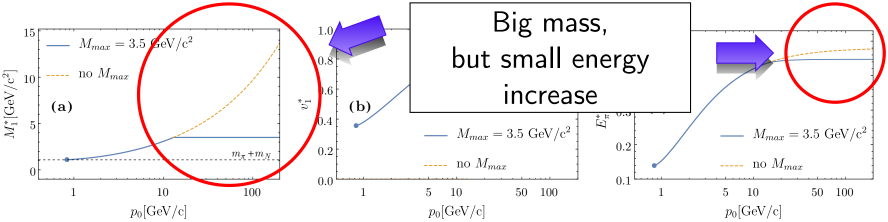

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UrQMD simulations **Comparison with experiment**

To fit experimental data cross-sections was multiplied on additional parameter.

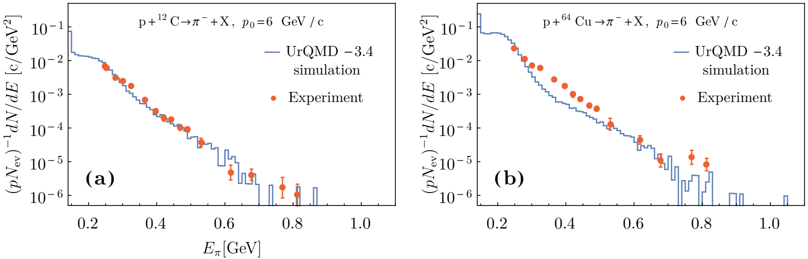
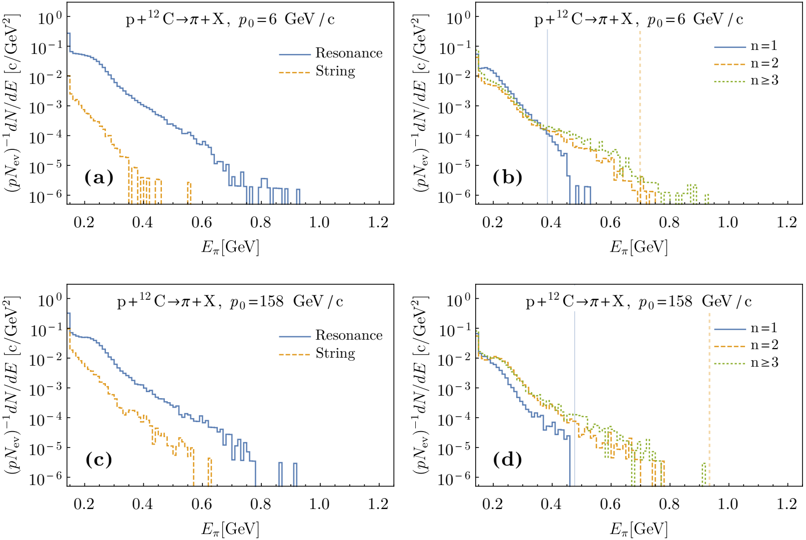


Figure: Comparison of $\pi(180^o)$ cross-sections with *Baldin et al.* data for different nuclei, (a): p+^{12}C, (b): p+^{64}Cu.

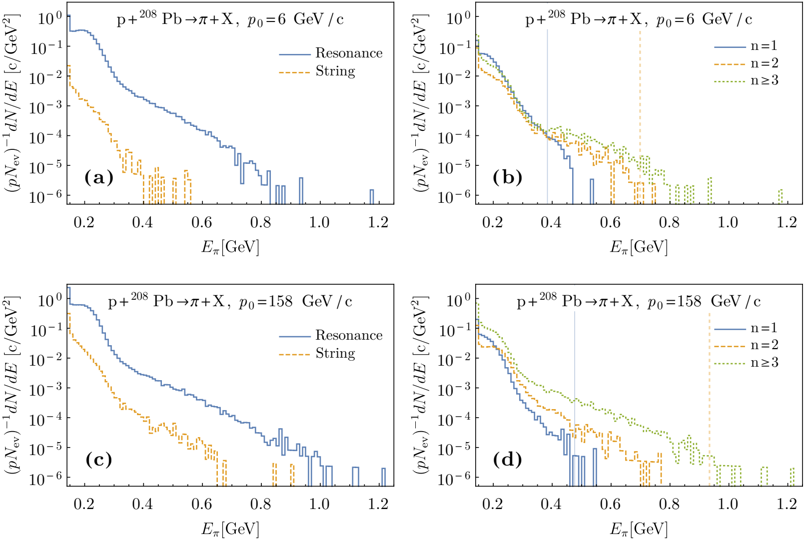
UrQMD simulations p+C collisions

Proton-^{12}C collisions at 6 GeV/c (up) and 158 GeV/c (down).



UrQMD simulations p+Pb collisions

Proton-^{208}Pb collisions at 6 GeV/c (up) and 158 GeV/c (down).



Summary

- Emission of $\pi(180^\circ)$ with maximal energies requires existence of intermediate objects with high mass;
- Cumulative particles production requires successive collisions with nuclear nucleons;
- While colliding with nucleons intermediate resonance could gain its mass and decrease its velocity even to negative values;
- Cumulative effect is a unique laboratory for studying hadron-like objects with extremely high mass, but this requires advanced detectors;
- We suggest to include hadron-string interactions in transport models.