Aspects of particle production in the CGC formalism

Phys. Rev. D **113**, 094009 (2026)

arXiv: 2603.24344 [hep-ph]

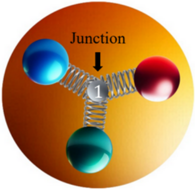
Ríchard Terra

Universidade of São Paulo
Instituto de Física

Advisor:
Prof. Dr. Fernando Silveira Navarra (IFUSP)
Co-advisor:
Prof. Dr. André V. Giannini (UFGD)

The Baryon Junction

- In this picture, the 3 valence quarks of a baryon are joined by an Y-like gluon string;
- The central point is called the “Fermat point".



It is a candidate for describing the proton structure.

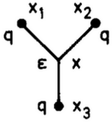
Why baryon junction?

G.C. Rossi and G. Veneziano, Phys. Rep. **63**, 153 (1980).

1) The Fermat point is necessary to keep baryon wave functions gauge invariant:

$B_3 = \mathrm{qqq}$ baryon

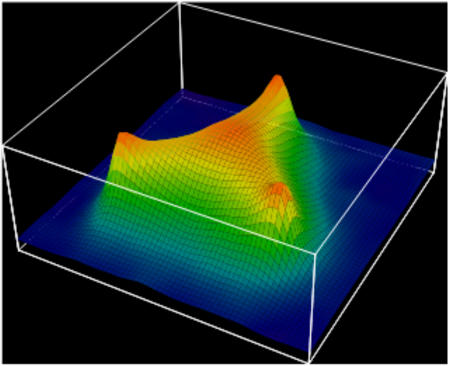
$$\varepsilon^{j_1 j_2 j_3}\left[\mathrm{P}\exp\left(\mathrm{i}g\int_{x_1}^{x} A_\mu \,\mathrm{d}x^\mu\right) q(x_1)\right]_{j_1} \left[\mathrm{P}\exp\left(\mathrm{i}g\int_{x_2}^{x} A_\mu \,\mathrm{d}x^\mu\right) q(x_2)\right]_{j_2} \left[\mathrm{P}\exp\left(\mathrm{i}g\int_{x_3}^{x} A_\mu \,\mathrm{d}x^\mu\right) q(x_3)\right]_{j_3}$$



Why baryon junction?

H. Suganuma, T. T. Takahashi, F. Okiharu and H. Ichie , AIP Conf. Proc. **756**, 123 (2005).

2) Lattice QCD simulations found Y-like flux tubes by studying the 3-quark potential:

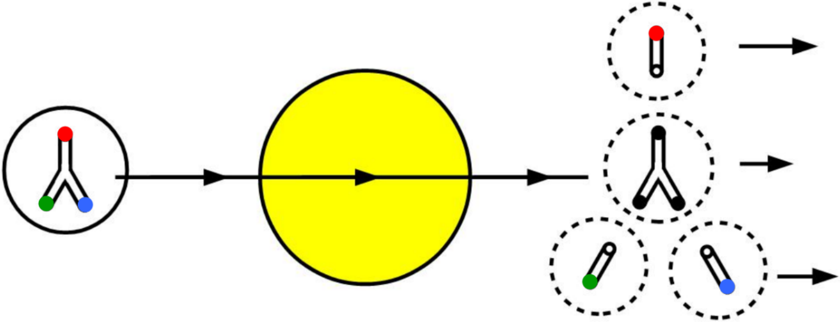


Why baryon junction?

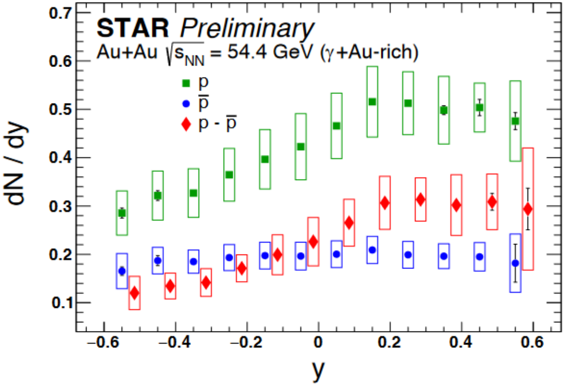
D. Kharzeev, Phys. Lett. B **378**, 238 (1996)

3) It provides an explanation for the excess of protons in the midrapidity region:

- Baryon stopping:

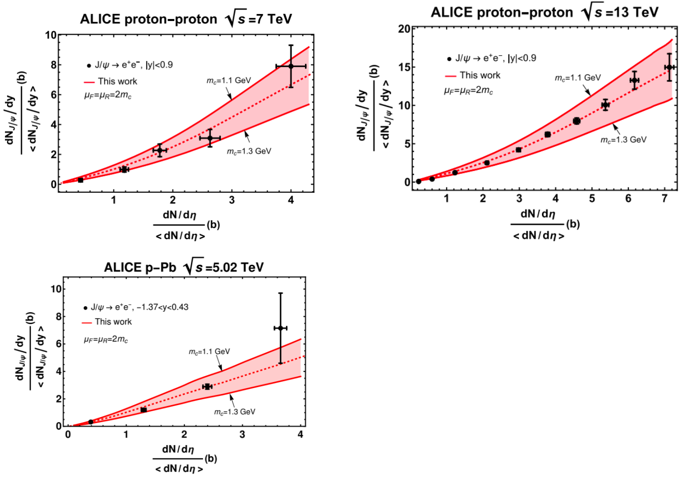


Why baryon junction?



[Star Collaboration], arXiv:2408.15441 [nucl-ex].

Baryon junction initial conditions can explain J/ψ relative yields in pp and pPb collisions:



R.Terra and F.S. Navarra, Phys. Rev. D **108**, 054002 (2023) e arXiv:2404.07743 [hep-ph].

The Baryon junction

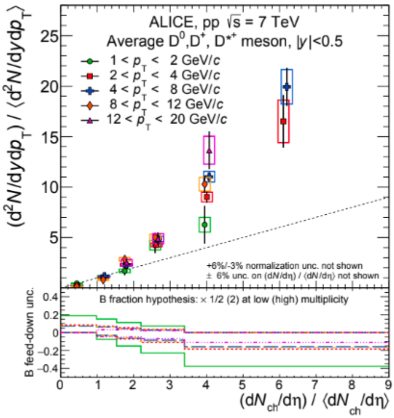
- The baryon junction is still a conjecture, which needs confirmation;

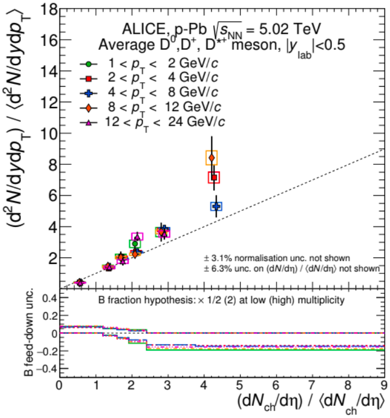
- We notice an international interest in searching for signatures of the junction;
- The main objective of this work is to use baryon junction initial conditions in high-energy collisions and study their effects on observables.

D-meson relative yields

J.Adam *et al.* [ALICE Collaboration], J. High Energ. Phys. **9**, 148 (2015).

J. Adam *et al.* [ALICE Collaboration], J. High Energ. Phys. **08**, 78 (2016).

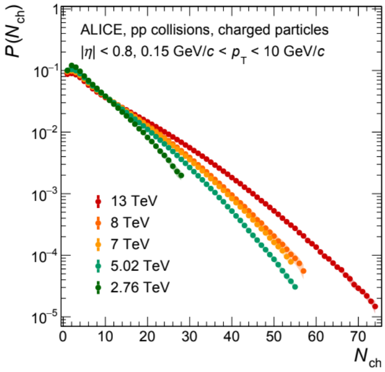


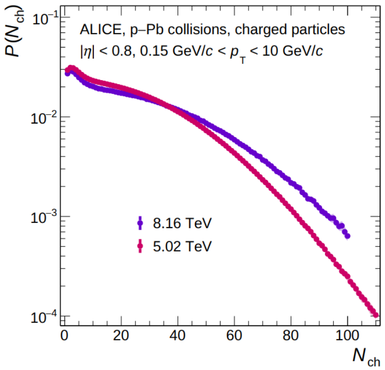


Multiplicity distributions

S. Acharya *et al.* [ALICE Collaboration], Phys. Lett. B **853**, 138700 (2024).

Probability of producing N particles in a collision:





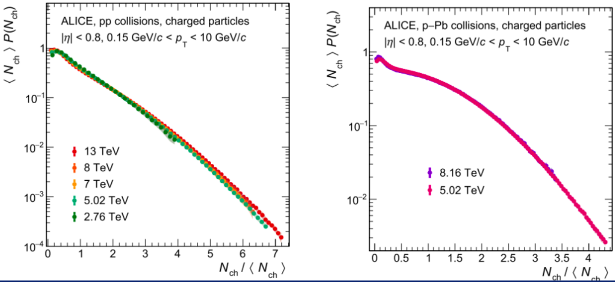
KNO scaling

Z. Koba, H. B. Nielsen and P. Olesen, Nucl. Phys. B **40**, 317 (1972).

For sufficiently high energies, the p(N) distributions scaled by their mean values should be energy independent:

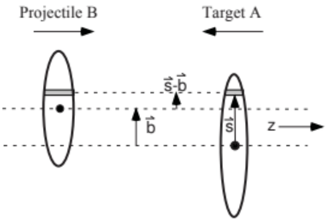
$$\langle n(s)\rangle P_n(s) = \Psi\left(\frac{n}{\langle n(s)\rangle}\right) . \tag{1}$$

Approximately valid for small pseudorapidity windows near $\eta = 0$:



Glauber Model

M.L. Miller *et al.*, Annu. Rev. Nucl. Part. Sci. **57**, 205 (2007).



For a given nucleon density $\rho(\vec{r})$, we calculate:

- Probability/area of finding a nucleon in the projectile/target (thikcness function):

$$T_A(\vec{s}) = \int \rho_A(\vec{s}, z_A) dz_A, \qquad T_B(\vec{s}) = \int \rho_B(\vec{s}, z_B) dz_B \,. \tag{2}$$

- Probability/area of occurring an interaction (overlap function):

$$T_{AB}(\vec{b}) = \int T_A(\vec{s})T_B(\vec{s}-\vec{b})d^2s\,. \tag{3}$$

Initial condition (analytical-BJ1)

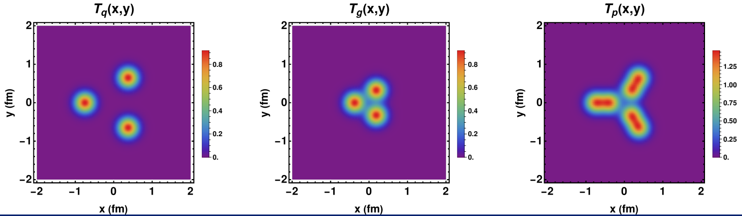
S. Deb, G. Sarwar, D. Thakur, P. Subramani, R. Sahoo and J. e. Alam, Phys. Rev. D **101**, 014004 (2020).

Thickness:

$$T_N(x, y) = T_N^q(x, y) + T_N^g(x, y) \tag{4}$$

$$T_N^q(x, y) = \frac{(1-\kappa)}{6\pi B_h^2} \sum_{i=1}^{3} \exp\left(- \frac{\Big(x - (x_p + x_i)\Big)^2 + \Big(y - (y_p + y_i)\Big)^2}{2B_h^2} \right) \tag{5}$$

$$T_N^g(x, y) = \frac{\kappa}{6\pi B_h^2} \sum_{i=1}^{3} \exp\left(- \frac{\Big(x - (x_p + \frac{x_i}{2})\Big)^2 + \Big(y - (y_p + \frac{y_i}{2})\Big)^2}{2B_h^2} \right) \tag{6}$$



The quarks are positioned in the vertices of an equilateral triangle:

$$\mathbf{r}_i = \frac{d}{2}\left(\cos(\phi_i + \alpha)\sin(\theta), \sin(\phi_i + \alpha)\sin(\theta), \cos(\theta) \right), \qquad (7)$$

where $d = 1.5$ fm, $\phi_1 = \pi/3$, $\phi_2 = -\pi/3$, $\phi_3 = -\pi$ are the structure parameters;

α and θ, drawn in each collision, give rotational degrees of freedom to the system;

$B_h = 0.17$ fm is the hot-spot size and half of them are gluon-like ($\kappa = 0.5$).

The overlap between a projectile nucleon in $\mathbf{r}_p = (x_p, y_p)$ and a target nucleon in $\mathbf{r}_a = (x_a, y_a)$ is given by:

$$T_{NN'}(b) = T^{qq}_{NN'}(b) + T^{gg}_{NN'}(b) + T^{gq}_{NN'}(b) + T^{qg}_{NN'}(b), \tag{8}$$

It can be split in four terms:

$$\begin{aligned} T^{qq}_{NN'}(b) &= \int T^q_N(x-b/2,y)T^q_{N'}(x+b/2,y)dxdy \\ &= \frac{(1-\kappa)^2}{36\pi B_h^2}\sum_{i=1}^{3}\sum_{j=1}^{3}\exp\left(-\frac{\Big(b+(x_p+x_i)-(x_a+x_j)\Big)^2+\Big((y_p+y_i)-(y_a+y_j)\Big)^2}{4B_h^2}\right), \end{aligned} \tag{9}$$

$$\begin{aligned} T^{gg}_{NN'}(b) &= \int T^g_N(x-b/2,y)T^g_{N'}(x+b/2,y)dxdy \\ &= \frac{\kappa^2}{36\pi B_h^2}\sum_{i=1}^{3}\sum_{j=1}^{3}\exp\left(-\frac{\Big(b+(x_p+x_i/2)-(x_a+x_j/2)\Big)^2+\Big((y_p+y_i/2)-(y_a+y_j/2)\Big)^2}{4B_h^2}\right), \end{aligned} \tag{10}$$

$$T^{gq}_{NN'}(b) = \int T^g_N(x-b/2,y)T^q_{N'}(x+b/2,y)dxdy \tag{11}$$
$$= \frac{\kappa(1-\kappa)}{36\pi B_h^2}\sum_{i=1}^{3}\sum_{j=1}^{3}\exp\left(-\frac{\Big(b+(x_p+x_i/2)-(x_a+x_j)\Big)^2+\Big((y_p+y_i/2)-(y_a+y_j)\Big)^2}{8B_h^2}\right),$$

$$T^{qg}_{NN'}(b) = \int T^q_N(x-b/2,y)T^g_{N'}(x+b/2,y)dxdy \tag{12}$$
$$= \frac{\kappa(1-\kappa)}{36\pi B_h^2}\sum_{i=1}^{3}\sum_{j=1}^{3}\exp\left(-\frac{\Big(b+(x_p+x_i)-(x_a+x_j/2)\Big)^2+\Big((y_p+y_i)-(y_a+y_j/2)\Big)^2}{8B_h^2}\right).$$

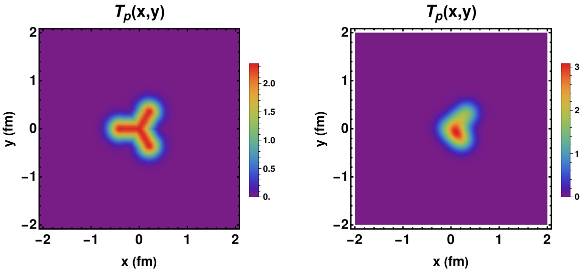
Initial conditions (numerical-BJ2)

H. Mäntysaari and B. Schenke, Phys. Rev. D **94**, 034042 (2016).

1) To position 3 quarks: $P(\mathbf{r}) = \frac{e^{-\frac{\mathbf{r}^2}{2B_r}}}{\left(2\pi B_r\right)^{3/2}}$, $B_r = 0.41^2$ fm^2;

2) To find the Fermat point;

3) To fill the flux tubes with Gaussians: $B_t = 0.15^2$ fm^2;



BJ2 initial conditions present more fluctuation possibilities than BJ1.

We approximate the overlap by a Gaussian with $B_r = 0.41^2$ fm^2:

$$T_{NN'}(b) = \frac{e^{-b^2/4B_r}}{4\pi B_r}\,. \tag{13}$$

Initial conditions (hard-sphere)

J. L. Albacete, A. Dumitru, H. Fujii and Y. Nara, Nucl. Phys. A **897**, 1 (2013).

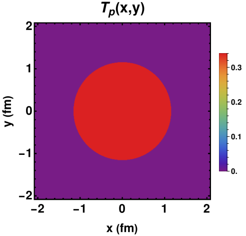
Thickness:

$$T(\mathbf{r}_\perp) = \frac{\Theta(\sqrt{\sigma_0/\pi} - r_\perp)}{\sigma_0}\,, \tag{14}$$

with $\sigma_0 = \sigma_{NN}^{inel}(\sqrt{s} = 200 \text{ GeV})$ as a reference;

Collision criterion:

$$d = \sqrt{\left(x_{proj} - x_{targ}\right)^2 + \left(y_{proj} - y_{targ}\right)^2} \leq \sqrt{\frac{\sigma_{NN}}{\pi}}\,. \tag{15}$$



Initial conditions (Gaussian)

A. H. Rezaeian, M. Siddikov, M. Van de Klundert and R. Venugopalan, Phys. Rev. D **87**, 034002 (2013).

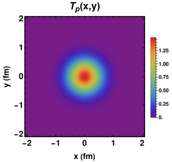
Thickness:

$$T_N(\mathbf{r}_\perp) = \frac{e^{-\frac{\mathbf{r}_\perp^2}{2B_p}}}{2\pi B_p}\,, \tag{16}$$

with $B_p \approx 4$ GeV^{-2}, estimated through comparisons with HERA measurements.

Overlap function:

$$T_{NN'}(b) = \frac{e^{-b^2/4B_p}}{4\pi B_p}\,. \tag{17}$$



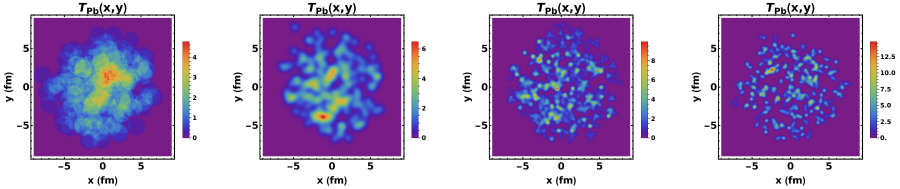
Initial conditions (Lead)

We sort 208 nucleons according to:

$$\rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}\,, \tag{18}$$

Thickness:

$$T_{Pb}(x,y) = \sum_{n=1}^{208} T_n(x,y)\,. \tag{19}$$



(a) Hard-sphere (b) Gaussian (c) BJ1 d) BJ2

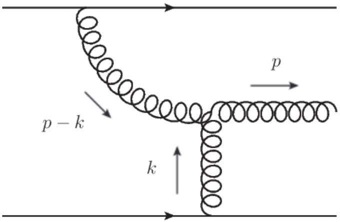
K_T-factorization

J. L. Albacete, A. Dumitru, H. Fujii and Y. Nara, Nucl. Phys. A **897**, 1 (2013).

Single-inclusive gluon production cross-section:

$$\frac{d\sigma^{A+B\to g}}{dy\, d^2p_T\, d^2\mathbf{r}_\perp} = \mathbf{K}\, \frac{2}{C_F\, p_T^2} \int^{p_T} \frac{d^2k_T}{4} \int d^2b\; \alpha_s(Q)\, \phi_p\left(\frac{|p_T+k_T|}{2}, x_1; b\right) \phi_T\left(\frac{|p_T-k_T|}{2}, x_2; R-b\right)$$

(20)



$2 \to 1$ kinematics:

$$x_{1,2} = \frac{p_T}{\sqrt{s}} e^{\pm y} \tag{21}$$

Unintegrated gluon distribution (UGD):

$$\phi_{KLN}(\mathbf{k}, x) = \frac{2C_F}{3\pi^2} \frac{(1-x)^4}{\alpha_s} \begin{cases} 1, & \text{, if } k \leq Q_s \\ (Q_s/k)^2 & \text{, if } k > Q_s \end{cases} \tag{22}$$

D. Kharzeev, E. Levin and M. Nardi, Phys. Rev. C **71**, 054903 (2005).

Saturation scale:

$$Q_s^2(x, \mathbf{r}_\perp) = T(\mathbf{r}_\perp)\ \frac{2\ \text{GeV}^2}{1.53\ \text{fm}^{-2}} \left(\frac{0.01}{x}\right)^{\bar{\lambda}}, \tag{23}$$

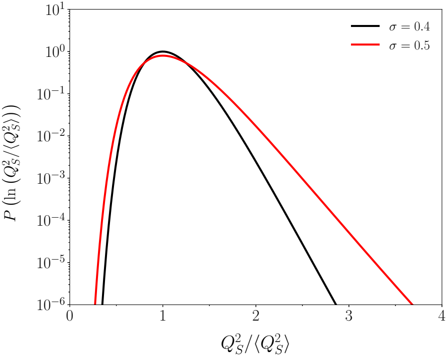
$\bar{\lambda} = 0.23$

J. L. Albacete, A. Dumitru and Y. Nara, J. Phys.: Conf. **316**, 012011 (2011).

Intrinsic Fluctuations

L. McLerran and P. Tribedy, Nucl. Phys. A **945**, 216 (2016)

$$P(\ln(Q^2/\left\langle Q^2\right\rangle)) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{\ln^2(Q(\mathbf{s}_\perp)^2/\left\langle Q(\mathbf{s}_\perp)^2\right\rangle)}{2\sigma^2}\right) \quad (24)$$



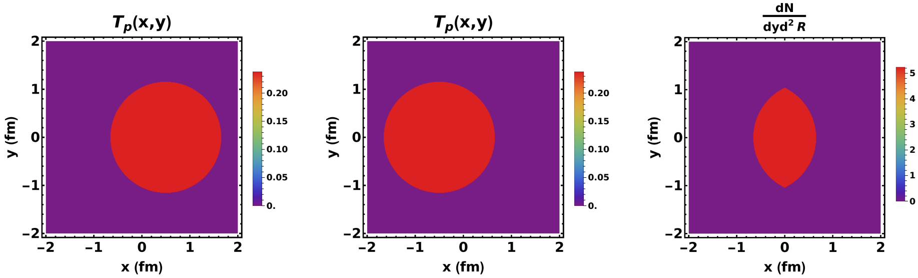
MCKT

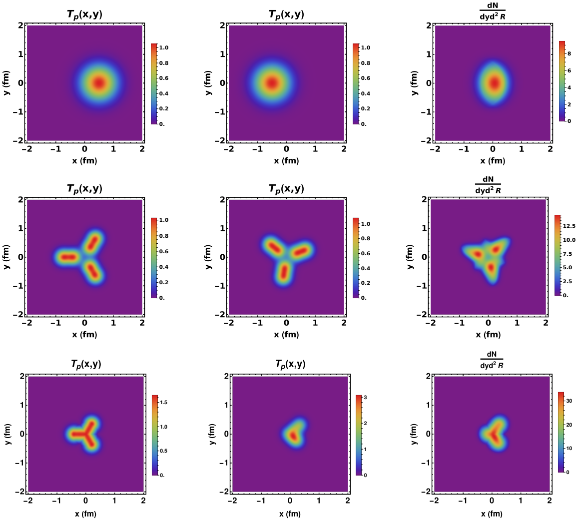
Monte Carlo event generator which convolutes Glauber initial conditions and k_T-factorization;

It calculates the gluon production in the overlap region;

We introduced BJ1 and BJ2 thickness and overlaps in the code;

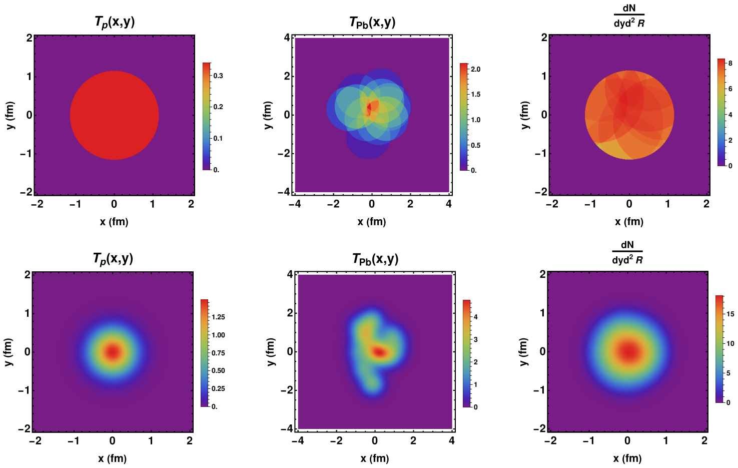
Example (hard-sphere):

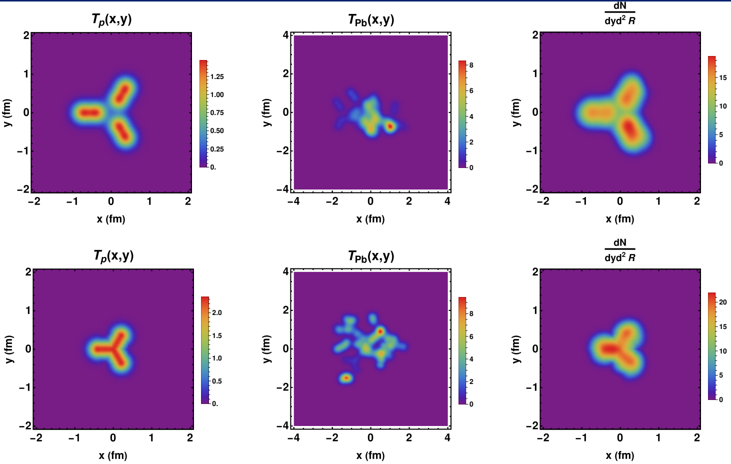




The gluon production region rarely reflects the exact shape of the proton in pp collisions.

Convolution (pPb)





In pPb collisions, the production region always present the proton shape.
$\Rightarrow$ higher sensibility to the proton structure than pp collisions.

Particle production

$y \to \eta$ Jacobian:

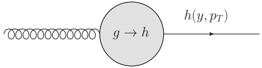
$$\frac{\cosh\eta}{\sqrt{\cosh^2\eta + m_\pi^2/p_T^2}} \tag{25}$$

We assume the parton-hadron duality to compute inclusive charged-particle production:

$$N_{ch} \propto N_{gluons} \tag{26}$$

$$\Rightarrow N_{ch} = \int d\eta \int d^2R \, \frac{dN}{d\eta\, d^2R} \tag{27}$$

For D-meson, we convolute the formalism with a $g \to D$ fragmentation function:

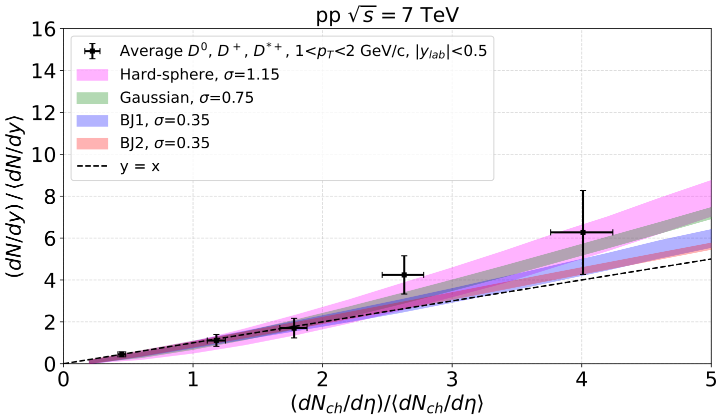


T. Kneesch, B. A. Kniehl, G. Kramer and I. Schienbein, Nucl. Phys. B **799**, 34 (2008).

Results (pp)

J.Adam *et al.* [ALICE Collaboration], J. High Energ. Phys. **9**, 148 (2015).

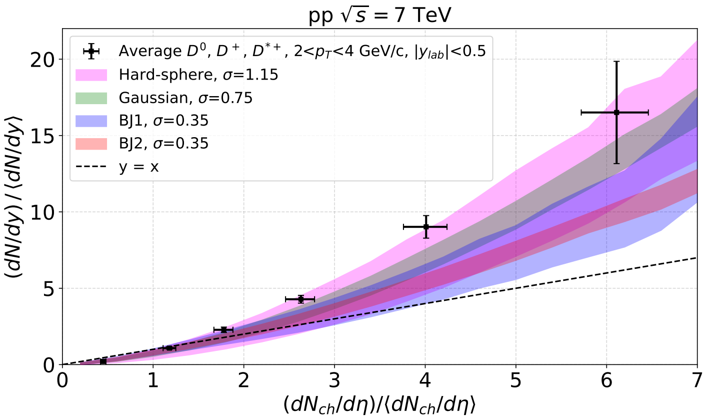
arXiv: 2603.24344 [hep-ph]



Results (pp)

J.Adam *et al.* [ALICE Collaboration], J. High Energ. Phys. **9**, 148 (2015).

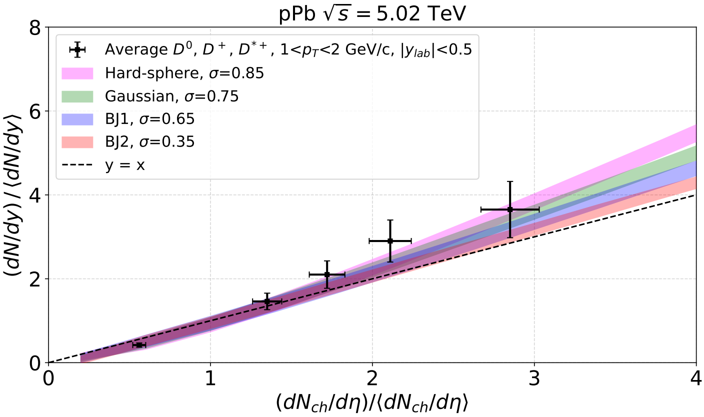
arXiv: 2603.24344 [hep-ph]



Results (pPb)

J. Adam *et al.* [ALICE Collaboration], J. High Energ. Phys. **08**, 78 (2016).

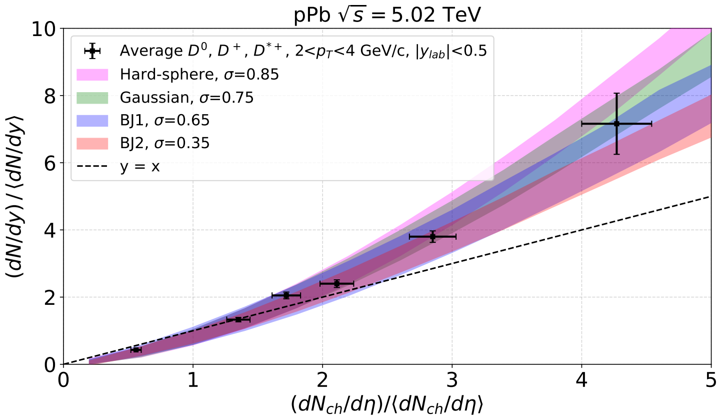
arXiv: 2603.24344 [hep-ph]



Results (pPb)

J. Adam *et al.* [ALICE Collaboration], J. High Energ. Phys. **08**, 78 (2016).

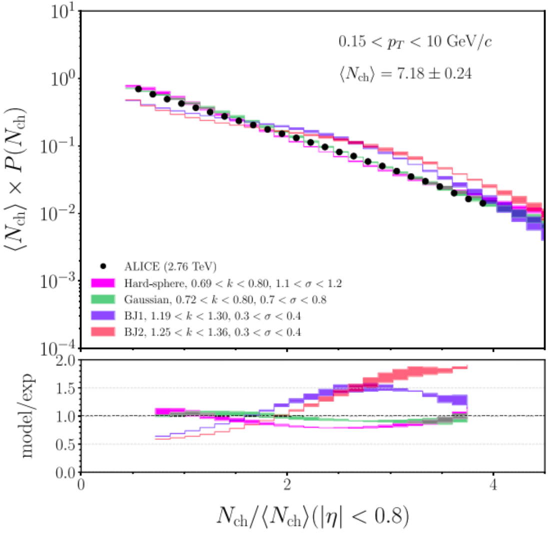
arXiv: 2603.24344 [hep-ph]



We could explain all data, but we could not constrain the proton structure because of the large experimental uncertainties.

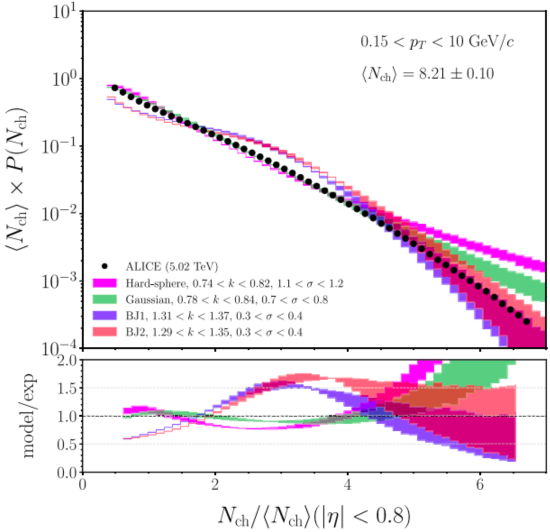
Results (pp)

R. Terra, A. V. Giannini and F. S. Navarra Phys. Rev. D **113**, 094009 (2026)



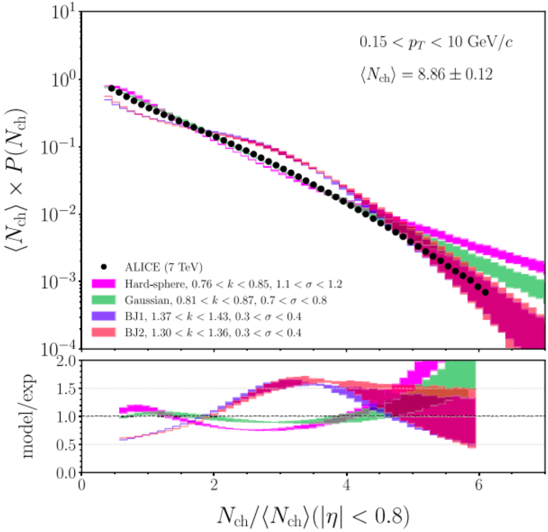
Results (pp)

R. Terra, A. V. Giannini and F. S. Navarra Phys. Rev. D **113**, 094009 (2026)



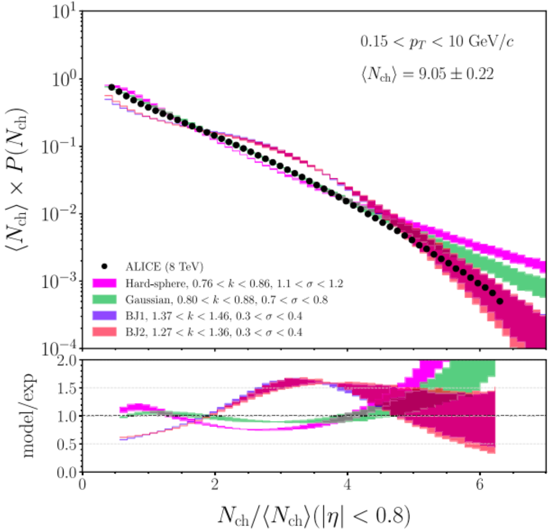
Results (pp)

R. Terra, A. V. Giannini and F. S. Navarra Phys. Rev. D **113**, 094009 (2026)



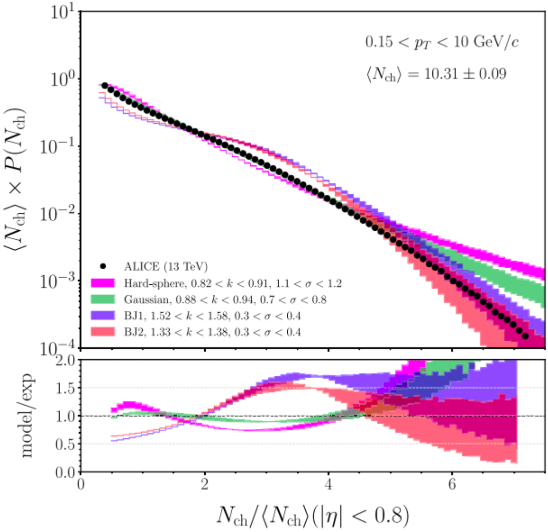
Results (pp)

R. Terra, A. V. Giannini and F. S. Navarra Phys. Rev. D **113**, 094009 (2026)



Results (pp)

R. Terra, A. V. Giannini and F. S. Navarra Phys. Rev. D **113**, 094009 (2026)

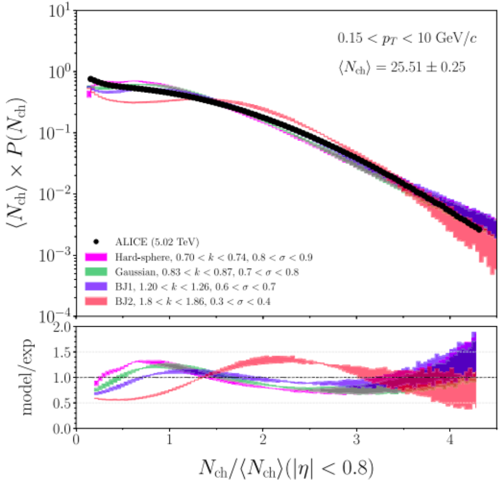


Partial conclusions (pp)

- At low energy ($\sqrt{s} = 2.76$ TeV), the Gaussian nucleon provided the best description of the data;
- For $\sqrt{s} = 5.02$ TeV and above, the Gaussian nucleon describes the data better up to $4 \times \langle N \rangle$, and overestimates them for higher multiplicities;
- The high-multiplicity data were described better by baryon junction initial conditions;
- We do not describe the very-low-multiplicity region ($N/\langle N \rangle \lesssim 1$) because it is dominated by diffractive events that are not accounted for by the formalism.

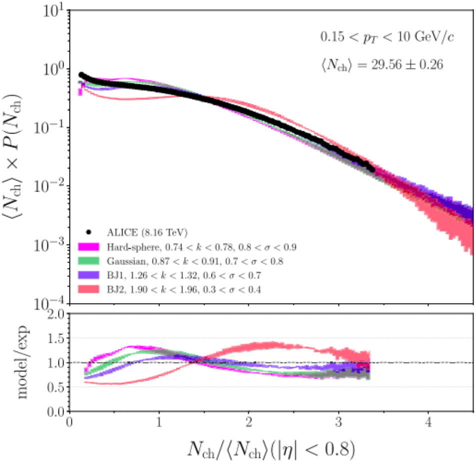
Results (pPb)

R. Terra, A. V. Giannini and F. S. Navarra Phys. Rev. D **113**, 094009 (2026)



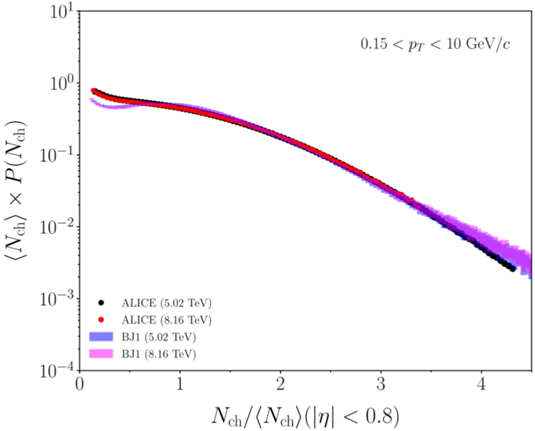
Results (pPb)

R. Terra, A. V. Giannini and F. S. Navarra Phys. Rev. D **113**, 094009 (2026)



BJ1 provides the best model/exp ratios.

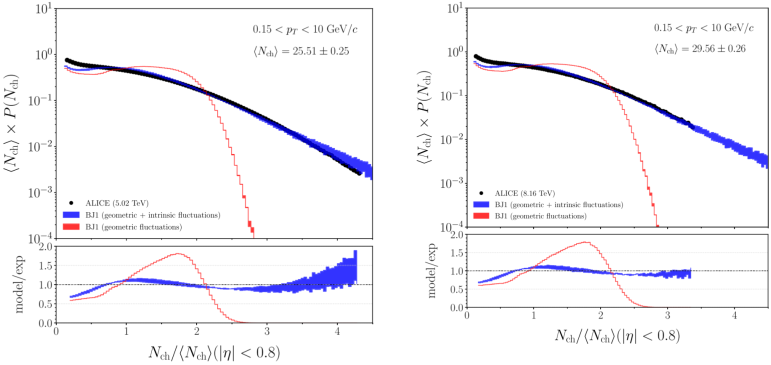
Results (pPb)



The theoretical results exhibit KNO scaling in pPb, just like the experimental measurements.

Are the intrinsic fluctuations important?

R. Terra, A. V. Giannini and F. S. Navarra Phys. Rev. D **113**, 094009 (2026)



They are essential!

Conclusions

- We implemented baryon junction initial conditions in the MCKT;
- We used k_T-factorization to account for the production of gluons, D mesons, and charged particles;
- We explained D-meson relative yields but we could not constrain the proton structure because of the large experimental uncertainties;
- The Gaussian initial conditions described better pp multiplicity distribution data at low energy and intermediate-multiplicity region at higher energies;
- The baryon junction initial conditions described better high-multiplicity and high-energy pp data;
- The analytical baryon junction described better pPb multiplicity distributions;

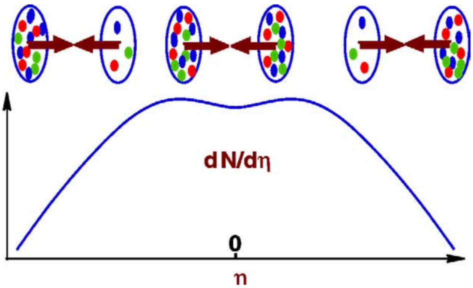
.

Final conclusions

- It is difficult to discriminate between different initial conditions using D-meson production and P(N);
- Probably anisotropies (v_2, v_3...) are more promising (work in progress);
- The baryon junction is competitive. It is favored both in pp collisions at the highest energies and in pPb collisions.

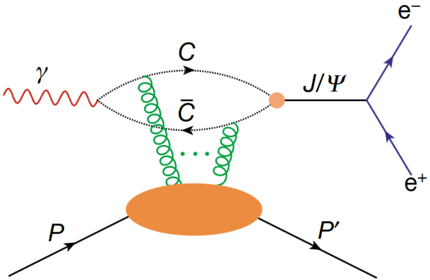
Thank you!

FAPESP

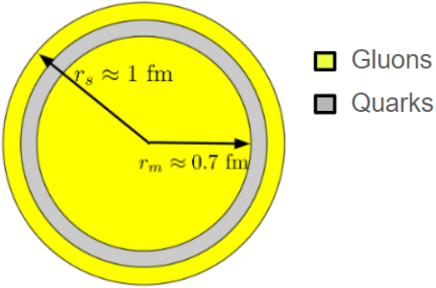

d N/dη
0
η

B. Duran, Z. E. Meziani, S. Joosten *et al.*, Nature **615**, 813 (2023).

Process measured at JLAB:



(a) J/ψ exclusive photoproduction.



(b) The proton gluon distribution.

- Important to access the gluon distribution inside the proton;
- What is the shape of the gluon distribution?

D. S. Kuzmenko and Yu. A. Simonov, Phys. Atom. Nucl. **66**, 950 (2003).

On the other hand, the Δ-like wave function

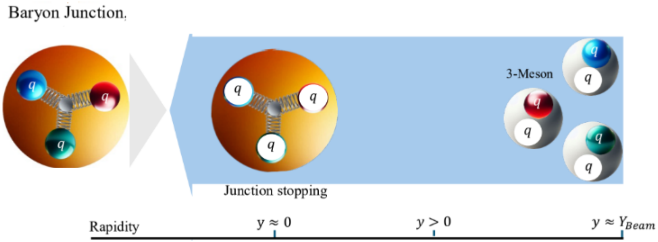
$$\psi_\Delta \propto \left[q_{\alpha\beta}(x)\Phi^{\beta}_{\gamma}(x,y)\right] \times \left[q_{\gamma\delta}(y)\Phi^{\delta}_{\epsilon}(y,z)\right] \times \left[q_{\epsilon\rho}(z)\Phi^{\rho}_{\alpha}(z,x)\right], \quad (28)$$

with

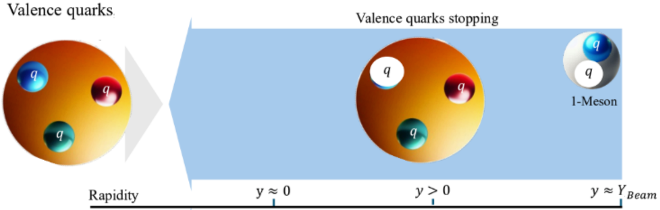
$$q_{\beta\gamma}(x) = \varepsilon_{\alpha\beta\gamma}q^{\alpha}(x) \;\; e \;\; \Phi^{\beta}_{\alpha}(x,y) = \left(P\,exp\left(ig\int A_\mu(z)dz_\mu\right)\right)^{\beta}_{\alpha}, \quad (29)$$

is not invariant under the transformation $q^{\alpha}(x) \rightarrow U^{\alpha}_{\beta}(x)q^{\beta}(x)$.

- With junction:



- Without junction:



N. Magdy, P. Tribedy, C. Y. Tsang and Z. Xu [arXiv: 2504.09826 [nucl-ex]].