CLHCP 2025

Study of femtoscopic emission sources in ALICE experiments and AMPT

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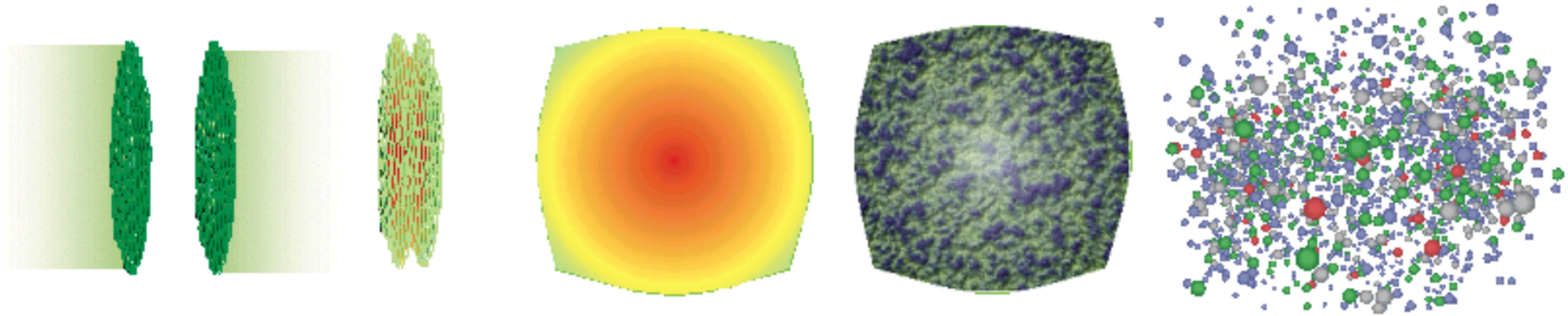
31 Oct, 2025

Outline

1. Introduction of femtoscopy
2. p&d emission source in Pb-Pb@5.02TeV ALICE Run 2
3. The pion emission source in pp@13.6TeV AMPT model
4. Summary

Relativistic Heavy-Ion Collision



"Pan cake" | Pre-equilibrium state dynamics | QGP Phase | Chemical freeze-out | Kinetic freeze-out → t

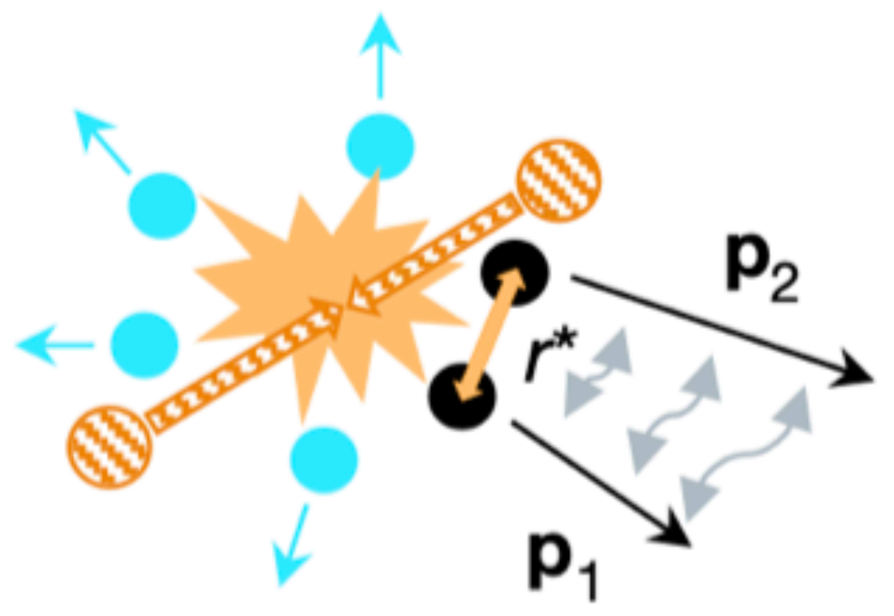
addressed. The small size, ∼10^{-14} m, and transient nature, ∼10^{-22} seconds, of the reactions preclude direct measurement of times or positions. Instead, femtoscopy must exploit measurements of asymptotic momenta. Correlations of two final-state particles at small relative momentum provide the most direct link to the size and lifetime of subatomic reactions (5–12). Because correlations from either

Femtoscopy

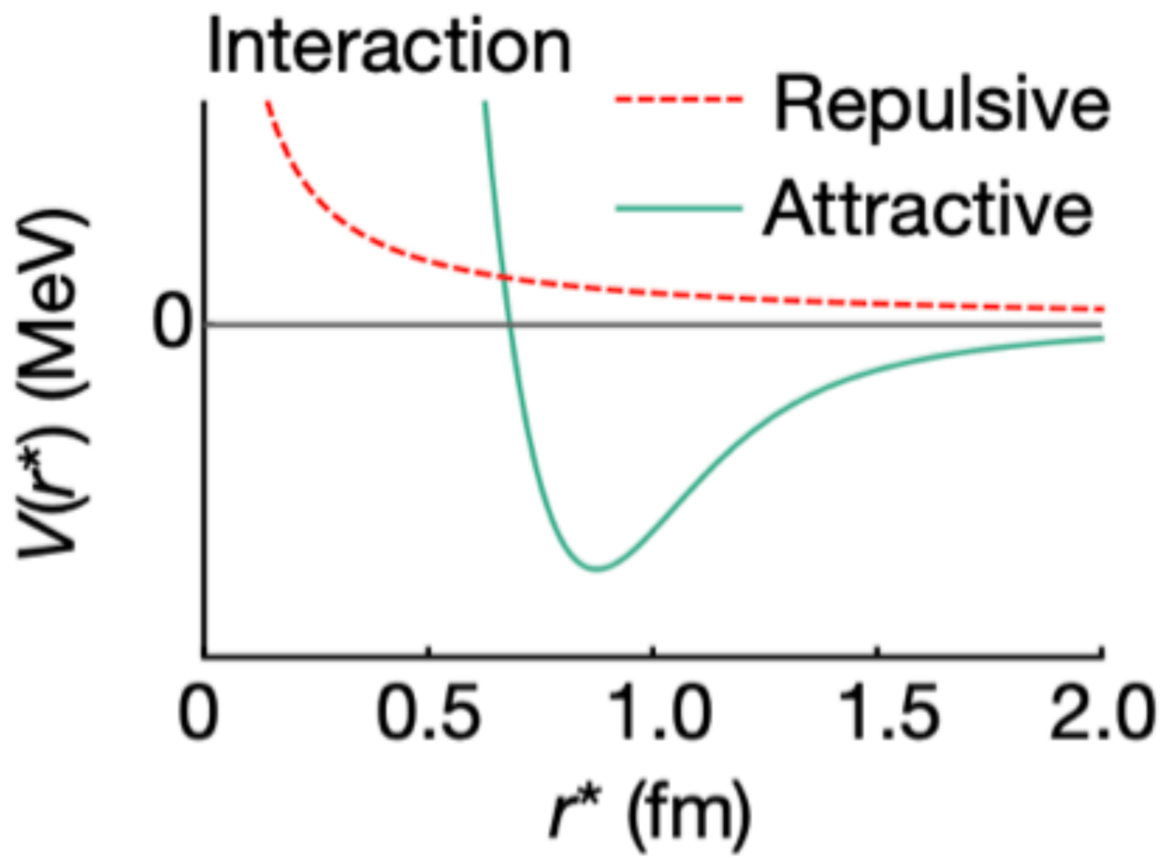
Larry McLerran's slides
https://indico.cern.ch/event/181834/contributions/313104/

Annual Review of Nuclear and Particle Science, 55 no.1, (2005) 357-402

Femtoscopy



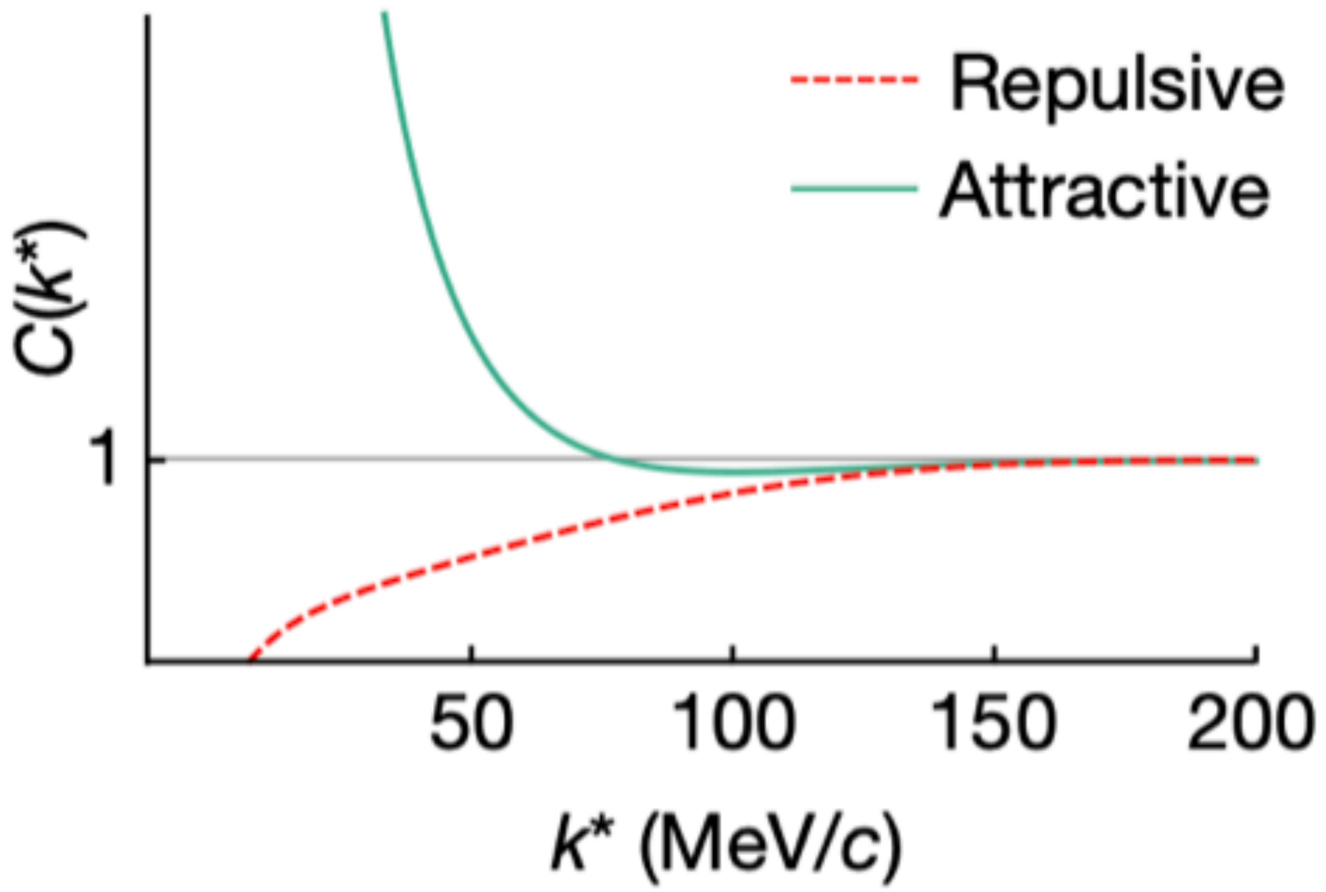
Emission source $S(r^*)$



Schrödinger equation

↓

Two-particle wavefunction $|\psi(\mathbf{k}^*, \mathbf{r}^*)|$



Correlation function

Measured in experiment

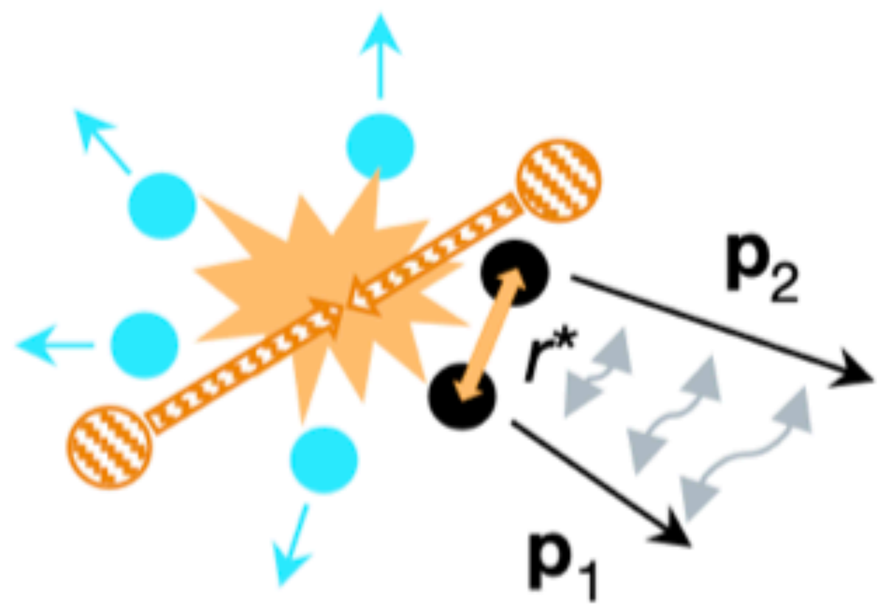
$$C(k^*) = \int S(r^*)|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2 d^3r^* = \xi(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$k^* = |\mathbf{p}_2^* - \mathbf{p}_1^*|/2$ in the pair rest frame

S.E. Koonin, PLB 70 43 (1977)
Annu. Rev. Nucl. Part. Sci. 71, 377 (2021)

Femtoscopy

- 1954, Hanbury Brown & Richard Q. Twiss(HBT) introduced the intensity interferometer concept to radio astronomy for measuring the tiny angular size of stars. (Philosophical Magazine. 45 (366): 663–682)
- 1981, R.Lednický, V.L.Lyuboshitz(Sov.J.Nucl.Phys. 35 (1982) 770), femtoscopy in relativistic heavy ion collision(L.P. Csernai; W. Greiner (1981), 99(2), 85–88)



Emission source S(r*)

Gaussian profile source function:

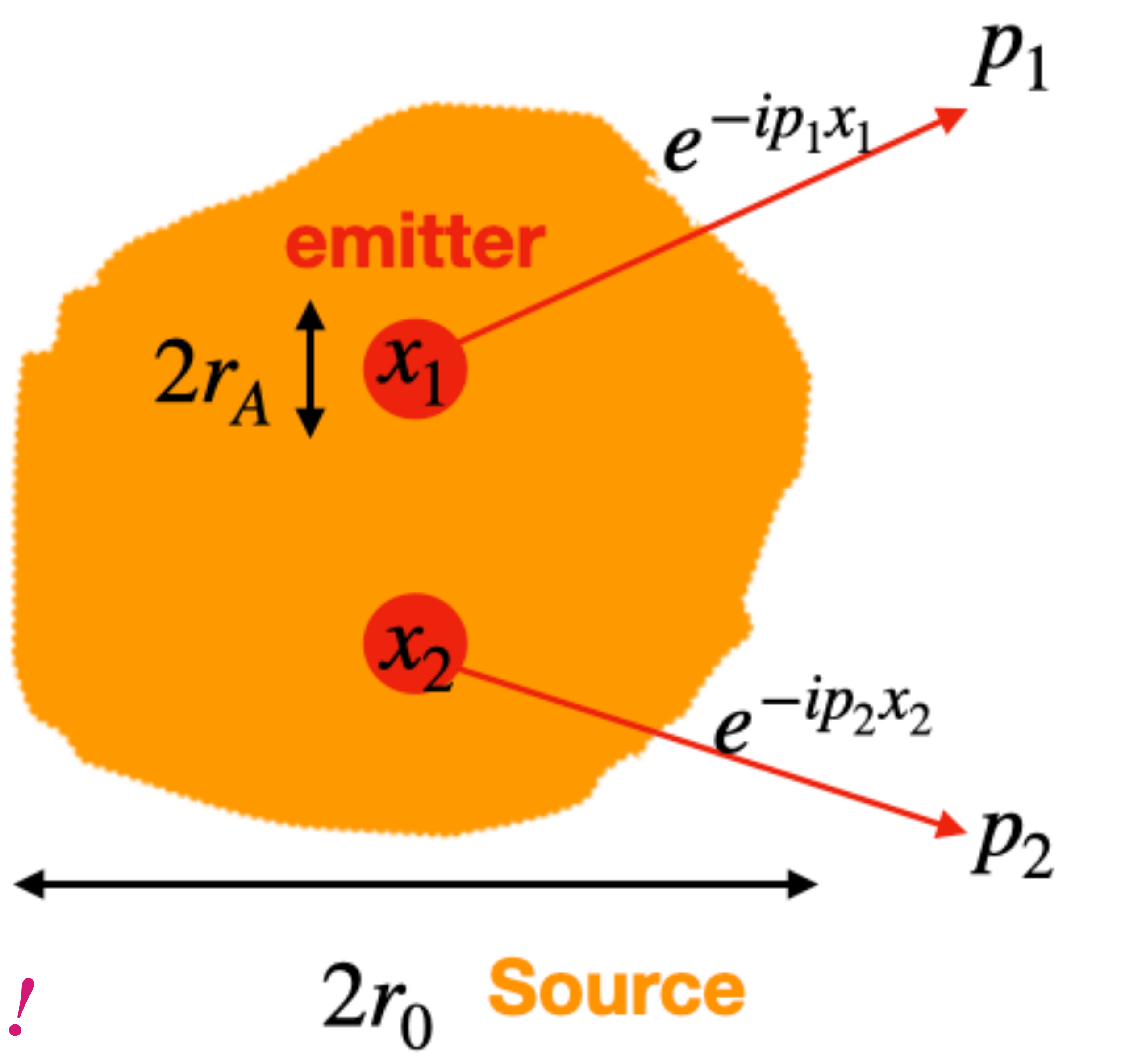
$$S(r^*) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp\left(-\frac{r^{*2}}{4r_0^2}\right)$$

r_0: Source radius

r_A: Emitter radius

$(r_A^2, \tau_A^2 \sim 0.1\ \mathrm{fm}^2)$

$r_A^2/2 \ll r_0^2, \quad \tau_A^2/2 \ll \tau_0^2$ ***Smooth approximation!***



$$C(k^*) = \int S(r^*)|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2 \mathrm{d}^3r^* = \xi(k^*)\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

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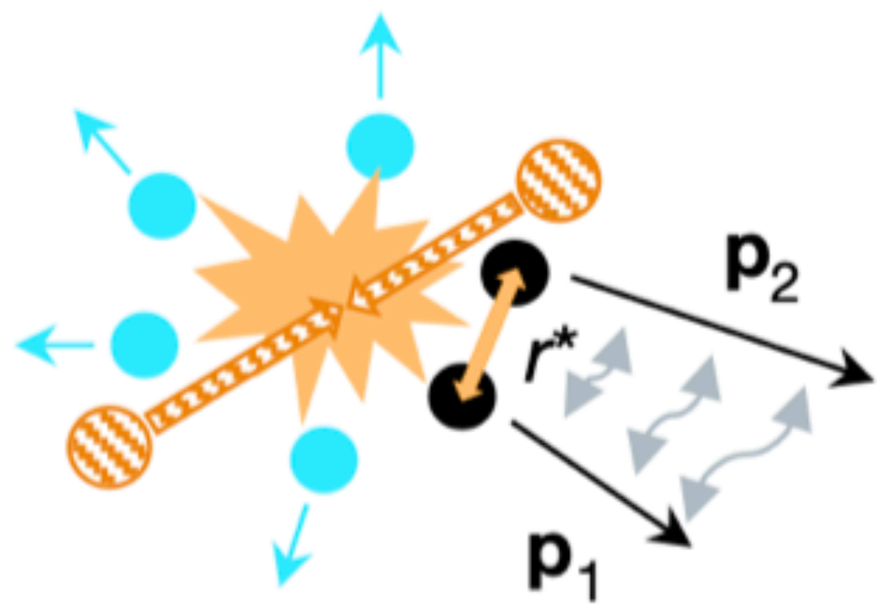
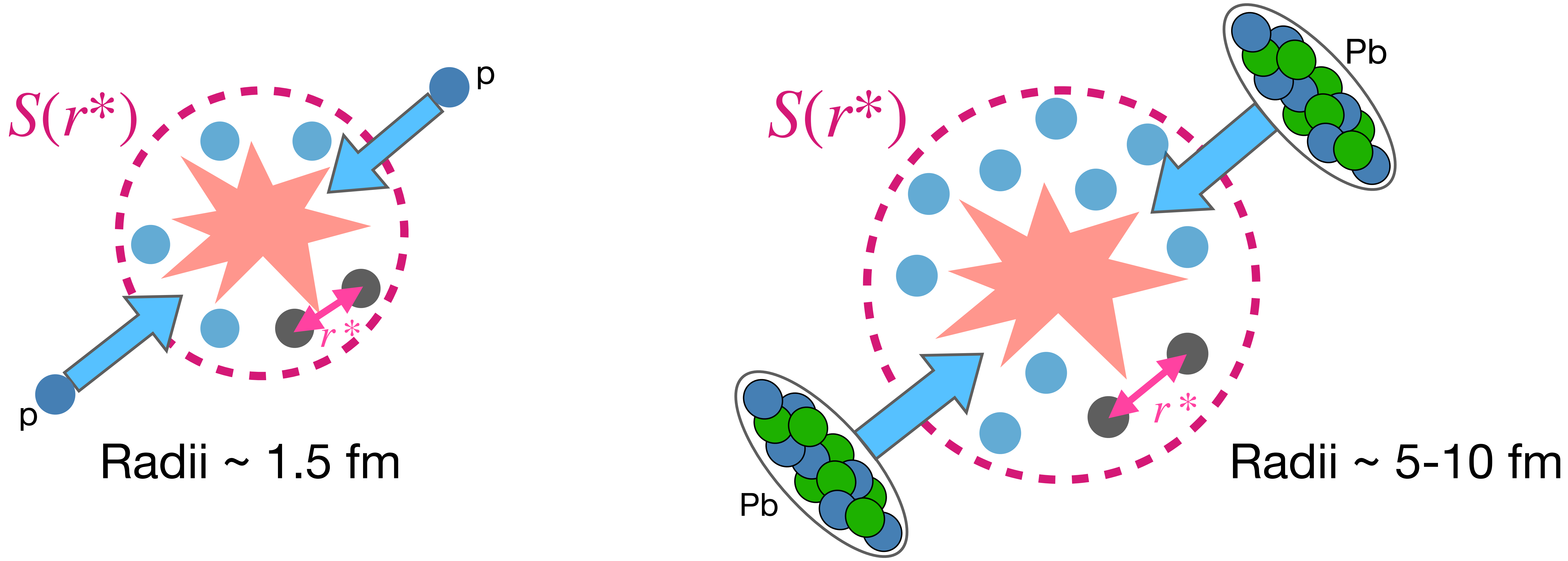
Source in Pb-Pb and pp



Emission source $S(r^*)$



The dash line circle : An effective surface (emission source)

The radii is the sigma value of source function, not the radius of this circle

- The common m_T -scaling has been observed both in pp and PbPb

$$C(k^*) = \int S(r^*)\,|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2\, d^3r^* = \xi(k^*)\,\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$$k^* = |\mathbf{p}_2^* - \mathbf{p}_1^*|/2 \text{ in the pair rest frame}$$

S.E. Koonin, PLB 70 43 (1977)
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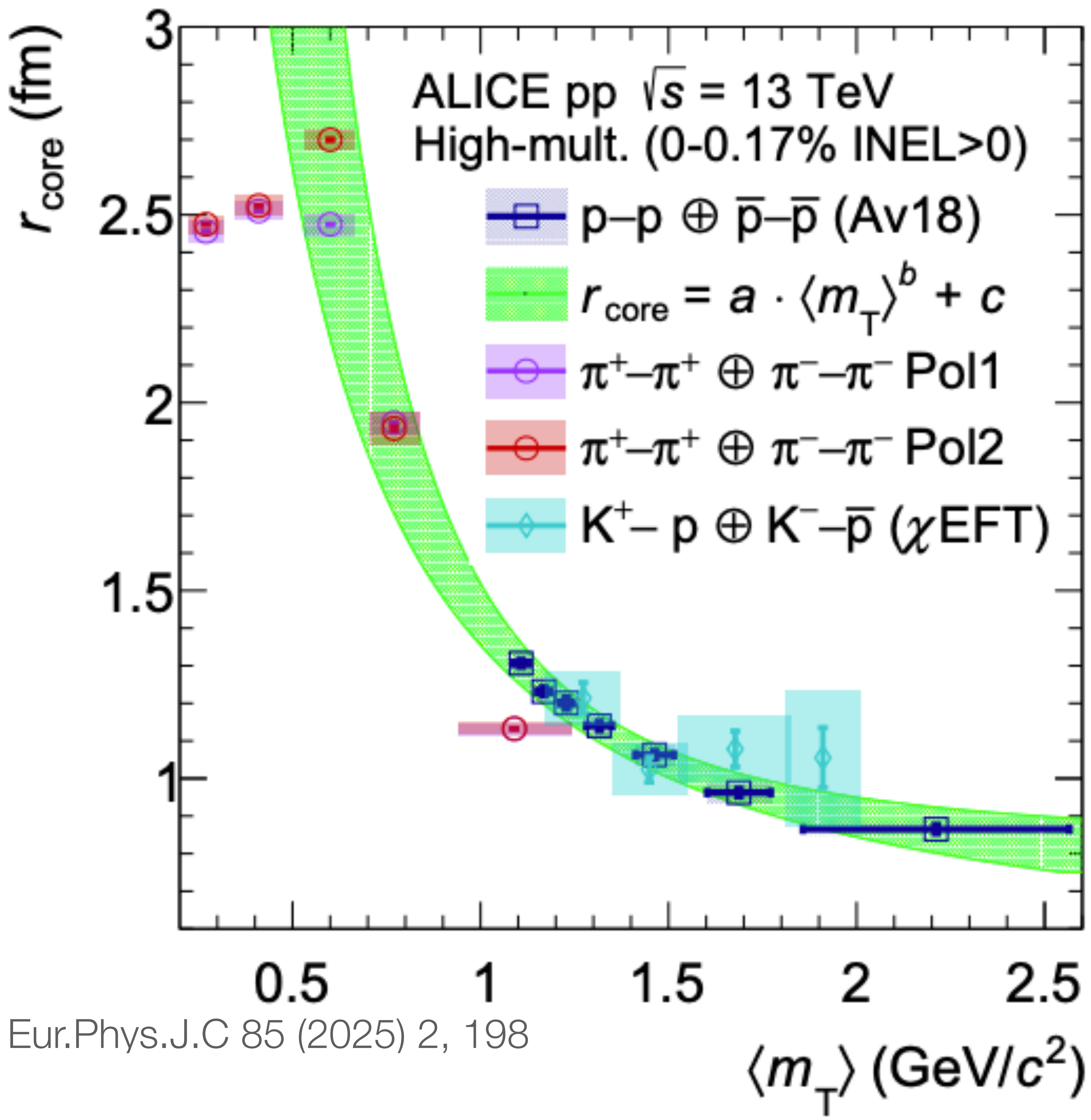
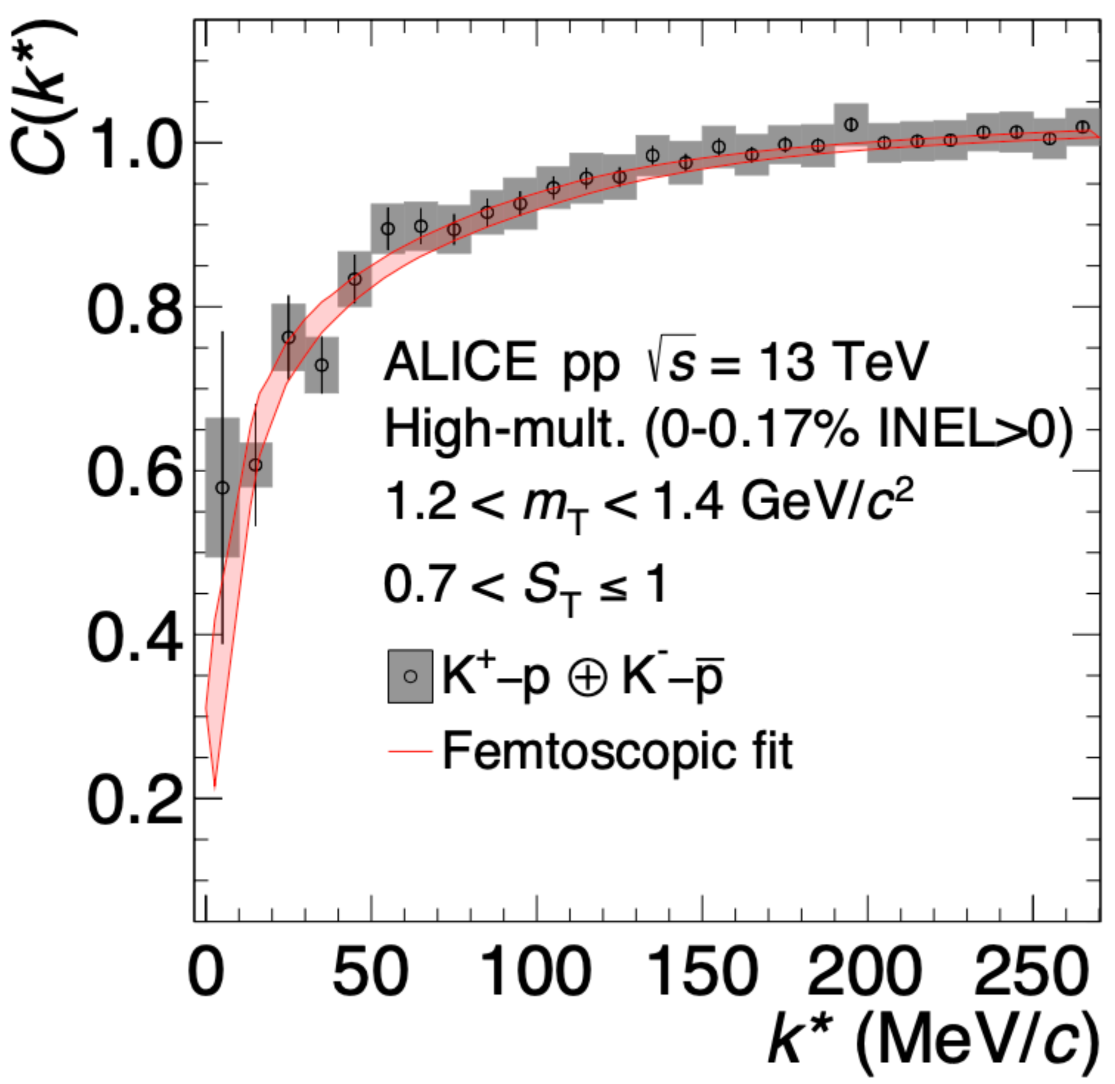
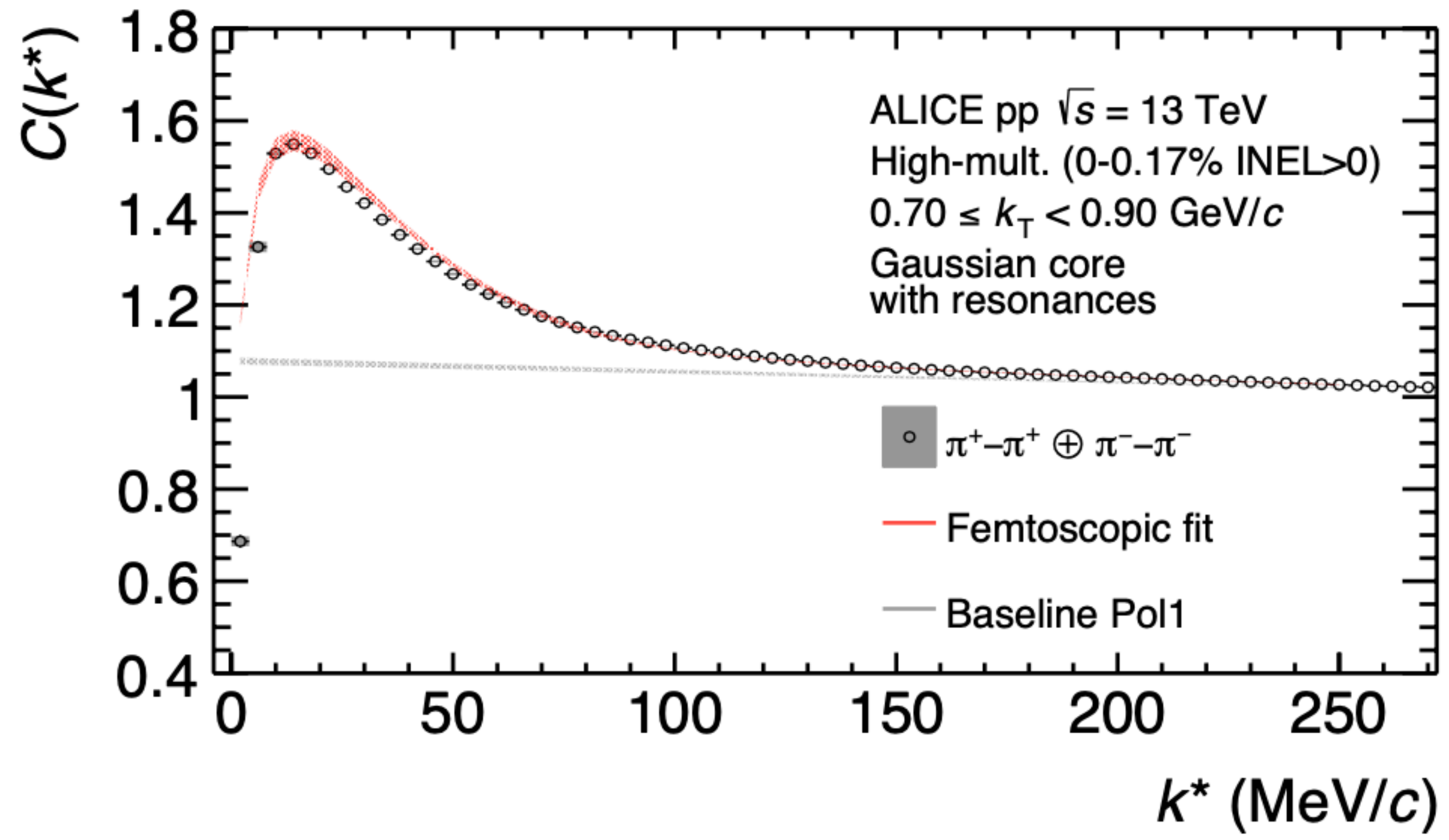
Assumption: A common source for different hadrons

$$m_\mathrm{T} = \sqrt{k_\mathrm{T}^2 + m_\mathrm{avg}^2} \qquad k_\mathrm{T} = \frac{1}{2}\left|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right|$$



Eur.Phys.J.C 85 (2025) 2, 198





✓ As m_T increases, the source size decrease

- **A higher** m_T corresponds to earlier particle generation **-> smaller source radius**
- **As** m_T **decreases**, low-momentum particles are more likely to be produced in a more homogeneous region **-> larger source radius**

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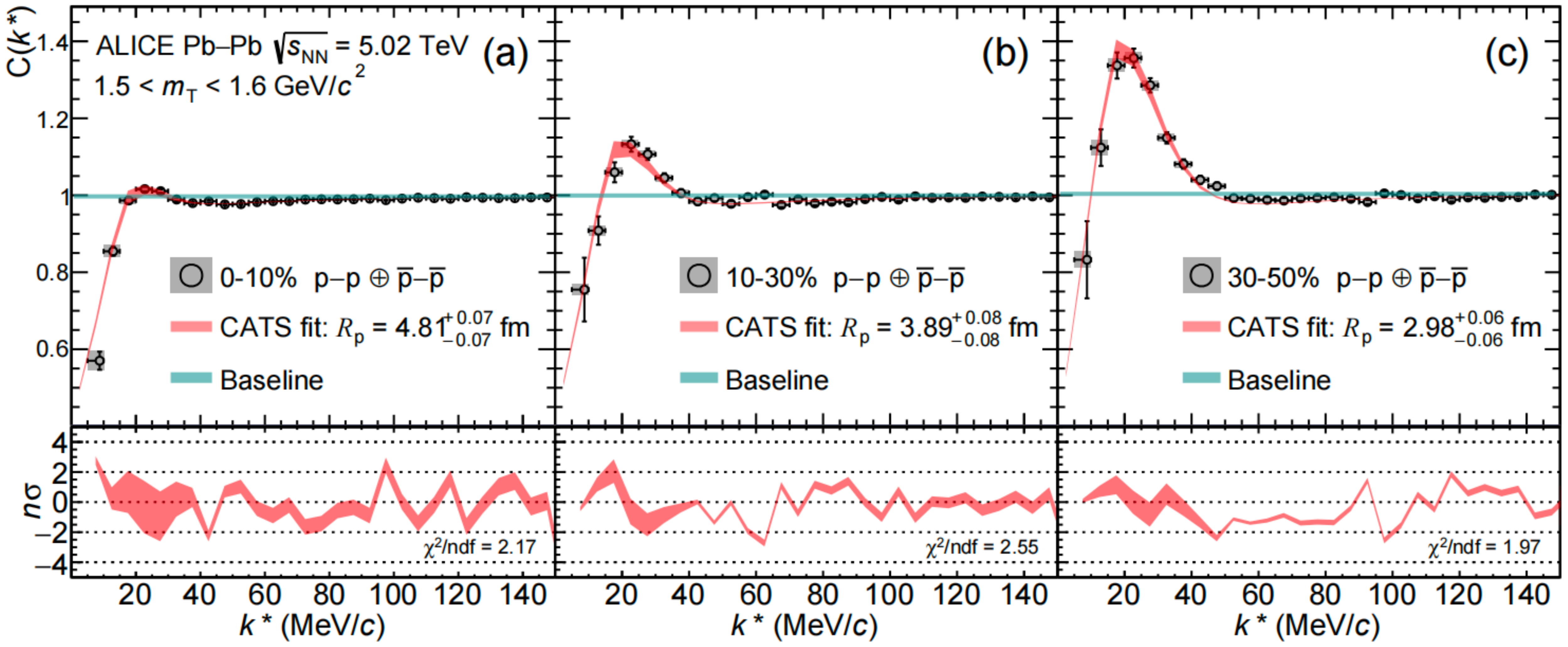
The R_{p} values are obtained from fitting the p-p correlation function across each m_T interval

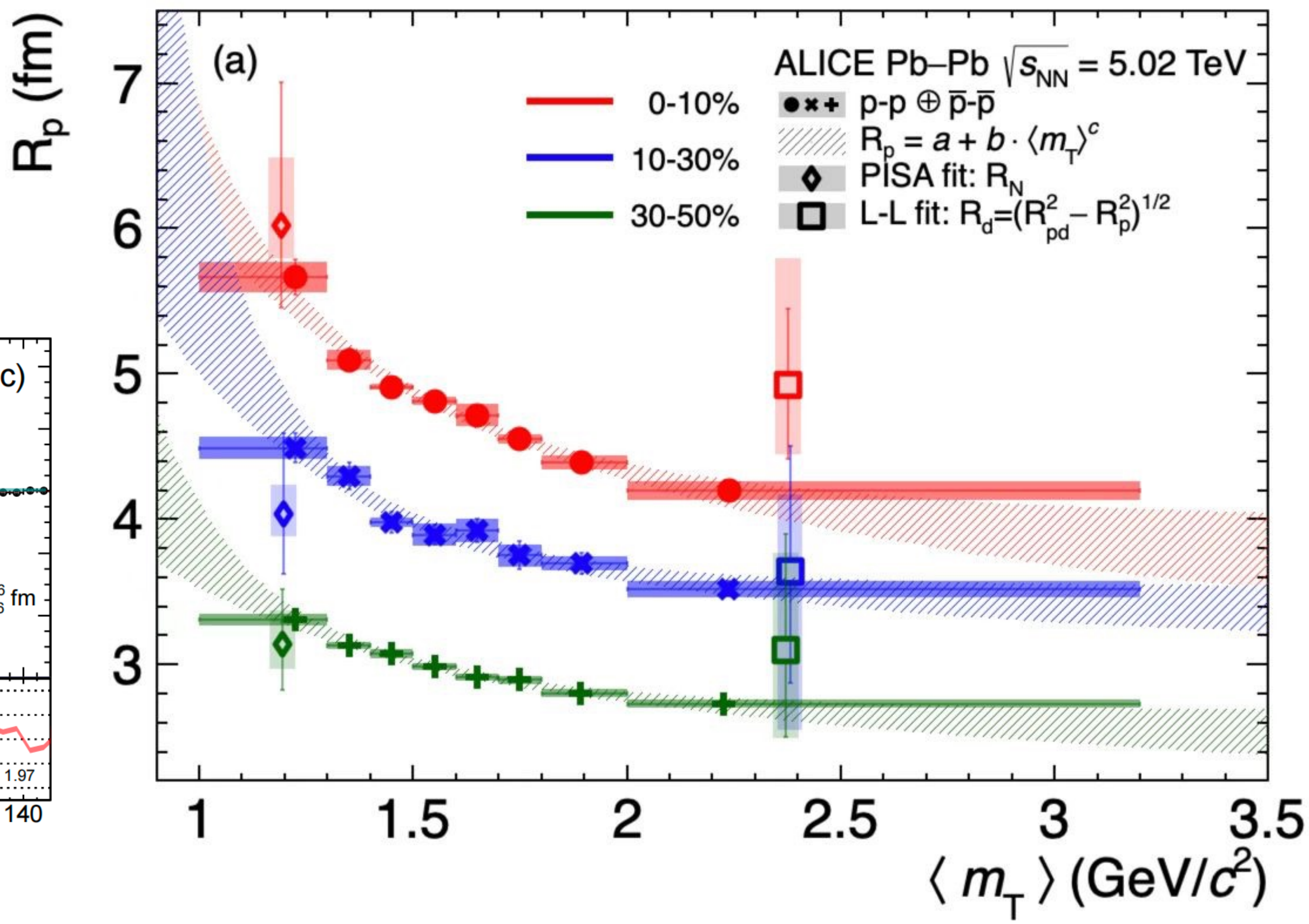
arXiv:2505.01061 [nucl-ex]

m_T power-law function: $R_{\mathrm{p}} = a + b \cdot \langle m_{\mathrm{T}} \rangle^c$

Theoretical $C(k^*)$:

CATS: Coulomb + QS+ Strong interaction



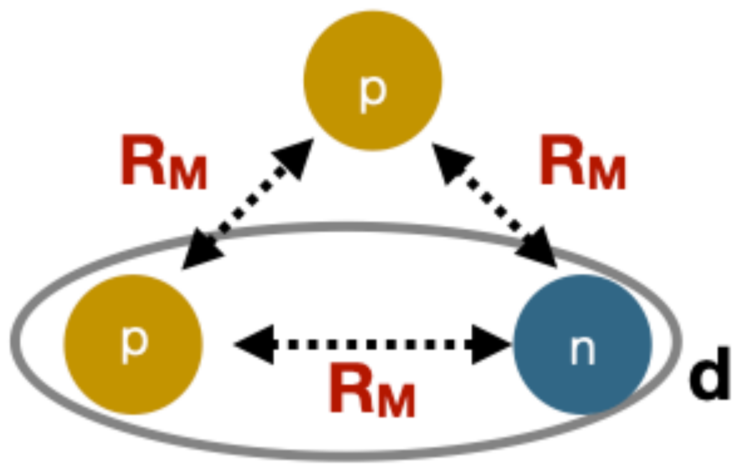


Nucleon source measurements

R_N is extracted by fitting p-d CF with Pisa model

arXiv:2505.01061 [nucl-ex]

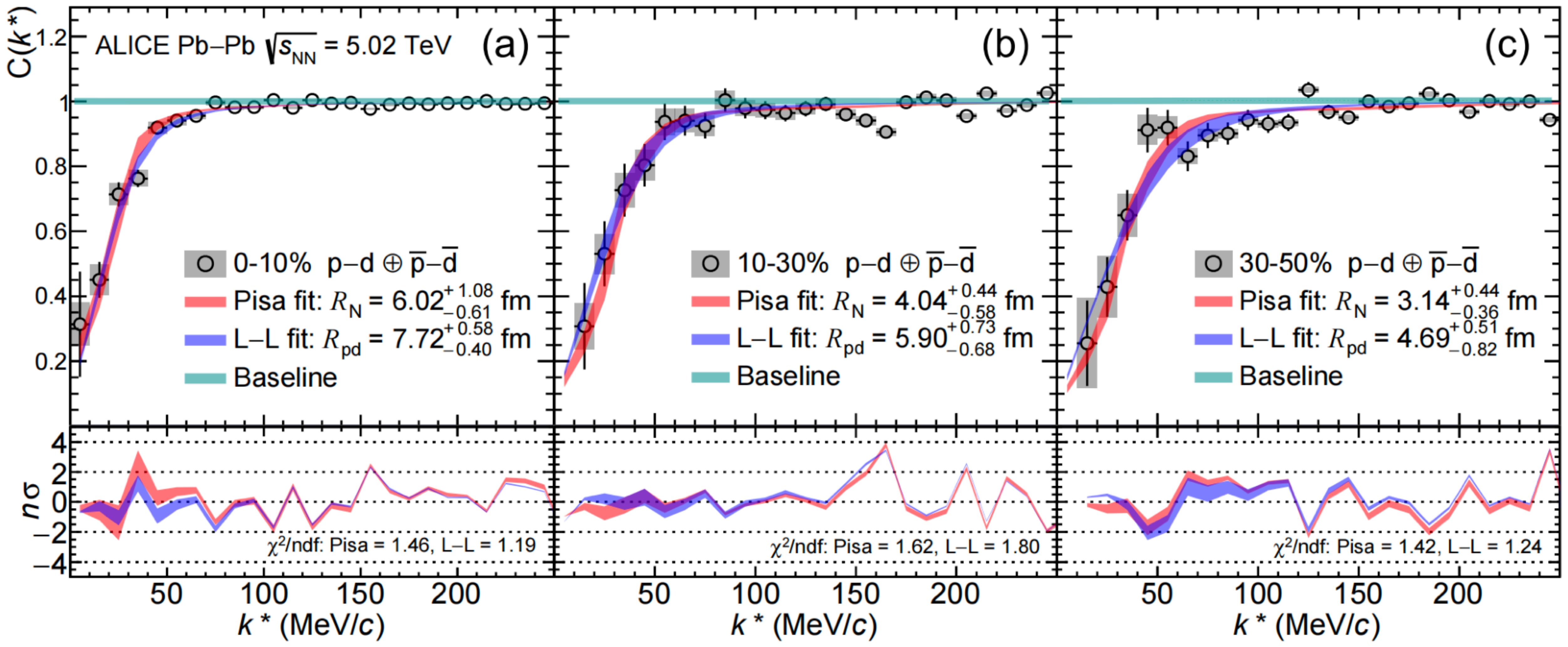
Pisa: M. Viviani, B. Singh et al. Phys. Rev. C 108, 064002 (2023)

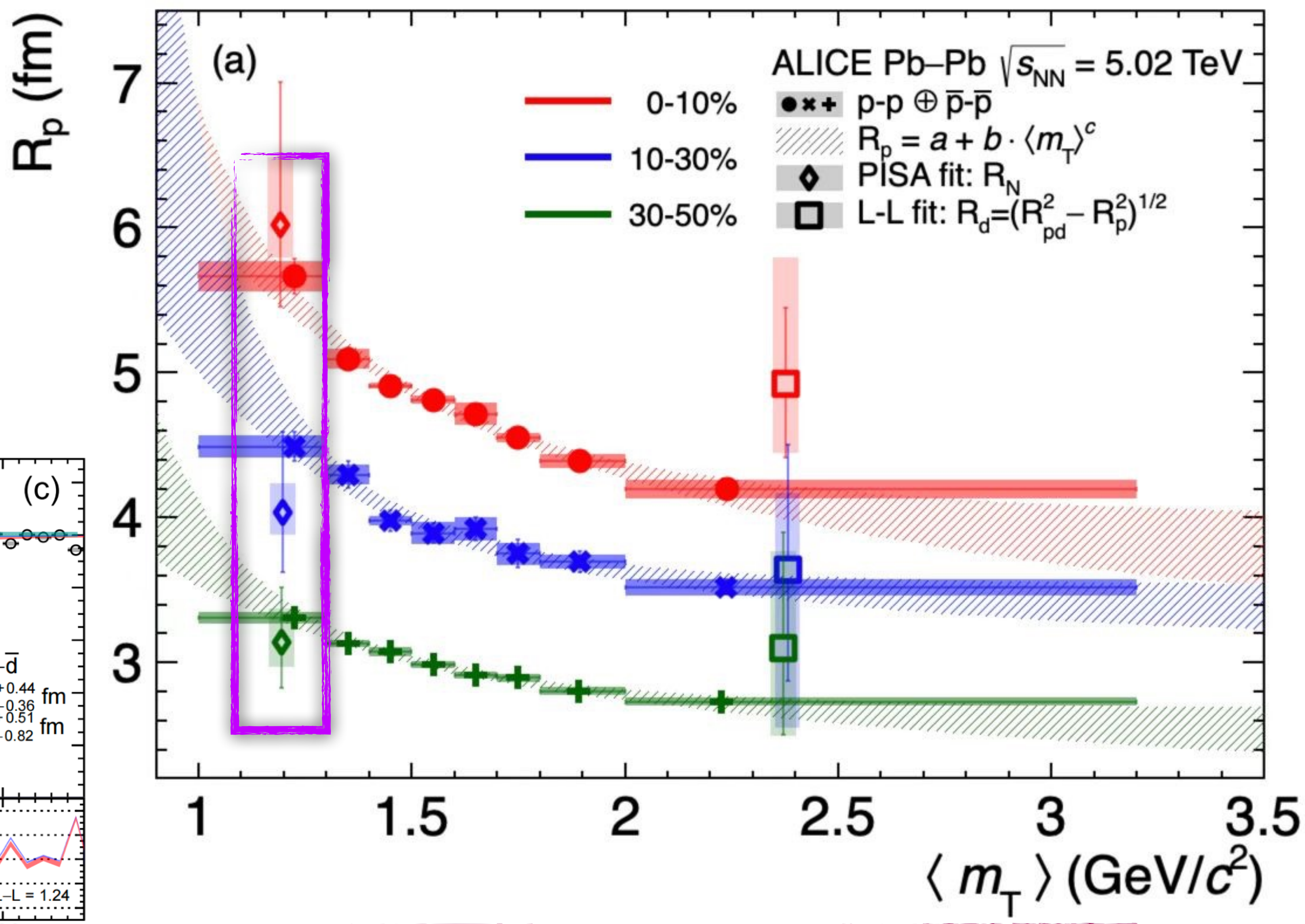


p-d as three body system

The m_T of a nucleon inside the p-d system :

$$m_T = \sqrt{\left(2k_T^{pd}/3\right)^2 + m_p^2}$$





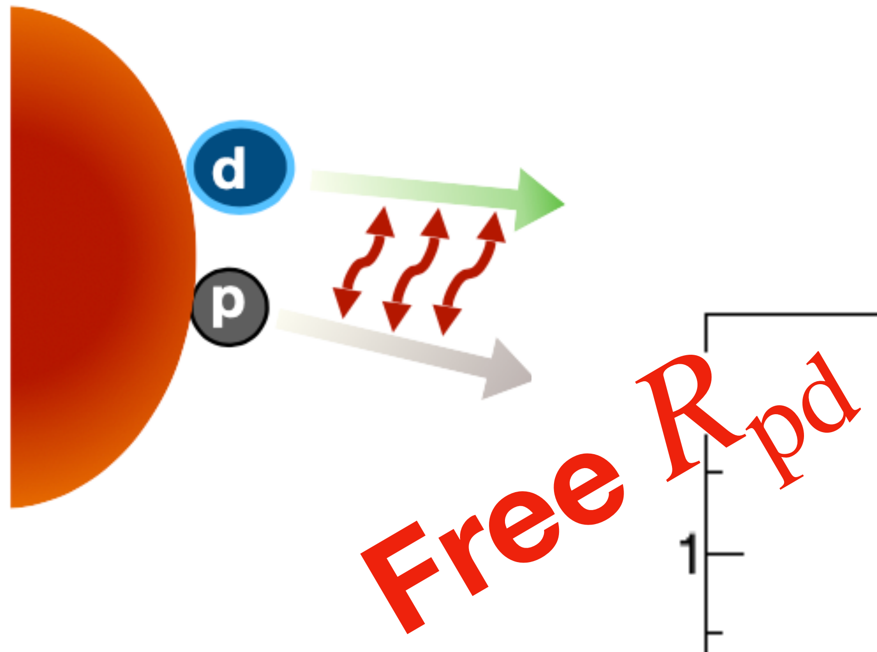
In agreement with the proton m_T -scaling

Proton-deuteron source measurements

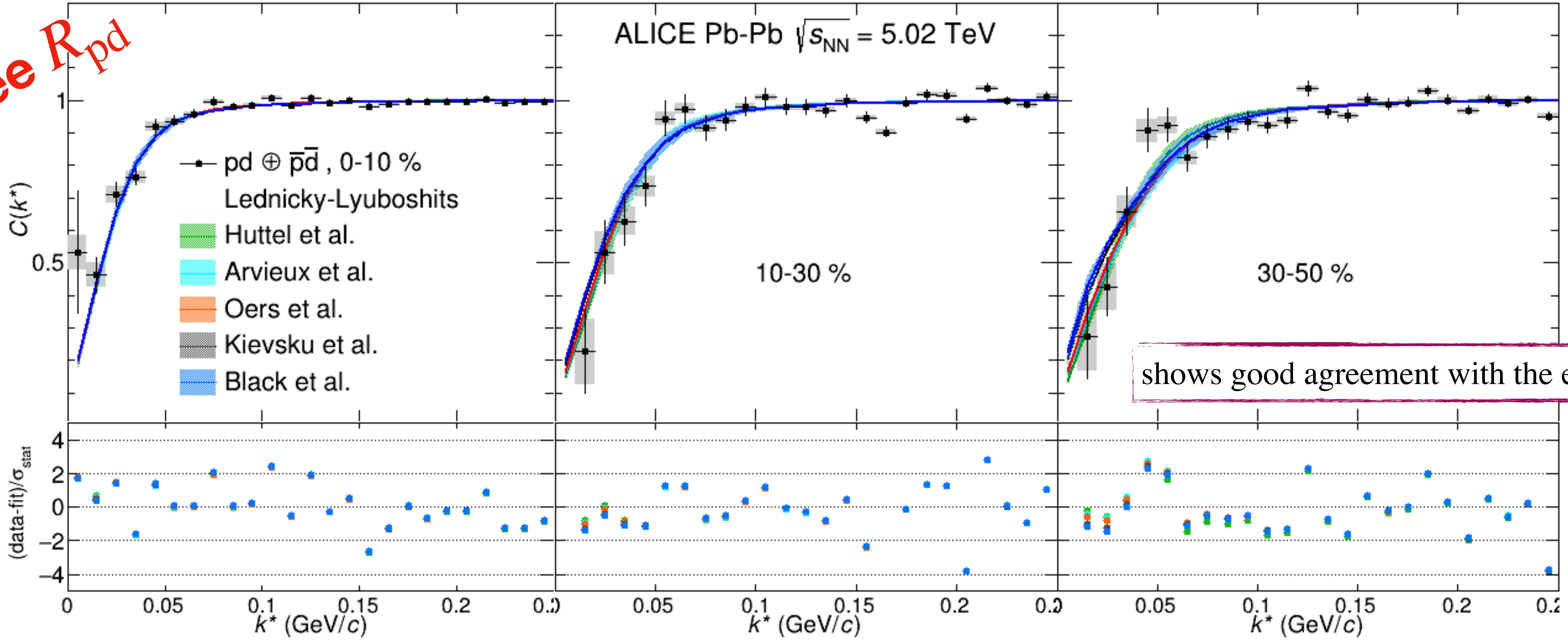
The R_{pd} values are obtained from fitting experimental p-d correlations using the L-L model

arXiv:2505.01061 [nucl-ex]

Two body system L-L model：



$$C(k^*)_{LL} = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f(k^*)^S}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} r_0} \right) + \frac{2\Re f(k^*)^S}{\sqrt{\pi} r_0} F_1(2k^* r_0) - \frac{\Im f(k^*)^S}{r_0} F_2(2k^* r_0) \right]$$



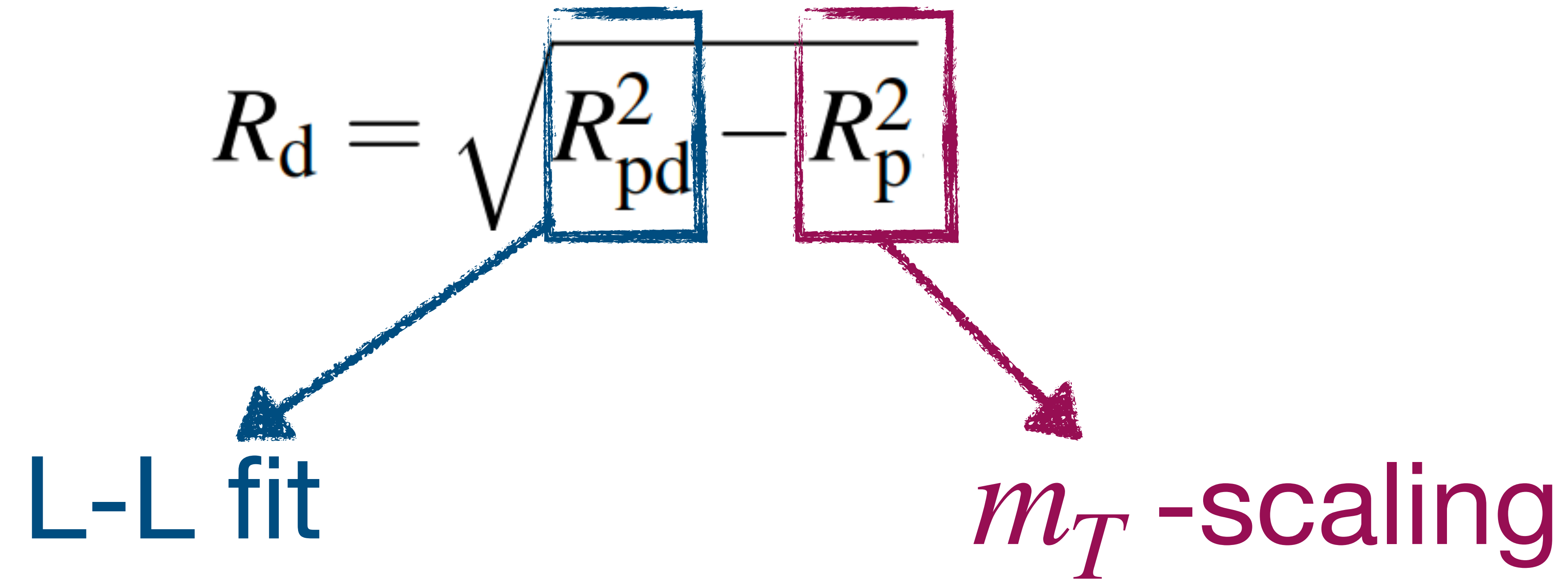
shows good agreement with the experimental data

Deuteron source measurements

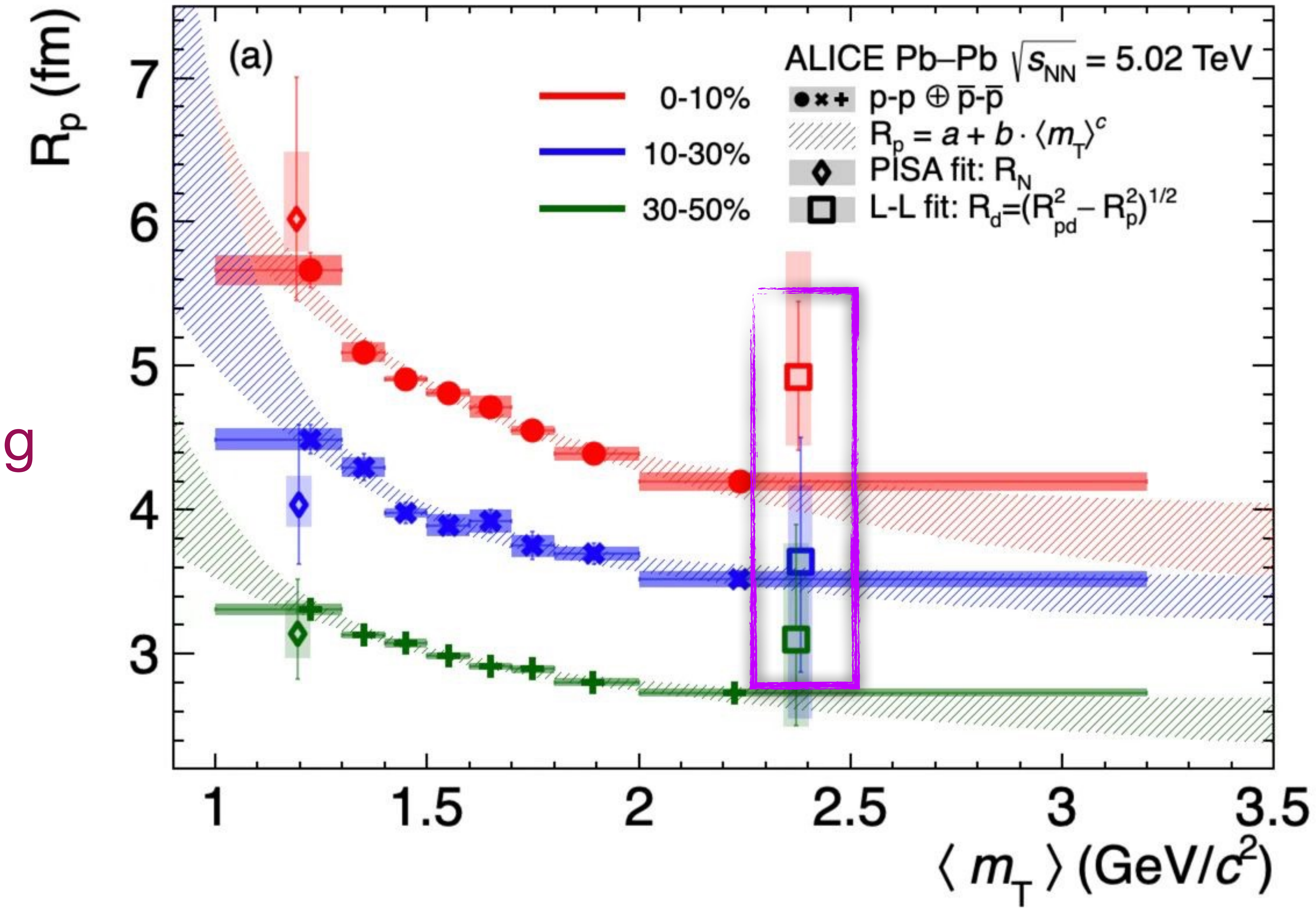
arXiv:2505.01061 [nucl-ex]

- The deuteron source size is extracted using the expression:

$$R_\mathrm{d} = \sqrt{R_\mathrm{pd}^2 - R_\mathrm{p}^2}$$



- Source sizes for deuteron are in agreement with m_T -scaling for p-p pairs
- Deuterons, share a common flow velocity with nucleons in PbPb collisions



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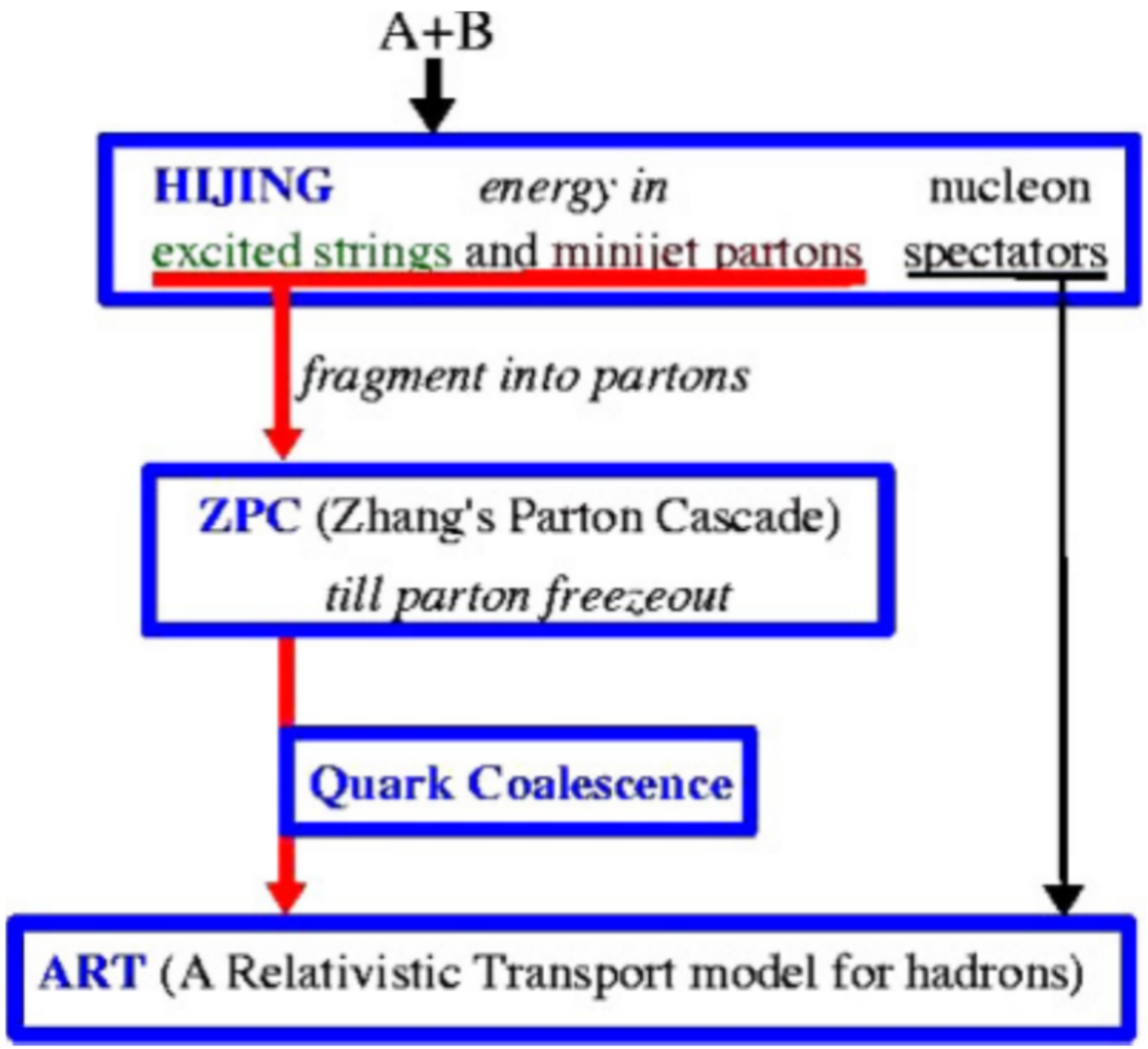
AMPT model

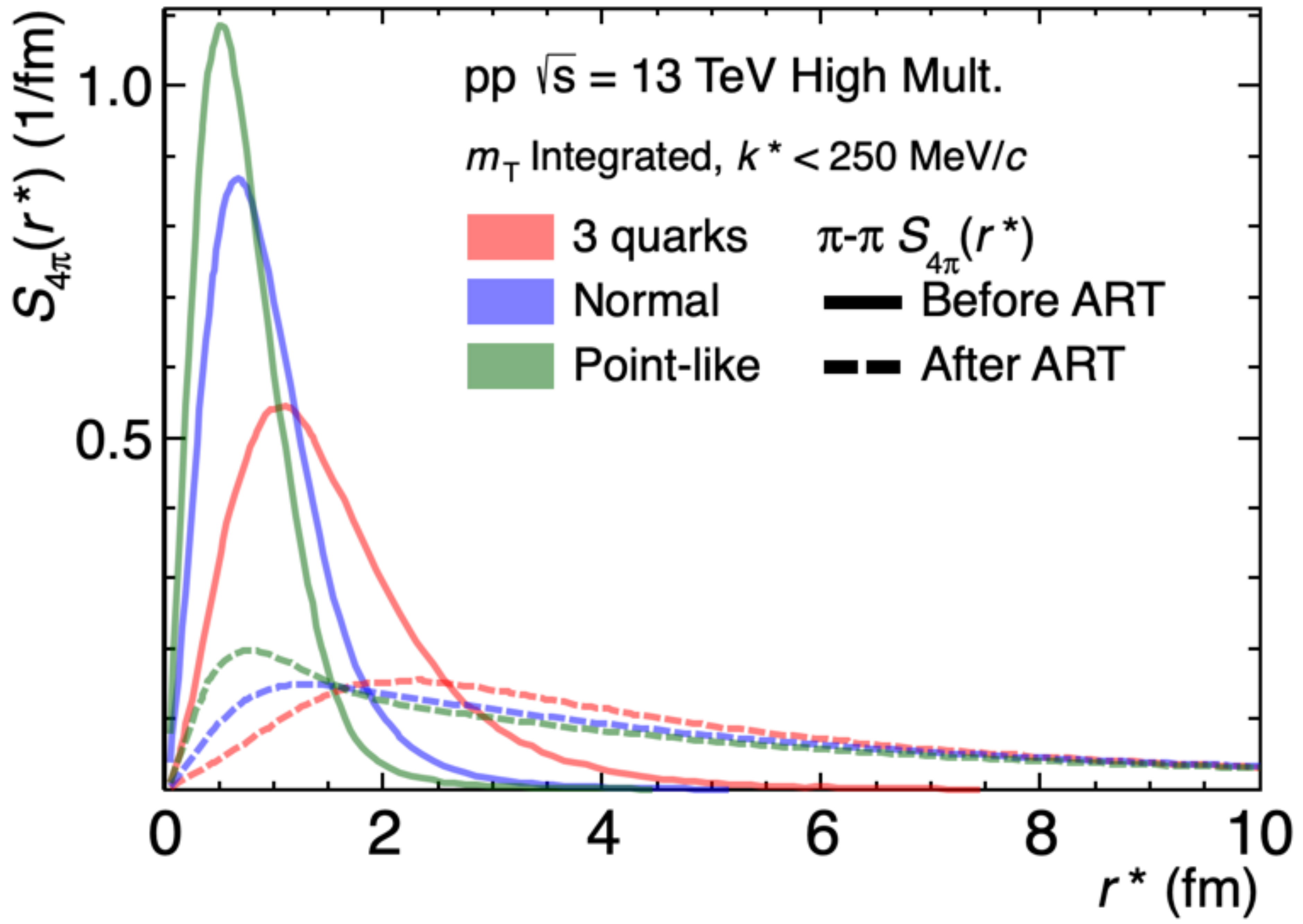
NUCL SCI TECH 36, 154 (2025)

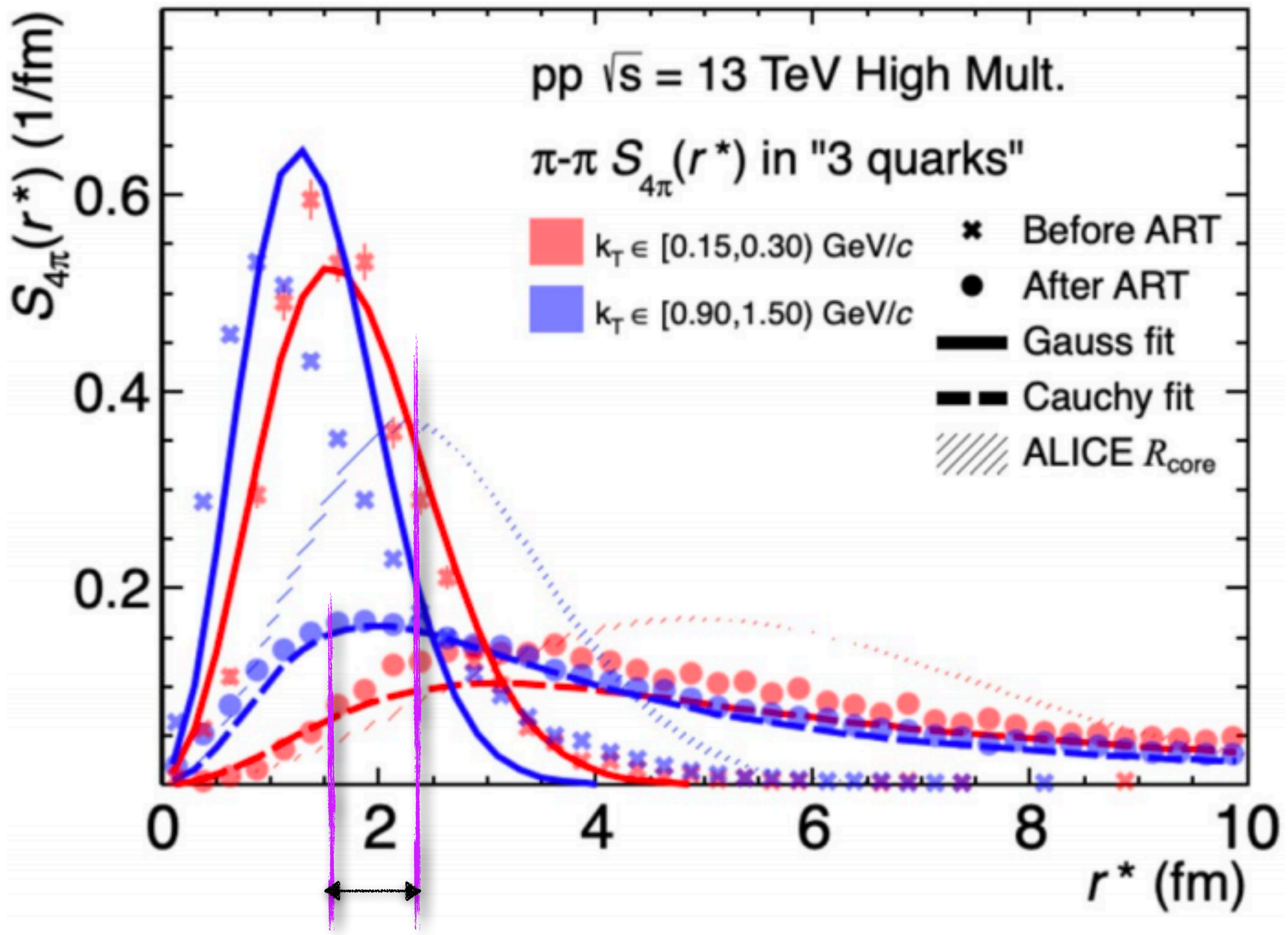


- AMPT（A Multi-Phase Transport Model）
- Been used extensively to study HICs, such as hadron production, collectivity and phase transitions
- First attempt to model the correlation function, emission source, and mT-scaling in AMPT

Effect of initial partonic distribution

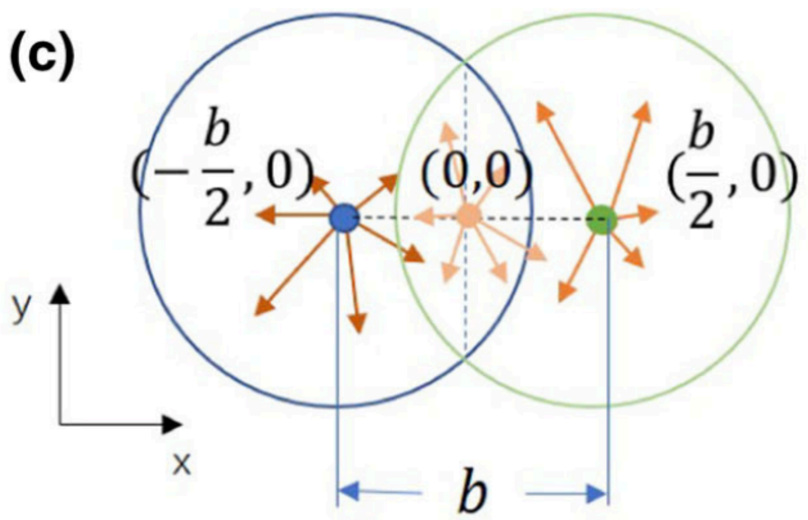
NUCL SCI TECH 36, 154 (2025)





3 quarks mode: a broader source function

Source function within the 3 quarks AMPT model :



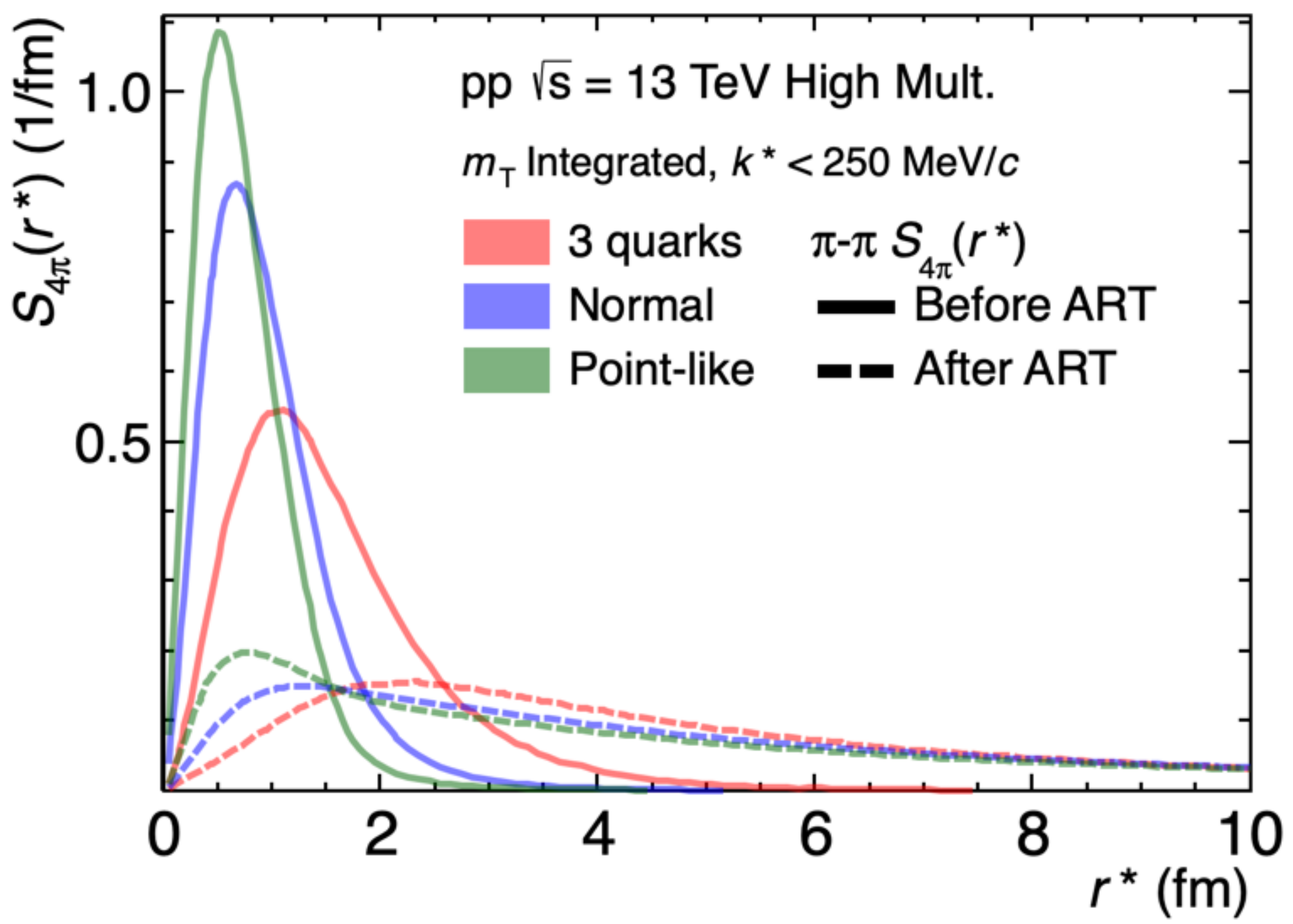
Eur. Phys. J. C (2021) 81:755

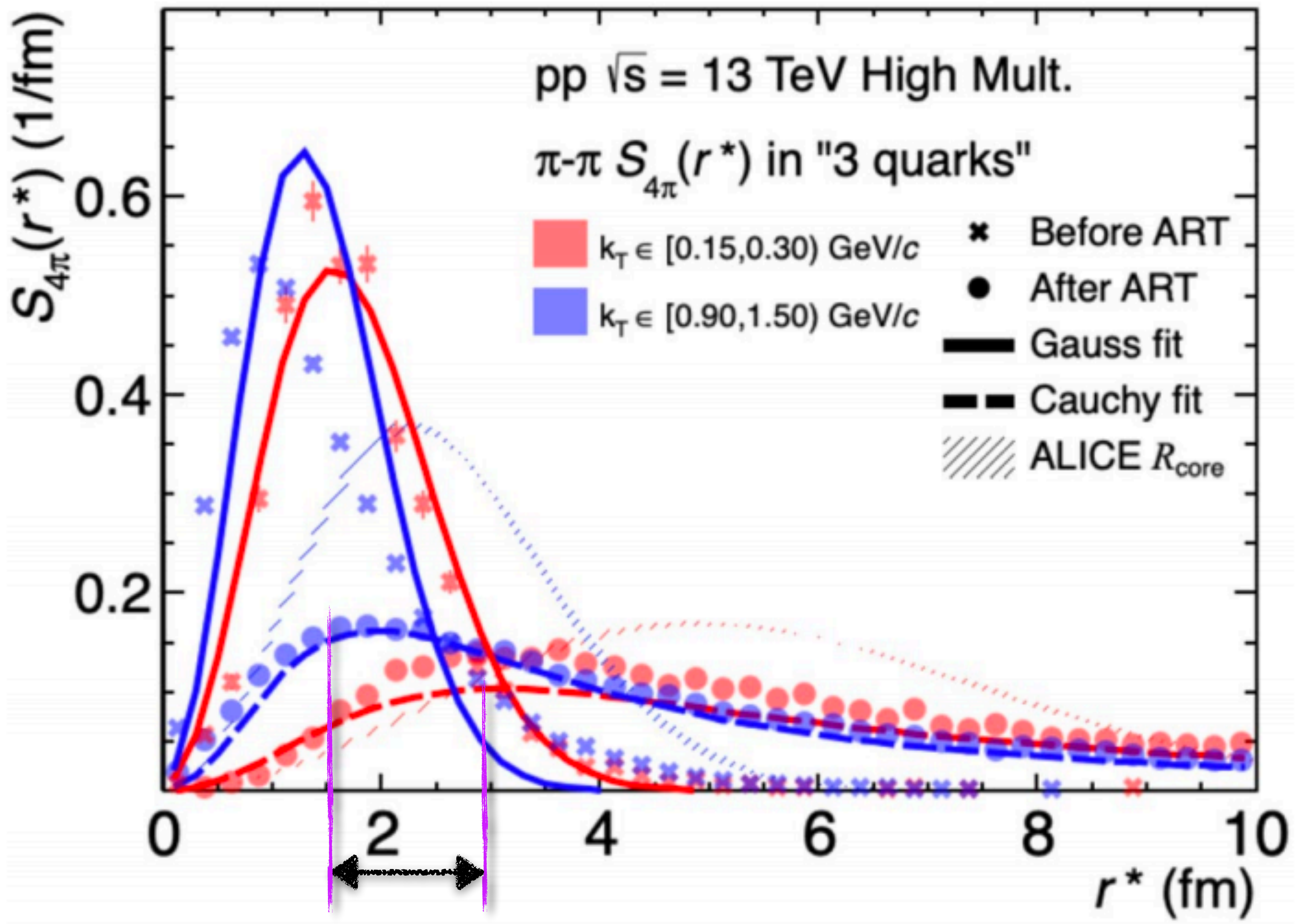
- 3 quarks: overlapping area
- Normal: (-b/2, 0) + (0,0) + (b/2,0)
- Point-like: Only (0,0)

- Source radius in the 3 quarks AMPT after-ART is smaller than the source from experimental data
- The normal and point-like are too small to adequately describe the data

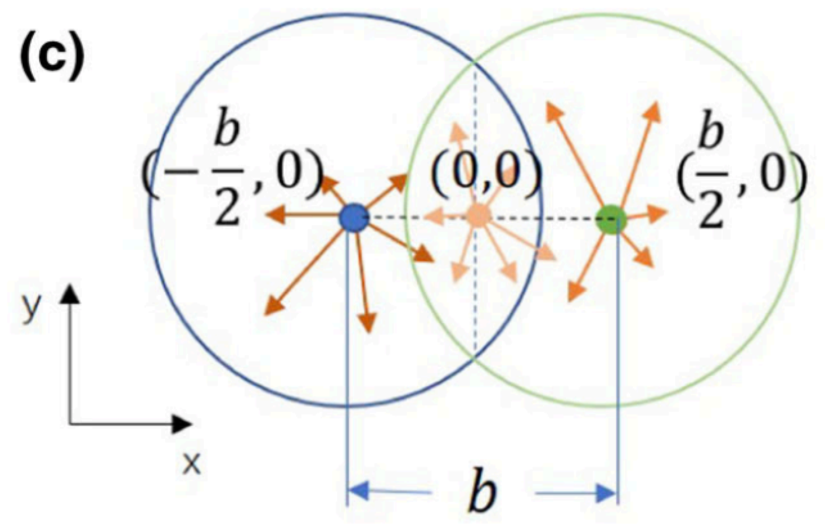
Effect of initial partonic distribution

NUCL SCI TECH 36, 154 (2025)





3 quarks mode: a broader source function



Eur. Phys. J. C (2021) 81:755

- 3 quarks: overlapping area
- Normal: (-b/2, 0) + (0,0) + (b/2,0)
- Point-like: Only (0,0)

Source function within the 3 quarks AMPT model :

- Source radius in the 3 quarks AMPT after-ART is smaller than the source from experimental data
- The normal and point-like are too small to adequately describe the data
- 2 k_T intervals : $S(r^*)$ decreases as k_T increases

Impact of resonance and hadronic scattering on the source

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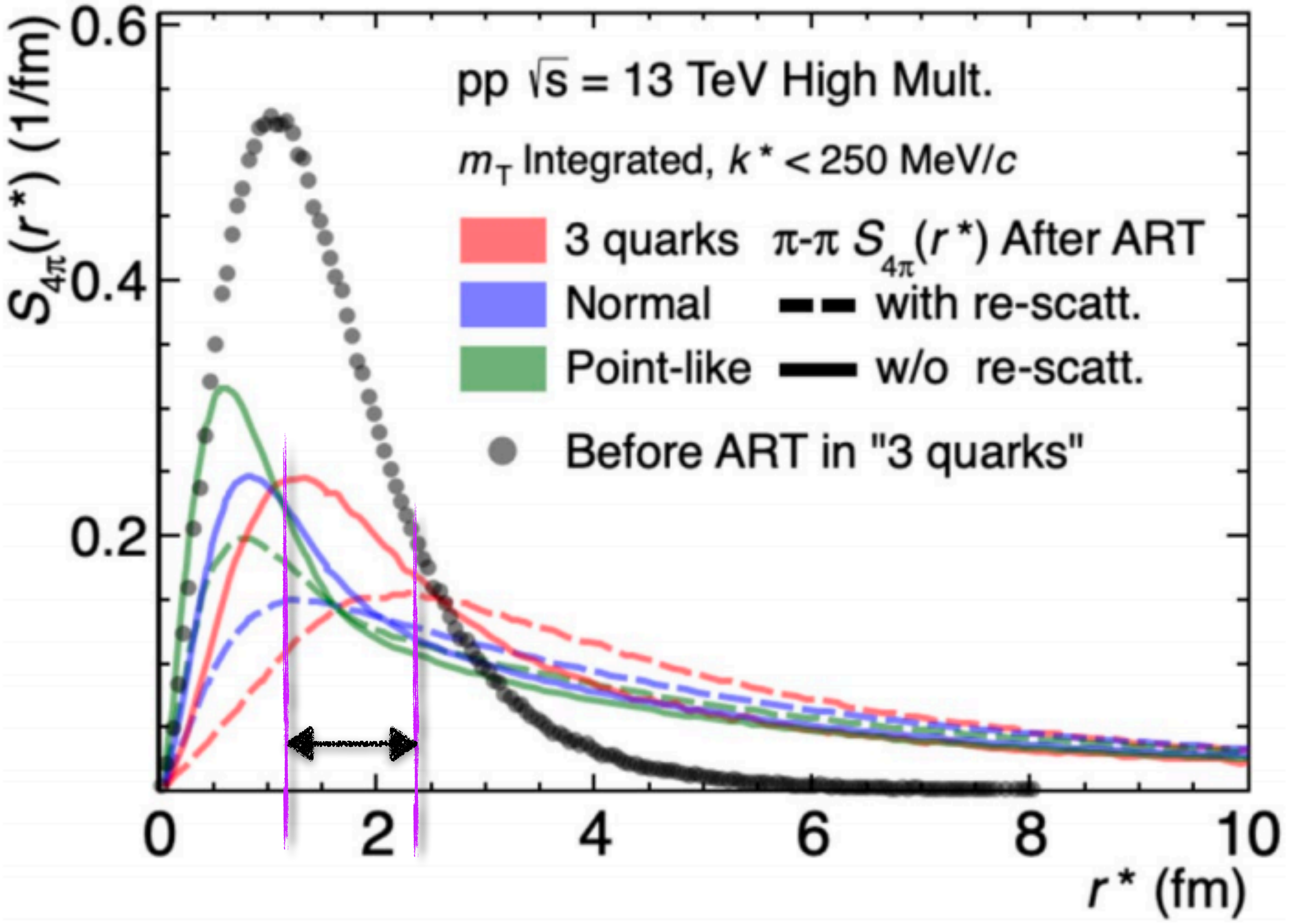
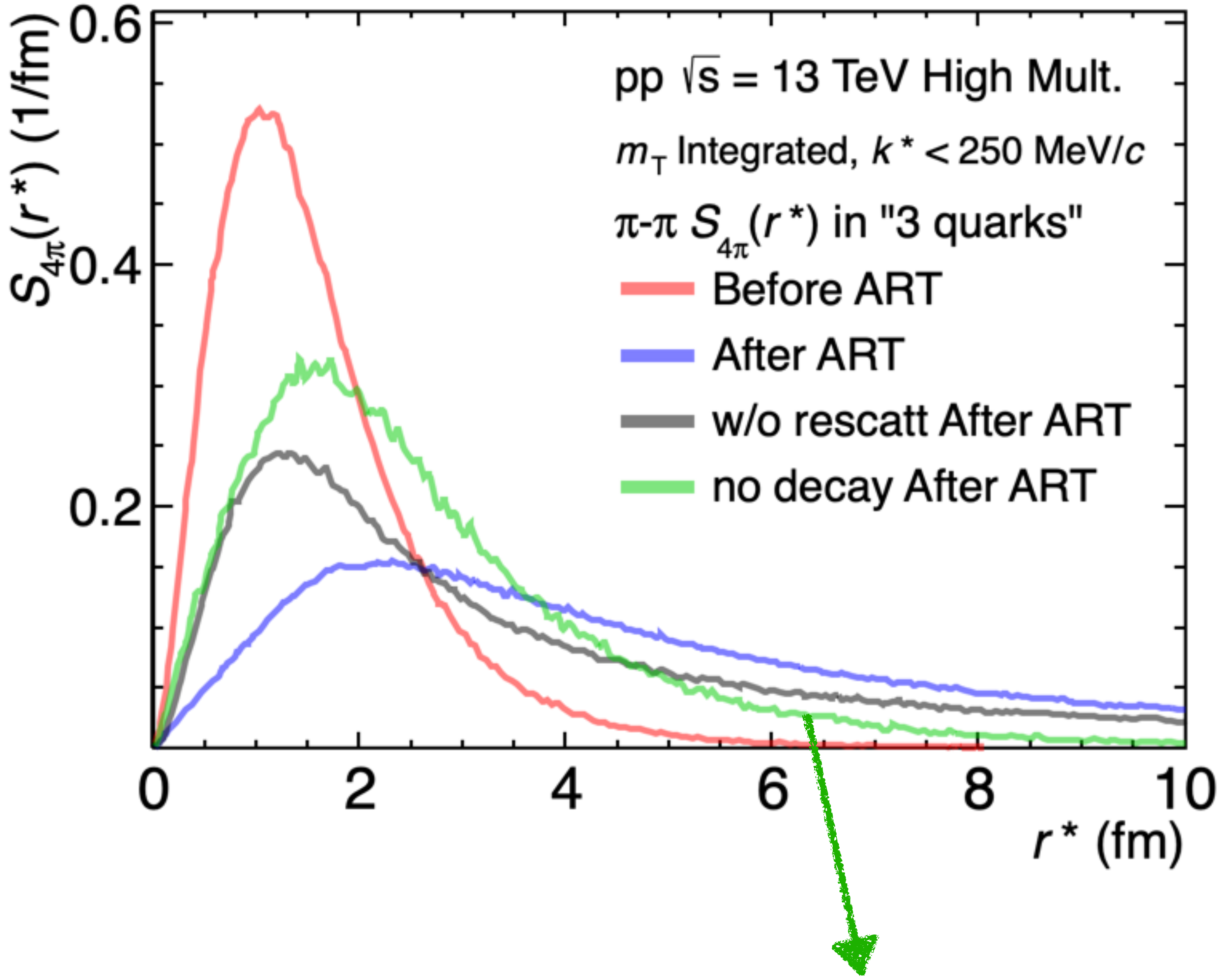
Source = Gauss Core + "resonance halo"

The hadronic interaction in ART : **strongly resonances** and **hadronic rescattering**





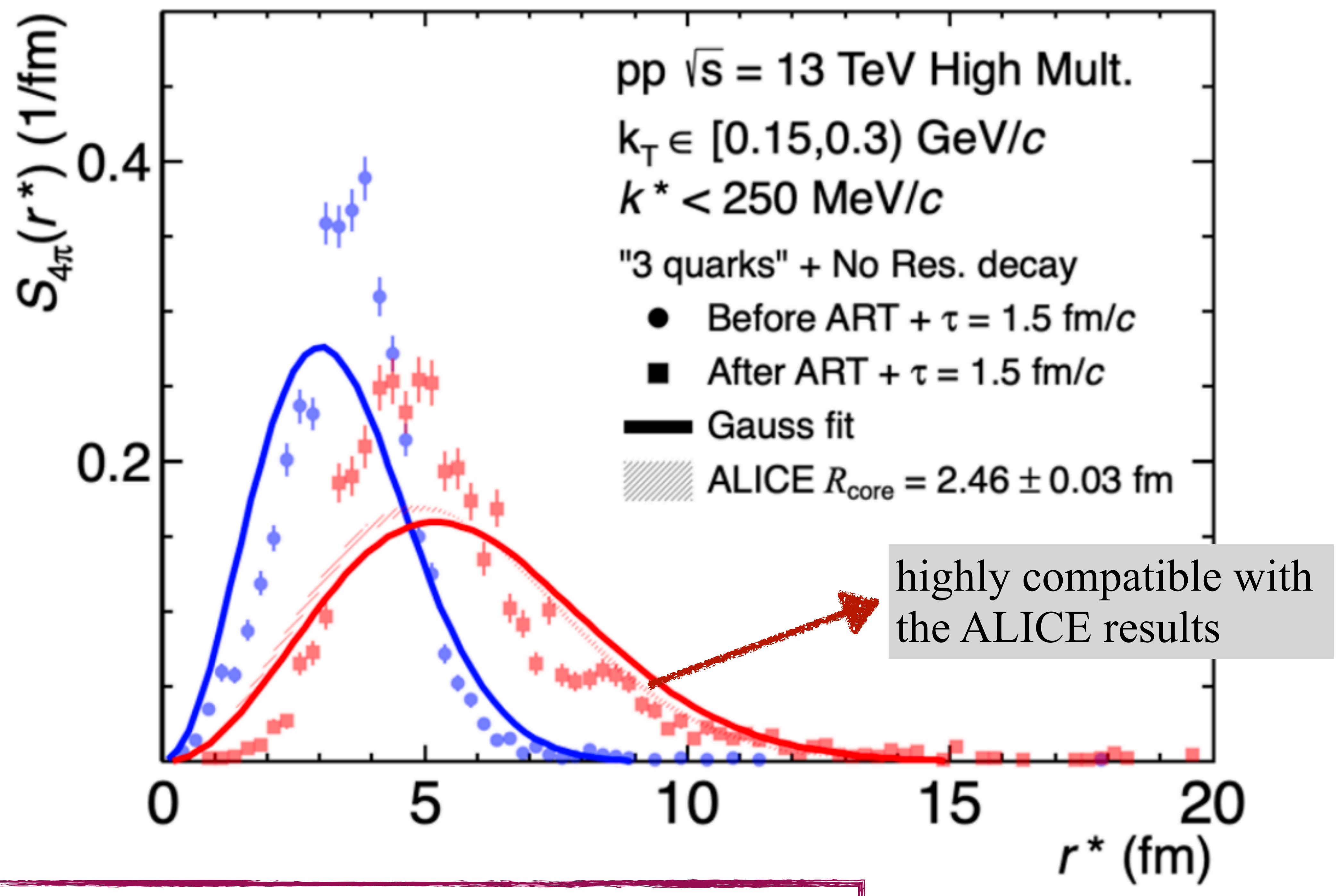
Compared rescattering off/on:

- Scattering cause the system to expand outward
- The long tail persists even when rescattering is off -> contribution from resonance decay

When no resonances (green), the tail of the relative source function is **signifcantly shorter**

Final source function and m_T -scaling

Source = Gauss Core + “resonance halo”



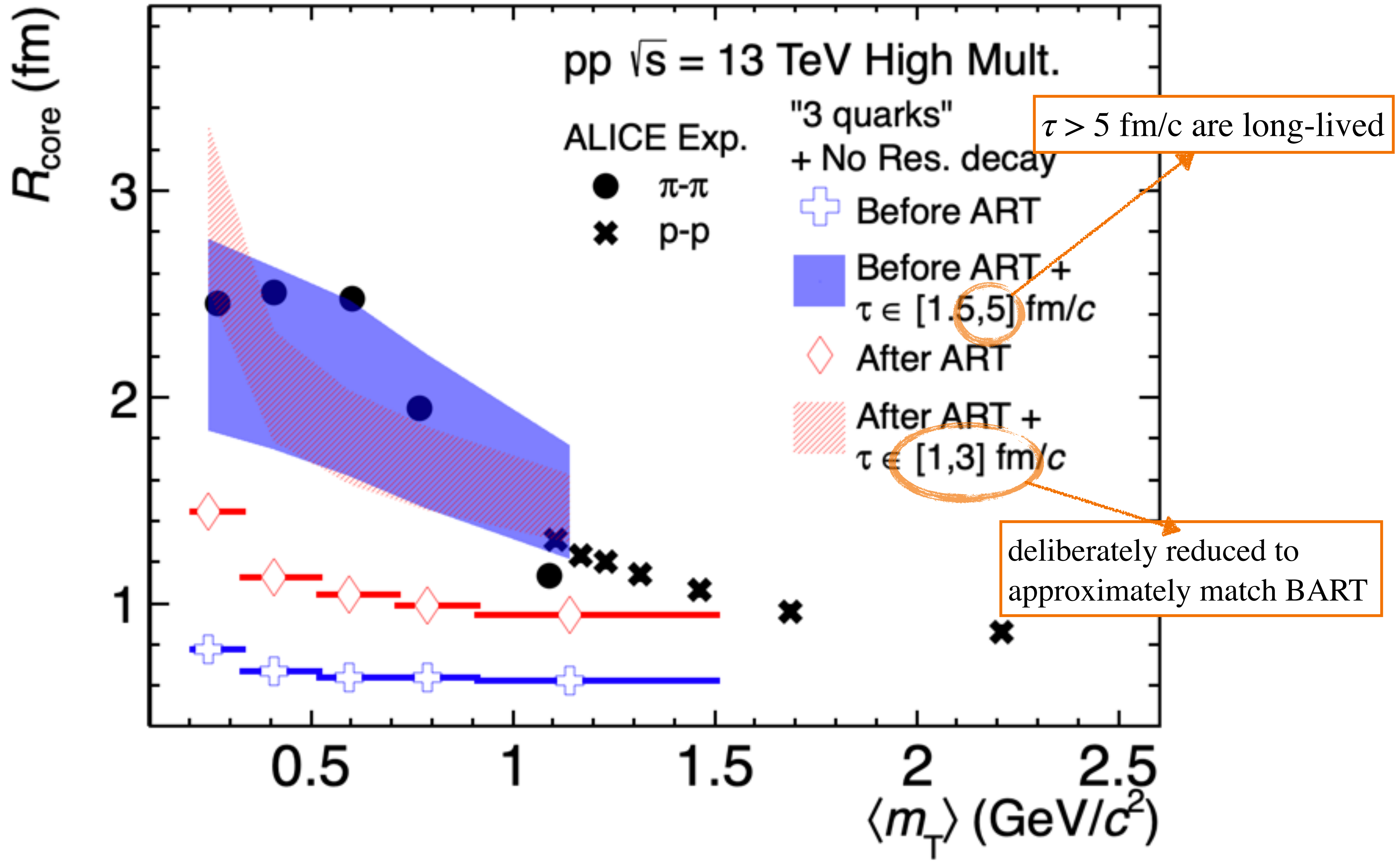
To understand core source

Emission time parameter τ :

- Hadrons are forced to travel along their original momentum directions for τ fm/c **without any hadronic interactions**
- An increase in the core source

m_T -scaling behavior of R_{core} in AMPT :

- Source radii decrease as m_T increases
- In good agreement with the data in the low m_T ranges



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Summary

1.p&d emission source in Pb-Pb@5.02TeV ALICE run 2

- Source size R_{p} ,R_{N}, R_{pd} and R_{d} are measured
- The source values obtained from the two- and three-body fits follow the m_T -scaling of the proton source radii
- Deuterons, as composite light nuclei, share a common flow velocity with nucleons in PbPb collisions

2.The pion emission source in p-p@13.6TeV AMPT model

- Clear m_T -scaling behavior was observed
- with an appropriate τ, AMPT can reproduce the ALICE measurements well
- AMPT provides a good environment to reveal the mechanisms behind the system size and m_T -scaling

Thank you !!

Back up

Correlation function in different k_T intervals

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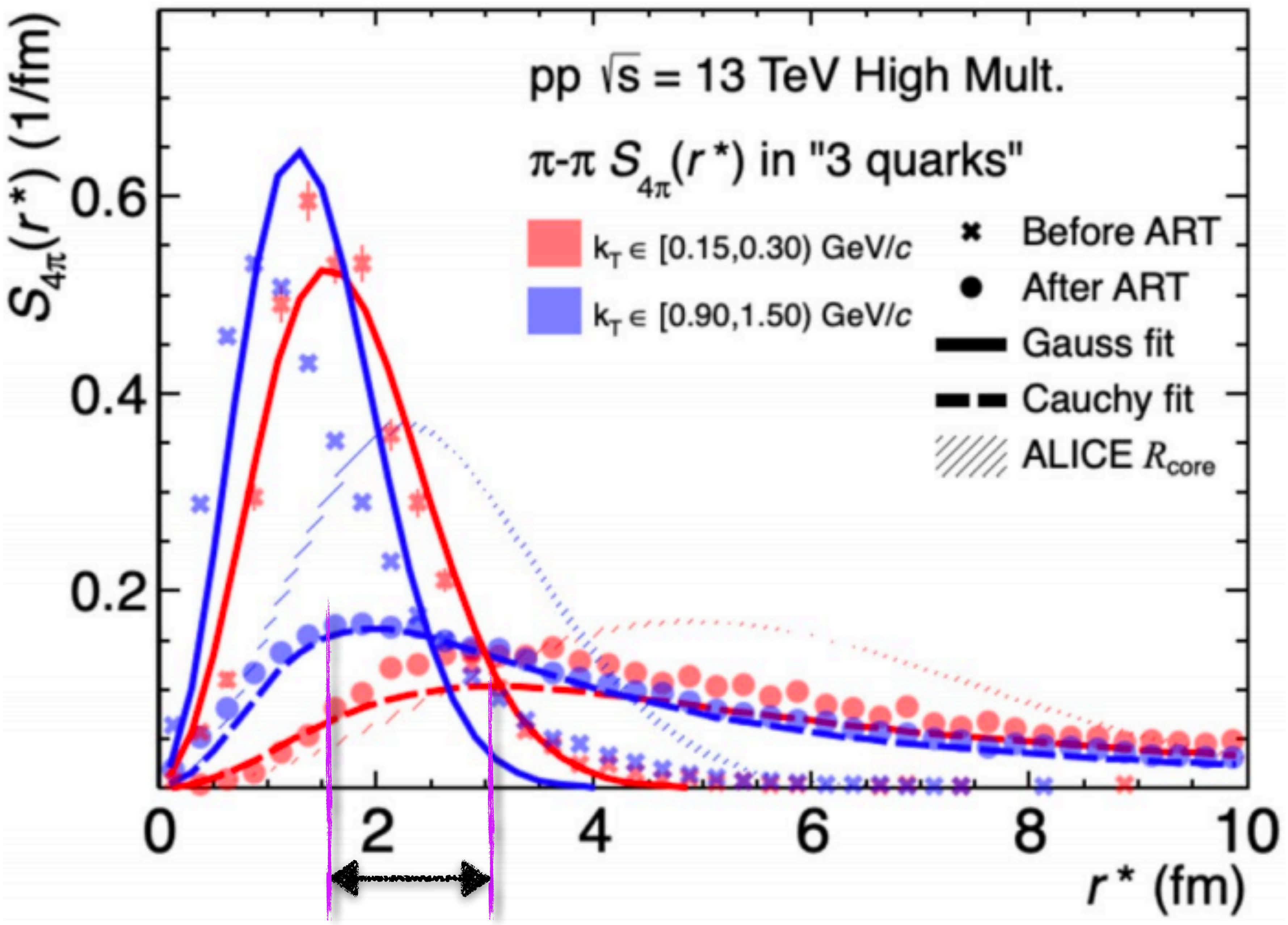
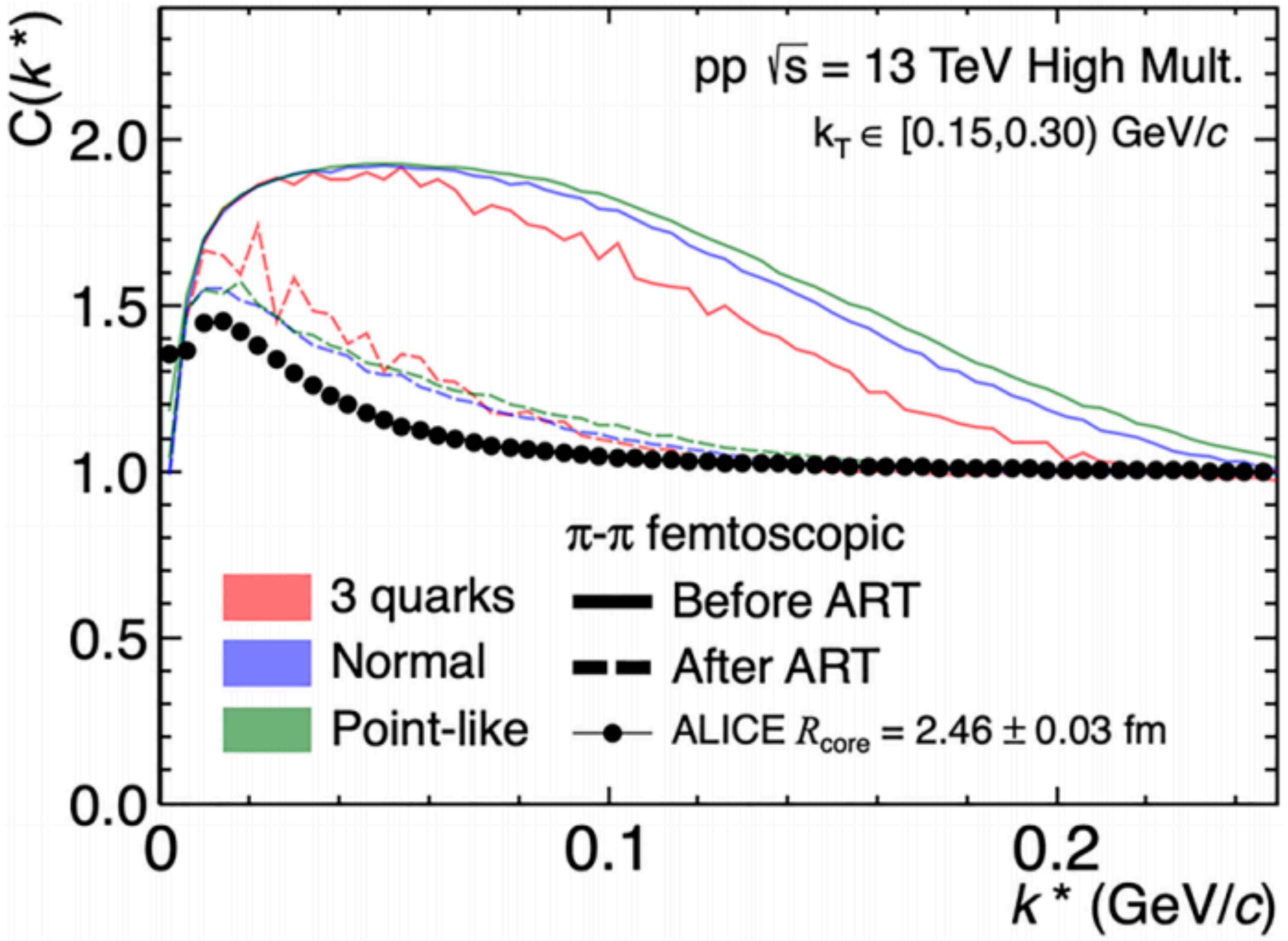
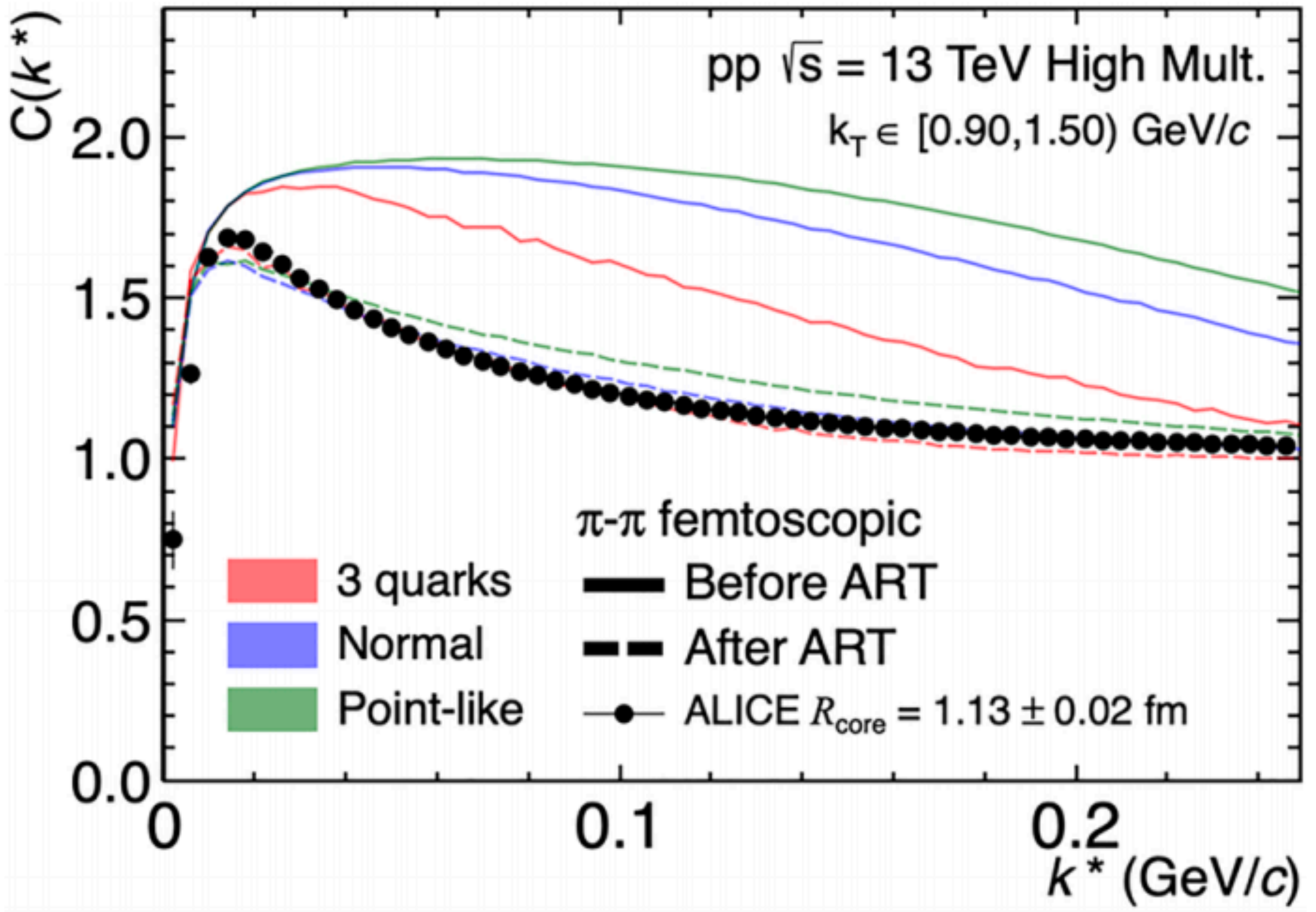


Source function within the 3 quarks AMPT model :

- 2 k_T intervals : $S(r^*)$ decreases as k_T increases



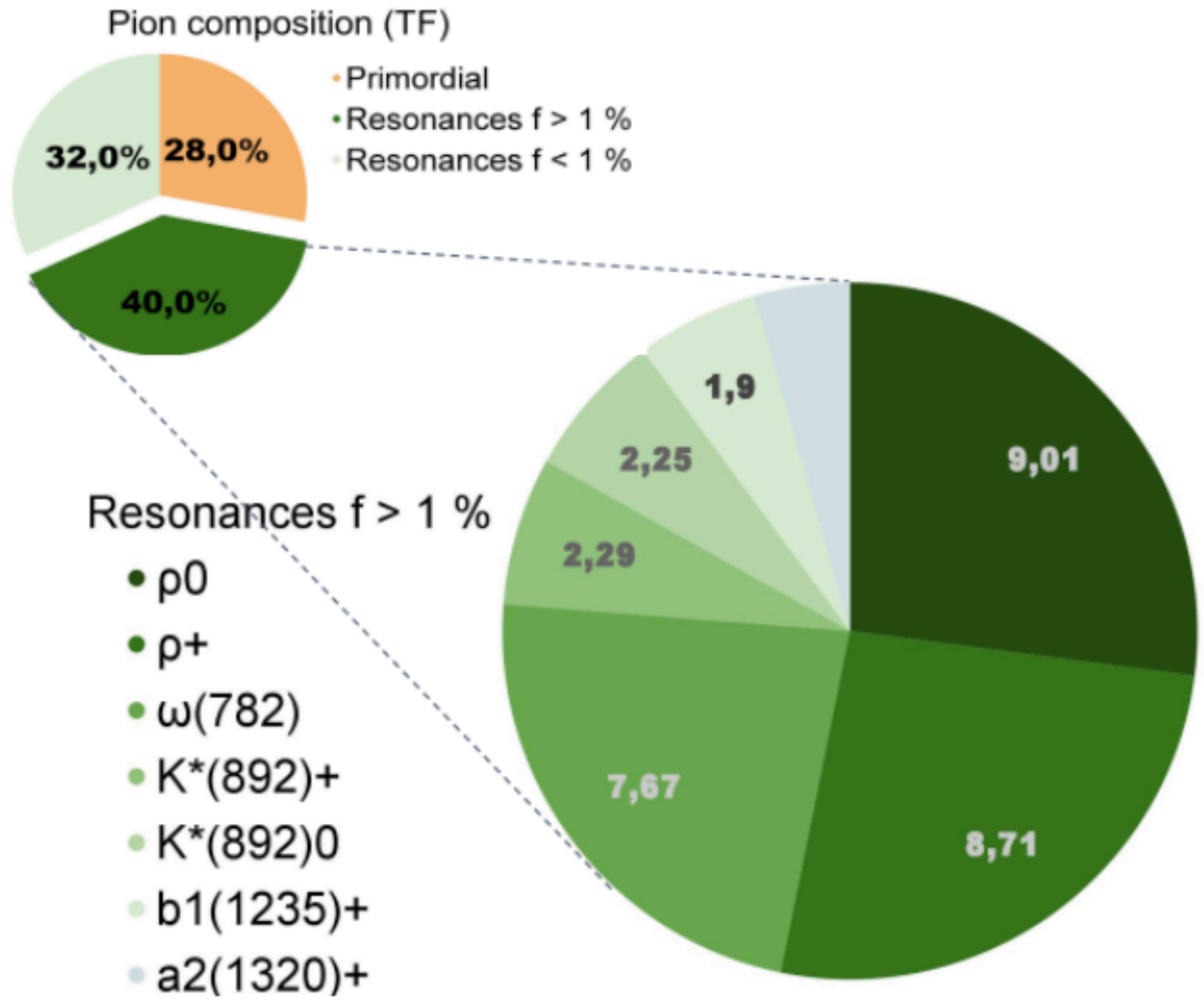


$\pi - \pi$ correlation function using CATS (ψ) + AMPT ($S(r^*)$)

- Approximate the experimental data to a certain extent
- C(k*) is less sensitive to the initial partonic distribution

$$C(k^*) = \int S(\boldsymbol{r}^*)|\psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2 d^3 r^*$$

$$k_T = \frac{1}{2}\left|\vec{p}_{T,1} + \vec{p}_{T,2}\right|$$

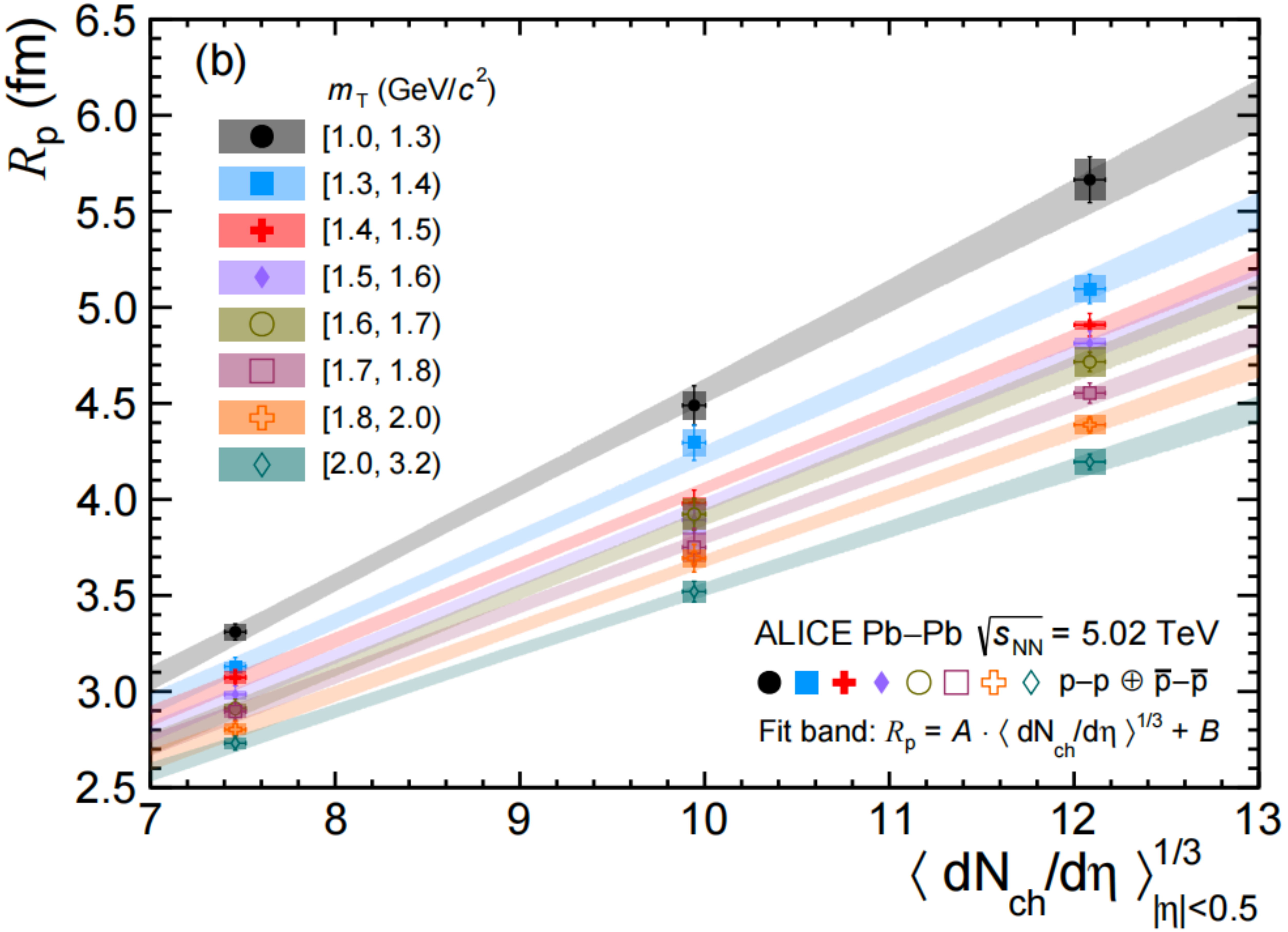


	SHM Fraction(%)	"3 quarks" Fraction(%)
primordial	28.0	46.3
strong resonances	72.0	53.7
Resonances		
$\rho(770)^0$	9.0	6.8
$\rho(770)^+$	8.7	13.9
$\omega(782)$	7.7	6.2
$K^*(892)^+$	2.3	4.3
$\bar{K}^*(892)^0$	2.6	4.2
$b_1(1235)^0$	1.9	-
$a_2(1320)^+$	1.5	-
η	1.5	19.9
$a_1(1260)^+$	1.4	-
$f_2(1270)$	1.4	-
$a_0(980)^+$	1.4	-
$h_1(1170)$	1.2	-

- Calculation carried out with Thermal-FIST [1,2]
  - Use statistical hadronization model [3]
  - **28 %** primordial, **72 %** resonances
- Summary parameters for RSM
  - m_{eff} = 1124 MeV
  - $c\tau_{eff}$ = 1.5 fm

- AMPT 中相关参数如下(不计入 $\omega(782)$ & η):
  $m_{\rm eff} = 0.77$ GeV$/c$; $c\tau_{\rm eff} = 1.33$ fm

[1] V. Vovchenko et al. PRC 100834 (2019)
[2] V. Vovchenko et al. CPC 100 (2019)
[3] F. Becattini Z. Phys. C 76 (1997)

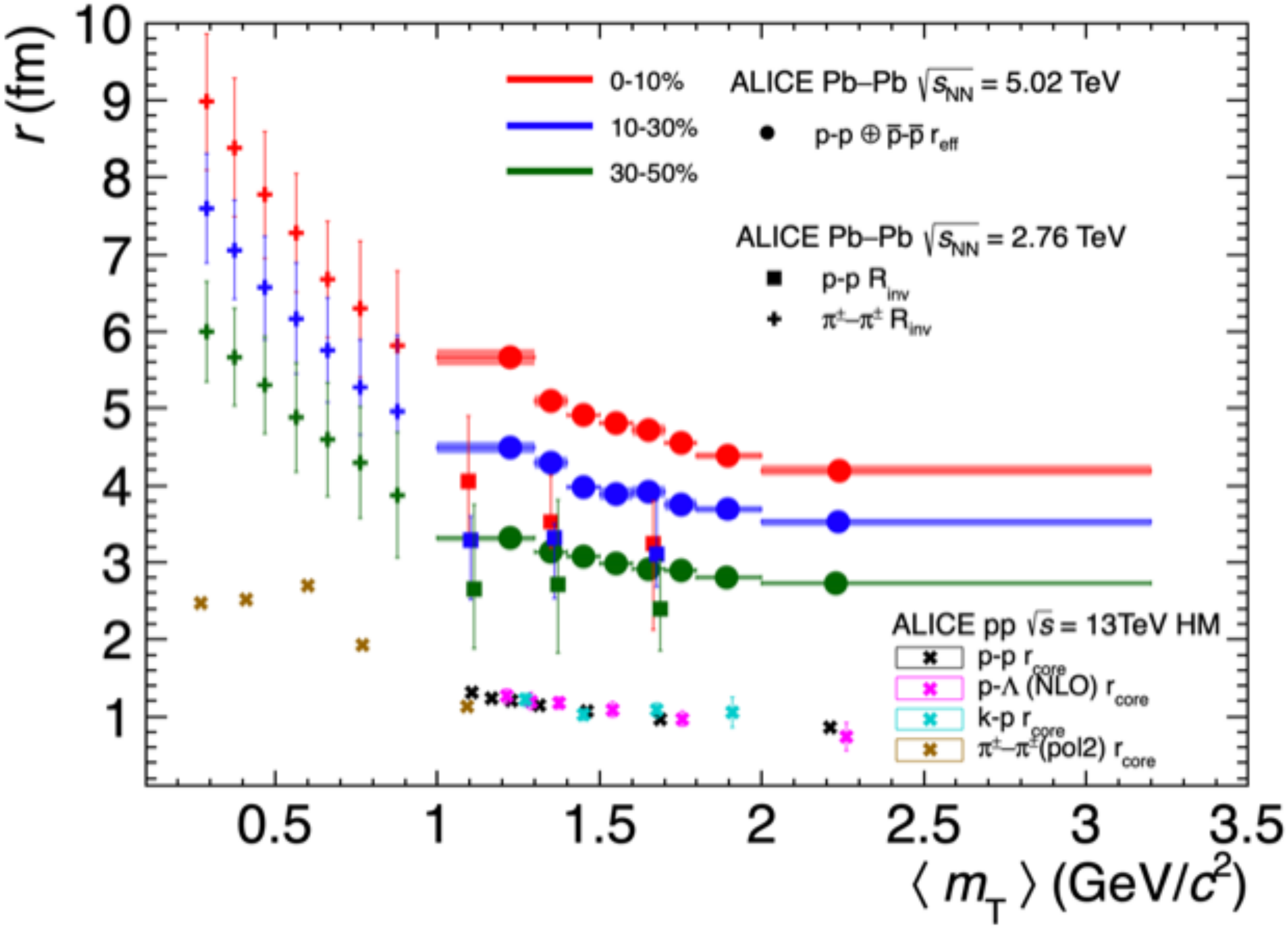


Gaussian source function:

$$S(\boldsymbol{r}^*) = \frac{1}{\left(2\pi R_{ij}^2\right)^{3/2}} \exp\left(-\frac{r^{*2}}{2R_{ij}^2}\right)$$

$$R_{\mathrm{ij}} = \sqrt{R_{\mathrm{i}}^2 + R_{\mathrm{j}}^2}$$

Identical : $R_{ii} = \sqrt{2} R_i$


r (fm)
0-10%
10-30%
30-50%
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
p-p ⊕ p̄-p̄ r_{eff}
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV
p-p R_{inv}
$\pi^{\pm}$–$\pi^{\pm}$ R_{inv}
ALICE pp $\sqrt{s}$ = 13TeV HM
p-p r_{core}
p-Λ (NLO) r_{core}
k-p r_{core}
$\pi^{\pm}$–$\pi^{\pm}$(pol2) r_{core}
⟨ m_T ⟩ (GeV/c^2)