Characterizing the particle-emitting source using femtoscopy in pp collisions at ALICE

arXiv:2004.08018
submitted to *Phys. Lett. B*

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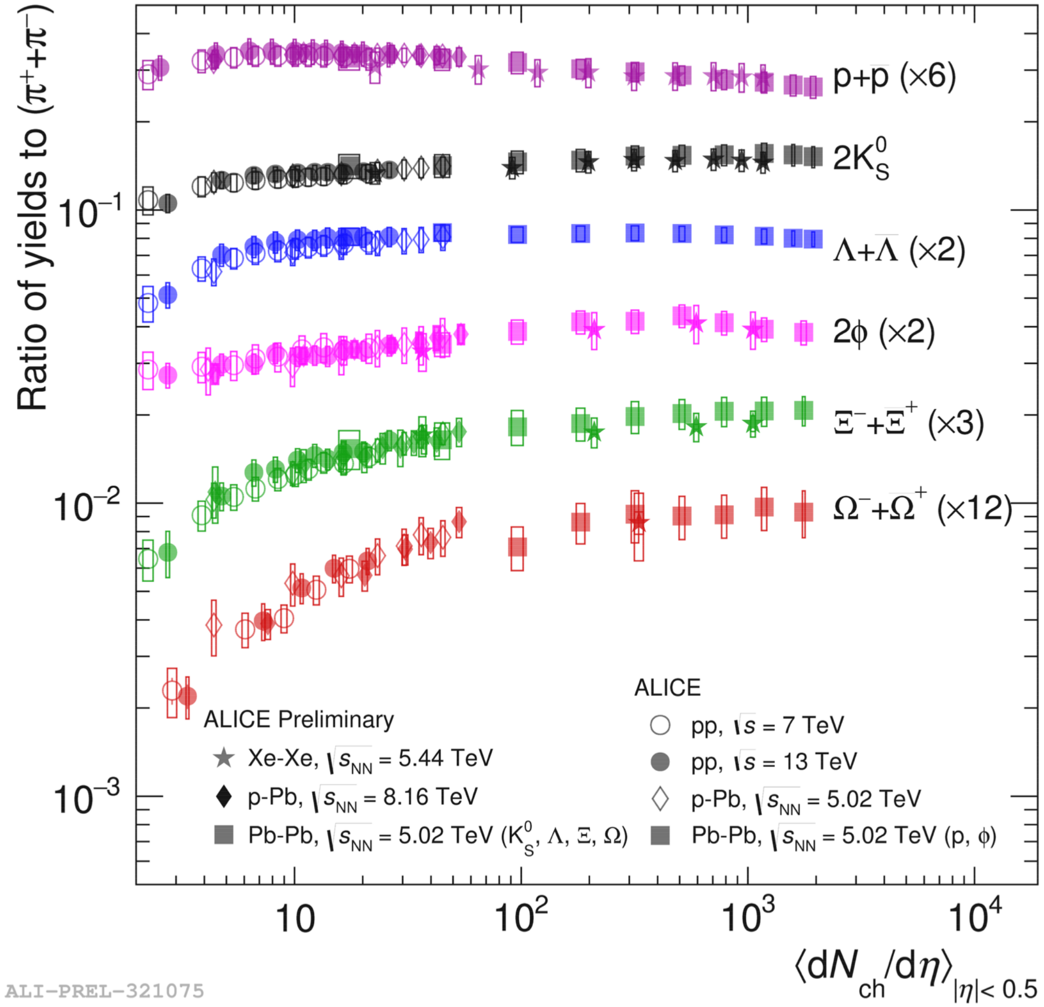
Technische Universität München
40th International Conference on High Energy Physics
Prague (online)
31.07.2020

SFB 1258 Neutrinos Dark Matter Messengers

ALICE

Deconfinement in small systems?



- Striking similarities between small and large collision systems
  - What is the origin?

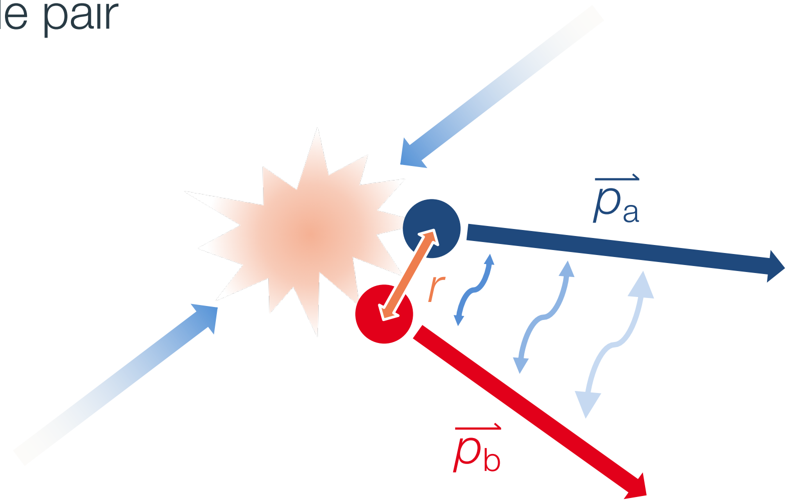
Femtoscopy as a complementary tool

$$C(k^*) = \mathcal{N} \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} = \int S(r) \; \left|\psi(\vec{k}^*, \vec{r})\right|^2 \mathrm{d}^3 r$$

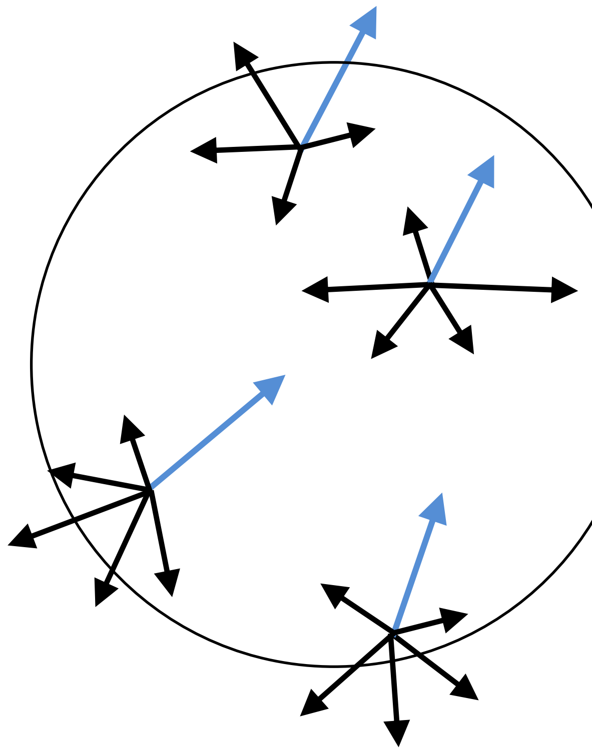
$k^* = | p_{\mathrm{a}}^* - p_{\mathrm{b}}^* |$ and $\vec{p_{\mathrm{a}}^*} + \vec{p_{\mathrm{b}}^*} = 0$

Emission source Two-particle wave function

- Study correlations in the relative momentum *k** distribution of a particle pair
- Traditionally used to study the space-time structure of the emission source with particles of known interaction
  - In particular π–π and K–K pairs

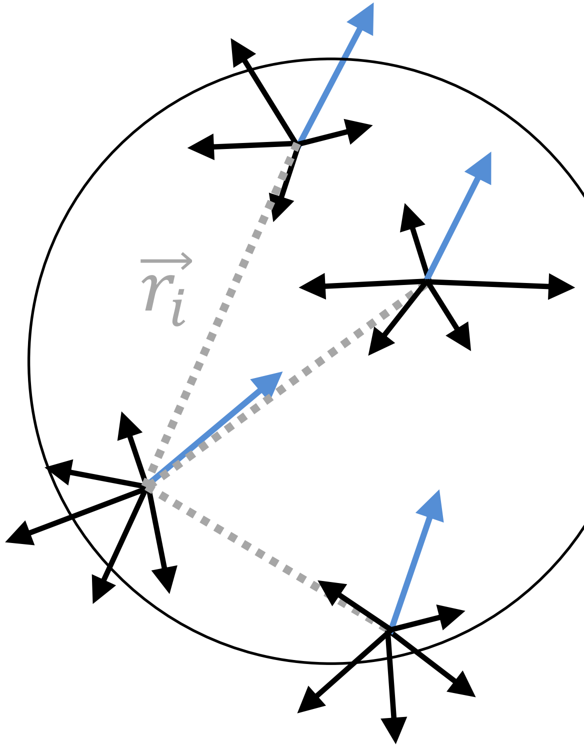


Length of homogeneity



- Correlations for femtoscopic measurements appear for small relative momenta
- Example I: Random emission
  - E.g. emission of particles from a thermal bath

Length of homogeneity



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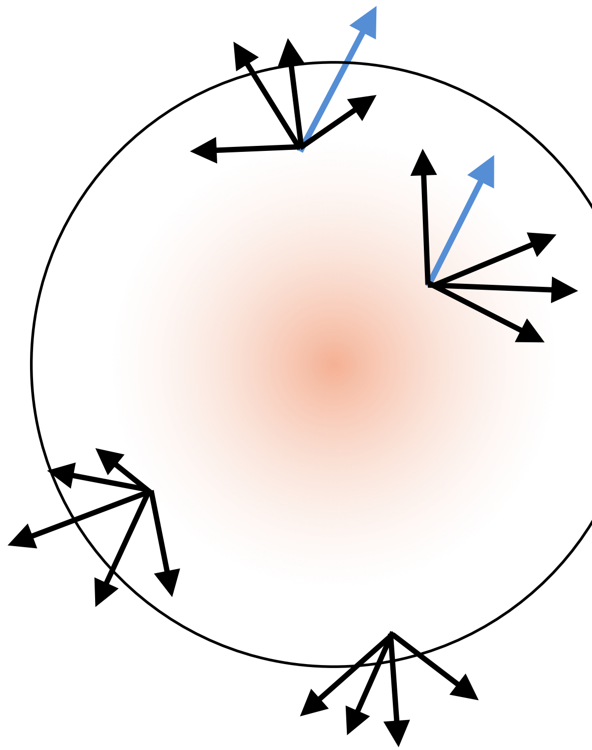

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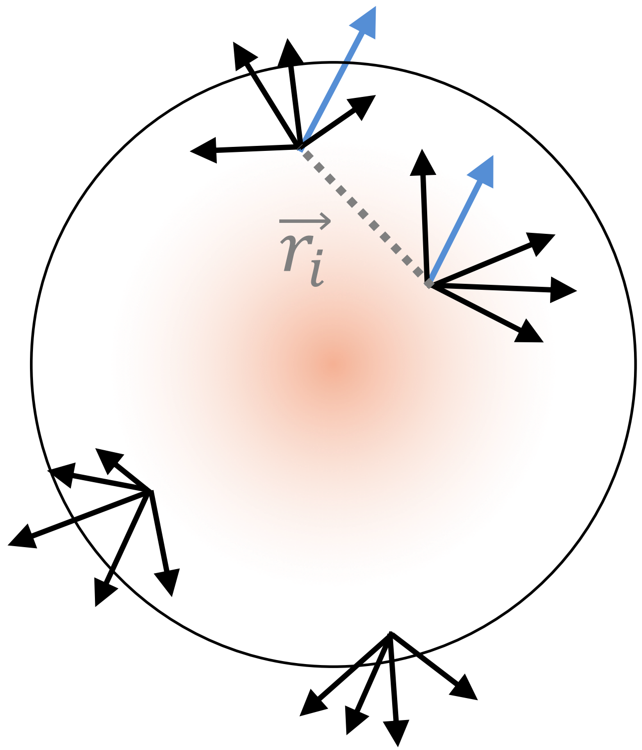
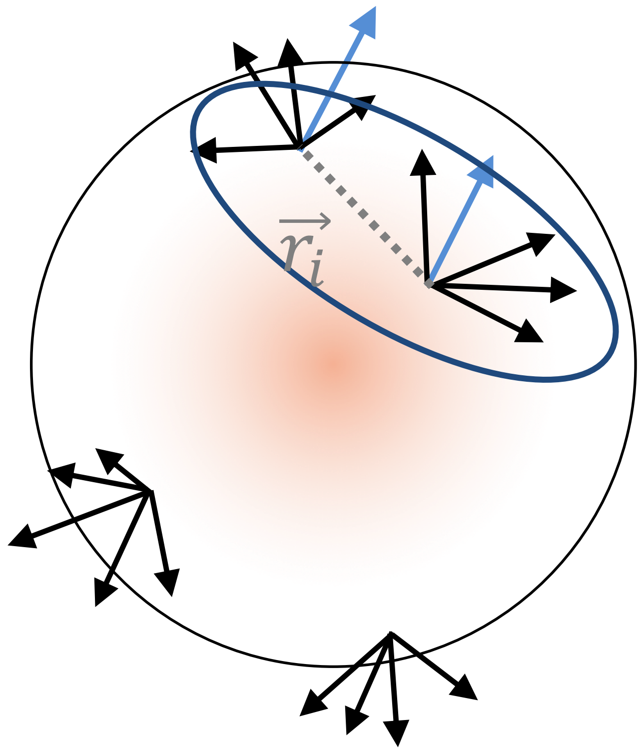
  - E.g. emission of particles from a thermal bath
- Example II: Collective emission of particles
  - E.g. (an-)isotropic flow

Length of homogeneity



- Correlations for femtoscopic measurements appear for small relative momenta
- Example I: Random emission
  - E.g. emission of particles from a thermal bath
- Example II: Collective emission of particles
  - E.g. (an-)isotropic flow
  - Correlations are created in a confined part of the reaction volume

Length of homogeneity



- Correlations for femtoscopic measurements appear for small relative momenta
- Example I: Random emission
  - E.g. emission of particles from a thermal bath
- Example II: Collective emission of particles
  - E.g. (an-)isotropic flow
  - Correlations are created in a confined part of the reaction volume
  - Femtoscopy measures the length of homogeneity

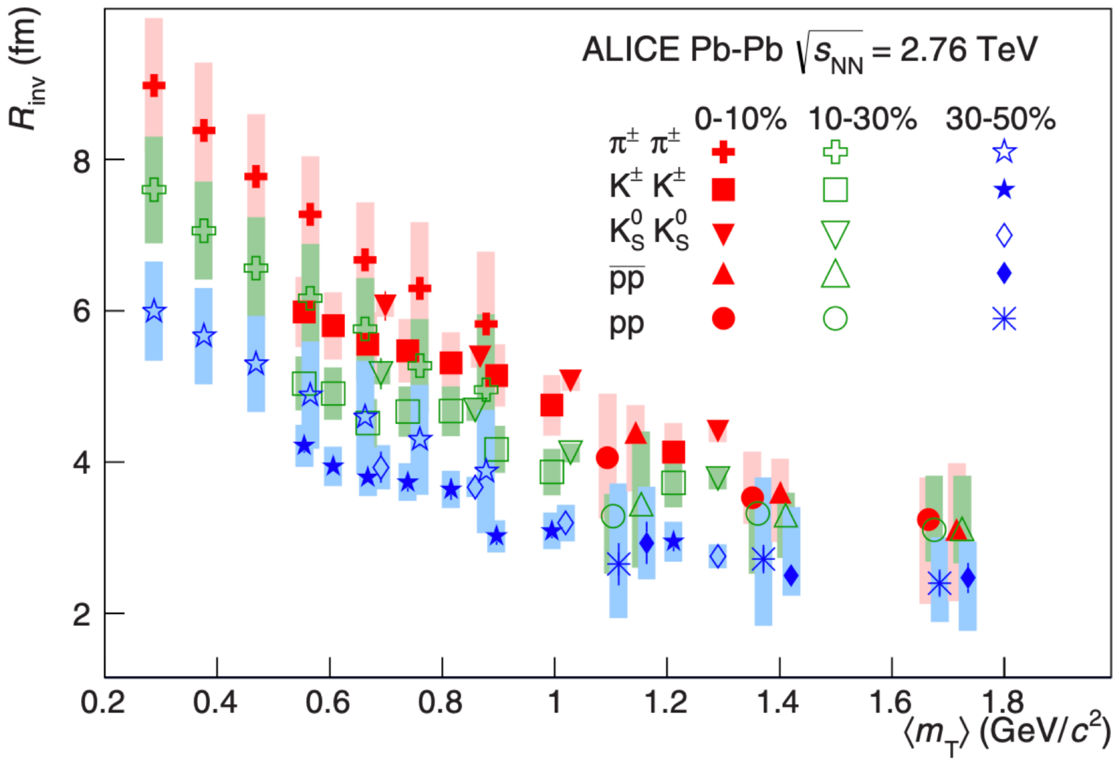
m_T scaling in Pb–Pb collisions

- Centrality dependence reflects simple geometric picture of the collision

- Power-law scaling with m_T as expected from hydrodynamic evolution

Scaling broken for pions – different interpretations

- Larger effect of Lorentz-boost for lighter particles
  A. Kisiel *et al.*, PRC 90 (2014) 064914
- Strong transverse flow
  V. Shapoval *et al.*, NPA 929 (2014) 1
  S. Akkelin *et al.*, PLB 356 (1995) 525
- Is m_T the right observable for scaling?
  Y. Sinyukov *et al.*, NPA 946 (2016) 227
  T. Humanic, JPG 45 (2018) 055101
- Strongly decaying resonances?



PRC 92 (2015) 054908

$$m_T = \sqrt{k_T^2 + m^2} \qquad k_T = \frac{1}{2}|p_{T,1} + p_{T,2}|$$

m_T scaling in pp collisions?

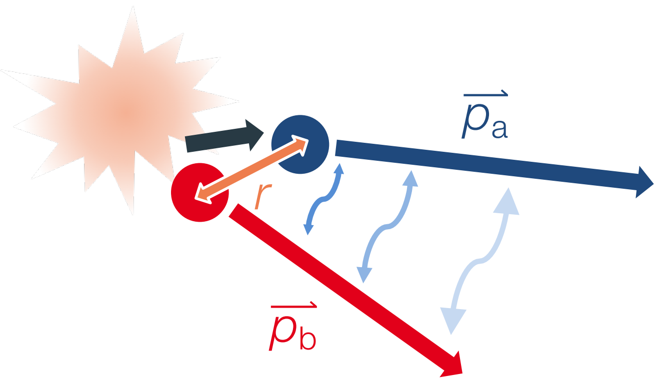
Similar trends as in Pb–Pb

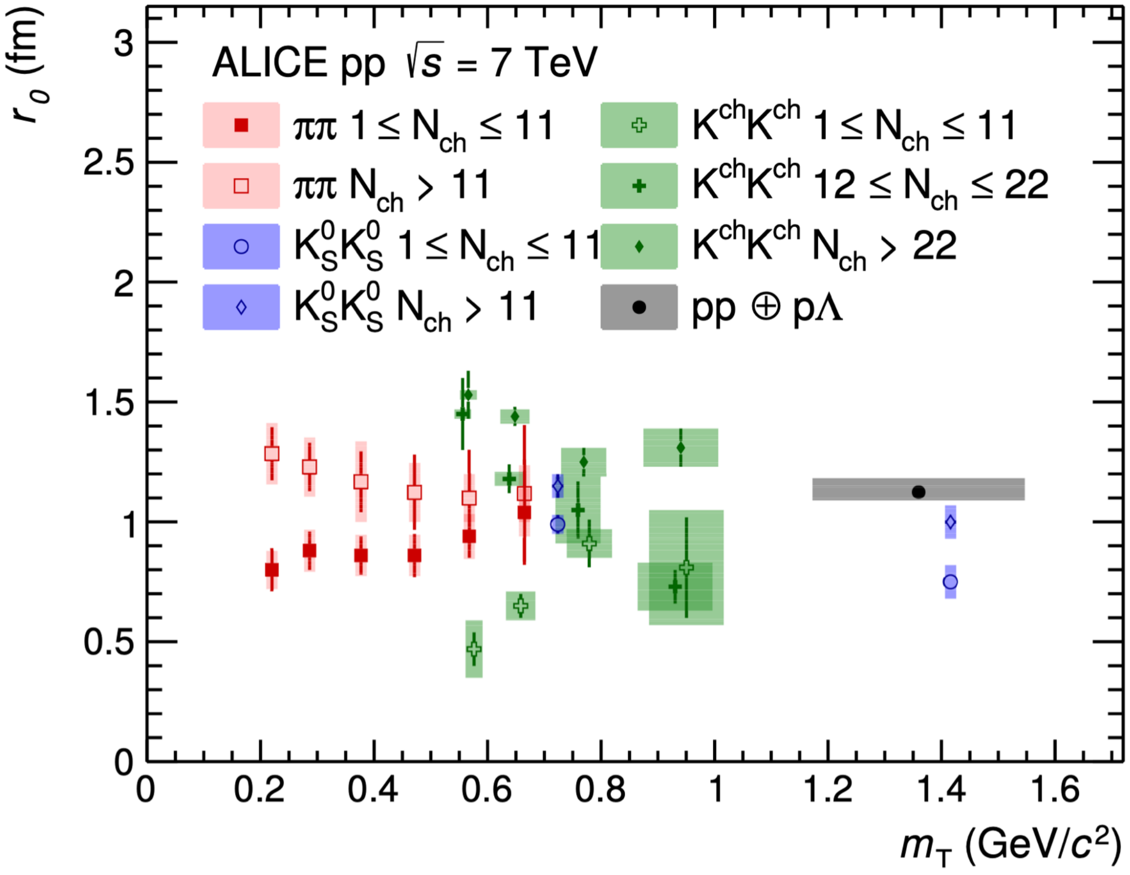
- Multiplicity dependence
- m_T scaling observed

No common scaling among the particles

- Modification of the source distribution due to strongly decaying resonances
- Even more important in small systems ($c\tau \sim r_{Inv}$)

→ Impact of resonances needs to be accounted for!





PRC 99 (2019) 024001

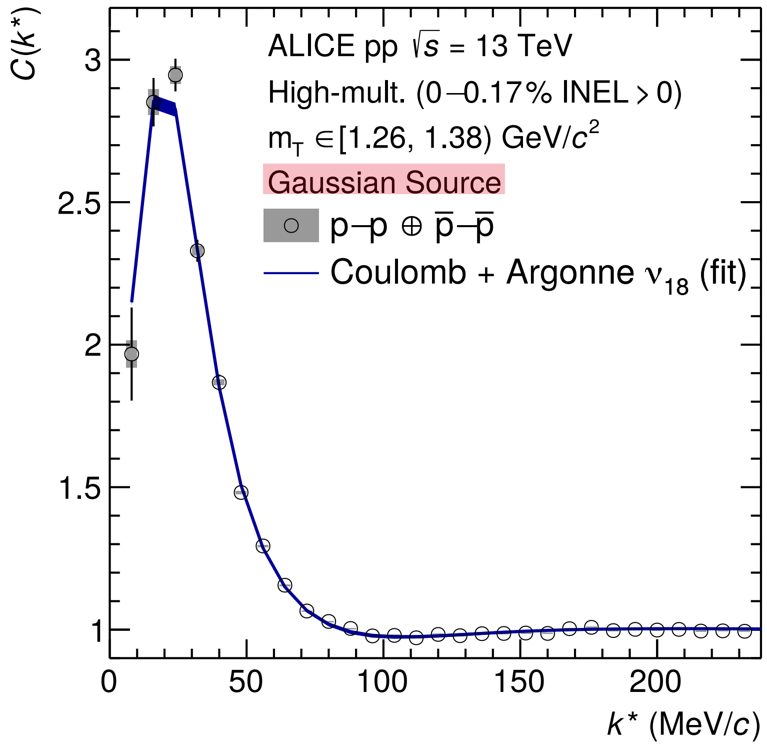
Baryon–baryon femtoscopy

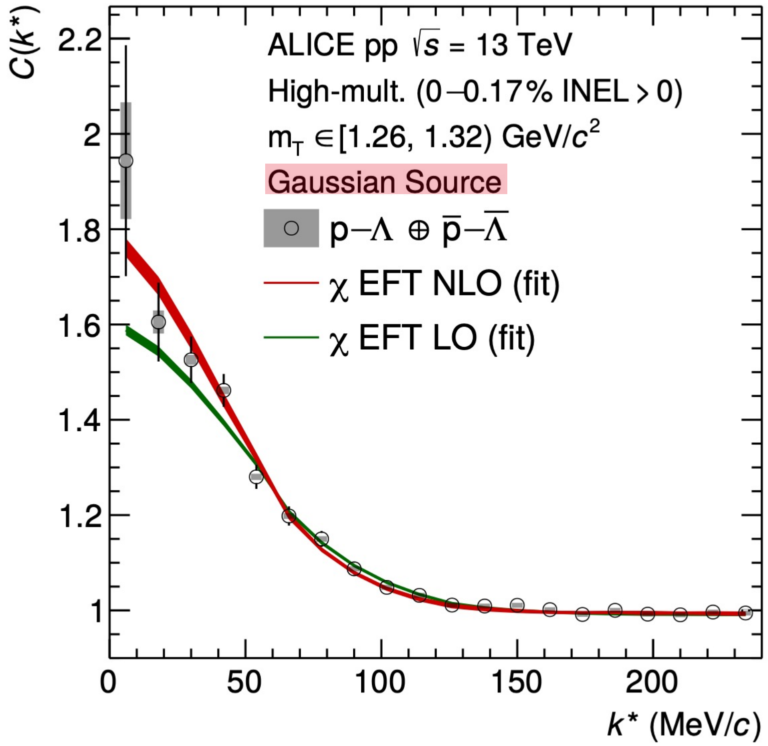
High-multiplicity pp collisions at $\sqrt{s}$ =13 TeV

arXiv:2004.08018 (submitted to *Phys. Lett. B*)

Gaussian source fits

arXiv:2004.08018

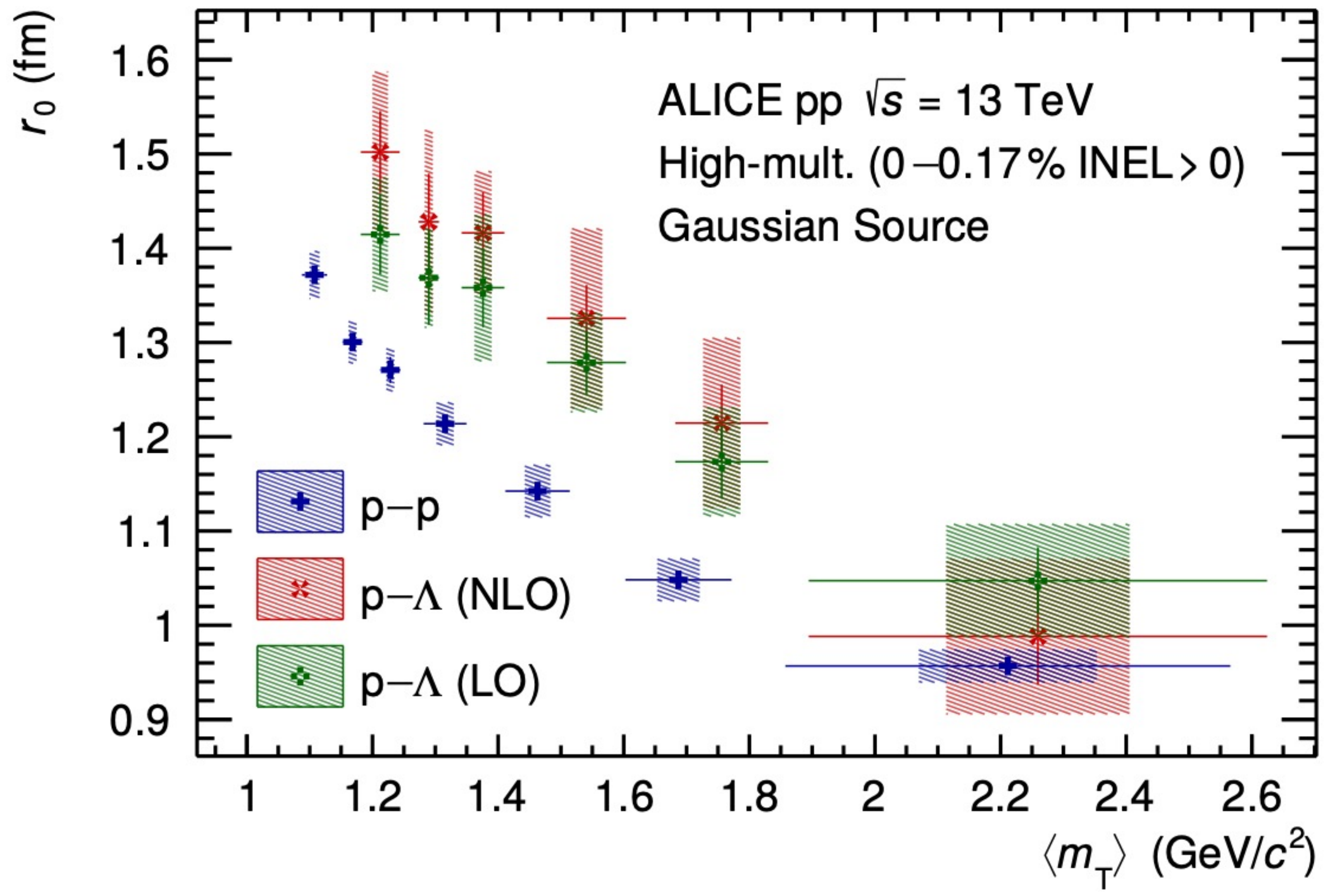




- Evaluation of $C(k^*)$ with the CATS framework
  D. Mihaylov *et al.*, EPJ C78 (2018) 394
  - p-p pairs: Quantum statistics, Coulomb and Strong (Argonne ν18) interaction
    R. Wiringa, *et al.*, PRC 51 (1995) 38.
  - p-Λ pairs: Strong interaction (χEFT LO & NLO)
    LO: H. Polinder *et al.*, NPA 779 (2006) 244, NLO: J. Haidenbauer *et al.*, NPA 915 (2013) 24

m_T scaling of the Gaussian source

arXiv:2004.08018



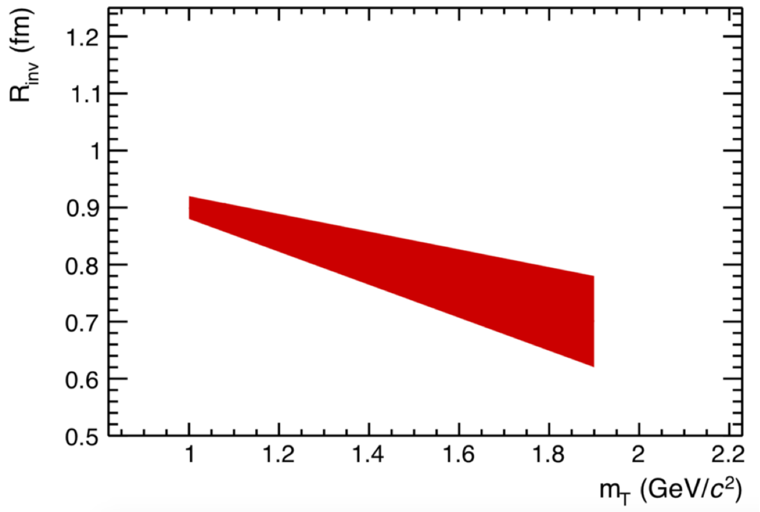
- Clear observation of m_T scaling of the source radii
  - Offset between source sizes of different pairs
  - No universal emission source?

The universal source model – baryons

arXiv:2004.08018

(An)isotropic flow + **Strongly decaying resonances**

Gaussian core ⊗ Exponential tail



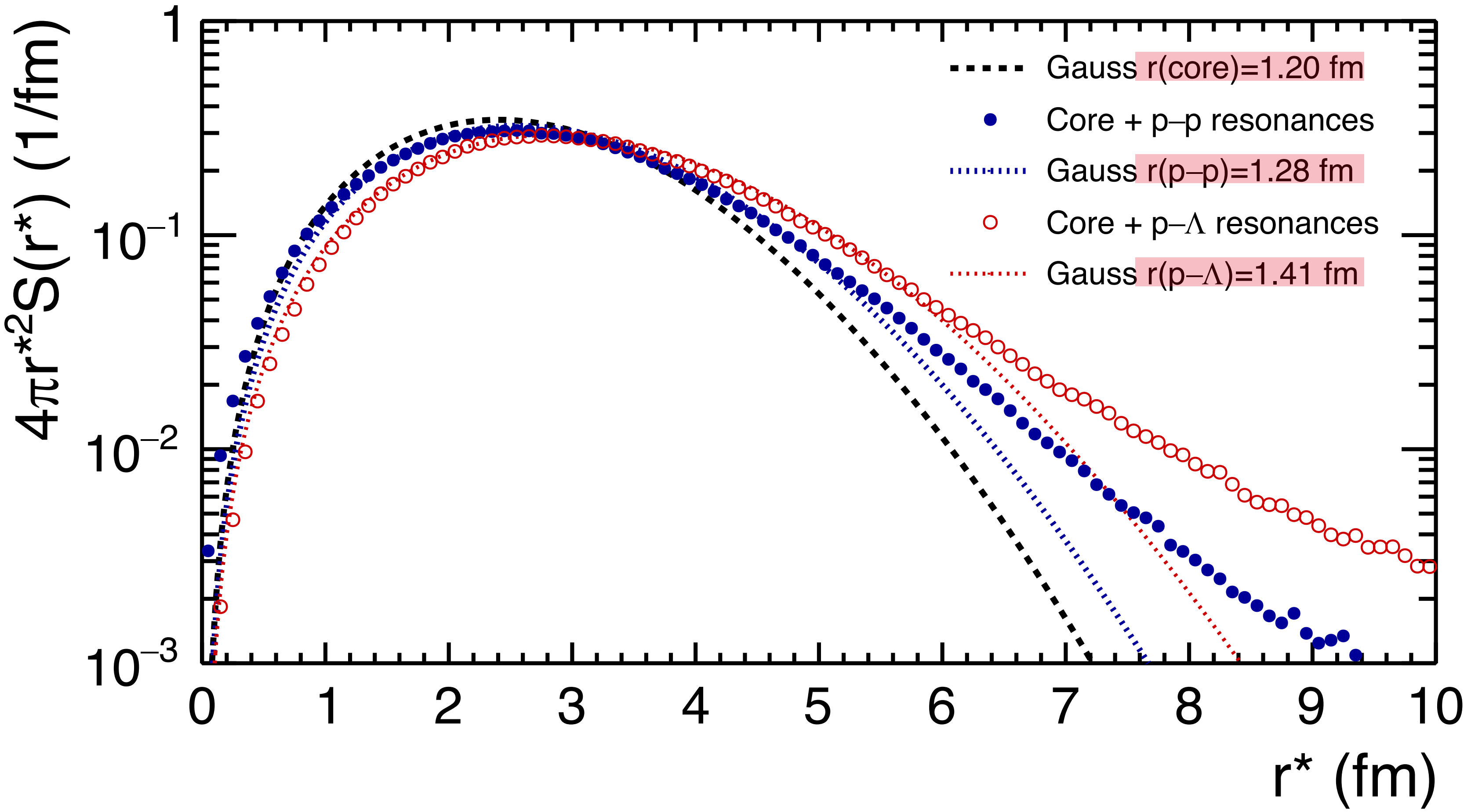
Particle	Primordial fraction	Resonances	
		$1 < c\tau < 2$ fm	$c\tau > 2$ fm
Proton	33 %	56 %	3 %
Lambda	34 %	8 %	58 %

Ingredients to the Universal Source Model

- Resonance yield from Statistical Hadronization Model (canonical approach)
  - Priv. Comm. with Prof. F. Becattini
    JPG38 (2011) 025002.
- Decay kinematics from EPOS
  - T. Pierog *et al.*, PRC 92 (2015) 034906.

How good is the Gaussian description?

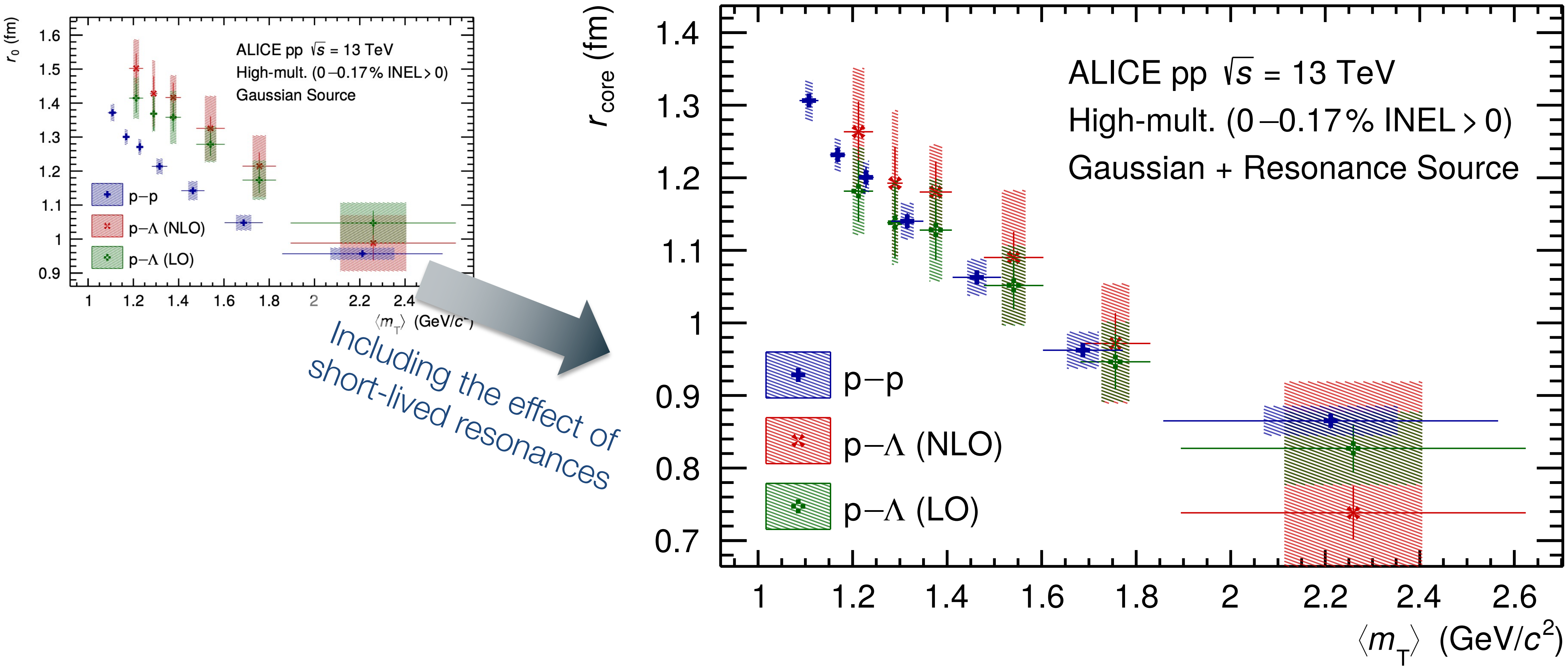
arXiv:2004.08018



- Description of the source distributions by a Gaussian up to ~ 6 fm
  - Largest modification of the core source for p-Λ pairs due to longer lifetime of resonances decaying to Λ

Is the source of p–p and p–Λ pairs universal?

arXiv:2004.08018



- **Common m_T scaling** for the core source extracted from p-p and p-Λ correlations
  - Motivation for a search of a universal particle source
  - Application of the formalism to π–π correlations

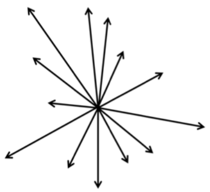
π–π femtoscopy

Minimum-bias pp collisions at $\sqrt{s}$ = 13 TeV

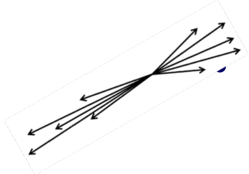
ALICE Preliminary

Event shape selection

- Experimentally challenging background from minijets
  - Event shape selection criteria → sphericity
    EPJ C72 (2012) 2124



$S_T \rightarrow 1$ (> 0.7) **Spherical events**
Jet structures suppressed
Thermal production dominates



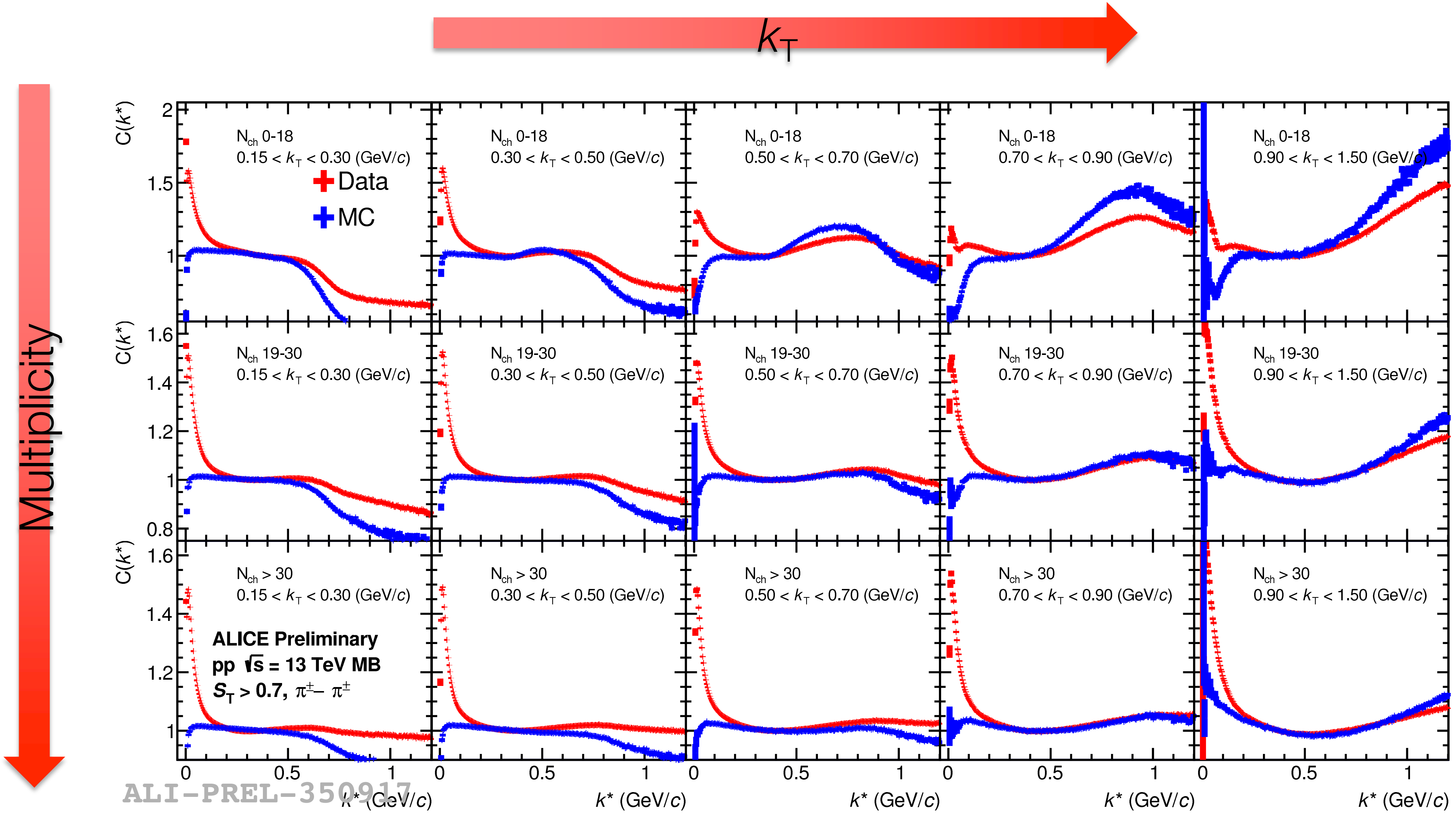
$S_T \rightarrow 0$ (< 0.3) **Jet-like events**
Jets, mini-jets

$$S_{xy}^{L} = \frac{1}{\sum_i p_{T\,i}} \sum_i \frac{1}{p_{T\,i}} \begin{pmatrix} p_{x\,i}^2 & p_{x\,i} p_{y_i} \\ p_{y_i} p_{x\,i} & p_{y_i}^2 \end{pmatrix}$$

$$S_{\mathrm{T}} = \frac{2\lambda_2}{\lambda_1 + \lambda_2}$$

  - Selection of spherical events only ($S_T > 0.7$)
    - Minijet contribution in the correlation functions strongly suppressed

Minijet background correction

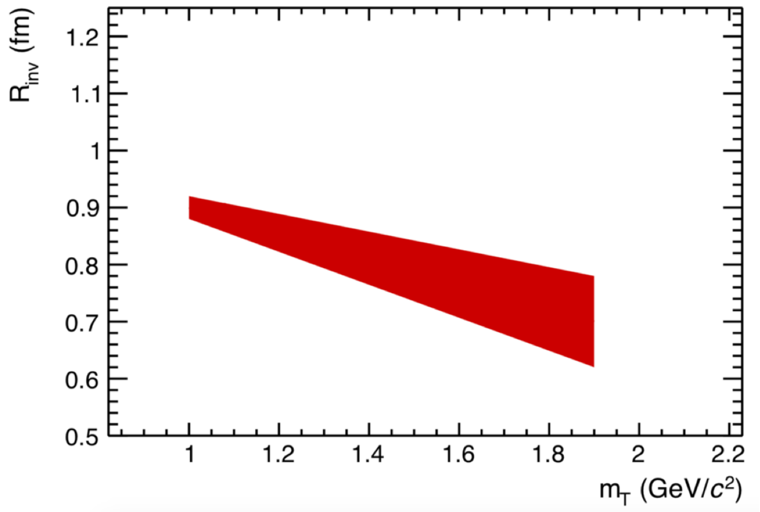


- Use Pythia 8 simulations to further suppress residual minijet background $\tilde{C}(k^*) = \frac{C_{\text{data}}(k^*)}{C_{\text{MC}}(k^*)}$

The universal source model – pions

(An)isotropic flow + **Strongly decaying resonances**

Gaussian core ⊗ Exponential tail



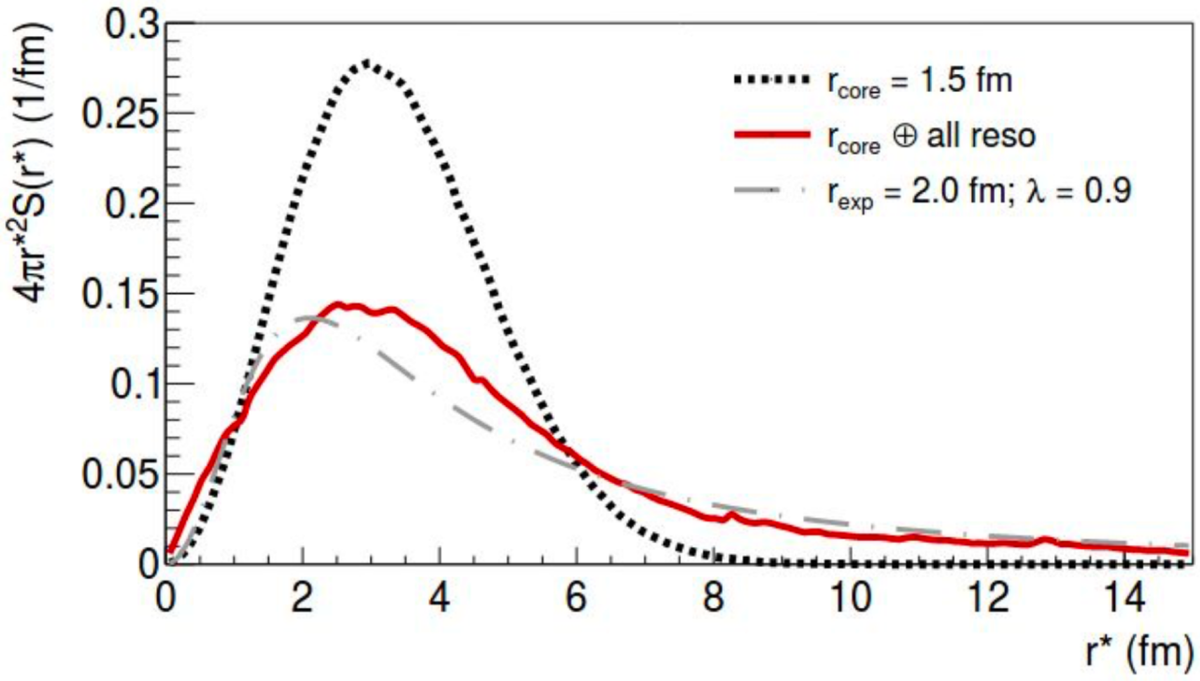
Primordial fraction	Resonances			
	$c\tau < 1$ fm	$1 < c\tau < 2$ fm	$2 < c\tau < 5$ fm	$c\tau > 5$ fm
28 %	15 %	35 %	10 %	12 %

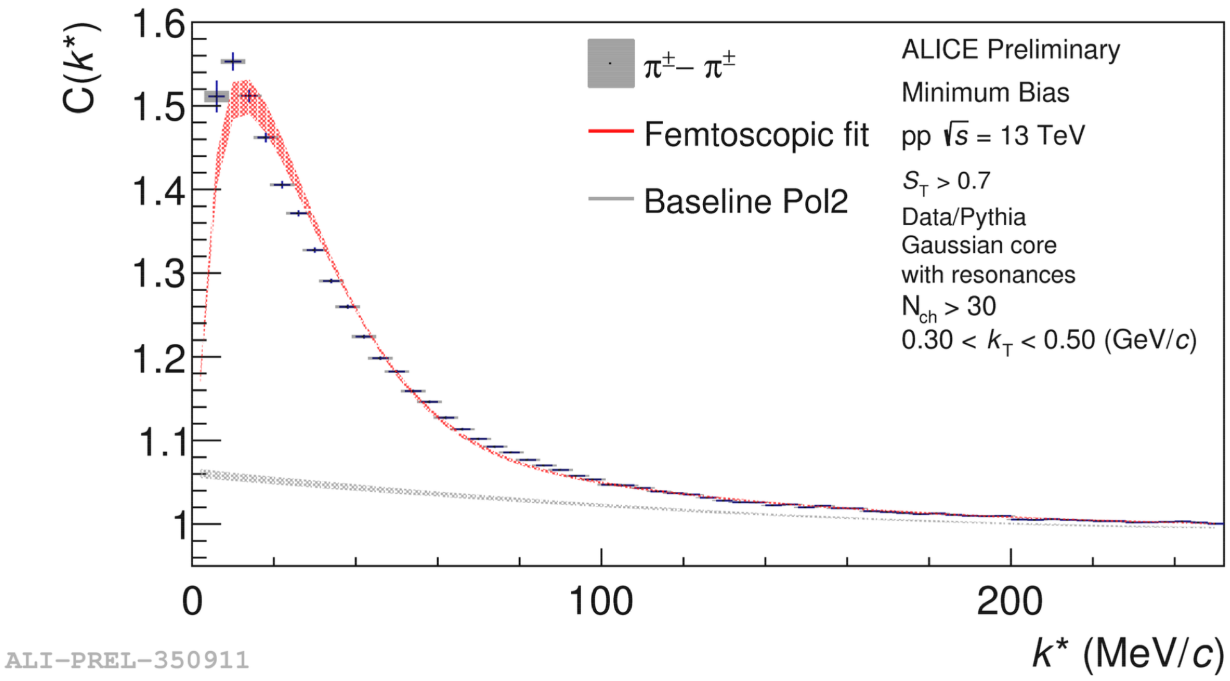
Flat contribution

Ingredients to the Universal Source Model

- Resonance contributions from Thermal-FIST
  - V. Vovchenko and H. Stoecker, CPC 244 (2019) 295
  - V. Vovchenko *et al.*, PRC 100 (2019) 054906
- Decay kinematics from EPOS
  - T. Pierog *et al.*, PRC 92 (2015) 034906.

Description of the π–π correlation function

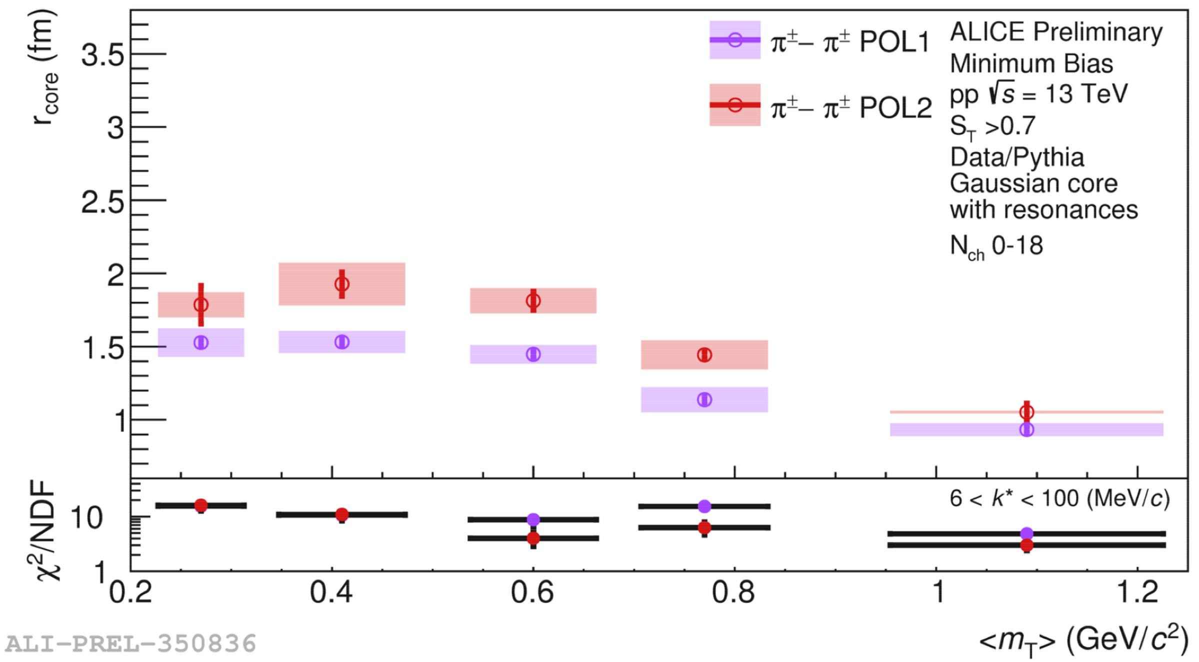




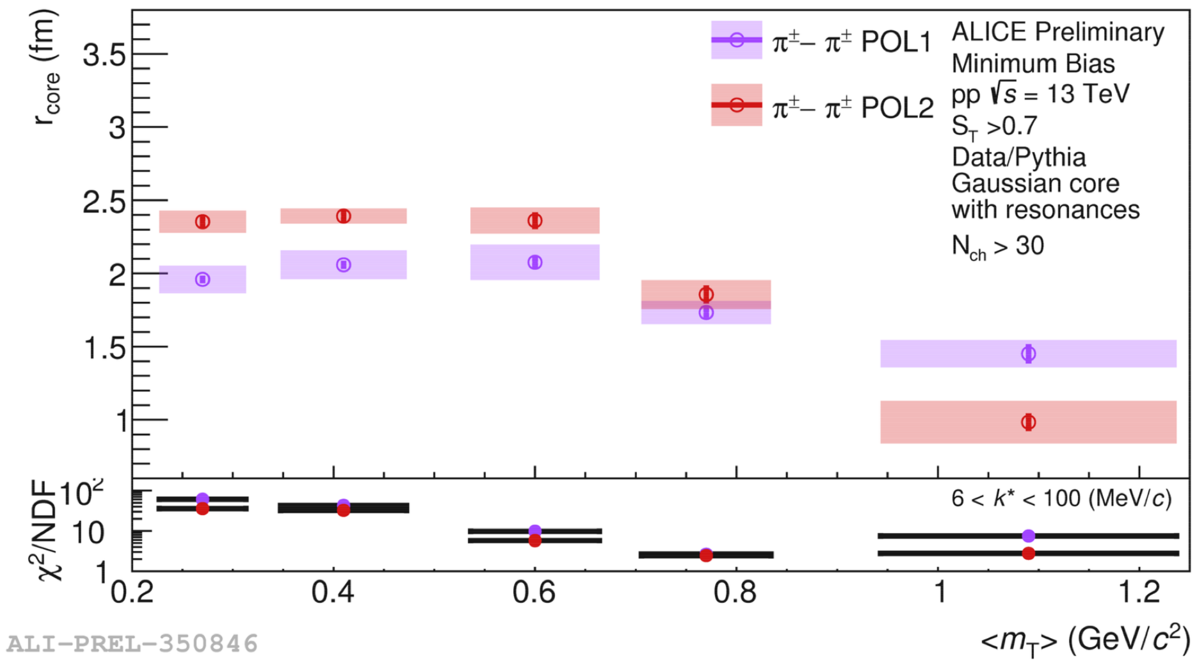
- Inclusion of strong decays leads to a Cauchy-type source distribution
- Decomposition of the CF following PRC 99 (2019) 024001
  - Lambda parameter **fixed from single-particle properties**
- Genuine π–π signal modeled with CATS using quantum statistics and Coulomb interaction
  - D. Mihaylov *et al.*, EPJ C78 (2018) 394

Observation of m_T scaling with π–π pairs

Low multiplicity



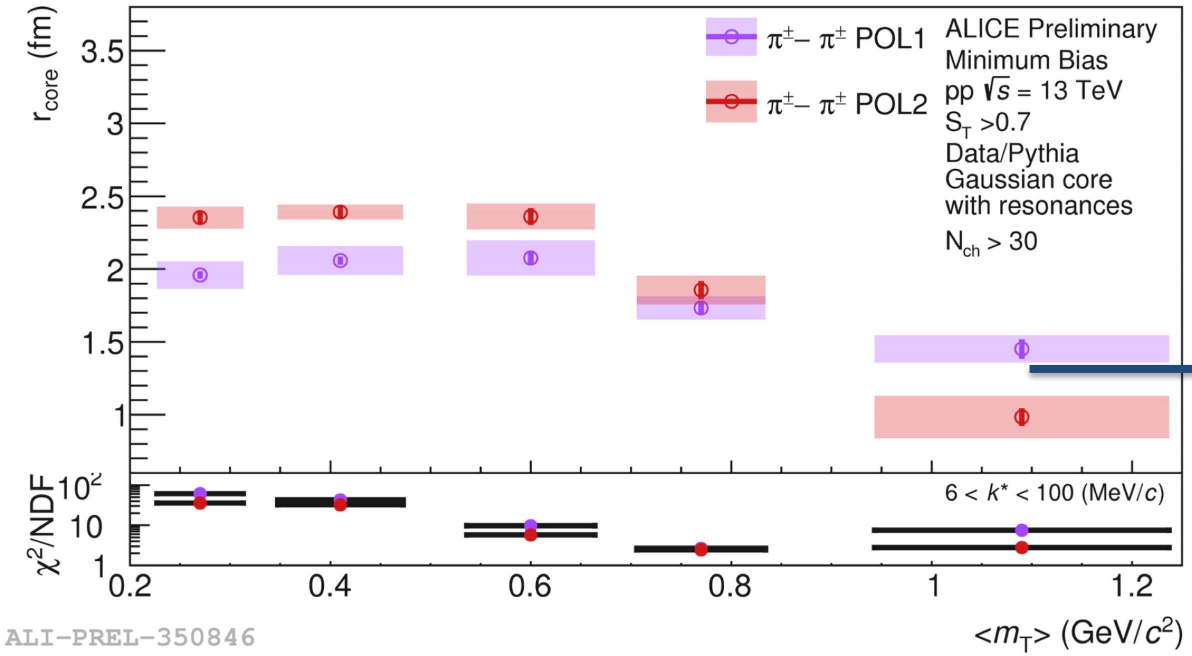
High multiplicity

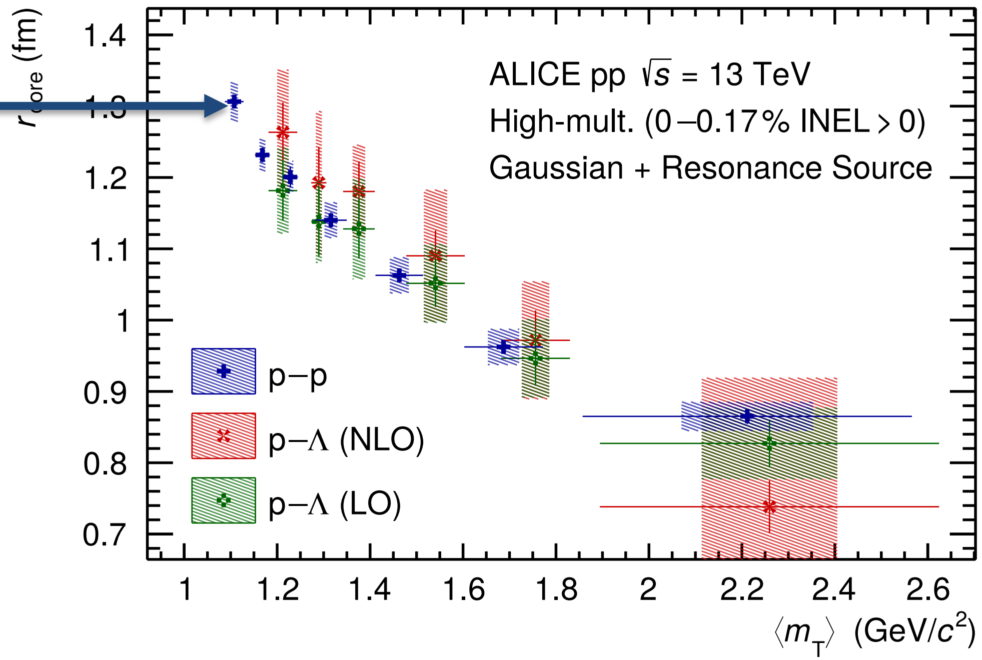


- Expected increase of the source size with multiplicity
- Appearance of **scaling at larger m_T**

Towards a universal particle source…

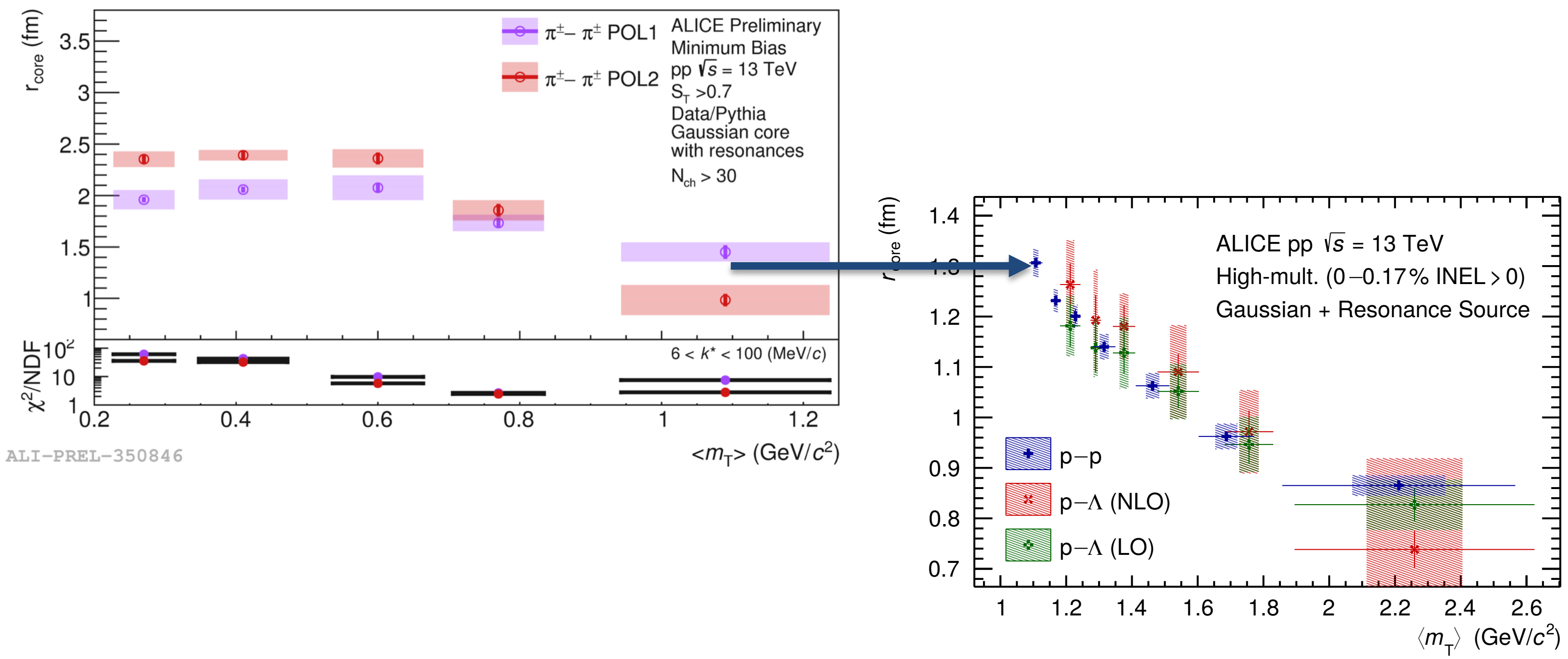
arXiv:2004.08018





- Indication of a universal particle source of all species
  - Take it with a grain of salt – different trigger, but comparable multiplicity
  - Further studies under way!

Summary



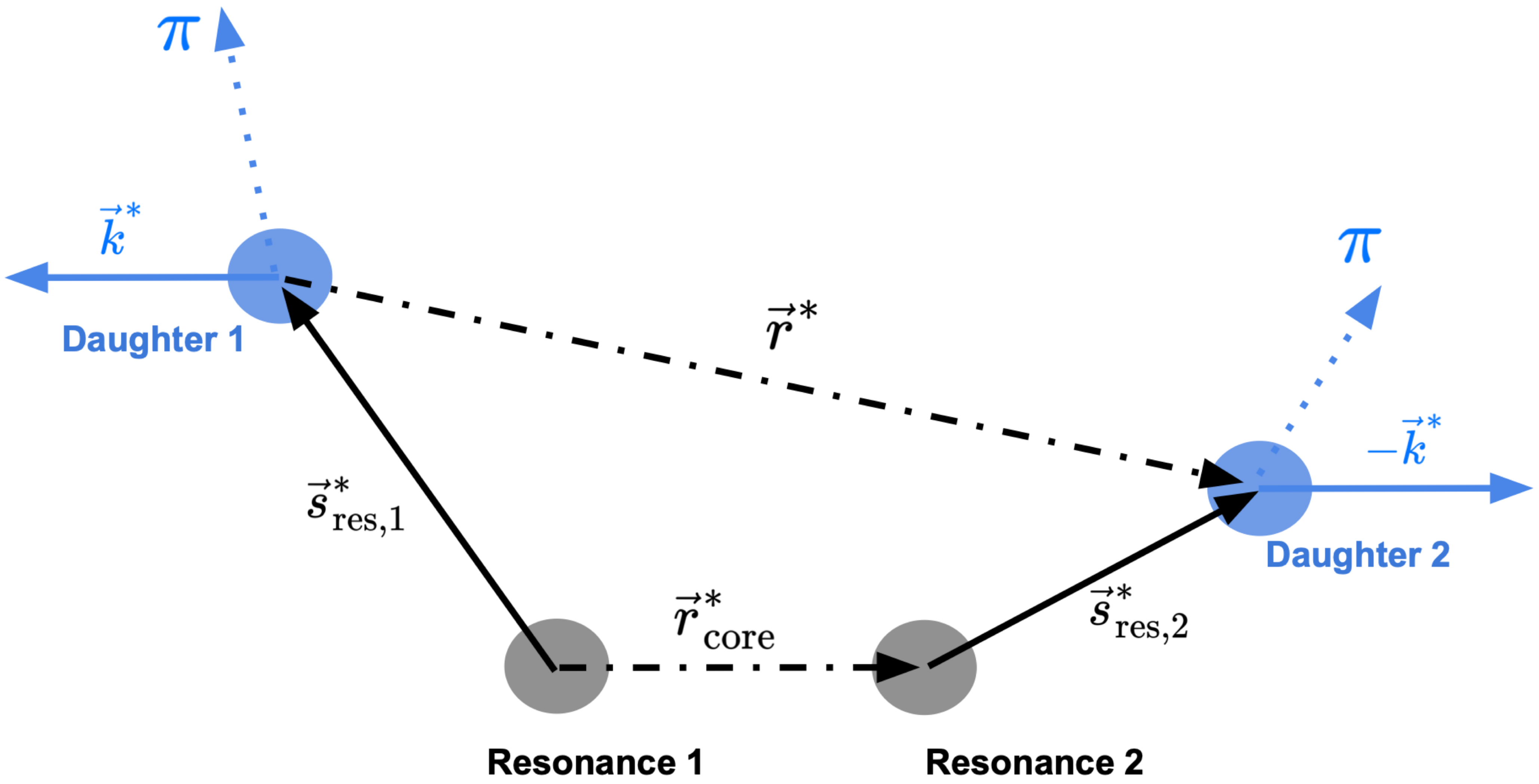
- Towards a common particle emission source in small systems
  - Quantitative treatment of the short-lived resonance contributions to p-p, p-Λ, and π-π correlations
  - Observation of a common m_T scaling of source sizes from p-p and p-Λ correlations

- Knowledge about the emission source allows for detailed interaction studies
  - See talk by O. Vazquez-Doce, Strong Interactions and Hadron Physics II, 29.7.2020, 18:20

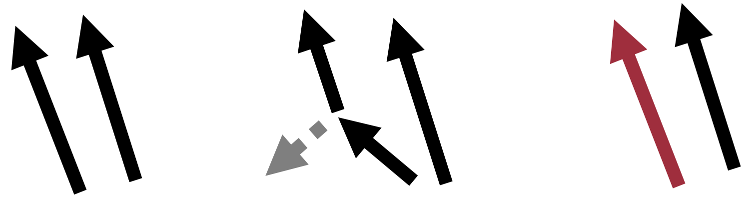
Thank you!

The universal source model

arXiv:2004.08018



Residual and non-femtoscopic correlations



$$C_{tot}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \ldots$$

Contributions from: genuine feed-down misidentifications

Decomposition of the correlation function following *Phys. Rev.* C 99 (2019) 024001

- Pair contributions quantified by single-particle purity ($\mathcal{P}_i$) and feed-down fractions (f_i)

$$\lambda_{ij} = \mathcal{P}_1 \cdot f_{i_1} \cdot \mathcal{P}_2 \cdot f_{j_2}$$

- Finite momentum resolution of the detector
- Non-flat baseline

p–p	
Pair	λ (%)
pp	67.0
$p_{\Lambda}p$	20.3
Flat	12.7

p–Λ	
Pair	λ (%)
pΛ	46.1
$p\Lambda_{\Sigma^0}$	15.4
$p\Lambda_{\Xi^-}$	8.5
Flat	30.0

π–π	
Pair	λ (%)
Primordial	66.4
Flat	33.6*

*) including strongly-decaying resonances with $c\tau$ > 5 fm

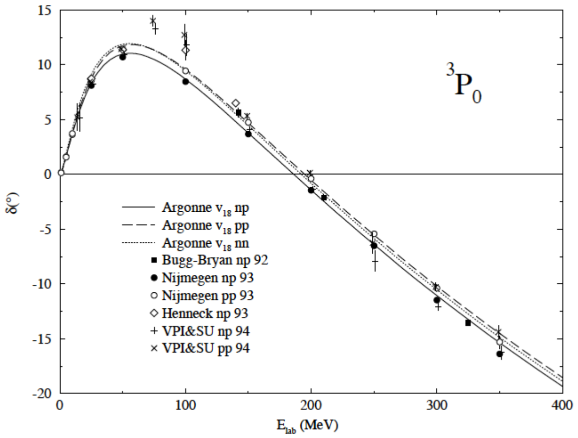
Computing the correlation function

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

- Evaluation of $C(k^*)$ within the CATS framework
  - D. Mihaylov *et al.*, *Eur. Phys. J.* **C78** (2018) 394

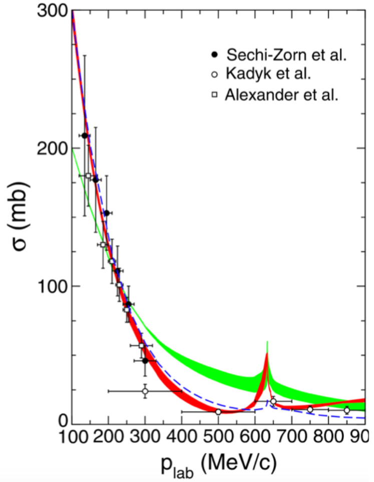
- Numerically solving the single-channel Schrödinger equation
  - p-p pairs: Quantum statistics, Coulomb and Strong (Argonne ν18) interaction
    - R. Wiringa, *et al.*, PRC 51 (1995) 38.
  - p-Λ pairs: Strong interaction (χEFT LO & NLO)
    - LO: H. Polinder *et al.*, NPA 779 (2006) 244
    - NLO: J.Haidenbauer *et al.*, NPA 915 (2013) 24

N–N → N–N



R. B. Wiringa, *et al.*, PRC 51 (1995) 38.

p–Λ → p–Λ

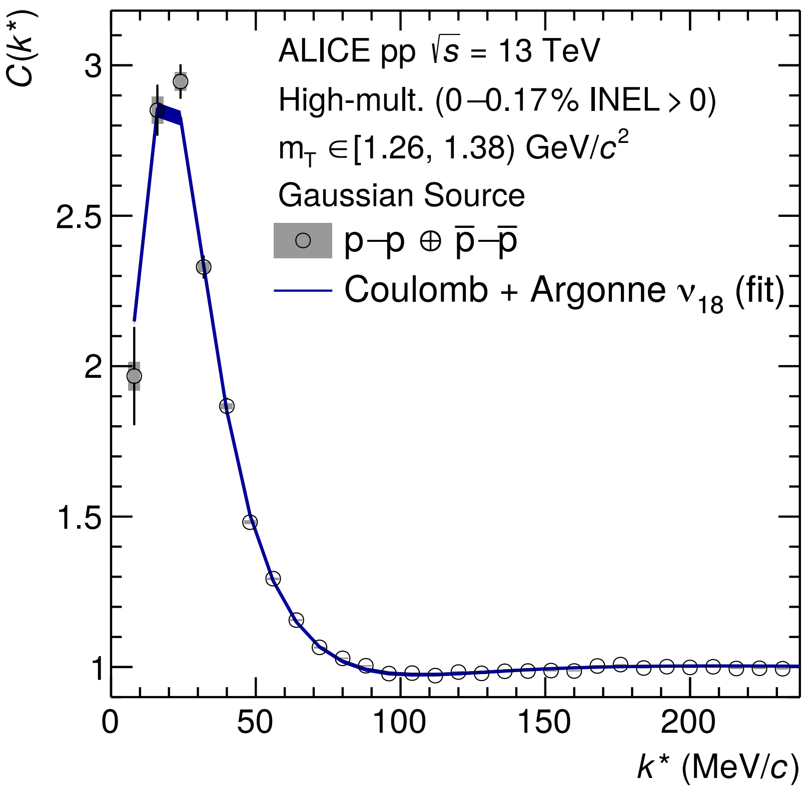


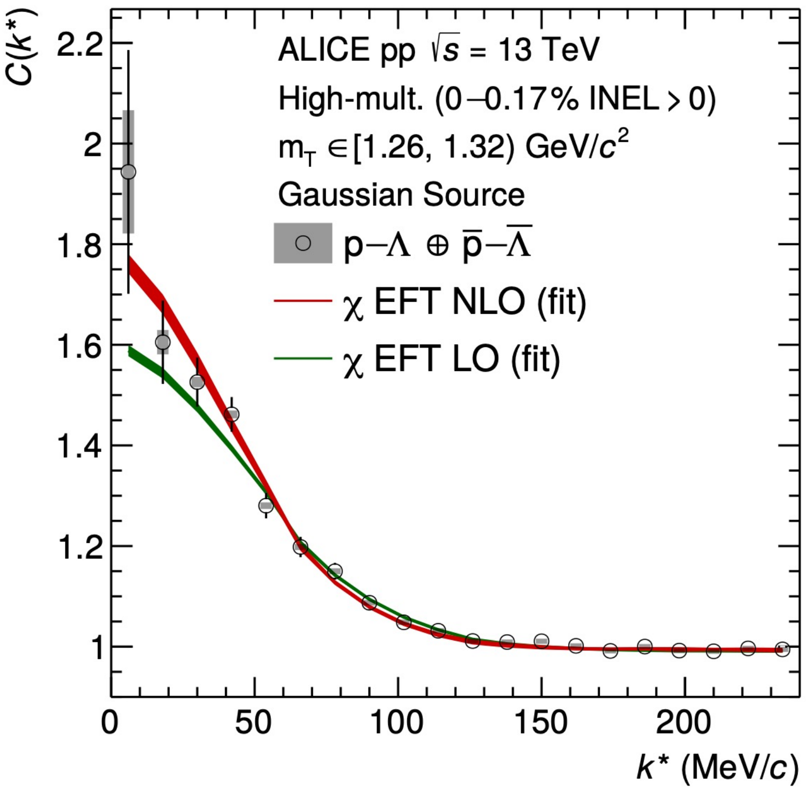
LO: H. Polinder *et al.*, NPA 779 (2006) 244
NLO: J.Haidenbauer *et al.*, NPA 915 (2013) 24

$$\hat{\mathcal{H}} \cdot \psi(\vec{k}^*,\vec{r}) = E \cdot \psi(\vec{k}^*,\vec{r})$$

$$\psi(\vec{k}^*,\vec{r})$$

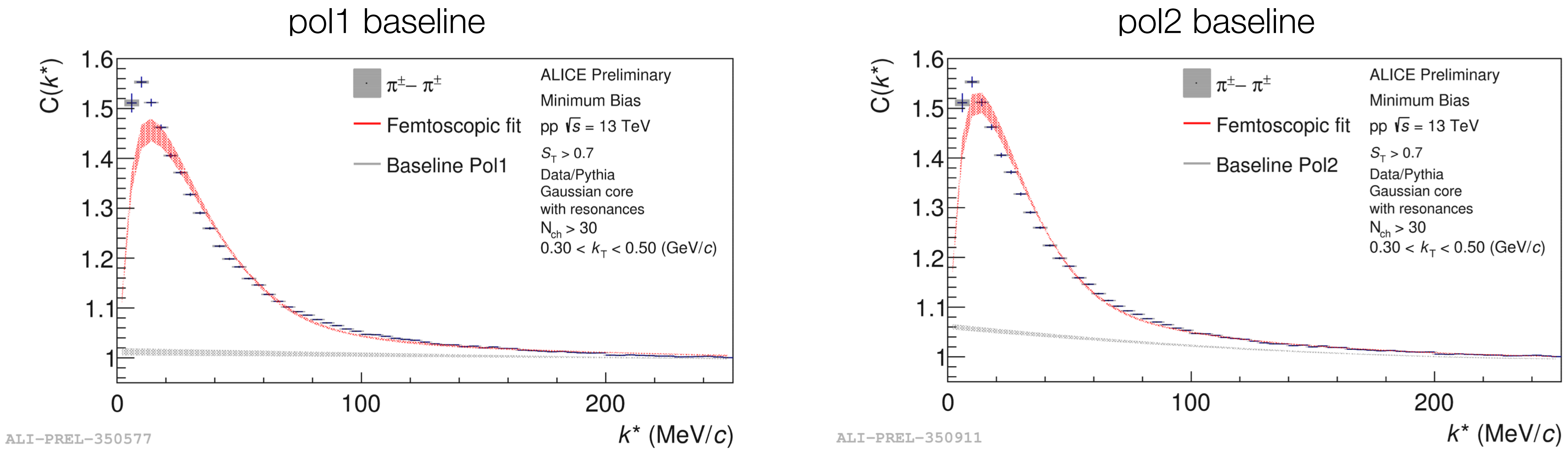
Gaussian source fits





- Is there a common scaling of the source size among different particle pairs?
  - Compare results extracted from p-p and p-Λ correlations

Description of the π–π correlation function



- Decomposition of the CF following *Phys. Rev.* C 99 (2019) 024001
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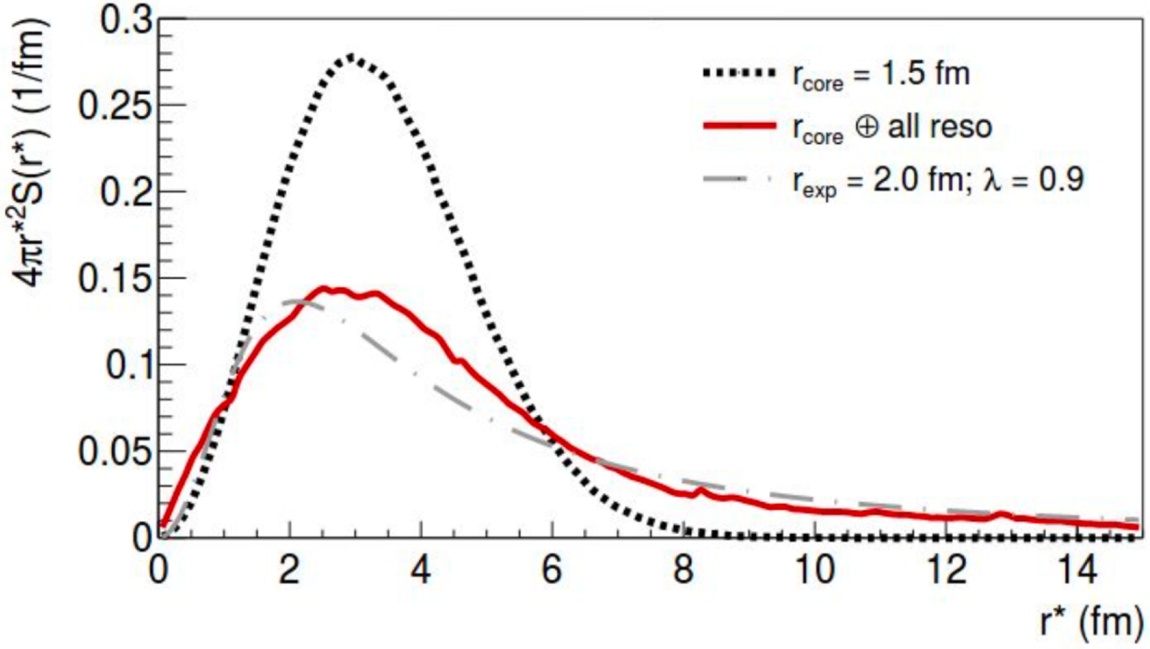
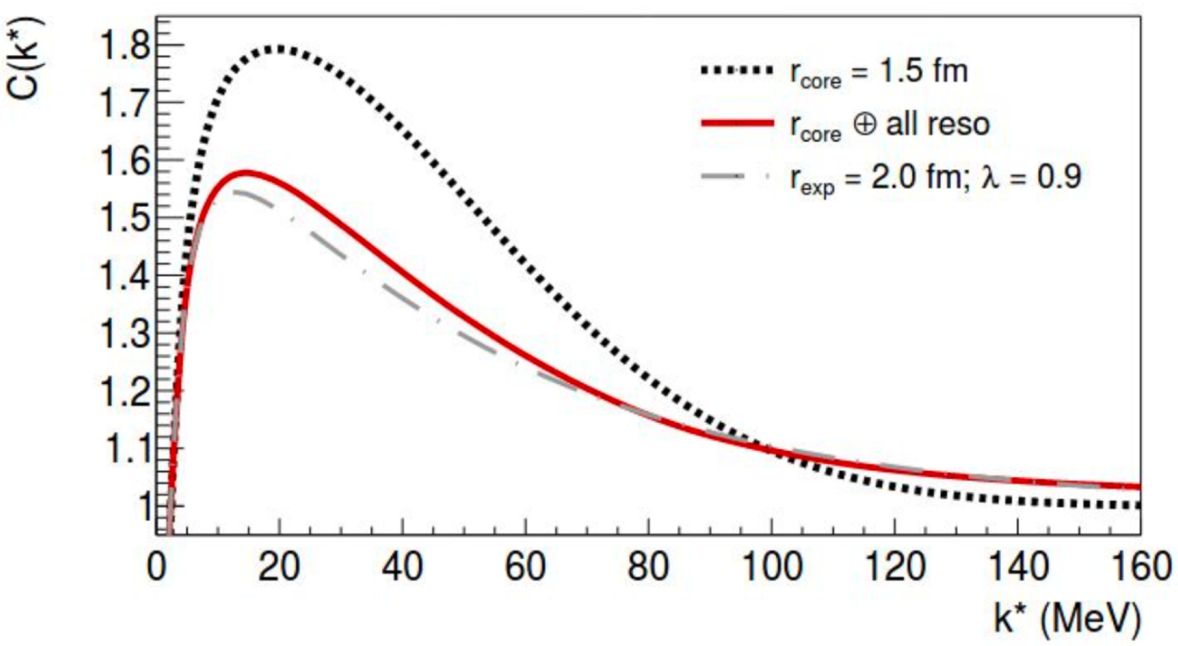
  - D. Mihaylov *et al.*, *Eur. Phys. J.* **C78** (2018) 394

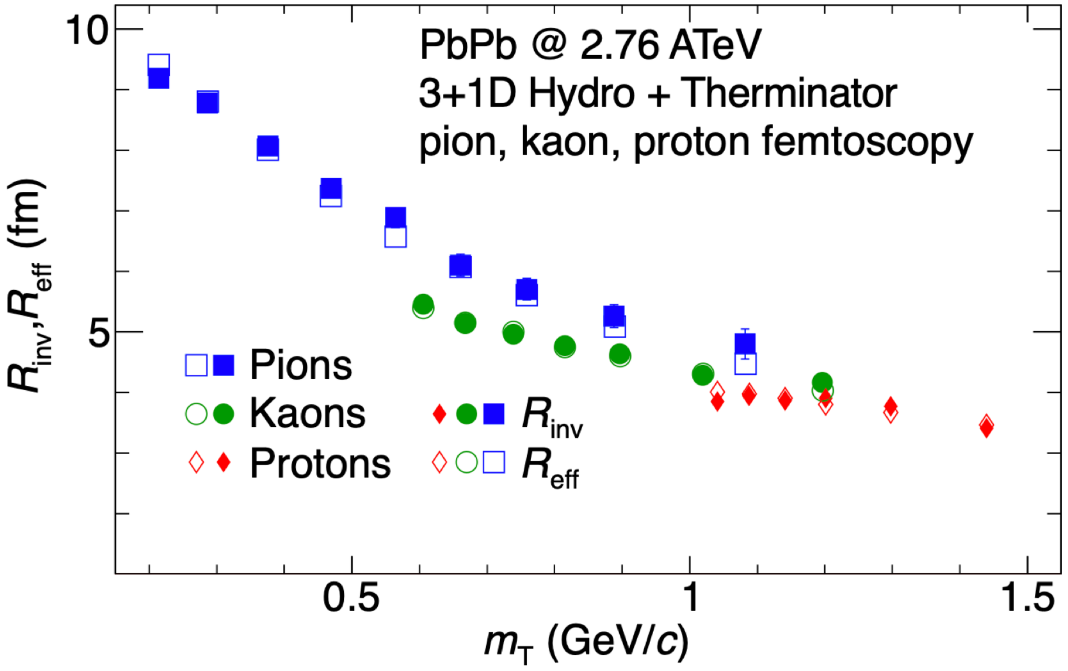
The overall π–π source shape



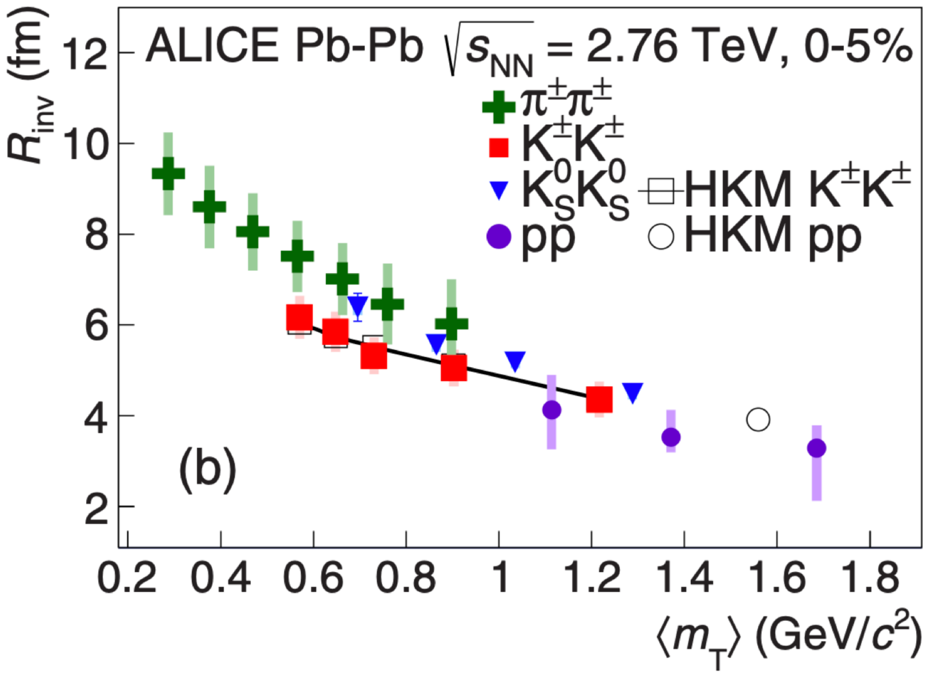


- Inclusion of strong decays leads to a Cauchy-type source distribution
  - Consistent with recent measurements, e.g. PRC 97 (2018) 064912 and PRC 97 (2018) 064911

m_T scaling in Pb–Pb



A. Kisiel et al., Phys. Rev. C 90 (2014) 064914



ALICE Collaboration, PRC 92 (2015) 054908
HKM: V. M. Shapoval *et al.*, NPA 929 (2014) 1

Larger effect of Lorentz-boost for lighter particles

Effect of rescatterings