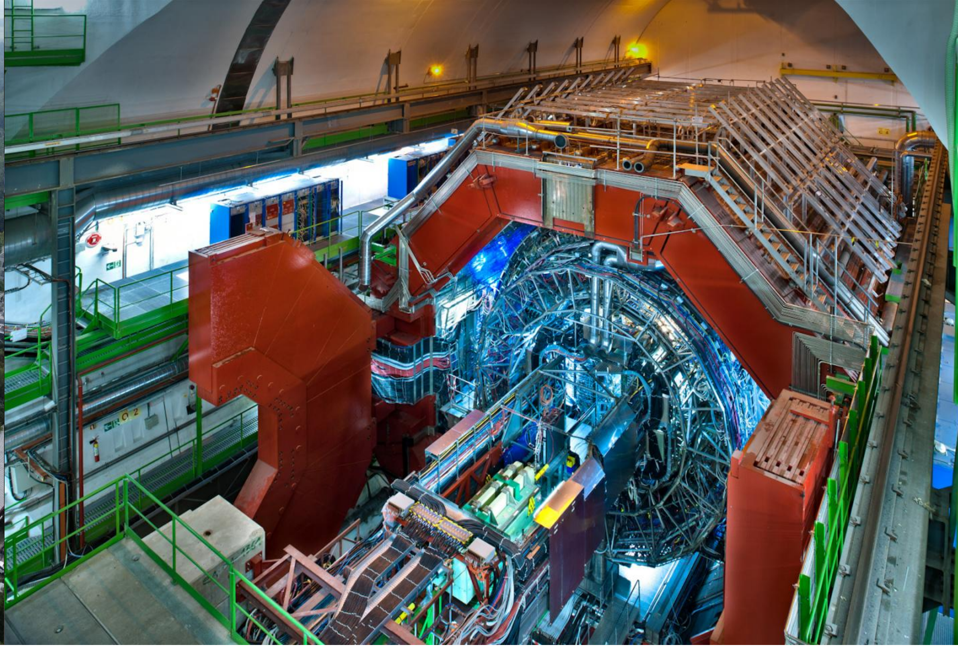
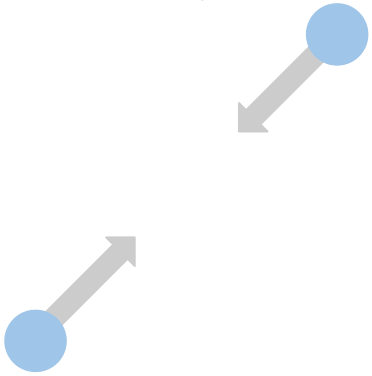


Femtoscopy for strong interaction studies

Maximilian Korwieser (TUM)
ECT*PANAM, 17.10.25

Femtoscopy in a nutshell

Ann.Rev.Nucl.Part.Sci.55:357-402, 2005



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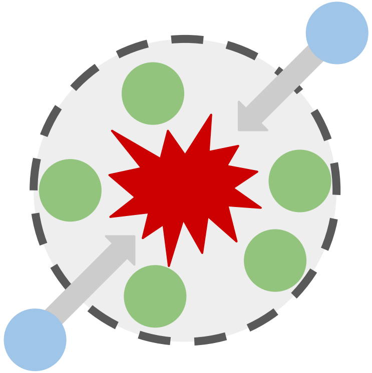

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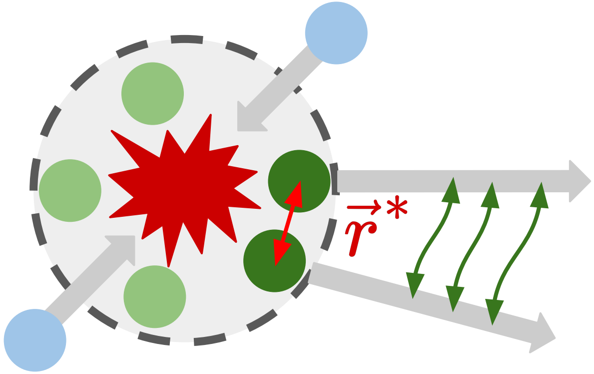

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Femtoscopy in a nutshell

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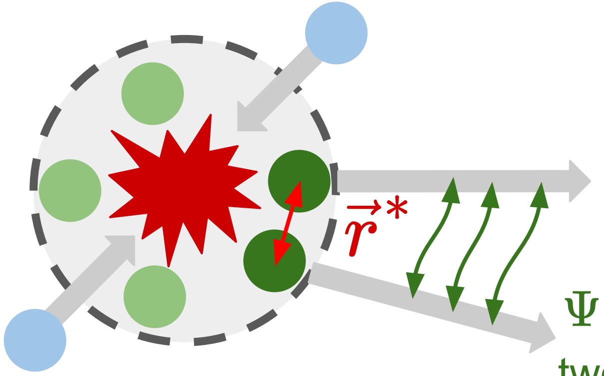
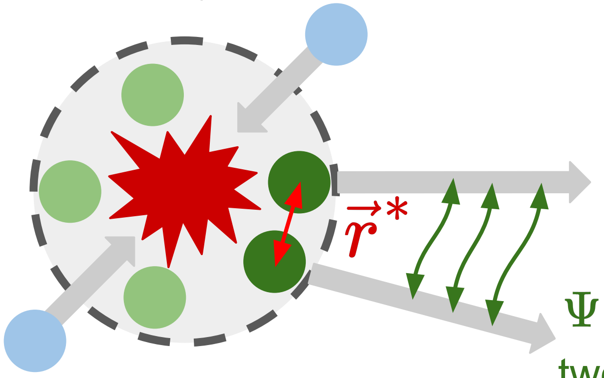


Femtoscopy in a nutshell

Ann.Rev.Nucl.Part.Sci.55:357-402, 2005



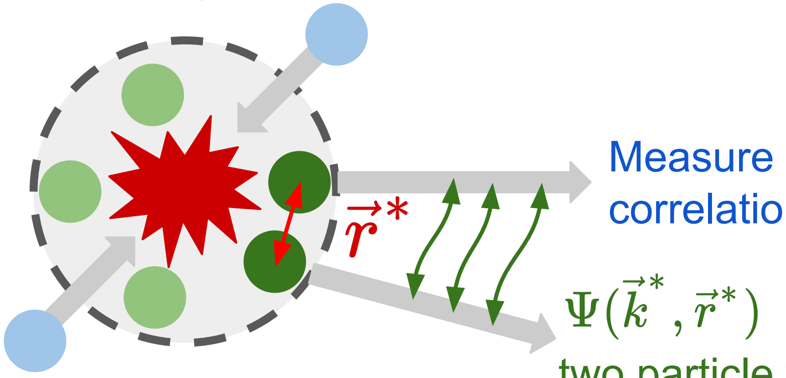
Measure the correlation function *C(k*)*

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

two particle wave function

Femtoscopy in a nutshell

Ann.Rev.Nucl.Part.Sci.55:357-402, 2005



Measure the
correlation function $C(k^*)$

two particle wave function

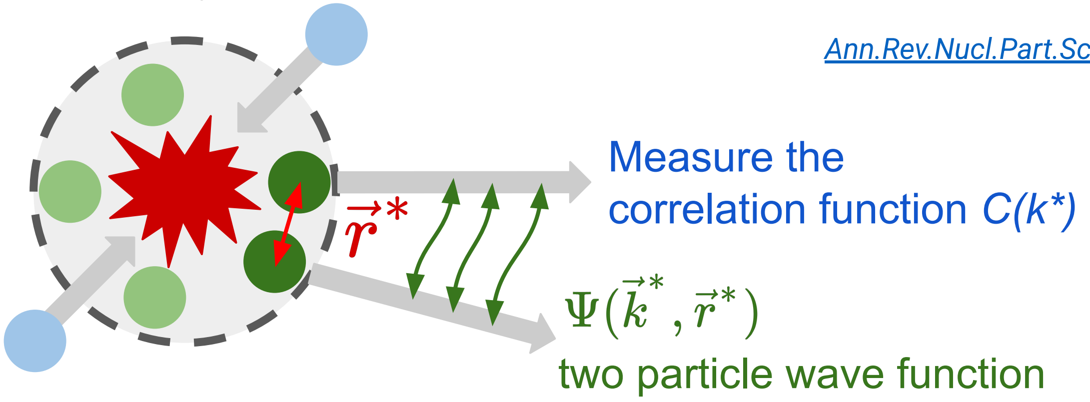
$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{SE}}(k^*)}{N_{\mathrm{ME}}(k^*)}$$

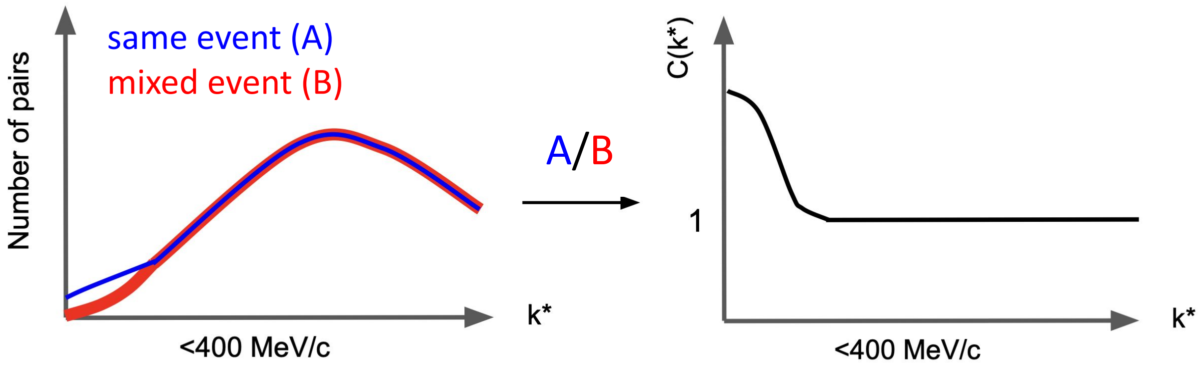
Particle pair observed in the same event

Particle pair constructed from different events

Femtoscopy in a nutshell

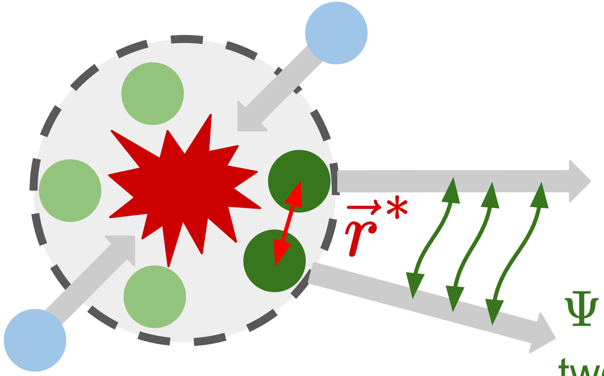
Ann.Rev.Nucl.Part.Sci.55:357-402, 2005





Femtoscopy in a nutshell

Ann.Rev.Nucl.Part.Sci.55:357-402, 2005

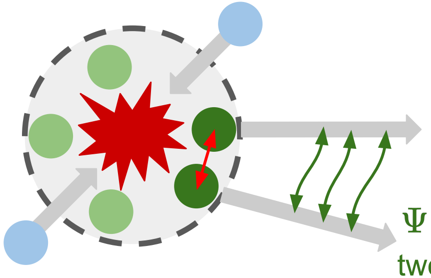


Measure the correlation function *C(k*)*

$\Psi(\vec{k}^*, \vec{r}^*)$
two particle wave function

$$C(k^*) = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

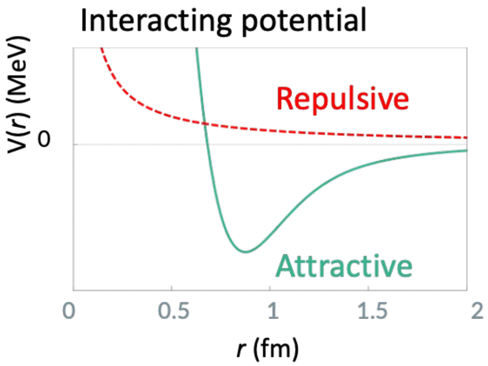
Femtoscopy in a nutshell

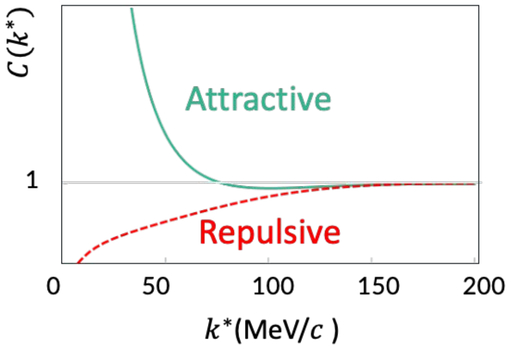


Measure the correlation function *C(k*)*

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

two particle wave function





Emission Source *S(r*)*

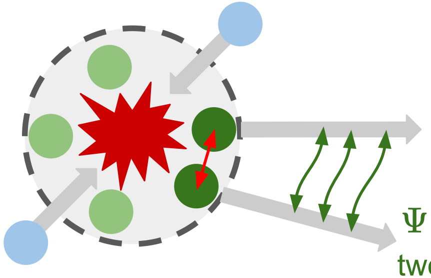
Schrödinger equation

Two-particle wave function

Correlation function *C(k*)*

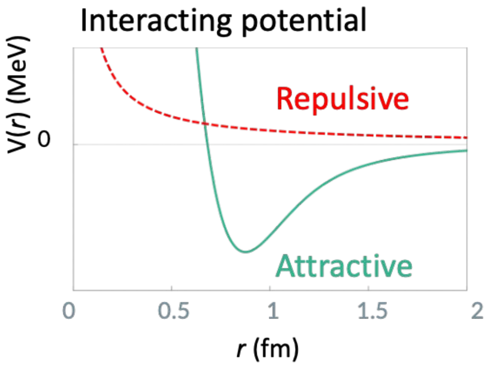
$$C(k^*) = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

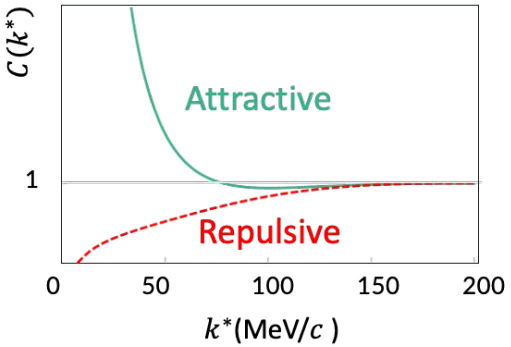
Femtoscopy in a nutshell



Measure the correlation function $C(k^*)$

$\Psi(\vec{k}^*, \vec{r}^*)$
two particle wave function





Emission Source $S(r^*)$

Schrödinger equation
Two-particle wave function

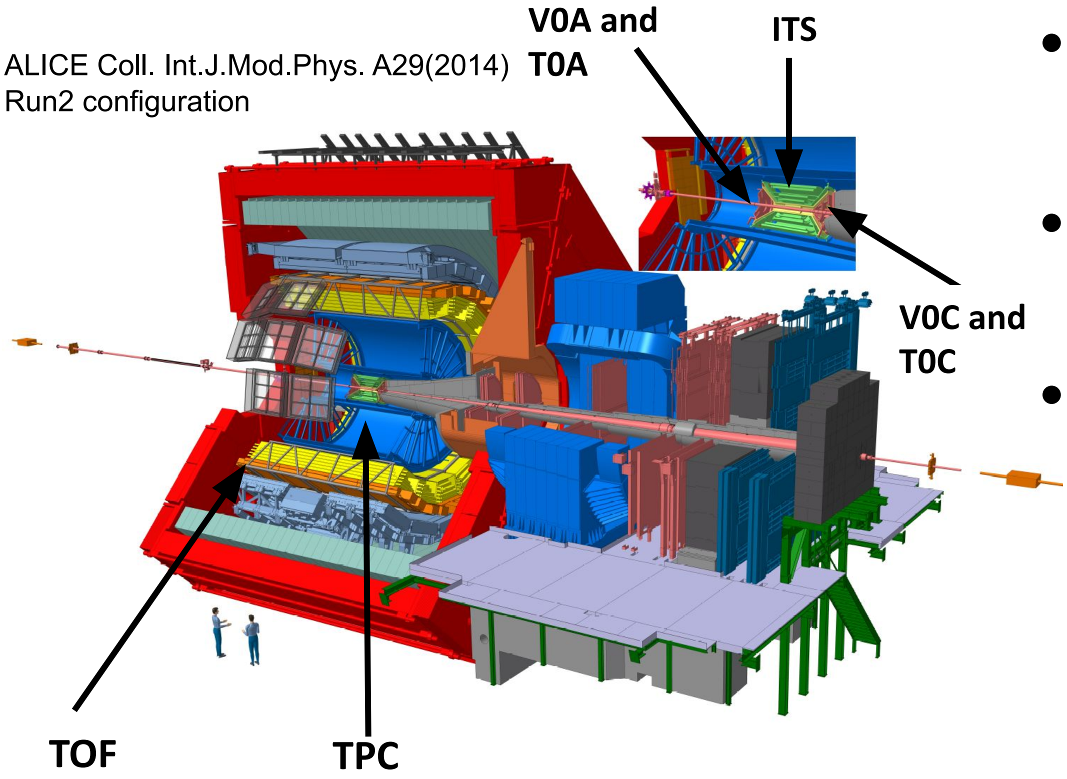
Correlation function $C(k^*)$

$$C(k^*) = \int S(r^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

- **Measure $C(k^*)$, use well known interaction, study $S(r^*)$**
- For evaluation of integral and $S(r^*)$ use CATS framework Eur.Phys.J.C 78 (2018) 5, 394

Femtoscopy at ALICE in Run2

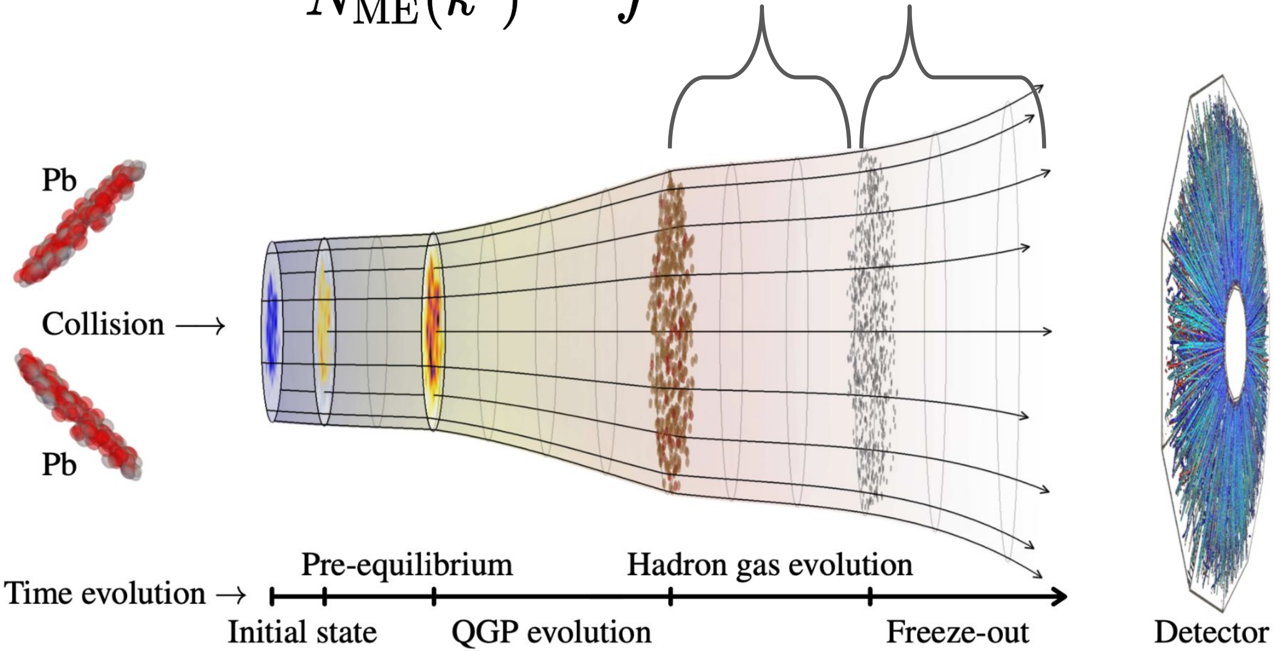
ALICE Coll. Int.J.Mod.Phys. A29(2014)
Run2 configuration



- HM pp collisions @ 13 TeV
  - 1 Billion evts. in Run2
- Direct detection of charged particles (π, K, p) by TPC and TOF
- Particle identification
  - Mean energy loss in TPC
  - Momentum reconstruction by TOF
  - Purity of about 99 % for π, K, p due to excellent PID capabilities

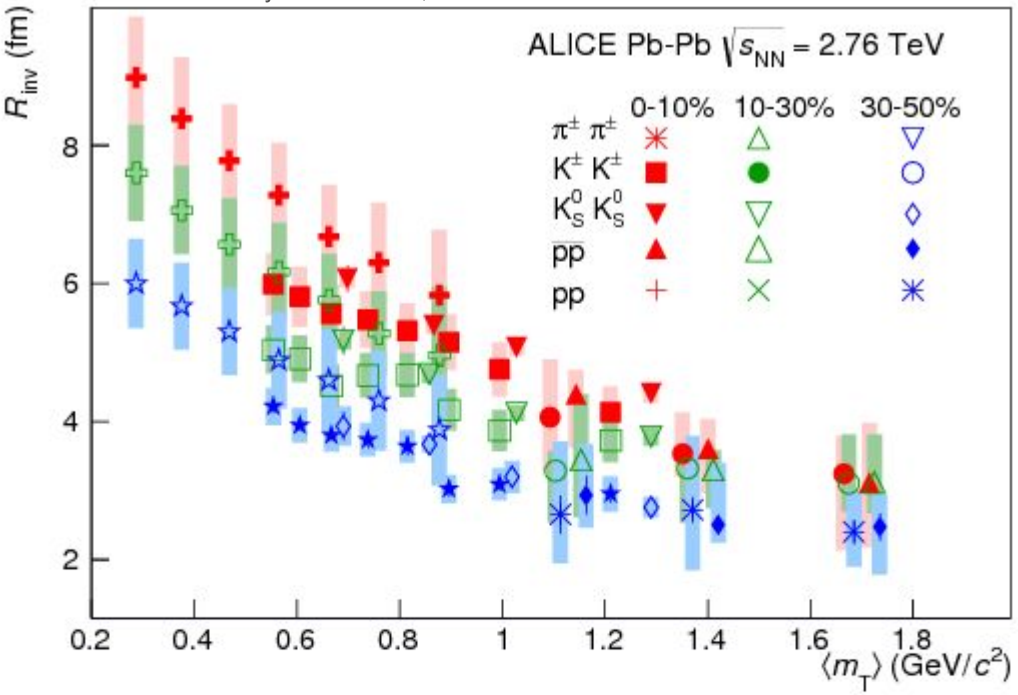
Femtoscopy in large systems

$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{SE}}(k^*)}{N_{\mathrm{ME}}(k^*)} = \int S(r^*)\left|\Psi(k^*)\right|^2 \mathrm{d}^3 r^* \xrightarrow{k^*\to\infty} 1$$

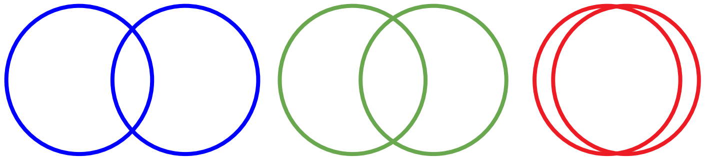


Baryon source in large systems

ALICE Phys. Rev. C **99**, 064901



- Centrality as a measure of the overlap



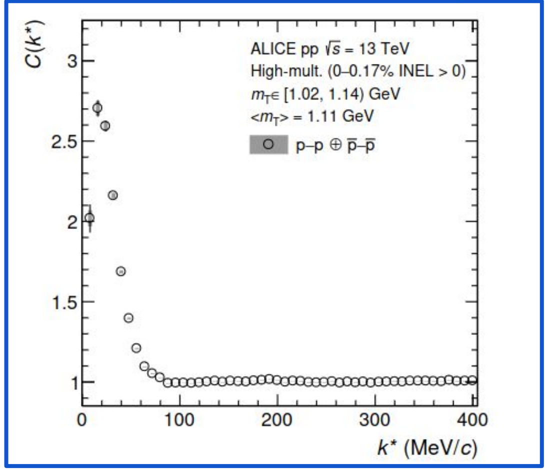
- Most simple ansatz for $S(r^*)$ is a Gaussian
- Scaling in Pb-Pb for identical pairs
- Dependence on centrality/multiplicity and transverse mass (m_T)

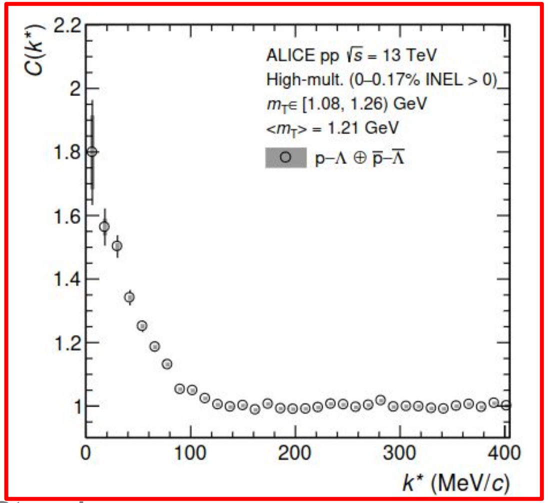
Baryon source in small systems

ALICE public note PUB-1378 (2023)

- Common source for all produced hadrons in small systems?
- Use p–p (well known interaction) to constrain the femtoscopic source
- Validate findings with p–Λ

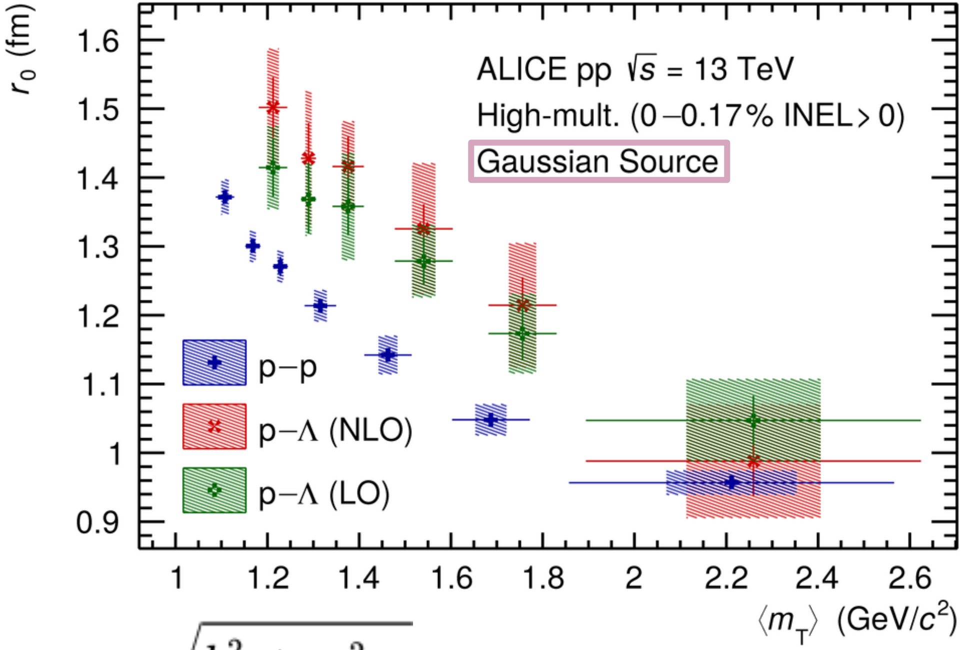
$$m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m_{\mathrm{avrg}}^2}$$
$$k_{\mathrm{T}} = \frac{1}{2}\left|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right|$$





Baryon source in small systems

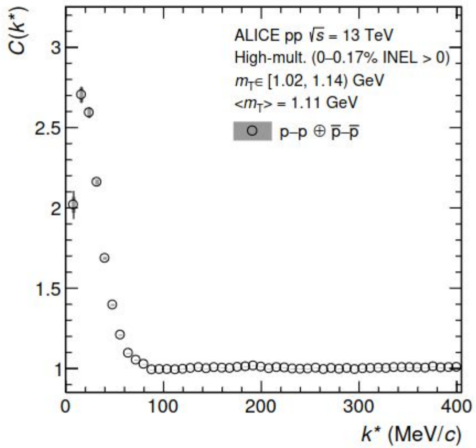
ALICE Coll. PLB 811 (2020)

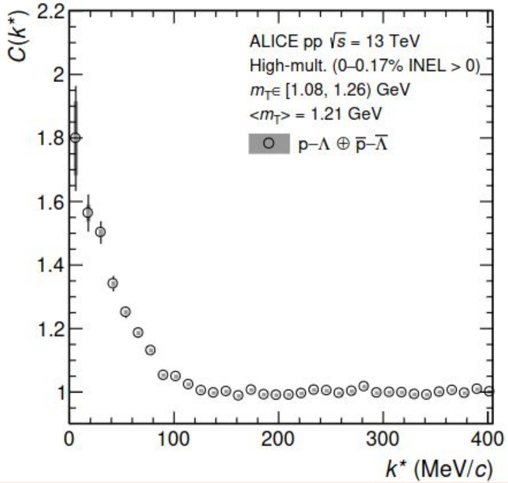


$$m_T = \sqrt{k_T^2 + m_{avrg}^2}$$

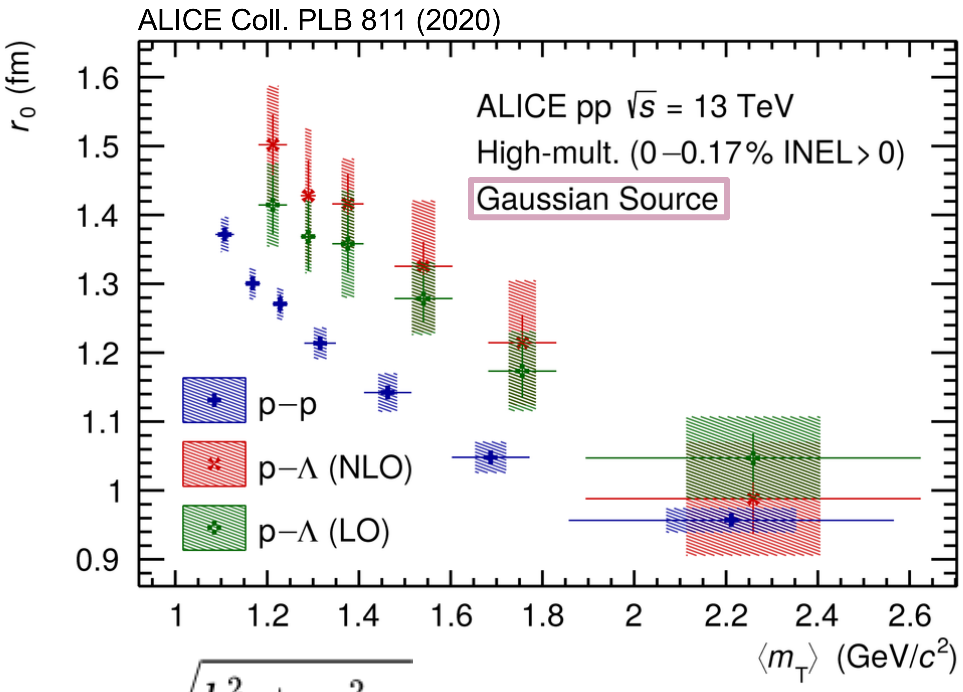
$$k_T = \frac{1}{2}|\vec{p}_{T,1} + \vec{p}_{T,2}|$$

ALICE public note PUB-1378 (2023)





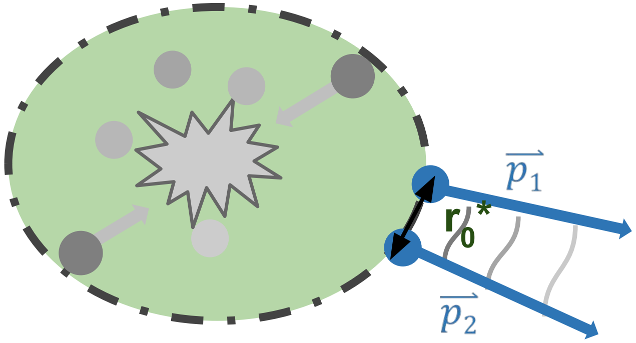
Baryon source in small systems



$$m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m_{\mathrm{avrg}}^2}$$

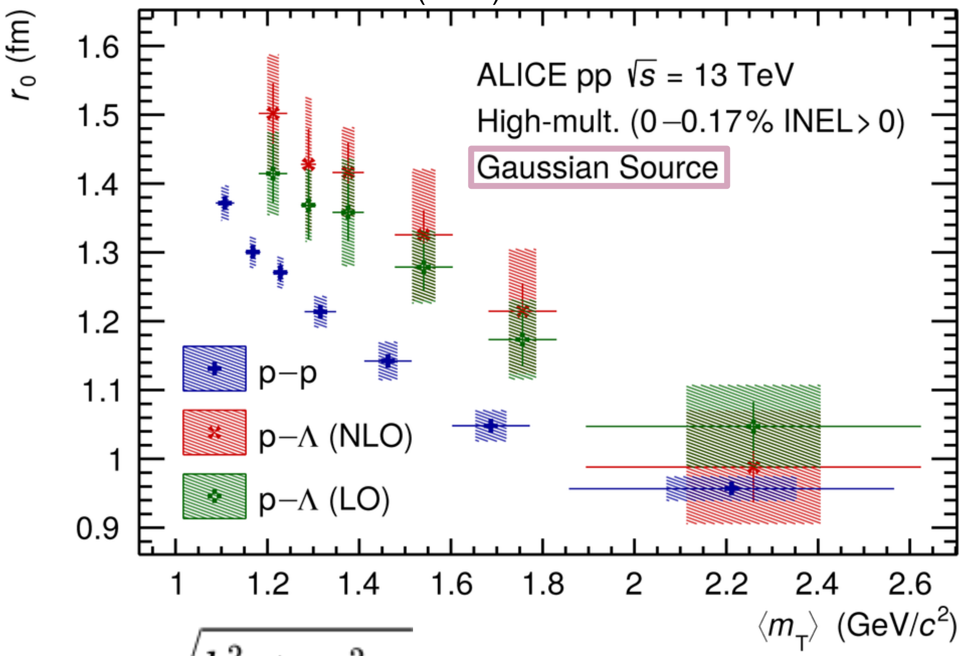
$$k_{\mathrm{T}} = \frac{1}{2}\left|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right|$$

- Scaling is expected for common radial flow velocity and hadronization time scale



Baryon source in small systems

ALICE Coll. PLB 811 (2020)



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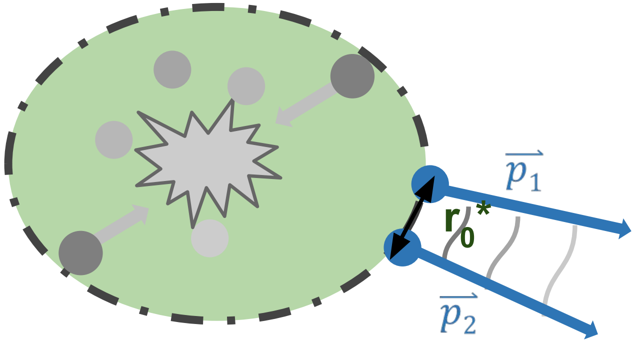
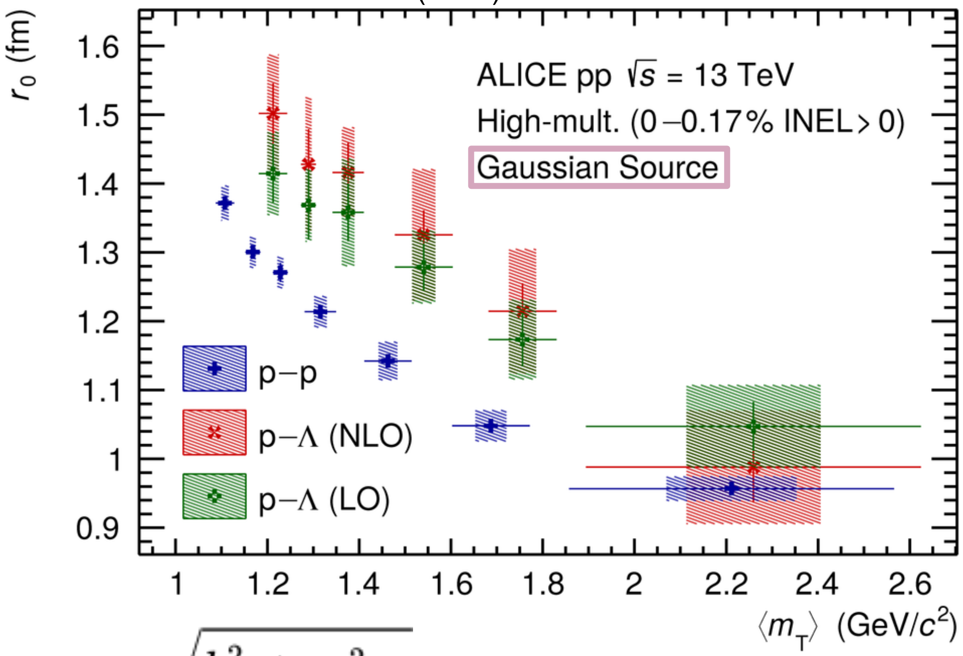
- Scaling is expected for common radial flow velocity and hadronization time scale
- Effects influencing the scaling include **non-gaussian** contributions to the source
  - **Feed down from resonances** [1,2]



[1] Y. Sinyukov et al. NPA 946 (2016)
[2] A. Widemann et al. PRC 865 56 (1997)

Baryon source in small systems

ALICE Coll. PLB 811 (2020)



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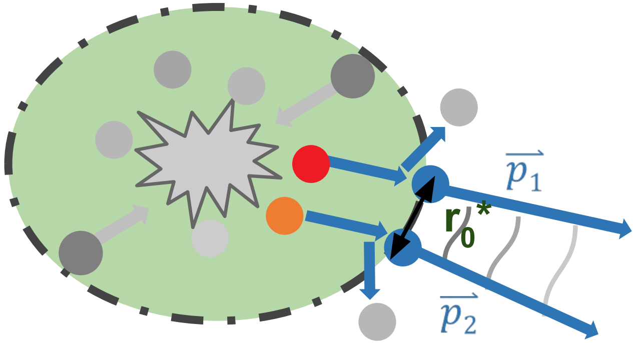

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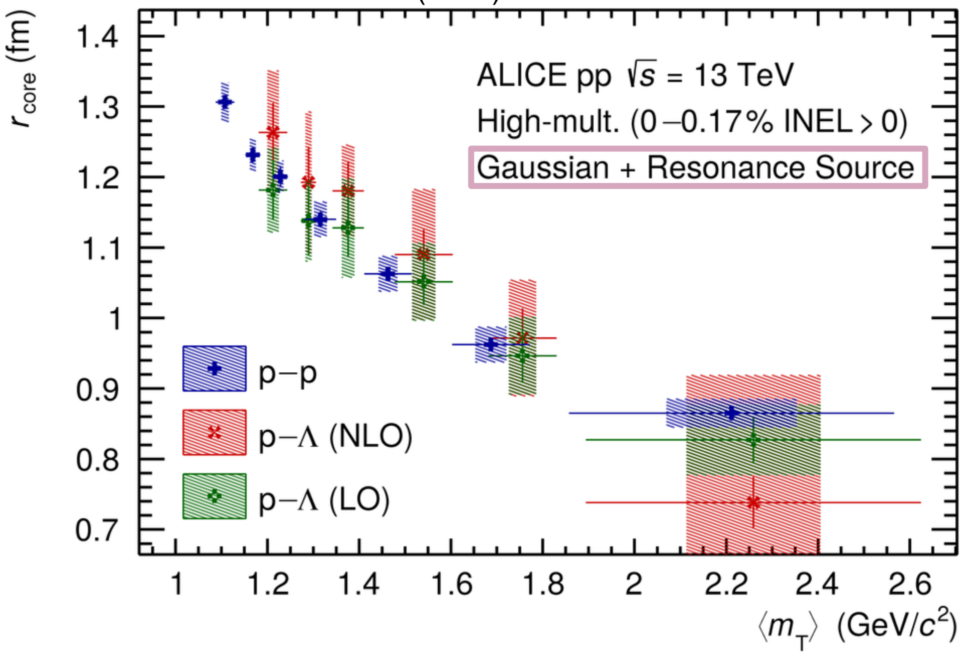
Common baryon source in small systems

ALICE Coll. PLB 811 (2020)

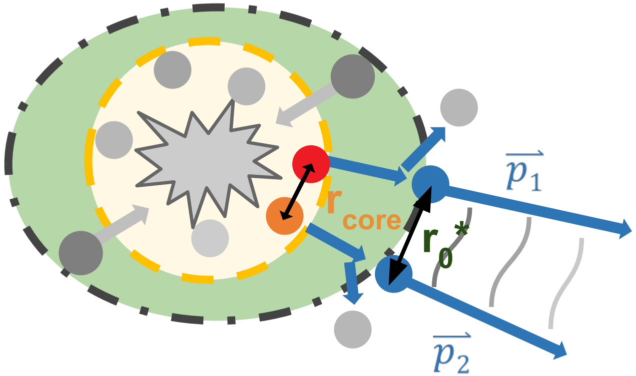


Access smaller m_T by studying π–π and meson-baryon correlations i.e. K^+–p

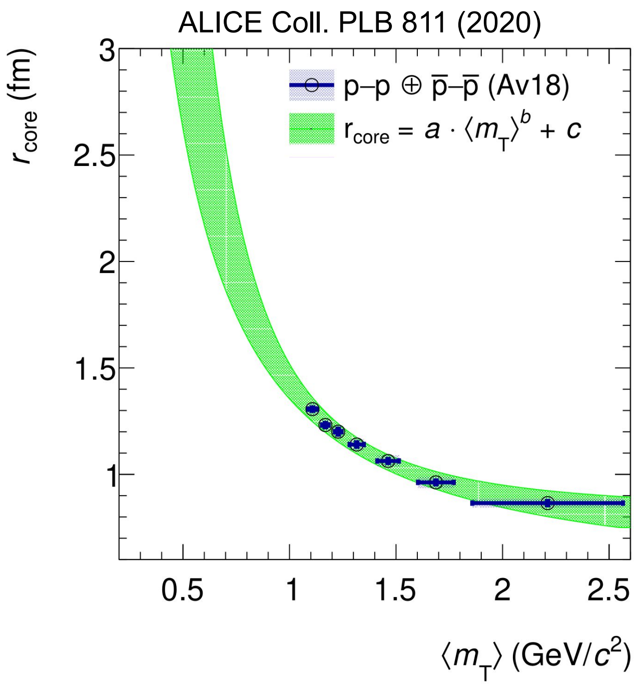
- Common scaling is restored by accounting for **non-gaussian** contributions

  ➔ Motivates the assumption of a universal particle source for baryons

- How well does the model perform for mesons? Is the scaling different?



Common baryon source in small systems



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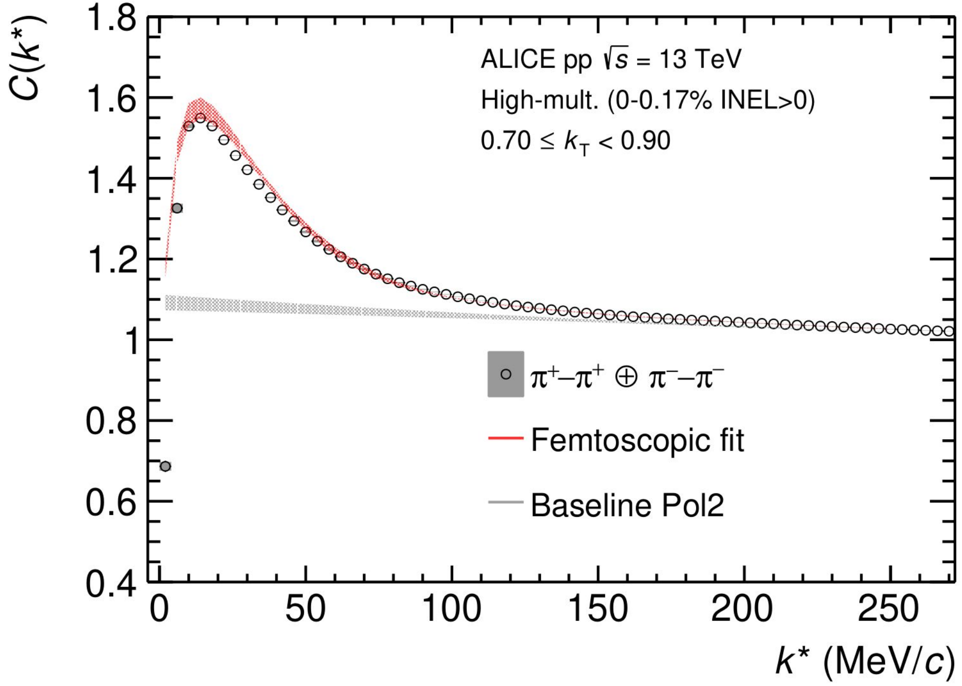
Access smaller m_T by studying π–π and meson-baryon correlations i.e. K^+–p

[1] Y. Sinyukov et al. NPA 946 (2016)
[2] A. Widemann et al. PRC 865 56 (1997)

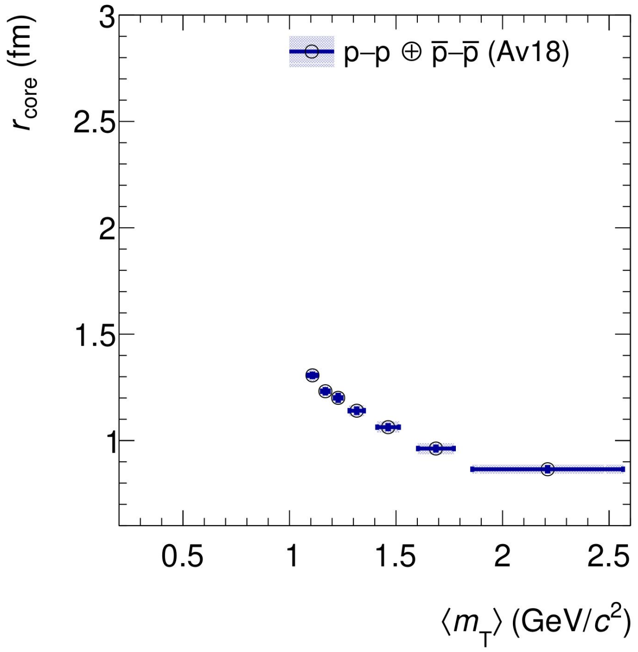
Measured two-particle correlation

ALICE Coll. *EPJC* 85 (2025) 2, 198



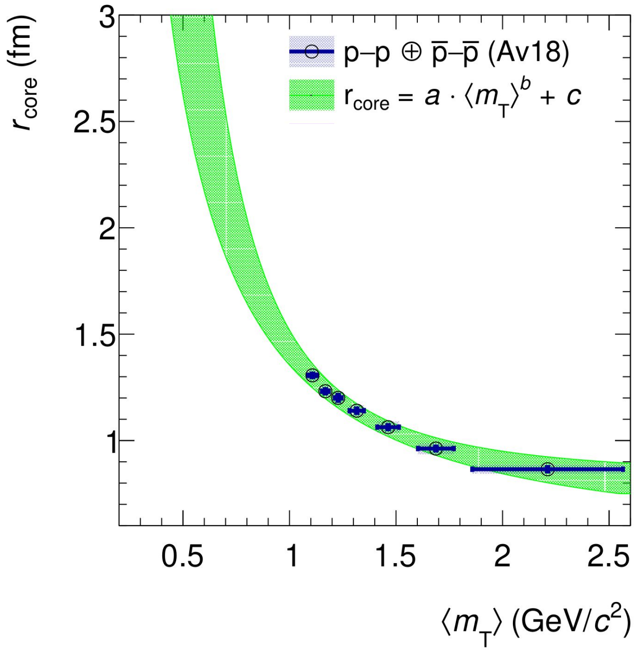
- Obtained in several m_T bins (# 5)
- Fit with $C^{\pi\pi}(k^*)$ with Pol1 **or** Pol2
  - Polynomial background term to account for residual background
  - Interaction governed by Coulomb interaction and Quantum Statistics

Core radius compared to previous results



- p–p taken from PLB 811 2020

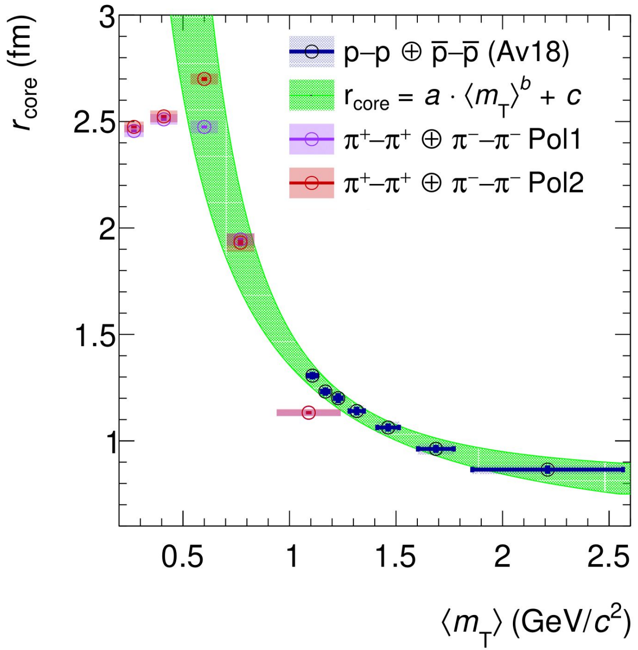
Core radius compared to previous results



- p–p taken from PLB 811 2020
- Parameterization and extrapolation of the r_{core} dependence

Core radius compared to previous results

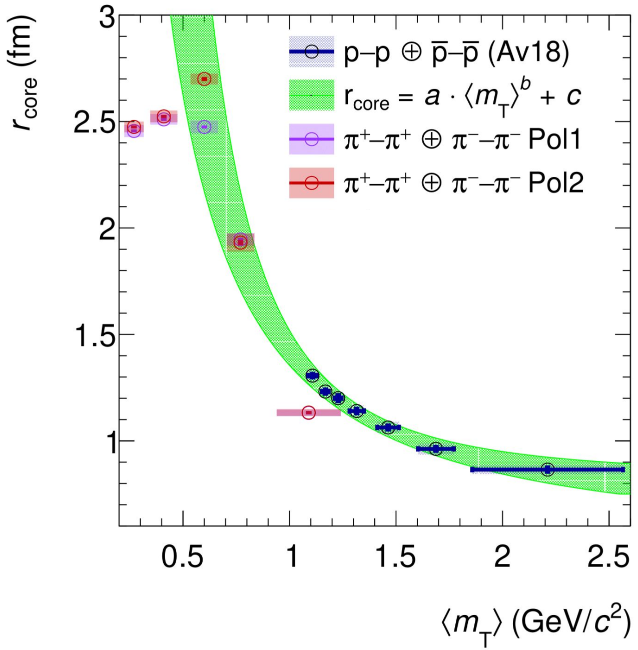
ALICE Coll. *EPJC* 85 (2025) 2, 198



- p–p taken from PLB 811 2020
- Parameterization and extrapolation of the r_{core} dependence
- π–π from this analysis (two background assumptions)

Core radius compared to previous results

ALICE Coll. *EPJC* 85 (2025) 2, 198

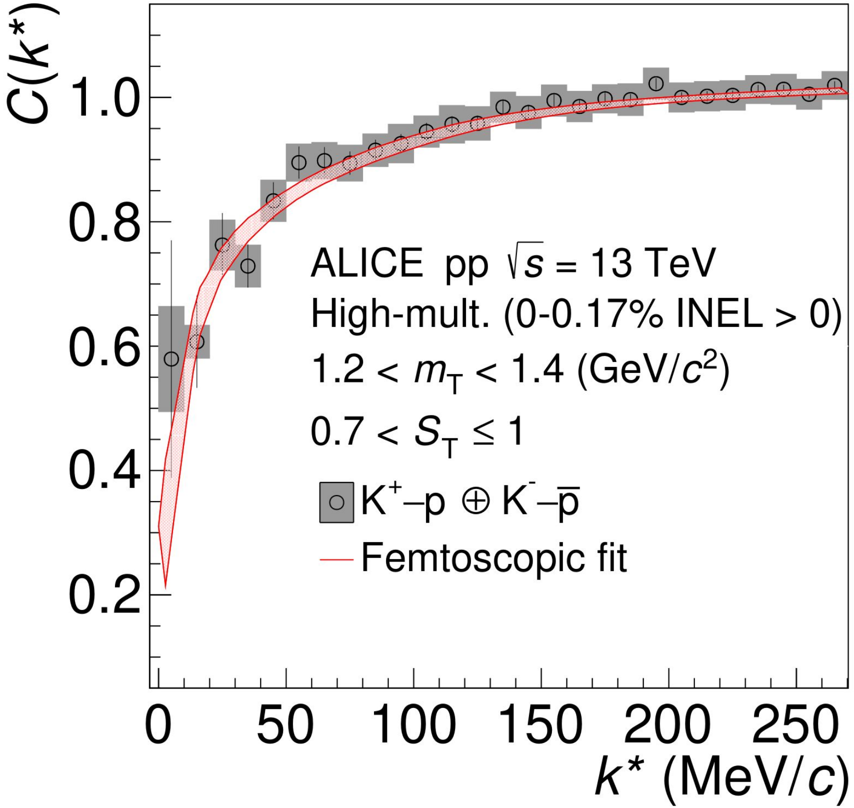


- p–p taken from PLB 811 2020
- Parameterization and extrapolation of the r_{core} dependence
- π–π from this analysis (two background assumptions)

- For m_T below 0.4 GeV/c^2 good agreement with parametrization
  - ➔ Saturation for π–π radii (**not** predicted by any model)

Measured two-particle correlation

ALICE Coll. *EPJC* 85 (2025) 2, 198

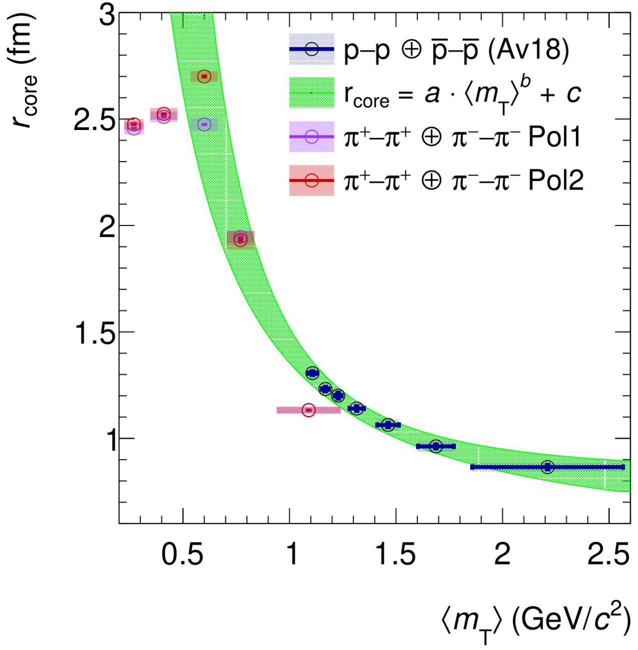


- Obtained in several m_T bins (# 4)
- Interaction is modeled by Coulomb interaction and χEFT [1]

[1] K. Aoki et al. PTEP 1 (2019)

Core radius compared to previous results

ALICE Coll. *EPJC* 85 (2025) 2, 198

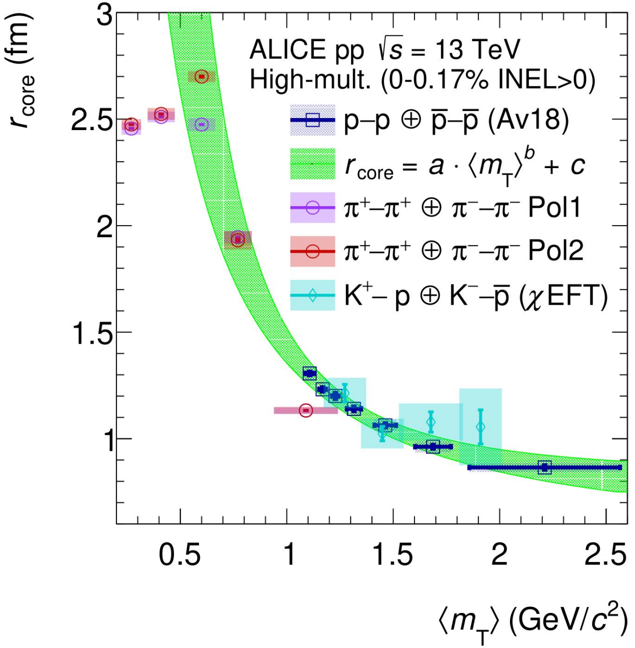


- p–p taken from PLB 811 2020
- Parameterization and extrapolation of the r_{core} dependence
- π–π from this analysis

- For m_T above 0.4 GeV/c^2 good agreement with parametrization
  - ➔ Saturation for π–π radii (not predicted by any model)

Core radius compared to previous results

ALICE Coll. *EPJC* 85 (2025) 2, 198

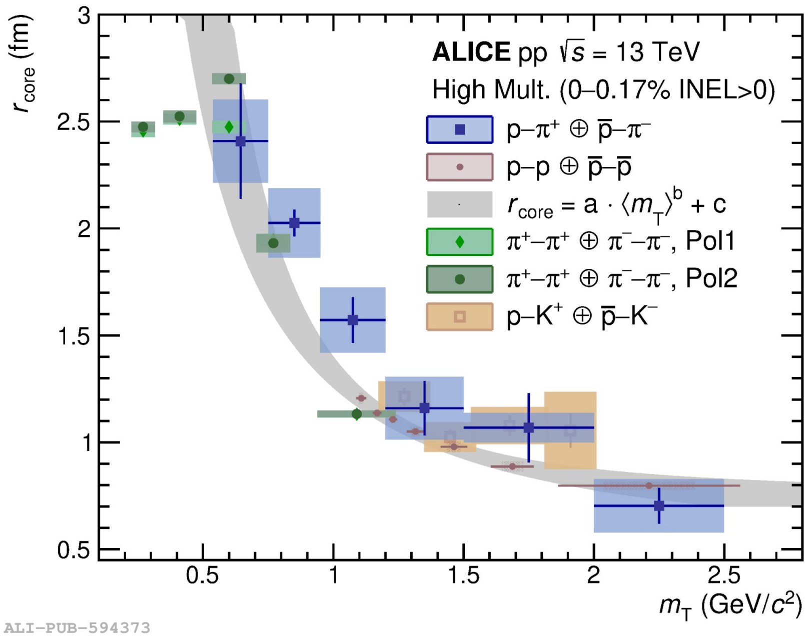


- p–p taken from PLB 811 2020
- Parameterization and extrapolation of the r_{core} dependence
- π–π from this analysis
- K^+–p from this analysis

- For m_T above 0.4 GeV/c^2 good agreement with parametrization
  - ➔ Evidence for a common source for **all** hadrons in pp

Current developments…

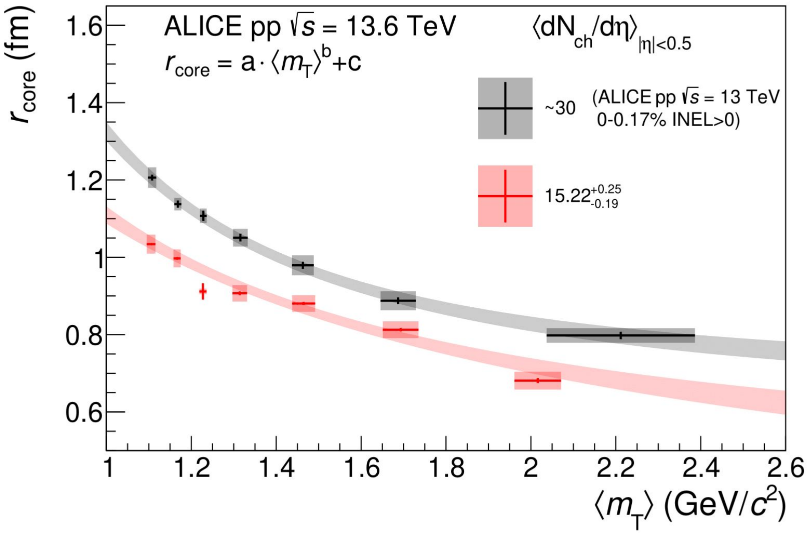
ALICE Coll. *EPJA* 61 (2025) 8, 194



- Adding **π–p** as second meson-baryon system

Current developments…

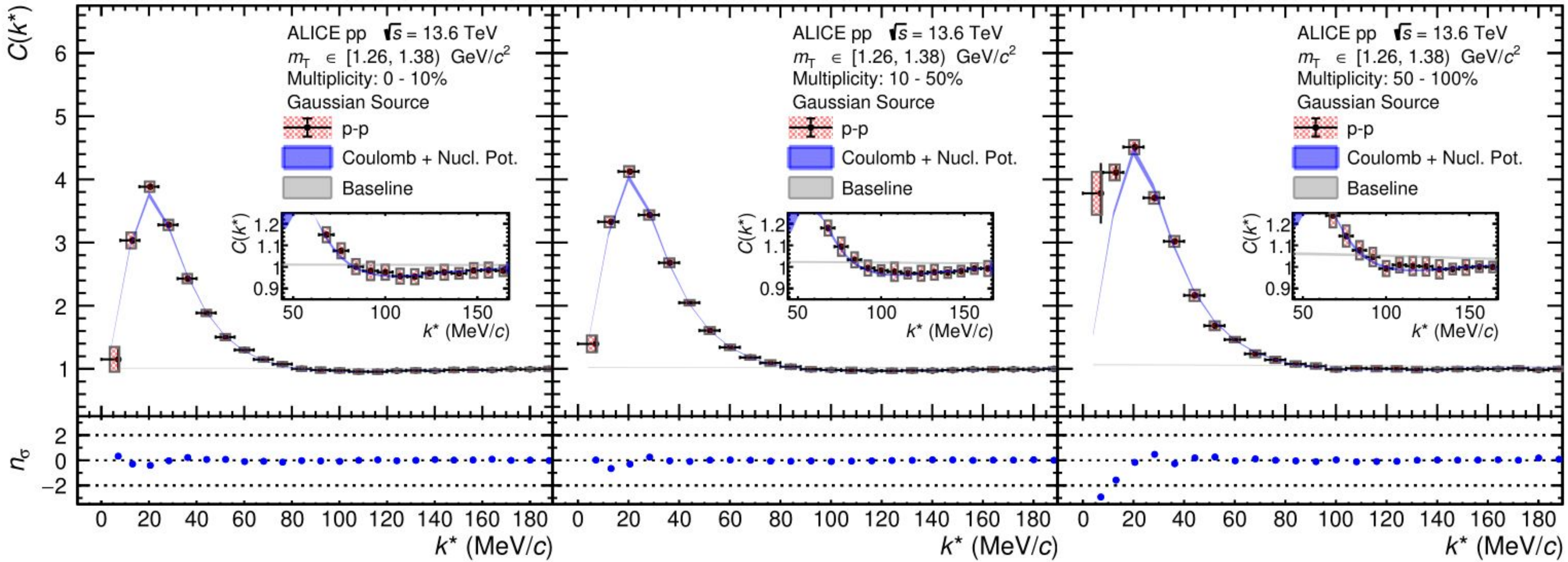
Paper in preparation



- Adding **π–p** as second meson-baryon system
- Studying source in Run3 data

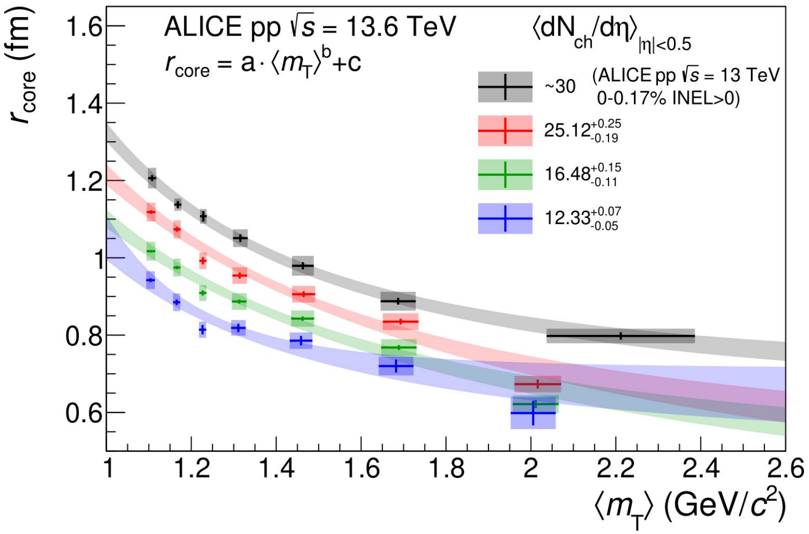
Current developments…

Paper in preparation



Current developments…

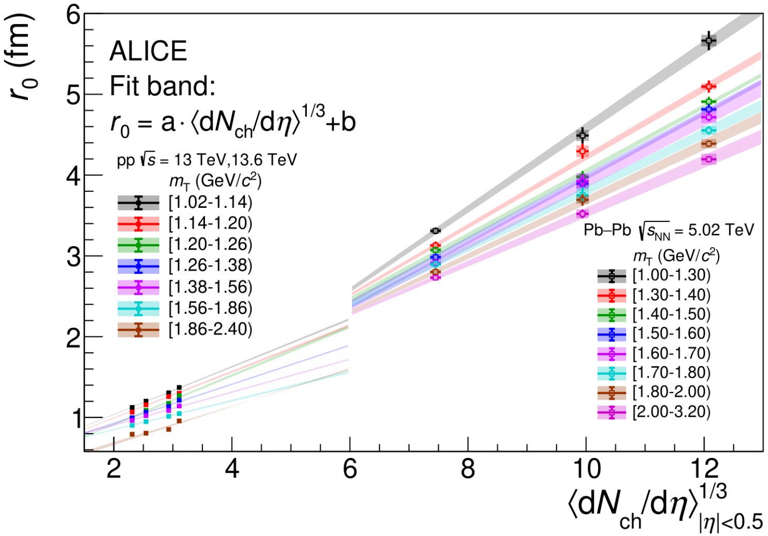
Paper in preparation



- Adding **π–p** as second meson-baryon system
- Studying source in Run3 data
  - Multi-differential study

Current developments…

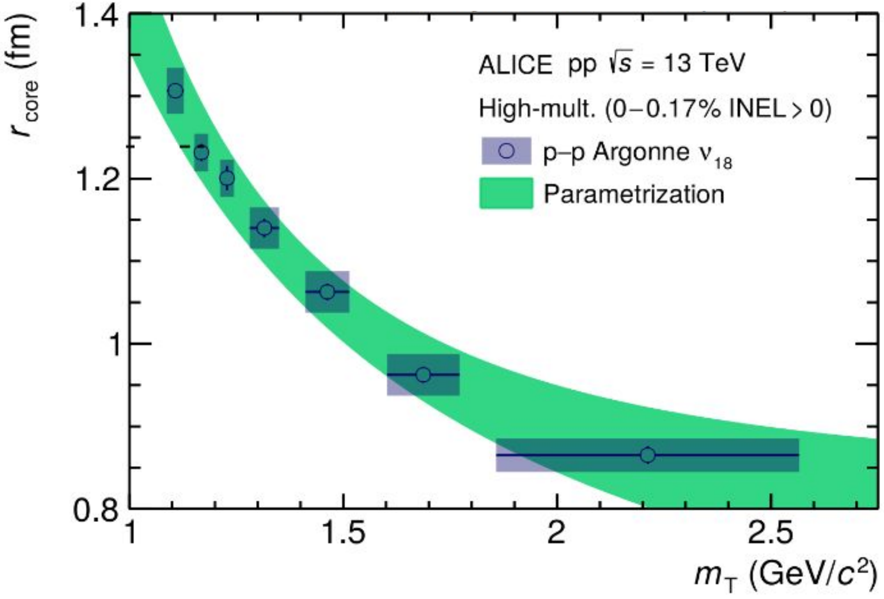
Paper in preparation



- Adding **π–p** as second meson-baryon system
- Studying source in Run3 data
  - Different trend to PbPb due to QGP?

Common baryon source in small systems

ALICE Coll. PLB 811 (2020)



- Centerpiece for high precision FSI studies
  - Enables the construction of $S(r^*)$

[1] Y. Sinyukov et al. NPA 946 (2016)
[2] A. Widemann et al. PRC 865 56 (1997)

Common baryon source in small systems

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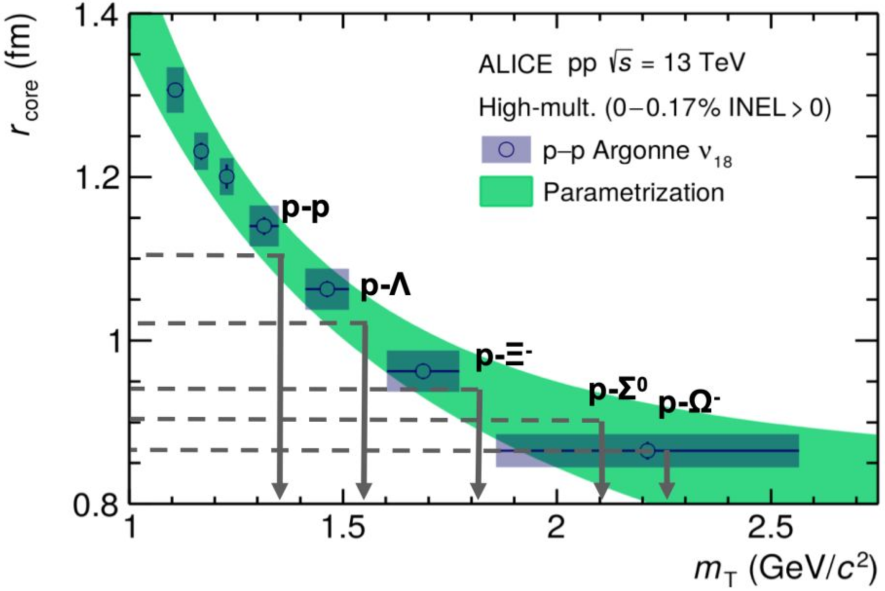

- Centerpiece for high precision FSI studies
  - Enables the construction of $S(r^*)$
- Recipe for the source
  - Obtain reference measurement
  - Employ RSM to obtain primordial $S(r^*)$
  - Calculate mean m_T of the pair
  - Employ RSM to add case specific resonances
    - Study final-state interactions

[1] Y. Sinyukov et al. NPA 946 (2016)
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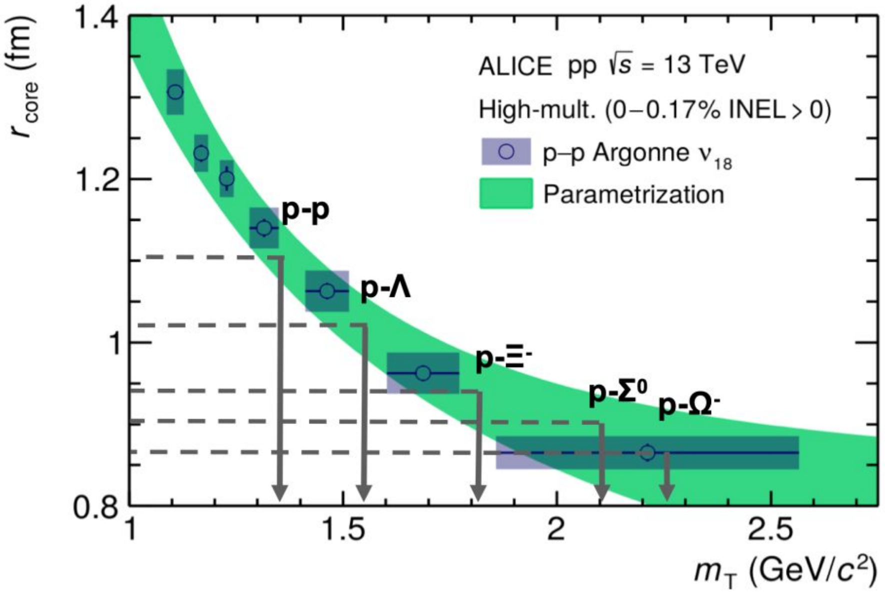
Common baryon source in small systems

ALICE Coll. PLB 811 (2020)

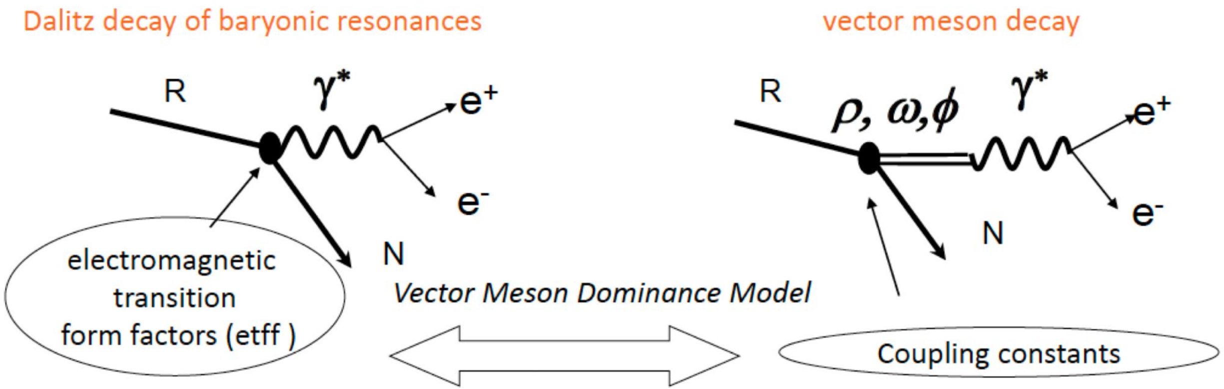


- Centerpiece for high precision FSI studies
  - Enables the construction of $S(r^*)$
- Recipe for the source
  - Obtain reference measurement
  - Employ RSM to obtain primordial $S(r^*)$
  - Calculate mean m_T of the pair
  - Employ RSM to add case specific resonances
    - Study final-state interactions

How to infer on scattering parameters form data?

[1] Y. Sinyukov et al. NPA 946 (2016)
[2] A. Widemann et al. PRC 865 56 (1997)

Vector meson nucleon interaction



- Usually probed by Vector Meson Dominance (VMD[1]) Models
  1: J. J. Sakurai, Phys. Rev. Lett. 22, 981 (1969)
  - Hadronic contribution to the photon propagator
  - Off-shell vector mesons

- Important to understand…
  - … in-medium dilepton production
  - … dynamically generated states N* and Δ* (pole positions) from unitarised chiral perturbation theory (UChPT[2])
    2: N. Kaiser, P. B. Siegel and W. Weise, Phys. Lett. B 362, 23 (1995)

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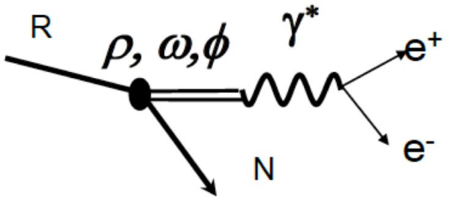
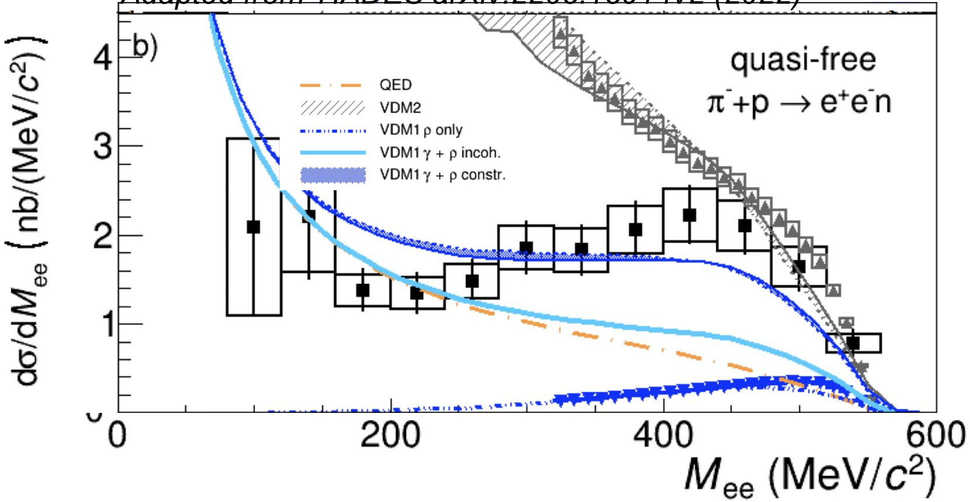
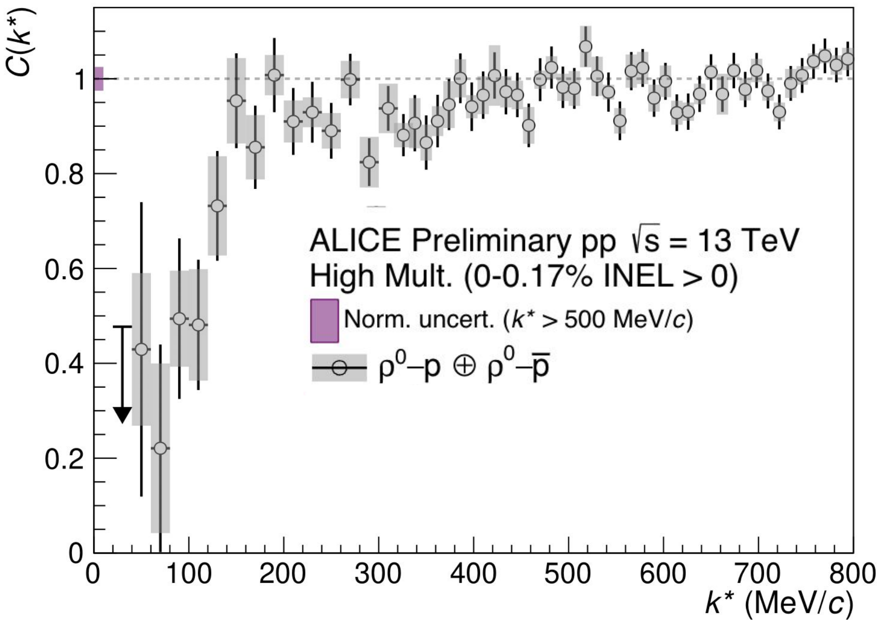


Adapted from HADES arXiv:2205.15914v2 (2022)



- Test of VMD at HADES
  - Low-energy beams (π)
  - M_{ee} excess compared to QED reference
- Excess modeled
  - With low-lying intermediate resonances (R) (N(1440), N(1520), N(1535) in a Rγ*N vertex)
- But how can one access the interaction between the ρ^0 and nucleon directly?

First direct observation of the ρ^0N coupling



1: *A. Feijoo, MK, L. Fabbietti PRD 111 (2025) 1, 014009*
2: *ALICE PRL 127 (2021)*

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  - Coupled channels: ρ^+n, ωp, ϕp, K*Λ, K*Σ
  - Includes dynamical states N*(1700) and N*(2000)
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Unitarised chiral perturbation theory for ρ^0–p

Interaction kernel V

$$T_{ij} = (1 - V_{il}G_l)^{-1} V_{lj}$$

Scattering Matrix T from i to j

Loop-function G

$$\psi_{ji}(k^*, r^*) = \delta_{ij} j_0(k^* r^*) + \int_{q \leq q_{\text{cut}}} d^3q\, j_0(q r^*) G_j(\sqrt{s}, q) T_{ji}(\sqrt{s}, k^*, q)$$

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- *Core Idea*
  - Extract LO interaction form **Chiral *L* + Hidden Gauge Symmetry**
  - Solve **Bethe–Salpeter Equation** in **coupled channels** ansatz[1]
- *Outcome*
  - Resonances as poles in *T*-Matrix
  - Extract scattering parameters from wavefunction

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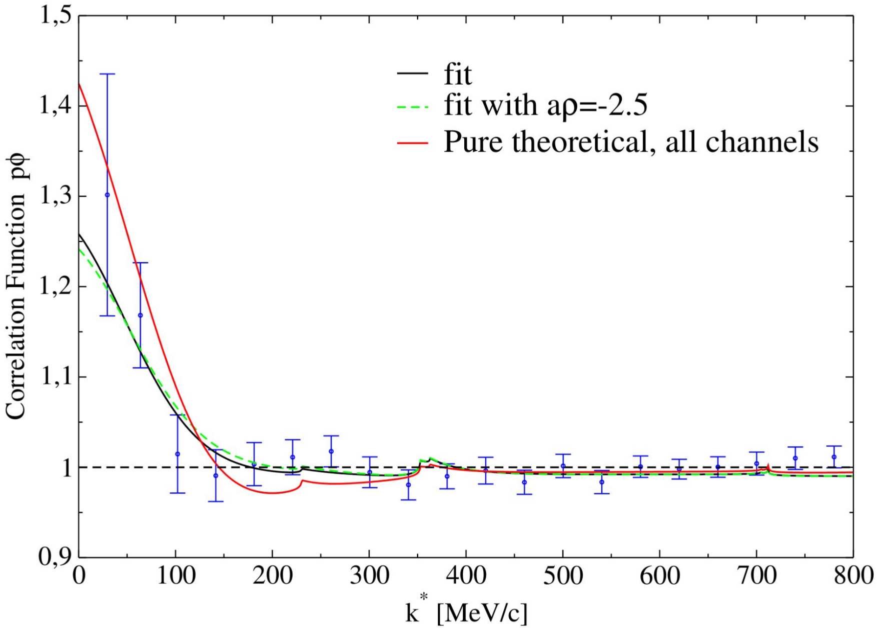

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- *Advantages over VMD*
  - *Naturally* accounts for int. dynamics coupled channels + resonances
    - Use ϕ–p CF result[2]
  - Based on gauge principle

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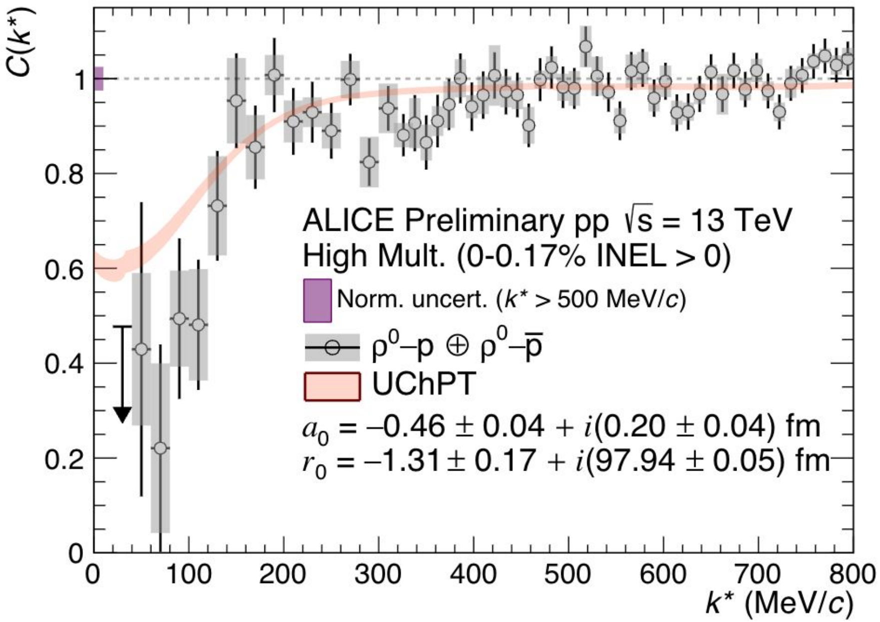
Prediction from UChPT for ρ^0–p



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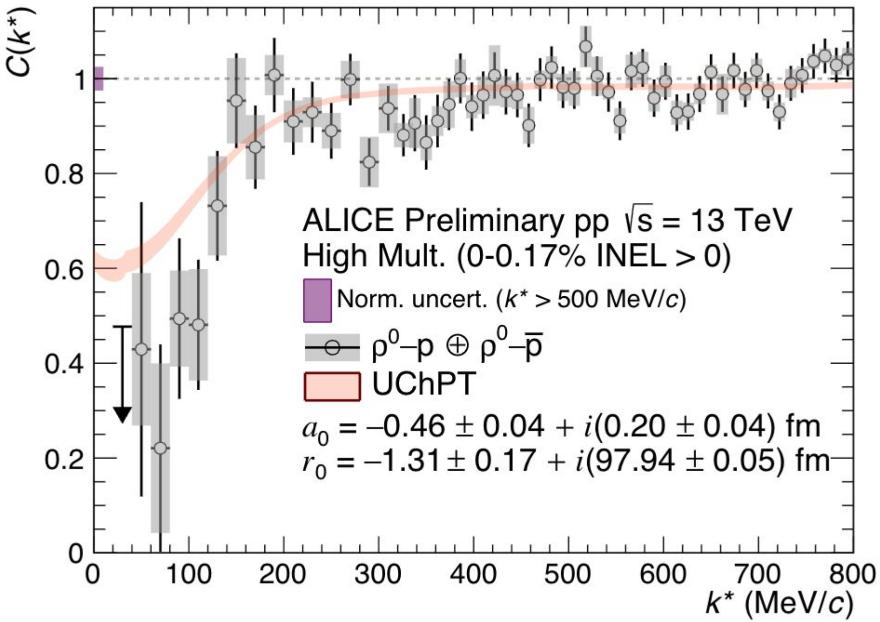
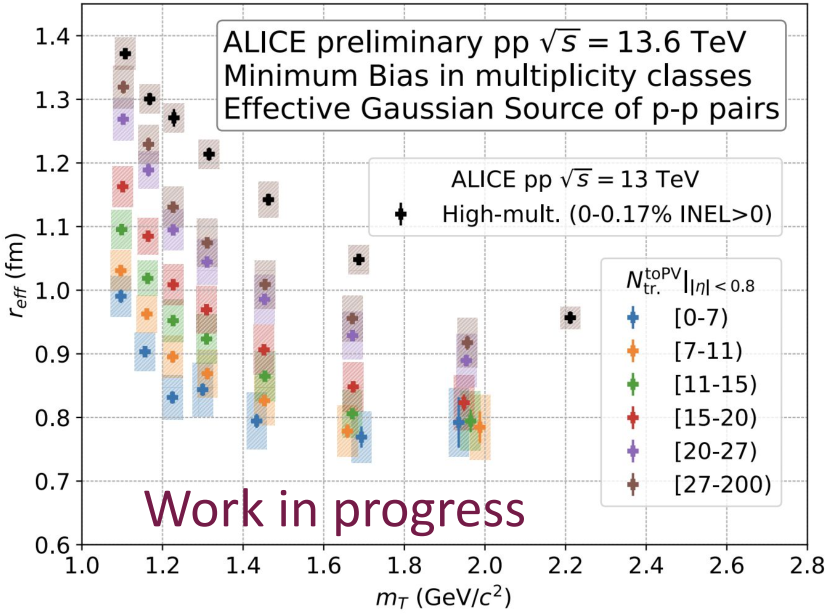
Take away



- Access to the interaction of the shortest-lived QCD state
- First direct measurement of the ρ^0p interaction with full phase information
- Implications
  - Benchmark VMD implementations
  - Basis for Chiral symmetry restoration studies
  - Collider based insight into QCD spectrum
- Paper submitted to PRL
  arXiv:2508.09867

Current developments…



- Adding π–p as second meson-baryon system
- Finalize calibration measurement of **p–p** in Run3
  - Foundation of high precision femtoscopic final state interaction studies

Back-up

Summary + Physics Message

Summary

- For the **first time** a quantitative description of the exponential source of pions is presented by **explicitly** considering the influence of short-lived resonances on a Gaussian core (RSM model)
- K^+–p and same charge π–π show agreement with the RSM assumption of a **universal** Gaussian core **source** for primordial particles
- Source radii reach saturation for m_T < 0.4 GeV/*c*

Physics Message

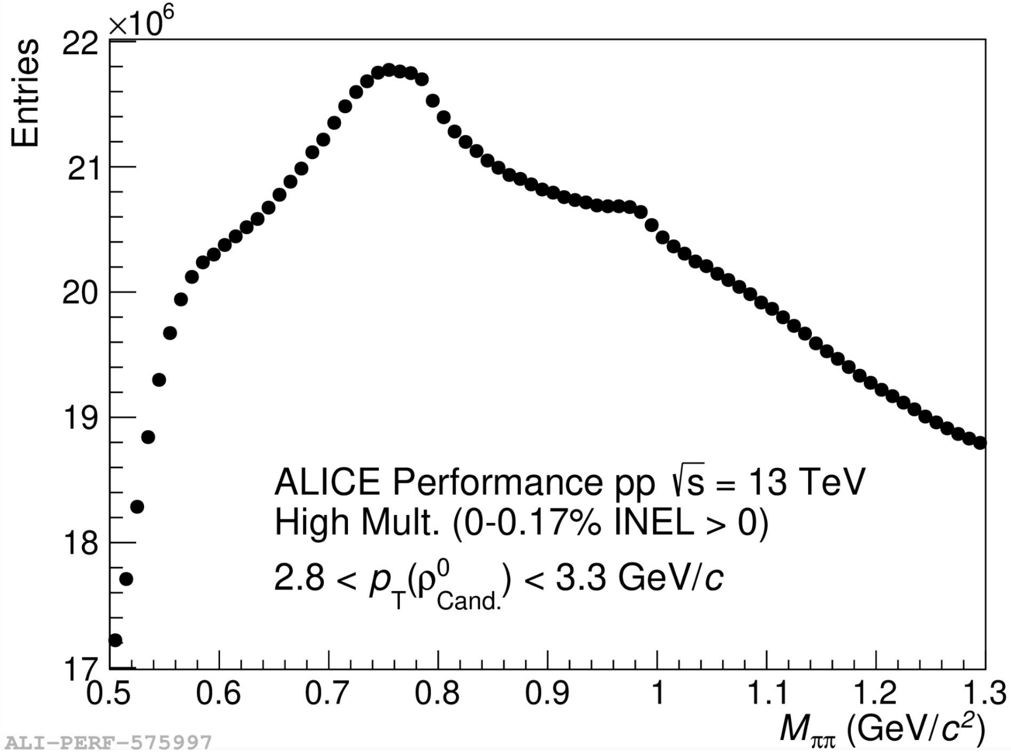
- A scaling behavior with m_T was observed for the extracted radii, **consistent** with previous baryon–baryon findings
- **Saturation** is observed

Outlook

- Available data to tune particle production coordinates in transport models
- Refine source model in order to account for saturation effects (CECA [1])

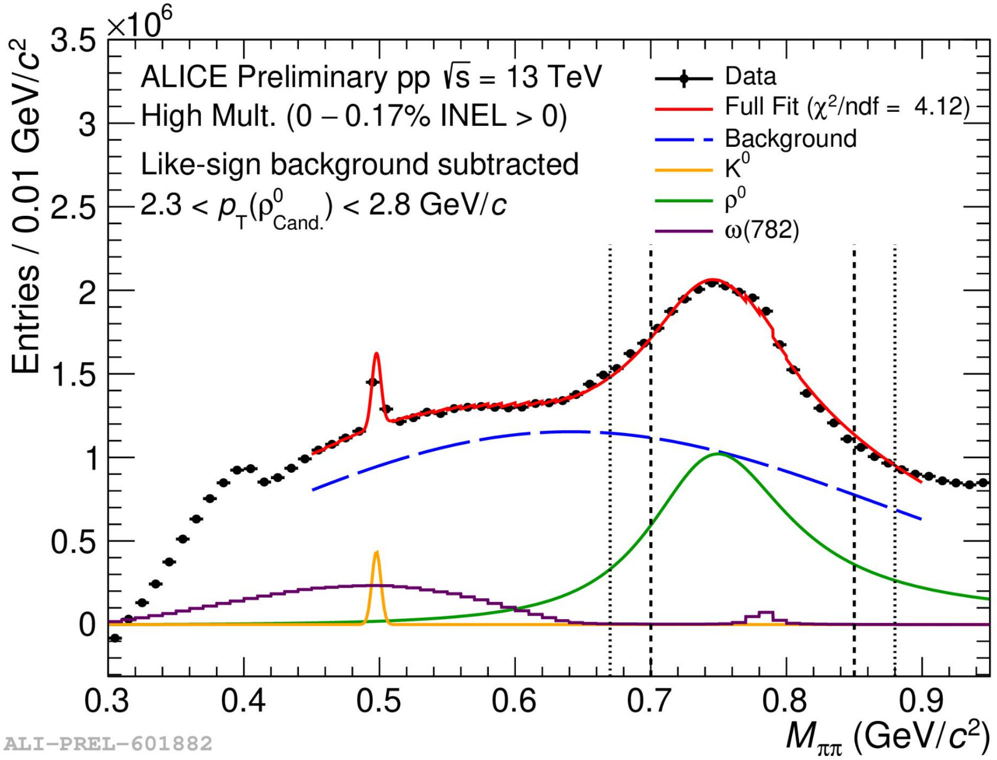
[1] D. Mihaylov et al. arXiv 2305.08441(2023)

Reconstruction of ρ^0



- Access to ρ^0 ($c\tau$ = 1.2 fm/c)
  - Pair all π in an event
    $\rho^0 \rightarrow \pi^+\pi^-$ (B.R. ≅ 100%)
- Purity of the ρ^0 around **3.26%**
  - Obtained by fit
- Two types of background
  - Combinatorial due to $(\pi\pi)_{\mathrm{Comb.}}$
  - Mini-jet correlations

Model $M_{\pi\pi}$ to access purity of ρ^0



Assess purity of ρ^0

- Pair all π in an event
- Record $M_{\pi\pi}$ vs p_T
- Fit projections

Method follows established procedures[1,2]

- Use LSB subtraction
- Model states with rBW/MC temp.
- Gaussian for K^0
- **Purity 3.26%**

For $p_T > 1.8$ GeV/c ρ^0-peak is visible

- translates to high m_T pairs
- **$1.64 < m_T < 3.77$ (GeV/c^2)**

1: STAR, PRL. 92 (2004) 092301
2: ALICE, PRC 99 (2019) 064901

Extraction of the genuine ρ^0–p correlation

$$C_{\text{measured}}(k^*) = C_{\text{minijet}}(k^*)\left[\lambda_{\rho^0\text{–p}} \cdot C_{\rho^0\text{–p}}(k^*)\right] + (1-\lambda_{\rho^0\text{–p}}) \cdot \left(\omega_{\text{left}} C_{\text{SB}}^{\text{left}}(k^*) + (1-\omega_{\text{left}}) C_{\text{SB}}^{\text{right}}(k^*)\right).$$

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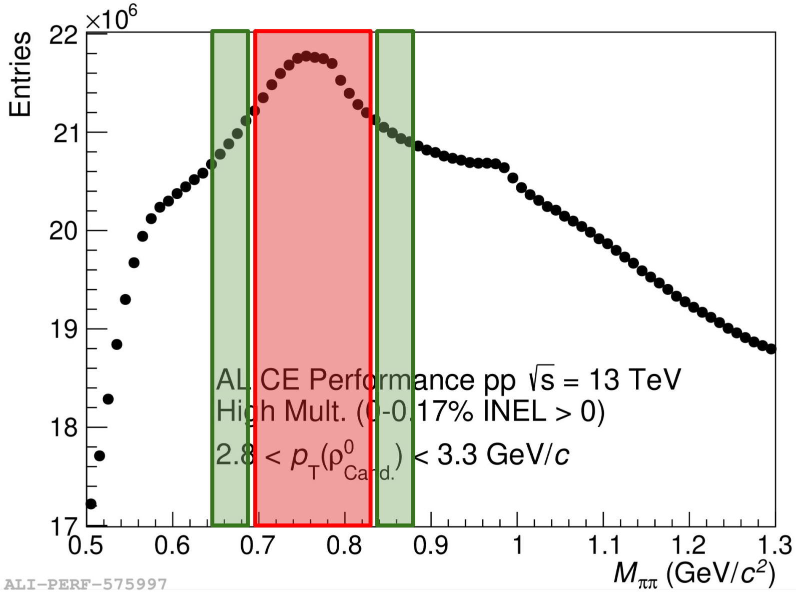
- Account for correlation of $(\pi\pi)_{\text{Comb.}}$ underneath ρ^0 signal
- Employ sideband (SB) analysis
  - Compute correlation function selecting $\rho^0_{\text{Cand.}}$ from left and right sideband region



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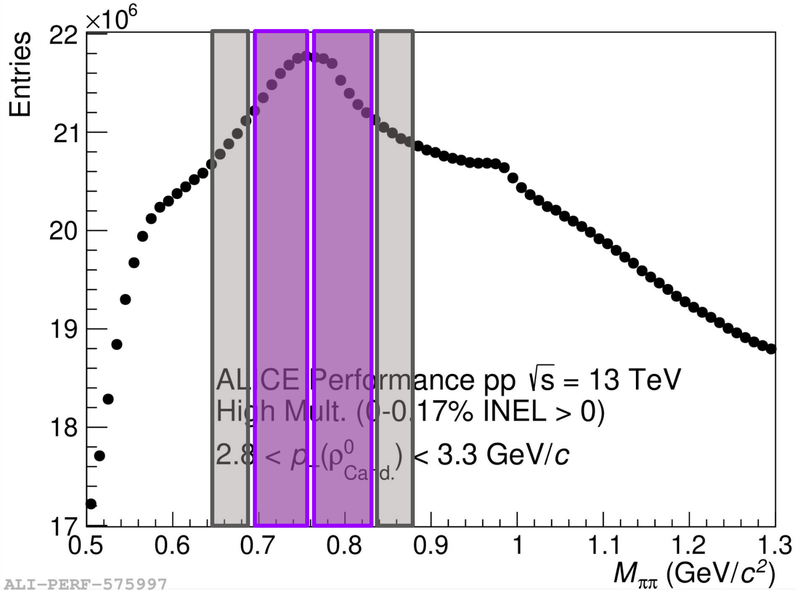
- Account for correlation of $(\pi\pi)_{\text{Comb.}}$ underneath ρ^0 signal
- Employ sideband (SB) analysis
  - Compute correlation function selecting $\rho^0_{\text{Cand.}}$ from left and right sideband region
  - Calculate weights by integration
  - Obtain SB correlation by a weighted average



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- Account for correlation of …
  - fake ρ^0-p by **SB subtraction**
    - SB left and right weighted (ω) with integral under ρ^0 peak
    - Take genuine ρ^0-p in SB into account
  - **Minijets** in ρ^0-p by dividing by SB (assume SB is dominated by Minijet)

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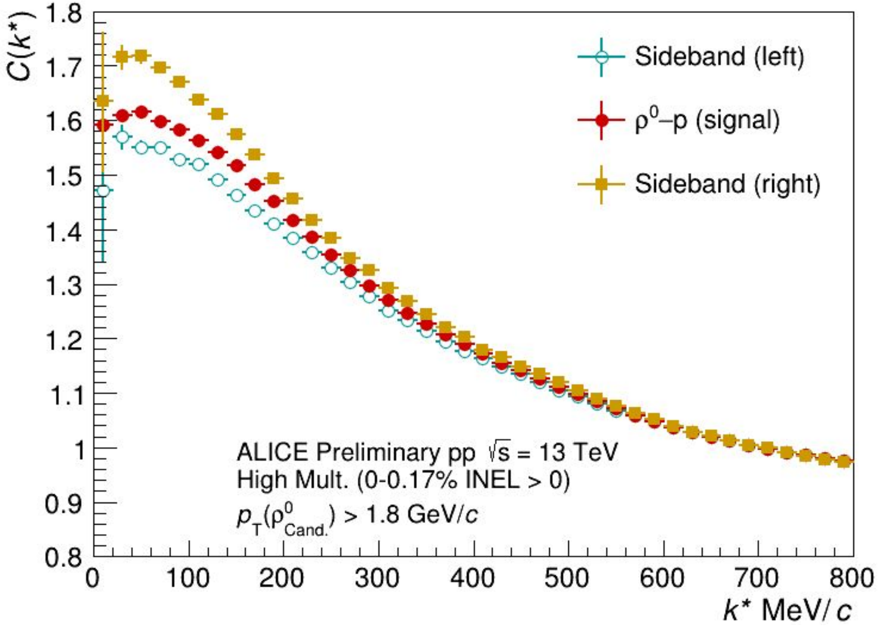
- Properly scaled by the **λ parameter**
  - Depends on the single-particle properties (purity and fractions)
  - dominated by the purity of ρ^0

Correlation function of signal and sidebands



- Normalisation 600 - 800 MeV/*c*
- Correlation in signal region
  - ρ^0-p final-state interaction
  - Minijet contribution
  - correlation from SB
- Corrections
  - Take ρ^0-p in SB into account
  - Subtract λ scaled SB

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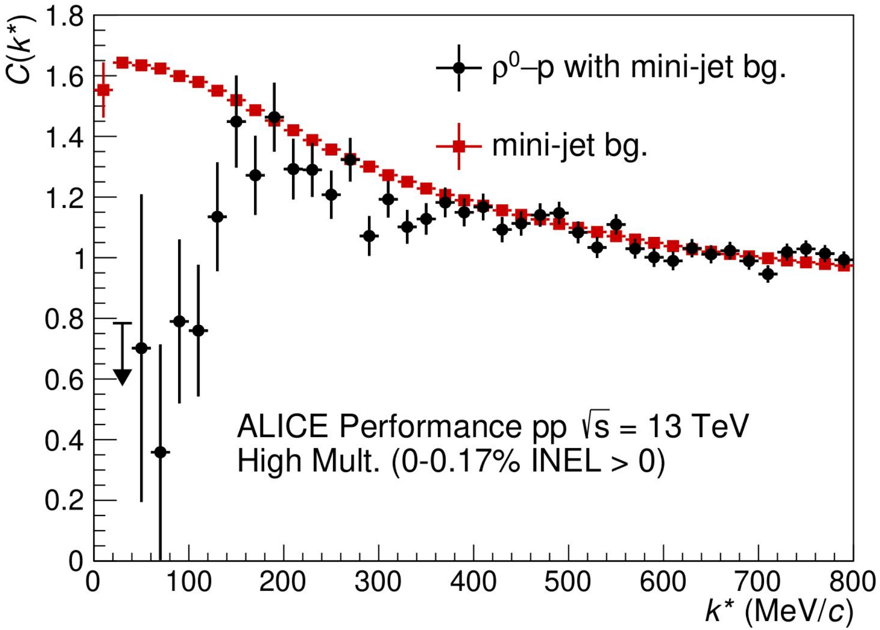
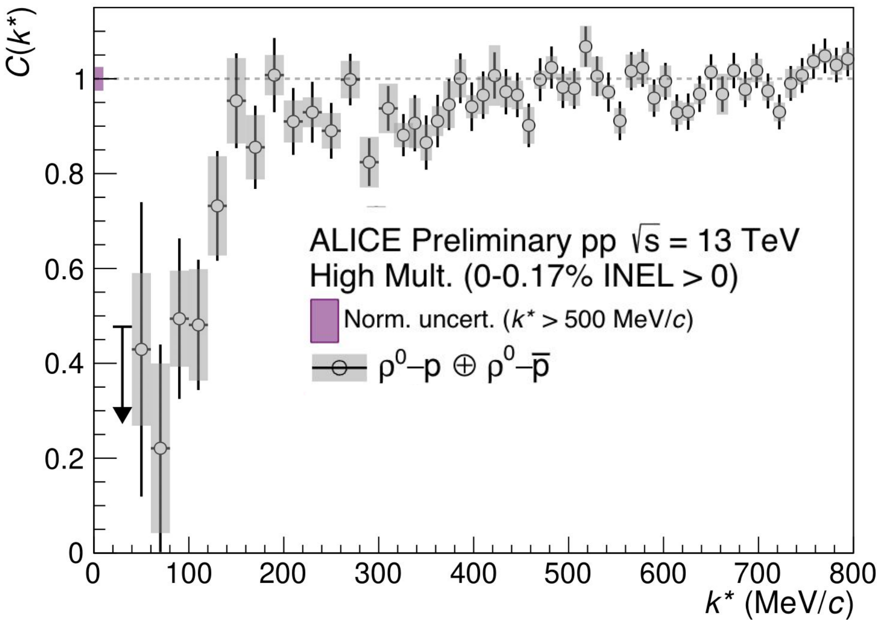
ρ^0-p correlation after SB subtraction



- Normalization region in 600–800 MeV/*c*
- **λ(= 2.7%)** dominated by ρ^0 purity
- Minijet contribution still present
- Corrections
  - Assumption: Minijet equals SB
  - Divide by SB as proxy for Minijet

$$C_{\rho^0-\mathrm{p}}(k^*) = \frac{1}{\boxed{C_{\mathrm{minijet}}}}\left\{\boxed{\frac{1}{\lambda_{\rho^0-\mathrm{p}}}\left[C_{\mathrm{measured}}(k^*) - (1-\lambda_{\rho^0-\mathrm{p}})C_{\mathrm{SB}}(k^*)\right]}\right\}.$$

First direct observation of the ρ^0N coupling



- Systematics obtained by varying selections
- nσ values w.r.t to unity (no interaction) for…
  - < 100 MeV/c: 3.6
  - < 120 MeV/c: 4.3
  - < 200 MeV/c: 4.0
- Coupled channels: ρ^+n, ωp, ϕp, K*Λ, K*Σ
- Other N* and Δ* states (4* in PDG)
  - N*(1700) below ρN threshold (1713 MeV)

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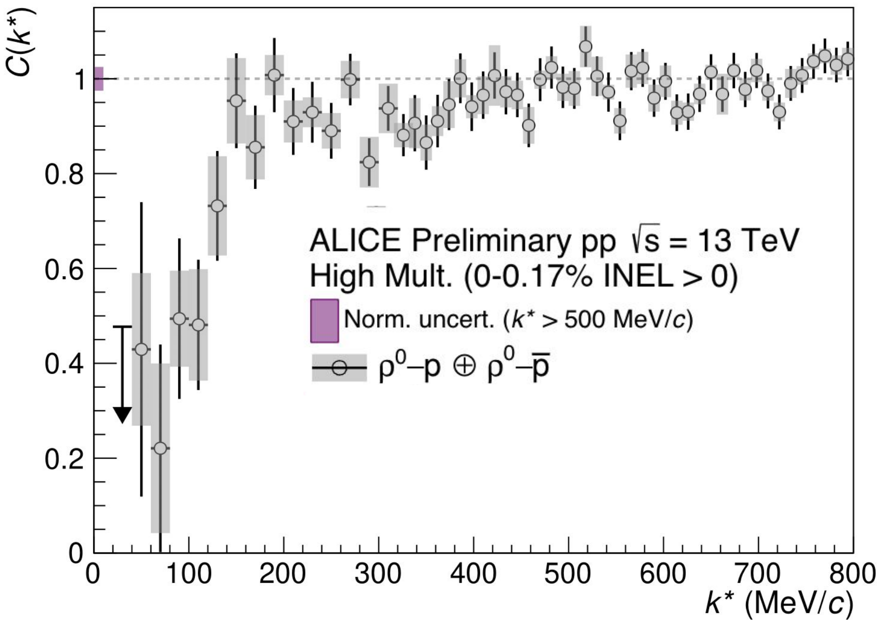

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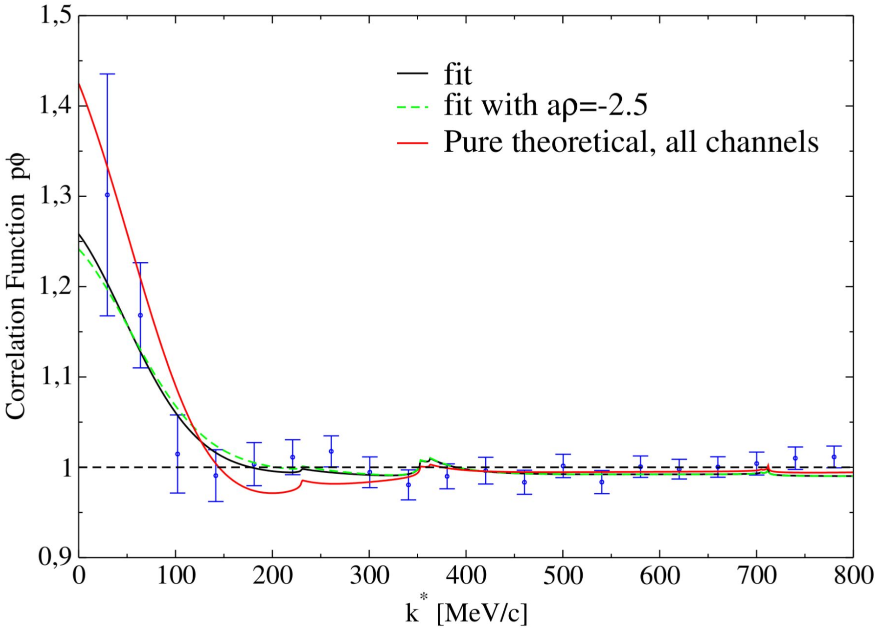

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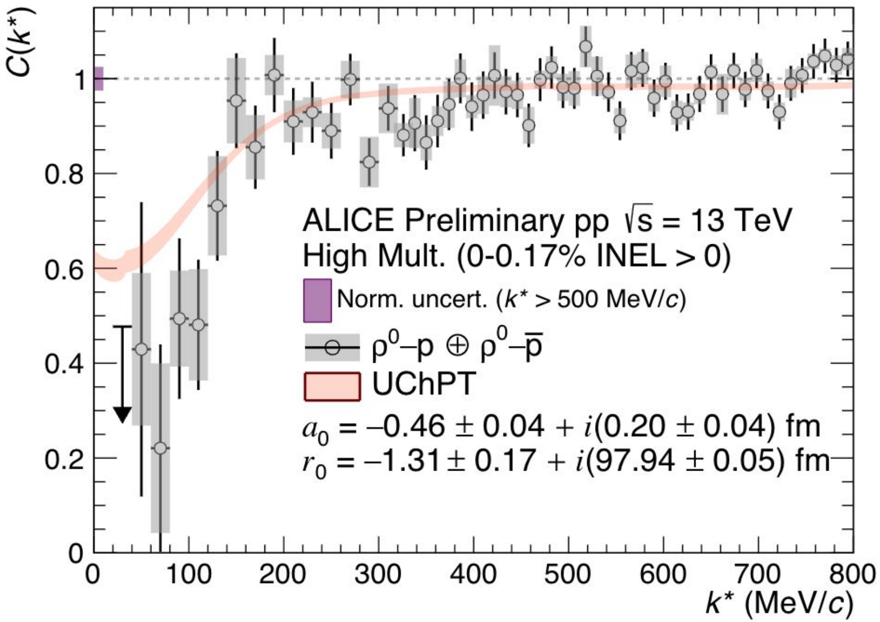

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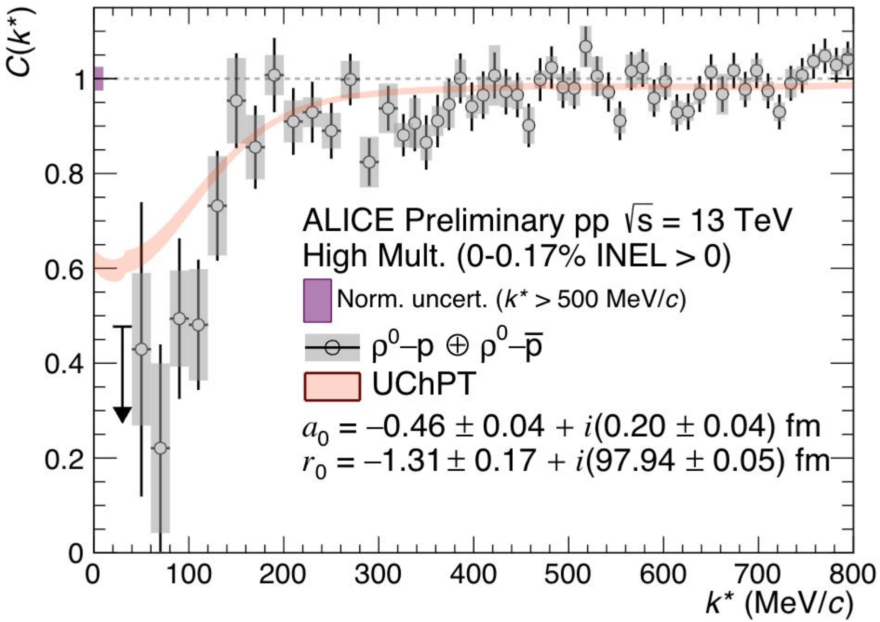

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  by **explicitl** … s on a Gaussian core
  (RSM m…
- K^+–p an… …mption
  of a **univ**…
- Source r…

Even more details about the π–π source were studied: Doubly differential as function of m_T and multiplicity on MB data set!

Same saturation behaviour as in high–mult. data set.
Scaling of the radii with multiplicity is observed.

Plots are in the back–up!

Physics Mess…

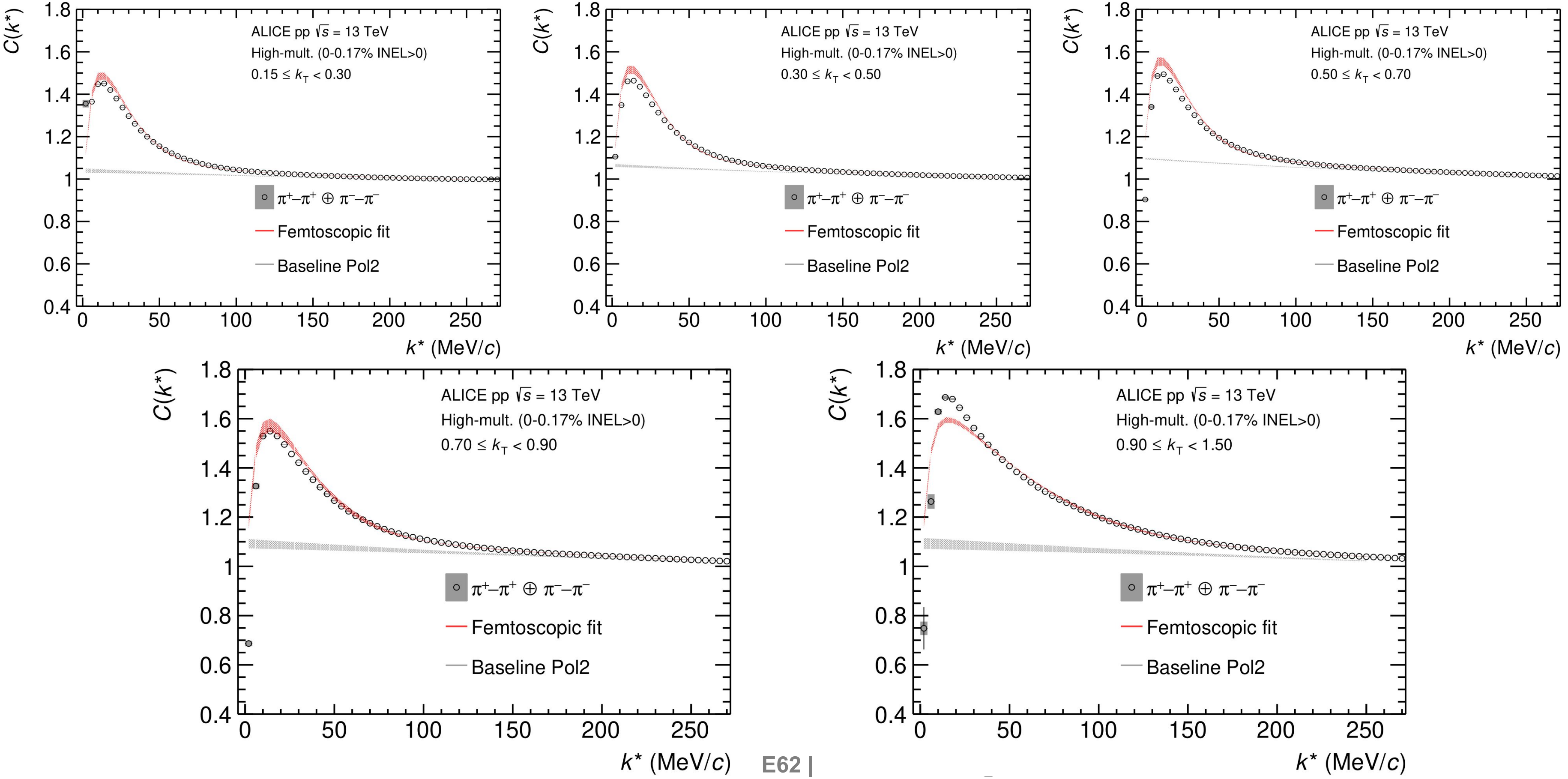
- A scaling…
  consiste…
- **Saturation** at is observed

Outlook

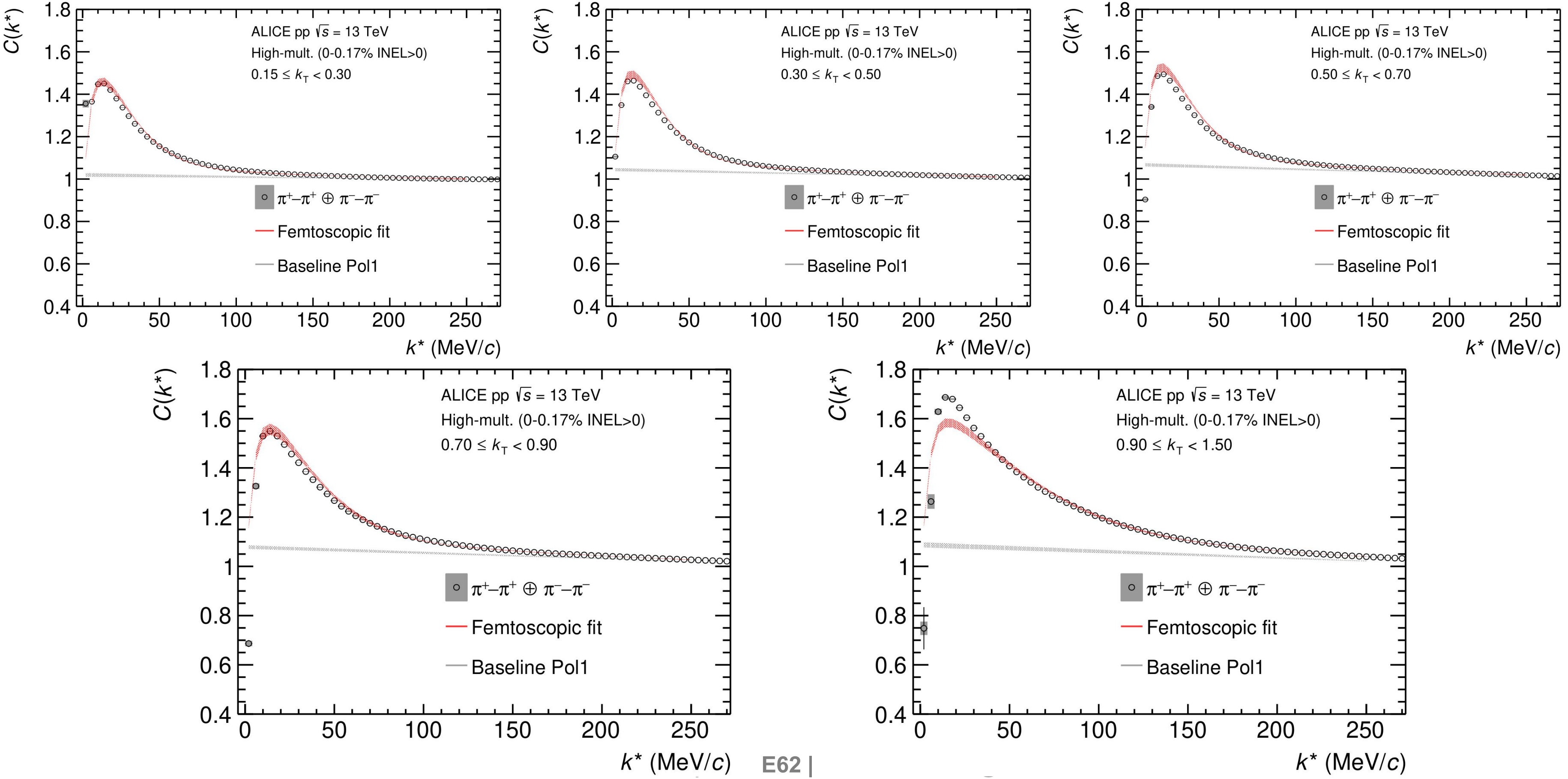
- Available data to tune particle production coordinates in transport models
- Refine source model in order to account for saturation effects (CECA [1])

[1] D. Mihaylov et al. arXiv 2305.08441(2023)

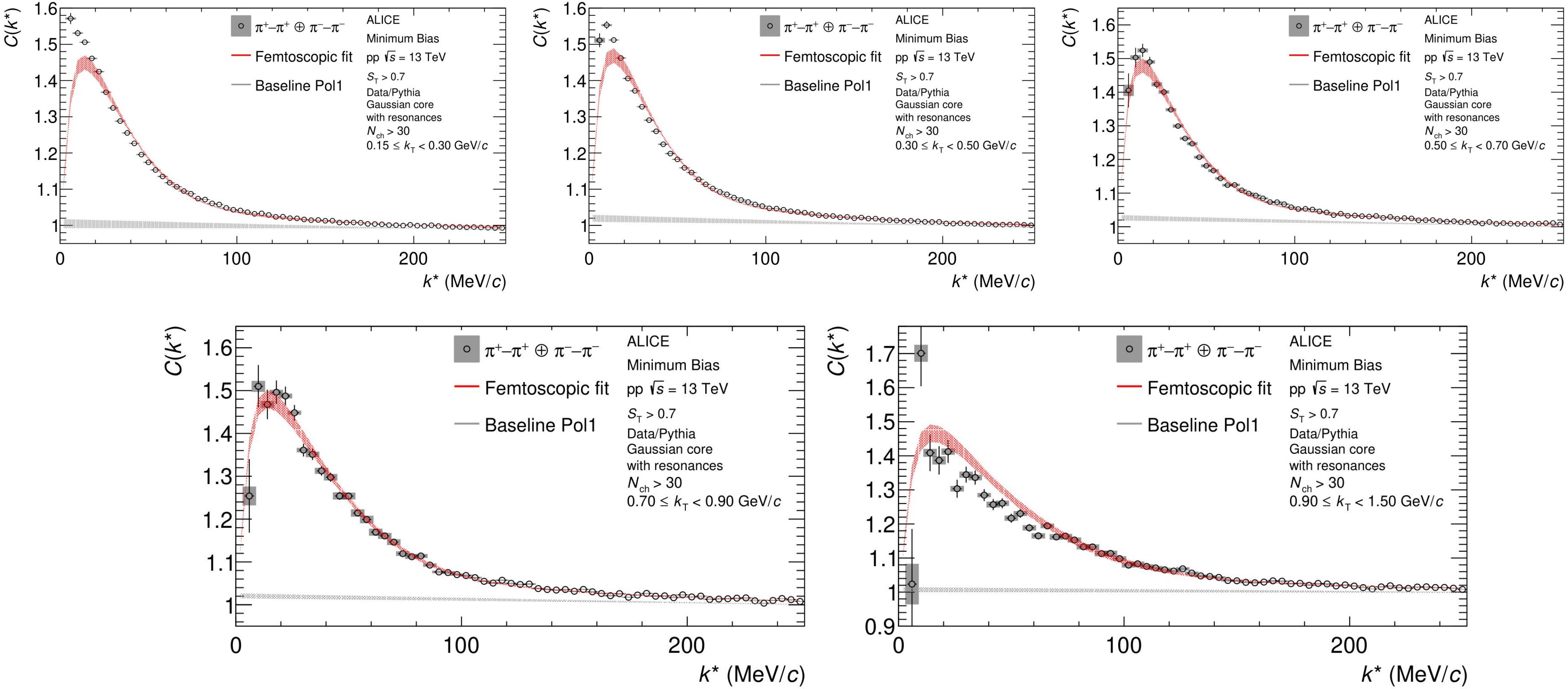
Results for HM π–π - Pol2



Results for HM π–π - Pol1



Results for N_{ch} > 30 - π–π - Data/Pythia - Pol1



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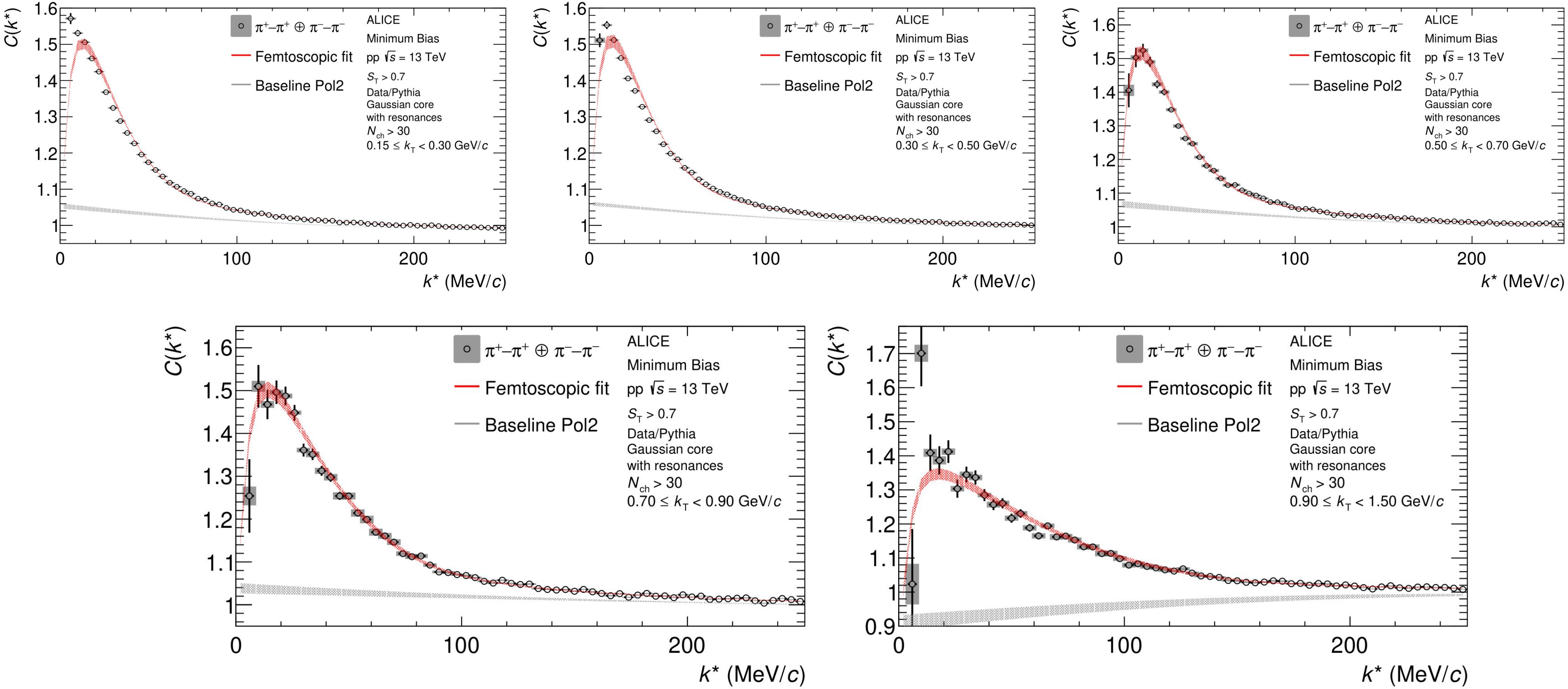
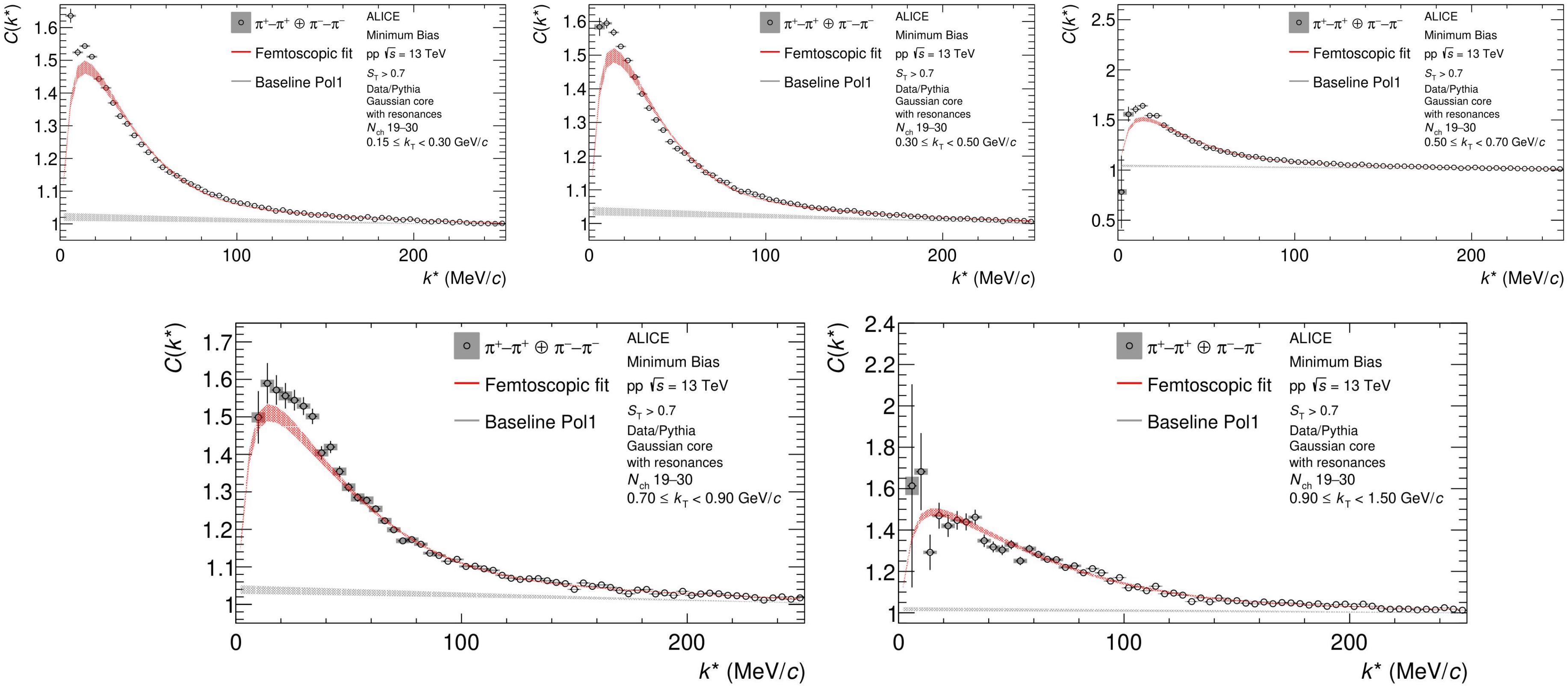


Results for 18< N_{ch}< 30 - π–π - Data/Pythia - Pol1



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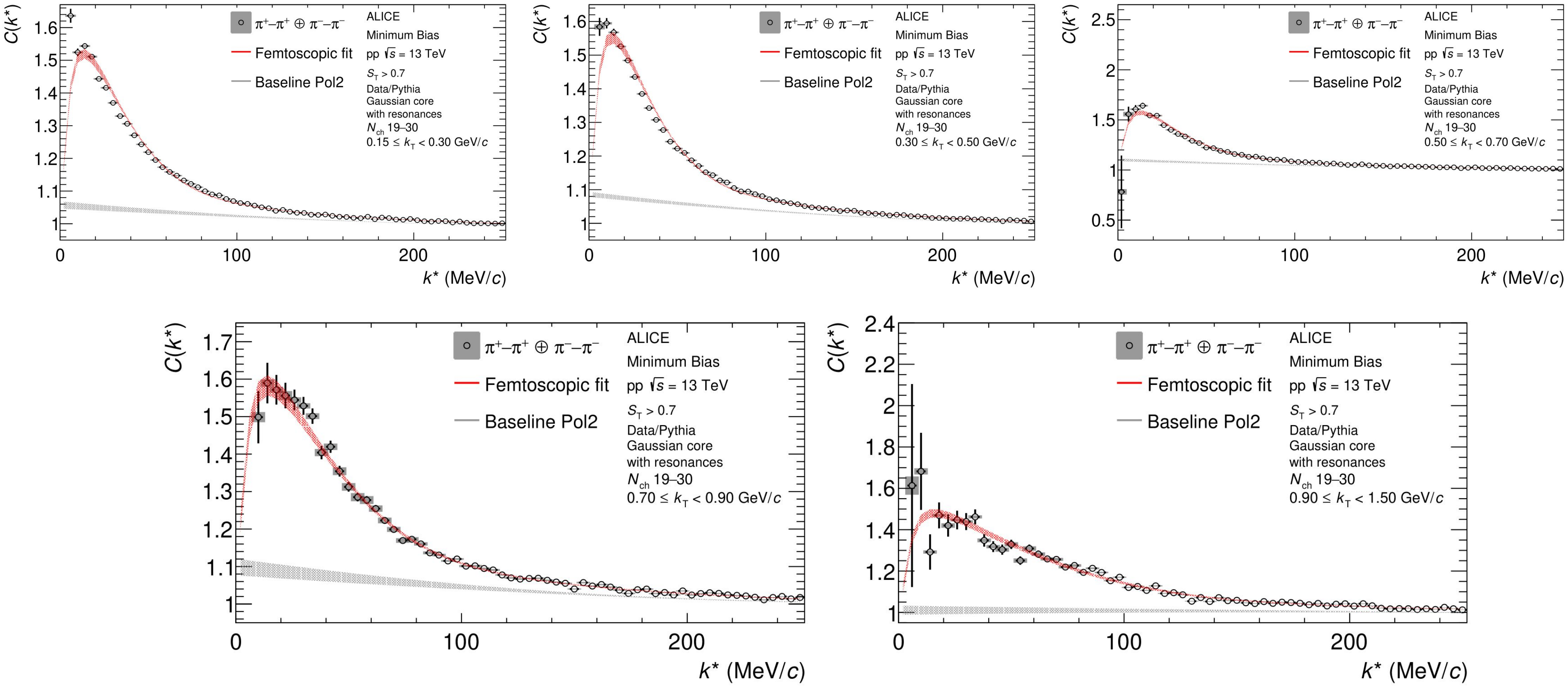

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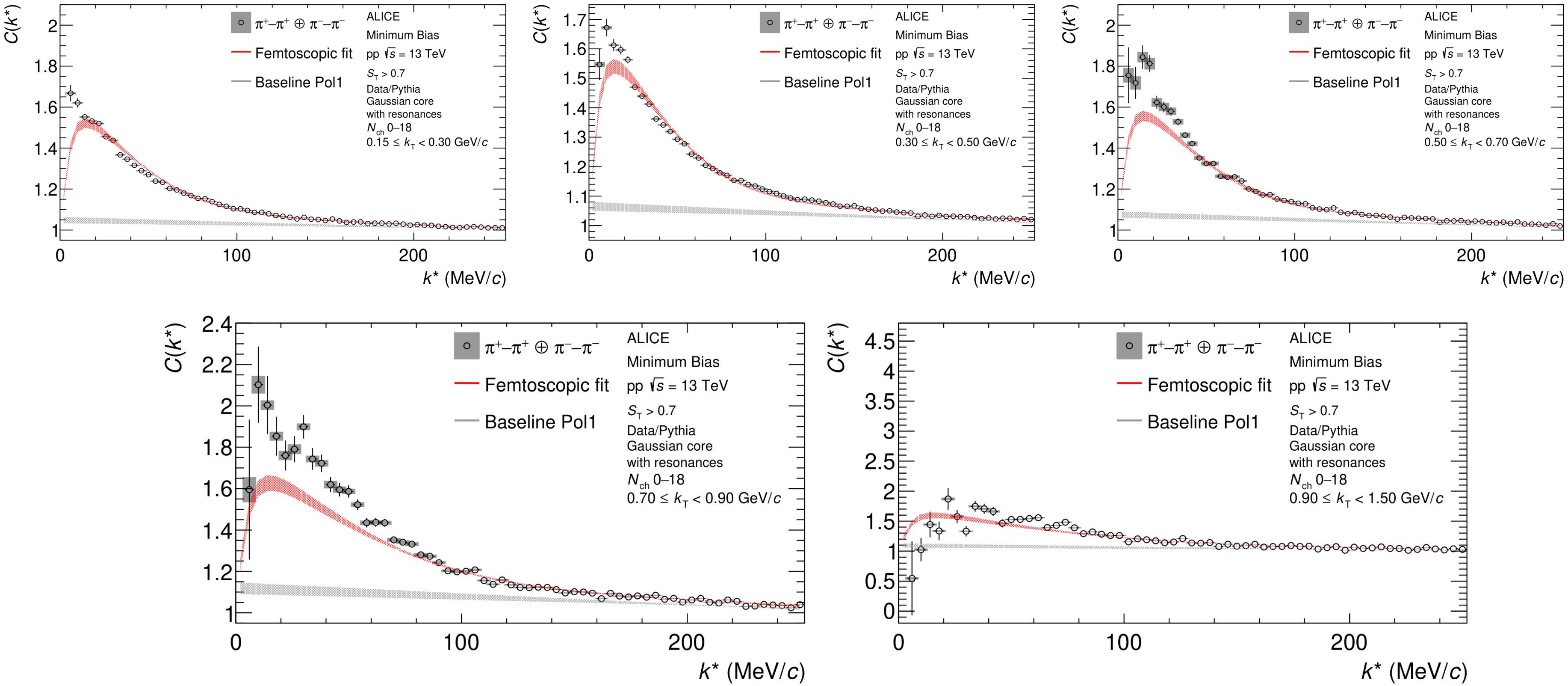
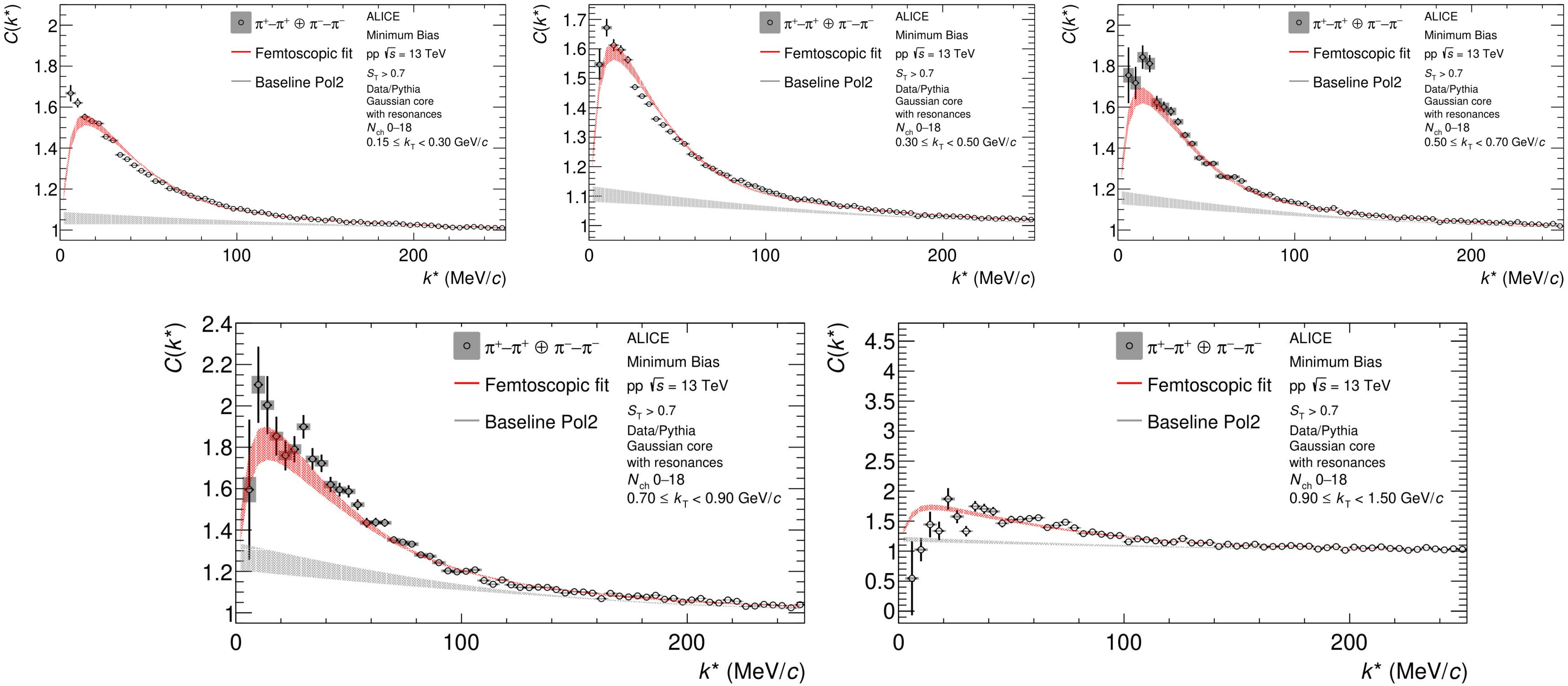


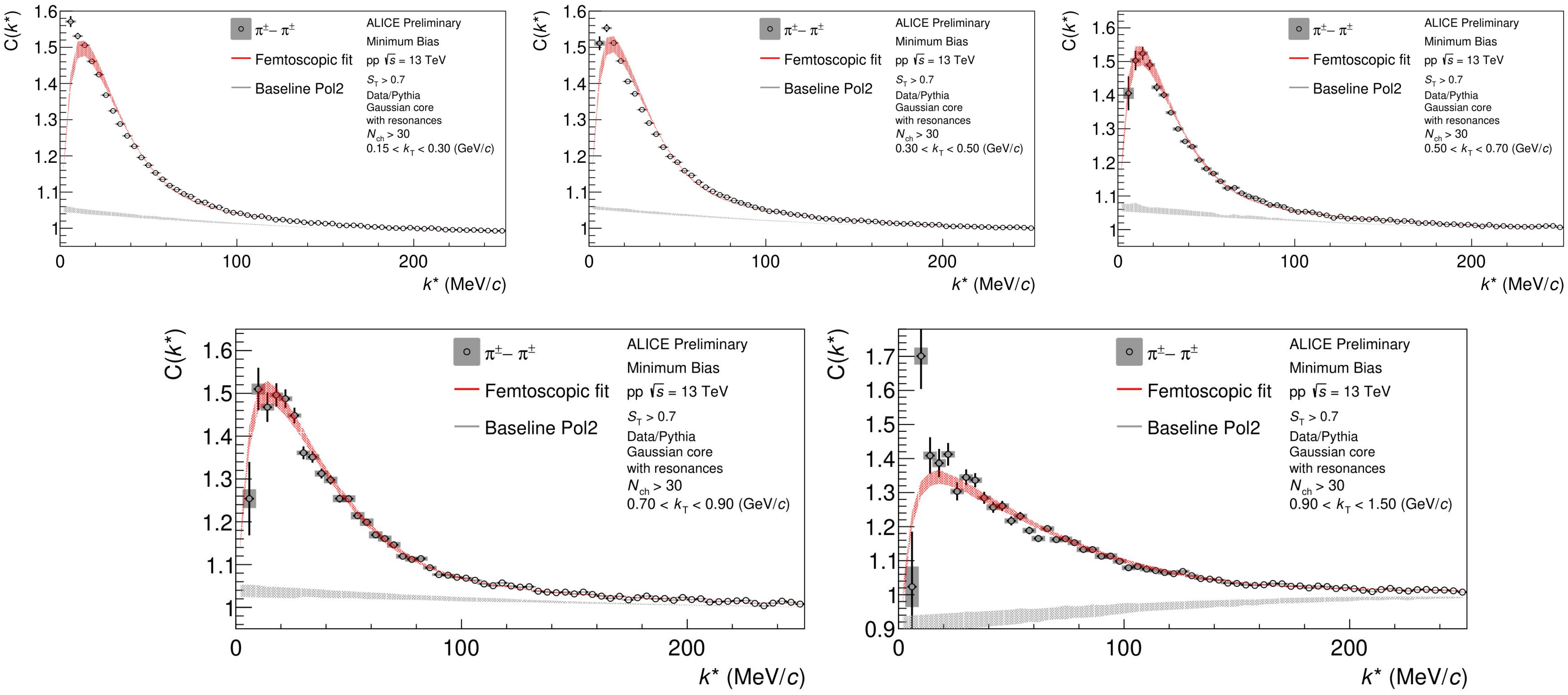
Maximilian Korwieser | TUM E62 | max.korwieser@tum.de

Results for N_{ch}< 18 - π–π - Data/Pythia - Pol2

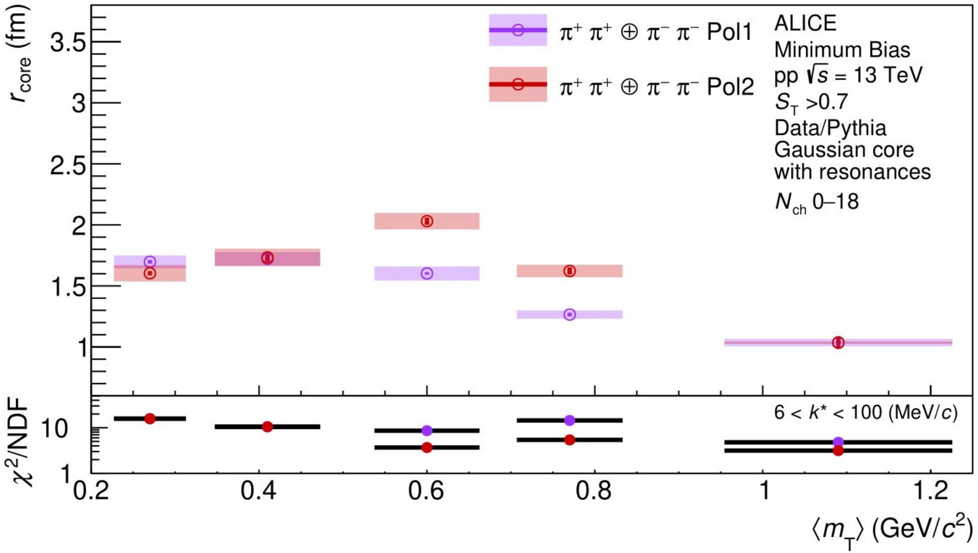


Maximilian Korwieser | TUM E62 | max.korwieser@tum.de

Results for Mult. [> 30] - Data/Pythia - Pol2

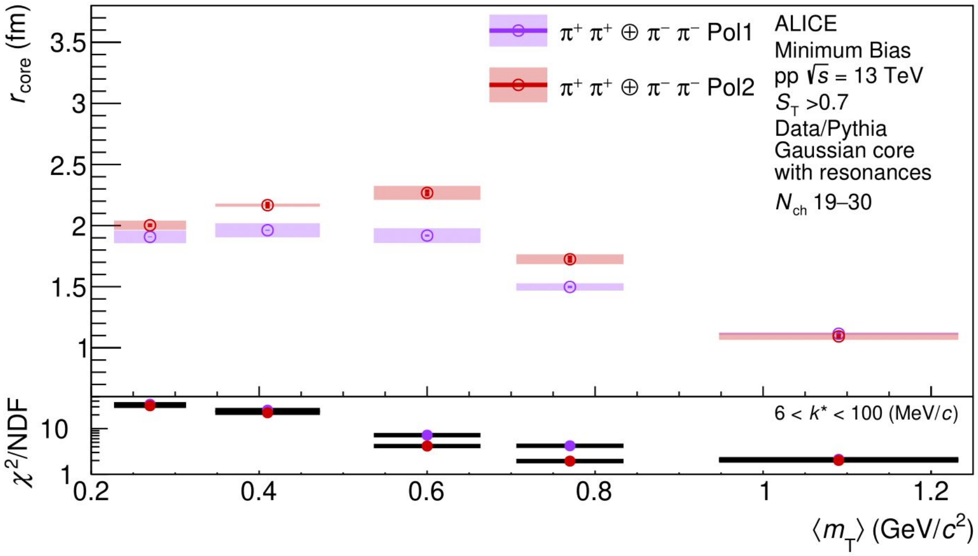


m_T Scaling for pions



- For m_T > 0.4 (GeV/c) scaling with m_T is found for all multiplicity bins
- The extracted r_{core} radii are increasing with multiplicity

m_T Scaling for pions



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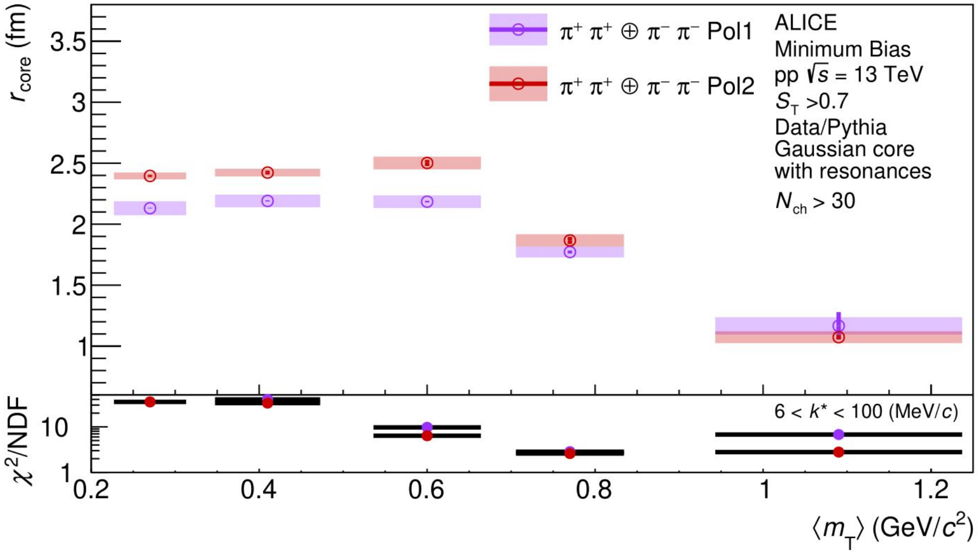
m_T Scaling for pions



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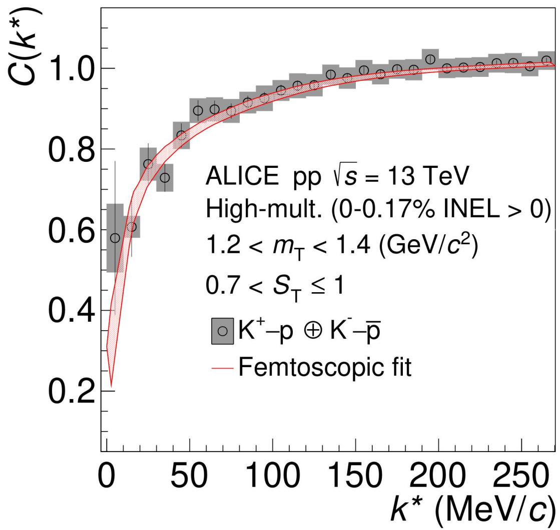
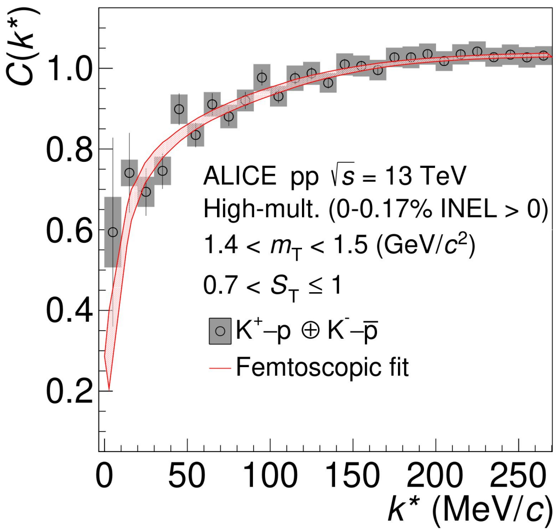
Fits to the K^+–p in HM

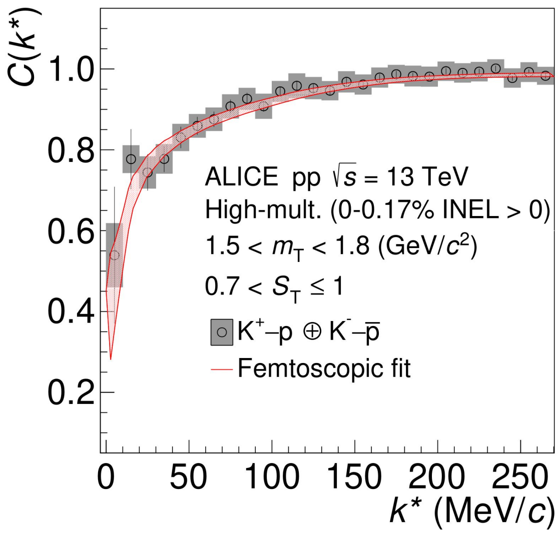


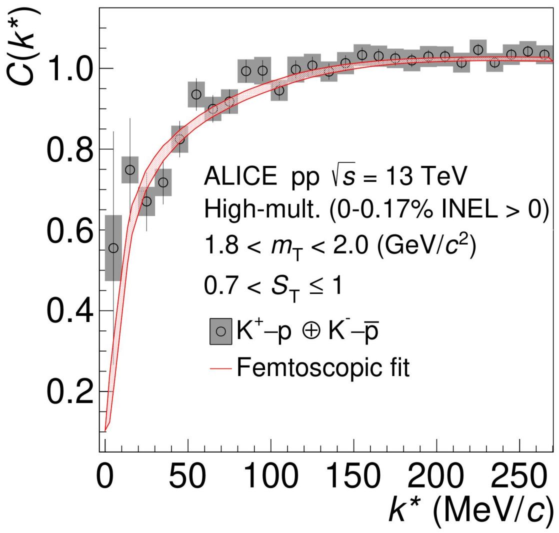


- Strong interaction is modeled by state-of-the-art χEFT
  [K. Aoki et al. PTEP 1 (2019)]

- Source is modeled with the RSM (as for π) and r_{core} extracted from the fit

Fits to the K^+–p in HM

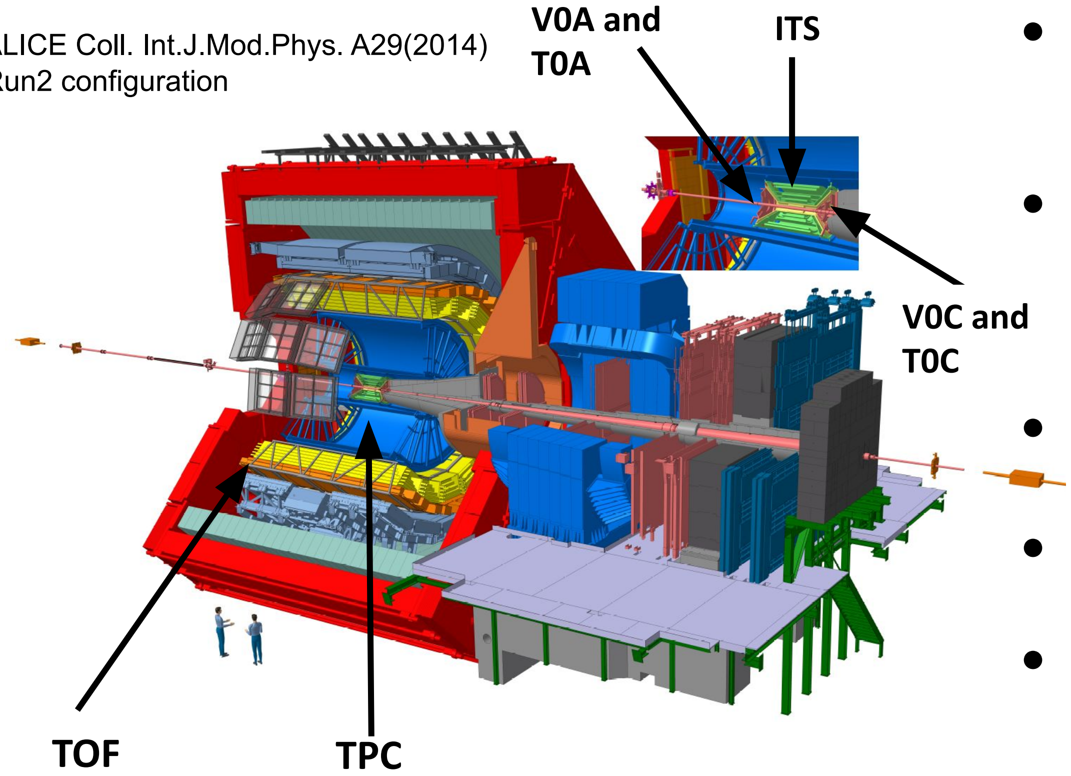




- Strong interaction is modeled by state-of-the-art χEFT
  [K. Aoki et al. PTEP 1 (2019)]
- Source is modeled with the RSM (as for π) and r_{core} extracted from the fit

ALICE detector

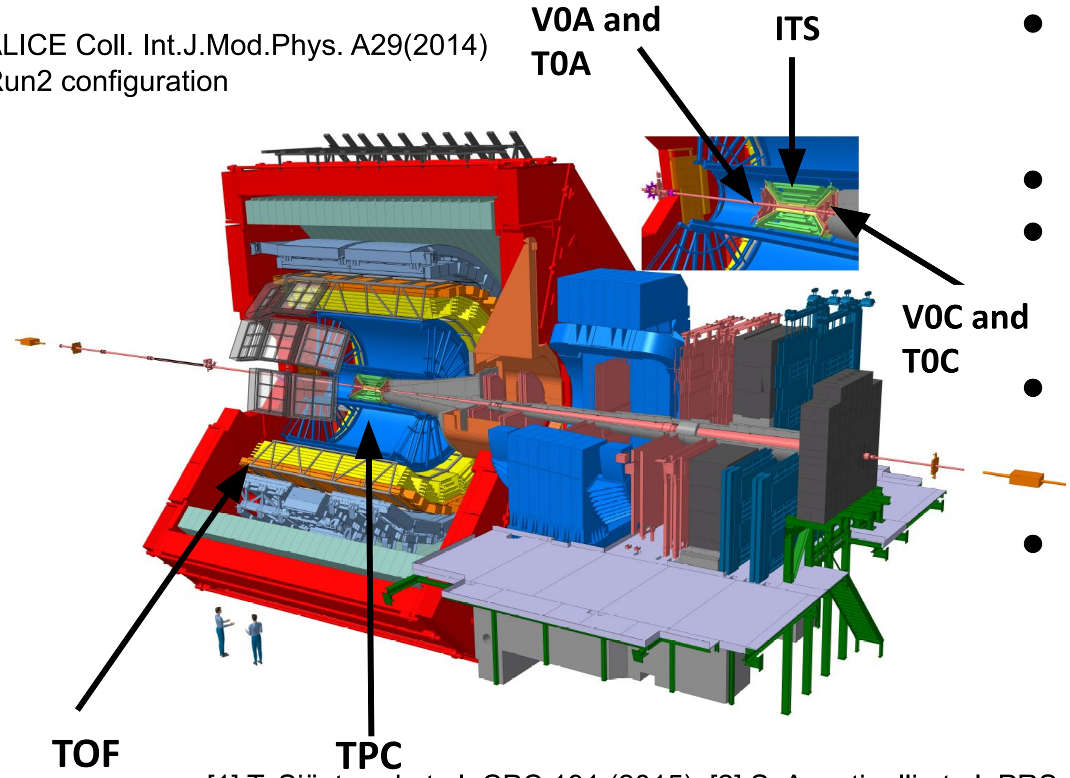
ALICE Coll. Int.J.Mod.Phys. A29(2014)
Run2 configuration



- Direct detection of charged particles (pions) by TPC and TOF
- Particle identification
  - Mean energy loss in TPC
  - Momentum reconstruction by TOF
- Primary vertex reconstruction by ITS
- Multiplicity estimates by V0
- Reference signal for TOF via T0

Analysis details

ALICE Coll. Int.J.Mod.Phys. A29(2014)
Run2 configuration



- MB pp collisions @ 13 TeV (1.9 x 10^9 evts.)

- Mult-Binning: [0-18], [19-30], [>30]
- kT-Binning: (0.15-0.3], (0.3-0.5], (0.5-0.7], (0.7-0.9], (0.9-1.5]

- General purpose Pythia 8 [1] evts. filtered by GEANT4 [2] used as MC

- Event cut on transverse sphericity [3] S_{XY} > 0.7 suppression of mini-jet background

[1] T. Sjöstrand et al. CPC 191 (2015), [2] S. Agostinelli et al. PRS A 506.3 (2003), [3] ALICE Coll. EPJC 72 (2012)

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Estimating the resonance contribution

ALICE

Resonances	$c\tau_{res}$ (fm)	Fraction (%)
ρ^0	1.3	9.01
ρ^+	1.3	8.71
$\omega(782)$	23.4	7.67
K*(892)+	3.9	2.29
$\bar{K}$*(892)0	3.9	2.25
b1(1235)+	1.4	1.90
a2(1320)+	1.8	1.48
η	150631.3	1.45
a1(1260)+	0.5	1.37
f2(1270)	1.1	1.36
a0(980)+	2.6	1.36
h1(1170)	0.5	1.18

Lifetime $c\tau$ (fm)	Fraction $\mathscr{F}$ (%)	$\langle m_{res}^{eff} \rangle$ (GeV/c)
Primordial	28.0	–
$c\tau_{res} < 1$	14.8	0.308
$1 < c\tau_{res} < 2$	34.8	0.526
$2 < c\tau_{res} < 5$	10.2	0.151
$c\tau_{res} > 5$	12.2	0.146

- Employ statistical hadronization model [1]
  - Describe system by statistical ensemble
  - Enforce conservation of quantum numbers
  - Predict yields
- Calculation carried out with Thermal-FIST [2,3]
  - Configure model to pp
  - B.R.s of strong decays fixed to PDG
  - Extract resonances
- Summary parameters for RSM
  - m_eff = 1124 GeV/c^2
  - cτ_eff = 1.5 fm
  - Select resonances cocktail in EPOS [4] for decay kinematics

[1] F. Becattini Z. Phys. C 76 (1997), [2] V. Vovchenko et al. CPC 100 2019,
[3] V. Vovchenko et al. PRC 100834 (2019), [4] K.Werner et al. PRC 92 (2015)

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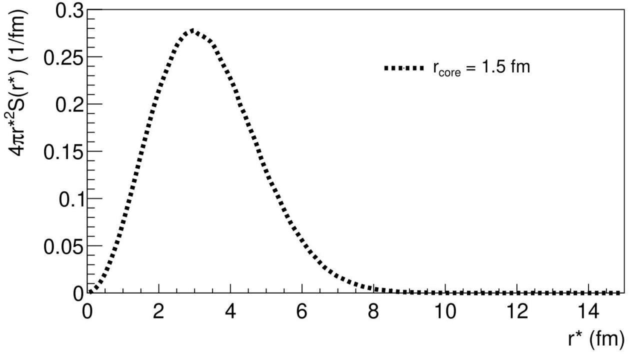
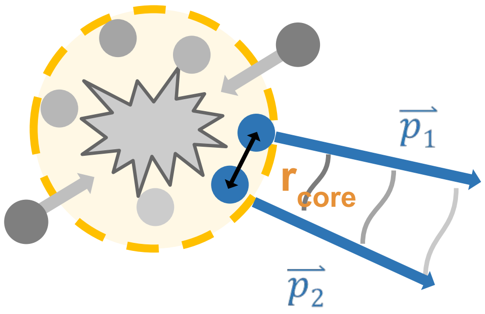
Universal Source Ansatz

ALICE Coll. PLB 811 (2020)

Gaussian core





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Universal Source Ansatz

ALICE Coll. PLB 811 (2020)

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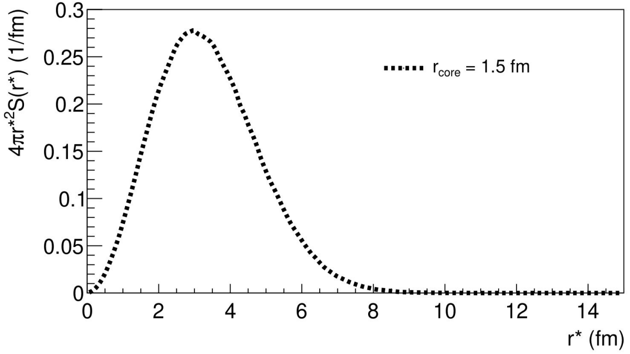
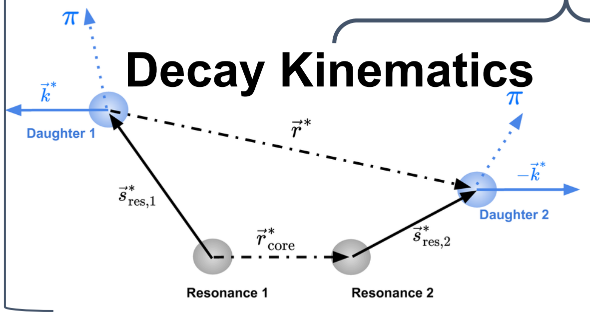


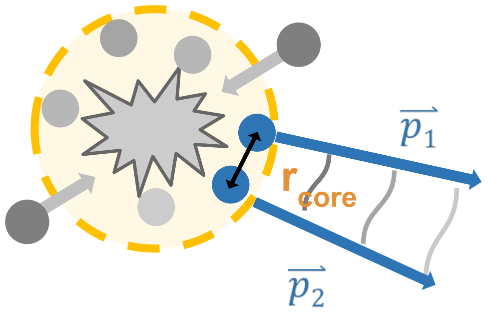
+

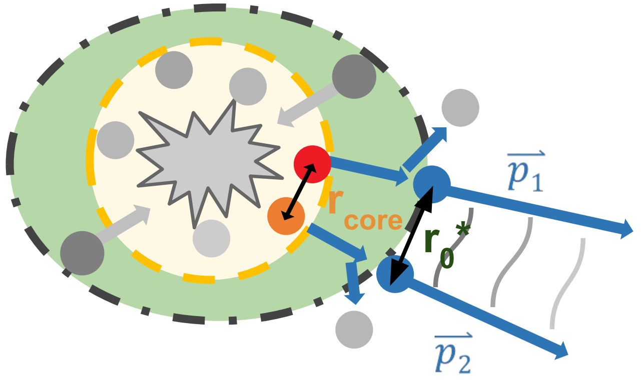
Non-Gaussian

Decay Kinematics ⊗ **Resonances**



Mean Lifetime
Mean Mass

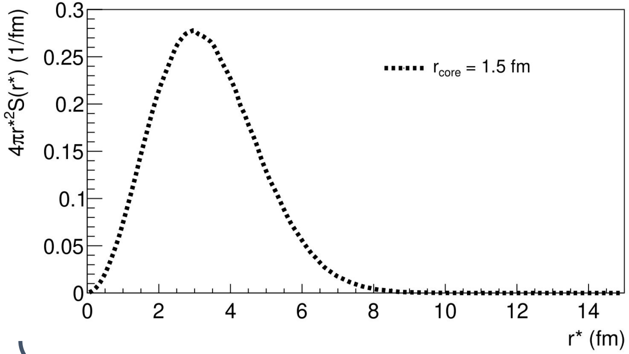




Universal Source Ansatz

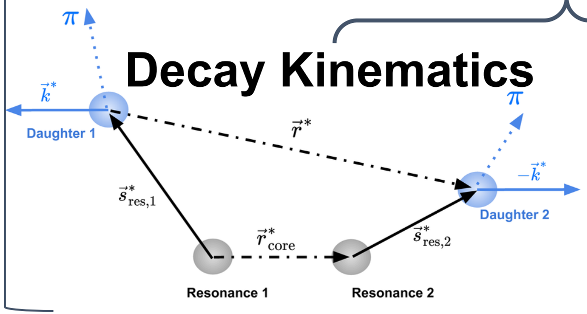
ALICE Coll. PLB 811 (2020)

Gaussian core



+

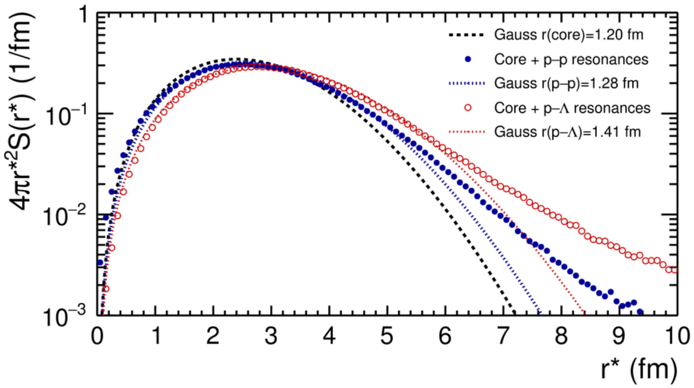
Non-Gaussian



Decay Kinematics ⊗ **Resonances**

Mean Lifetime
Mean Mass

Source



Decomposition of the Correlation Function

$$C_{\text{model}}(k^*) = \textbf{???}$$

But *what* is measured?

- Does purity play a role?
- What about feed-down weak decays?
- Do we have background?

Decomposition of the Correlation Function

$$C_{\mathrm{model}}(k^*) = 1/C_{\mathrm{MC}}(k^*) \cdot (\lambda_{\mathrm{gen}} C_{\mathrm{gen}}(k^*) + \lambda_{\mathrm{feed}} + \lambda_{\mathrm{misid}})$$

Decomposition of the Correlation Function

$$C_{\mathrm{model}}(k^*) = 1/C_{\mathrm{MC}}(k^*) \cdot (\lambda_{\mathrm{gen}} C_{\mathrm{gen}}(k^*) + \lambda_{\mathrm{feed}} + \lambda_{\mathrm{misid}})$$

Model for genuine interaction

- Bose-Einstein quantum statistics
- Coulomb interaction

Decomposition of the Correlation Function

66.4 % 31.6 % 2 %

$$C_{\mathrm{model}}(k^*) = 1/C_{\mathrm{MC}}(k^*) \cdot (\lambda_{\mathrm{gen}} C_{\mathrm{gen}}(k^*) + \lambda_{\mathrm{feed}} + \lambda_{\mathrm{misid}})$$

Model for genuine interaction

- Bose-Einstein quantum statistics
- Coulomb interaction

Introduce λ-parameter

- Each component has a weight
- C(k*) = 1, for feed-down and misidentified
- Evaluated by MC studies

Decomposition of the Correlation Function

$$C_{\text{model}}(k^*) = 1/C_{\text{MC}}(k^*) \cdot (\lambda_{\text{gen}} C_{\text{gen}}(k^*) + \lambda_{\text{feed}} + \lambda_{\text{misid}})$$

66.4 % (λ_{gen}), 31.6 % (λ_{feed}), 2 % (λ_{misid})

Model for genuine interaction

- Bose-Einstein quantum statistics
- Coulomb interaction

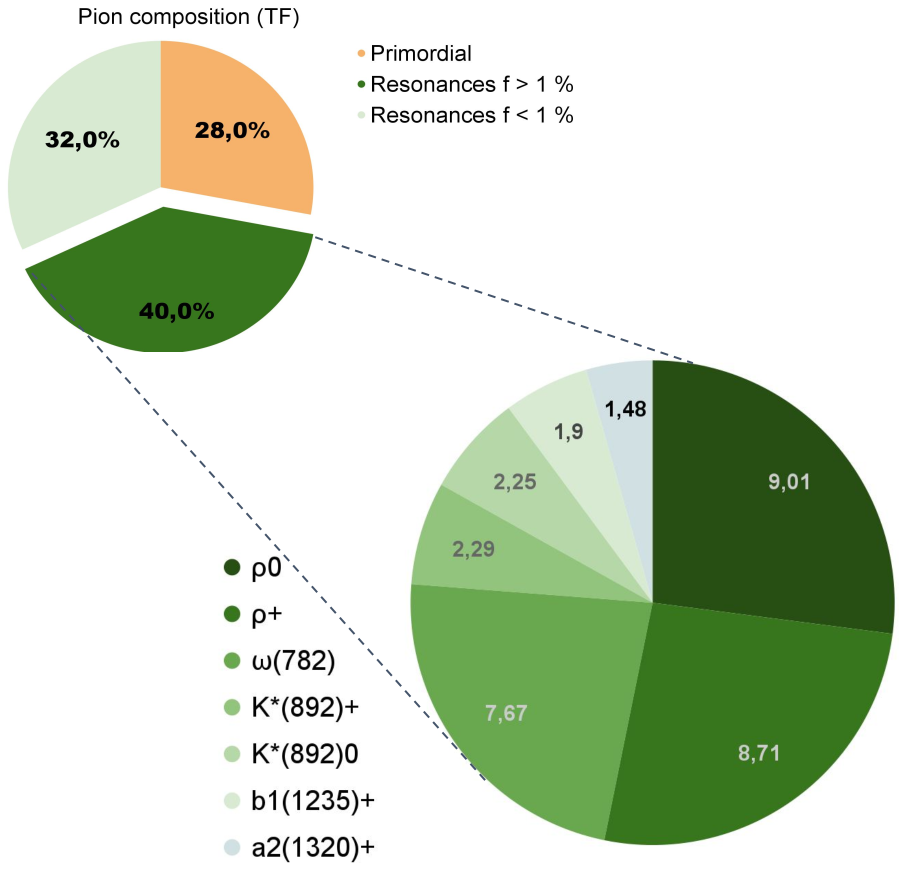
Correct for non-femto effects

- Divide by C(*k**) obtained from MC
- Collimated production often called ‘mini-jet’

Introduce λ-parameter

- Each component has a weight
- C(*k**) = 1, for feed-down and misidentified
- Evaluated by MC studies

Estimating the resonance contribution



- Calculation carried out with Thermal-FIST [1,2]
  - Use statistical hadronization model [3]
  - **28 %** primordial, **72 %** resonances

- Summary parameters for RSM
  - $\langle m_{eff} \rangle = 1124$ GeV/c^2
  - $\langle c\tau_{eff} \rangle = 1.5$ fm
  - Select resonances cocktail in EPOS [4] for decay kinematics

[1] V. Vovchenko et al. PRC 100834 (2019)
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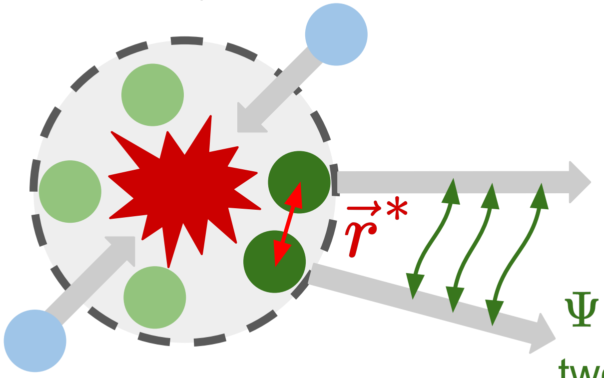
[3] F. Becattini Z. Phys. C 76 (1997)
[4] K.Werner et al. PRC 92 (2015)

Femtoscopy in a nutshell

Ann.Rev.Nucl.Part.Sci.55:357-402, 2005



Measure the correlation function *C(k*)*

$\Psi(\vec{k}^*, \vec{r}^*)$
two particle wave function

$$C(k^*) = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

- **Measure $C(k^*)$, 'fix' interaction, study $S(r^*)$**
- For evaluation of integral and $S(r^*)$ use CATS framework Eur.Phys.J.C 78 (2018) 5, 394

Femto accomplishments

- Study final-state interactions of exotic pairs
- Needs **precise** understanding of the source

- Access final state interactions
  - Complementary to scatterings experiments
  - Many measured for the first time

➔ Valentina Mantovani Sarti (C5):
"Accessing the strong interaction between Λ baryons and kaons with femtoscopy at LHC"
➔ Wioleta Rzęsa (C5):
"A study of K^-–d and K^+–d interactions via femtoscopy technique"

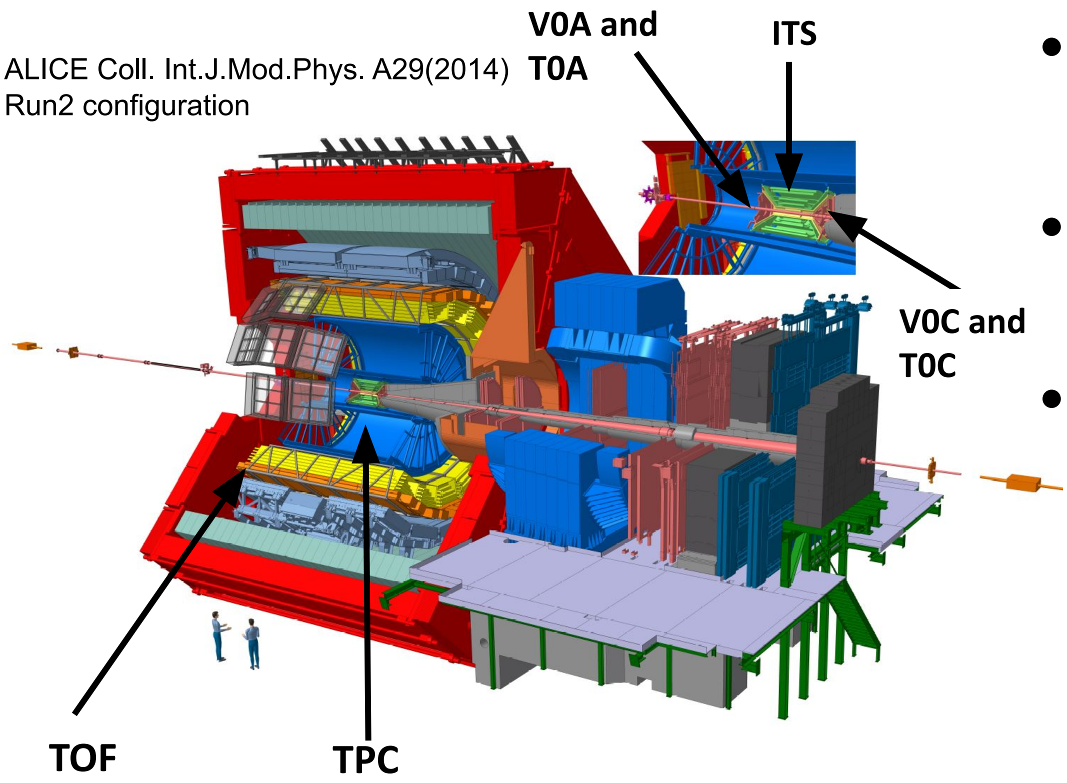
anti)Λ,

- Enables theory comparisons
  - Tests of LQCD
  - χEFT

➔ Albert Feijoo (C5):
"Correlation Function constraints on S=-2 meson–baryon interaction from UChPT."

Femtoscopy at ALICE in HM pp 13 TeV

ALICE Coll. Int.J.Mod.Phys. A29(2014)
Run2 configuration



- HM pp collisions @ 13 TeV
  - 1 Billion evts. in Run2
- Direct detection of charged particles (π, K, p) by TPC and TOF
- Particle identification
  - Mean energy loss in TPC
  - Momentum reconstruction by TOF
  - Purity of about 99 % for π, K, p due to excellent PID capabilities

Plethora of femtoscopic results

nature

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Article | Published: 09 December 2020

Unveiling the strong interaction among hadrons at the LHC

ALICE Collaboration

Nature **588**, 232–238(2020) | Cite this article

Metrics

Abstract

One of the key challenges for nuclear physics today is to understand from first principles the effective interaction between hadrons with different quark content. First successes have been achieved using techniques that solve the dynamics of quarks and gluons on discrete space-time lattices[1,2]. Experimentally, the dynamics of the strong interaction have been studied by scattering hadrons off each other. Such scattering experiments are difficult or

- Analyses so far…

ALICE Collaboration	*System*
PRC 99 (2019) 2, 024001	p–p, p–*Λ*
PLB 797 (2019), 134822	*Λ–Λ*
PRL 123 (2019), 112002	p–*Ξ*
PLB 805 (2020), 135419	p–*Σ0*
PLB 811 (2020), 135849	p–p, p–*Λ*
Nature 588 (2020) 232-238	**p–*Ω***
PRL 127 (2021), 172301	p–*ϕ*
PLB 833 (2022), 137272	p–*Λ*
PLB 829 (2022), 137060	p–*(anti)*p, p–*(anti)Λ*, *Λ–(anti)Λ*
PRD 106 (2022) 5, 052010	p–*D*
PLB (2022), 137223	*Λ–Ξ*
EPJC 83 (2023) 4, 340	*K*–p
PLB 845 (2023), 138145	*Λ–K*

Not using universal source

PRL 124 (2020), 09230	*(anti)K*–p
PLB 822 (2021), 136708	*(anti)K*–p

Plethora of femtoscopic results

ALICE

nature

- Femtoscopy …
  - allows to access the final state interaction between ‘all kinds of’ hadrons
  - is a complementary method to traditional scattering experiments

studied by scattering hadrons off each other. Such scattering experiments are difficult or

- Analyses so far…

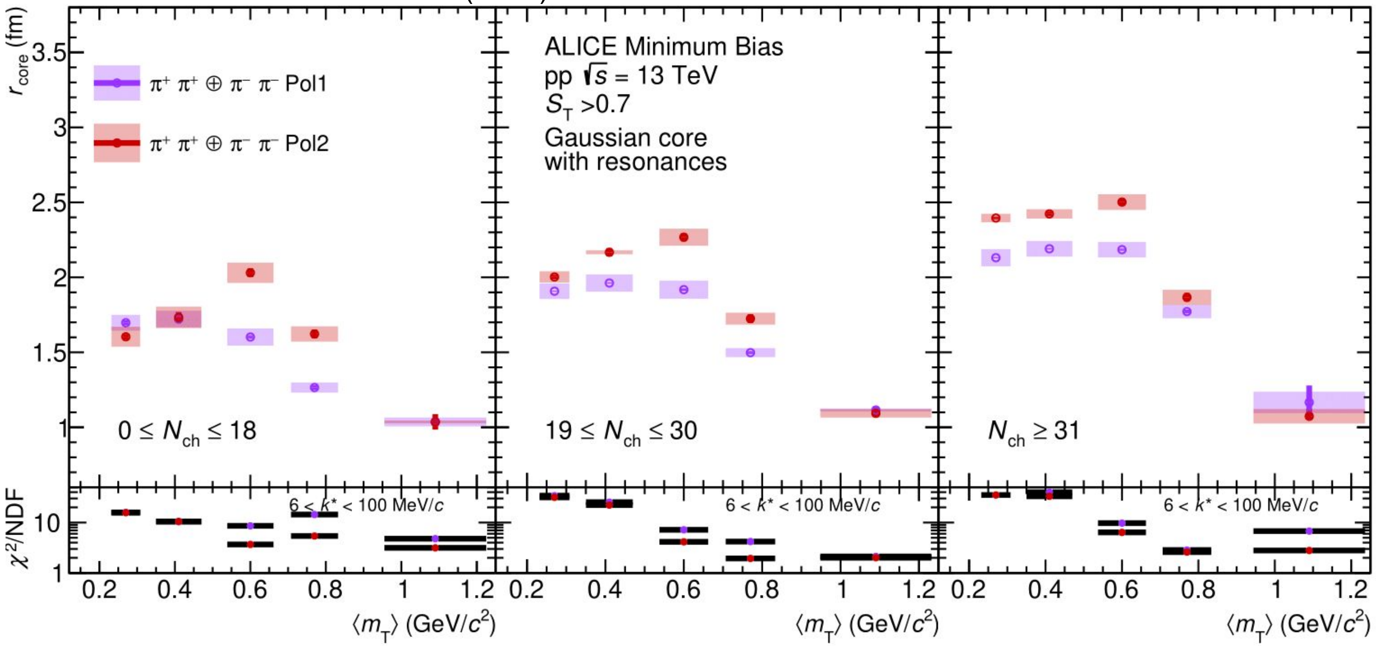
ALICE Collaboration	*System*
PRC 99 (2019) 2, 024001	p–p, p–*Λ*
PLB 797 (2019), 134822	*Λ–Λ*
PRL 123 (2019), 112002	p–*Ξ*
PLB 805 (2020), 135419	p–*Σ0*
PLB 811 (2020), 135849	p–p, p–*Λ*
Nature 588 (2020) 232-238	**p–*Ω***
PRL 127 (2021), 172301	p–*ϕ*
PLB 833 (2022), 137272	p–*Λ*
PLB 829 (2022), 137060	p–*(anti)*p, p–*(anti)Λ*, *Λ–(anti)Λ*
PRD 106 (2022) 5, 052010	p–*D*
PLB (2022), 137223	*Λ–Ξ*
EPJC 83 (2023) 4, 340	*K*–p
PLB 845 (2023), 138145	*Λ–K*

Not using universal source

PRL 124 (2020), 09230	*(anti)K*–p
PLB 822 (2021), 136708	*(anti)K*–p

Intermezzo for MB analysis of π–π

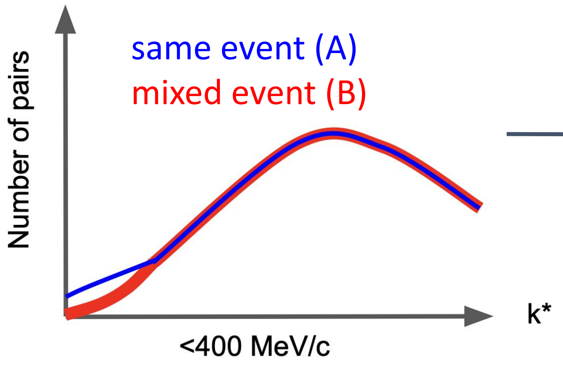
ALICE Coll. arXiv:2311.14527(2023)



- Studied double differential in multiplicity and m_T
  - Scaling with multiplicity
  - Consistent trend across multiplicities

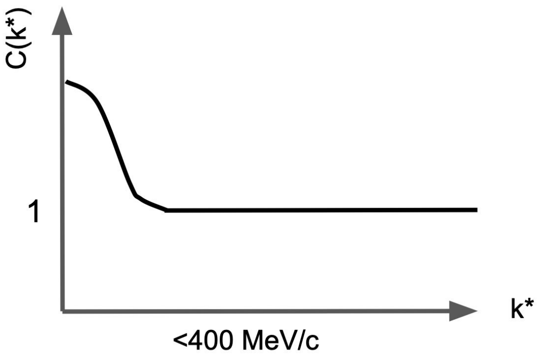
Femtoscopy in a nutshell

[M.Lisa et. al. Ann.Rev.Nucl.Part.Sci.55:357-402, 2005]



A/B

Correlation function



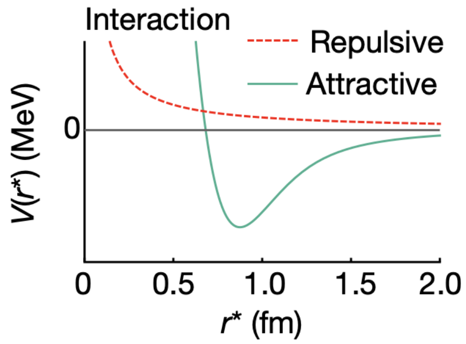
Experiment

$$C(k^*) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} = \mathcal{N}\frac{A(k^*)}{B(k^*)}$$

- Obtain pairs form
  - same event (*A*)
  - uncorrelated sample (*B*)
- Understand data
  - purity, fractions (feed-down)
  - background?

Femtoscopy in a nutshell

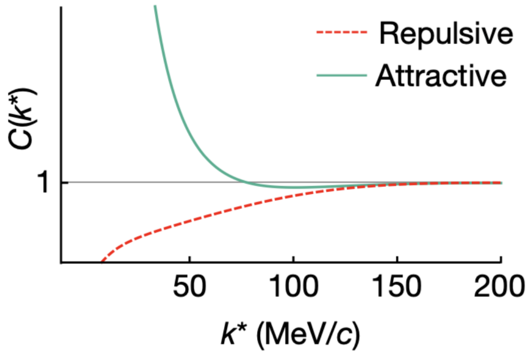
M.Lisa et. al. Ann.Rev.Nucl.Part.Sci.55:357-402, 2005



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

Solves Schrödinger eq.

Correlation function



Theory

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

- Calculate $\psi(r^*, k^*)$
  - QS + Coulomb or χEFT
- **Model $S(r^*)$**
  - Gaussian core
  - Resonance tails
    - Abundances ? (Thermal model)
- CATS framework [1]

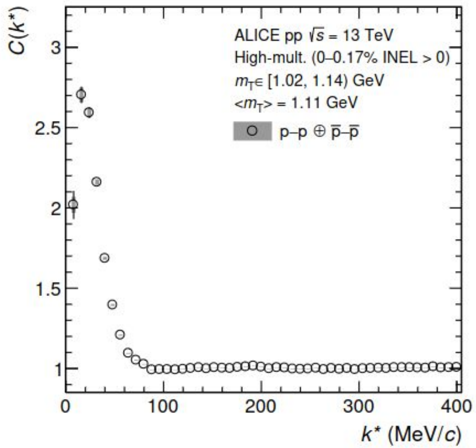
[1] D. Mihaylov et al. EPJC78(2018) 394

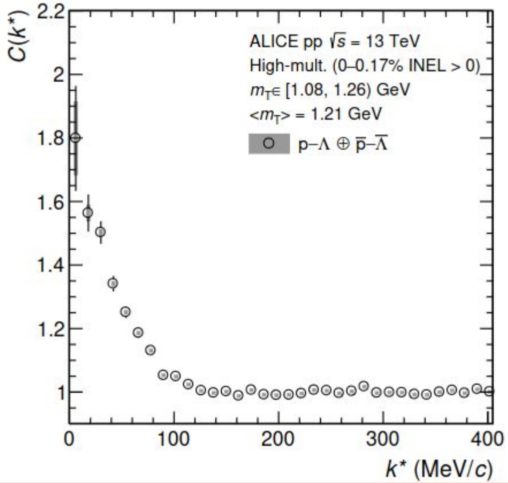
Baryon source in small systems

ALICE public note PUB-1378 (2023)

- Common source for all produced hadrons in small systems?
- Use p–p (well known interaction) to constrain the femtoscopic source
- Validate findings with p–Λ

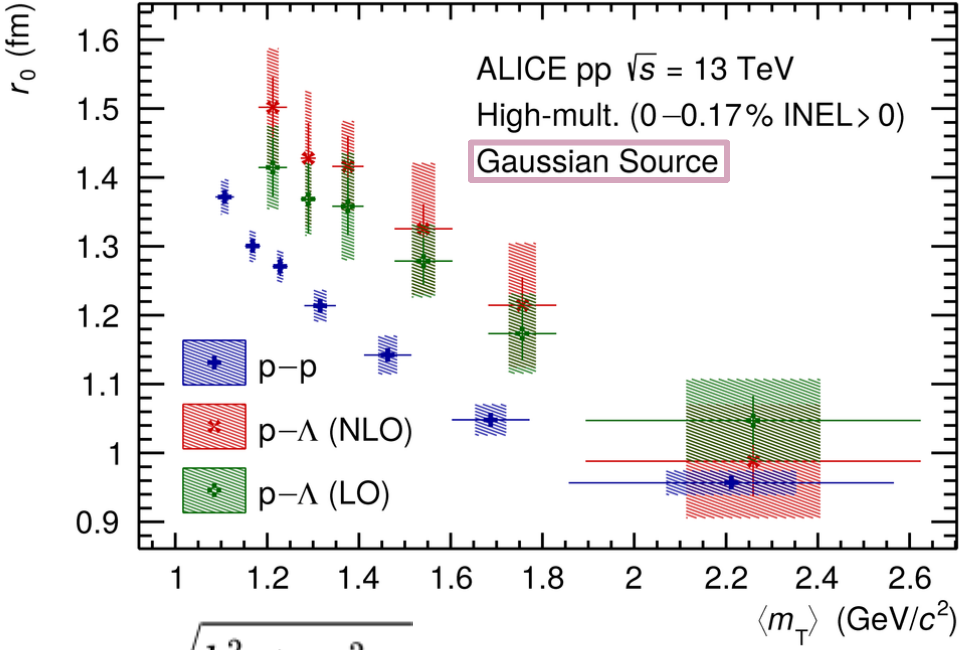
$$m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m_{\mathrm{avrg}}^2}$$
$$k_{\mathrm{T}} = \frac{1}{2}\left|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right|$$





Baryon source in small systems

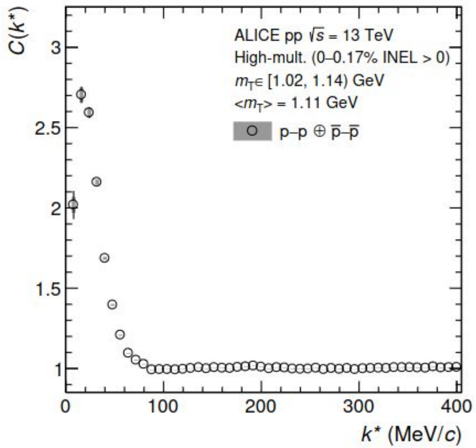
ALICE Coll. PLB 811 (2020)

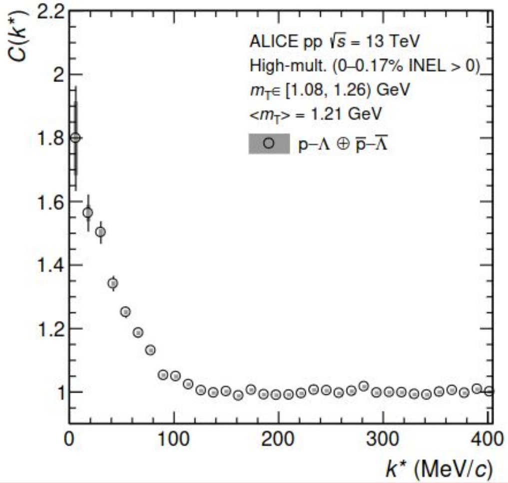


$$m_T = \sqrt{k_T^2 + m_{avrg}^2}$$

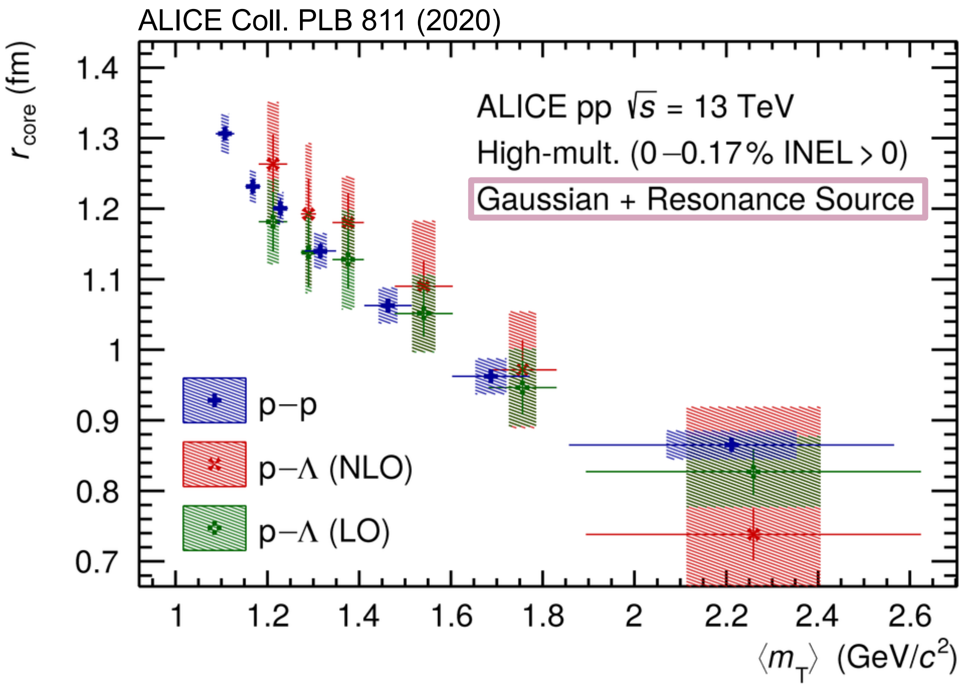
$$k_T = \frac{1}{2}|\vec{p}_{T,1} + \vec{p}_{T,2}|$$

ALICE public note PUB-1378 (2023)





Common baryon source in small systems

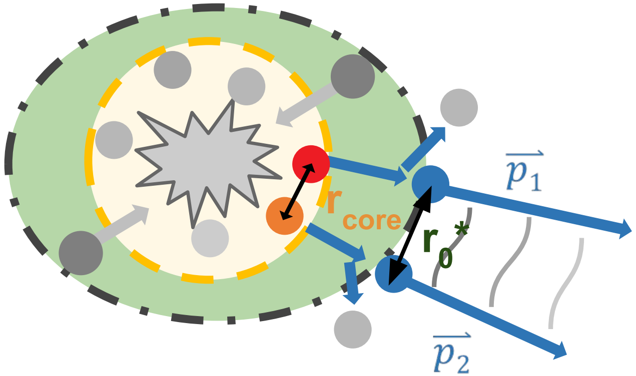


Access smaller m_T by studying π–π and meson-baryon correlations i.e. K^+–p

- Common scaling is restored by accounting for **non-gaussian** contributions

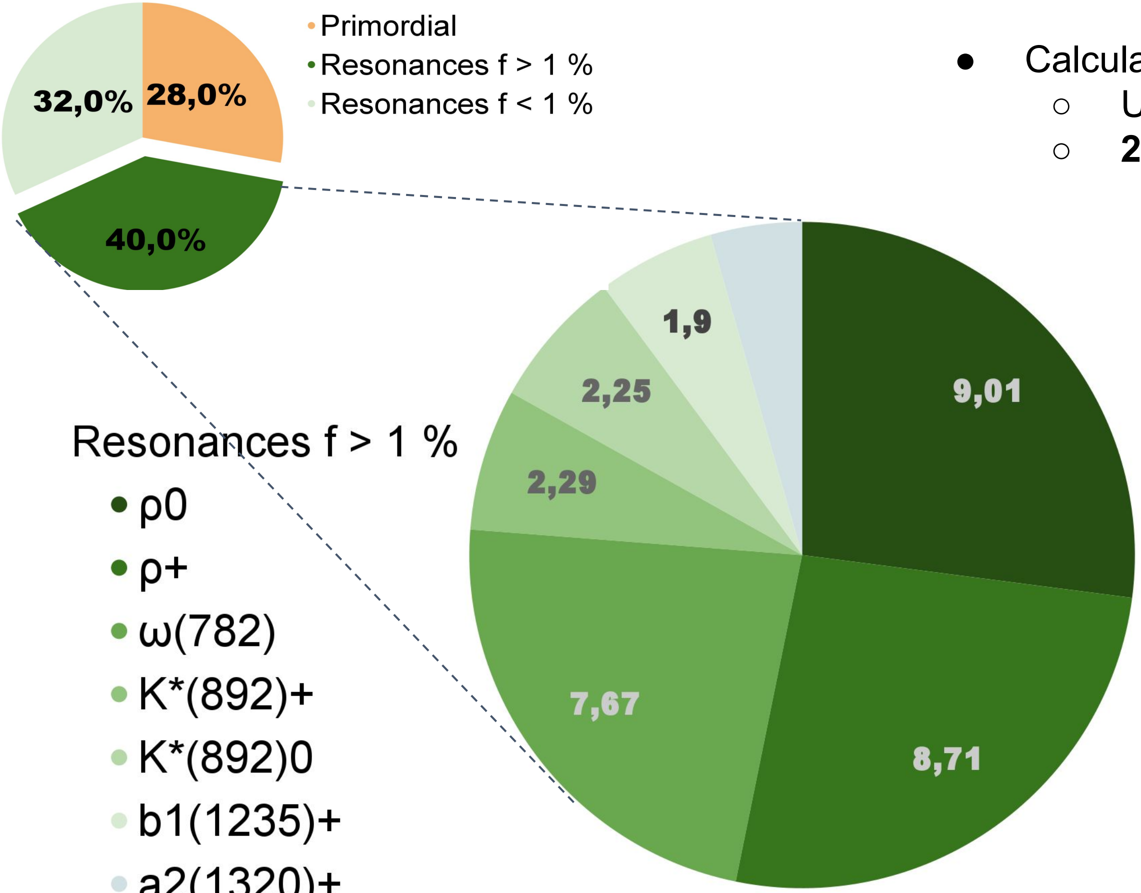
  ➔ Motivates the assumption of a universal particle source for baryons

- How well does the model perform for mesons? Is the scaling different?



Estimating the resonance contribution (π)

Pion composition (TF)



Resonances f > 1 %
- ρ0
- ρ+
- ω(782)
- K*(892)+
- K*(892)0
- b1(1235)+
- a2(1320)+

- Calculation carried out with Thermal-FIST [1,2]
  - Use statistical hadronization model [3]
  - **28 %** primordial, **72 %** resonances

- Summary parameters for RSM
  - m_{eff} = 1124 GeV/c^2
  - $c\tau_{eff}$ = 1.5 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)

Region of homogeneity and m_T scaling

Region of homogeneity: "size and shape of the phase space cloud of outgoing particles whose velocities have ***specific*** magnitude and direction."

A simple case: "For an infinite volume, the size of this region is set by the length one must move, before **collective velocity** *overcomes* **the thermal velocity**."

M. Lisa *et.al Ann.Rev.Nucl.Part.Sci.* 55 (2005) 357-402

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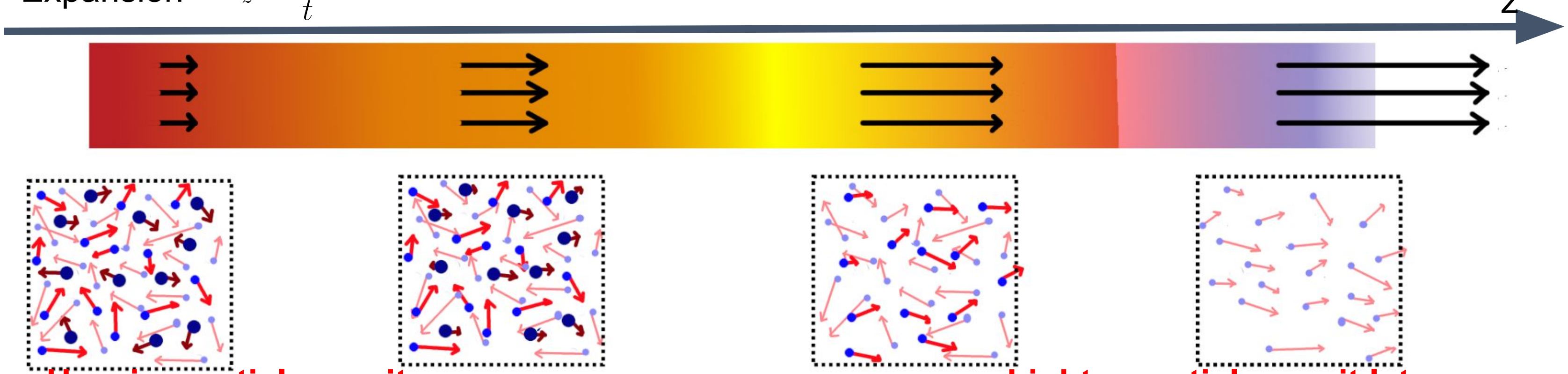
$$\text{homogeneity length} = \frac{\text{thermal velocity}}{\text{fluid velocity gradient}}$$

$$\text{thermal velocity} \sim \sqrt{\frac{T}{m_T}}$$

Expansion $v_z = \frac{z}{t}$



Heavier particles emit sooner

Lighter particles emit later

Region of homogeneity and m_T scaling

Region of homogeneity: "size and shape of the phase space cloud of outgoing particles whos

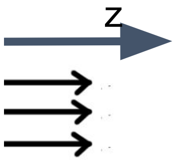
A si ... st mov

- What smallest/largest source size can we achieve?
  - We expect a simpler evolution in pp
  - How to deal with resonances?
- How does the source evolve in small systems?
  - No scaling at all?
  - Or scaling i.e. a hint of collectivity in small systems?

homo

$$\sqrt{\frac{T}{m_T}}$$

Expa



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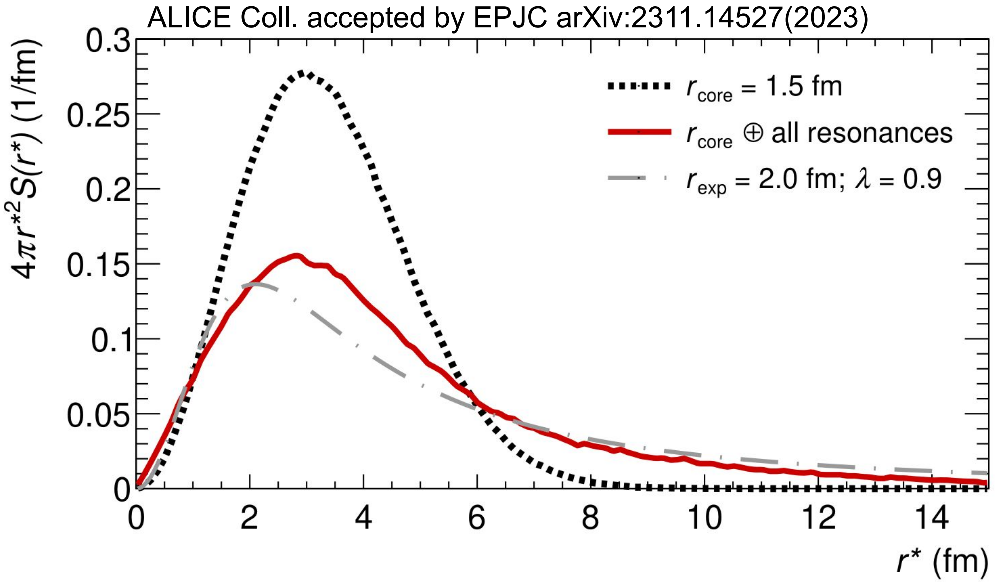
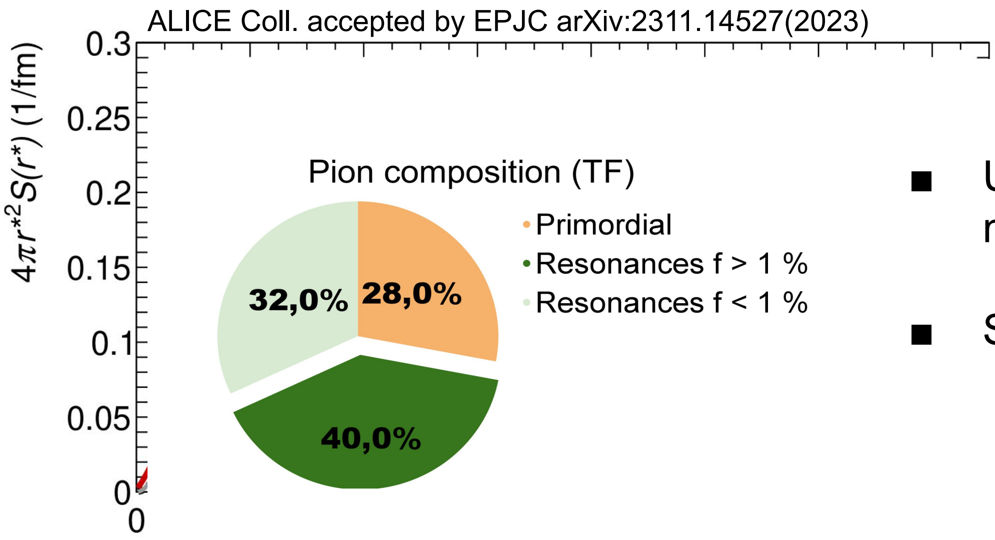
Study the effect of the resonances



- Example calculation using CATS [1]
- Comparison of exponential source with resonance source model (RSM)
  - Exponential mimics RSM
  - Obtained radii differ
  - RSM provides quantitative insight of resonance contributions
- Resonances explain previous findings of exponential type source for π–π

[1] D. Mihaylov et al. EPJC 78 (2018)

Study the effect of the resonances



- Using statistical hadronisation model [1, 2, 3]
- Summary parameters
  - m_{eff} = 1124 GeV/c^2
  - $c\tau_{eff}$ = 1.5 fm

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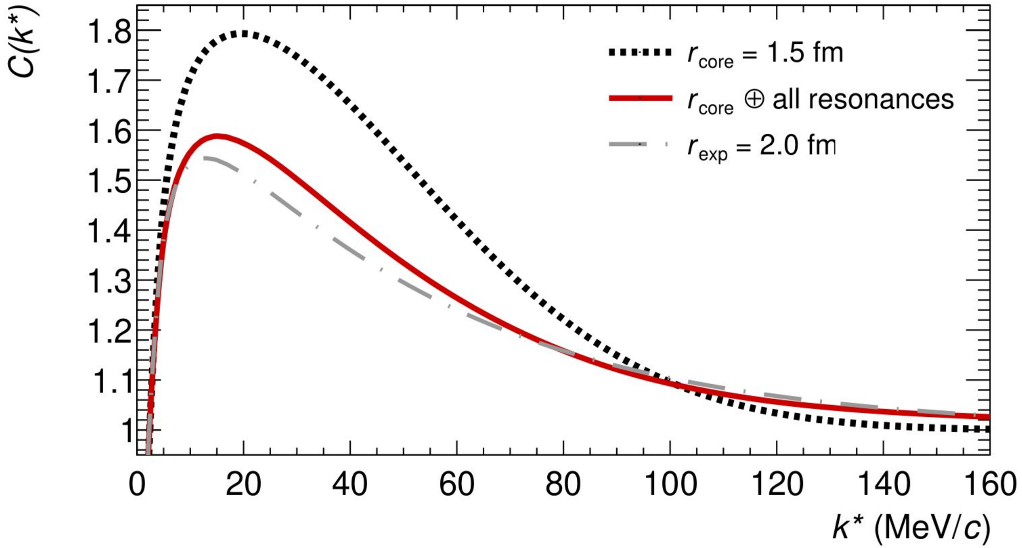
Study the effect of the resonances

ALICE Coll. accepted by EPJC arXiv:2311.14527(2023)



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