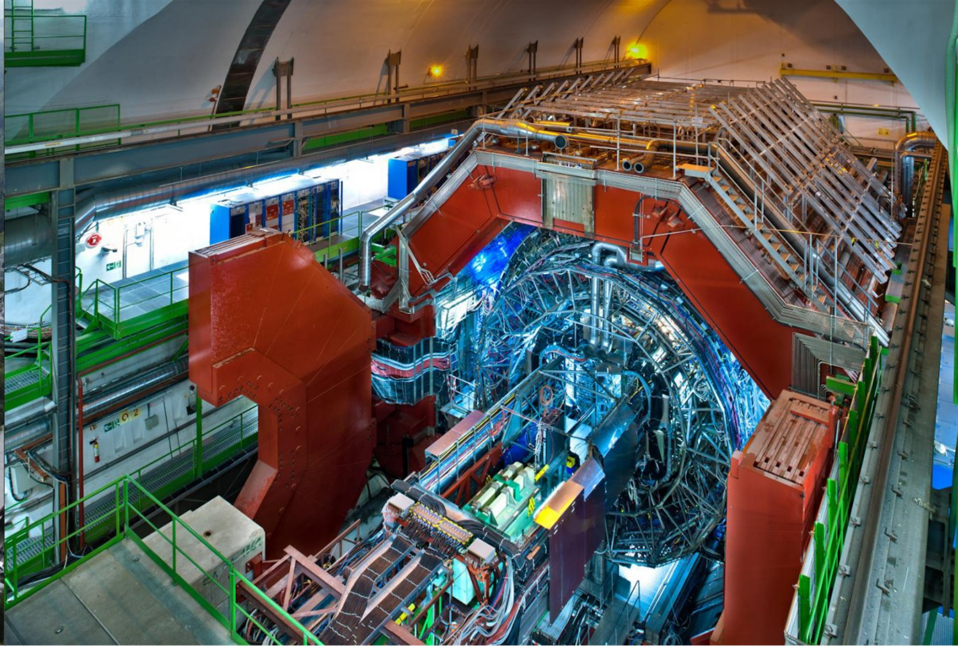


Towards a common particle-emitting source in HM pp at 13 TeV for mesons and baryons with ALICE

Maximilian Korwieser (TUM) on behalf of the ALICE Collaboration
EMMI Workshop, Trieste, 03.-07. July 2023
203/07/23 15:00 - 15:30

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

Femtoscopy a powerful tool

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

- Access final state interactions
  - Complementary to scatterings experiments
  - Access interaction between short-lived particles
  - 3-body studies

➔ Dimitar Mihaylov (today):
“Hadron-hadron correlation”

➔ Emma Chizzali (today):
“D-hadron interaction from correlation measurements”

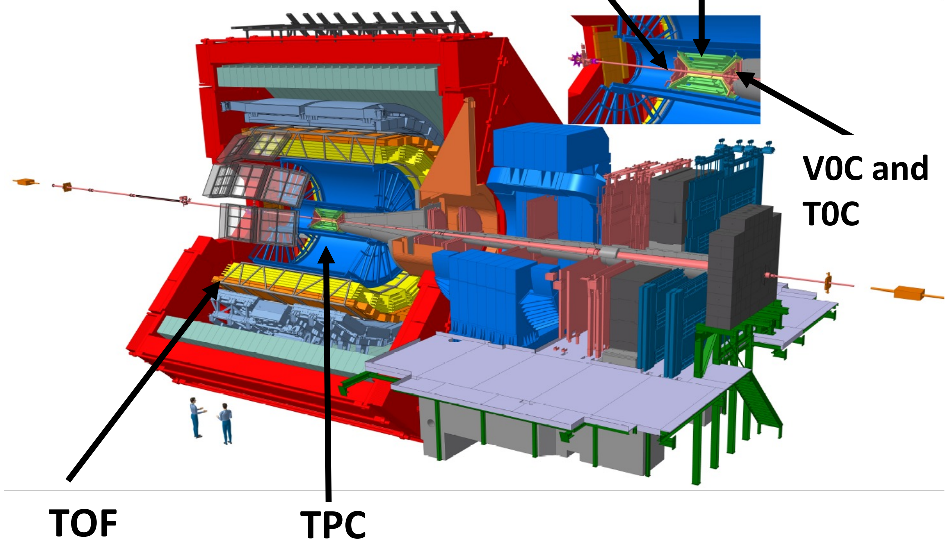
➔ Oton Vazques Doce (today)
“Experimental insight into the KN strong interaction”

➔ Laura Serksnyte (Wednesday)
“3-body interactions of hardons in pp collisions with ALICE”

➔ Raffaele Del Grande (Thursday)
“Proton-phi bound state”

Femtoscopy at ALICE in HM pp 13 TeV

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



- Direct detection of charged particles (π, K, p) by TPC and TOF
- Purity of about 99 % for π, K, p due to excellent PID capabilities

- HM pp collisions @ 13 TeV
  - Particles produced with relative distances of *O*(1 fm)
  - 1 Billion events in Run2

- Analyses so far…

  ALICE Collaboration

  PRC 99 (2019) 2, 024001

  PLB 797 (2019), 134822

  PRL 123 (2019), 112002

  PLB 805 (2020), 135419

  PLB 811 (2020), 135849

  Nature 588 (2020) 232-238

  PRL 127 (2021), 172301

  PLB 833 (2022), 137272

  PLB 829 (2022), 137060

  PRD 106 (2022) 5, 052010

  PLB (2022), 137223

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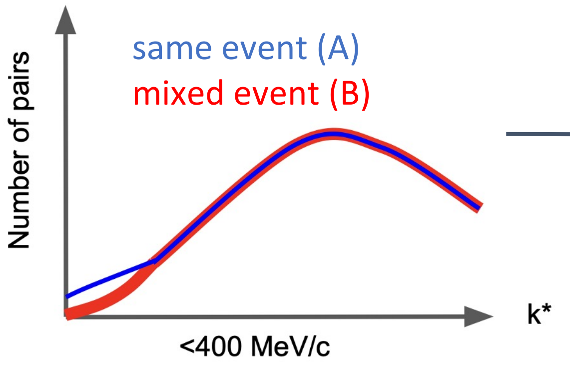
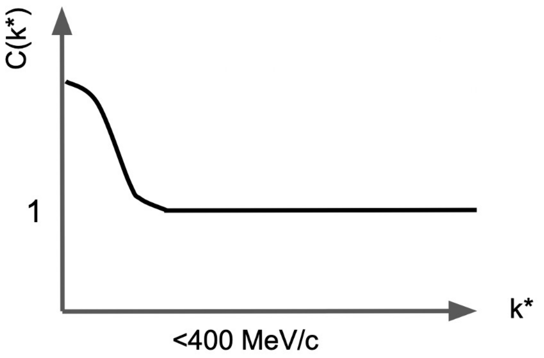
Femtoscopy in a nutshell



A/B

Correlation function



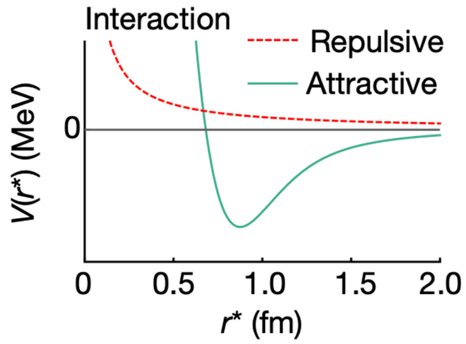
[M. Lisa et. al. Ann.Rev.Nucl.Part.Sci.55:357-402, 2005]

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
  - correlated sample (*A*): pairs from the *same* event
  - uncorrelated sample (*B*): pairs from *different* events
- Understand data
  - purity, feed-down
  - background?
  - …

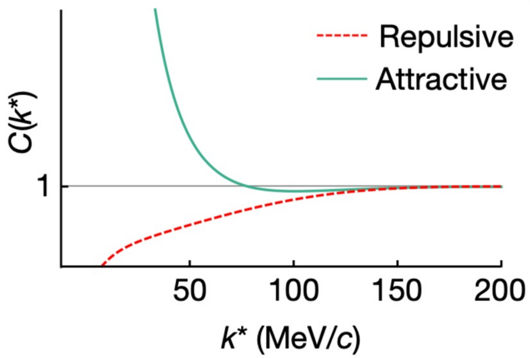
Femtoscopy in a nutshell



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

Solves Schrödinger eq.

Correlation function



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

Theory

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

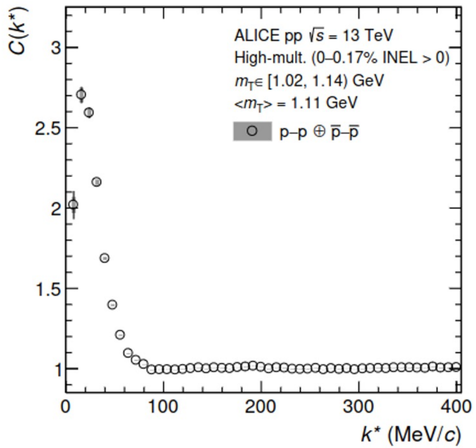
- **Model *S(r*)***
  - Gaussian, Exponential, …
  - Resonances?
- Calculate $\psi(r^*, k^*)$
  - QS, Coulomb, χEFT, …
- Evaluation:
  CATS framework [1]

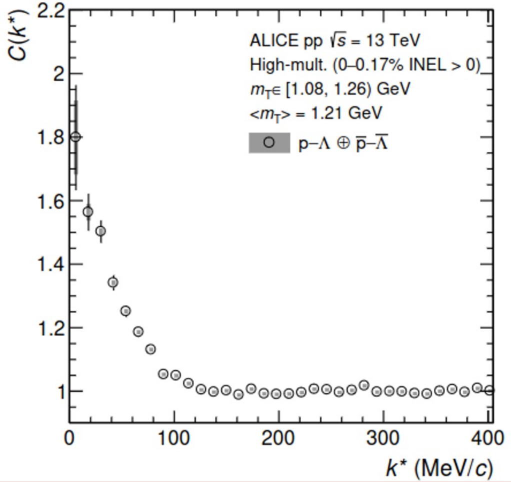
[1] D. Mihaylov et al. EPJC78(2018) 394

Baryon source in HM pp 13 TeV

ALICE public note PUB-1378 (2023)

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



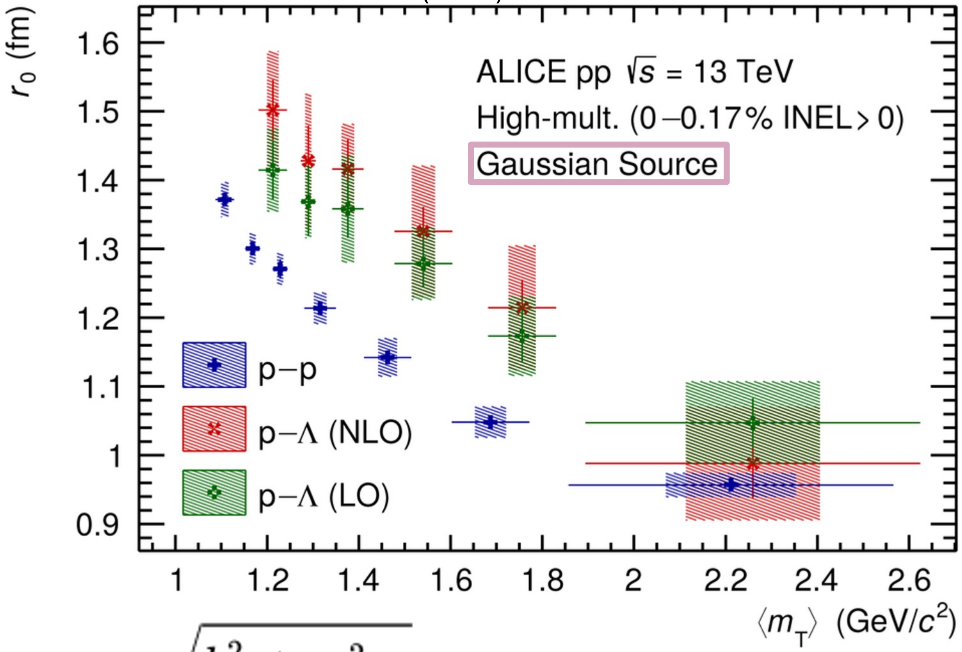


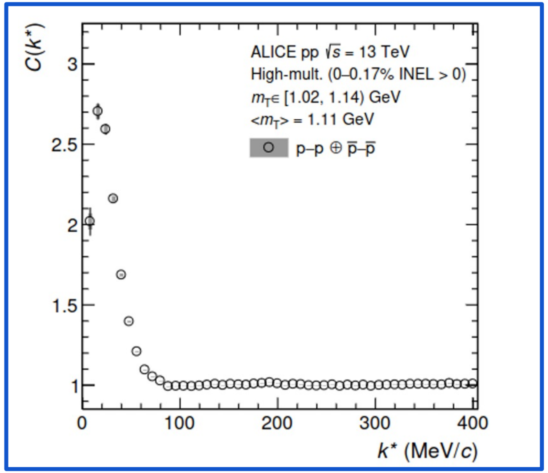
$$m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m_{\mathrm{avrg}}^2}$$
$$k_{\mathrm{T}} = \frac{1}{2}\left|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right|$$

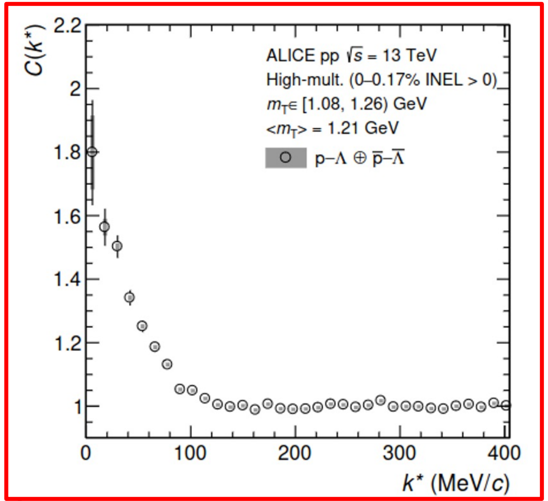
Baryon source in HM pp 13 TeV

[ALICE public note PUB-1378 (2023)](#)

ALICE Coll. PLB 811 (2020)







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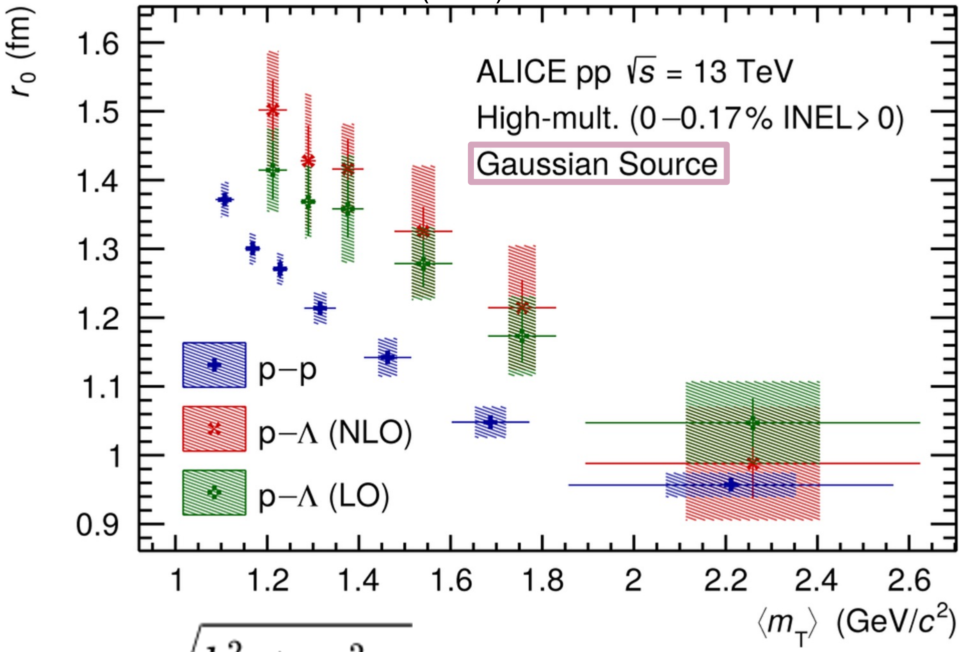
$$k_{\mathrm{T}} = \frac{1}{2}\left|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right|$$

Baryon source in HM pp 13 TeV

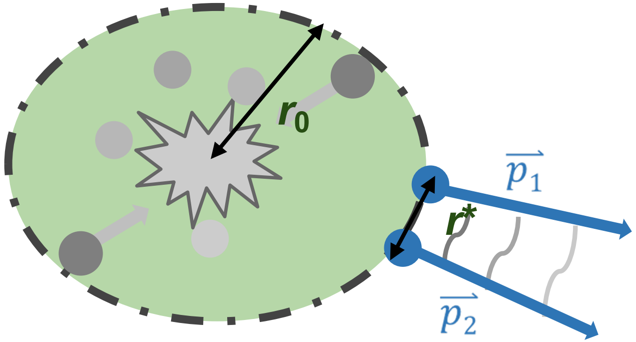
ALICE Coll. PLB 811 (2020)



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

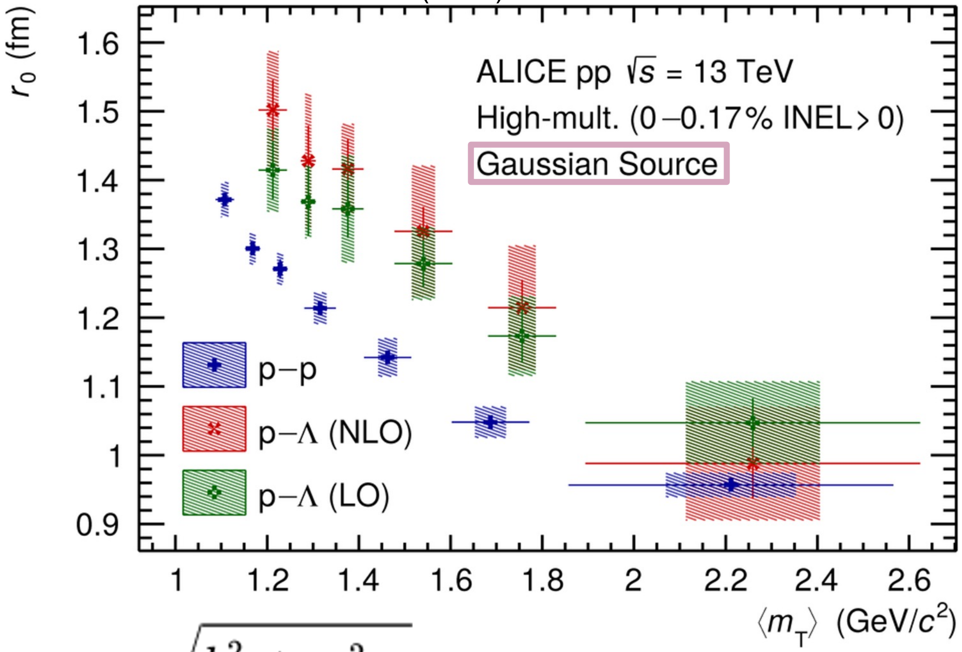
$$k_{\mathrm{T}} = \frac{1}{2}|\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}|$$

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



Baryon source in HM pp 13 TeV

ALICE Coll. PLB 811 (2020)

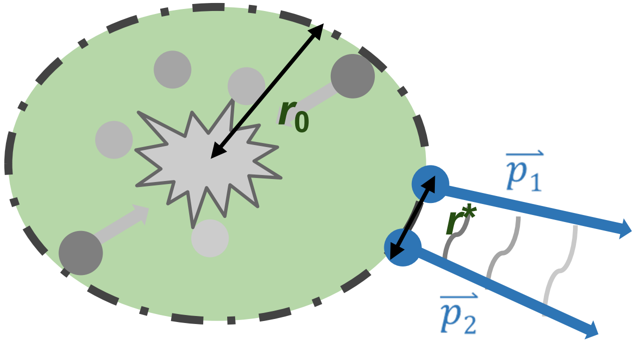


$$m_T = \sqrt{k_T^2 + m_{avrg}^2}$$

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

- Scaling is expected for common radial flow velocity and hadronization time scale
- Effects influencing the scaling include **non-gaussian** contributions to the source

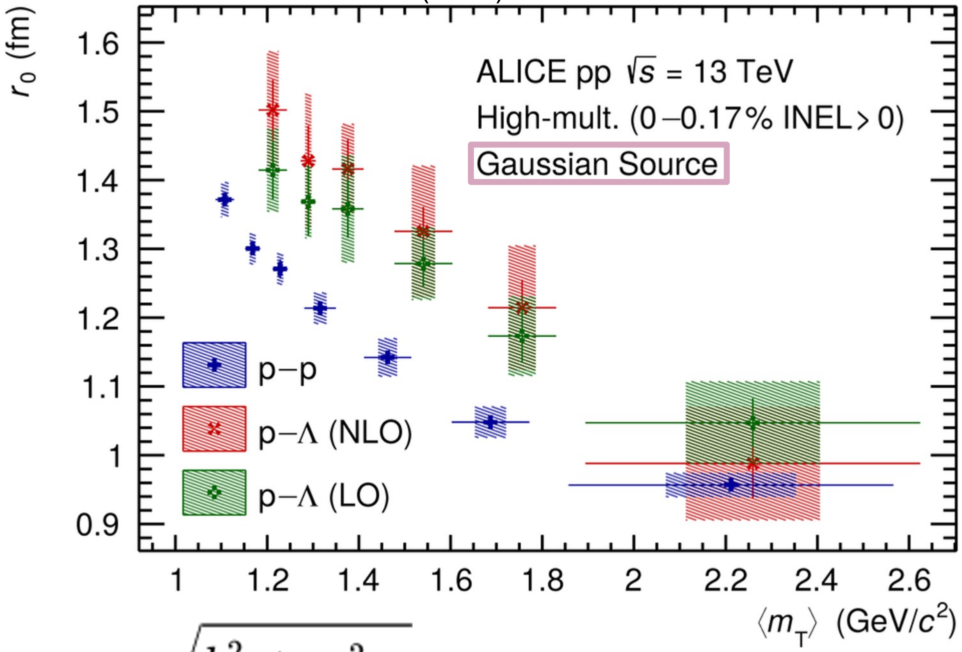
  - **Feed down from resonances** [1,2]



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

Baryon source in HM pp 13 TeV

ALICE Coll. PLB 811 (2020)

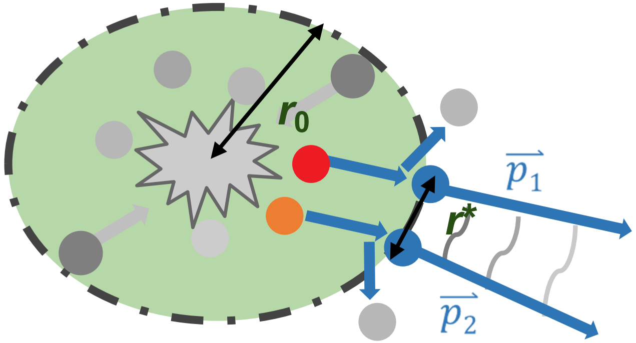


$$m_T = \sqrt{k_T^2 + m_{avrg}^2}$$

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

- Scaling is expected for common radial flow velocity and hadronization time scale
- Effects influencing the scaling include **non-gaussian** contributions to the source

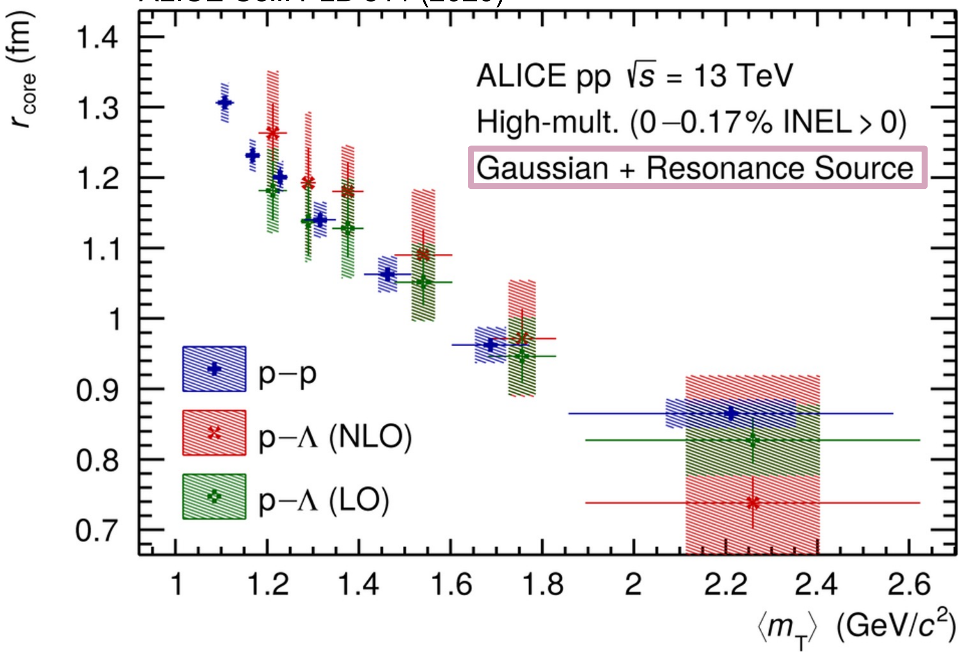
  - **Feed down from resonances** [1,2]
  - **2/3** of protons stem from resonances



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

Common baryon source in HM pp 13 TeV

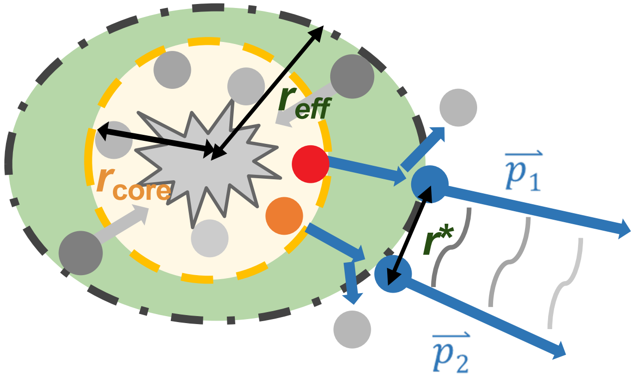
ALICE Coll. PLB 811 (2020)



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

  ➔ Motivates the assumption of a universal particle source for baryons

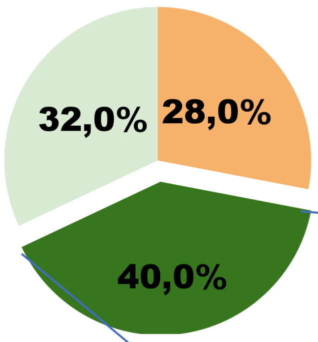
- How well does the source resonance model (RSM) perform for mesons? Is the scaling different?



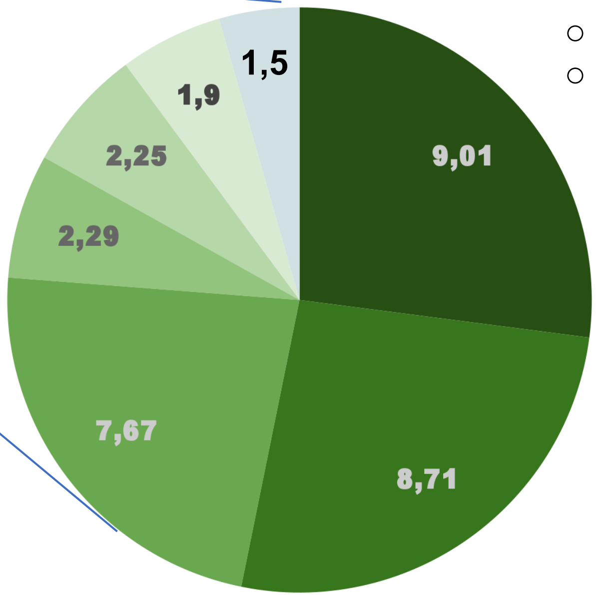
Access smaller m_T by studying π–π and meson-baryon correlations with K^+–p

Estimating the resonance contribution for pions

Pion composition (TF)



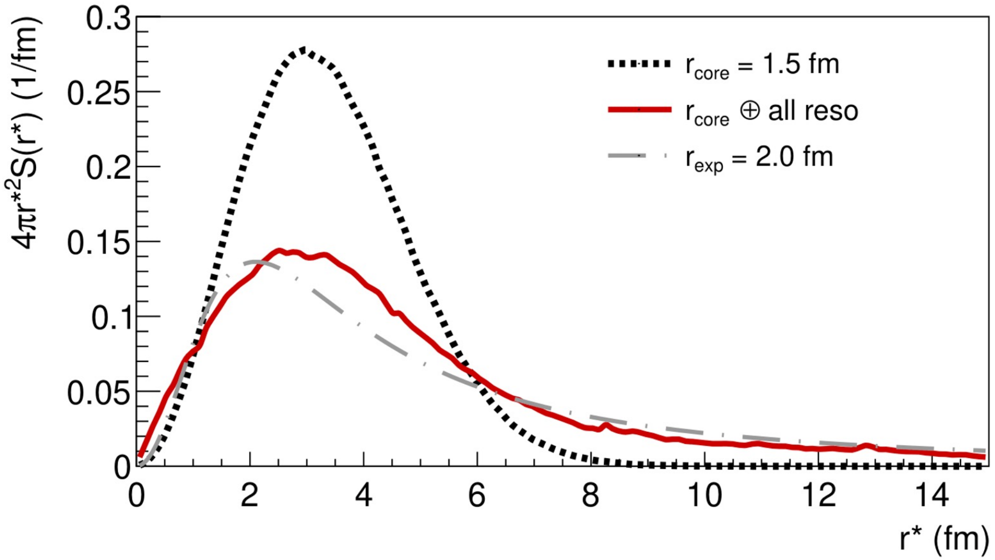
Resonances f > 1 %
- ρ0
- ρ+
- ω(782)
- K*(892)+
- K*(892)0
- b1(1235)+
- a2(1320)+



- 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
  - $c\tau_{\mathrm{eff}}$ = 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)

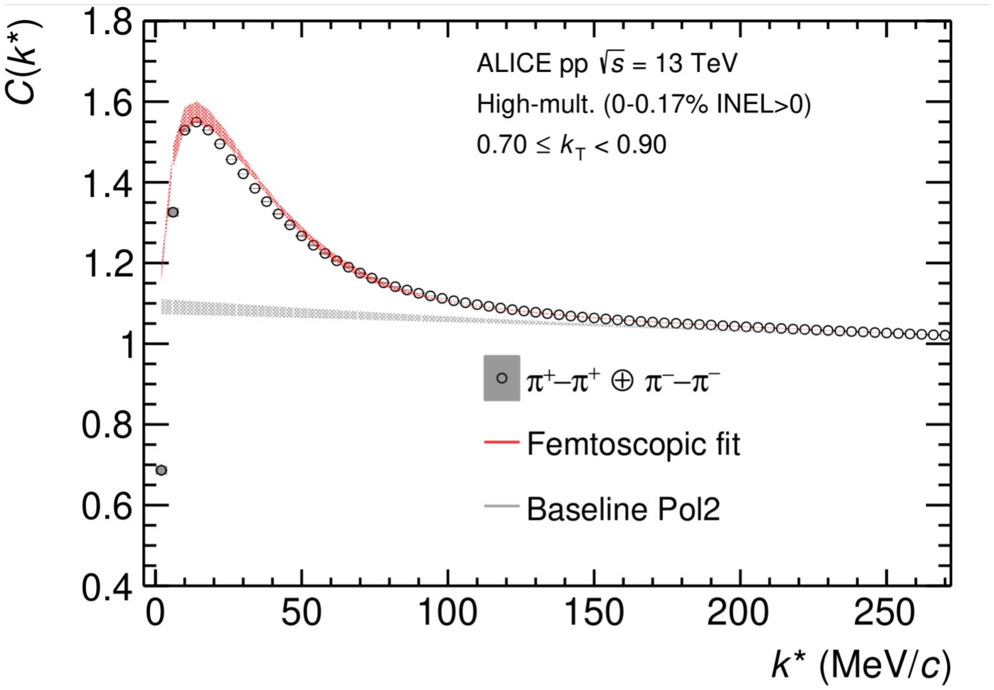
Study the effect of the resonances



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

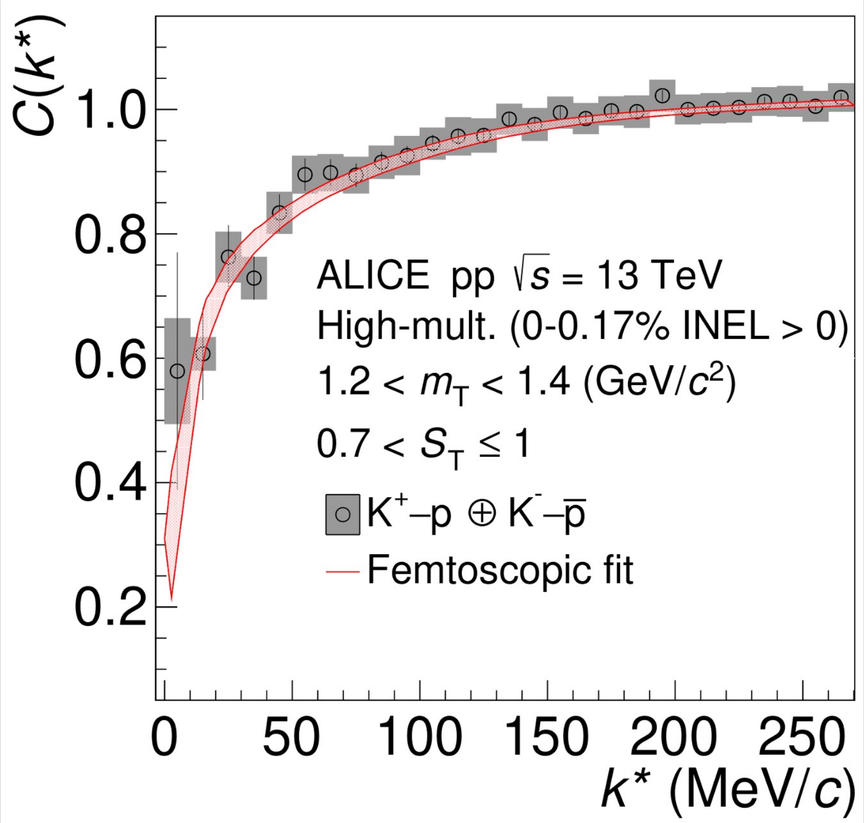
- Example calculation using CATS [1]
- Comparison of exponential source with RSM
  - Exponential mimics RSM
  - Obtained radii differ
  - RSM provides quantitative insight of resonance contributions
- Resonances explain previous findings of exponential type source for π–π

Measured π–π correlation HM pp 13 TeV



- Obtained in several m_T bins
- Fit with $C^{\pi\pi}(k^*)$ = Pol(k^*) x $C^{Femto}(k^*)$
  - Pol1 **or** Pol2 to account for residual background
  - Interaction is modeled by Coulomb interaction and Quantum Statistics
  - $C^{Femto}(k^*)$ corrected for purtiy and fractions by λ parameter formalism
  - Extract $\boldsymbol{r}_{\mathbf{core}}$ for each m_T bin

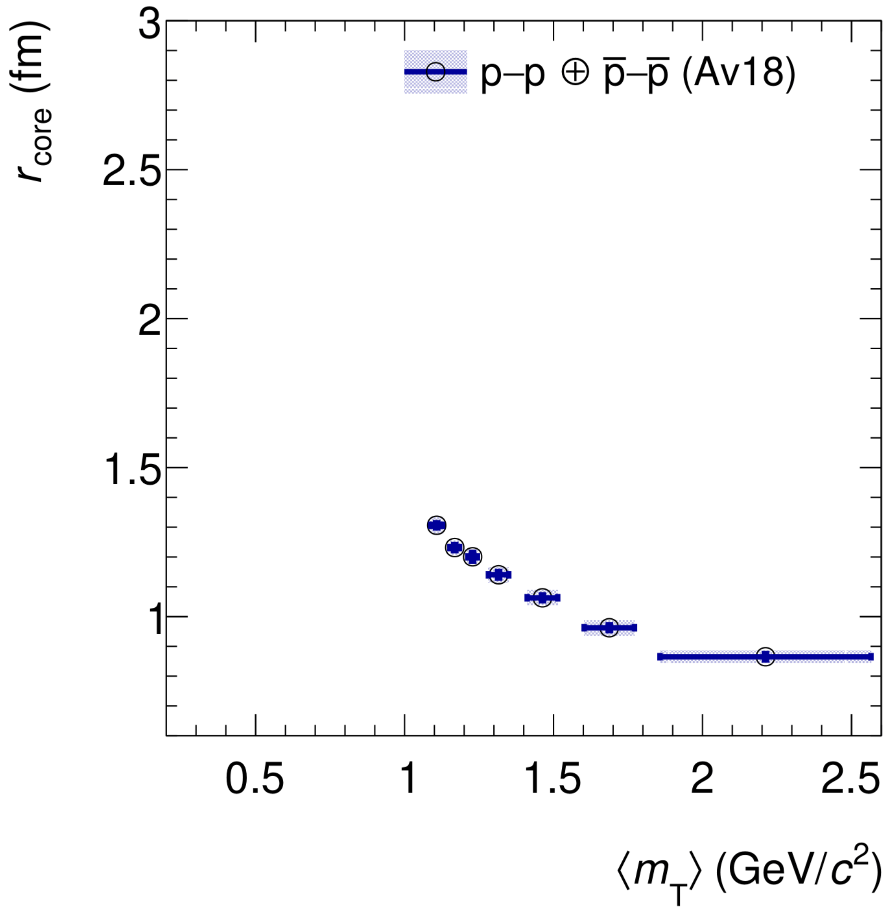
Measured K⁺–p correlation HM pp 13 TeV



- Obtained in several m_T bins
- Fit with $C^{Kp}(k^*)$ = Pol(k^*) x $C^{Femto}(k^*)$
  - Pol0 **or** Pol1 to account for residual background
  - Interaction is modeled by Coulomb interaction and χEFT [1]
  - $C^{Femto}(k^*)$ corrected for purity and fractions by λ parameter formalism
  - Extract $\boldsymbol{r_{core}}$ for each m_T bin

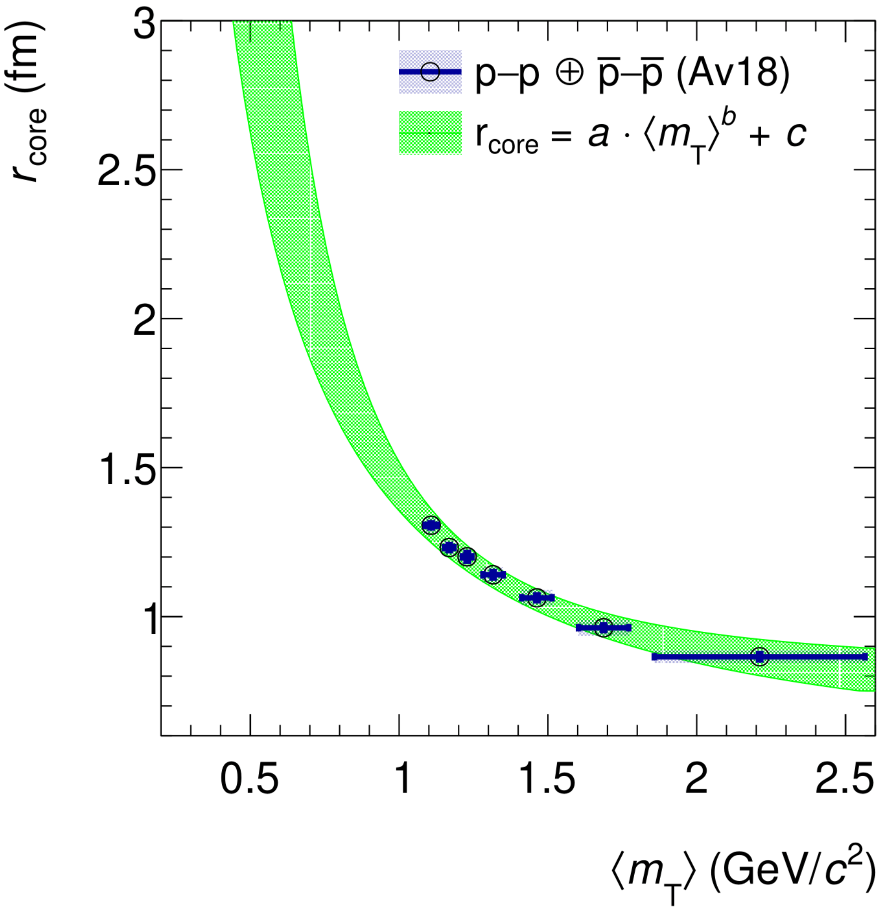
[1] K. Aoki et al. PTEP 1 (2019)

r_{core} compared to previous results in HM pp 13 TeV



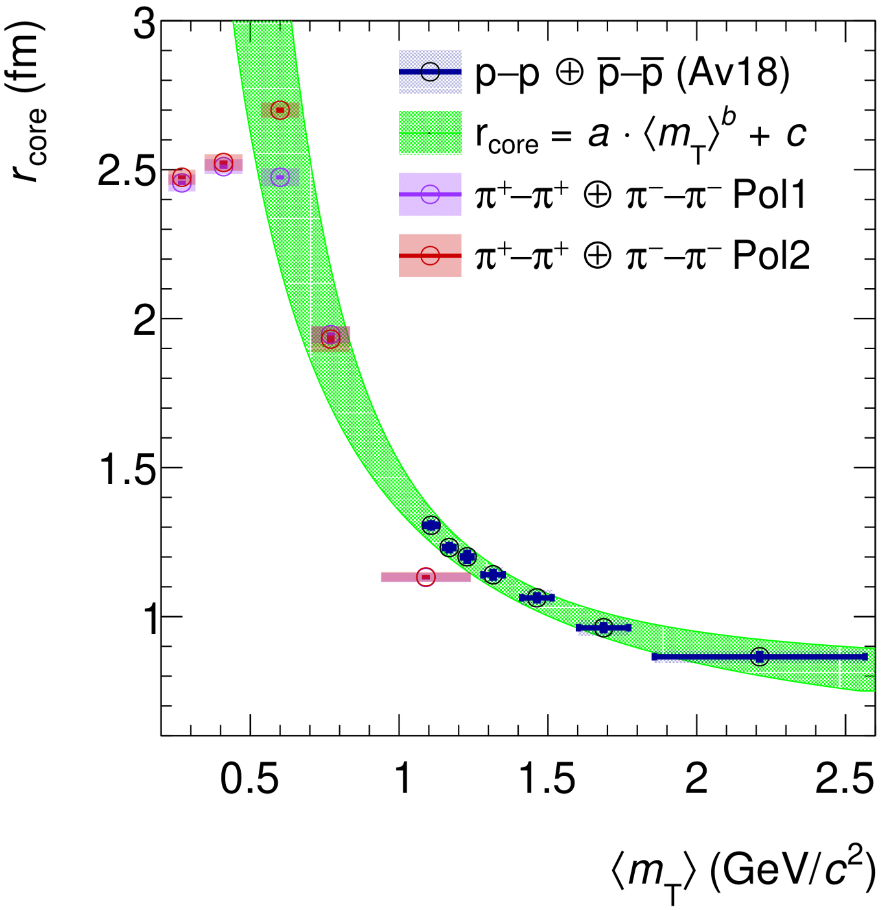
- p–p taken from PLB 811 2020

r_{core} compared to previous results in HM pp 13 TeV



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

r_{core} compared to previous results in HM pp 13 TeV



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

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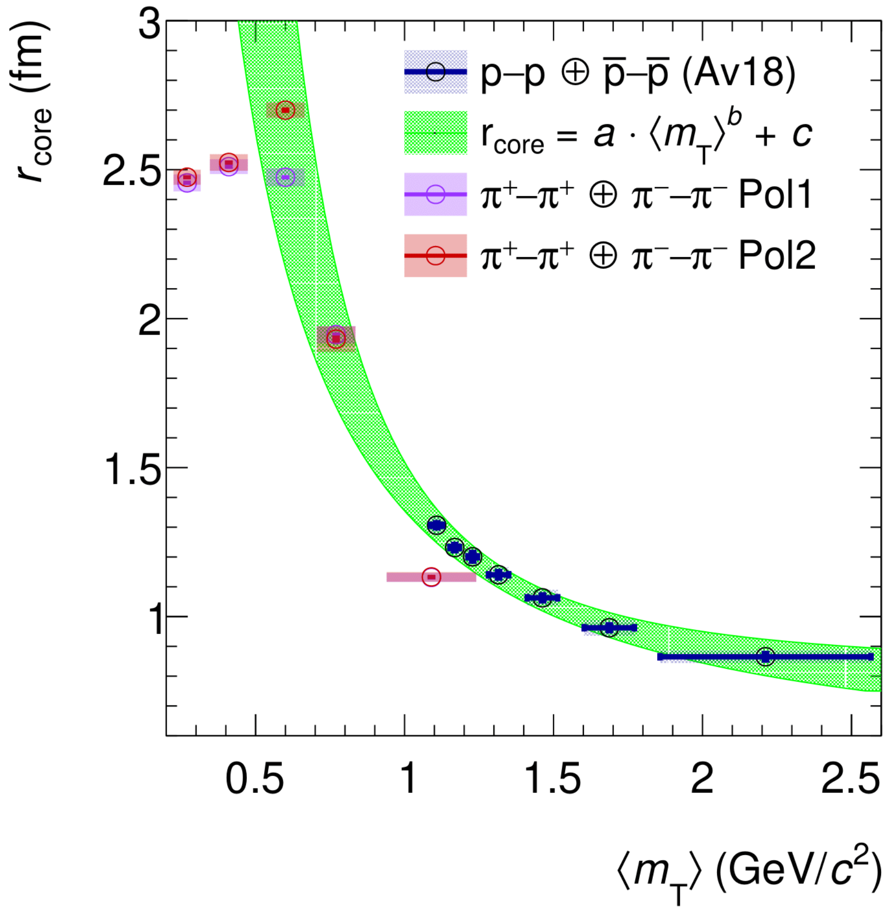
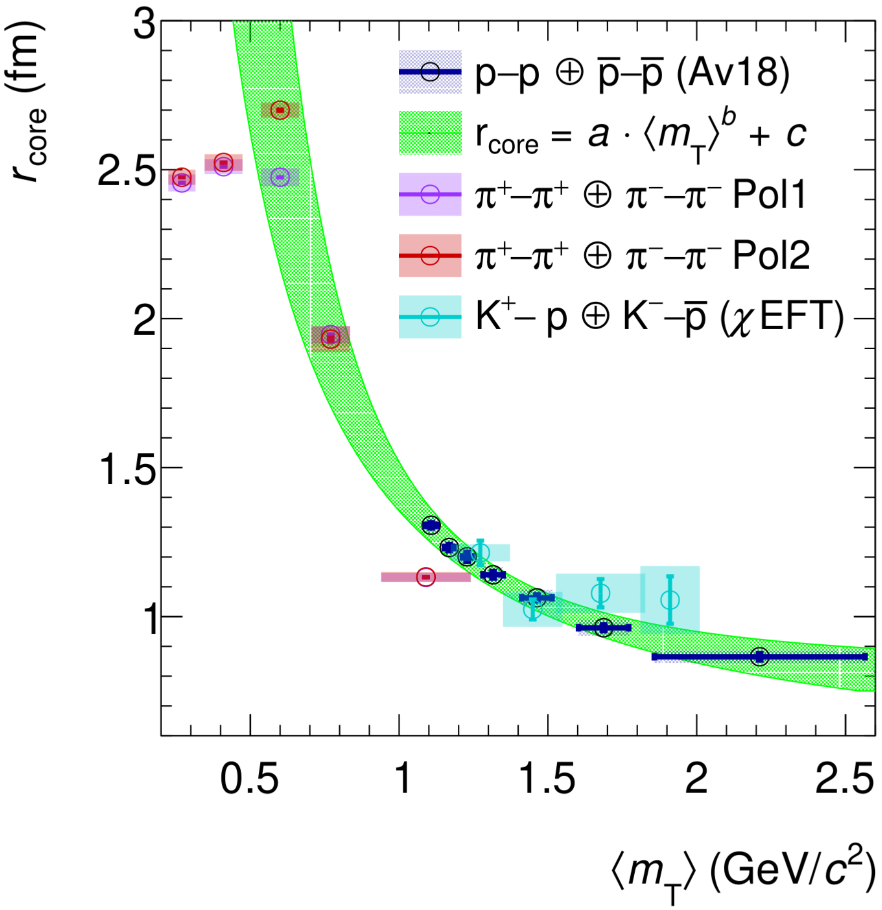


- p–p taken from PLB 811 2020
- Parameterization and extrapolation of the r_{core} dependence
- π–π from this analysis
- For m_T above 0.4 GeV/c^2 good agreement with parametrization
  - ➔ Saturation for π–π radii (not predicted by any model)

r_{core} compared to previous results in HM pp 13 TeV

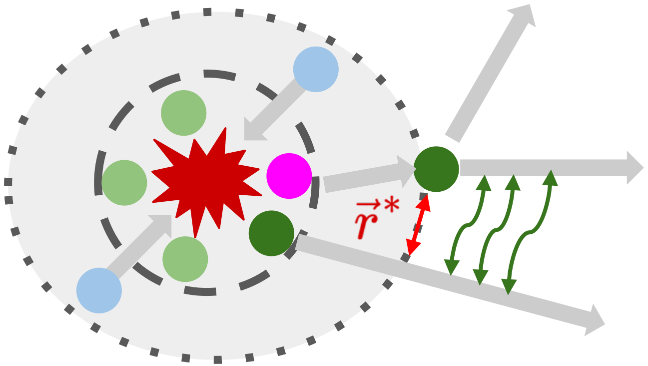


- p–p taken from PLB 811 2020
- Parameterization and extrapolation of the r_{core} dependence
- π–π from this analysis
- K^+–p from this analysis
- For m_T above 0.4 GeV/c^2 good agreement with parametrization
  - ➔ Evidence for a common source for all mesons and baryons in HM pp at 13 TeV

Common Emission in CATS (CECA)

A new numerical framework arXiv 2305.08441

- Goal: generic modeling of particle emission in small systems, including kinematic effects such as the m_T scaling and applicable to N-body problems



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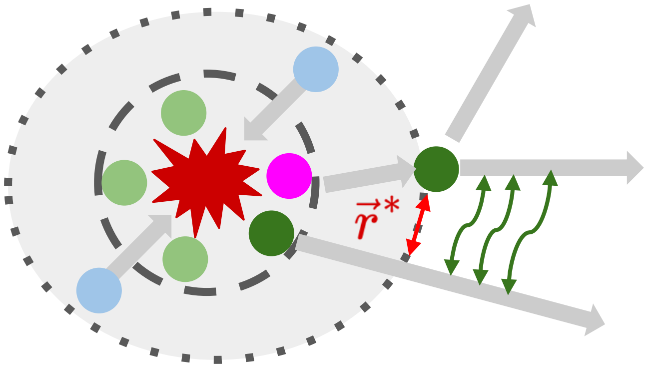

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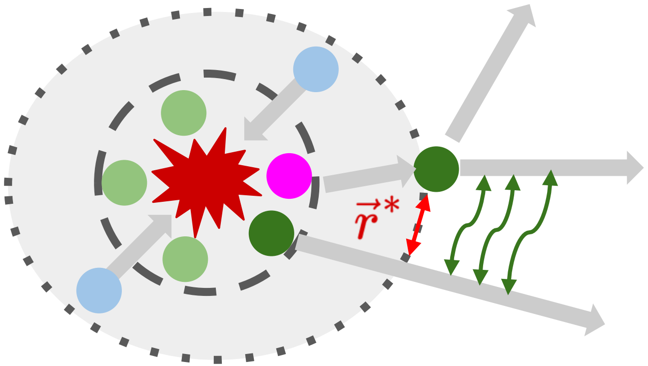
- Generation of events, containing point-like particles with well defined spatial and momentum coordinates



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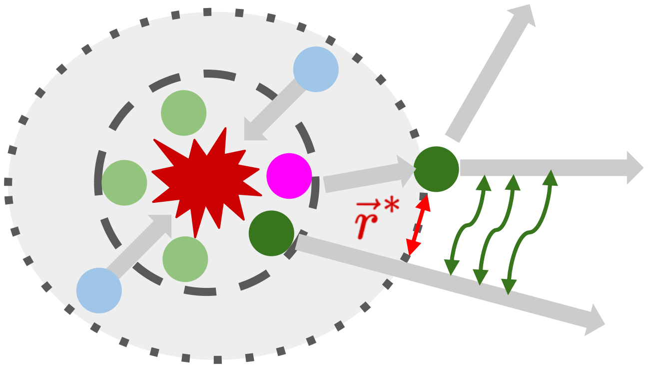
- Generation of events, containing point-like particles with well defined spatial and momentum coordinates
- Generate both primordial particles and resonances



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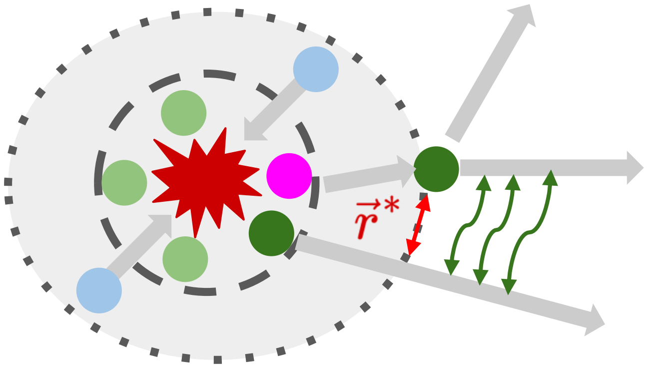
- Monte-Carlo simulation based on the properties of single particle emission
- Generation of events, containing point-like particles with well defined spatial and momentum coordinates
- Generate both primordial particles and resonances
- Group the particles into pairs and extract the source based on those of $k^* < 100$ MeV/c

The modelling is effective and based on three parameters. To be tested on ALICE data.

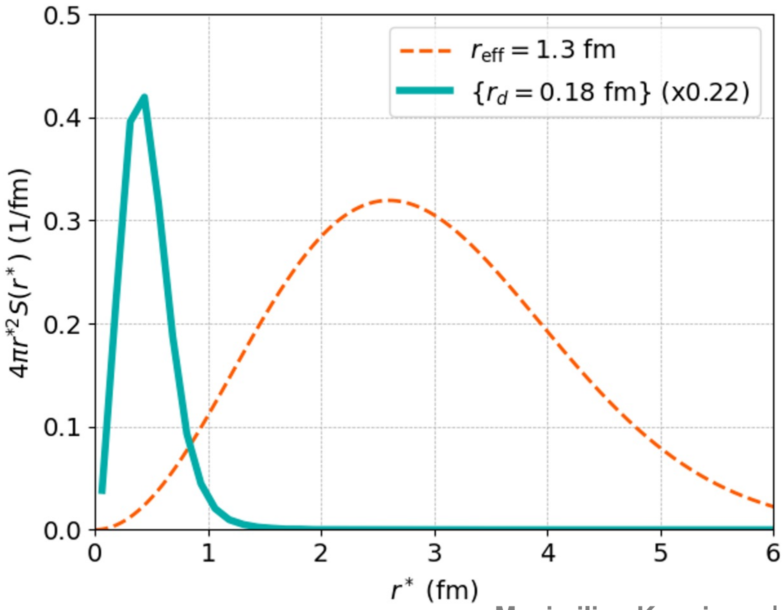


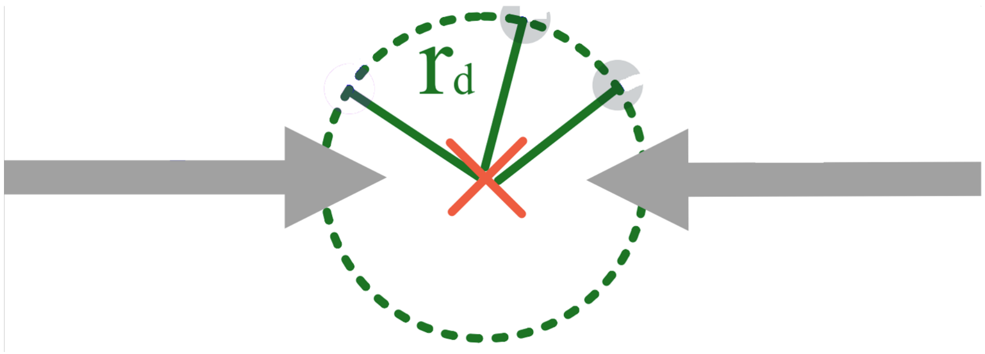
CECA: The common source

Displacement parameter

- Random Gaussian **displacement** around the collision point
- Sample the momentum

In this example: proton p_T distributions from ALICE [Eur. Phys. J. C, 80(8):693, 2020]

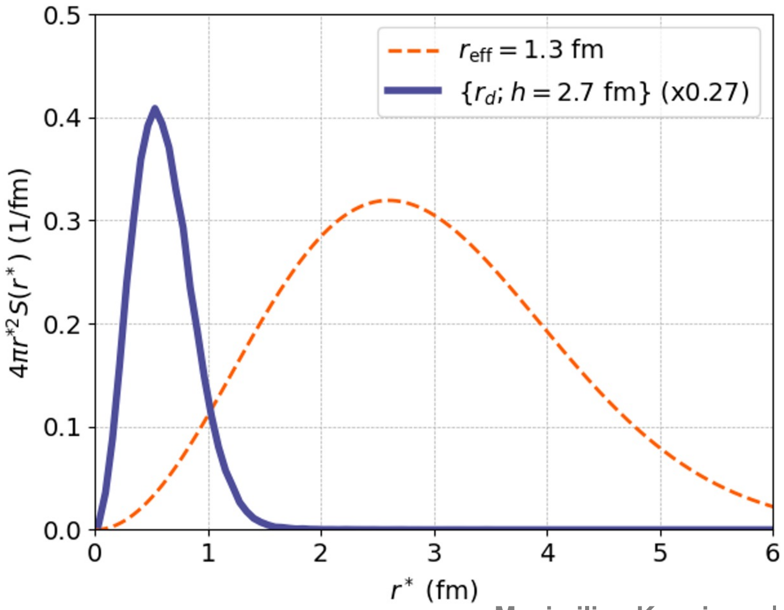


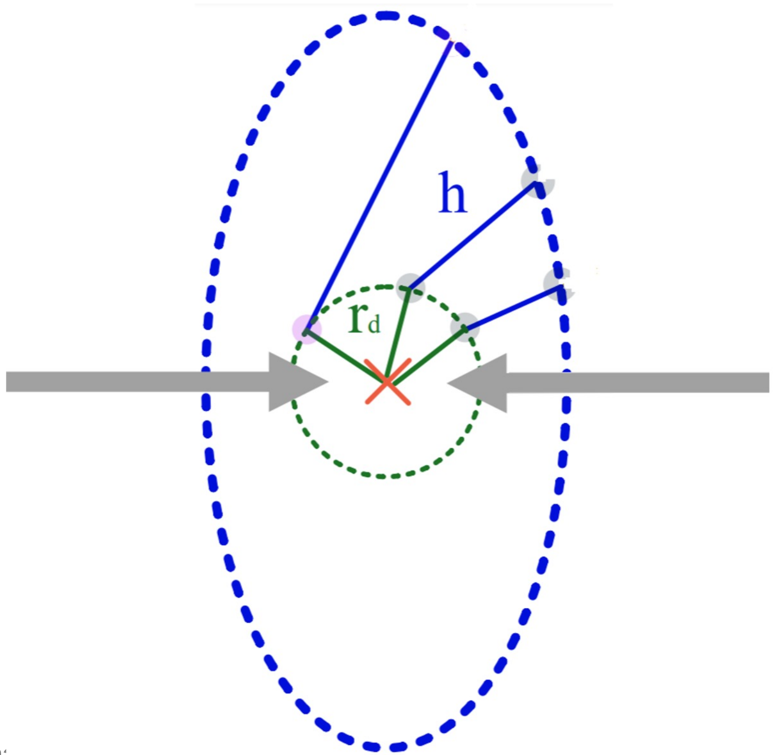


CECA: The common source

Hadronization parameter

- Propagate the particles on a straight trajectory until they intersect an ellipsoidal surface around the collision point

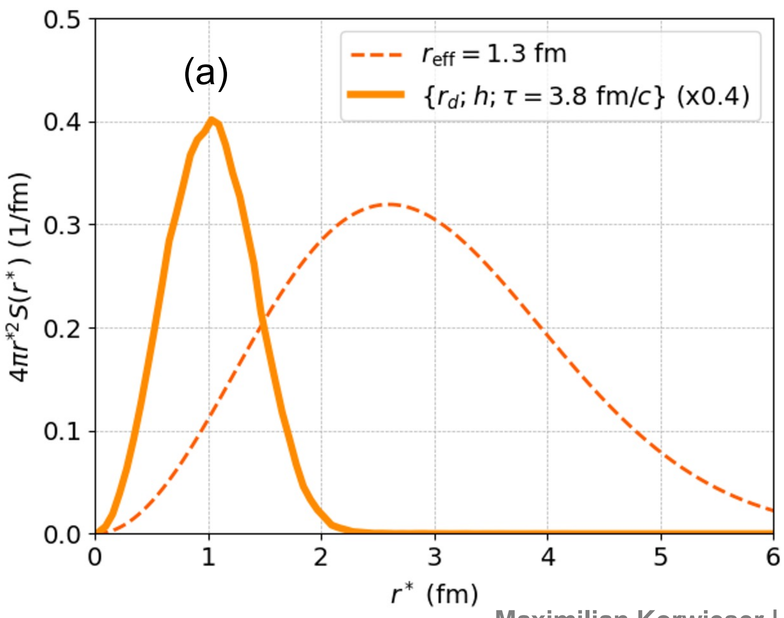


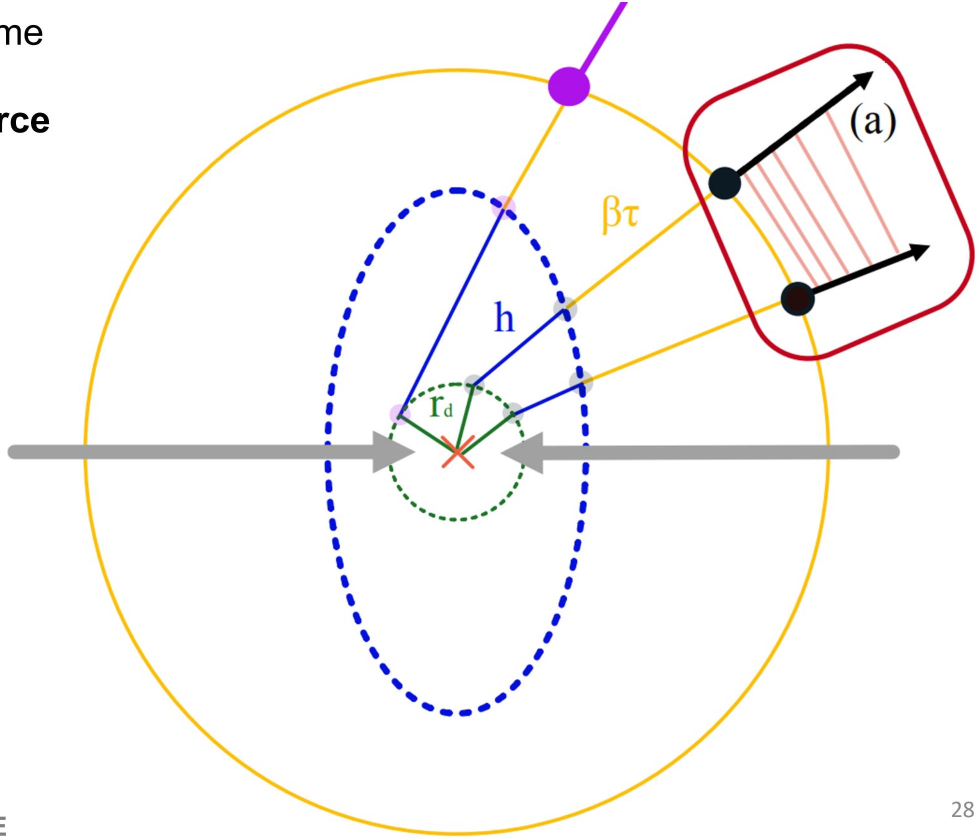


CECA: The common source

Free-streaming phase

- Propagate each particle for a fixed amount of time τ, based on the velocity $\beta = p/\gamma m$
- The resulting distribution is the **primordial source**

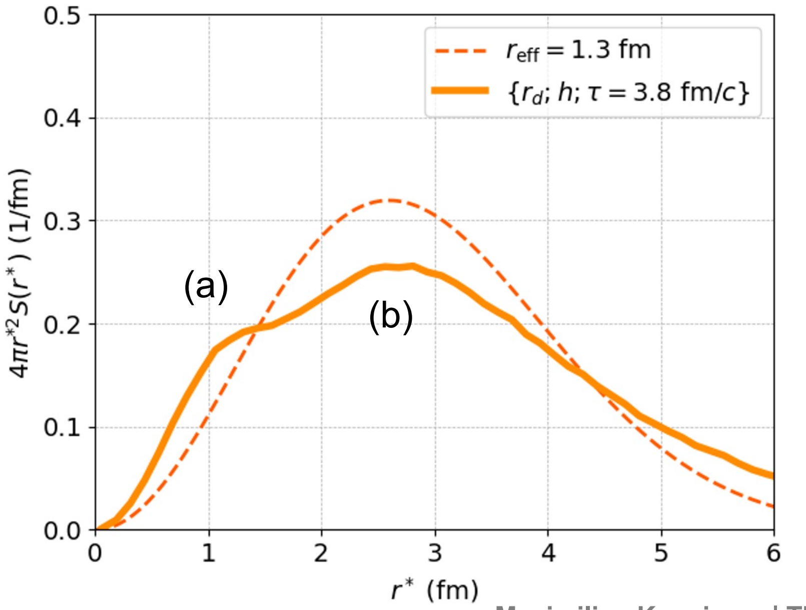


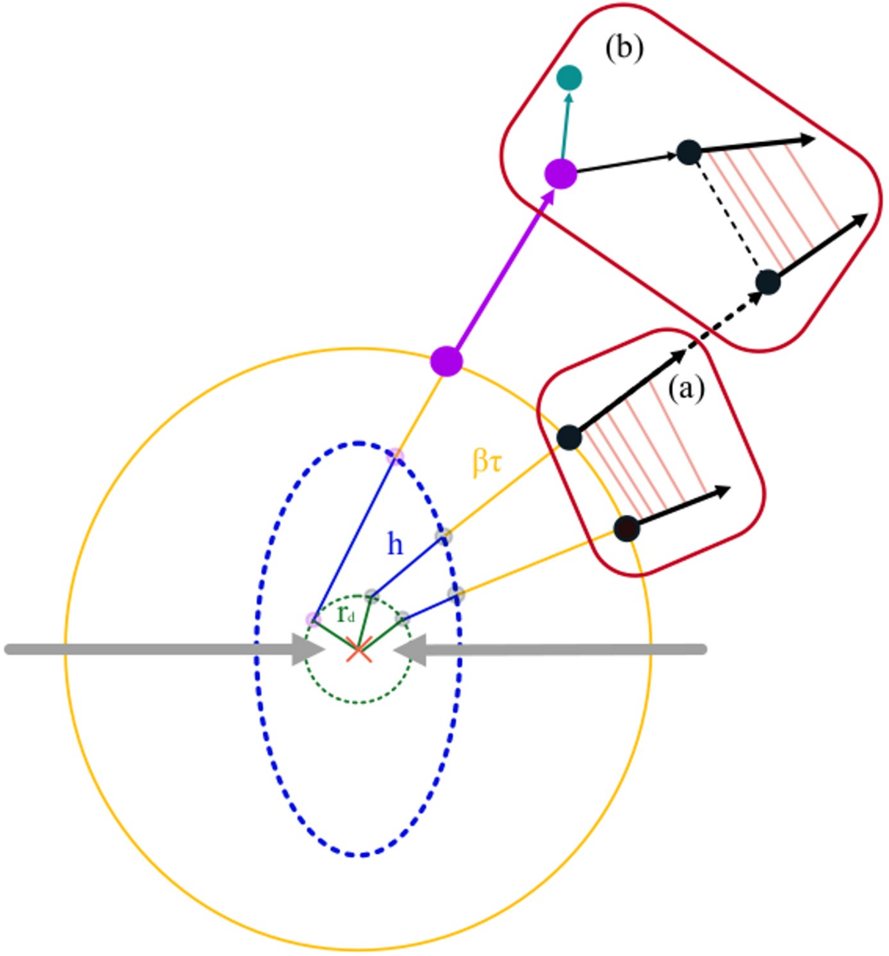


CECA: The common source

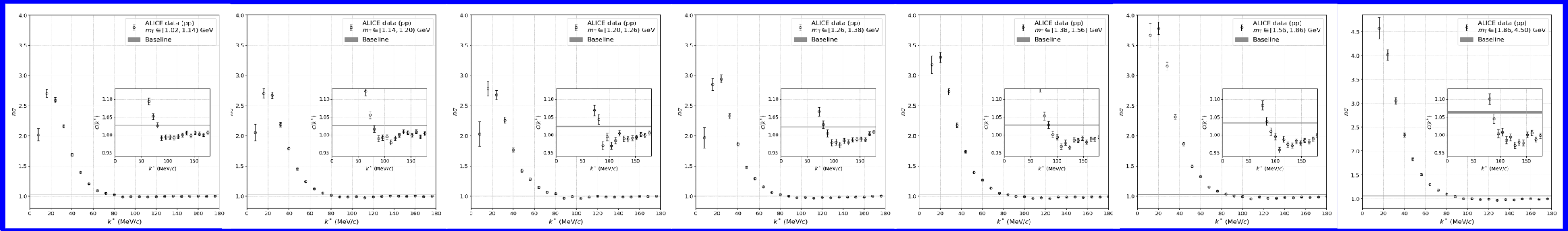
An example for pp pairs

- Decay short-lived resonances and group the final particles into pairs, after equalizing their time. **N.B. ⅔ of the protons stem from resonances!**

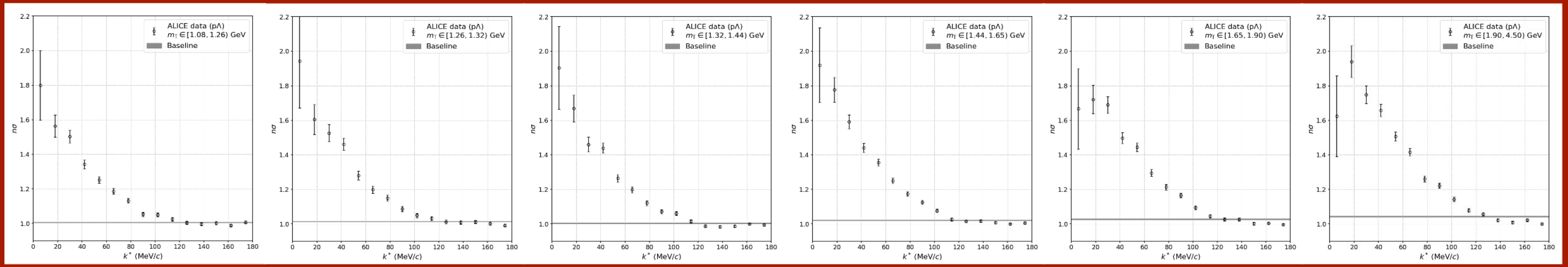




ALICE data: pp and pΛ correlations



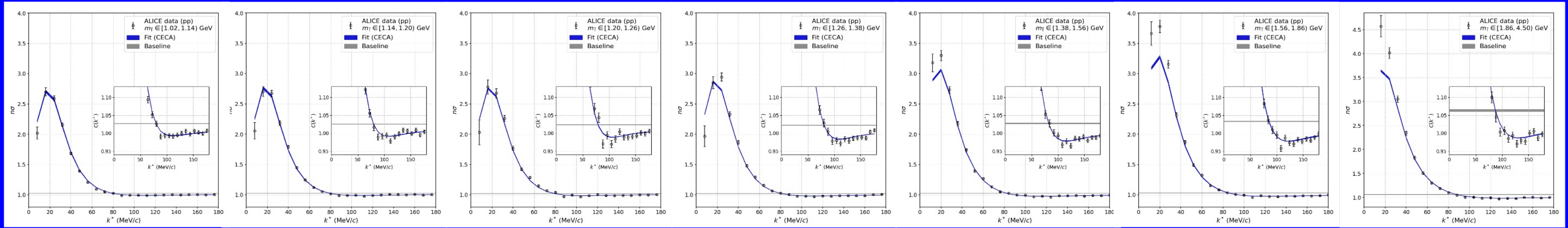
mT



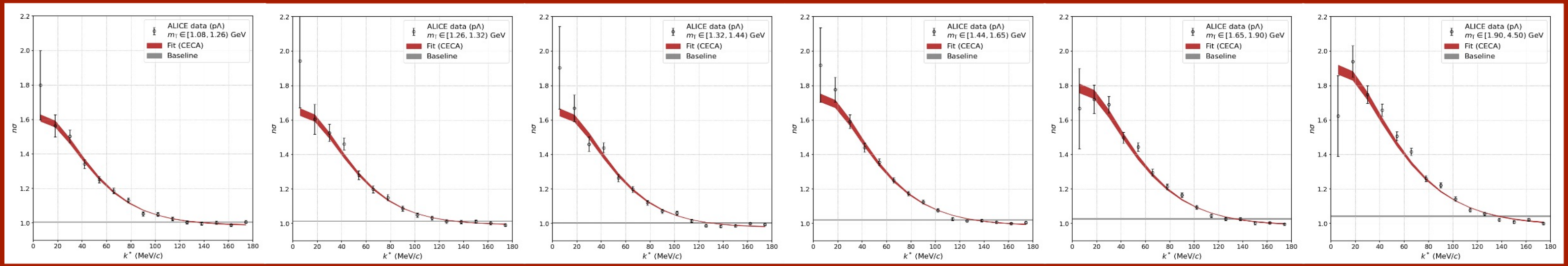
Data: High-multiplicity pp collisions @ 13 TeV from ALICE

[Phys.Lett.B 811 (2020) 135849]

ALICE data + CECA: pp and pΛ correlations

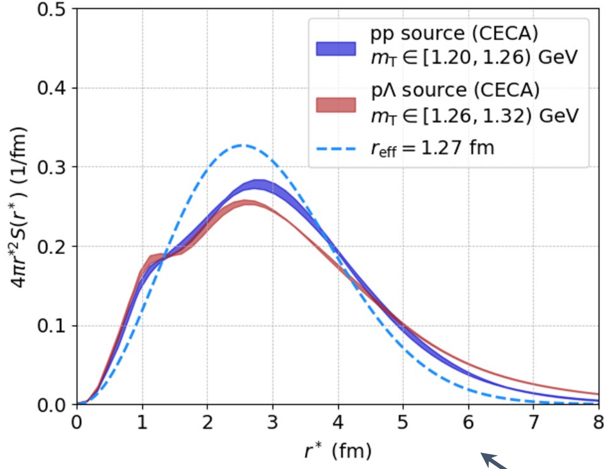


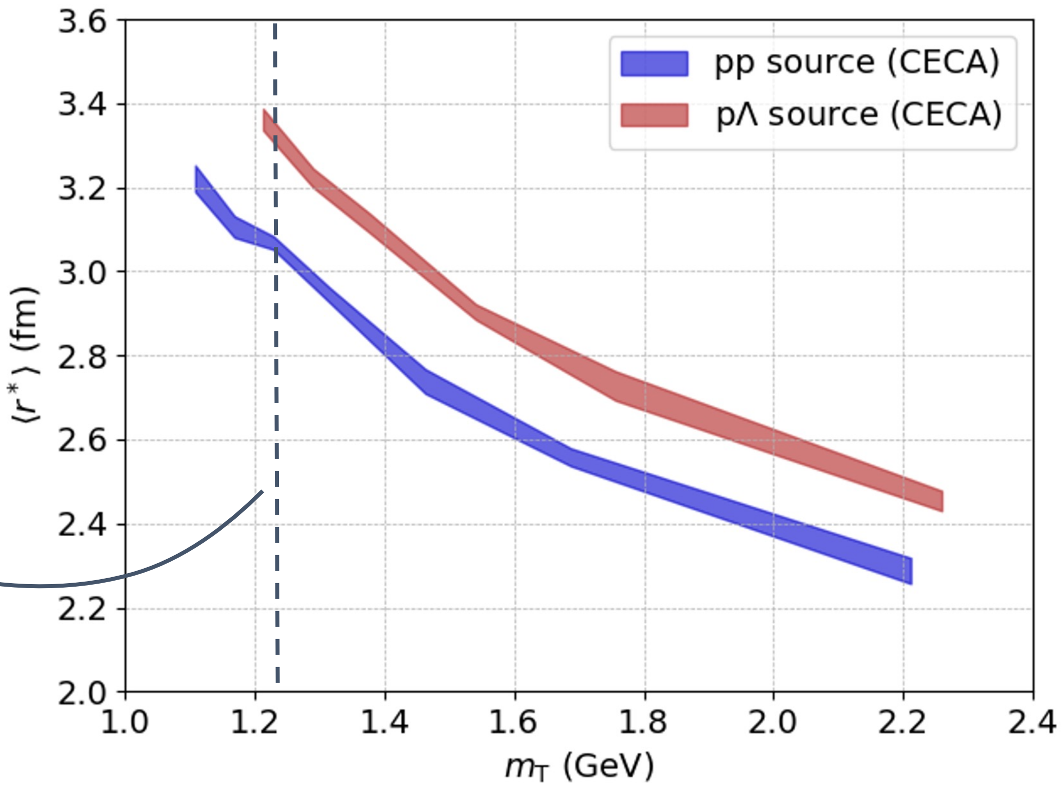
mT



- pp interaction: fixed to the Argonne v18 potential Phys. Rev. C, 51:38–51, 1995
- pΛ interaction: Usmani potential, short-range repulsive core fitted Phys. Rev. C, 29:684–687, 1984
- **A combined fit of the m_T differential pp and pΛ correlations!**

CECA: Source distribution m_T scaling





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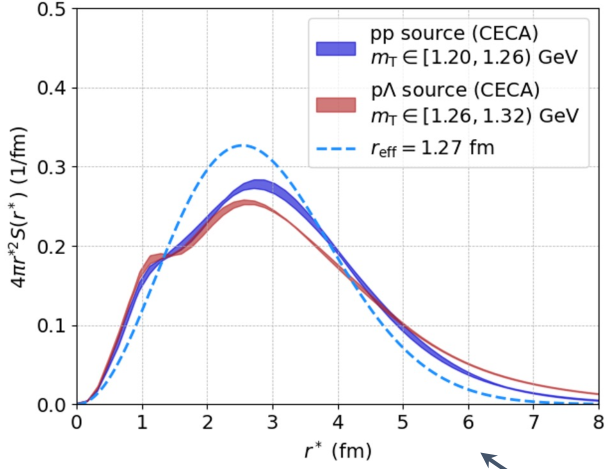

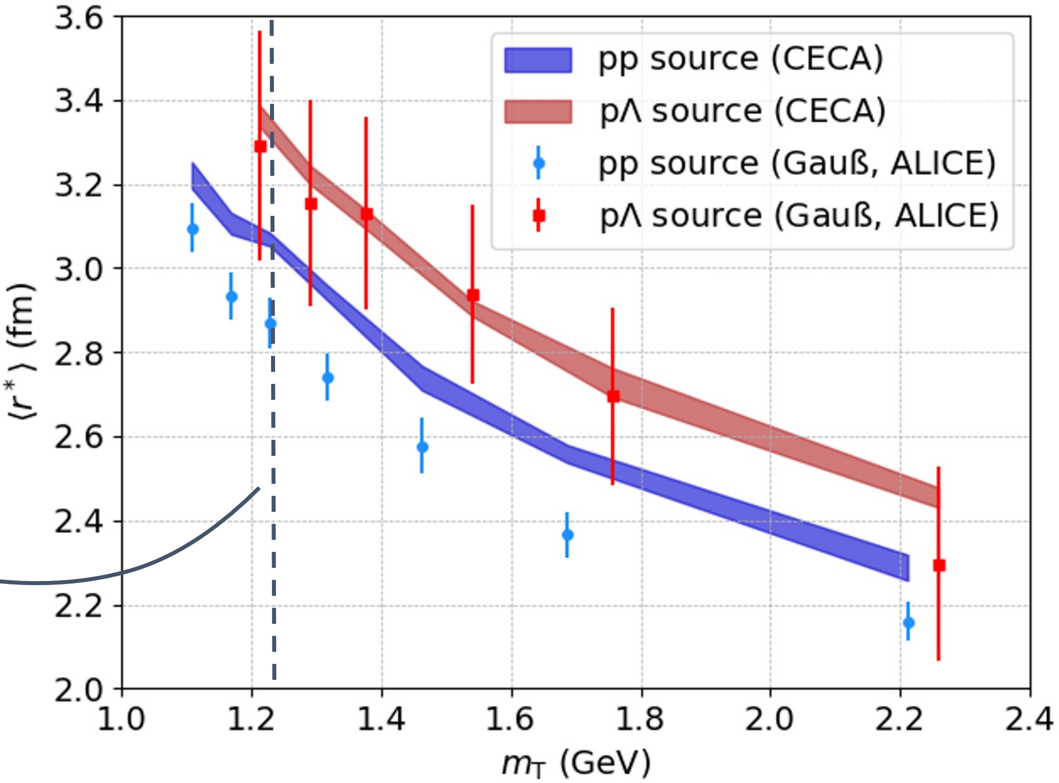

ALICE data + CECA: Results of pΛ fit

	Usmani	Usmani (NLO19)	Usmani (Fit)
χ^2	-	473	371
d (fm)	-	0.288 ± 0.013	0.176 ± 0.005
h_T (fm)	-	$3.23^{+0.05}_{-0.30}$	$2.68^{+0.06}_{-0.04}$
τ (fm/c)	-	$3.26^{+0.16}_{-0.04}$	$3.76^{+0.05}_{-0.03}$
f_0 (fm)	2.88	2.88	2.88
f_1 (fm)	1.66	1.41	1.15 ± 0.07

- Usmani potential [1] tuned to NLO19 yields higher χ^2/243 compared to a fit with free repulsive core parameters

- Fit prefers a reduced strength in the $^3S_1$ channel:
  - In this investigation, only the $^3S_1$ channel parameters were varied
  - The $^1S_0$ channel is related to binding energy of the hypertriton

[1] A. R. Bodmer et al. PRC 29 (1984)

Summary + Outlook

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^2

- New source model: CECA enables fit of **space-momentum correlations**!
- Already validated with p–p and p–Λ experimental data
- Femtoscopic data prefer reduced strong interaction strength in $^3S_1$

Outlook

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

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

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Summary + Outlook

Summary

- For the **first time** a quantitative description of the exponential source of pions is presente… resonances on a Gaussia…
- K^+–p ar… umption of a **uni**…
- Source …
- New so… **relations**!
- Already…
- Femtosc… s_1

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!

Outlook

- Available data to tune particle production coordinates in transport models
- Refine source model in order to account for saturation effects (CECA [1])
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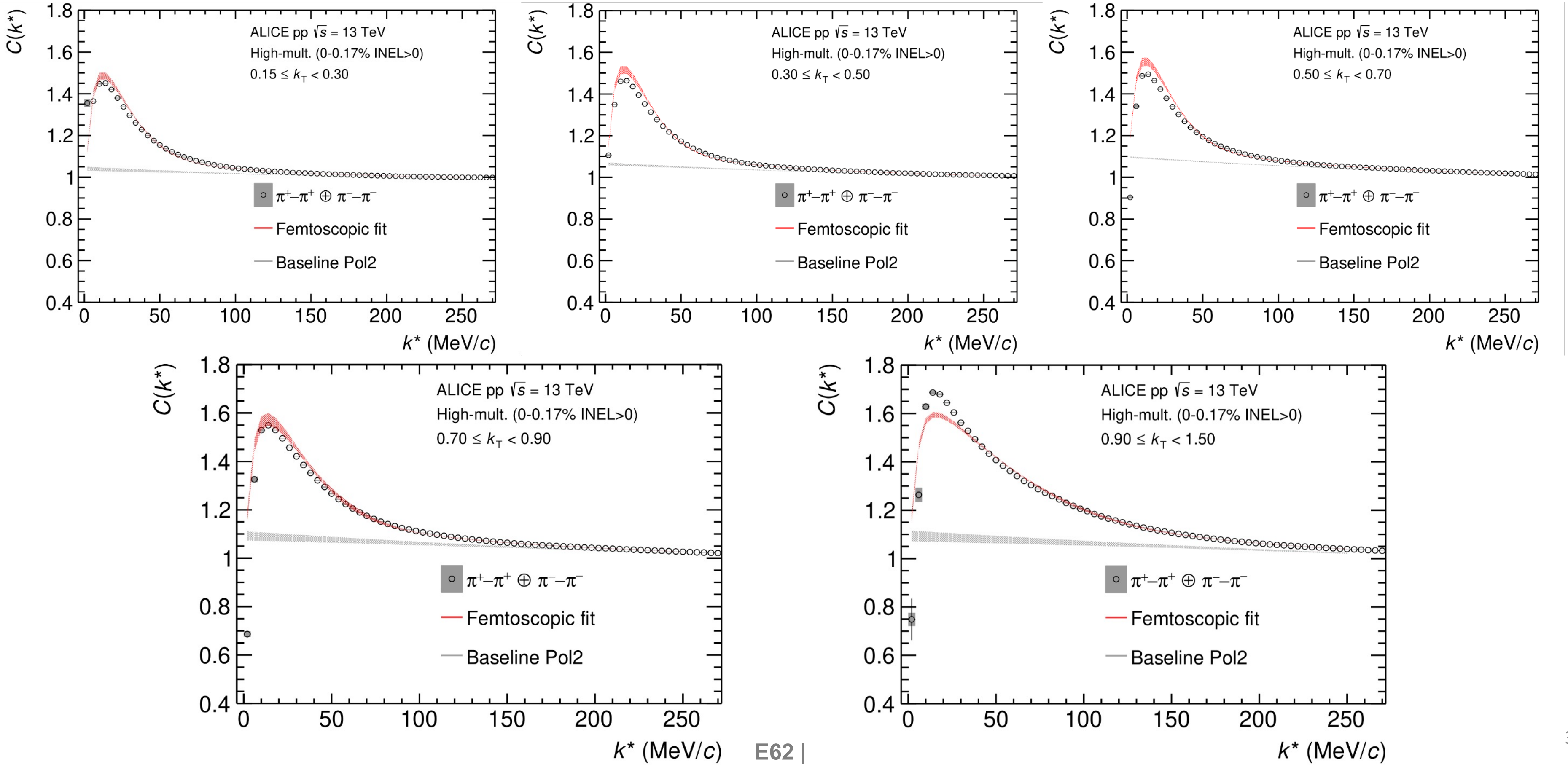
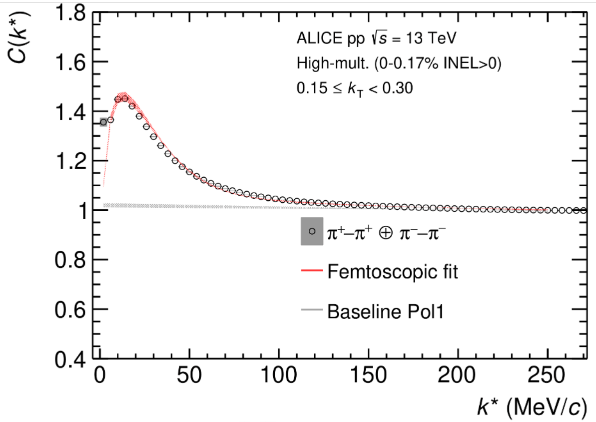
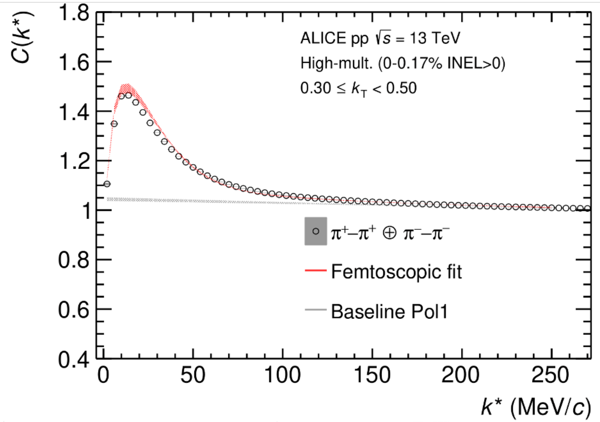
[1] D. Mihaylov et al. arXiv 2305.08441(2023)

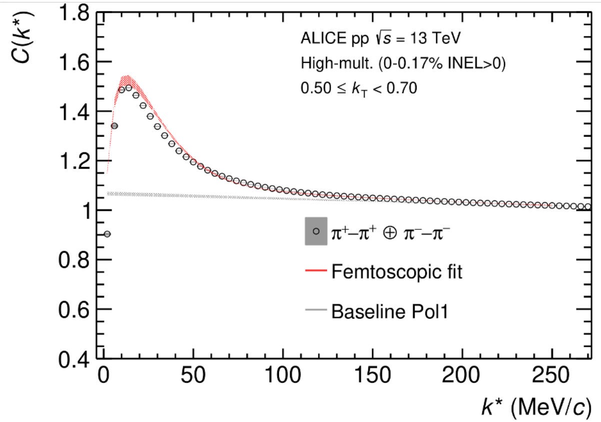
Results for HM π–π - Pol2

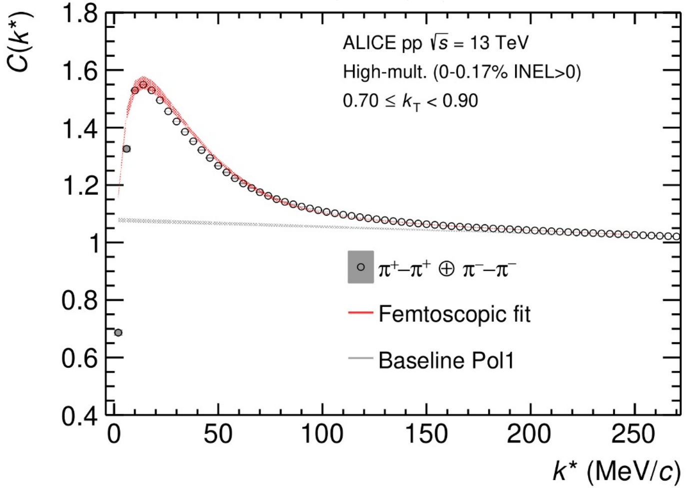


Results for HM π–π - Pol1

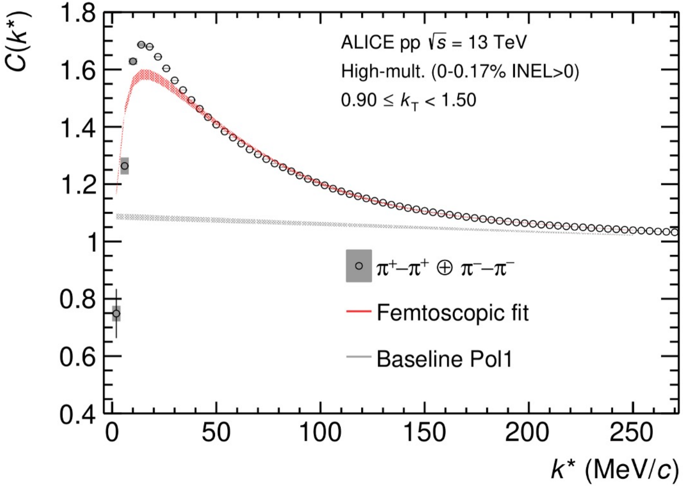




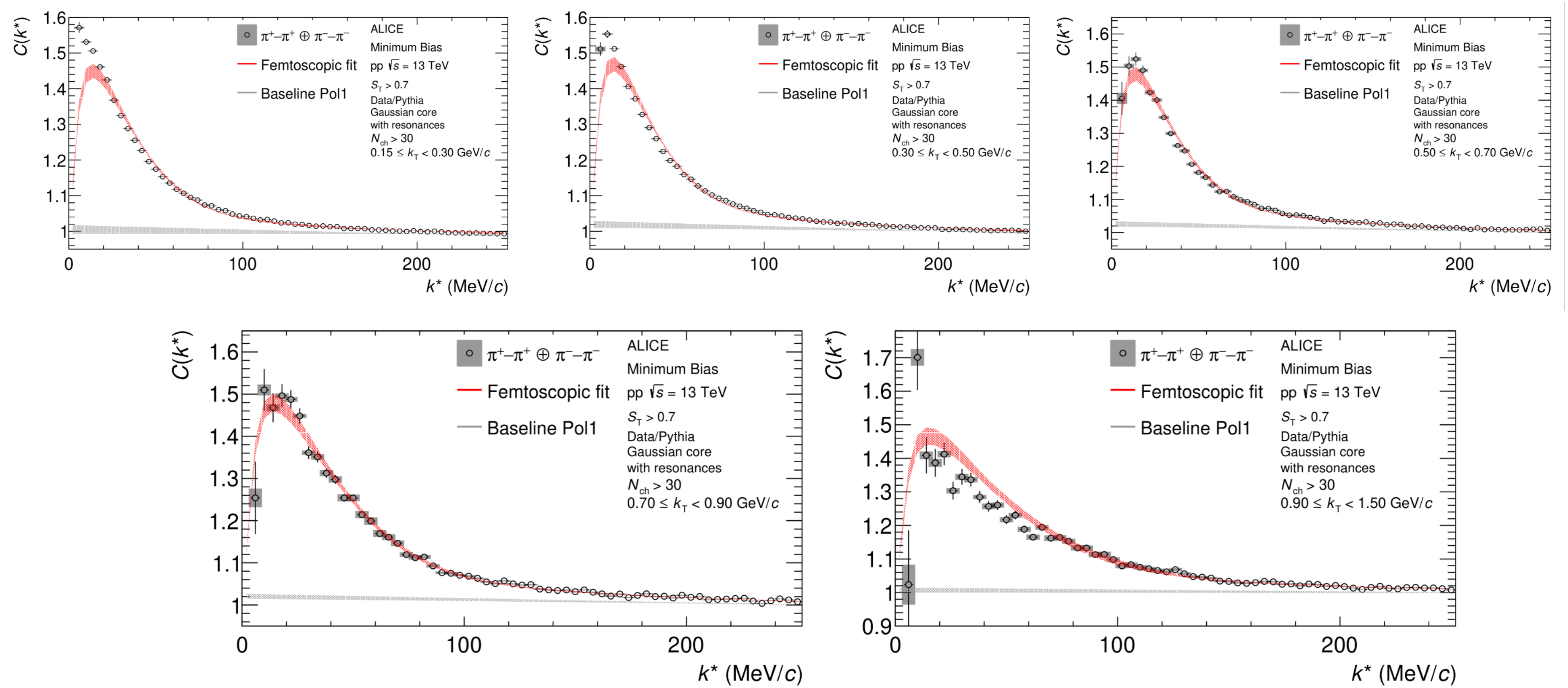




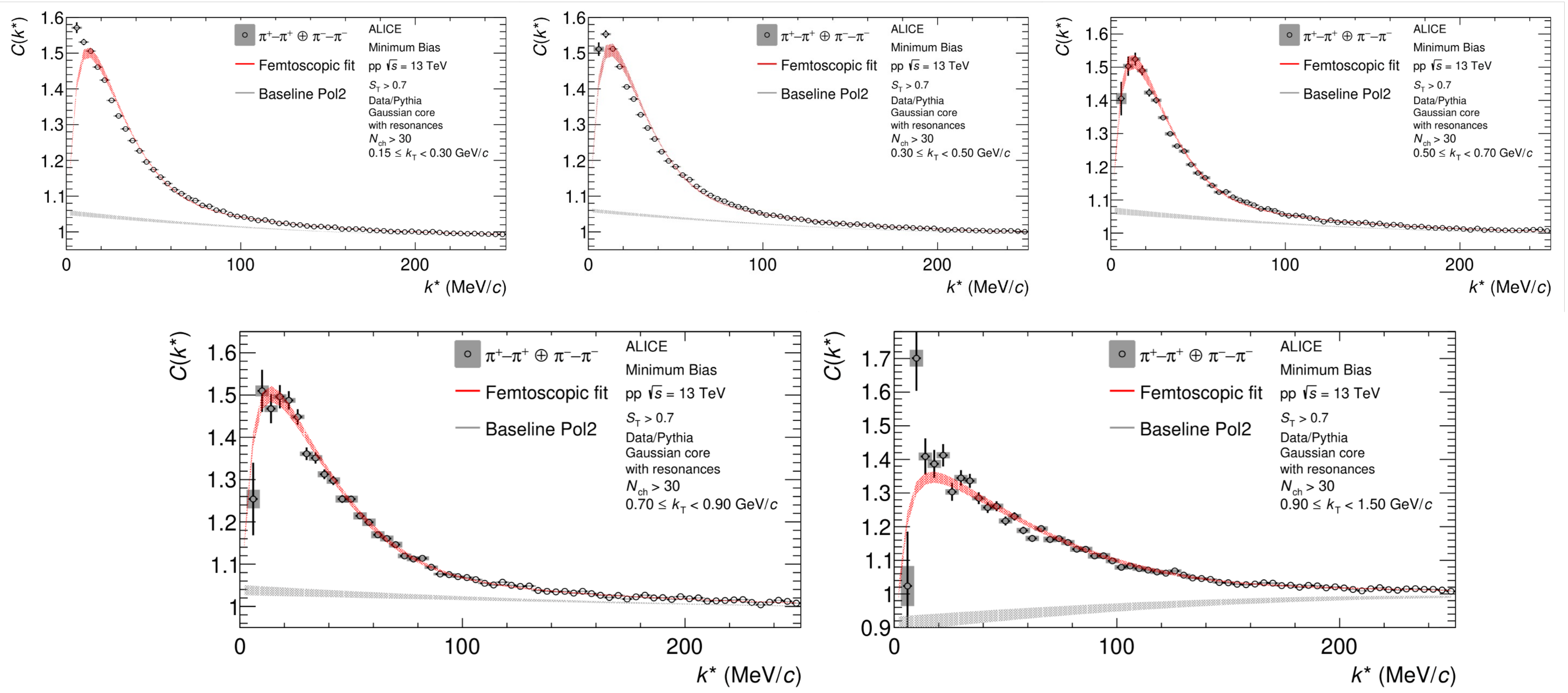
E62 |



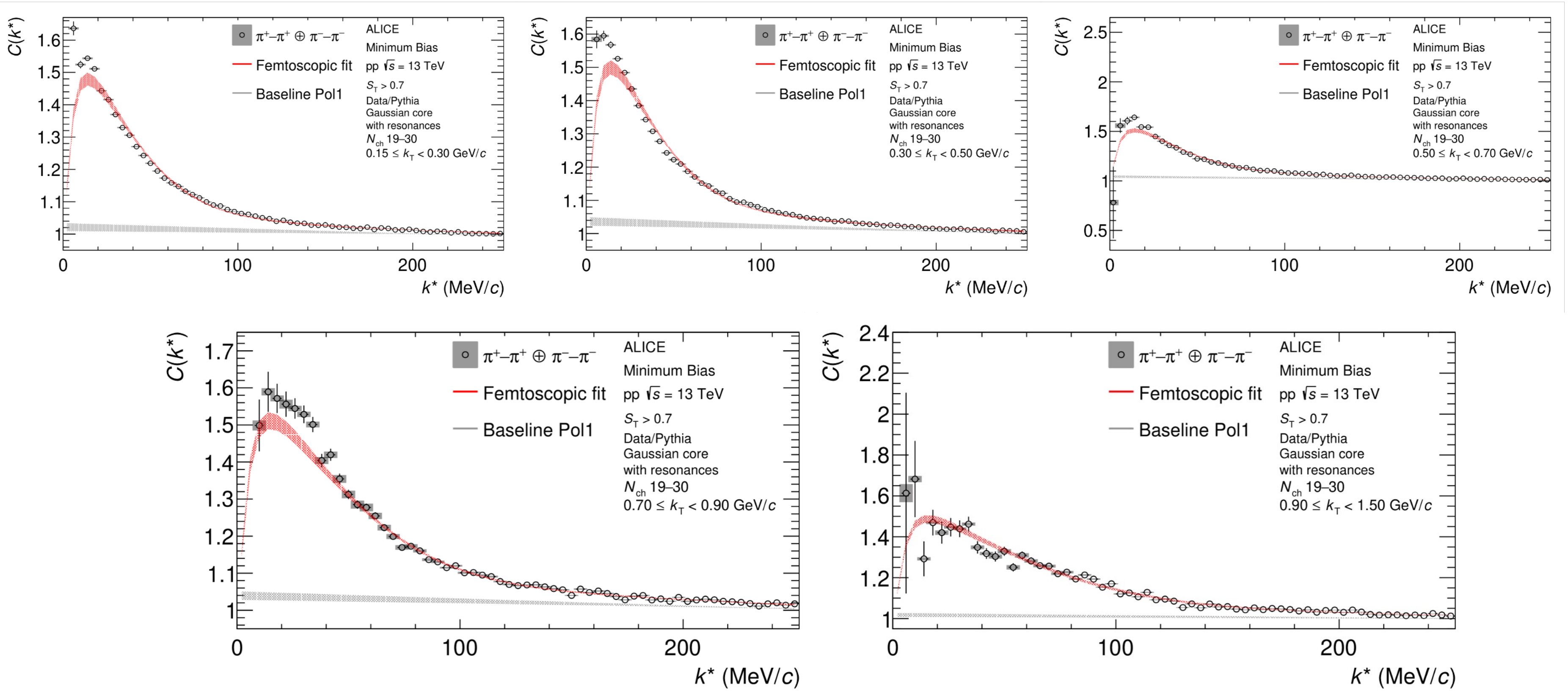
Results for N_{ch} > 30 - π–π - Data/Pythia - Pol1



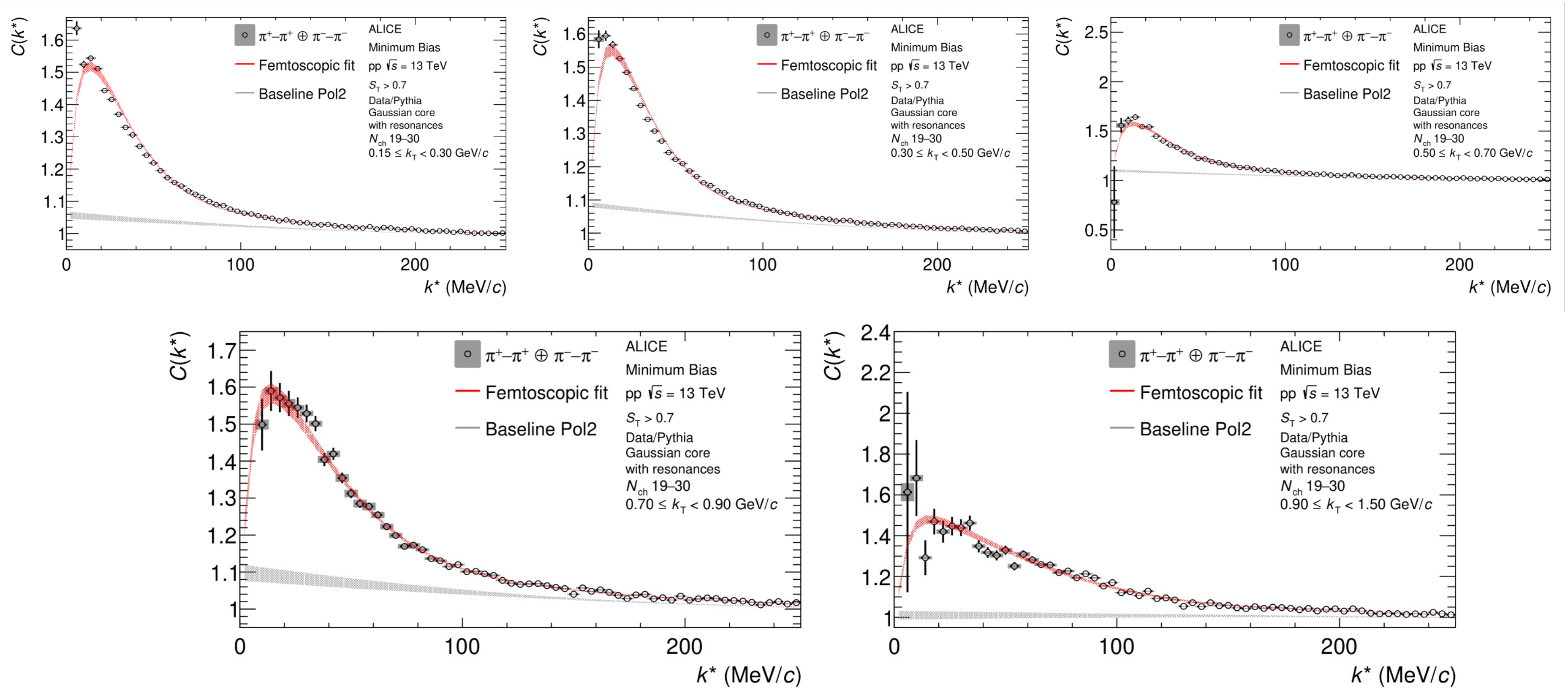
Results for N_{ch} > 30 - π–π - Data/Pythia - Pol2



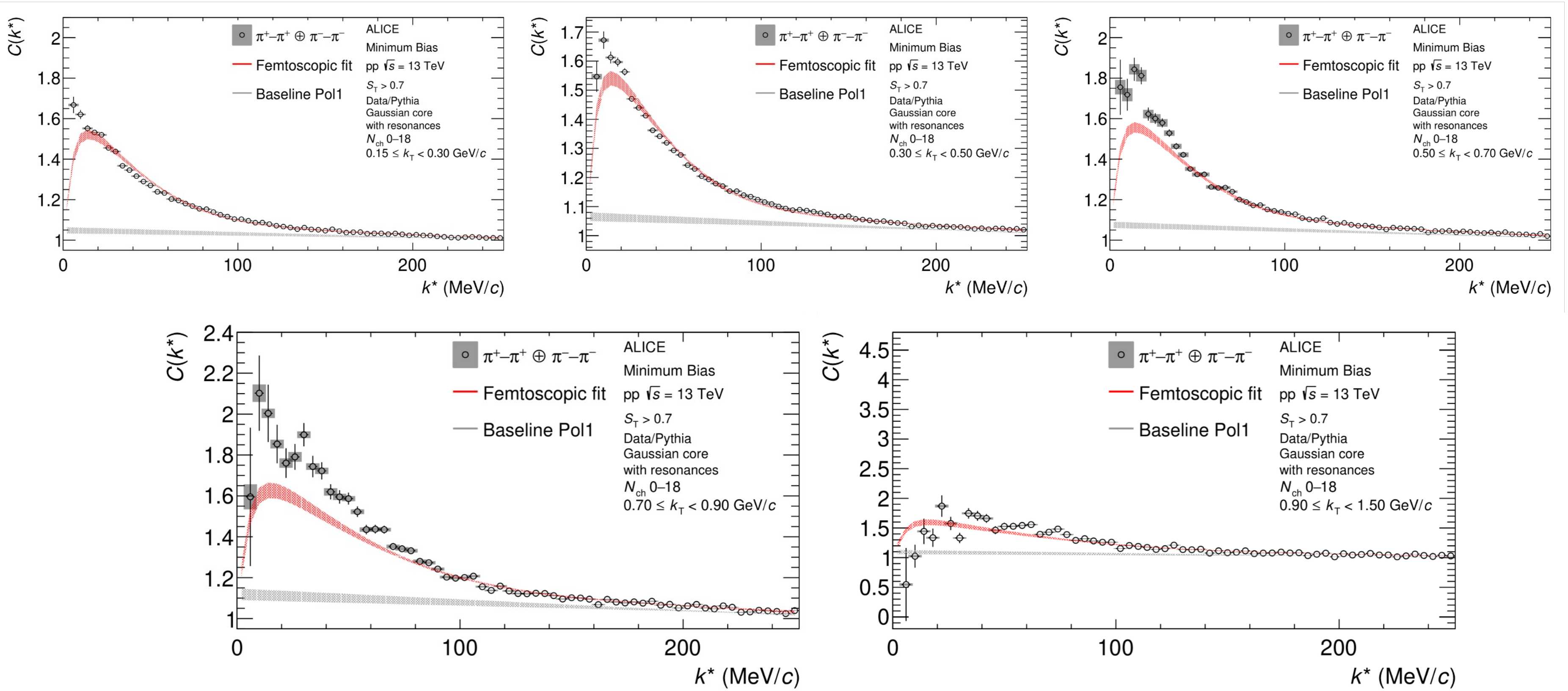
Results for 18< N_{ch}< 30 - π–π - Data/Pythia - Pol1



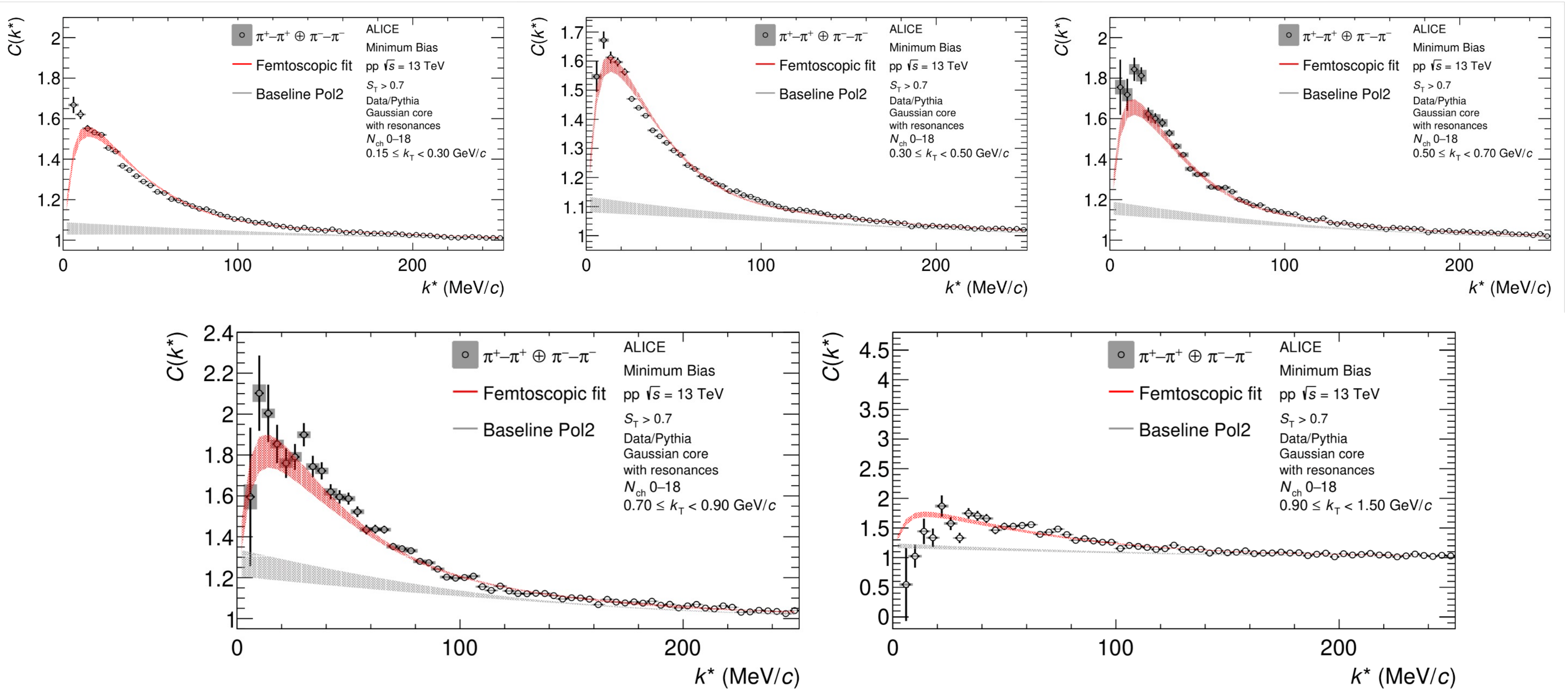
Results for 18< N_{ch}< 30 - π–π - Data/Pythia - Pol2



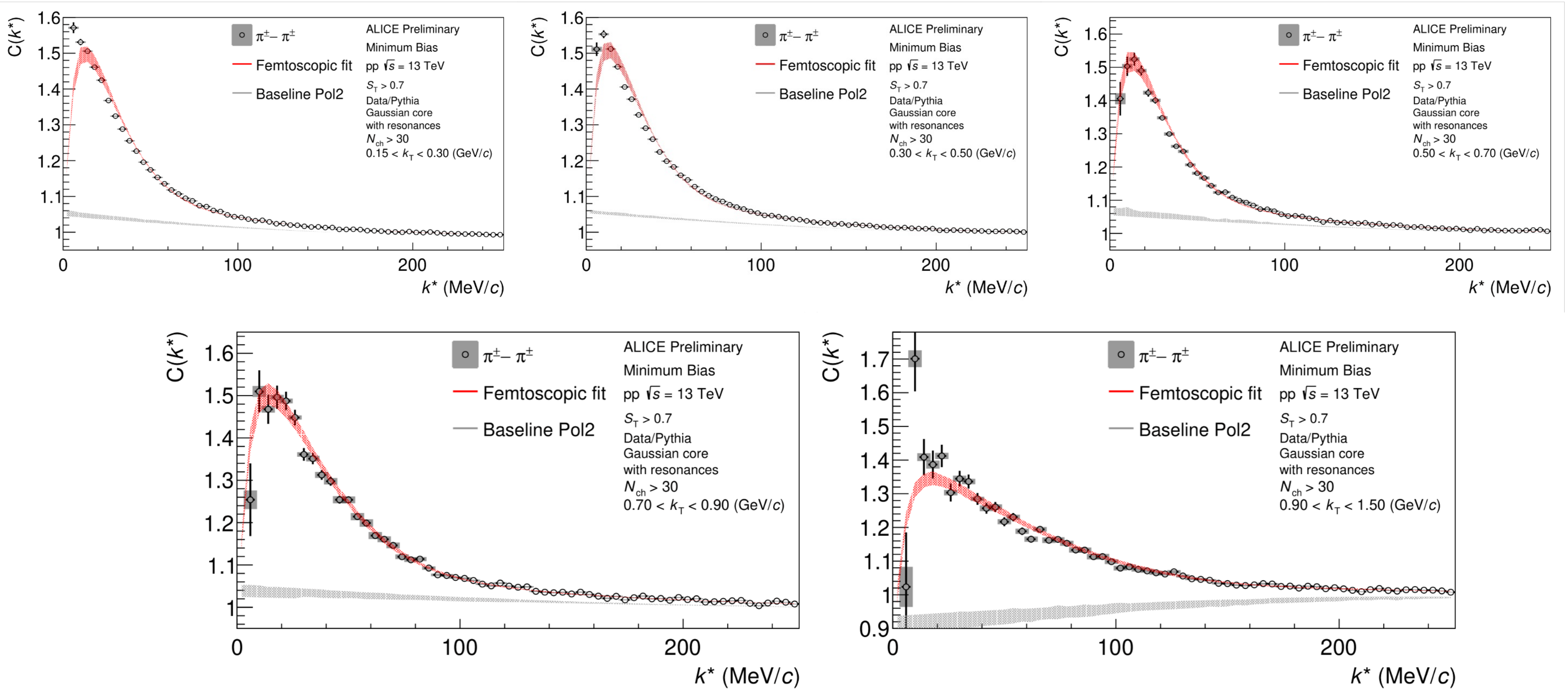
Results for N_{ch}< 18 - π–π - Data/Pythia - Pol1



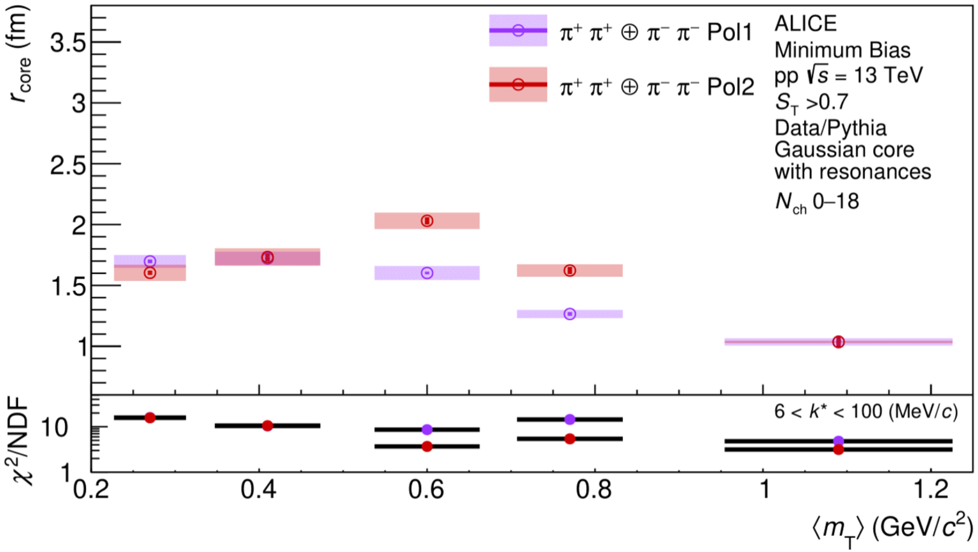
Results for N_{ch}< 18 - π–π - Data/Pythia - Pol2



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

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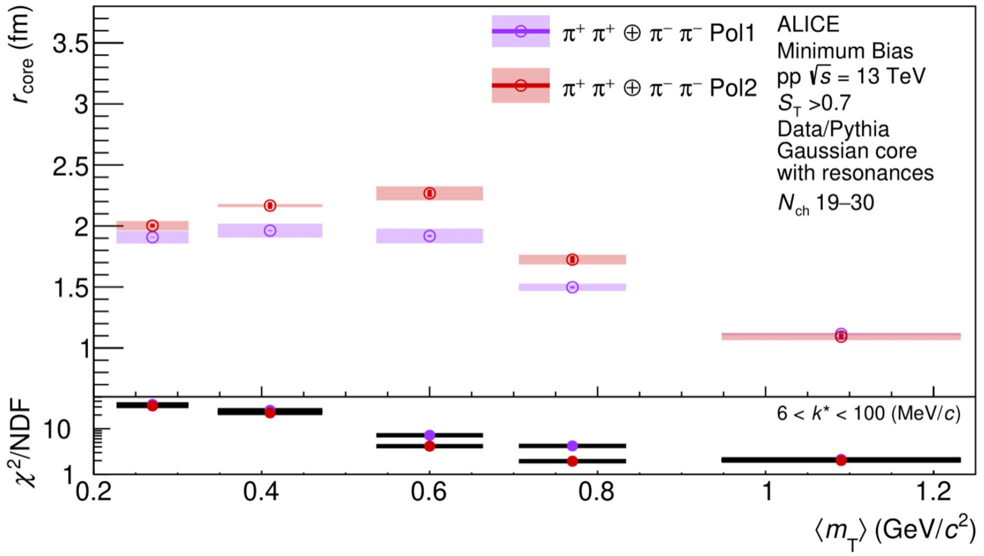

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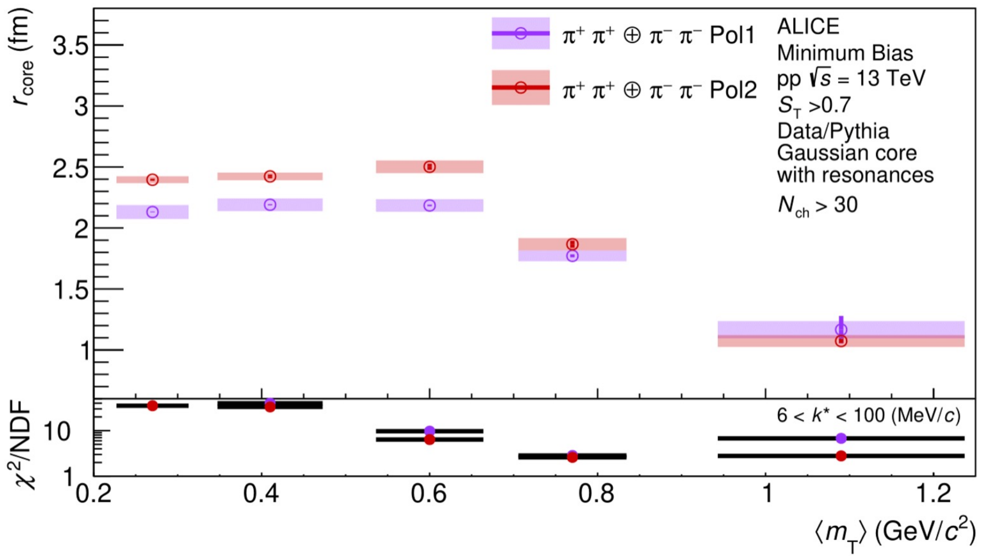

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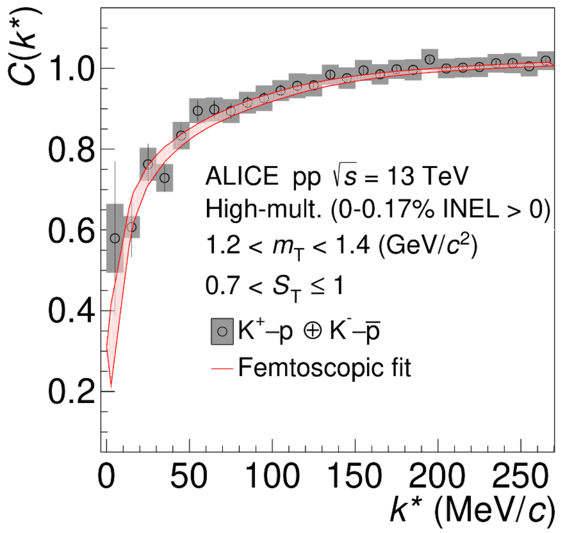
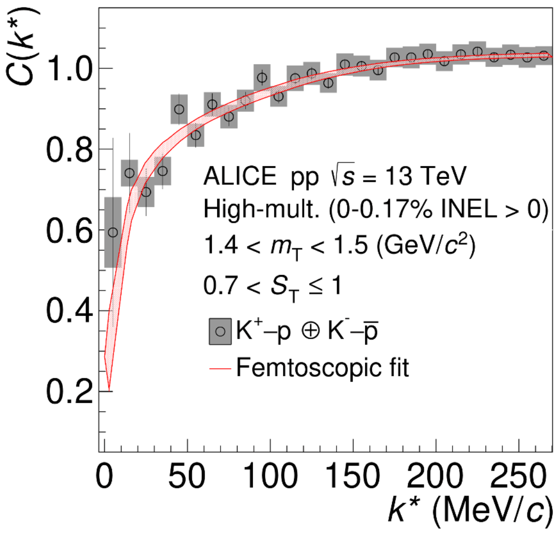
Fits to the K^+–p in HM

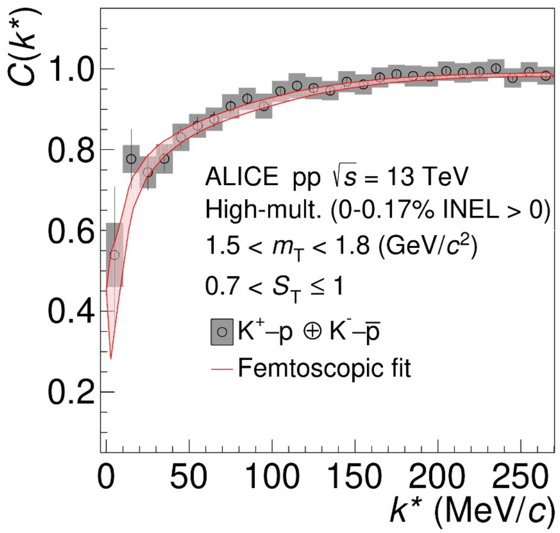


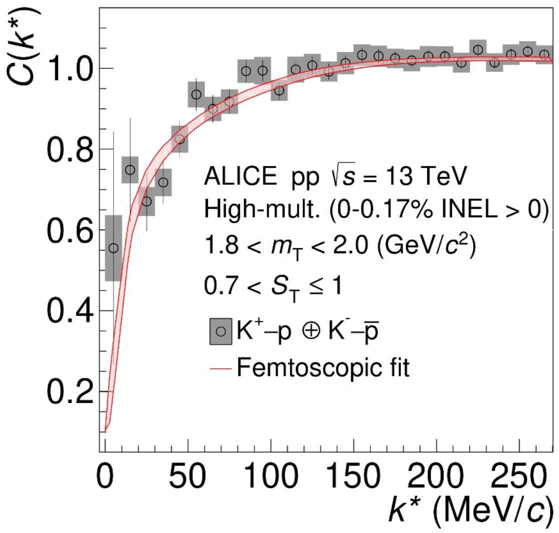


- Strong interaction is modeled by state-of-the-art χEFT
  [K. Aoki et al. PTEP 1 (2019)]

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

Fits to the K⁺–p in HM





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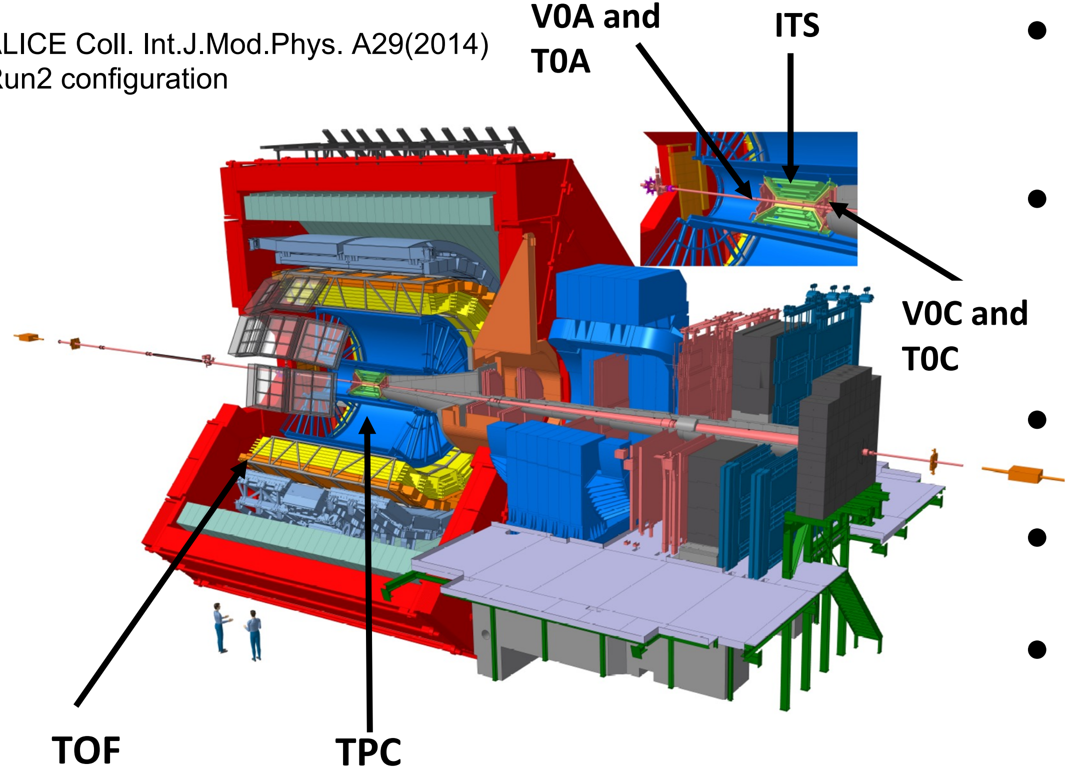
ALICE detector

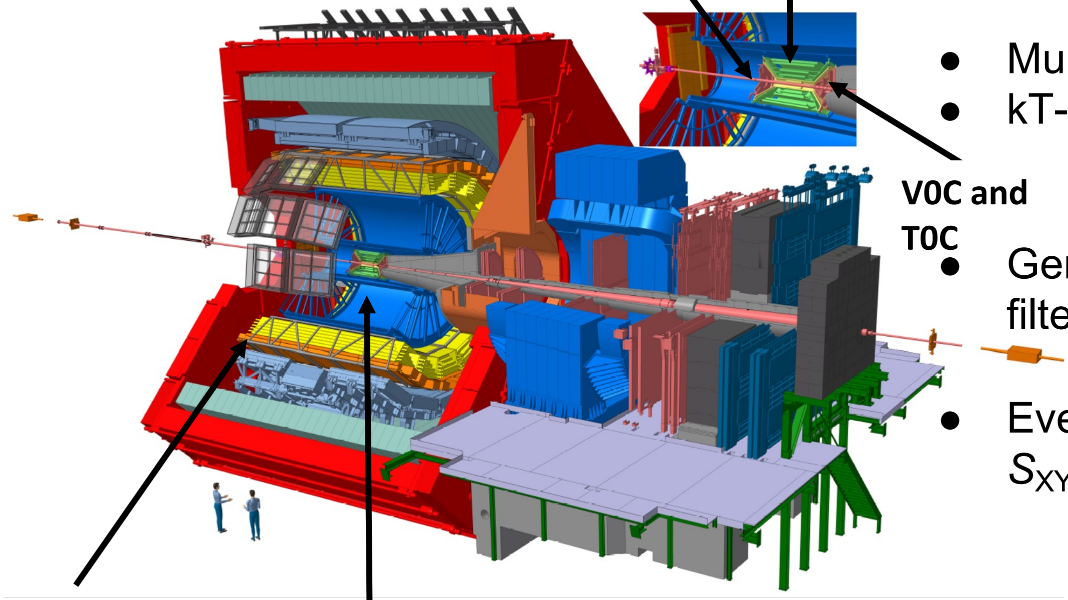
ALICE Coll. Int.J.Mod.Phys. A29(2014)
Run2 configuration



- 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)

Estimating the resonance contribution

Resonances	$c\tau_{res}$ (fm)	Fraction (%)
ρ^0	1.3	9.01
ρ^+	1.3	8.71
ω(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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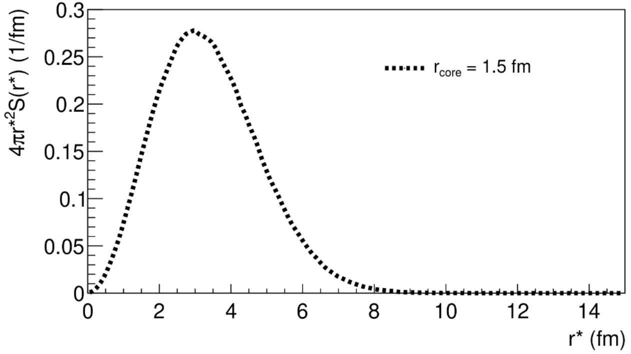
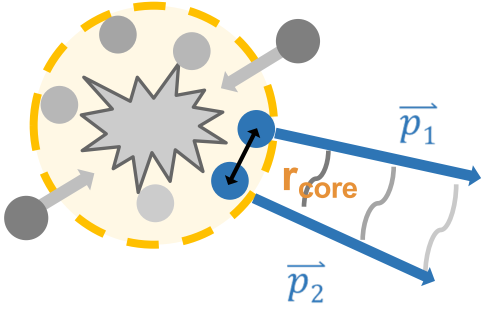
Universal Source Ansatz

ALICE Coll. PLB 811 (2020)

Gaussian core





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ALICE Coll. PLB 811 (2020)

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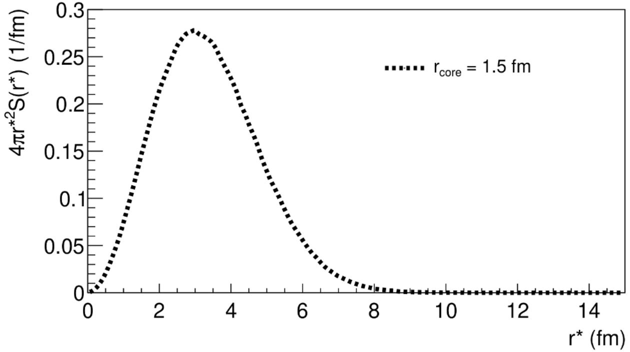
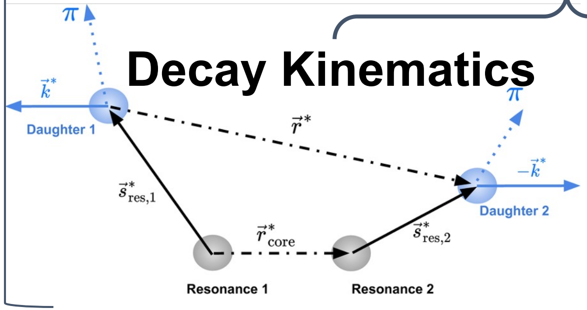


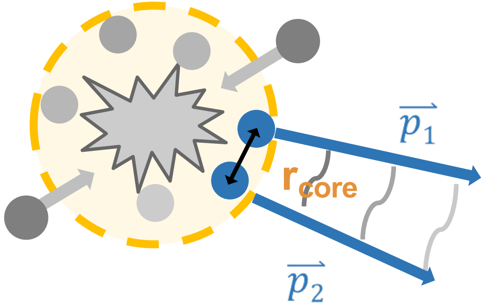
+

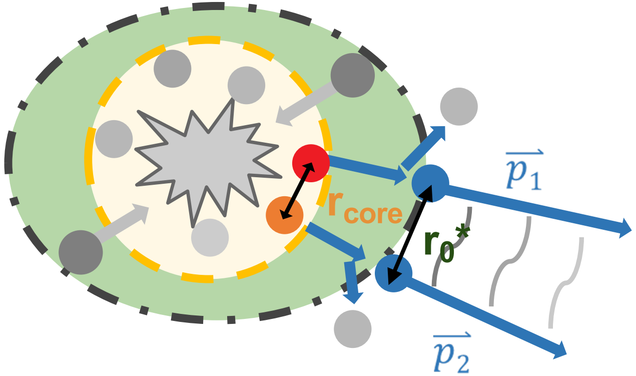
Non-Gaussian

Decay Kinematics $\otimes$ **Resonances**



Mean Lifetime
Mean Mass





Universal Source Ansatz

ALICE Coll. PLB 811 (2020)

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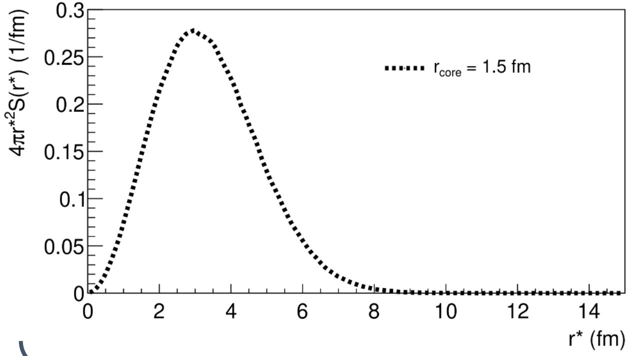
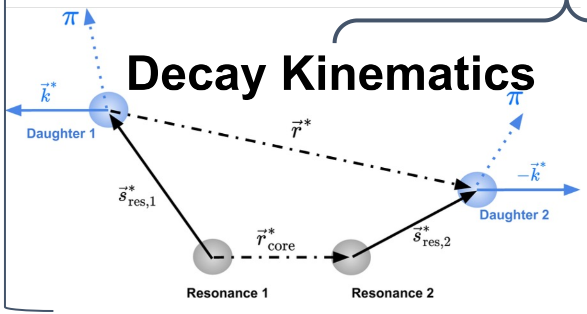


+

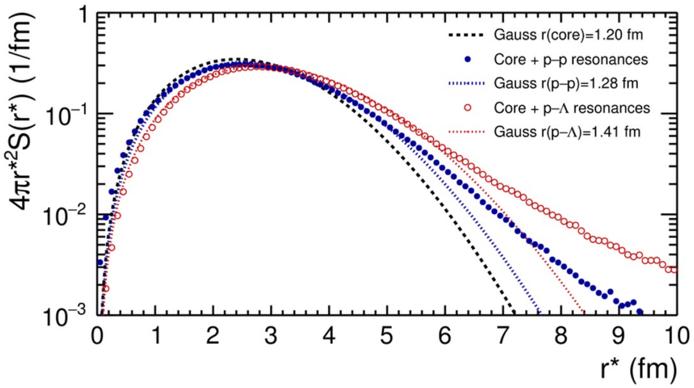
Non-Gaussian

Decay Kinematics ⊗ **Resonances**



Mean Lifetime
Mean Mass

Source



Decomposition of the Correlation Function

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

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

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

Model for genuine interaction

- Bose-Einstein quantum statistics
- Coulomb interaction

Decomposition of the Correlation Function

$$C_{\mathrm{model}}(k^*) = 1/C_{\mathrm{MC}}(k^*) \cdot (\underbrace{\lambda_{\mathrm{gen}}}_{66.4\,\%} C_{\mathrm{gen}}(k^*) + \underbrace{\lambda_{\mathrm{feed}}}_{31.6\,\%} + \underbrace{\lambda_{\mathrm{misid}}}_{2\,\%})$$

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

$$C_{\mathrm{model}}(k^*) = 1/\boxed{C_{\mathrm{MC}}(k^*)} \cdot \left(\underbrace{\lambda_{\mathrm{gen}}}_{66.4\ \%}\boxed{C_{\mathrm{gen}}(k^*)} + \underbrace{\lambda_{\mathrm{feed}}}_{31.6\ \%} + \underbrace{\lambda_{\mathrm{misid}}}_{2\ \%}\right)$$

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

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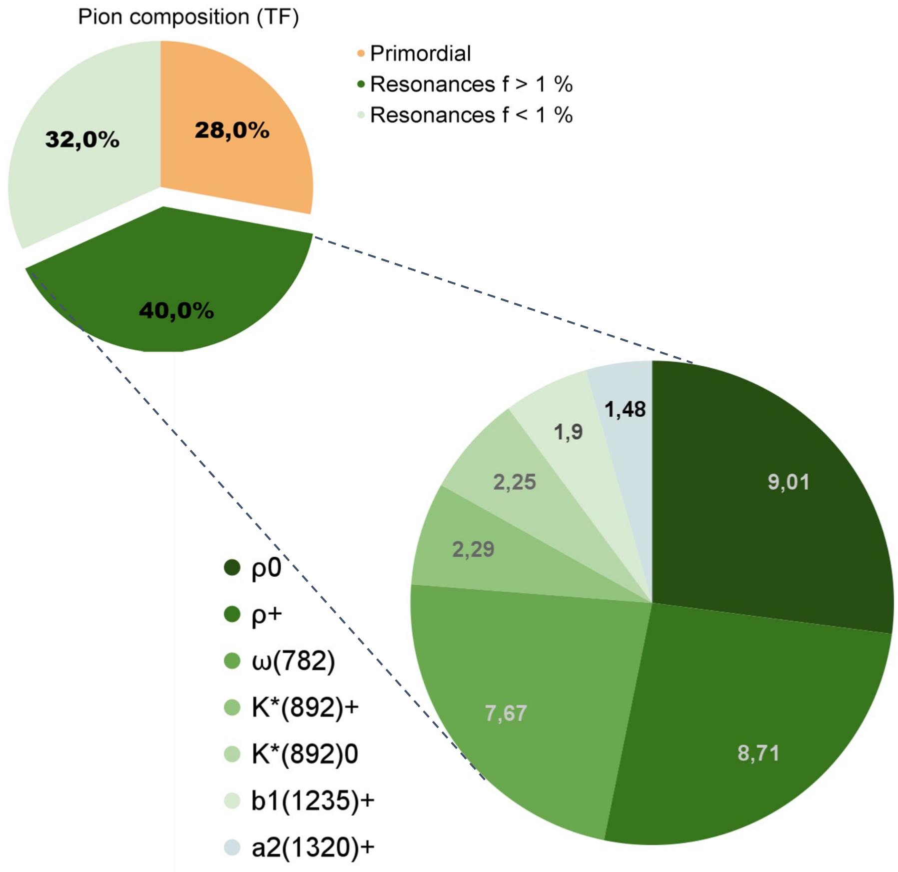
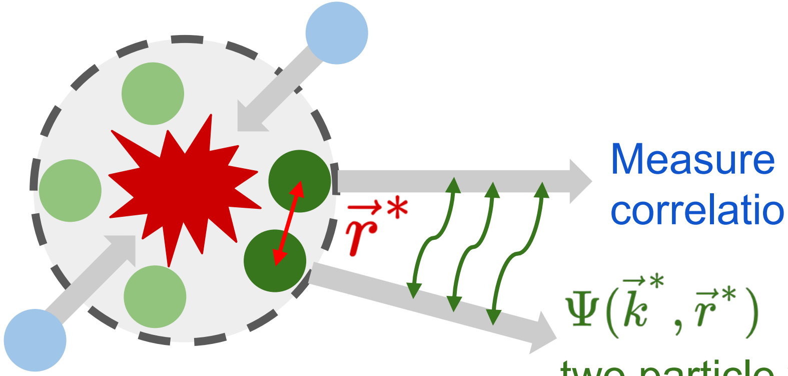
Estimating the resonance contribution



- 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
  - $\langle c\tau_{\mathrm{eff}} \rangle = 1.5$ fm
  - Select resonances cocktail in EPOS [4] for decay kinematics

[1] V. Vovchenko et al. PRC 100834 (2019)
[2] V. Vovchenko et al. CPC 100 (2019)
[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*)*

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

- **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]