Femtoscopy employed to study low energy scattering @ LHC

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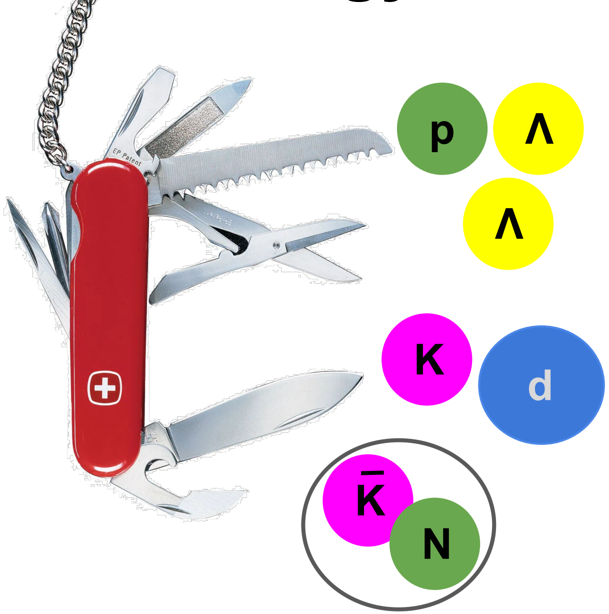
5th June 2023, Genoa, Italy

TUM
150 Jahre culture of excellence
HIM HELMHOLTZ Helmholtz-Institut Mainz
European Commission
Horizon 2020 European Union funding for Research & Innovation

Femtoscopy employed to study low energy scattering @ LHC



Valentina Mantovani Sarti
A laboratory for QCD
Hadrons in hot and nuclear environment: Monday 14:30

Marcel Lesch
Constraining the equation of state
Hadron decays, production and interaction: Thursday 15:12

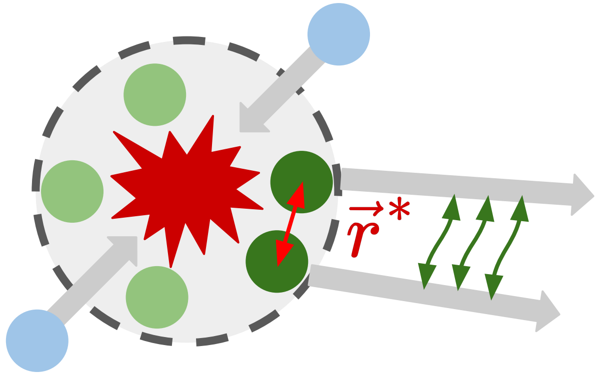
Laura Šerkšnytė
Three-body interactions
Hadron decays, production and interaction Wednesday 15:12

Wioleta Rzęsa
Study of Kd interactions
Hadron decays, production and interaction: Wednesday 14:24

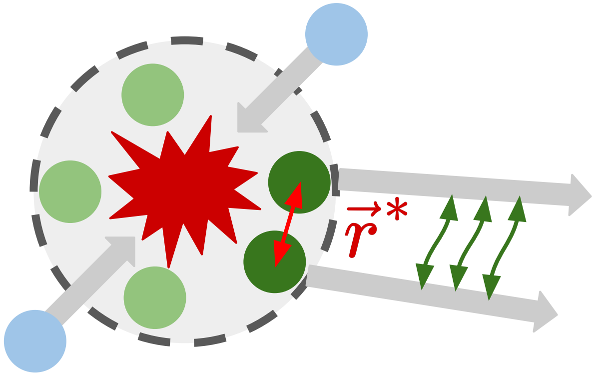
Ramona Lea
Constraining coupled channels dynamics
Hypernuclei and kaonic atoms: Thursday 15:42

Femtoscopy

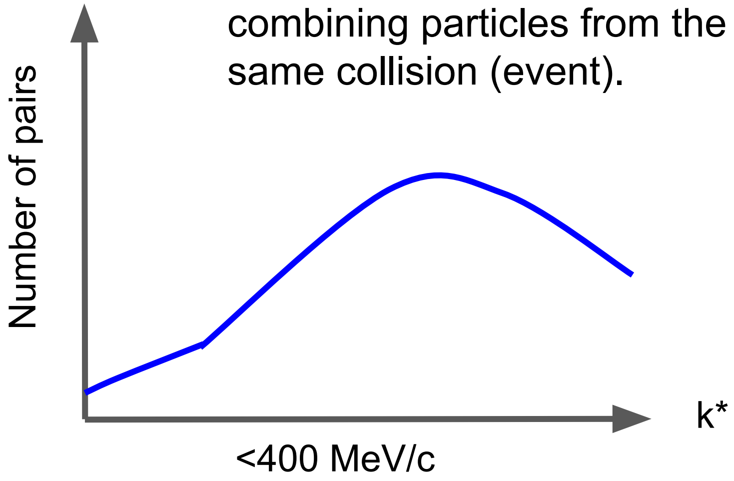
Overview



Femtoscopy
Overview

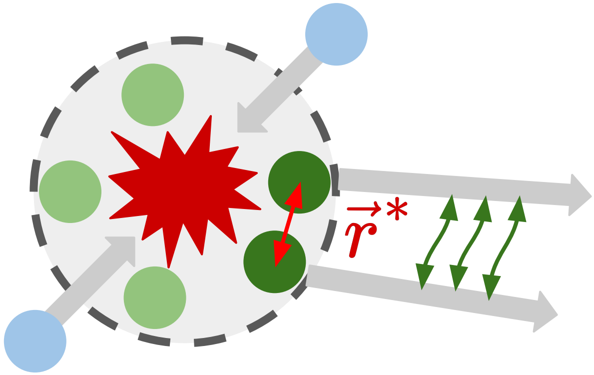


- ***Same event sample (SE)*:** Correlated pairs, obtained by combining particles from the same collision (event).

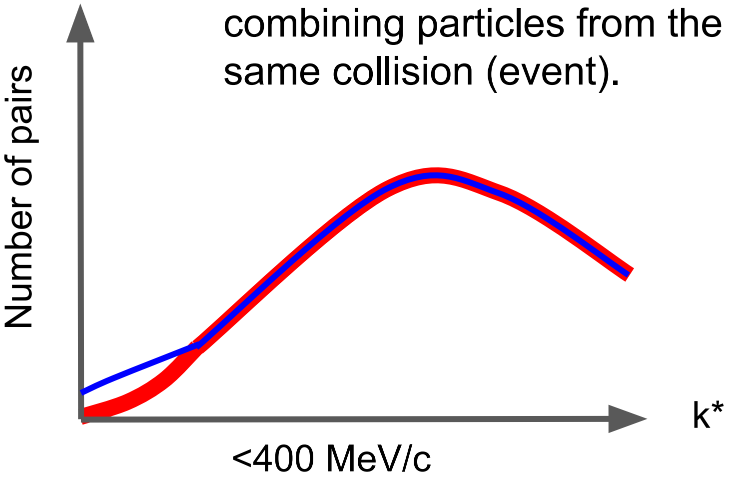


Femtoscopy

Overview

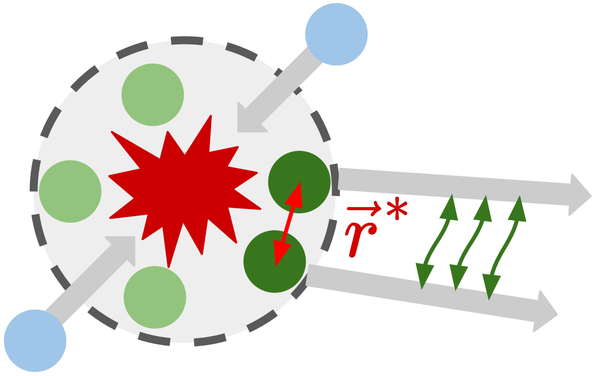


- ***Same event sample (SE)*:** Correlated pairs, obtained by combining particles from the same collision (event).
- ***Mixed event sample (ME)*:** Uncorrelated pairs, obtained by combining particles from two different collisions (events).

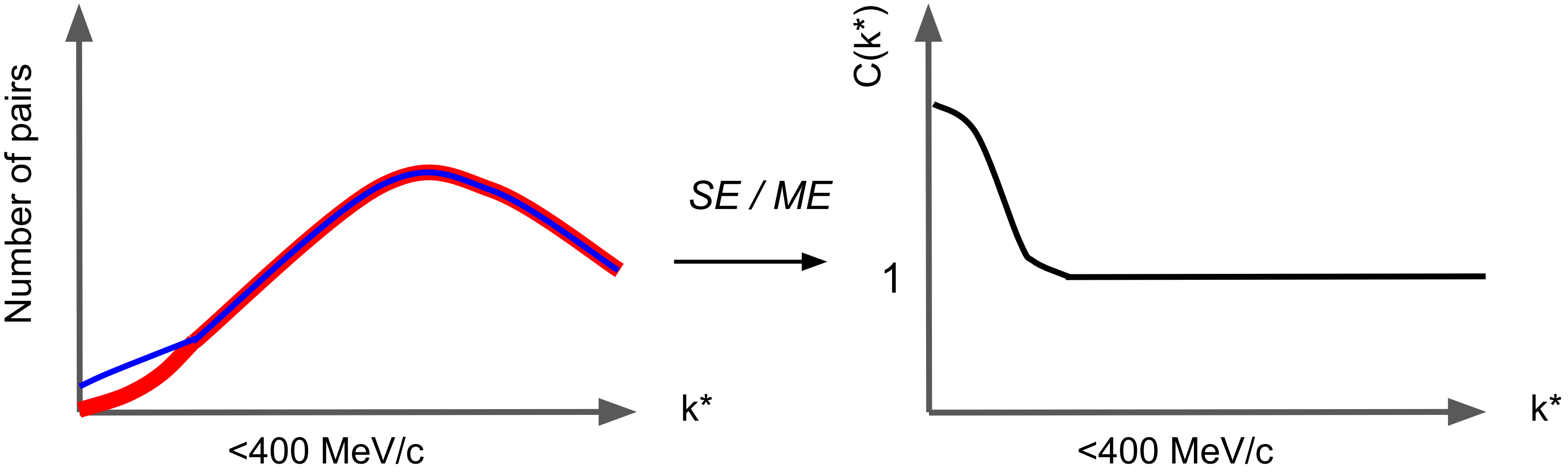


Femtoscopy

Overview

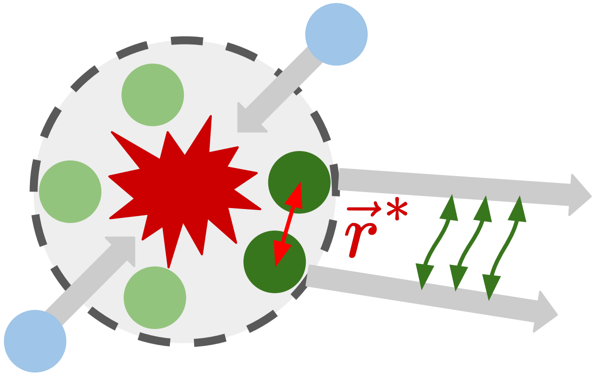


- The ***correlation function C(k*)*** = *SE / ME*, ideally equal to unity in the absence of any correlations.

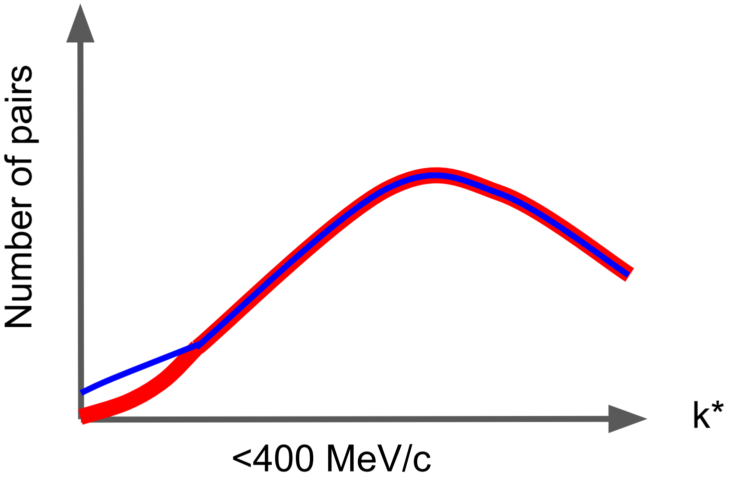


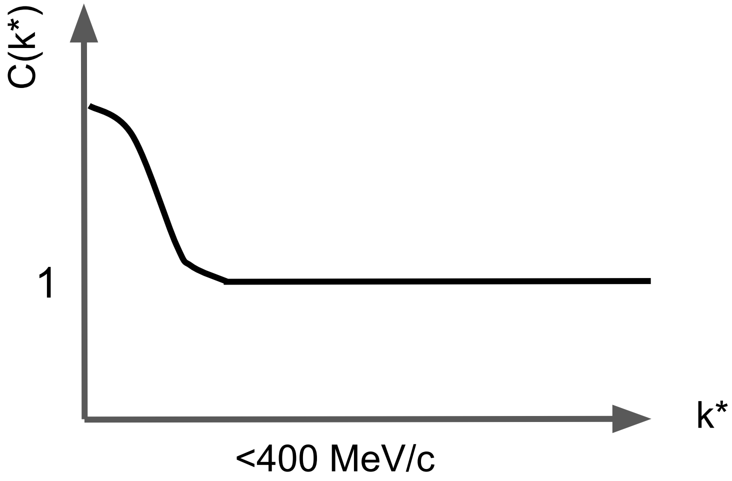
Femtoscopy

Overview



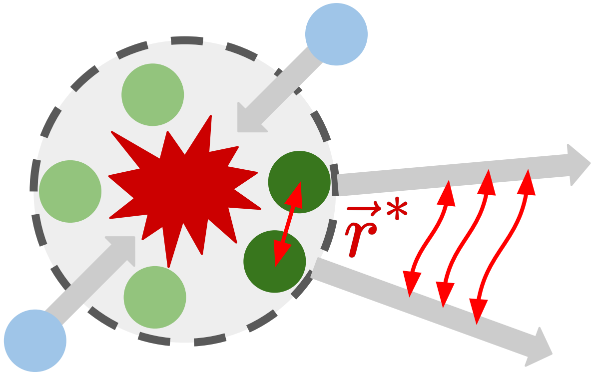
- **Attractive** final state interaction (FSI)



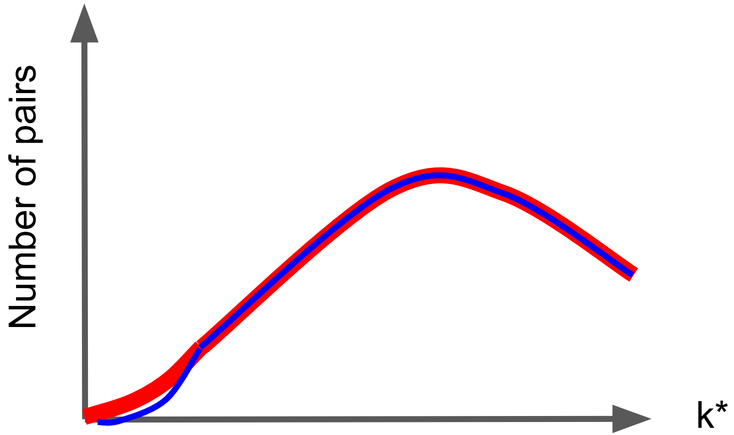


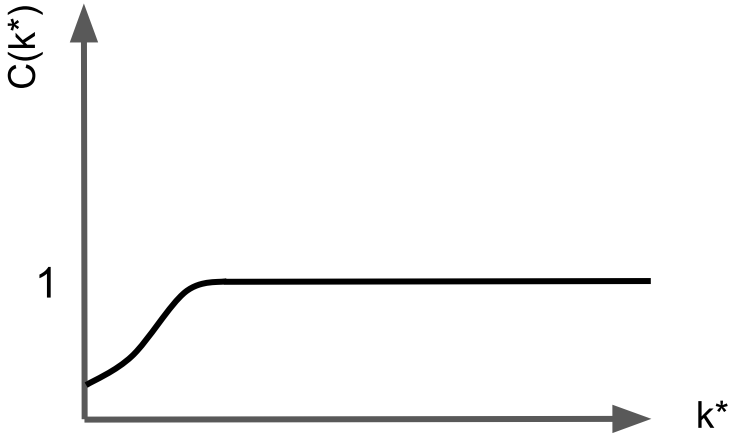
Femtoscopy

Overview



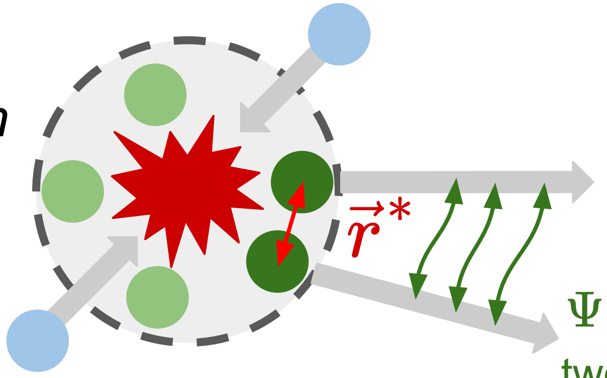
- **Repulsive** final state interaction (FSI).





Femtoscopy

Koonin-Pratt equation



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

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

Relative distance and ½ relative momentum evaluated in the pair rest frame

- Measure C(k*), fix S(r*), study the interaction.
- CATS framework to evaluate the above integral Eur.Phys.J.C 78 (2018) 5, 394

Femtoscopy

In theory …

Femtoscopy

In reality …

Femtoscopy

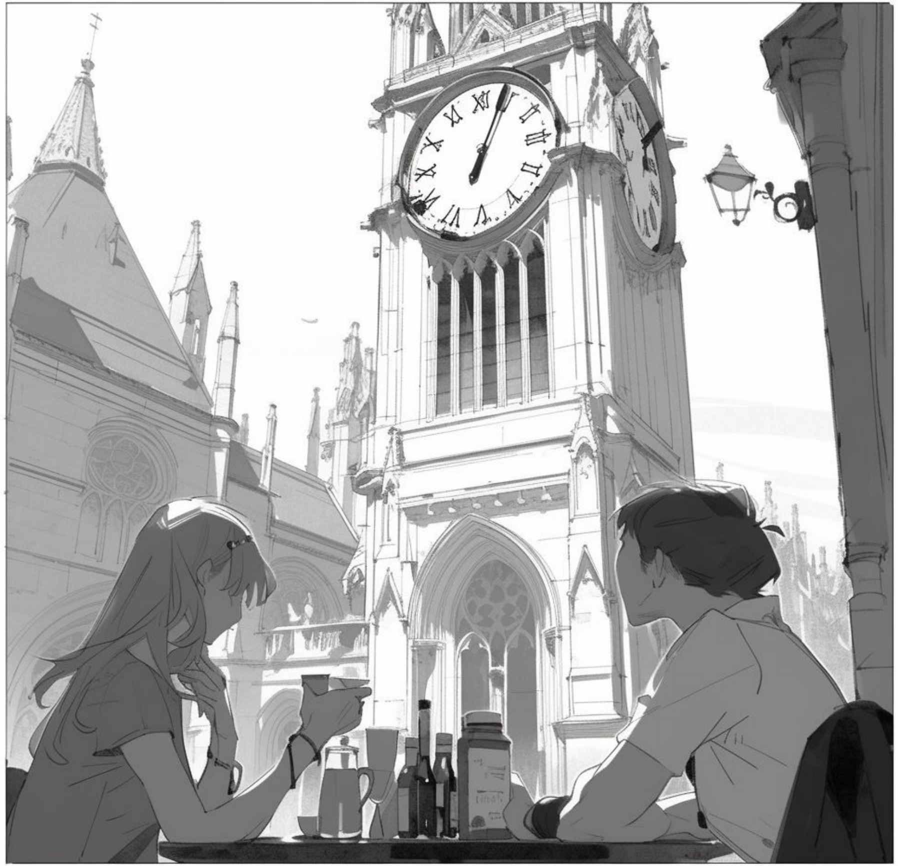
In reality …

- Momentum resolution
- Feed-down from secondaries
- Misidentifications
- Non-femtoscopic baseline
- Source function

Femtoscopy
The details

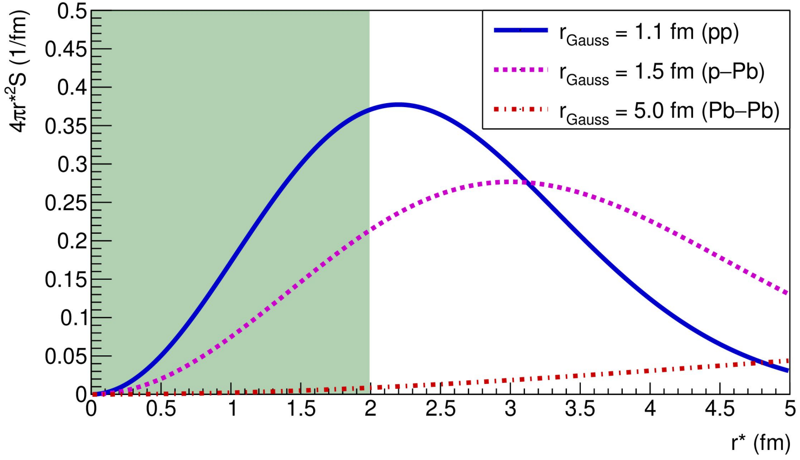
In backup and over coffee

- **Momentum resolution**
- **Feed-down from secondaries**
- **Misidentifications**
- **Non-femtoscopic baseline**
- Source function



Source function

In small collision systems



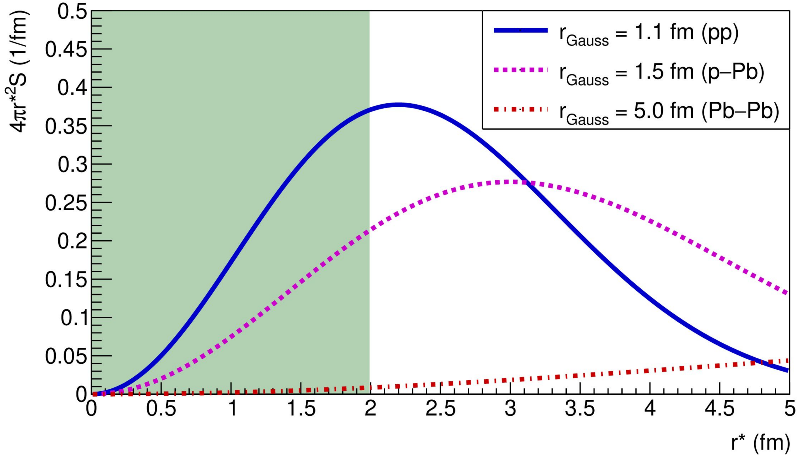
- Momentum resolution
- Feed-down from secondaries
- Misidentifications
- Non-femtoscopic baseline
- **Source function**

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

measure **fix** **study**

Source function

In small collision systems



- Momentum resolution
- Feed-down from secondaries
- Misidentifications
- Non-femtoscopic baseline
- **Source function**

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

measure **fix** **study**

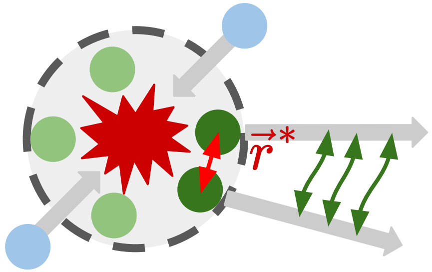
- **Common source** for all produced particles in **small collision systems**?
- Use pp pairs (known interaction) to constrain the **source**.

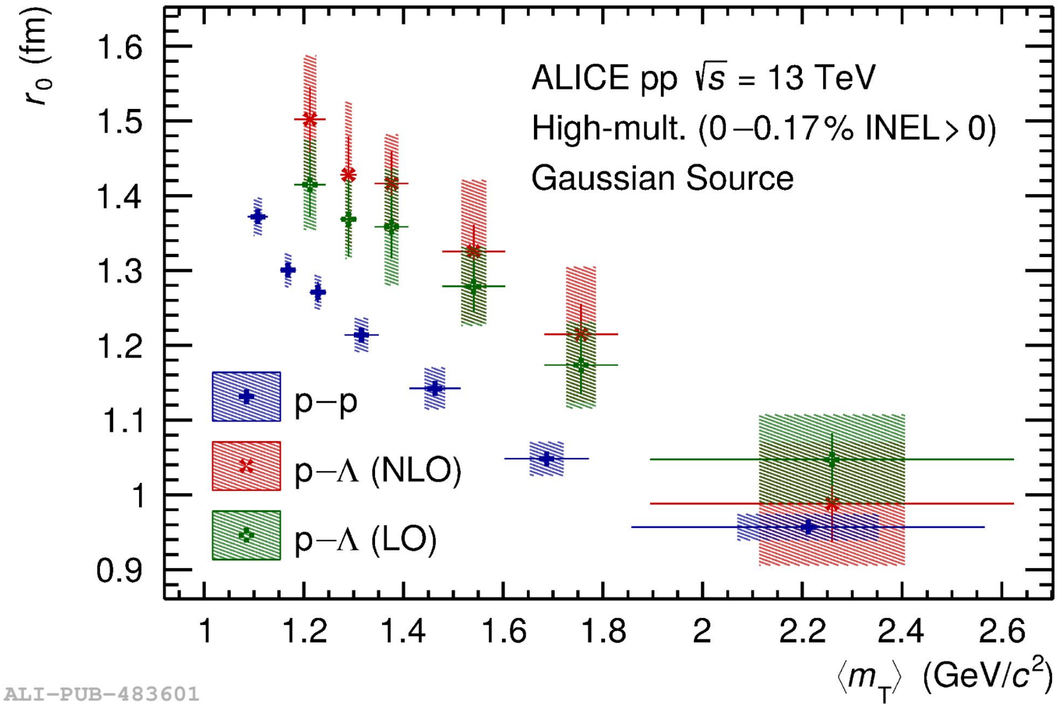
Source function: ALICE results

mT scaling of the pp and pΛ source

Phys.Lett.B 811 (2020) 135849

Perfect Gaussian





Source function: ALICE results

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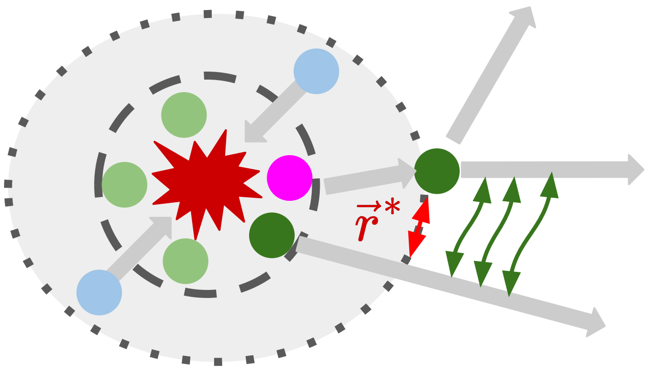
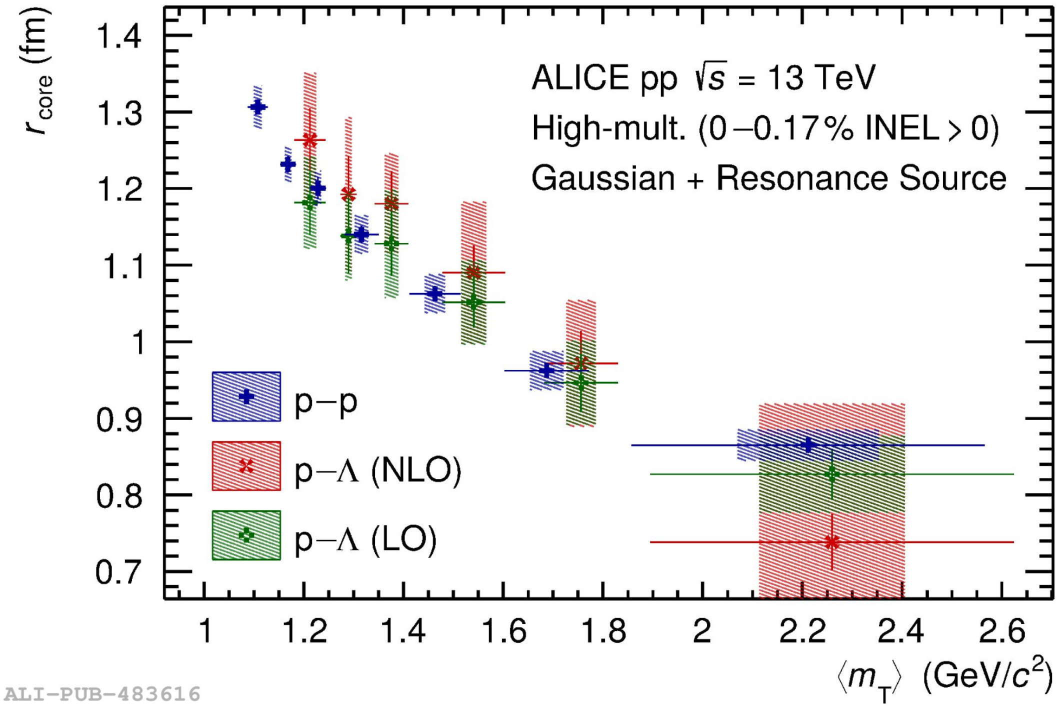
Gaussian core + resonances





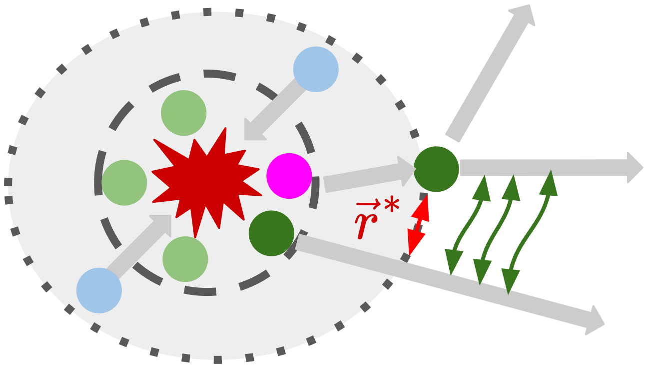
ALI-PUB-483616

Common Emission in CATS (CECA)

A new numerical framework [arXiv 2305.08441]

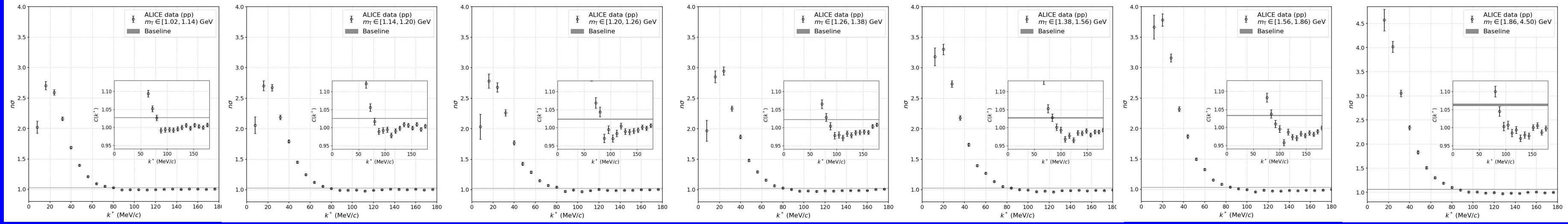
- Goal: generic modeling of particle emission in small systems, including kinematic effects such as the mT scaling and applicable to N-body problems
- Monte-Carlo simulation based on the properties of single particle emission
- Generation of events, containing point-like particles with well defined spatial 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

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

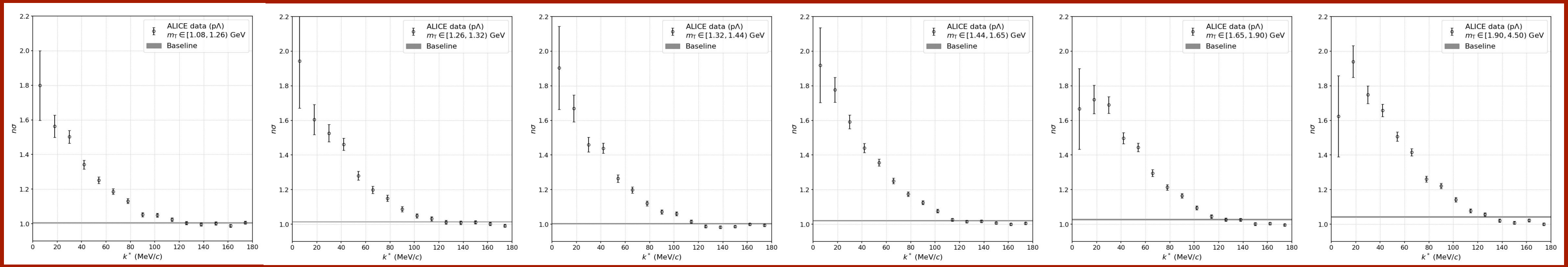


ALICE data

pp and *pΛ* correlations



mT

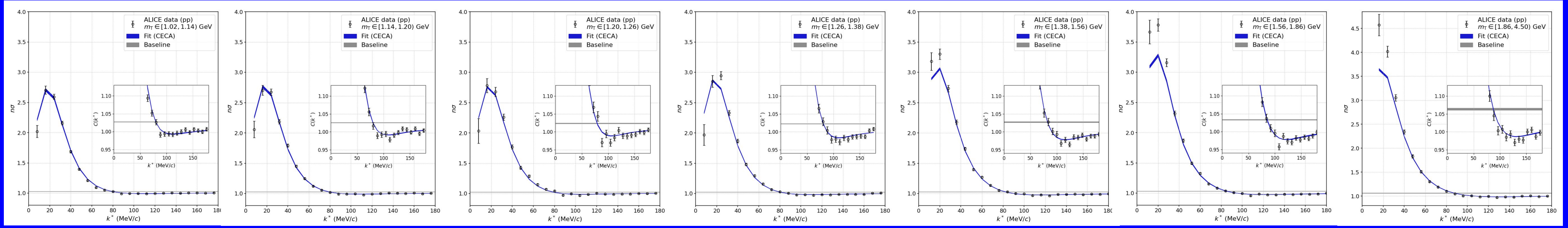


Data: High-multiplicity pp collisions @ 13 TeV from ALICE

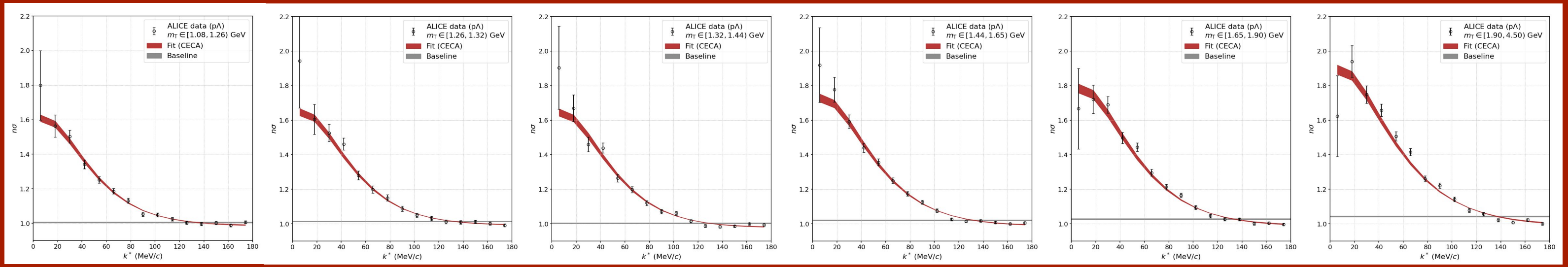
Phys.Lett.B 811 (2020) 135849

ALICE data + CECA

One source to rule them all



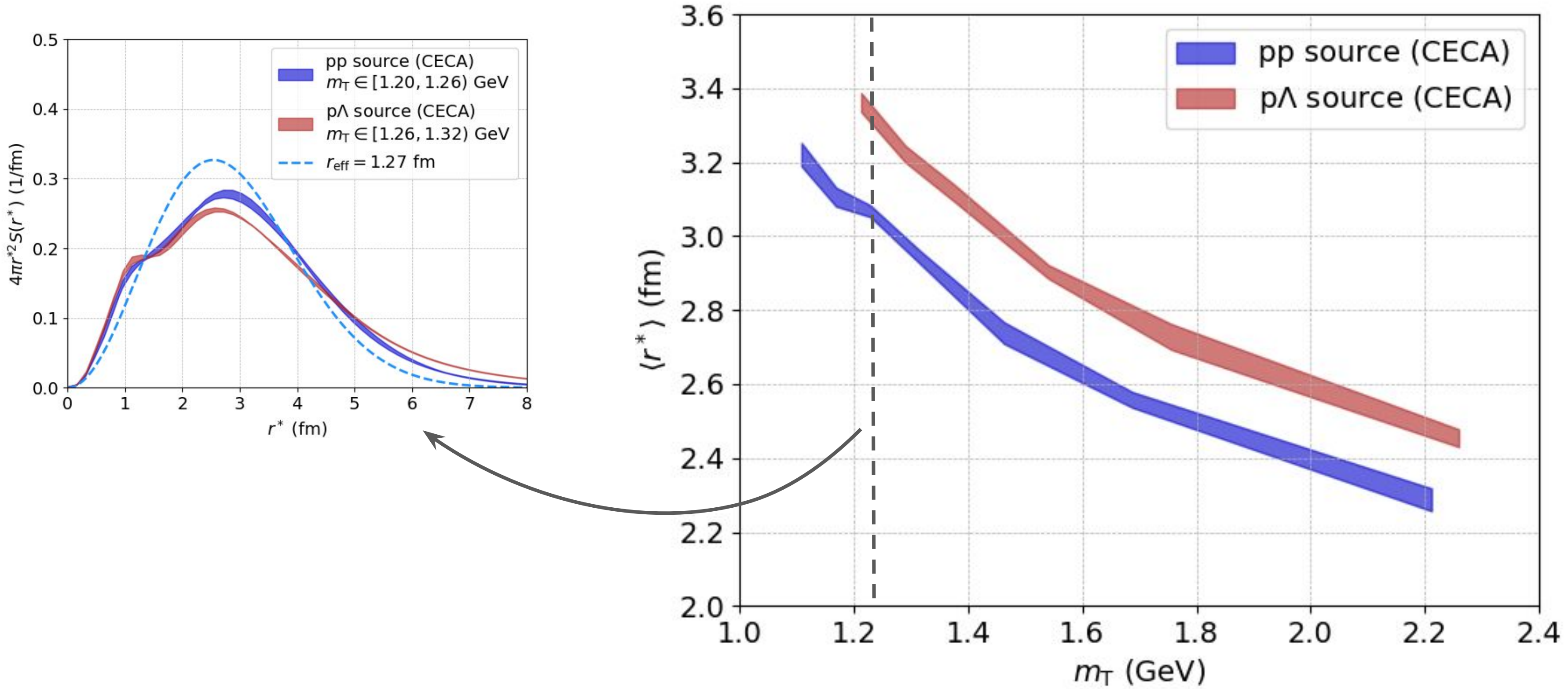
mT



A combined fit of the mT differential pp and pΛ correlations!

ALICE data + CECA

Source distribution mT scaling



ALICE data + CECA

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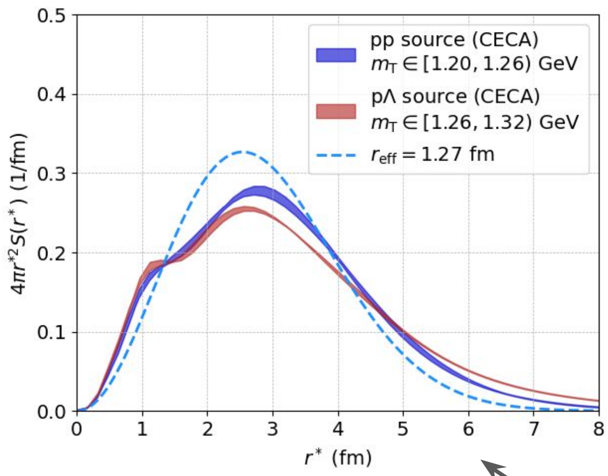
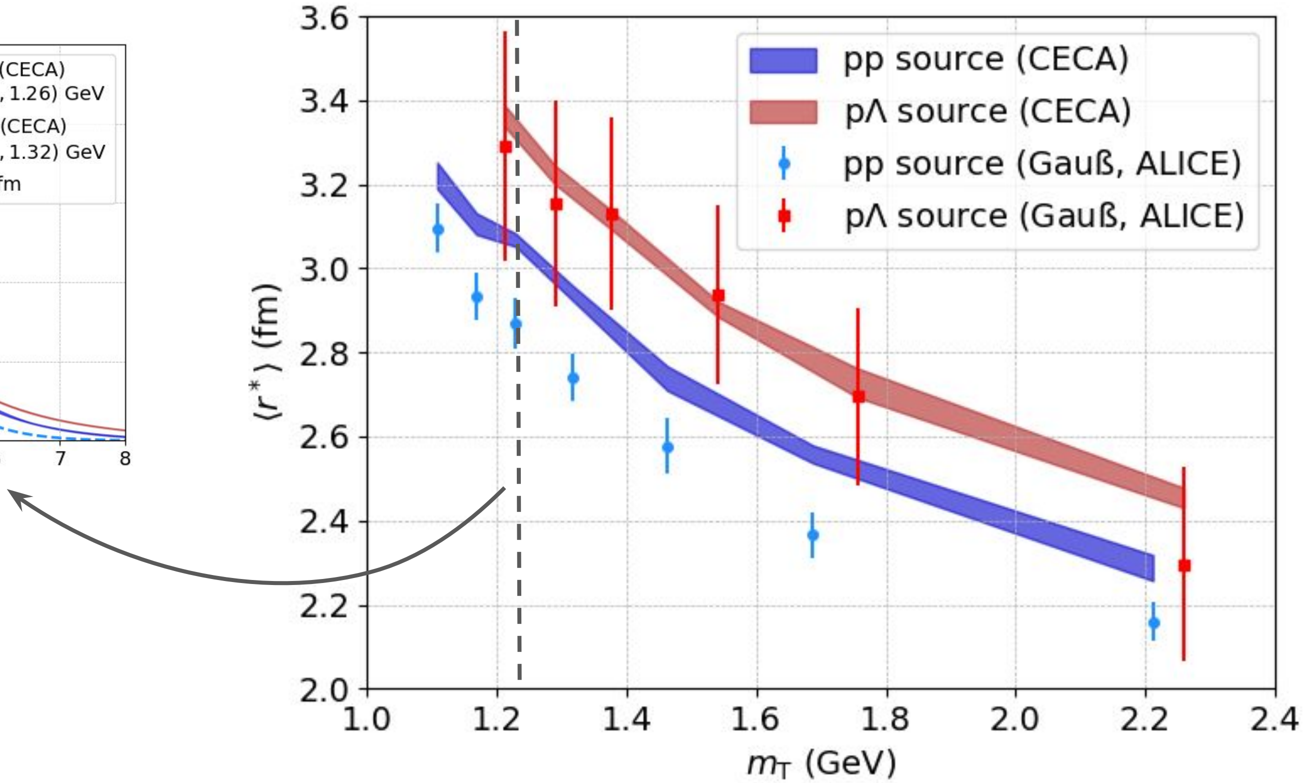
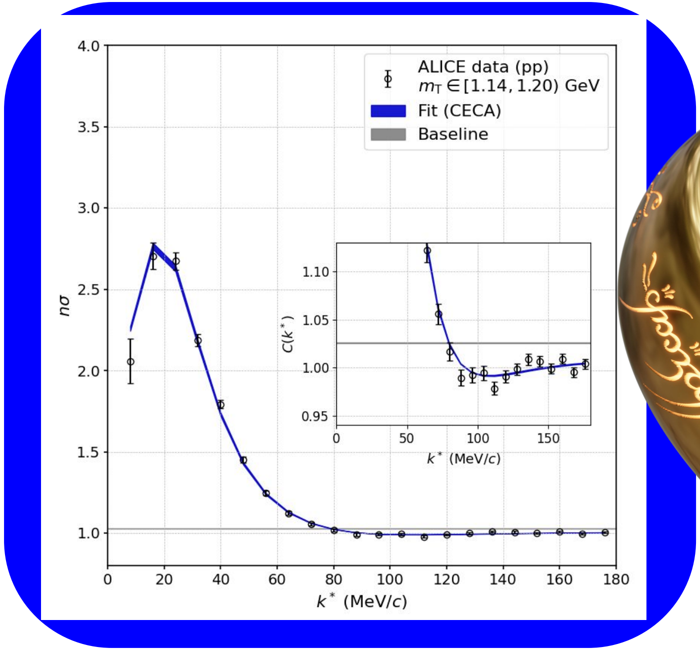


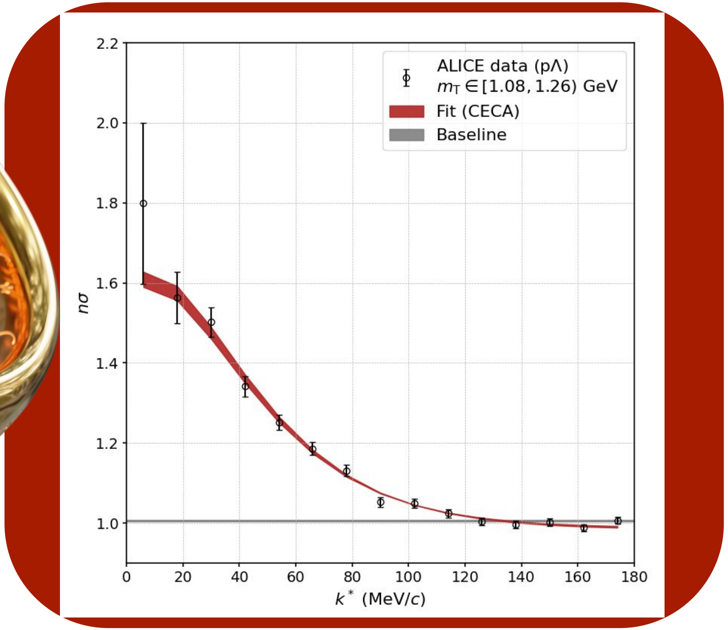


ALICE data + CECA

One source to rule them all

- pp interaction: 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]

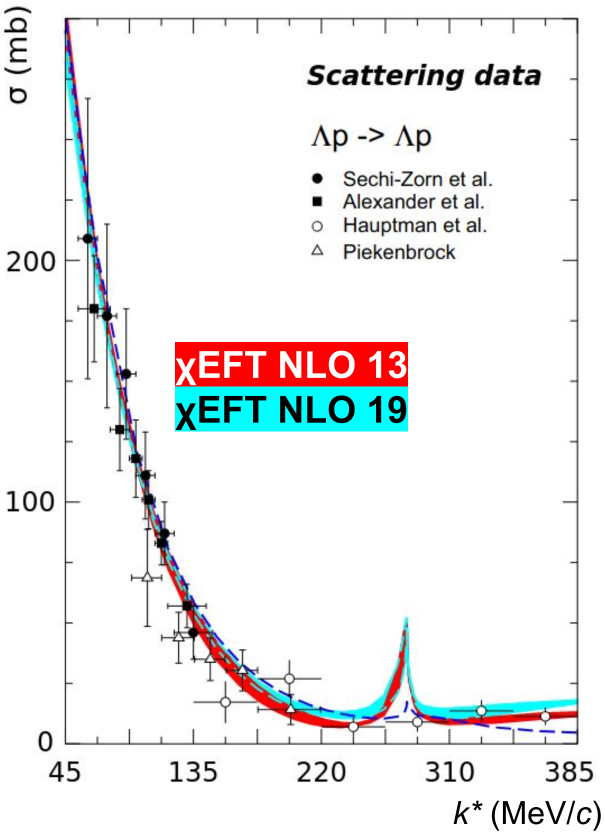




A combined fit of the mT differential pp and pΛ correlations!

ALICE data + CECA

pΛ interaction



Eur.Phys.J.A 56 (2020) 3, 91

- State of the art modeling:
  χEFT tuned to (low precision) scattering data
- Outlook: combined analysis of scattering and femtoscopy data

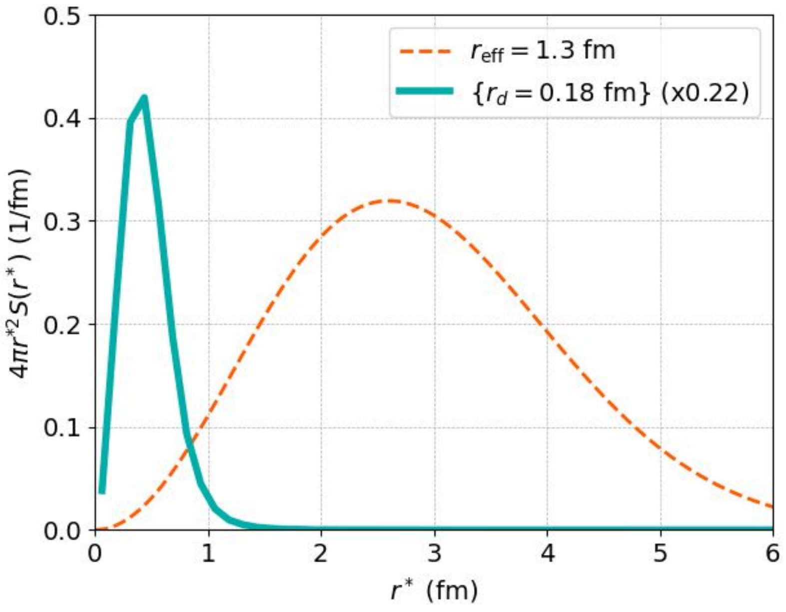
Potential	Constrained to	f(S=0) (fm)	**f(S=1) (fm)**
χEFT NLO13	Scat. data	2.91	**1.54**
χEFT NLO19	Scat. data	2.91	**1.41**
χEFT NNLO	Scat. data	2.80	**1.56**
Usmani	Scat. data	2.88	**>1.26**
Usmani	Femtoscopy	2.88	**1.15 ± 0.07**

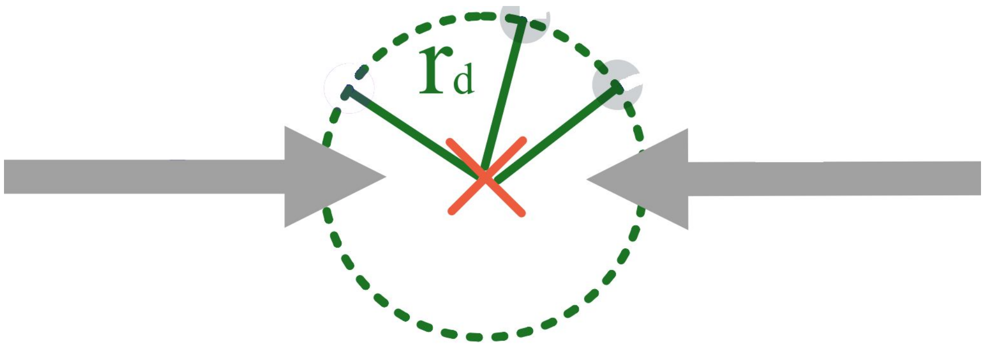
CECA: The common source

Displacement parameter

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

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

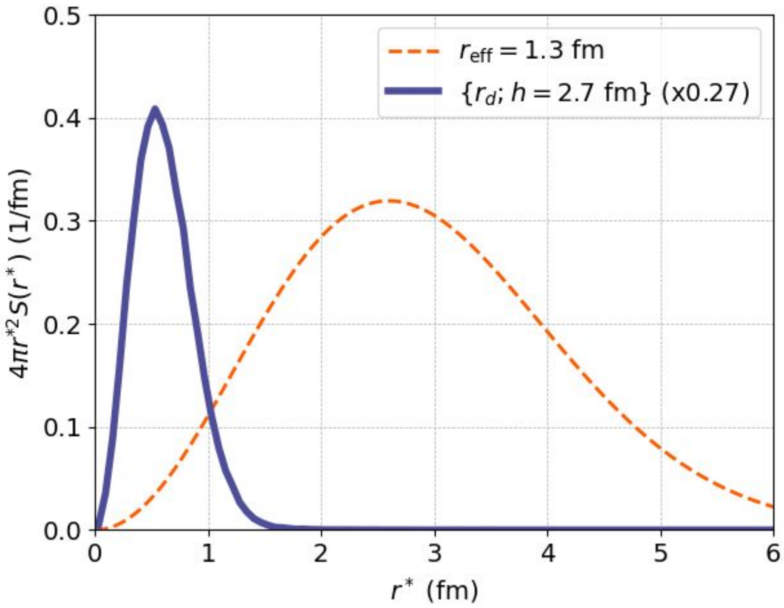


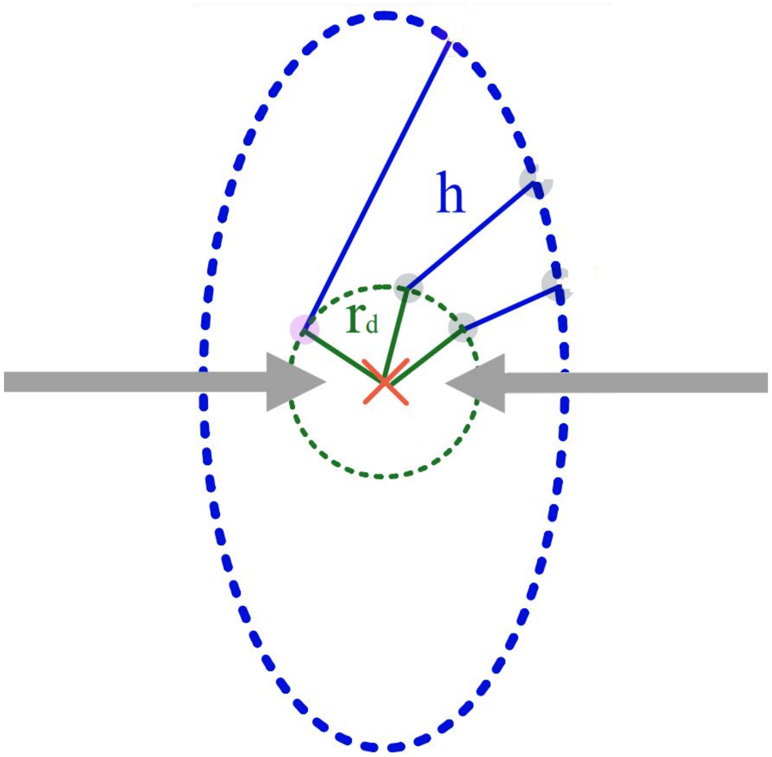


CECA: The common source

Hadronization parameter

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

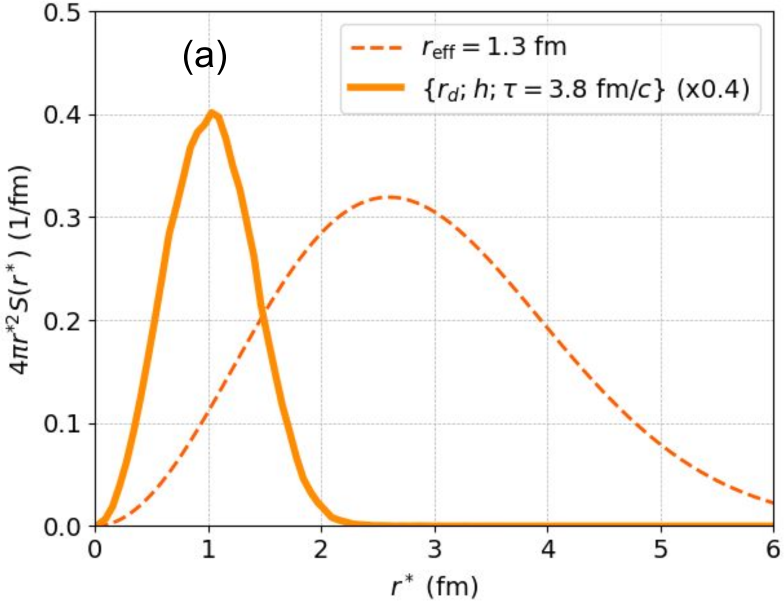


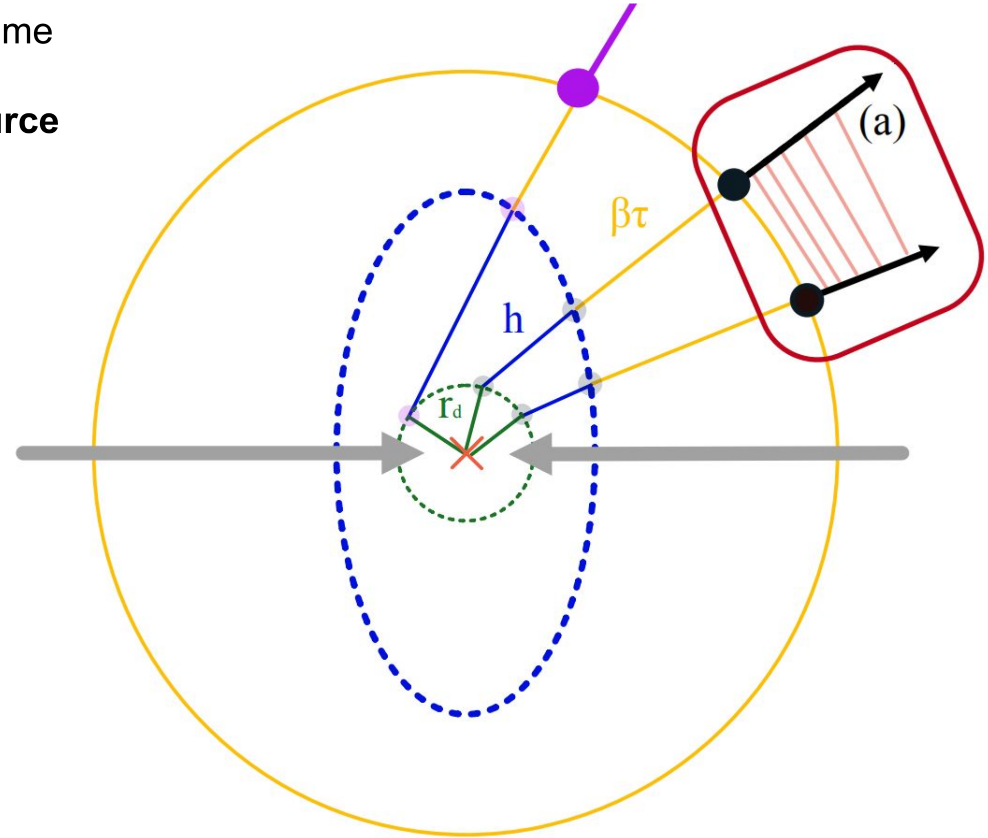


CECA: The common source

Free-streaming phase

- Propagate each particle for a fixed amount of time τ, based on the velocity β=p/γm
- The resulting distribution is the **primordial source**

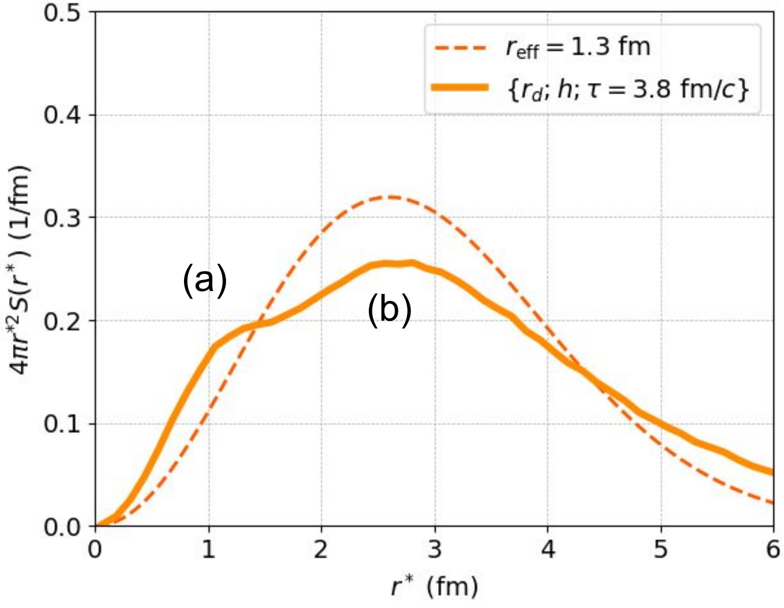


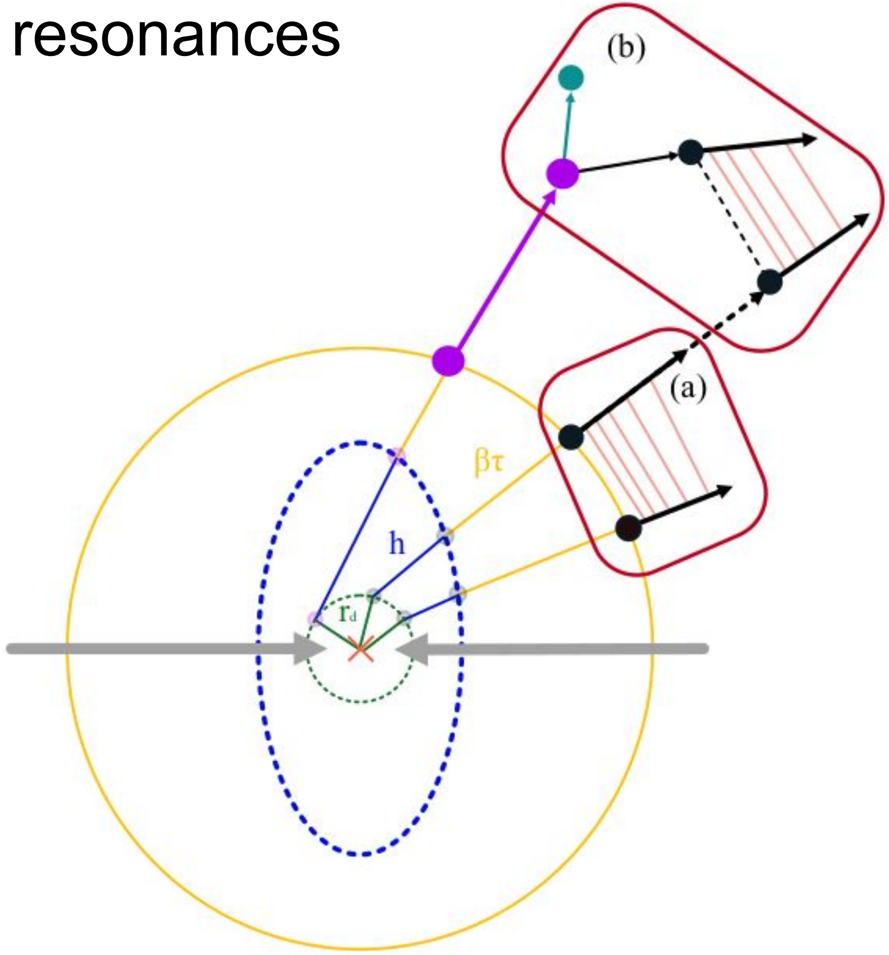


CECA: Production through resonances

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!**





Summary

- Femtoscopy as a tool to model low momentum scattering

- A new framework, CECA, has been developed and used to describe the particle emission in small collision systems
  → ***applicable to model the emission of any hadron in pp collisions!***

- New constraints for the pΛ interaction, by a combined fit of mT differential measurements of the pp and pΛ correlations

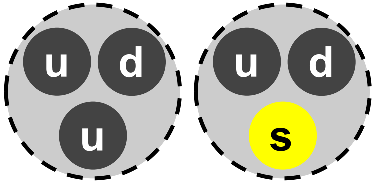
- Many other applications of femtoscopy will be shown at HADRON

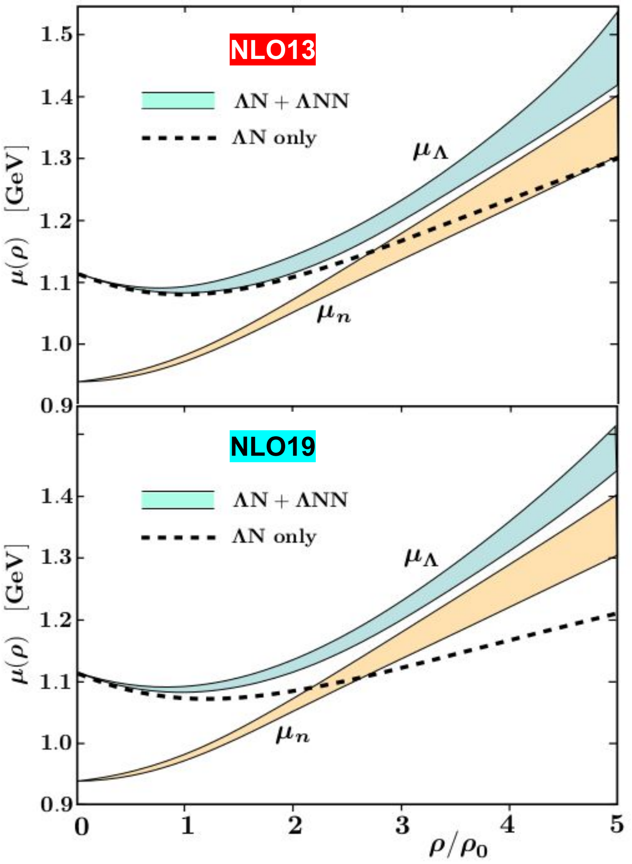
Outlook:

- Extend the CECA framework to the meson sector, as well as 3-body studies

pΛ interaction

Chiral effective field theory (χEFT)





- The Next-to-Leading Order (NLO) calculation can be fine tuned to reproduce existing data using different parameters.
- NLO13 has slightly stronger 2-body attraction in vacuum. NLO19 leads to stronger 3-body repulsion in-medium.
- Within this model, Λs cannot form inside neutron stars! **This will explain the existence of measured massive neutron stars (M > 2 M⊙).**
- **Experimental data is needed for both the 2-body and 3-body interaction** to obtain any quantitative conclusions.

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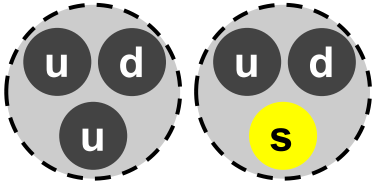
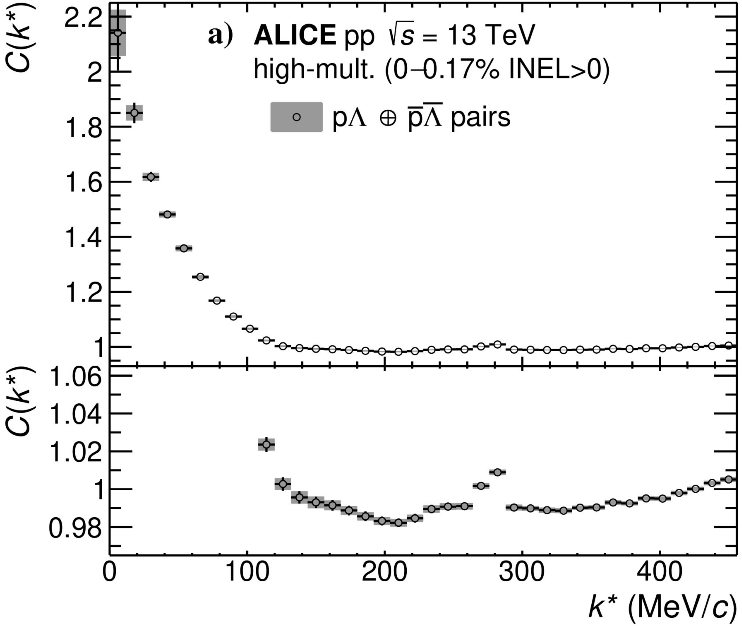
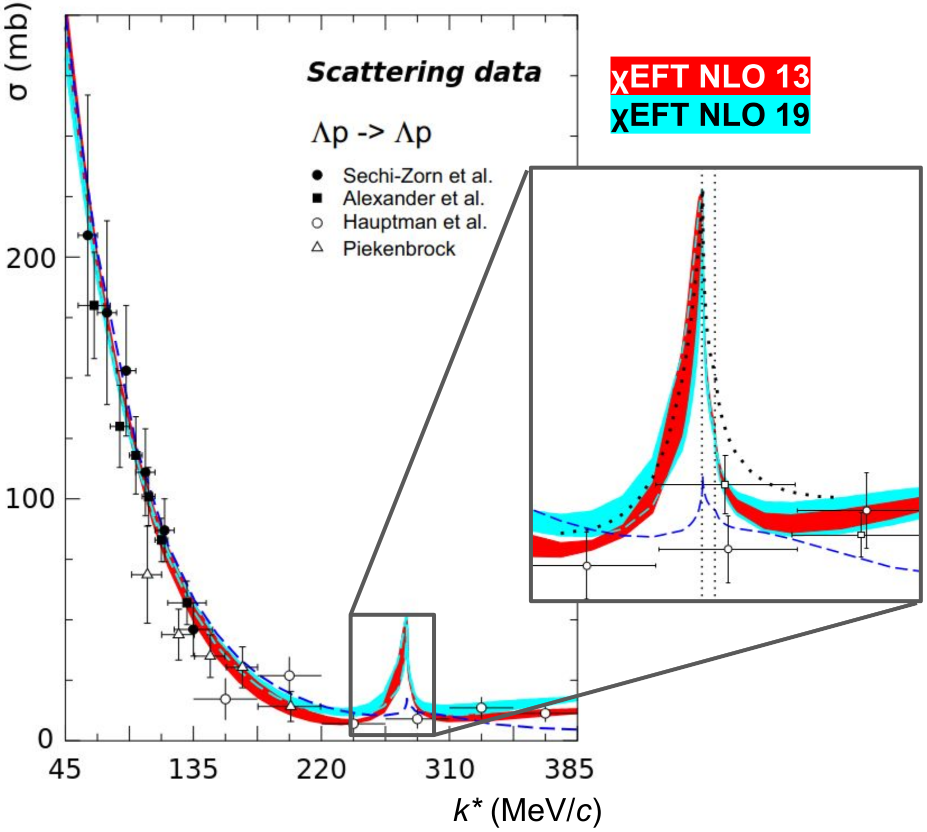
pΛ interaction

The femto era begins!







Based on arXiv:2104.04427, accepted by PLB

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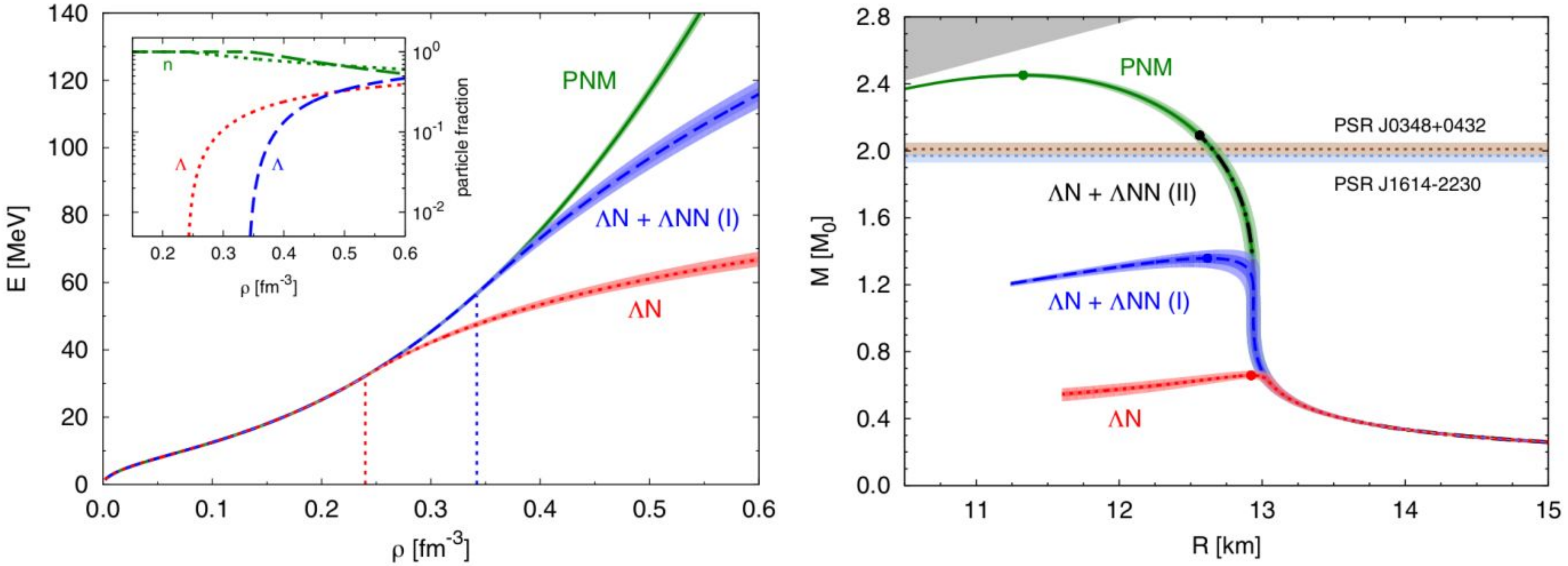
Neutron stars (NS)

Nuclear Equation of State (EoS) and Mass-Radius relation



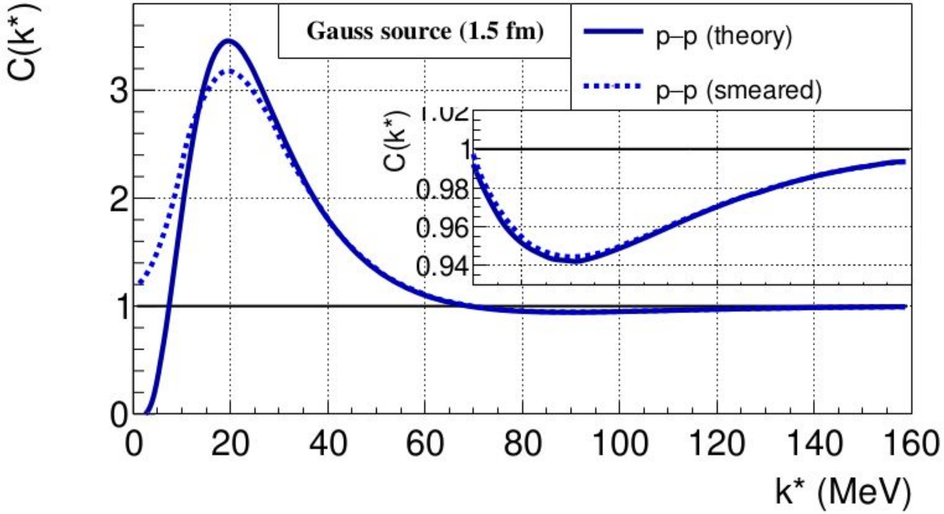
PRL 114 (2015) 9, 092301

A soft EoS, allowing hyperons within NS, leads to an underprediction of measured NS masses. This is known as the **hyperon puzzle.**

Femtoscopy

Example for pp

- **Momentum resolution**
- Feed-down from secondaries
- Misidentifications
- Non-femtoscopic baseline
- Source function

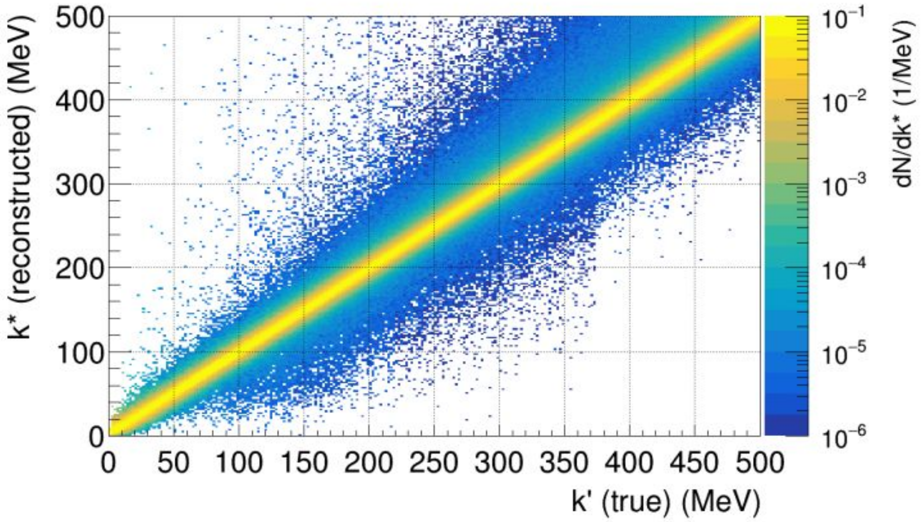


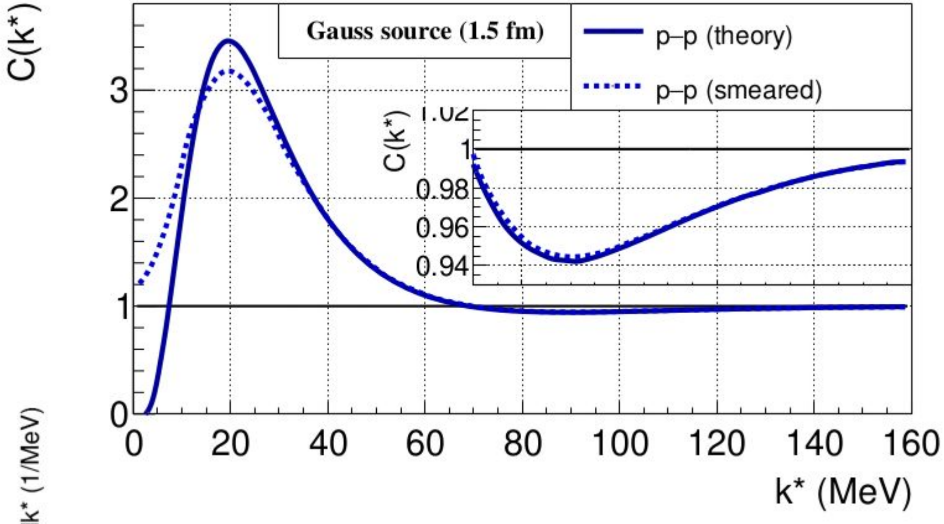
a) unfold

b) apply the resolution to the theory

Femtoscopy
Example for pp

- **Momentum resolution matrix (W)**





a) unfold

b) apply the resolution to the theory (exact)

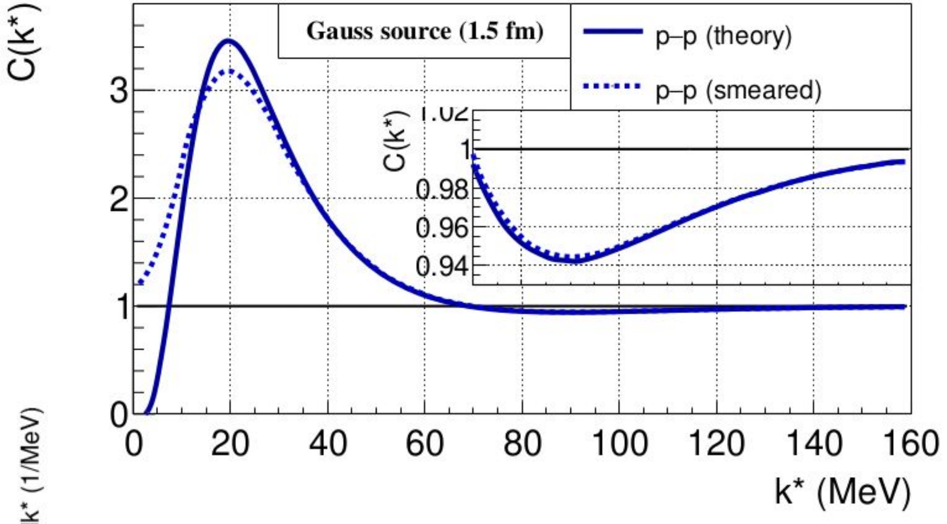
true (unfolded) mixed-event / correlation

$$C(k^*) = \int W(k', k^*) \cdot \frac{M'(k')}{M(k^*)} C'(k')\, dk'$$

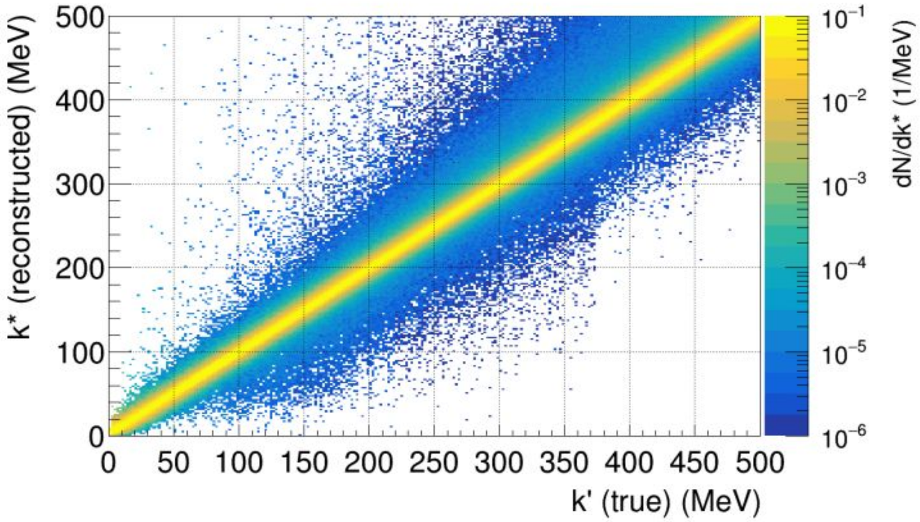
measured mixed-event

Femtoscopy

Example for pp



- **Momentum resolution matrix (W)**



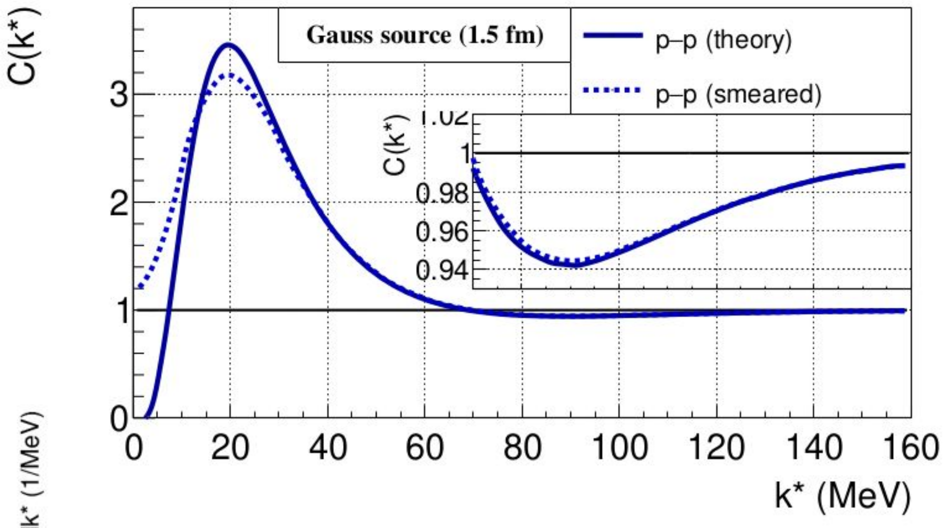
a) unfold

b) apply the resolution to the theory (good approx.)

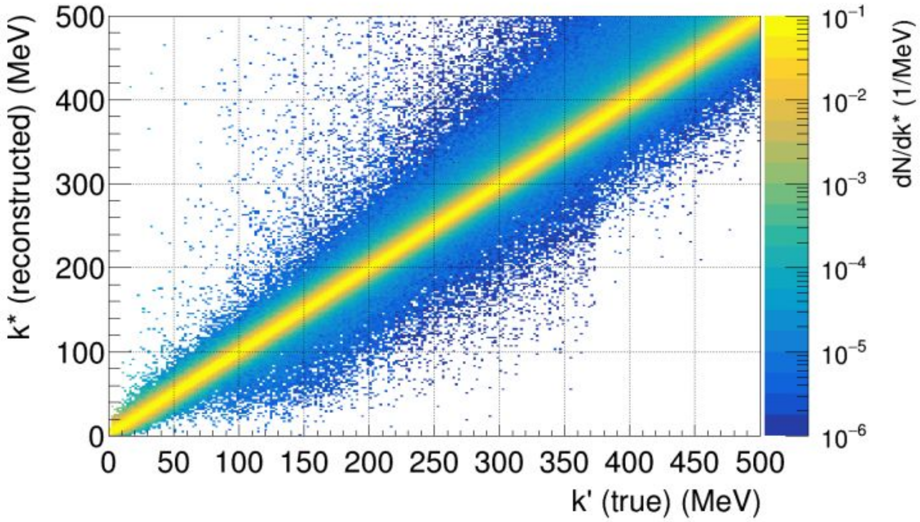
$$C(k^*) \approx \int W(k', k^*) \cdot \frac{M(k')}{M(k^*)} C'(k')\, dk'$$

measured mixed-event

Example for pp



- **Momentum resolution matrix (W)**



a) unfold

b) apply the resolution to the theory (bad approx.)

$$C(k^*) \approx \int W(k', k^*) \cdot \frac{M(k')}{M(k^*)} C'(k')\, dk'$$

Femtoscopy

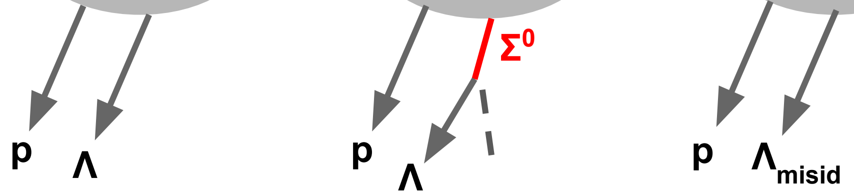
Example for pΛ

$$C_{\mathrm{exp}}(k^*) = b(k^*)\,C_{\mathrm{th}}(k^*) = b(k^*)\sum_i \lambda_i C_{\mathrm{th},i}(k^*)$$

Non-femto baseline

- Momentum resolution
- **Feed-down from secondaries**
- **Misidentifications**
- **Non-femtoscopic baseline**
- Source function

$$\lambda_0 C_{\mathrm{th},0}(k^*) + \lambda_1 C_{\mathrm{th},1}(k^*) + \lambda_2 C_{\mathrm{th},2}(k^*) \cdots$$



Modeled using χEFT

corrected for using a "sideband" analysis

Femtoscopy

Example for pΛ

$$C_{\text{exp}}(k^*) = b(k^*)\,C_{\text{th}}(k^*) = b(k^*)\sum_i \lambda_i C_{\text{th},i}(k^*)$$

- Momentum resolution
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Tip of the day

Always assume that even corrected data is systematically biased at least up to a normalization constant!