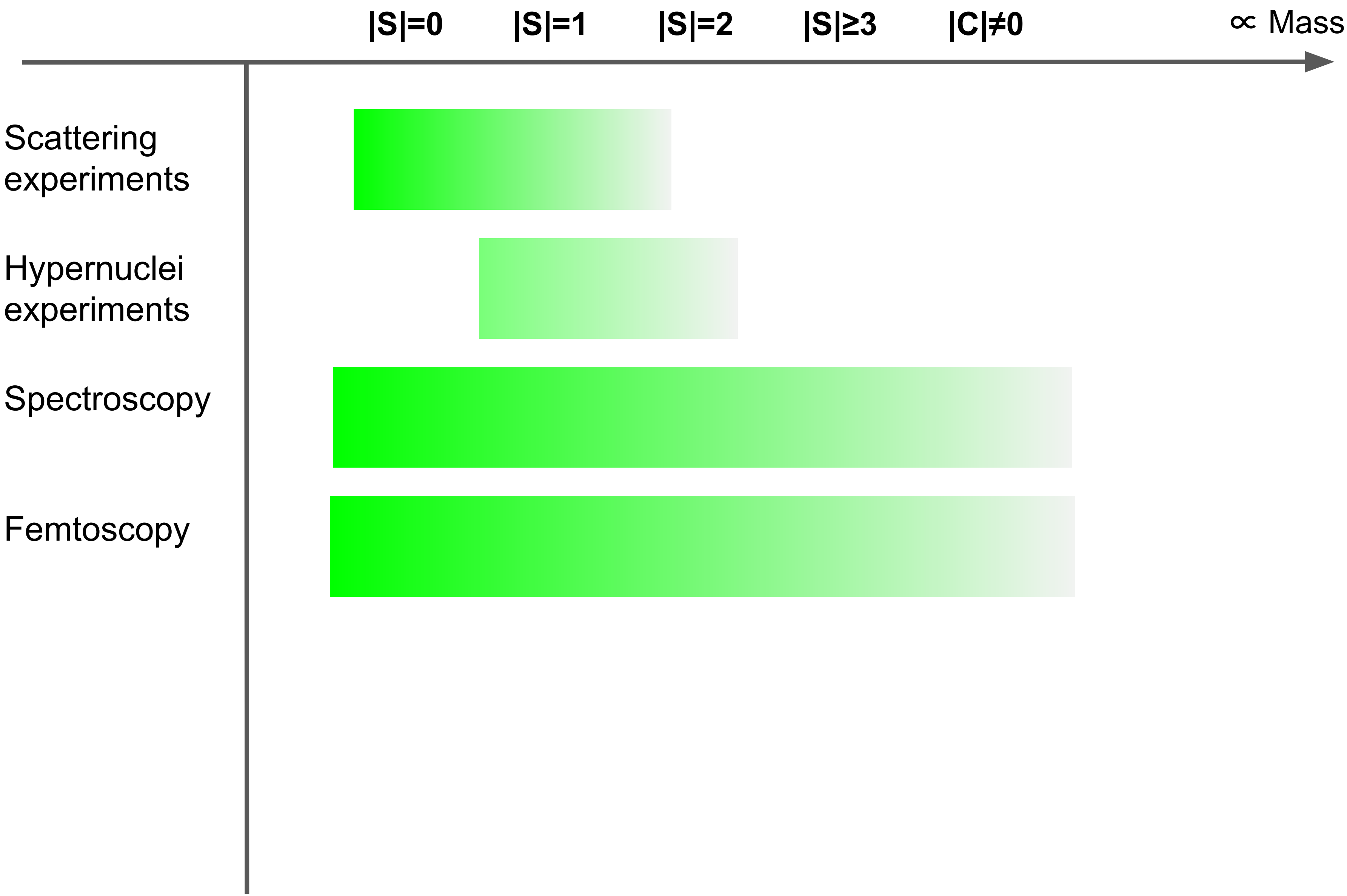
Studying low-energy scattering using correlation techniques at the LHC

Dimitar Mihaylov

6^{th} November 2023, Catania, Italy

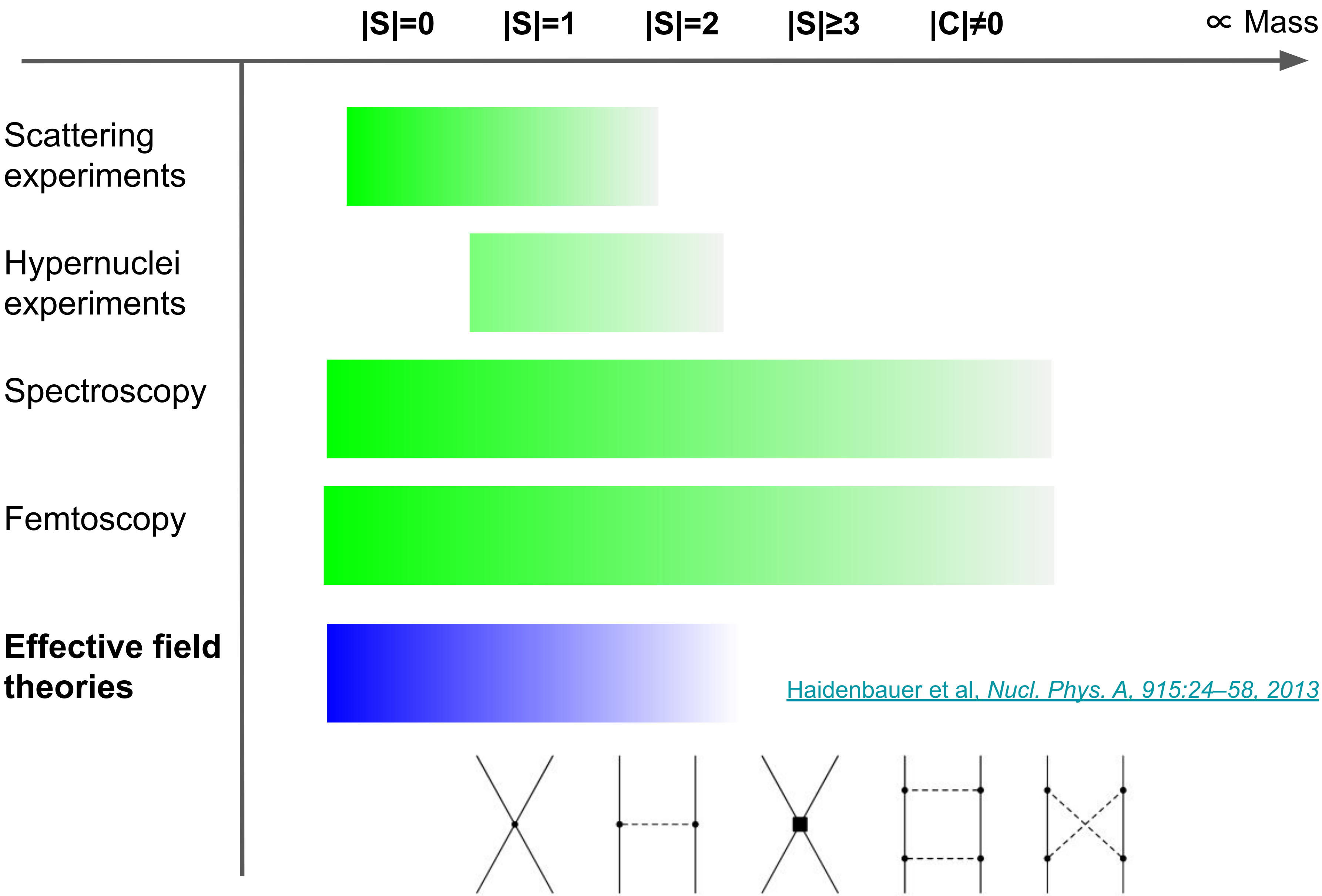
Hadron-hadron interaction

Theory *vs* ***experiment***



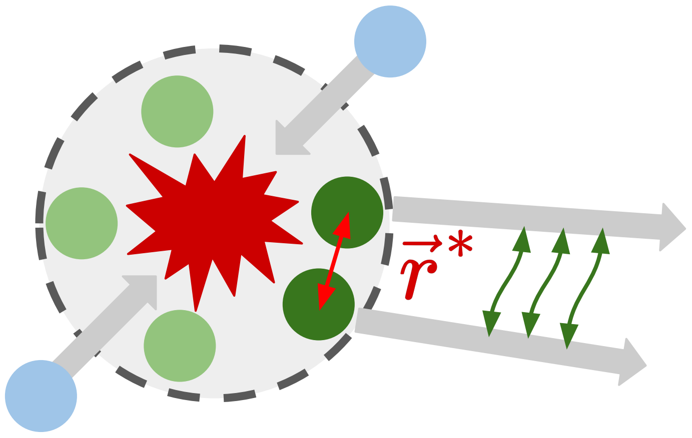
Hadron-hadron interaction

Theory vs *experiment*



Femtoscopy

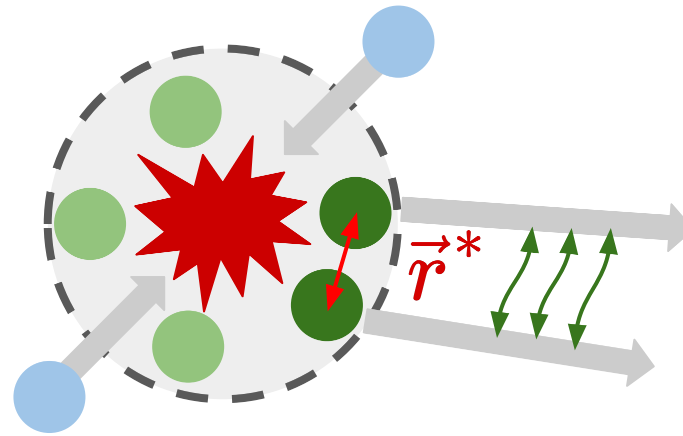
Overview



Femtoscopy

Koonin-Pratt equation

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



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

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
  Mihaylov et al. *EPJC* 78 (2018) 5, 394

Femtoscopy

Workflow

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

Measure

Fix

Study

Femtoscopy

The emission source

1) ALICE Coll. Phys.Lett.B 811 (2020) 135849
2) Mihaylov and Gonzalez Gonzalez, EPJC 83 (2023) 7, 590

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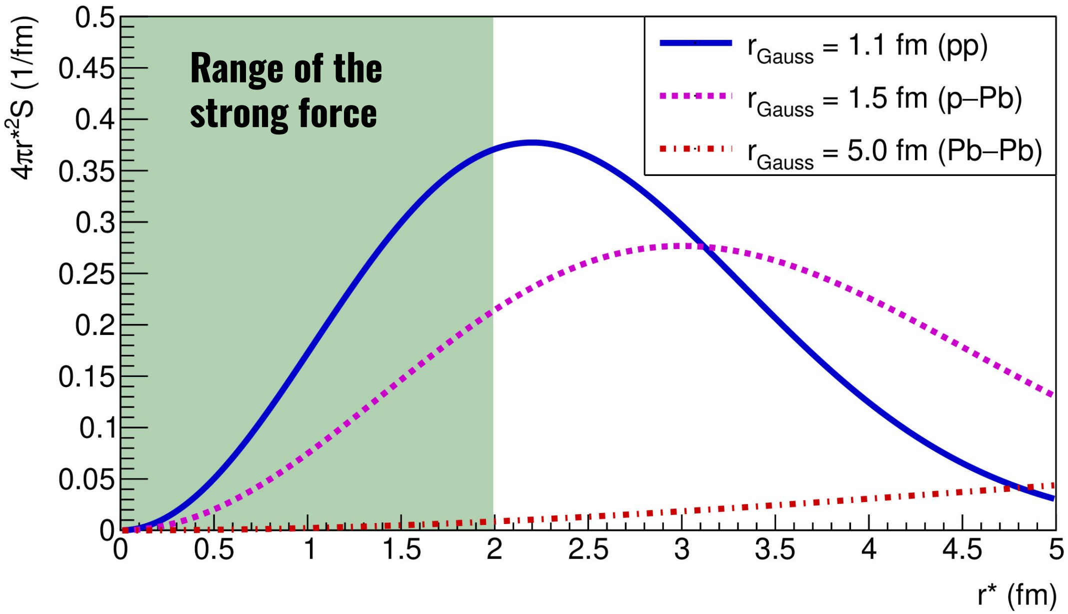

- Enhanced sensitivity in **small collision systems (pp)**

Femtoscopy

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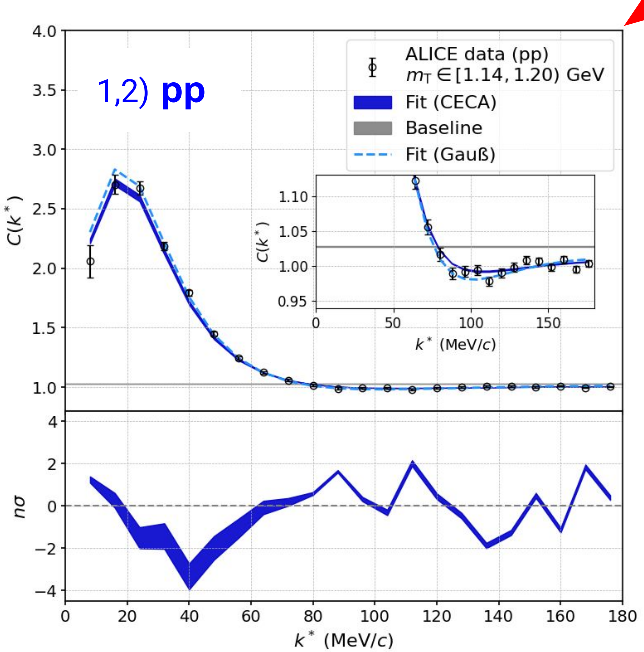

- Enhanced sensitivity in **small collision systems (pp)**
- **Common emission source for all baryons**
- The **pp correlation** can be used to **evaluate S(r*)**

Femtoscopy

The emission source

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2) Mihaylov and Gonzalez Gonzalez, EPJC 83 (2023) 7, 590
3) ALICE Coll. *Nature 588 (2020) 232-238*

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

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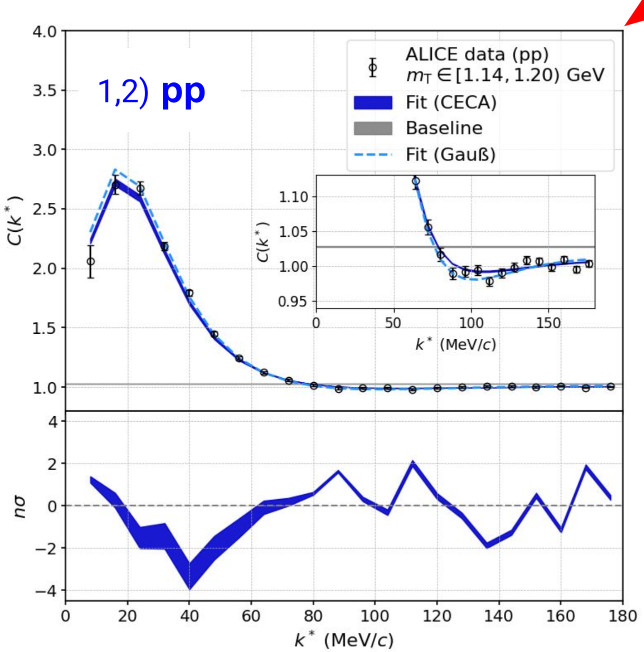
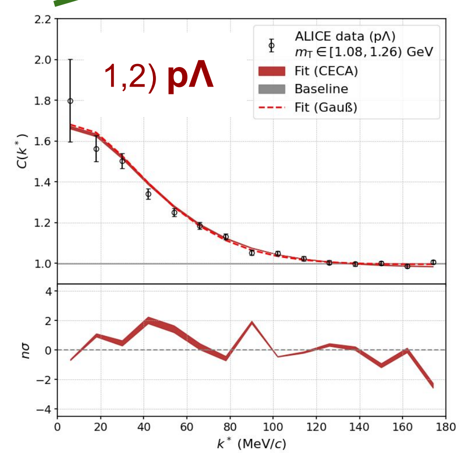
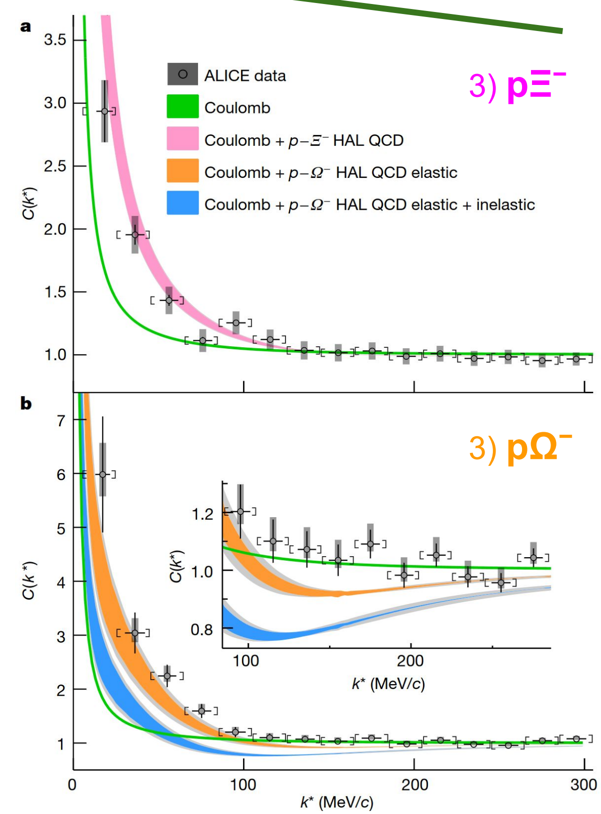
Study







Femtoscopy

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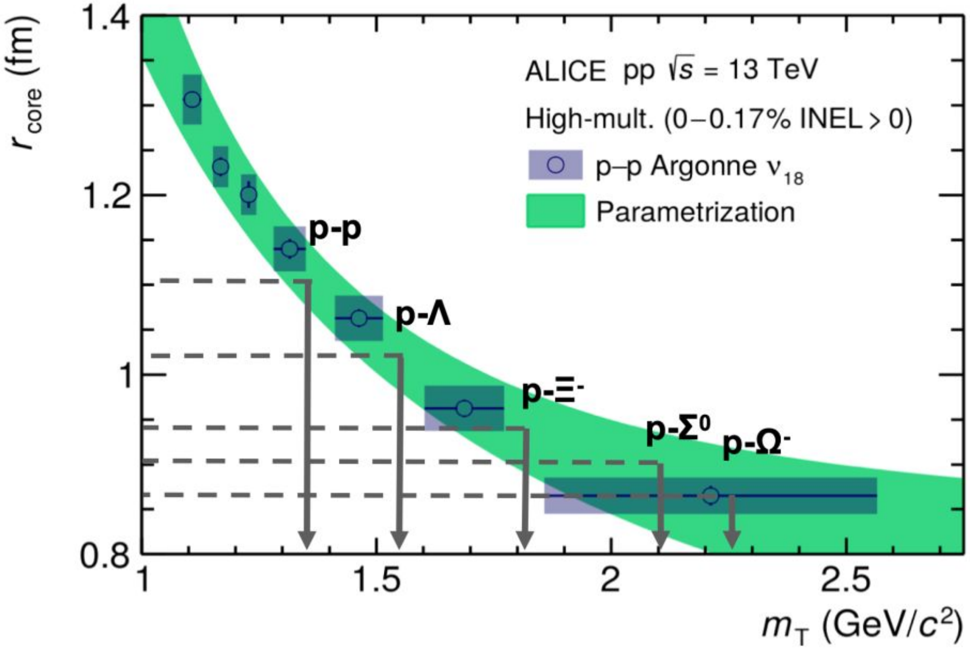
Measure Fix Study

Based on 1)



- Enhanced sensitivity in **small collision systems (pp)**
- **Common emission source for all baryons**
- The **pp correlation** can be used to **evaluate S(r*)**
- The same source can be used to **study the final state interaction** for **ANY** other **baryon-baryon** pair

Femtoscopy

The emission source

ALICE Coll. *Phys.Lett.B 811 (2020) 135849*
Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590

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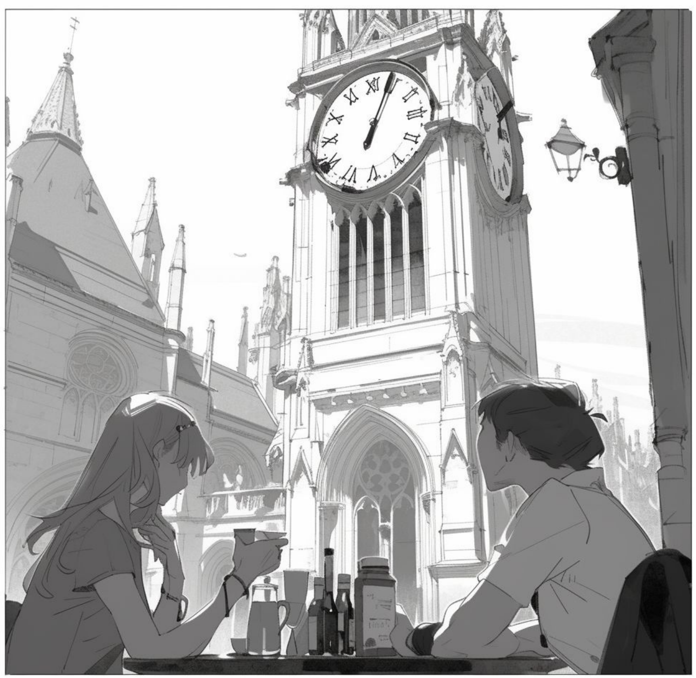
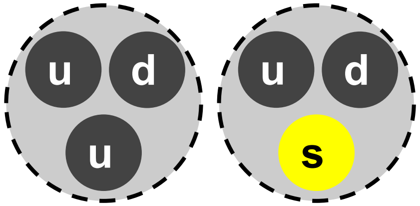


ALL details up for discussion over lunch / coffee!

NOW let's move to physics results

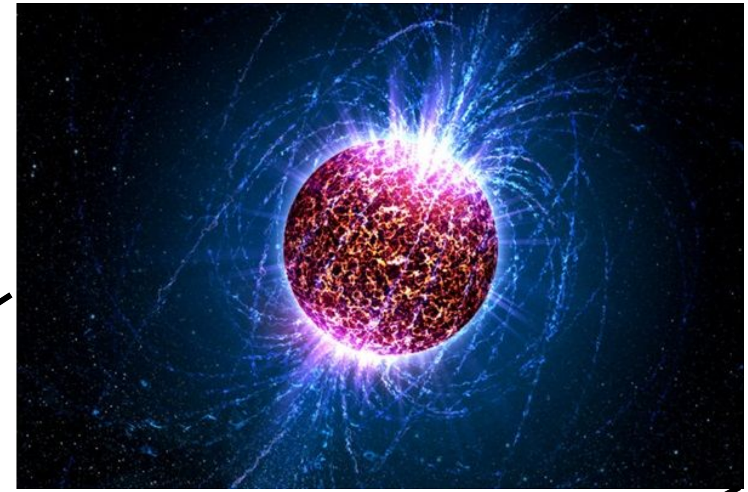
pΛ correlations

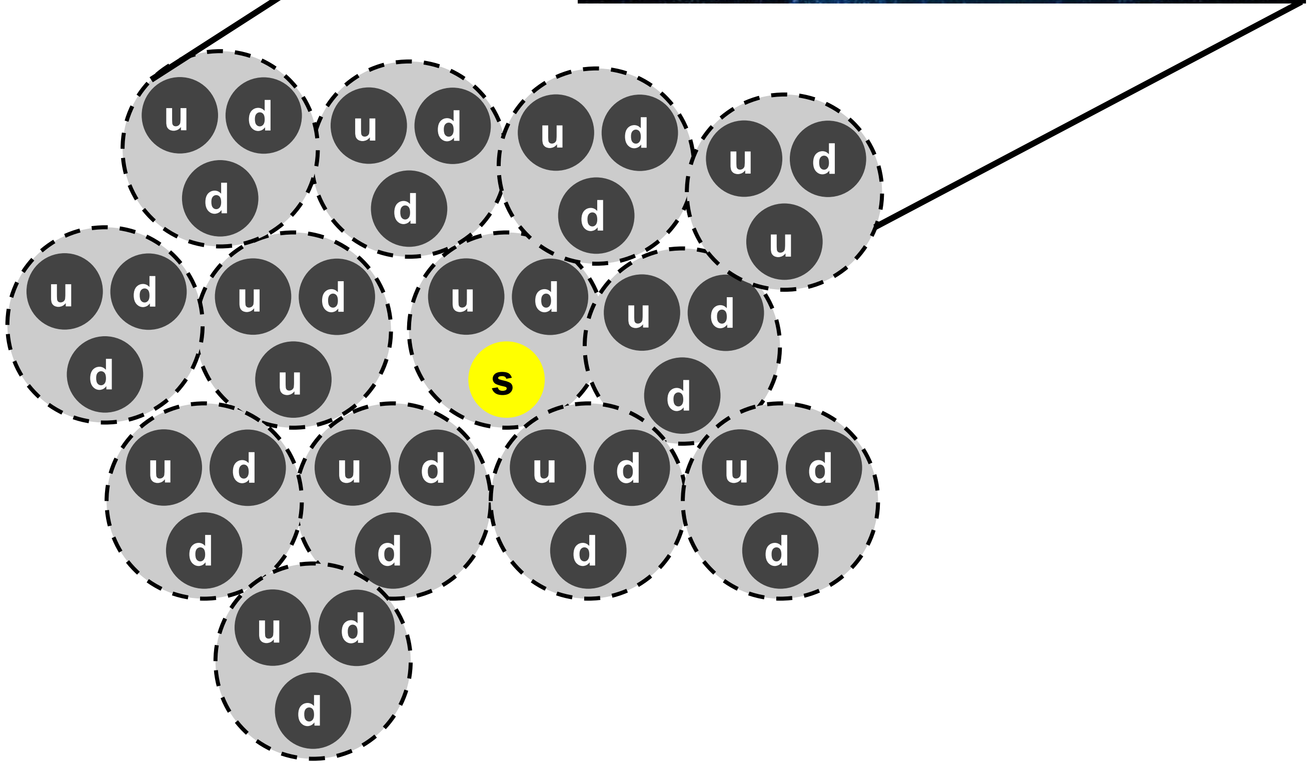


pΛ correlations

Motivation

- Dense nuclear matter, as found in **neutron stars**, may provide favourable conditions for **hyperons** to form.





pΛ correlations

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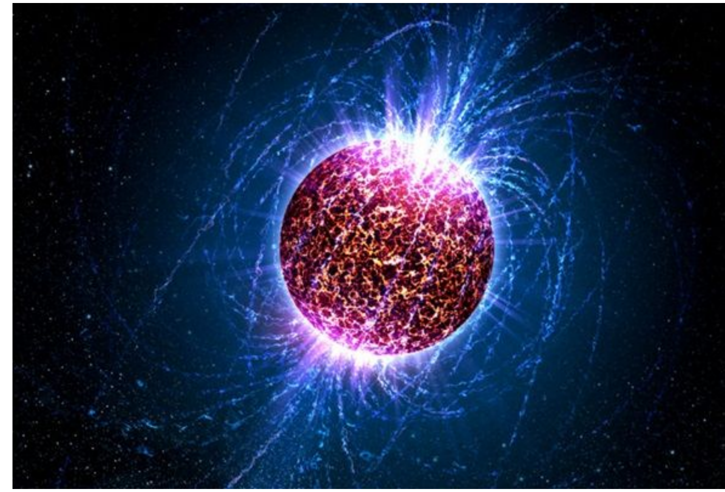

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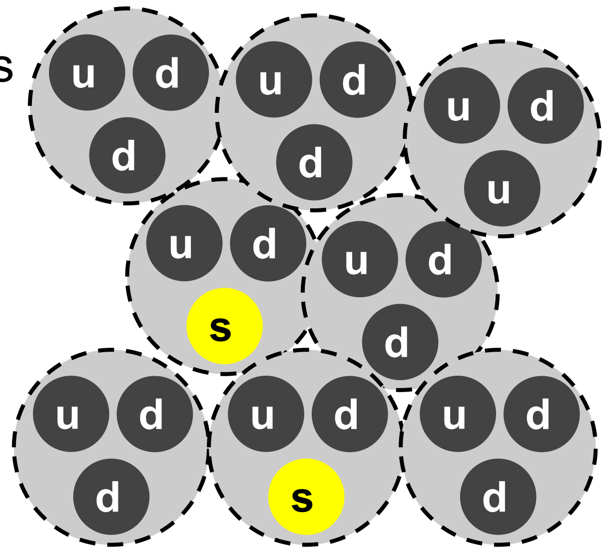
- **The hyperon puzzle**:
  The appearance of hyperons is in contradiction with the existence of the largest measured masses of neutron stars.



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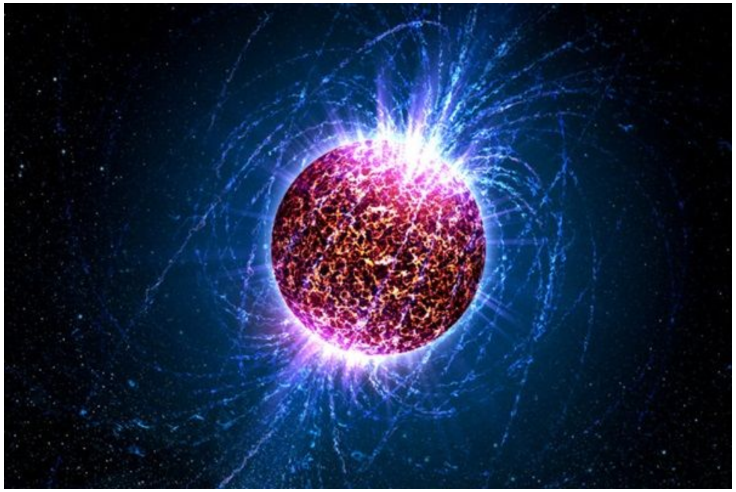
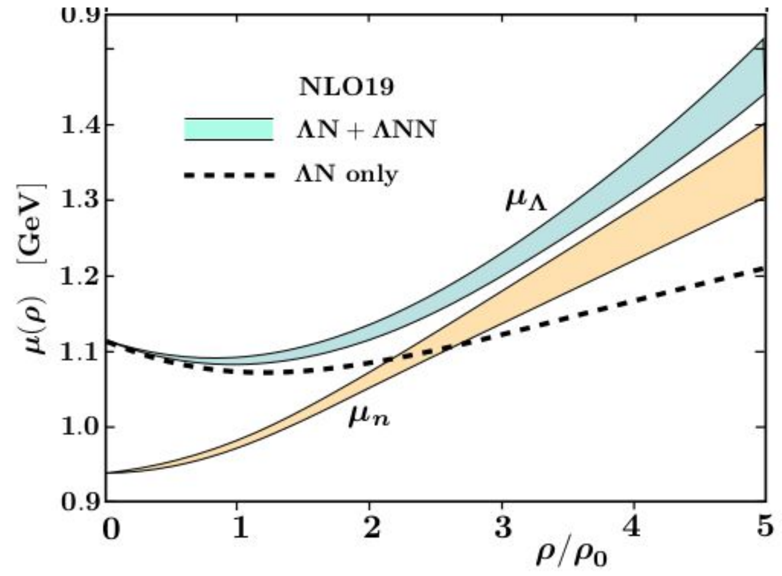
  A repulsive three-body NNΛ force will prevent the chemical potential μ_Λ of becoming favorable for Λ formation.





[Gerstung et al.](#)
[*Eur.Phys.J.A 56 (2020) 6, 175*](#)

pΛ correlations

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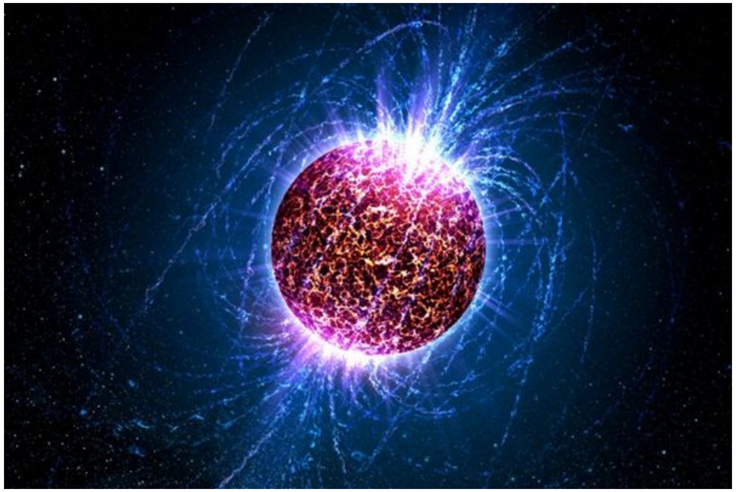
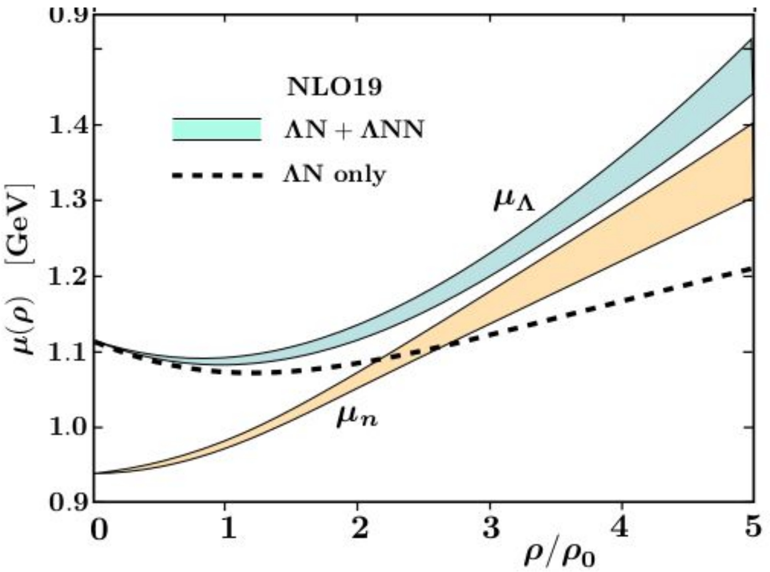
  A repulsive three-body NNΛ force will prevent the chemical potential μ_Λ of becoming favorable for Λ formation.

- The interplay between the **two- and the three-body forces** is crucial to obtain a realistic nuclear **equation of state**!
  Friday: Oton Vazquez Doce



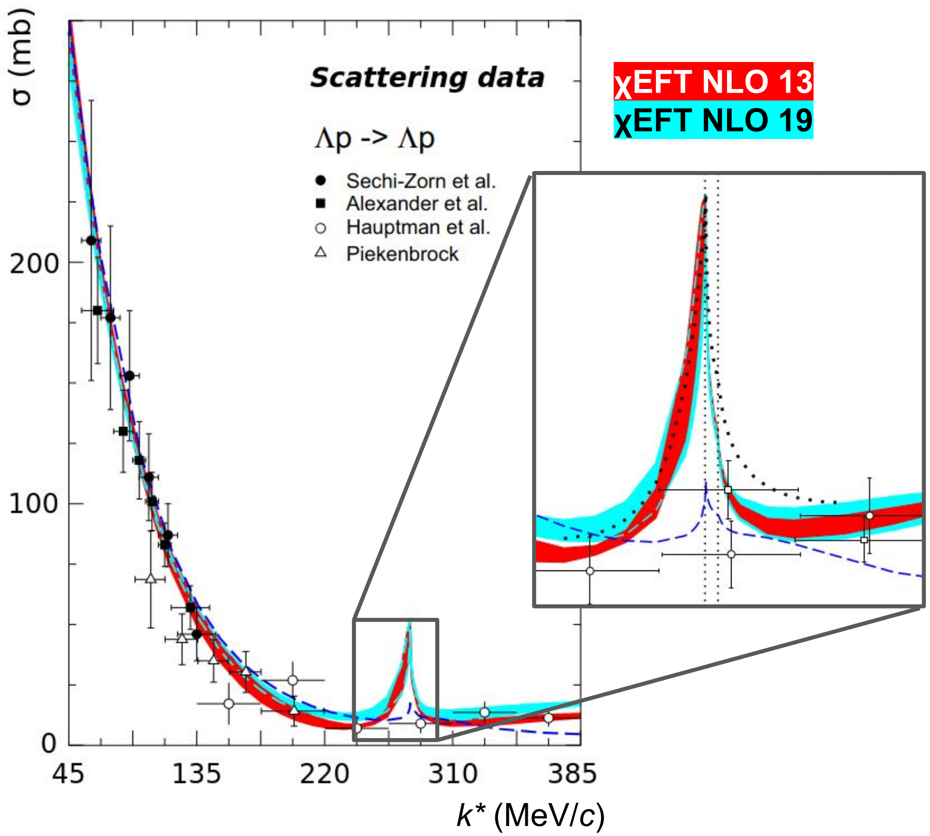


Gerstung et al.
Eur.Phys.J.A 56 (2020) 6, 175

pΛ interaction

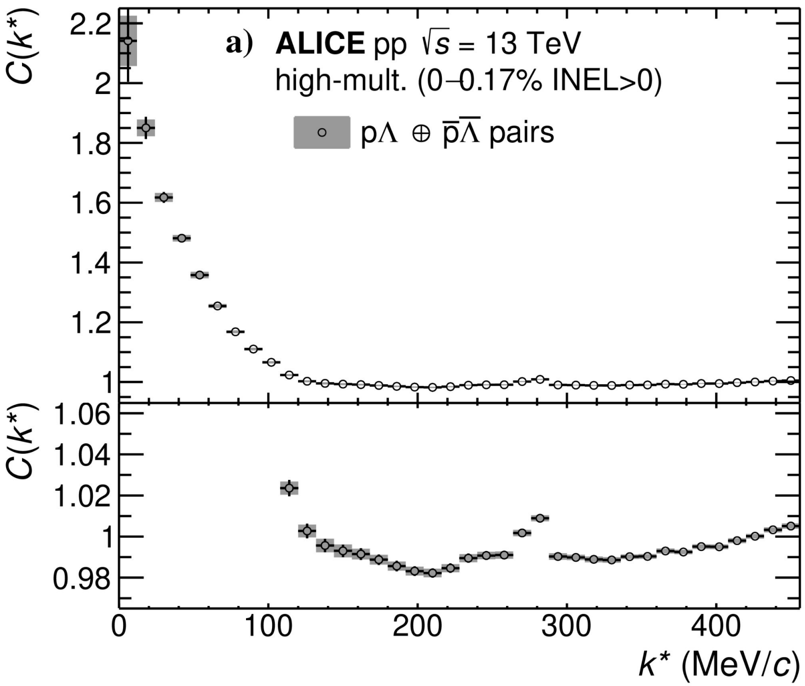
***Scattering** and femtoscopy data*

Haidenbauer et al. *Eur.Phys.J.A 56 (2020) 3, 91*



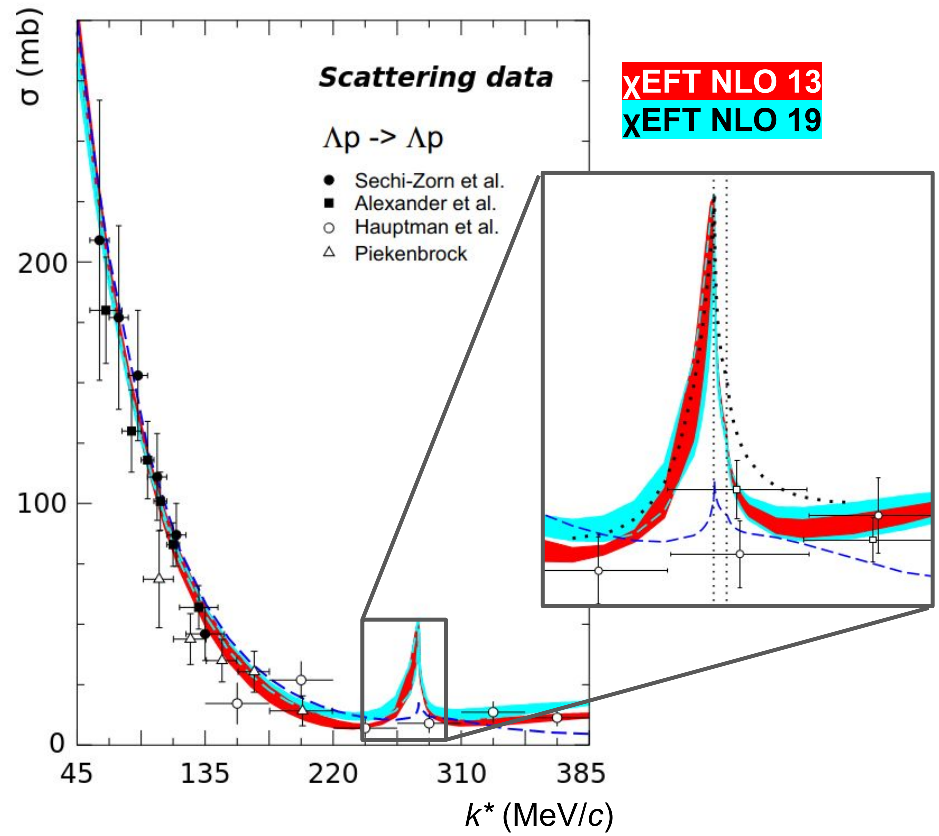
pΛ interaction

*Scattering and **femtoscopy** data*



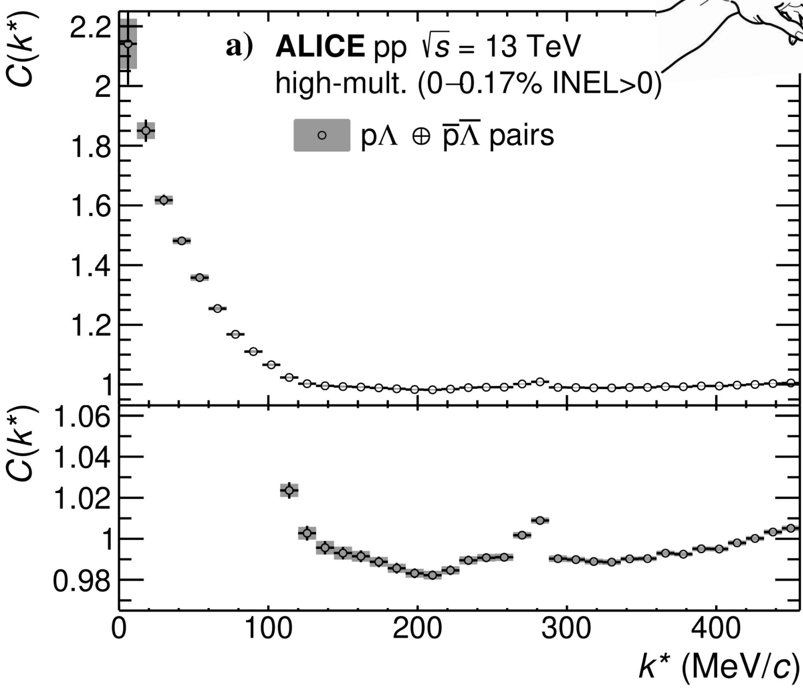
Based on [ALICE Coll. *PLB 833 (2022), 137272*]

[Haidenbauer et al. *Eur.Phys.J.A 56 (2020) 3, 91*]



pΛ interaction

A combined analysis



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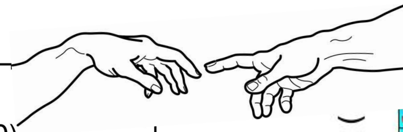

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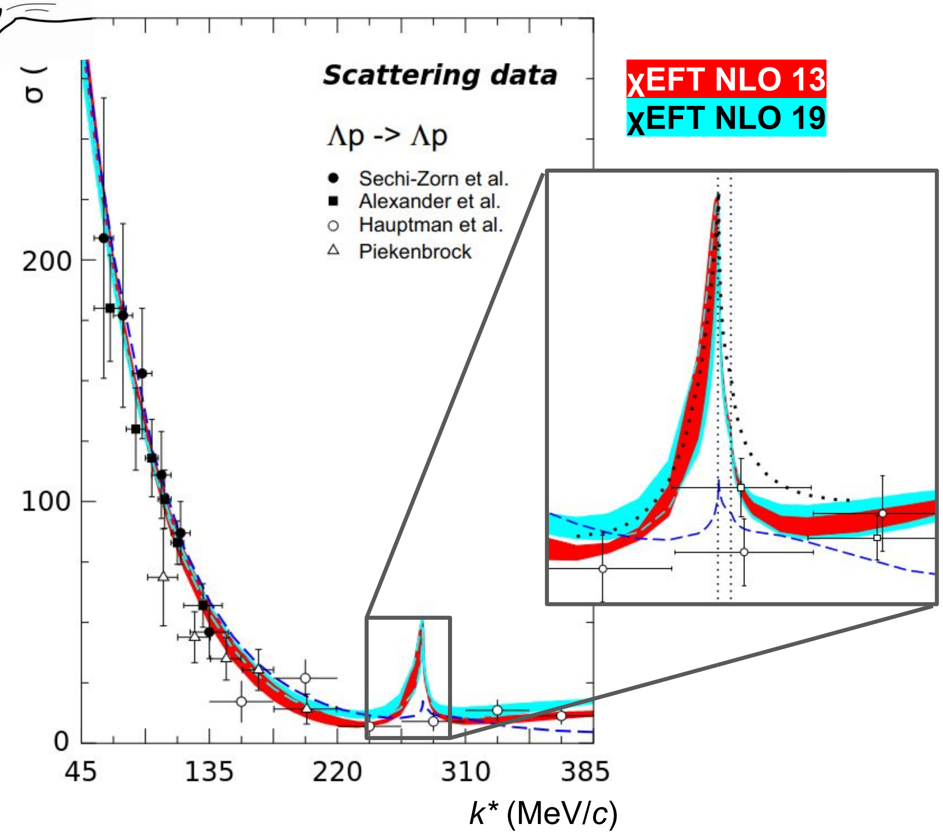

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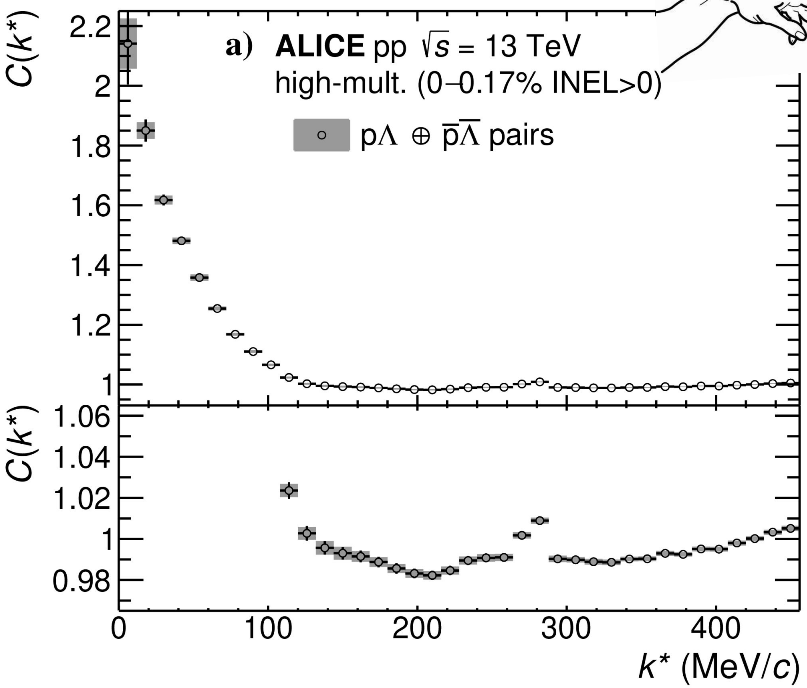

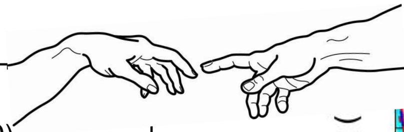

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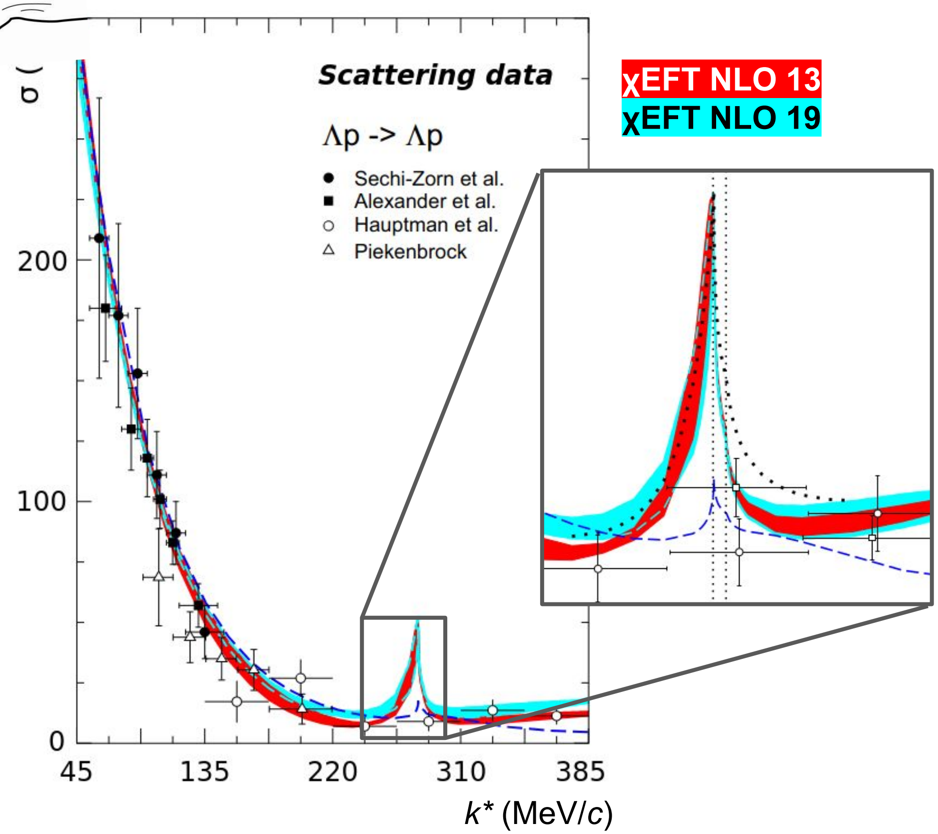


Based on [ALICE Coll. *PLB 833 (2022), 137272*]

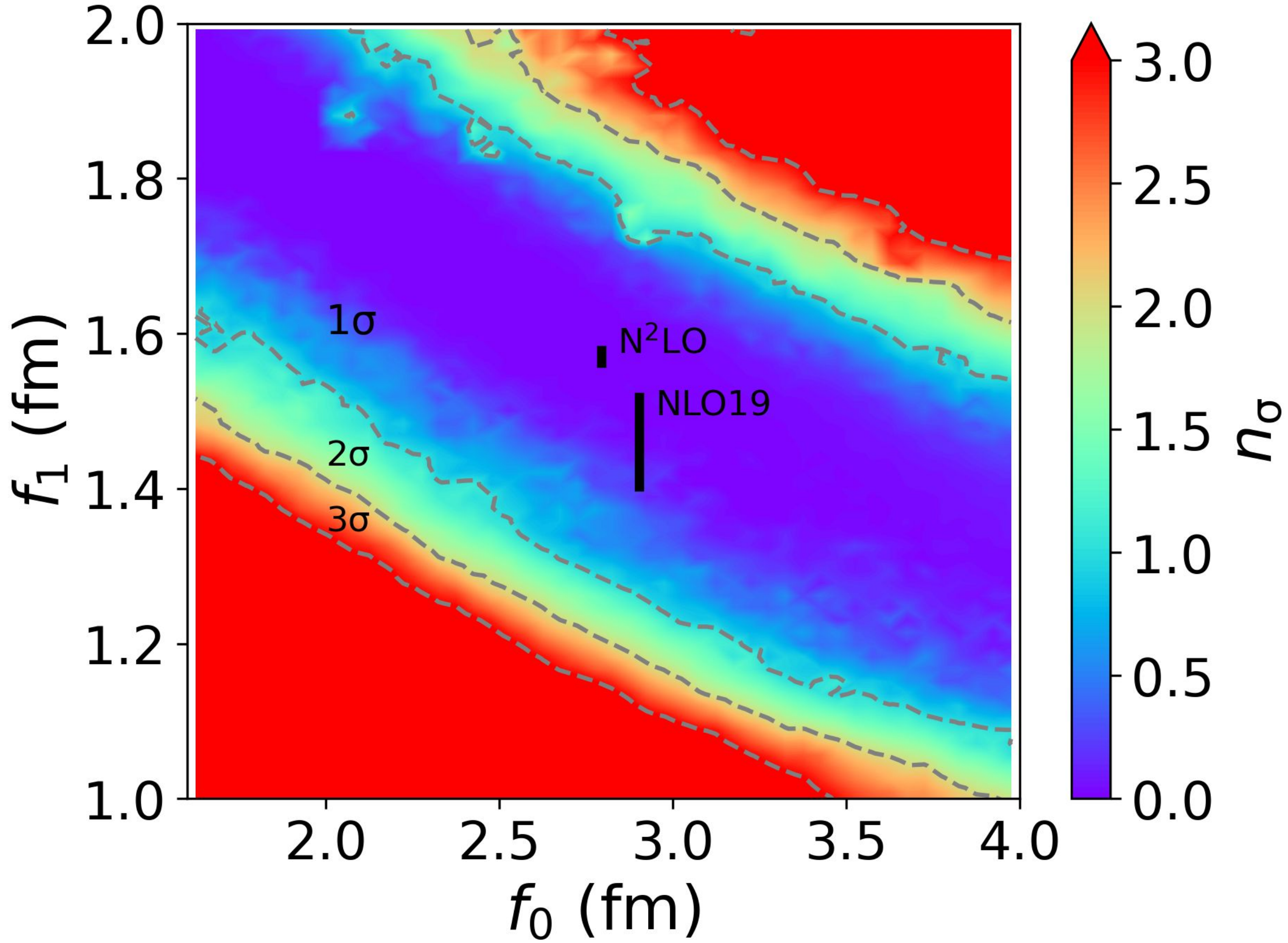
- pΛ interaction: Usmani potential, short-range repulsive core fitted
  [Usmani et al, PRC, 29:684–687, 1984]
- Femtoscopy: mT differential fit of pp (source) and pΛ (interaction) correlations
  [Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590]
- Scattering: fit of the cross section

pΛ scattering parameters

Constrained to scattering data

WORK IN PROGRESS
in collaboration with **J. Haidenbauer**

- Following *EPJC* 83 (2023) 7, 590, create an exclusion plot for the single/triplet pΛ scattering length, using **only scattering data**



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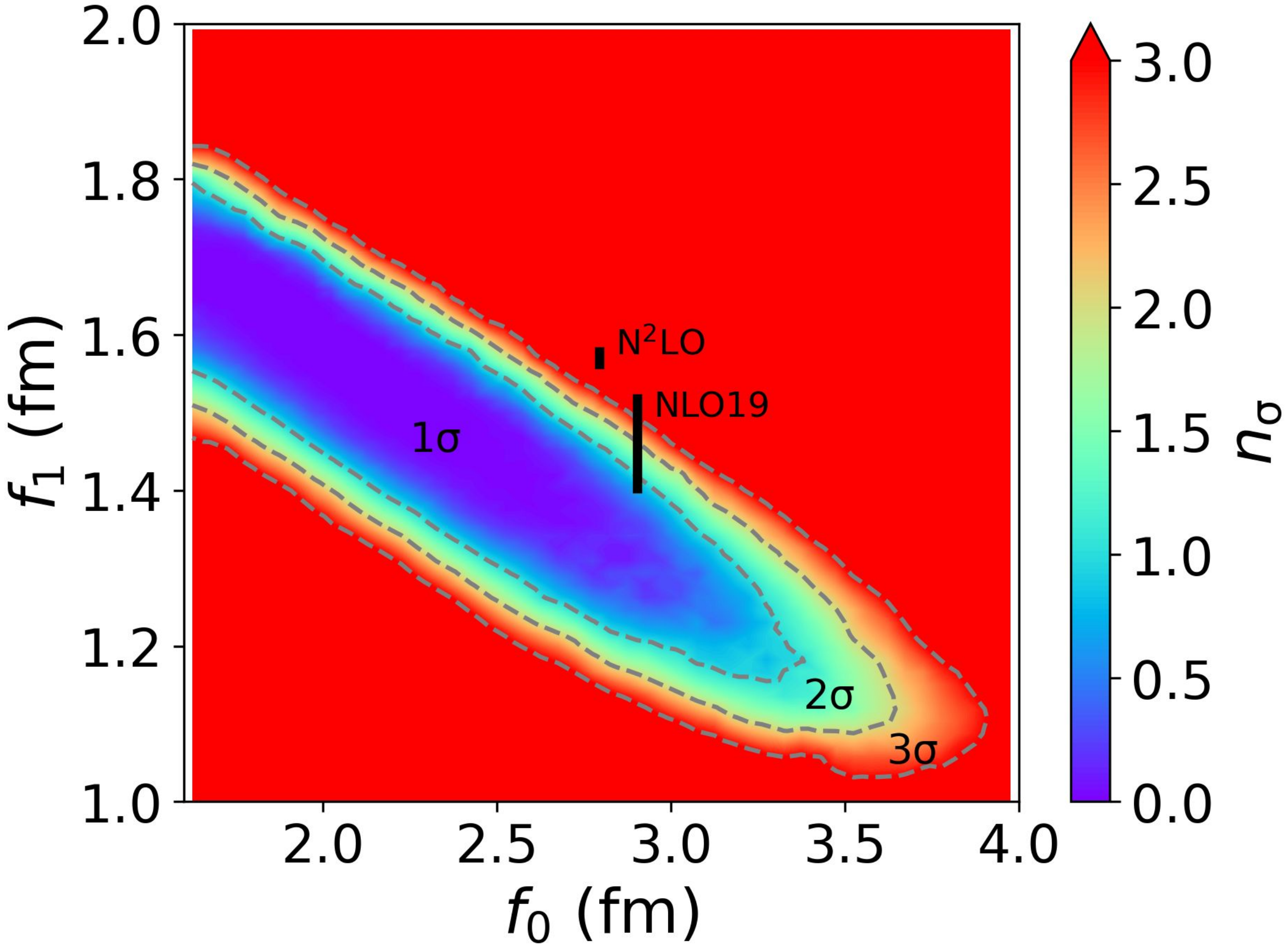
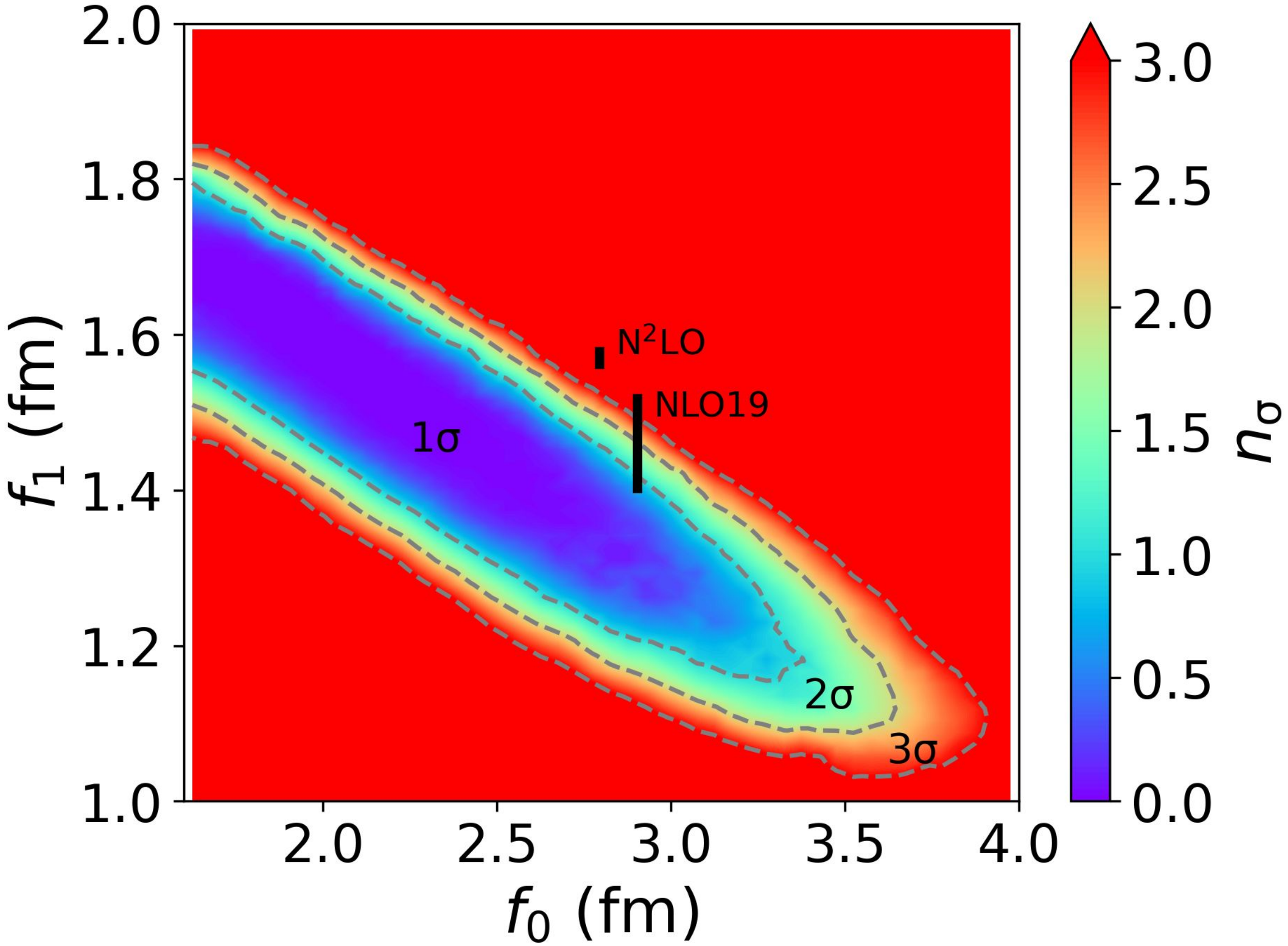


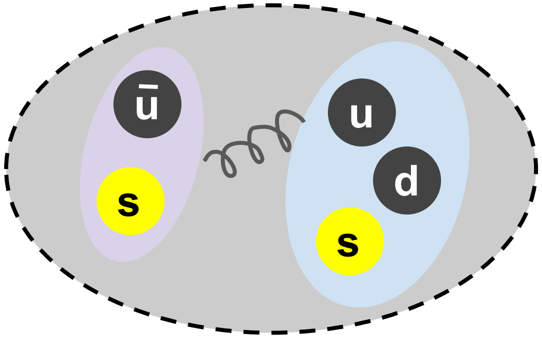
Next steps

- New parameterization(s) of the χEFT
- Obtain the in-medium $U_\Lambda(\rho)$ potential
- Ultimately: a data-driven EoS

  Collaborating with I. Vidana, L. Fabbietti, V. Mantovani, J. Schaffner Bielich, J. Haidenbauer

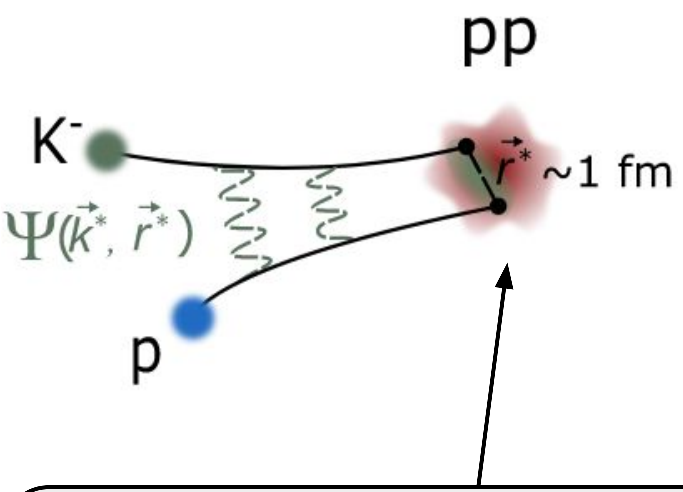


Coupled channel dynamics



Coupled channels and resonances

Introduction

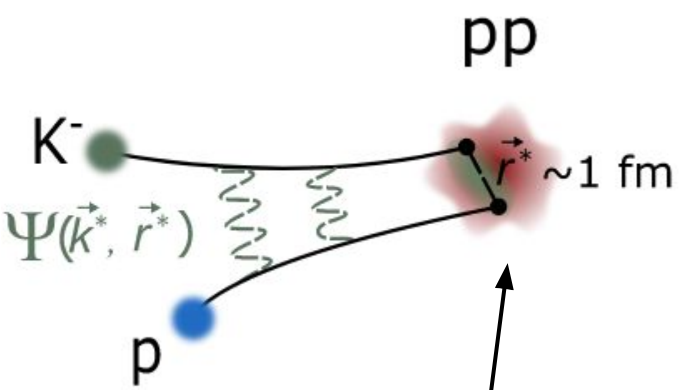


The initial state is NOT fixed

Can be any XY system with quantum numbers equal to pK, such as $\pi\Sigma$, nK^0 etc.

Coupled channels and resonances

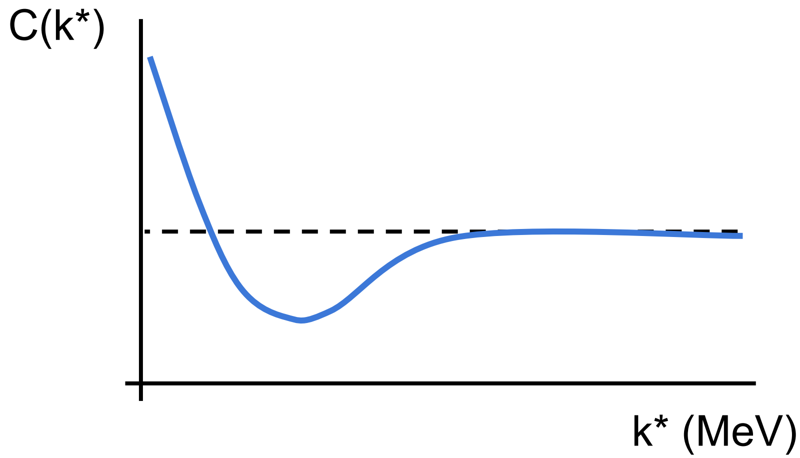
Introduction



The initial state is NOT fixed

The elastic channel is trivial

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



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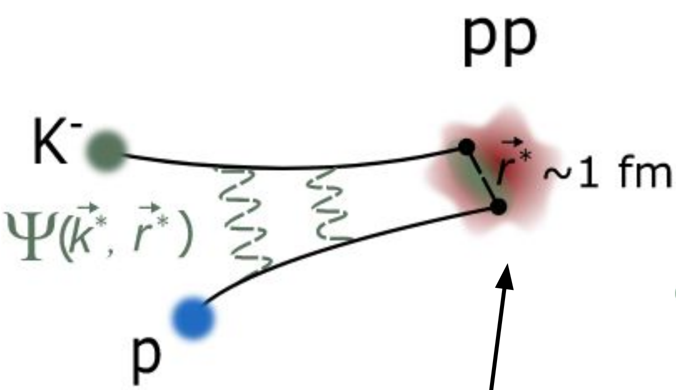
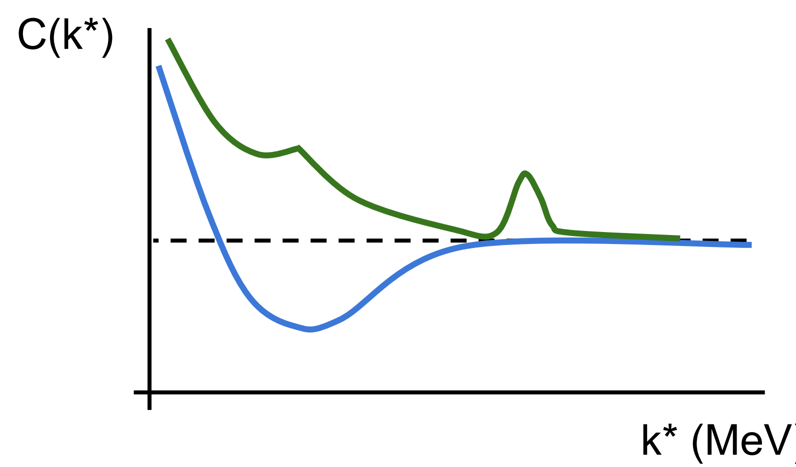


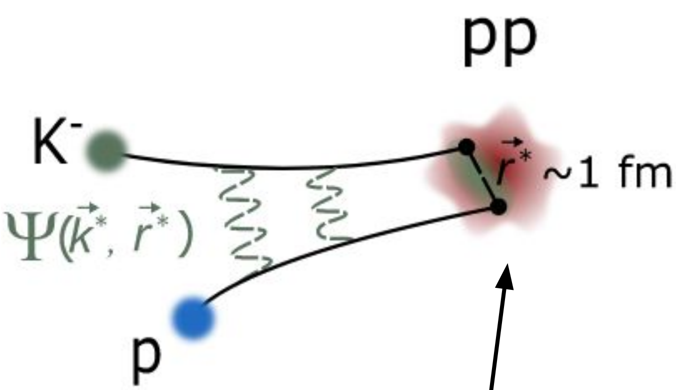
$$C(k^*)_{CC} = C(k^*) + \sum_j \omega_j \int S_j(r^*) \left|\Psi_j(\vec{k}^*, \vec{r}^*)\right|^2 d^3 r^*$$

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

The initial state is NOT fixed

Any other "source" of pairs adds up to the correlation signal





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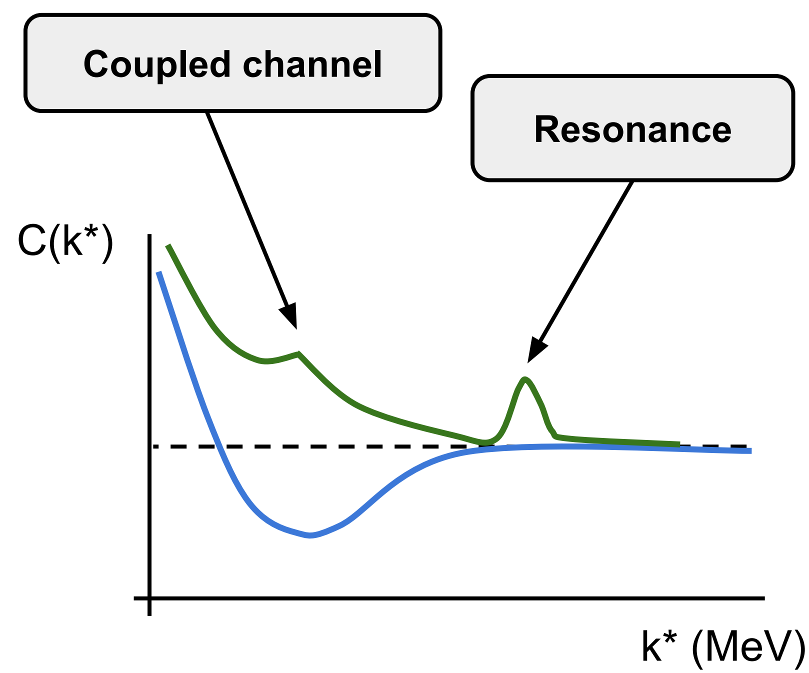
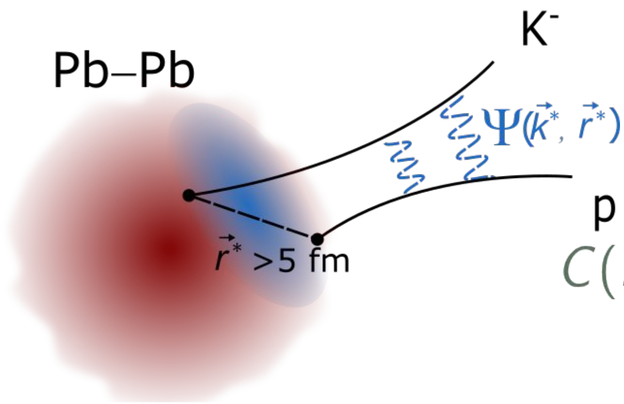


Coupled channels and resonances

System size

[*ALICE Coll, EPJC 83 (2023) 4, 340*](#)
[*Kamia et el, PRL 124 13, 2020*](#)



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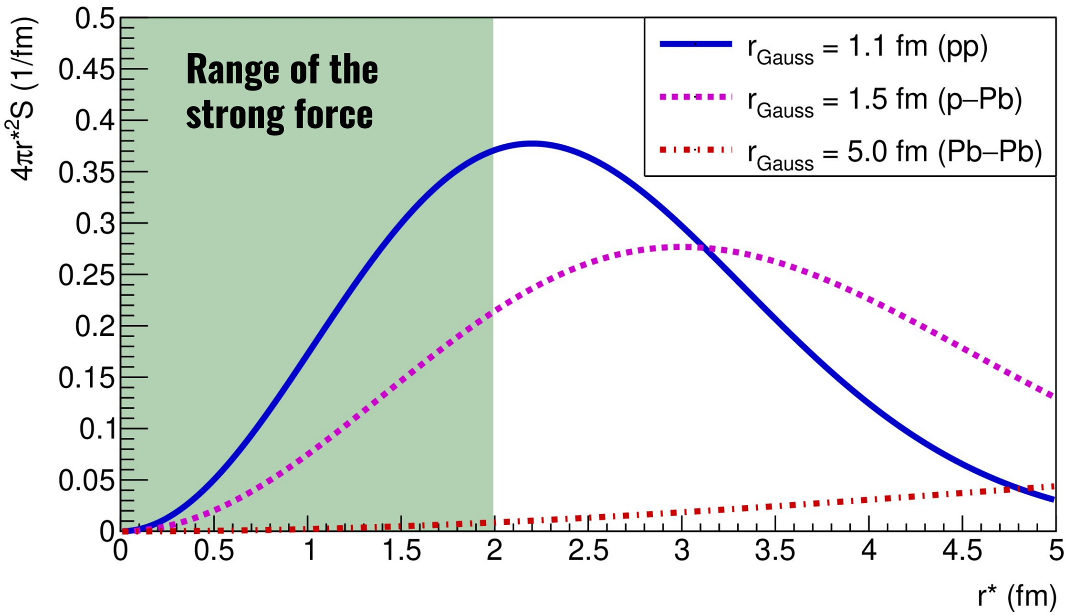
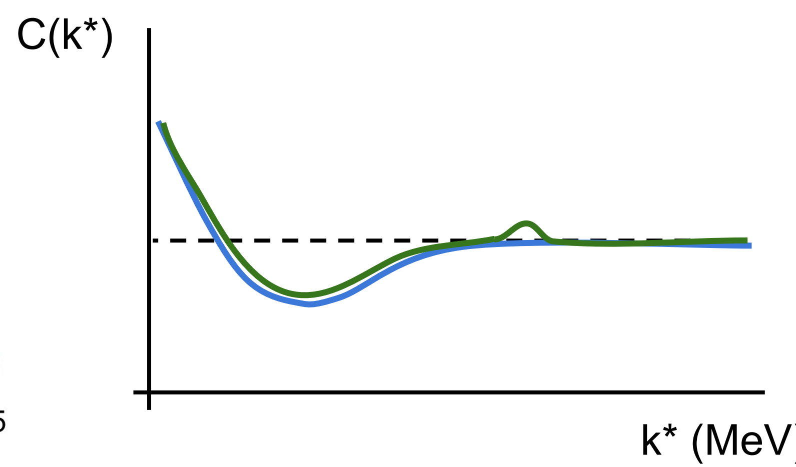
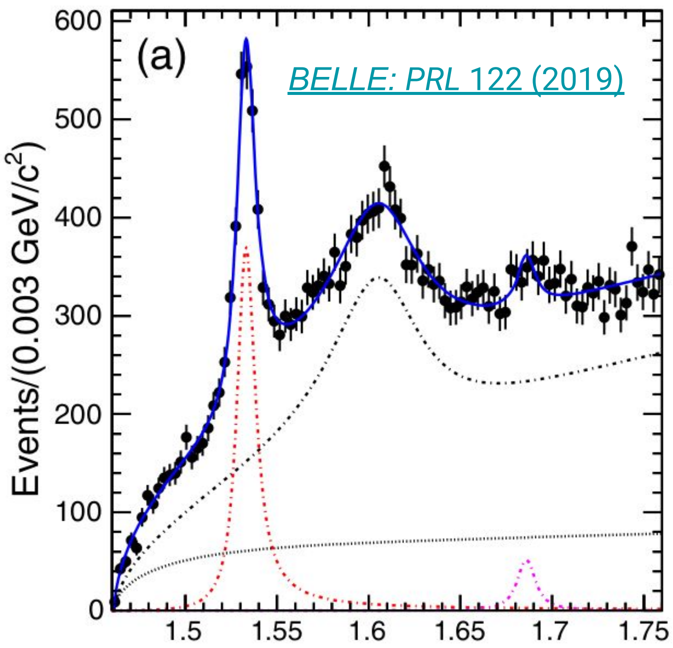
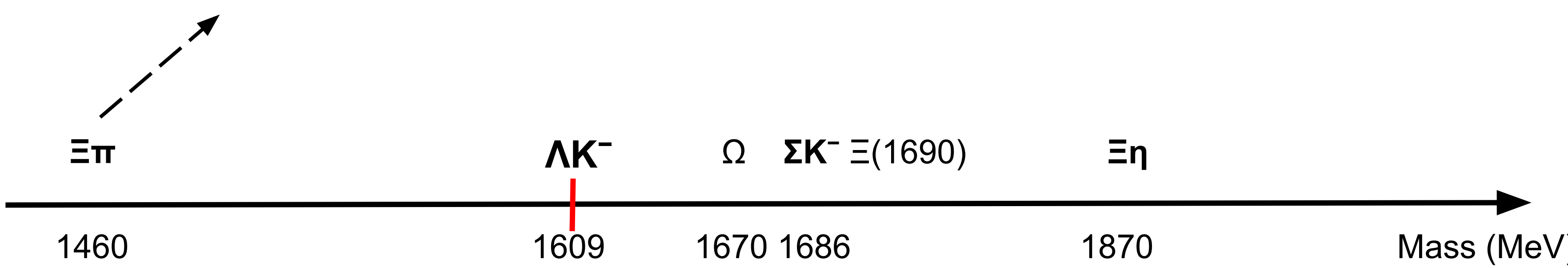




ΛK⁻ correlations

Overview





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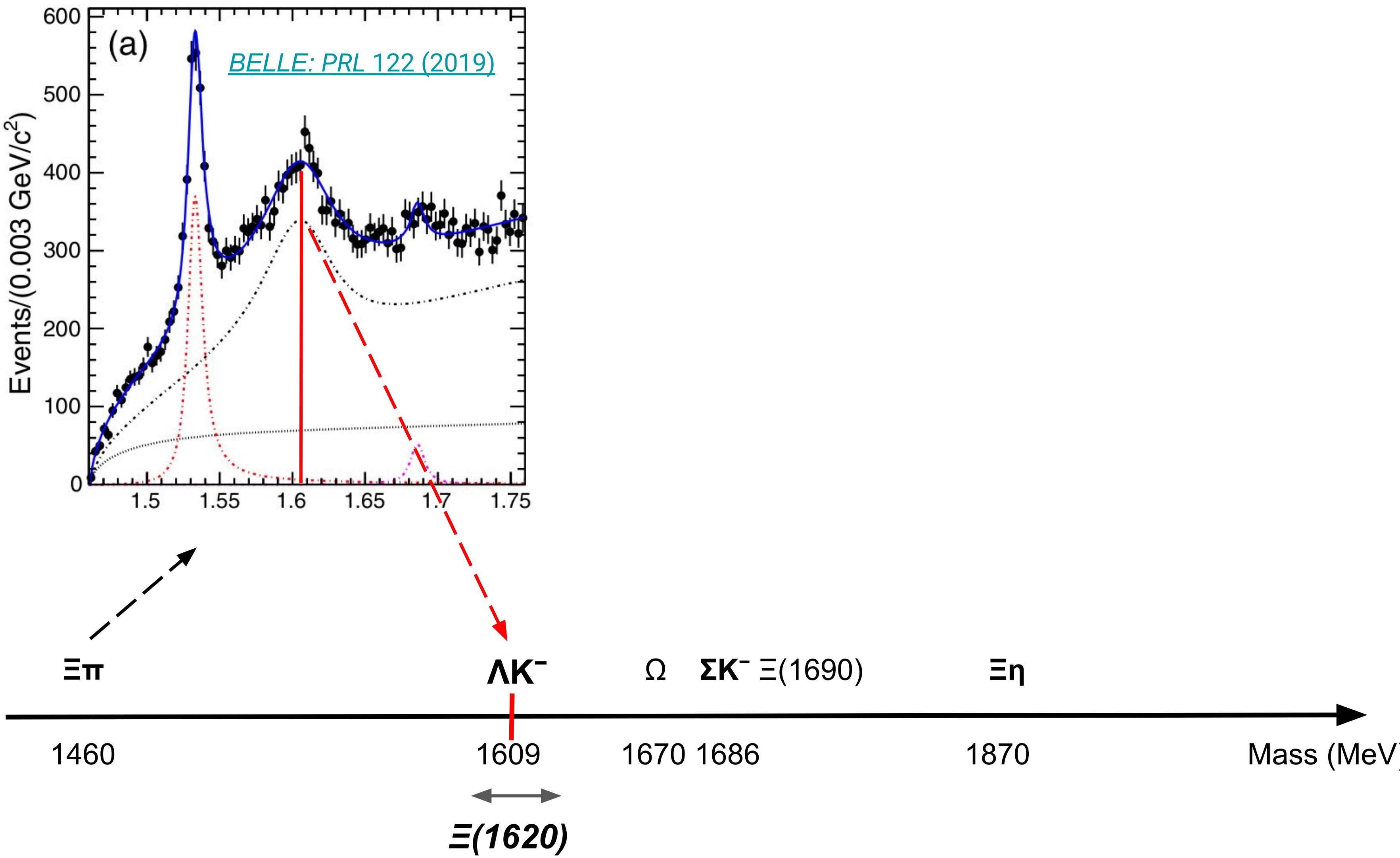
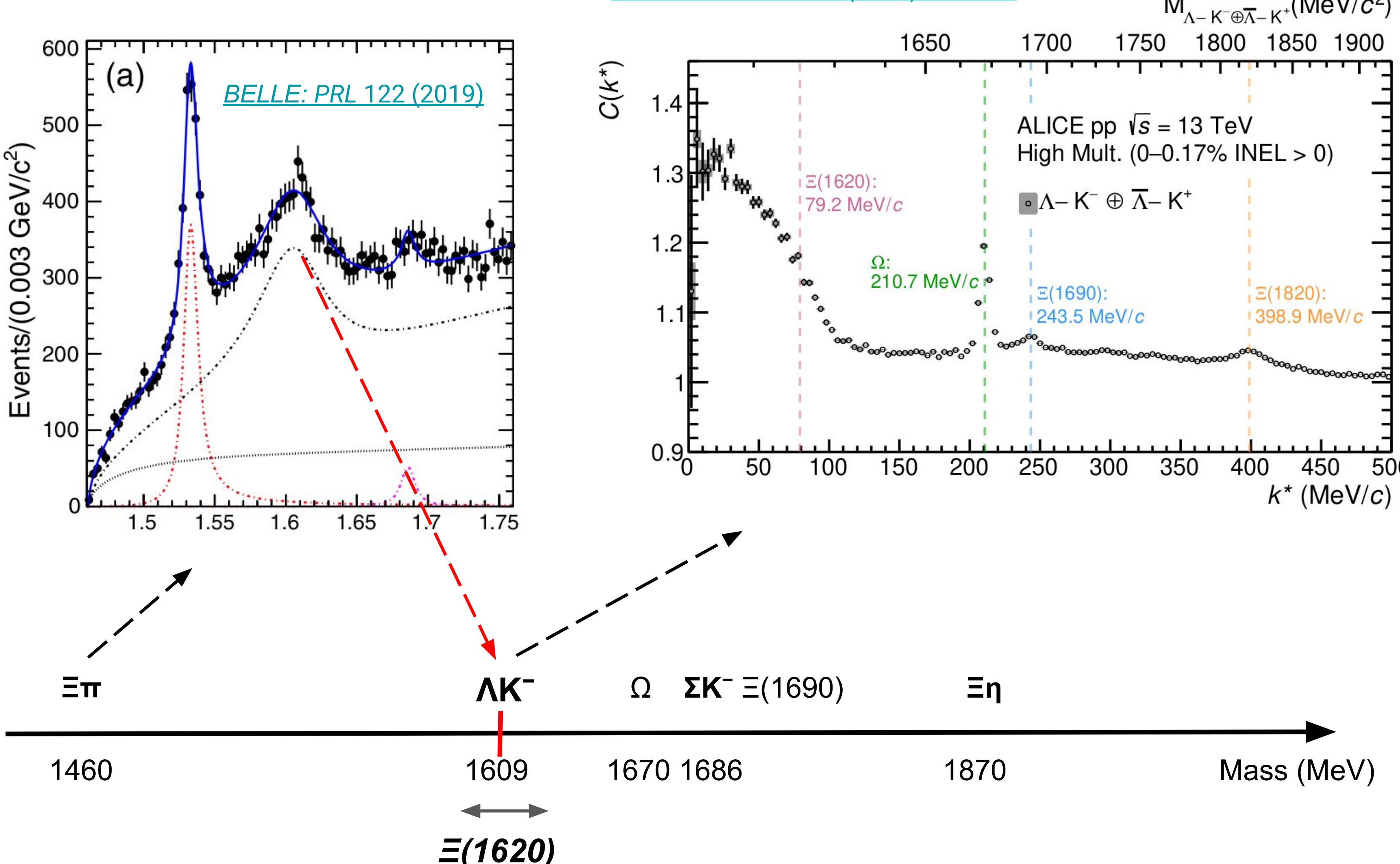


ΛK⁻ correlations

ALICE result

ALICE Coll. *PLB 845 (2023), 138145*



ΛK⁻ correlations

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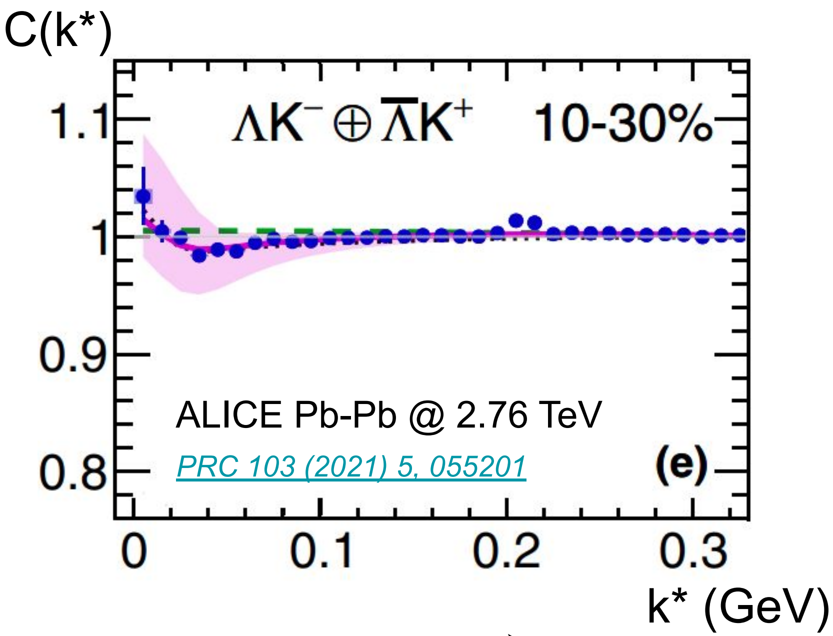

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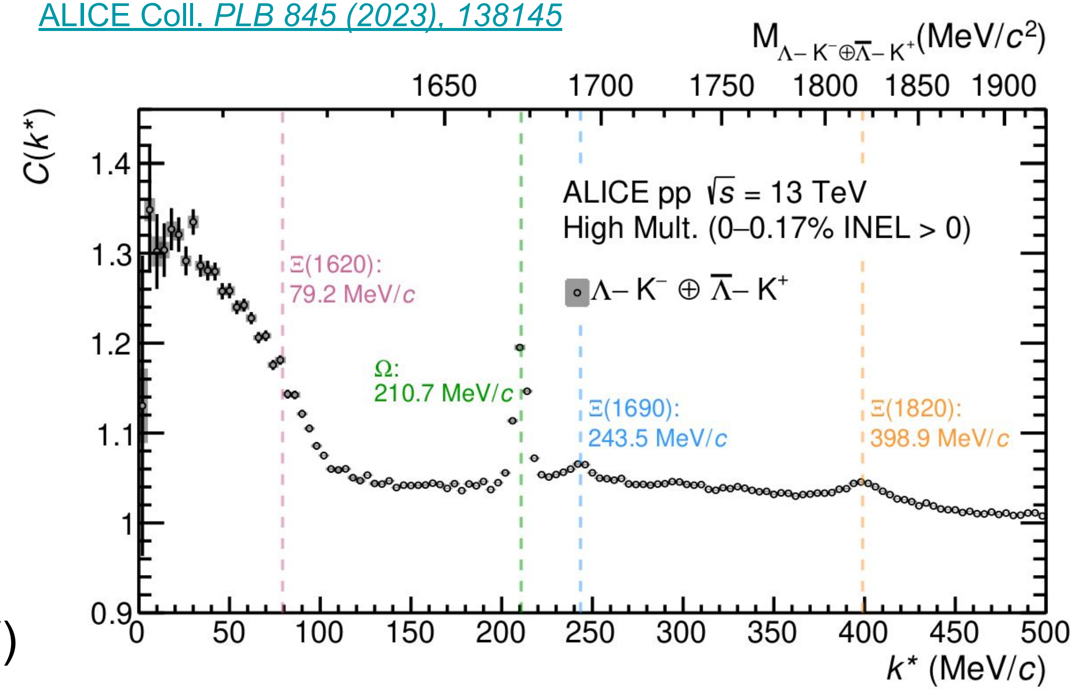
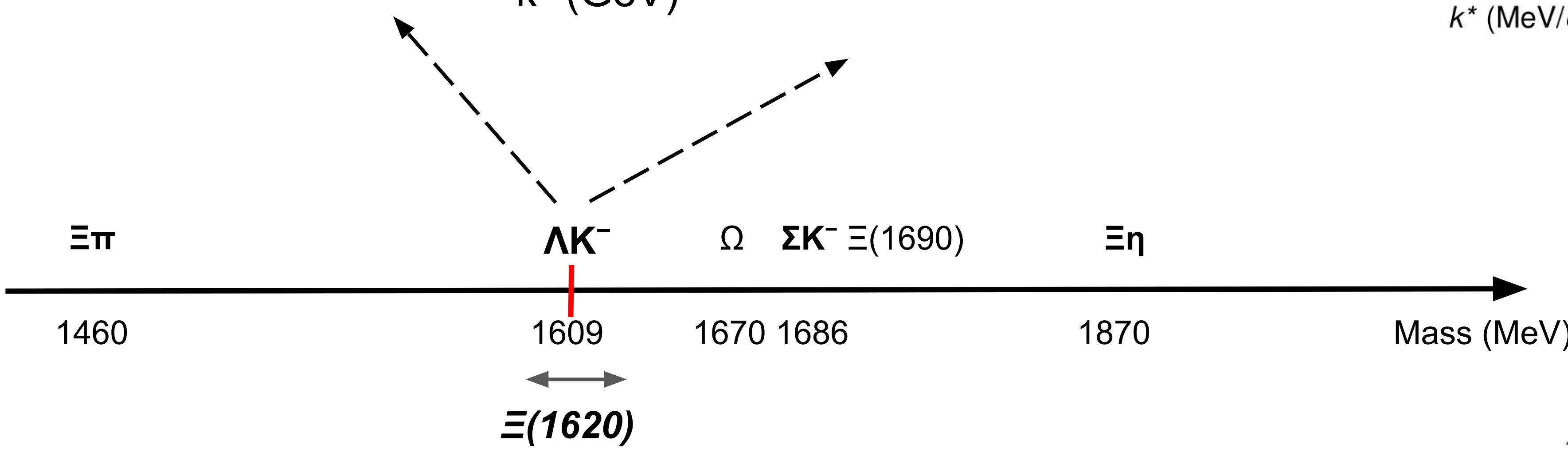
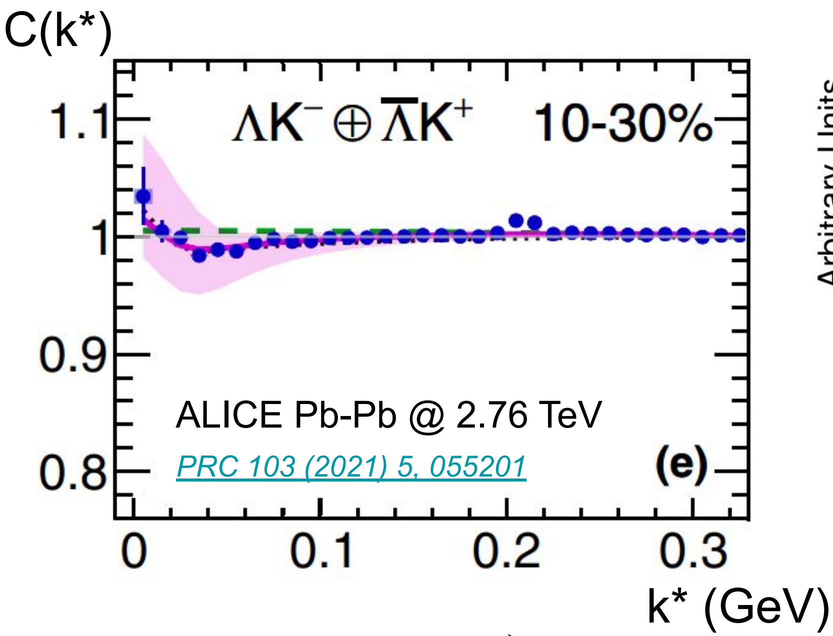


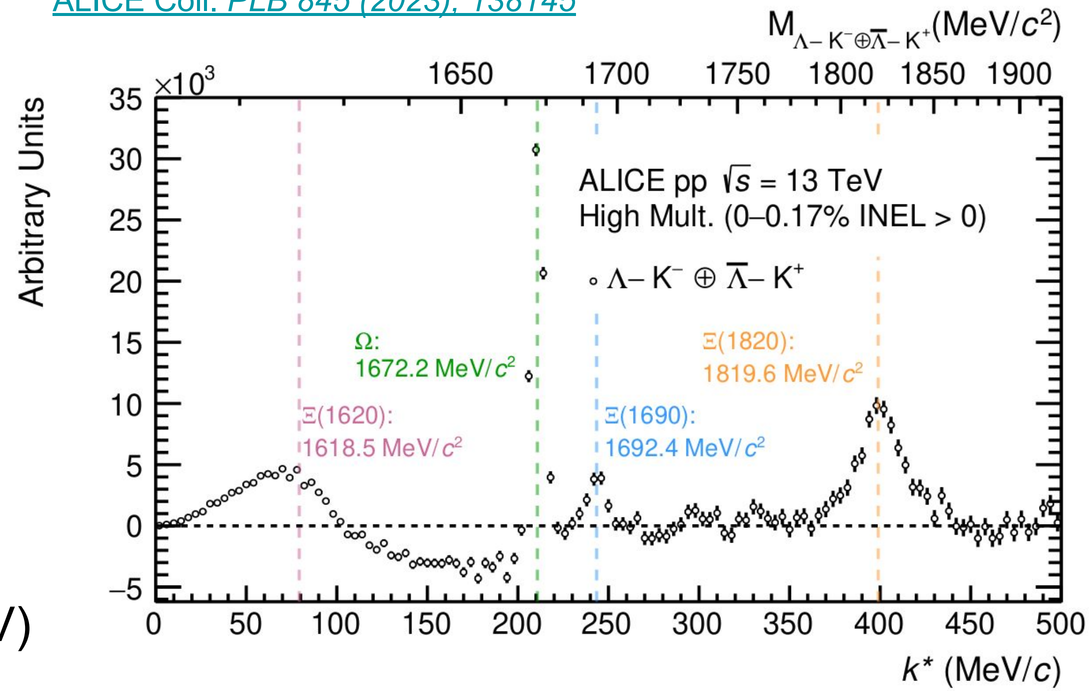


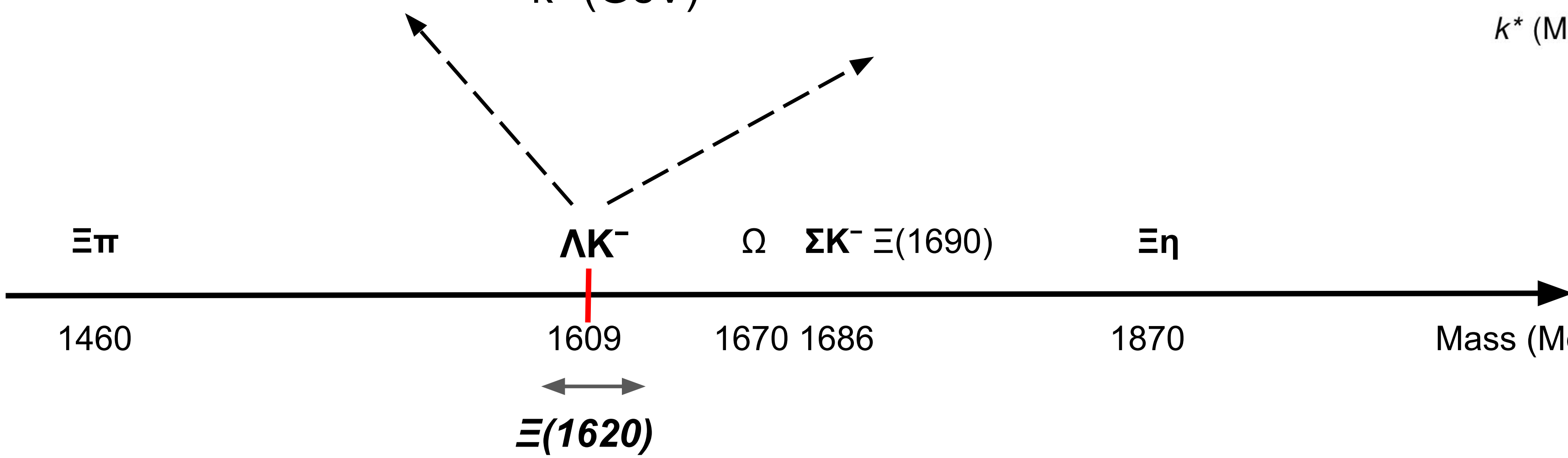
ΛK⁻ correlations

Invariant mass

ALICE Coll. *PLB 845 (2023), 138145*







ΛK^- correlations

Modelling

$$C(k^*)_{CC} = \int S(r^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3 r^* + \sum_j \omega_j \int S_j(r^*) \left|\Psi_j(\vec{k}^*, \vec{r}^*)\right|^2 d^3 r^*$$

Elastic $\Lambda K^- \rightarrow \Lambda K^-$

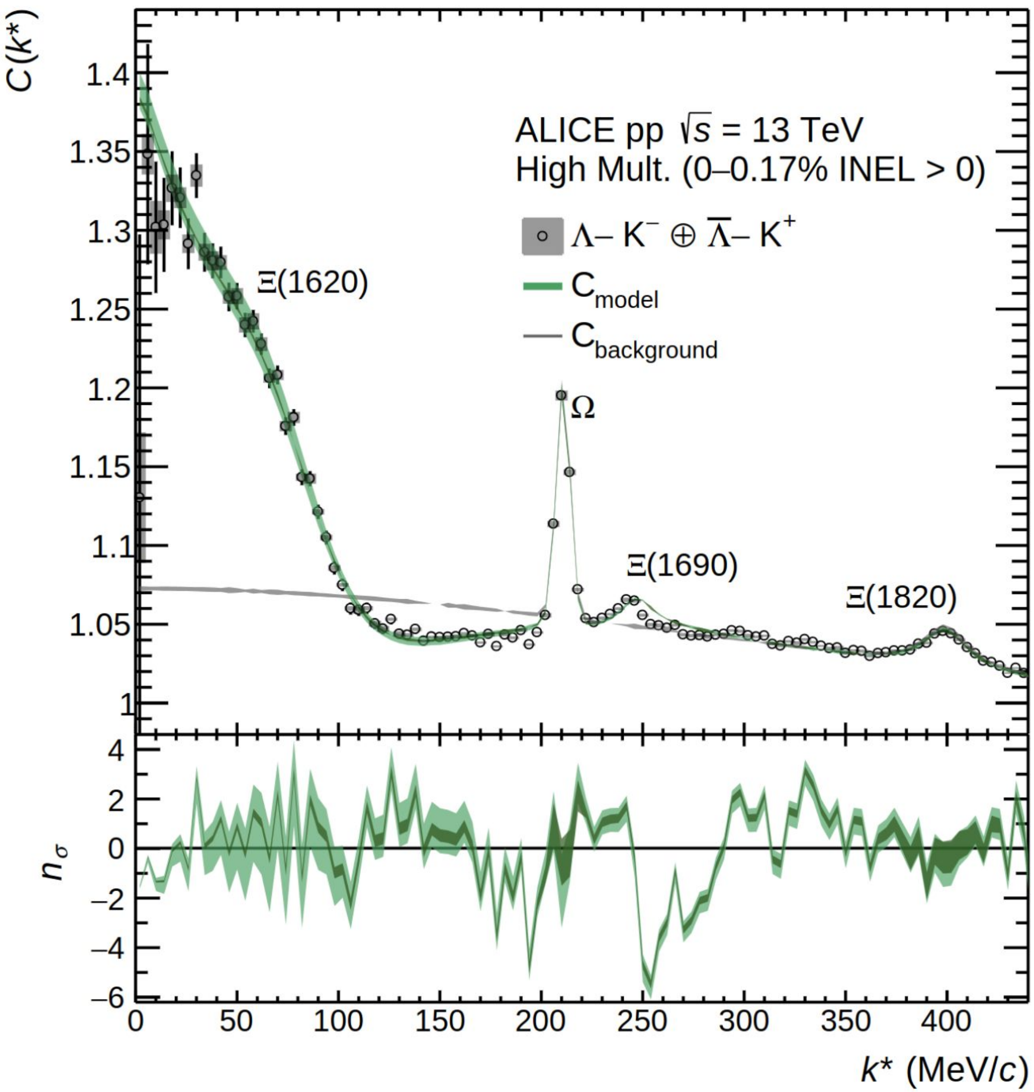
Inelastic $\Xi\pi, \bar{\Sigma}K, \Xi\eta \rightarrow \Lambda K^-$

- ω_j: weight of each initial state
- Wave functions modeled by state-of-the-art **UχPT** at NLO in CC formalism
  - Ξ(1620) and Ξ(1690) are dynamically generated states
  - **Fine-tune (fit) the relevant parameters to ALICE data**
  - Details on Friday by **Isaac Vidana**

ΛK^{-} correlations

Constraining the theory

Mantovani Sarti et al, arXiv:2309.08756



- Fit LECs and SCs to the measured ALICE ΛK^{-} correlation
- How does the $\Xi(1620)$ pole scenario look like?

ΛK⁻ correlations

Constraining the theory

Mantovani Sarti et al, arXiv:2309.08756

Table II. Poles, couplings and compositeness of the resonances generated by the VBC $S = -2$ meson-baryon interaction at NLO. The number between brackets in the first column denotes the channel threshold energy in MeV.

mass M:	1616.18 MeV		1670.43 MeV	
width Γ:	23.03 MeV		7.17 MeV	
Riemann sheet:	$(---+++)$		$(---+++)$	
	$\lvert g_i \rvert$	$\lvert g_i^2 dG/dE \rvert$	$\lvert g_i \rvert$	$\lvert g_i^2 dG/dE \rvert$
$\pi^- \Xi^0$(1454)	0.50	0.013	0.17	0.0014
$\pi^0 \Xi^-$(1456)	0.33	0.006	0.41	0.0079
$K^- \Lambda$(1609)	0.92	0.155	0.06	0.0003
$K^- \Sigma^0$(1686)	1.24	0.099	2.30	0.836
$\bar{K}^0 \Sigma^-$(1695)	1.51	0.135	1.32	0.215
$\eta \Xi^-$(1868)	2.97	0.243	0.16	0.0009
Experimental Ξ^*:	Ξ(1620) [18]		Ξ(1690) [56]	
mass M:	$1610.4 \pm 6.0^{+5.9}_{-3.5}$ MeV		1690 ± 10 MeV	
width Γ:	$59.9 \pm 4.8^{+2.8}_{-3.0}$ MeV		20 ± 15 MeV	

Ξ(1620) pole
Mainly molecular nature composed of KΣ
NEW PARADIGM!

Ξ(1690) pole
Virtual state
Mainly coupled to KΣ

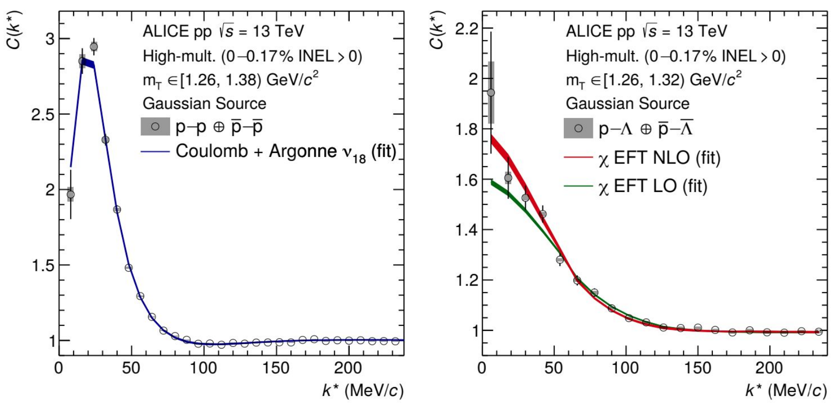
Summary

- **Femtoscopy** as a tool to access **low-energy scattering**
- **pΛ** system requires **less two-body attraction**
  => ongoing efforts to constrain the parameters of χEFT
- Studying coupled channels and near-threshold resonances
- **K^-Λ** correlation requires non-resonant and a **resonant** part to the scattering amplitude
  => confirmation of the **Ξ(1620)** → **K^-Λ**
  => preliminary theoretical constraints
  → **Ξ(1620)** as a **molecular** state **coupling** strongly to **K^-Σ**

BACKUP

The emission source

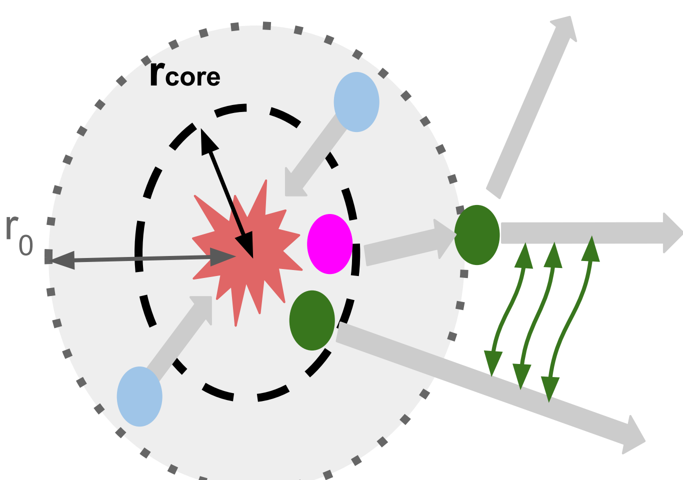
ALICE Coll. *Phys.Lett.B 811 (2020) 135849*



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

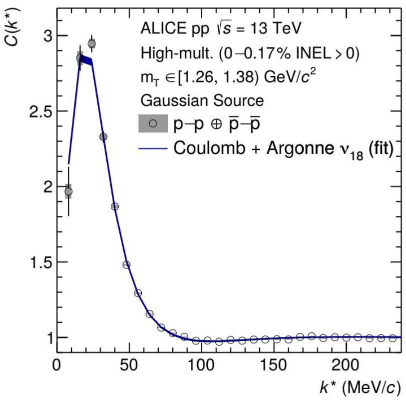
Measure   Fix   Study

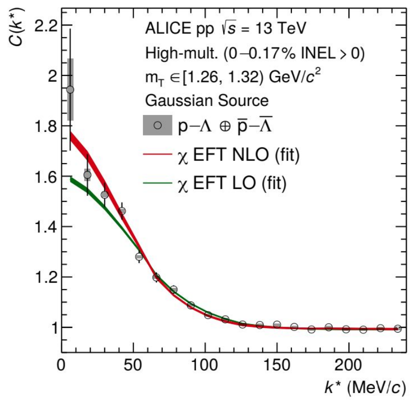
- Enhanced sensitivity in **small collision systems (pp)**
- **Common emission source for all baryons?**
- Particle production through **decays of short lived resonances** (cτ~fm) increases effective source size
- The **pp correlation** can be used to **evaluate S(r*)**, based on the known interaction
- The same source can be used to **study the final state interaction** for **ANY** other **baryon-baryon** pair



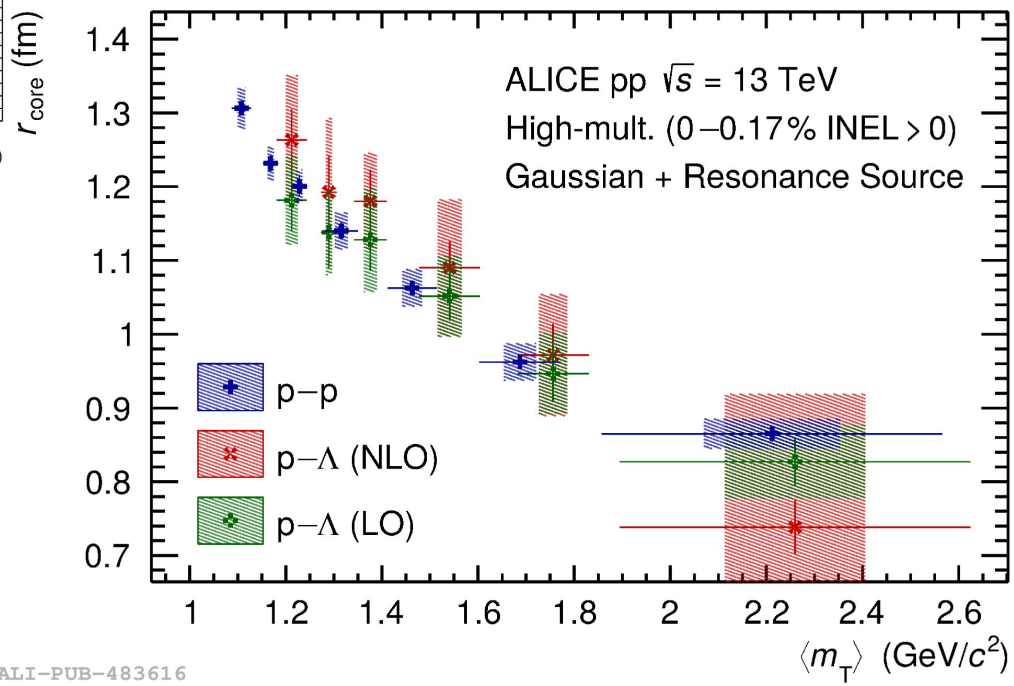
The common core source

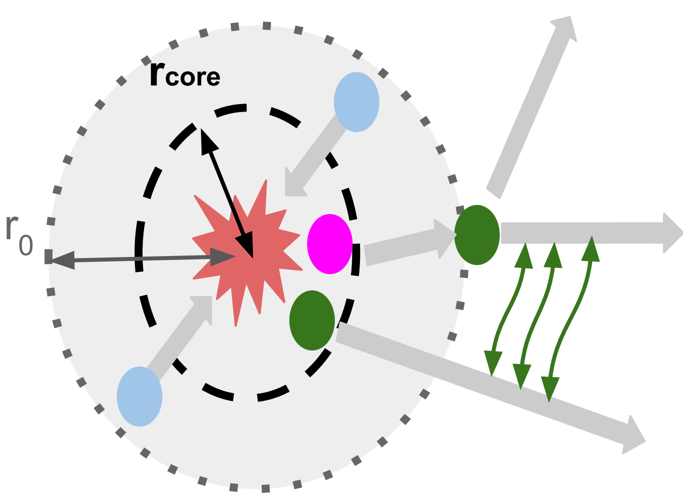
[ALICE Coll. *Phys.Lett.B 811 (2020) 135849*](#)





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

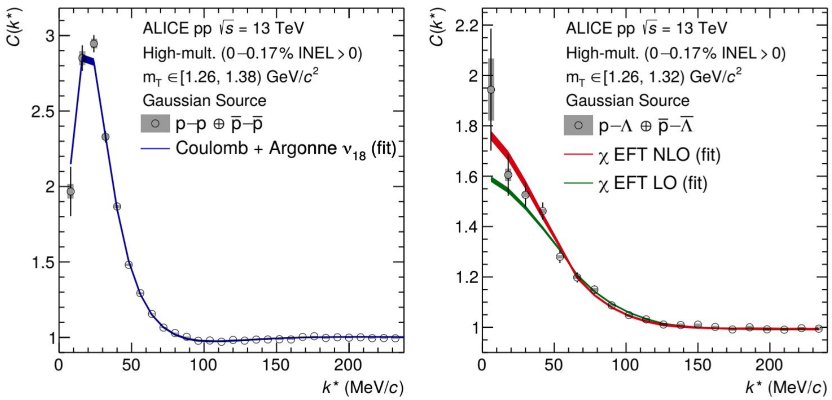




- Ongoing analysis in ππ and pK show compatible results

The common core source

[ALICE Coll. *Phys.Lett.B 811 (2020) 135849*]



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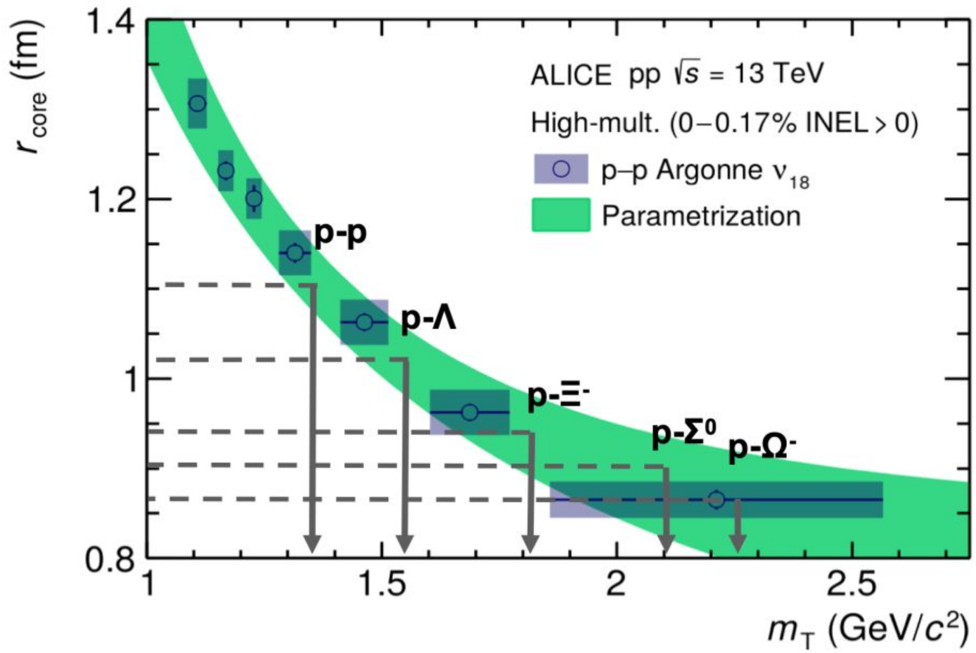
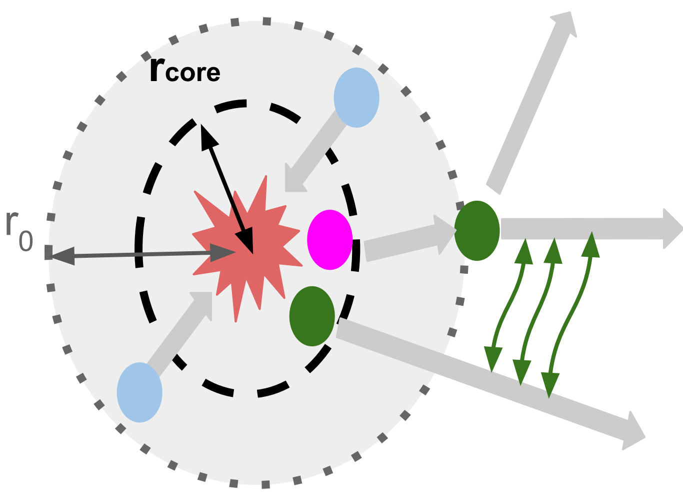
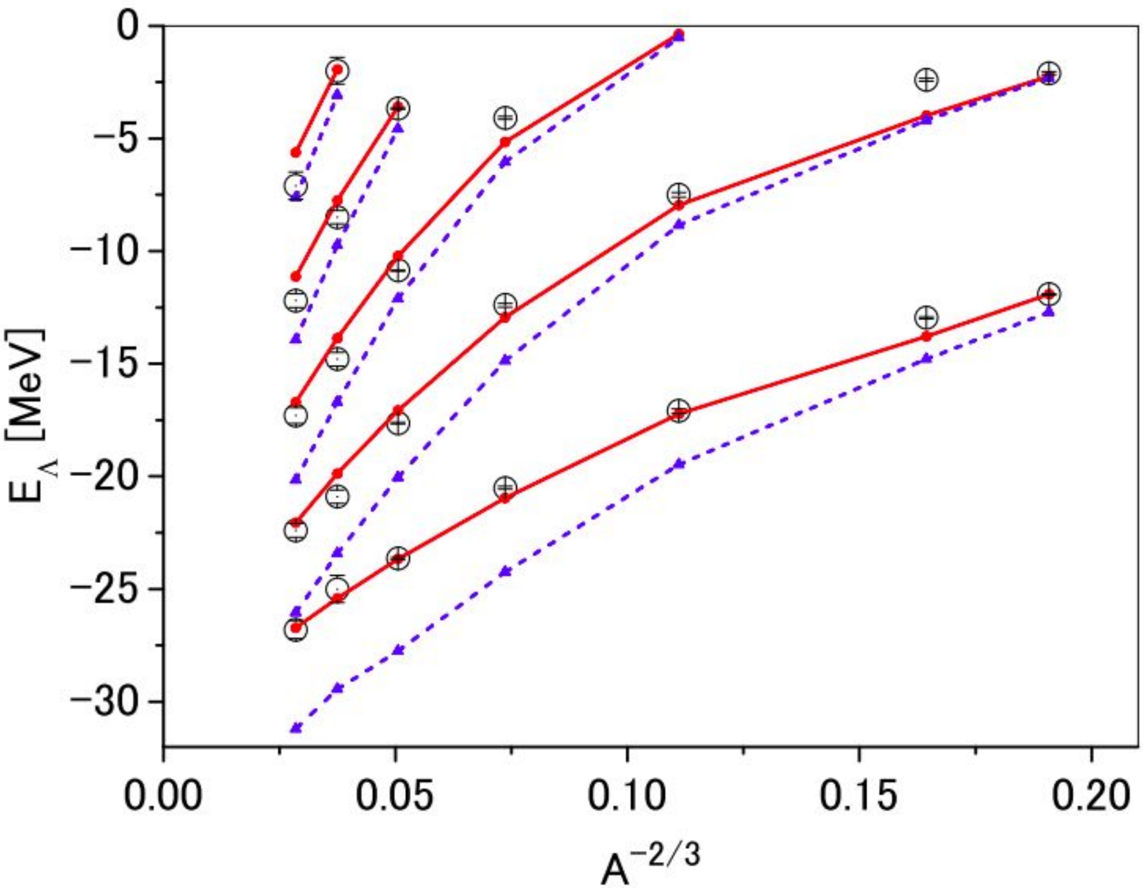




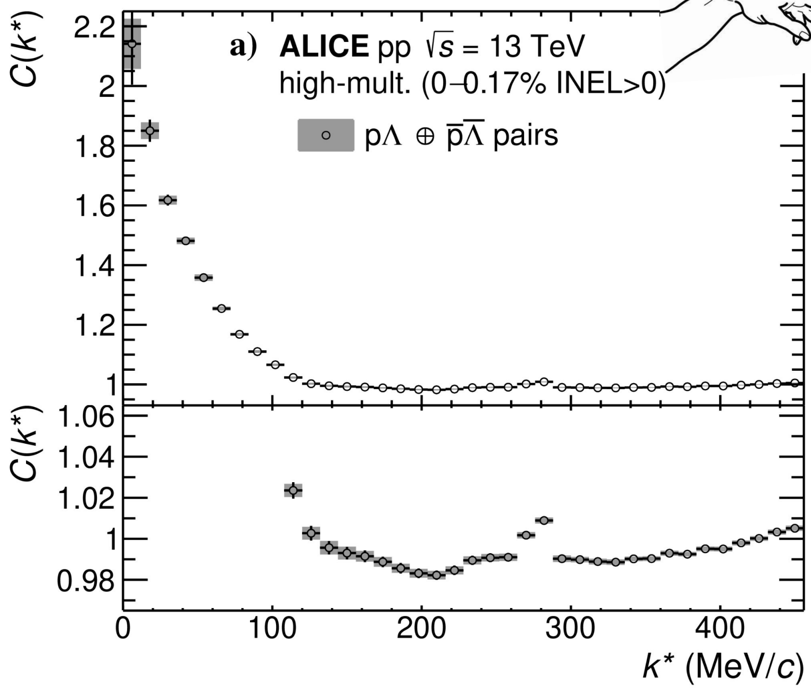
- Ongoing analysis in ππ and pK show compatible results

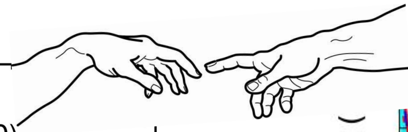
pΛ: hypernuclei



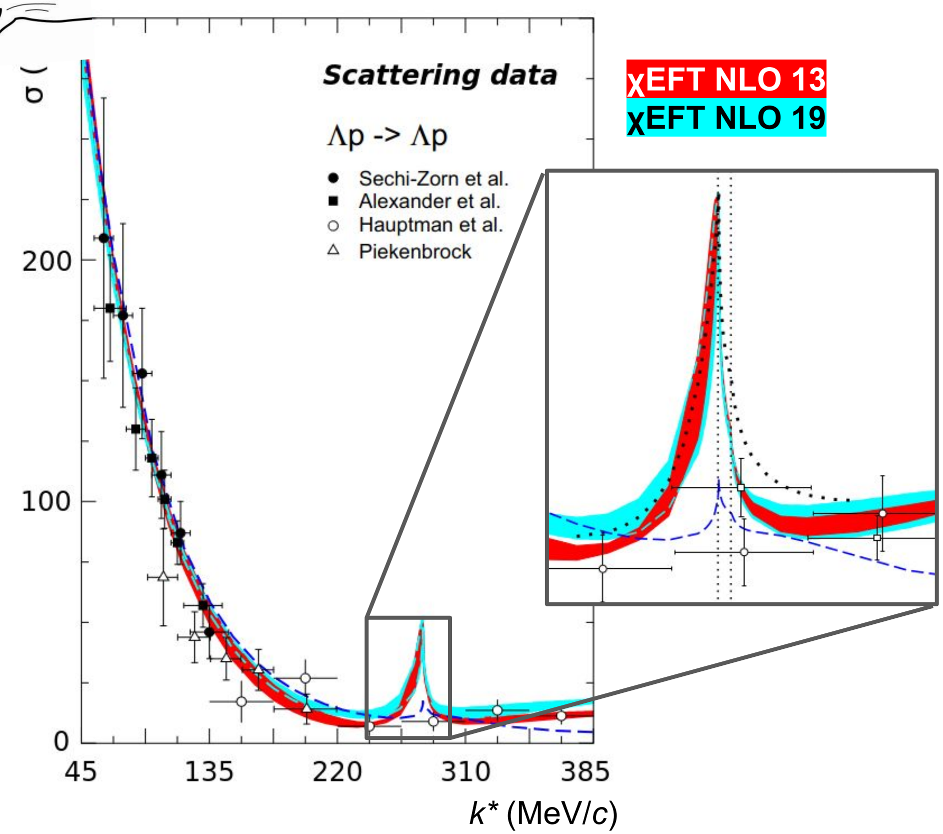
Phys. Rev. C **99**, 044003 (2019)

pΛ interaction
mT integrated analysis



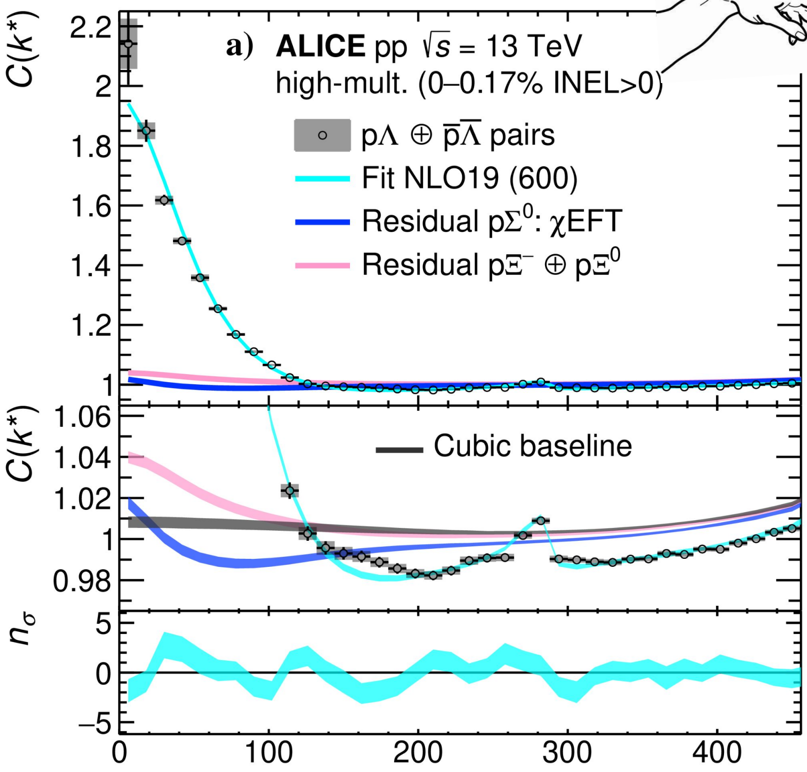


[Haidenbauer et al. *Eur.Phys.J.A 56 (2020) 3, 91*]

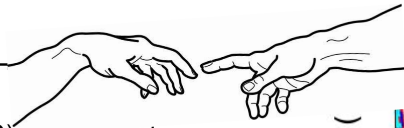


Based on [ALICE Coll. *PLB 833 (2022), 137272*]

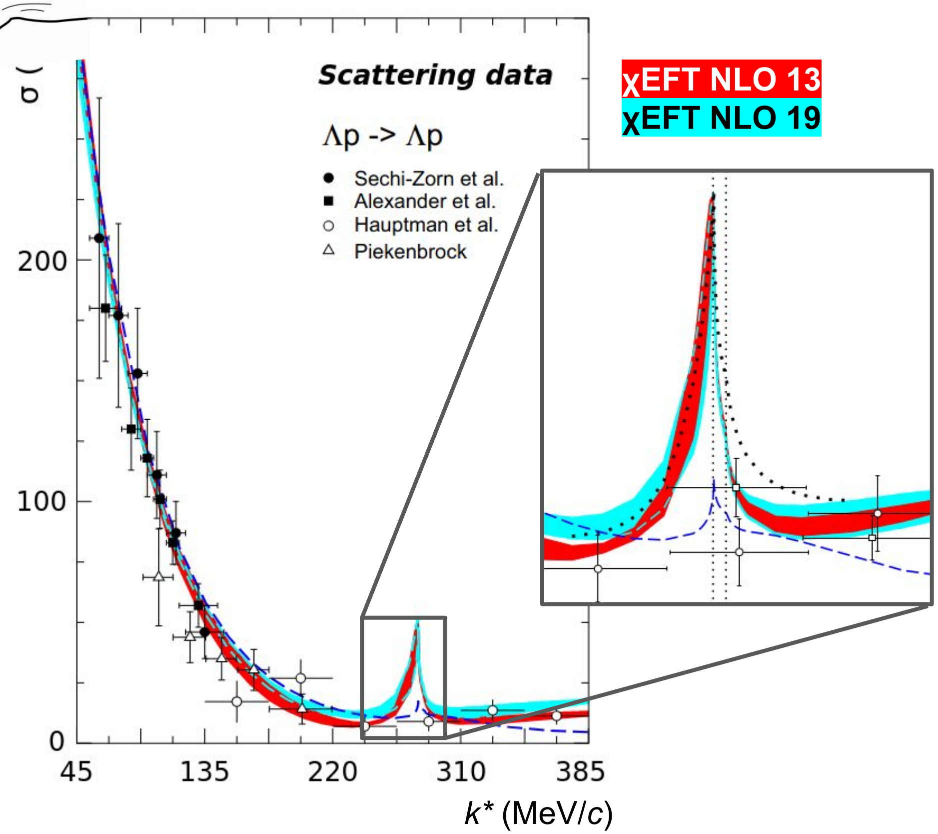
pΛ interaction
mT integrated analysis



ALICE Coll. *PLB 833 (2022), 137272*

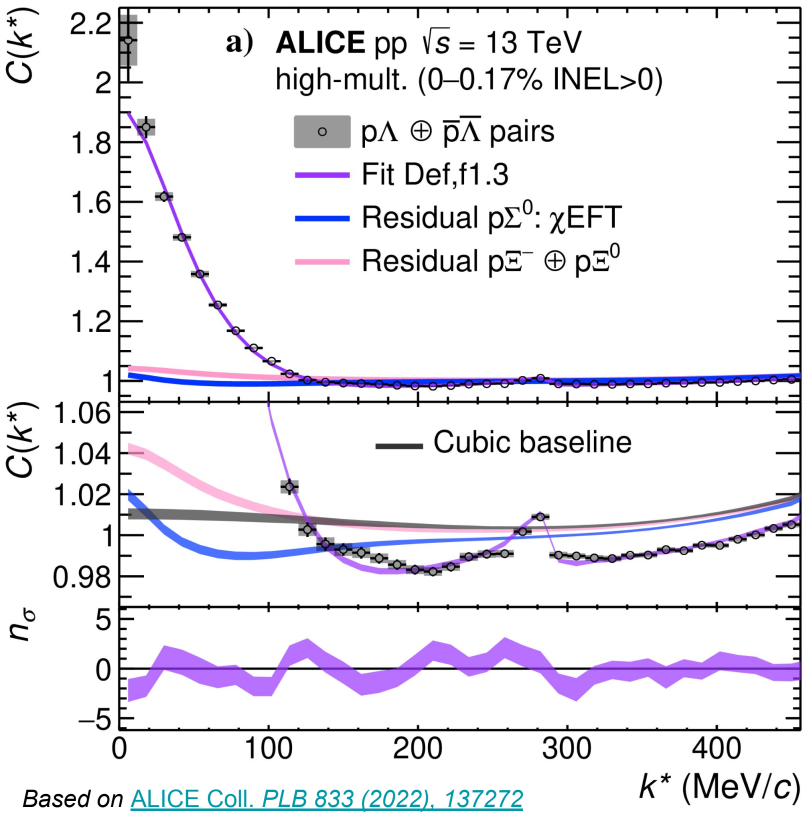


Haidenbauer et al. *Eur.Phys.J.A 56 (2020) 3, 91*



- The NLO19 parameterization overshoots the data at low k* (**3.2 σ**).
- Johann Haidenbauer prepared a NLO wave function, where the scat. length of the 3S1 channel has been reduced (1.45 →1.30 fm), which would still be compatible with existing data.

pΛ interaction
mT integrated analysis



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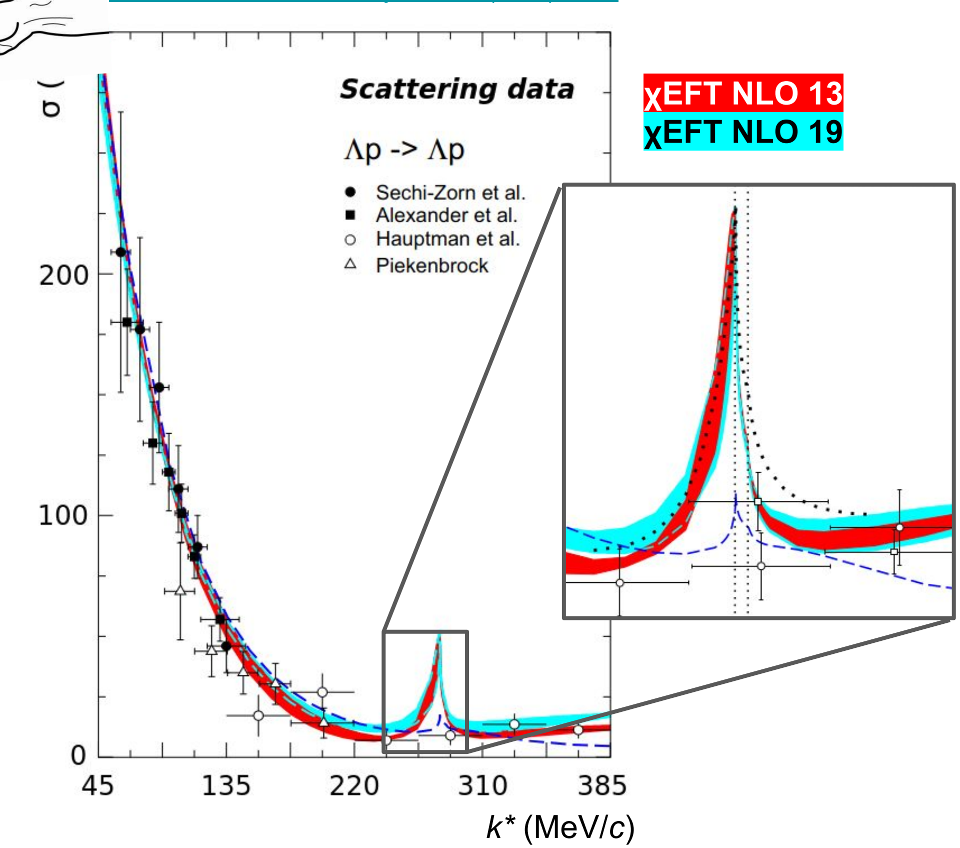
[Haidenbauer et al. *Eur.Phys.J.A 56 (2020) 3, 91*]



- The NLO19 parameterization overshoots the data at low k* (3.2 σ).
- Johann Haidenbauer prepared a NLO wave function, where the scat. length of the 3S1 channel has been reduced (1.45 →1.30 fm), which would still be compatible with existing data. **nσ ~ 2.4**

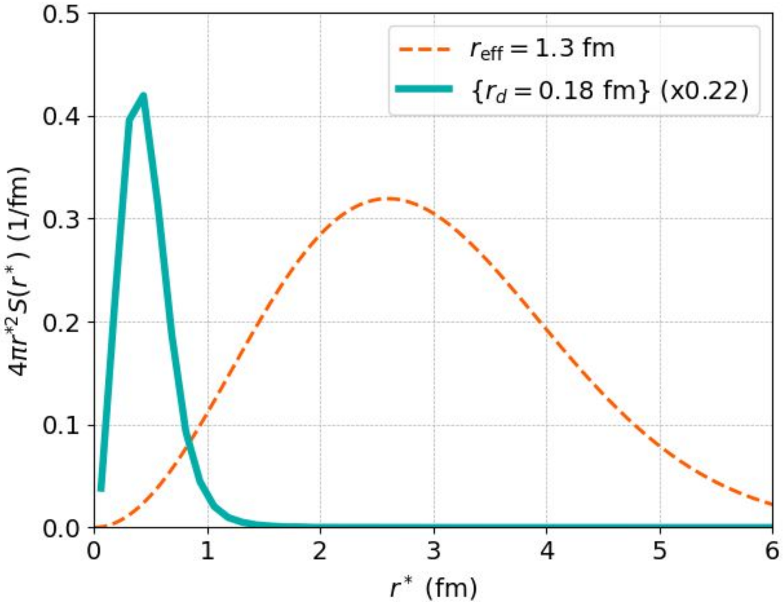
CECA: The common source

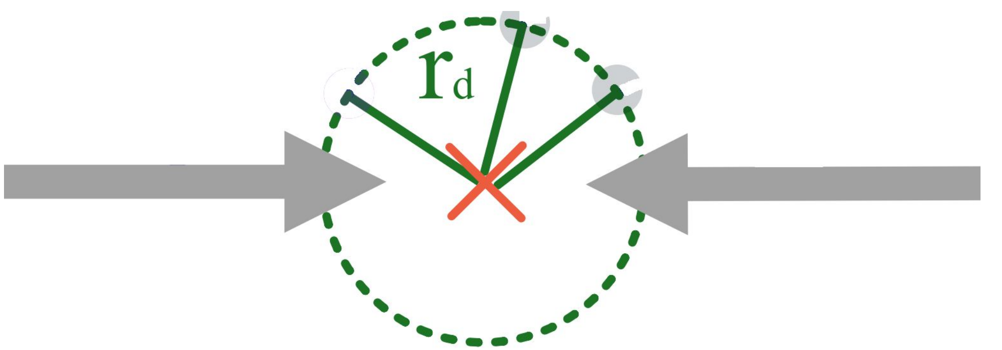
Mihaylov and Gonzalez Gonzalez, EPJC 83 (2023) 7, 590

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



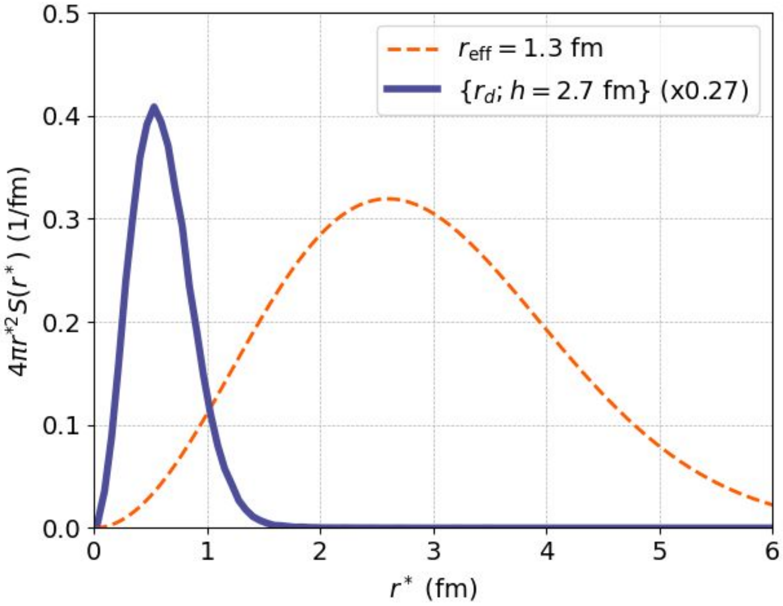


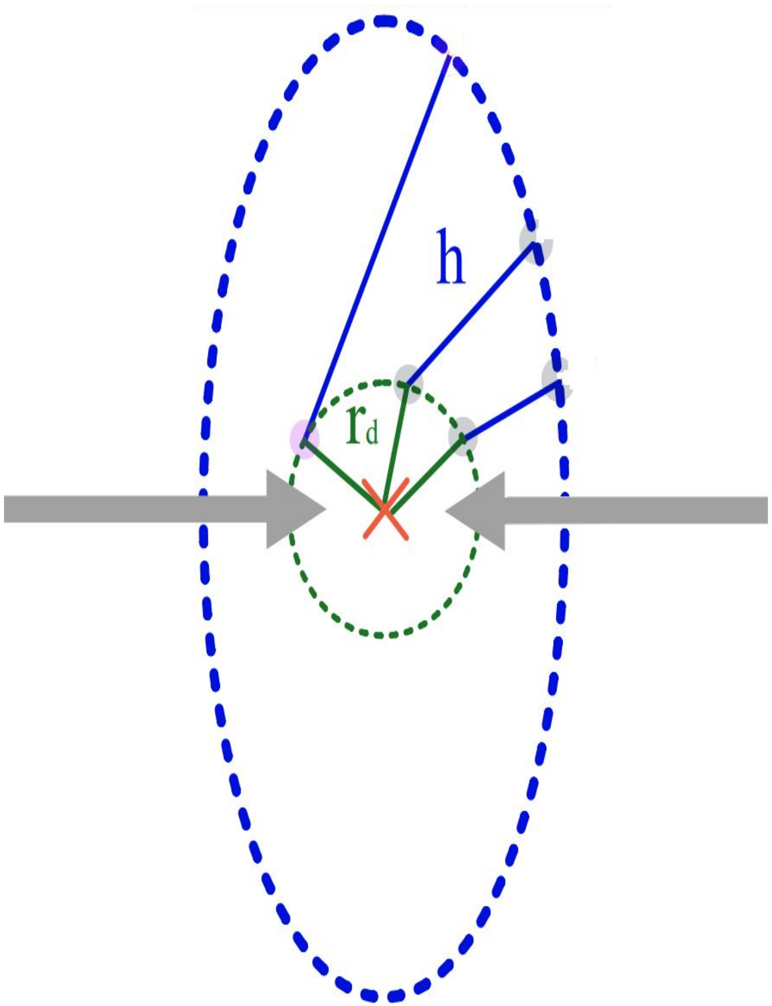
CECA: The common source

[Mihaylov and Gonzalez Gonzalez, EPJC 83 (2023) 7, 590](#)

Hadronization parameter

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

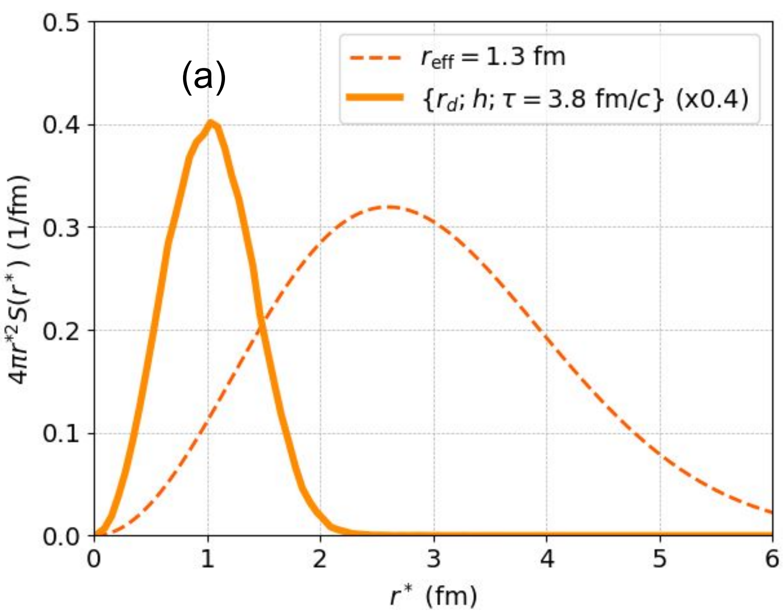


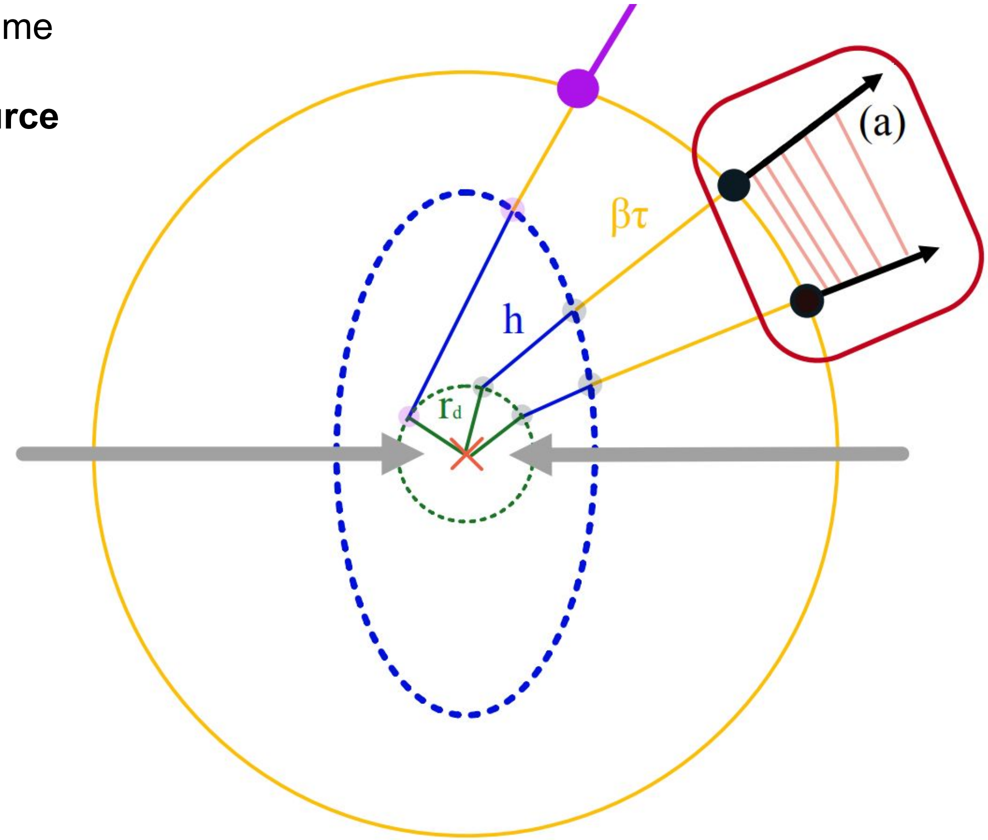


CECA: The common source

Free-streaming phase
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**

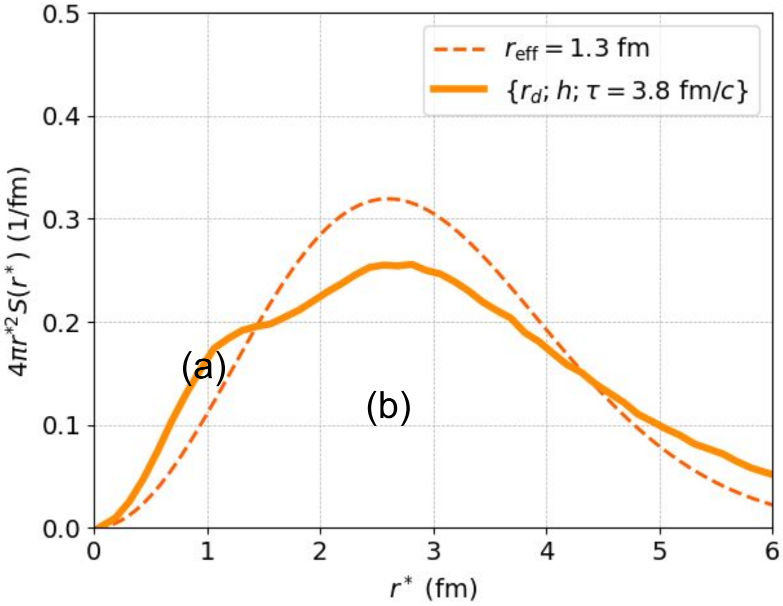


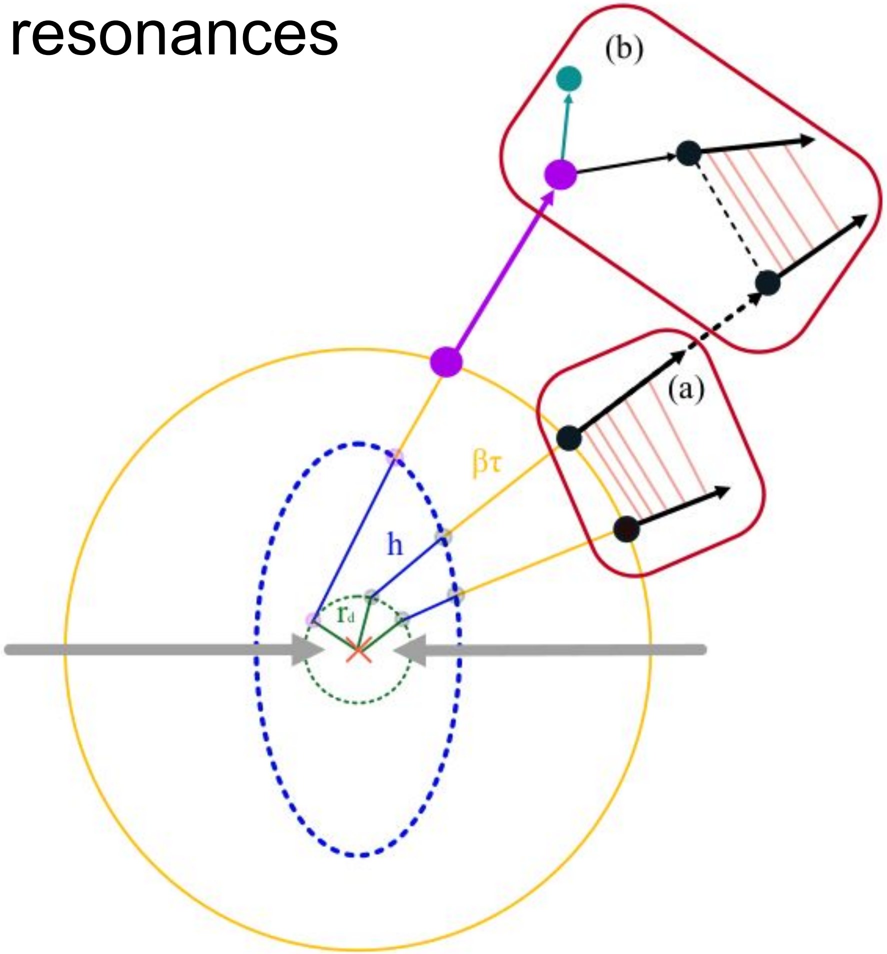


CECA: Production through resonances

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!

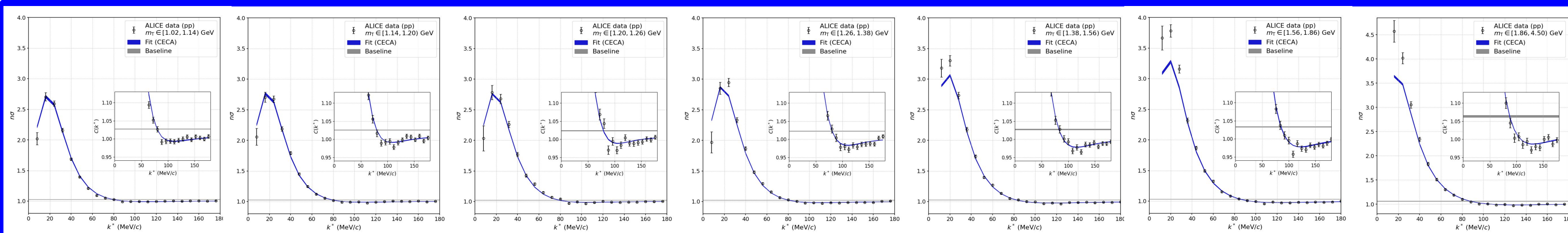




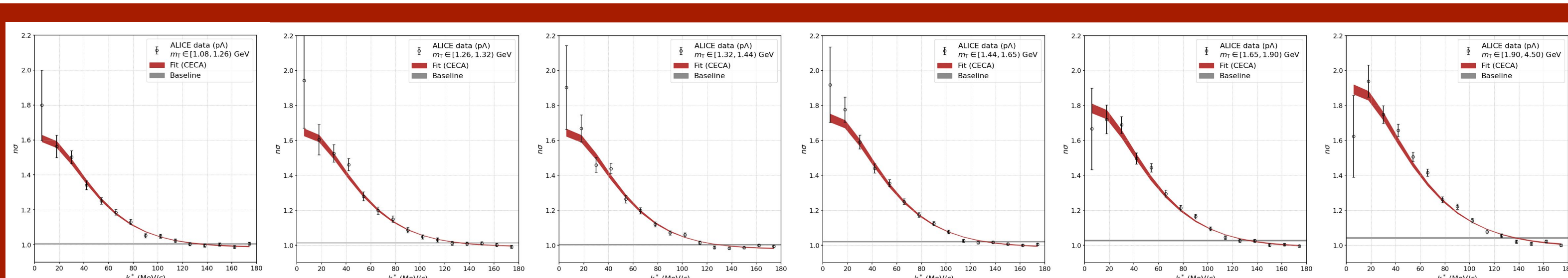
Mihaylov and Gonzalez Gonzalez, EPJC 83 (2023) 7, 590

ALICE data + CECA

One source to rule them all



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 mT differential pp and pΛ correlations!**

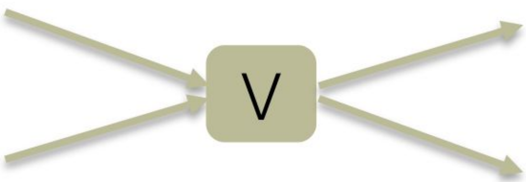
ΛK^- correlations

[1] R. Lednicky, V. Lyuboshits SJNP 35 (1982)
[2] F. Giacosa et al. EPJA 57 (2021), 12, 336

Modelling

- Lednický-Lyuboshits (LL) formula[1]
  Connects C(k*) to the **scattering amplitude**

Non resonant



Assuming the effective-range expansion

+

Resonant

Assuming a Flattè-like amplitude[2] for Ξ(1620)

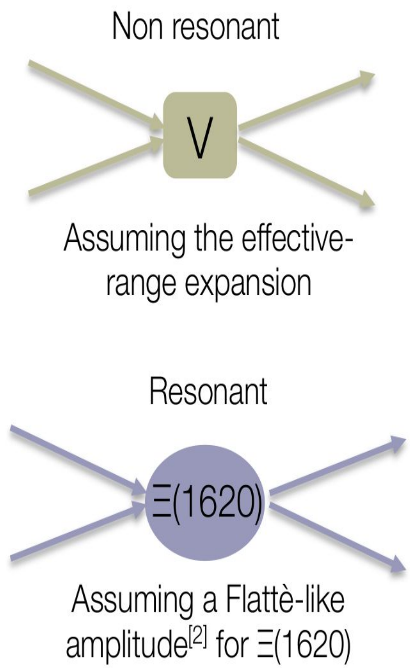
$$C_{\text{gen}}(k^*) = \omega C_{\text{LL}}^{\text{non-res}}(k^*) + (1-\omega) C_{\text{LL}}^{\text{res}}(k^*)$$

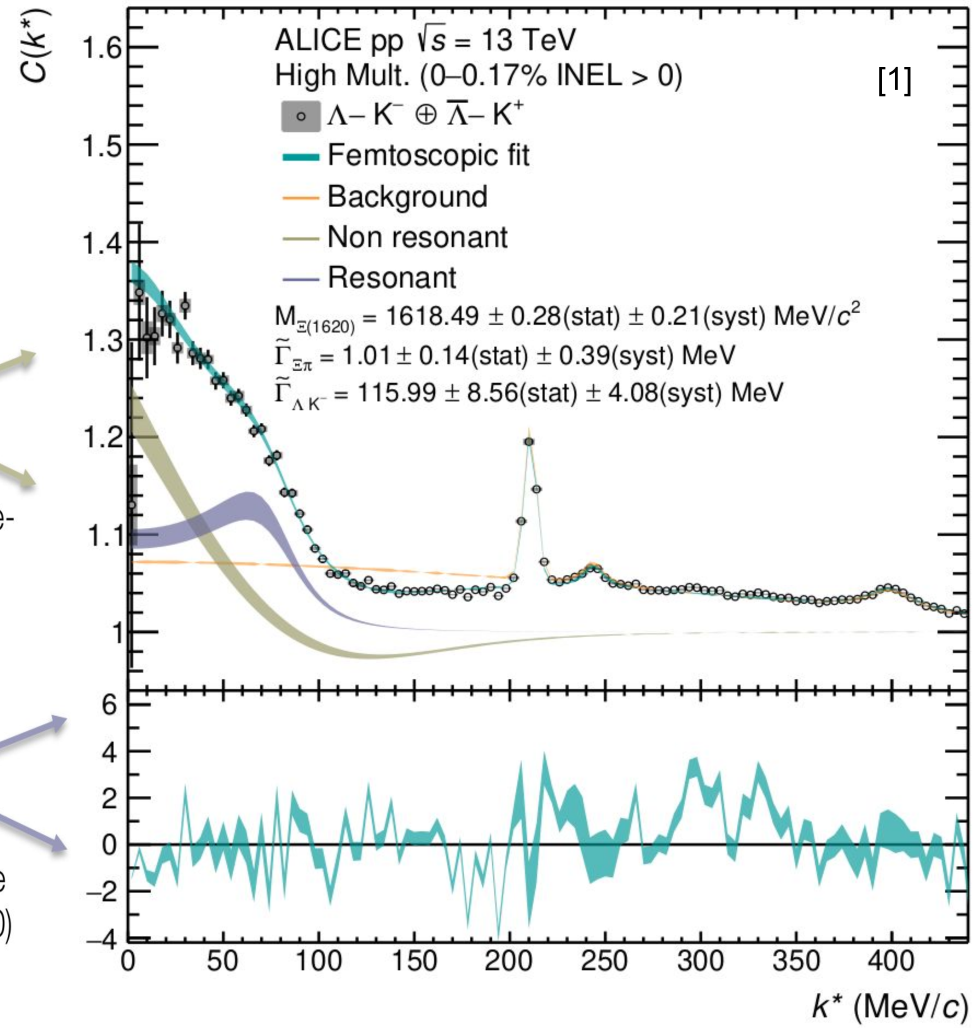
ΛK^- correlations

Results

- Indication of a large coupling of $\Xi(1620)$ to ΛK^-

$$M_{\Xi(1620)} = 1618.49^{\pm 0.28(stat)}_{\pm 0.21(syst)}$$





[1] ALICE Coll. arXiv: 2305.19093
[2] F. Giacosa et al. EPJA 57 (2021), 12, 336

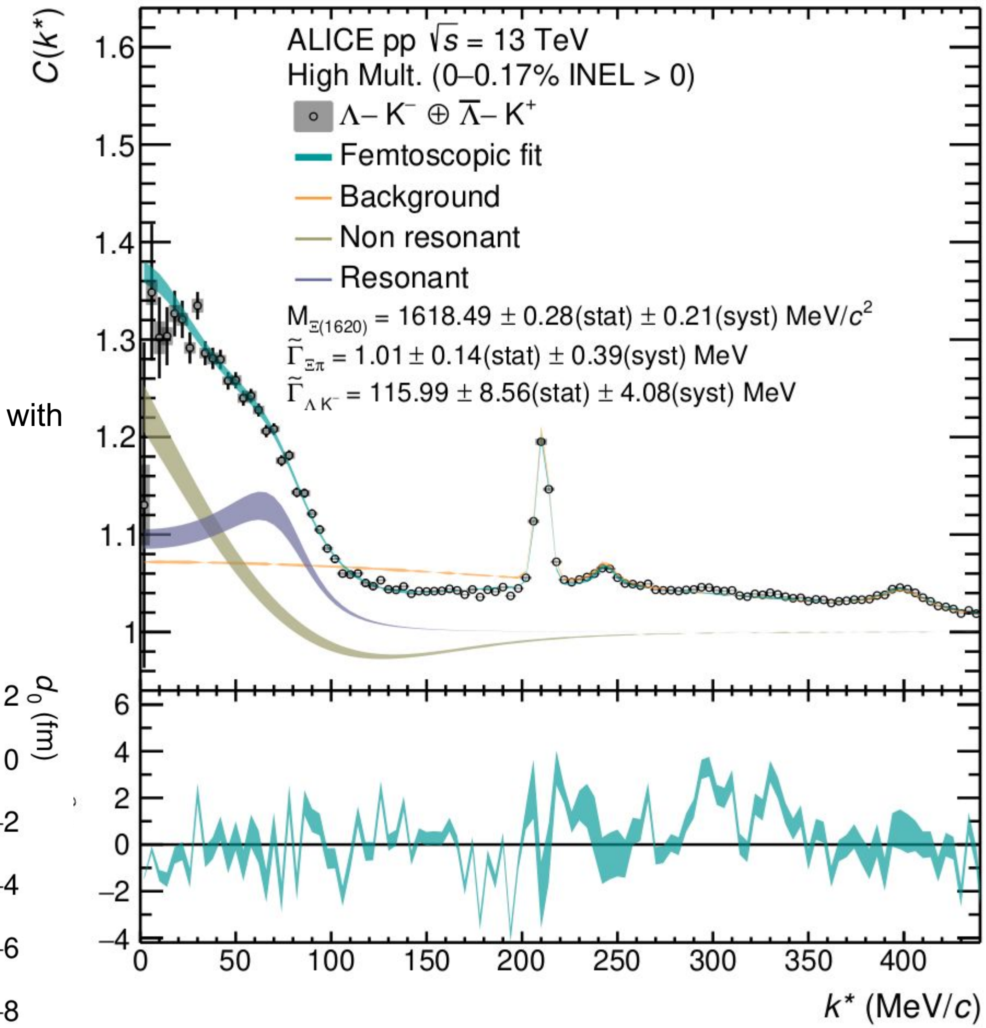
ΛK⁻ correlations

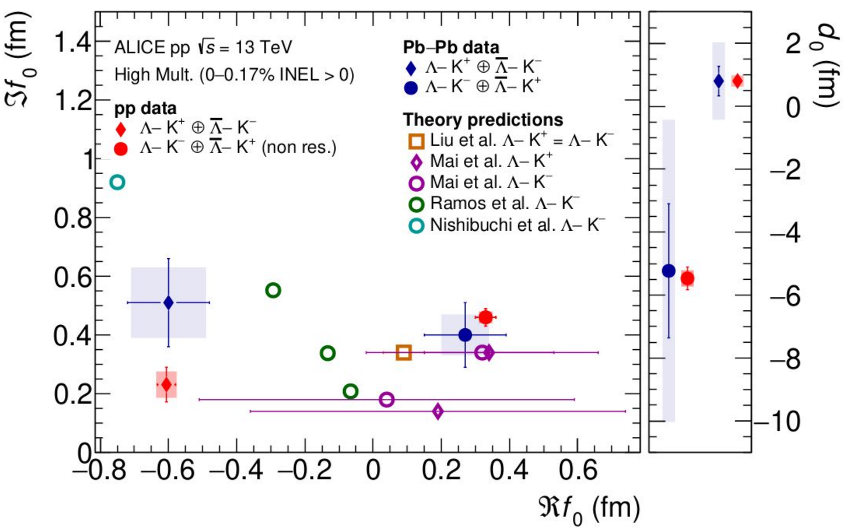
Results

- Indication of a large coupling of Ξ(1620) to ΛK⁻

$$M_{\Xi(1620)} = 1618.49^{\pm 0.28(stat)}_{\pm 0.21(syst)}$$

- Non-resonant scattering parameters in agreement with ALICE Pb-Pb results
  PRC 103 (2021)), 5, 055201





[ALICE Coll. arXiv: 2305.19093](#)