Constraining the N–Λ ↔ N–Σ coupled-system using femtoscopy at the LHC

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STRANU: HOT TOPICS IN STRANGENESS NUCLEAR AND ATOMIC PHYSICS

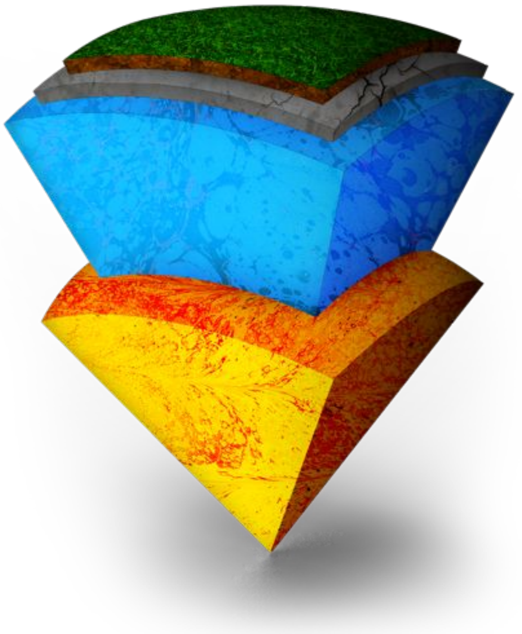
24 May 2021 — 28 May 2021

Do Hyperons appear in Neutron Stars?

Dimensions
R ~ 10 - 15 km
M ~ 1.5 - 2 $M_\odot$

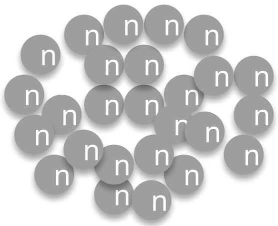
Outer Crust
Ions, electron gas,
Neutrons

Inner Core
Neutrons?
Protons?
Hyperons?
Kaon condensate?
Quark Matter?



Determination of the EoS challenging

- Particle composition of NS?
- Interaction among constituents?



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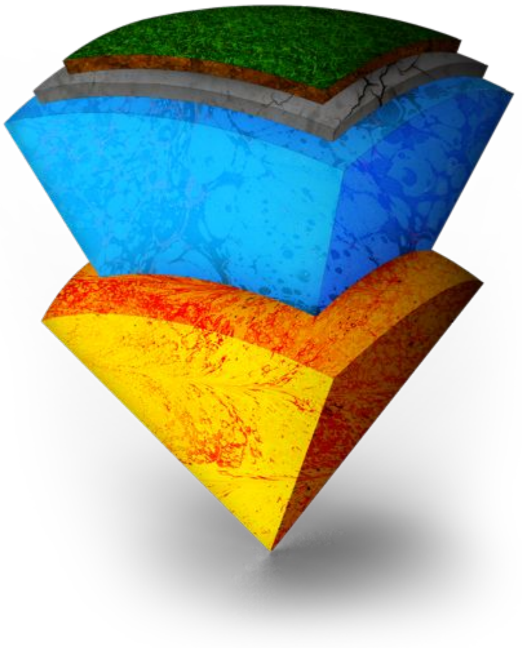
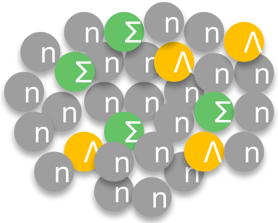


Determination of the EoS challenging

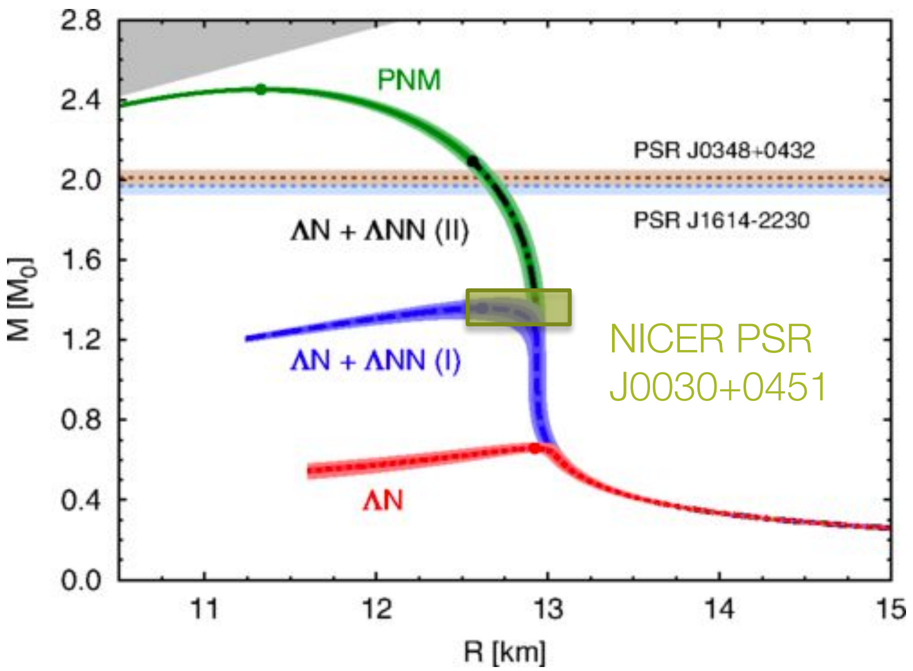
- Particle composition of NS?
- Interaction among constituents?

Considering energetically favourable scenarios

- Naively introduce Λ and other hyperons



Constraints from Astrophysics



Lonardoni et al. Phys. Rev. Lett 114, 092301 (2015)

‘Hyperon-Puzzle’

- Hyperonic EoS in compatible with observations

Potential solutions

- Procure high precision measurements of N-Y interaction
- Provide constraints for genuine NNY-forces

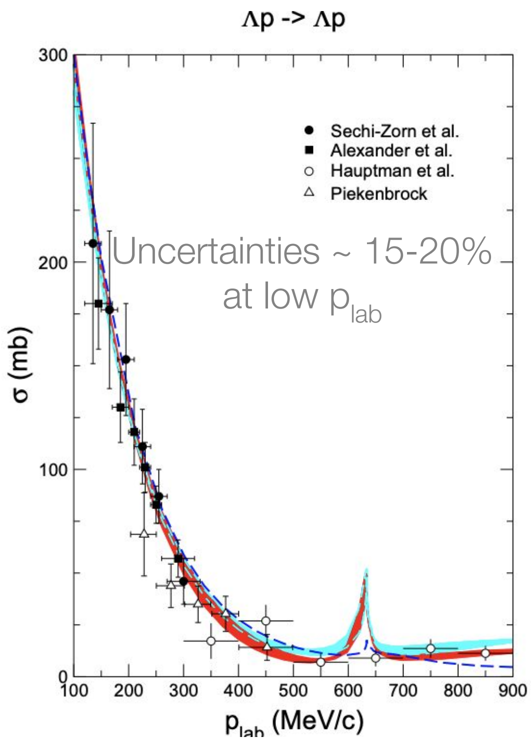
p-Λ Interaction and role of the N-Σ coupling

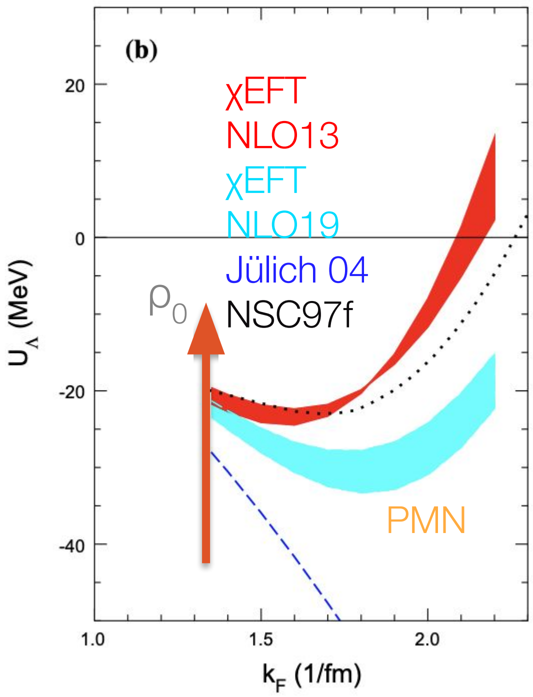
Experimental efforts

- Large uncertainties for low momenta
- No observation of predicted cusp from N–Λ ↔ N–Σ

Theory efforts

- N–Λ ↔ N–Σ affects Λ behaviour at finite density
- Implications for ΛNN(*)

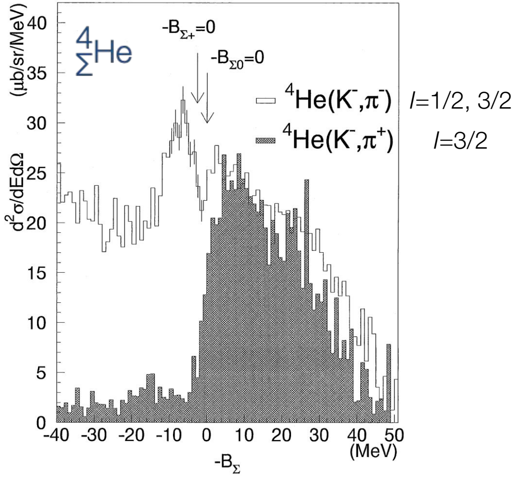




NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meiβner, Eur.Phys.J.A 56 (2020)
(*)D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175

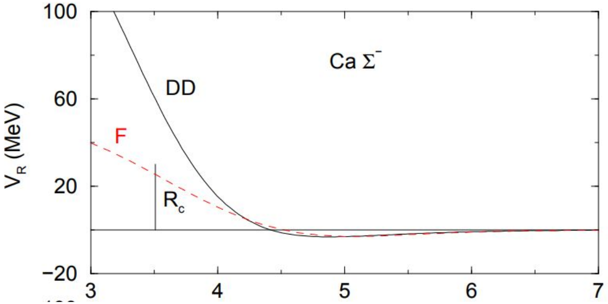
Knowledge about N-Σ interaction

Σ hypernuclei



T. Nagae *et al.*, *Phys. Rev. Lett.* 80 (1998) 1605.

Σ⁻ atomic data



G. Backenstoss *et al.*, *Phys. Lett.* B33 (1970) 230.
E. Friedman and A. Gal, *Phys. Rept.* 452 (2007) 89.

Theory predictions

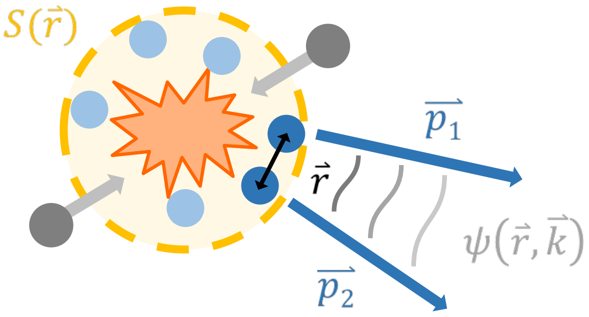
Model	U_Σ (MeV)
NSC97f	-16.1
ESC16	-3.3
fss2	7.5
HAL QCD	14.6
χEFT (NLO)	17.1

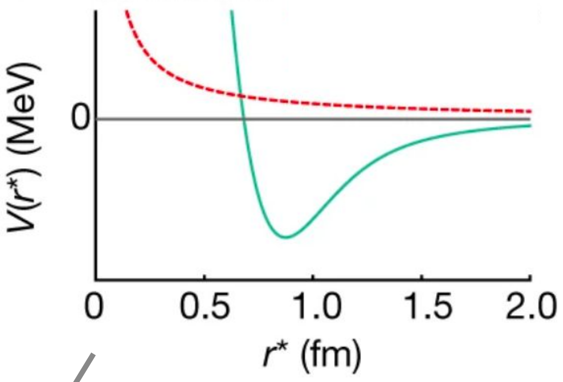
T. Rijken *et al.*, *Phys. Rev.* C59 (1999) 21.
M. Nagels *et al.*, *Phys. Rev.* C99 (2019) 044003.
Y. Fujiwara *et al.*, *Prog. Part. Nucl. Phys.* 58 (2007) 439.
HAL QCD Collab., *AIP Conf. Proc.* 2130 (2019) 020002.
J. Haidenbauer *et al.*, *Nucl. Phys.* A915 (2013) 24.

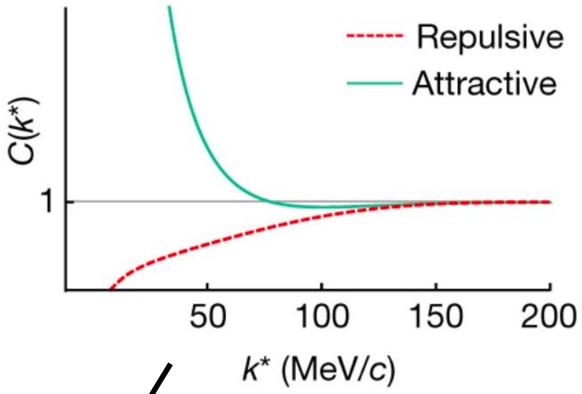
Inventory of theoretical models

- Strongly isospin dependent interaction
- Different scattering parameters predicted by different models

Basics of Femtoscopy







Schrödinger Equation for relative Wavefunction

$$C(k^*) = \int S(\vec{r}^*) \left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^* = \mathcal{N}\,\frac{\mathrm{N}_{same}(k^*)}{\mathrm{N}_{mixed}(k^*)} \xrightarrow{k^*\to\infty} 1$$

Relative momentum $k^* = \frac{1}{2} \mid \mathrm{p}_1^* - \mathrm{p}_2^* \mid$ and $\overrightarrow{\mathrm{p}_1^*} + \overrightarrow{\mathrm{p}_2^*} = 0$

Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

The emitting source

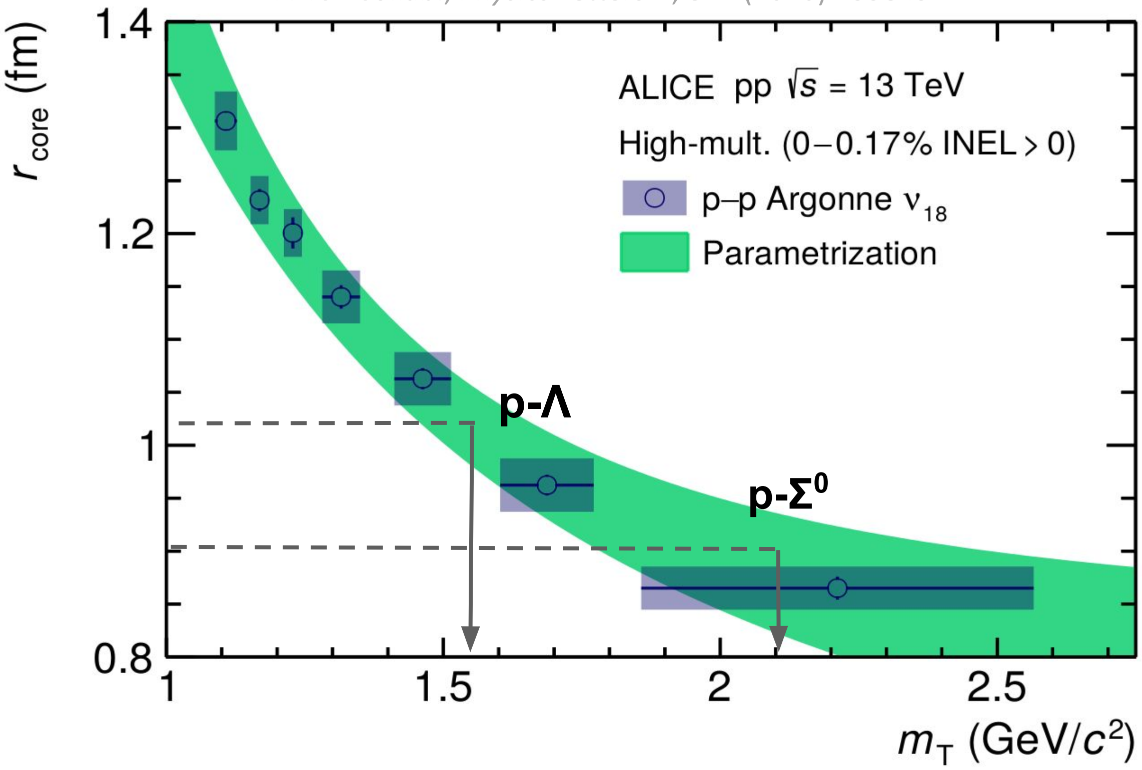
Universal source model

- r_{core} fixed for each pair based on $<m_T>$
- Particle-specific resonances are added to the core

Core radii

- $r_{core}(p\Lambda) = 1.02$, $r_{eff}(p\Lambda) = 1.23$
- $r_{core}(p\Sigma^0) = 0.91$, $r_{eff}(p\Sigma^0) = 1.25$

ALICE Collab., *Physics Letters B*, 811 (2020) 135849



Femtoscopy: Overview Coupled-Channels

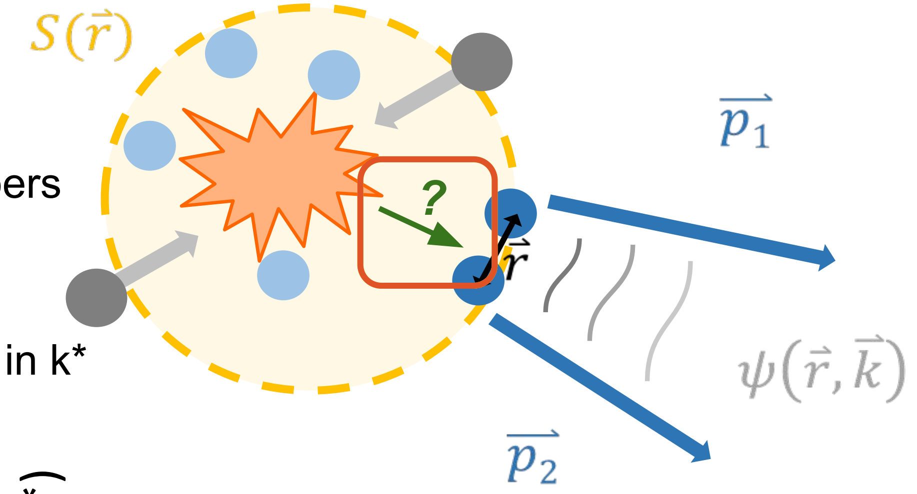
‘Coupled-Channels’

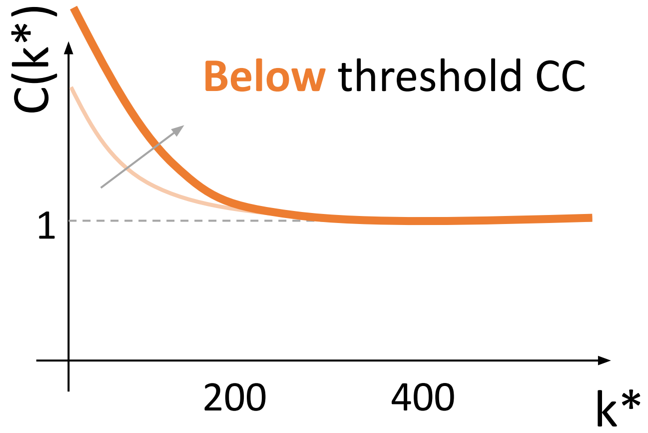
- Different pair with matching quantum numbers

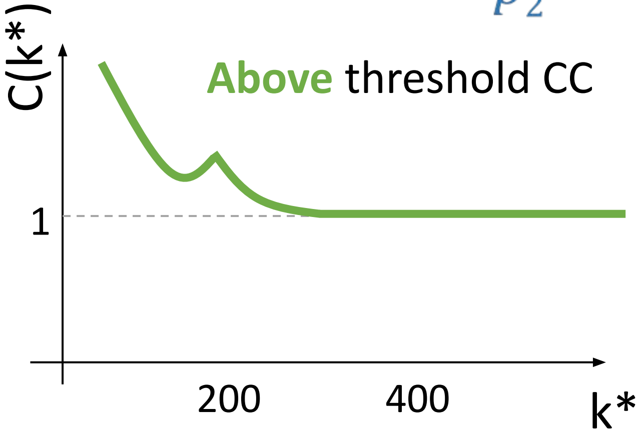
J. Haidenbauer, Nucl.Phys.A 981 (2019) 1
Y. Kamiya et al., Phys.Rev.Lett. 124 (2020) 13

Emerging threshold effects

- **Above**: Cusp-structure at channel opening in k*
- **Below**: Enhanced of CF at small k*

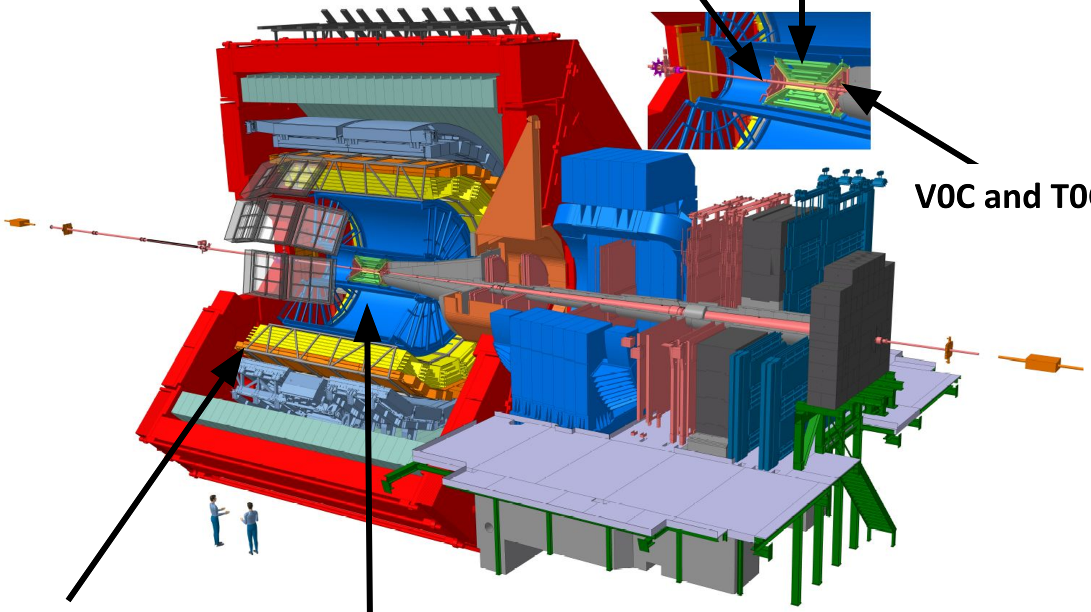






Femtoscopy in ALICE

Scheme based on
Int.J.Mod.Phys. A29 (2014) 1430044



Data analysis

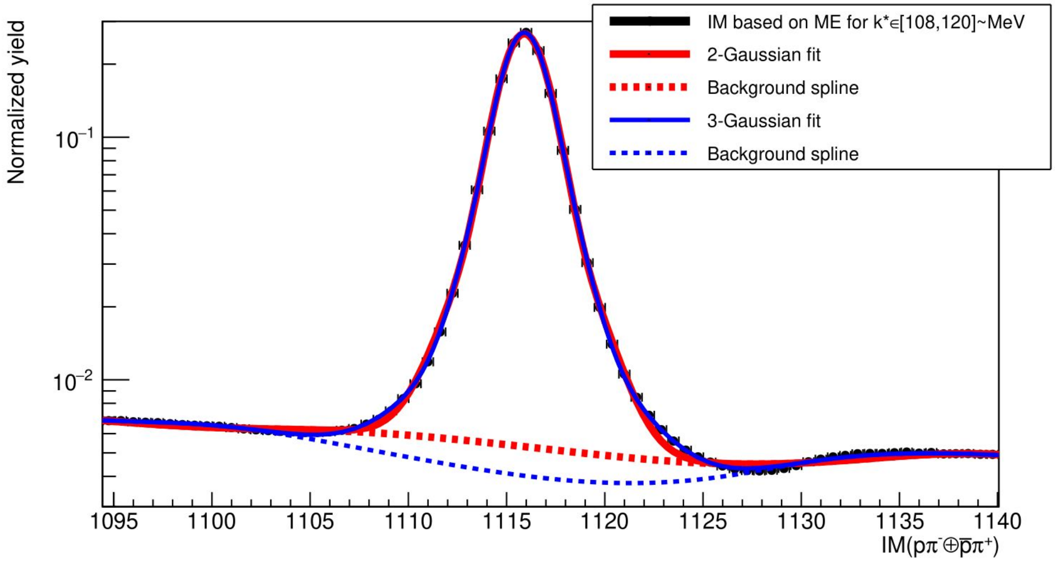
- Data set **pp 13 TeV** (1000 M **high multipl. events**)
- Direct detection of charged particles (protons, kaons, pions)
- Reconstruction of hyperons:

$$\Sigma^0 \rightarrow \gamma\Lambda \quad \text{(B.R.: ~100\%)}$$
$$\Lambda \rightarrow p\pi^- \quad \text{(B.R.: ~64\%)}$$

- # of pairs for k*< 200 MeV/*c*:
  - p-Σ0 ~ 1120
  - p-Λ ~ 13 x 10^5

p-Λ Analysis: Purity of Λ candidates

$$C_{exp}(k^*) = P_\Lambda C_{corrected}(k^*) + (1 - P_\Lambda) C_{p\tilde{\Lambda}}(k^*)$$



Explanation

- Purity of the reconstructed Λ

Derivation

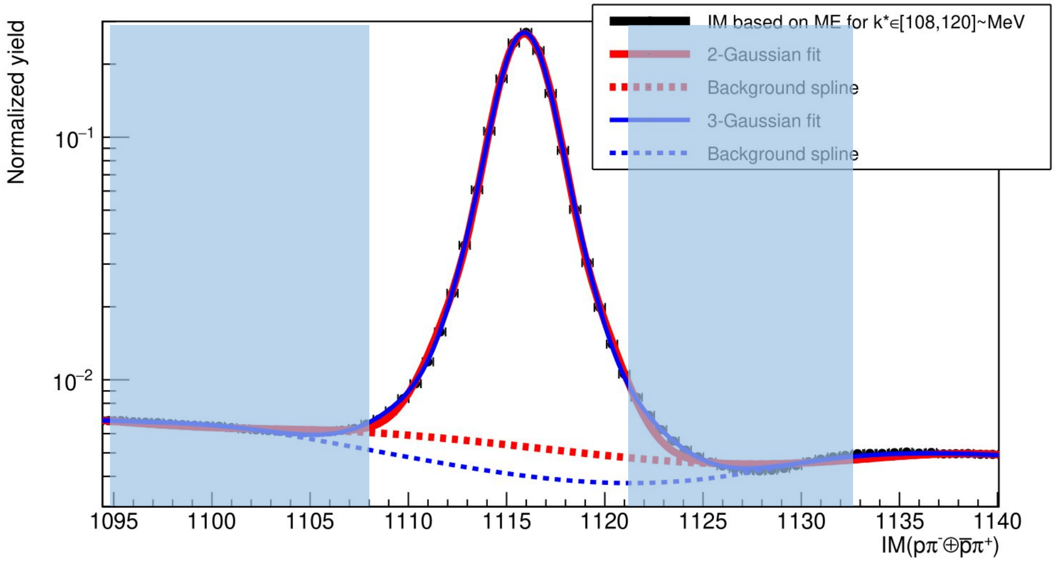
- Double gaussian fit to invariant mass spectrum yields P(Λ) = 95.3 % [P(p) = 99.4 %]

p-Λ Analysis: Sideband Analysis

$$C_{exp}(k^*) = P_\Lambda C_{corrected}(k^*) + (1 - P_\Lambda) C_{p\tilde{\Lambda}}(k^*)$$

p

Λ_{misid}



Explanation

- CF obtained from a '**sideband analysis**'

Derivation

- Pair p with Λ of a mass which is outside 3-8σ-band away of nominal mass

p-Λ Analysis: λ Parameters

$$C_{exp}(k^*) = P_\Lambda C_{corrected}(k^*) + (1 - P_\Lambda) C_{p\tilde{\Lambda}}(k^*)$$

$$b(k^*)[\lambda_{p\Lambda} C_{p\Lambda}(k^*) + \lambda_{p(\Sigma^0)} C_{p(\Sigma^0)}(k^*) + \lambda_{p(\Xi)} C_{p(\Xi)}(k^*) + \lambda_{ff} + \lambda_{\tilde{p}\Lambda}]$$

Explanation

- In order to quantify each single contribution use the formalism of λ parameters

$$\lambda_{ij} = f_i p_i f_j p_j$$

fraction **purity**

Derivation

- Purity as before
- Fractions determined data driven (CPA template fits)

p-Λ Analysis: λ Parameters

$$C_{exp}(k^*) = P_\Lambda C_{corrected}(k^*) + (1 - P_\Lambda) C_{p\tilde{\Lambda}}(k^*)$$

$$b(k^*)[\lambda_{p\Lambda} C_{p\Lambda}(k^*) + \lambda_{p(\Sigma^0)} C_{p(\Sigma^0)}(k^*) + \lambda_{p(\Xi)} C_{p(\Xi)}(k^*) + \lambda_{ff} + \lambda_{\tilde{p}\Lambda}]$$

47.1% | 15.7% | 19.0% | 17.6% | 0.6%

Explanation

- In order to quantify each single contribution use the formalism of λ parameters

Derivation

- Purity as before
- Fractions determined data driven (CPA template fits)

Pair	λ (%)
p-Λ	47.1
p-Σ0	15.7
p-Ξ	19.0
Flat-feeddown	17.6
p~-Λ	0.6

p-Λ Analysis: Modeling the feeddown

$$C_{exp}(k^*) = P_\Lambda C_{corrected}(k^*) + (1 - P_\Lambda) C_{p\tilde{\Lambda}}(k^*)$$

$$b(k^*)[\lambda_{p\Lambda} C_{p\Lambda}(k^*) + \lambda_{p(\Sigma^0)} C_{p(\Sigma^0)}(k^*) + \lambda_{p(\Xi)} C_{p(\Xi)}(k^*) + \lambda_{ff} + \lambda_{\tilde{p}\Lambda}]$$

p Λ p Σ^0 p Ξ^-

Modeled using χEFT

Modeled using HAL QCD lattice potentials(*)

Note

- **p-Σ^0** : Not well known
- **p-Ξ^-** : Known from femtoscopic measurements(**)

(*)T. Hatsuda Front. Phys. 13(6), 132105 (2018))

(**) ALICE Coll. Phys. Rev. Lett 123, (2019) 112002

ALICE Coll. Nature 588, 232–238 (2020)

p-Λ Analysis: Baseline

$$C_{exp}(k^*) = P_\Lambda C_{corrected}(k^*) + (1 - P_\Lambda) C_{p\tilde{\Lambda}}(k^*)$$

$$b(k^*)[\lambda_{p\Lambda} C_{p\Lambda}(k^*) + \lambda_{p(\Sigma^0)} C_{p(\Sigma^0)}(k^*) + \lambda_{p(\Xi)} C_{p(\Xi)}(k^*) + \lambda_{ff} + \lambda_{\tilde{p}\Lambda}]$$

Explanation

- Non-femtoscopic background

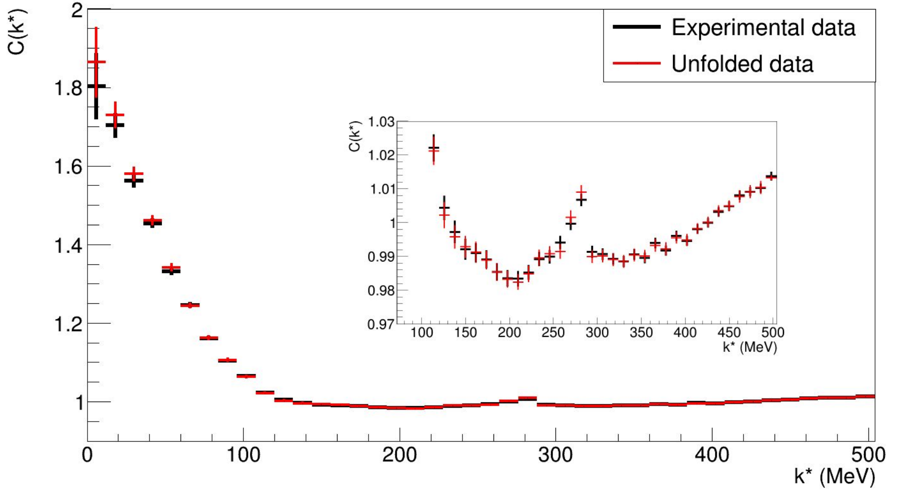
p-Λ Analysis: Final CF

$$C_{exp}(k^*) = P_\Lambda C_{corrected}(k^*) + (1 - P_\Lambda) C_{p\tilde{\Lambda}}(k^*)$$

CF used in fits

- Signal of interest corrected for residual mis-identifications and **unfolded** for momentum resolution
  - Effect most pronounced at k* < 60 MeV/*c* → changes up to 2%

$$C_{corrected}(k^*) = \frac{C_{exp}(k^*) + (1 - P_\Lambda) C_{p\tilde{\Lambda}}(k^*)}{P_\Lambda}$$



p-Λ Interaction: Femtoscopics result

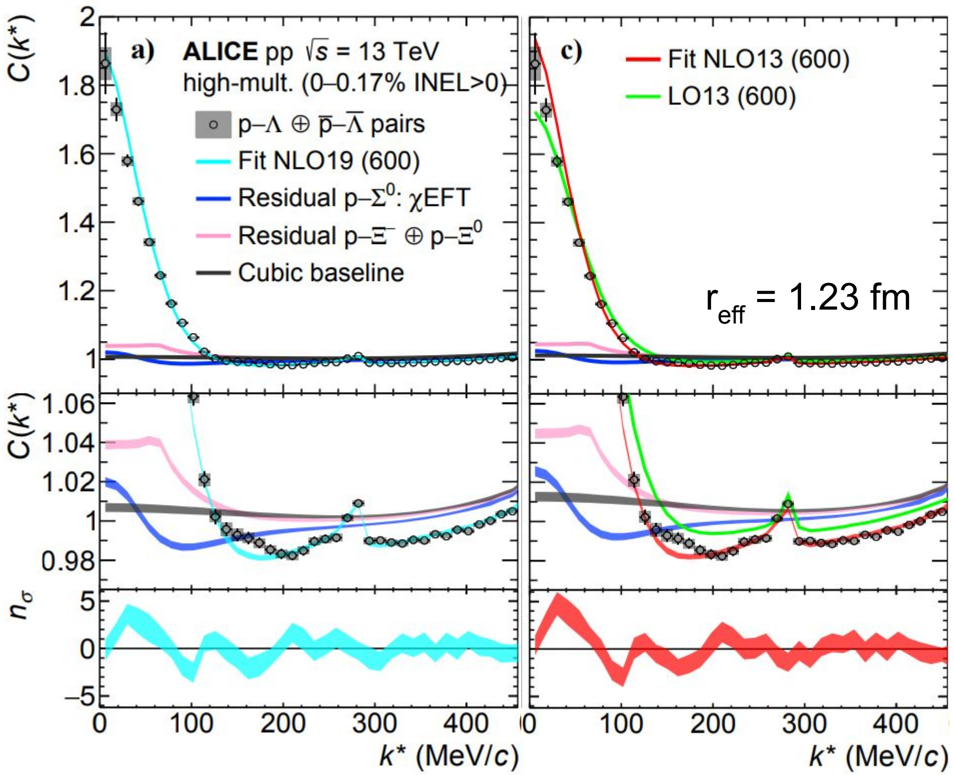
ALICE collab., arXiv:2104.04427 submitted to PRL

New Results

- **First observation** of cusp from N–Λ ↔ N–Σ
- High precision data down to low k*

Discussion

- NLO19 (600) preferred
  - less (enhanced) attractive Λ interaction in vacuum (at high densities)
  - requires more repulsive NNΛ
  - deviations > 3σ



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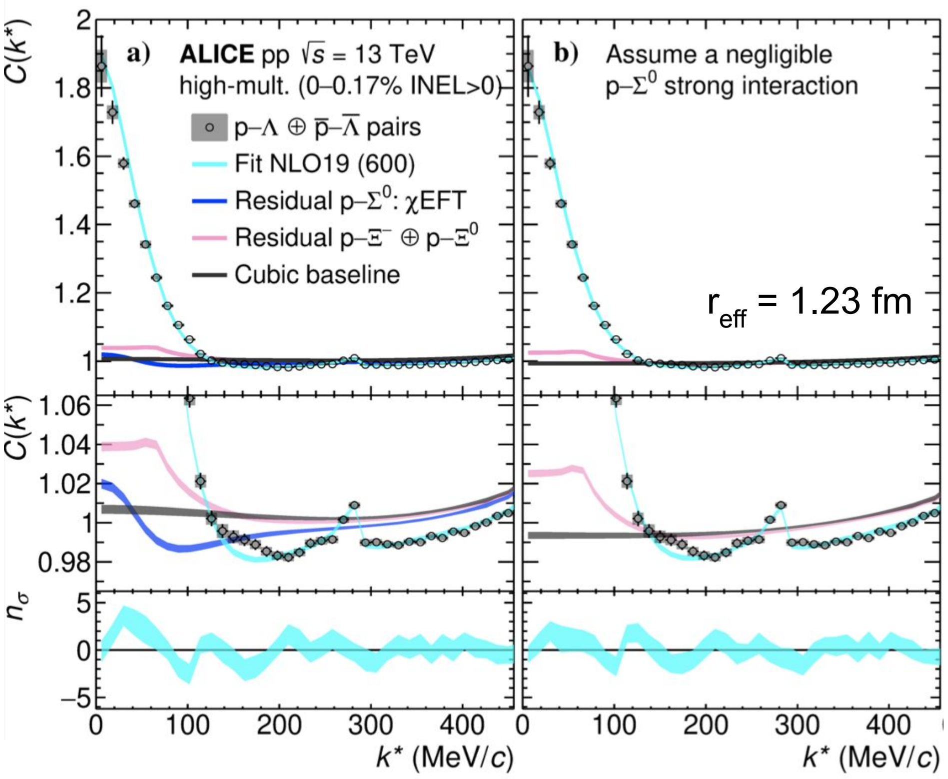
New Results

- **First observation** of cusp from N–Λ ↔ N–Σ
- High precision data down to low k*

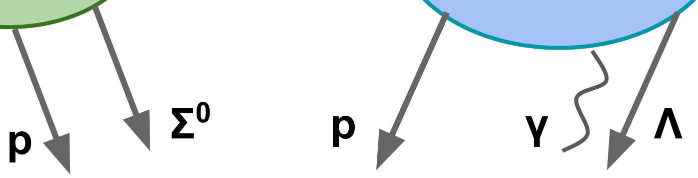
Discussion

- Negligible interaction for p-Σ^0 is favoured

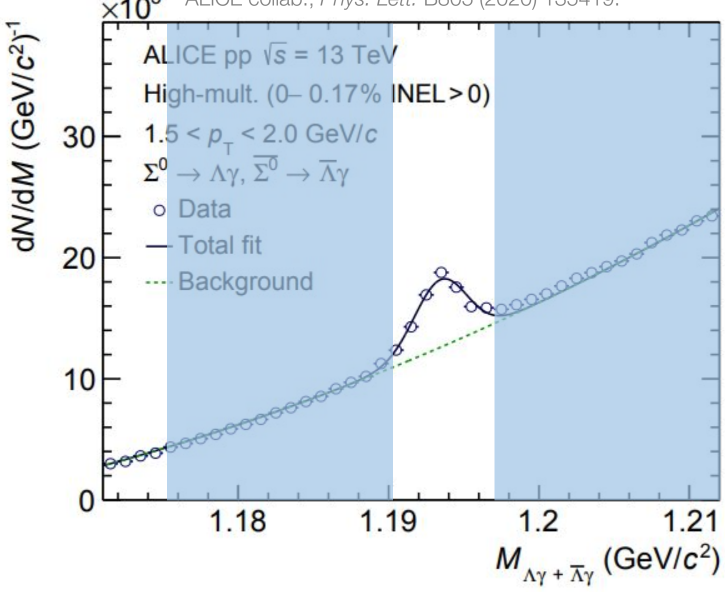


p-Σ^0 Analysis: Modeling the CF

$$C_{exp}(k^*) = b(k^*)[\lambda_{p\Sigma^0} C_{p\Sigma^0}(k^*) + \lambda_{p(\gamma\Lambda))} C_{p(\gamma\Lambda))}(k^*) + \lambda_{ff} + \lambda_{\tilde{p}\Sigma^0}]$$



ALICE collab., *Phys. Lett.* B805 (2020) 135419.



Explanation

- **Genuine** CF
- CF obtained from a '**sideband analysis**'

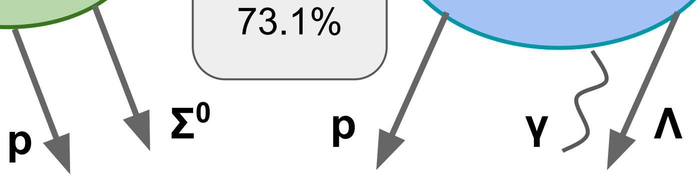
Derivation

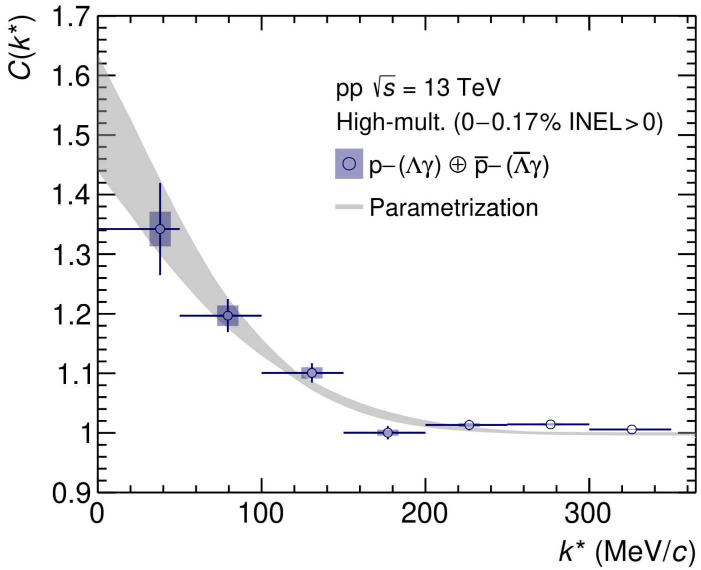
- Pair p with Σ^0 of a mass which is outside 3-8σ-band away of nominal mass

p-Σ^0 Analysis: Sideband Analysis

$$C_{exp}(k^*) = b(k^*)[\lambda_{p\Sigma^0} C_{p\Sigma^0}(k^*) + \lambda_{p(\gamma\Lambda))} C_{p(\gamma\Lambda))}(k^*) + \lambda_{ff} + \lambda_{\tilde{p}\Sigma^0}]$$

$\lambda_{p\Sigma^0}$: 22% $\quad$ $\lambda_{p(\gamma\Lambda))}$: 73.1% $\quad$ λ_{ff}: 4.7% $\quad$ $\lambda_{\tilde{p}\Sigma^0}$: 0.2%





'**sideband analysis**'

- CF is dominated by contributions from the sidebands
- Modeled by Gaussian distribution

Note

- The CF obtained from sidebands is the 'reference' in this study

p-Σ^0 Interaction: Femtoscopic results

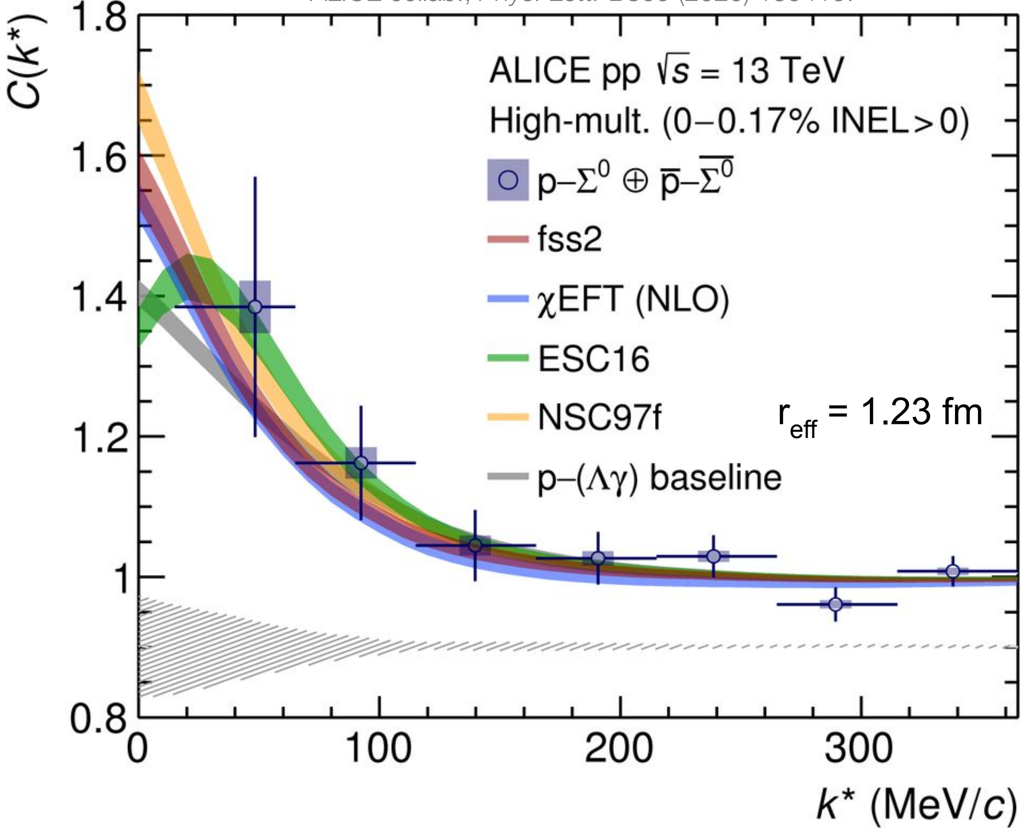
New Results

- **<u>First observation</u>** of N–Σ interaction

Discussion

- CF consistent with reference baseline obtained from sidebands
  - shallow attractive interaction of p-Σ
  - indicates positive sign for potential

ALICE collab., *Phys. Lett.* B805 (2020) 135419.



Summary & Outlook

<u>High precision measurement of p-Λ</u>

- **High resolution of cusp structure N–Λ ↔ N–Σ**
- Favours NLO19 (600):
  - less (enhanced) attractive Λ interaction in vacuum (at high densities)
  - necessitates more repulsive NNΛ

=> High quality data available for model tuning
=> Probing the genuine 3-body forces with high precision femtoscopy in RUN3

<u>First successful observation of p-Σ</u>

- In favour of shallow strong interaction
- Indicates positive sign for single particle potential

=> Clarification of the role of Σ within reach with RUN3 data

Summary & Outlook

High p

- **Hig**
- Fav

=> Hig
=> Pro

First s

- In fa
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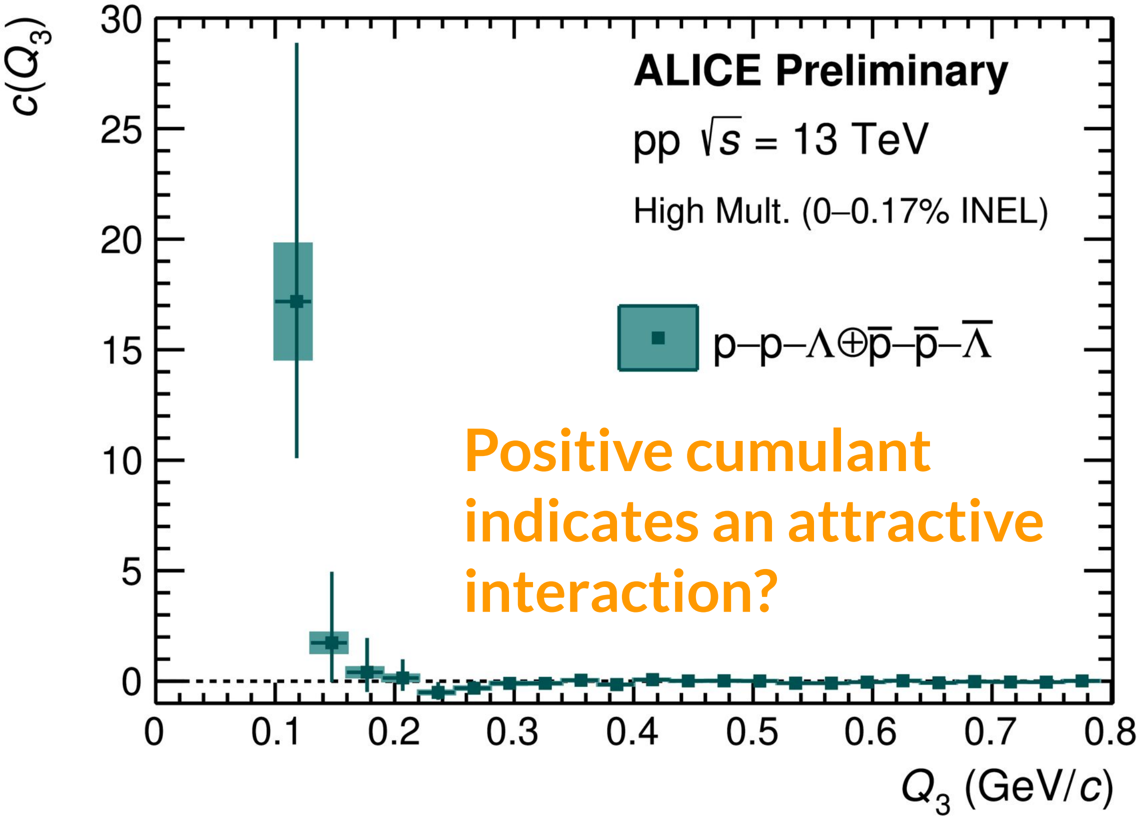

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UN3

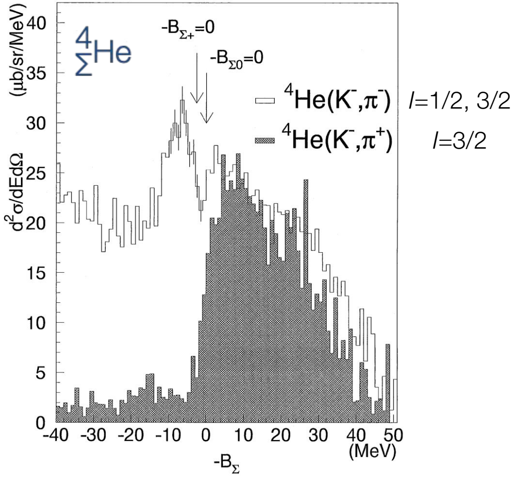
Back-up

Back-up

- NΣ additional slides with comments about exp.data till now
- Femtoscopy: Information about the source
- Reconstruction of $\Sigma0$ with ALICE
- Reconstruction of Λ with ALICE
- CC-modified Koonin-Pratt eqn.
- Details on the unfolding procedure

Knowledge about N-Σ

Σ hypernuclei



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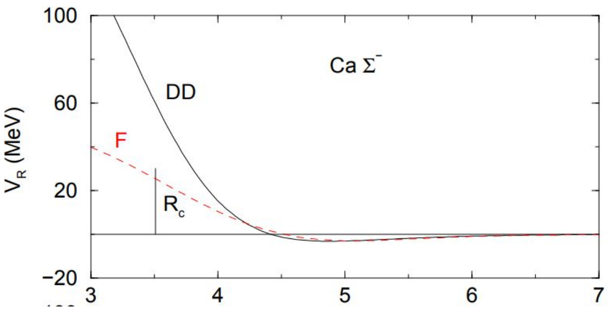
Σ⁻ atomic data

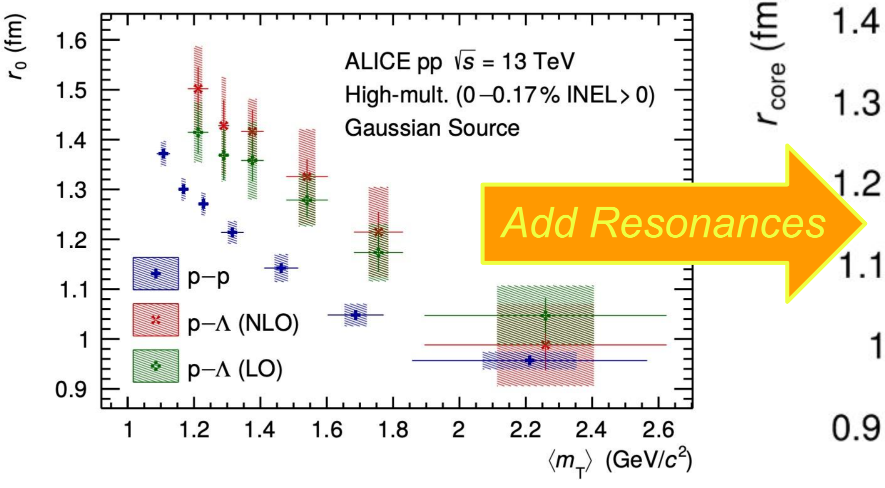


G. Backenstoss *et al.*, *Phys. Lett.* B33 (1970) 230.
E. Friedman and A. Gal, *Phys. Rept.* 452 (2007) 89.

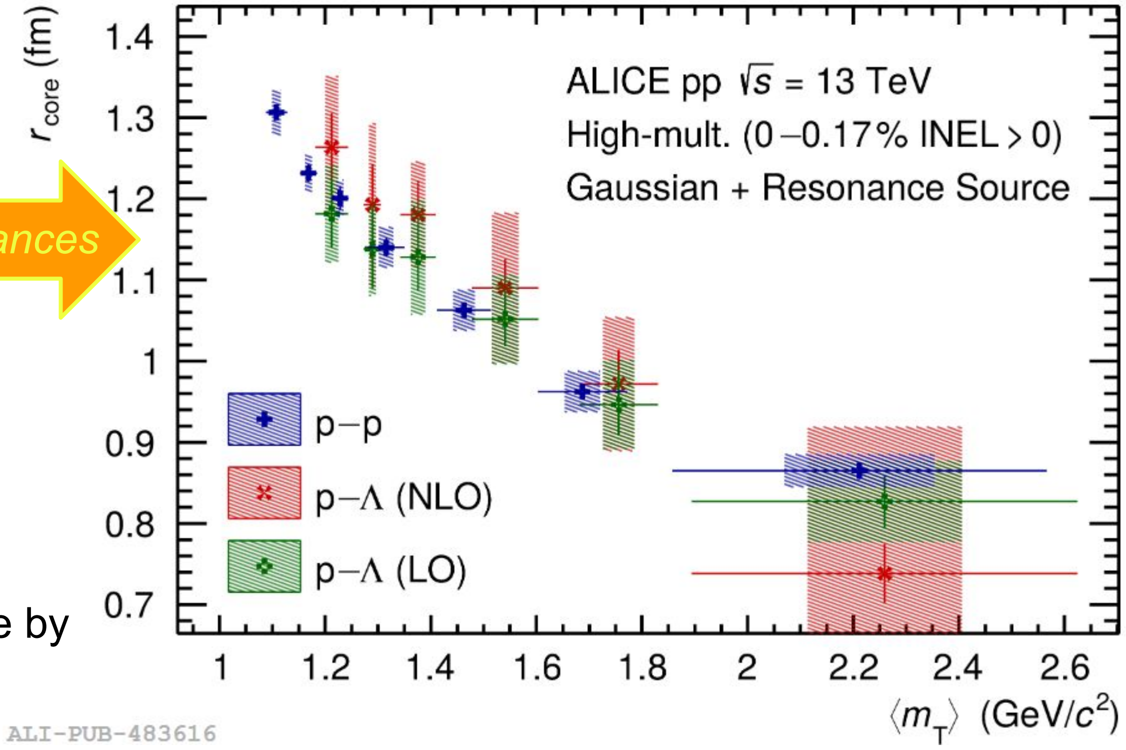
Inventory of experimental data

- Few events of hypernuclei
- Optical potential derived from atomic data

Femtoscopy: Source



ALICE Collab., *Physics Letters B*, 811 (2020) 135849



Source modifications

- Increase in apparent source size by short lived strongly-decaying resonances (e.g. Δ)

Femtoscopy: Source

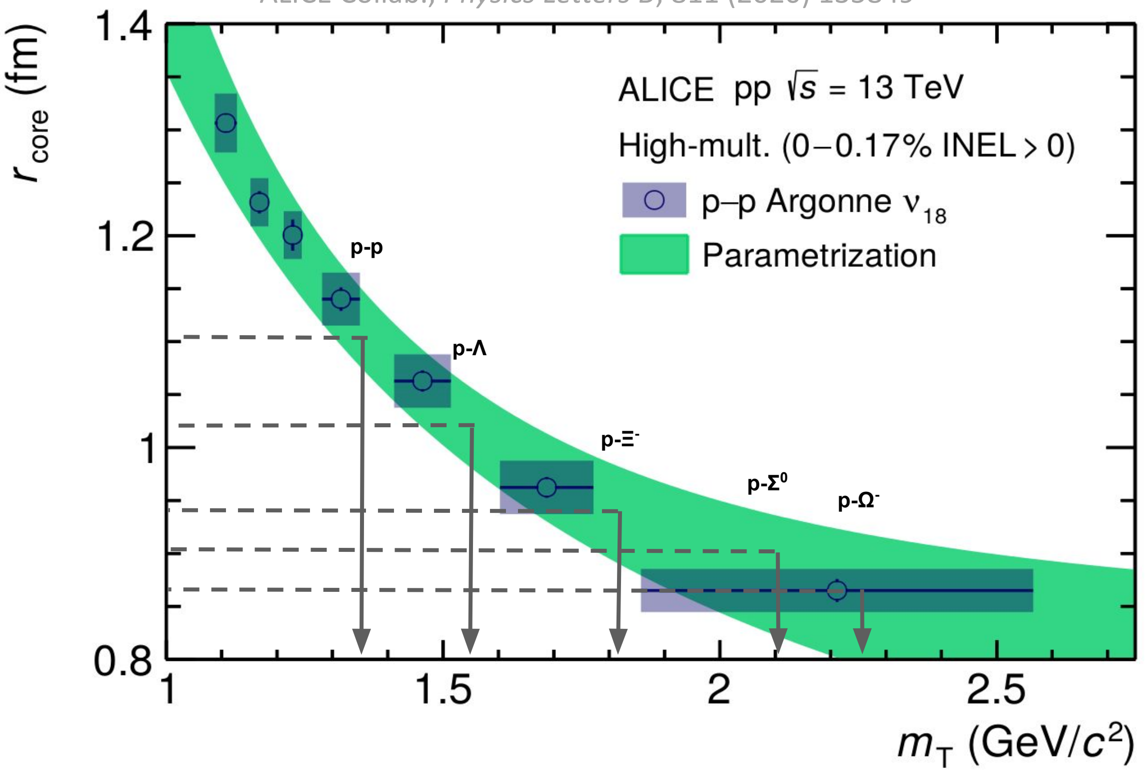
ALICE Collab., *Physics Letters B*, 811 (2020) 135849

Universal source model

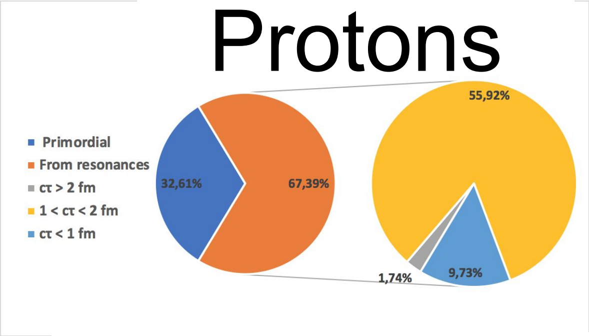
- r_{core} fixed for each pair based on <m_T>
- Particle-specific resonances are added to the core

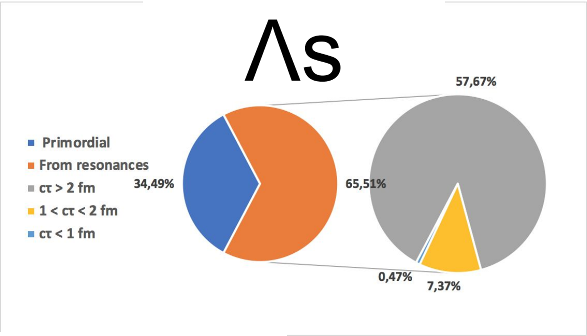
Notice

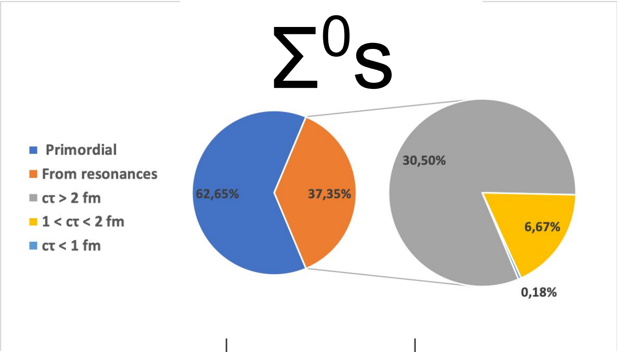
- Small radii probe large densities

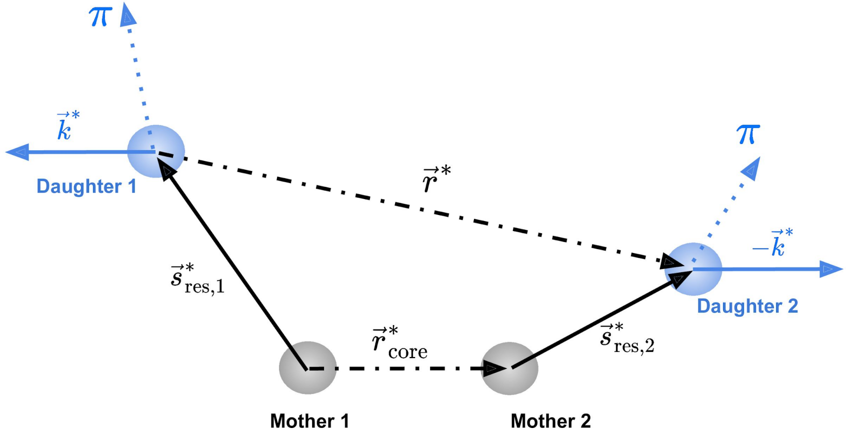


Femtoscopy: Source Resonances









Particle	$M_{\rm res}$ [MeV]	$\tau_{\rm res}$ [fm]
p	1361.52	1.65
Λ	1462.93	4.69
Σ^0	1581.73	4.28

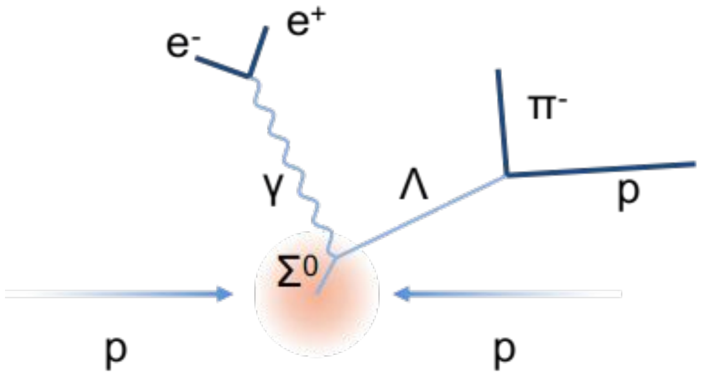
$$s = \beta\gamma\tau_{\rm res} = \frac{p_{\rm res}}{M_{\rm res}}\tau_{\rm res}$$

$$E(r, M_{\rm res}, \tau_{\rm res}, p_{\rm res}) = \frac{1}{s}\exp\left(-\frac{r}{s}\right)$$

Reconstruction of Σ

Reconstruction

- Target channel γΛ (B.R. 100%)
  - Λ identification subsequent decay into $p\pi^-$ (B.R 64%)
  - γ measurement via pair conversion (prob. 8% in ALICE central barrel)



Dataset

- ALICE Run 2 data
- High-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV

Reconstruction of Λ

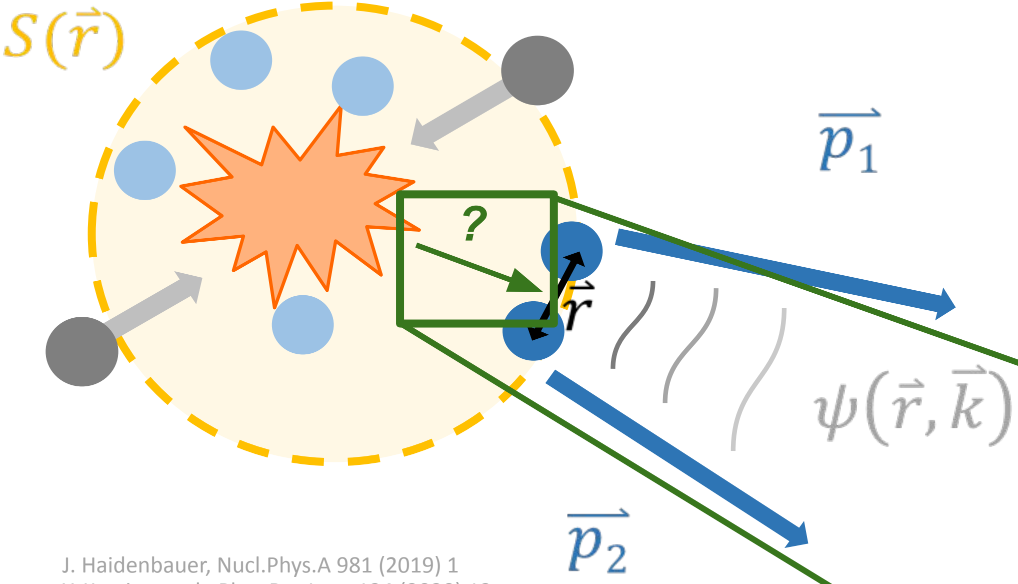
Reconstruction

- Target channel $p\pi^-$ (B.R 64%)

Dataset

- ALICE Run 2 data
- High-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV

Femtoscopy: Overview Coupled-Channels (CC)



J. Haidenbauer, Nucl.Phys.A 981 (2019) 1
Y. Kamiya et al., Phys.Rev.Lett. 124 (2020) 13

'Coupled-Channels' (cc)

- Different pair with matching quantum numbers

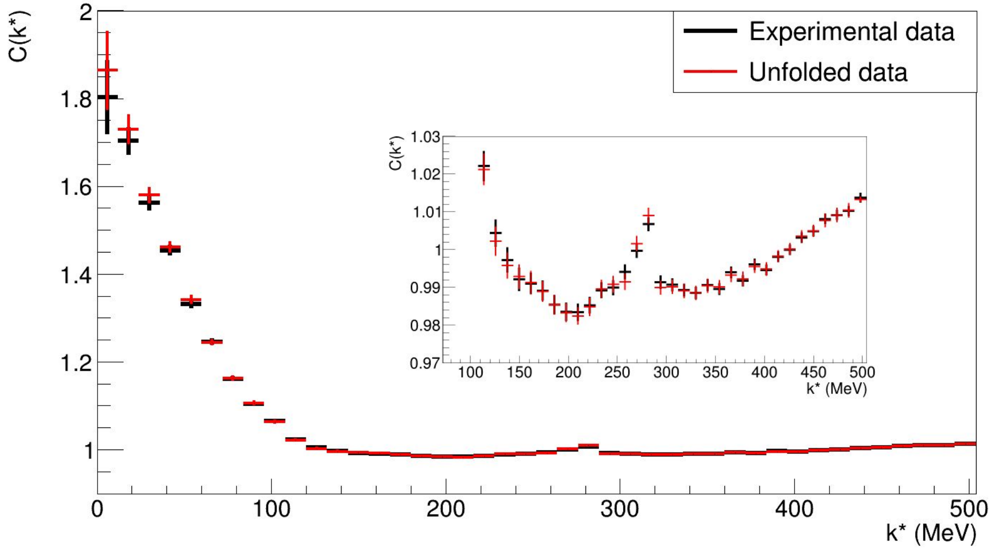
  N–Λ ↔ N–Σ

- **ω** = 0.33 (Iso-spin symmetry)

$$C(k^*) = \int S(\vec{r}^*)|\psi(\vec{k}^*,\vec{r}^*)|d^3\vec{r}^* + \sum_{cc}\omega_{cc}\int S_{cc}(\vec{r}^*)|\psi_{cc}(\vec{k}^*,\vec{r}^*)|d^3\vec{r}^*$$

Unfolding for momentum resolution

- Motivation: more convenient representation for theorists to test their models.
- Method: **brute force**.
  Each fitted correlation function (45 fit x 2 purity x 2 sideband variations, 180 in total) is unfolded by:
  - Fitting the experimental correlation, by applying the smearing on the theoretical curve.
  - The theory curve providing the best χ^2 is used as an initial guess for the unfolded correlation.
  - The unfolded correlation is bootstrapped and folded to the exp. data, until a better χ^2 is found.
  - Repeated until obtaining a χ^2/DataPoints < 0.2.



Formula up-keep

\lambda_{gen} C_{th,gen(k^*)+\lambda_{p\Sigma^0} C_{th,p\Sigma^0}(k^*)
+\lambda_{p\Xi^-} C_{th,p\Xi^-}(k^*)+~...~ +\lambda_{misid} C_{th,misid}(k^*)+

b(k^*)[\lambda_{p\lambda}C_{th,p\lambda}(k^*)+\lambda_{p\Sigma^0}
C_{th,p\Sigma^0}(k^*) +\lambda_{p\Xi^-}
C_{th,p\Xi^-}(k^*)+\lambda_{ff}+\lambda_{\tilde{p}\Lambda}]

C_{exp}(k^*) =
b(k^*)[\lambda_{p\Sigma^0}C_{p\Sigma^0}(k^*)+\lambda_{p(\gamma\Lambda))}
C_{p(\gamma\Lambda))}(k^*)+\lambda_{ff}+\lambda_{\tilde{p}\Sigma^0}]