Constraining the equation of state of neutron stars with femtoscopy measurements by ALICE

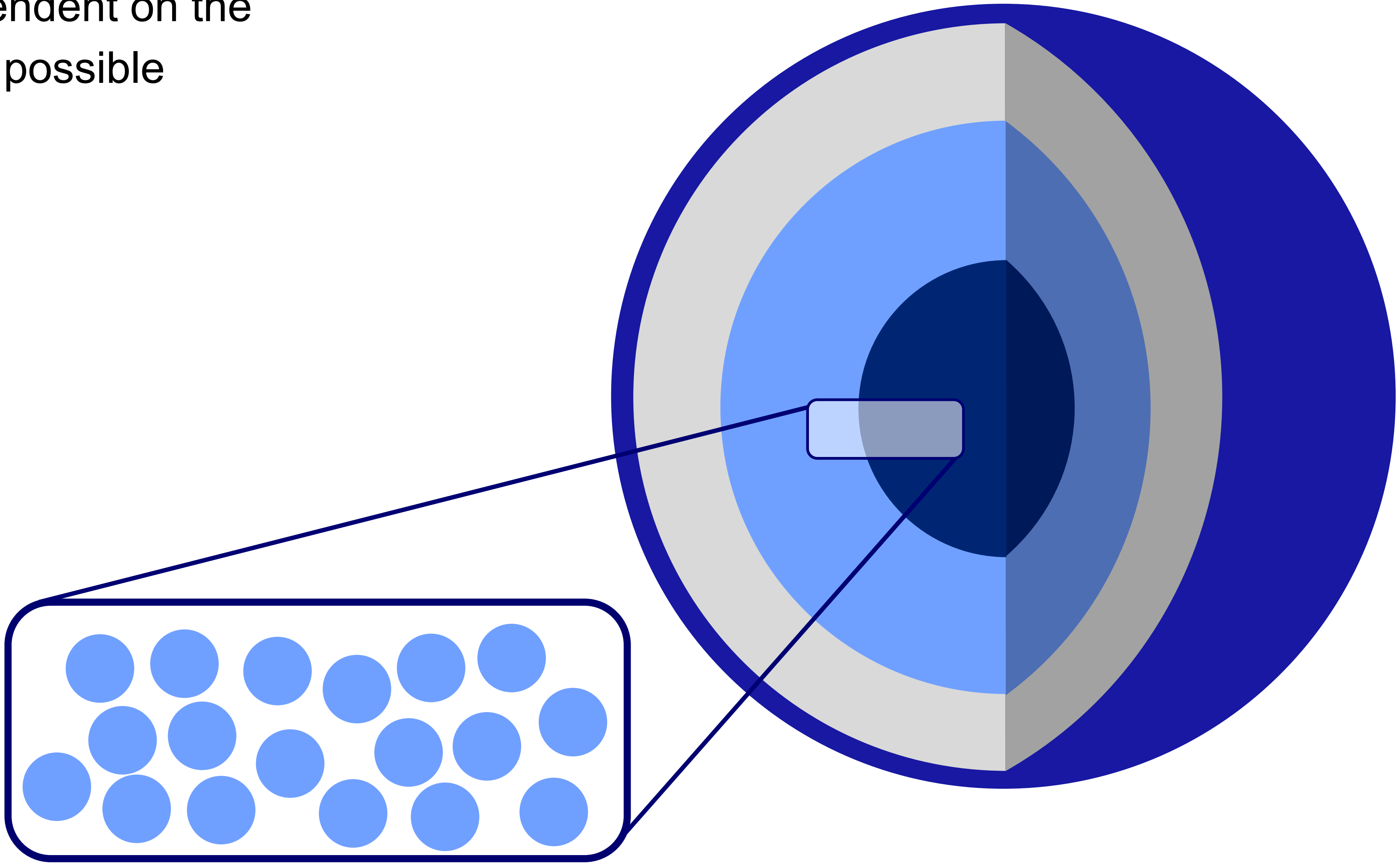
Marcel Lesch
on behalf of the ALICE Collaboration

Technical University of Munich

08th of June 2023
HADRON 2023

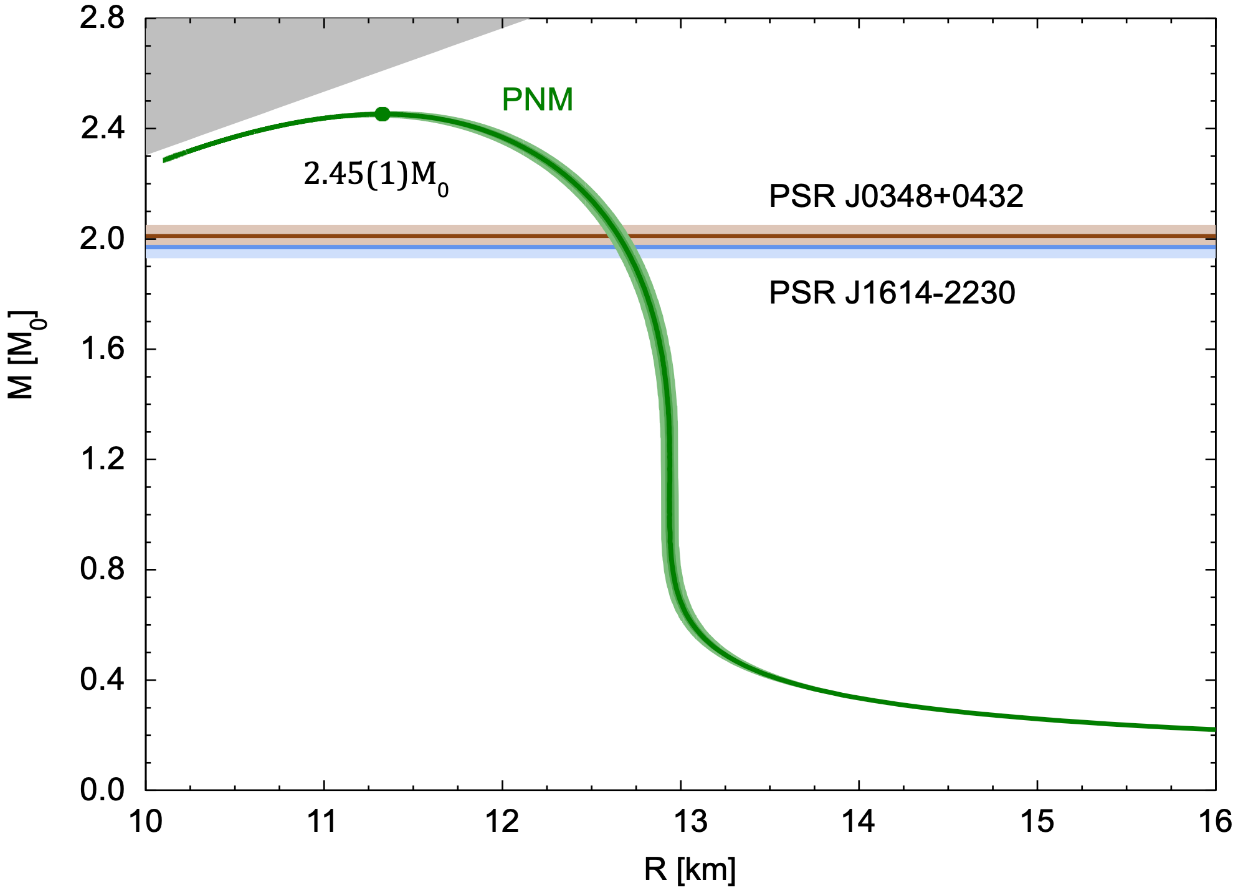
Neutron Stars and the Hyperon Puzzle

- Equation of state (EoS) dependent on the particle composition and the possible interactions between them



Neutron Stars and the Hyperon Puzzle

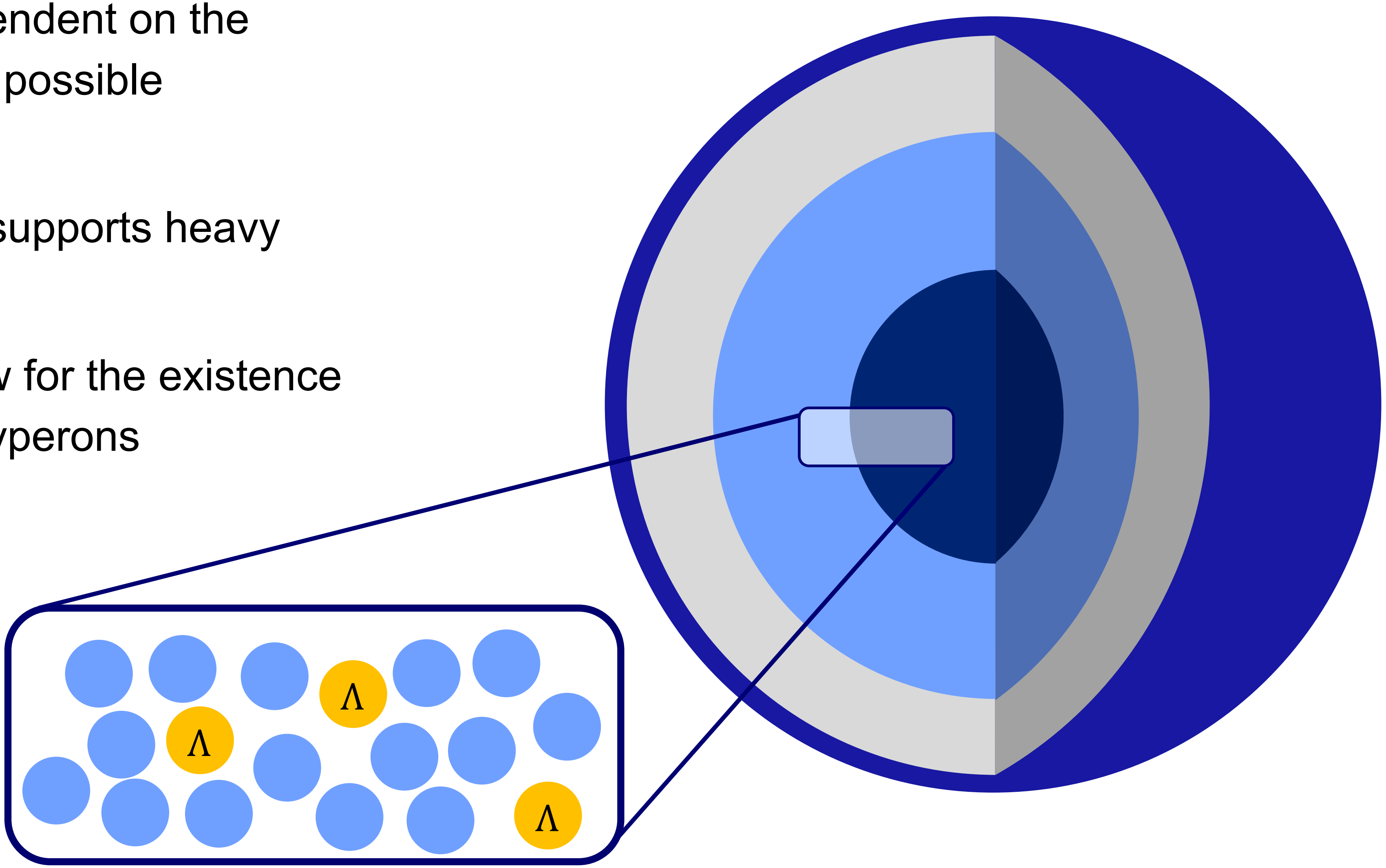
- Equation of state (EoS) dependent on the particle composition and the possible interactions between them
- Pure neutron matter (PNM) supports heavy neutron stars of $2M_\odot$



Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

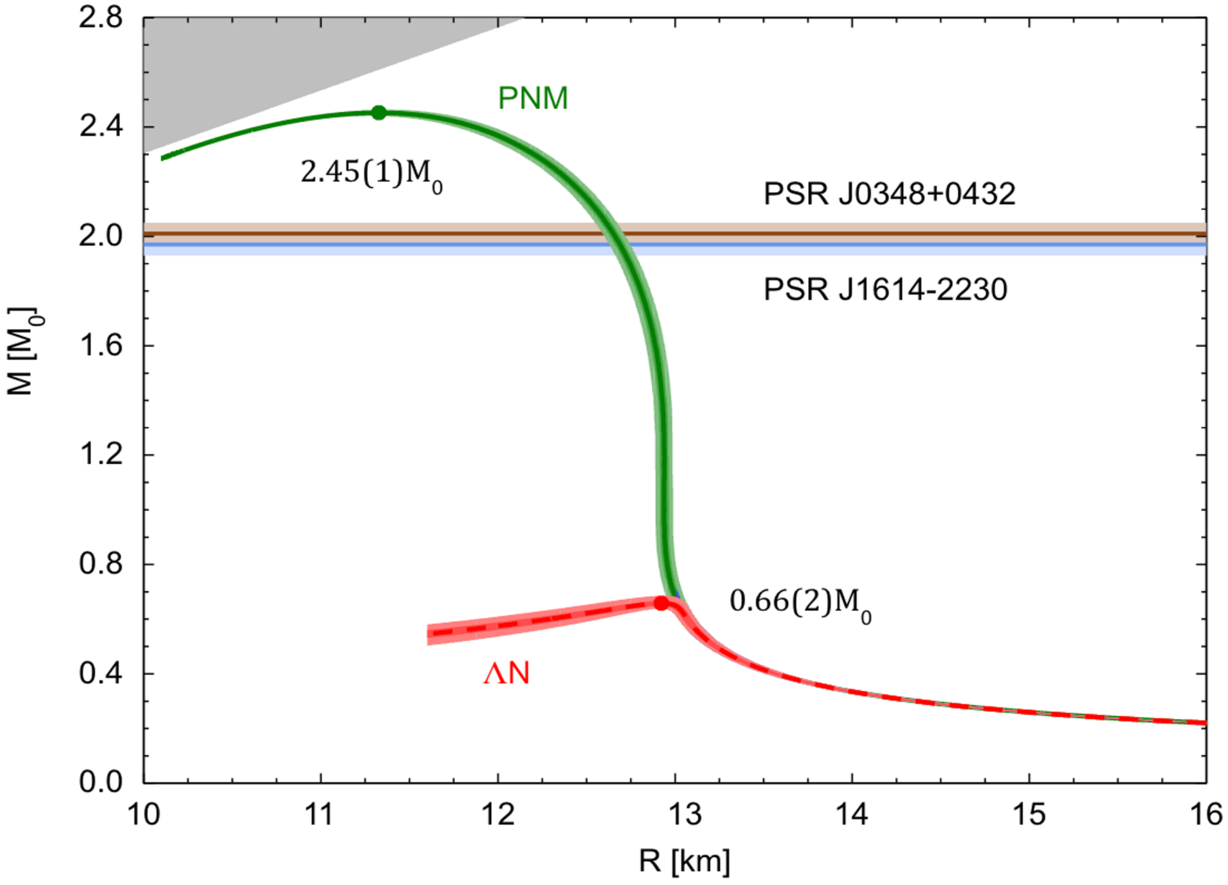
Neutron Stars and the Hyperon Puzzle

- Equation of state (EoS) dependent on the particle composition and the possible interactions between them
- Pure neutron matter (PNM) supports heavy neutron stars of $2M_\odot$
- High baryonic densities allow for the existence of strange particles, e.g. Λ hyperons



Neutron Stars and the Hyperon Puzzle

- However: EoS can soften with appearance of Λ hyperons
  $\rightarrow$ cannot support heavy neutron stars

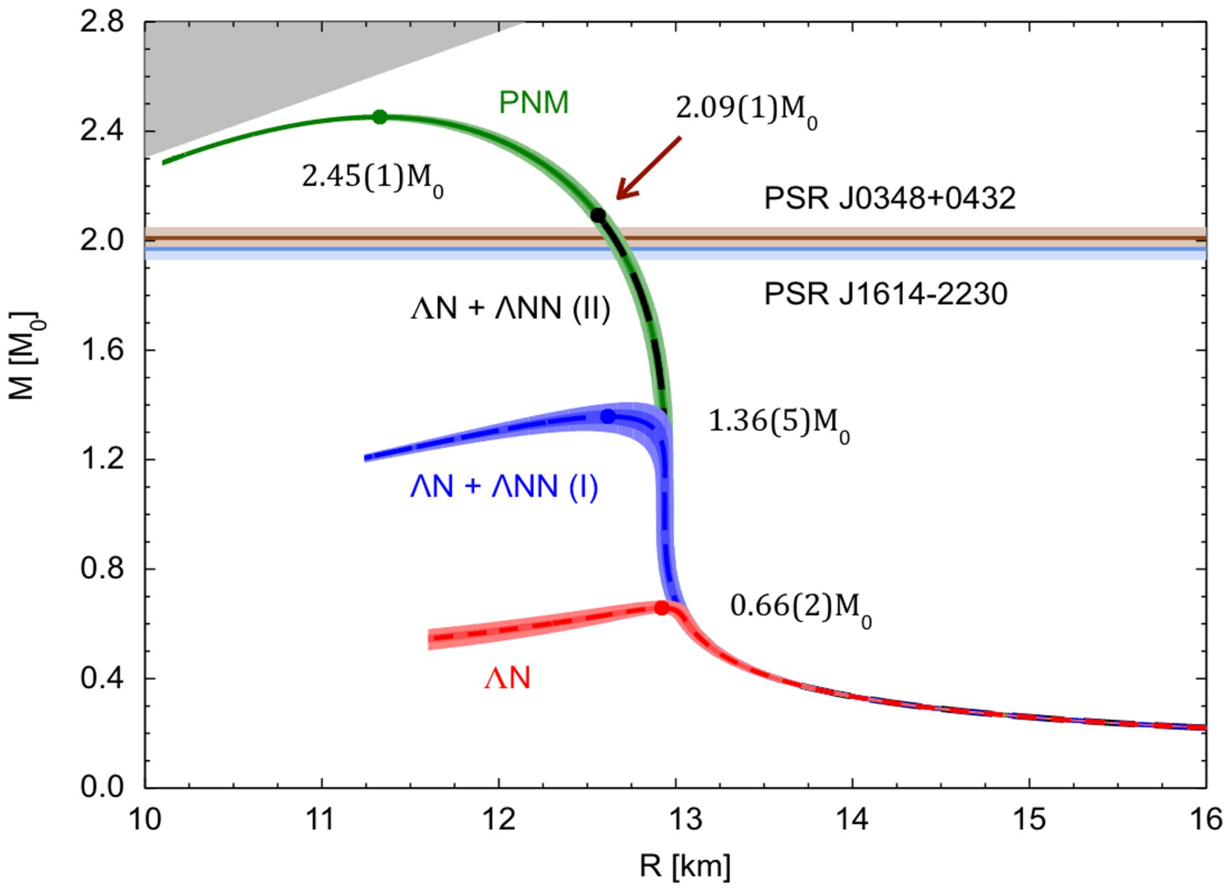


Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

Neutron Stars and the Hyperon Puzzle

- However: EoS can soften with appearance of Λ hyperons
  $\rightarrow$ cannot support heavy neutron stars
- Three-body interactions such as ΛNN play an important role

More on ΛNN: Talk by Laura Šerkšnytė, 07.06.2023, 15:15

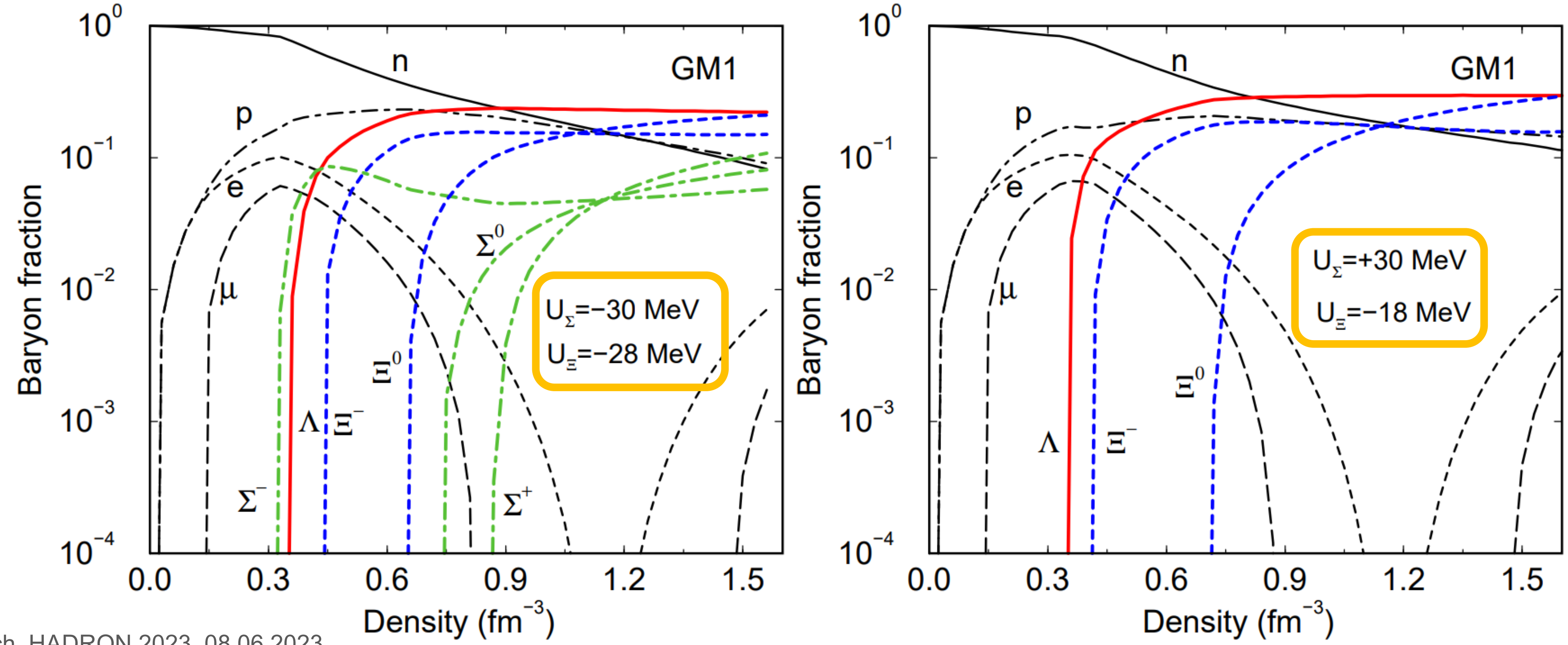


Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

Hyperons in Neutron Stars

- Situation more complex:
  Appearance of multiple hyperon species possible, also Ξ and Σ

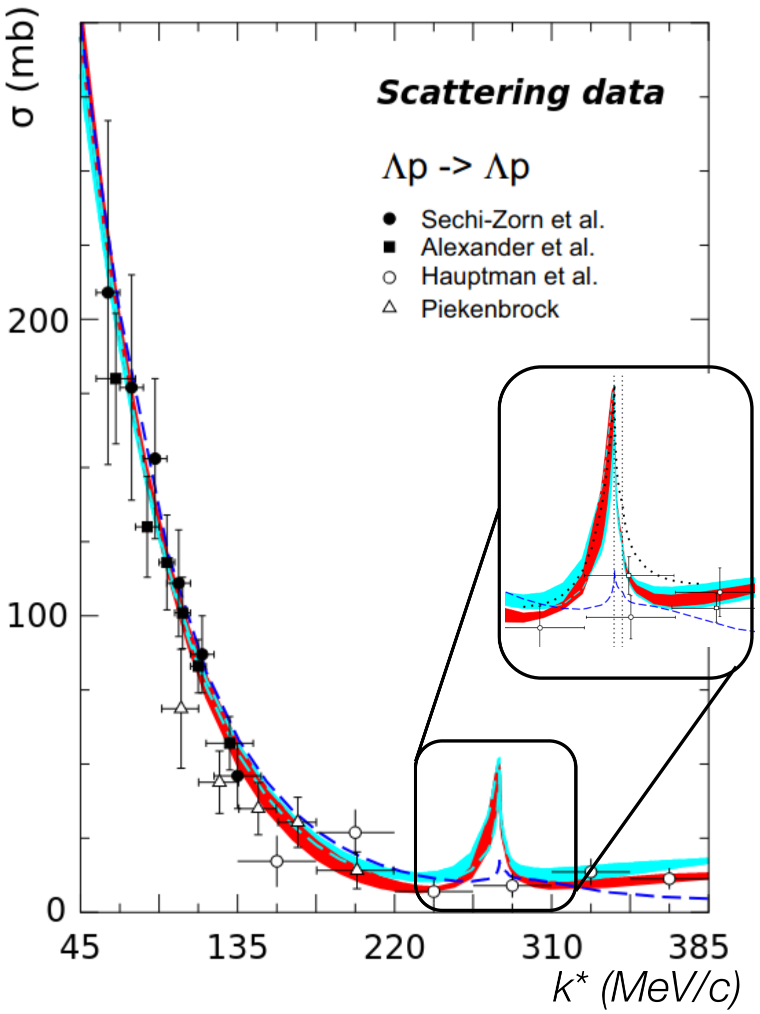
- Modelling of hyperons at large densities depends on hyperon-nucleon interactions
  → constrain from experimental data needed



J. Schaffner-Bielich
NPA 835 (2010) 279

$p\Lambda$ Data before Femtoscopy

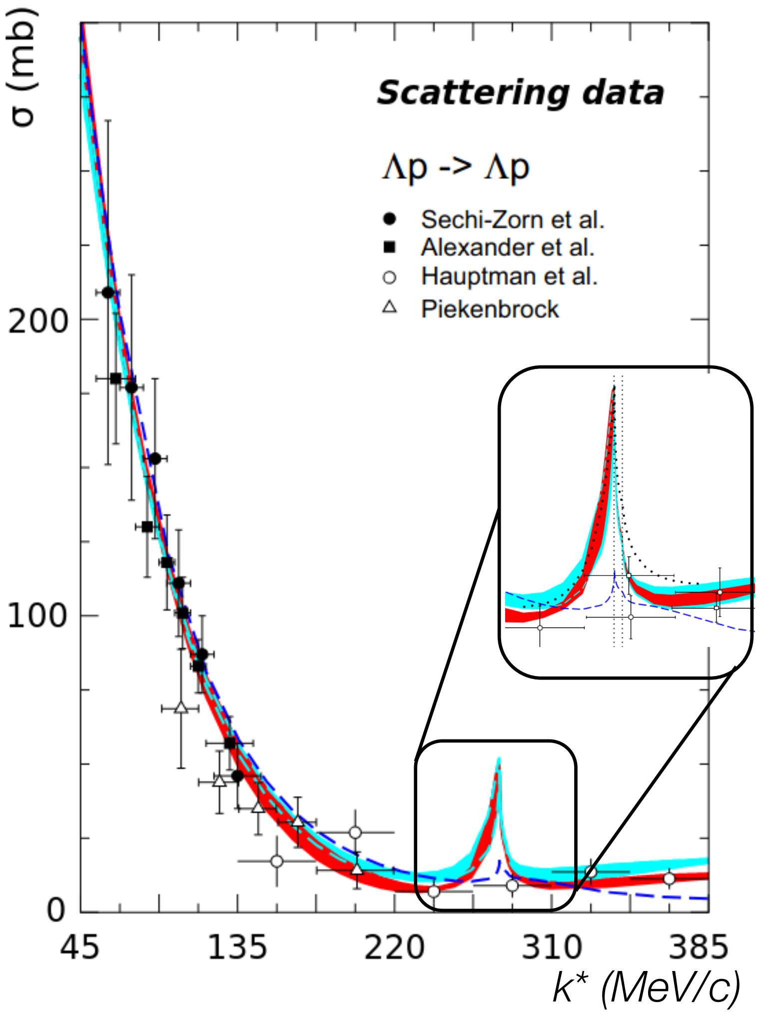
- Scattering data limited to relative momenta above 40 MeV
- ΣN coupling not visible in scattering data
- Scattering data cannot differentiate between χEFT NLO13 and NLO19

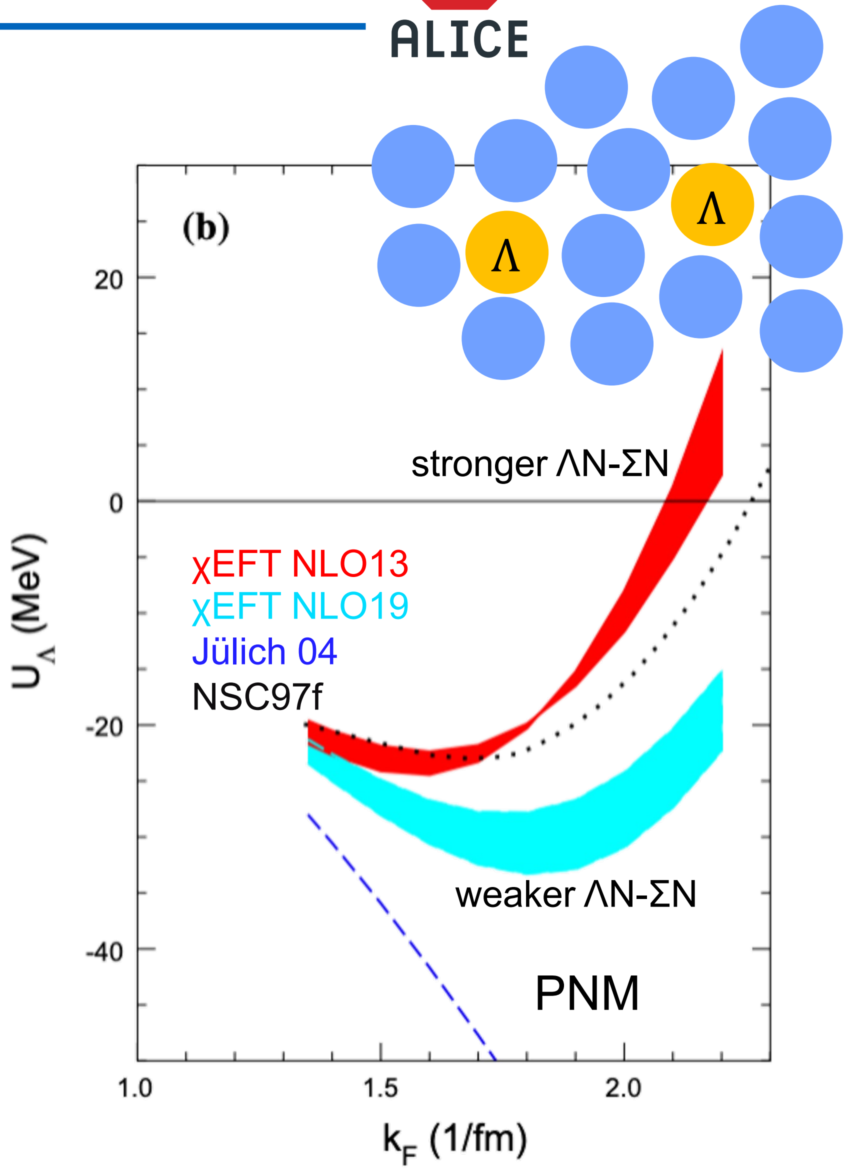


NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)

$p\Lambda$ Data before Femtoscopy

- Scattering data limited to relative momenta above 40 MeV
- ΣN coupling not visible in scattering data
- Scattering data cannot differentiate between χEFT NLO13 and NLO19
- ΣN coupling drives the behaviour of Λ at finite density → important for the EoS of NS

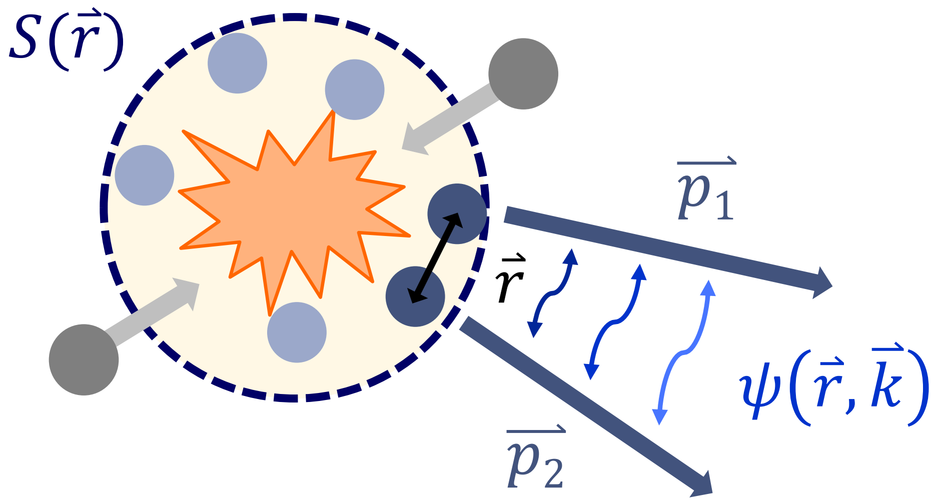




NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meiβner, Eur.Phys.J.A 56 (2020)

Two-body Femtoscopy

L. Fabbietti and V. Mantovani Sarti, O. Vazquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377-402



More information about femtoscopy:
Valentina Mantovani Sarti, 05.06.2023, 14:30
Dimitar Mihaylov, 05.06.2023, 17:40

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

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

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

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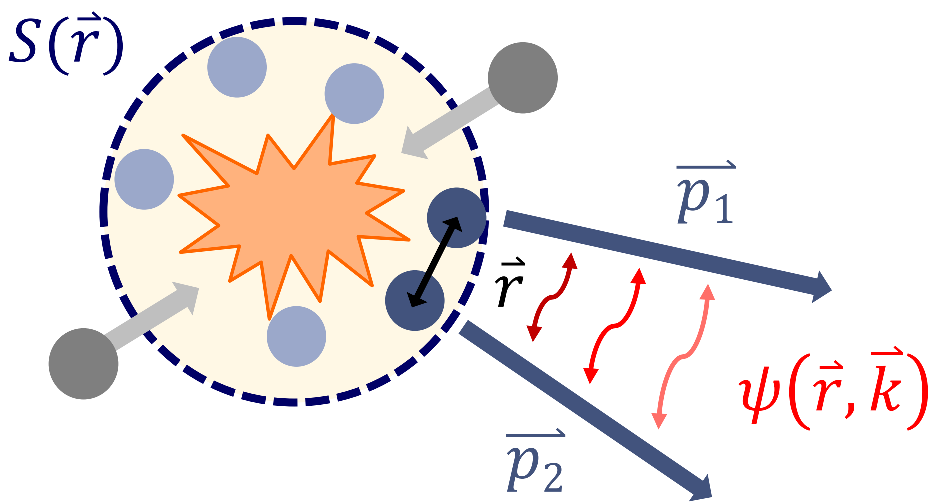

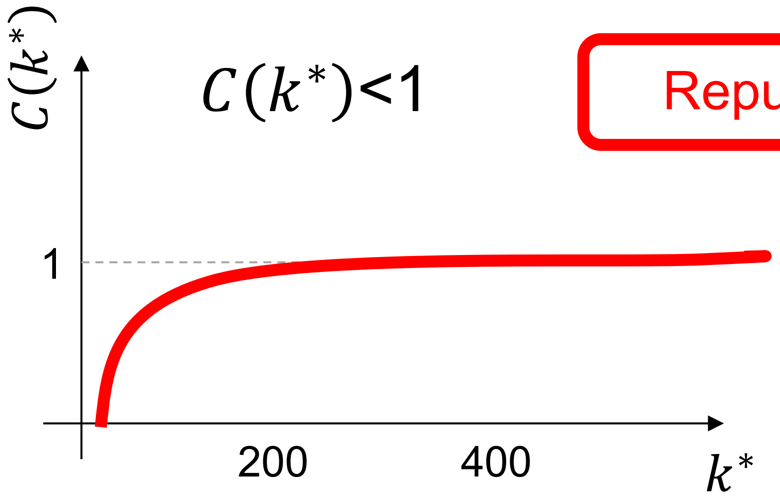

Repulsion

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

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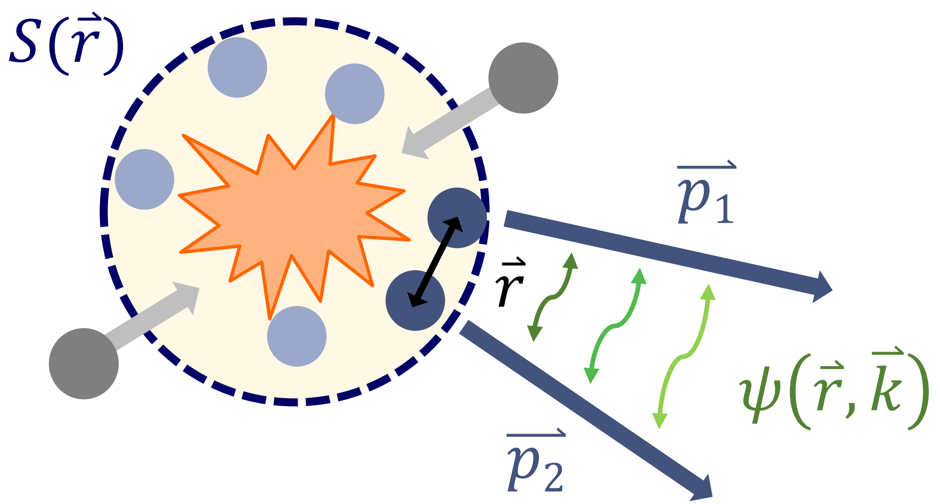

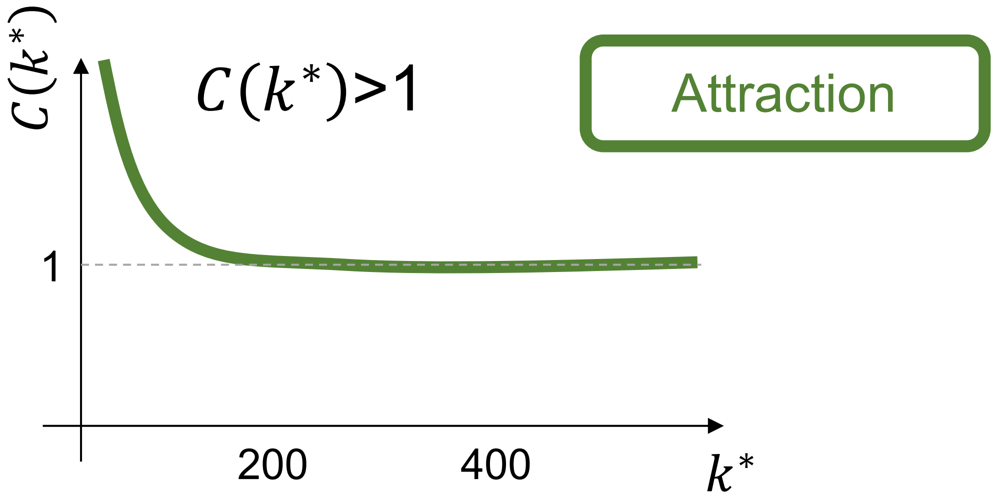

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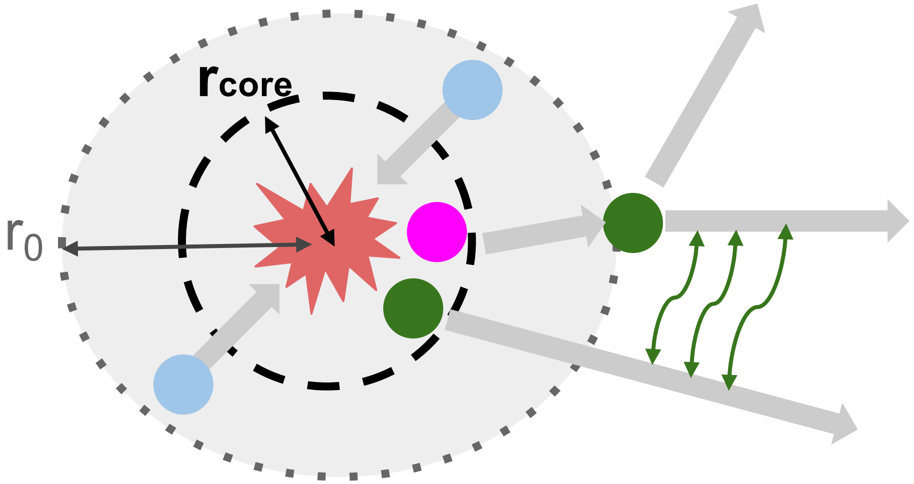
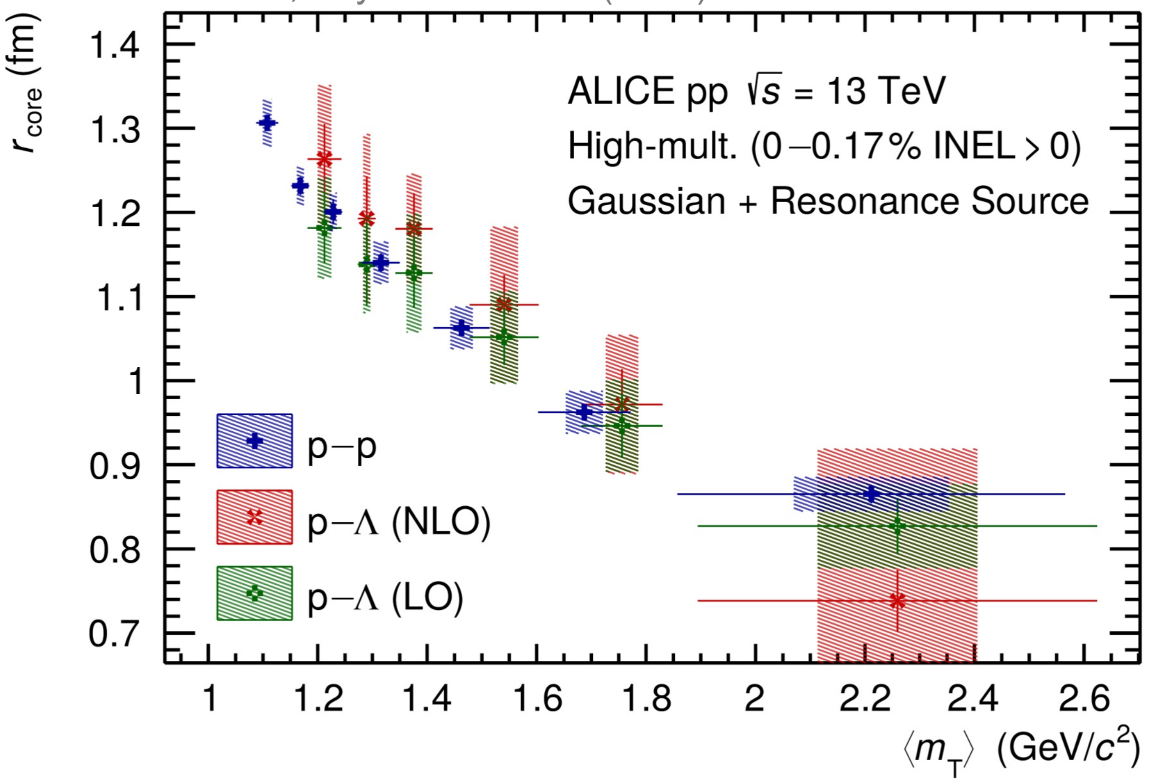
A Common Source for Baryon Emission

- Source distribution of particles from Gaussian core (r_{core}) and decay of short lived particles
- Common source for pp and $p\Lambda$ pairs!
- Measurement from pp
  → r_{core} constrained for any baryon-baryon pair!



ALICE, Phys. Lett. B 811 (2020) 135849



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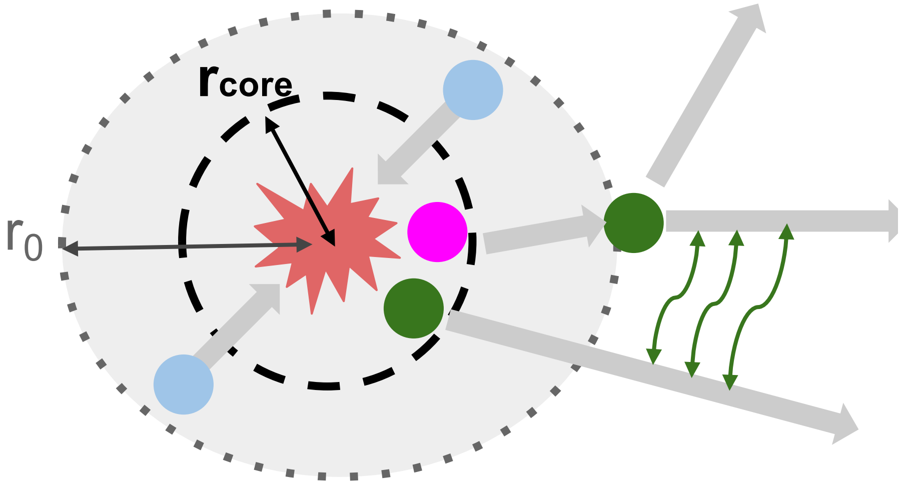
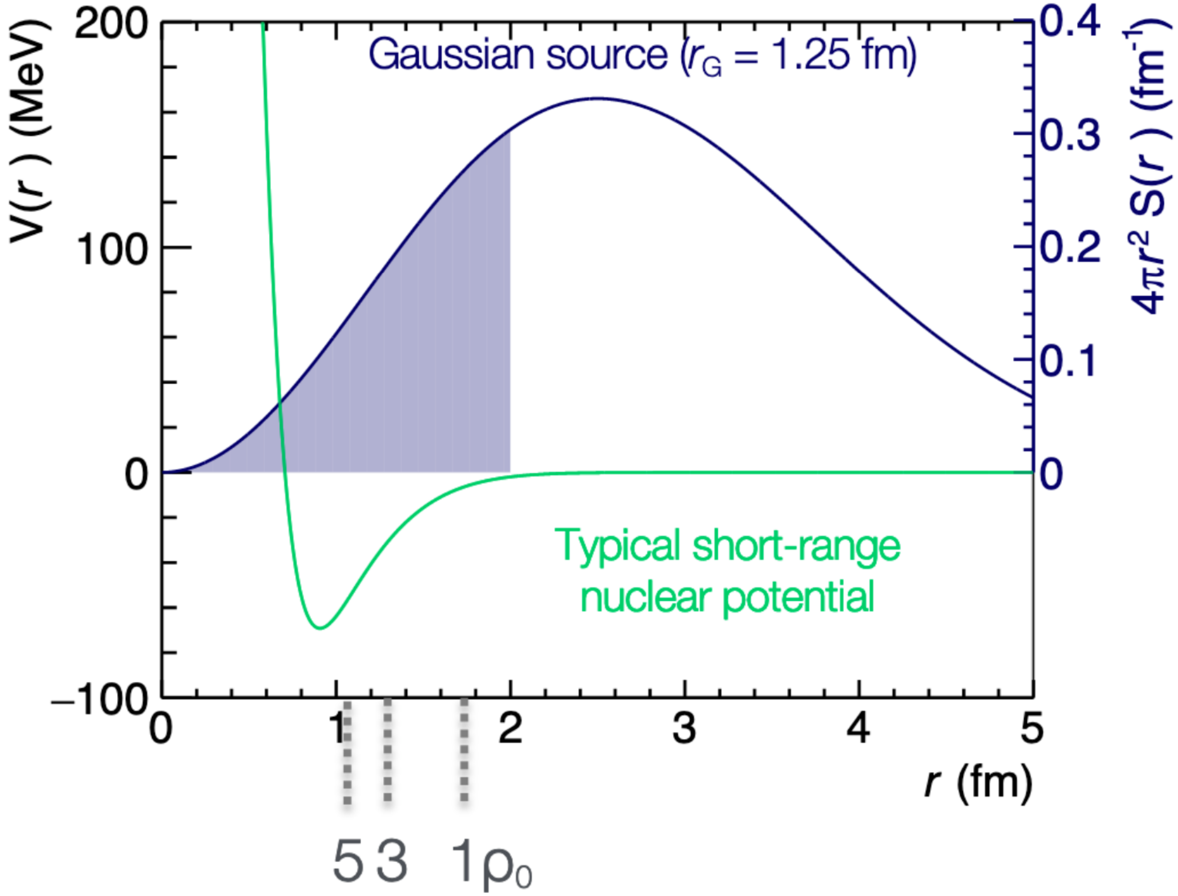
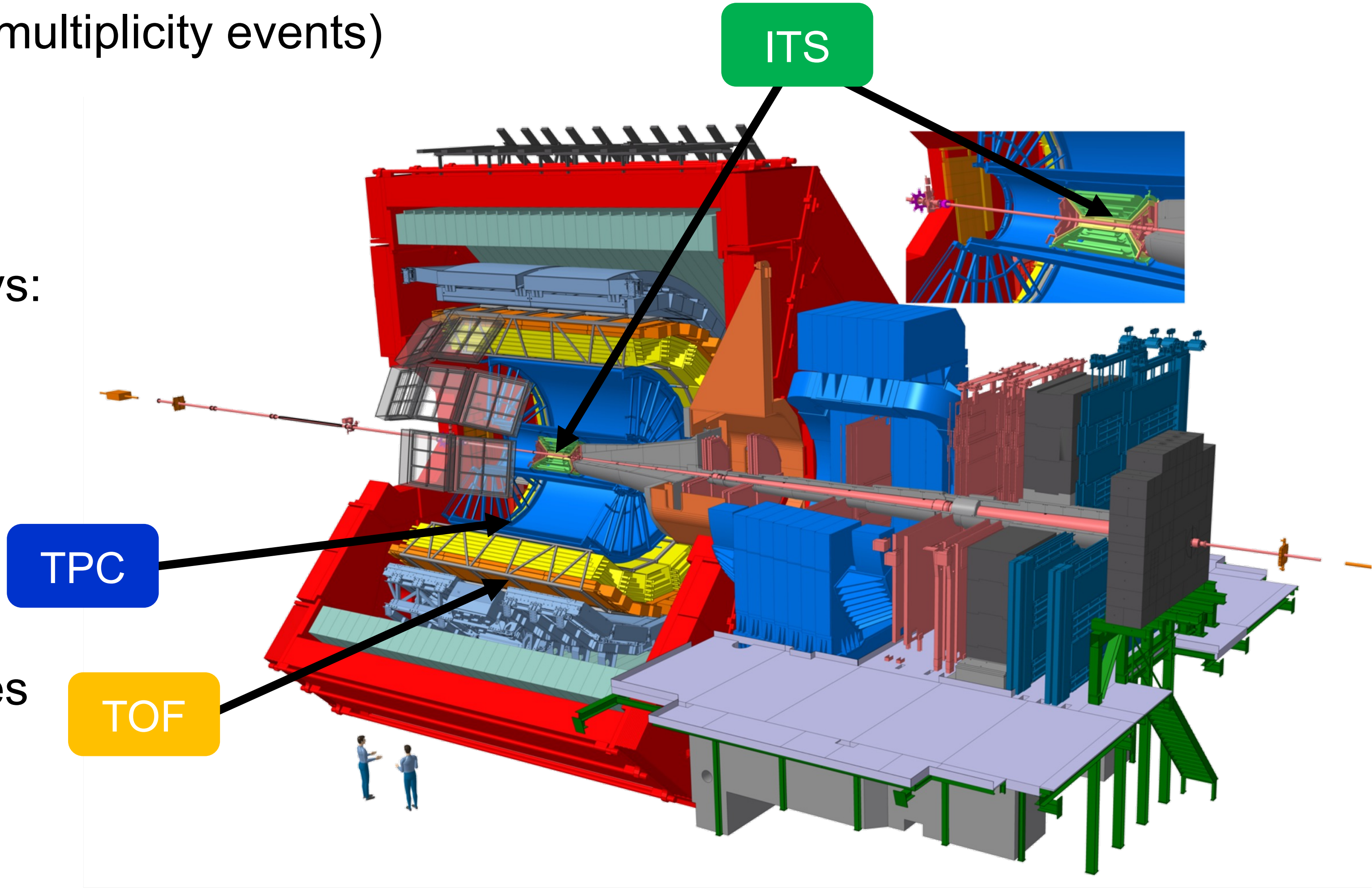




More information on the source:
Talk by Dimitar Mihaylov, 05.06.2023, 17:40

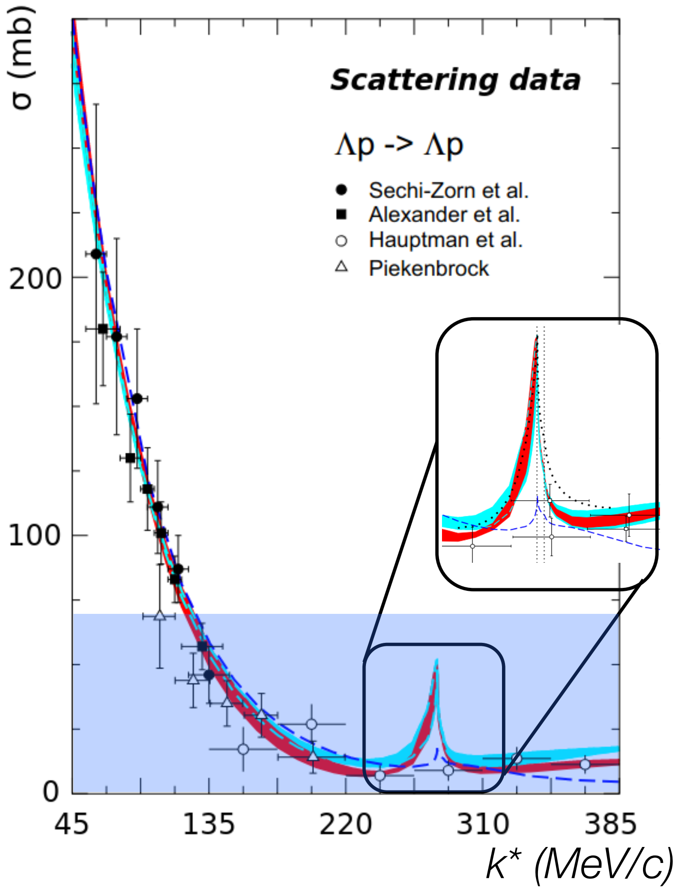
ALICE - A Large Ion Collider Experiment

- Data set: pp at $\sqrt{s}$ = 13 TeV (10^9 high-multiplicity events)
- Direct detection of charged particles (protons, kaons, pions, deuterons)
- Reconstruction of hyperons via decays:
  - $\Xi^- \rightarrow \Lambda + \pi^-$
  - $\Sigma^0 \rightarrow \Lambda + \gamma$
  - $\Lambda \rightarrow p + \pi^-$
- Very good PID capabilities of the detector resulting in very pure samples



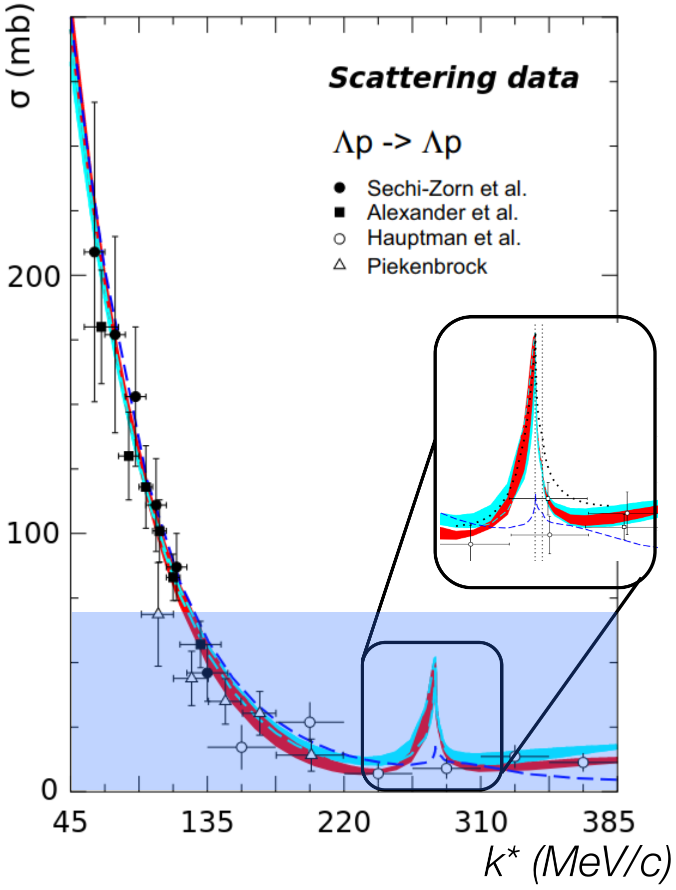
A. Tauro, “ALICE Schematics” (2017), CERN CDS

$p\Lambda$ Results before

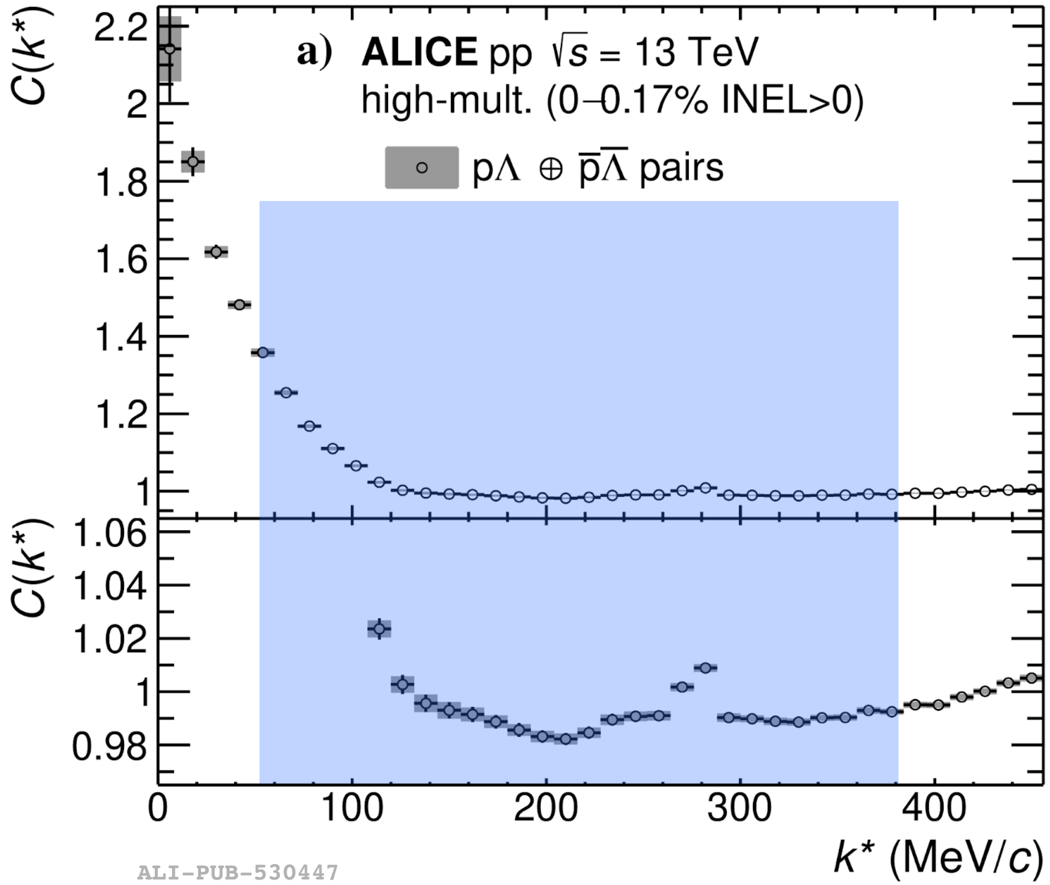


$p\Lambda$ Results before and after Femtoscopy

- Extension of the kinematic range
  → Measurement down to zero relative momentum
- Improvement of precision in data of factor 25
  → Uncertainties < 1 % !
- First experimental evidence of $\Lambda N - \Sigma N$ coupled channel



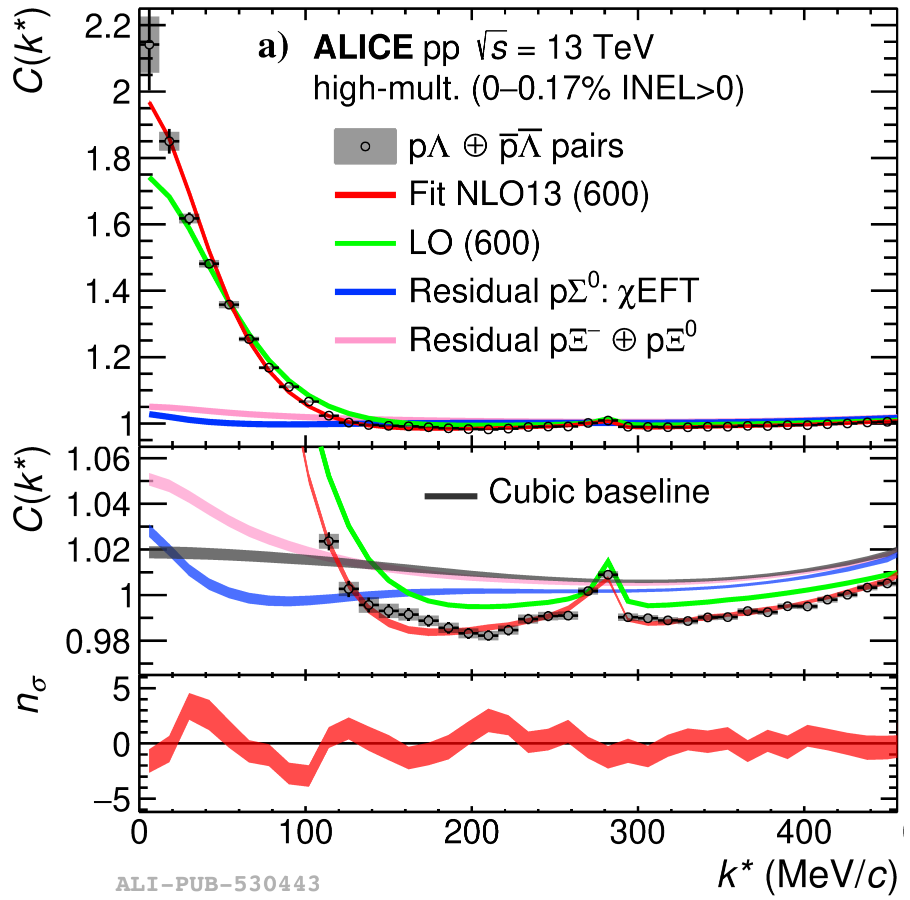
ALICE Coll. PLB 833 (2022), 137272



$p\Lambda$ Results with Femtoscopy

- New insights into $\Lambda N - \Sigma N$ dynamics

Fit with NLO13



n_σ~ 4.5 for k* < 110 MeV/c

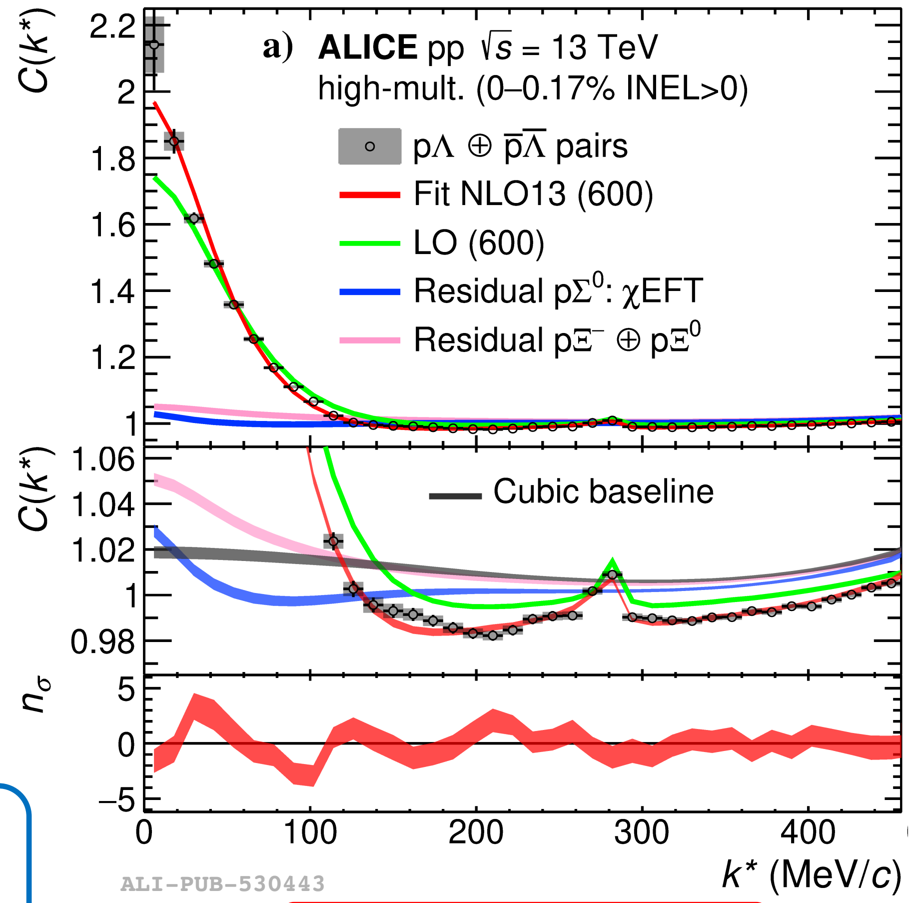
ALICE, PLB 833 (2022), 137272

$p\Lambda$ Results with Femtoscopy

- New insights into $\Lambda N - \Sigma N$ dynamics
- NLO19 potentials favoured:
  - $\rightarrow$ weaker $\Lambda N - \Sigma N$ coupling
  - $\rightarrow$ significant attraction of Λ at high densities
  - $\rightarrow$ large ΛNN repulsion needed

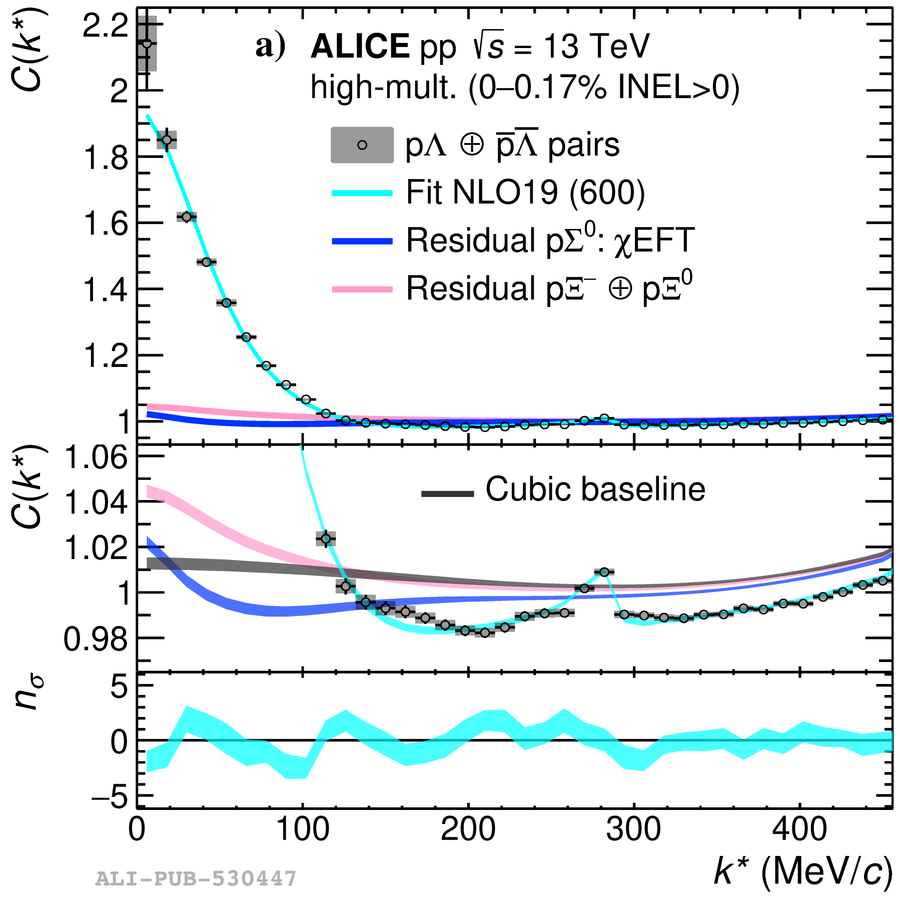
More on ΛNN: Talk by Laura Šerkšnytė, 07.06.2023, 15:15

Fit with NLO13



n_σ~ 4.5 for k* < 110 MeV/c

Fit with NLO19



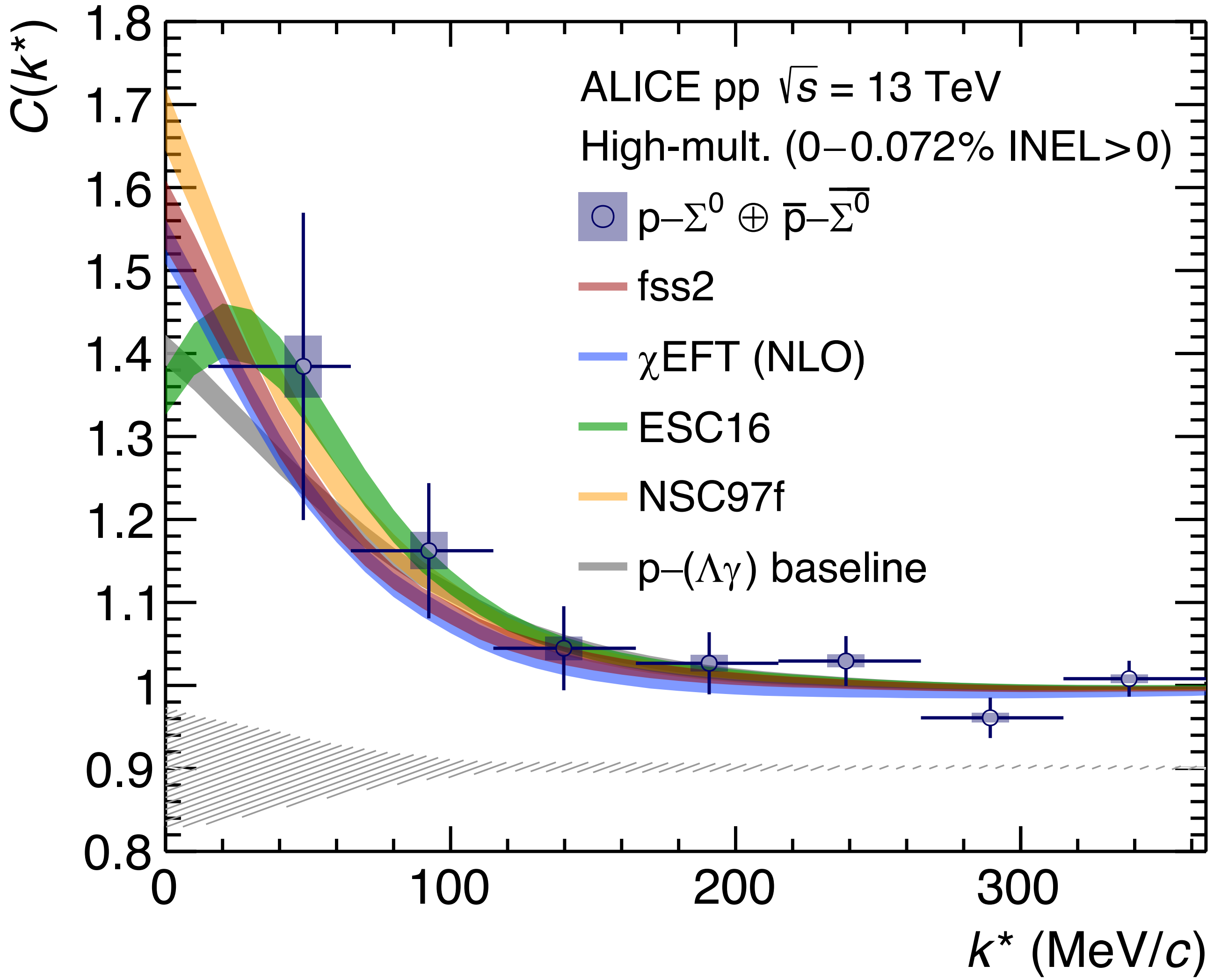
n_σ~ 3.2 for k* < 110 MeV/c

ALICE, PLB 833 (2022), 137272

The $p\Sigma^0$ Interaction

- Reconstruction of Σ^0 via decay to $\Lambda + \gamma$
- $p\Sigma^0$ compatible to the baseline
- $p\Sigma^0$ femtoscopy already possible in Run 2
  → stay tuned for data of Run 3 for higher statistics!

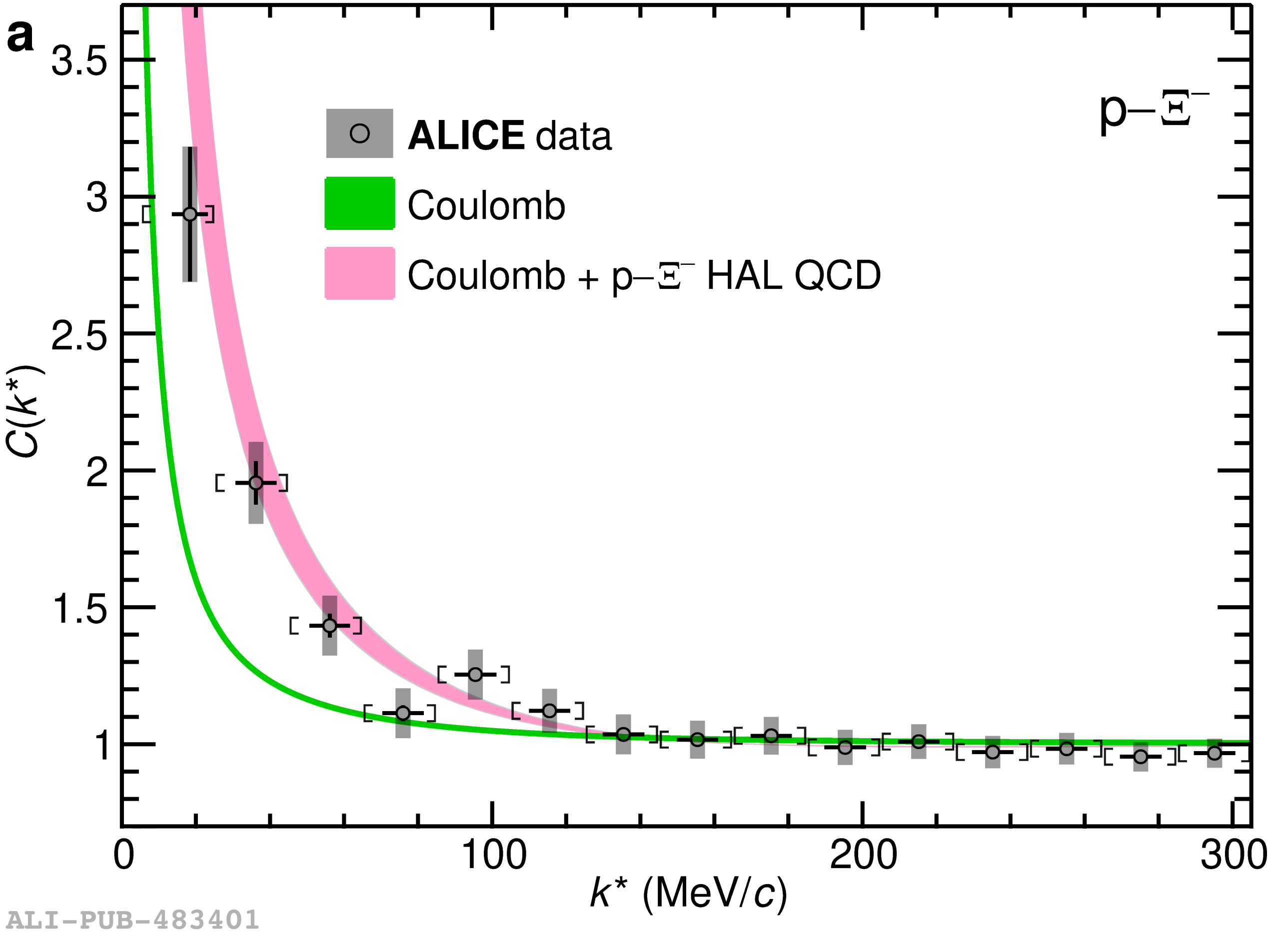
ALICE, PLB 805 (2020) 135419



The “strangest” System: $p\Xi^-$

- Reconstruction of Ξ^- via decay to $\Lambda + \pi^-$
- Coulomb interaction only cannot describe the data
  → attractive strong interaction needed
- Lattice QCD calculations for $p\Xi^-$ by HAL QCD collaboration
  HAL QCD, Nucl.Phys.A 998 (2020) 121737
- One of the first direct tests of Lattice QCD

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

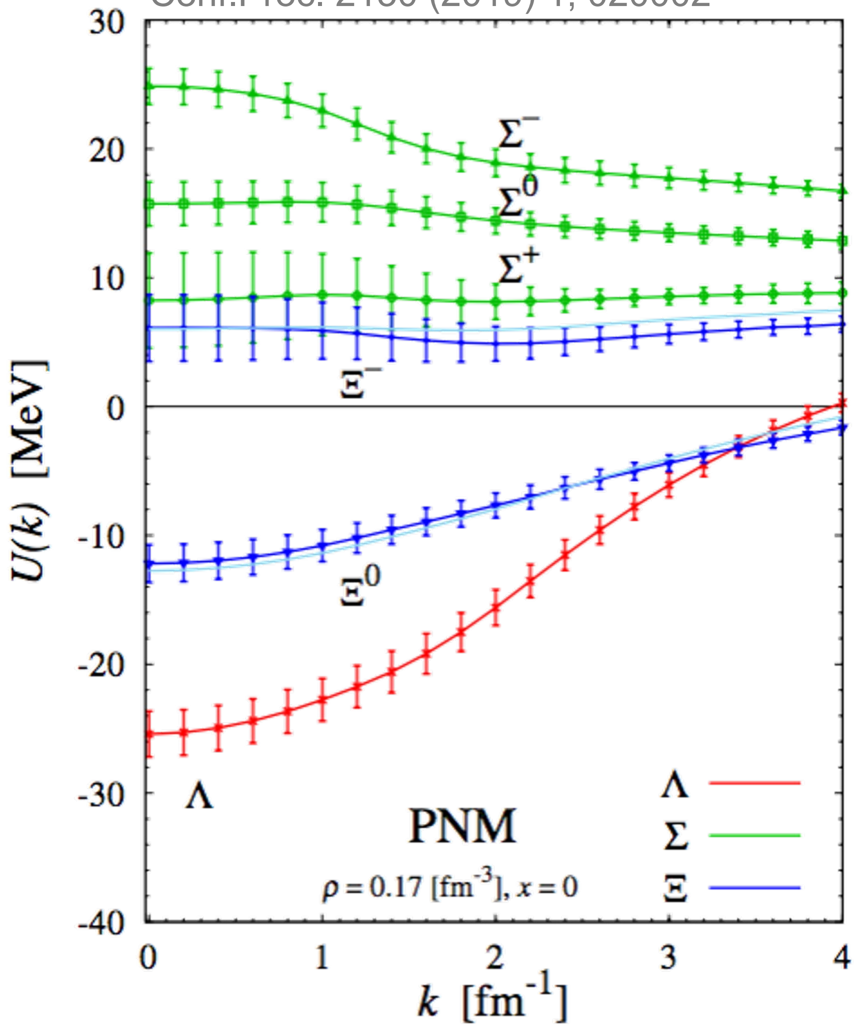


Single Particle Potential of Ξ^-

- HAL QCD potential of $p\Xi^-$ tested/verified with femtoscopic data
- Extraction of single-particle potential U_Ξ by HAL QCD Collaboration
  $\rightarrow$ predictions in PNM:
  $U_\Xi \sim +6\ \mathrm{MeV}$
  HAL QCD Coll., PoS INPC2016 (2016) 277

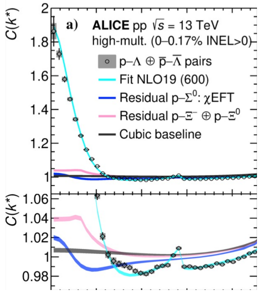
  $\rightarrow$ stiffening of the EoS

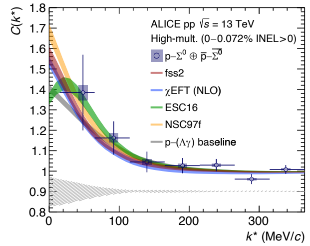
HAL QCD Collaboration, AIP Conf.Proc. 2130 (2019) 1, 020002

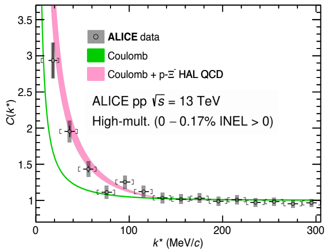


Updating the EoS

Two-body interaction

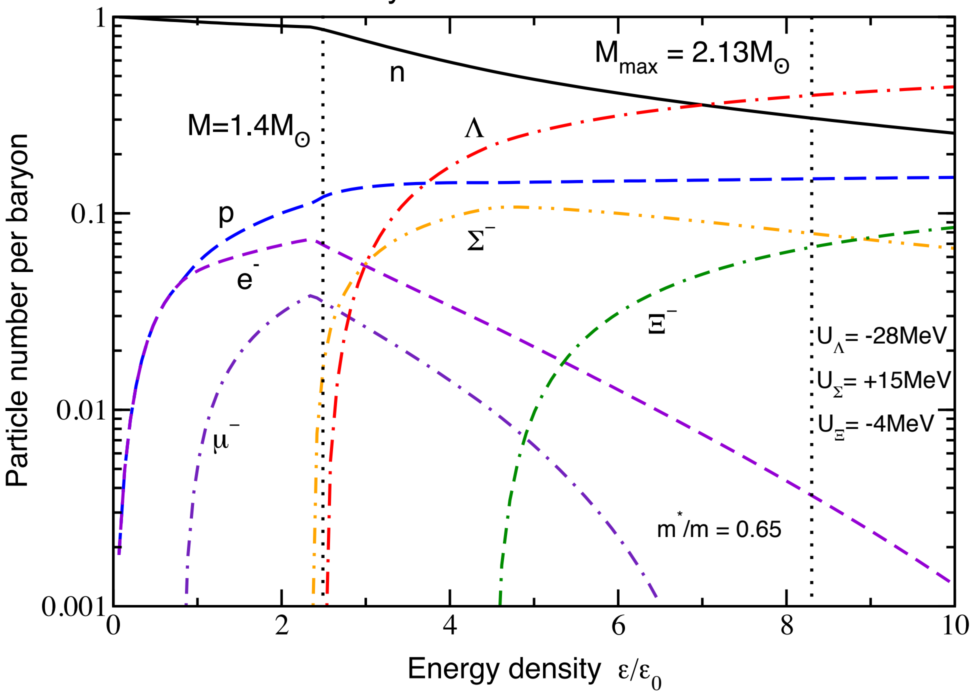






Single-particle potentials EoS

Courtesy J. Schaffner-Bielich 2020

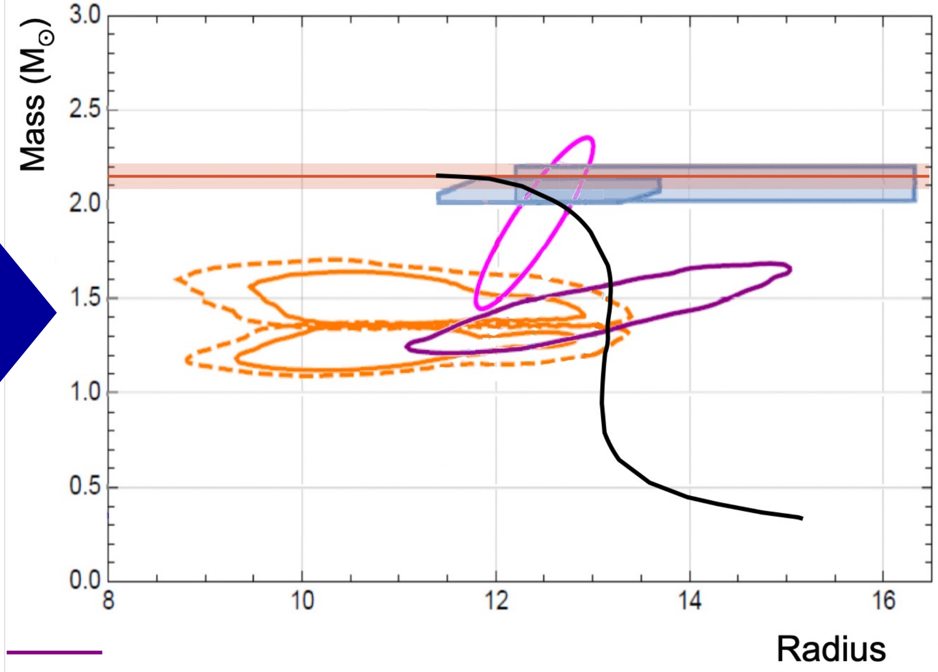


This is only an example!

V. Mantovani Sarti, L. Fabbietti,O. Vazquez-Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)
S. Weissenborn et al., J. NPA 881 (2012)
J. Schaffner-Bielich, I. Mishustin, PRC 53 (1996)
N. Hornick et al., PRC 98 (2018)

Mass vs Radius relation for hyperon stars

Adapted from J. Schaffner-Bielich and B. Dönigus 2020



NICER experiment: M.C Miller et al. AJL 918 (2021)

Mass measurement: H. T. Cromartie et al. Nature Astron. 4 (2019)

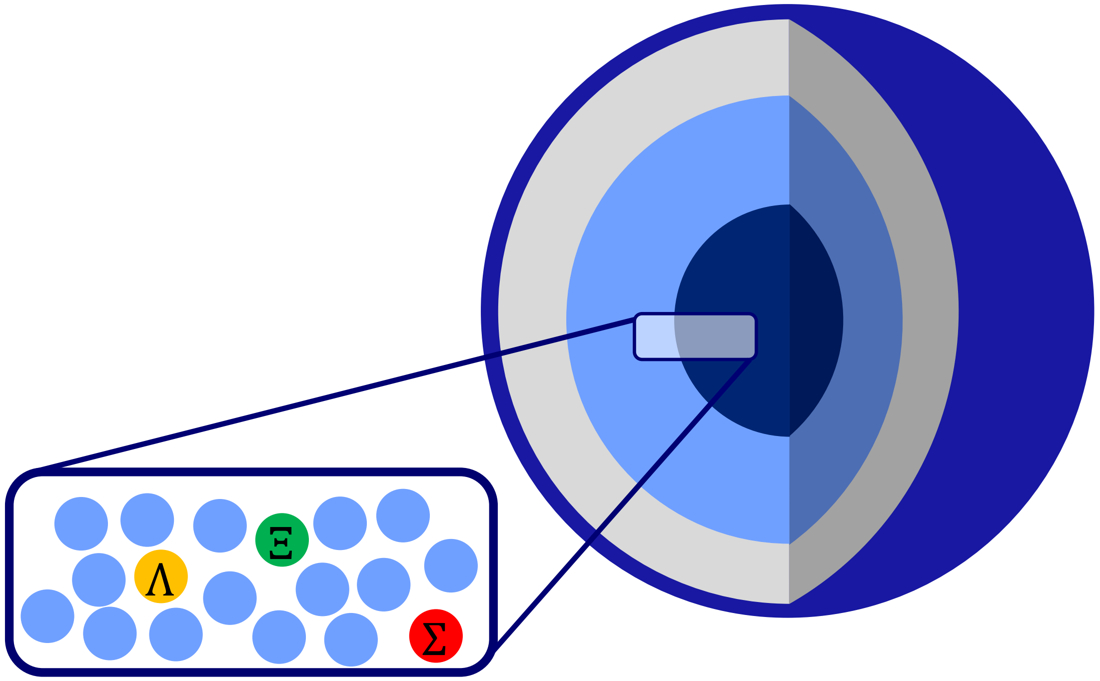
Gravitational waves data: B. P. Abbott et al. PRL 119 (2017)

Summary and Outlook

Femtoscopy with ALICE in small collision systems at the LHC:

- Study of previously difficult accessible hyperon-nucleon interactions
  - First direct tests of Lattice QCD ($p\Xi^-$)
  - Sensitivity to different models with consequences for the EoS of neutron stars ($p\Lambda$)
- Hyperon puzzle is solved?

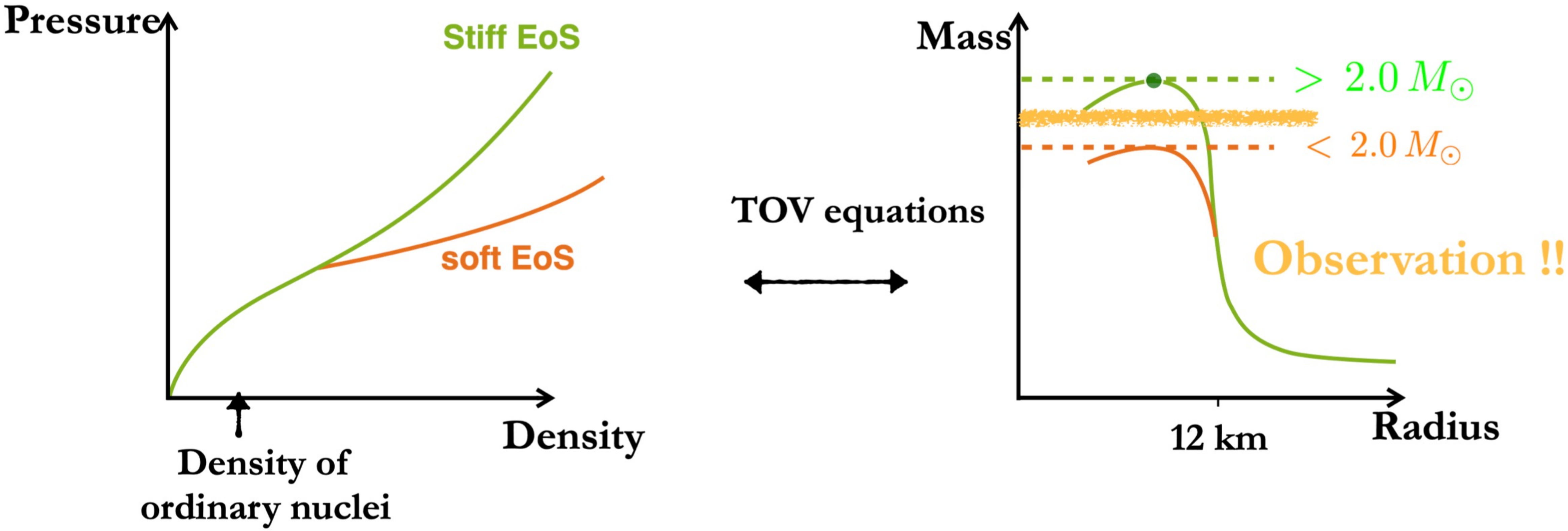
  Precision measurements of ΣN and three-body interactions necessary
  $\rightarrow$ Stay tuned for Run 3!



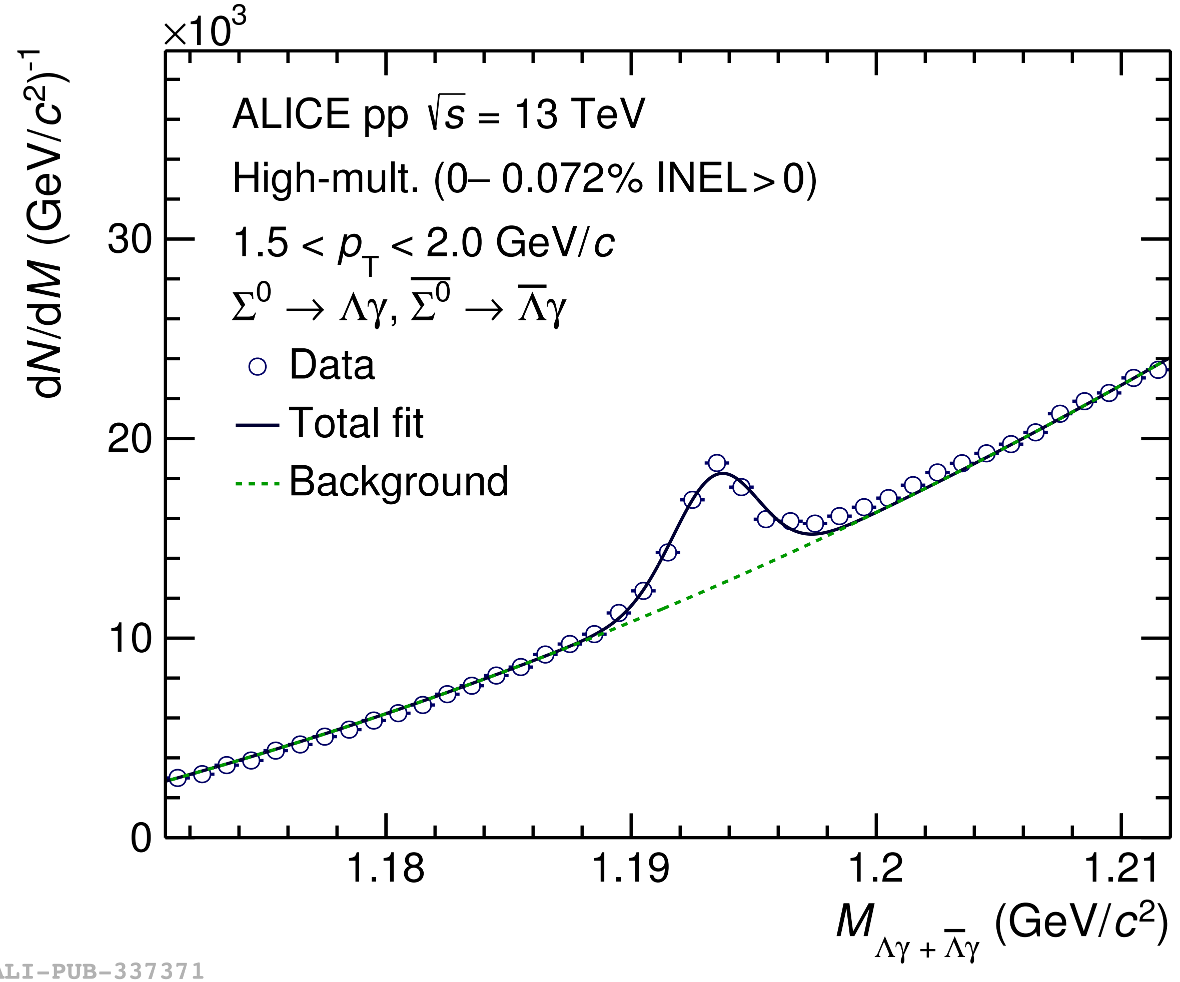
Other Femtoscopy Talks:
Valentina Mantovani Sarti, 05.06.2023, 14:30
Dimitar Mihaylov, 05.06.2023, 17:40
Wioleta Rzęsa, 07.06.2023, 14:24
Laura Šerkšnytė, 07.06.2023, 15:15
Ramona Lea, 08.06.2023, 15:45

Backup

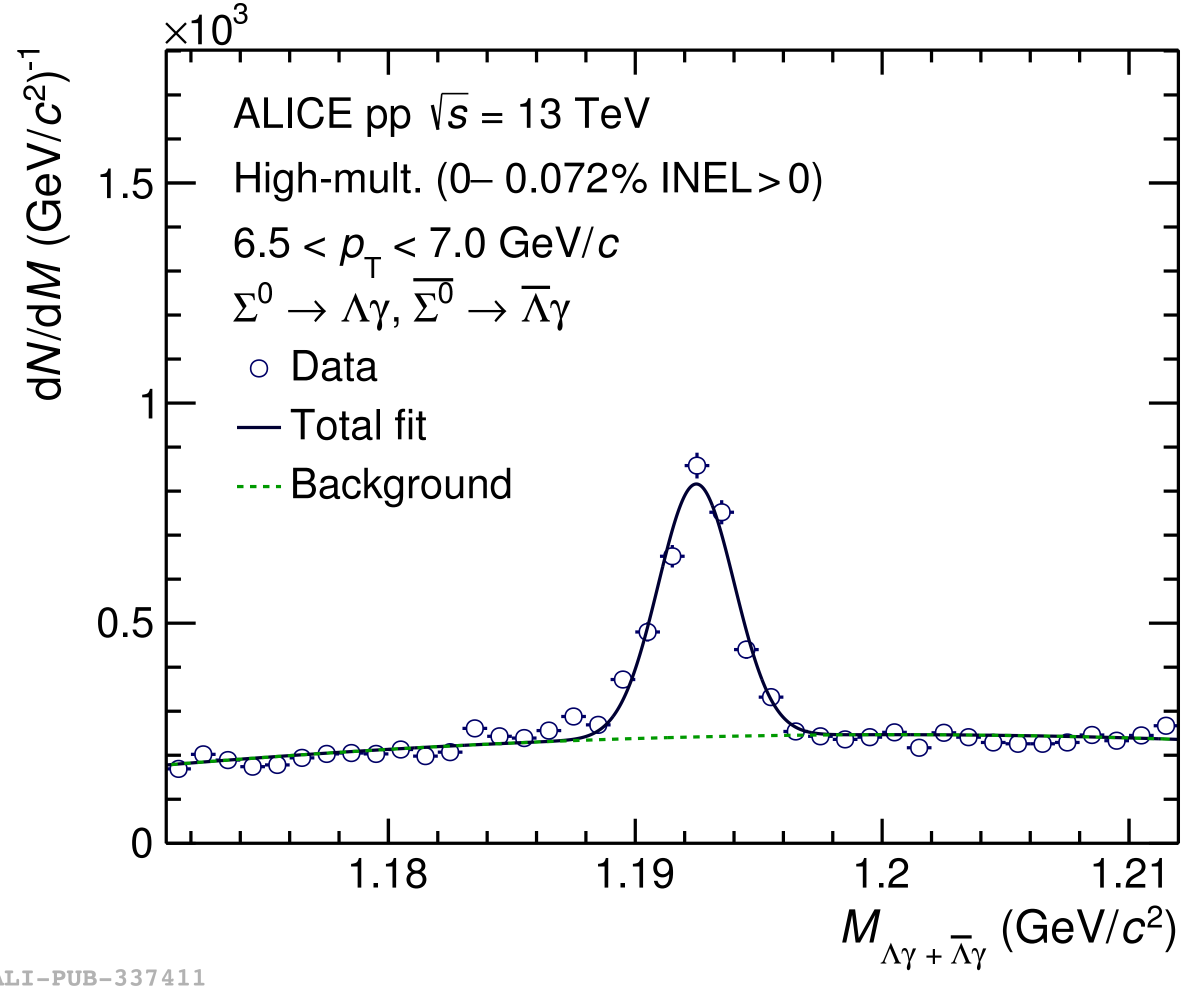
Neutron Stars EoS



Σ^0 Invariant Mass



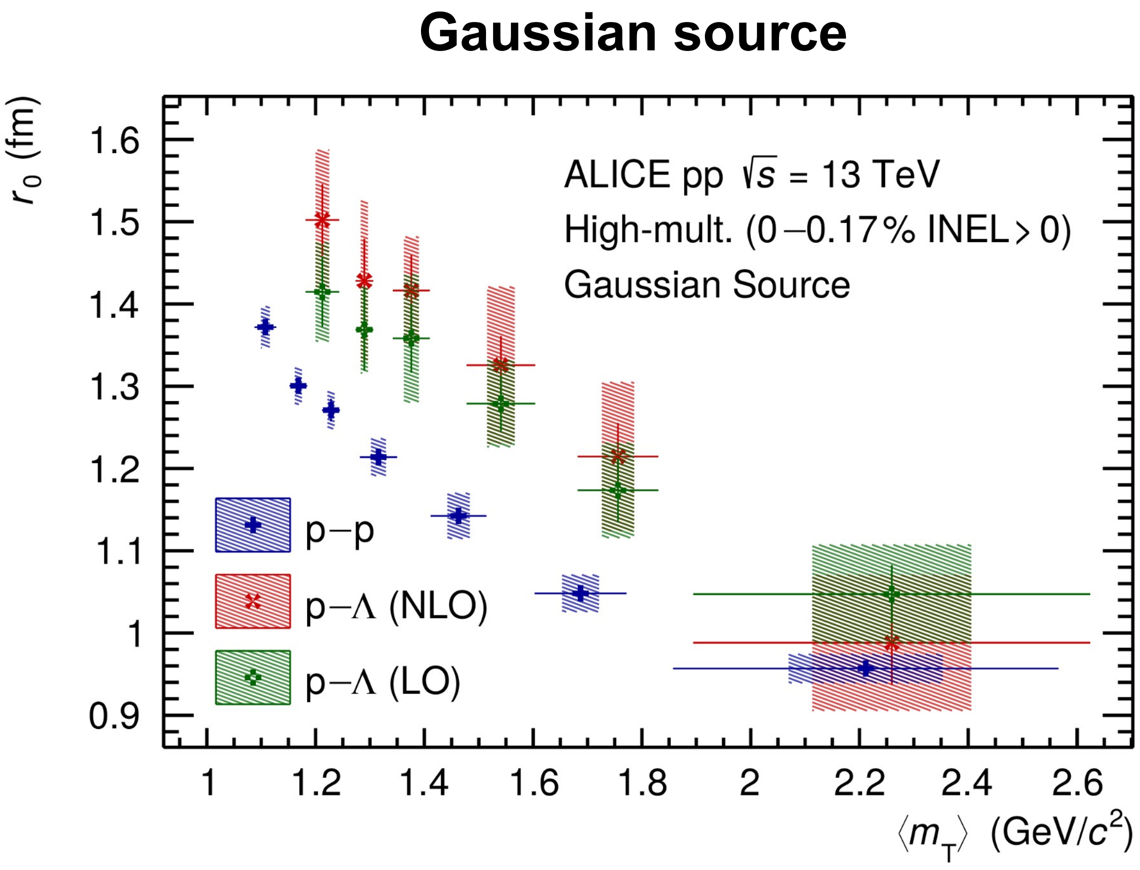
ALI-PUB-337371



ALI-PUB-337411

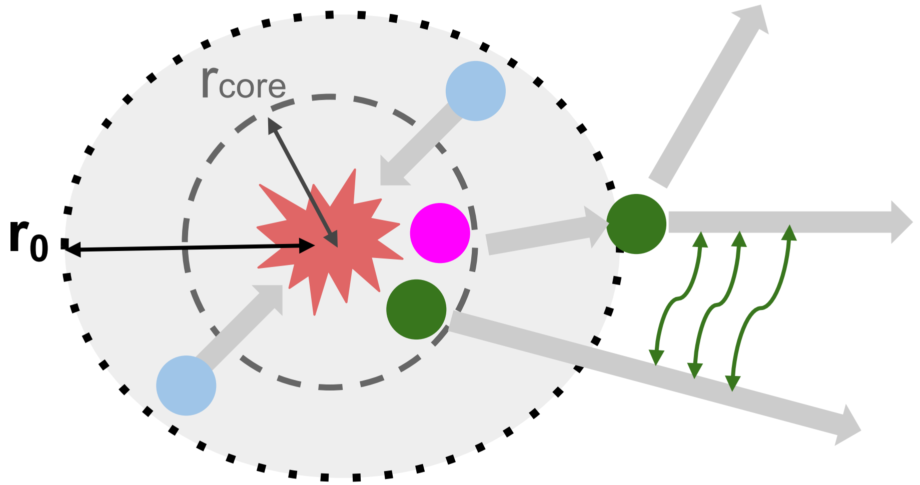
A common source – Gaussian Profile

ALICE, Phys. Lett. B 811 (2020) 135849



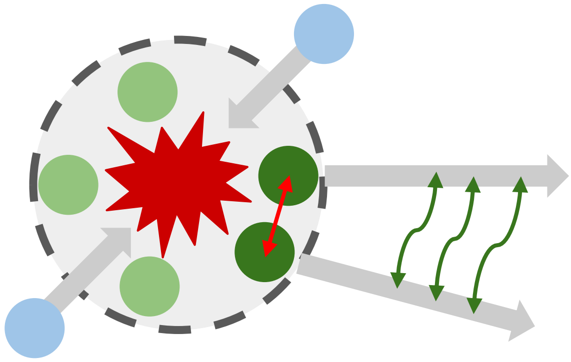
Different source size for p-p and p-Λ pairs

- The Statistical Hadronization Model tells us: c.a. ⅔ of protons and Λs stem from resonances.
  The average lifetimes (cτ) are:
  1.6 fm for X→proton
  4.7 fm for X→Λ
- **Production through short-lived resonances**

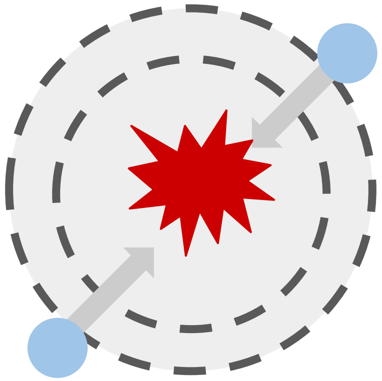


Emission source – Possible Profiles

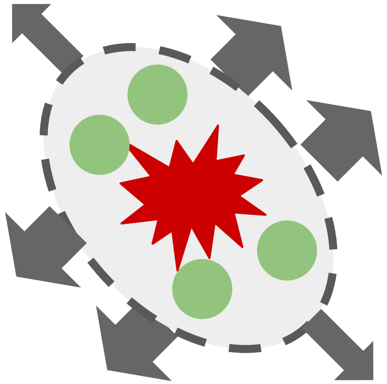
Perfect Gaussian

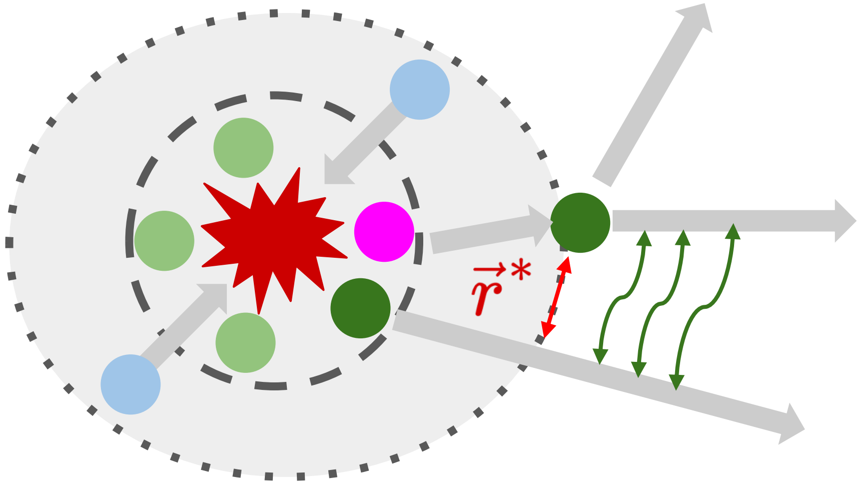


Radial flow
Expansion with const. velocity,
different effect on different masses



Local modifications
due to elliptic flow

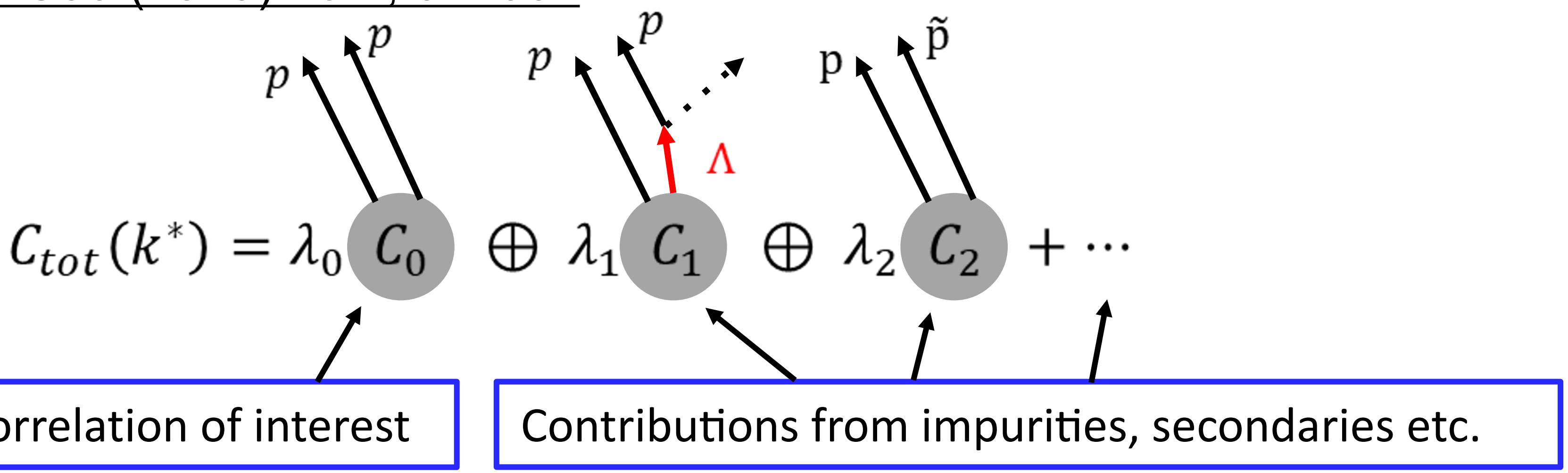




- Resonances with cτ ~ 1 fm (Δ,N*, etc.) introduce an exponential tail to the source
- Different for each particle species

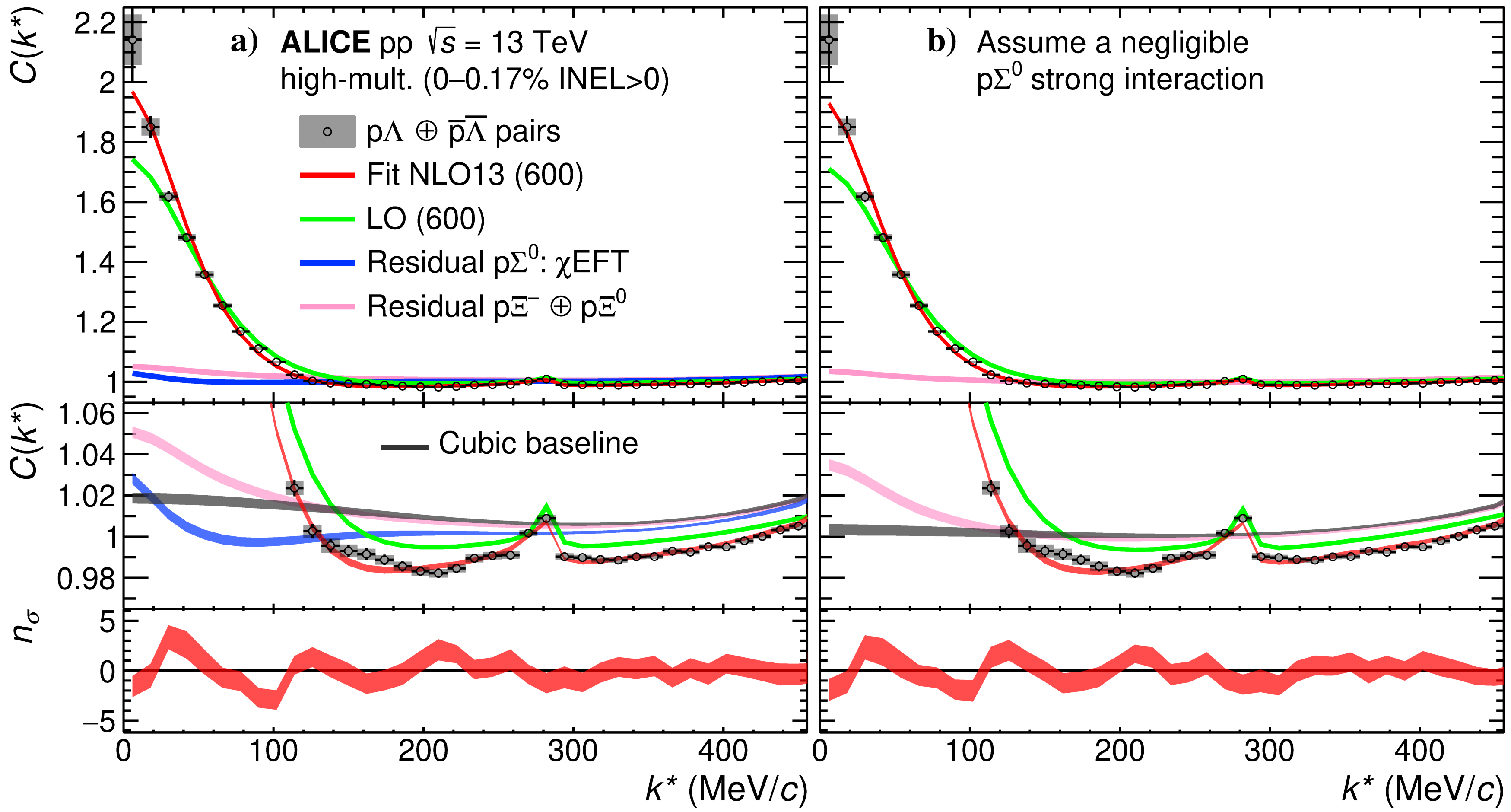
Femtoscopy - Decomposition of C(k*)

- Amount of impurities and secondaries based on a data-driven MC study as done in Phys.Rev. C99 (2019) no.2, 024001



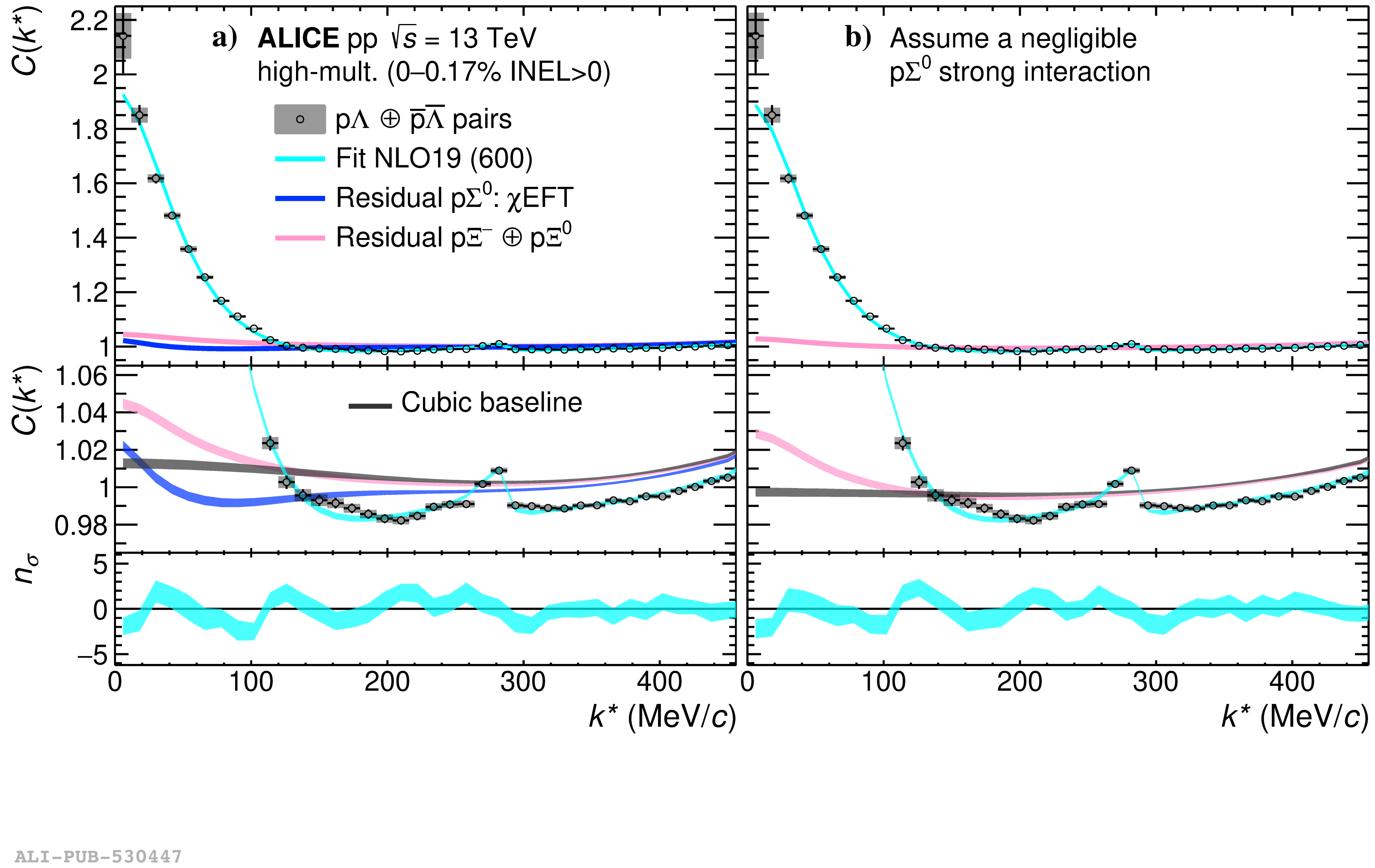
- Purity ($\mathcal{P}$) from fits to the invariant mass distribution or MC data
- Feed-down fractions (f) from MC template fits
- $\lambda_i = \mathcal{P}_{i_1} f_{i_1} \mathcal{P}_{i_2} f_{i_2}$, where $i_{1,2}$ denote the two particles of the i-th contribution

$p\Lambda$ Results with Femtoscopy

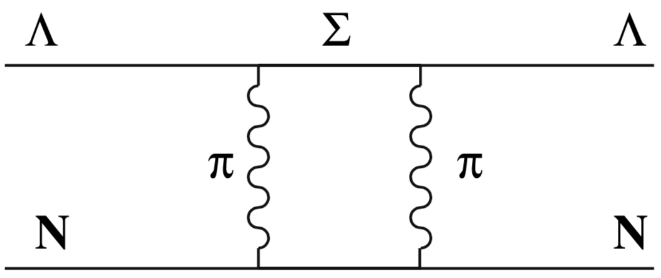


ALI-PUB-530443

$p\Lambda$ Results with Femtoscopy

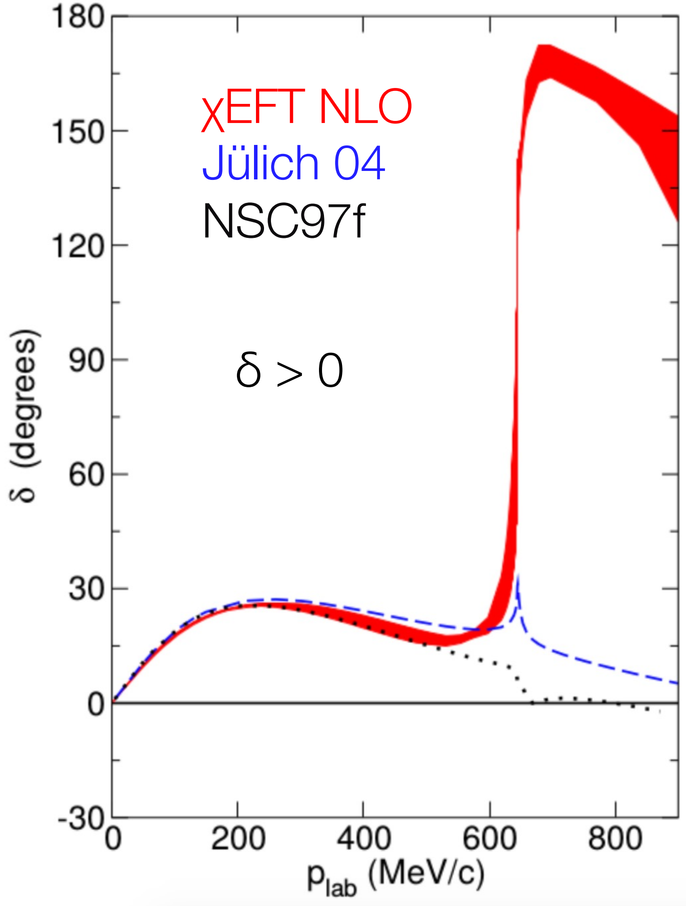


Influence of the $\Lambda N - \Sigma N$ coupled channel (vacuum)

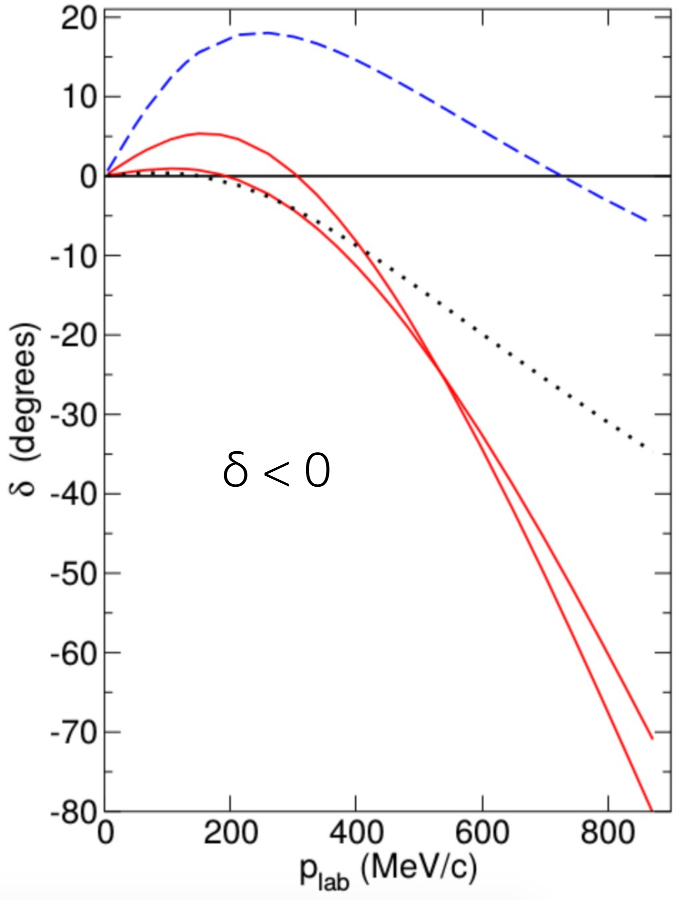


- Small mass difference between Σ and Λ: ~80 MeV/c
- Repulsion for Λp when the $\Lambda N - \Sigma N$ coupled channel is neglected

Λp $^3S_1$ with the $\Lambda N - \Sigma N$ coupling

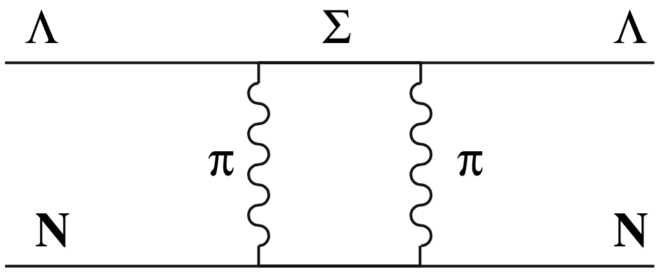


Λp $^3S_1$ w/o the $\Lambda N - \Sigma N$ coupling



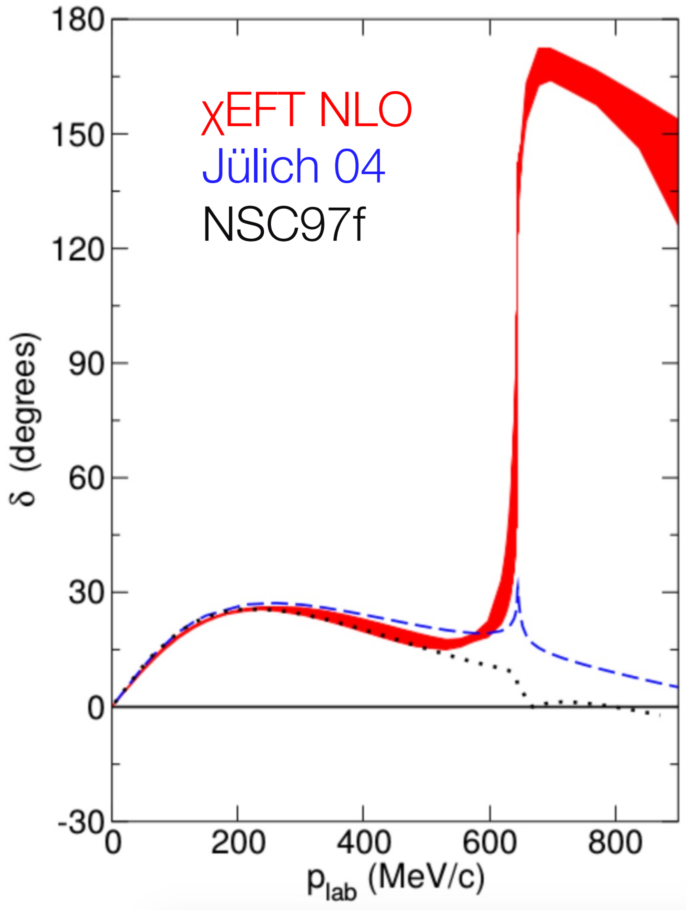
J. Haidenbauer *et al.*, Eur. Phys. A (2017) 53, 121.

Influence of the $\Lambda N - \Sigma N$ coupled channel

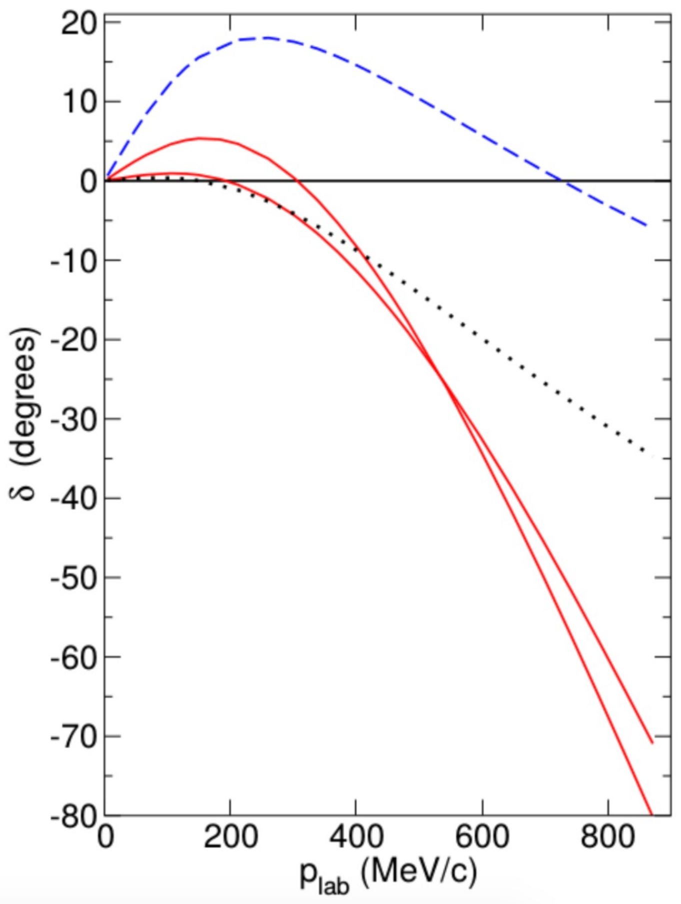


- $\Lambda N - \Sigma N$ acts as an effective attraction
- Repulsion for Λp when the $\Lambda N - \Sigma N$ coupled channel is neglected
  - strong coupling $\Longrightarrow$ dispersion repulsive effects $\Longrightarrow$ Shift of hyperon appearance towards higher densities
  - weak coupling $\Longrightarrow$ more attractive $U_\Lambda(\rho_0,0)$

Λp $^3S_1$
with the $\Lambda N - \Sigma N$ coupling



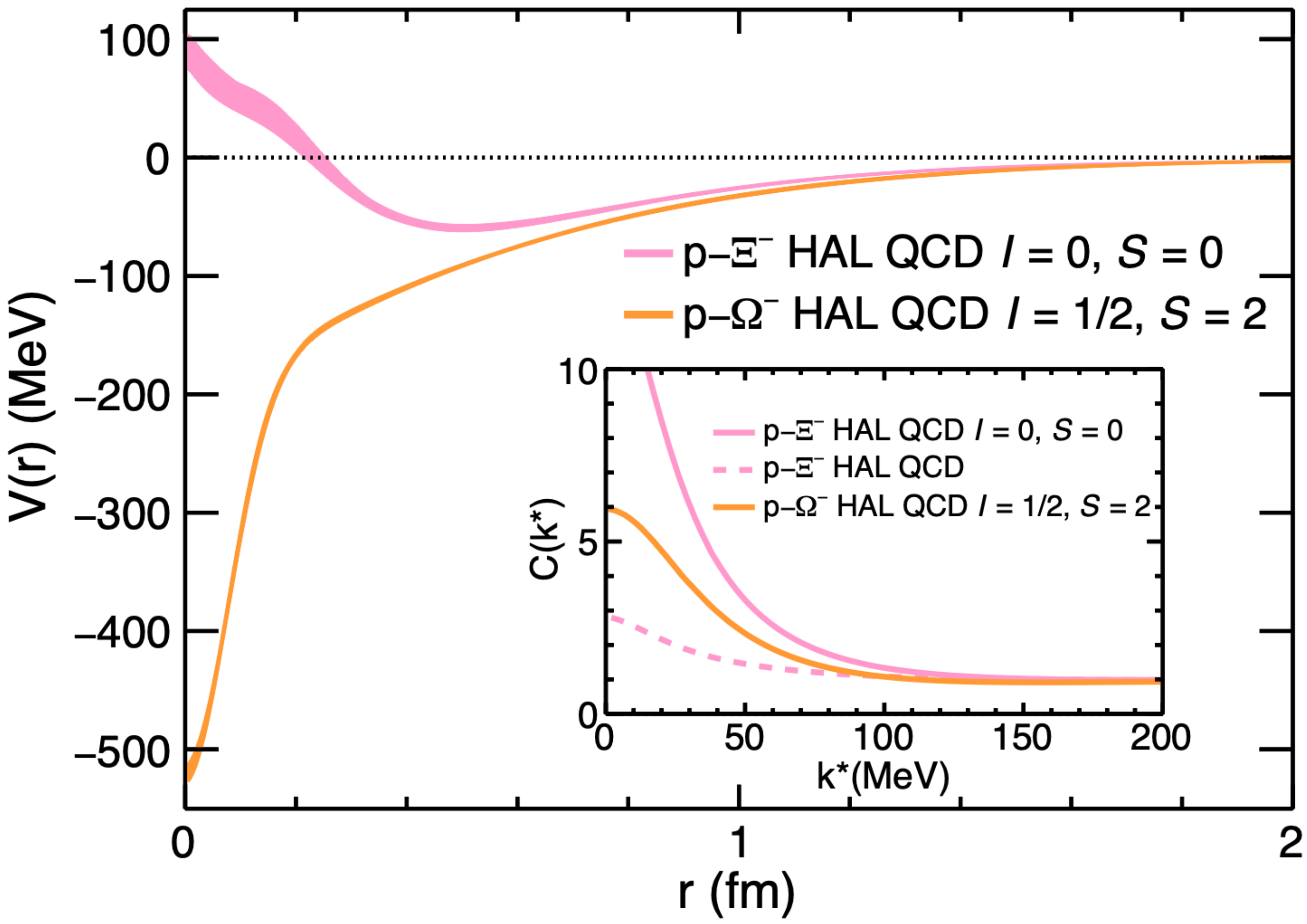
Λp $^3S_1$
w/o the $\Lambda N - \Sigma N$ coupling



J. Haidenbauer *et al.*, Eur. Phys. A (2017) 53, 121.

$p\Xi^-$ Potential

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



Ξ^- Potential

- Extraction of single-particle potential U_Ξ by HAL QCD Collaboration
- Predictions in SNM: