Λ-Λ and p-Ξ^- interaction measurements with femtoscopy in ALICE

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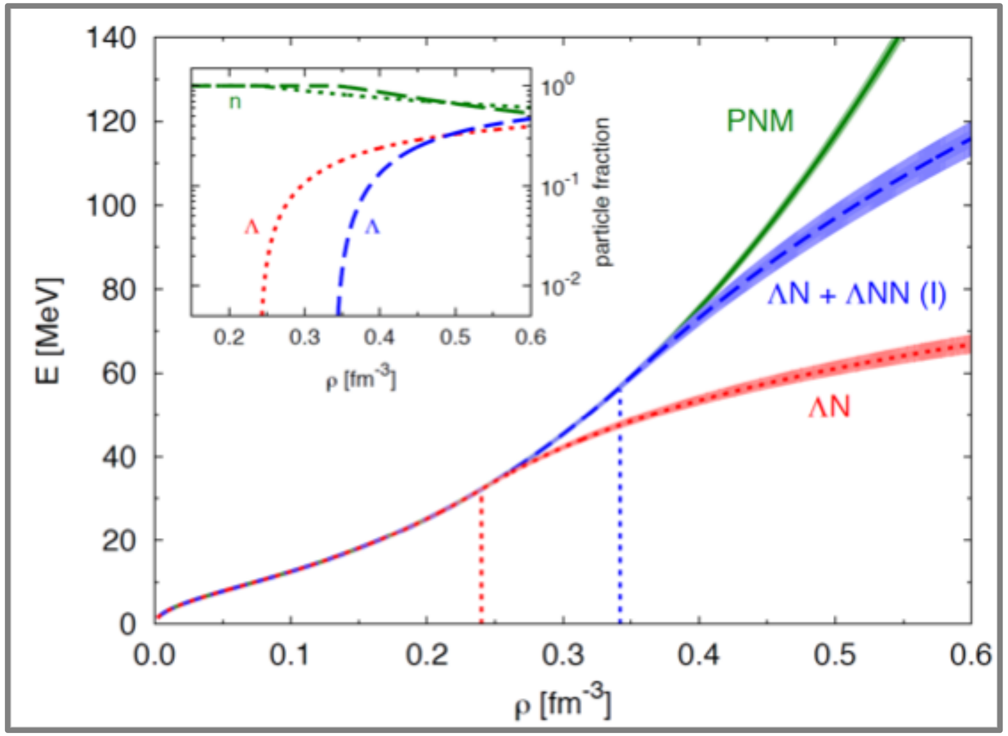
QNP SATELLITE WORKSHOP – TOKAI CAMPUS 11 NOVEMBER 2018

Outline

1. Hyperon-Nucleon and Hyperon-Hyperon interactions in Neutron Stars
2. Femtoscopy at ALICE experiment
3. Results pp 13 TeV and p-Pb 5.02 TeV
   - Λ-Λ correlation function and the existence of H di-baryon
   - First observation of the p-Ξ^- strong attractive potential
4. Summary and Outlooks

Hyperon Puzzle in Neutron Stars

- **Hyperons** production becomes **energetically favorable** at **moderate-large densities** in **dense neutron-rich matter**
- Threshold **strongly** depends on the **Y-N interaction**



- The appearance of Hyperons **softens** the EoS

D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

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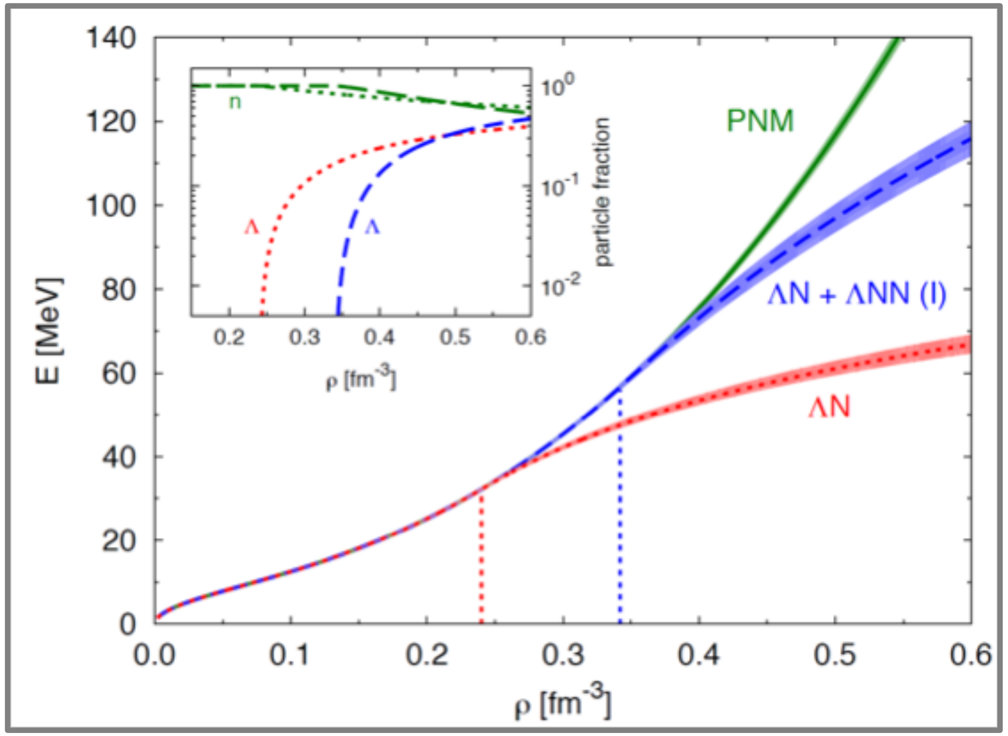
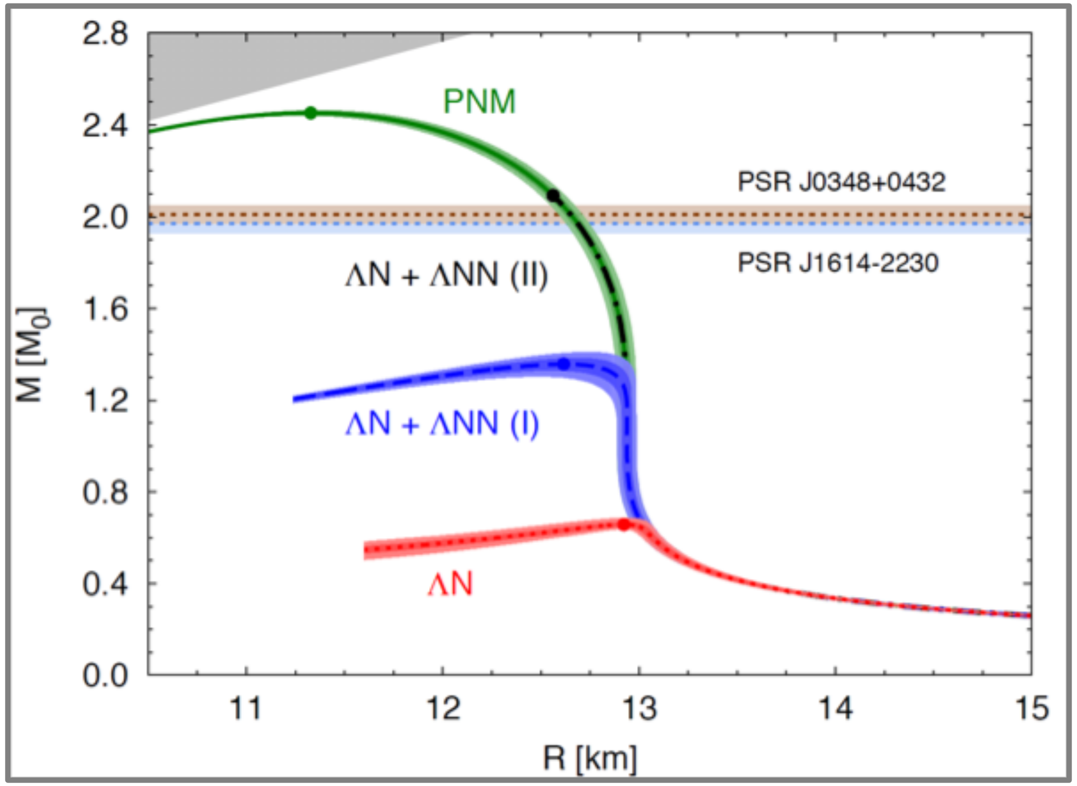
- The appearance of Hyperons **softens** the EoS
- **Maximum NS masses get smaller⇒HYPERON PUZZLE**



TOV

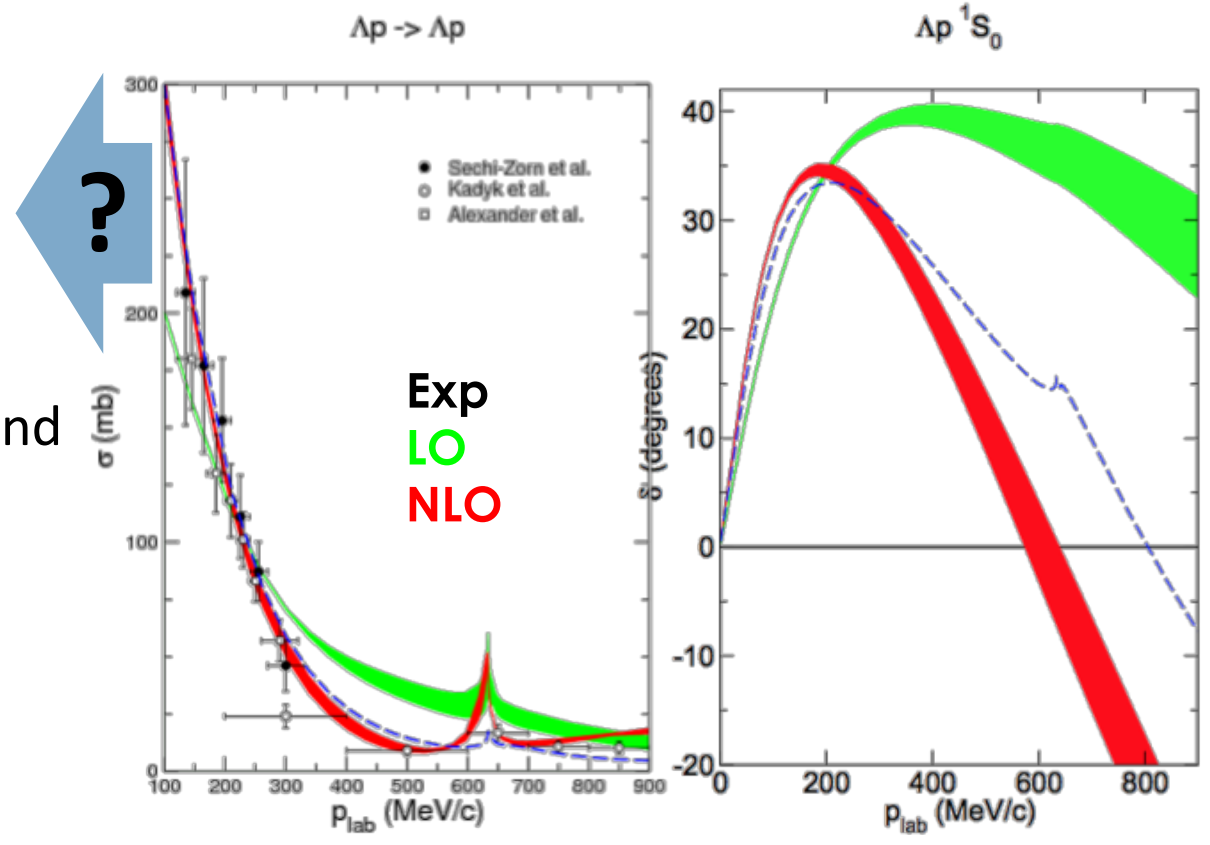


D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

YN and YY interactions: the traditional ways

- Scattering experiments / Hypernuclei data

- **SCATTERING DATA:**
- Constraint only on pΛ/pΣ interaction
  - Data from scattering experiments from 1968 and 1971 in bubble chambers
  - Production threshold: $p_{LAB} \gtrsim 100$ MeV



LO: H. Polinder, J.H., U. Meiβner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

YN and YY interactions: scattering experiments

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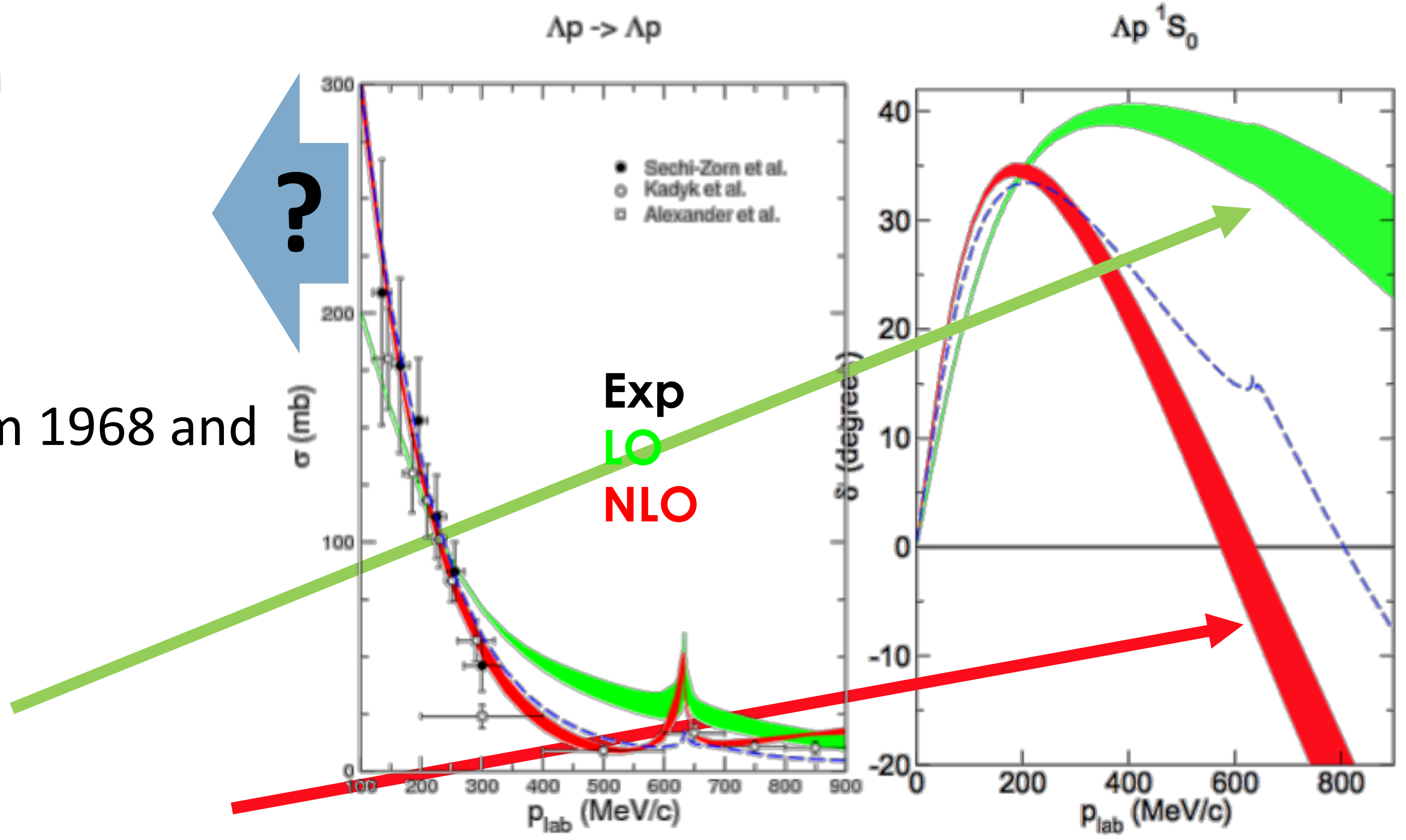
- **SCATTERING DATA:**
- Constraint only on pΛ/pΣ interaction

  - Data from scattering experiments from 1968 and 1971 in bubble chambers
  - Production threshold: $p_{LAB} \gtrsim 100$ MeV
  - Cannot probe low momentum region



LO: ALWAYS ATTRACTIVE

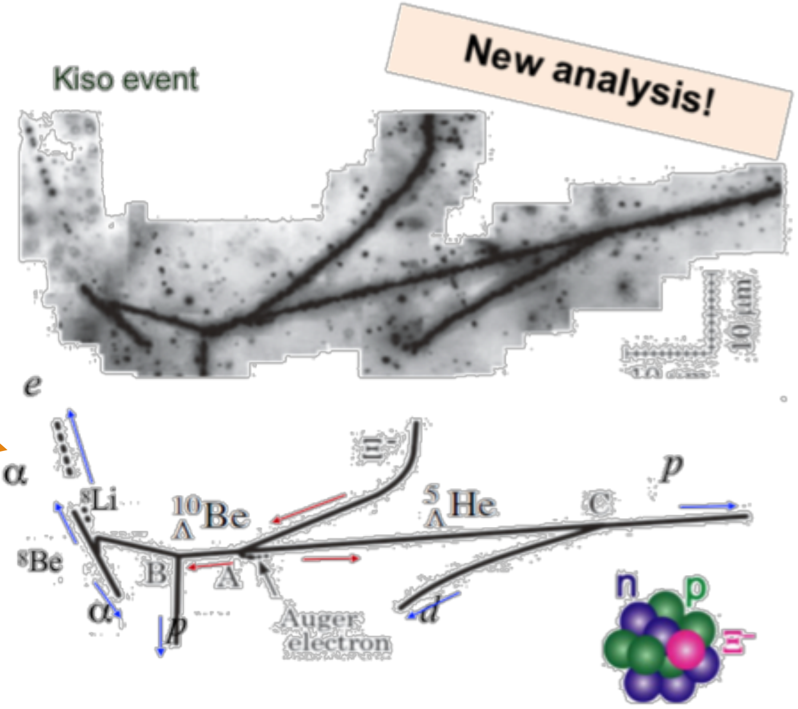
NLO: BECOMES REPULSIVE ⇒ REPULSIVE CORE

LO: H. Polinder, J.H., U. Meiβner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

YN and YY interactions: hypernuclei

- **HYPERNUCLEI DATA:**
  - **Λ hypernuclei** data: $B_{\Lambda nucleus}$= 30 MeV
  - **Ξ hypernuclei** data show **shallow attractive** interaction [Kiso Evt]
  - **ΛΛ hypernuclei** exist as well showing **weakly attraction** [Nagara Evt]
  - **Σ hypernuclei: nothing known so far!**

Courtesy H. Tamura, Bormio Winter Meeting 2018



$$\Xi^- + {}^{14}N \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$$

The first clear Ξ hypernucleus

$$B_{\Xi^-} = 4.38 \pm 0.25\ \text{MeV},$$
$$-\ 1.11 \pm 0.25\ \text{MeV}$$

K. Nakazawa et al. PTEP 2015, 033D02

YN and YY interactions: hypernuclei

- **HYPERNUCLEI DATA:**
  - **Λ hypernuclei** data: $B_{\lambda nucleus}$= 30 MeV [ref]
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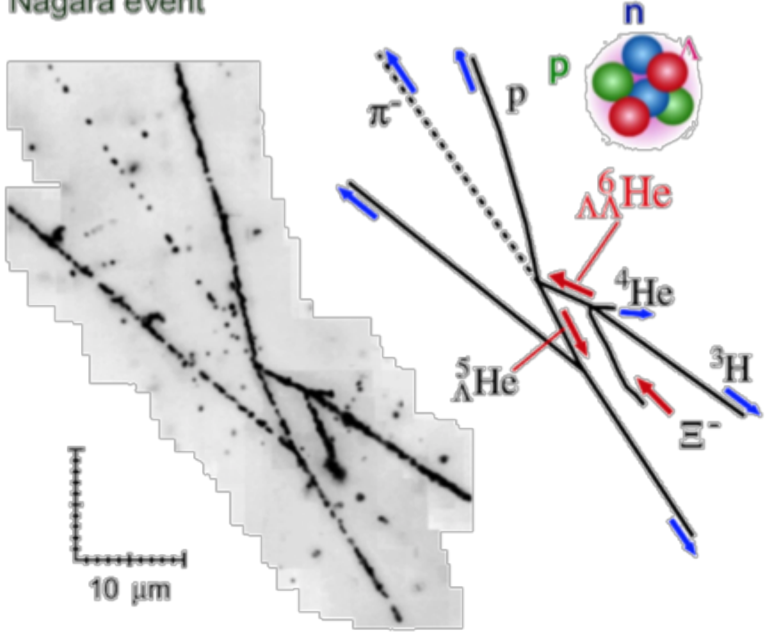
Nagara event



$^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$

$\Delta B_{\Lambda\Lambda}$= 0.67±0.17 MeV

H. Takahashi et al., PRL 87 (2001) 212502

Λ-Λ is weakly attractive

Take home message

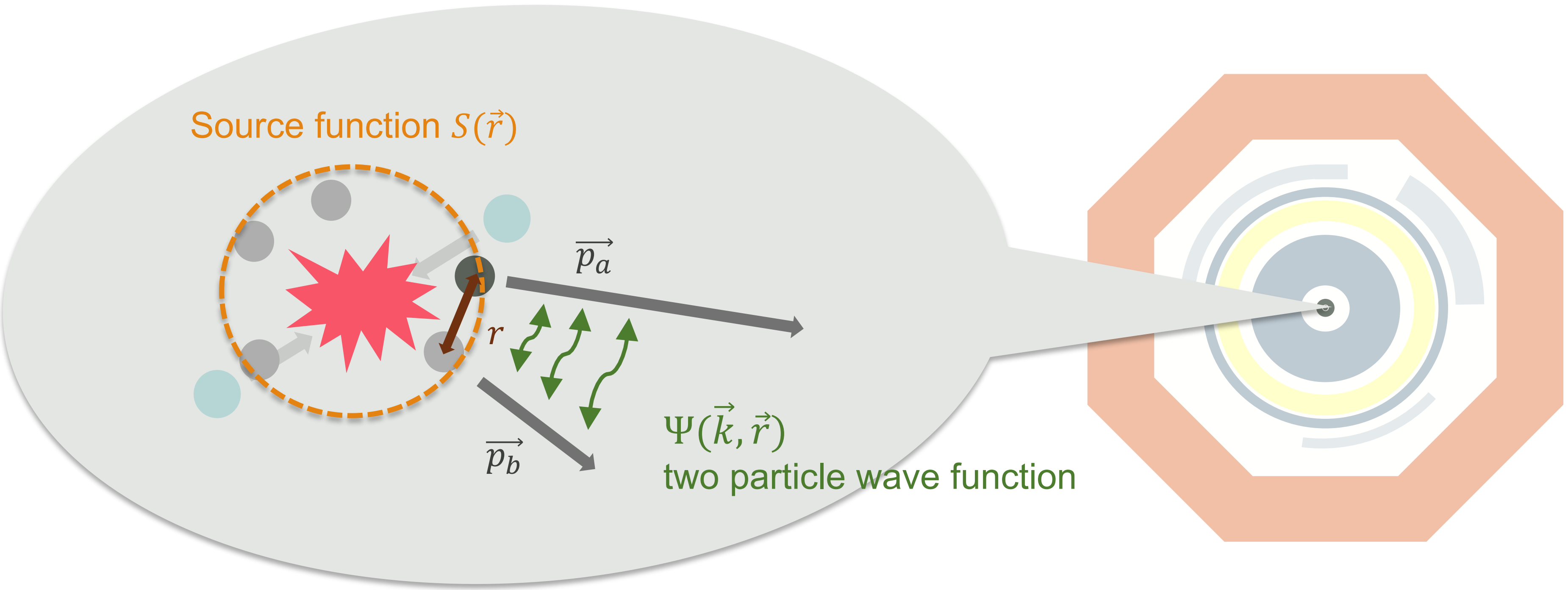
- Hyperon-nucleon and hyperon-hyperon interactions are fundamental ingredients for the EoS of NSs but unfortunately already in vacuum they are still not well fully understood

- Scattering experiments cannot be applied to all hyperon species and cannot access the low-momentum range

- Hypernuclei experiments are based on single events and their interpretation is model dependent

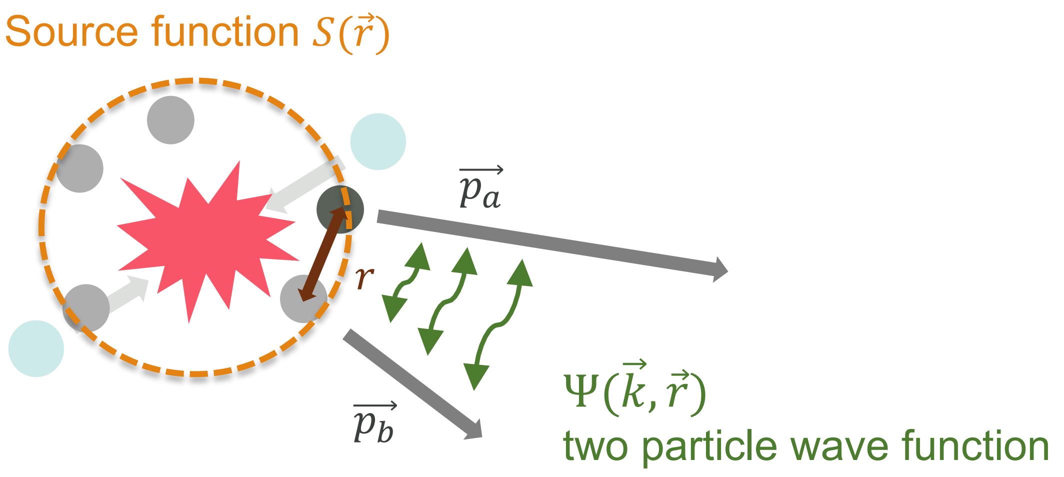
- How can we do the next step?
  Femtoscopy

Basics of Femtoscopy



- Look for particle pairs
- Measure the relative momentum k distribution in your experimental set up
- Search for correlations

Key observable: the correlation function



Statistical definition ***Experimental definition*** ***Theoretical definition***

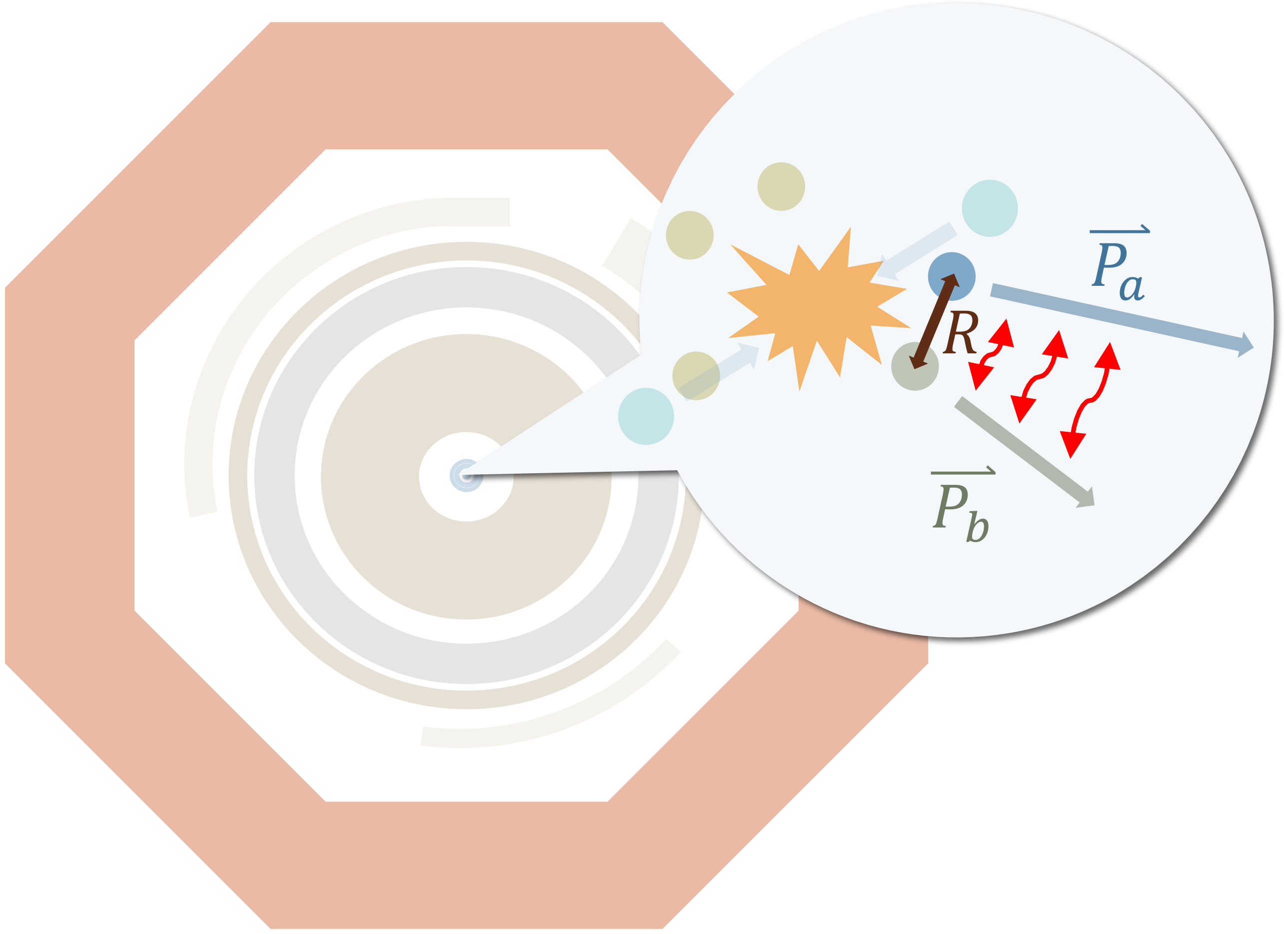
$$C(k) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{\mathrm{Same}}(k)}{N_{\mathrm{Mixed}}(k)} = \int S(\vec{r})\left|\Psi(\vec{k},\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k\to\infty} 1$$

Single-particle momenta

Relative distance / reduced momentum in the rest frame of the pair

Lisa, Pratt, Wiedemann,Solz, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

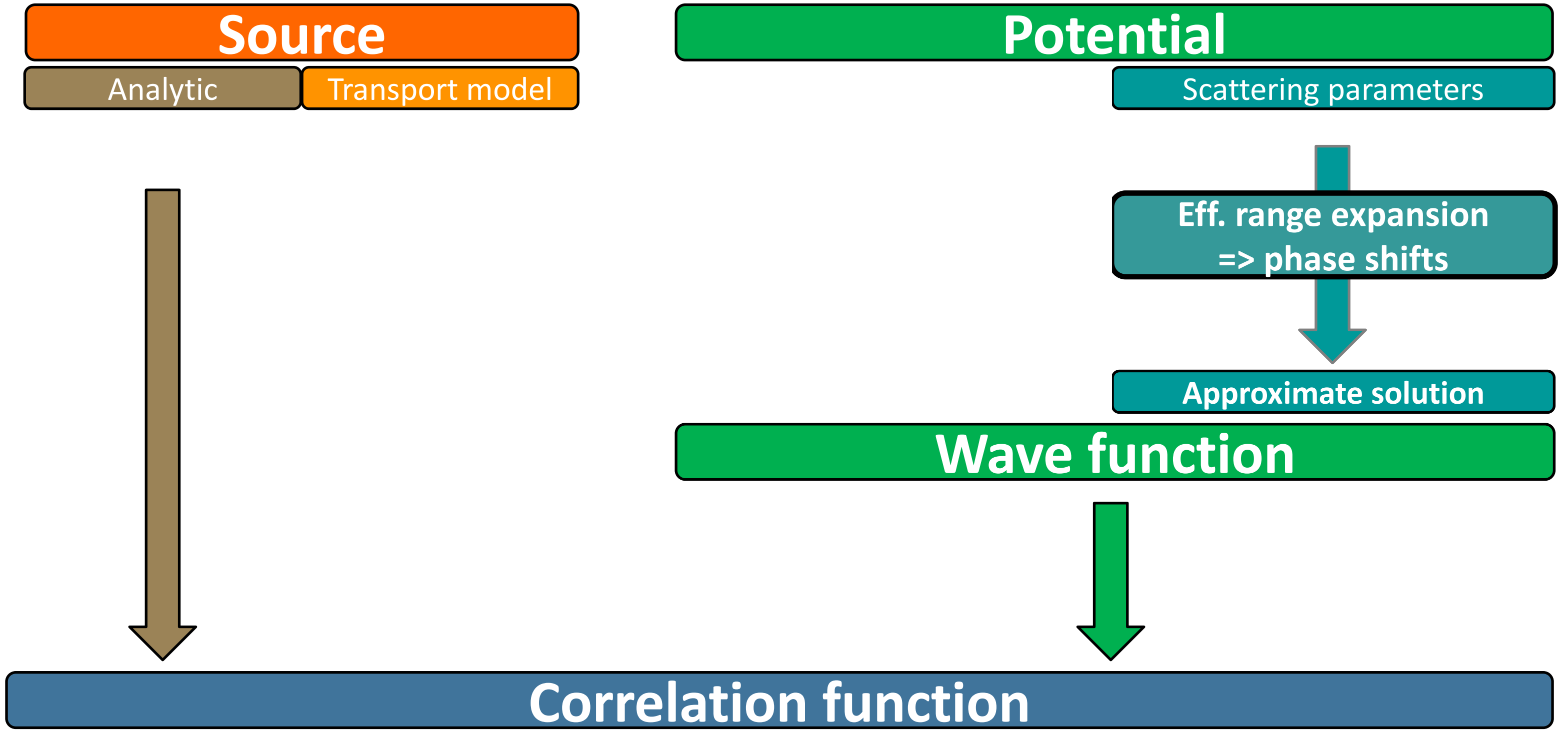
Femtoscopy at A Large Ion Collider Experiment



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

- We measure **p-p**, **p-Λ**, **Λ-Λ**, **p-Ξ**
- Proton identification with TPC and TOF
- Reconstruction of hyperons
  - $\Lambda \rightarrow p\pi^-$ (BR ~ 64%)
  - $\Xi^- \rightarrow \Lambda\pi^-$ (BR ~ 100%)
- Datasets:
  - **pp 7 TeV:** **3.4·10^8 Events**
  - **pp 13 TeV:** **10·10^8 Events**
  - **p-Pb 5.02 TeV:** **6.0·10^8 Events**
- Assumption of a **common Gaussian source**
  ⇒ fixing the radius from **p-p**
  ⇒ **p-Λ**, **p-Ξ** and **Λ–Λ** Correlation Function to study the interaction

Lednicky Model

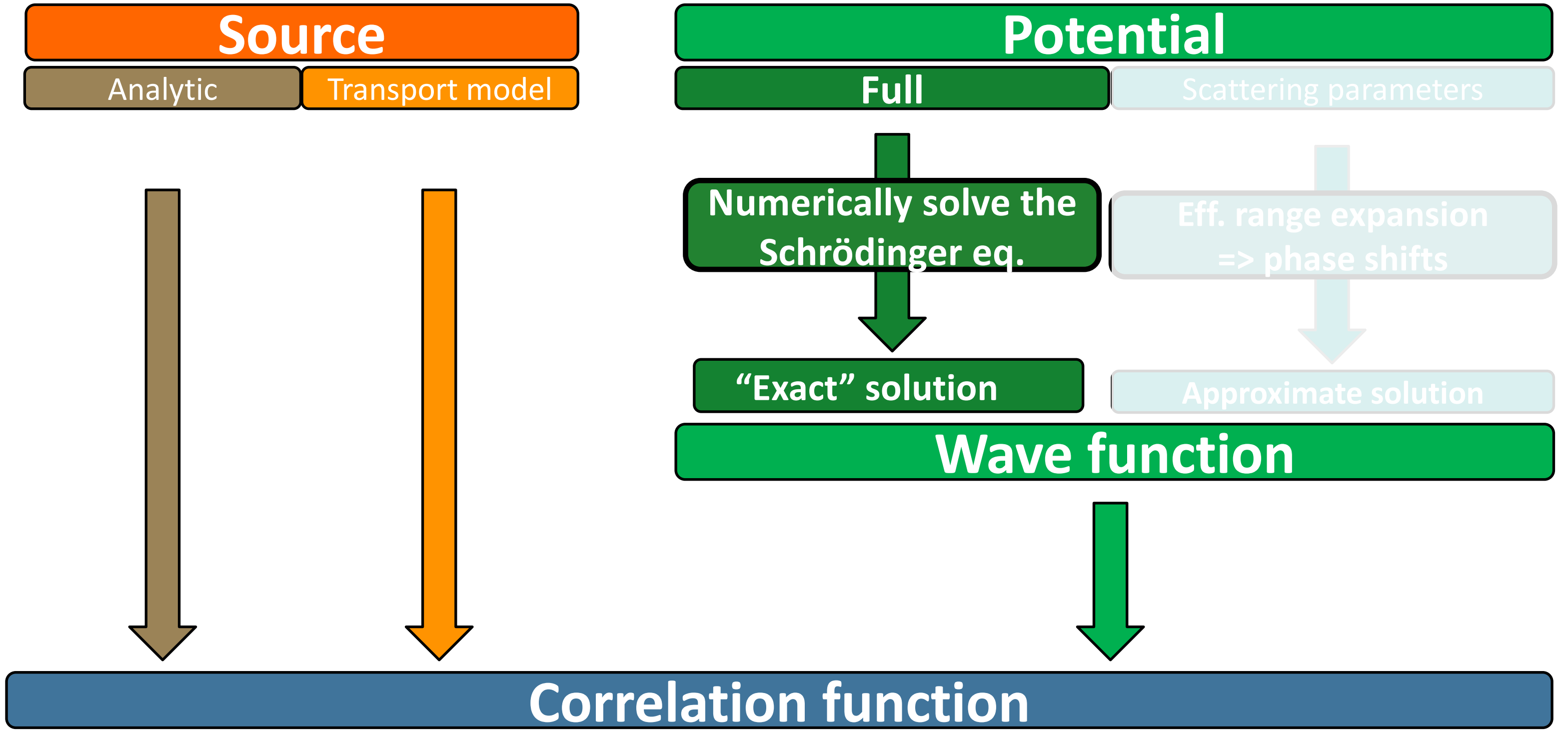


$$C(k) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k)}{R_G^{\Lambda p}} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} R_G^{\Lambda p}} \right) + 2 \frac{\mathcal{R} f^S(k)}{\sqrt{\pi} R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{\mathcal{I} f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right]$$

Depends on scattering parameters, might locally break down for small sources

R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)].

CATS – Correlation Analysis Tool Using the Schrödinger Equation

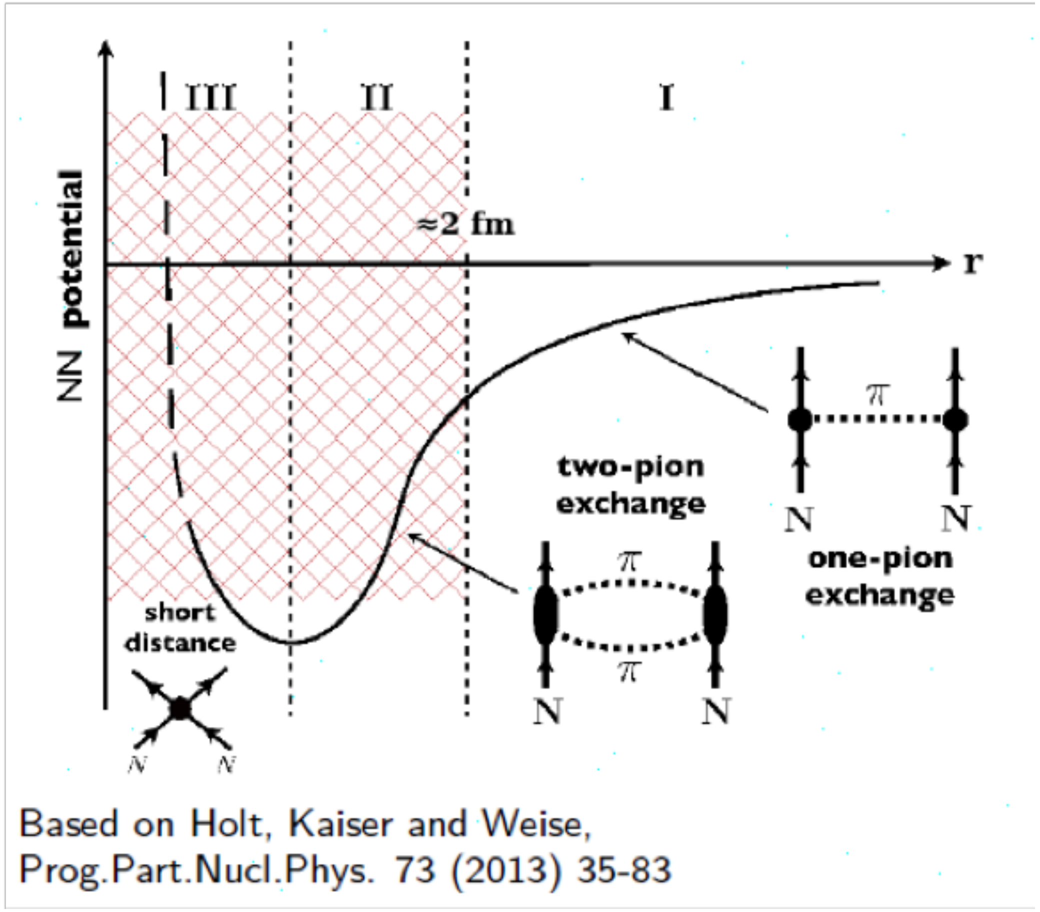


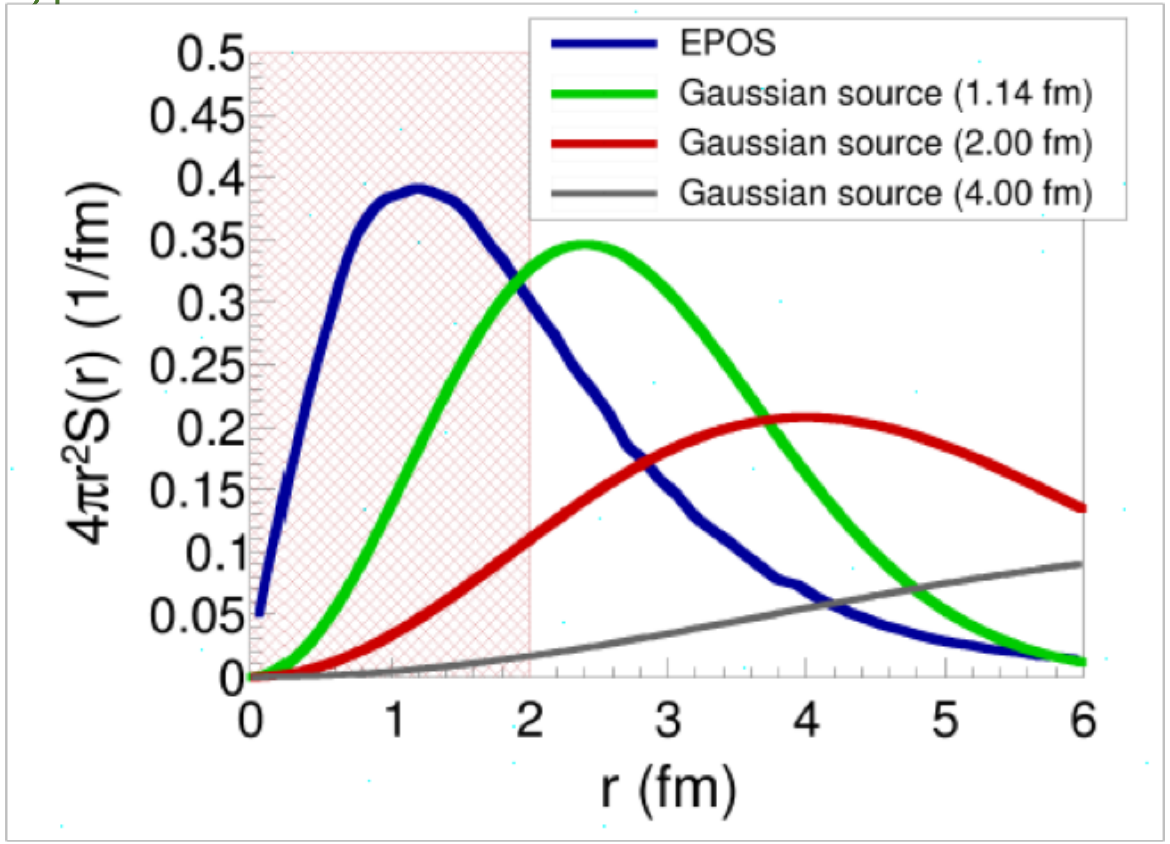
$$C(k) = \int S(\vec{r},k)\,|\psi(\vec{r},k)|^2\, d\vec{r} \xrightarrow{k\to\infty} 1$$

(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)

Length scales involved in Femtoscopy

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

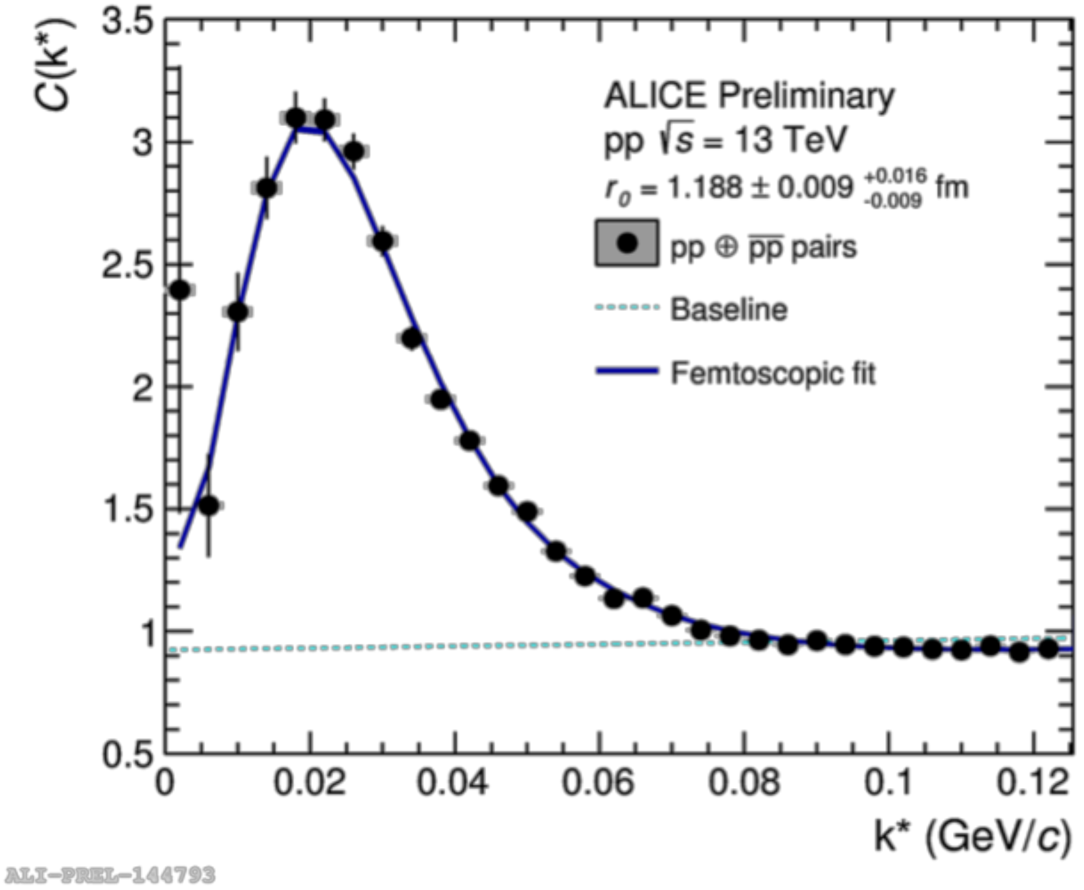


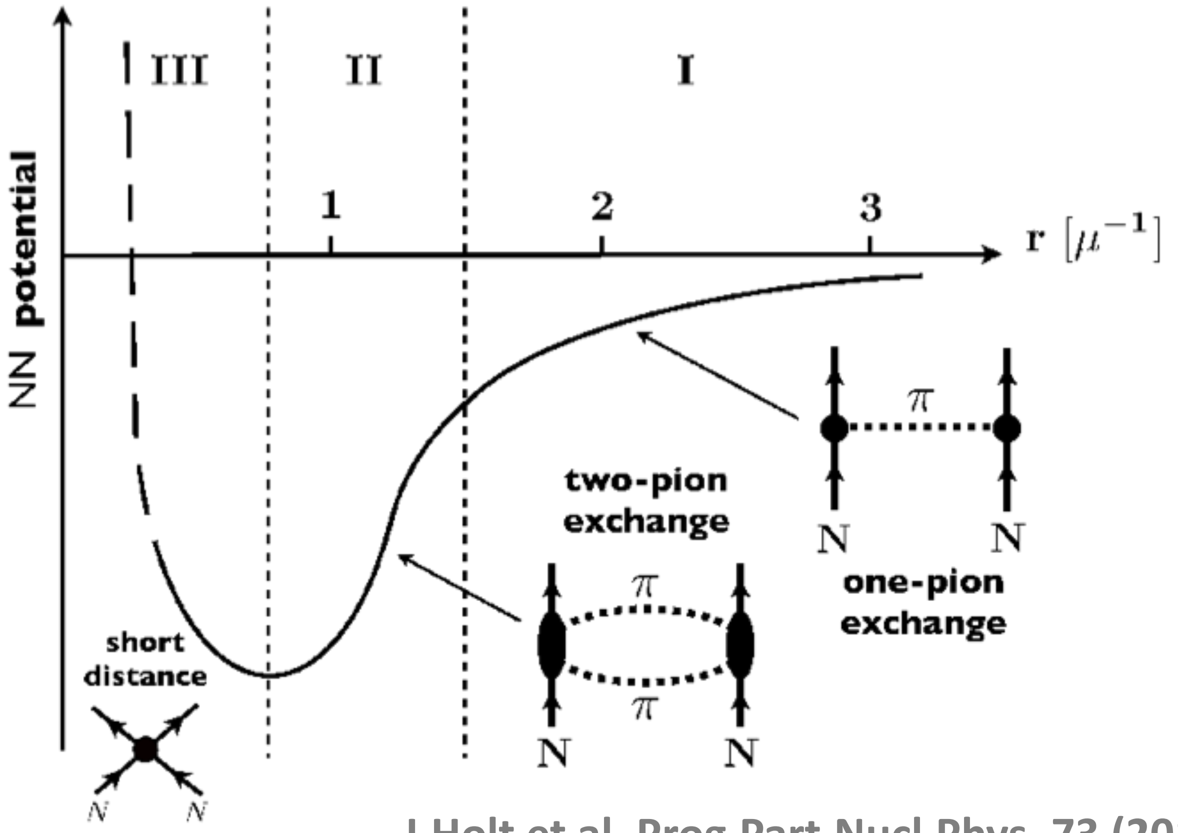


- A-A collisions: $R_{\text{Gauß}} \sim 4$ fm
- **p-A collisions: $R_{\text{Gauß}} \sim 2$ fm**
- **p-p collisions: $R_{\text{Gauß}} \sim 1$ fm**

Correlation function and Interactions

$$C(k^*) \longrightarrow \begin{cases} > 1 \text{ attraction} \\ = 1 \text{ no interaction} \\ < 1 \text{ repulsion} \end{cases}$$





J.Holt et al, Prog.Part.Nucl.Phys. 73 (2013)

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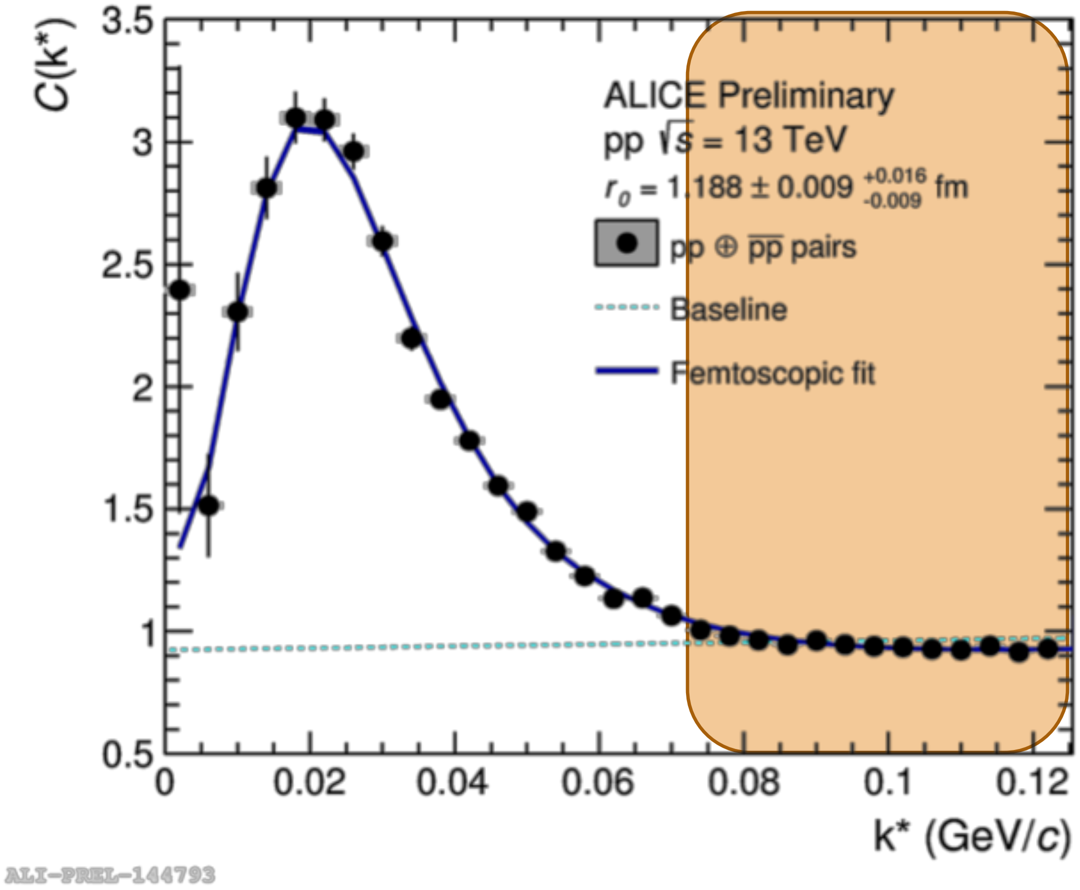

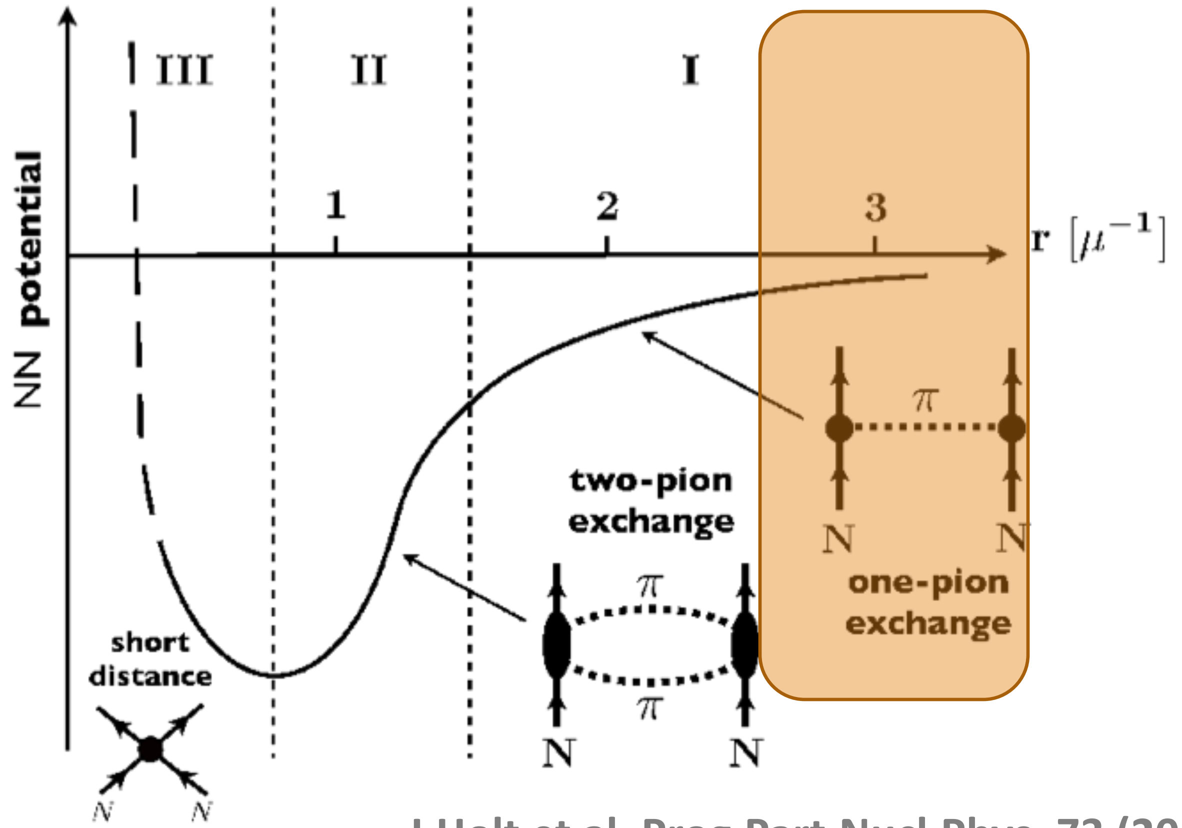

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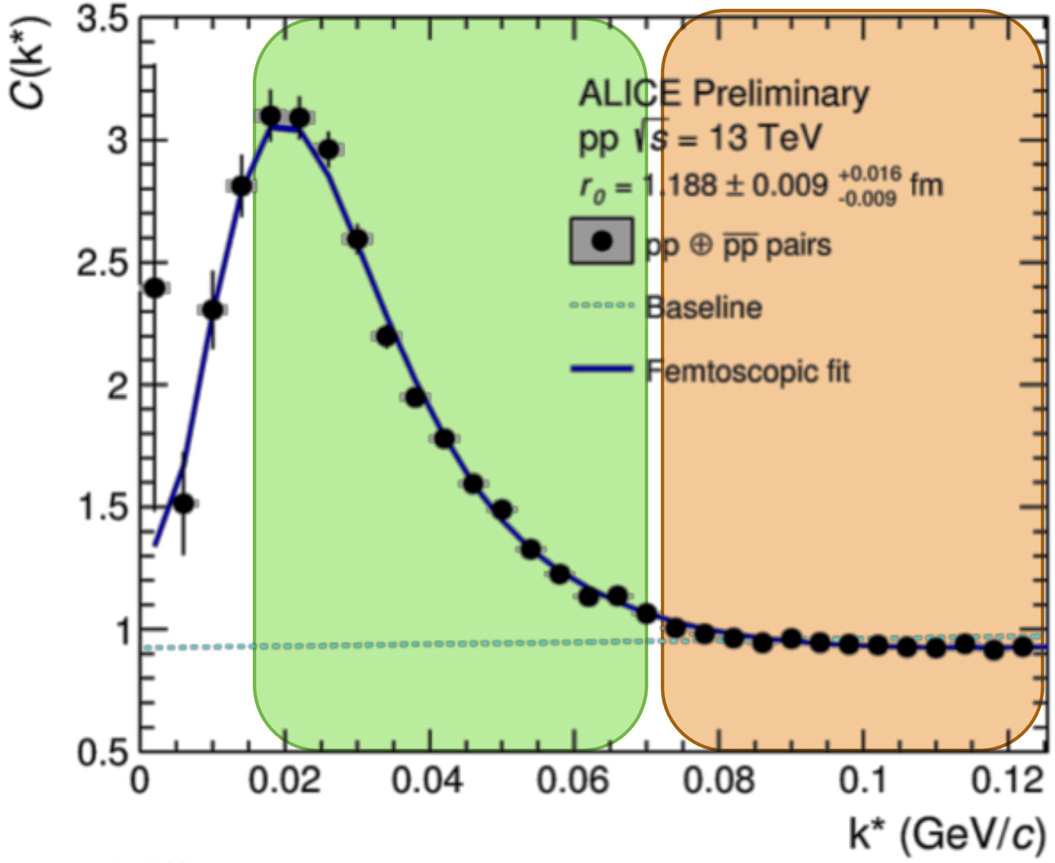
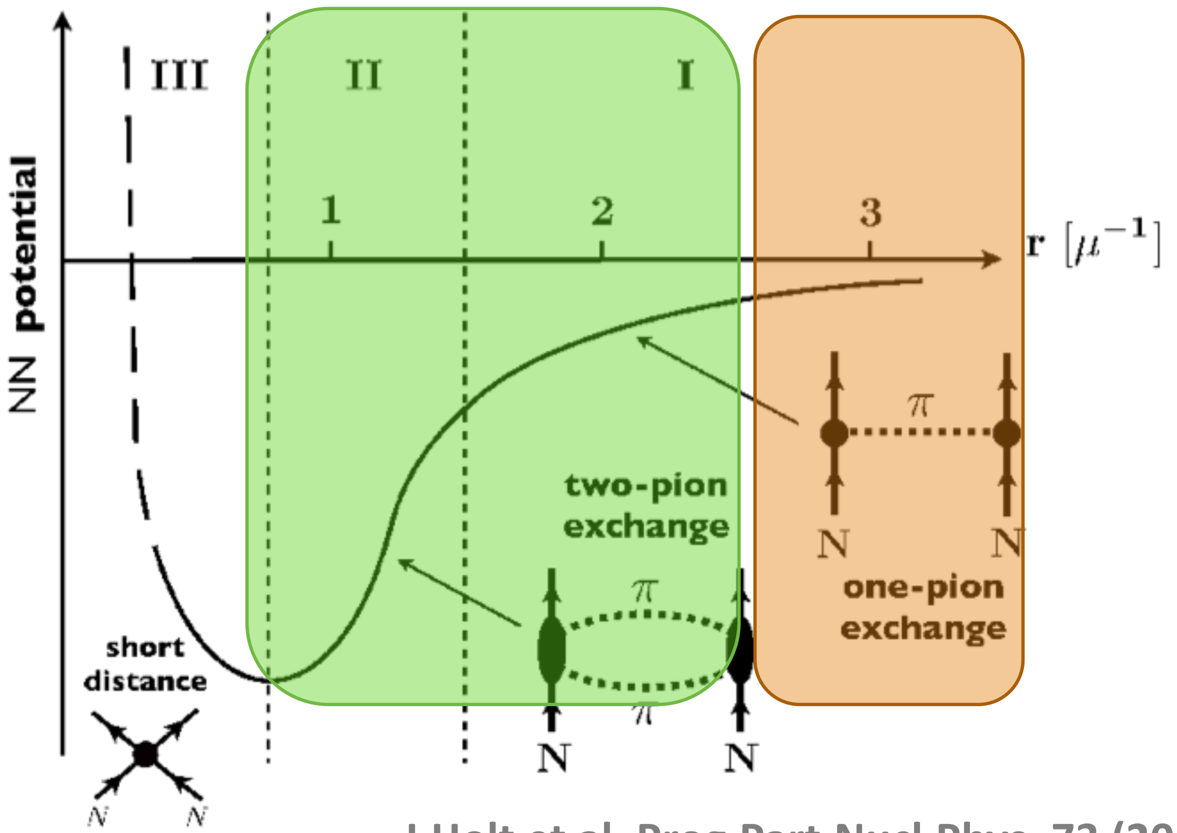
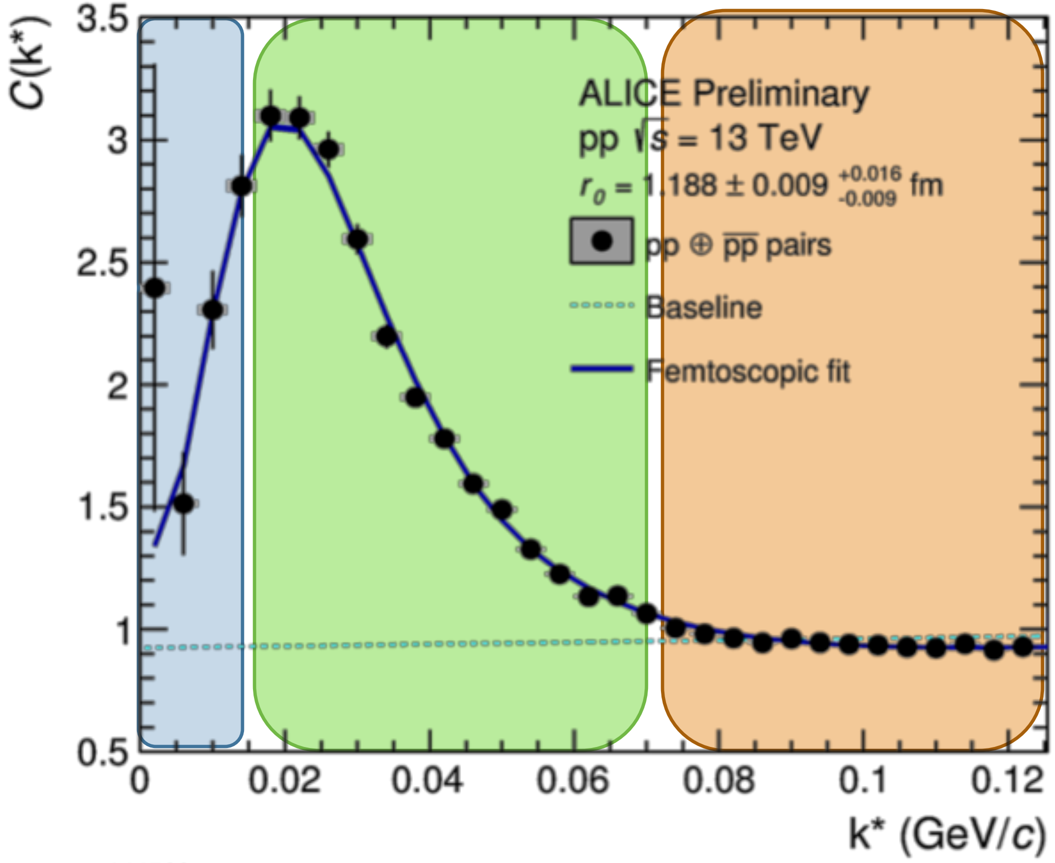


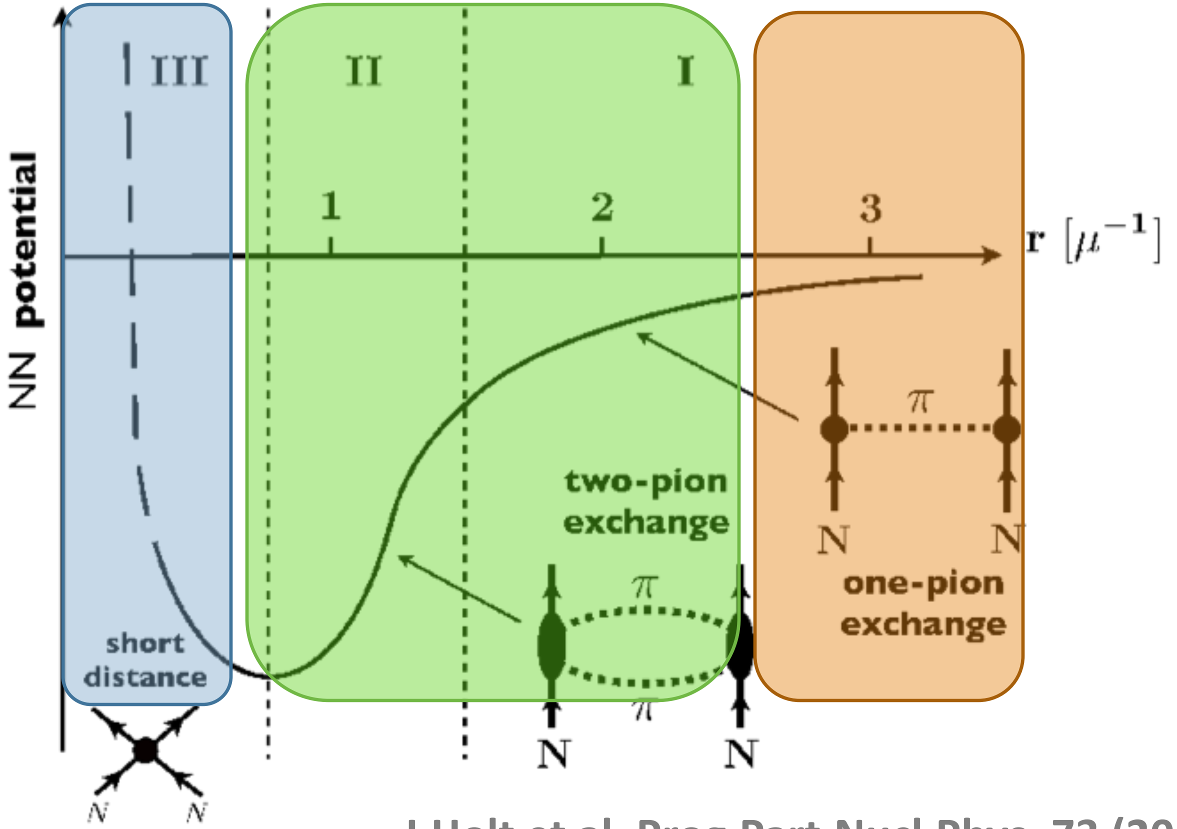


J.Holt et al, Prog.Part.Nucl.Phys. 73 (2013)

Correlation function and Interactions

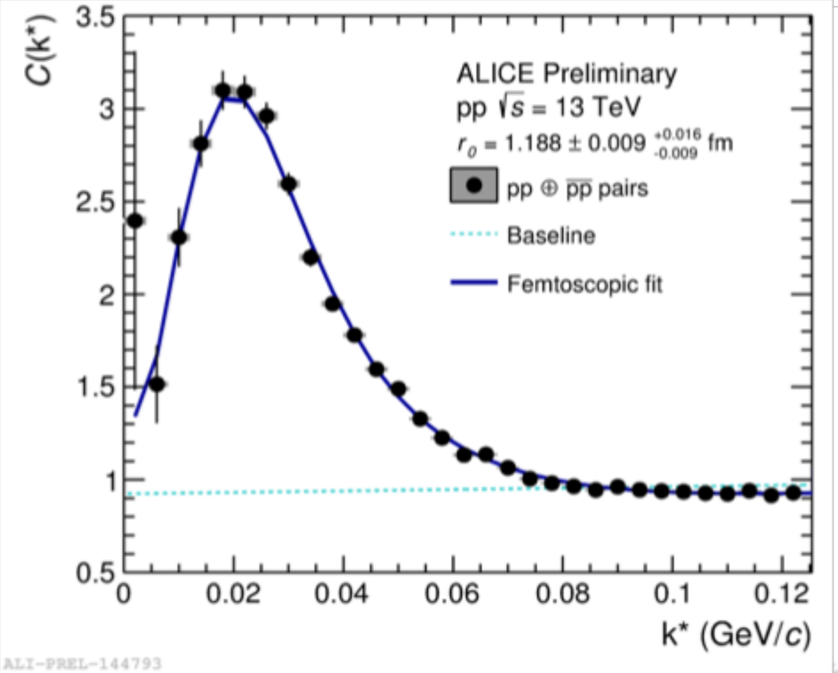
$C(k^*) \longrightarrow$
- > 1 attraction
- $= 1$ no interaction
- < 1 repulsion

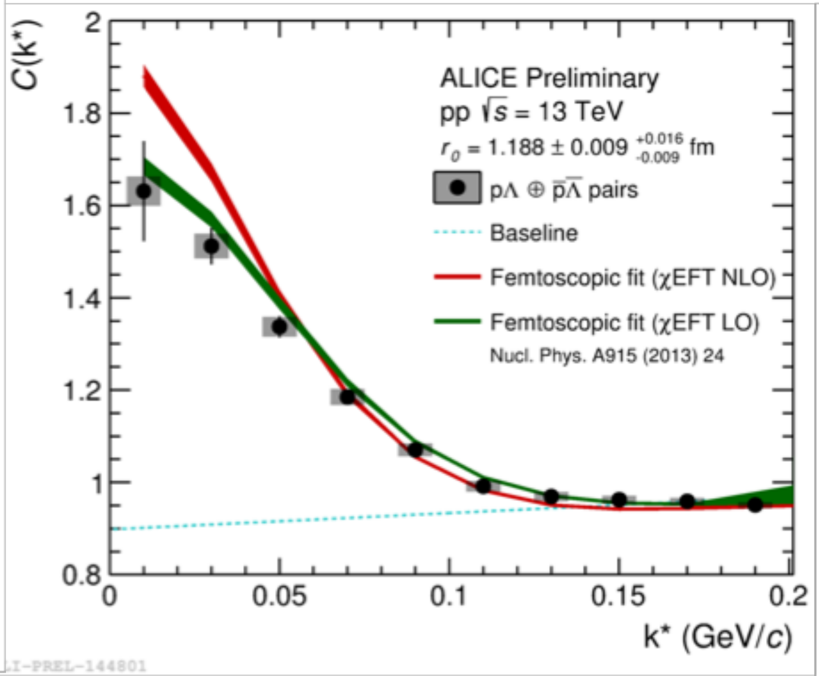


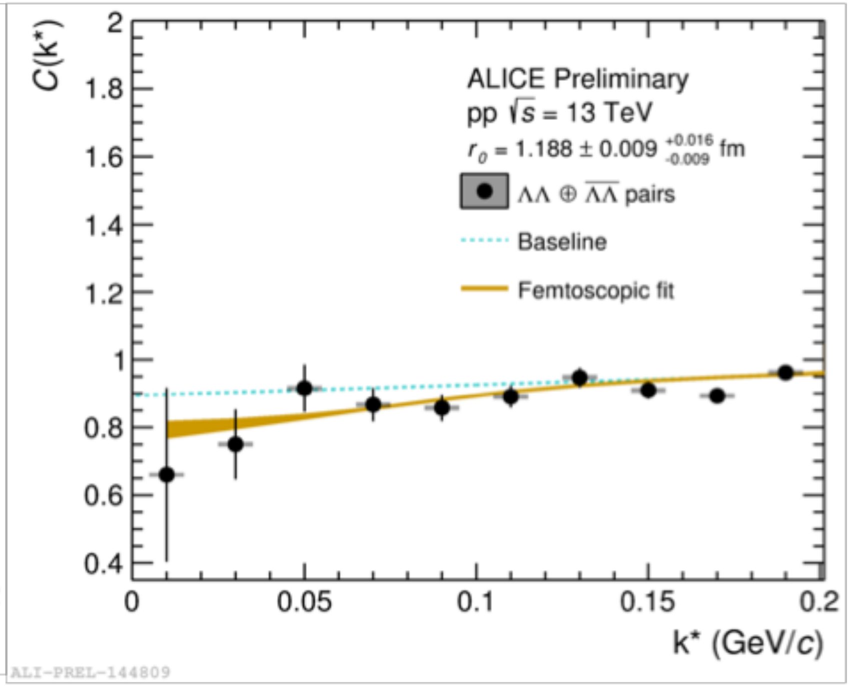


J.Holt et al, Prog.Part.Nucl.Phys. 73 (2013)

Results - pp collisions $\sqrt{s} = 13$ TeV

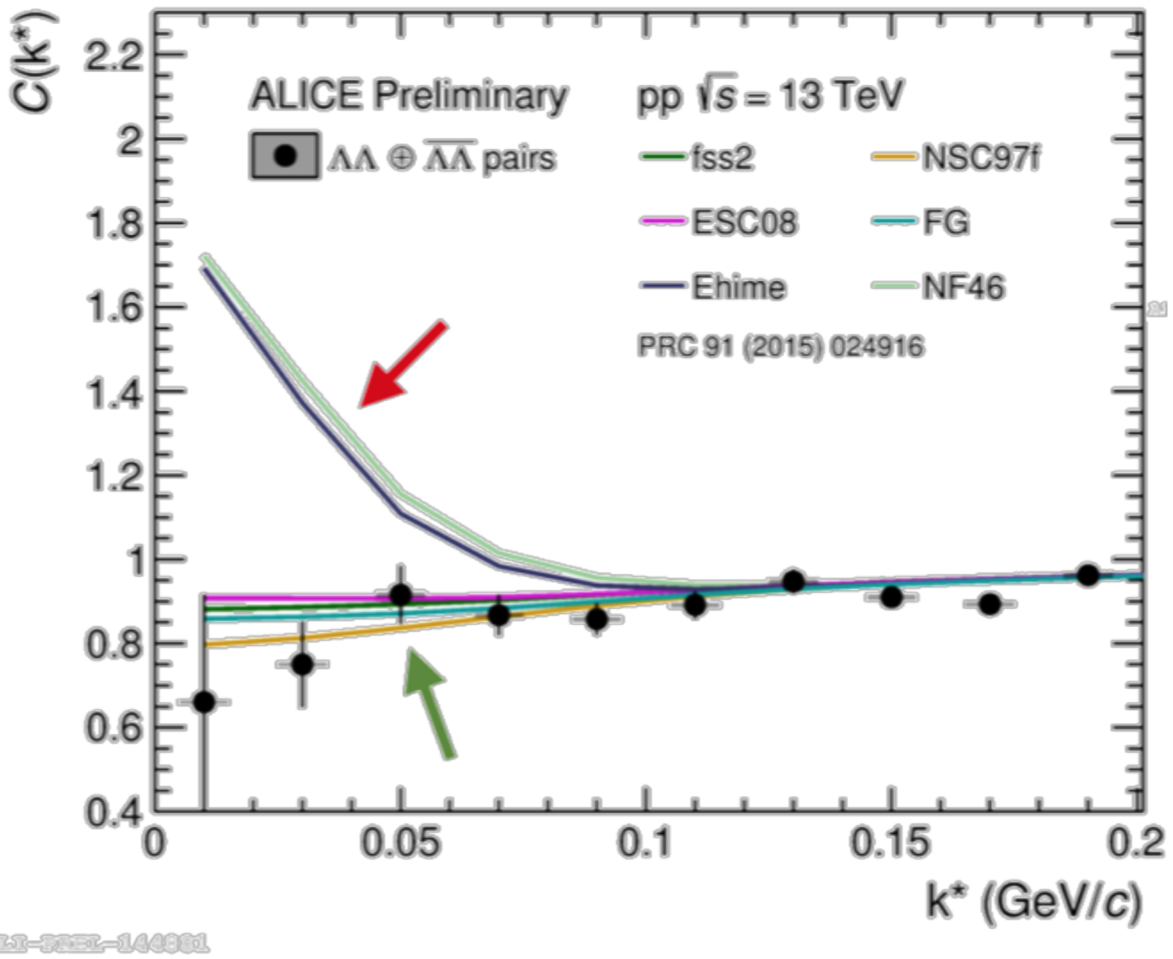






- Gaussian source and Argonne v_{18} potential describes the p-p correlation function
  - Source size of the **pp (7 TeV)** system **r_0=1.14 fm** **(ALICE Coll. arXiv:1805.12455)**
  - Source size of the **pp (13 TeV)** system **r_0=1.19 fm**
  - Source size of the **p-Pb (5.02 TeV)** system **r_0=1.38 fm**
- p-Λ correlation ⇒ strong sensitivity to the source ⇒ more investigations on the effect of collective phenomena and resonance decays are ongoing

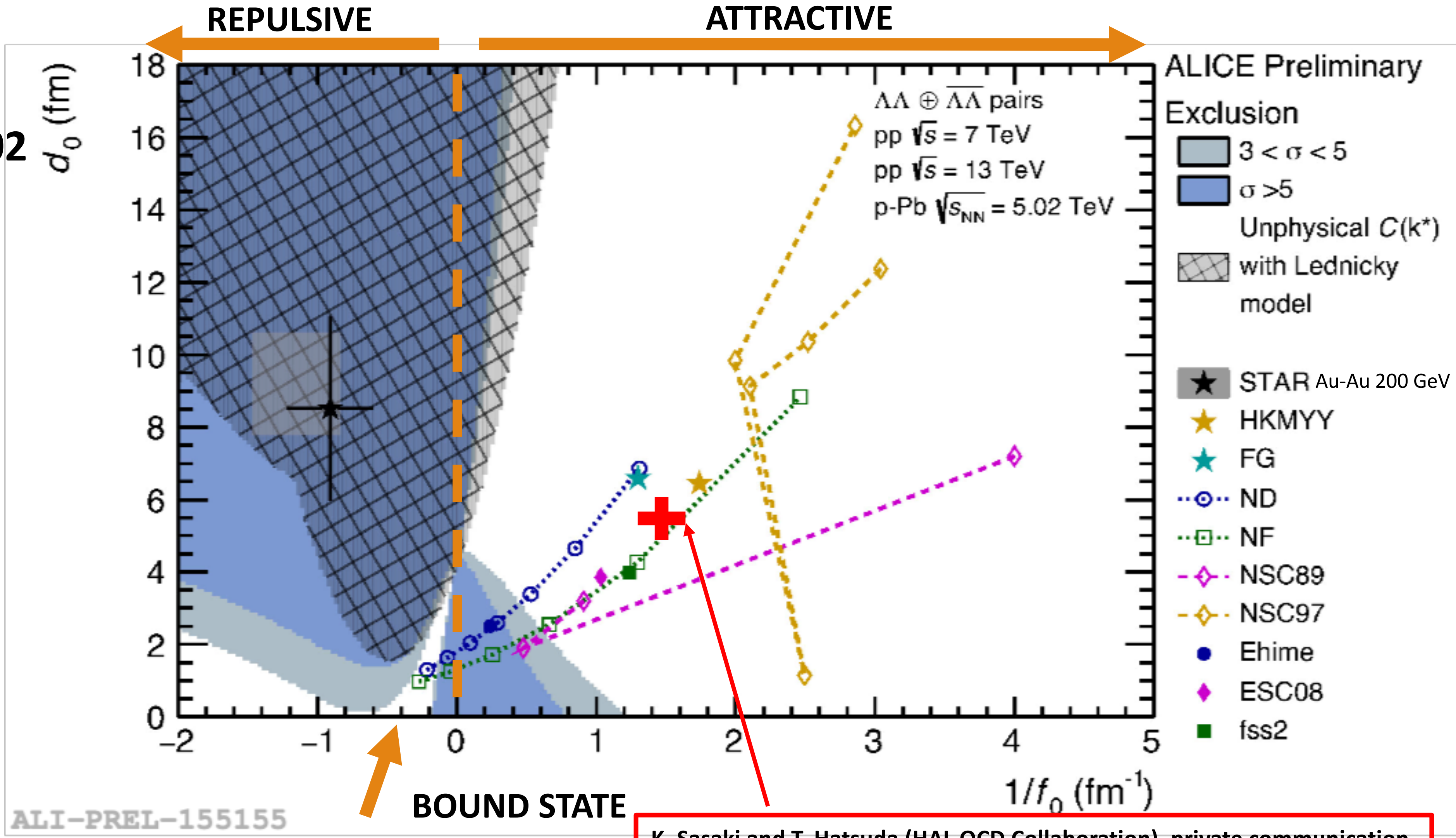
Λ–Λ interaction potentials



- Different model predictions for Λ-Λ correlation function
- X^2 evaluation with all combined datasets and evaluate the agreement model/data in number of σ deviations

Λ–Λ Correlations: Combined Exclusion Plot

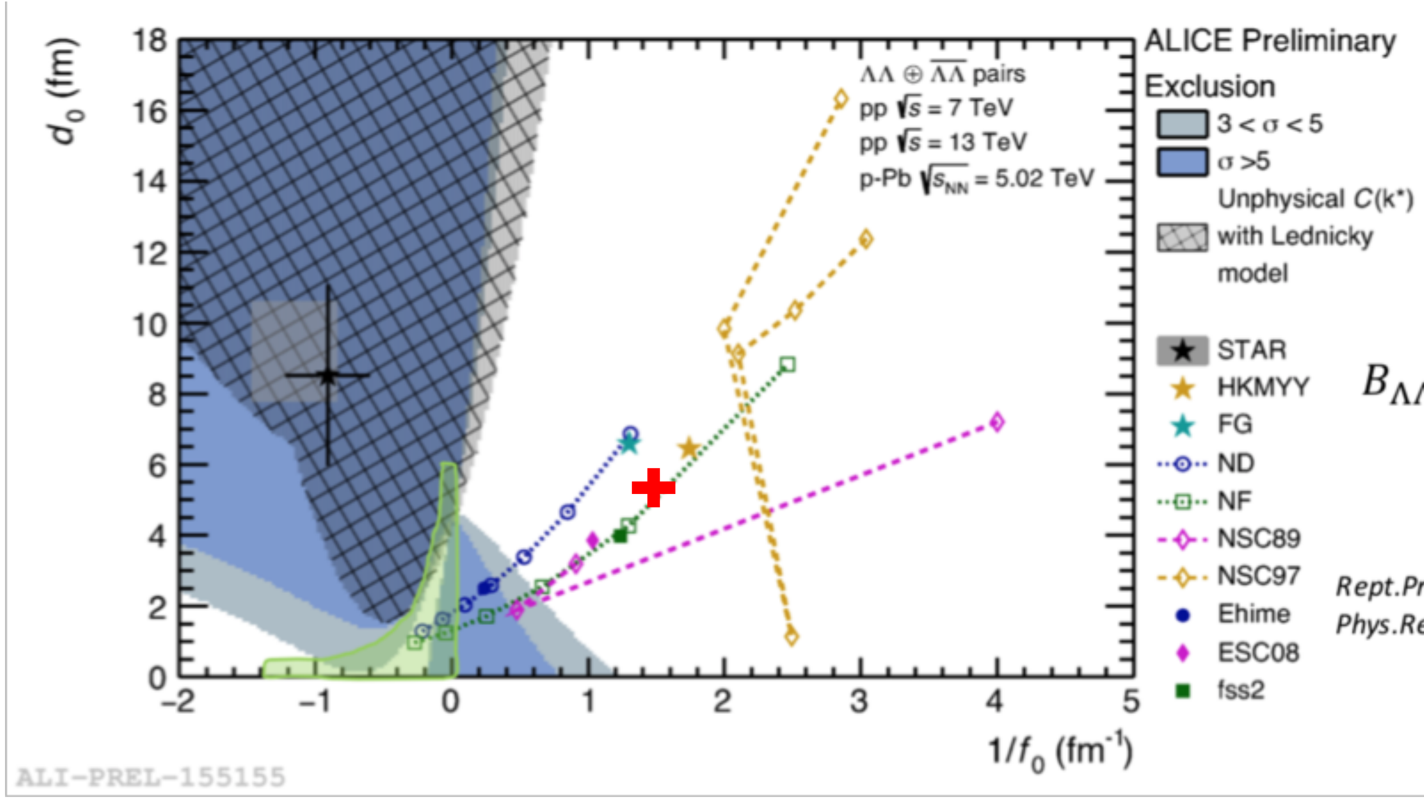
- Combination of all available datasets: **pp 7 TeV, pp 13 TeV, p-Pb 5.02 TeV**
- **Full scan** of scattering parameters space with the **Lednicky model**
- Test of the **agreement between data and the prediction by the Lednicky model by nσ**



K. Sasaki and T. Hatsuda (HAL QCD Collaboration), private communication

(STAR data: STAR coll. Phys.Rev.Lett. 114 (2015) no.2,022301)

H-dibaryon binding energies

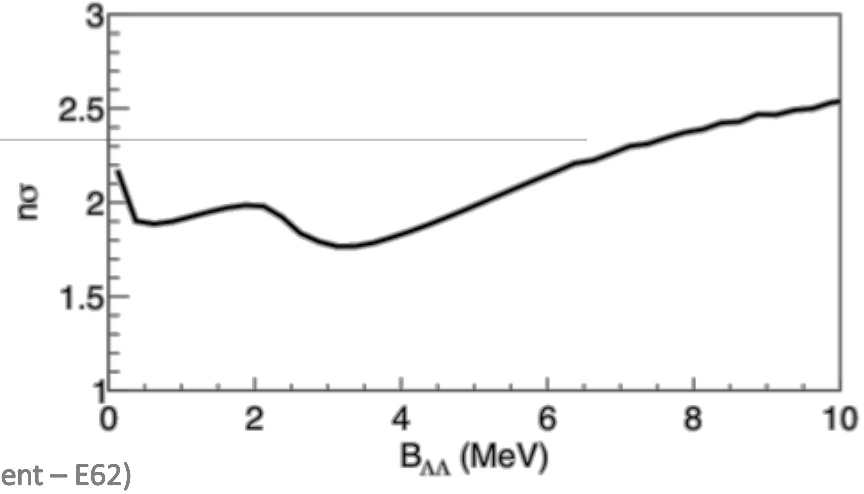


$$B_{\Lambda\Lambda} = \frac{1}{m_\Lambda d_0^2}\left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\right)^2$$

Femto sign convention!

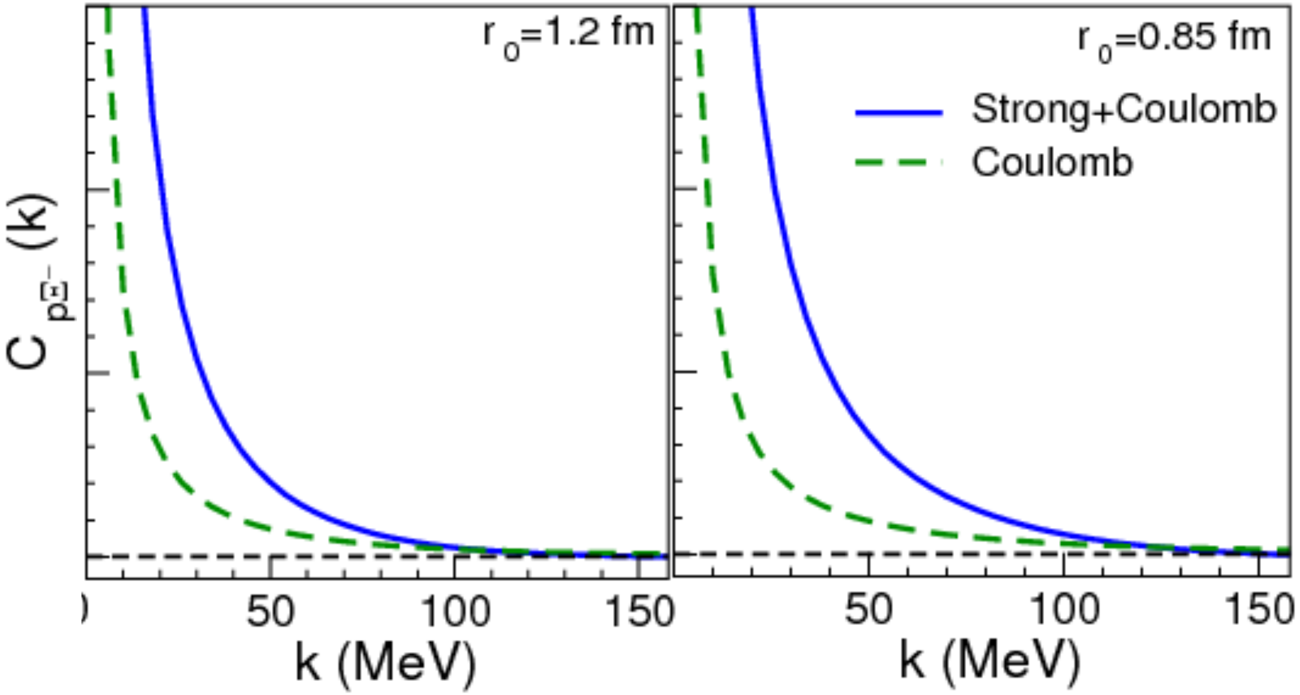
Rept.Prog.Phys. 80 (2017) no.5, 056001

Phys.Rev.Lett. 120 (2018) 212001

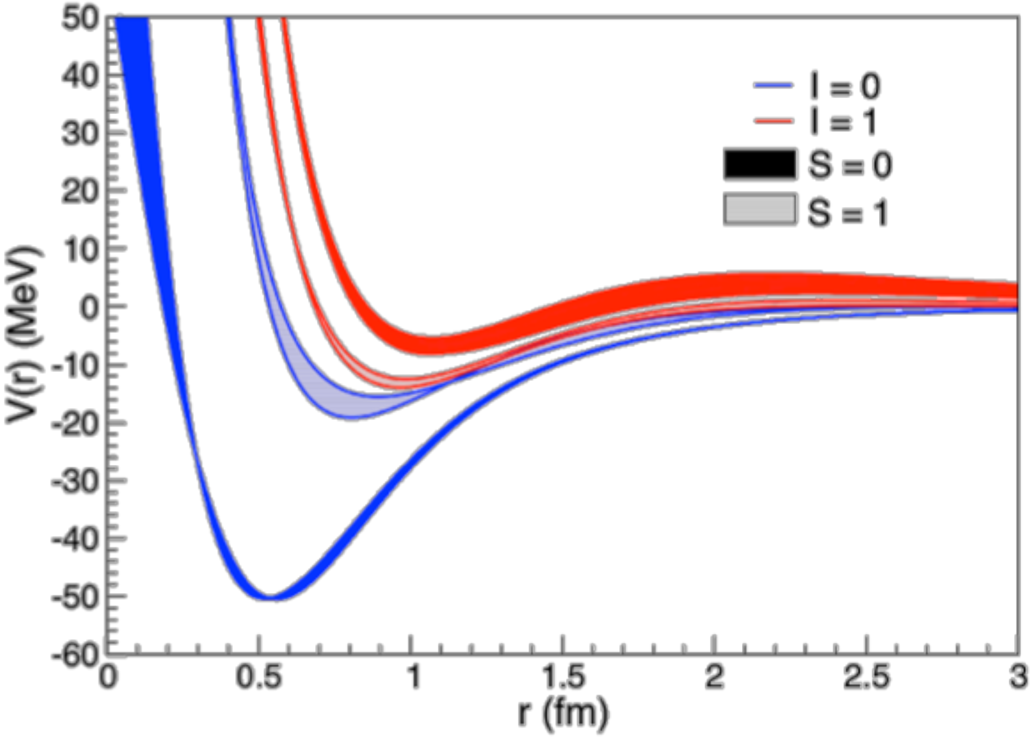


- Set tight constraints on the allowed binding energies
- Development of **MC bootstrap method** to provide a solid confidence region for scattering parameters and hence $B_{\Lambda\Lambda}$

Theoretical p-Ξ^- Correlation function



D.L.Mihaylov, V.M.S, O.W.Arnold, L.Fabbietti, B.Hohlweger, A.M.Mathis, Eur.Phys.J. C78 (2018) no.5,394



Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)

- Comparison **Coulomb-only/Coulomb+Strong**
- Strong potential from preliminary calculations from HAL-QCD collaboration

$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

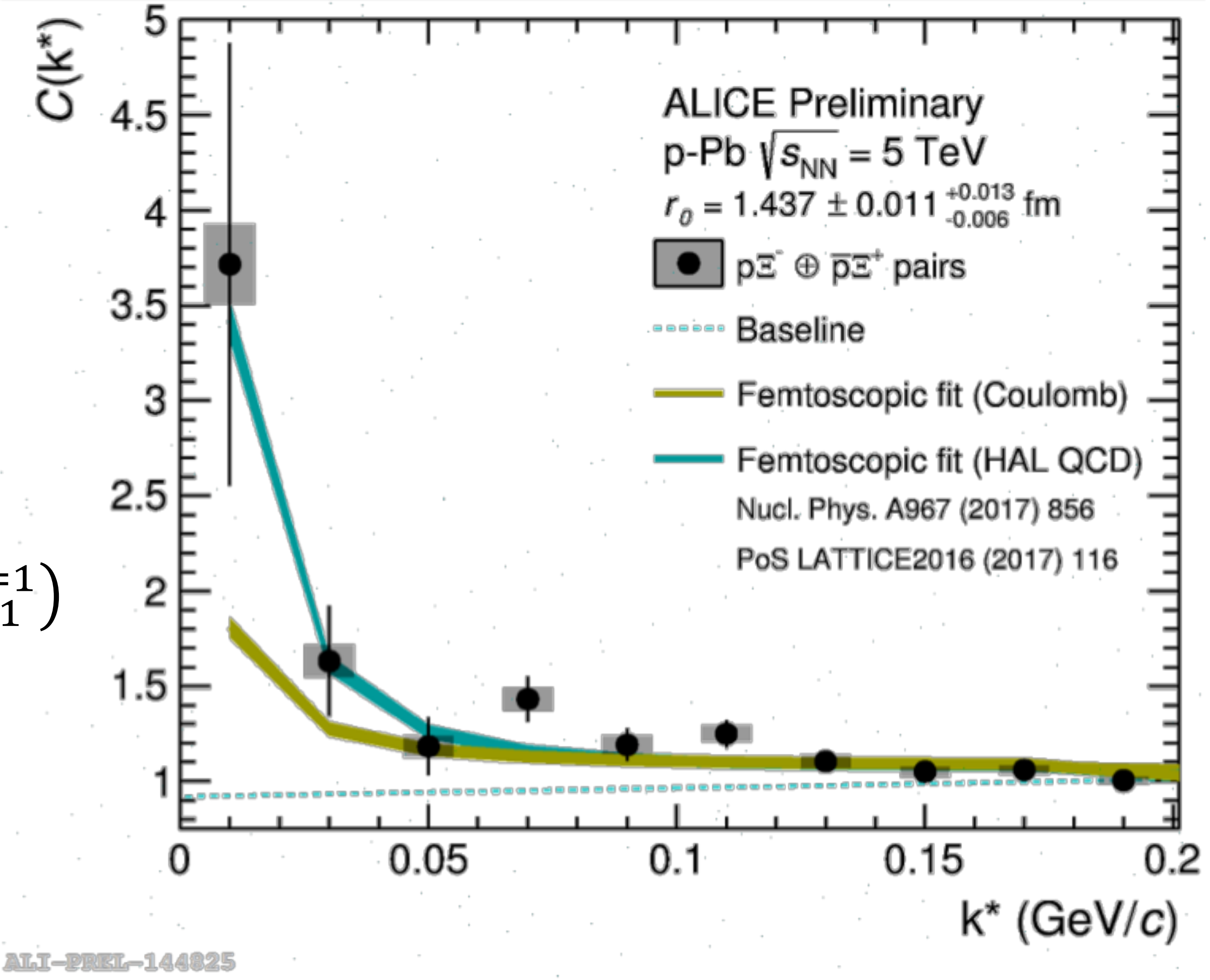
p-Ξ^- Correlation Function in p-Pb 5.02 TeV

- **First observation of strong attractive interaction in p-Ξ^-**
- modeled with preliminary QCD strong potential by the HAL QCD collaboration

  Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116

$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

COULOMB-ONLY HYPHOTESIS EXCLUDED AROUND 3σ



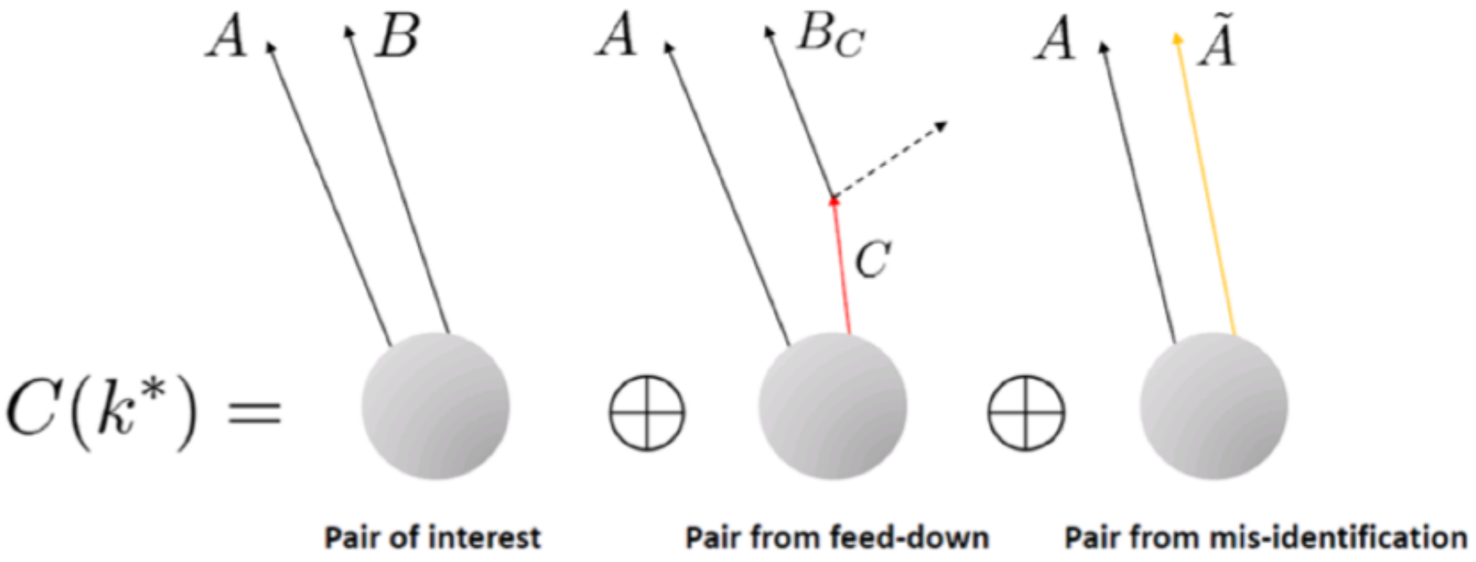
Summary and Outlook:

- **Femtoscopy** is an excellent tool to study **interactions of particle pairs**
  - Significant sensitivity to the interaction potentials
  - For hyperons, accesses novel regions not constrained by scattering experiments
- **Λ-Λ analysis** strongly constrains the parameter space for the Λ-Λ interaction ⇒ the existence of H-dibaryons seems to be disfavored **(ALICE coll., Phys. Lett. B 752)**
- Observation of **attractive p-Ξ^- interaction for the first time** ⇒ set constraints on the average potential of Ξ hyperons at finite density for NS EoS
- Extending the study to more hyperons-nucleon pairs (p-Ω, p-Σ^0) and in the future to three-body interactions
- In RUN3 (from 2021 on) we expect factor 100 in statistics!

Backup Slides

The experimental correlation function

$$C(\overrightarrow{p_a}, \overrightarrow{p_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})} = \mathcal{N}\frac{N_{SE}(k)}{N_{ME}(k)}$$



Decomposition of the p-p correlation function

$$\{pp\} = pp + p_\Lambda p + p_\Lambda + p_\Lambda + p_{\Sigma^+}p + p_{\Sigma^+}p_{\Sigma^+} + p_\Lambda p_{\Sigma^+} + \tilde{p}p + \tilde{p}p_\Lambda + \tilde{p}p_{\Sigma^+} + \tilde{p}\tilde{p},$$

- Purity from MC (Pythia 8)
- Feed-down fractions from MC template fits to the DCA_{xy} distribution

	p–p
Pair	λ [%]
pp	75.19
$p_\Lambda p$	15.06
$p_\Lambda p_\Lambda$	0.75
$p_{\Sigma^+}p$	6.46
$p_{\Sigma^+}p_{\Sigma^+}$	0.14
$p_\Lambda p_{\Sigma^+}$	0.65
$\tilde{p}p$	1.52
$\tilde{p}p_\Lambda$	0.15
$\tilde{p}p_{\Sigma^+}$	0.07
$\tilde{p}\tilde{p}$	0.01

Decomposition of the p-Λ correlation function

$$\{p\Lambda\} = p\Lambda + p\Lambda_{\Xi^-} + p\Lambda_{\Xi^0} + p\Lambda_{\Sigma^0} + p_\Lambda\Lambda + p_\Lambda\Lambda_{\Xi^-} + p_\Lambda\Lambda_{\Xi^0} + p_\Lambda\Lambda_{\Sigma^0} + p_{\Sigma^+}\Lambda + p_{\Sigma^+}\Lambda_{\Xi^-} + p_{\Sigma^+}\Lambda_{\Xi^0} + p_{\Sigma^+}\Lambda_{\Sigma^0} + \tilde{p}\Lambda + \tilde{p}\Lambda_{\Xi^-} + \tilde{p}\Lambda_{\Xi^0} + \tilde{p}\Lambda_{\Sigma^0} + p\tilde{\Lambda} + p_\Lambda\tilde{\Lambda} + p_{\Sigma^+}\tilde{\Lambda} + \tilde{p}\tilde{\Lambda}.$$

- Purity from fits to the invariant mass distribution
- Feed-down fractions from MC template fits to the cosα distribution

Pair	p–Λ λ [%]
$p\Lambda$	52.42
$p\Lambda_{\Xi^-}$	6.94
$p\Lambda_{\Xi^0}$	6.94
$p\Lambda_{\Sigma^0}$	17.47
$p_\Lambda\Lambda$	5.25
$p_\Lambda\Lambda_{\Xi^-}$	0.69
$p_\Lambda\Lambda_{\Xi^0}$	0.69
$p_\Lambda\Lambda_{\Sigma^0}$	1.75
$p_{\Sigma^+}\Lambda$	2.25
$p_{\Sigma^+}\Lambda_{\Xi^-}$	0.30
$p_{\Sigma^+}\Lambda_{\Xi^0}$	0.30
$p_{\Sigma^+}\Lambda_{\Sigma^0}$	0.75

Pair	p–Λ λ [%]
$\tilde{p}\Lambda$	0.53
$\tilde{p}\Lambda_{\Xi^-}$	0.07
$\tilde{p}\Lambda_{\Xi^0}$	0.07
$\tilde{p}\Lambda_{\Sigma^0}$	0.18
$p\tilde{\Lambda}$	2.95
$p_\Lambda\tilde{\Lambda}$	0.30
$p_{\Sigma^+}\tilde{\Lambda}$	0.13
$\tilde{p}\tilde{\Lambda}$	0.03

Decomposition of the Λ-Λ correlation function

$$\{\Lambda\Lambda\} = \Lambda\Lambda + \Lambda\Lambda_{\Sigma^0} + \Lambda_{\Sigma^0}\Lambda_{\Sigma^0} + \Lambda\Lambda_{\Xi^0} + \Lambda_{\Xi^0}\Lambda_{\Xi^0} + \Lambda\Lambda_{\Xi^-} + \Lambda_{\Xi^-}\Lambda_{\Xi^-} + \Lambda_{\Sigma^0}\Lambda_{\Xi^0} + \Lambda_{\Sigma^0}\Lambda_{\Xi^-} + \Lambda_{\Xi^0}\Lambda_{\Xi^-} + \tilde{\Lambda}\Lambda + \tilde{\Lambda}\Lambda_{\Sigma^0} + \tilde{\Lambda}\Lambda_{\Xi^-} + \tilde{\Lambda}\Lambda_{\Xi^0} + \tilde{\Lambda}\tilde{\Lambda}.$$

Lambda properties obtained from the Λ purity and the $\cos\alpha$ template fits

Λ–Λ	
Pair	λ [%]
$\Lambda\Lambda$	36.54
$\Lambda\Lambda_{\Sigma^0}$	24.36
$\Lambda_{\Sigma^0}\Lambda_{\Sigma^0}$	4.06
$\Lambda\Lambda_{\Xi^0}$	9.67
$\Lambda_{\Xi^0}\Lambda_{\Xi^0}$	0.64
$\Lambda\Lambda_{\Xi^-}$	9.67
$\Lambda_{\Xi^-}\Lambda_{\Xi^-}$	0.64
$\Lambda_{\Sigma^0}\Lambda_{\Xi^0}$	3.22
$\Lambda_{\Sigma^0}\Lambda_{\Xi^-}$	3.22
$\Lambda_{\Xi^0}\Lambda_{\Xi^-}$	1.28

Λ–Λ	
Pair	λ [%]
$\tilde{\Lambda}\Lambda$	4.11
$\tilde{\Lambda}\Lambda_{\Sigma^0}$	1.37
$\tilde{\Lambda}\Lambda_{\Xi^0}$	0.54
$\tilde{\Lambda}\Lambda_{\Xi^-}$	0.54
$\tilde{\Lambda}\tilde{\Lambda}$	0.12

Decomposition of the p-Ξ correlation function

$$\begin{aligned}\{p\Xi^-\} = {} & p\Xi^- + p\Xi^-_{\Xi^-(1530)} + p\Xi^-_{\Xi^0(1530)} + p\Xi^-_{\Omega} + p_{\Lambda}\Xi^- + p_{\Lambda}\Xi^-_{\Xi^-(1530)} \\ & + p_{\Lambda}\Xi^-_{\Xi^0(1530)} + p_{\Lambda}\Xi^-_{\Omega} + p_{\Sigma^+}\Xi^- + p_{\Sigma^+}\Xi^-_{\Xi^-(1530)} + p_{\Sigma^+}\Xi^-_{\Xi^0(1530)} + p_{\Sigma^+}\Xi^-_{\Omega} \\ & + \tilde{p}\Xi^- + \tilde{p}\Xi^-_{\Xi^-(1530)} + \tilde{p}\Xi^-_{\Xi^0(1530)} + \tilde{p}\Xi^-_{\Omega} + p\tilde{\Xi}^- + p_{\Lambda}\tilde{\Xi}^- + p_{\Sigma^+}\tilde{\Xi}^- + \tilde{p}\tilde{\Xi}^- .\end{aligned}$$

Feeding from

- Ω (BR very small)
- $\Xi^0(1530)$ and $\Xi^-(1530)$
  - Isospin partners: assume to be produced in the same amount
  - $\Xi(1530)/\Xi^-$ = 0.32 (https://doi.org/10.1140/epjc/s10052-014-3191-x)
  - BR($\Xi^0(1530) \to \Xi^-$) = 2/3
  - BR($\Xi^-(1530) \to \Xi^-$) = 1/3

p–Ξ	
Pair	λ [%]
$p\Xi^-$	52.40
$p\Xi^-_{\Xi^-(1530)}$	8.32
$p\Xi^-_{\Xi^0(1530)}$	16.65
$p\Xi^-_{\Omega}$	0.67
$p_{\Lambda}\Xi^-$	5.25
$p_{\Lambda}\Xi^-_{\Xi^-(1530)}$	0.83
$p_{\Lambda}\Xi^-_{\Xi^0(1530)}$	1.67
$p_{\Lambda}\Xi^-_{\Omega}$	0.07
$p_{\Sigma^+}\Xi^-$	2.25
$p_{\Sigma^+}\Xi^-_{\Xi^-(1530)}$	0.36
$p_{\Sigma^+}\Xi^-_{\Xi^0(1530)}$	0.71
$p_{\Sigma^+}\Xi^-_{\Omega}$	0.03

p–Ξ	
Pair	λ [%]
$\tilde{p}\Xi^-$	0.53
$\tilde{p}\Xi^-_{\Xi^-(1530)}$	0.08
$\tilde{p}\Xi^-_{\Xi^0(1530)}$	0.17
$\tilde{p}\Xi^-_{\Omega}$	0.01
$p\tilde{\Xi}^-$	8.67
$p_{\Lambda}\tilde{\Xi}^-$	0.87
$p_{\Sigma^+}\tilde{\Xi}^-$	2.25
$\tilde{p}\tilde{\Xi}^-$	0.09

Some numbers

pp@13 TeV

Particle	# baryons
p	113.7 x 10^6
$\bar{p}$	97.4 x 10^6
Λ	22.3 x 10^6
$\bar{\Lambda}$	21.0 x 10^6
Ξ^-	509 x 10^3
Ξ^+	527 x 10^3

Pair	# of pairs k* < 200 MeV/c
$p-p$	190 x 10^3
$\bar{p}-\bar{p}$	140 x 10^3
$p-\Lambda$	62 x 10^3
$\bar{p}-\bar{\Lambda}$	49 x 10^3
$\Lambda-\Lambda$	5659
$\bar{\Lambda}-\bar{\Lambda}$	5243
$p-\Xi^-$	407
$\bar{p}-\Xi^+$	364

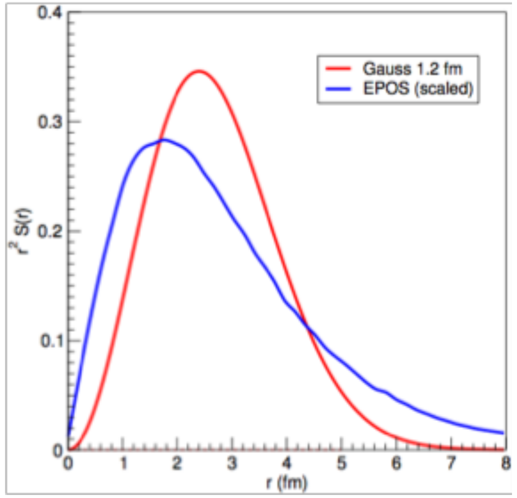
P-Pb @ 5.02 TeV

Particle	Candidates
p	155 x 10^6
$\bar{p}$	133 x 10^6
Λ	26 x 10^6
$\bar{\Lambda}$	24 x 10^6
Ξ	0.9 x 10^6
$\bar{\Xi}$	0.9 x 10^6

Combinations	Pairs (k*< 200 MeV/c)
$p-p$	517 x 10^3
$\bar{p}-\bar{p}$	370 x 10^3
$p-\Lambda$	127 x 10^3
$\bar{p}-\bar{\Lambda}$	62 x 10^3
$\Lambda-\Lambda$	13 x 10^3
$\bar{\Lambda}-\bar{\Lambda}$	12 x 10^3
$p-\Xi$	1.8 x 10^3
$\bar{p}-\bar{\Xi}$	1.3 x 10^3

Epos Source

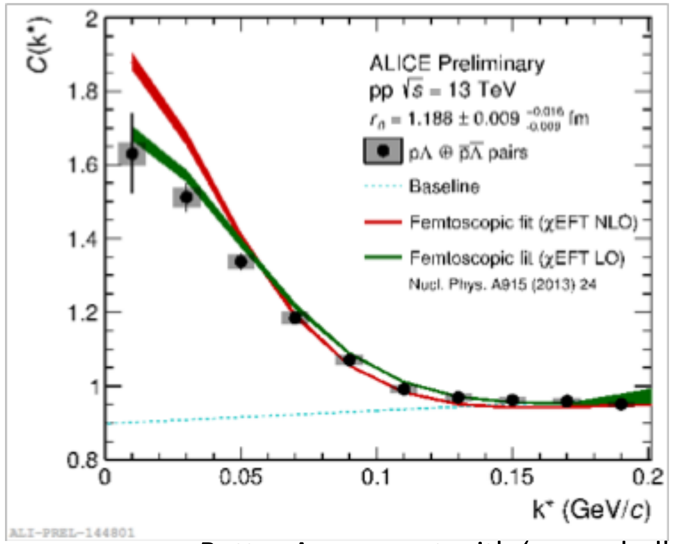
(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)



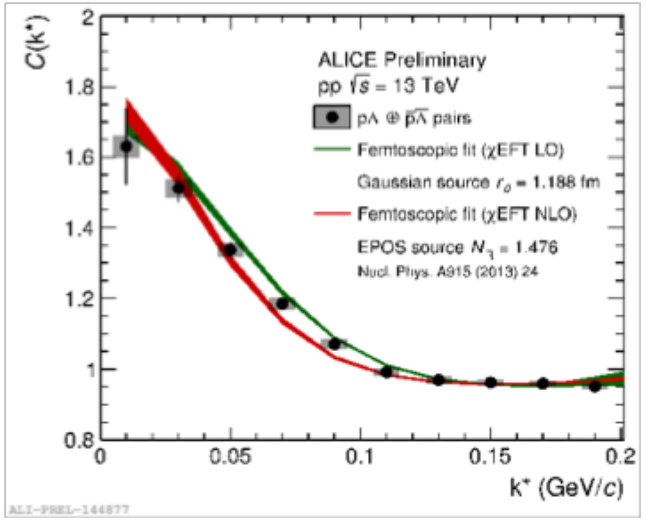
Source with a non-Gaussian shape
Maximum at smaller R and long tail

Test with 'expanded' EPOS for pp 13 TeV

Gaussian Source



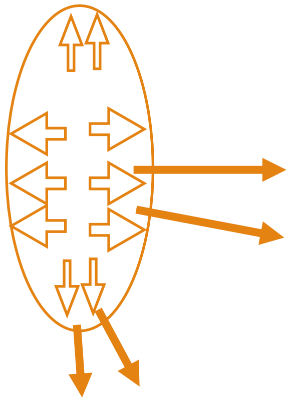
EPOS Source



Better Agreement with 'expanded' EPOS for NLO for p-Λ correlations

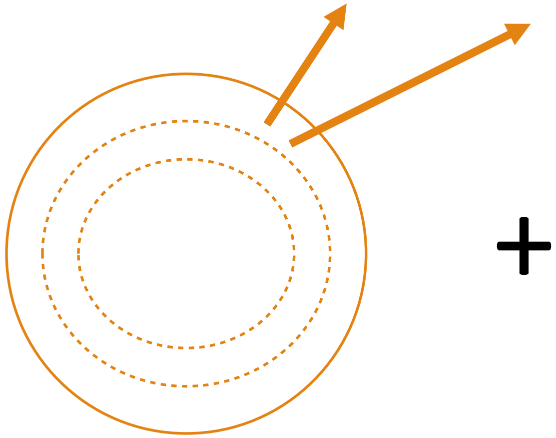
Collective Effects and Strong Decays

Elliptic flow



+

Radial flow



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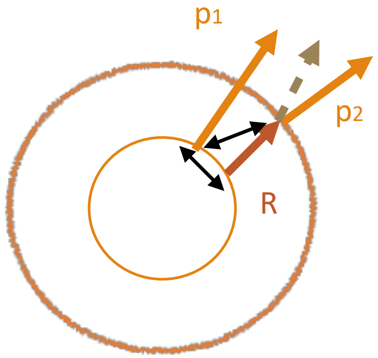
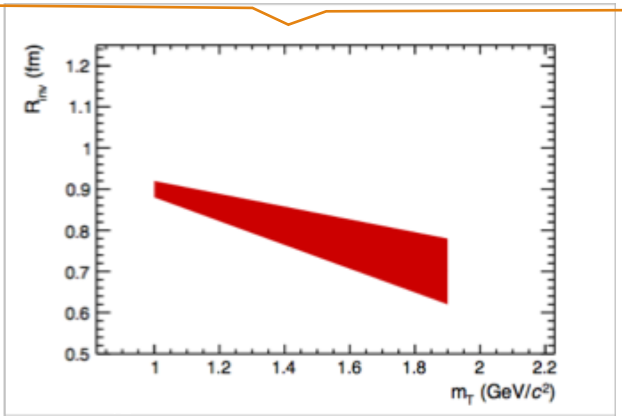
Strong decays of broad resonances

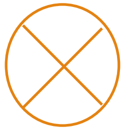


anisotropic pressure gradients within the source

Expanding source with constant velocity
different effect on different masses

p, Λ, Ξ, K are 'fed' by resonances with different masses and lifetimes



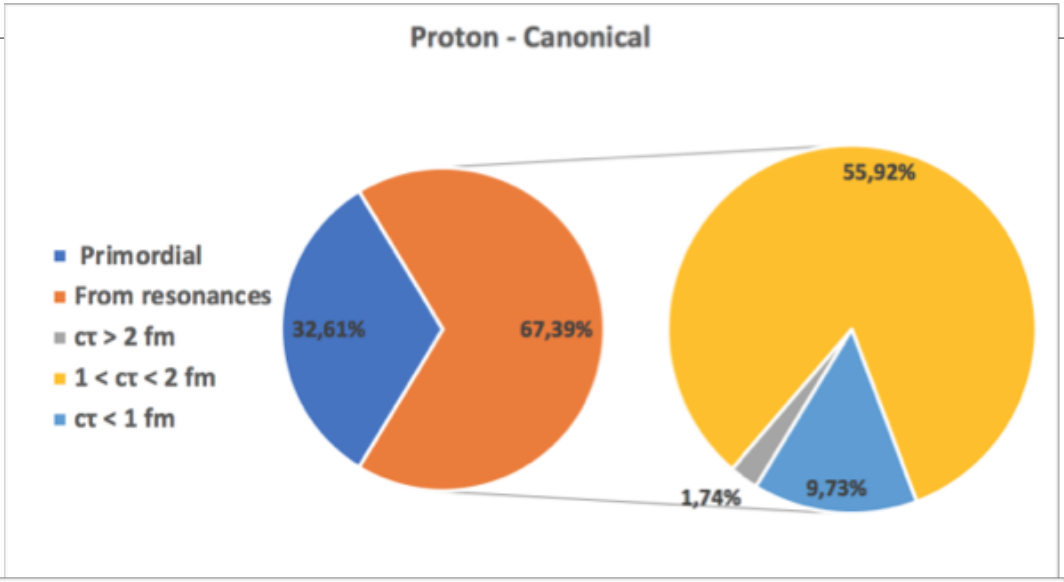


Strong decays of Specific resonances

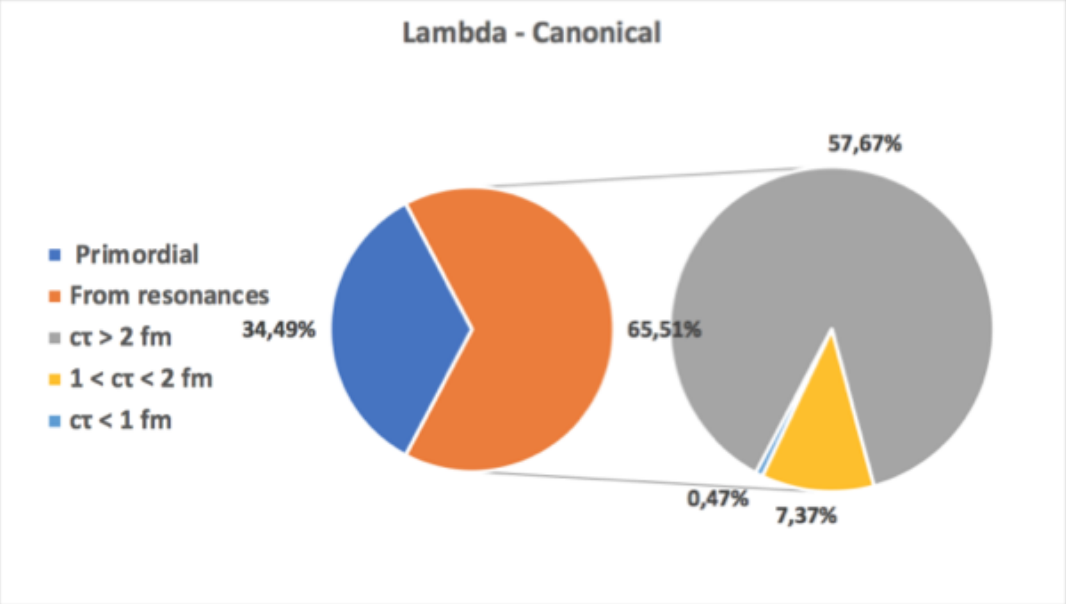
Valentina Mantovani Sarti (TUM Physics Department – E62)

Which Resonances?

Courtesy F. Becattini

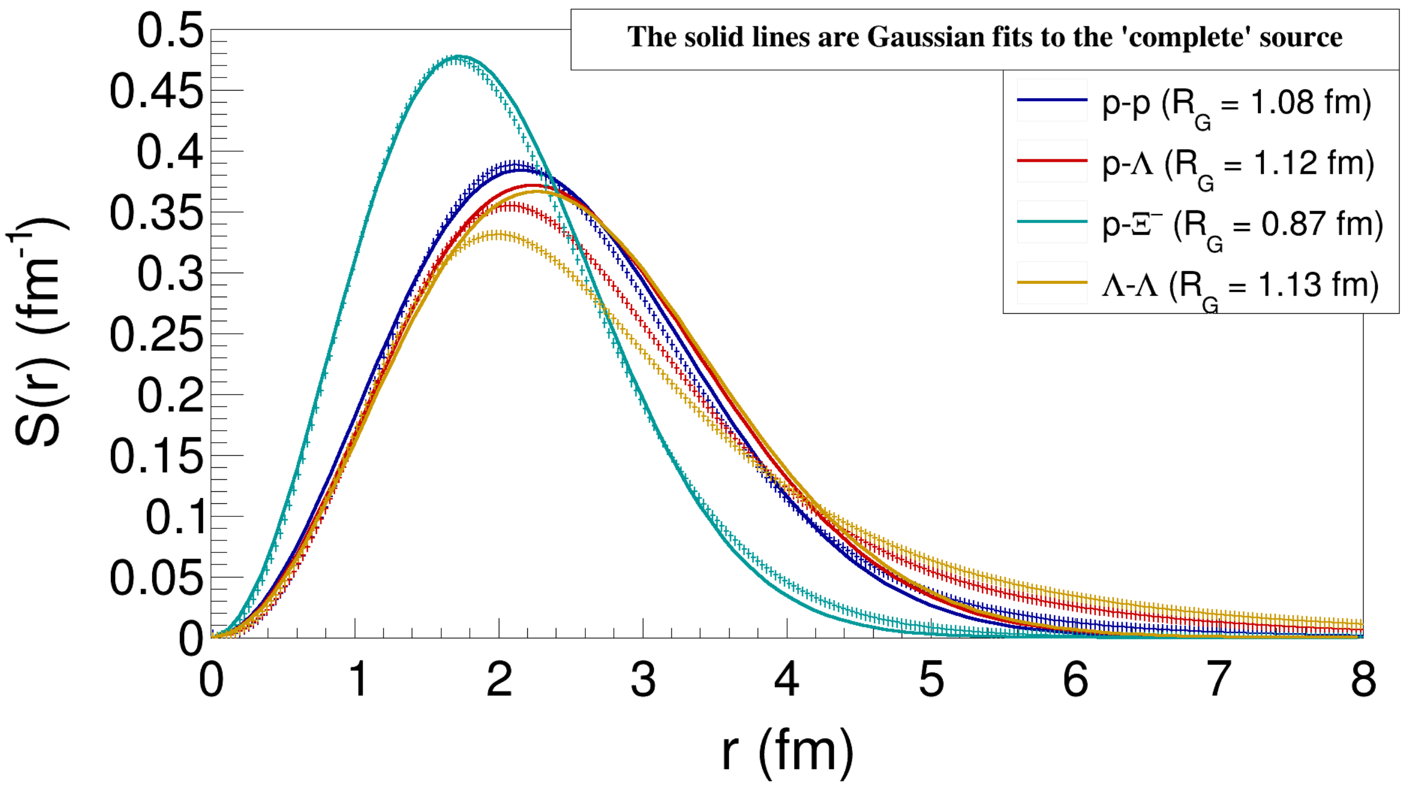


cτ > 2 fm (2.5-12 fm)	Σ(1670), Λ(1520),..
1 < cτ <2 fm	Λ(1600),Δ(1232)...
cτ < 1 fm	Δ(1600),N(1440),....
M_{eff} [MeV]	tau_{eff} [fm]
1368.92	1.6

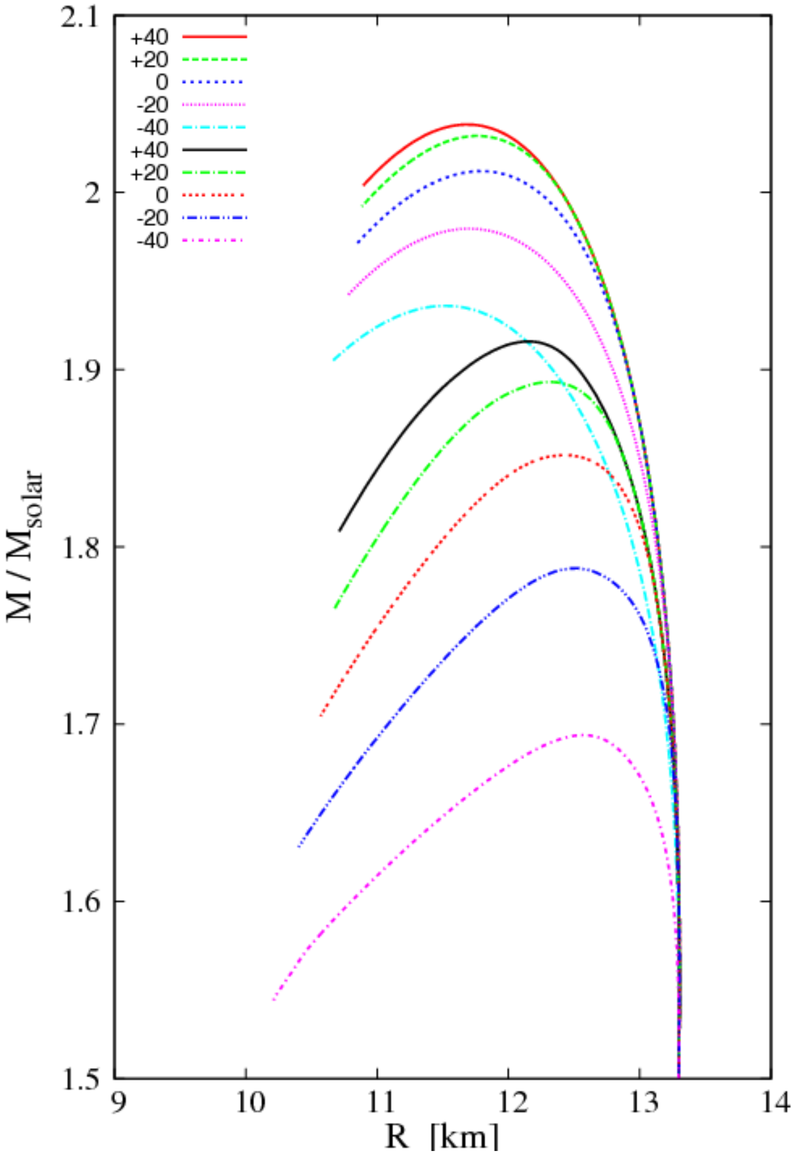


cτ > 2 fm (mainly 5 fm)	Σ(1385) mainly.
1 < cτ <2 fm	N(1710), Σ(1915),...
cτ < 1 fm	N(1720) only
M_{eff} [MeV]	tau_{eff} [fm]
1461.46	4.78

Source Distributions



p-Ξ⁻ interaction and Neutron Stars

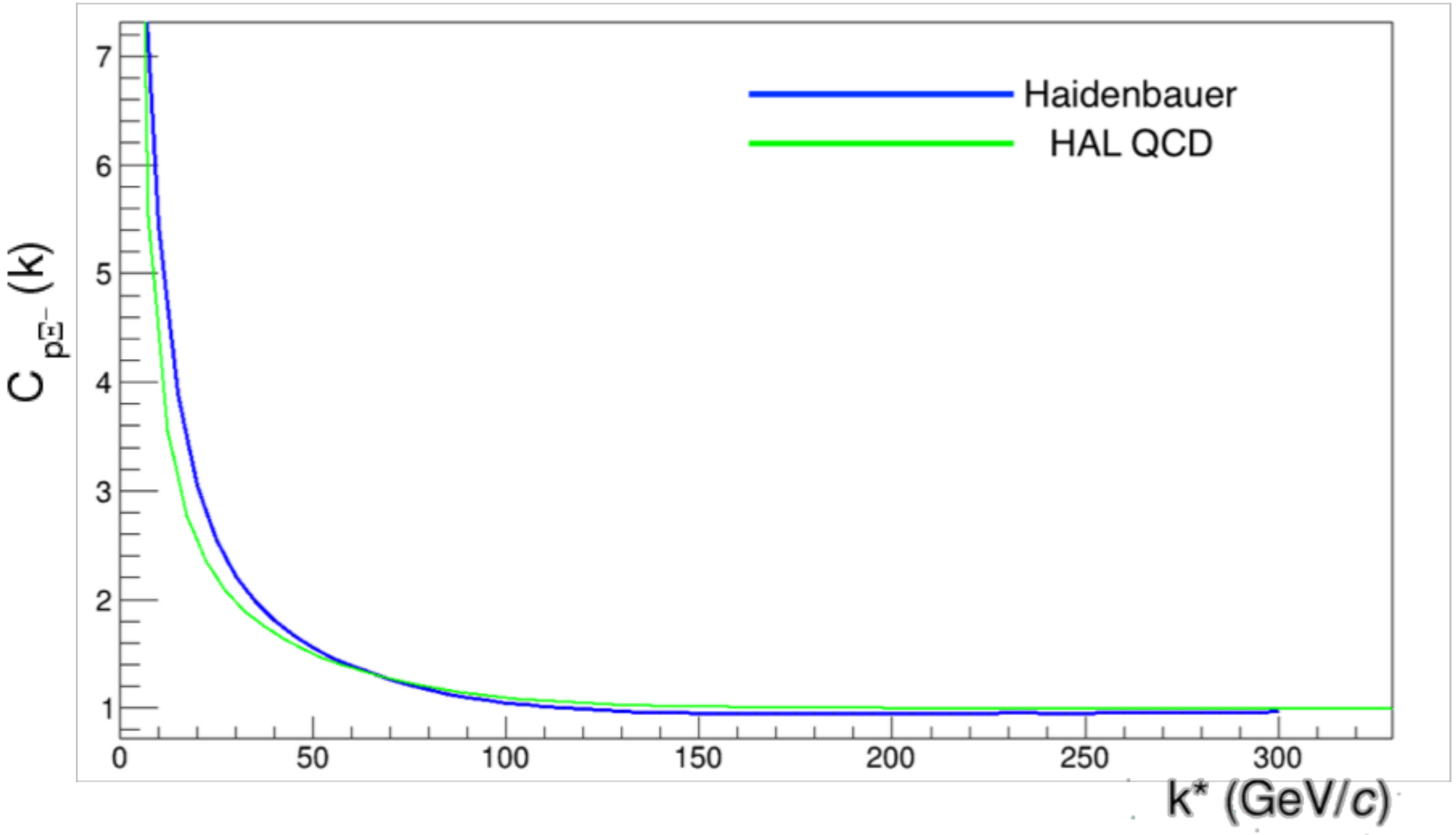


- If the in-medium N-Ξ potential is not attractive, the EoS becomes stiffer
- Ultimately this drives the allowed mass of neutron stars up (even above 2 solar masses)
- A complication: in the case of neutron stars only the n-Ξ interaction is important, but for us neutrons are not detectable

	I=0	I=1	Detectable
n-Ξ⁻	X	✓	No
p-Ξ⁰	X	✓	Difficult
p-Ξ⁻	✓	✓	Yes

- Experimentally challenging to isolate the I=1 channel

Theoretical p-Ξ^- Correlation function

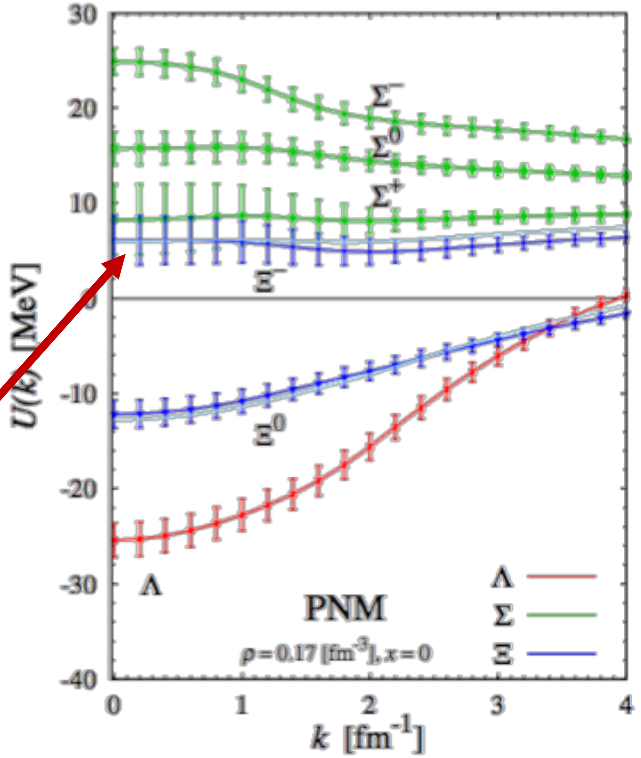


- Comparison **HAL-QCD/χEFT from recent work by Haidenbauer and Meissner (arxiv:1810.04883)**

Single particle potentials from Lattice

- NS environment ⇒ **P**ure **N**eutron **M**atter
- Tested HAL-QCD potential in vacuum with ALICE ⇒ Brueckner-Hartree-Fock many-body calculations ⇒ U_Y single-particle potential of hyperons in nucleonic matter
- At saturation density in PNM:

U_{Ξ^-} slightly repulsive

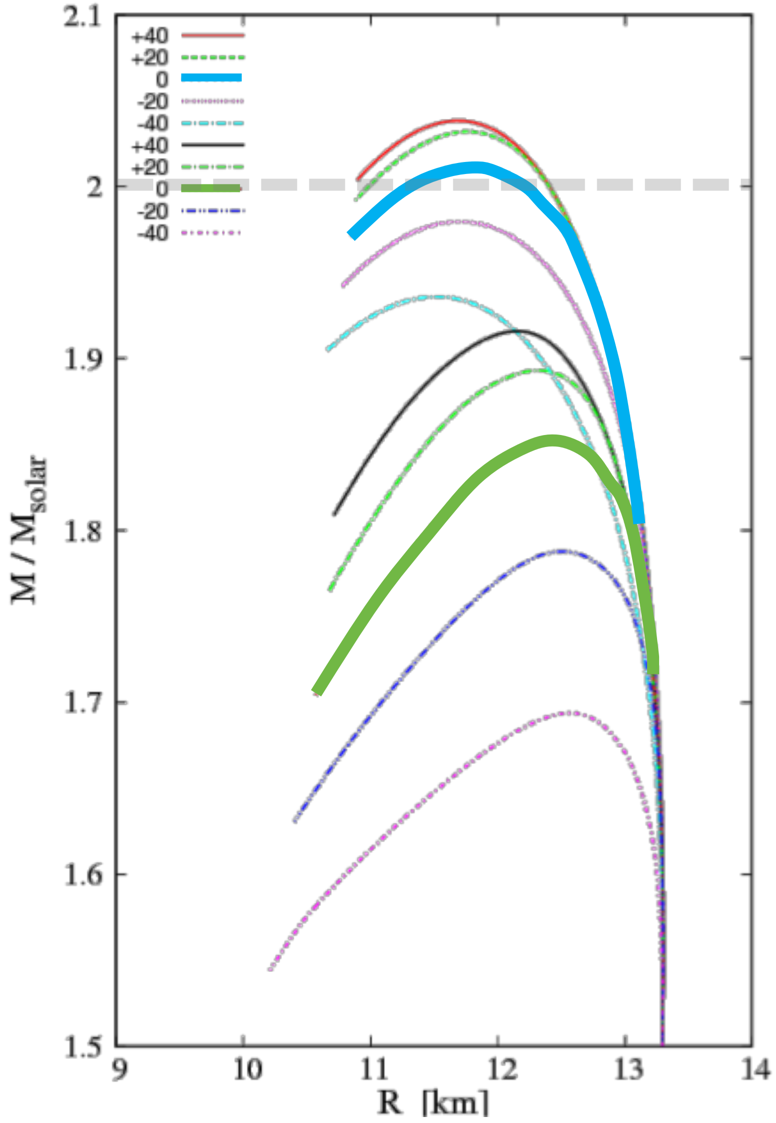


HAL-QCD Collaboration, arXiv:1809.08932 (2018)

Consequences for Neutron Stars

- Single-hyperon potential fundamental ingredient in EoS for NSs

- **Repulsive interaction⇒Production of Ξ^- pushed to higher densities ⇒ stiffer EoS, higher masses**



Weissborn et al., NPA881 (2012) 62-77

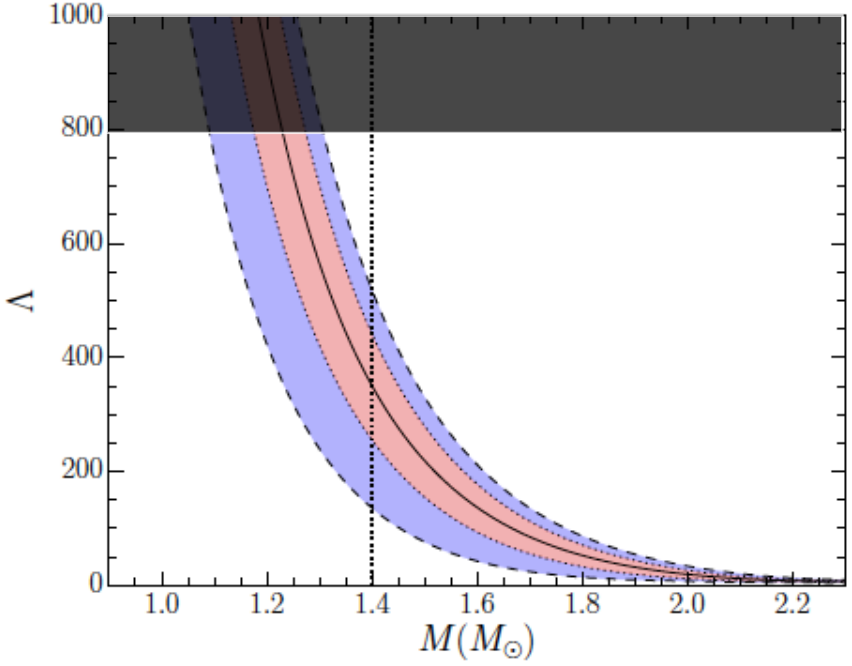
Recent Constraints from Gravitational Waves

not constraining really very much so far…

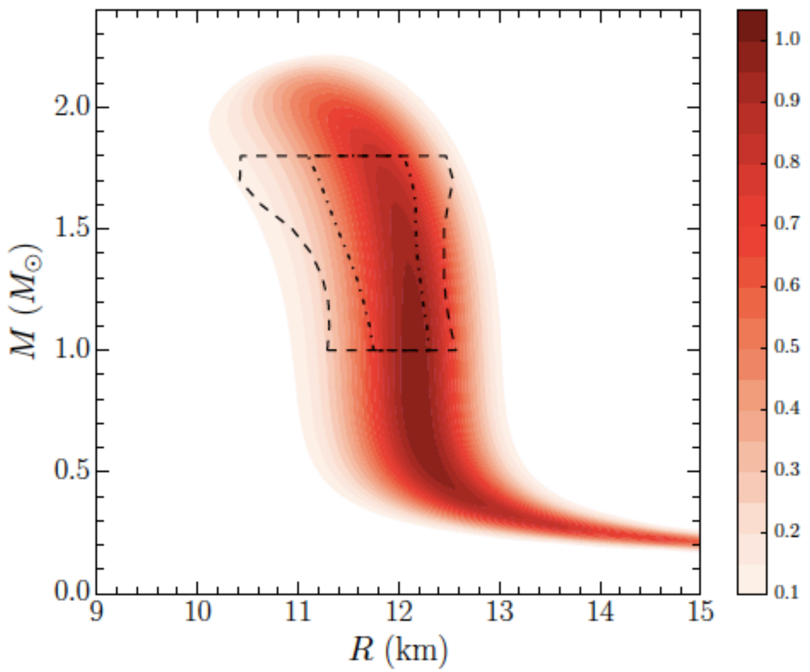
Tidal Deformability Λ : measurement of the NS deformability, upper limit extracted from GW170817

B. P. Abbott et al. (LIGO Scienti c Collaboration and Virgo Collaboration), Phys. Rev. Lett. 119, 161101 (2017).

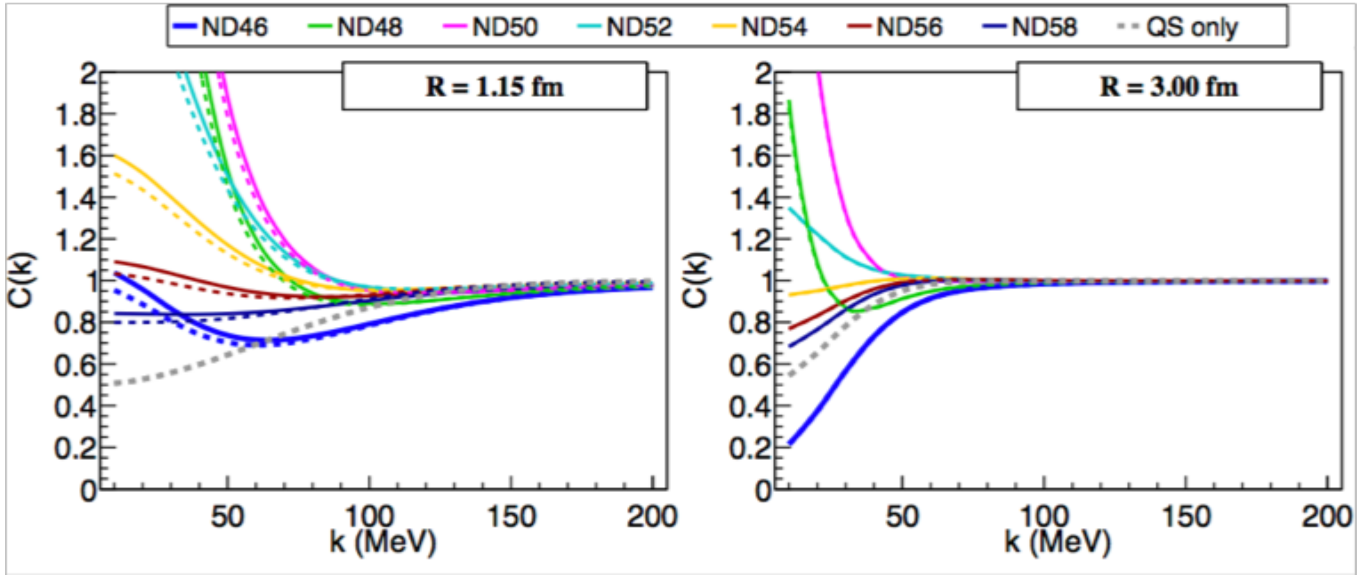
Nuclear EoS including 2N and 3N interactions are consistent with these constraints

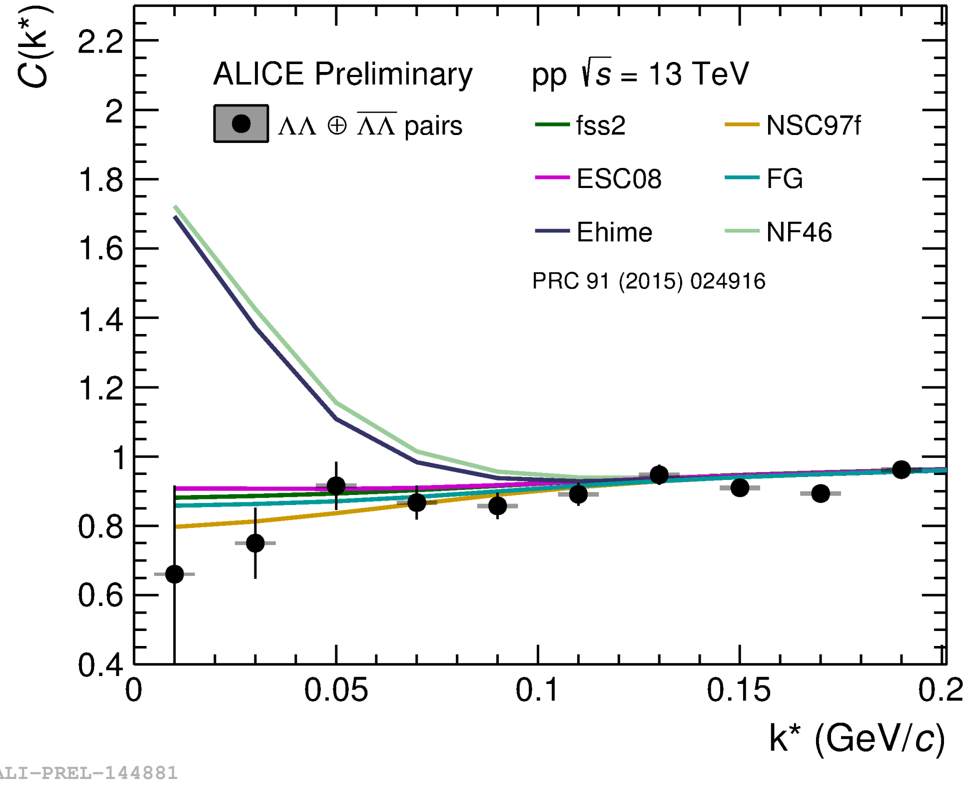


Y. Lim, J.W. Holt Phys.Rev.Lett. 121 (2018) no.6, 062701



Λ-Λ Correlations: Predictions with Lednicky

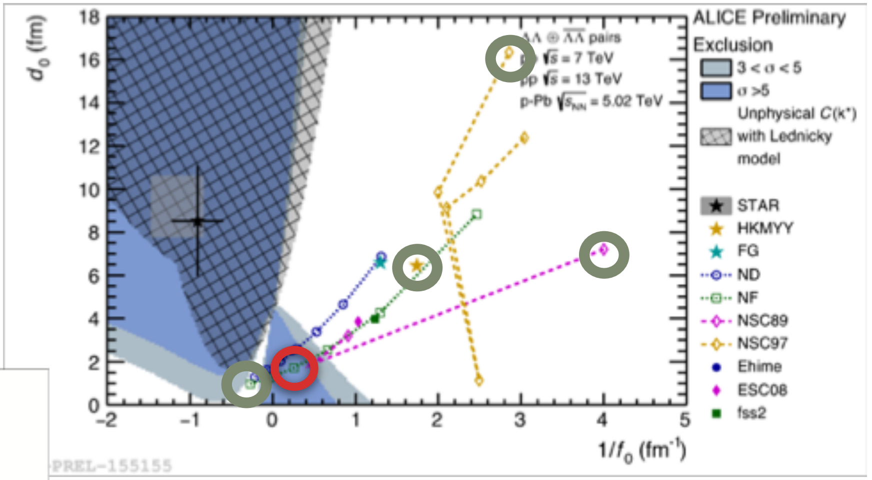


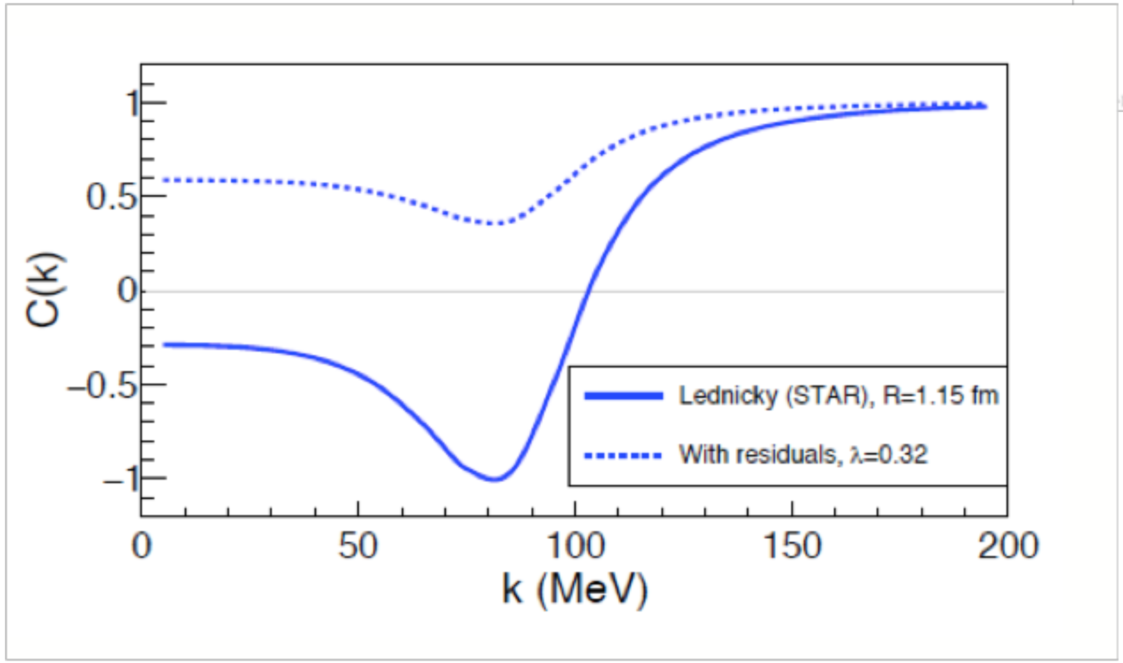


- Curves represent different points in the Λ-Λ exclusion plot
- For scattering parameters in the region $a_0 > 0$ the correlation function is not sensitive

Non Physical Region and STAR parameters

- Lednicky model breaks down for small radii, large effective ranges and negative scattering parameters
- It shows although at most 10% deviation from CATS in the region of positive scattering parameters





The unique opportunity of small sources