Scattering experiments with hyperons and nucleons at the LHC

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E62 – Dense and Strange Matter

Non-equilibrium Dynamics (NeD-2018) Varadero, Cuba

Outline

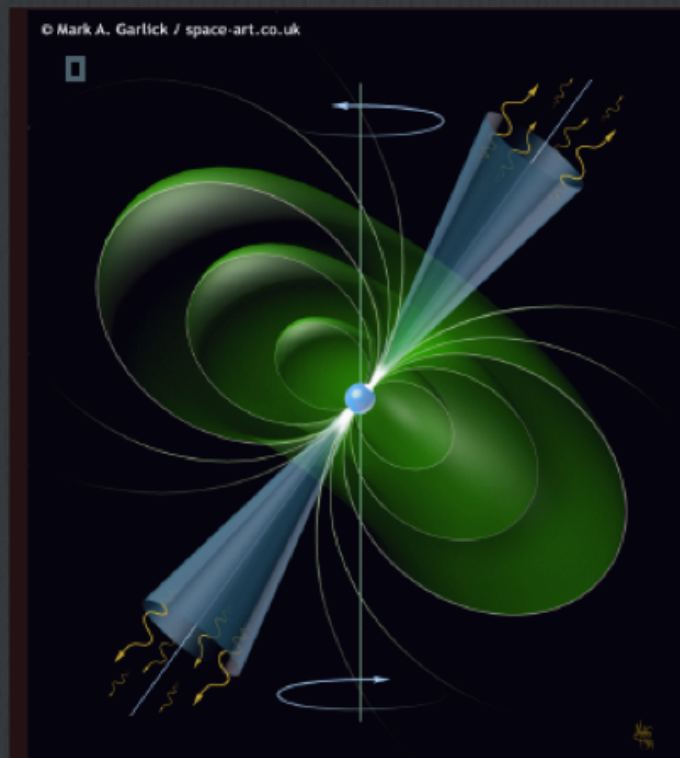
- The Hyperon Puzzle in Neutron Stars
- Experimental Method to Study the Hyperon-nucleon interaction

- Correlation Functions (the Femtoscopy Method)
    - Theoretical Description of the correlation function
    - CATS

- Experimental Results: RUN1 and RUN2
    - p+p Collisions at 7 TeV and 13 TeV, p+Pb at 5.02 TeV measured by ALICE
    - pp, pΛ ,$\Lambda\Lambda$, pΞ^- Correlations

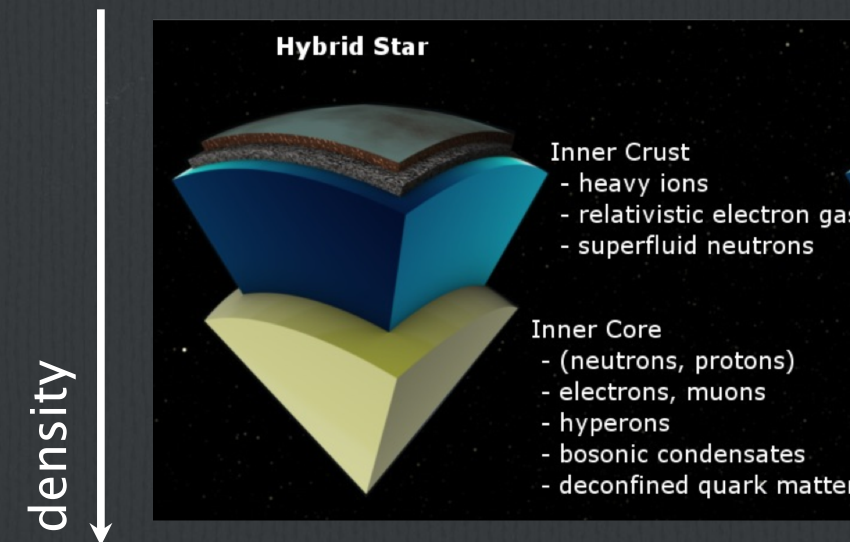
- Outlook

Facts about Neutron Stars



R ~ 10–15 km

M ~ 1.5 $M_\odot$

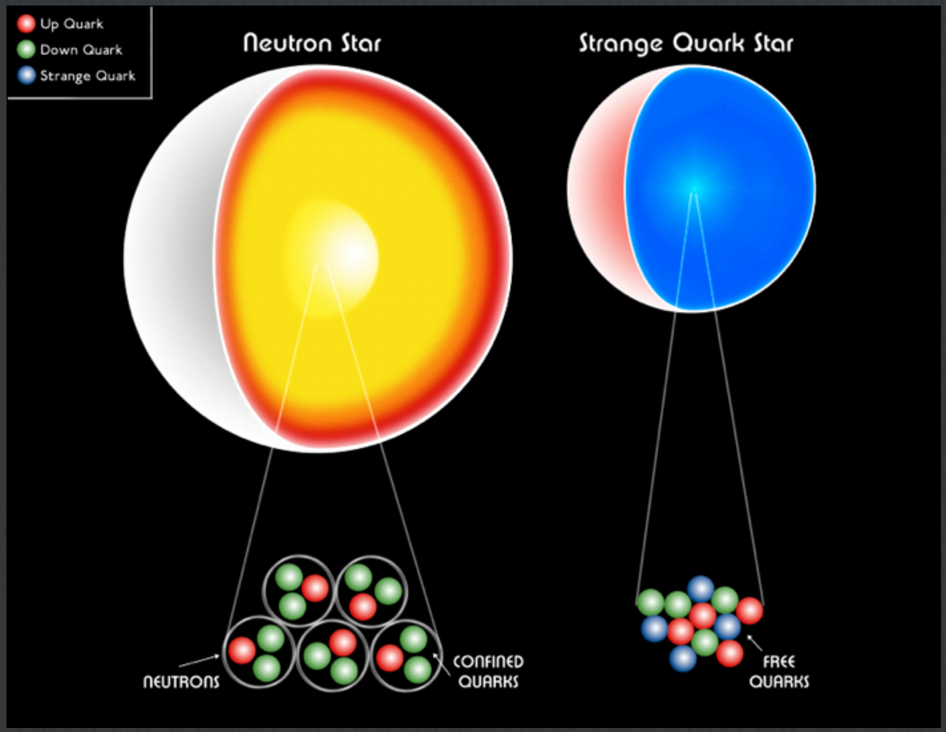


- Very high density in the interior
- Strong magnetic fields
- Rotating object emitting Synchrotron radiation in Radio-Frequency (Pulsar character)
- Mass measured in binary systems with White Dwarfs (Shapiro Delay, WD Spectroscopy)
- Radius Measurement very difficult
- Masses ranging from 1.4 $M_\odot$ to 2 $M_\odot$

What is inside Neutron Stars??

Speculations about Neutron Stars

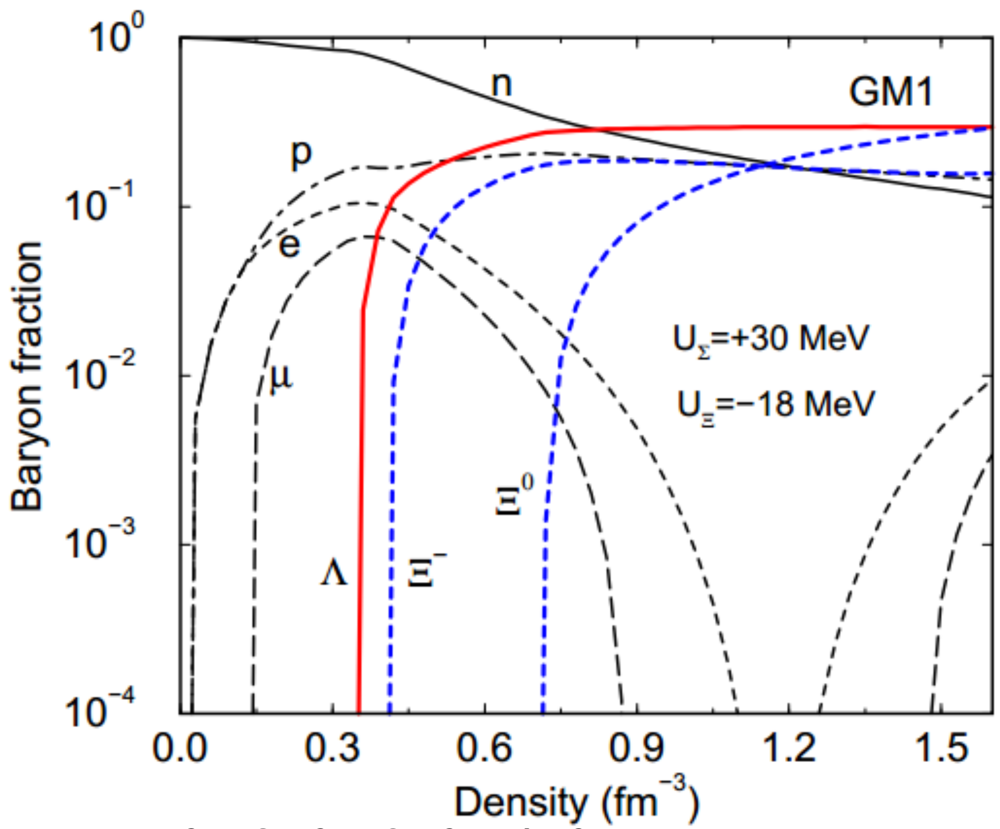
NSF, universetoday.com



- Hadron composition
  - Only Nucleons
  - Antikaons-Nucleons condensate
  - Nucleons and Hyperons
- Nuclear Pasta
  - lasagne
  - spaghetti
- Quark star (Color super-conducting strange quark matter)

The Hyperon Puzzle in Neutron Stars

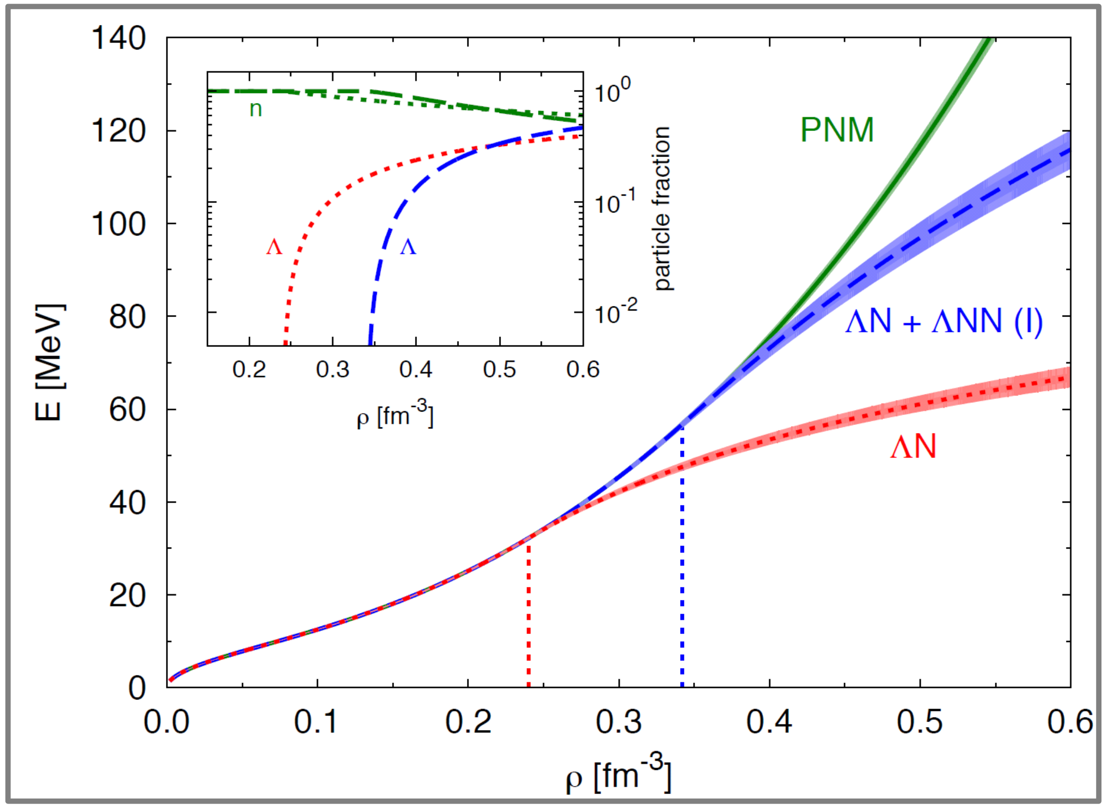
Hyperons should appear in dense neutron-rich matter starting from moderate large densities
Threshold depends on the Y-N interaction



ϱ0 2ϱ0 3ϱ0 4ϱ0 …..

J. Schaffner-Bielich, NPA 804 (2008)

The appearance of Hyperons softens the EoS



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

The Hyperon Puzzle in Neutron Stars

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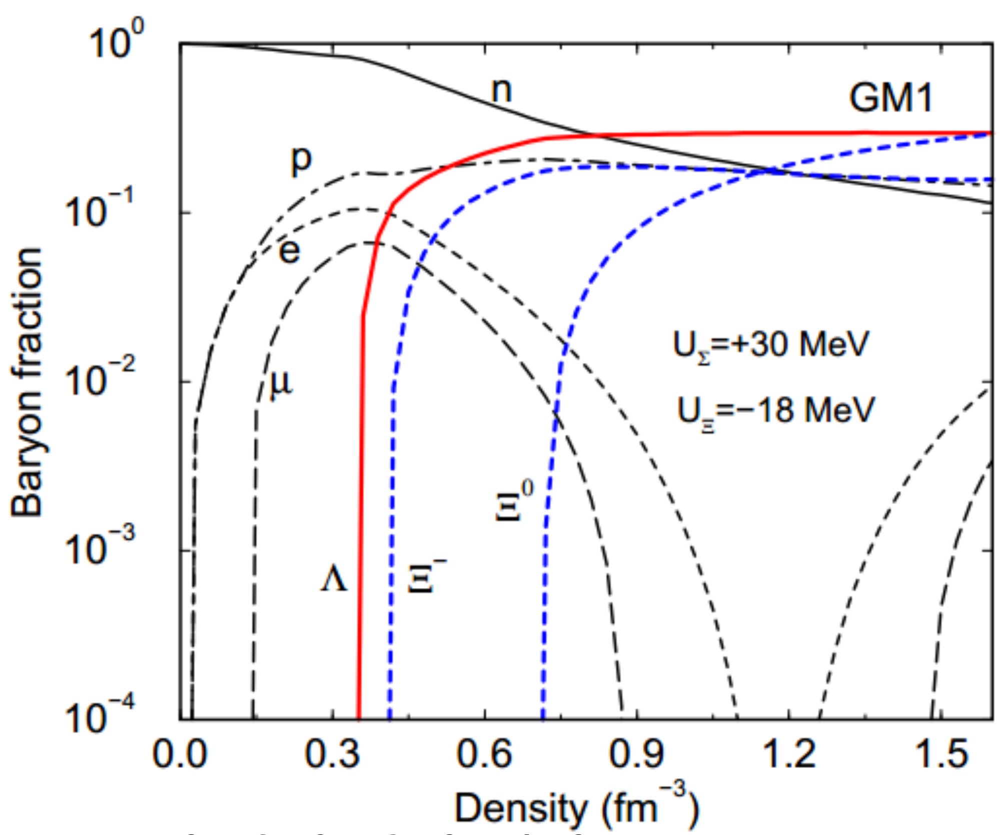
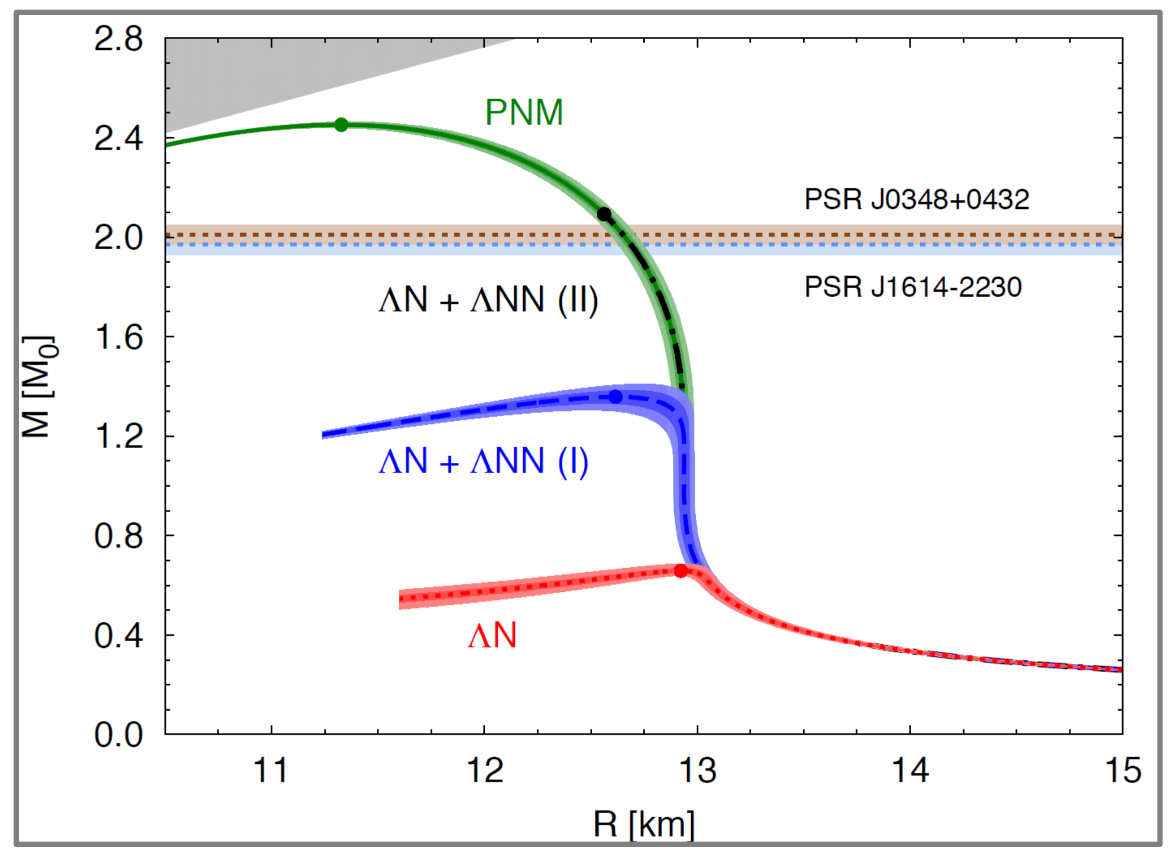


ϱ0 2ϱ0 3ϱ0 4ϱ0 …..

J. Schaffner-Bielich, NPA 804 (2008)

The appearance of Hyperons softens the EoS

⇨ <u>Maximum NS masses get smaller</u>

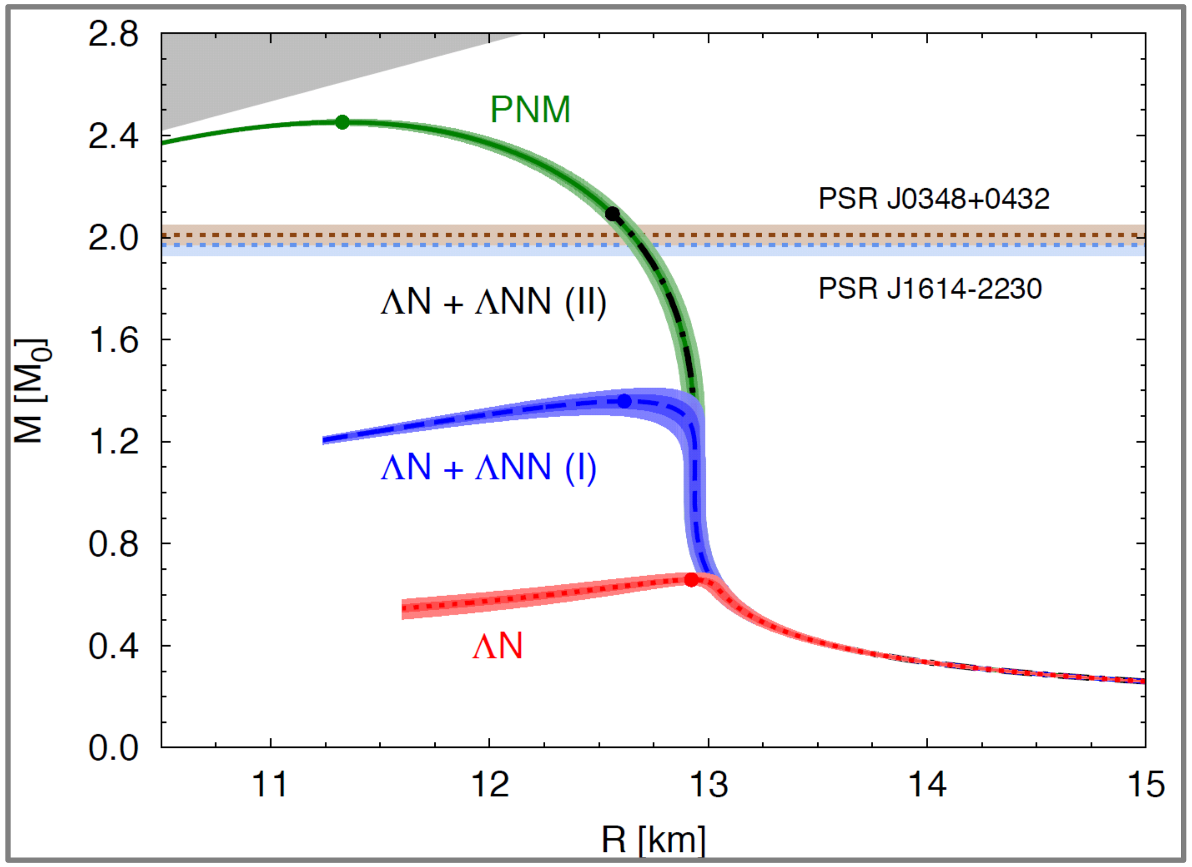


D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

The Hyperon Puzzle in Neutron Stars

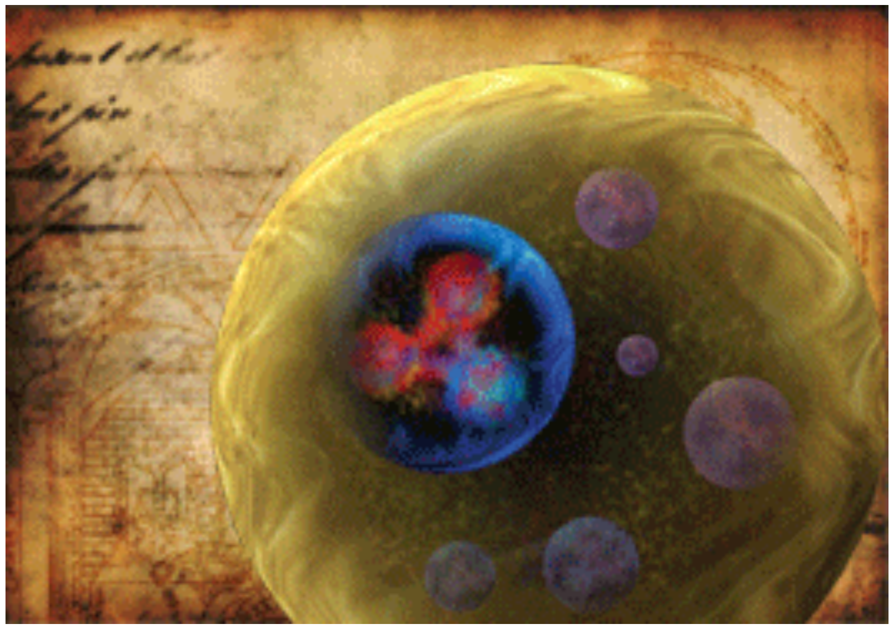
- Repulsive 3 body interaction shifts onset of hyperon production to larger densities and allows for higher masses
  - Not well constrained
- To understand the role of hyperons in neutron stars more constraints on the hyperon-neutron force are needed

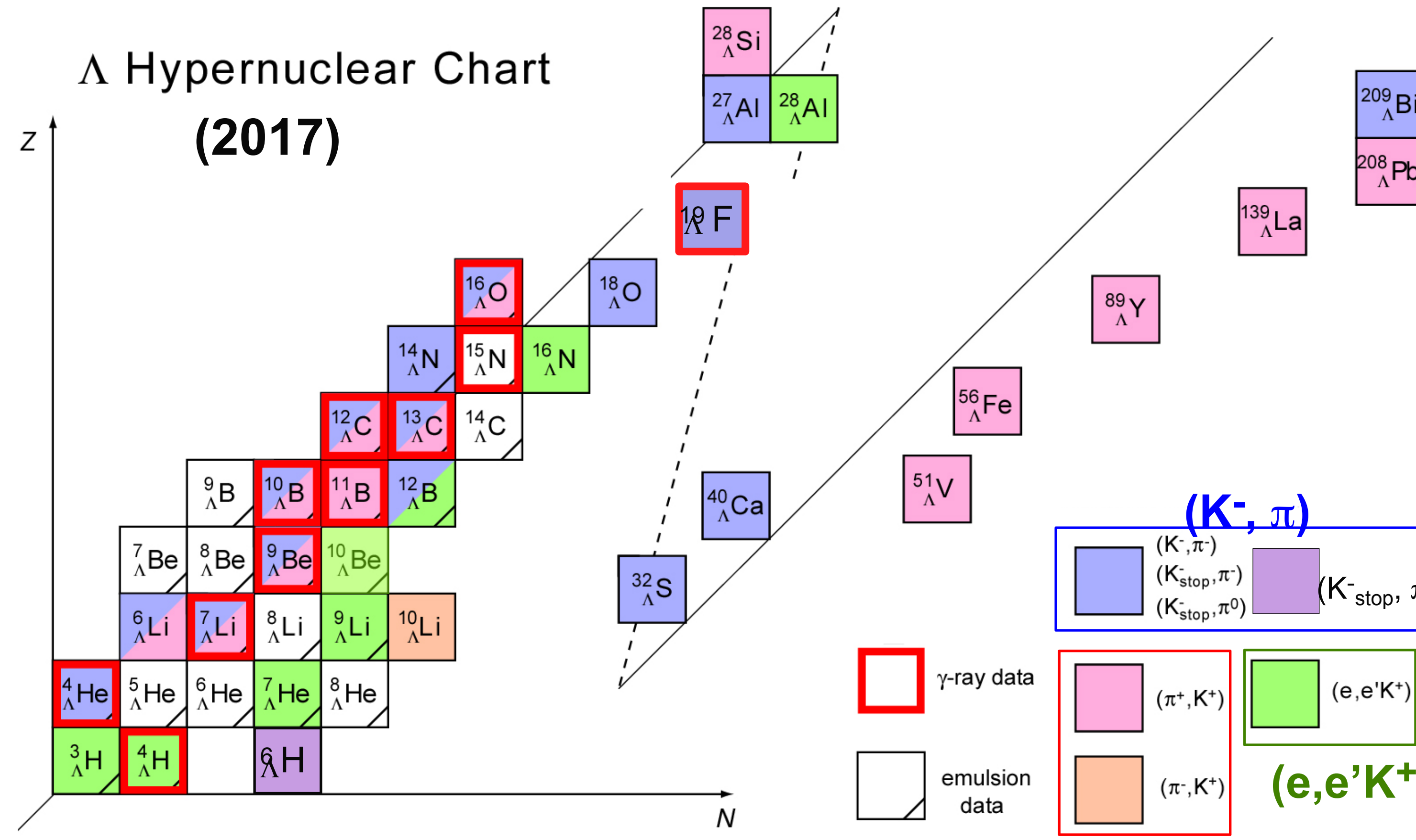
$$\Lambda N,\ \Sigma N,\ \Xi N....$$
$$\Lambda NN,\ \Sigma NN,\ ....$$



Experimental Methods I

http://eaae-astronomy.org/blog/?cat=254





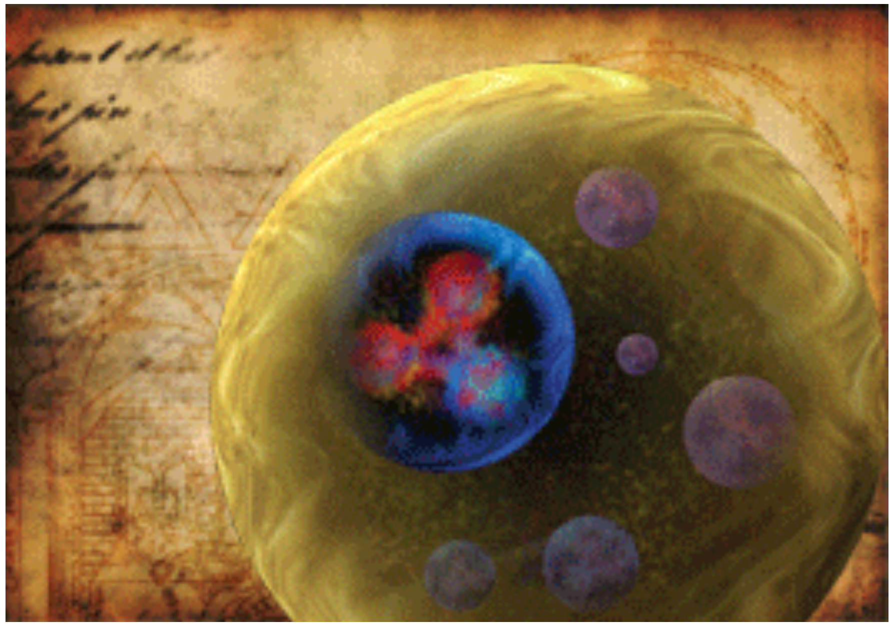
Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006)

Hypernuclei can be produced

Binding Energy of Λ to nucleus = 30 MeV

Experimental Methods I

http://eaae-astronomy.org/blog/?cat=254



Hypernuclei can be produced
Binding Energy of Λ to nucleus = 30 MeV

Nothing is known about Σ - hypernuclei

Experimental Methods I

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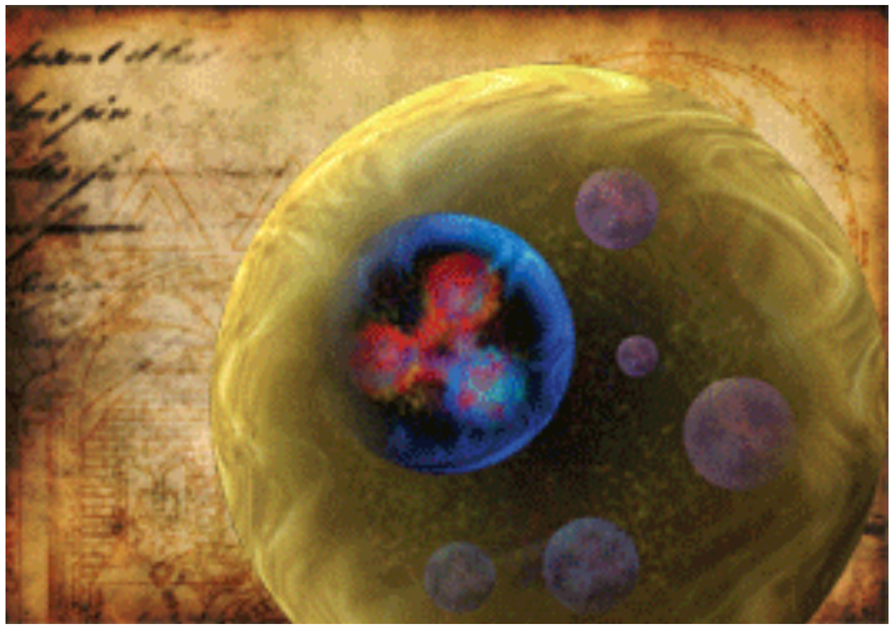


Hypernuclei can be produced
Binding Energy of Λ to nucleus = 30 MeV

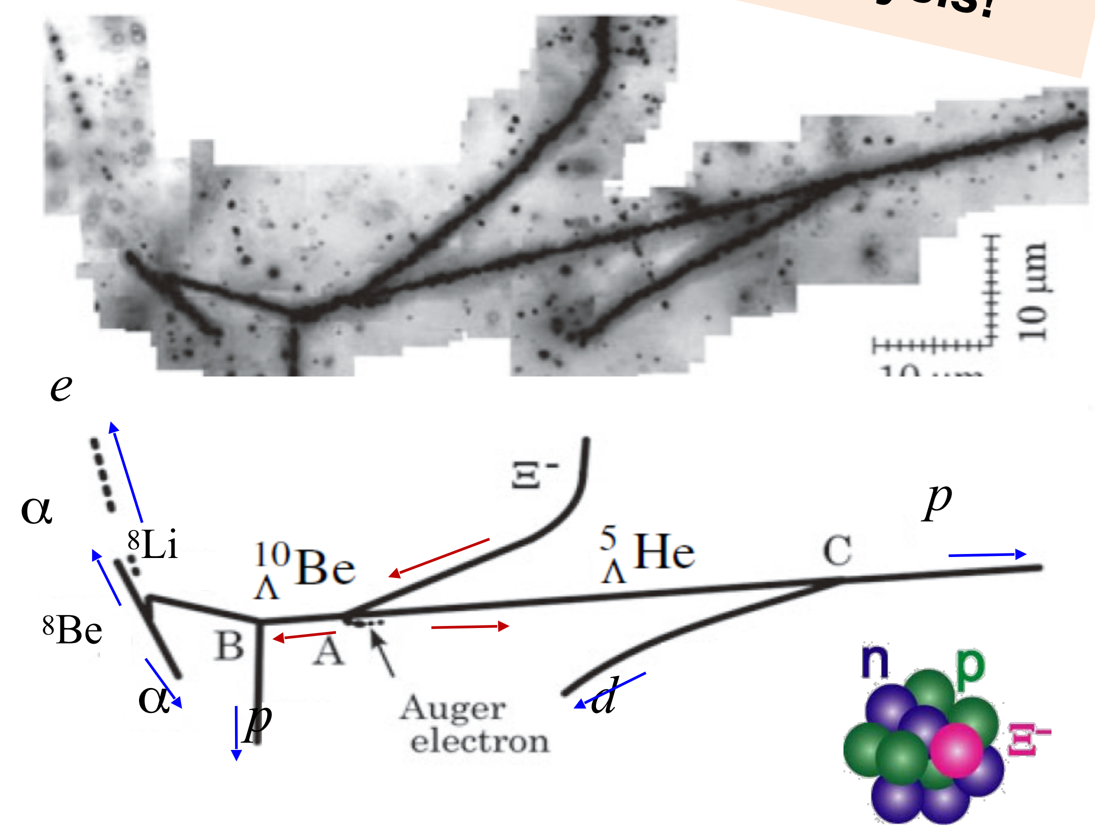
Nothing is known about Σ - hypernuclei

Ξ - Hypernuclei shows a shallow attractive interaction

Courtesy H. Tamura, Bormio Winter Meeting 2018

New analysis!

Kiso event



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

The first clear Ξ hypernucleus

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

K. Nakazawa et al. PTEP 2015, 033D02

Experimental Methods I

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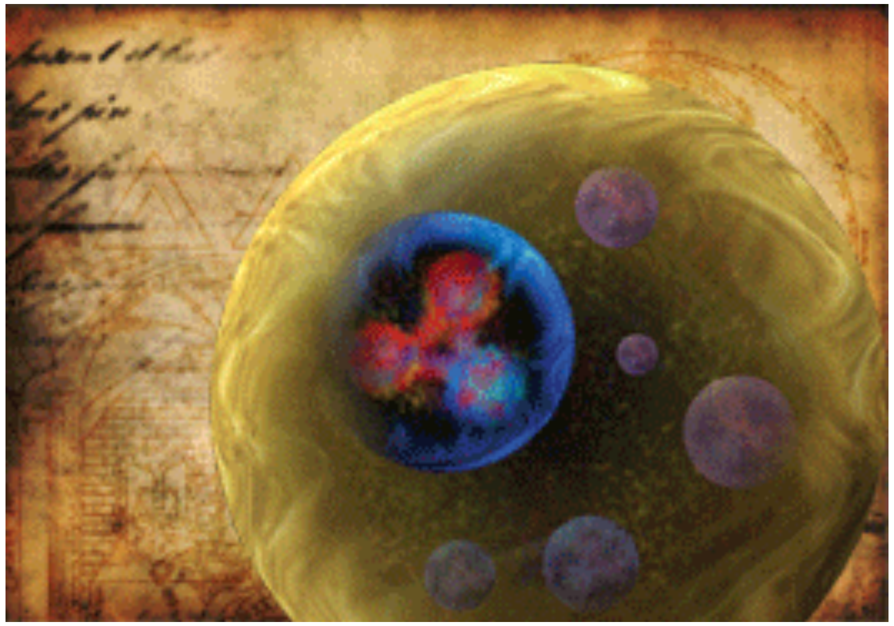
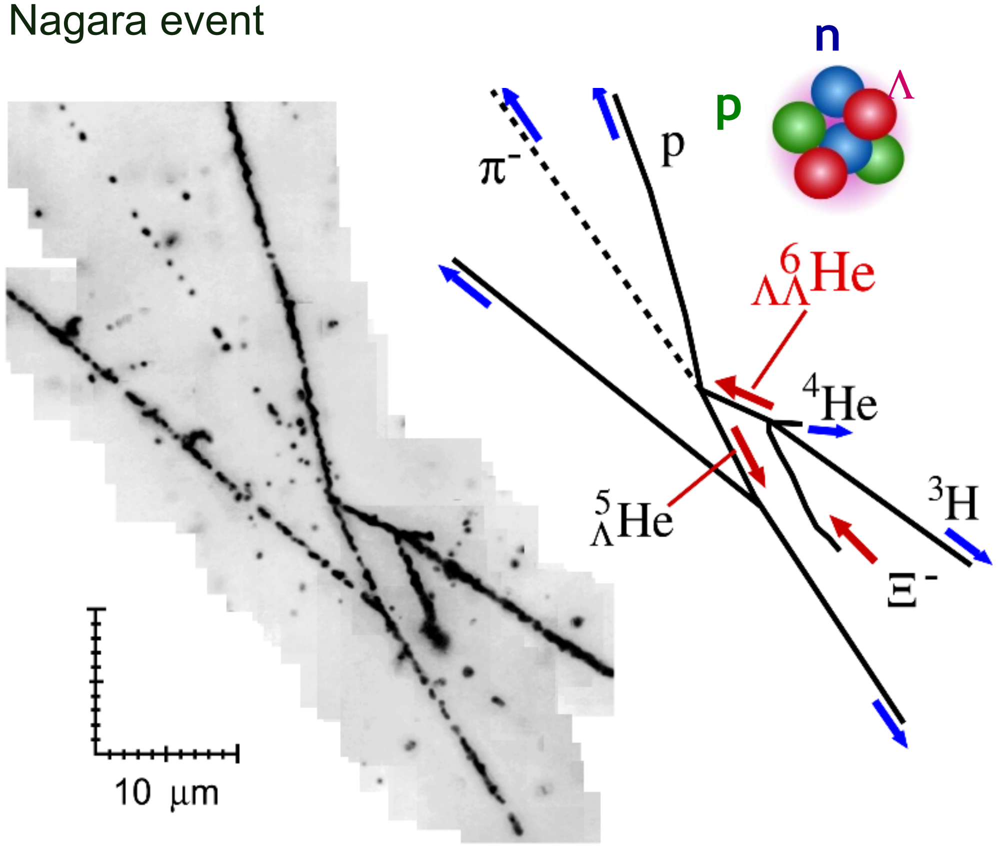


Nagara event



Hypernuclei can be produced

Binding Energy of Λ to nucleus = 30 MeV

Nothing is known about Σ - hypernuclei

Ξ - Hypernuclei shows a shallow attractive interaction

Even $\Lambda\Lambda$-hypernuclei exists

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

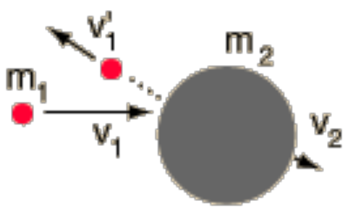
$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

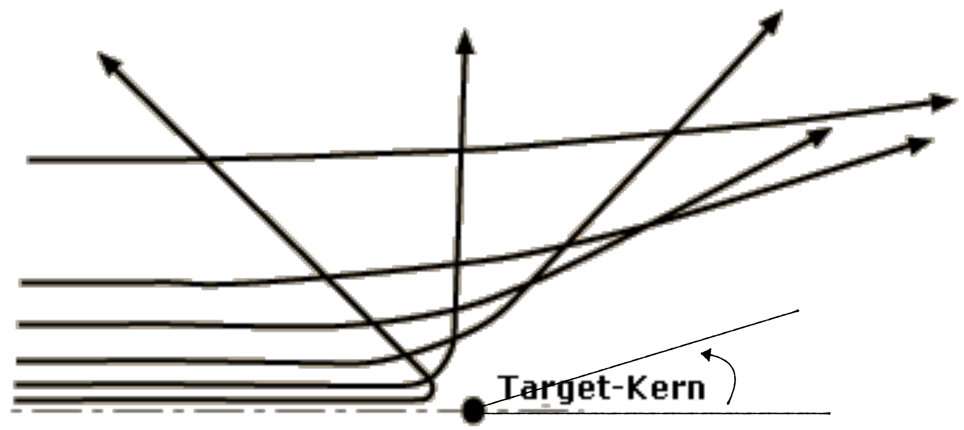
H. Takahashi et al., PRL 87 (2001) 212502

Λ-Λ is weakly attractive

Scattering Data and Interaction Parameters

Scattering experiments -> Extraction fo the differential cross section





$$\longrightarrow \quad \frac{d\sigma}{d\Omega}$$

Expansion in partial waves:

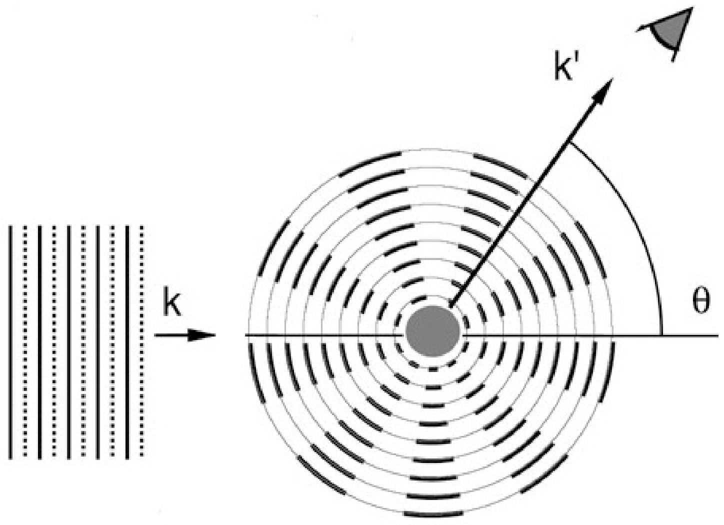
$$\sigma = \frac{4\pi}{k^2} \sum_{l} (2l + 1) \sin^2(\delta_l).$$

What are these shifts?

Scattering Data and Interaction Parameters

If we set, $\psi(\mathbf{r}) \simeq e^{i\mathbf{k}\cdot\mathbf{r}} + f(\theta)\frac{e^{ikr}}{r}$

$$f(\theta) = \sum_{\ell=0}^{\infty}(2\ell+1)f_\ell(k)P_\ell(\cos\theta)$$



$$f_l(k) = \frac{e^{2i\delta_l(k)} - 1}{2ik}$$

$\delta_\ell(k)$ **Phase Shifts**

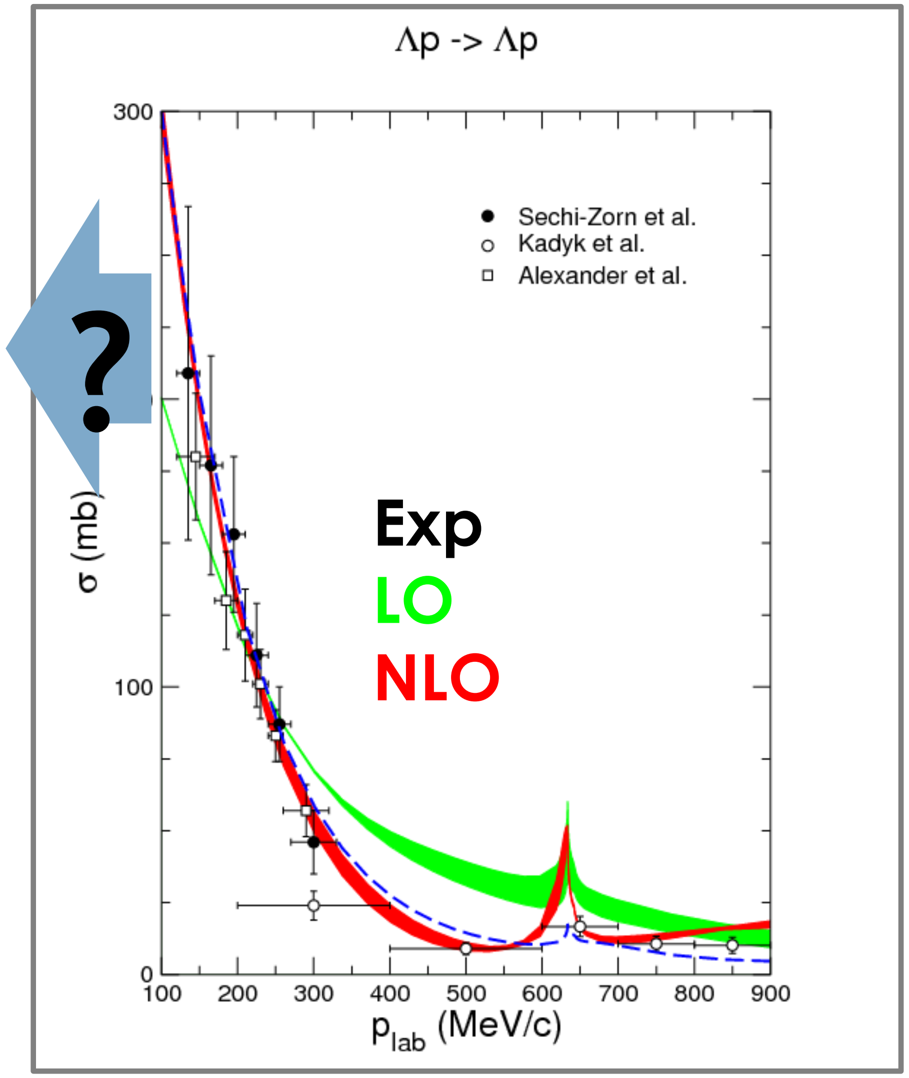
$f(\theta)$ of the scattered wave clearly depends on the interacting potential between beam and target.
By measuring the scattering cross-section one can infer on the scattering parameters and determine the interaction (to some extend)

$$a_0 = -\lim_{k\to 0}\frac{1}{k}\tan\delta_0(k).$$

l=0 -> s-wave only!!

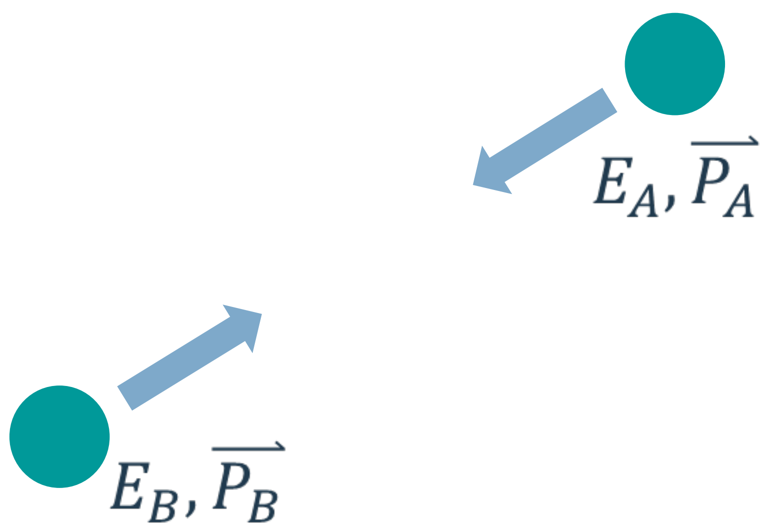
Global Proton-Λ Scattering Data

- Data from scattering experiments from 1968 and 1971 in bubble chambers
  - $K^- + p \rightarrow \Sigma^0 + \pi^0, \Sigma^0 \rightarrow \Lambda + \gamma$
  - Production threshold for Λ's : $\mathrm{p} \gtrsim 100$ MeV
- Different type of measurement needed to obtain constraints at low momentum
- Can we use Femtoscopic measurements?

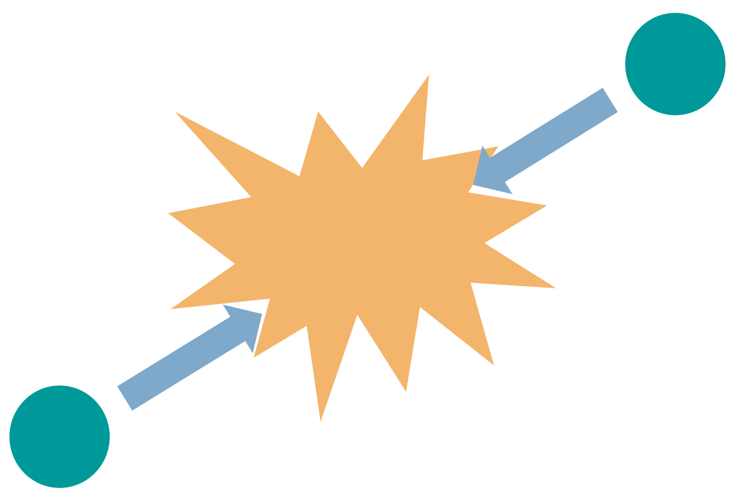


LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

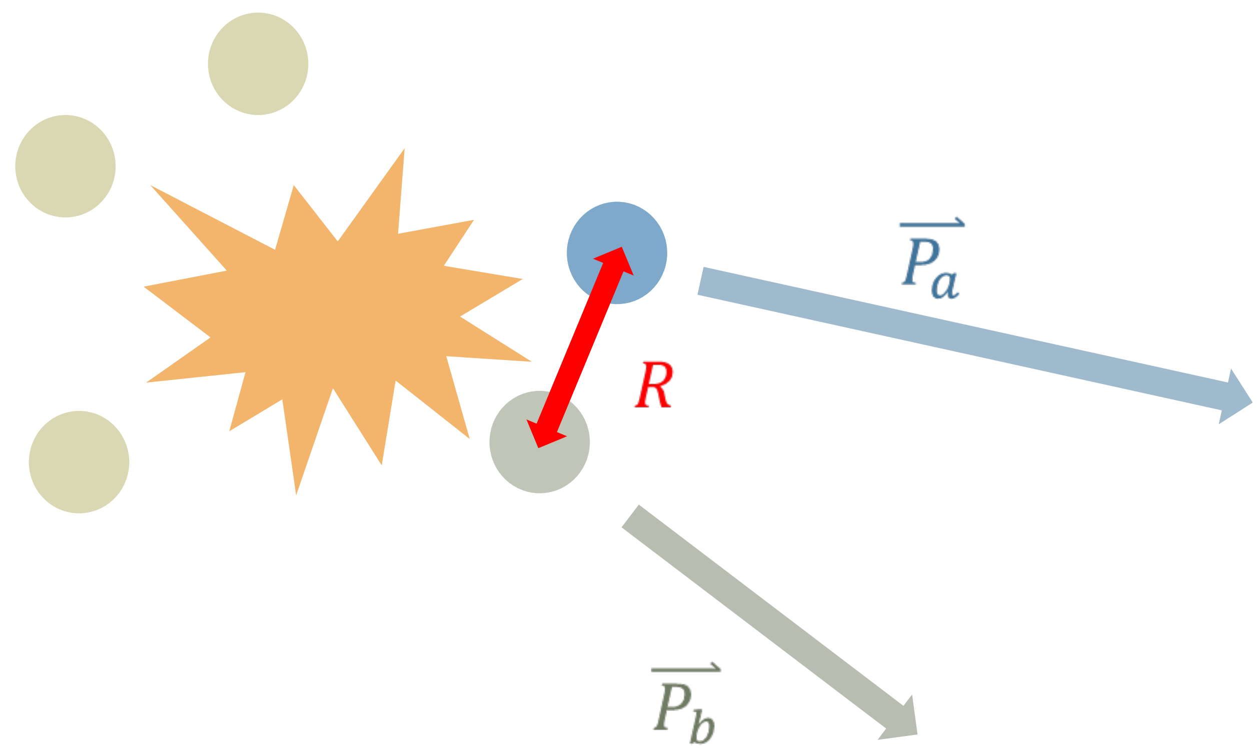
Nuclear Collisions



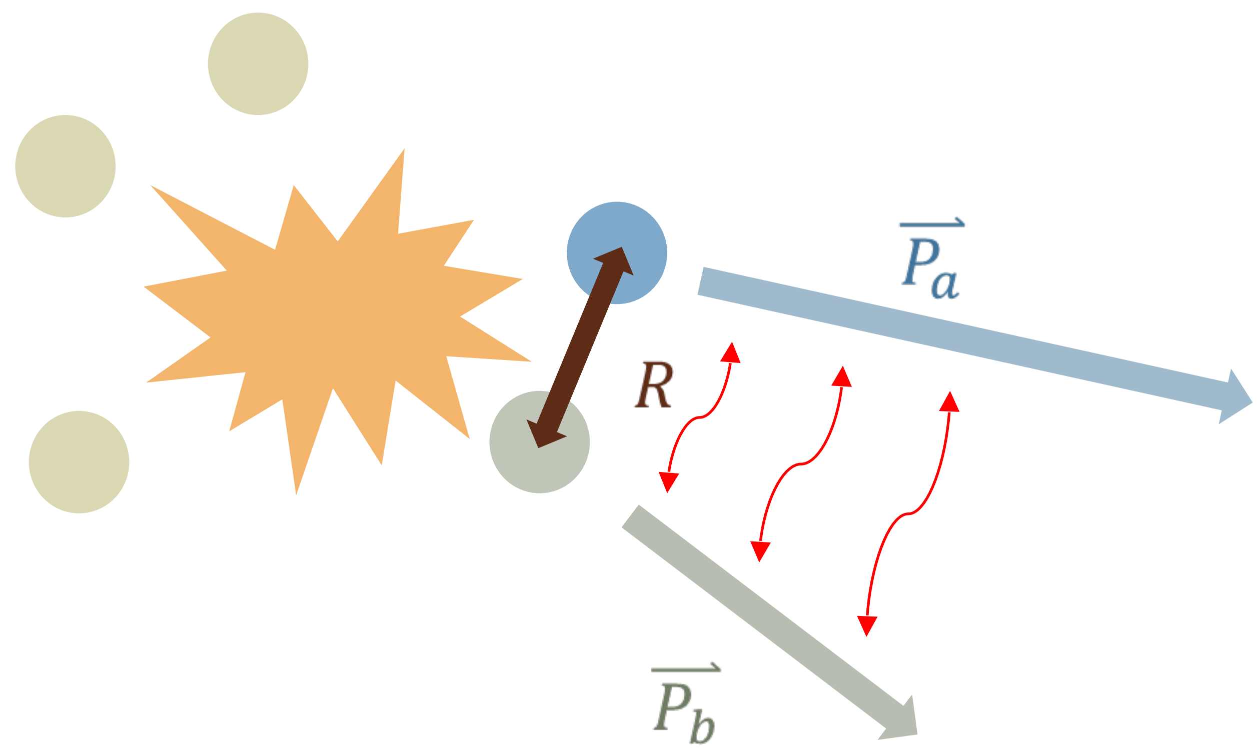
Nuclear Collisions



Particle Production



Particle Propagation



The Correlation Function

Theoretical formulation of the Correlation Function:

$$C(\overrightarrow{\boldsymbol{p}_a}, \overrightarrow{\boldsymbol{p}_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})} = C(k) = \int S(\vec{\boldsymbol{r}}, k)|\psi(\vec{\boldsymbol{r}}, k)|^2 \, d\vec{\boldsymbol{r}}$$

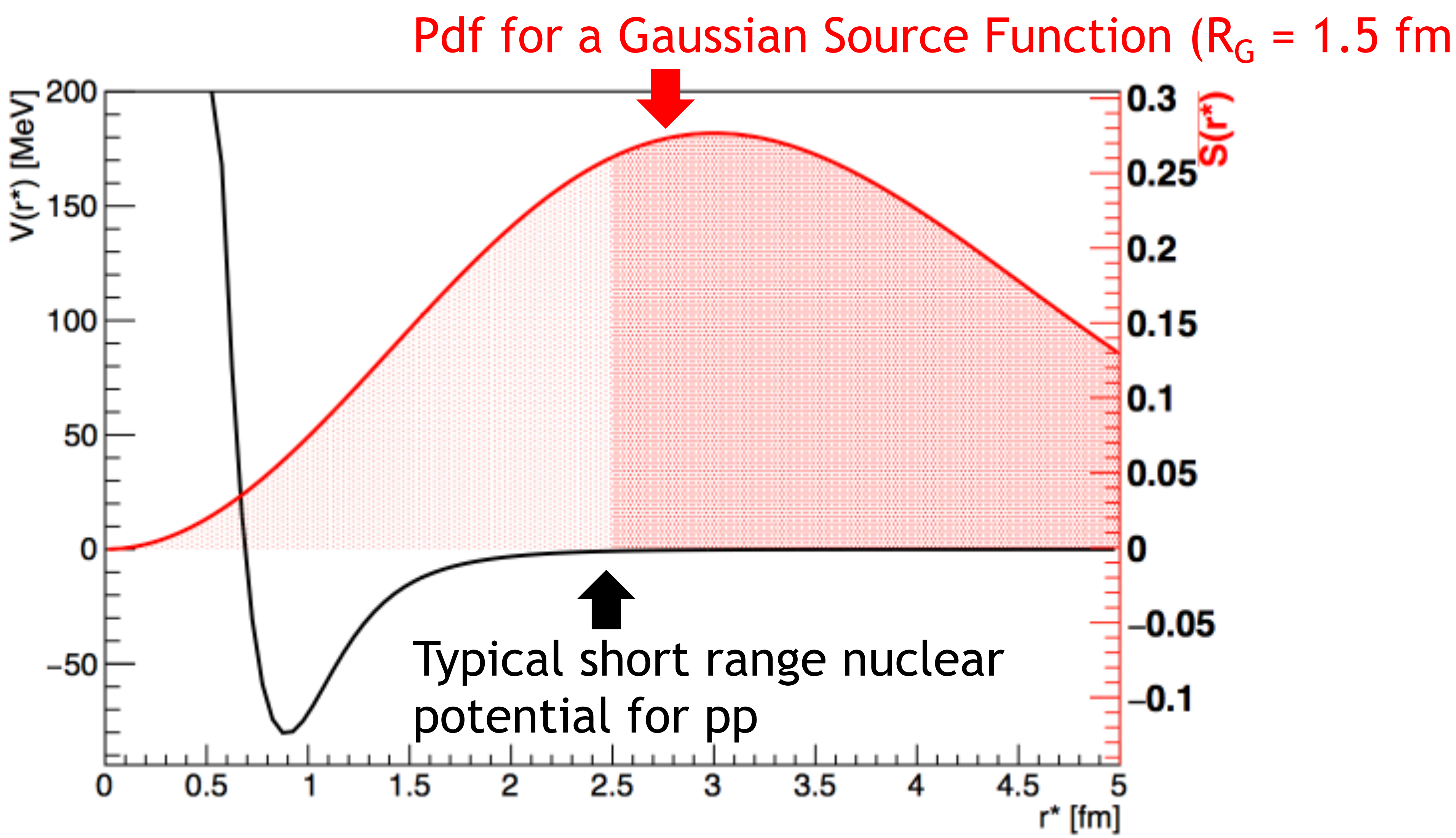
Source

Wave Function

If we know about the **source**, we can learn about the **interaction**

Fix the parametrization of the source by fitting the pp and Λp Correlation Function simultaneously to test different models of the pΛ interaction

Small Source -> Repulsive Core

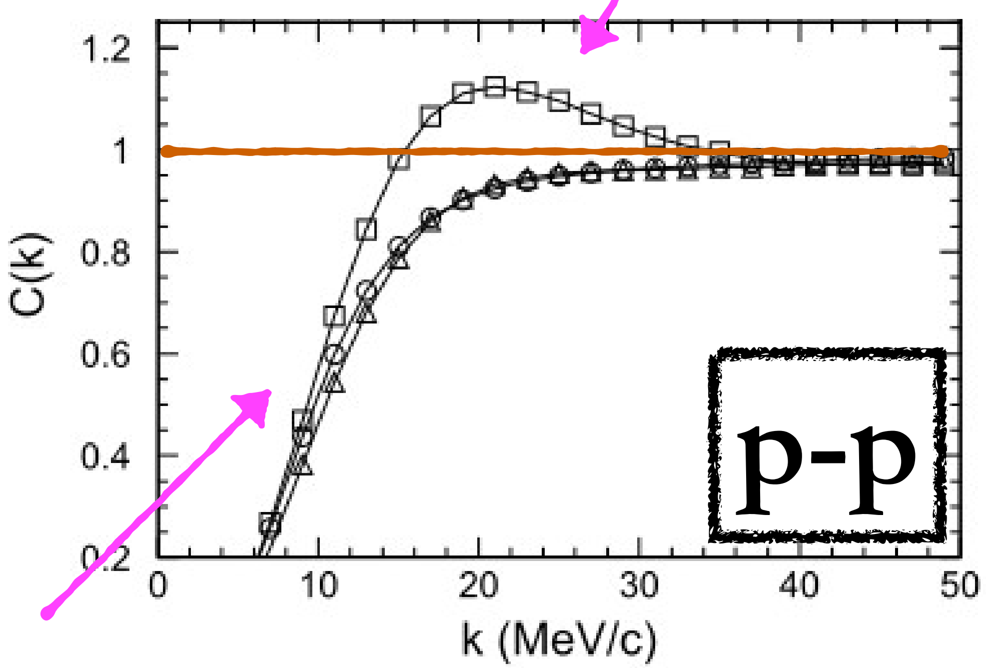


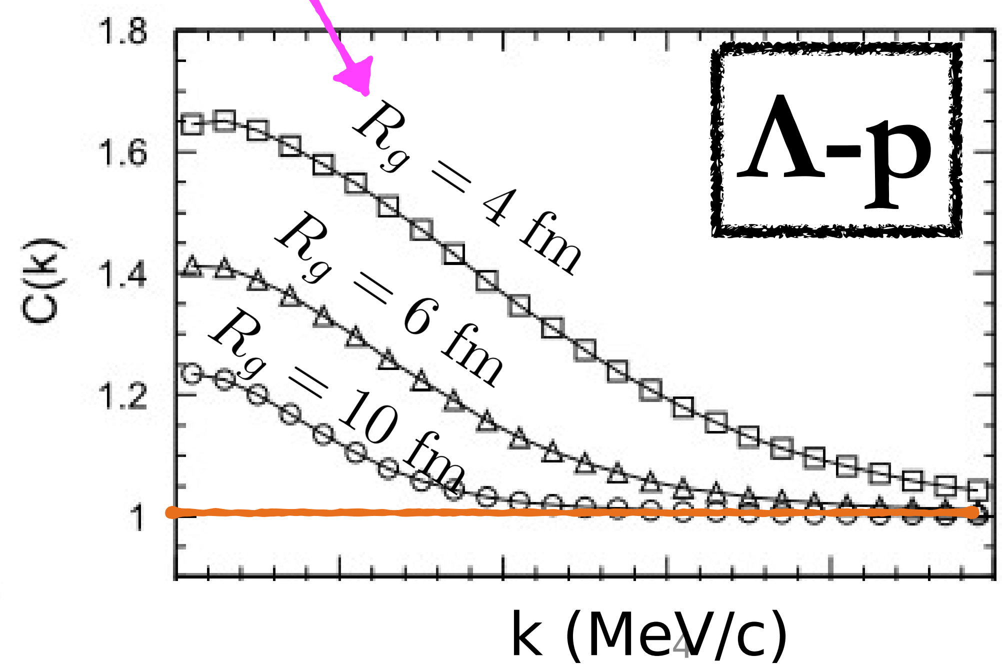
Small Radii provided by pp Collisions at the LHC (r ~ 1.2 fm)

Typical Correlation Functions for HIC

F. Wang and S. Pratt, Phys. Rev. Lett. 83, 3138 (1999).

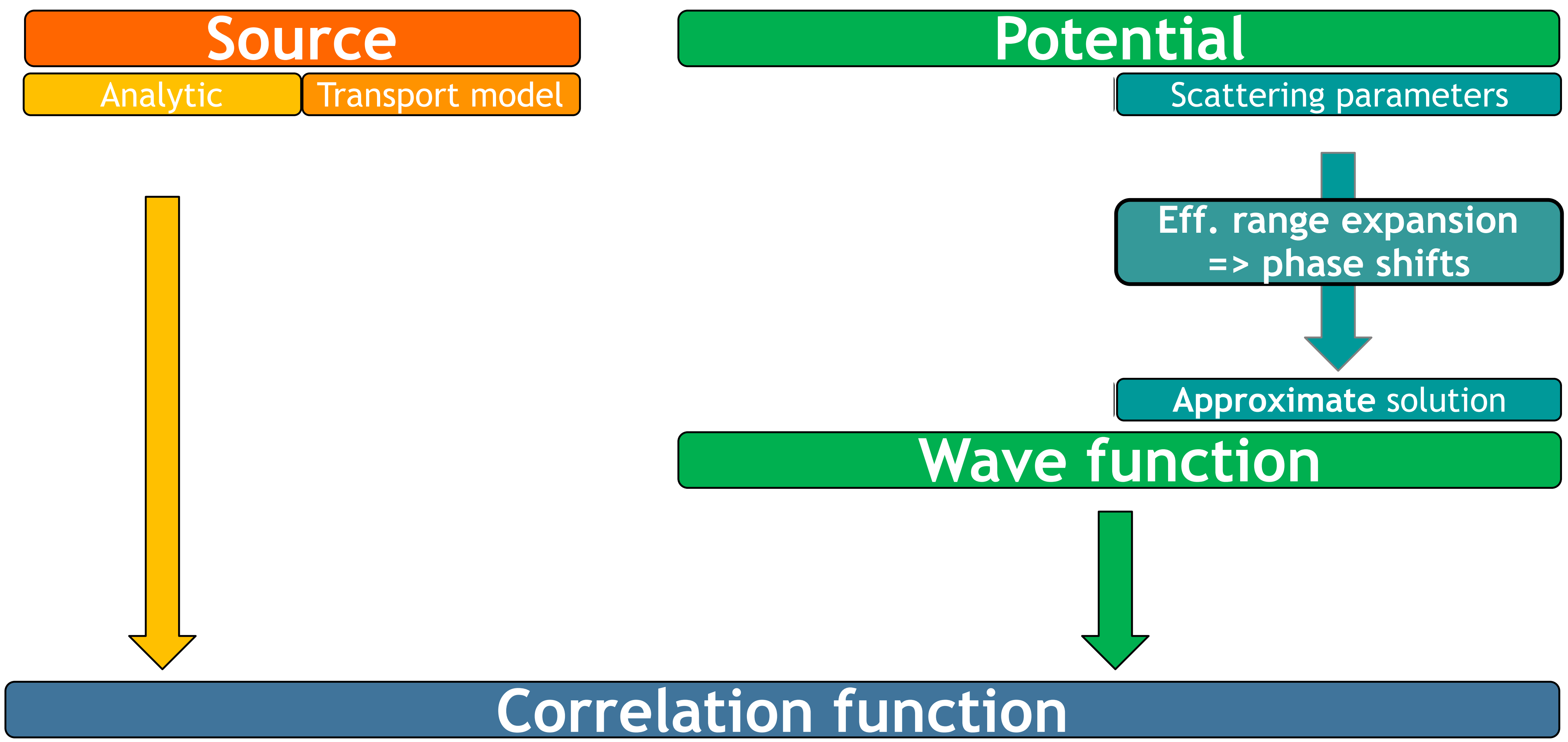
Strong Attraction C(k)>1





Coulomb Repulsion C(k)<1

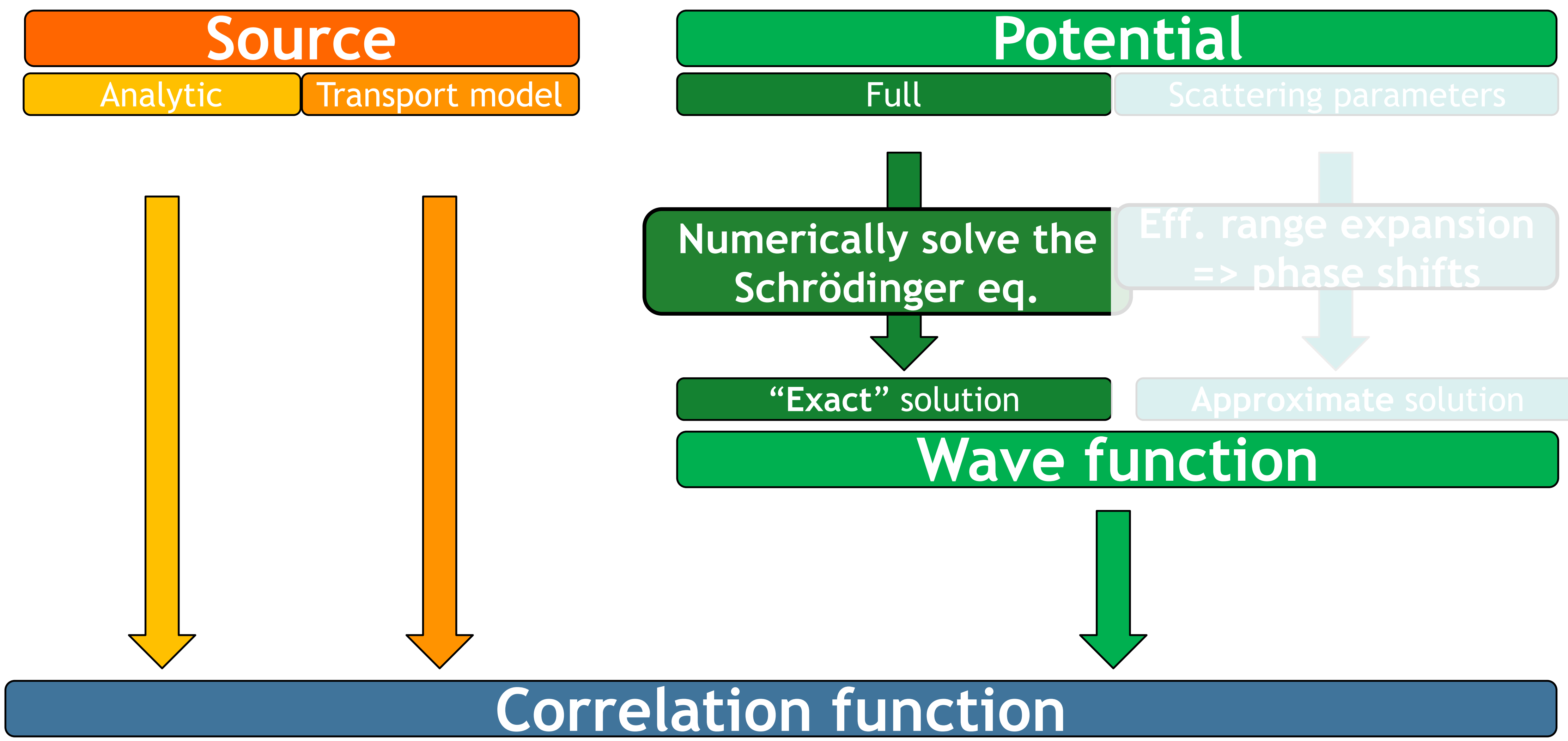
Lednicky Model



CATS – Correlation Analysis Tool Using the Schrödinger Equation

https://arxiv.org/abs/1802.08481

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



The pp Correlation Function

- Governed by:
  - Coulomb Interaction
  - Strong Interaction
  - Quantum Statistics
- Koonin Fit Function
  - Assumes a **Gaussian source** of size R_G

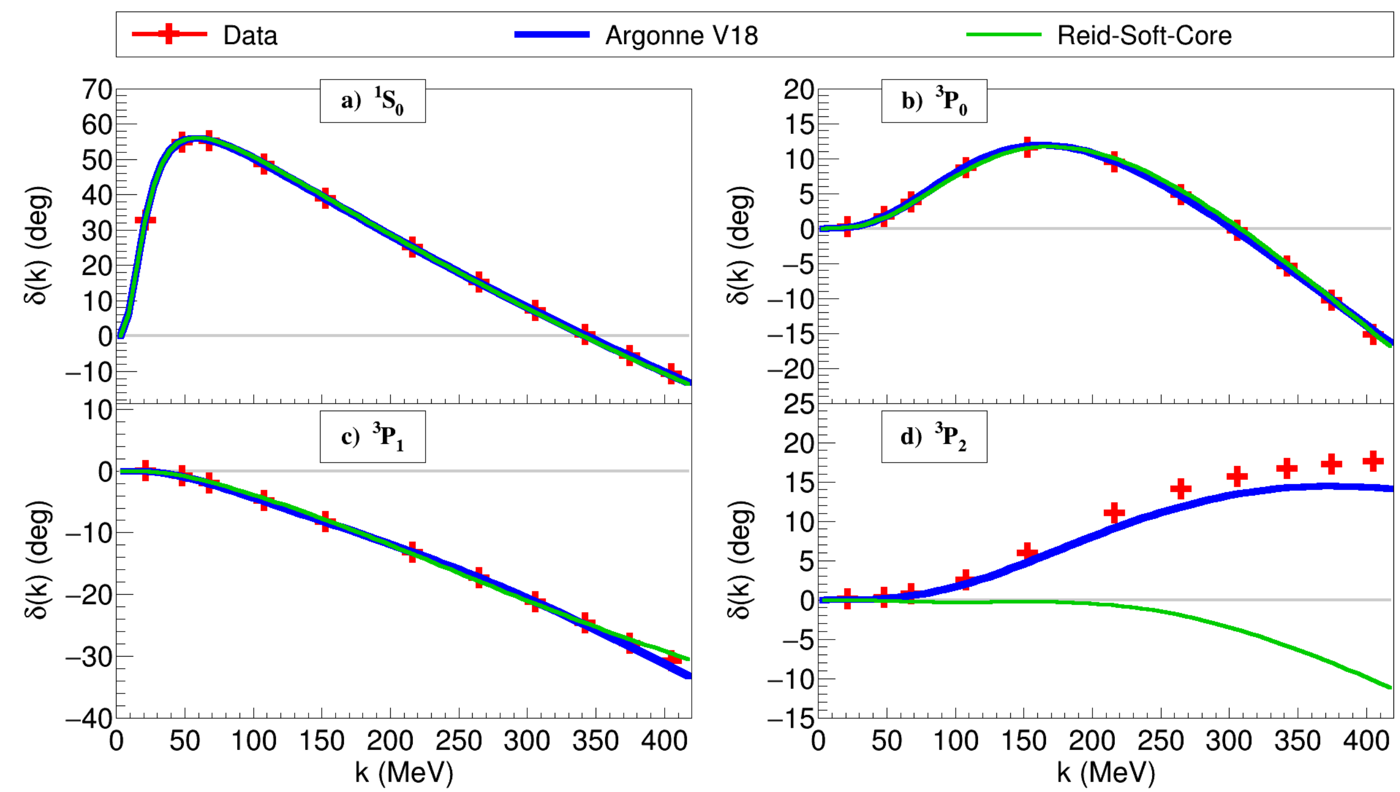
$$C(k) = \int dr^3 \phi_{rel}^2(r,k) \exp\left(-\frac{r^2}{4R_G^2}\right)$$

S. E. Koonin, Phys. Lett. B 70 (1977) 43
S. Pratt et al., Nucl. Phys. A 566 (1994) 103c

  - ϕ_{rel} from solving the Schrödinger Equation with the **known potentials** for the Coulomb and Strong interaction

CATS

https://arxiv.org/abs/1802.08481



The Λp Correlation Function

- Governed by:
  - Strong Interaction
  - No Coulomb Interaction
- Lednický model
  - Assumes a **Gaussian source** of size R_G
  - Based on the effective Range expansion
  - The interaction is modeled using the **scattering length** (f_0) and the **effective range** (d_0)

CATS

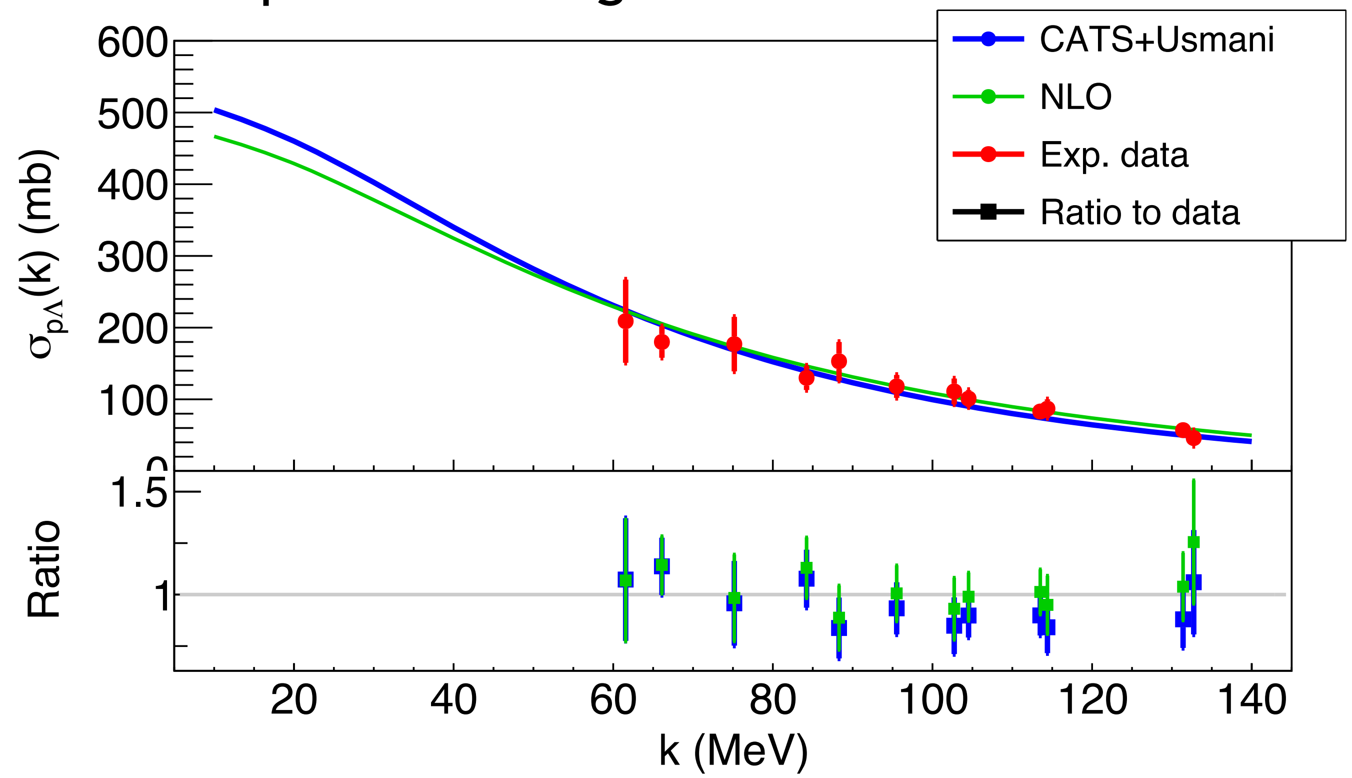
R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)].

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

The Λp Correlation Function

- Governed by:
  - Strong Interaction
  - No Coulomb Interaction
- **Strong Interaction:**
  - Usmani Potential
  - xEFT NLO wave function
  - Lattice Potential (soon?**?**)

https://arxiv.org/abs/1802.08481



CATS ⇨ $$C(k) = \int S(\vec{r},k)|\psi(\vec{r},k)|^2\, d\vec{r}$$

The Experimental Correlation Function

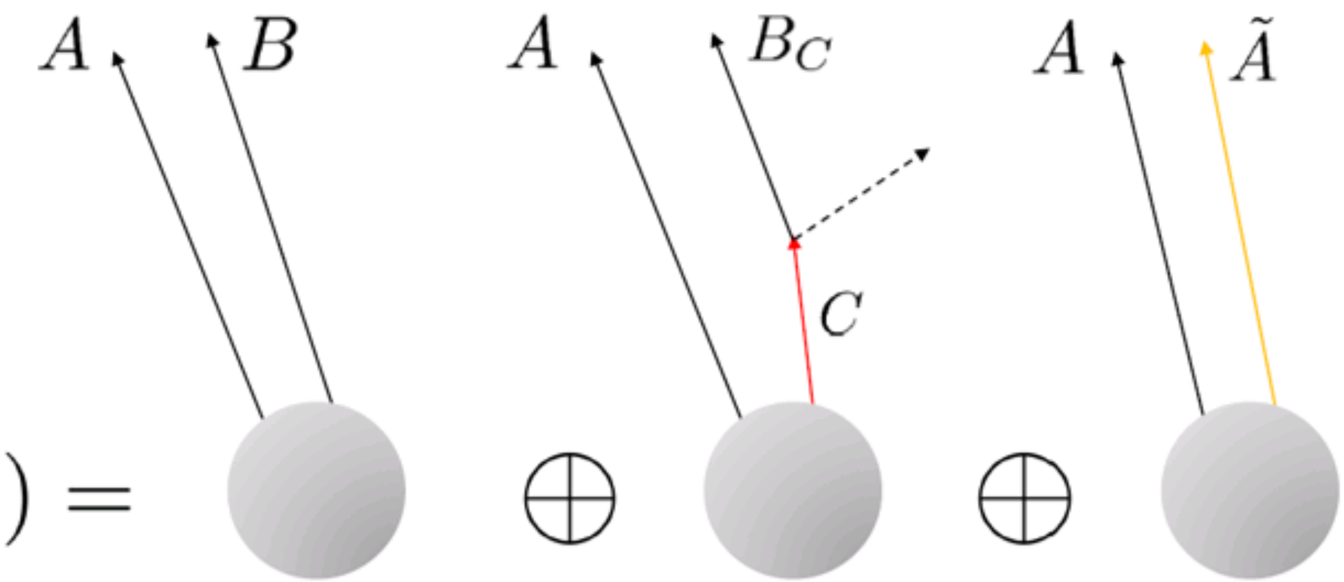
$$C(\overrightarrow{\boldsymbol{p}_a}, \overrightarrow{\boldsymbol{p}_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})} = \mathcal{N}\frac{N_{SE}(k)}{N_{ME}(k)}$$

SFB 1258 Neutrinos Dark Matter Messengers

The Experimental Correlation Function

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

$C(k^*) =$



Pair of interest　　Pair from feed-down　　Pair from mis-identification

The Experimental Correlation Function

$$C(\overrightarrow{\boldsymbol{p}_a},\overrightarrow{\boldsymbol{p}_b}) = \frac{P(\overrightarrow{p_a},\overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})} = \mathcal{N}\frac{N_{SE}(k)}{N_{ME}(k)} = \lambda_1 C_1(k) + \lambda_2 C_2(k) + \cdots$$

Correlation function of interest

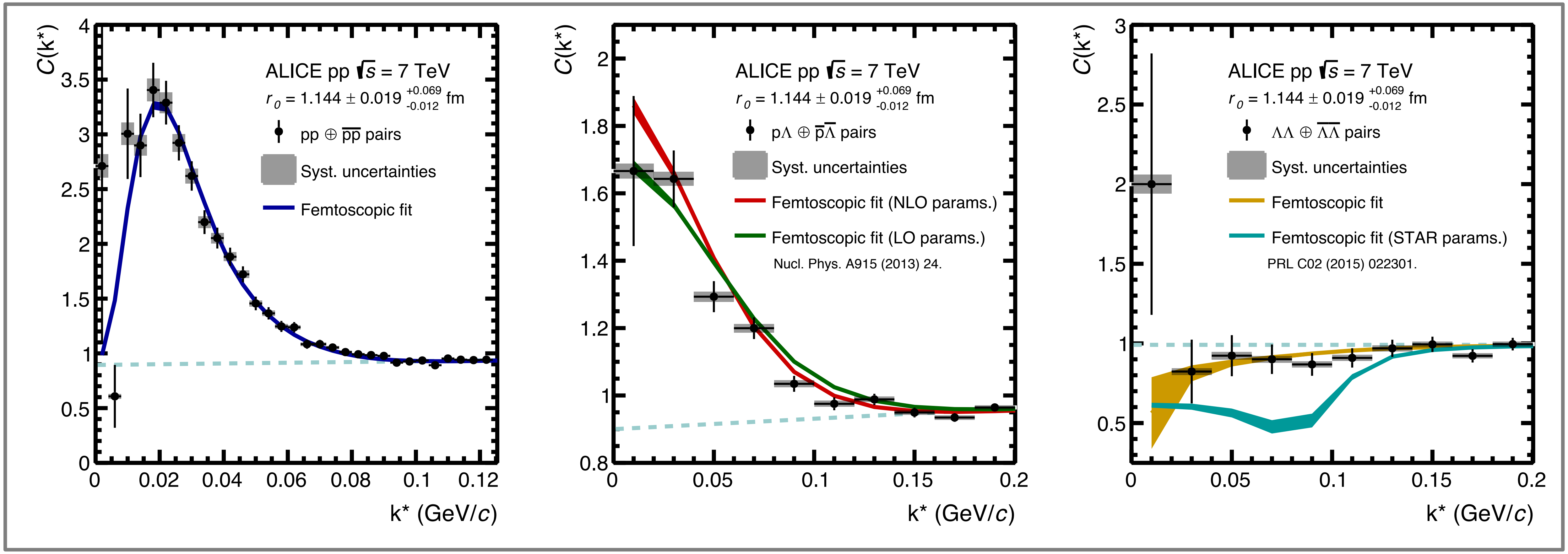
Contributions from impurities, secondaries etc.

λ Parameters can be related to measured single-particle quantities, e.g. Purity $\mathcal{P}$ or feed-down fractions f

(PhD Thesis of O. Arnold - https://www.das.ktas.ph.tum.de/DasDocs/Public/PhD_Theses/arnold-oliver_thesis.pdf)

Fit of the pp, Λp and $\Lambda\Lambda$ Correlation Function

RUN1 ~ 250 MeVts

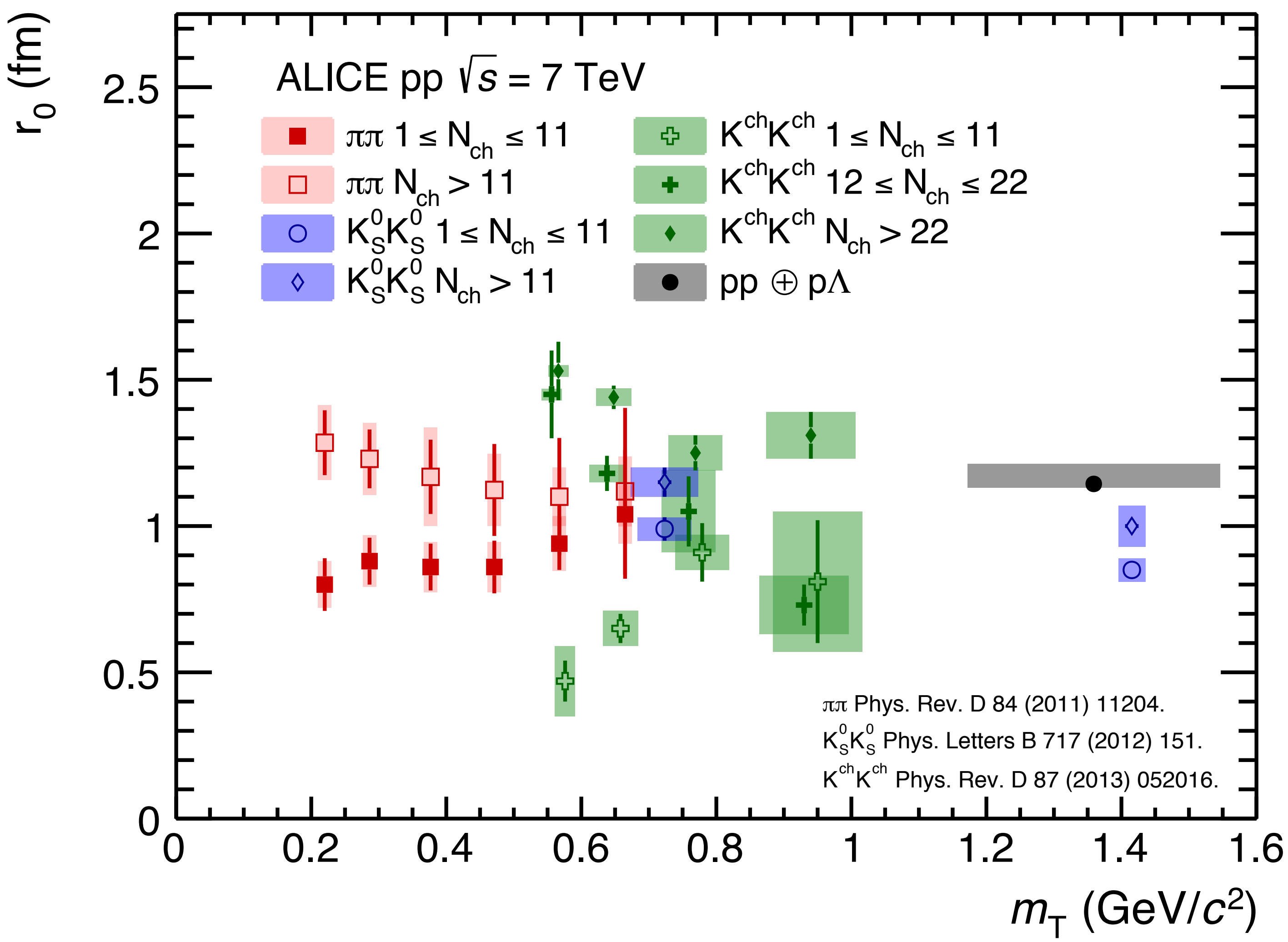


$$C_{baseline}(k^*) = a \cdot k^* + b$$

Paper currently under collaboration revision

Radius

ALICE Phys. Lett. B717 (2012), pp. 151–161. Neutral Kaons femtoscopy
ALICE Phys. Rev. D87.5 (2013), p. 052016. Charged Kaons femtoscopy



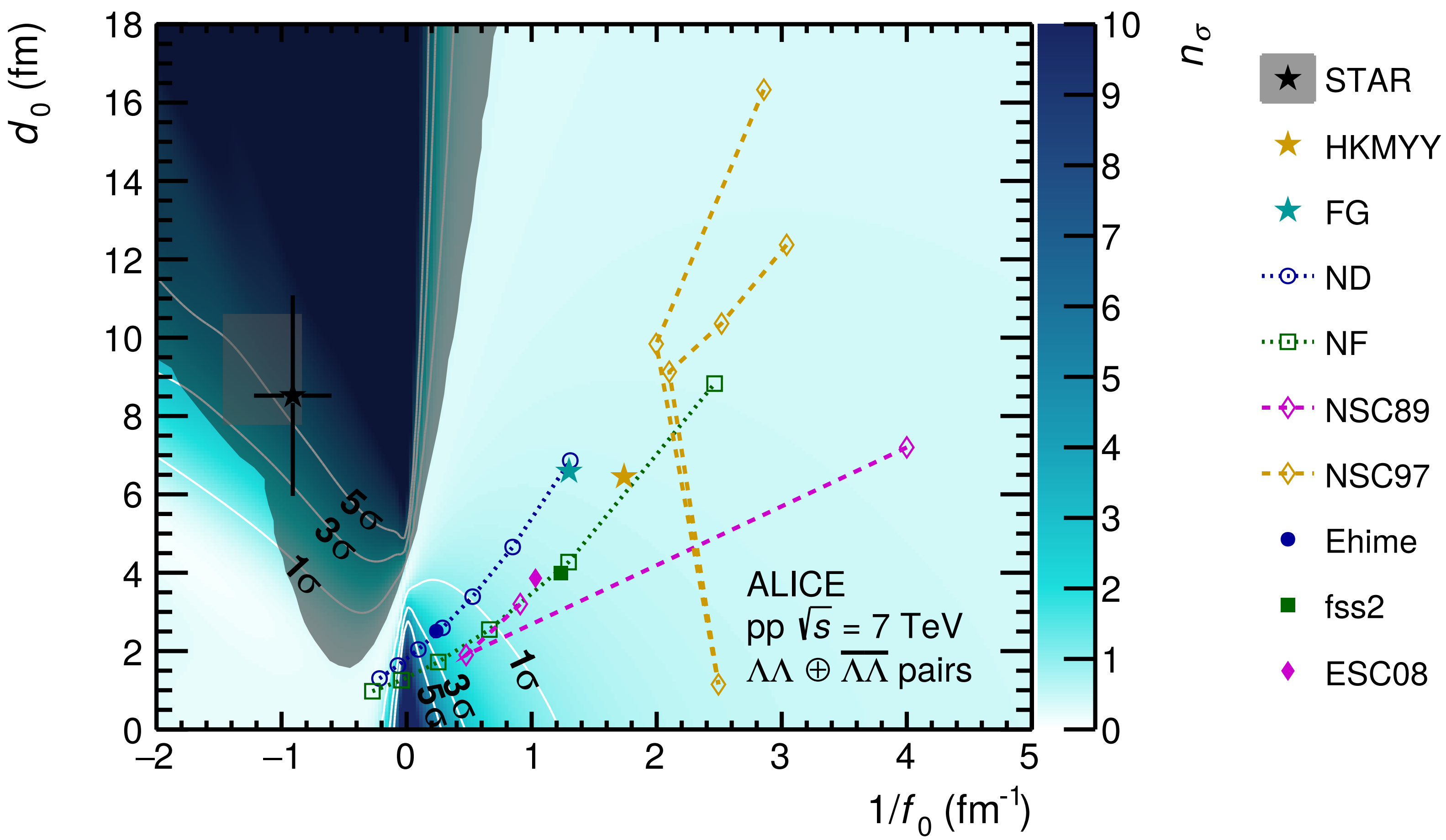
Paper currently under collaboration revision

The ΛΛ Correlation Function

Scattering Parameters, Effective range= defines the range of the interaction

$$a_0 = -\lim_{k \to 0} \frac{1}{k} \tan \delta_0(k).$$

l=0 -> s-wave only!!



Comparison to models e.g. meson exchange models like Nijmegen, boson exchange potential Ehime

- STAR results of the same measurement in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV/c excluded by 6.8 σ

Models from: Phys. Rev. C, 91, 024916 (2015)

Statistics for RUN2 (p+p 13 TeV)

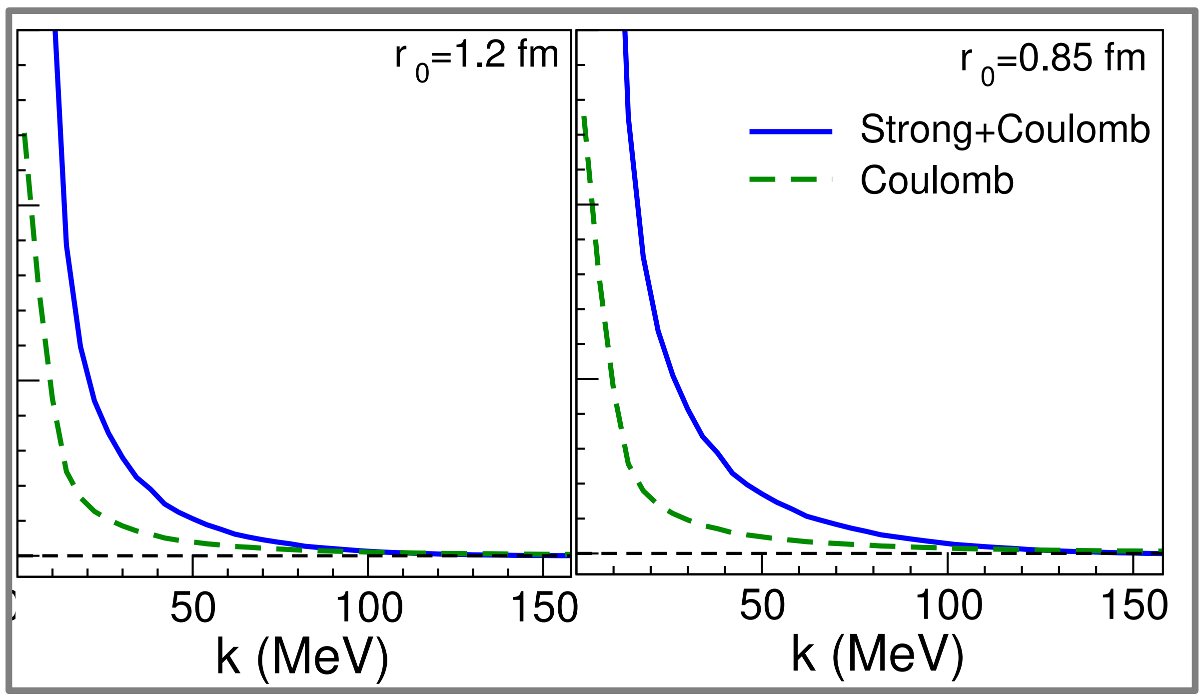
1020 Mevts (RUN1~250 Mevts)

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

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

The $p - \Xi^-$ Correlation Function

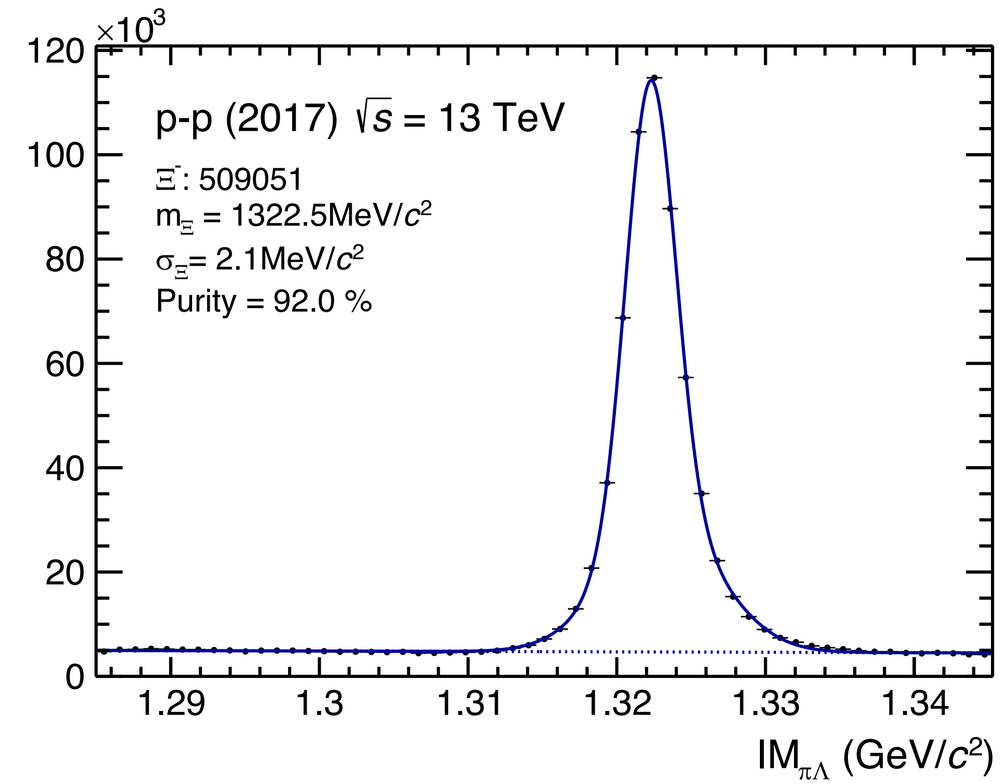
- **Preliminary** calculations by the HAL QCD Collaboration
- Taking the strong interaction into account creates a significantly different Correlation function than Coulomb only



arXiv:1702.06241 , Nuclear Physics A 967 (2017) 856–859

CATS

- Decay mode $\Xi^{\pm} \rightarrow \Lambda + \pi$
  $p + \pi$



Statistics for RUN2 (p+Pb 5.02 TeV)

550 Mevts (RUN1~250 Mevts)

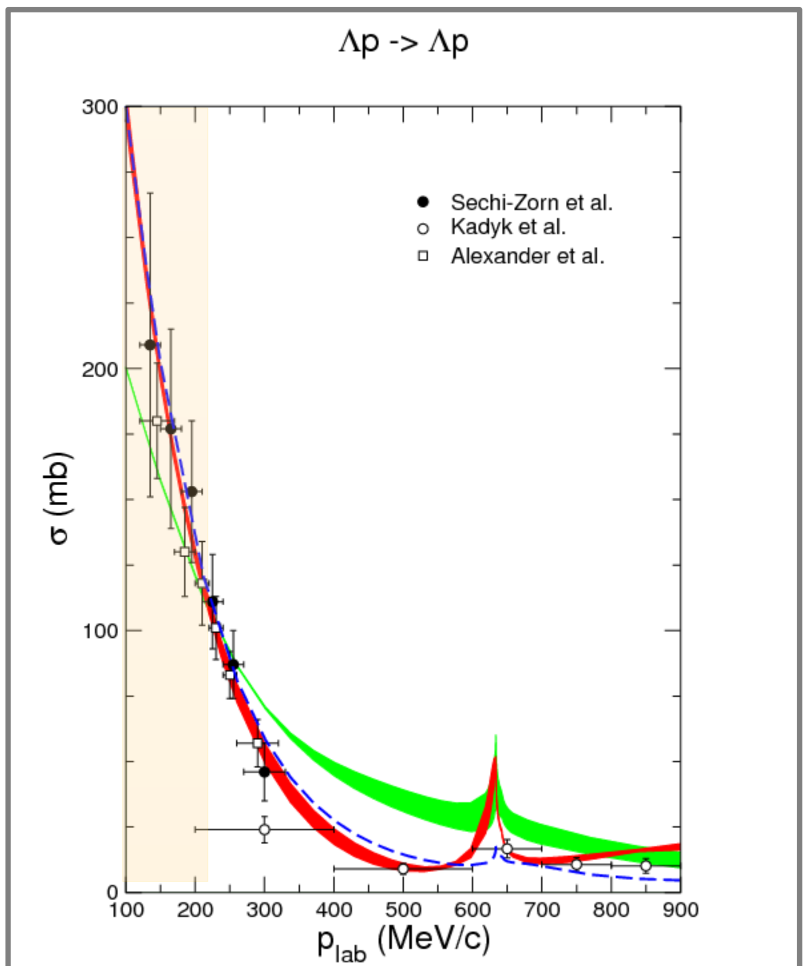
Particle	Candidates
p	155 x 10^6
$\bar{p}$	133 x 10^6
Λ	26 x 10^6
$\bar{\Lambda}$	24 x 10^6
Ξ	0.9 x 10^6
$\bar{\Xi}$	0.9 x 10^6

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

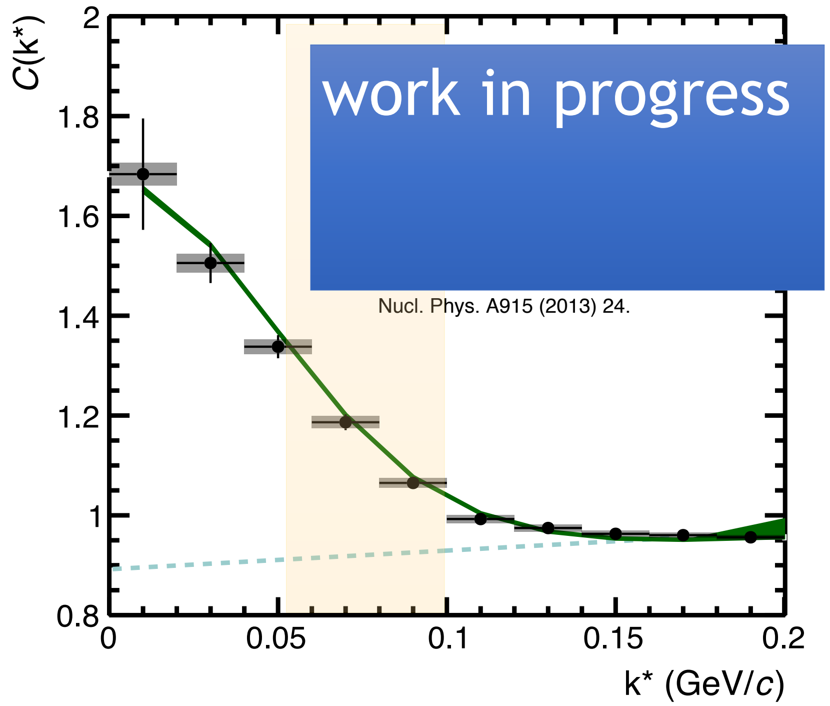
New ‘scattering’ data

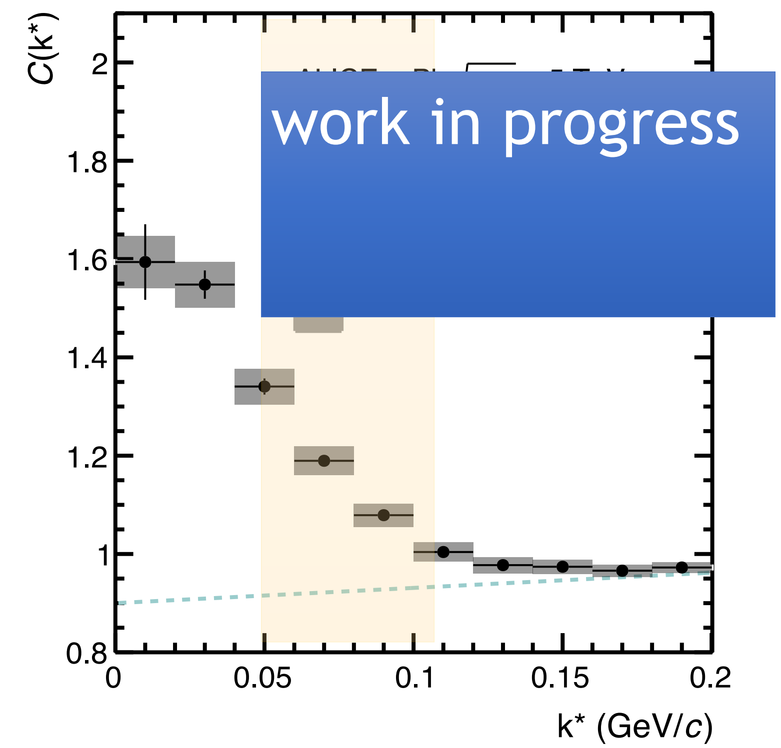
$$\Lambda + p \rightarrow \Lambda + p$$

Hyperon Beams at CERN



Femtoscopy in pp collisions at the LHC with ALICE



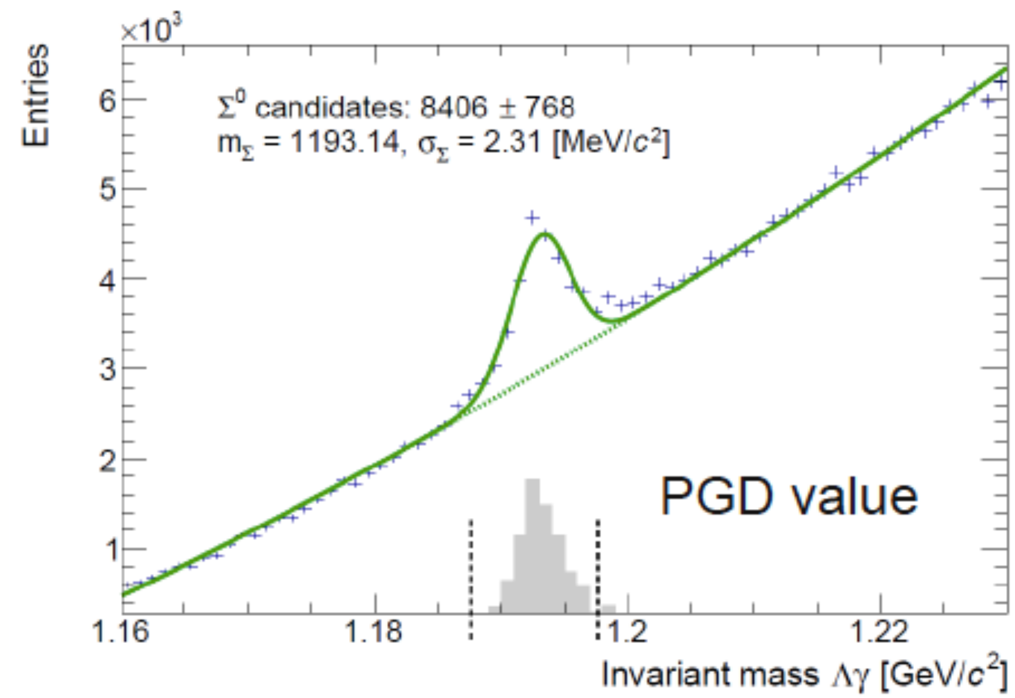


Hyperon-Nucleon interactions can be studied with higher precision

Future prospects of Femtoscopy

Finalise RUN2 Analysis

-> Pin Down $\Lambda\Lambda$ scattering parameters
-> Detailed study of Λp
-> Extend the technique to $\Sigma,\ \Xi\ and\ \Omega$



RUN2 - LHC16l (326M events, pass1)

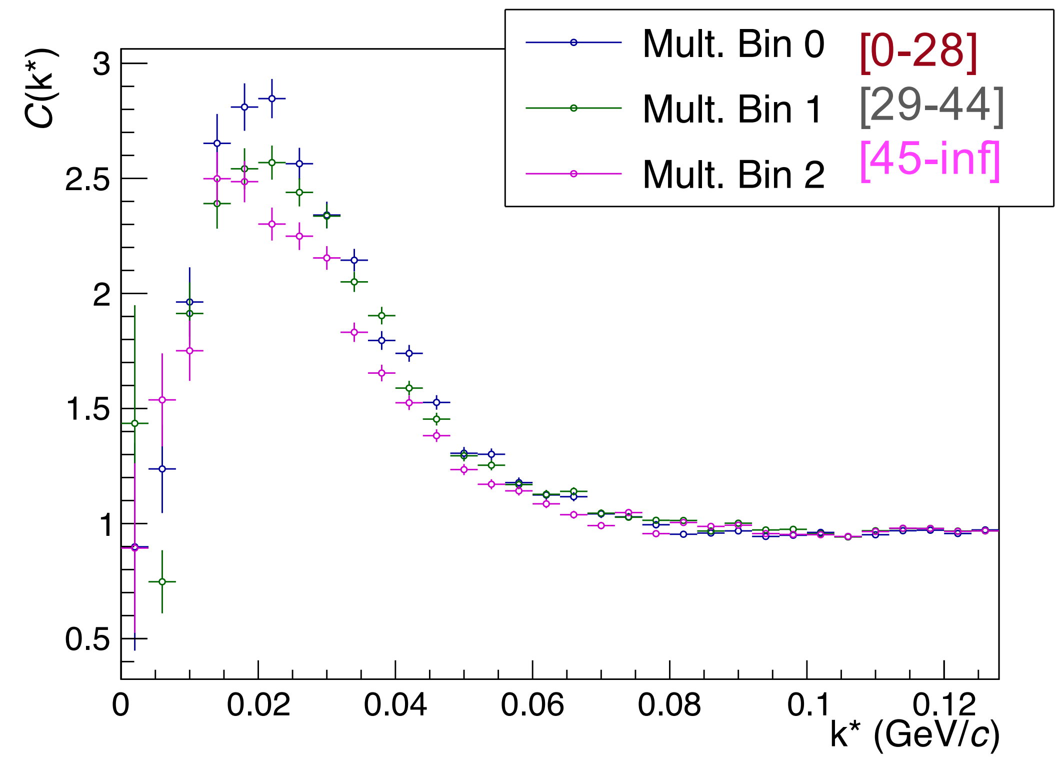
In RUN3 (from 2020 on) we expect factor 100 in statistics, but Hight Mult. Trigger….

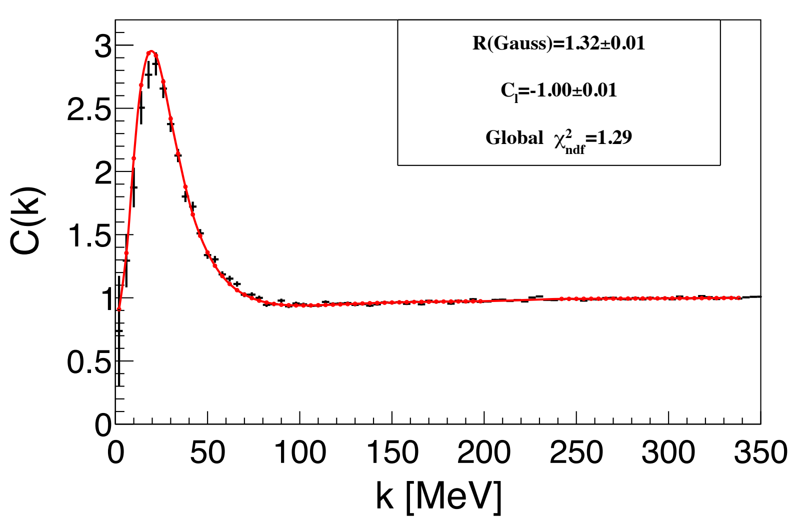
Development of a general framework able to fit the femtoscoy correlations of ALL the reactions and pair combinations measured at the LHC by ALICE and.. beyond…

FEMTO GANG

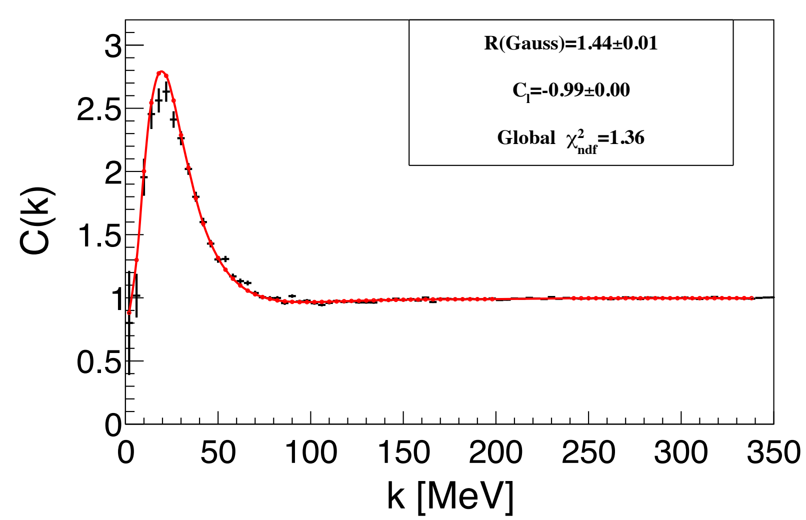
pp Fits in different multiplicity bins

- Strong dependence of the source radius on the event multiplicity
  - 0-28: 1.32 fm
  - 29-44: 1.44 fm
  - 45-inf: 1.54 fm
- Will be accounted for by weights

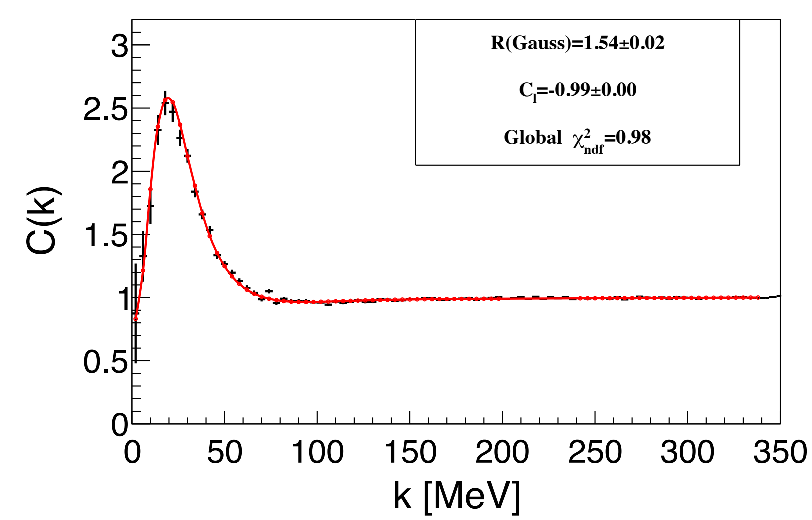




Mult. Bin 0



Mult. Bin 1



Mult. Bin 2

Decomposition of the Correlation Functions

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

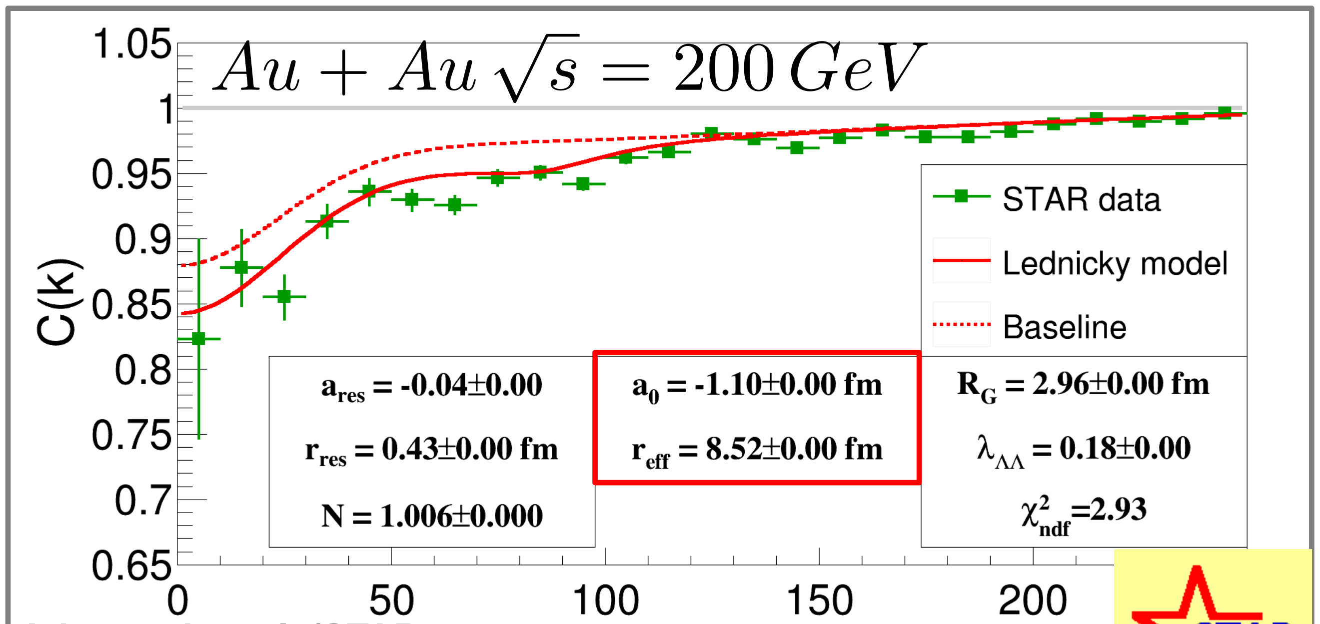
$$\{p\Lambda\} = p\Lambda + p\Lambda_{\Xi^-} + p\Lambda_{\Xi^0} + p\Lambda_{\Sigma^0} + p_\Lambda\Lambda + p_\Lambda\Lambda_{\Xi^-}$$
$$+ p_\Lambda\Lambda_{\Xi^0} + p_\Lambda\Lambda_{\Sigma^0} + p_{\Sigma^+}\Lambda + p_{\Sigma^+}\Lambda_{\Xi^-} + p_{\Sigma^+}\Lambda_{\Xi^0} + p_{\Sigma^+}\Lambda_{\Sigma^0}$$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

Secondary contributions from measurements

Pair	Percentage %
pp	75
$p_\Lambda p$	16
$p_\Lambda p_\Lambda$	1
$p_{\Sigma^+}p$	6
$p_{\Sigma^+}p_{\Sigma^+}$	0
$p_{\Sigma^+}p_\Lambda$	0
$\tilde{p}p$	2
$\tilde{p}\tilde{p}$	0

Pair	Percentage %
$p\Lambda$	49
$p\Lambda_{\Xi^-}$	10
$p\Lambda_{\Xi^0}$	10
$p\Lambda_{\Sigma^0}$	16
$p_\Lambda\Lambda$	5
$p_\Lambda\Lambda_{\Xi^-}$	1
$p_\Lambda\Lambda_{\Xi^0}$	1
$p_\Lambda\Lambda_{\Sigma^0}$	2
$p_{\Sigma^+}\Lambda$	0
$p_{\Sigma^+}\Lambda_{\Xi^-}$	0
$p_{\Sigma^+}\Lambda_{\Xi^0}$	1
$p_{\Sigma^+}\Lambda_{\Sigma^0}$	2
$\tilde{p}\Lambda$	1
$p\tilde{\Lambda}$	2
$\tilde{p}\tilde{\Lambda}$	0

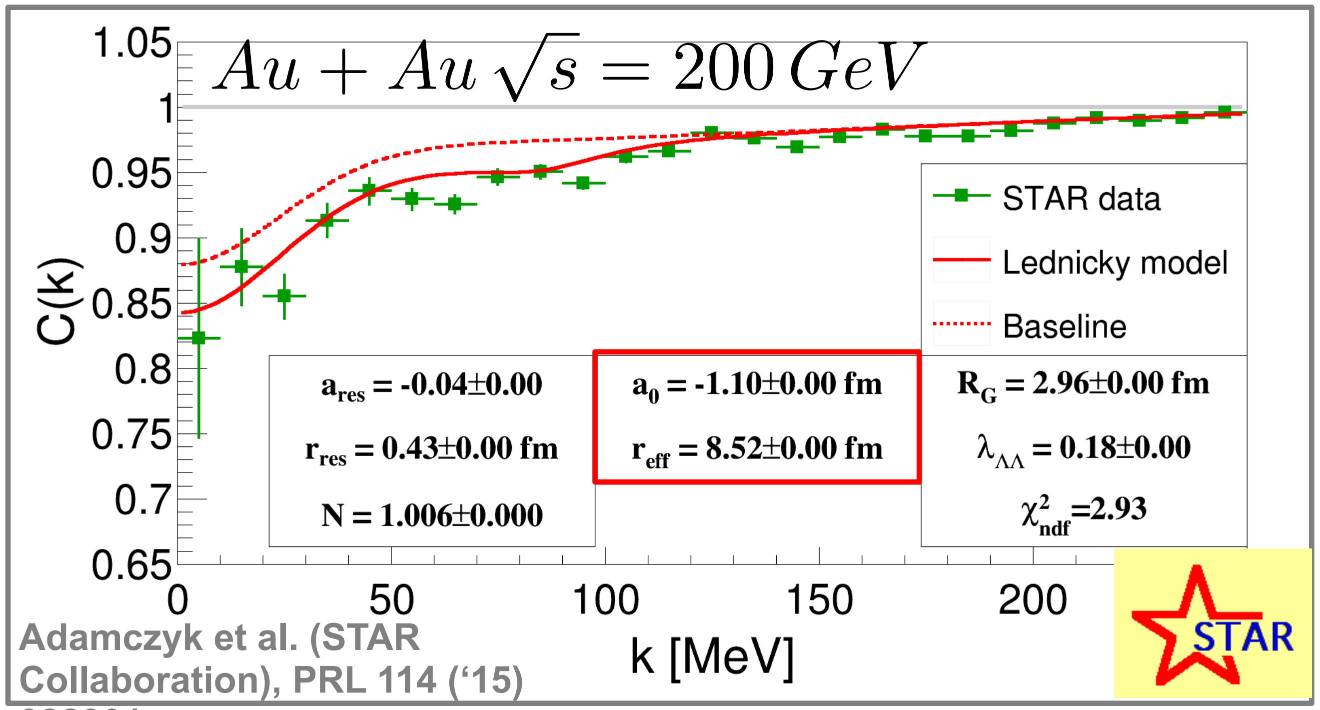
The ΛΛ Correlation Function



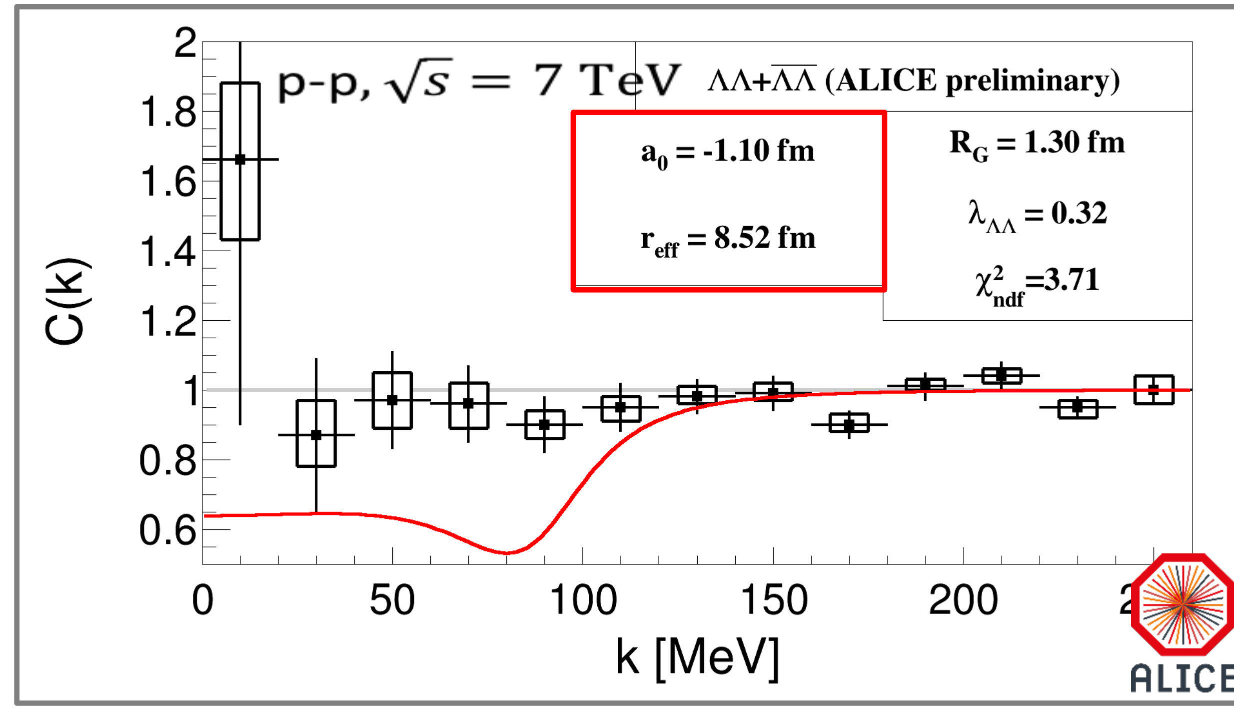
Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301

Previous results from Heavy Ion Collisions (Au+Au) at 200 AGeV published values of the scattering length that compatible with either a slightly repulsive interaction or a bound state!!!

The $\Lambda\Lambda$ Correlation Function



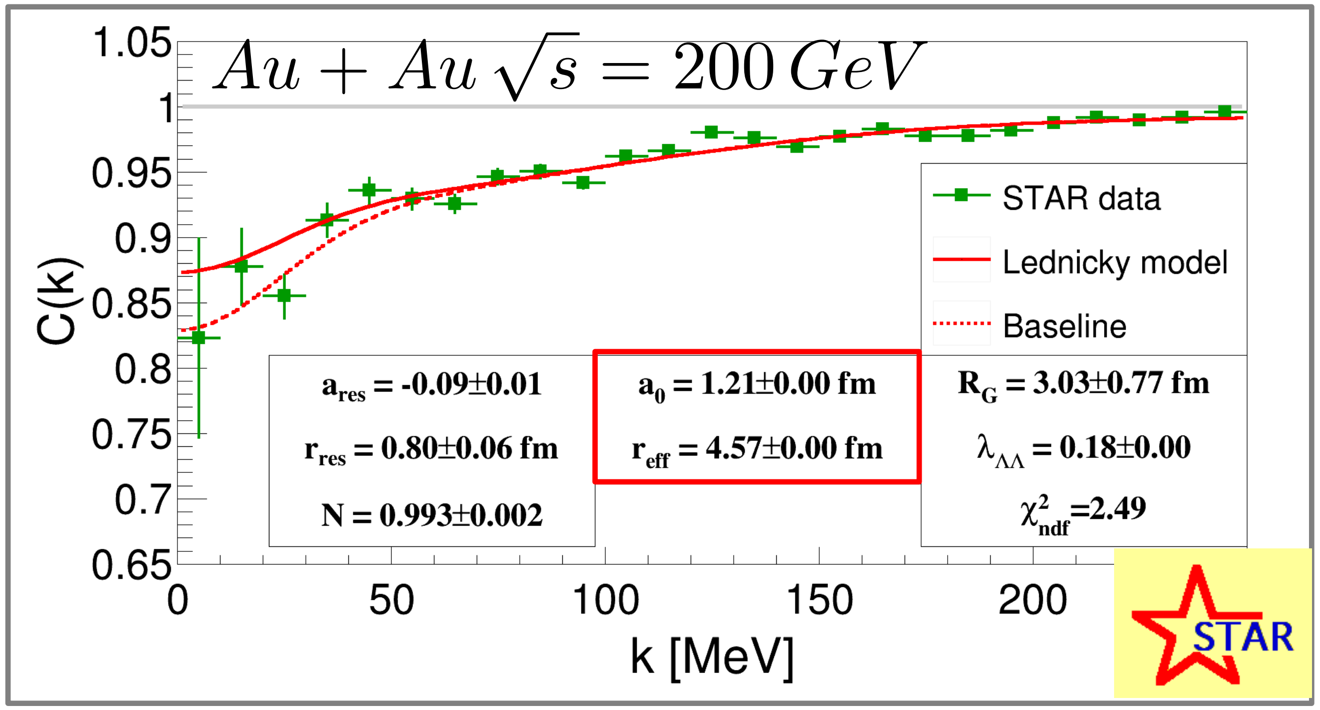
Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301

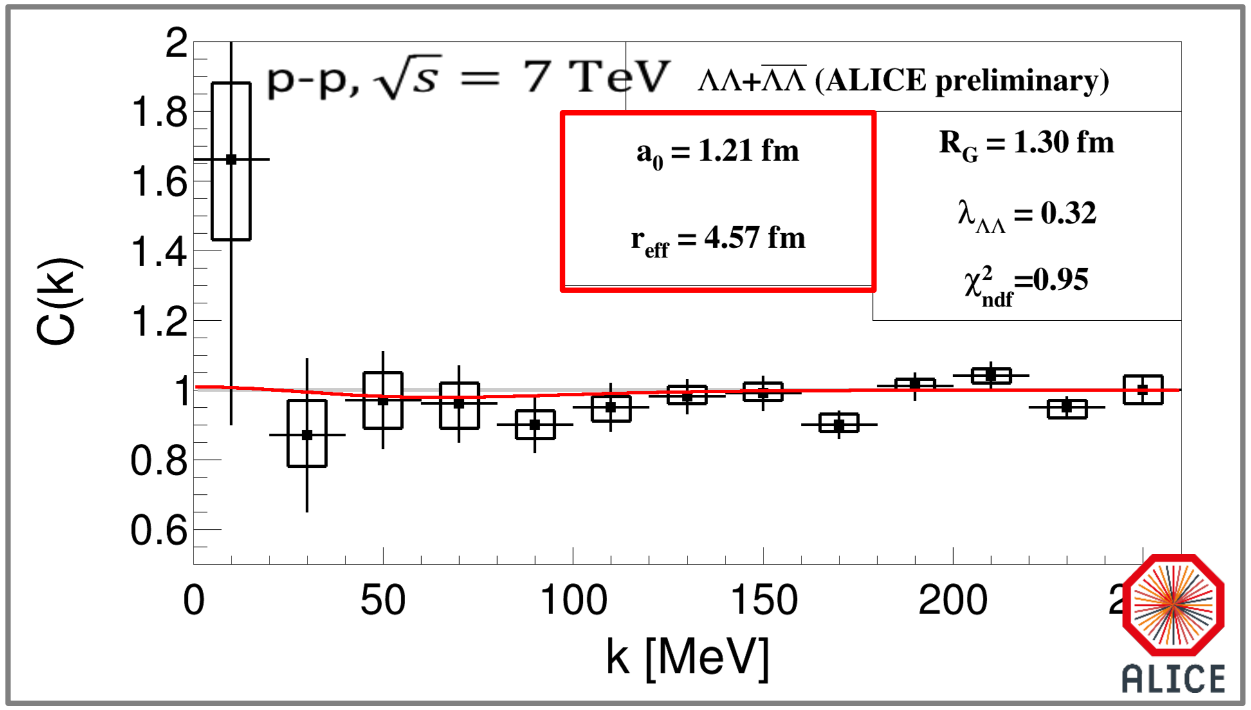


Previous results from Heavy Ion Collisions (Au+Au) at 200 AGeV published values of the scattering length that compatible with either a slightly repulsive interaction or a bound state!!!

This does not match at all with other data!!

The ΛΛ Correlation Function





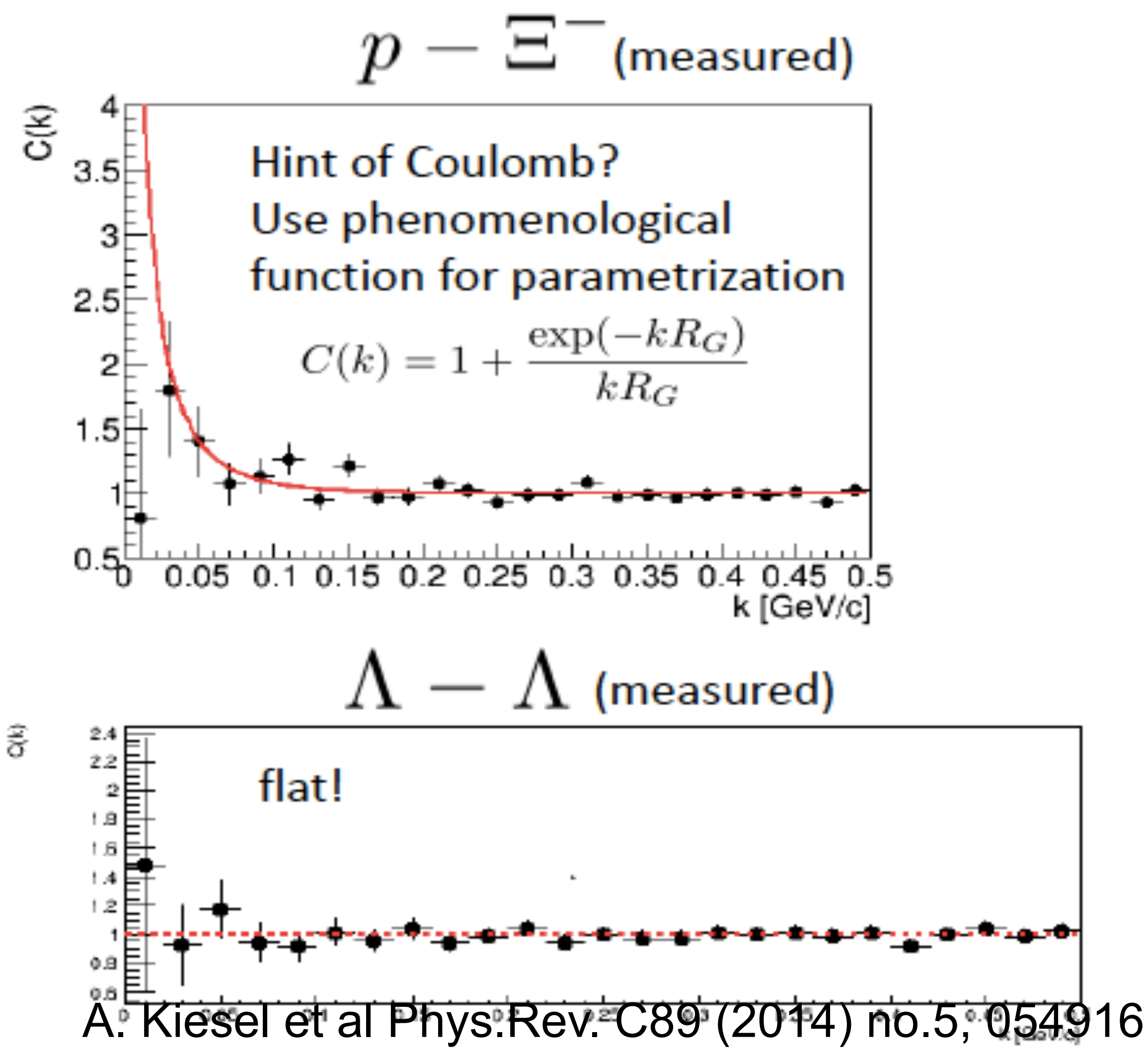
Previous results from Heavy Ion Collisions (Au+Au) at 200 AGeV published values of the scattering length that compatible with either a slightly repulsive interaction or a bound state!!!

Our data are compatible with a slightly attractive interaction

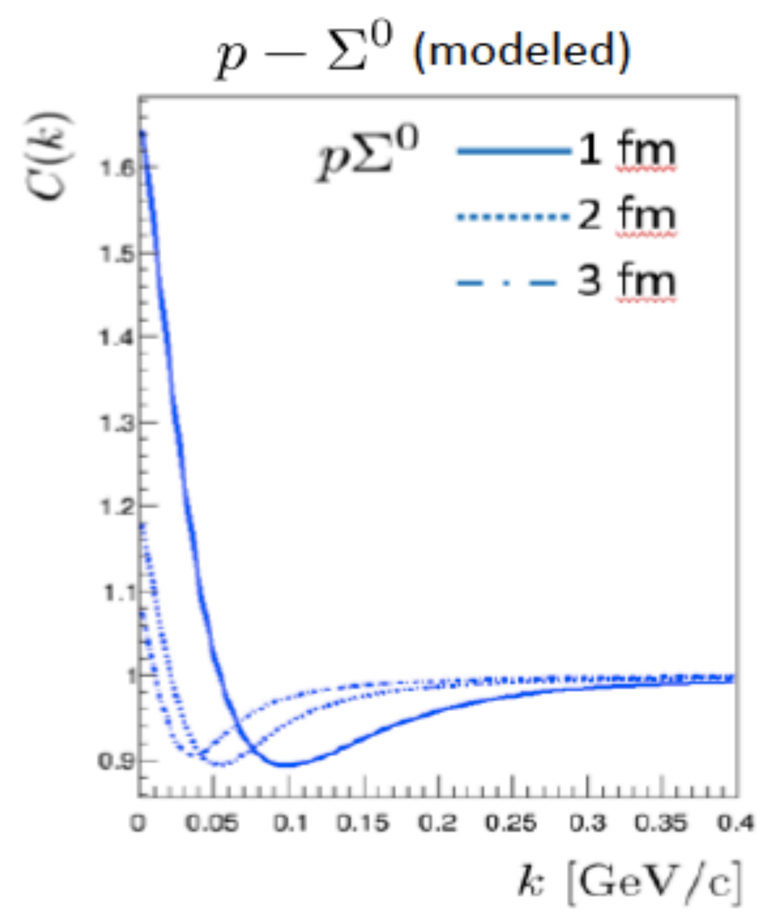
Considered Shapes

https://indico.cern.ch/event/562339/contributions/2271695/attachments/1322381/1983690/oarnold_Update_LambdaP_aug100816.pdf

Study of the theoretical prediction for the $p\Sigma^0$ correlation in



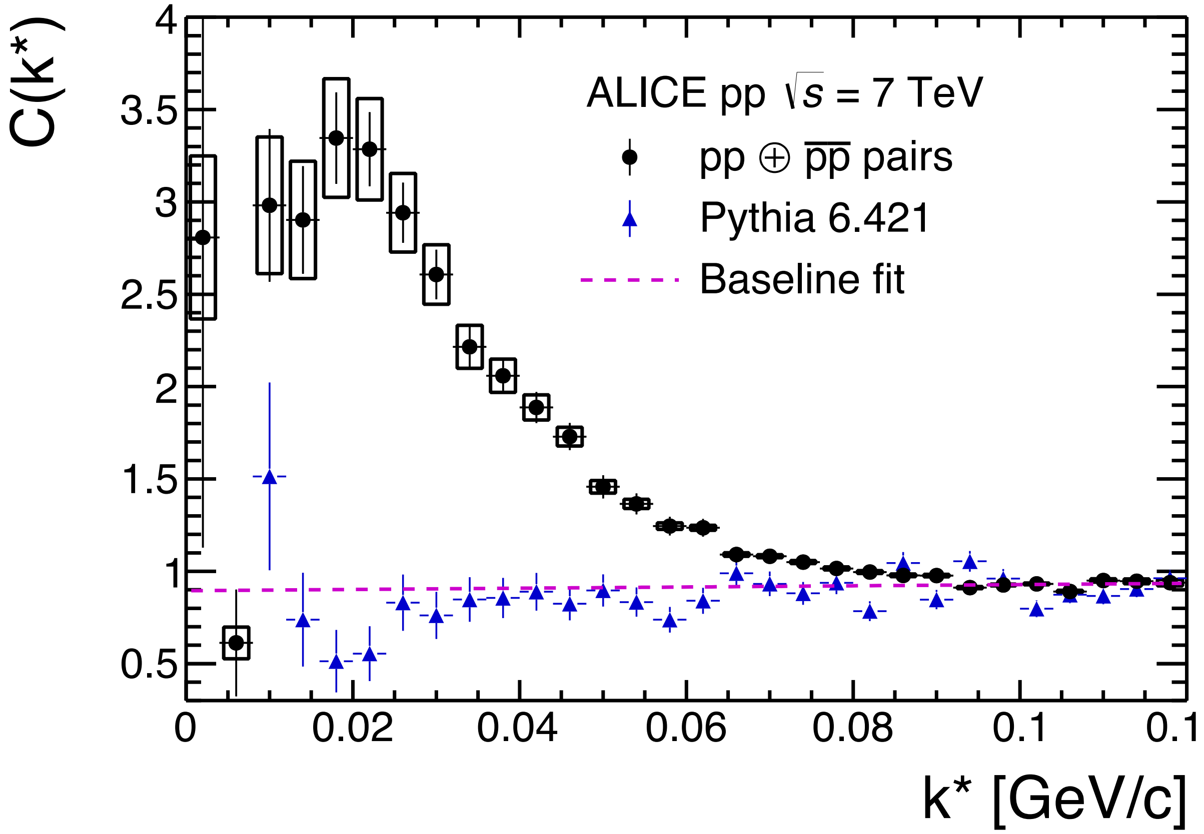
A. Kiesel et al Phys.Rev. C89 (2014) no.5, 054916



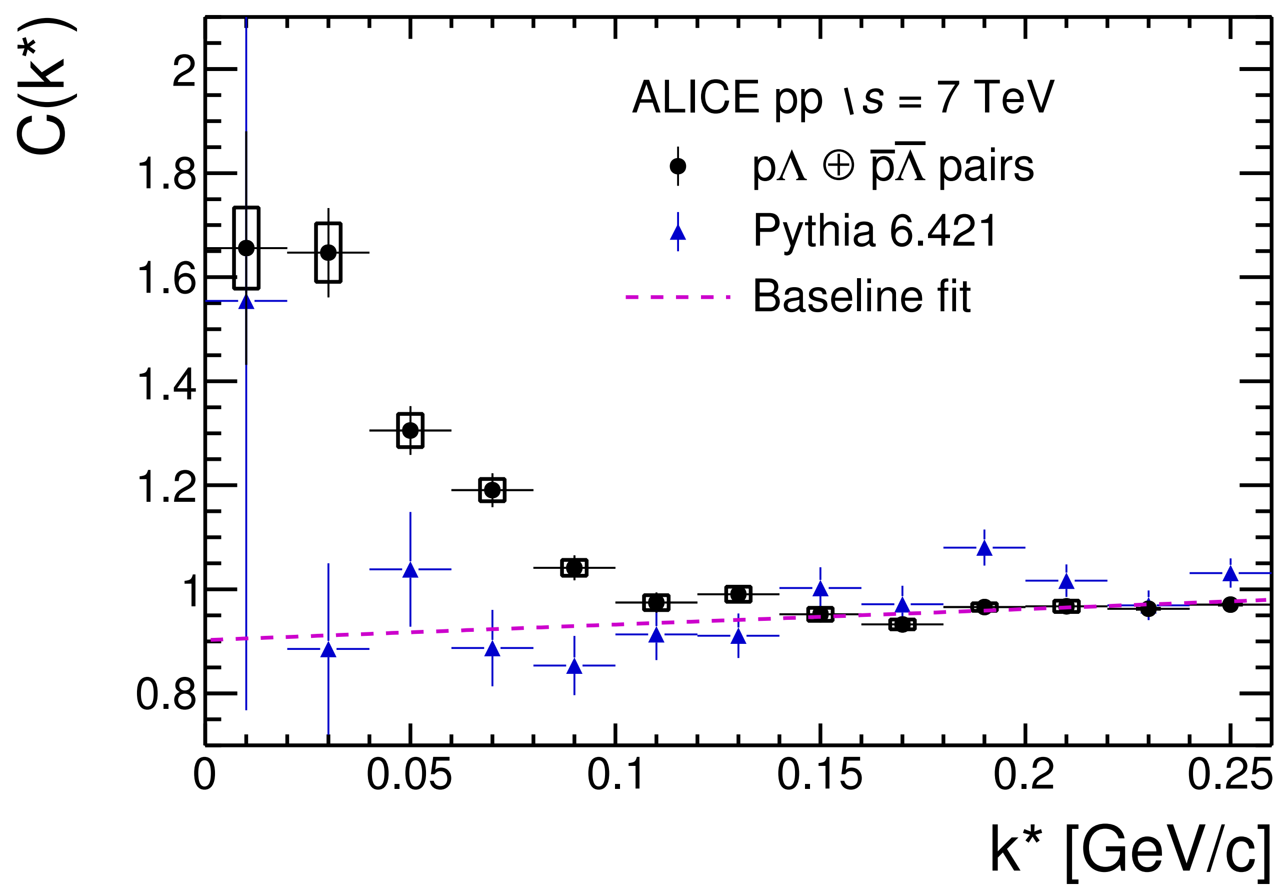
arXiv:0704.3290

http://inspirehep.net/record/1283372

Pythia low k*

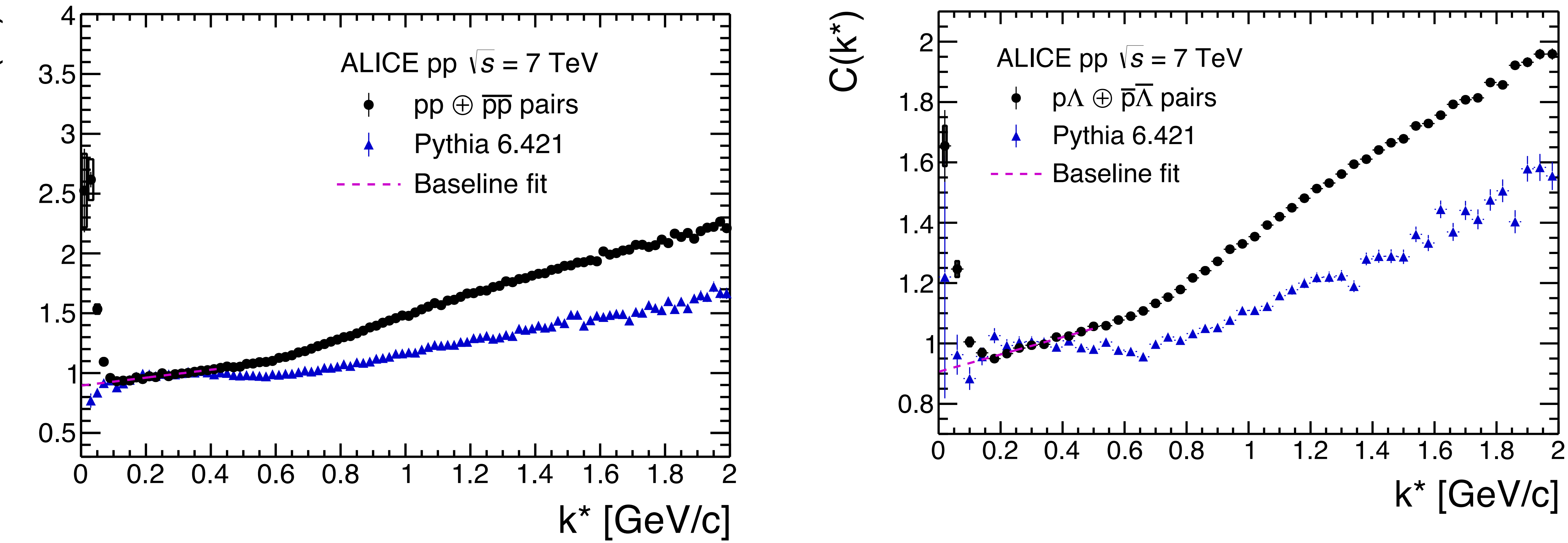


ALICE pp √s = 7 TeV
pp ⊕ $\overline{pp}$ pairs
Pythia 6.421
Baseline fit
C(k*)
k* [GeV/c]



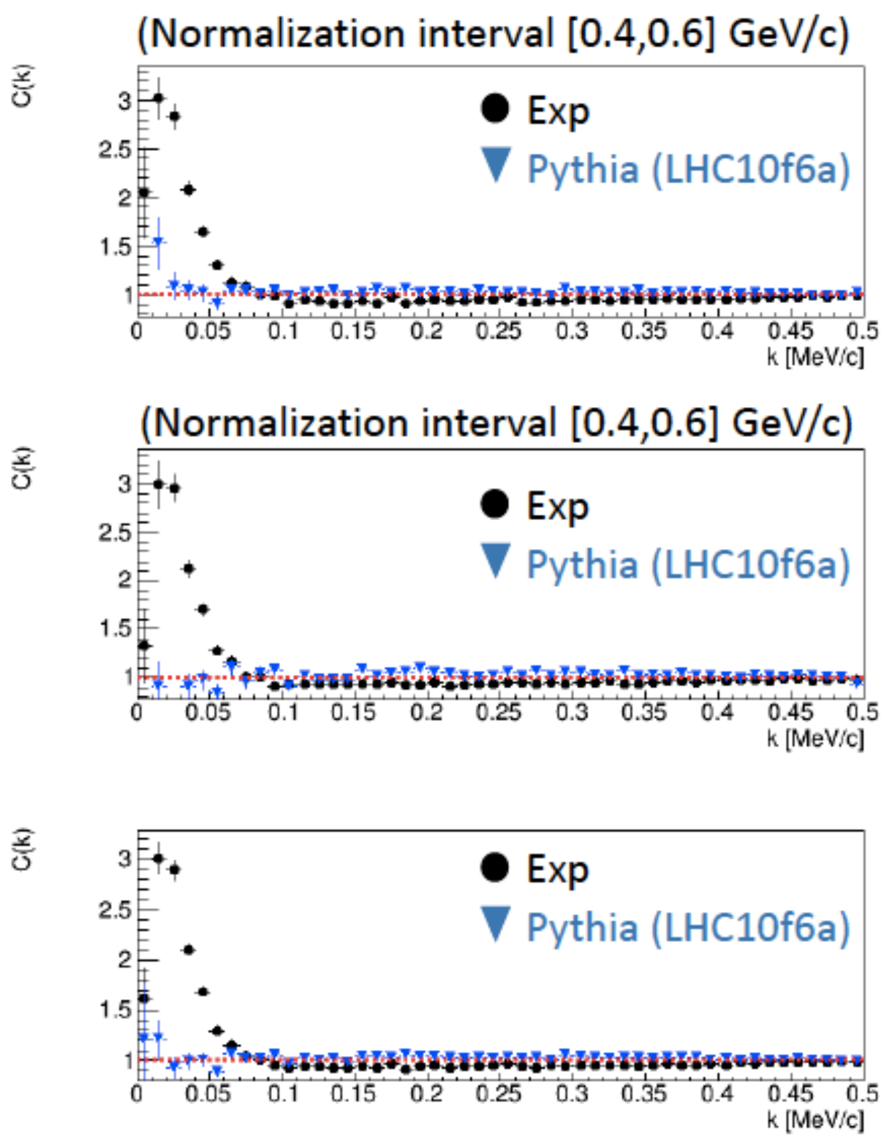
ALICE pp √s = 7 TeV
pΛ ⊕ $\overline{p}\overline{\Lambda}$ pairs
Pythia 6.421
Baseline fit
C(k*)
k* [GeV/c]

Pythia high k*



Minijets Background

orrelations:

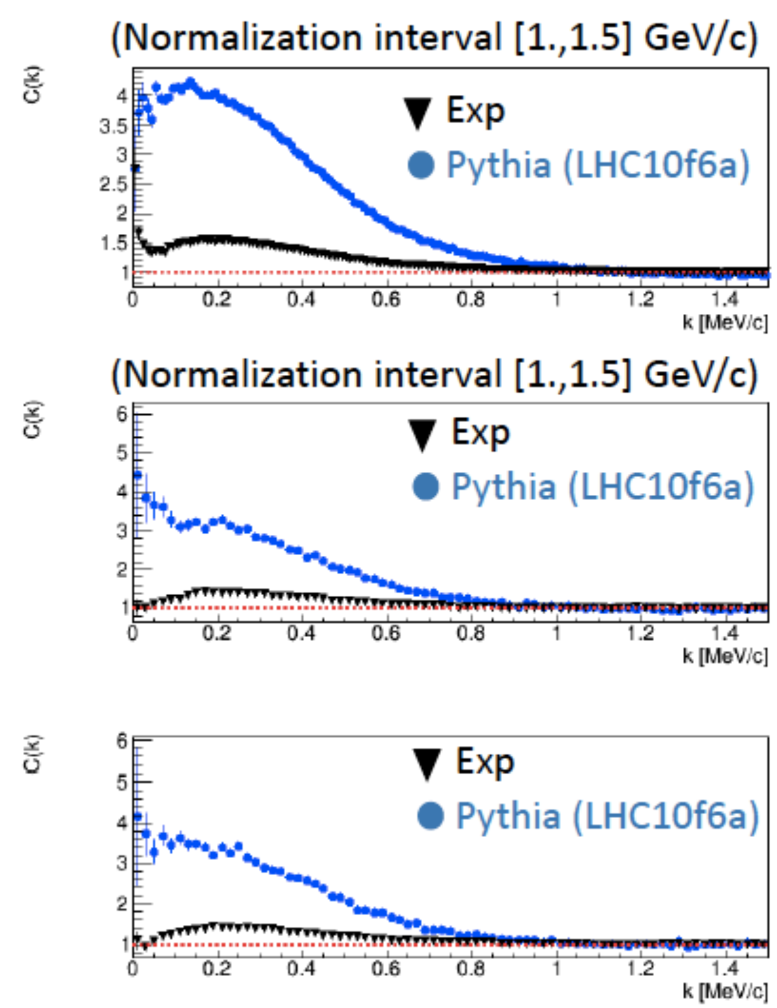


pp

$\bar{p}\bar{p}$

$pp + \bar{p}\bar{p}$

n Correlations:



$p\bar{p}$

$p\bar{\Lambda}$

$\bar{p}\Lambda$

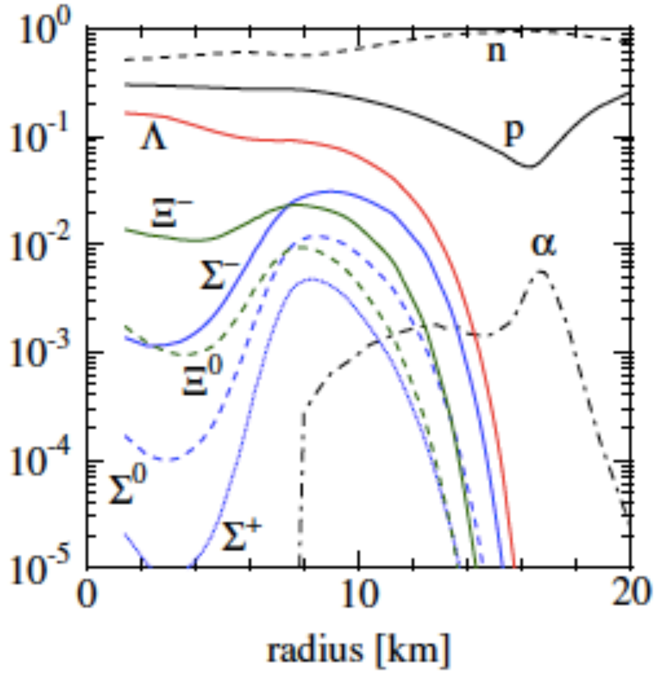
6

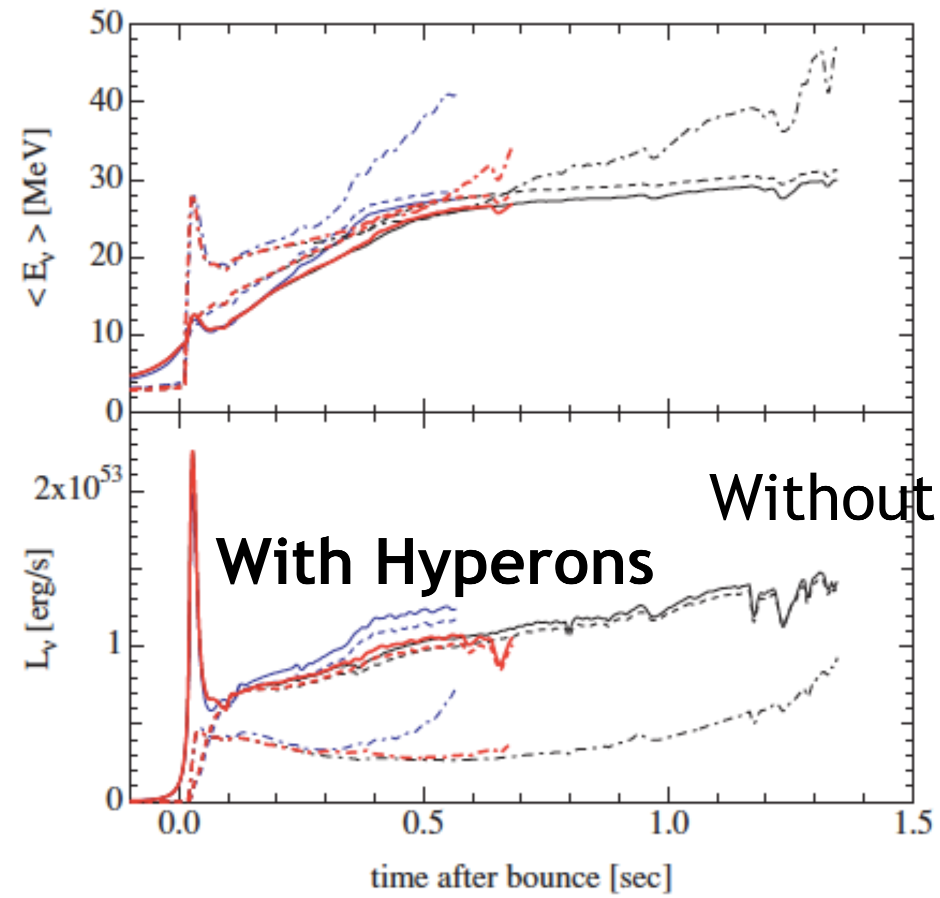
Why we need the EoS?

Time Evolution of the Neutrino Emission in failed Supernovae depends on the Equation of State of the proto-Neutron star
The neutrino emission from the accreting proto-neutron star with the hyperonic EOS stops much earlier than the corresponding case with a nucleonic EOS

K. Sumiyoshi et al. APJ690:L43–L46, 2009

Hyperons Fraction 680 ms after the bounce





Decomposition of the p-Λ correlation function

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

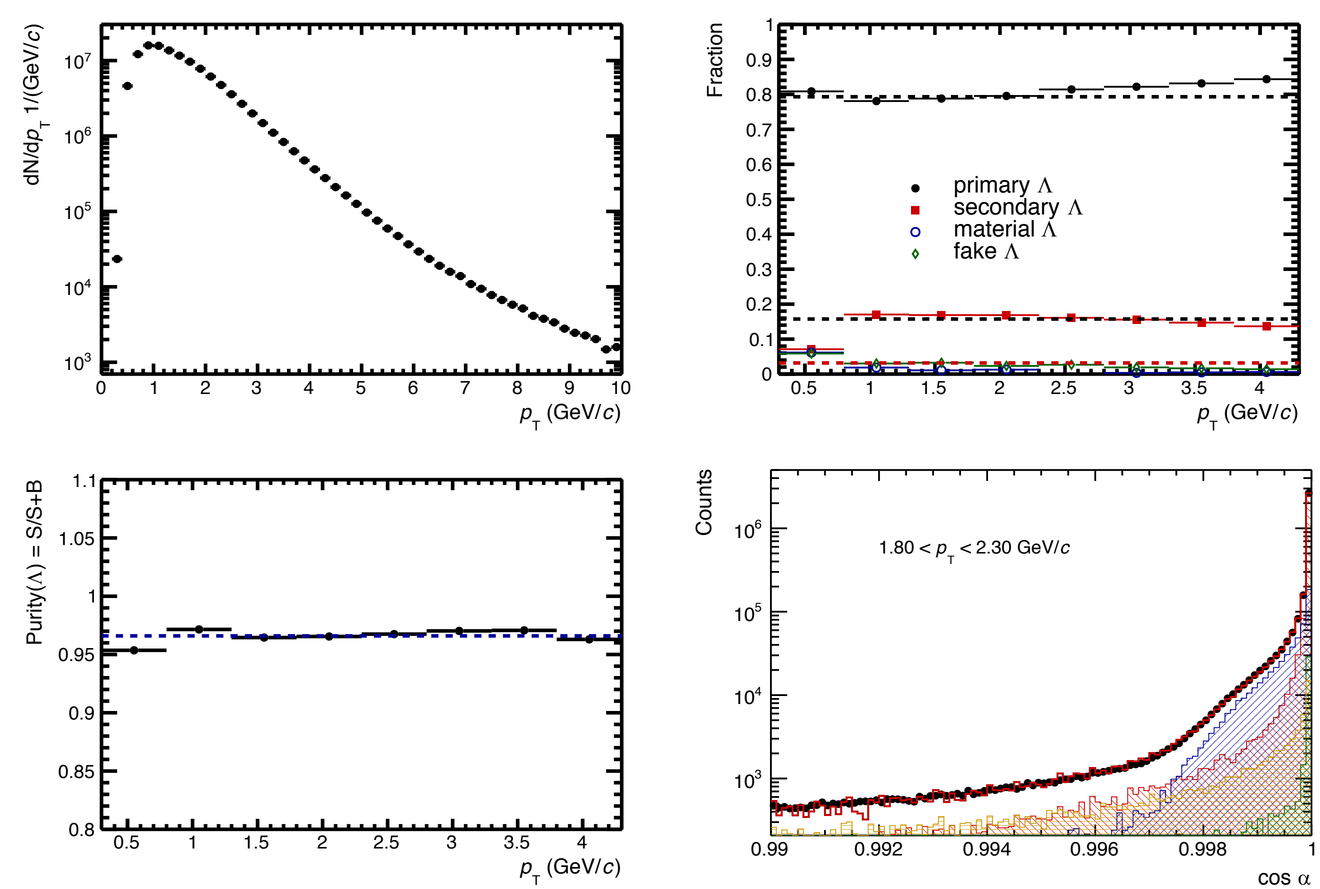
- Purity from fits to the invariant mass distribution
- Feed-down fractions from MC template fits to the cosα distribution

p–Λ

Pair	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

p–Λ

Pair	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 p-Ξ correlation function

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

- 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($\Xi^0(1530) \rightarrow \Xi^-$) = 2/3
    - BR($\Xi^-(1530) \rightarrow \Xi^-$) = 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

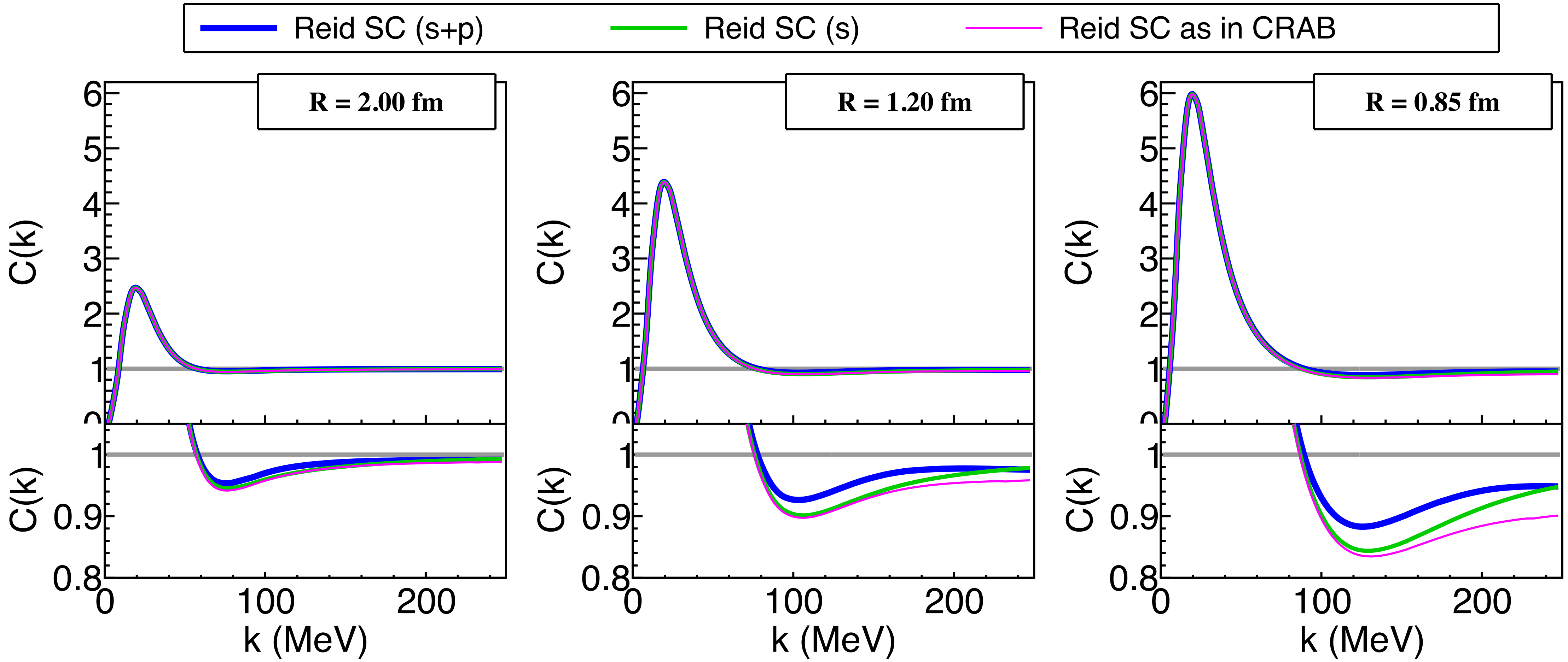
p–Ξ

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

Typical Correlation functions for p-p Collisions

https://arxiv.org/abs/1802.08481

pp Correlations



Stronger signal for small systems