Precise tests of the hadron-hadron strong interaction via femtoscopy with ALICE

Otón Vázquez Doce (TUM)
for the ALICE Collaboration

XVIII International Conference on Hadron Spectroscopy and Structure (HADRON2019)
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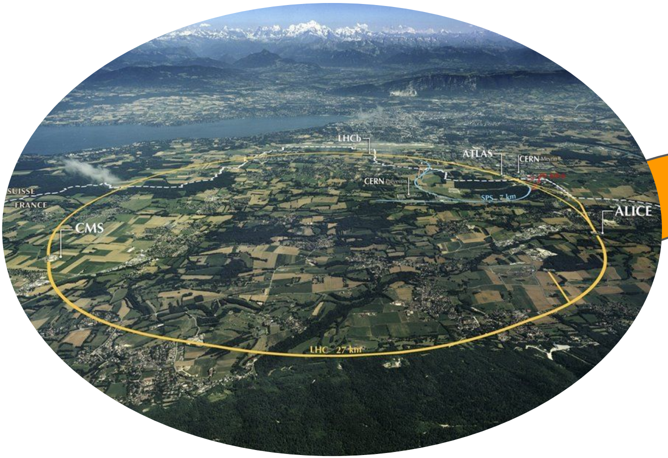
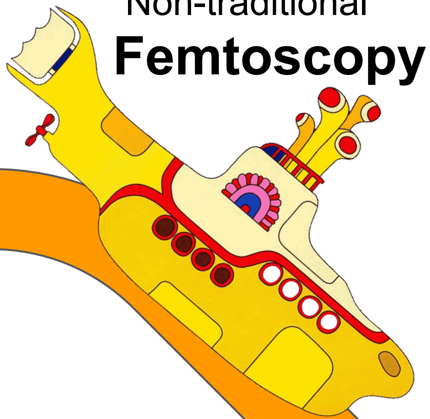
Outline



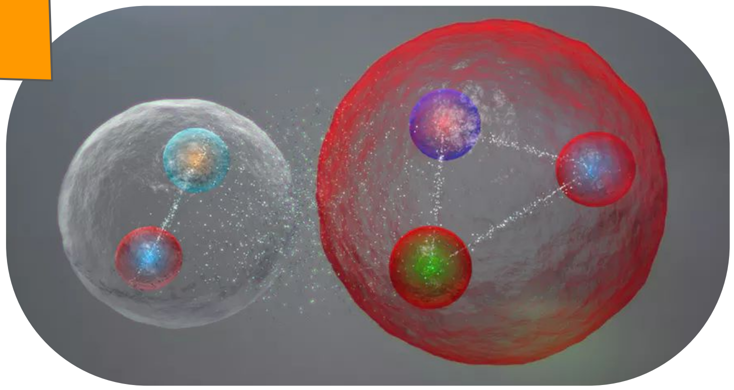
LHC: **High-energy physics**



“Non-traditional”

Femtoscopy

Hadron physics



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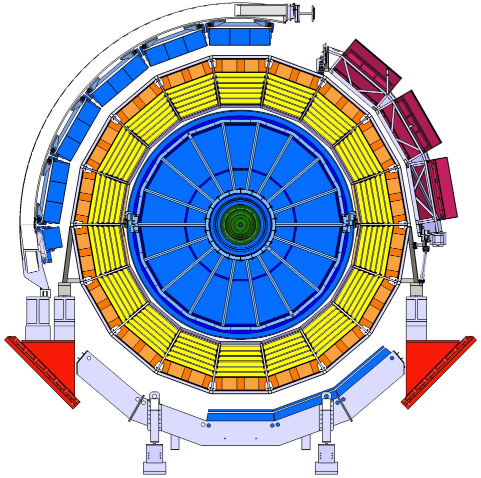
<u>ALICE experiment at the LHC</u>



Used datasets:
- **pp** 13 TeV: $15 \cdot 10^8$ MB events
- **pp** 13 TeV: $15 \cdot 10^8$ High-Mult events
- **p-Pb** 5.02 TeV: $6.0 \cdot 10^8$ MB events

Tracking and PID:
- Inner Tracking System (**ITS**)
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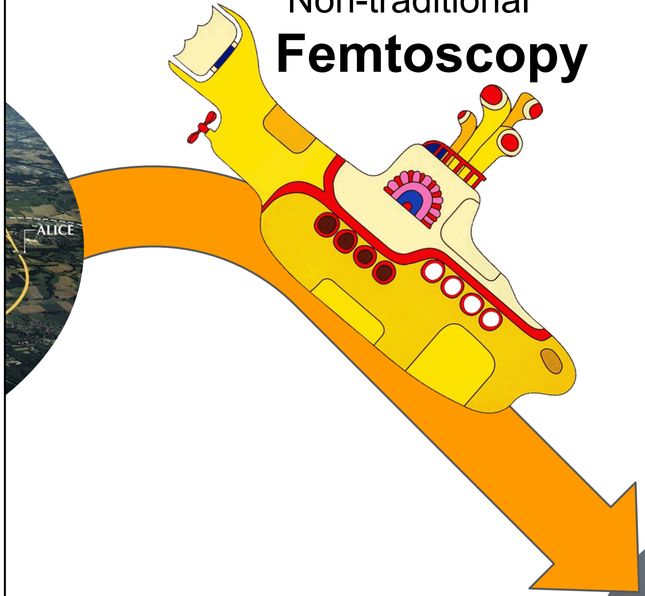

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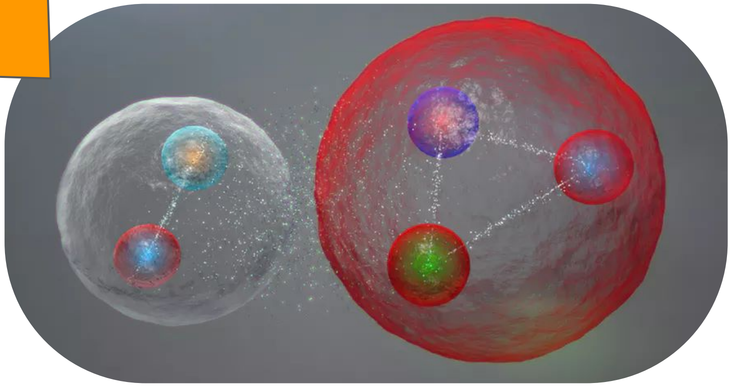

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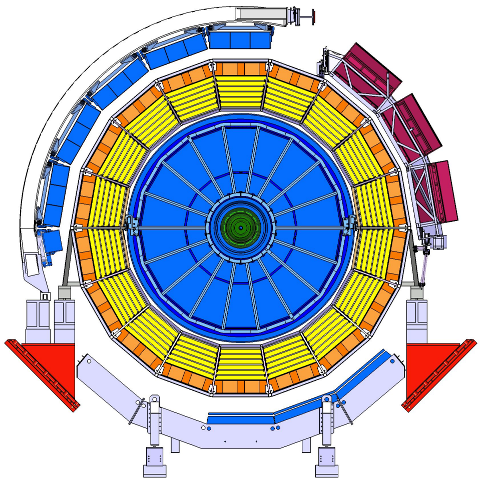

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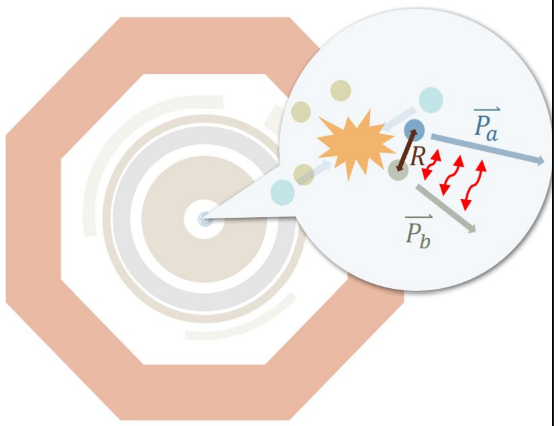
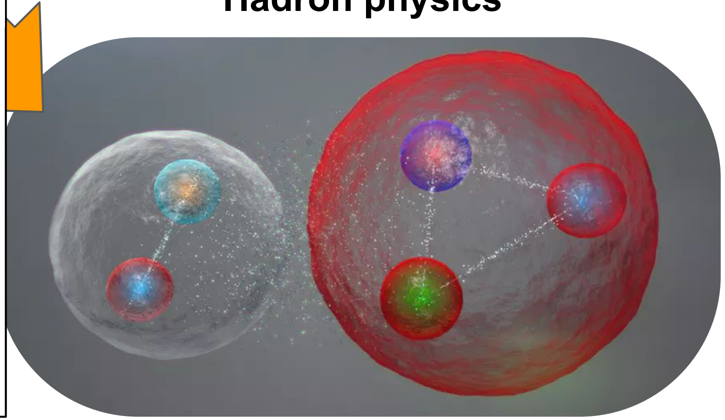


Study of correlations of hadron-hadron pairs from small sources:

p-p, p-$K^{+/-}$, p-Λ, Λ-Λ, **p-Σ^0, p-Ξ^-, p-Ω^-**

Reconstruction of hyperons
- Λ→pπ (BR ~ 64%)
- Σ^0→Λγ (BR ~ 100%)
- Ξ→Λπ (BR ~ 100%)
- Ω→ΛK (BR ~ 68%)

Hadron physics



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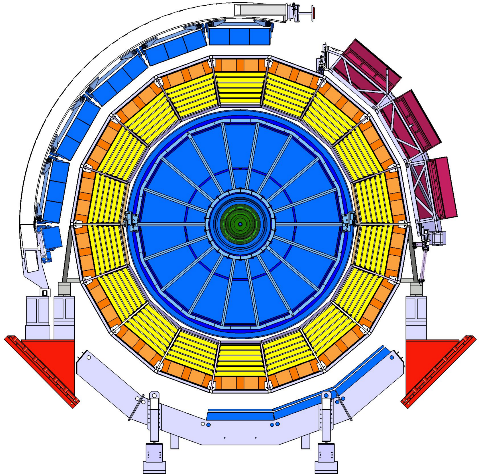

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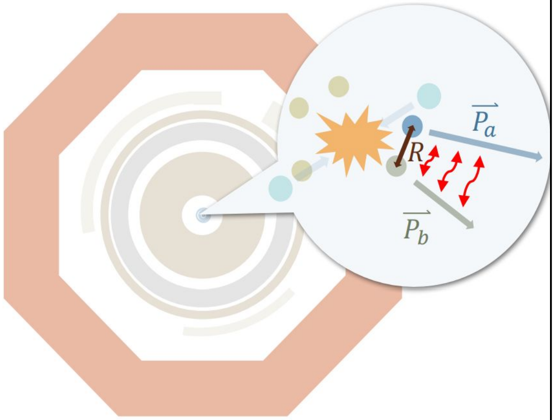

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Hadron physics

- Study the **interaction of hadrons with strange content**. While N-N interaction are well known and constrained by precise scattering data, **constructing YN, YY potentials is very challenging.**
- **Recent developments**
  - Lattice-QCD
  - Chiral effective field theory
  - Meson exchange models
- Models are constrained by data with limited precision due to the experimental difficult with strange particle beams: Scattering data, hypernuclei, search for bound states, exotic atoms, etc.
- **Femtoscopy** with ALICE delivers **precise data** in the low momentum range, in a region **not accessible with other approaches**, with consequences on the **possible appearance of hyperons in neutron stars** and the **existence of strange di-baryons**.

Femtoscopy as a tool for studying h-h interactions

Based on the correlation function $C(k^*) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})}$

k* = reduced relative momentum with $\overrightarrow{p_a^*} + \overrightarrow{p_b^*} = 0$

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

- >1 ⇒ **Attractive** interaction
- <1 ⇒ **Repulsive** interaction

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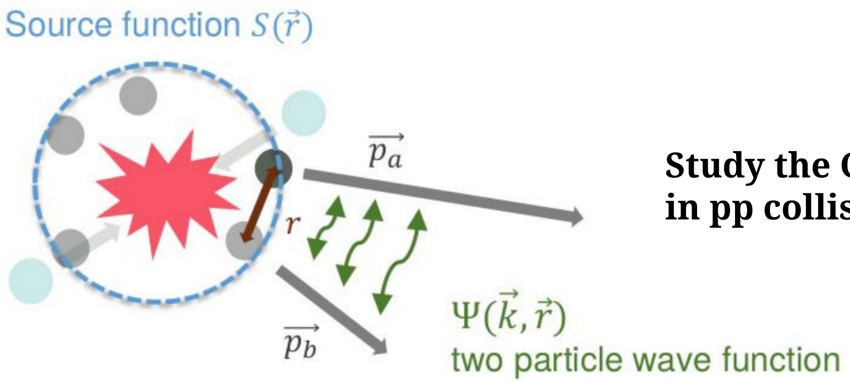
Source

Relative wave function:
Sensitivity to the interaction potential

Theory



Study the C(k*) of hadron-hadron pairs in pp collisions ⇒ small particle source (~1 fm)

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Relative wave function:
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Theory

Experimentally: $C(k^*) = \mathcal{N} \frac{N_{Same}(k^*)}{N_{Mixed}(k^*)}$

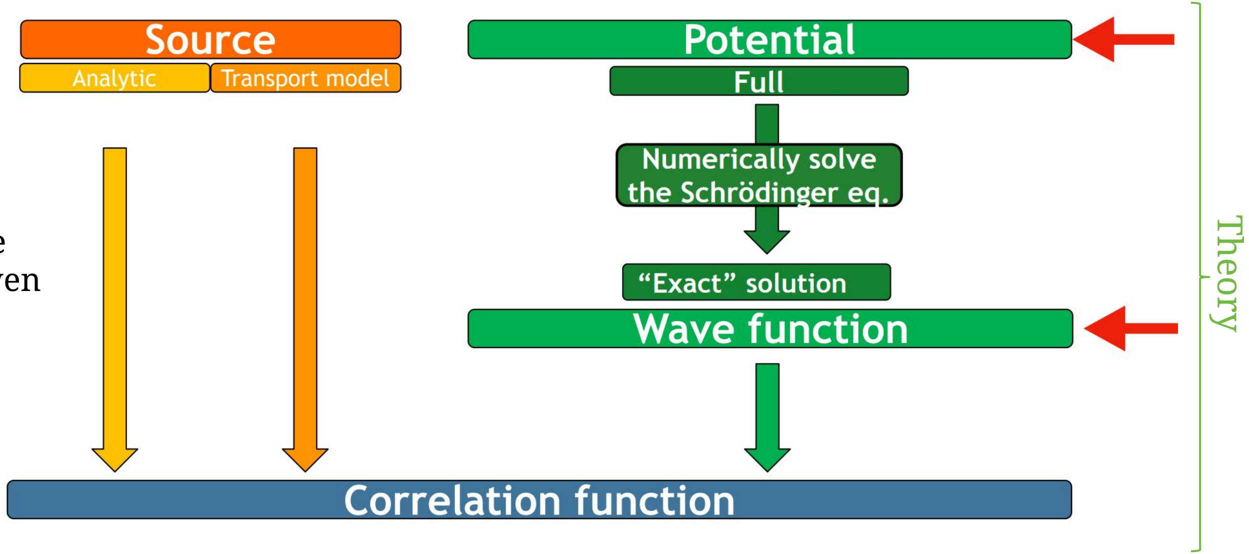
Generally, the experimental correlation function accounts for the genuine correlation and it is affected by residual correlations and finite momentum resolution.

Experiment

CATS: Correlation Analysis Tool Using the Schrödinger Equation

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

Provides a exact solution computing the correlation function from the model given a local potential or wave function form.



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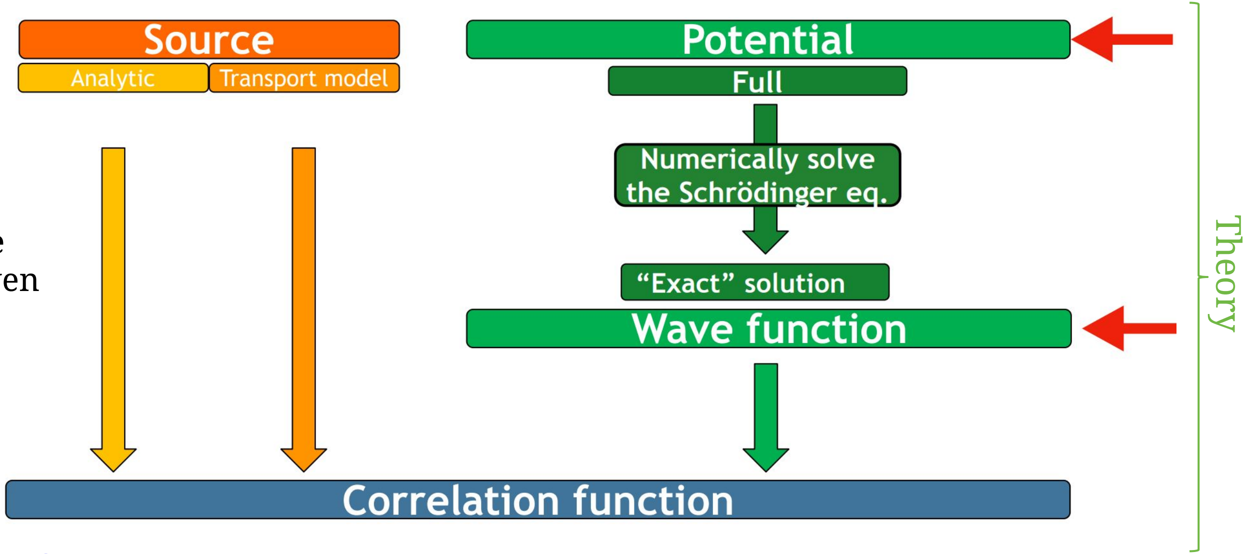
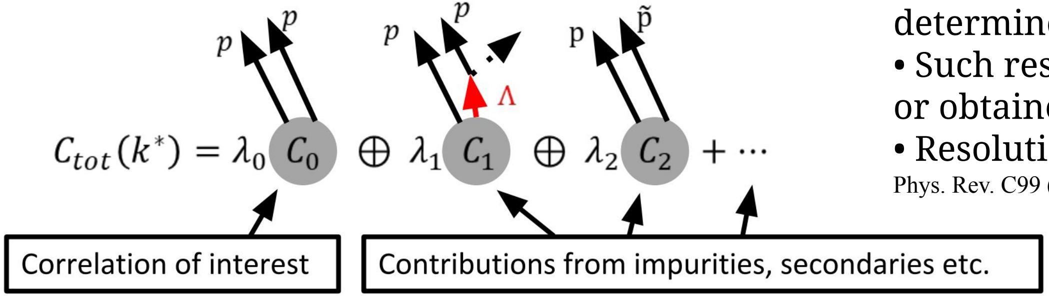


Decomposition of the correlation function



- Purities and contributions from weak decays determined from fits to experimental data
- Such residual correlations modelled (weak decays) or obtained from data (impurities)
- Resolution effects applied to the fit function

Phys. Rev. C99 (2019) no.2, 024001

Experiment

Setting the **source**

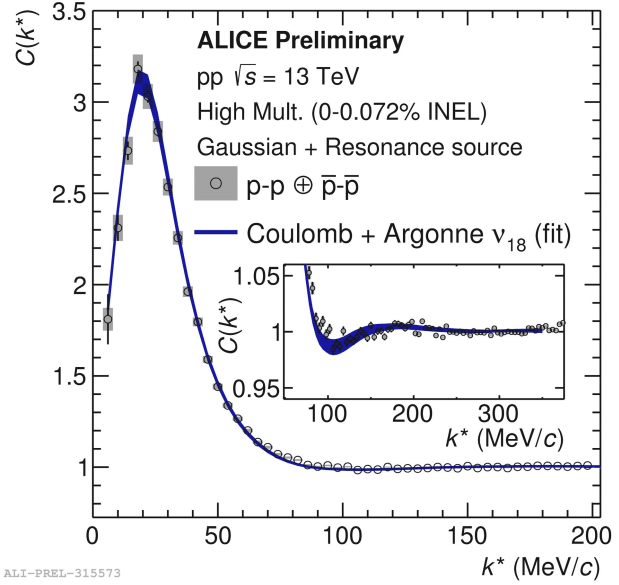
Ansatz: in small collision systems the source is similar for all baryon-baryon, baryon-meson pairs

The characteristics of the source are **determined from femtoscopic analysis of the p-p correlation**:
Assume a p-p known interaction → determination of the source size

- **Consider <m_T> dependence of the source due to collective effects:**
  - Femtoscopic p-p fits performed differentially in <m_T> bins
  - <m_T> dependence cross-checked with p-Λ analysis
- **Effect of strong short-lived resonances** computed for all hadrons
  - Statistical hadronization model in the canonical approach

Priv. comm. Prof. F. Becattini, J.Phys. G38 (2011) 025002

p-p femtoscopy



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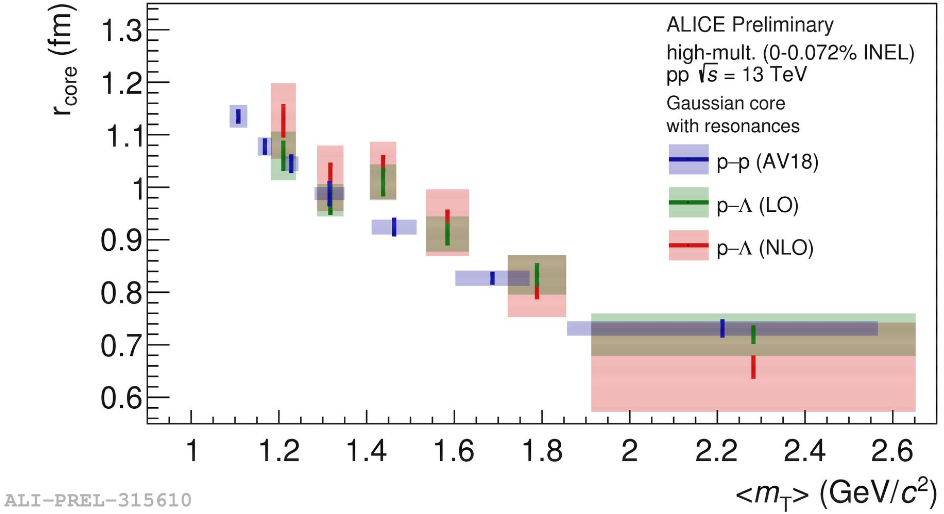

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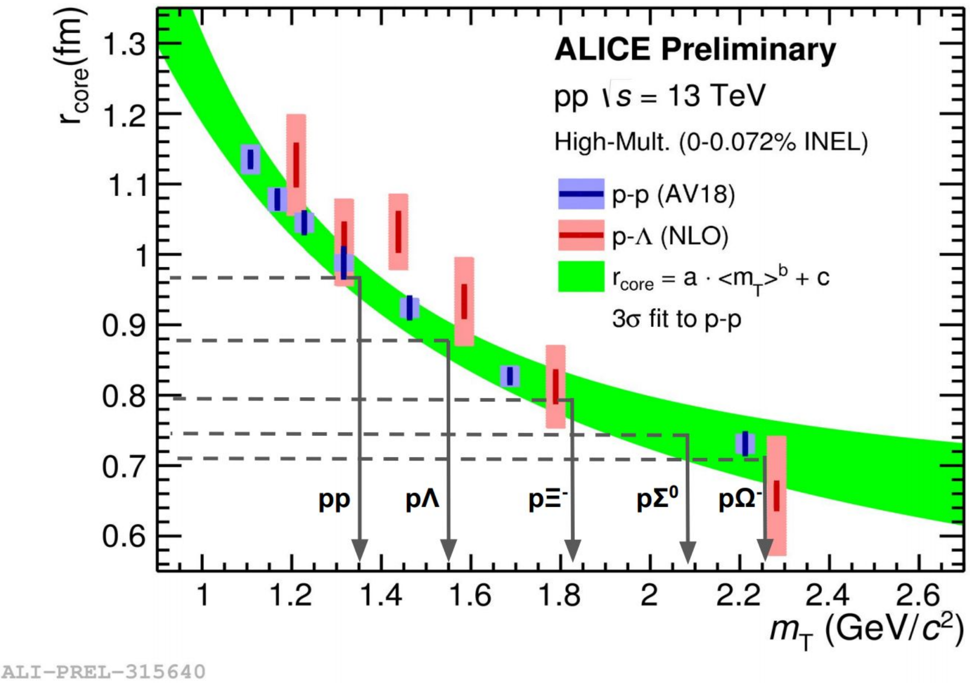


Parametrization with exponential law $r_{core} = a \cdot \langle m_T \rangle^b + c$

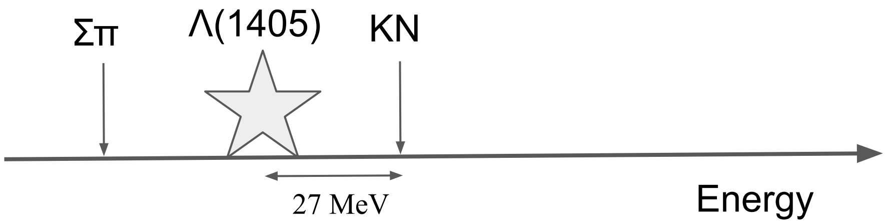
Fit parameters:
a ∈ [0.65 , 0.83]
b ∈ [-1.2 , -2.2]
c ∈ [0.36 , 0.66]

The p-Λ, p-Σ^0, p-Ξ^-, p-Ω^- sources are **determined given the pair $\langle m_T \rangle$:**

p-Λ: r_{core}= 0.88 ± 0.03 fm
p-Ξ^-: r_{core}= 0.80 ± 0.03 fm
p-Σ^0: r_{core}= 0.75 ± 0.04 fm
p-Ω^-: r_{core}= 0.73 ± 0.05 fm

K-p femtoscopy: The KN interaction

- K^+p interaction is well established
- K^-p features a strong attraction
  - appearance of the Λ(1405) below threshold
  - Λ(1405): antiKN-Σπ molecular state



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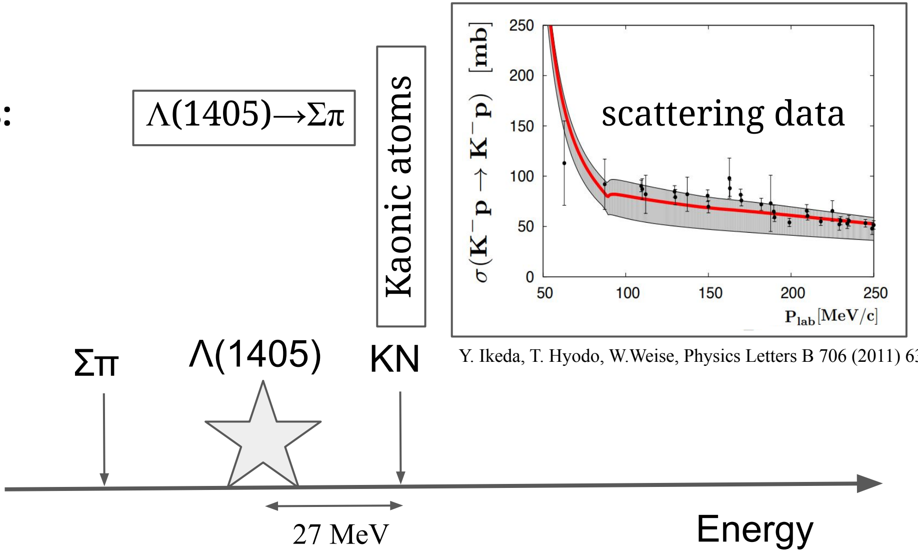

Y. Ikeda, T. Hyodo, W.Weise, Physics Letters B 706 (2011) 63

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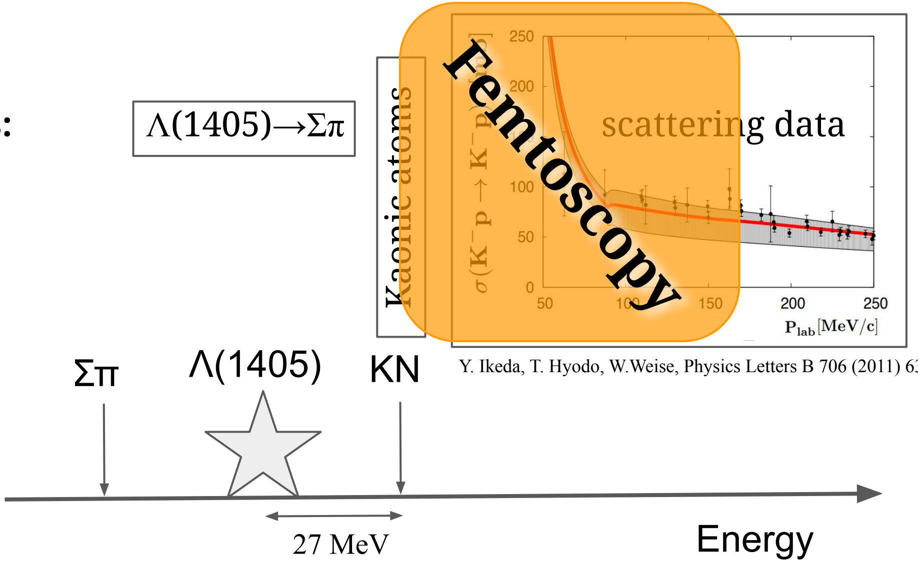

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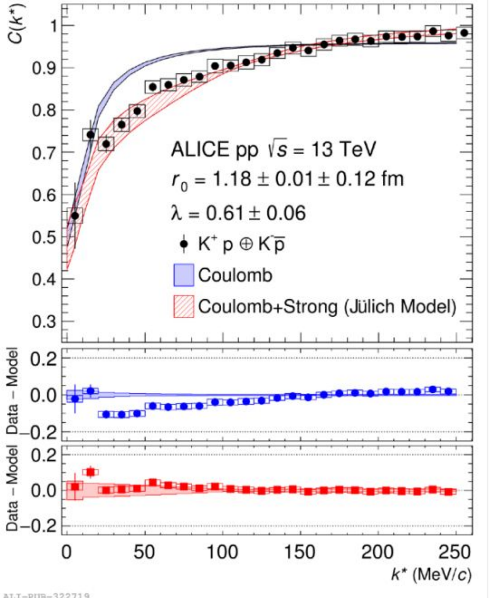
K-p femtoscopy in pp collisions

ALICE Collaboration, arXiv:1905.13470[nucl-ex]



- Radius obtained from inclusive p-p correlation

  $r_0 = 1.18 \pm 0.01 \pm 0.12$ fm
- K^+p correlation used as a benchmark to study K^-p

  Jülich meson exchange model: Eur.Phys.J. A47 (2011) 18

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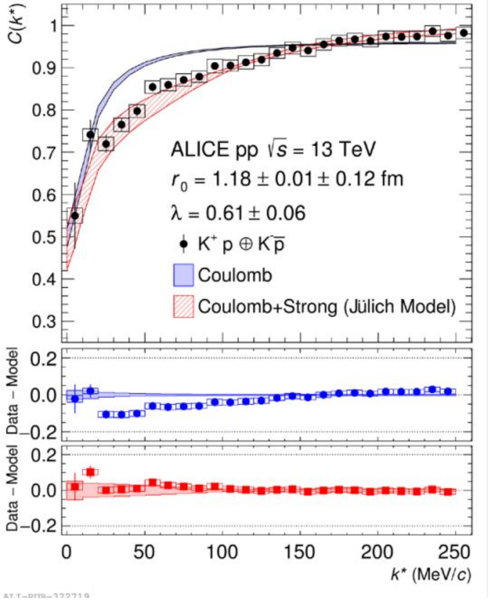

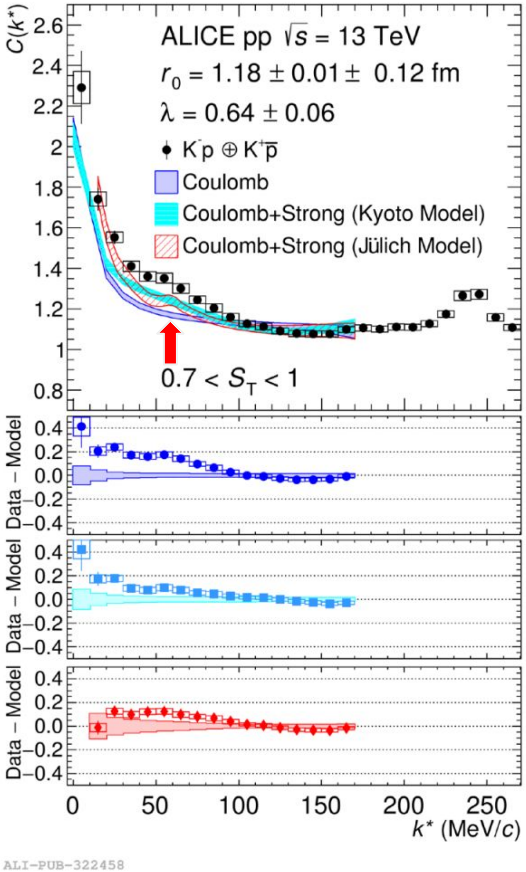

Kyoto Model: Phys. Rev. C93 no. 1, (2016) 015201
Jülich Model: Nucl. Phys. A981 (2019)

⇒ Bump close to the $K^0 n$ threshold→(58 MeV/c in CM frame)

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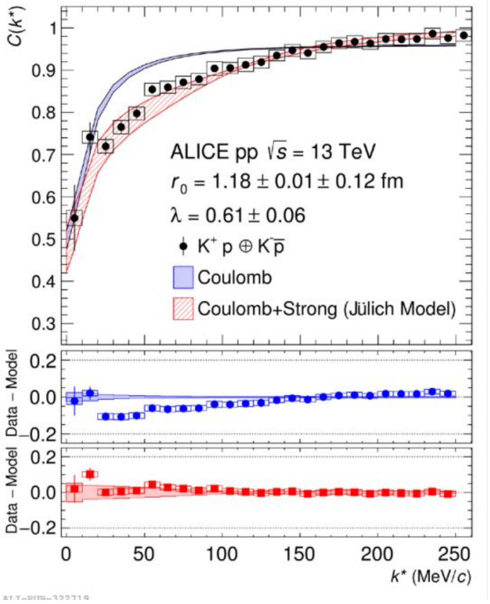

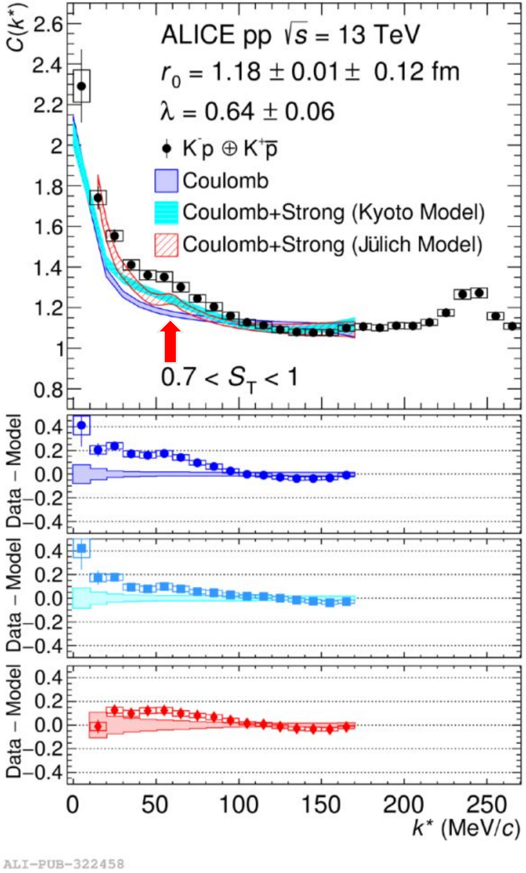

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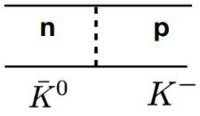
First experimental evidence of the opening of the K^0n isospin breaking channel

Coupled channel effect

$$M(K^-p) + 5\,\text{MeV} = M(n\bar{K}^0)$$



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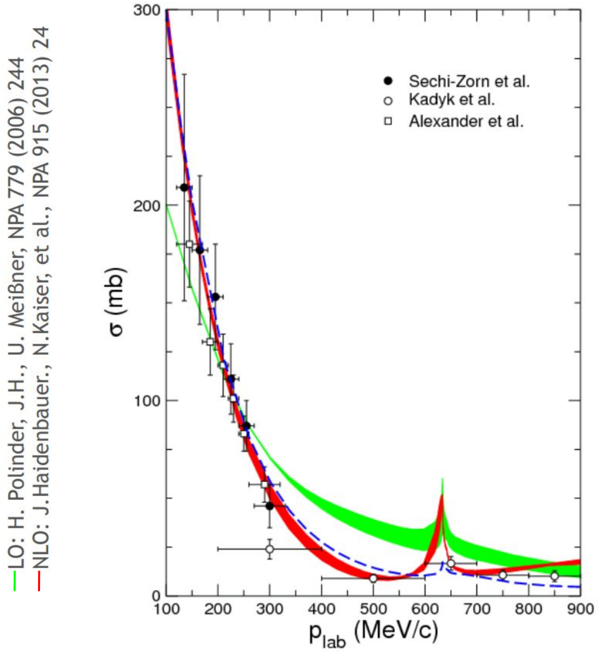
→ Analysis in p-Pb 5.02TeV as a function of charged multiplicity: Interaction changes as a function of the particle distance

p-Λ femtoscopy in High-mult pp collisions



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- No experimental evidence of the cusp due to ΣN/ΛN coupling, responsible for the appearance of a repulsive short range component in the Λp interaction

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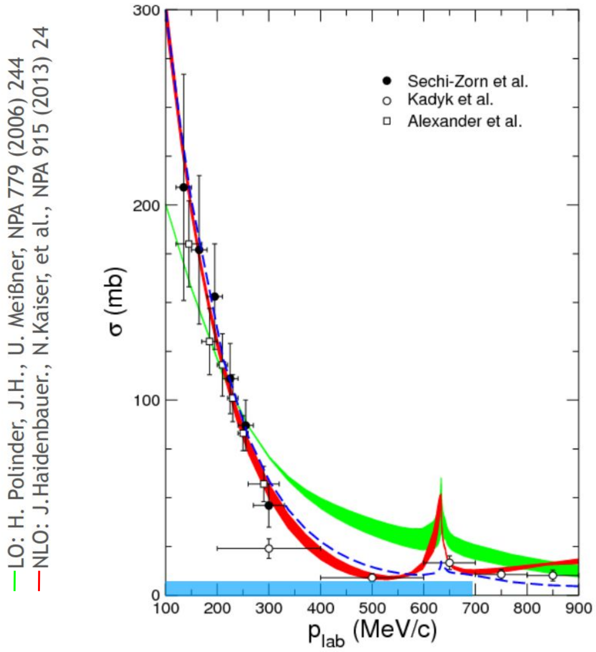

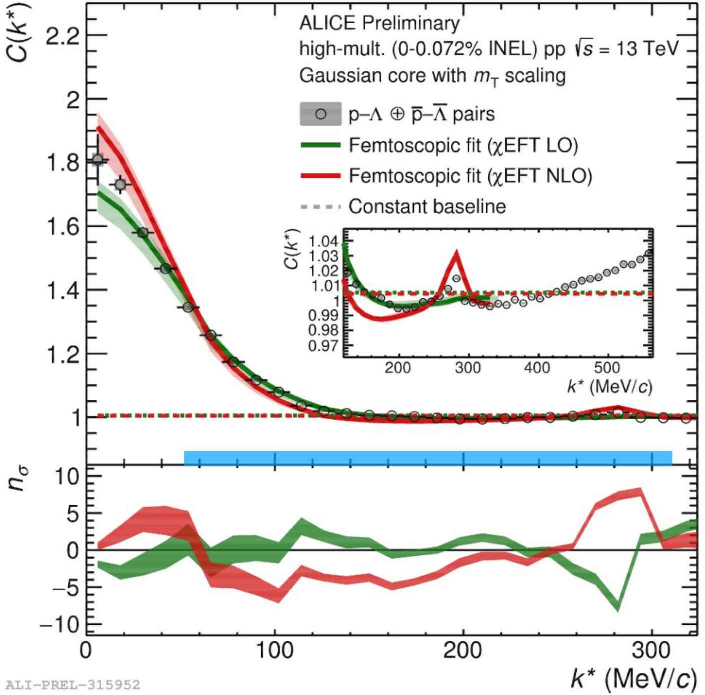

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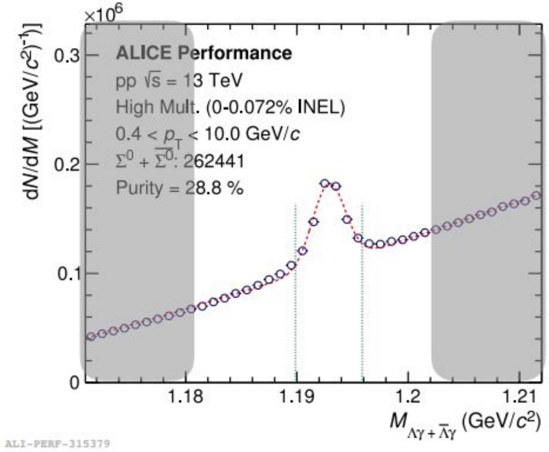
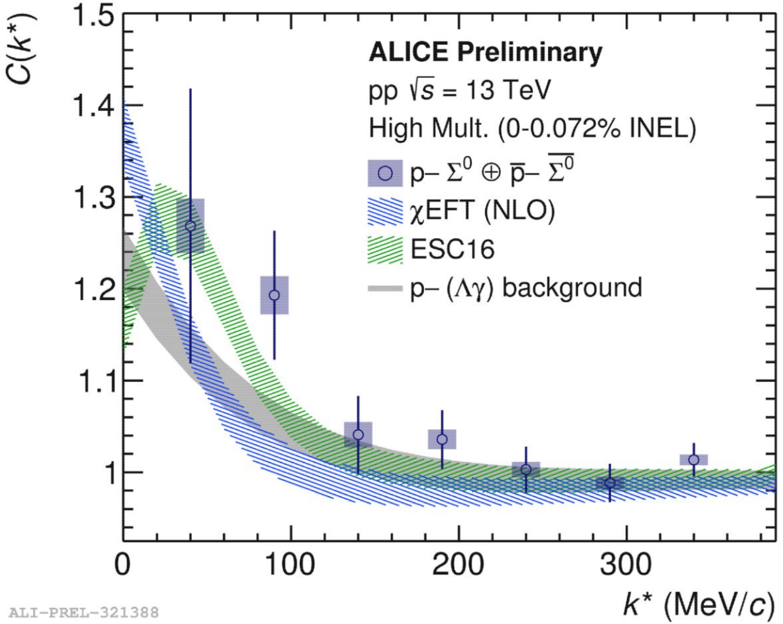
- Extension of the kinematic range and **improved precision.**
- **Clear experimental evidence** of the cusp
- LO and NLO calculations within xEFT fail to reproduce the data

p-Σ^0 femtoscopy in High-mult pp collisions

Identification via $\Sigma^0 \rightarrow \Lambda\gamma$ (BR ~ 100%)



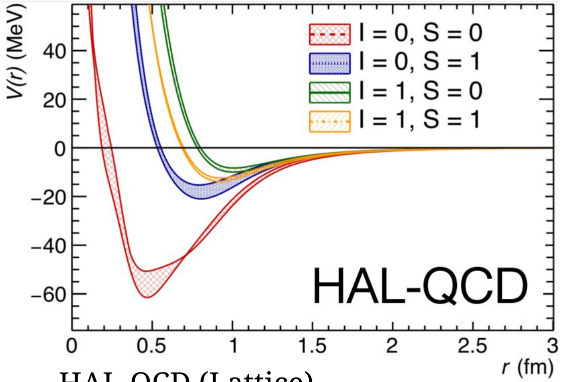


Models for the p-Σ^0 interaction:

- Chiral effective theory at NLO J. Haidenbauer et al., Nucl. Phys. A 915 (2013) 24
- Meson Exchange model (ESC16) M. M. Nagels, T. A. Rijken, Y. Yamamoto, PRC 99 (2019) 044003

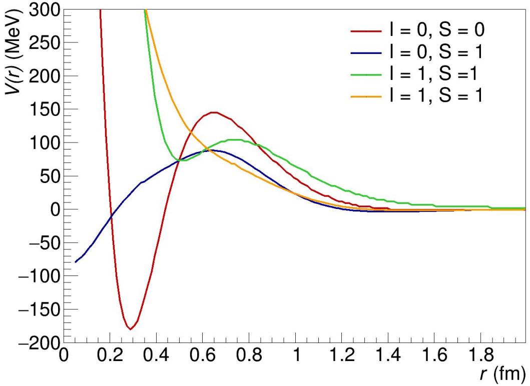
The p-Σ^0 wave function is used as input to CATS

Models of the p-Ξ- potential:



HAL-QCD (Lattice)

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



ESC16L Meson exchange model

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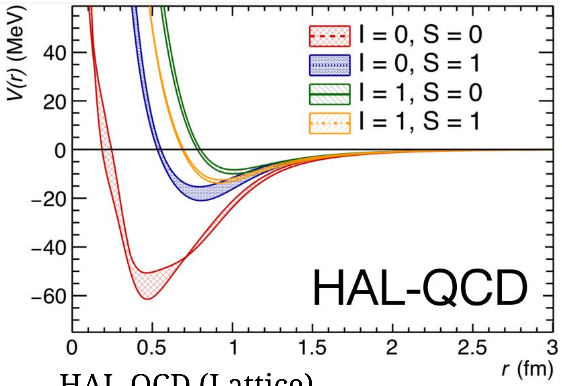

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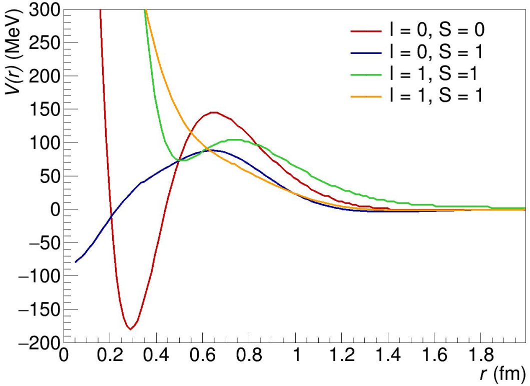

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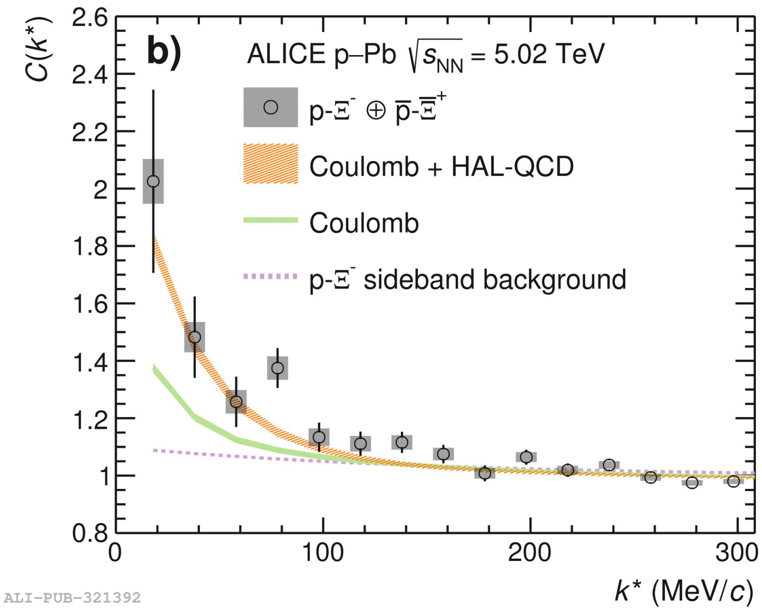
p-Ξ$^-$ in p-Pb at 5.02 TeV

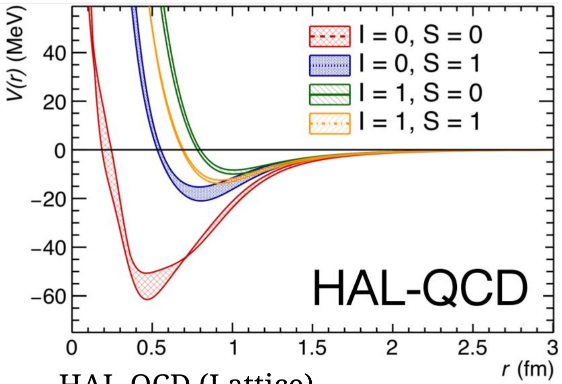


"First observation of an attractive interaction between a proton and a multi-strange baryon" ALICE Coll. ArXiv:1904.12198 [nucl-ex]

- Coulomb excluded (>4σ)
- Compatible with Lattice (HAL-QCD) calculations

$r_0 = 1.427 \pm 0.007$ (stat.) $^{+0.001}_{-0.014}$ (syst.) fm (-20%, resonances)

Models of the p-Ξ- potential:



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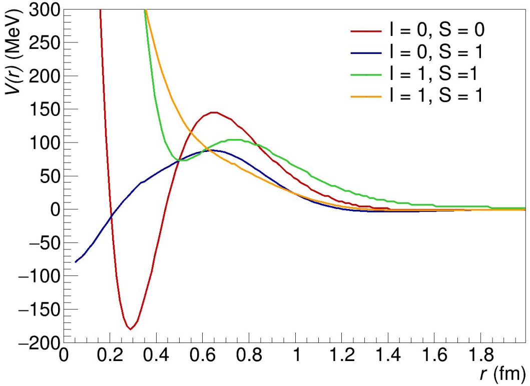

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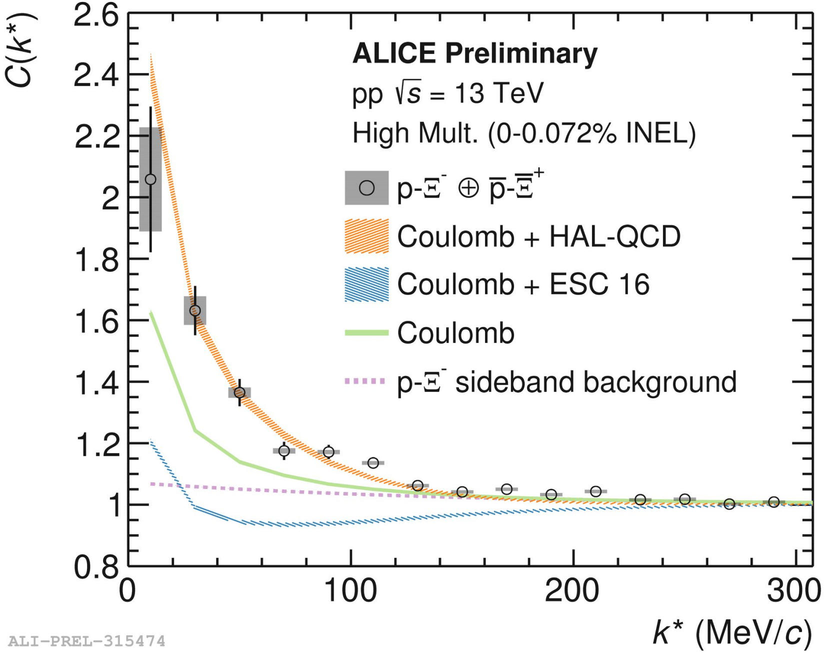
p-Ξ⁻ in p-p High. Mult.



- Coulomb only: > 5.7 σ
- HAL-QCD Potential: (1.3-2.5) σ
- ESC16 Potential: > 18 σ

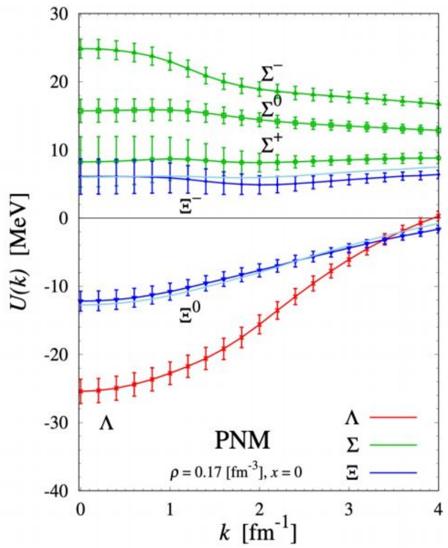
} → Hypernuclei data described by both HAL-QCD and ESC16

r_{source} = 0.80 fm (+resonances)

p-Ξ^-: Implications for NS with hyperon content

In medium: Many body interaction,
average Ξ^- Single particle potential (U_{Ξ^-})

<u>Lattice QCD:</u>
U_{Ξ^-} moves from slightly repulsive in symmetric nuclear matter to **slightly repulsive U_{Ξ^-}~6 MeV in pure neutron matter (NS)**



p-Ξ^-: Implications for NS with hyperon content

In medium: Many body interaction, average Ξ^- Single particle potential (U_{Ξ^-})

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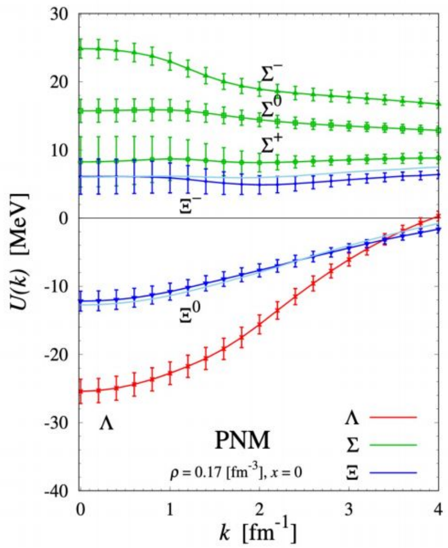
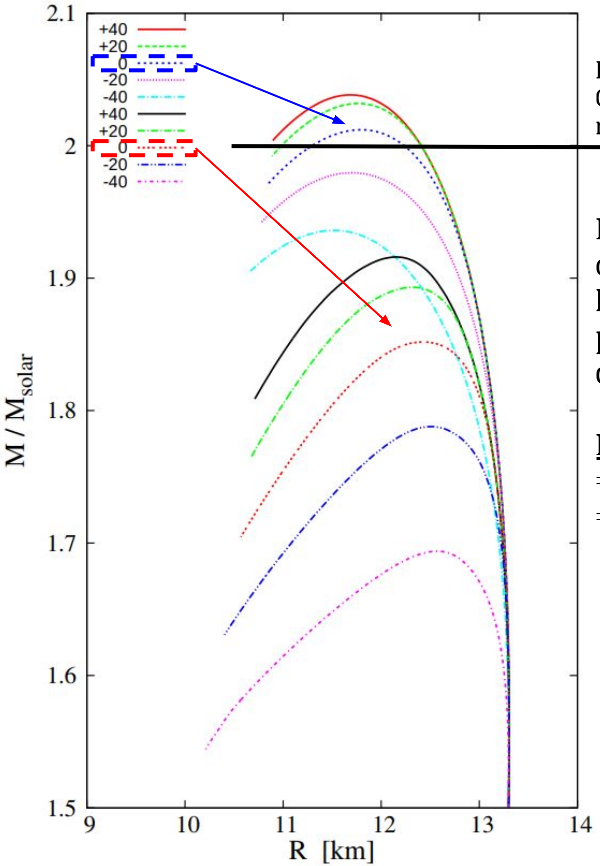




Experimental constraint: Observation of ~2 solar masses NS

RMF models: Equation Of State of neutron-rich matter with hyperon content. Use single particle potential at saturation densities as input

<u>Repulsive interaction:</u>

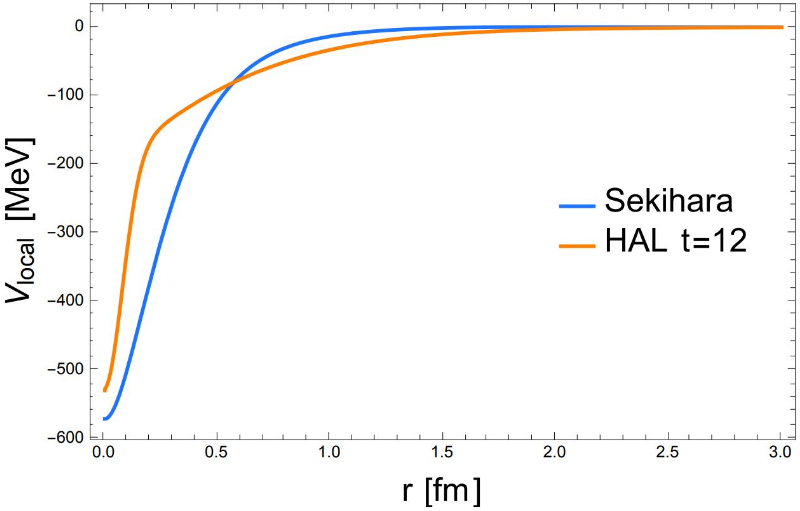
⇒ Ξ pushed to high densities

⇒ **stiffer EoS**, higher masses

Models of the p-Ω^- interaction

- Lattice **HAL-QCD** potential with physical quark masses T. Iritani et al., arXiv:1810.03416
  - m_π = 146 MeV/c^2, m_K = 525 MeV/c^2
- **Sekihara**: Meson-exchange model T. Sekihara et al., Phys. Rev. C 98, 015205 (2018)
  - Short range attractive interaction fitted to previous HAL-QCD scattering parameters

Predicted strong attraction at all distances implies the **formation of a pΩ^- dibaryon**

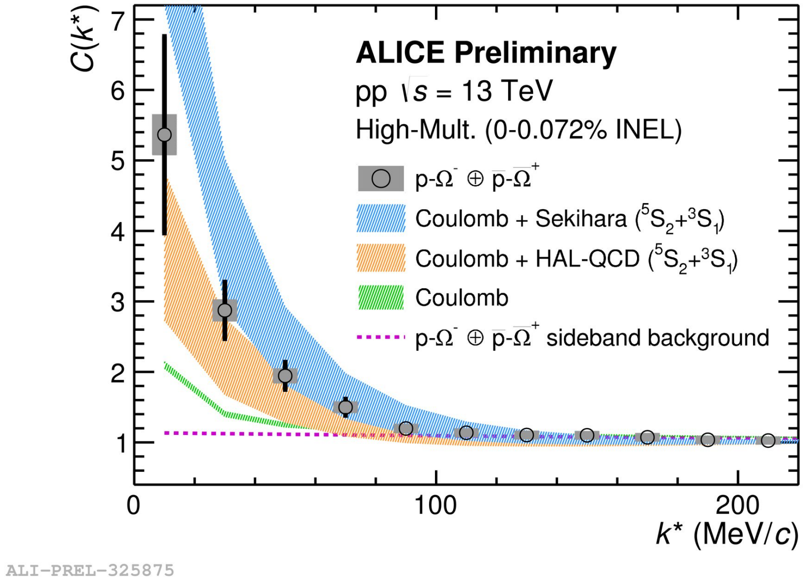


Model	pΩ^- binding energy (strong interaction only)
HAL-QCD	1.54 MeV
Sekihara	0.1 MeV

+1 MeV with Coulomb

→ Models provide so far only $^5S_2$ channel (weight ⅝)
For $^3S_1$ channel, two extreme assumptions: total absorption or attaction as $^5S_2$

Results: p-Ω^- correlation function in pp HM



r_{source} = 0.73 fm (+resonances)

"Coulomb only" scenario discarded by ALICE data (> 6 σ) showing the attractive character of the interaction

Precision of ALICE data exceeds the theoretical predictions

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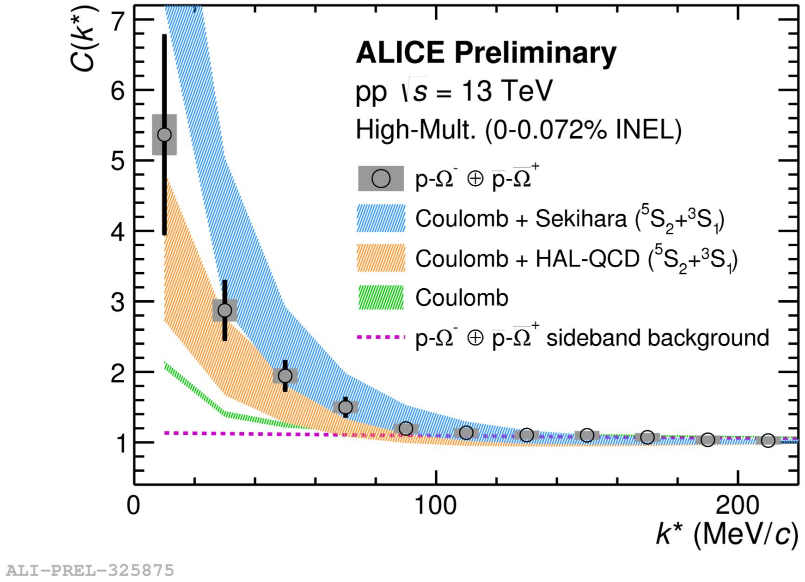

r_{source} = 0.73 fm (+resonances)

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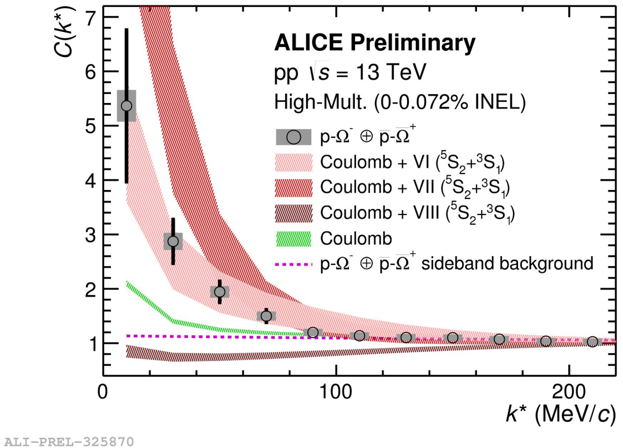
Precision of ALICE data exceeds the theoretical predictions

Comparison with the model favoured by STAR data
STAR Coll. Phys. Lett. B790 (2019) 490-497

V_{III}: Ad-hoc fit to previous HAL-QCD calculations with non-physical quark masses with pΩ dibaryon E_b = 27 MeV



Outlook

ALICE delivers the **precise data** to test the hadron-hadron interaction with strangeness content.
- The LHC provides a unique and precise testing of the strong interaction at distances lower than 1 fm and we extract relevant information on two-body interactions within dense matter.

The comparison of the ALICE data in small systems with the expectation from the models is **very sensitive to the shape of the model potential**.
- Femtoscopic data substitutes/complement the scattering data, hypernuclei and other approaches.

RUN3/4 will provide the possibility of carrying out new studies and investigate 3-body interactions.

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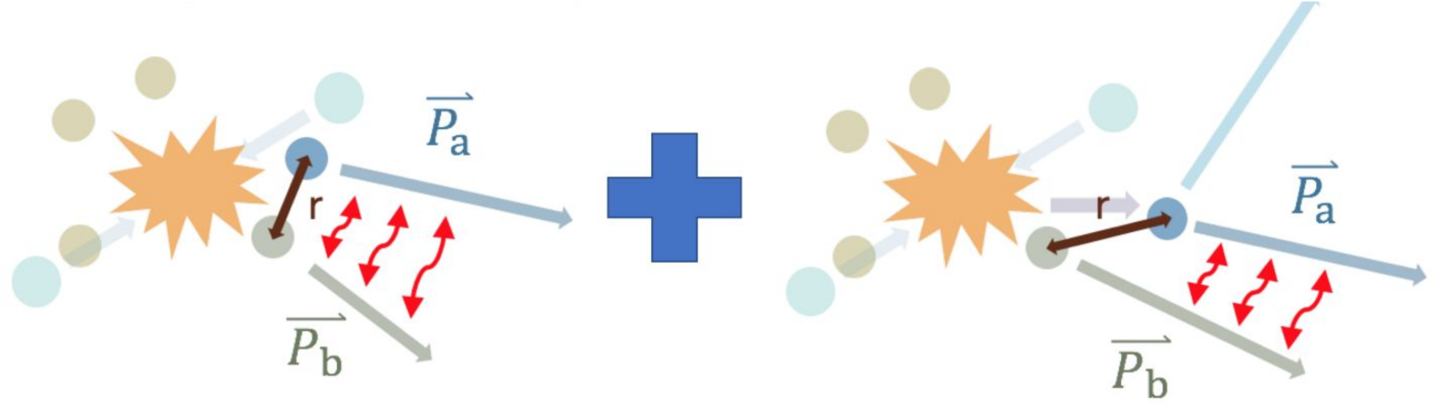
THANK YOU!

Effect of resonances in the source

Resonances with $c\tau >> r_0$
- Decrease of the correlation strength
- Taken into account by the λ **parameters**

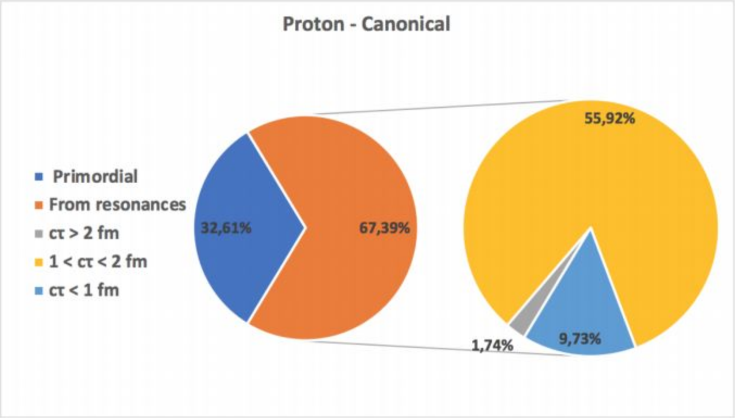
Resonances with $c\tau \sim r_0 \sim 1$ fm:
- Introduce an **exponential tale**
  - example: N*(Γ~150-200 MeV), Δ (Γ~150 MeV), etc
  - Specific exponential modulation to each pair due to different strong decaying resonances feeding to the different particle species

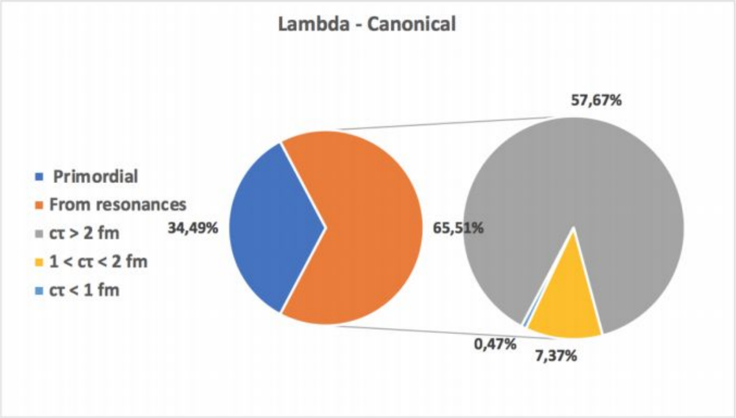


Details on resonances

Amount of resonances: Canonical approach of the statistical hadronization model (SHM)

- $T = 166$ MeV & $\gamma_s \sim 0.8$ (Private Comm Prof. F. Becattini, J. Phys. G38 (2011) 025002)





- For Ξ and no Ω contributions!
- Average mass and average cτ determined by the weighted average values of all resonances

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

Modelling the source including resonances

Gaussian Core

$$G(r, r_{core}) = \frac{2\sqrt{\pi}r^2}{r_{core}^3}\exp\left(\frac{r^2}{4r_{core}^2}\right)$$

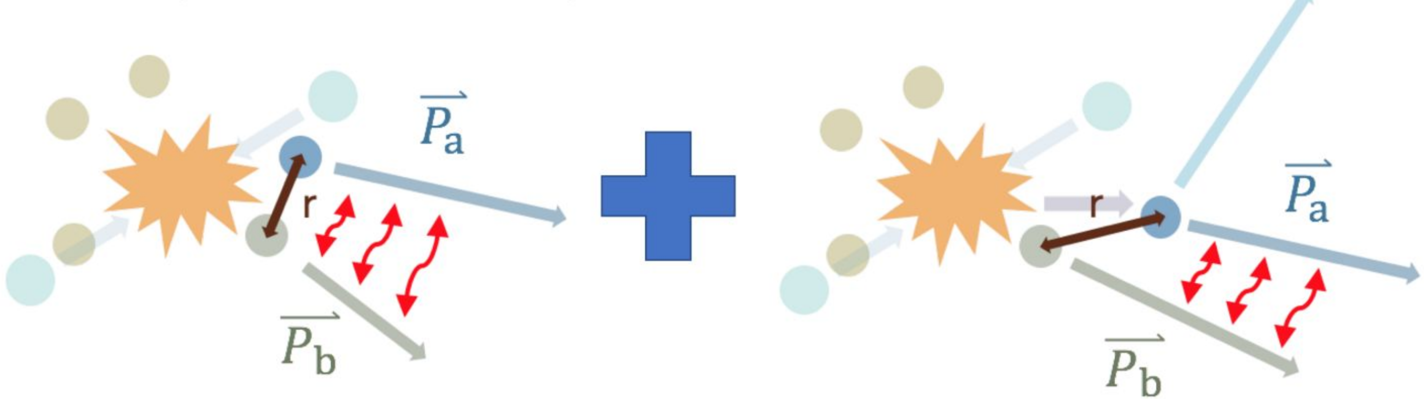
- Shared between particle pairs
- Scales as a function of m_T

Exponential resonance tail

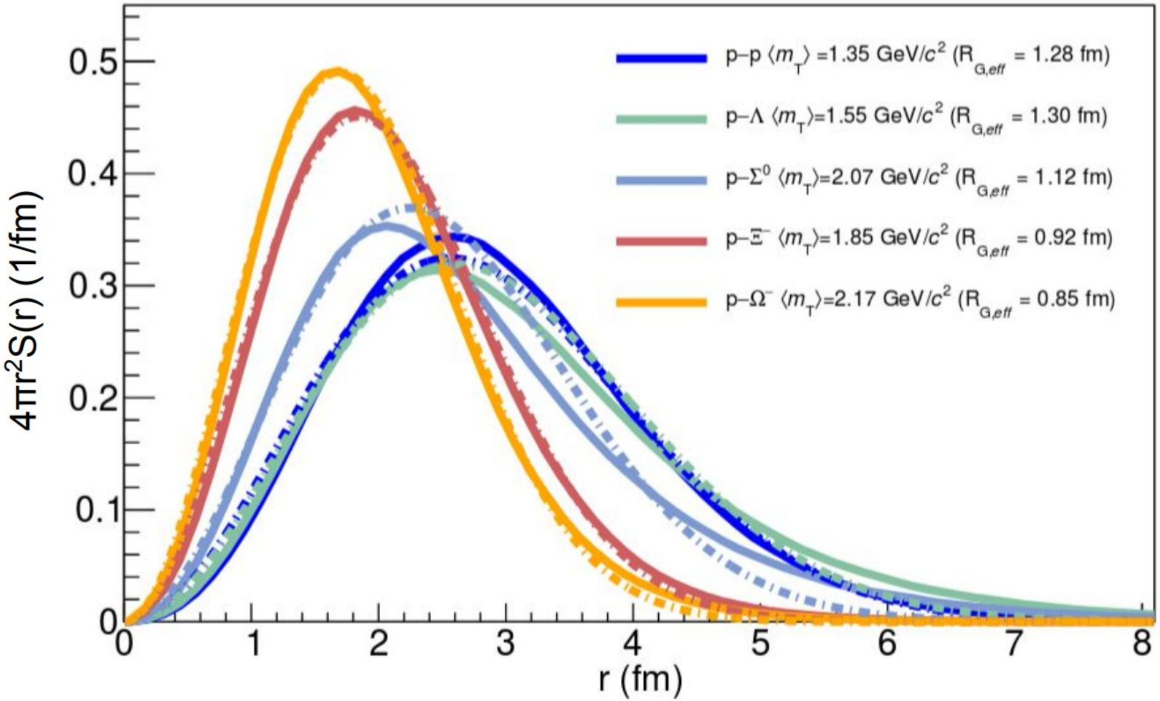
$$E(r, M_{res}, \tau_{res}, p_{res}) = \frac{1}{s}\exp(-\frac{r}{s})$$

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

- Specific modulation of each pair



Gaussian core + resonances



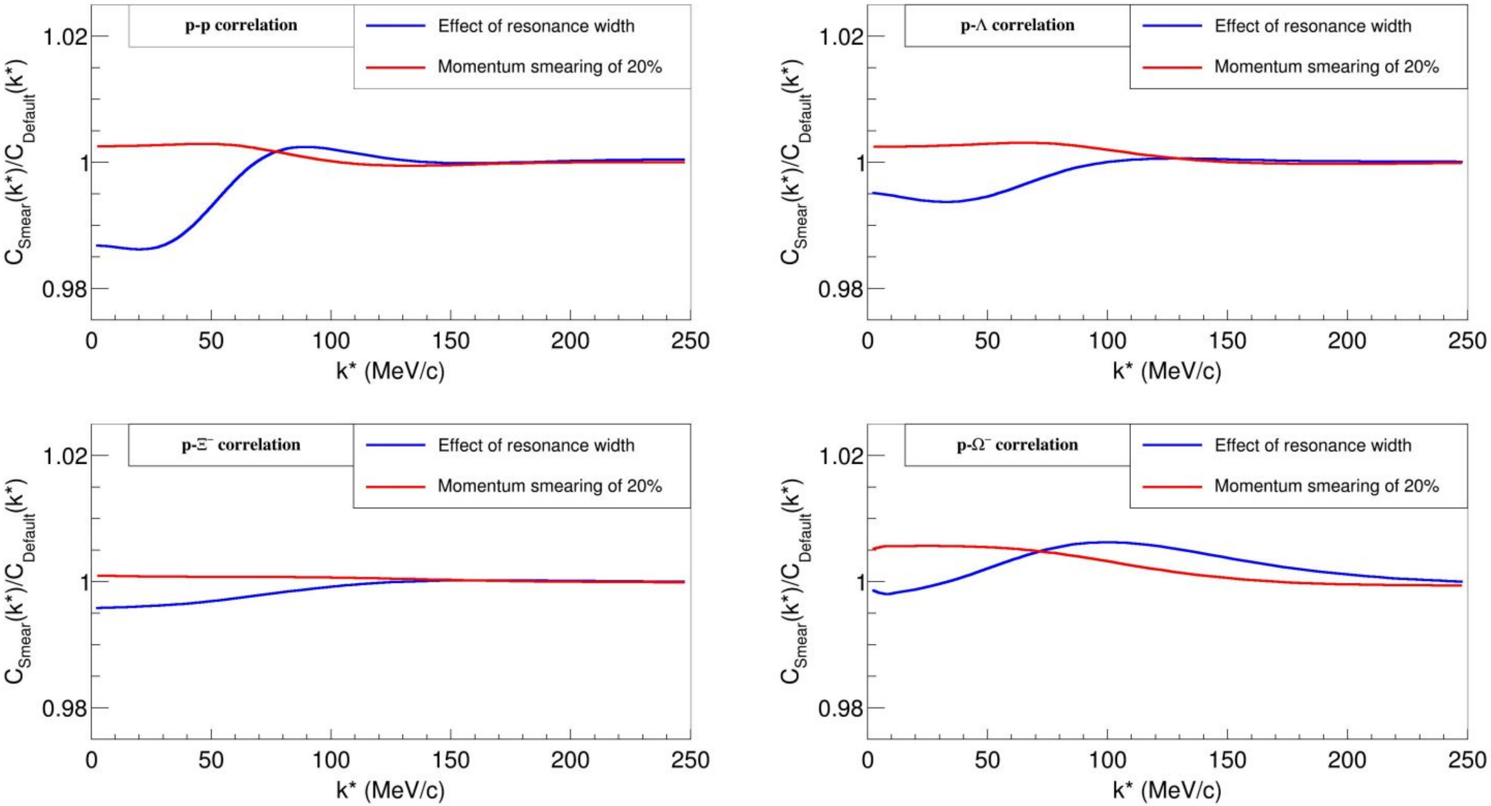
Solid line: Source distribution including the effect of resonances

Dashed line: Fit with an effective Gaussian

- Direct fit of the p-p correlation function yields similar radius

- Resonance contribution to Omega yield negligible.
- Modification of the gaussian core for p-Omega pairs coming only from resonances contribution to the proton yield

Effect on the source when smearing resonances

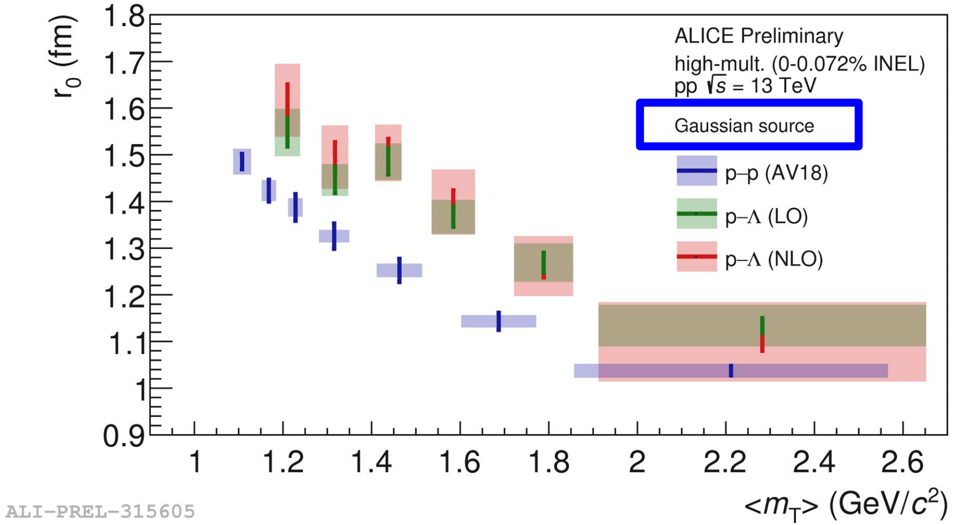


Setting the **source**

Ansatz: in small collision systems the source is similar for all baryon-baryon, baryon-meson pairs

The characteristics of the source are **determined from femtoscopic analysis of the p-p correlation**:
Assume a p-p known interaction → determination of the source size

- **Consider <m_T> dependence of the source due to collective effects:**
  - Femtoscopic p-p fits performed differentially in <m_T> bins
  - <m_T> dependence cross-checked with p-Λ analysis
- **Effect of strong short-lived resonances** computed for all hadrons



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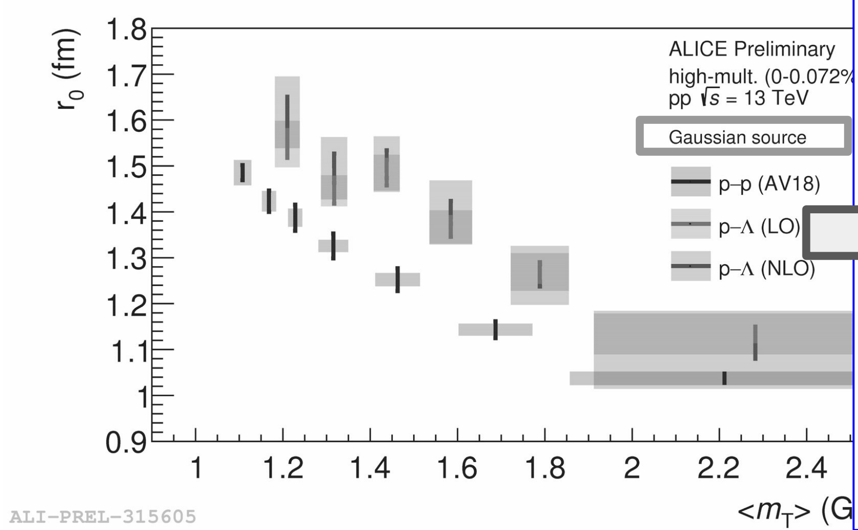
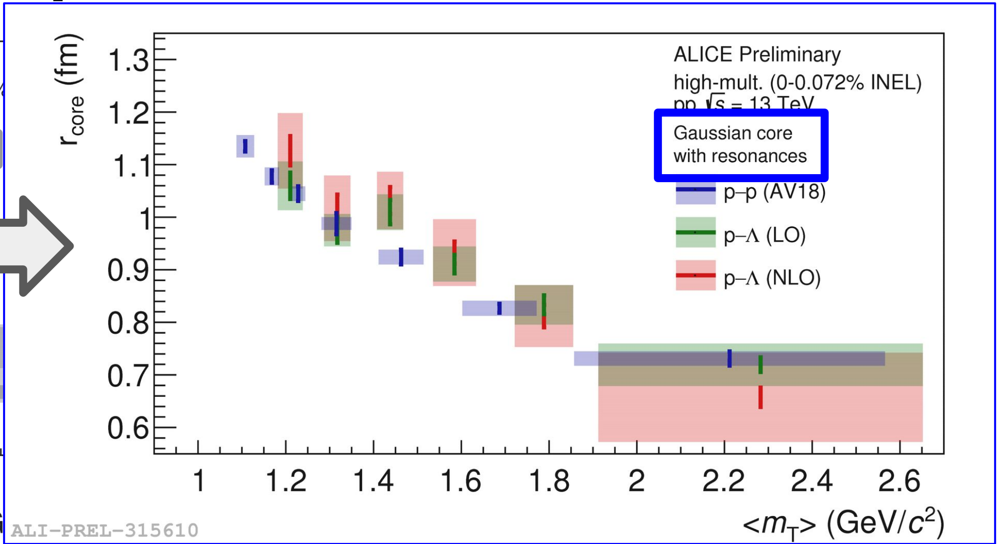
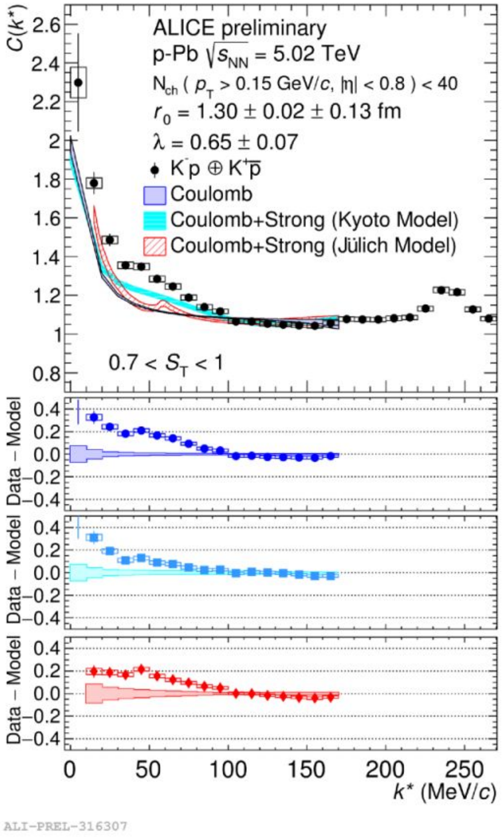


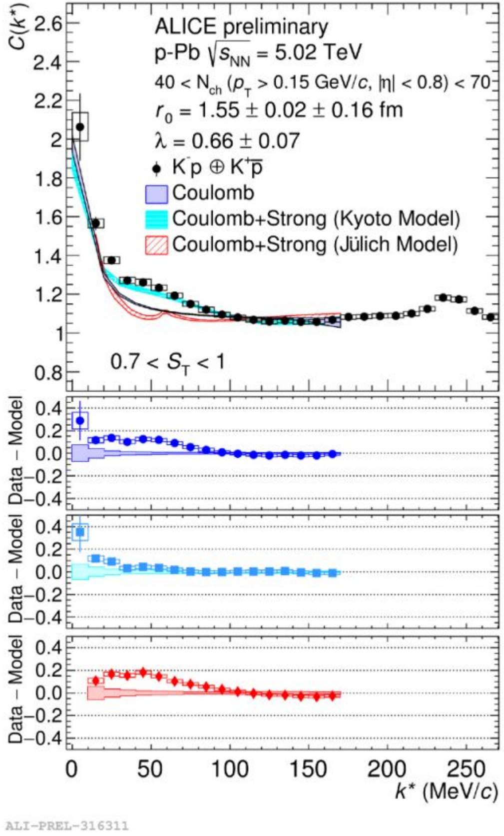


K-p femtoscopy in p-Pb collisions

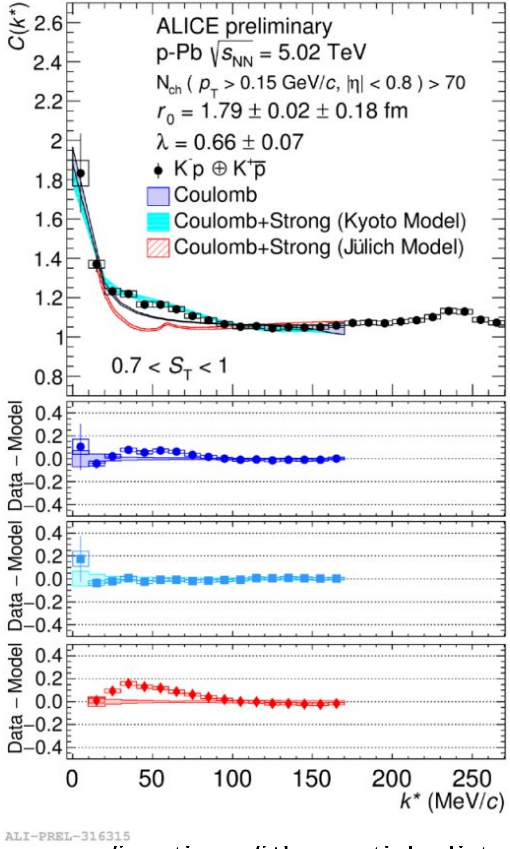
m<40



40<m<70



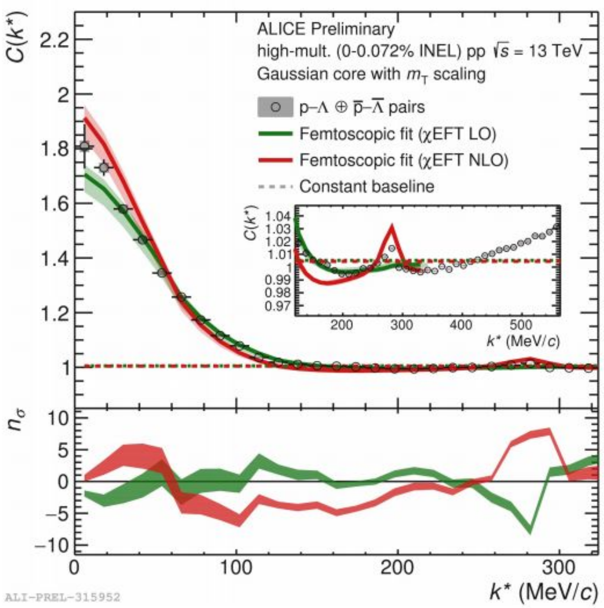
m>70



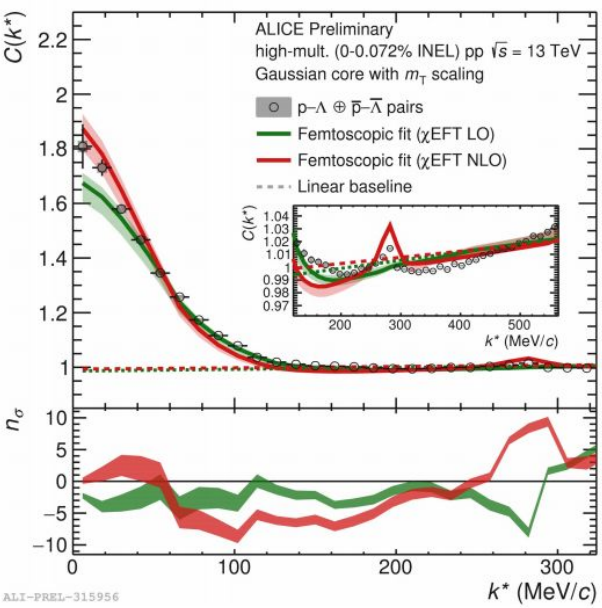
→ Analysis in p-Pb 5.02TeV as a function of charged multiplicity: Interaction changes as a function of the particle distance

p- Correlation function: baseline

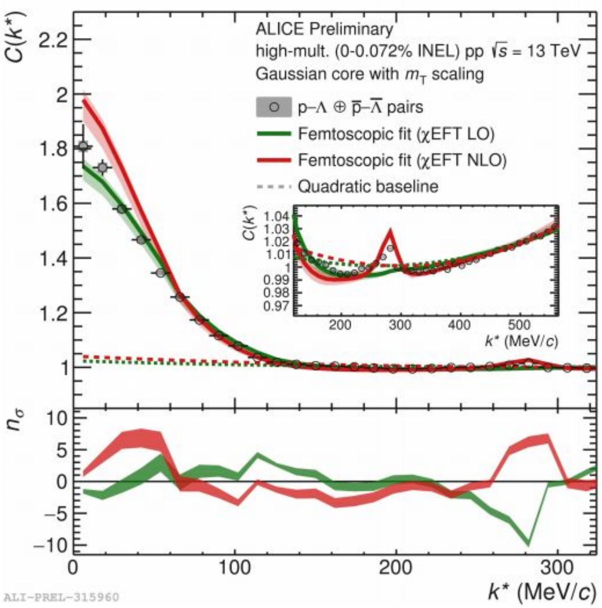
Constant baseline



Linear baseline



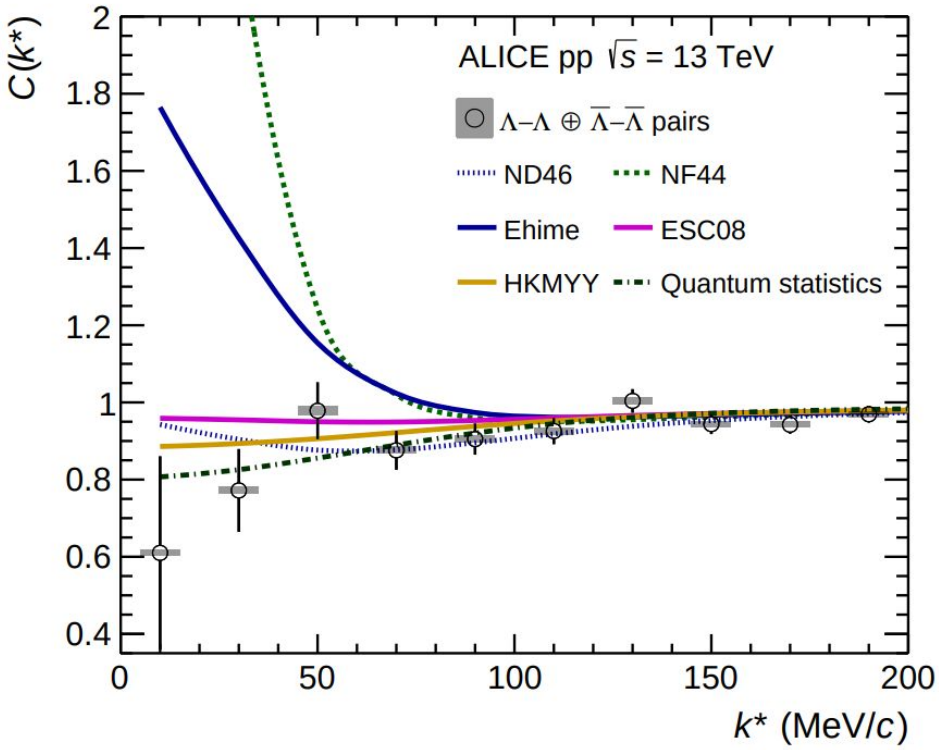
Quadratic baseline

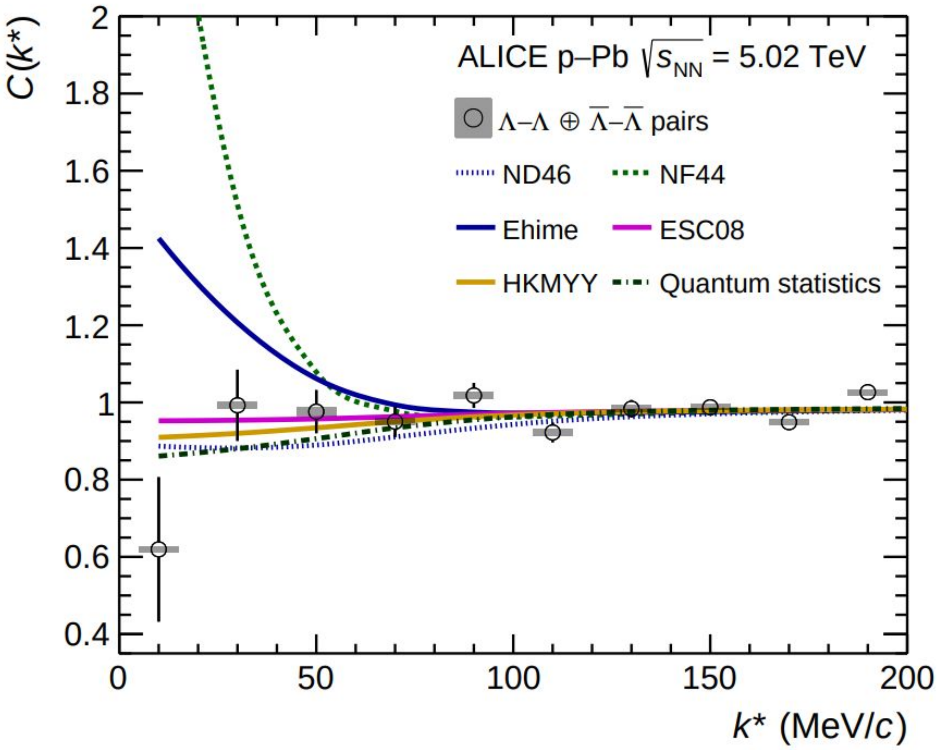


Best fit for LO: nσ>8

Best fit for NLO: nσ>10

Λ-Λ analysis


ALICE pp $\sqrt{s}$ = 13 TeV
Λ–Λ ⊕ $\overline{\Lambda}$–$\overline{\Lambda}$ pairs
ND46
NF44
Ehime
ESC08
HKMYY
Quantum statistics
C(k*)
k* (MeV/c)


ALICE p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Λ–Λ ⊕ $\overline{\Lambda}$–$\overline{\Lambda}$ pairs
ND46
NF44
Ehime
ESC08
HKMYY
Quantum statistics
C(k*)
k* (MeV/c)

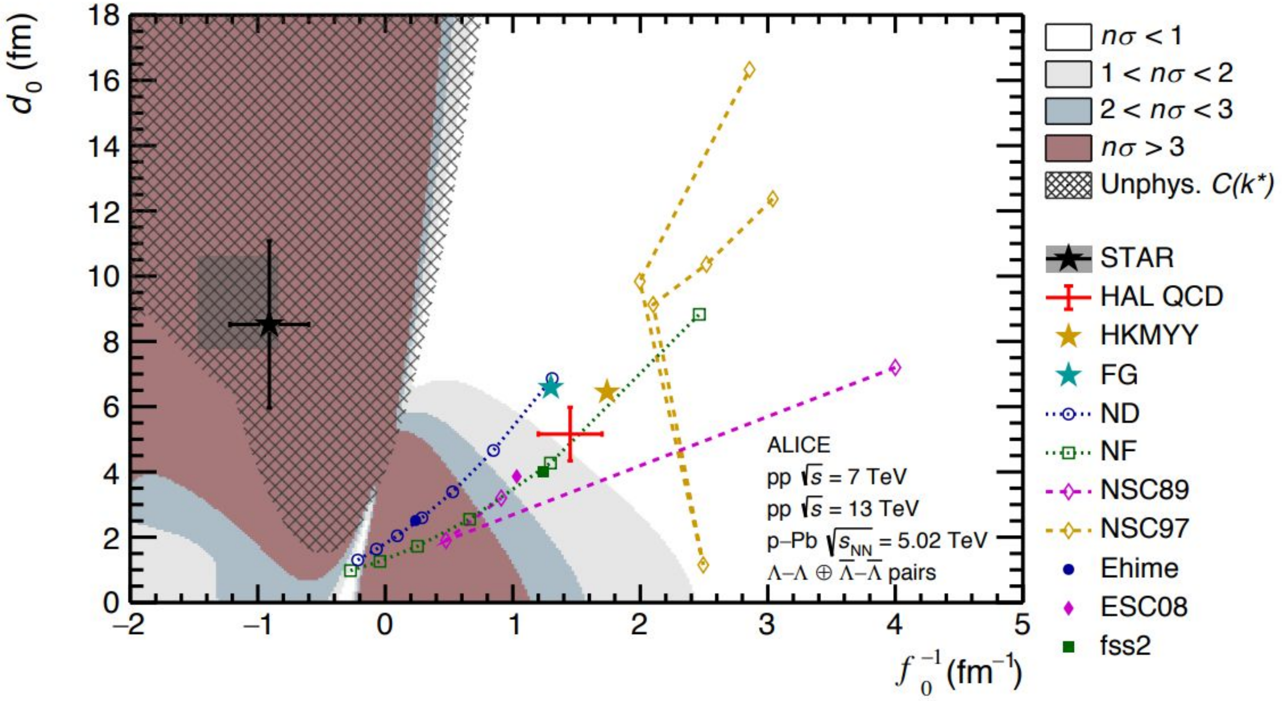
Λ-Λ analysis: Exclusion plot

Combination of all analyzed datasets

- pp 7 & 13 TeV
- p-Pb 5.02 TeV

Test of the agreement between data and the prediction by the Lednicky model in number of sigmas

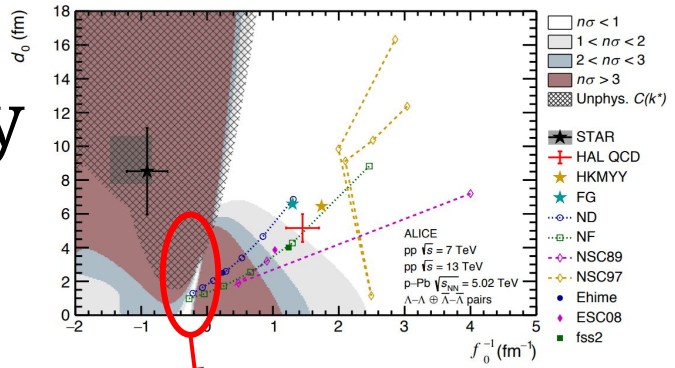
- Under the hypothesis of a common Gaussian source
- Small source size limits the prediction power of the Lednicky model

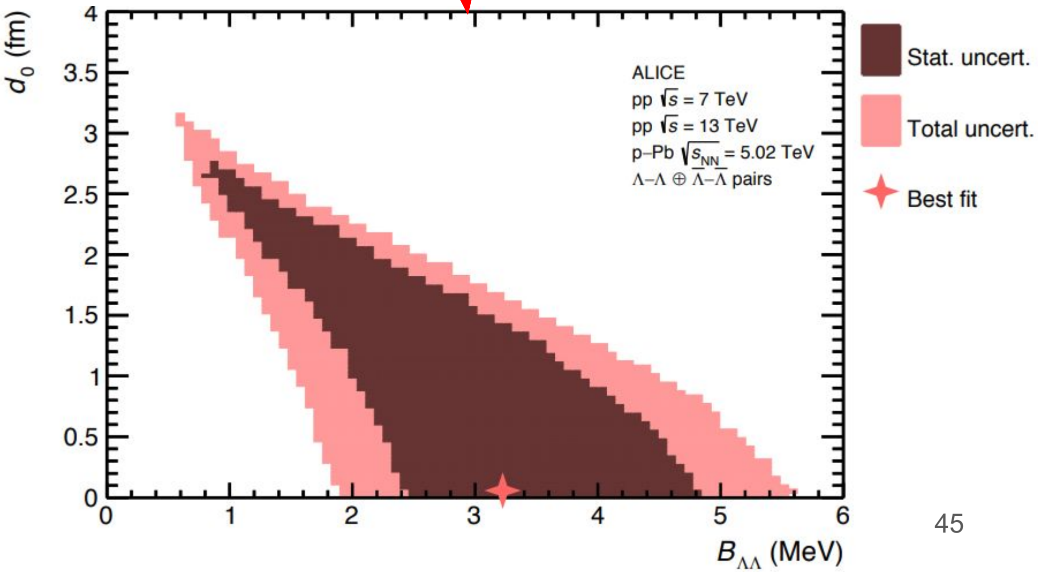


Λ-Λ analysis: Upper limit for the H-Dibaryon binding energy

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

S. Gonbgyo et al., PRL 120(2018) 212001
P. Naidon and S. Endo, Rept. Prog. Phys. 80 (2017) 056001





- H-Dibaryon: Tight constraints on the allowed binding energy:

$$B_{\Lambda-\Lambda} = 3.2^{+1.6}_{-2.4}\ (\text{stat.})^{+1.8}_{-1.0}\ (\text{syst.})\ \text{MeV}$$

- More stringent than previous measurements

- For more details see arXiv:1905.07209

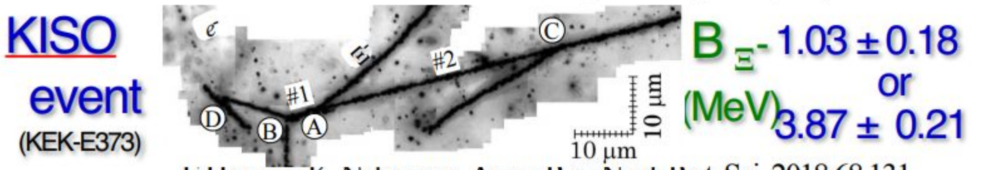
Kiso Event

Implies an attractive interaction

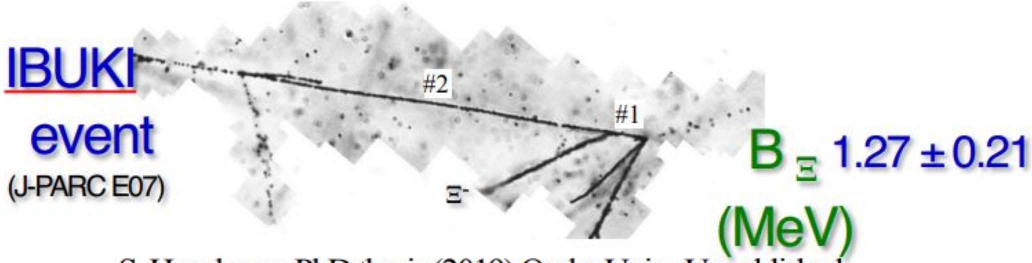
Deeply bound Ξ^--^{14}N systems

0.174 MeV:3D atomic state

Prog. Theor. Phys. 105 (2001) 627.



E.Hiyama, K. Nakazawa, Annu. Rev. Nucl. Part. Sci. 2018.68.131



S. Hayakawa, PhD thesis (2019) Osaka Univ., Unpublished

p-Ξ^- potential in pure neutron matter

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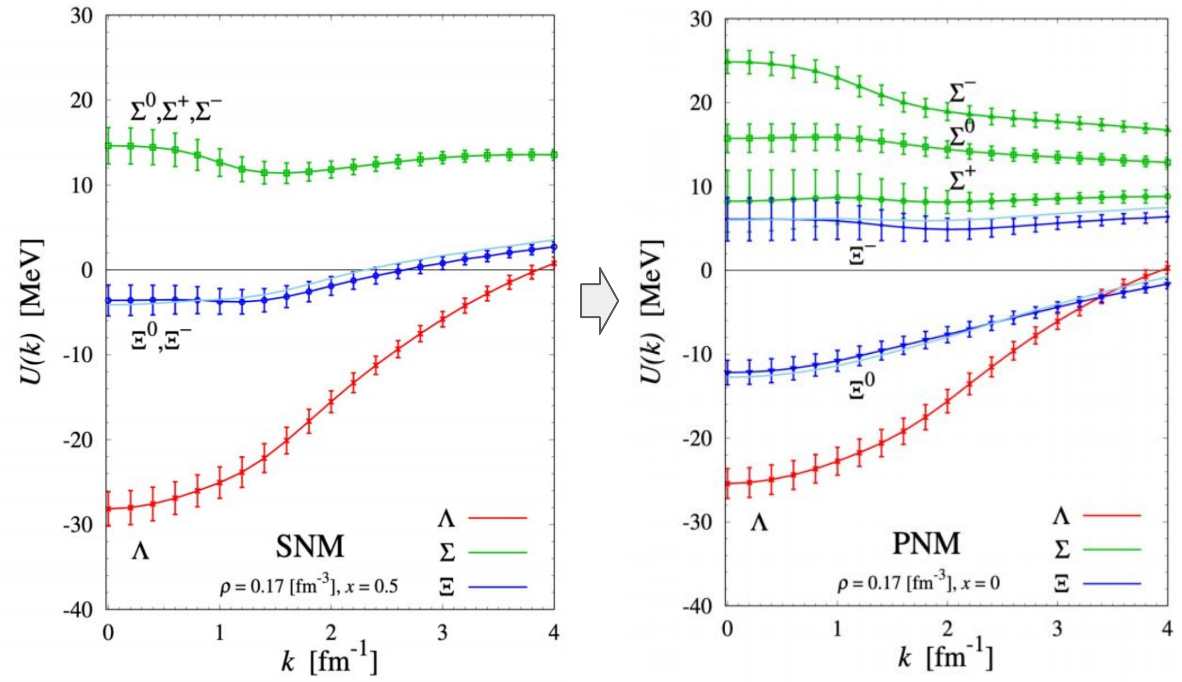

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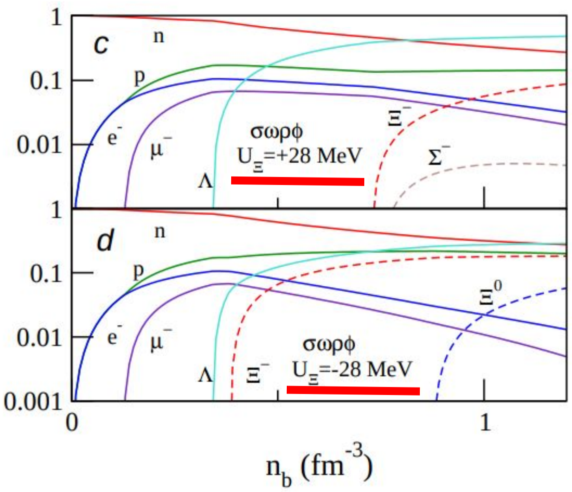
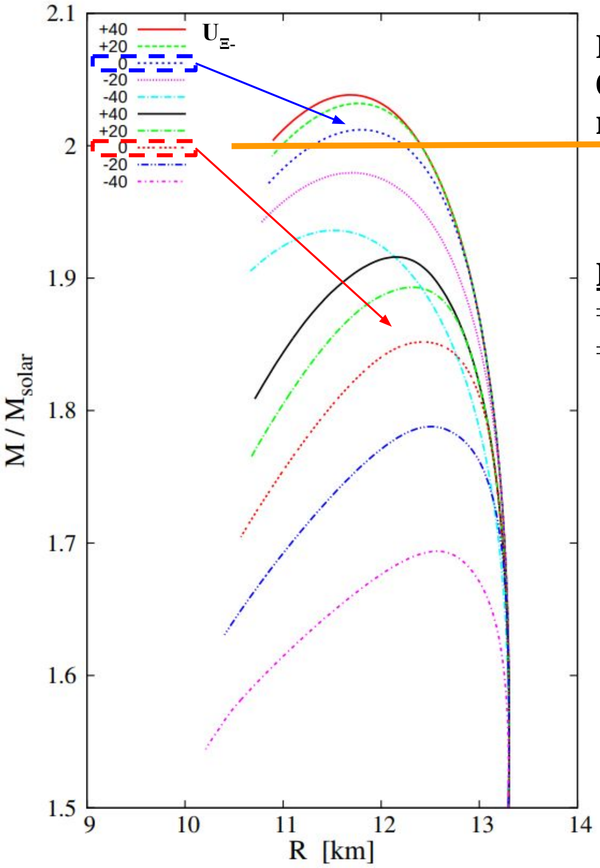
- RMF models: Equation Of State (EoS) of neutron-rich matter with hyperon content

→ use single particle potential at saturation densities as input





Experimental constraint: Observation of ~2 solar masses NS

<u>Repulsive interaction:</u>
⇒ Ξ pushed to high densities
⇒ **stiffer EoS**, higher masses

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

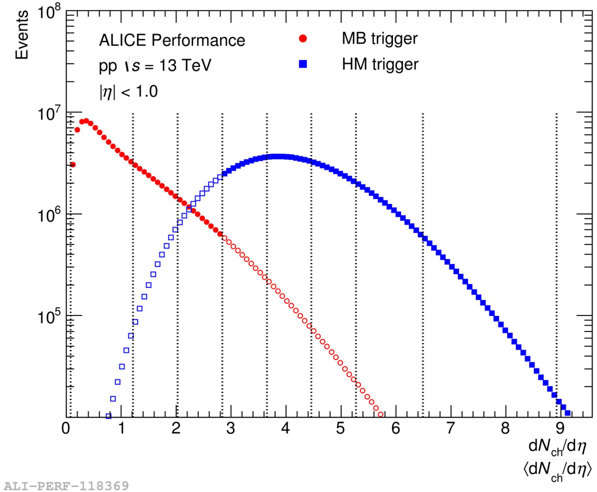
p-Ξ: Future challenges

- For the future: Study correlation function of the excited $\Xi^0(1530)$ state
- $\Xi^0(1530) \rightarrow \Xi^- + \pi^+$
- I = 1 & S = 1 + 2

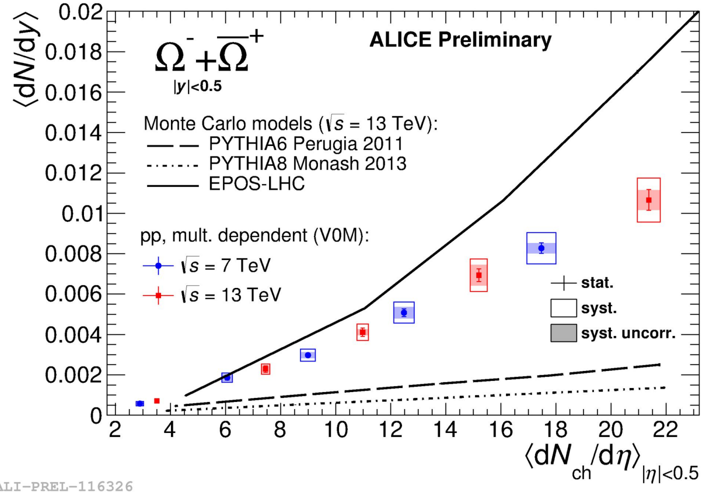
	I = 0	I = 1	Detectable
n-Ξ^-	✗	✓	No
p-Ξ^0	✗	✓	Difficult
p-Ξ^-	✓	✓	Yes
p-Ξ^+	✓	✗	Difficult

ALICE pp High Multiplicity data

- Analyzed 10^9 events data of ALICE Run2 (2016, 2017, 2018), pp collisions at $\sqrt{s}$ = 13 TeV
- **High multiplicity trigger**: 0.1% highest multiplicity with respect to Minimum Bias events (V0M, forward rapidities: $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$).
  - Increased yield of Ω baryon



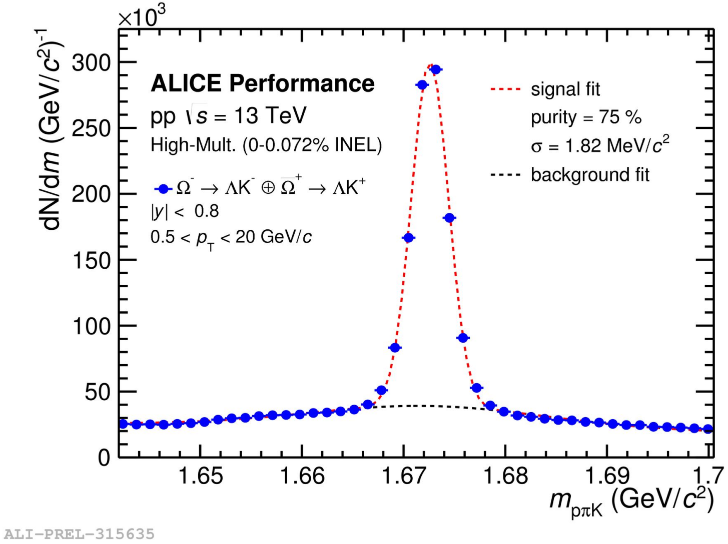
ALI-PERF-118369



ALI-PREL-116326

Selection of Ω^- candidates

- Identified by its decay: $\Omega^- \rightarrow \Lambda K^- \rightarrow (p\pi^-)K^-$
- Total of 1.2×10^6 selected (Ω^-+Ω^+) candidates
- **Purity** of the sample = **75%**
- Sidebands analysis delivers the shape of the background correlation function



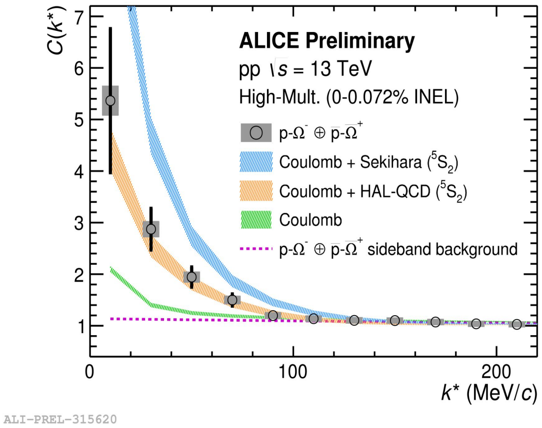
p-Ω^-: comparison with models

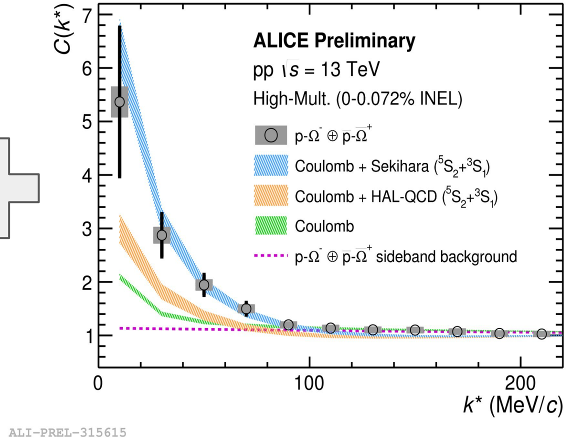
Assume two different (~extreme) scenarios for the computation of the $^3S_1$ channel:

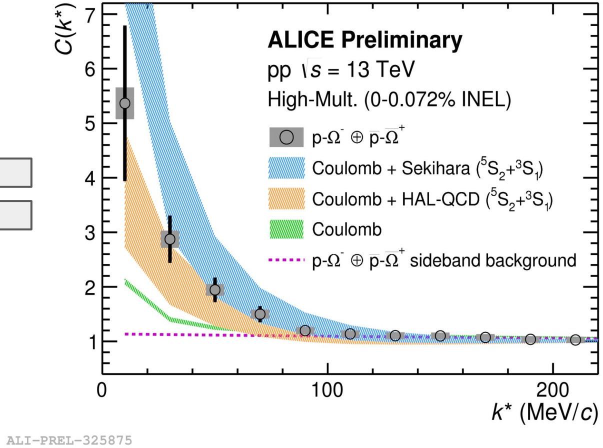
1.- Complete absorption in the $^3S_1$ channel (à la Morita et al.) **with updated r_0**

- r_0 choosen from the condition $|V_{I,II,III}| < |V_{Coulomb}|$ for $r > r_0$
- Using the same condition with latest HAL-QCD potential may result in a substantially increased value for r_0 → negligible

2.- Complete elastic model for $^3S_1$ with a "similar" attraction **as $^5S_2$**

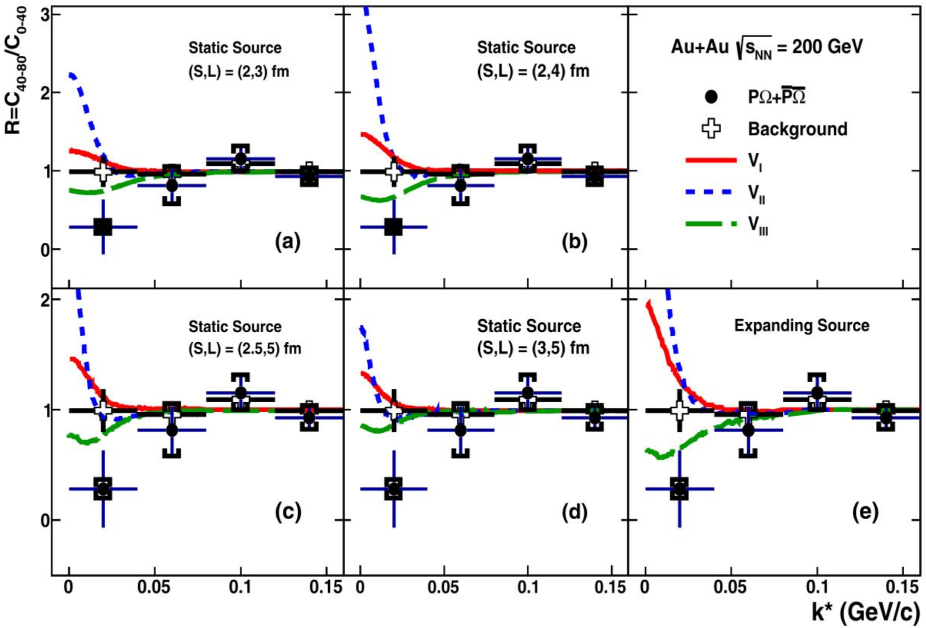






Previously available experimental data: STAR

- Study of the p-Ω^- correlation function in Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV STAR Collaboration. Phys. Lett. B790 (2019) 490-497
- Observable: ratio of the correlation function peripheral/central collisions.
- Comparison with Lattice QCD calculations (with large masses)



- Test different fits to Lattice QCD data (delivering **three different binding energies of the NΩ**):

Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
$\mathbf{E_b}$ (MeV)	–	6.3	26.9
$\mathbf{a_0}$ (fm)	−1.12	5.79	1.29
$\mathbf{r_{eff}}$ (fm)	1.16	0.96	0.65

[24] K. Morita, A. Ohnishi, F. Etminan, T. Hatsuda, Phys. Rev. C 94 (2016), 031901

STAR data favor V_{III}, with $\mathbf{E_b}$ **= 27 MeV**

Lattice HAL-QCD potential with heavy quarks

- Based on Lattice calculations with heavy quark masses F. Etminan et al.(HAL QCD Collaboration),Nucl. Phys. A928,89(2014)
  - m_π = 875 MeV/c^2
  - m_K = 916 MeV/c^2
- Used in the STAR pΩ analysis in Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV
- Lattice calculations fitted by an attractive Gaussian core + an attractive tail, varying the range parameter at long distance (b_5)
  - $\mathbf{V_{II}}$: best fit to Lattice calculations
  - $\mathbf{V_I}$ / $\mathbf{V_{III}}$: weaker / stronger attraction

$$V(r) = b_1 e^{-b_2 r^2} + b_3(1 - e^{-b_4 r^2})(e^{-b_5 r}/r)^2$$

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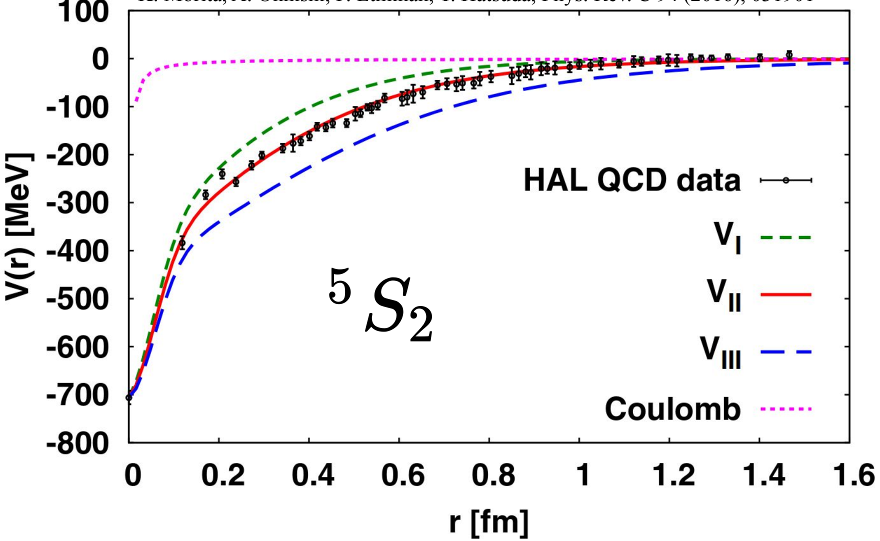

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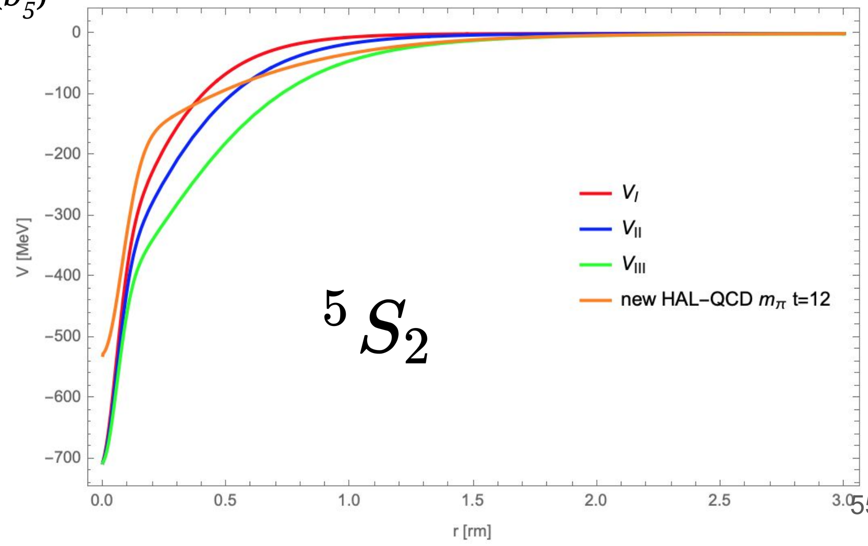
- Lattice calculations fitted by an attractive Gaussian core + an attractive tail, varying the range parameter at long distance (b_5)
  - $\mathbf{V_{II}}$: best fit to Lattice calculations
  - $\mathbf{V_I}$ / $\mathbf{V_{III}}$: weaker / stronger attraction

$$V(r) = b_1 e^{-b_2 r^2} + b_3(1 - e^{-b_4 r^2})(e^{-b_5 r}/r)^2$$

Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

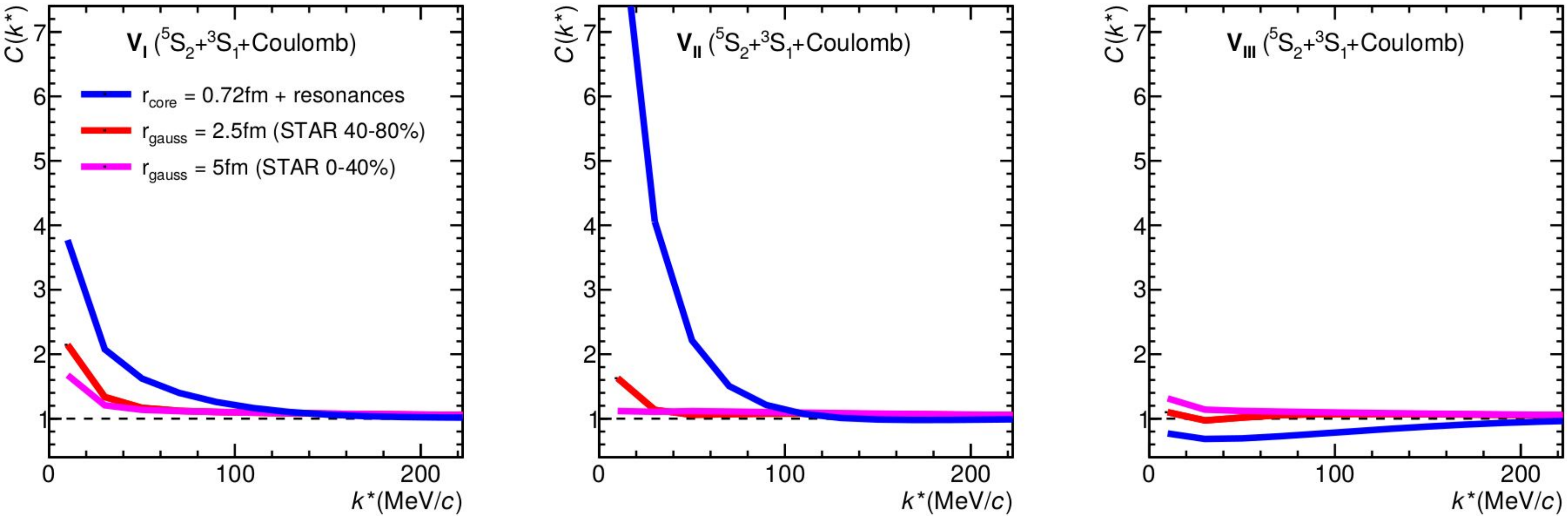
Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
$\mathbf{E_b}$ (MeV)	–	6.3	26.9
$\mathbf{a_0}$ (fm)	−1.12	5.79	1.29
$\mathbf{r_{eff}}$ (fm)	1.16	0.96	0.65



Sensitivity of ALICE and STAR data

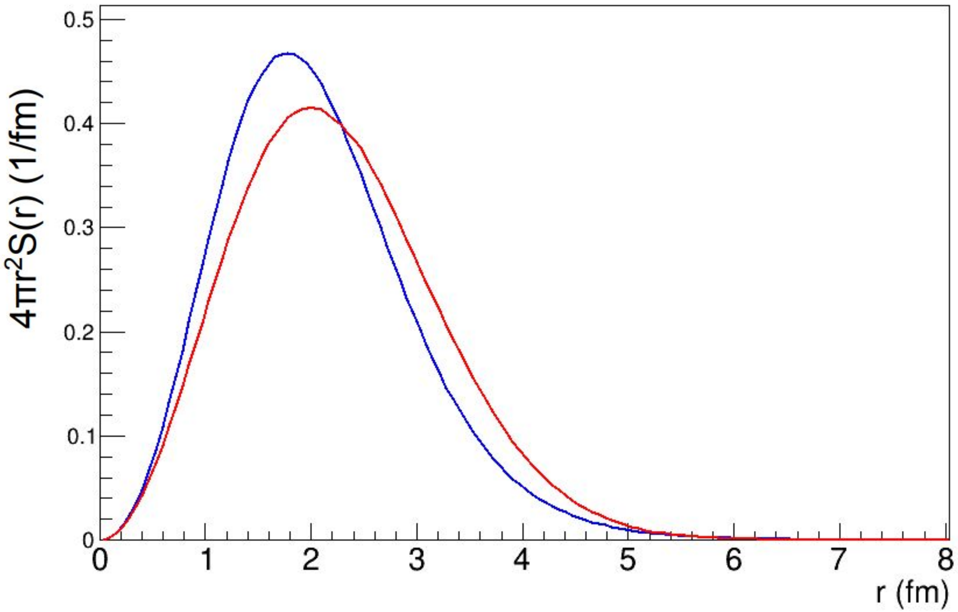
- Expected correlation function from heavy quark Lattice QCD potentials
- **Smaller radius** source offers the ideal conditions to test the models
- **Better purity** of ALICE data increases the **sensitivity** of the test

purity 75% (ALICE)

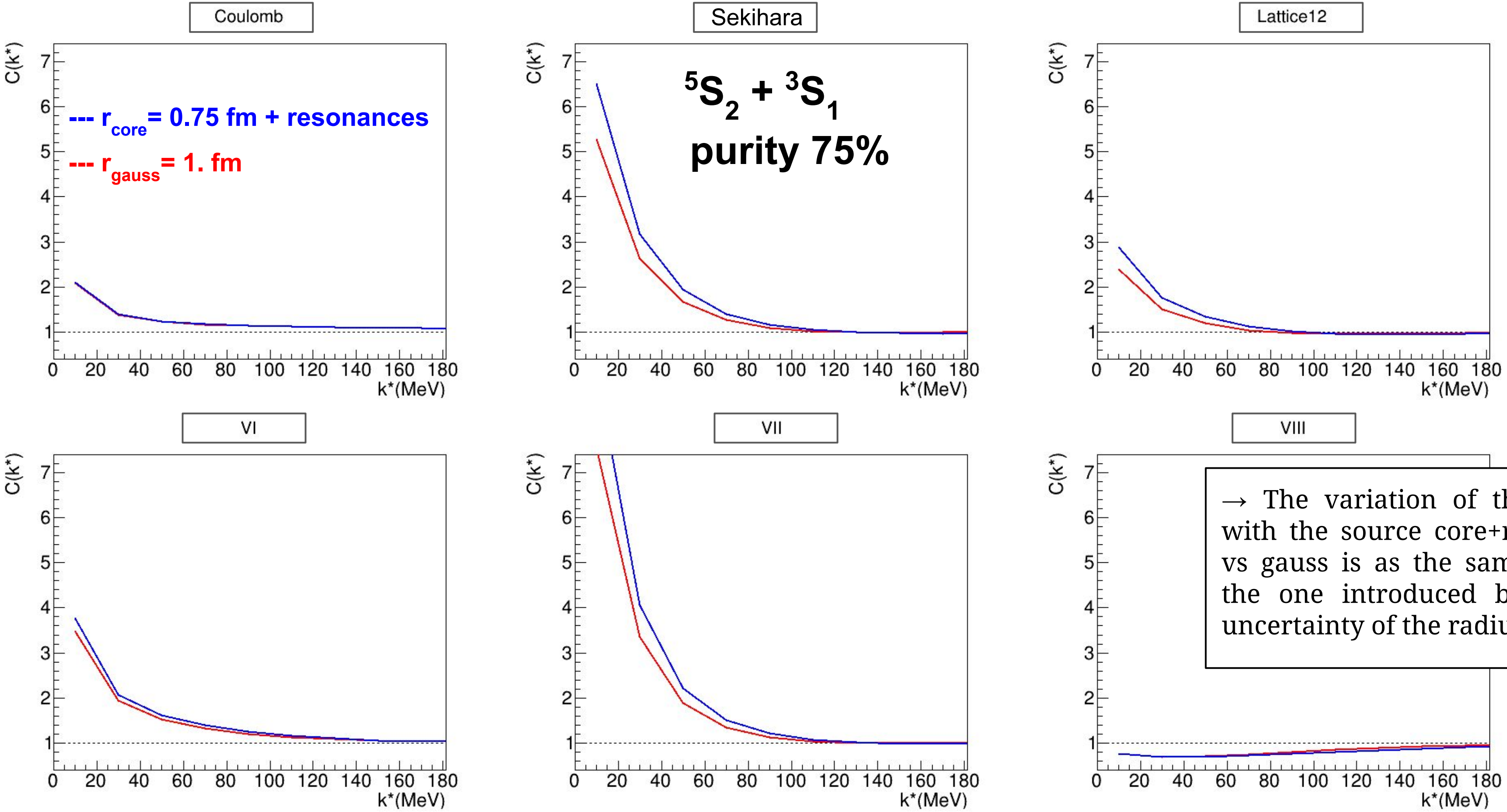


p-Ω^- Correlation function: source dependence

- Comparison of the C(k*) for the different models for different source assumptions
- Size of the source determined from p-p fitted radius vs <m_T>
  - core gaussian source + resonances effects
  - pure gaussian source



p-Ω⁻ Correlation function: source dependence



→ The variation of the models with the source core+resonances vs gauss is as the same level as the one introduced by the the uncertainty of the radius size

p-Ω^- Correlation function ($^5S_2$) with distance cutoff

- Correlation function from $^5S_2$ channel with cutoff in r (for $r < r_{cutoff} \Rightarrow V = 0$)
- **HAL-QCD with physical quark masses (t=12): maximum of the $C(k^*)$ for $r_{cutoff} = 0.5$ fm**