First experimental test of HAL QCD lattice calculations for the multi strange hyperon-nucleon interaction with ALICE

Dimitar Mihaylov
for the ALICE collaboration
at QM 2019
6th November 2019, Wuhan, China

The goal

Study the **interaction** between a **proton** and **multi-strange baryons** Ξ^-(ssd) Ω^-(sss)
A fundamental problem in hadron physics (e.g. relevant for the nuclear equation of state)

The theory

- **Lattice QCD potentials** (HAL-QCD Collaboration)
  - *p-Ξ^-: predicted attractive interaction*
    → Consequences for the possible appearance in neutron stars
  - *p-Ω^-: predicted very attractive interaction*
    → Opens the door for a NΩ di-baryon

The experimental knowledge

- p-Ξ^-: hypernuclei (Kiso event) *K. Nazakawa et al. PTEP 2015, 033D02*
- p-Ω^-: Femtoscopy by STAR in Au-Au collisions *STAR Collaboration. Phys. Lett. B790 (2019) 490-497*

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

V0A and T0A   **ITS**

V0C and T0C

TOF   **TPC**
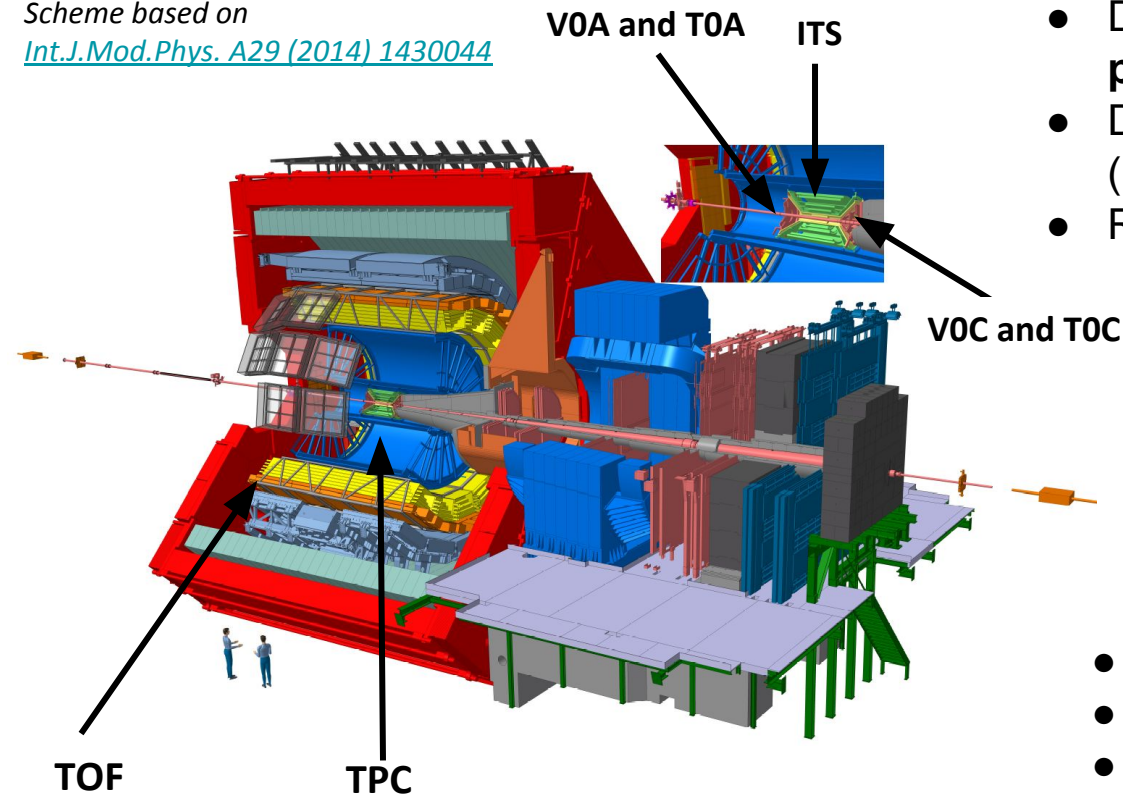
- Data set:
  pp 13 TeV (1000 M **high multipl. events**)
- Direct detection of charged particles (protons, kaons, pions)
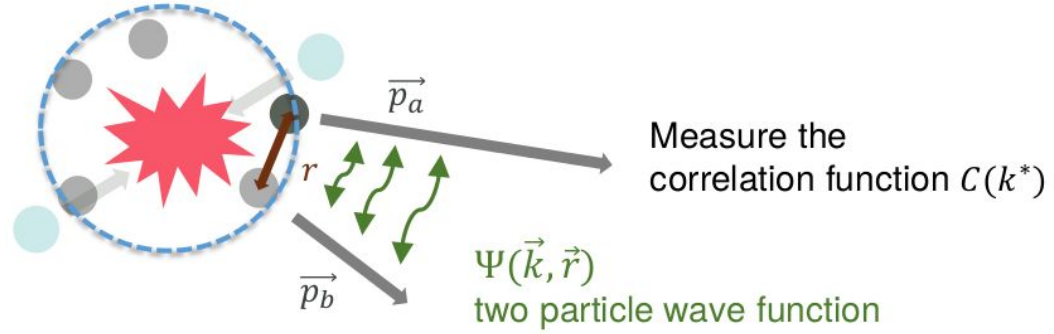- Reconstruction of hyperons:
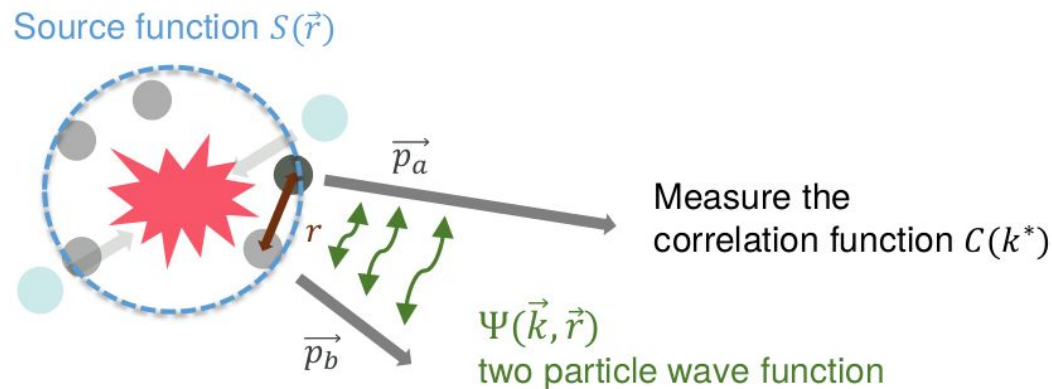
$$\Xi^- \to \Lambda \pi^- \to p \pi^- \pi^-$$
$$\Omega^- \to \Lambda K^- \to p \pi^- K^-$$

The very good PID capabilities of the detector result in very pure samples!

- The purity of the protons is > 99%
- The purity of Ξ^- is 92%
- The purity of Ω^- is 75%

3

Source function $S(\vec{r})$

$\overrightarrow{p_a}$

Measure the correlation function $C(k^*)$

r

$\Psi(\vec{k}, \vec{r})$
two particle wave function

$\overrightarrow{p_b}$

Femtoscopy
Overview

Source function $S(\vec{r})$

Measure the correlation function $C(k^*)$

$\Psi(\vec{k}, \vec{r})$
two particle wave function

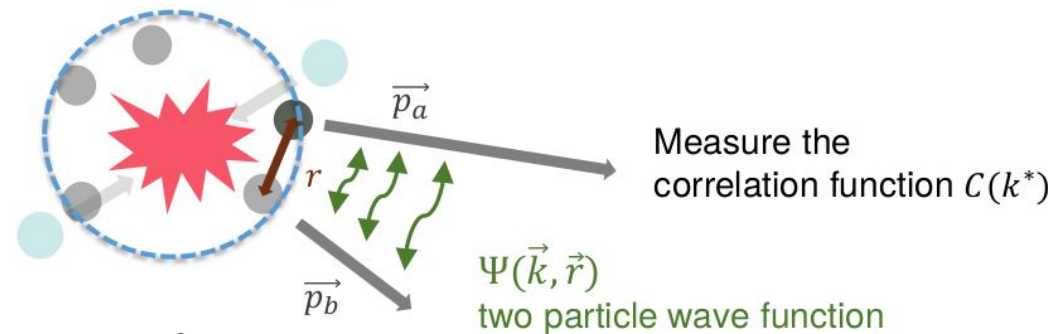**_Statistical definition_** **_Experimental definition_** **_Theoretical definition_**

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

Single-particle momenta

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

- Modelling/fitting performed using CATS
  Eur.Phys.J. C78 (2018) no.5, 394

Source function $S(\vec{r})$

$\vec{p_a}$

Measure the correlation function $C(k^*)$

$\Psi(\vec{k}, \vec{r})$
two particle wave function

$\vec{p_b}$

Theoretical definition

**Small collision systems (pp) probe the "inner" part of the interaction.
Assumption: The source is similar for all produced baryons.**

Further details in the talk of Prof. Laura Fabbietti

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

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

- Modelling/fitting performed using CATS
  Eur.Phys.J. C78 (2018) no.5, 394

6
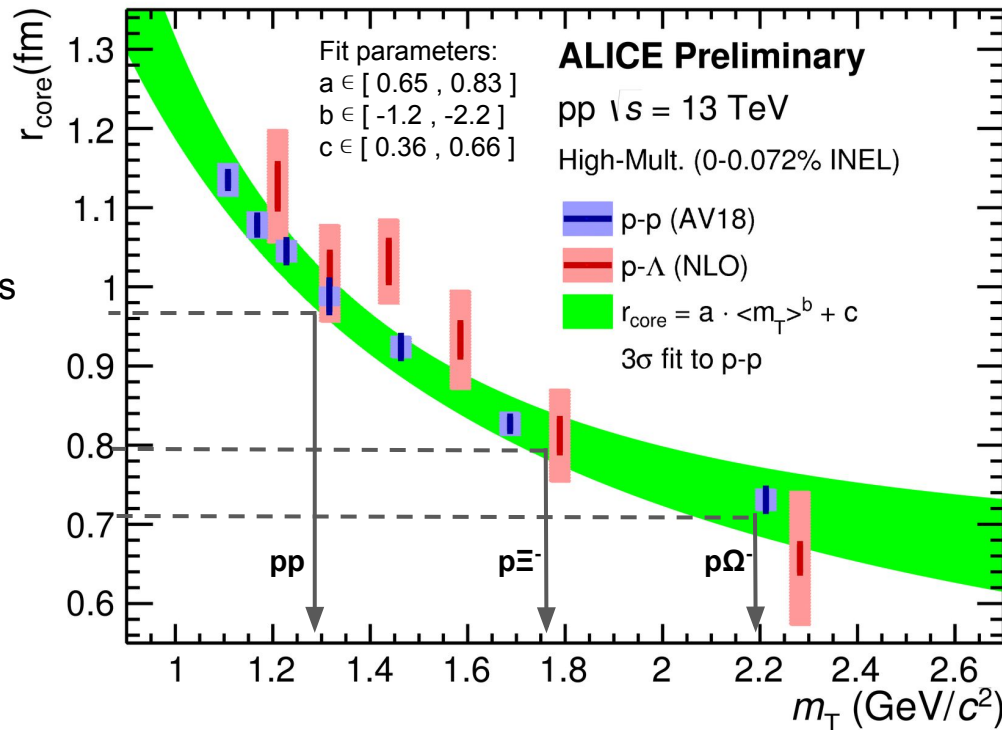
- The effects of **short-lived resonances** are modeled by assuming a **"core" Gaussian** source, from which resonances and primordial particles are emitted.

- The resonances are added to the "core"

- Fix the value of r_{core} of each particle species based on their $<m_T>$

p-Ξ^- : r_{core} = 0.80 ± 0.03 fm
r_{eff} = 0.92 fm (Gaussian)

p-Ω^- : r_{core} = 0.73 ± 0.05 fm
r_{eff} = 0.85 fm (Gaussian)

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

ALICE Preliminary

pp √s = 13 TeV

High-Mult. (0-0.072% INEL)

p-p (AV18)

p-Λ (NLO)

r_{core} = a · $<m_T>^b$ + c

3σ fit to p-p

ALI-PREL-315640

N-Ξ⁻ interaction

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

N-Ξ⁻ interaction

	I=0	I=1	Detectable
n-Ξ⁻	✘	✓	No
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p-Ξ⁻	✓	✓	Yes

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p-Ξ⁻	✓	✓	Yes

HAL-QCD: AIP Conf.Proc. 2130 (2019) no.1, 020002

- Null Hypothesis: Coulomb only
- HAL QCD Potential
- NEW: Potential by Nijmegen group
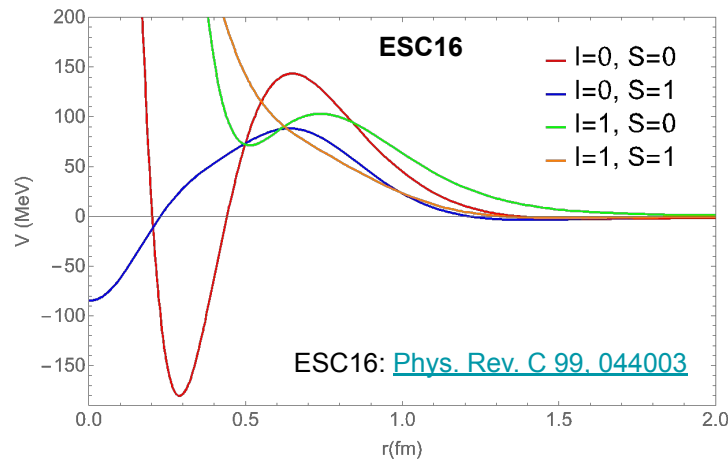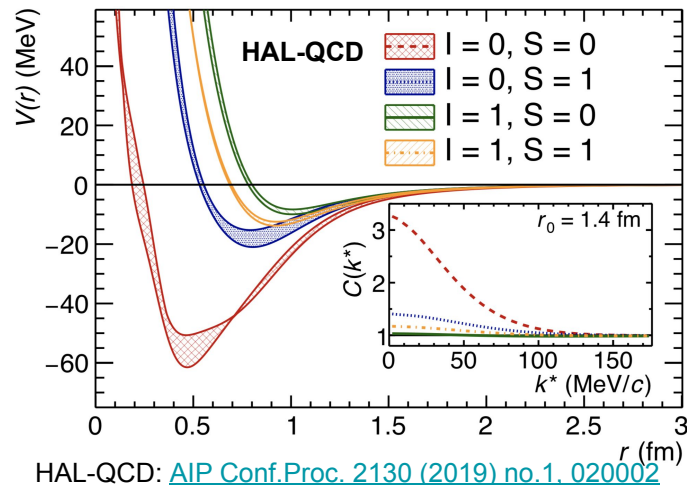
HAL-QCD
- I = 0, S = 0
- I = 0, S = 1
- I = 1, S = 0
- I = 1, S = 1

$r_0 = 1.4$ fm

ESC16
- I=0, S=0
- I=0, S=1
- I=1, S=0
- I=1, S=1

ESC16: Phys. Rev. C 99, 044003

Results for p-Ξ⁻

Published results for p-Pb collisions
Phys. Rev. Lett. 123, 112002 (2019)
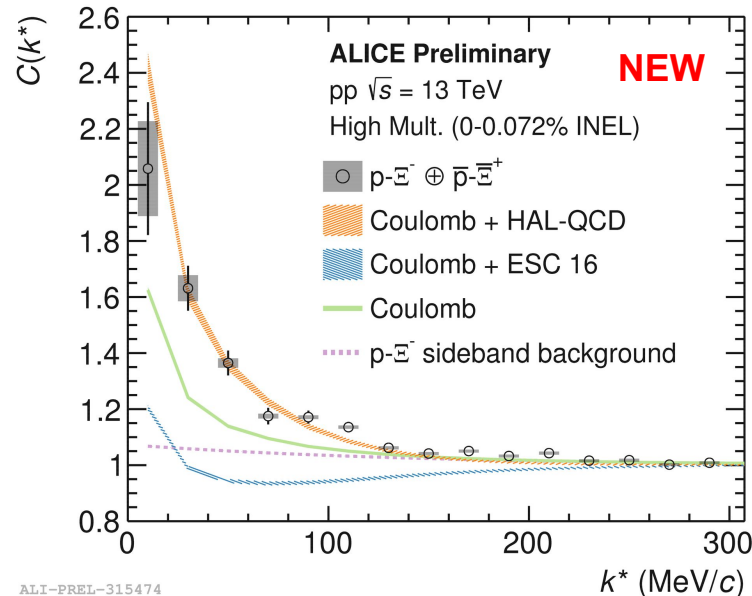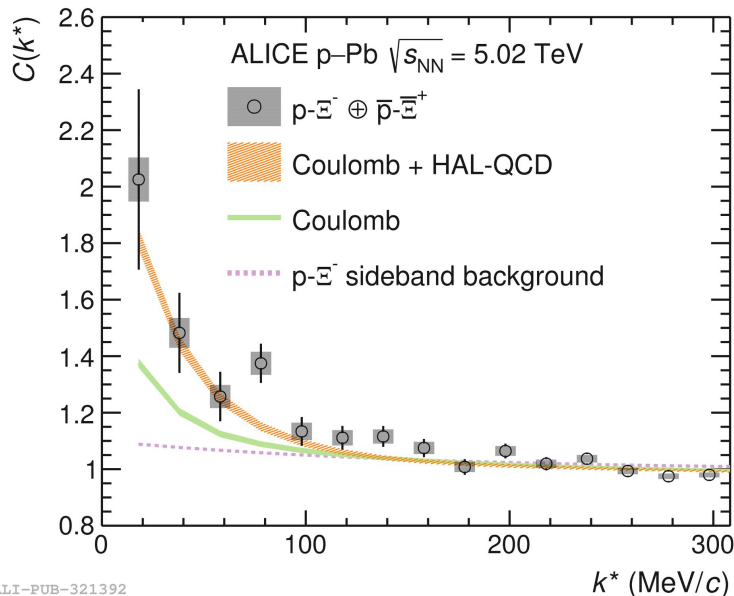"**First Observation of an Attractive Interaction between a Proton and a Cascade Baryon**"

ALI-PUB-321392

Results for p-Ξ⁻

Published results for p-Pb collisions
Phys. Rev. Lett. 123, 112002 (2019)
"**First Observation of an Attractive Interaction between a Proton and a Cascade Baryon**"

ALI-PUB-321392

ALI-PREL-315474
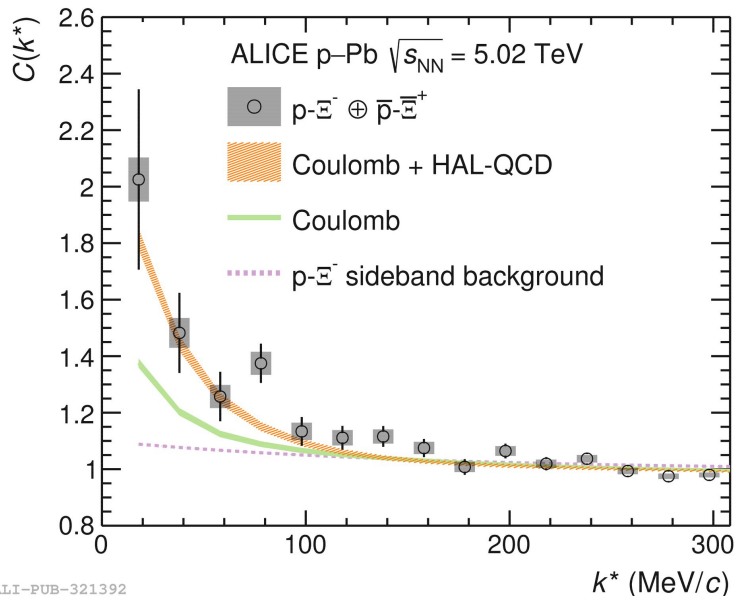
- An enhanced statistical significance of the **agreement with Lattice calculations**[*]
- The **ESC 16 is excluded** => important for hypernuclei studies
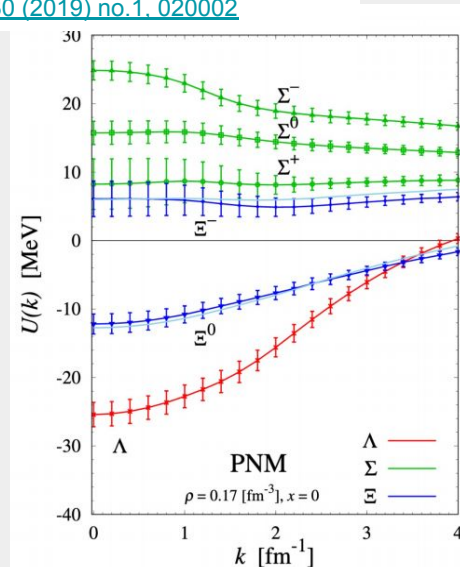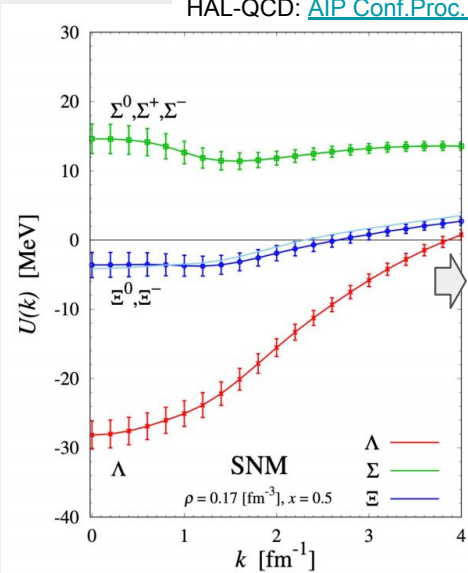
[*] Nucl.Phys. A967 (2017) 856-859

p-Ξ⁻ potential in pure neutron matter

HAL-QCD: AIP Conf.Proc. 2130 (2019) no.1, 020002

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

Lattice QCD:
Prediction for **repulsive $U_{Ξ^-}$ ~6 MeV in pure neutron matter**
=> **The existence of Ξ⁻ in neutron stars is disfavored.**

- An enhanced statistical significance of the **agreement with Lattice calculations**[*]
- The **ESC 16 is excluded** => important for hypernuclei studies

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*) Nucl.Phys. A967 (2017) 856-859

Models for the p-Ω⁻ interaction

- Lattice **HAL-QCD** potential with <u>physical quark masses</u> ($^5S_2$ channel) Phys.Lett. B792 (2019) 284-289
  - $m_\pi = 146$ MeV/c^2
  - $m_K = 525$ MeV/c^2

- **Sekihara:** <u>Meson-exchange model</u> ($^5S_2$ channel) T. Sekihara et al., Phys. Rev. C 98, 015205 (2018)
 - Short range attractive interaction fitted to previous HAL-QCD scattering parameters
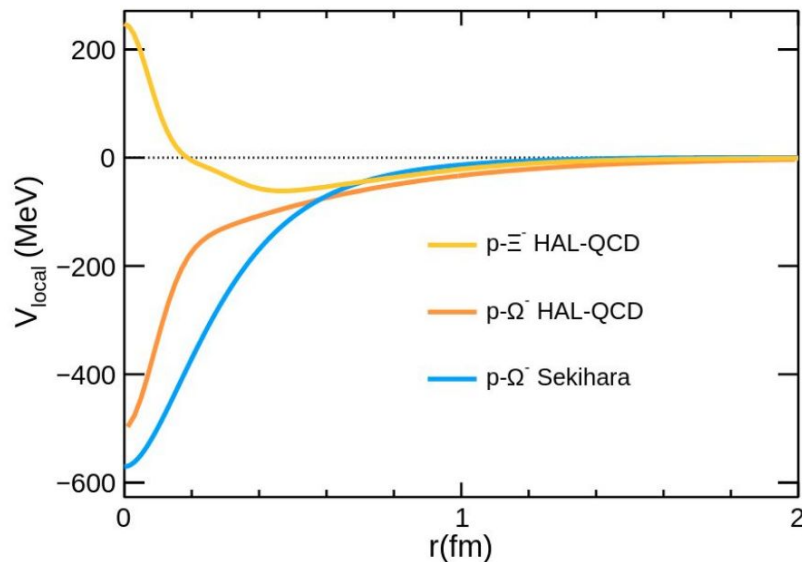
Model	pΩ⁻ binding energy (strong interaction only)
HAL-QCD	1.54 MeV
Sekihara	0.1 MeV

+1 MeV with Coulomb

→ Models provide so far only $^5S_2$ channel (weight ⅝)
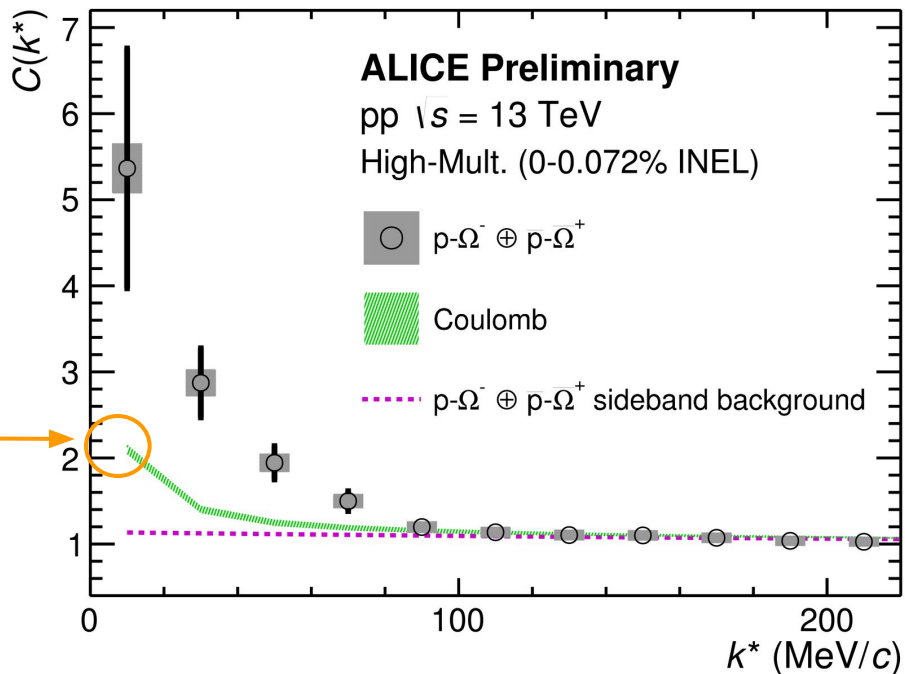
Results for p-Ω⁻

ALI-DER-337400

- "Coulomb only" scenario discarded by ALICE data (> 6 σ) showing the attractive character of the interaction
- More attractive than p-Ξ⁻
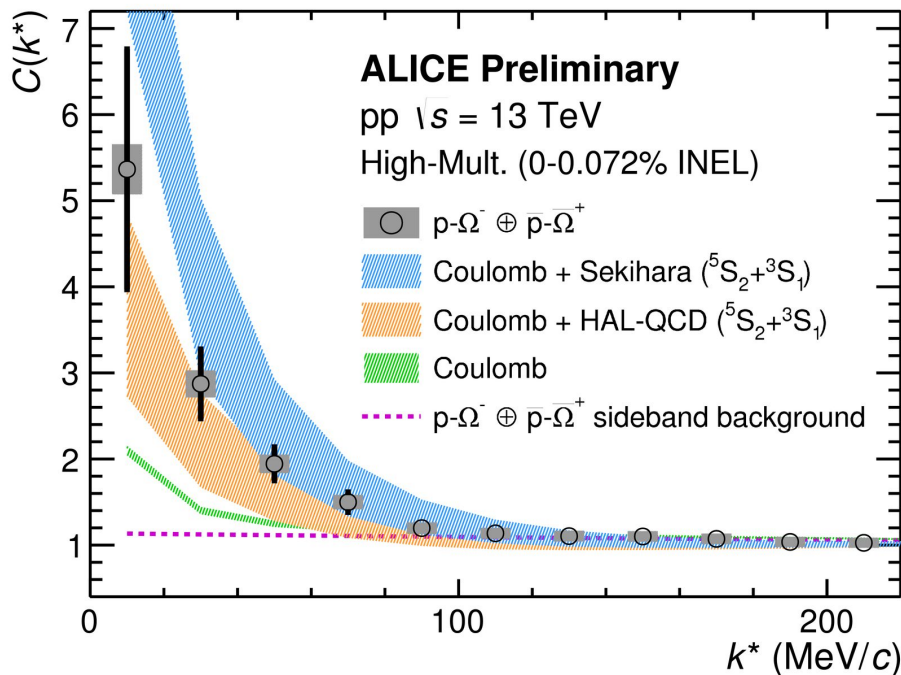
- "Coulomb only" scenario discarded by ALICE data (> 6 σ) showing the attractive character of the interaction
- More attractive than p-Ξ^-
- Large uncertainties on the theory due to the $^3S_1$ channel
- Precision of ALICE data exceeds the theoretical predictions

p-Ω^- : r_{core} = 0.73 ± 0.05 fm
r_{eff} = 0.85 fm (Gaussian)

ALI-PREL-325875

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Summary and outlook
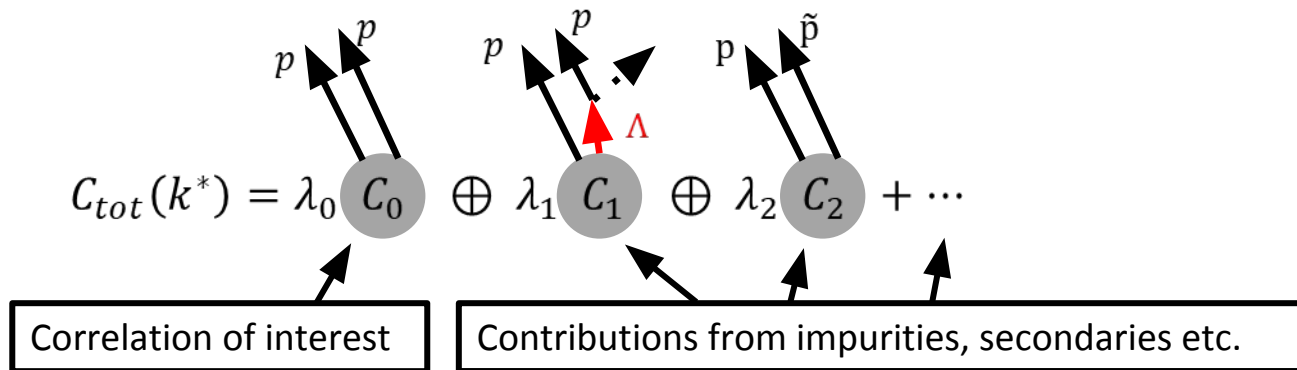
- ALICE delivers the first **precise data** to test **p-Ξ and p-Ω** interaction
- Both system show an **attractive** nature of the strong interaction
- **p-Ξ** is well described by lattice computations, which are compatible with **stiffer equation of state**
- **p-Ω** is **not compatible** with a **large binding energy**
- **p-Ω** is very **sensitive** to the **source** size
  Important to study different collision systems

- Improve the systematic uncertainties
- Study the p-Ω correlation for different collision systems (source sizes), e.g. p-Pb
- Study p-$\overline{\Xi}^+$
- Run 3/4 will provide even higher statistics:
  Achieve higher precision
  Study additional isospin systems such as p-Ξ^0
  Possibly access Ω-Ω correlation

Thank you for your attention!
感謝諸位的時間

Pirin mountain, Bulgaria

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

$$C_{tot}(k^*) = \lambda_0\, C_0 \,\oplus\, \lambda_1\, C_1 \,\oplus\, \lambda_2\, C_2 + \cdots$$

| Correlation of interest | Contributions from impurities, secondaries etc. |

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

Reconstruction of Ξ⁻ and Ω⁻
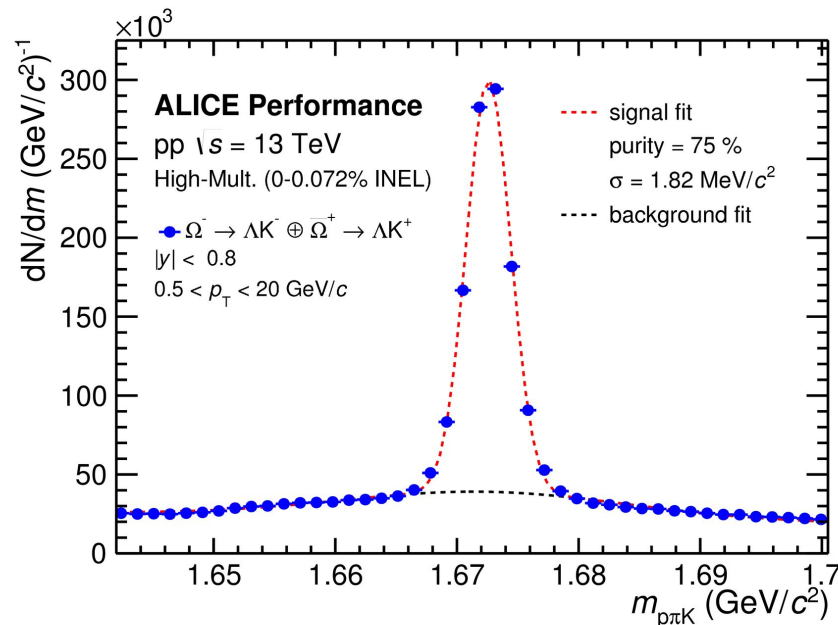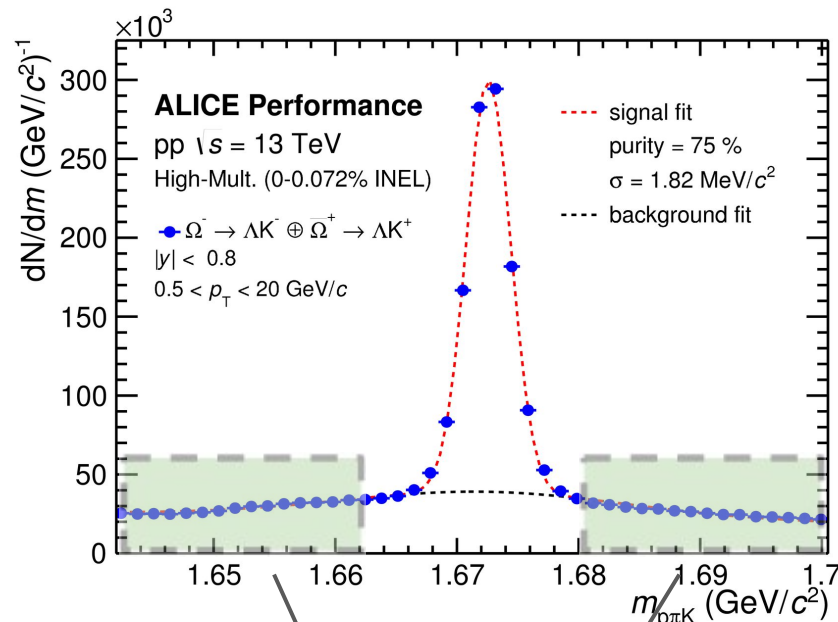
Data: **pp collisions** at $\sqrt{s}$ = 13 TeV
- Analyzed 10^9 events
- **High multiplicity** trigger

9.3×10^6 **Ξ⁻⊕Ξ⁺** selected candidates
- identified by $\Xi \rightarrow \Lambda\pi \rightarrow (p\pi)\pi$
- **Purity 92%**.
- 3×10^4 p-Ξ⁻⊕p-Ξ⁺ pairs at $k^* < 200$ MeV/c

1.2×10^6 **Ω⁻⊕Ω⁺** selected candidates
- identified by $\Omega \rightarrow \Lambda K \rightarrow (p\pi)K$.
- **Purity 75%**.
- 0.6×10^6 p-Ω⁻⊕p-Ω⁺ pairs (700 at $k^* < 100$ MeV/c)

ALICE Performance
pp $\sqrt{s}$ = 13 TeV
High-Mult. (0-0.072% INEL)
$\Omega^- \rightarrow \Lambda K^- \oplus \overline{\Omega}^+ \rightarrow \overline{\Lambda}K^+$
$|y| < 0.8$
$0.5 < p_T < 20$ GeV/c

signal fit
purity = 75 %
$\sigma = 1.82$ MeV/c^2
background fit

LI-PREL-315635

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Data: **pp collisions** at $\sqrt{s}$ = 13 TeV
- Analyzed 10^9 events
- **High multiplicity** trigger

9.3×10^6 **Ξ⁻⊕Ξ⁺** selected candidates
- identified by Ξ→Λπ→(pπ)π
- **Purity 92%**.
- 3×10^4 p-Ξ⁻⊕p-Ξ⁺ pairs at k^*<200 MeV/c

1.2×10^6 **Ω⁻⊕Ω⁺** selected candidates
- identified by Ω→ΛK→(pπ)K.
- **Purity 75%**.
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ALICE Performance
pp $\sqrt{s}$ = 13 TeV
High-Mult. (0-0.072% INEL)
$\Omega^- \to \Lambda K^- \oplus \bar{\Omega}^+ \to \Lambda K^+$
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background fit

LI-PREL-315635

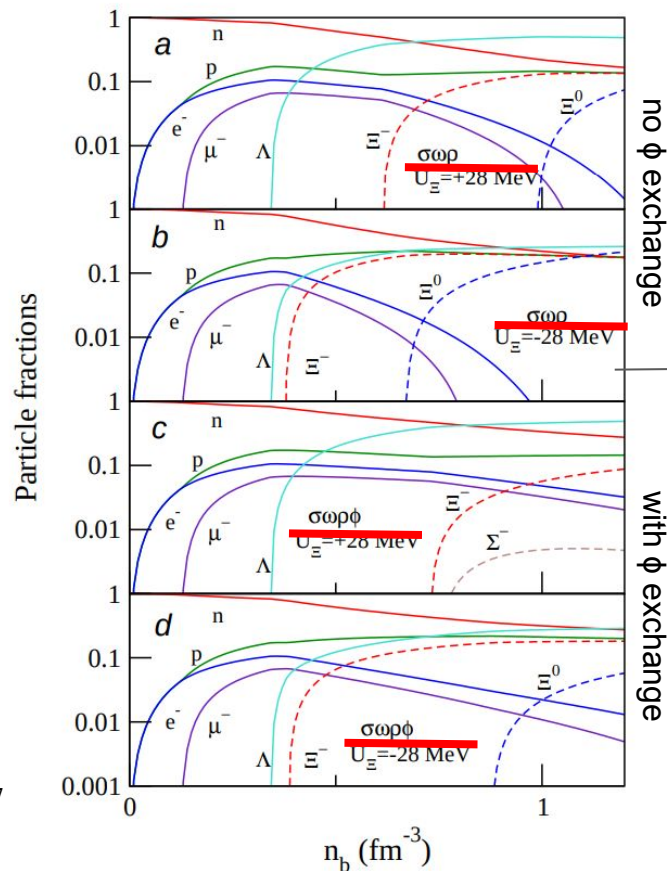- sidebands analysis to describe the background under the signal peak

RMF models: EOS of neutron-rich matter with hyperon content

→ use single particle potential at saturation densities as input

$$U_{NN}(\rho_0), \; \boxed{U_{\Lambda N}(\rho_0)}, \; \boxed{U_{\Sigma N}(\rho_0)}, \; U_{\Xi N}(\rho_0)$$

-30 MeV · · · · · · +30 MeV · · · · · · **variable →**

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

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RMF models: EOS of neutron-rich matter with hyperon content

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densities as input

$$U_{NN}(\rho_0), \boxed{U_{\Lambda N}(\rho_0)}, \boxed{U_{\Sigma N}(\rho_0)}, U_{\Xi N}(\rho_0)$$

   -30 MeV   +30 MeV   **variable →**

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

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

Previous experimental data: STAR
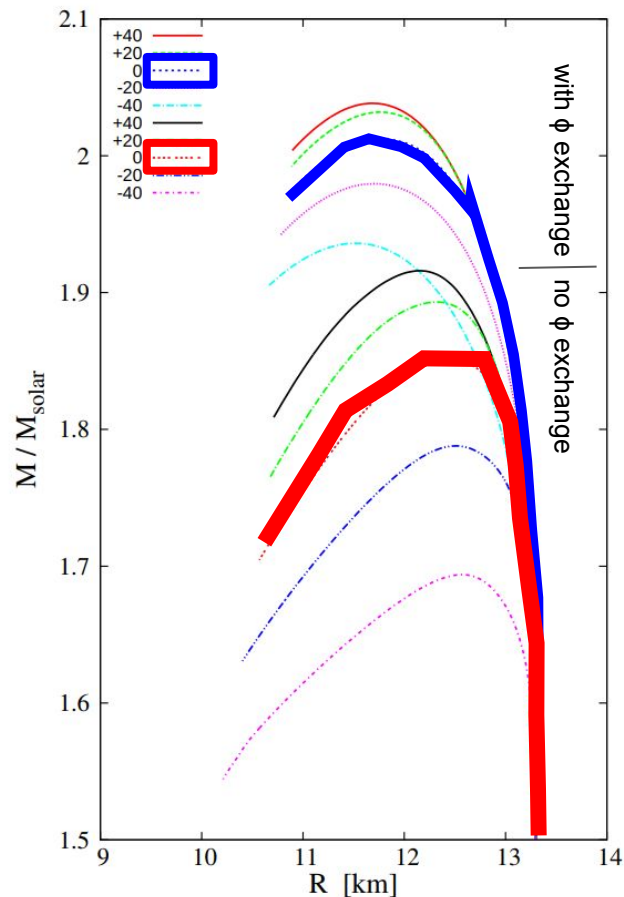
- Study of the p-Ω^- correlation function in Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV STAR Collaboration. Phys. Lett. B790 (2019) 490-497
- Observable: ratio of the correlation function peripheral/central collisions.
- Comparison with Lattice QCD calculations (with large masses)
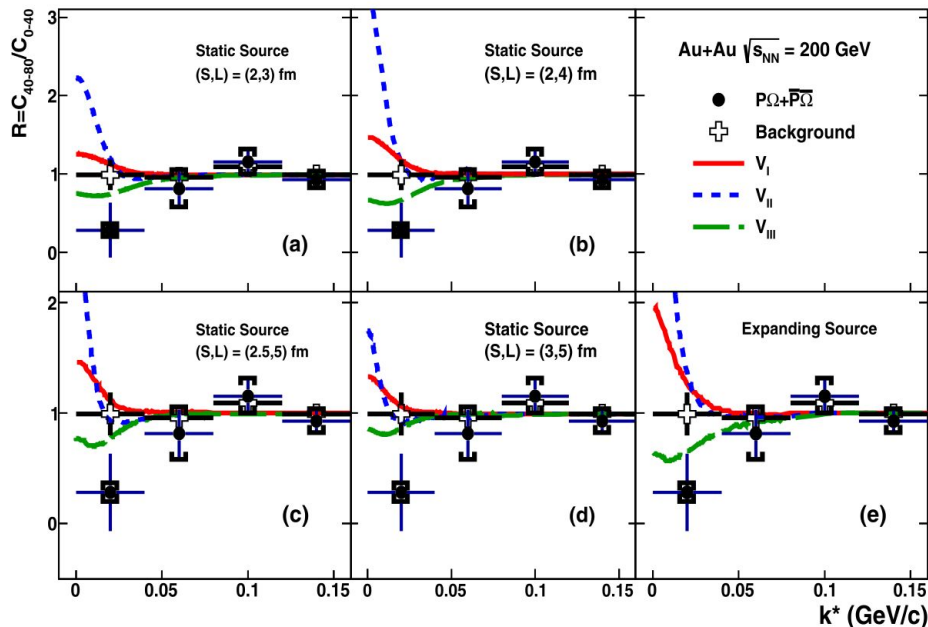
- Test different fits to Lattice QCD data (delivering **three different binding energies of the NΩ**):

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

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

[24] K. Morita, A. Ohnishi, F. Etminan, T. Hatsuda, Phys. Rev. C 94 (2016), 031901
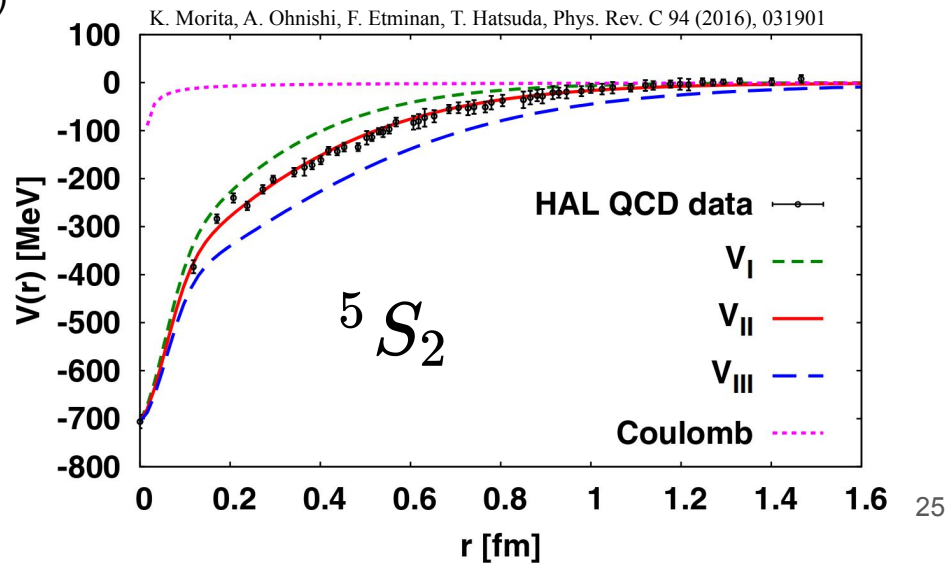
STAR data favor V_{III}, with **E_b = 27 MeV**

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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)
  - V_{II}: best fit to Lattice calculations
  - V_I / 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 (E_b), scattering length (a_0) and effective range (r_{eff}) for the Spin-2 proton–Ω potentials [24].

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

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Calculations provide the potential shape for the $^5S_2$ channel (weight ⅝).

Currently, no model for the other channel in S-wave interaction, $^3S_1$ (weight ⅜).
Requires coupled channel treatment.
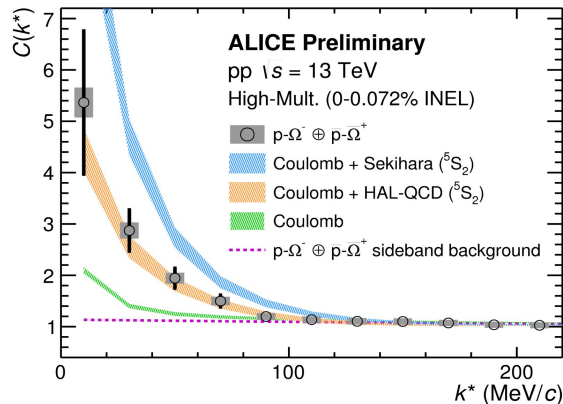Assume two different (~extreme) scenarios:

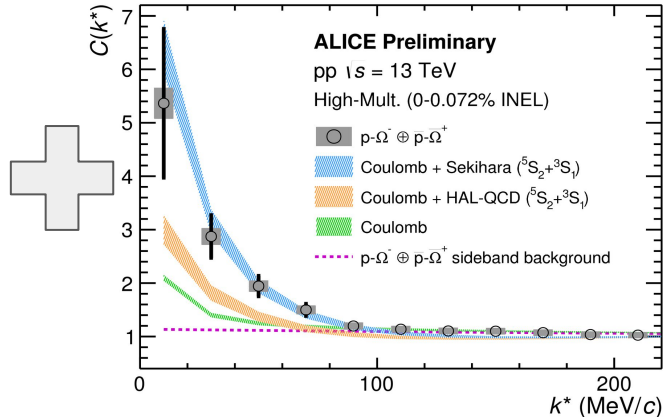1.- Complete absorption for distances $r < r_0$.
   r_0 chosen from the condition $|V(^5S_2)| < |V(\text{Coulomb})|$ for $r > r_0$
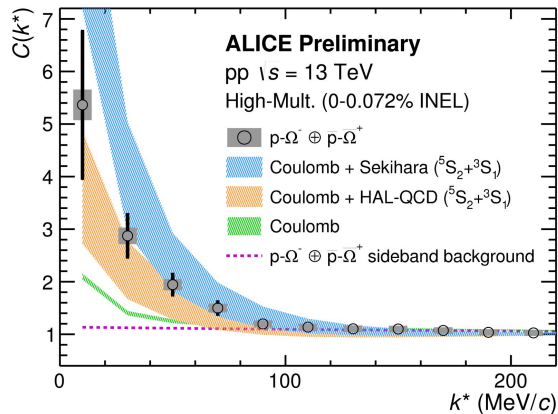   K. Morita, A. Ohnishi, F. Etminan, T. Hatsuda, Phys. Rev. C 94 (2016), 031901

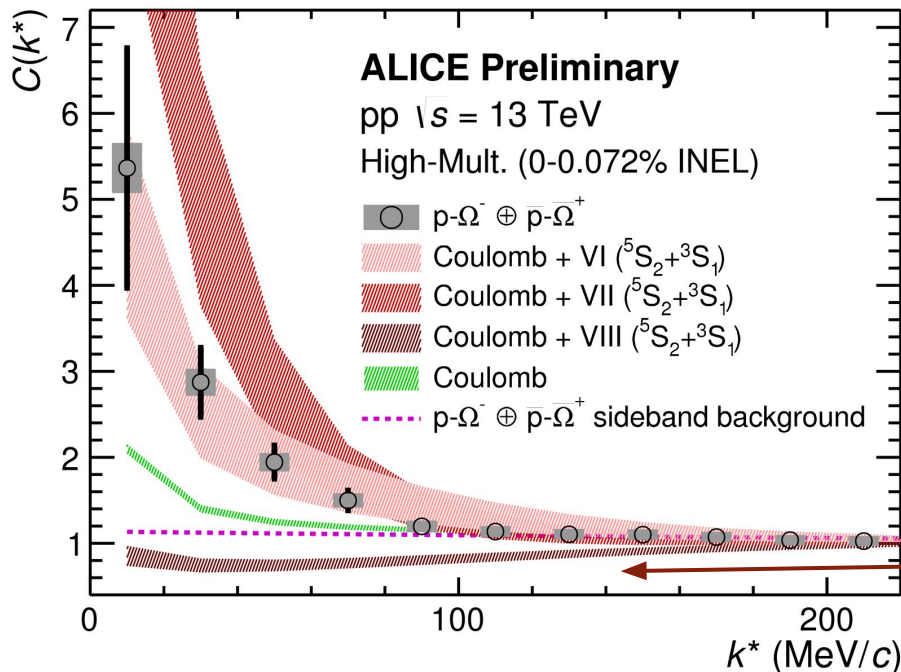2.- Complete elastic with a similar attraction as $^5S_2$

Results for p-Ω⁻

ALI-PREL-315620

ALI-PREL-315615

ALI-PREL-325875

Results for p-Ω⁻

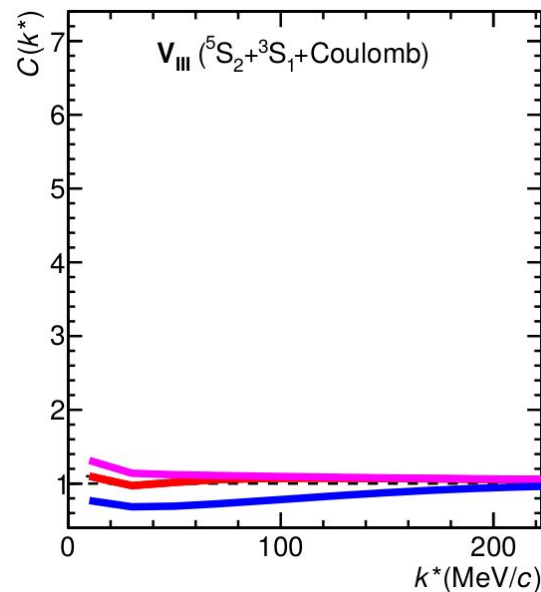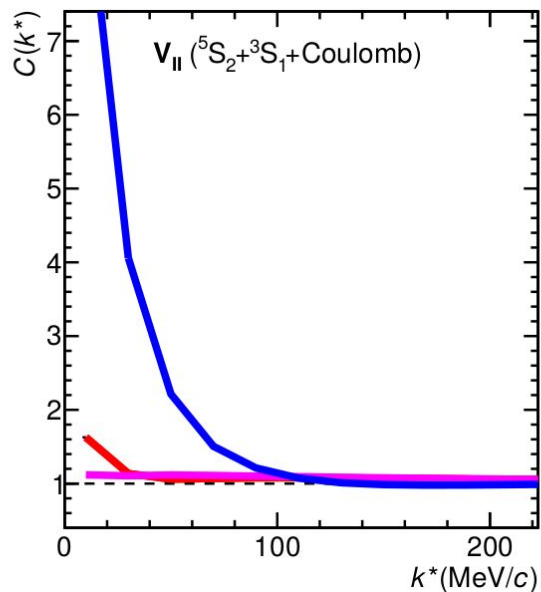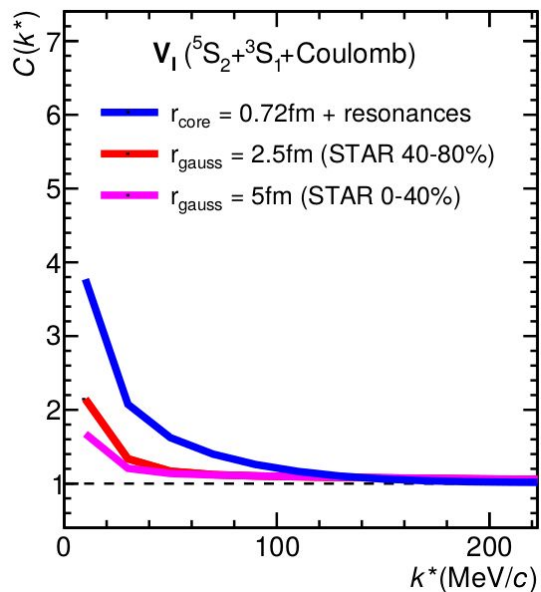"Coulomb only" scenario discarded by ALICE data (> 6 σ) showing the attractive character of the interaction

Precision of ALICE data exceeds the theoretical predictions
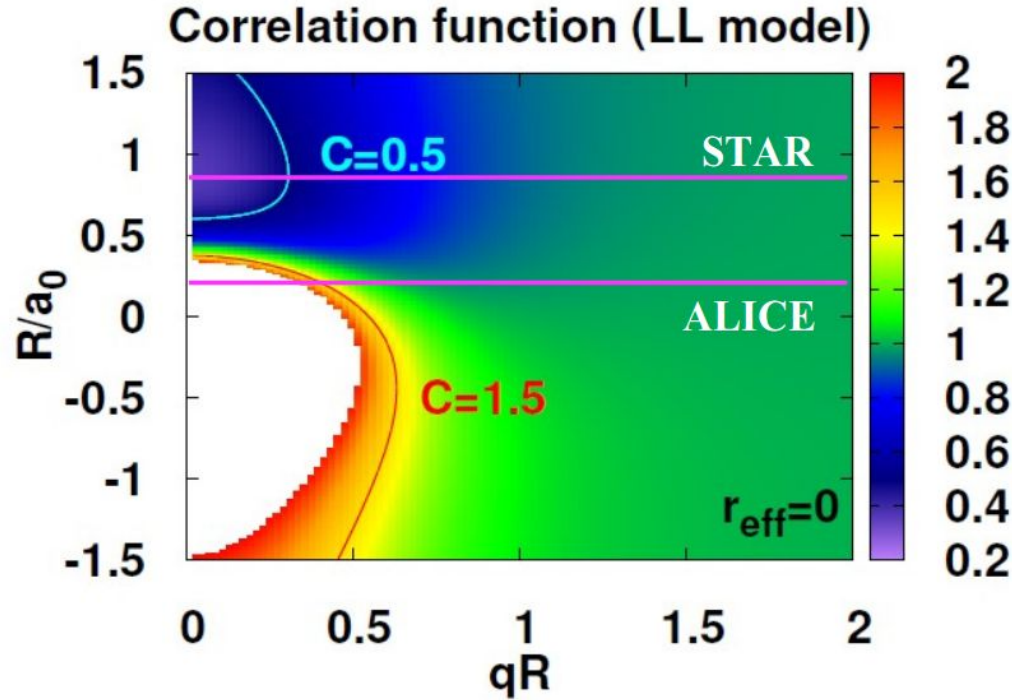
r_{core} = 0.73 ± 0.05 fm (+ resonances)

Comparison with the model favoured by STAR data:

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

In figure:

ALICE Preliminary
pp $\sqrt{s}$ = 13 TeV
High-Mult. (0-0.072% INEL)

p-Ω⁻ ⊕ p̄-Ω̄⁺
Coulomb + VI ($^5S_2 + ^3S_1$)
Coulomb + VII ($^5S_2 + ^3S_1$)
Coulomb + VIII ($^5S_2 + ^3S_1$)
Coulomb
p-Ω⁻ ⊕ p̄-Ω̄⁺ sideband background

$C(k^*)$
k^* (MeV/c)

ALI-PREL-325870

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- 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)

V_I ($^5S_2+^3S_1+$Coulomb)

- r_{core} = 0.72fm + resonances
- r_{gauss} = 2.5fm (STAR 40-80%)
- r_{gauss} = 5fm (STAR 0-40%)

V_{II} ($^5S_2+^3S_1+$Coulomb)

V_{III} ($^5S_2+^3S_1+$Coulomb)

$C(k^*)$

k^*(MeV/c)

Sensitivity to the source size

Correlation function (LL model)

C=0.5   STAR

C=1.5   ALICE

$r_{eff}=0$

a_0 (pΩ)~ 3.4 fm, R(ALICE)~0.7 fm, R(STAR)~3 fm

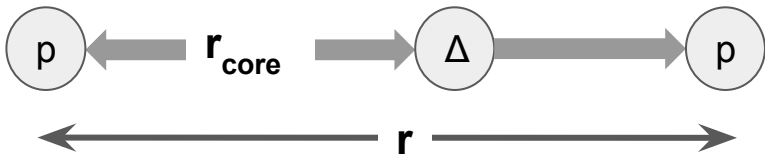*Plot from the presentation of Prof. Akira Ohnishi during the FemTUM19 workshop*

- 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
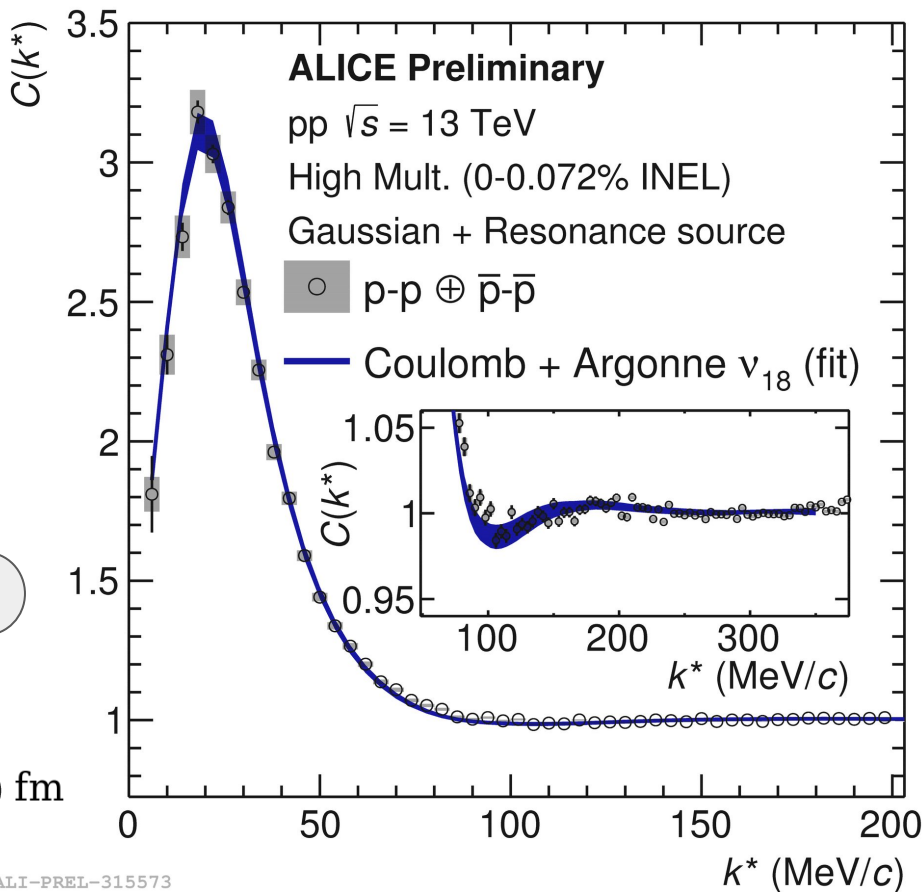- For **VI potential (<u>no bound state</u>) $C(k^*)$ always increases** with decreasing r_{cutoff}
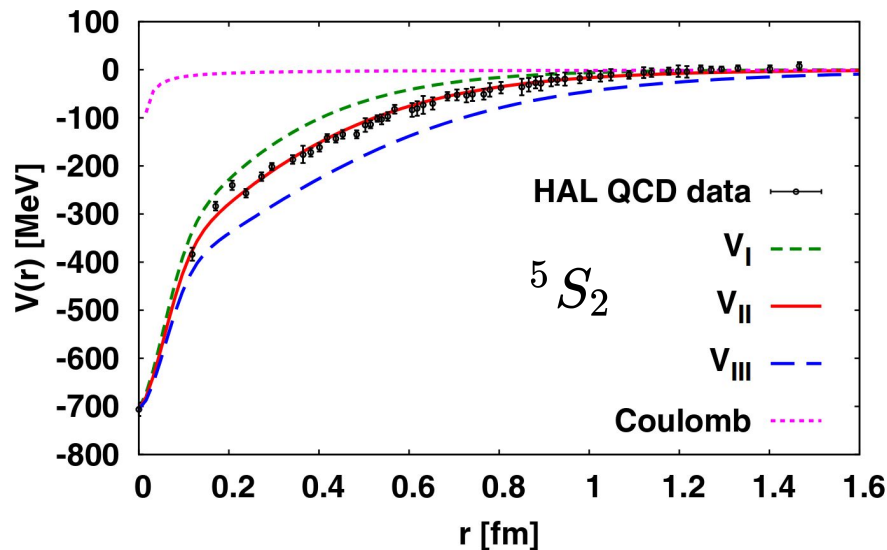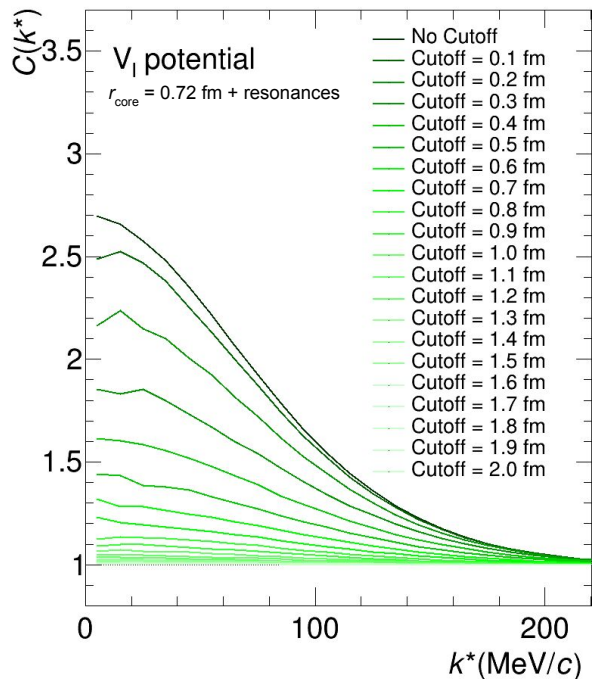
- Effects of momentum resolution and feed-down contributions are applied to the fit function.

- The effects of short-lived resonances are modeled by assuming a "core" source, from which resonances and primordial particles are emitted.
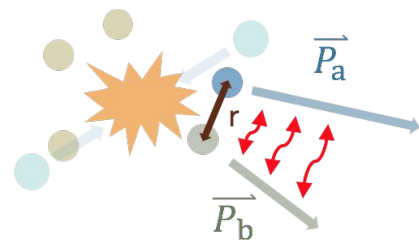
p ⟵ r_{core} ⟶ Δ ⟶ p

⟵ r ⟶

- $r_{core} = 0.995 \pm 0.006 (\text{stat.})^{+0.024}_{-0.022} (\text{syst.}) \text{ fm}$

ALICE Preliminary
pp $\sqrt{s} = 13$ TeV
High Mult. (0-0.072% INEL)
Gaussian + Resonance source
○ p-p ⊕ p̄-p̄
— Coulomb + Argonne ν_{18} (fit)

ALI-PREL-315573

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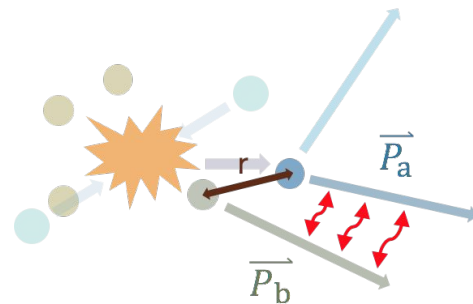# The source function
Effect of short-lived resonances

- Effects of **strong resonances** on the correlation function
  - **Introduction of an exponential tail**→ non-gaussian contribution
  - **Resonances with cτ ~ r_0~ 1 fm**
    N* (Γ ~ 150 - 200 MeV)
    Δ (Γ ~ 150 MeV)…
- The modification is **different** for the **distinct particle species**
- The amount of resonances determined within a **Statistical Hadronization Model** in the canonical approach (Priv. Comm. With Prof. F. Becattini, see for details J.Phys. G38 (2011) 025002)
- The momentum of the resonance computed based on the assumption of a 2-body decay into a final momentum of k*=0

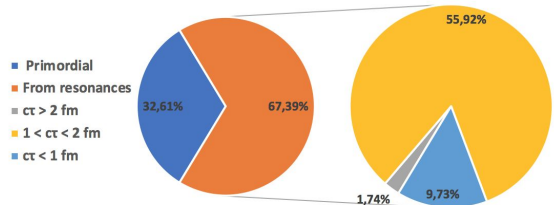$$s = \beta\gamma\tau_{\text{res}} = \frac{p_{\text{res}}}{M_{\text{res}}}\tau_{\text{res}}$$

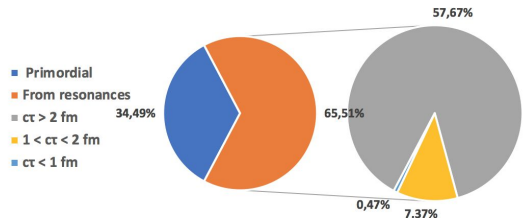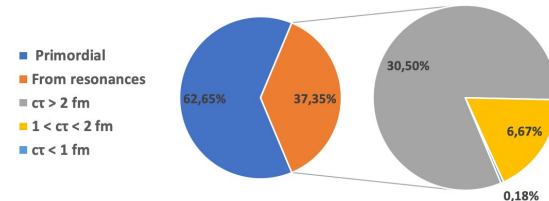$$E(r, M_{\text{res}}, \tau_{\text{res}}, p_{\text{res}}) = \frac{1}{s}\exp\left(-\frac{r}{s}\right)$$

vs.

The source function
Effect of short-lived resonances

Protons

Λs

Σ⁰s

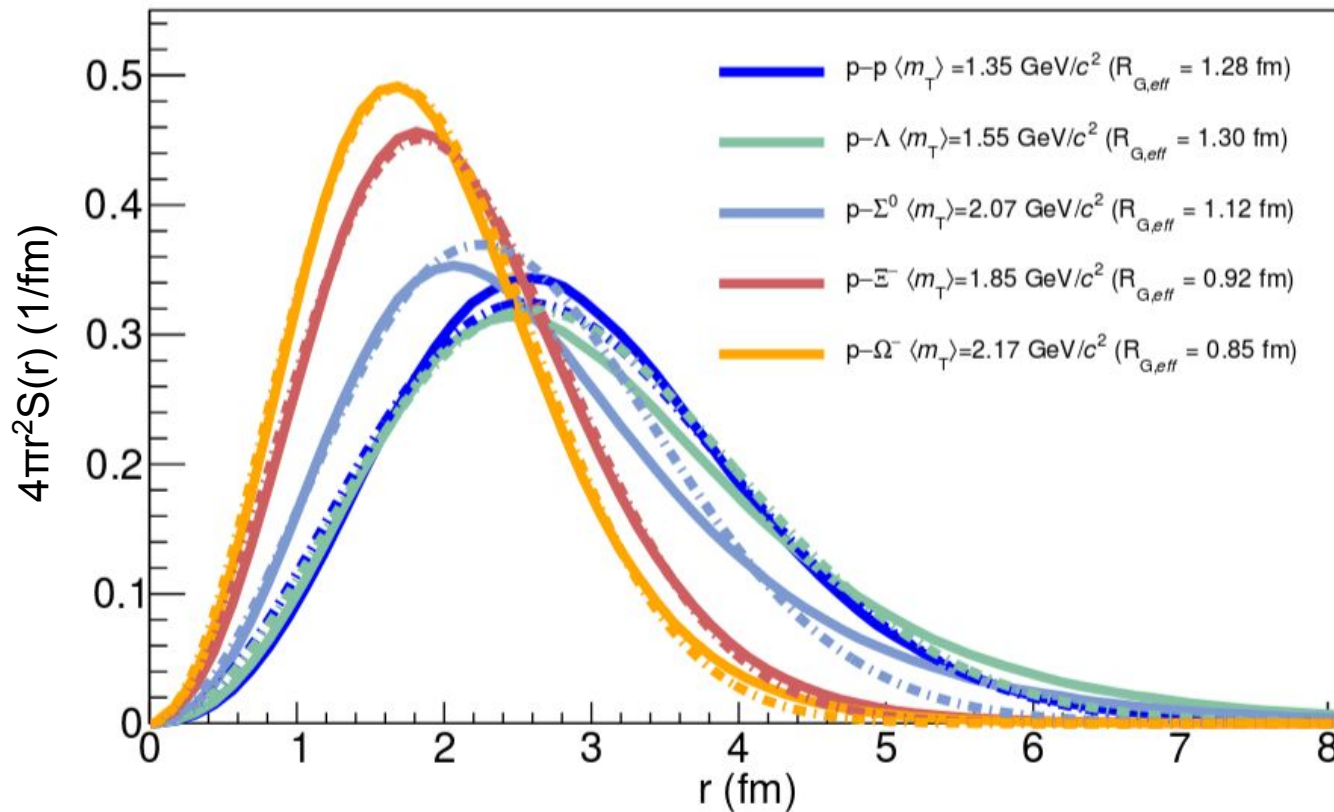- For Ξ^- and Ω^- **no contributions**!
- Average mass and average cτ determined by the weighted average values of all resonances

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

Gaussian core + resonances

The source (based on <mT>)

- Radius for **pure Gaussian** or **Gaussian core + Res**. taken from p-p <mT> scaling with the specific value of average m_T mass for each pair (see slides **11**-**12**)

Effect on the source when smearing the resonances