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

Otón Vázquez Doce (TUM)
for the ALICE Collaboration

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Outline

LHC: High-energy physics

“Non-traditional” Femtoscopy

Hadron physics

HADRON-HADRON STRONG INTERACTION VIA FEMTOSCOPY WITH ALICE

Otón Vázquez Doce (TUM)
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ALICE experiment at the LHC

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

Tracking and PID:
- Inner Tracking System (\textbf{ITS})
- Time Projection Chamber (\textbf{TPC})
- Time Of Flight (\textbf{TOF})
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“Non-traditional Femtoscopy”

Study of correlations of hadron-hadron pairs from small sources:
- **p-p**, **p-K^+/−**, **p-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%)
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Reconstruction of hyperons
- $Λ \rightarrow p\pi$ (BR $\sim 64\%$)
- $Σ^0 \rightarrow Λ\gamma$ (BR $\sim 100\%$)
- $Ξ \rightarrow Λ\pi$ (BR $\sim 100\%$)
- $Ω \rightarrow ΛK$ (BR $\sim 68\%$)

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 $C(k^*) = \frac{P(p_a, p_b)}{P(p_a)P(p_b)}$

$k^* = \text{reduced relative momentum with } \vec{p}_a + \vec{p}_b = 0$

Theoretically formulated:

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

$>1 \Rightarrow \text{Attractive interaction}$

$<1 \Rightarrow \text{Repulsive interaction}$
Femtoscopy as a tool for studying h-h interactions

Based on the correlation function

\[ C(k^*) = \frac{P(p_a, p_b)}{P(p_a)P(p_b)} \]

\( k^* \) = reduced relative momentum with \( \vec{p}_a^* + \vec{p}_b^* = 0 \)

Theoretically formulated:

\[ C(k^*) = \int S(\vec{r}, k) |\psi(\vec{r}, k)|^2 d\vec{r} \]

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

Relative wave function:
Sensitivity to the interaction potential

Study the \( C(k^*) \) of hadron-hadron pairs in pp collisions ⇒ small particle source (~1 fm)
Femtoscopy as a tool for studying h-h interactions

Based on the correlation function $C(k^*) = \frac{P(p_a, p_b)}{P(p_a)P(p_b)}$ where $k^* = \text{reduced relative momentum with } p_a^* + p_b^* = 0$

Theoretically formulated:

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

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

Generally, the experimental correlation function accounts for the genuine correlation and it is affected by residual correlations and finite momentum resolution.
**CATS: Correlation Analysis Tool Using the Schrödinger Equation**

Provides an 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

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-\( \Lambda \) analysis

- **Effect of strong short-lived resonances** computed for all hadrons
  - Statistical hadronization model in the canonical approach

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  - \(<m_\perp>\) dependence cross-checked with p-Λ analysis

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Setting the source

Parametrization with exponential law $r_{\text{core}} = a \cdot <m_T>^b + c$

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

The $p-\Lambda$, $p-\Sigma^0$, $p-\Xi^-$, $p-\Omega^-$ sources are determined given the pair $<m_T>$:
- $p-\Lambda$: $r_{\text{core}} = 0.88 \pm 0.03$ fm
- $p-\Xi^-$: $r_{\text{core}} = 0.80 \pm 0.03$ fm
- $p-\Sigma^0$: $r_{\text{core}} = 0.75 \pm 0.04$ fm
- $p-\Omega^-$: $r_{\text{core}} = 0.73 \pm 0.05$ fm
K-p femtoscopy: The KN interaction

- $K^+p$ interaction is well established
- $Kp$ features a strong attraction
  - appearance of the $\Lambda(1405)$ below threshold
  - $\Lambda(1405)$: anti$K\Sigma\pi$ molecular state
K-p femtoscopy: The KN interaction

- K⁺p interaction is well established
- Kp features a strong attraction
  - appearance of the Λ(1405) below threshold
  - Λ(1405): antiKN-Σπ molecular state
- Kp scattering data and kaonic hydrogen data used to constrain the amplitude below threshold

Experiments: 

\[ \Lambda(1405) \rightarrow \Sigma\pi \]

Kaonic atoms

\[ \Sigma_T \quad \Lambda(1405) \quad KN \]

scattering data


27 MeV

Energy
K-p femtoscopy: The KN interaction

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- $Kp$ features a strong attraction
  - appearance of the $\Lambda(1405)$ below threshold
  - $\Lambda(1405)$: antiKN-$\Sigma\pi$ molecular state
- $Kp$ scattering data and kaonic hydrogen data used to constrain the amplitude below threshold
K-p femtoscopy in pp collisions

- Radius obtained from inclusive p-p correlation
  \[ r_0 = 1.18 \pm 0.01 \pm 0.12 \text{ fm} \]
- K\(^+\)p correlation used as a benchmark to study K\(^-\)p
K-p femtoscopy in pp collisions

- Radius obtained from inclusive p-p correlation
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- K’p correlation used as a benchmark to study K’p


\[ \Rightarrow \text{Bump close to the K}^0\text{n threshold} \rightarrow (58 \, \text{MeV/c in CM frame}) \]
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⇒ Bump close to the K^0 n threshold → (58 MeV/c in CM frame)

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

Coupled channel effect

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

→ Analysis in p-Pb 5.02 TeV as a function of charged multiplicity:
Interaction changes as a function of the particle distance
p-Λ femtoscopy in High-mult pp collisions

Previous experimental constraints:
- Scarce scattering data
- 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
p-Λ femtoscopy in High-mult pp collisions

Previous experimental constraints:
- Scarce scattering data
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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-Σ⁰ femtoscopy in High-mult pp collisions

Identification via Σ⁰ → Λγ (BR ~ 100%)

Models for the p-Σ⁰ interaction:

The p-Σ⁰ wave function is used as input to CATS
Models of the p-Ξ- potential:

**HAL-QCD (Lattice)**


**ESC16L Meson exchange model**

Models of the p-$\Xi^-$ potential:

\[ V(r) \quad (\text{MeV}) \]

- $l = 0, s = 0$
- $l = 0, s = 1$
- $l = 1, s = 0$
- $l = 1, s = 1$

**HAL-QCD**

HAL-QCD (Lattice)

**ESC16L Meson exchange model**

**p-$\Xi^-$ in p-Pb at 5.02 TeV**

\[ C(k^*) \text{ vs. } k^* \quad (\text{MeV/c}) \]

- **ALICE p-Pb** $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
- p-$\Xi^-$ + $\bar{p}$-$\Xi^-$
- Coulomb + HAL-QCD
- Coulomb
- $p-$-$\Xi^-$ sideband background

"First observation of an attractive interaction between a proton and a multi-strange baryon" ALICE Coll. ArXiv:1904.12198 [nucl-ex]
- Coulomb excluded (>4$\sigma$)
- Compatible with Lattice (HAL-QCD) calculations

\[ r_0 = 1.427 \pm 0.007 \text{ (stat.)}^{+0.001}_{-0.014} \text{ (syst.) fm \ (-20\%, resonances)} \]
Models of the p-Ξ- potential:

- **HAL-QCD (Lattice)**
  

- **ESC16L Meson exchange model**
  

### p-Ξ- in p-p High. Mult.

- **Coulomb** only: $> 5.7 \sigma$
- **HAL-QCD Potential**: $(1.3-2.5) \sigma$
- **ESC16 Potential**: $> 18 \sigma$

→ Hypernuclei data described by both HAL-QCD and ESC16

$r_{\text{source}} = 0.80 \text{ fm} (+\text{resonances})$
**p-Ξ⁻**: Implications for NS with hyperon content

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

**Lattice QCD:**
\( U_{\Xi} \) moves from slightly repulsive in symmetric nuclear matter to **slightly repulsive** \( U_{\Xi^-} \sim 6 \) MeV in pure neutron matter (NS)
**p-Ξ⁻: Implications for NS with hyperon content**

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**Lattice QCD:**
$U_\Xi$ moves from slightly repulsive in symmetric nuclear matter to **slightly repulsive** $U_\Xi \sim 6$ MeV in **pure neutron matter** (NS)

**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

**Repulsive interaction:**
⇒ Ξ pushed to high densities ⇒ **stiffer EoS**, higher masses
Models of the p-Ω⁻ interaction

- **Lattice HAL-QCD** potential with **physical quark masses** \( m_\pi = 146 \text{ MeV}/c^2, m_K = 525 \text{ MeV}/c^2 \)
- **Sekihara**: **Meson-exchange model**
  - Short range attractive interaction fitted to previous HAL-QCD scattering parameters

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

<table>
<thead>
<tr>
<th>Model</th>
<th>pΩ⁻ binding energy (strong interaction only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAL-QCD</td>
<td>1.54 MeV</td>
</tr>
<tr>
<td>Sekihara</td>
<td>0.1 MeV</td>
</tr>
<tr>
<td></td>
<td>+1 MeV with Coulomb</td>
</tr>
</tbody>
</table>

\( \rightarrow \) Models provide so far only \(^5S_2\) channel (weight \( \frac{5}{6} \))

For \(^3S_1\) channel, two extreme assumptions: total absorption or attraction as \(^5S_2\)
Results: $p-\Omega^-$ correlation function in pp HM

“Coulomb only” scenario discarded by ALICE data (> 6 $\sigma$) showing the attractive character of the interaction

Precision of ALICE data exceeds the theoretical predictions

$r_{\text{source}} = 0.73$ fm (+resonances)
Results: $p-\Omega^-$ correlation function in pp HM

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Precision of ALICE data exceeds the theoretical predictions

Comparison with the model favoured by STAR data


$V_{\text{III}}$: Ad-hoc fit to previous HAL-QCD calculations with non-physical quark masses with $p\Omega$ 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 $\lambda$ 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)
- $T = 166 \text{ MeV} \& \gamma_s \approx 0.8$ (Private Comm Prof. F. Becattini, J. Phys. G38 (2011) 025002)

- For $\Xi$ and no $\Omega$ contributions!
- Average mass and average $c_t$ determined by the weighted average values of all resonances

<table>
<thead>
<tr>
<th>Particle</th>
<th>$M_{\text{res}}$ [MeV]</th>
<th>$\tau_{\text{res}}$ [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>1361.52</td>
<td>1.65</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>1462.93</td>
<td>4.69</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>1581.73</td>
<td>4.28</td>
</tr>
</tbody>
</table>
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

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

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

- Specific modulation of each pair
Gaussian core + resonances

- 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

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  - **Effect of strong short-lived resonances** computed for all hadrons

![Graphs showing dependence of $r_0$ and $r_{core}$ on $<m_T>$](image-url)
→ 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: no > 8

Best fit for NLO: no > 10
Λ-Λ analysis

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

- 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 $\Xi^-14N$ systems

0.174 MeV: 3D atomic state

$B_{\Xi^-} 1.03 \pm 0.18 \text{ (MeV)}$ or $3.87 \pm 0.21$

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

IBUKI event
(J-PARC E07)

$B_{\Xi} 1.27 \pm 0.21 \text{ (MeV)}$
p-Ξ^- potential in pure neutron matter

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

Lattice QCD: 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

- 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

Repulsive interaction:
  ⇒ 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 Ξ^0(1530) state
- Ξ^0(1530) → Ξ^- + π^+
- I = 1 & S = 1 + 2

<table>
<thead>
<tr>
<th></th>
<th>I = 0</th>
<th>I = 1</th>
<th>Detectable</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Ξ^-</td>
<td>X</td>
<td>✓</td>
<td>No</td>
</tr>
<tr>
<td>p-Ξ^0</td>
<td>X</td>
<td>✓</td>
<td>Difficult</td>
</tr>
<tr>
<td>p-Ξ^-</td>
<td>✓</td>
<td>✓</td>
<td>Yes</td>
</tr>
<tr>
<td>p-Ξ^+</td>
<td>✓</td>
<td>X</td>
<td>Difficult</td>
</tr>
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</table>
ALICE pp High Multiplicity data

- **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 $\Omega$ baryon
Selection of $\Omega^-$ candidates

- Identified by its decay: $\Omega^- \rightarrow \Lambda K^- \rightarrow (p\pi^-)K^-$
- Total of $1.2 \times 10^6$ selected ($\Omega^- + \Omega^+$) 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 $|V_{I,II,III}| < |V_{\text{Coulomb}}|$ for $r > r_0$
   - Using the same condition with latest HAL-QCD potential may result in a substantially increased value for $r_0 \to$ 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 √s_{NN} = 200GeV
- 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):

<table>
<thead>
<tr>
<th>Spin-2 pΩ potentials</th>
<th>V_I</th>
<th>V_{II}</th>
<th>V_{III}</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_b (MeV)</td>
<td>−</td>
<td>6.3</td>
<td>26.9</td>
</tr>
<tr>
<td>a_0 (fm)</td>
<td>−1.12</td>
<td>5.79</td>
<td>1.29</td>
</tr>
<tr>
<td>r_{eff} (fm)</td>
<td>1.16</td>
<td>0.96</td>
<td>0.65</td>
</tr>
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</table>


STAR data favor V_{III} with E_b = 27 MeV
Lattice HAL-QCD potential with heavy quarks

- Based on Lattice calculations with heavy quark masses
  - \( m_\pi = 875 \text{ MeV}/c^2 \)
  - \( m_K = 916 \text{ MeV}/c^2 \)

- Used in the STAR p\(\Omega\) analysis in Au-Au collisions at \( \sqrt{s_{NN}} = 200\text{GeV} \)

- 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 (\( r_{\text{eff}} \)) for the Spin-2 proton-\(\Omega\) potentials [24].

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

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

<table>
<thead>
<tr>
<th>Spin-2 p$\Omega$ potentials</th>
<th>$V_I$</th>
<th>$V_{II}$</th>
<th>$V_{III}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_b$ (MeV)</td>
<td>–</td>
<td>6.3</td>
<td>26.9</td>
</tr>
<tr>
<td>$a_0$ (fm)</td>
<td>–1.12</td>
<td>5.79</td>
<td>1.29</td>
</tr>
<tr>
<td>$r_{\text{eff}}$ (fm)</td>
<td>1.16</td>
<td>0.96</td>
<td>0.65</td>
</tr>
</tbody>
</table>
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

```plaintext
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

\[ 5S_2 + ^3S_1 \]

\[ \text{purity 75\%} \]

\[ r_{\text{core}} = 0.75 \text{ fm + resonances} \]
\[ r_{\text{gauss}} = 1. \text{ fm} \]

→ 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 \(r < r_{\text{cutoff}} \Rightarrow V = 0\))
- HAL-QCD with physical quark masses (t=12): maximum of the \(C(k^*)\) for \(r_{\text{cutoff}} = 0.5\) fm