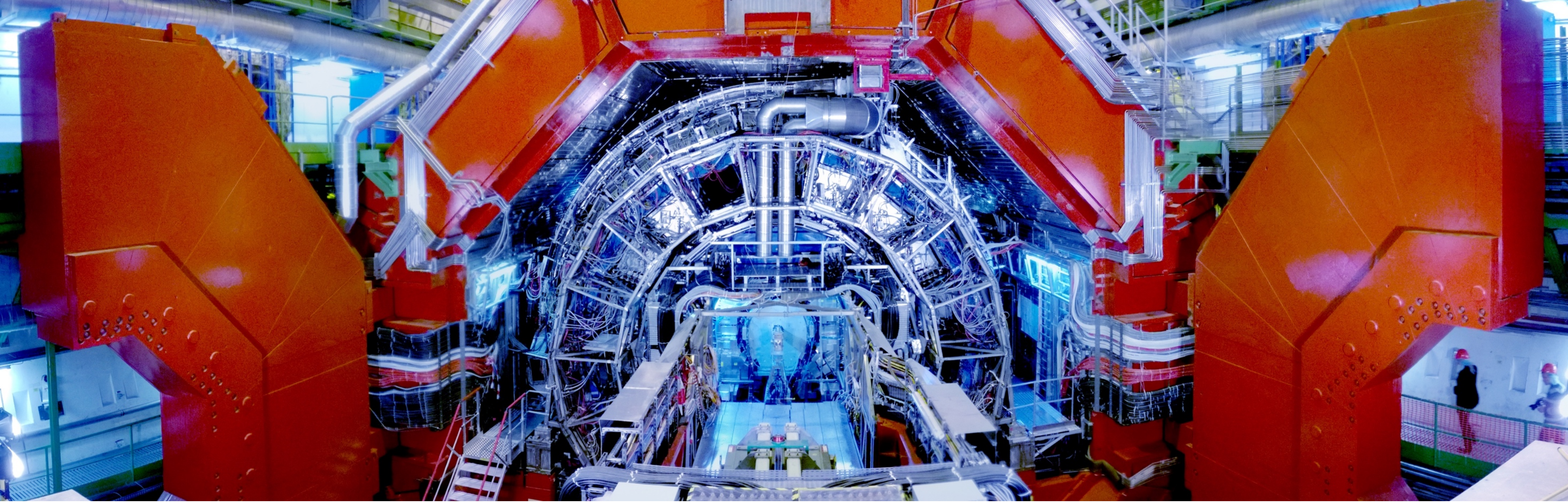


Hyperon-baryon and hyperon-hyperon interaction from two-particle correlations at the LHC Energies

Laura Fabbietti, Bernhard Hohlweger, Ramona Lea, Valentina Mantovani Sarti, Andreas Mathis, Dimitar Mihaylov, Oton Vazquez Doce (FemtoGang)

Technische Universität München

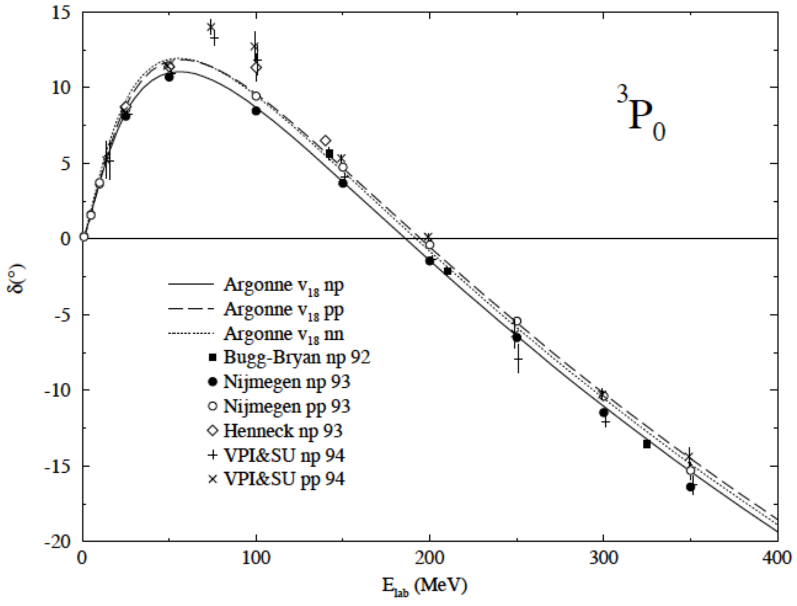
BMBF Forschungsschwerpunkt ALICE Experiment 202

SFB 1258 Neutrinos Dark Matter Messengers

3rd EMMI Workshop: Anti-matter, hyper-matter and exotice production at the LHC

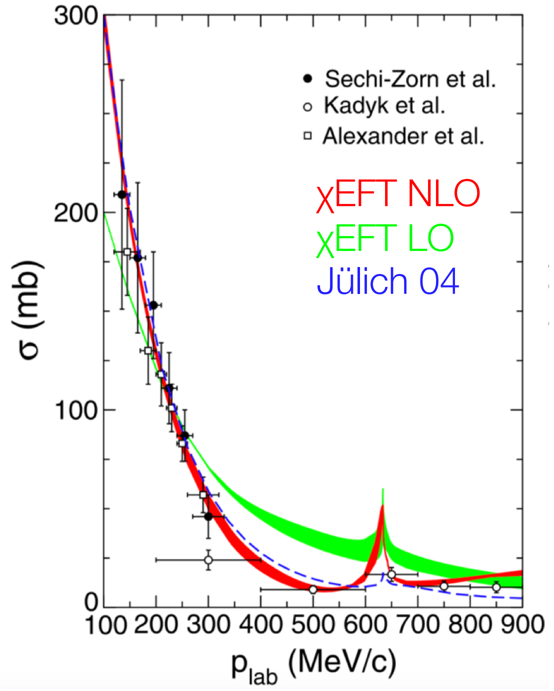
Strong interaction among (strange) hadrons

N–N → N–N



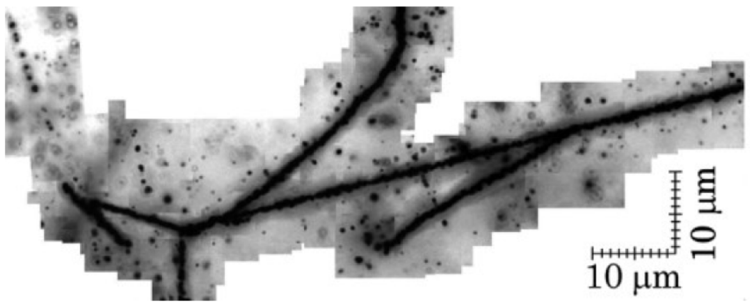
R. B. Wiringa, *et al.*, PRC 51 (1995) 38-51.

p–Λ → p–Λ



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

Ξ^- hypernuclei



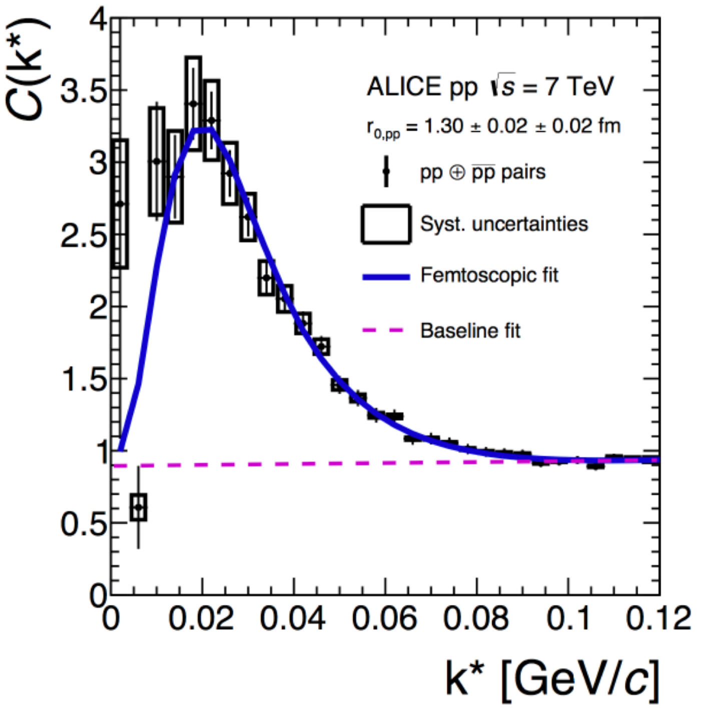
K. Nakazawa *et al.*, PTEP 2015, 033D02

- (High precision) measurements conducted with different experimental techniques

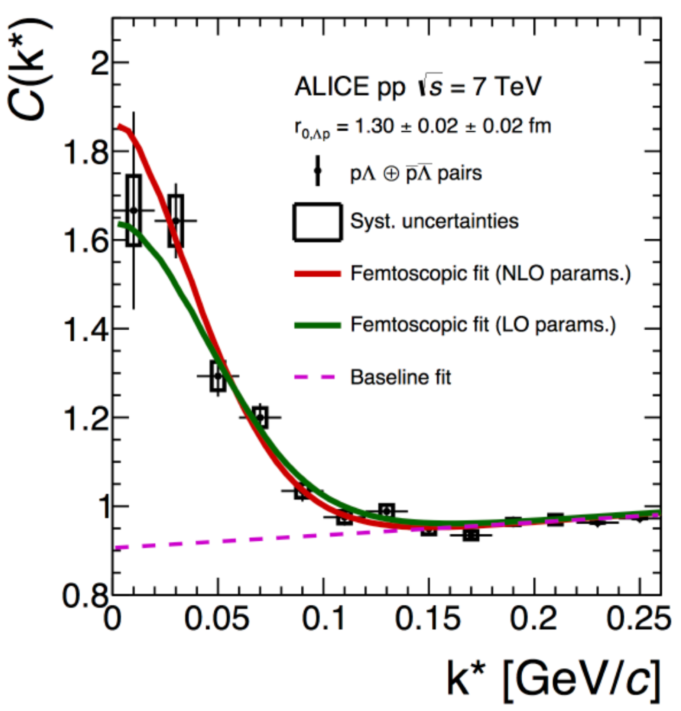
Plots shown at the 2nd EMMI Workshop in Turin 2017

p-p, $\sqrt{s} = 7$ TeV

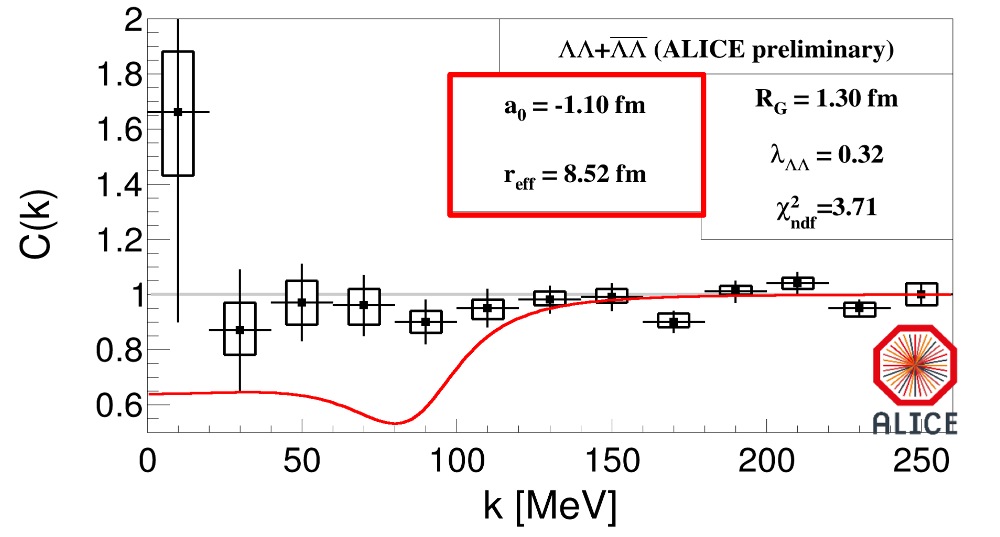
pp Correlation



pΛ Correlation



ΛΛ Correlation

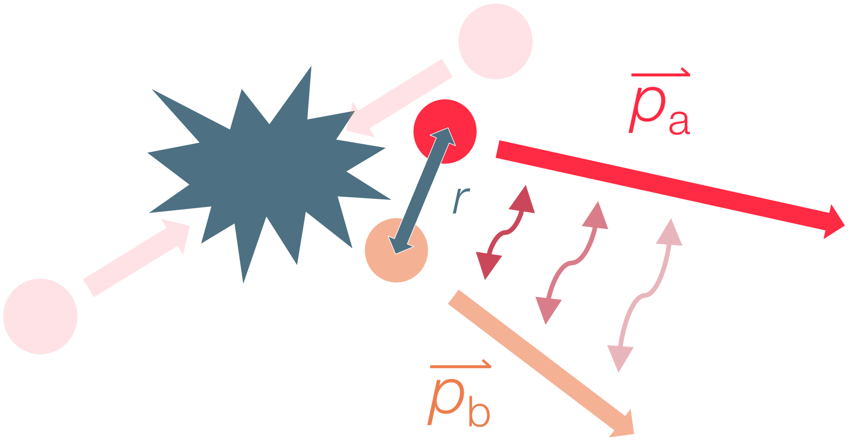


Non-traditional femtoscopy to study the FSI

$$C(k^*) = \mathcal{N} \cdot \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int S(r)\ |\Psi(k^*, r)|^2\, d^3r\ = \begin{cases} > 1 \text{ (attractive interaction)} \\ < 1 \text{ (repulsive interaction)} \end{cases}$$

Emission source — Two-particle wave function

- Study correlations in the relative momentum k^* distribution of a particle pair
- Traditionally used to study the geometry of the emission source with particles of known interaction
- Reversing the paradigm of femtoscopy
  - Study the interaction among the particles



Non-traditional femtoscopy to study the FSI

$$C(k^*) = \mathcal{N} \cdot \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int S(r)\ |\Psi(k^*, r)|^2\, d^3r\ = \begin{cases} > 1 \text{ (attractive interaction)} \\ < 1 \text{ (repulsive interaction)} \end{cases}$$

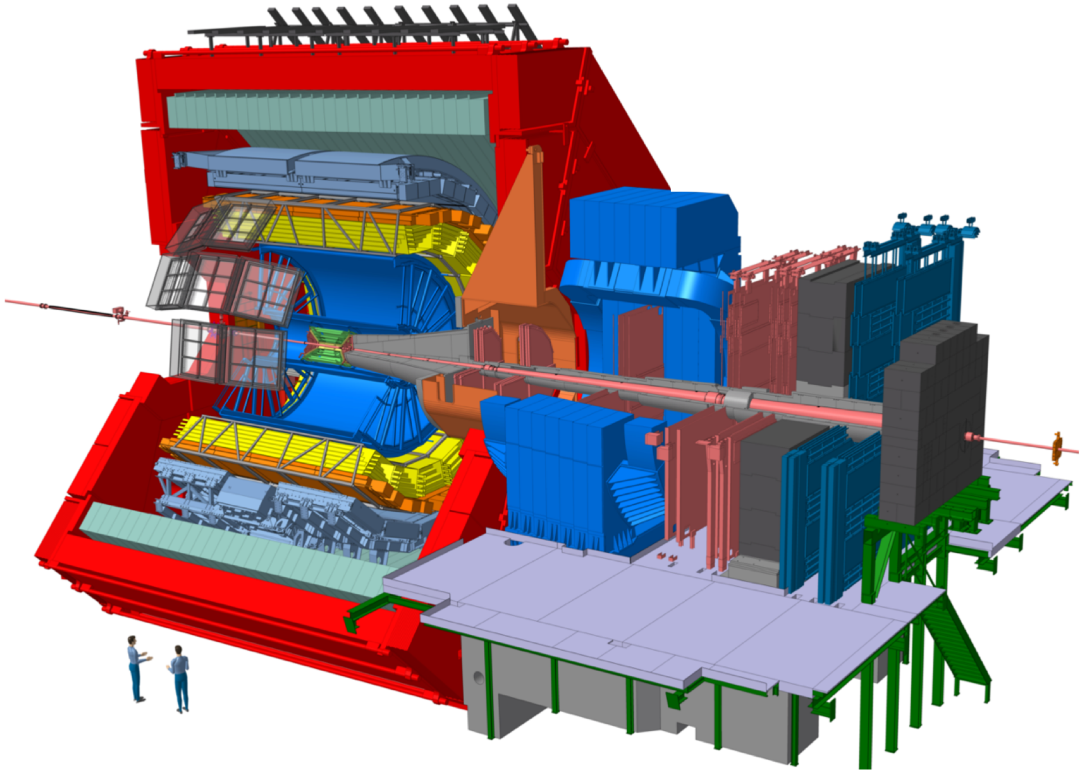
Emission source   Two-particle wave function

- C(k^*) can be evaluated under the prerequisite that the source is known
  - numerically using the CATS framework (D.L. Mihaylov et al, Eur. Phys. J. C78 (2018) no.5, 394)
    Solves the Schrödinger equation for any strong interaction potential, Coulomb interaction and effects of quantum statistics
  - analytically using the Lednický-Lyuboshits approach (R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53, 770 (1982))
    The interaction is modelled using the scattering length (f_0) and the effective range (d_0)

ALICE – A Large Ion Collider Experiment

- Excellent particle identification in large kinematic range with the TPC (d*E*/dx) and TOF
- Direct detection of charged particles (p, K, π)
- Reconstruction of hyperons
  - $\Lambda \rightarrow p\pi^-$
  - $\Sigma^0 \rightarrow \Lambda\gamma$
  - $\Xi^- \rightarrow \Lambda\pi^-$
  - $\Omega^- \rightarrow \Lambda K^-$

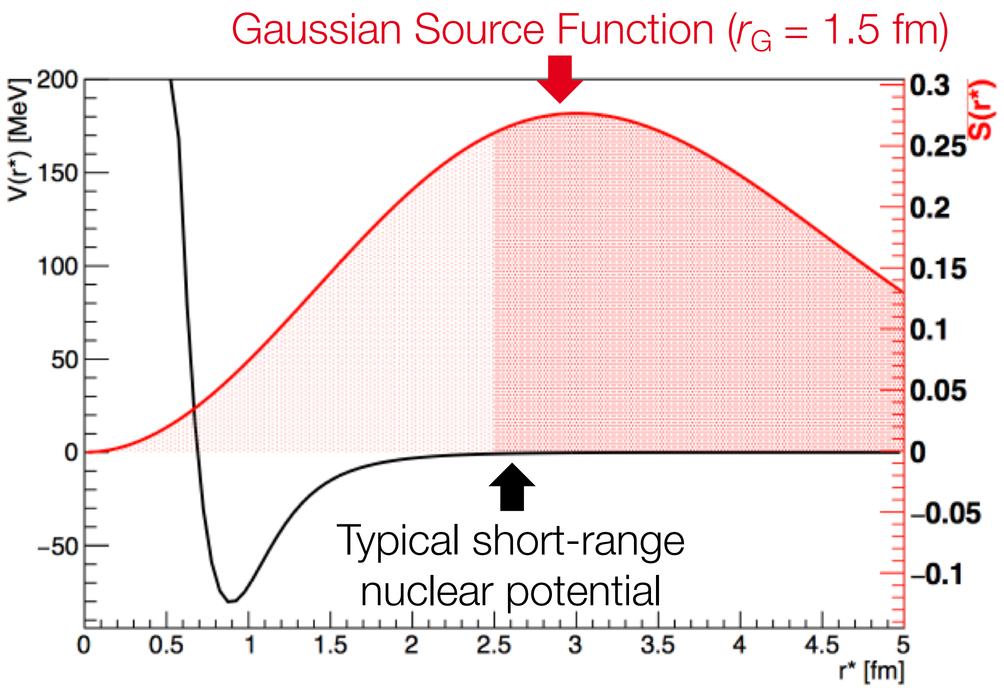
System	# events
pp 7 TeV	3.4 × 10^8 minimum bias
p–Pb 5.02 TeV	6.0 × 10^8 minimum bias
pp 13 TeV	15 × 10^8 minimum bias
	10 × 10^8 high multiplicity (0-0.072% INEL)

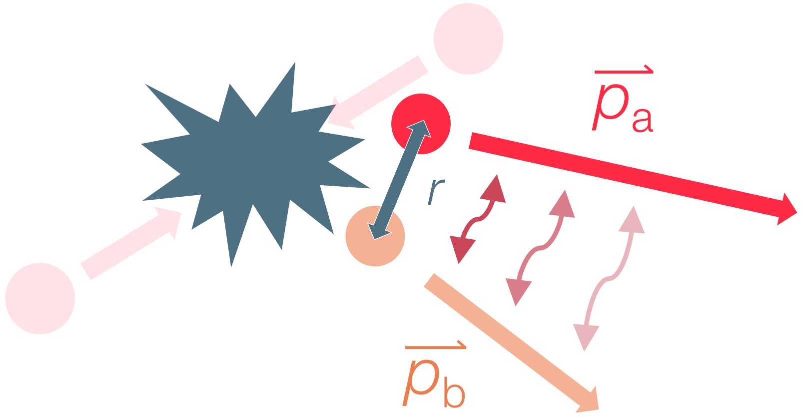


Run 1 (2009 – 2013)
Pb–Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV
p–Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV
pp @ $\sqrt{s}$ = 0.9, 2.76, **7**, 8 **TeV**

Run 2 (2015 – 2018)
Pb–Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV
Xe–Xe @ $\sqrt{s_{NN}}$ = 5.44 TeV
p–Pb @ $\sqrt{s_{NN}}$ = 5.02, 8.16 **TeV**
pp @ $\sqrt{s}$ = 5, **13 TeV**

The unique benefit of small sources

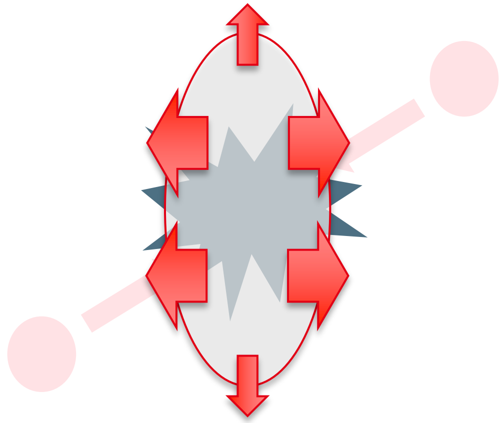


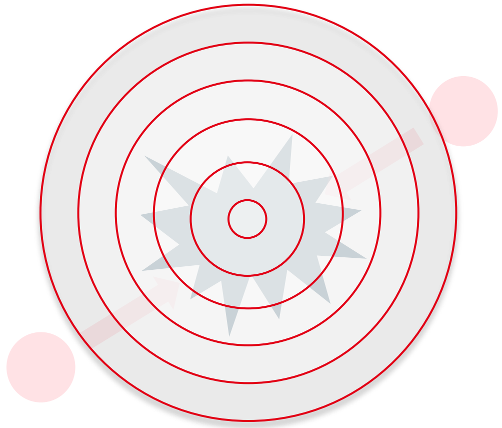


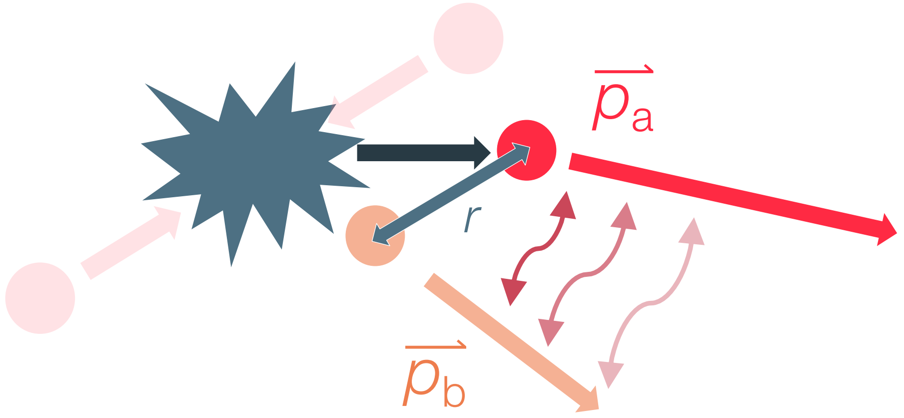
- Small particle-emitting source created in pp and p–Pb collisions at the LHC
  - Essential ingredient for detailed studies of the strong interaction
  - Assuming the same particle source for all pairs
- **p–p correlation** is used to constrain the source, since Coulomb and Strong interactions are well known
- K^+–p correlation is used as a cross-check (see talk by Laura Fabbietti on Tuesday)

Collective effects and strongly decaying resonances

(An)isotropic flow + Strongly decaying resonances







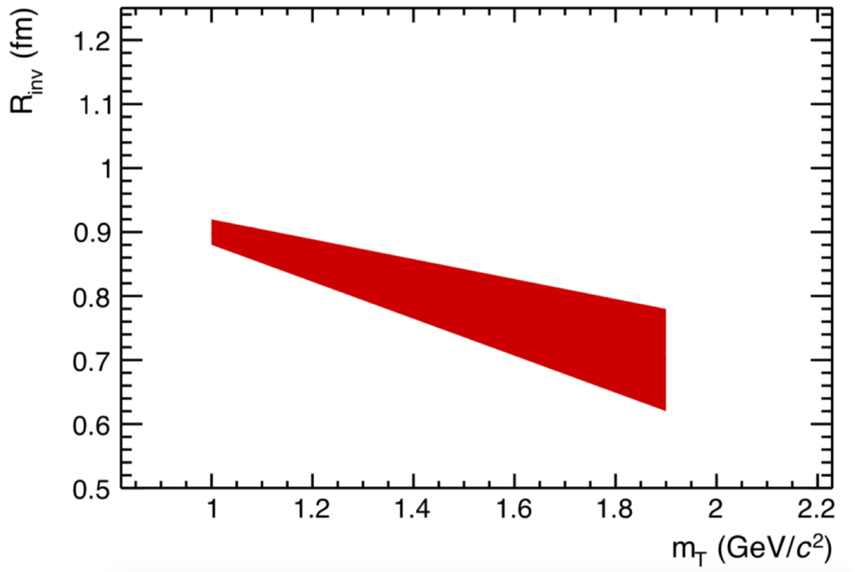
- *(An)isotropic pressure gradients* affect the emission
  - Initial geometric anisotropies introduce a transverse modulation
  - Expanding source with *common velocity field*
- Affects particles depending on their mass

- Resonances with $c\tau \sim r_0 \sim 1$ fm (Δ, N*) introduce an *exponential tail* to the source
- Different for each particle species!

Collective effects and strongly decaying resonances

(An)isotropic flow + **Strongly decaying resonances**

Gaussian core ⊗ Exponential tail



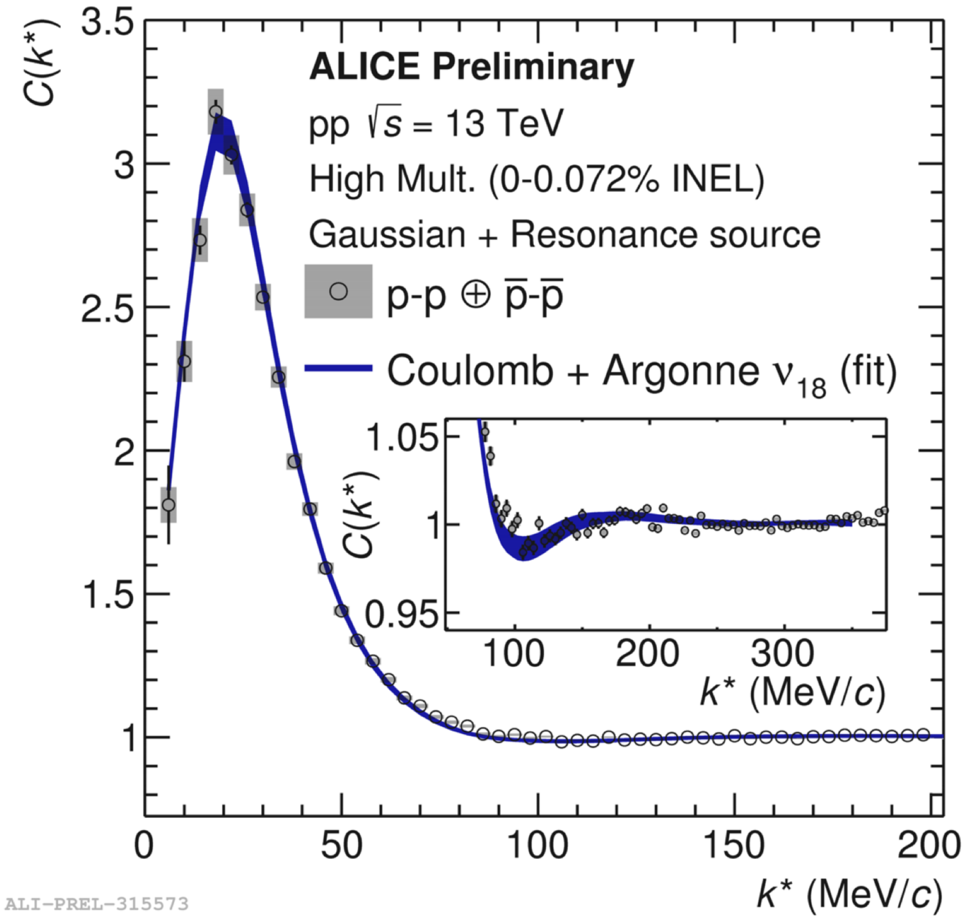
Particle	Primordial fraction	Resonances	
		$1 < c\tau < 2$ fm	$c\tau > 2$ fm
Proton	33 %	56 %	2 %
Lambda	35 %	8 %	58 %

- Yield of resonances determined from Canonical Statistical Hadronization Model
- Priv. Comm. with Prof. F. Becattini
  J.Phys. G38 (2011) 025002.

Application of the model to p–p correlations

(An)isotropic flow + **Strongly decaying resonances**

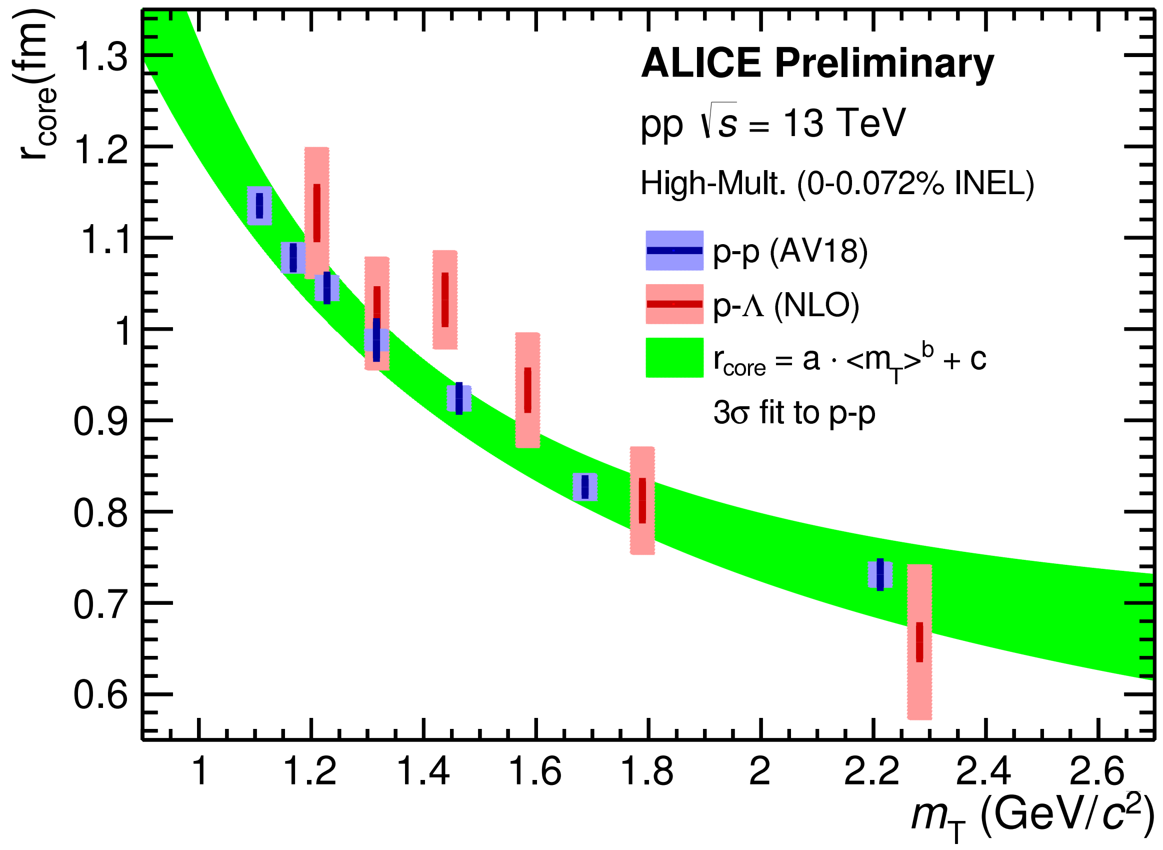
Gaussian core $\otimes$ Exponential tail



$$r_{\mathrm{Core}} = 0.995 \pm 0.005 \; ^{+0.024}_{-0.022} \text{ fm}$$

$$r_{\mathrm{Eff}} = 1.249 \pm 0.008 \; ^{+0.024}_{-0.021} \text{ fm}$$

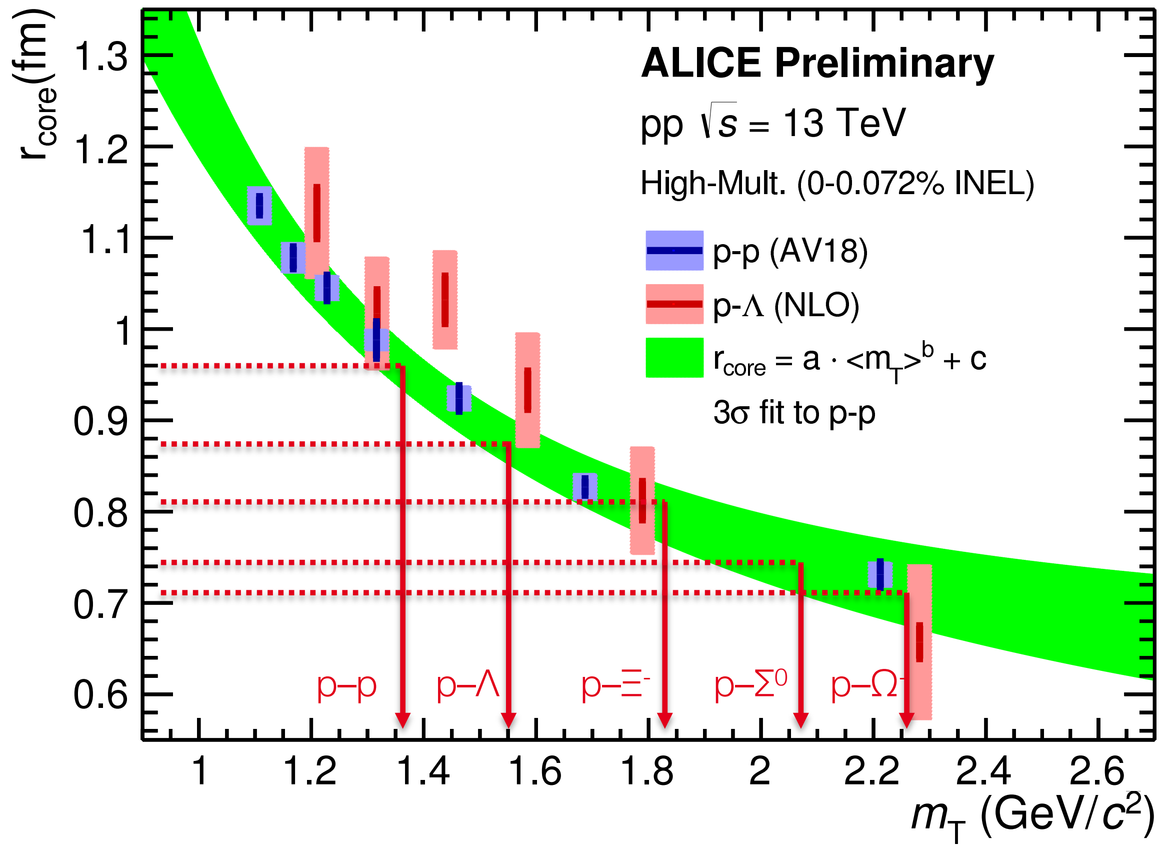
m_T dependence of the Gaussian *core* radius



ALI-PREL-315640

- Core radius for p–p and p–Λ in good agreement

m_T dependence of the Gaussian *core* radius

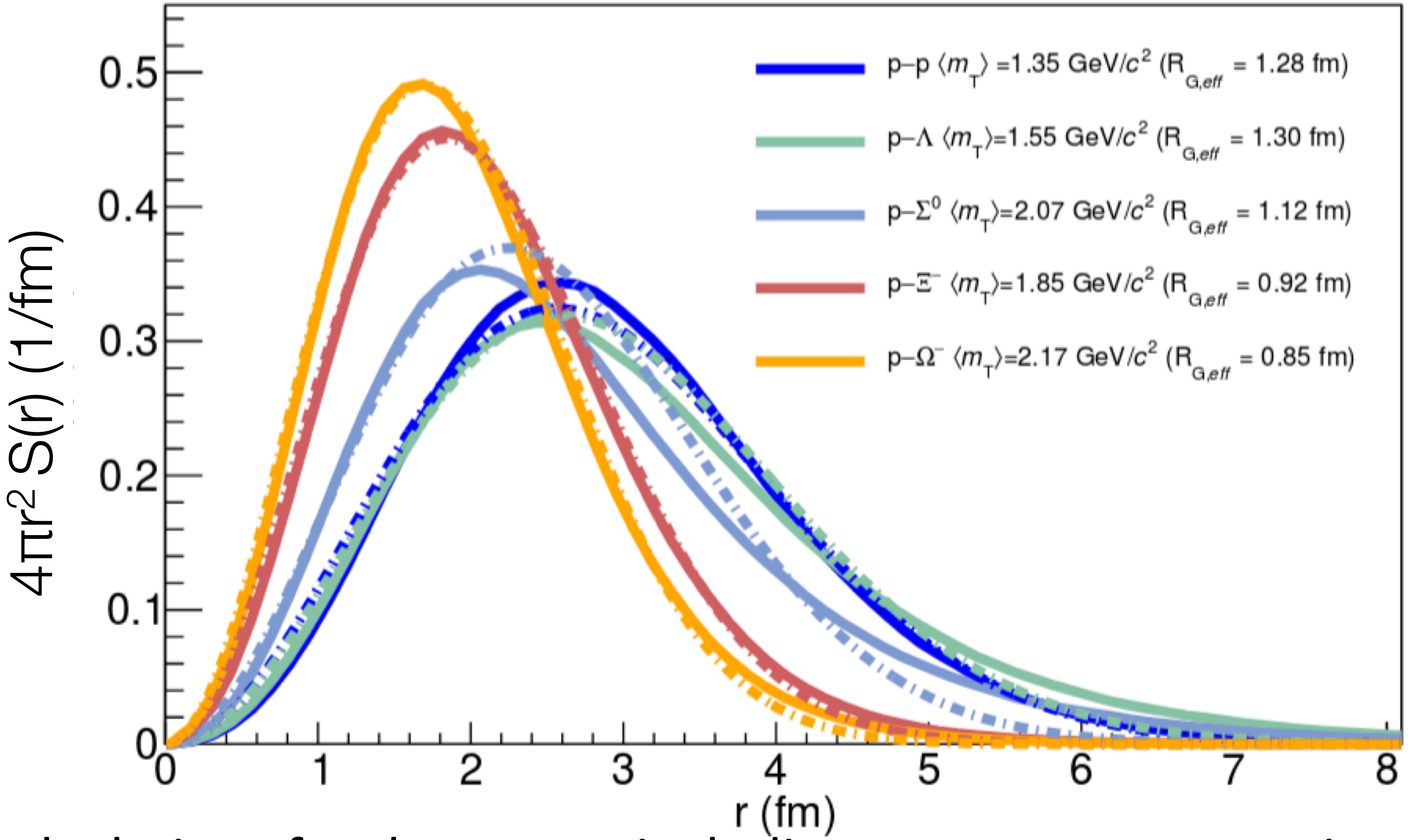


ALI-PREL-315640

Pair	r_{Core} (fm)	r_{Eff} (fm)
p–p	1.00	1.25
p–Λ	0.88	1.30
p–Σ^0	0.75	1.14
p–Ξ^-	0.80	0.92
p–Ω^-	0.73	0.85

- Fix the value of r_{Core} of each particle species based on their $\langle m_T \rangle$
  - Add specific resonance contribution to obtain the corresponding pair source

Source r_{Core} + resonances



More precise calculations for the source including strong resonances just completed.

Radii decrease by 7%

Femtoscopy with Λ and Σ baryons

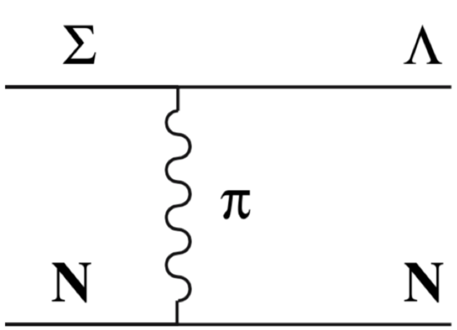
Precision and pioneering feasibility studies in the |S| = 1 sector

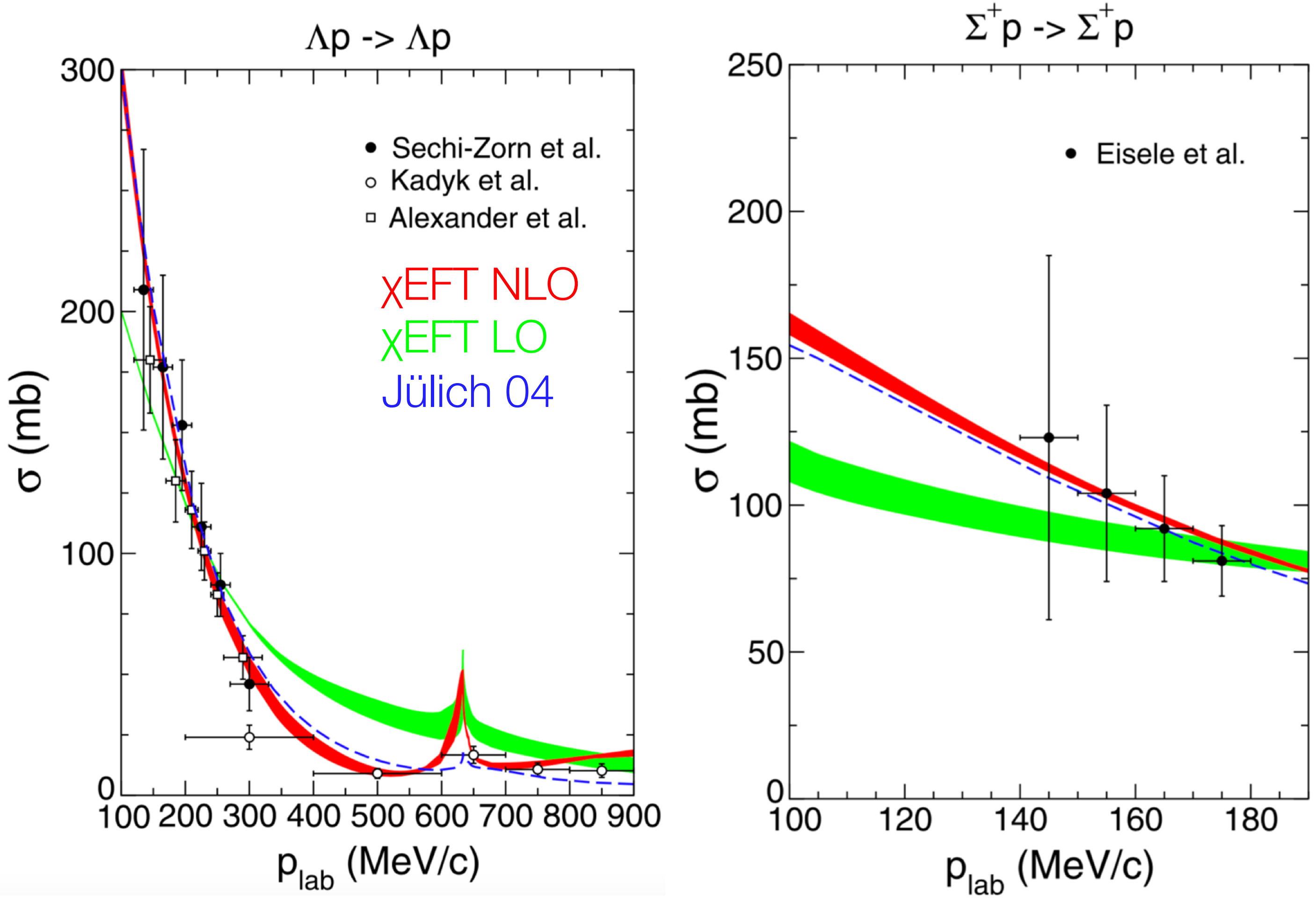
ALICE Collaboration, arXiv:1910.14407

pp $\sqrt{s}$ = 13 TeV (high mult.)

|S| = 1 sector – Λ and Σ baryons

- Scarce experimental data
  - No constraints at lab momenta below 100 MeV/*c*
- Theoretical predictions for cusp in Λ–N due to the Σ–N - Λ–N coupling
  - Coupling introduces a repulsive short range component in the p–Λ interaction

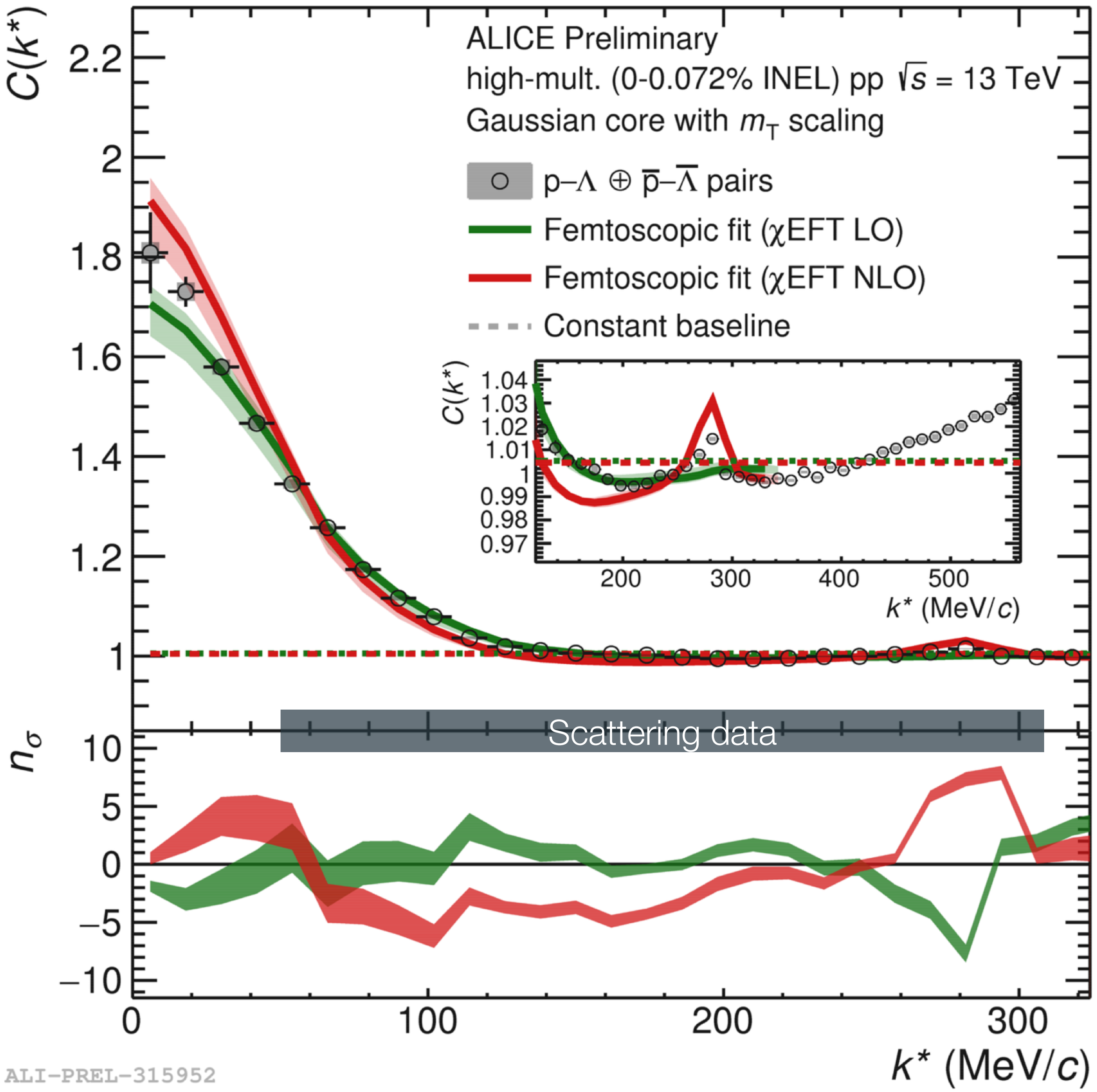




J. Haidenbauer et al., Nucl. Phys. A 915 (2013) 24.

p–Λ – entering a precision era

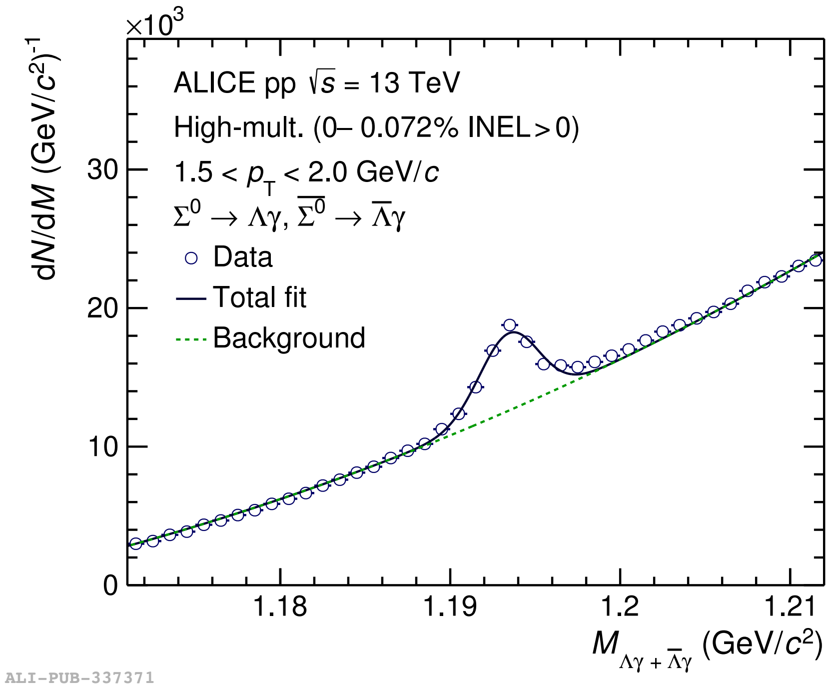
- Significant extension of the kinematic range
- Clear experimental evidence for the cusp
- Different variations of the baseline
  - Constant, linear & quadratic
  - Best fit for LO: $n_\sigma > 8$
  - Best fit for NLO: $n_\sigma > 10$
- Entering a precision era!

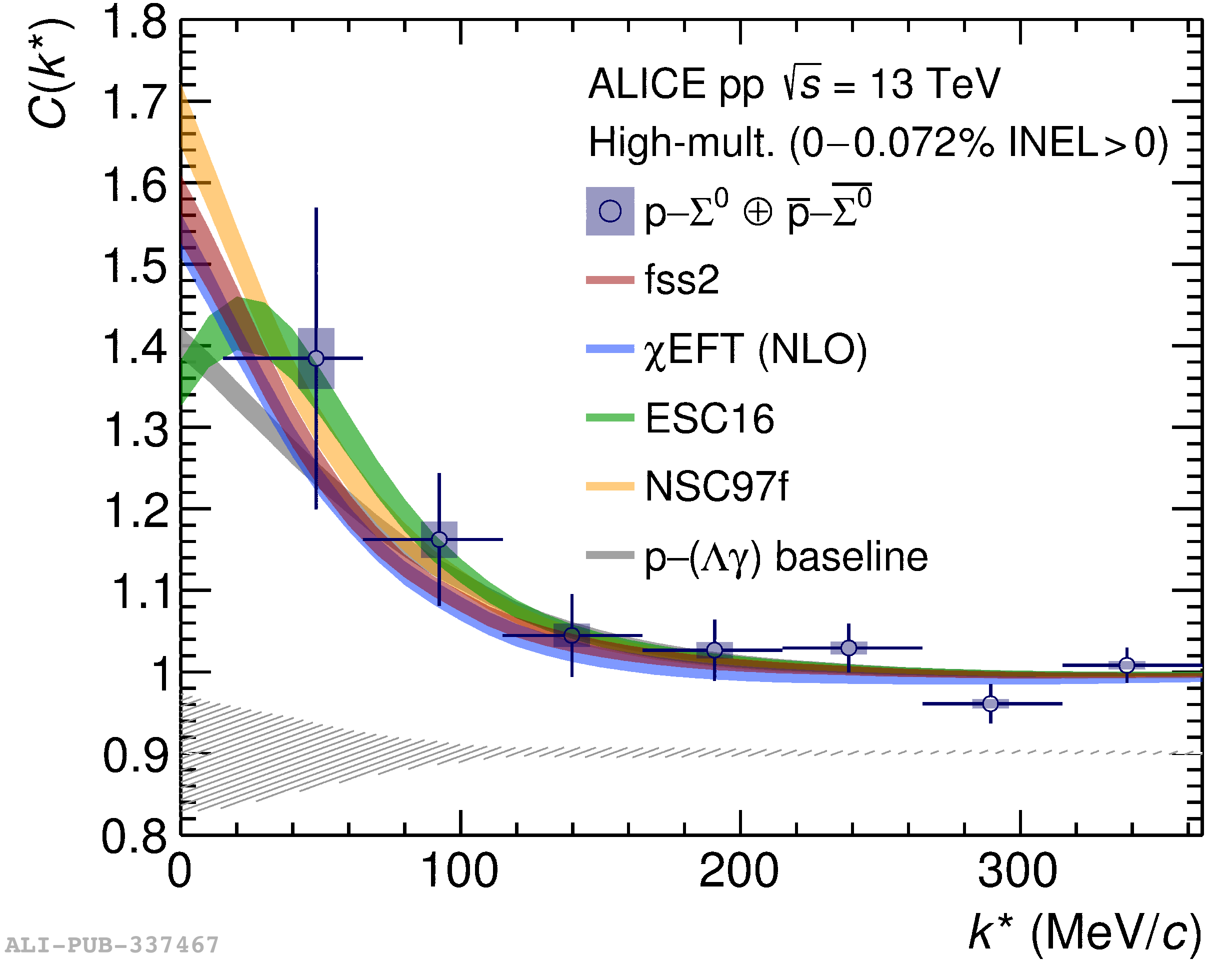


p–Σ⁰ – first measurement of the correlation function

ALICE Collaboration, arXiv:1910.14407

- $\Sigma^0 \rightarrow \Lambda\,\gamma$ (BR: almost 100 %)
  - Identification of the photon via conversions
  - Significant contribution from correlated p–(Λγ) background due to low purity
- Significant differences among the models will allow decisive measurements in future





χEFT: J. Haidenbauer et. al, Nucl. Phys. A915 (2013) 24–58.
NSC97f: T. A. Rijken et. al, Phys. Rev. C59 (1999) 21–40
ESC16: M. M. Nagels et. al, Phys. Rev. C99 (2019) 044003
fss2: Y. Fujiwara et al., Prog. Part. Nucl. Phys. 58, 439–520 (2007)

p–Ξ^- femtoscopy

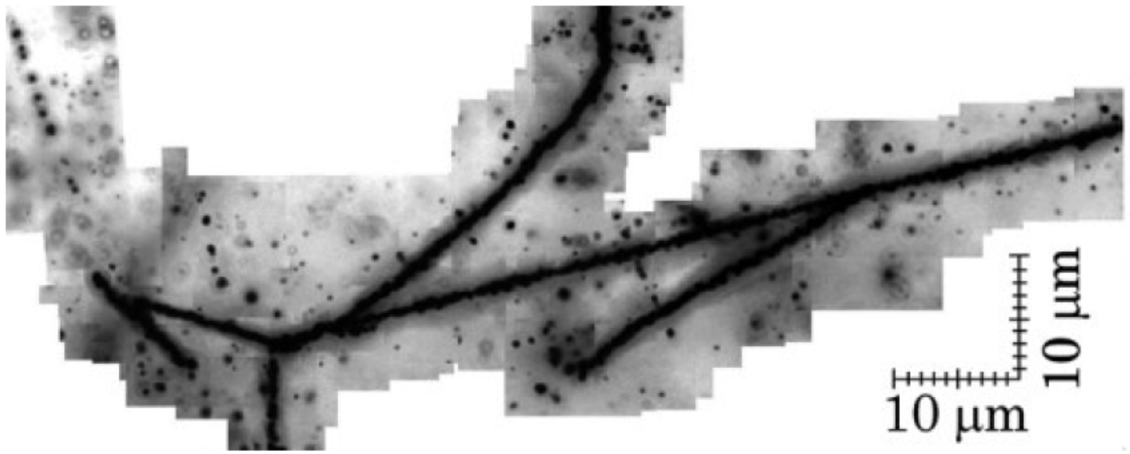
Benchmarking lattice QCD

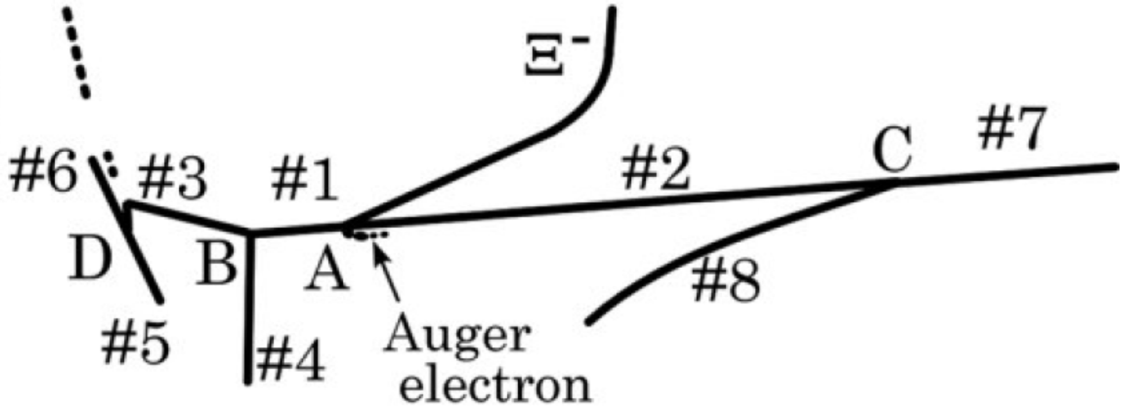
ALICE Collaboration, Phys. Rev. Lett. 123 (2019) 112002

pp $\sqrt{s}$ = 13 TeV (high mult.)
p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Experimental constraints on N–Ξ interaction

- Kiso and Ibuki Event: Ξ^- hypernuclei
  - Points towards an attractive interaction
  - Hyper nucleus binding energy $B_{\Xi^-} \sim 1$ MeV



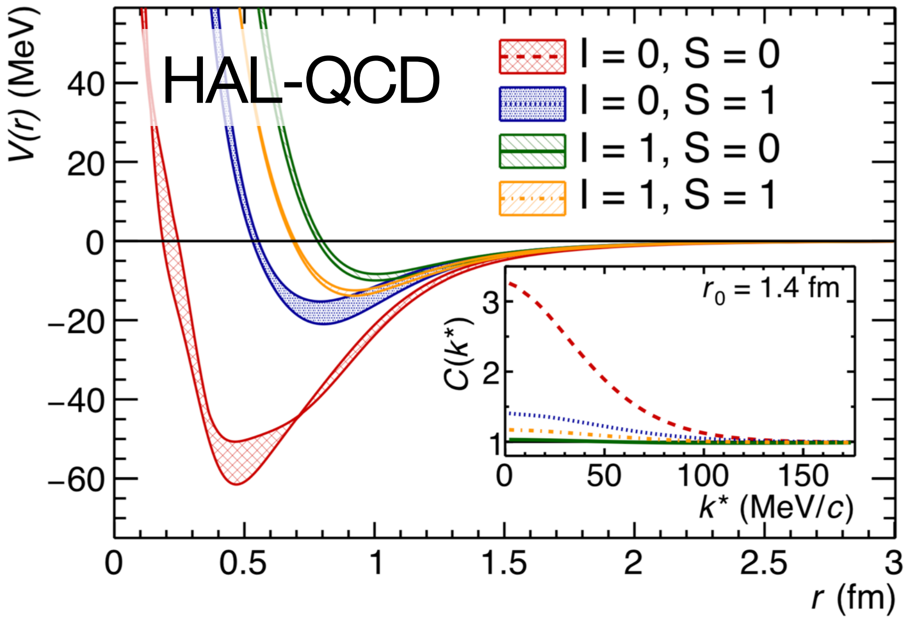


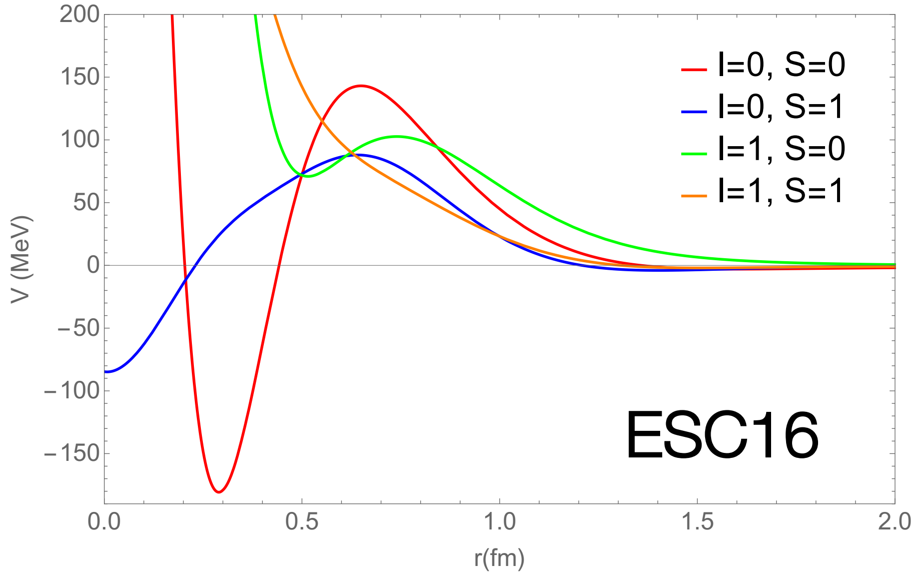
K. Nakazawa *et al.*, PTEP 2015, 033D02

Theoretical treatment of the N–Ξ interaction

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

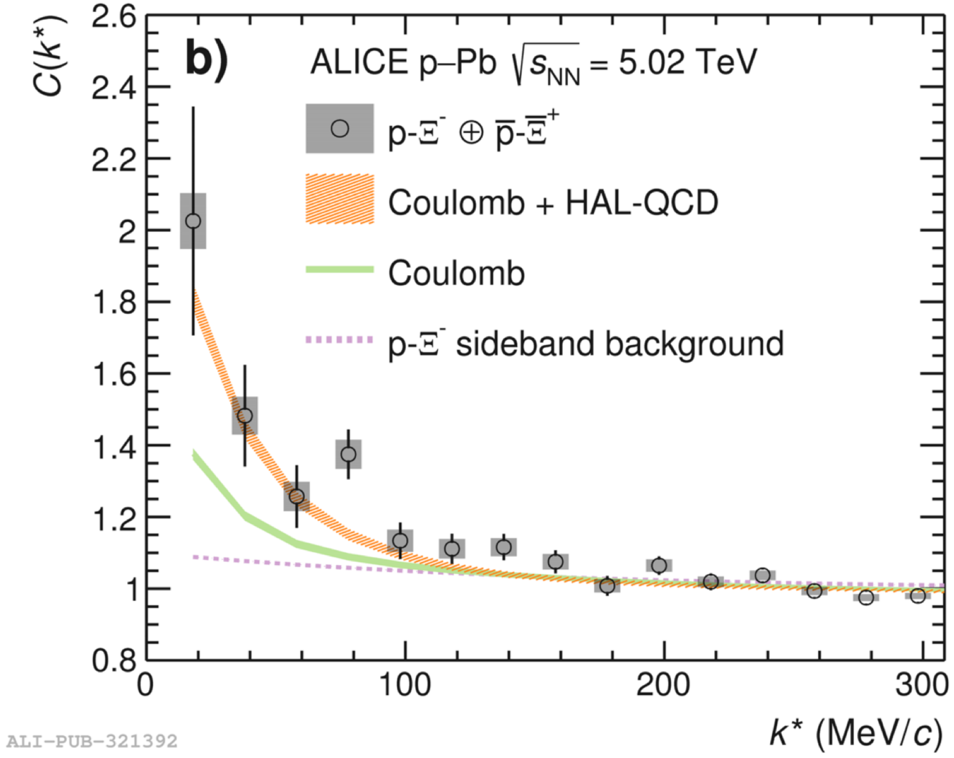
- Null Hypothesis: Coulomb only
- HAL QCD Potential with physical meson masses
  HAL QCD Collaboration, arXiv:1809.08932
  - m_π = 146 MeV/c^2
  - m_K = 525 MeV/c^2
- ESC16 potential by Nijmegen group
  M. M. Nagels et. al, Phys. Rev. C99 (2019) 044003





Benchmarking lattice QCD with p–Ξ^- correlations

ALICE Collaboration, PRL 123 (2019) 112002



Source for pΞ^-

r_{Core} = 0.80 ± 0.03 fm

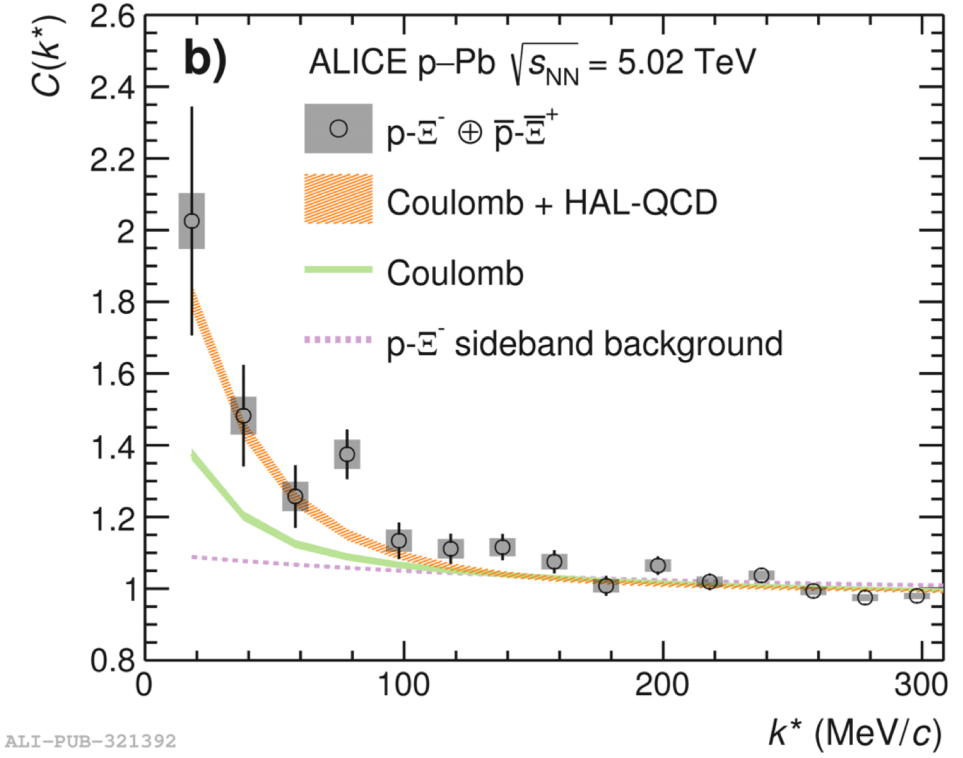
r_{Eff} = 0.92 ± 0.05 fm

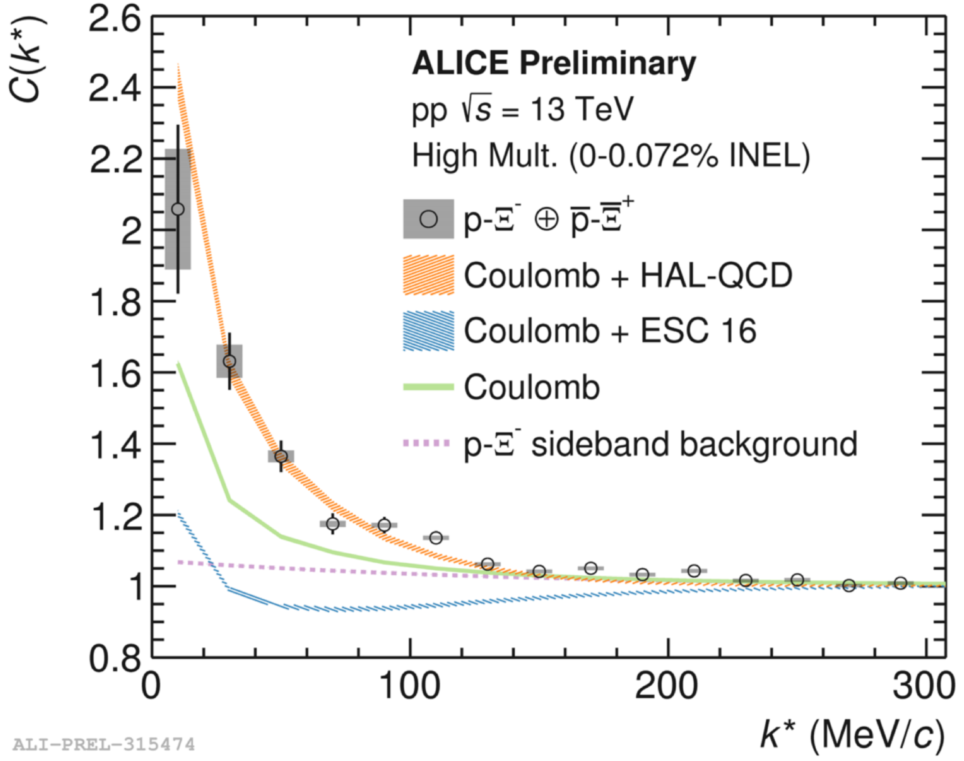
First observation of the strong interaction in p–Ξ^-

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

Benchmarking lattice QCD with p–Ξ⁻ correlations

ALICE Collaboration, PRL 123 (2019) 112002





First observation of the strong interaction in p–Ξ⁻

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

p–Ξ⁻ in pp 13 TeV (high mult.)

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

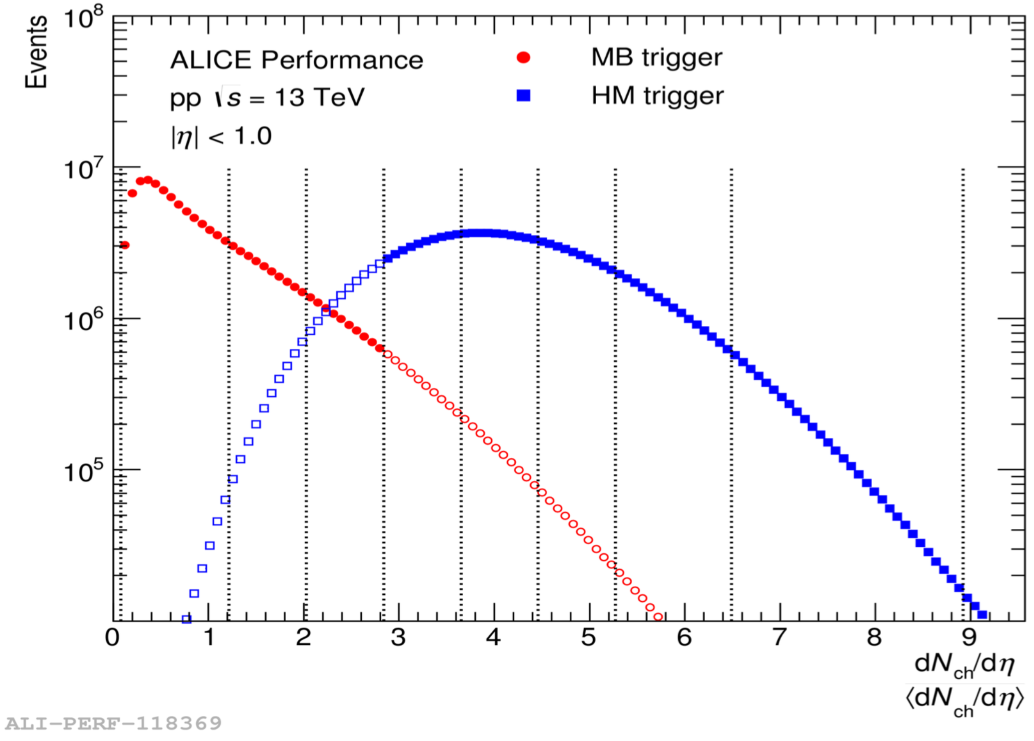
p–Ω femtoscopy

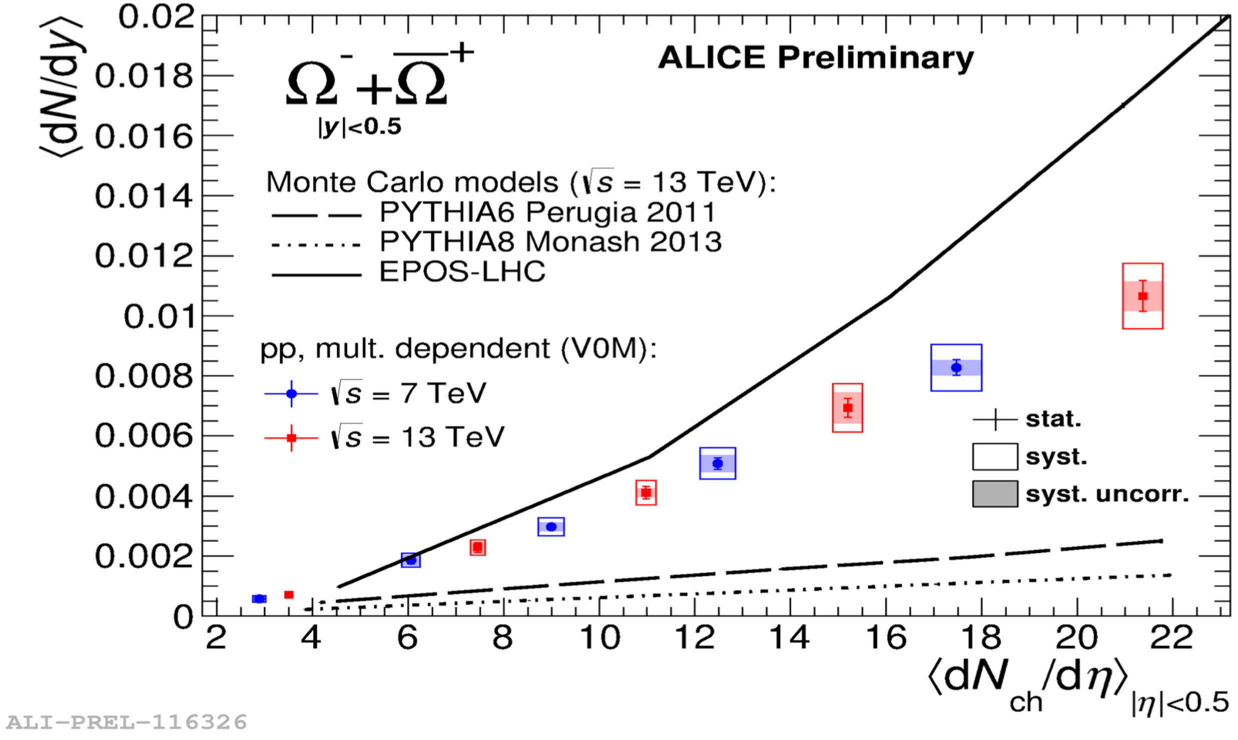
Benchmarking lattice QCD and Search for Bound States

pp $\sqrt{s}$ = 13 TeV (high mult.)

ALICE pp High Multiplicity Data

- **High multiplicity trigger**: 0.1% highest multiplicity with respect to Minimum Bias events (V0M, forward rapidities: 2.8 < η < 5.1, –3.7 < η < –1.7).
  - Increased yield of Ω baryon





Ω^- Reconstruction

- Identified by its decay: $\Omega^- \rightarrow \Lambda K^- \rightarrow (p\pi^-)K^-$
- Total of 1.2×10^6 selected $(\Omega^-+\Omega^+)$ candidates:
  - 0.6×10^6 p-Ω- ⊕ p-Ω+ pairs
  - 11×10^3 pairs at k*<300 MeV/c
  - 700 pairs at k*<100 MeV/c
- Purity of the preliminary sample **75%**

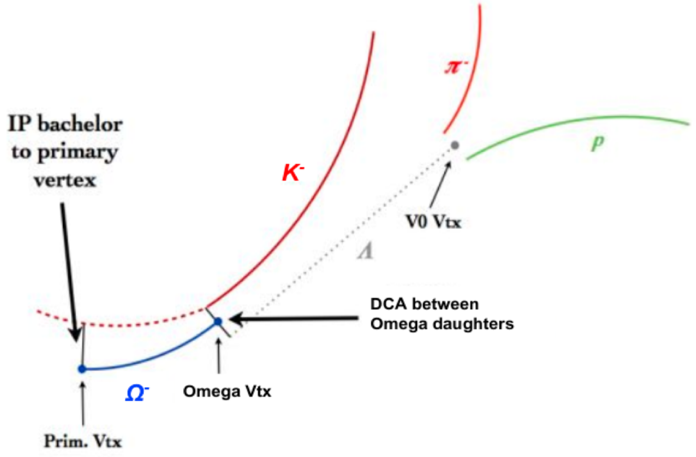
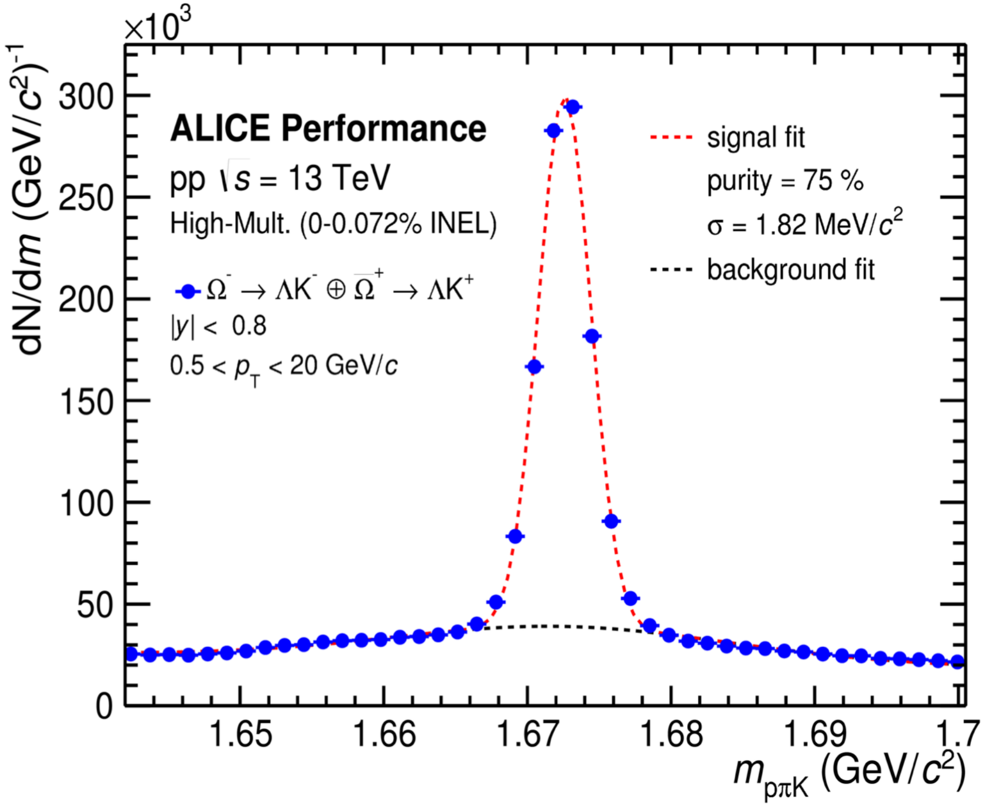
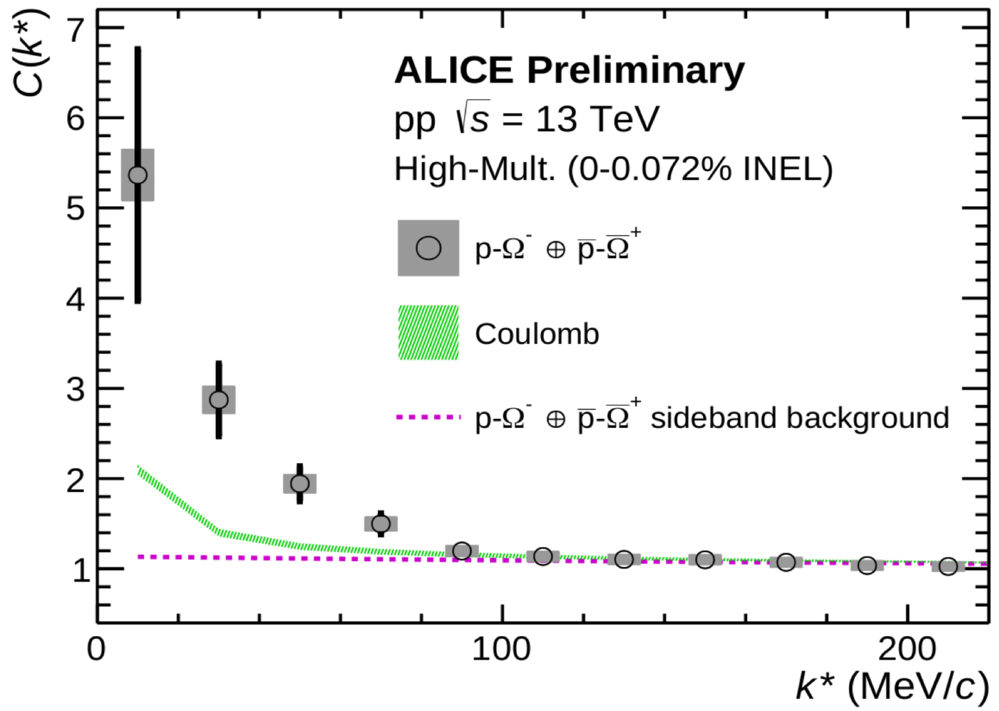


Fig. 2: Sketch of the Ω⁻ decay and identification.



p-Ω^- correlation function in pp HM

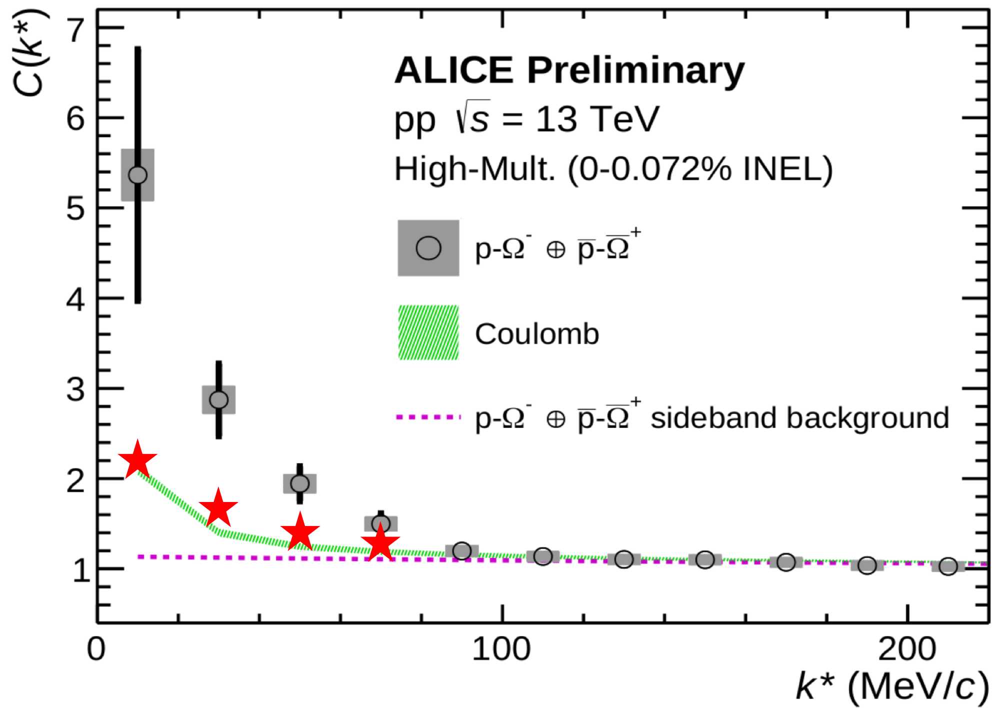


- "Coulomb only" scenario discarded by ALICE data (> 6σ) showing the attractive character of the interaction
- Source for pΩ-

  r_{Core}= 0.73 ± 0.05 fm (without Resonances)

  r_{Eff}= 0.85 ± 0.07 fm

p-Ω⁻ correlation function in pp HM

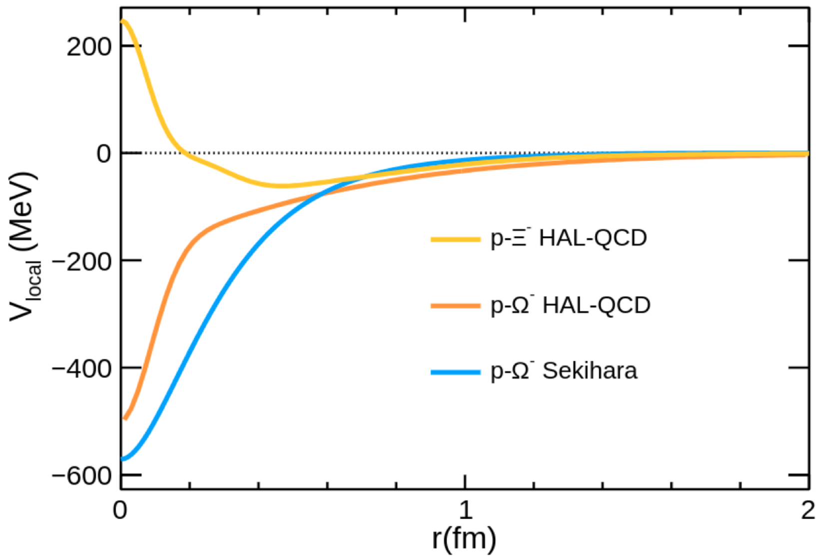


- “Coulomb only” scenario discarded by ALICE data (> 6σ) showing the attractive character of the interaction
- Source for pΩ-

  r_{Core}= 0.73 ± 0.05 fm (without Resonances)

  r_{Eff}= 0.85 ± 0.07 fm

★ $p\Xi^-$ Experimental Correlation



p-Ω^- Interaction Potentials

- Lattice **HAL-QCD** potential with physical quark masses ($^5S_2$ channel)
  - m_π = 146 MeV/c^2
  - m_K = 525 MeV/c^2

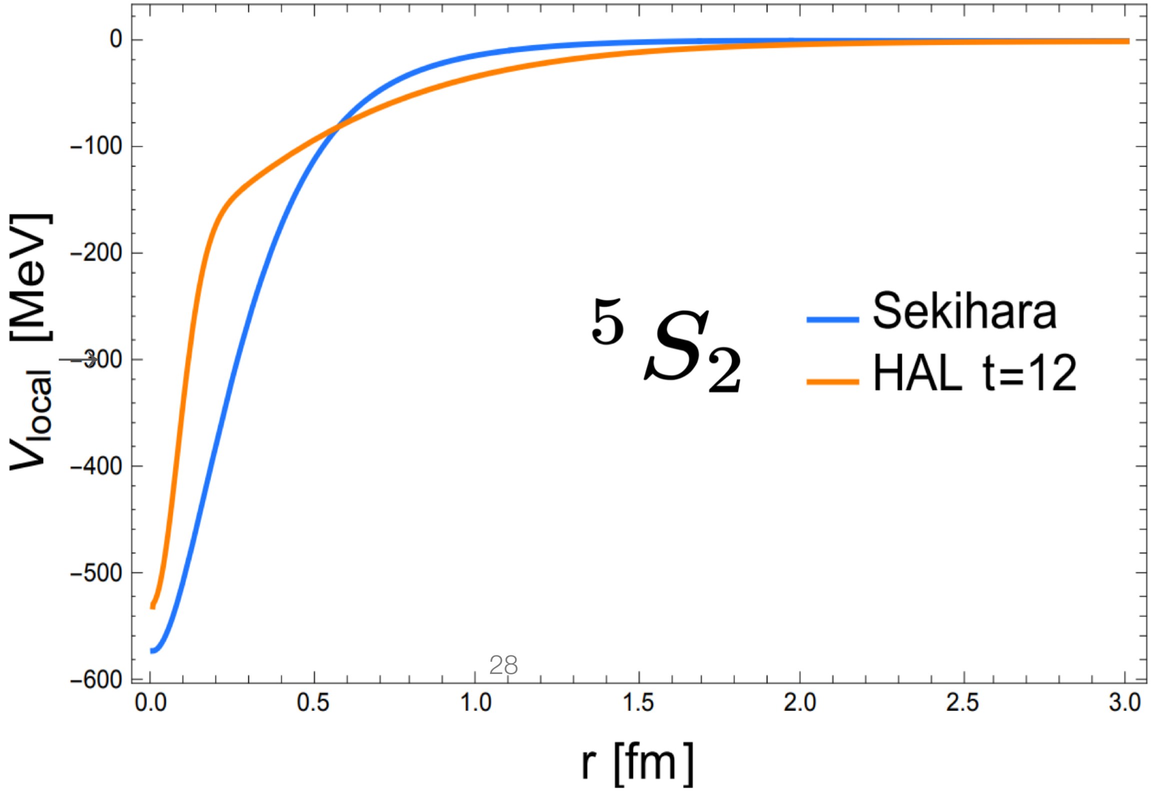
  T. Iritani et al., arXiv:1810.03416

- **Sekihara**: Meson-exchange model ($^5S_2$ channel)
  - Short range attractive interaction fitted to HAL-QCD scattering parameters
  - Includes inelastic channels (strong decays into XΞ) small contributions in the S-wave interaction

  T. Sekihara et al., Phys. Rev. C 98, 015205 (2018)

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)

Model to Data Comparison

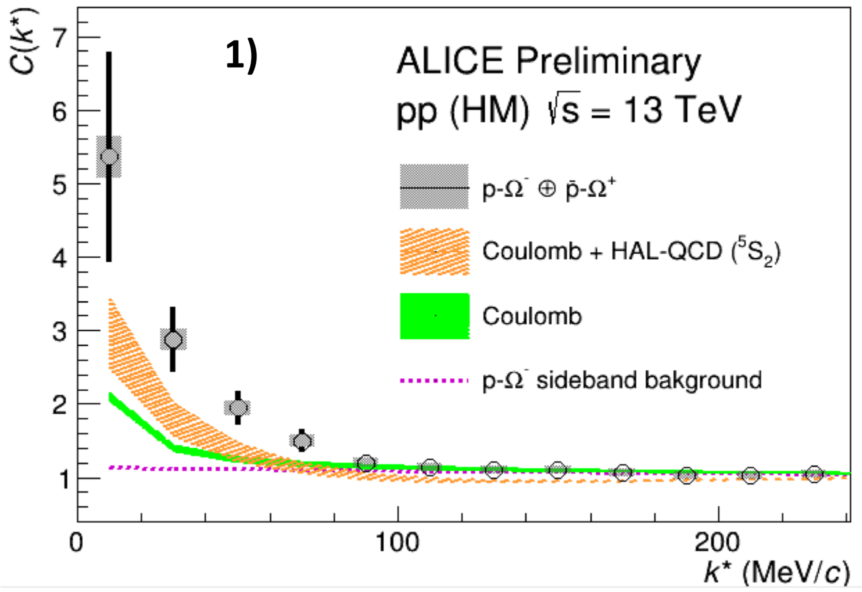
Calculations provide the potential shape for the $^5S_2$ channel (weight ⅝). **Currently, no model for the other channel in S-wave interaction, $^3S_1$ (weight ⅜)**. Requires coupled channel treatment.

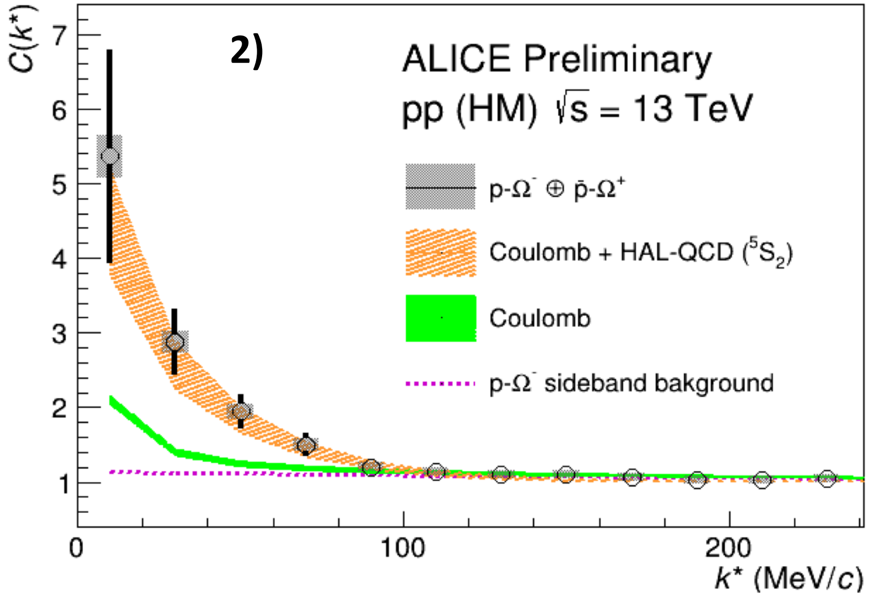
Assume <u>two different (~extreme) scenarios</u>:

1.- Complete absorption for distances $r < r_0$. K. Morita, A. Ohnishi, F. Etminan, T. Hatsuda, Phys. Rev. C 94 (2016), 031901

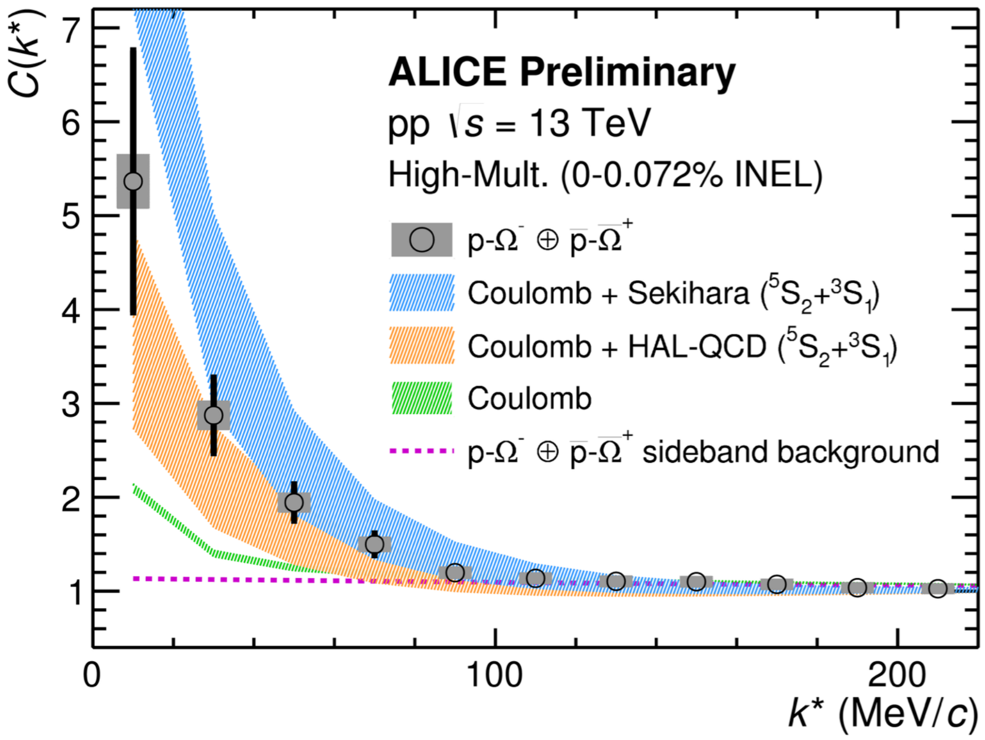
$r_0 = 2$fm, chosen from the condition $|V(^5S_2)| < |V(\text{Coulomb})|$ for $r > r_0$

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





Model to Data Comparison

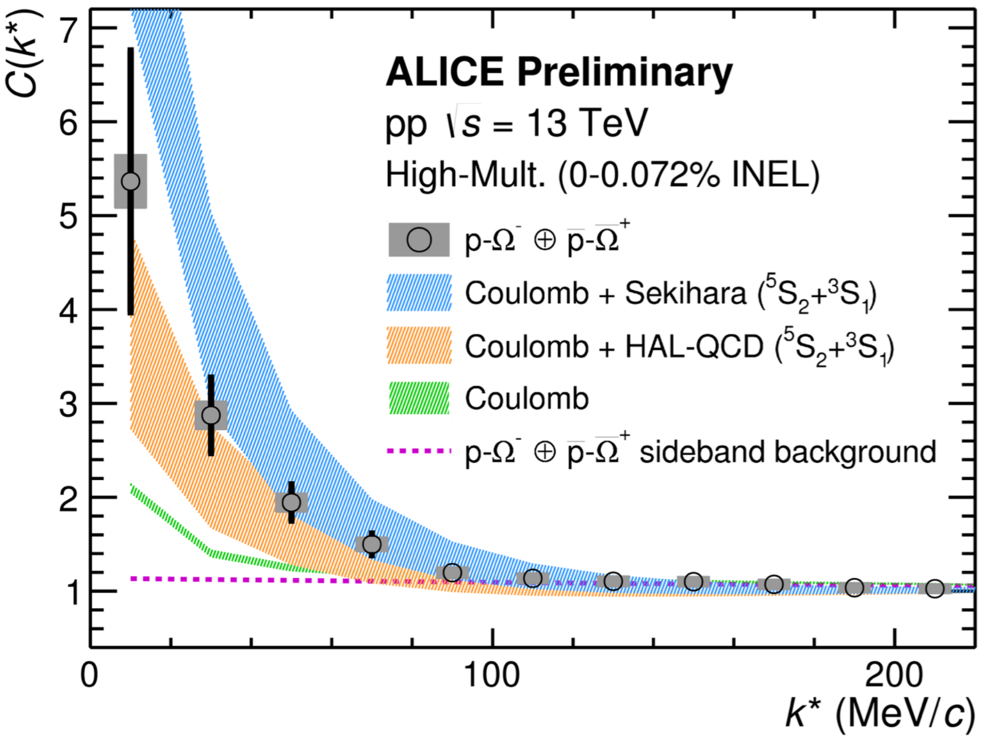


ALI-PREL-325875

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

Precision of ALICE data exceeds the theoretical predictions

Model to Data Comparison



ALI-PREL-325875

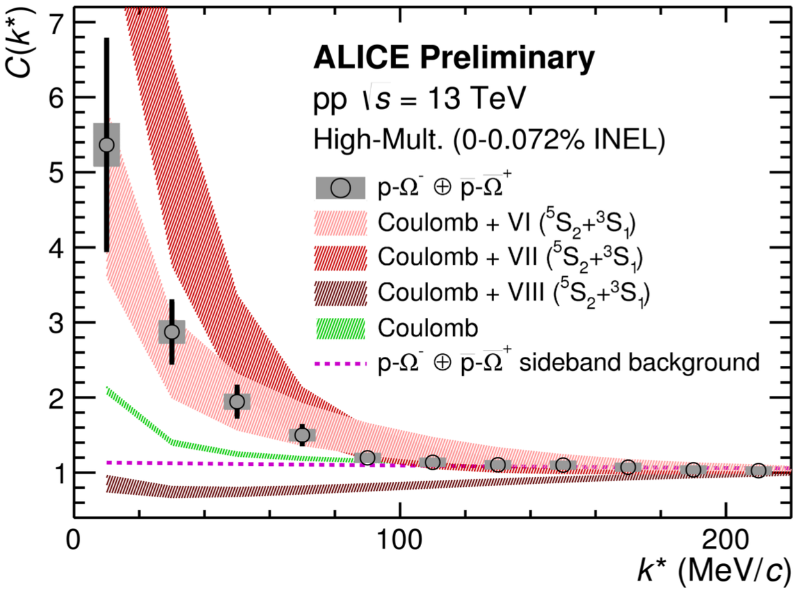
"Coulomb only" scenario discarded by ALICE data (> 6 σ) showing the attractive character of the interaction

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

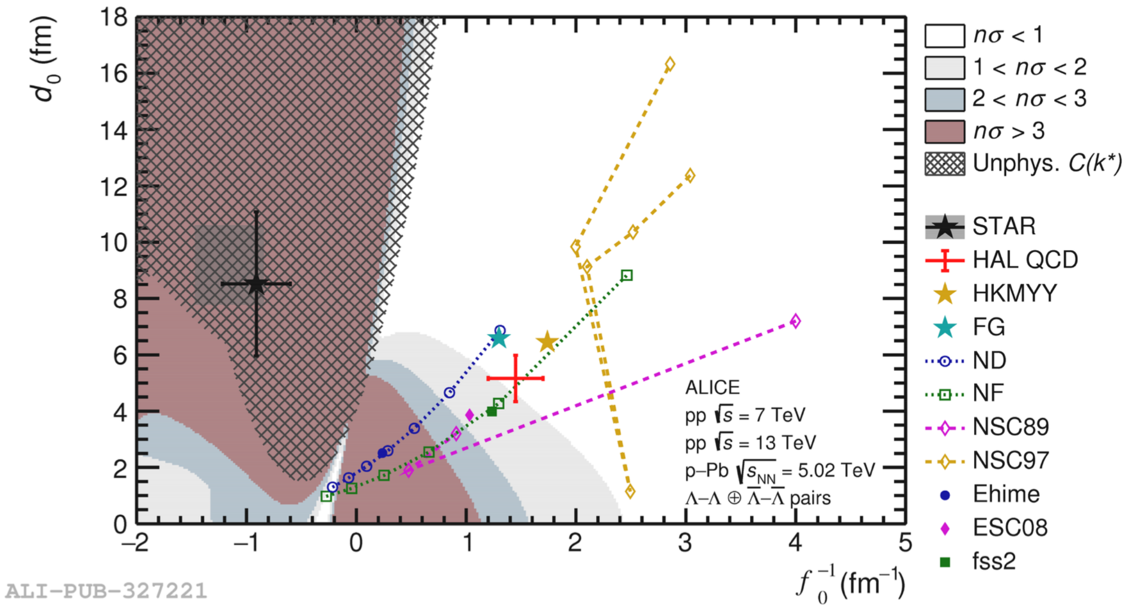


ALI-PREL-325870

What I did not show

ΛΛ Exclusion Plot

ALICE Collaboration, PLB 797 (2019) 134822

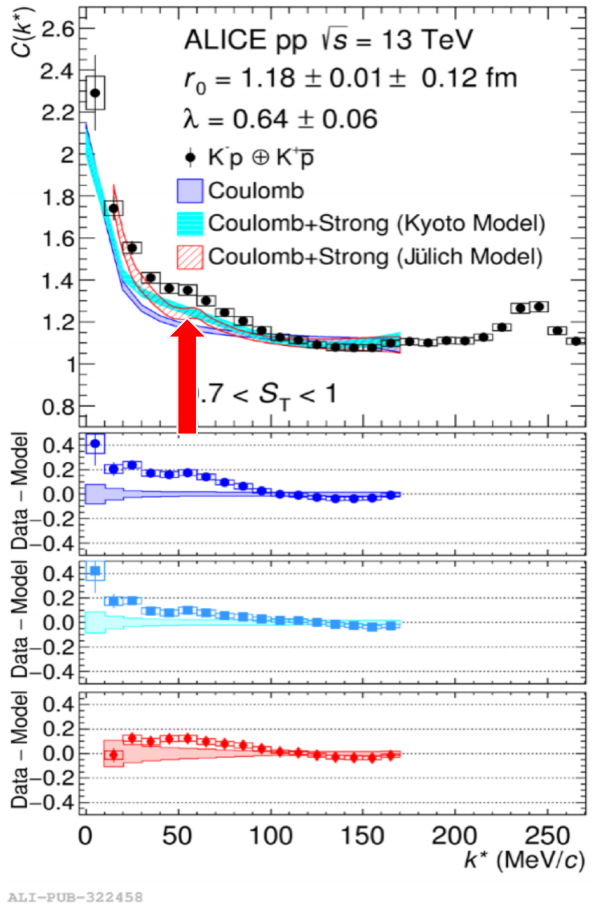


H-Dibaryon: Tight constraints on the allowed binding energy

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

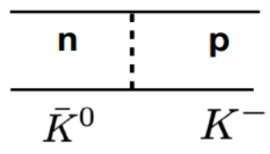
pK⁻ Interaction

ALICE Collaboration, arXiv:1905.13470[nucl-ex]



Coupled channel effect

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



Summary

- ALICE provides **precise data** to test hadron-hadron interactions

- Entering the precision era in the |S| = 1 sector
  - Experimental confirmation of cusp effect in p–Λ
  - Measurements feasible even in the Σ sector

- p–Ξ^- correlations show attractive strong interaction
  - Validation of lattice QCD potentials at physical quark masses

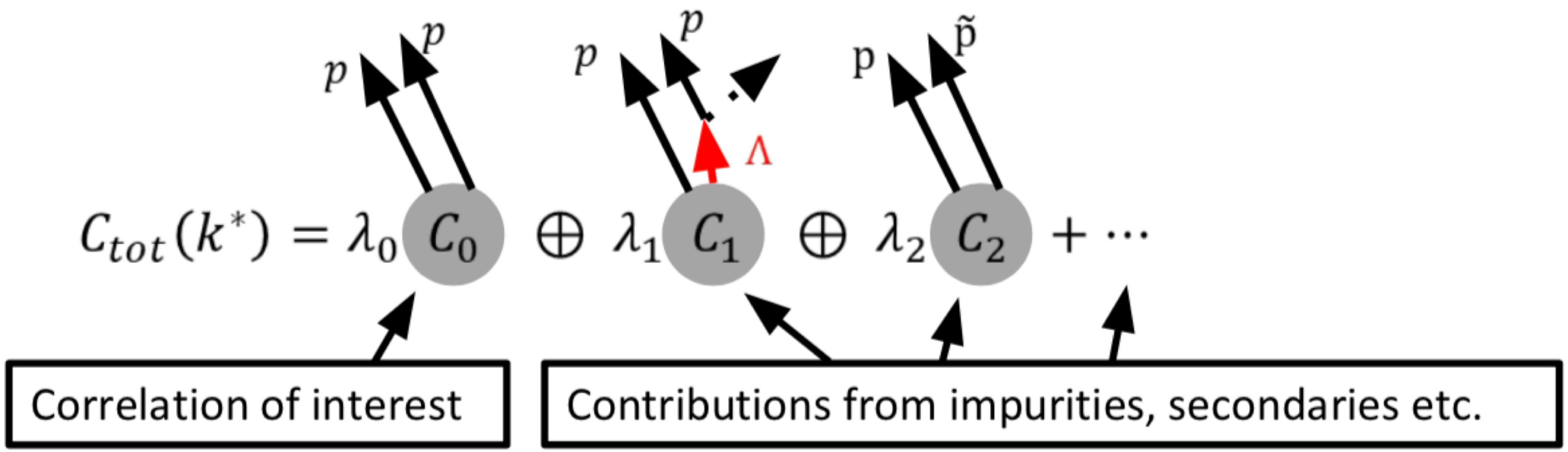
- p-Ω^- correlations shows attractive strong interaction
  - Data more precise than models. Weakly bound state not excluded

- Upcoming results: p–d, B-$\bar{B}$ and p–ϕ

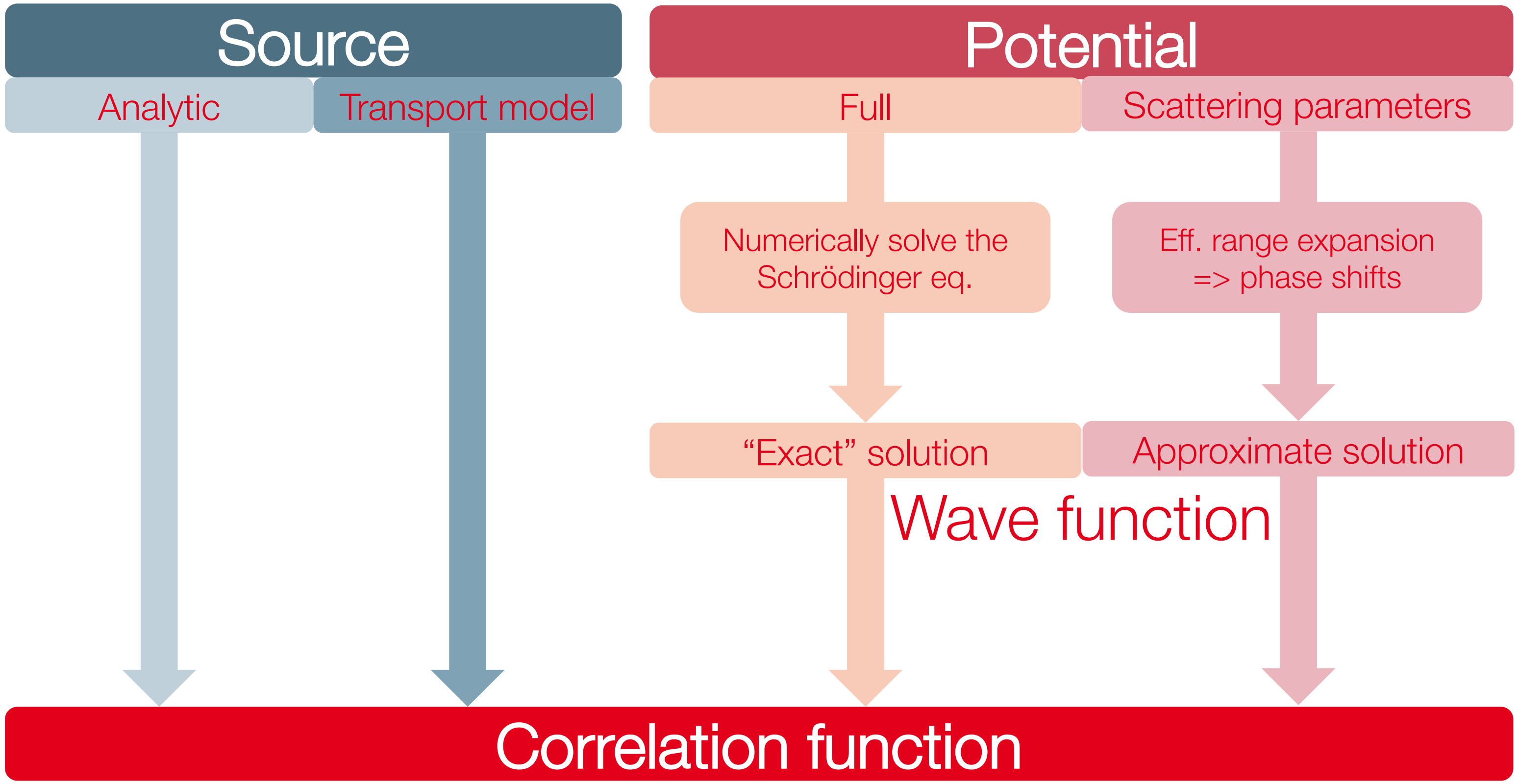
Thank you for your attention!

Decomposition of the correlation function

- Purities, fake fraction and material secondaries are determined either from simulations or template fits for single particles
  - ALICE Collab. PRC 99 (2019), 024001.
- The contribution of weak decays is obtained from MC
- Resolution effects applied to the fit function



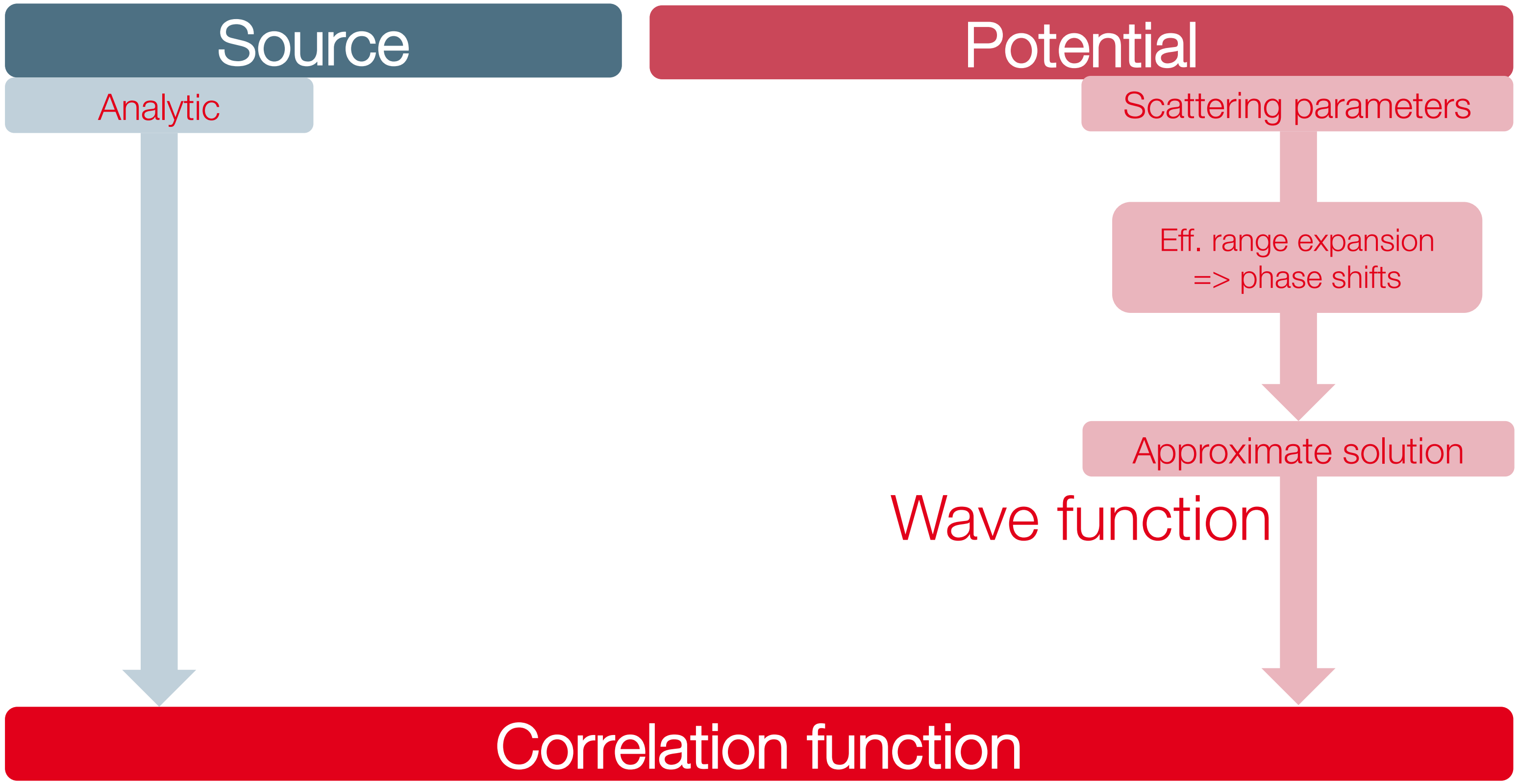
Modelling the correlation function



$$C(k^*) = \frac{P(\mathbf{p}_a, \mathbf{p}_b)}{P(\mathbf{p}_a)P(\mathbf{p}_b)} = \mathcal{N} \cdot \frac{N_{same}}{N_{mixed}} = \int S(r) \; |\Psi(k^*, \vec{r})|^2 \, d\vec{r}$$

Emission source — Two-particle wave function

Lednicky model

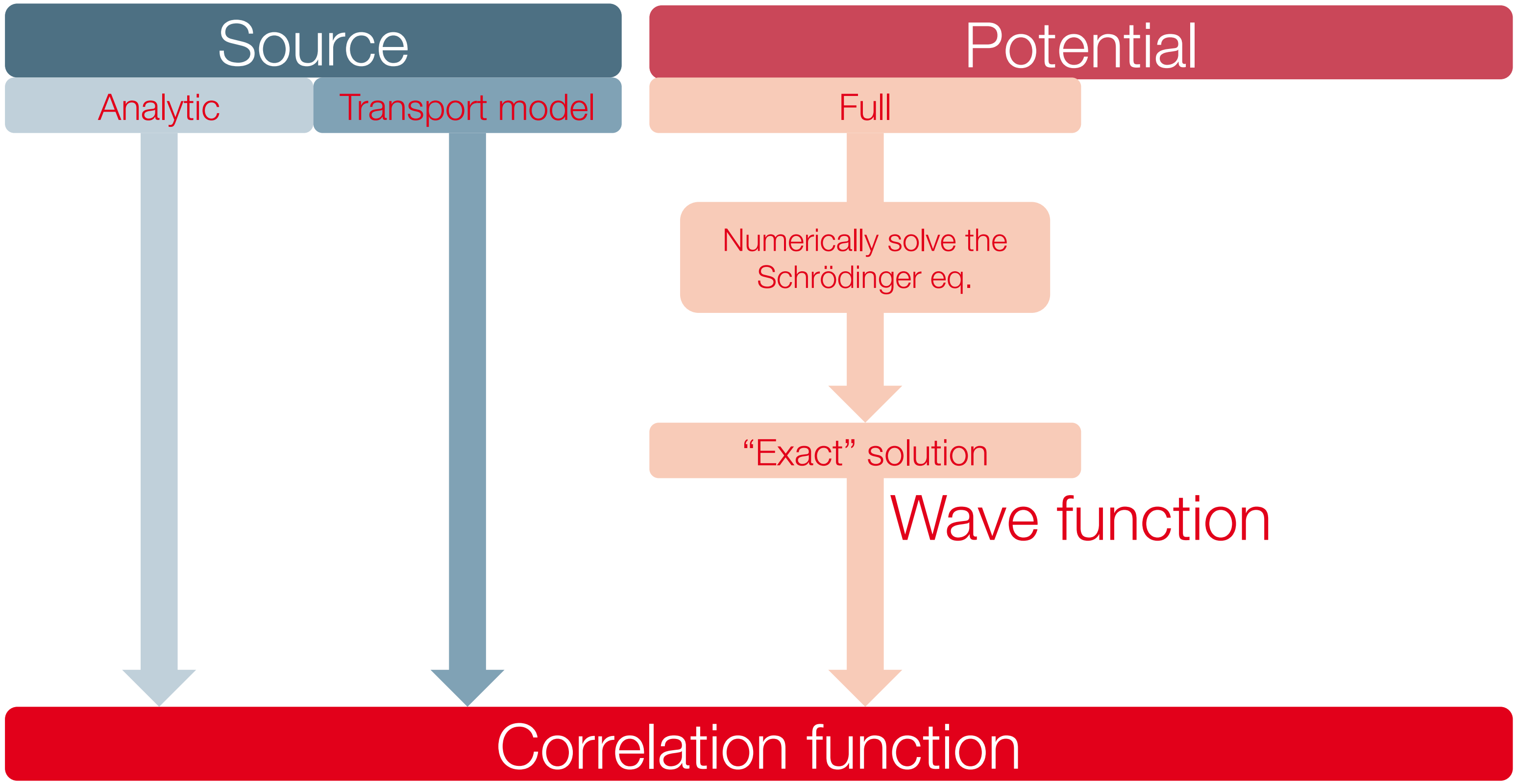


$$C(k) = 1+\sum_S \rho_S \left[\frac{1}{2}\left|\frac{f^S(k)}{R_G^{\Lambda p}}\right|^2 \left(1-\frac{d_0^S}{2\sqrt{\pi}R_G^{\Lambda p}}\right) + 2\frac{\mathcal{R}f^S(k)}{\sqrt{\pi}R_G^{\Lambda p}}F_1(QR_G^{\Lambda p}) - \frac{\mathcal{I}f^S(k)}{R_G^{\Lambda p}}F_2(QR_G^{\Lambda p})\right]$$

R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53, 770 (1982)

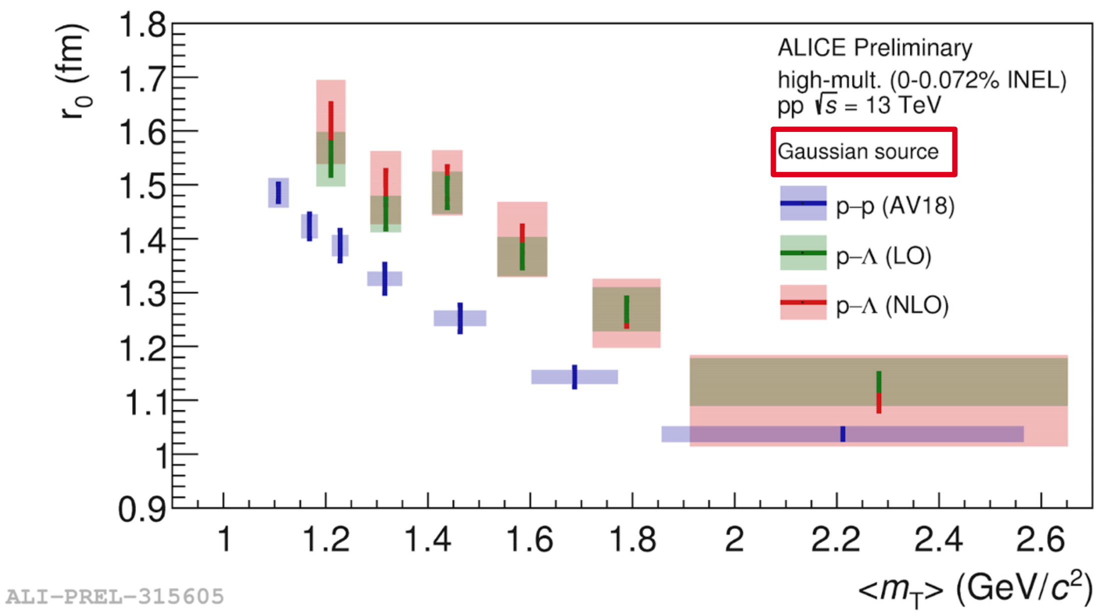
- Might locally break down for small sources

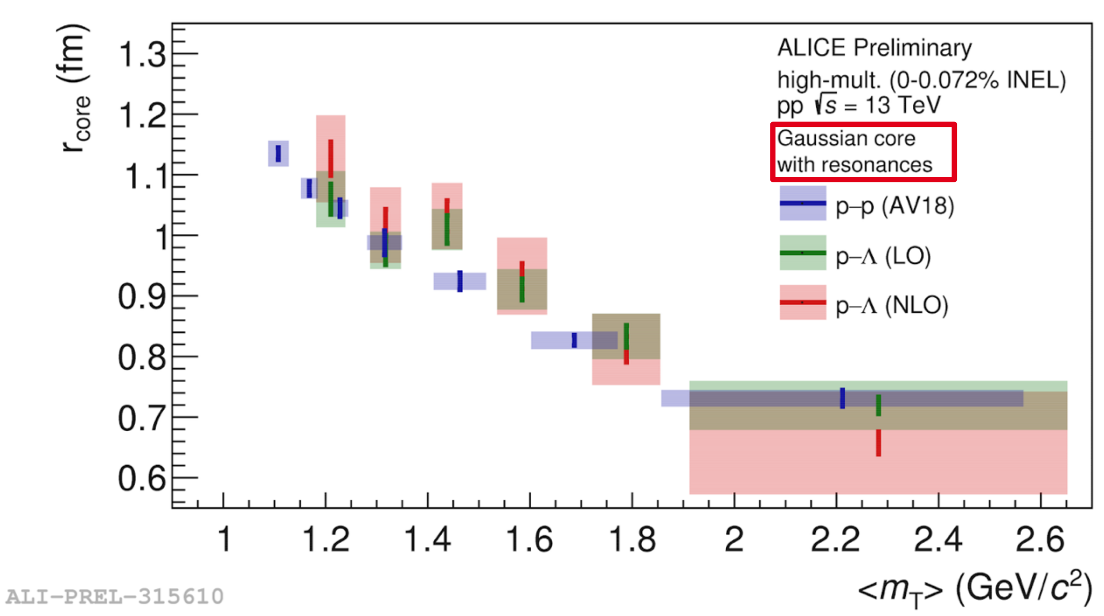
CATS



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

The source function

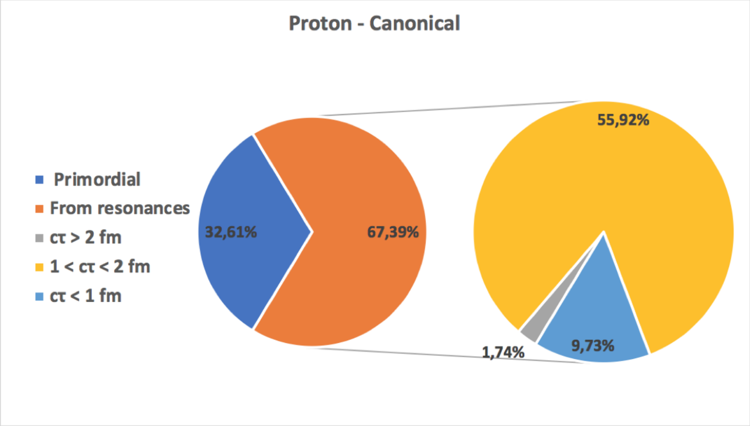


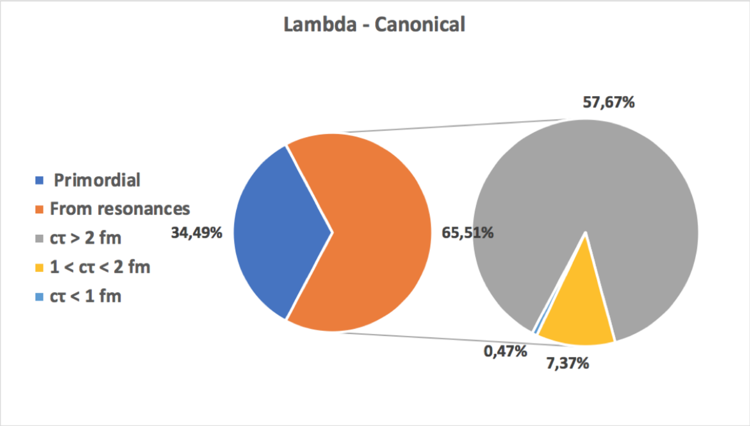


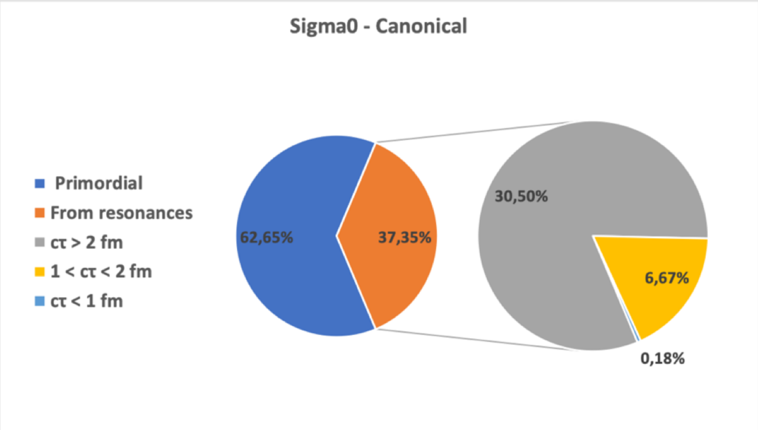
- Each $<m_T>$ bin fitted independently with the two source models
- The results are compared for p-p and p-Λ correlation
- Our Ansatz: The scaling should be the same.
  - The basic MC model works

Details on short-lived resonances

Private Comm. Prof. F. Becattini, J. Phys. G38 (2011) 025002



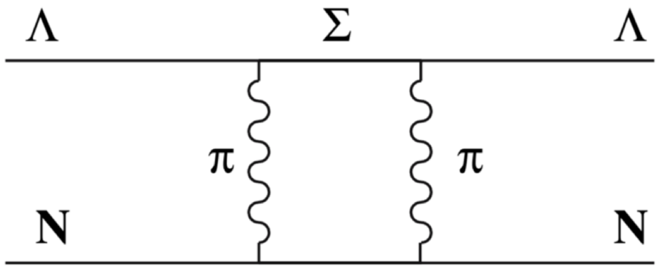




- For Ξ^- and Ω^- **no contributions**!
- Average mass and average cτ determined by the weighted average values of all resonances

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

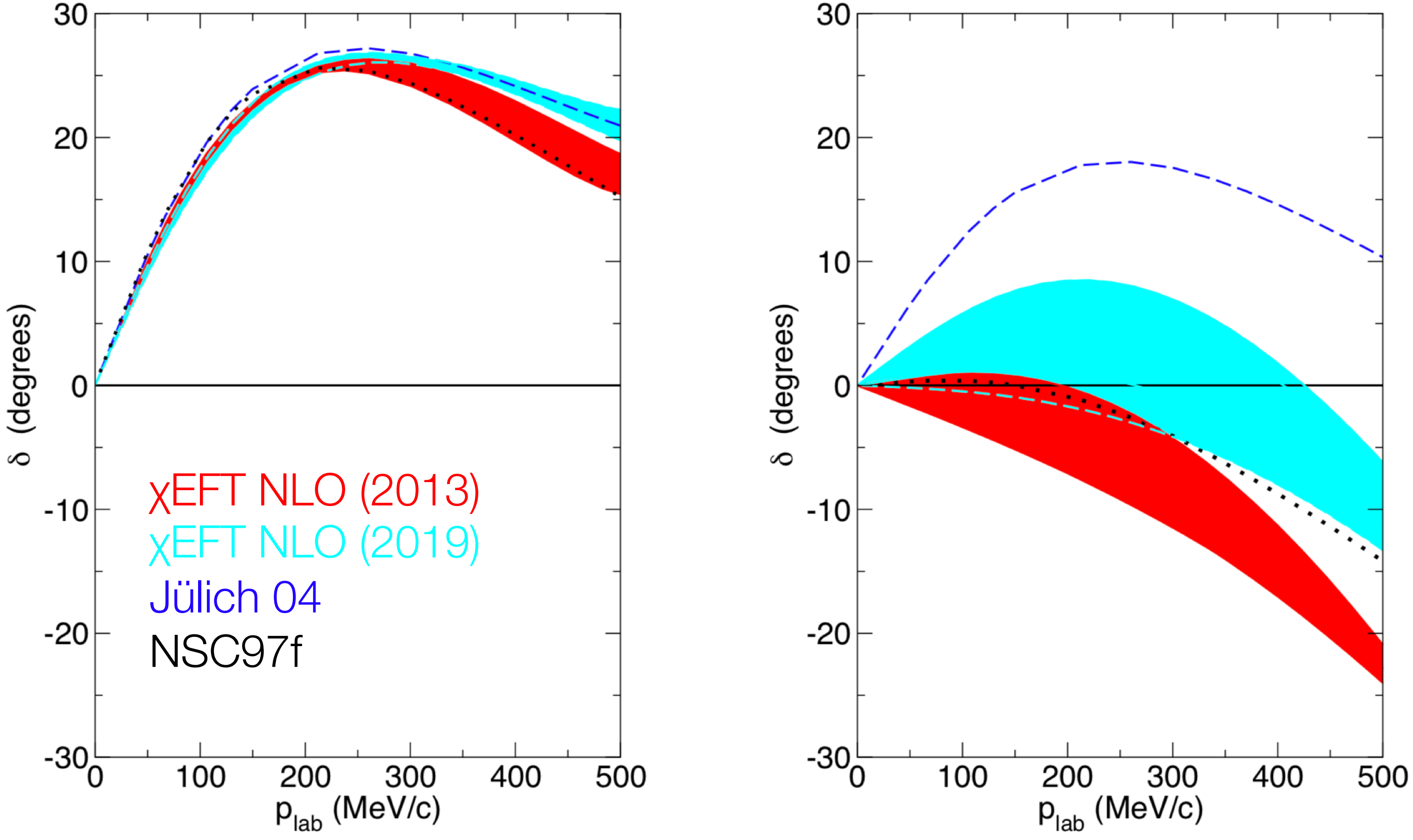
Influence of the Σ-N – Λ-N coupled channel



- Small mass difference between Σ and Λ: ~80 MeV/*c*
- Repulsion for Λ-p when the Σ-N – Λ-N coupled channel is neglected
  - Shift of hyperon appearance towards higher densities

Λ-p $^3S_1$
with the Σ-N – Λ-N coupling

Λ-p $^3S_1$
w/o the Σ-N – Λ-N coupling



J. Haidenbauer *et al.*, arXiv:1906.11681.

Σ^0 Reconstruction

$\Sigma^0 \rightarrow \Lambda\,\gamma$ (BR: almost 100 %)

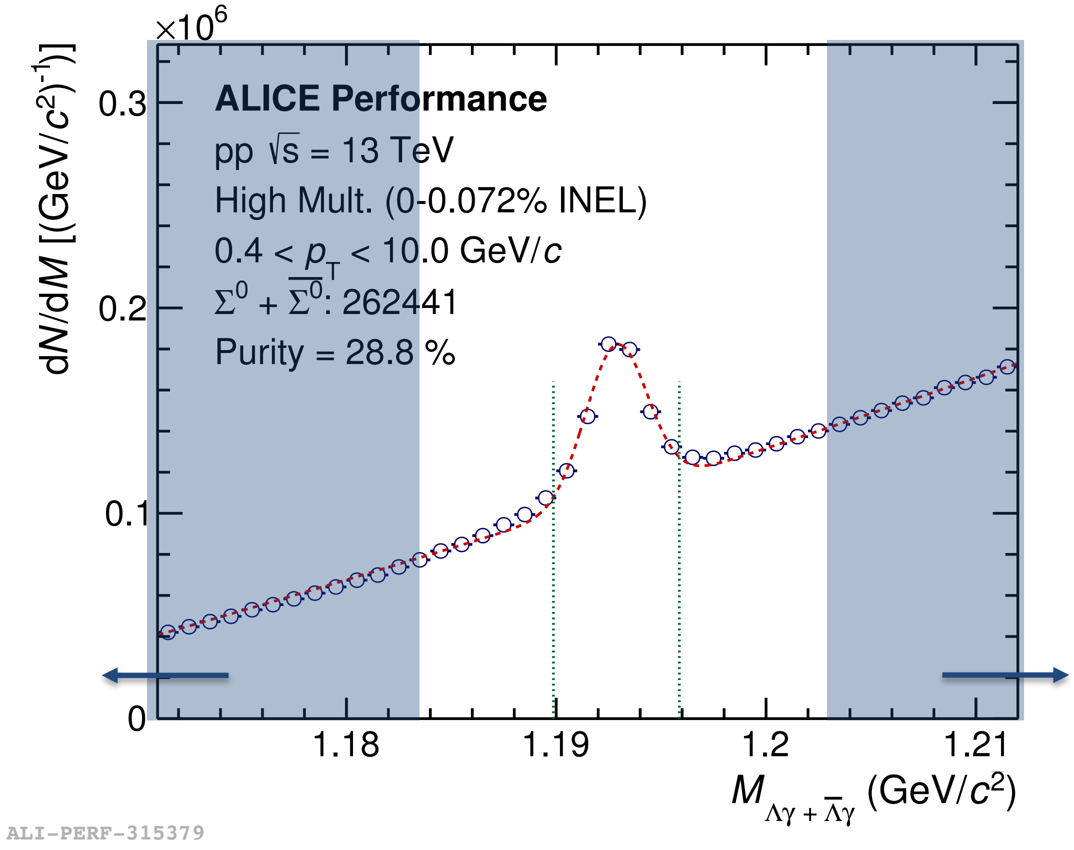
- Identification of the subsequent decays in the ALICE central barrel (ITS – TPC)

Photon conversion

- Conversion in detector material of ITS and TPC
  - $X / X_0 = (11.4 \pm 0.5)$ %
- Conversion probability ~ 8% in ALICE central barrel

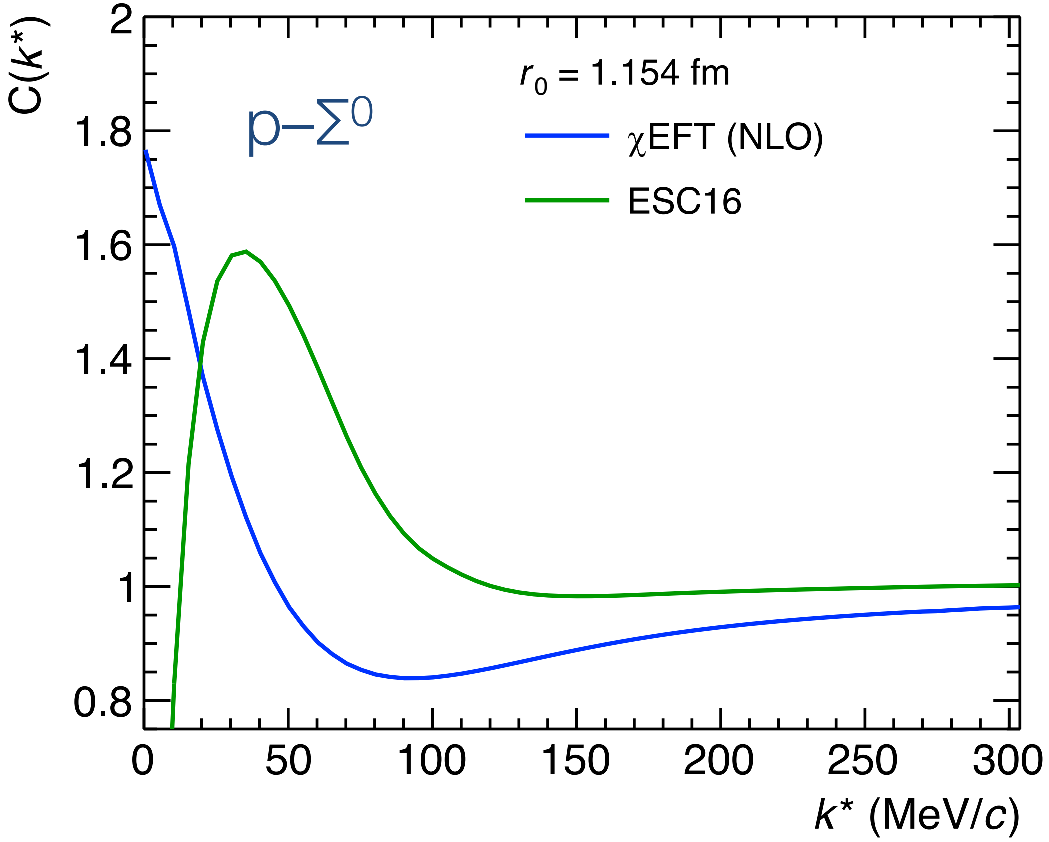
Sidebands

- Quantify the impact of the 30 % purity
- Investigation of the correlation in the sidebands crucial



|S| = 1 sector – Λ and Σ baryons

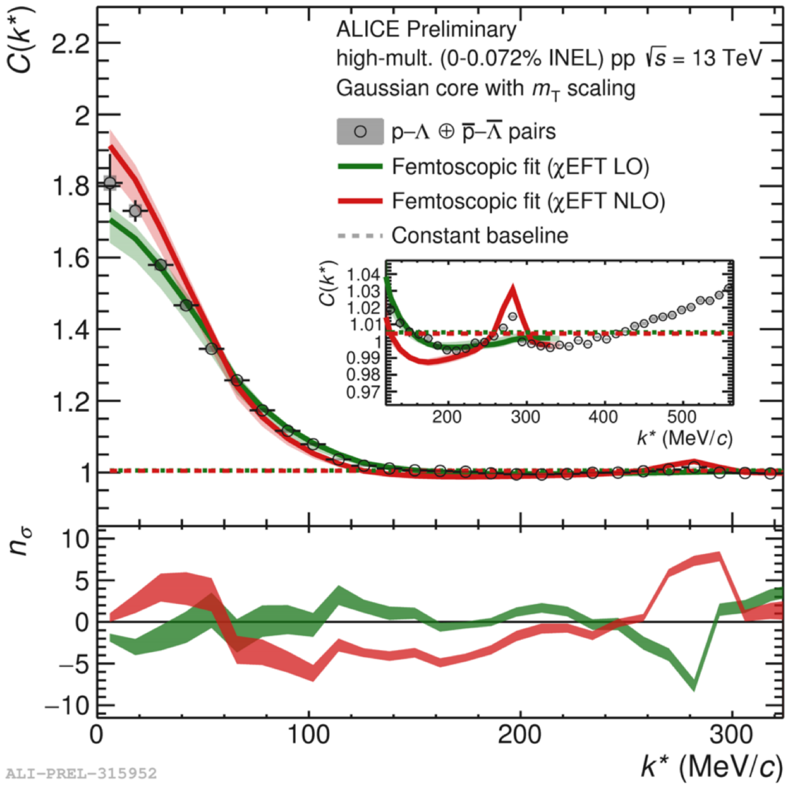
- Scarce experimental data
  - No constraints at lab momenta below 100 MeV/*c*
- Theoretical predictions for cusp in Λ–N due to the Σ–N - Λ–N coupling
  - Coupling introduces a repulsive short range component in the p–Λ interaction
  - **Not experimentally confirmed so far**
- State-of-the-art models yield a consistent description of Λ–N
  - Σ–N is far less constrained



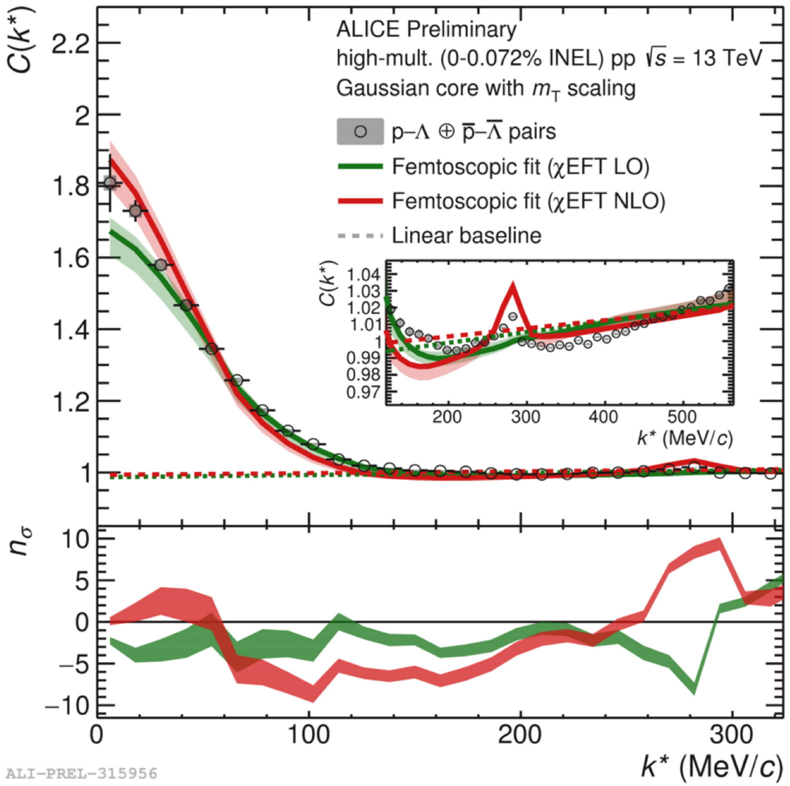
χEFT (NLO): J.Haidenbauer et al., NPA 915 (2013), 24.
ESC16: M. M. Nagels, T. A. Rijken, and Y. Yamamoto, PRC 99 (2019) 044003.

p–Λ results in pp 13 TeV (high multiplicity)

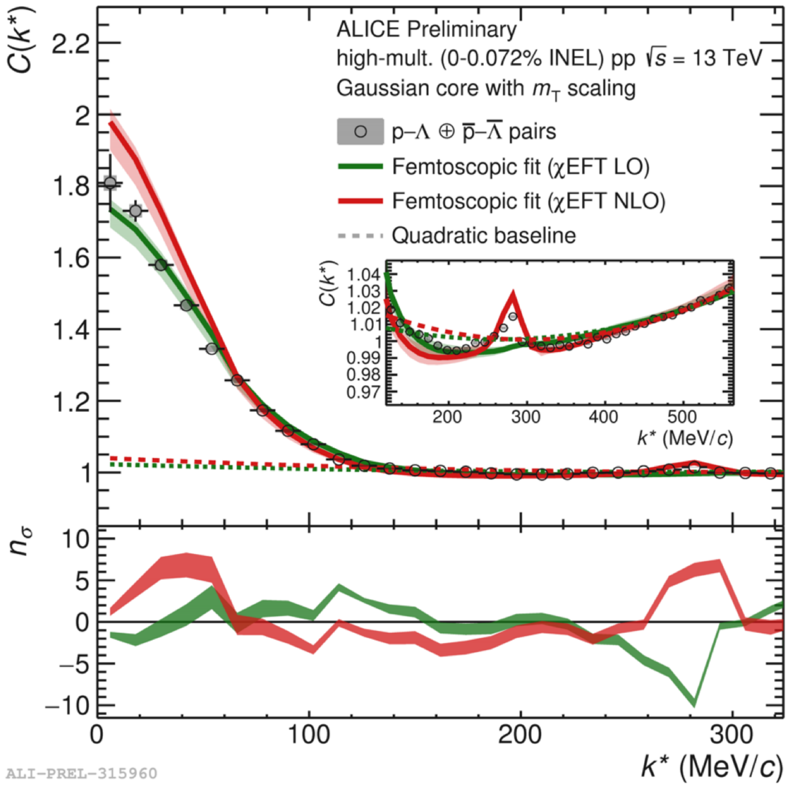
Constant baseline



Linear baseline



Quadratic baseline

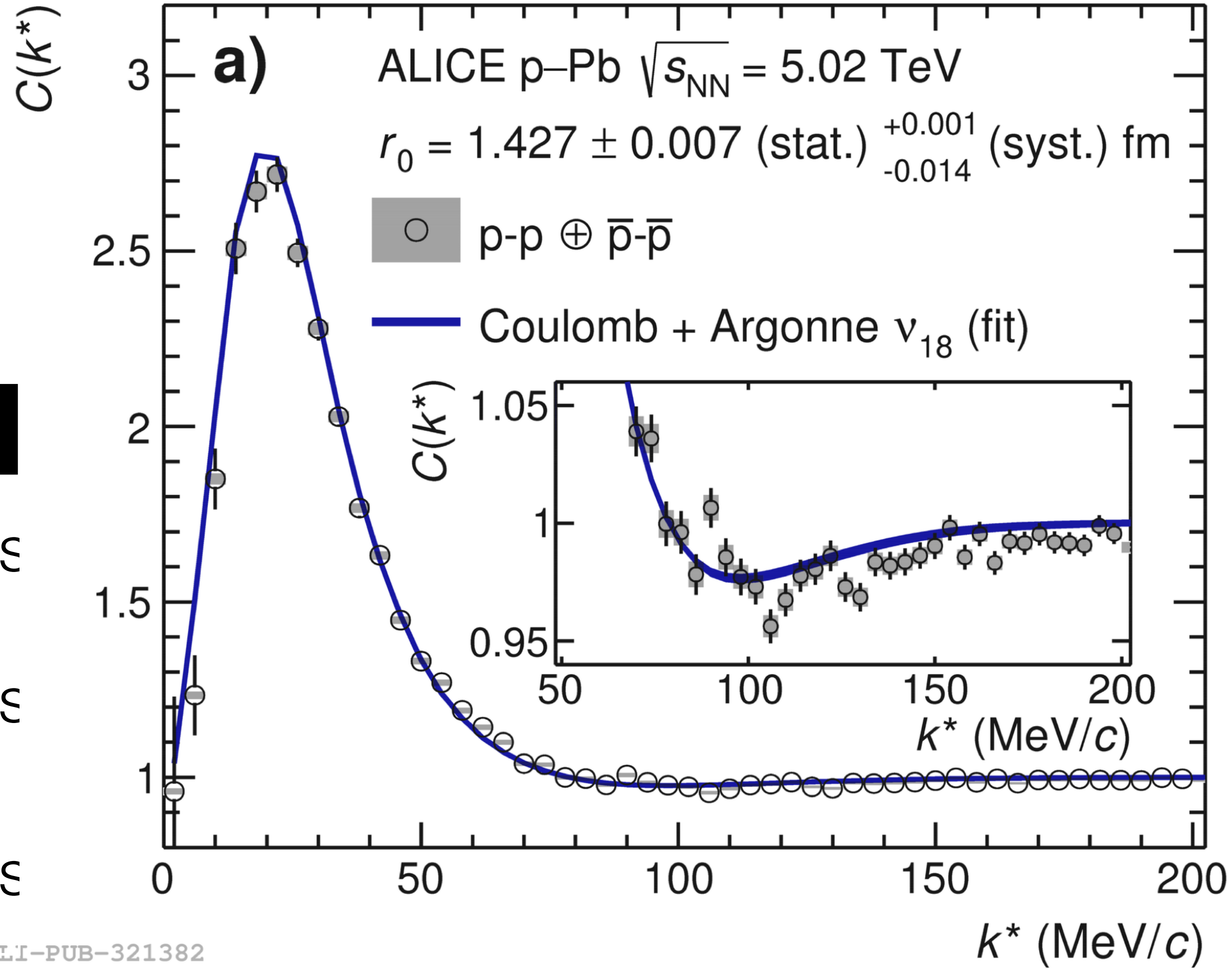


- Different variations of the baseline: Constant, linear & quadratic
  - Best fit for LO: $n_\sigma > 8$
  - Best fit for NLO: $n_\sigma > 10$

Lambda – Lambda: Constraining the source

- Assumption: $S(\boldsymbol{r})$ Gaussian and same for all particle pairs
  - p-p interaction: well known
- Source sizes for the three systems:

System	Radius
pp 7 TeV	$1.125 \pm 0.018(\text{stat.})^{+0.058}_{-0.035}$(s
pp 13 TeV	$1.182 \pm 0.008(\text{stat.})^{+0.005}_{-0.002}$(s
p-Pb 5 TeV	$1.427 \pm 0.007(\text{stat.})^{+0.001}_{-0.014}$(s



Comparison between different pp-interactions