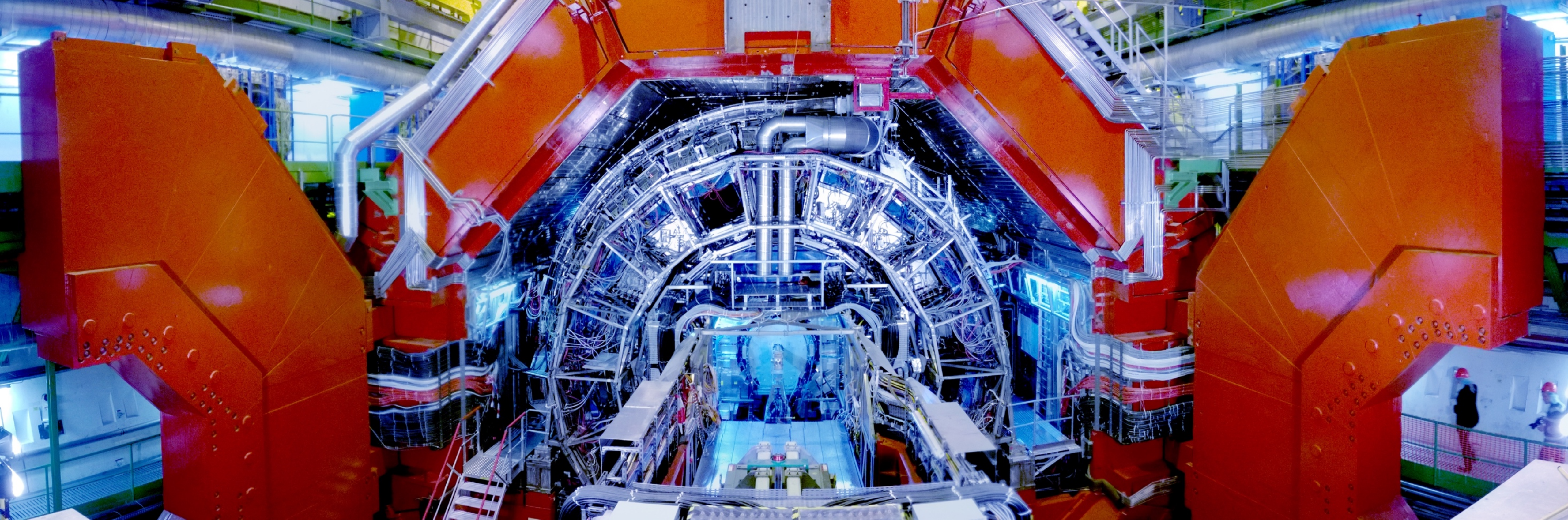


Constraining Hyperon-Nucleon and Hyperon-Hyperon interactions with femtoscopy in ALICE

Andi Mathis on behalf of the ALICE Collaboration
Technische Universität München

24th European Conference on Few-Body Problems in Physics

2 September 2019

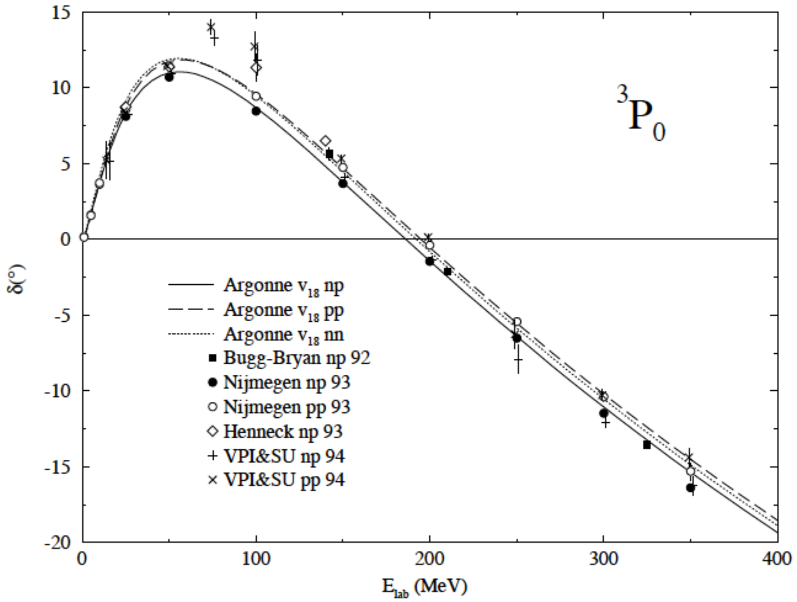
SFB 1258 Neutrinos Dark Matter Messengers

Outline

- Short motivation
- Constraining the particle source
- Testing models with hadronic degrees of freedom
- Benchmarking lattice QCD
- Outlook

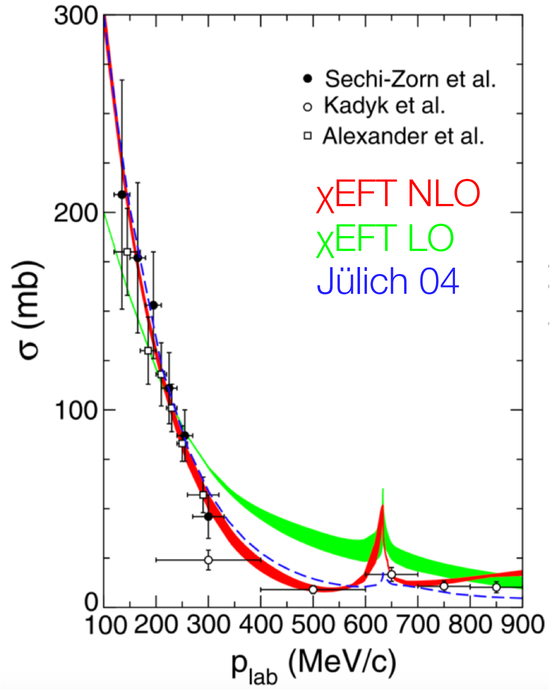
Strong interaction among (strange) hadrons

N–N → N–N



R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, PRC 51 (1995) 38-51.

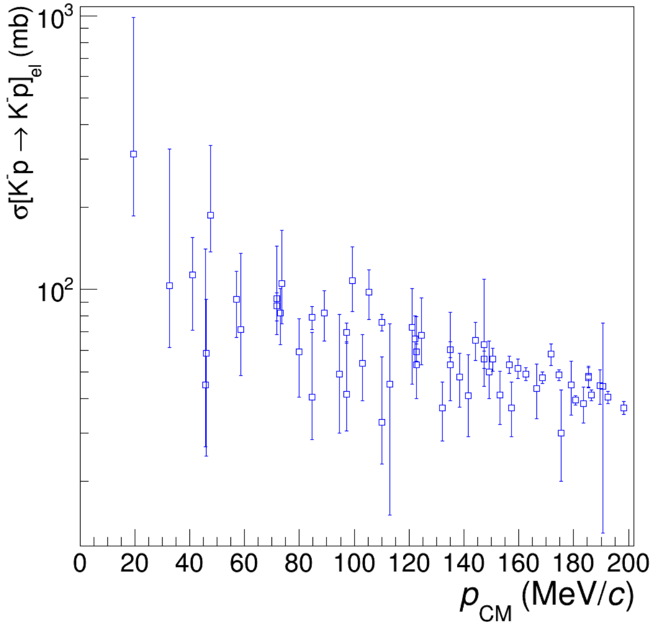
p–Λ → p–Λ



LO: H. Polinder, J.Haidenbauer, U. Meiβner, NPA 779 (2006) 244.

NLO: J.Haidenbauer., N.Kaiser *et al.*, NPA 915 (2013) 24.

p–K$^-$ → p–K$^-$



M. Tanabashi et al. (Particle Data Group), PRD 98, 030001 (2018).

- (High precision) measurements conducted with scattering experiments

Theoretical predictions

	Lattice QCD	Chiral Effective Field Theory	Meson-Exchange Models
General properties	• **Quarks** and **gluons** are the degrees of freedom • Coupled channels are included • Allows for bound states • **Not fitted to scattering data** but with physical pion and kaon masses	• **Hadronic** degrees of freedom • Ordered scheme with **higher order loops** • Obeys SU(3) symmetry • Coupled channels included • Coupling constants **fitted to scattering data**	• **Hadronic** degrees of freedom • Phenomenological models with interactions **at tree level** • Obeys SU(3) symmetry • Coupled channel included • Some models do not allow for bound states • Coupling constants **fitted to scattering data**
K–p	✗	✓	✓
p–p	✗	✓ N^3LO	✓
p–Λ	✗	✓ NLO	✓
Λ–Λ	✓	✗	✓
p–Σ^0	✗	✓ NLO	✓
p–Ξ^-	✓	✓	✓
p–Ω^-	✓	✗	✓

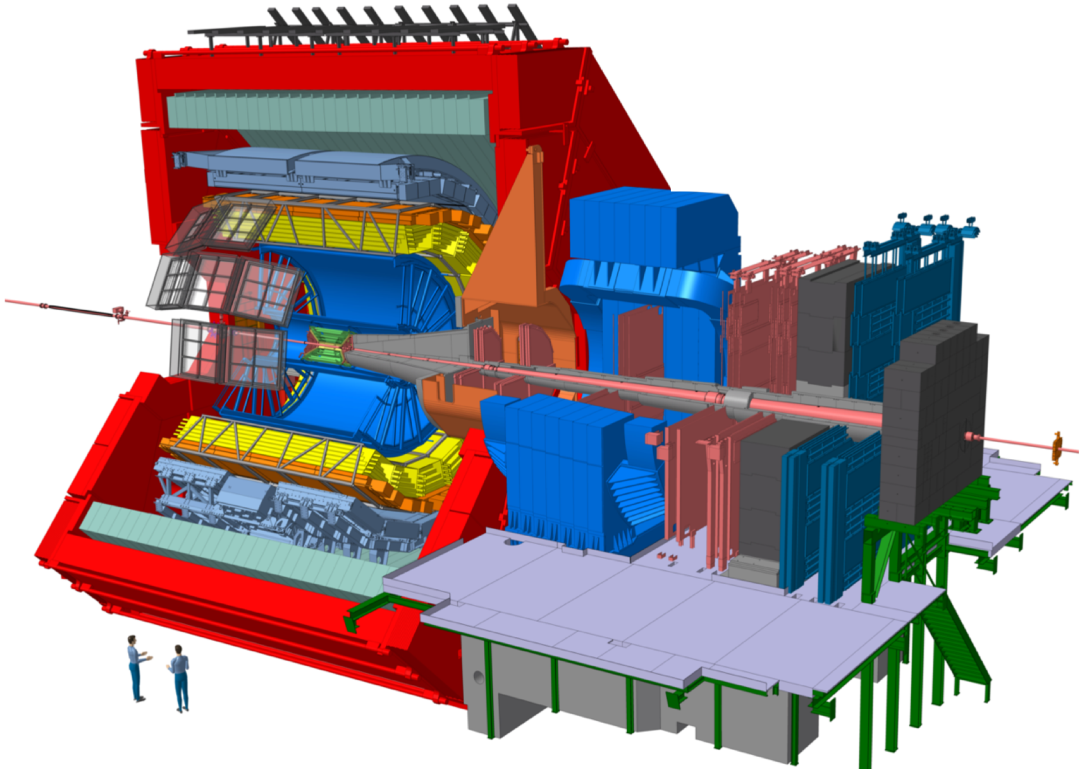
Theoretical predictions

	Lattice QCD	Chiral Effective Field Theory	Meson-Exchange Models
General properties	• **Quarks** and **gluons** are the degrees of freedom • Coupled channels are included • Allows for bound states • **Not fitted to scattering data** but with physical pion and kaon masses	• **Hadronic** degrees of freedom • Ordered scheme with **higher order loops** • Obeys SU(3) symmetry • Coupled channels included • Coupling constants **fitted to scattering data**	• **Hadronic** degrees of freedom • Phenomenological models with interactions **at tree level** • Obeys SU(3) symmetry • Coupled channel included • Some models do not allow for bound states • Coupling constants **fitted to scattering data**
K–p	✗	✓	✓
p–p	✗	✓ N^3LO	✓
p–Λ	✗	✓ NLO	✓
Λ–Λ	✓	✗	✓
p–Σ^0	✗	✓ NLO	✓
p–Ξ^-	✓	✓	✓
p–Ω^-	✓	✗	✓

ALICE – A Large Ion Collider Experiment

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

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

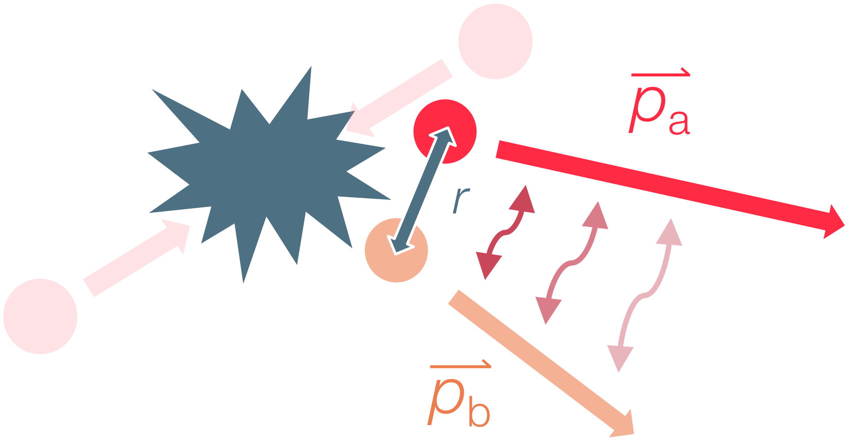
Run 2 (2015 – 2018)
Pb–Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV Xe–Xe @ $\sqrt{s_{NN}}$ = 5.44 TeV
p–Pb @ $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV
pp @ $\sqrt{s}$ = 5, 13 TeV

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
  - All detectable particle species can be studied!



Non-traditional femtoscopy to study the FSI

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

Emission source   Two-particle wave function

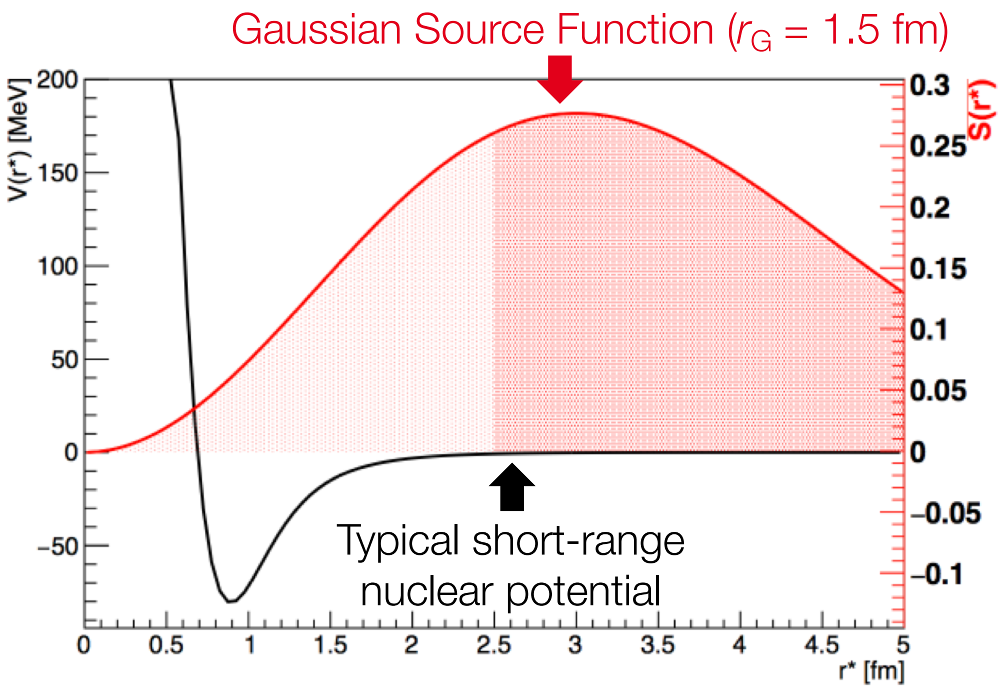
- C(k^*) can be evaluated
  - **numerically** using the **CATS framework** (D.L. Mihaylov et al, Eur. Phys. J. C78 (2018) no.5, 394)
    Solves the Schrödinger equation for any strong interaction potential, Coulomb interaction and effects of quantum statistics
  - **analytically** using the **Lednicky model** (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)

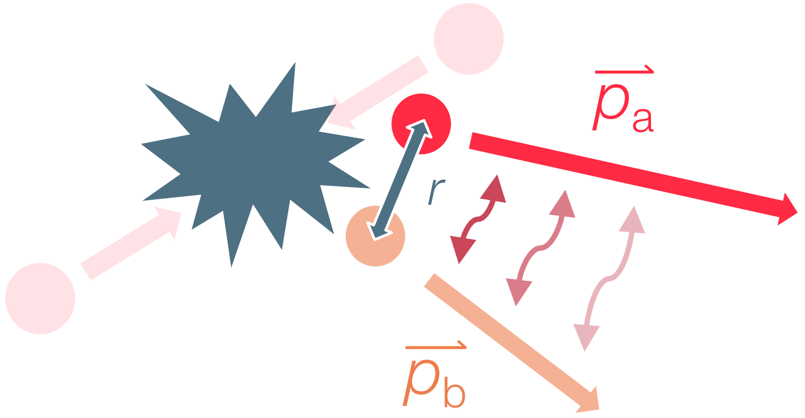
- Under the prerequisite that the source is known

Constraining the particle source

Using known interactions

The unique benefit of small sources

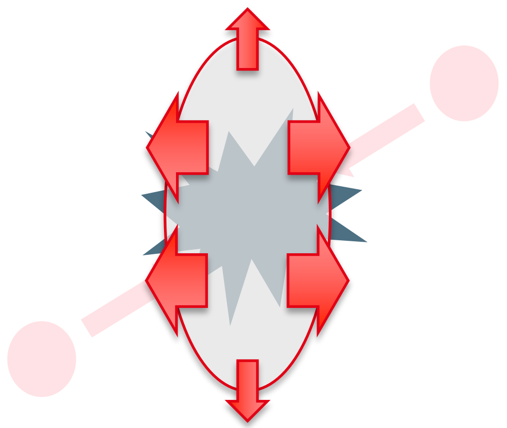


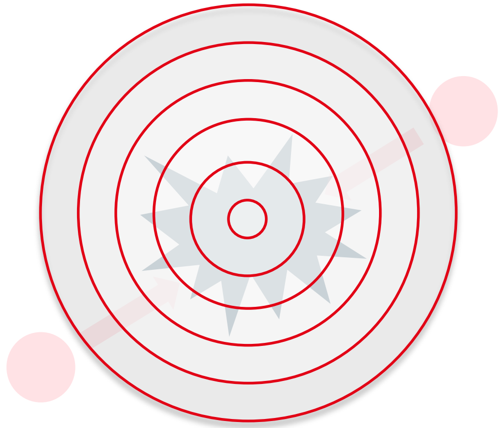


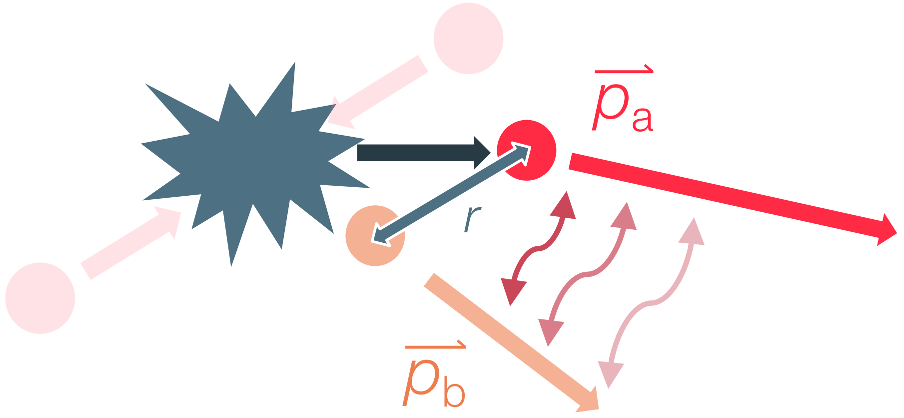
- Small particle-emitting source created in pp and p–Pb collisions at the LHC
  - Essential ingredient for detailed studies of the strong interaction
- **p–p correlation** is used to constrain the source, since Coulomb and Strong interactions are well known
- K^+–p correlation is used as a cross-check since also for this channel the Coulomb and Strong interactions are known

Collective effects and strongly decaying resonances

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







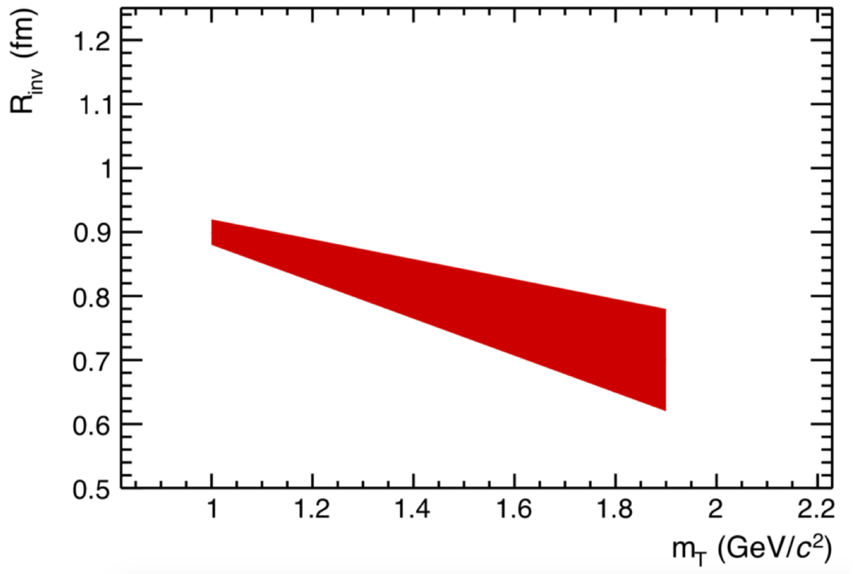
- *(An)isotropic pressure gradients* affect the emission
  - Initial geometric anisotropies introduce a transverse modulation
  - Expanding source with *common velocity field*
- Affects particles depending on their mass

- Resonances with cτ ~ r_0 ~ 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



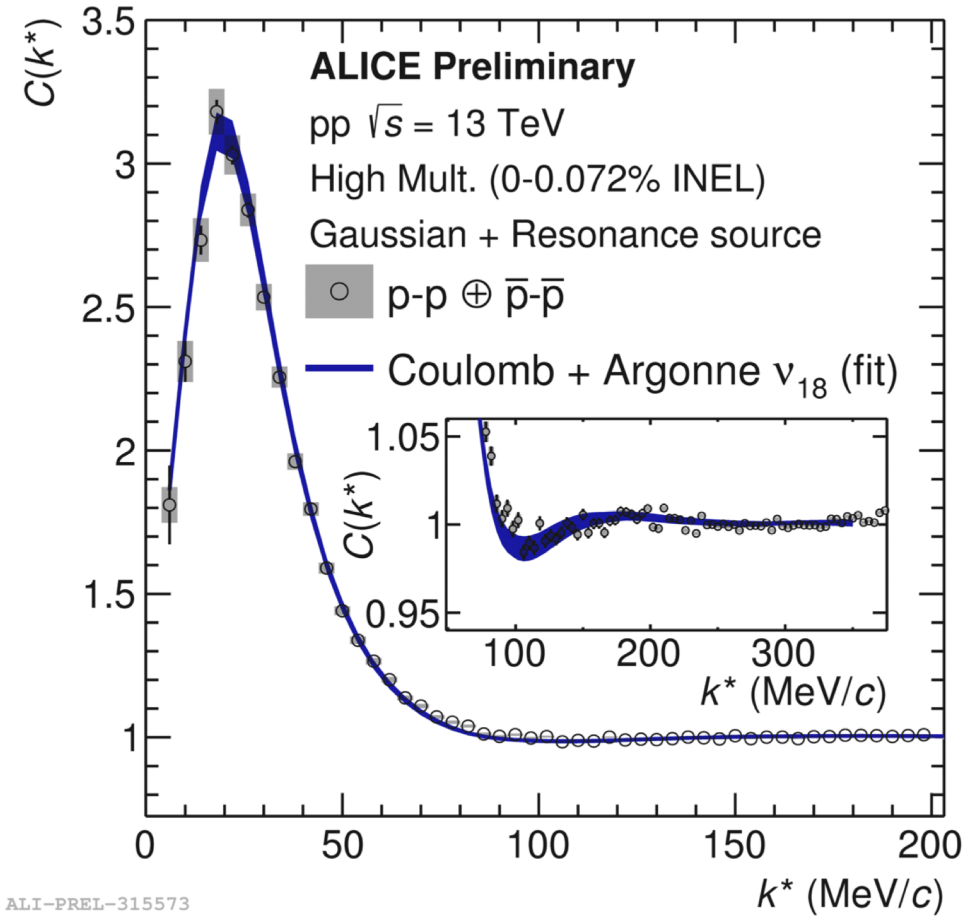
Particle	Primordial fraction	Resonances	
		$1 < c\tau < 2$ fm	$c\tau > 2$ fm
Proton	33 %	56 %	2 %
Lambda	35 %	8 %	58 %

- Amount of resonances determined within the Statistical Hadronization Model in the canonical approach
- 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**

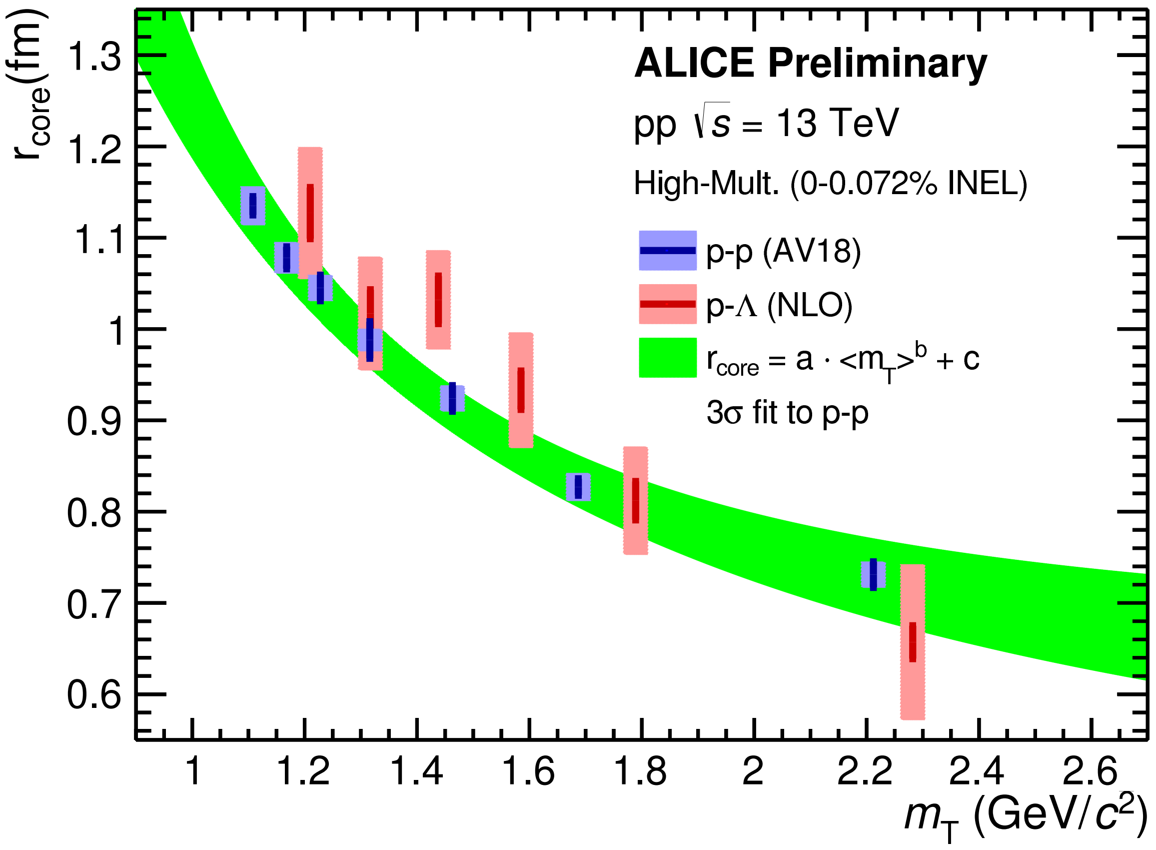
Gaussian core ⊗ Exponential tail



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

$$r_{Eff} = 1.332 \pm 0.006 \,^{+0.029}_{-0.027}\ \text{fm}$$

m_T dependence of the Gaussian *core* radius

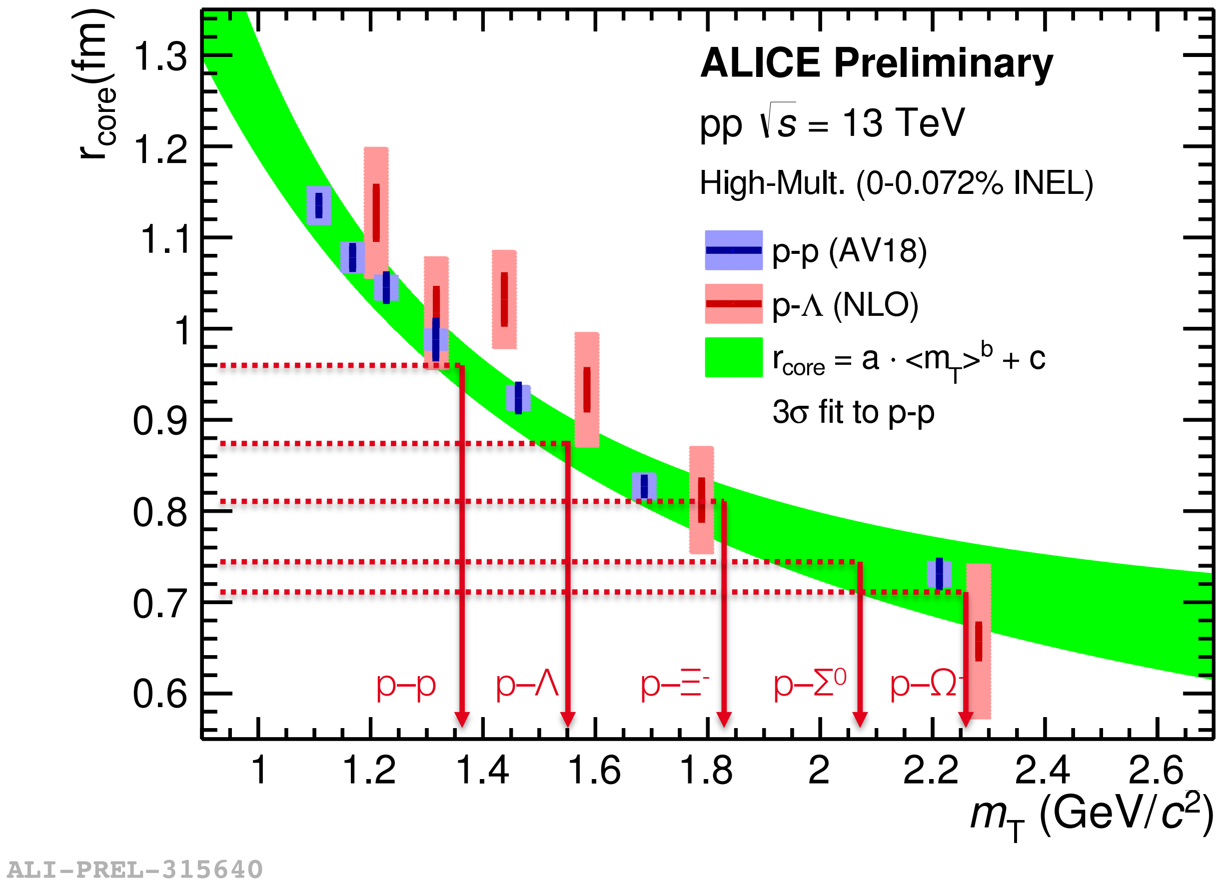


ALI-PREL-315640

- Core radius for p–p and p–Λ in good agreement
  - Observation of a universal particle-emitting source

m_T dependence of the Gaussian *core* radius

D. Mihaylov (ALICE)
WPCF2019



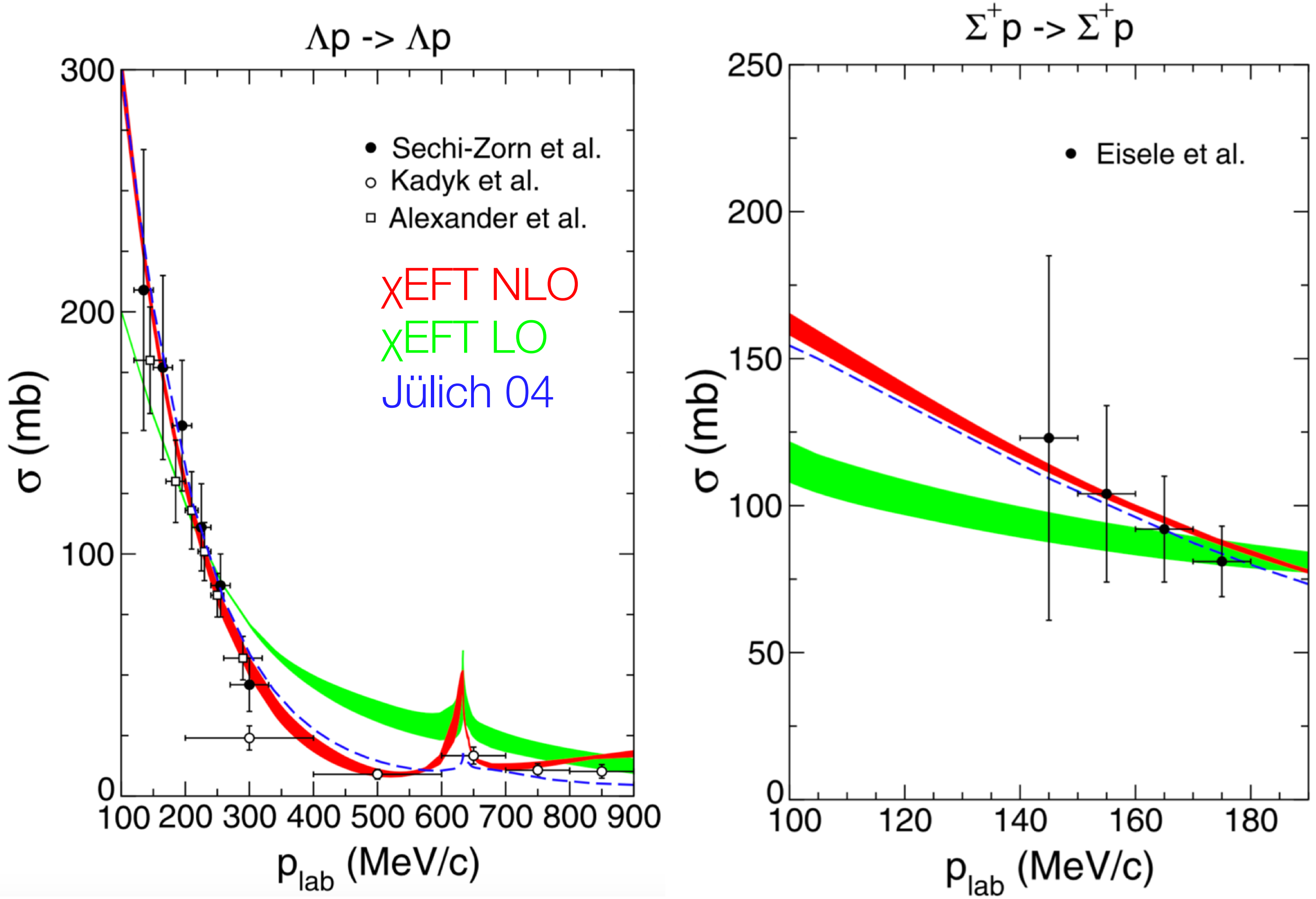
- Fix the value of r_{Core} of each particle species based on their $\langle m_T \rangle$

Testing models with hadronic degrees of freedom

The $|S| = 1$ sector

$|S| = 1$ sector – Λ and Σ baryons

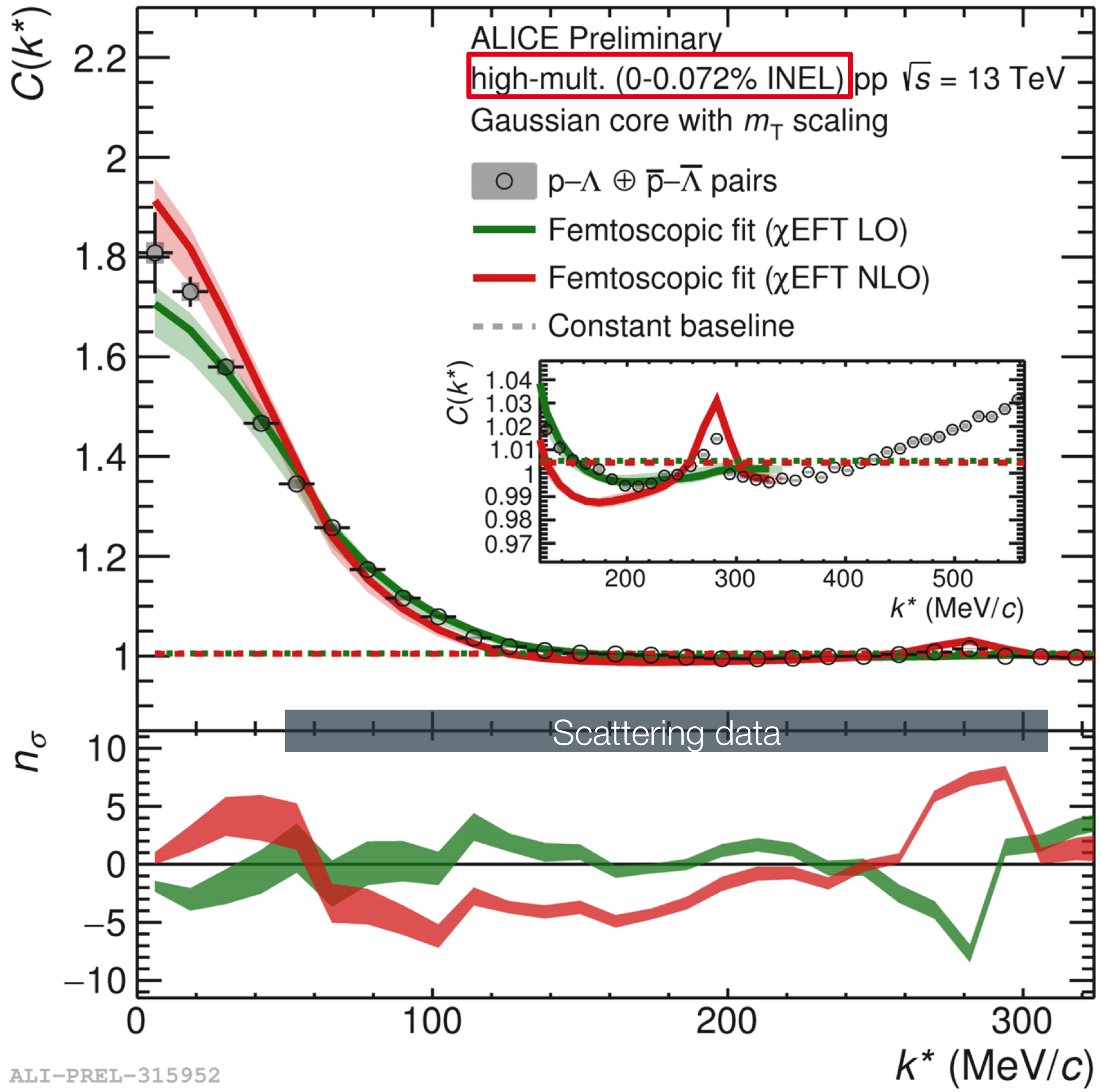
- Scarce experimental data
  - No constraints at lab momenta below 100 MeV/*c*
- Theoretical predictions for cusp in Λ–N due to the Σ–N - Λ–N coupling
  - Coupling introduces a repulsive short range component in the p–Λ interaction
  - Not experimentally confirmed so far



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

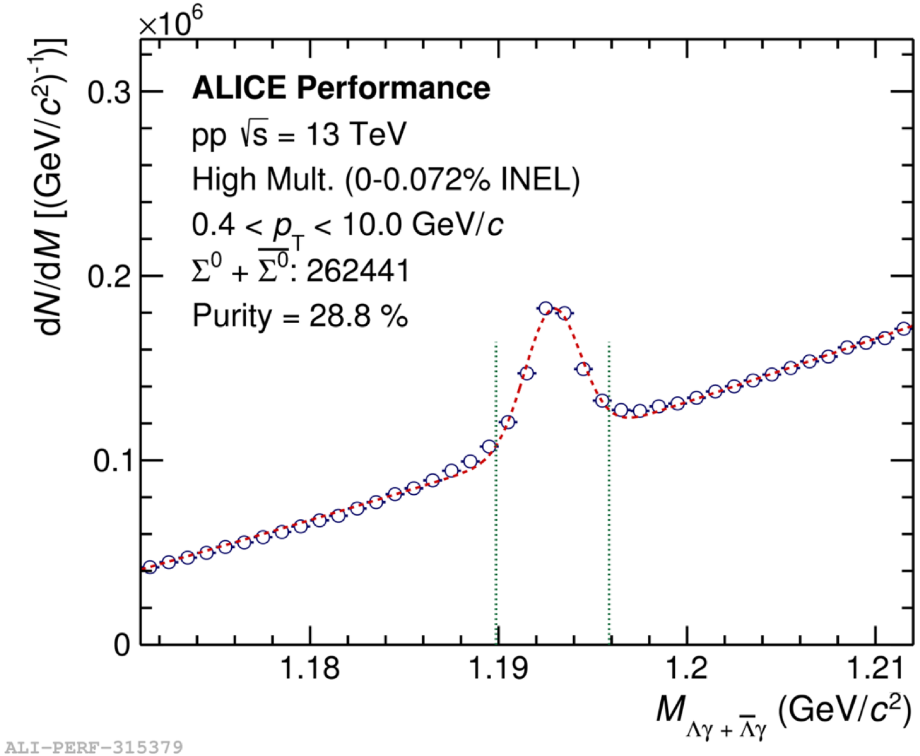
p–Λ results in pp 13 TeV (high multiplicity)

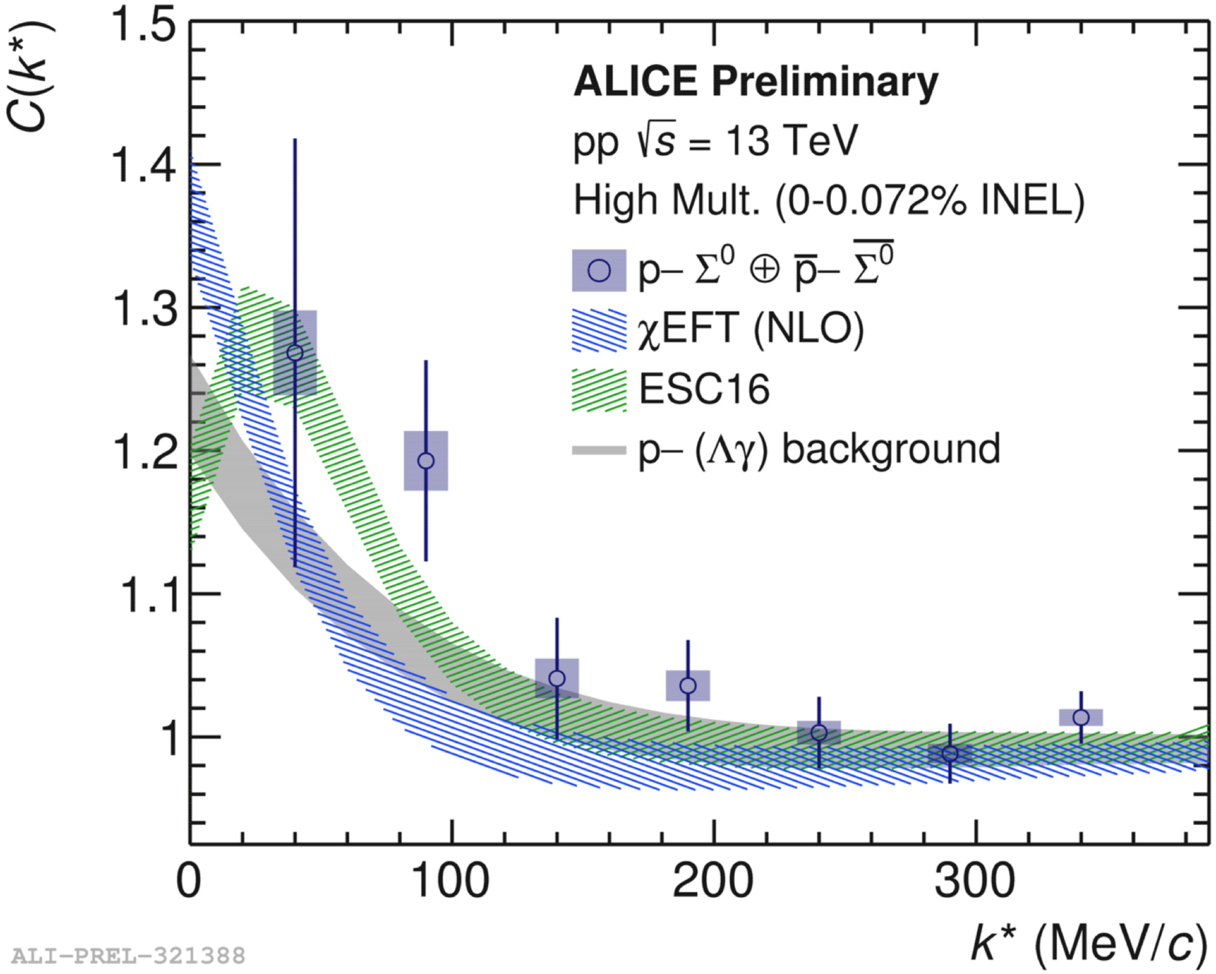
- Significant extension of the kinematic range
- Clear experimental evidence for the cusp
- Different variations of the baseline
  - Constant, linear & quadratic
  - Best fit for LO: $n_\sigma > 8$
  - Best fit for NLO: $n_\sigma > 10$
- LO and NLO calculations of the interaction within χEFT **fail to reproduce the data**
  - Entering a precision era!



p–Σ^0 results in pp 13 TeV (high multiplicity)

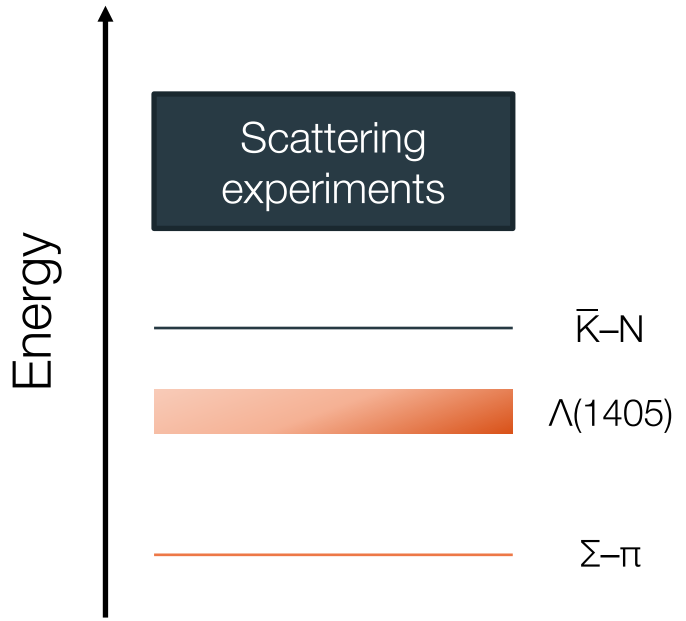
- $\Sigma^0 \rightarrow \Lambda\,\gamma$ (BR: almost 100 %)
  - Identification of the photon via conversions
  - Significant contribution from correlated p–($\Lambda\gamma$) background due to low purity

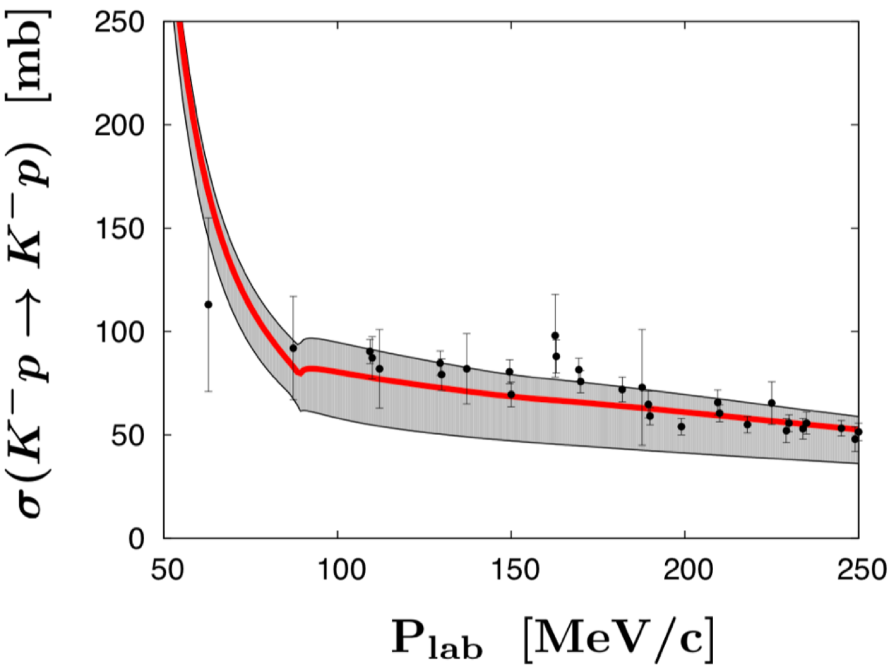




χEFT (NLO): J.Haidenbauer *et al.*, NPA 915 (2013), 24.
ESC16: M. M. Nagels, T. A. Rijken, and Y. Yamamoto, PRC 99 (2019) 044003.

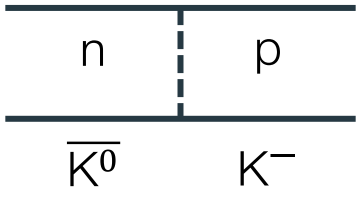
|S| = 1 sector – Kaons





Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98.

- $\bar{K}$–N - Σ–π form a molecular state: Λ(1405)
- K^-–p scattering data and kaonic hydrogen data are employed to constrain the amplitude also below the KN threshold
- Coupled channel effects

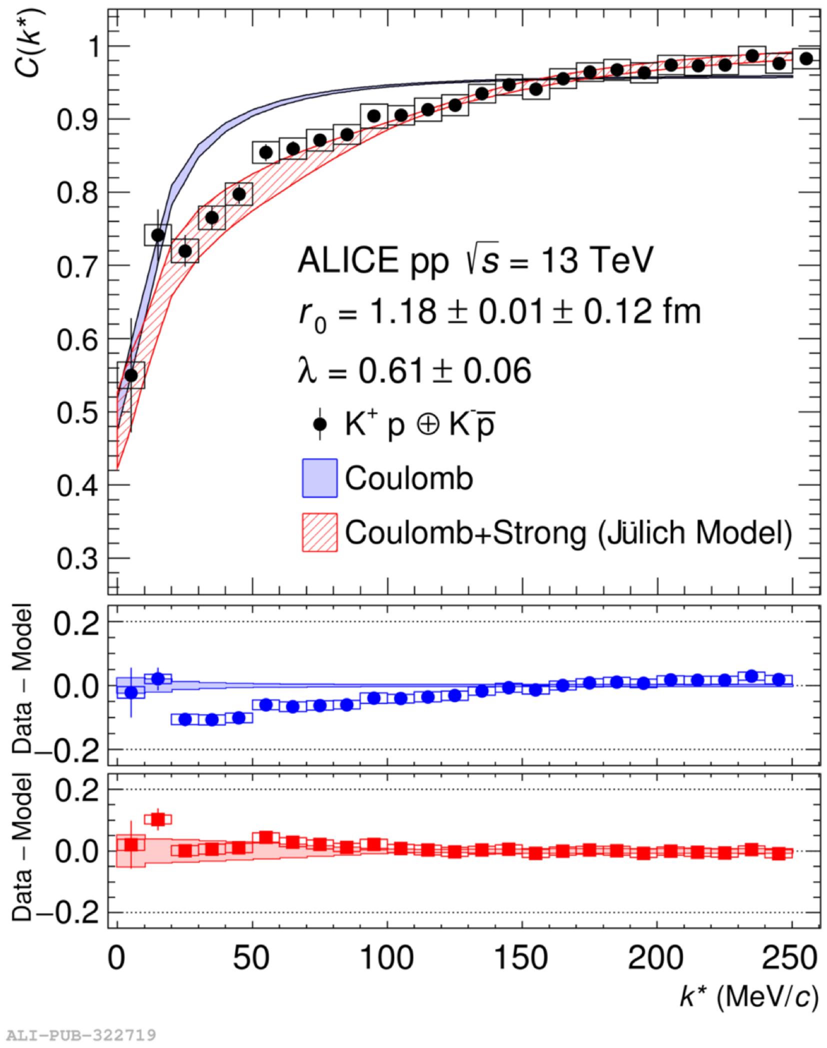


$$M(K^- p) + 5\ \text{MeV} = M(n\bar{K}^0)$$

p–K⁺ results for pp 13 TeV (min. bias)

ALICE Collaboration, arXiv:1905.13470 (submitted to PRL)

- Radius obtained from inclusive p–p correlation
  - K⁺–p correlation used as a benchmark to study K⁻–p

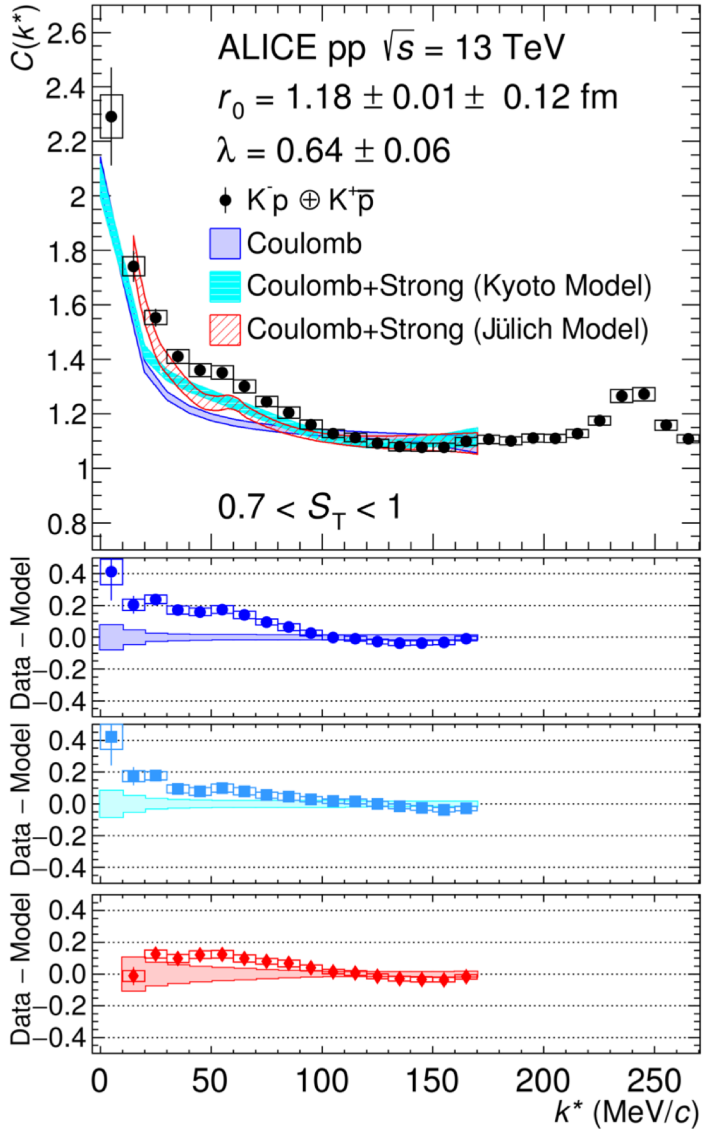


p–K⁻ results for pp 13 TeV (min. bias)

R. Lea (ALICE)
WPCF2019

ALICE Collaboration, arXiv:1905.13470 (submitted to PRL)

- Radius obtained from inclusive p–p correlation
  - K^+–p correlation used as a benchmark to study K^-–p
- Observation of a bump close to the K^0–n threshold
  - 58 MeV/*c* in the CM frame
- **First experimental evidence of the opening of the K^0–n isospin breaking channel**



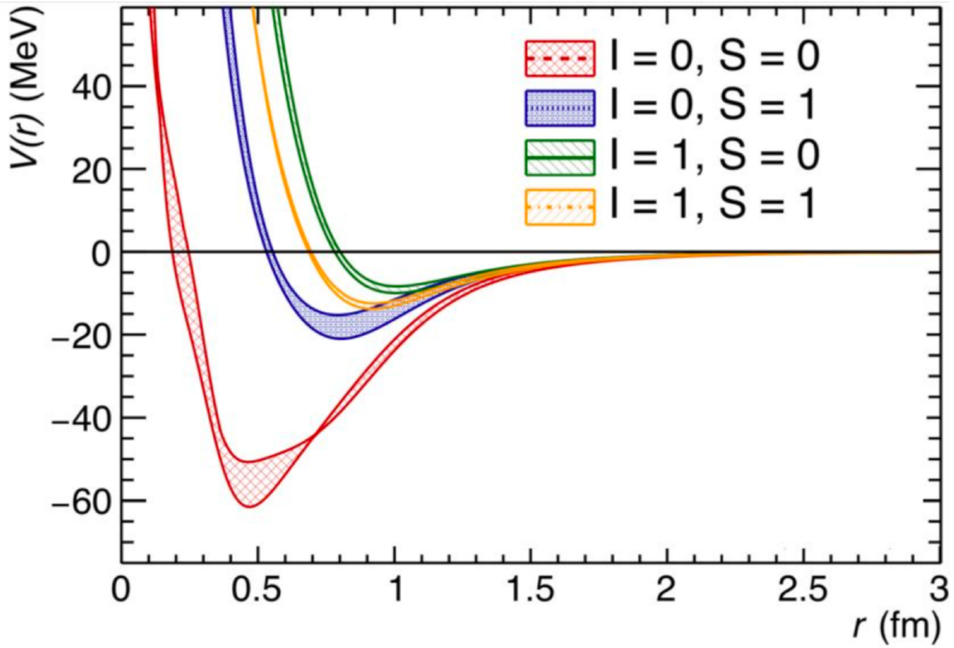
Benchmarking lattice QCD

The |S| > 1 sector

Lattice QCD models of the potentials

p–Ξ⁻

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

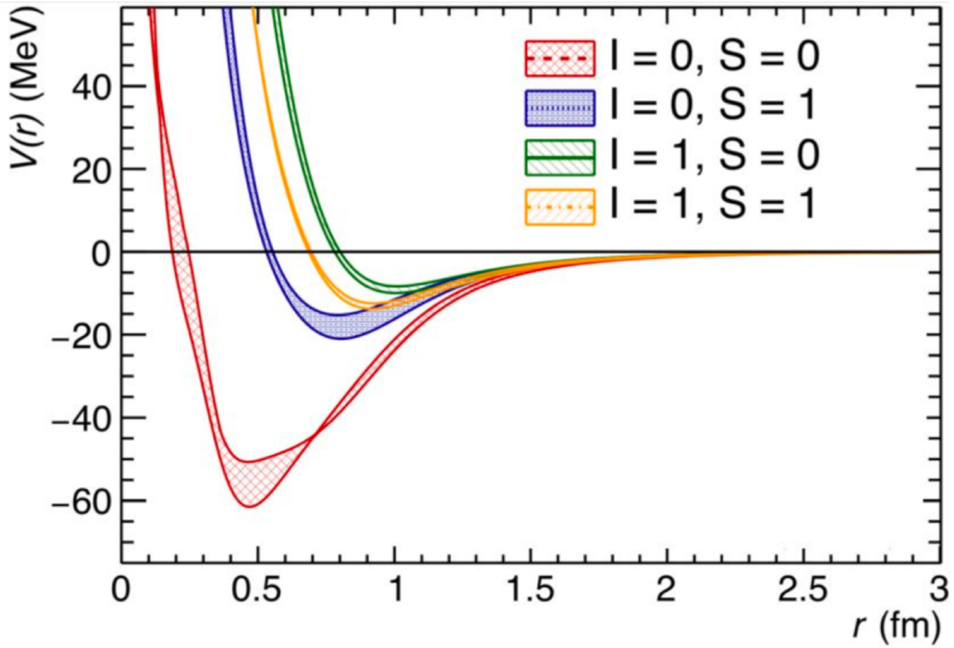


- HAL QCD potential with physical meson masses
  - m_π = 146 MeV/c^2
  - m_K = 525 MeV/c^2
- For p–Ξ⁻ : Statistical weights of different I, S combinations $C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$

Lattice QCD models of the potentials

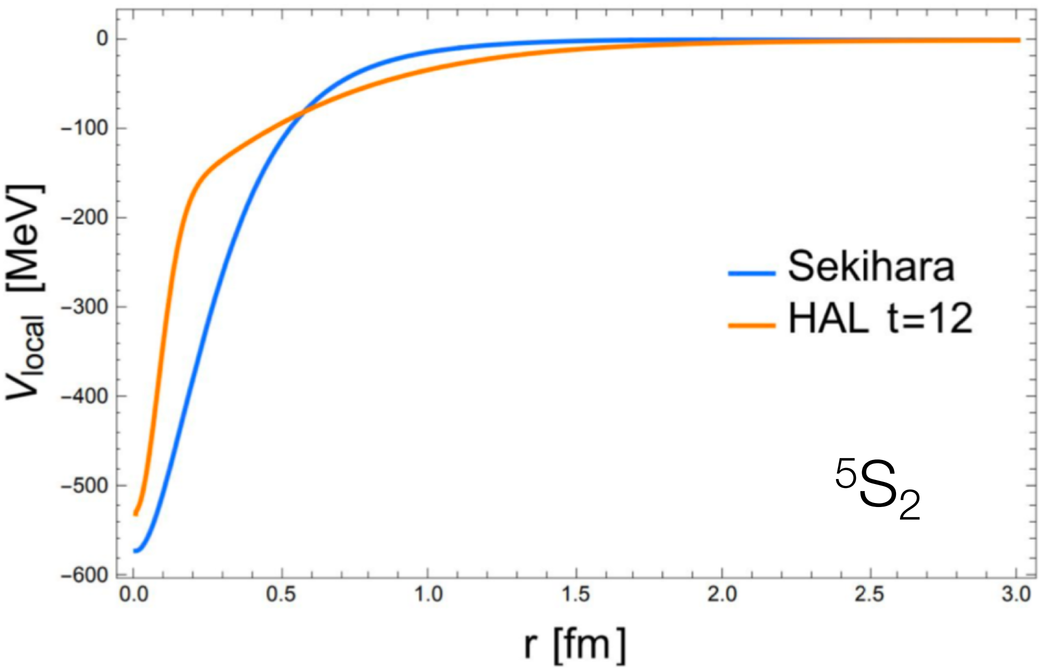
p–Ξ^-

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



p–Ω^-

T. Iritami *et al.*, arXiv:1810.03416

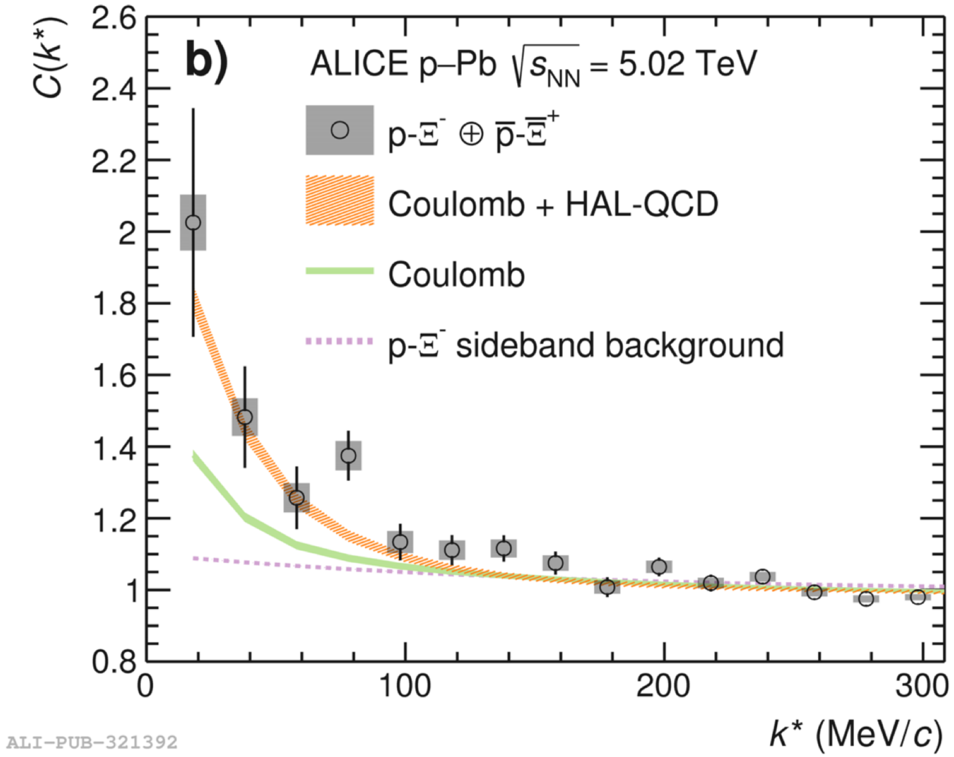


- HAL QCD potential with physical meson masses
  - m_π = 146 MeV/c^2
  - m_K = 525 MeV/c^2

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

+1 MeV with Coulomb

Benchmarking lattice QCD in p–Pb 5.02 TeV

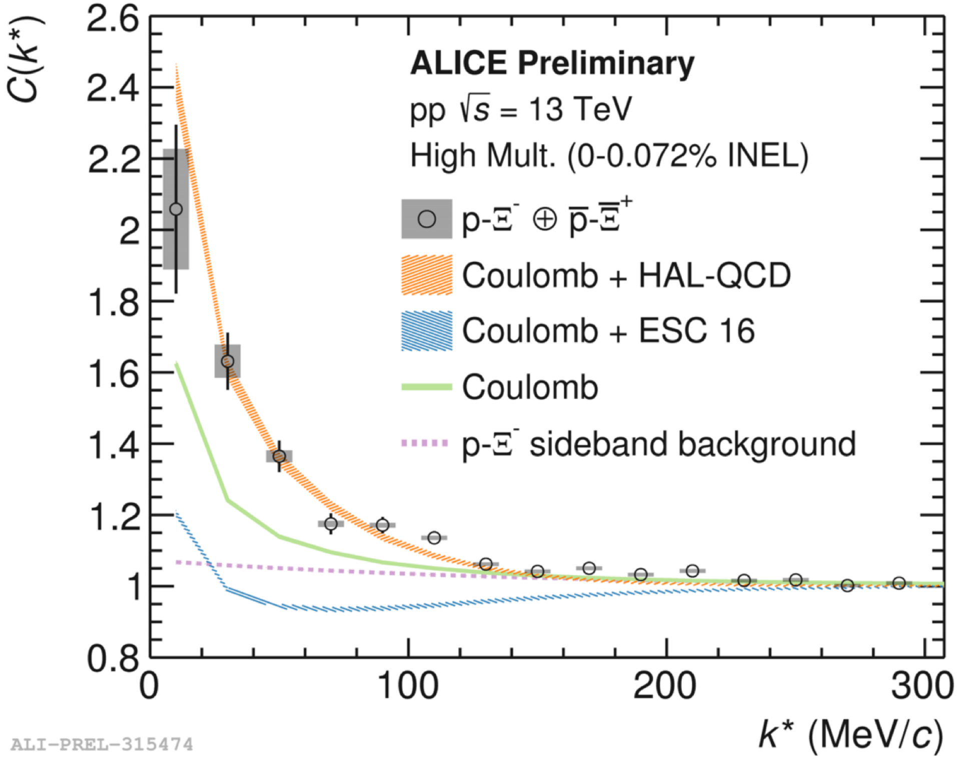


First observation of the strong interaction in p–Ξ^-

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

ALICE Collaboration, arXiv:1904.12198, PRL (in press)

Benchmarking lattice QCD in pp 13 TeV (high mult.)

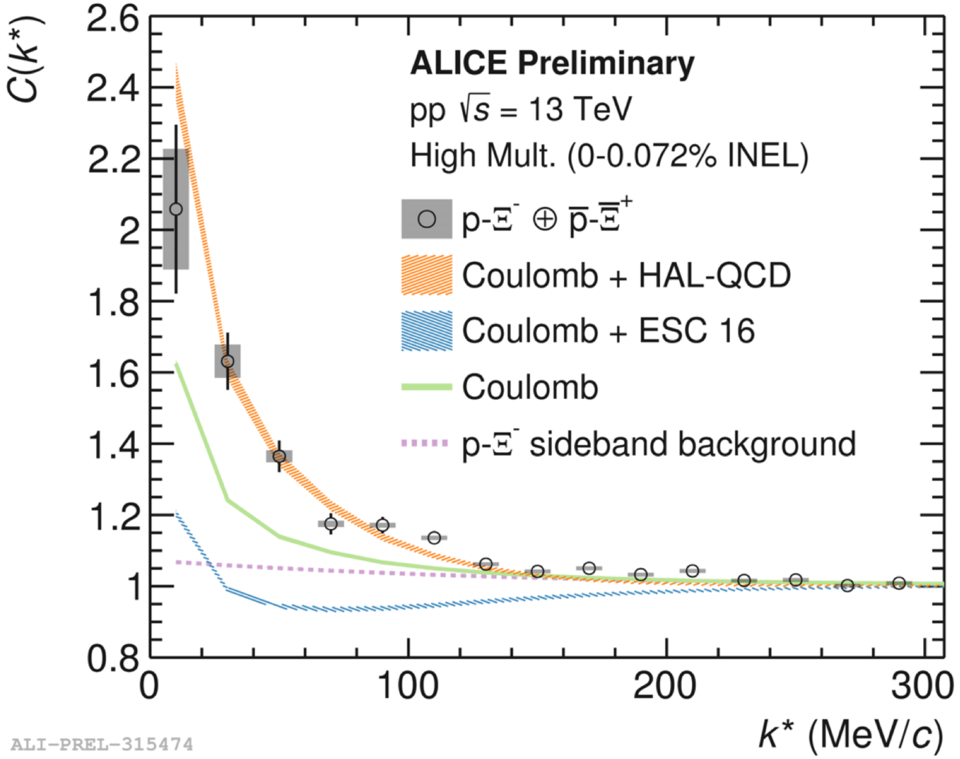


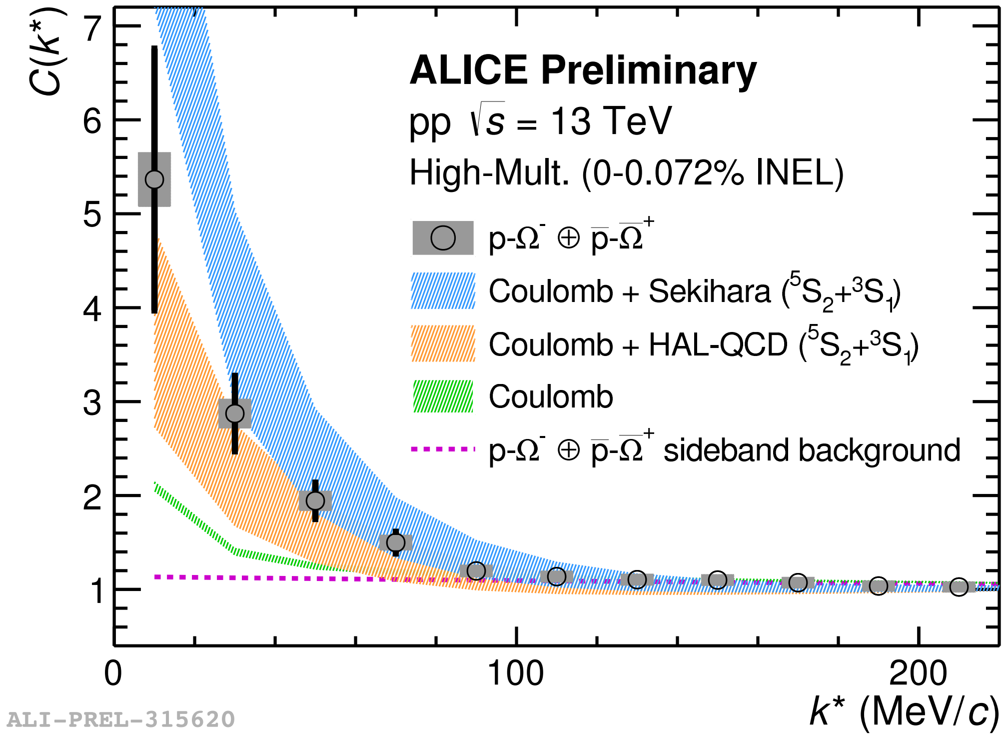
p–Ξ⁻ in pp 13 TeV (high mult.)

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

Benchmarking lattice QCD

O. Vazquez-Doce (ALICE)
WPCF2019





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^- in pp 13 TeV (high mult.)

- Coulomb-only scenario excluded (> 6 σ)
- Precision of ALICE data exceeds the theoretical predictions
- Measurement of the attractive character of the interaction

Summary

- ALICE provides **precise data** to test hadron-hadron interactions
- Experimental confirmation of cusp effects in p–Λ and p–K^-
- Entering the precision era in the |S| = 1 sector
  - Providing constraints with unprecedented precision for theory
- Validation of lattice QCD potentials at physical quark masses
- Upcoming results: p–d and p–ϕ
- Measurements in **RUN3 and RUN4** will allow for more differential studies and investigations of three-body interactions

Thank you for your attention!

… and stay tuned for more results!