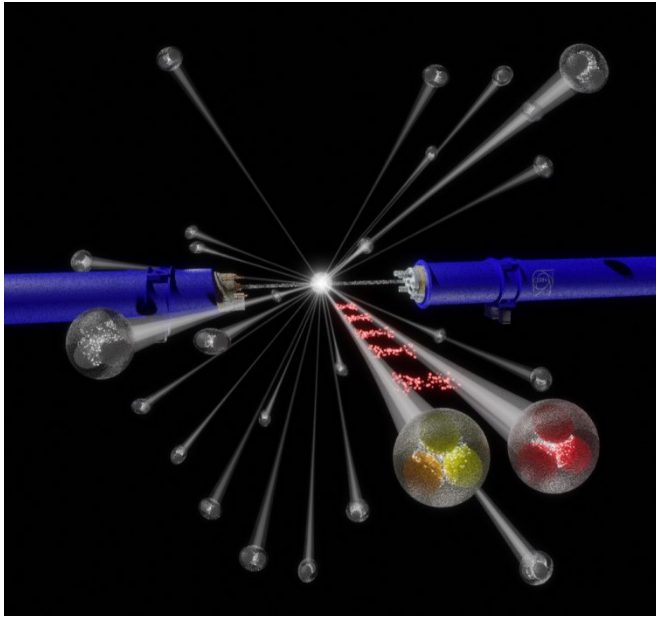


https://cds.cern.ch/record/2746022

# Study of hyperon–nucleon and kaon–nucleon interactions at the LHC

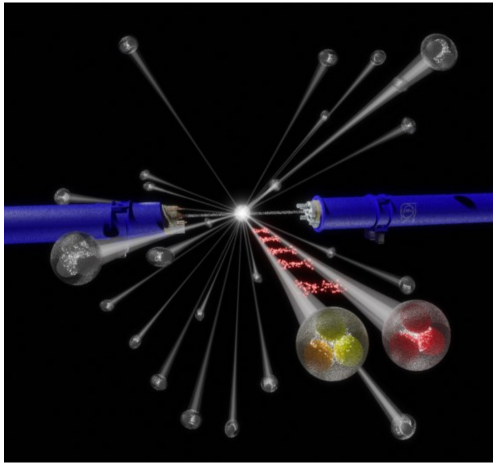
Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar

Stefan Heckel (Technical University of Munich)

February 3, 2021

# Outline

- Motivation: Why to study hadron–hadron interactions involving strangeness?
- Method: Femtoscopy upside down
- Experiment: ALICE (a heavy-ion experiment)
- First step: Constraining the source
- Results: Hyperon–nucleon and kaon–nucleon interactions
- Summary
- More to come...



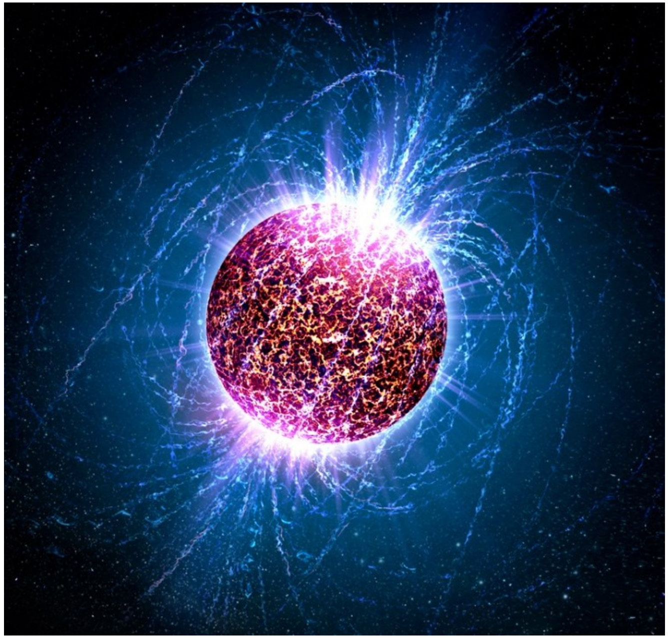
https://cds.cern.ch/record/2746022

# Motivation

Why to study hadron–hadron interactions involving strangeness?

# Motivation: the unknown interior of neutron stars

- Neutron stars: dense and compact objects
- Dimensions:
  R ~ 10 – 15 km
  M ~ 1 – 2 $M_{\odot}$
- Outer Crust:
  Ions, electron gas, Neutrons
- Inner Core:
  Neutrons?
  Protons?
  Hyperons?
  Quark Matter?



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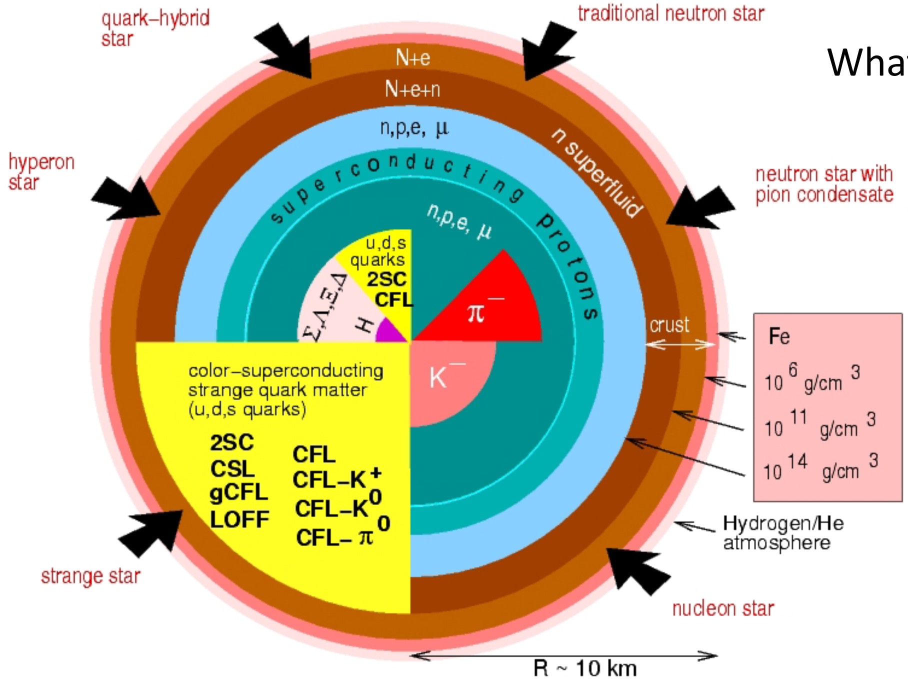



What is the Equation of state (EoS)?

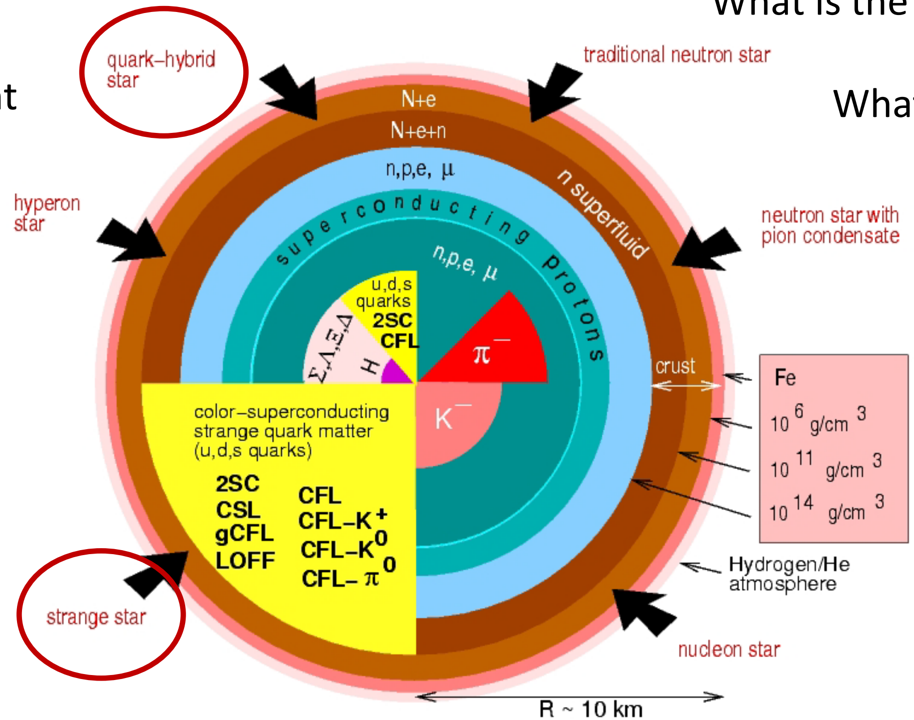
What are the constituents to consider?

How do they interact?

What do we want to (and what can we) measure at the LHC?

# Motivation: the unknown interior of neutron stars

- ALICE: the dedicated heavy-ion experiment at the LHC
- Aims to study the Quark-Gluon Plasma




What is the Equation of state (EoS)?

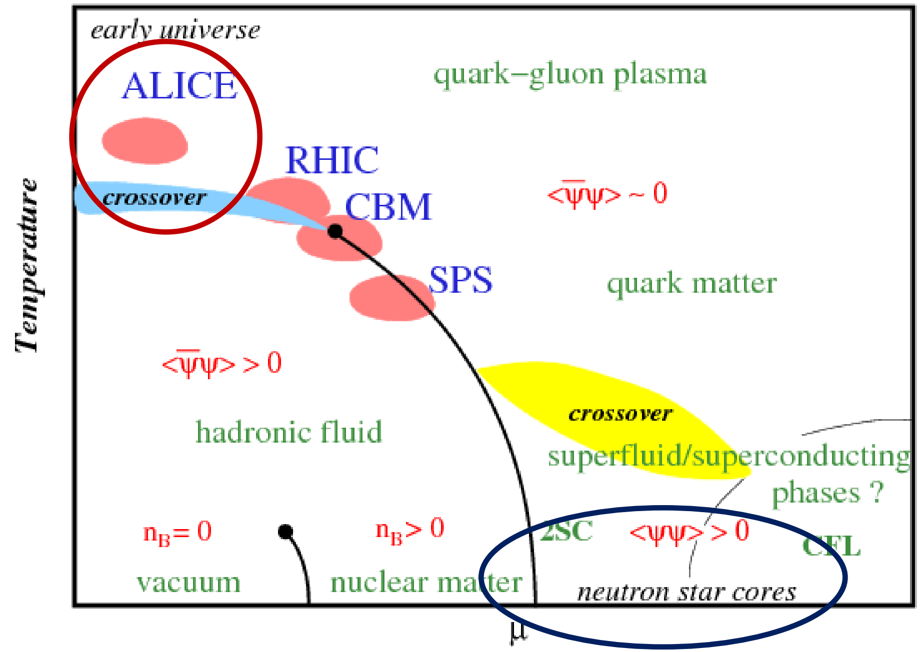
What are the constituents to consider?

How do they interact?

What do we want to (and what can we) measure at the LHC?

# Motivation: a look at the QCD phase diagram

- ALICE: the dedicated heavy-ion experiment at the LHC
- Aims to study the Quark-Gluon Plasma
- But: in a completely different regime of temperature and baryon density!

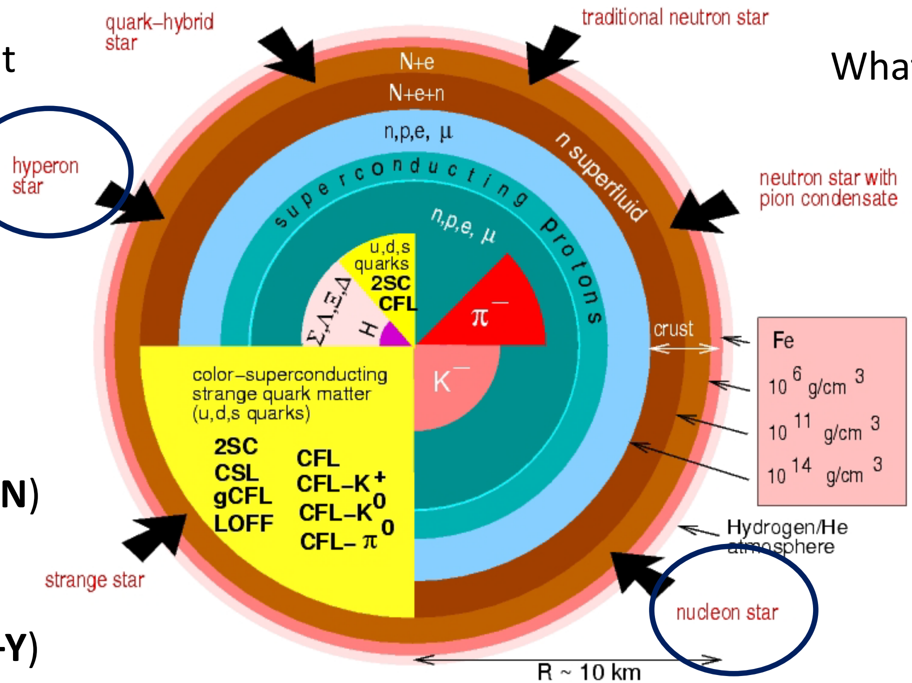



Neutron stars? somewhere down here...

# Motivation: the unknown interior of neutron stars

- ALICE: the dedicated heavy-ion experiment at the LHC
- Aims to study the Quark-Gluon Plasma
- But is also able to measure:

  hyperon-nucleon (**Y–N**)
  kaon-nucleon (**K–N**)
  and even
  hyperon-hyperon (**Y–Y**)
  interactions



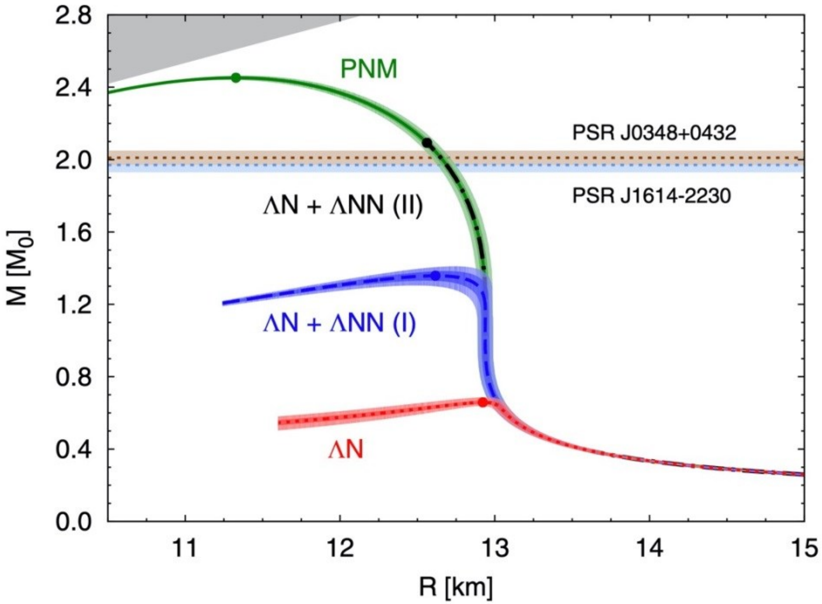

What is the Equation of state (EoS)?

What are the constituents to consider?

How do they interact?

What do we want to (and what can we) measure at the LHC?

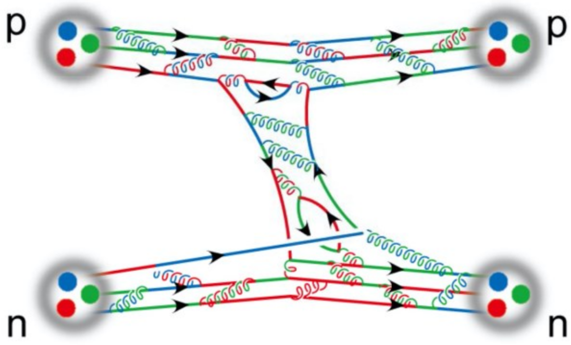
# Motivation: strangeness in the EOS of neutron stars




Phys. Rev. Lett. 114 (2015) 092301

- At high densities production of strange baryons may be favoured
- Expected: softening of the EOS, not able to explain measured neutron stars with $M \gtrsim 2\ M_{\odot}$
- Precise knowledg of hyperon-nucleon interactions needed
- Possible solution when 3-body forces included → see outlock
- Note: ALICE measures interactions in small systems, i.e. in vacuum

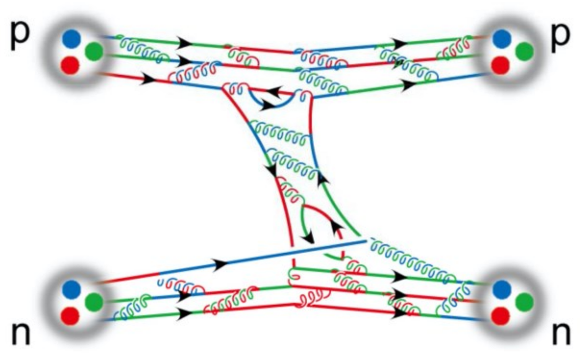
# Motivation: theory – nuclear interactions and QCD

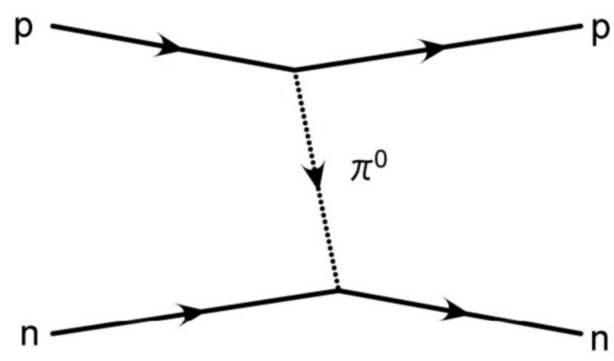



- Non-perturbative regime of QCD:
  - Calculations with lattice QCD
  - Computationally challenging
  - How to get hadronic observables e.g. potentials?

https://www.int.washington.edu/PROGRAMS/talent13/Lectures.htm

# Motivation: theory – nuclear interactions and QCD



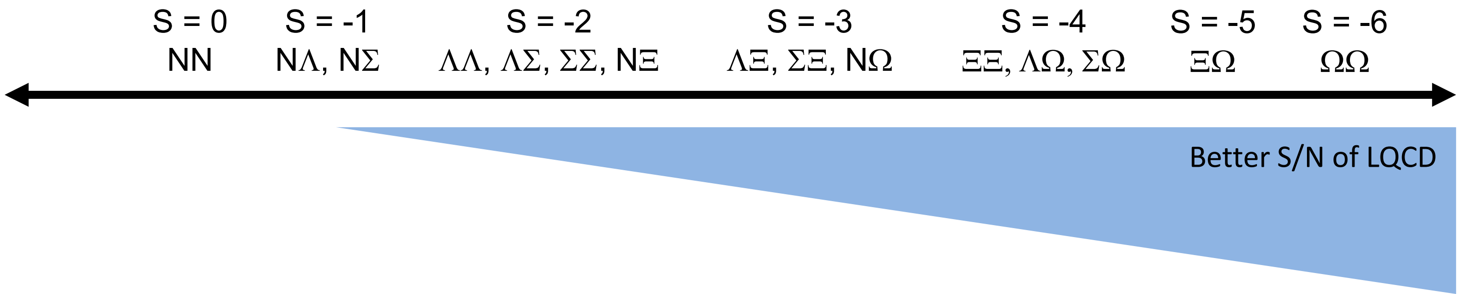




- Non-perturbative regime of QCD:
  - Calculations with lattice QCD
  - Computationally challenging
  - How to get hadronic observables e.g. potentials?

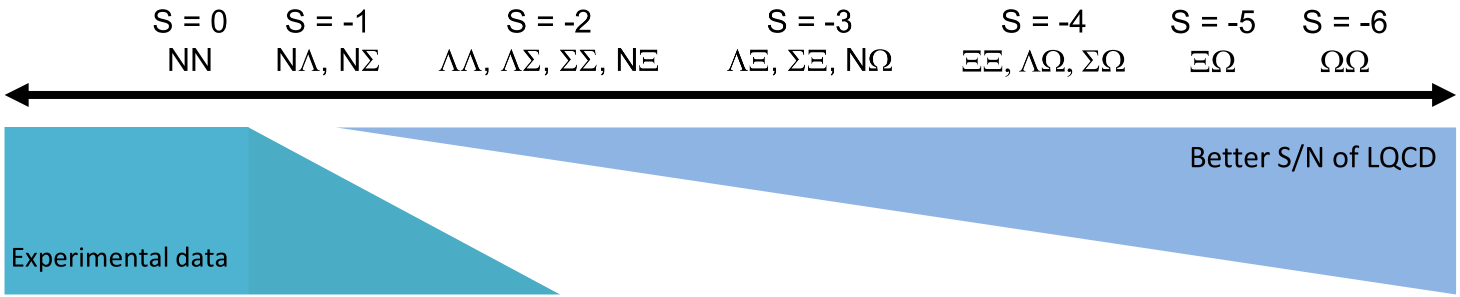
- Starting from an effective Lagrangian:
  - Calculations with chiral effective field theory
  - Hadrons as degrees of freedom
  - Chiral Perturbation theory

https://www.int.washington.edu/PROGRAMS/talent13/Lectures.htm

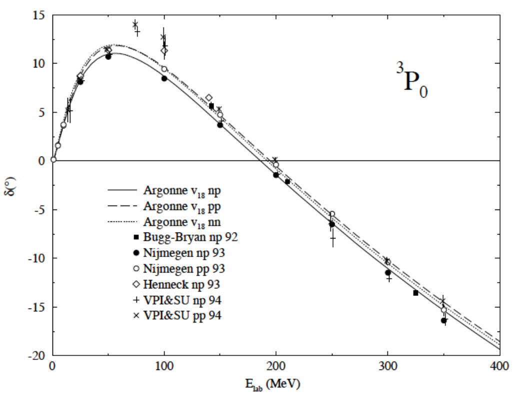
# Motivation: theory vs. available experimental data



# Motivation: theory vs. available experimental data

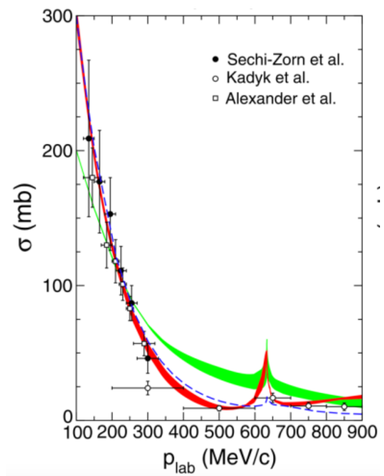



N–N → N–N



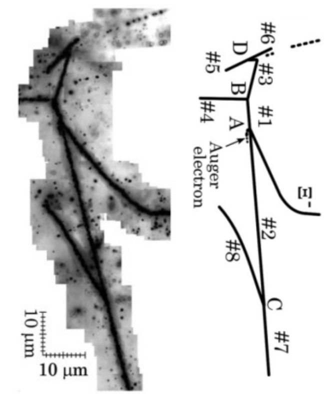

R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, PRC 51 (1995) 38-51.

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

Ξ Hypernucleus



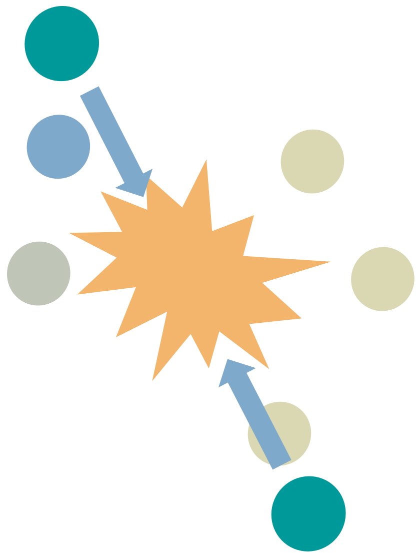

K. Nakazawa et al., PTEP 2015, 033D02

# Method

Femtoscopy upside down

# Method: two-particle correlation function

- In a collision of two ions or hadrons...



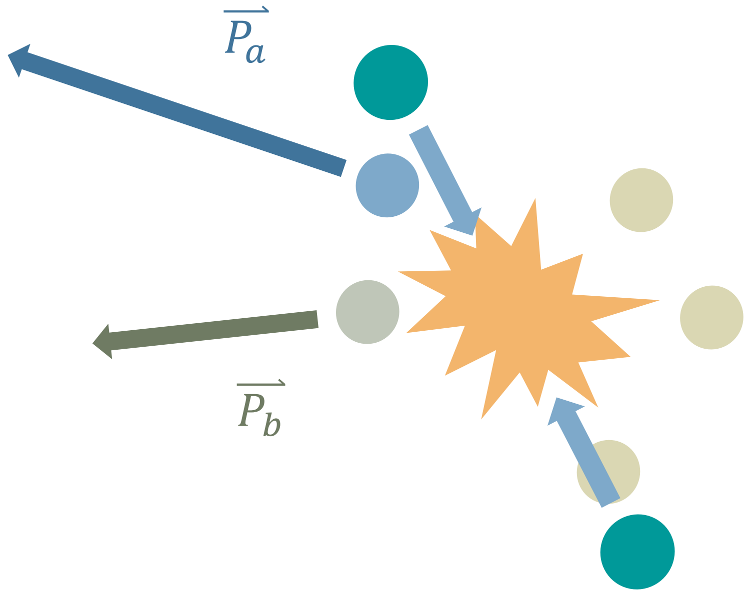
# Method: two-particle correlation function

- In a collision of two ions or hadrons...
- ... particles are created, where pairs have relative momenta

$$k^* = \frac{1}{2}|p_a^* - p_b^*|$$

- in the pair rest frame, i.e.

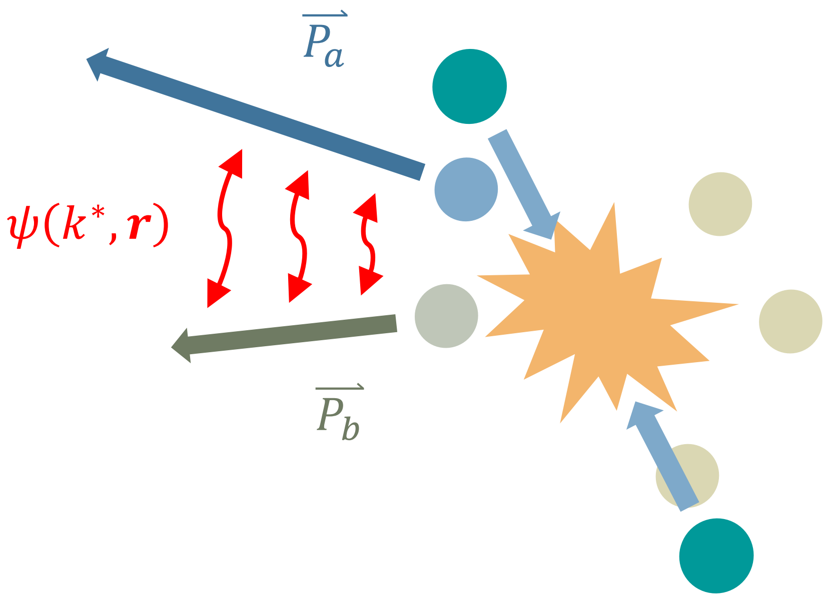
$$p_a^* + p_b^* = 0$$



# Method: two-particle correlation function

- Now you can study correlations in the $k^*$ distribution of pairs:

  - Attractive interaction: $C(k^*) > 1$
  - Repulsive interaction: $C(k^*) < 1$

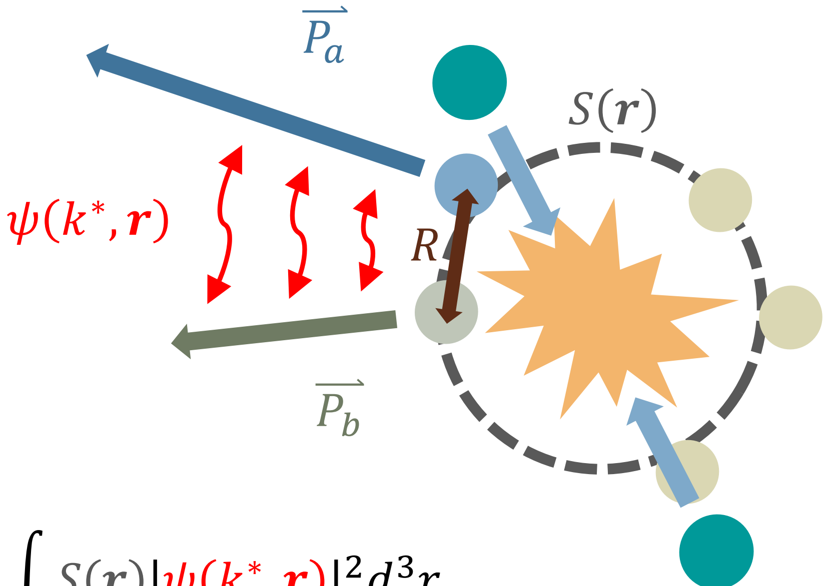



$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$\mathrm{k}^* = \frac{1}{2}|\mathrm{p}_\mathrm{a}^* - \mathrm{p}_\mathrm{b}^*|$ and $\mathrm{p}_\mathrm{a}^* + \mathrm{p}_\mathrm{b}^* = 0$

# Method: two-particle correlation function

- Now you can study correlations in the $k^*$ distribution of pairs
- Two-particle correlation function $C(k^*)$ connected to the:
  - Source: $S(\boldsymbol{r})$
  - Two-particle wave function: $\psi(k^*, \boldsymbol{r})$



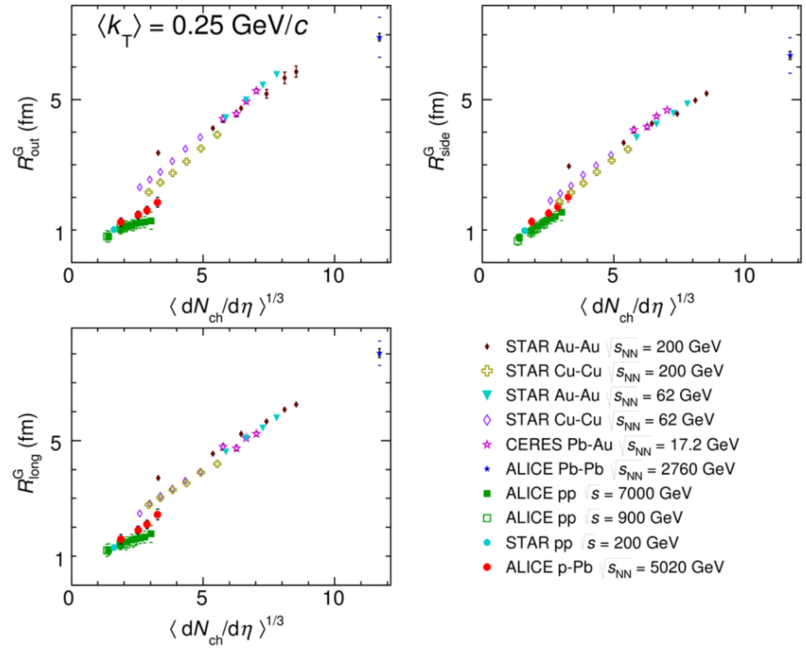

$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(\boldsymbol{r}) |\psi(k^*, \boldsymbol{r})|^2 d^3 r$$

$\mathrm{k}^* = \frac{1}{2} |\mathrm{p}_\mathrm{a}^* - \mathrm{p}_\mathrm{b}^*|$ and $\mathrm{p}_\mathrm{a}^* + \mathrm{p}_\mathrm{b}^* = 0$

**C**orrelation **A**nalysis **T**ool using the **S**chrödinger Equation:
D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394

# Method: two-particle correlation function

- Originally used to constrain the source
- If the interaction ($\psi(k^*, \boldsymbol{r})$) is known, you can determine the source size $S(\boldsymbol{r})$



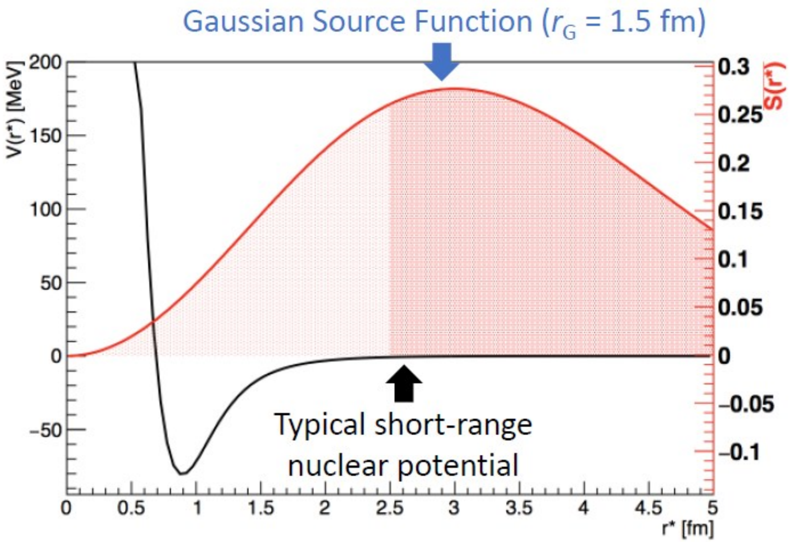

$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(\boldsymbol{r}) |\psi(k^*, \boldsymbol{r})|^2 d^3 r$$

ALICE, Phys. Rev. C 91 (2015) 034906

$$\mathrm{k}^* = \frac{1}{2} |\mathrm{p}_\mathrm{a}^* - \mathrm{p}_\mathrm{b}^*| \text{ and } \mathrm{p}_\mathrm{a}^* + \mathrm{p}_\mathrm{b}^* = 0$$

# Method: two-particle correlation function

- Now we turn the method around
- If the source size $S(\boldsymbol{r})$ is known, you can determine the interaction ($\psi(k^*, \boldsymbol{r})$)
- Thus, first we have to get the source size




$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(\boldsymbol{r}) |\psi(k^*, \boldsymbol{r})|^2 d^3r$$

$\mathrm{k}^* = \frac{1}{2} |\mathrm{p}_\mathrm{a}^* - \mathrm{p}_\mathrm{b}^*|$ and $\mathrm{p}_\mathrm{a}^* + \mathrm{p}_\mathrm{b}^* = 0$

- Small source sizes give rise to pronounced correlation signal
- At the LHC: pp and p–Pb collisions

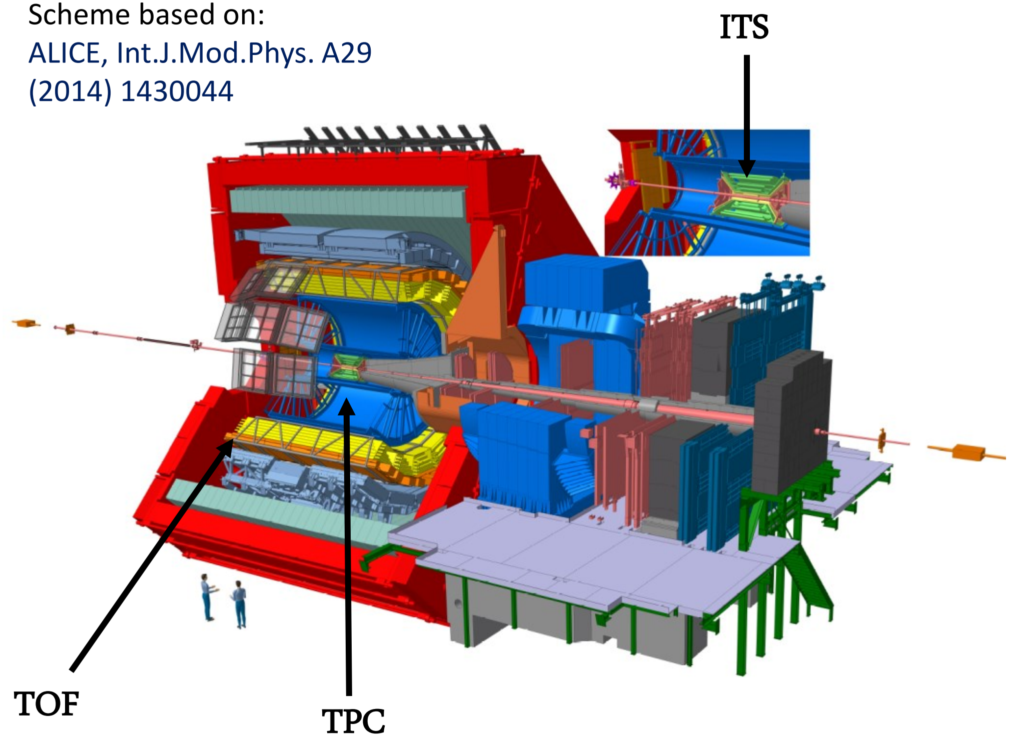
# Experiment

ALICE (A Large Ion Collider Experiment)

# Experiment: ALICE

- ALICE is designed to study bulk properties of the Quark-Gluon Plasma:
  - Precise particle tracking (ITS+TPC)
  - Due to low magnetic field (0.5 T) tracking down do low momenta
  - Excellent particle identification (esp. but not only: TPC and TOF)

Scheme based on:
ALICE, Int.J.Mod.Phys. A29 (2014) 1430044



# Experiment: ALICE

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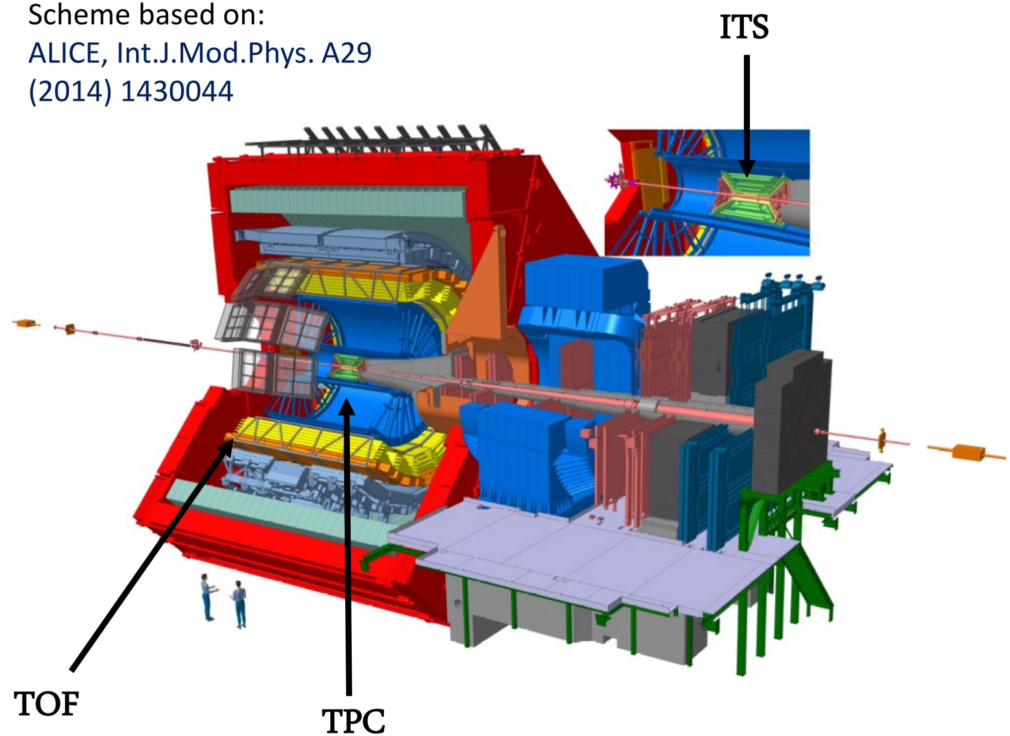
  - Precise particle tracking (ITS+TPC)
  - Due to low magnetic field (0.5 T) tracking down do low momenta
  - Excellent particle identification (esp. but not only: TPC and TOF)
- This is exactly what we need for low-momentum correlation studies of identified particles!

Scheme based on:
ALICE, Int.J.Mod.Phys. A29 (2014) 1430044

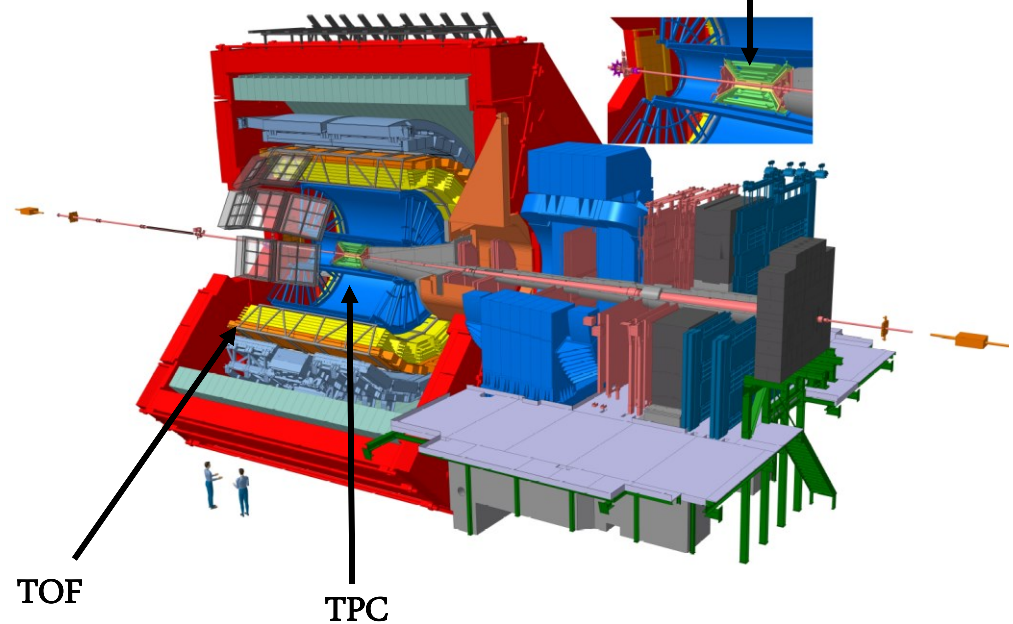


# Experiment: ALICE

- Direct detection of charged particles (p, K, π)
- Reconstruction of hyperons via decays:
  - $\Lambda \rightarrow p\pi^-$
  - $\Sigma^0 \rightarrow \Lambda\gamma$
  - $\Xi^- \rightarrow \Lambda\pi^-$
  - $\Omega^- \rightarrow \Lambda K^-$

| System | # events |
| --- | --- |
| pp 7 TeV | 3.4 x $10^8$ minimum bias (MB) |
| p–Pb 5.02TeV | 6.0 x $10^8$ MB |
| pp 13 TeV | 15 x $10^8$ MB |
| | 10 x $10^8$ high multiplicity (HM) (0–0.17% INEL>0) |

Scheme based on:
ALICE, Int.J.Mod.Phys. A29 (2014) 1430044

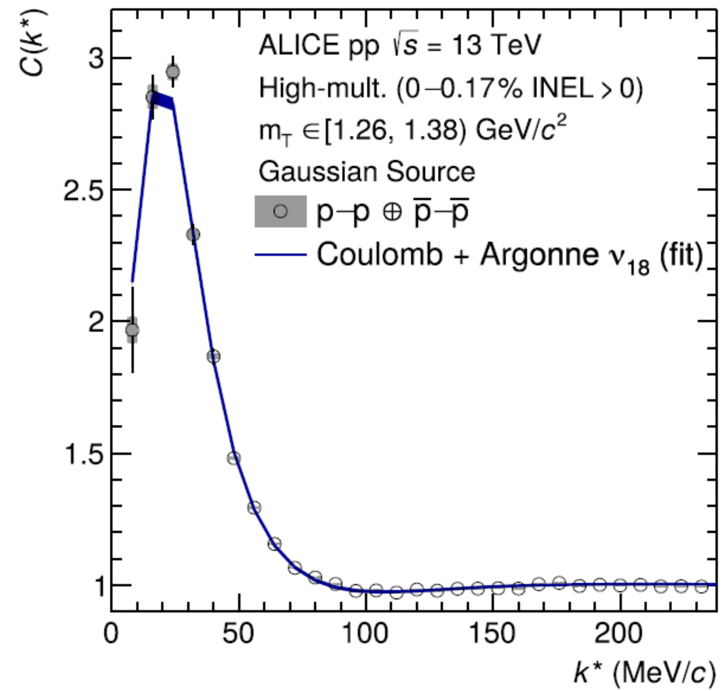


# First step

Constraining the source

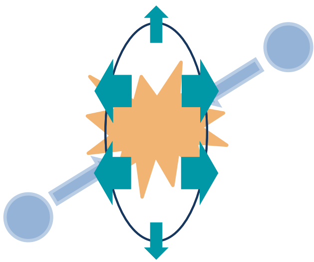
# First step: constraining the source

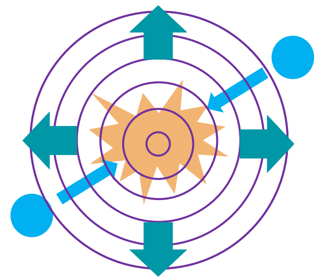
- For the p-p correlation, the interaction ($\psi(k^*, \boldsymbol{r})$) is well known
- We measure $C(k^*)$ for p-p pairs and fit with Coulomb + Argonne $v_{18}$ potential
- Is the source universal for all particle pairs?




ALICE, Phys.Lett. B 811 (2020) 135849

# First step: possible influence due to collective effects





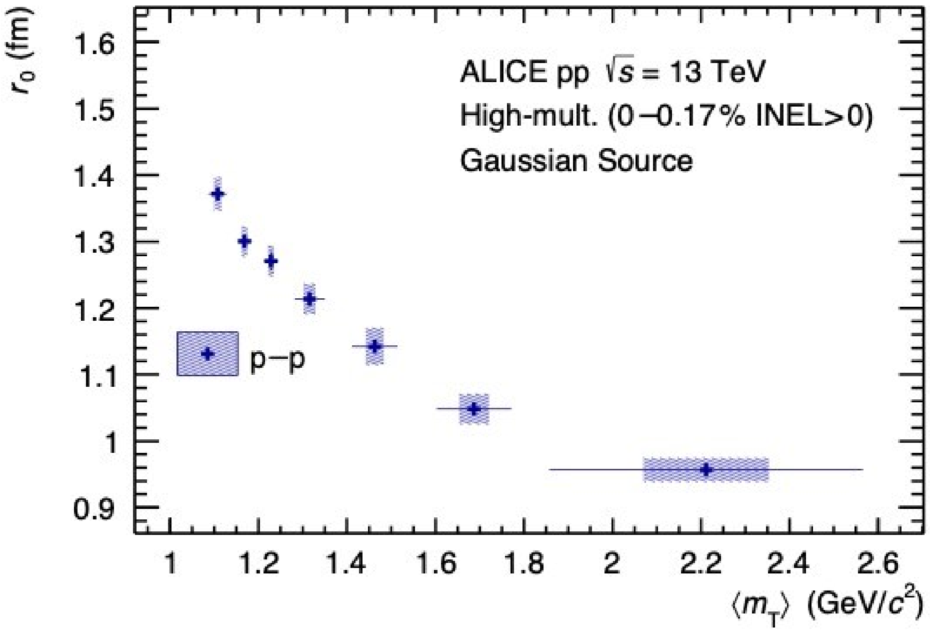
Anisotropic + radial
pressure gradients

Different effect on different masses

→ Scaling of radii with transverse mass:

$$m_T = \sqrt{k_T^2 + m_{avg}^2},\ k_T = \frac{1}{2}(p_{T,1} + p_{T,2})$$

# First step: a Gaussian core

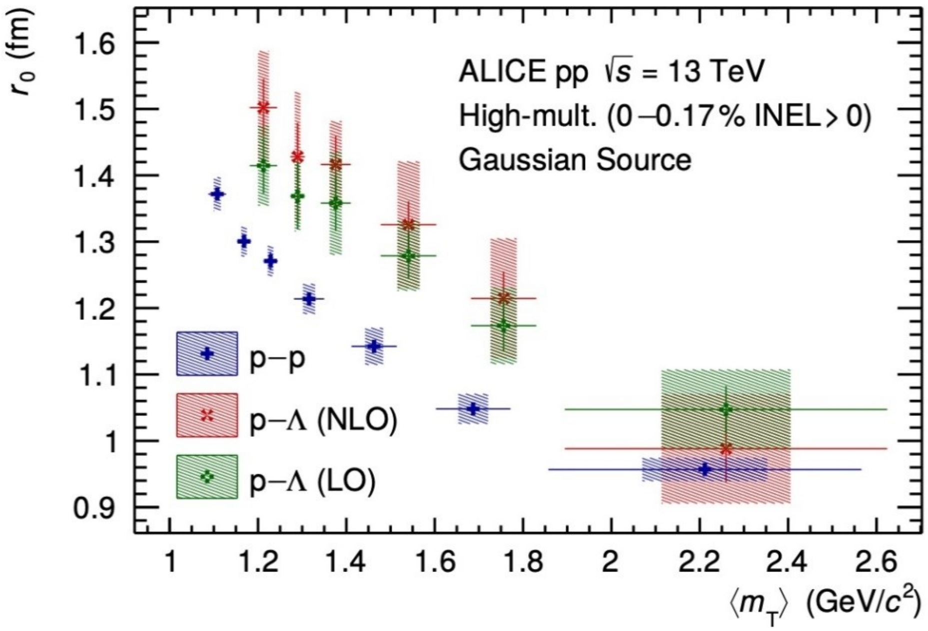



ALICE, Phys.Lett. B 811 (2020) 135849

Radii measured from the p-p correlation function:

- Pure Gaussian radii $r_0$
- $m_T$ scaling of radii in elementary collisions

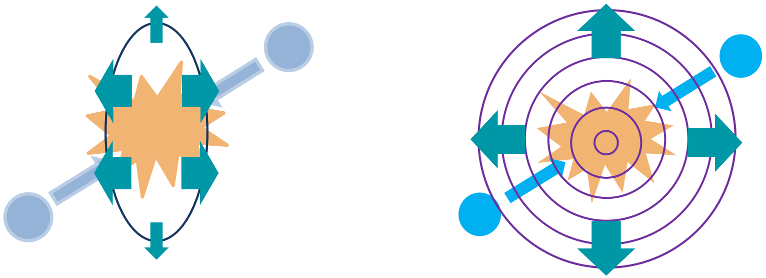
# First step: a Gaussian core




ALICE, Phys.Lett. B 811 (2020) 135849

Radii measured from the p-p and p-Λ correlation functions:

- Pure Gaussian radii $r_0$
- $m_T$ scaling of radii in elementary collisions
- Difference between the measured source sizes

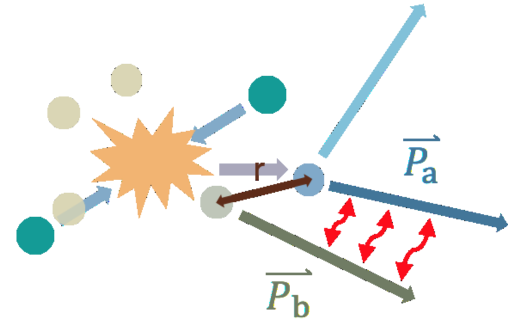


Anisotropic + radial
pressure gradients

Different effect on different masses

→ Scaling of radii with transverse mass $m_T$

→ Gaussian core



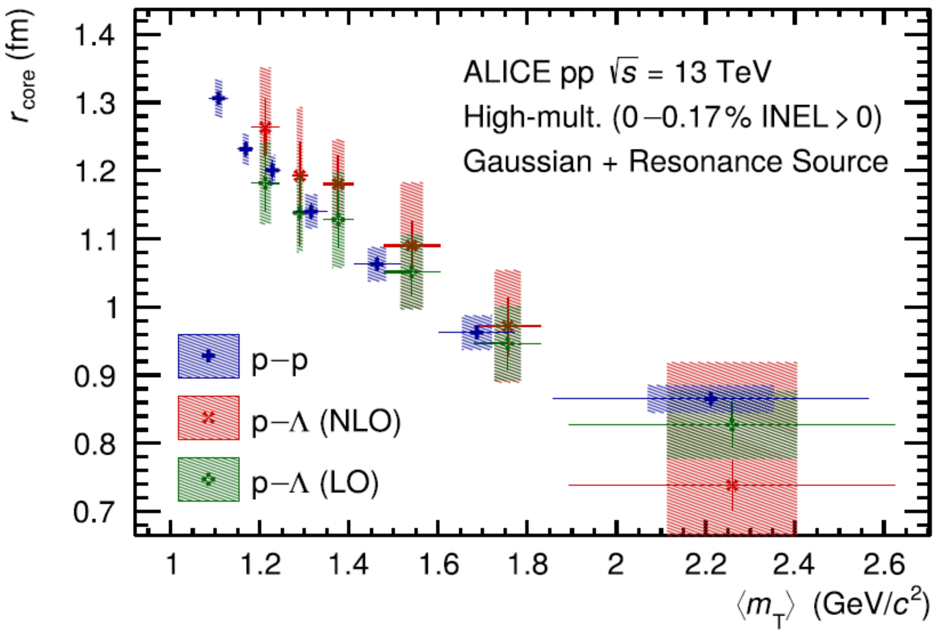

Resonances with cτ ~ $r_0$ ~ 1 fm ($\Delta^{++}$, $N^*$, $\Sigma^*$)

| Particle | Primordial fraction | Resonances <cτ> |
|---|---|---|
| Proton | 33 % | 1.6 fm |
| Lambda | 34 % | 4.7 fm |

U. Wiedemann U. Heinz, PRC 56 (1997) R610

→ Exponential modification of the Gaussian Core

# First step: a Gaussian source with resonances




ALICE, Phys.Lett. B 811 (2020) 135849

Radii measured from the p-p and p-Λ correlation functions:

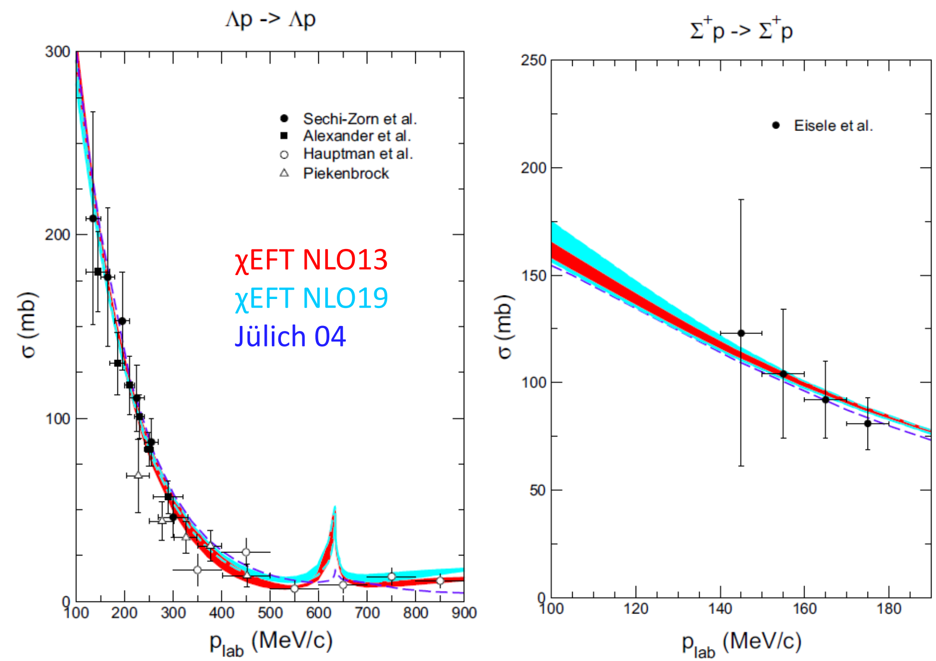
- Gaussian core radii $r_{core}$
- $m_T$ scaling of radii in elementary collisions
- Evidence of a universal emmission source of baryons

# Results

Hyperon–nucleon and kaon–nucleon interactions

# Results: S = –1, Λ and Σ baryons

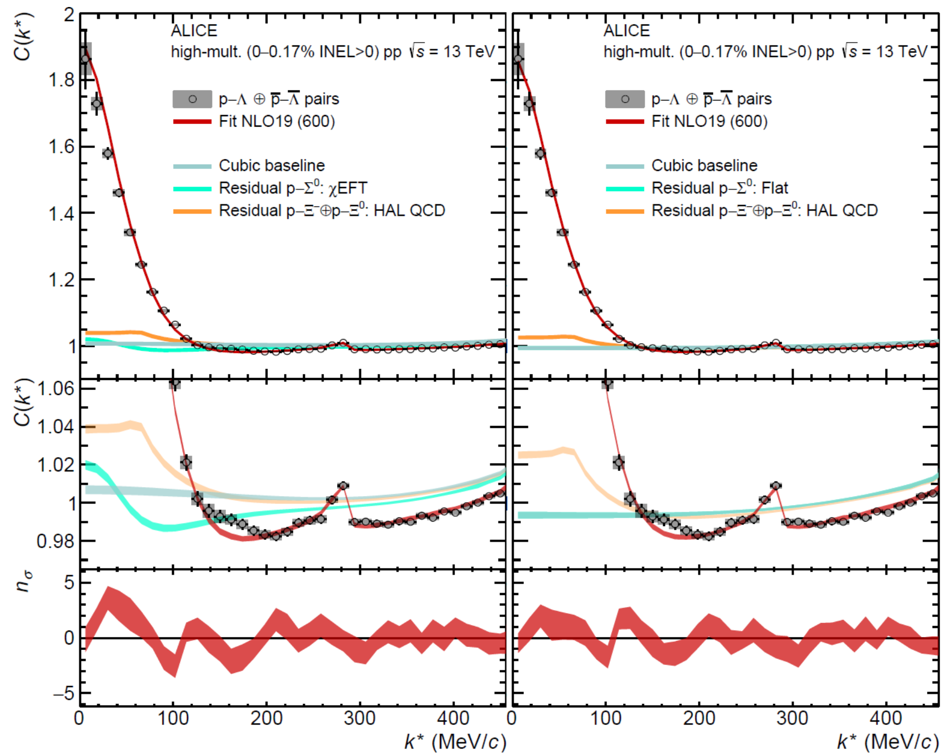
- Scarce experimental data
- No constraints at lab momenta below 100 MeV/c
- Theoretical predictions for cusp in Λ–N due to the Σ–N ↔ Λ–N coupling
- Coupling introduces a repulsive short range component in the p–Λ interaction




J. Haidenbauer et al., Eur. Phys. J. A 56 (2020) 91

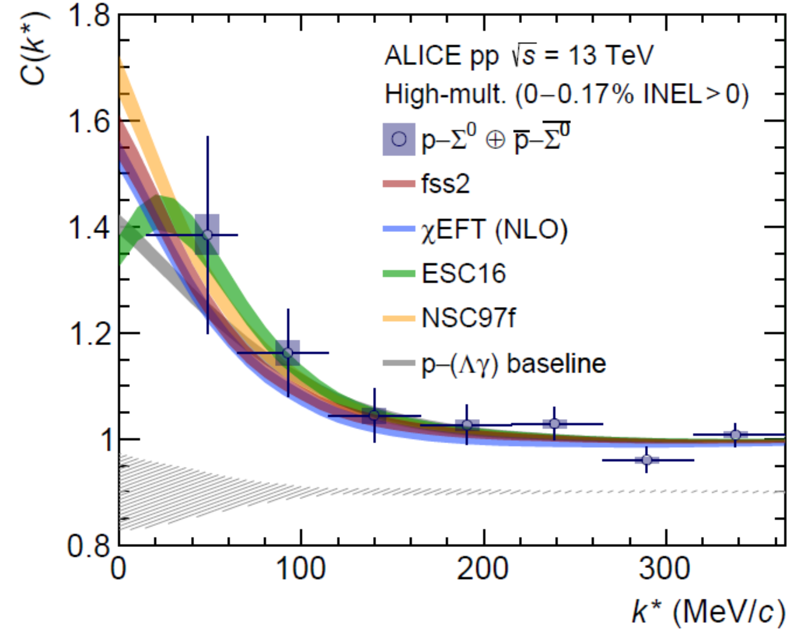
# Results: p–Λ in 13 TeV pp collisions (HM)

- Significant extension of the kinematic range
- Clear experimental evidence for the cusp
- Different variations of the residual p–$\Sigma^0$ correlation: from χEFT or flat
- LO χEFT failed to reproduce the data, recent NLO19 with better description, but still some deviations
- Entering a precision era!



# Results: p–$\Sigma^0$ in 13 TeV pp collisions (HM)

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

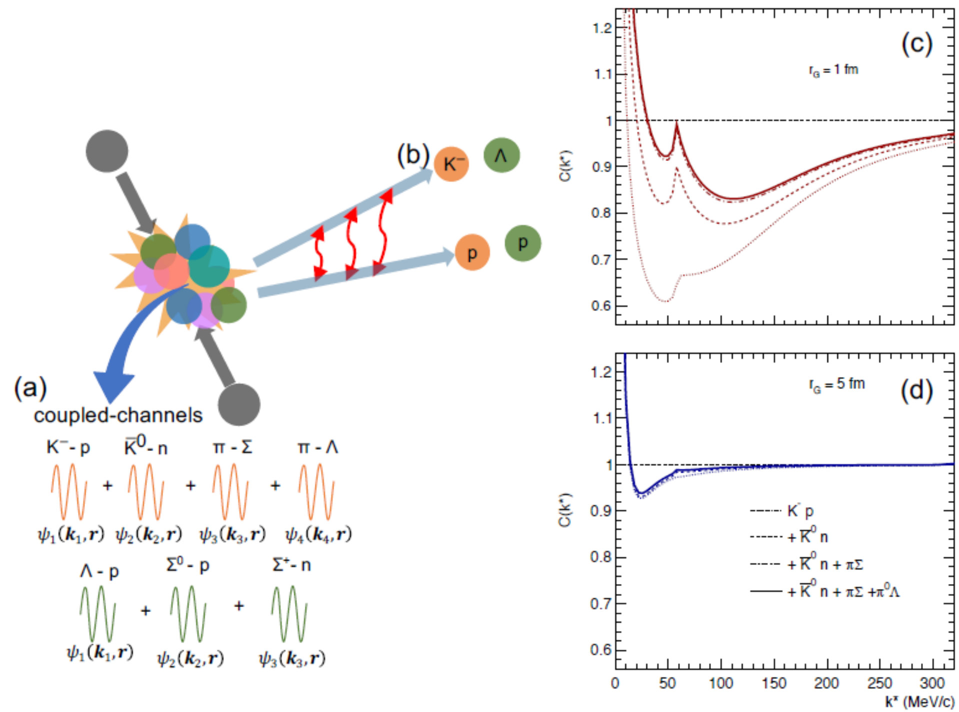



ALICE, Phys.Lett. B 805 (2020) 135419

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

# Results: kaon–nucleon interactions and coupled channels

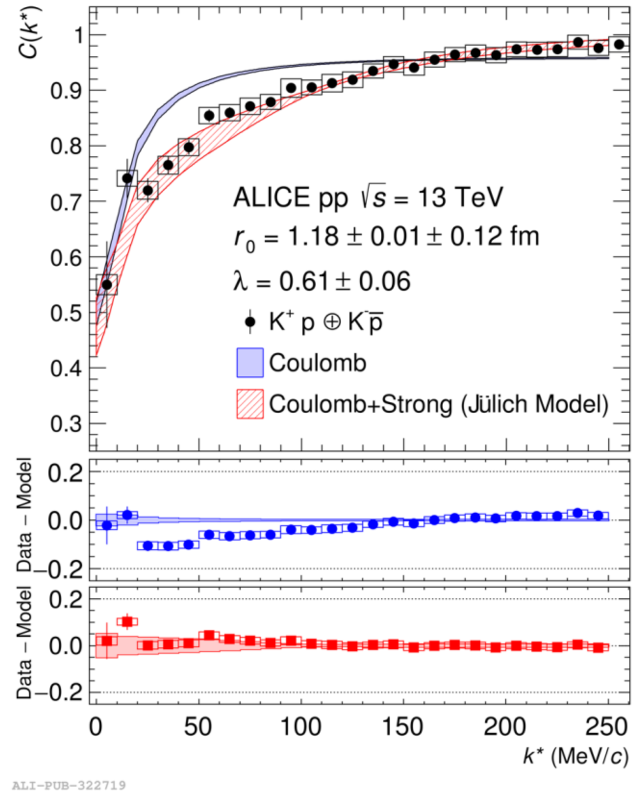
- In K–N interactions, two coupled channels expected
- Should have a visible effect on the correlation function:
  - Λ(1405), below threshold → overall increase of CF
  - $\overline{K}^0$–n, above threshold → cusp structure




L. Fabbietti et al., arXiv:2012.09806

# Results: $K^+$–p in 13 TeV pp collisions (MB)

- $K^+$–p correlations:
  - Known very well from scattering experiments
  - No inelastic channels
  - Used as a benchmark to study $K^-$–p
- Radius obtained from inclusive p–p correlation

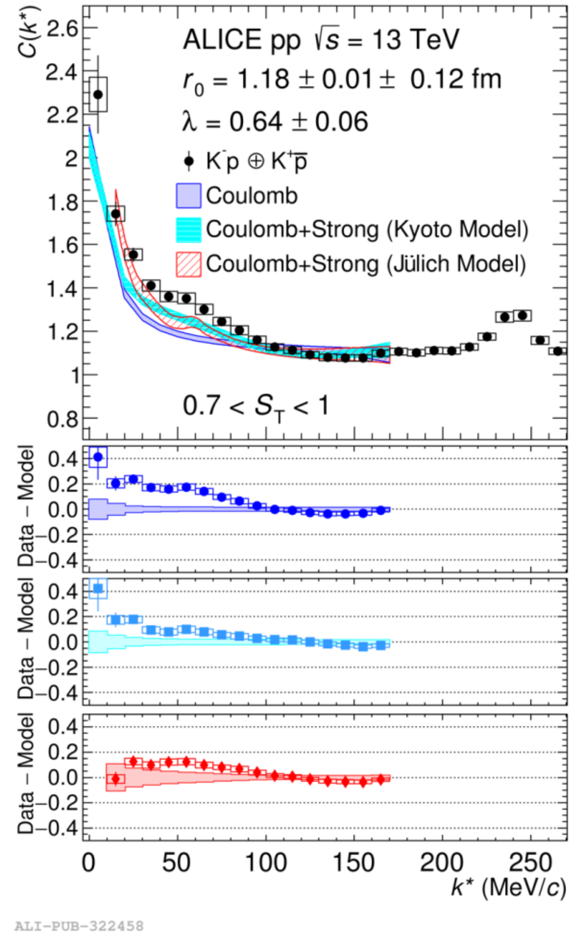



ALICE,
Phys. Rev. Lett. 124 (2020) 092301

Jülich: J. Haidenbauer, Nucl. Phys. A 981 (2019) 1

# Results: $K^-$–p in 13 TeV pp collisions (MB)

- $K^-$–p correlations:
  - Observation of a cusp structure close to the $\overline{K}^0$–n threshold
  - Corresponds to 58 MeV/c in CM frame
- First experimental evidence of the opening of the $\overline{K}^0$–n coupled channel!
- Study in p–Pb and peripheral Pb–Pb collisions ongoing:
  - Coupled channel effects expected to decrease with increasing source size




ALICE, Phys. Rev. Lett. 124 (2020) 092301

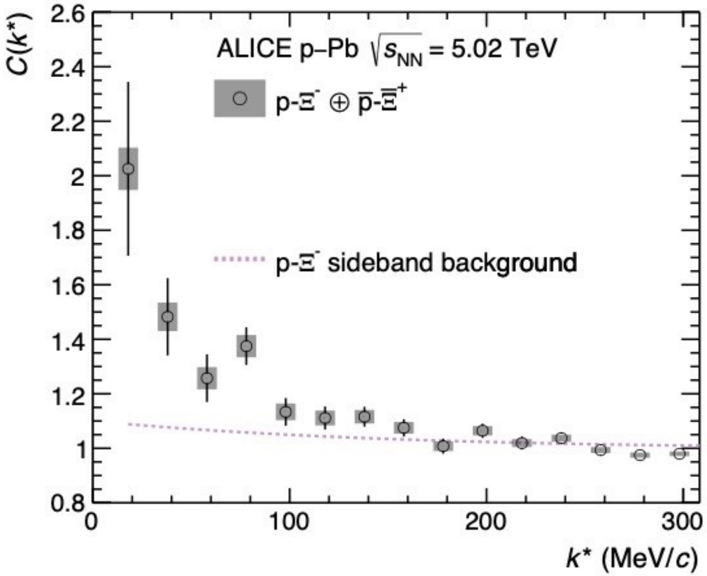
Jülich: J. Haidenbauer, Nucl. Phys. A 981 (2019) 1
Kyoto: K. Miyahara and T. Hyodo, Phys. Rev. C 93 (2016) 015201

# Results: S = –2, p–Ξ⁻ in 5.02 TeV p–Pb and 13 TeV pp (HM)

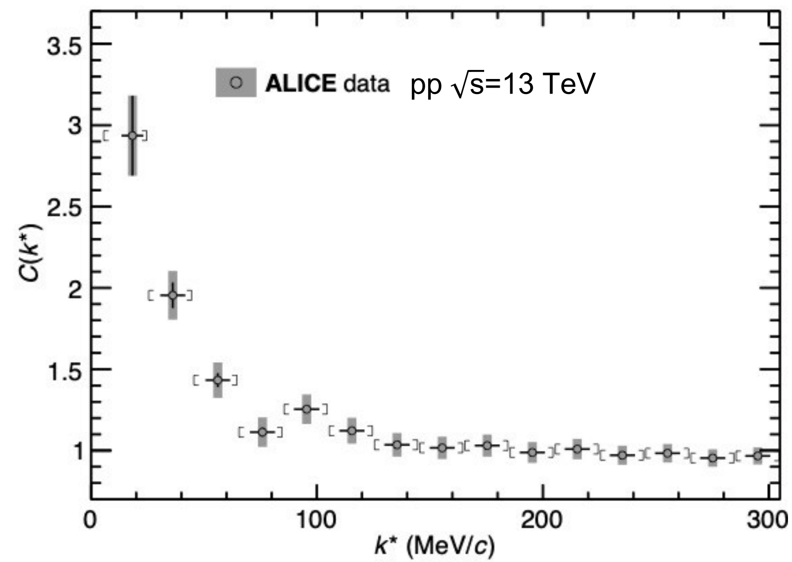
- p–Ξ⁻ correlation function in two collision systems

- Source sizes:

| | |
|---|---|
| pp 13 TeV HM | 1.25 fm |
| p-Pb 5.02 TeV MB | 1.43 fm |



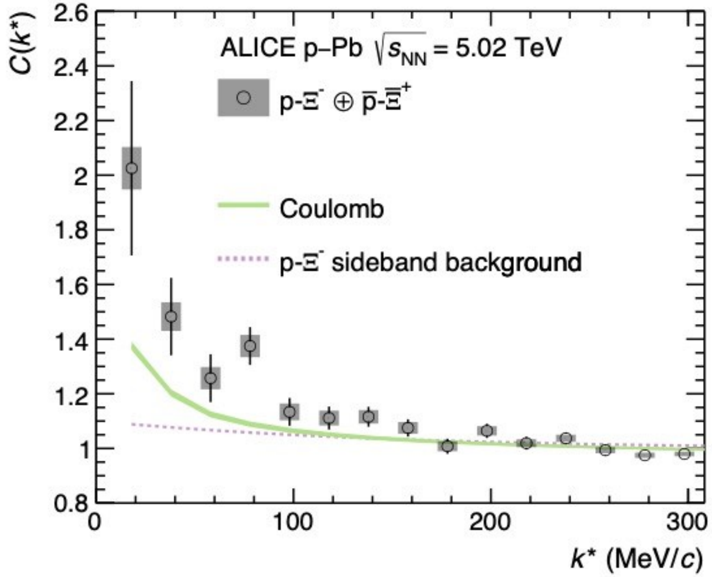

ALICE, Phys. Rev. Lett. 123 (2019) 112002



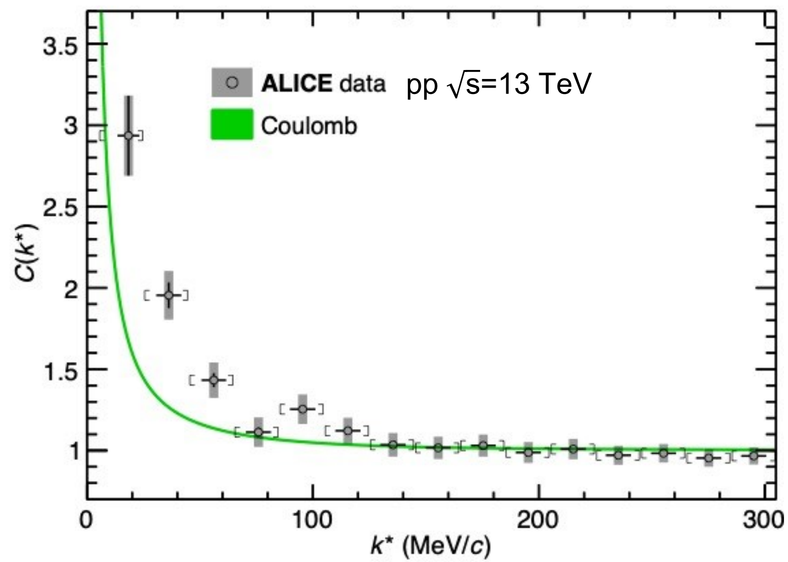

ALICE, Nature 588 (2020) 7837, 232

# Results: S = –2, p–$\Xi^-$ in 5.02 TeV p–Pb and 13 TeV pp (HM)

- Clear enhancement above the Coulomb prediction
- First observation of an attractive strong interaction between a proton and a $\Xi^-$ baryon



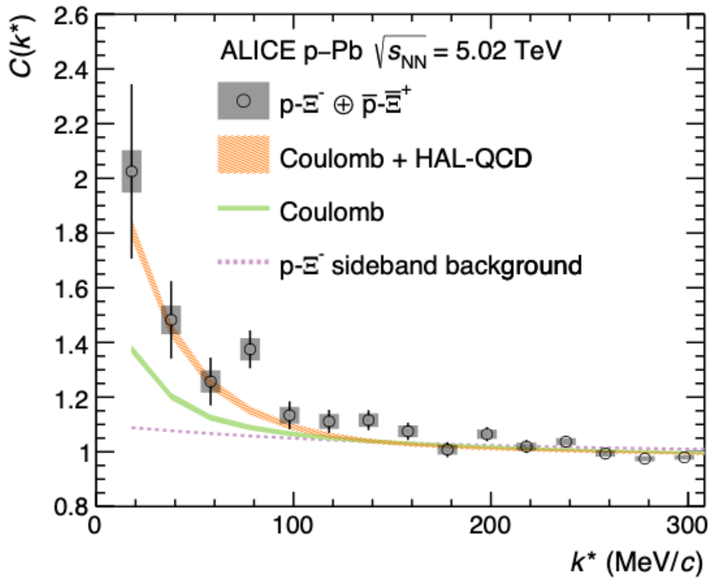

ALICE, Phys. Rev. Lett. 123 (2019) 112002



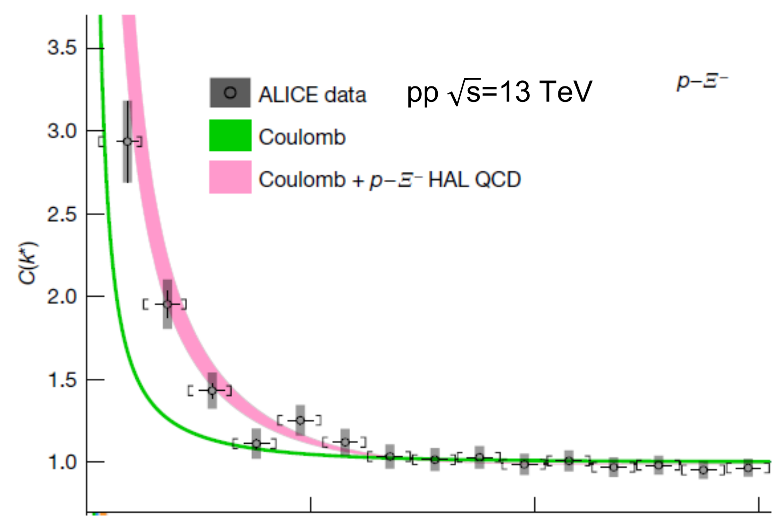

ALICE, Nature 588 (2020) 7837, 232

# Results: S = –2, p–Ξ⁻ in 5.02 TeV p–Pb and 13 TeV pp (HM)

- Validation of HAL QCD lattice predictions
- First direct measurement using the femtoscopy method

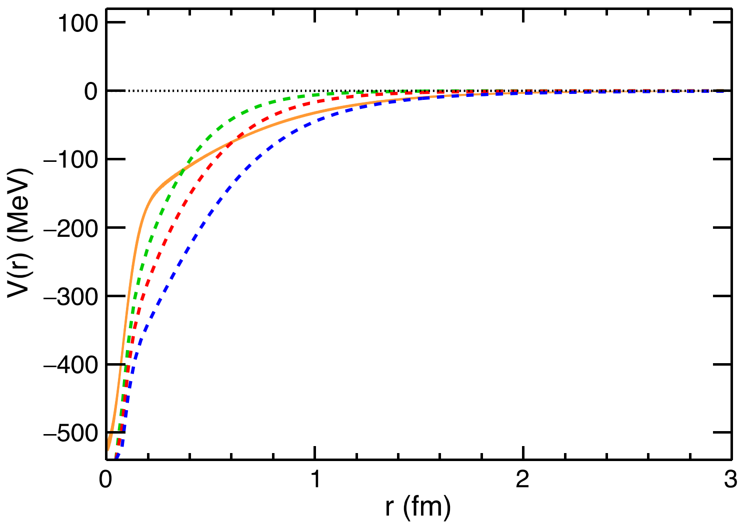



ALICE, Phys. Rev. Lett. 123 (2019) 112002




ALICE, Nature 588 (2020) 7837, 232

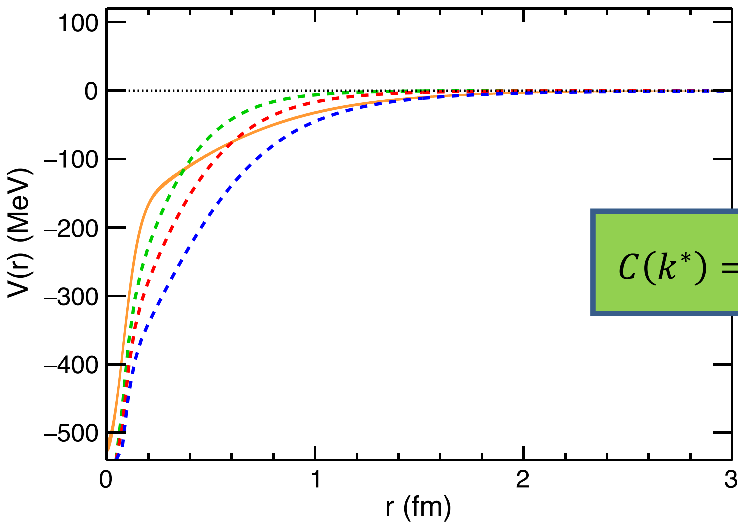
# Results: S = –3, p–$\Omega^-$ interactions




K. Morita et al., Phys. Rev. C 101 (2020) 015201

- Several rather similar potentials for the p–$\Omega^-$ interaction...

# Results: S = –3, p–Ω$^-$ interactions




$r_{\text{eff}} = 0.95$ fm

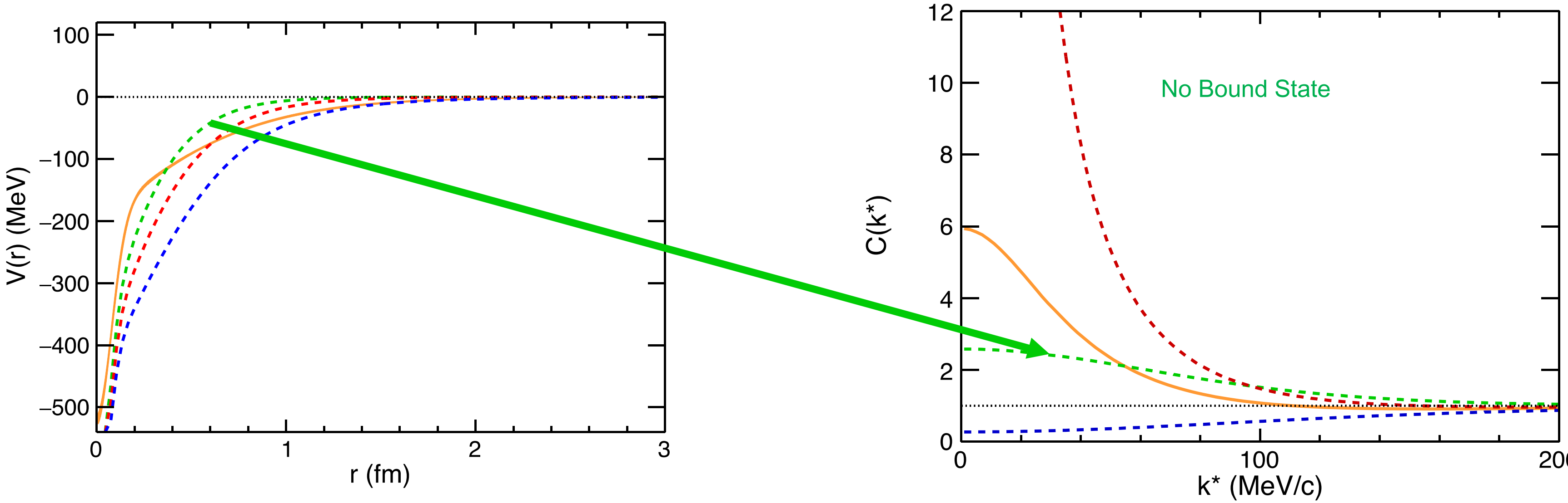
$$C(k^*) = \int S(\boldsymbol{r}) |\psi(k^*, \boldsymbol{r})|^2 d^3r$$

$$\hat{\mathcal{H}} \cdot \psi(k^*, \boldsymbol{r}) = \mathrm{E} \cdot \psi(k^*, \boldsymbol{r})$$

K. Morita et al., Phys. Rev. C  101 (2020) 015201

- ... transform into...

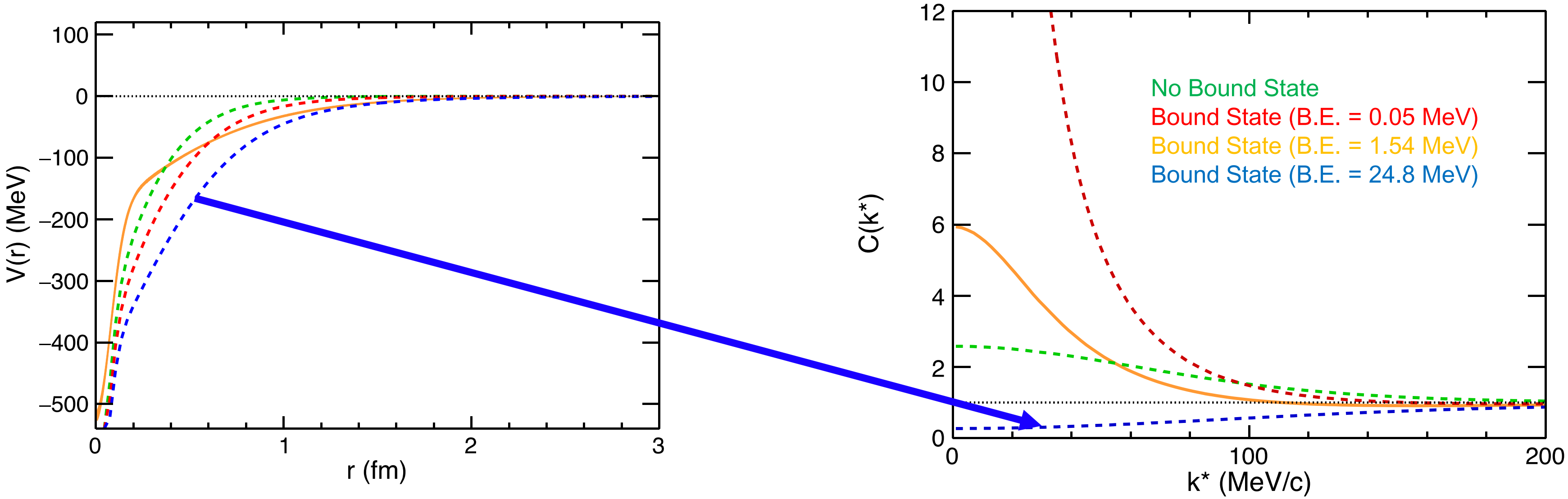
# Results: S = –3, p–$\Omega^-$ interactions




K. Morita et al., Phys. Rev. C 101 (2020) 015201

- ... quite different correlation functions!

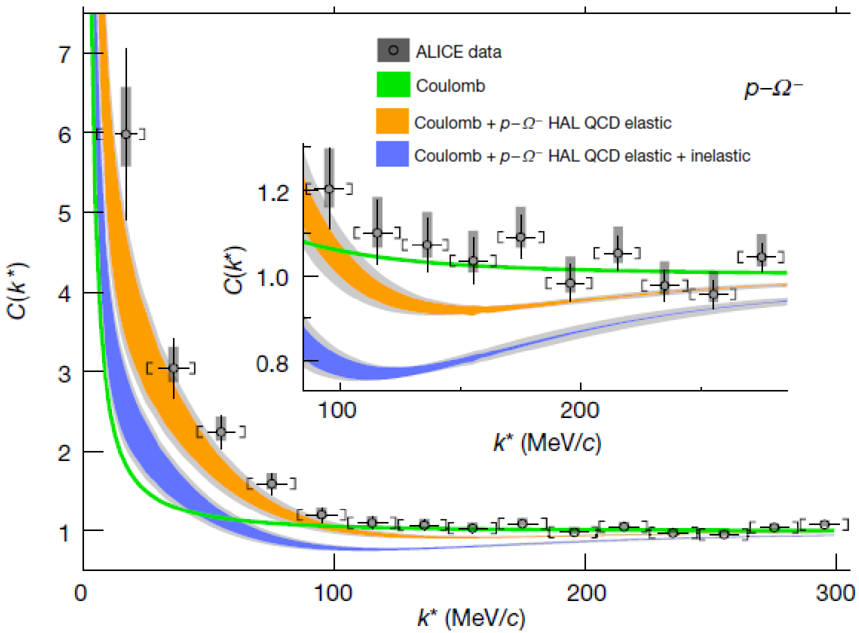
# Results: S = –3, p–$\Omega^-$ interactions




K. Morita et al., Phys. Rev. C 101 (2020) 015201

- In case of a bound state: prediction sensitive to the binding energy
- Femtoscopy in small systems sensitive to minor differences in the interaction potentials

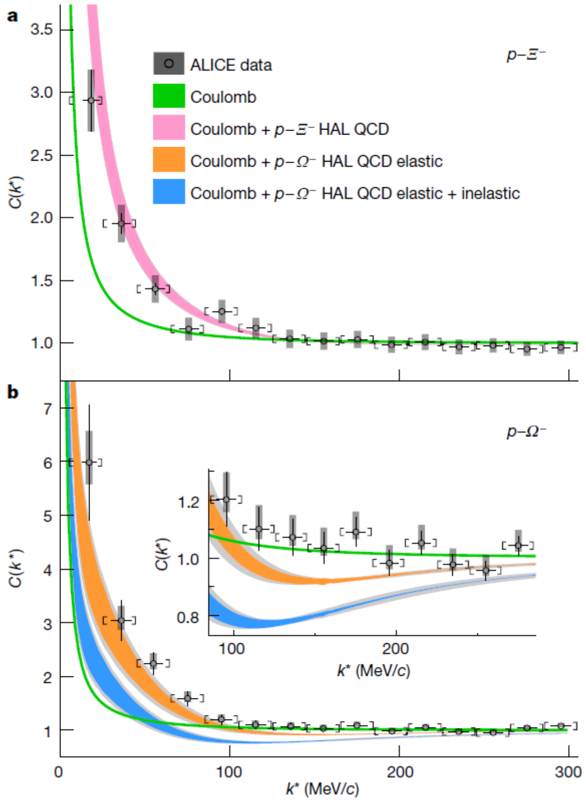
# Results: p–$\Omega^-$ in 13 TeV pp collisions (HM)

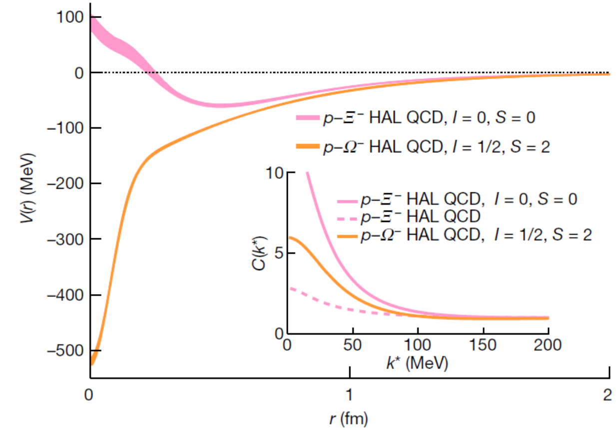



ALICE, Nature 588 (2020) 7837, 232

- Enhancement above Coulomb
  → Observation of the strong interaction
- Missing potential of the $^3S_1$ channel
  → Test of two cases:
  1. **Total Absorption by inel. channels**
  2. **Neglecting inel. channels**
- Data more precise than the first principle calculations
- So far, no indication for a bound state

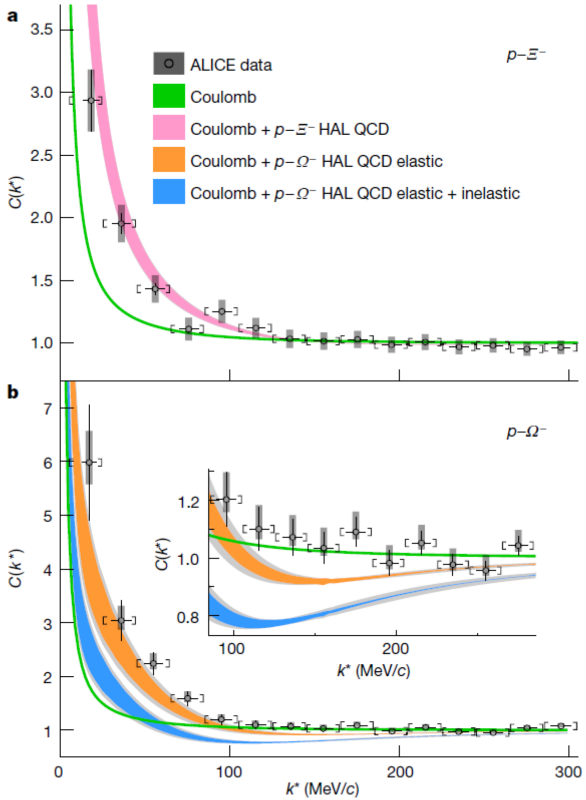
# Results: p–$\Xi^-$ → back to neutron stars



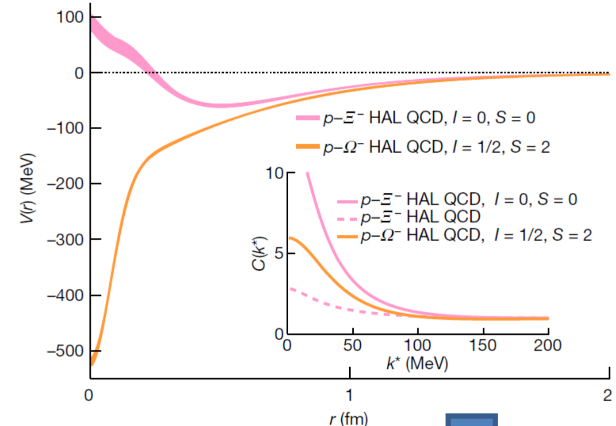




ALICE, Nature 588 (2020) 7837, 232

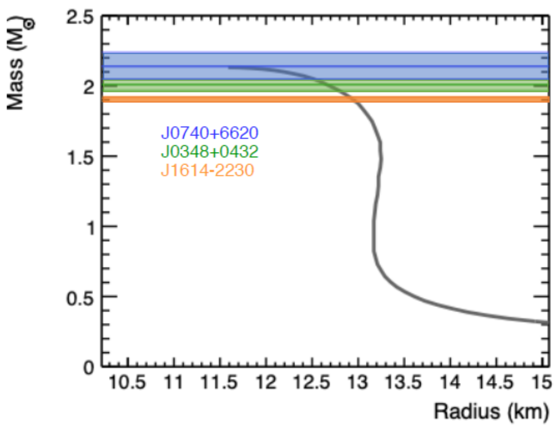
# Results: p–Ξ⁻ → back to neutron stars




ALICE, Nature 588 (2020) 7837, 232



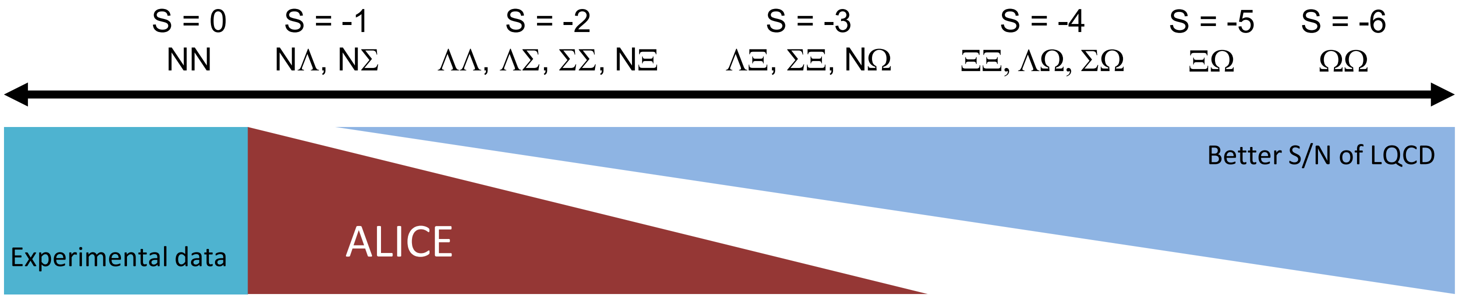

- Repulsive core of p–Ξ⁻ interaction leading to stiffer neutron star EOS
- Masses > 2 $M_\odot$ can be reached

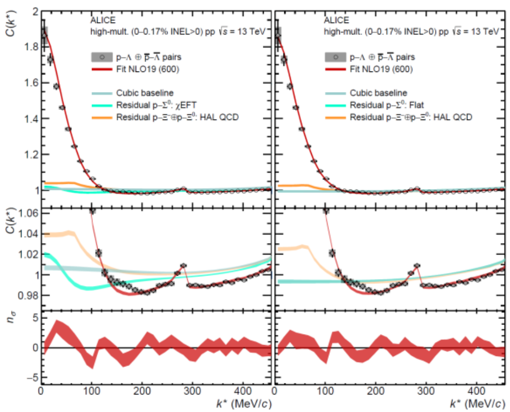


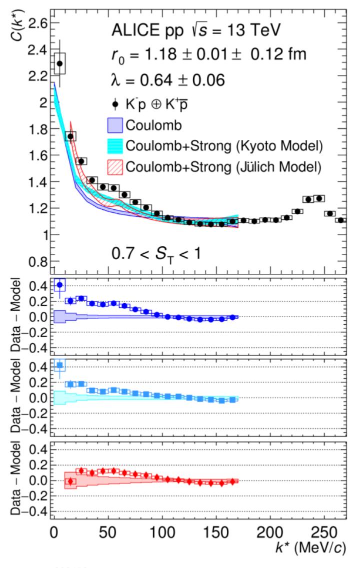
# Summary

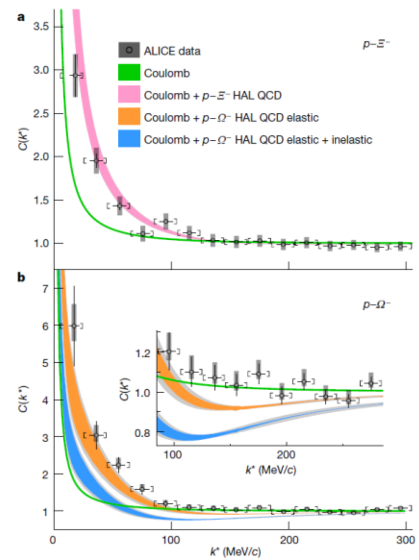
And more to come...

# Summary



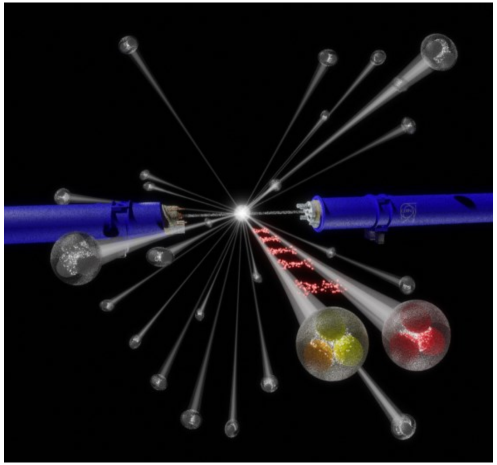

**ALICE has entered the precision aera of femtoscopic measurements!**

# Summary: ALICE publications

- Phys. Rev. C 99 (2019) 024001: p–p, p–Λ, and Λ–Λ in 7 TeV pp (LHC Run 1)
- Phys. Lett. B 797 (2019) 134822: Λ–Λ in 13 TeV pp and 5 TeV p–Pb
- Phys. Rev. Lett. 123 (2019) 112002: p–$\Xi^-$ in 5 TeV p–Pb
- Phys.Lett. B 805 (2020) 135419: p–$\Sigma^0$ in 13 TeV pp
- Phys. Rev. Lett. 124 (2020) 092301: $K^-$–p in 13 TeV pp
- Phys.Lett. B 811 (2020) 135849: common baryon source
- Nature 588 (2020) 7837, 232: p–$\Xi^-$ and p–$\Omega^-$ in 13 TeV pp

And the mathematical framework:

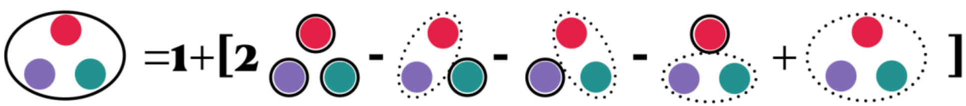
- D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394: CATS

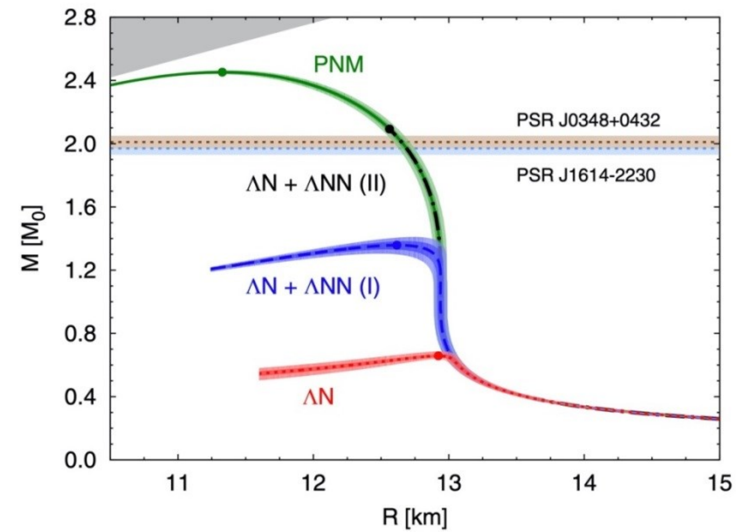


https://cds.cern.ch/record/2746022

# More to come…

- Getting back to the three-body interactions:
  - No direct measurement of ΛNN available
  - Extraction of the genuine ppΛ three-body force via cumulants, following: PRC 89 (2014) 024911
  - Run 3 & 4 data samples will provide a high-precision measurement




Phys. Rev. Lett. 114 (2015) 092301

# More to come...

- Getting back to the three-body interactions:
  - No direct measurement of ΛNN available
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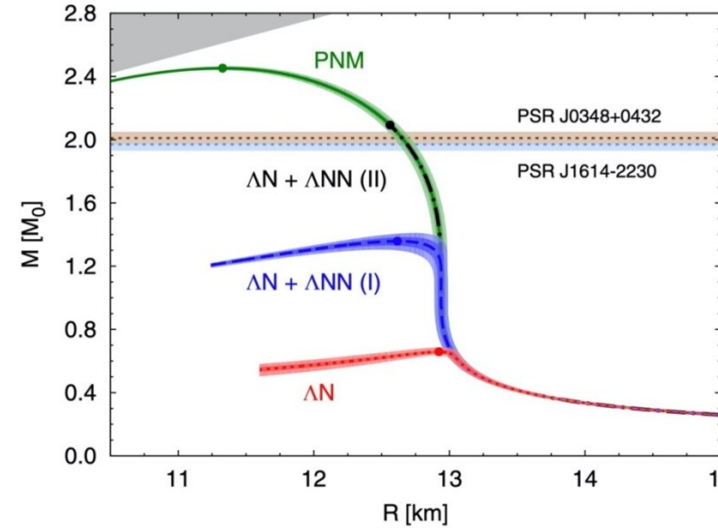
  - Run 3 & 4 data samples will provide a high-precision measurement


- p–Φ: determine scattering parameters, study possible coupled channels or bound states
- p–d: study the underlying 2+3 body interactions
- Λ–d: spin dependence, doublet and quartet, the latter connected to Λ–N interaction
- the charm sector?
- ...

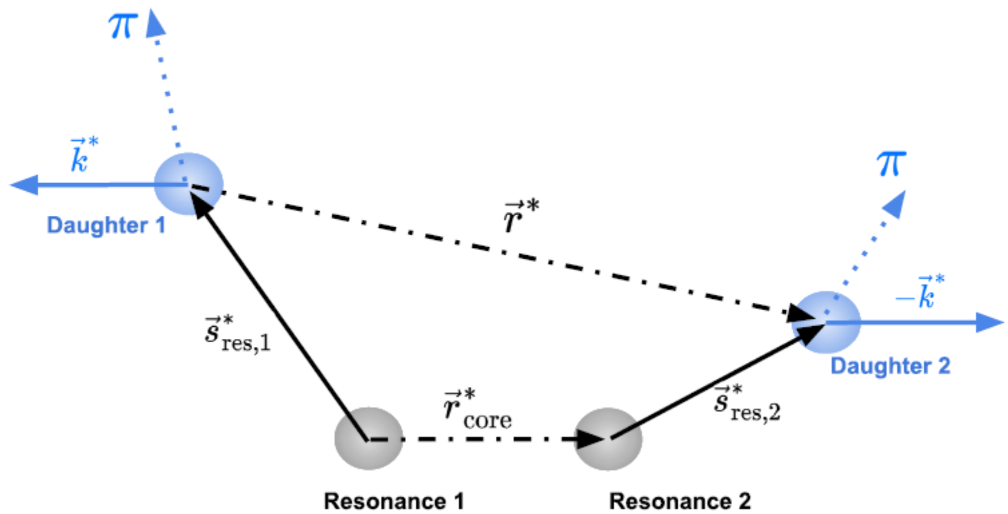



Phys. Rev. Lett. 114 (2015) 092301

**Thanks a lot for your attention!**

# BACKUP

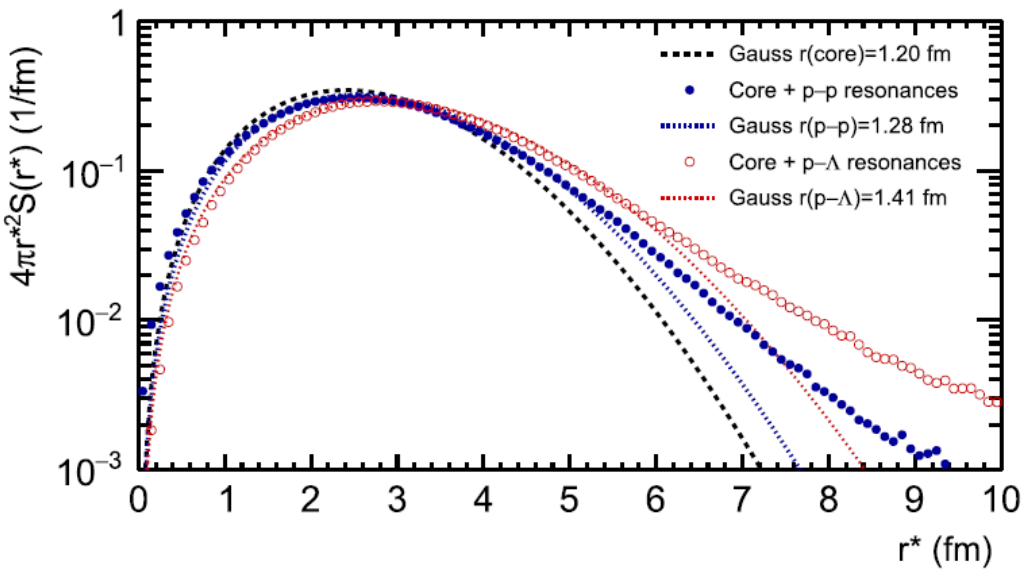
# First step: a Gaussian source with resonances




- Modification of the pure Gaussian core radius $r_{core}$ into the larger effective radius $r^*$
- Due to strong resonance with short decay lengths of the order of 1 fm

ALICE, Phys.Lett. B 811 (2020) 135849

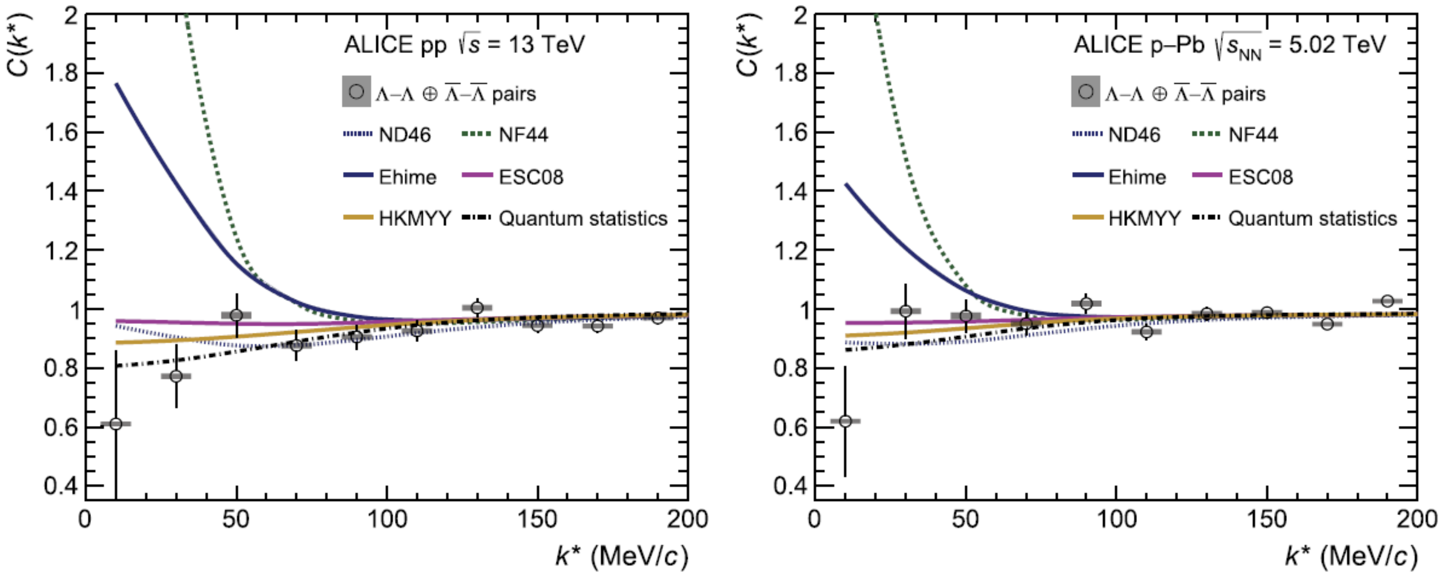
# First step: a Gaussian source with resonances




- Source functions for p–p and p–Λ correlations
- Dots: Folding a common Gaussian core with an exponential tail from resonances
- Dashed line: the corresponding Gaussian core with $r_{core}$ = 1.2 fm
- Dotted lines: pure Gaussian distributions

ALICE, Phys.Lett. B 811 (2020) 135849

# Results: Λ–Λ in 13 TeV pp and 5 TeV p–Pb collisions

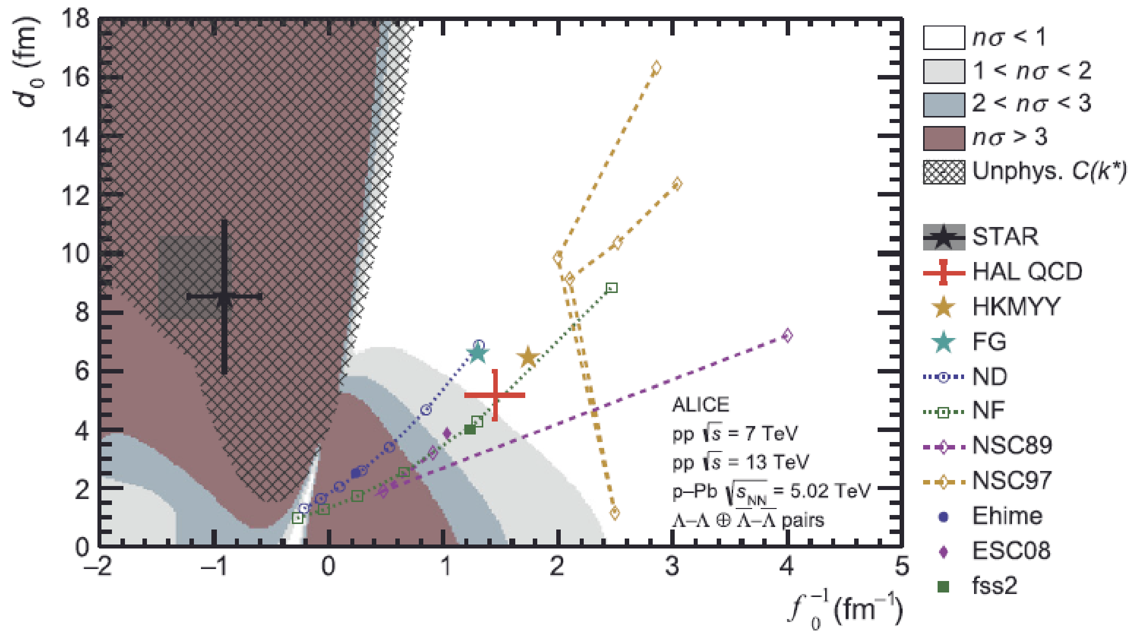



Phys. Lett. B 797 (2019) 134822

- Λ–Λ correlation functions in 13 TeV pp (left) and 5 TeV p–Pb collisions (right)
- In addition, several models are shown for comparison

# Results: Λ–Λ in 13 TeV pp and 5 TeV p–Pb collisions

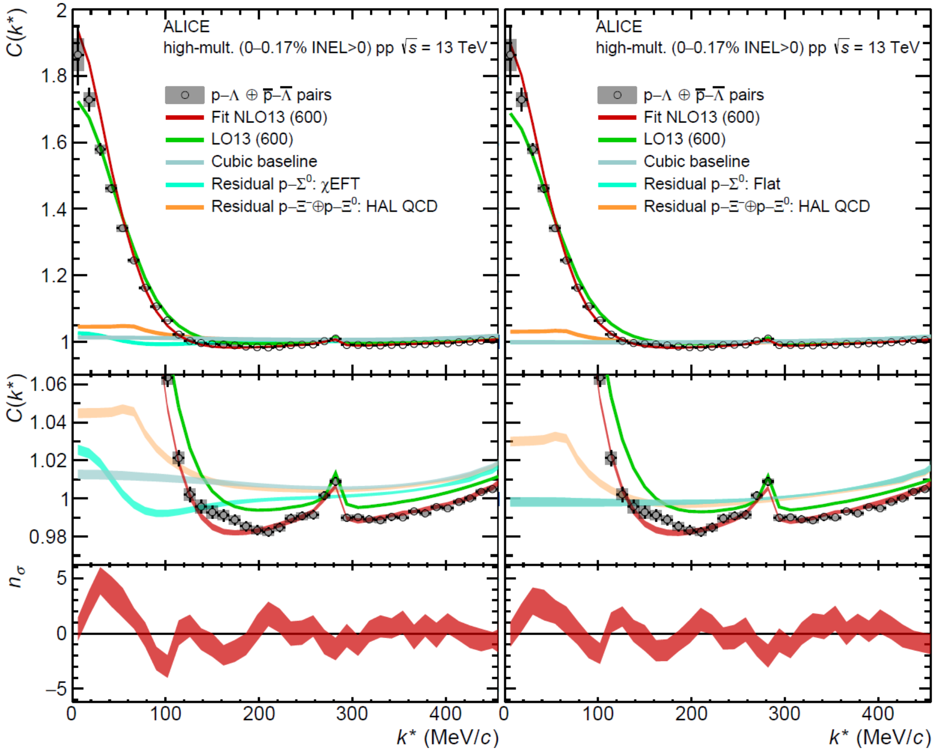
- Exclusion plot for scattering parameters obtained using the Λ–Λ correlation functions in several data sets
- Black hashed region: Lednicky gives unphysical correlation
- Small region for bound state still allowed at small negative $f_0^{-1}$ and $d_0 < 4$ fm



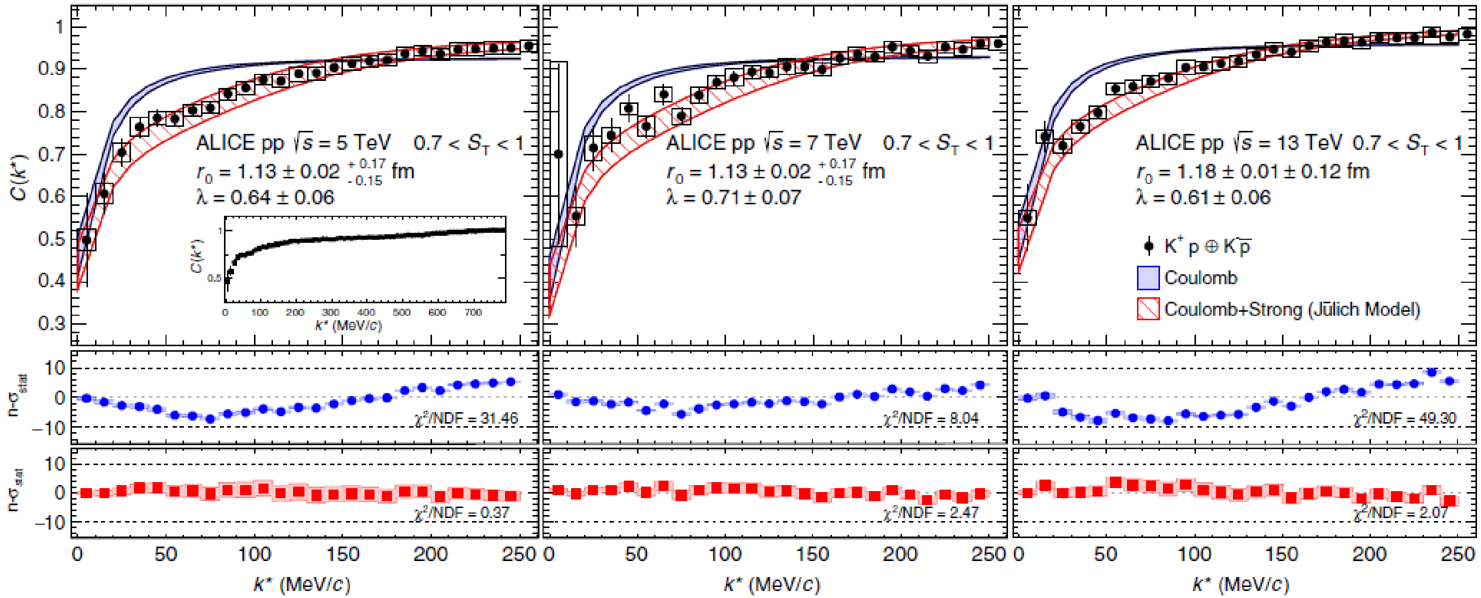

Phys. Lett. B 797 (2019) 134822

## Results: p–Λ in 13 TeV pp collisions (HM)

- Significant extension of the kinematic range
- Clear experimental evidence for the cusp
- Different variations of the residual p–$\Sigma^0$ correlation: from χEFT or flat
- LO χEFT failes to reproduce the data, NLO13 better, but not as good as NLO19
- Entering a precision era!



# Results: $K^+$–p in pp collisions (MB)

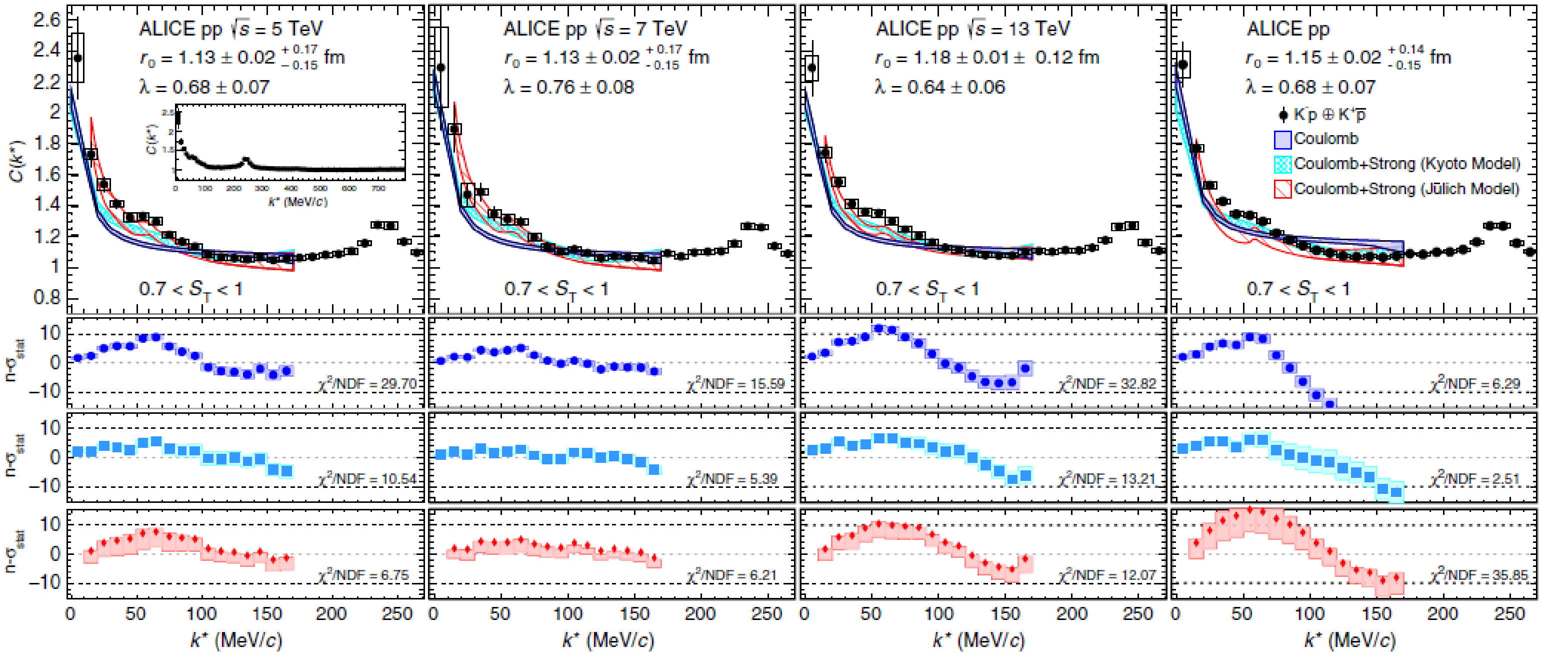



- $K^+$–p correlations in pp collisions at various energies:
  - Known very well from scattering experiments
  - No inelastic channels
  - Used as a benchmark to study $K^-$–p

ALICE,
Phys. Rev. Lett. 124 (2020) 092301

Jülich: J. Haidenbauer,
Nucl. Phys. A 981 (2019) 1

# Results: K⁻–p in pp collisions (MB)




ALICE,
Phys. Rev. Lett. 124 (2020) 092301

- K⁻–p correlations in pp collisions at various energies :
  - Observation of a cusp structure close to the $\overline{K}^0$–n threshold
  - Corresponds to 58 MeV/c in CM frame

Jülich: J. Haidenbauer, Nucl. Phys. A 981 (2019) 1
Kyoto: K. Miyahara and T. Hyodo, Phys. Rev. C 93 (2016) 015201