Unveiling the strong interaction among hadrons at the LHC

ALICE

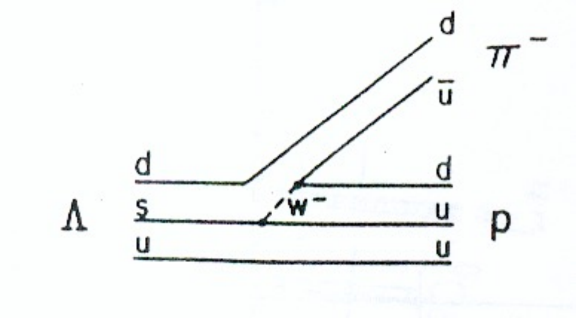
ALICE Collaboration, Nature 588 (2020) 232-238

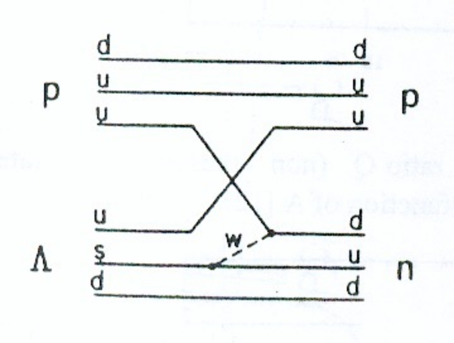
Aim – understanding from first principles effective interactions between hadrons with different quark content

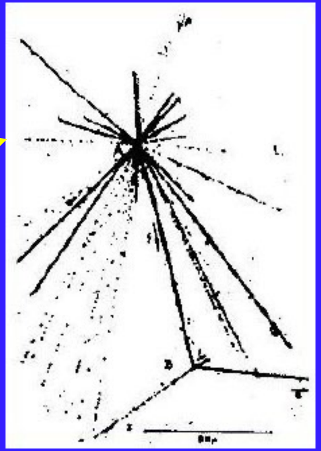
For high energies perturbative techniques are used to calculate such phenomena
For low energies one can use the finite lattice calculations

Experiment – hadron scattering – relative easy for stable hadrons, very difficult for unstable ones, thus high quality measurements exist only for hadrons containing *u* & *d* quarks

- Good constraints for NN interaction
- Small statistics of scattering data for hyperons – mainly data from hypernuclei
- ~1000 **Λ**-hypernuclei and one $^{14}_{\Xi}$N discovered by now (first hypernuclei discovered by Danysz and Pniewski in 1953)







Knowledge of N-Y & Y-Y interactions is important for the neutrons stars physics

In principle, the only source of information on strong interactions involving hyperons

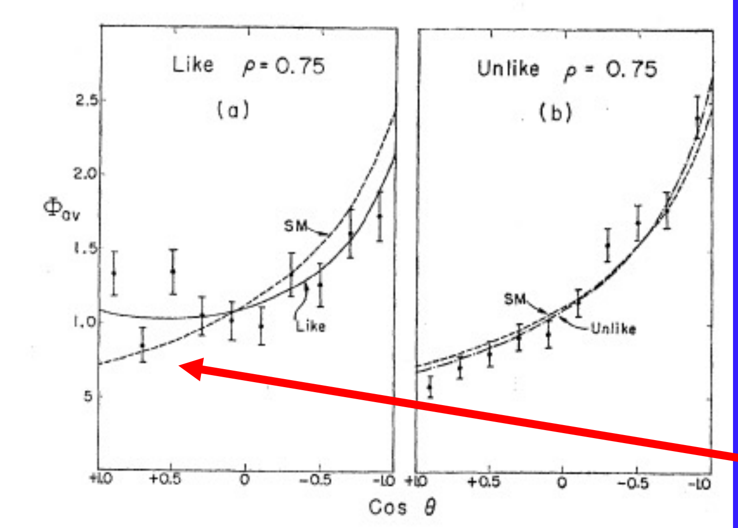
New approach based on femtoscopy

What is the femtoscopy - some history

1960 – Phys. Rev. 120 nr 1
G. Goldhaber, S Goldhaber, W. Lee, A. Pais
„Influence of Bose-Einstein Statistics on the Antiproton-Proton Annihilation Process”

$$p\,\overline{p} \rightarrow 3\pi^{+}3\pi^{-}$$

1.05 GeV/c, 30’’ propane buble chamber



$$\phi = \frac{number\ of\ pairs\ with\ \vartheta > {}^{\pi}/_{2}}{number\ of\ pairs\ with\ \vartheta < {}^{\pi}/_{2}}$$

$\Phi_{like} = 1.23 \pm 0.10$
$\Phi_{unlike} = 2.06 \pm 0.12$

The effect is due to pairs with a small relative momenta

Explanation based on quantum statistic

Wave function of identical bosons must be symmetric

GGLP approach ⟶ $\boxed{\Phi_{like} \propto \exp(\Delta p \cdot \rho)}$

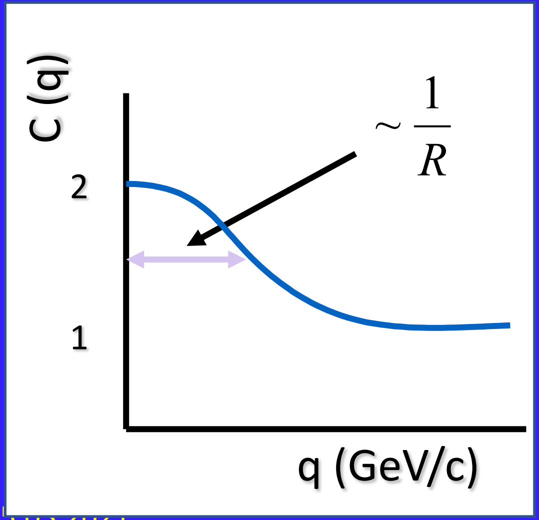
Data can be described assuming the size of the interaction region ρ ~ 1fm
⟶ about ½ of the size required by the statistical model
(SM at the previous plot) to describe the multiplicity data

Another approach - Kopylov, Podgoretskii, Cocconi (1974)
- use the HBT-like correlations to measure sizes

Pion wave function is a plane wave (the scattering length in the s-wave is ~ 0.3 fm)

$$|\psi(p_1,p_2)|^2 \propto \cos(q\cdot x), \quad x = x_1 - x_2, q = p_1 - p_2$$

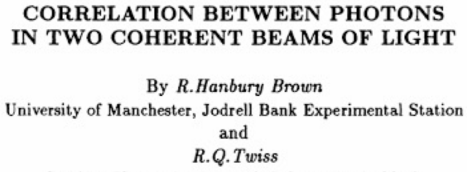
This should be integrated over the source distribution



Early parametrization were static – they didn't take into account the source expansion.
The latter was introduced by S. Pratt in eighties

Boson interferometry in astronomy

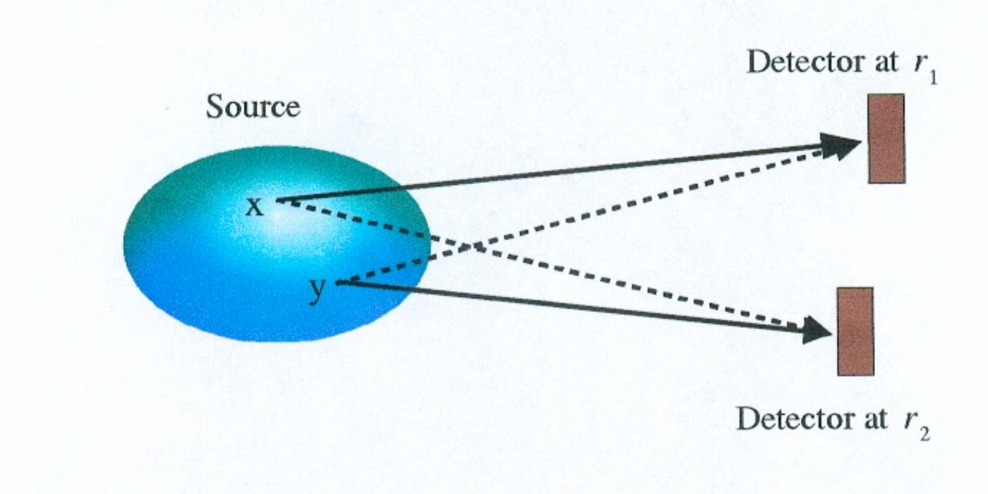
R. Hanbury-Brown, R.Q. Twiss (HBT) – astronomy (1954)

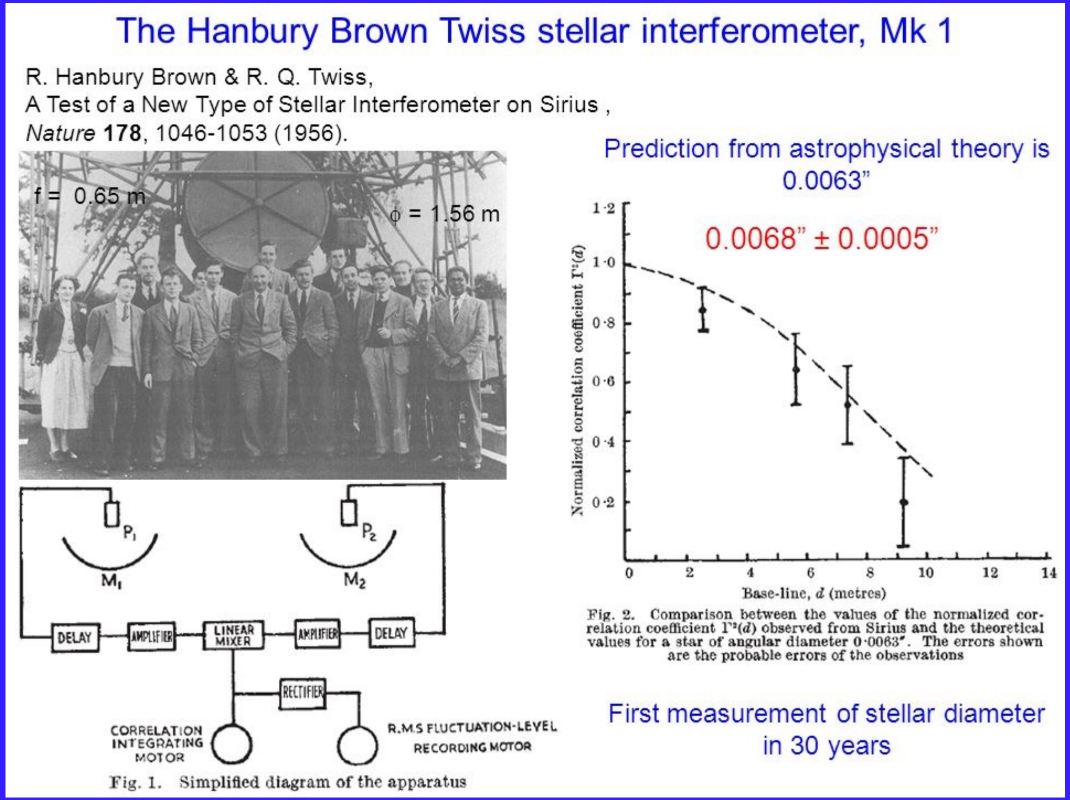


CORRELATION BETWEEN PHOTONS
IN TWO COHERENT BEAMS OF LIGHT

By *R. Hanbury Brown*
University of Manchester, Jodrell Bank Experimental Station
and
R. Q. Twiss
Services Electronics Research Laboratory, Baldock

Correlations of identical bosons can be used for measurements of the size of the source.
It's so-called intensity interferometry, or interferometry of the second order





The Hanbury Brown Twiss stellar interferometer, Mk 1

R. Hanbury Brown & R. Q. Twiss,
A Test of a New Type of Stellar Interferometer on Sirius ,
Nature **178**, 1046-1053 (1956).

Fig. 1. Simplified diagram of the apparatus

Prediction from astrophysical theory is 0.0063"

0.0068" ± 0.0005"

Fig. 2. Comparison between the values of the normalized correlation coefficient $\Gamma^2(d)$ observed from Sirius and the theoretical values for a star of angular diameter 0·0063". The errors shown are the probable errors of the observations

First measurement of stellar diameter in 30 years

Famous quotes

Interference between two photons can never occur P. A. M. Dirac “The Principles of Quantum Mechanics”

In fact to be a surprising number of people the idea that the arrival of two photons at two separated Detectors can ever be correlated was not only heretical but patently absurd, as they told us so in no uncertain terms

It was a long way from being able to calculate , whether it would be sensitive enough to measure a star… my education in physics has stopped far short of the quantum theory. Perhaps just as well ignorance is sometimes a bliss in science – both quotes by R. Hanbury-Brown

General application in high energy physics

G. I. Kopylov, M. I. Podgoretsky - general case

Small angle correlations including final-state interactions

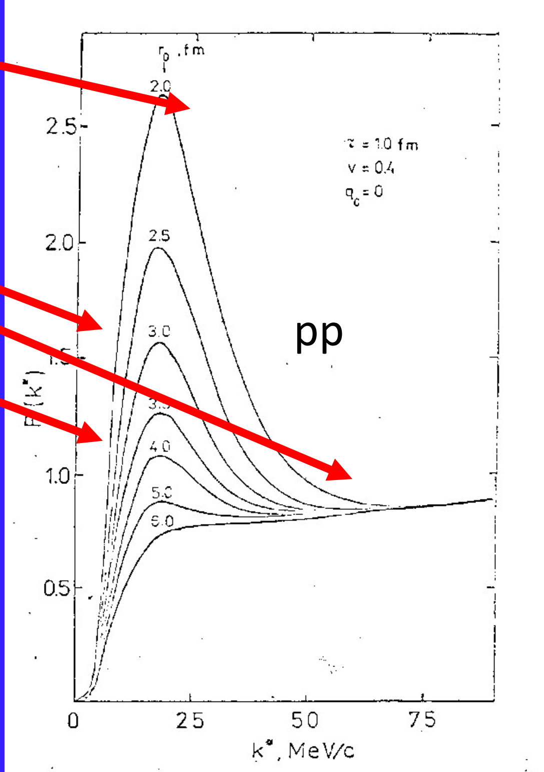
R. Lednický, V.L. Lyuboshitz (1981)

$$C(p,q) = A_c(k^*)\left[1 + B_0(q,p,r,\tau) + B_1(q,p,r,\tau)\right]$$

B_0 – quantum statistics
B_1 – final state strong interactions
A_c – Coulomb interactions

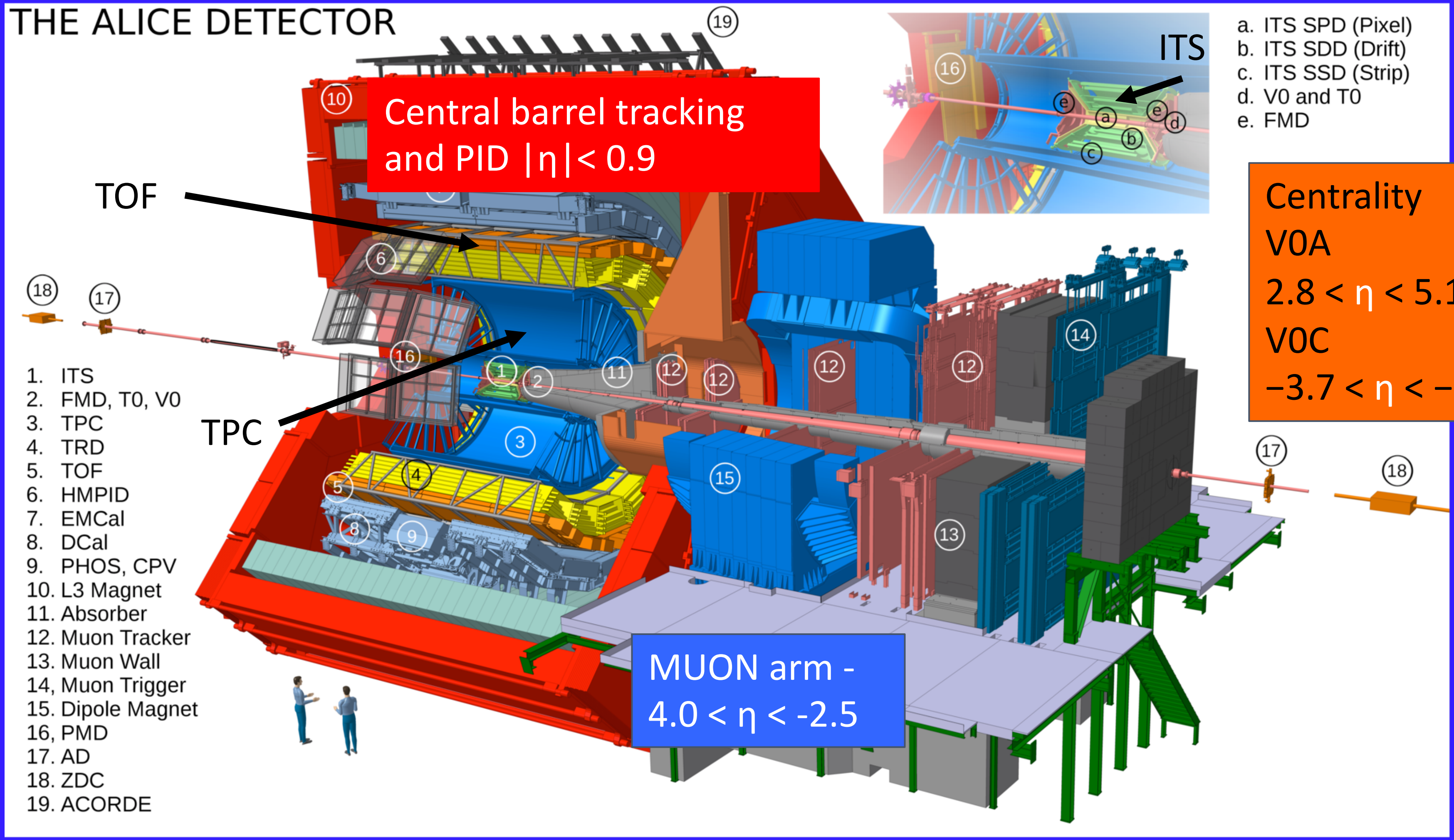
This formula describes also correlations of nonidentical particles

R. Lednický: Femtoscopy is more adequate name than interferometry



A Large Ion Collider Experiment

- Excellent particle identification capabilities over a wide p_T range 0.1-20 GeV/c
- Good momentum resolution ~1-5% for p_T = 0.1-50 GeV/c



Central barrel tracking and PID |η|< 0.9

TOF

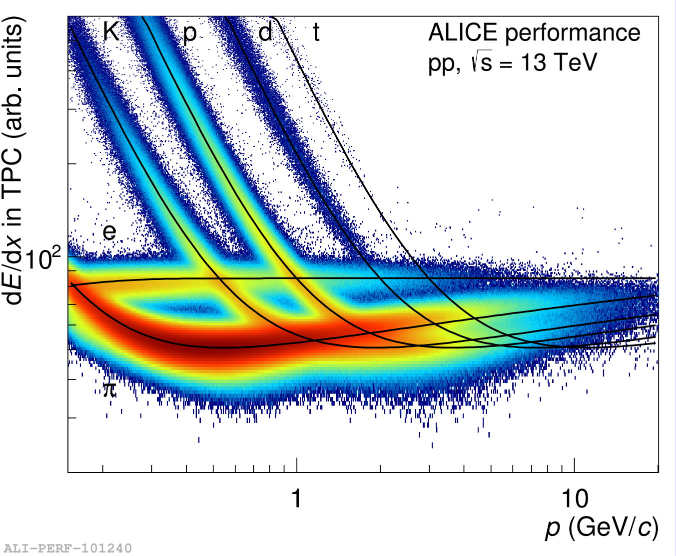
TPC

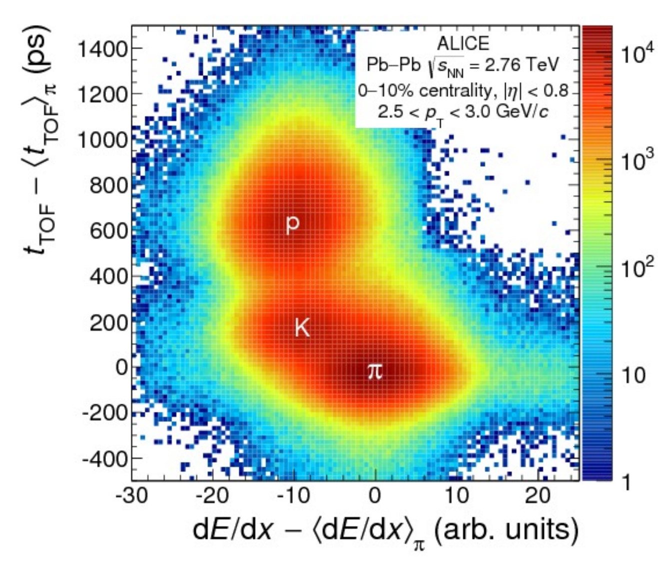
Centrality
V0A
2.8 < η < 5.1
V0C
−3.7 < η < −1.7

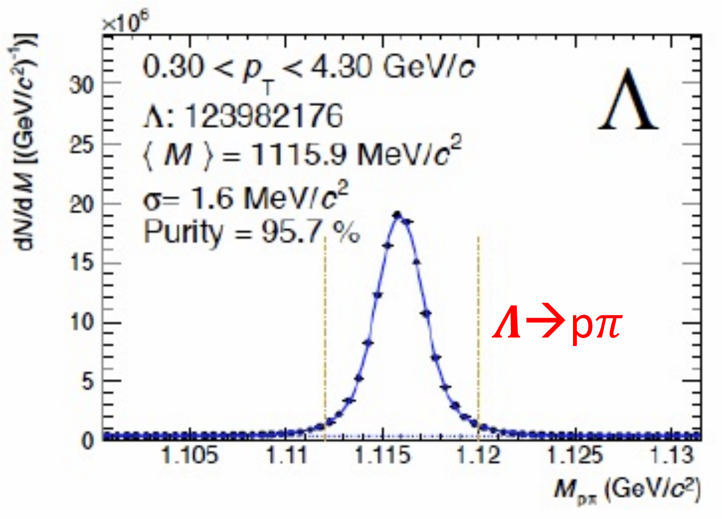
MUON arm -
4.0 < η < -2.5

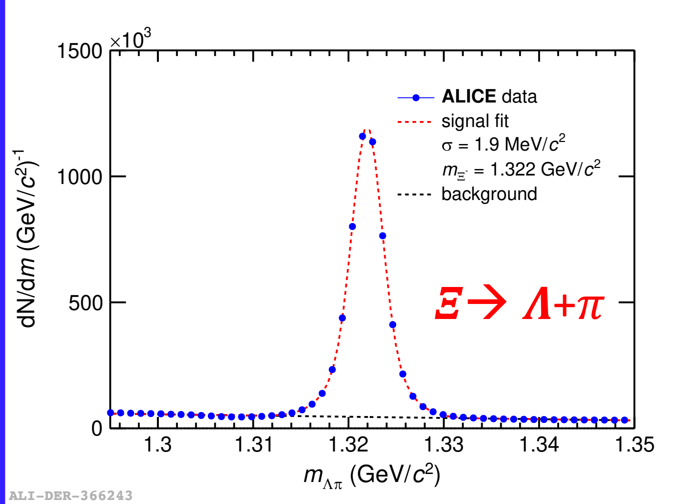
Particle identification in ALICE

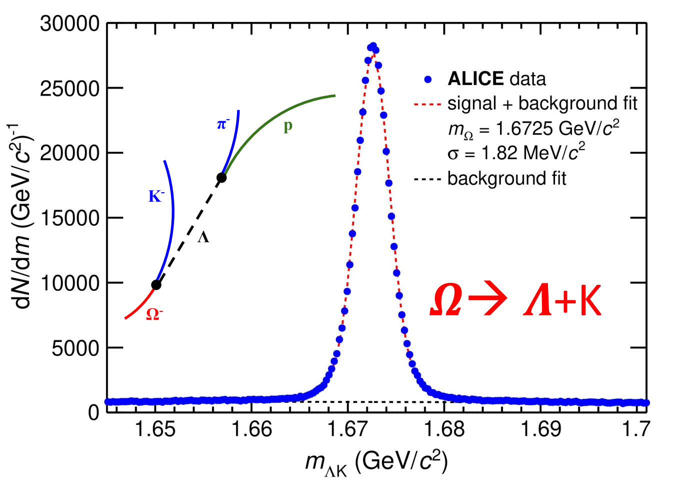
- Pion, kaon and proton identification via dE/dx and TOF
- Hyperon identification with decay topology and invariant mass analysis





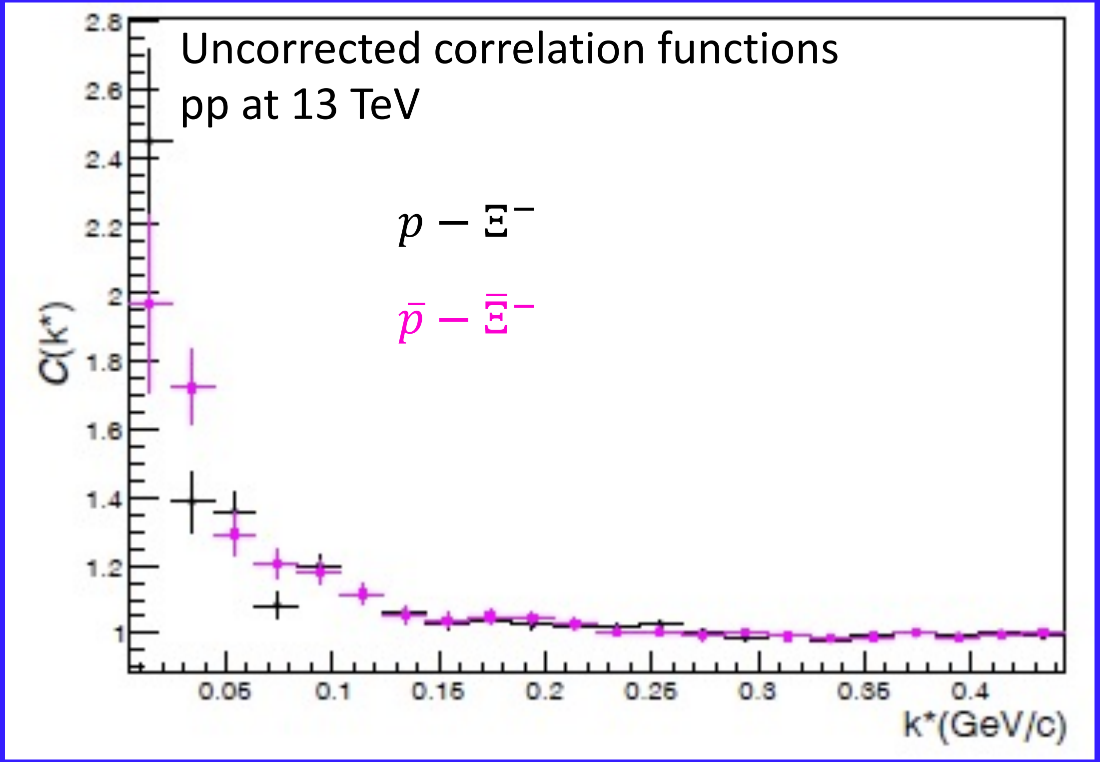






Measured correlation function

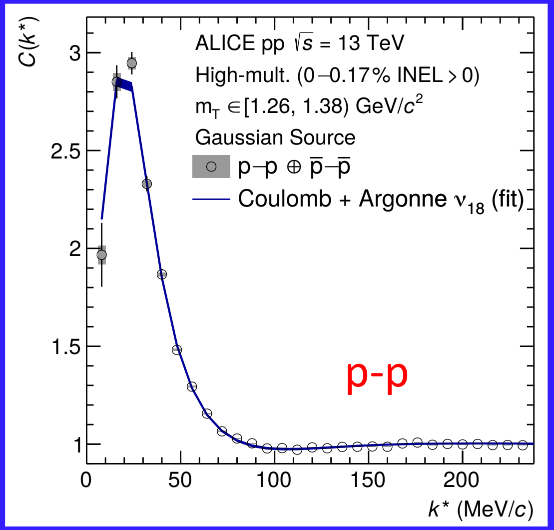
$$C(k^*) = \int S(r)\, |\psi(\vec{k}^{\,*}, \vec{r})|^2\, d^3r = \varsigma(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

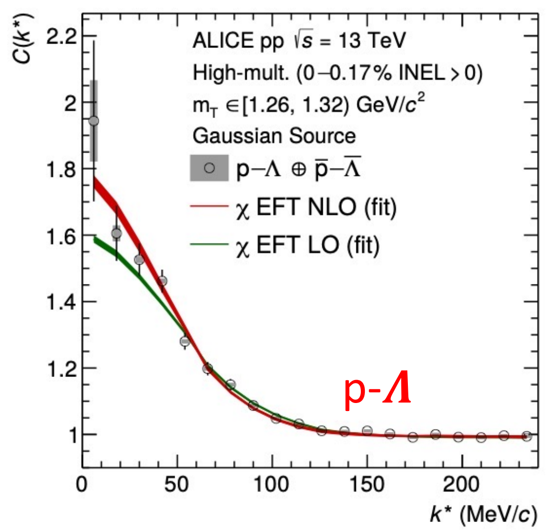

Uncorrected correlation functions
pp at 13 TeV

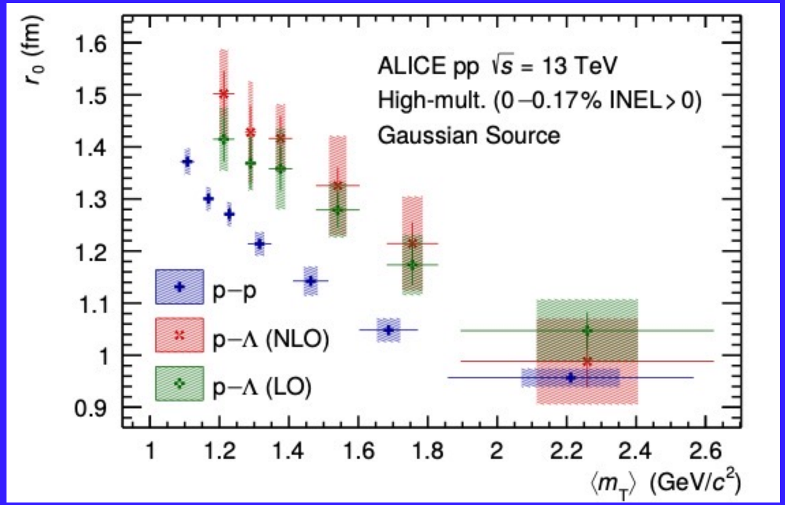
Corrections $\varsigma(k^*)$:

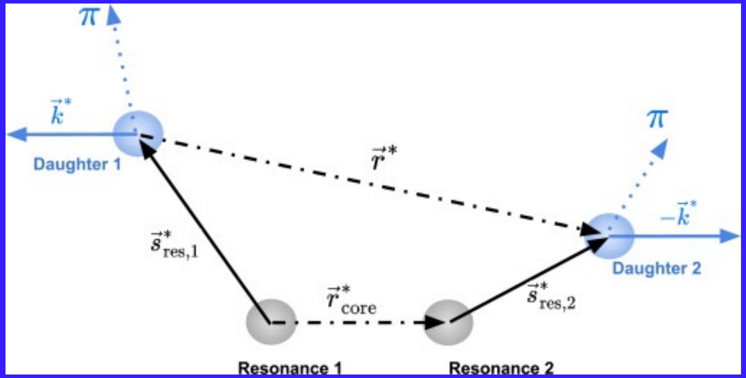
- Detector effects
- Misidentified baryons
- Proton or hyperon yields from resonances (feed-down)
- Non-femtoscopic background (energy-momentum conservation, mini-jets,…)

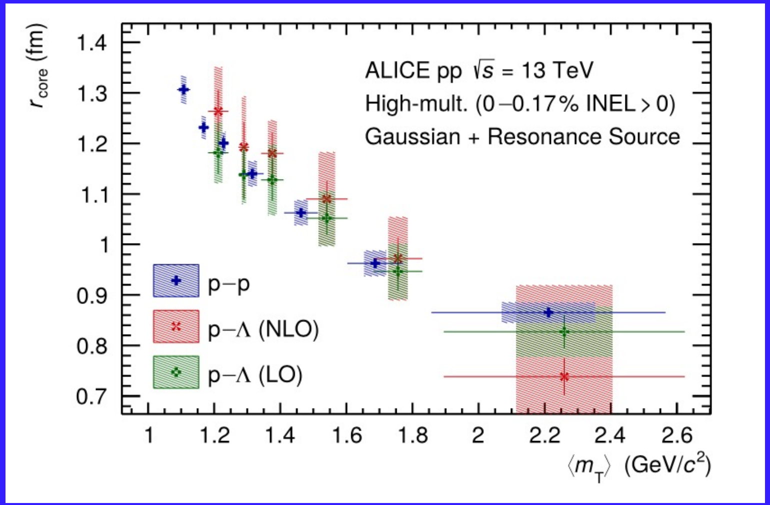
Earlier results on pp and pΛ femtoscopy – common baryon source











- All baryon pairs with included resonances show common m_T scaling

→ Indication of common baryon source

→ One can use p-p correlation to fix source size for other baryon pairs

→ Gaussian source with r_{eff} = 1.02±0.05 (0.95±0.06) fm used for the p-*Ξ* (p-*Ω*) emission

New results on $p\Xi^-$ and $p\Omega^-$ strong interactions

System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011 2015 2018	2.76 5.02 5.02	~75 μb^{-1} ~250 μb^{-1} ~0.9 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13	~200 μb^{-1}, ~100 μb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1}, ~59 pb^{-1}

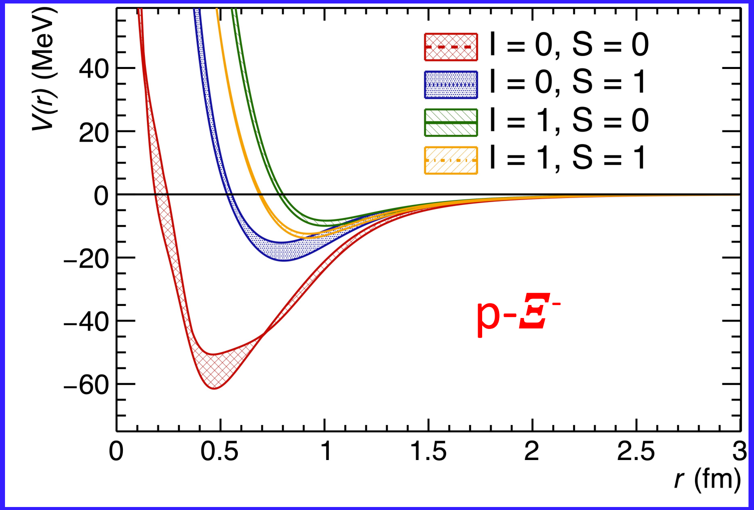
- Energy and system dependence studies of particle production are possible
- Large statistics of pp, p-Pb and Pb-Pb collisions at the same $\sqrt{s_{NN}}$

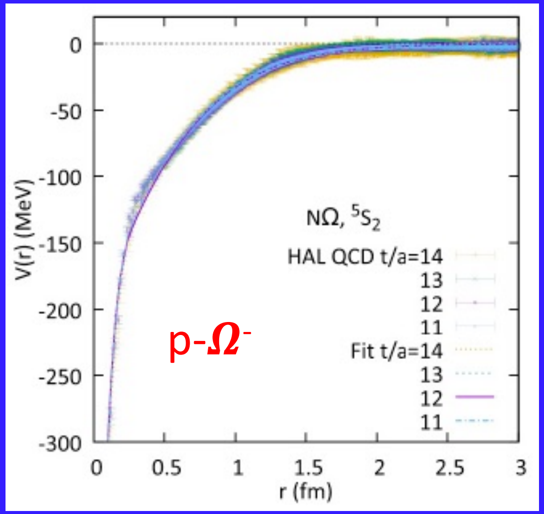
- pp at 13 TeV (high multiplicity) and p-Pb at 5 TeV used for p-Ξ and p-Ω correlation measurements

What does the lattice QCD say about pΞ and pΩ interactions?

Hadrons to Atomic nuclei HAL from Lattice QCD

HAL QCD Coll., NPA 998 (2020) 121737, PLB 792 (2019) 284





- p-***Ξ*** interaction in four channels: isospin (I = 0,1) and spin (S=0,1)
  - Attractive with repulsive core at small distances
- p-***Ω*** interaction in $^5S_2$ (I=1/2, S=2) channel
  - Attractive in the whole range
  - After inclusion Coulomb interaction prediction of bound state with binding energy ~ 2.5 MeV
- p-***Ω*** interaction in $^3S_1$ state does not include yet inelastic channels (e.g. p***Ω*** → ***ΛΞ***)

p-*Ξ* correlation function in pp at 13 TeV

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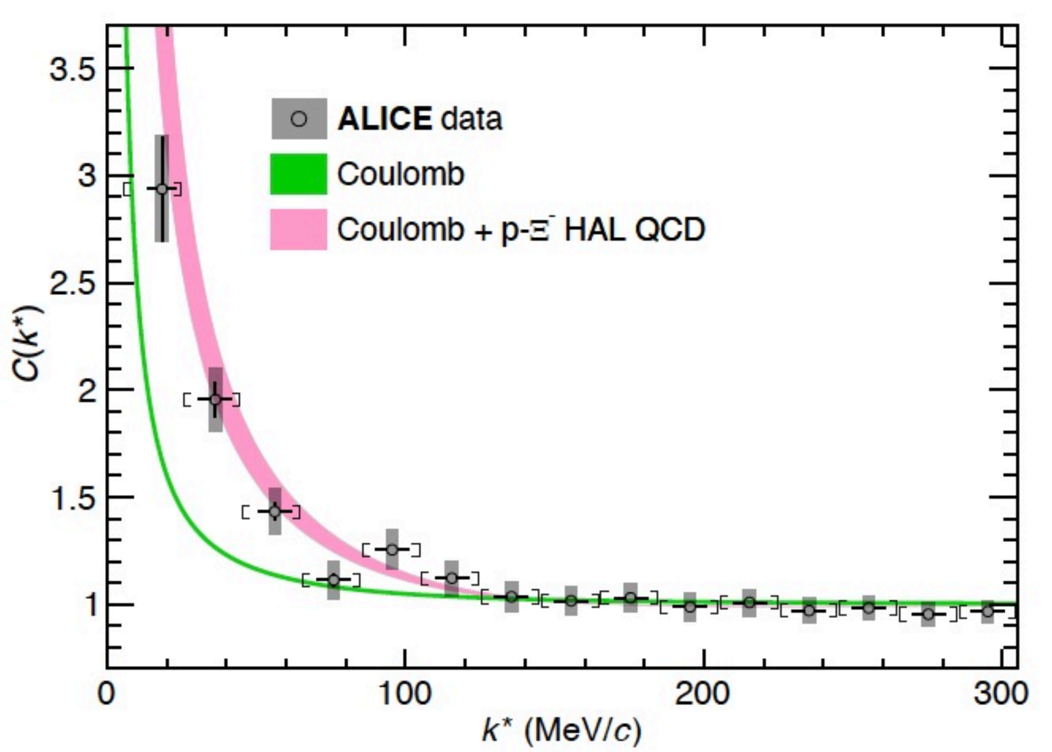
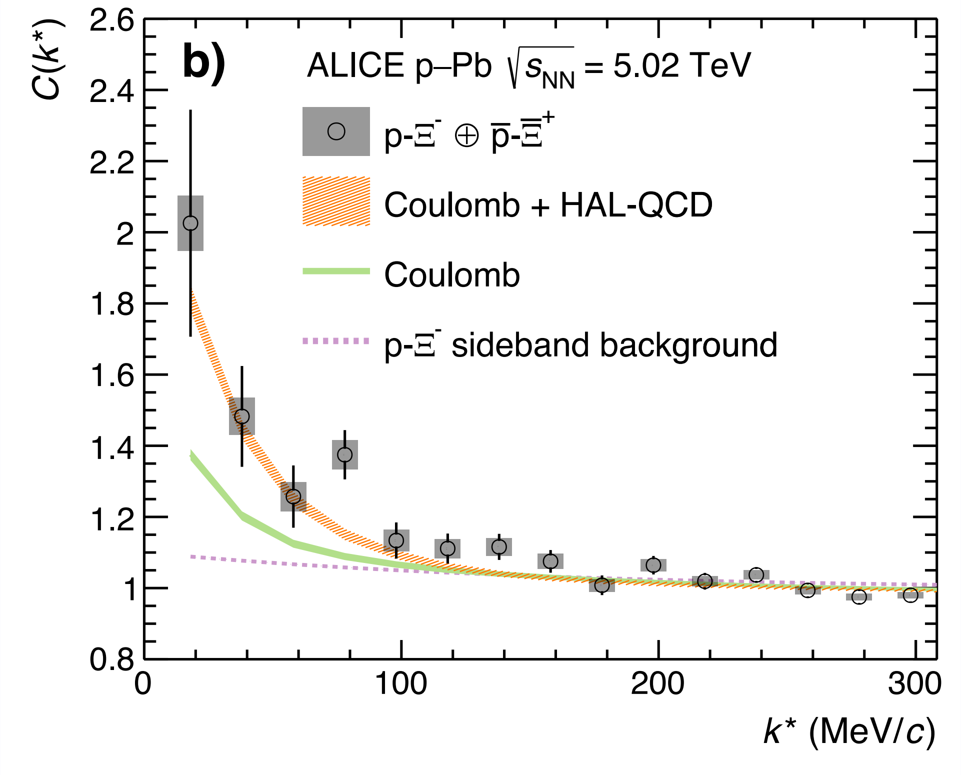


- p-*Ξ* interaction is attractive
- No indication of bound state in data
- p-*Ξ* interaction stronger than Coulomb → observation of strong interaction
- Coulomb + HAL QCD in agreement with p-*Ξ* measurements

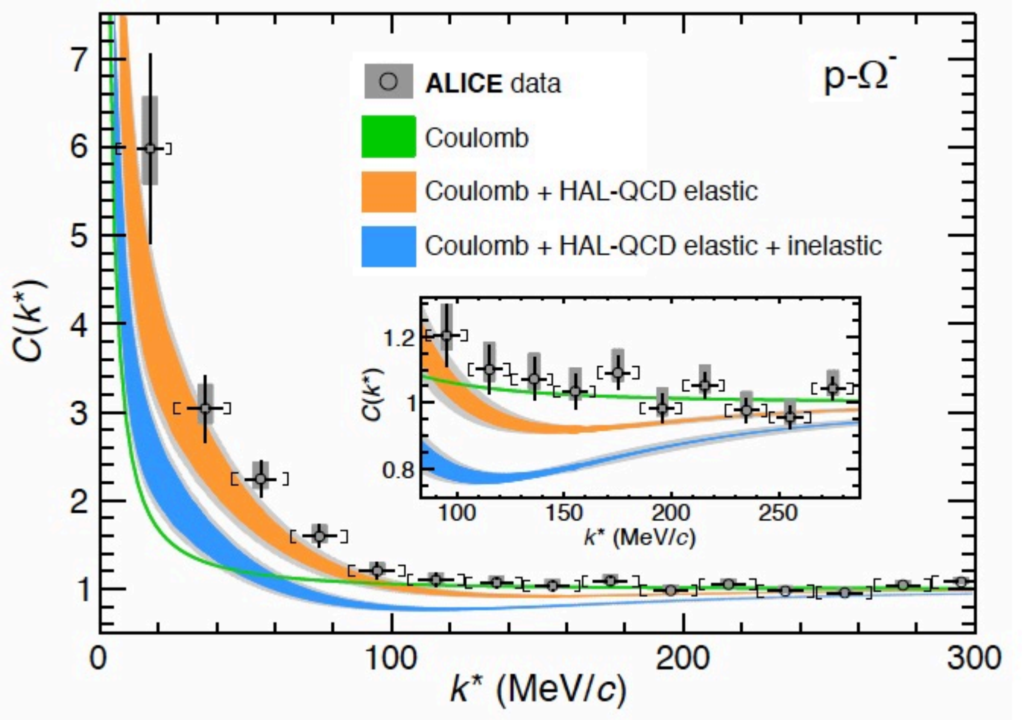
p-Ξ correlation function in p-Pb at 5 TeV

ALICE PRL 123, 112002 (2019)



- p-Ξ interaction is attractive
- No indication of bound state in data
- p-Ξ interaction stronger than Coulomb → observation of strong interaction
- Coulomb + HAL QCD in agreement with p-Ξ measurements

p-***Ω*** correlation function in pp at 13 TeV



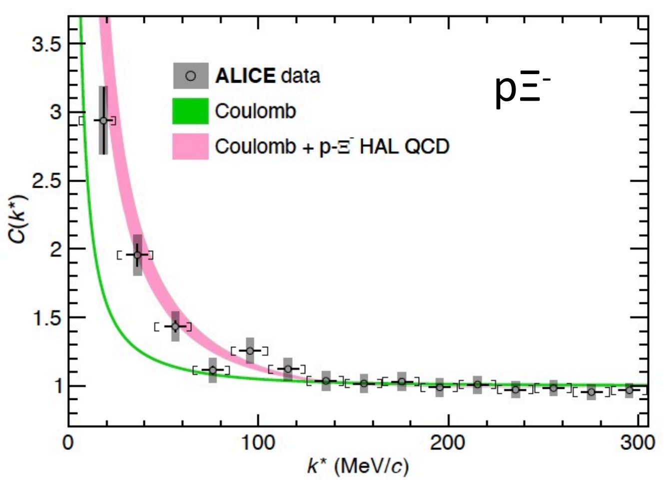
- p-***Ω*** interaction is attractive
- No indication of bound state in data
- p-***Ω*** interaction stronger than Coulomb → observation of strong interaction

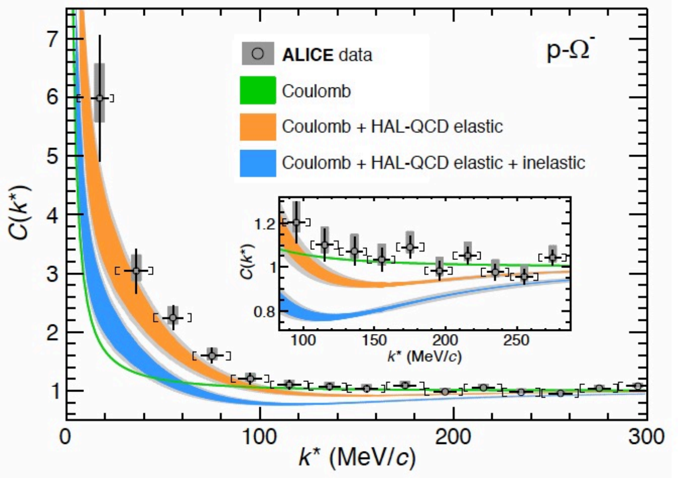
- Calculations underestimate p-***Ω*** measurements for both cases tested for missing p-***Ω*** inelastic channels in $^3S_1$ state
  - Inelastic channel dominated by absorption
  - Neglecting inelastic channel

Summary

- ALICE unveils the strong interaction between stable and unstable baryons (p-***Ξ*** and p-***Ω***) in pp and p-Pb collisions at the LHC
- The precisely measured p-***Ξ*** and p-***Ω*** correlation functions show attractive interaction for small relative momentum $k^* < 100$ MeV/c
- P-Ω interactions much stronger than p-Ξ (factor of ~2)
- No indication of bound states

- Calculations including final-state Coulomb and strong (HAL QCD potential) interaction
  - Good agreement with p-***Ξ*** results in both pp and p-Pb collisions
  - Underestimate p-***Ω*** results (missing inelastic channels in $^3S_1$ state) for both limiting cases
  - Formation of bound p-***Ω*** state (not seen in data at the moment)





Outlook

- ALICE plans (anti)baryon-(anti)baryon correlation measurements in future LHC Run3 and Run4 including
    - p***Ω*** correlations in p-Pb collisions
    - ***ΛΞ*** and ***ΣΞ*** (p***Ω*** strangeness rearrangement channels) in pp and p-Pb collisions
    - and others…