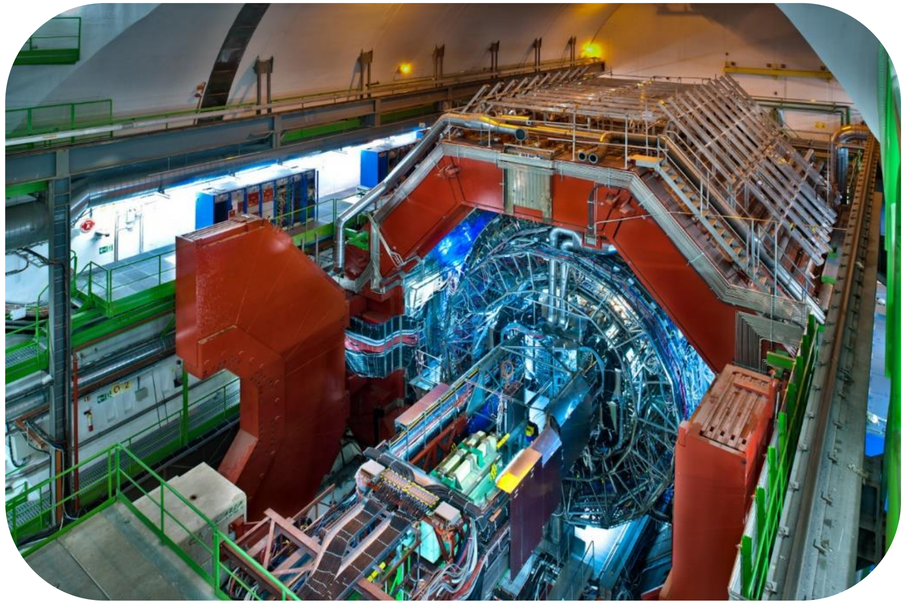
Studying the size of the emitting source of particles and their strong interaction using femtoscopy

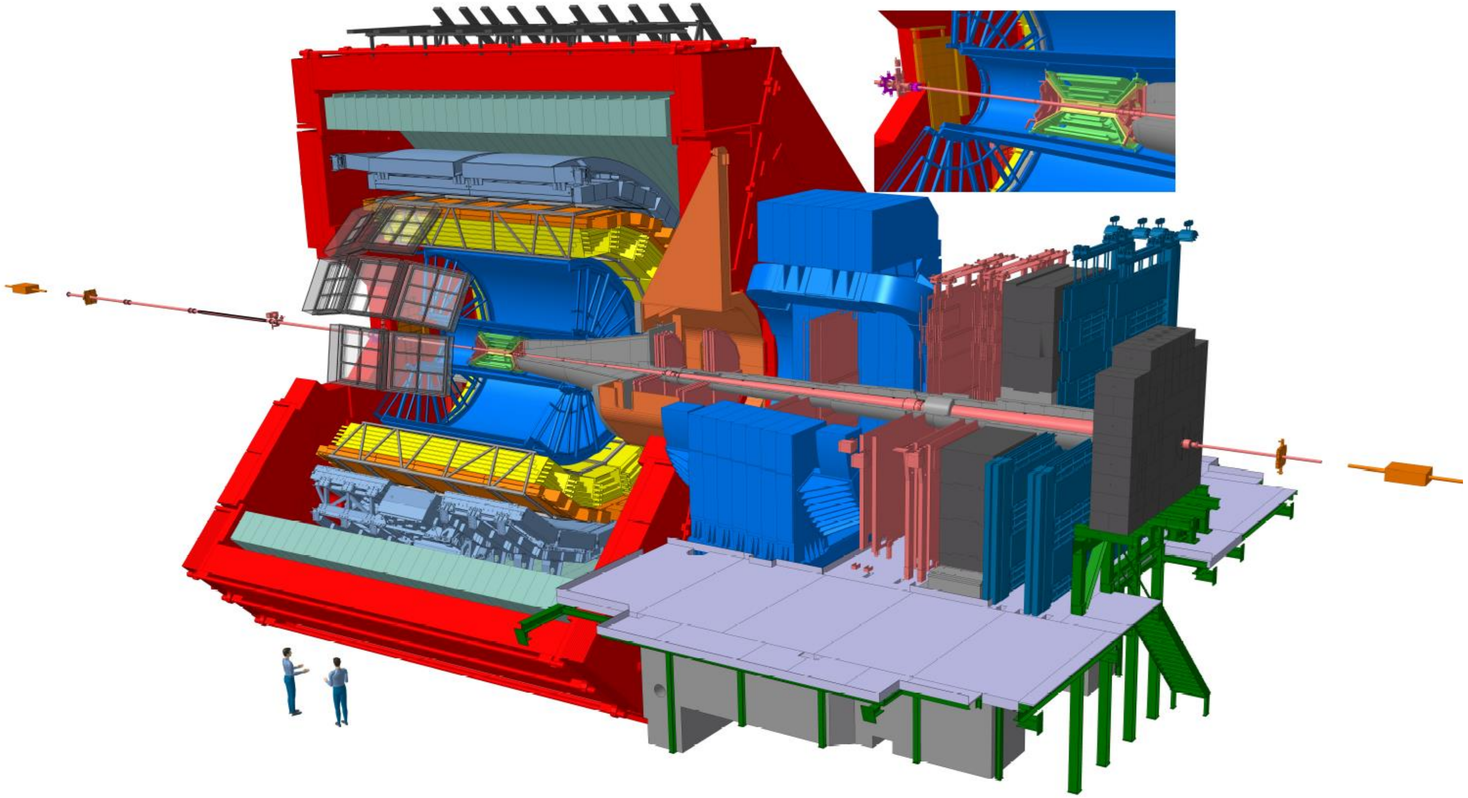
Rogochaya Elena

for the ALICE Collaboration



ALICE detector

ALICE,Int.J.Mod.Phys.A29(2014)1430044



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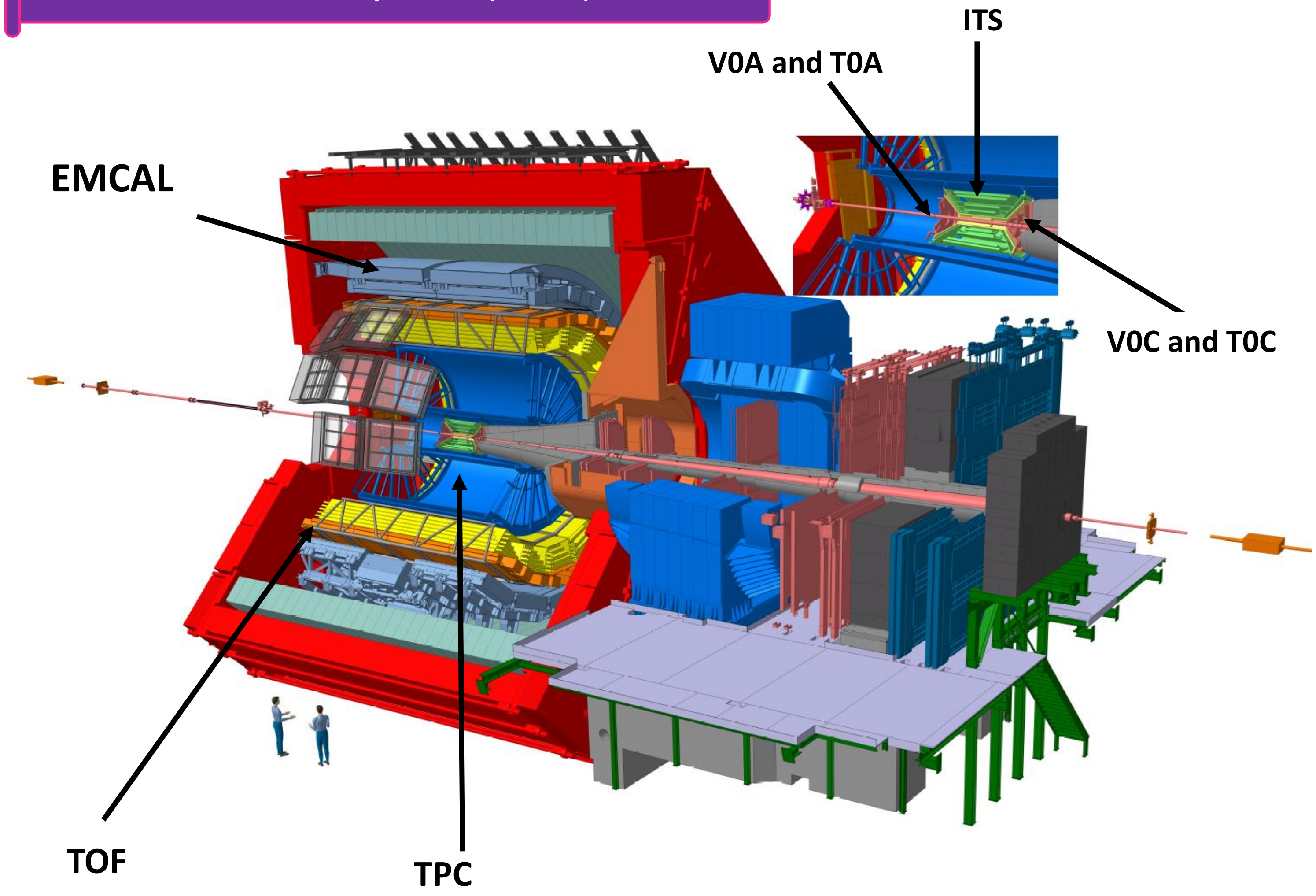

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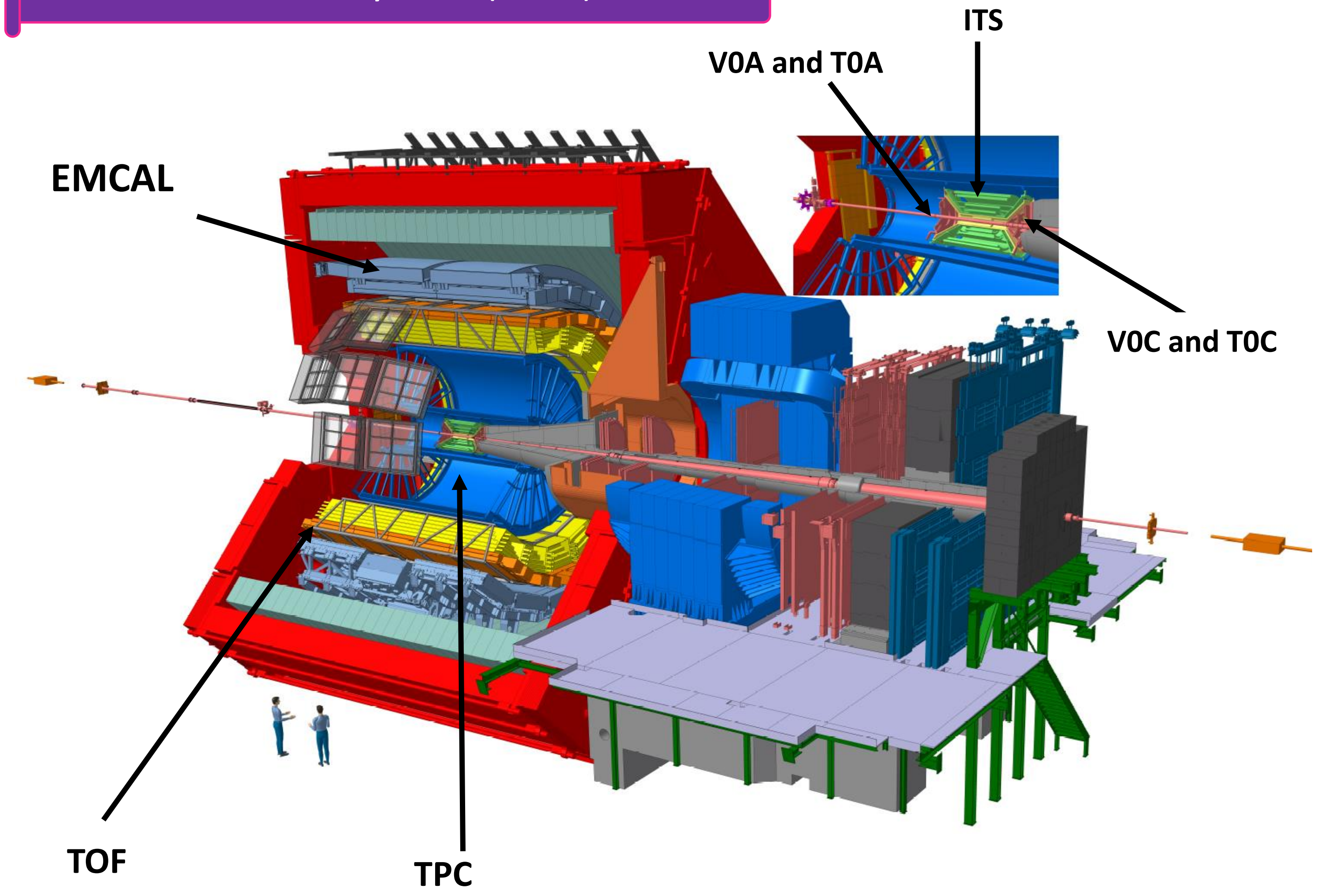

- *Abundant production of strange hadrons at the LHC*
- Good PID and momentum resolution → *good opportunity to study particle correlations in momentum space*

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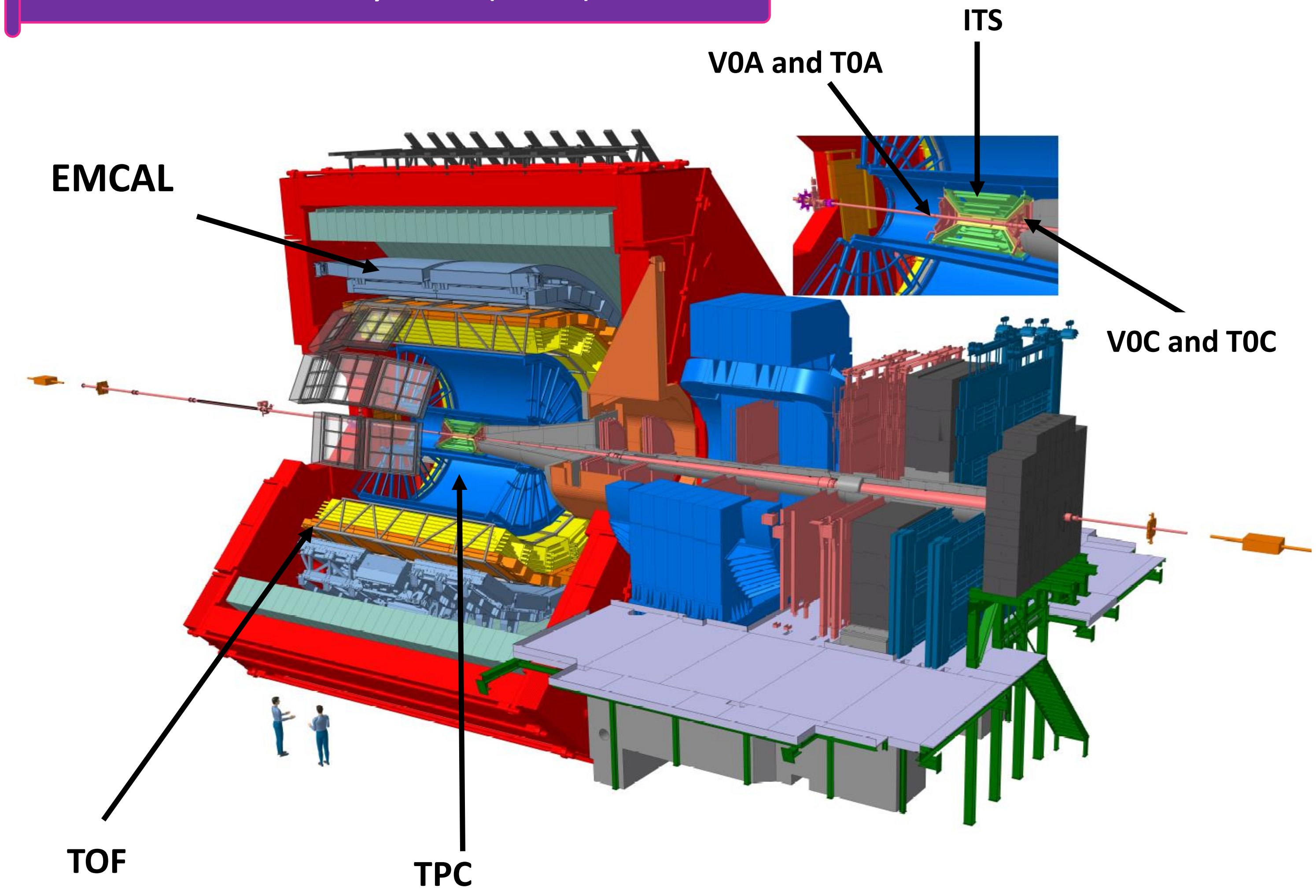

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Data sets (Run 2):

- pp 13 TeV (1000 M high multiplicity events)
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- Direct detection of charged particles (p, K, π)

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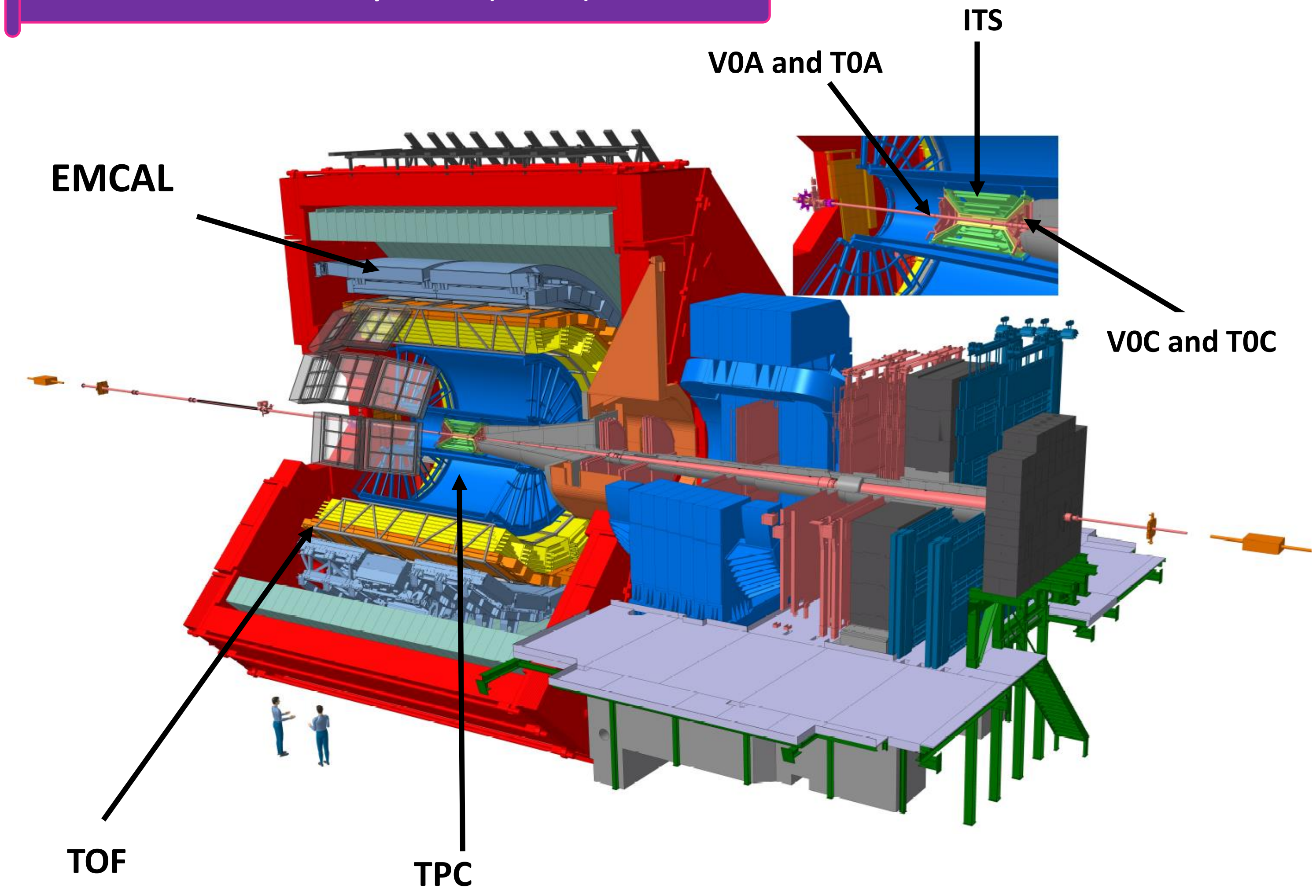

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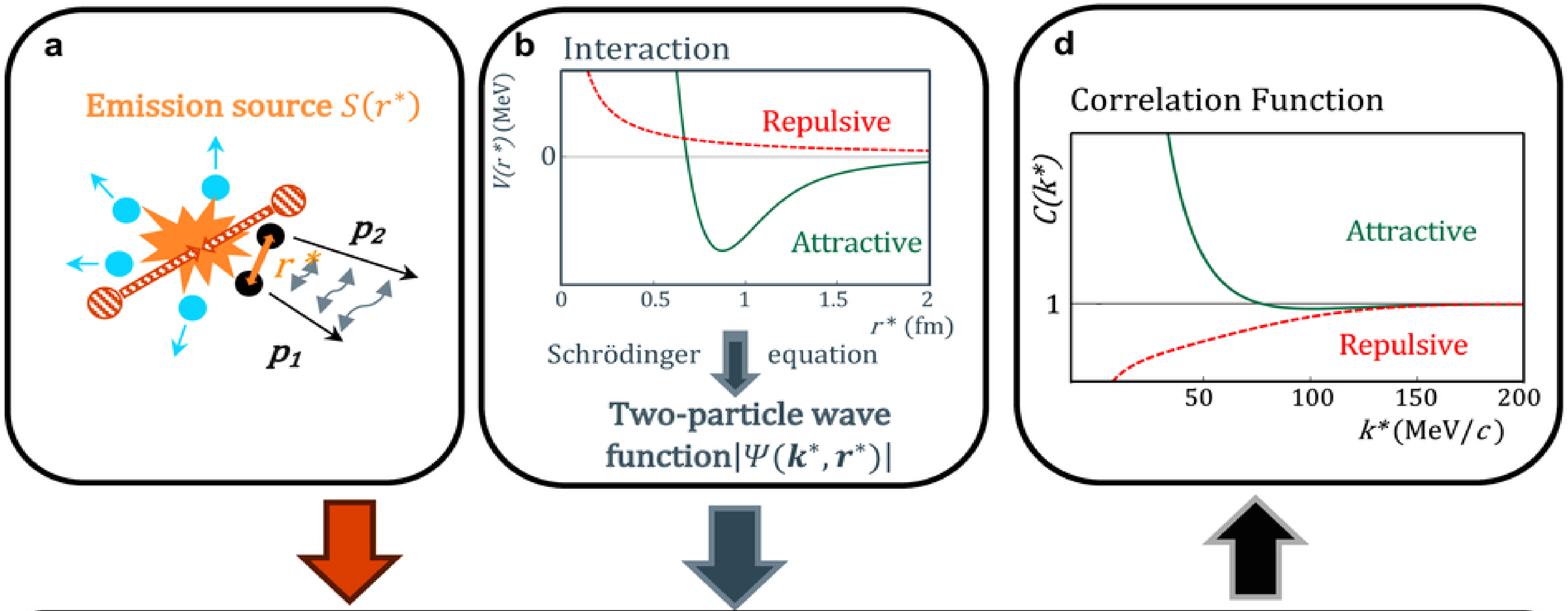
The very good PID capabilities of the detector result in very pure samples!

Femtoscopy



c

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

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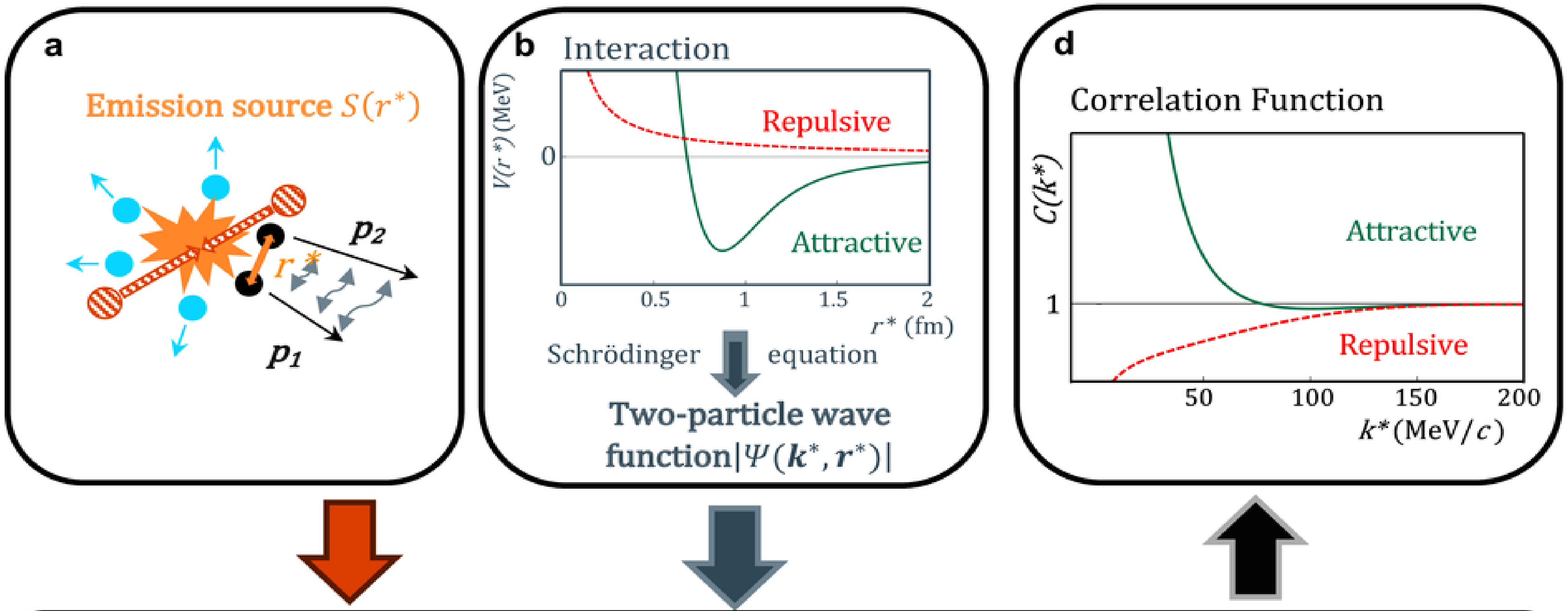

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Source $S(r^*)$ emitting pairs of hadrons at a relative distance r^*.

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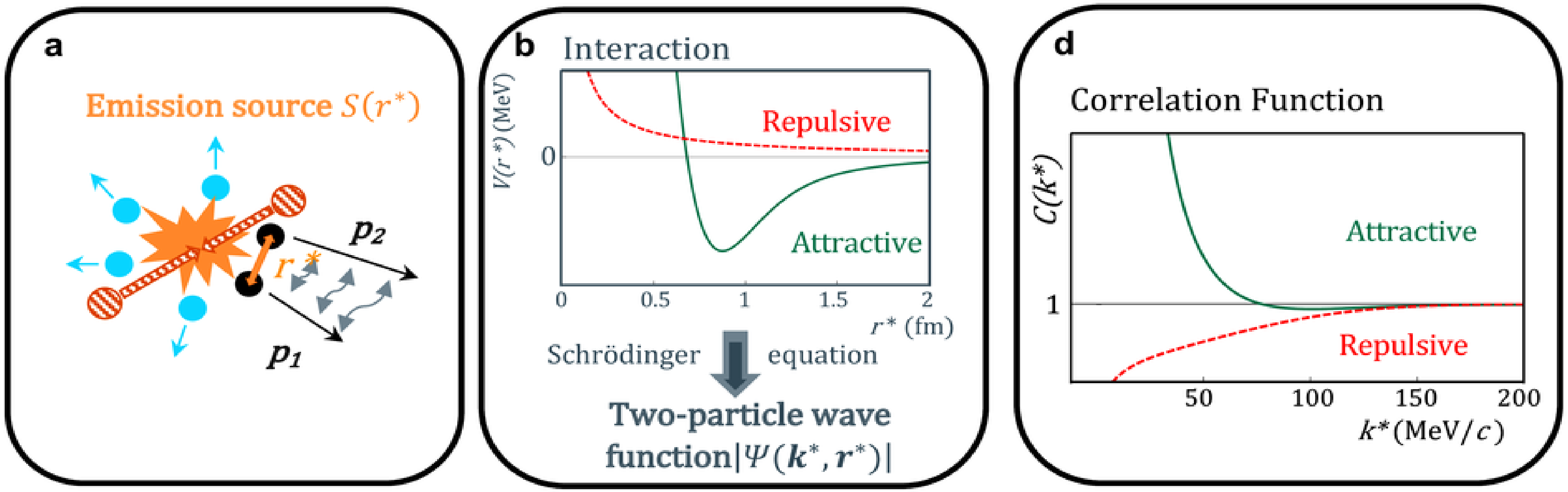

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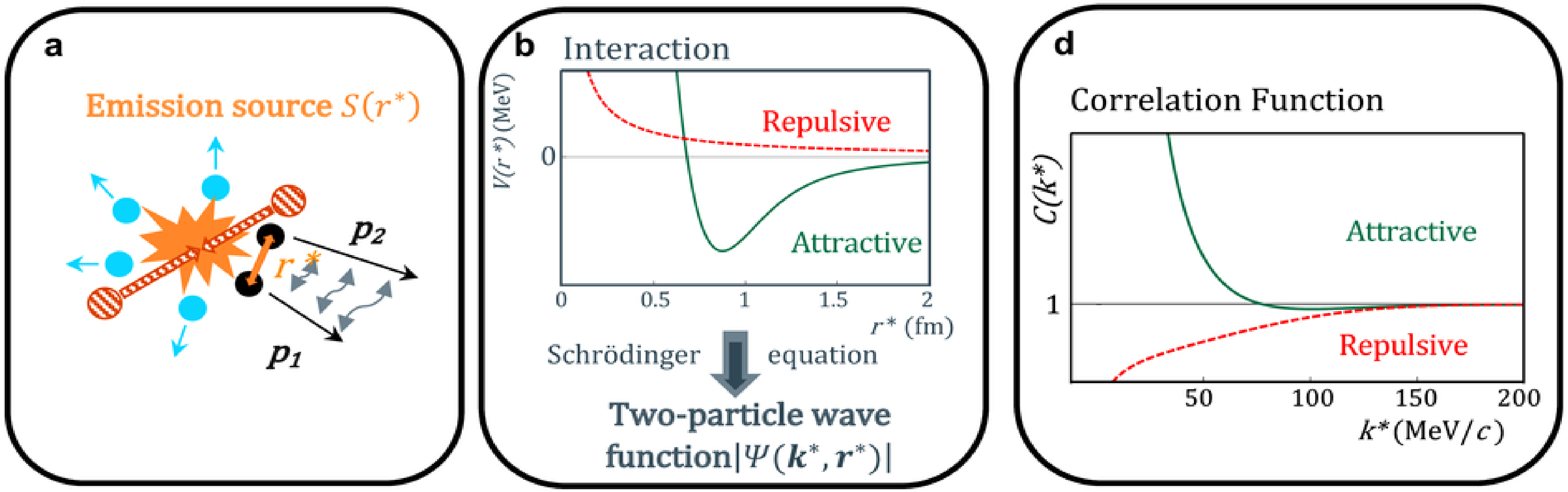
CATS (**C**orrelation **A**nalysis **T**ool using the **S**chrödinger equation) – to calculate $\Psi(\boldsymbol{k}^*, \boldsymbol{r}^*)$.

D. Mihaylov et al., EPJC78(2018)394

$$k^* = \frac{|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|}{2}$$ - pair relative momentum

Femtoscopy



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$N_{\mathrm{same}}(k^*)$ and $N_{\mathrm{mixed}}(k^*)$ – k^* distributions of hadron pairs from same and different collisions, respectively;
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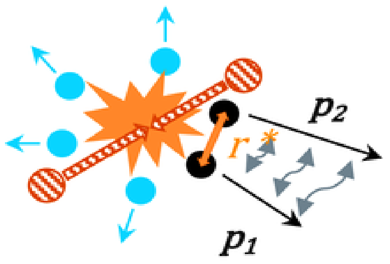
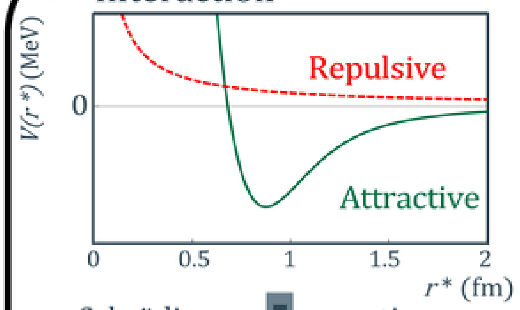
Femtoscopy

a



b Interaction

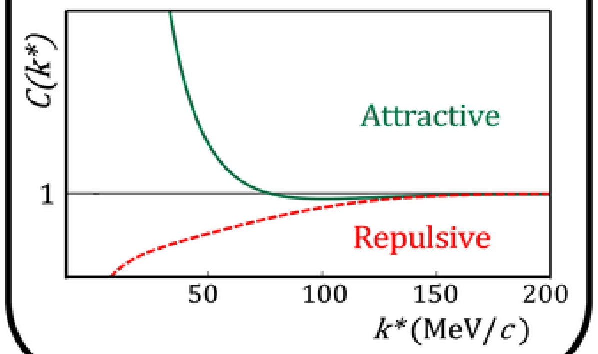


Schrödinger equation

Two-particle wave function $|\Psi(\boldsymbol{k}^*, \boldsymbol{r}^*)|$

d

Correlation Function



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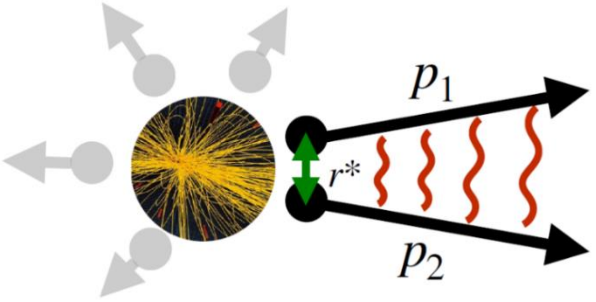
What femtoscopy can study?

- Dynamics of medium created in high-energy collisions to test (hydrodynamic) models of hadron interactions
- Properties of strong interaction with high precision in small collision systems
- Exotic particles (multi-strange and even charm) which are otherwise not accessible with scattering experiments

Two-particle femtoscopy



Correlation femtoscopy: measurement of space–time characteristics R, $c\tau$ ~fm of particle production source using particle correlations due to the effects of quantum statistics (QS) and final-state interactions (FSI).

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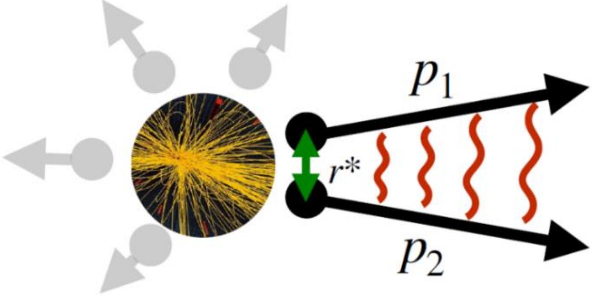

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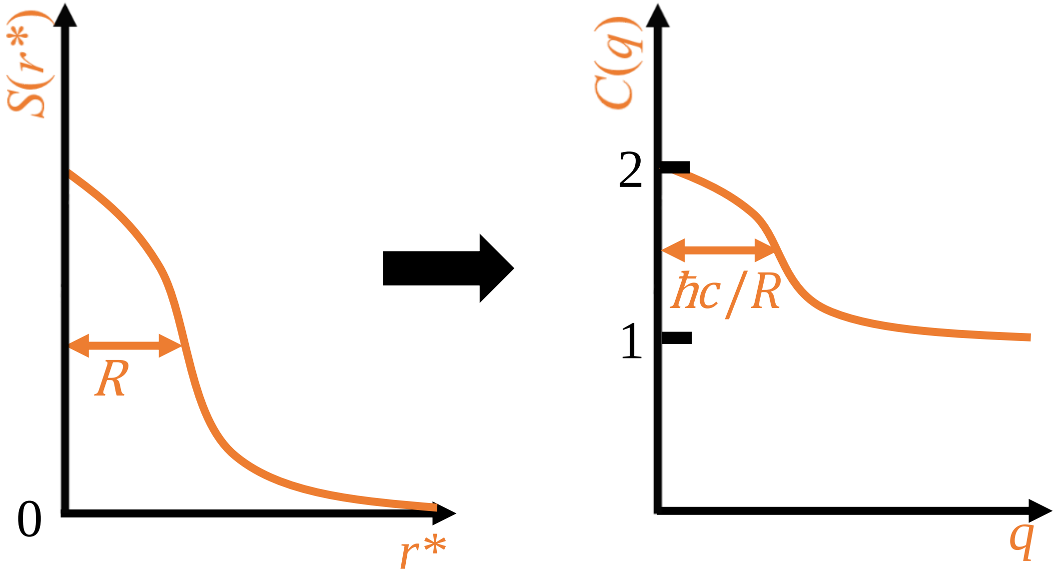

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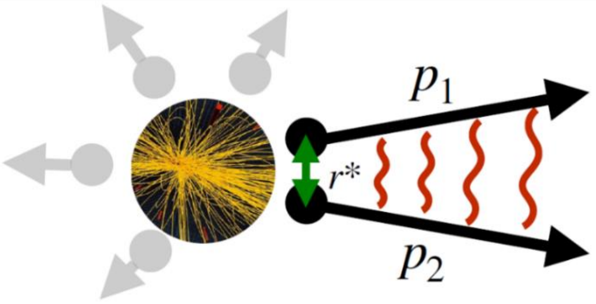

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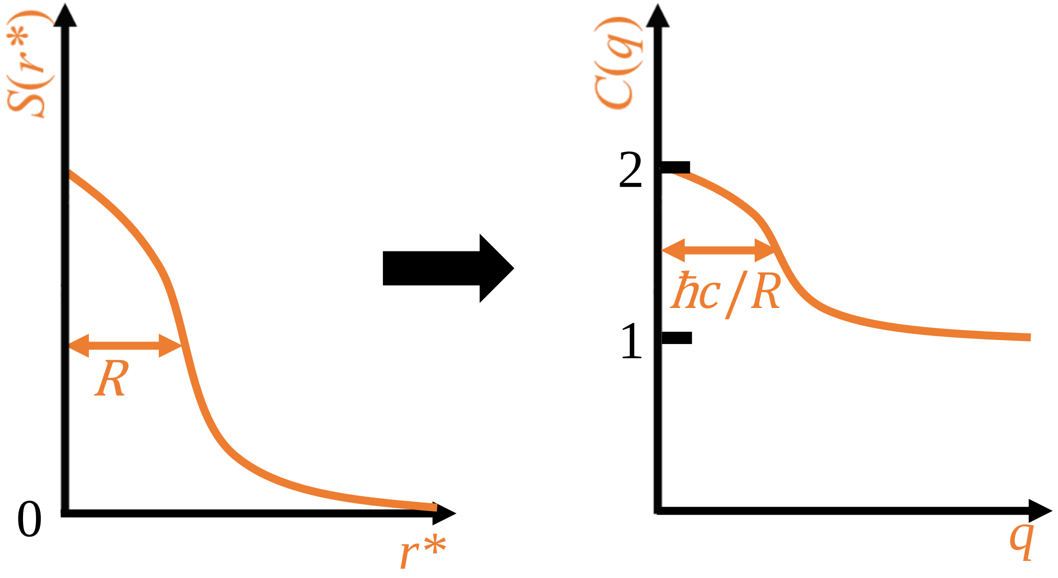


Two-particle correlation function (CF):

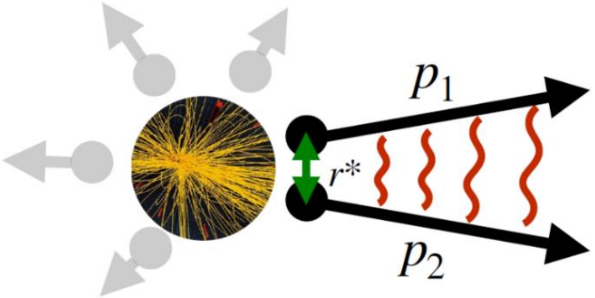
Theory: $C(q) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_1(p_2)}$, $C(\infty) = 1$

Experiment: $C(q) = \frac{S(q)}{B(q)}$, $q = p_1 - p_2 = 2k^*$

$S(q)$ - pairs from the same event

$B(q)$ - pairs from different events

Two-particle femtoscopy



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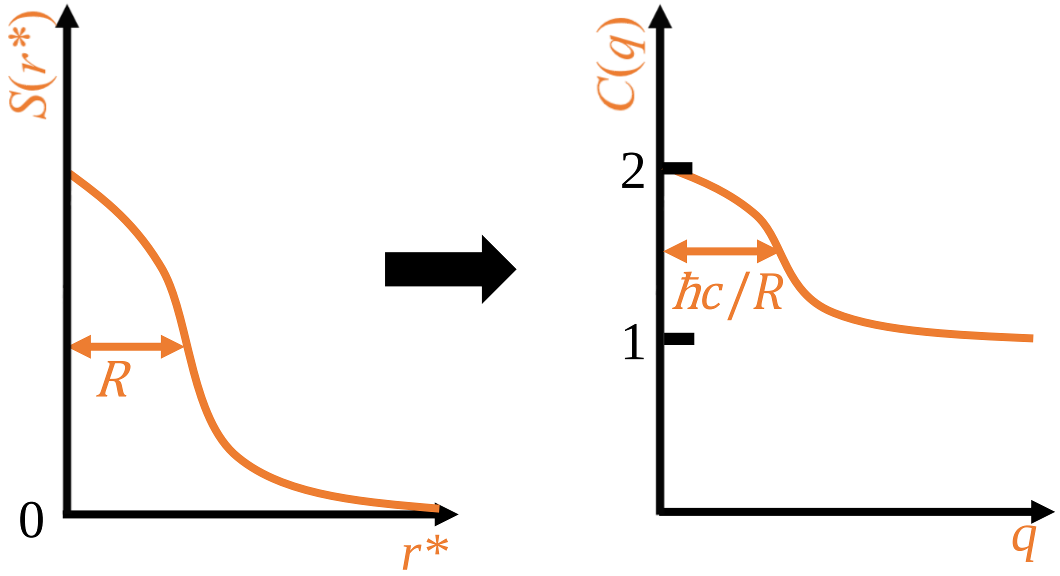

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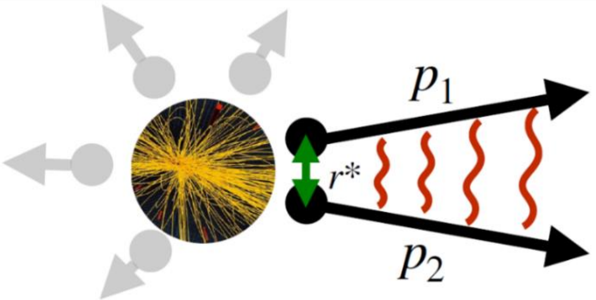
1D CF: $C(q_{\text{inv}}) = 1 + \lambda e^{-R_{\text{inv}}^2 q_{\text{inv}}^2}$

R_{inv} – source size in *Pair Reference Frame*

λ – correlation strength

Two-particle femtoscopy



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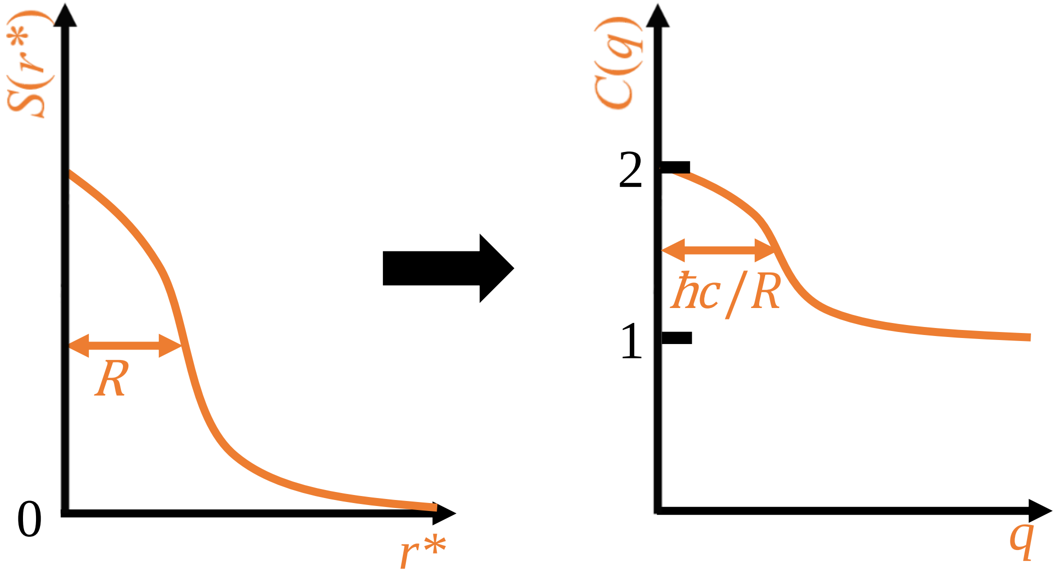

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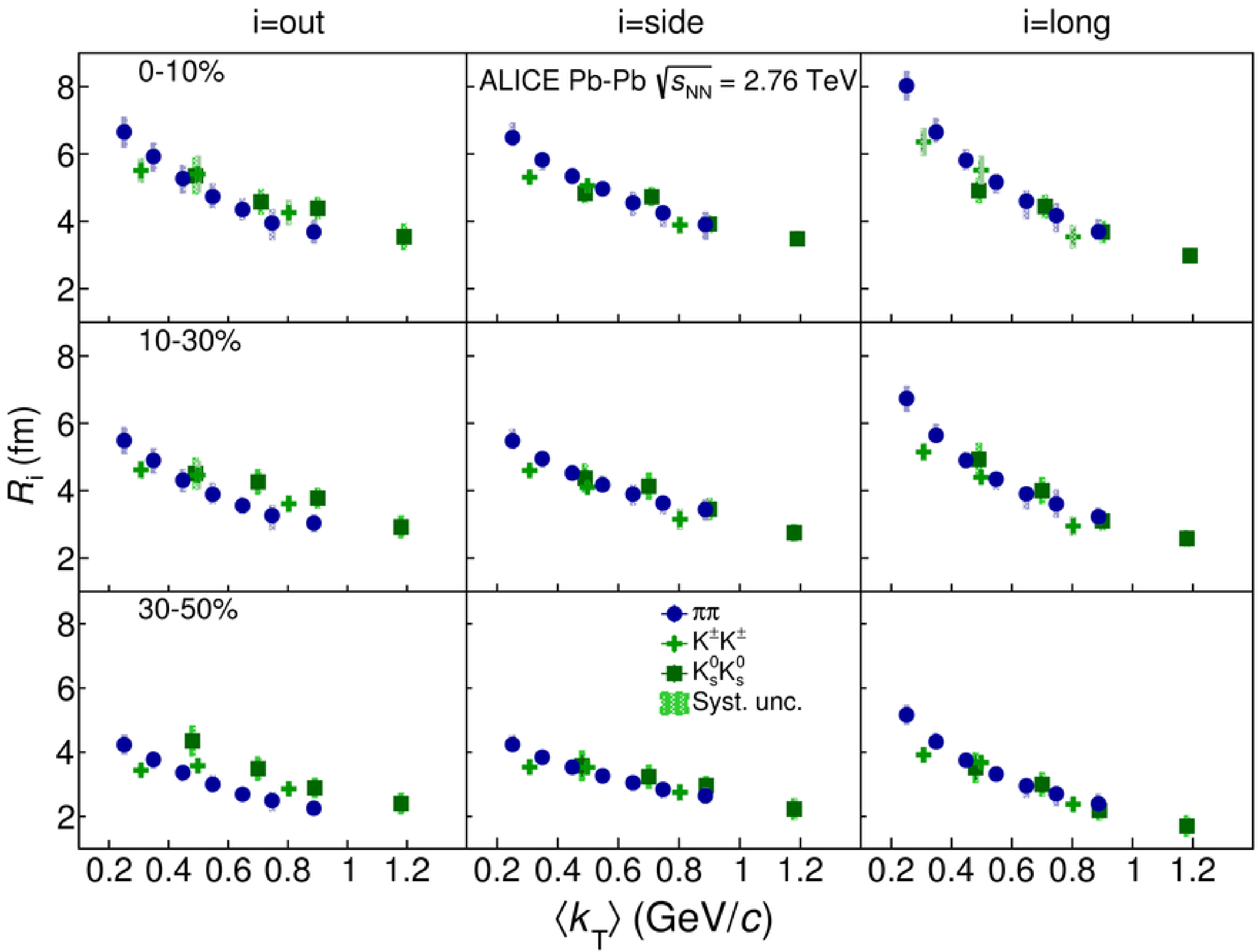
3D CF: $C(q_{\mathrm{out}}, q_{\mathrm{side}}, q_{\mathrm{long}}) = 1 + \lambda e^{-R_{\mathrm{out}}^2 q_{\mathrm{out}}^2 - R_{\mathrm{side}}^2 q_{\mathrm{side}}^2 - R_{\mathrm{long}}^2 q_{\mathrm{long}}^2}$

R_{out}, R_{side}, R_{long} – source size in *Longitudinally Co-Moving System*

$K^{\pm}K^{\pm}$: 3D analysis in Pb–Pb

ALICE, PRC96(2017)064613



- R decrease with increasing pair transverse momentum $k_T = |\vec{p}_{T,1} + \vec{p}_{T,2}|/2$ and for decreasing centrality →

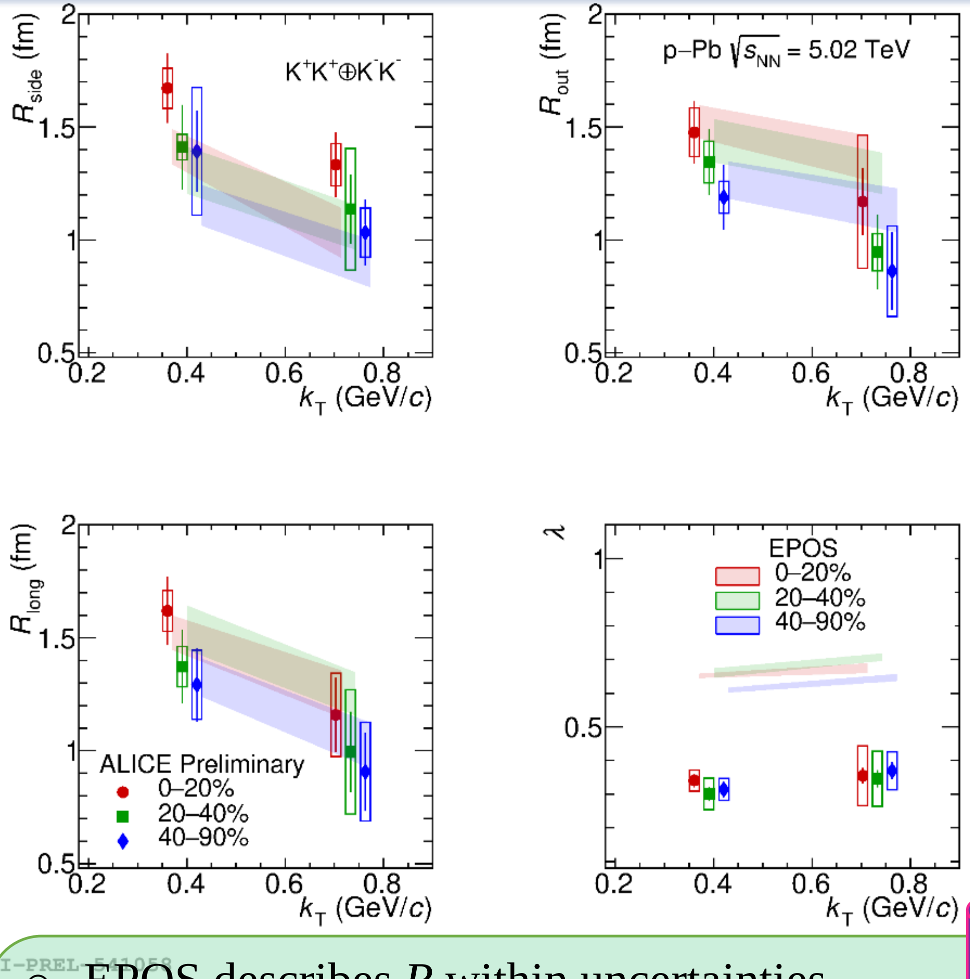
hydrodynamic expansion of matter created in heavy-ion collisions

- k_T scaling observed for pions and kaons

predicted by HKM+UrQMD cascade model

Yu.M.Sinyukov et al., NPA946(2016)227

K±K±: 3D analysis in p–Pb

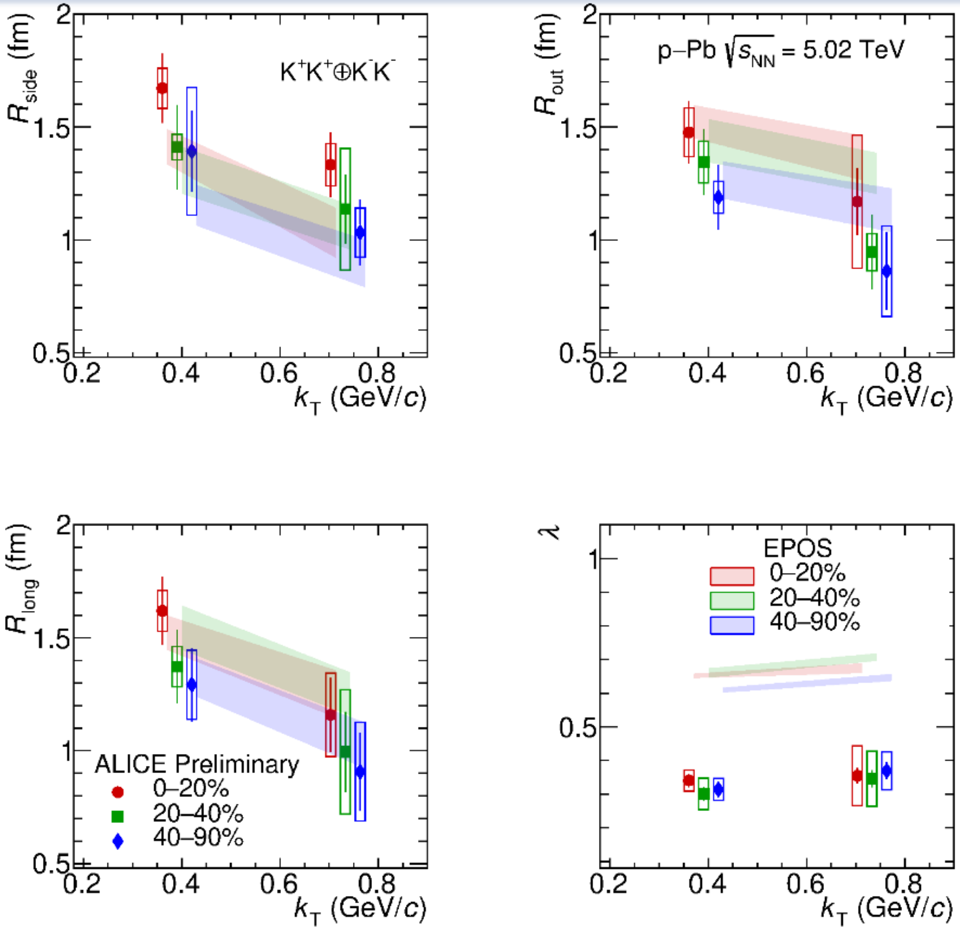


- *R* decrease with increasing k_T and for decreasing centrality → *hydrodynamic expansion of matter created in p–Pb collisions*

K.Werner et al., PRC89(2014)064903

- EPOS describes *R* within uncertainties
- Indication that EPOS underestimates R_{side} for central collisions
- EPOS overestimates λ due to kaons from long-lived resonances like K*

$K^{\pm}K^{\pm}$: 3D analysis in p–Pb



- At similar multiplicities, $\pi^{\pm}$ and $K^{\pm}$ radii coincide within uncertainties
- Available data are not enough to say whether k_T/m_T scaling occurs in p–Pb

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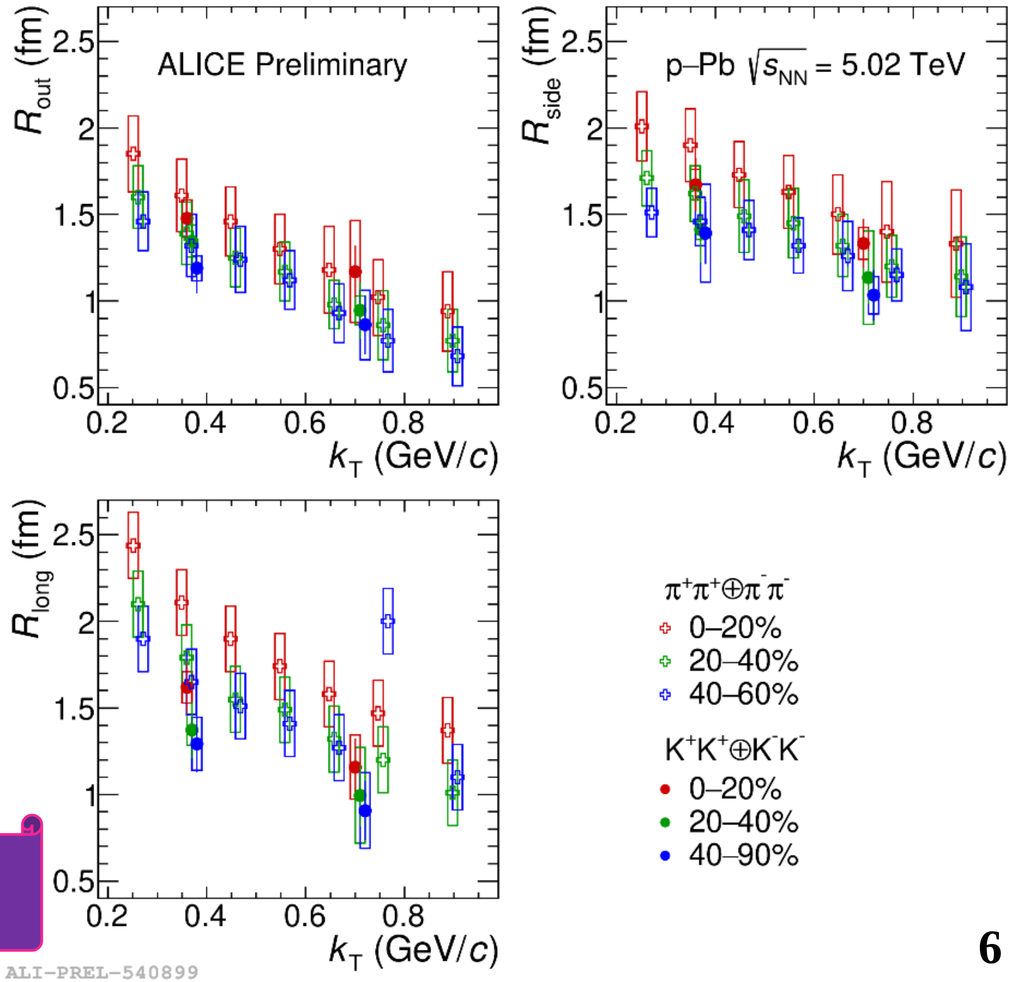

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K.Werner et al., PRC89(2014)064903

$\pi^{+}\pi^{+}\oplus\pi^{-}\pi^{-}$:

ALICE, PRC91(2015)034906

$K^{\pm}K^{\pm}$: Maximal emission time

Yu.M.Sinyukov et al., NPA946(2016)227
V.M.Shapoval et al., EPJA56,10(2020)260

Estimate the lifetime of the expanding fireball associated with the moment when the number of correlated particles emitted from the source is maximum.

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Yu.M.Sinyukov et al., NPA946(2016)227
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1. Fit pion and kaon spectra → strength of collective flow α_{π}, α_{K} and temperature of maximal emission T extracted
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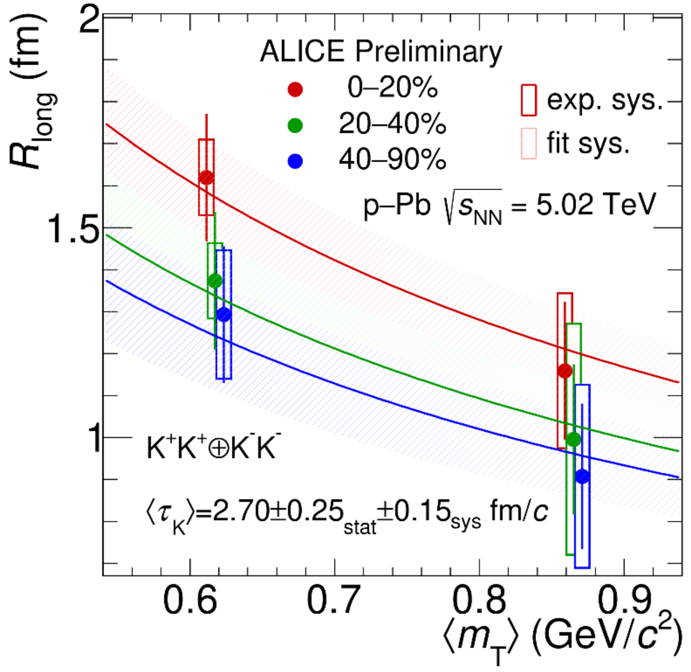

ALI-PREL-540893

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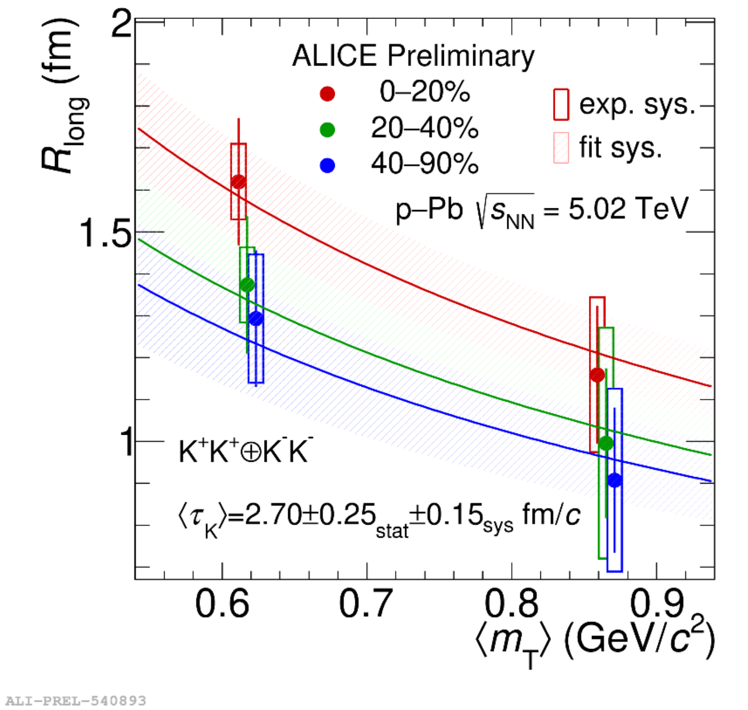
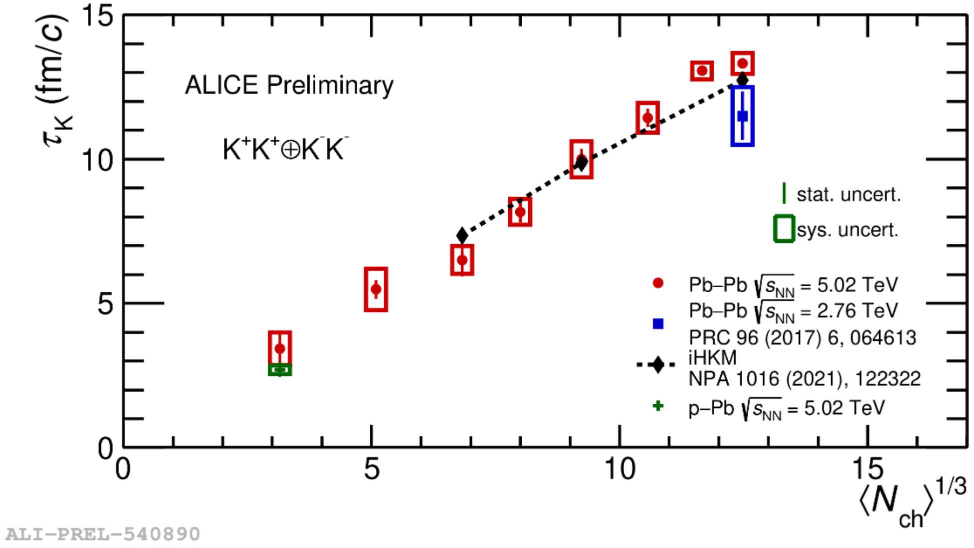


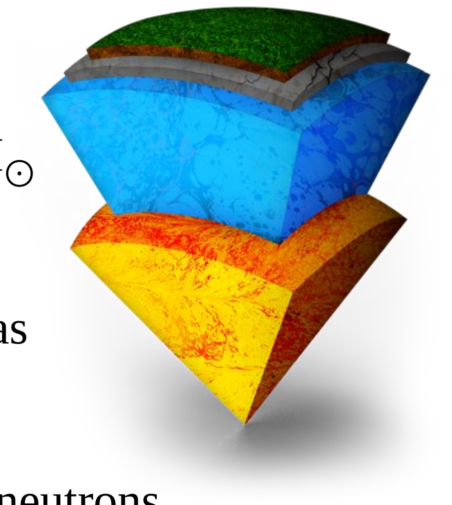


- τ_{K} decreases for more peripheral events →
  larger sources freeze-out later
- τ_{K} in p–Pb ≈ τ_{K} for the most peripheral Pb–Pb (70–90% centrality interval) at 5.02 TeV →
  medium created in p–Pb and peripheral Pb–Pb evolves similarly
- More data are needed to see the trend of τ_{K} with multiplicity

Neutron stars and EoS

Neutron stars (NS): very dense, compact objects

Dimensions
$R \sim 10 - 15$ km
$M \sim 1.2 - 2.2\ M_{\odot}$



Outer Crust
Ions, electron gas

Inner Crust
Ions, electrons, neutrons

Inner Core
Neutrons?
Protons?
Hyperons?
Kaon condensate?
Quark Matter?

EoS:
- What are the constituents to consider?
- How do they interact?

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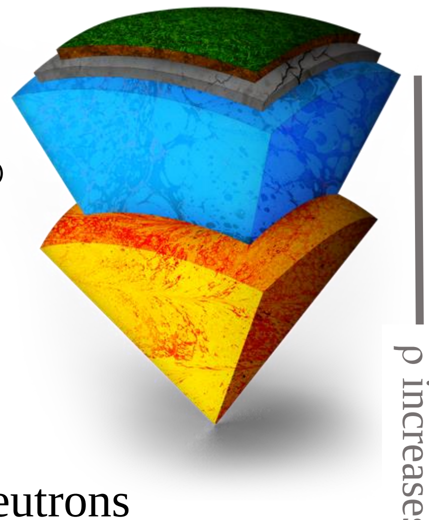

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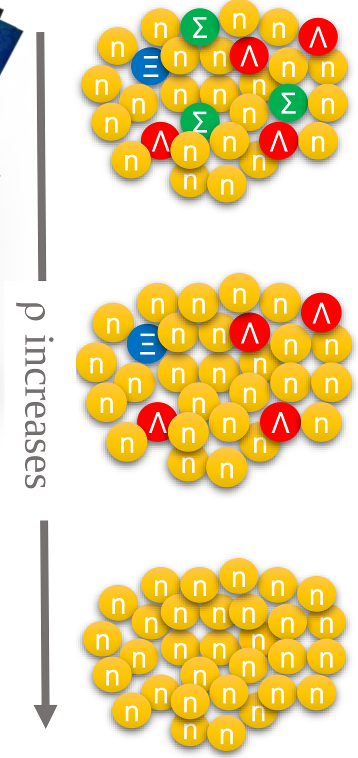

- EoS (of dense matter/NS) *is increasingly sensitive to the three-body forces* with increasing density
- Difference in EoS *difference in mass-to-radii relation for NS*
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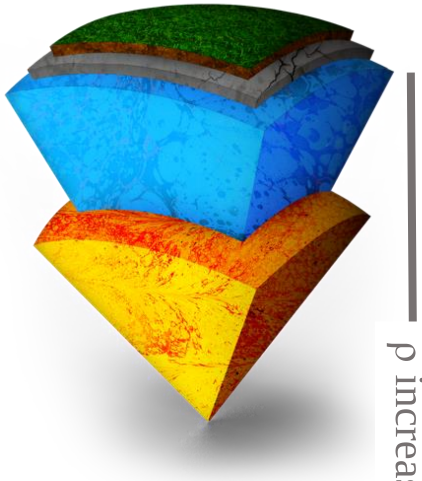

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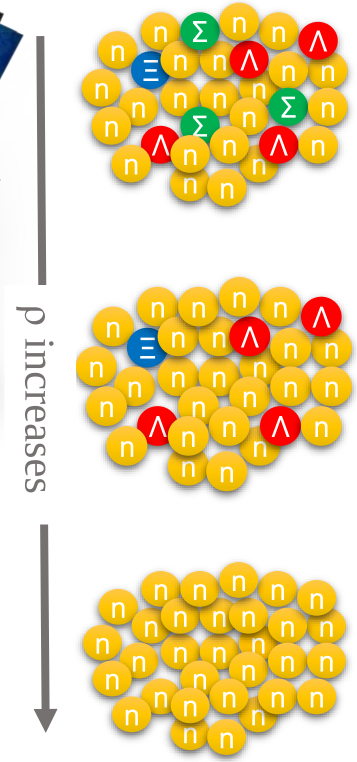

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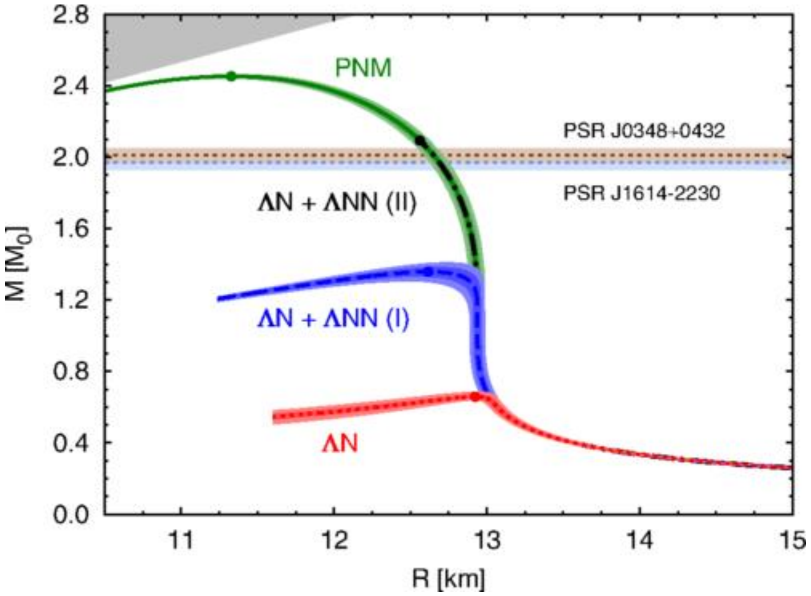

D.Lonardoni et al., PRL114(2015)092301

Neutron stars and EoS

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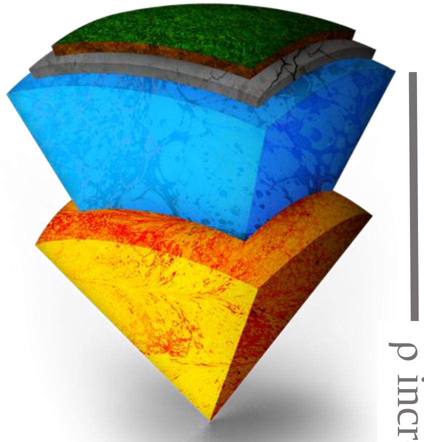

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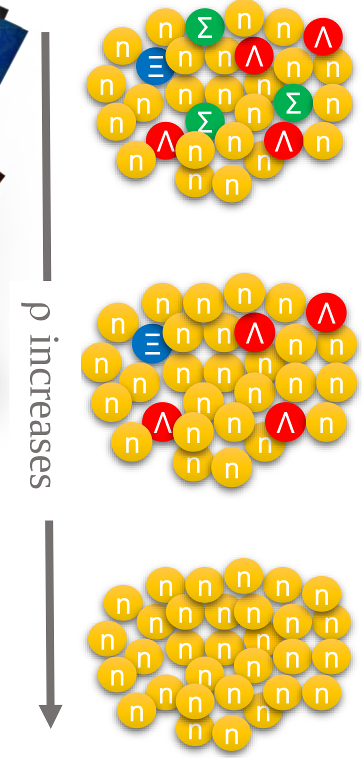

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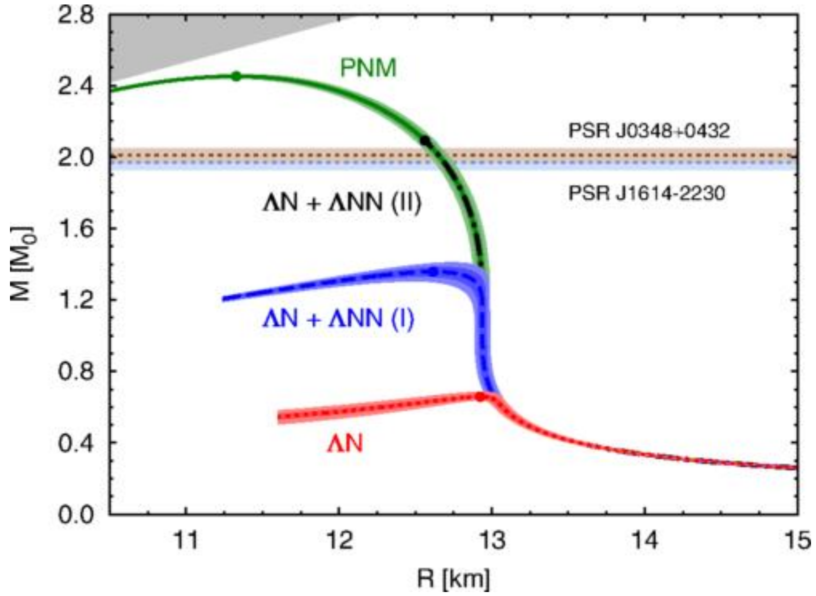


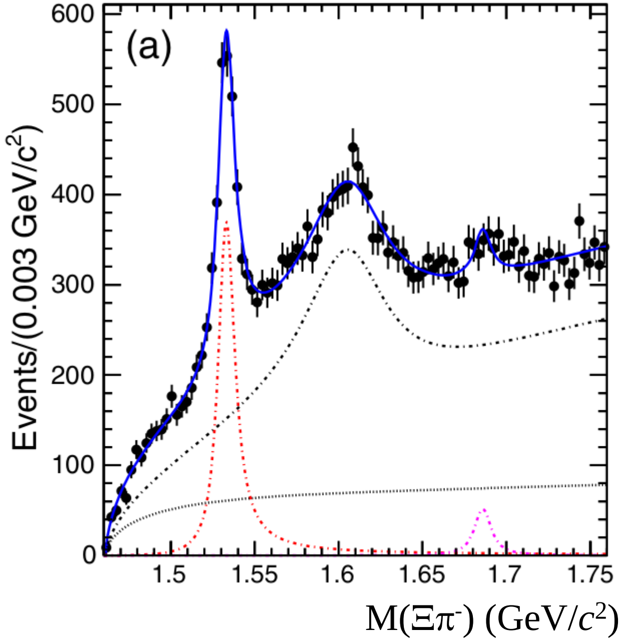
D.Lonardoni et al., PRL114(2015)092301

New observables are required to solve the three-body problem!

Λ-K⁻ correlations

BELLE, PRL122(2019)0725013

Access the strong interaction between Λ and K



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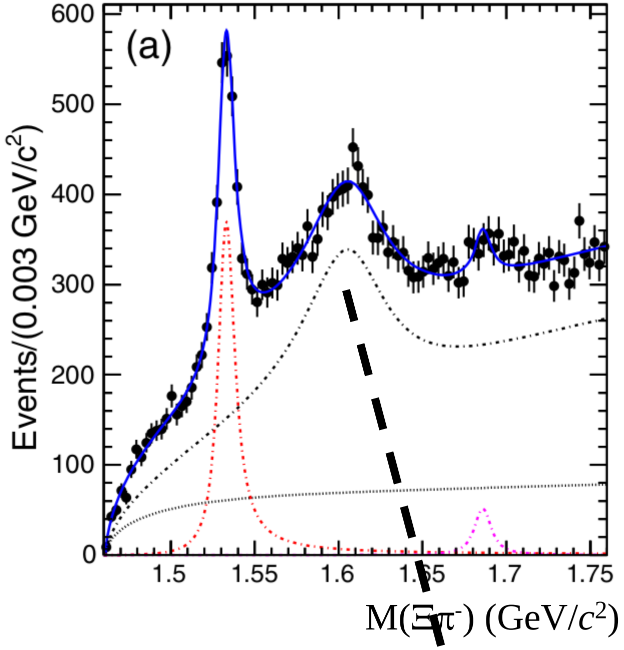
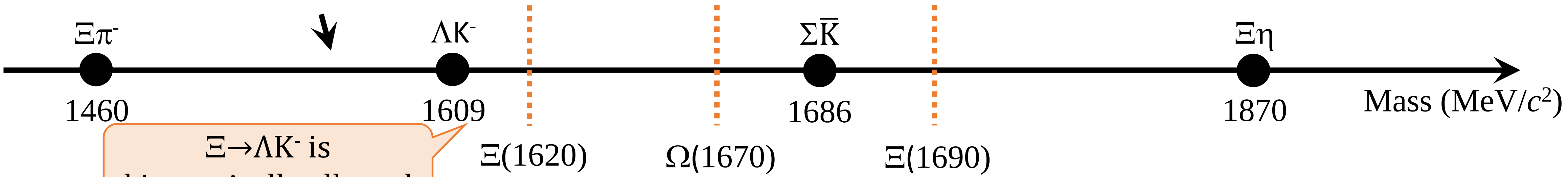
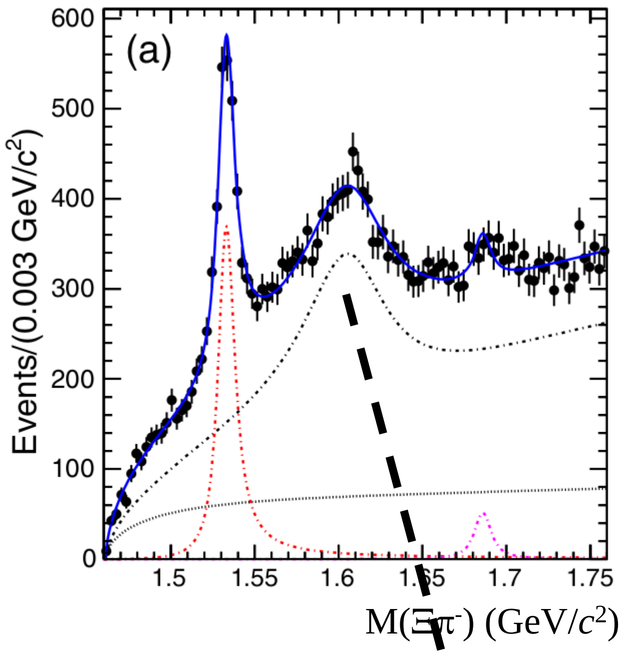


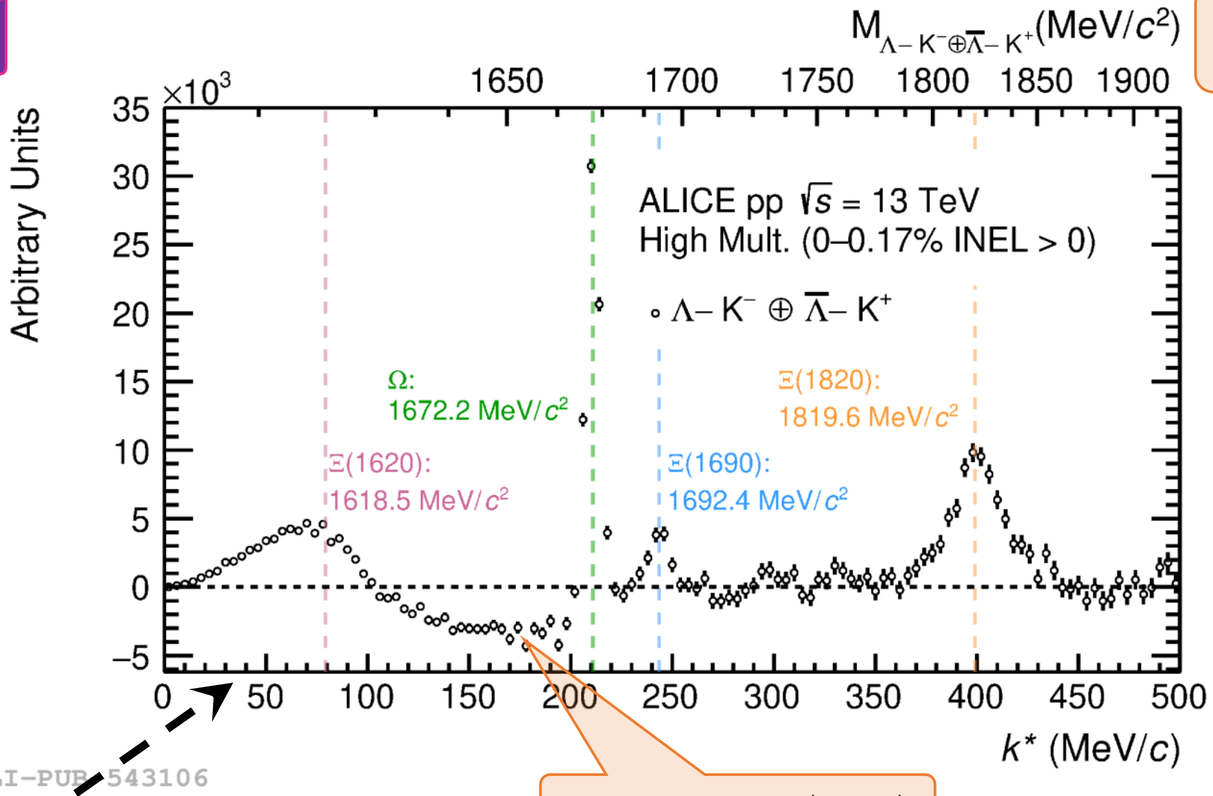


$\Xi \to \Lambda K^-$ is kinematically allowed

Λ-K⁻ correlations

BELLE, PRL122(2019)0725013

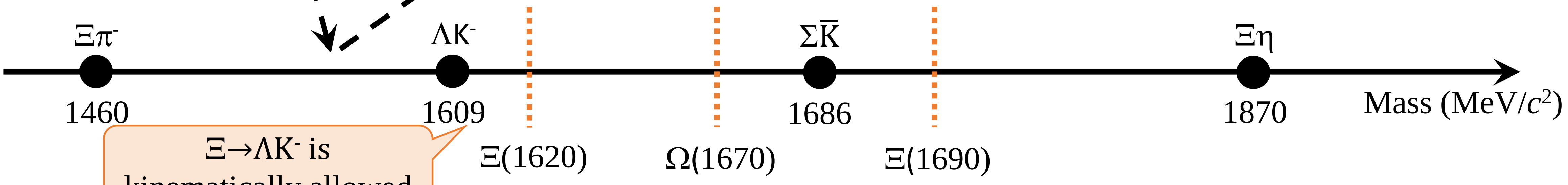




Access the strong interaction between Λ and K

ALICE, arXiv:2305.19093

non-resonant part



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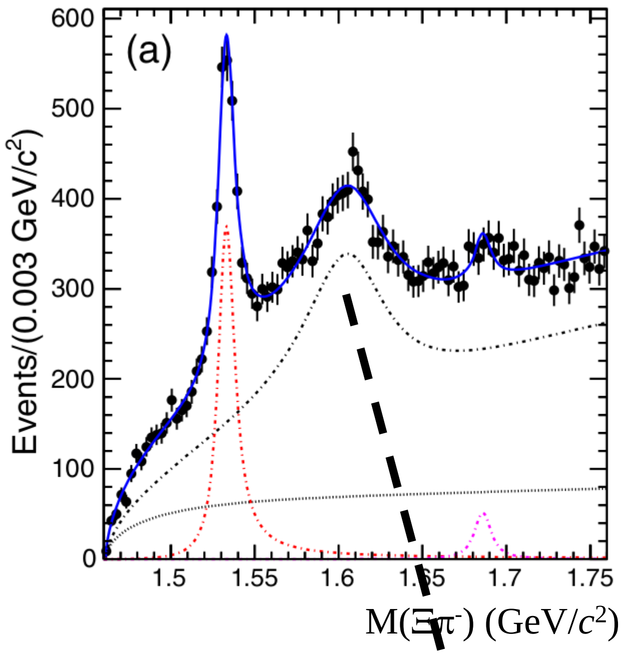
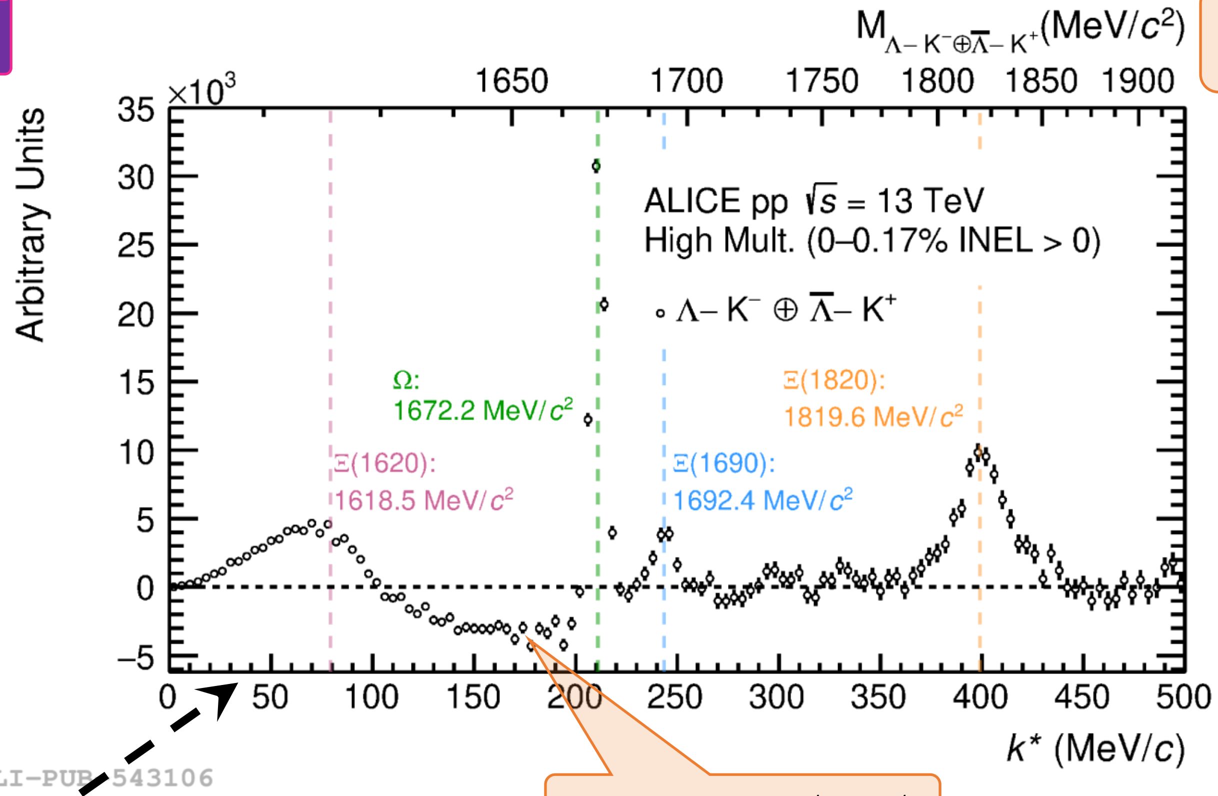
BELLE, PRL122(2019)0725013



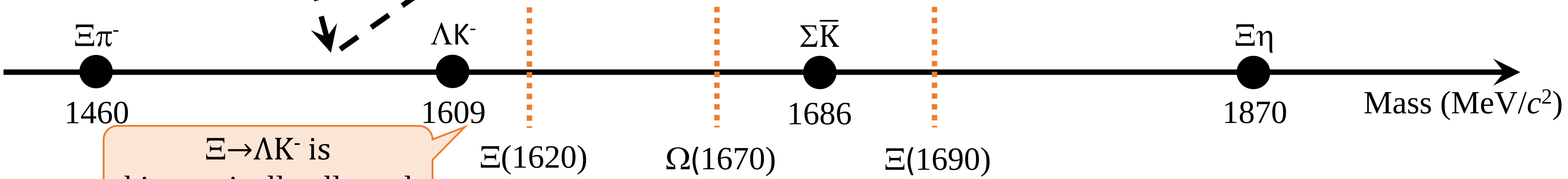


Access the strong interaction between Λ and K

ALICE, arXiv:2305.19093

non-resonant part

Λ-K⁻ interaction is crucial in the understanding of the Ξ(1620)!



Ξ→ΛK⁻ is kinematically allowed

Λ-K⁻ correlations

$$C(k^*) = C_{\text{model}}(k^*)\left(a(1 + bk^{*2} + ck^{*3}) + \sum_j \omega_j\, C^j_{\text{inel}}(k^*)\right)$$

$\Lambda K^- \to \Lambda K^-$, Ξ(1620)

$\Xi\pi, \bar{\Sigma}K, \Xi\eta \to \Lambda K^-$

- ω_j – amount of initial-state particles
- Ξ(1620) shares the same quantum numbers as Λ-K⁻ ⟶ strongly coupled states
- Comparison with UχPT at LO and χPT at NLO

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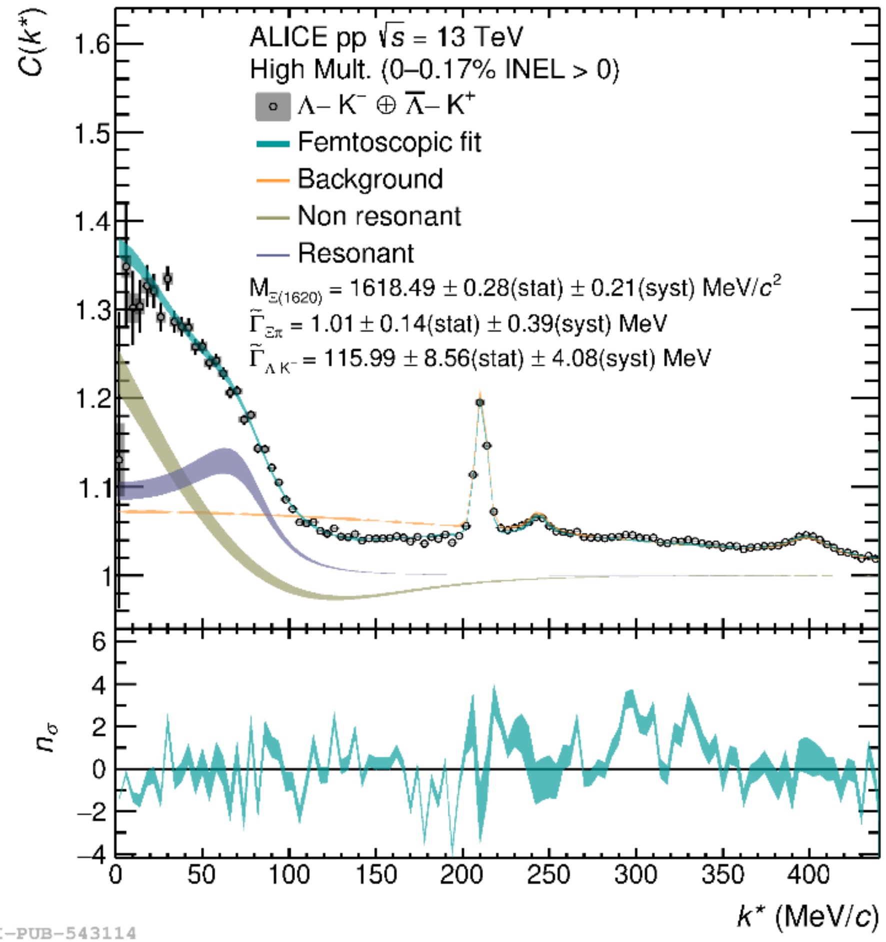

ALI-PUB-543114

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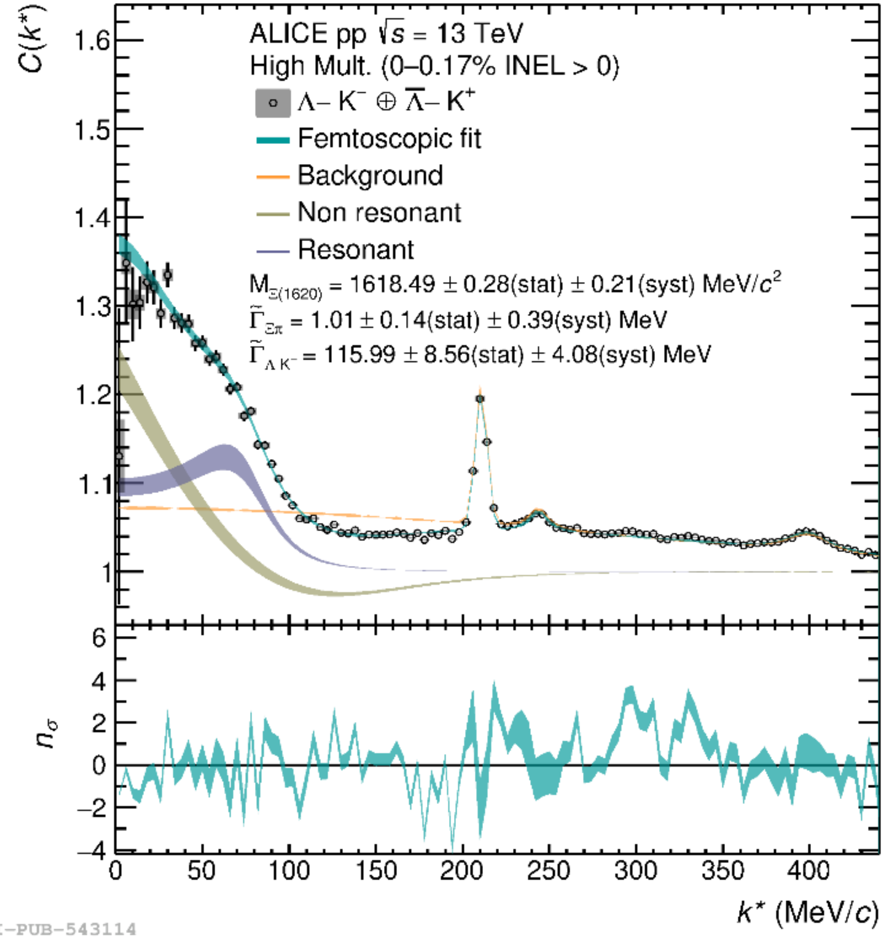


- Scattering parameters for Λ-K⁻ (non-resonant) from Lednický–Lyuboshits approach, in agreement with Pb–Pb ALICE results

ALICE, PRC103(2021)055201

- Attractive strong interaction for Λ-K⁻
- Masses and widths of Ξ(1620), Ω, Ξ(1690), Ξ(1870)
- Constraints for low-energy effective theories describing the meson–baryon interaction ($S = -2$ sector)
- Investigation of Ξ(1620) – *possibly dynamically generated molecular state*

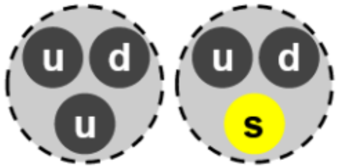
p-Λ correlations

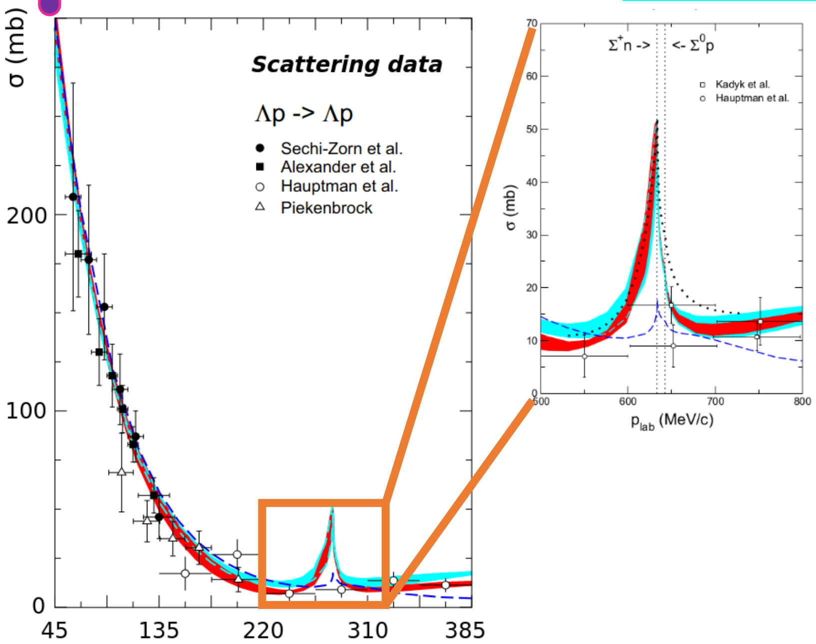
J.Haidenbauer et al., EPJA56(2020)3,91

χEFT NLO 13

χEFT NLO 19

Small amount of available experimental data in the region of NΛ↔NΣ cusp.





Differences in the coupling to NΣ, and in the interplay between two- and three-body forces. Important for EoS.

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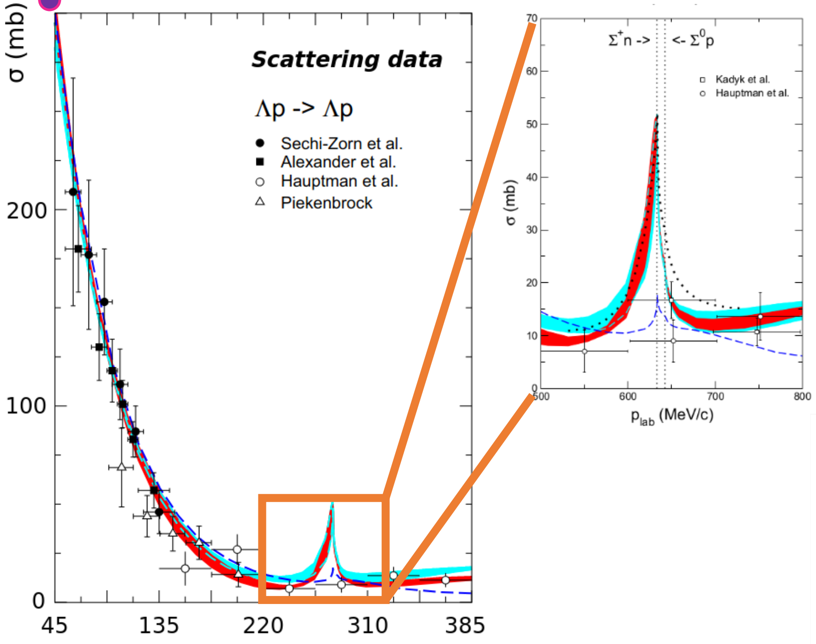

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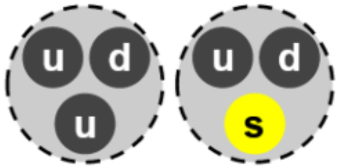

Cusp is observed with very high precision in p-Λ CF.

Superior **precision at low momenta** over existing data.

ALICE, PLB833(2022)137272

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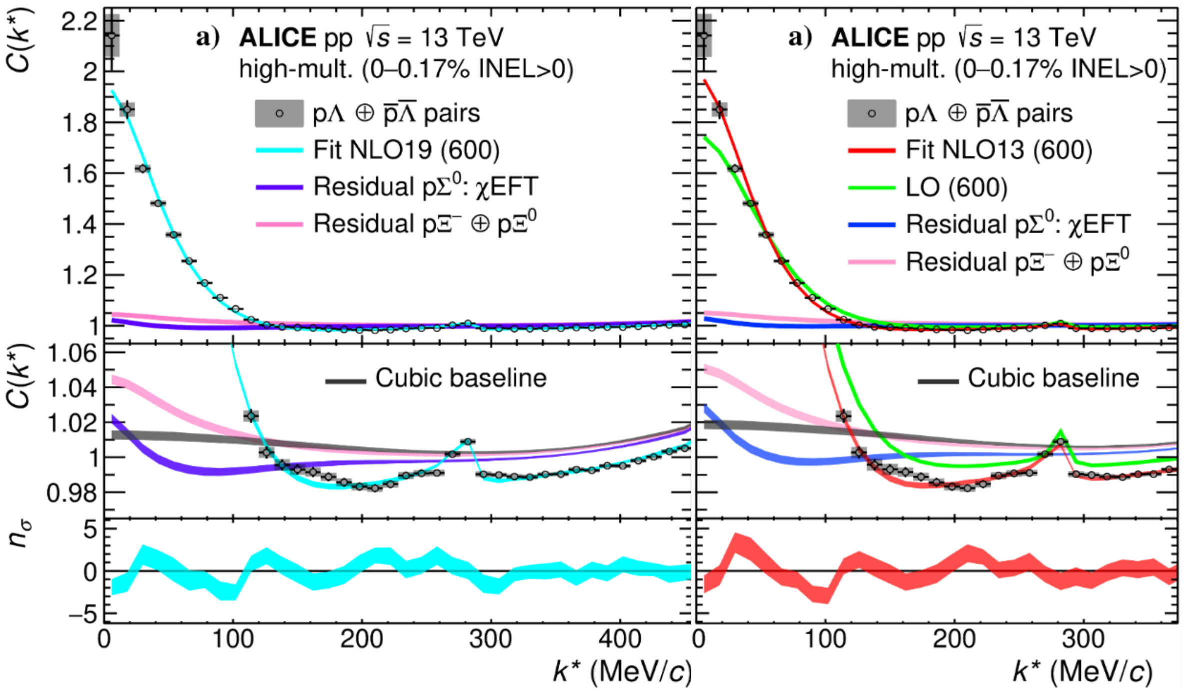

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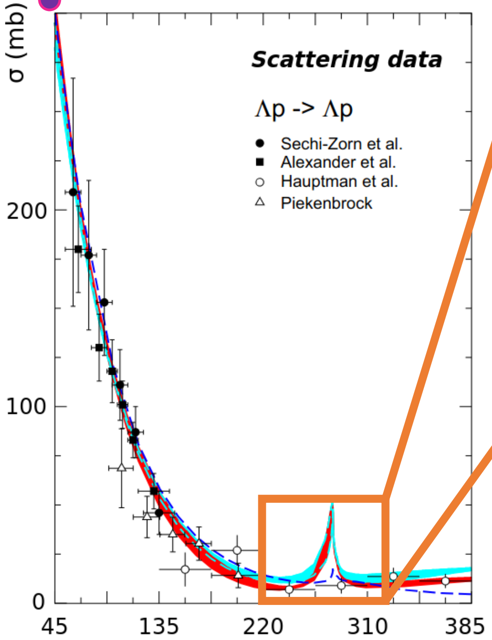

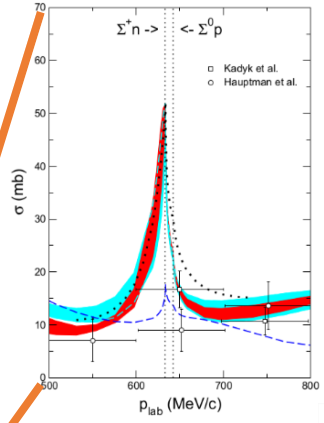

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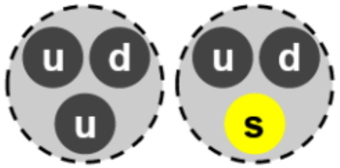

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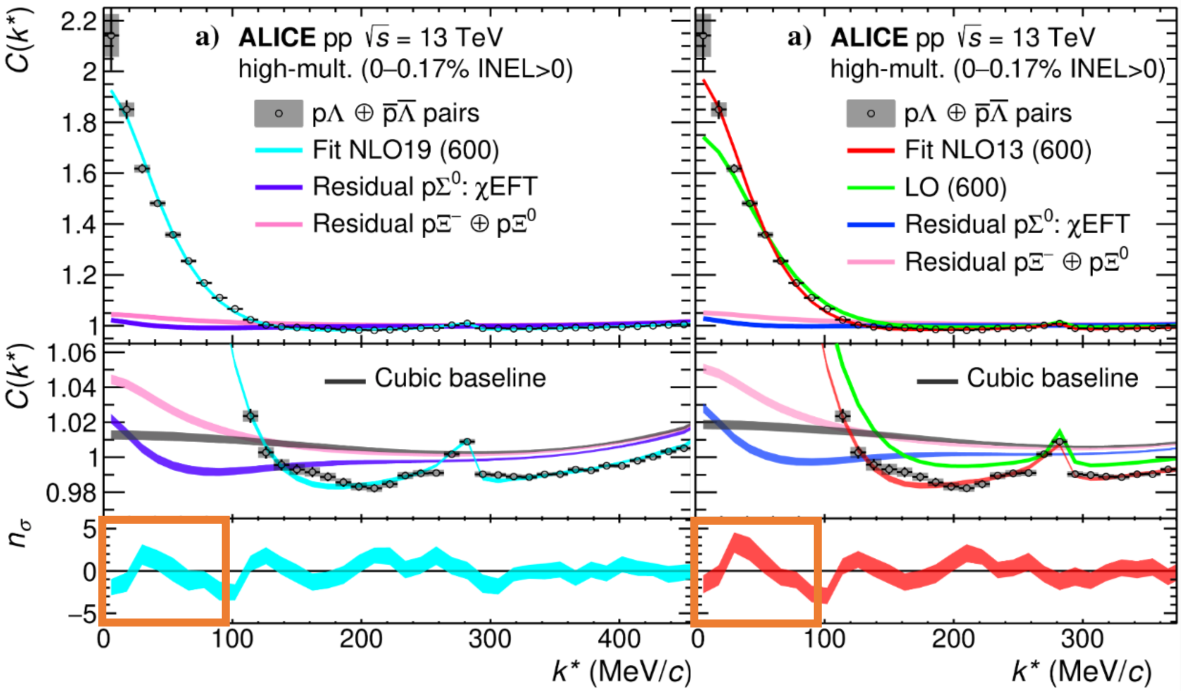

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NLO13 deviates by ~4σ at low k*.

NLO19 deviates by ~3σ at low k*.
Preference towards the NLO19.

p-Λ correlations

J.Haidenbauer et al., EPJA56(2020)3,91

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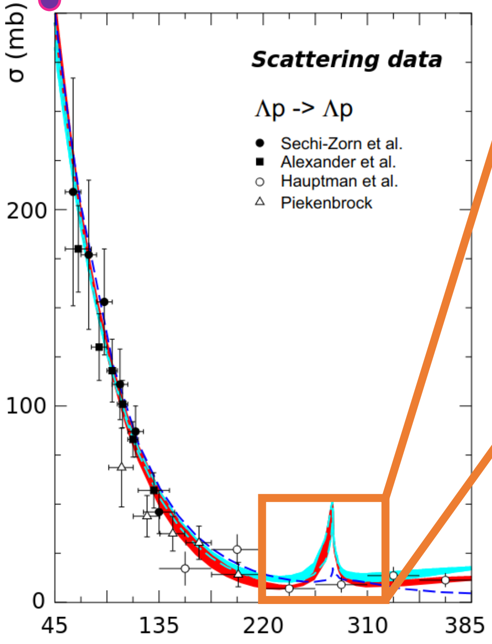

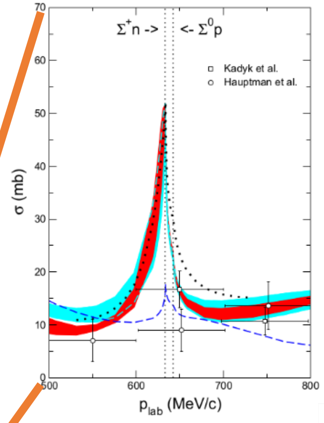

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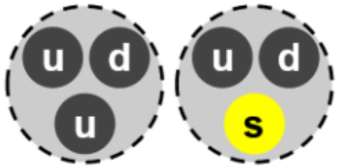

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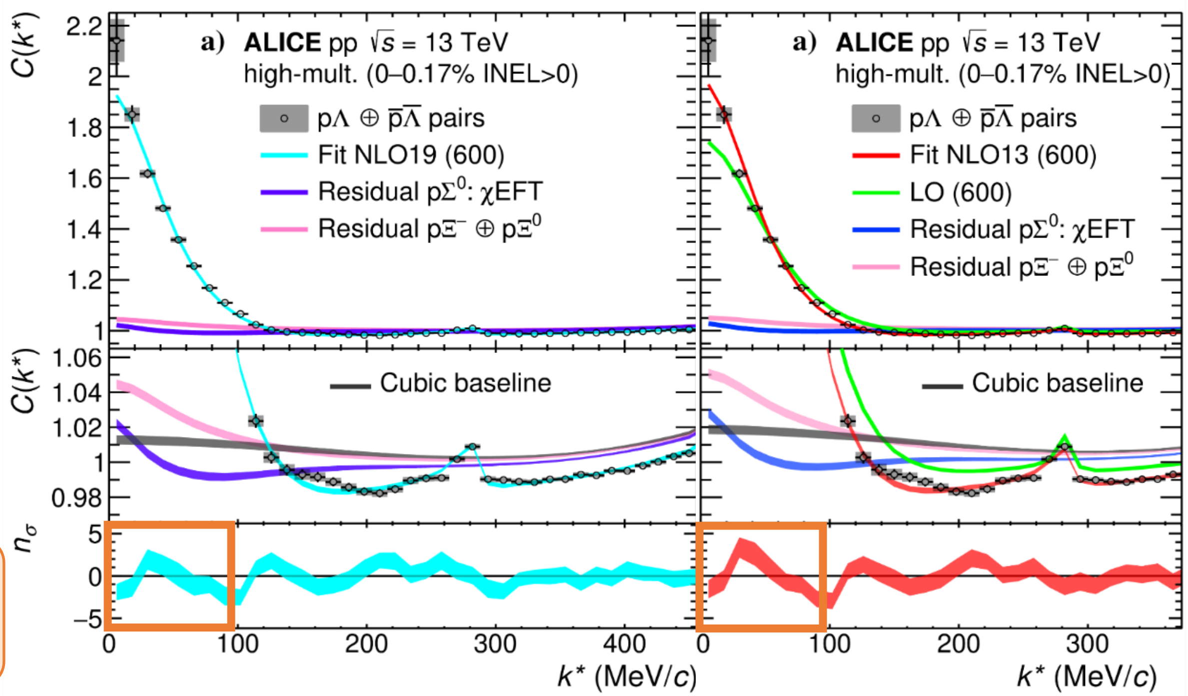
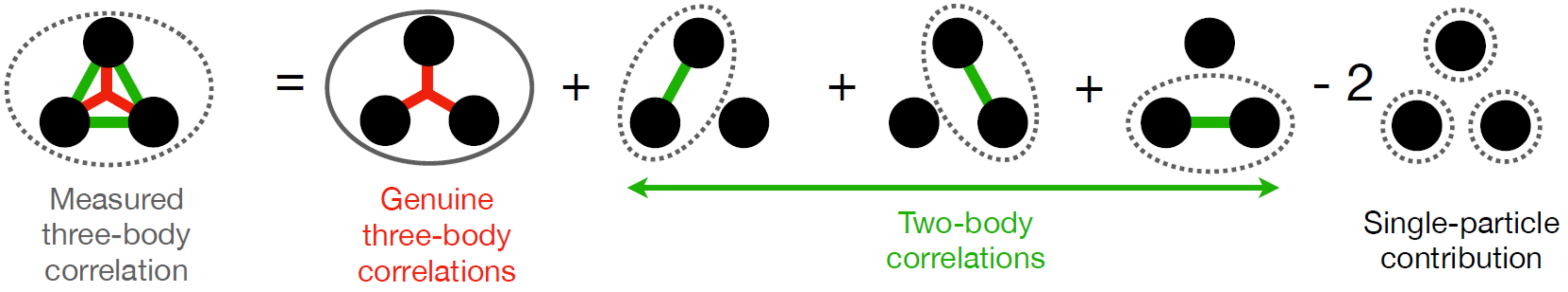


NLO13 deviates by ~4σ at low k*.

Further improvement of the NLO model is possible!

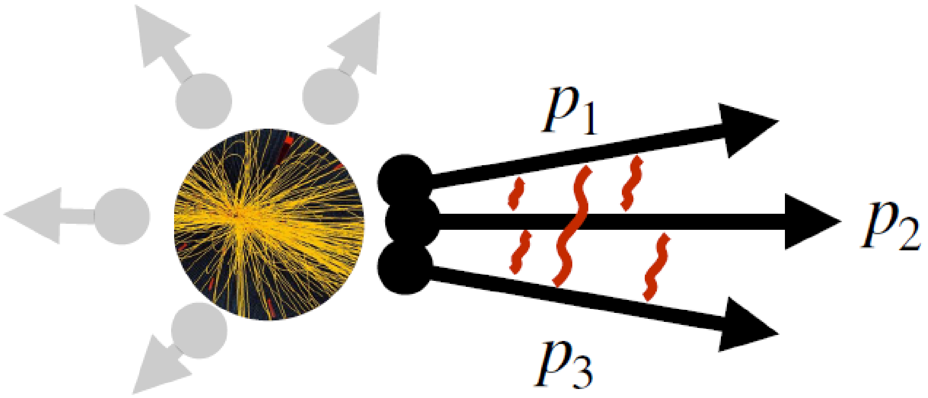
NLO19 deviates by ~3σ at low k*.
Preference towards the NLO19.

Three-particle femtoscopy



Calculated employing Kubo's cumulants

R.Kubo, J. Phys. Soc. Jpn. 17(1962)1100



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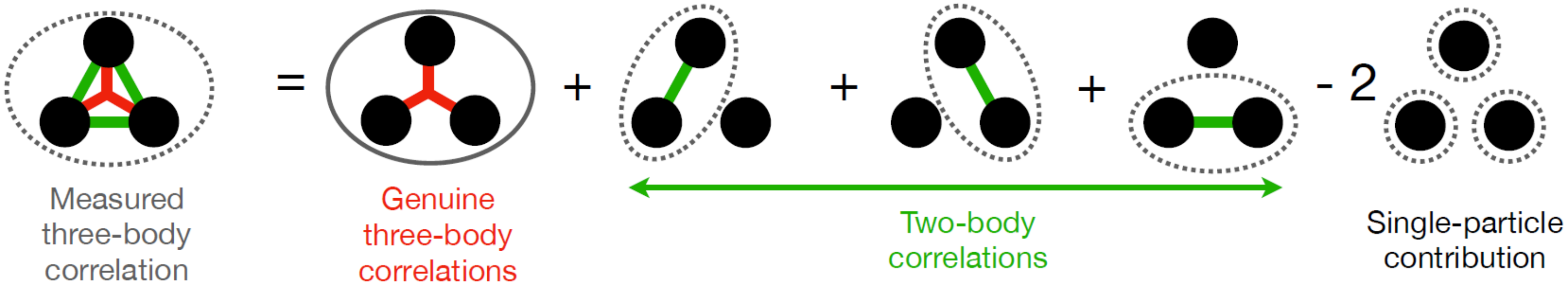

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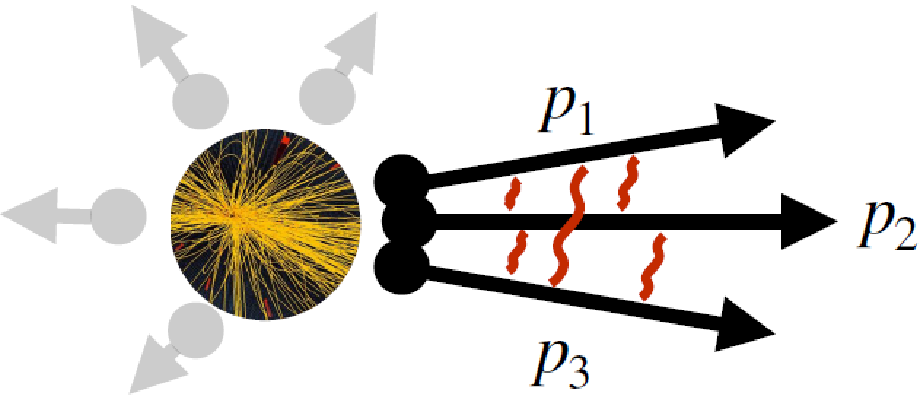

Experiment:

$$C(Q_3) = \mathcal{N} \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$

$$q_{ij} = \frac{2m_j}{m_i + m_j} p_i - \frac{2m_i}{m_i + m_j} p_j$$

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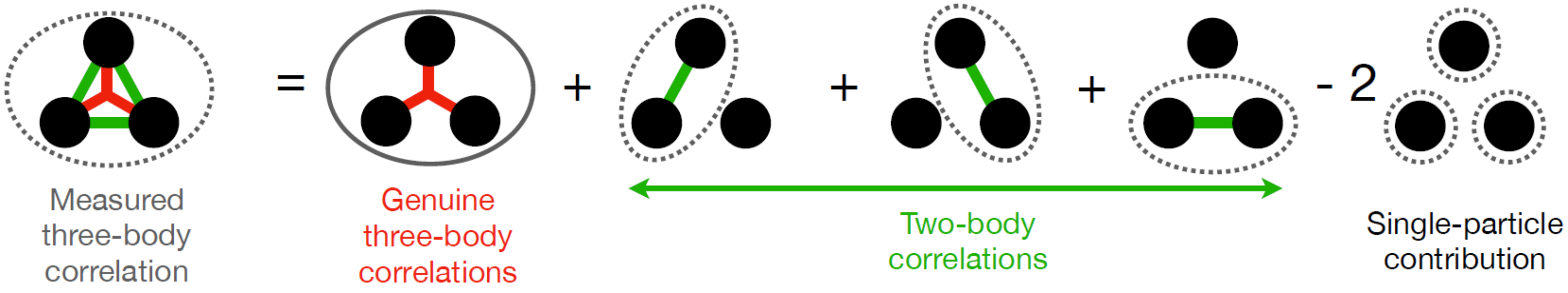

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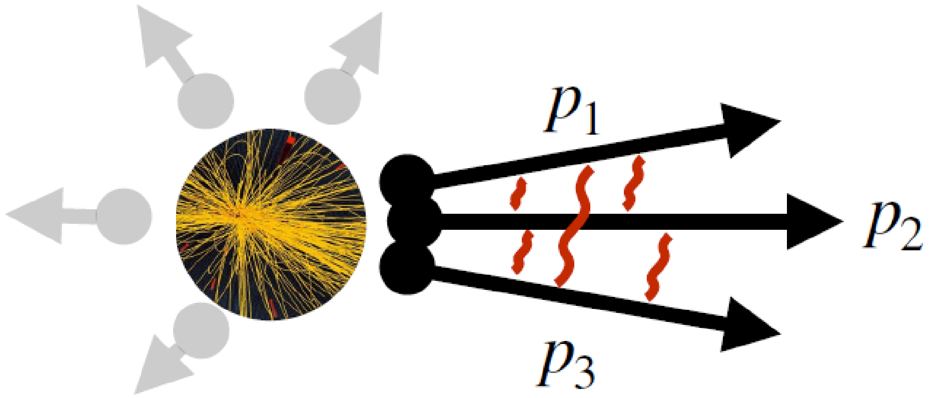

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Theory: two-body interactions + three-body interaction

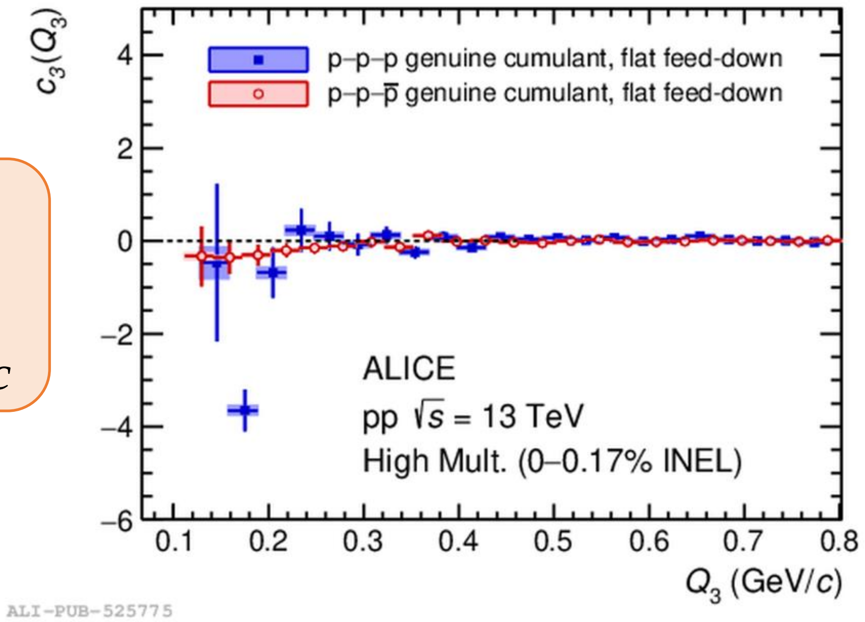
$$C_3(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)=\iiint S_3(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)|\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)|^2 d^3r_1 d^3r_2\, d^3r_3$$

p-p-p and p-p-Λ correlations

ALICE, EPJA59(2023)145

- *Negative cumulant for p-p-p*
- Possible forces at play:
  - Pauli blocking at the three-particle level
  - Three-body strong interaction
  - Long-range Coulomb

Statistical significance: $n_\sigma = 6.7$ for $Q_3 < 0.4$ GeV/c



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- Only two identical and charged particles (p-p in p-p-Λ combination) →

main expected contribution from three-body strong interaction

- Relevant measurement for EoS of NS

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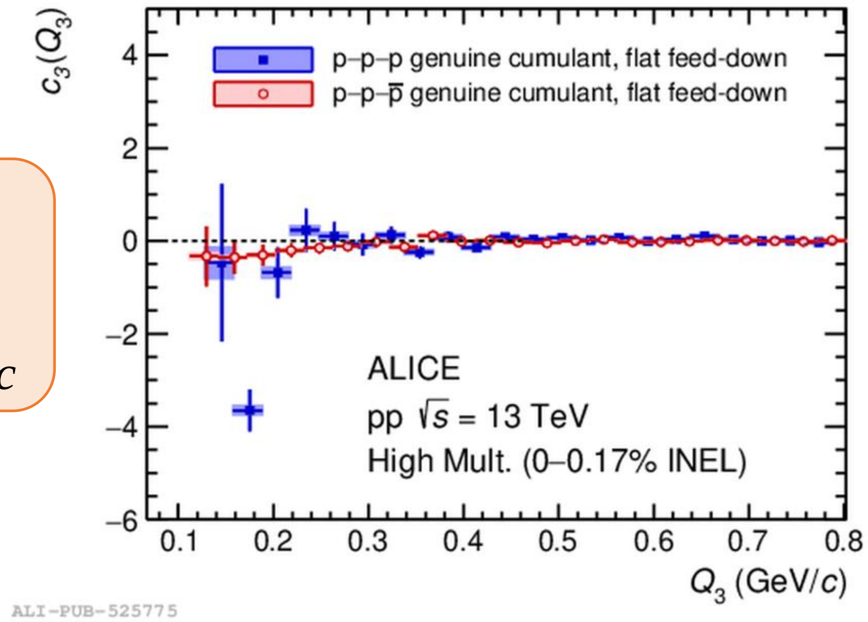

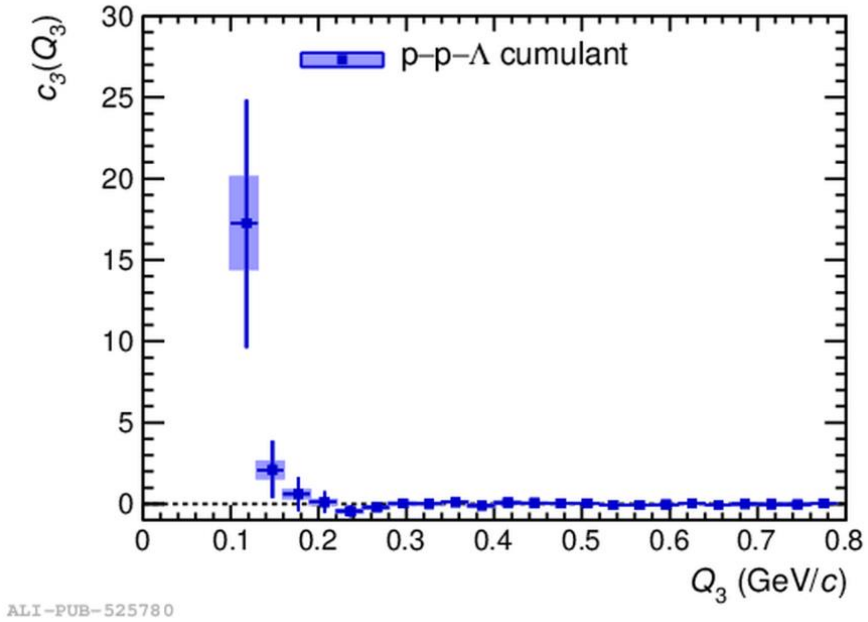

Statistical significance: n_σ= 0.8 for Q_3 < 0.4 GeV/c

p-p-p and p-p-Λ correlations

ALICE, EPJA59(2023)145

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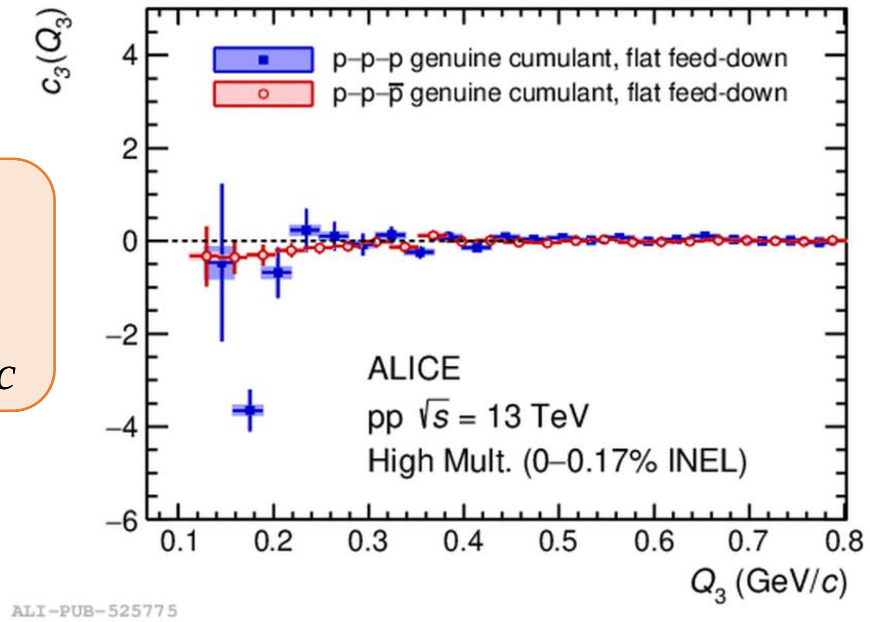

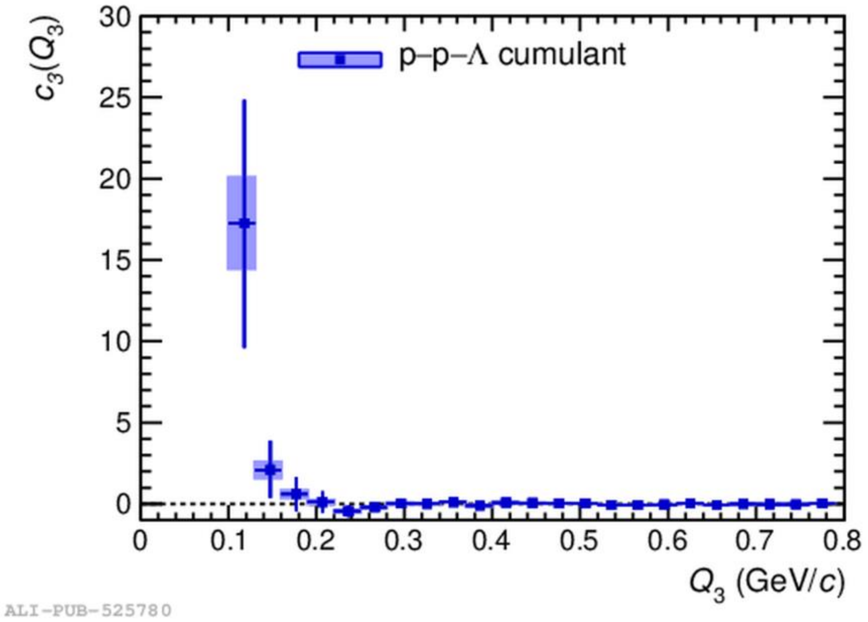

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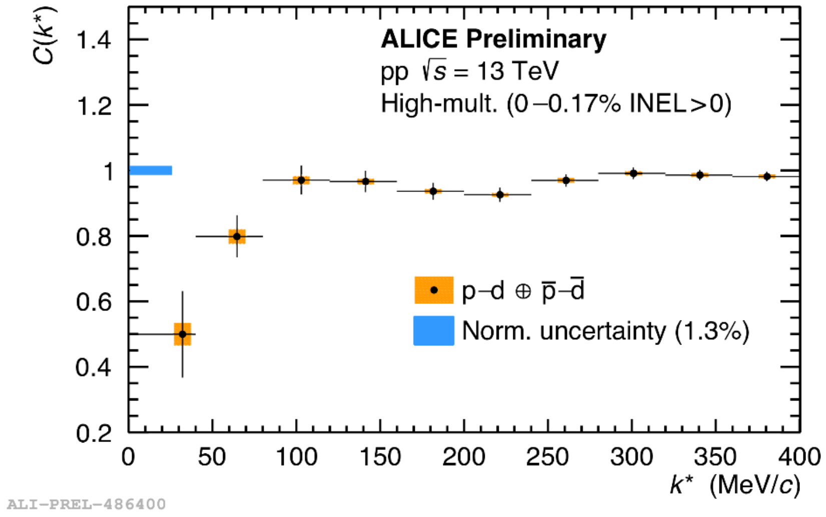
Final constraints on three–body interactions will arrive with Run 3 data.
Already under investigation with special trigger for p-p-Λ!

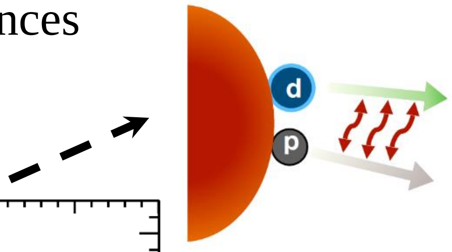
p-d correlations

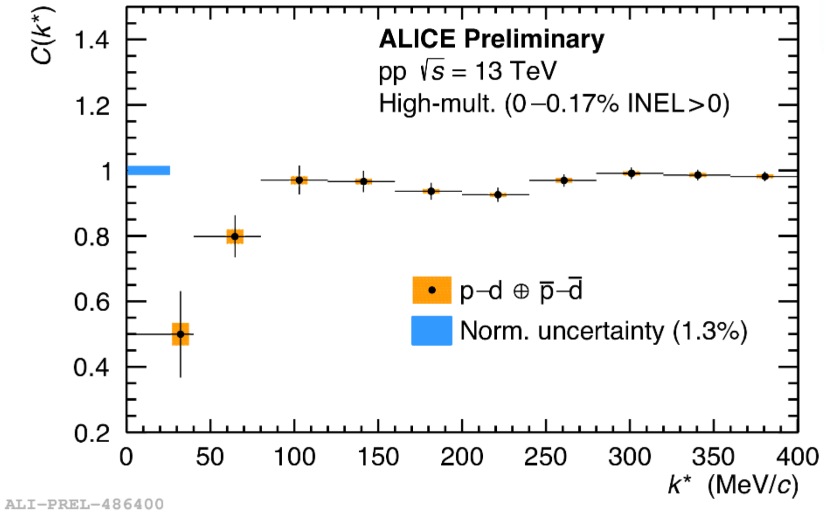


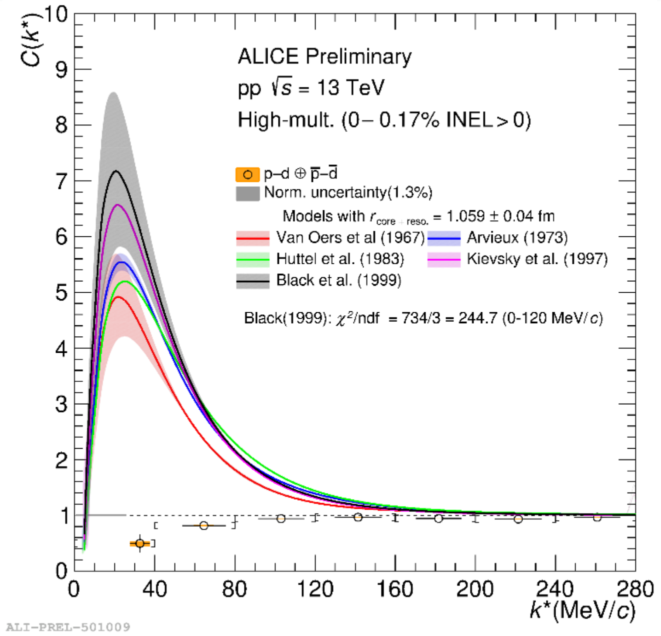
p-d correlations

ALICE, PLB811(2020)135849

Two contributions to $r_{\mathrm{eff}}^{\mathrm{p-d}}$:
Gaussian core + decaying resonances







- Effective two-body system
- Coulomb + strong interactions via Lednický model; only s-wave

R.Lednický, Phys.Part.Nucl.40(2009)307

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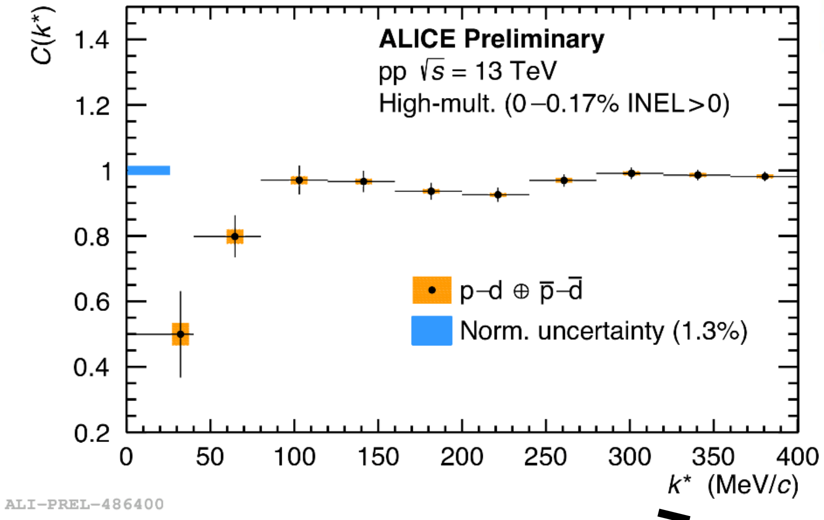

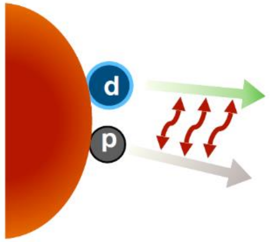

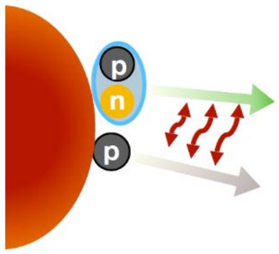

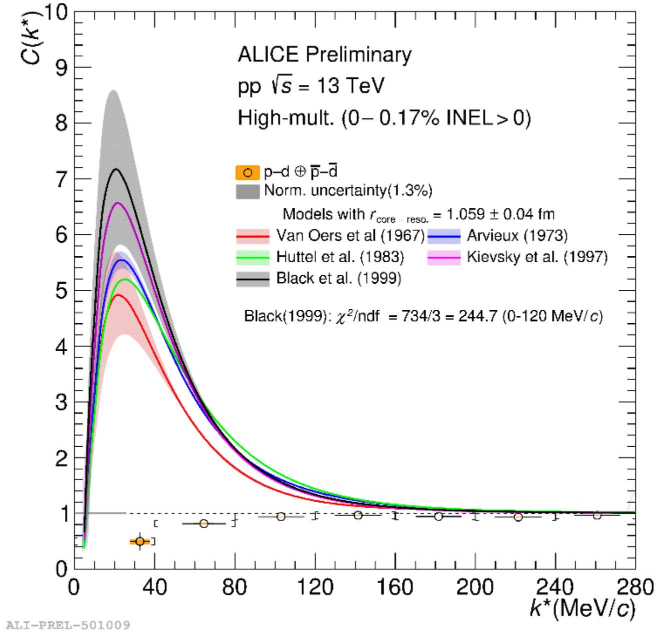

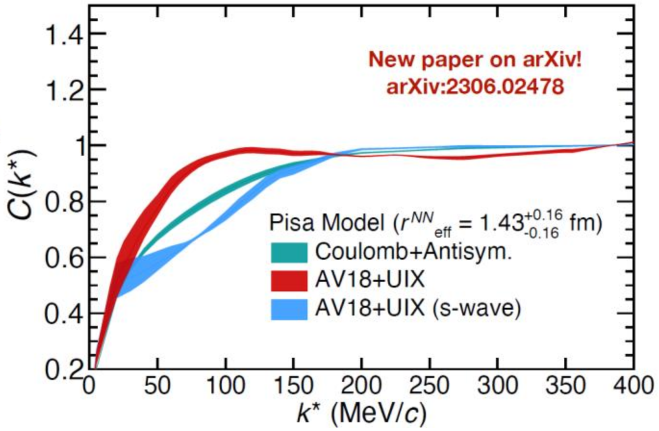

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R.B.Wiringa et al., PRC51(1995)38

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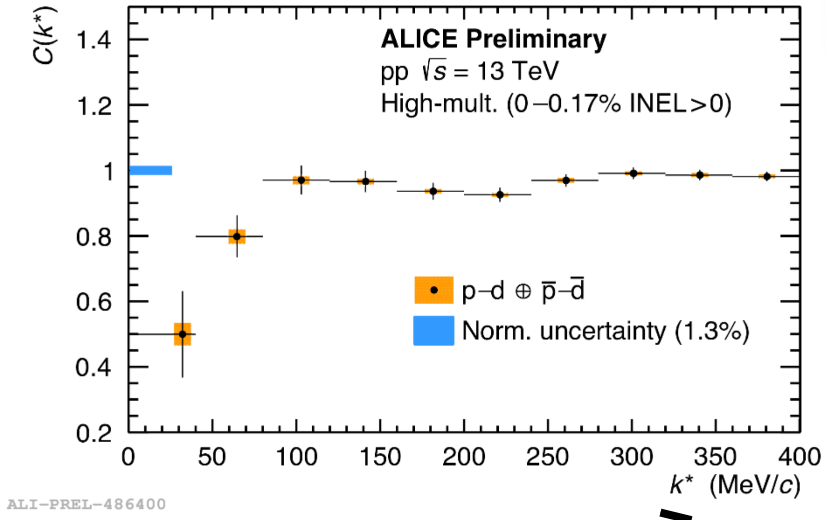

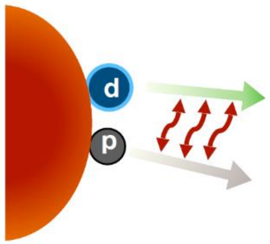

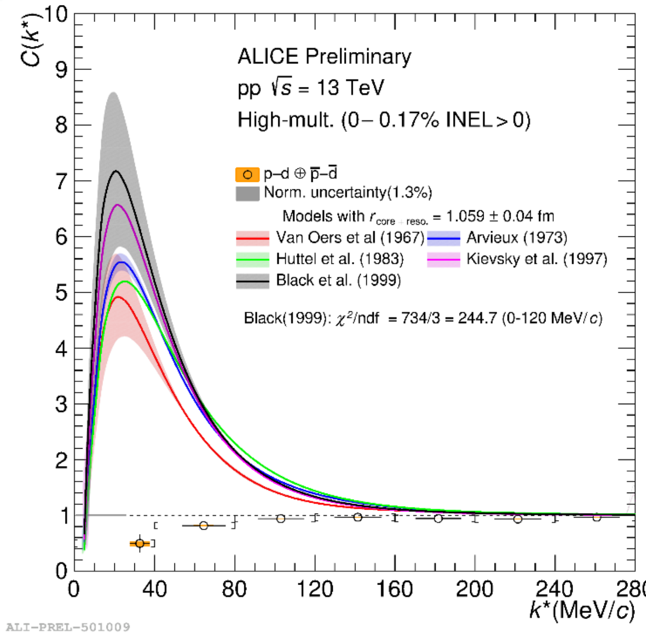

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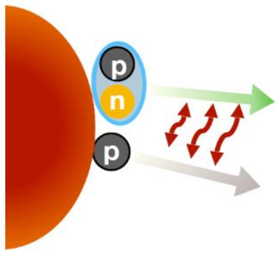

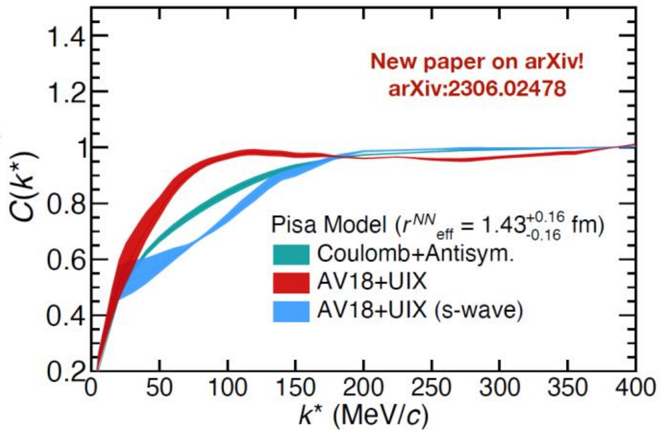

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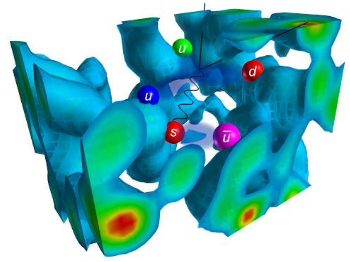
p-d system is sensitive to the three-body dynamics and also the three-body interaction!

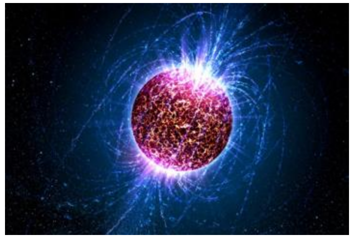
Summary

- Collective effects in medium created in high-energy collisions via
  - **$K^{\pm}K^{\pm}$ correlations** in p–Pb
- Coupled channel dynamics and resonances via
  - **Λ-K^{-}** in pp: nature of $\Xi(1620)$
- EoS, physics of NS and many-body forces via
  - **p-Λ and p-p-Λ** in pp: a great opportunity to further constrain chiral theory and get realistic EoS
  - **p-d** in pp: indirect measurements of three-body forces

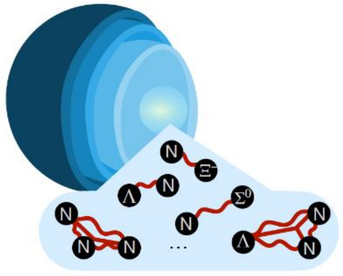
Hadron-hadron interactions

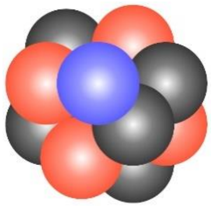


EoS of neutron stars



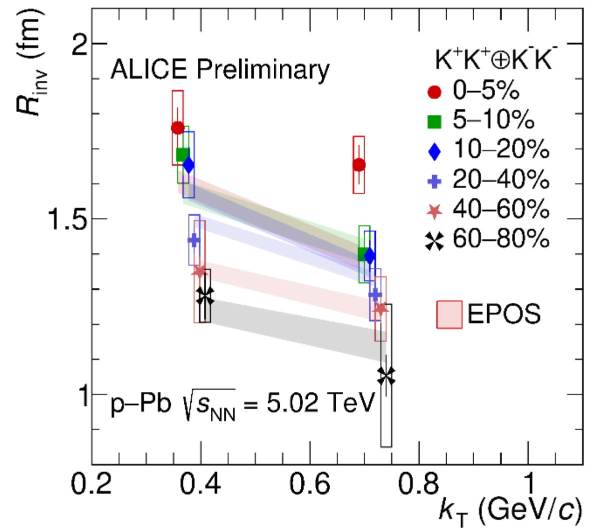
Properties of nuclei and hypernuclei



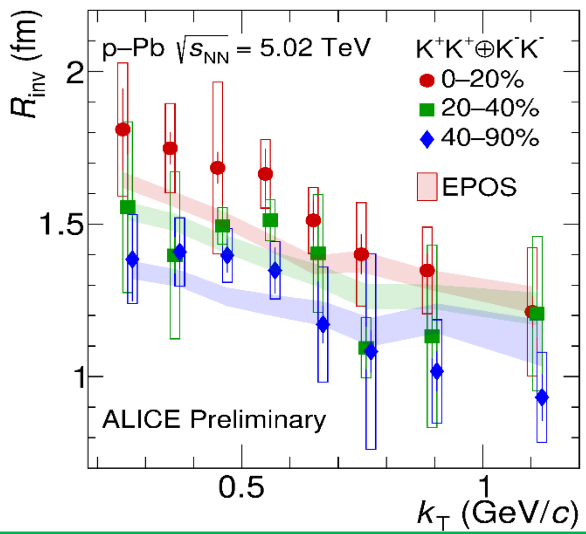


Thank you for your attention!

Backup: K±K± 1D analysis, experiment vs EPOS

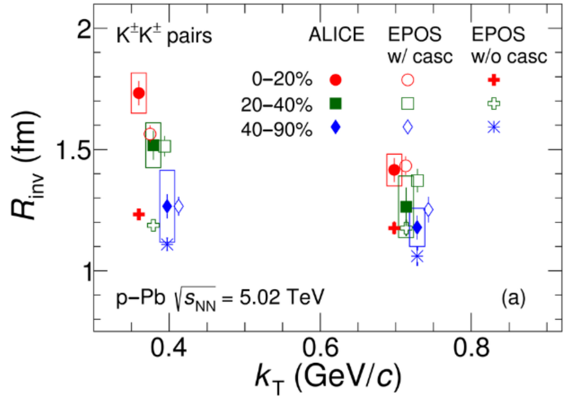


ALI-PREL-541070



ALI-PREL-541062

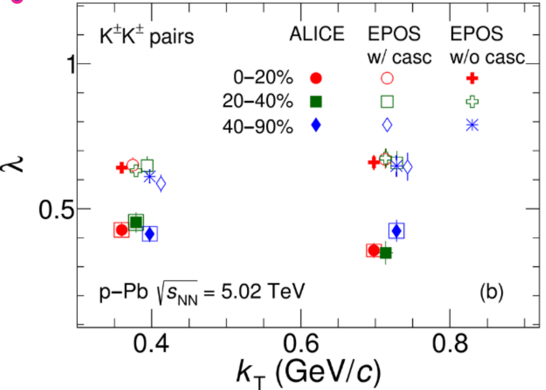
- R_{inv} decreases with k_{T} and for decreasing centrality → hydrodynamic expansion of matter created in p–Pb collisions
- EPOS with UrQMD cascade describes R_{inv}



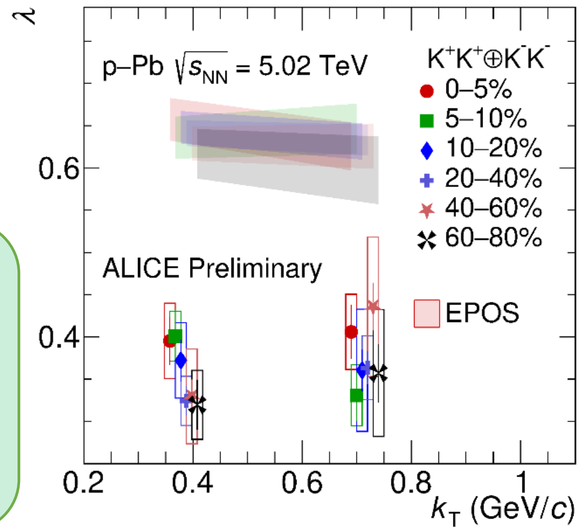
ALICE, PRC100(2019)024002

- EPOS does not describe R_{inv} for central collisions

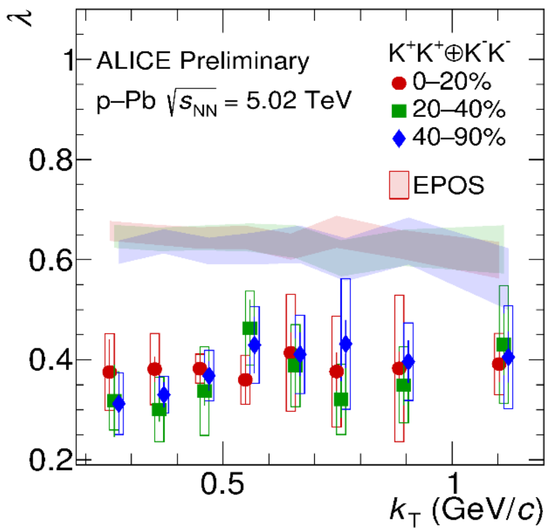
ALICE, PRC100(2019)024002



- λ does not change with multiplicity and k_{T}
- EPOS overestimates λ due to kaons from long-lived resonances like K*

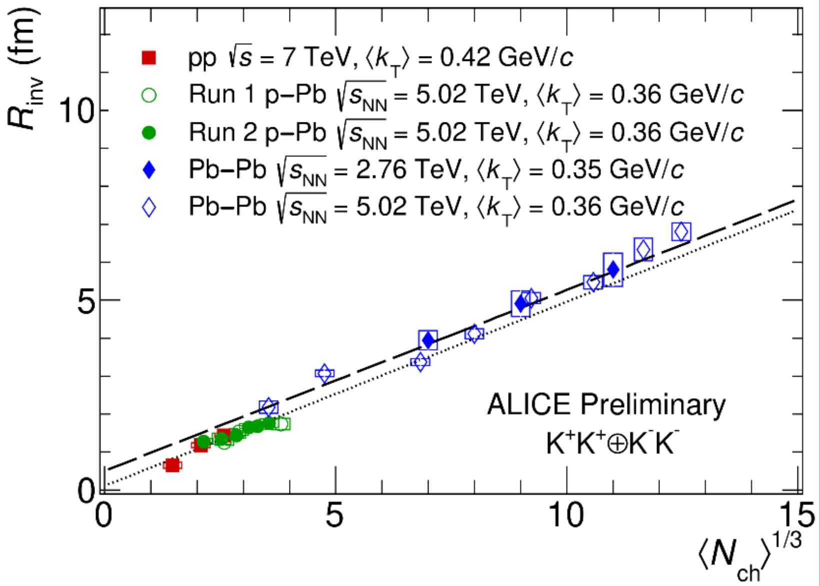


ALI-PREL-541074

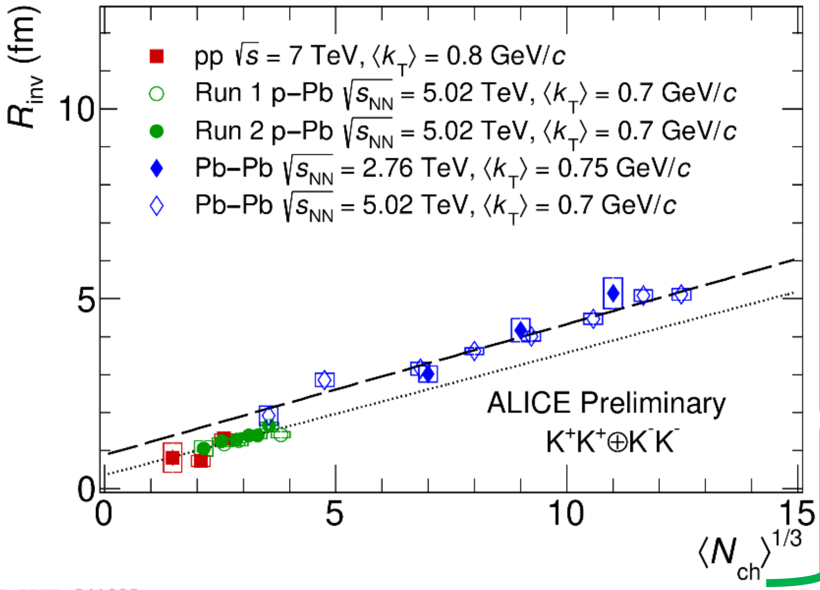


ALI-PREL-541066

Backup: K±K± 1D analysis, pp, p-Pb, Pb-Pb



ALI-PREL-541028



ALI-PREL-541025

ALICE, PLB739(2014)139

- at similar multiplicity,

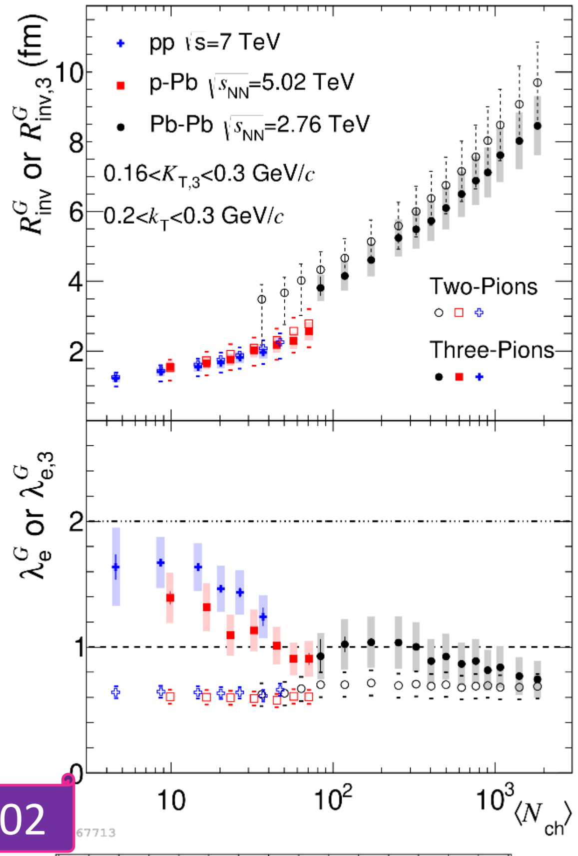
$\pi^{\pm}$: R_{inv}(p–Pb) is ~5-15% > R_{inv} (pp)

$K^{\pm}$: R_{inv}(pp) ≈ R_{inv}(p–Pb)

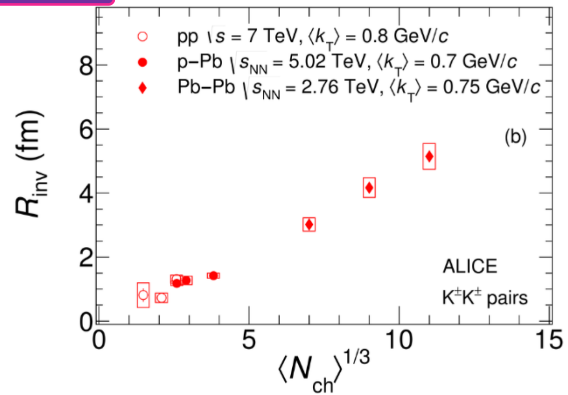
disfavors models which incorporate substantially stronger collective expansion in p–Pb as compared to pp collisions

- R_{inv}(Pb–Pb) is 35-55% > R_{inv}(p–Pb)

importance of different initial conditions or significant collective expansion even in peripheral Pb–Pb



ALICE, PRC100(2019)024002



- at similar multiplicity,

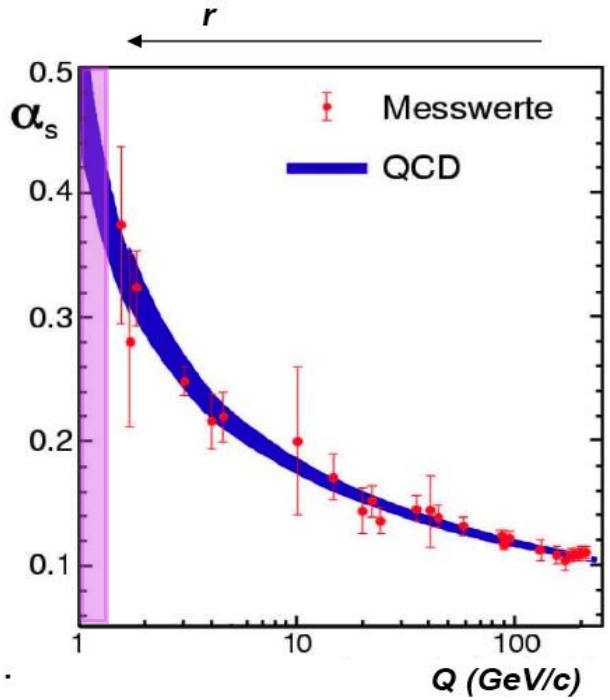
R_{inv}(p–Pb) ≈ R_{inv}(pp),

R_{inv}(Pb–Pb) > R_{inv}(p-Pb)

- R_{inv}(pp&p–Pb) are not on the same curve as R_{inv}(Pb–Pb), gap increases with increasing k_T

Backup: Strong interactions

Confinement

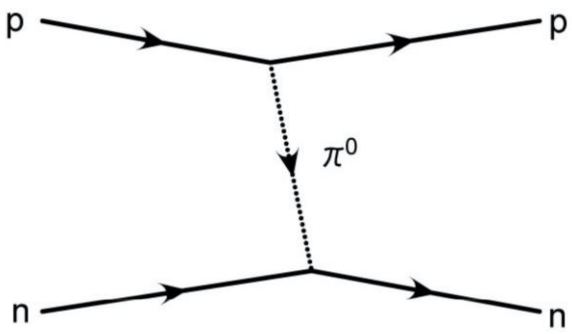


Asymptotic freedom

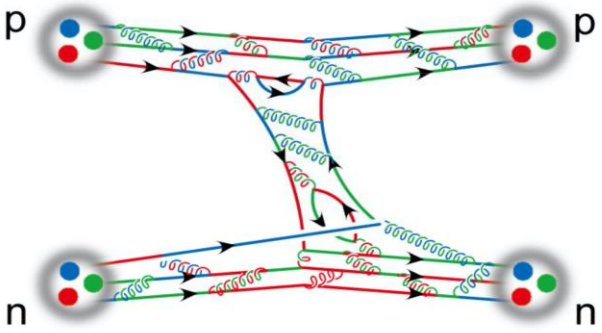
Running coupling constant defines the boundaries of low-energy QCD

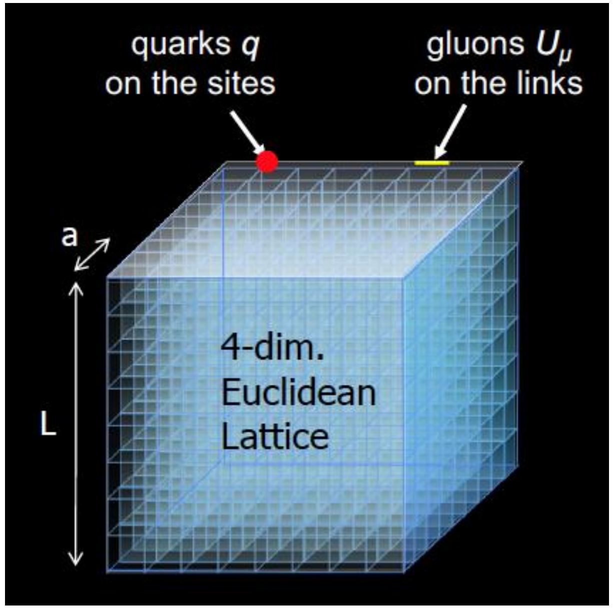
- Q ~1 GeV, R ~ 1 fm
- No perturbative methods are applicable

I. Effective theories with hadrons as degrees of freedom:

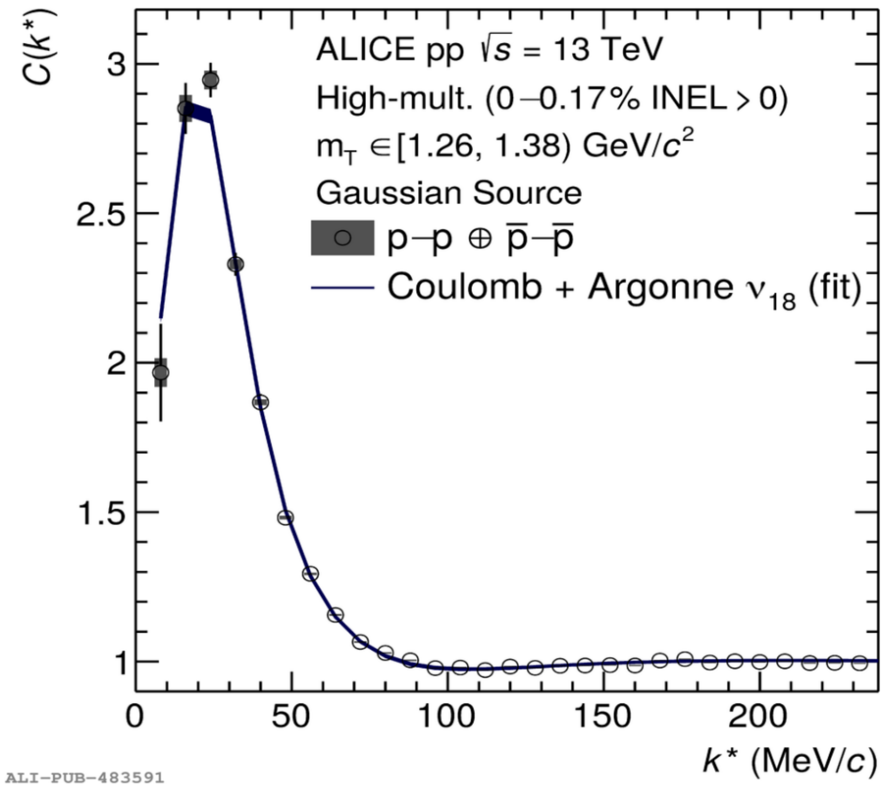


II. Lattice QCD - interaction starting from quarks and gluons:





Backup: Femtoscopy with small sources



ALICE, PLB811(2020)135849

Parametrize p-p and p-Λ r_{core} points

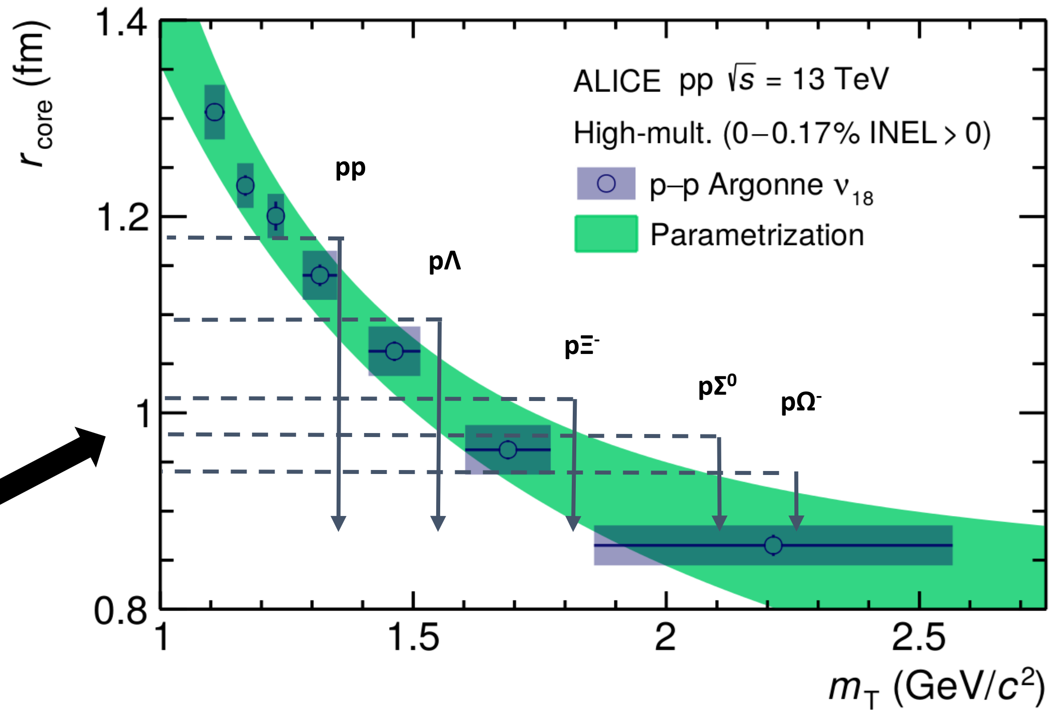
→ calculate r_{core} for any other baryon pairs (taking into account the resonance contribution!)

→ calculate source functions

→ calculate related correlation functions

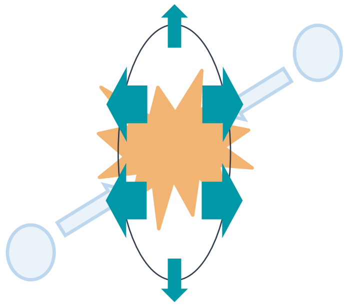
p-p correlation function as benchmark:

- Genuine p-p correlation function is calculated
- Source radius is extracted from *C* fit
- The same is done for p-Λ → r_{core}^{p-p} and $r_{core}^{p-\Lambda}$ scale with m_T when contributions of strongly decaying resonances are taken into account



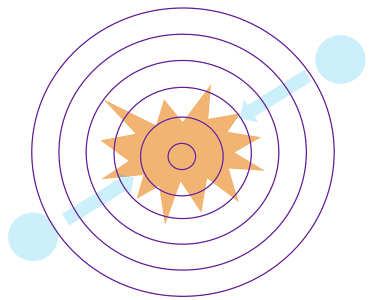
Backup: Femtoscopy with small sources

Elliptic flow



Anisotropic pressure gradients within the source

Radial flow



- Expanding source with constant velocity
- Different effect on different masses

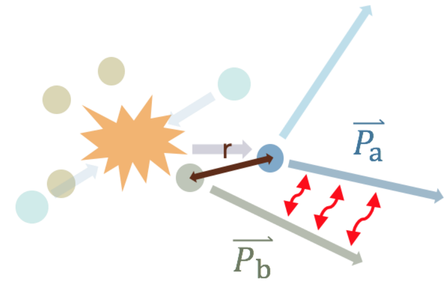
Position-momentum correlations

Measured emitting source sizes decrease with increasing $k_{\mathrm{T}} = |\vec{p}_{\mathrm{T}}^{\,a} + \vec{p}_{\mathrm{T}}^{\,b}|/2$ or $m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m^2}$, m – average mass of the particle pair

$\otimes$

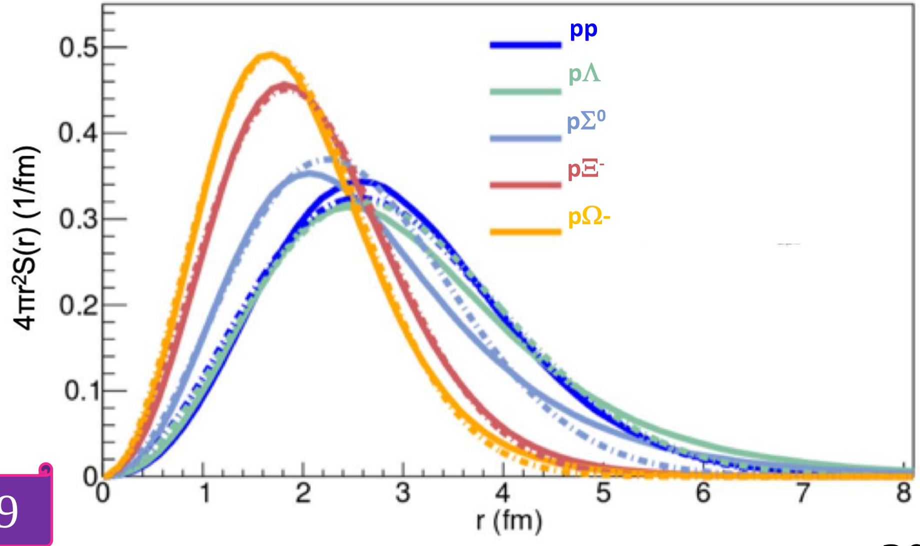
Strong decays of broad resonances

U.A.Wiedemann, U.W.Heinz, Phys.Rept.319(1999)145



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

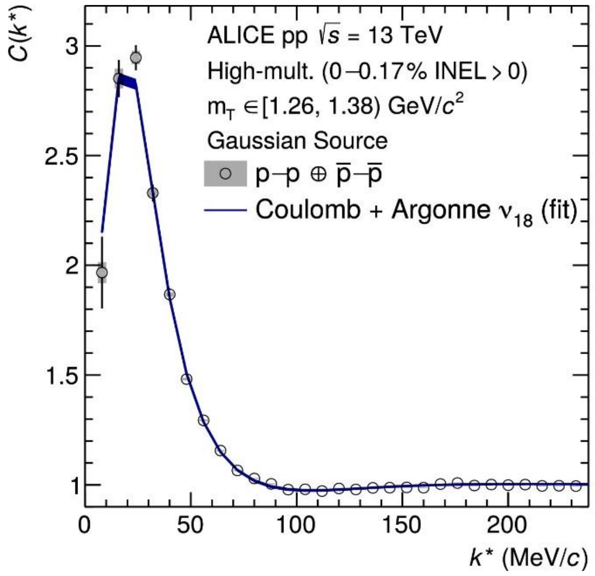
Effective source = Gaussian + Resonances:

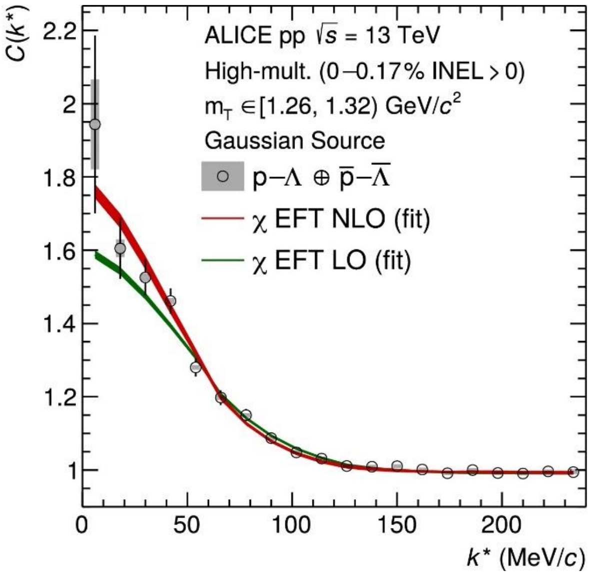


ALICE, PLB811(2020)135849

Backup: p-p and p-Λ interactions from pp at 13 TeV

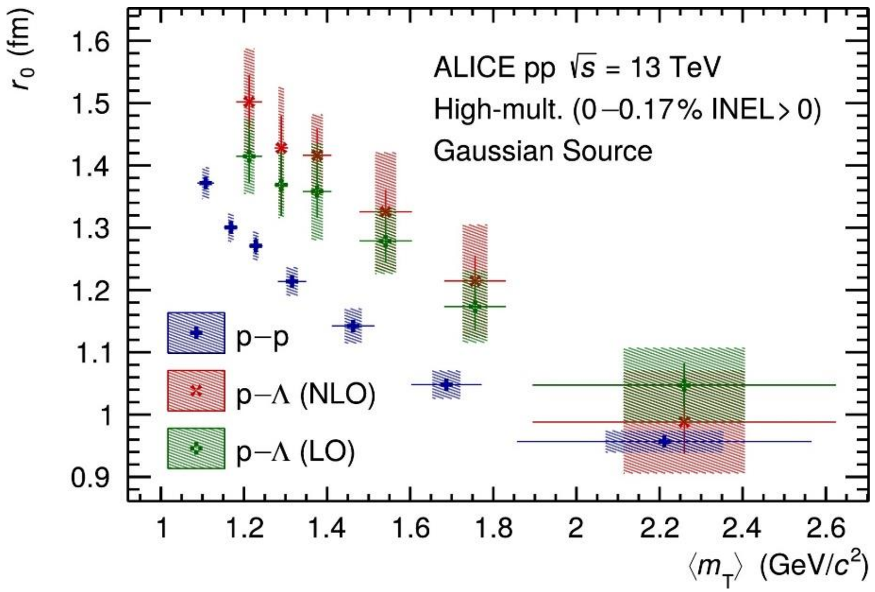
ALICE, PLB811(2020)135849





Protons and Λs originate from the same source

⇑



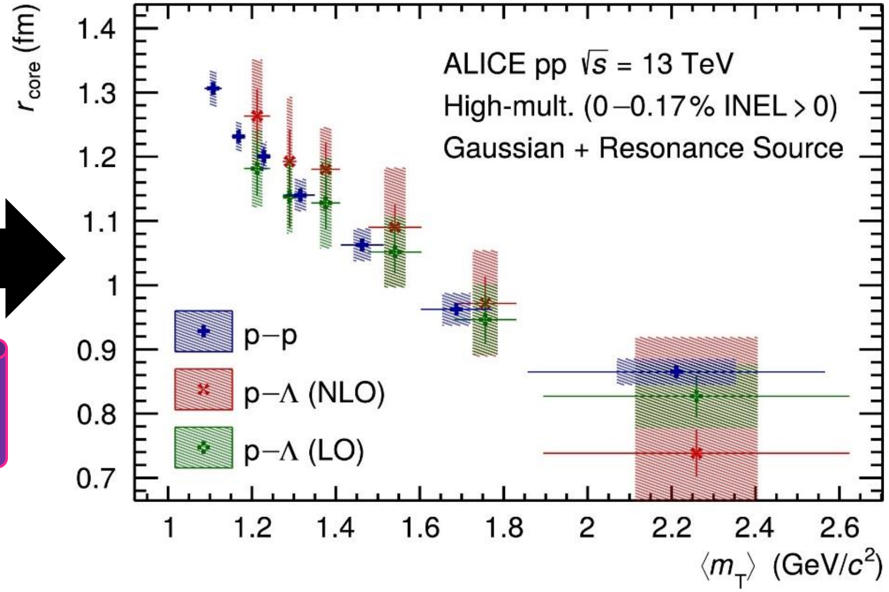
Effect of strong resonances

by Statistical Hadronization Model

F.Becattini et al., J.Phys.G38(2011)025002

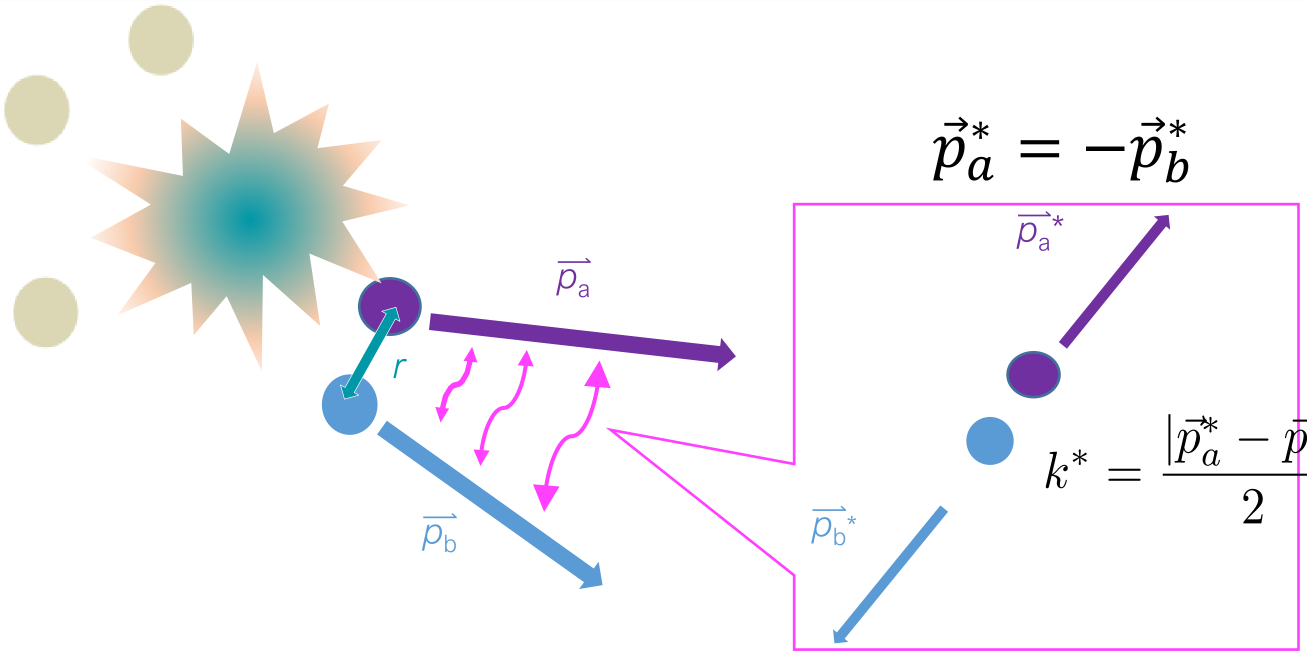
and EPOS

T.Pierog et al., PRC92(2015)034906



Backup: Reference frames

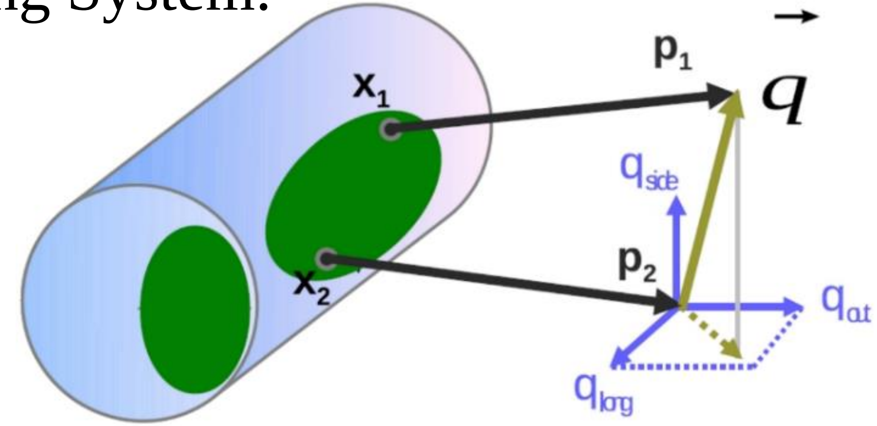
Pair Reference Frame:



$$\vec{p}_a^* = -\vec{p}_b^*$$

$$k^* = \frac{|\vec{p}_a^* - \vec{p}_b^*|}{2}$$ - pair relative momentum

Longitudinally Co-Moving System:



q_{long} ‖ beam direction

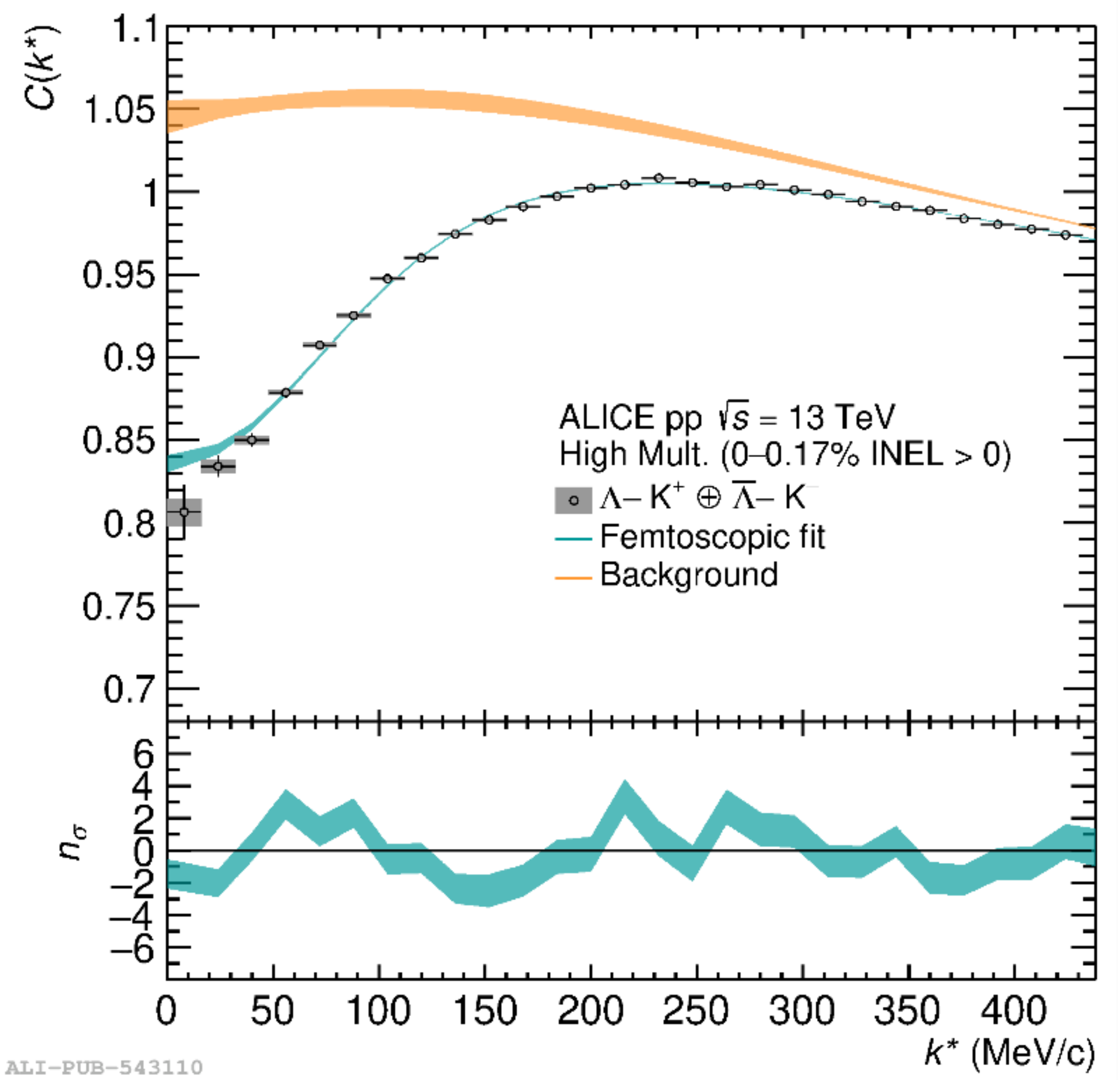
q_{out} ‖ transverse pair momentum k_T

$q_{side} \perp (q_{out}, q_{long})$

$(\vec{p}_1 + \vec{p}_2) \perp q_{long}$

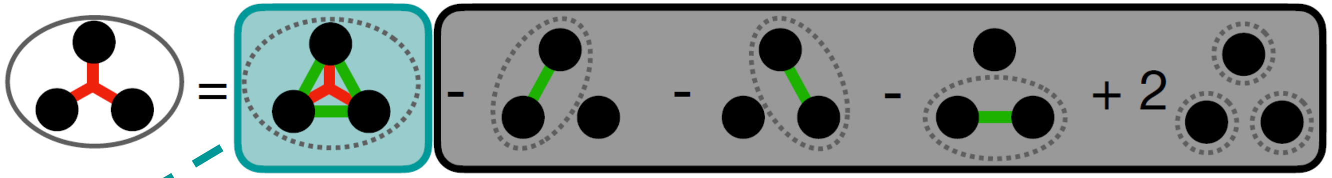
Backup: Λ-K^+ correlations

ALICE, arXiv:2305.19093

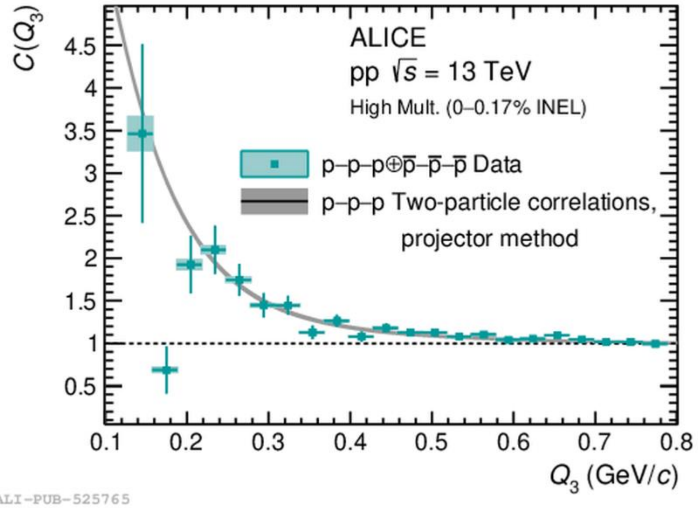


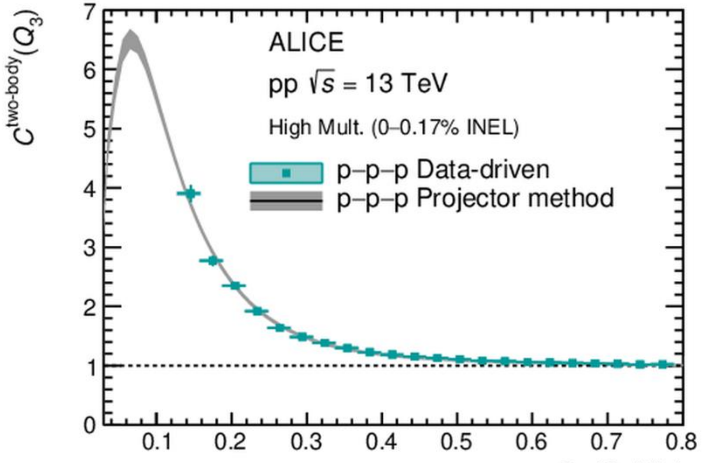
- Scattering parameters for ΛK^+ and ΛK^- (non-resonant) are in agreement with measurements performed by ALICE in Pb–Pb ALICE, PRC103(2021)055201
- Repulsive strong interaction is observed for Λ-K^+, attractive – for Λ-K^-

Backup: p-p-p and p-p-Λ lower-order contributions



Lower-order contributions under control!

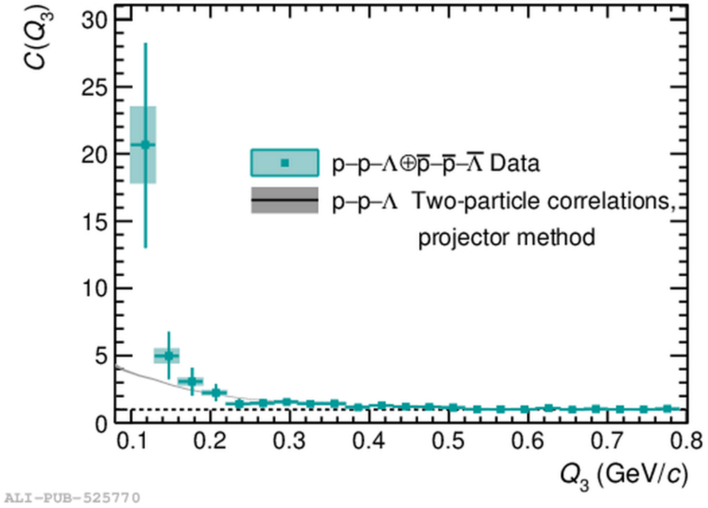


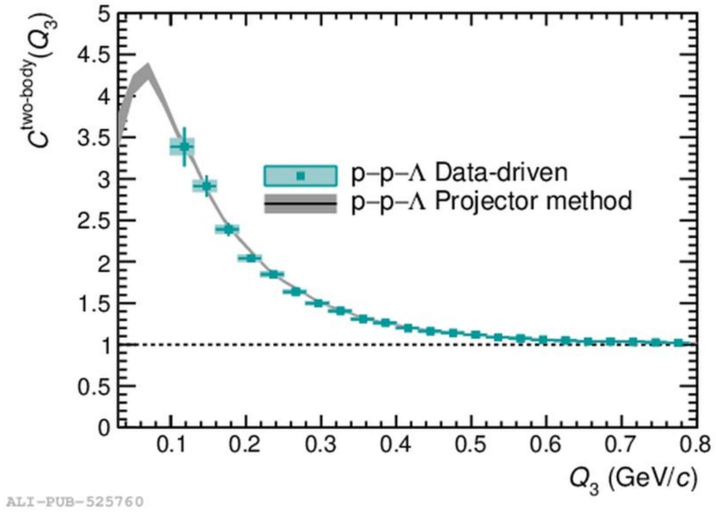


Two methods of calculation:

- *Data-driven method*: event mixing
- *Projector method*: project two-body correlation function on the three-particle phase space

Del Grande, Šerkšnytė et al., EPJC82(2022)244





ALICE, arXiv:2206.03344