TWENTY-SECOND LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

August, 21-27, 2025

MOSCOW STATE UNIVERSITY

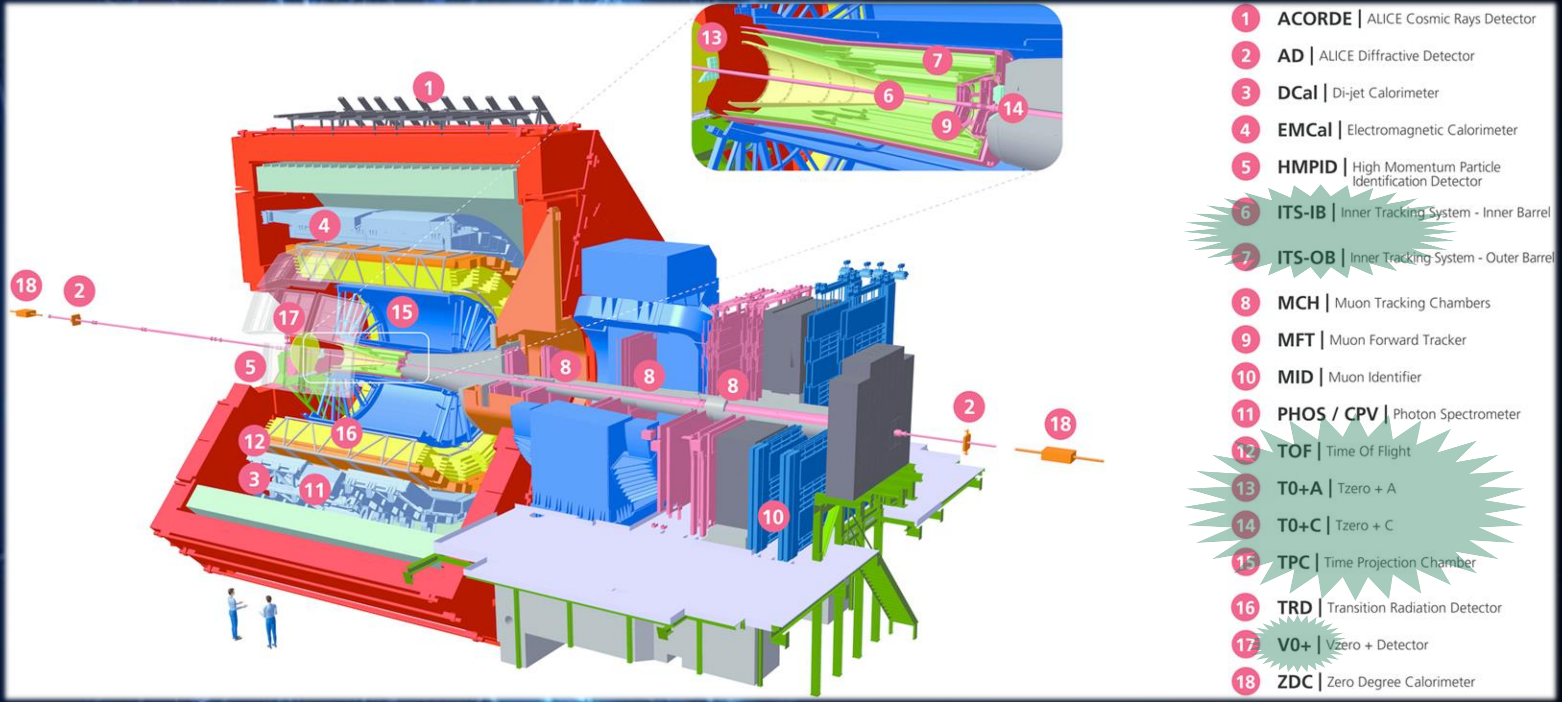
Femtoscopy with ALICE at the LHC

Elena Rogochaya
(JINR, Russia)
for the ALICE Collaboration

CERN

ALICE detector

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



- Abundant production of strange hadrons at the LHC.
- Good PID and momentum resolution: *good opportunity to study particle correlations in momentum space.*
- Direct detection of charged particles (p, K, π).

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

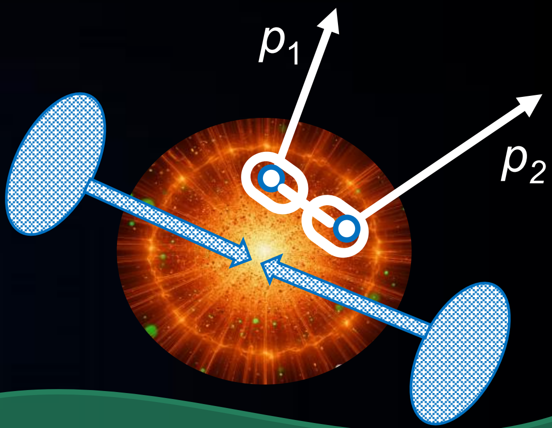
What femtoscopy can study?

I. Dynamics of medium created in high-energy collisions.

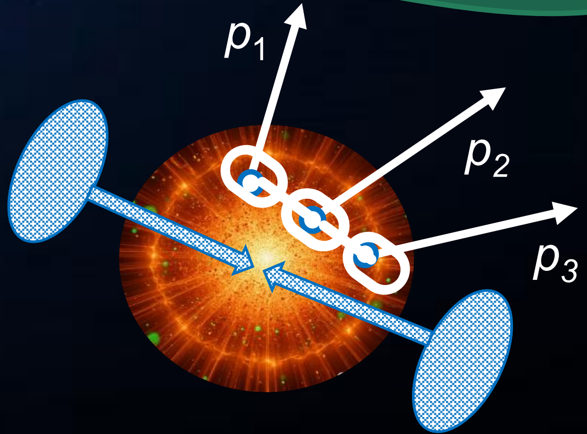
II. Hadronic interactions including multi-strange particles and resonances.

III. Exotic particles (including charm).

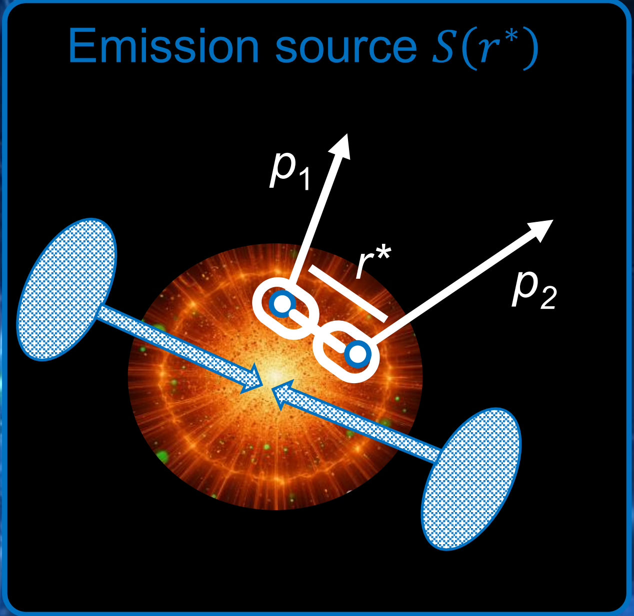
IV. 3-body interactions (e.g. in EoS of neutron stars).

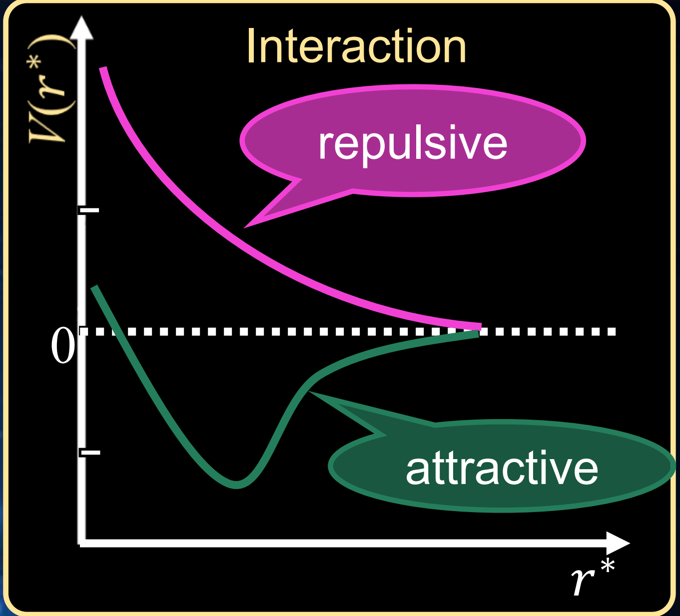


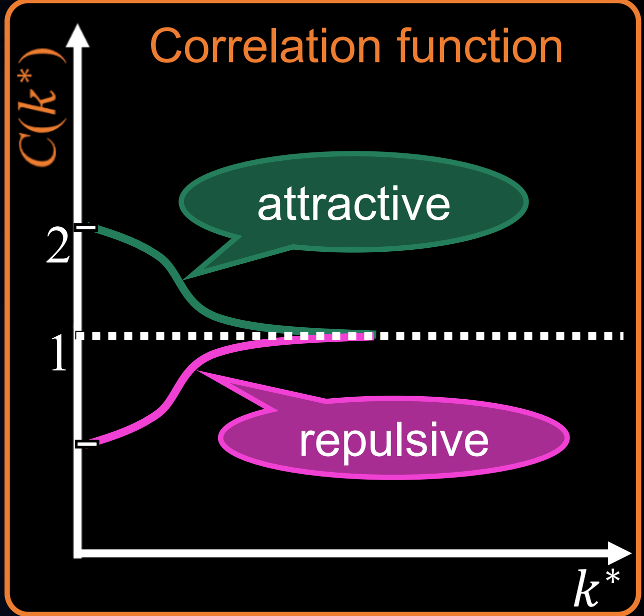
Correlation femtoscopy: measurement of space-time characteristics R, $c\tau$ ~fm=10^{-15} m of particle production source created in high-energy collisions using particle correlations due to the effects of quantum statistics and final-state interactions.



2-particle femtoscopy







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

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

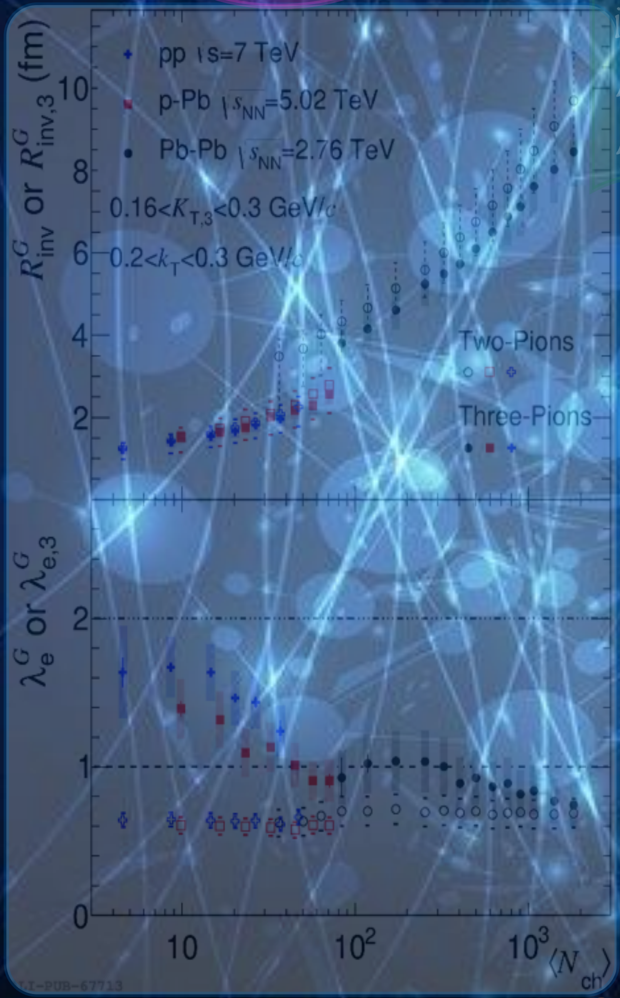
$N_{\mathrm{same}}(k^*)$ and $N_{\mathrm{mixed}}(k^*)$ – k^* distributions of hadron pairs from same and different collisions, respectively; $\mathcal{N}$ – normalization

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

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

I: 1D

π±π±

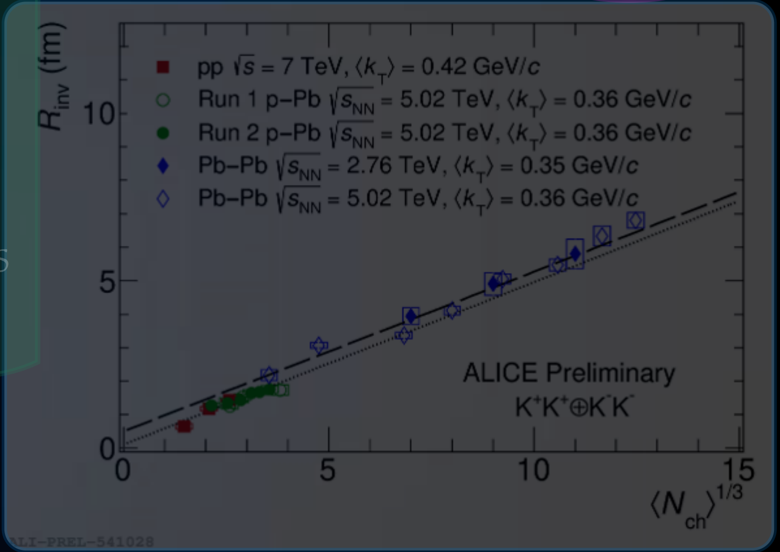


ALICE,PLB739(2014)139

At similar multiplicity, indication that $R_{\rm inv}$(pp)≈$R_{\rm inv}$(p–Pb) $R_{\rm inv}$(Pb–Pb)>$R_{\rm inv}$(p–Pb)

- At similar multiplicity, $R_{\rm inv}$(p–Pb) ≈ $R_{\rm inv}$(pp), $R_{\rm inv}$(Pb–Pb) > $R_{\rm inv}$(p–Pb)
- $R_{\rm inv}$(pp&p–Pb) do not lie on the same curve as $R_{\rm inv}$(Pb–Pb), gap increases with increasing k_T

K±K±

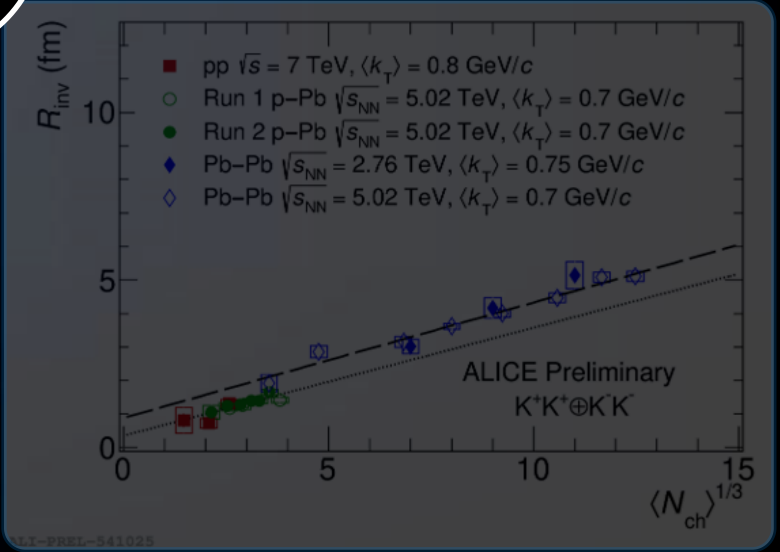


Bowler–Sinyukov fit:

$$C(q_{\rm inv}) = 1 + \lambda e^{-R_{\rm inv}^2 q_{\rm inv}^2}$$

$R_{\rm inv}$ – source size in *PRF* (**slide 19** in Backup),

λ – correlation strength



- Models incorporating substantially stronger collective expansion in p–Pb as compared to pp collisions disfavored.
- Importance of different initial conditions.
- Significant collective expansion even in peripheral Pb–Pb.

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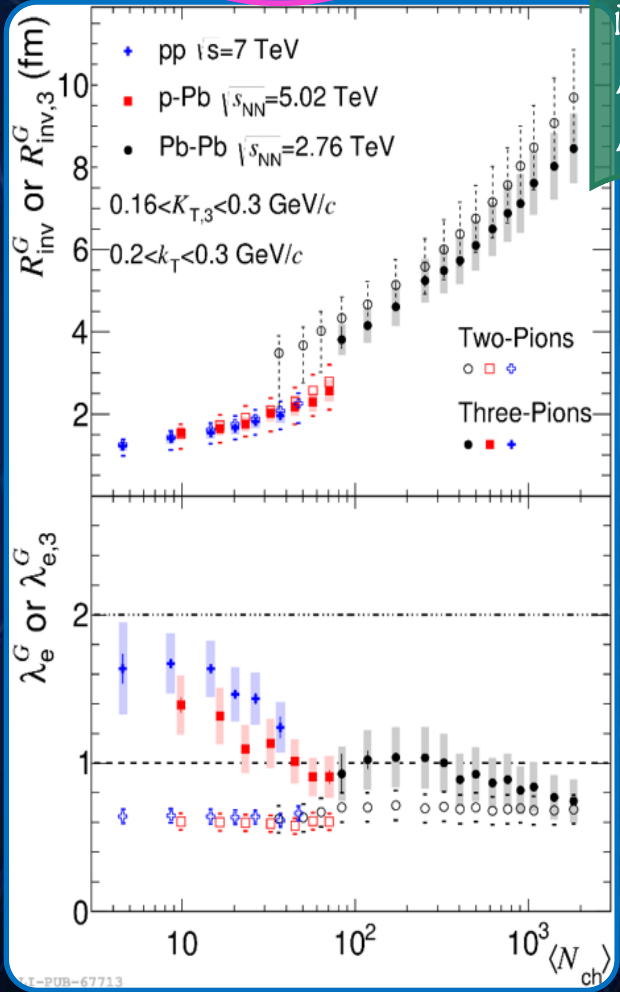

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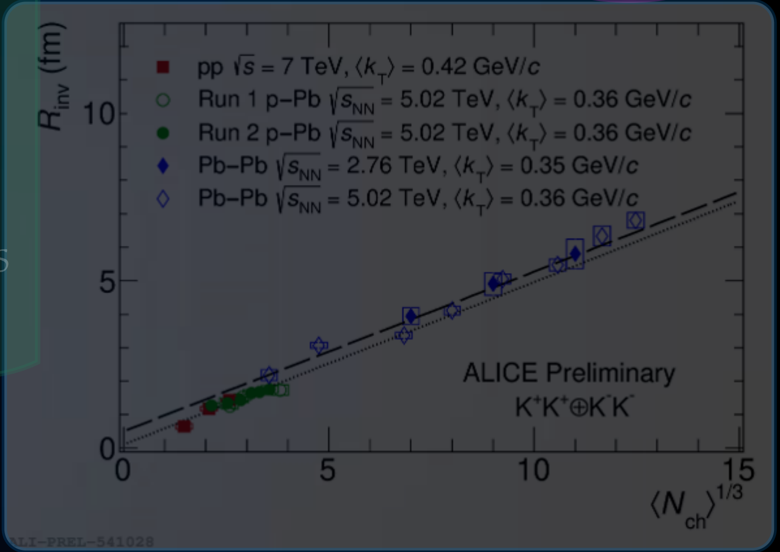
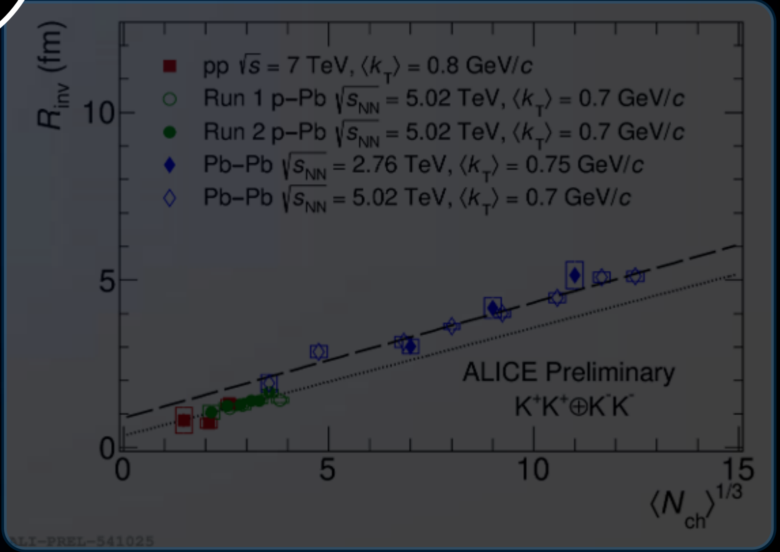
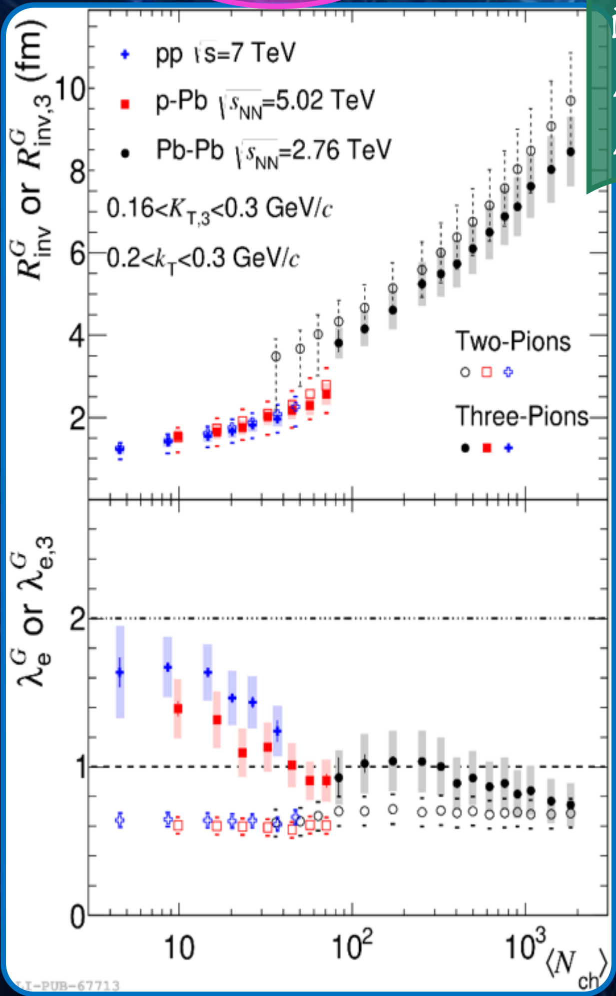




I: 1D

$\pi^{\pm}\pi^{\pm}$



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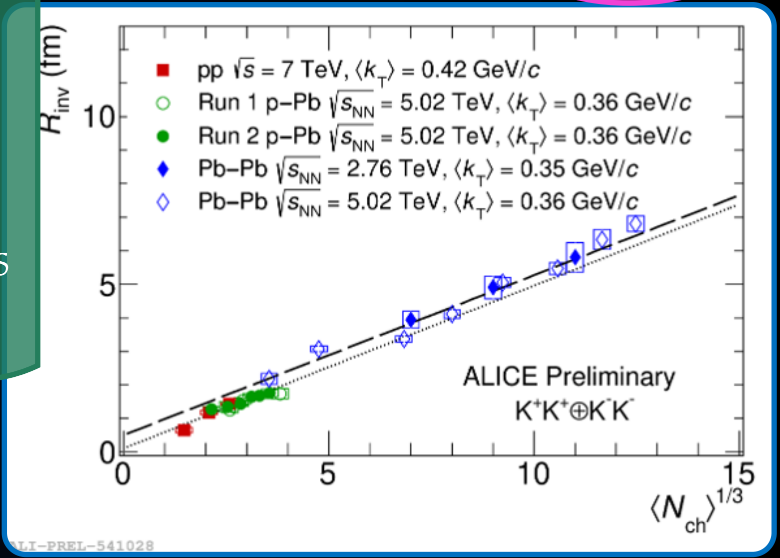

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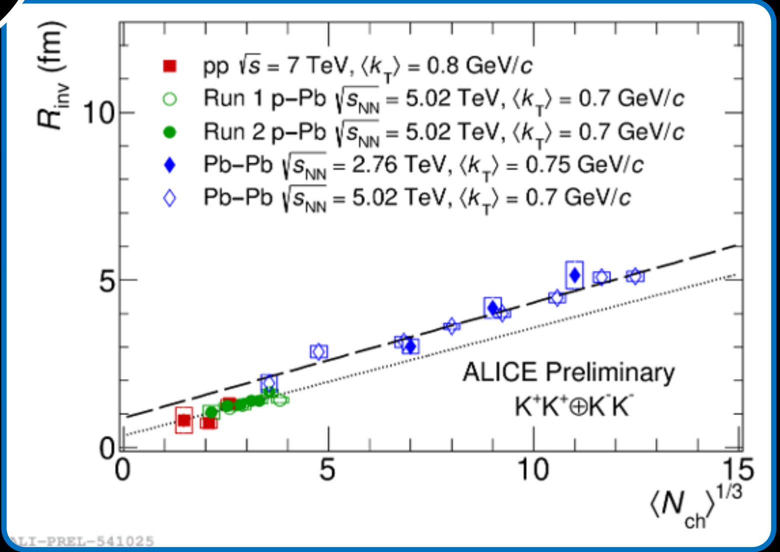

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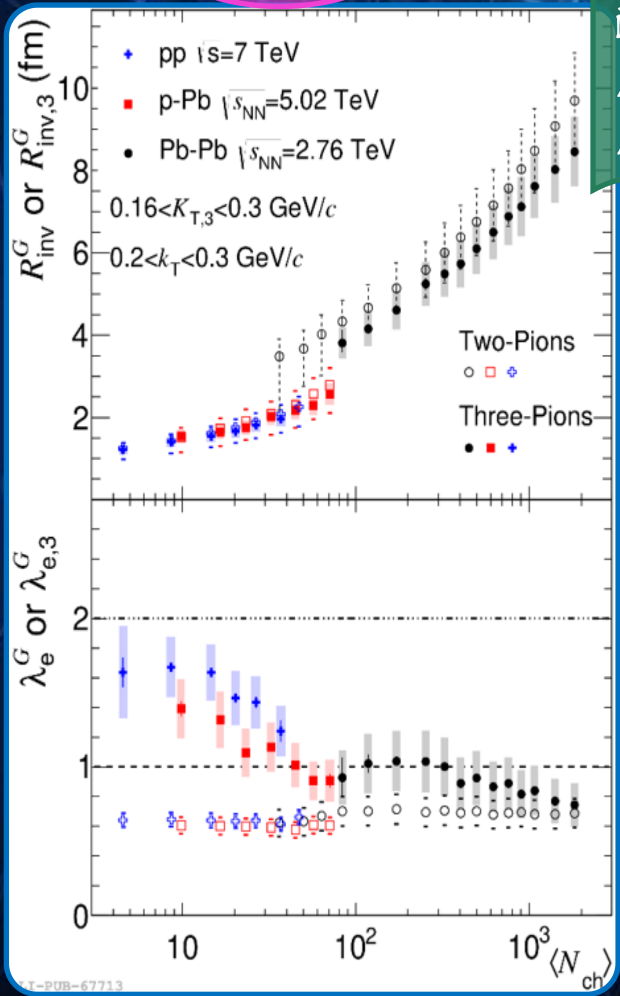

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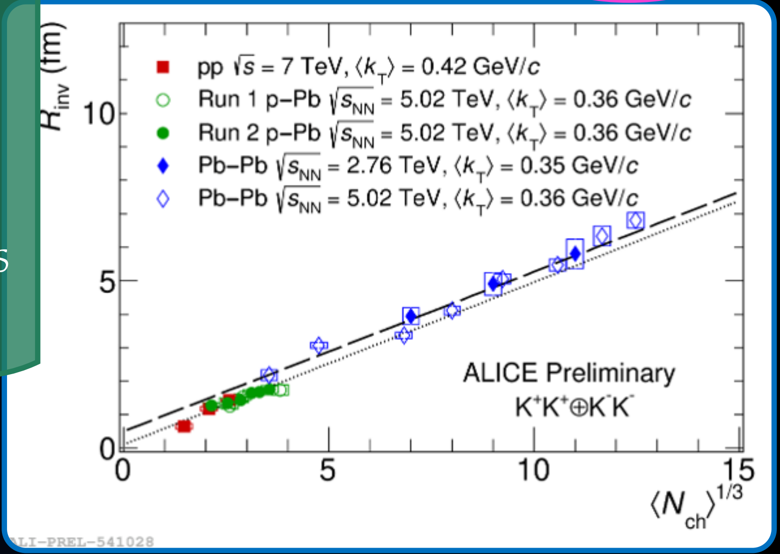

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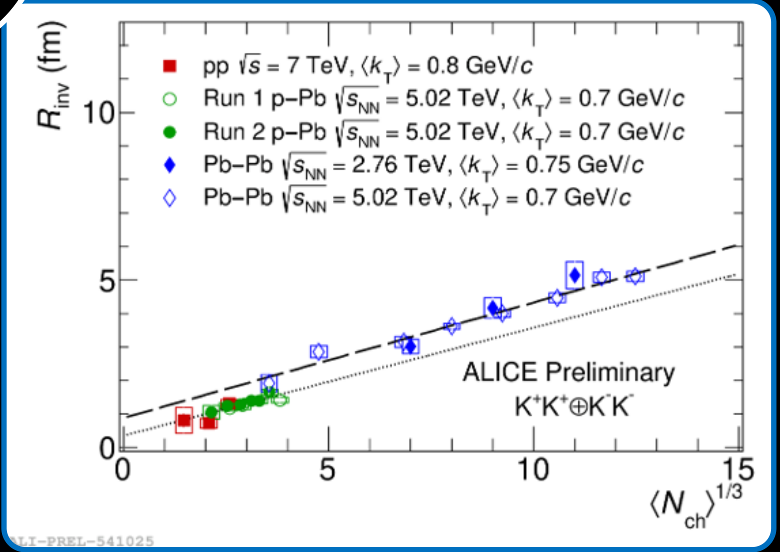
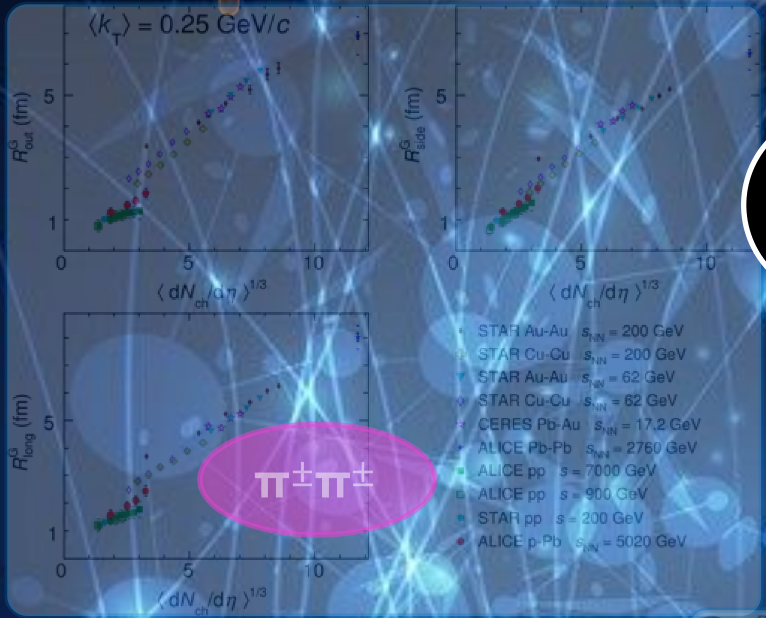


I: 3D

ALICE, PRC91(2015)034906

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

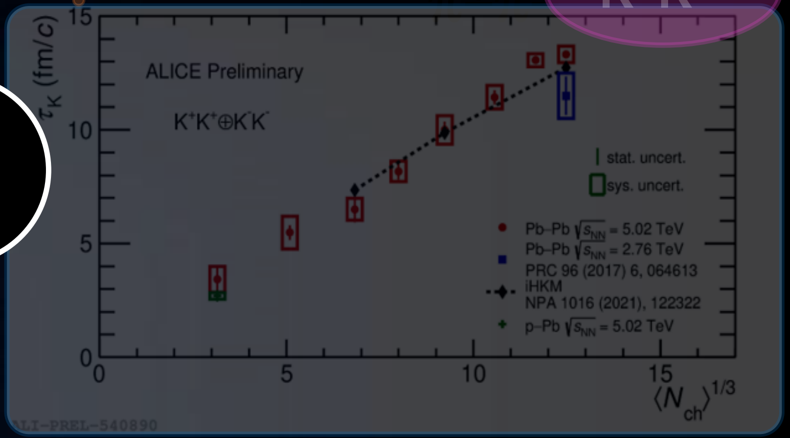


Bowler–Sinyukov fit:

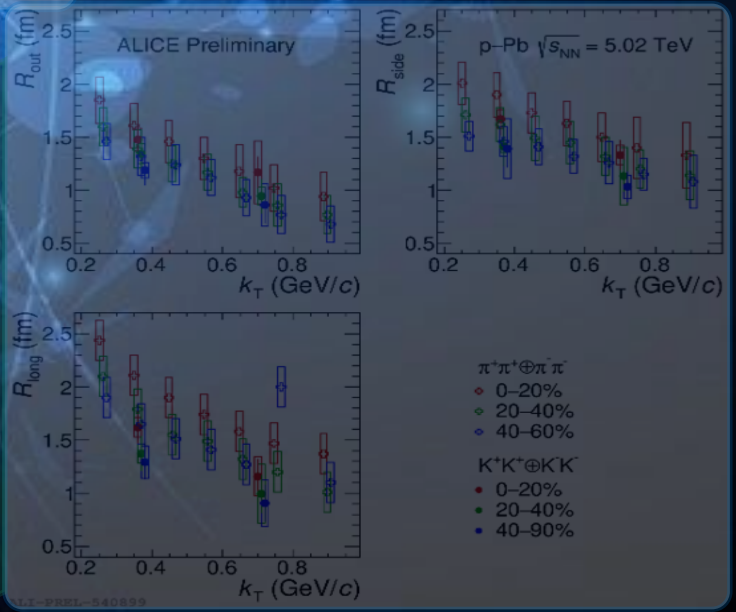
$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda e^{-R^2_{out}q^2_{out} - R^2_{side}q^2_{side} - R^2_{long}q^2_{long}}$$

R_{out}, R_{side}, R_{long} – source size in *LCMS*

(**slide 19** in Backup)



τ_K - lifetime of the expanding fireball associated with the moment when the number of correlated particles emitted from the source is maximal.



- At similar multiplicities, R for π±π± and K±K± agree within uncertainties

π and K productions evolve similarly after collision

- Available data are not enough to say whether k_T or m_T scaling occurs in p–Pb.

- τ_K decreases for more peripheral collisions

larger sources emit kaons slower

- τ_K for p–Pb ≈ τ_K for the most peripheral Pb–Pb (70–90% centrality interval) at 5.02 TeV

K production evolves similarly in p–Pb and peripheral Pb–Pb

- More data are needed to see the trend of τ_K with multiplicity in p–Pb.

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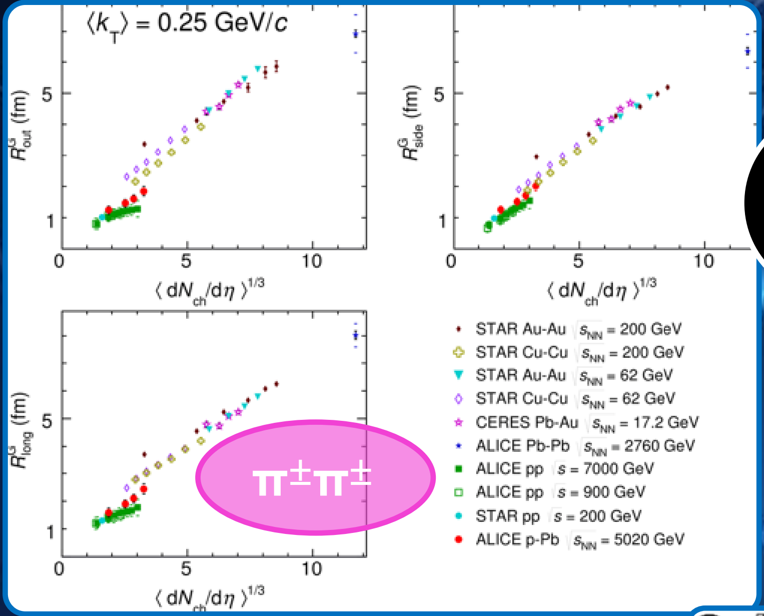

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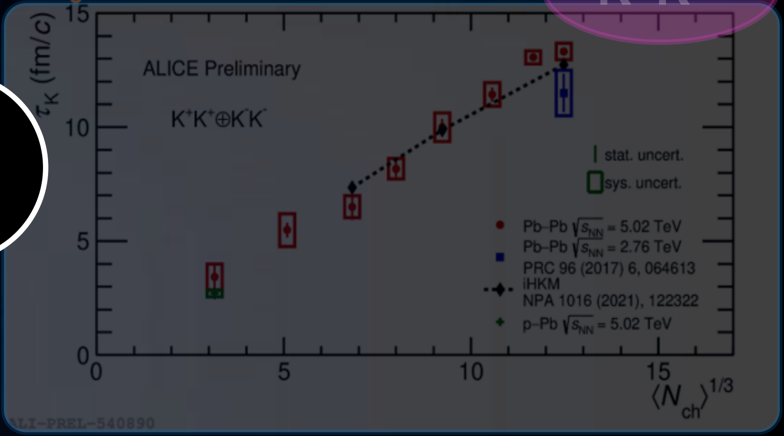

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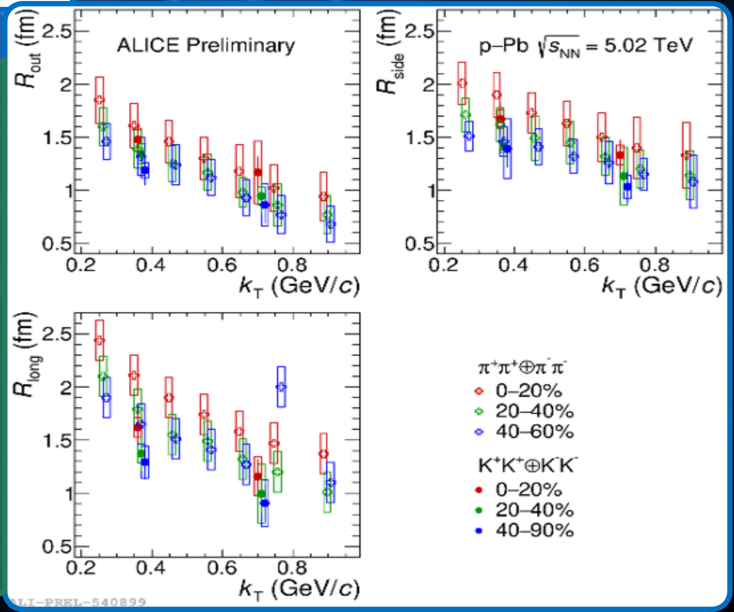

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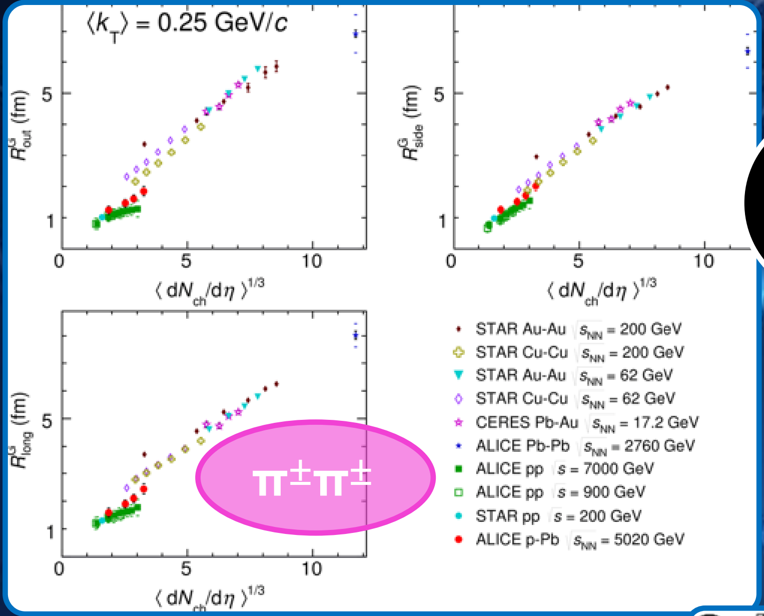

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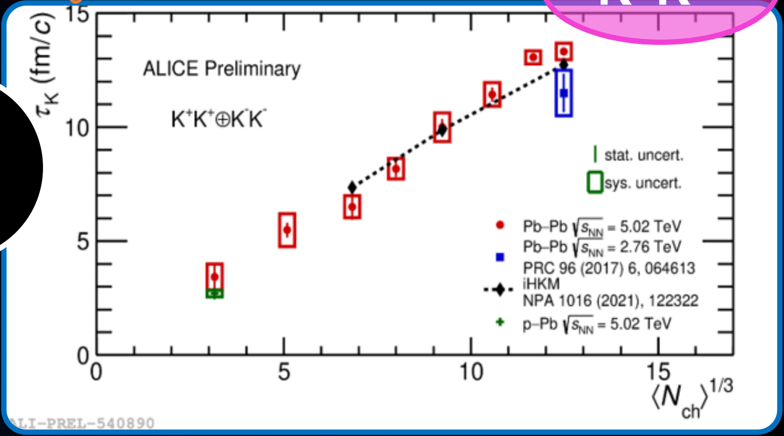

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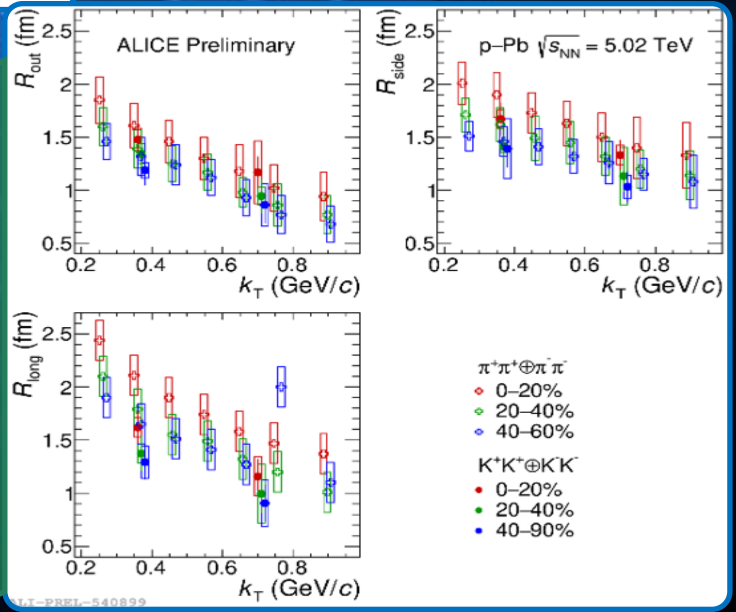

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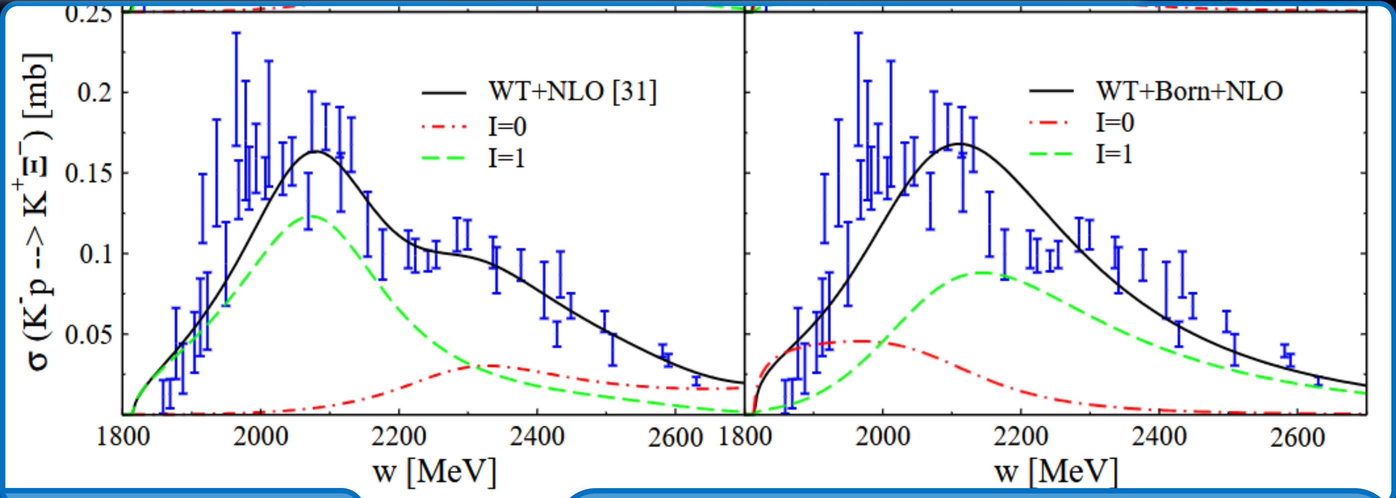
II: S=-1 sector ⇝ K⁻p



1. *AntiKaonic hydrogen*

SIDDHARTA,PLB704(2011)113

$\bar{K}$N system at threshold is a sensitive testing ground for low-energy QCD, especially for the explicit chiral symmetry breaking.

2. *Scattering experiments*

M.Mai,Eur.Phys.J.Spec.Top. 230(2021)1593

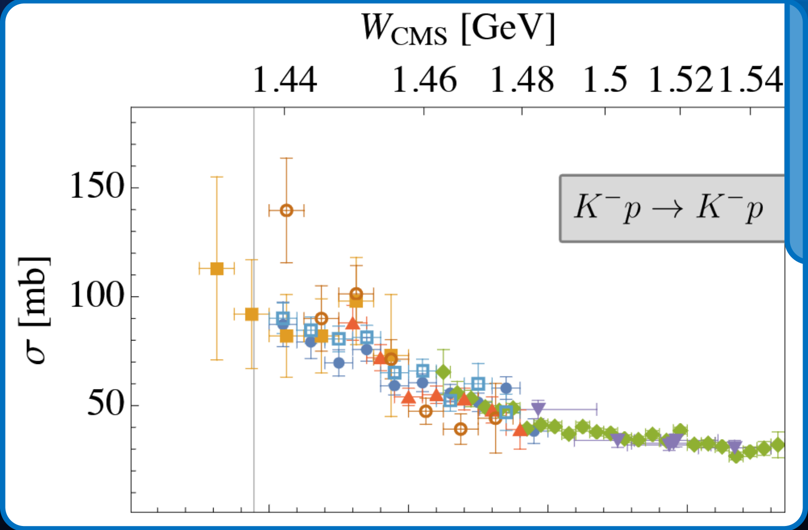
formation of Λ(1405) below $\bar{K}$N threshold

3. $\bar{K}N \rightarrow K^{+}\Xi^{-}$

A.Feijoo et al., PRC99(2019)035211

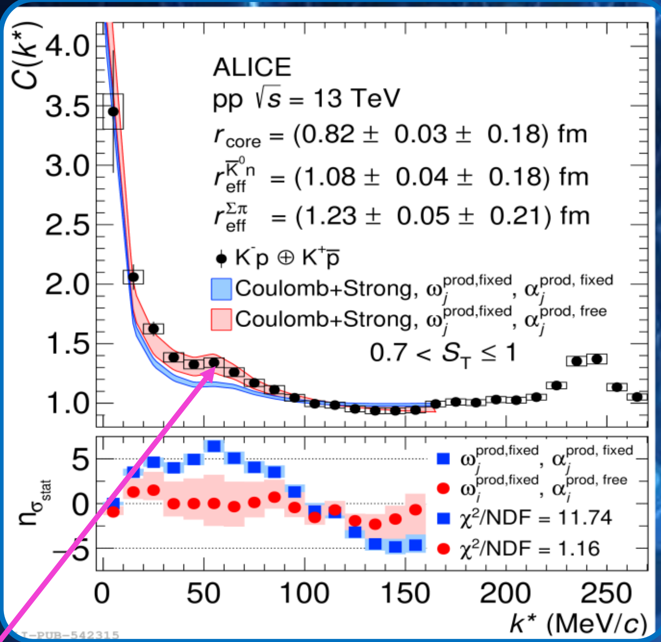
Chiral SU(3) EFT:

- fixing of the NLO constants
- incorporating channels sensitive to the I=1 component

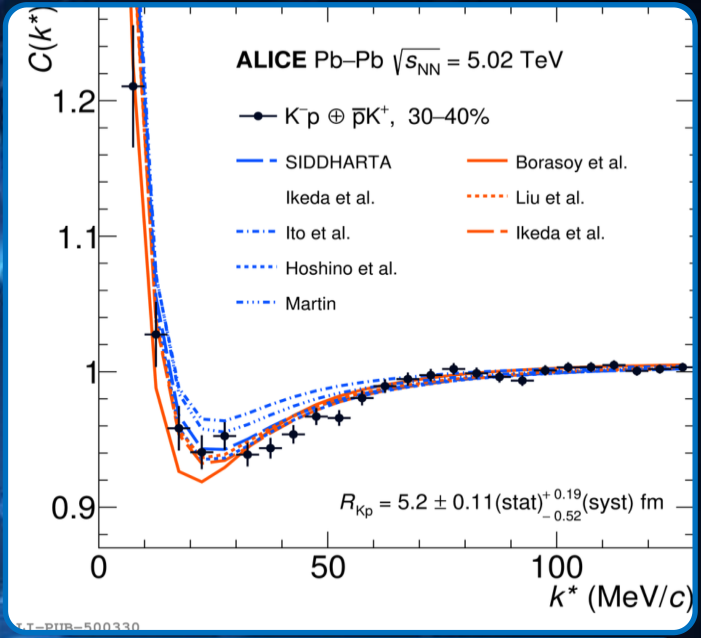


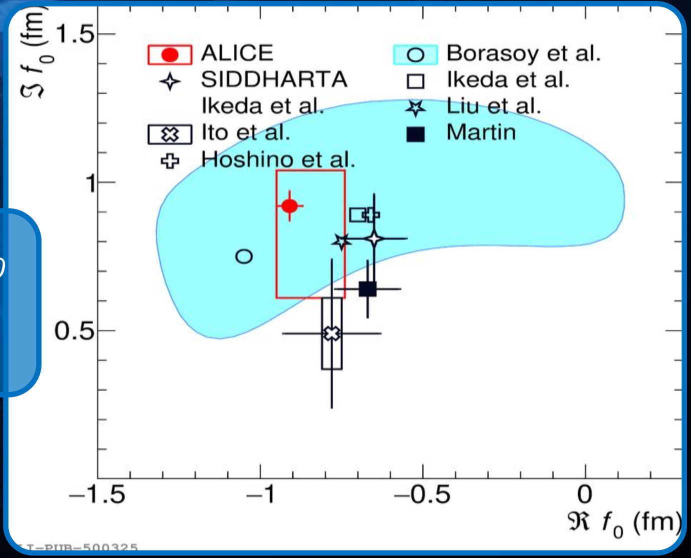
4. Femtoscopy delivers high-precision data close to threshold and on several inelastic channels.

II: S=–1 sector ⇝ K^-p



Model does not reproduce the strength of the $\bar{K}^0 n$ channel.





Scattering parameters $\Re f_0$ and $\Im f_0$ in Pb–Pb are compatible with AntiKaonic-hydrogen.

More on S=–1 on **slide 22** in Backup!

Femtoscopy delivers:

- The most precise data above K^-–p threshold.
- Crucial input for low-energy chiral effective potentials.
- Quantitative test of coupled channels.
- Determination of the scattering parameters.

Data:

- ***pp:*** ALICE,PRL124(2020)092301
- ***pp, p–Pb, Pb–Pb:*** ALICE,EPJC83(2023)340
- ***Pb–Pb:*** ALICE,PLB822(2021)136708

Strong interaction: Kyoto model

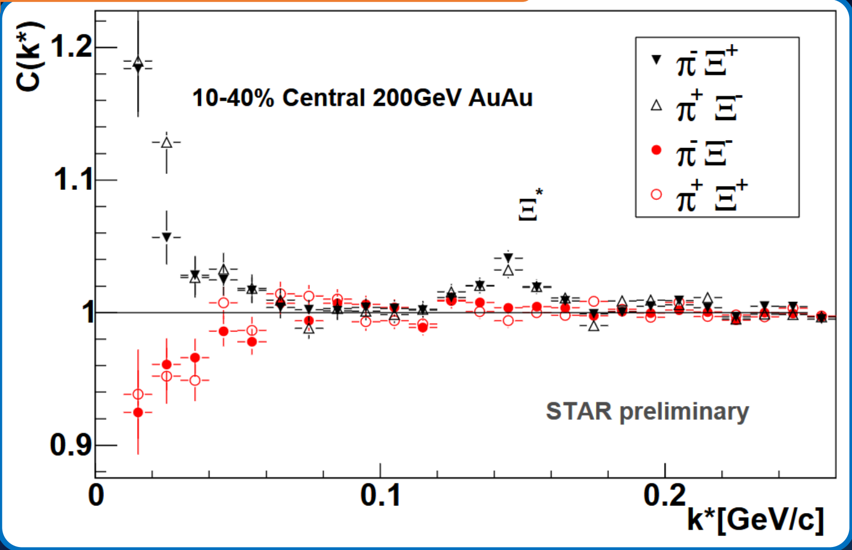
K.Miyahara et al., PRC98(2018)2,025201

Fit to the scattering parameters:

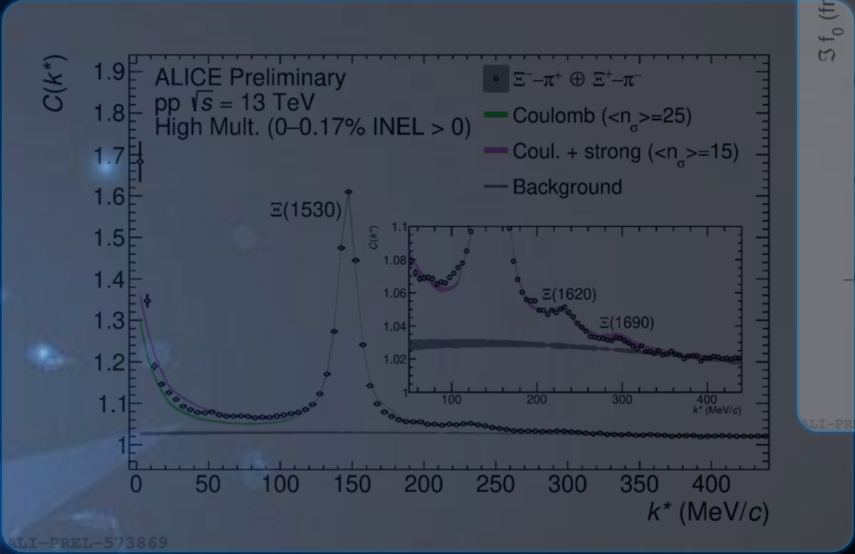
R.Lednický, Phys.Atom.Nucl.67(2004)72

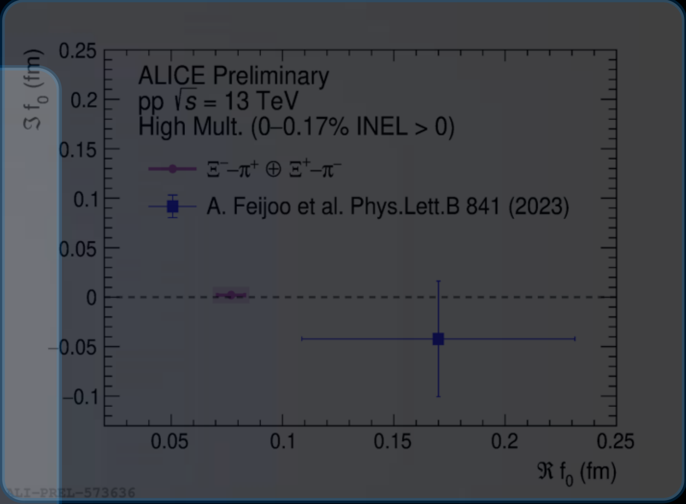
II: S=–2 sector ⇝ $\Xi^-\pi^+$

STAR,NPA774(2006)603



Enhancement in the low k^* region described by Coulomb FSI.





- Ξ(1620) and Ξ(1690) modeled with a Breit–Wigner distribution

masses and widths compatible with previous spectroscopic measurements

- Model:

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

- Rather shallow attractive interaction.
- NLO chiral potentials constrained to S=-1 data are compatible with ALICE results.

More on S=–2 on **slide 23** in Backup!

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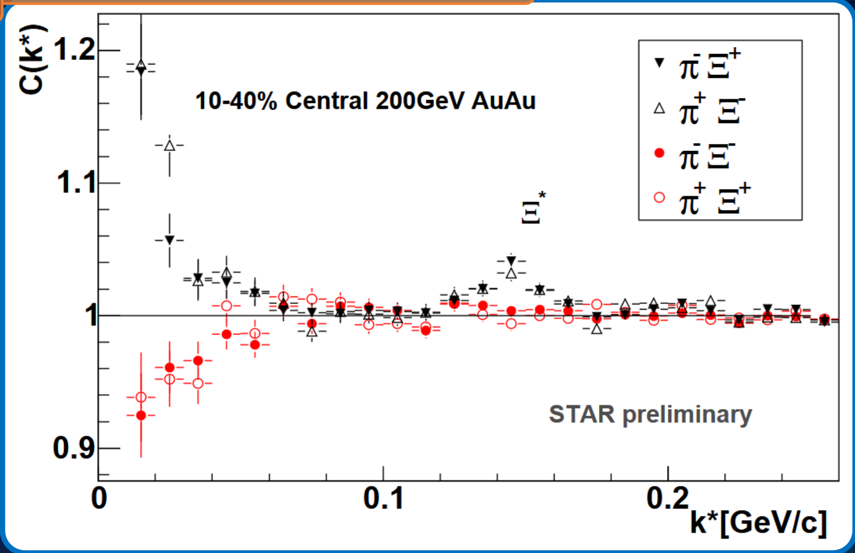
STAR,NPA774(2006)603



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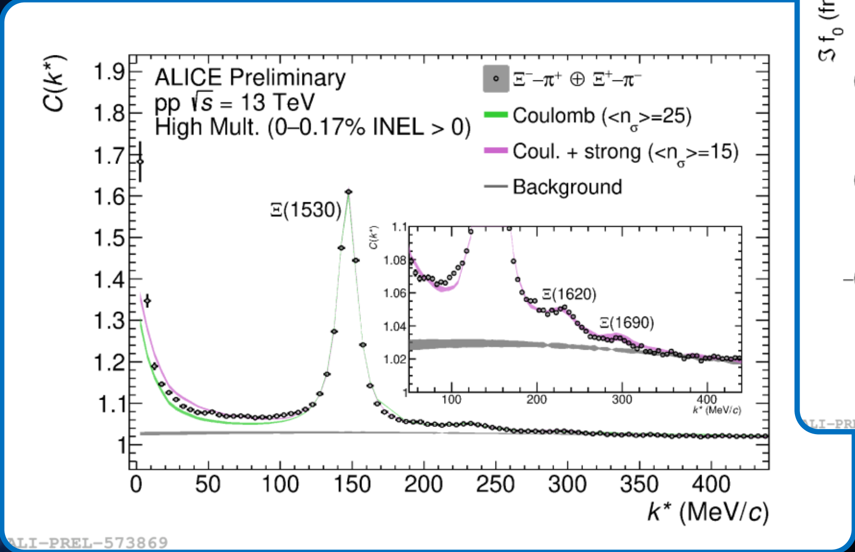

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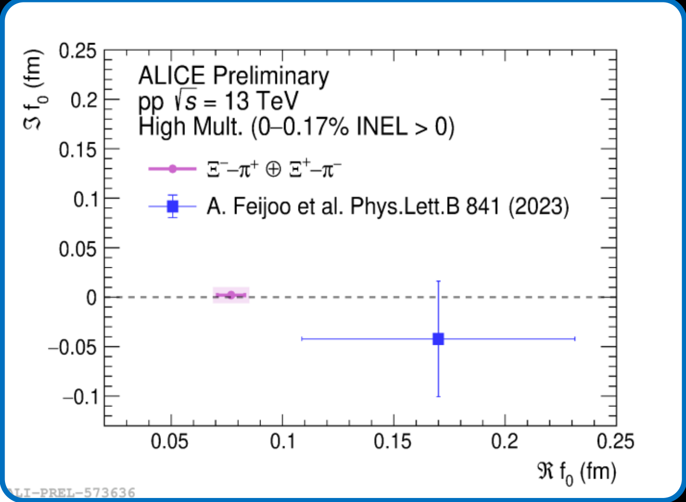

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II: Vector meson–nucleon interaction ⇝ $\rho^0 p$

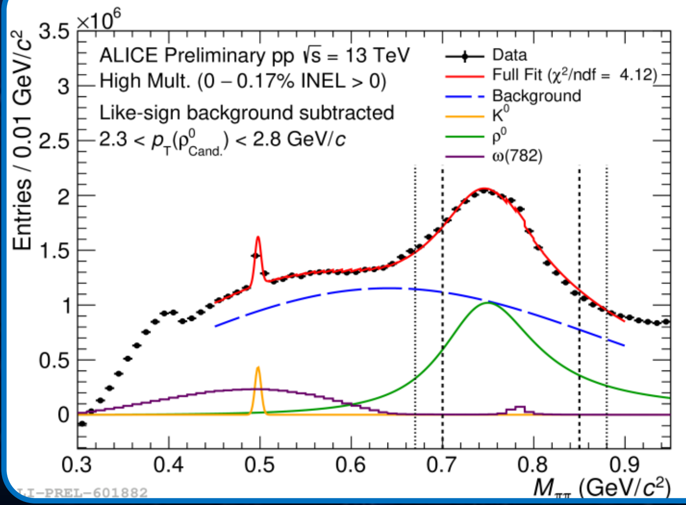
Usually probed by vector meson dominance models (VMD): J.J.Sakurai,PRL22(1969)981

- hadronic contribution to the photon propagator
- off-shell vector mesons

Femtoscopy helps test of:

- in-medium dilepton production
- dynamically generated states N* and Δ* (pole positions) from unitarized chiral perturbation theory UChPT:

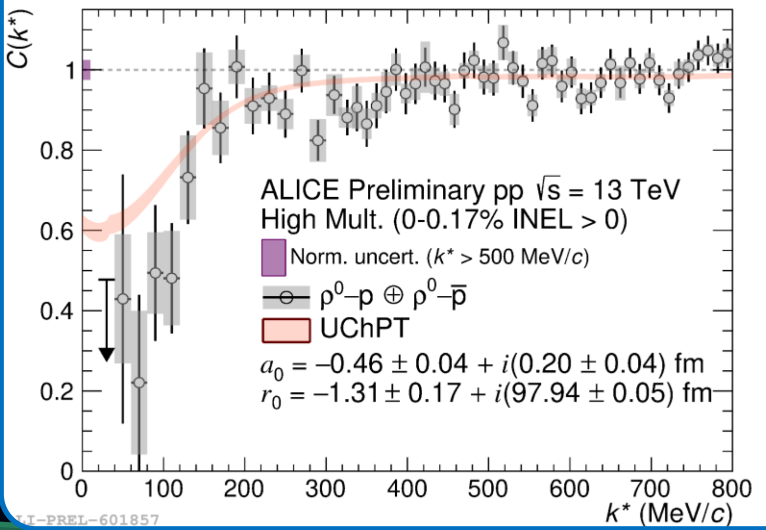
N.Kaiser,P.B.Siegel,W.Weise, PLB362(1995)23



- ρ_0 identified using invariant mass spectrum analysis of $\pi^+\pi^-$.
- Correlated background removed by subtraction of the like-sign invariant mass spectrum.
- Purity of ρ_0 is 3.26±0.03%.

Fit using UChPT: A.Feijoo,M.Korwieser,L.Fabbietti, PRD111(2025)1,014009

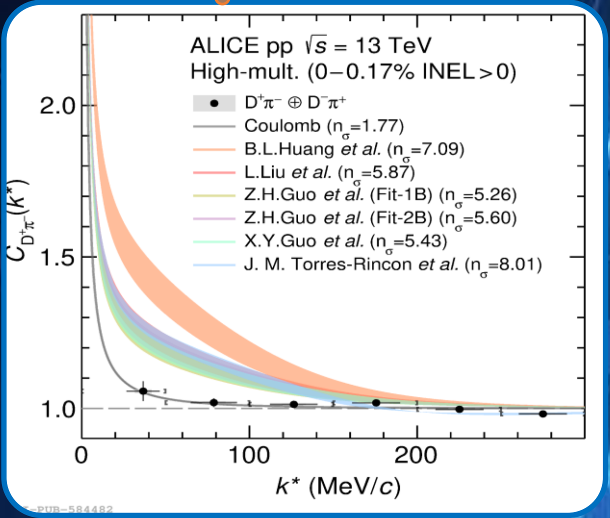
- Coupled-channel ($\rho^+ n$, ωp, ϕp, $K^*\Lambda$, $K^*\Sigma$) framework
- Simultaneous fit to ϕ–p correlation ALICE,PRL127(2021)172301
- Including width of ρ_0

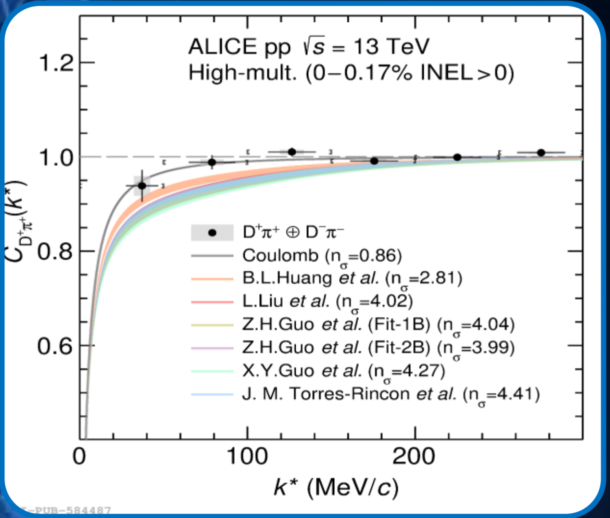


- First direct measurement of ρ^0N coupling. *Far above low-lying resonance states traditionally used.*
- Test of VMD models.

III: Dπ & DK interactions

ALICE,PRD110(2024)032004

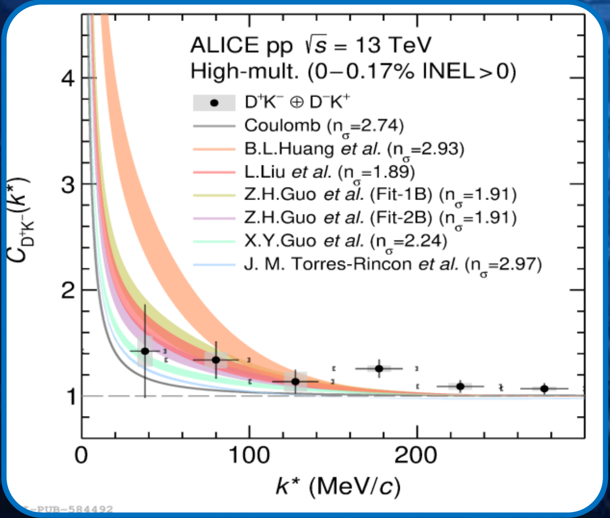


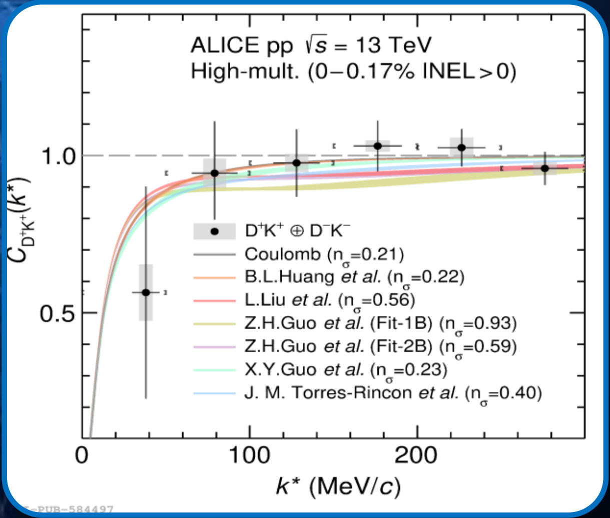


- Measured Dπ &DK interactions in all charged combinations.
- Compatible with Coulomb-only for Dπ, more data needed for DK.

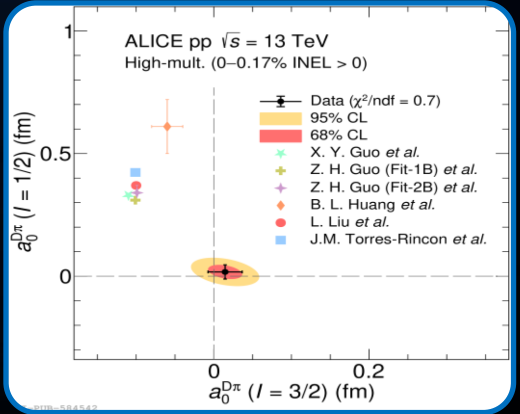
Shallow strong interaction between charm and light-flavor mesons.

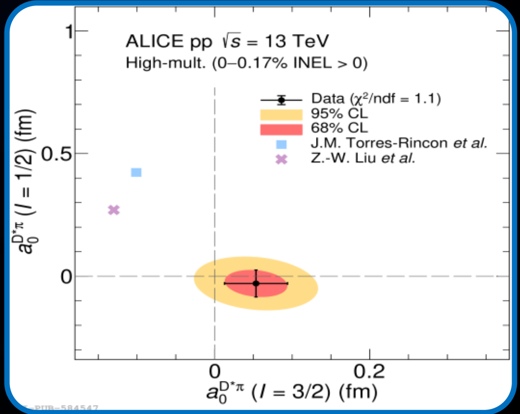
- Tension with models for all correlation functions.





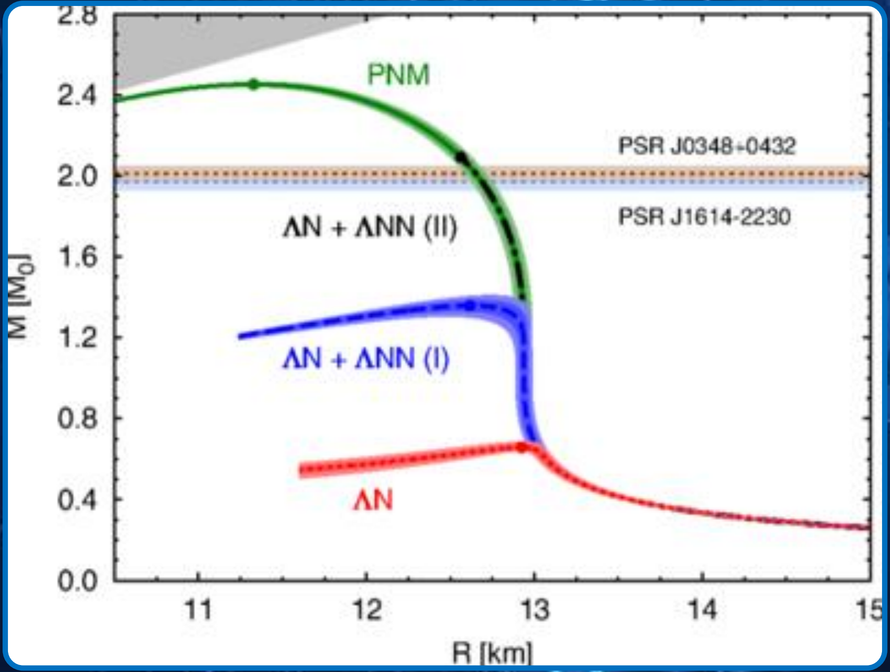
- Small scattering parameters.
- Compatible with heavy-quark spin symmetry.





Improved statistical uncertainty in ongoing Run 3.

IV: EoS of neutron stars



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

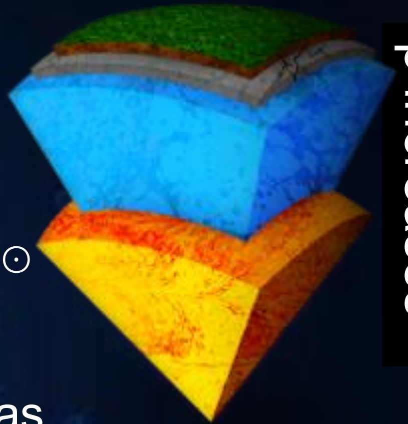
Neutron stars (NS):
very dense, compact objects

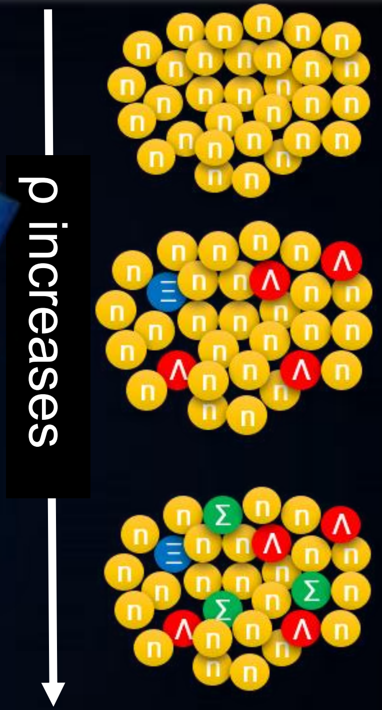
Dimensions
R ~ 10 – 15 km
M ~ 1.2 – 2.2 $M_{\odot}$

Outer Crust
Ions, electron gas

Inner Crust
Ions, electrons, neutrons

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

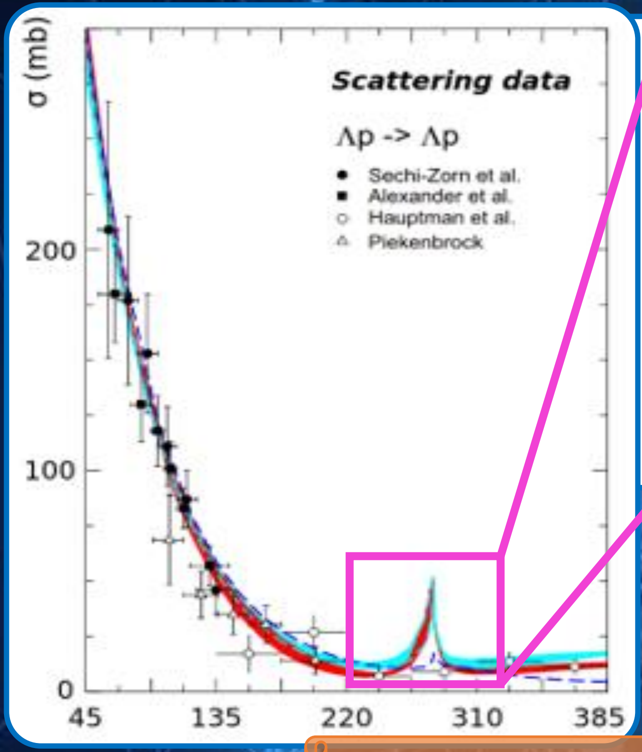


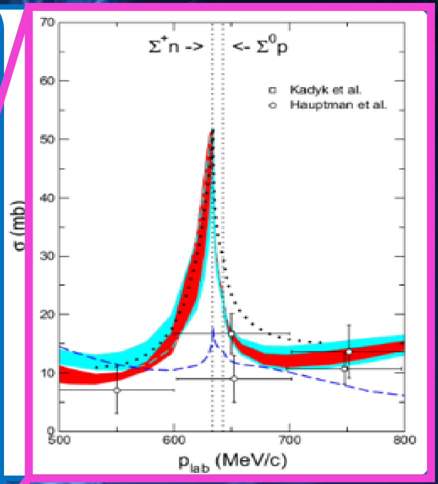


Femtoscopy could provide experimental measurements needed to study 2- and 3-body effects!

- EoS (of dense matter/NS): *is increasingly sensitive to the 3-body forces with increasing density.*
- Difference in EoS *difference in mass-to-radius relation for NS.*
- 3-body interaction models are *fitted to reproduce measured (hyper)nuclei properties.*

- Momentum range extended to $k^* \approx 10$ MeV/c.
- Femtoscopy data resolve the cusp region.
- Sensitivity to different ΛN interaction models.
- Best agreement with NLO19.



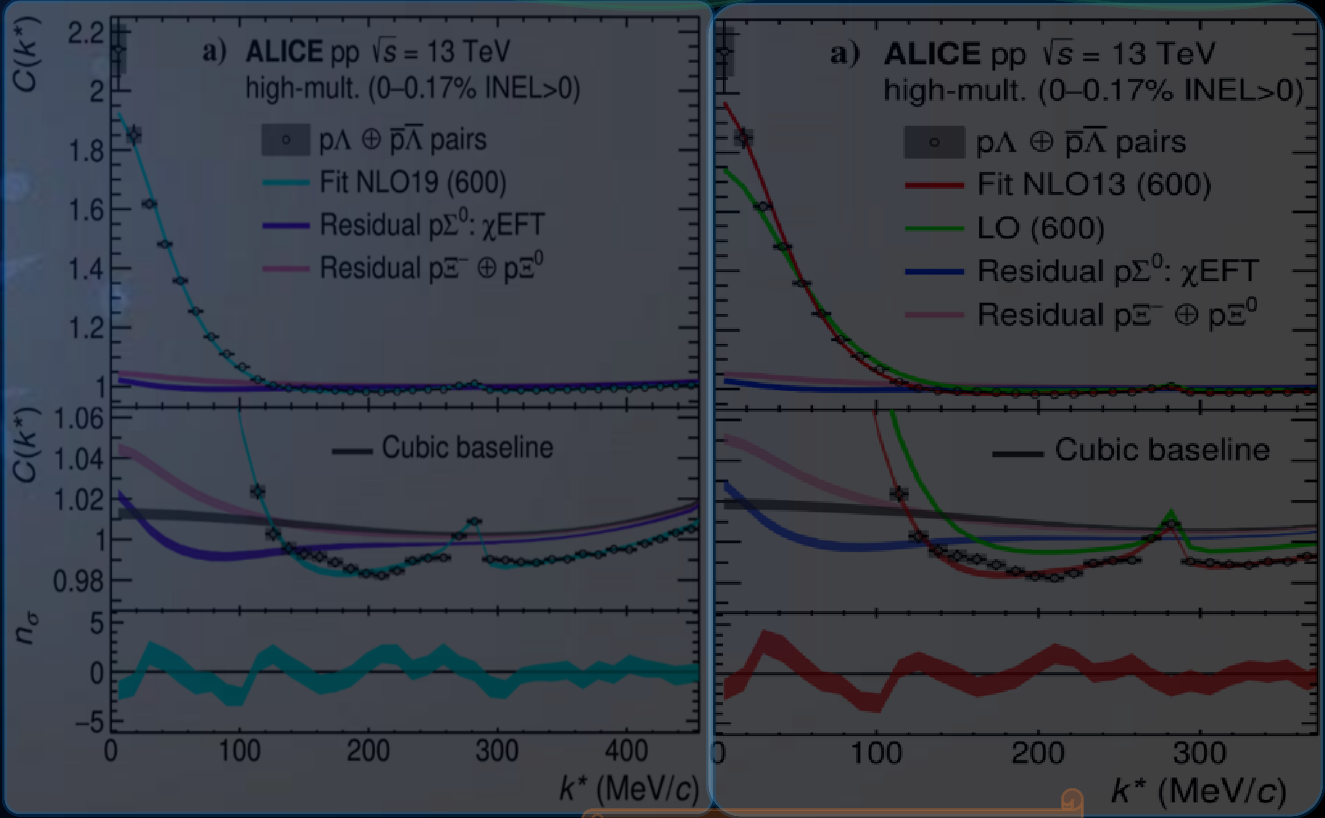


χEFT NLO 13

χEFT NLO 19

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

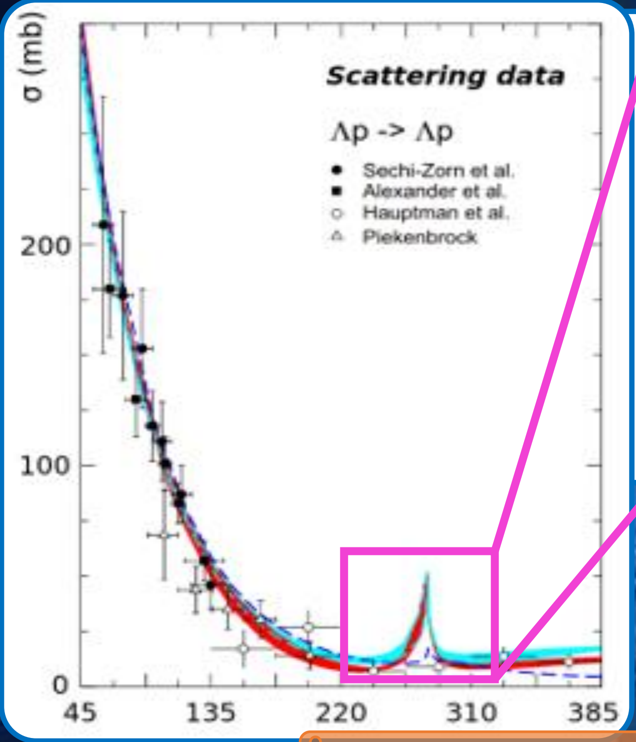
Available scattering experimental data in the region of NΛ↔NΣ cusp do not allow distinguishing between the existing theoretical approaches.

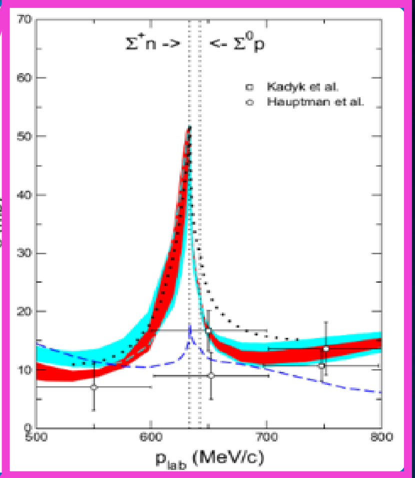


ALICE, PLB833(2022)137272

Further improvement of the NLO model is possible!

IV: pΛ interactions





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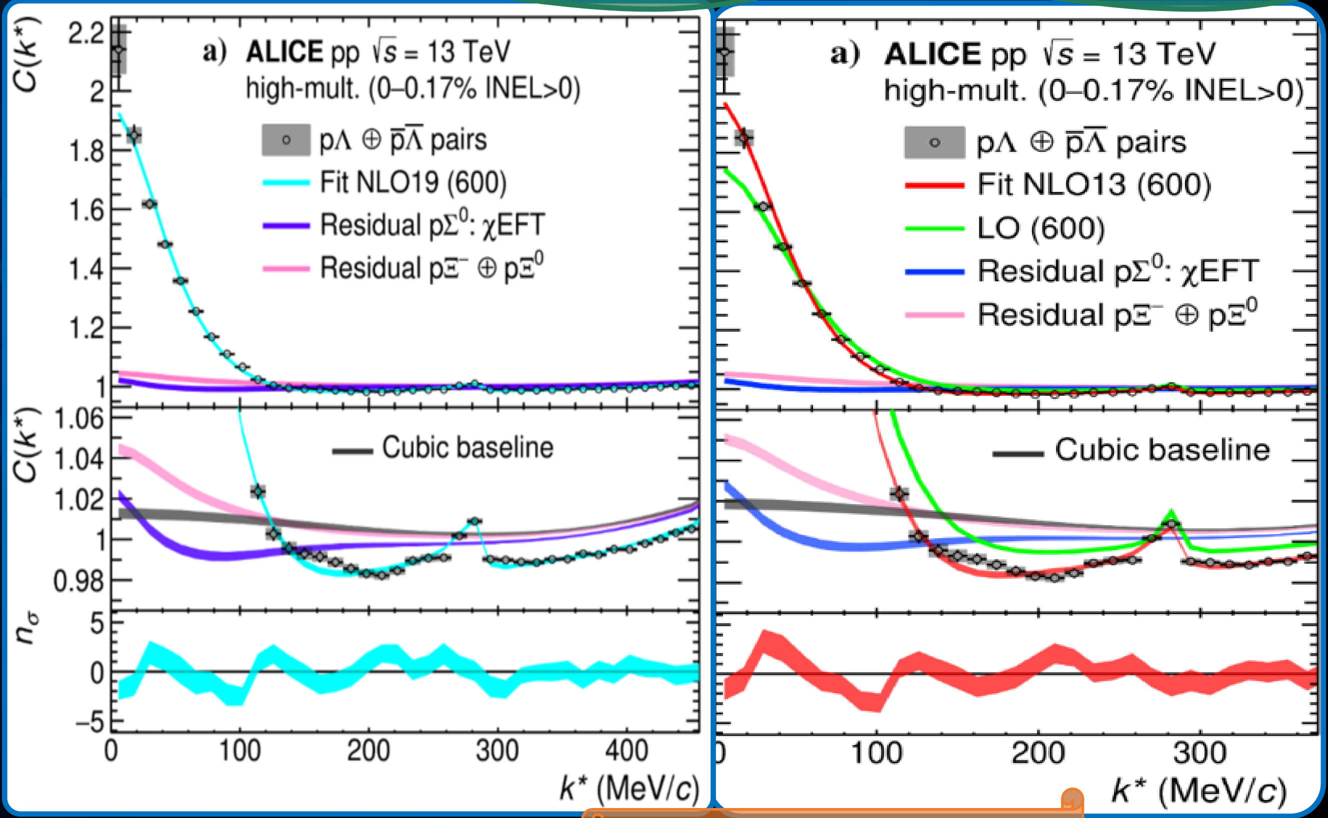
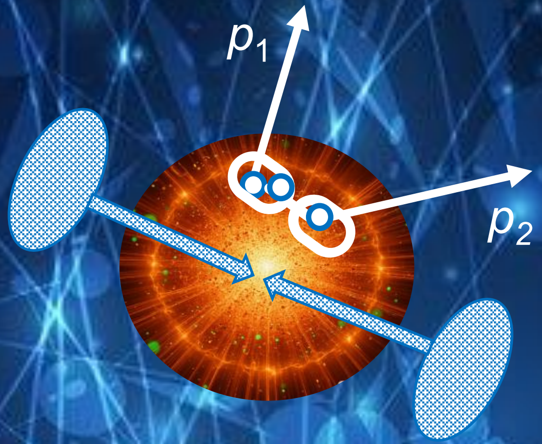
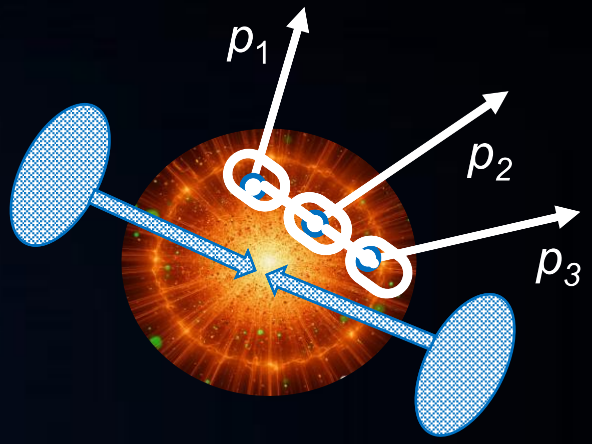


ALICE, PLB833(2022)137272

Further improvement of the NLO model is possible!

IV: 3-particle interactions





3-particle interactions:

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

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

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

Hadron–deuteron interactions:

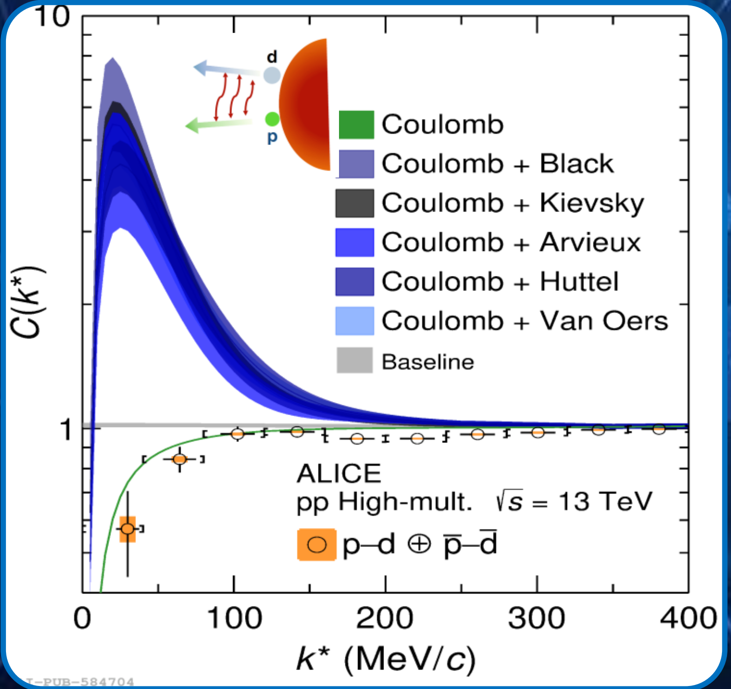
pair relative momentum: $k^* = \frac{|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|}{2}$

$$C(k^*) = \mathcal{N} \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

IV: pd interactions

Effective 2-body p-d system:
Lednický–Lyuboshits approach

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



Simple s-wave, asymptotic, 2-body approach is not enough to describe the data.

3-body system:

Argonne V18 for 2-body potential

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

Urbana IX (UIX) for genuine 3-body potential

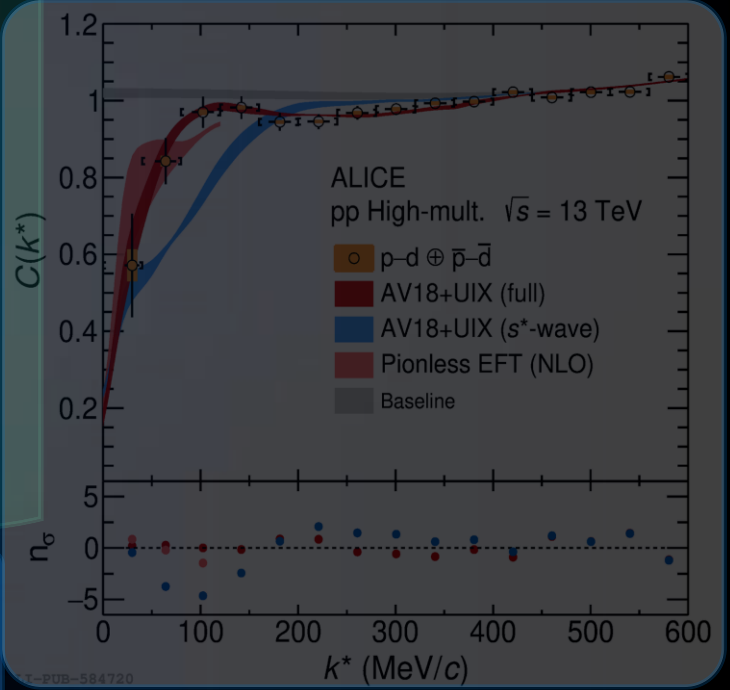
B.S.Pudliner et al., PRC56(1997)1720

- *Coulomb only* not okay.
- *EFT NLO (s-wave)* not okay.
- *EFT NLO (s+p+d waves)* okay.

Full 3-body dynamics is necessary to describe the data.

M.Viviani et al., PRC108(2023)6,064002

ALICE, Phys.Rev.X14(2024) 031051



More precise experimental measurements in future to distinguish between different scenarios of d production!

IV: pd interactions

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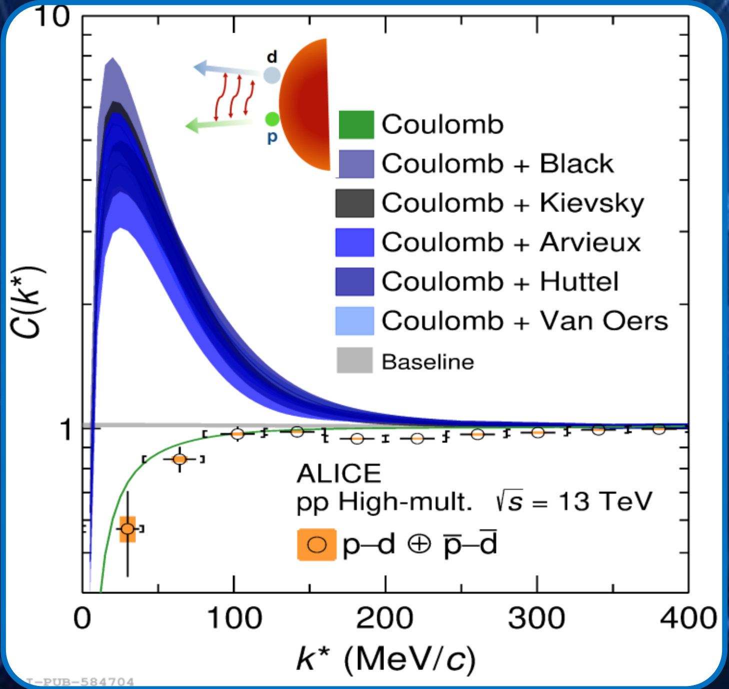

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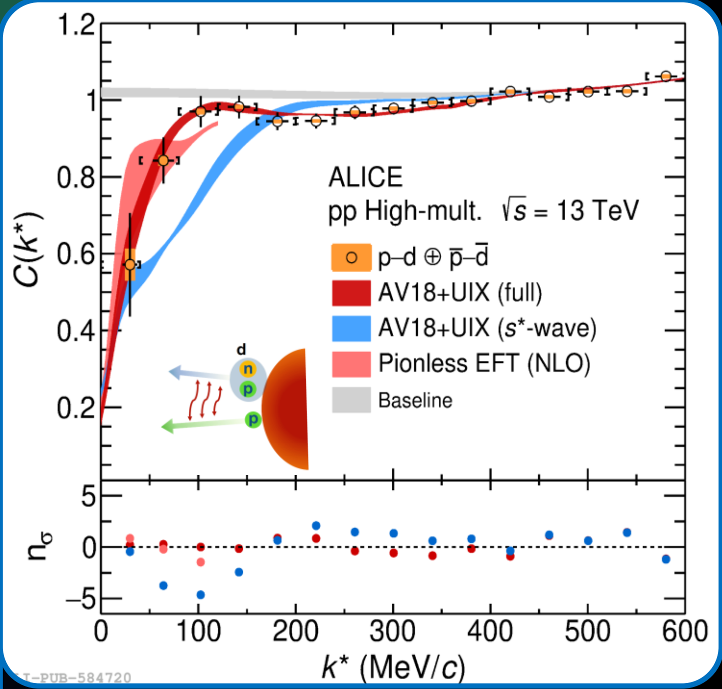
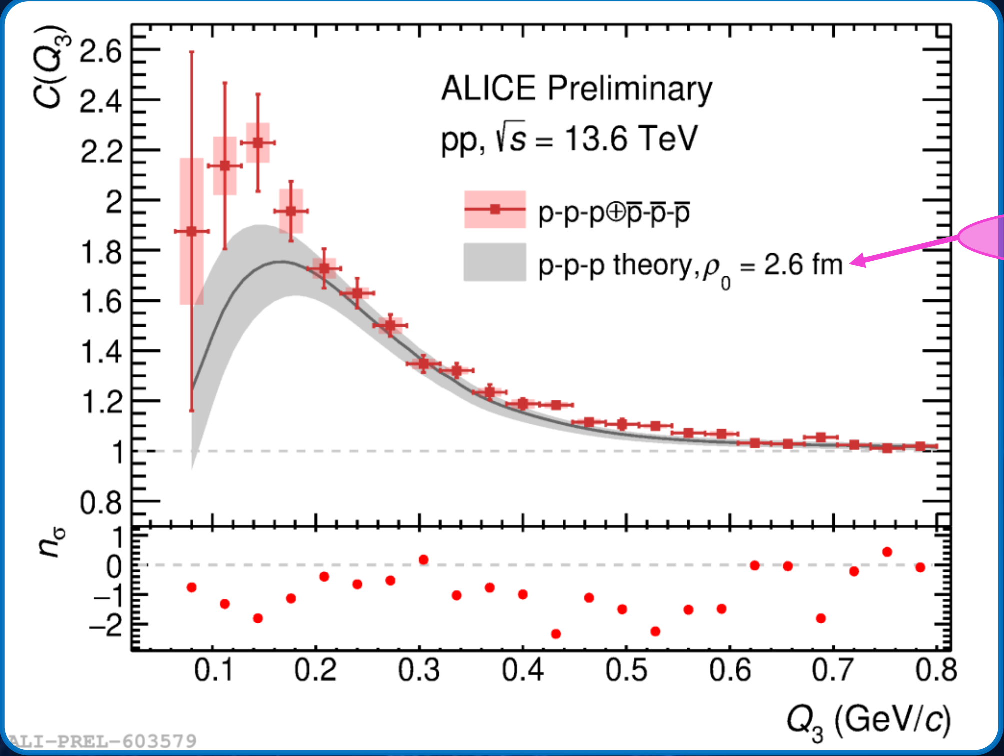


More precise experimental measurements in future to distinguish between different scenarios of d production!

IV: ppp interactions

Novel way to study many-body interactions via three free baryon scattering 3→3.



ρ_0 is hyperradius

(*) First full 3-body calculations:

A.Kievsky, L.Šerkšnytė et al., PRC109(2024)3,034006

Wave function via (*):

- strong AV18
- 3-body Coulomb interaction
- quantum statistics
- negligible contribution from UIX 3-body potential

New Run 3 results:

- higher statistical precision
- lower Q_3 achieved than in Run 2

ALICE, EPJA59(2023)7,145

More on 3-body interactions on **slide 24** in Backup!

Conclusion

- **Bowler-Sinyukov fit:**
  - study of collective expansion of matter created in pp/p–Pb/Pb–Pb collisions
  - investigation of particle production evolution after a collision
- **Correlations including strange particles:**
  - novel high-precision constraints on S=-1 and S=-2 baryon interactions (effective chiral potentials)
  - determination of scattering parameters
  - study of resonant structures appearing in various correlating pairs
  - test vector meson dominance models
- **Correlations including exotic particles:**
  - precision data on hadron–hadron interactions to study exotic states including charm particles
- **3-particle correlations:**
  - test/development of 3-body interaction models based on the pd, ppp, ppΛ data (useful input for EoS of NS)

More results in femtoscopy (not mentioned in this talk):

- Femtoscopy in pp collisions [slides 20 and 21]: common particle emitting source
- Kd, πd [QCHSC2024]: full isospin dependence of the interaction – a fundamental problem in the strangeness sector in the low-energy regime of QCD
- pΩ^- [ALICE,Nature588(2020)232]: Coulomb + strong HAL QCD (Hadrons to Atomic nuclei from Lattice QCD)
- $\Lambda\Xi^-$ [ALICE,PLB844(2022)137223]: test Lattice QCD calculations
- K^+K^- [ALICE,PRC107(2023)054904], $K^0_S K^0_S$ [QM2025], $K^\pm_S K^0_S$ [ALICE,PLB833(2022)137335]: test hydrodynamic models of ultra-relativistic collisions, study resonances
- πK [ALICE,PLB813(2021)136030]: spatio-temporal separation between sources of different particle species
- pΣ^+ [QM2025]: novel input for EoS with hyperons for NS
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And even more!

Conclusion

ALICE

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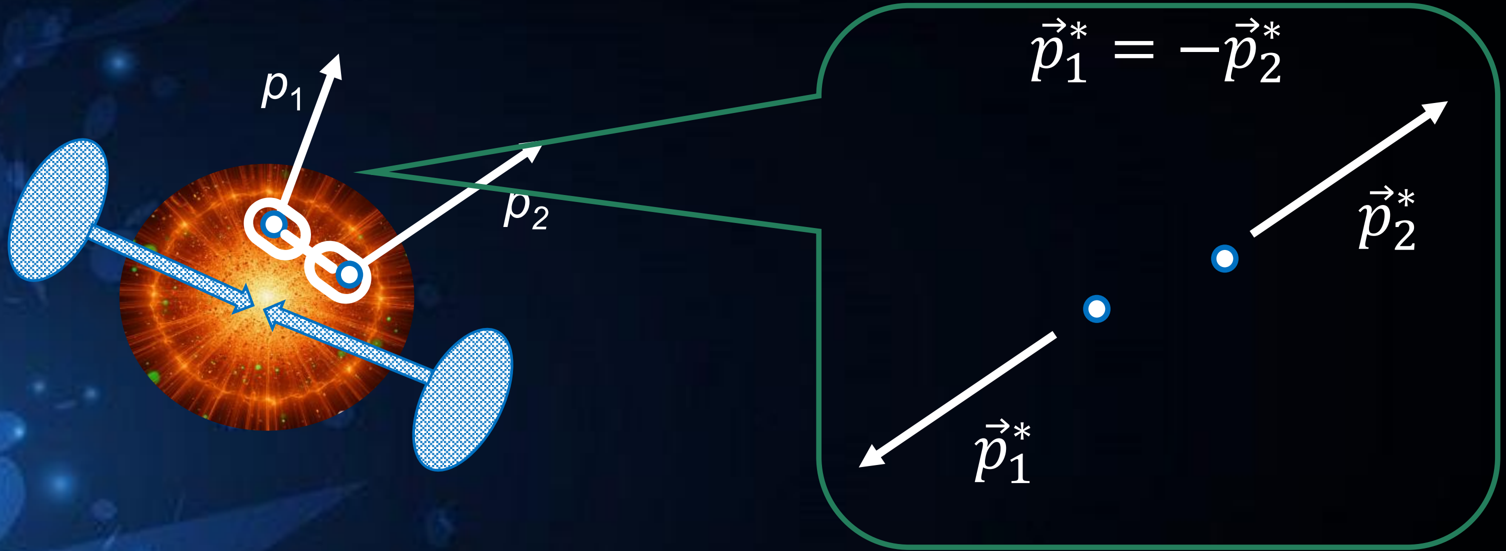
And even more!

The end

Thank you for your attention!

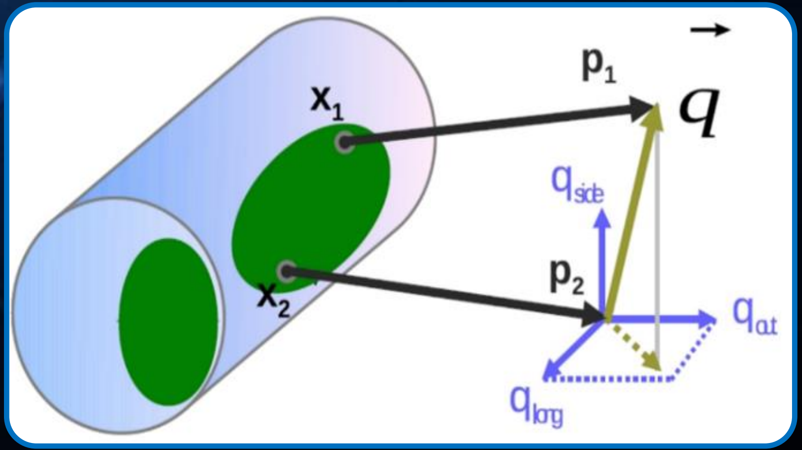
Backup: Reference frames

Pair Reference Frame:



Longitudinally Co-Moving System:

M.A.Lisa et al., Ann.Rev.Nucl.Part.Sci.55(2005)357



q_{long} ‖ beam direction

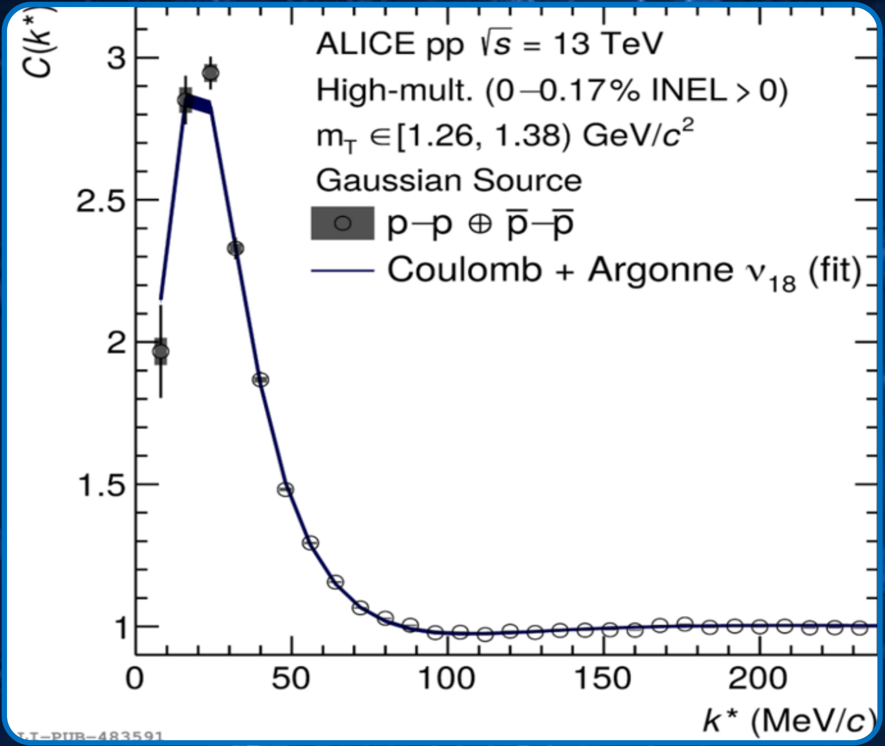
q_{out} ‖ pair transverse momentum k_T

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

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

Backup: Baryon source size

ALICE,PLB811(2020)135849

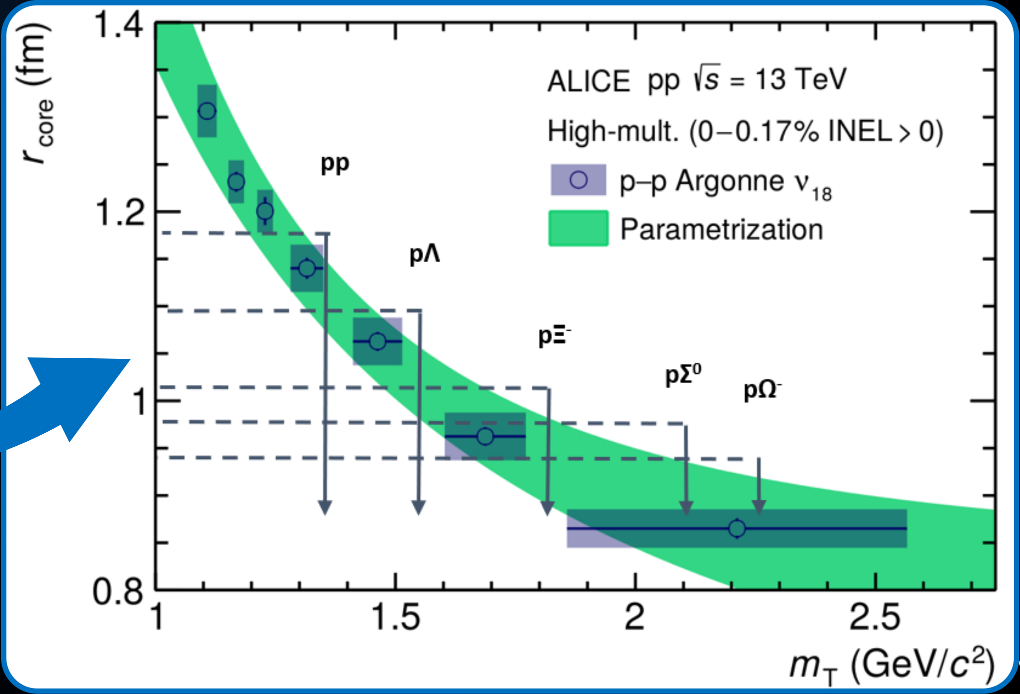


Parametrize p-p and p-Λ r_{core} points:

- 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:

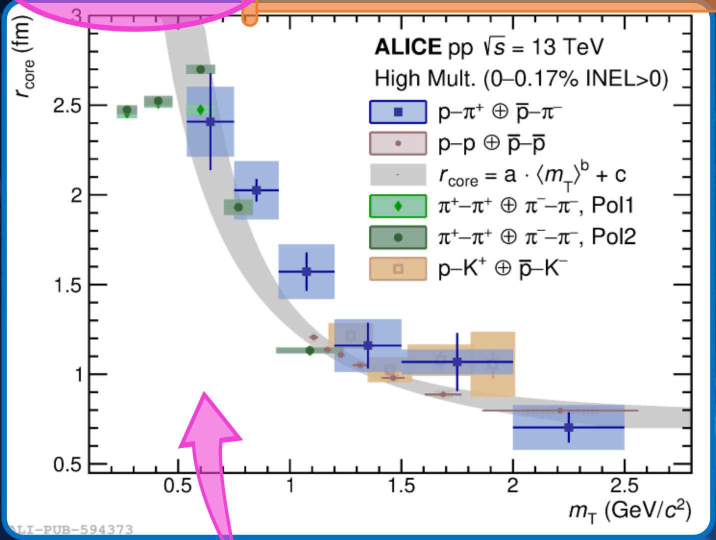
- Genuine p-p correlation function is calculated.
- Source radius is extracted from *C* fit.
- *The same is done for p-Λ* $\rightarrow r_{core}^{p-p}$ *and* $r_{core}^{p-\Lambda}$ *scale with* m_T *when contributions of strongly decaying resonances are taken into account.*



Backup: Common particle emitting source

Run 2

ALICE,arXiv:2502.20200



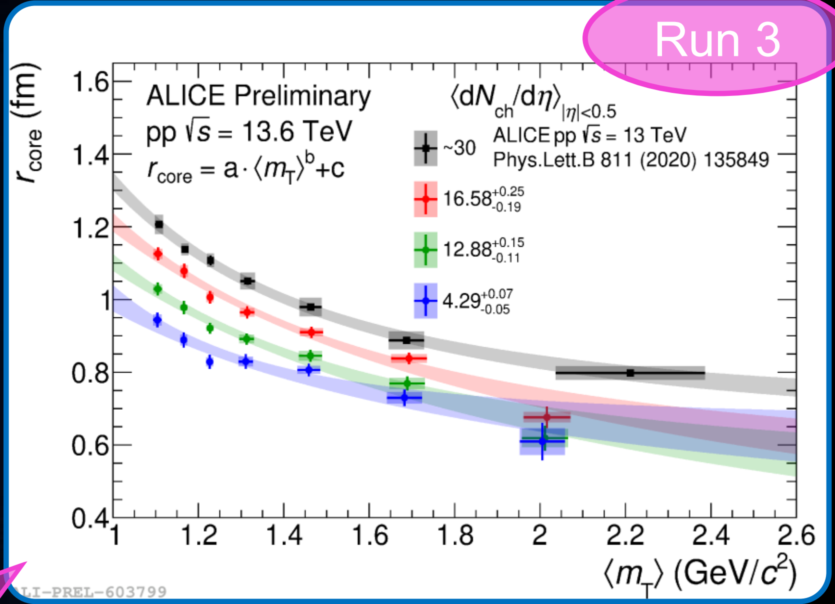
Fit theoretical model (with CATS) to measured CF to access the source function by studying particle pairs with well-known (pp, for example) interactions:

- AV18 potential and RSM model

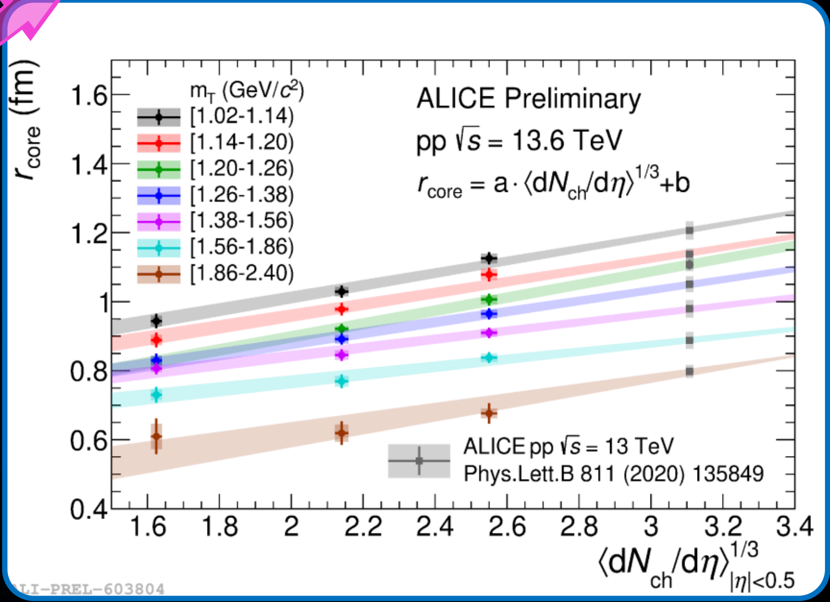
ALICE,PLB811(2020)135849

- Coulomb interaction

Run 3



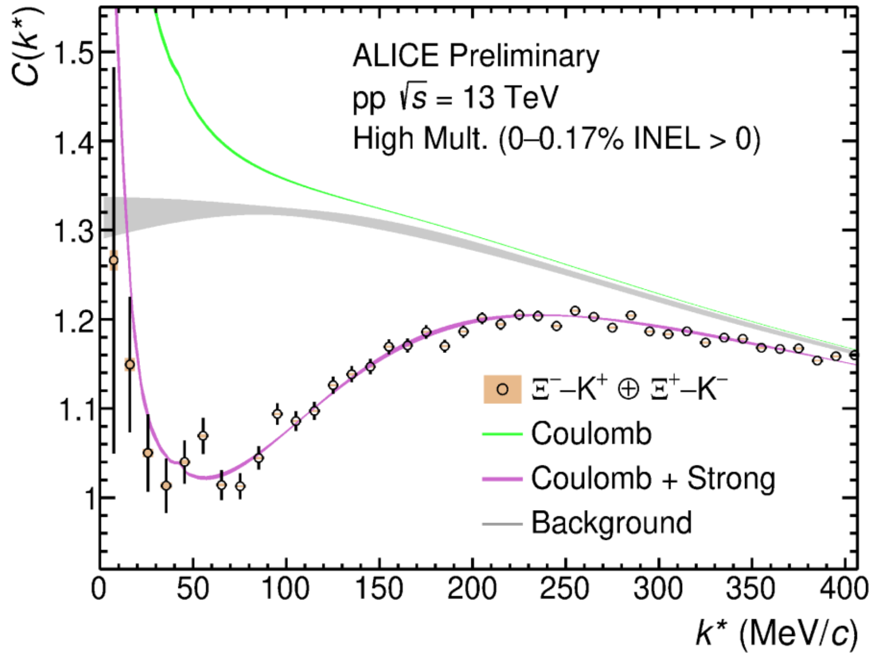
- ○ Similar m_T scaling of r_{core} for many different particle pairs.
- ○ Differential study of pp interaction with ALICE in Run 3 for future femtoscopic measurements
  - m_T scaling observable even at very low multiplicities.
  - r_{core} increases linearly with cubic root of multiplicity.



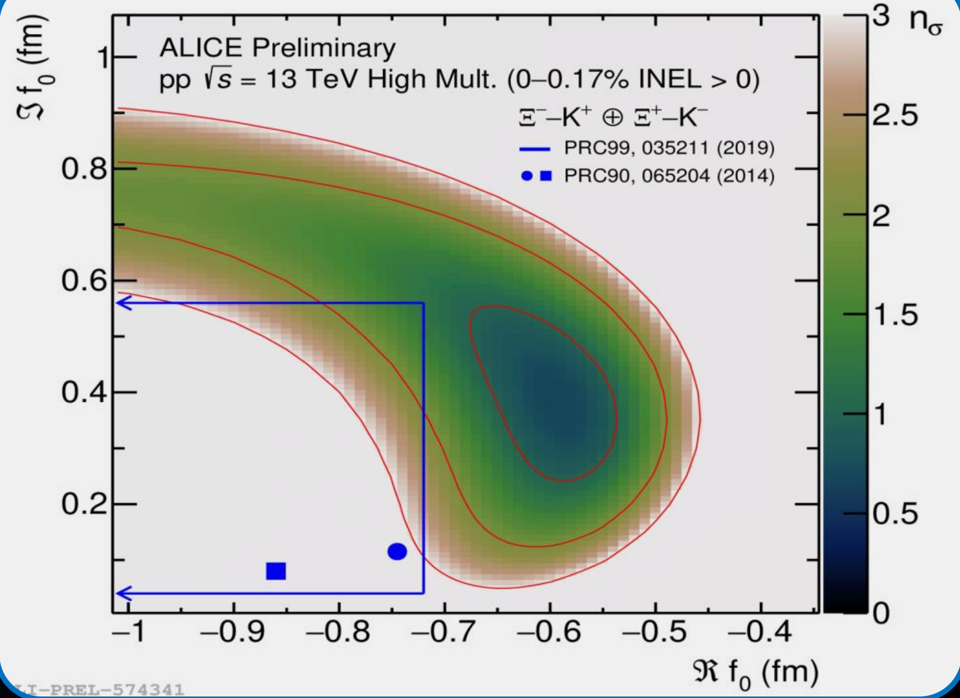
Future femtoscopic measurements:

- ○ Further studies of systems with strangeness and charm.
- ○ Precision measurements of genuine three-body correlations with dedicated software triggers.

Backup: S=-1 sector ⇝ $\Xi^- K^+$



Allowed values for the scattering length f_0 from state-of-the-art chiral calculations at NLO and phenomenological potentials constrained to available scattering data *with better precision thanks to femtoscopy*.

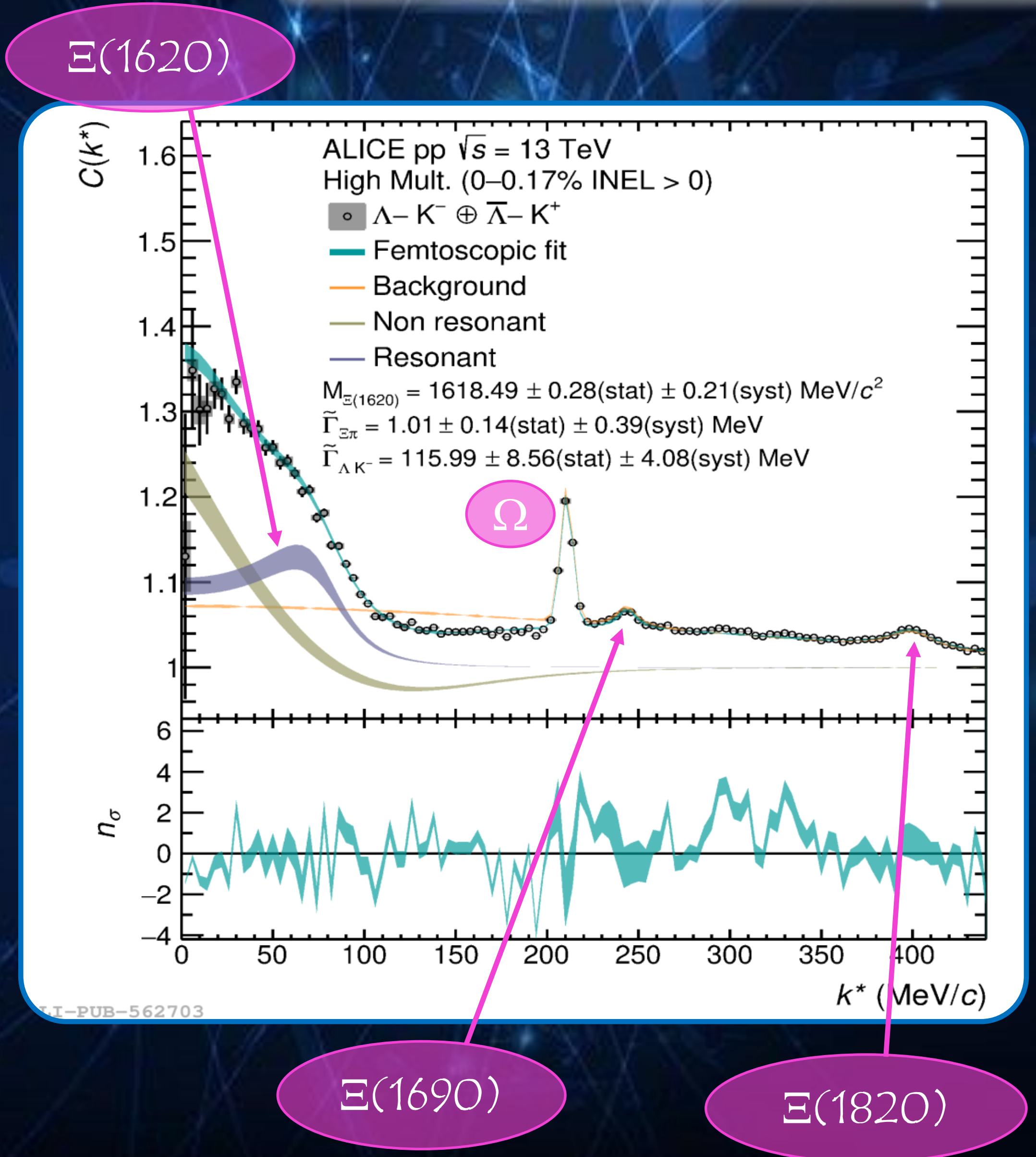


- Most precise data at low momenta on the interaction between Ξ and K → *important constraints for I=1 channel of S=-1 meson–baryon interaction*
- Model: R.Lednický, Phys.Part.Nucl.40(2009)307

Coulomb (s-wave only) + strong repulsive interaction → *assumption agrees with the data*

Back to slide 8

Backup: S=-2 sector ⇝ ΛK⁻



Study of resonant structures present in the measured ΛK⁻ correlation function in pp collisions:

ALICE, PLB845(2023)138145

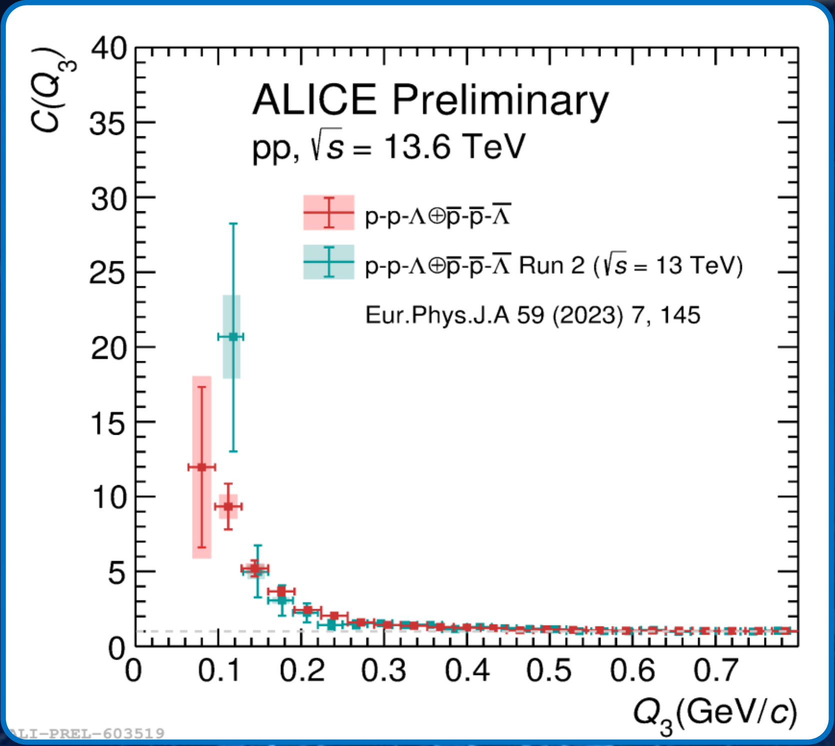
Constrain effective chiral potentials:

V.Mantovani Sarti et al., PRD110(2024)1,L011505

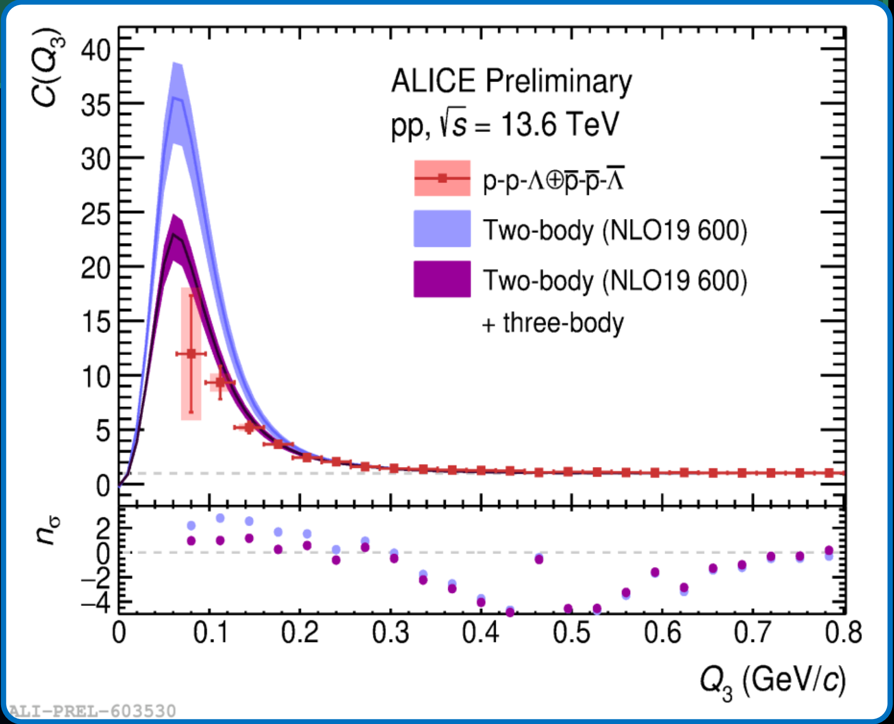
- large sensitivity of femtoscopy data to NLO low-energy constants
- Ξ(1620): not a πΞ-KΛ molecule but a narrower ηΞ bound state with small or negligible coupling to other channels
- Ξ(1690): KΣ quasi-bound state

Back to slide 9

IV: ppΛ interactions



- *Wave function:* E.Garrido et al., PRC 110 (2024) 5, 054004
- *2-body:* scattering parameters based on χEFT NLO19 600
- *3-body:* Gaussian potential tuned to hypertriton binding energy



- Relevant measurement for EoS of NS
- Sensitivity to 3-body repulsive p–p–Λ interaction

- Overall agreement with Run 2 results ALICE, EPJA59(2023)7,145
- Higher precision achieved with Run 3 data

Calculations are preliminary:
- interaction in higher partial waves to include
- different potential shapes to test

Back to **slide 16**