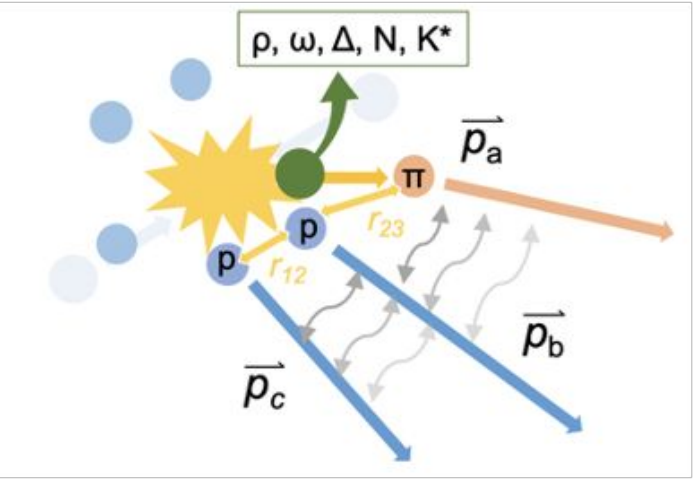
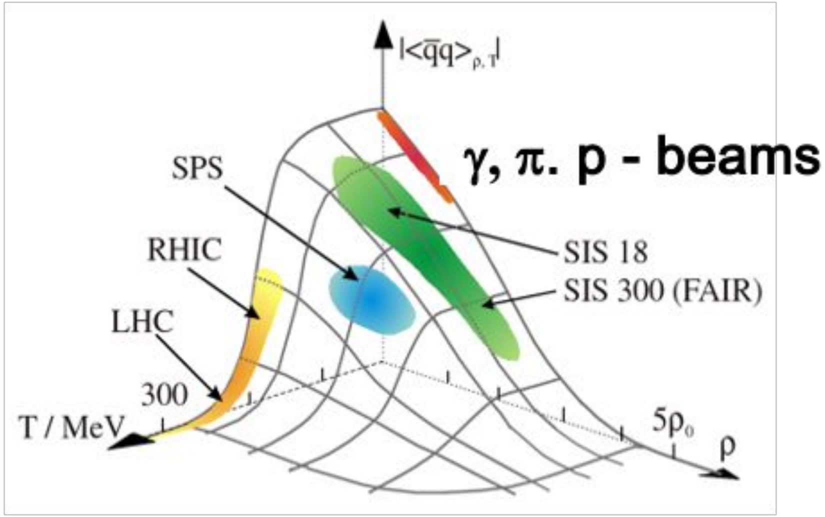
Studying chiral symmetry restoration employing many body femtoscopy





Klimt, Lutz, Weise PLB 249 (1990) 386

M. Korwieser, L.Fabbietti
Technical University of Munich, E62

8th of November 2024

WPCF 2024, Toulouse

Chiral symmetry in a nutshell

$$L_{QCD}^{m=0} = \bar{\psi}(i\gamma_\mu D^\mu)\psi - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- Chiral symmetry (CS) is manifest in the QCD lagrangian density for massless quarks
- A consequence is parity doubling, i.e. mass degenerate states of opposite parity $(\text{spin})^{\text{parity}}$

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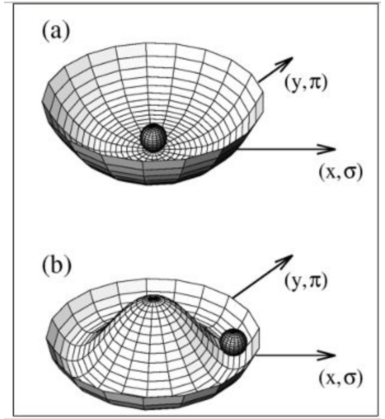

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- **Spontaneous breaking** of CS breaks this degeneracy
  - The QCD vacuum is **not** invariant!!

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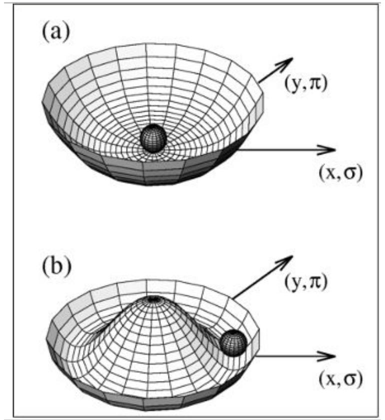
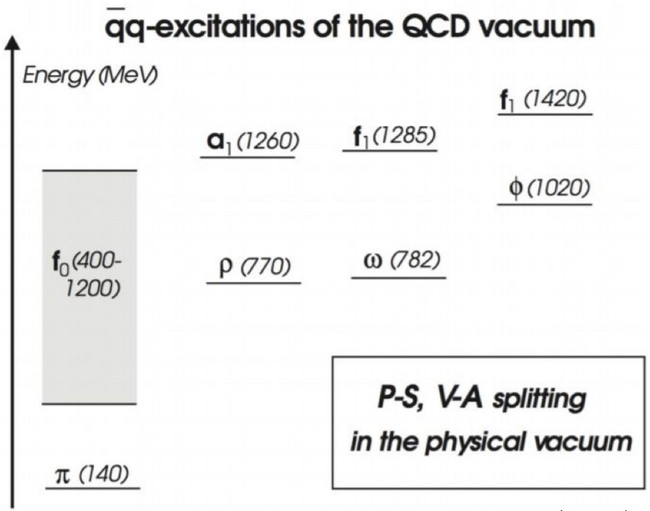
- **Order parameter** is the chiral condensate <qq>*

$$< 0|q\bar{q}|0 >$$

*very simplified notation





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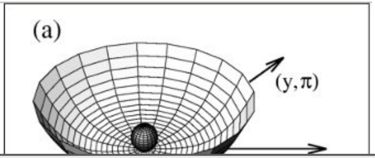

How to connect <qq> to hadronic properties?

Can we control the amount of CS violation?

- **Order parameter** is the chiral condensate <qq>* $< 0|q\bar{q}|0 >$

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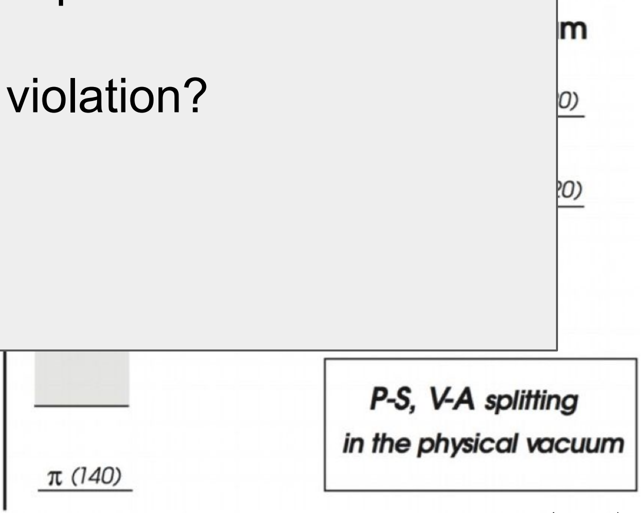

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Observables linked to the <qq> condensate

QCD Sum Rules

S. Weinberg, Phys. Rev. Lett. 18 (1967) 507

$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

Chiral symmetry restoration manifests itself through mixing of vector and axial-vector correlators

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Directly links <qq> to hadron masses!

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Gell-Mann Oakes Renner (GOR) Relation

Gell-Mann Oakes and Renner Phys. Rev. 175 (1968) 2195

$$m_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u + m_d) < u\bar{u} + d\bar{d} >$$

π Decay Constant in vacuum

$$f_\pi = 93.3\,\mathrm{MeV}$$

It relates the pion mass and decay constants to the value of the condensate (spontaneous chiral symmetry breaking) and the values of the quark masses (explicit chiral symmetry breaking)

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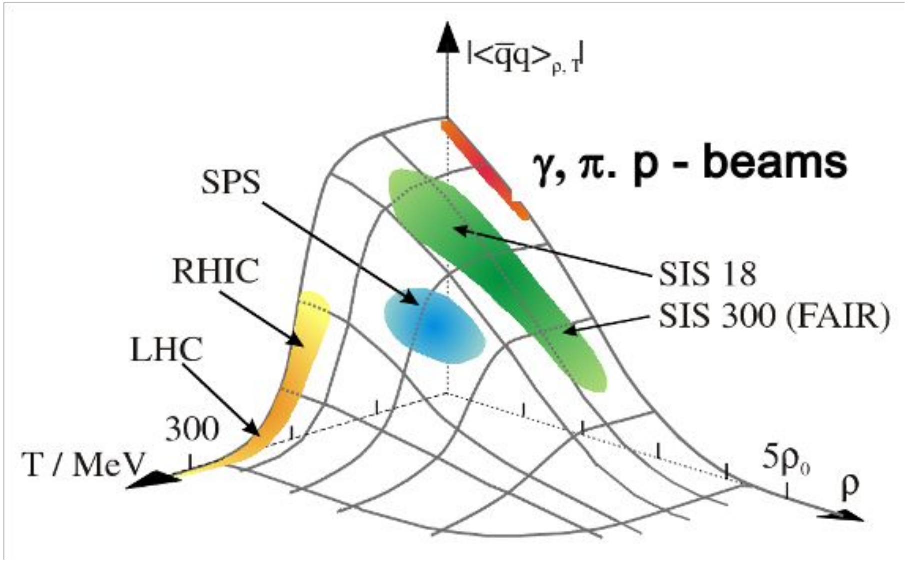
Chiral Symmetry Restoration

$$\langle \bar{q}q \rangle \approx -(240\,\mathrm{MeV})^3 \times N_f$$



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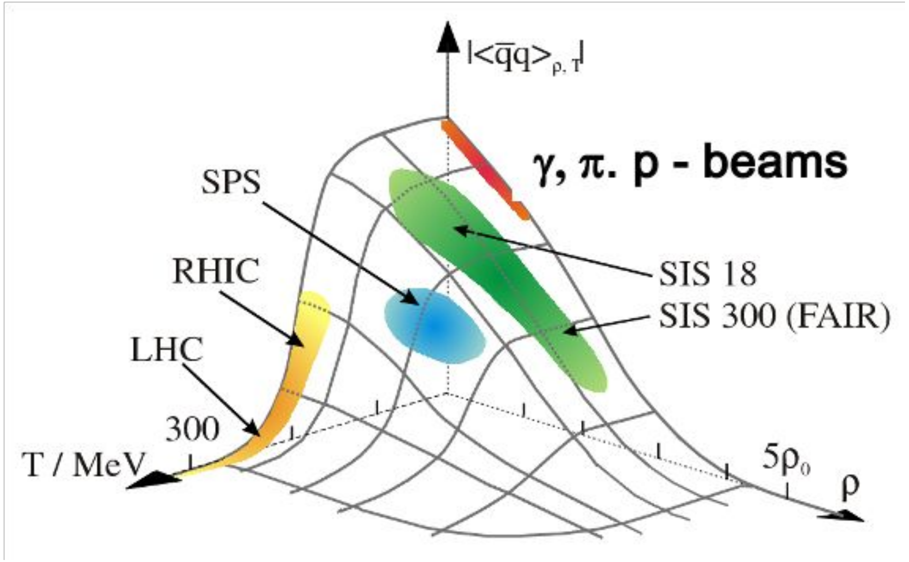

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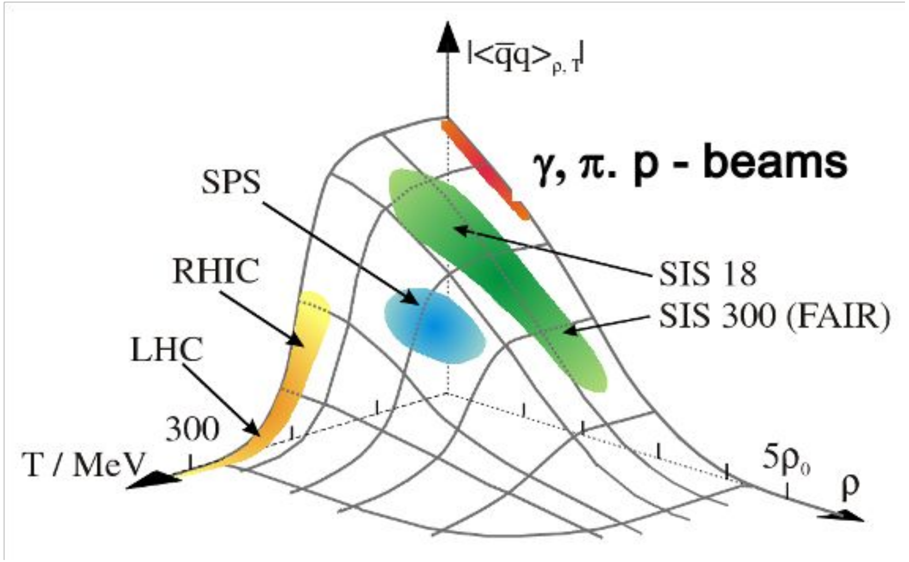

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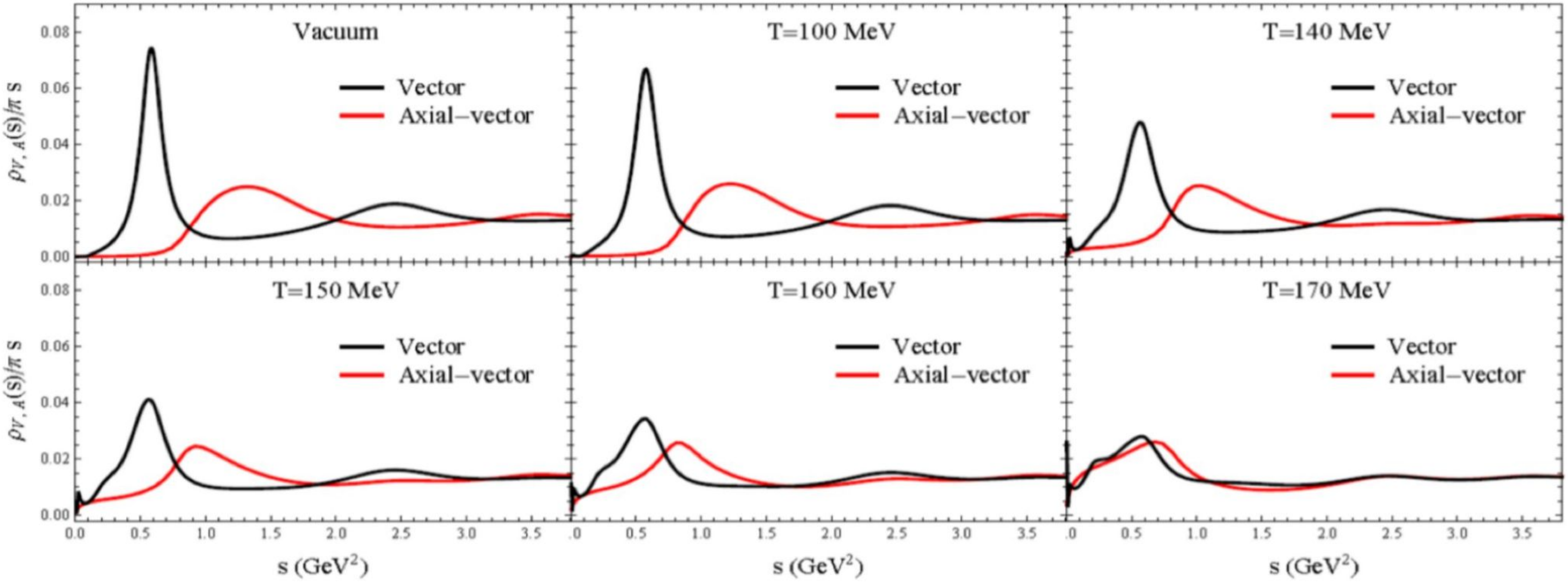
How to measure degree of restoration experimentally?

- Study excitation functions of hadrons
  - Modifications expected in-medium
  - Degeneracy of chiral partners


Vacuum
T=100 MeV
T=140 MeV
T=150 MeV
T=160 MeV
T=170 MeV
Vector
Axial−vector
$\rho_{V,A}(S)/\pi\, S$
s (GeV^2)

Chiral Symmetry Restoration

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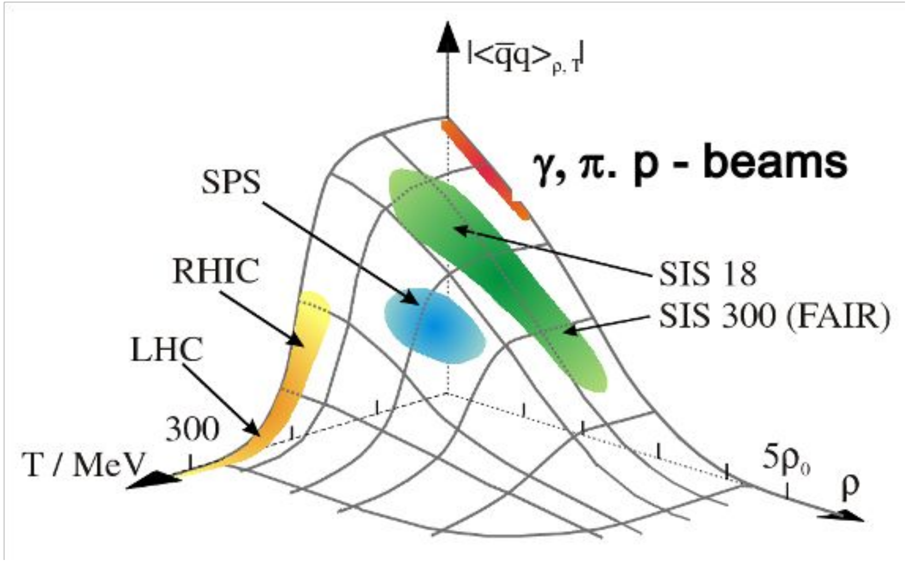

Klimt, Lutz, Weise PLB 249 (1990) 386

- Value of <qq> is predicted to drop for increasing temperature (T) and density (ρ)

How to measure degree of restoration experimentally?

- Many searches for CSR on-going
  - Recently with pionic atoms
    piAF Coll. Nature Physics 19 (2023)
  - Line shape analyses of ρ
    NA61 EPJC 61 (2009)
  - Study of M(ee) to access ρ meson modifications
    HADES Coll. arXiv:2205.15914v2

Chiral Symmetry Restoration

$\langle \bar{q}q \rangle \approx -(240\,\mathrm{MeV})^3 \times N_f$

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Add a completely new complementary approach at colliders

Exploit **recent** developments of the femtoscopic methods

drop

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ration

oing

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  HADES Coll. arXiv:2205.15914v2

Courtesy of L. Fabbietti

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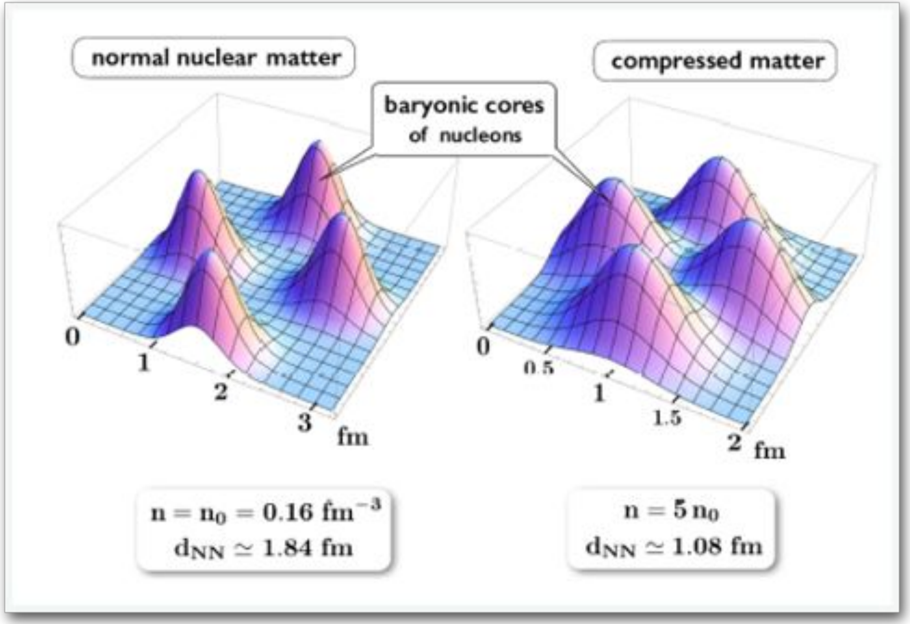

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Courtesy of L. Fabbietti

Idea in a nutshell

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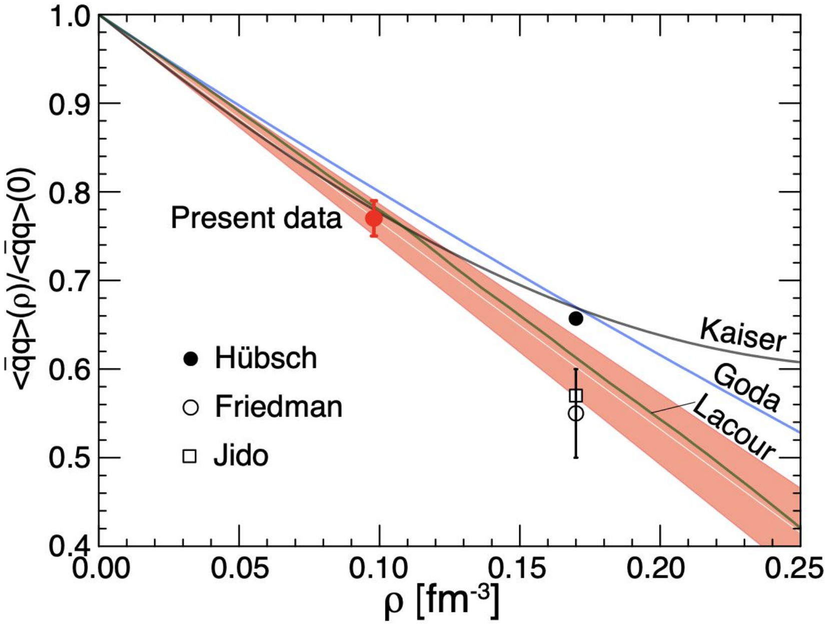
    - Already at ⅔ n_0 drop of <qq> of approx. 23%
      piAF Coll. Nature Physics 19 (2023)



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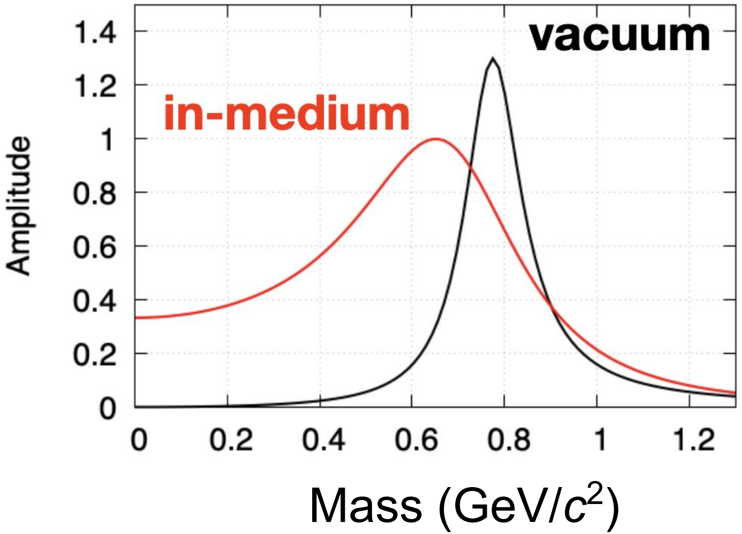

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Courtesy of L. Fabbietti

Experimental work

- Systematically approach many-body effects
  - Measure two-body correlations
  - Establish procedure for many-body femtoscopy
  - Tag particles surrounded by close-by nucleons

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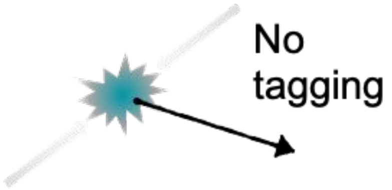

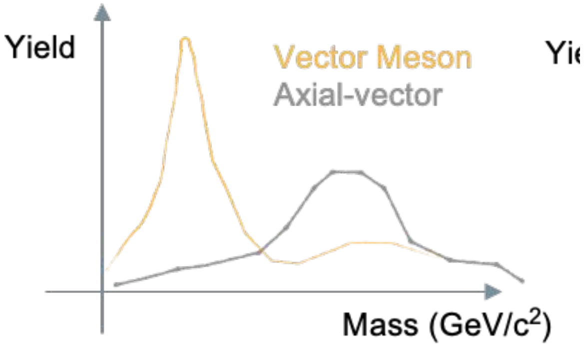

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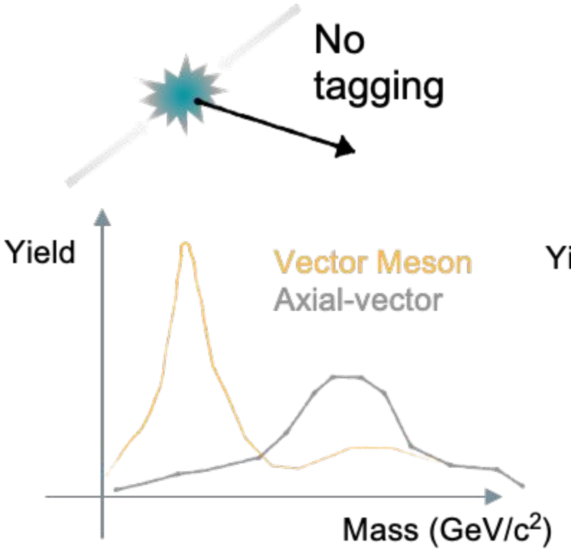

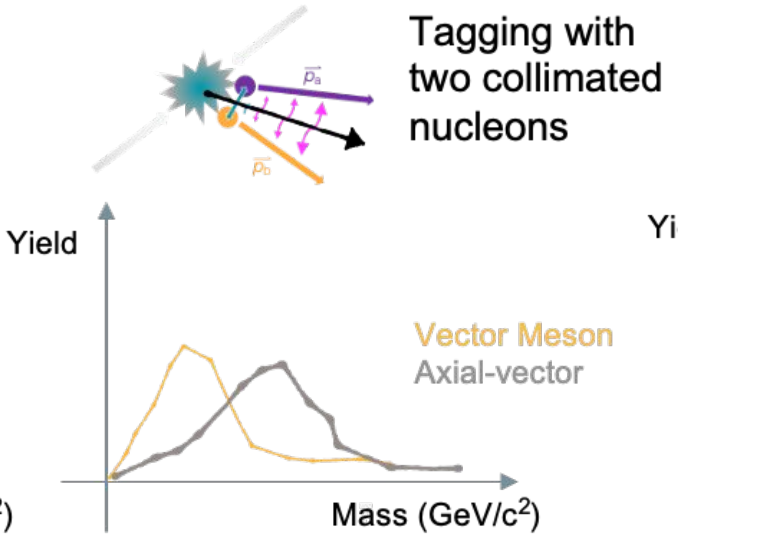

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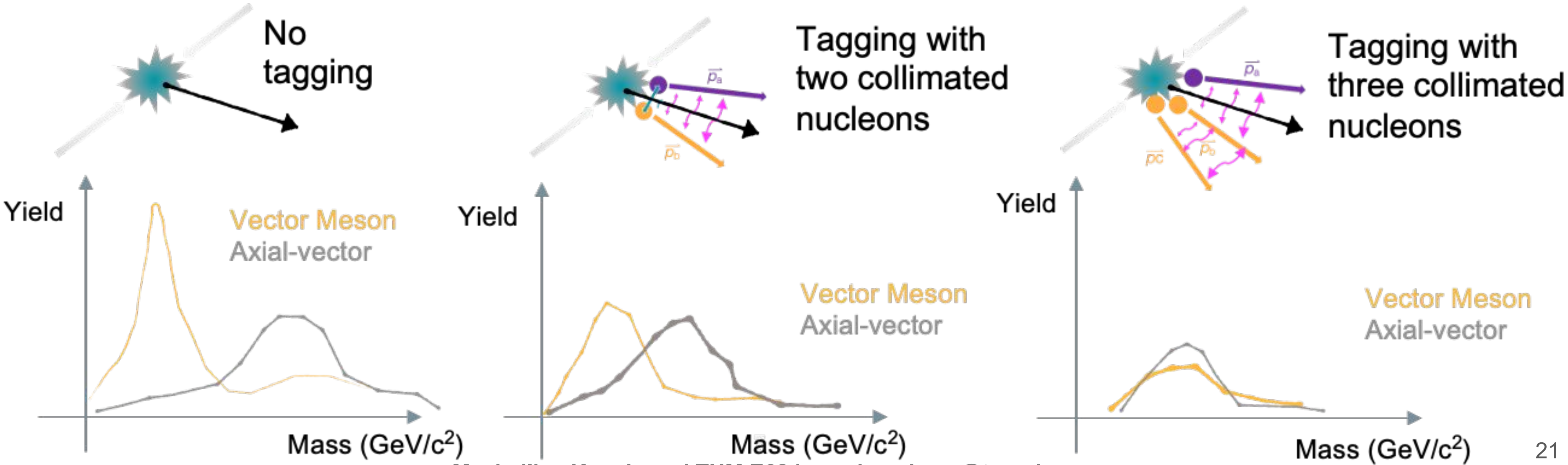


Small sources in pp at the LHC

See also talks of
D. Mihaylov and M. Lesch

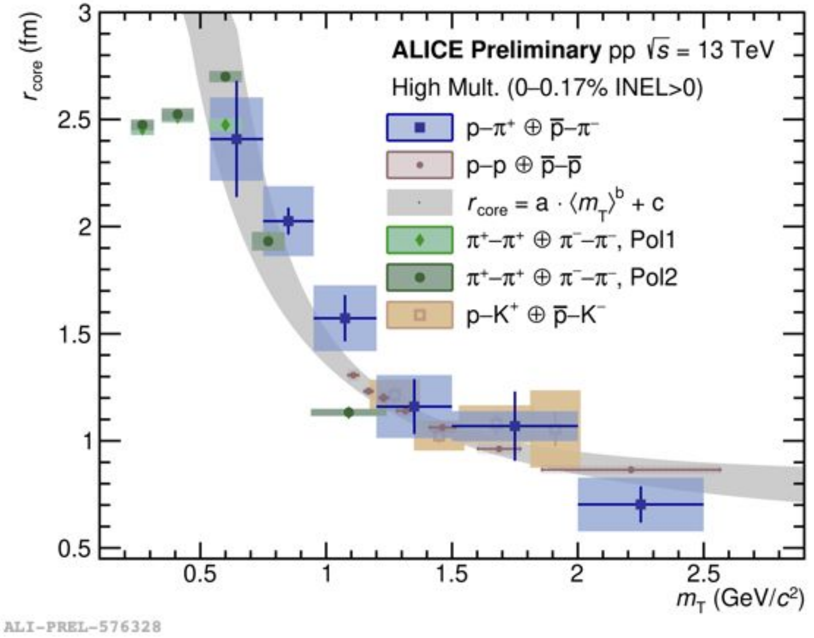
- Emitting source function anchored to p-p correlation function

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

- Two-component model

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4 r_{core}^2}\right) \times$$ Effect of short lived resonances (cτ ~ 1 fm)

- Universal source for all hadrons (cross-check with K^+-p, π-π, p-Λ, p-π)
- **Small particle-emitting source created in pp collisions at the LHC**



ALICE Coll., arXiv:2311.14527 accepted by EPJC
ALICE Coll., PLB, 811 (2020), 135849
ALICE Coll, paper in preparation

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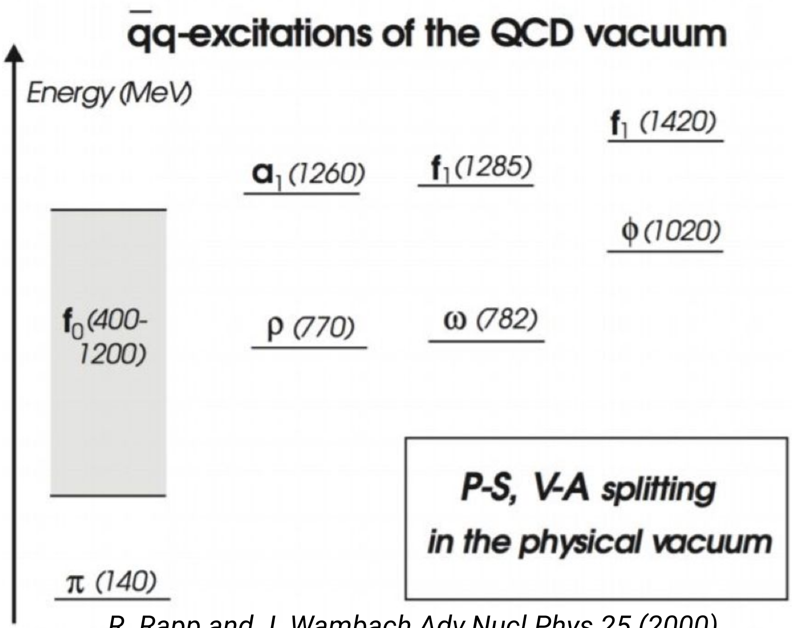
Do we see vector meson baryon interactions?



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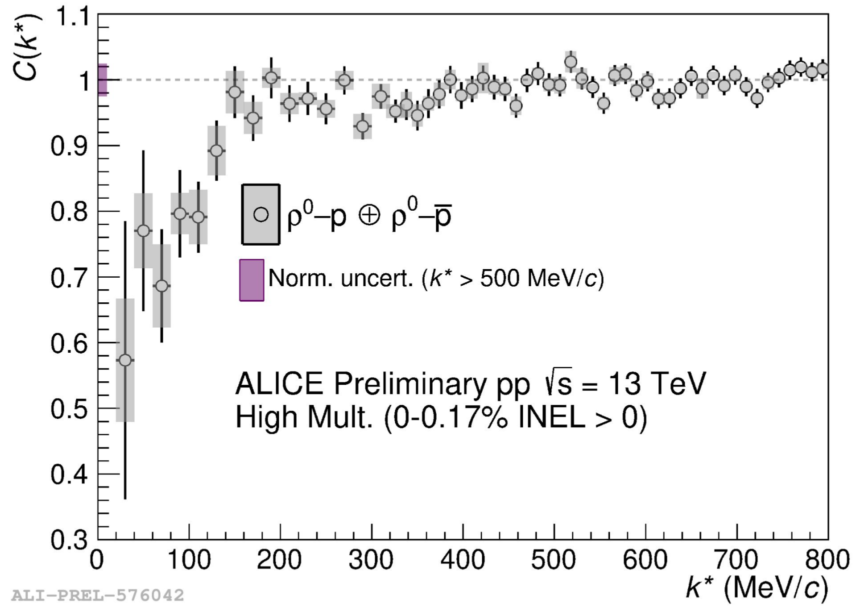
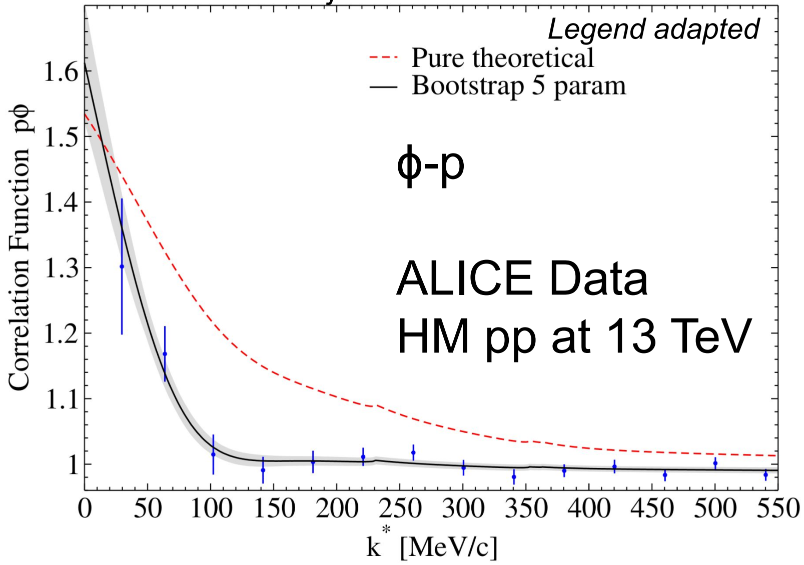


ALICE Coll. PRL 127 (2021)
A . Feijoo et. al. arXiv:2407.01128



- ALICE already measured ϕ-p and recently the ρ^0-p correlations!
- With Run3 potentially other vector meson baryon correlations are within reach
  - by usage of triggers and wealth of data

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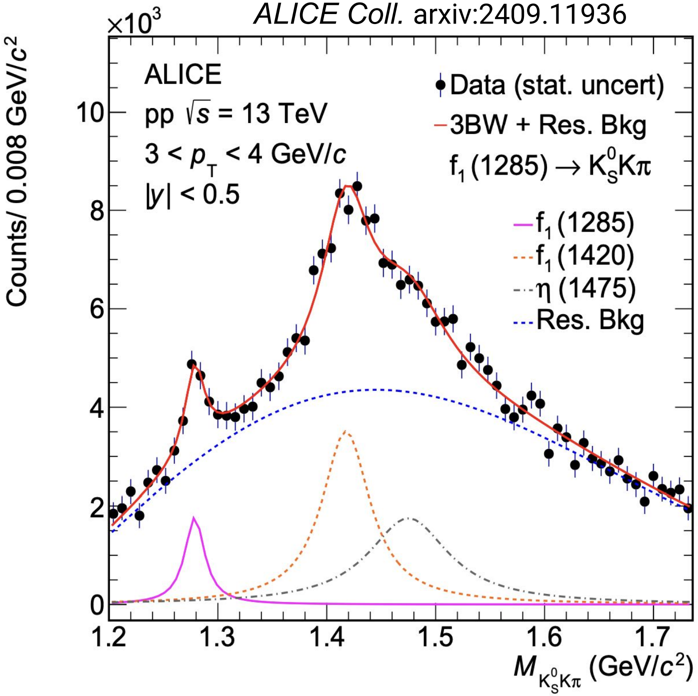
ALICE Coll. arxiv:2409.11936



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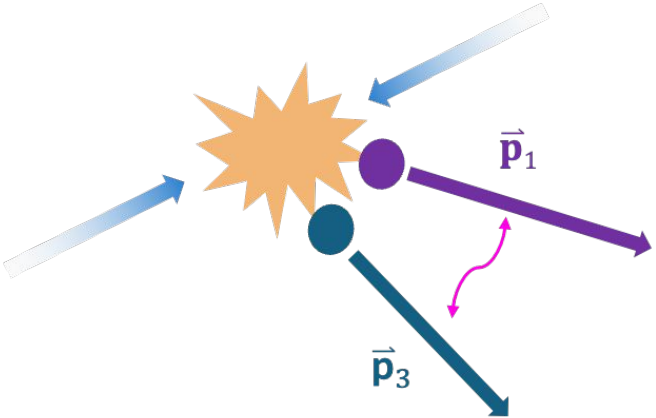
Extending the femtoscopy to many body studies



Correlation function:

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

relative momentum:

$$k^* = \frac{1}{2}\left|\vec{p}_a + \vec{p}_b\right|$$

relative distance:

$$r^*$$

M.Lisa, S. Pratt et al., ARNPS 55 (2005), 357-402
L. Fabbietti et al., ARNPS 71 (2021), 377-402

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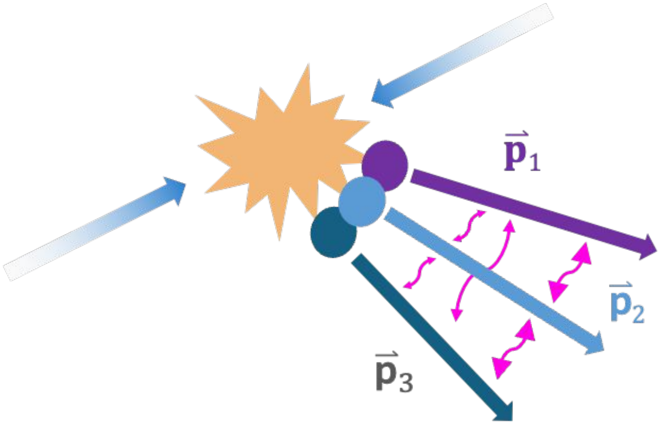

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$$C(Q_3) = \int S(\rho)|\psi(Q_3, \rho)|^2 \rho^5 \, d\rho$$

Hyper-momentum:

$$Q_3 = 2\sqrt{k_{12}^2 + k_{23}^2 + k_{31}^2}$$

R. Del Grande et al. EPJC 82 (2022) 244
ALICE Coll., EPJ A 59, 145 (2023)

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L. E. Marcucci et al., Front. in Phys. 8, 69 (2020).

See also talk of M. Lesch

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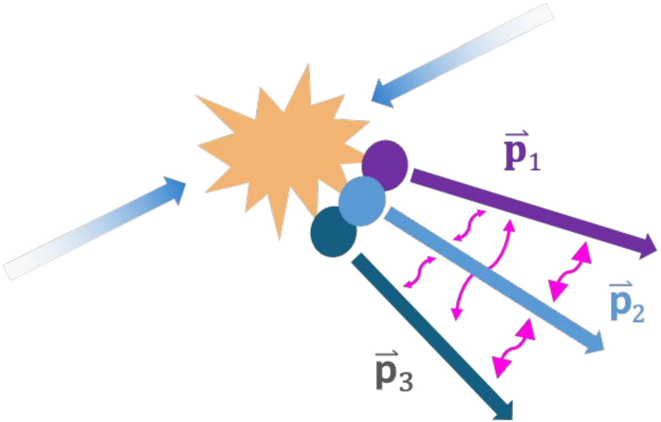

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HADES Coll. arXiv:2402.09280 (2024), proceedings

Theory (ALICE):
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M. Viviani et al, PRC 108 (2023) 6, 064002
A. Kievsky, et al., PRC 109 (2024) 3, 034006
E. Garrido et al., arXiv: 2408.01750 (2024)

Three-body analyses in

- pp collisions at ALICE: p-p-p, p-p-Λ, p-p-K^{+-}, p-p-π^{+-}, K-d, p-d, Λ-d
- Au-Au collisions at STAR: p-d, d-d
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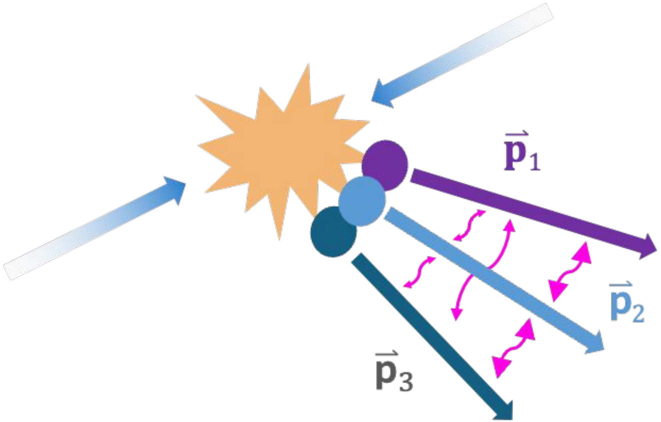

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πNN and πNNN correlations as testbed

Courtesy of L. Fabbietti

- Employ multi-correlation technique to study πNN and πNNN interactions in small colliding systems → doorway to access ‚large densities‘
- Lower order well under control’ plethora of πN and πNN scattering data

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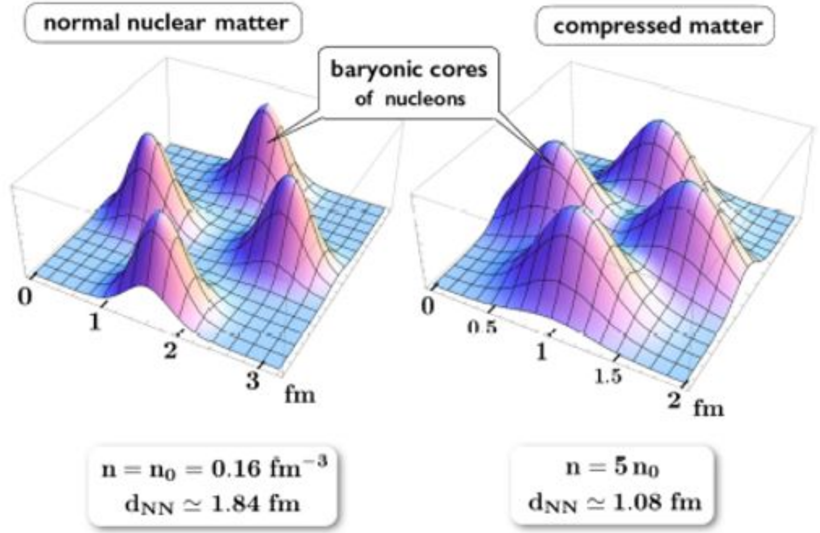
π properties in-medium

Momentum Correlations in pp collisions (or p-Pb, peripheral Pb-Pb)



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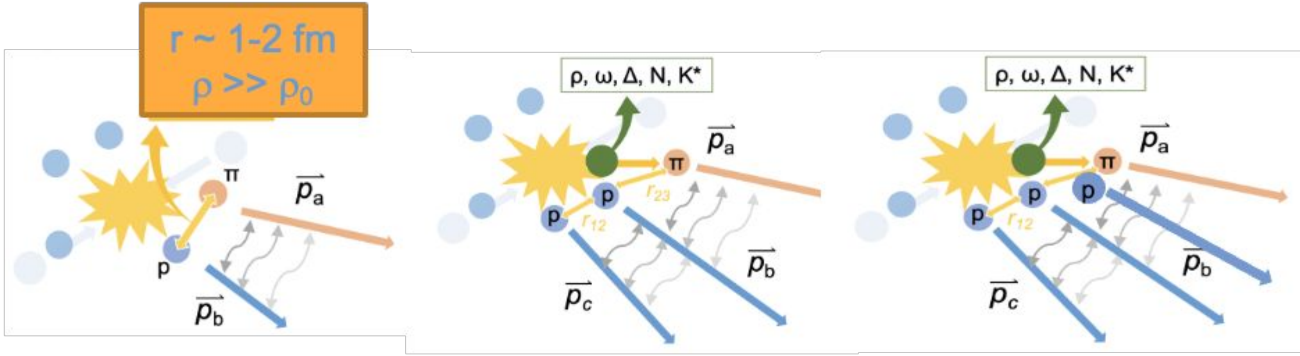

$f_{\pi N}$ $\quad$ $f_{\pi NN}$ $\quad$ $f_{\pi NNN} \propto f^*_{\pi}$

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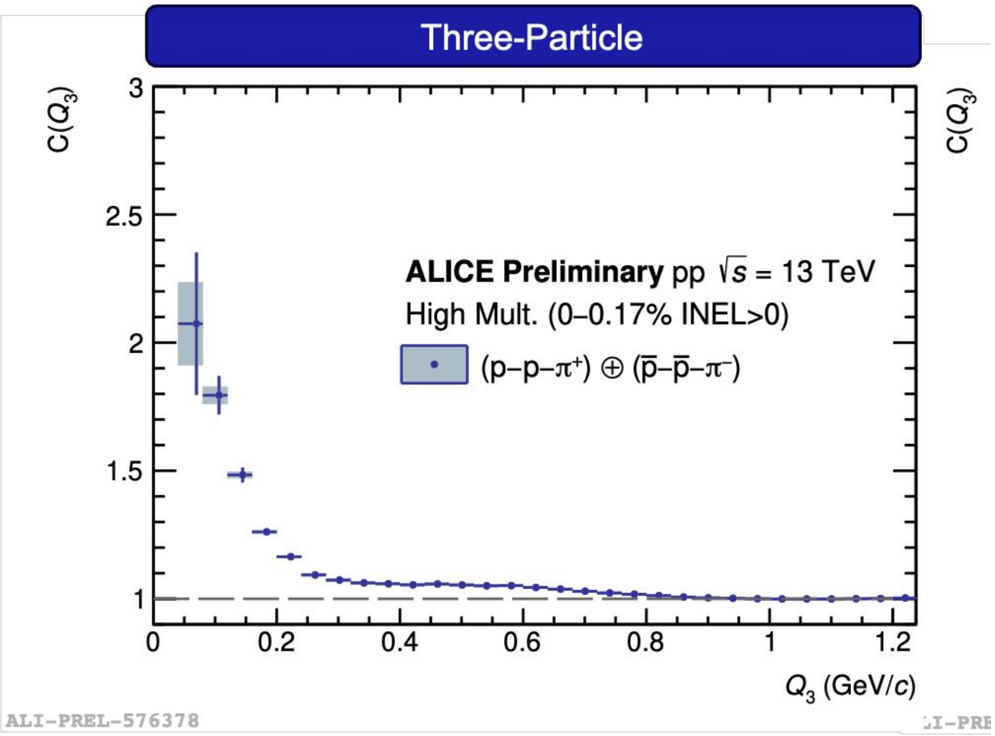
Do we see genuine πNN correlations?



- Paper in preparation
- 2B and 3B correlation measured
- Model available for 2B but missing full 3B calculations at the moment
- Hint of 3B effects observed using Kubo's cumulant method [1] (see back-up!)

[1] J. Phys. Soc. Jpn. 17, pp. 1100-1120 (1962)

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  - Establish procedure for many-body femtoscopy
  - Tag particles surrounded by close-by nucleons

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Future plans for πNN, πNNN and πNNNN

- Measure the correlations systematically starting from 2 body

- Perform a differential (m_T, multiplicity) analysis to pin down the particle emitting source

- Stimulate theory efforts to calculate predictions for the many body correlation function
    - Extract in-medium pion decay constant

$$f_{\pi NNN} \propto f_{\pi}^{*}$$

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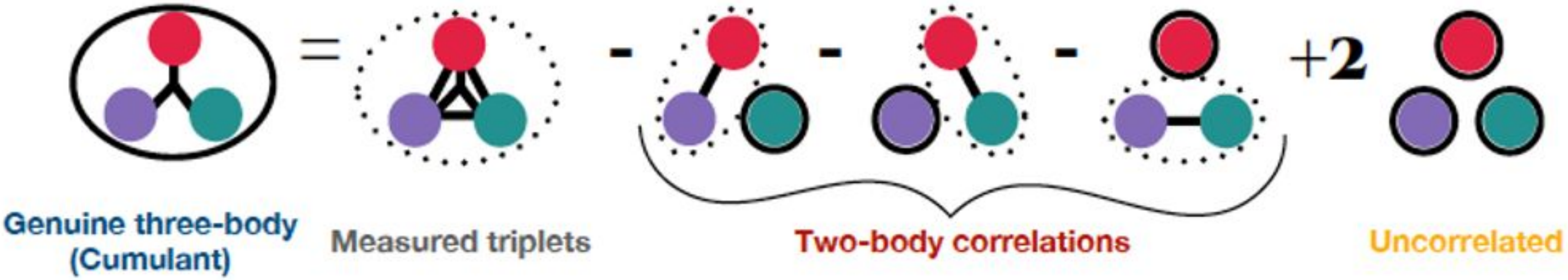
Back-up

Do we see genuine πNN correlations?



- Measured three particle correlation function includes both two-body and genuine three-body interactions.

- We use Kubo's cumulant method [1] for the same pair distribution and define a femtoscopic cumulant to access genuine 3B correlation [2].

[1] J. Phys. Soc. Jpn. 17, pp. 1100-1120 (1962)
[2] ALICE Coll., Phys.Rev.C 89 (2014) 2, 024911

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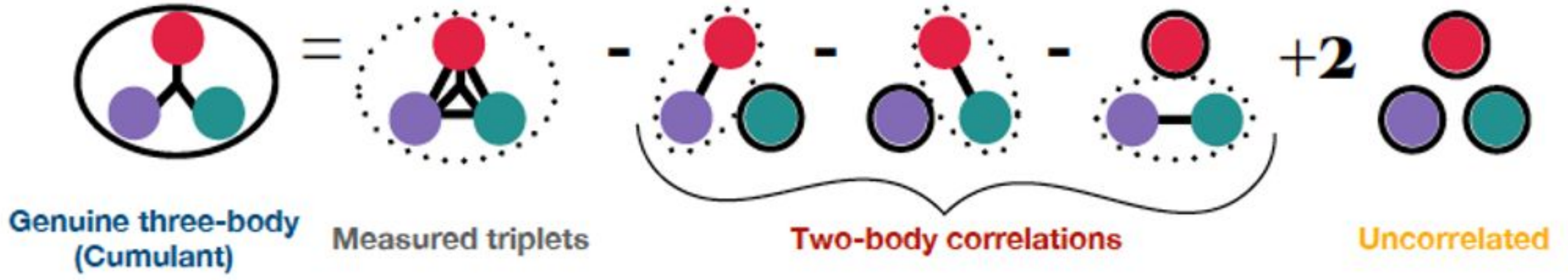
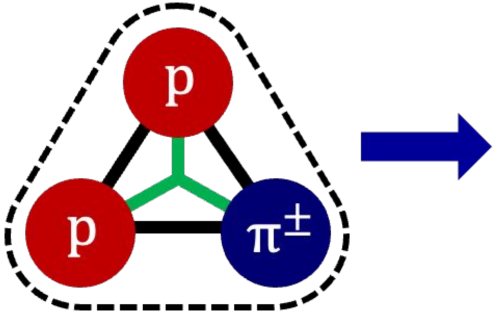
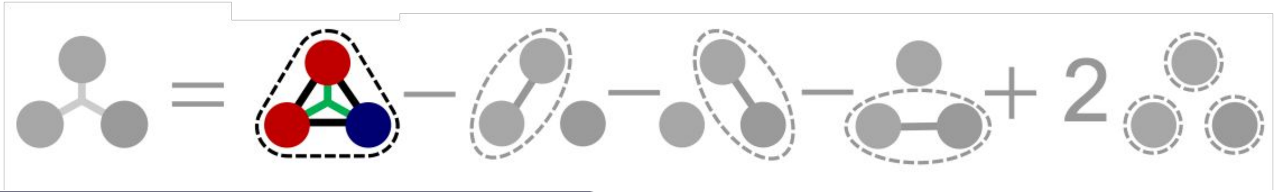
Do we see genuine πNN correlations?

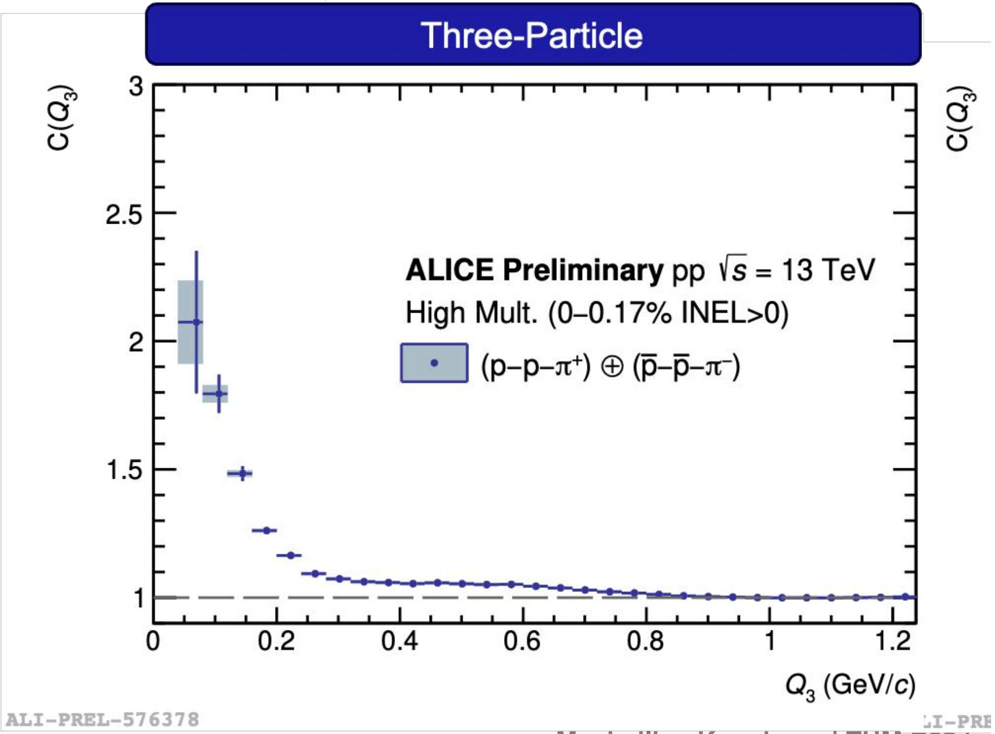




$$C(Q_3) = \mathcal{N}\frac{\mathrm{N_{same}}(Q_3)}{\mathrm{N_{mixed}}(Q_3)}$$

Do we see genuine πNN correlations?





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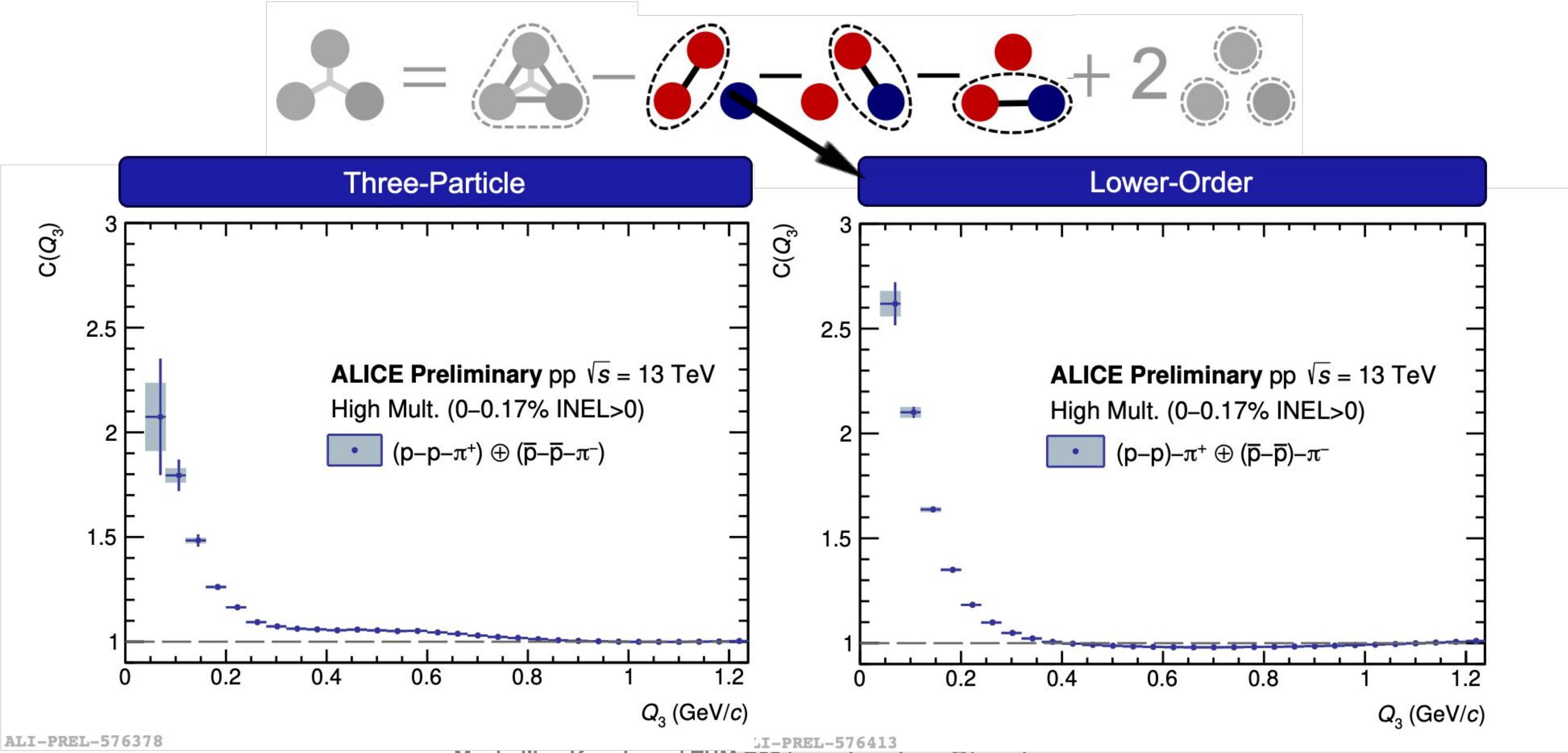
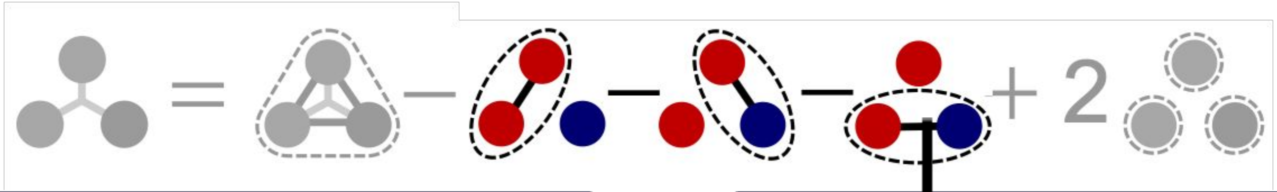
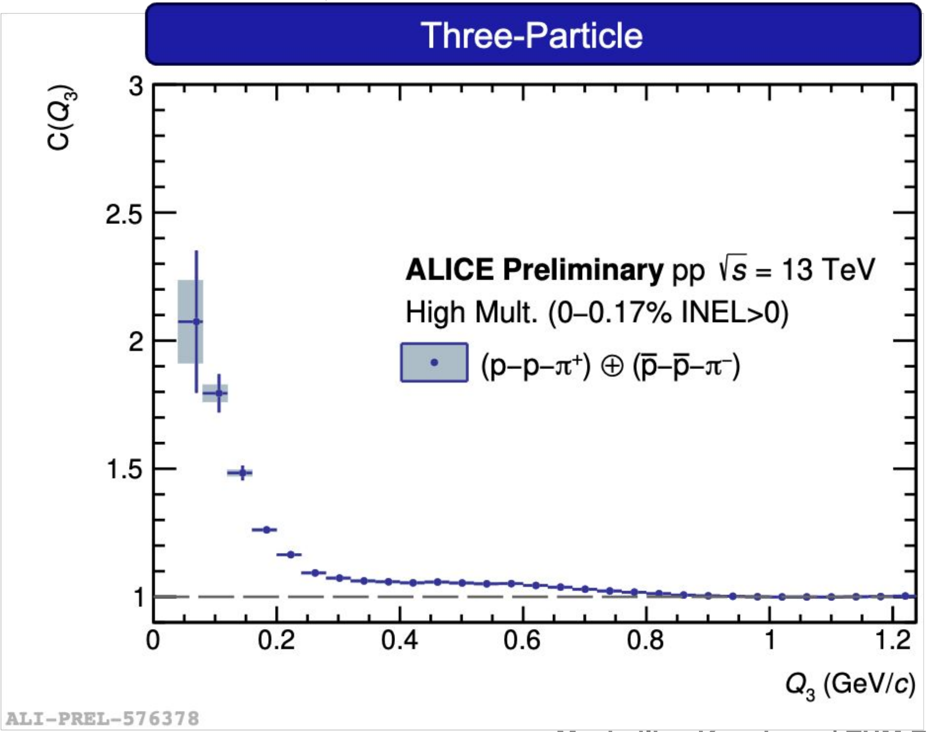
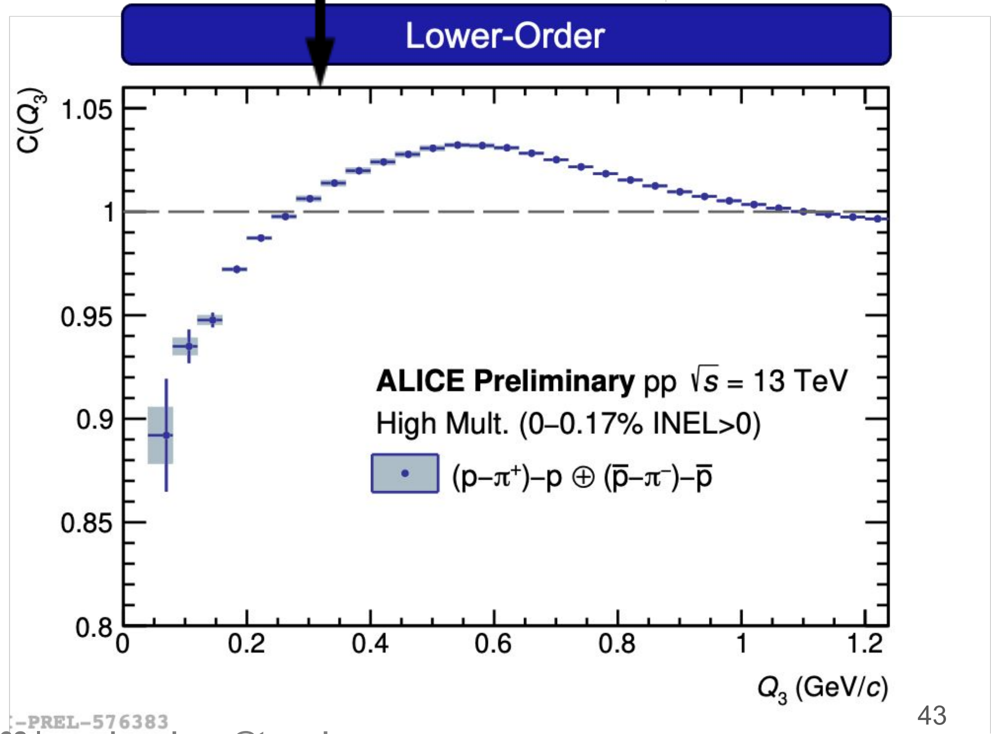


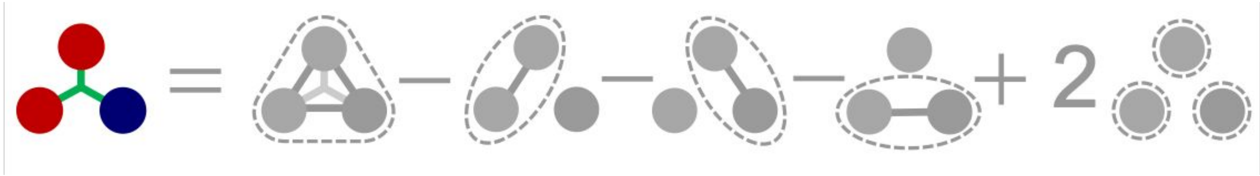
Do we see genuine πNN correlations?

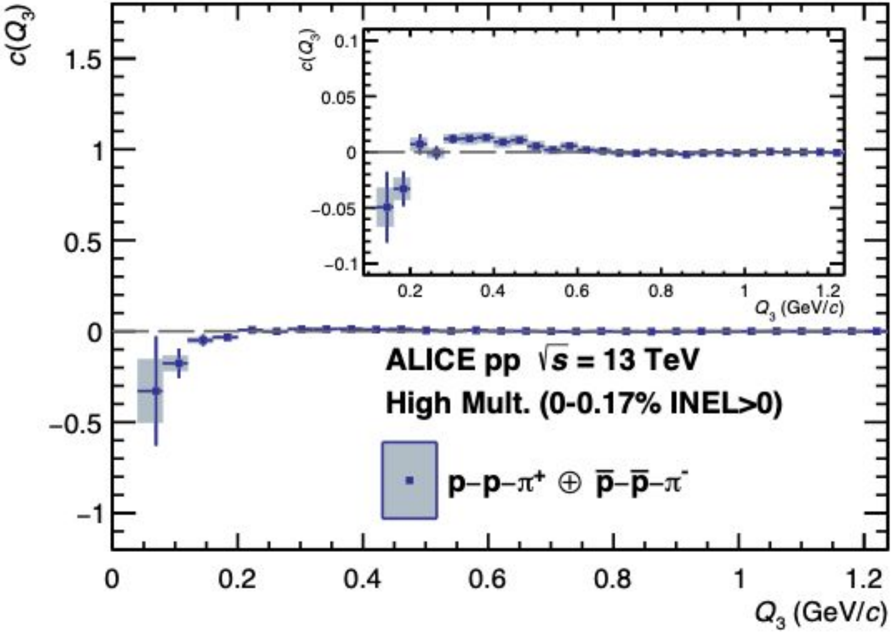






Do we see genuine πNN correlations?





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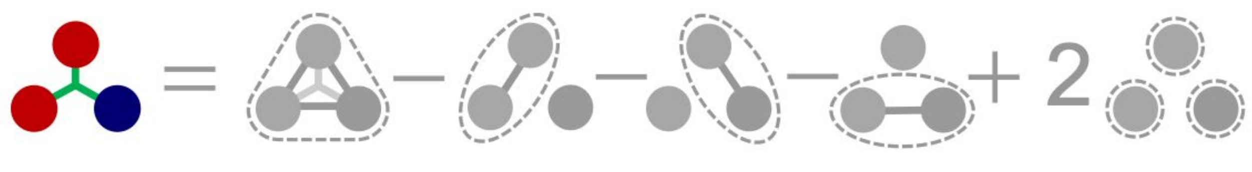
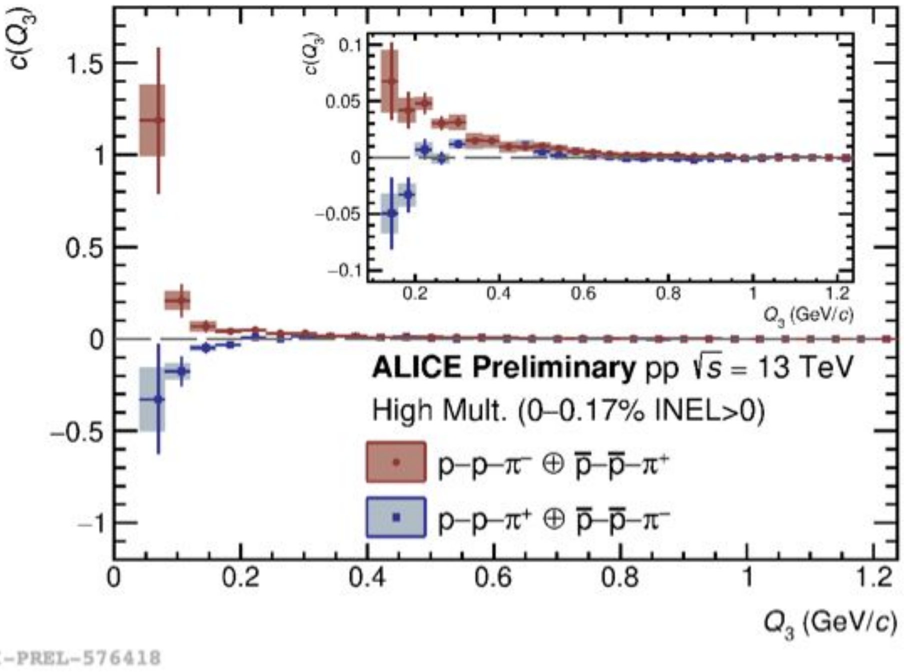
Do we see genuine πNN correlations?



- In both cases cumulant compatible with zero for large Q_3
  → No three-body effects

- Three-body effects for small $Q_3 < 200$ MeV/c
  Repulsion for π^+pp
  Attraction for π^-pp



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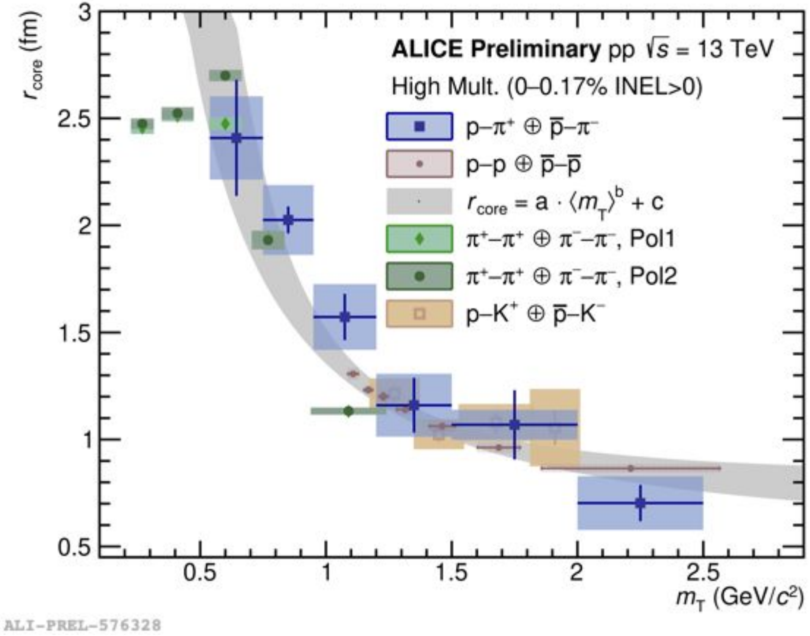
Constraining the source

- Three-particle source as independent Gaussian emitter

$$S(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3) = S(\boldsymbol{x}_1)\, S(\boldsymbol{x}_2)\, S(\boldsymbol{x}_3)$$

r_{12} r_{23}

- Pair radii r_{12}, r_{23}, r_{31} obtained from common source model using the m_T of the pairs in the triplets.

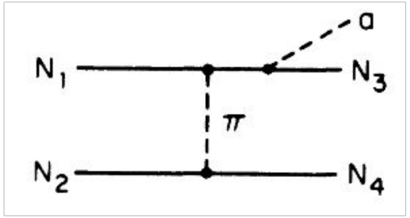


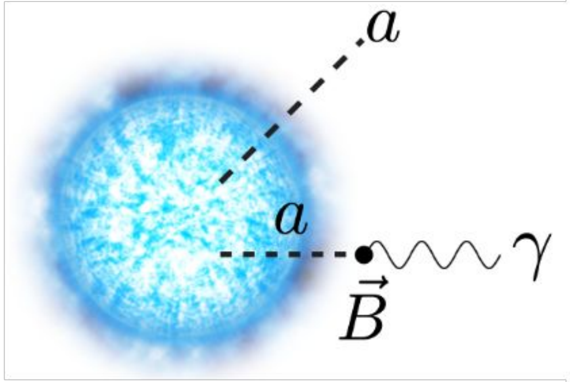
ALICE Coll., arXiv:2311.14527 accepted by EPJC
ALICE Coll., PLB, 811 (2020), 135849
ALICE Coll, paper in preparation

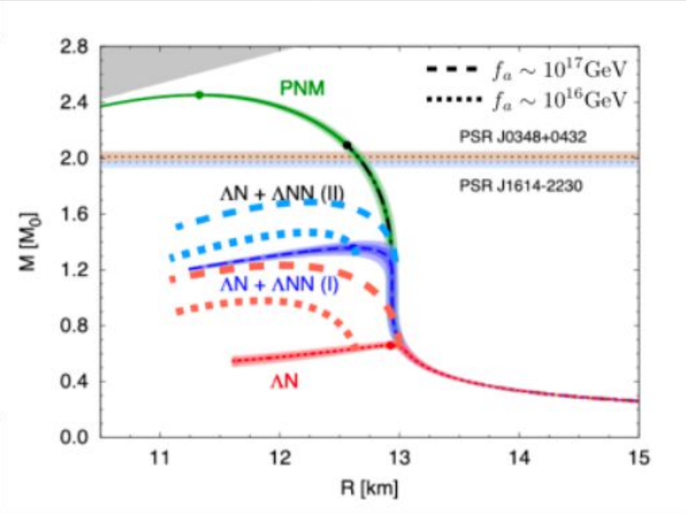
An additional motivation.. Beyond standard model

Axions are good candidate to stabilize the otherwise very soft hadronic equation of state of neutron stars

(Raffelt '06 hep-ph/0611350)







➡ The challenge is to determine the in-medium properties of axions

➡ Connection to the in-medium pion properties

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An additional motivation.. Beyond standard model

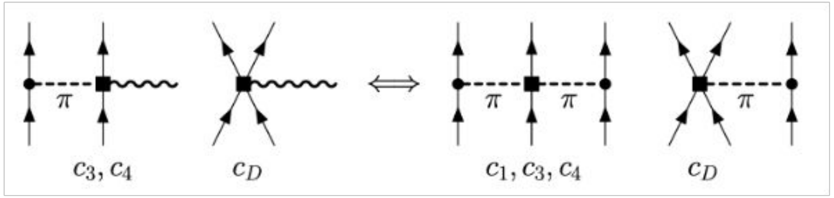
Axion-Nucleon coupling

$$c_N \frac{\partial_\mu a}{2 f_a} \bar{N} \gamma^\mu \gamma_5 N, \quad N = p, n$$

RB, Springmann, Serra, Weiler '20

$$\frac{(g_A)_n}{(g_A)_0} = \frac{(\Delta u - \Delta d)_n}{(\Delta u - \Delta d)_0} \simeq 1 + n \left(\frac{c_D}{4 (g_A)_0 f_\pi^2 \Lambda_\chi} - \frac{1}{3 f_\pi^2} \left(2c_4 - c_3 + \frac{1}{2M} \right) \right)$$

(Schwenk et. al. 1103.3622)



Pion in medium properties not known … either need higher order nucleon pion interactions in vacuum or some way to measure directly …