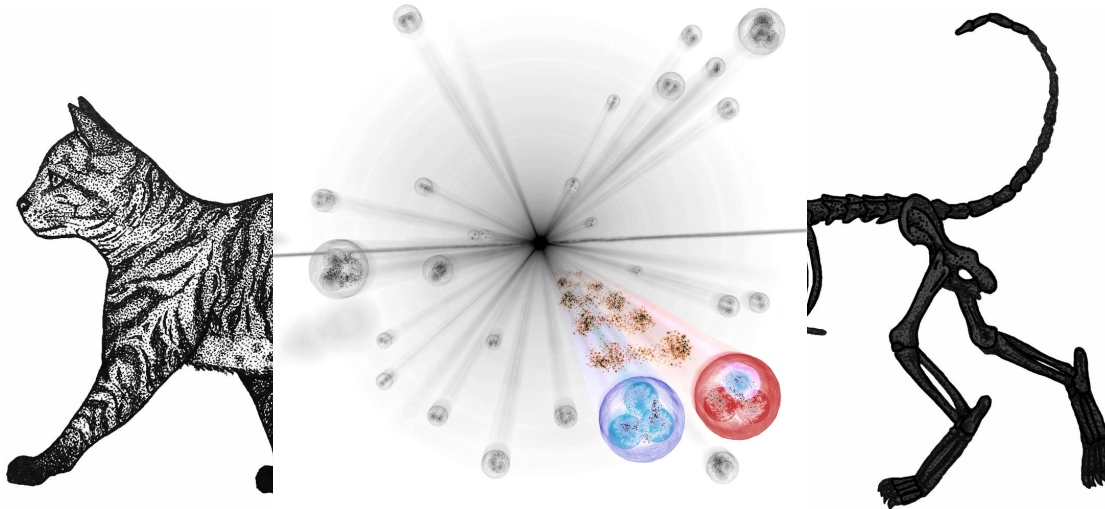




Strong hadron-hadron interactions with femtoscopy

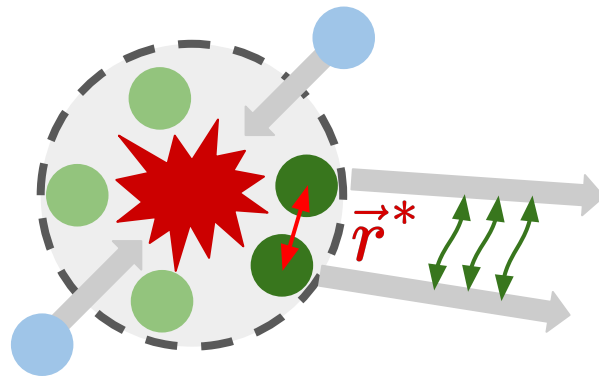
Dimitar Mihaylov on behalf of the LHC experiments



Femtoscscopy @ LHC

Koonin-Pratt equation

[Lisa et al.](#)
[Ann.Rev.Nucl.Part.Sci.55:357-402, 2005](#)



two-particle relative momentum
 $q = 2 \cdot k^*$

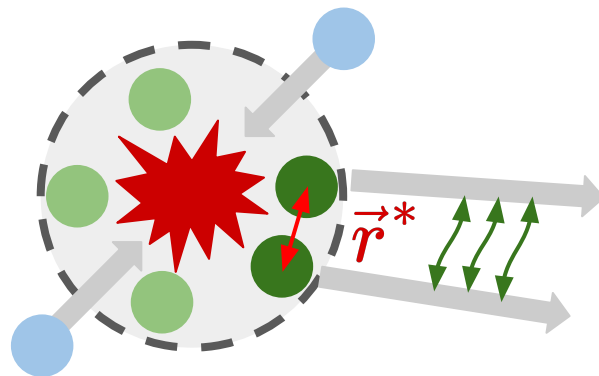
$\Psi(\vec{k}^*, \vec{r}^*)$
two-particle wave function

$$C(k^*) = \frac{N_{\text{SE}}(k^*)}{N_{\text{ME}}(k^*)} = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \rightarrow \infty} 1$$

Femtoscscopy @ LHC

Koonin-Pratt equation

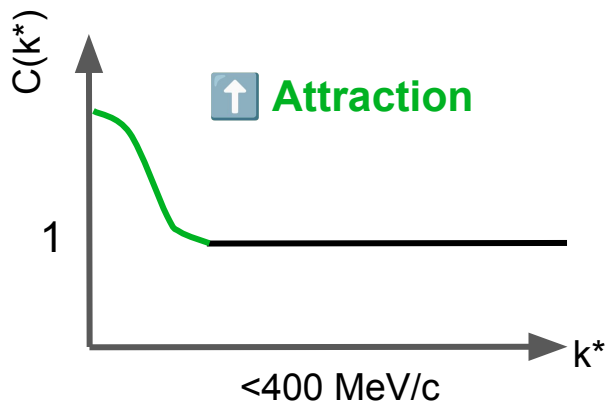
[Lisa et al.](#)
[Ann.Rev.Nucl.Part.Sci.55:357-402, 2005](#)



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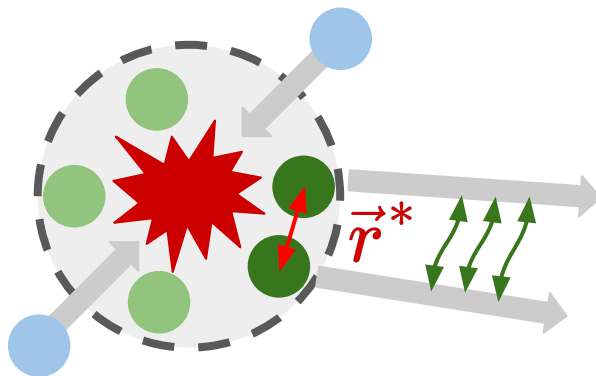
$$C(k^*) = \frac{N_{SE}(k^*)}{N_{ME}(k^*)} = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \rightarrow \infty} 1$$



Femtoscscopy @ LHC

Koonin-Pratt equation

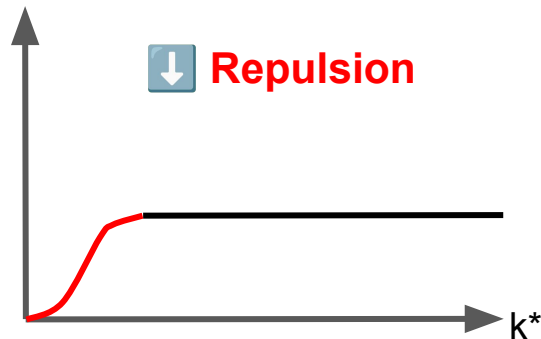
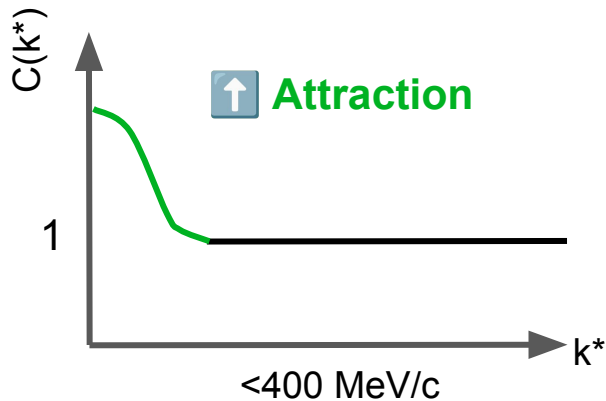
[Lisa et al.](#)
[Ann.Rev.Nucl.Part.Sci.55:357-402, 2005](#)



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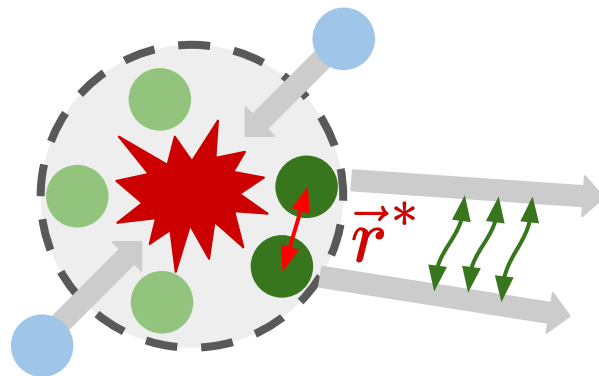
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Femtoscscopy @ LHC

Koonin-Pratt equation

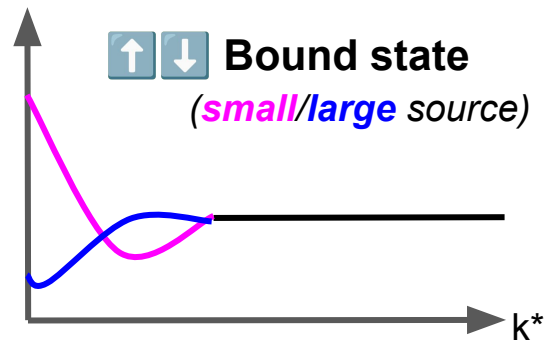
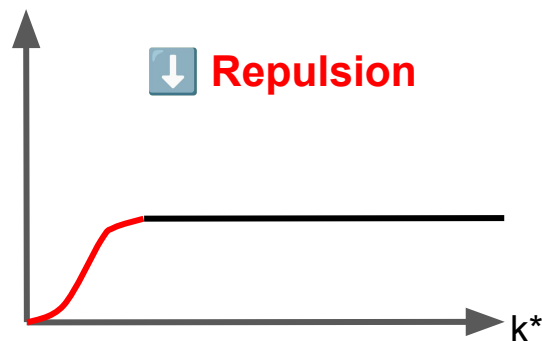
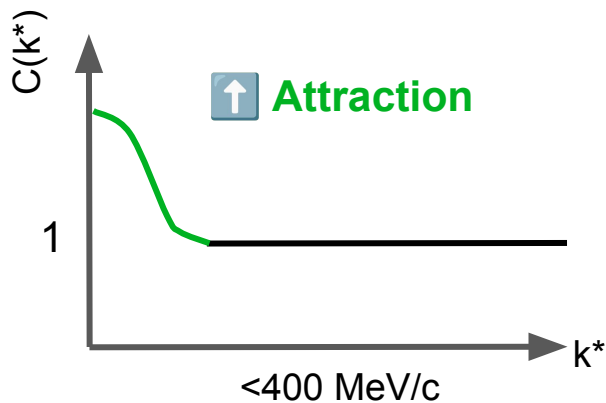
[Lisa et al.](#)
[Ann.Rev.Nucl.Part.Sci.55:357-402, 2005](#)



two-particle relative momentum
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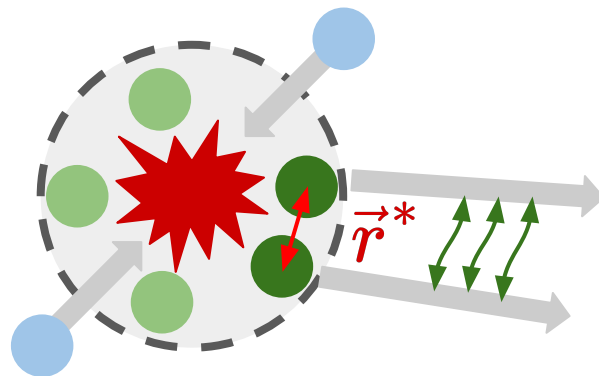
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Femtoscscopy @ LHC

Koonin-Pratt equation

[Lisa et al.](#)
[Ann.Rev.Nucl.Part.Sci.55:357-402, 2005](#)



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FIX



Femtoscscopy @ LHC

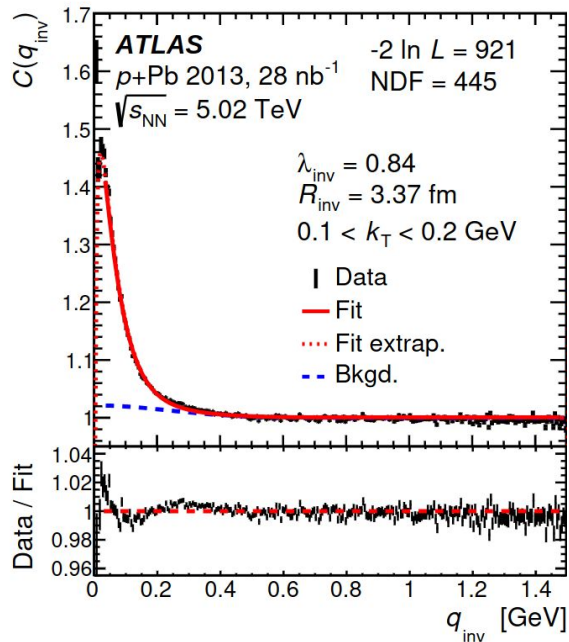
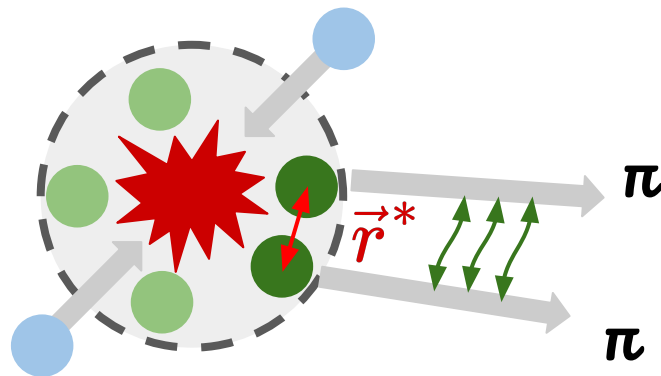
$\pi\pi$ correlations



p -Pb collisions @ 5.02 TeV

20-30% centrality

[PRC 96 \(2017\) 6. 064908](#)



Femtoscscopy @ LHC

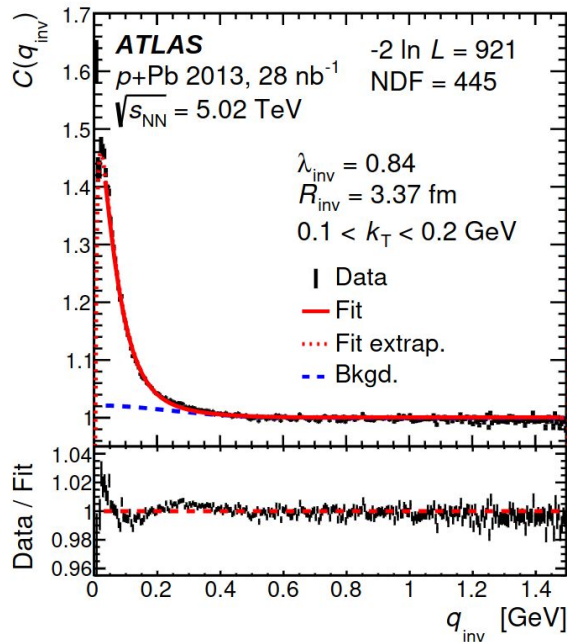
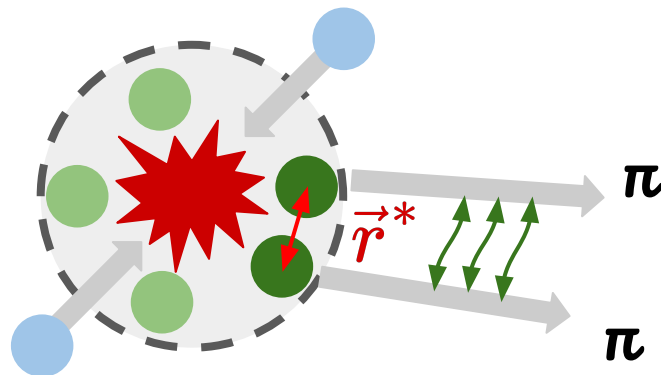
$\pi\pi$ correlations



p -Pb collisions @ 5.02 TeV

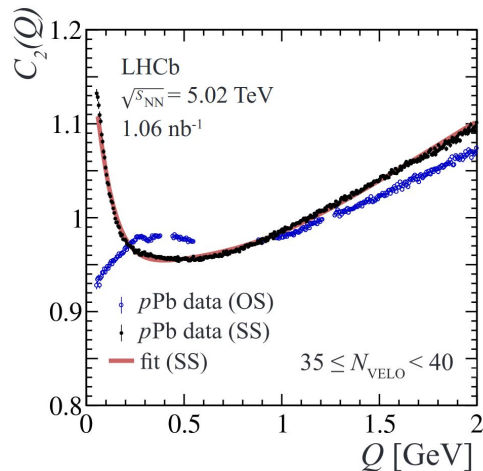
20-30% centrality

[PRC 96 \(2017\) 6. 064908](#)



Similar results by LHCb

[JHEP 09 \(2023\) 172](#)



Femtoscscopy @ LHC

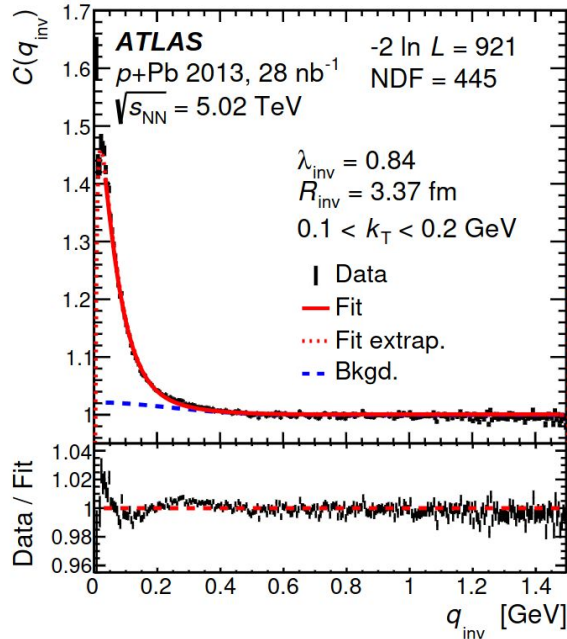
$\pi\pi$ correlations



p -Pb collisions @ 5.02 TeV

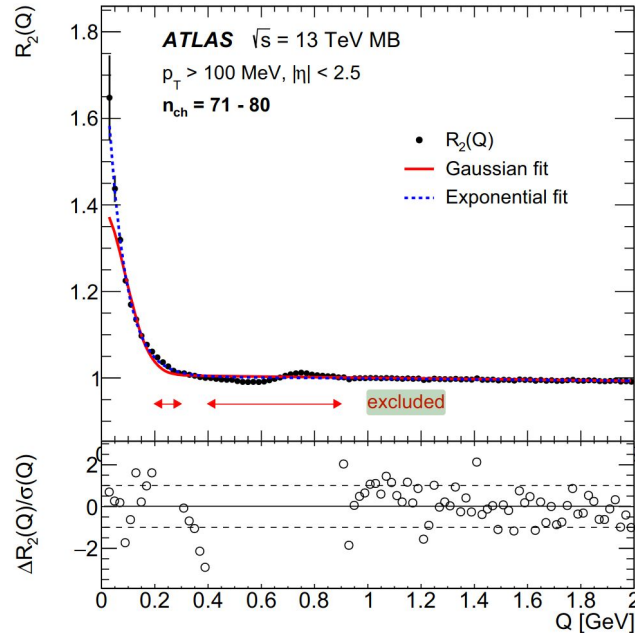
20-30% centrality

[PRC 96 \(2017\) 6. 064908](#)



pp collisions @ 13 TeV

[EPJC 82 \(2022\) 7. 608](#)



- $\pi\pi$ correlations well described by a Cauchy source (exp. correlation) in small coll. systems

- Also measured by
CMS [JHEP 03 \(2020\) 014](#)
LHCb [JHEP 12 \(2017\) 025](#)



- Equivalent studies and use of Lévy distribution in HI collisions by **CMS** [PRC 109 \(2024\) 2](#)



- The non-Gaussian profile (in small systems) may be related to production from resonances

Femtoscscopy @ LHC

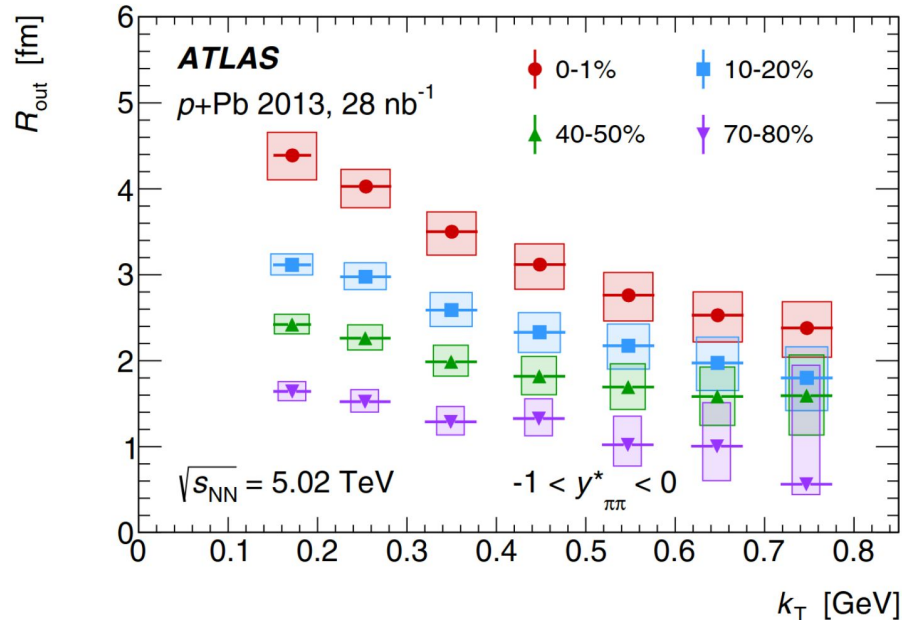
Emission source

- k_T (m_T) scaling observed in p-Pb and Pb-Pb collision and associated with collectivity

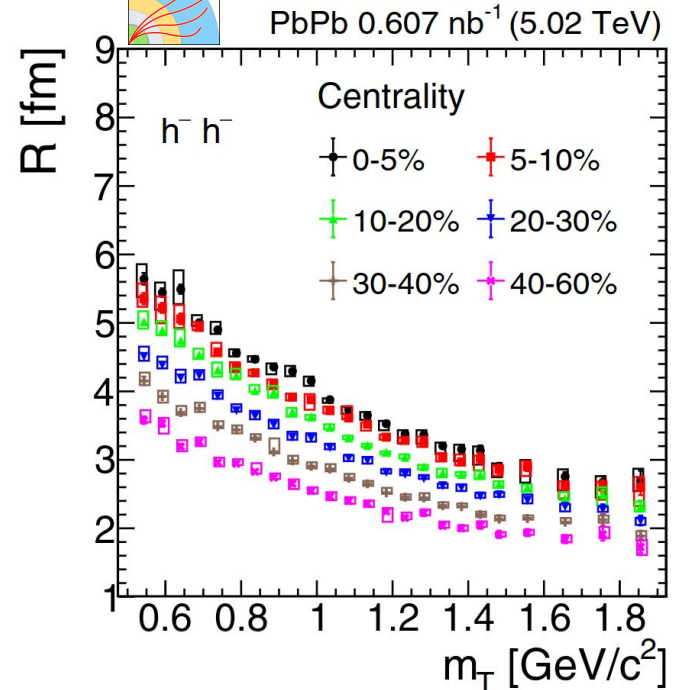


p-Pb collisions @ 5.02 TeV

[PRC 96 \(2017\) 6. 064908](#)



[PRC 109 \(2024\) 2](#)



Femtoscscopy @ LHC

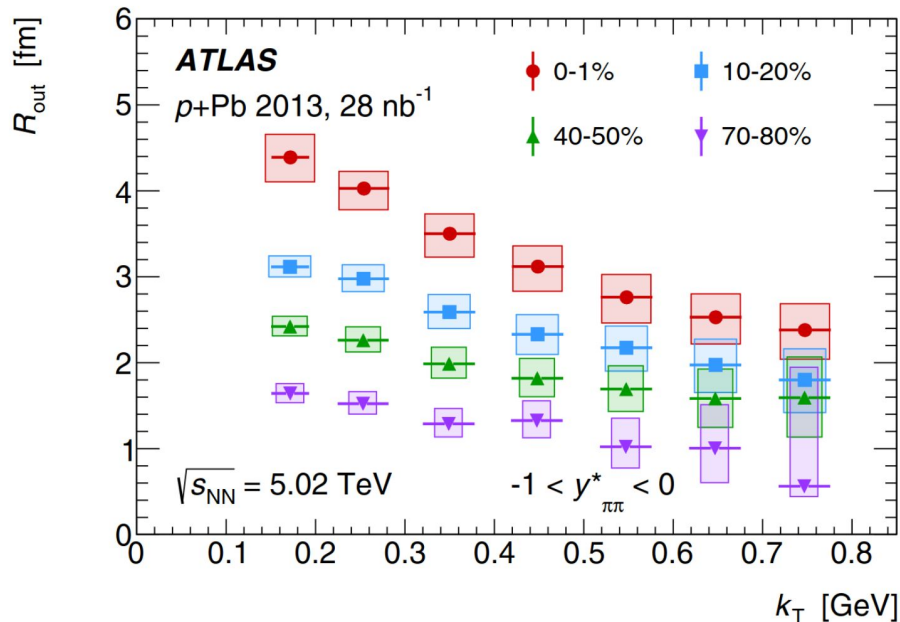
Emission source

- Similar results in pp collisions



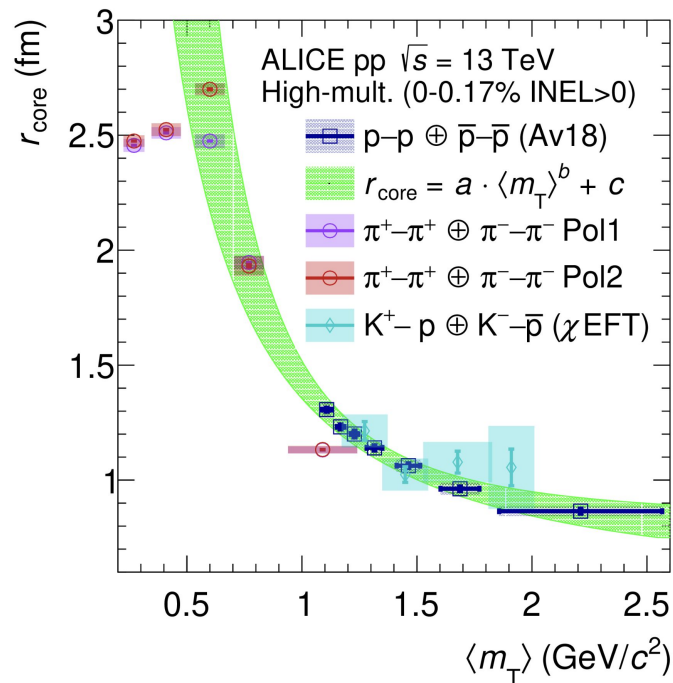
p-Pb collisions @ 5.02 TeV

[PRC 96 \(2017\) 6. 064908](#)



pp collisions @ 13 TeV

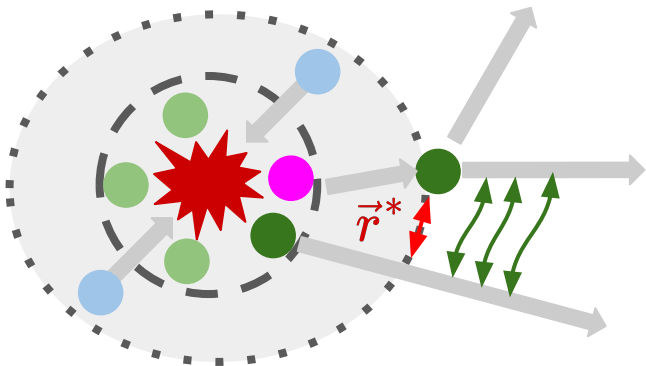
[arXiv 2311.14527 \(2024\)](#)



Femtoscscopy @ LHC

Emission source in pp collisions

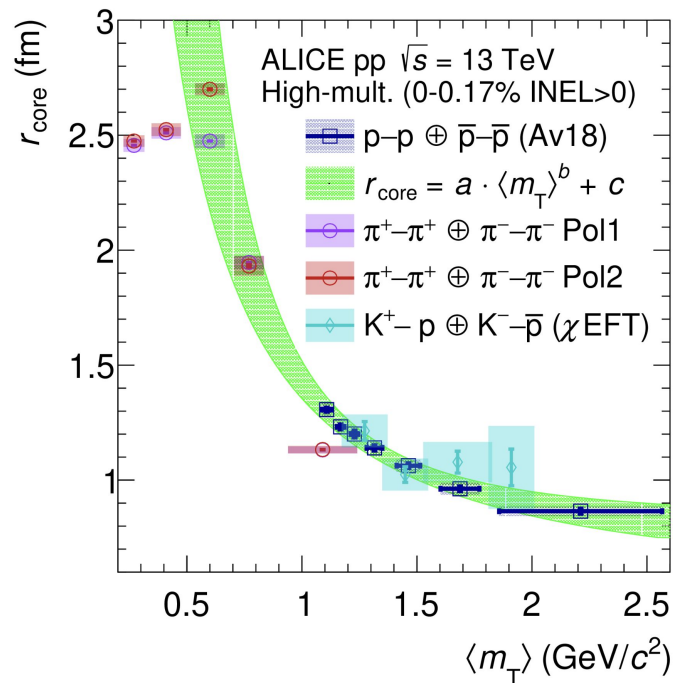
- Resonances with $\tau \sim 1$ fm (Δ, N^* , etc.) introduce an exponential tail to the source
- Different for each particle species



ALICE

pp collisions @ 13 TeV

[arXiv 2311.14527 \(2024\)](https://arxiv.org/abs/2311.14527)



Femtoscscopy @ LHC

Emission source in pp collisions

- Resonances with $\sigma_T \sim 1$ fm (Δ, N^* , etc.) introduce an exponential tail to the source
- Different for each particle species

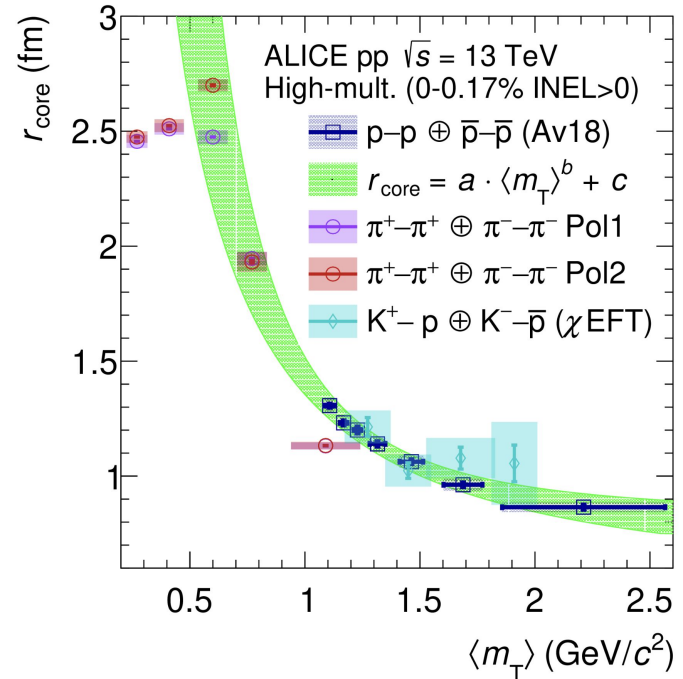
- A common Gaussian source for all hadrons in pp collisions
Allows to FIX the emission source from pairs of known interactions and study the interaction for more exotic species!



ALICE

pp collisions @ 13 TeV

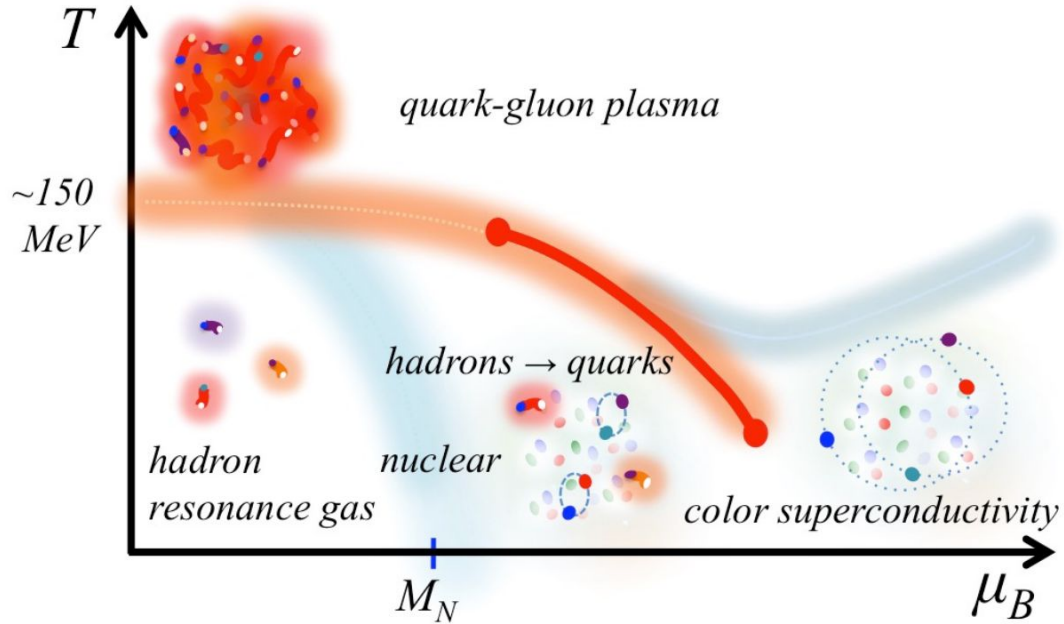
[arXiv 2311.14527 \(2024\)](https://arxiv.org/abs/2311.14527)



Hadron-hadron interactions

Quantum chromodynamics

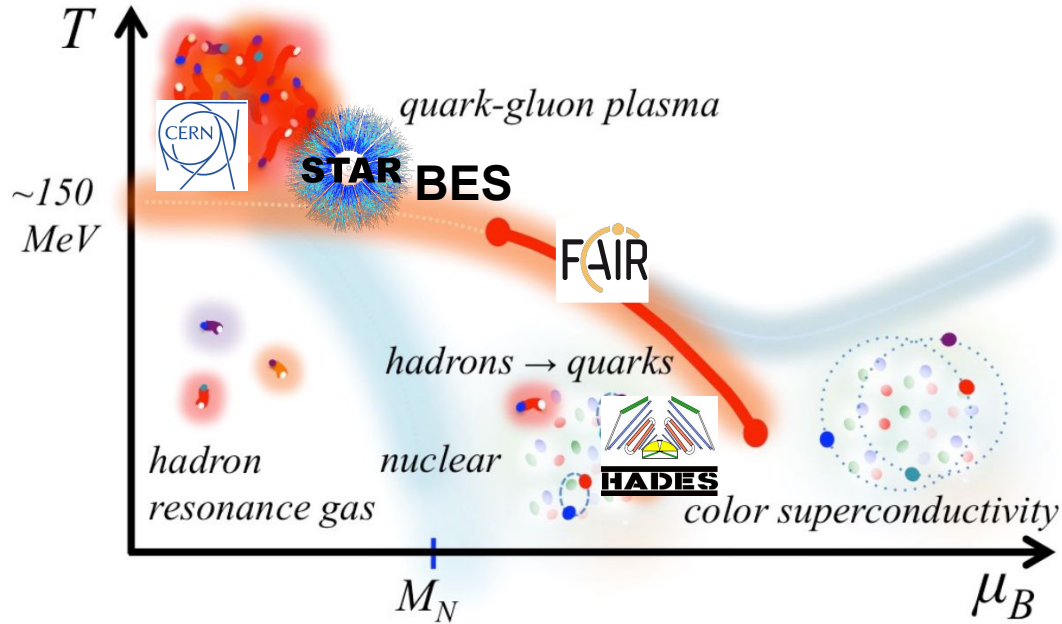
[G. Baym et al. Rept.Prog.Phys. 81 \(2018\) 5, 056902](#)



Hadron-hadron interactions

Quantum chromodynamics

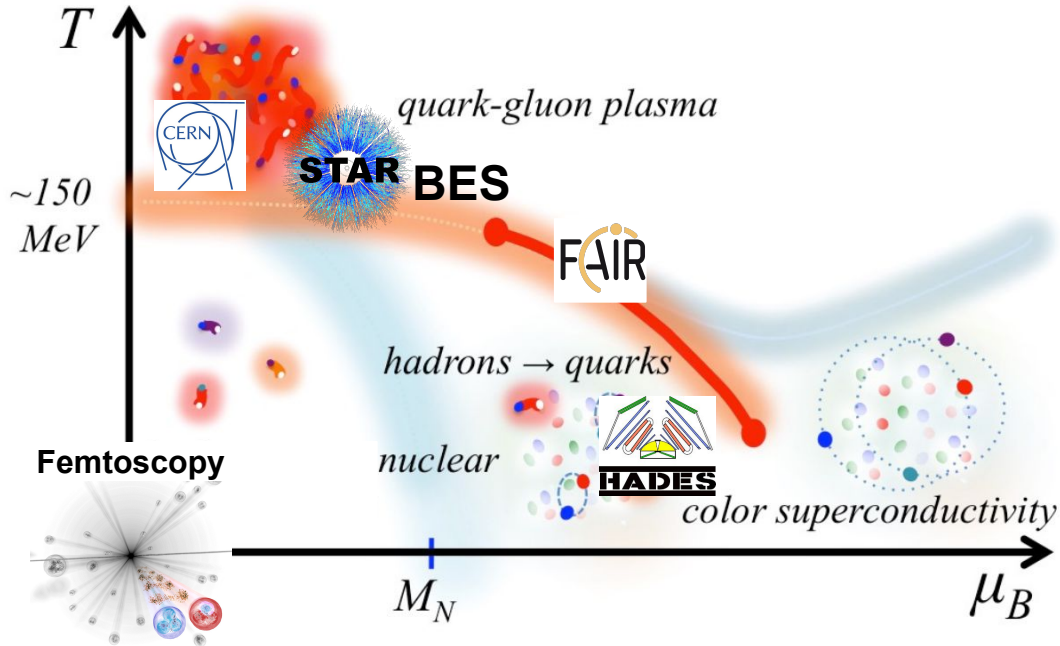
[G. Baym et al. Rept.Prog.Phys. 81 \(2018\) 5, 056902](#)



Hadron-hadron interactions

Quantum chromodynamics

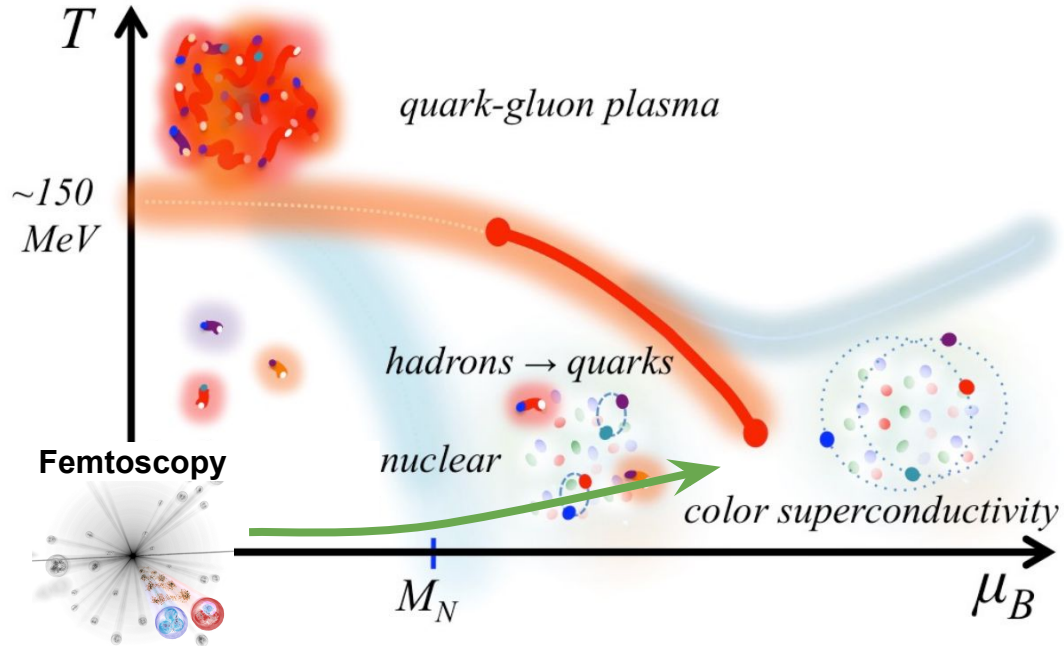
[G. Baym et al. Rept.Prog.Phys. 81 \(2018\) 5, 056902](#)



Hadron-hadron interactions

Neutron stars

[G. Baym et al. Rept.Prog.Phys. 81 \(2018\) 5, 056902](#)

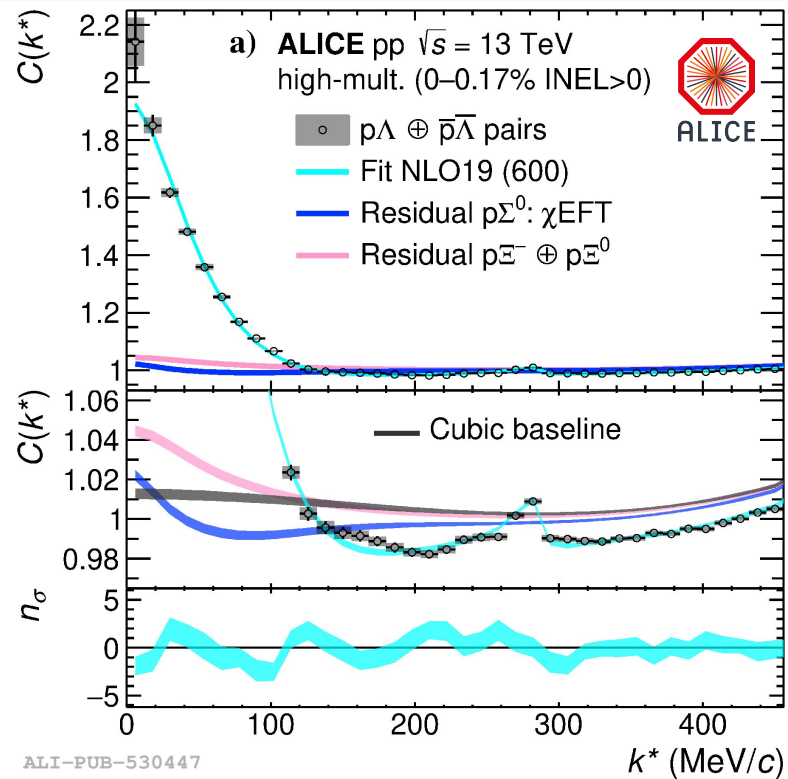
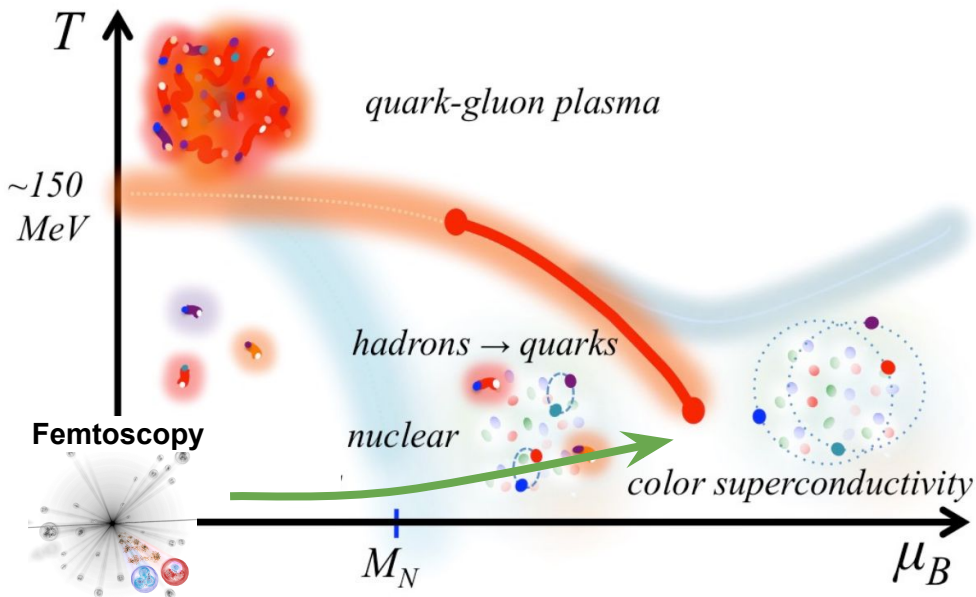


Hadron-hadron interactions

Neutron stars: $p\Lambda$

- High-precision “low-energy scattering data”, inaccessible with scattering experiments

[G. Baym et al. Rept.Prog.Phys. 81 \(2018\) 5, 056902](#)



ALI-PUB-530447

Data: [ALICE Coll. PLB 833 \(2022\) 137272](#)

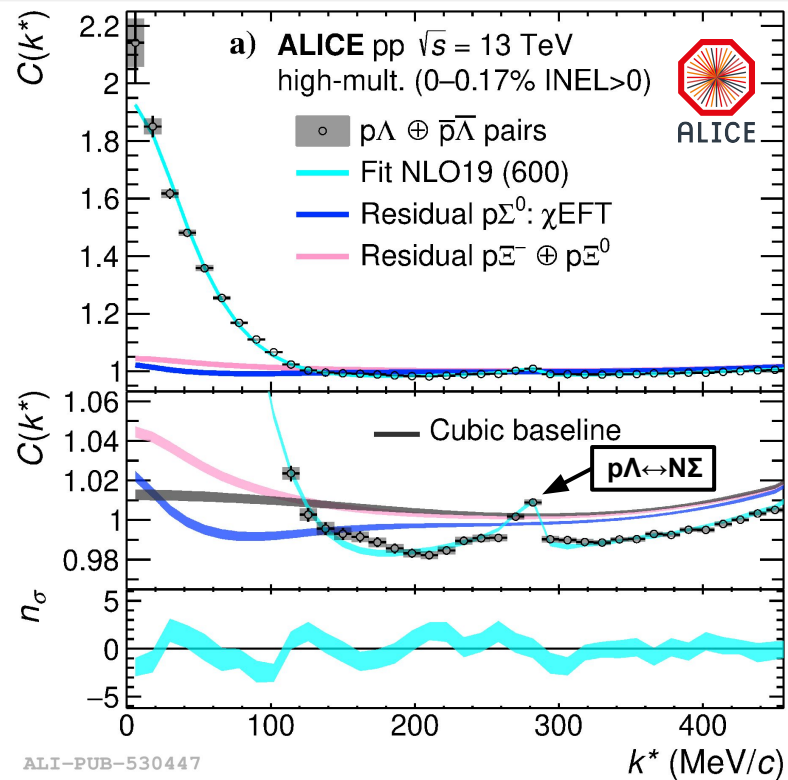
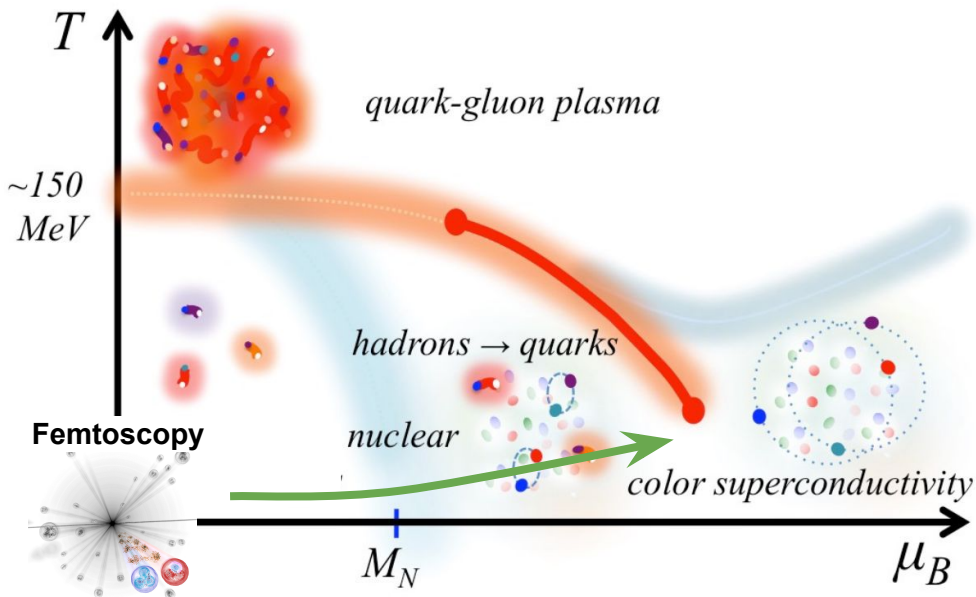
Model: [Haidenbauer et al. EPJA 56 \(2020\) 3, 91](#)

Hadron-hadron interactions

Neutron stars: $p\Lambda$

- High-precision “low-energy scattering data”, inaccessible with scattering experiments

[G. Baym et al. Rept.Prog.Phys. 81 \(2018\) 5, 056902](#)



ALI-PUB-530447

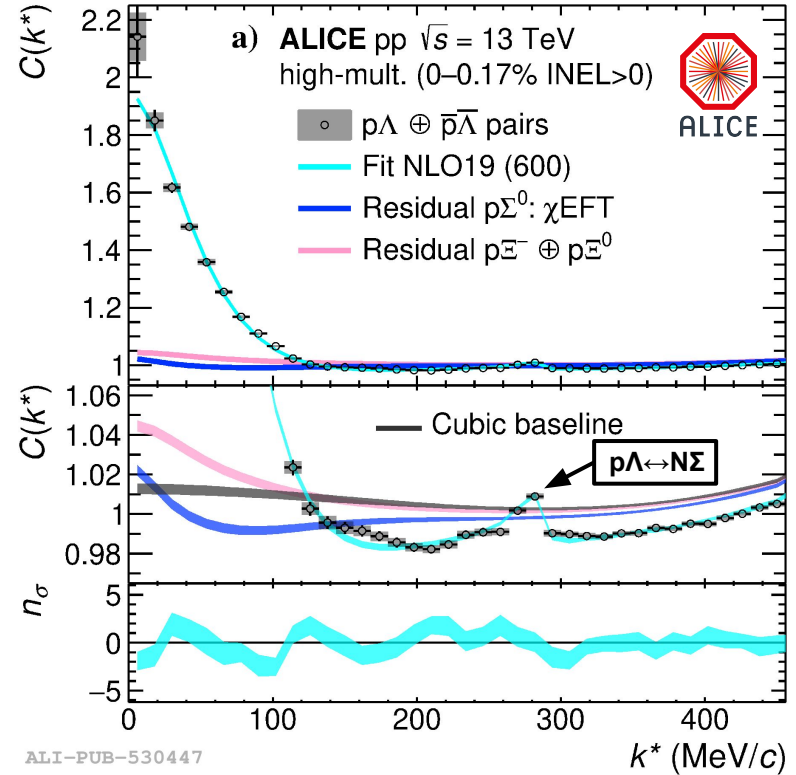
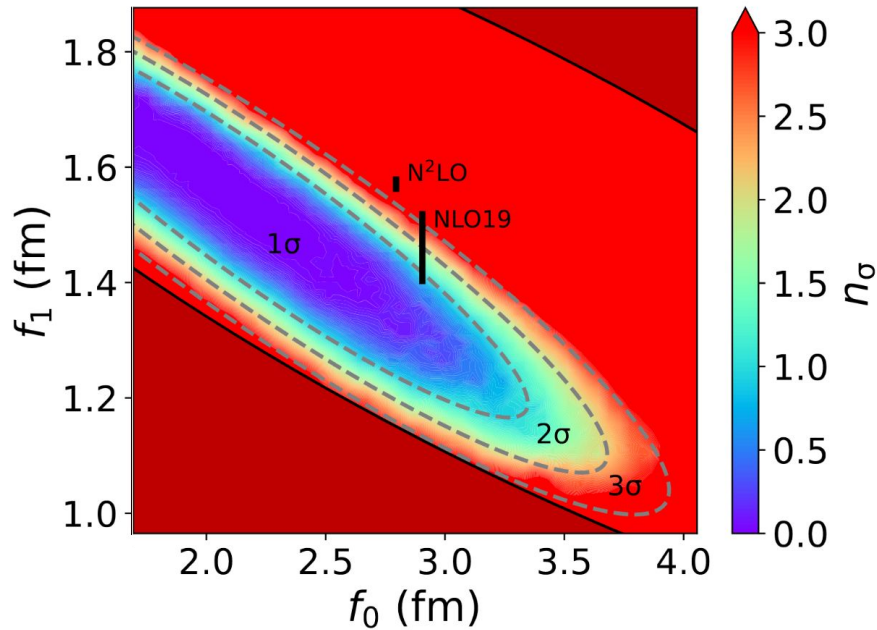
Data: [ALICE Coll. PLB 833 \(2022\) 137272](#)

Model: [Haidenbauer et al. EPJA 56 \(2020\) 3, 91](#)

Hadron-hadron interactions

Neutron stars: $p\Lambda$

NEW: Combined analysis of femtoscopic and scattering data



ALI-PUB-530447

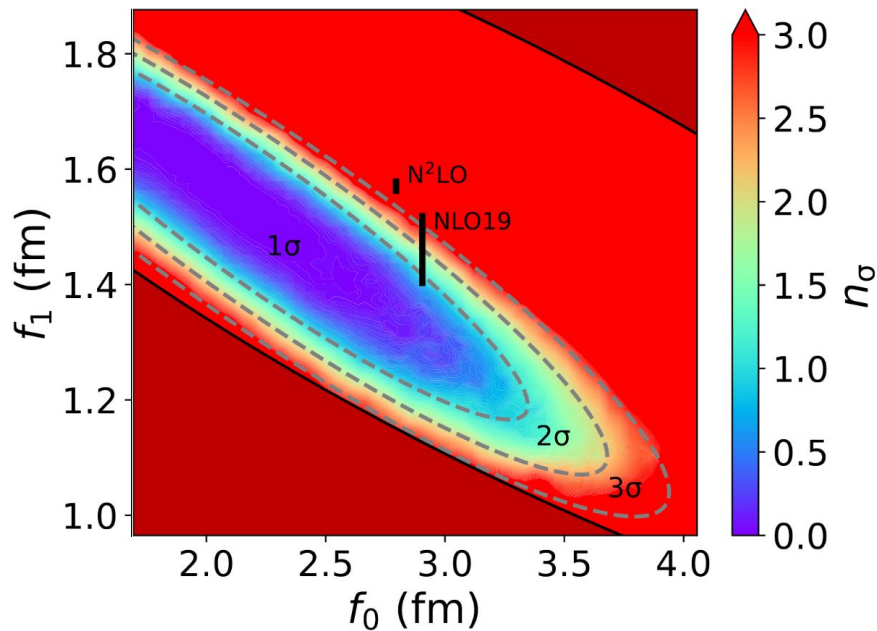
Data: [ALICE Coll. PLB 833 \(2022\) 137272](#)

Model: [Haidenbauer et al. EPJA 56 \(2020\) 3, 91](#)

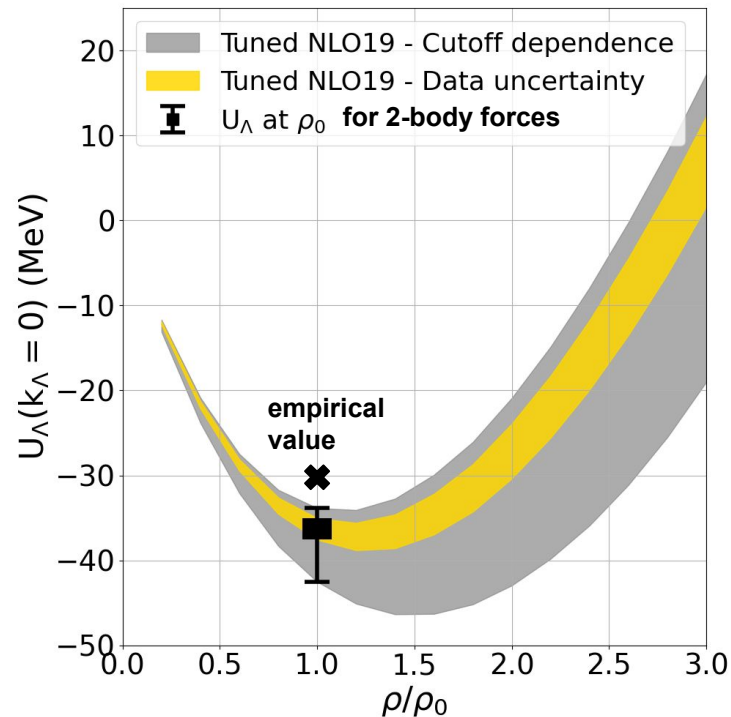
Hadron-hadron interactions

Neutron stars / equation of state

NEW: Combined analysis of femtoscopic and scattering data



New parameterizations of the χ EFT
Compatible with repulsive 3-body forces



Three body interactions

Using proton-deuterons

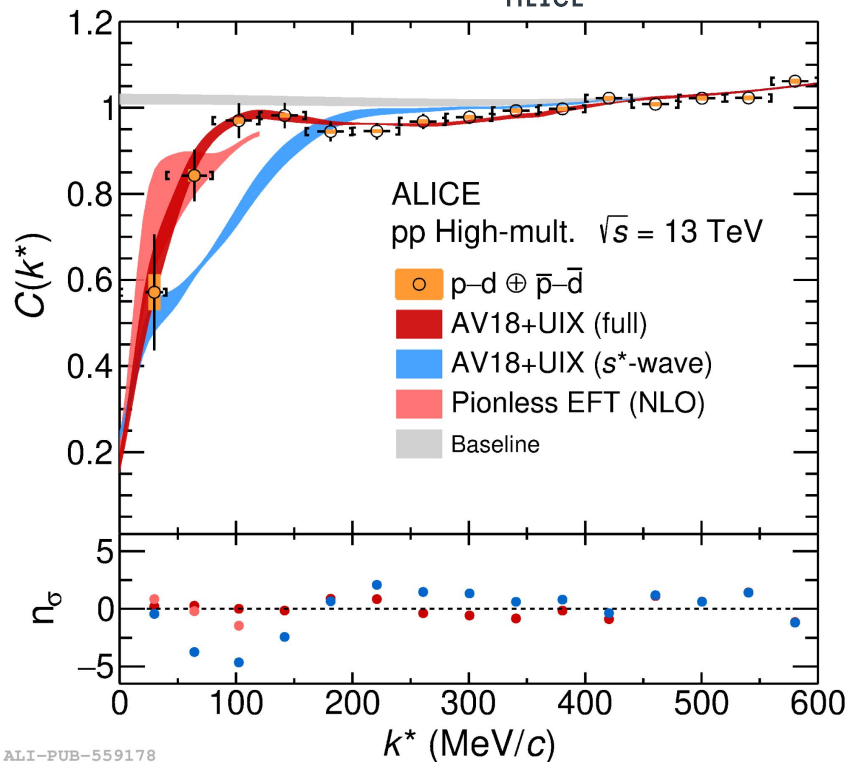
Monday 9:30 AM: Marco Van Leeuwen

Monday 5:45 PM: Paolo Gandini

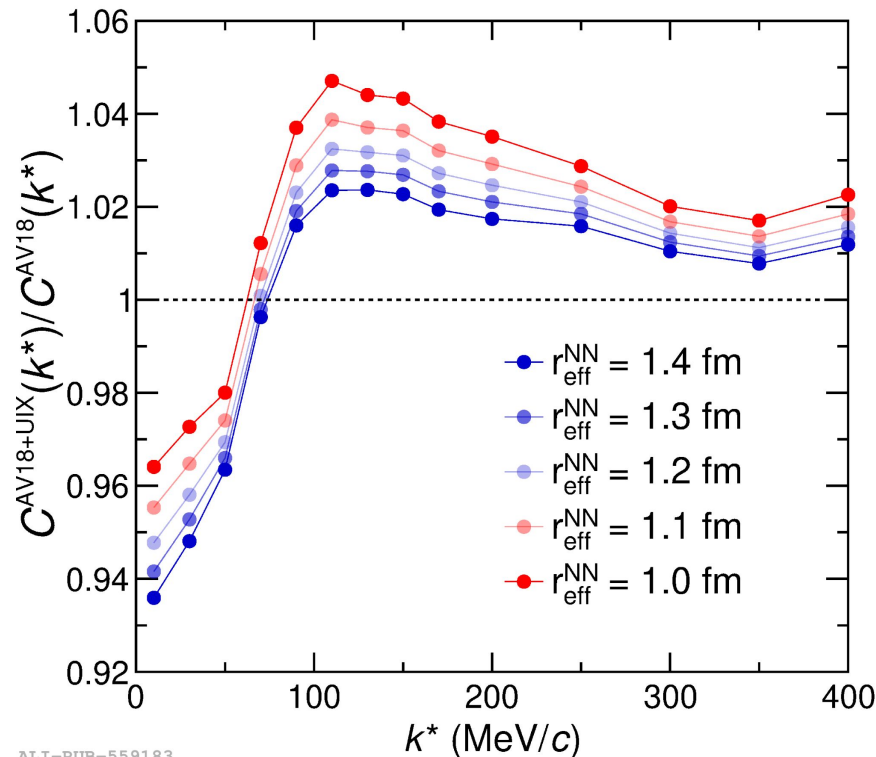


ALICE

[arXiv 2308.16120 \(2023\)](https://arxiv.org/abs/2308.16120)



- Expected genuine 3-body effect from UIX ~2-4%



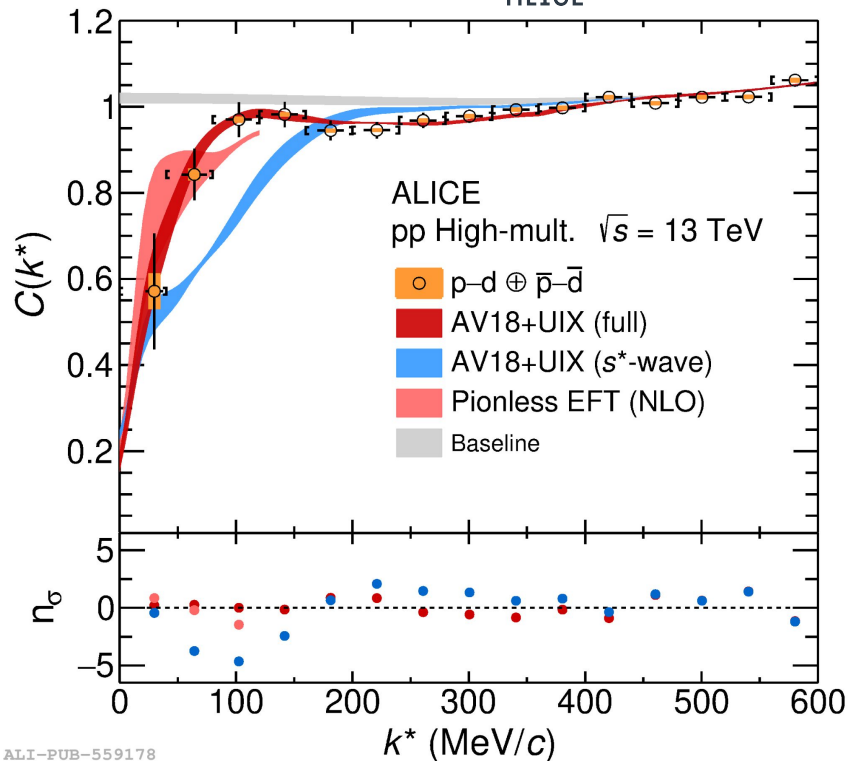
Three body interactions

Using proton-deuterons



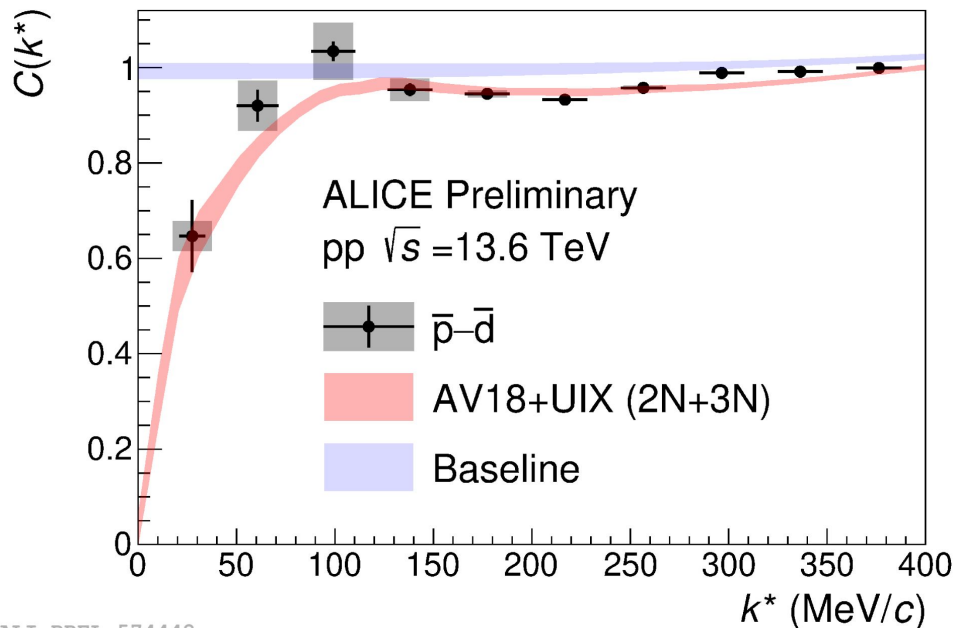
[arXiv 2308.16120 \(2023\)](https://arxiv.org/abs/2308.16120)

ALICE



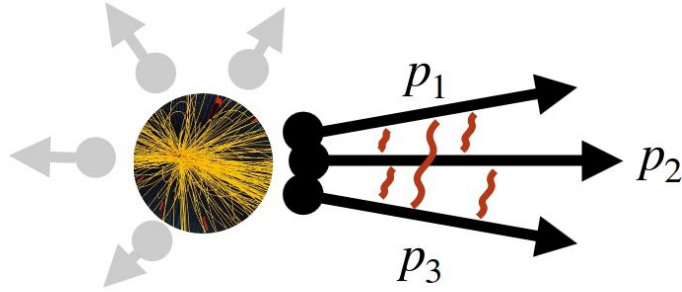
ALI-PREL-574442

NEW: Run 3 data analysis in progress



Three body interactions

Prospects with femtoscopy



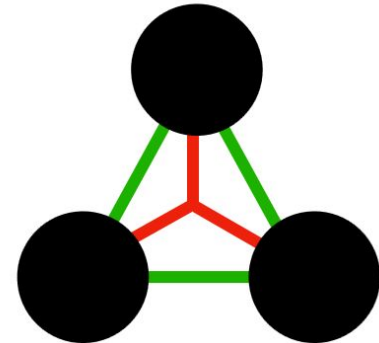
$$C(Q_3) = \mathcal{N} \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

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

Two particle rel. momenta

Three-particle correlation function incorporates

- two-body interactions
- three-body interaction



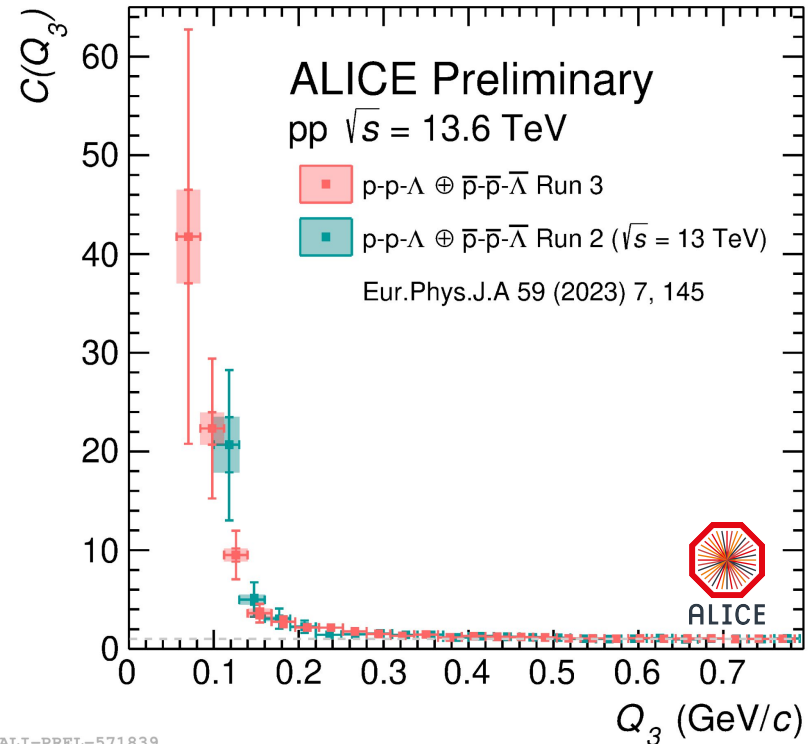
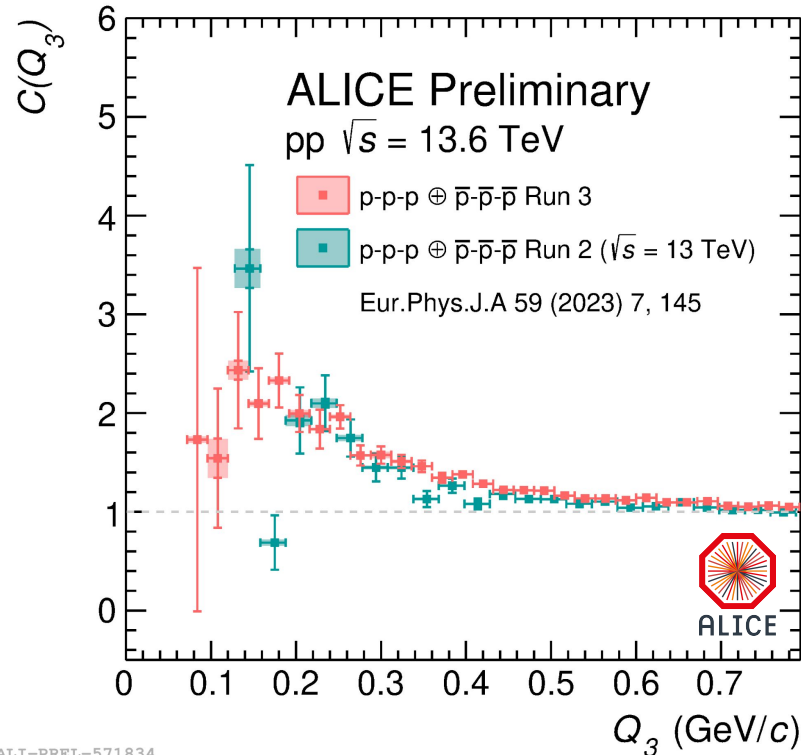
Three body interactions

Prospects with femtoscopy

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Monday 5:45 PM: Paolo Gandini

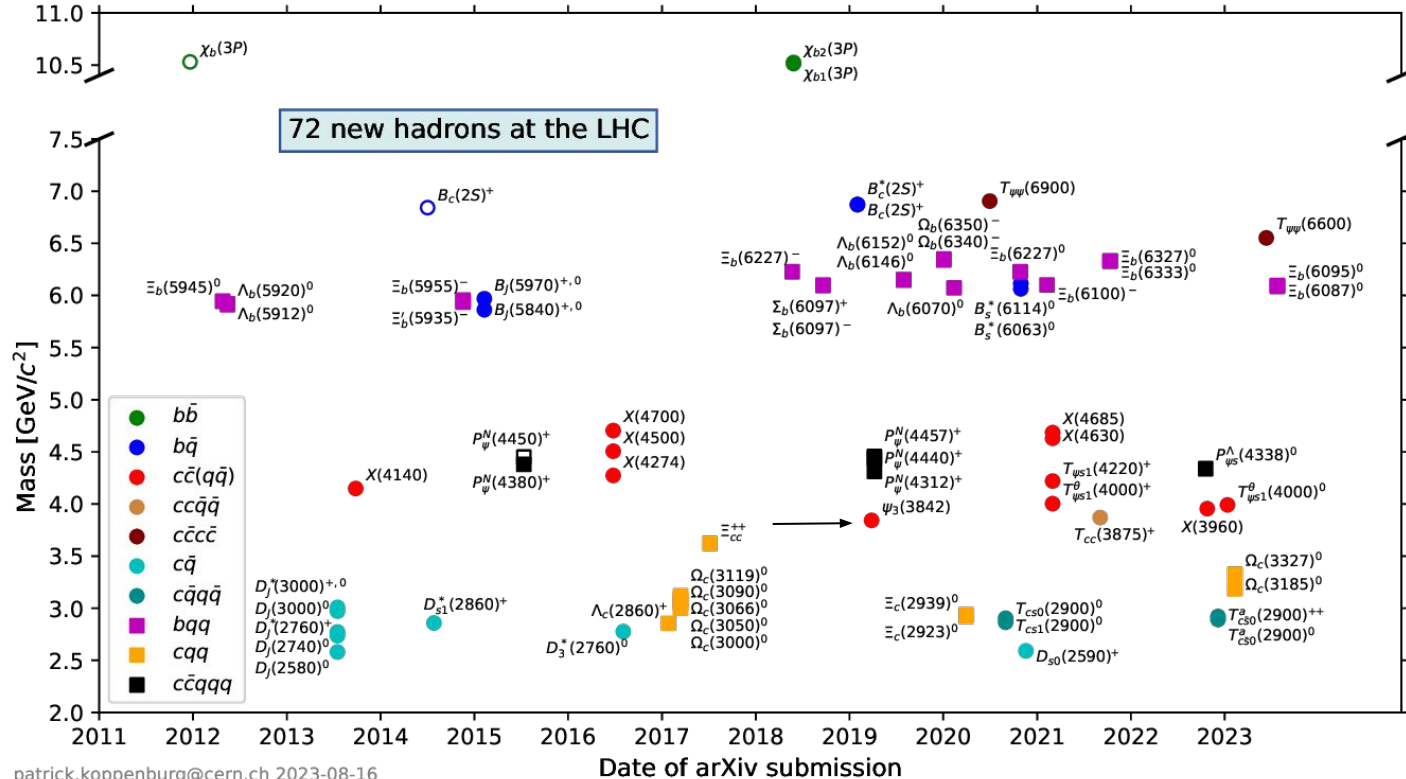
NEW preliminary results, following up the pilot results from [EPJA 59 \(2023\) 7, 145](#)



Exotic states

Spectroscopy

<https://www.nikhef.nl/~pkoppenb/particles.html>

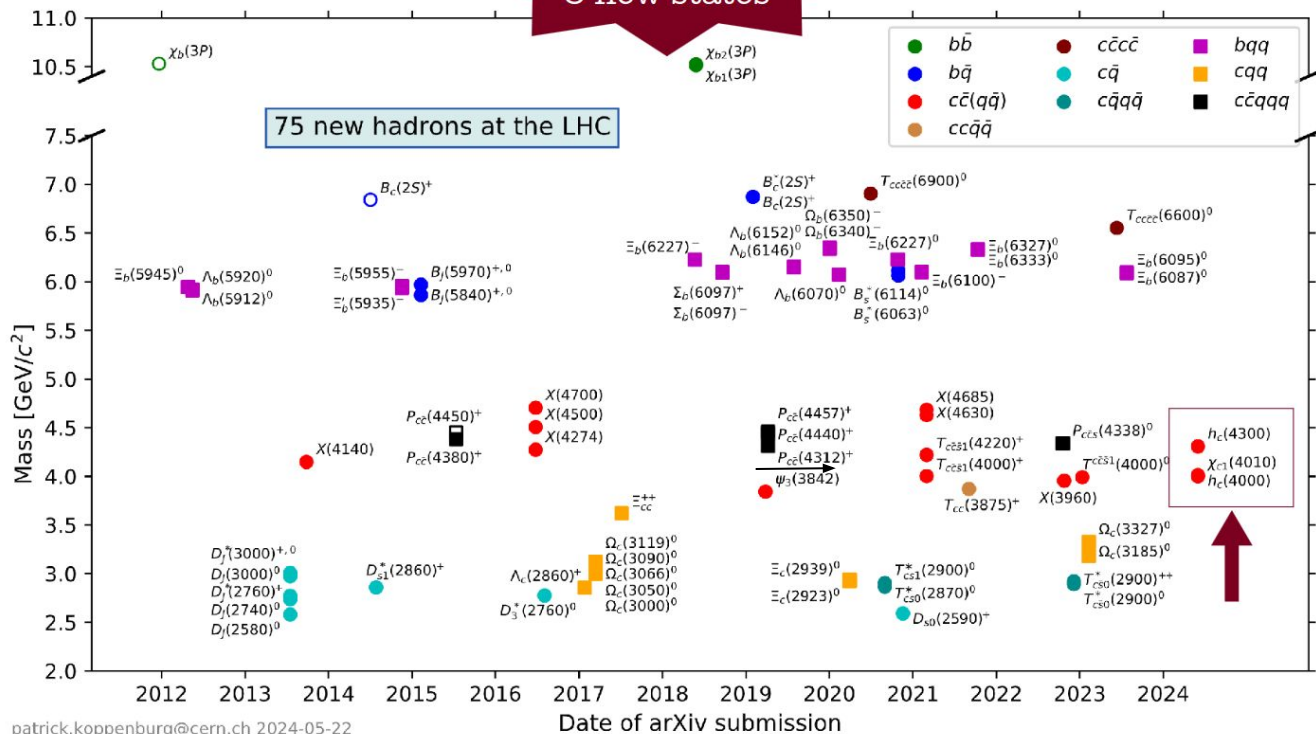


Exotic states

Spectroscopy

slide from Paolo Gandini (Monday)

SPOILER ALERT
3 new states



Exotic states

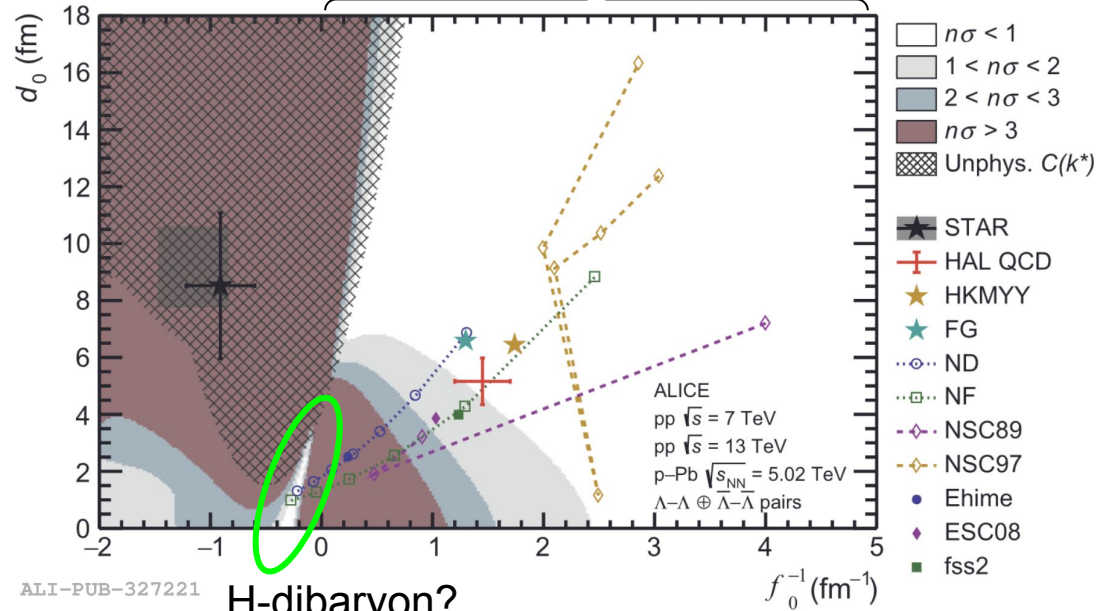
Femtosceny: $\Lambda\Lambda$



ALICE

[PLB 797 \(2019\) 134822](#)

Non-binding attractive interaction



ALI-PUB-327221

H-dibaryon?

Exotic states

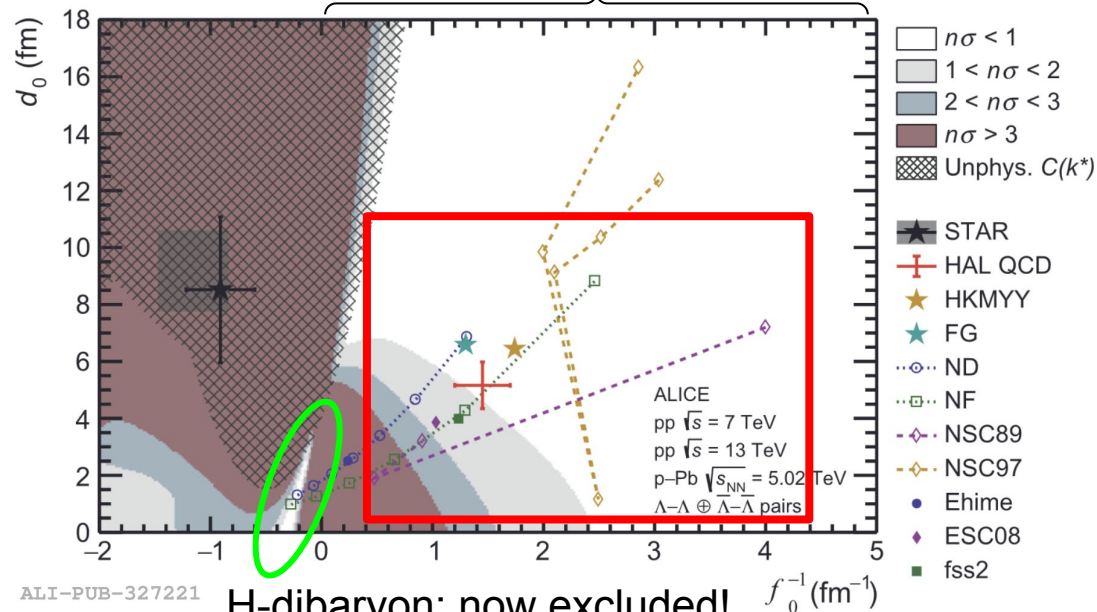
Femtoscopy: $\Lambda\Lambda$



ALICE

[PLB 797 \(2019\) 134822](#)

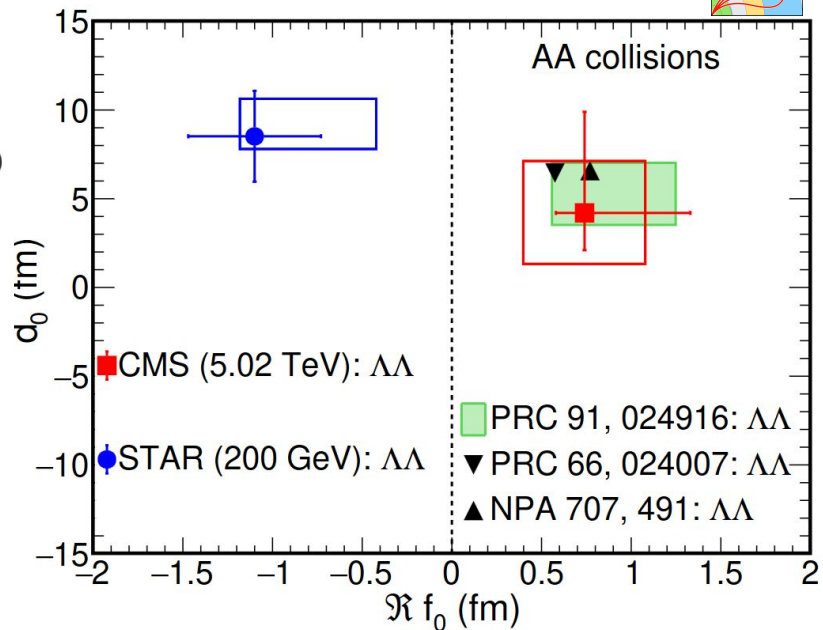
Non-binding attractive interaction



H-dibaryon: now excluded!

NEW results

[arXiv 2301.05290 \(2023\)](#)



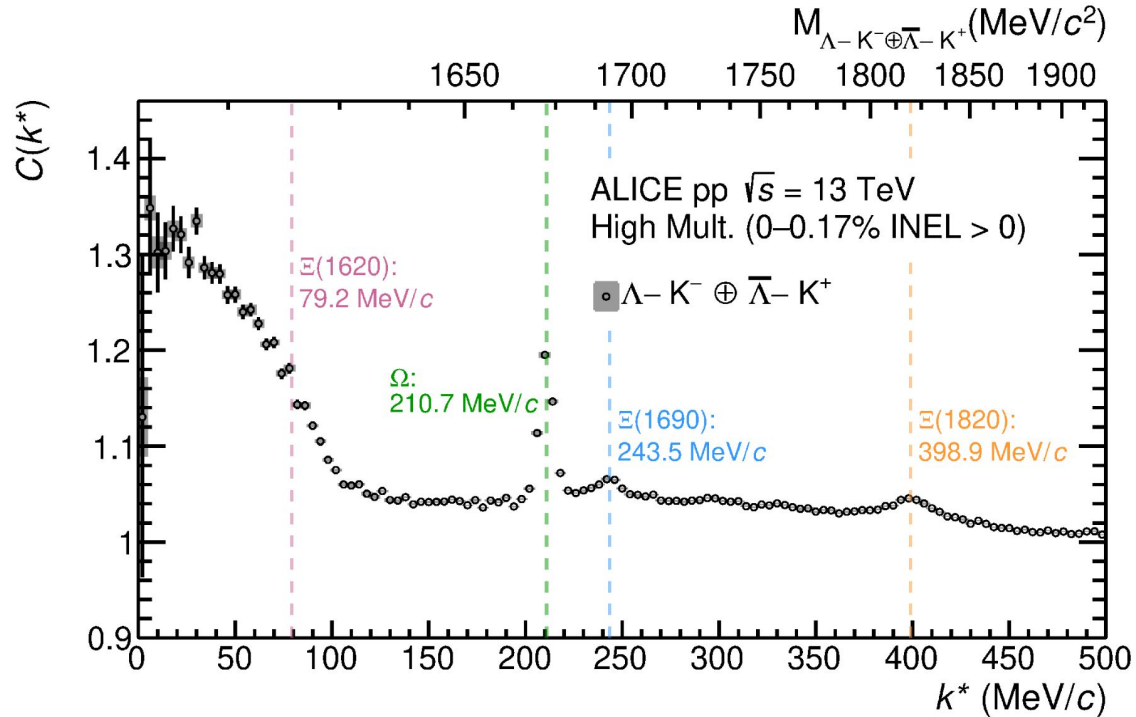
Exotic states

Femtoscscopy: ΛK^-



ALICE

Data: [ALICE Coll. PLB 845 \(2023\) 138145](#)



- Strongly coupled system
 $\Xi\pi, \Lambda K^-, \Sigma K^-, \Xi\eta$
- Presence of multiple resonances

Exotic states

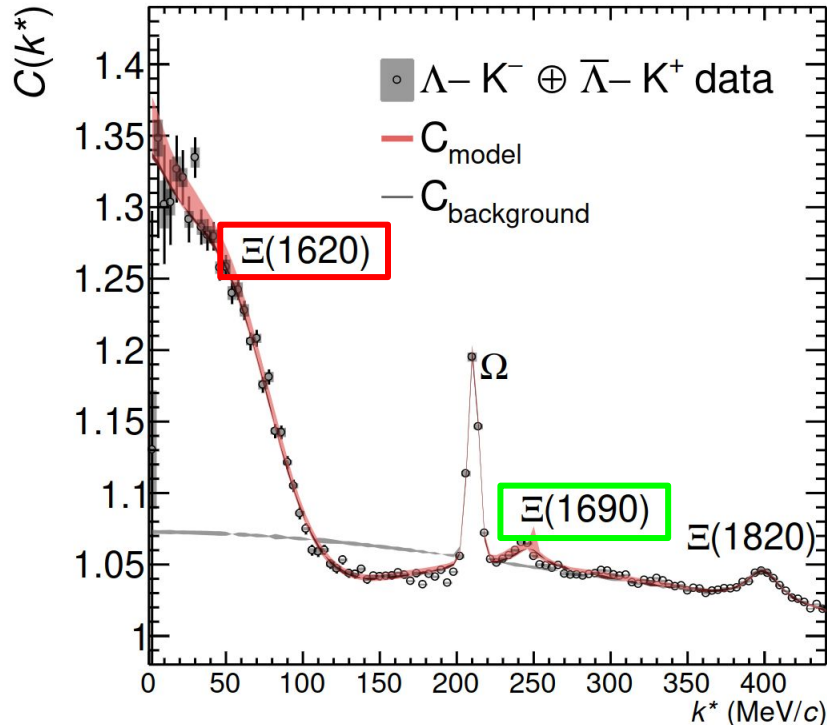
Femtoscscopy: ΛK^-



ALICE

Data: [ALICE Coll. PLB 845 \(2023\) 138145](#)

Modelling: [Mantovani et al. arXiv:2309.08756 \(2023\)](#)



- A unique experimental input in understanding the nature of exotic states
- Will help to better constrain the low-energy QCD effective lagrangian
- Fit using a state of the art effective lagrangian at NLO
Dynamically generated $\Xi(1620)$ and $\Xi(1690)$
- Complementary data to spectroscopy

Exotic states

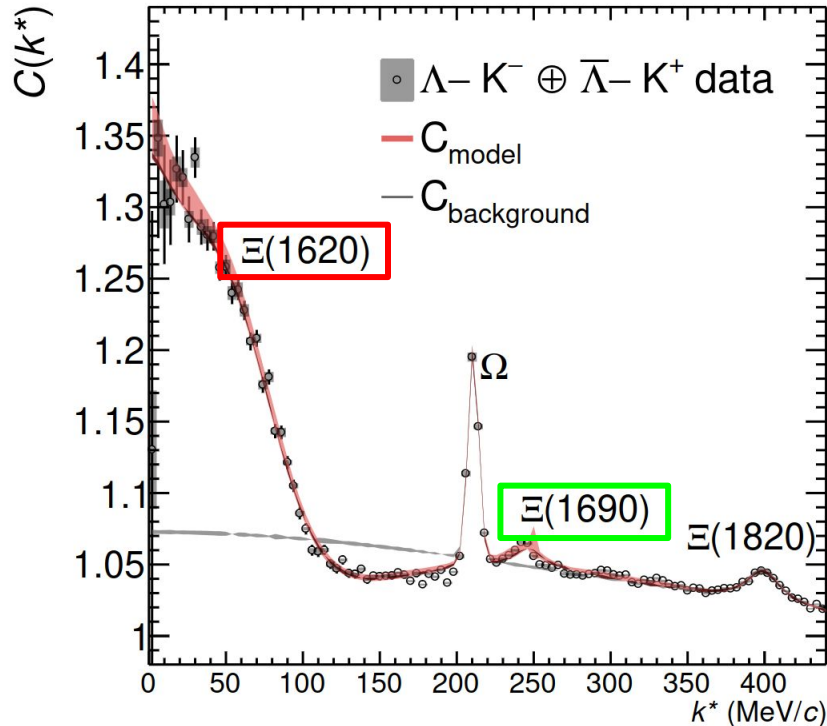
Femtoscscopy: ΛK^- and $\Xi\pi$



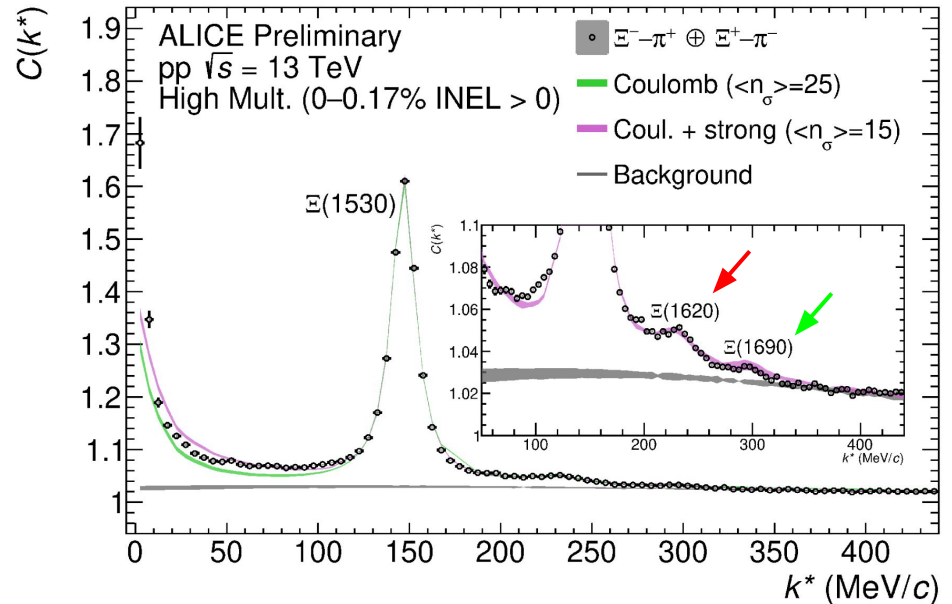
ALICE

Data: [ALICE Coll. PLB 845 \(2023\) 138145](#)

Modelling: [Mantovani et al. arXiv:2309.08756 \(2023\)](#)



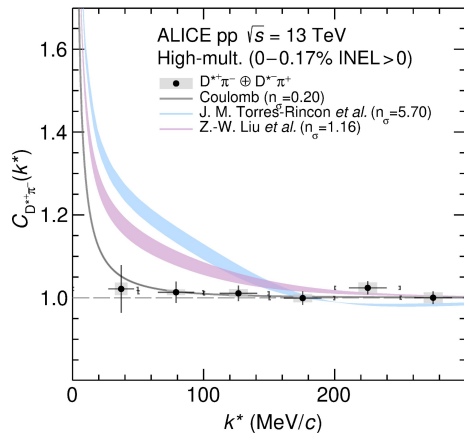
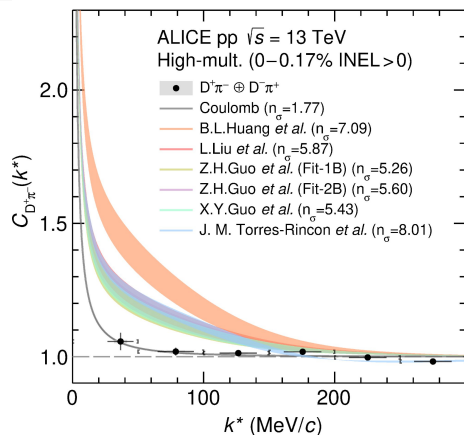
- Measure multiple coupled-channels to achieve improve the constraining power



ALI-PREL-573869

Exotic states

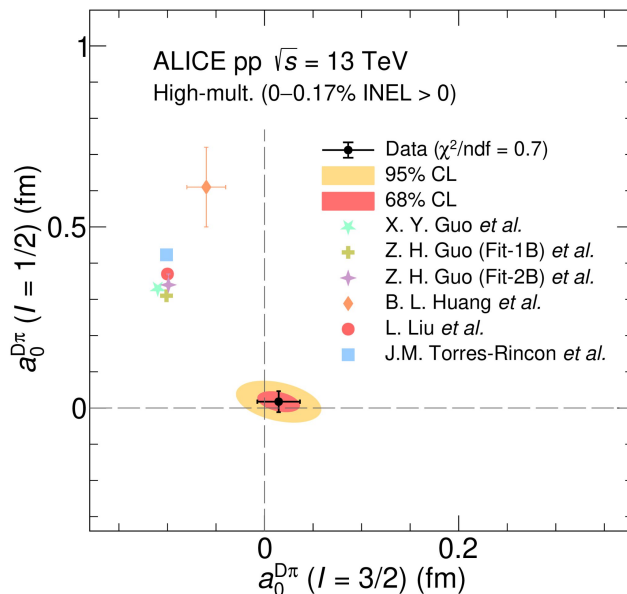
Charmed femtoscopy



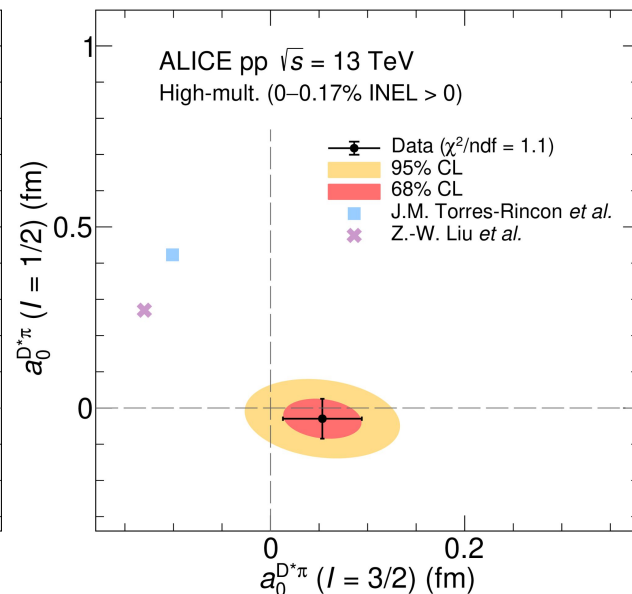
ALICE

[arXiv 2401.13541 \(2024\)](https://arxiv.org/abs/2401.13541)

- Providing experimental constraints for the theoretical models

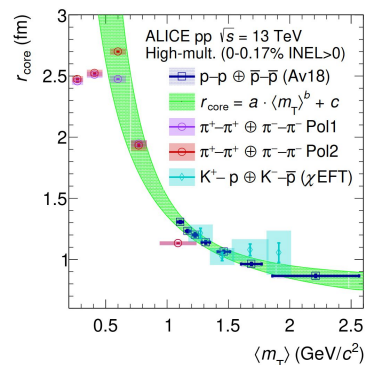
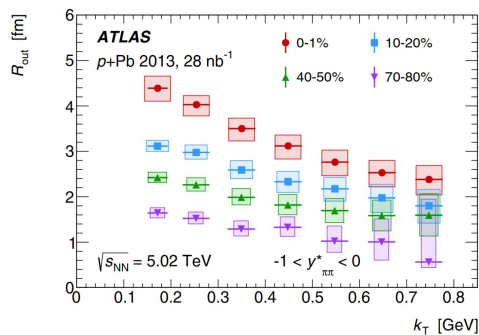
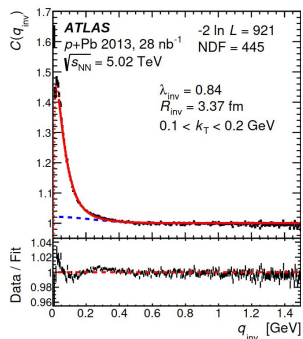
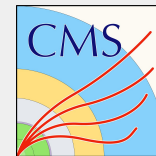


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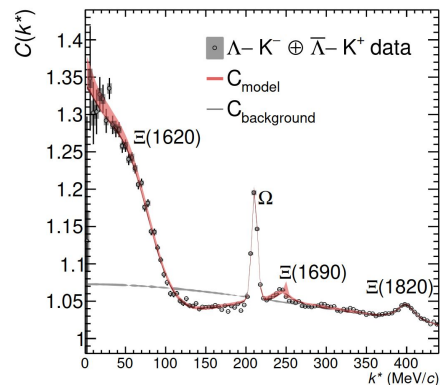
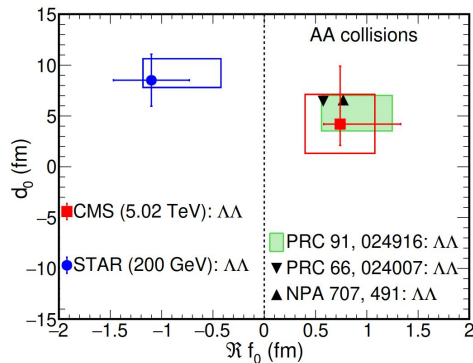
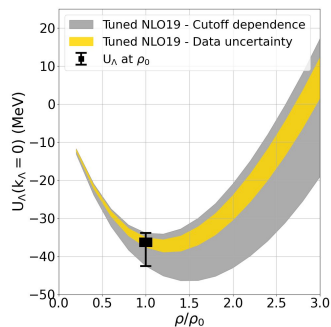


ALI-PUB-568979

Unity makes strength

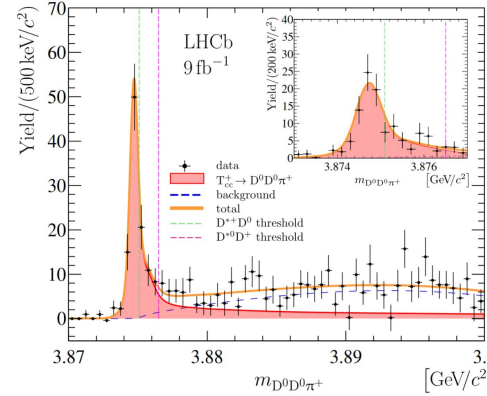
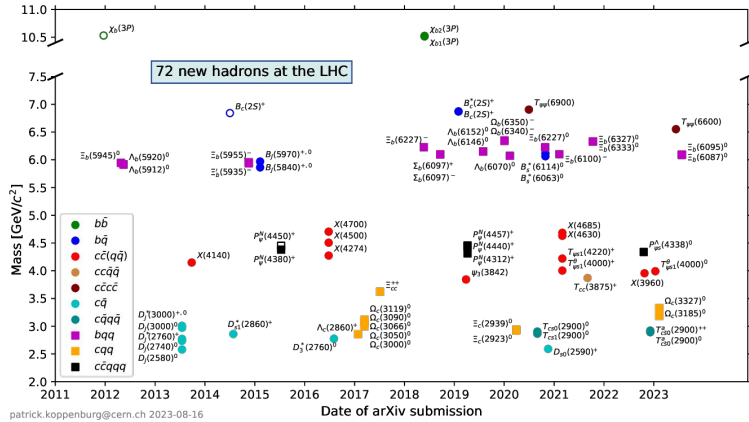
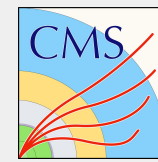


Study the emission



Study the interaction

Unity makes strength

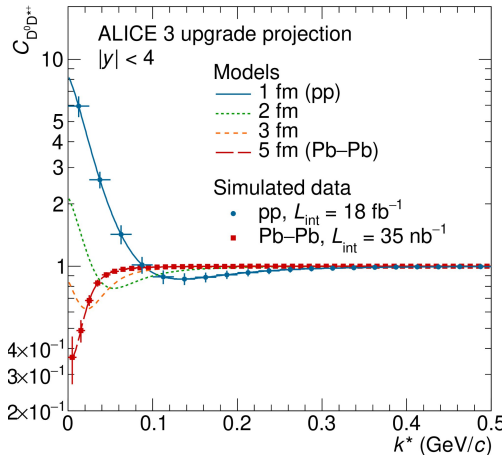


Discover new states

Gearing up for the future:

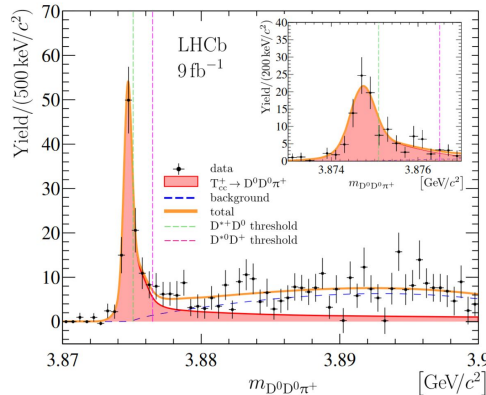
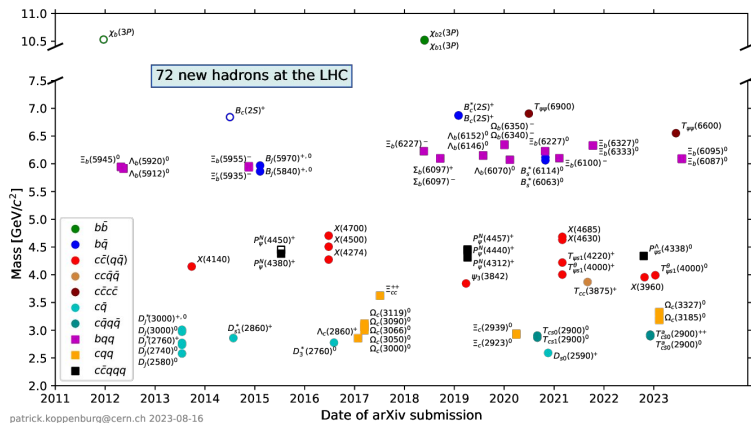
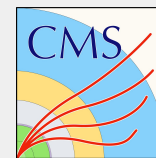
Online triggers in place for ALICE

New software triggers for LHCb



Study their properties

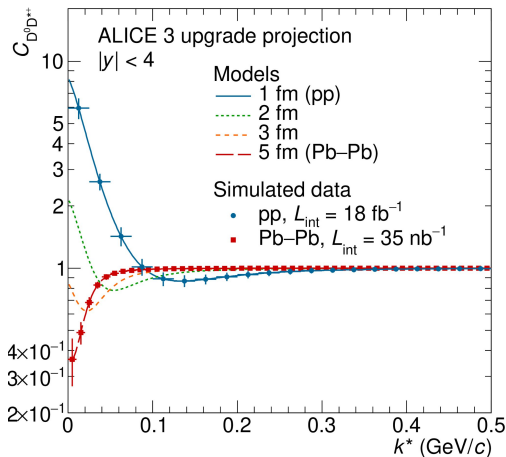
Unity makes strength



Discover new states

Thank you for your attention!

Questions?



Study their properties