WPCF 2024

Demystifying the interior of neutron stars with femtoscopy at ALICE

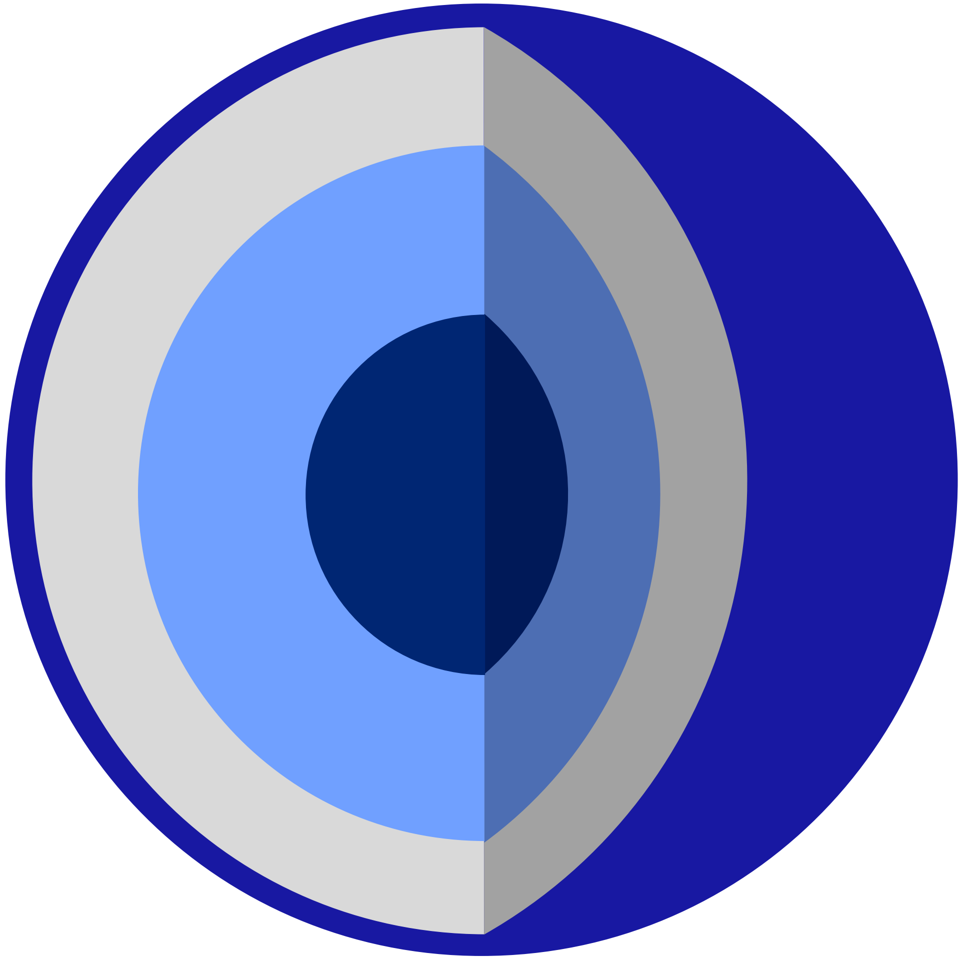
Marcel Lesch
on behalf of the ALICE Collaboration

Technical University of Munich

08th of November 2024
WPCF 2024, Toulouse France

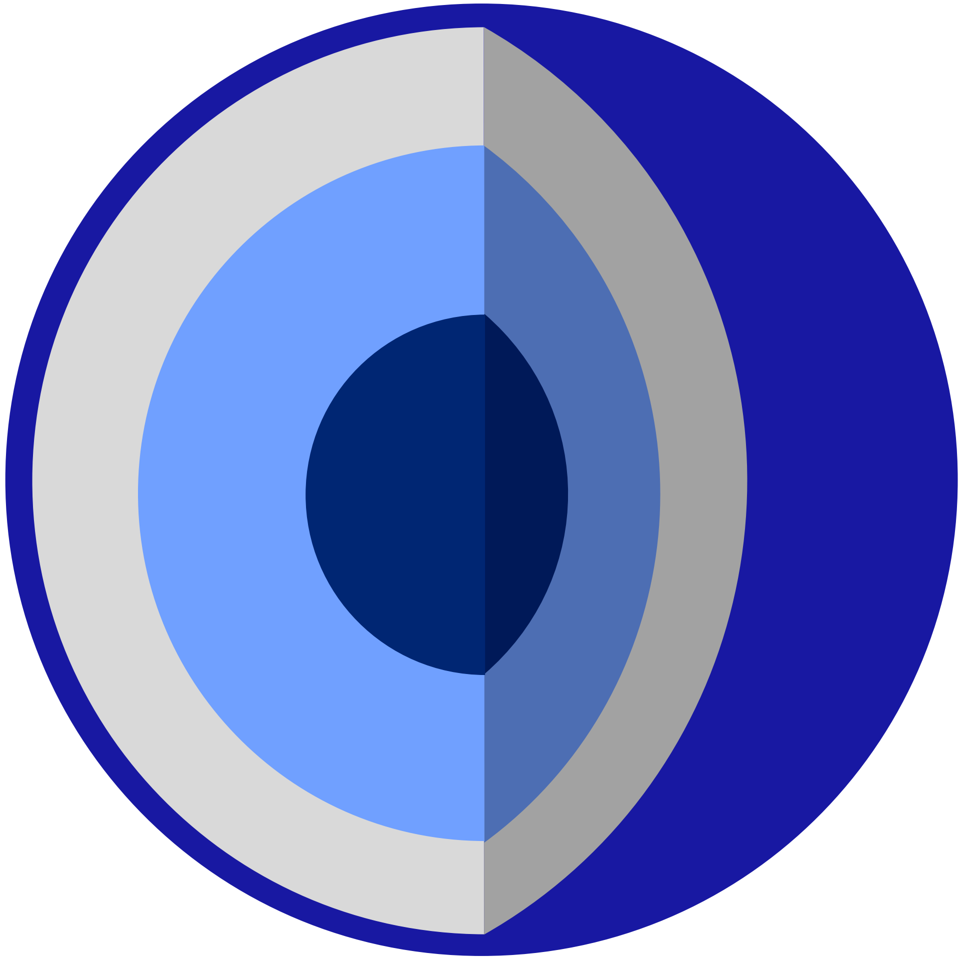
Neutron stars

- Final product of supernova explosions
- Very compact objects:
  - $M \approx 1\text{–}2\ M_{\odot}$
  - $R \approx 10\text{–}15$ km (~ size of Toulouse area!)



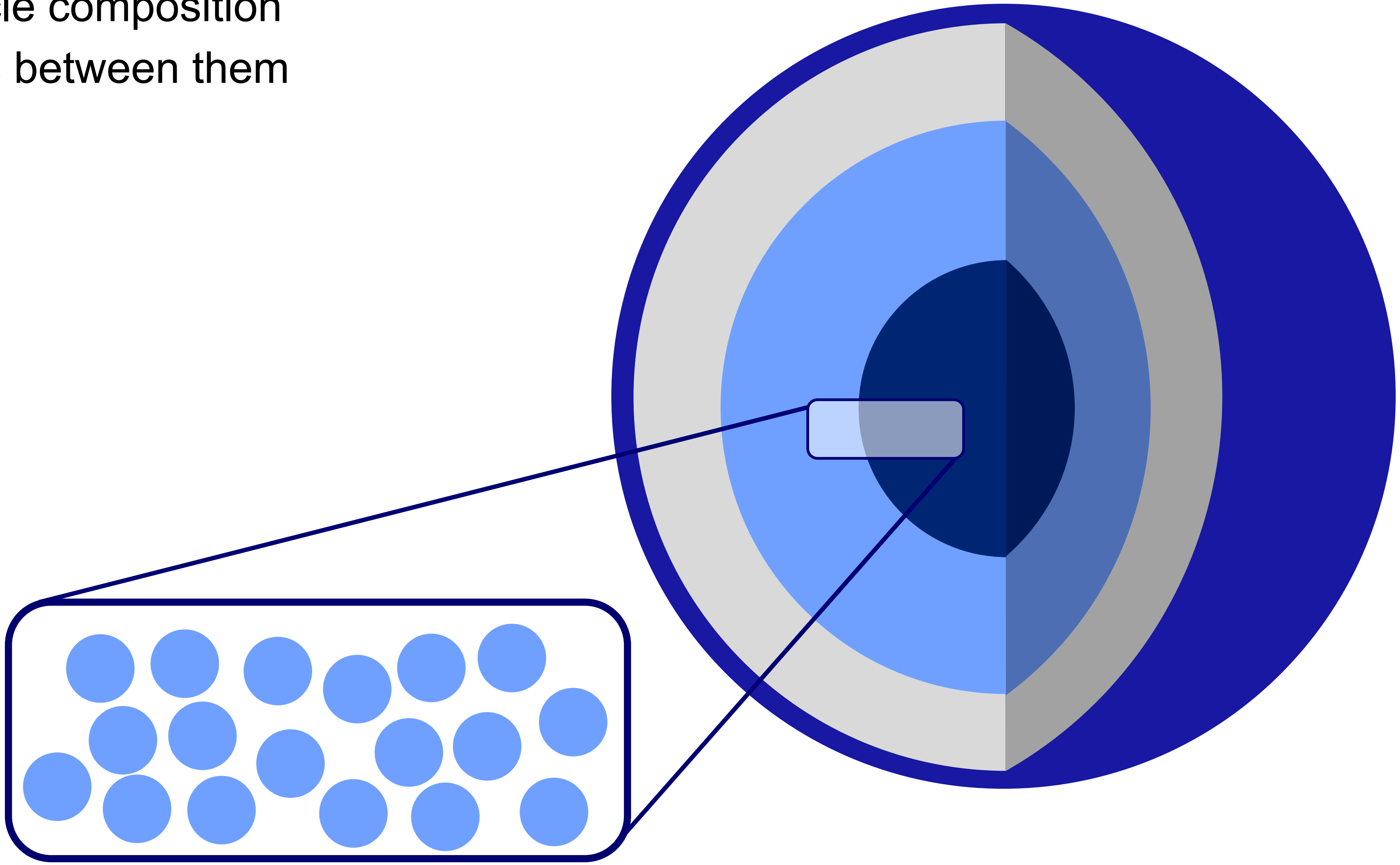
Neutron stars

- Final product of supernova explosions
- Very compact objects:
  - $M \approx 1-2\ M_{\odot}$
  - $R \approx 10-15$ km (~ size of Toulouse area!)
- Very dense and rather cold objects:
  - extreme densities of several ρ_0
  - T_{max} ~ few MeV



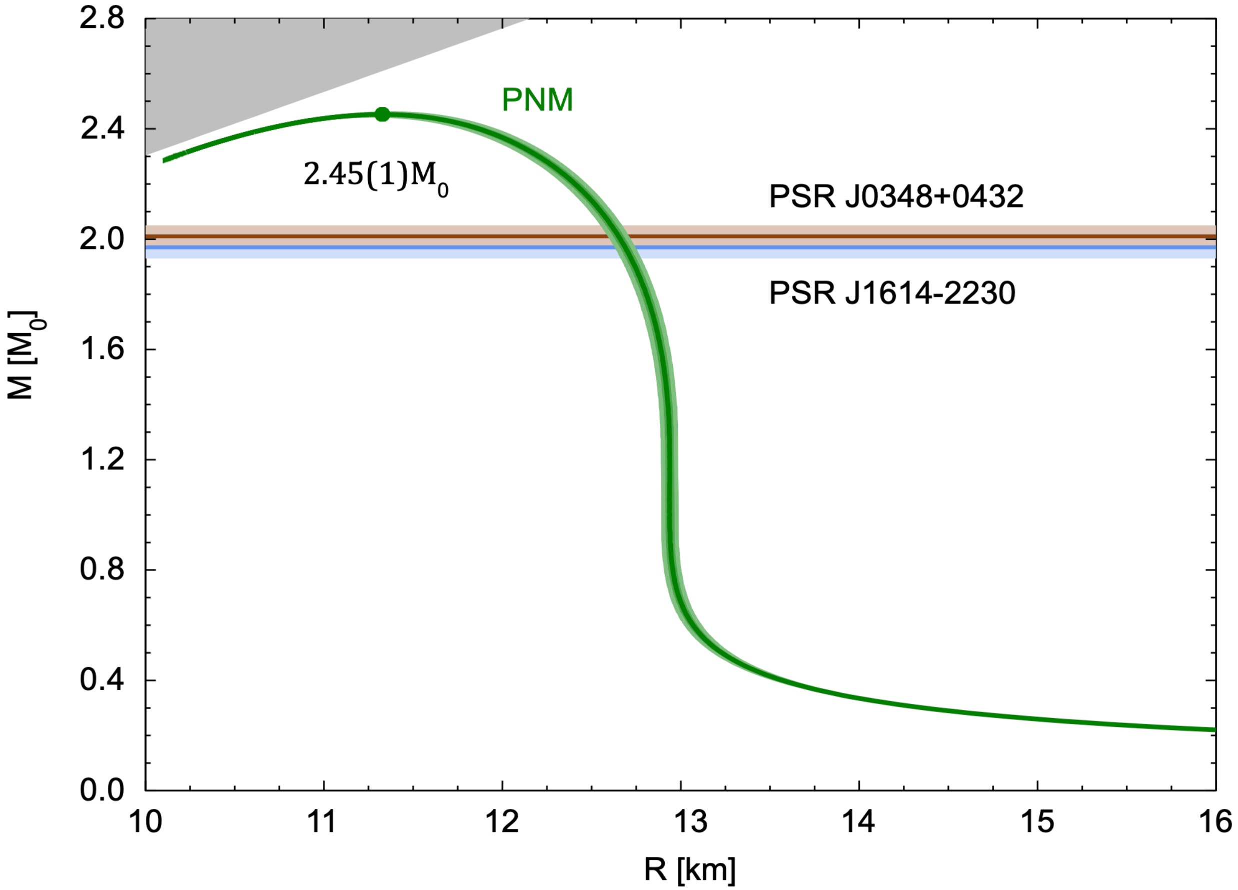
Neutron stars

- EoS dependent on the particle composition and the possible interactions between them



Neutron stars

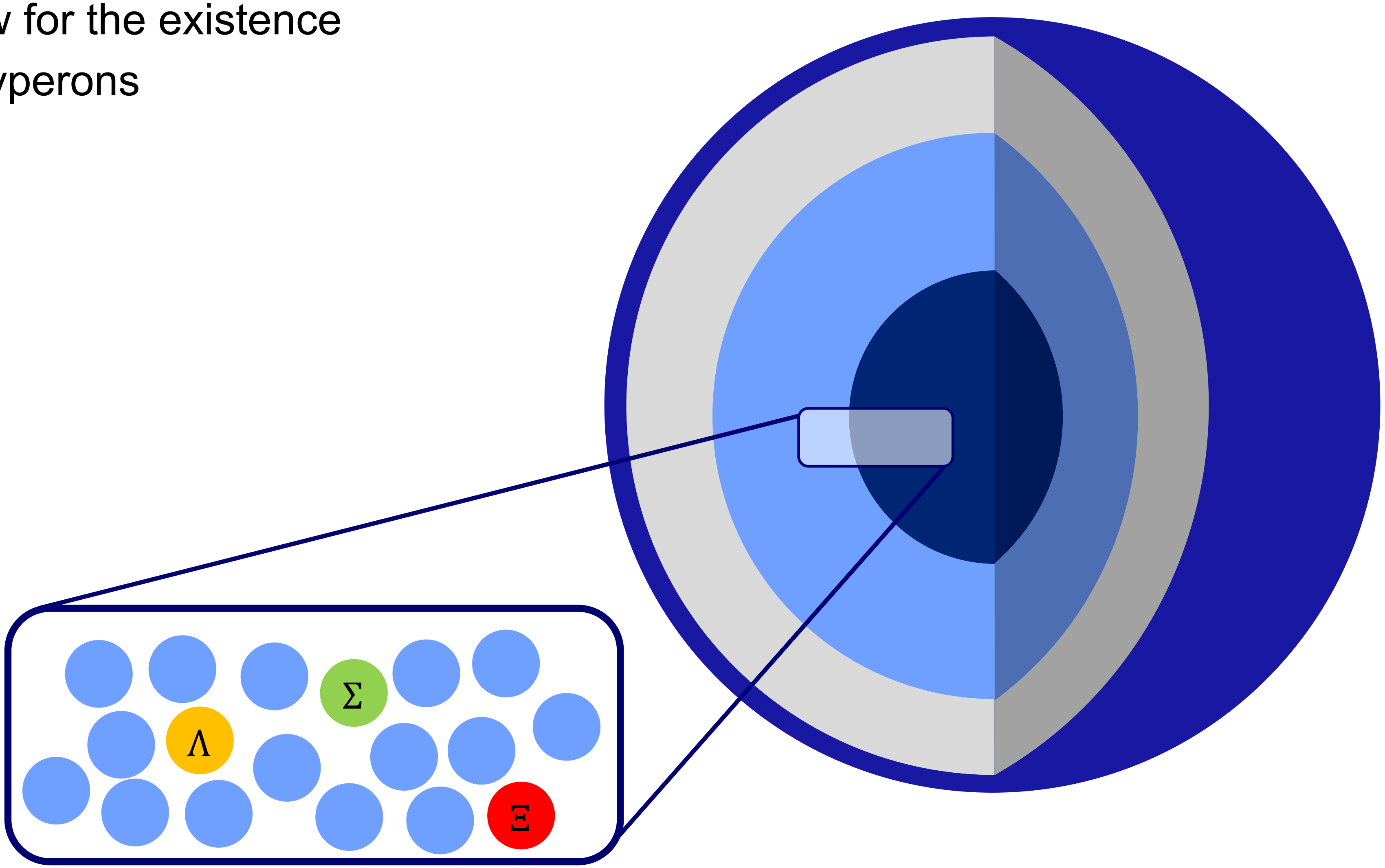
- EoS dependent on the particle composition and the possible interactions between them
- EoS linked to masses and radii of neutron stars via TOV equations
- Pure neutron matter (PNM) supports heavy neutron stars of $2M_\odot$



Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

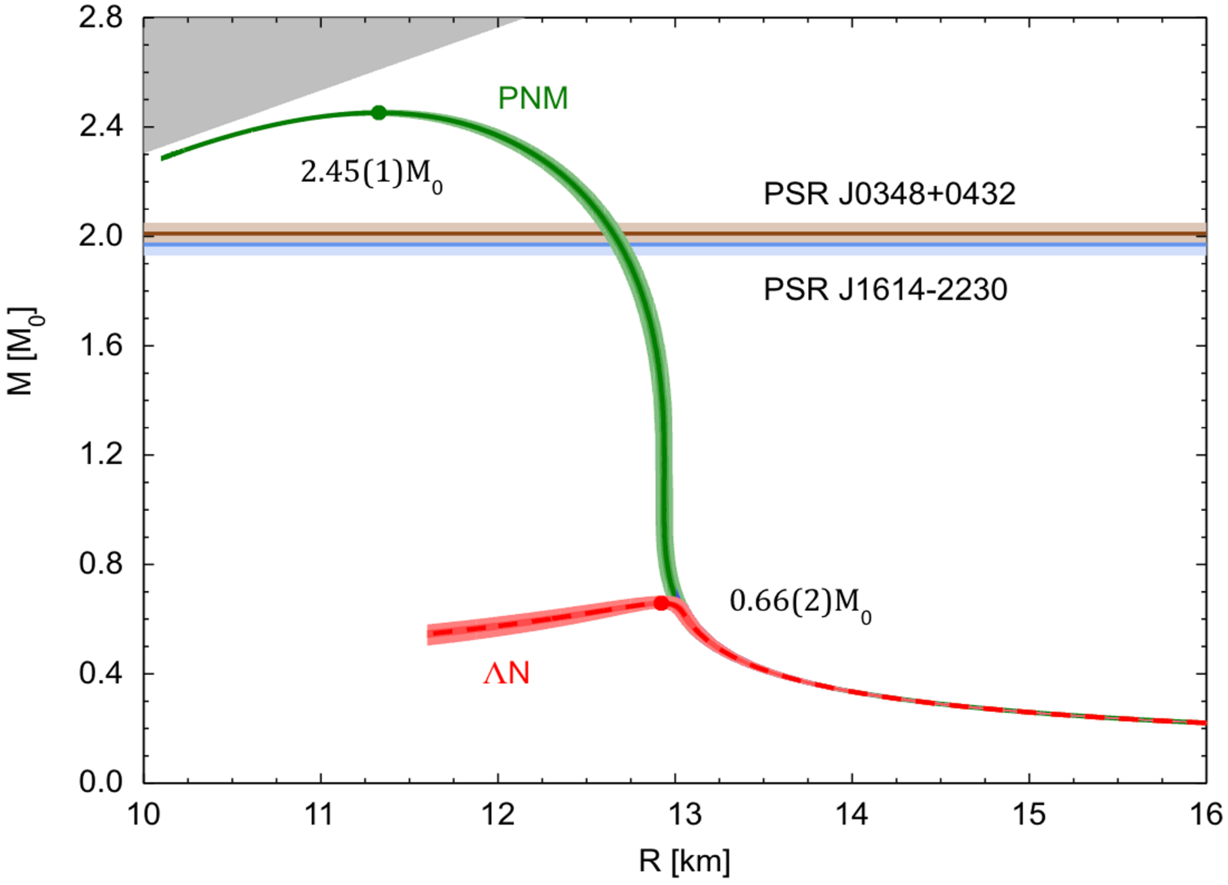
Neutron stars and the hyperon puzzle

- High baryonic densities allow for the existence of strange particles, e.g. Λ hyperons



Neutron stars and the hyperon puzzle

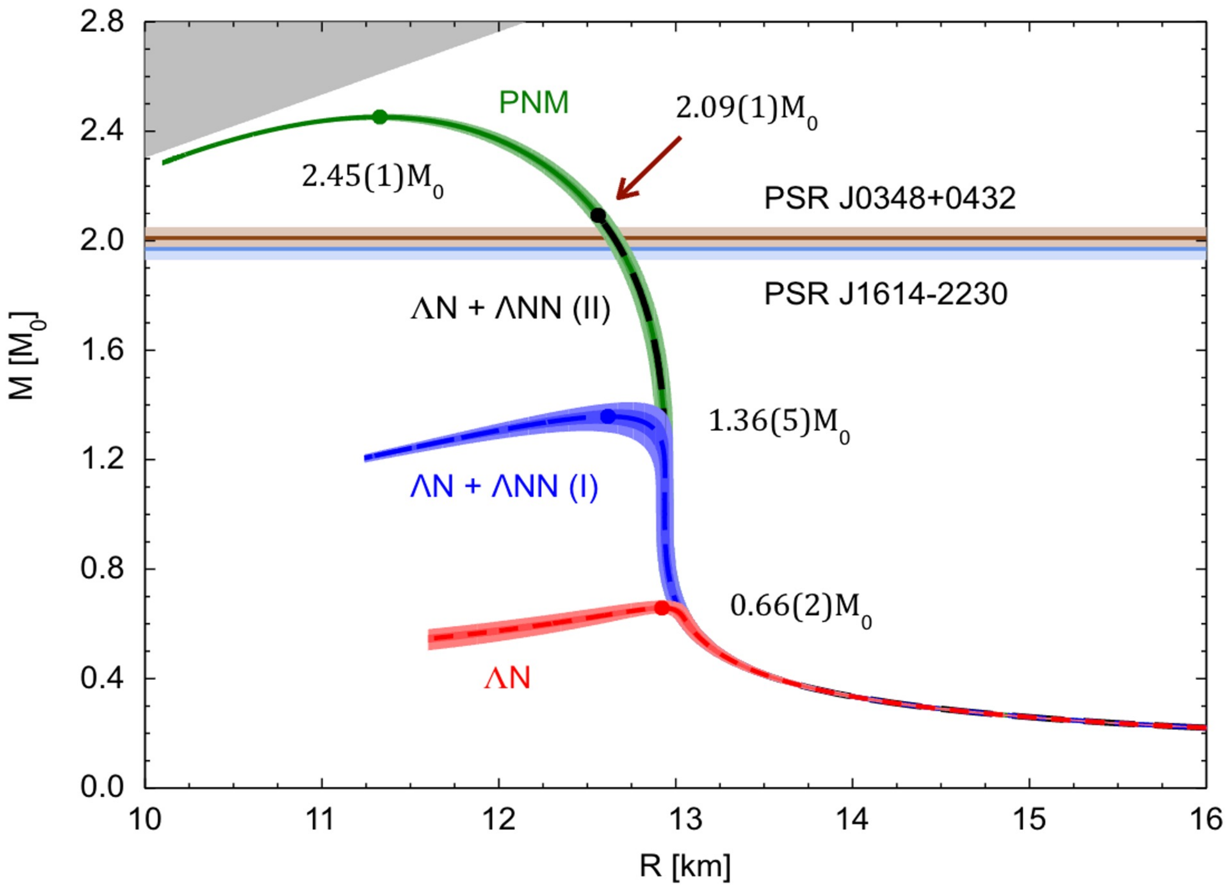
- High baryonic densities allow for the existence of strange particles, e.g. Λ hyperons
- However: EoS softens with appearance of Λ hyperons
  → cannot support heavy neutron stars



Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

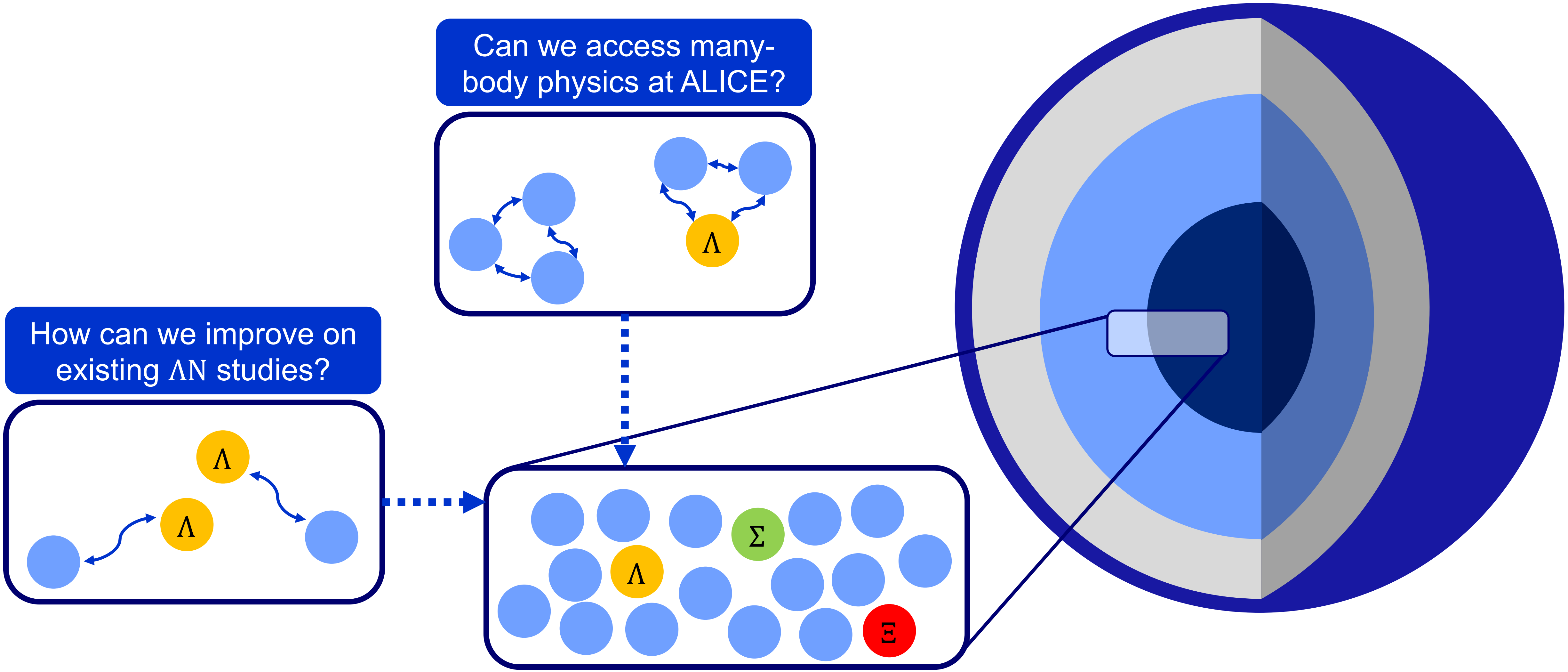
Neutron stars and the hyperon puzzle

- High baryonic densities allow for the existence of strange particles, e.g. Λ hyperons
- However: EoS softens with appearance of Λ hyperons
  → cannot support heavy neutron stars
- Three-body interactions such as ΛNN play an important role



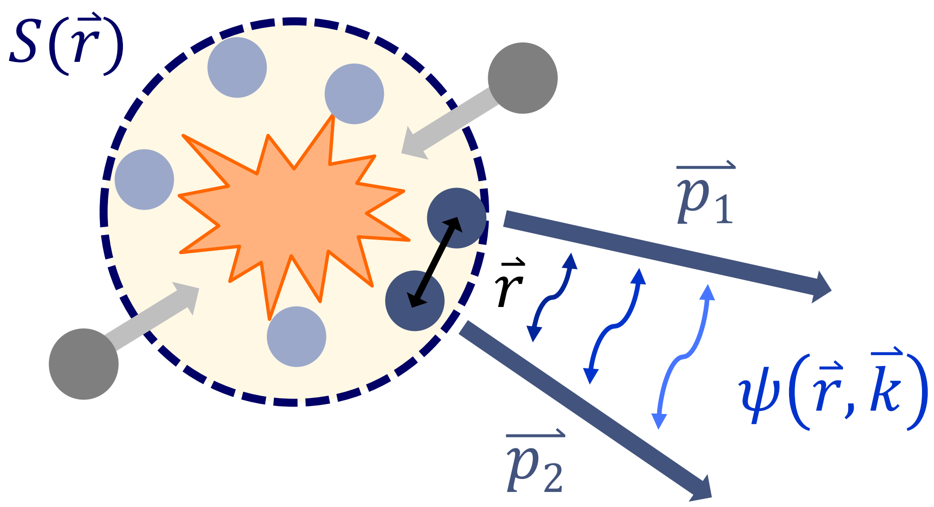
Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)

On today's menu



Two-body femtoscopy

L. Fabbietti and V. Mantovani Sarti and O. Vazquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377-402



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

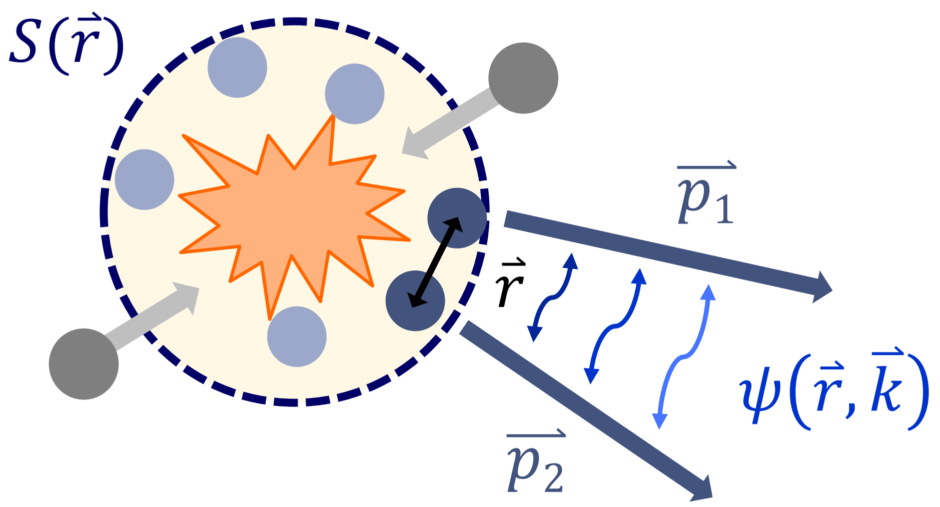
theoretical definition | experimental definition

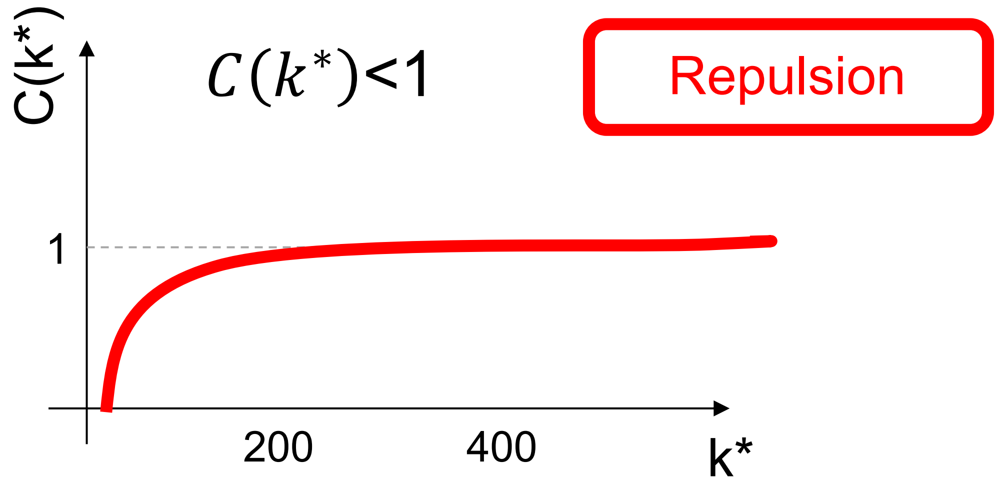
Relative momentum $\vec{k}^* = \frac{1}{2} \mid \vec{p}_1^* - \vec{p}_2^* \mid$ and $\vec{p}_1^* + \vec{p}_2^* = 0$

Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

Two-body femtoscopy

L. Fabbietti and V. Mantovani Sarti and O. Vazquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377-402





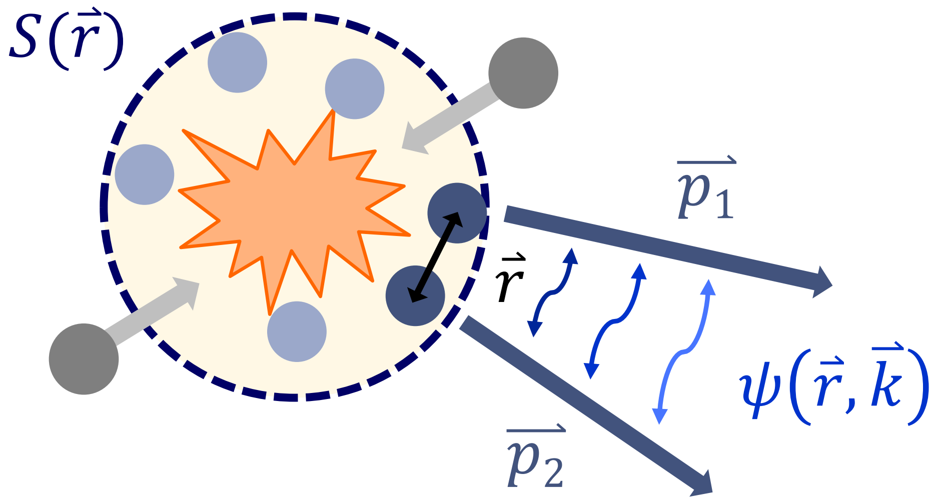
$$C(k^*) = \int \underbrace{S(\vec{r}^*)\left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^*}_{\text{theoretical definition}} = \underbrace{\mathcal{N}\frac{\mathrm{N_{same}}(k^*)}{\mathrm{N_{mixed}}(k^*)}}_{\text{experimental definition}}$$

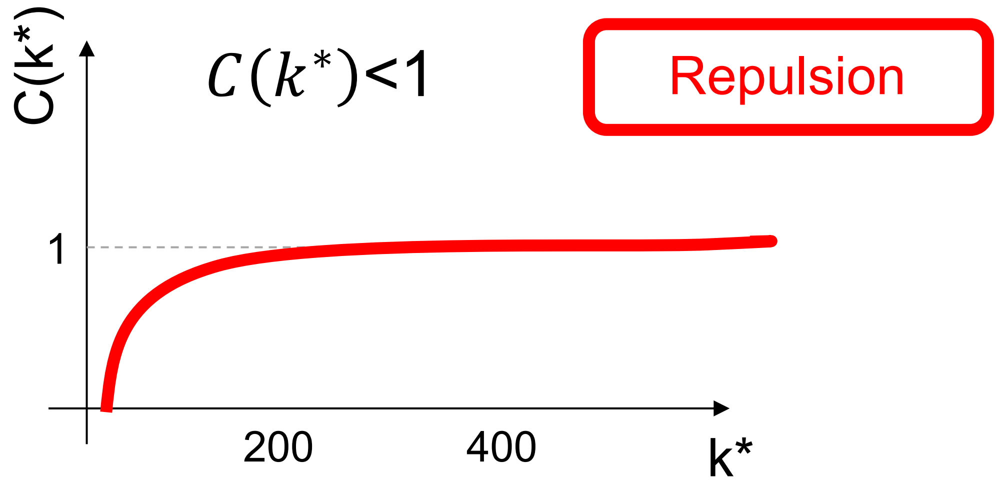
Relative momentum $\vec{k}^* = \frac{1}{2} \mid \vec{p}_1^* - \vec{p}_2^* \mid$ and $\vec{p}_1^* + \vec{p}_2^* = 0$

Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

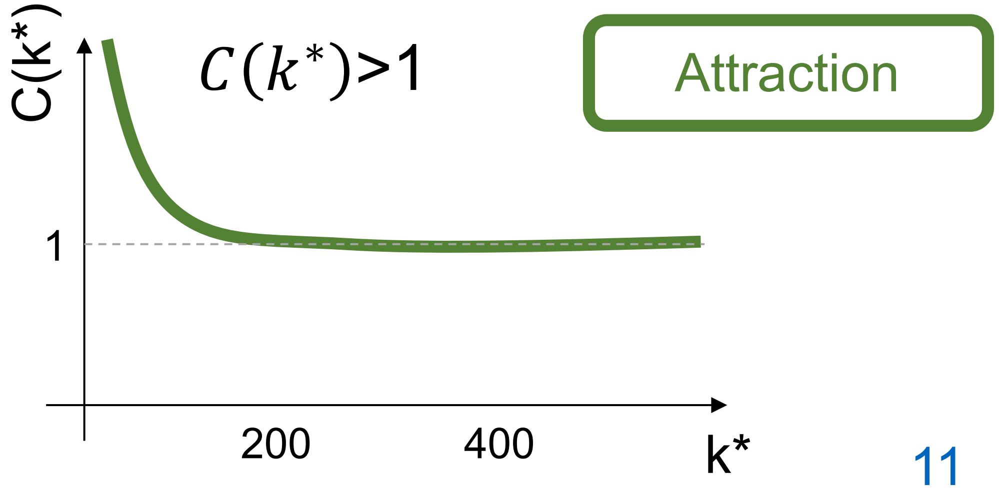
Two-body femtoscopy

L. Fabbietti and V. Mantovani Sarti and O. Vazquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377-402





$$C(k^*) = \underbrace{\int S(\vec{r}^*)\left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^*}_{\text{theoretical definition}} = \underbrace{\mathcal{N}\frac{\mathrm{N_{same}}(k^*)}{\mathrm{N_{mixed}}(k^*)}}_{\text{experimental definition}}$$



Relative momentum $\vec{k}^* = \frac{1}{2} \mid \vec{p}_1^* - \vec{p}_2^* \mid$ and $\vec{p}_1^* + \vec{p}_2^* = 0$

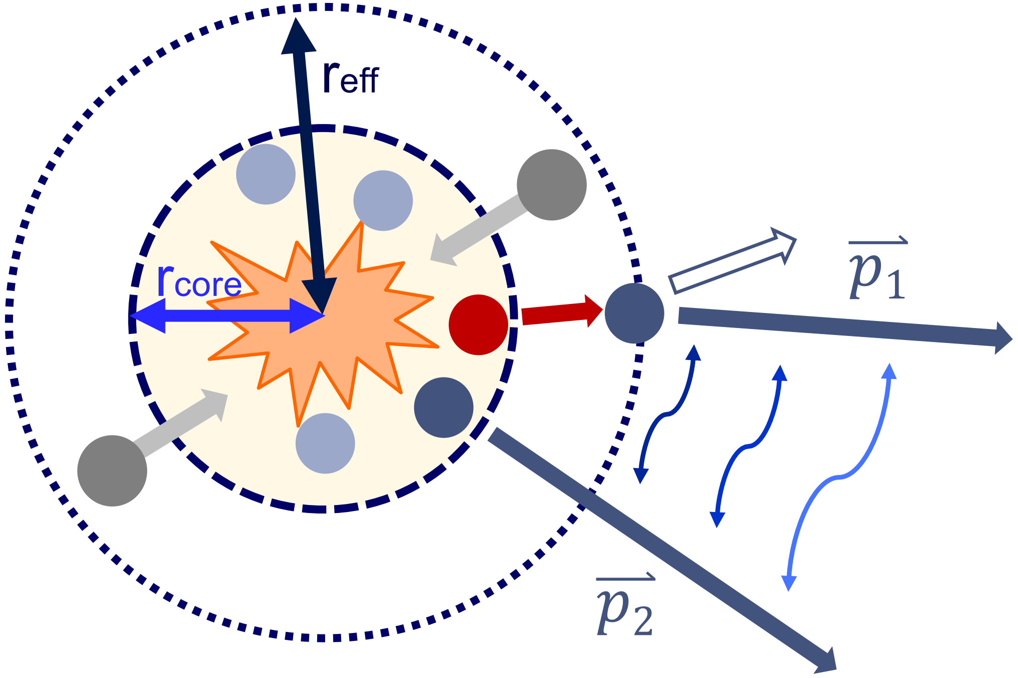
Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

The source in pp collisions

- Source modelling involves
  - core source of primordial particles (Gaussian)
  - contributions from short-lived resonances

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \otimes \text{(Resonance contributions)}$$

ALICE, PLB 811 135849, 2020



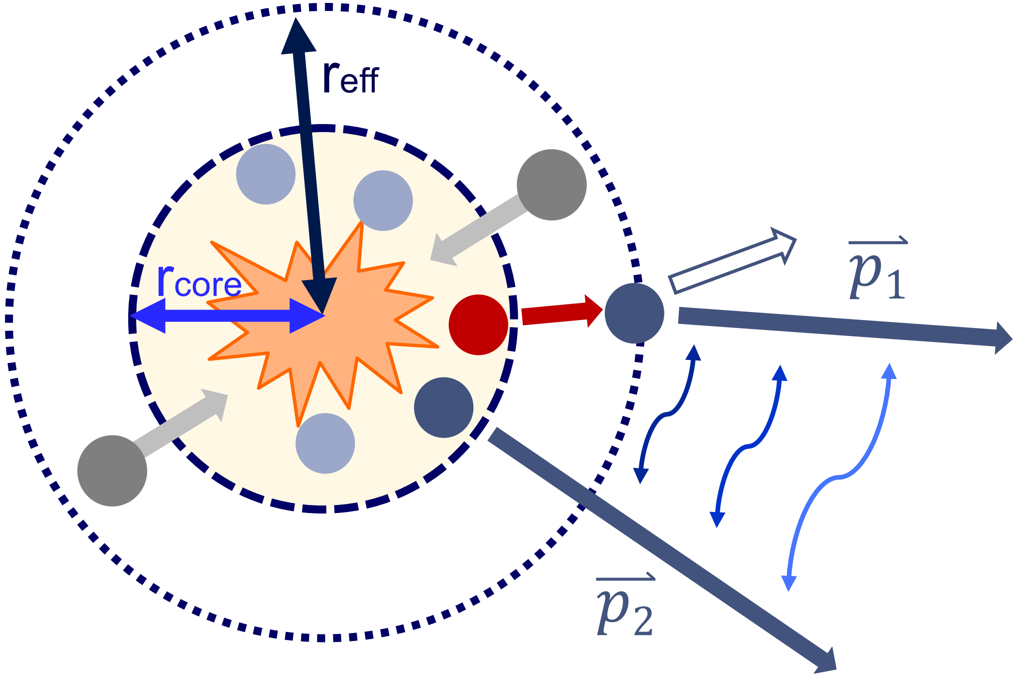
The source in pp collisions

- Source modelling involves
  - core source of primordial particles (Gaussian)
  - contributions from short-lived resonances

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4 r_{core}^2}\right) \otimes (\text{Resonance contributions})$$

ALICE, PLB 811 135849, 2020

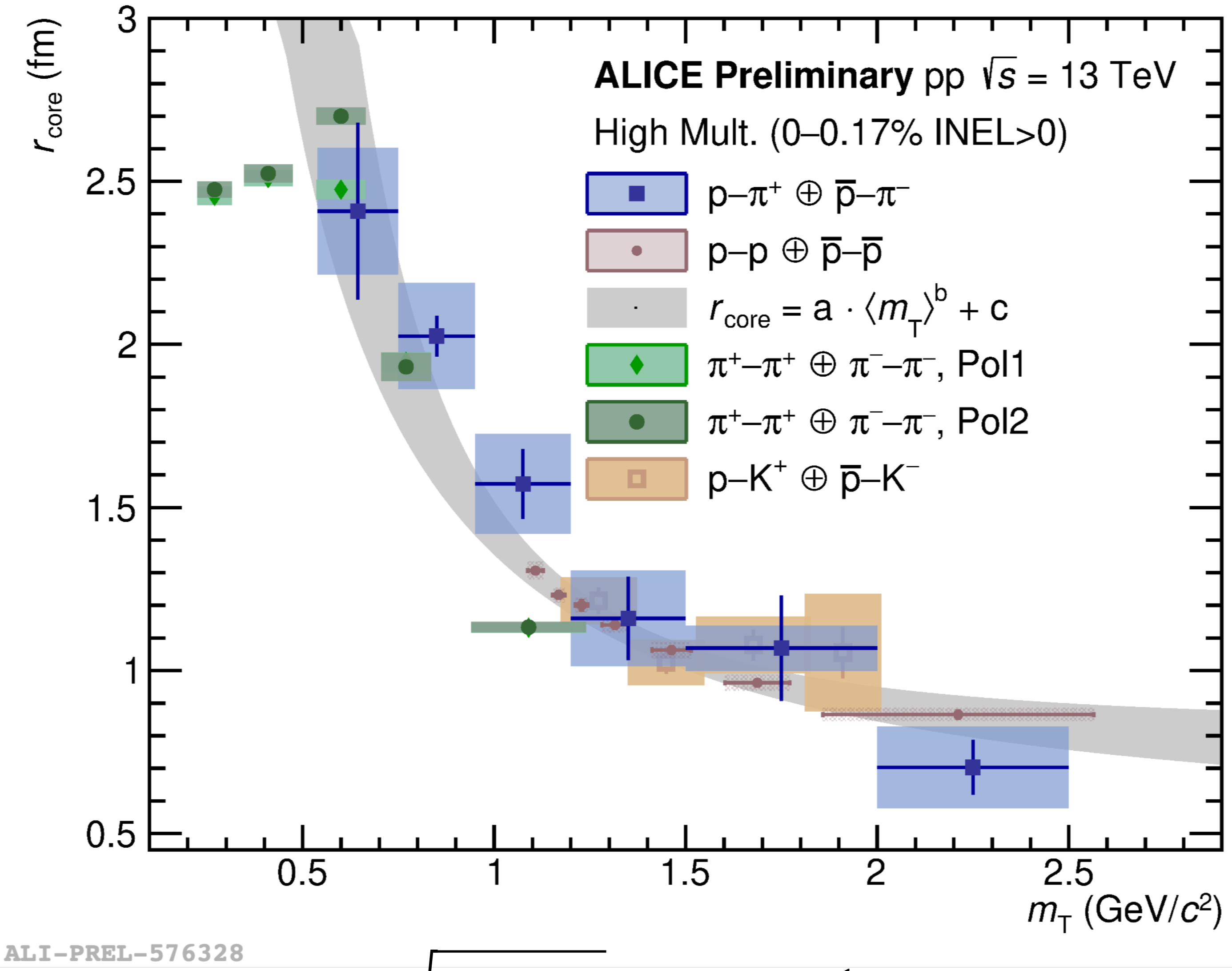
- Resonance contributions
  - dependent on the particle species
  - **fixed** from statistical hadronization model and EPOS
- Particle-emitting source can be studied using particle pairs with known interaction



A common ~~baryon~~ hadron source in pp collisions!

- Particle-emitting source studied with
  - pp ALICE, PLB 811 135849, 2020
  - pK^{+} ALICE, arXiv:2311.14527
  - $\pi^{\pm}\pi^{\pm}$ ALICE, arXiv:2311.14527
  - $p\pi^{\pm}$ (paper in preparation)
- Common source for all hadrons in high-multiplicity pp collisions!
- Source scaling allows to extract the source size of particle pairs with unknown interaction

→ Possibility to study interaction for exotic pairs (strange and charm sector)

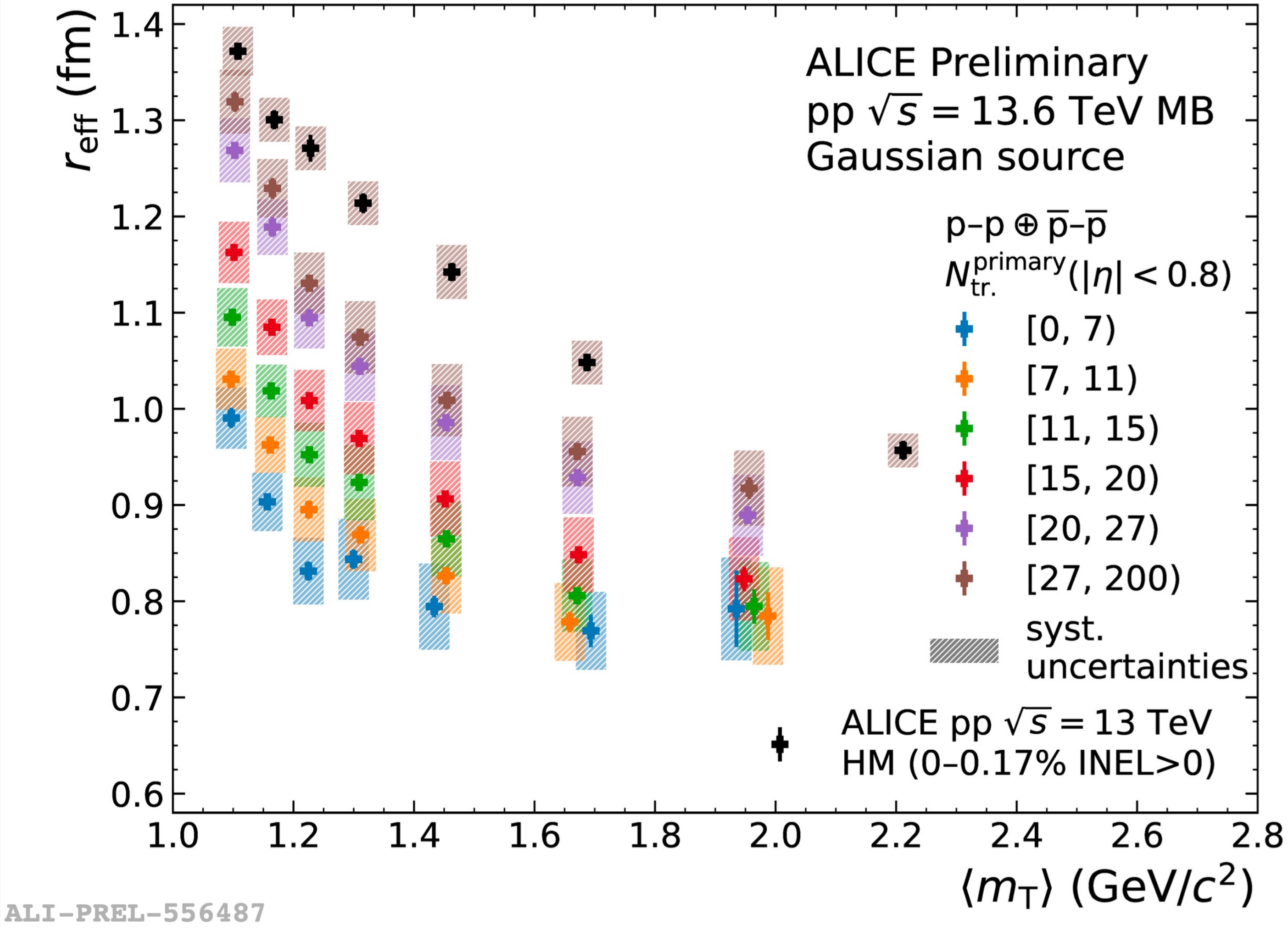


$$m_{\mathrm{T}} = \sqrt{\bar{m}^2 + k_{\mathrm{T}}^2} \text{ and } \vec{k}_{\mathrm{T}} = \frac{1}{2}\left[\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right]$$

Source studies in LHC Run 3 pp collisions

- Particle-emitting source studied with ALICE in LHC Run 3 MB pp collisions
- First ever multi-differential studies of the source using pp correlations
  - dependent on the pair m_{T}
  - dependent on the multiplicity
- Paper in preparation

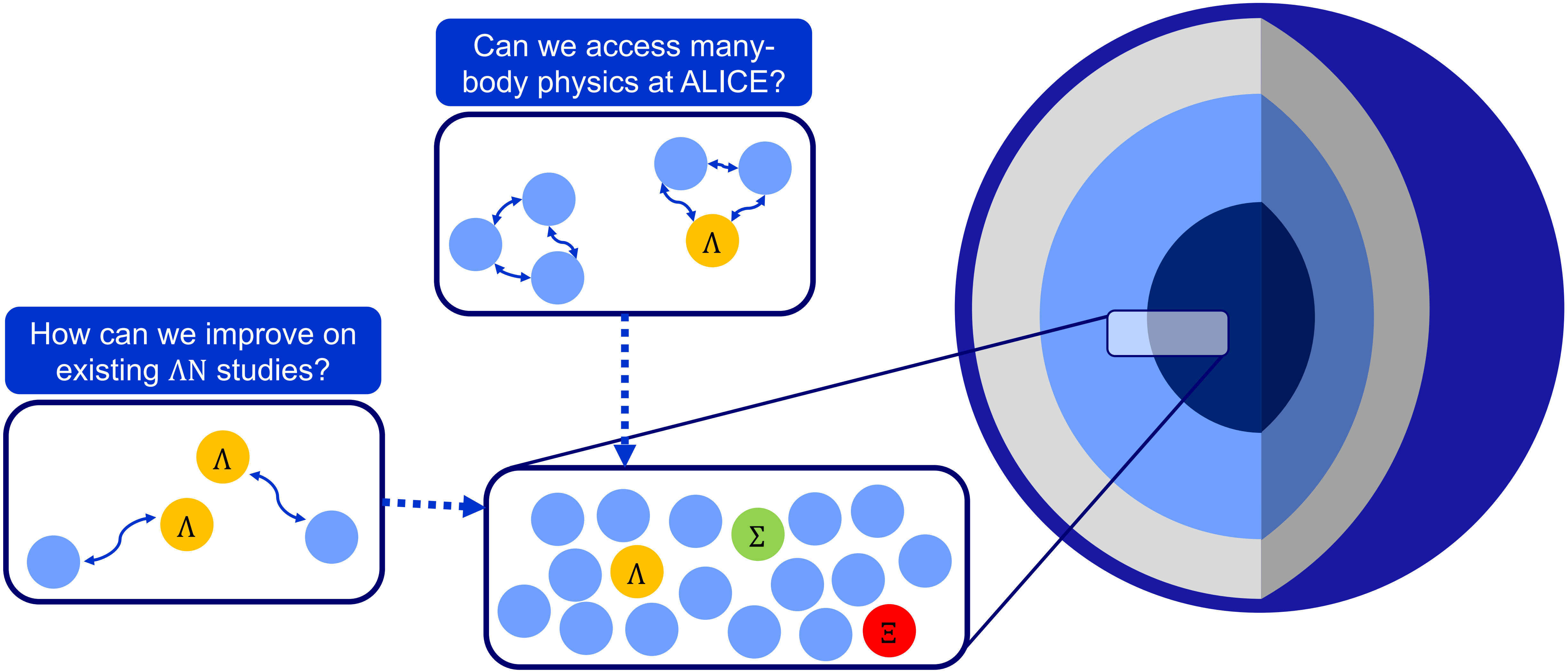
More on the source:
- CECA source model, D. Mihaylov (04th of November 11:10)
- Source in Run 3 Pb–Pb collisions with ALICE, G. Romanenko (04th of November 12:00)



On today's menu

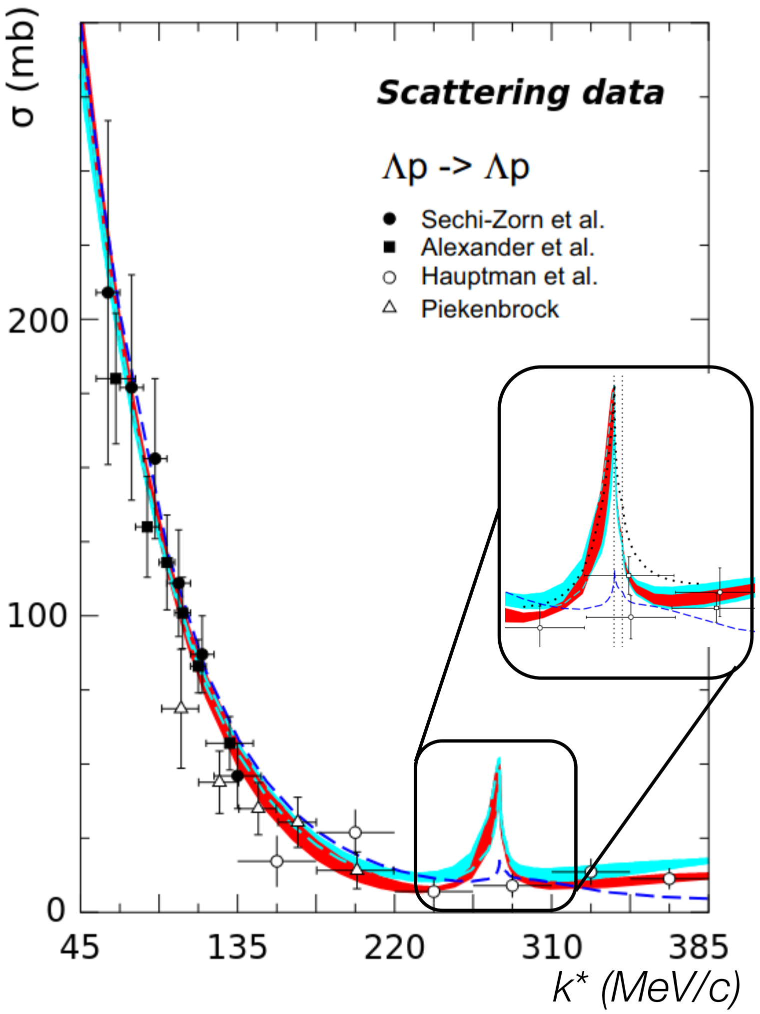
Can we access many-body physics at ALICE?

How can we improve on existing ΛN studies?



pΛ scattering data

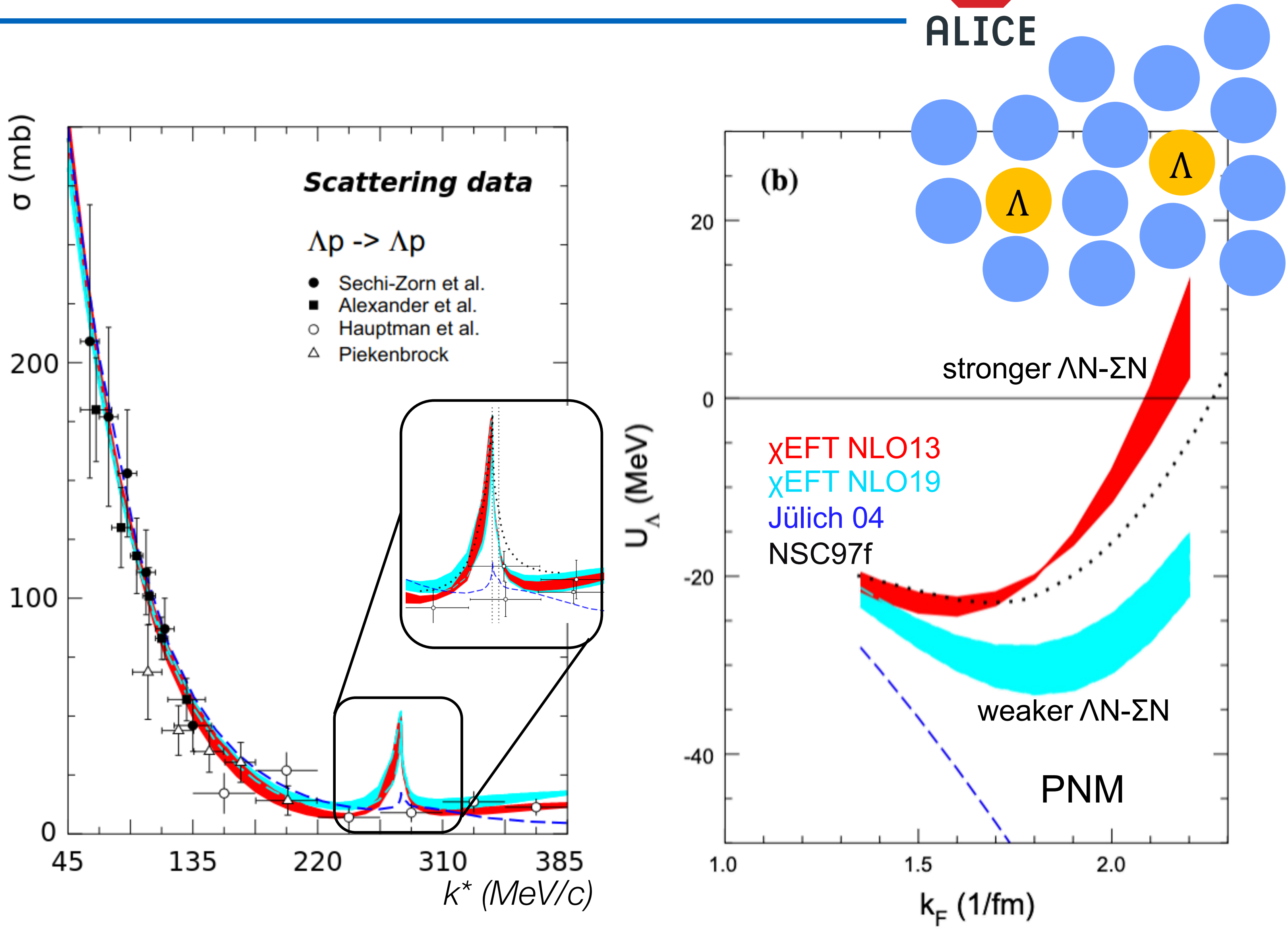
- Scattering data limited to relative momenta above 40 MeV
- ΣN coupling not visible in scattering data
- χEFT NLO13 and NLO19 can both describe the available scattering data



NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meiβner, Eur.Phys.J.A 56 (2020)

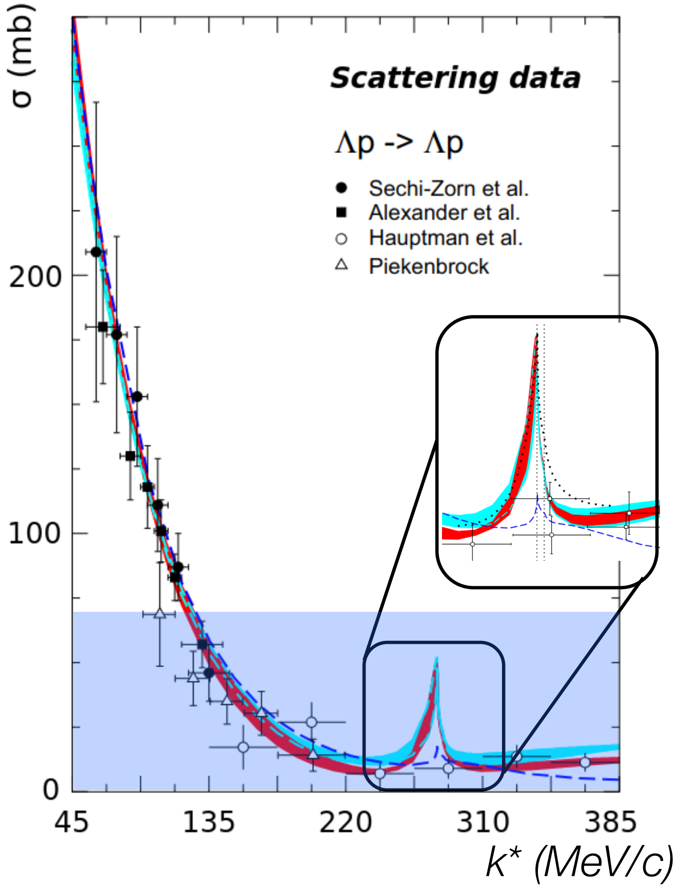
pΛ scattering data

- Scattering data limited to relative momenta above 40 MeV
- ΣN coupling not visible in scattering data
- χEFT NLO13 and NLO19 can both describe the available scattering data
- ΣN coupling drives the behaviour of Λ at finite density → important for the EoS of NS



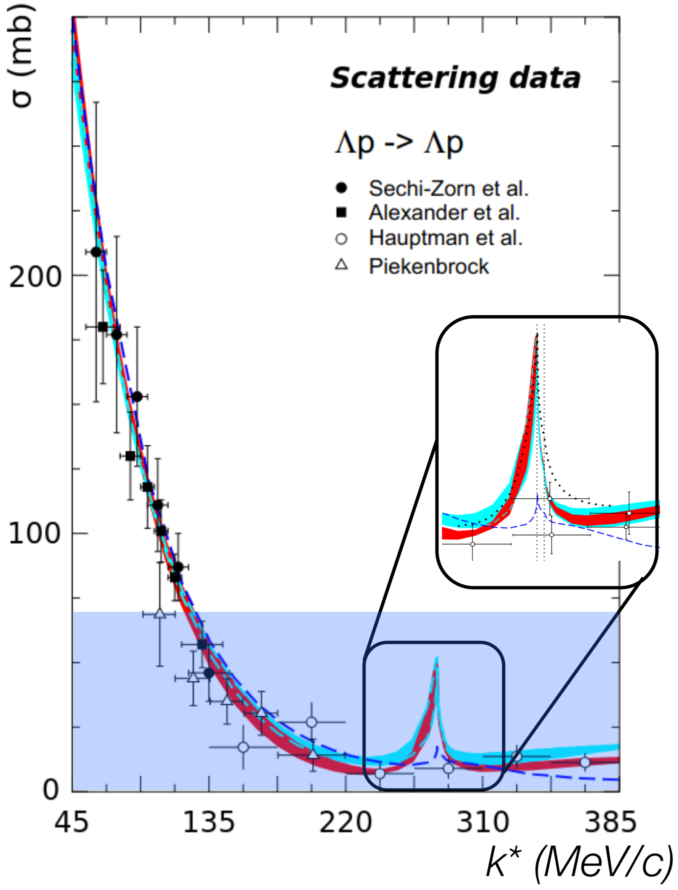
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meiβner, Eur.Phys.J.A 56 (2020)

pΛ results before

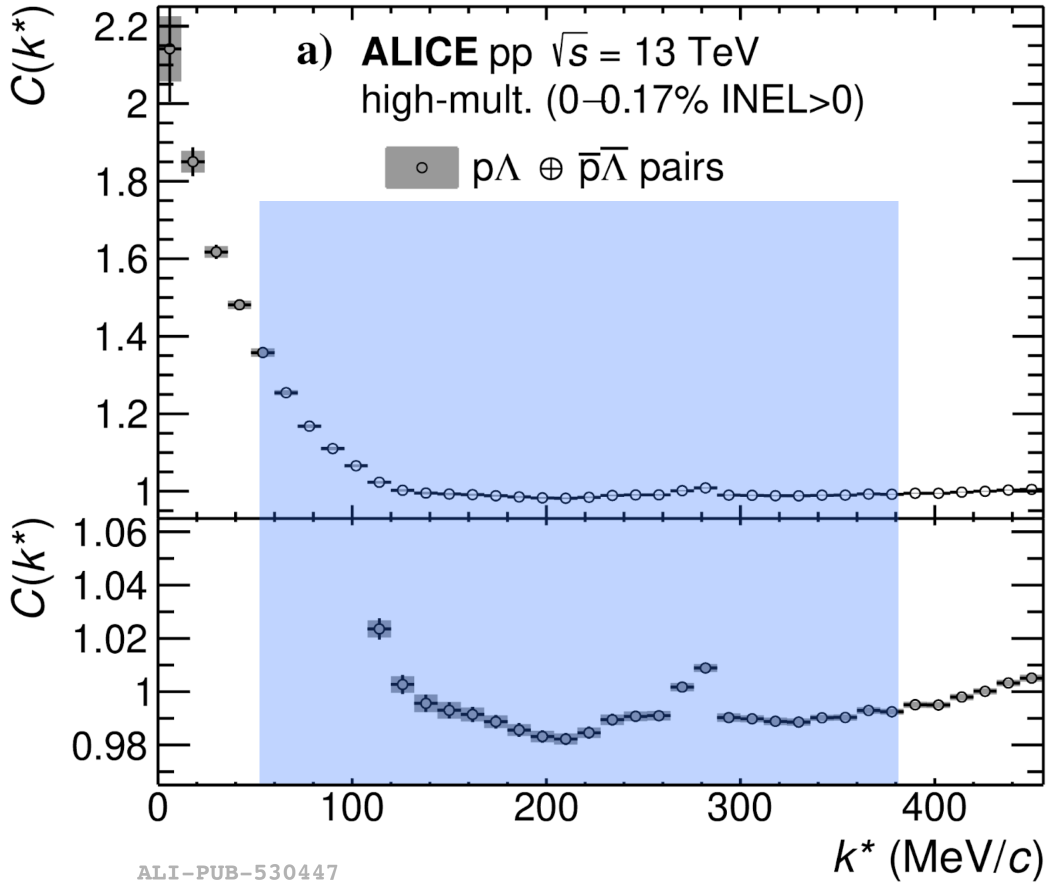


pΛ results before and after femtoscopy

- Extension of the kinematic range
  → Measurement down to zero relative momentum
- Improvement of precision in data of factor 25
  → Uncertainties < 1 % !
- First experimental observation of $\Lambda N - \Sigma N$ coupled channel in a 2→2 reaction



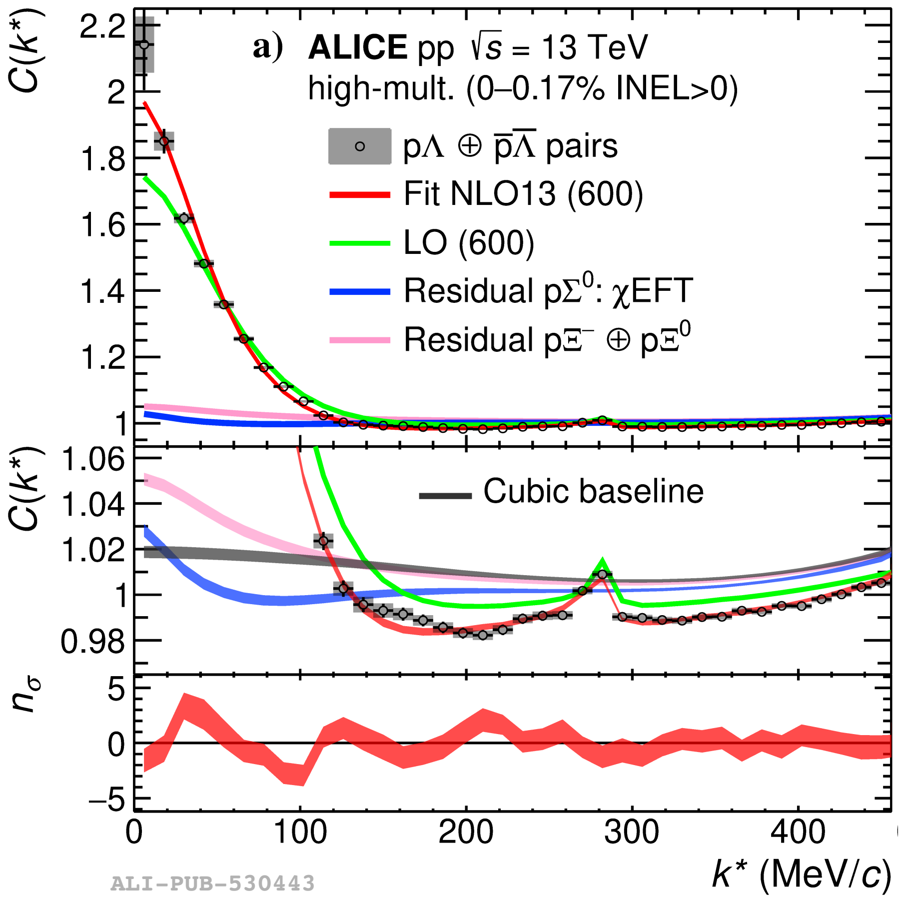
ALICE Coll. PLB 833 (2022), 137272



pΛ results with femtoscopy

- New insights into $\Lambda N - \Sigma N$ dynamics

Fit with NLO13



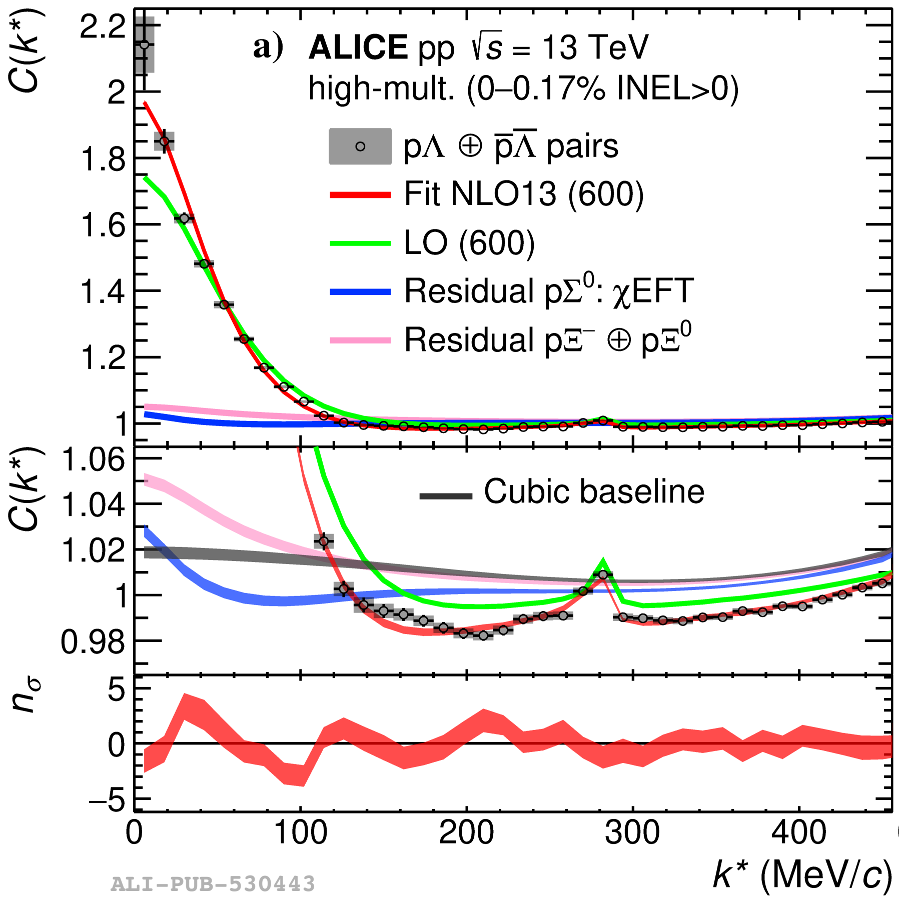
n_σ~ 4.5 for k^* < 110 MeV/c

ALICE, PLB 833 (2022), 137272

pΛ results with femtoscopy

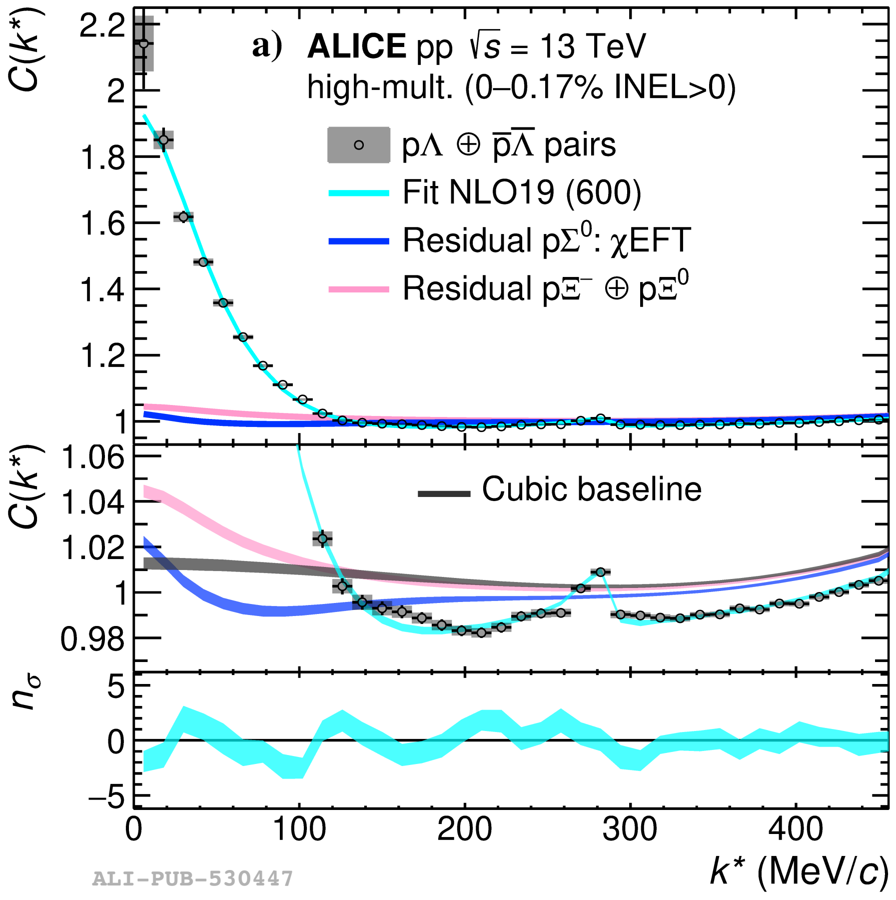
- New insights into $\Lambda N - \Sigma N$ dynamics
- NLO19 potentials favoured:
  → weaker $\Lambda N - \Sigma N$ coupling
  → significant attraction of Λ at high densities
  → large ΛNN three-body repulsion needed

Fit with NLO13



n_σ~ 4.5 for k^* < 110 MeV/c

Fit with NLO19



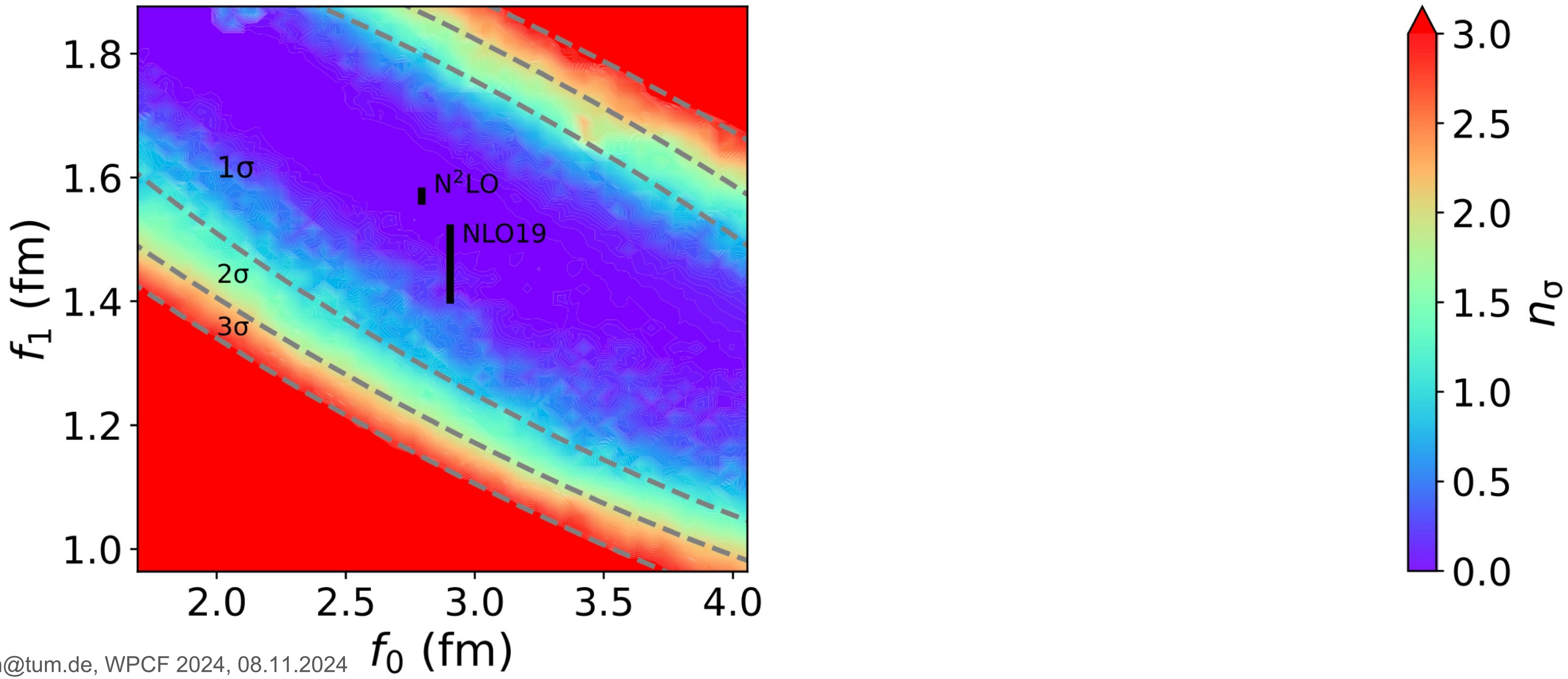
n_σ~ 3.2 for k^* < 110 MeV/c

ALICE, PLB 833 (2022), 137272

Constraints on χ_{eft}-models

- Femtoscopic data by ALICE constrains the allowed phase-space of scattering lengths in triplet and singlet states! D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

Scattering Data only

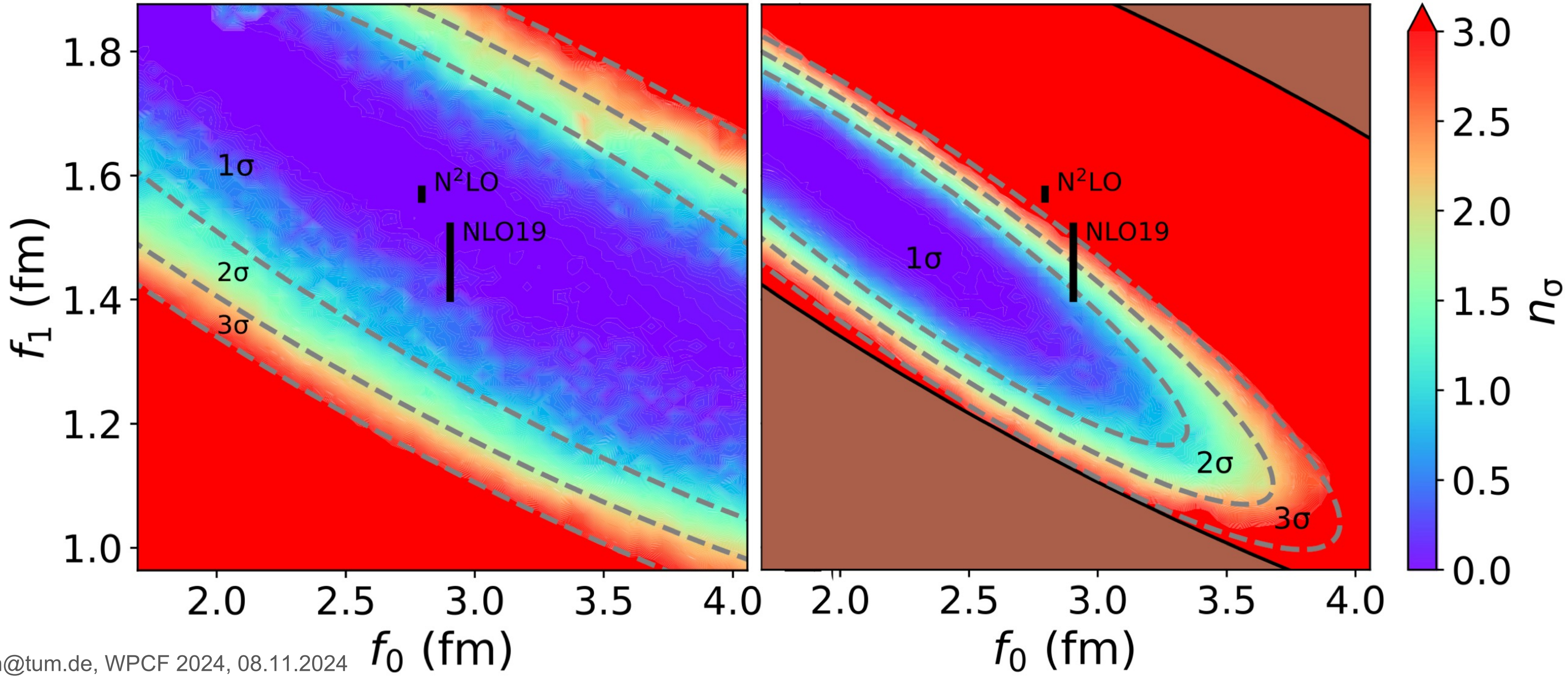


Constraints on χ_{eft}-models

- Femtoscopic data by ALICE constrains the allowed phase-space of scattering lengths in triplet and singlet states! D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

Scattering Data only

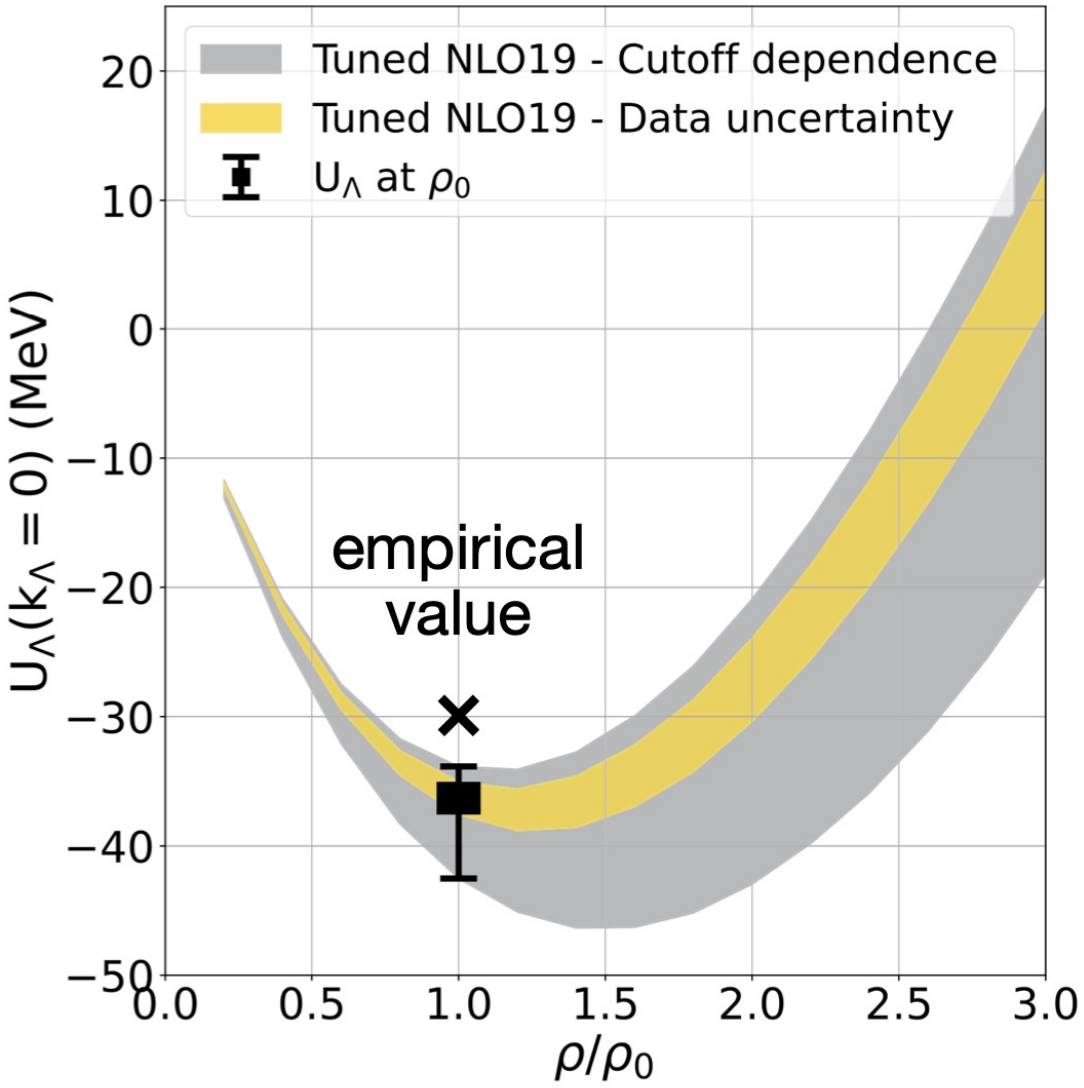
Scattering & Femto Data



Constraining the Λ in-medium behaviour

- Evaluation of the in-medium single-particle potential U_Λ based on two-body interaction only → results in $-36.3 \pm 1.3(\mathrm{stat.})^{+2.5}_{-6.2}(\mathrm{syst.})\mathrm{MeV}$
- More bound than the semi-empirical value of $\mathrm{U}_\Lambda \approx -30\ \mathrm{MeV}$ from hypernuclei studies

→ Repulsive three-body $\Lambda\mathrm{NN}$ interaction needed!



D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

Just one of many

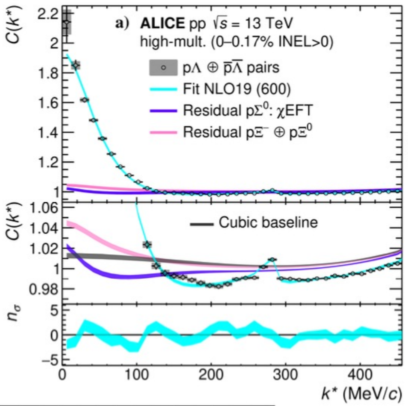
|S| = 0
NN

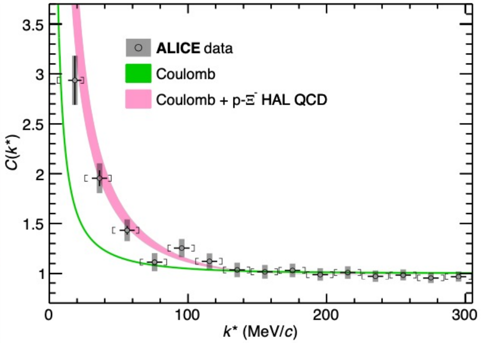
|S| = 1
NΛ, NΣ

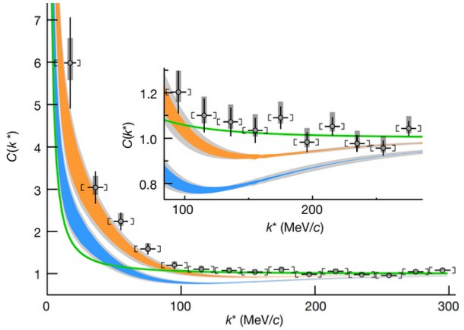
|S| = 2
ΛΛ, NΞ

|S| = 3
ΛΞ, NΩ

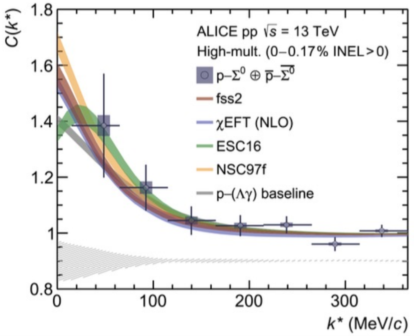
|S| > 3
ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ

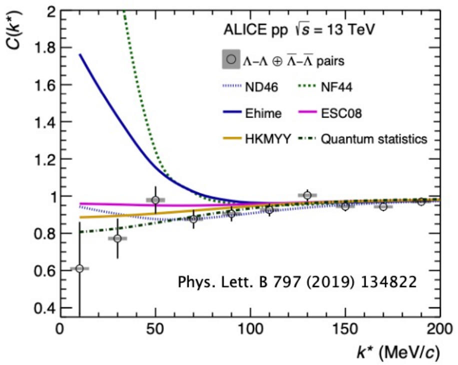


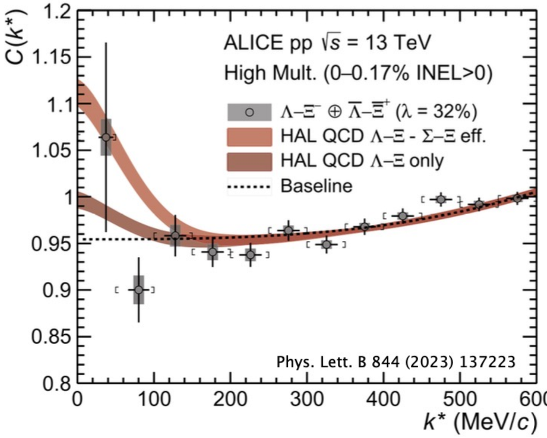


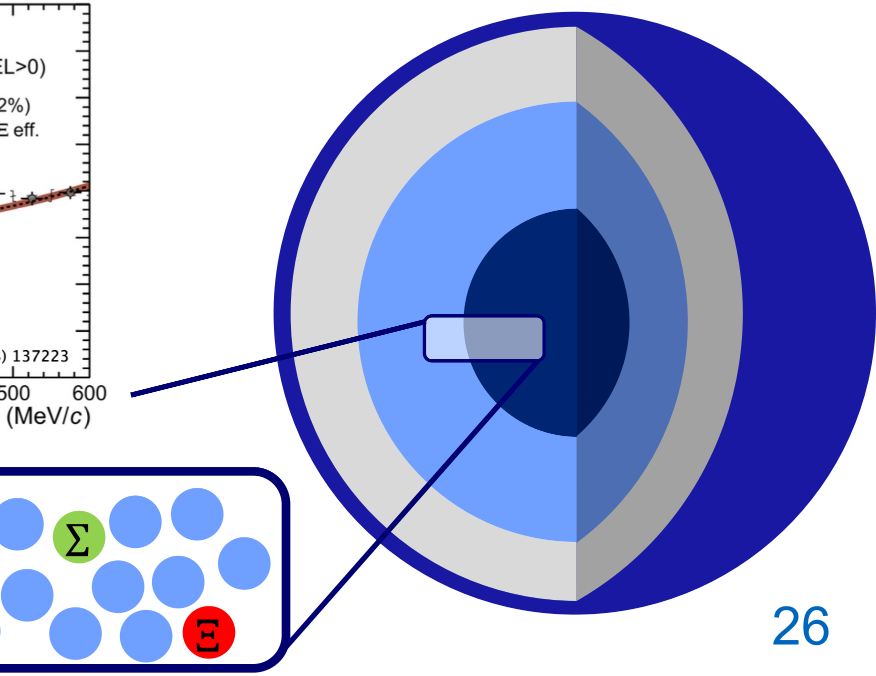


Ongoing efforts to combine all results into one single constraint for EoS

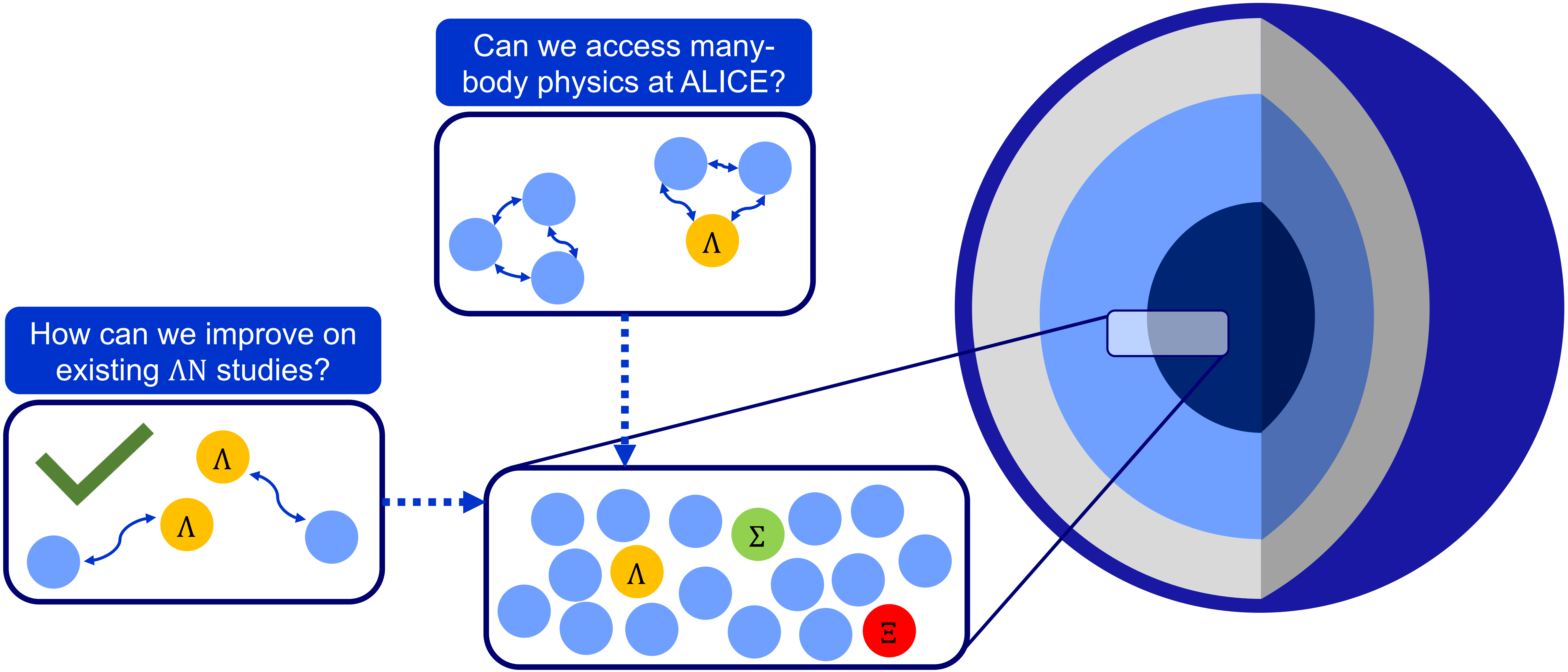






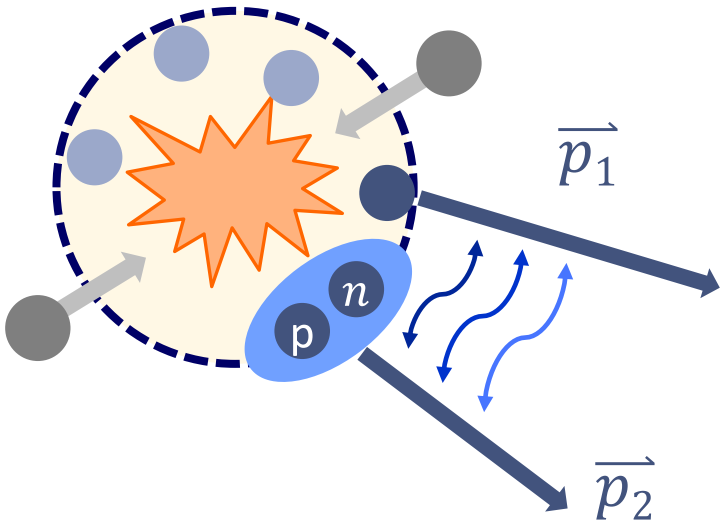


On today's menu



Accessing three-body interactions

Study of hadron-deuteron interactions

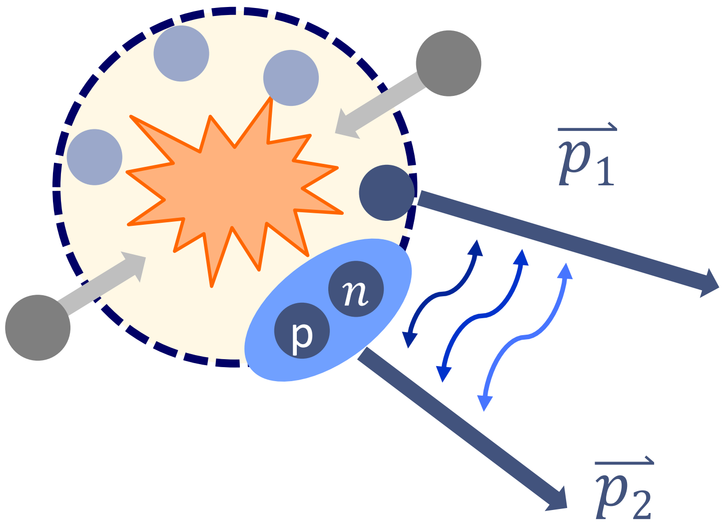


- Performed by ALICE with the study of K-d and p-d system
- Recently published in PRX 14 (2024) 031051

More on hadron-deuteron systems:
Talk by B. Singh, 06th of November 13:55

Accessing three-body interactions

Study of hadron-deuteron interactions



- Performed by ALICE with the study of K-d and p-d system
- Recently published in PRX 14 (2024) 031051

More on hadron-deuteron systems:
Talk by B. Singh, 06th of November 13:55

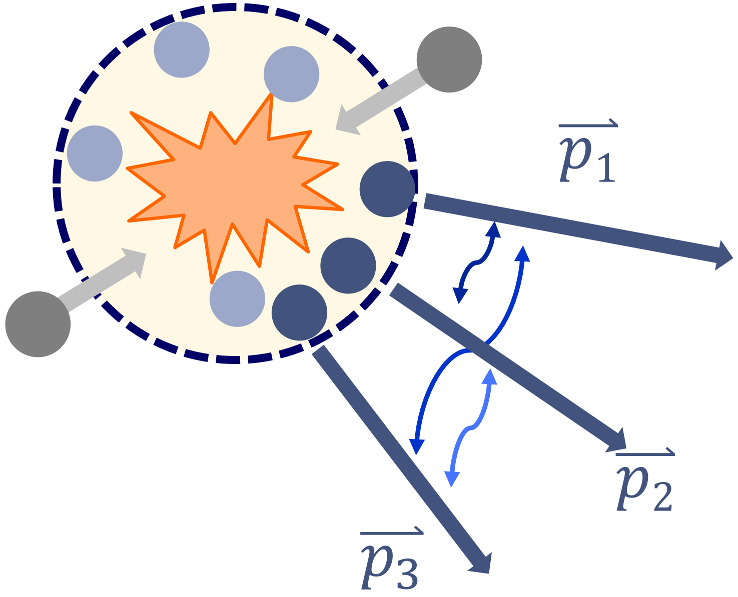
Study correlations among three unbound hadrons

- Use Lorentz-invariant hyper-momentum Q_3

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{13}^2}$$

- Accessible in the experiment

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



and in the theory:

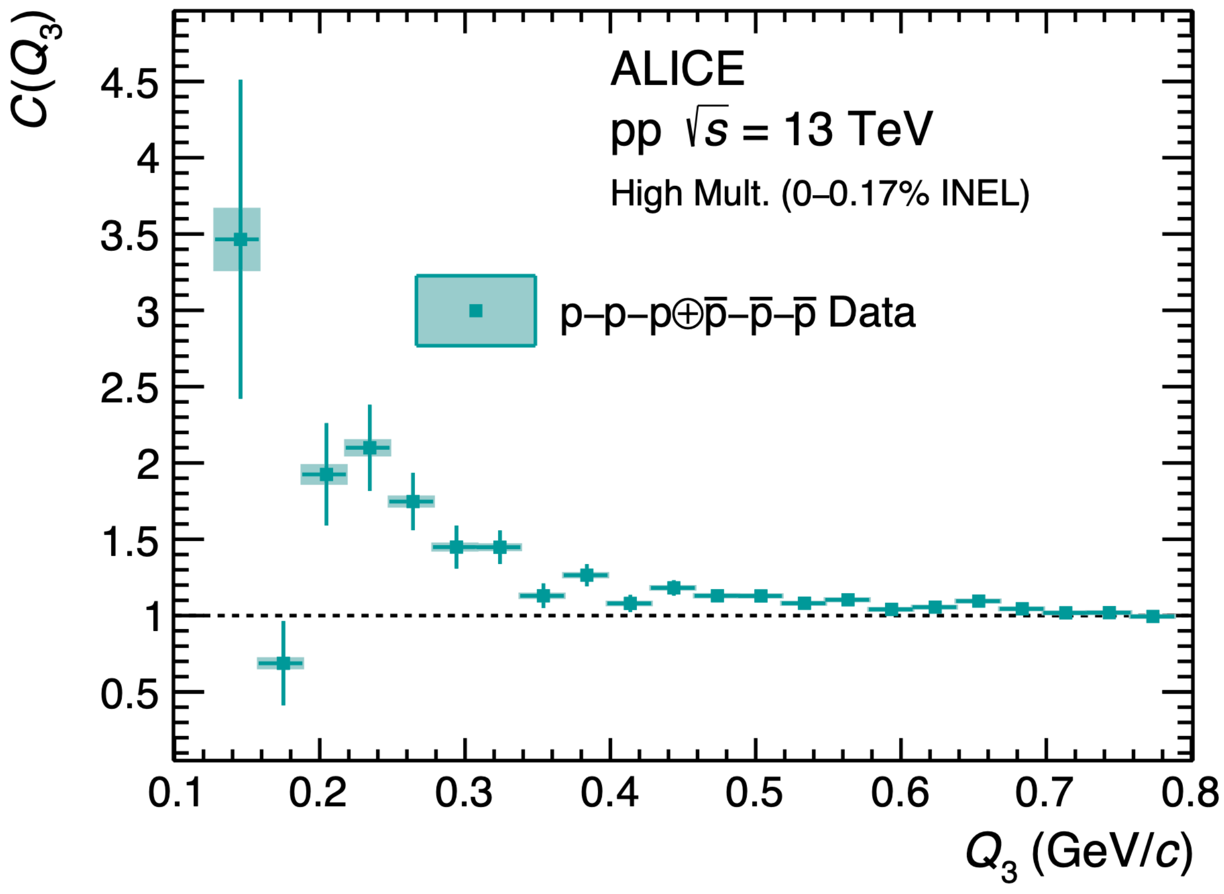
$$C(Q_3) = \int S(\rho)|\Psi(Q_3,\rho)|^2\rho^5 d\rho$$

A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

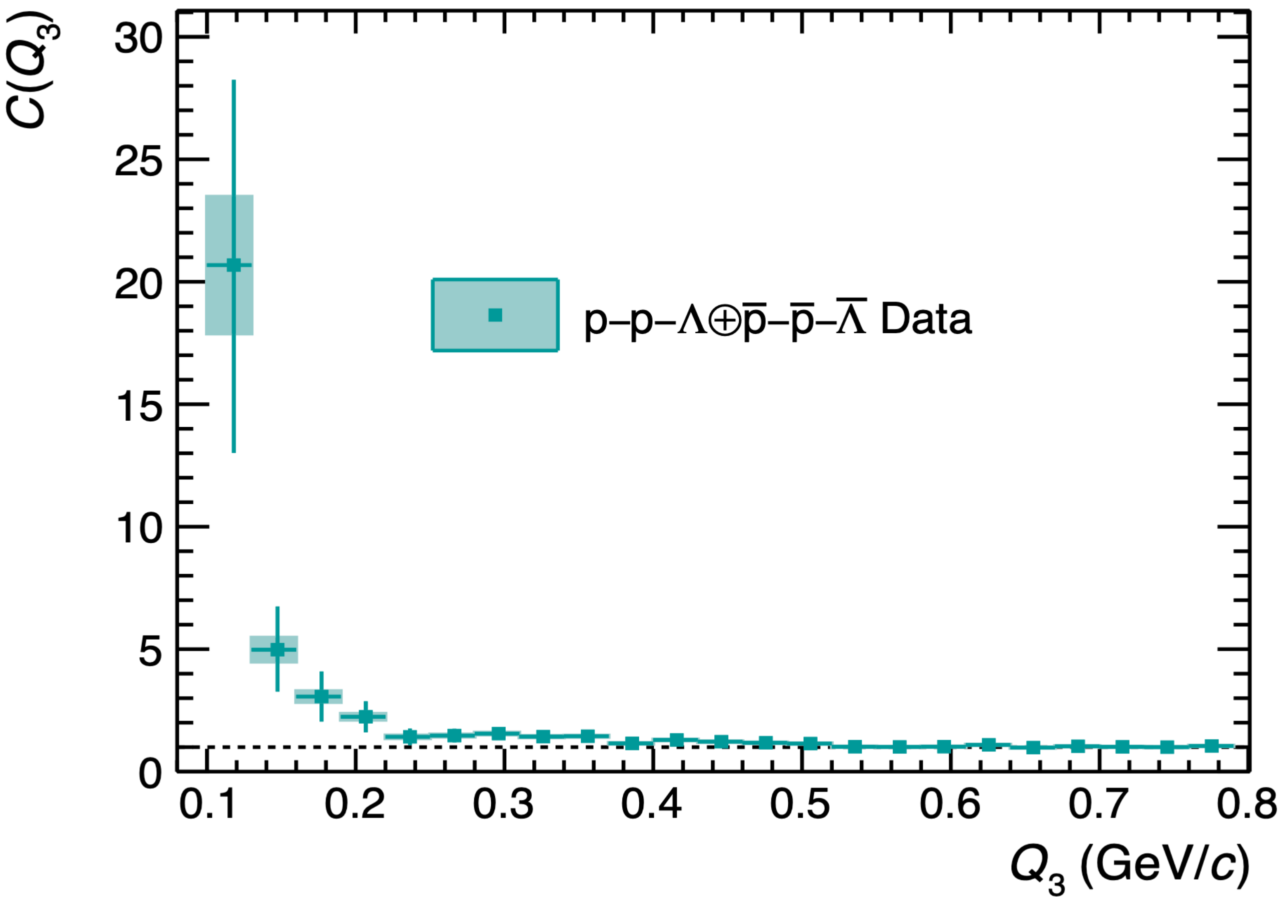
Accessing 3 → 3 scattering processes!

First experimental study of ppp and ppΛ

ALICE Coll., EPJ A 59, 145 (2023)



ALICE Coll., EPJ A 59, 145 (2023)

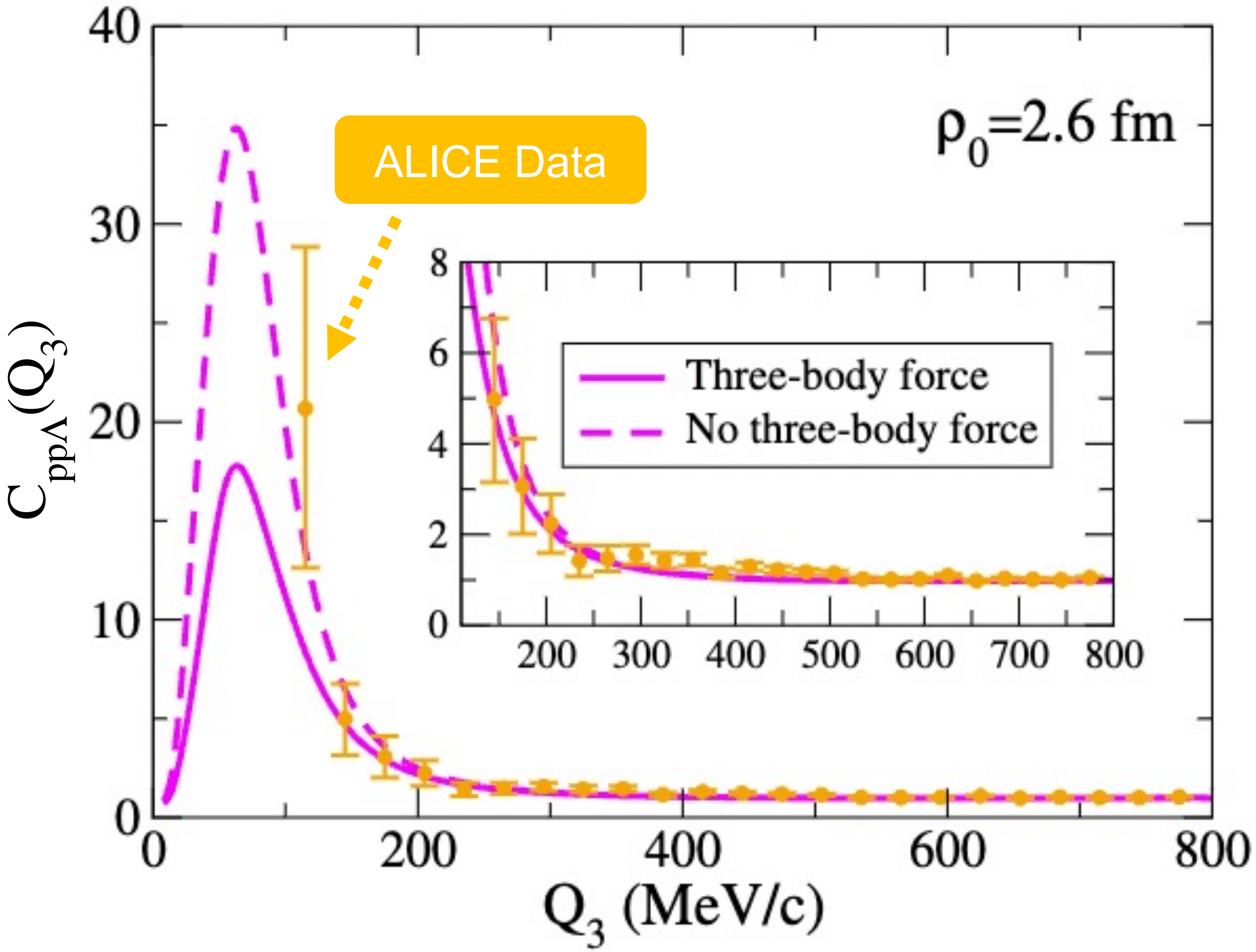


… and other three-particle correlations (p-p-K, p-p-π)

More on p-p-π by M. Korwieser (08[th] of November 15:55)

Theoretical studies on ppΛ

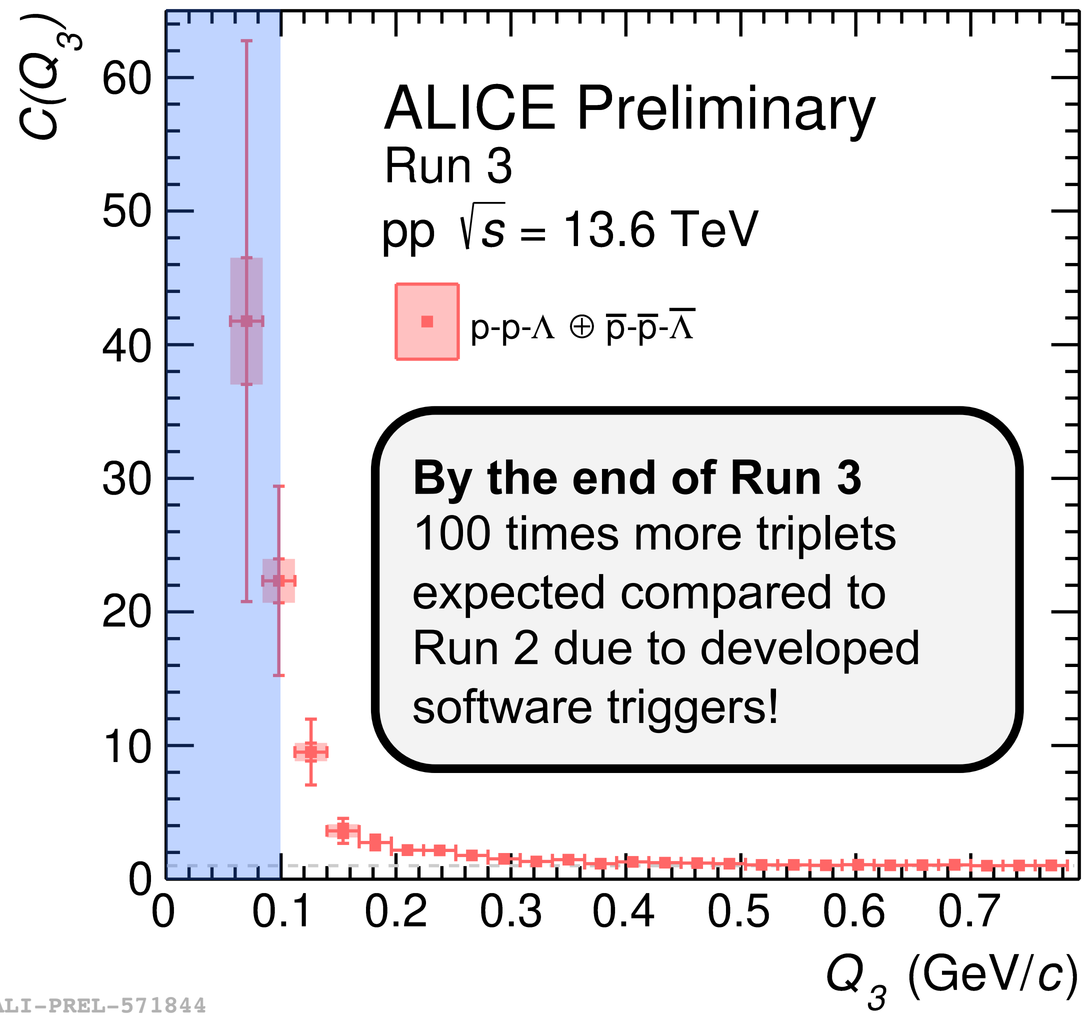
- Three-particle emission source modelled as three single-particle emitters constrained to data
- Modelling includes experimental corrections (e.g. feed-down)
- Gauss NLO19 (600): 40% effect of three-body interactions
- Most interesting region $Q_3 < 100\ \mathrm{MeV}$ not yet accessed by data



E. Garrido et al., arXiv: 2408.01750 (2024)

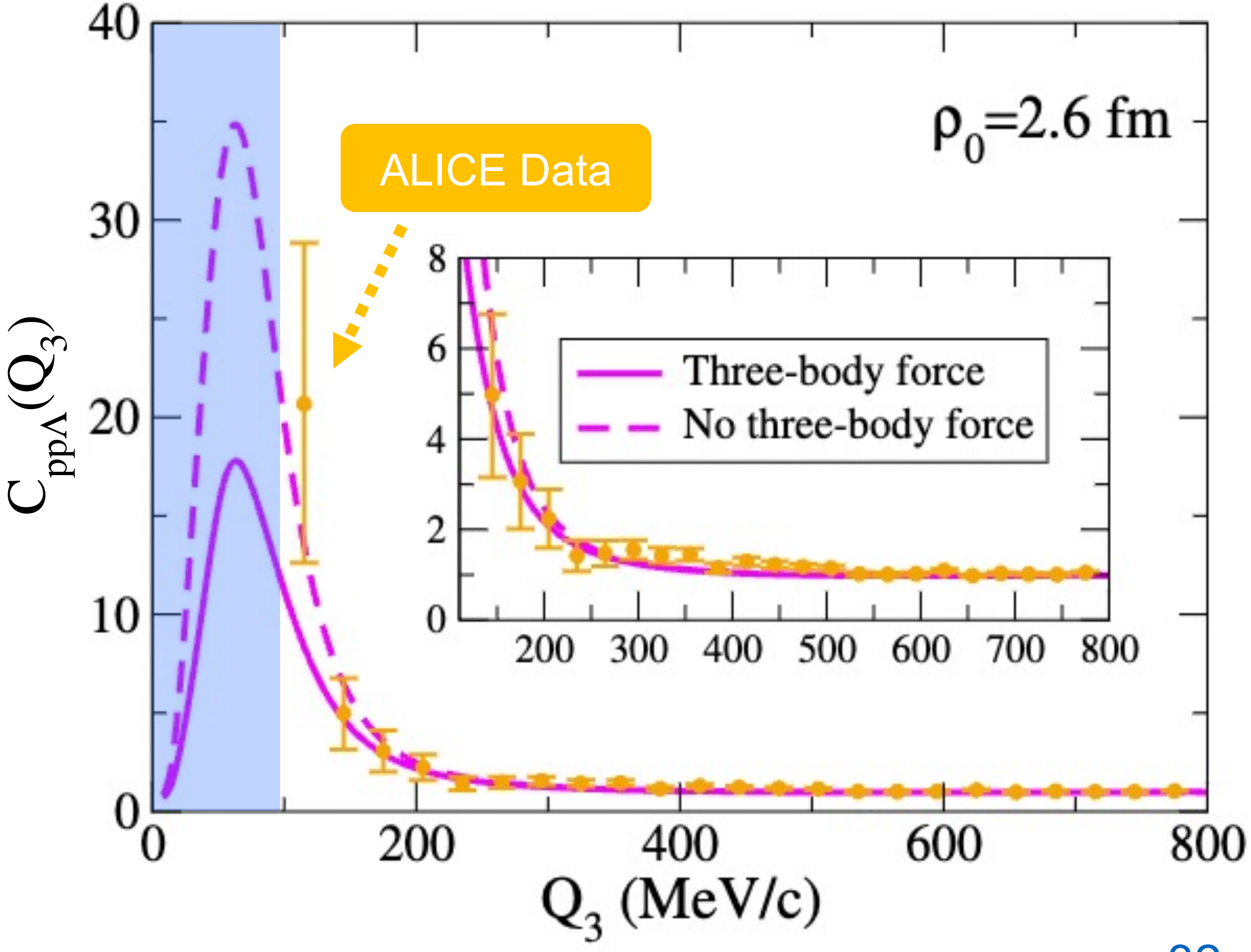
The future of experimental ppΛ Data

ALICE Run 3 (2022 data only)



By the end of Run 3
100 times more triplets expected compared to Run 2 due to developed software triggers!

ALICE Run 2



E. Garrido et al., arXiv: 2408.01750 (2024)

What to take home

- Neutron Stars as a laboratory for nuclear matter at extreme conditions
- ALICE delivers a wide range of experimental results accessing
  - hadron-emitting source
  - exotic two-body interactions
  - three-body hadronic interactions
- ALICE femtoscopy data as an important input and constraint for theoretical models

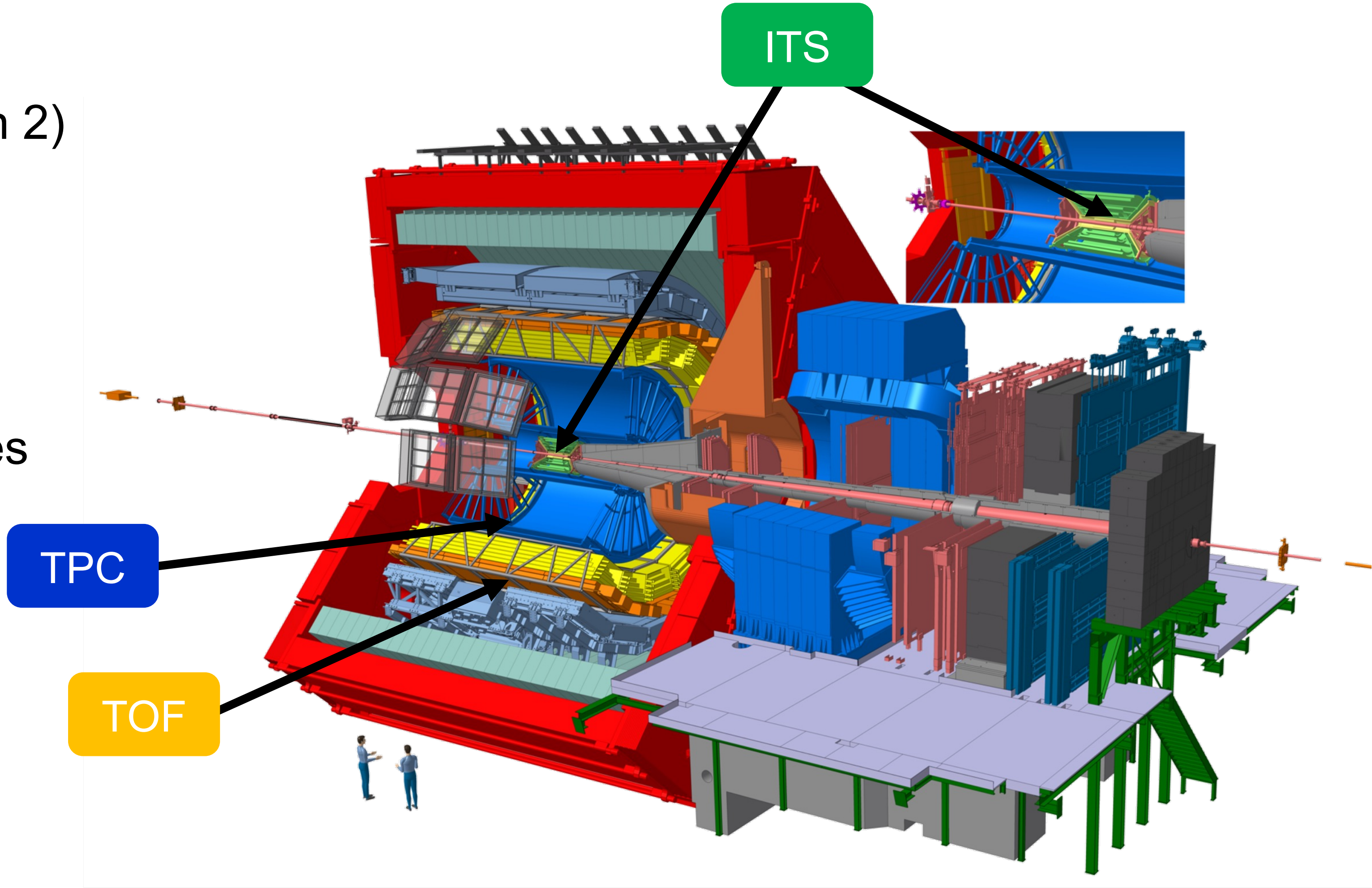
What to take home

- Neutron Stars as a laboratory for nuclear matter at extreme conditions
- ALICE delivers a wide range of experimental results accessing
  - hadron-emitting source
  - exotic two-body interactions
  - three-body hadronic interactions
- ALICE femtoscopy data as an important input and constraint for theoretical models

Backup

ALICE - A Large Ion Collider Experiment

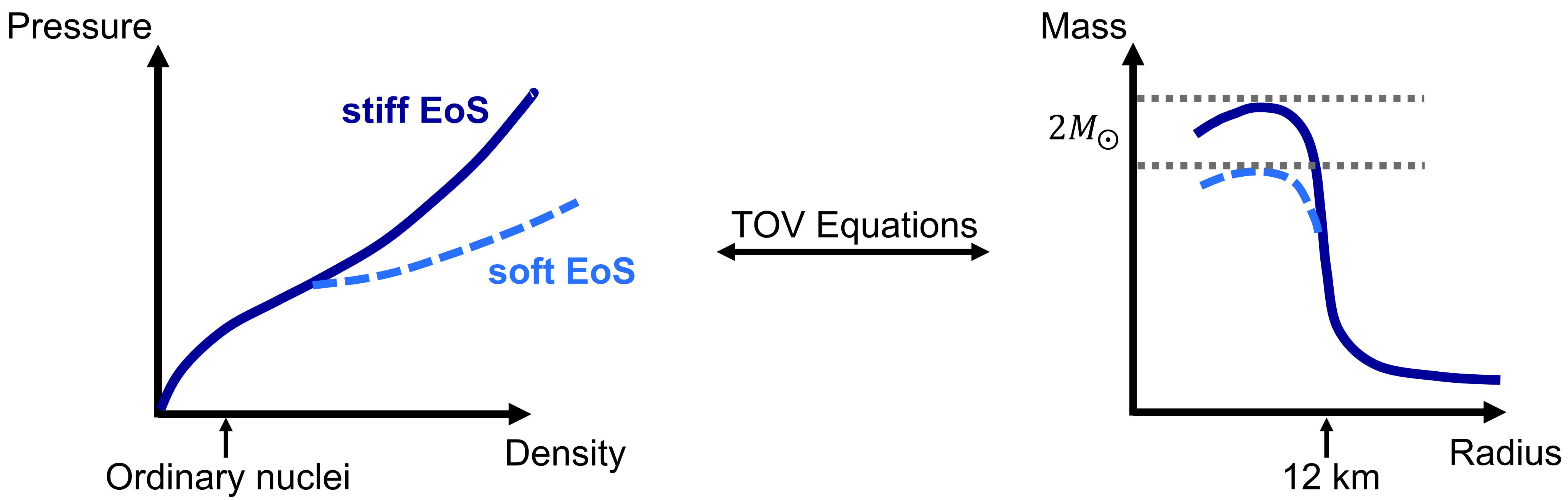
- pp at $\sqrt{s}$ = 13 TeV
- 10^9 high-multiplicity (HM) events (Run 2)
- Direct detection of charged particles (protons, kaons, pions, deuterons)
- Very good PID capabilities of the detector resulting in very pure samples (protons ~ 98%, pions 99%)



A. Tauro, "ALICE Schematics" (2017), CERN CDS

Neutron Stars

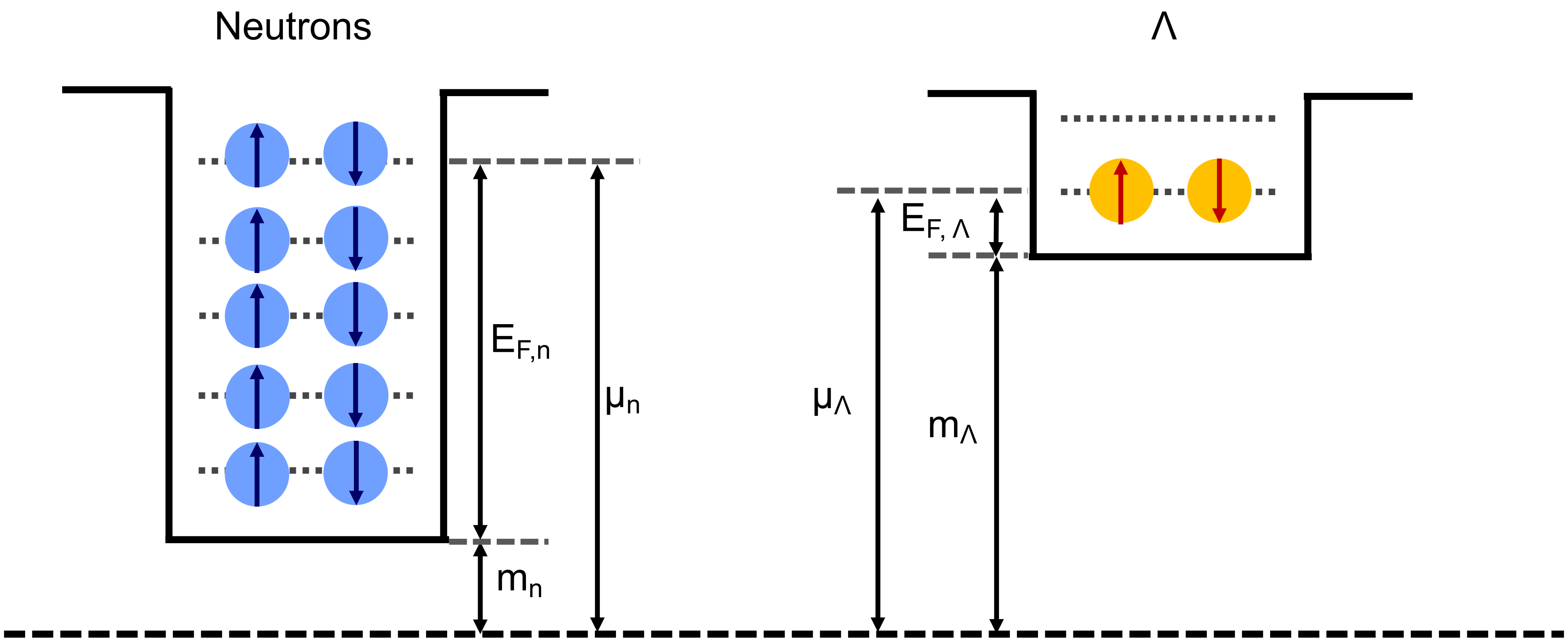
- EoS dependent on the particle composition and the possible interactions between them
- EoS linked to masses and radii of neutron stars via TOV equations



Neutron Stars and the Hyperon Puzzle

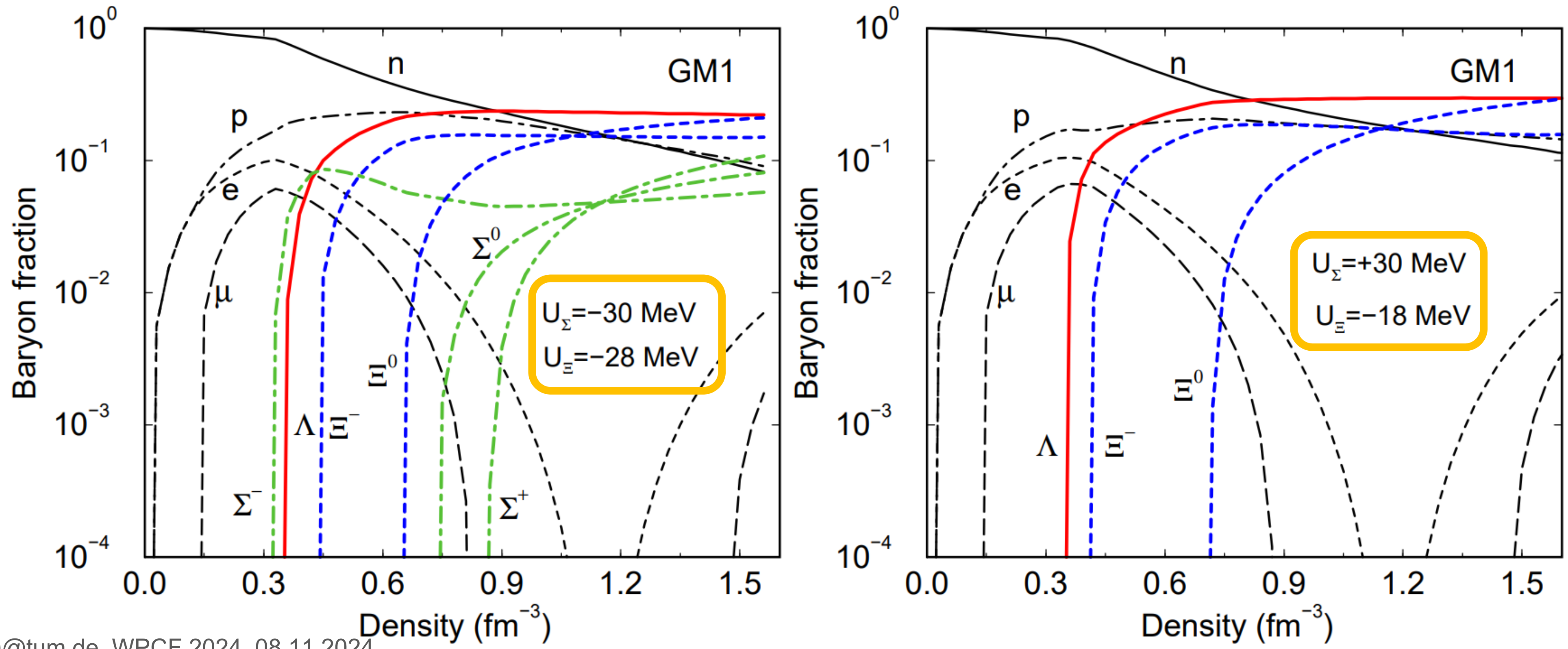
- Chemical potential μ = m + Fermi energy
- Fermi energy increases with density

→ $\mu_n = \mu_\Lambda$: conversion into baryons with strangeness (hyperons)



Hyperons in Neutron Stars

- Situation more complex:
  Appearance of multiple hyperon species possible, also Ξ and Σ
- Modelling of hyperons at large densities depends on hyperon-nucleon interactions
  → constrain from experimental data needed

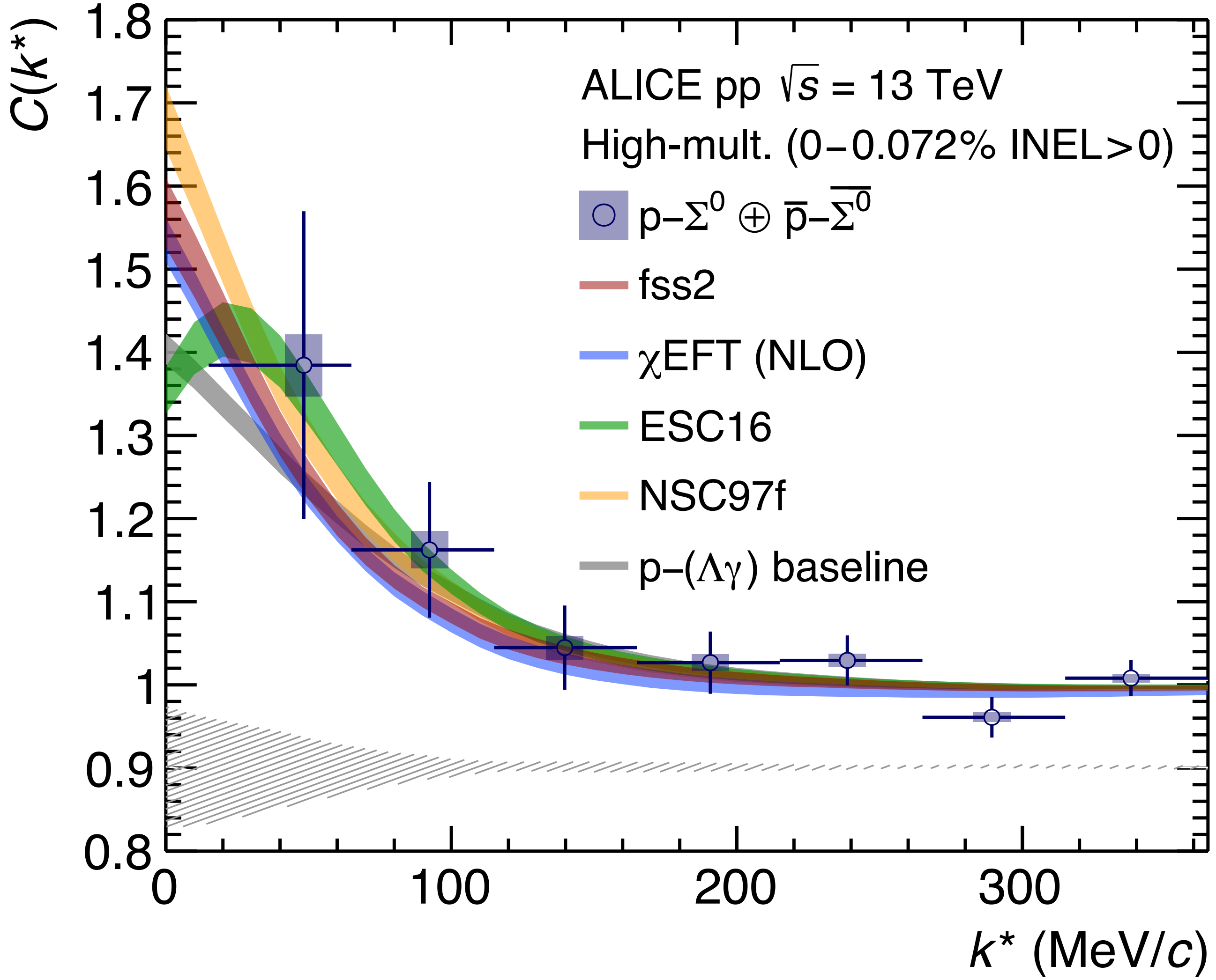


J. Schaffner-Bielich
NPA 835 (2010) 279

The $p\Sigma^0$ Interaction

- Reconstruction of Σ^0 via decay to $\Lambda + \gamma$
- $p\Sigma^0$ compatible to the baseline
- $p\Sigma^0$ femtoscopy already possible in Run 2
  → stay tuned for data of Run 3 for higher statistics!

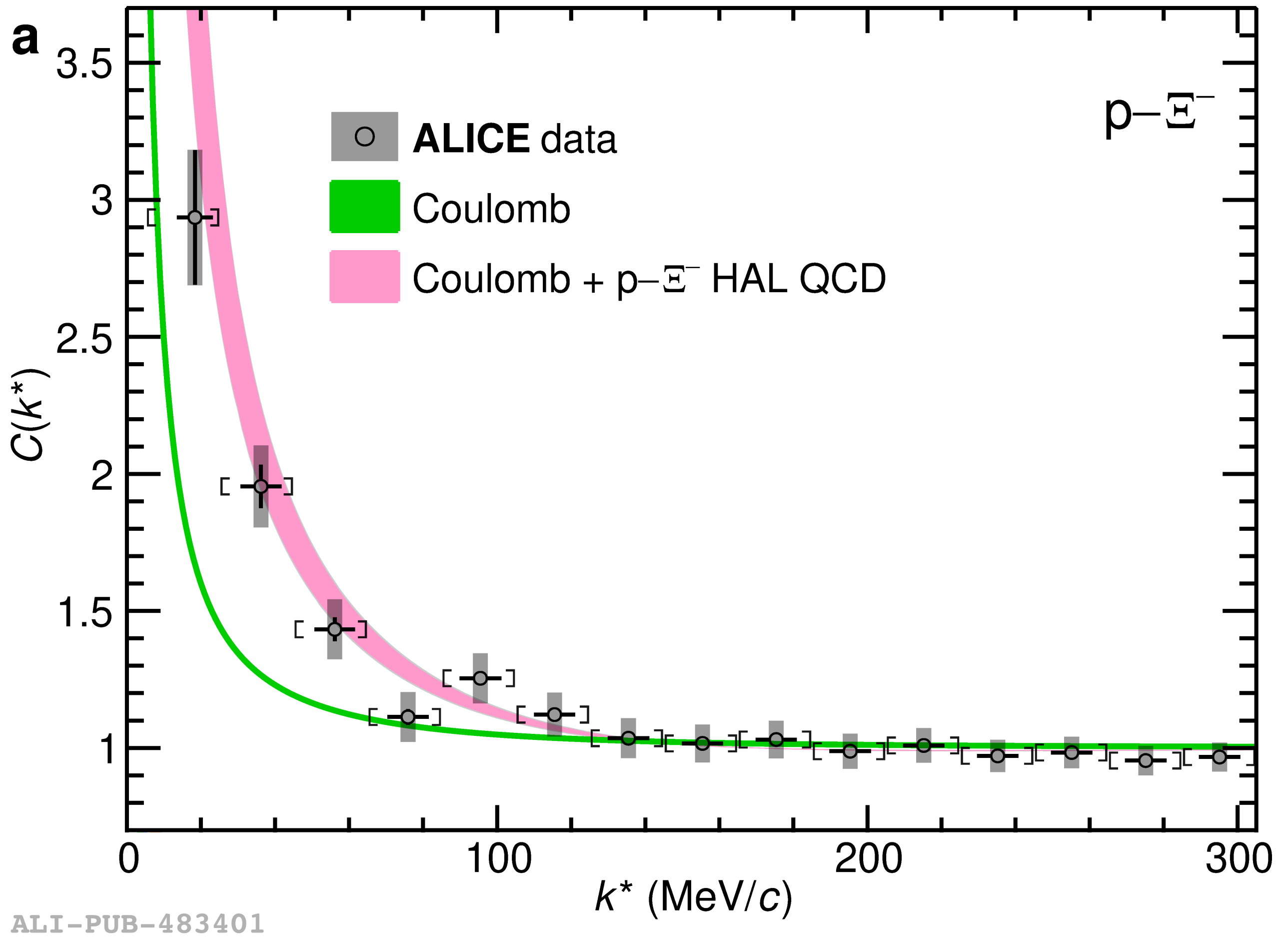
ALICE, PLB 805 (2020) 135419



The “strangest” System: $p\Xi^-$

- Reconstruction of Ξ^- via decay to $\Lambda + \pi^-$
- Coulomb interaction only cannot describe the data
  → attractive strong interaction needed
- Lattice QCD calculations for $p\Xi^-$ by HAL QCD collaboration
  HAL QCD, Nucl.Phys.A 998 (2020) 121737
- One of the first direct tests of Lattice QCD

ALICE Coll. Nature 588, 232–238 (2020)

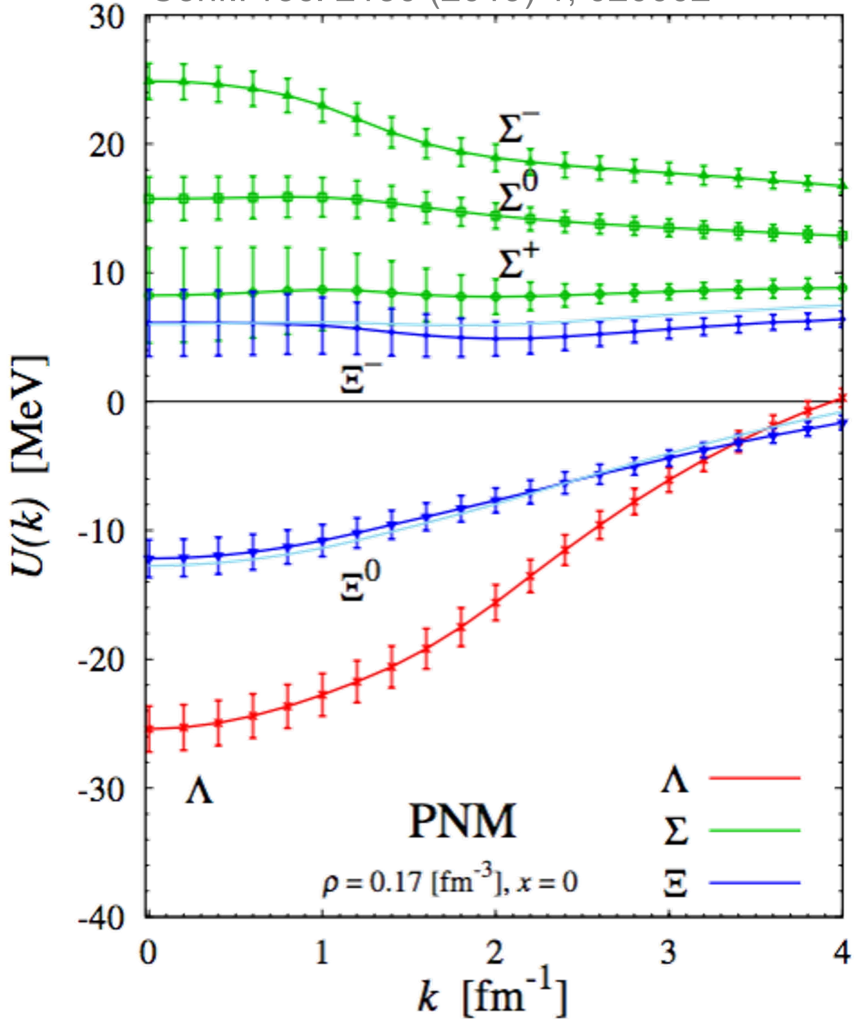


Single Particle Potential of Ξ^-

- HAL QCD potential of $p\Xi^-$ tested/verified with femtoscopic data
- Extraction of single-particle potential U_Ξ by HAL QCD Collaboration
  → predictions in PNM:
  $U_\Xi \sim +6\ \mathrm{MeV}$
  HAL QCD Coll., PoS INPC2016 (2016) 277

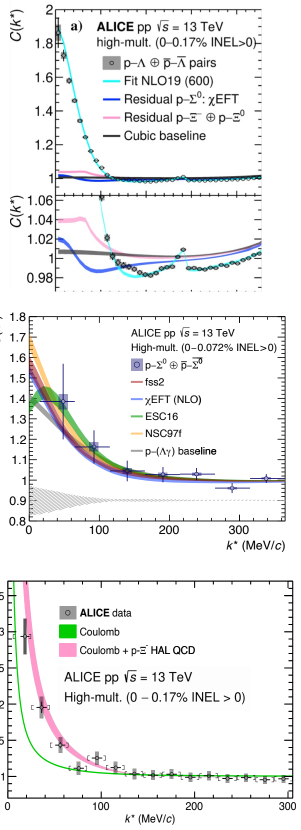
  → stiffening of the EoS

HAL QCD Collaboration, AIP Conf.Proc. 2130 (2019) 1, 020002



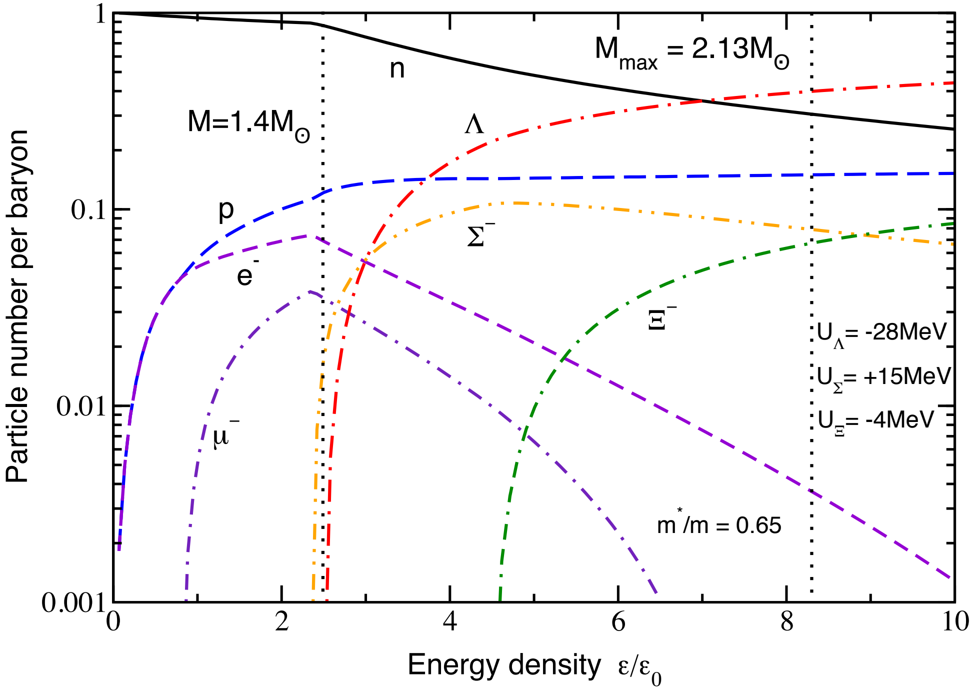
Updating the EoS

Two-body interaction



Single-particle potentials EoS

Courtesy J. Schaffner-Bielich 2020

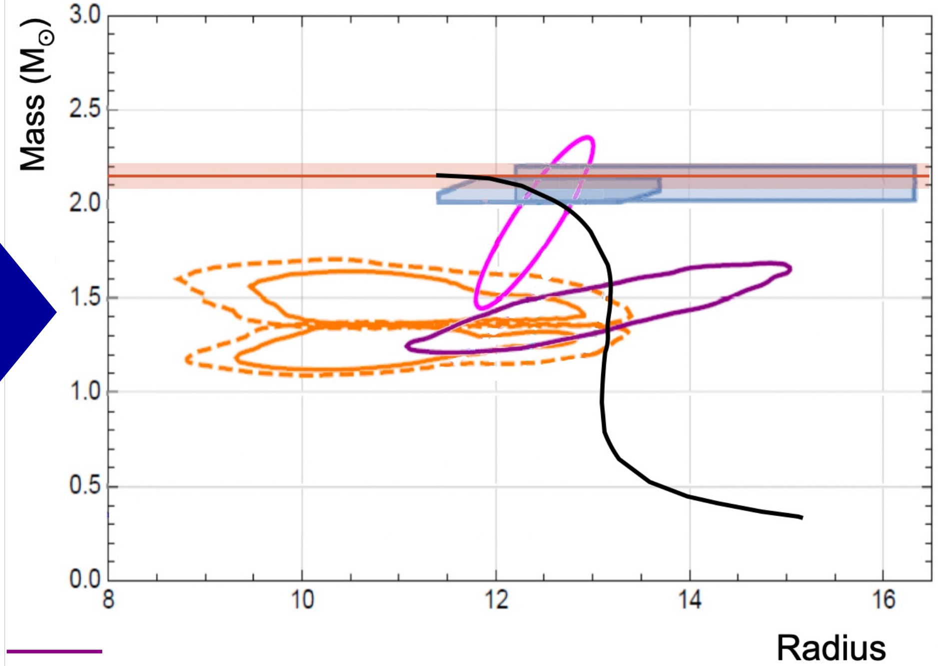


This is only an example!

V. Mantovani Sarti, L. Fabbietti,O. Vazquez-Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)
S. Weissenborn et al., J. NPA 881 (2012)
J. Schaffner-Bielich, I. Mishustin, PRC 53 (1996)
N. Hornick et al., PRC 98 (2018)

Mass vs Radius relation for hyperon stars

Adapted from J. Schaffner-Bielich and B. Dönigus 2020



NICER experiment: M.C Miller et al. AJL 918 (2021)

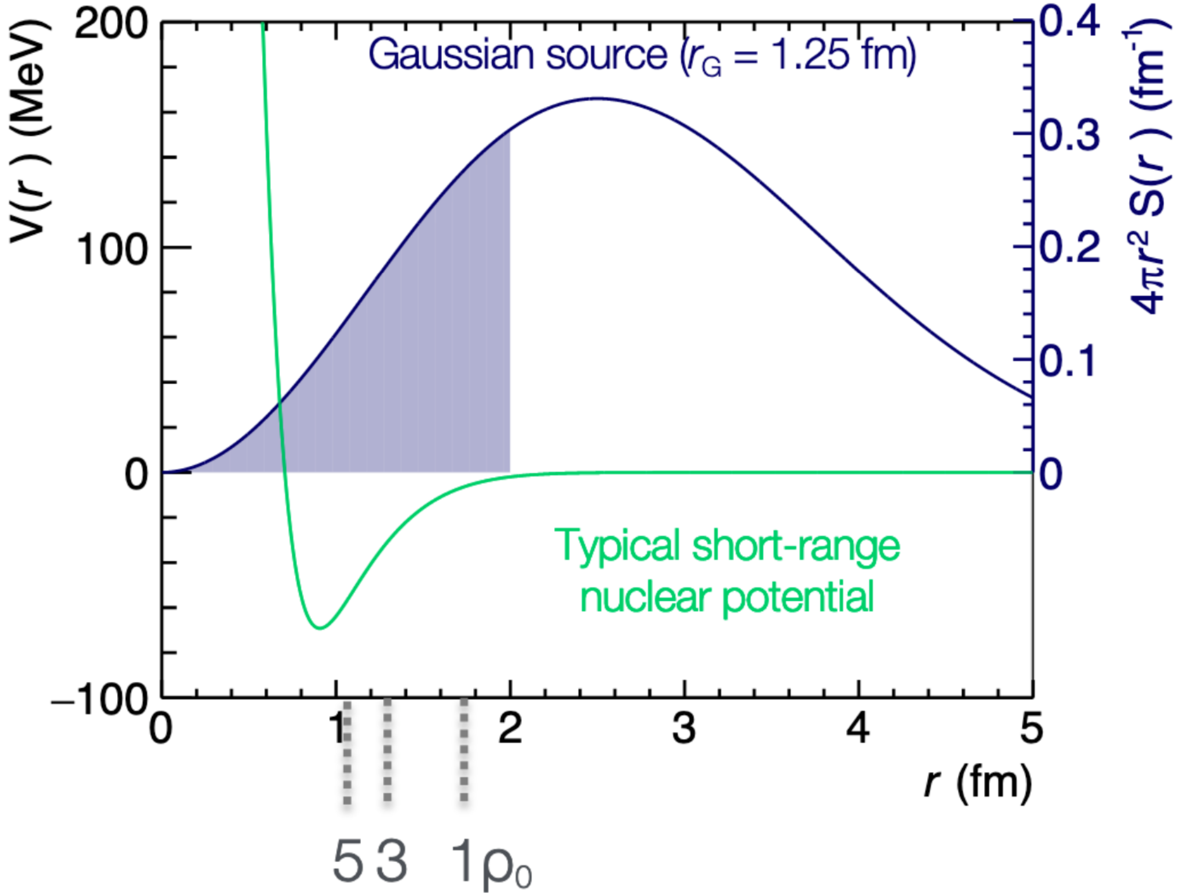
Mass measurement: H. T. Cromartie et al. Nature Astron. 4 (2019)

Gravitational waves data: B. P. Abbott et al. PRL 119 (2017)

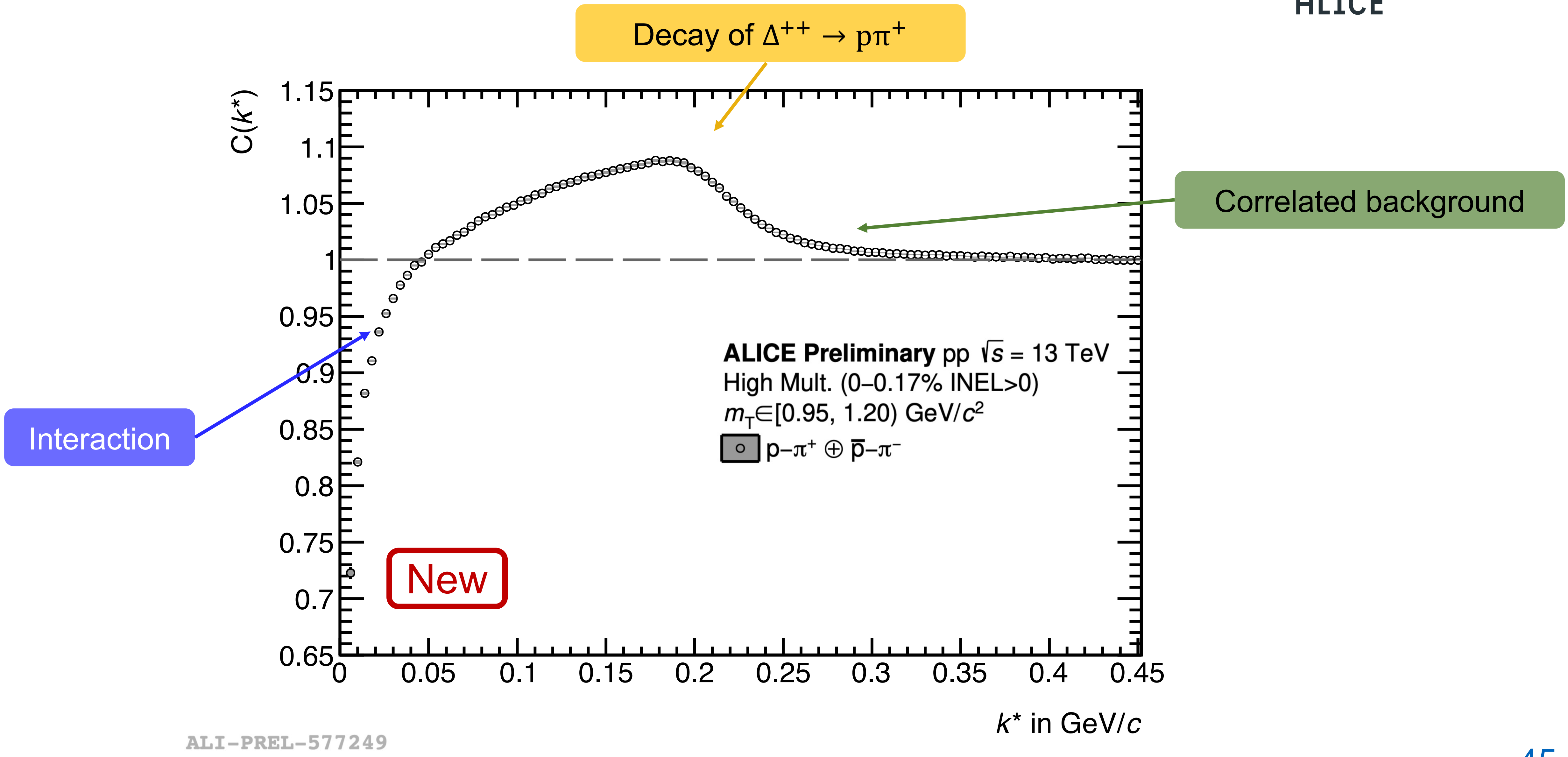
Source in pp Collisions

- Nuclear force with short range of a few fm
- Emission of particle pairs in pp collisions at close distances

→ **Ideal for studying the short-ranged strong interaction**



Two-particle correlation function of $p\pi^+$



Fitting of data of $p\pi^+$

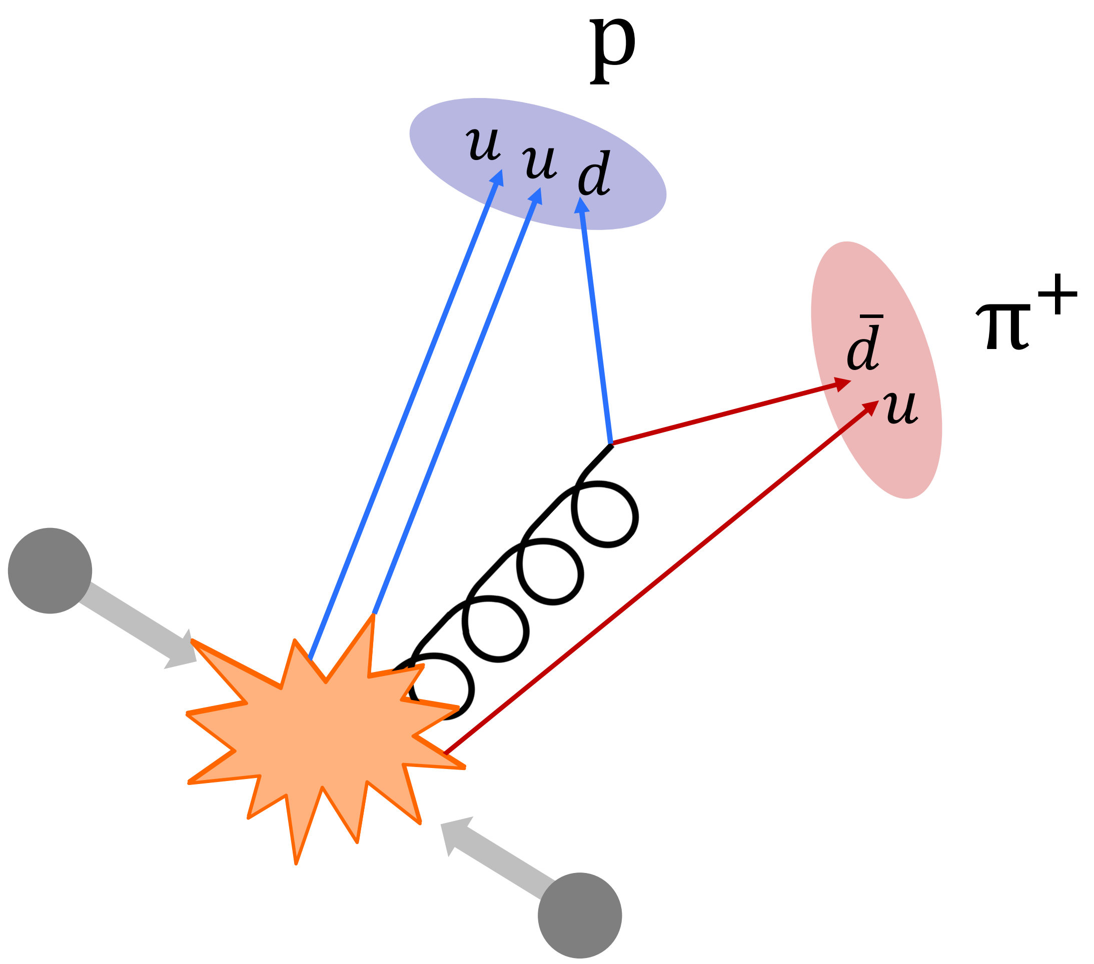
$$C_{\text{total}} = \mathcal{N} \times \text{[redacted]} \times \text{[redacted]} + \text{[redacted]}$$

Fitting of data of $p\pi^+$

$$C_{\text{total}} = \mathcal{N} \times C_{\text{bckg}} \times$$ [redacted] $$+$$ [redacted]

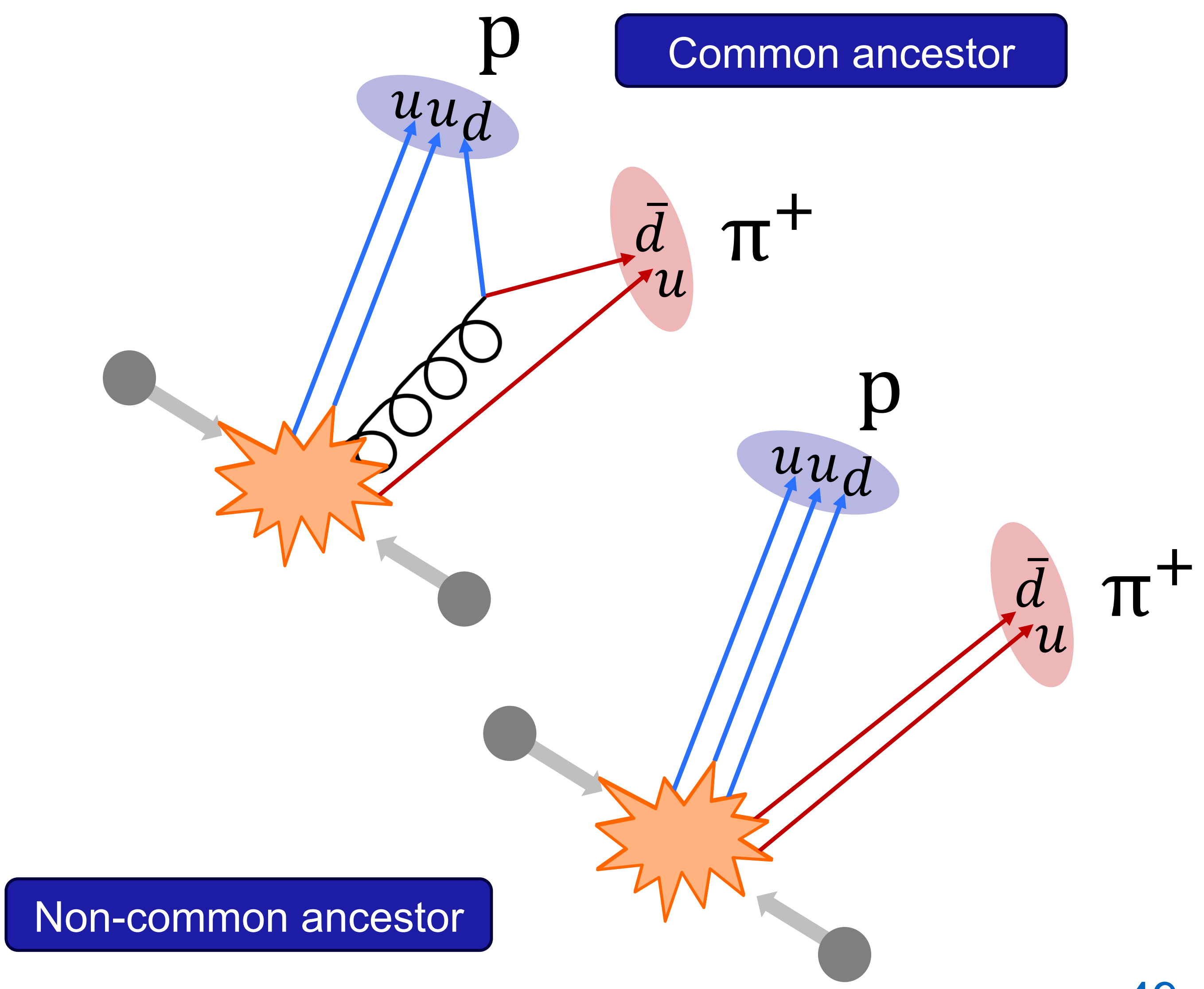
Background contribution

- Correlated background due to “mini-jet” contribution from hadronization process



Background contribution

- Correlated background due to "mini-jet" contribution from hadronization process
- Background modelled with MC simulations using Pythia:
  - Obtain MC correlation function for pairs with common and non-common partonic origin (ancestors) separately
  - Use common C_{c} and non-common C_{nc} as templates to build the background
  - $C_{\mathrm{bckg}} = \mathcal{N} \times [w_{\mathrm{c}} C_{\mathrm{c}} + (1 - w_{\mathrm{c}}) C_{\mathrm{nc}}]$



Fitting of data of pπ^+

$C_{\mathrm{total}} = \mathcal{N} \times C_{\mathrm{bckg}} \times$ [redacted] $+$ [redacted]

- Background C_{bckg} via MC templates, controlled by w_{c}

Fitting of data of $p\pi^+$

$$C_{\text{total}} = \mathcal{N} \times C_{\text{bckg}} \times [\lambda_{\text{Gen}} C_0 + (1 - \lambda_{\text{Gen}})] + \text{[redacted]}$$

- Background C_{bckg} via MC templates, controlled by w_{c}
- Interaction $C_0(r_{\text{core}})$ Coulomb + strong interaction (fixed from scattering lengths)

M. Hoferichter et al., Phys.Rept. 625 (2016) 1–88
M. Hennebach et al., EPJA 50 (2014) 12, 190

M. Hoferichter et al., Phys.Rept. 625 (2016) 1-88.

	$p\pi^+$	$p\pi^-$
Scattering Length	-0.125 fm	0.121 fm

Fitting of Data $p\pi^+$

$$C_{\mathrm{total}} = \mathcal{N} \times C_{\mathrm{bckg}} \times [\lambda_{\mathrm{Gen}} C_0 + (1 - \lambda_{\mathrm{Gen}})] + N_{\Delta} PS(p_{\mathrm{T}}, T) \times Sill(M_{\Delta}, \Gamma_{\Delta})$$

- Background C_{bckg} via MC templates, controlled by w_{c}
- Interaction $C_0(r_{\mathrm{core}})$ Coulomb + strong interaction (fixed from scattering lengths)

  M. Hoferichter et al., Phys.Rept. 625 (2016) 1–88
  M. Hennebach et al., EPJA 50 (2014) 12, 190

- Resonance description: Sill distribution $Sill(M_{\Delta}, \Gamma_{\Delta})$, M_{Δ} fixed to 1215 MeV

  F. Giacosa et al., EPJA 57 (2021) 12

- $PS(p_{\mathrm{T}}, T)$ phase-space factor

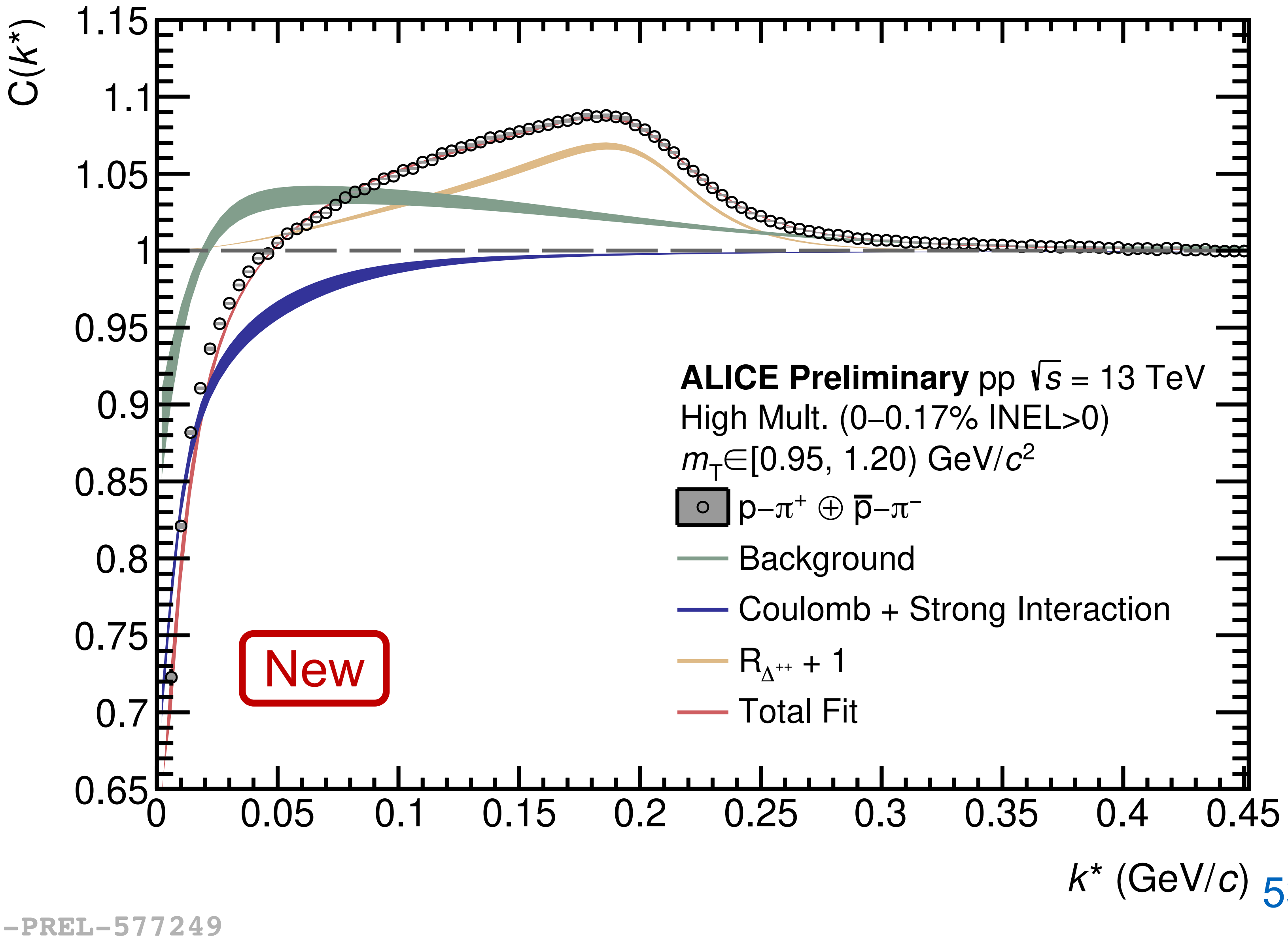
$$PS(p_{\mathrm{T}}, T) \propto \frac{m}{\sqrt{m^2 + p_{\mathrm{T}}^2}} \times \exp\left(-\frac{\sqrt{m^2 + p_{\mathrm{T}}^2}}{T}\right)$$

- Fit between between 0 and 450 MeV in *k**

Fitting of the pπ^{+} correlation function

- Fit procedure repeated for different pair transverse mass ranges

- $m_{\mathrm{T}} = \sqrt{\bar{m}^2 + k_{\mathrm{T}}^2}$ and
$\vec{k}_{\mathrm{T}} = \frac{1}{2}\left[\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2}\right]$



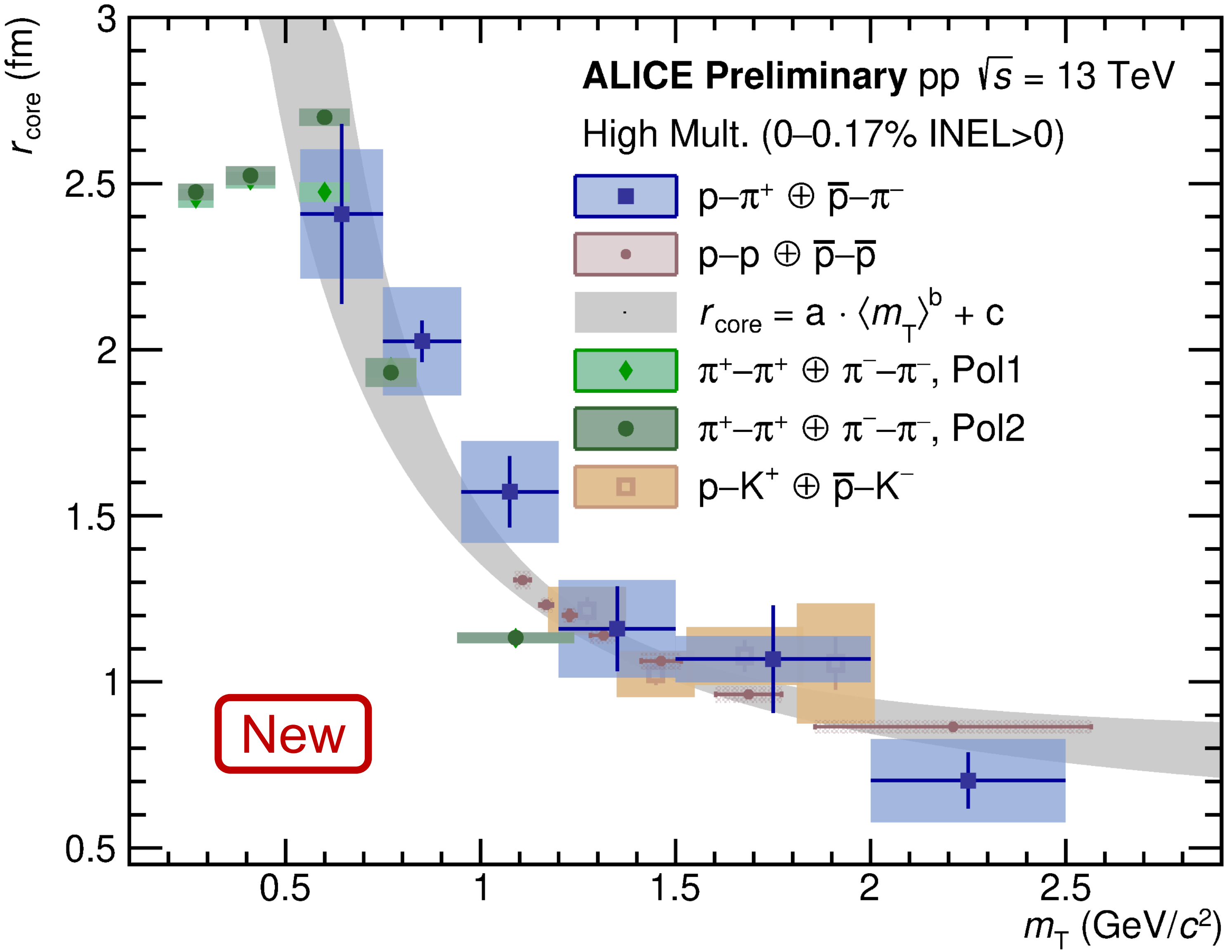
Core radius scaling $p\pi^+$

- r_{core}: size of emission source of **primordial** particles
- r_{core} of $p\pi^+$ follows common scaling of $pp, pK^+, \pi^\pm\pi^\pm$ in pp collisions

ALICE, PLB, 811:135849, 2020

ALICE, arXiv:2311.14527, EPJC in press

→ Common emission source for all hadrons



ALI-PREL-576328

Fitting of data $p\pi^+$

$$C_{\text{total}} = \mathcal{N} \times C_{\text{bckg}} \times [\lambda_{\text{Gen}} C_0 + (1 - \lambda_{\text{Gen}})] + N_\Delta PS(p_{\text{T}}, T) \times Sill(M_\Delta, \Gamma_\Delta)$$

- Background C_{bckg} via MC templates, controlled by w_{c}
- Interaction $C_0(r_{\text{core}})$ Coulomb + strong interaction (fixed from scattering lengths)

  M. Hoferichter et al, Phys.Rept. 625 (2016) 1-88
  M. Hennebach et al, Eur.Phys.J.A 50 (2014) 12, 190

- Sill distribution $Sill(M_\Delta, \Gamma_\Delta)$, M_Δ fixed to 1215 MeV

  F. Giacosa et al, Eur.Phys.J.A 57 (2021) 12

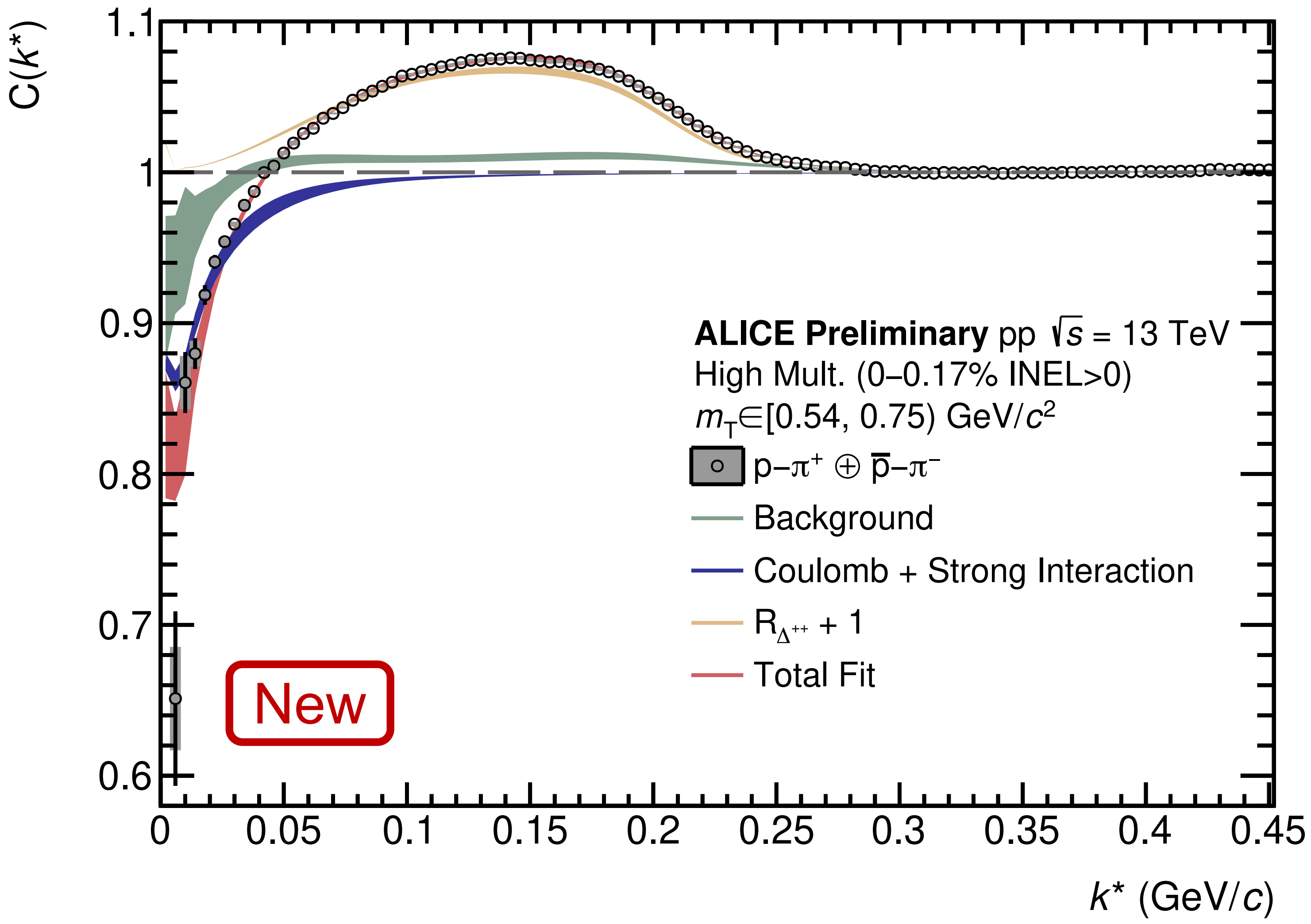
- $PS(p_{\text{T}}, T)$ phase-space factor

$$PS(p_{\text{T}}, T) \propto \frac{m}{\sqrt{m^2 + p_{\text{T}}^2}} \times \exp\left(-\frac{\sqrt{m^2 + p_{\text{T}}^2}}{T}\right)$$

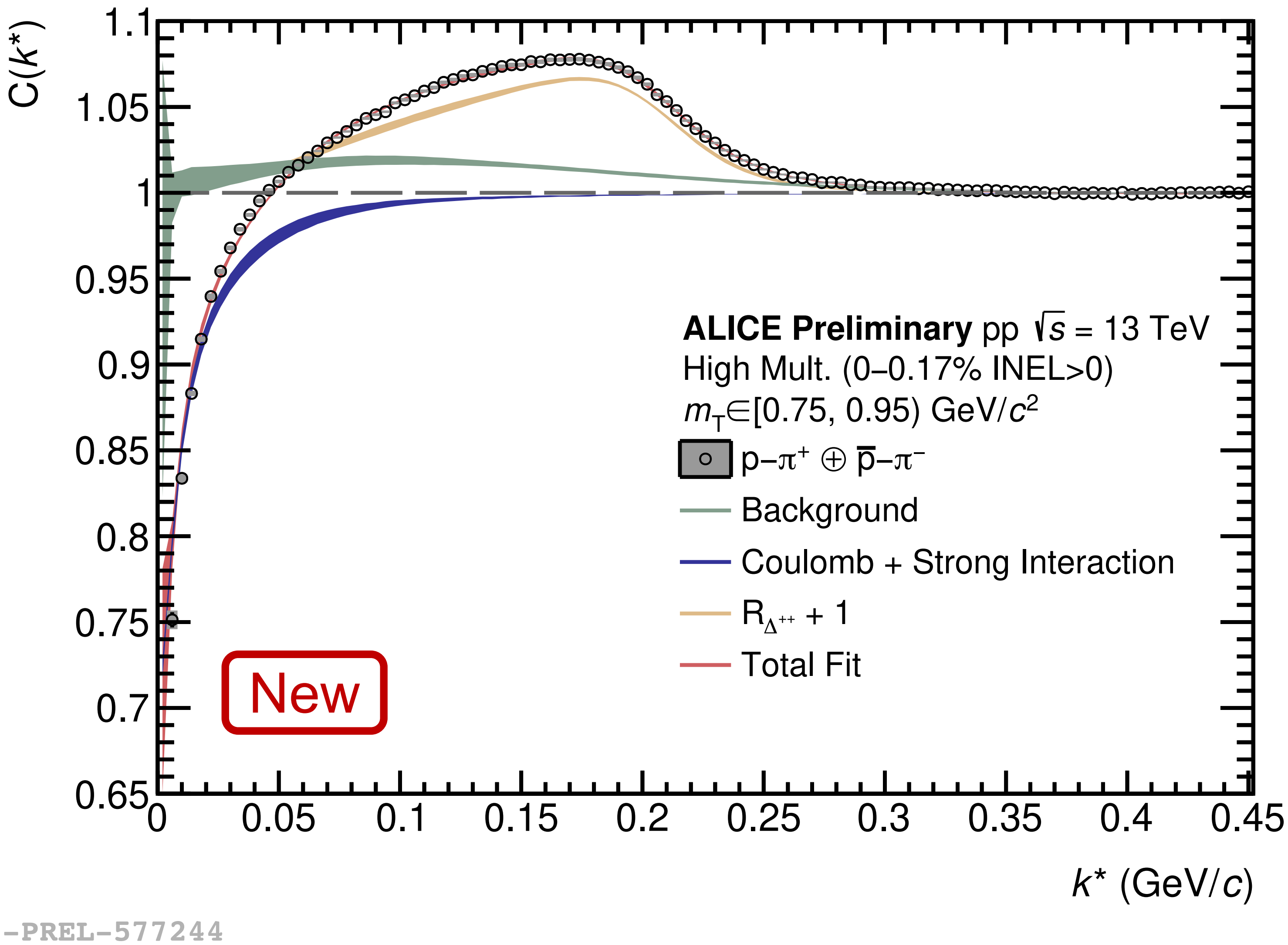
- Fit between between 0 and 450 MeV in k*

Free Parameters of the fit:
- Overall normalisation N
- w_c
- r_{core}
- Scaling of Δ^{++} N_Δ
- T (kinetic decoupling temp.)
- Width of Δ^{++}

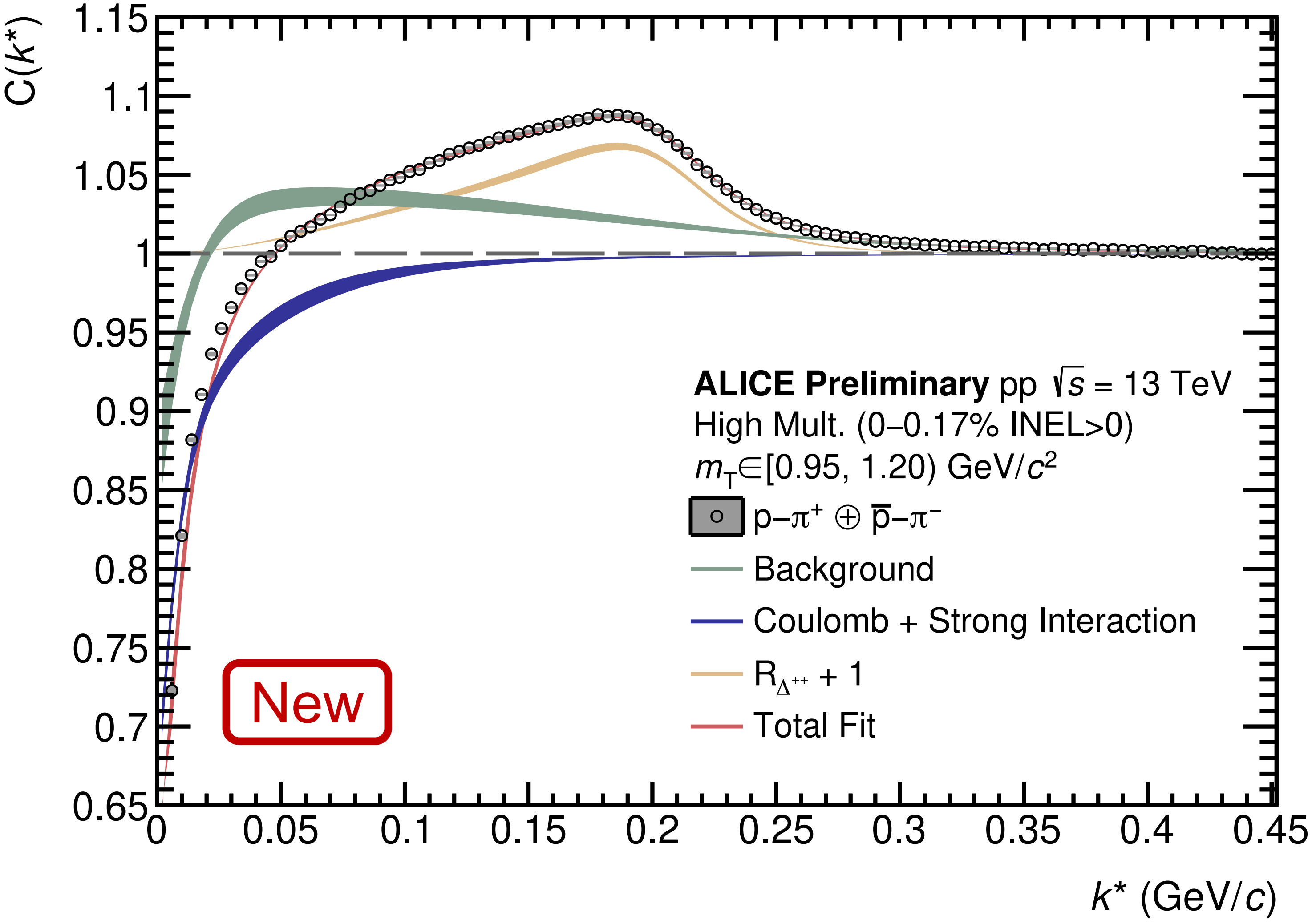
$p\pi^+$ - m_T interval 1



$p\pi^+$ - m_T interval 2

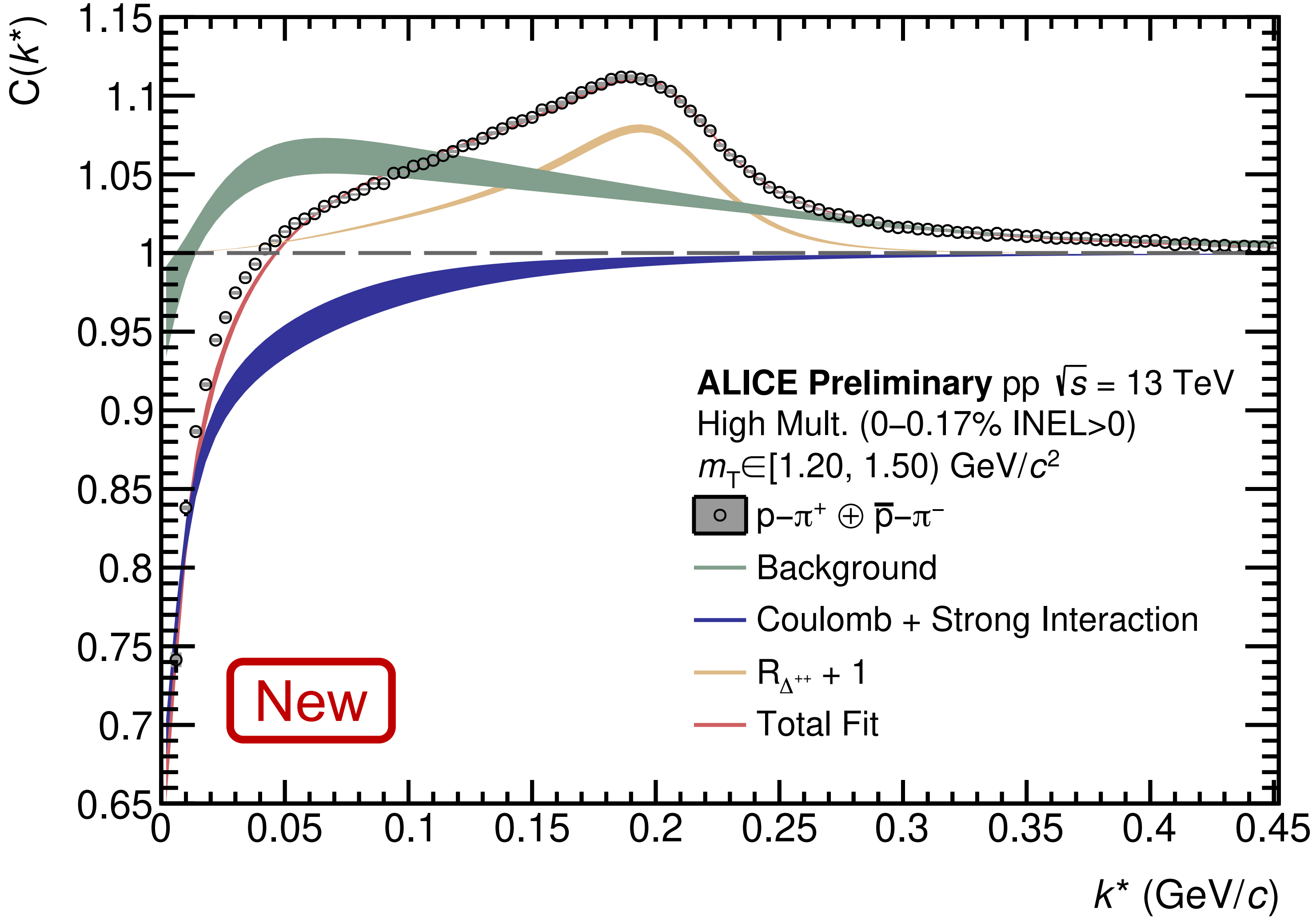


$p\pi^+$ - m_T interval 3



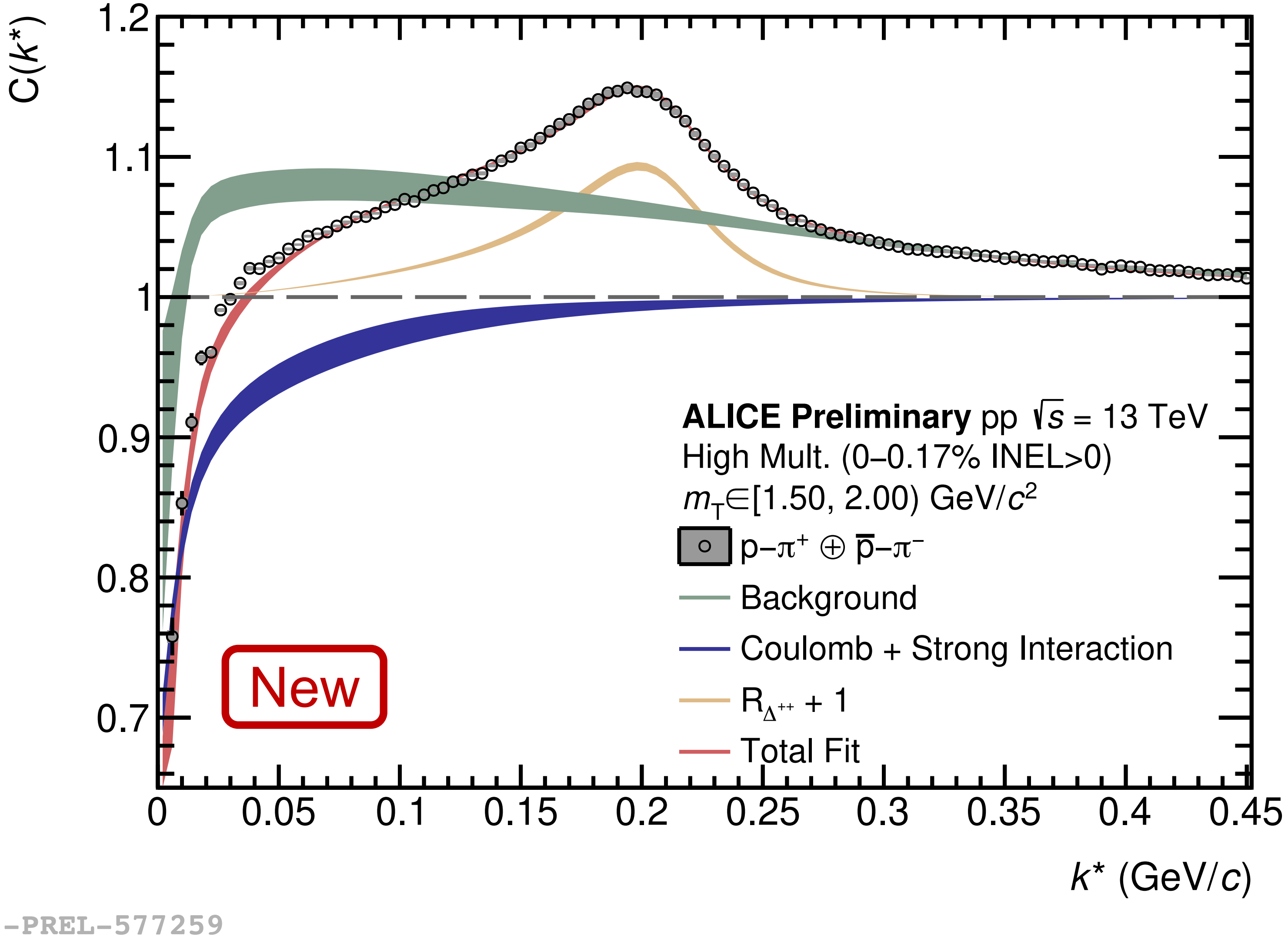
ALI-PREL-577249

$p\pi^+$ - m_T interval 4

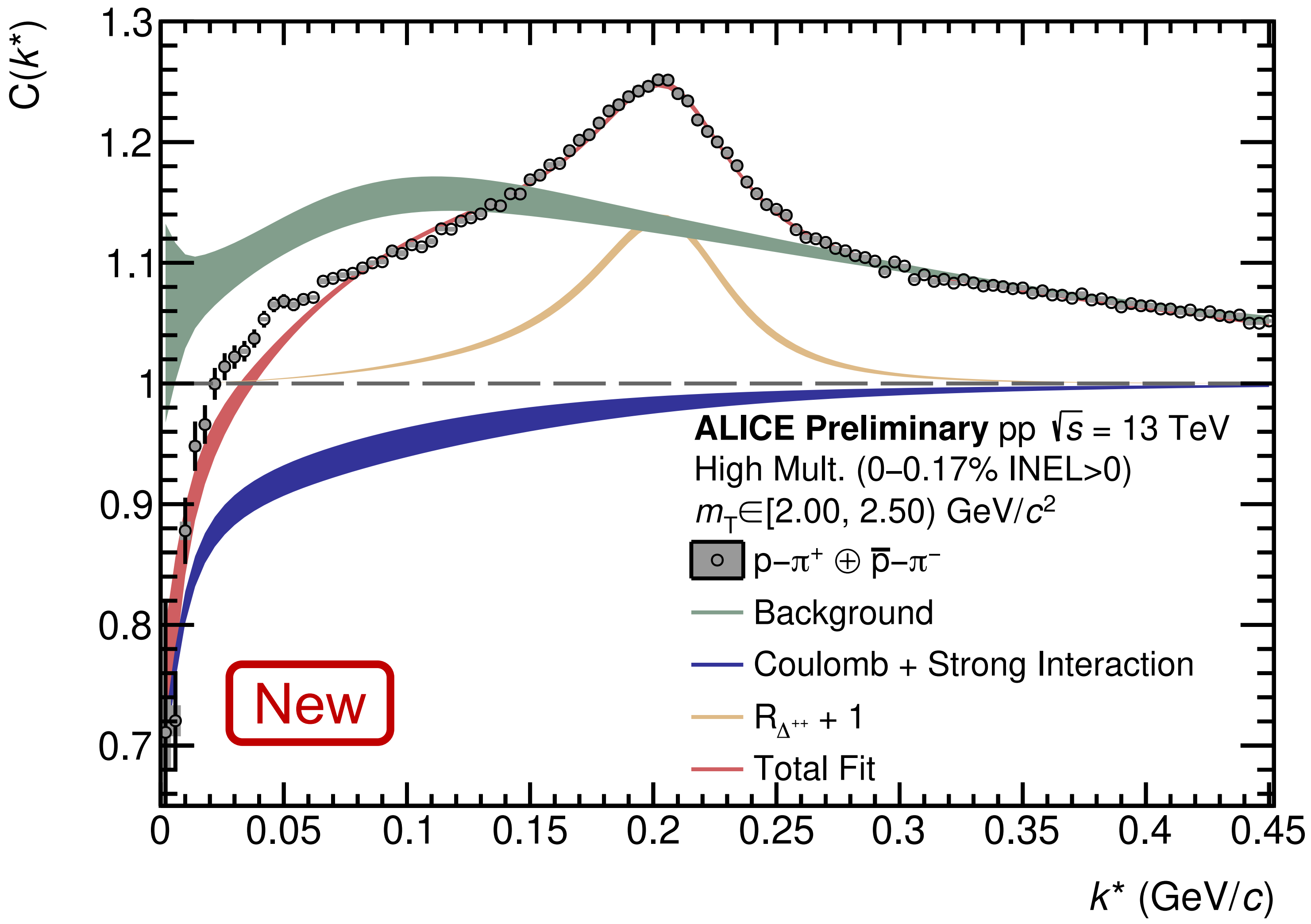


ALI-PREL-577254

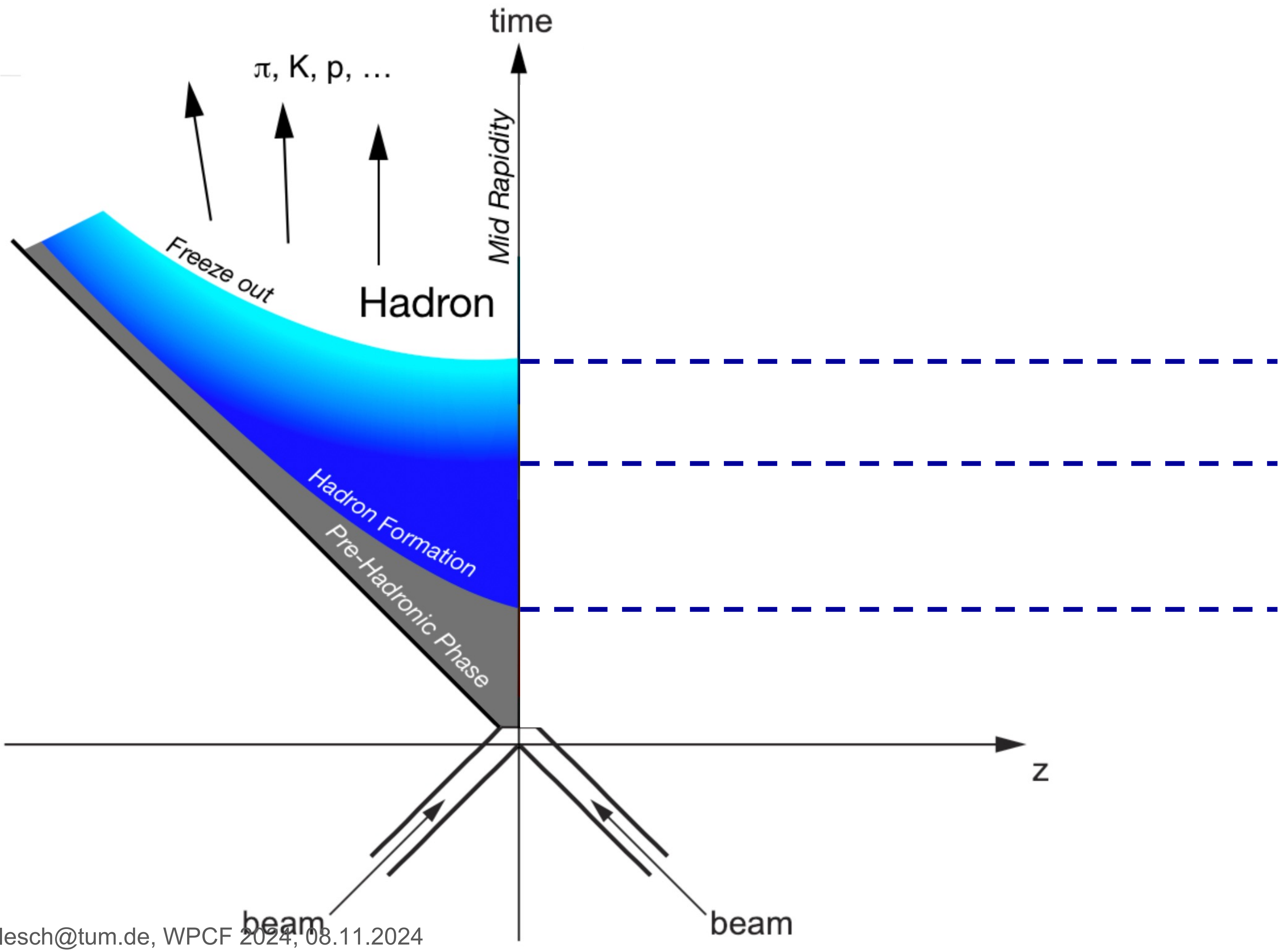
$p\pi^+$ - m_T interval 5



$p\pi^+$ - m_T interval 6



About the life of the Δ^{++}

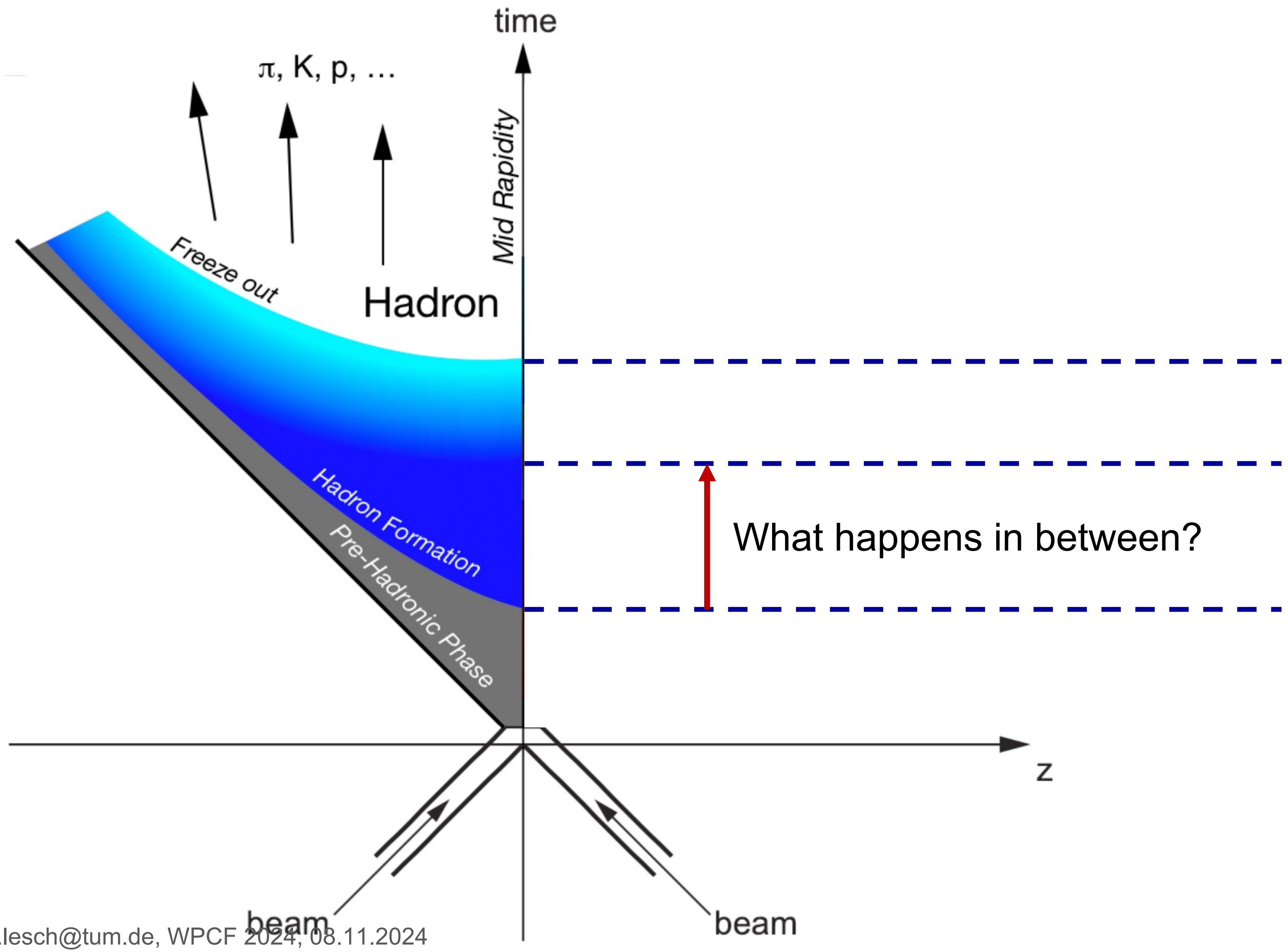


Kinetic freezout
→ characterized by T_{ch}

Decay of the $\Delta^{++} \rightarrow p\pi^{+}$

Formation of the Δ^{++}
(and all other hadrons)
→ characterized by T_{ch}

About the life of the Δ^{++}



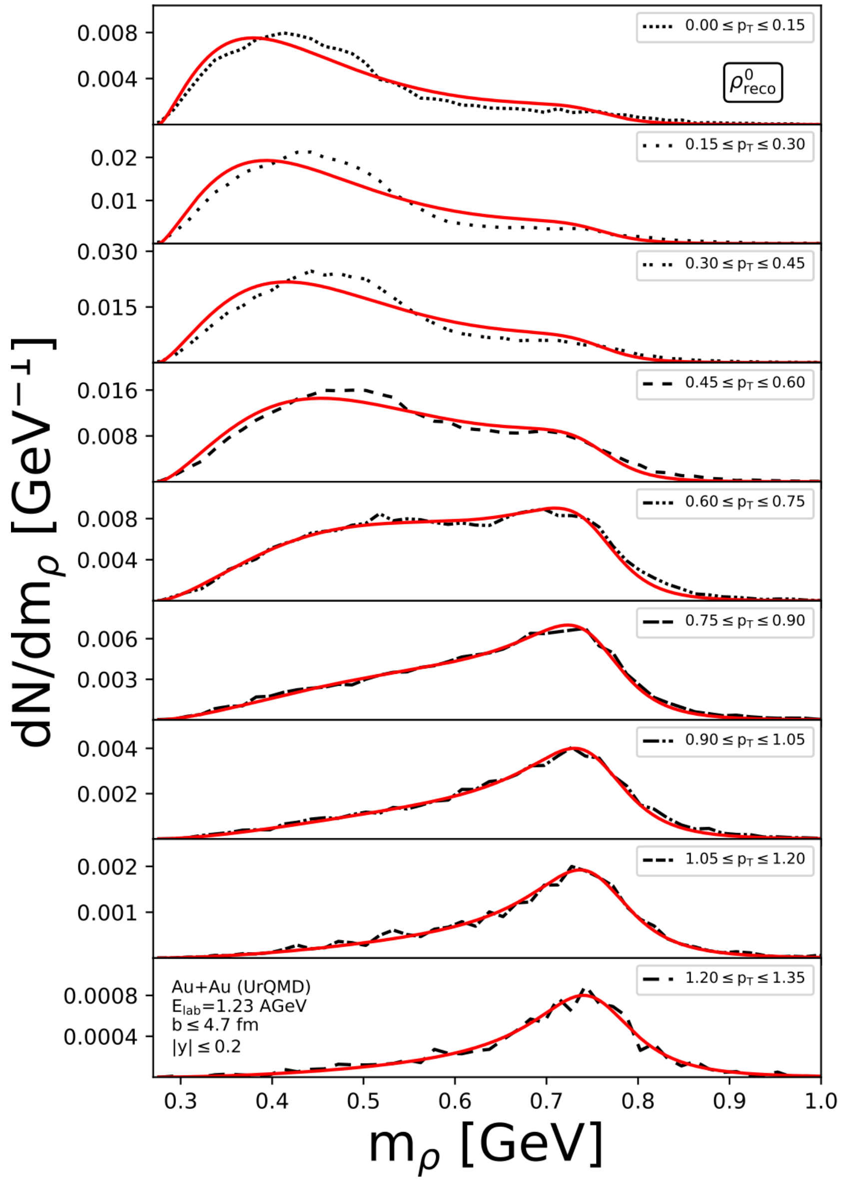
Kinetic freezout
→ characterized by T_{ch}

Decay of the $\Delta^{++} \rightarrow \mathrm{p}\pi^{+}$

Formation of the Δ^{++}
(and all other hadrons)
→ characterized by T_{ch}

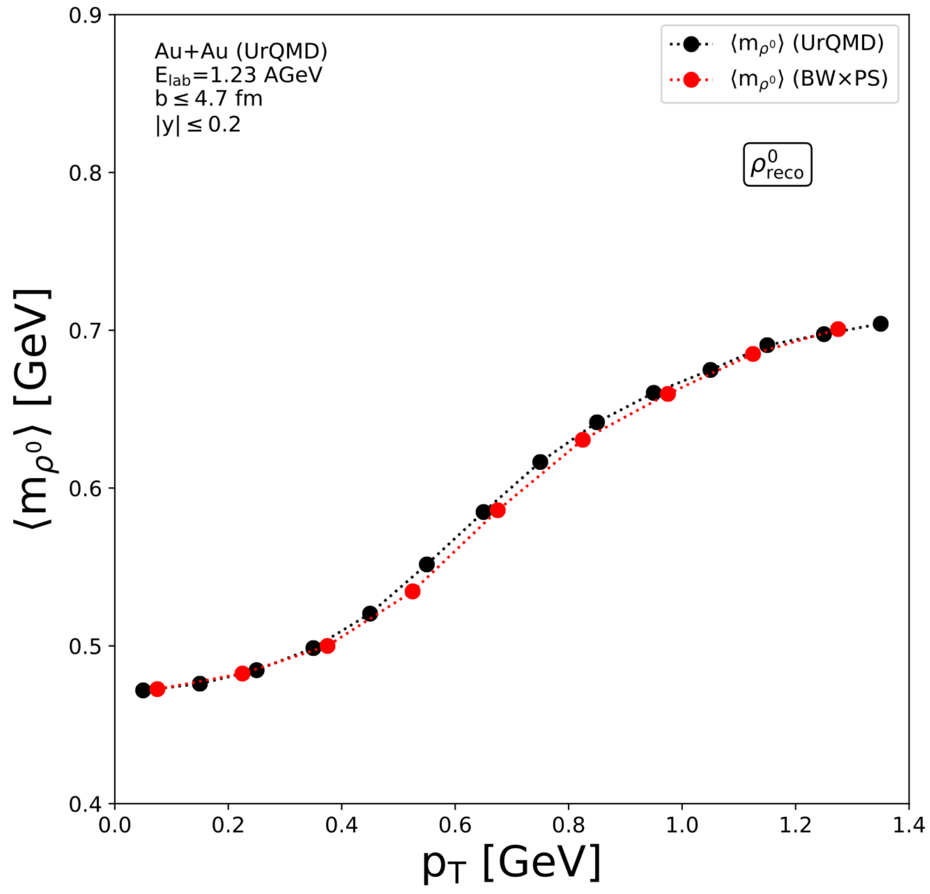
Rescattering of the Δ^{++}

- Paper: Tom Reichert, Marcus Bleicher, Nucl.Phys.A 1028 (2022) 122544
- Study of kinetic mass shifts of ρ(770) and K*(892) in Au+Au reactions at E_{beam} = 1.23 AGeV with UrQMD
- Fitting of Data with PS x BW
- However: Temperature not fixed to chemical freezout but free parameter

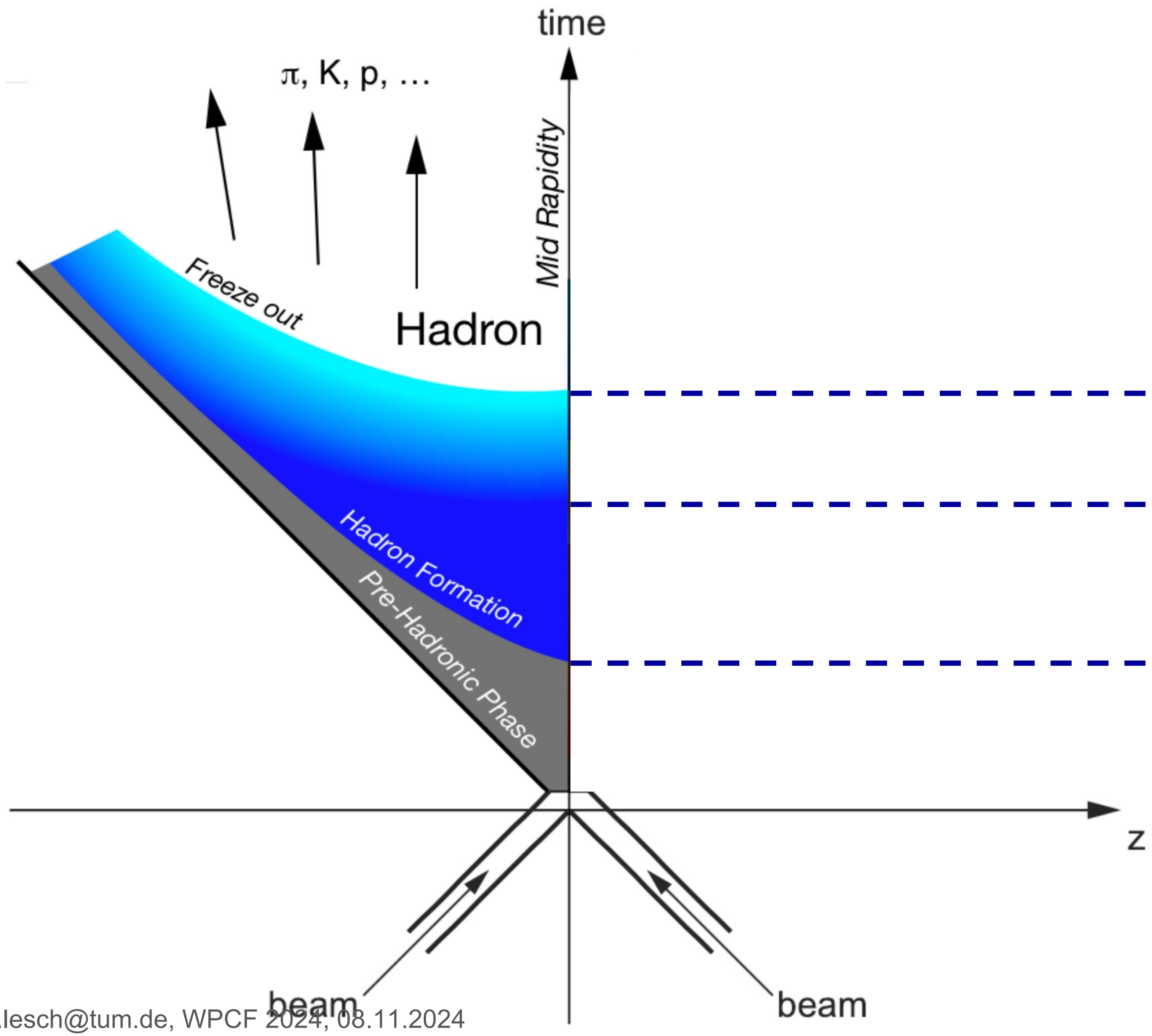


Rescattering of the Δ^{++}

- Paper: Tom Reichert, Marcus Bleicher, Nucl.Phys.A 1028 (2022) 122544
- Study of kinetic mass shifts of ρ(770) and K*(892) in Au+Au reactions at E_{beam} = 1.23 AGeV with UrQMD
- Fitting of Data with PS x BW
- However: Temperature not fixed to chemical freezout but free parameter ("Kinetic Decoupling Temperature")
  → good agreement between UrQMD and fit



About the life of the Δ^{++}



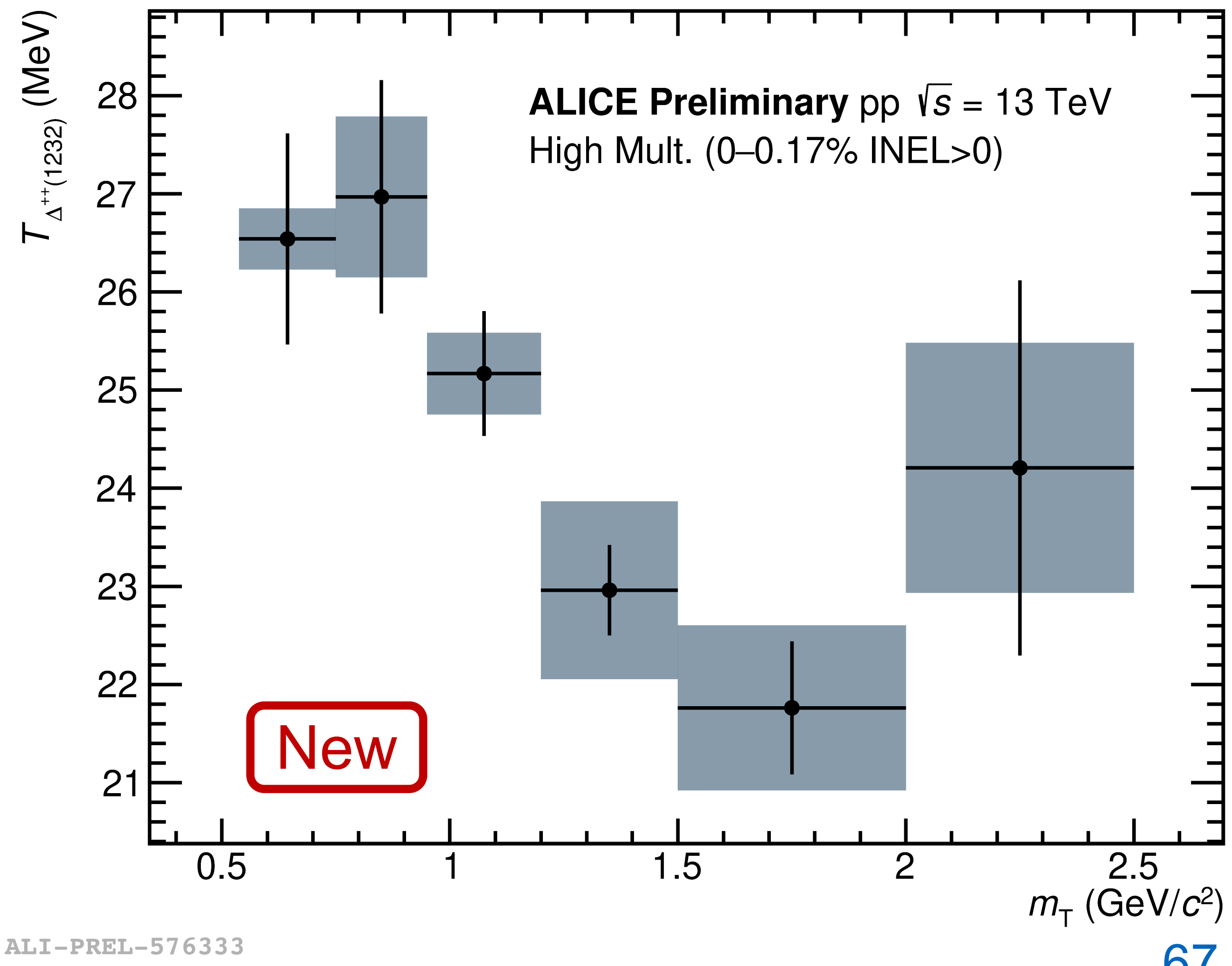
Kinetic freezout
→ characterized by T_{ch}

Decay of the $\Delta^{++} \rightarrow p\pi^{+}$
→ characterized by T_{dec}

Formation of the Δ^{++}
(and all other hadrons)
→ characterized by T_{ch}

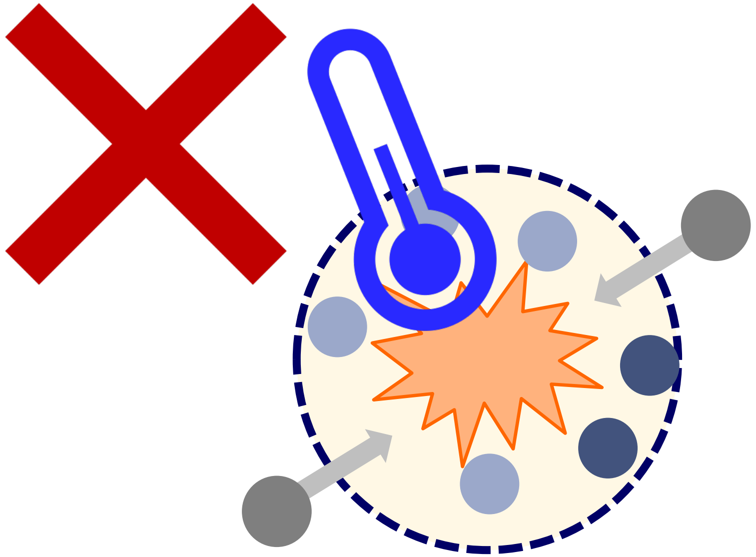
Kinetic decoupling temperature Δ^{++}

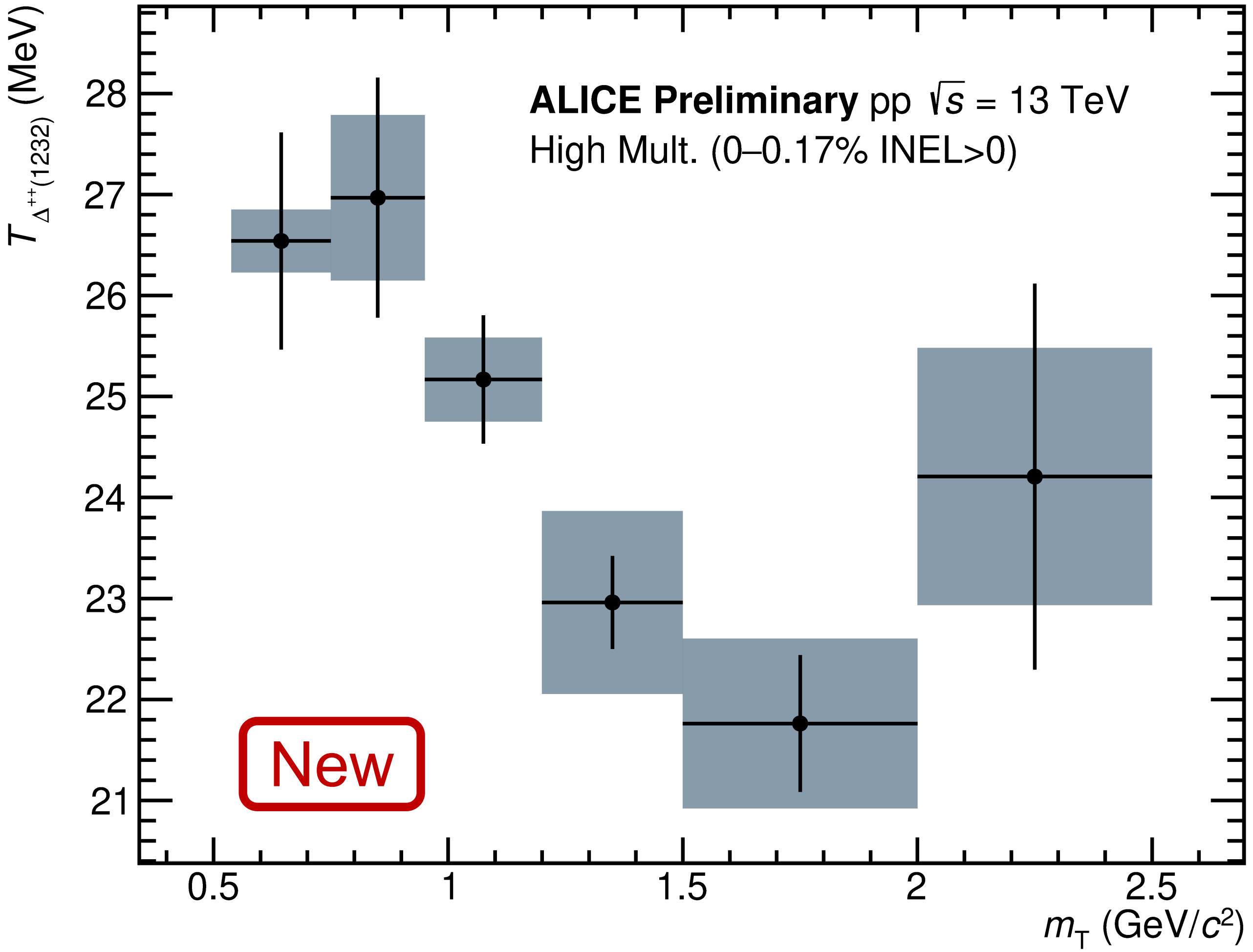
- Low “decoupling temperature” of about 25 MeV



Kinetic decoupling temperature Δ^{++}

- Low "decoupling temperature" of about 25 MeV
- This does not mean that pp collisions are cold!

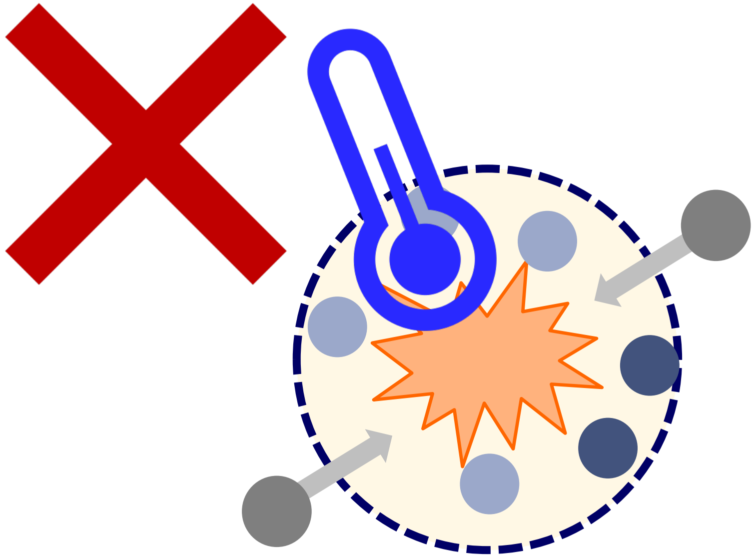




Kinetic decoupling temperature Δ^{++}

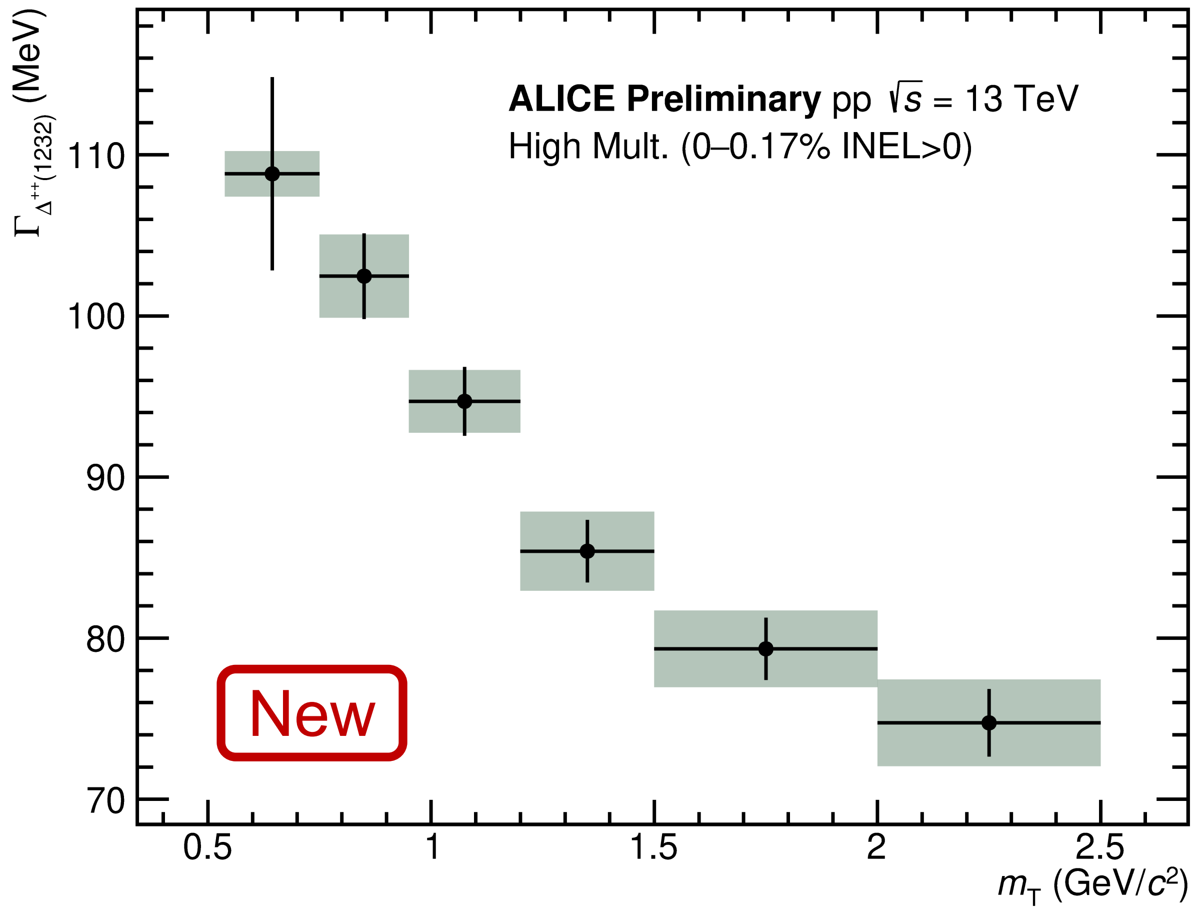
- Low "decoupling temperature" of about 25 MeV
- This does not mean that pp collisions are cold!
- We see a modification of the phase space of resonance due to regeneration phase $\boldsymbol{\Delta} \leftrightarrow \boldsymbol{N\pi}$

→ hadronic moshpit for the $\boldsymbol{\Delta}^{++}$

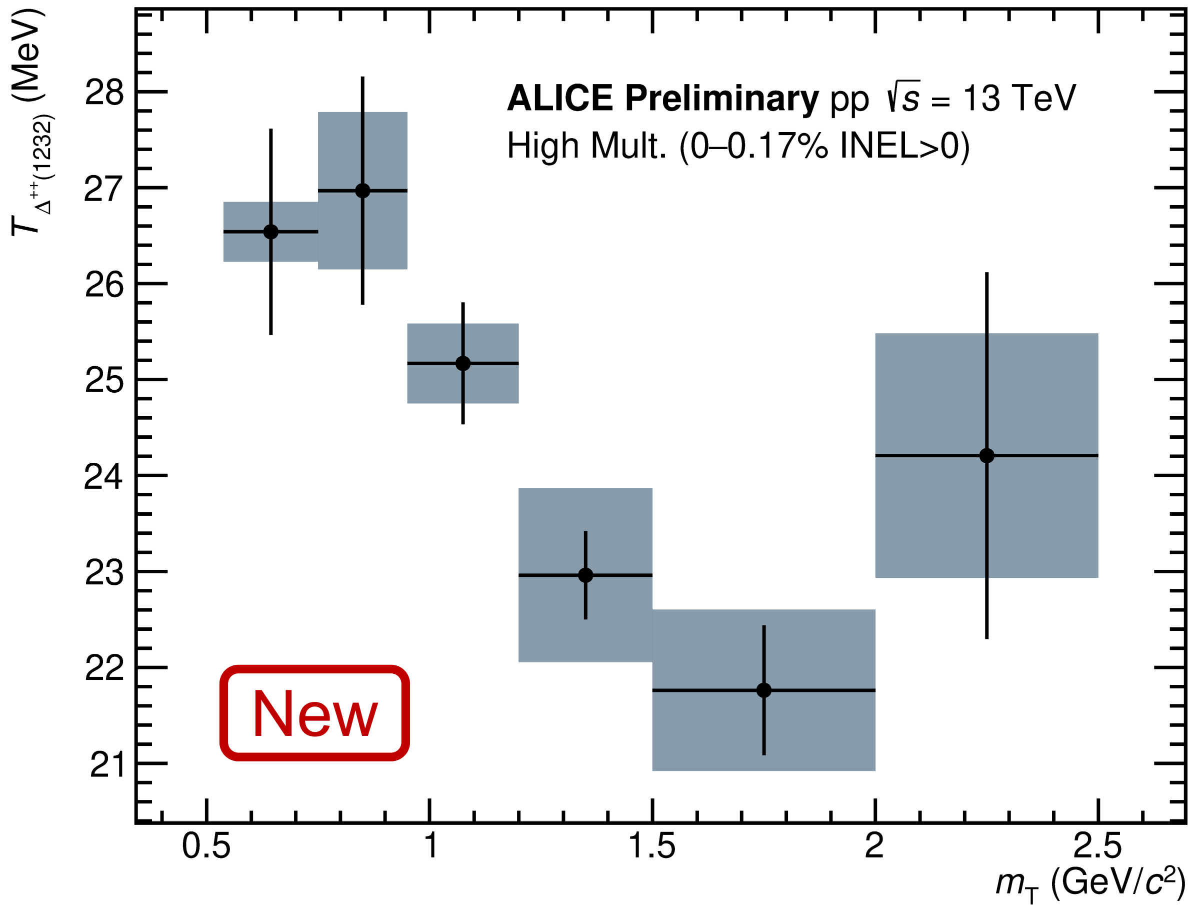


Width & kinetic decoupling temperature Δ^{++}

- Width constant ~ 90 MeV
- Low "decoupling temperature" → modification of the phase space of resonance



ALI-PREL-576423



ALI-PREL-576333

Fitting of data $p\pi^-$

$$C_{\text{total}} = N \times C_{\text{bckg}} \times [\lambda_{\text{Gen}} C_0 + (1-\lambda_{\text{Gen}})] + N_\Delta PS(p_T, T) \times Sill(M_\Delta, \Gamma_\Delta) + N_\Lambda Gaus(M_\Lambda, \Gamma_\Lambda)$$

- Background $C_{\text{bckg}} = [\,1 + N_B(w_c C_c + (1-w_c)C_{NC} - 1) + Sill(M_2, \Gamma_2) + Sill(M_3, \Gamma_3)]$
- Interaction C_0 Coulomb + strong interaction (fixed from scattering lengths)

  M. Hoferichter et al, Phys.Rept. 625 (2016) 1-88.
  M. Hennebach et al, Eur.Phys.J.A 50 (2014) 12, 190
- $Sill(M_\Delta, \Gamma_\Delta)$ Sill distribution, M_Δ fixed to 1215 MeV

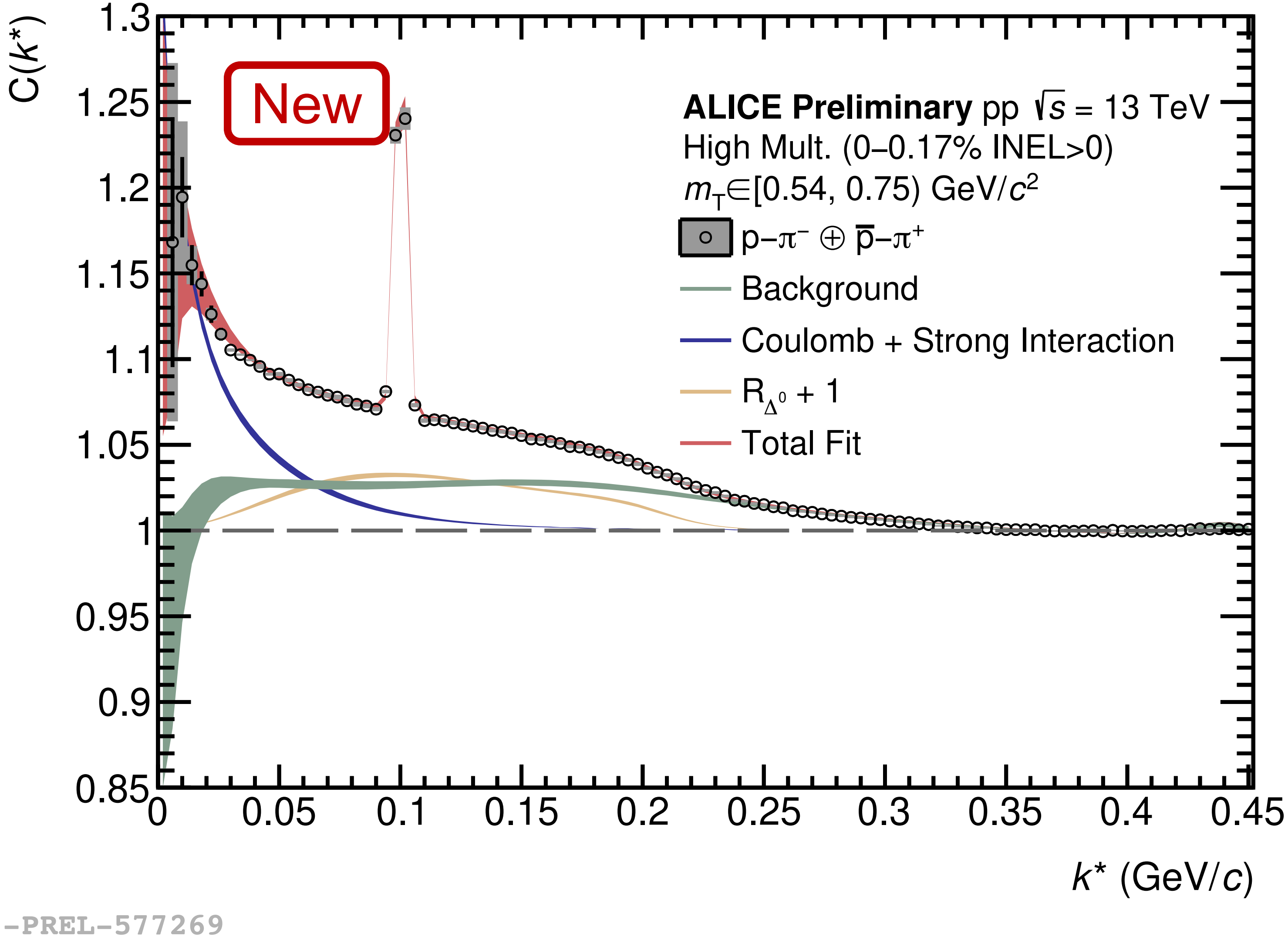
  F. Giacosa et al, Eur.Phys.J.A 57 (2021) 12
- $PS(p_T, T)$ phase-space factor

$$PS(p_T, T) \propto \frac{m}{\sqrt{m^2+p_T^2}} \times \exp\left(-\frac{\sqrt{m^2+p_T^2}}{T}\right)$$

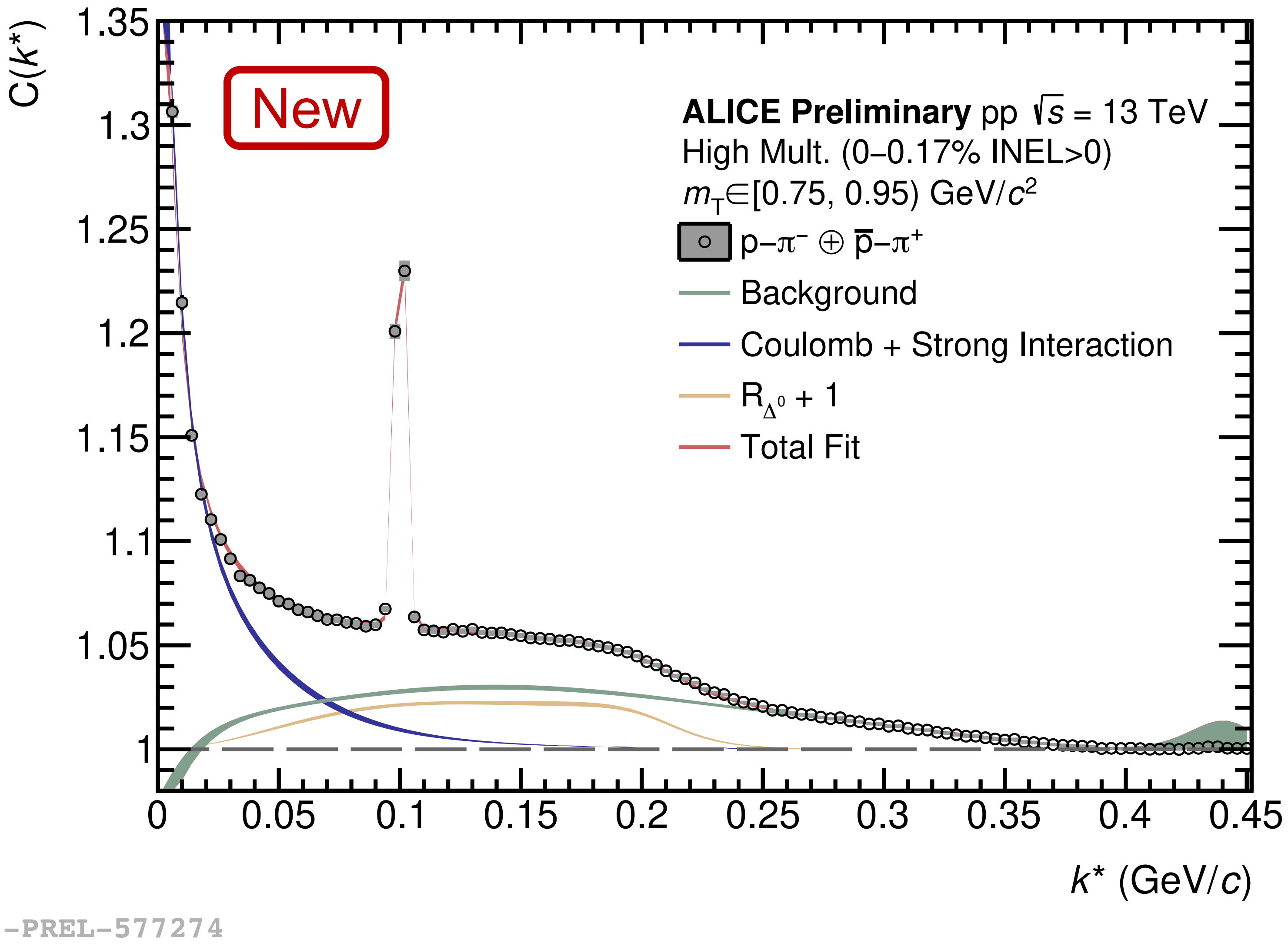
- Fit between between 0 and 450 MeV in k*

Free Parameters of the fit:
- Overall normalisation
- w_c & N_B
- r_{core}
- Scaling of Δ^0 N_Δ
- T (kinetic decoupling temp.)
- Width of Δ^0
- Scaling of Λ N_Λ
- Mass of Λ
- Width of Λ

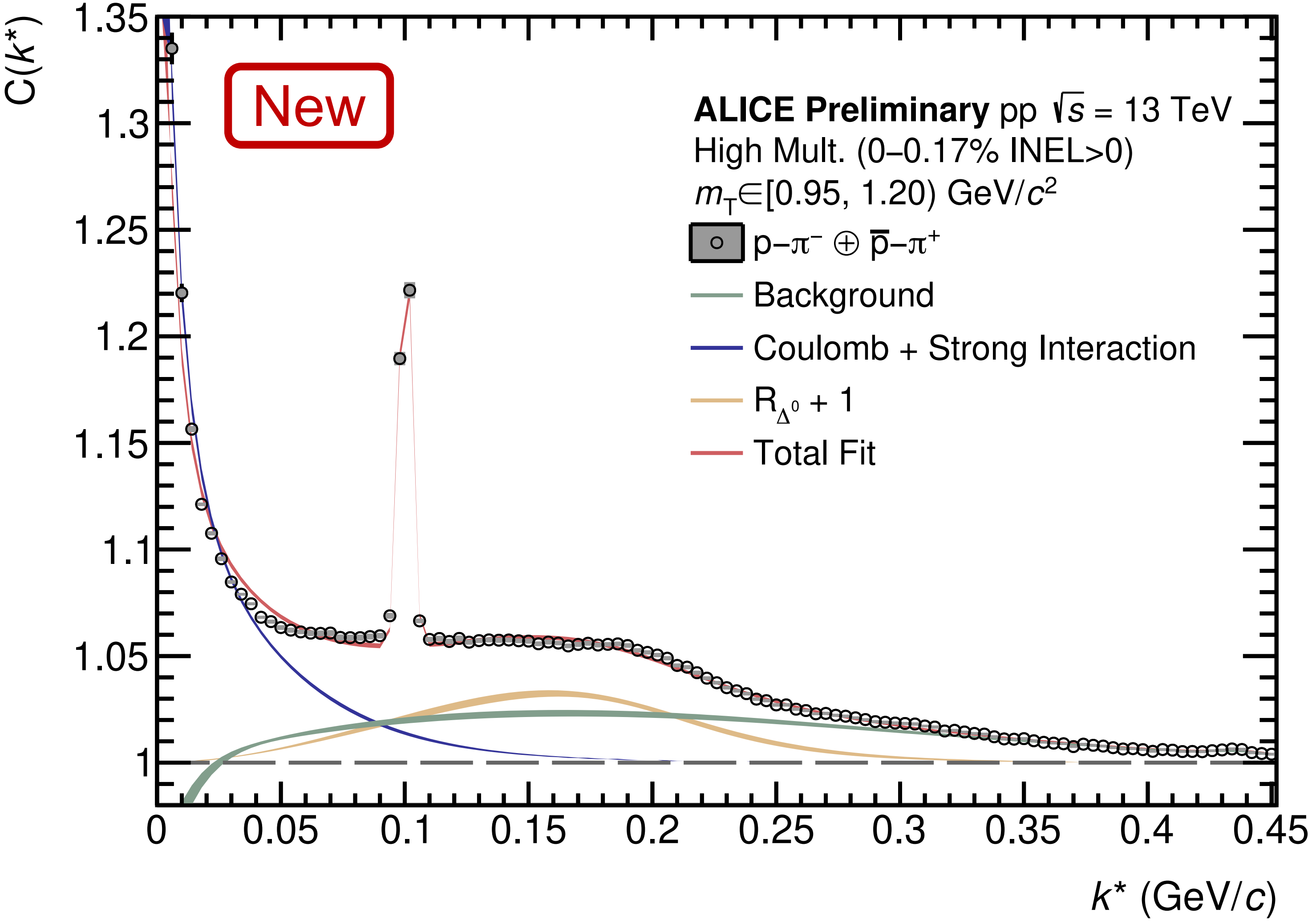
$p\pi^{-}$ - m_T interval 1



$p\pi^-$ - m_T interval 2

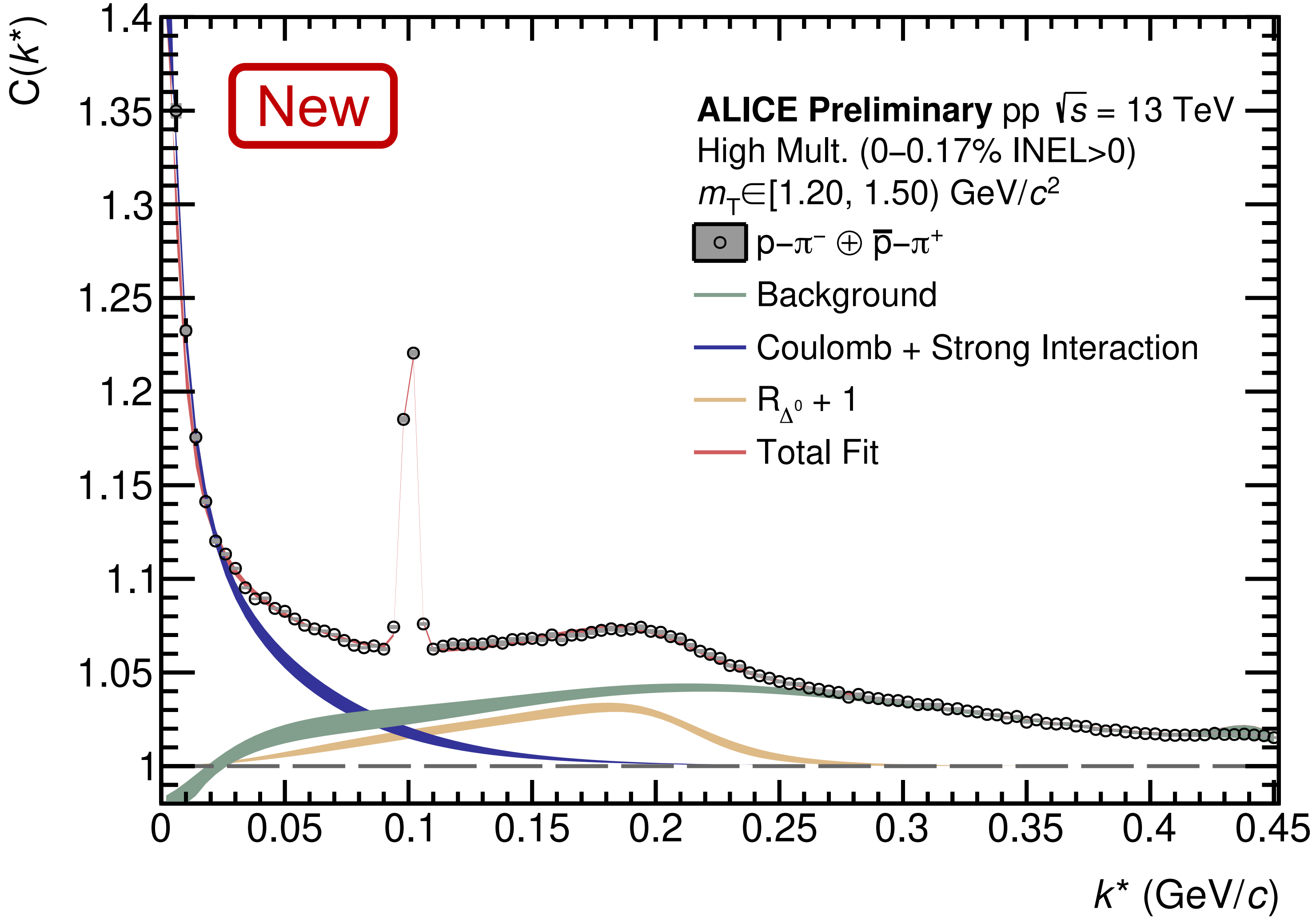


$p\pi^-$ - m_T interval 3



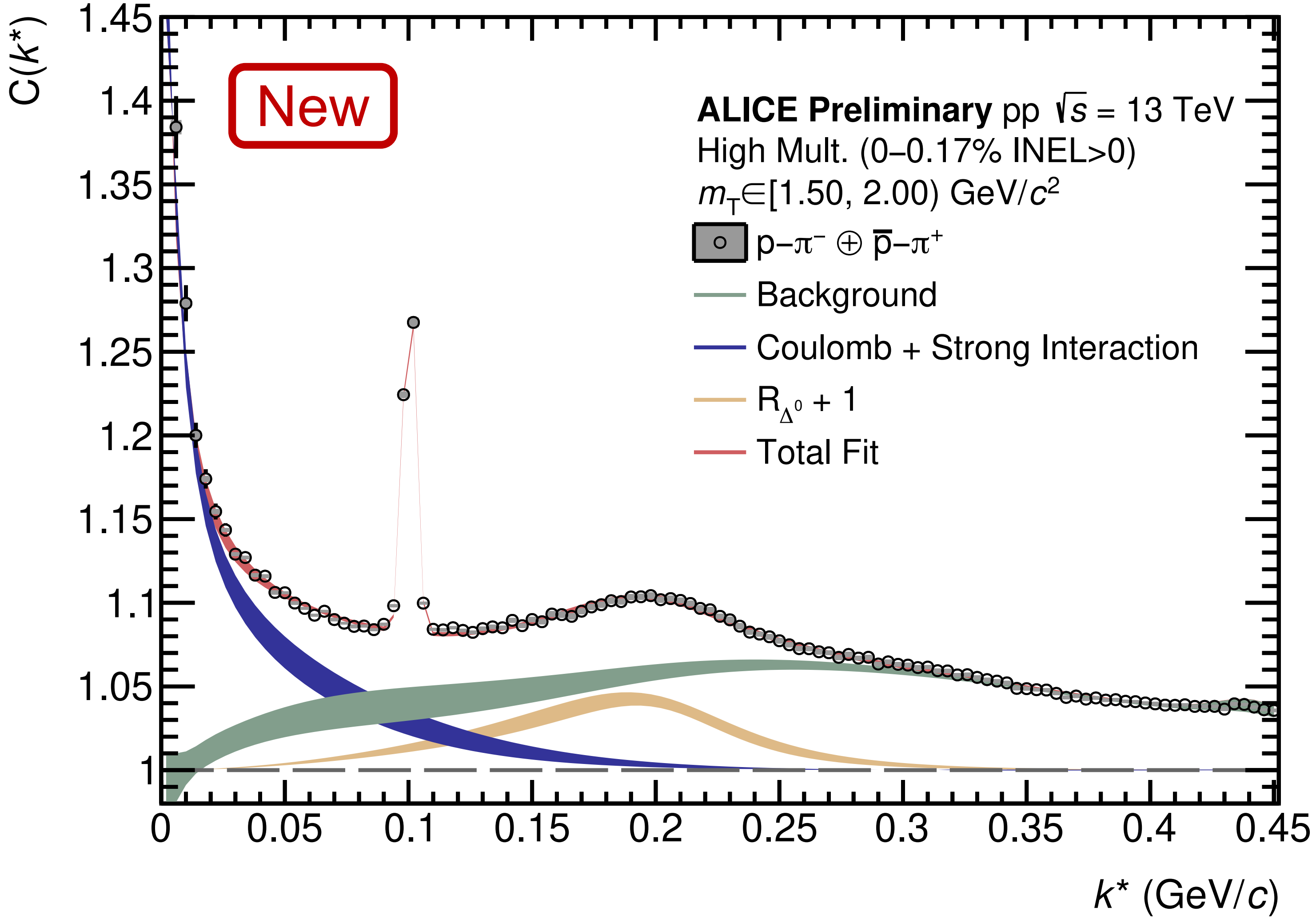
ALI-PREL-577279

$p\pi^-$ - m_T interval 4



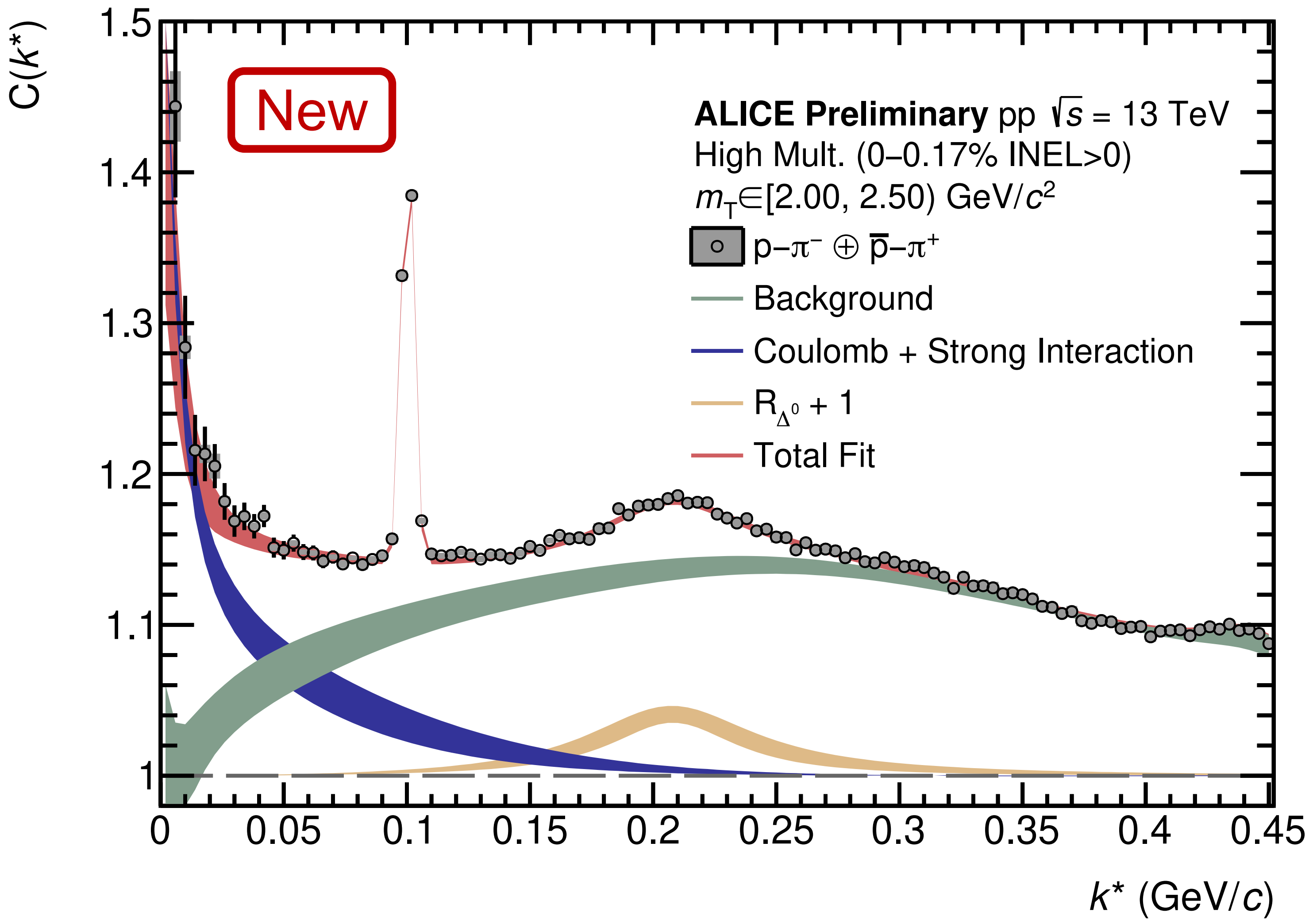
ALI-PREL-577284

pπ⁻ - m_T interval 5

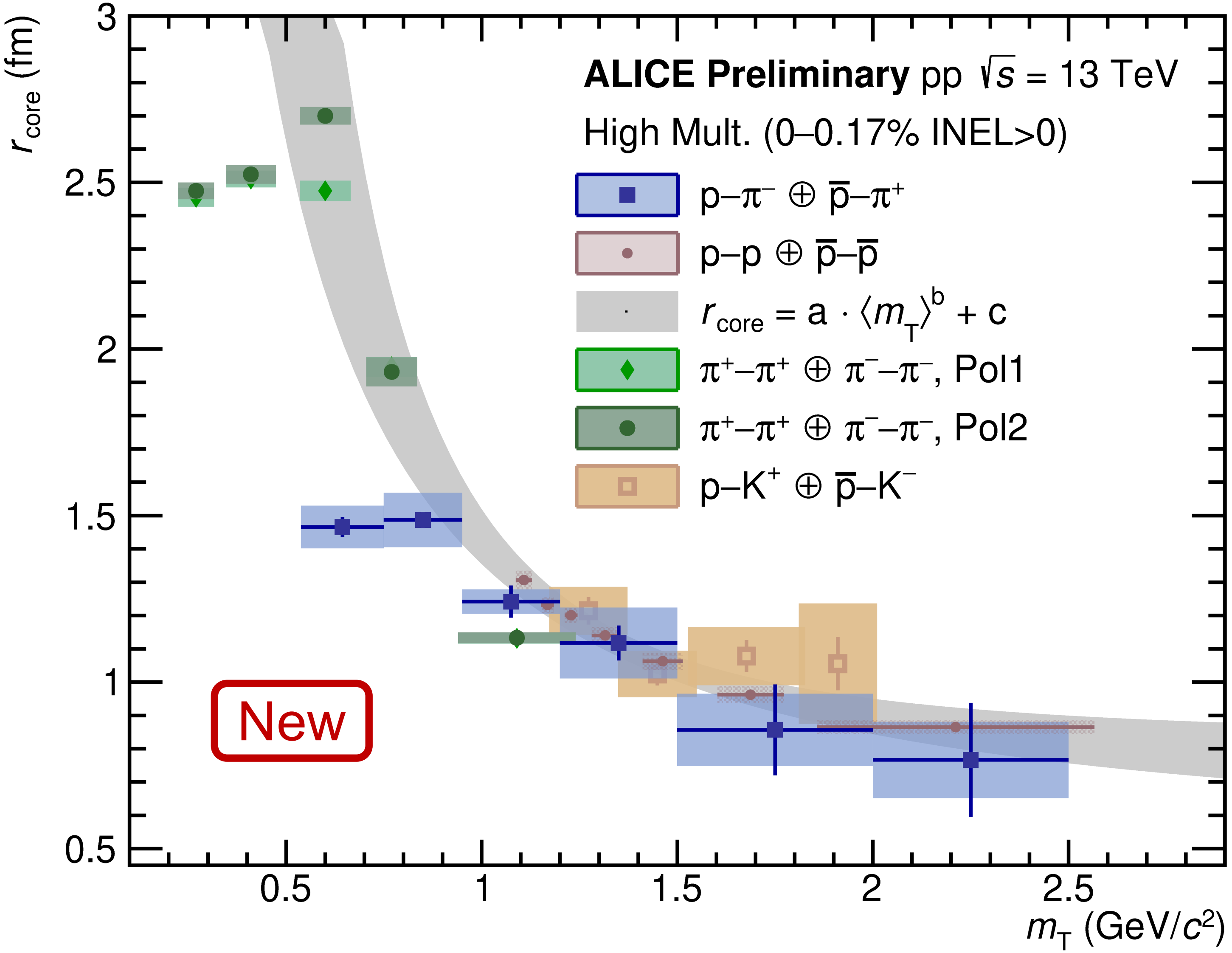


ALI-PREL-577289

pπ$^-$ - m_T interval 6

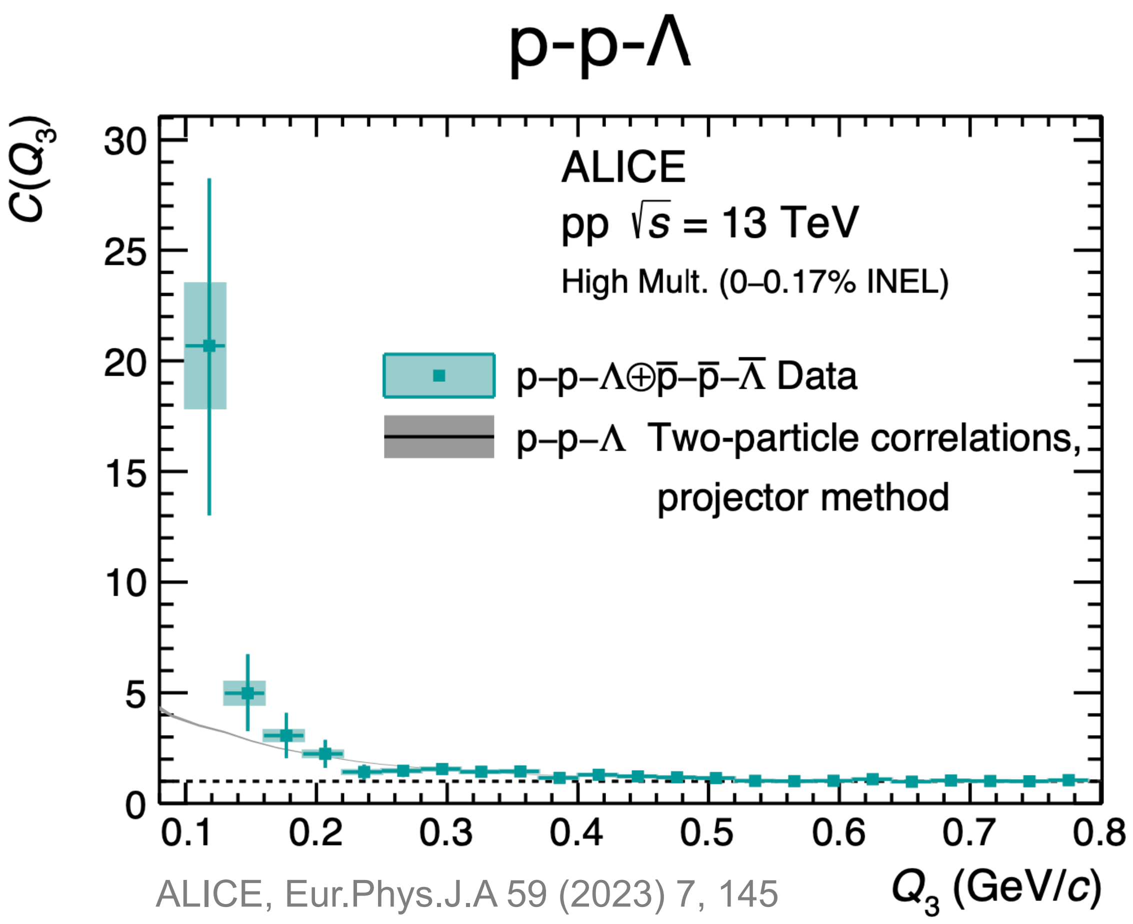


ALI-PREL-577294

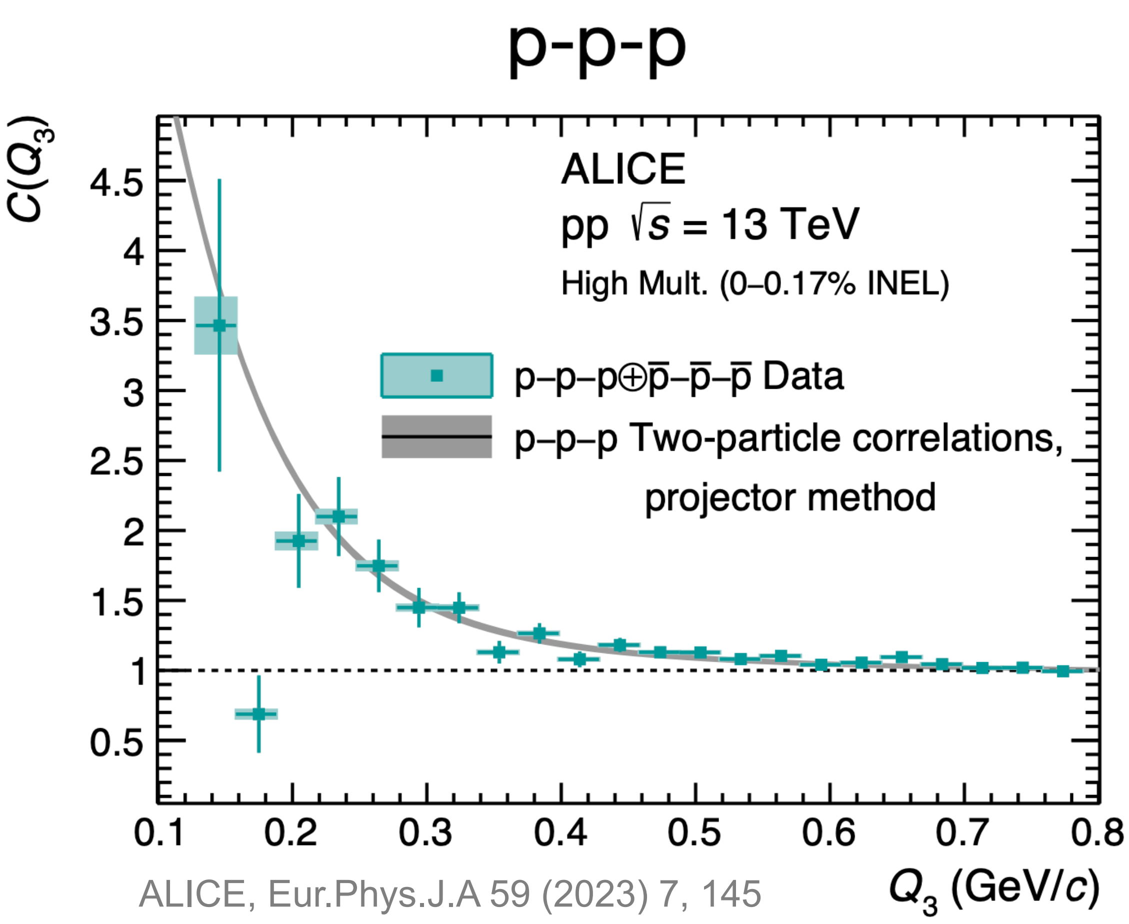

ALICE Preliminary pp $\sqrt{s}$ = 13 TeV
High Mult. (0–0.17% INEL>0)
p–π⁻ ⊕ p̄–π⁺
p–p ⊕ p̄–p̄
$r_{core} = a \cdot \langle m_T \rangle^b + c$
π⁺–π⁺ ⊕ π⁻–π⁻, Pol1
π⁺–π⁺ ⊕ π⁻–π⁻, Pol2
p–K⁺ ⊕ p̄–K⁻
New
r_{core} (fm)
m_T (GeV/c^2)
0.5
1
1.5
2
2.5
3
ALI-PREL-576368

Backup Three-Body

Other Three-Body Studies



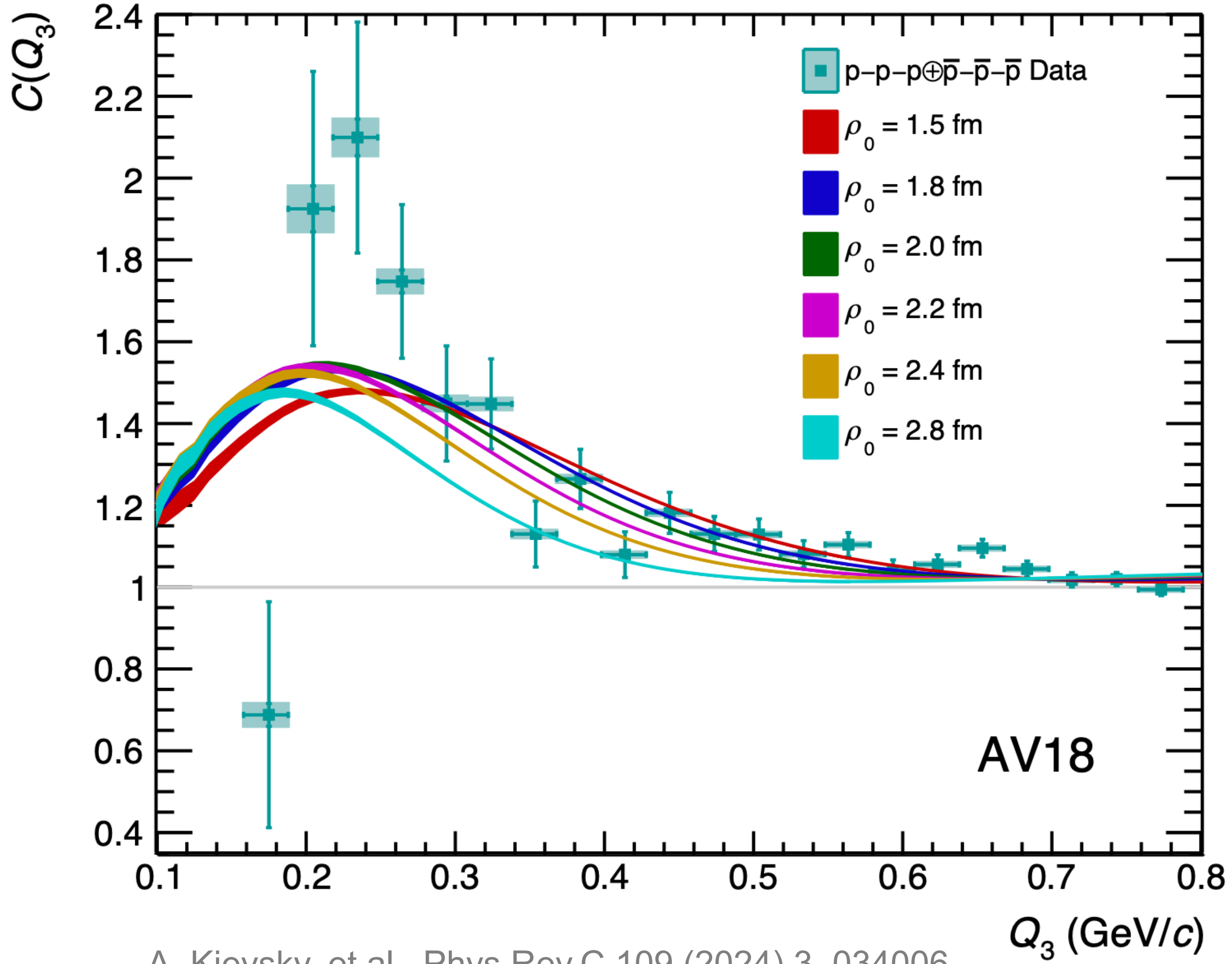
ALICE, Eur.Phys.J.A 59 (2023) 7, 145



ALICE, Eur.Phys.J.A 59 (2023) 7, 145

First theoretical results on ppp

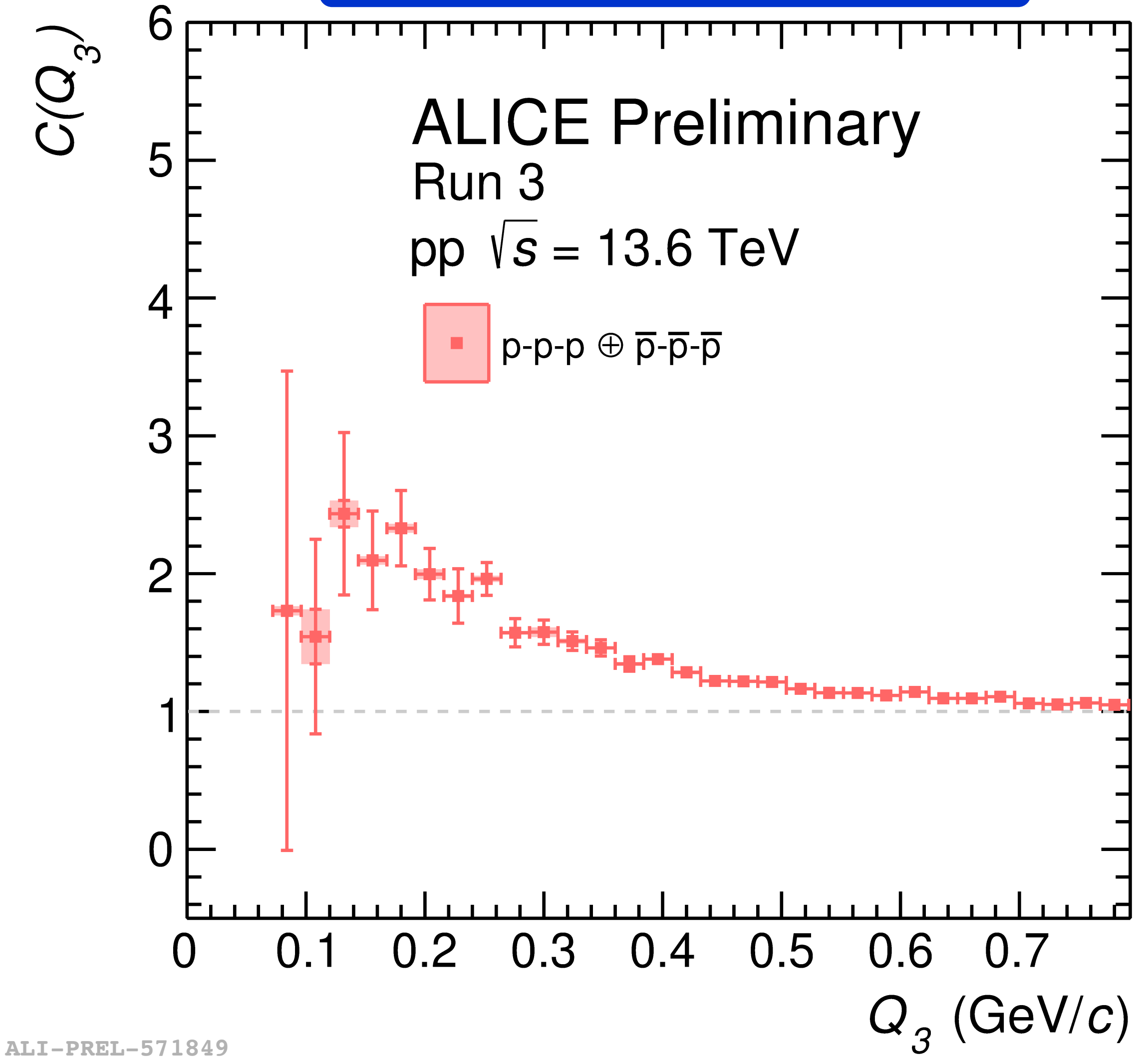
- Three-particle emission source modelled as three-single particle emitters constrained to data
- Shape qualitatively describes the data
- Considered effects:
  - pp strong interaction (AV18)
  - Coulomb
  - Pauli-Blocking on three-particle level
  - No three-body forces



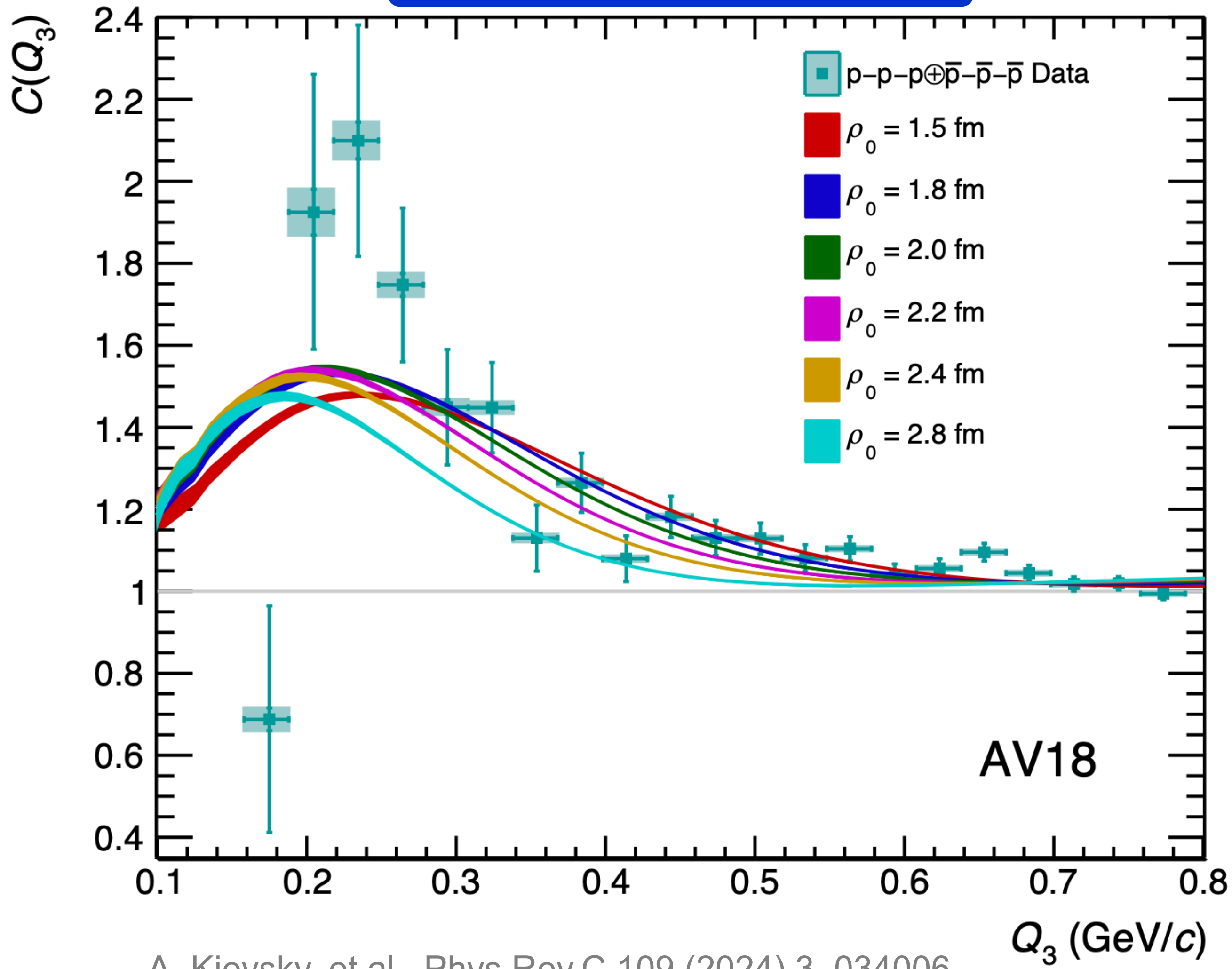
A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

The future of ppp studies

ALICE Run 3 (2022 data only)



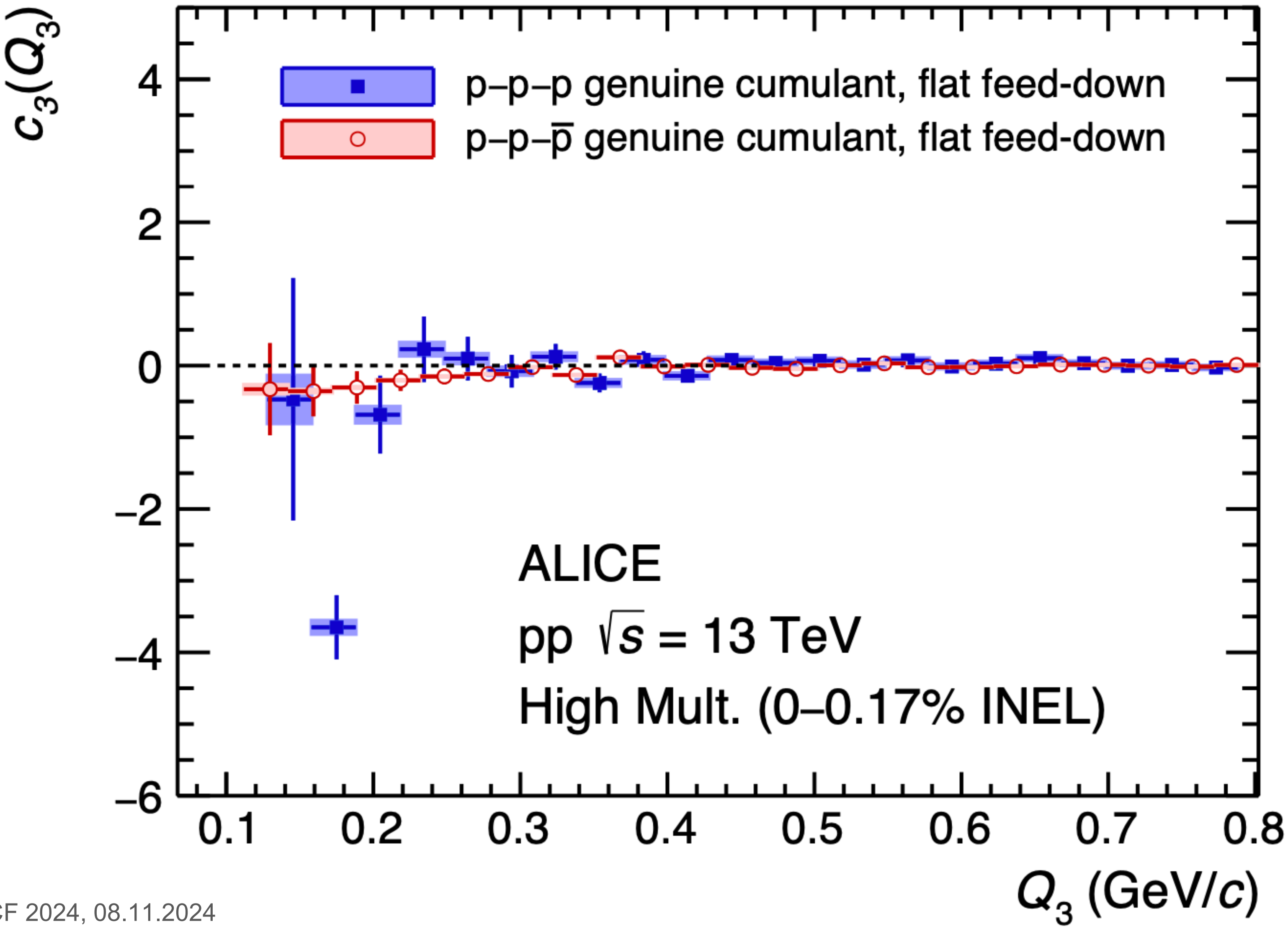
ALICE Run 2



A. Kievsky, et al., Phys.Rev.C 109 (2024) 3, 034006

Other Three-Body Studies

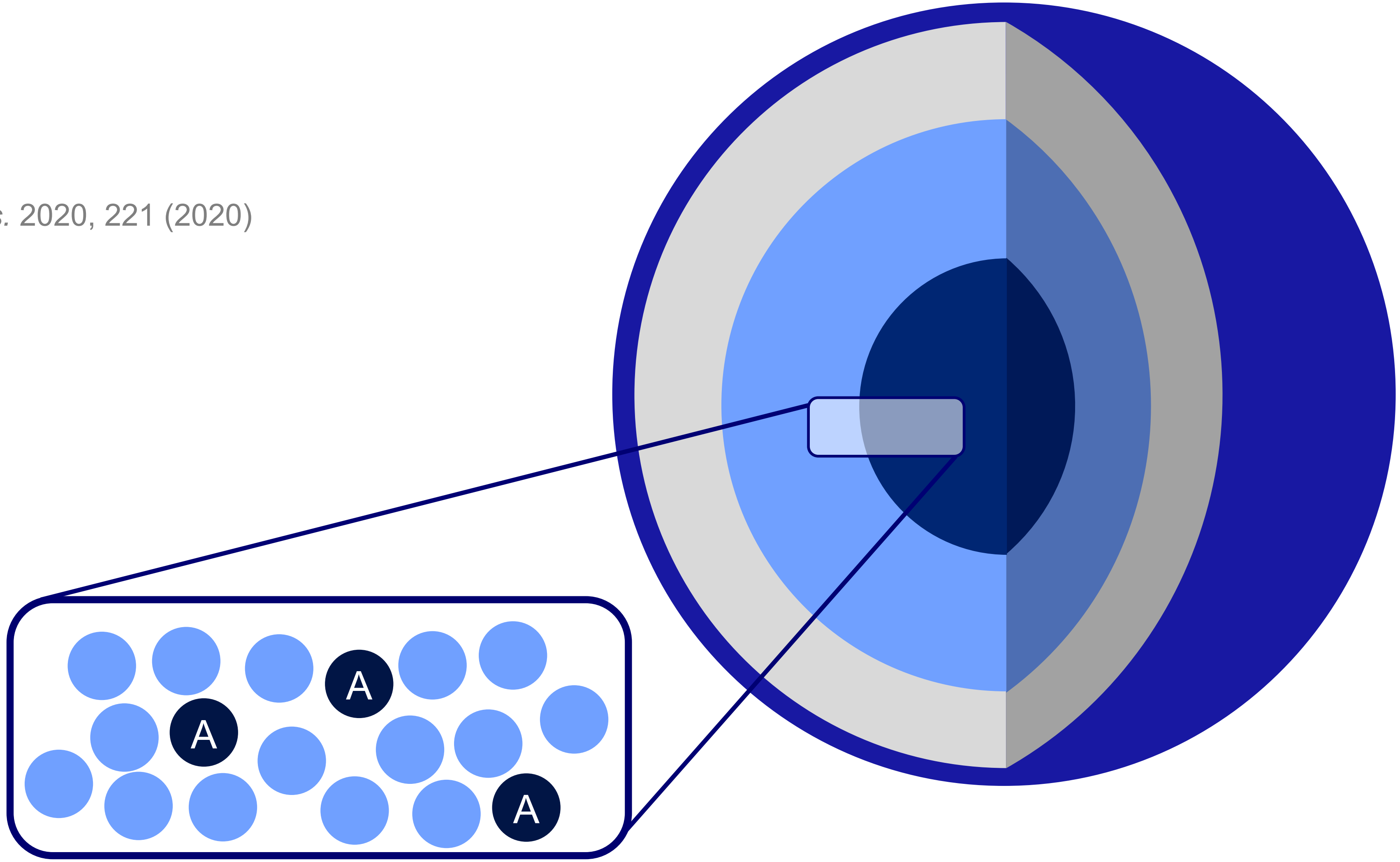
ALICE, Eur.Phys.J.A 59 (2023) 7, 145



Neutron Stars and QCD Axions

- Impact of axion on the EoS
  → Can lead to stiffer EoS

Reuven Balkin et al, *J. High Energ. Phys.* 2020, 221 (2020)
Reuven Balkin et al, arXiv 2307.14418

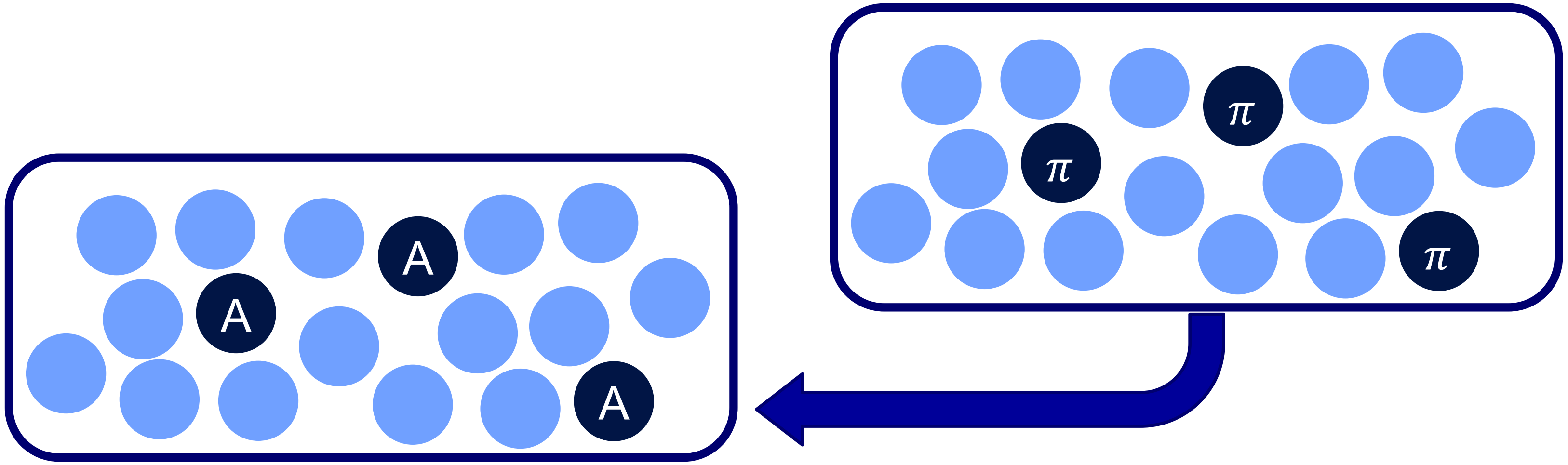


Neutron Stars and QCD Axions

- Impact of axion on the EoS
  → Can lead to stiffer EoS

- Axion properties linked to in-medium properties of pion

  Reuven Balkin et al, *J. High Energ. Phys.* 2020, 221 (2020)
  Reuven Balkin et al, arXiv 2307.14418

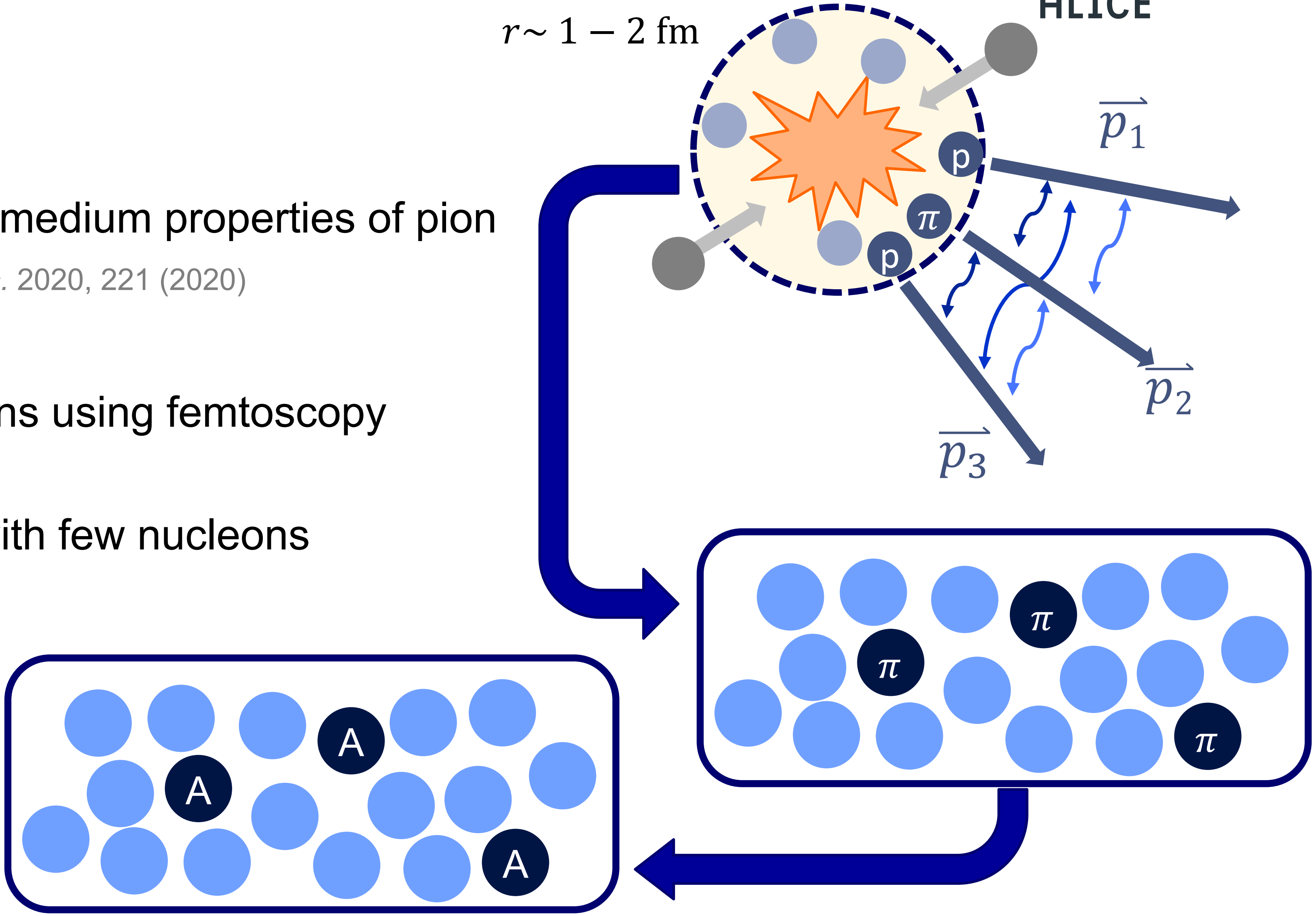


Neutron Stars and QCD Axions

- Impact of axion on the EoS
  → Can lead to stiffer EoS
- Axion properties linked to in-medium properties of pion

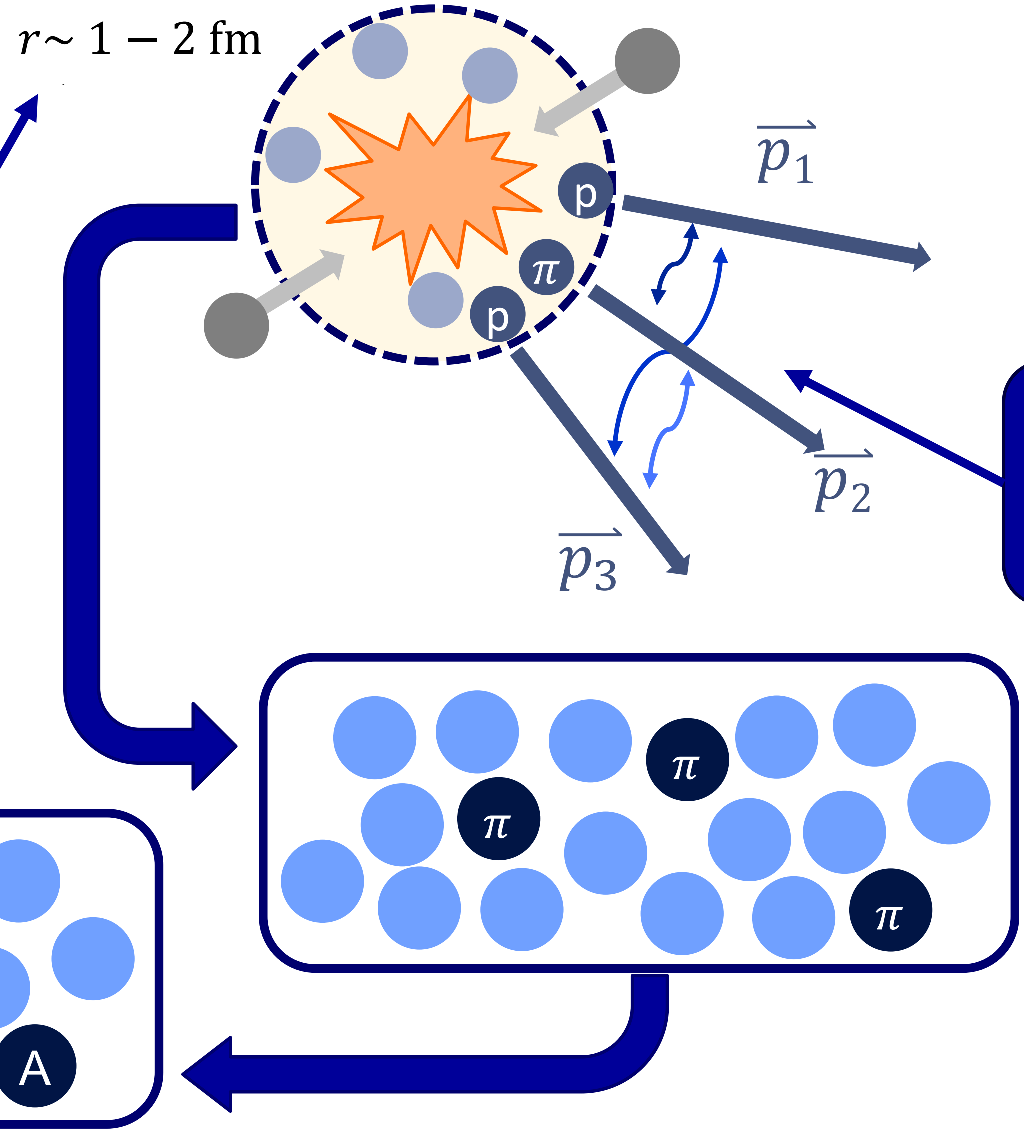
  Reuven Balkin et al, *J. High Energ. Phys.* 2020, 221 (2020)
  Reuven Balkin et al, arXiv 2307.14418

Goal: Study of $pp\pi^{\pm}$ interactions using femtoscopy in small colliding systems
→ Access dynamics of pions with few nucleons



On todays Menu

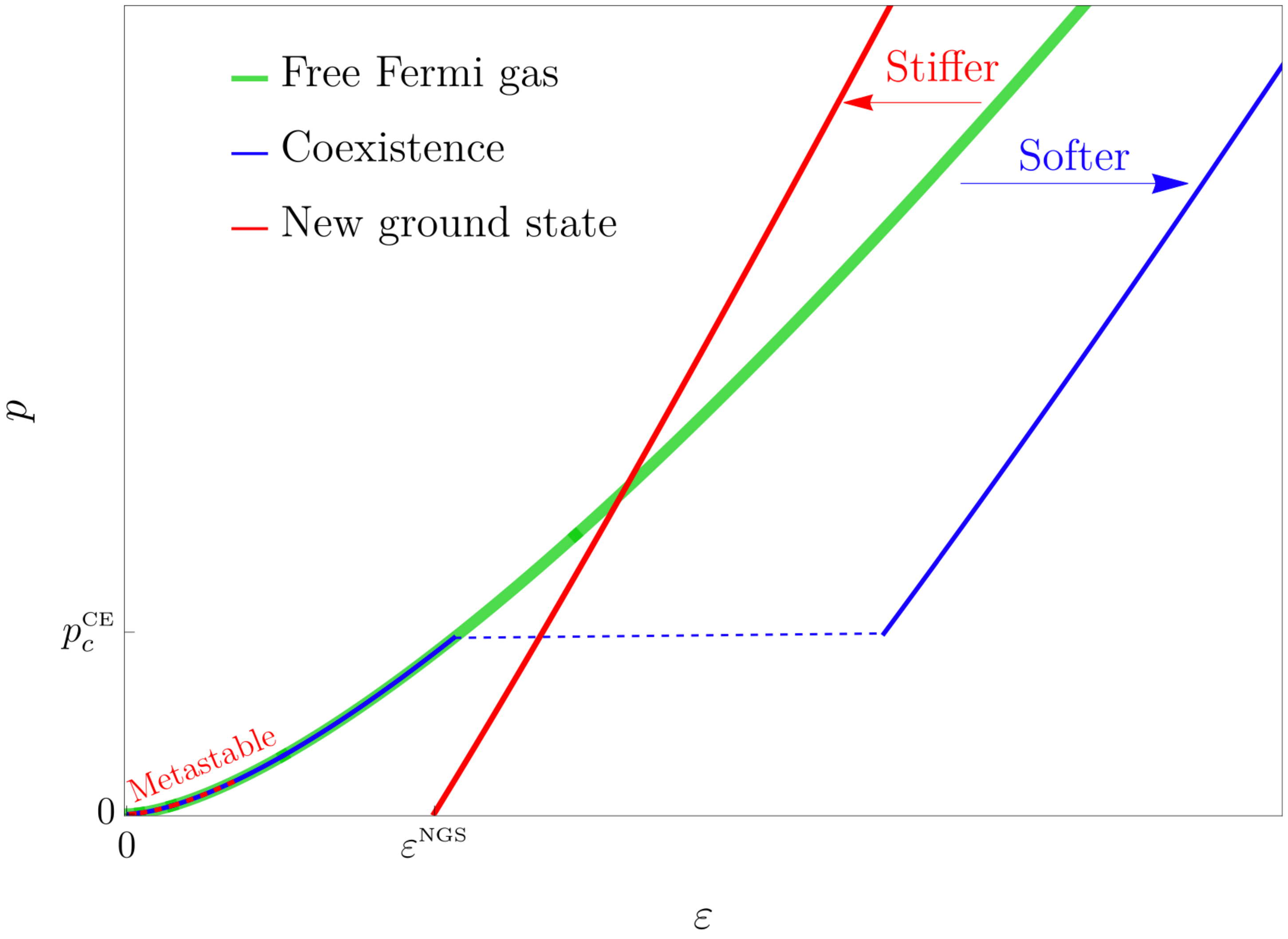
Emission at small distances for $p\pi^{\pm}$ systems?
→ probed via two-particle femtoscopy of $p\pi^{\pm}$



Do we see effects beyond pairwise interactions in $pp\pi^{\pm}$?

Axions in Neutron Stars

- Sourcing of a scalar reduces the nucleon mass and provides an additional energy density and pressure source
- Neutron stars in the new ground st[a]te can be significantly heav- ier than QCD equations of state currently predict



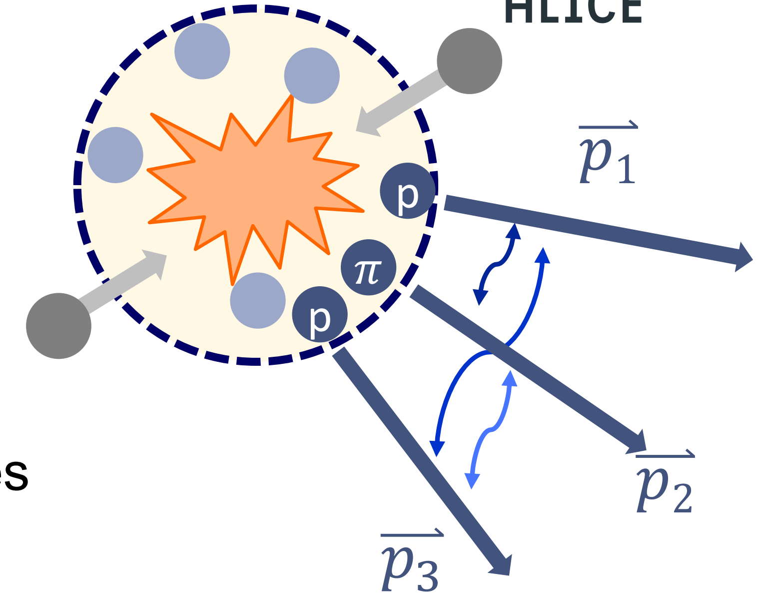
Three-Body Femtoscopy

- Pair relative momentum not applicable in three-body system
  → Use Lorentz-invariant hyper-momentum Q_3

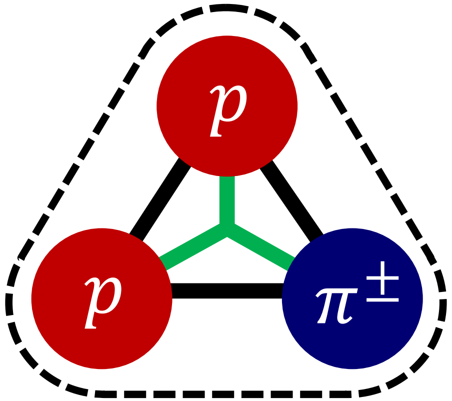
Three-Body Femtoscopy

- Pair relative momentum not applicable in three-body system
  → Use Lorentz-invariant hyper-momentum Q_3

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{13}^2}$$



- Three-particle correlation functions: 3 → 3 scattering processes

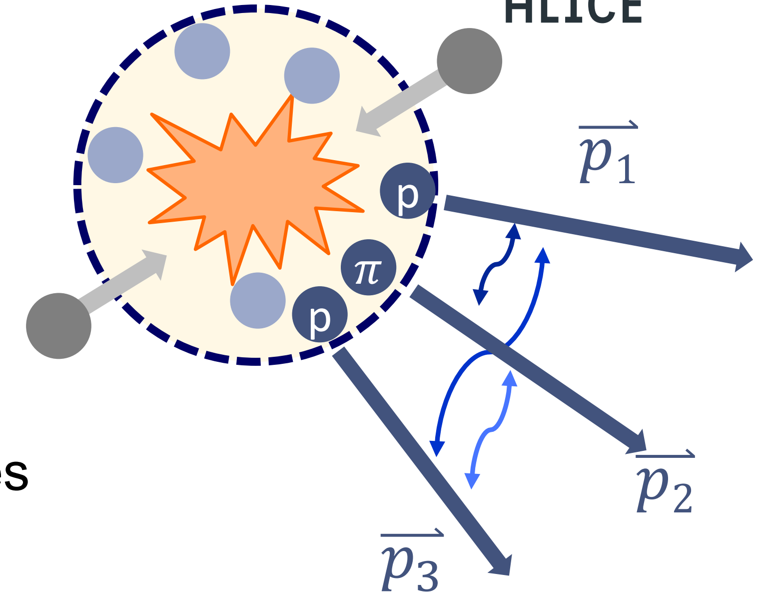


$$C(Q_3) = \mathcal{N}\,\frac{\mathrm{N}_{same}(Q_3)}{\mathrm{N}_{mixed}(Q_3)}$$

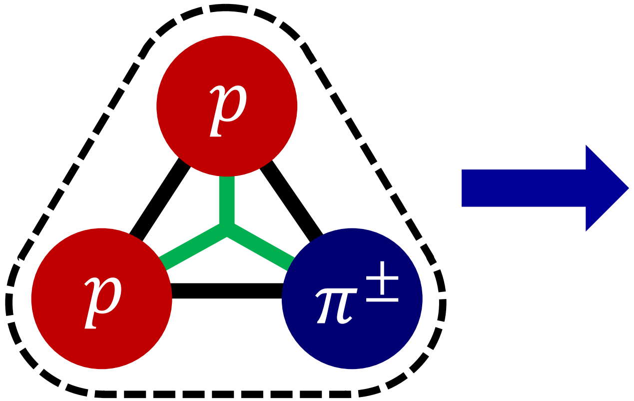
Three-Body Femtoscopy

- Pair relative momentum not applicable in three-body system
  → Use Lorentz-invariant hyper-momentum Q_3

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{13}^2}$$



- Three-particle correlation functions: 3 → 3 scattering processes



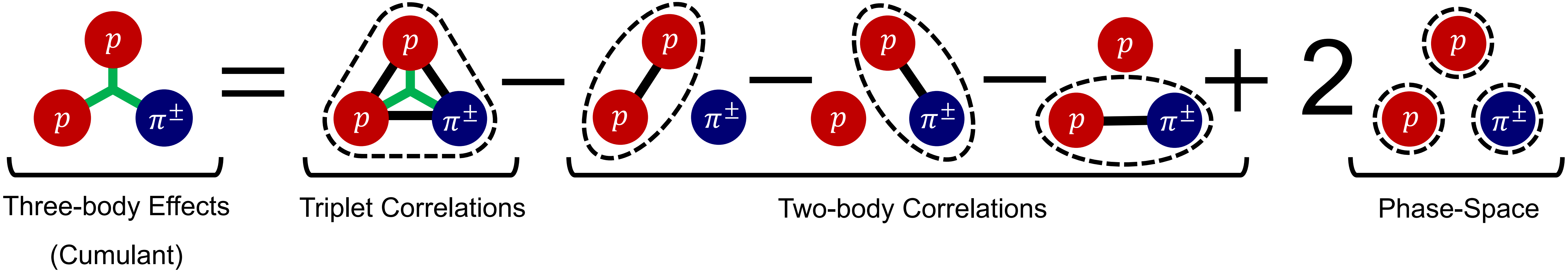
$$C(Q_3) = \mathcal{N}\frac{\mathrm{N}_{same}(Q_3)}{\mathrm{N}_{mixed}(Q_3)}$$

- Challenge of isolating three-body effects
  → Effects of two-body and potential three-body interactions in the system

Smoking Guns of Three-Body Interactions

- Kubo cumulant decomposition:

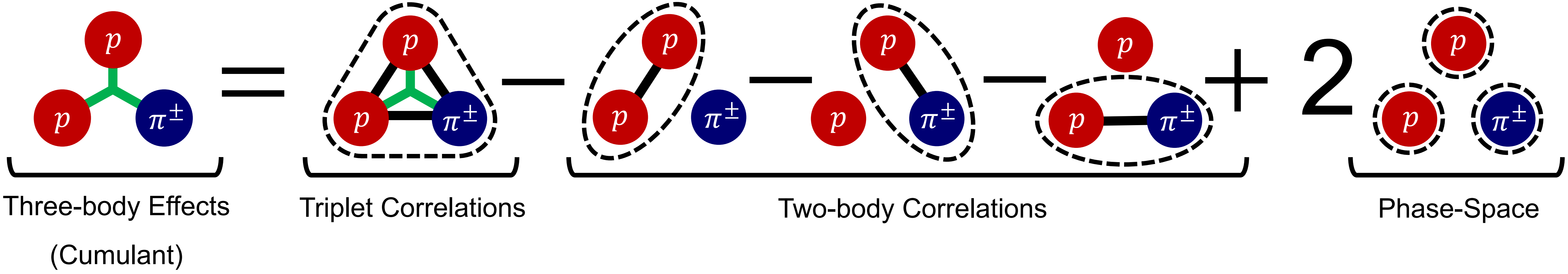
  R. Kubo, Journal of the Physical Society of Japan 17 no. 7, (1962) 1100–1120



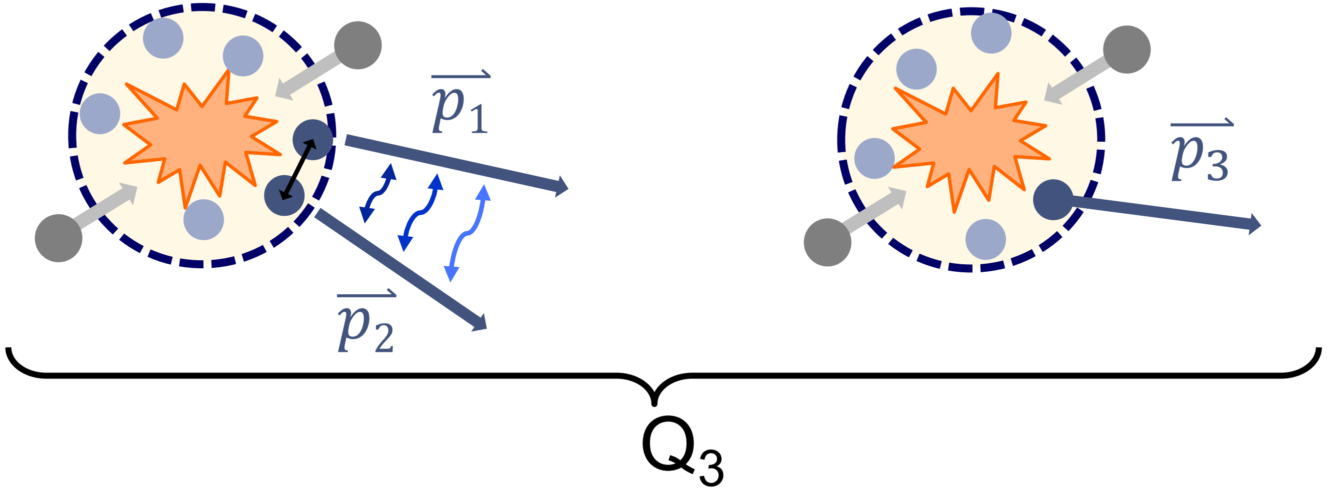
Smoking Guns of Three-Body Interactions

- Kubo cumulant decomposition:

  R. Kubo, Journal of the Physical Society of Japan 17 no. 7, (1962) 1100–1120

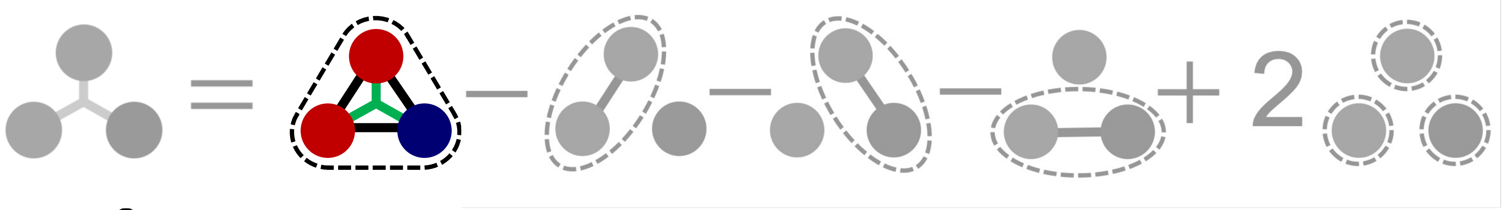


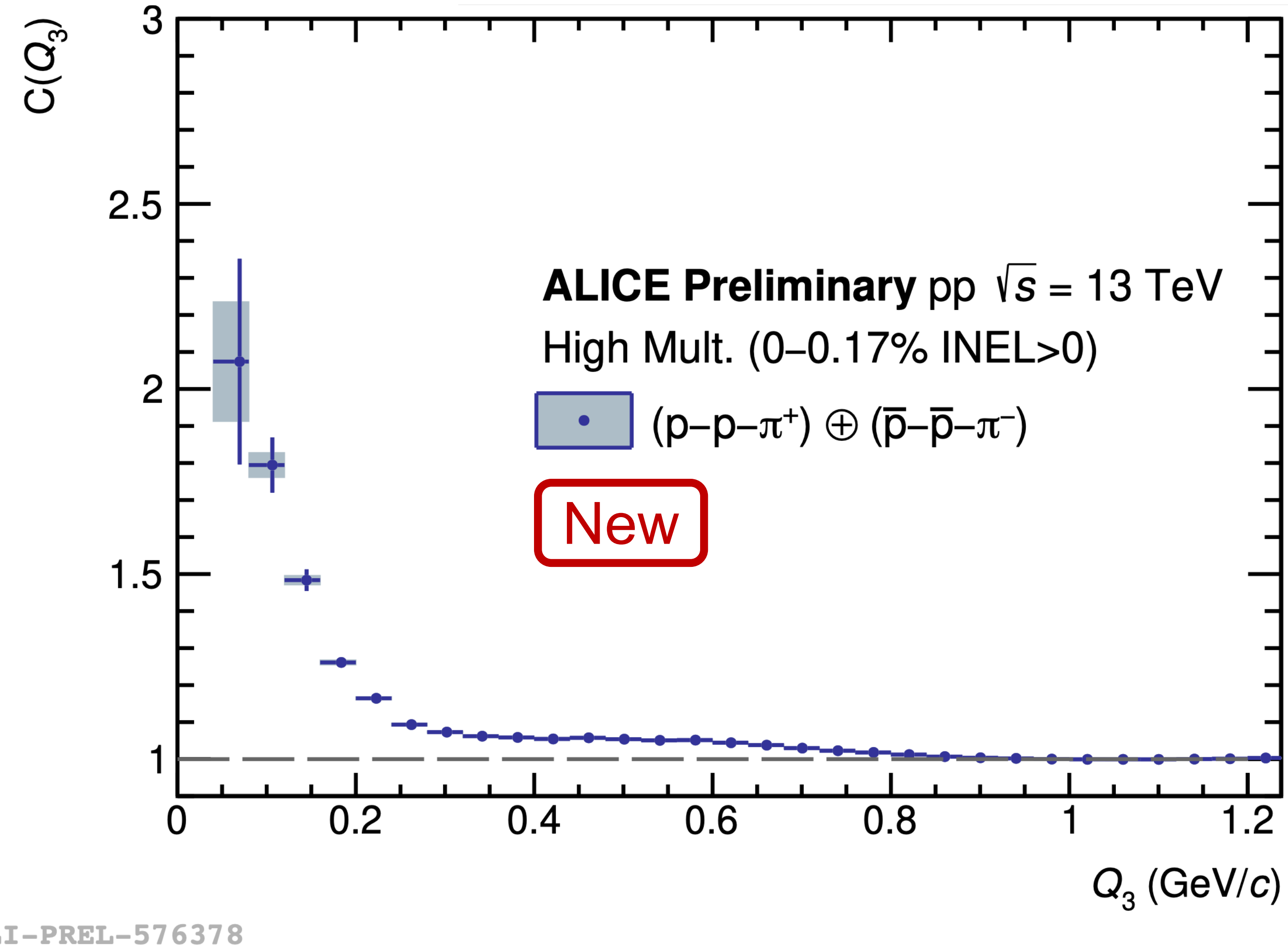
- Lower-order contributions estimated in a data-driven way using the same and mixed events distributions



Three-particle correlation function of ppπ^+

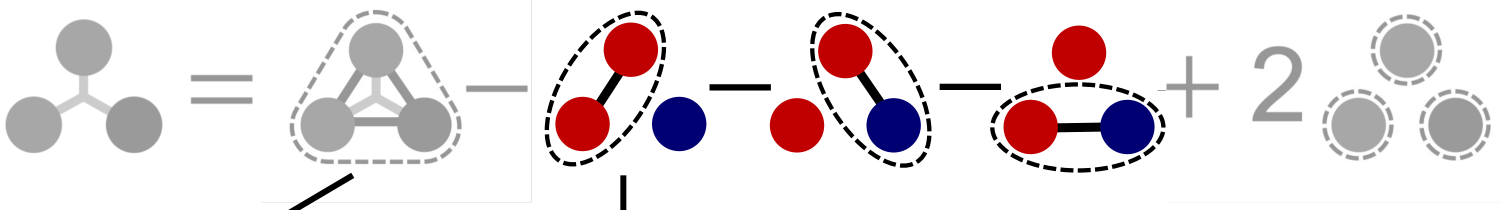
- Overall attractive effects in triplet correlation function
- Signal consisting of two-body and potential three-body effects

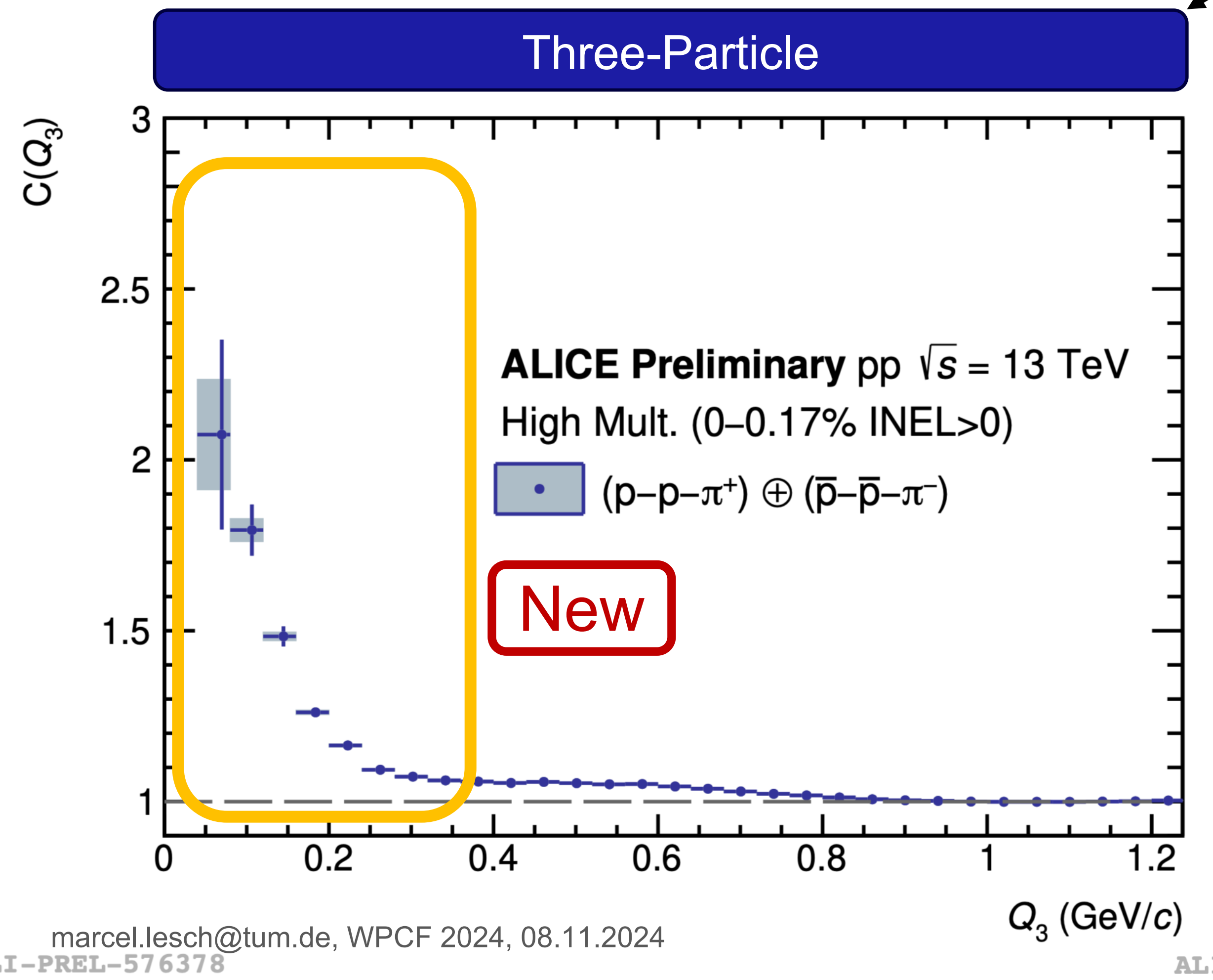


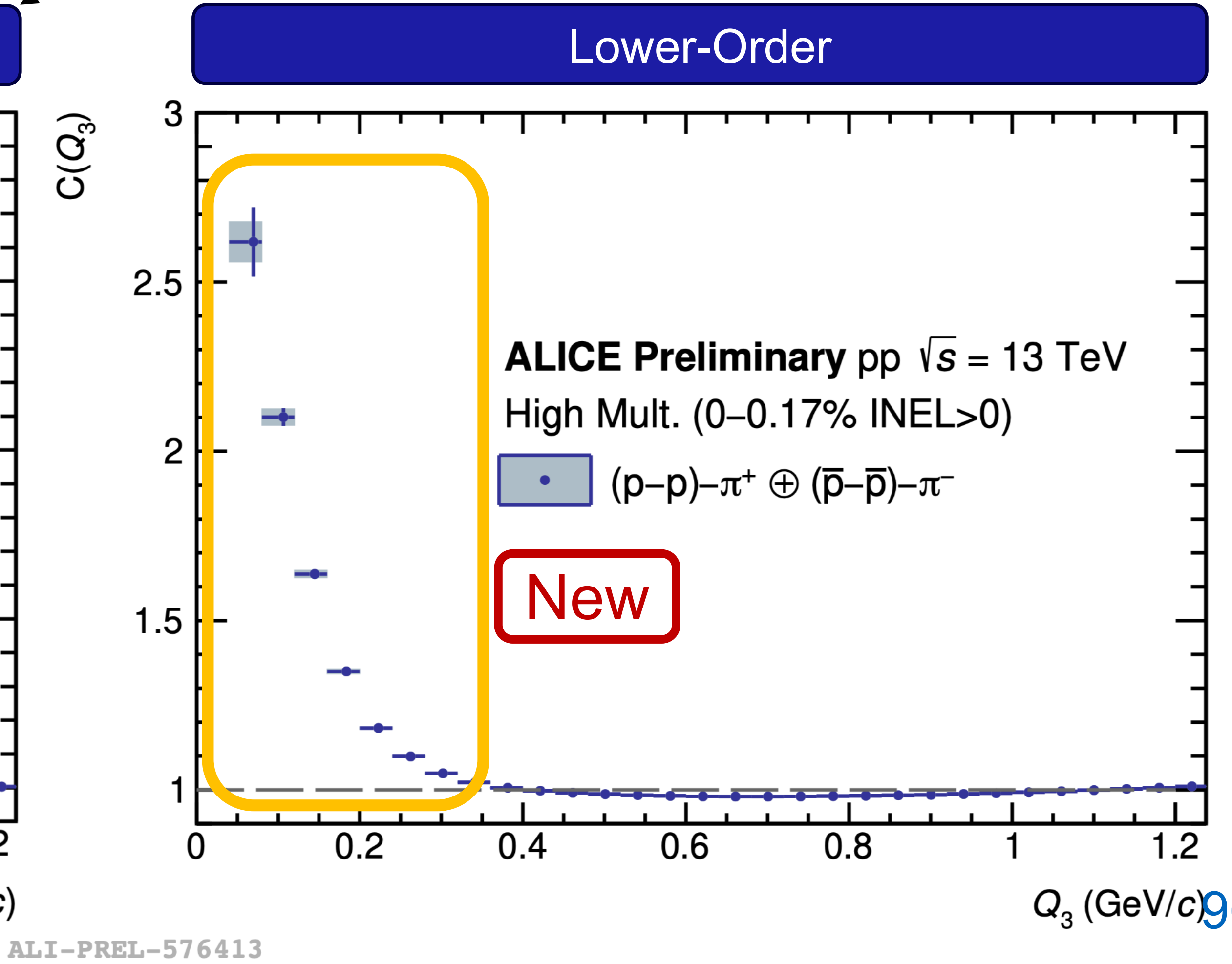


Two-particle contributions of ppπ^+

- Contribution from attractive strong interaction of pp

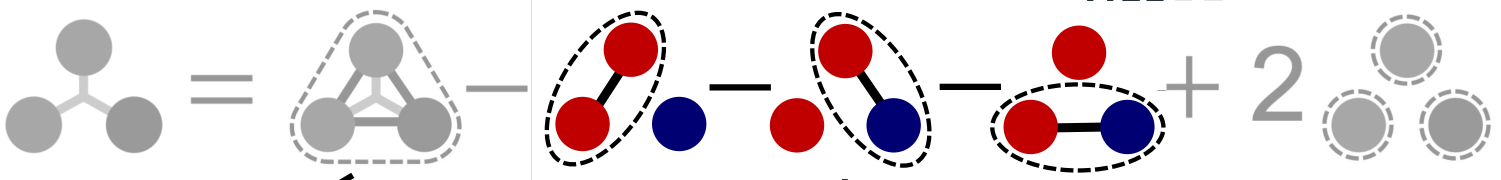


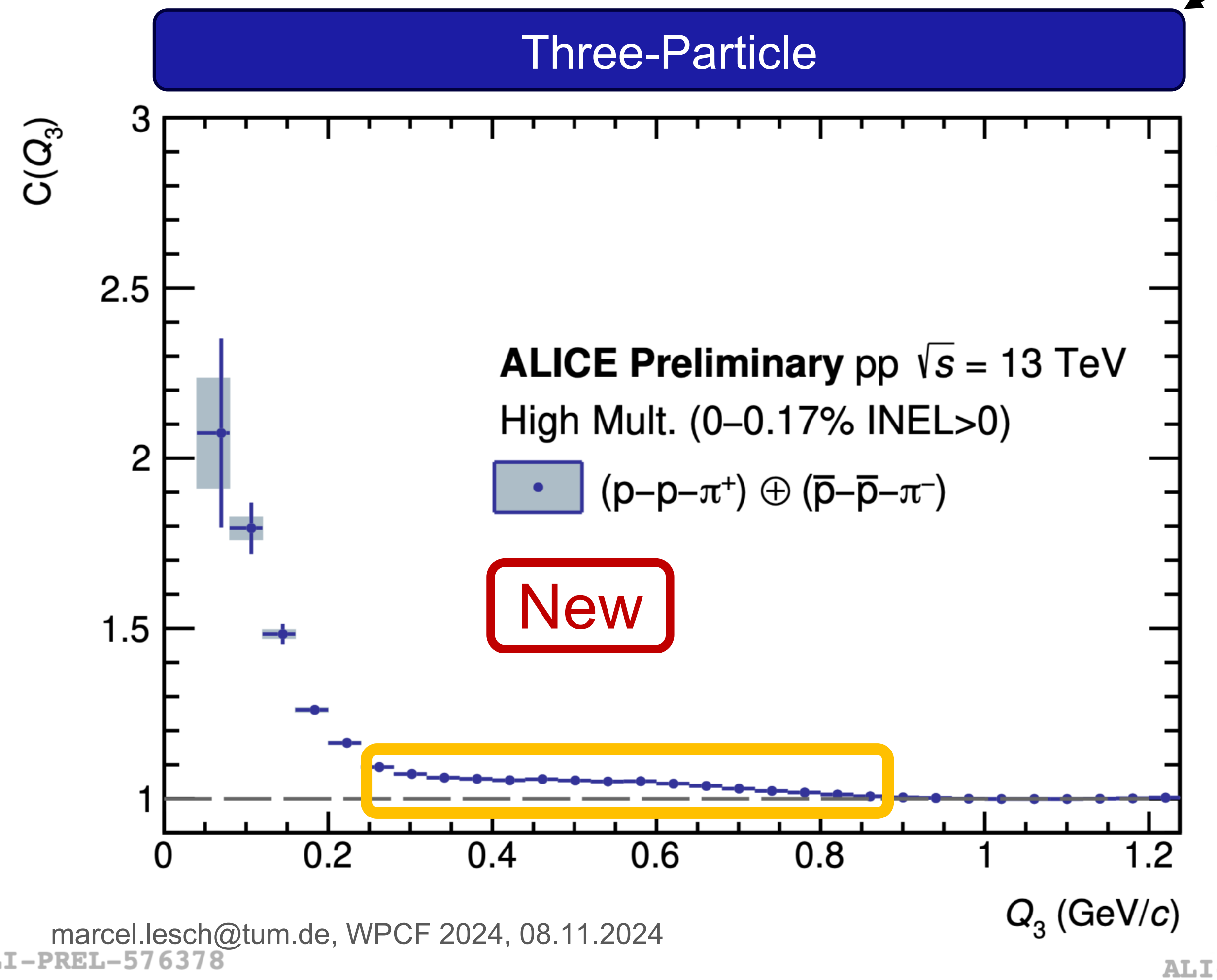


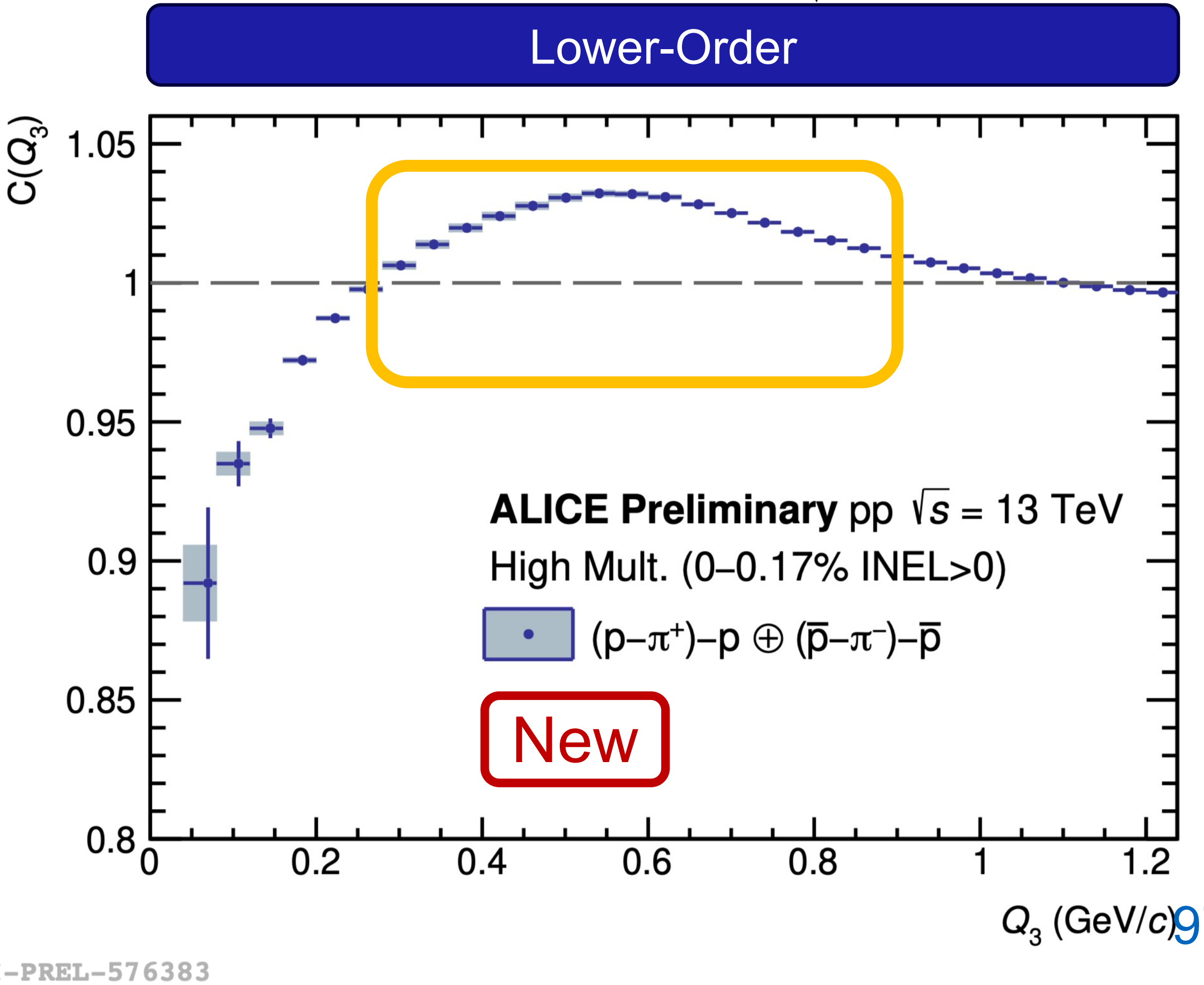


Two-body contributions of ppπ^+

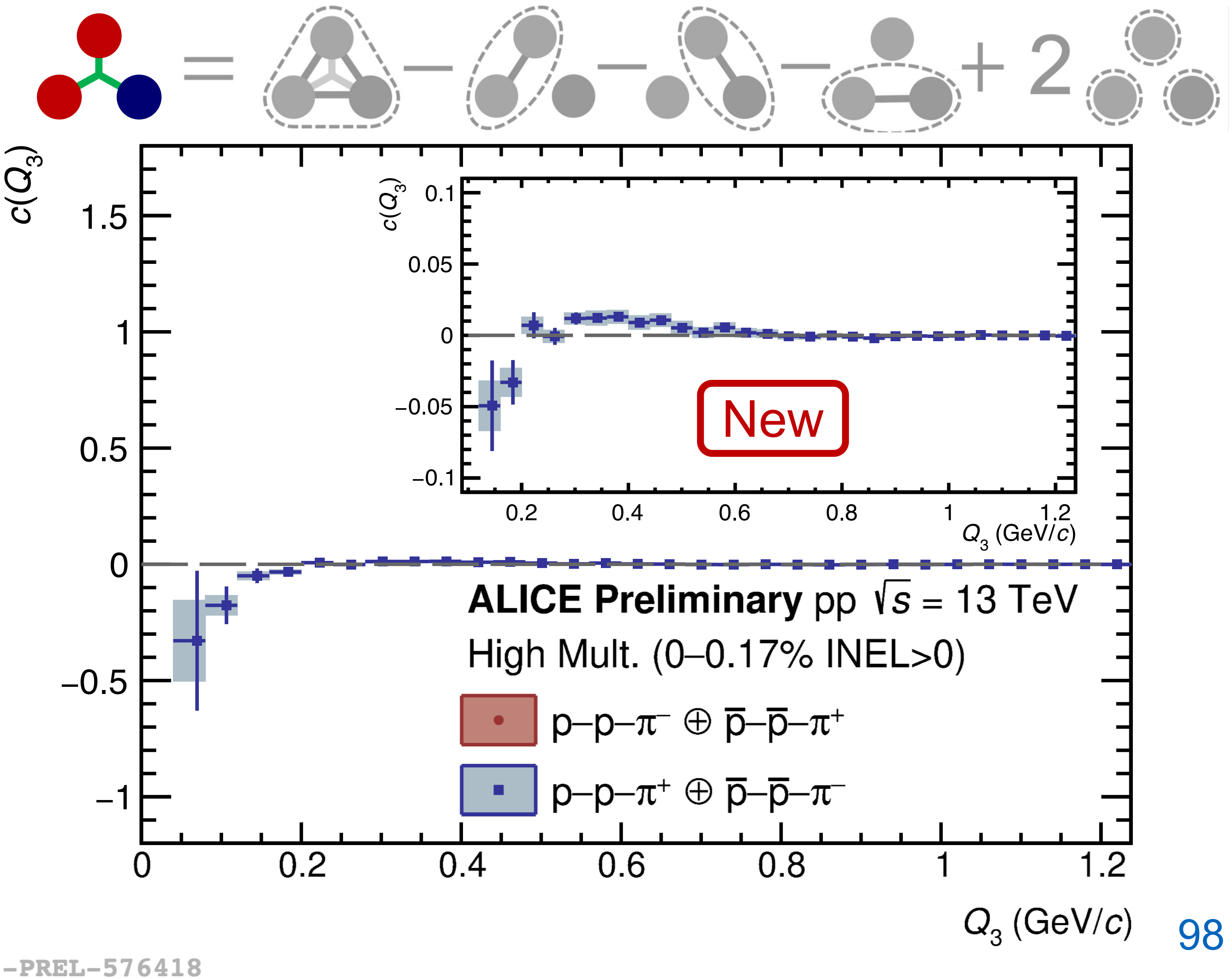
- Visible contribution from $\Delta^{++}(1232) \rightarrow p\pi^+$





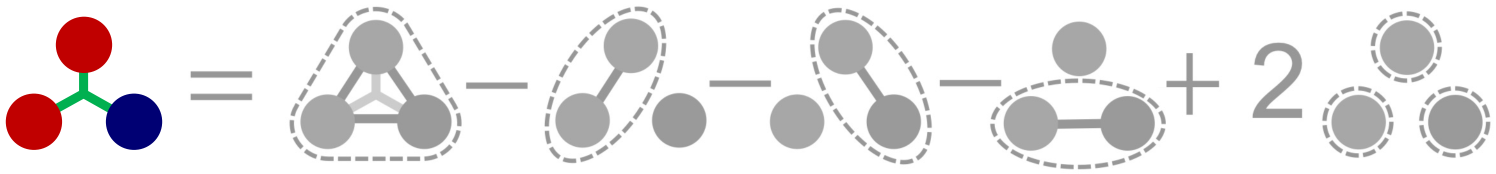


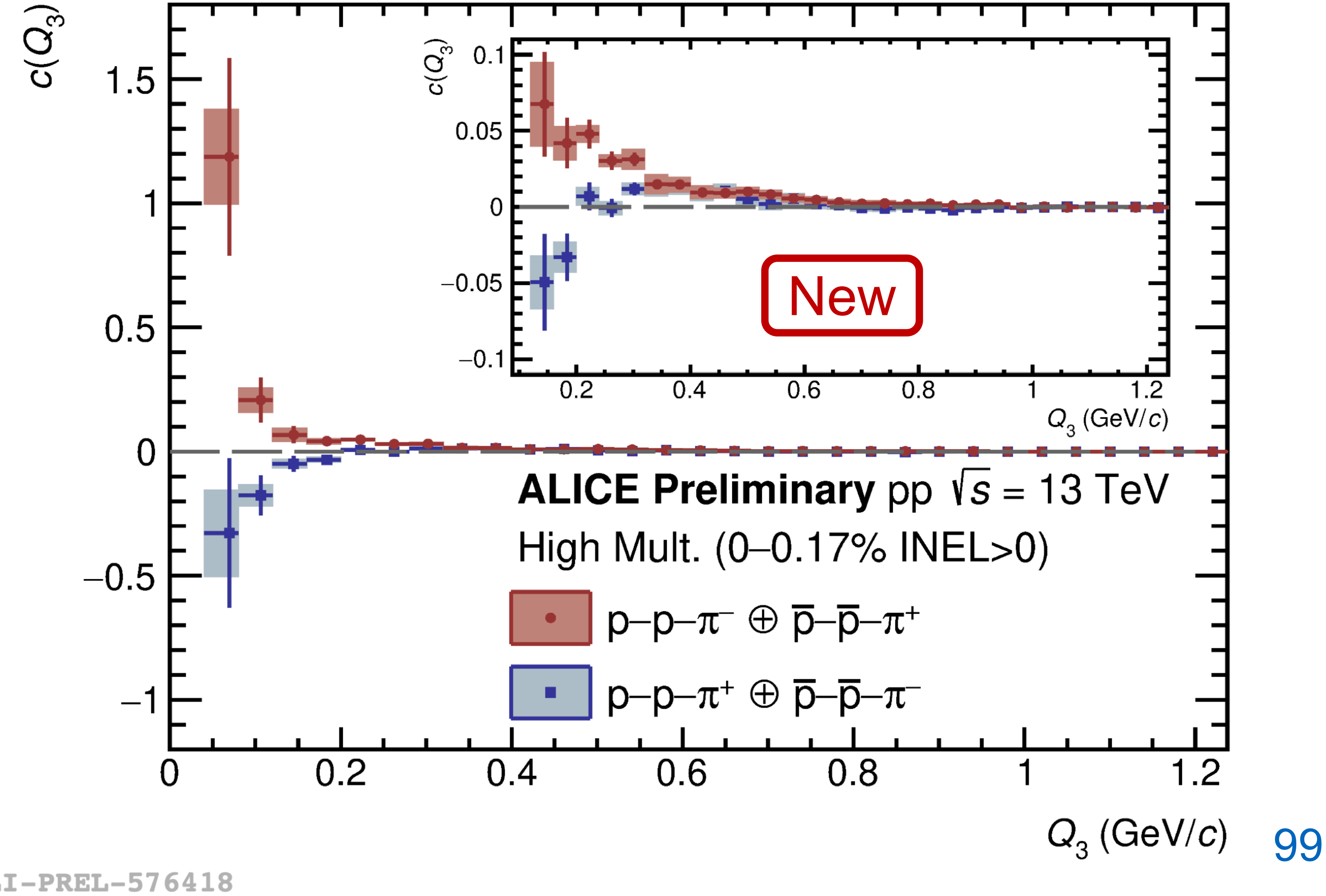
Three-body effects in ppπ$^{\pm}$



Three-body effects in $pp\pi^{\pm}$

- 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 $pp\pi^{+}$
  - Attraction for $pp\pi^{-}$





Three-Body Effects in $pp\pi^{\pm}$

- Statistical significance:

Q_3 range in GeV	n_σ for	
	$pp\pi^{+}$	$pp\pi^{-}$
0.04 - 0.16	1.84	2.83
0.16 - 0.68	3.23	8.34
0.04 - 0.68	3.46	8.64

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