Accessing the coupled-channels dynamics with femtoscopy correlations at LHC

V. Mantovani Sarti (TUM) on behalf of the ALICE Collaboration

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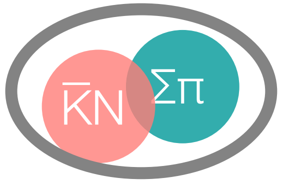
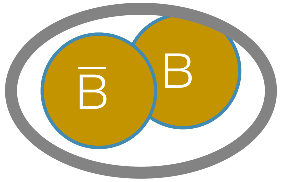
22nd edition
Particles and Nuclei International Conference

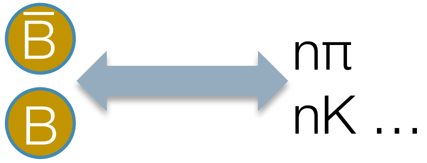
Motivation: inelastic channels in h-h interactions

- Coupled-channel dynamics widely present in hadron-hadron strong interactions
  - Close in mass and same quantum numbers (e.g.B,S,Q)
  - On-shell and off-shell processes from one channel to the other
- Can be at the origin of several phenomena
  - Molecular states as Λ(1405) → interplay of $\bar{K}N$–Σπ
- Annihilation dynamics for B–$\bar{B}$ interactions
  - Multi-meson channels below threshold

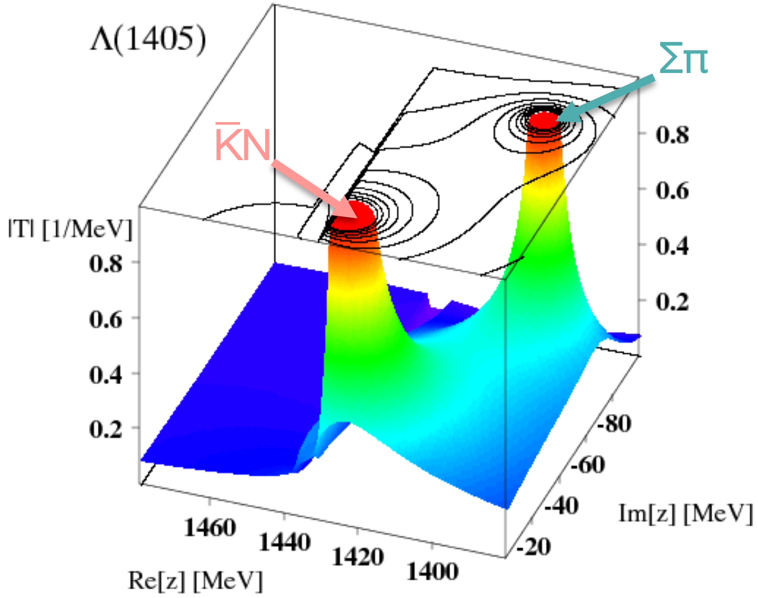
See A. Ohnishi´s talk in previous session

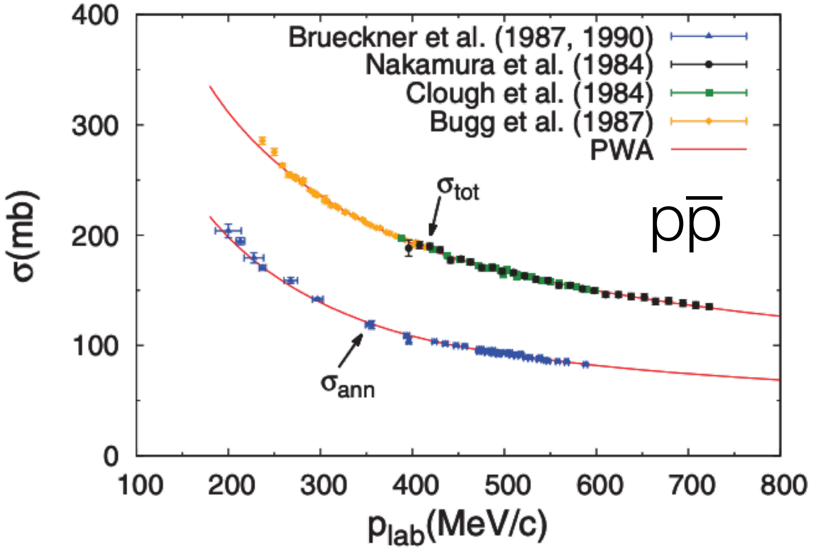






Prog.Part.Nucl.Phys. 67 (2012) 55-98

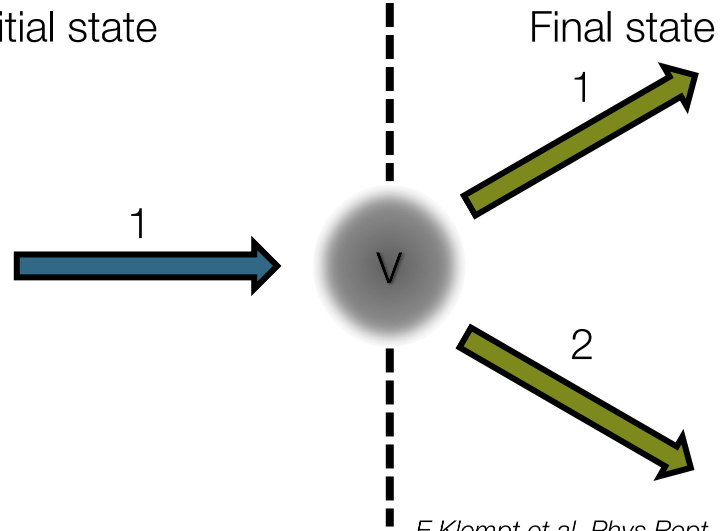




D.Zhou and R.G. E. Timmermans PRC86 (2012)

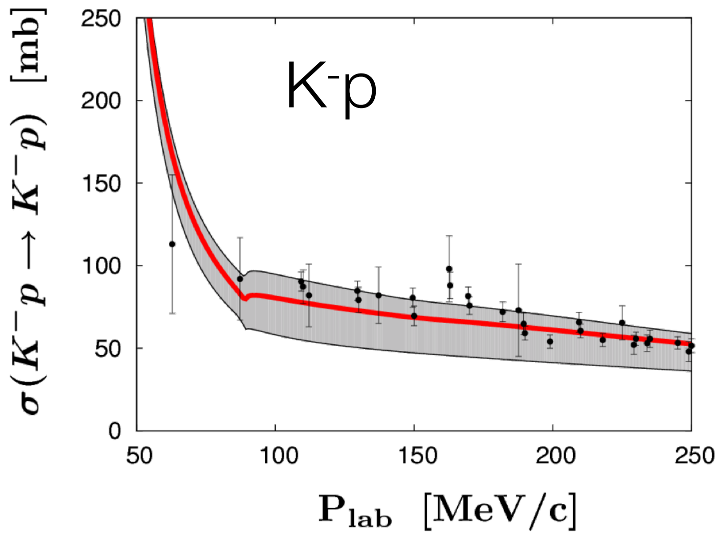
Scattering experiments…

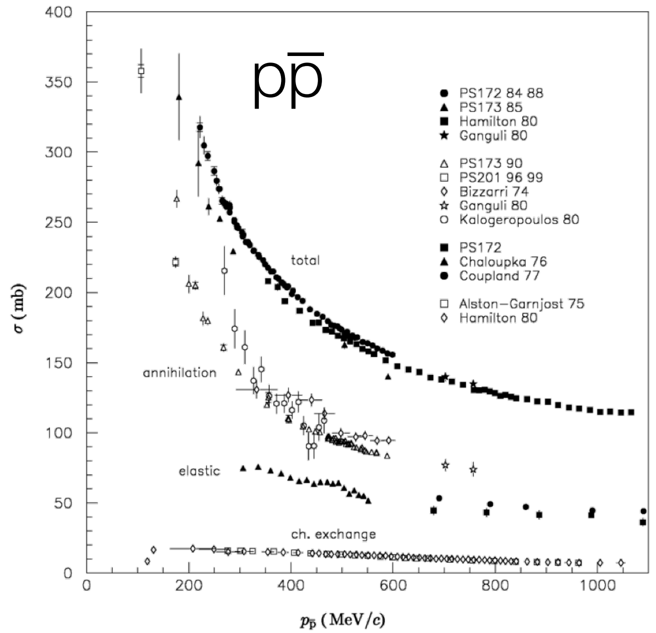
- Fixed initial state (e.g.K$^-$) and different final states:
  - Elastic scattering: 1→1
  - Inelastic scattering: 1→2,3…
- Measurement of the cross section in different channels
- Disadvantages:
  - Not accessible down to zero momenta
  - Large uncertainties
  - Limited to few h-h interactions



E.Klempt et al. Phys.Rept. 368 (2002) 119-316

G.S. Abrams et al. Phys.Rev. 139 (1965) B454-B457

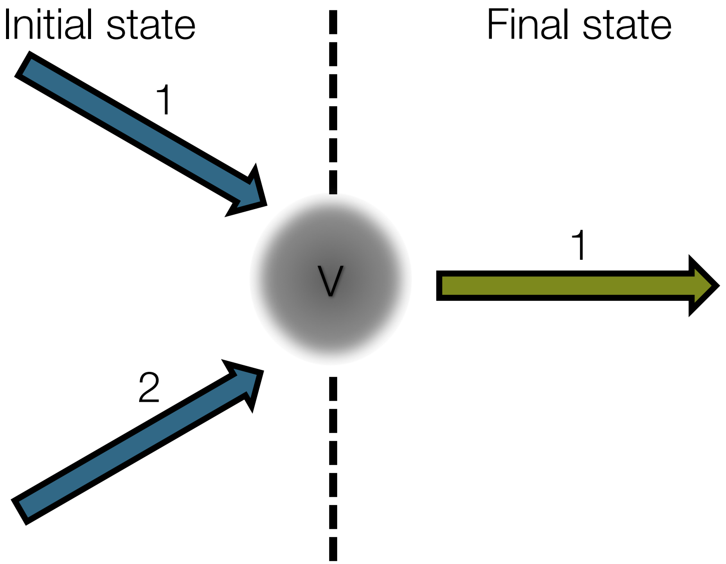




… and now femtoscopy at ALICE

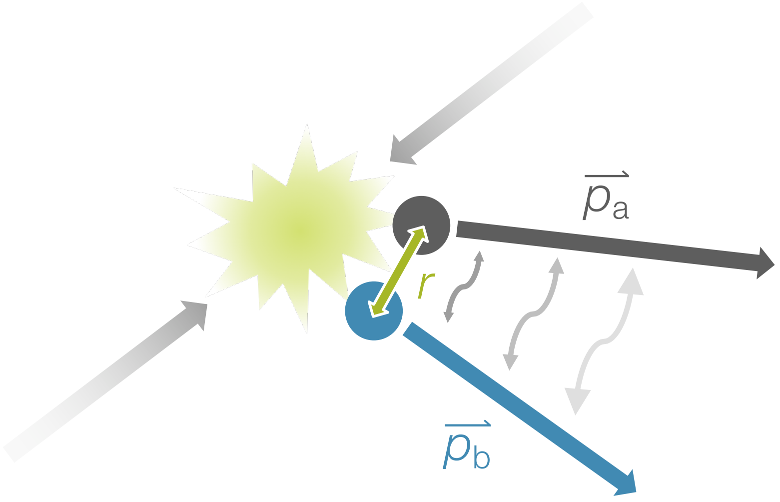
- Fixed final state with the measured pair and all possibe initial states
  - inclusive measurement: 1,2,3,4,… → 1

$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} \begin{cases} > 1 \text{ attraction} \\ = 1 \text{ no inter.} \\ < 1 \text{ repulsion} \end{cases}$$



- Access to any particle-pair interaction as long as enough statistics is available
  - Baryon-baryon sector widely investigated in ALICE Run 2

PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
arXiv:2104.04427
arXiv:2105.05578
arXiv:2105.05683
arXiv:2105.05190

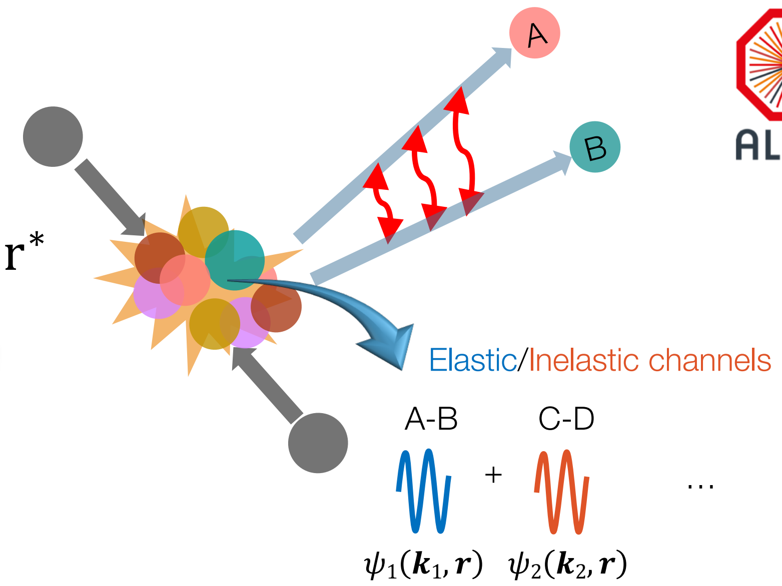


Inelastic channels in femtoscopy

$$C(k^*) = \int S(\vec{r}^*)\,\left|\psi_{1\to1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3r^* + \sum_{j\neq1} w_j \int S(\vec{r}^*)\left|\psi_{j\to1}(\vec{k}_j^*,\vec{r}^*)\right| d^3r^*$$

elastic
A-B → A-B

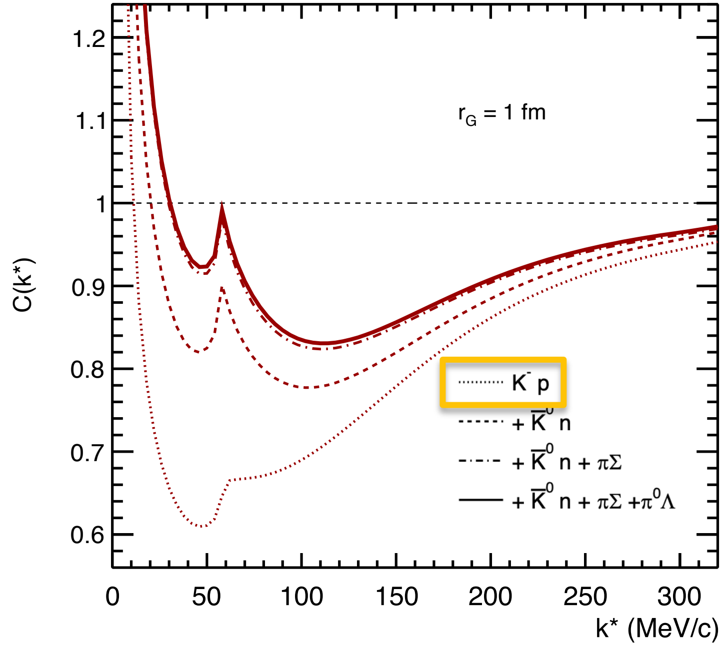
inelastic
C-D → A-B, …



- Wave functions $\psi_{j\to1}(k_j^*,r^*)$
  - Above threshold ($E \gtrsim M_{pair}$) → cusp structure e.g. $\bar{K}^0 n$
  - Below threshold ($E < M_{pair}$) → shift upward of CF e.g. $\Sigma\pi$

- Conversion weights w_j related to the produced pairs as initial states and coupling strength

- Correlation function is sensitive to inelastic channels but how does the emitting source enter?

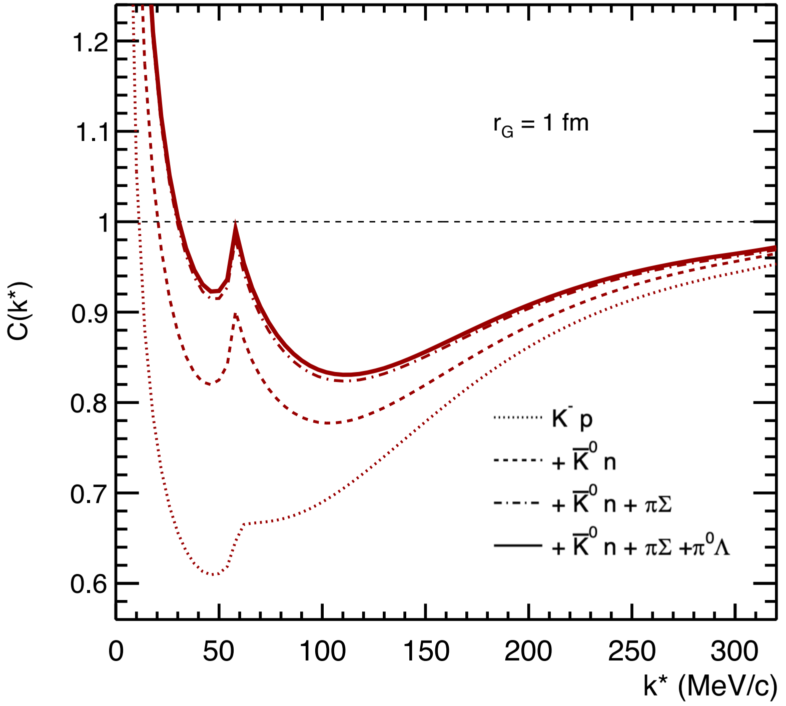


J. Haidenbauer Nucl.Phys.A 981 (2019)
Y. Kamiya et al. Phys.Rev.Lett. 124 (2020)
V.M.S., L. Fabbietti, O. Vazquez-Doce 2012.09806

Small vs large colliding systems

- Inelastic contributions negligible as the source size increases → mostly driven by the elastic interaction

$$C(k^*) = \int S(\vec{r}^*) \left|\psi_{1\to1}(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^* + \sum_{j\neq1} w_j \int S(\vec{r}^*)\left|\psi_{j\to1}(\vec{k}_j^*, \vec{r}^*)\right| d^3r^*$$



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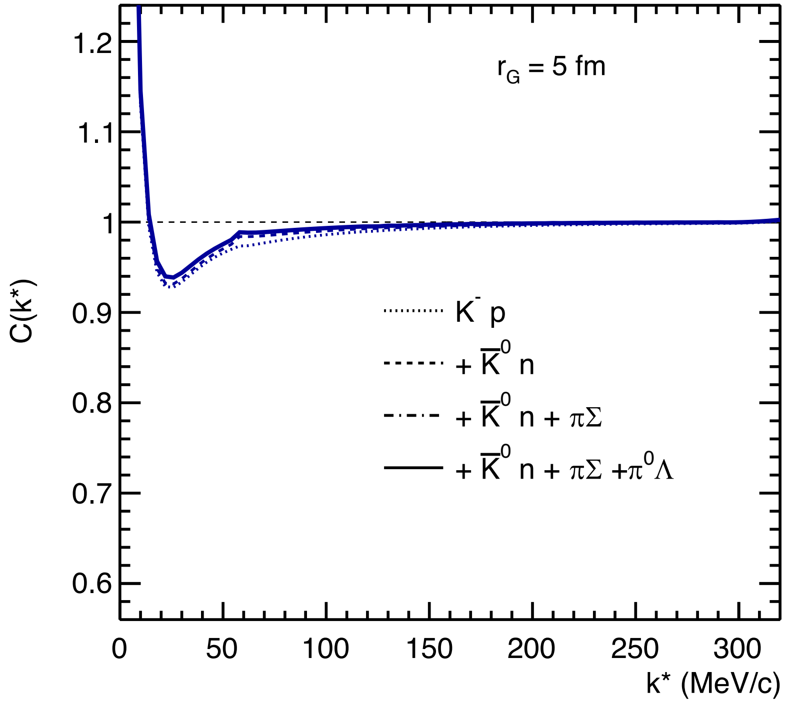

J. Haidenbauer Nucl.Phys.A 981 (2019)
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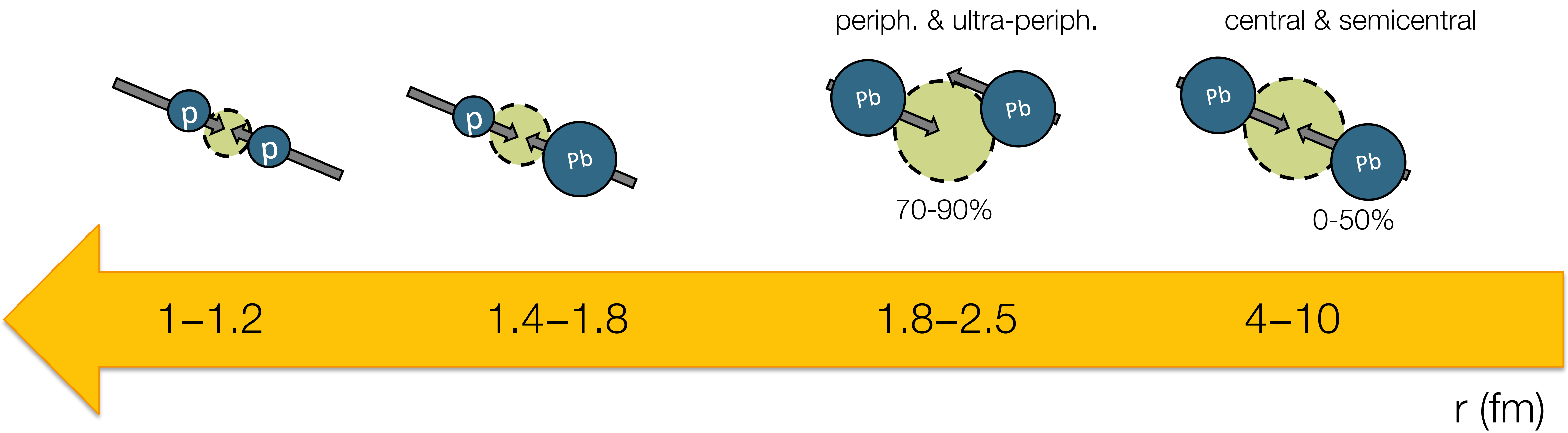
Small vs large colliding systems

- At ALICE by changing the colliding system we can probe distances ranging from 1 fm up to 10 fm



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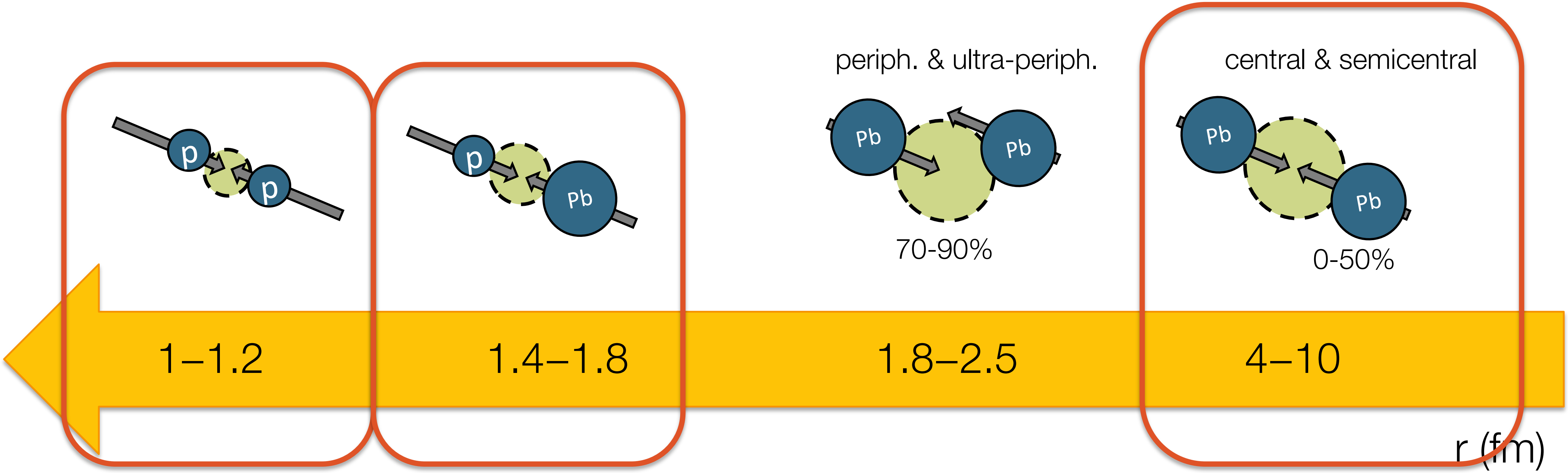


K-p and K+p in pp 5,7,13 TeV, p–Pb and Pb–Pb 0-50% 5.02 TeV

$p\bar{p}$,p-$\bar{\Lambda}$ and Λ-$\bar{\Lambda}$ in pp HM 13 TeV and Pb–Pb 5.02 TeV

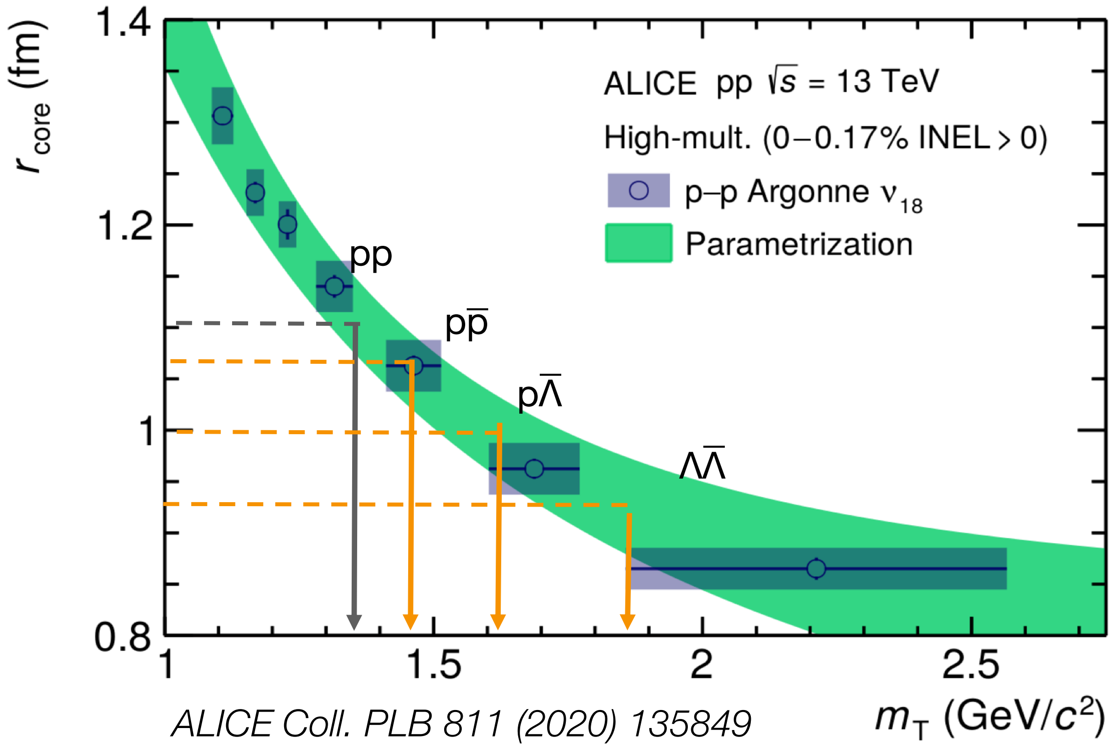
Fixing the source

In pp collisions:

- Two main contributions
  - **Common Gaussian core** r_{core} from <m_T> scaling due to collective effects (p-p, K^+-p)
  - **Strongly decaying resonances** contributions
- Effective Gaussian with r_G ~1-1.2 fm

In Pb–Pb collisions a gaussian source is assumed:

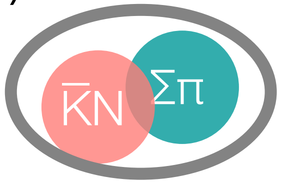
- Fixed from K^+–p and B–B pairs
- Scaling of the source size with m_T in agreement with previous measurements at 2.76 TeV



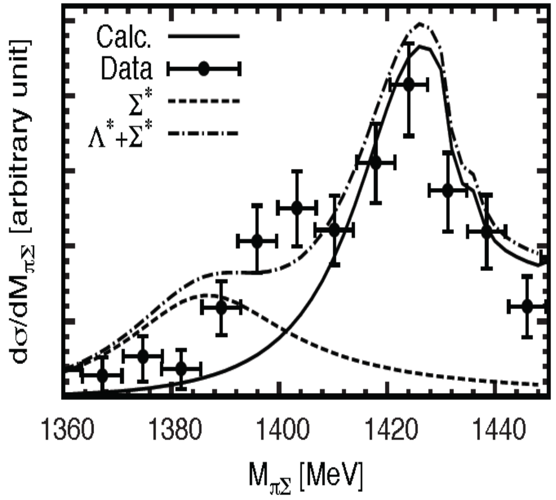
ALICE Coll. PLB 811 (2020) 135849

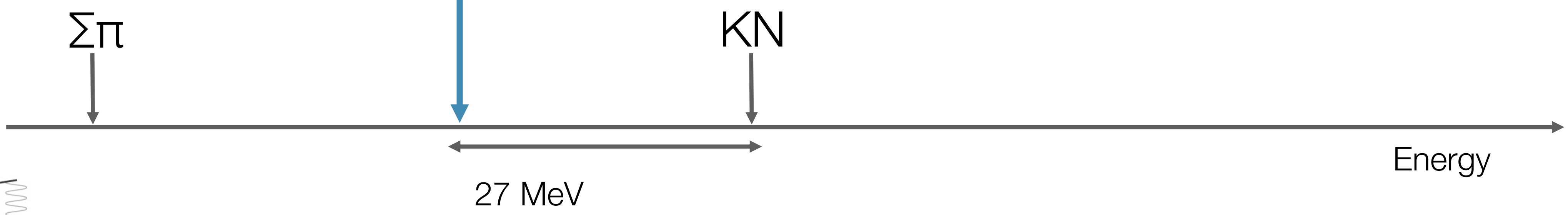
K^-–p and K^+–p femtoscopy

Λ(1405) molecular state



Λ(1405)→Σπ





K⁻–p femtoscopy: the antiKaon-nucleon interaction

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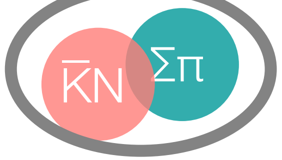
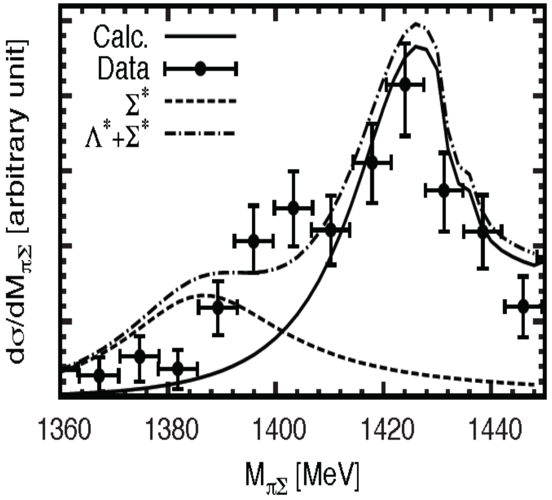


Λ(1405)→Σπ

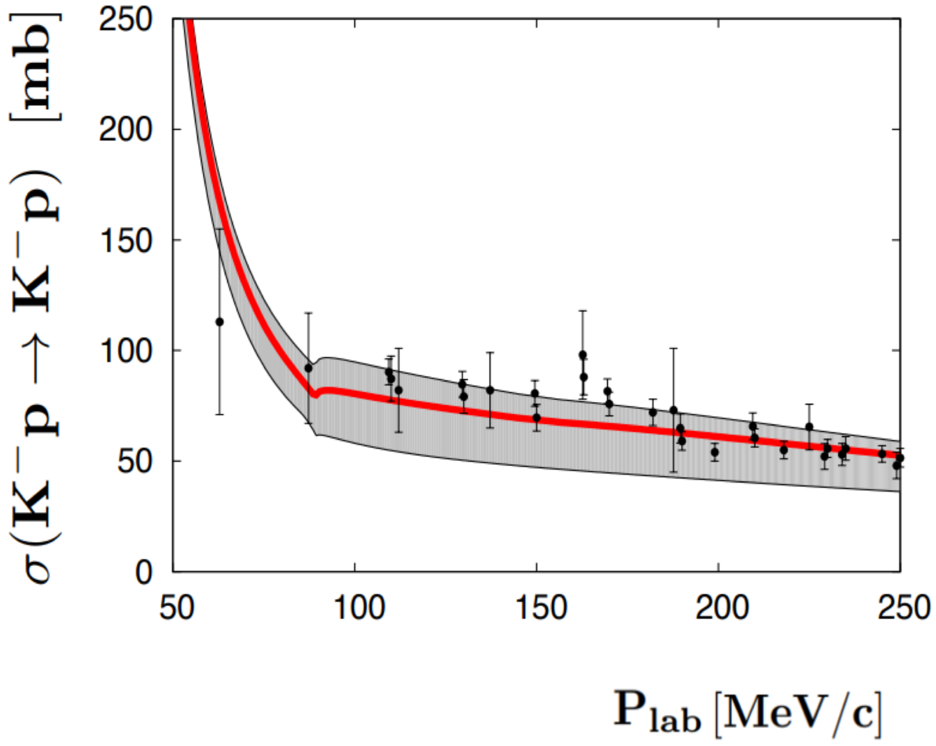


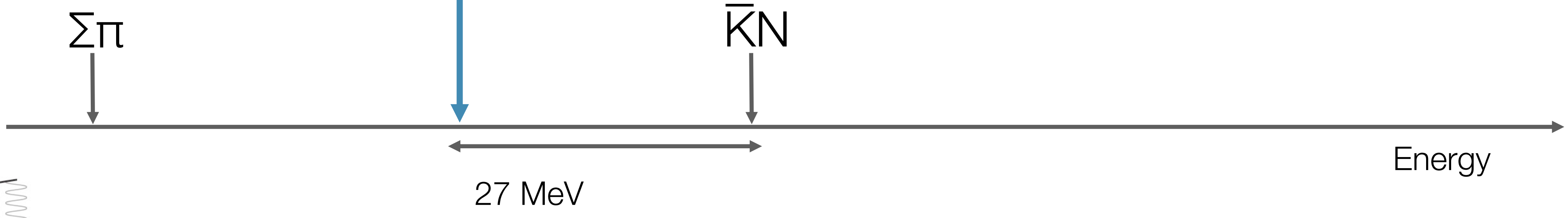
Kaonic hydrogen

SIDDHARTA Coll. PLB 704 (2011)

Scattering Experiments

Ikeda et al. Nucl.Phys.A 881 (2012)





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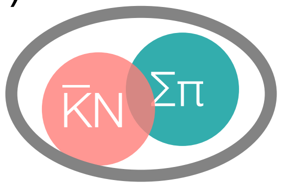

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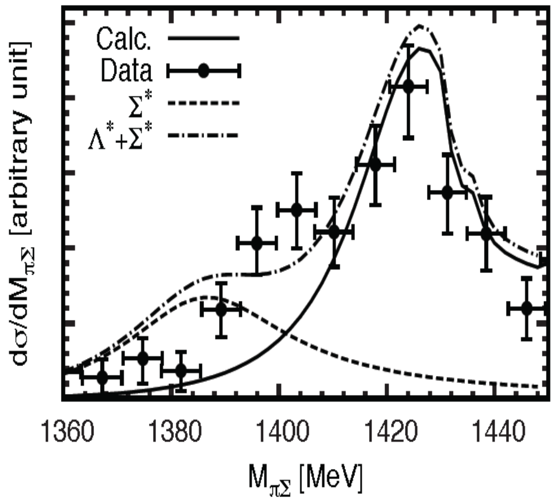

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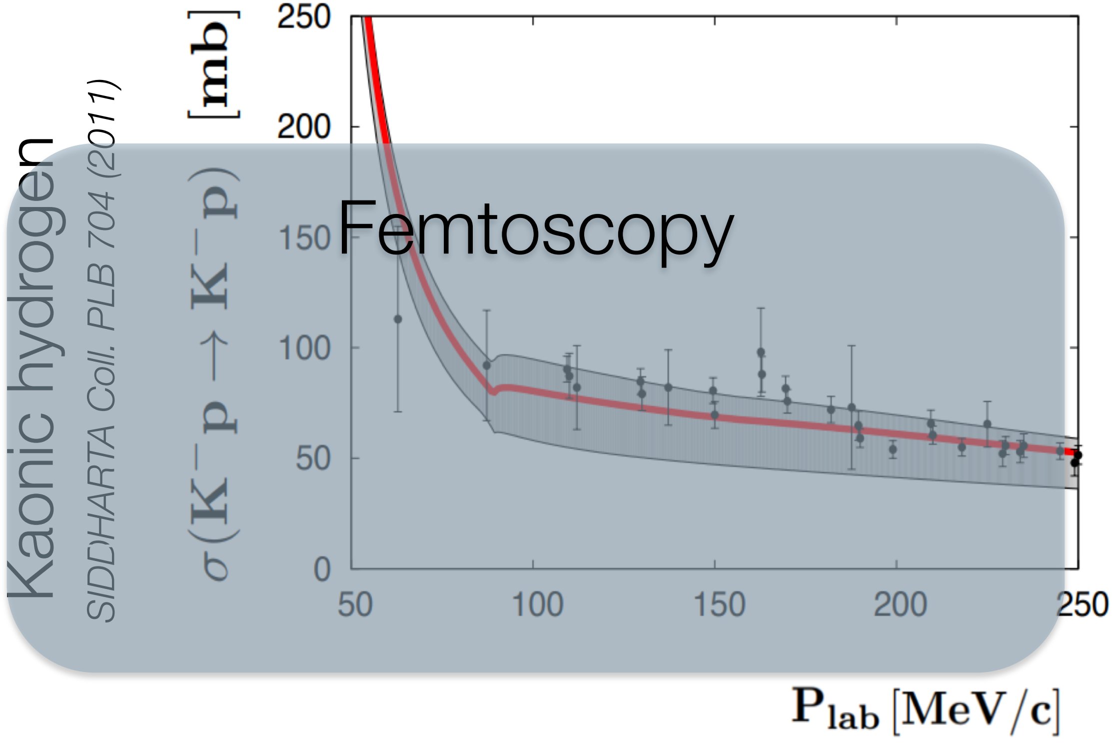
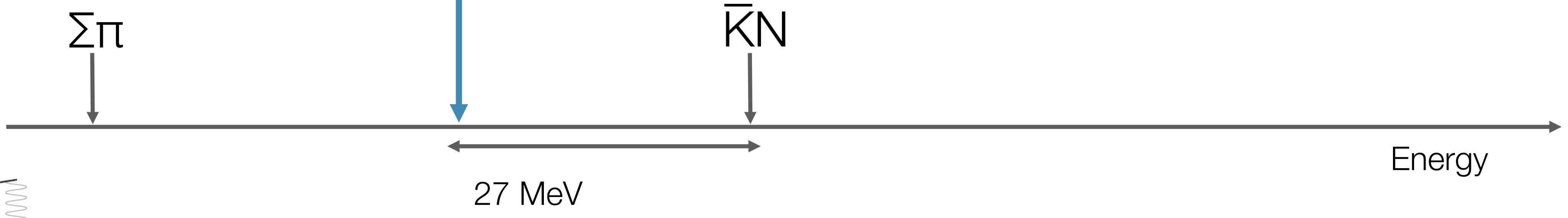
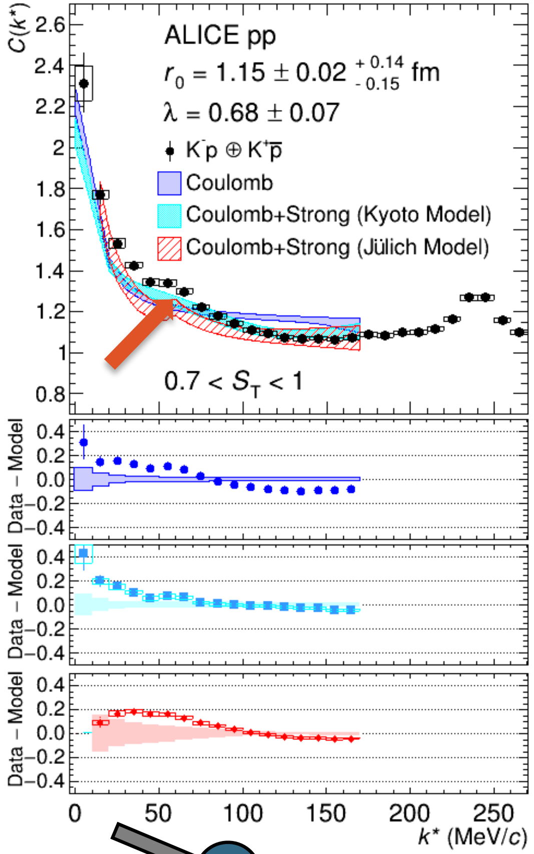


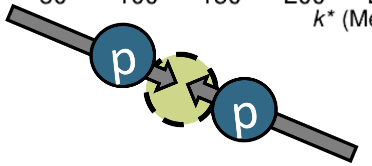


K⁻–p femtoscopy in different colliding systems

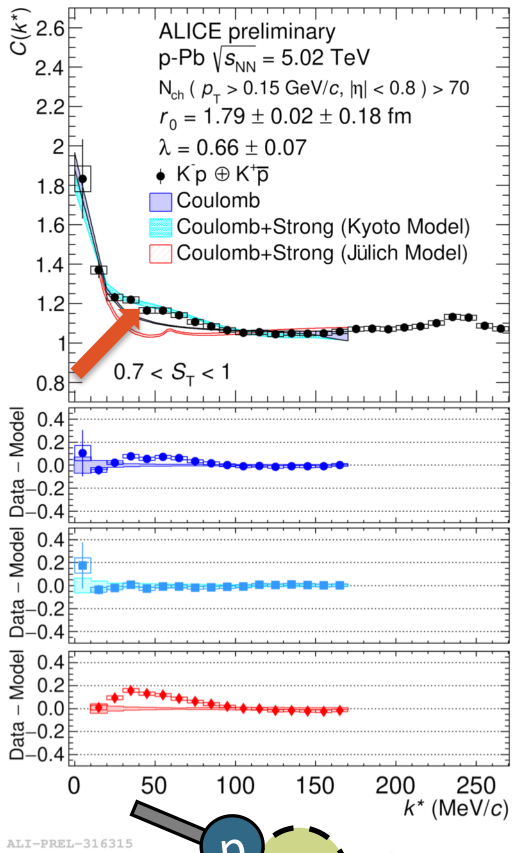
- Disappearance of $\overline{K}^0$–n cusp at k*~ 60 MeV/*c* as the source increases

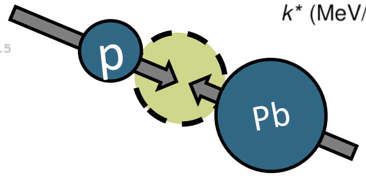
ALICE Coll. Phys.Rev.Lett. 124 (2020) 9, 092301



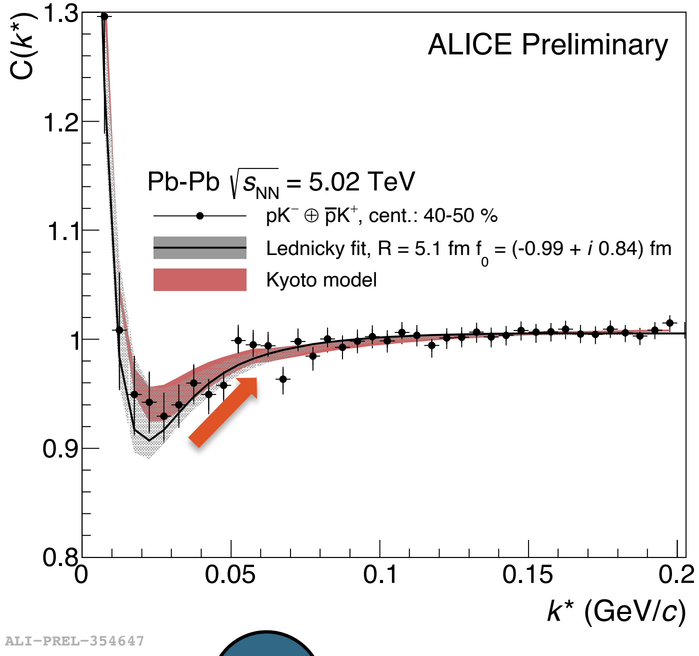


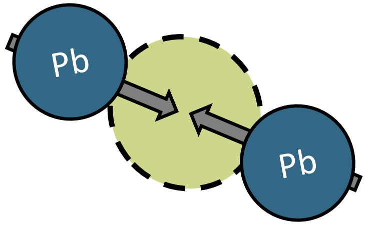
Paper in preparation

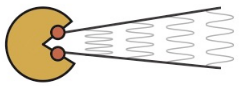




ALICE Coll. arXiv: 2105.05683





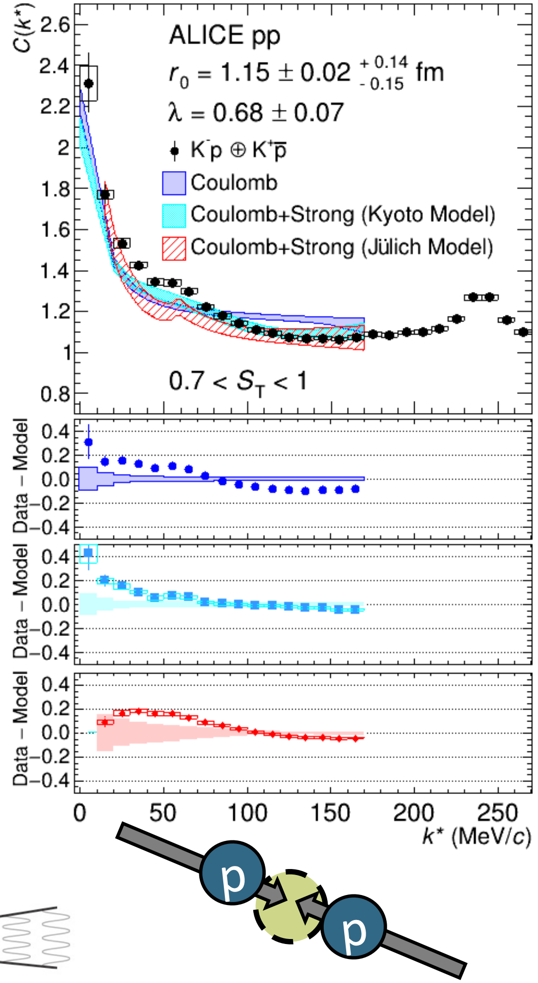


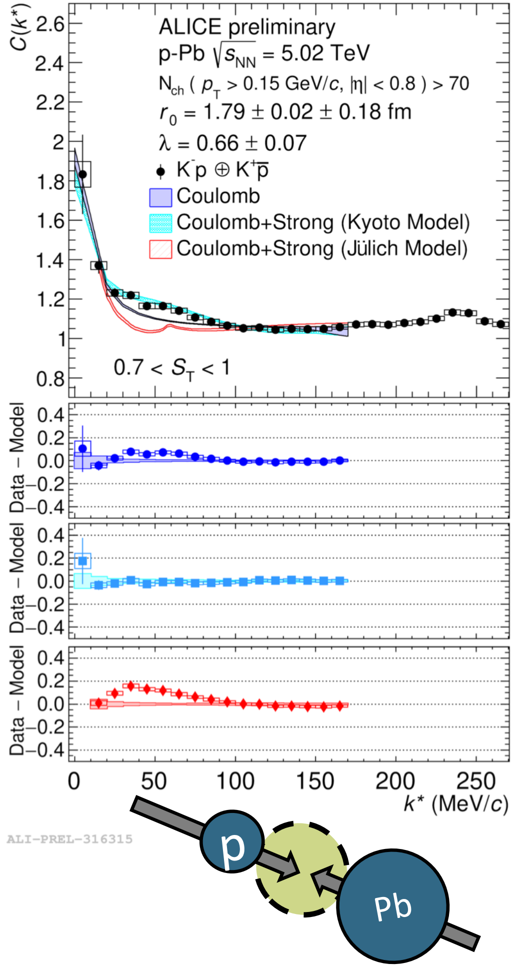
assuming w_j = 1

K^-–p femtoscopy in different colliding systems

- Disappearance of $\bar{K}^0$–n cusp at k*~ 60 MeV/*c* as the source increases
- χEFT Kyoto potential describes the data in all three systems
- Pb–Pb data well described by Lednicky single channel → negligible contribution from inelastic channels
- Pb–Pb results in agreement with scattering parameters from kaonic hydrogen

Ikeda et al. Nucl.Phys.A 881 (2012), PLB706 (2011)
Kamiya et al. PRL 124 (2020)
Mihayara et al. PRC95 (2017)





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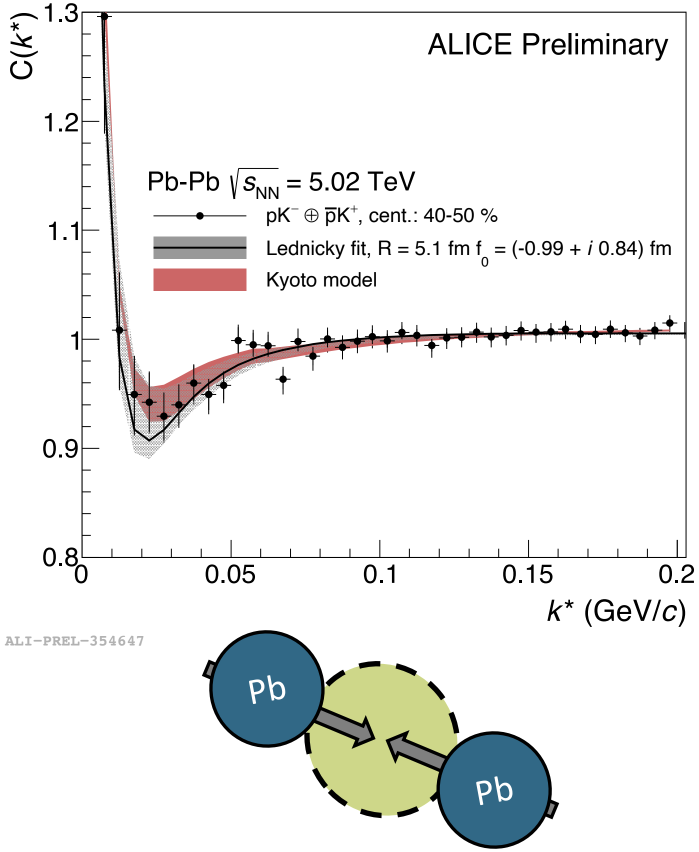
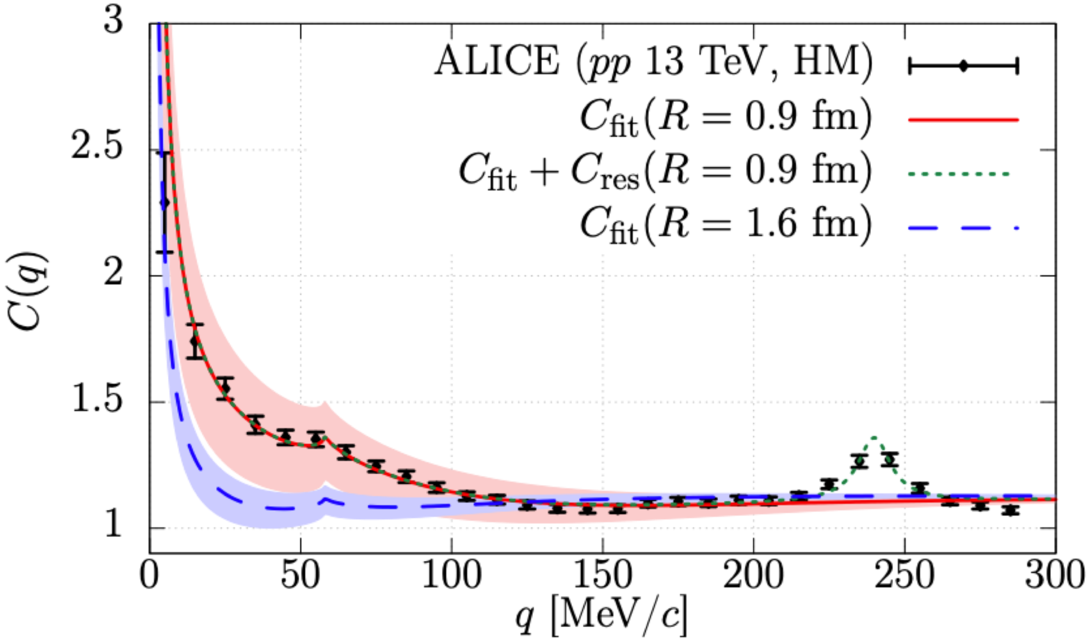


What is next?

- Modification of the conversion weights leads to a better agreement with the data
  – *see Phys.Rev.Lett. 124 (2020) 13, 132501*
- Study on conversion weights in pp, p–Pb and Pb-Pb
  – still agreement data/model?
  – provide constraints for the $\overline{K}^0$n coupling
- Extend the femtoscopic studies to K-d pairs in all colliding systems

Y. Kamiya et al. Phys.Rev.Lett. 124 (2020) 13, 132501

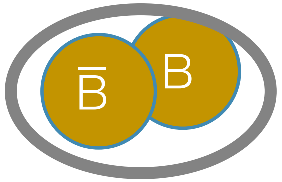


Work in progress with
Dr. Y. Kamiya
Prof. A. Ohnishi
Prof. T. Hyodo

Baryon-antibaryon femtoscopy

The baryon-antibaryon interaction

Predictions for Baryonia??



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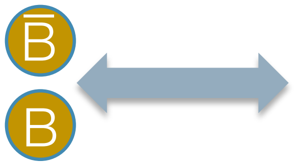

nπ
nK …

Annihilation dynamics
nπ,nK,πK,…

Energy

E. Klempt et al. Phys. Rept. 413 (2005)
E. Klempt et al. Phys. Rept. 368 (2002)
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J. Haidenbauer et al. JHEP 1707 (2017)

The baryon-antibaryon interaction

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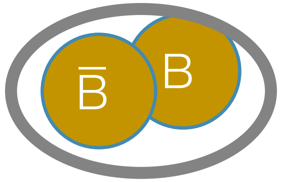

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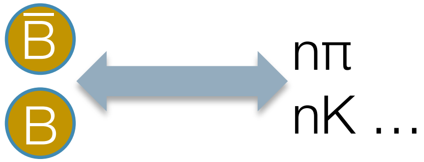
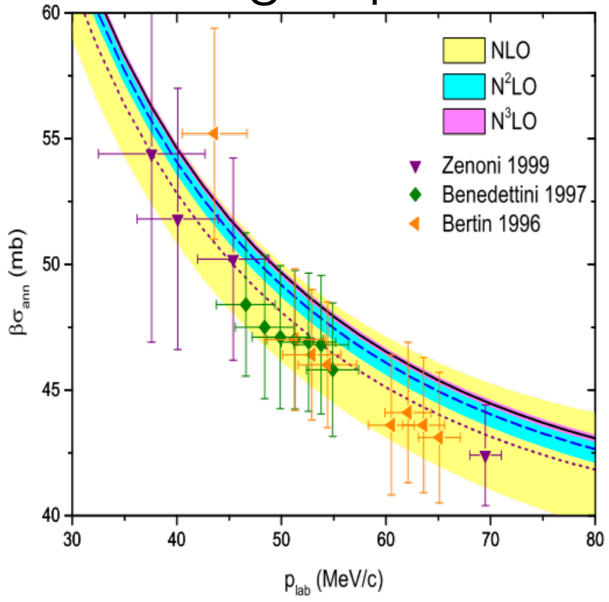


Annihilation dynamics
nπ,nK,πK,…

antiproton atoms

p-p̄

Scattering Experiments



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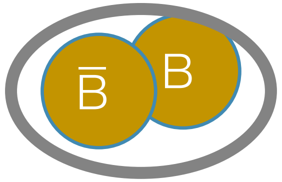

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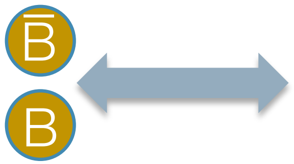

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nπ,nK,πK,…

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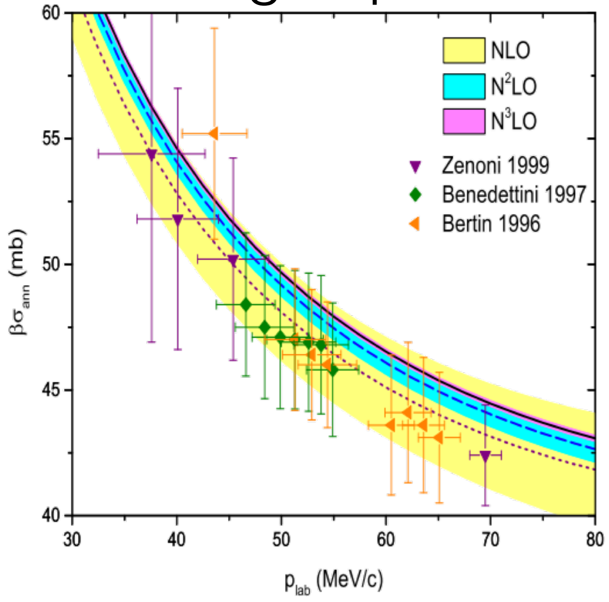

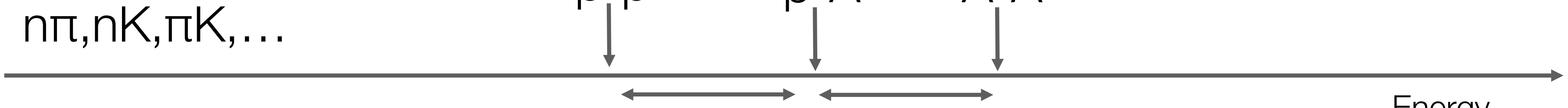

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The baryon-antibaryon interaction

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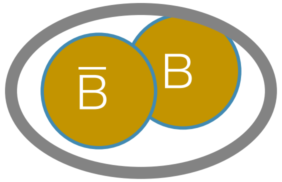

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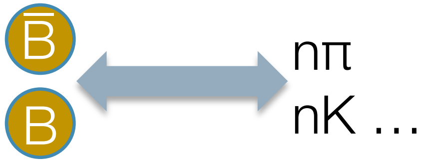

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nπ,nK,πK,…

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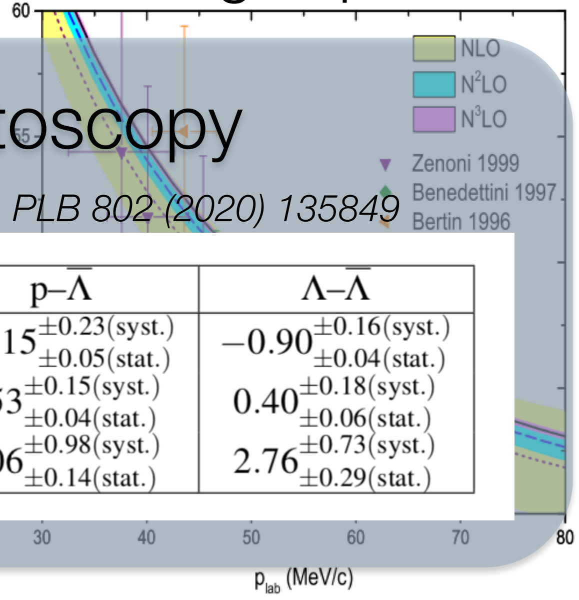
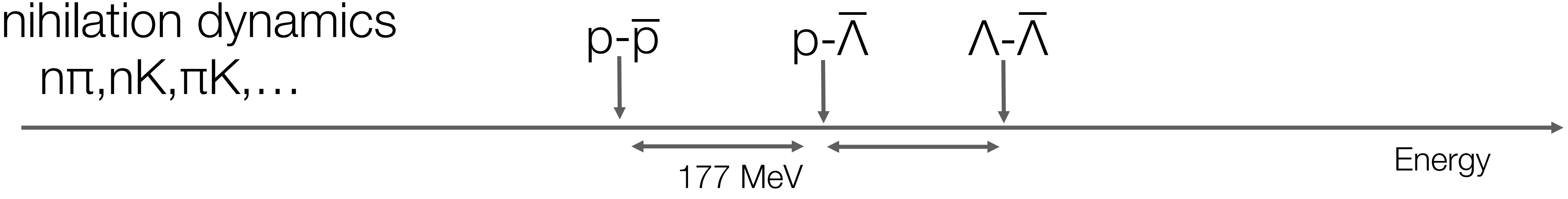


antiproton atoms

Femtoscopy

ALICE Coll. PLB 802 (2020) 135849

Parameter	p–$\overline{\Lambda}$	Λ–$\overline{\Lambda}$
$Re(f_0)$ (fm)	$-1.15^{\pm0.23(\mathrm{syst.})}_{\pm0.05(\mathrm{stat.})}$	$-0.90^{\pm0.16(\mathrm{syst.})}_{\pm0.04(\mathrm{stat.})}$
$Im(f_0)$ (fm)	$0.53^{\pm0.15(\mathrm{syst.})}_{\pm0.04(\mathrm{stat.})}$	$0.40^{\pm0.18(\mathrm{syst.})}_{\pm0.06(\mathrm{stat.})}$
d_0 (fm)	$3.06^{\pm0.98(\mathrm{syst.})}_{\pm0.14(\mathrm{stat.})}$	$2.76^{\pm0.73(\mathrm{syst.})}_{\pm0.29(\mathrm{stat.})}$



E. Klempt et al. Phys. Rept. 413 (2005)
E. Klempt et al. Phys. Rept. 368 (2002)
D.Zhou and R.G. E. Timmermans PRC86 (2012)
J. Haidenbauer et al. JHEP 1707 (2017)

Results on p-$\overline{\text{p}}$: modeling the correlation

elastic $\quad$ n-$\bar{\text{n}}$ → p-$\overline{\text{p}}$

$$C_{\text{p}-\overline{\text{p}}}(k^*) = \int S(r)|\psi_{p\bar{p}\to p\bar{p}}|^2 d^3r + \int S(r)|\psi_{n\bar{n}\to p\bar{p}}|^2 d^3r$$

- Chiral Effective Field Theory at N³LO (with n-$\bar{\text{n}}$ coupled-channel) wavefunctions with Coulomb
  - S and P waves, tuned to scattering data and protonium

J. Haidenbauer et al. JHEP 1707 (2017)
D.Mihailov et al. Eur.Phys.J.C 78 (2018) 5, 394
Haidenbauer et al.,PRD 92 (2015) 5, 054032

Results on p-$\bar{p}$: modeling the correlation

elastic | n-$\bar{n}$ → p-$\bar{p}$ | multi-meson annihilation channels

$$C_{p-\bar{p}}(k^*) = \int S(r)|\psi_{p\bar{p}\to p\bar{p}}|^2 d^3r + \int S(r)|\psi_{n\bar{n}\to p\bar{p}}|^2 d^3r + \sum_{PW} \rho_{PW}\,\omega_{PW} \int S(r)|\psi^{PW}_{p\bar{p}\to p\bar{p}}|^2 d^3r$$

- Chiral Effective Field Theory at N^{3}LO (with n-$\bar{n}$ coupled-channel) wavefunctions with Coulomb
  - S and P waves, tuned to scattering data and protonium

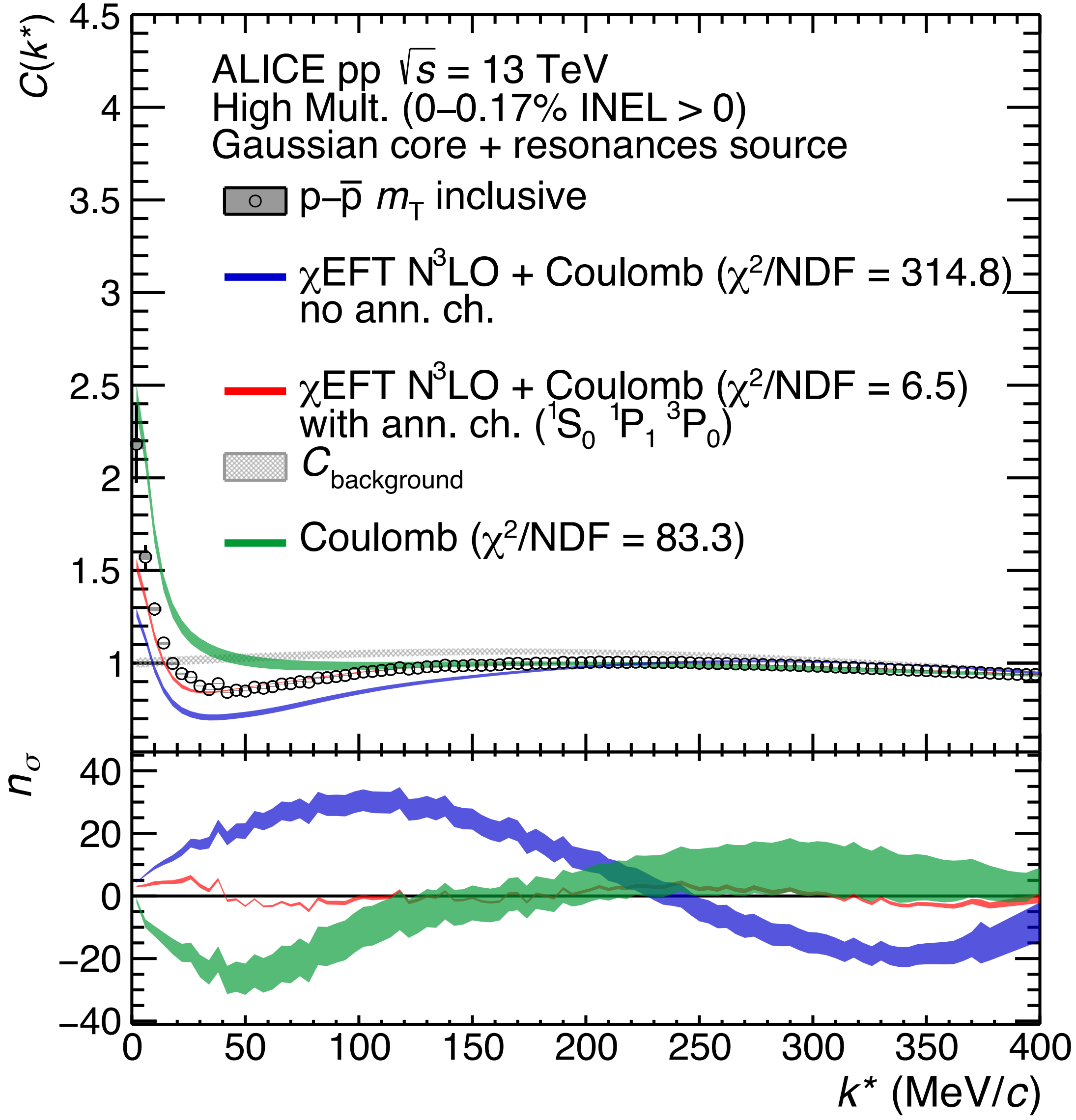
- Approximate inclusion of annihilation channels (X→ p-$\bar{p}$) using the Migdal-Watson approximation
  - elastic WF rescaled by a coupling weight ω_{PW} to be fitted to data
  - Investigation on the shape of each PWs to reduce number of parameters
    - $^1S_0$ for S states
    - $^3P_0$ and $^1P_1$ for P states

- Calculations performed with CATS framework

J. Haidenbauer et al. JHEP 1707 (2017)
D.Mihailov et al. Eur.Phys.J.C 78 (2018) 5, 394
Haidenbauer et al.,PRD 92 (2015) 5, 054032

Results on p-$\bar{p}$: modeling the correlation

- No cusp of n-$\bar{n}$ opening at k*~ 50 MeV/c → in agreement with charge-exchange cross-sections
- rise of CF at low k*
  - no agreement with Coulomb only
  - χEFT calculations with no explicit CC terms do not reproduce the data at low k*
  - evidence of annihilation channels feeding into p-$\bar{p}$ pairs



ALICE Coll. arXiv: 2105.05190

Correlation function for p-$\bar{p}$

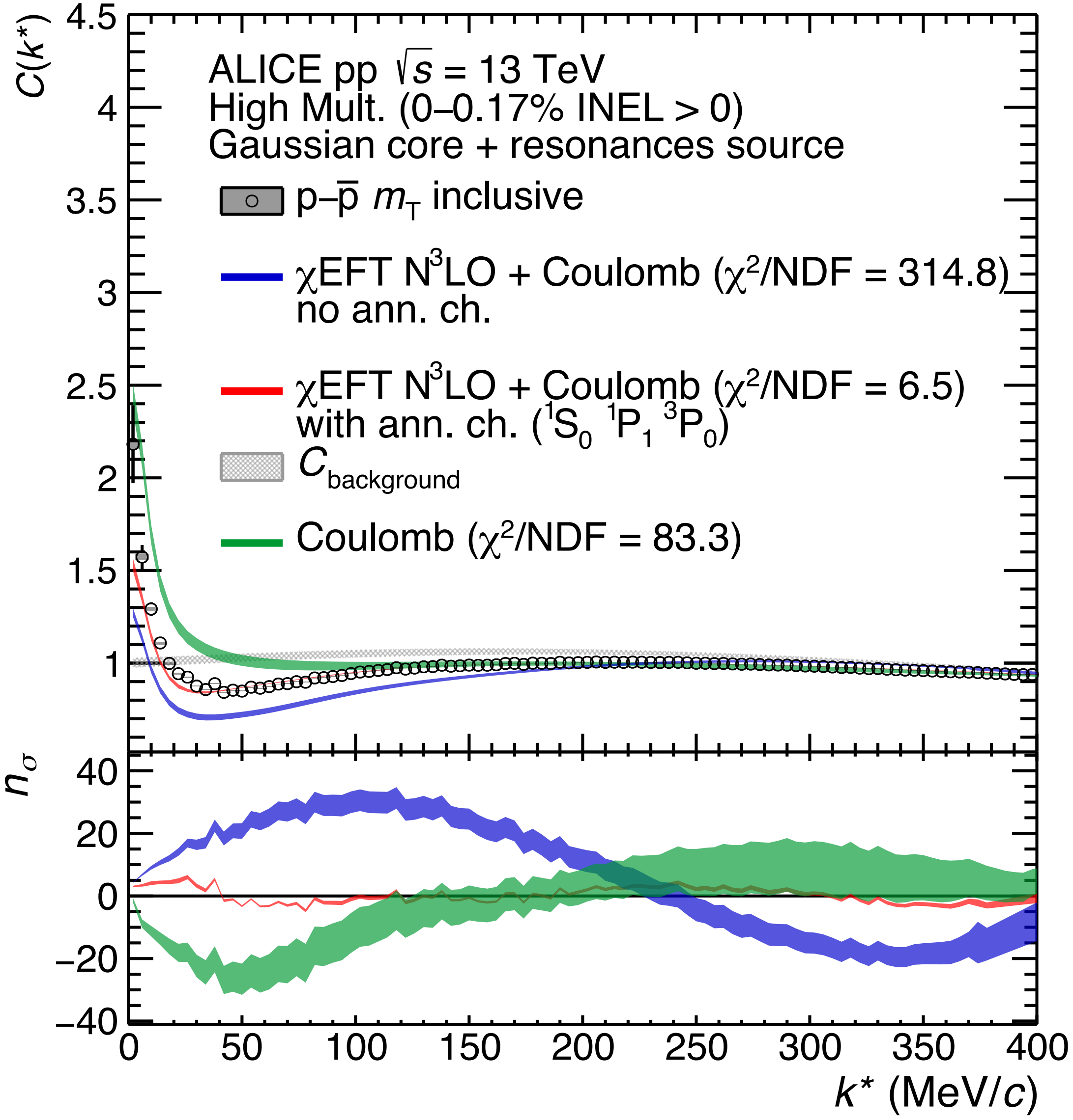
- No cusp of n-$\bar{n}$ opening at k*~ 50 MeV/c → in agreement with charge-exchange cross-sections

- rise of CF at low k*
  - no agreement with Coulomb only
  - χEFT calculations with no explicit CC terms do not reproduce the data at low k*
  - evidence of annihilation channels feeding into p-$\bar{p}$ pairs

- **Annihilation channels X→ p-$\bar{p}$ included**
  - better agreement with the data is obtained
  - Dominant coupling weights in $^3P_0$ and $^1S_0$

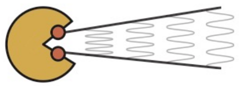
    ω_{3P0}= 40.04 ± 4.06 (stat) ± 4.24 (syst)

    ω_{1S0}= 1.19 ± 0.10 (stat) ± 0.19 (syst)



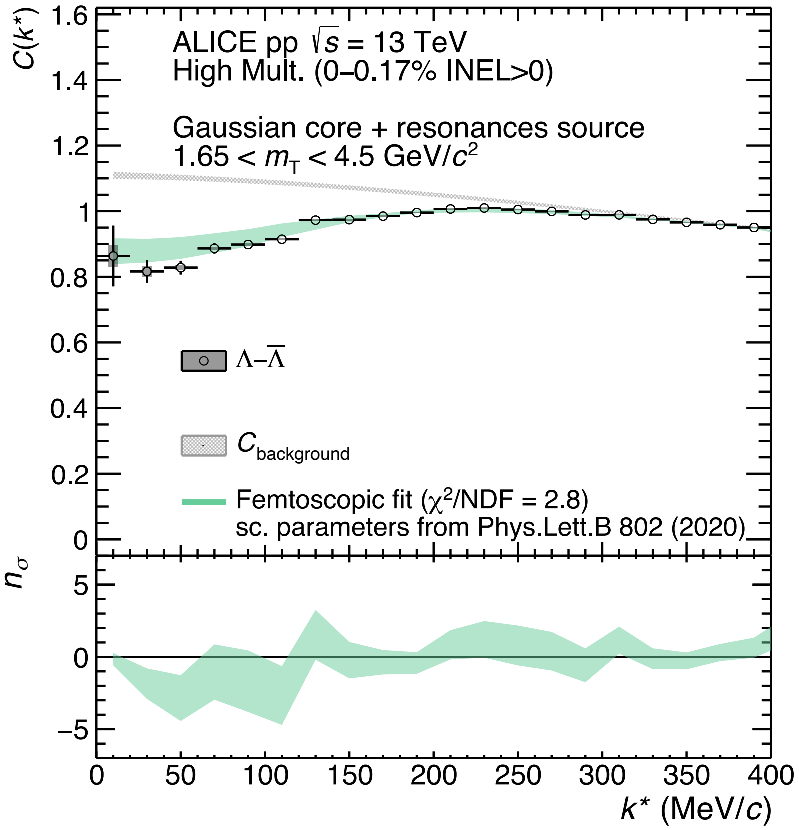
PWA: D.Zhou and R.G. E. Timmermans PRC86 (2012)

ALICE Coll. arXiv: 2105.05190



Results on Λ-$\bar{\Lambda}$ and p-$\bar{\Lambda}$ femtoscopy

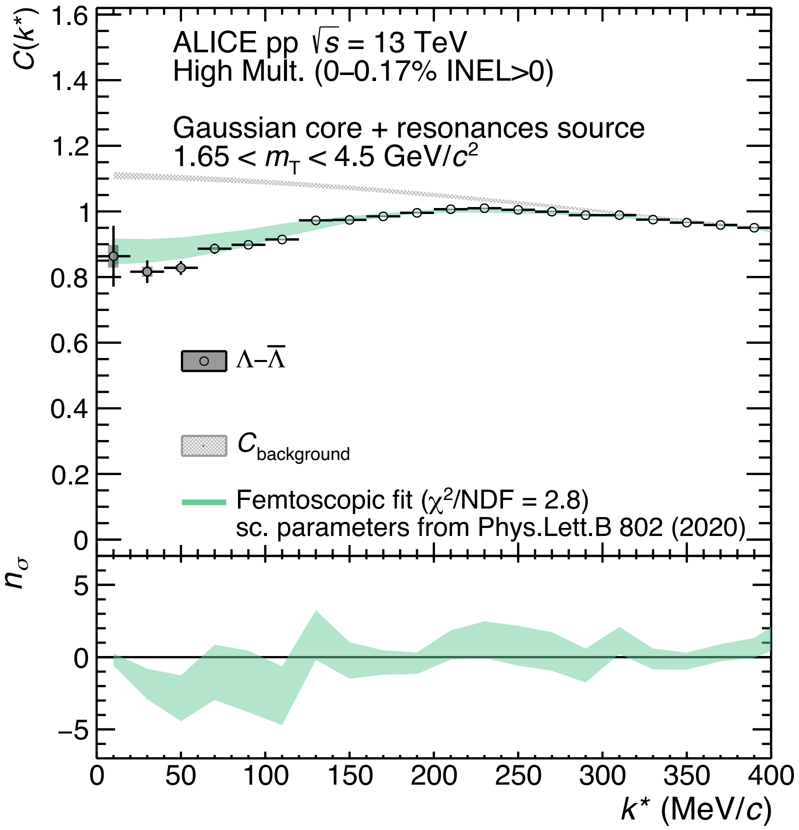
- No exact wavefunctions available → single-channel Lednicky-Lyuboshits formula
- Assuming the scattering parameters obtained in Pb-Pb
  - nice agreement with Λ-$\bar{\Lambda}$ data → inelastic part present but not dominant

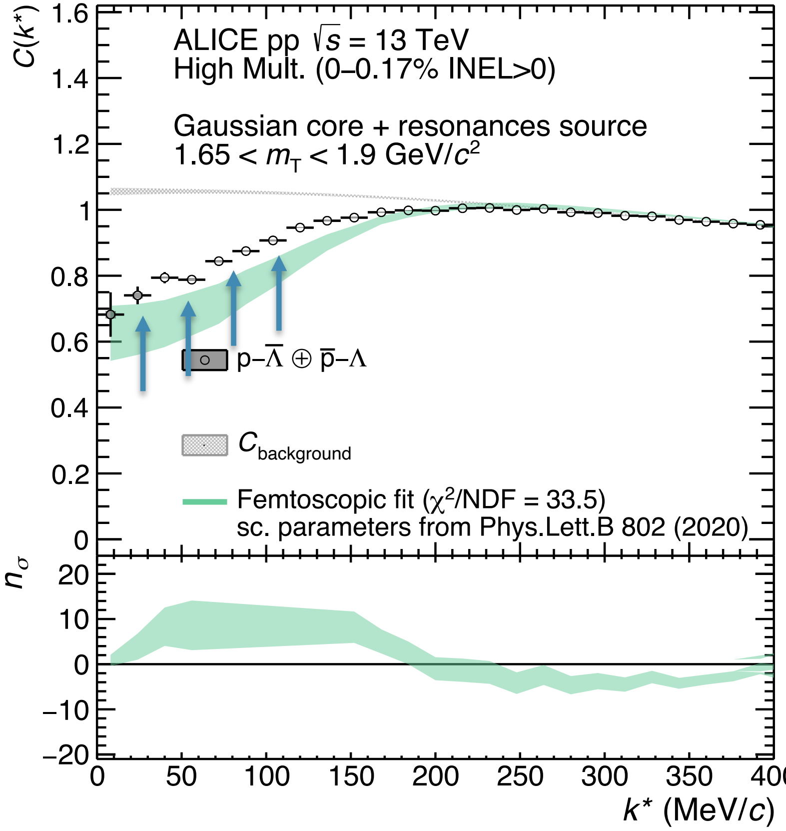


ALICE Coll. arXiv: 2105.05190

Results on Λ-$\bar{\Lambda}$ and p-$\bar{\Lambda}$ femtoscopy

- No exact wavefunctions available → single-channel Lednicky-Lyuboshits formula
- Assuming the scattering parameters obtained in Pb-Pb
  - nice agreement with Λ-$\bar{\Lambda}$ data → inelastic part present but not dominant
  - underestimate of p-$\bar{\Lambda}$ data → large coupling to multi-meson annihilation channels

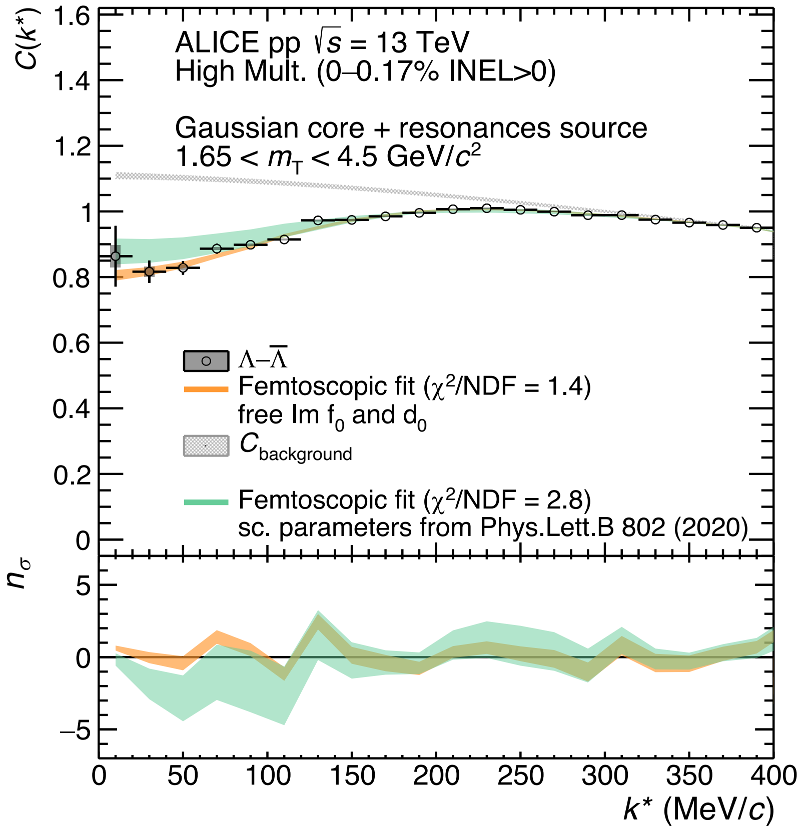


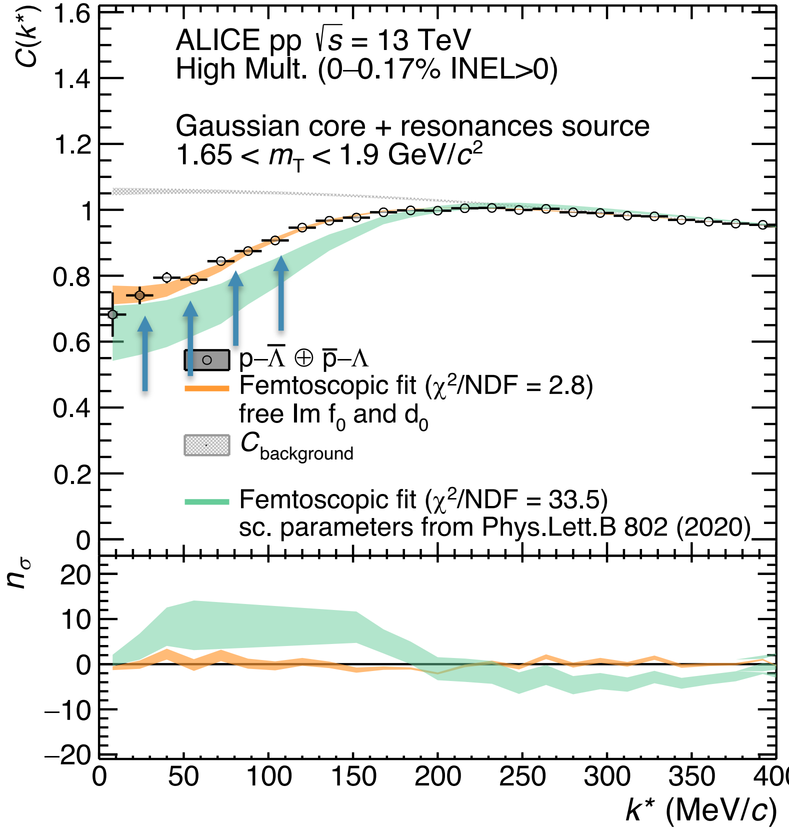


ALICE Coll. arXiv: 2105.05190

Results on Λ-$\bar{\Lambda}$ and p-$\bar{\Lambda}$ femtoscopy

- Elastic part $\mathrm{Re}(f_0)$ fixed from Pb-Pb data, free inelastic $\mathrm{Im}(f_0)$ and d_0
  - extracted values for Λ-$\bar{\Lambda}$ are compatible with Pb-Pb scatt. pars
  - to reproduce p-$\bar{\Lambda}$ data $\mathrm{Im}f_0$ has to increased by a factor ~ 5.3
- Larger presence of multi-meson annihilation channels in p-$\bar{\Lambda}$ → no bound-states?



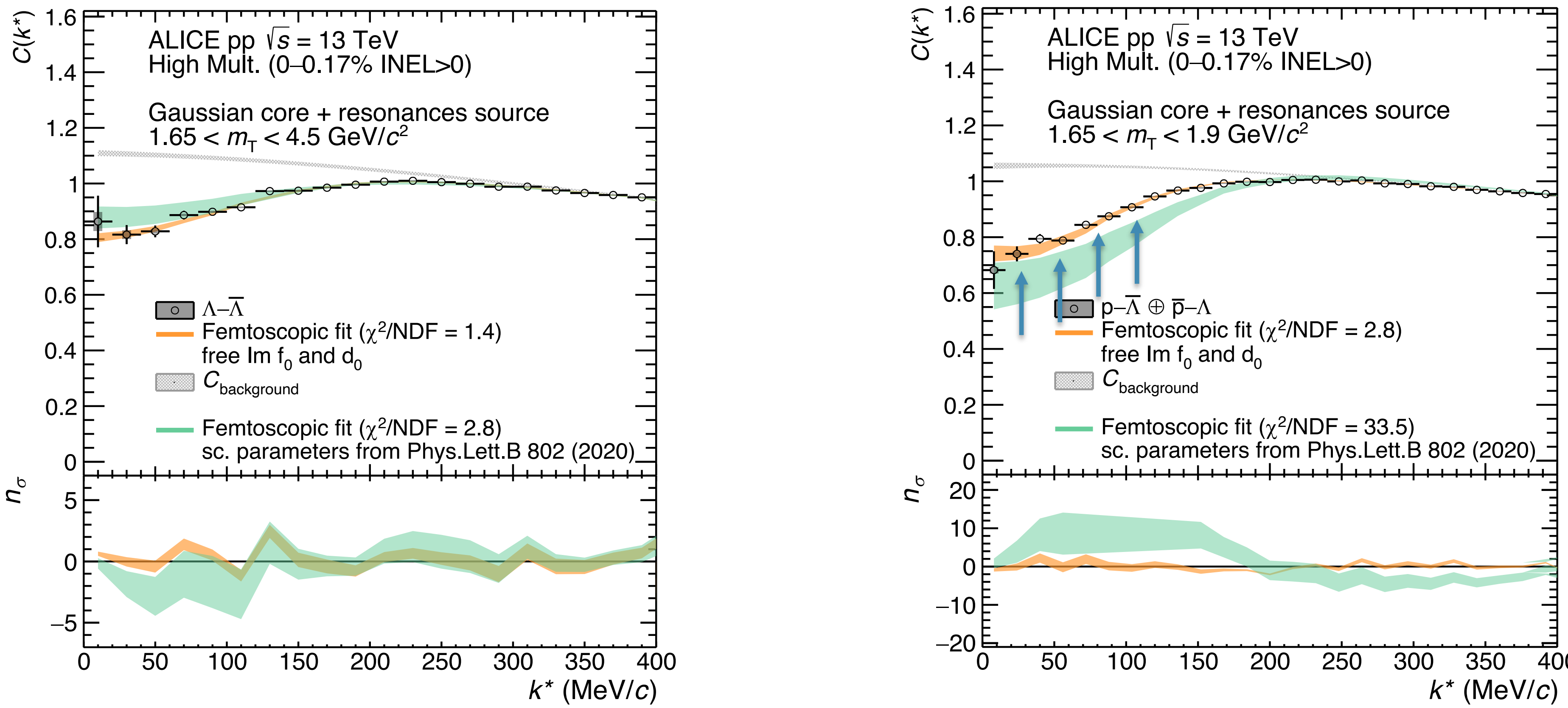


ALICE Coll. arXiv: 2105.05190

Results on Λ-$\bar{\Lambda}$ and p-$\bar{\Lambda}$ femtoscopy

- Estimates based on kinematics (EPOS) and SU(3) flavour symmetry for 2-meson channels (ππ,πK)
  - similar amount of p-$\bar{\Lambda}$ and Λ-$\bar{\Lambda}$ pairs at low k* (~6.4%)
  - coupling strength from meson-baryon SU(3) lagrangian provides largest coupling for p-$\bar{\Lambda}$

$$\frac{g_{2M\to p-\bar{\Lambda}} \times N_{2M\to p-\bar{\Lambda}}}{g_{2M\to \Lambda-\bar{\Lambda}} \times N_{2M\to \Lambda-\bar{\Lambda}}} \approx 6.3$$



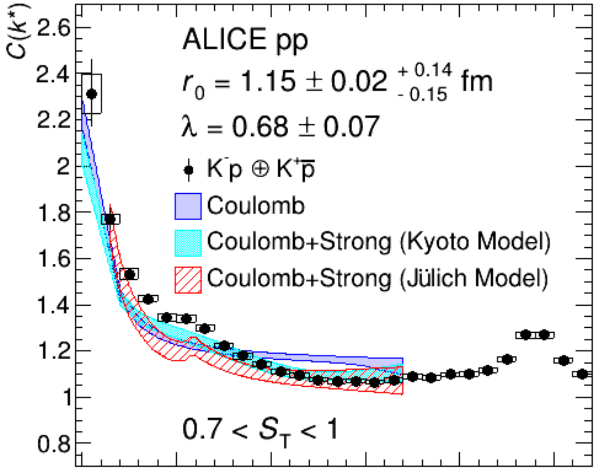
ALICE Coll. arXiv: 2105.05190

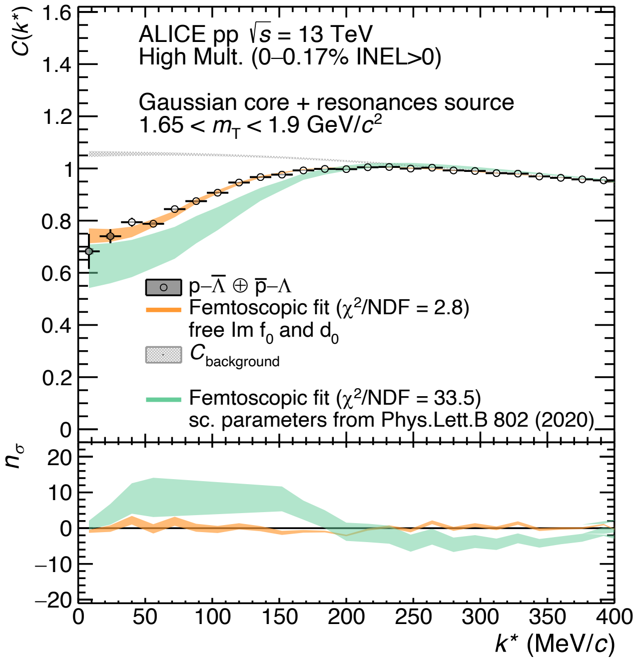
Conclusions

- Femtoscopy in small colliding systems
  - high-precision data at low momenta
  - sensitive to inelastic channels

- K^-–p in pp, p–Pb and Pb–Pb collisions
  - first experimental evidence of $\overline{K}^0$–n channel
  - disappearance of CC contributions in Pb–Pb data
  - extend the analysis with detailed study on conversion weights

- Baryon-antibaryon in pp collisions
  - Λ-$\overline{\Lambda}$ results annihilation not dominant and room for baryonia
  - p-$\overline{p}$ and p-$\overline{\Lambda}$ large presence of annihilation channels → no formation of bound states?
  - need for theoretical input on p-$\overline{\Lambda}$ and Λ-$\overline{\Lambda}$ interactions

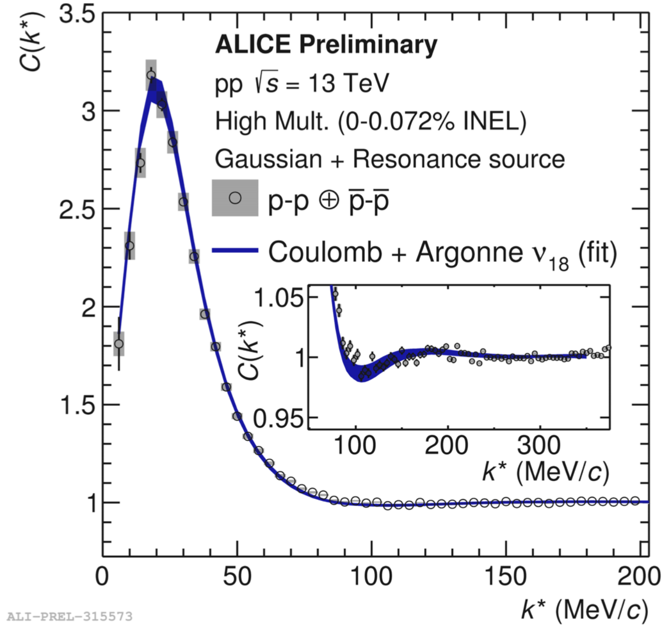




Additional slides

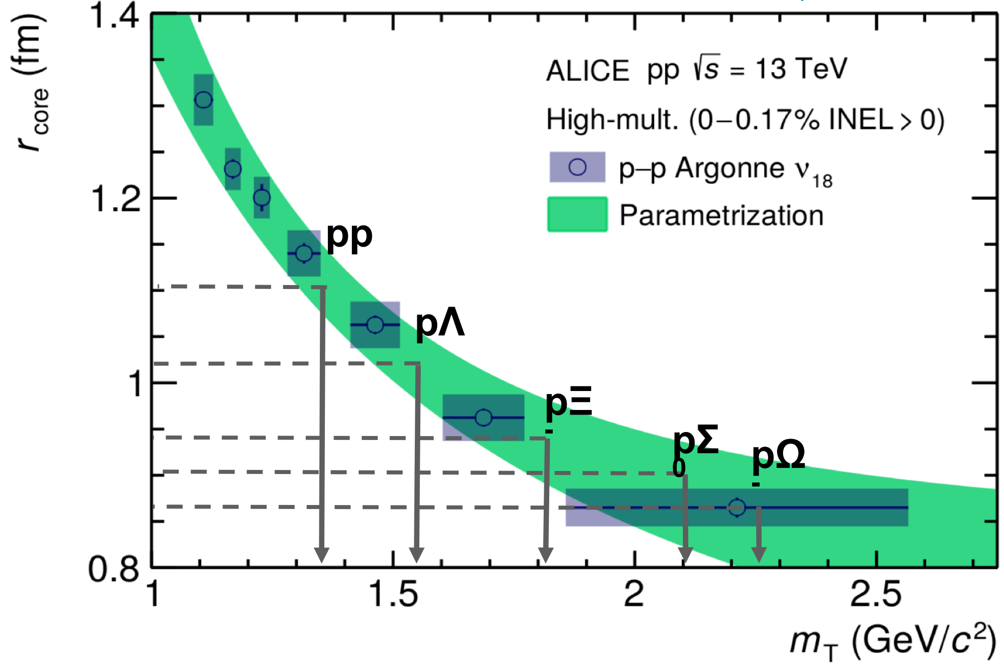
Small Sources: Collective Effects and Strong Resonances

Fit with a 'core' Gaussian + Resonances

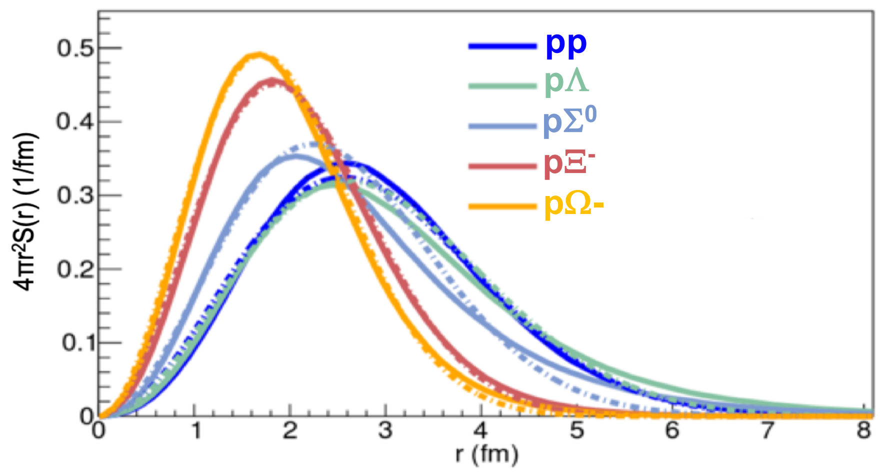


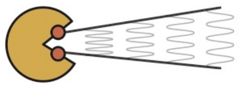
Core Radius

arXiv:2004.08018 accepted in PLB



Effective Radius



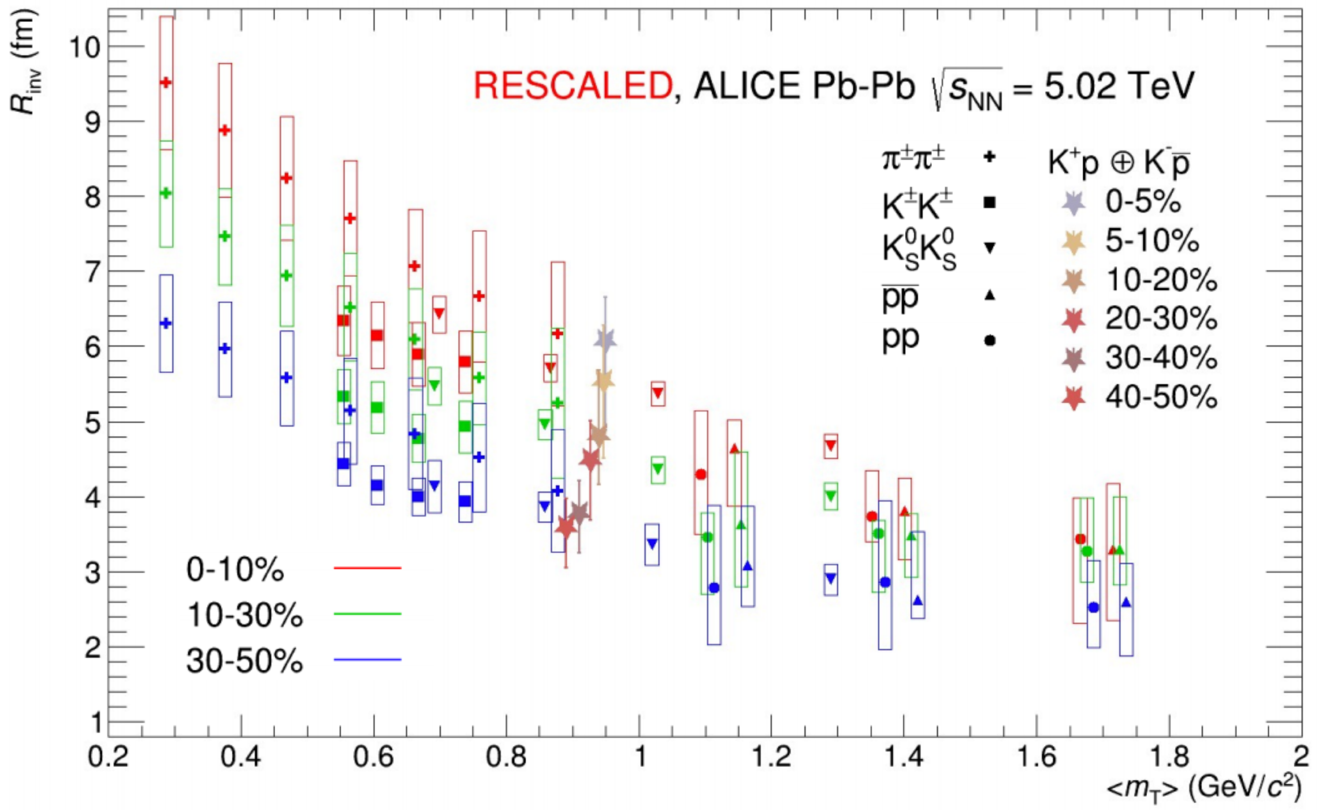


Pair	r_{Core} [fm]	r_{Eff} [fm]
pp	0.96	1.28
pΛ	0.88	1.3
$p\Sigma^0$	0.75	1.12
$p\Xi^-$	0.8	0.92
pΩ-	0.73	0.85

Fixing the source: Pb–Pb collisions

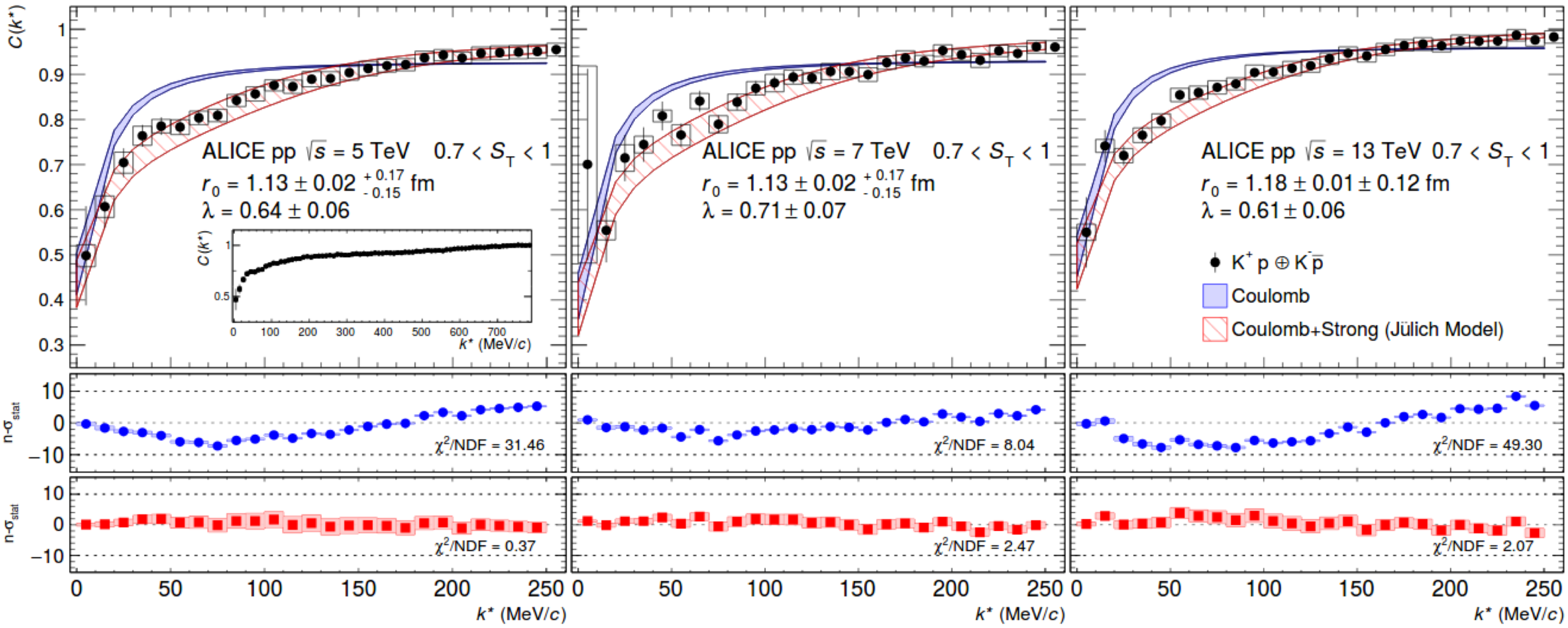
- Evolution of the system in heavy-ion is affected by freeze-out and rescattering → scaling with multiplicity and m_T

- For Pb–Pb studies at 5.02 TeV:
  - radius for B–$\overline{B}$ pairs same as for B-B
  - radius for K-p fixed from K+p
    - agreement with rescaled results on pion, protons and kaon pairs at 2.76 TeV

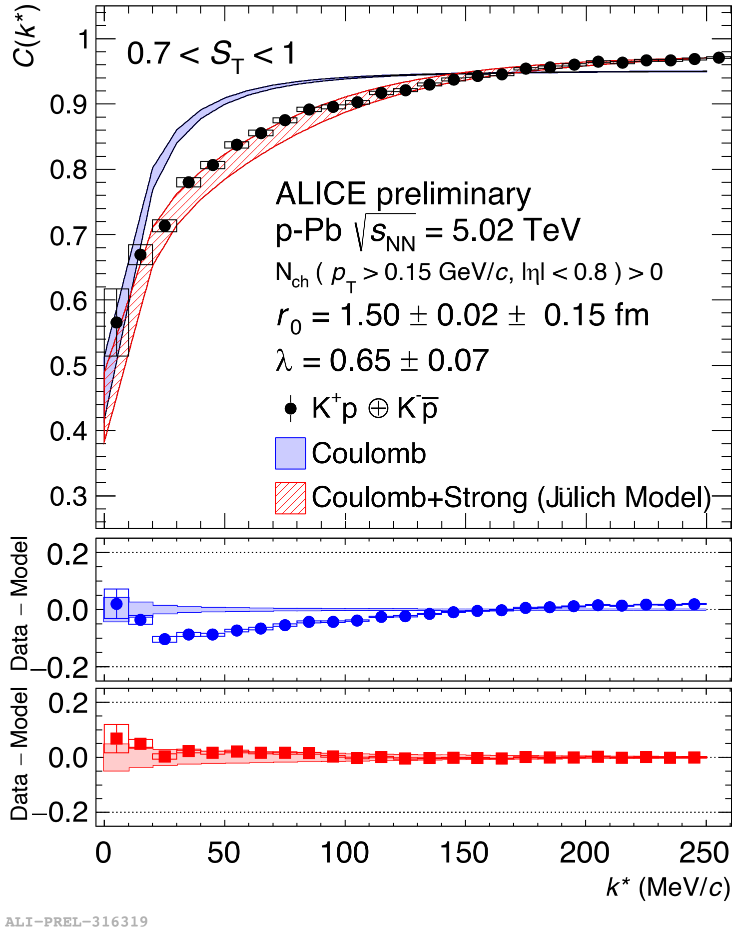


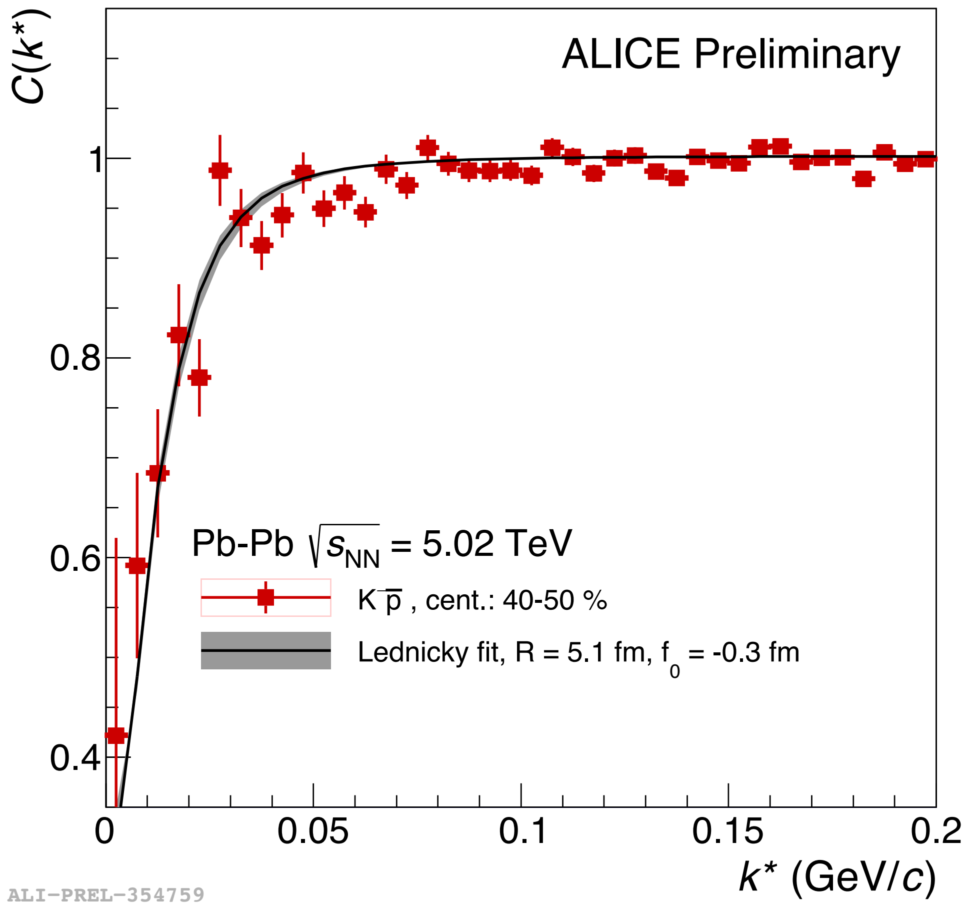
K^+p correlations in pp

ALICE Coll. Phys.Rev.Lett. 124 (2020) 9, 092301



K⁺p correlations in p–Pb and Pb–Pb



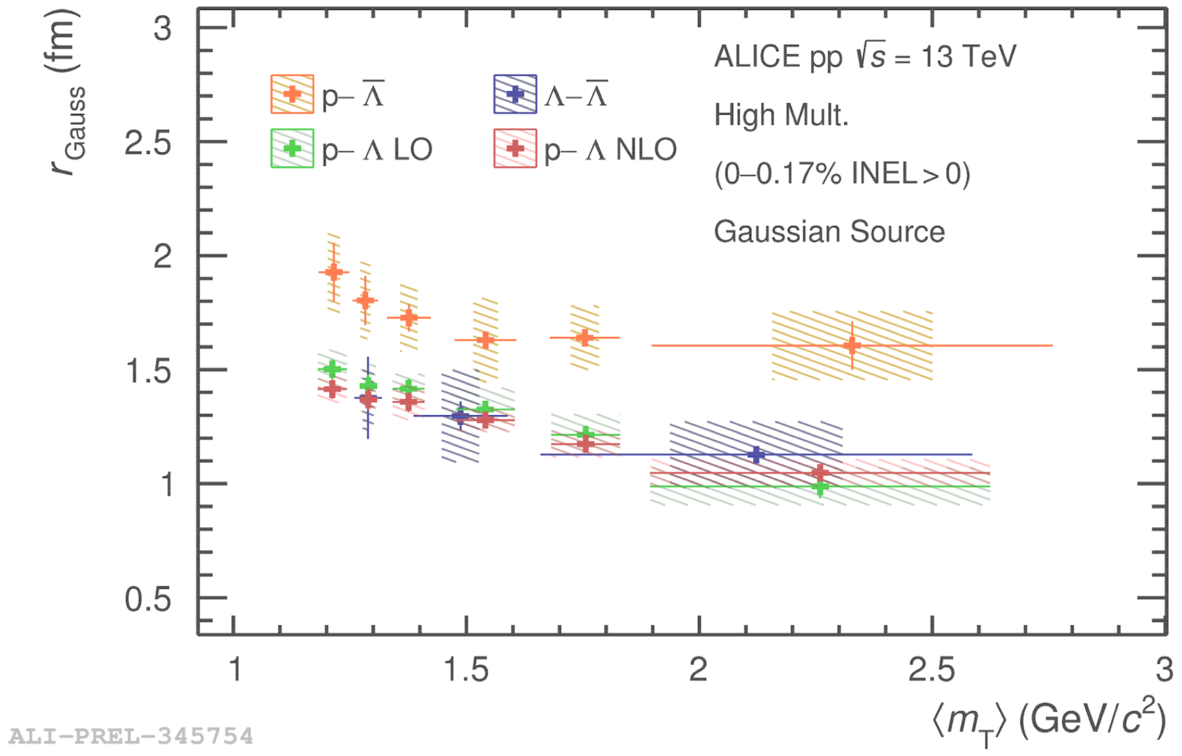


Scaling of the source in p-$\bar{\Lambda}$ and Λ-$\bar{\Lambda}$

- Λ-antiΛ correlation function: well reproduced by Lednicky-Lyuboshits (Pb–Pb), extracted radius in agreement with B-B scaling

- p-antiΛ correlation function: well reproduced by Lednicky-Lyuboshits, **BUT extracted radius larger wrt to B-B scaling**

- **Physical interpretation**: p-antiΛ is more coupled-channels contributions (supported by $SU(3)_f$ considerations) ⇒ larger amount of inelastic channels translates into larger radius



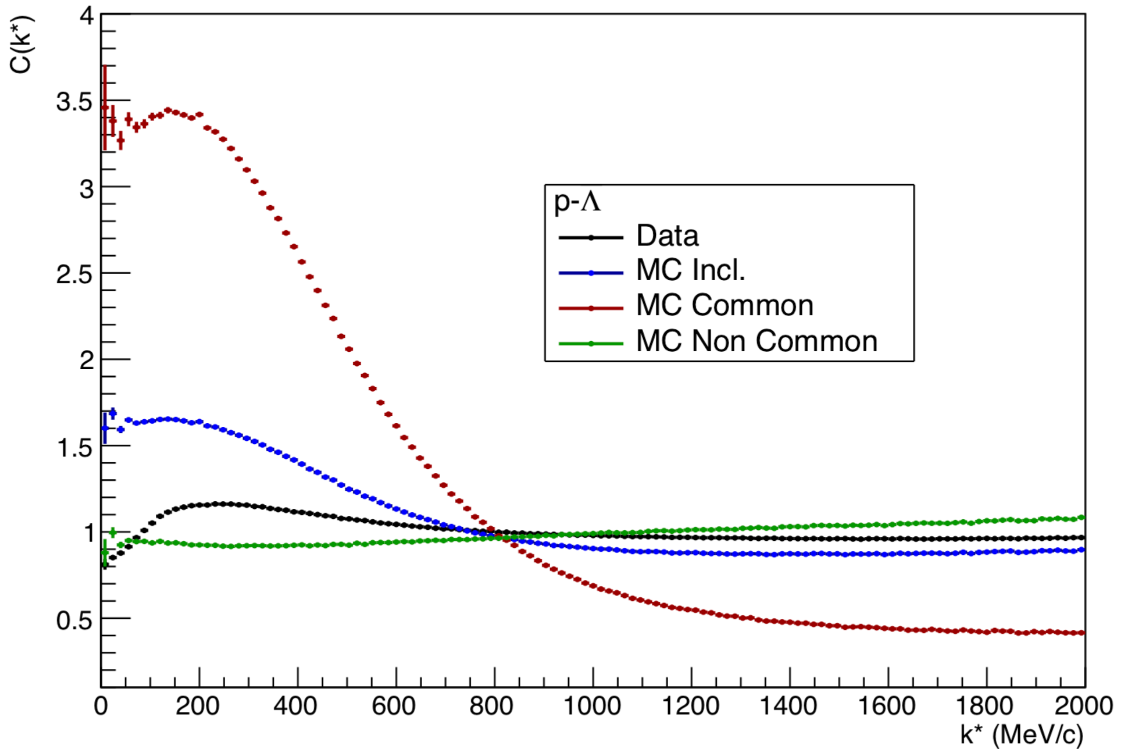
Mini-jet Background

- Large background that cannot be removed by applying S_T / S_0 cuts ⇒ results are obtained WITHOUT any S_T/S_0 cuts

- Use of Pythia to model the background:
  - **jetty contributions** ⇒ particles from **Common ancestors**
  - **non-jetty part** ⇒ particles from **Non Common Ancestors**

$$C_{mini-jet}(k^*) = [w_C C_C(k^*) + (1 - w_C) C_{NC}(k^*)]$$

- Weigths w_C to be fitted to data since they cannot be anchored to ΔηΔϕ correlations (more than a rescaling is needed)



Fit procedure in B–$\overline{\text{B}}$ femtoscopy

- Residual contributions included through λ parameters (DCA/CPA Template Fits)

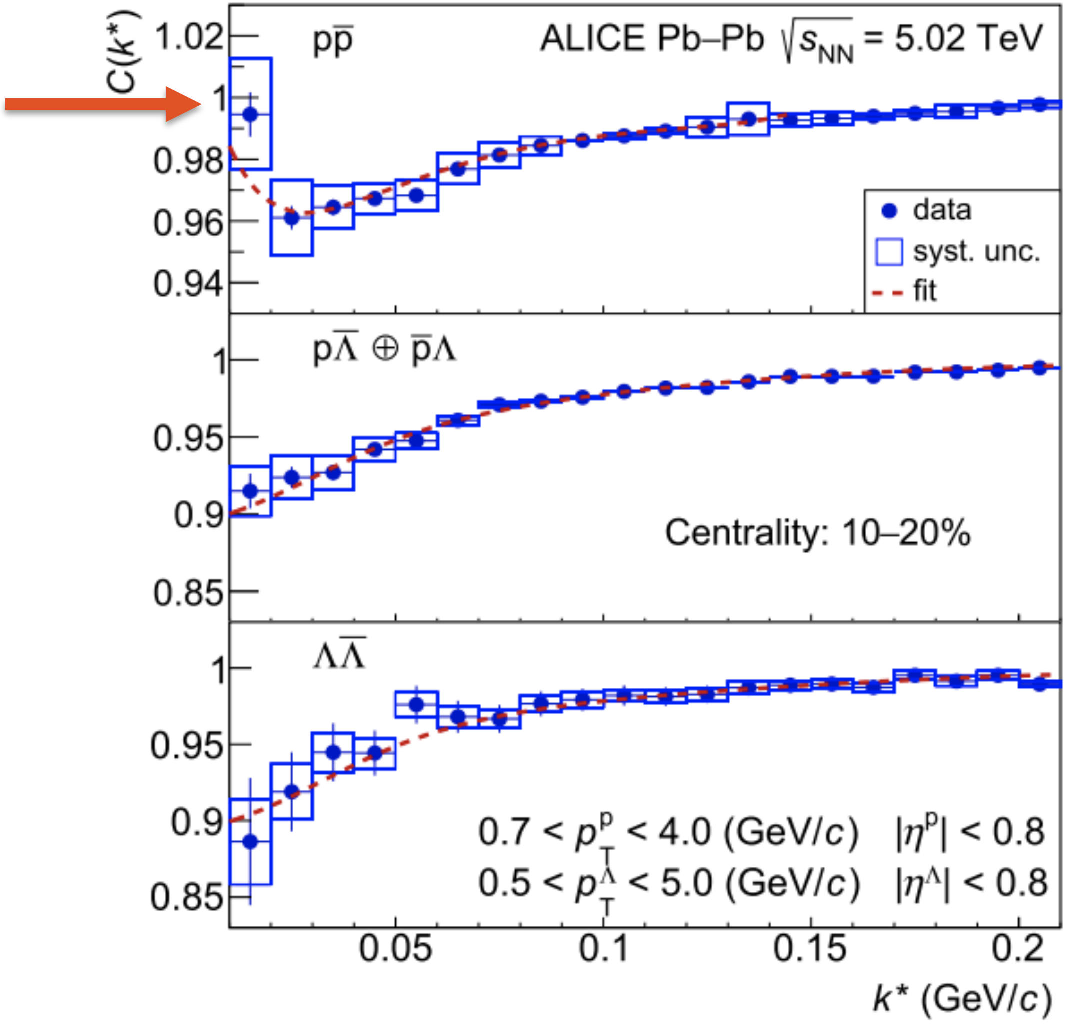
- Non-femtoscopic background:
  - Mini-jet background ⇒ Shape fixed by Ancestors Template
  - Large k* kinematics effects ⇒ Pol1/Pol2 (prefit in k* [400-2500] MeV/c and kept fixed in the final fit)

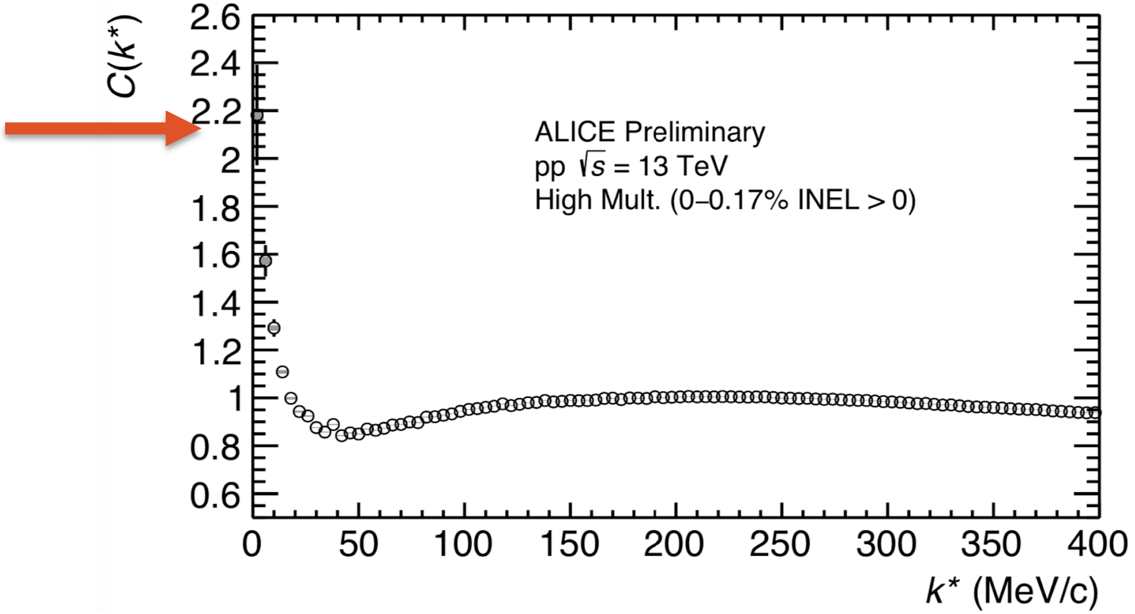
$$C_{BCKG}(k^*) = [w_C C_C(k^*) + (1 - w_C) C_{NC}(k^*) + (a + bk^* + c(k^*)^2)]$$

- Total correlation function:
  - Free parameters: weigths w_C, Norm N_D
  - Coupled-channel modeling affects ONLY C_{model}

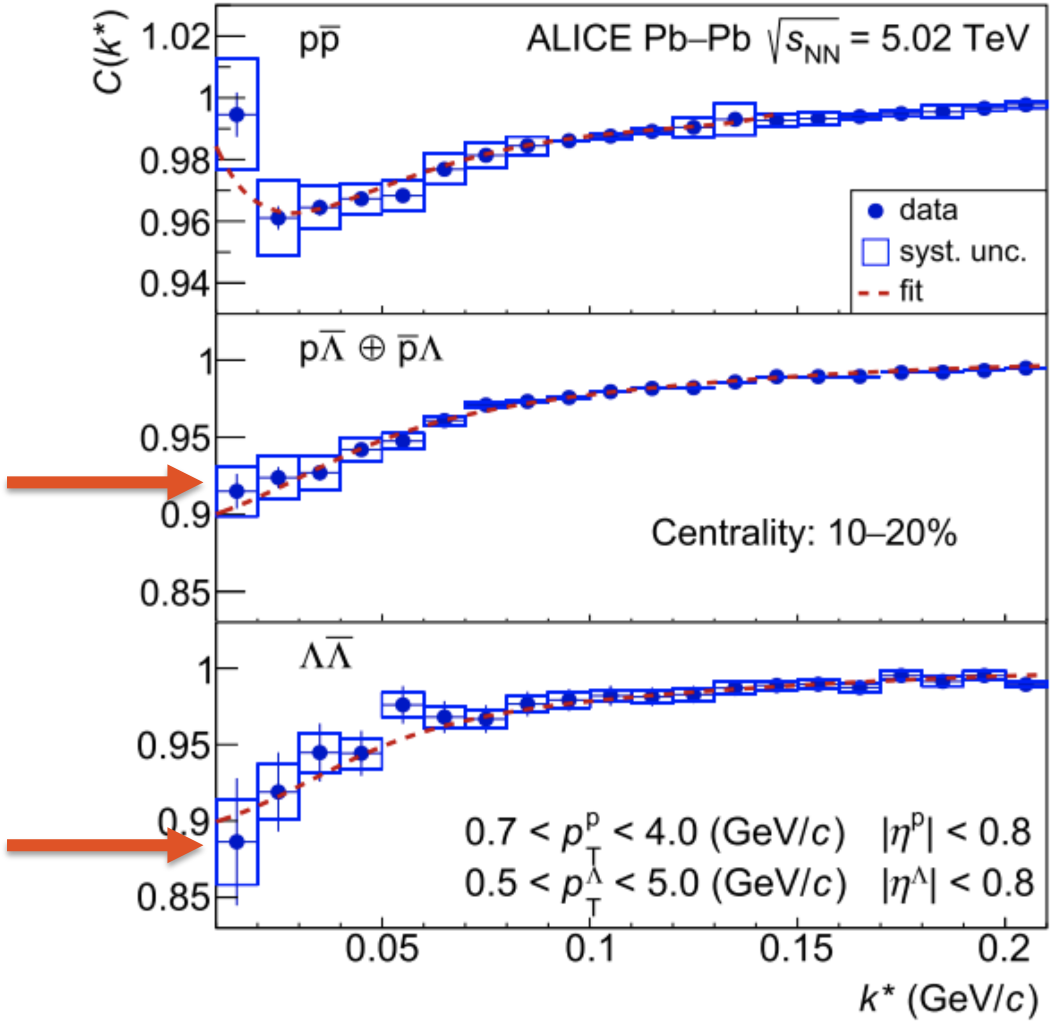
$$C_{tot}(k^*) = N_D \cdot C_{model}(k^*) \cdot C_{BCKG}(k^*),$$

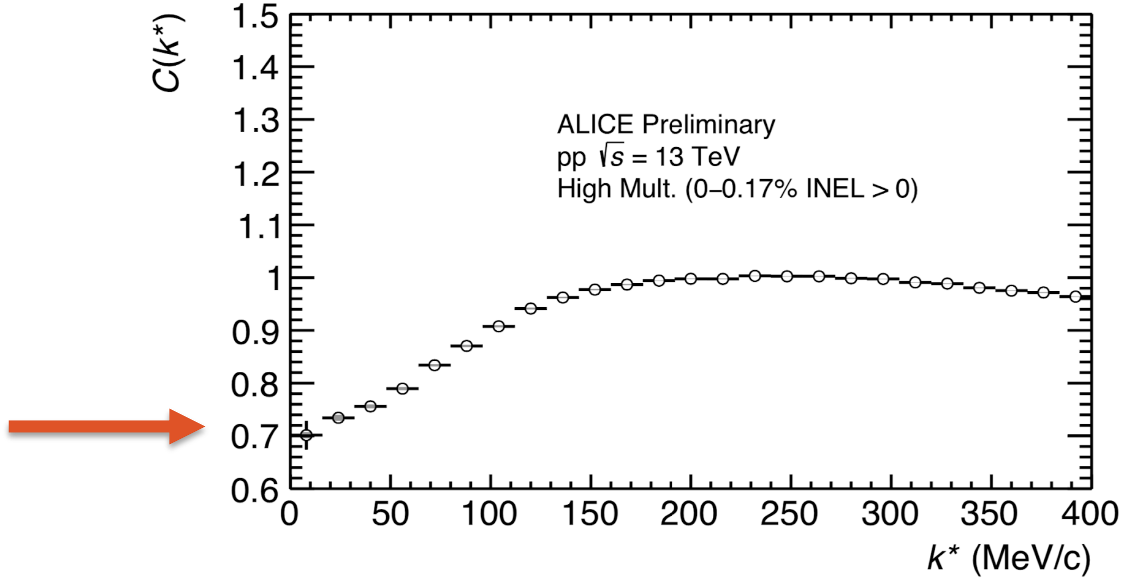
Comparison Pb–Pb and pp data in B-antiB

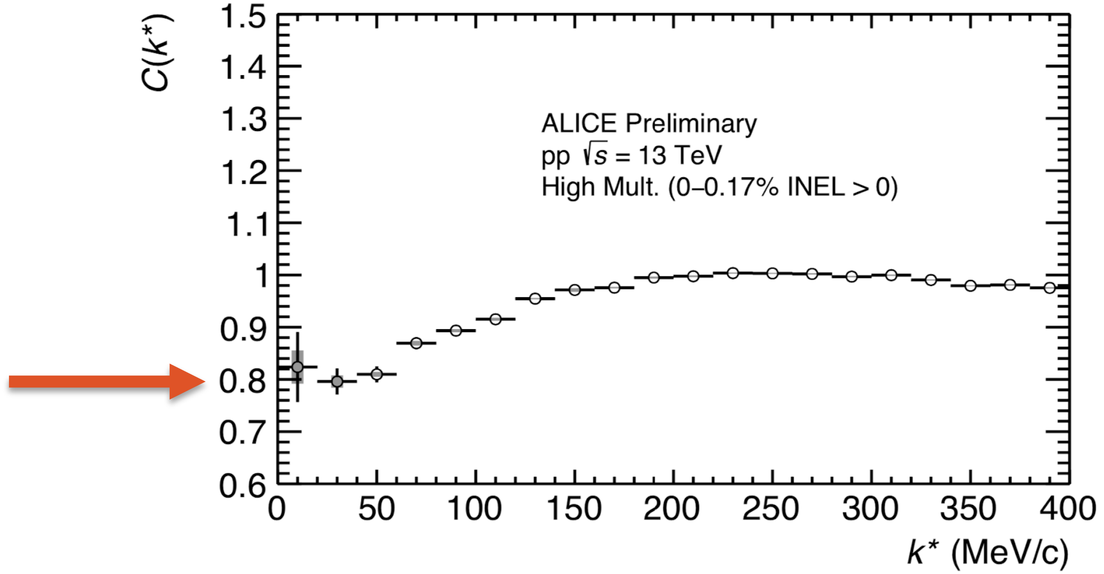




Comparison Pb–Pb and pp data in B-antiB







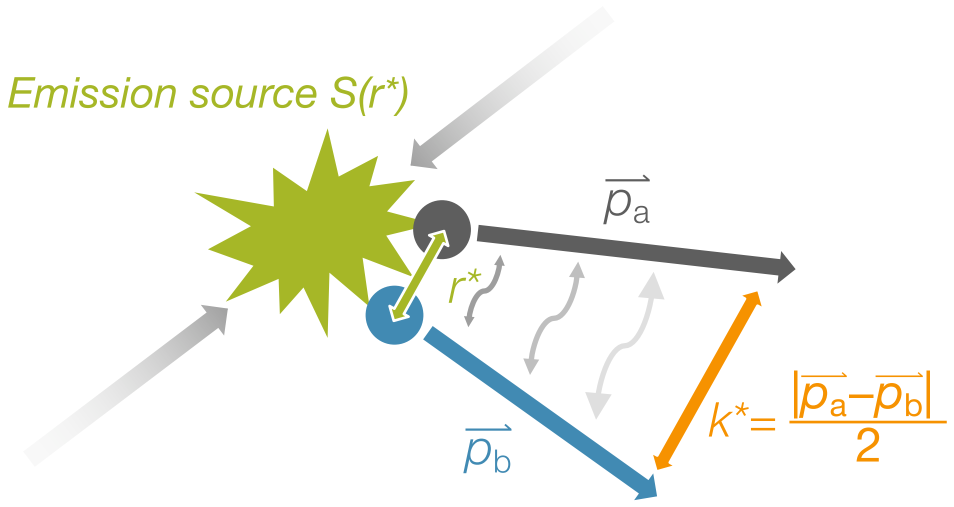
Coupled channel wave functions

- Pairs close in mass with the same quantum numbers: e.g. p–Ξ^- and Λ–Λ
- Schrödinger equation of one pair → Equation system of all 1, … , N pairs

$$\hat{\mathcal{H}} \cdot \psi = \mathrm{E} \cdot \psi \mapsto \begin{pmatrix} \hat{\mathcal{H}}_{11} & \cdots & \hat{\mathcal{H}}_{1\mathrm{N}} \\ \vdots & \ddots & \vdots \\ \hat{\mathcal{H}}_{\mathrm{N}1} & \cdots & \hat{\mathcal{H}}_{NN} \end{pmatrix} \cdot \begin{pmatrix} \psi_1 \\ \vdots \\ \psi_N \end{pmatrix} = E \cdot \begin{pmatrix} \psi_1 \\ \vdots \\ \psi_N \end{pmatrix}$$

-

1) Coupled channels influence the elastic channels of the two-particle wave function ψ_j



Emission source S(r*)
$\vec{p}_a$
r*
$\vec{p}_b$
$k^* = \frac{|\vec{p}_a - \vec{p}_b|}{2}$