Constraining coupled channels dynamics using femtoscopic correlations with ALICE at the LHC

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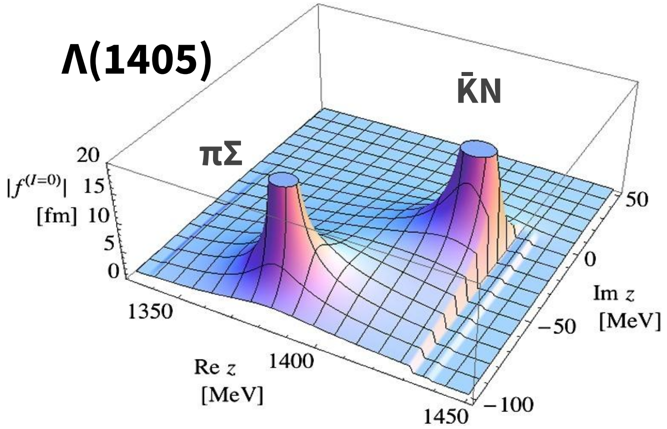
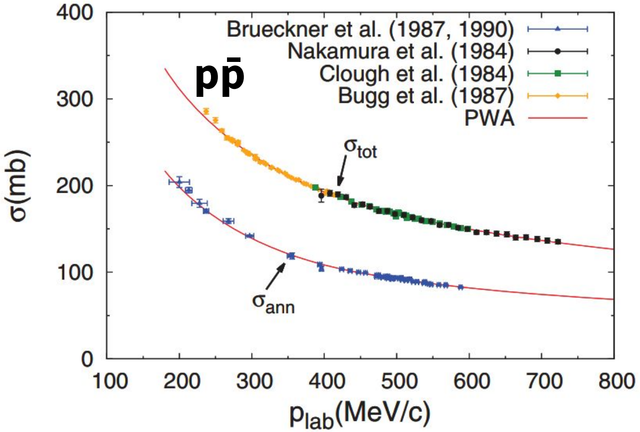
Motivation: inelastic channels in h-h interactions

- 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 K̄N−Σπ
- Annihilation dynamics for B−B̄ interactions
  - Multi-meson channels below threshold

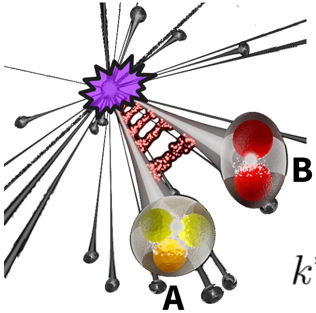


Y. Kamiya et al., NPA 954 (2016) 41-57
T. Hyodo et al., PPNP 67 (2012)
U. Meißner and T. Hyodo: PDG review (2020) (Section 83)



D. Zhou and R. Timmermans PRC 86, 044003 (2012)

Two-particle momentum correlation…



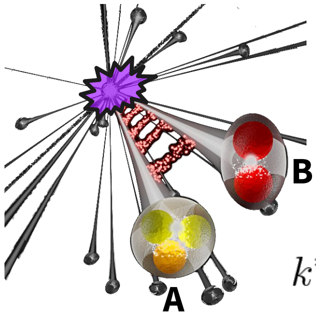
$$k^* = \frac{|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|}{2}$$

More details in Valentina Mantovani Sarti presentation

$$C_{\mathrm{A-B}}(k^*) = \int S_{1\to1}(\vec{r}^{\,*}) \left|\psi_{1\to1}(\vec{k}^{\,*}, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} + \sum_j \omega_j^{\mathrm{prod}} \int S_j(\vec{r}^{\,*}) \left|\psi_{j\to1}(\vec{k}^{\,*}, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} = \mathcal{N}(k^*) \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

R. Lednický, et. al. Phys. At. Nucl. 61 (1998)
J. Haidenbauer NPA 981 (2018)
Y. Kamiya et al., PRL 124 (2020) 132501

Two-particle momentum correlation…



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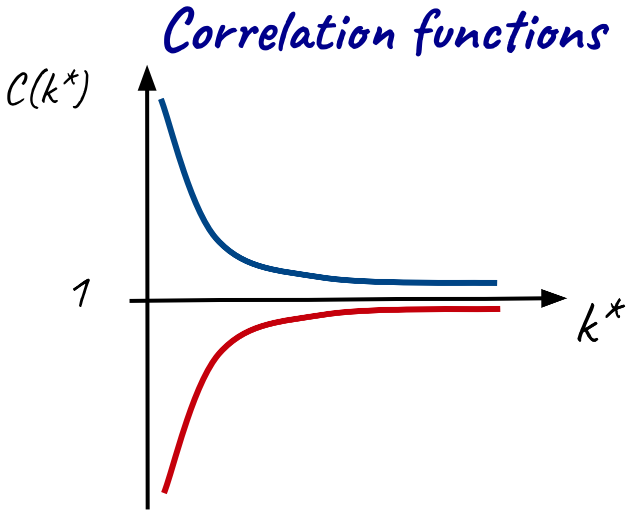

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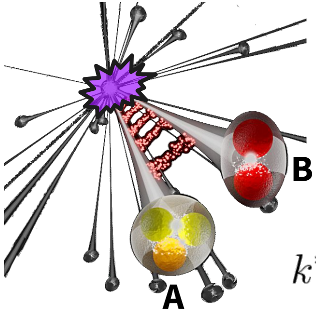

$$k^* = \frac{|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|}{2}$$

Emission source $S(\vec{r}^{\,*})$

$$C_{\mathrm{A-B}}(k^*) = \int S_{1\to1}(\vec{r}^{\,*}) \left|\psi_{1\to1}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} + \sum_j \omega_j^{\mathrm{prod}} \int S_j(\vec{r}^{\,*}) \left|\psi_{j\to1}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} = \mathcal{N}(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

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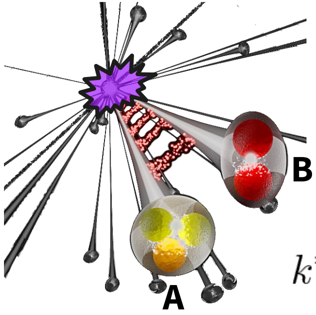
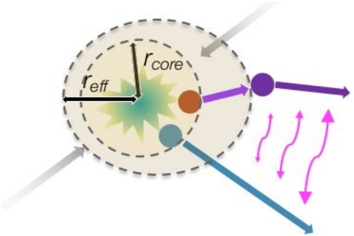


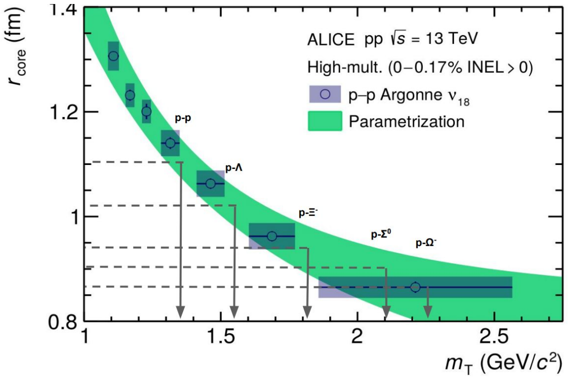
$$k^* = \frac{|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|}{2}$$

Emission source $S(\vec{r}^{\,*})$

The emitting source in small colliding systems

- Data-driven analysis on p–p and p–Λ pairs
  - Possible presence of collective effect → m_T scaling of the core radius
  - Contribution of strongly decaying resonances with cτ ~1 fm
- Common universal core source for mesons and baryons





PLB 811 (2020) 135849

More details in Dimitar Mihaylov presentation

$$C_{\mathrm{A-B}}(k^*) = \int S_{1\to1}(\vec{r}^{\,*}) \left|\psi_{1\to1}(\vec{k}^{\,*}, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} + \sum_j \omega_j^{\mathrm{prod}} \int S_j(\vec{r}^{\,*}) \left|\psi_{j\to1}(\vec{k}^{\,*}, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} = \mathcal{N}(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

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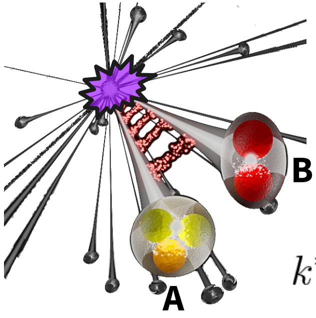
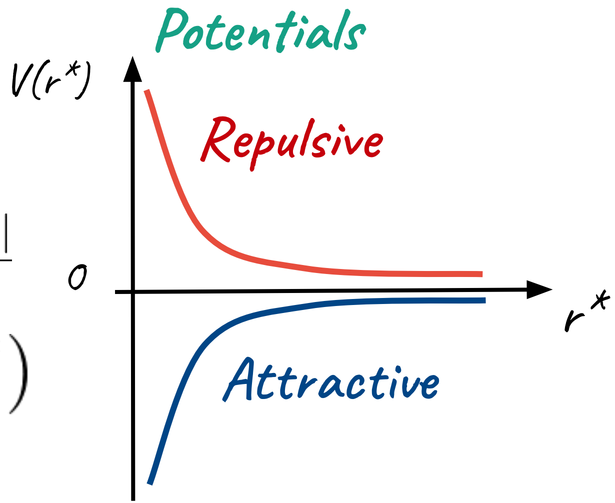
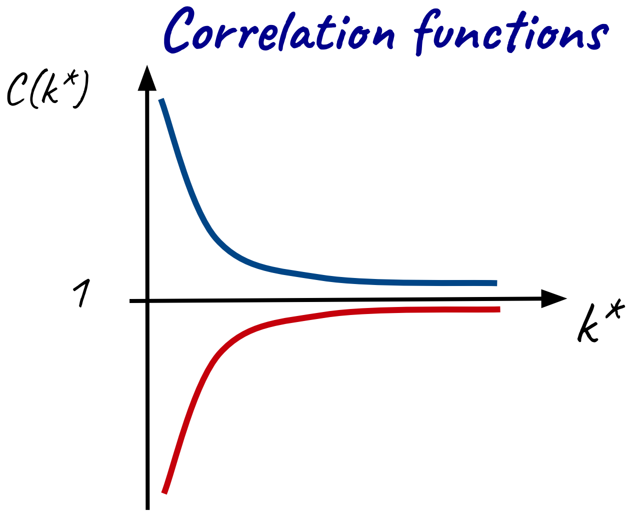


$$k^* = \frac{|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|}{2}$$

Emission source $S(\vec{r}^{\,*})$





Two-particle wave function:
elastic A-B → A-B

Two-particle wave function:
inelastic C-D → A-B, …

$$C_{\mathrm{A-B}}(k^*) = \int S_{1\to1}(\vec{r}^{\,*}) \left|\psi_{1\to1}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} + \sum_j \omega_j^{\mathrm{prod}} \int S_j(\vec{r}^{\,*}) \left|\psi_{j\to1}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} = \mathcal{N}(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

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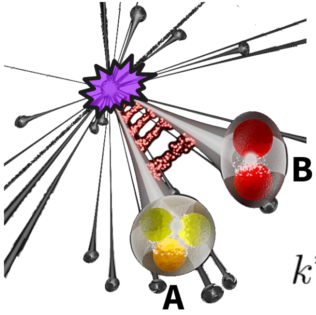
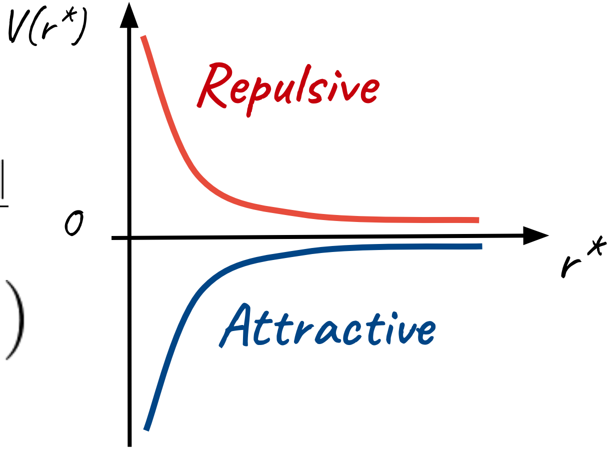
ALICE



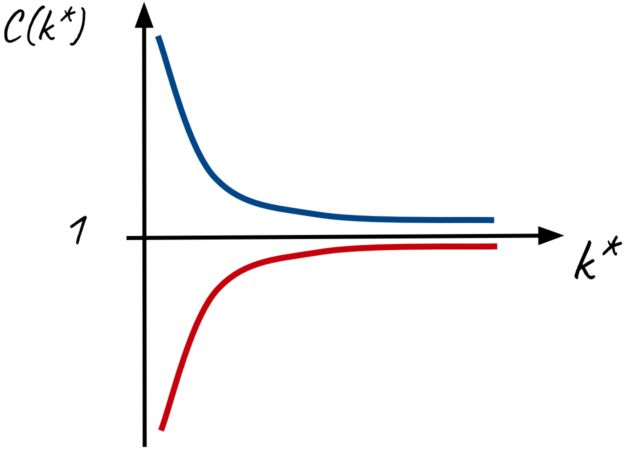
$$k^* = \frac{|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|}{2}$$

Emission source $S(\vec{r}^{\,*})$

Potentials



Correlation functions



Two-particle wave function: elastic A-B → A-B

Two-particle wave function: inelastic C-D → A-B, ...

$$C_{\mathrm{A-B}}(k^*) = \int S_{1\rightarrow 1}(\vec{r}^{\,*}) \left|\psi_{1\rightarrow 1}(\vec{k}^{\,*}, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} + \sum_j \omega_j^{\mathrm{prod}} \int S_j(\vec{r}^{\,*}) \left|\psi_{j\rightarrow 1}(\vec{k}^{\,*}, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} = \mathcal{N}(k^*) \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

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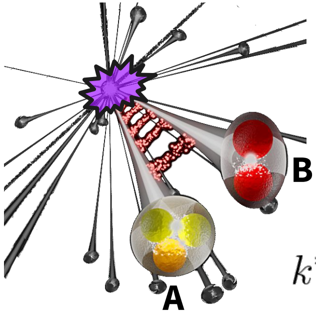
Two-particle momentum correlation…



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

Emission source $S(\vec{r}^{\,*})$

- Conversion weights (ω_j^{prod})
  - control coupled channels (CC) contribution
  - depend on primary yield and kinematics
    - thermal models and transport models

$$C_{\mathrm{A-B}}(k^*) = \int S_{1\to1}(\vec{r}^{\,*})\left|\psi_{1\to1}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} + \sum_j \omega_j^{\text{prod}} \int S_j(\vec{r}^{\,*})\left|\psi_{j\to1}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} = \mathcal{N}(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

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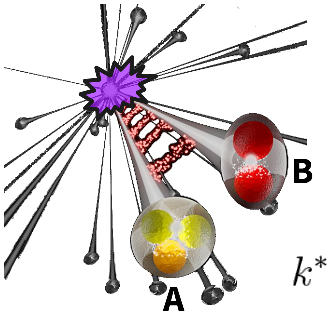

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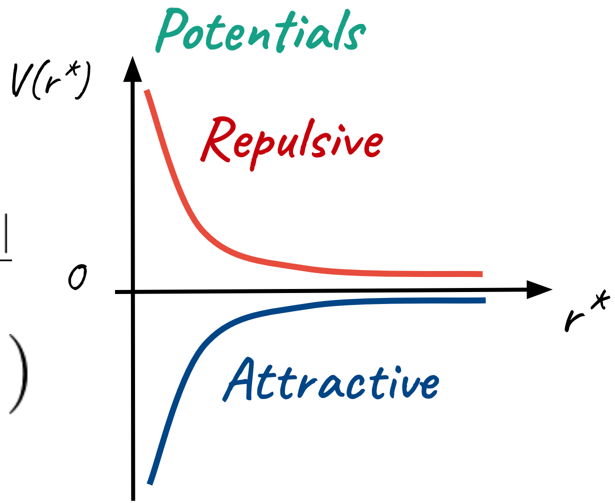
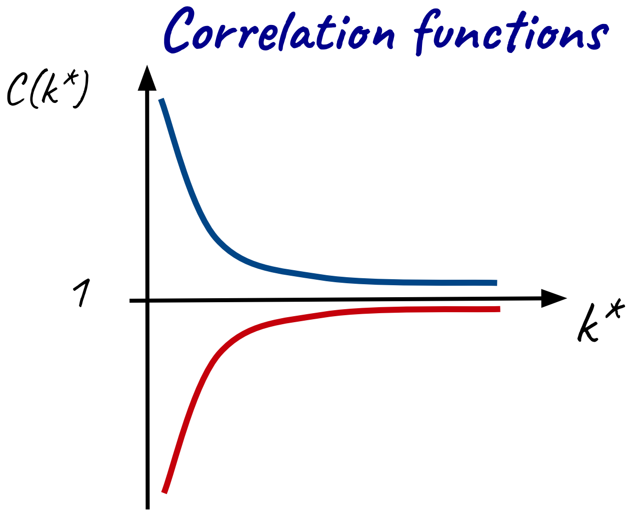
Emission source $S(\vec{r}^{\,*})$





$$C_{A-B}(k^*) = \int S_{1\to1}(\vec{r}^{\,*}) \left|\psi_{1\to1}(\vec{k}^{\,*}, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} + \sum_j \omega_j^{\text{prod}} \int S_j(\vec{r}^{\,*}) \left|\psi_{j\to1}(\vec{k}^{\,*}, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*} = \mathcal{N}(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

⇒ Measure ***C(k*)*** → fixing the source $S(\vec{r}^{\,*})$, study the interaction

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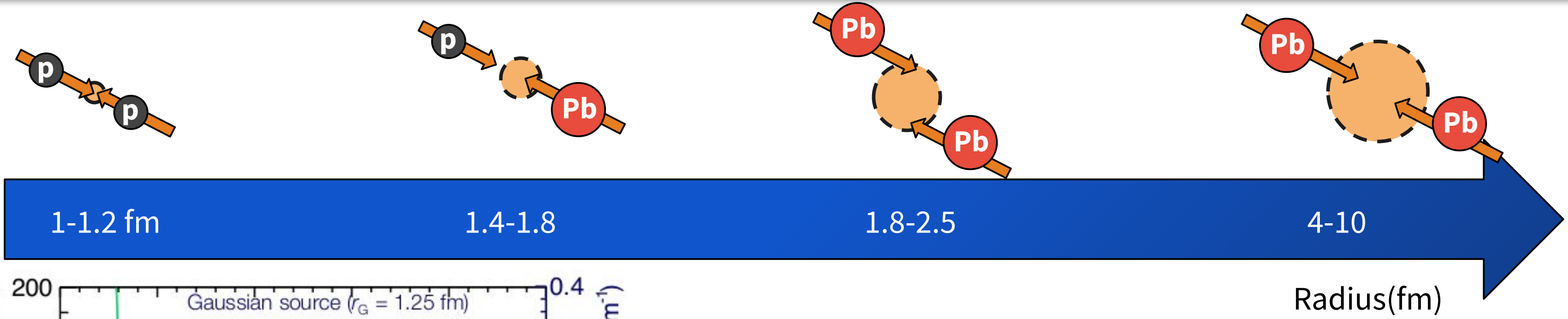
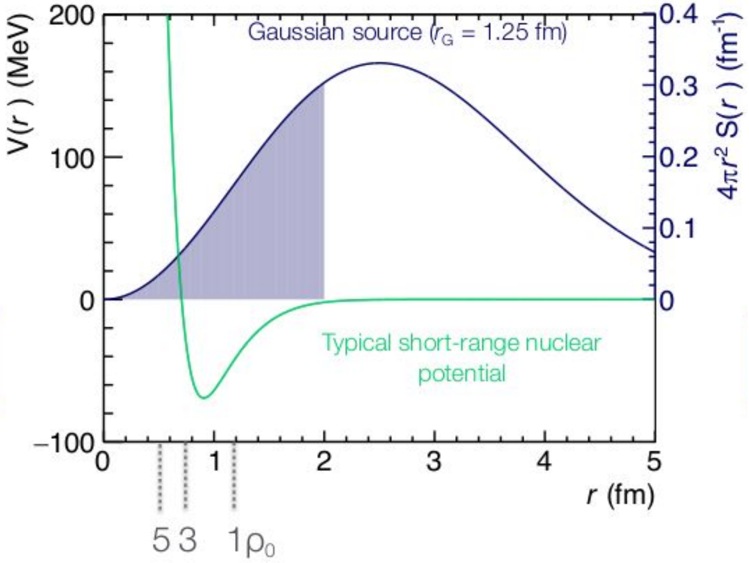
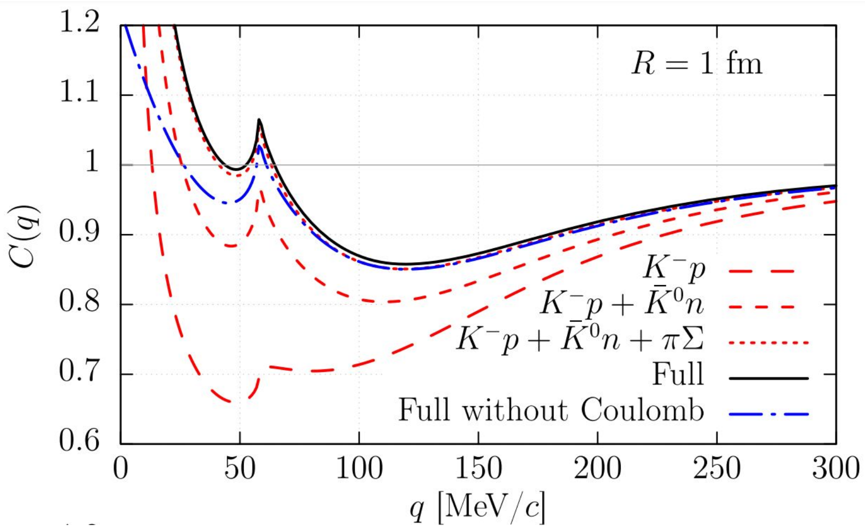
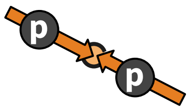
… from small to large systems



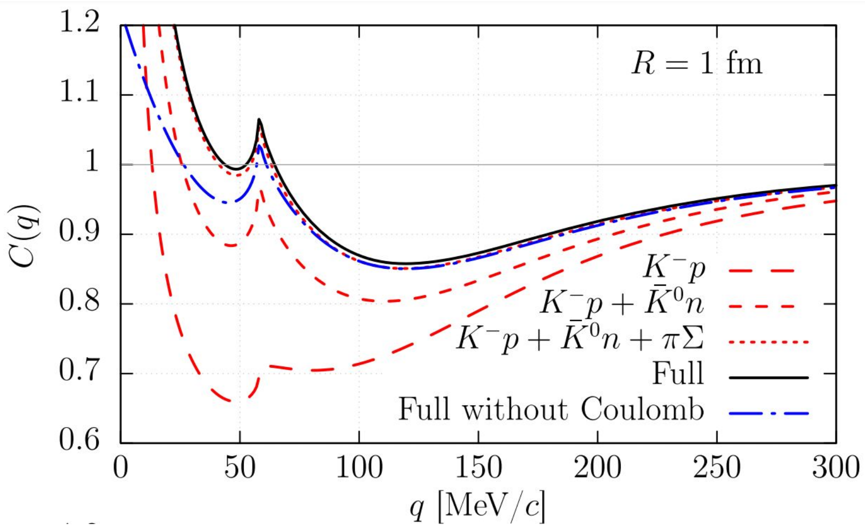


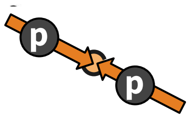
- By changing the colliding system it is possible to probe interaction distances ranging from ~1 fm up to ~10 fm

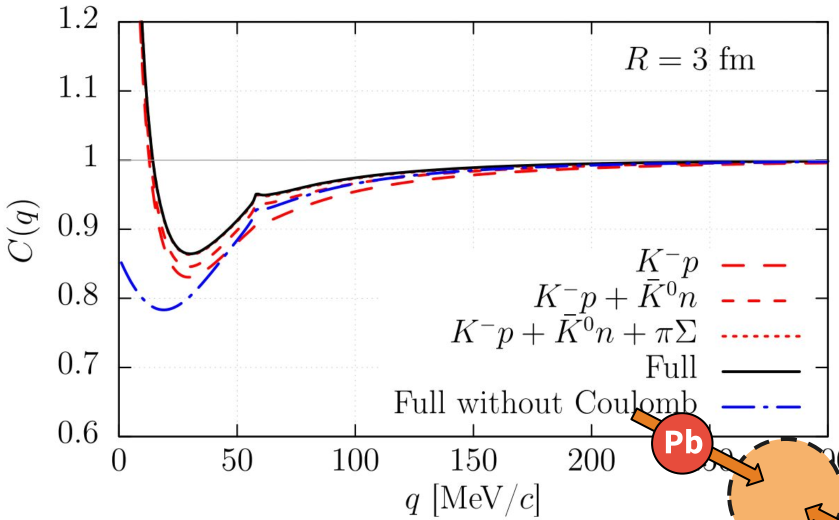


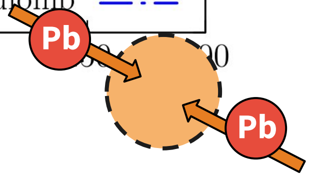


$$C_{\mathrm{A-B}}(k^*) = \int S_{1\to1}(\vec{r}^*) \left|\psi_{1\to1}(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^* + \sum_j \omega_j^{\mathrm{prod}} \int S_j(\vec{r}^*) \left|\psi_{j\to1}(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^* = \mathcal{N}(k^*) \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$







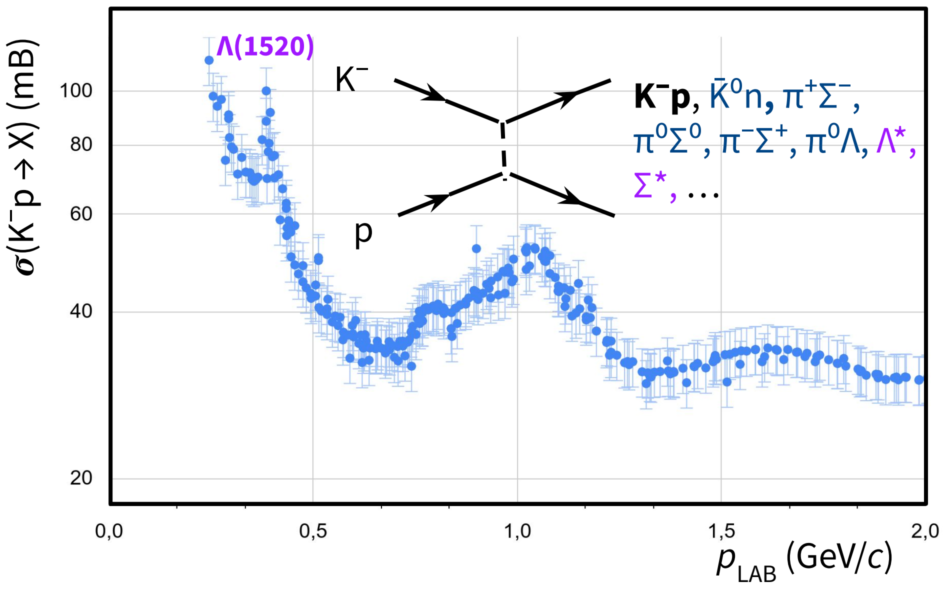


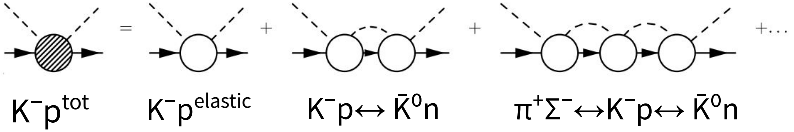
- System-size survey
  - For large radii contribution from CC gets negligible → elastic scattering

$$C_{\mathrm{A-B}}(k^*) = \int S_{1\to1}(\vec{r}^*)\left|\psi_{1\to1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^* + \sum_j \omega_j^{\mathrm{prod}} \int S_j(\vec{r}^*)\left|\psi_{j\to1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^* = \mathcal{N}(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

K^-p interaction

K⁻p interaction

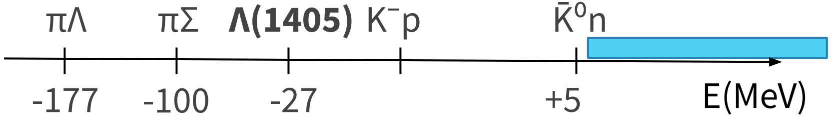




Particle Data Group Phys.Rev. D98 (2018) no.3, 030001
SIDDHARTA Collaboration PLB704 (2011) 113

K⁻p interaction

- deeply attractive
- several **resonances**
- several **coupled channels** (K̄⁰n, π⁺Σ⁻, π⁰Σ⁰, π⁻Σ⁺,π⁰Λ)
  - K̄N ↔πΣ dynamics: formation of the **Λ(1405)**, ~27 MeV below K⁻p threshold
    - state-of-the-art chiral models (χEFT) are in agreement above threshold
    - large discrepancies in the region below threshold
    - constraint at threshold by SIDDARTHA measurement of kaonic hydrogen 1*s* level shift and width
      - scattering length



K⁻p from small to large systems

$$C_{\mathrm{K^-p}}(k^*) = \int d^3\vec{r}^{\,*} S_{\mathrm{K^-p}}(\vec{r}^{\,*}) \left|\psi_{\mathrm{K^-p}}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 + \sum_j \omega_j \int d^3\vec{r}^{\,*} S_j(\vec{r}^{\,*}) \left|\psi_j(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2$$

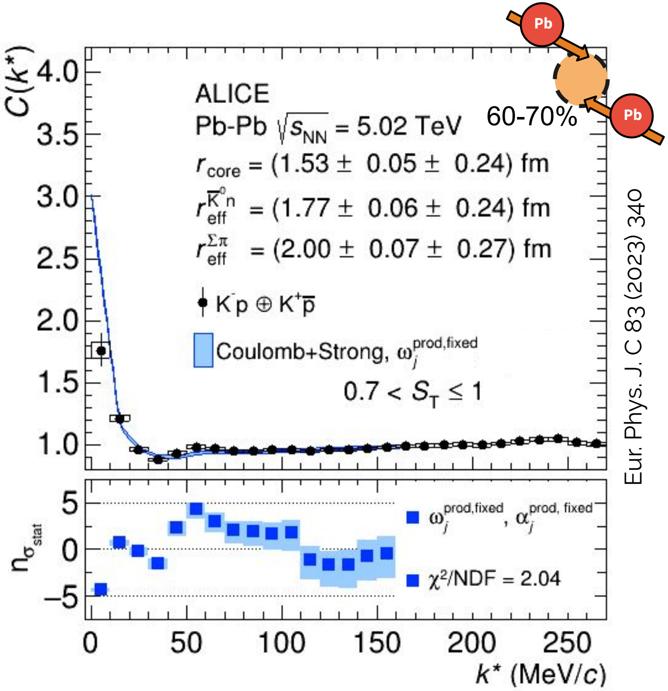
Each coupled channel is accounted in the ω_j weights

- primary production yields fixed from thermal model (Thermal-FIST) [1]
- estimate amount of pairs in kinematic region sensitive to final state interactions
- distribute particles according to blast-wave model [2,3,4]
- normalize to expected yield of K⁻p

[1] V. Vovchenko et al., PRC 100 no. 5 (2019)
[2] E. Schnedermann et al., PRC 48 (1993)
[3] ALICE Collaboration, PLB 728 (2014)
[4] ALICE Collaboration, PRC 101 no. 4 (2020)

K^-p from small to large systems

$$C_{K^-p}(k^*) = \int d^3\vec{r}^{\,*} S_{K^-p}(\vec{r}^{\,*}) \left|\psi_{K^-p}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 + \sum_j \omega_j \int d^3\vec{r}^{\,*} S_j(\vec{r}^{\,*}) \left|\psi_j(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2$$



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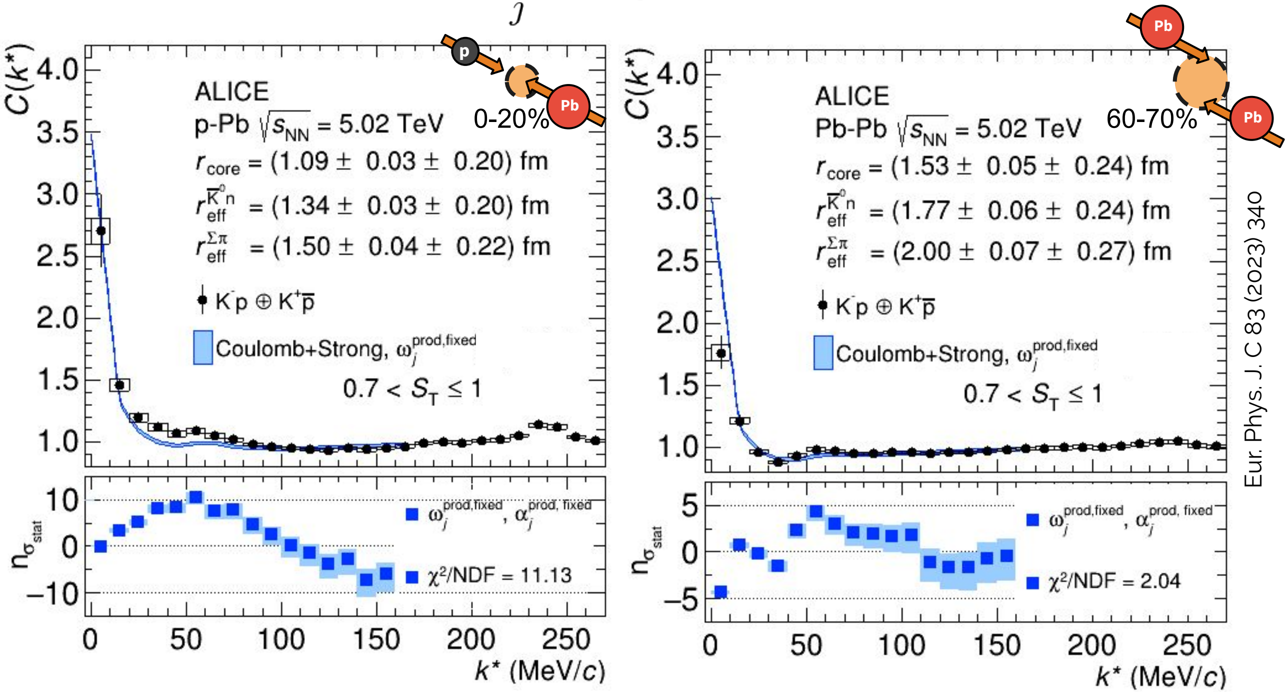
K⁻p from small to large systems

$$C_{K^-p}(k^*) = \int d^3\vec{r}^*S_{K^-p}(\vec{r}^*)\left|\psi_{K^-p}(\vec{k}^*,\vec{r}^*)\right|^2 + \sum_j \omega_j \int d^3\vec{r}^*S_j(\vec{r}^*)\left|\psi_j(\vec{k}^*,\vec{r}^*)\right|^2$$



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K⁻p from small to large systems

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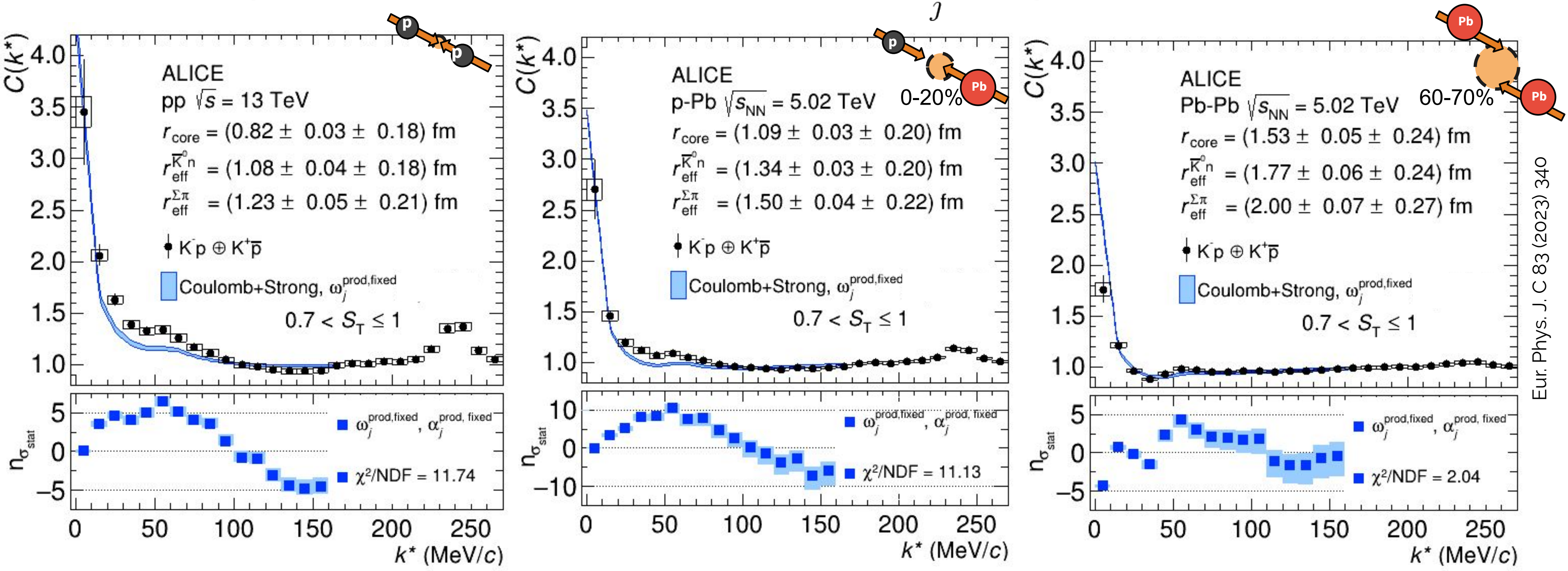

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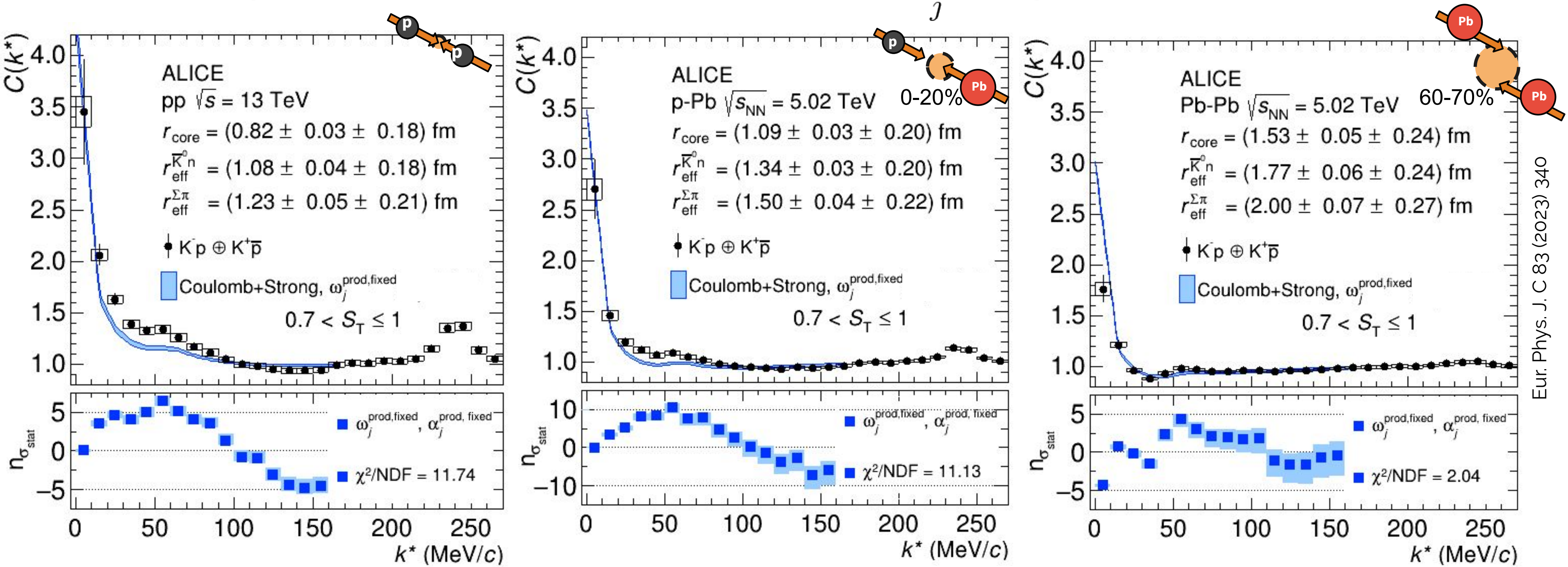
$K^{-}p$ from small to large systems

$$C_{K^-p}(k^*) = \int d^3\vec{r}^{\,*} S_{K^-p}(\vec{r}^{\,*}) \left|\psi_{K^-p}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 + \sum_j \omega_j \int d^3\vec{r}^{\,*} S_j(\vec{r}^{\,*}) \left|\psi_j(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2$$



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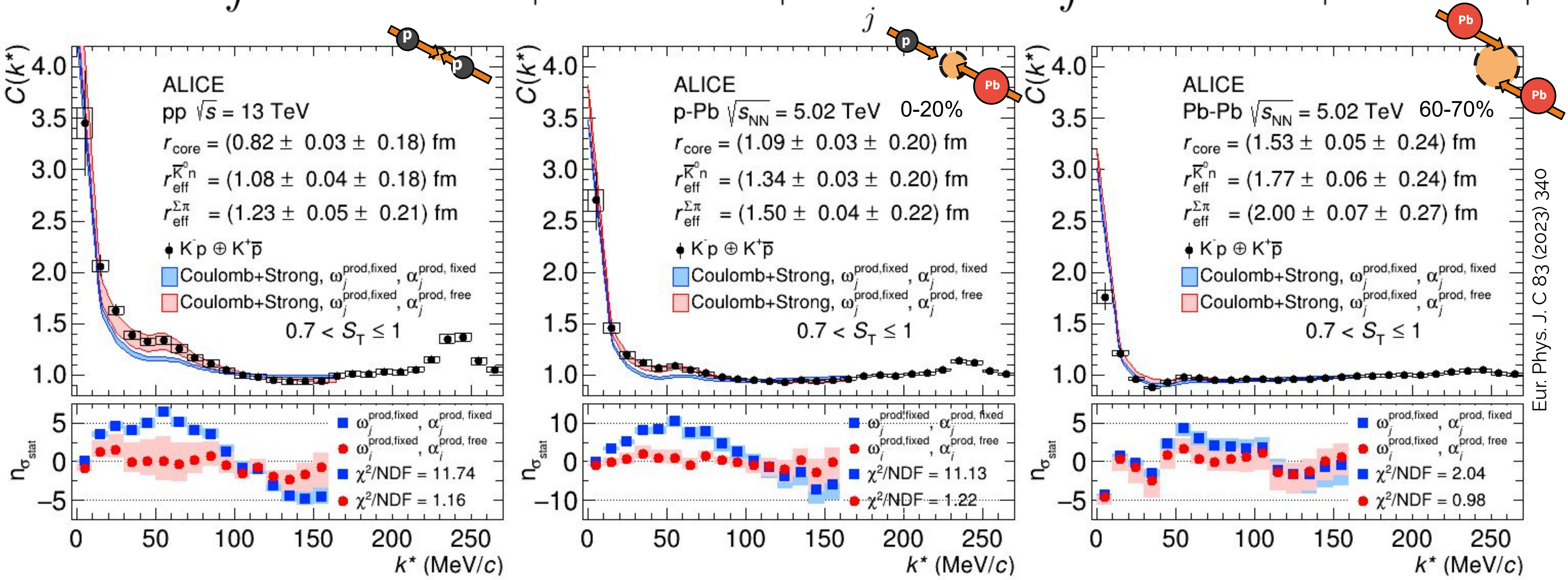
State-of-the-art Kyoto Model is not able to describe the data from small to large source size

K⁻p from small to large systems

$$C_{\mathrm{K}^-p}(k^*) = \int d^3\vec{r}^{\,*} S_{\mathrm{K}^-p}(\vec{r}^{\,*}) \left|\psi_{\mathrm{K}^-p}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 + \sum_j \omega_j^{prod} \cdot \alpha_j \int d^3\vec{r}^{\,*} S_j(\vec{r}^{\,*}) \left|\psi_j(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2$$

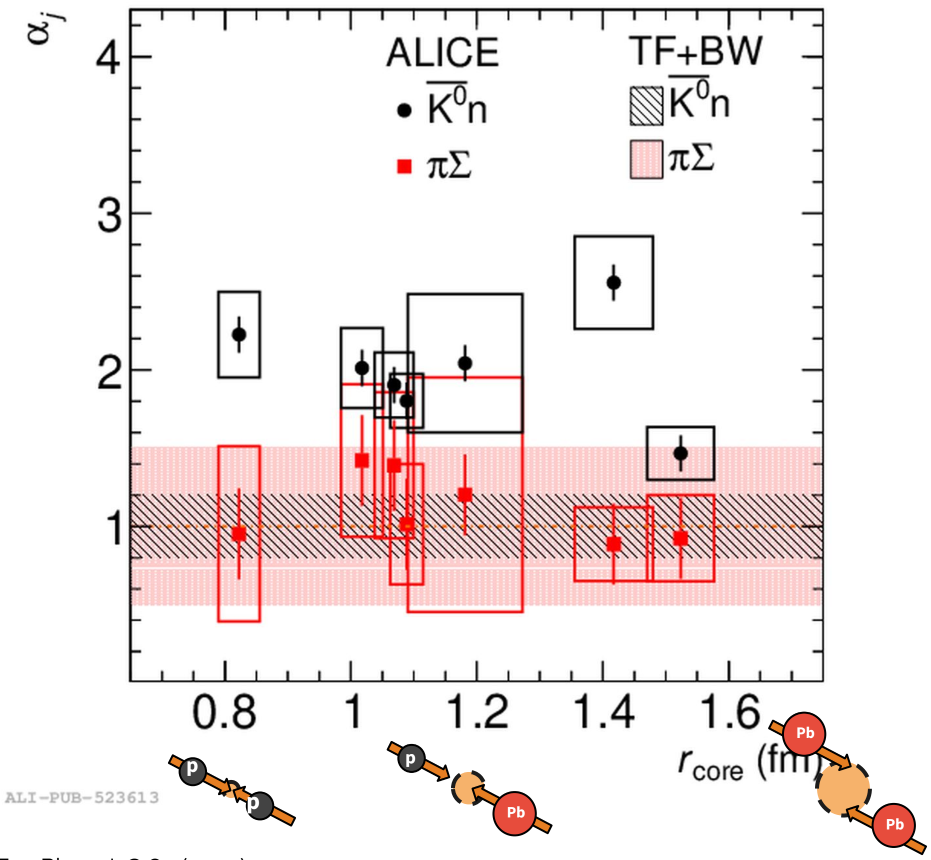
K^-p from small to large systems

$$C_{K^-p}(k^*) = \int d^3\vec{r}^{\,*} S_{K^-p}(\vec{r}^{\,*}) \left|\psi_{K^-p}(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2 + \sum_j \omega_j^{prod} \cdot \alpha_j \int d^3\vec{r}^{\,*} S_j(\vec{r}^{\,*}) \left|\psi_j(\vec{k}^{\,*},\vec{r}^{\,*})\right|^2$$



A correction factor α_j is introduced to quantify the model-to-data deviation

K^-p from small to large systems



- Unique constraint and direct access to $K^-p \leftrightarrow \bar{K}^0n$ and $K^-p \leftrightarrow \pi\Sigma$ dynamics
- $\alpha_{\bar{K}^0-n}$ deviates from unity:
  - $K^-p \leftrightarrow \bar{K}^0n$ currently implemented in Kyoto χEFT is too weak
  - fine tuning of Kyoto χEFT is needed and data from hadron-hadron collisions have to be taken into account

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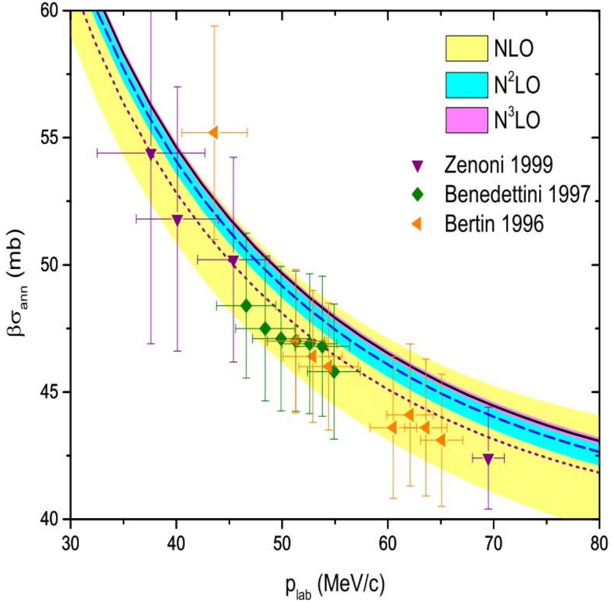
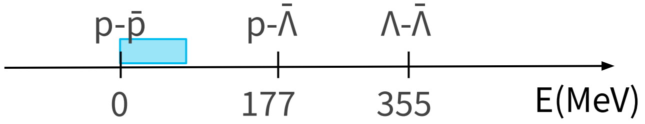
The baryon-antibaryon interaction

- B–B̄ interaction at low energies dominated by annihilation processes
  - B–B̄ ↔nπ, nK, πK, …
- pp̄
  - Low-energy scattering experiments available only down to p_{lab} ≈ 200 MeV/c
  - At threshold level shifts and widths of p–p̄ atoms
    - Existence of baryonia states?
- p-Λ̄ and Λ-Λ̄:
  - experimental informations very scarce
    - only available data pp̄ → ΛΛ̄

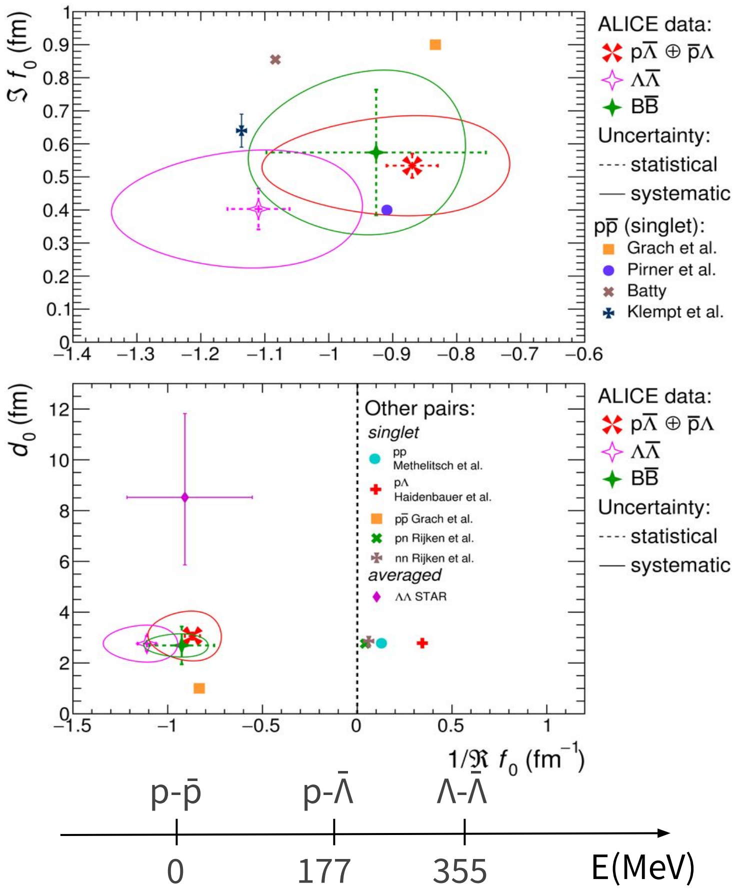




E. Klempt et al. Phys. Rept. 413 (2005)
E. Klempt et al. Phys. Rept. 368 (2002)
D. Zhou and R.G. E. Timmermans PRC86 (2012)
J. Haidenbauer et al. JHEP 1707 (2017)

The baryon-antibaryon interaction

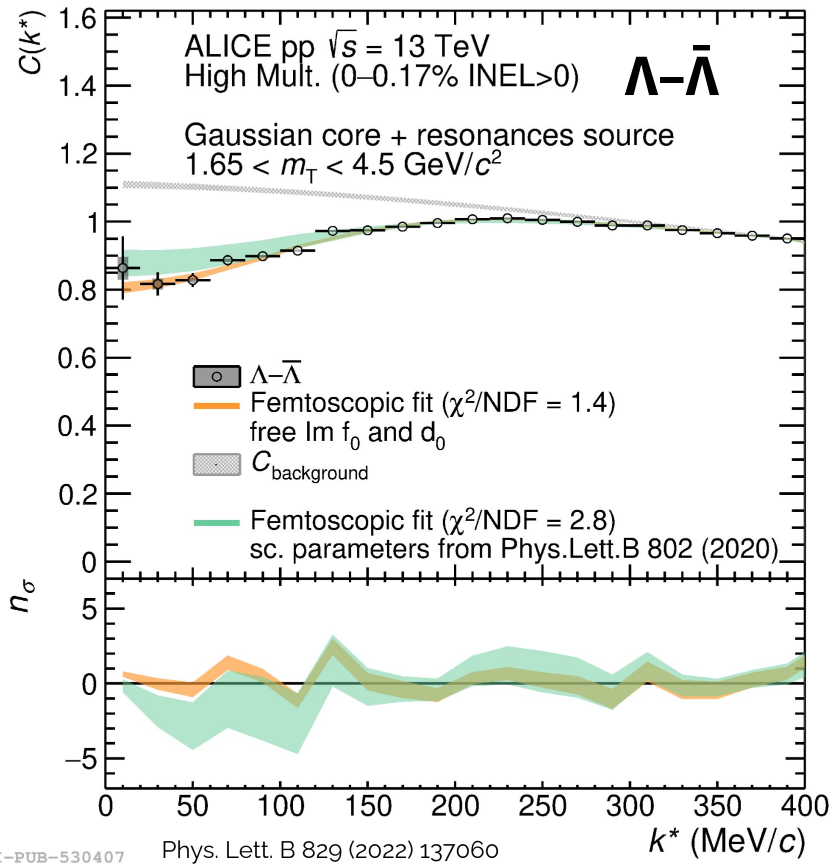
- $B-\bar{B}$ interaction at low energies dominated by annihilation processes
  - $B-\bar{B} \leftrightarrow n\pi, nK, \pi K, \ldots$
- $p\bar{p}$
  - Low-energy scattering experiments available only down to $p_{lab} \approx 200$ MeV/c
  - At threshold level shifts and widths of $p-\bar{p}$ atoms
    - Existence of baryonia states?
- p-$\bar{\Lambda}$ and Λ-$\bar{\Lambda}$:
  - experimental informations very scarce
    - only available data $p\bar{p} \rightarrow \Lambda\bar{\Lambda}$
- Two-particle momentum correlation measured by ALICE for $p-\bar{p}$, $p-\bar{\Lambda}$ and $\Lambda-\bar{\Lambda}$
  - spin-averaged scattering parameters in agreement for all $B-\bar{B}$ pairs → the annihilation part for all $B-\bar{B}$ pairs is similar at the same relative momentum



Phys. Lett. B 802 (2020) 135223

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

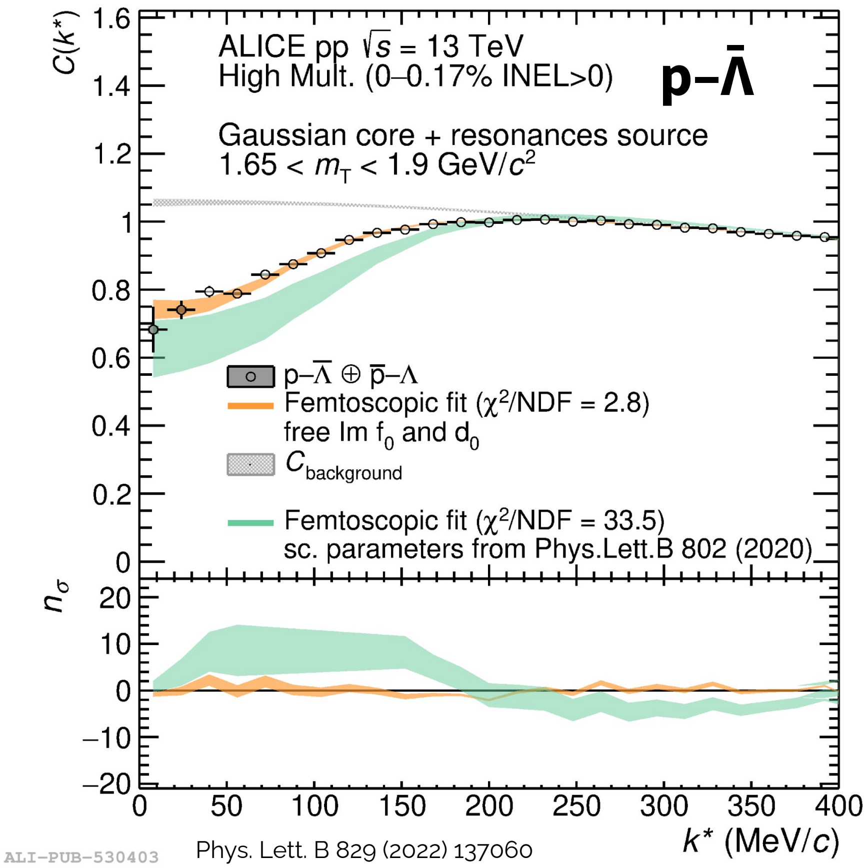
- No exact wave functions available → single-channel Lednický-Lyuboshits formula
- Assuming the scattering parameters obtained in Pb−Pb
  - nice agreement with Λ–$\bar{\Lambda}$ data
    - inelastic part present but not dominant



Phys. Lett. B 829 (2022) 137060

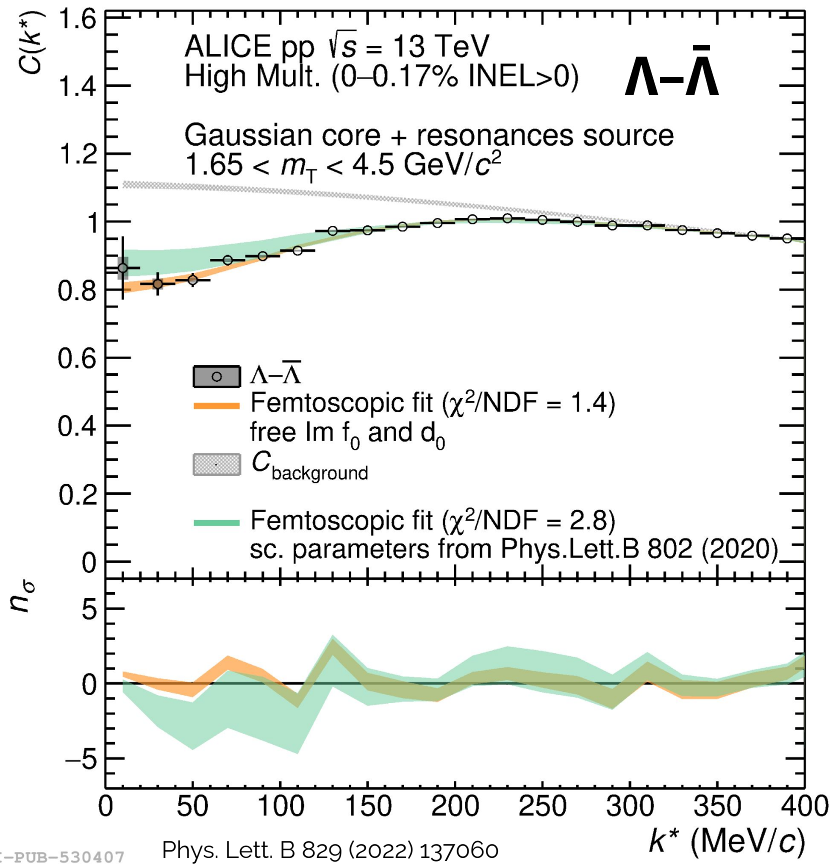
Results on Λ–$\bar{\Lambda}$ and p–$\bar{\Lambda}$ femtoscopy

- No exact wave functions available → single-channel Lednický-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



Phys. Lett. B 829 (2022) 137060

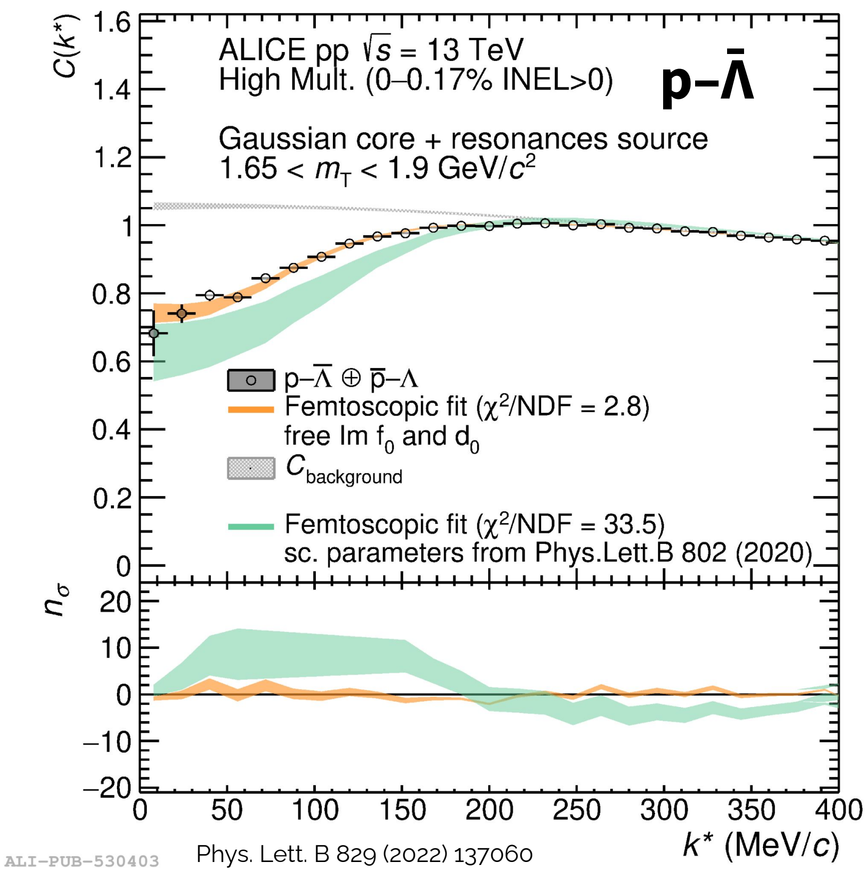
- Elastic part $\Re(f_0)$ and fixed from Pb–Pb data, free inelastic $\Im(f_0)$ and d_0
  - Extracted values for Λ–$\bar{\Lambda}$ are compatible with Pb–Pb scattering parameters



Phys. Lett. B 829 (2022) 137060

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

- Elastic part $\Re(f_0)$ and fixed from Pb–Pb data, free inelastic $\Im(f_0)$ and d_0
  - Extracted values for Λ–$\bar{\Lambda}$ are compatible with Pb–Pb scattering parameters
  - to reproduce p–$\bar{\Lambda}$ data $\Im(f_0)$ has to be increased by a factor ~ 5.3
    - Larger presence of multi-meson annihilation channels in p–$\bar{\Lambda}$
      - no bound state?

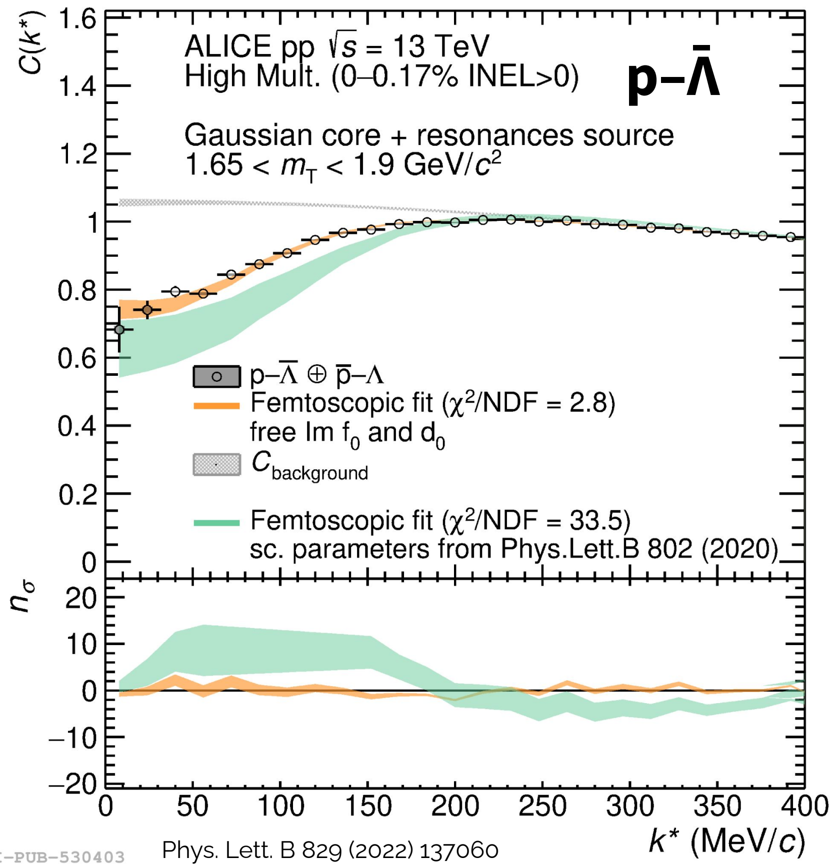


Phys. Lett. B 829 (2022) 137060

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

- Estimate based on kinematics (EPOS) and SU(3) flavor symmetry for 2-meson channels ($\pi\bar{\pi}$, $\pi\bar{K}$)
  - Similar amount of p–$\bar{\Lambda}$ and Λ–$\bar{\Lambda}$ pairs at low k^*(~6.4%)
  - coupling strength from meson-baryon SU(3) lagrangian for p–$\bar{\Lambda}$ ~ 3 times larger than Λ–$\bar{\Lambda}$

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



Phys. Lett. B 829 (2022) 137060

Conclusions and outlook

- Momentum correlation technique applied to data collected at the LHC in different collision systems
  - high-precision data at low momenta
  - sensitivity to inelastic channels as a function of the source size
- KN and $\bar{K}$N interaction: New constraints for low-energy QCD chiral models
  - First experimental access to coupled channels dynamics ($K^-p \leftrightarrow \bar{K}^0n$, $K^-p \leftrightarrow \pi\Sigma$, $K^-p \leftrightarrow \pi\Lambda$)
  - Data-model tension in description of K^-p interaction:
    - $K^-p \leftrightarrow \bar{K}^0n$ currently implemented in state-of-the-art Kyoto χEFT is too weak
- Baryon-antibaryon in pp collisions
  - Λ–$\bar{\Lambda}$: annihilation not dominant and room for baryonia
  - p–$\bar{\Lambda}$: large presence of annihilation channels → no formation of bound states?
  - Need for theoretical input on p–$\bar{\Lambda}$ and Λ–$\bar{\Lambda}$ interactions

Conclusions and outlook

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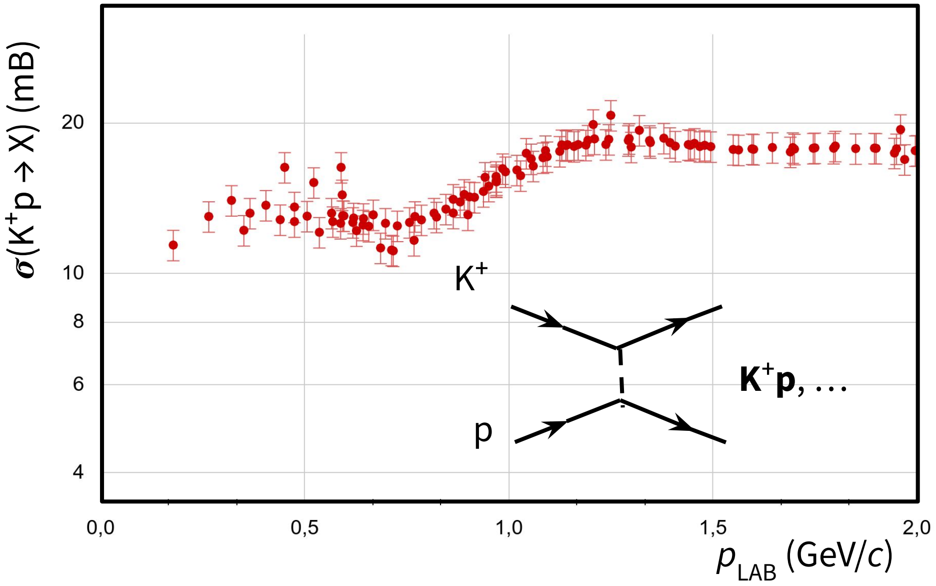
More details on two(three) particles interactions:

- Valentina Mantovani Sarti
- Dimitar Mihaylov
- Wioleta Rzęsa
- Laura Šerkšnytė
- Marcel Lesch

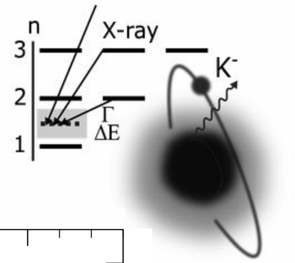
Backup

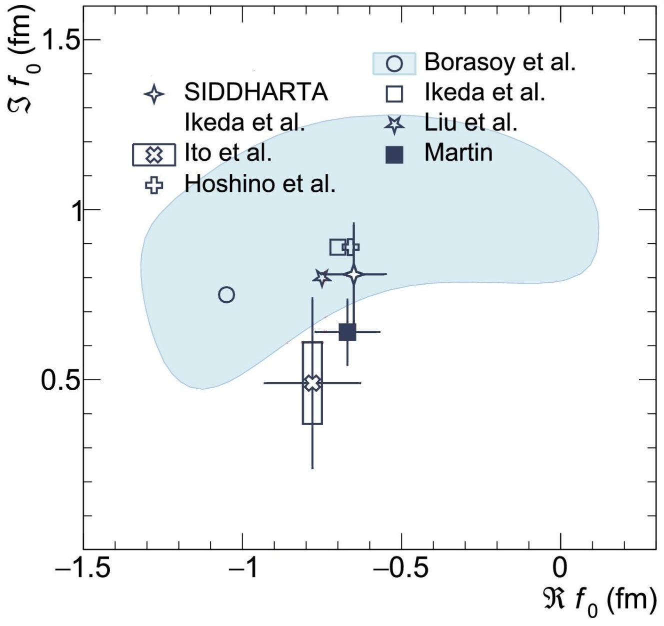


- **K^+p interaction**
  - Repulsive (due to Coulomb and strong interactions)
  - No coupled channels
  - No resonances
    - well known [1]

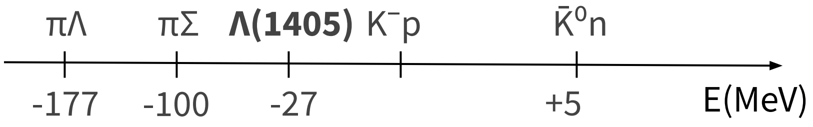
[1] K. Aoki and D. Jido, PTEP 2019 no. 1, (2019) 013D01 (arXiv:1806.00925 [nucl-th])

K⁻p interaction and Λ(1405)





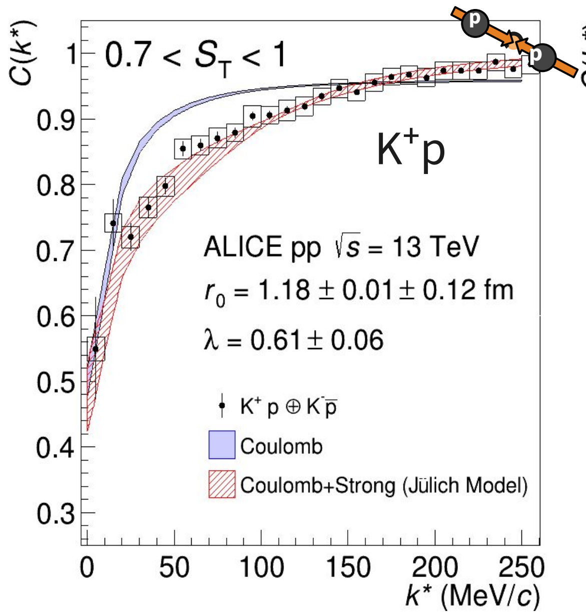
- Nature of Λ(1405): dynamically generated resonance
  - Models based on below-threshold extrapolations
    - positions of pole are model dependent (relative contributions not measured experimentally)
    - state-of-the-art chiral models (χEFT) are in agreement above threshold
    - large discrepancies in the region below threshold
    - constraint at threshold by SIDDARTHA measurement [1] of kaonic hydrogen 1s level shift and width
      - scattering length

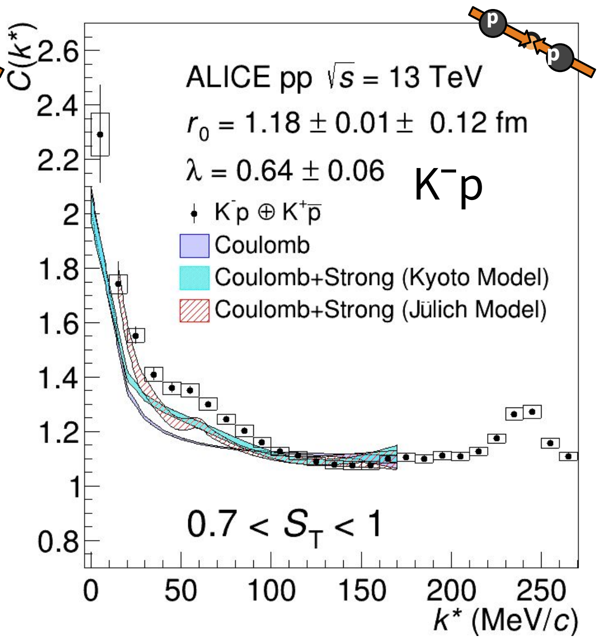


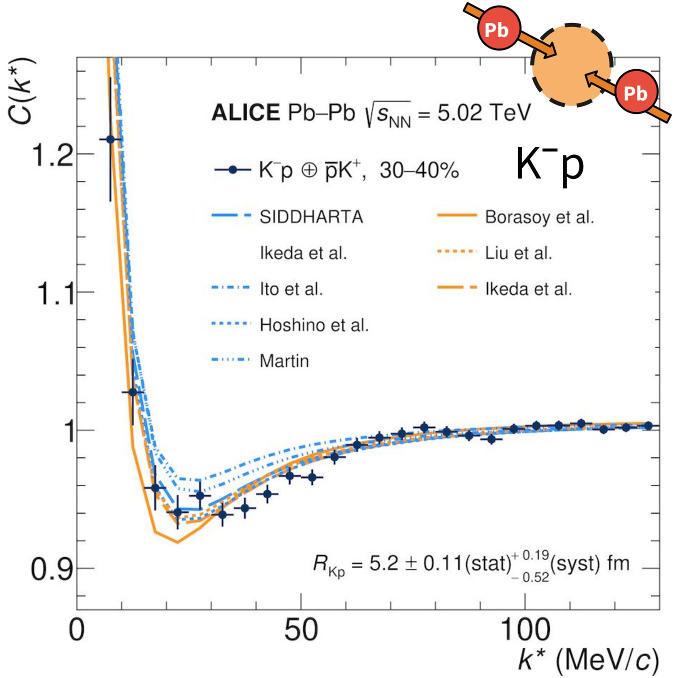
[1] SIDDHARTA Collaboration PLB704 (2011) 113

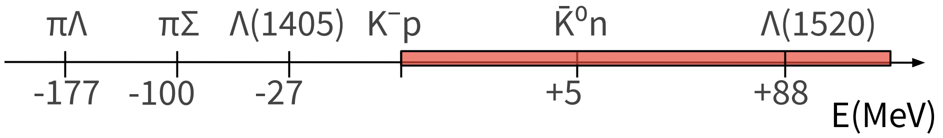
KN and K̄N interactions : the game changer

Two-particle momentum correlation measured with ALICE at the LHC









PRL 124 (2020) 9, 092301
Fit: CATS D. L. Mihaylov et al., EPJ C78 (2018) 5, 394)
PLB 822 (2021) 136708

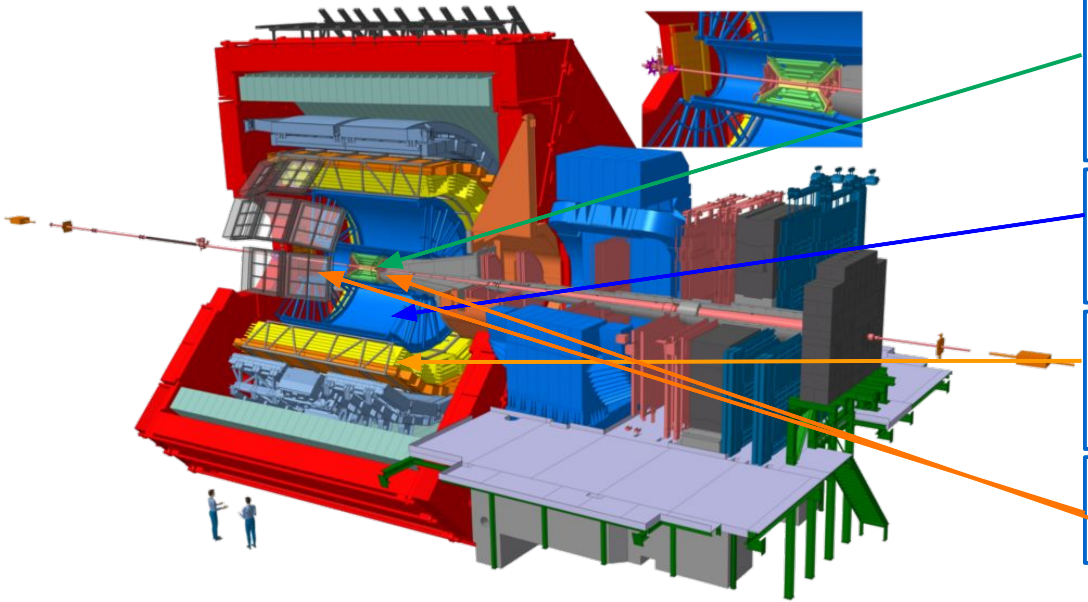
KN and $\bar{K}$N interactions : the game changer

Two-particle momentum correlation measured with ALICE at the LHC

- **KN** and **$\bar{K}$N** interaction
  - ALICE Collaboration PRL 124 (2020) 9, 092301
  - ALICE Collaboration PLB 822 (2021) 136708
  - ALICE Collaboration arXiv: 2205.15176
- **and other interactions:**
  - pp, pΛ, ΛΛ: ALICE Collaboration PRC 99(2019)
  - ΛΛ: ALICE Collaboration PLB 797 (2019) 134822
  - pΞ: ALICE Collaboration PRL 123 (2019) 134822
  - pΣ^0:ALICE Collaboration PLB 805 (2020) 135419
  - pΩ: ALICE Collaboration Nature 588 (2020) 232-238
  - pϕ: ALICE Collaboration PRL 127 (2021) 172301
  - B-$\bar{B}$:ALICE Collaboration PLB B 829 (2022) 137060
  - pΛ: ALICE Collaboration arXiv:2104.04427
  - pD: ALICE Collaboration arXiv:2201.05352
  - ΛΞ: ALICE Collaboration arXiv:2204.10258
  - ppp and ppΛ: ALICE Collaboration arXiv:2206.03344

ALICE

ALICE particle identification capabilities are unique. Almost all known techniques are exploited: specific energy loss (dE/dx), time of flight, transition radiation, Cherenkov radiation, calorimetry and decay topology (V0, cascade).



Inner Tracking System (ITS) :
- Primary vertex
- Tracking
- Particle identification via dE/dx

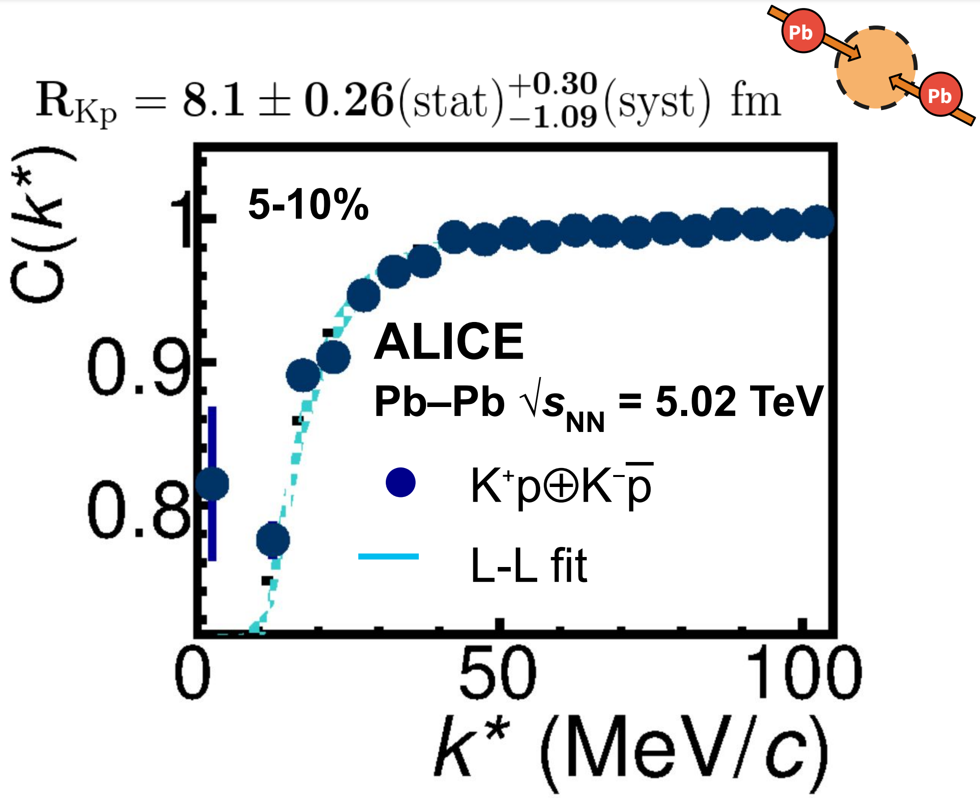
Time Projection Chamber (TPC):
- Global tracking
- Particle identification via dE/dx

Time Of Flight (TOF):
- Particle identification via velocity measurement

V0 (A-C): Trigger, beam-gas event rejection, centrality, multiplicity classes

ALICE Collaboration Int. J. Mod. Phys. A 29 (2014) 1430044

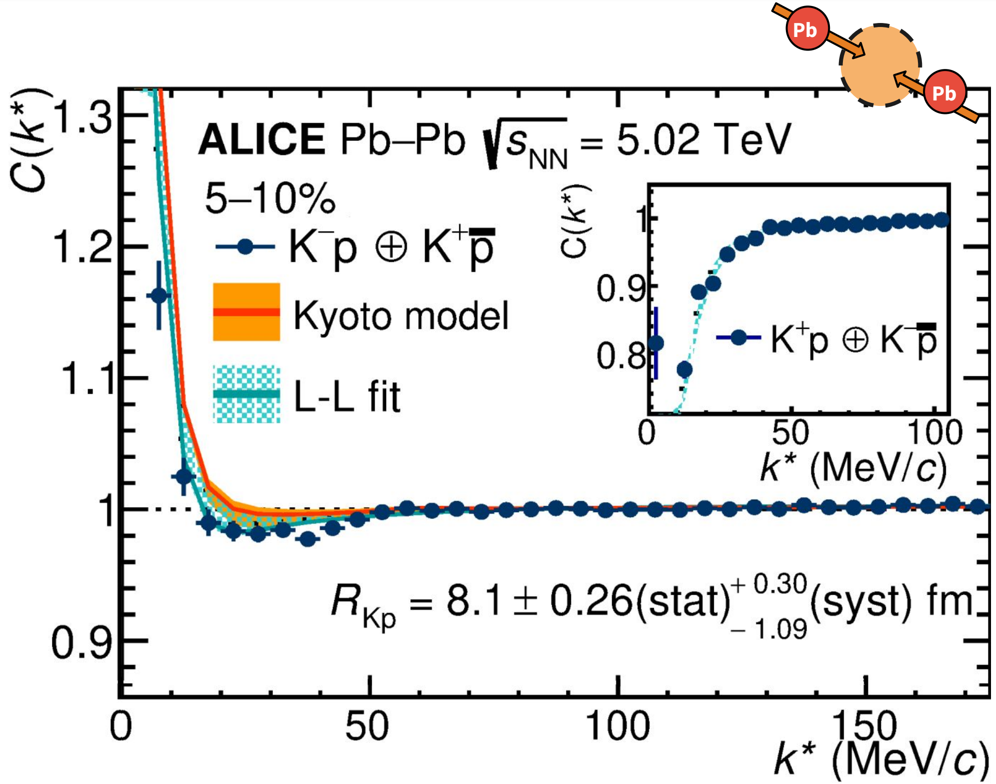
K^-p in large systems



- K^+p used to extract source size
  - Gaussian source
  - Lednický-Lyuboshitz (LL) fit to extract r_{eff}

PLB 822 (2021) 136708

K⁻p in large systems



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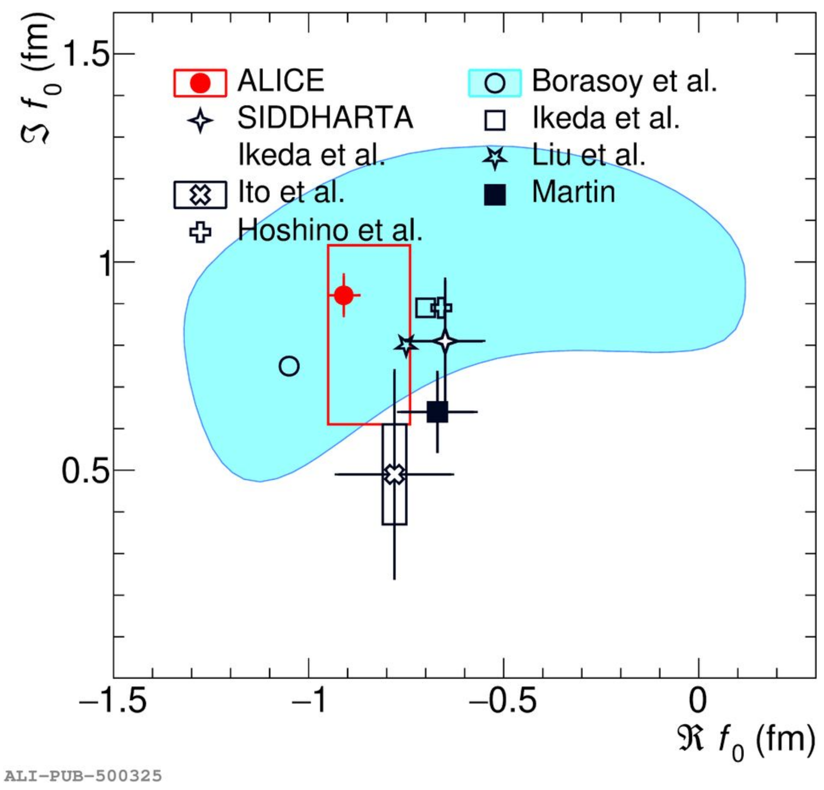
- Use Lednický-Lyuboshitz (LL) fit to extract $\Re f_0$ and $\Im f_0$

PLB 822 (2021) 136708

K^-p in large systems



PLB 822 (2021) 136708

- K^+p used to extract source size
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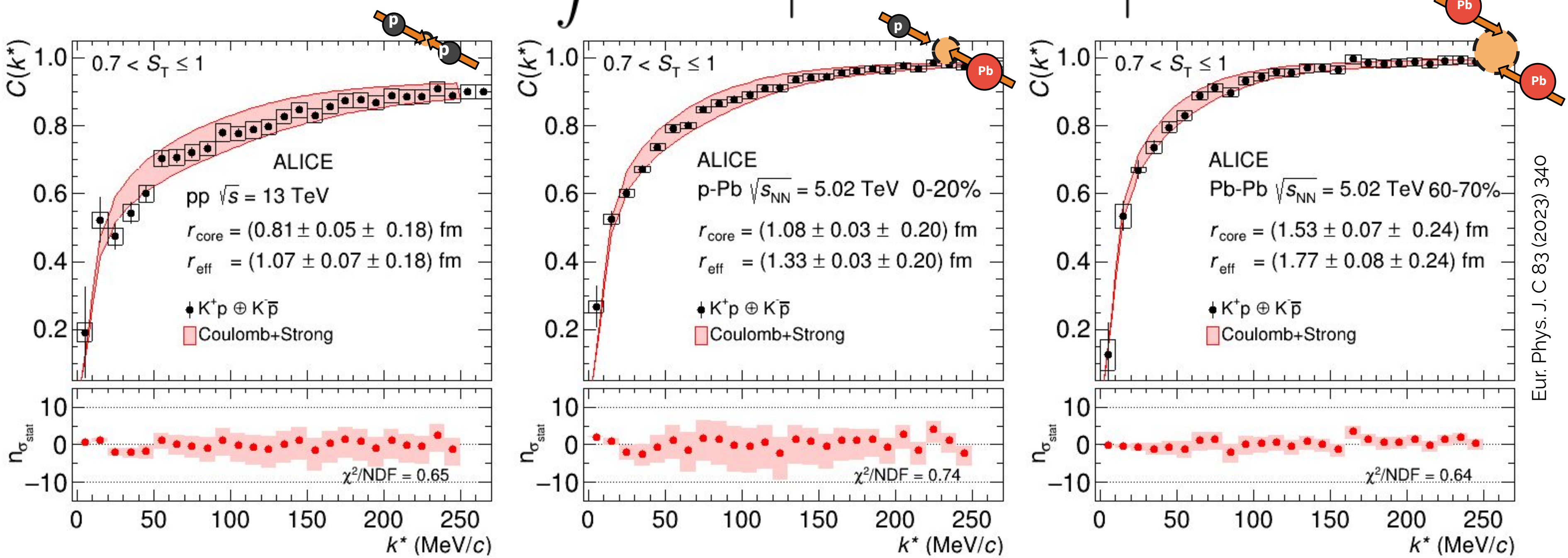
- Large system: no coupled channels (as in Kyoto model)
- Use Lednický-Lyuboshitz (LL) fit to extract $\Re f_0$ and $\Im f_0$
- $\Re f_0$ and $\Im f_0$ in agreement with available data and calculations
  - Alternative to exotic atoms and scattering experiments!

Kp emitting source

$$C(k^*) = \int S(\vec{r}^{\,*}) \left|\psi_{\mathrm{K^+p}}(\vec{k}^*, \vec{r}^{\,*})\right|^2 d^3\vec{r}^{\,*}$$



Eur. Phys. J. C 83 (2023) 340

The data are well reproduced by the assumed K⁺p interaction and different r_{core} are extracted

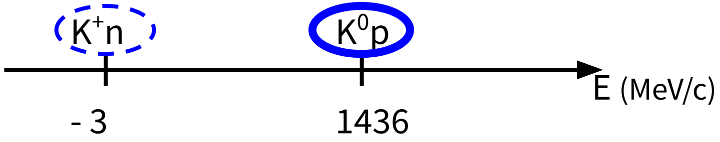
Fit: CATS D. L. Mihaylov et al., EPJ C78 (2018) 5, 394

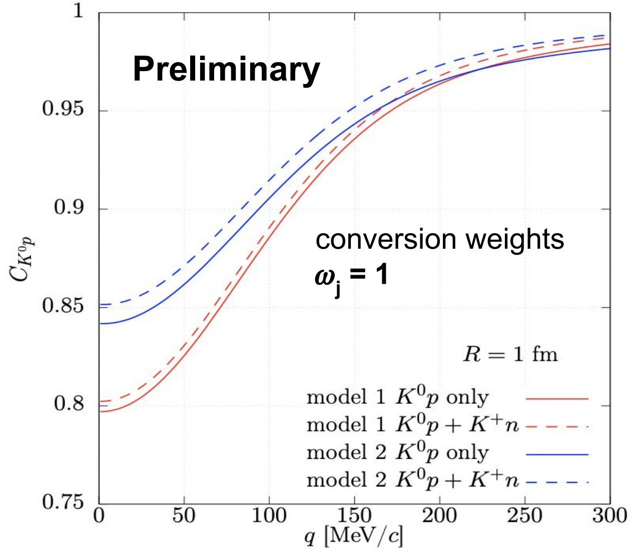
Accessing KN and K̄N interaction with K⁰

- K^0_s –p system is a combination of strong eigenstates

$$|K^0_s p\rangle = \frac{1}{\sqrt{2}}\left[|K^0 p\rangle - |\bar{K}^0 p\rangle\right] \Rightarrow C_{K^0_s p} = \frac{1}{2}\left[C_{K^0 p} + C_{\bar{K}^0 p}\right]$$

- Weak strong repulsion
- 1 CC below threshold: K^+n
  - predicted to be a weak coupling
- Calculations from **A**oki-**J**ido χEFT model for KN[1]





Courtesy of Y. Kamiya

[1] K. Aoki and D. Jido, PTEP 2019, 013D01 (2019), 1806.00925.

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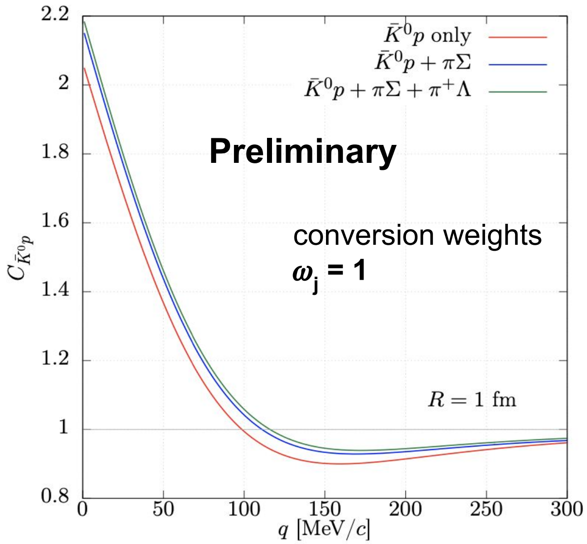
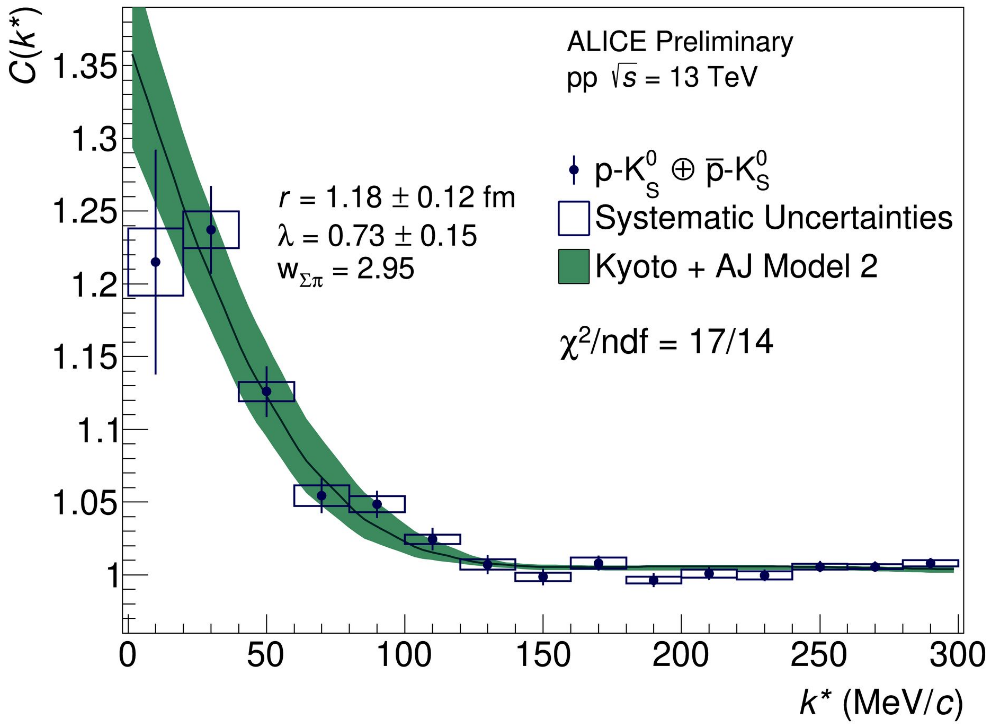
- Moderate attraction
- 3 CC below threshold: $\pi^0\Sigma^+$, $\pi^+\Sigma^0$, $\pi^+\Lambda$
    - large $\pi\Sigma$ coupling (as in K^-–p)
- Calculations from **Kyoto** χEFT model for K̄N used for K^-p [1,2]



Courtesy of Y. Kamiya

[1] K. Miyahara, et al., PRC98, 025201 (2018), arXiv: 1804.08269
[2] Y.Kamiya, et al., PRL124 (2020) 132501

K^0_S–p interaction



ALI-PREL-487651

- Gaussian source function with r=1.18±0.12 fm [1]
- $K^0p(\bar{p})$ and $\bar{K}^0(\bar{p})$ ψ with CC provided by Kyoto χEFT
- Conversions weights $\omega = 1$ for K^0p, K^+n, and $\pi^+\Lambda$; $\omega_{\Sigma\pi} = 2.95$ [2]

- **Model describes data within 2σ between 0 and 300 MeV/*c***
  - State-of-the-art theory well describes the experimental data
    - Small caveat: source not (yet) studied in details

[1] ALICE Collaboration, PRL 124, 092301 (2020)
[2] Y.Kamiya, et al., PRL 124 132501 (2020)

Contributions to the experimental correlation function

- Fit of the $C(k^*) = C_{data}(k^*)/C_{baseline}(k^*)$ to obtain the parameters of the strong interaction between K^0_S and p($\bar{p}$) is performed with the function:

$$C(k^*) = \left[1 + \lambda_{genuine}\left(C_{FSI}(k^*) - 1\right) + \sum_{i,j} \lambda_{ij}\left(C_{ij}(k^*) - 1\right)\right] \cdot Norm$$

- $\lambda_{genuine}$: Fraction of identified and primary particles, used as $C_{FSI}(k^*)$ weight
- $C_{FSI}(k^*) - 1$: Final-state interactions contribution
- $\sum_{i,j} \lambda_{ij}\left(C_{ij}(k^*) - 1\right)$: Contribution linked to the presence of misidentified particles
- $Norm$: Normalization

$$\sum_{i,j} \lambda_{ij}\left(C_{ij}(k^*) - 1\right) = \lambda_{\tilde{K}}\left(C_{\tilde{K}}(k^*) - 1\right) + \lambda_{\tilde{p}(\tilde{\bar{p}})}\left(C_{\tilde{p}(\tilde{\bar{p}})}(k^*) - 1\right)$$

K^0_S–p correlation function fit with Lednický-Lyuboshitz

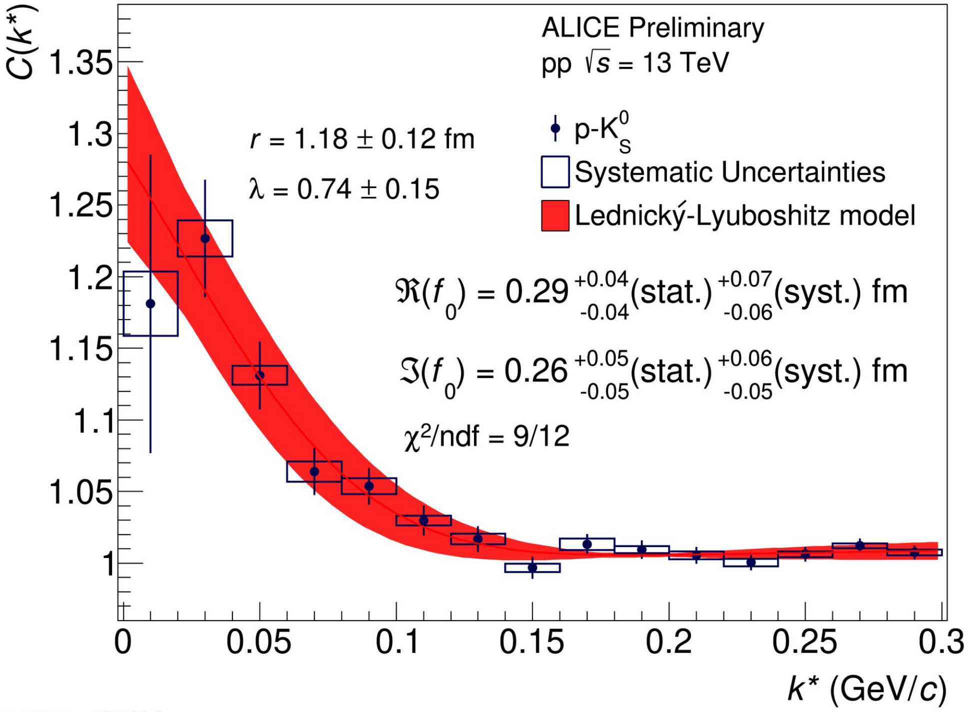
$$C_{FSI}(k^*) = \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f(k^*)}{R} \right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi}R}\right) + \frac{2\Re f(k^*)}{\sqrt{\pi}R} F_1(2k^*R) - \frac{\Im f(k^*)}{R} F_2(2k^*R) \right]$$

$$C_{Lednicky}(k^*) = 1 + C_{FSI}(k^*)$$

Scattering amplitude:

$$f(k^*) = \left(\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^* \right)^{-1}$$

- f_0 scattering length, d_0 effective range of interaction
  - $\Re f_0, \Im f_0$ estimated parameters
- **$\Re f_0$ >0 : attractive interaction**
- **$\Im f_0$ ≠0 : presence of annihilation processes**



ALI-PREL-487626

Resonances used for πΣ(Λ) source (π)

- For modeling the source every resonance with a $c\tau > 8$ fm is taken out and the yields properly renormalized. These resonance are used to determine the decay-kinematics with EPOS.

Primordial fraction	Resonance fractions			
	$c\tau < 1$ fm	$1 < c\tau < 2$ fm	$2 < c\tau < 5$ fm	$c\tau > 5$ fm
28 %	15 %	35 %	10 %	12 %

$\langle m(\pi)\rangle = 1124$ MeV/c^2

$\langle c\tau(\pi)\rangle = 1.5$ fm

Resonance	ρ^0	ρ^+	ω	$K(892)^{**}$
Yield (in %)	9.01	8.71	7.67	2.29

Only resonances which contribute more then 2% to total yield are shown

Resonances used for $\pi\Sigma(\Lambda)$ source ($\Sigma\Lambda$)

- For modeling the source every resonance with a $c\tau > 8$ fm is taken out and the yields properly renormalized. These resonance are used to determine the decay-kinematics with EPOS.

Primordial fraction	Resonance fractions			
	$c\tau < 1$ fm	$1 < c\tau < 2$ fm	$2 < c\tau < 5$ fm	$c\tau > 5$ fm
26 %	0 %	5 %	5 %	64 %

$\langle m(\Sigma)\rangle = 1463$ MeV/c^2

$\langle c\tau(\Sigma)\rangle = 4.7$ fm

Resonance	Σ^0	Σ^{*0}	Σ^{*+}	Σ^{*-}
Yield (in %)	27	12	12	12

Only resonances which contribute more then 2% to total yield are shown

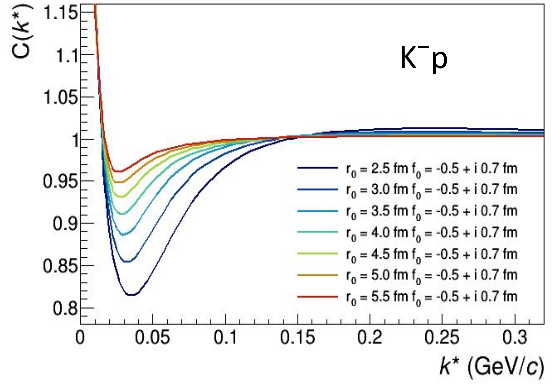
Lednický-Lyuboshitz model

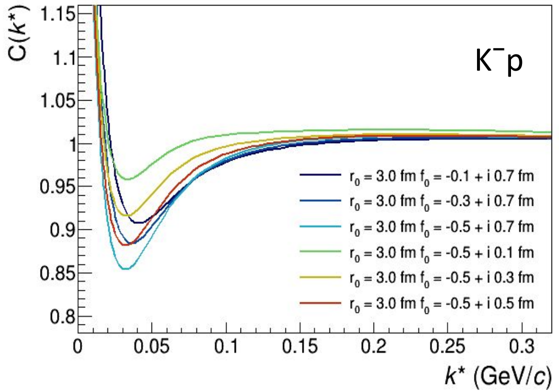
$$C(\mathbf{k}^*) = \frac{\int S(\mathbf{r}^*,\mathbf{k}^*)|\psi(\mathbf{r}^*,\mathbf{k}^*)|^2}{\int S(\mathbf{r}^*,\mathbf{k}^*)} \mathrm{d}^4 r^*$$

$$|\psi(r^*,k^*)| = \sqrt{A_C(\eta)}\left[exp(-ik^*r^*)F(-i\eta,1,i\xi) + f_c(k^*)\frac{G}{r^*}\right]$$

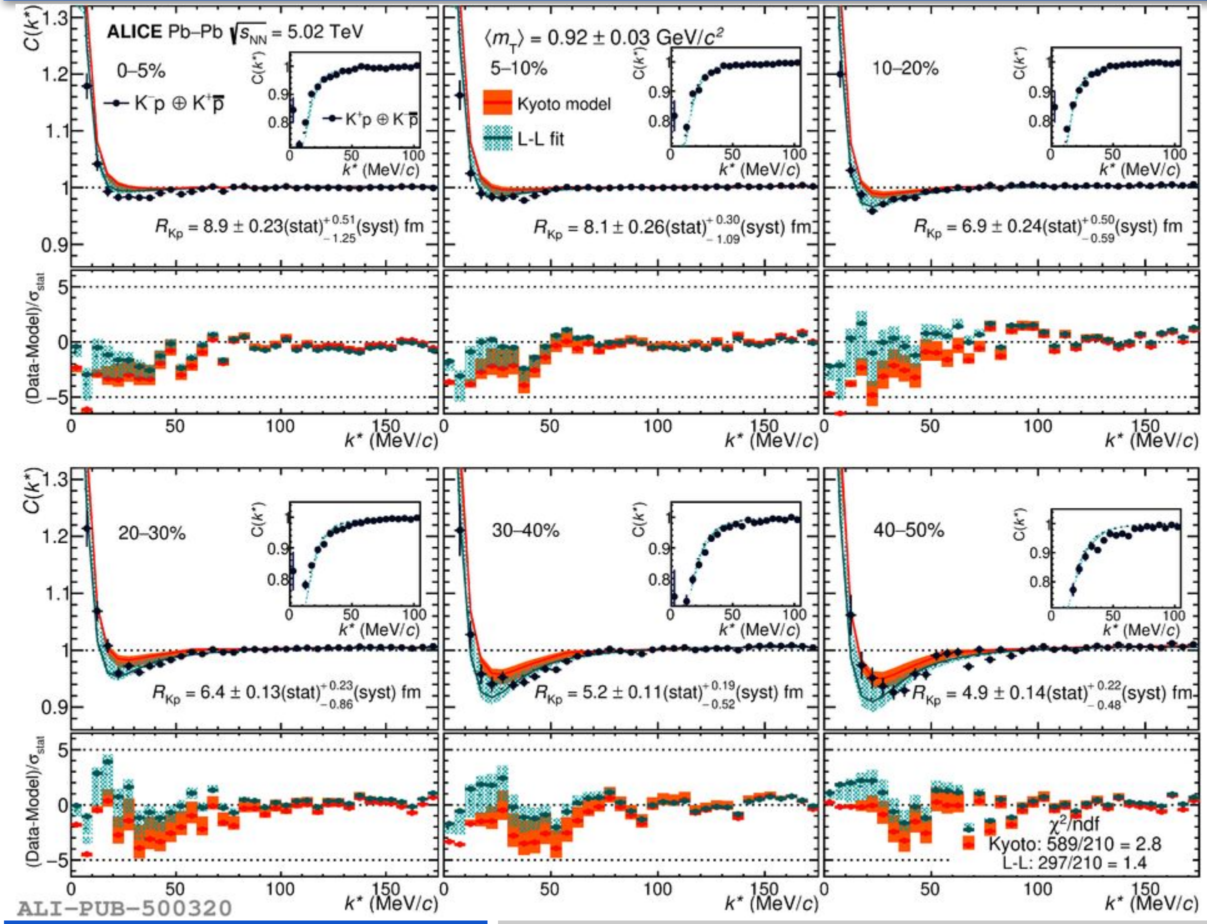
$$f_c(k^*) = \left(\frac{1}{f_0} + \frac{d_0 \cdot k^{*2}}{2} - \frac{-2h(k^* a_c)}{s_c} - ik^* A_C(k^*)\right)^{-1}$$

- Numerically solvable (strong+Coulomb)
- **3 parameters:** $\Re f_0$, $\Im f_0$ and source r define the correlation function.
- $d_0 = 0$ (zero effective range approx.)





Kaon-proton in Pb–Pb



- No K^0n structure
- Simultaneous description (and fit) of the correlation functions for 6 centralities (0-50%) with two parameters and 6 radii
- Radii constrained from K^+p

Modeling the correlation p$\bar{\text{p}}$ correlation

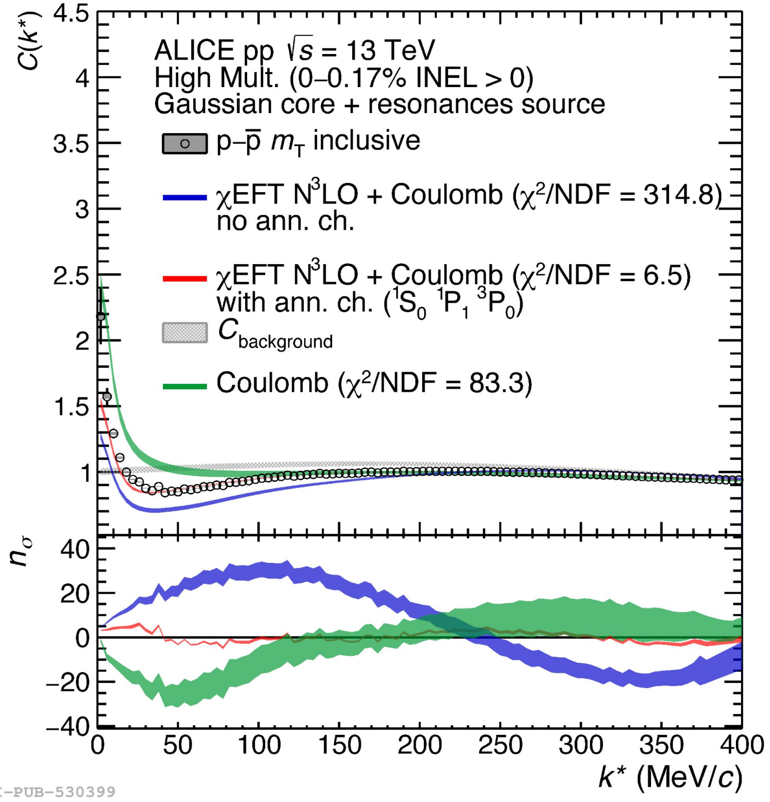
elastic | n-n̄ → p-p̄ | multi-meson annihilation channels

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

- **Chiral Effective Field Theory at N^{3}LO** (with n-n̄: **coupled-channel**) wavefunctions with Coulomb
  - S and P waves, tuned to scattering data and protonium
- **Approximate inclusion of annihilation channels** (X→ p-p̄) 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

Results on p$\bar{p}$: modelling the correlation

- No cusp of n-n̄: 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-p̄ pairs
- Annihilation channels X→ p-p̄
  - 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)



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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)

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

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

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

Comparison Pb–Pb and pp data in B-antiB