Two and three-body interactions among kaons and nucleons tested at the LHC

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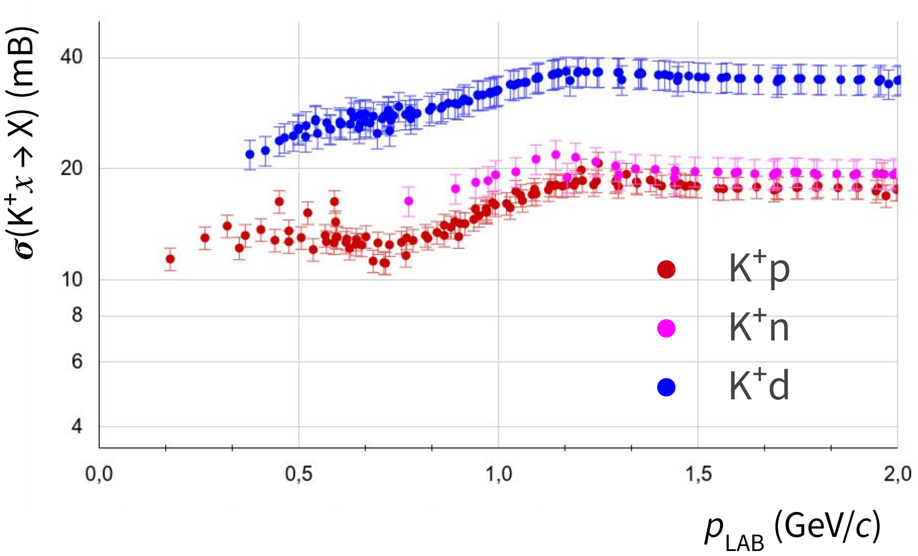
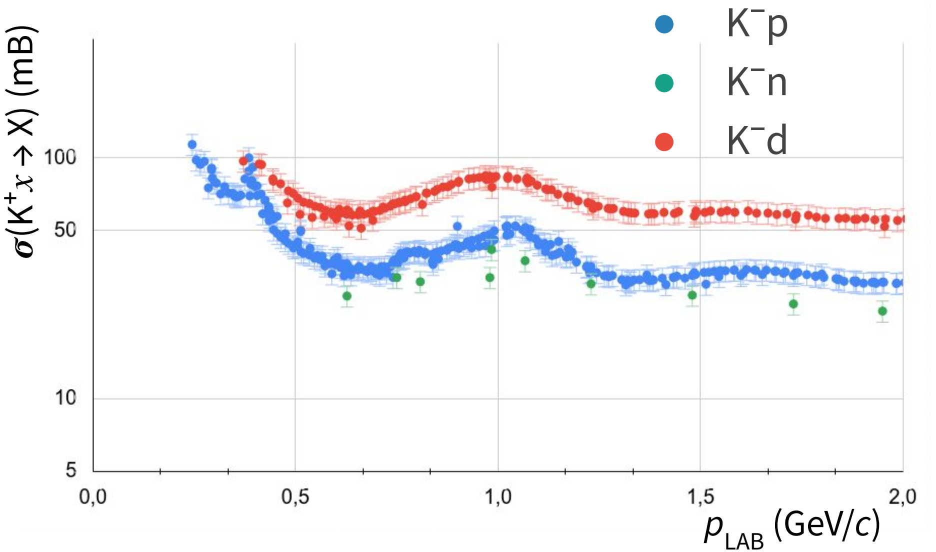
SQM 2022 - The 20th International Conference on Strangeness in Quark Matter

KN and $\bar{K}$N interactions and how to study them

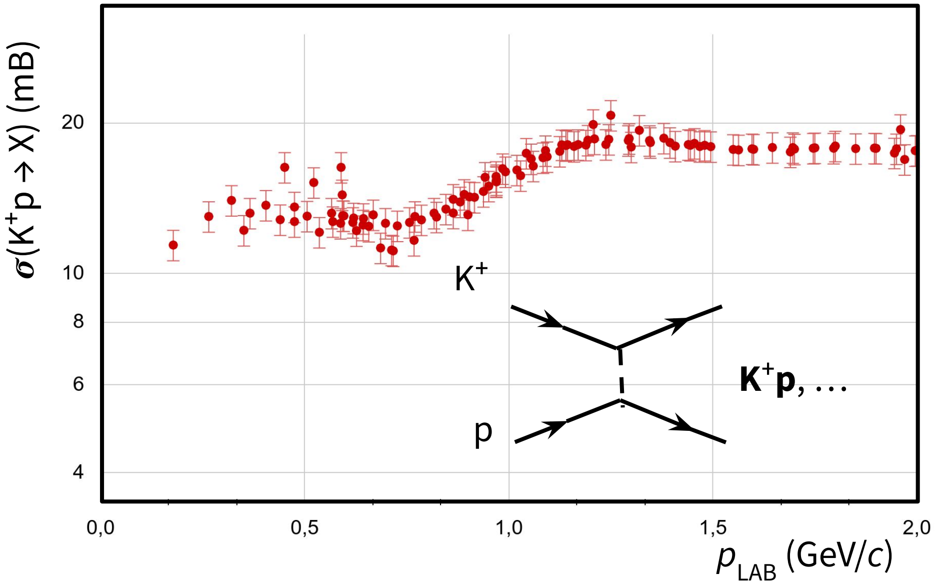
- Kaon (K) nucleon (N) and anti-Kaon $\bar{K}$N interactions are fundamental for the study of low-energy QCD
  - K = K^+ (u,$\bar{s}$), K^0(d$\bar{s}$); $\bar{K}$ = K^-(s$\bar{u}$), $\bar{K}^0$ (s,$\bar{d}$)
- Traditionally, these interaction are studied by <u>scattering experiments</u> (K^+(p,n,d) and K^-(p,n,d)) at low energies
  - few experimental measurements with big uncertainties and not at low-energy p_{lab} < 50 MeV/c





Particle Data Group Phys.Rev. D98 (2018) no.3, 030001

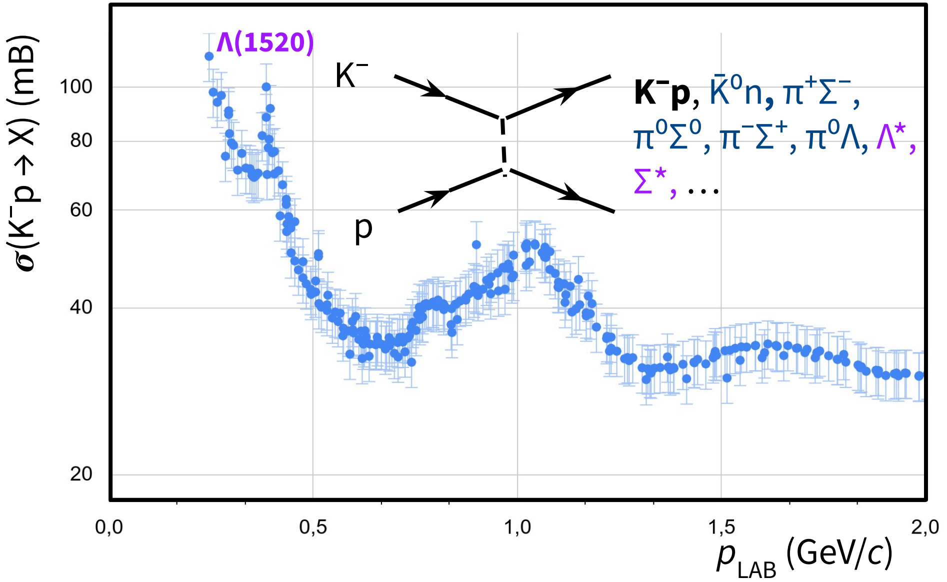
K^+p interaction



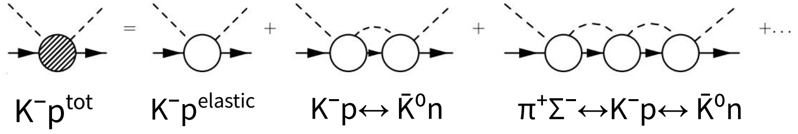
- **K^+p interaction**
  - Repulsive (due to Coulomb and strong interactions)
  - No coupled channels
  - No resonances
    - well known [1]

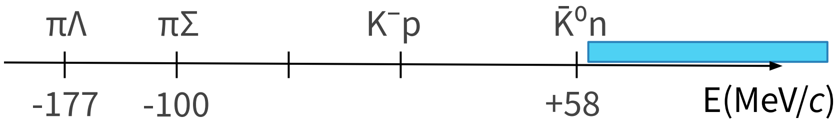
[1] K. Aoki and D. Jido, PTEP 2019 no. 1, (2019) 013D01 (arXiv:1806.00925 [nucl-th])

K⁻p interaction

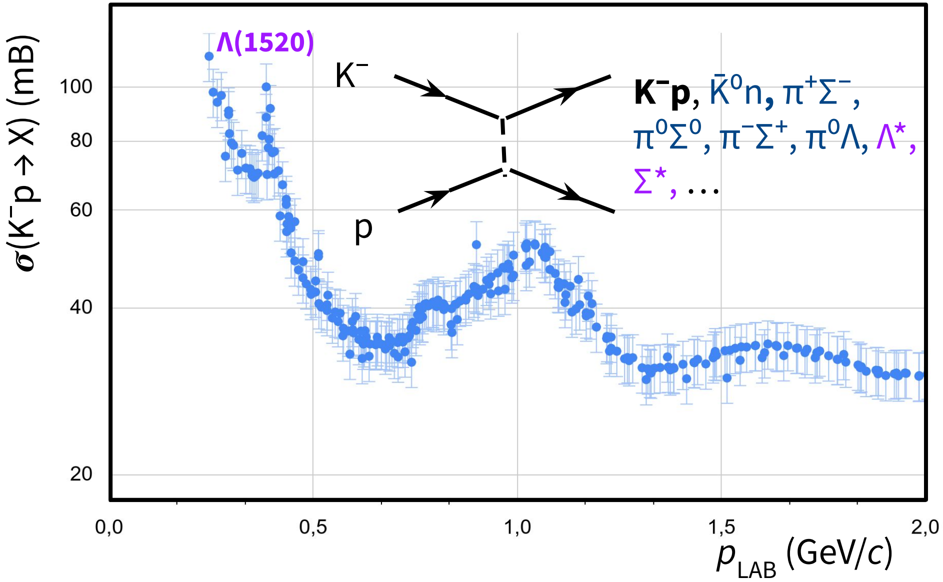


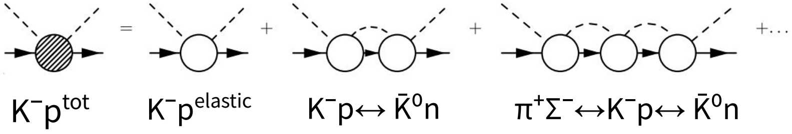
- **K⁻p interaction**
  - deeply attractive
  - several **resonances**
  - several **coupled-channels** ($\bar{K}^0n$, $\pi^+\Sigma^-$, $\pi^0\Sigma^0$, $\pi^-\Sigma^+$, $\pi^0\Lambda$)
    - systems close to the K⁻p threshold and with the same quantum numbers





K^-p interaction





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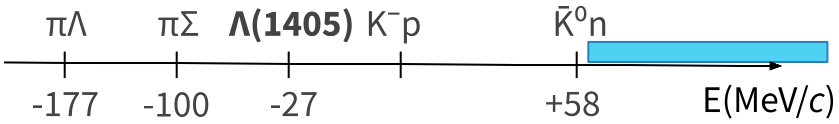
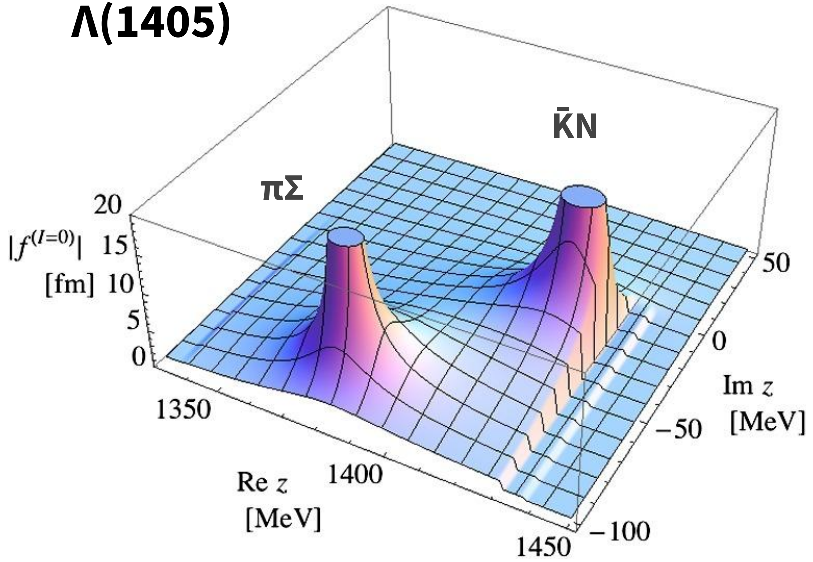
  - several **resonances**
  - several **coupled-channels** ($\bar{K}^0n$, $\pi^+\Sigma^-$, $\pi^0\Sigma^0$, $\pi^-\Sigma^+$, $\pi^0\Lambda$)
    - systems close to the K^-p threshold and with the same quantum numbers
    - $\bar{K}N \leftrightarrow \pi\Sigma$ dynamics leads to the formation of the **Λ(1405)**, ~27 MeV below K^-p threshold

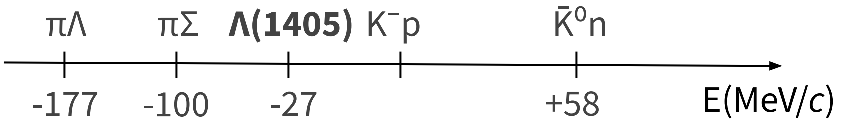


K⁻p interaction and Λ(1405)

Λ(1405)



- Nature of Λ(1405): dynamically generated resonance
  - Models based on below-threshold extrapolations
    - pole positions is model dependent (relative contributions not measured experimentally)



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

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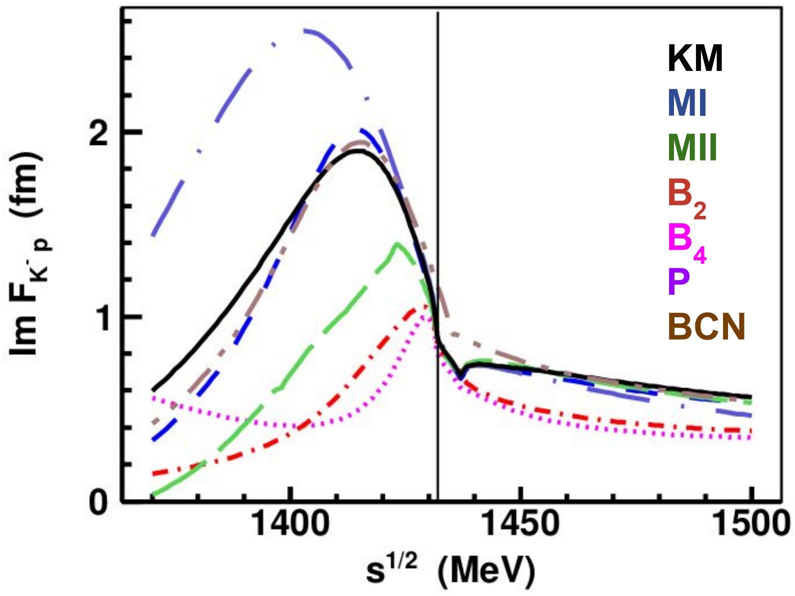

A. Cieplý et al, arxiv:2001.08621

- KM Y. Ikeda, et al. NPA 881 (2012) 98
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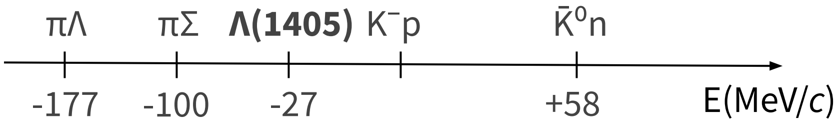

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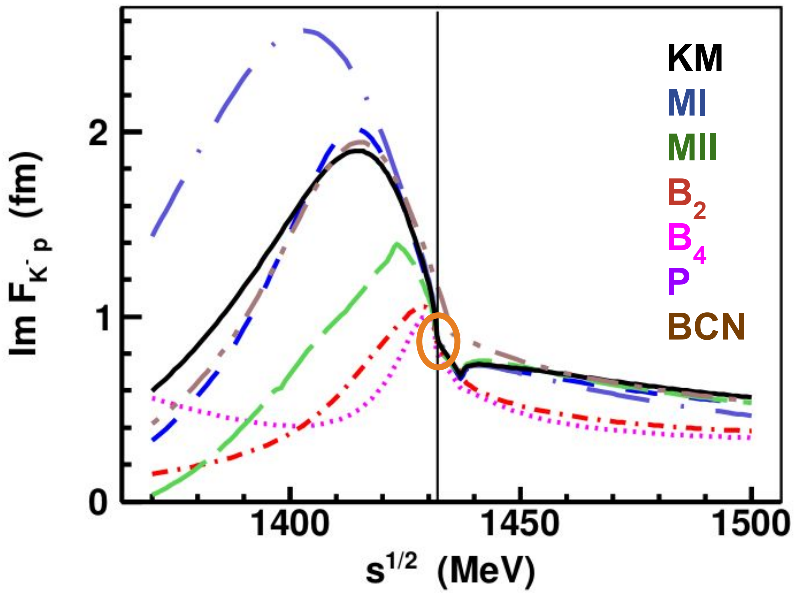

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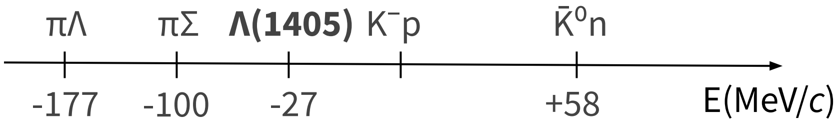

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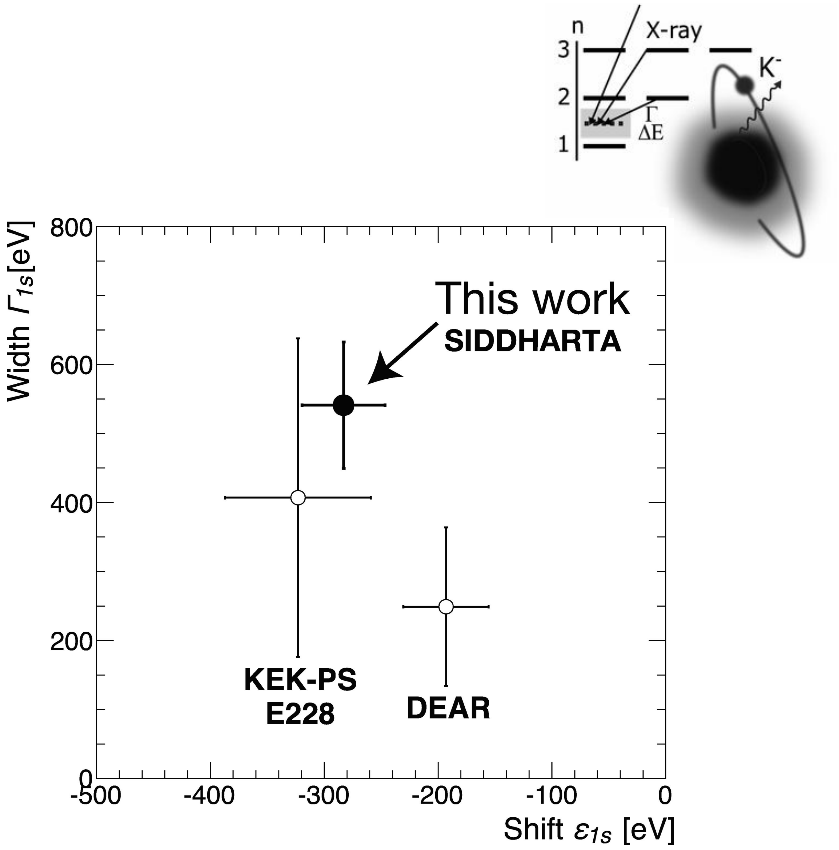

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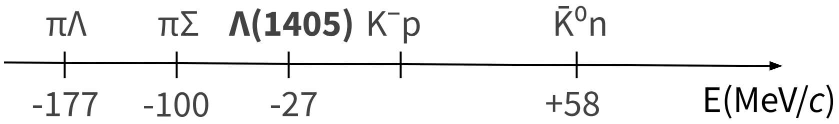
    - Constraint at threshold by SIDDARTHA measurement [1] of kaonic hydrogen 1s level shift and width



[1] SIDDHARTA collaboration PLB704 (2011) 113

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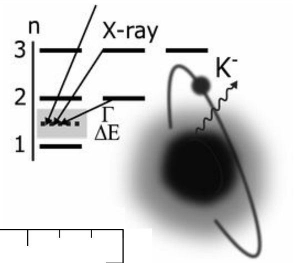

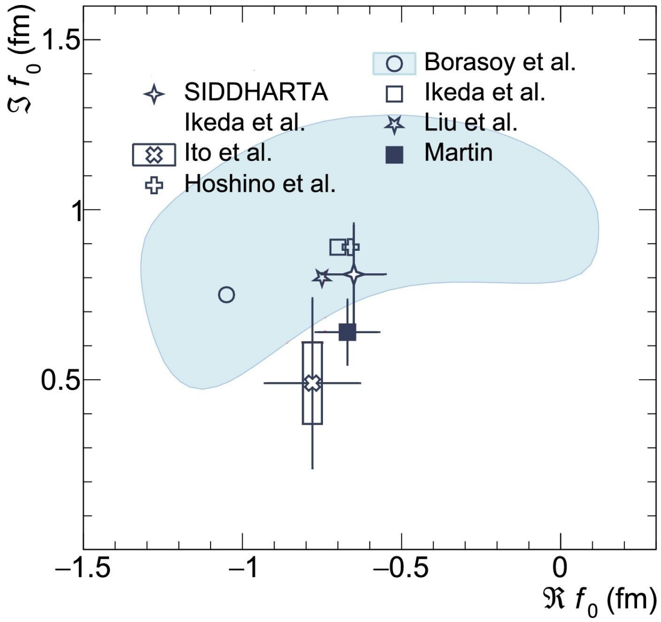

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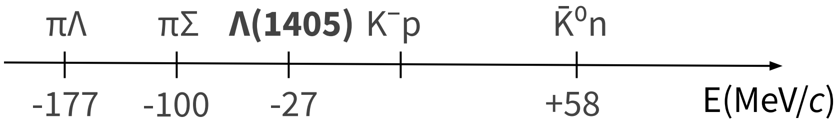
      - scattering length



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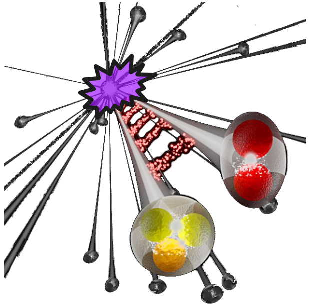
KN and $\bar{K}$N interactions : the game changer

Two particle momentum correlation measured with ALICE at the LHC

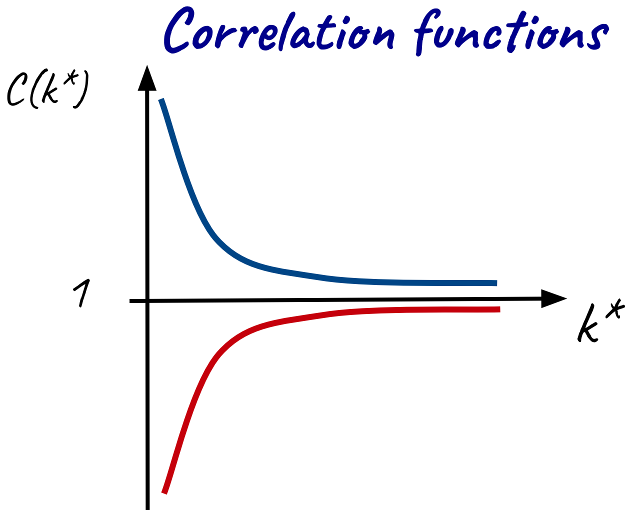
- **KN** and **$\bar{K}$N** interaction
  - ALICE collaboration PRL 124 (2020) 9, 092301
  - ALICE collaboration PLB 822 (2021) 136708
  - ALICE collaboration arXiv: 2205.15176

- **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

Two particle momentum correlation…

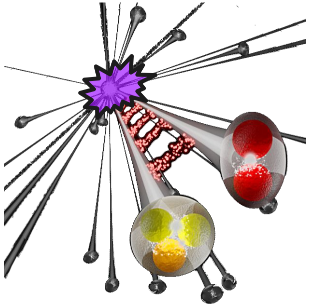


$$k^* = \frac{|\vec{p}_1 - \vec{p}_2|}{2}$$



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

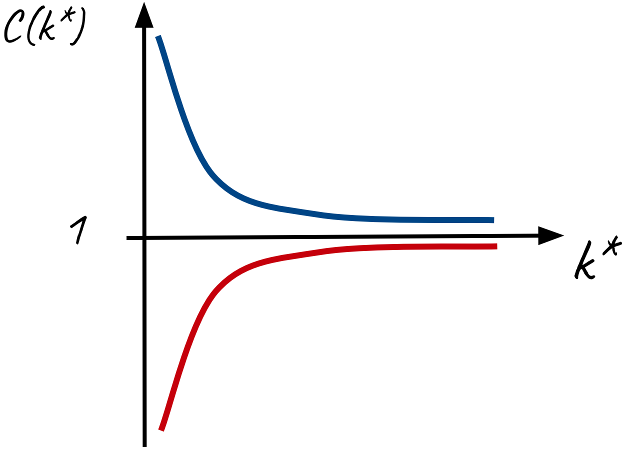
Two particle momentum correlation...



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

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

Correlation functions



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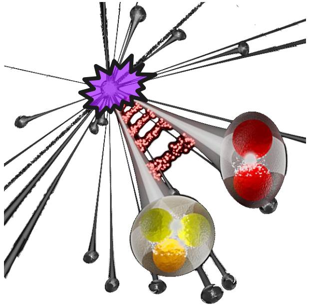
Two particle momentum correlation…



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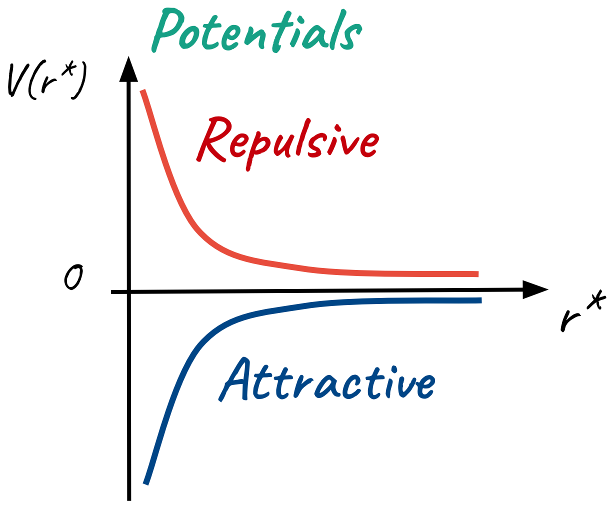
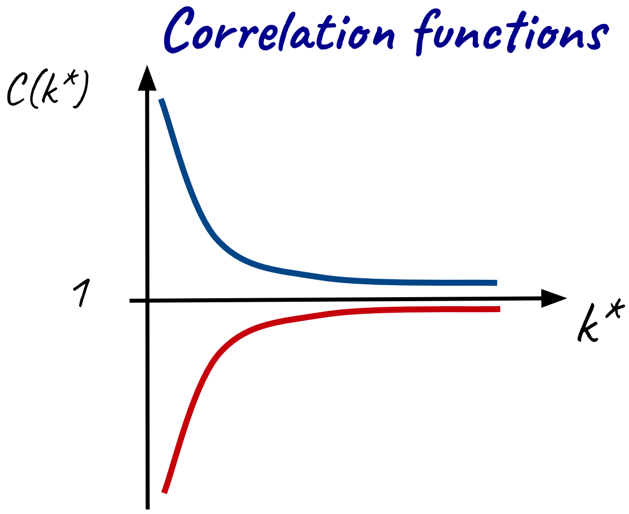
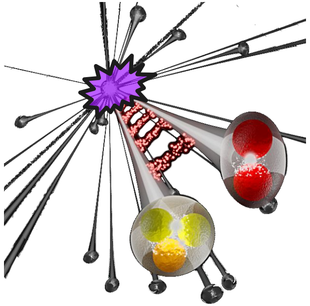




Two-particle wave function

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

Two particle momentum correlation…



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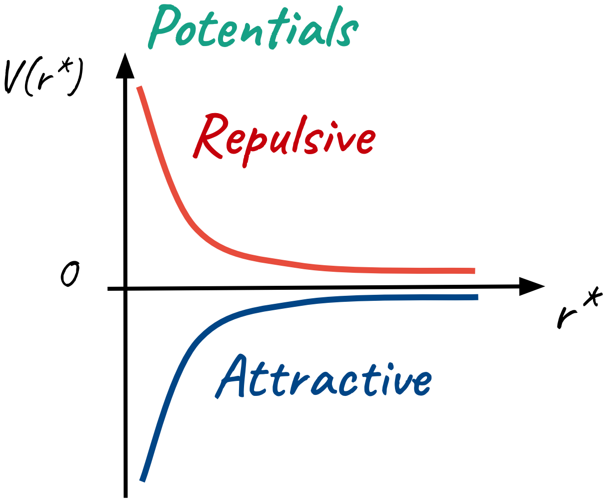

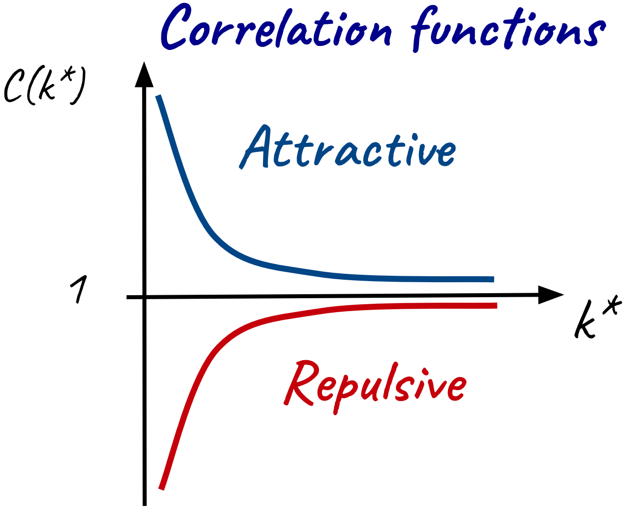

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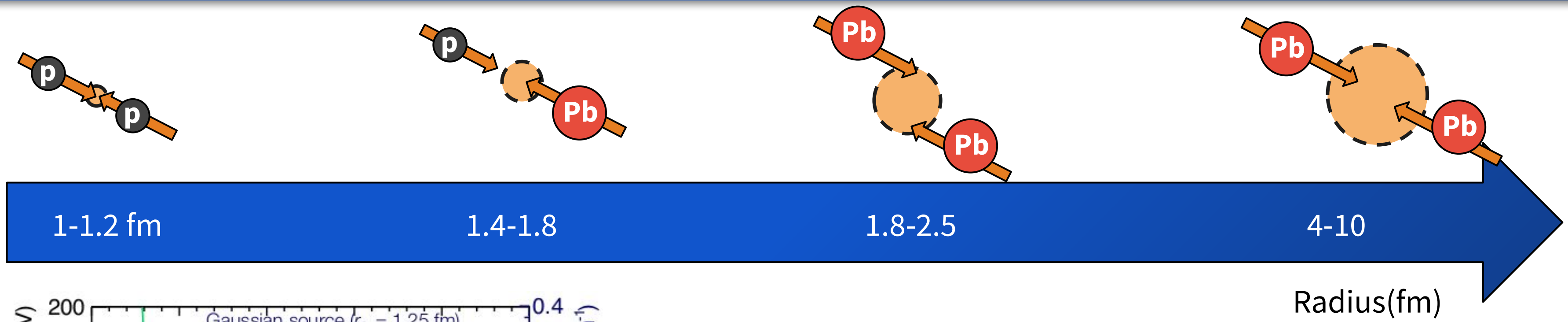
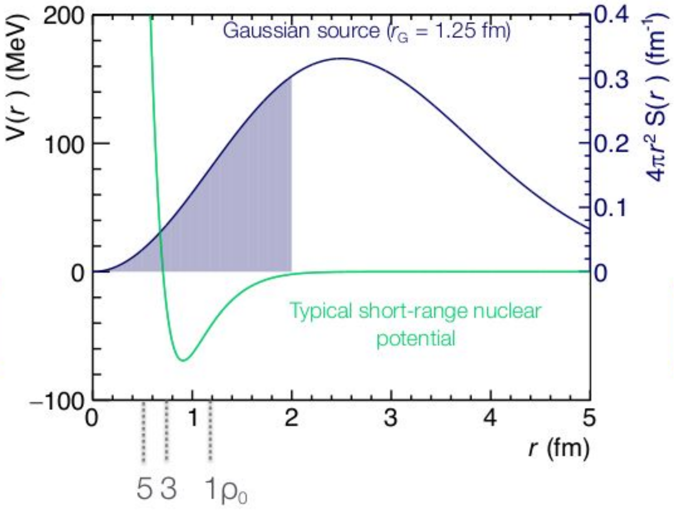
Measure *C(k*)* → fixing the source S(*r**), study the interaction

… from small to large systems

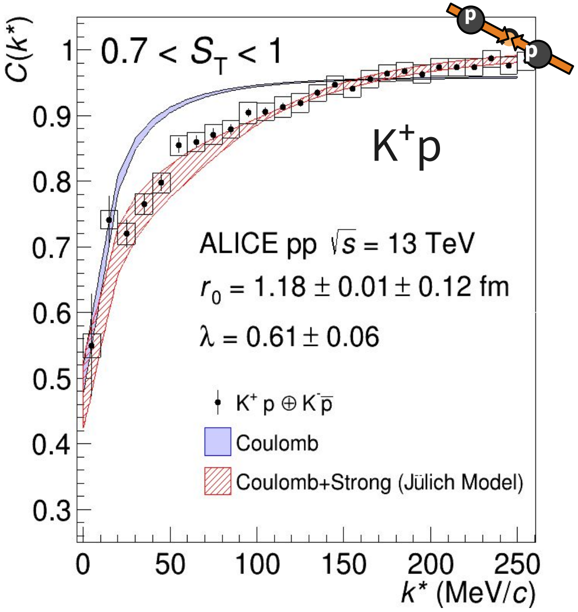




- By changing the colliding system it is possible to probe interaction distances ranging from ~1 fm up to ~10 fm

KN and K̄N interactions : the game changer

Two particle momentum correlation measured with ALICE at the LHC



- The Coulomb-only potential is not able to describe K$^+$p interaction and the introduction of the strong potential is needed to fit the data:
  - CFs are sensitive to the strong interaction

ALICE collaboration PRL 124 (2020) 9, 092301
Fit: CATS D. L. Mihaylov et al. EPJ C78 (2018) 5, 394)

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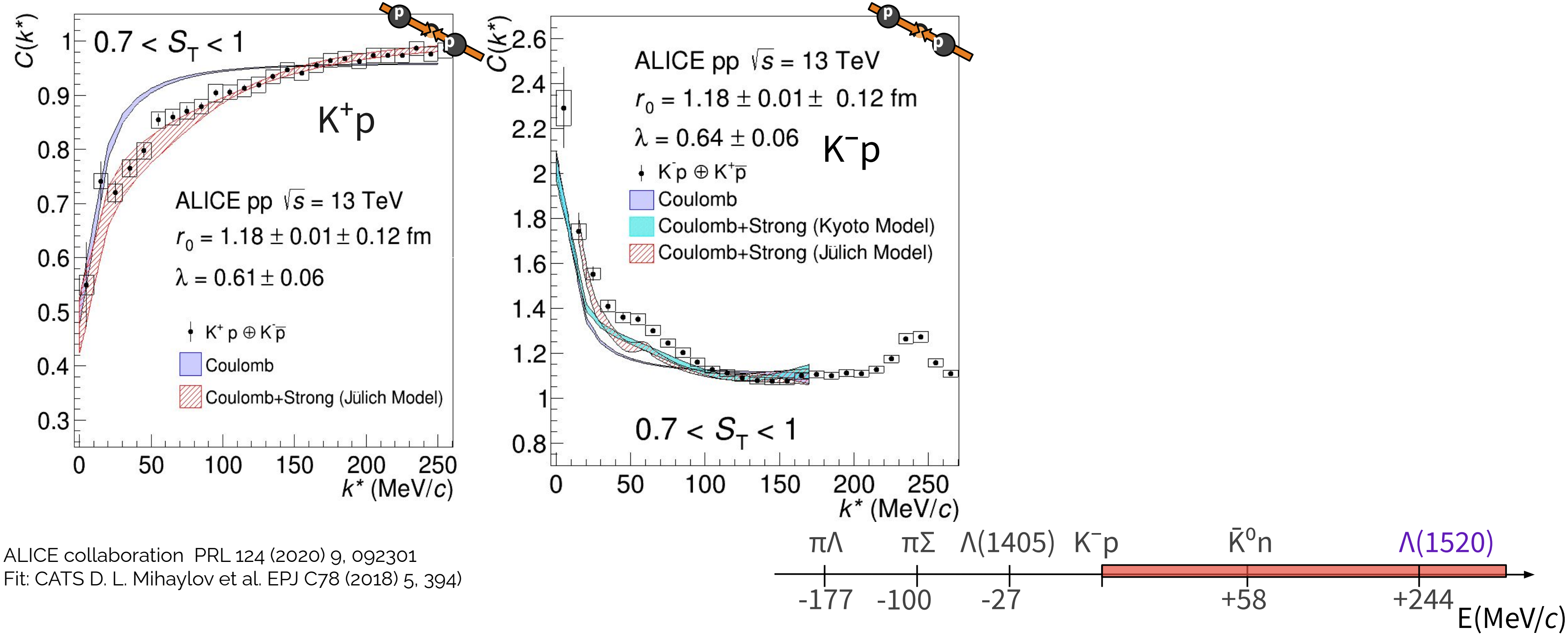

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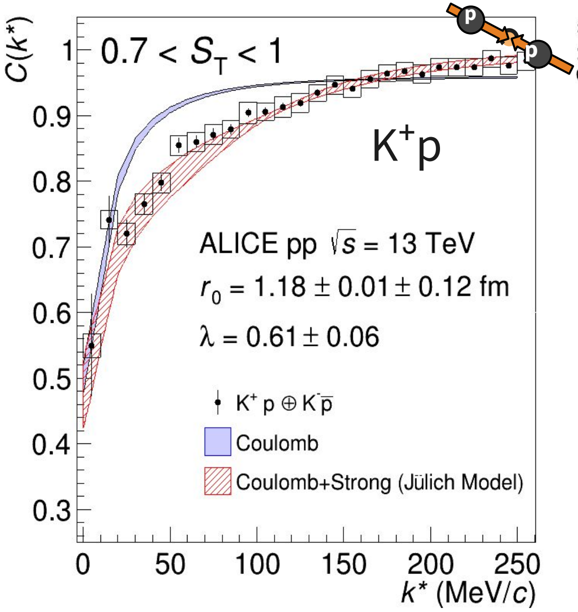

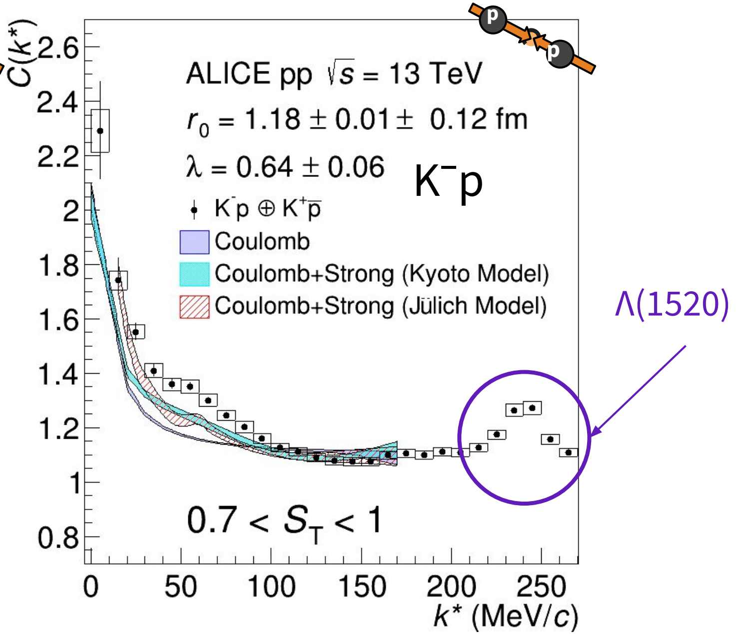

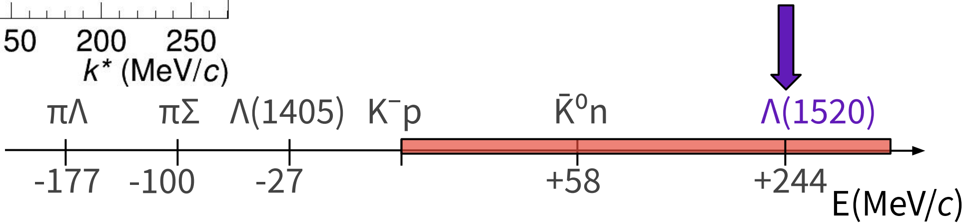

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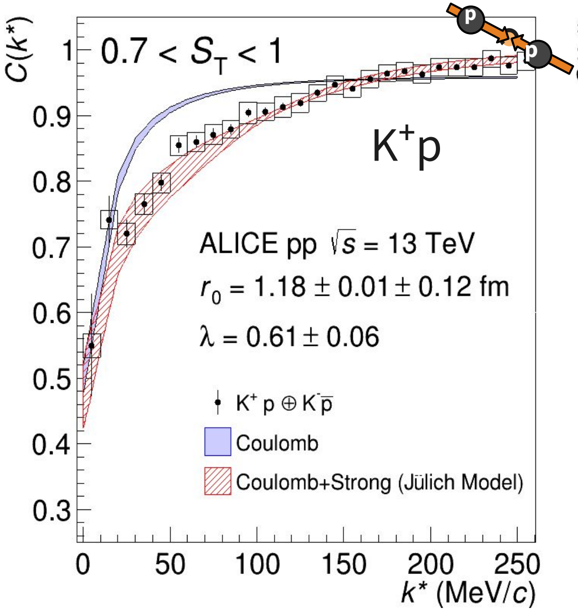

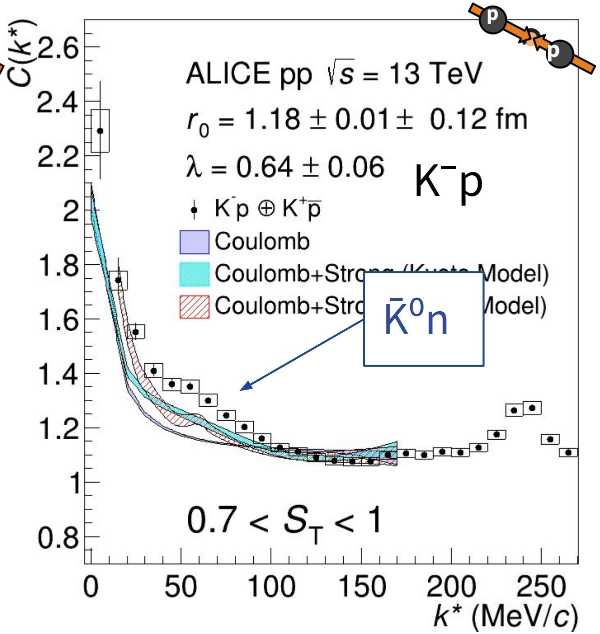

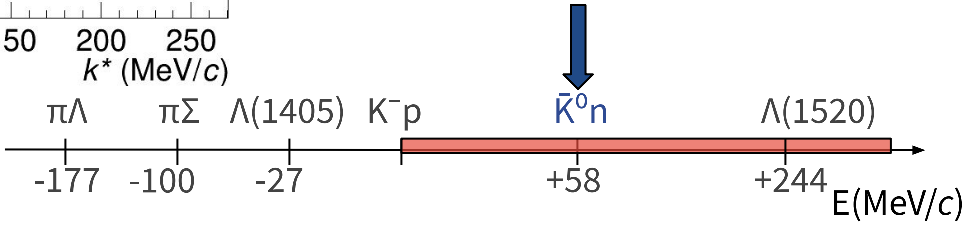

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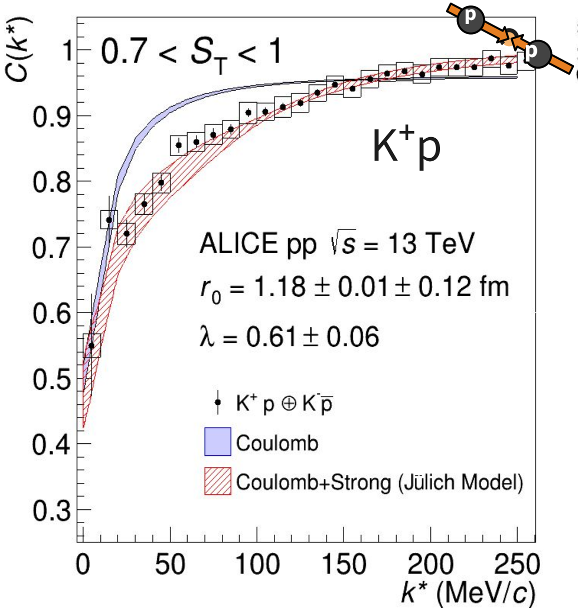

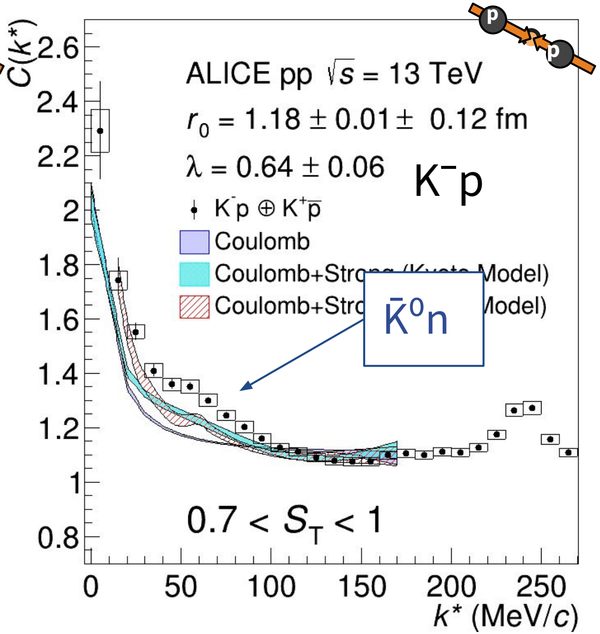

- First experimental evidence for the opening of the $\bar{K}^0n$ channel
- New constraints for low-energy QCD chiral models

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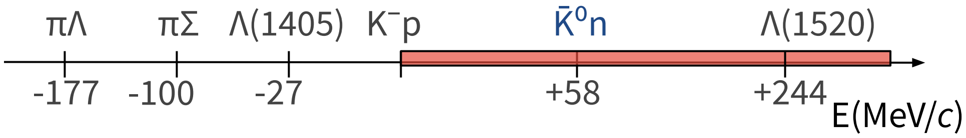

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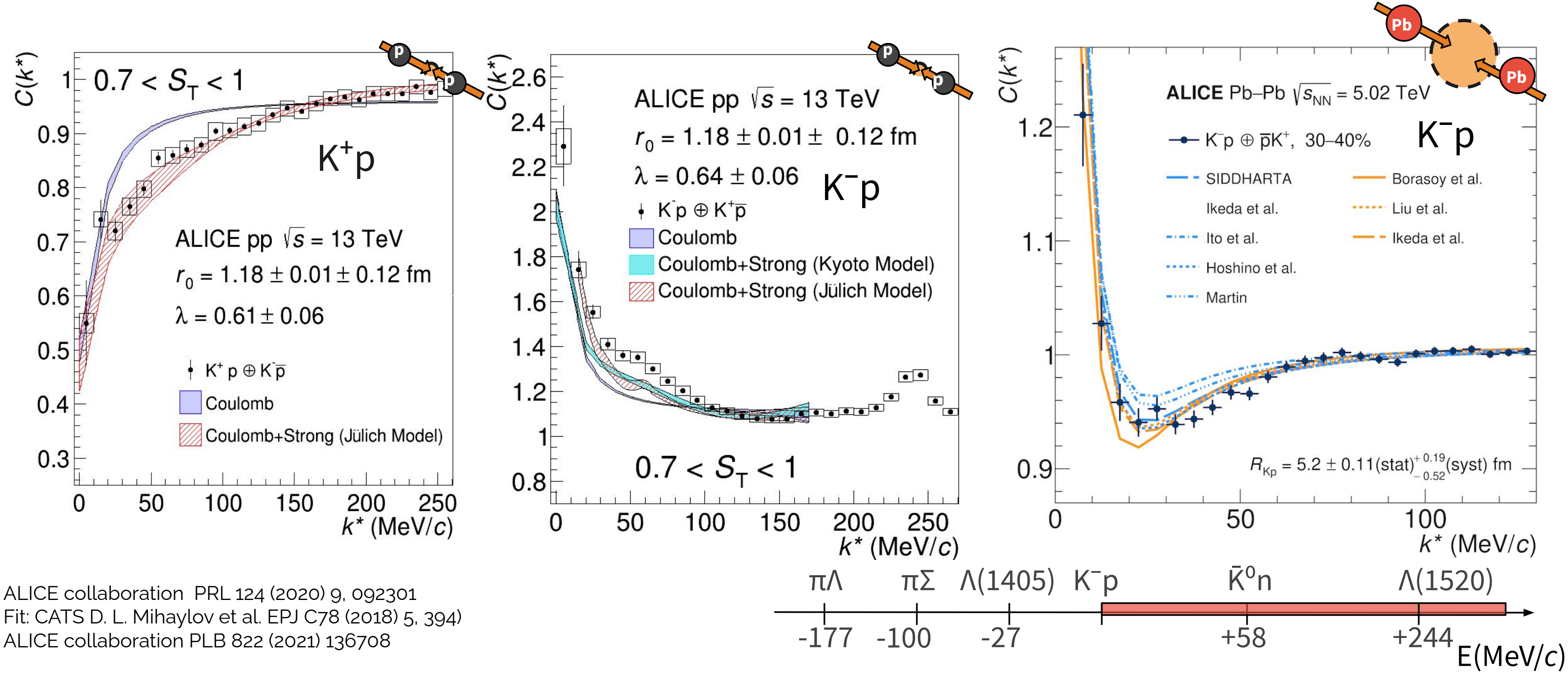


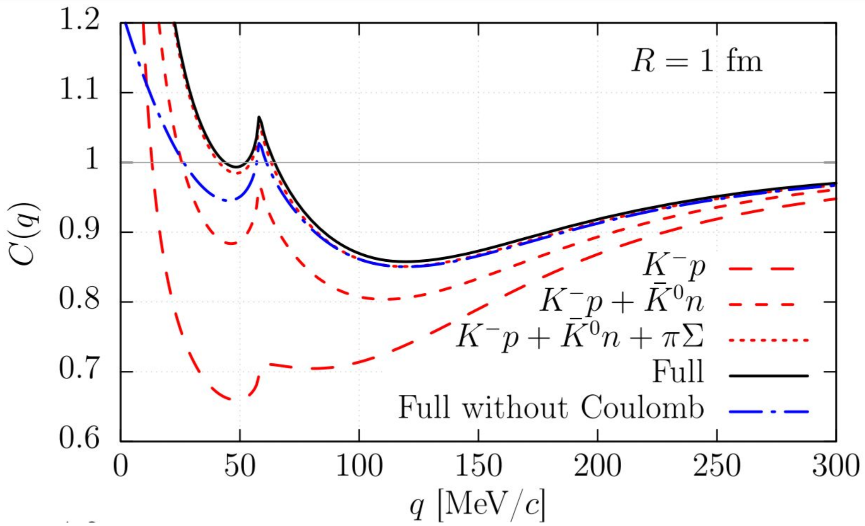
ALICE collaboration PRL 124 (2020) 9, 092301
Fit: CATS D. L. Mihaylov et al. EPJ C78 (2018) 5, 394
ALICE collaboration PLB 822 (2021) 136708

K^-p interaction: improved chiral model

Koonin-Prat formula for coupled channels (CC)

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

$j = \bar{K}^0 n,\ \pi^0\Sigma^0, \pi^+\Sigma^-, \pi^-\Sigma^+, \pi^0\Lambda$



- Coupled-channel are short-range features of the strong interaction
  - the shape and strength of the correlation function are modified at small distances
- Improved Kyoto chiral model to describe CC potential V_j
- Conversion weights (ω_j)
  - control CC contribution
  - depend on primary yield and kinematics

Y. Kamiya et al, PRL 124 (2020) 132501, arXiv:1911.01041

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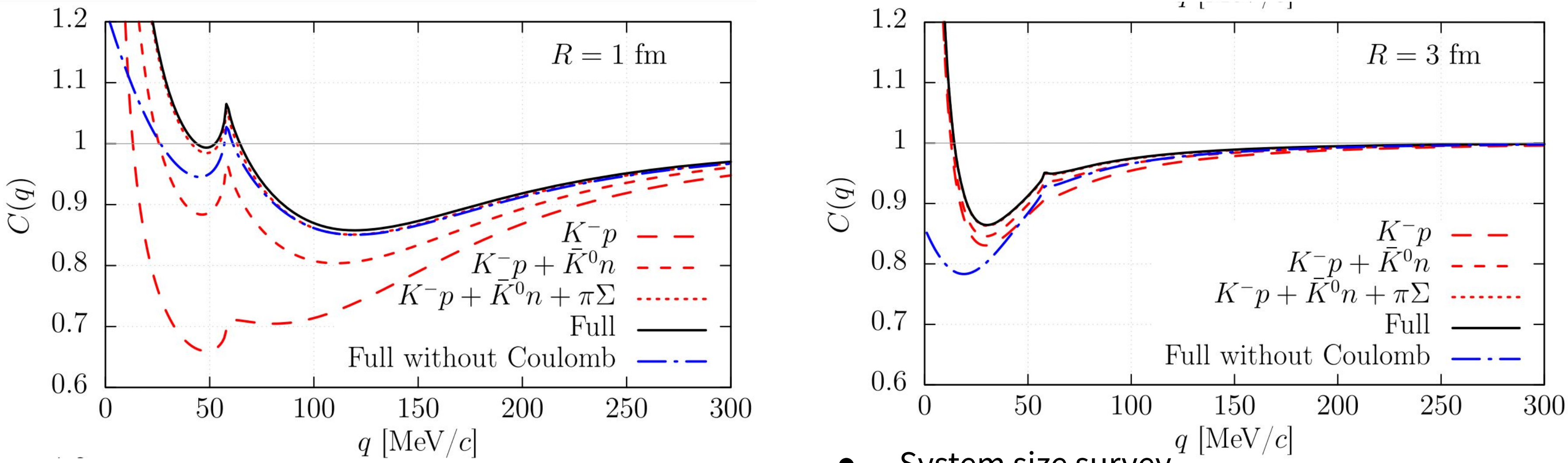
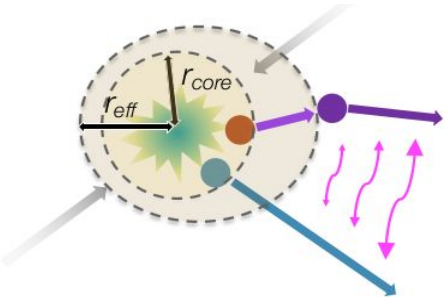


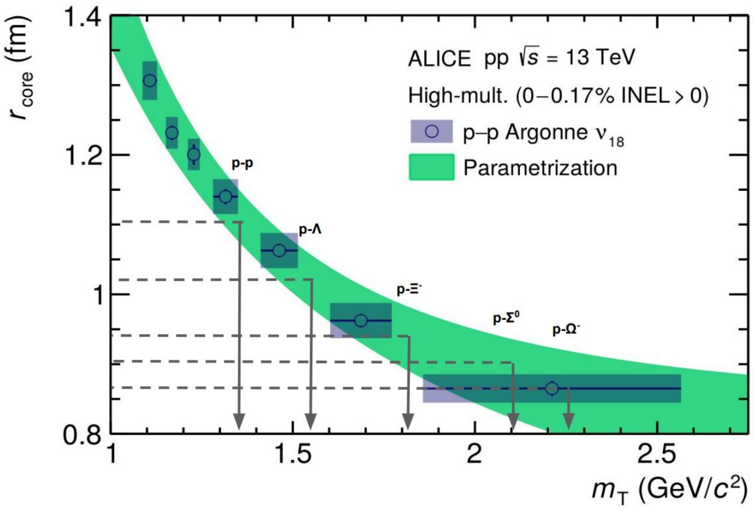
- System size survey
  - For large radii contribution from CC gets negligible → elastic scattering

Y. Kamiya et al, PRL 124 (2020) 132501, arXiv:1911.01041

The emitting source in small colliding systems

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





ALICE Collaboration PLB 811 (2020) 135849

The emitting source in small colliding systems

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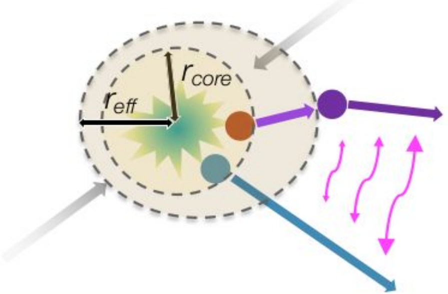
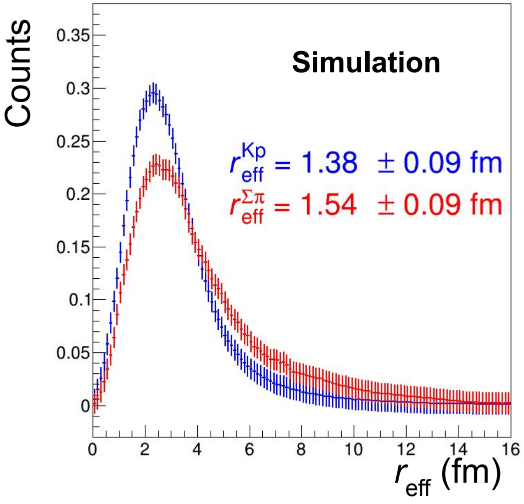
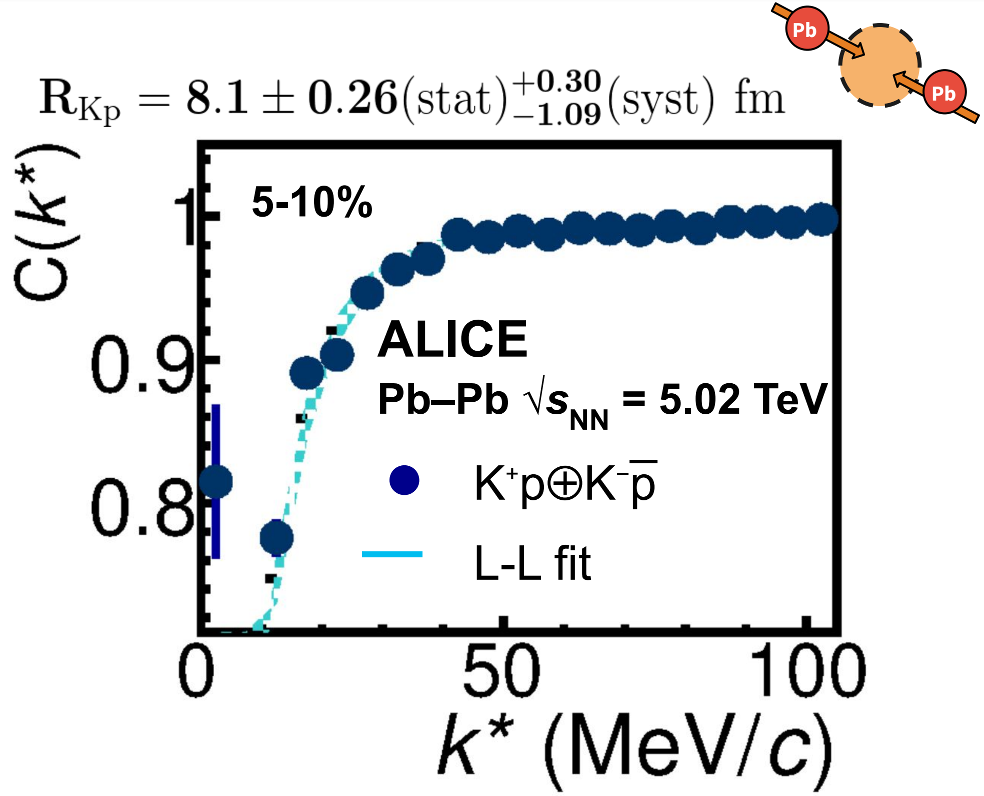


- What about meson-baryon pairs?
  - K^+p interaction is well known → extract r_{core} for Kp pairs
    - For small systems:
      - build effective sources for Kp($\bar{K}^0$n) and one for πΣ (πΛ) pairs using different resonances



ALICE Collaboration arXiv: 2205.15176

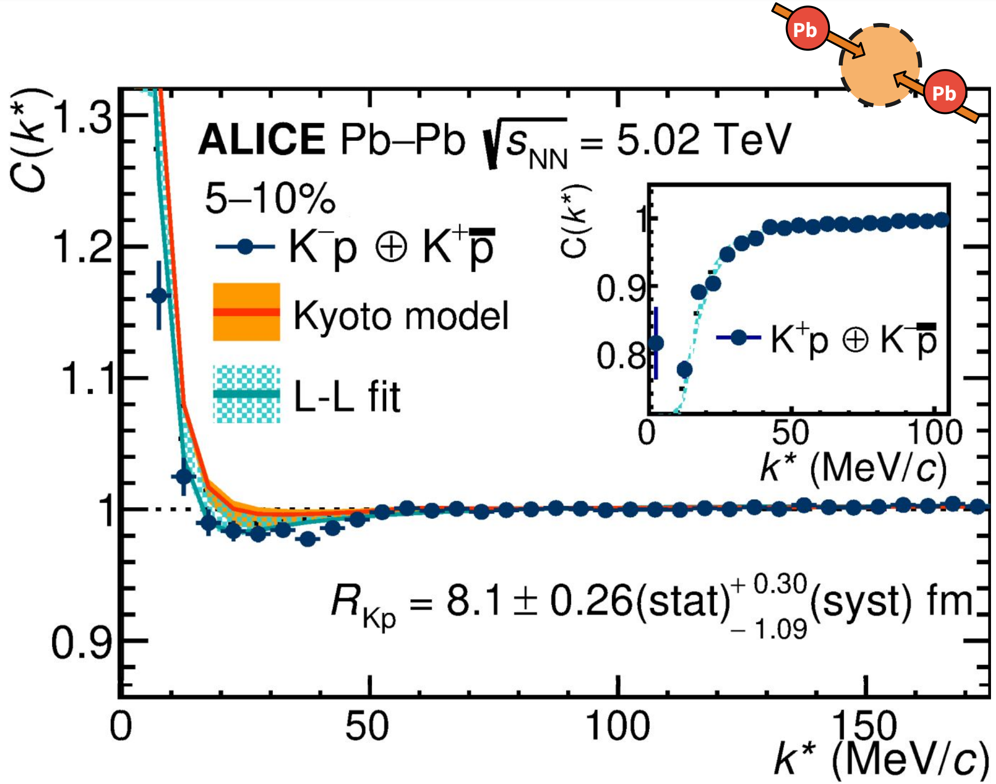
K^-p in large systems



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

ALICE collaboration PLB 822 (2021) 136708

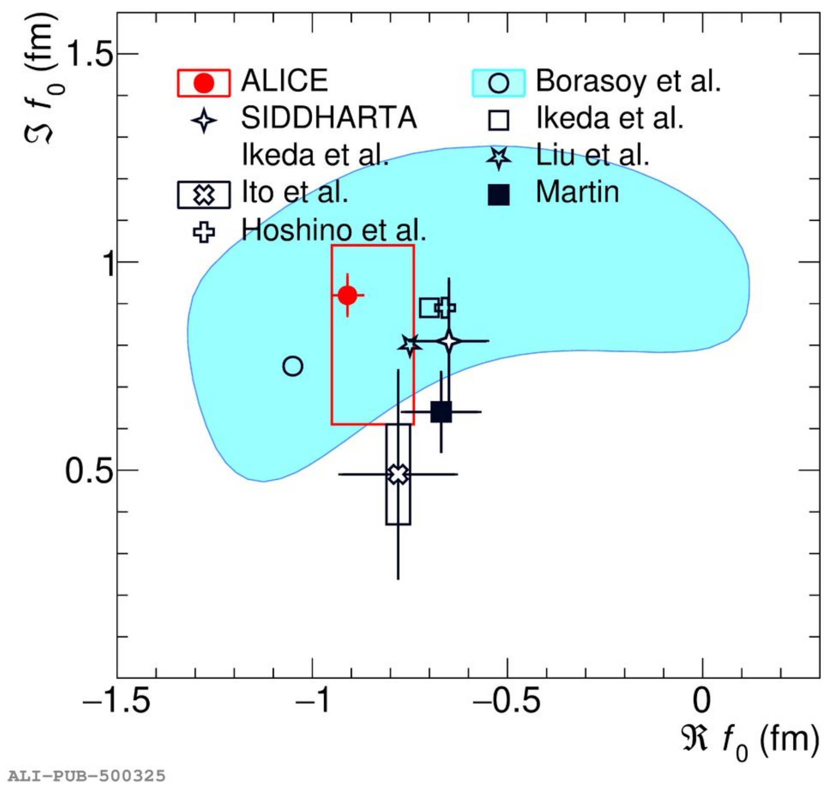
K⁻p in large systems



ALICE collaboration PLB 822 (2021) 136708

- K^+p used to extract source size
  - Gaussian source
  - Lednický-Lyuboshitz (LL) fit to extract r_{eff}
- Large system: no coupled channels (as in Kyoto model)
- Use Lednický-Lyuboshitz (LL) fit to extract $\Re f_0$ and $\Im f_0$

K^-p in large systems



ALICE collaboration PLB 822 (2021) 136708

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

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 channels is accounted in the ω_j weights

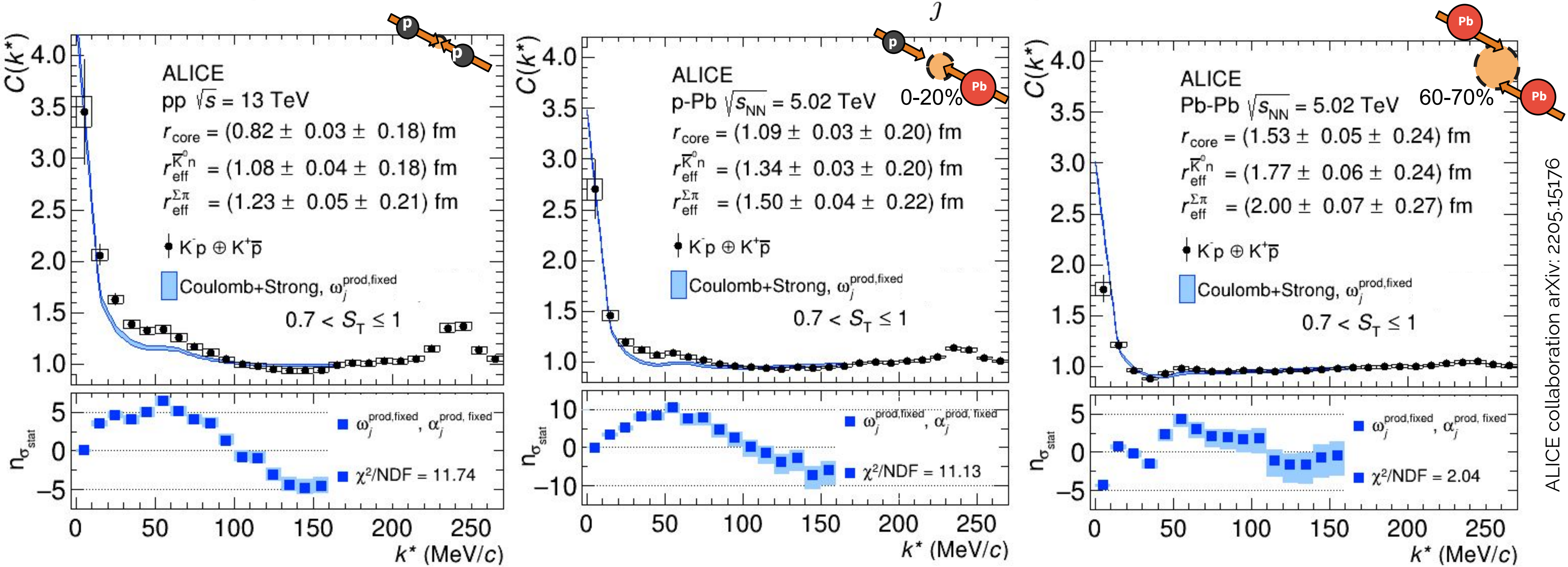
- primary production yields fixed from thermal model (Thermal-FIST) [1]
- estimate amount of pairs in FSI sensitive kinematic region
- distribute particles according to blast-wave model [2,3,4]
- normalize to expected yield of K^-p

[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)

Maximilian Korwieser, PA-Light-flavor and Strangeness 14/06/22

K⁻p from small to large systems

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



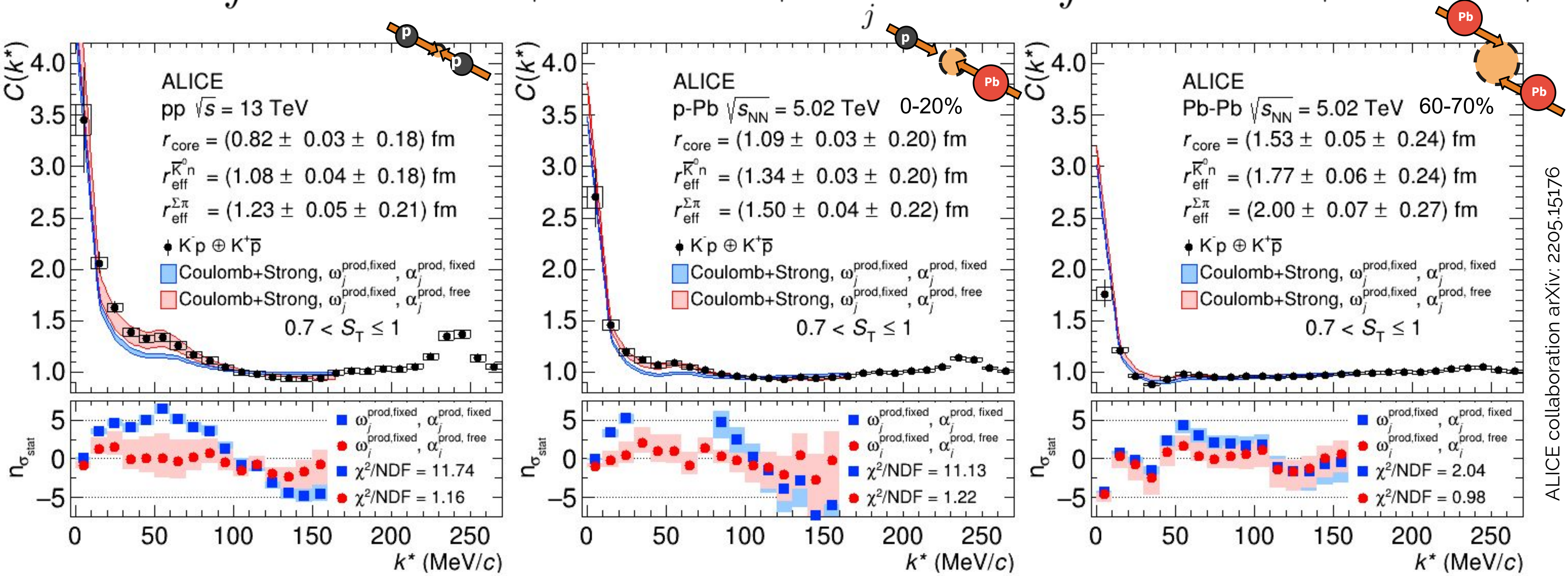
State-of-the art Kyoto Model is not able to describe the data from small to large source size

K⁻p from small to large systems

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

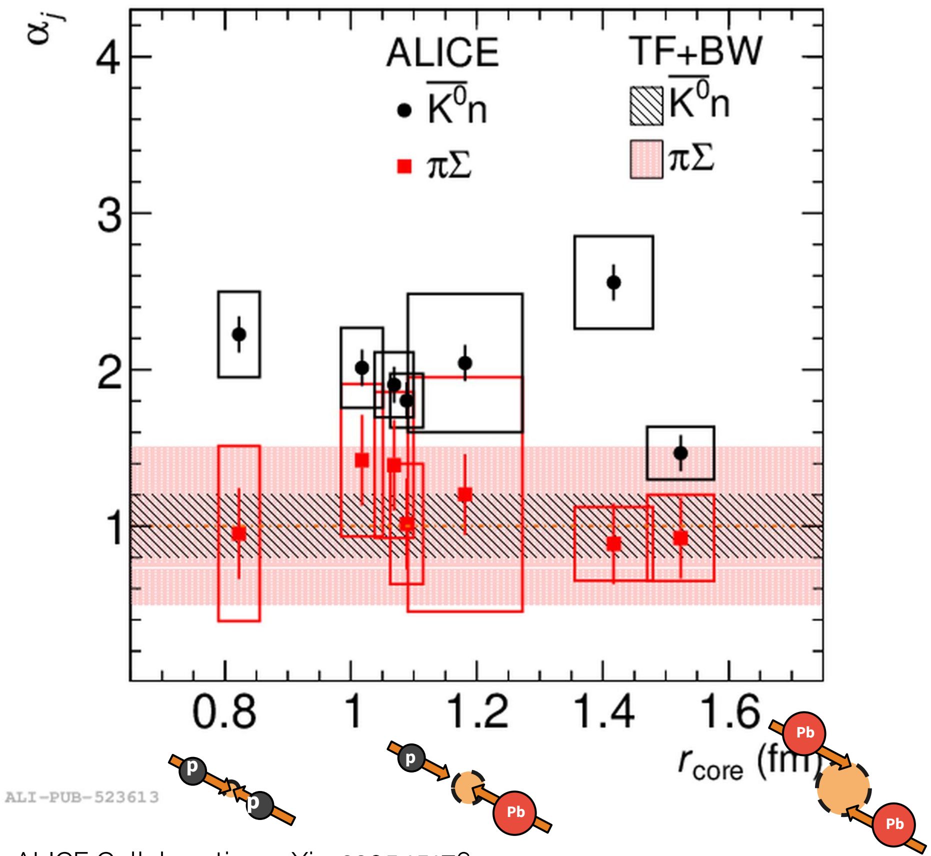
K^-p from small to large systems

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



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

K⁻p from small to large systems

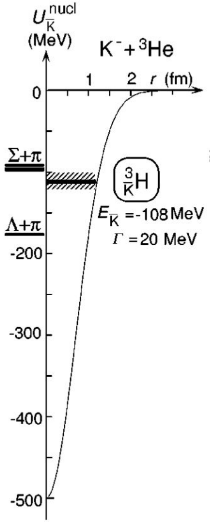


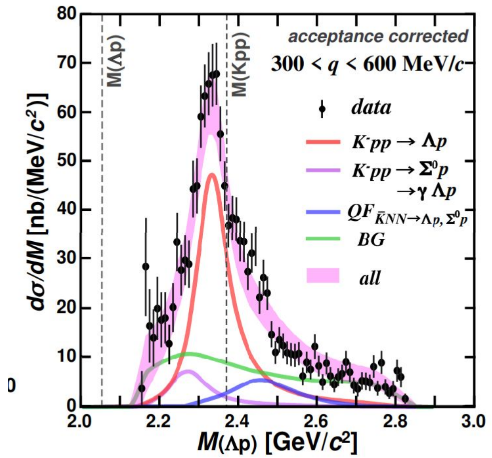
ALICE Collaboration arXiv: 2205.15176

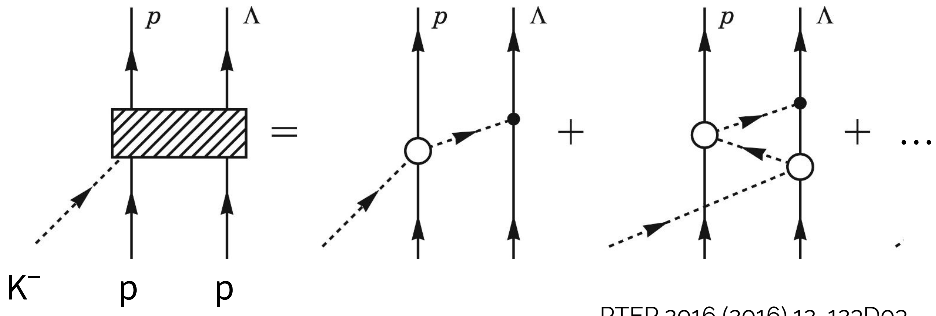
- Unique constraint and direct access to $K^-p \leftrightarrow \bar{K}^0 n$ and $K^-p \leftrightarrow \pi\Sigma$ dynamics
- $\alpha_{\bar{K}^0-n}$ deviates from unity:
  - $K^-p \leftrightarrow \bar{K}^0 n$ currently implemented in Kyoto χEFT is too weak
  - fine tuning of Kyoto χEFT is needed and data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

What about many-body systems?

- K̄NN: exotic bound states of anti-kaon with nucleons predicted more than 30 years ago [1,2] due to the strongly attractive K̄N interaction in I = 0 channel
- First positive experimental evidence of the p-p-K^- bound state by the E15 Collaboration [3]
- **Next experimental challenge: genuine three-body interaction measurements**



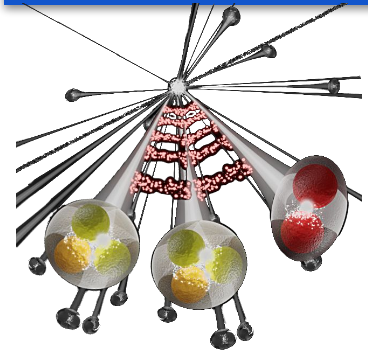




[1]S. Wycech, NPA 450 (1986) 399c;
[2]Y. Akaishi, T. Yamazaki, PRC 65 (2002) 044005
[3]J-PARC E15 Collaboration PRC 102, 044002 (2020)

PTEP 2016 (2016) 12, 123D03

Investigating three-hadron hadronic interactions at LHC



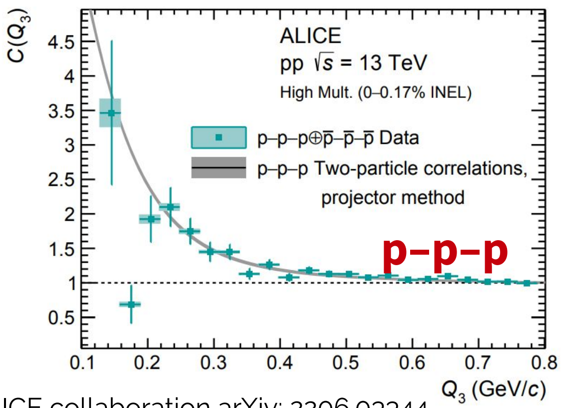
Bhawani Singh, PA-OtherTopics - 15/06/22

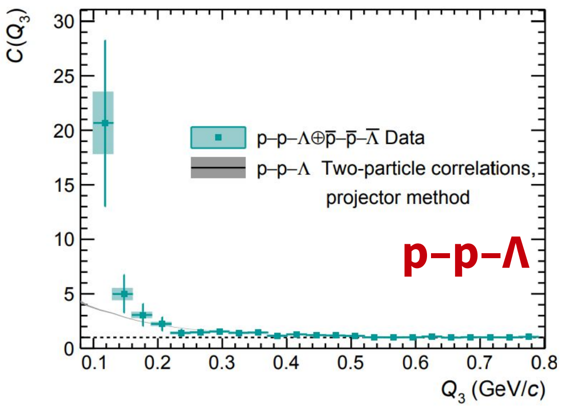
Three-particle correlation function

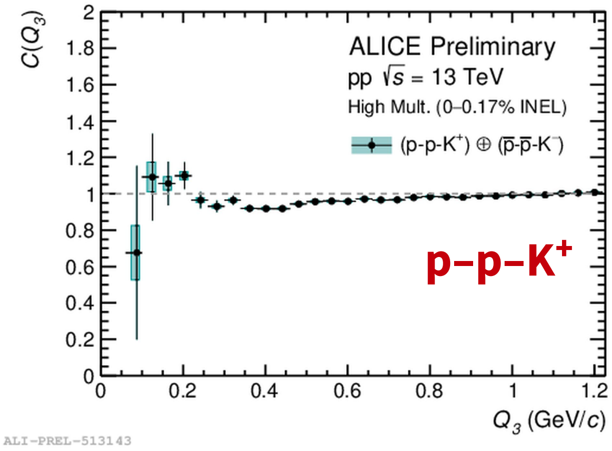
$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) = \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1)P(\mathbf{p}_2)P(\mathbf{p}_3)} = \mathcal{N}\frac{N_{\mathrm{same}}(Q_3)}{N_{\mathrm{mixed}}(Q_3)}$$

The Lorentz invariant Q_3 is defined as: $Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$

$$q_{ij}^{\mu} = (p_i - p_j)^{\mu} - \frac{(p_i - p_j)P_{ij}}{P_{ij}^2}P_{ij}^{\mu} \qquad P_{ij} = p_i + p_j$$







ALICE collaboration arXiv: 2206.03344

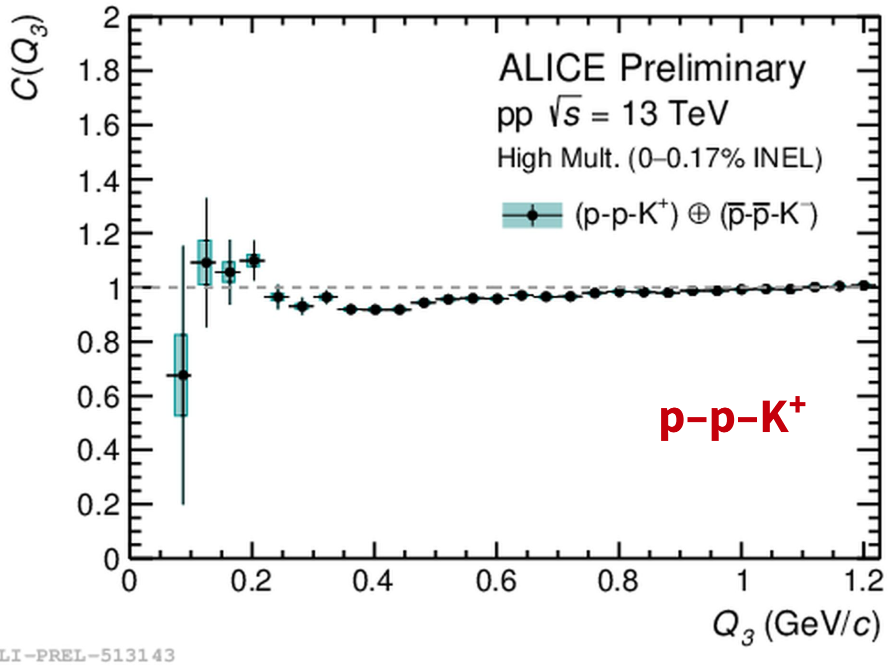
p–p–K⁺ and p–p–K⁻ correlation functions

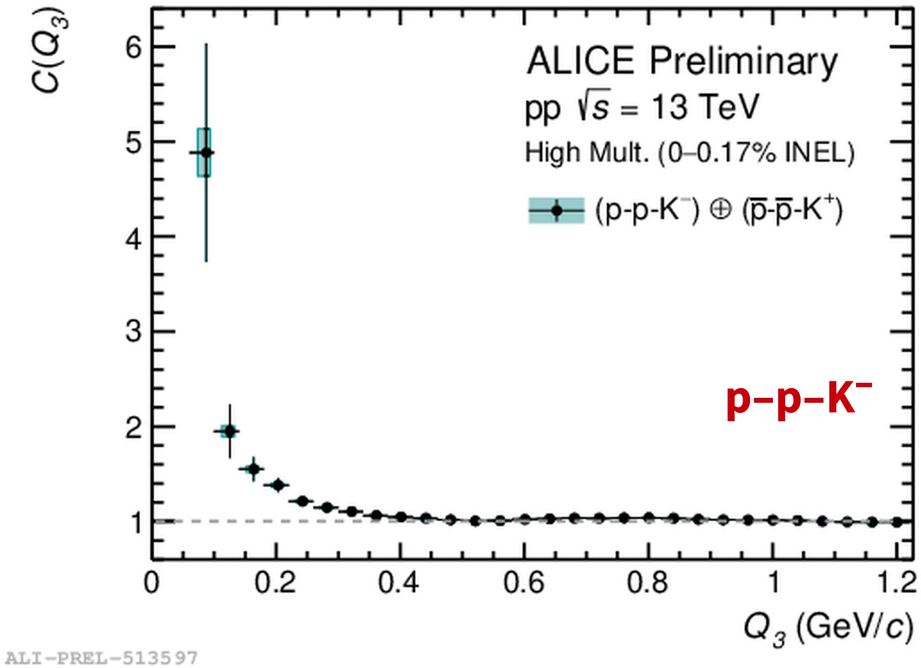
$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$

Cumulant: genuine 3-body correlations

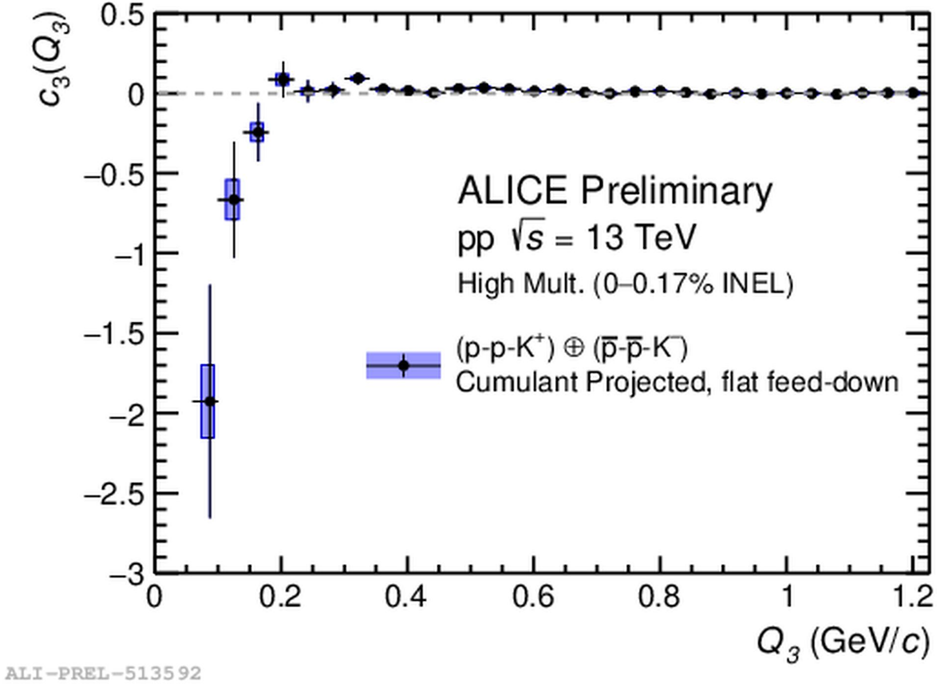
Measured triplets:include two- and three-particle correlations

Lower-order correlations





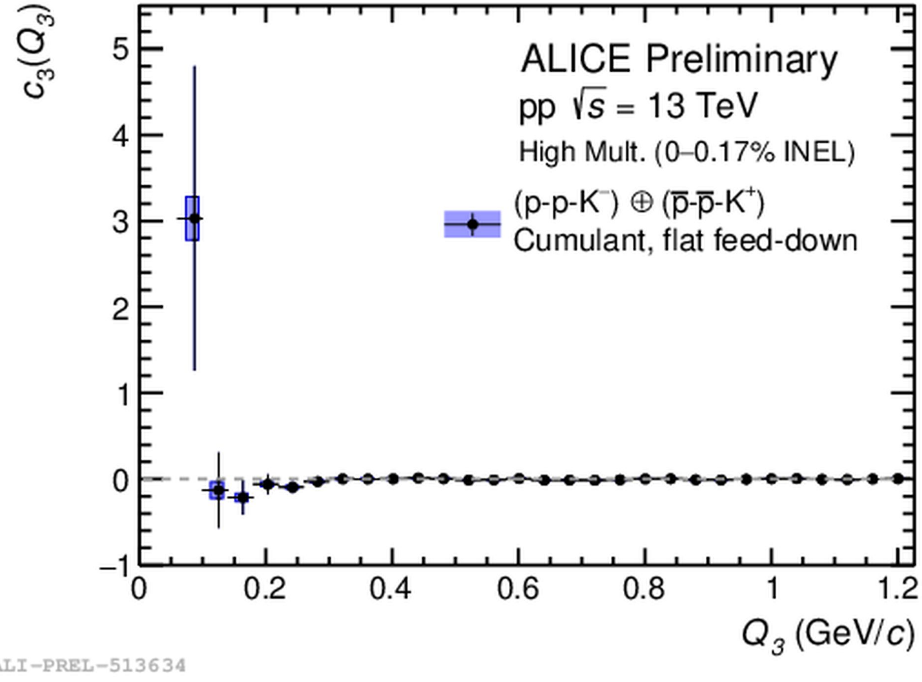
Genuine 3-body correlations



- **Statistical significance:**
  - n_σ = 2.3 for Q_3 < 0.4 GeV/*c*
- **Conclusions:**
  - The measured cumulant is compatible with zero within the uncertainties
  - Above 180 MeV/*c*, the genuine three-body effects do to not contribute significantly in the dynamics of the p-p-K^+ system

p–p–K⁻ cumulant

Genuine 3-body correlations



- **Statistical significance:**
  - n_σ = 0.5 for Q_3 < 0.4 GeV/c
- **Conclusion:**
  - The measured cumulant is consistent with zero within uncertainties
- ***Genuine three-body effects are not significant in p-p-K⁻ systems***
  - The measurement confirms that three-body strong interaction is not relevant in the formation of the exotic kaonic bound states

Conclusions

- Momentum correlation technique applied to data collected at the LHC in different collision systems
  - Unique way to access 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
  - First direct measurement of p-p-K^+ and p-p-K^- interaction
    - cumulants compatible with 0, no evidence of a genuine three-body force
      - kaonic bound state formation driven by two-body forces
- More precision studies within reach with large statistics in LHC Run 3 & 4
  - Unique way to access coupled-channels dynamics in the meson-baryon sector: open a new era in the charm sector!

BACKUP

Conclusions

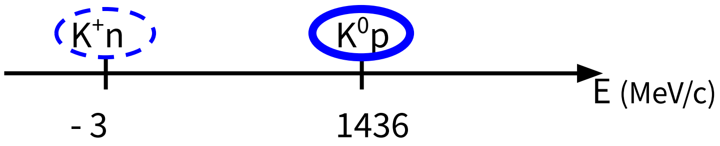
- Momentum correlation technique applied to data collected at the LHC in different collision systems
    - Unique way to access KN and $\bar{K}$N interaction: New constraints for low-energy QCD chiral models
        - First experimental access to coupled channels dynamics ($K^-p \leftrightarrow \bar{K}^0n$, $K^-p \leftrightarrow \pi\Sigma$, $K^-p \leftrightarrow \pi\Lambda$)
        - 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
        - Direct access to K^0_sp ($Kp + \bar{K}p$) interaction:
            - state-of-the-art theory Kyoto χEFT well describes the experimental data
    - First direct measurement of p-p-K^+ and p-p-K^- interaction
        - cumulants compatible with 0, no evidence of a genuine three-body force
            - kaonic bound state formation driven by two-body forces
- More precision studies within reach with large statistics in Run 3 & 4!

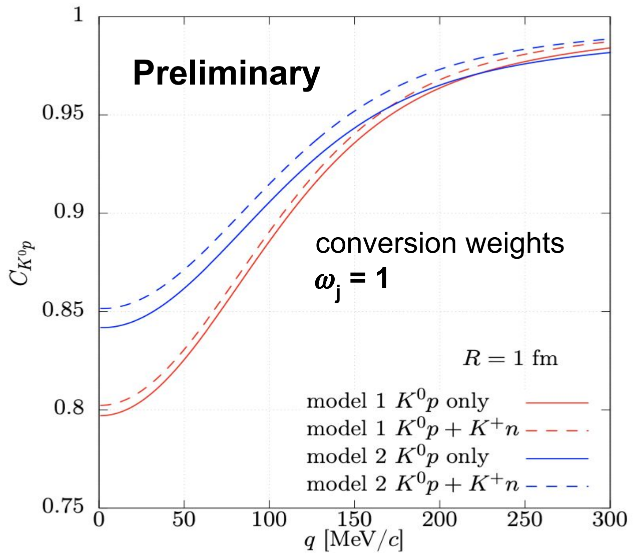
Accessing KN and $\bar{K}$N interaction with K^0

- 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.

Accessing KN and K̄N interaction with K^0

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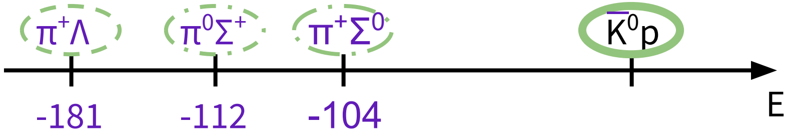
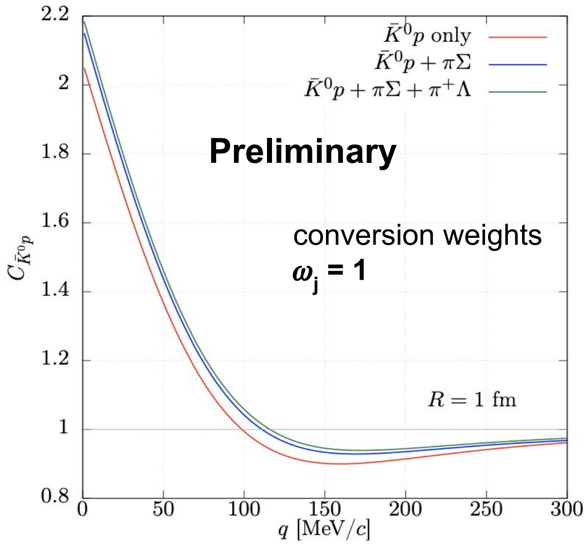
$$|K^0_s p\rangle = \frac{1}{\sqrt{2}}\left[|K^0 p\rangle - |\bar{K}^0 p\rangle\right] \Rightarrow C_{K^0_s p} = \frac{1}{2}\left[C_{K^0 p} + C_{\bar{K}^0 p}\right]$$

- 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 KN̄ used for K^-p [1,2]

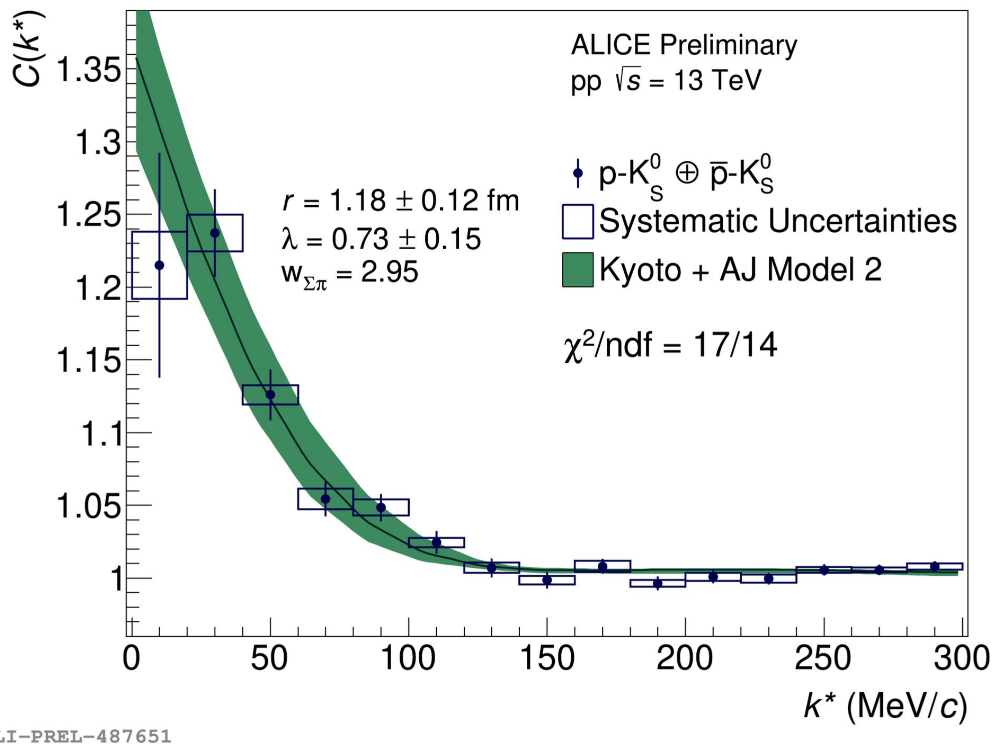




Courtesy of Y. Kamiya

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

K^0_S–p interaction

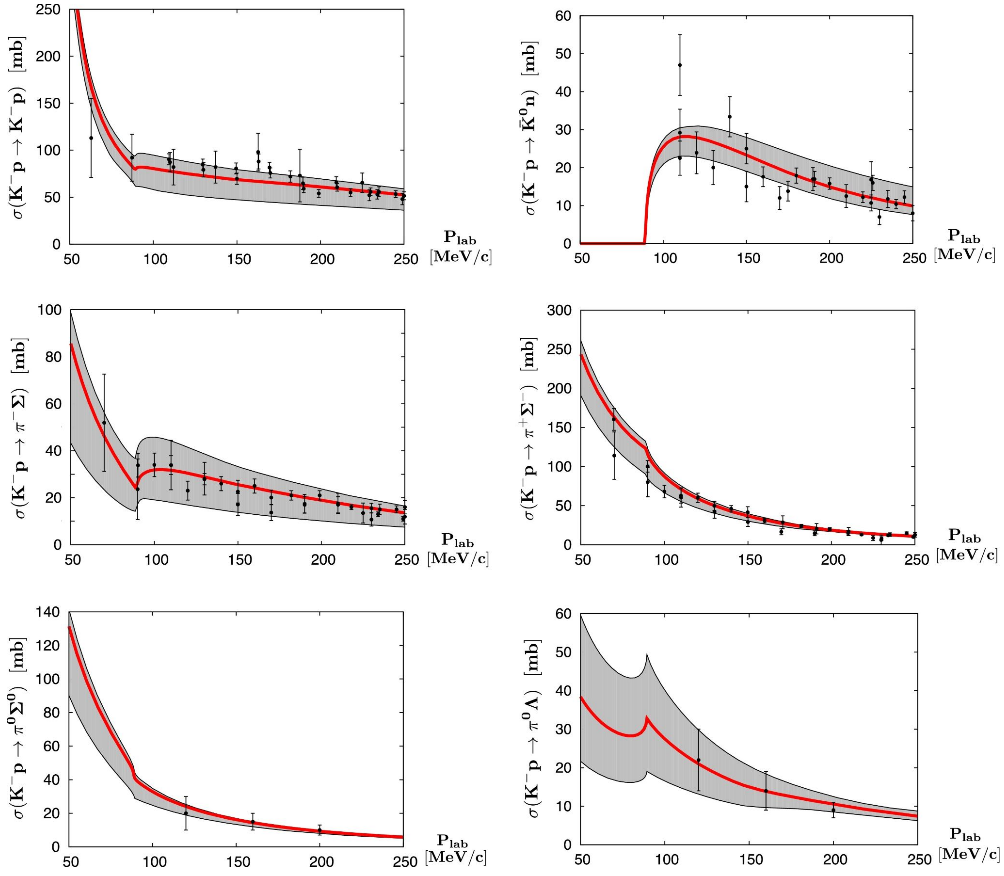


- Gaussian source function with r=1.18±0.12 fm [1]
- $K^0p(\bar{p})$ and $\bar{K}^0(\bar{p})$ ψ with CC provided by Kyoto χEFT
- Conversions weights $\omega = 1$ for K^0p, K^+n, and $\pi^+\Lambda$; $\omega_{\Sigma\pi} = 2.95$ [2]

- **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)

Best fit of K⁻p observables: cross section data



Y. Ikeda et al, PLB Volume 706, (2011),63-67

$\bar{K}N$ scattering lengths

- Deser-type relation connects shift ε_{1s} and width Γ_{1s} to the real and imaginary part of a_{K^-p} and a_{K^-d}:

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-p} = 412\,\tfrac{eV}{fm}\, a_{K^-p}$$

done by SIDDHARTA

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-d} = 601\,\tfrac{eV}{fm}\, a_{K^-d}$$

aim of SIDDHARTA-2

- one can obtain the isospin dependent antikaon-nucleon scattering lengths

$$a_{K^-p} = \frac{a_0(I=0) + a_1(I=1)}{2}$$

$$a_{K^-d} = \frac{1}{2}\frac{m_N + m_K}{m_N + \frac{m_K}{2}}(3a_1 + a_0) + C$$

➢ Fundamental inputs of low-energy QCD effective field theories

Resonances used for πΣ(Λ) source (π)

- For modeling the source every resonance with a cτ > 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			
	cτ < 1 fm	1 < cτ < 2 fm	2 < cτ < 5 fm	cτ > 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 %

$<m(\Sigma)> = 1463$ MeV/c^2

$<c\tau(\Sigma)> = 4.7$ 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

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(p̄) 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

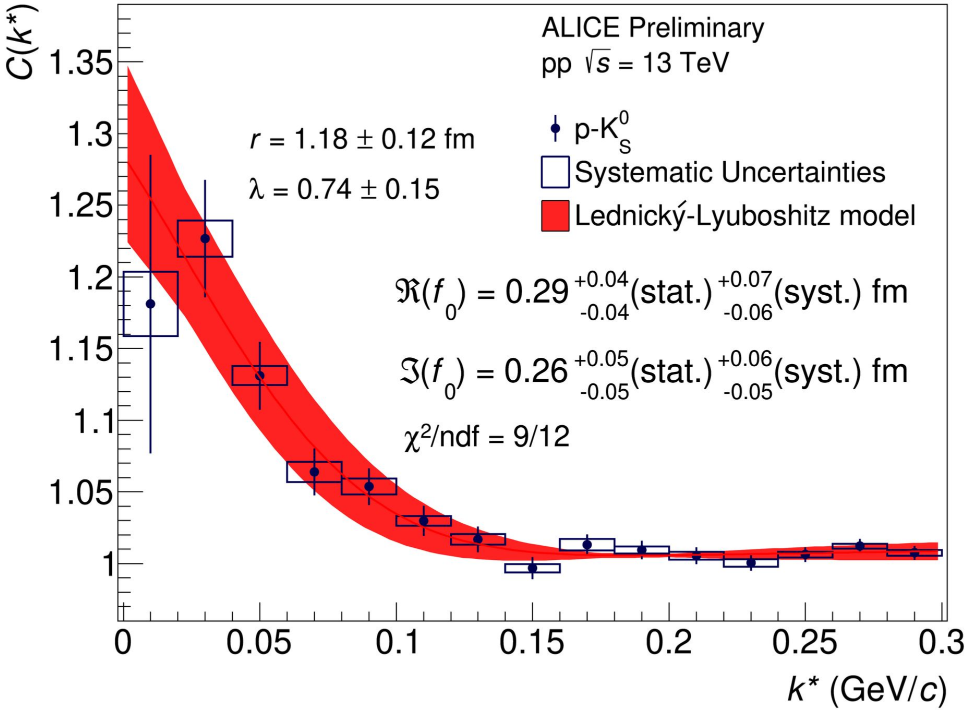
$$C_{FSI}(k^*) = \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f(k^*)}{R} \right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi}R}\right) + \frac{2\Re f(k^*)}{\sqrt{\pi}R} F_1(2k^*R) - \frac{\Im f(k^*)}{R} F_2(2k^*R) \right]$$

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

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

Kaon-proton interaction - Large systems

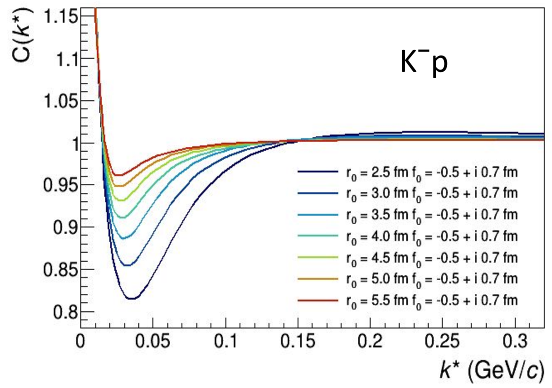
Lednický-Lyuboshitz model

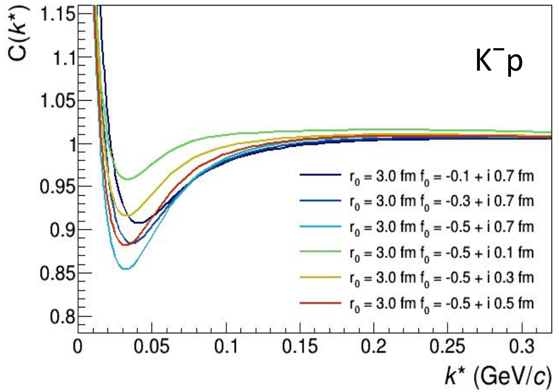
$$C(\mathbf{k}^*) = \frac{\int S(\mathbf{r}^*,\mathbf{k}^*)|\psi(\mathbf{r}^*,\mathbf{k}^*)|^2}{\int S(\mathbf{r}^*,\mathbf{k}^*)} \mathrm{d}^4 r^*$$

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

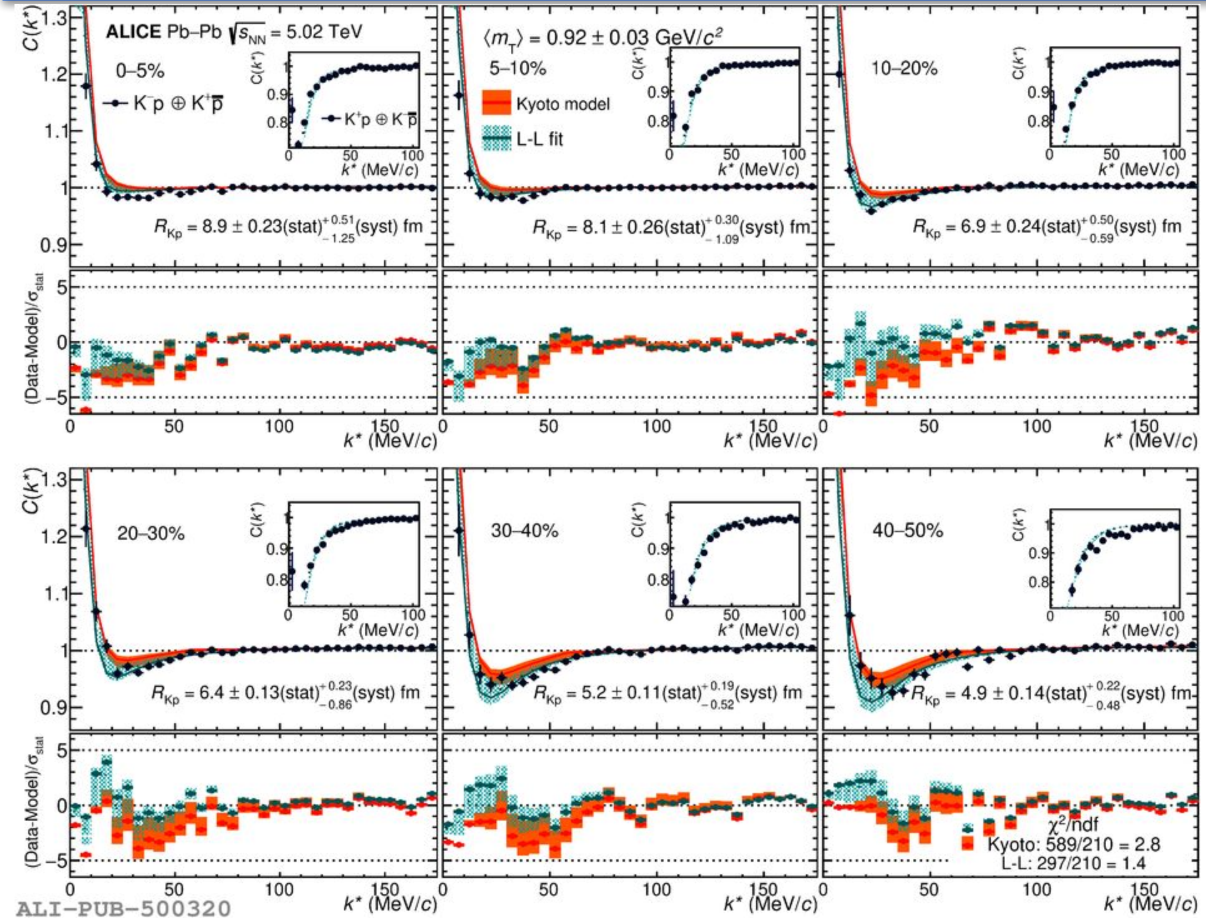
$$f_c(k^*) = \left(\frac{1}{f_0} + \frac{d_0 \cdot k^{*2}}{2} - \frac{-2h(k^* a_c)}{s_c} - ik^* A_C(k^*)\right)^{-1}$$

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





Kaon-proton in Pb–Pb

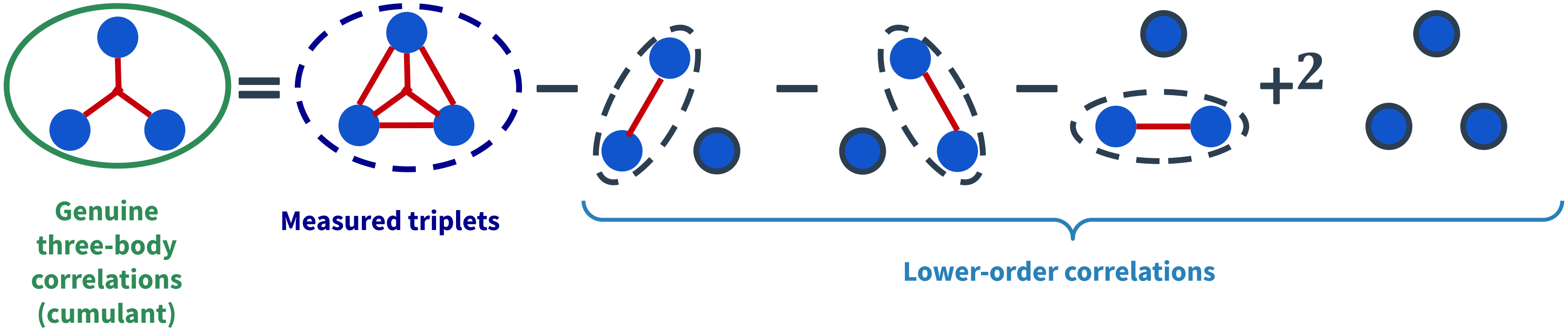


- No K^0n structure
- Simultaneous description (and fit) of the correlation functions for 6 centralities (0-50%) with two parameters and 6 radii
- Radii constrained from K^+p

Kubo's cumulant expansion method

- Genuine three-particle correlations isolated using the Kubo's cumulant expansion method:

R. Kubo, J. Phys. Soc. Jpn. 17(7), 1100–1120 (1962)



- In terms of correlation functions:

$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$

Lower-order contributions evaluation

Data-driven approach

- Using the **same** and **mixed-events** distributions:

$$C([\mathbf{p}_1,\mathbf{p}_2],\mathbf{p}_3)=\frac{N_2(\mathbf{p}_1,\mathbf{p}_2)\,N_1(\mathbf{p}_3)}{N_1(\mathbf{p}_1)\,N_1(\mathbf{p}_2)\,N_1(\mathbf{p}_3)}$$

- The scalar Q_3 is calculated from the measured single-particle momenta

$$(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)\rightarrow Q_3$$

Projector method

R. Del Grande, L. Šerkšnytė et al, Eur.Phys.J.C 82 (2022) 3, 244

- Using the two-body correlation function of the pair (1,2).
- A kinematic transformation from

$$k^*_{12}(\text{pair}) \rightarrow Q_3(\text{triplet})$$
$$C_2(k^*_{12}) \rightarrow C_3(Q_3)$$

is performed.

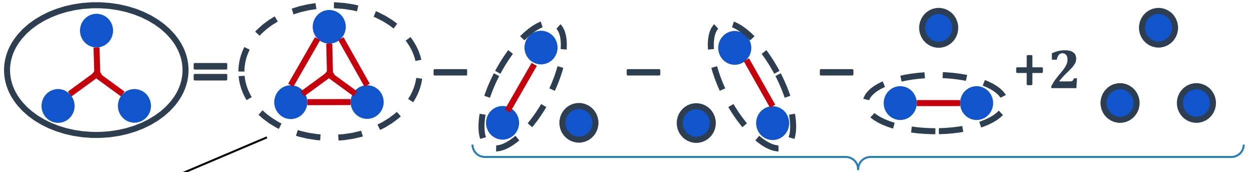
- For the pair (*i*, *j*) we have

$$C_3^{ij}(Q_3)=\int \underbrace{C_2(k^*_{ij})}_{\text{two-body correlation function}}\underbrace{W_{ij}(k^*_{ij},Q_3)}_{\text{projector}}dk^*_{ij}$$

two-body correlation function

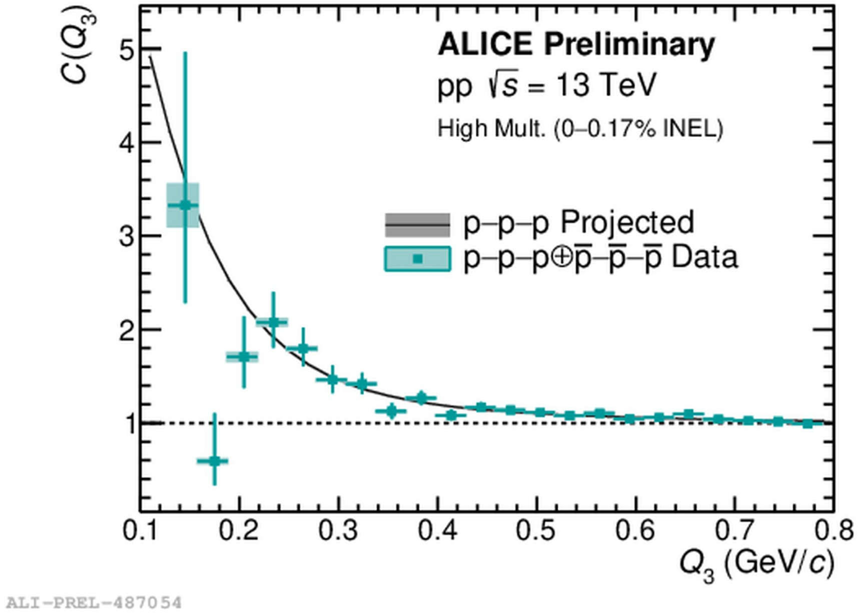
projector

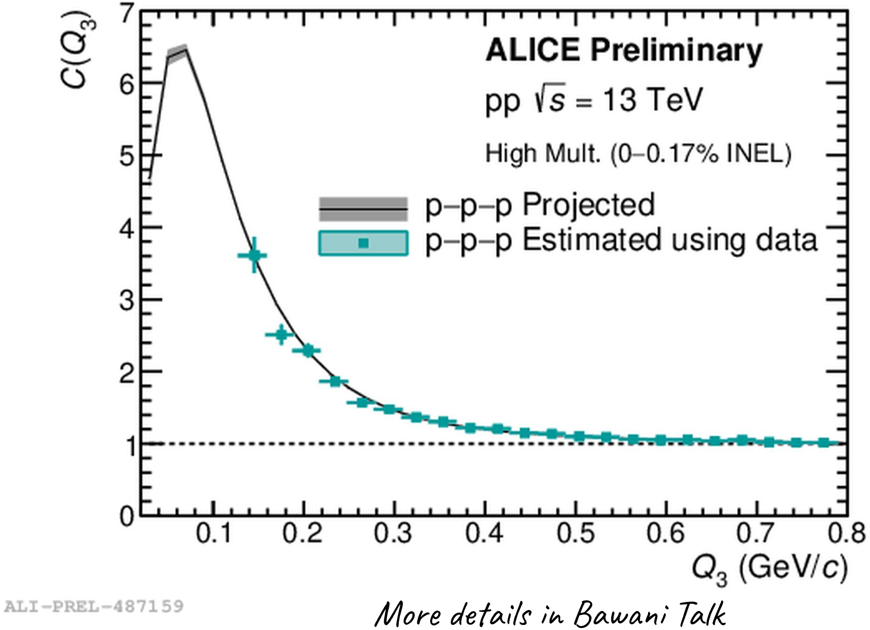
p–p–p correlation function



p-p-p correlation function

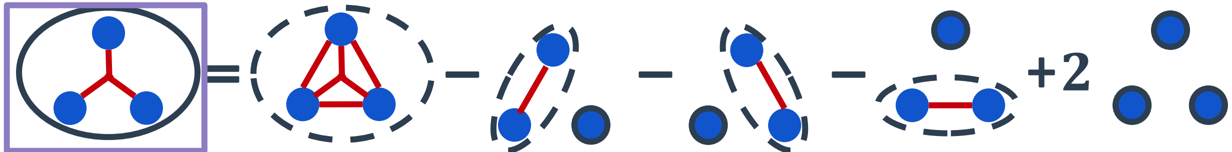
Lower-order correlations



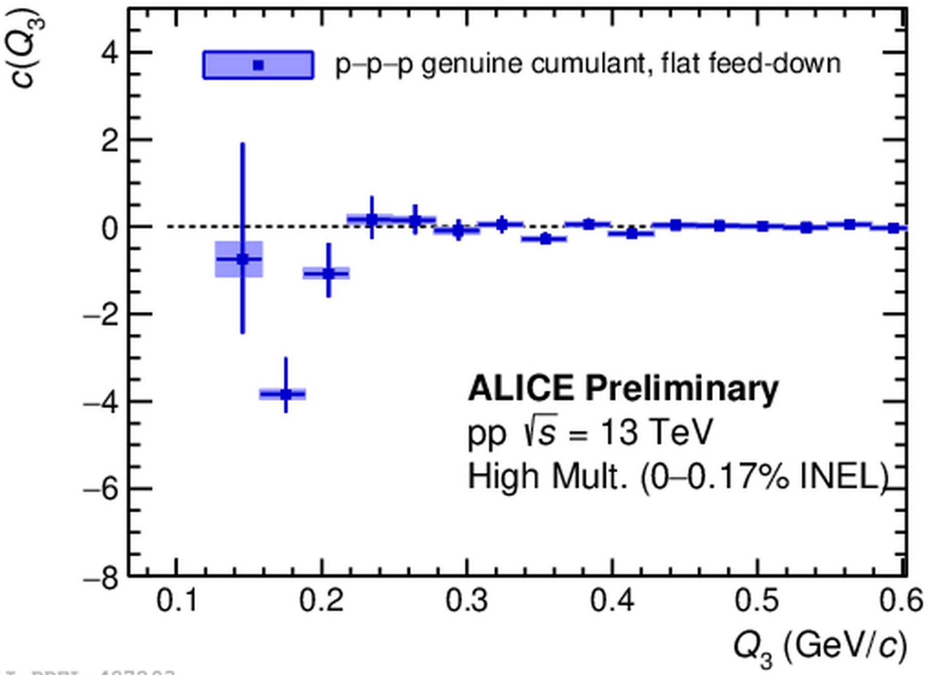


More details in Bawani Talk

p–p–p cumulant



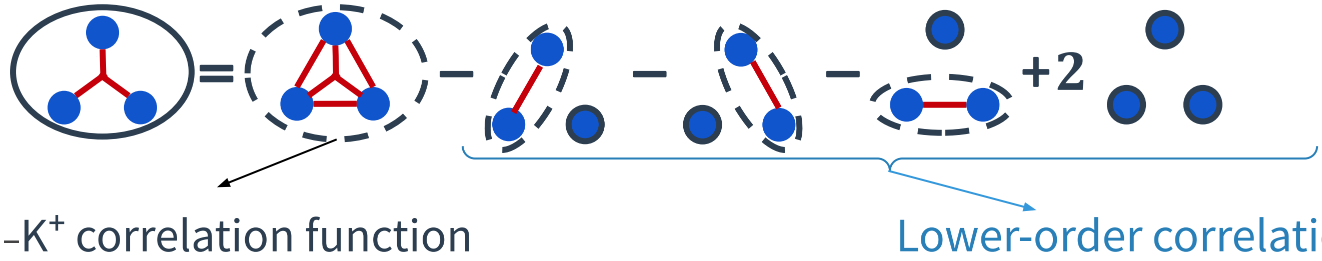
cumulant (Flat feed-down from the resonances is considered)

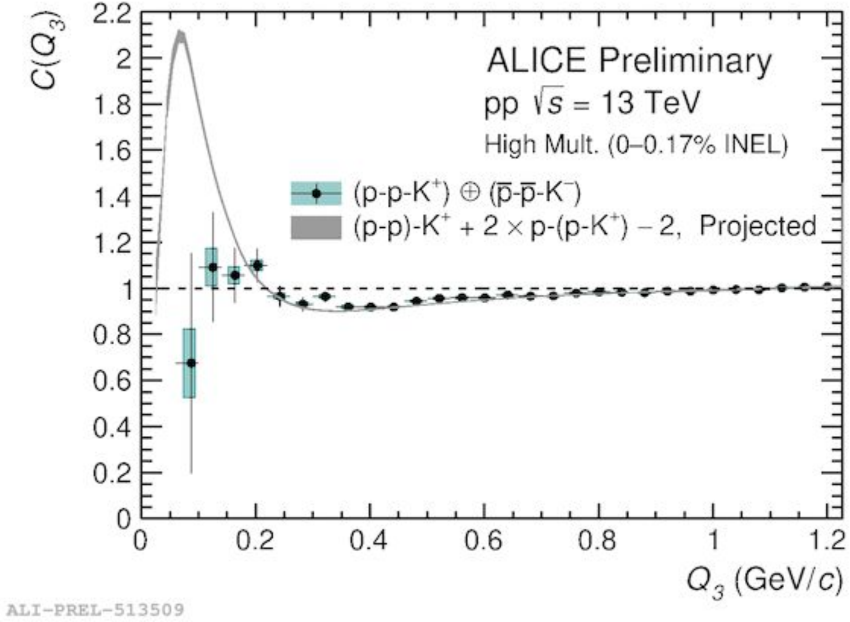


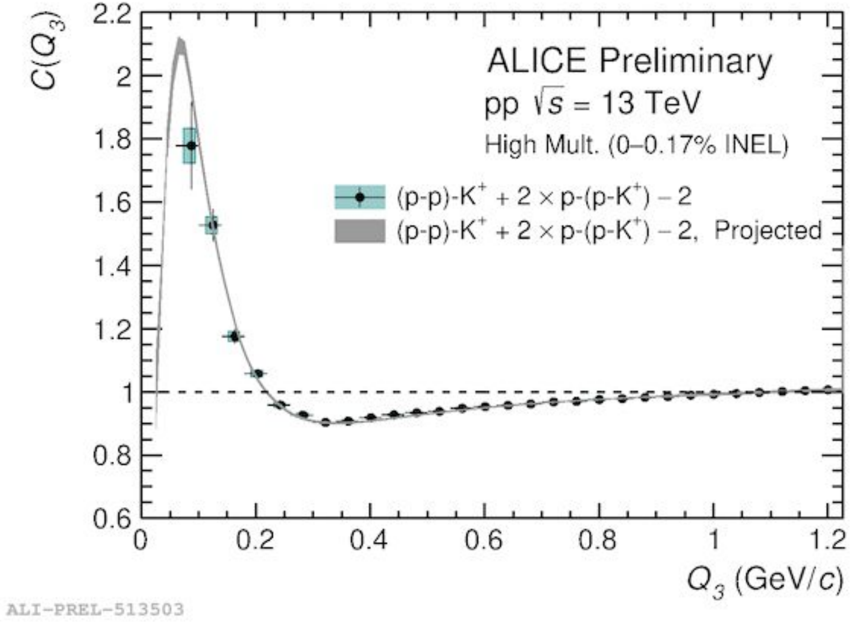
ALI-PREL-487203

- **Statistical significance:**
  - n_{σ} = 6.7 for Q_3 < 0.4 GeV/*c*
- **Conclusion:**
  - Presence of a genuine three-body effect in p–p–p
- *Possible interpretations:*
  - Pauli blocking at the three-particle level
  - long-range Coulomb interaction effects
  - three-body strong interaction
    - Collaboration with A. Kievsky, L. Marcucci and M. Viviani (Pisa University - INFN) for the theoretical interpretation.

p–p–K⁺ and p–p–K⁻ correlation functions

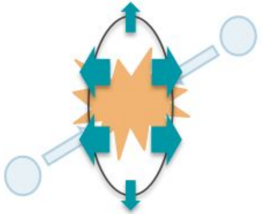






Small Sources: Collective Effects and Strong Resonances

Elliptic flow



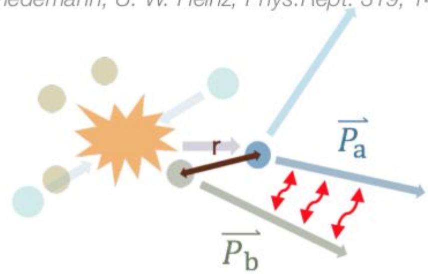
Anisotropic pressure gradients within the source

Radial flow

- Expanding source with constant velocity
- Different effect on different masses

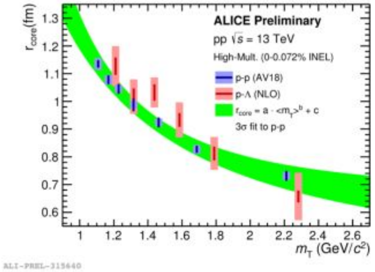
Strong decays of broad resonances

U. A. Wiedemann, U. W. Heinz, Phys.Rept. 319, 145-230 (1999)



- Resonances with $c\tau \sim r_0 \sim 1$ fm (Δ^*, N^*, Σ^*) introduce an exponential tail to the source
- Different for each particle species

Core Radius



⊗

Strong decays of specific resonances