SQM 2024
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

Novel constraints for the multi-strange meson-baryon interaction using correlation measurements with ALICE

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

Strangeness in Quark Matter – SQM 2024
Strasbourg 3-7 June 2024

Deutsche Forschungsgemeinschaft
MA 8660/1-1

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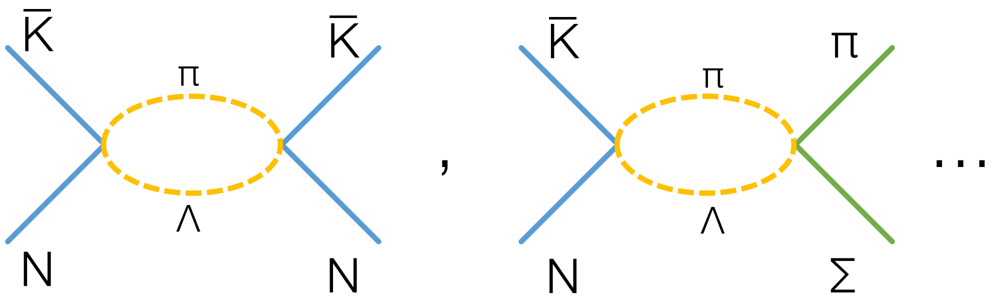
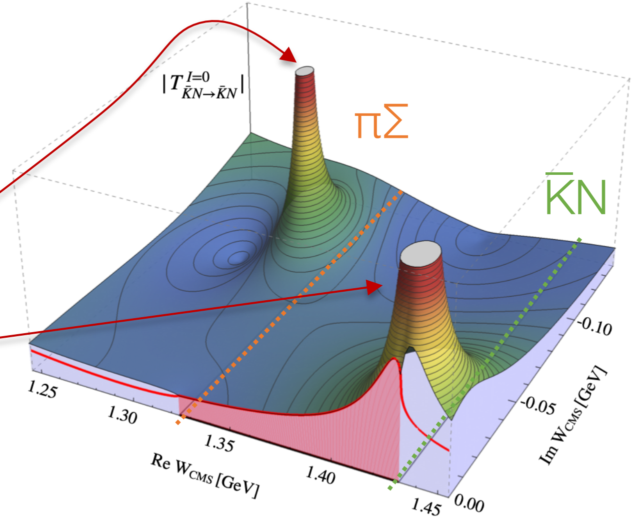
Multi-strange meson-baryon systems and exotic states

- Interactions between mesons and baryons involving strangeness
  - Possibility to study nature and properties of exotic states



- Presence of a rich coupled-channel dynamics
  - Systems sharing same quantum numbers (B,S,Q), relatively close in mass
  - On- and off-shell processes from one channel to the other

- Several candidates for exotic states with molecular nature
  - Typically observed close to channel thresholds
  - Main example given by the two-pole Λ(1405) state
    J. M.M. Hall et al. PRL 114 (2015) 13
    U. G. Meißner Symmetry 12 (2020) 6, 981



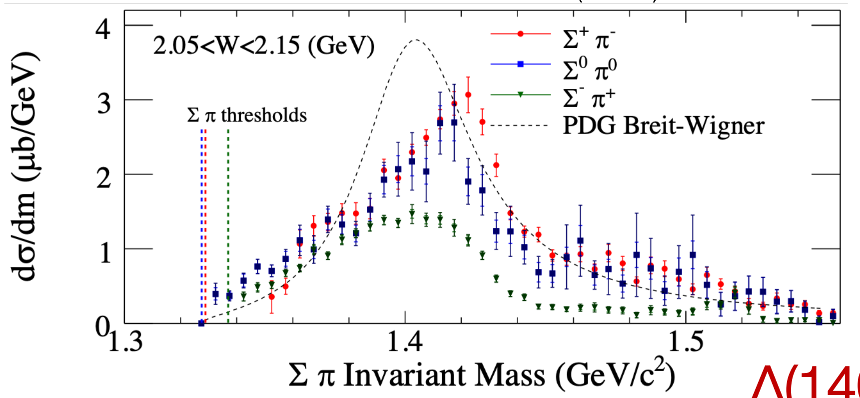
M. Mai EPJST 230 (2021) 6

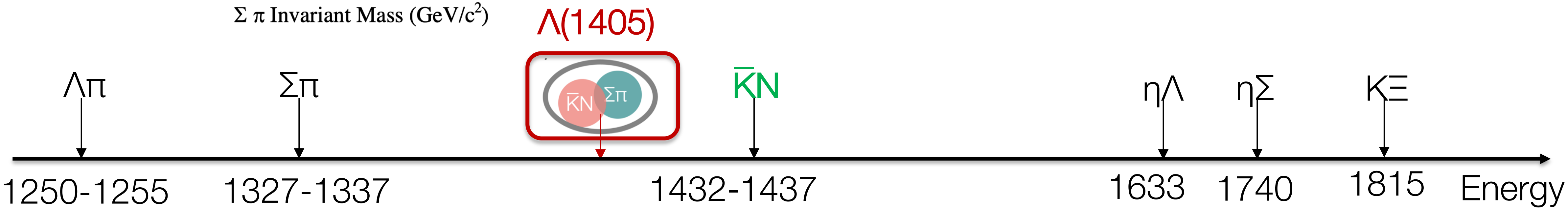
Overview of the S=-1 meson-baryon interaction

- Large attractive interaction in isospin I=0 channel
  - Responsible for formation of Λ(1405) below $\bar{K}N$ threshold

Photoproduction experiments

CLAS Coll. PRC 88 (2013)





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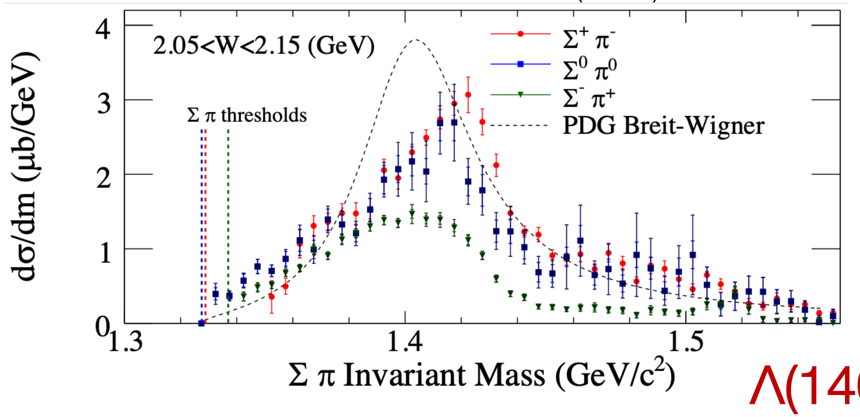
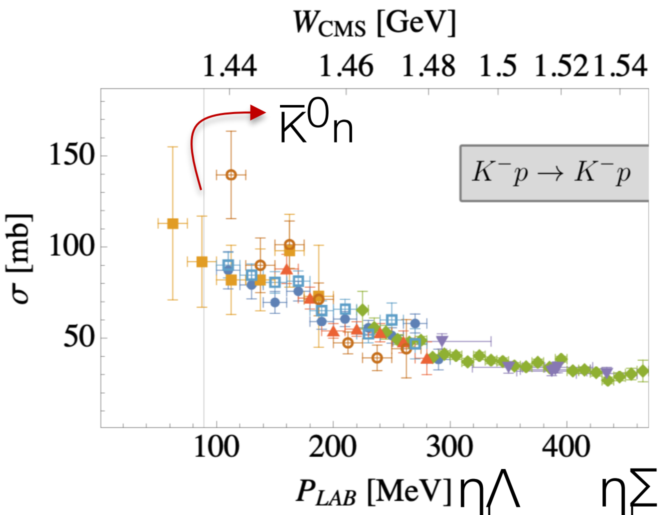


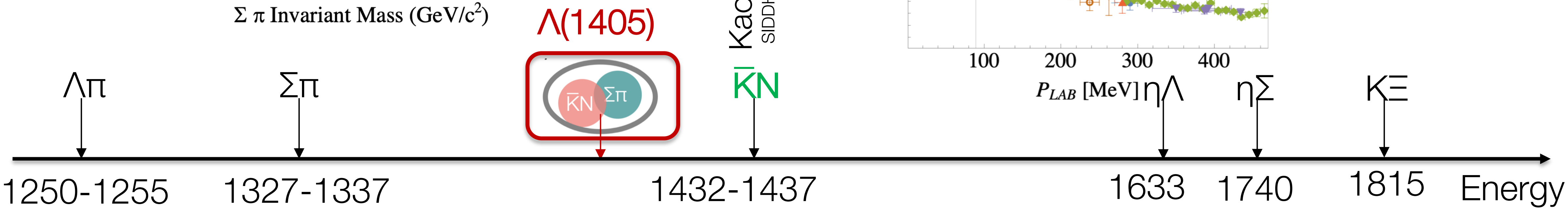
Scattering experiments

M. Mai EPJST 230 (2021) 6



Kaonic hydrogen

SIDDHARTA PLB 704 (2011)



Overview of the S=-1 meson-baryon interaction

- Large attractive interaction in isospin I=0 channel
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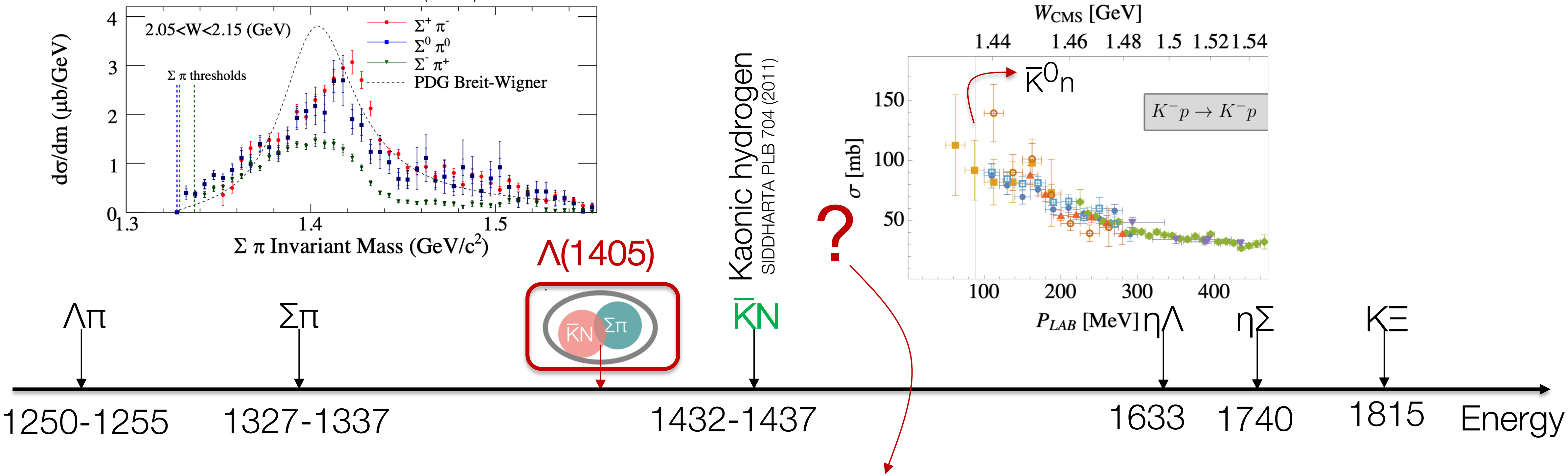
CLAS Coll. PRC 88 (2013)

Scattering experiments
M. Mai EPJST 230 (2021) 6



Need for high-precision data close to K̄N threshold!!

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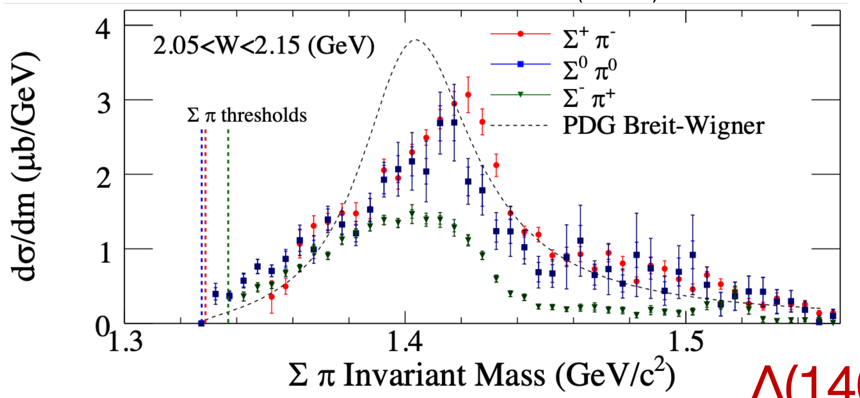
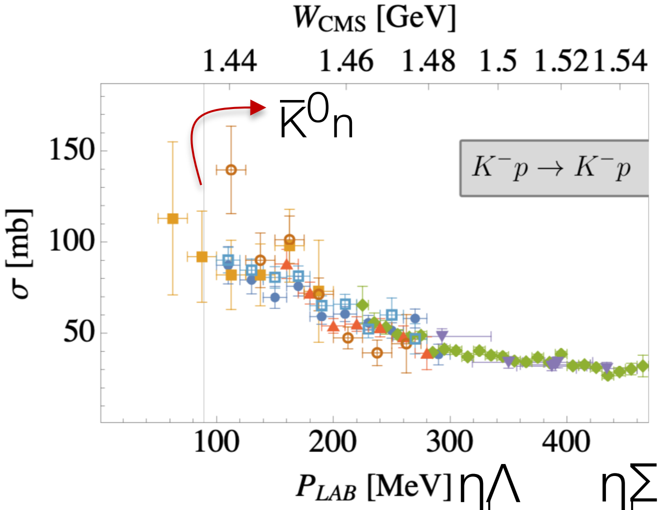


Scattering experiments

M. Mai EPJST 230 (2021) 6



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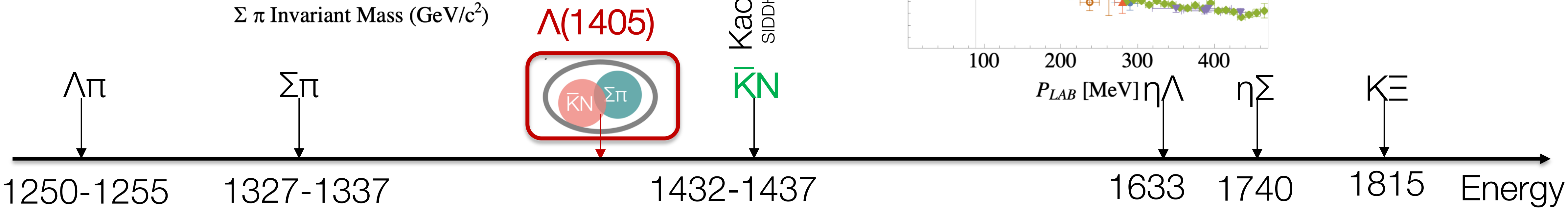

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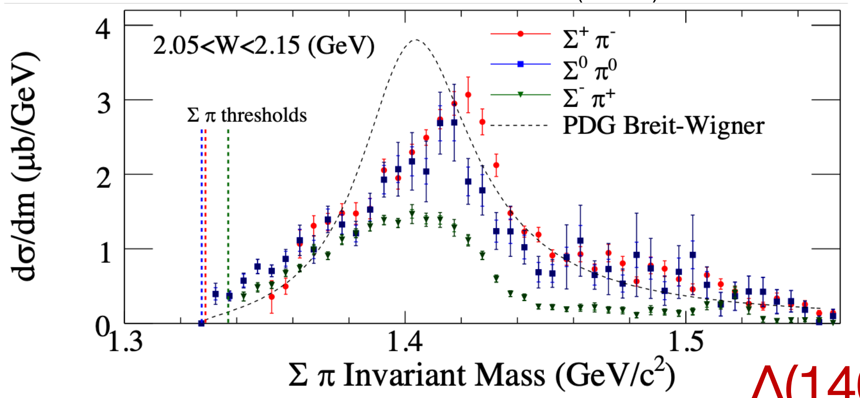
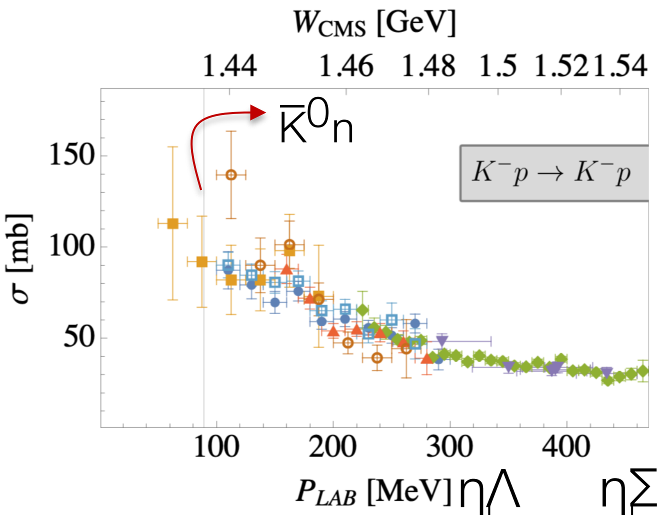
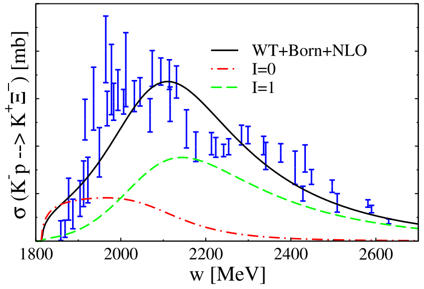


Scattering experiments

M. Mai EPJST 230 (2021) 6



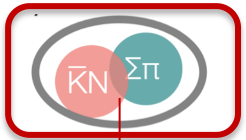
Sensitivity to I=1component



Data: K-p → X and NLO UχPT calc.
A. Feijoo, et al. PRC 99 (2019) 3

Kaonic hydrogen
SIDDHARTA PLB 704 (2011)

Λ(1405)

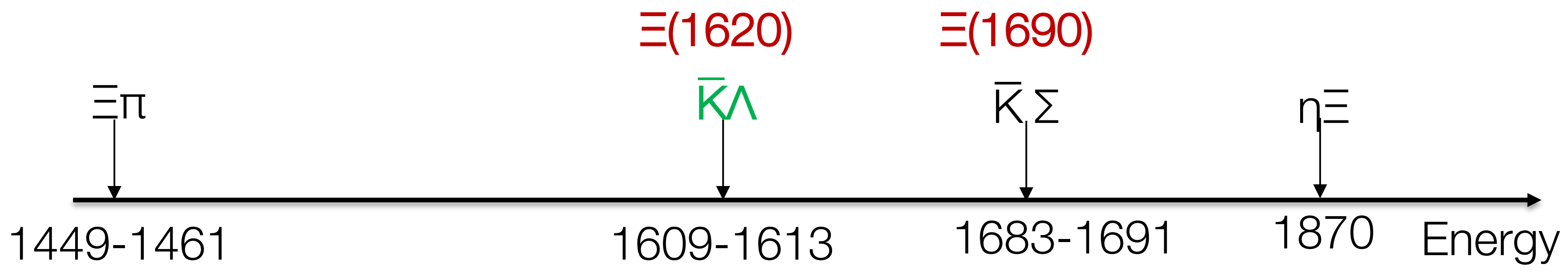


Λπ	Σπ	Λ(1405)	K̄N	ηΛ	ηΣ	KΞ	
1250-1255	1327-1337		1432-1437	1633	1740	1815	Energy

Need for experimental constraints on as many channels as possible

Moving to the S=-2 sector

- Scattering experiments challenging with increasing strangeness
  - $\Xi(1620)$ lying across the $\bar{K}\Lambda$ threshold as molecular candidate, poorly known



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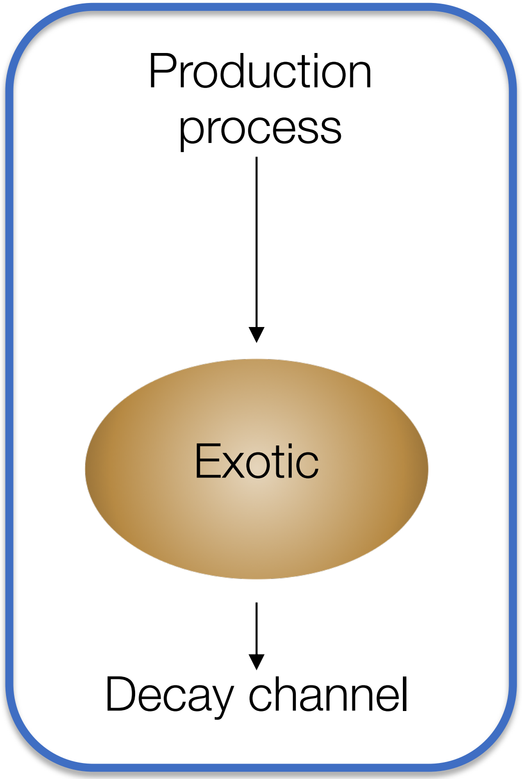
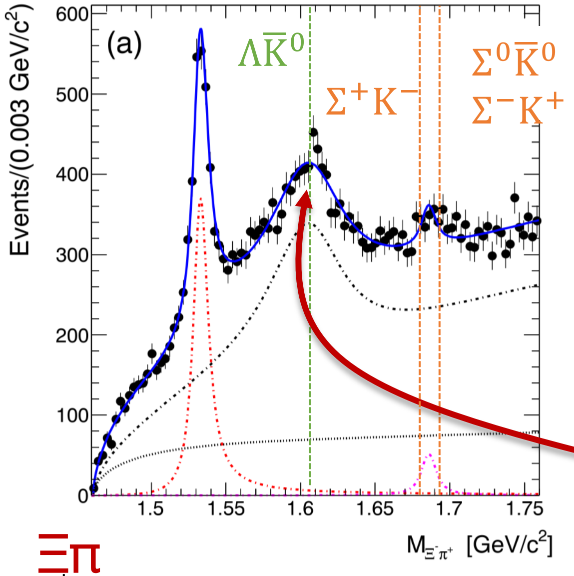
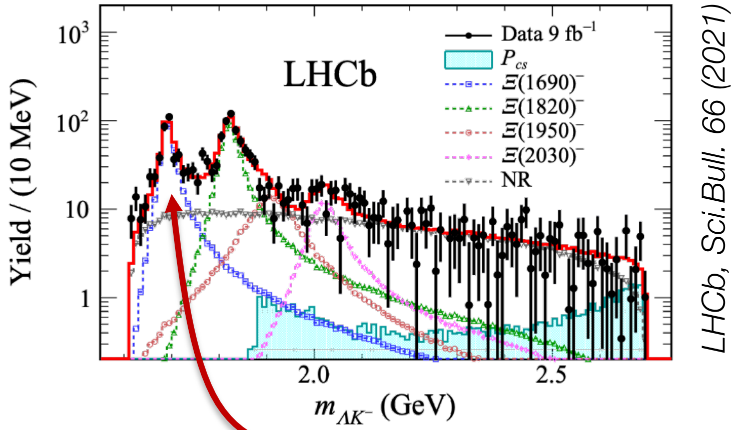
- Intensive searches via **spectroscopy measurements** with **different production mechanism**

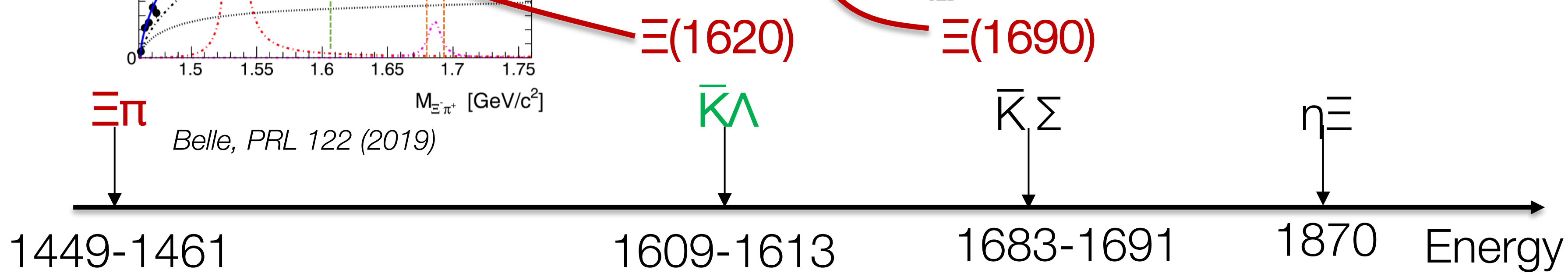




Belle, PRL 122 (2019)



LHCb, Sci.Bull. 66 (2021)



Combine different production mechanisms/decay channels to reveal the state's nature

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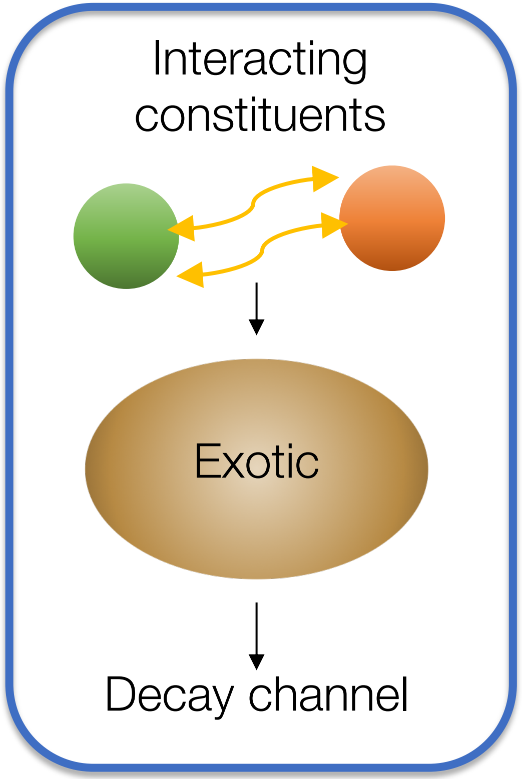
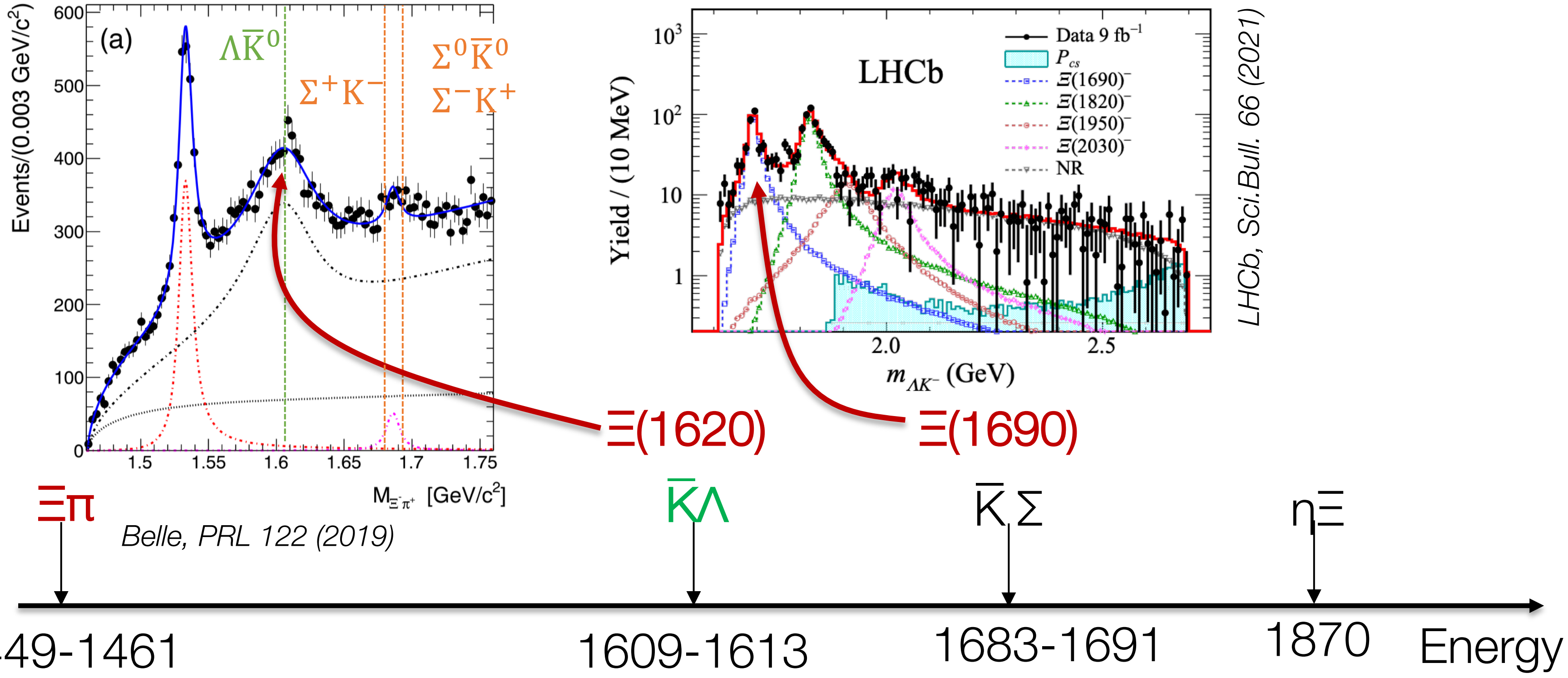




Belle, PRL 122 (2019)

LHCb, Sci.Bull. 66 (2021)

Accessing the interaction between the constituents

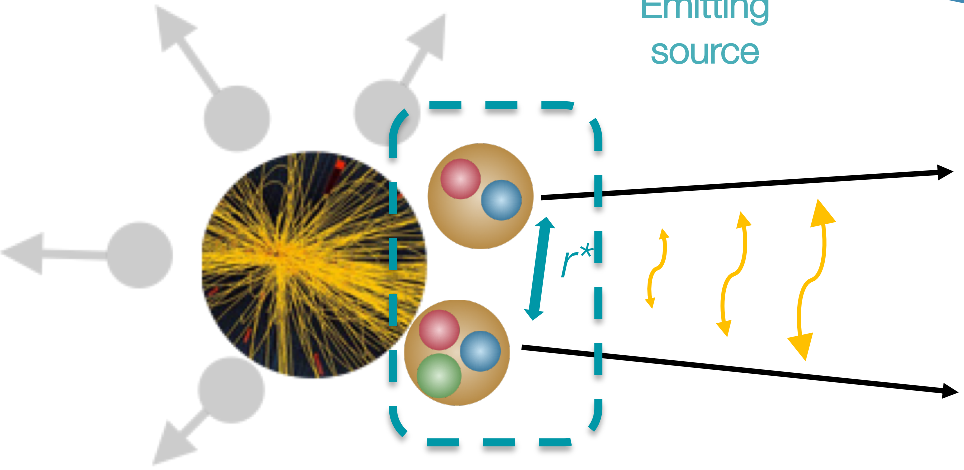
Investigating exotic states with correlations

- Accessing hadronic final-state interaction with correlation functions measured in pp collisions

  M.Lisa, S. Pratt et al, ARNPS. 55 (2005), 357-402, L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

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

Emitting source



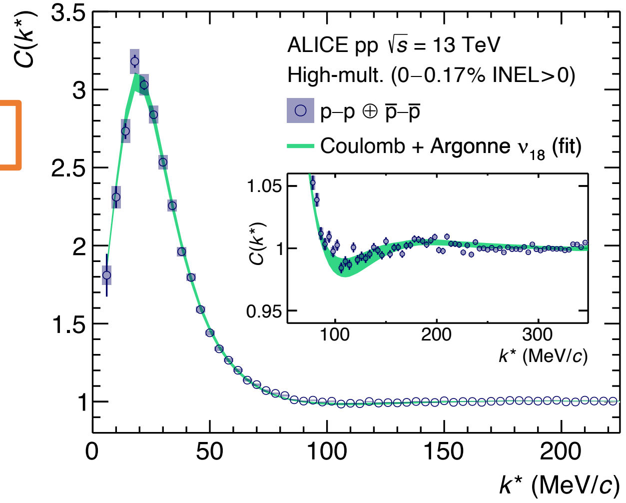
r^* ~1-2 fm

ALICE measurements shown today in high-multiplicity pp collisions at 13 TeV

→ **Emitting source anchored to p-p correlation data** [3]

→ Interparticle distances ~1-2 fm

A. Riedel Tr1-LF Wed. 09:30



ALICE Coll. PLB 811 (2020)

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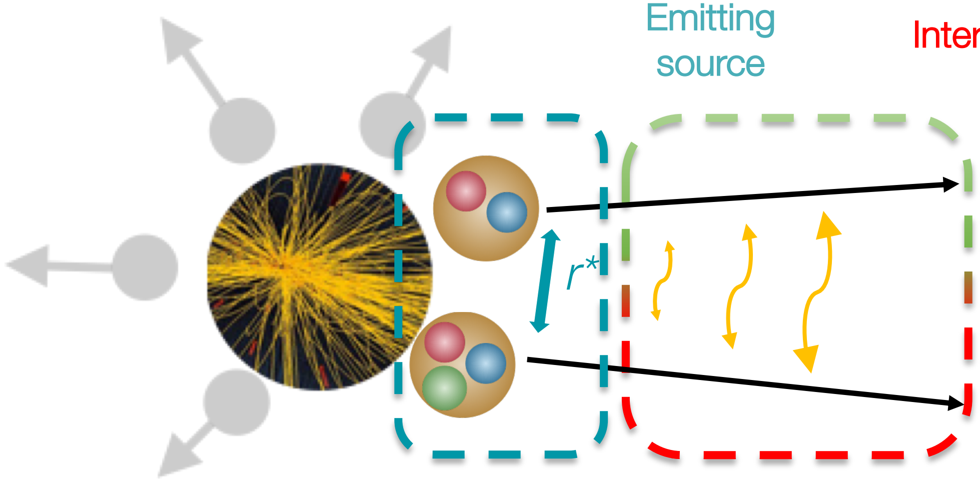
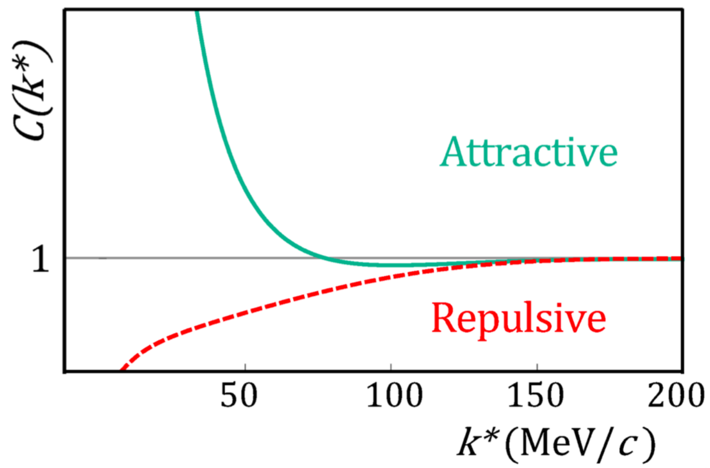
Emitting source

Interaction



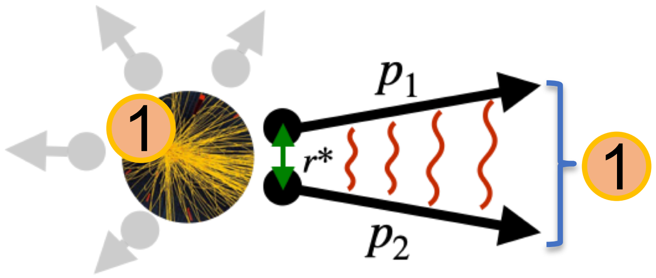
ALICE Coll. Nature 588 (2020) 232-238



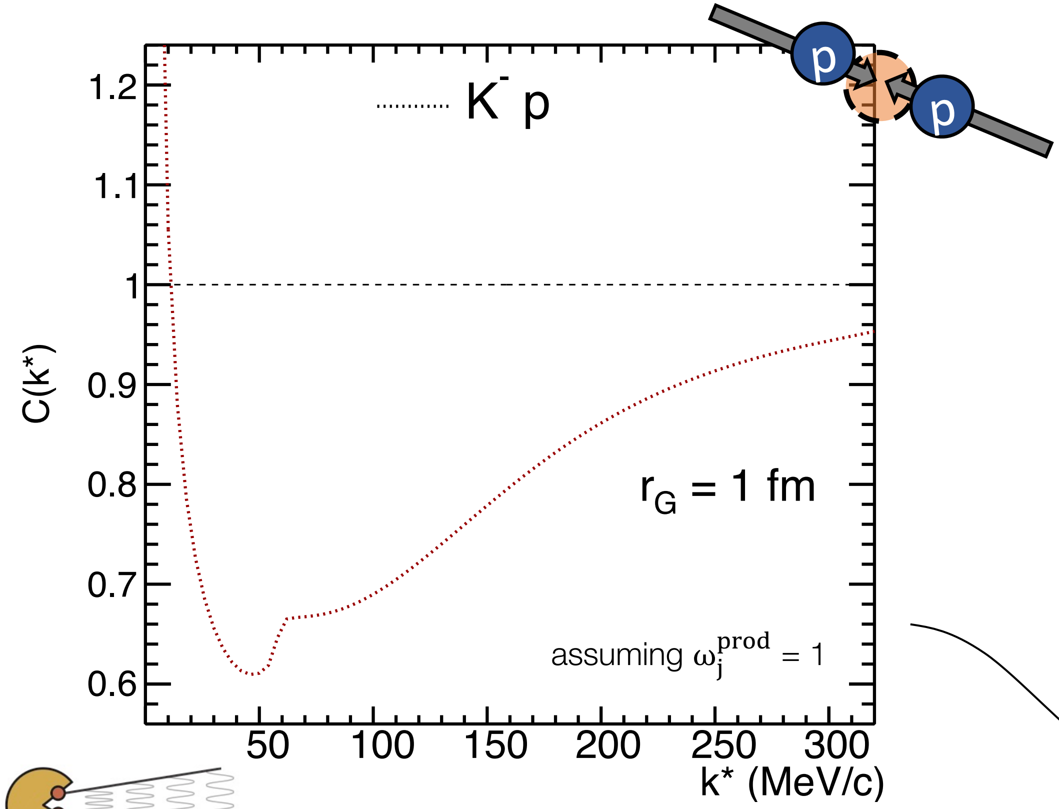
Correlation mapping 1-to-1 the nature of the interaction

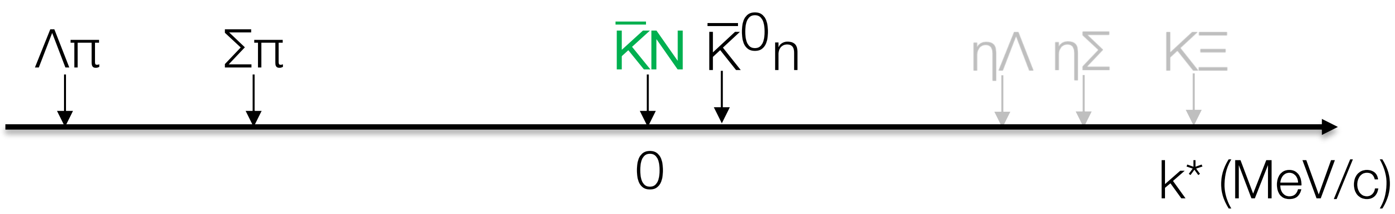
T. Humanic Tr1-LF Tue. 09:10
R. Del Grande Thur. 17:30

Coupled-channels dynamics in femtoscopy



$$C(k^*) = \underbrace{\int S_1(\vec{r}^*)\,\left|\psi_{1\to 1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3r^*}_{\text{elastic } 1 \to 1}$$





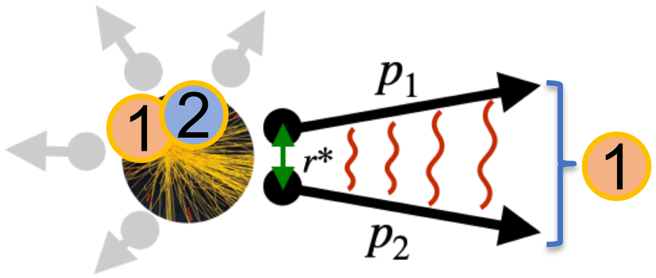
For more details: J. Haidenbauer NPA 981 (2019), Y. Kamiya et al. PRL 124 (2020)
L. Fabbietti, VMS, O. Vazquez Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)

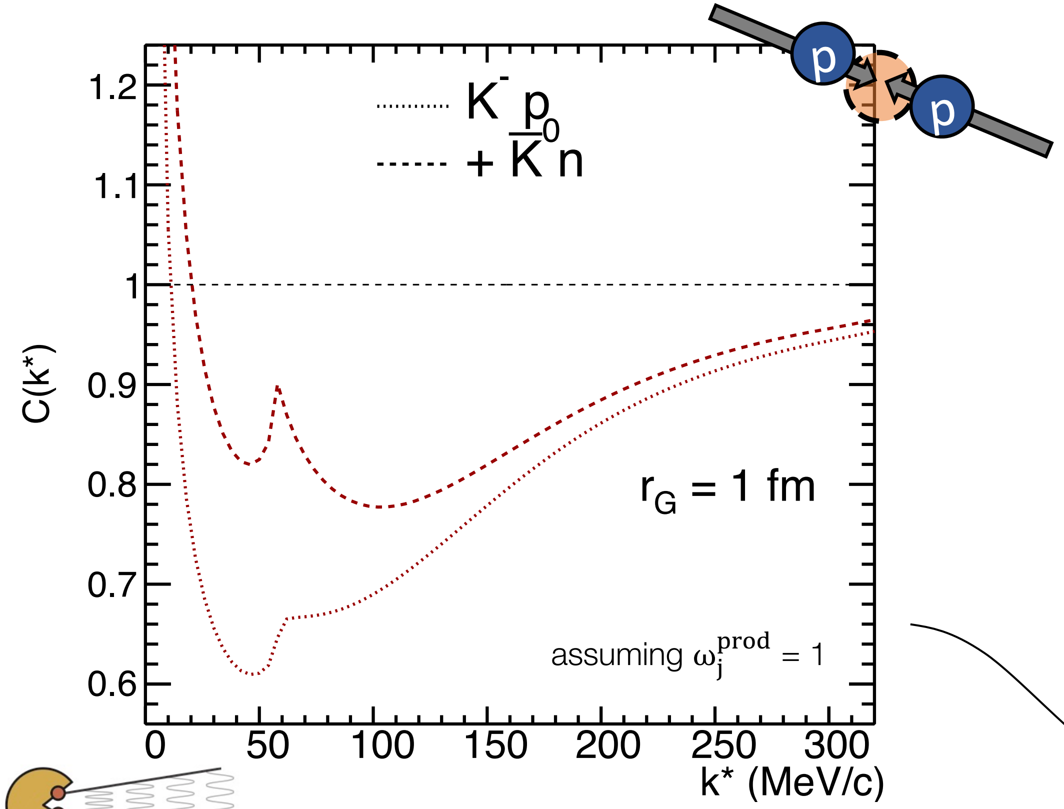
Coupled-channels dynamics in femtoscopy

$$C(k^*) = \int S_1(\vec{r}^*)\ \left|\psi_{1\to1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3r^* + \sum_{j\neq1} \omega_j^{prod} \int S_j(\vec{r}^*)\ \left|\psi_{j\to1}(\vec{k}_j^*,\vec{r}^*)\right|^2 d^3r^*$$

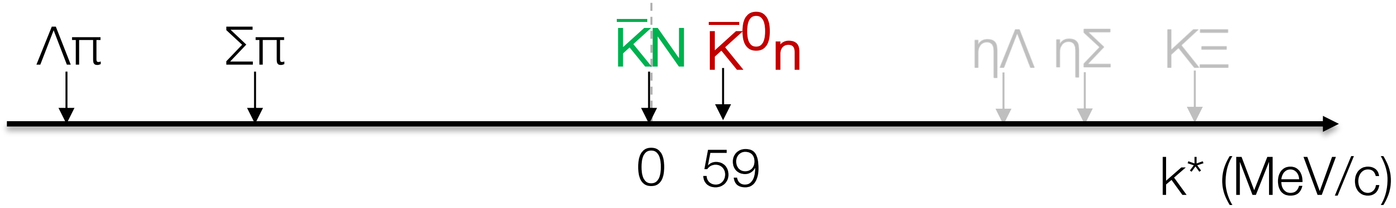
elastic
1 → 1

inelastic
2,.. → 1





Above threshold:
modify the shape of CF
→ cusp structure e.g. $\overline{K}^0 n$



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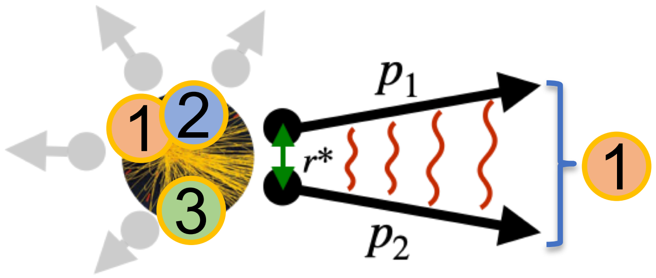
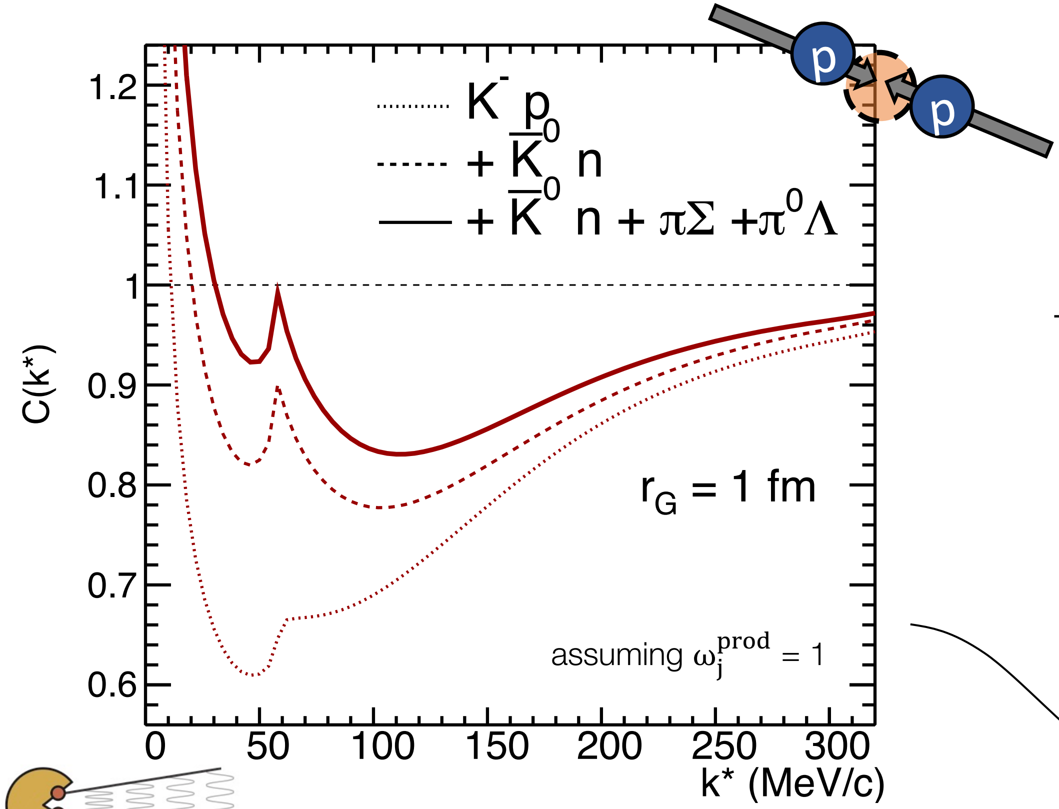
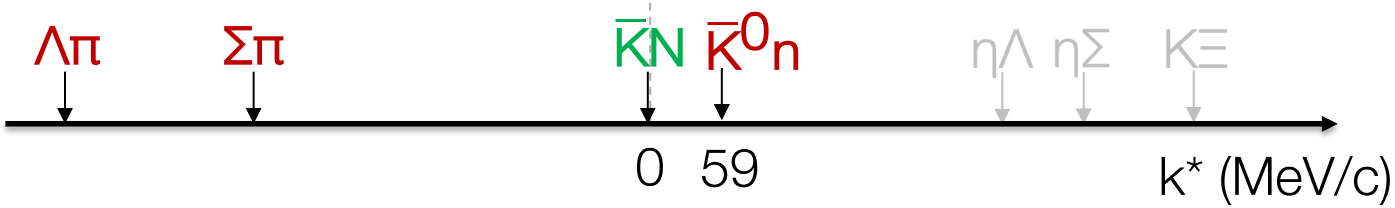




Below threshold:
increase the strength of CF
→ shift upward of CF e.g. $\Sigma\pi$

Above threshold:
modify the shape of CF
→ cusp structure e.g. $\bar{K}^0 n$



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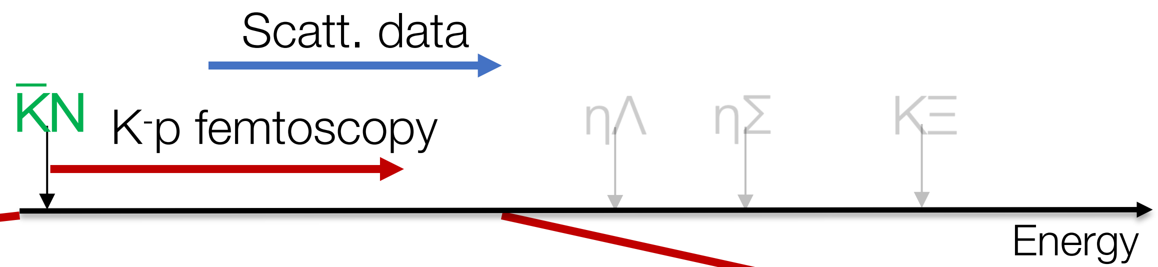
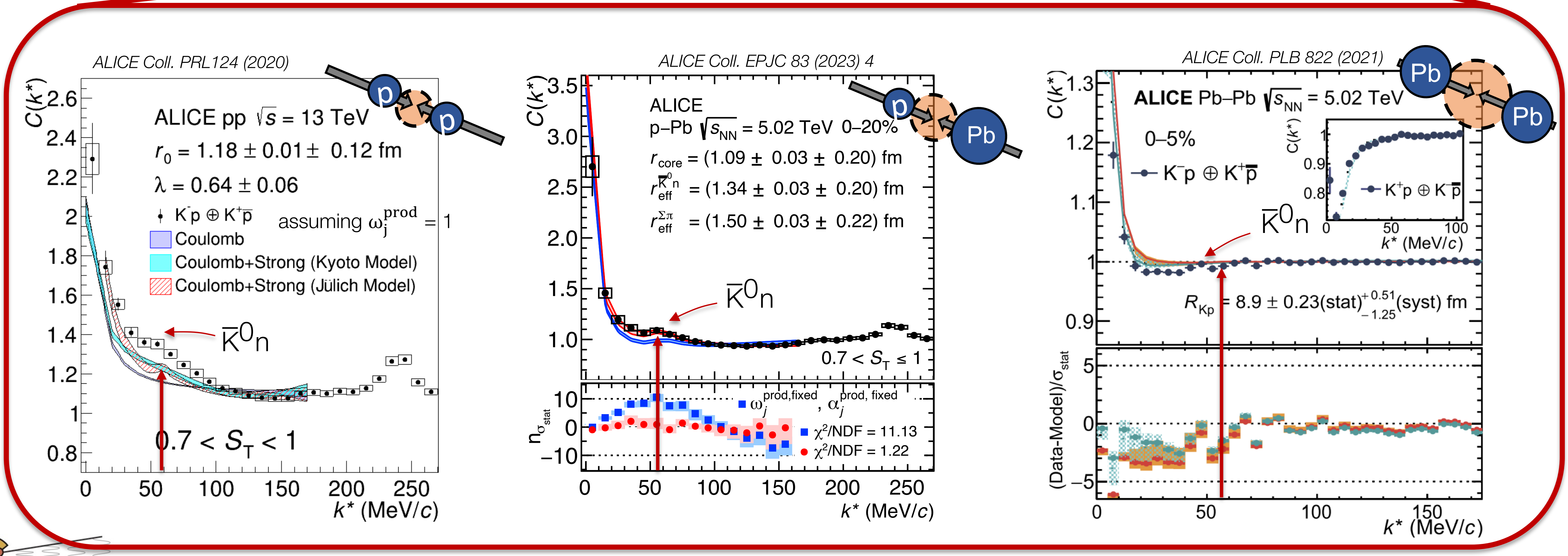
High-precision data on S=-1 sector above threshold

- **Most precise data** above K⁻p threshold
- Crucial input for low-energy chiral effective potentials





Accessing the Ξ^-K^+ system with femtoscopy

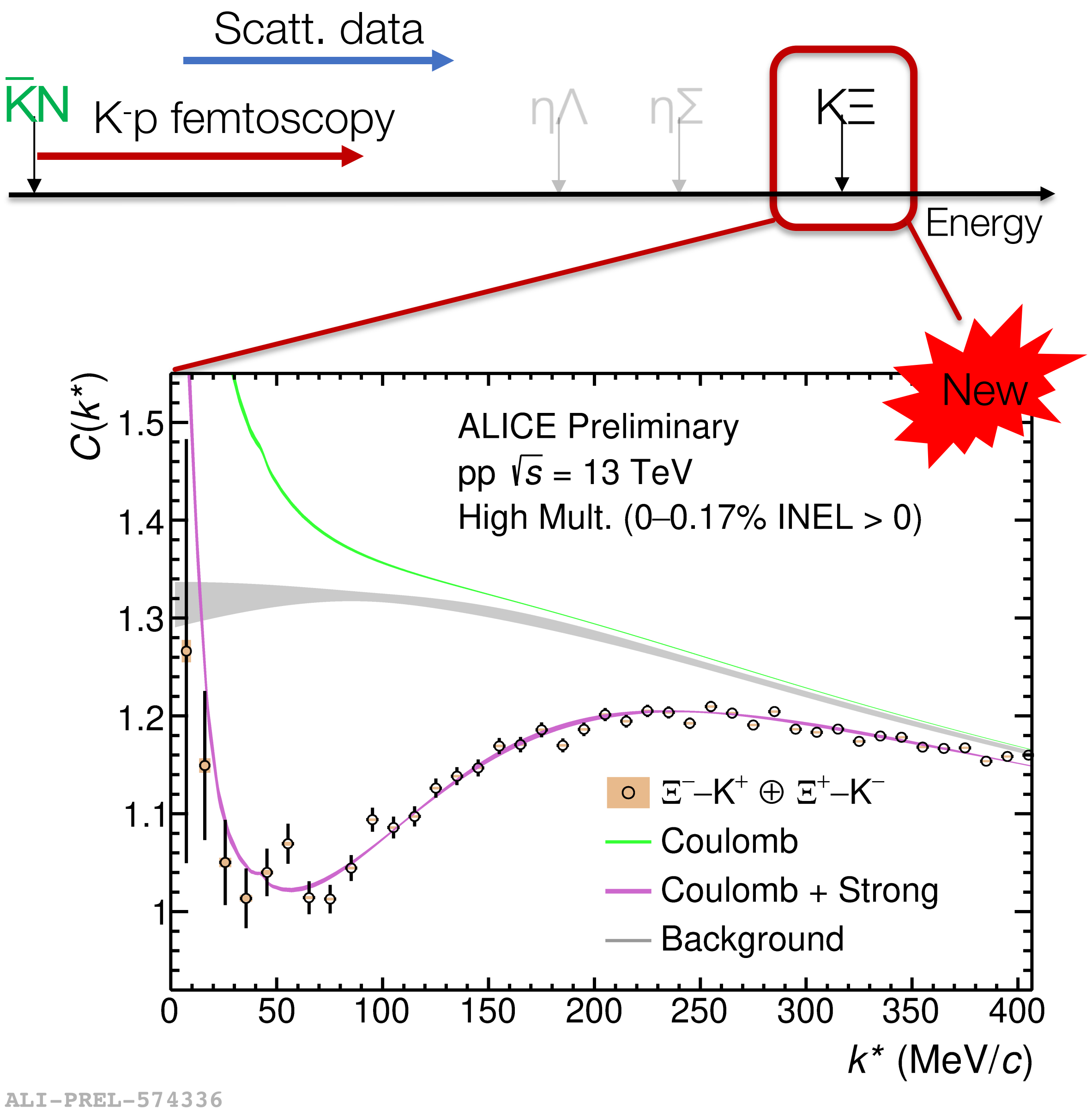
- Most precise data at low momenta on the interaction between Ξ and kaons
  - Important constraints for I=1 channel of S=-1 meson-baryon interaction

- Modeled assuming Lednicky-Lyuboshits wavefunction with Coulomb (S-wave only)
  R. Lednicky, Phys.Part.Nucl.40:307-352,2009
  - Coulomb + strong repulsive interaction well in agreement with the data

- Determination of scattering length from best fit

$$\Re f_0 = -0.61^{\pm 0.02(stat)}_{\pm 0.07(syst)}$$

$$\Im f_0 = \mathbf{0.41}^{\pm 0.04(stat)}_{\pm 0.11(syst)}$$



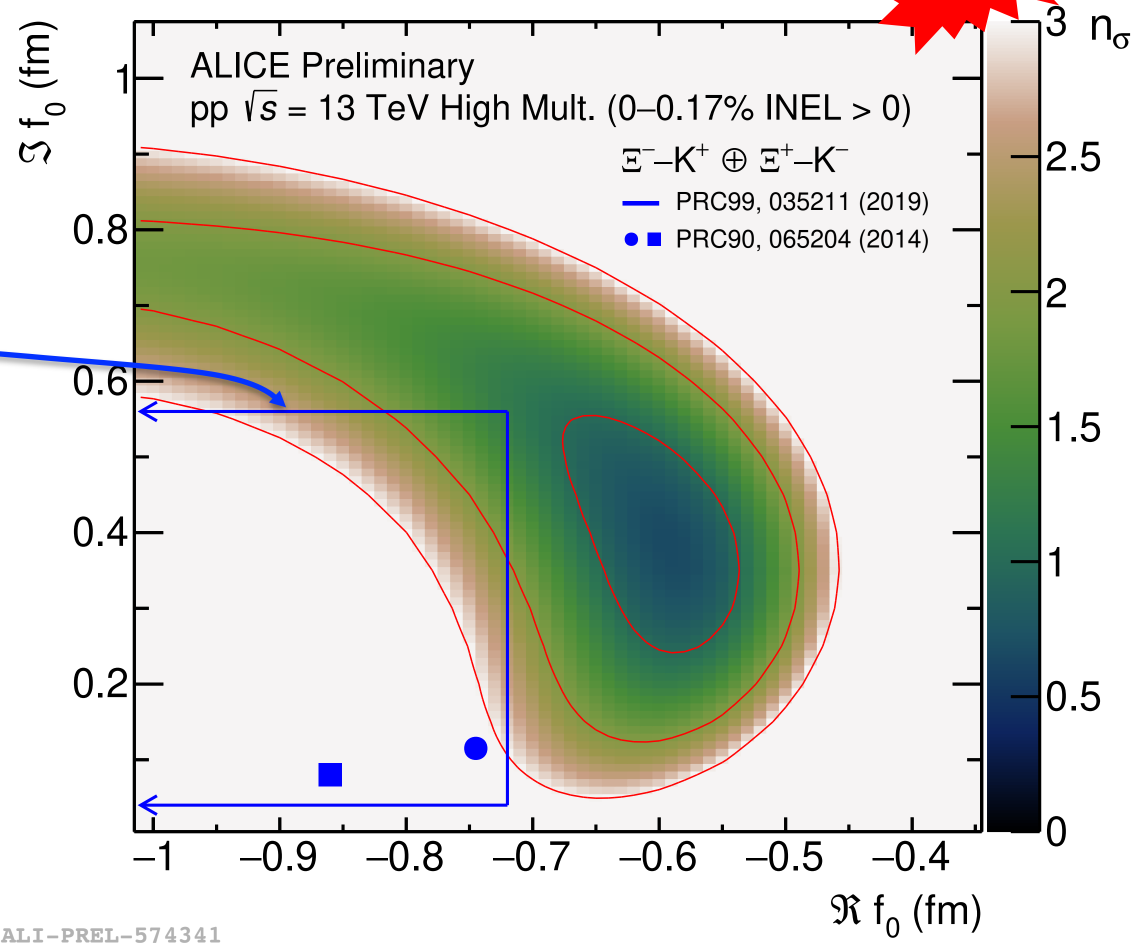
Constraining the scattering parameters of $\Xi^{-}K^{+}$ pairs

- Comparison of data with modeling assuming different values of $(\Re f_0, \Im f_0)$
  - Delivered in terms of number of standard deviations (nσ) in $k^* \in [0,250]$ MeV/c

- Allowed values for f_0 from **state-of-the-art chiral calculations** at next-to-leading order and phenomenological potentials **constrained** to **available scattering data**

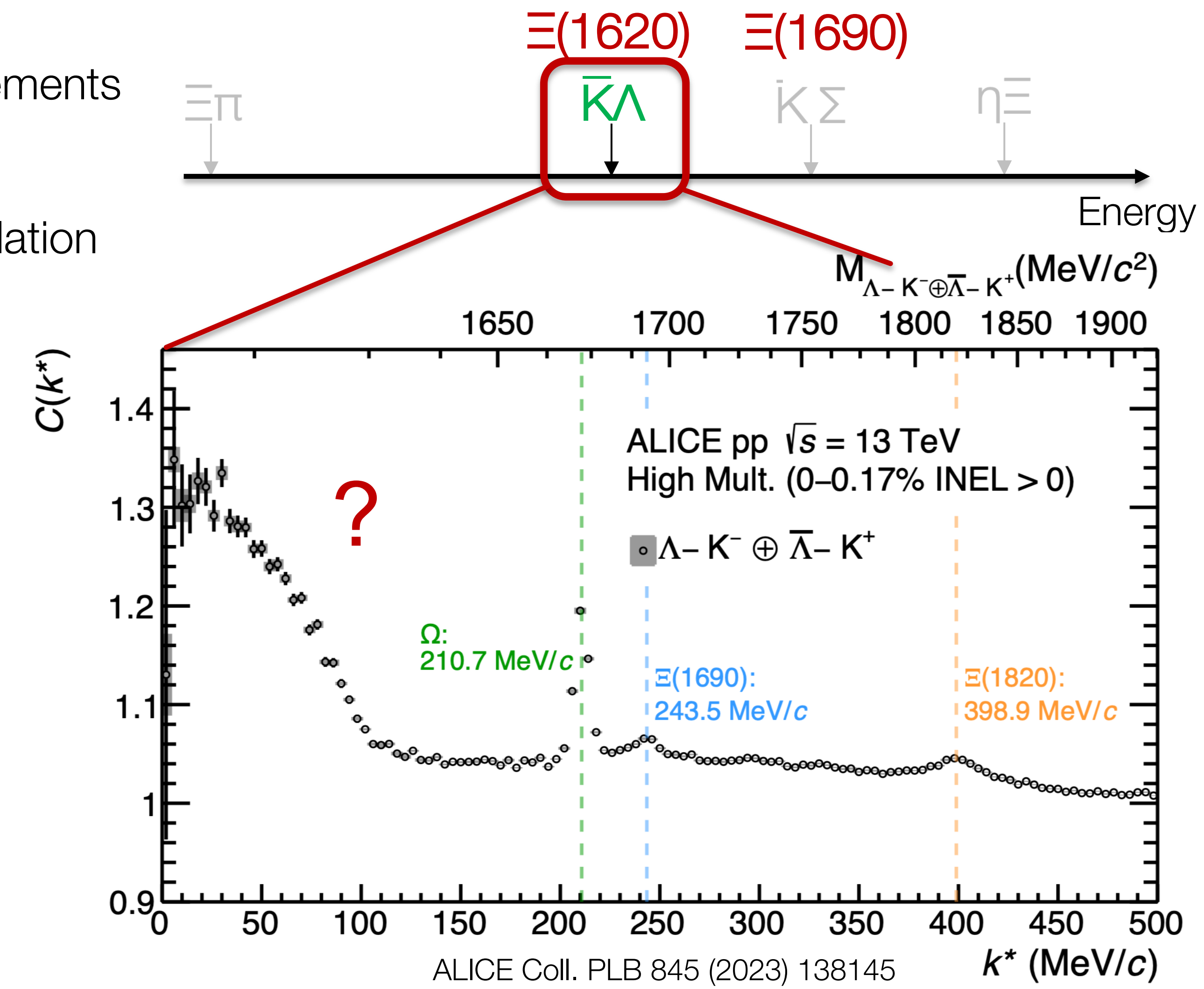
Higher precision constraints can be delivered with correlation data

New



Accessing the S=-2 meson-baryon interaction

- Extending previous Pb–Pb femtoscopic measurements to pp collisions
  ALICE Coll. PRC 103 (2021)
- Several structures present in the measured correlation



ALICE Coll. PLB 845 (2023) 138145

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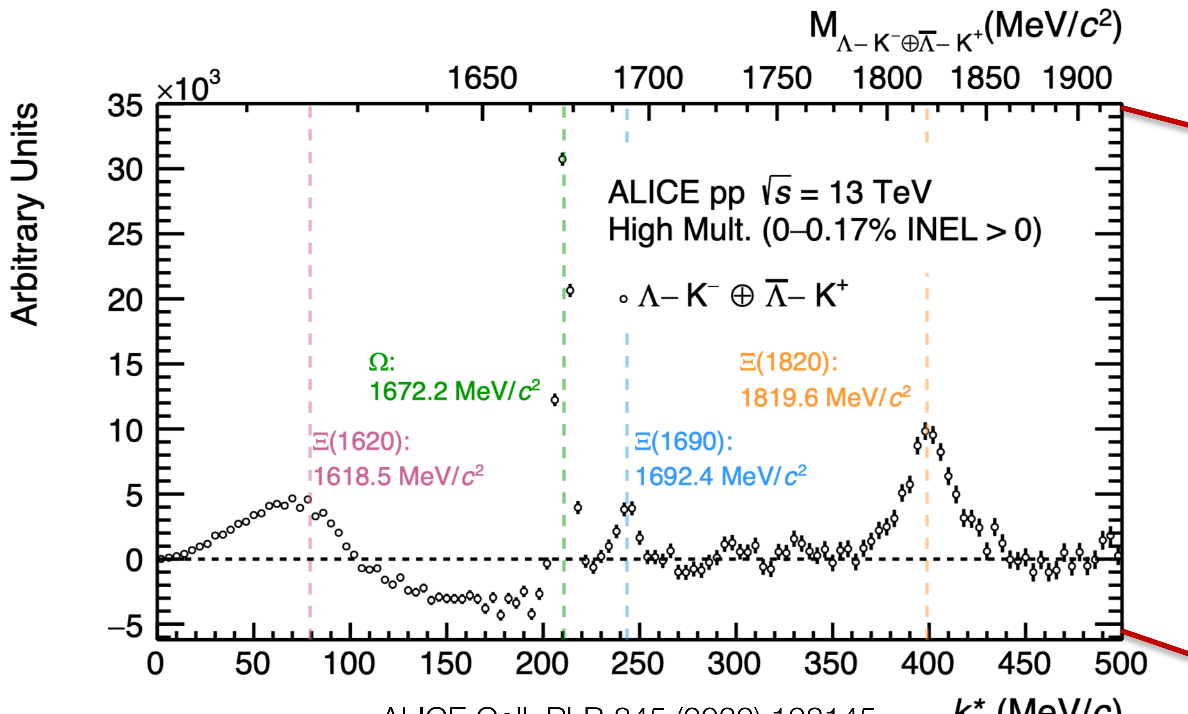
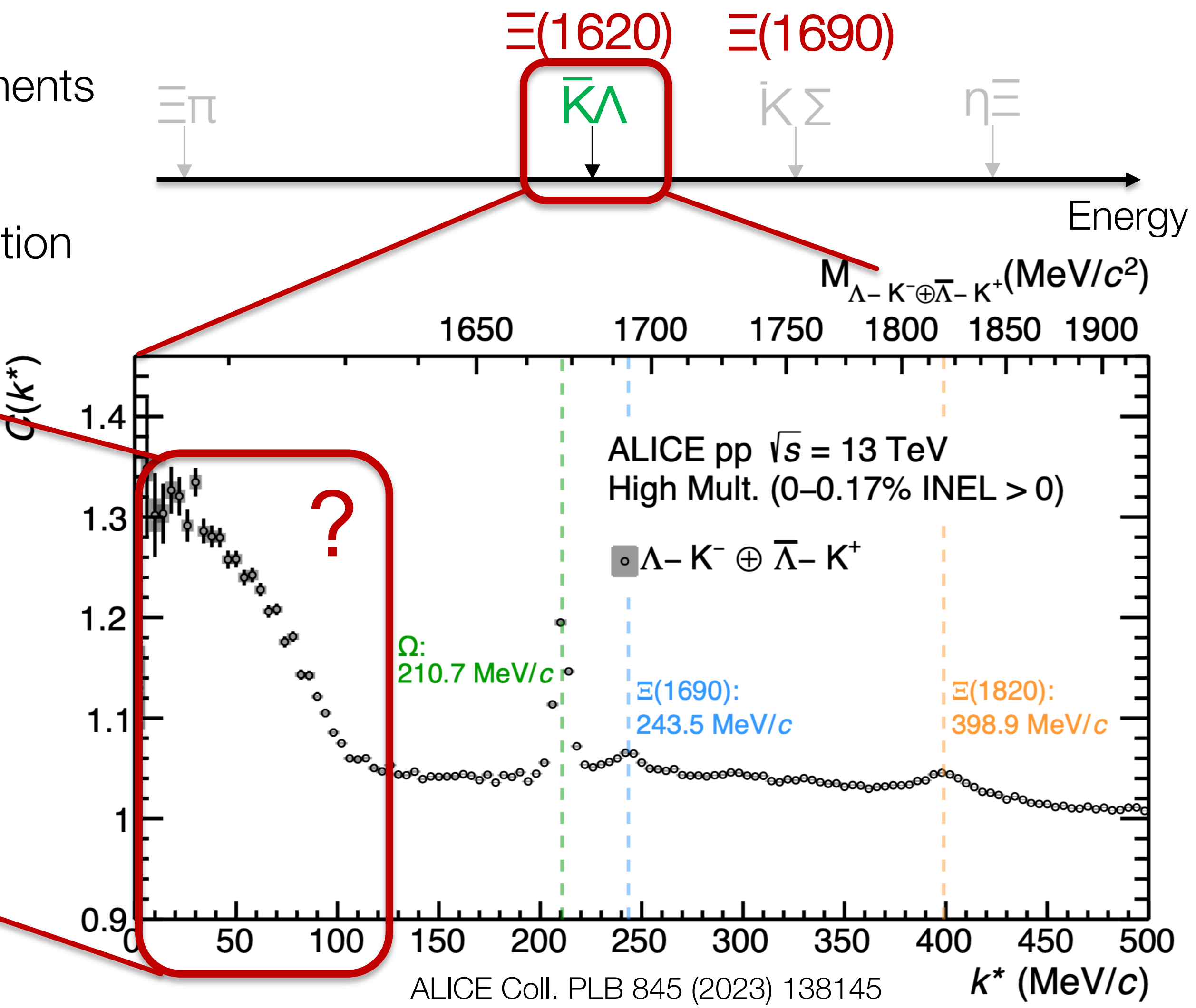


ALICE Coll. PLB 845 (2023) 138145

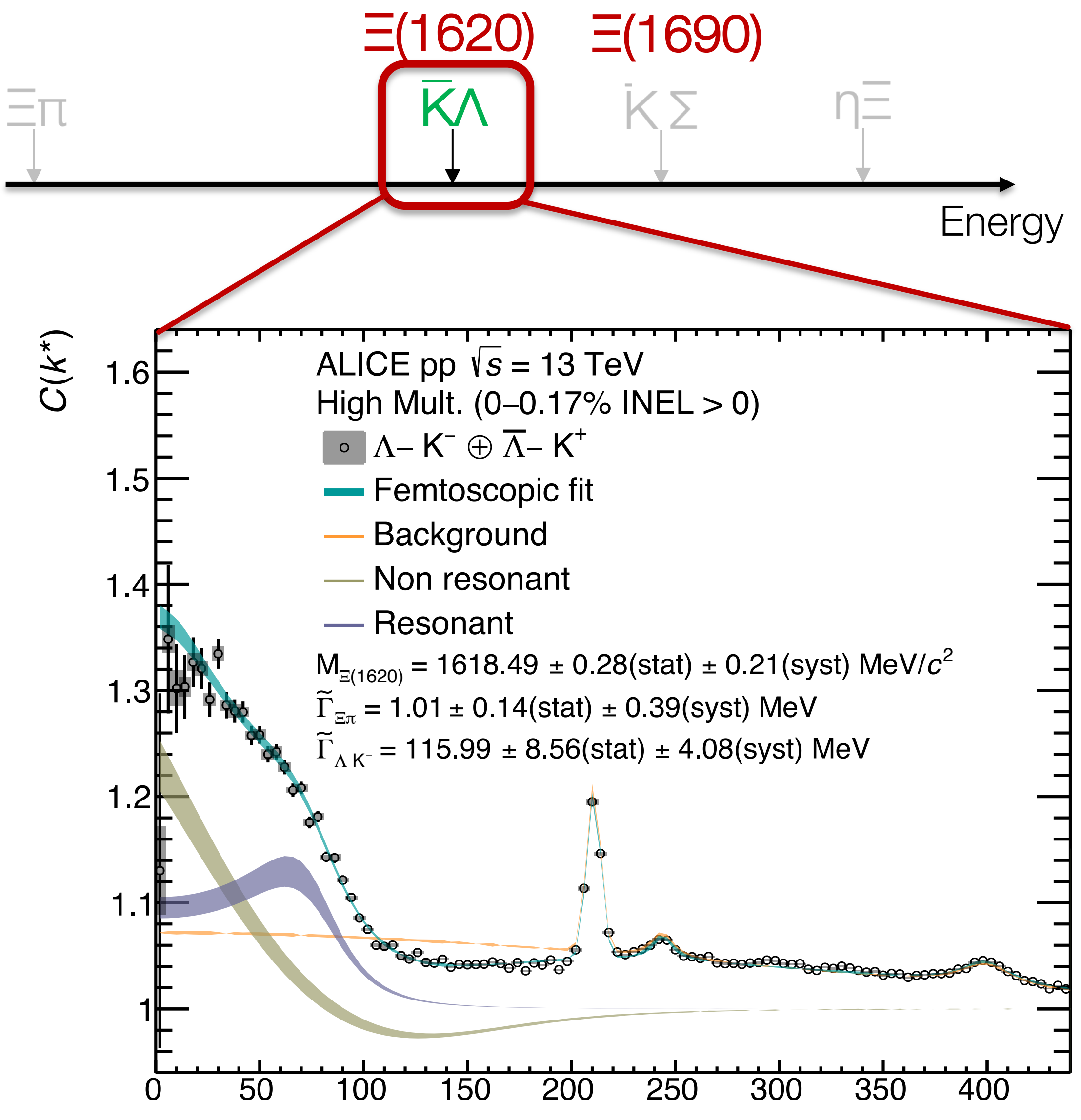


ALICE Coll. PLB 845 (2023) 138145

First experimental evidence of Ξ(1620) decay into ΛK^-

$K^{-}\Lambda$ correlations and the S=-2 meson-baryon sector

- Most precise data for ΛK^{-} down to threshold
- Model well reproduces the data in the whole k* region
  → Interplay between **resonant (Flatté-like)** and **non-resonant** interaction
- **Ξ(1620) and Ξ(1690) properties**
  → Overall compatible with previous Belle and LHCb results
  → Indication of a large coupling of Ξ(1620) to ΛK^{-}
- Possibility to employ these data constrain effective chiral potentials to explore this multi-strange sector
  VMS, Feijoo et al. arXiv: 2309.08756



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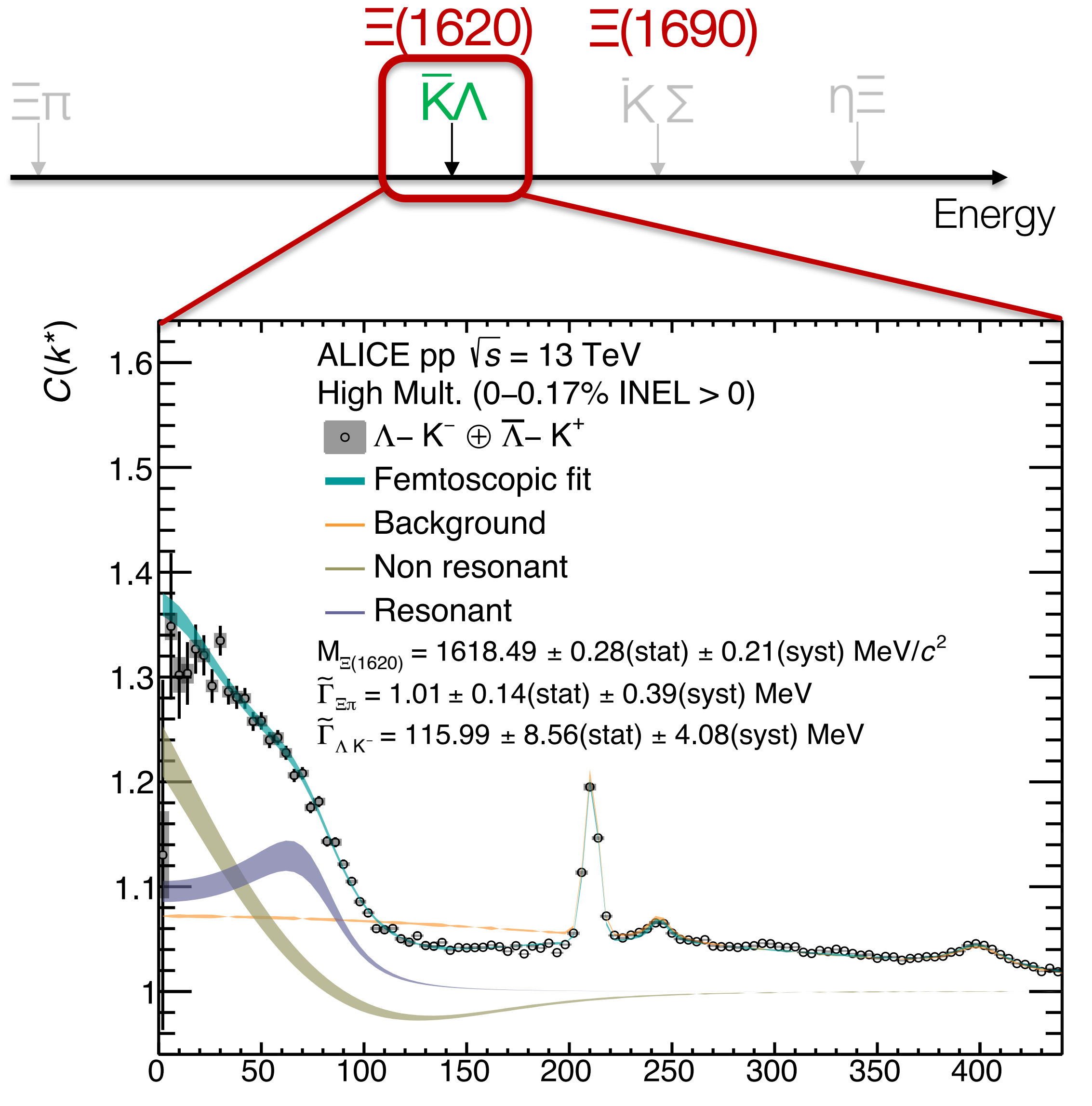
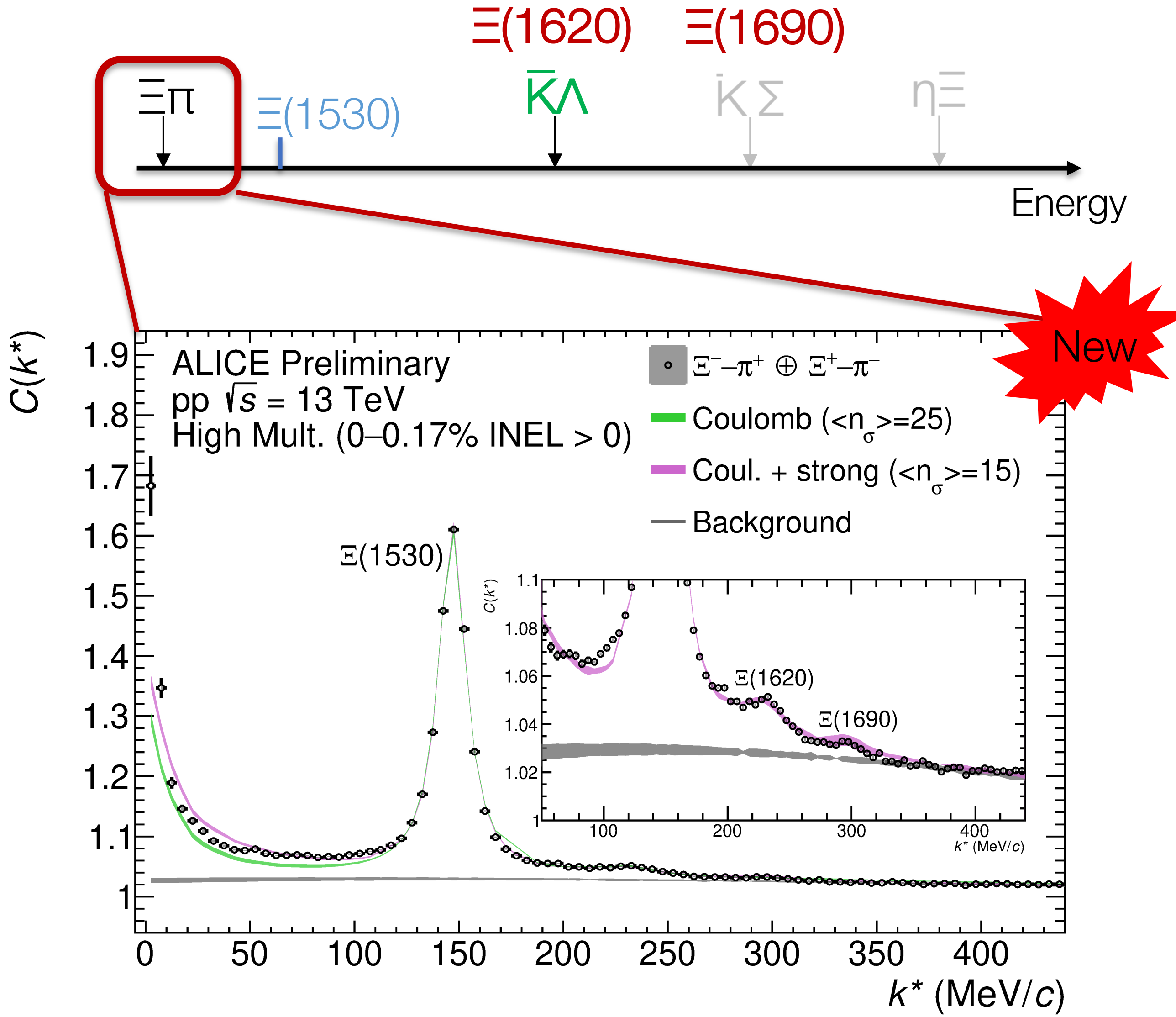


ALICE Coll. PLB 845 (2023) 138145

Can we access with correlations other channels?

The $\Xi^-\pi^+$ correlation in pp collisions

- Most precise data for $\Xi^-\pi^+$ down to threshold
- Several states visible in the measured correlation
  - $\Xi(1530)^0 \rightarrow \Xi^-\pi^+$ (B.R. 100%)
  - $\Xi(1620)$ and $\Xi(1690)$ as observed by Belle
- Same modeling as in Ξ^-K^+
  R. Lednicky Phys.Part.Nucl.40:307-352,2009
  - Evidence of strong attractive interaction
- $\Xi(1620)$ and $\Xi(1690)$ modeled with a Breit-Wigner distribution
  - Mass and widths compatible with previous spectroscopic measurements



ALI-PREL-573869

Scattering parameters for the $\Xi^{-}\pi^{+}$ interaction

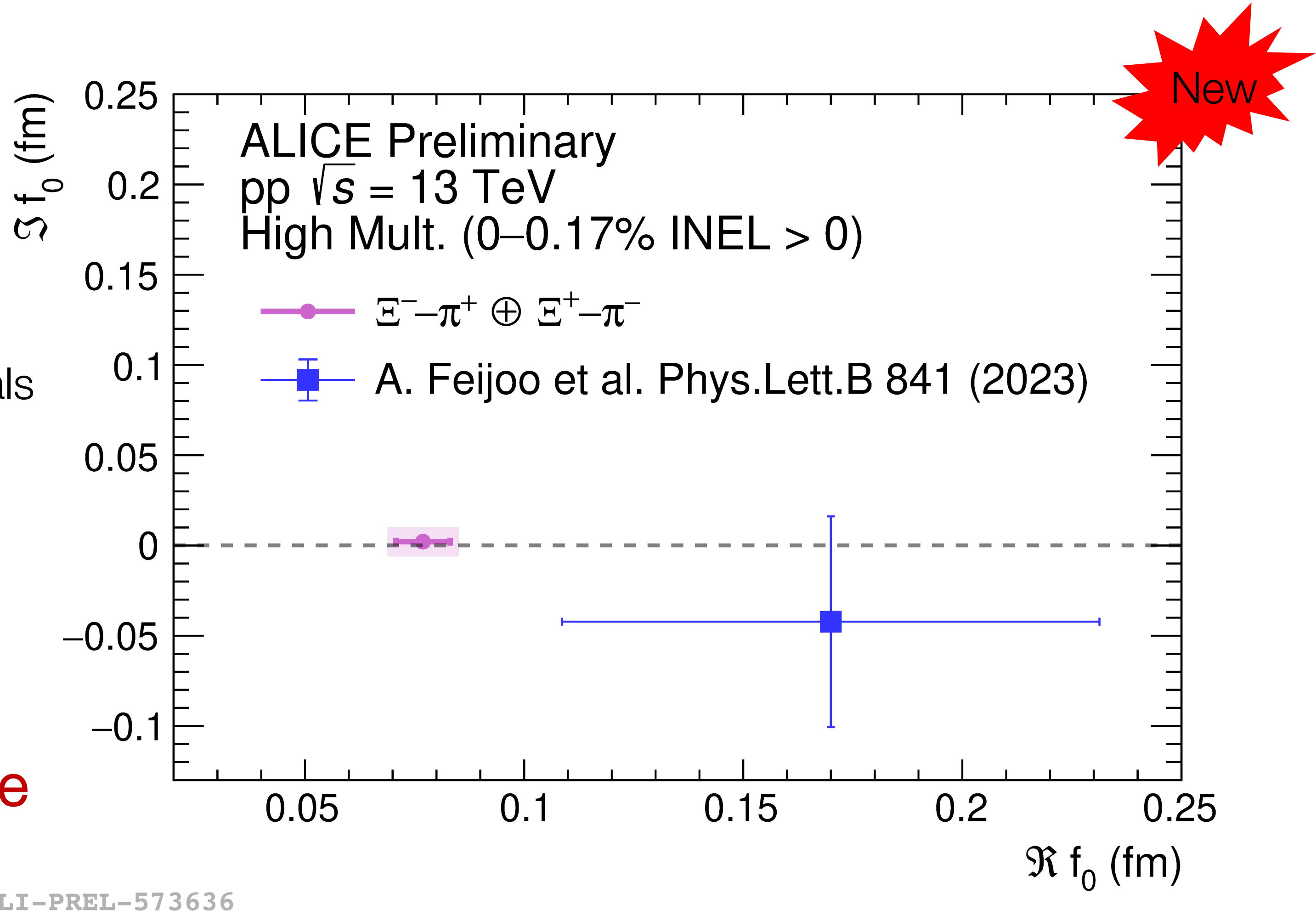
- Rather shallow attractive interaction

$$\Re f_0 = 0.089^{\pm 0.007(stat)}_{\pm 0.009(syst)}$$

$$\Im f_0 = \mathbf{0.007}^{\pm 0.003(stat)}_{\pm 0.005(syst)}$$

- Available predictions from NLO chiral potentials constrained to S=-1 data affected by large uncertainties
  A. Feijoo et al. PLB 841 (2023), 137927
  Erratum PLB 853 (2024) 138660
  – Overall compatible with our results

Novel high-precision data available to constrain this multi-strange meson-baryon sector!



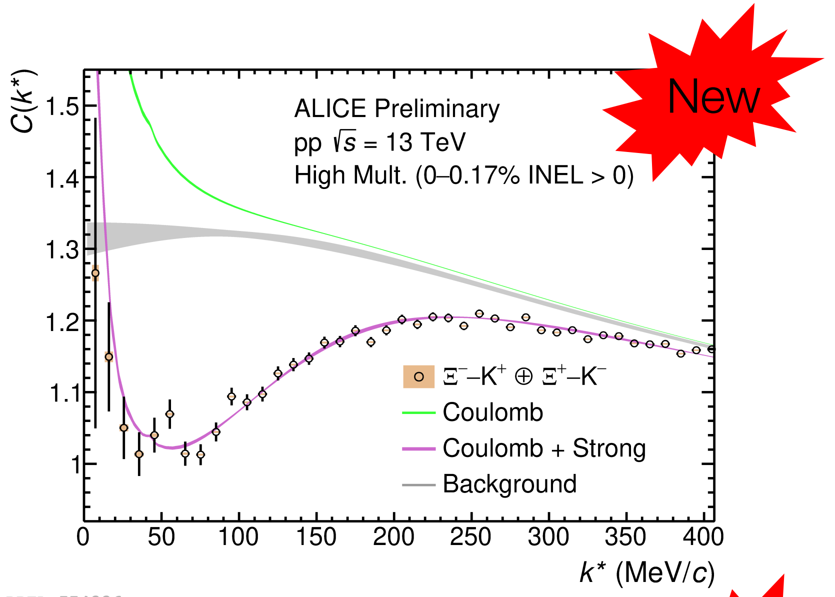
waiting for approved figure

Conclusions and outlooks

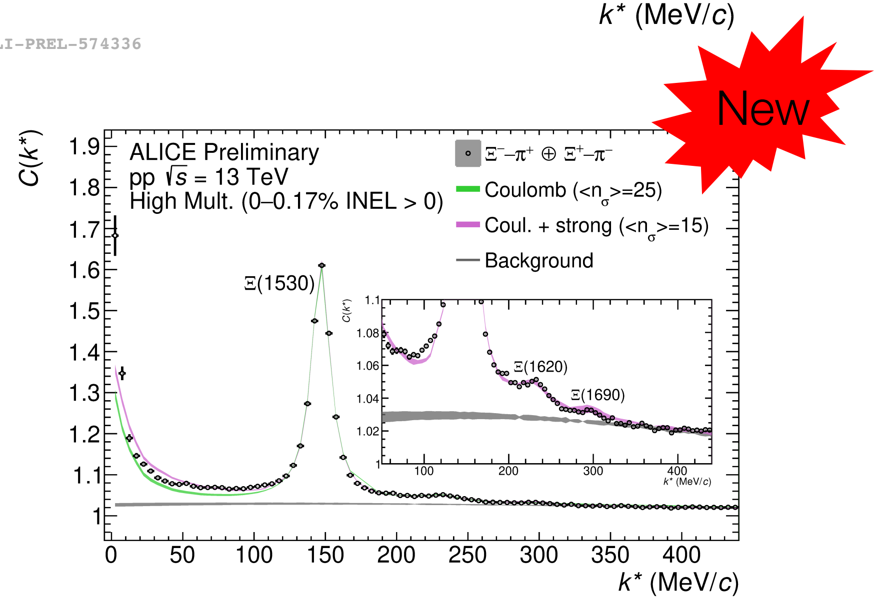
- Most precise data on ΞK and Ξπ at low momenta available
  - Novel high-precision constraints on S=-1 and S=-2 baryon interactions available with correlation data
  - Input for low-energy effective chiral lagrangians
- Femtoscopy technique as a complementary tool to provide high-precision data on hadron-hadron interactions to study exotic states
- Possibility to explore other relevant systems in these sectors with on-going Run 3!

Femtoscopy ALICE talks at SQM:
M. Arslandok Mon. 10:45
T. Humanic Tr1-LF Tue. 09:10
R. Del Grande Thur. 17:30
A. Riedel Tr1-LF Wed. 09:30

Femtoscopy ALICE posters at SQM:
N. Agrawal Tue. 18:30



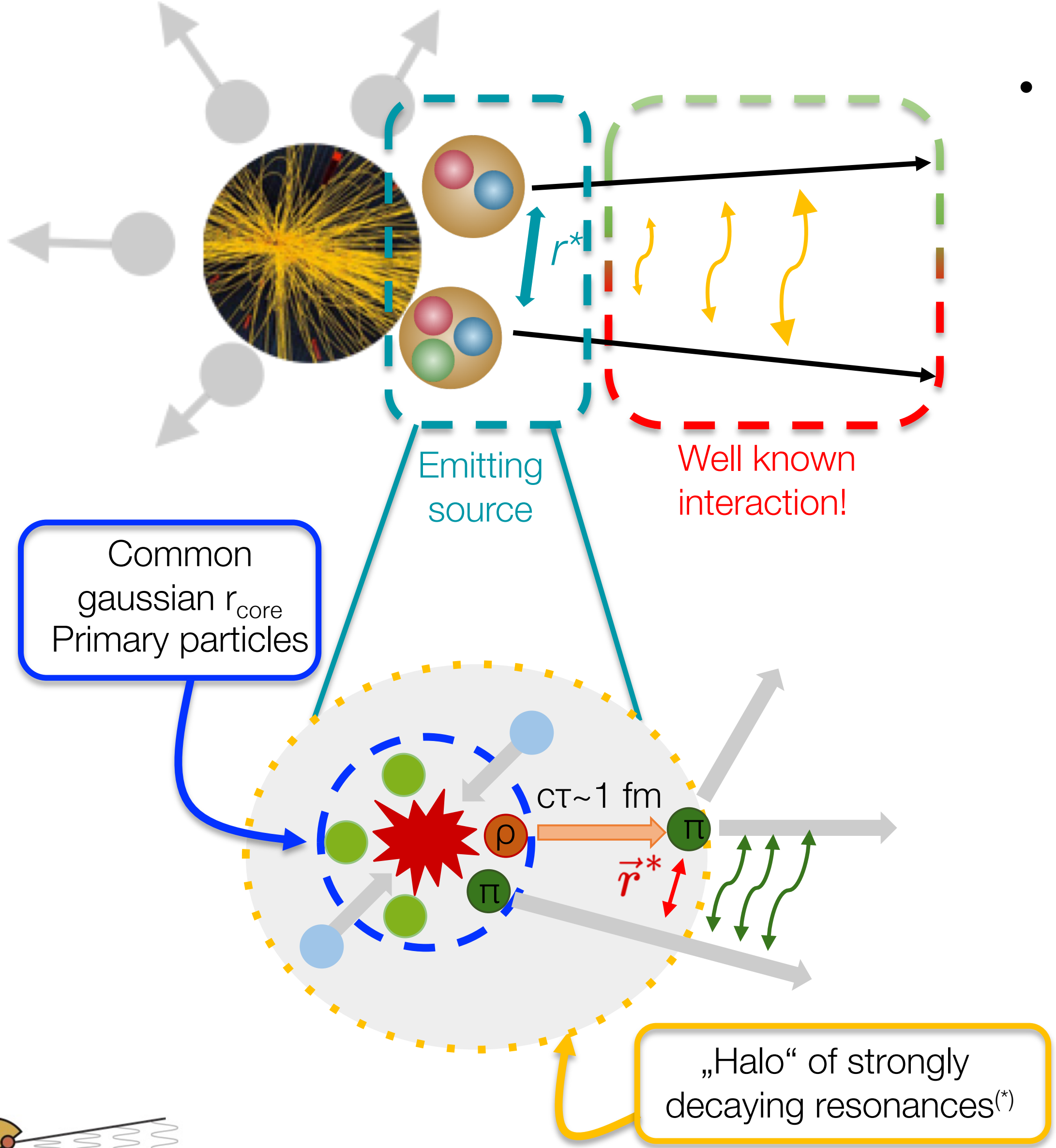
ALI-PREL-574336



ALI-PREL-573869

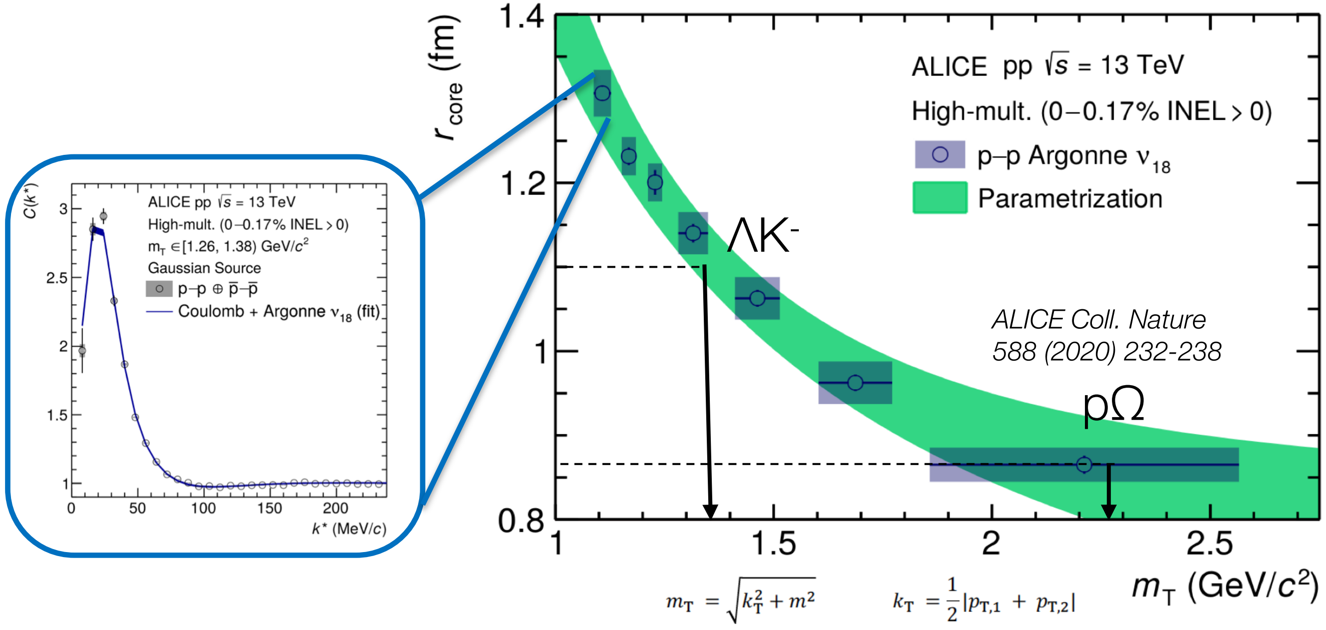
Additional slides

The emitting source in pp collisions



- Modeled in a data-driven way using p-p correlations, most known interaction!!

Based on ALICE Coll. PLB 811 (2020) 135849
(*) U. A. Wiedemann, U. W. Heinz, Phys.Rept. 319, 145-230 (1999)



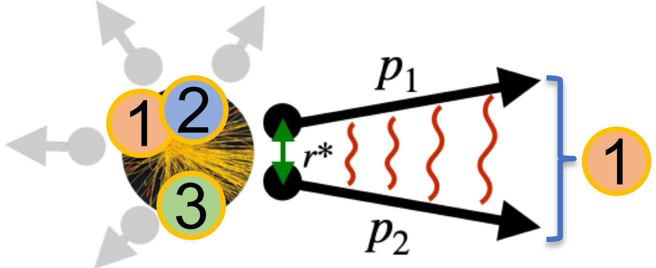
- Fixing of the source at corresponding <m_T>
  → Direct access to the interaction
  → Interparticle distances ~1-2 fm

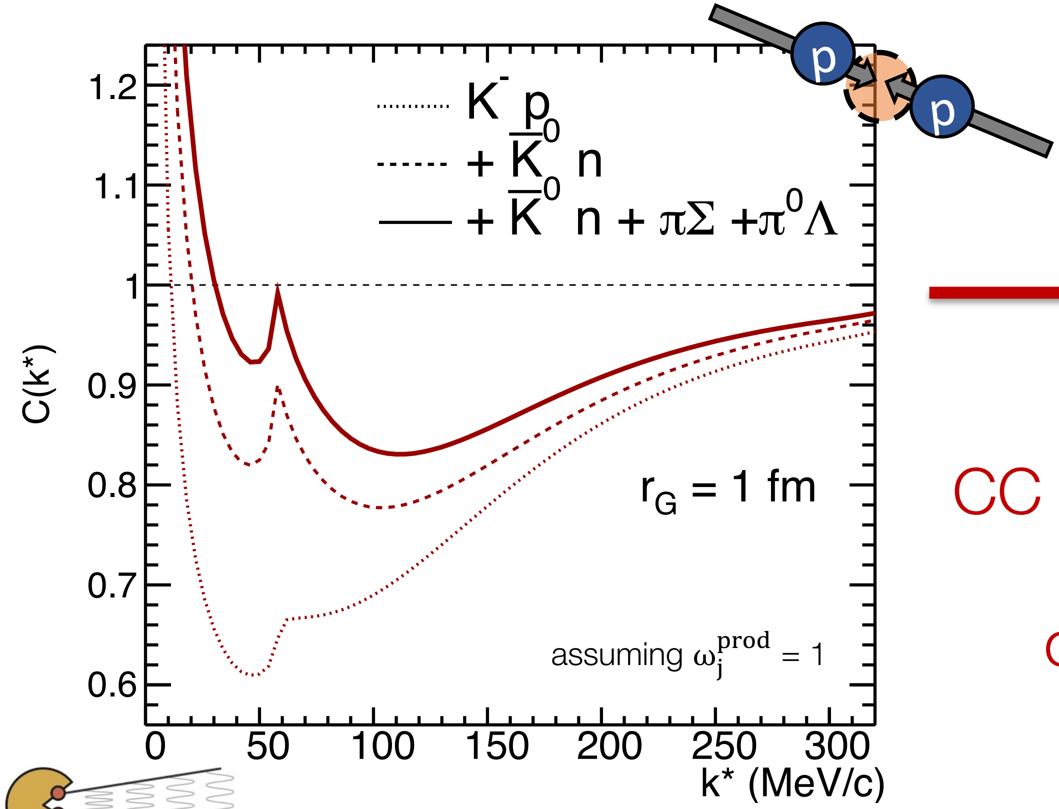
Coupled-channels dynamics and source size

$$C(k^*) = \underbrace{\int S_1(\vec{r}^*)\,\left|\psi_{1\to1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3r^*}_{\text{elastic } 1\to1} + \underbrace{\sum_{j\neq1}\omega_j^{prod}\int S_j(\vec{r}^*)\,\left|\psi_{j\to1}(\vec{k}_j^*,\vec{r}^*)\right|^2 d^3r^*}_{\text{inelastic } 2,3,\ldots\to1}$$

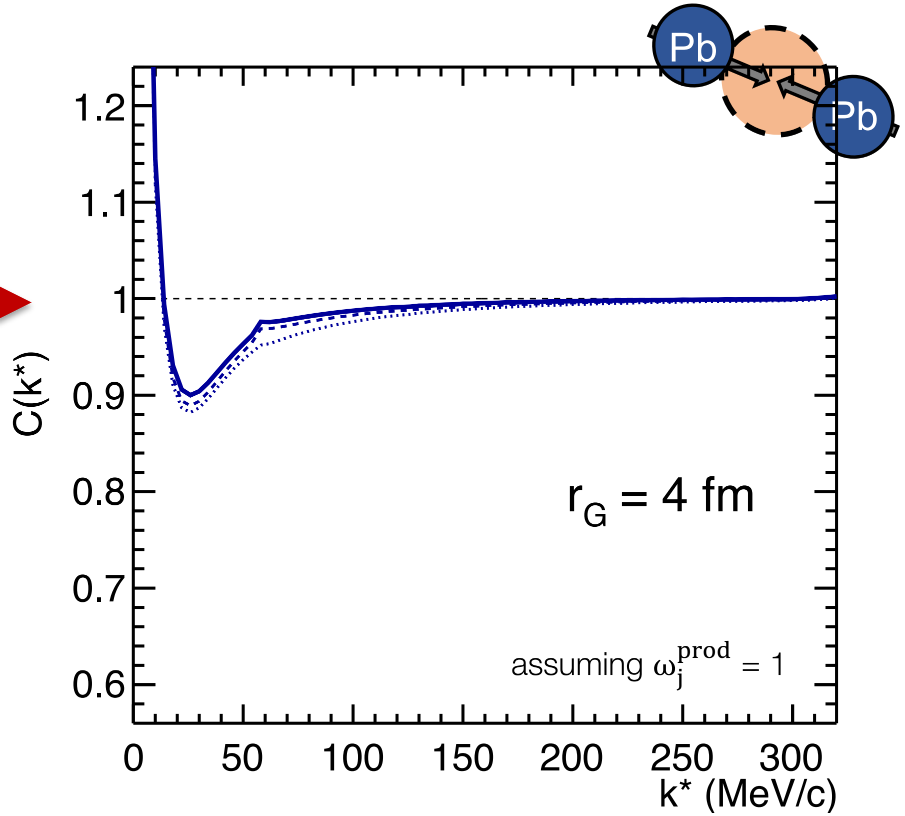
elastic
1 → 1

inelastic
2,3,… → 1





CC effect on correlation reduced in large colliding systems



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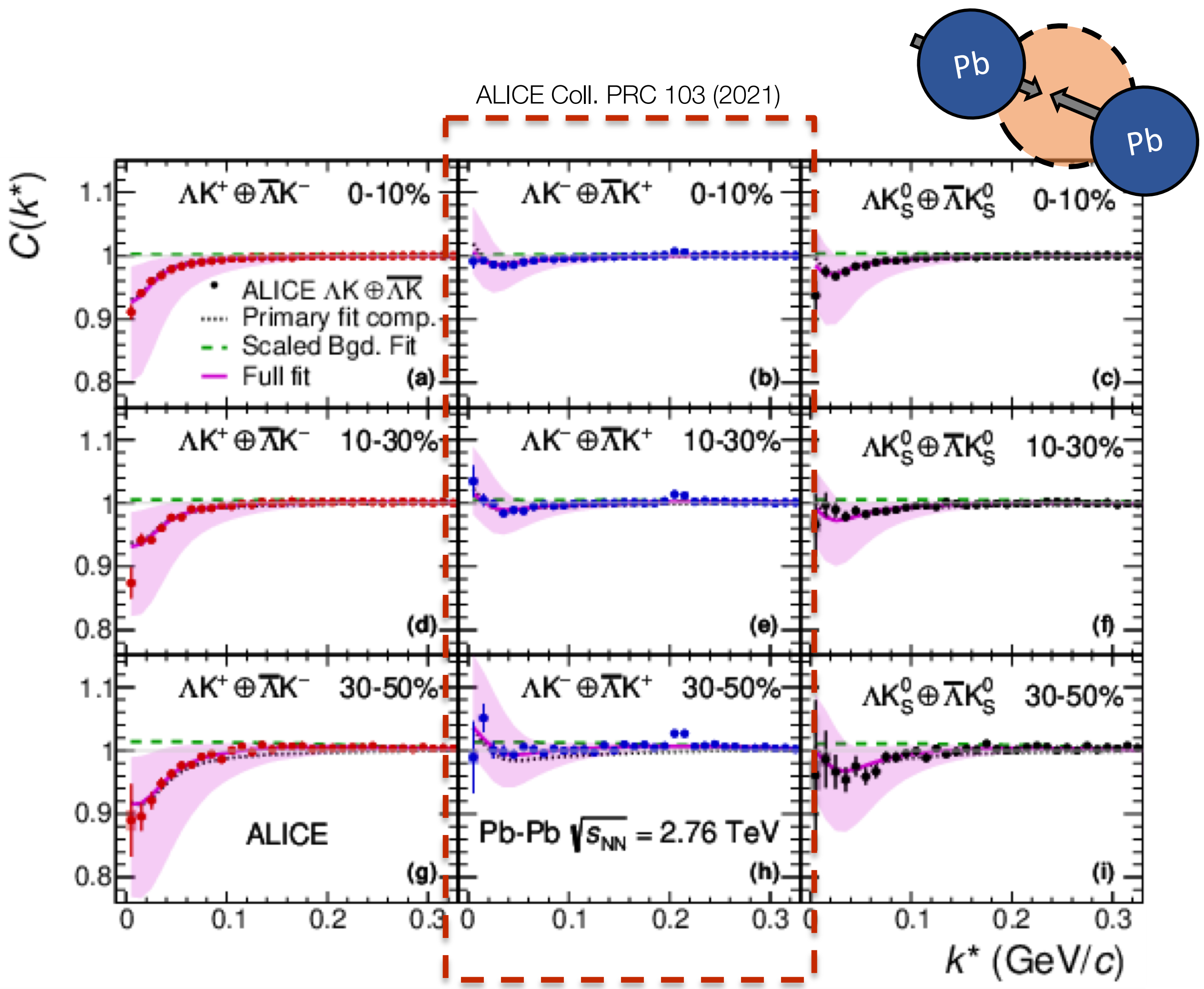
Moving to $K^-\Lambda$ correlations…

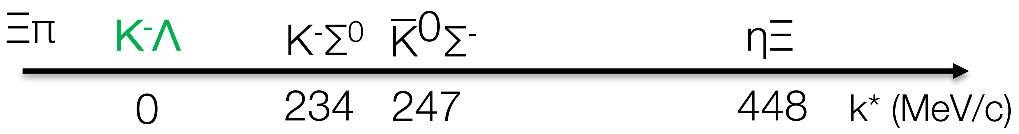
- Correlations measured in Pb-Pb collisions
  → No particular cusps or structure visible
  → First measurements of $\Lambda\overline{K}$ scattering parameters!

How does the correlation look like in pp collisions?

Can we shed light on the nature of Ξ(1620) and Ξ(1690) states with correlations?

ALICE Coll. PRC 103 (2021)





Scattering parameters for ΛK^-

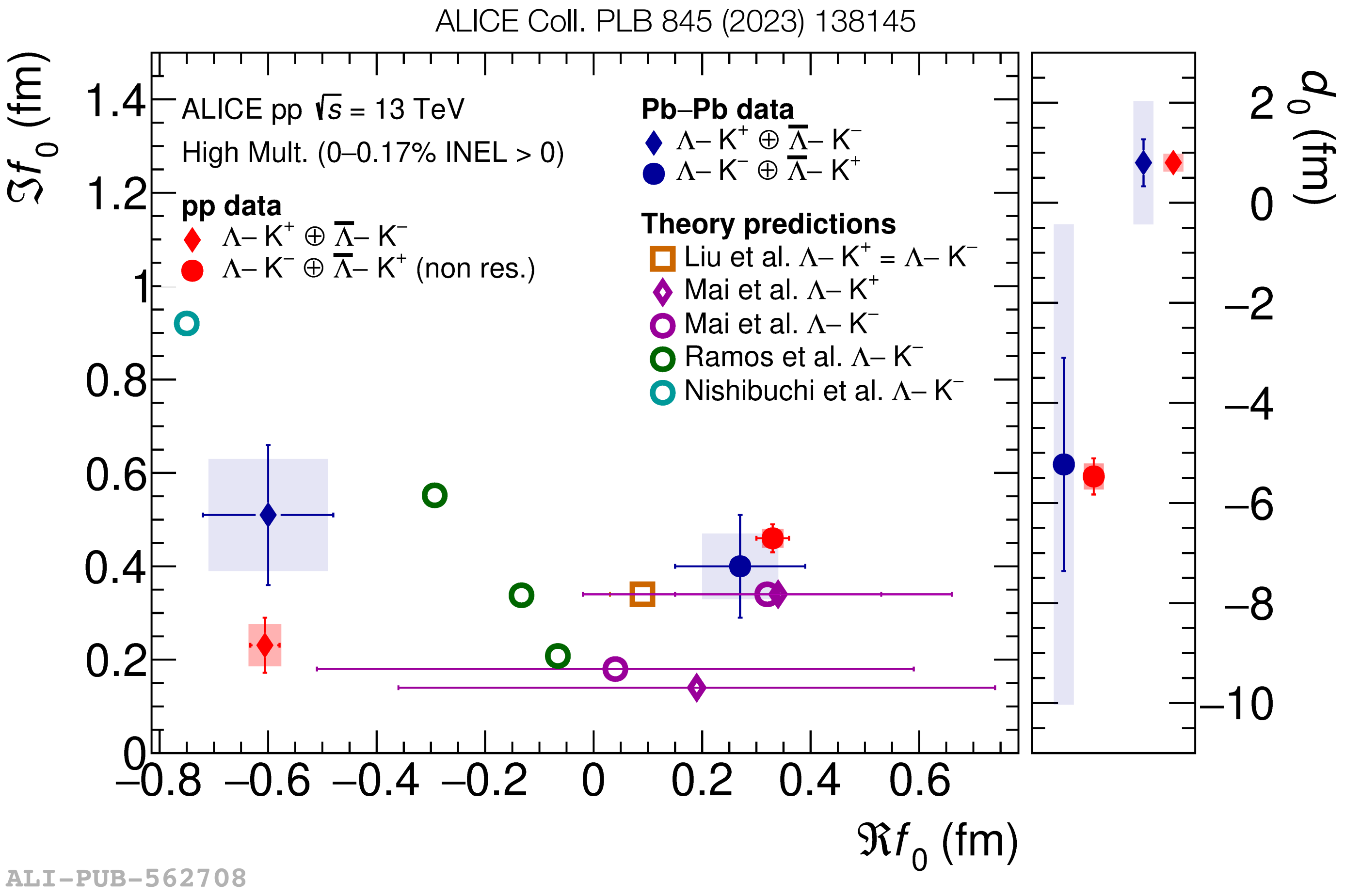
- Indication of an attractive non-resonant interaction
  → In agreement with ALICE Pb-Pb results[1]

- Available models far from converging on similar results

  → Parameters fixed based on SU(3) flavour symmetry, isospin symmetry

  → Mainly anchored to πN or $\bar{K}N$ data

  → Ξ(1620) typically lying below threshold



UχPT at LO: Ramos et al. PRL 89 (2002), Nishibuchi et al. EPJ Web Conf 271 (2022)
χPT at NLO: Liu et al. PRD 75 (2007), Mai et al. PRD 80 (2009)

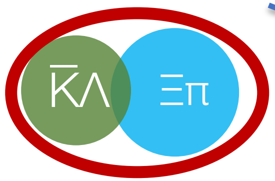
Creating an invariant mass plot

The approach adopted is the same as in a typical resonance analysis:

1. Raw signal: Pair (ΛK^-) and AntiPair (antiΛK^+) for SE data
2. Subtract the uncorrelated background: as in resonance analysis we use the ME data, normalized to SE in a region outside the signal (k^* in 500-800 MeV/c)
3. Subtract the uncorrelated background
   a. $(SE\text{-}ME)_{data}$
4. The residual background from mini-jet is left, and we can use MC to subtract it
   a. as done for data we obtain $(SE\text{-}ME)_{MC}$
   b. fitting $(SE\text{-}ME)_{MC}$ with Pol4 and subtracting it from $(SE\text{-}ME)_{data}$
5. Obtaining the final IM spectrum as a function of the energy

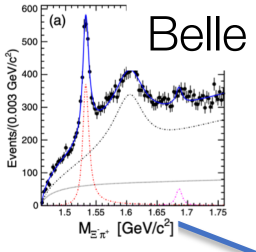
Femtoscopy era in the S=-2 meson-baryon sector

- First combined effort in constraining the low-energy constants of an effective chiral lagrangian to correlation data

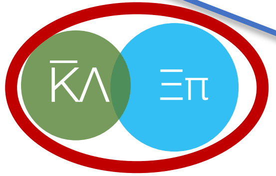


A. Ramos, E. Oset PRL 89 (2002)

Only contact terms
|S|=1 data



Belle Coll.

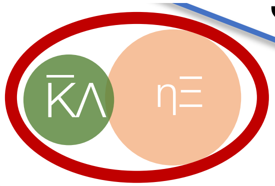


With NLO terms
|S|=1 data

A. Feijoo et al. PLB 841 (2023)

Today

ΛK⁻ femto

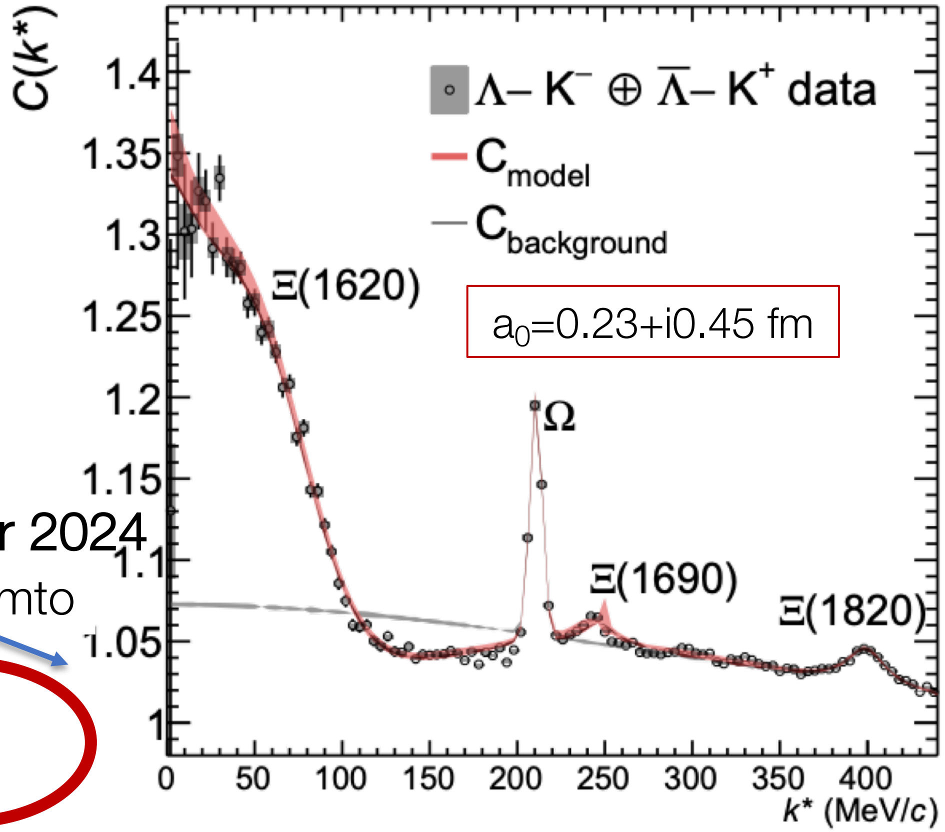


Summer 2024

Ξπ femto

…

VMS, A. Feijoo et al. arXiv: 2309.08756



Work in collaboration with:
Dr. A. Feijoo, Dr. I. Vidana, Prof. A. Ramos, Prof. F. Giacosa,
Prof. T. Hyodo and Dr. Y. Kamiya

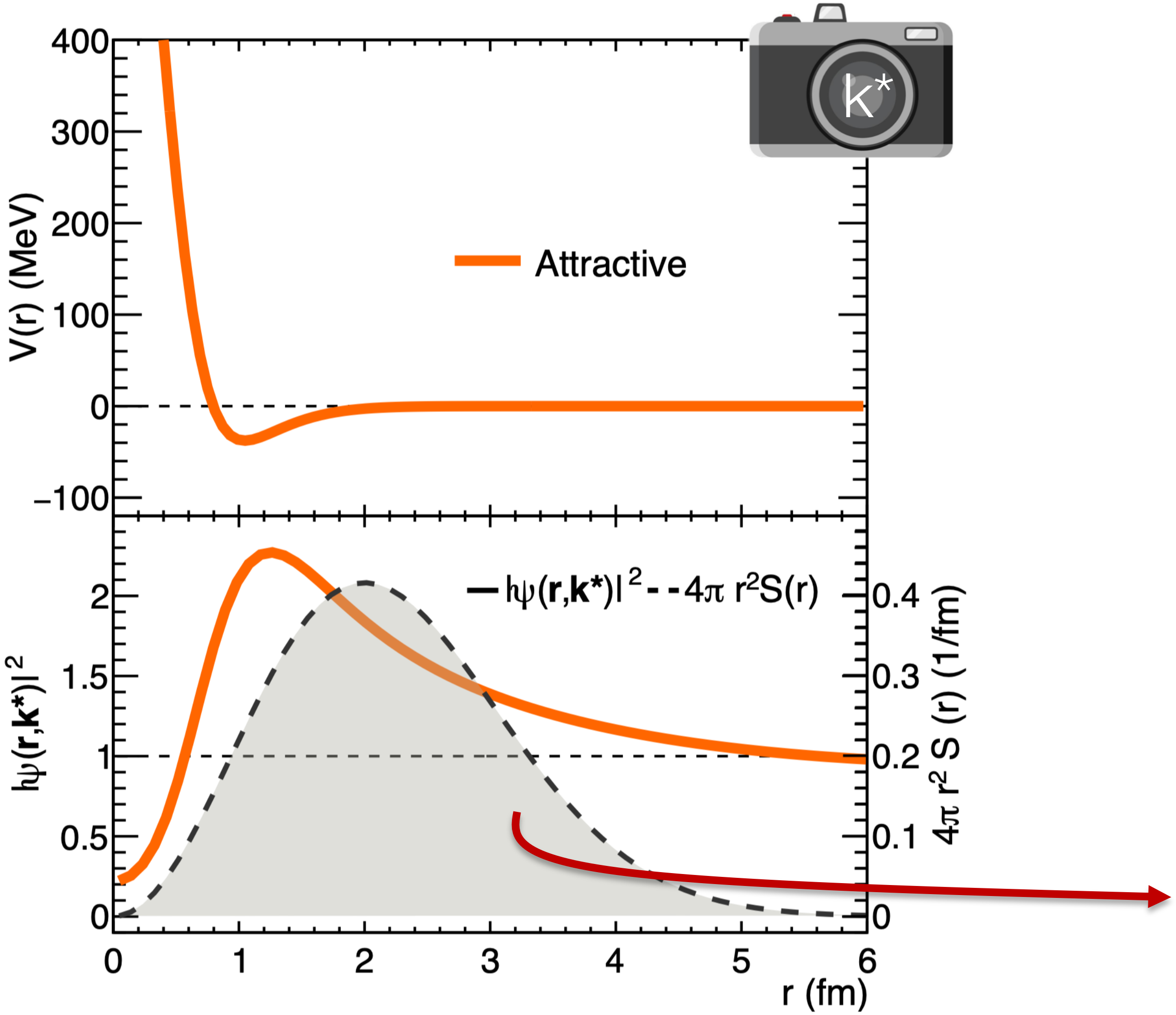
Towards a combined fit of all available data in this sector!!

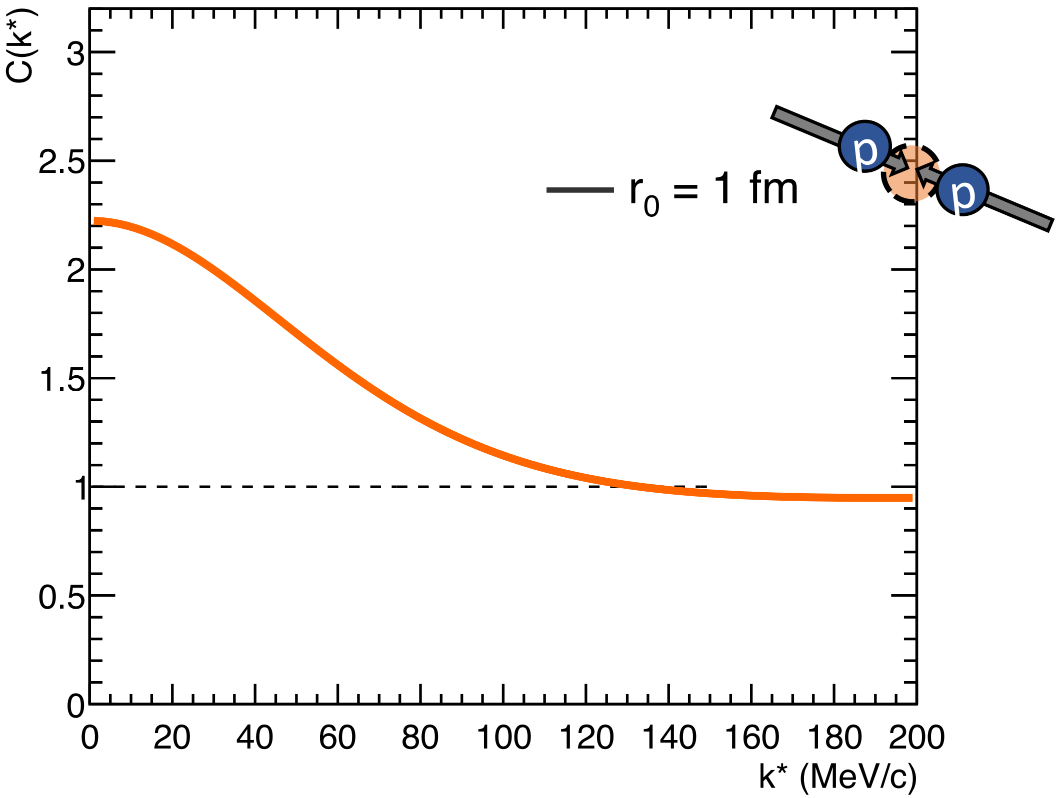
(Preliminary work done on contact terms for pΛ)
Mihaylov, Haidenbauer, VMS PLB 850 (2024) 138550

From small to large colliding systems

"What's inside the integral"

$$C(k^*) = \int S(\vec{r}^*)\ \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^*$$



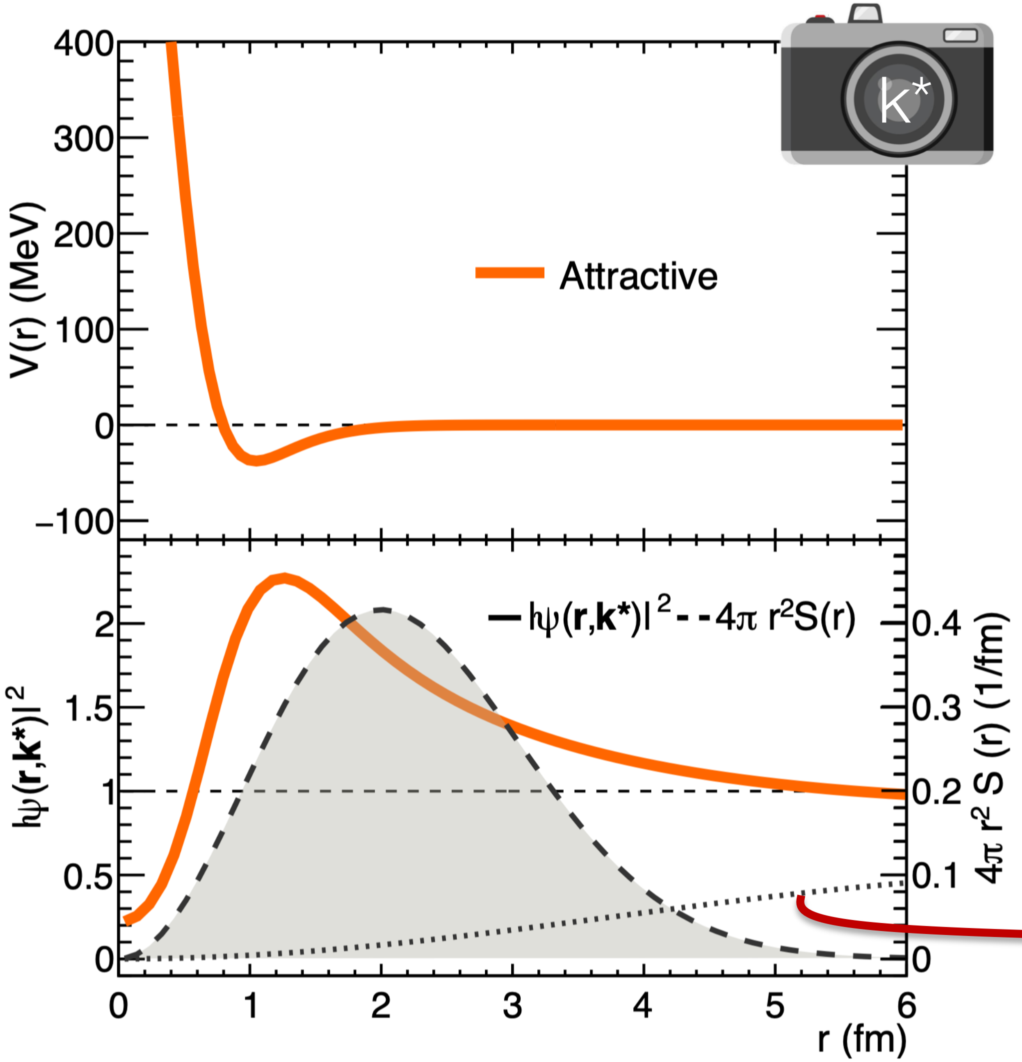


Accessing short-range dynamics in pp collisions

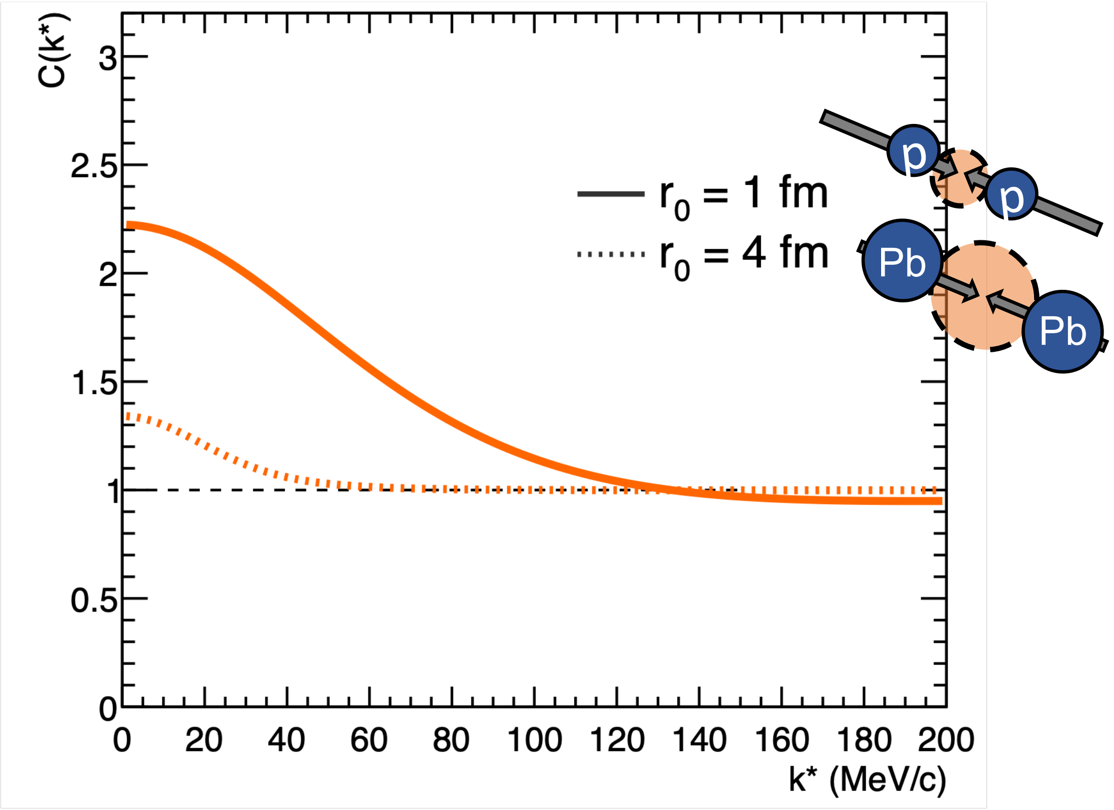
L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

From small to large colliding systems

"What's inside the integral"



$$C(k^*) = \int S(\vec{r}^*)\ |\psi(\vec{k}^*,\vec{r}^*)|^2\ d^3\vec{r}^*$$

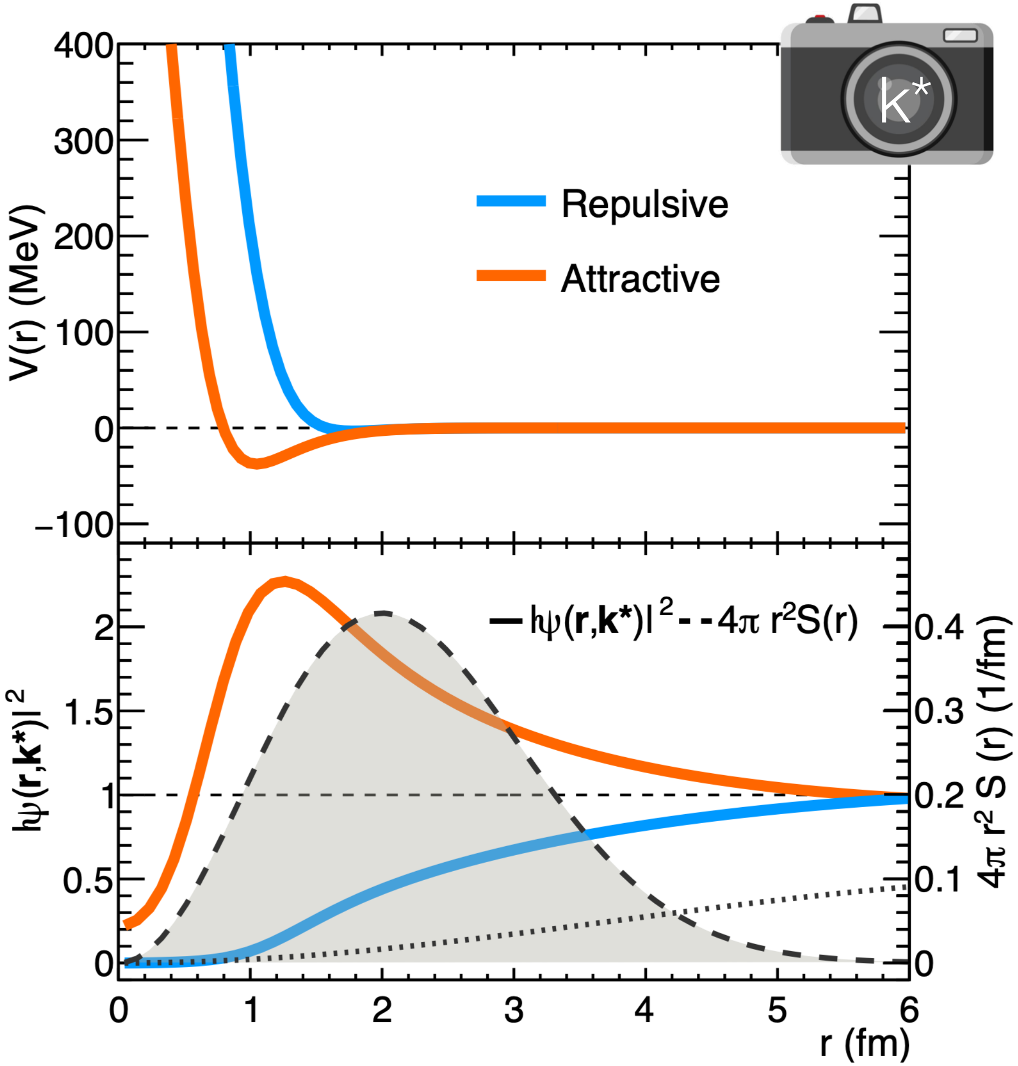


Decrease of signal strength for large source sizes

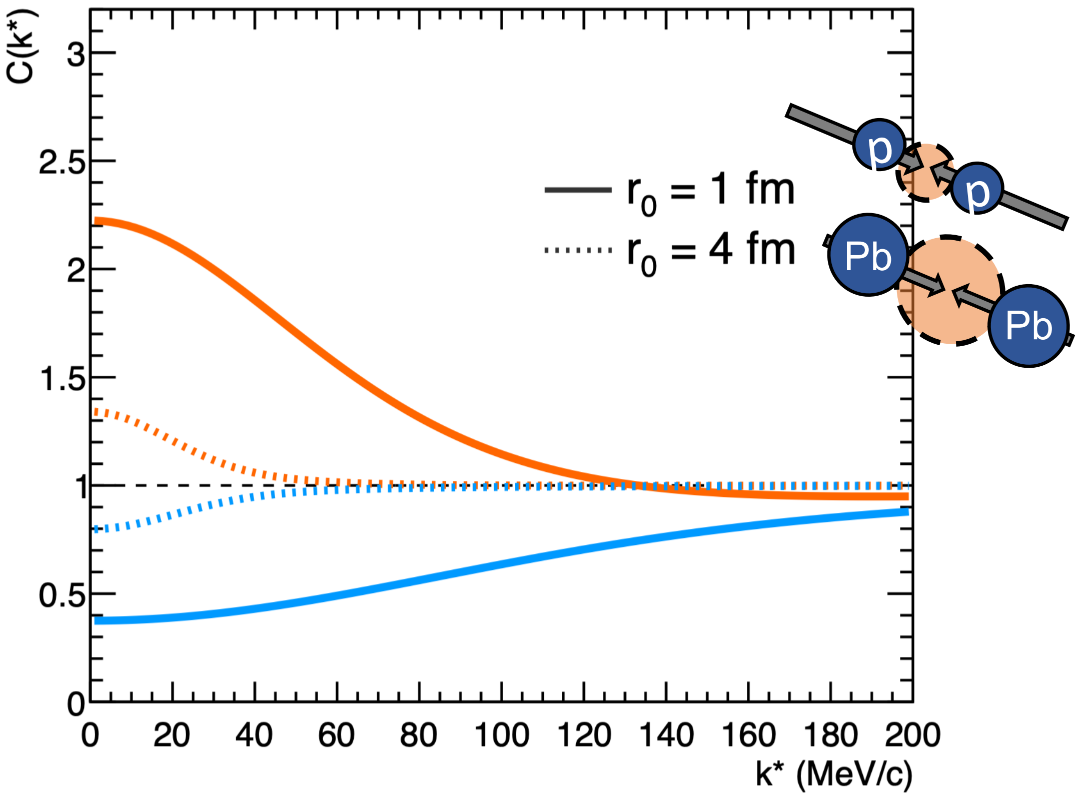
L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

From small to large colliding systems

"What's inside the integral"



$$C(k^*) = \int S(\vec{r}^*)\ \left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^*$$



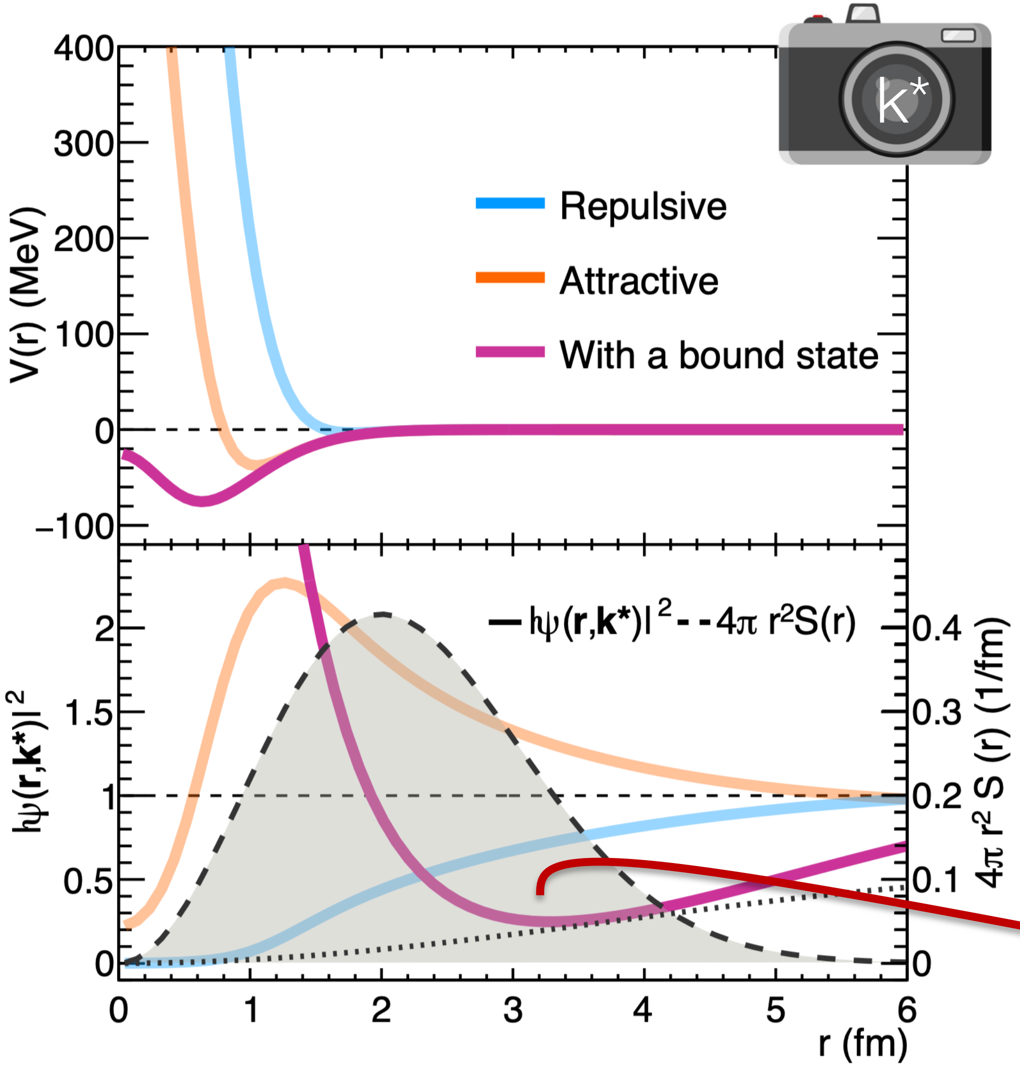
$$C(k^*) \begin{cases} > 1 & \text{Attractive (no BS)} \\ < 1 & \text{Repulsive} \end{cases}$$

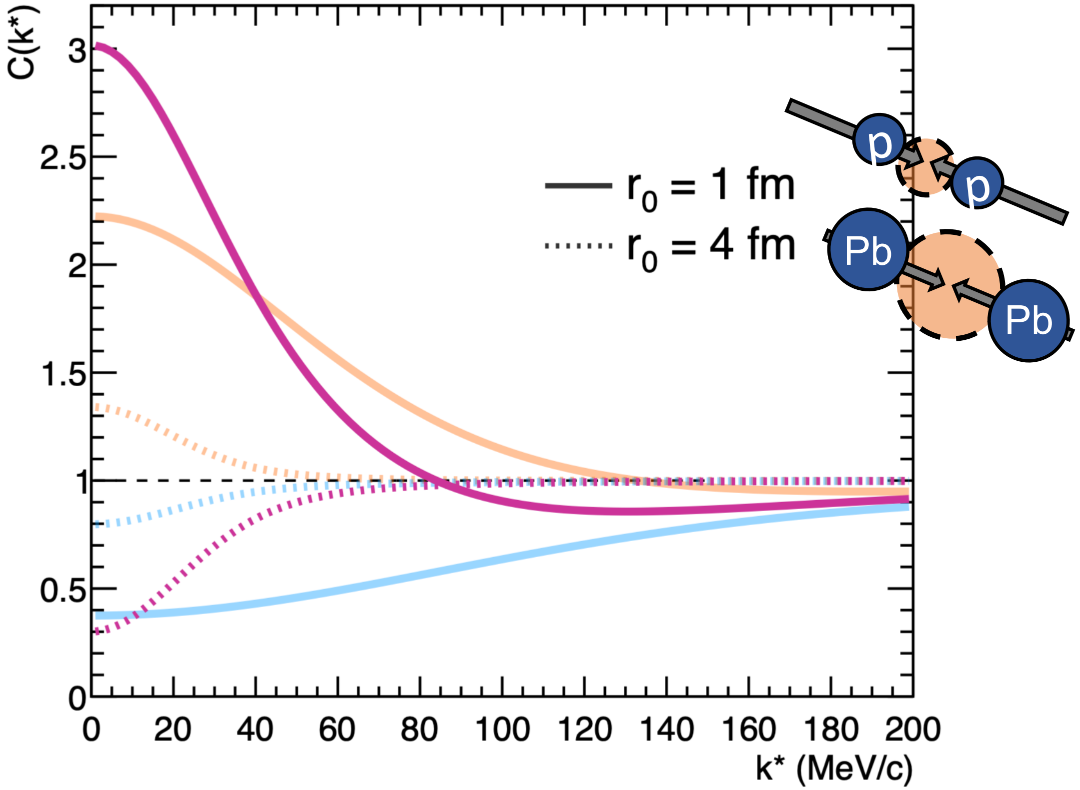
L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

A clear signature for bound states

"What's inside the integral"

$$C(k^*) = \int S(\vec{r}^*)\ \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^*$$





Correlation flips around unity when a bound state is present!

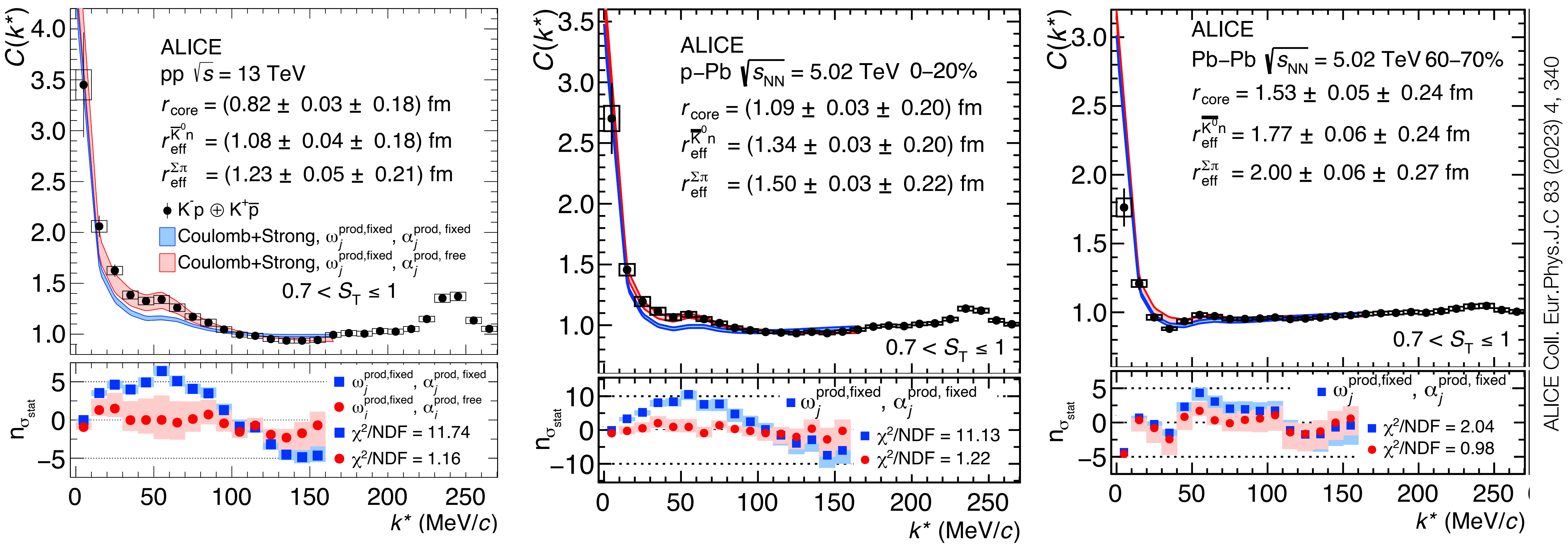
L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

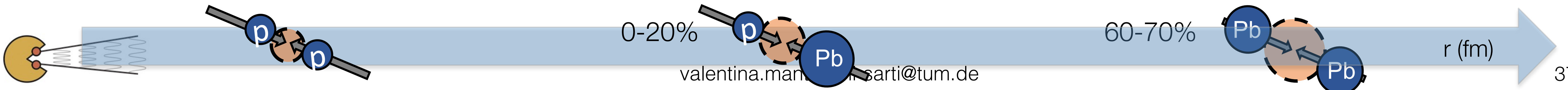
K⁻–p femtoscopy in different colliding systems

Fit the scaling factor needed for the model to reproduce the data

$$C(k^*) = \int S(r)\,|\psi_{1\to1}(k^*, r)|^2\, d^3r + \sum_{j=\Sigma\pi,\bar{K}^0 n} \alpha_j \cdot \omega_j^{prod} \int S_j(r)\, |\psi_{j\to1}(k_j^*, r)|^2\, d^3r$$

χEFT Kyoto model:
Ikeda et al. NPA 881 (2012), PLB706 (2011)
Kamiya et al. PRL 124 (2020)
Mihayara et al. PRC95 (2017)





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Extracted strong weights for Σπ and $\overline{K}^0$ n channels

Unique constraint and direct access to $K^- p \leftrightarrow \overline{K}^0 n$ and $K^- p \leftrightarrow \Sigma\pi$ dynamics

- Σπ consistent with unity
- deviation from unity for $\overline{K}^0$ n
  - $K^- p$ - $\overline{K}^0$ n coupling too weak in chiral potentials
  - update the scattering amplitude of KN–πΣ–πΛ system by including correlation measurements to available kaonic hydrogen and scattering data

ALICE Coll. Eur.Phys.J.C 83 (2023) 4, 340