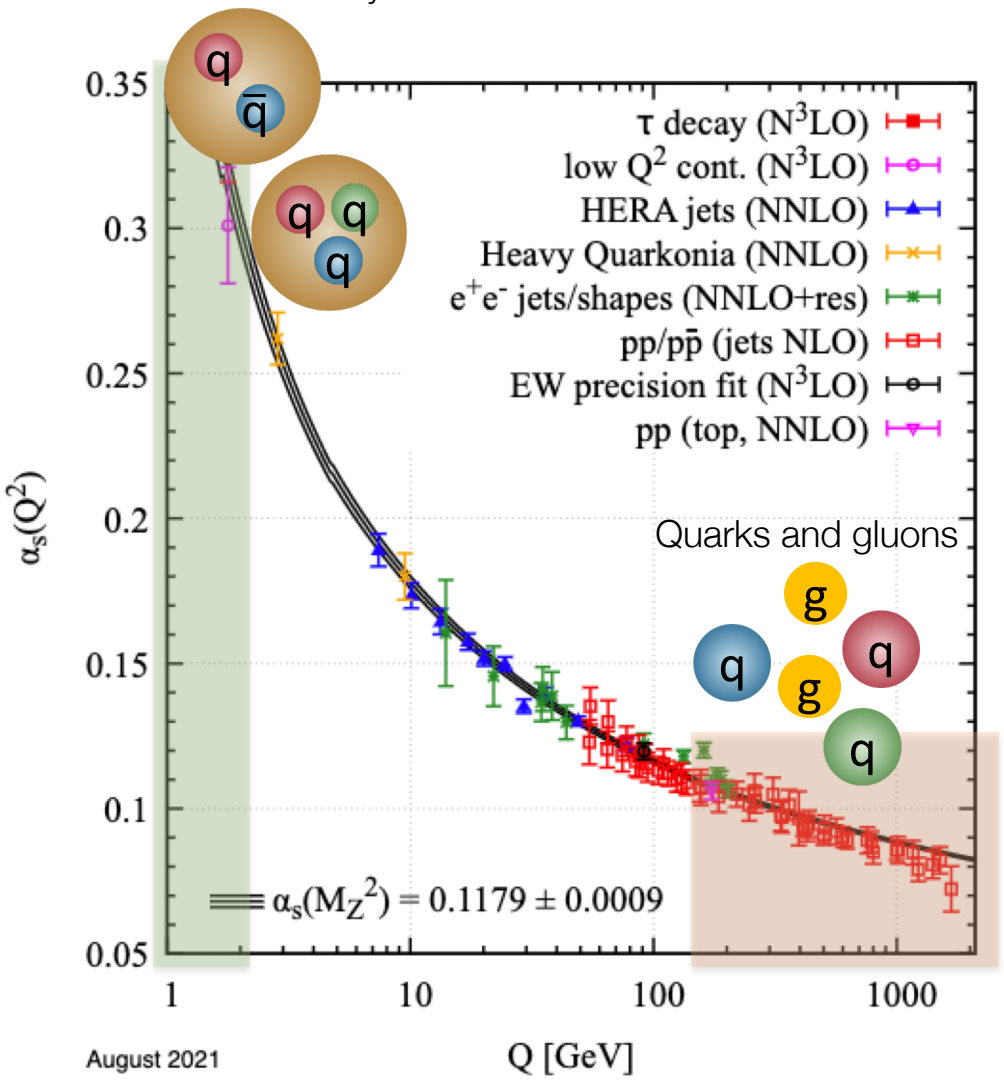
V. Mantovani Sarti (TUM)
DPG Spring Meeting 11-15 March 2024

Molecular and bound states searches with femtoscopy

MA 8660/1-1

Strong interaction between hadrons

Mesons and baryons



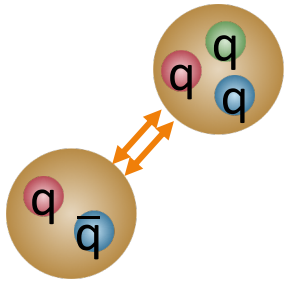
PDG, Prog.Theor.Exp.Phys 2022, 083C01(2022)

- Understanding how QCD evolves from high-energy to low-energy regime

How do hadrons emerge?

How do hadrons interact?

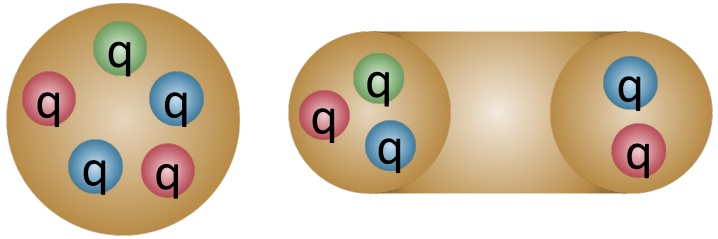
2-body and many-body interactions



M. Küßner HK 12.1 Tue 11:00

How is the QCD spectrum organized?

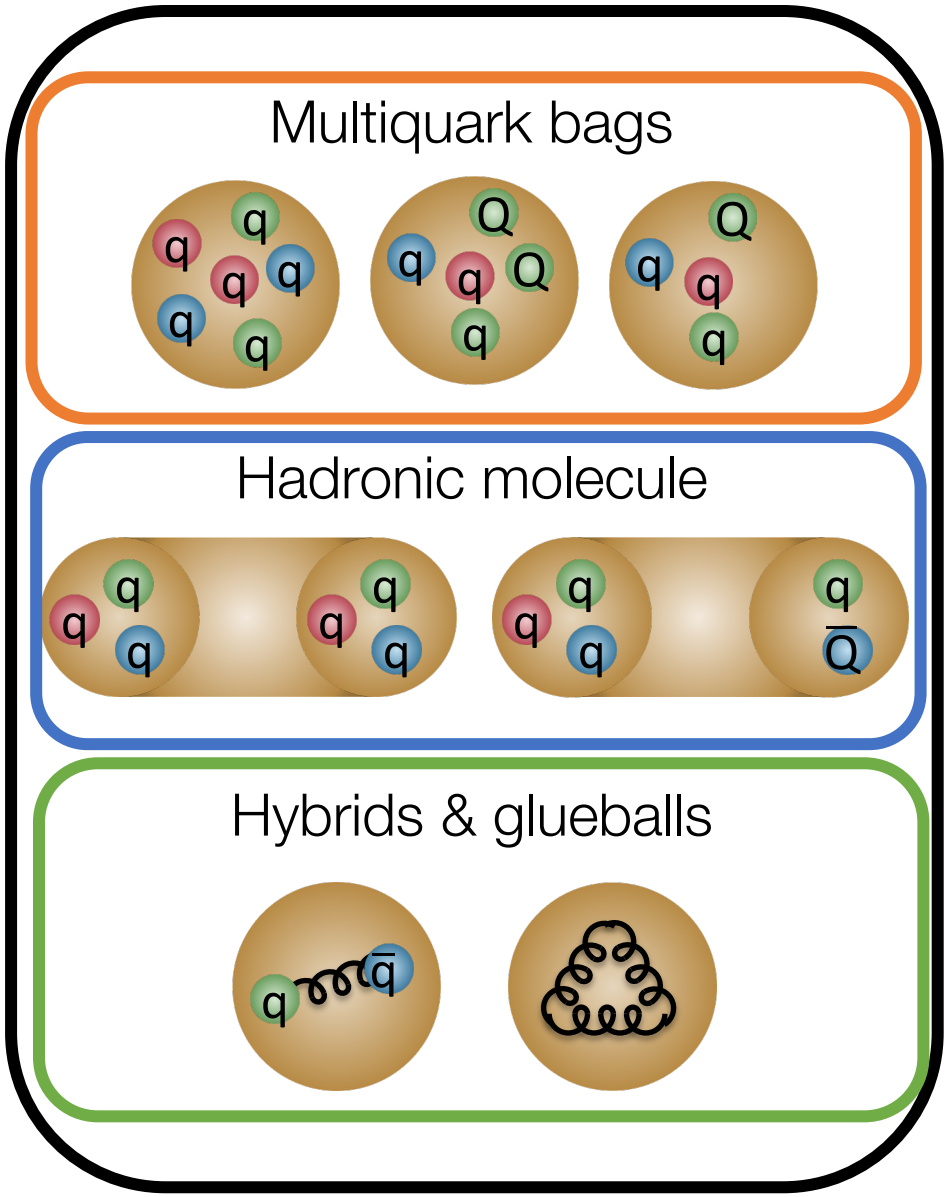
Bound states/resonances
Conventional and exotic states



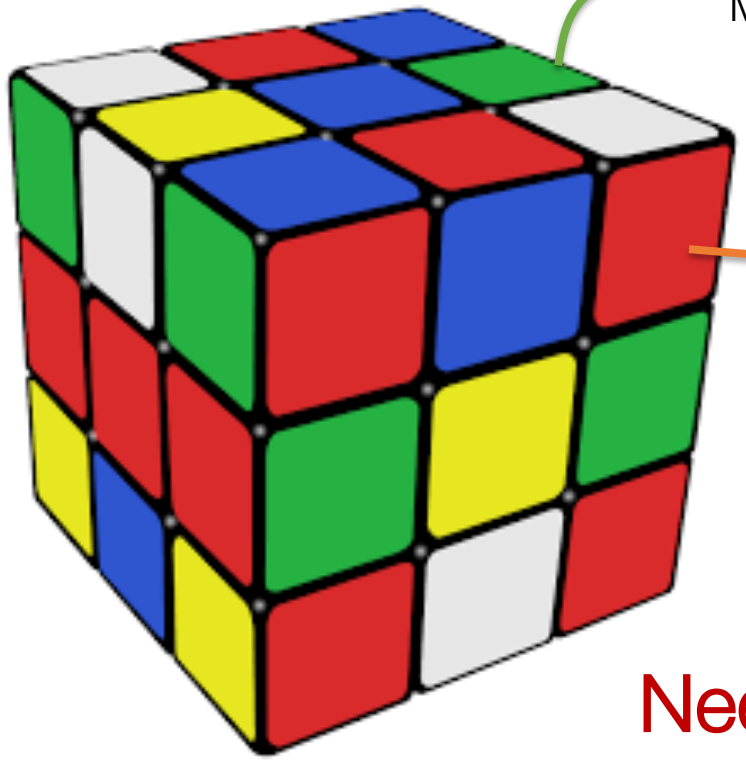
Exotic states in QCD and where to find them

- Color-neutral states beyond (qqq)/(q$\bar{q}$)
  $\chi_{c1}(3872)$: *Belle Coll. PRL 91 (2003) 262001*

- Multiquark bags
  - several candidates and observations in the **heavy-quark sector**
    $T^{a}_{cs0}(2900)^{++,0}$: *LHCb Coll. PRL 131 (2023) 4, 041902*
  - Candidates also in **light sector**, very broad states, very challenging!
    PDG: Review on light meson spectroscopy
  - **Dibaryons** state might also fit in this category
    H. Clement Prog.Part.Nucl.Phys. 93 (2017) 195
- Hadronic molecules
  - Case of the Λ(1405), similar candidates in other meson-baryon strangeness sectors, e.g. Ξ(1620)
  - Candidates also in heavy-quark sector, e.g T_{cc}^{+}
- And more…



Exotic states to probe the many facets of QCD



Exotics, resonances, …

Many examples in the strange and heavy-quark sectors

Coupled-channel dynamics

Need to be understood to assess existence and nature of observed states

Need to measure systematically as many channels as possible

Need for complementary experimental constraints

Need for advanced analysis/modeling approaches

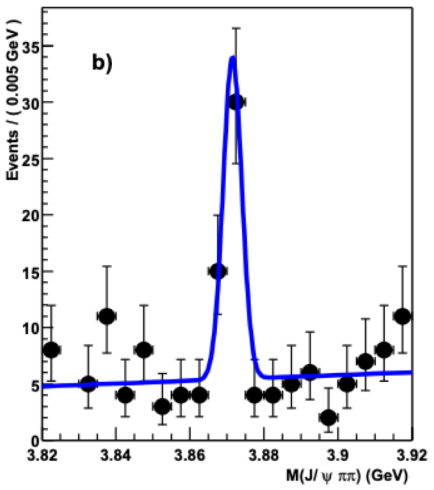
Joint effort theory-experiment!

Hunting for exotic states: a broad experimental effort

- Intensive searches via spectroscopy measurements
- Several collaborations with different production mechanism
  - Hadronic/e^+e^- colliders, fixed target experiments, photoproduction experiments

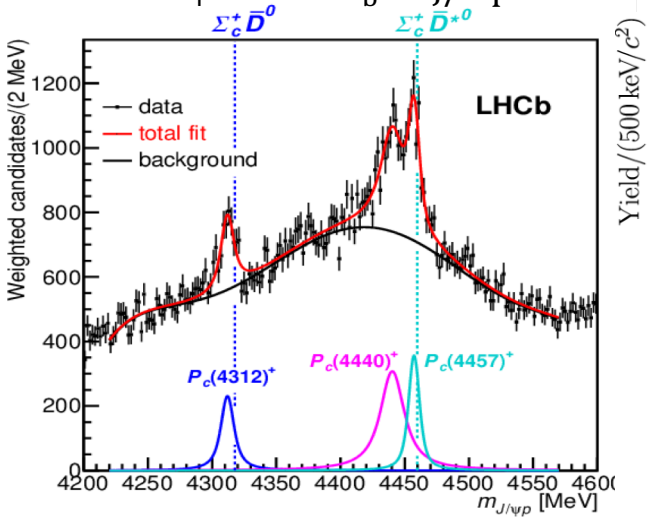
R.F.Lebed et al. Prog.Part.Nucl.Phys. 93 (2017) 143-194

X(3872) in $B^{\pm} \to K^+\pi^+\pi^- J/\Psi$



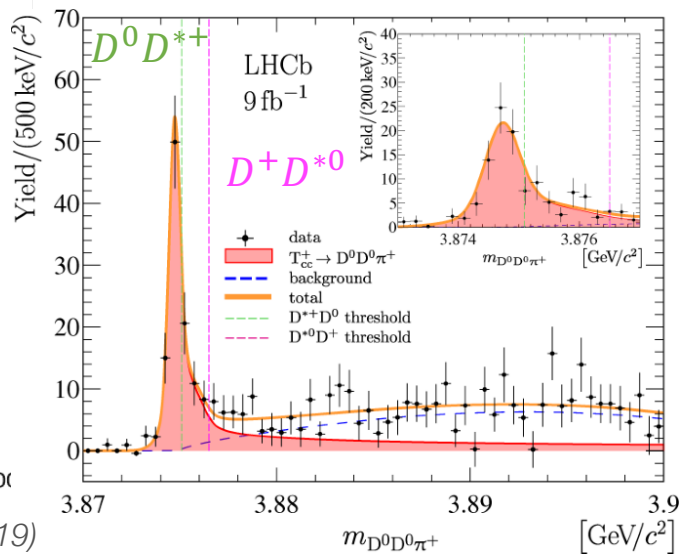
Belle Coll. PRL 91 (2003) 262001

Pentaquarks in $\Lambda_b \to J/\Psi p K^-$[1]

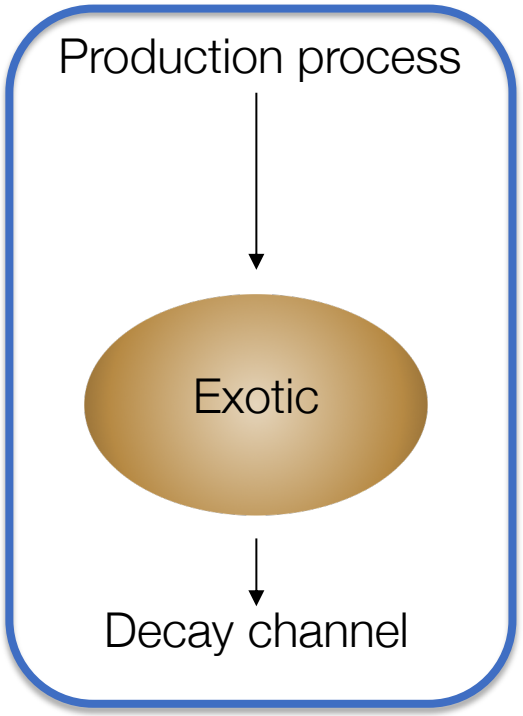


LHCb coll. PRL 115 (2015), PRL 122 (2019)

$T_{cc}^+(3875)$



LHCb, Nature Physics 18 (2022)



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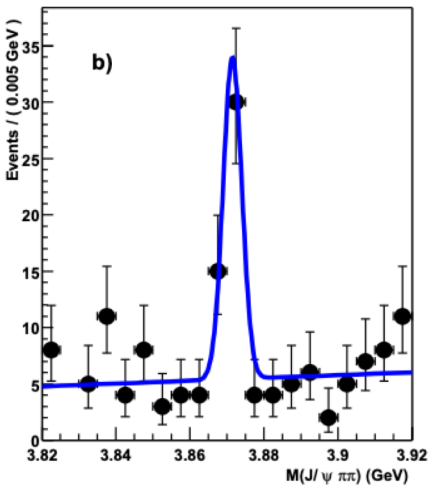

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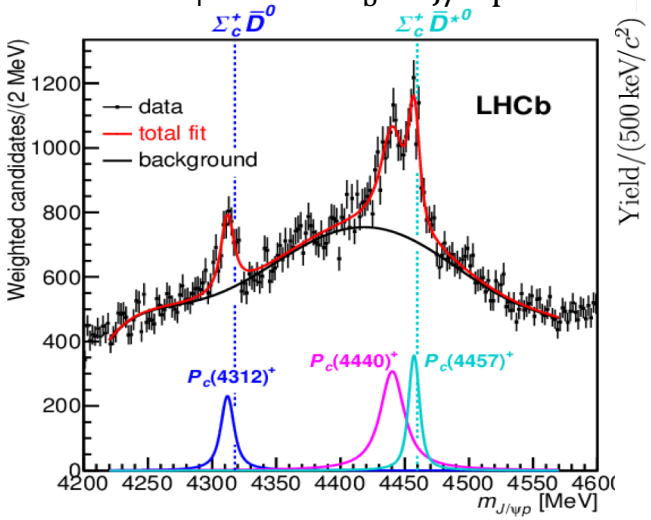

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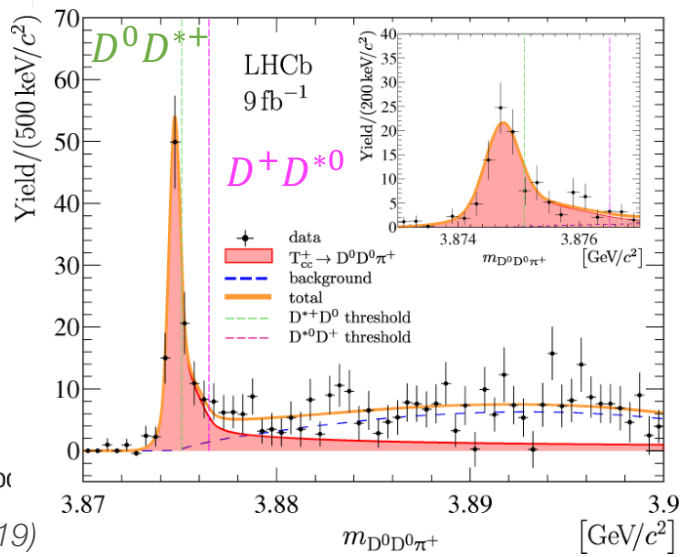

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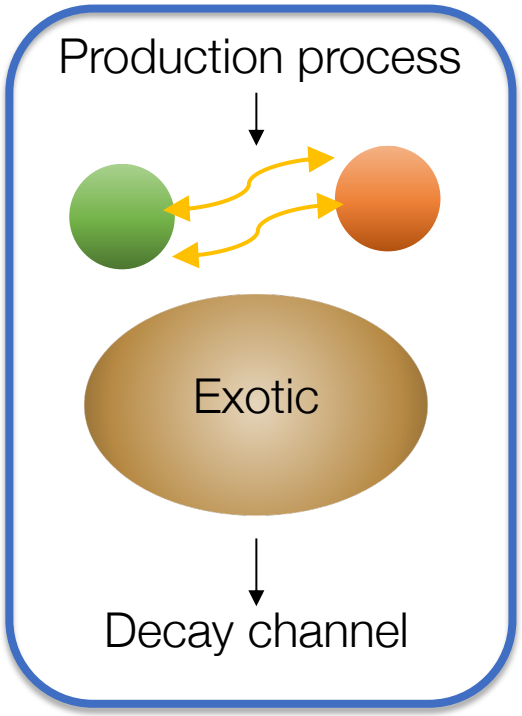
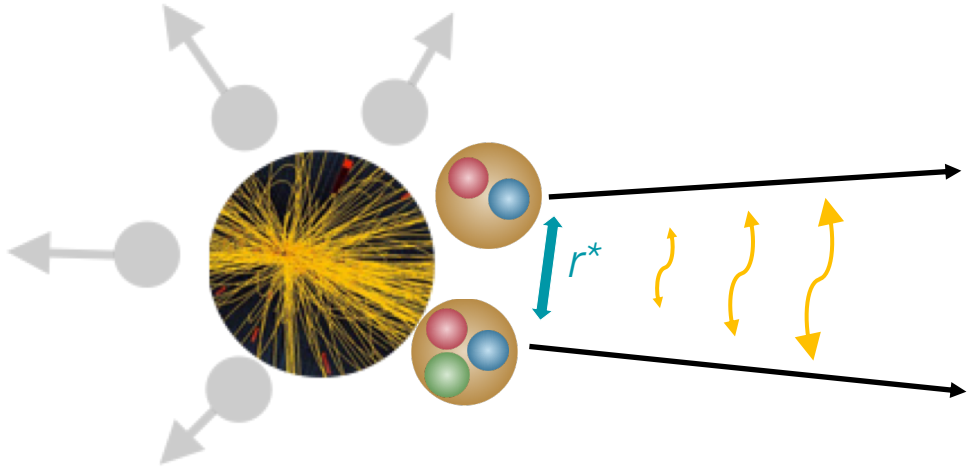


Accessing the interaction between the constituents

Investigating exotic states with correlations

- Accessing interaction between the constituents 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

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



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

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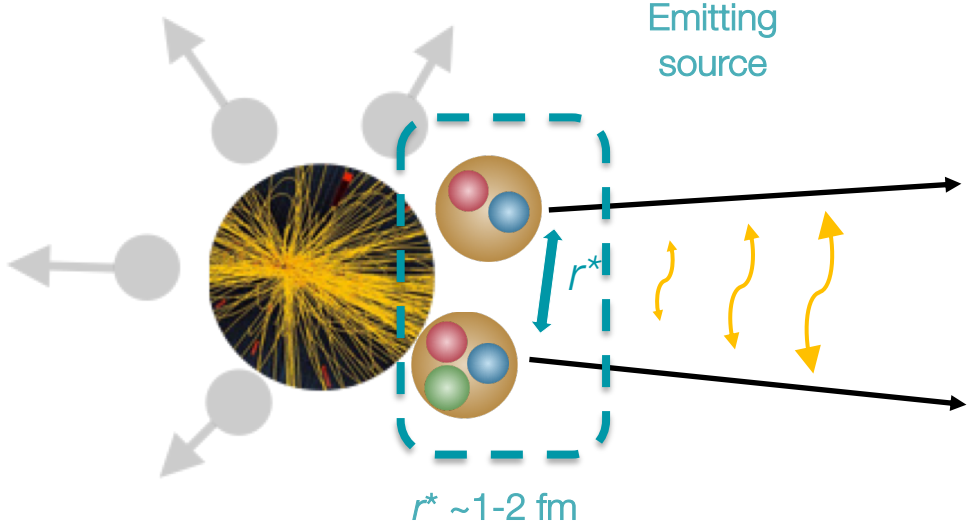
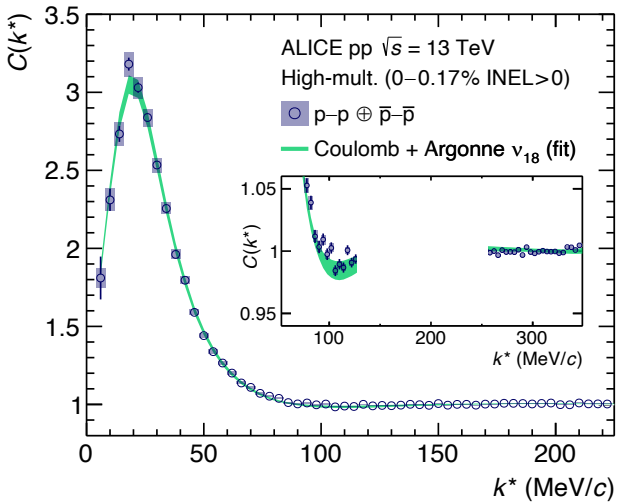


Emitting source constrained with p-p correlation data
ALICE coll., PLB, 811 (2020), 135849
→ Interparticle distances ~1-2 fm



M. Korwieser HK 71.3, Thu 16:15
M. Lesch HK 57.4, Wed 18.30
D. Wang HK 71.4, Thu 16:30
G.Mantzaridis, J. Gonzalez HK. 72.52

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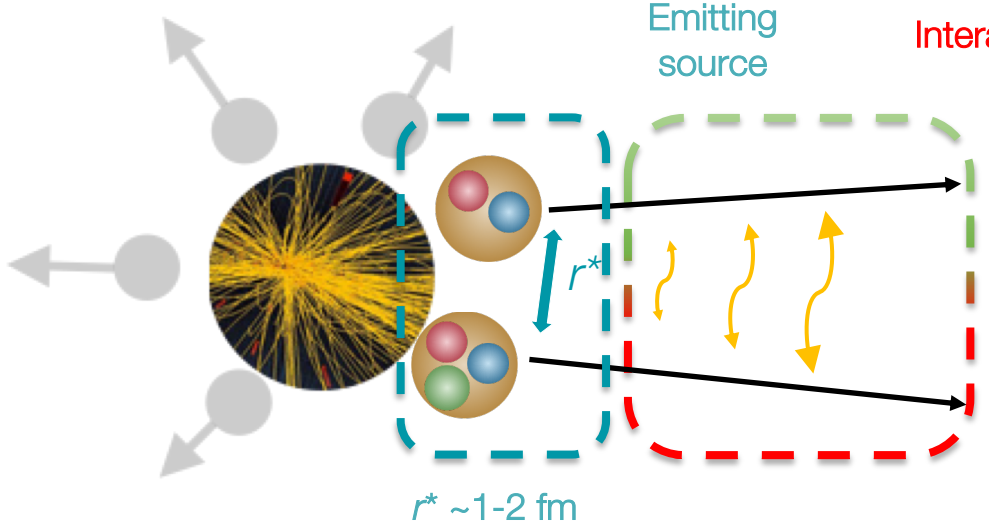
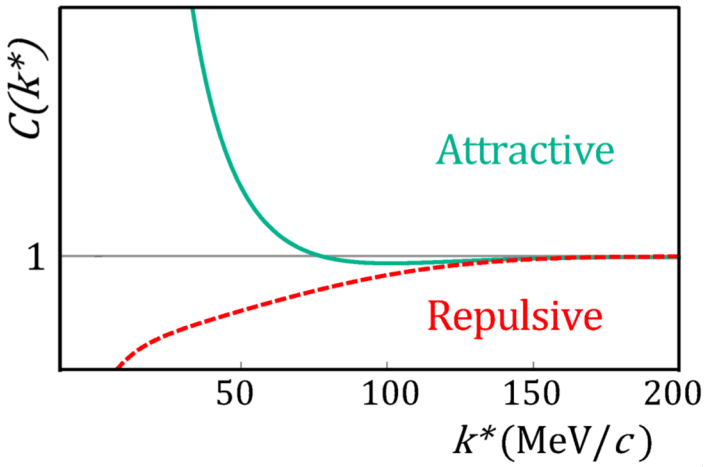
Emitting source

Interaction



ALICE Coll. Nature 588 (2020) 232-238

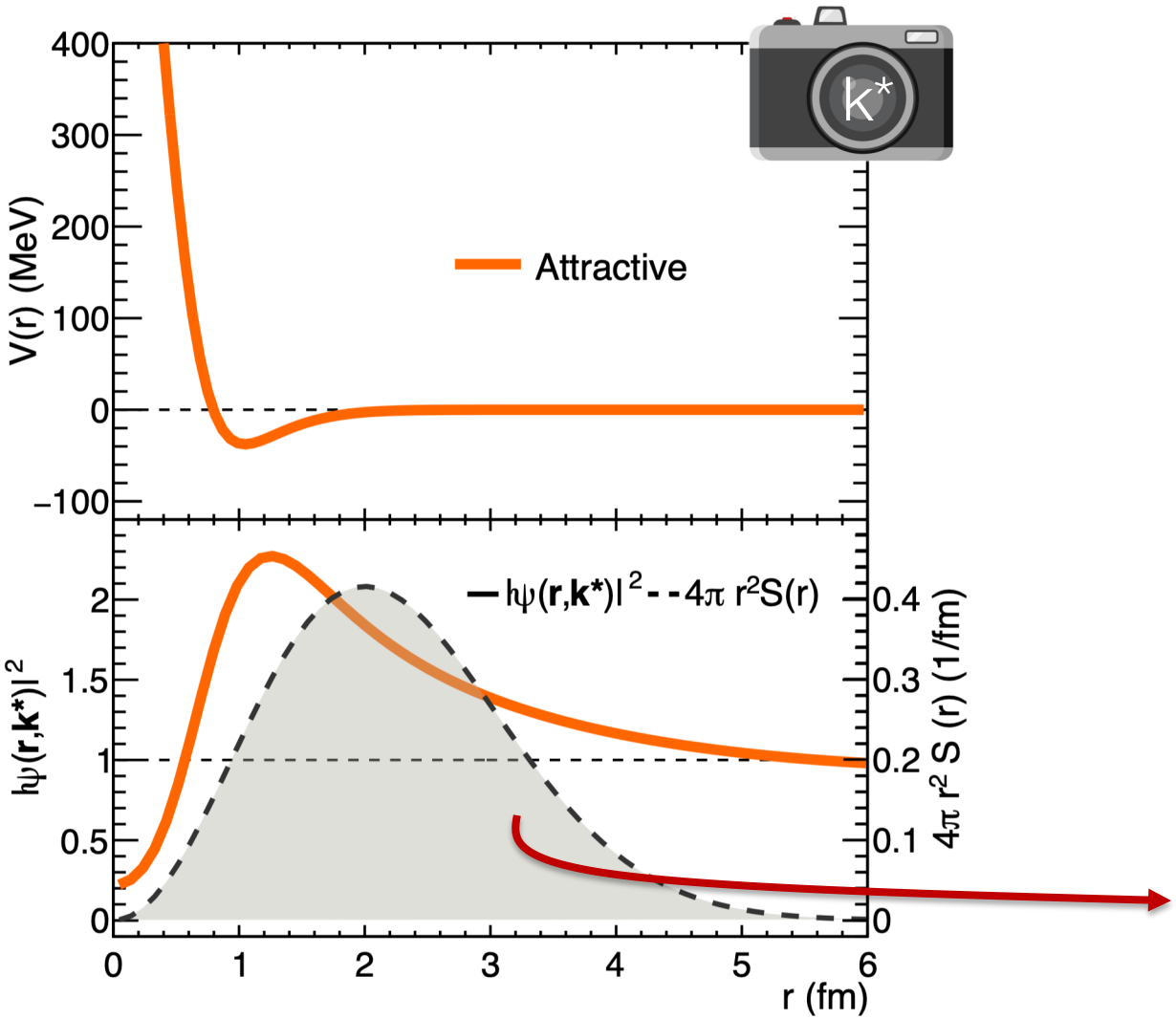


Correlation mapping 1-to-1

the nature of the interaction

From small to large colliding systems

"What's inside the integral"



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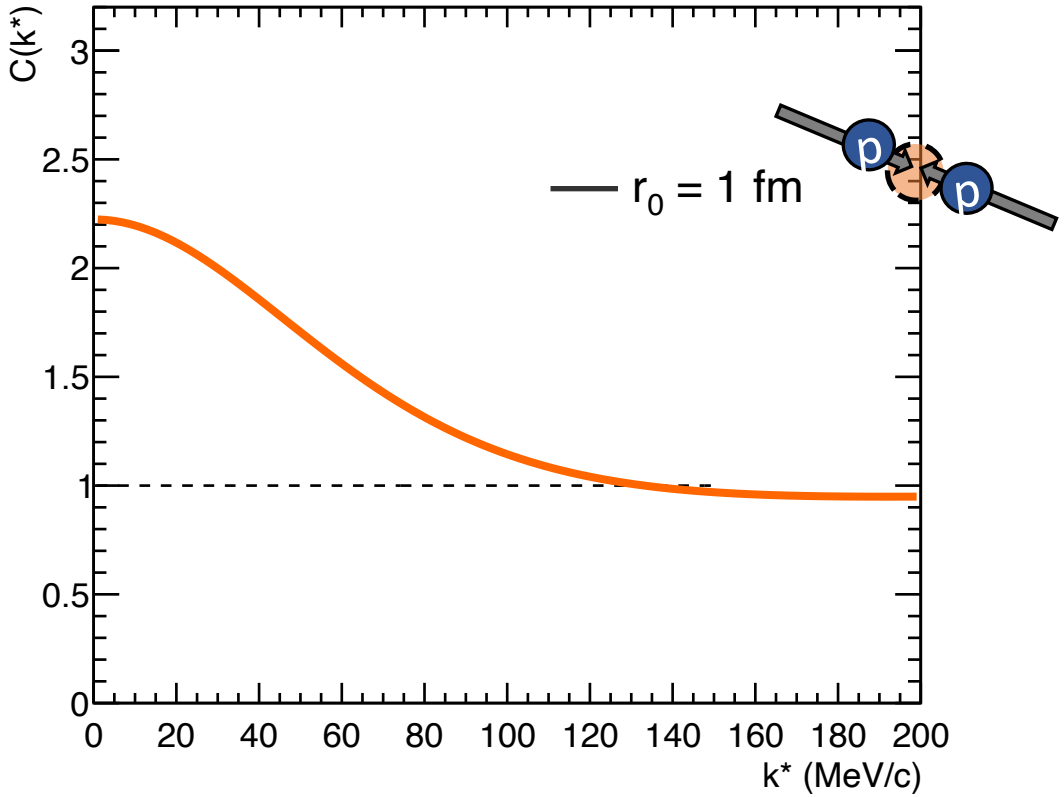
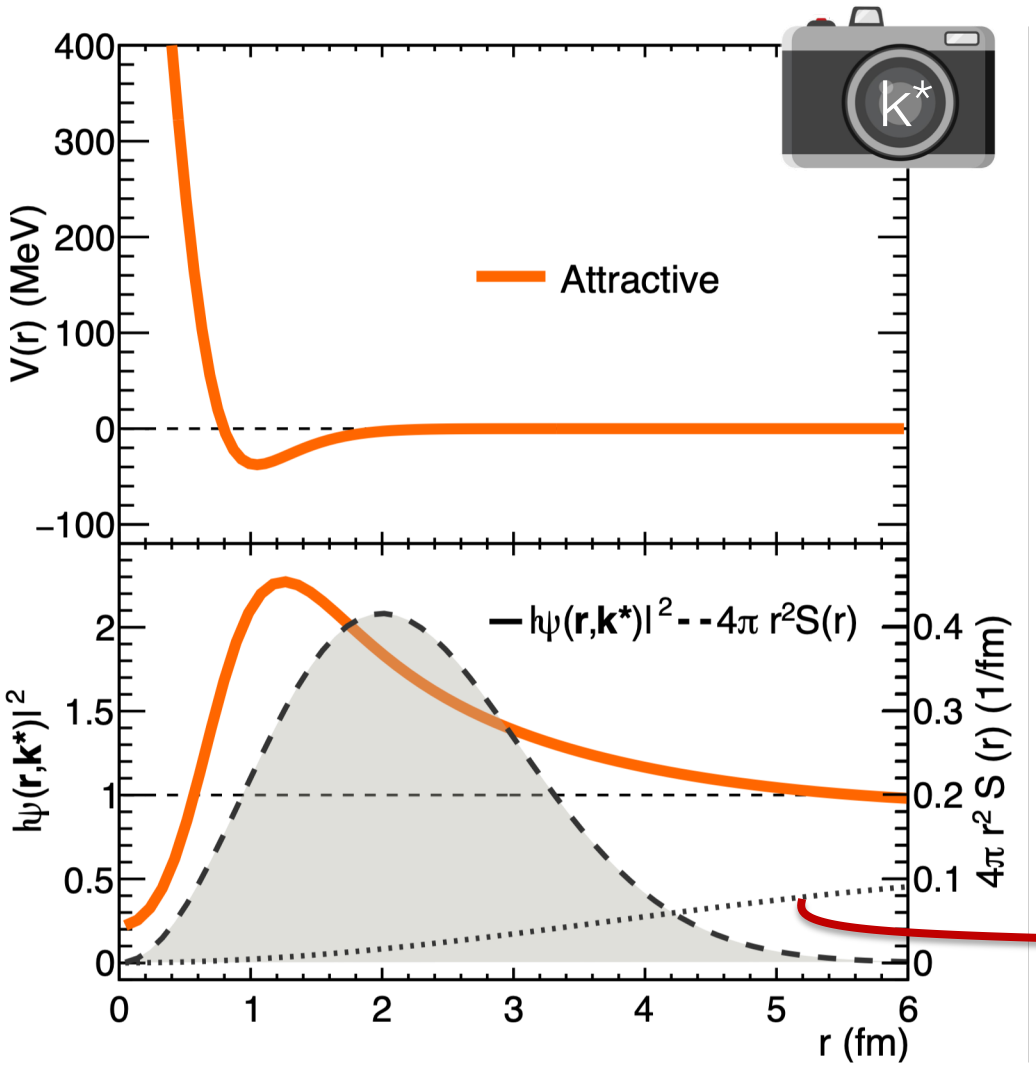


Accessing short-range dynamics in pp collisions

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

From small to large colliding systems

‘‘What‘s inside the integral“



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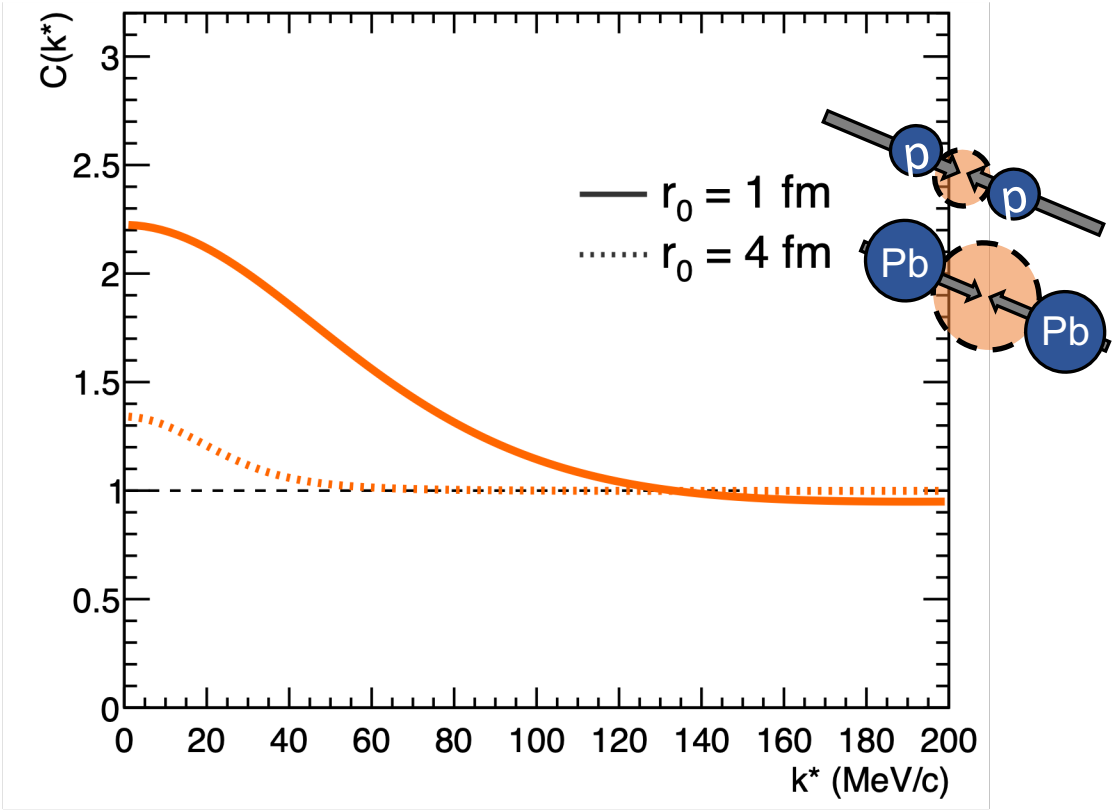
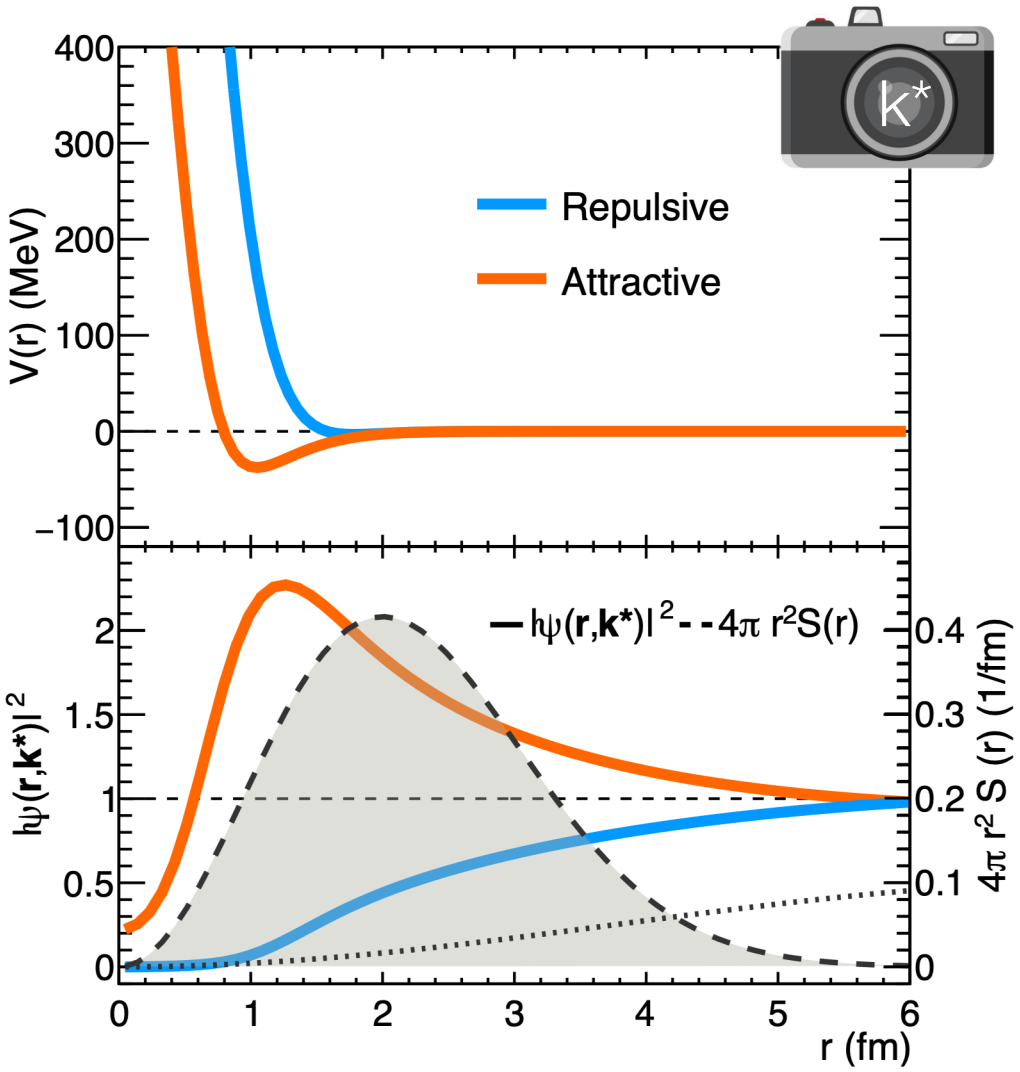


Decrease of signal strength for large source sizes

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

From small to large colliding systems

"What's inside the integral"



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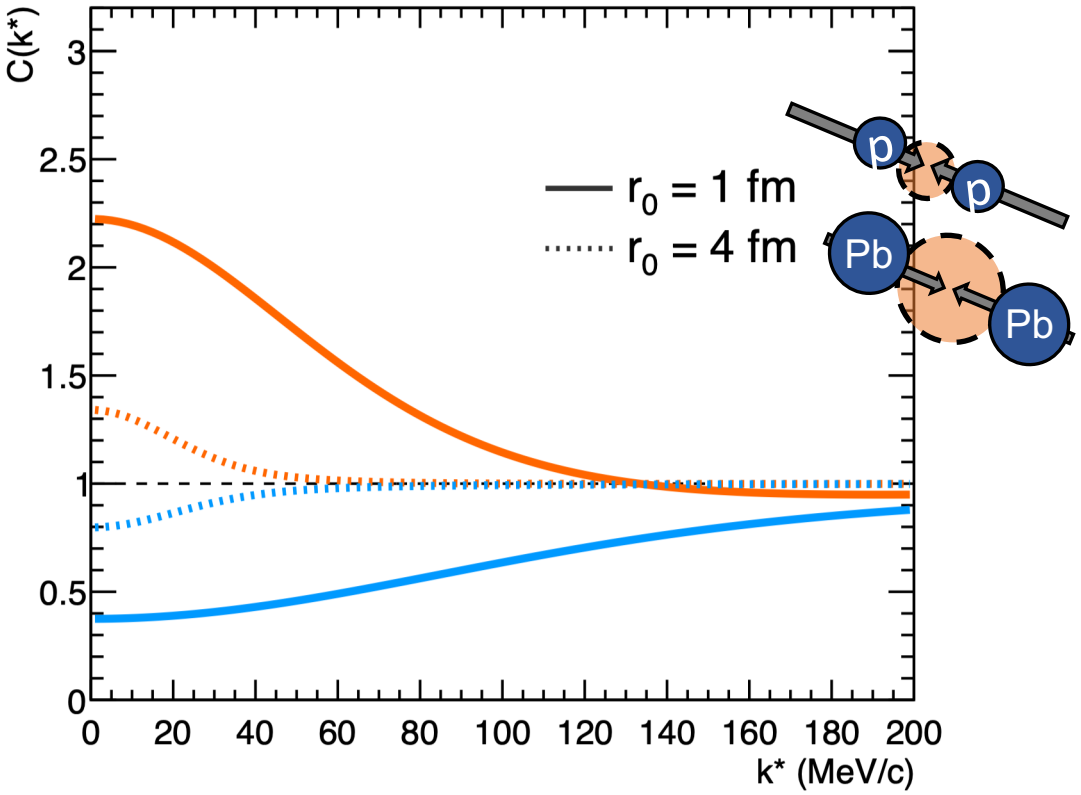
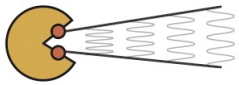


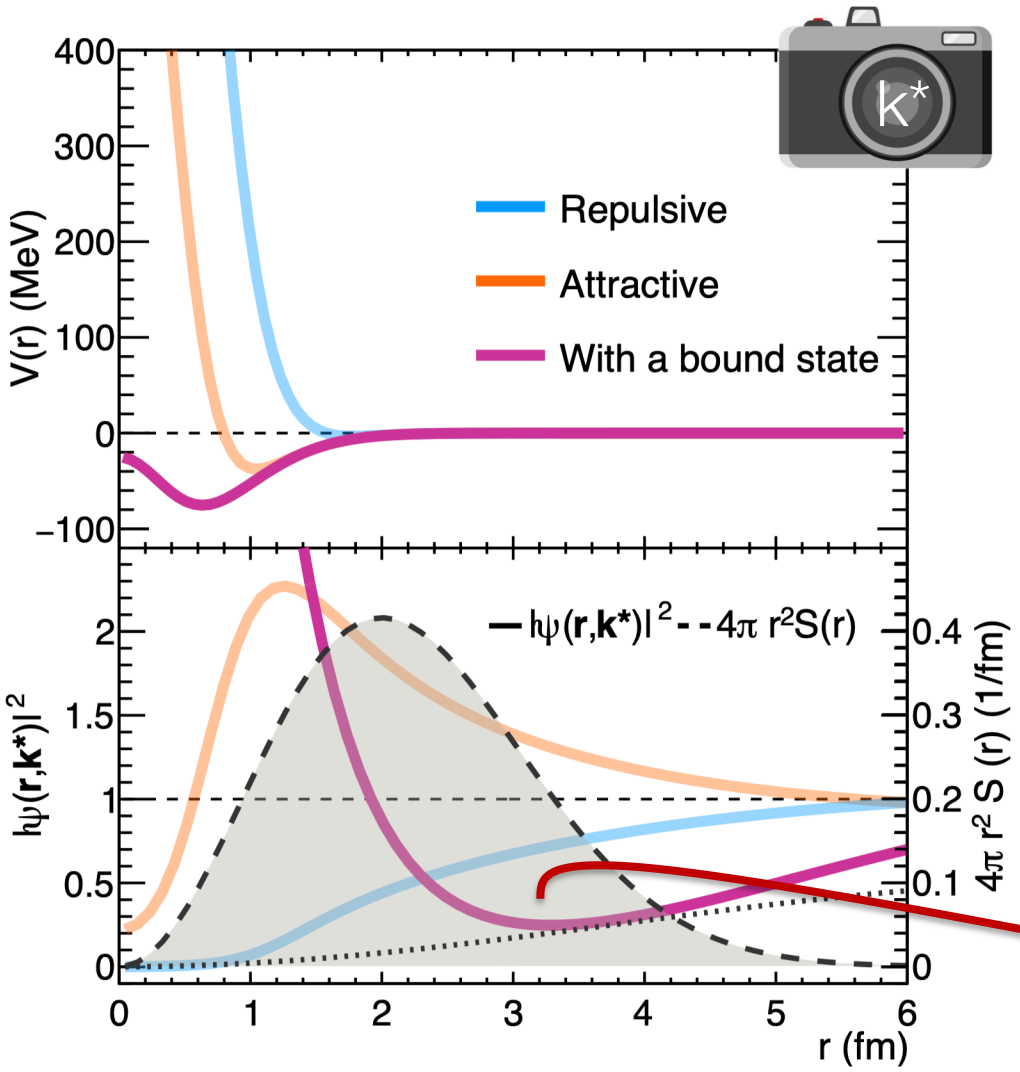
$$C(k^*) \begin{cases} > 1 & \text{Attractive (no BS)} \\ < 1 & \text{Repulsive} \end{cases}$$



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

A clear signature for bound states

"What's inside the integral"



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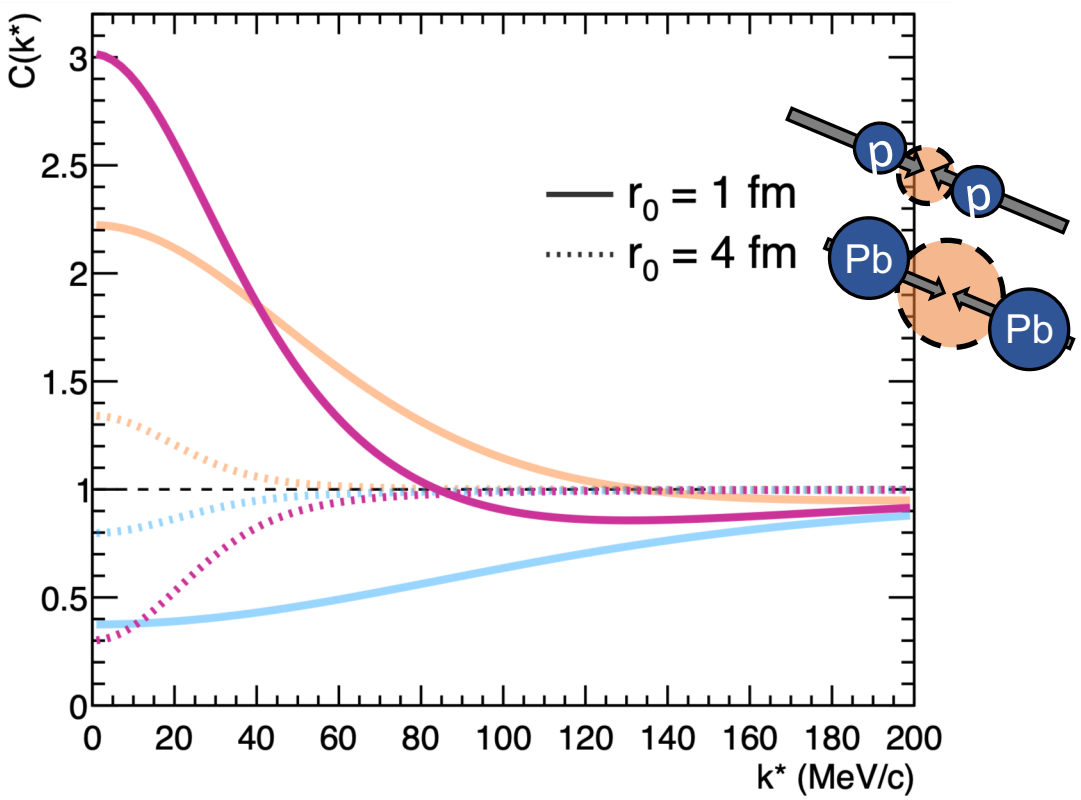
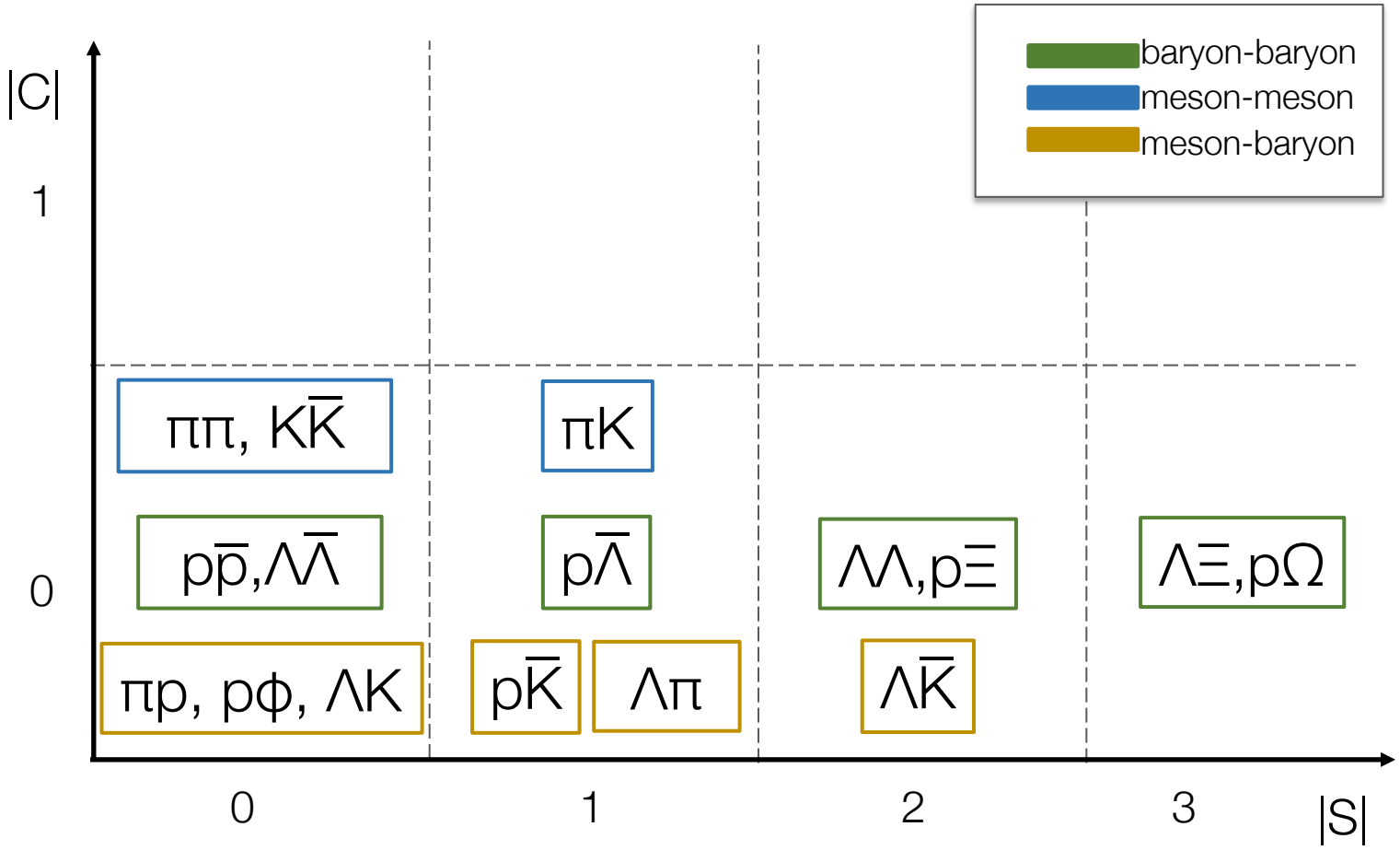


Correlation flips around unity when a bound state is present!

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

What can correlations do for bound states and exotics

High-precision correlation data on many interactions involving exotic/bound states



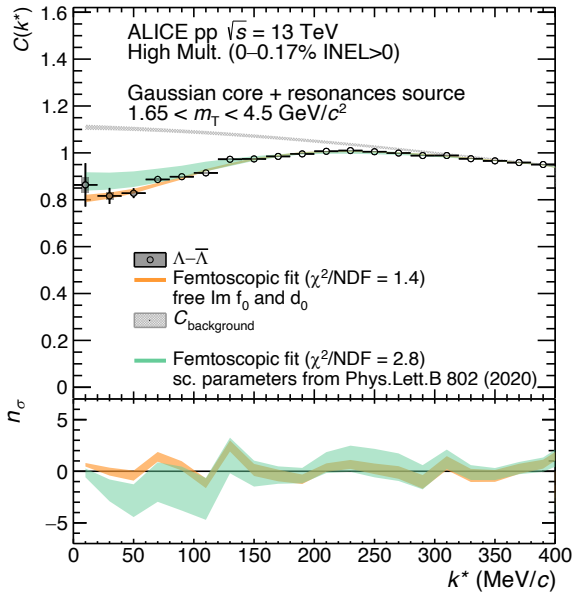
What can correlations do for bound states and exotics

High-precision correlation data on many interactions involving exotic/bound states

- Widely explored the **light and strange sector with LHC Run 2**

Dibaryon candidates

$B\bar{B}$, H-dibaryon, $N\Omega$



ALICE Coll. PLB 829 (2022), PLB 802 (2020)

|C|

1

0

Tetraquark candidates in light meson sector

$a_0(980)$ with $K^0_S K^0_S$, $K^*_0(700)$ with $\pi^\pm K^0_S$

ALICE Coll. arXiv: 2312.12830

ALICE Coll. PLB 833, 137335 (2022);

PLB 790, 22 (2019); PLB 774, 64 (2017)

baryon-baryon

meson-meson

meson-baryon

$\pi\pi$, $K\bar{K}$

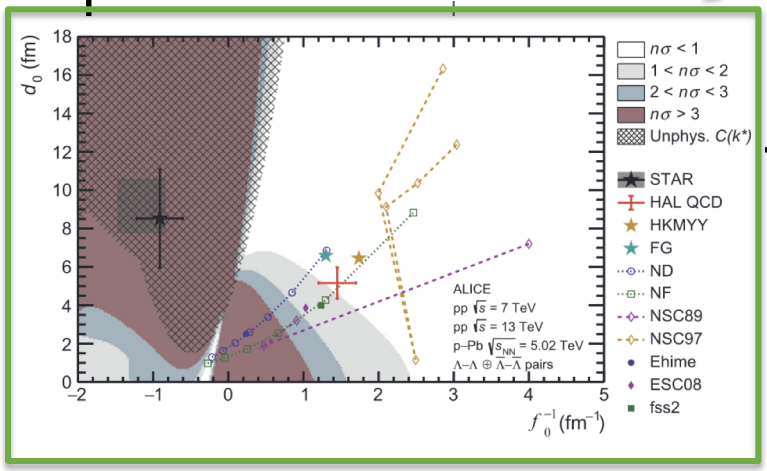
πK

$p\bar{p}$,$\Lambda\bar{\Lambda}$

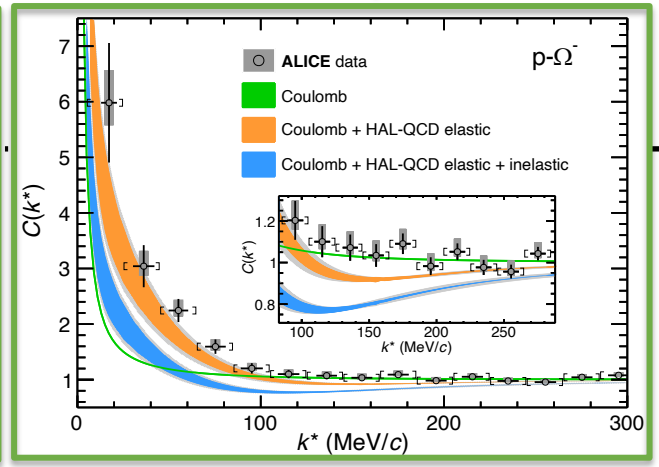
$p\bar{\Lambda}$

$\Lambda\Lambda$,$p\Xi$

$p\Omega$, $\Lambda\Xi$



ALICE Coll. PLB 797 (2019) 134822



ALICE Coll. Nature 588 (2020) 232-238

|S|

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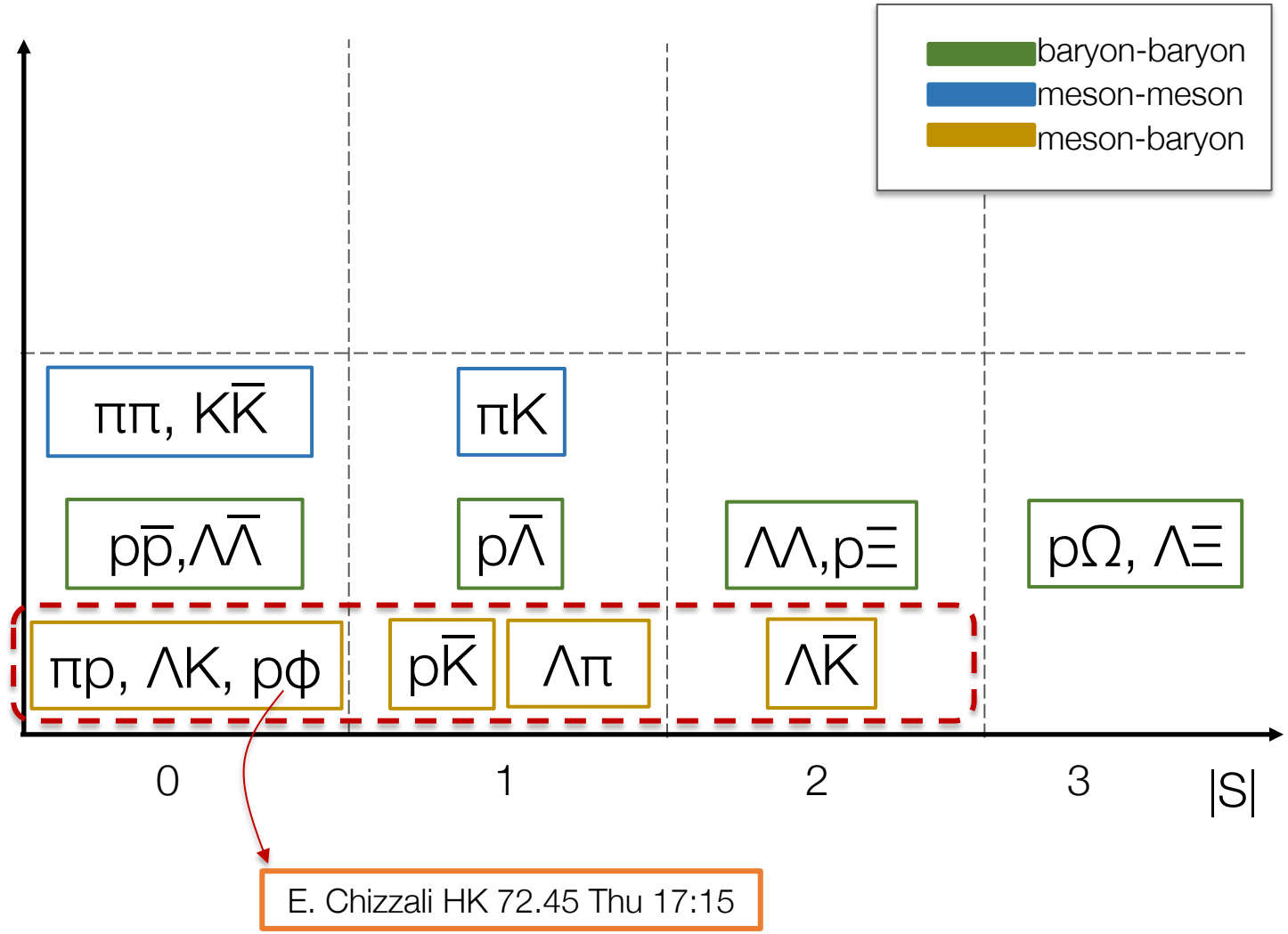
High-precision correlation data on many interactions involving exotic/bound states

Novel data on |S|=0,1,2 meson-baryon interaction

Molecular states and more: Λ(1405), Ξ*,N*,…



M. Mai Eur.Phys.J.ST 230 (2021) 6, 1593-1607
A. Feijoo et al. Phys.Lett.B 841 (2023) 137927
Y.-F. Wang et al. Phys.Rev.C 109 (2024) 1, 015202

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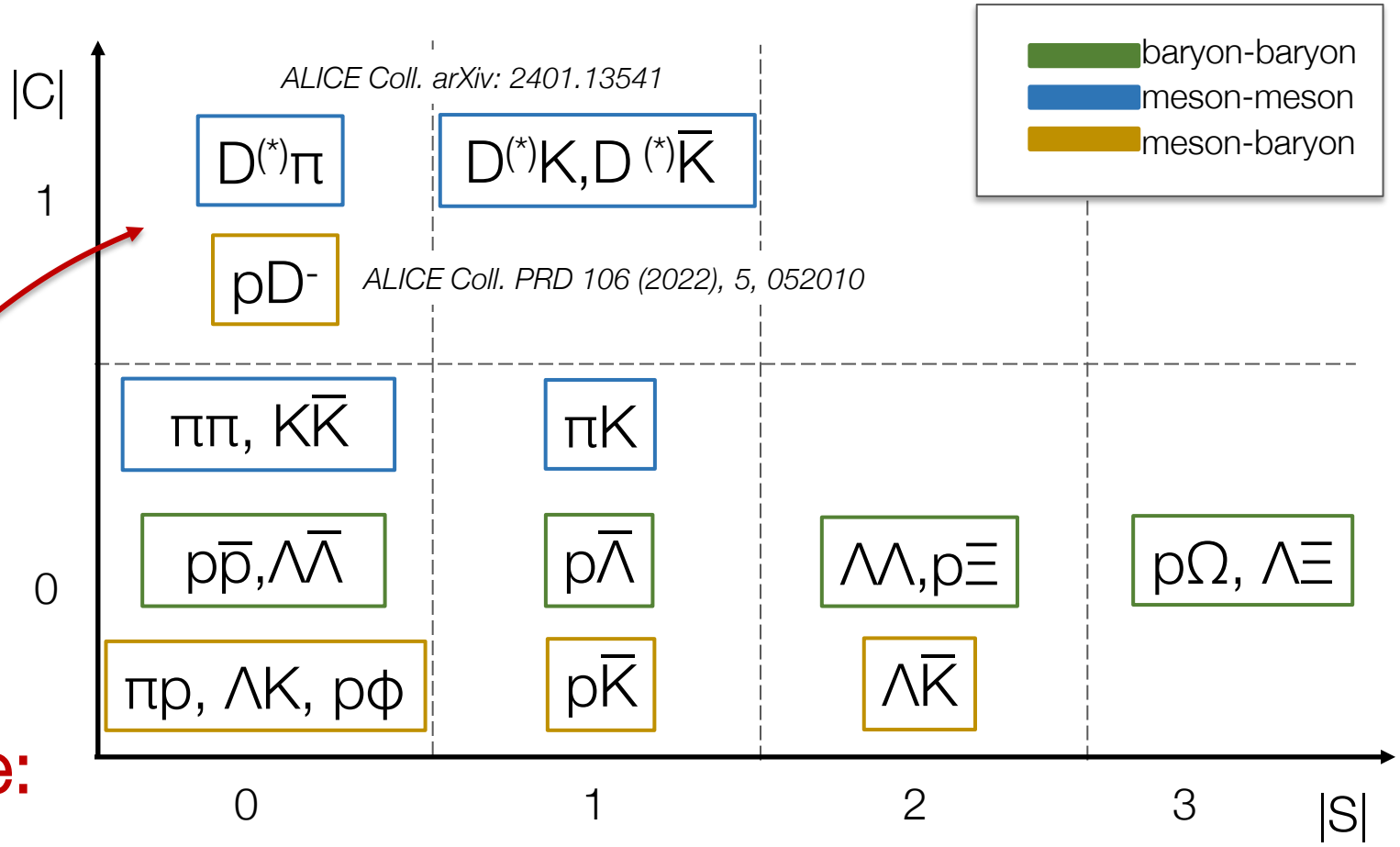


First "scattering" data available also in the charm sector

Molecular states and more:

Λ_c^*, $D_0^*(2300)$, $D_{s0}^*(2317)$, ...

D. Battistini HK 71.6 Thu 17:00

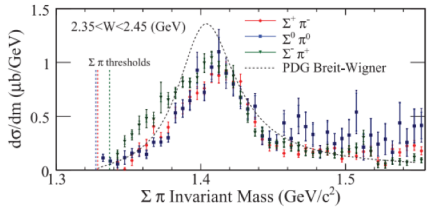
Meson-baryon interactions with strangeness

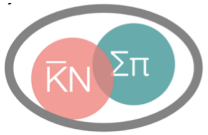
S = -1 Strangeness

$\bar{K}N$

Photoprod. experiments

K. Moriya et al., PRC87, 035206(2013).



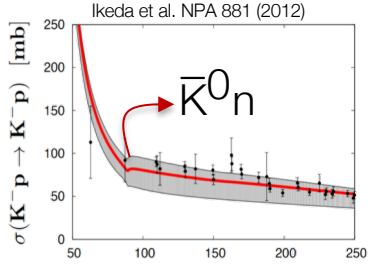


Kaonic hydrogen

SIDDHARTA PLB 704 (2011)

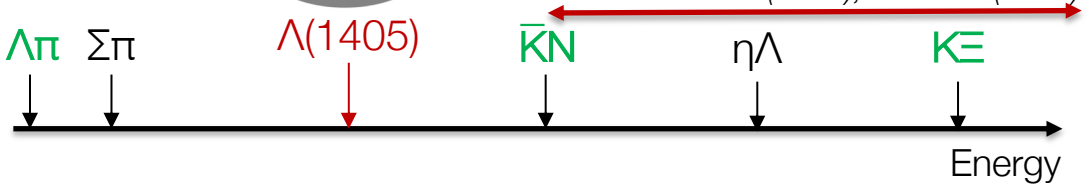
Scattering experiments

Ikeda et al. NPA 881 (2012)



Femtoscopy

ALICE Coll. PRL 124 (2020), PLB 822 (2021),EPJC 83 (2023)



Improve understanding on Λ(1405) molecular state

- K^-p correlations in different colliding systems
- Preliminary Λπ data — M. Di Costanzo HK 57.3 Wed 18:15
- Possibility to explore Σπ in on-going LHC Run 3

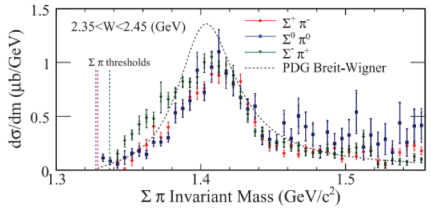
Meson-baryon interactions with strangeness

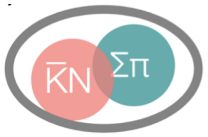
S = -1 S = -2 Strangeness

$\bar{K}N$

Photoprod. experiments

K. Moriya et al., PRC87, 035206(2013).





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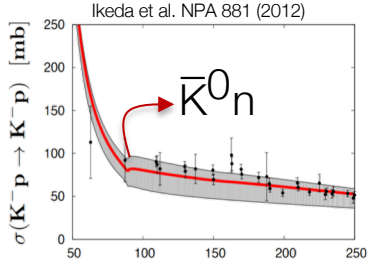

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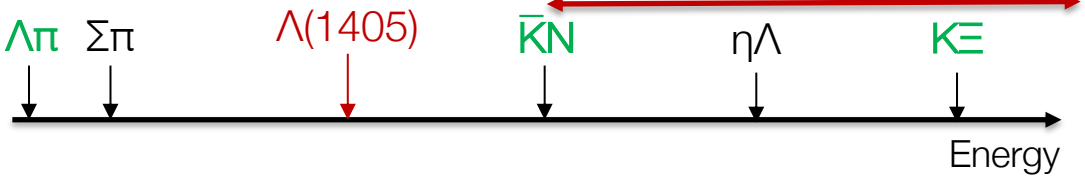
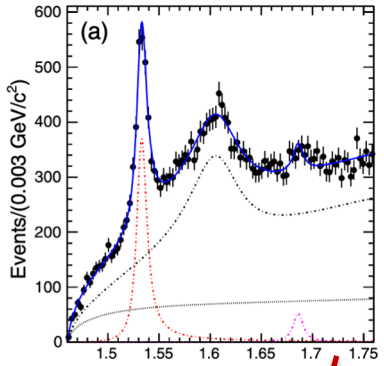


Improve understanding on Λ(1405) molecular state

- K^-p correlations in different colliding systems
- Preliminary Λπ data — M. Di Costanzo HK 57.3 Wed 18;15
- Possibility to explore Σπ in on-going LHC Run 3

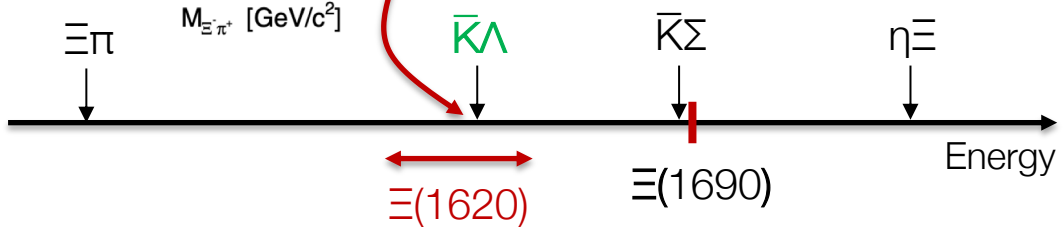
$\bar{K}\Lambda$

Belle Coll. PRL 122 (2019)



Femtoscopy in Pb-Pb

ALICE Coll. PRC 103 (2021), CMS Coll. arXiv: 2301.05290



Similar scenario for Ξ(1620) state?

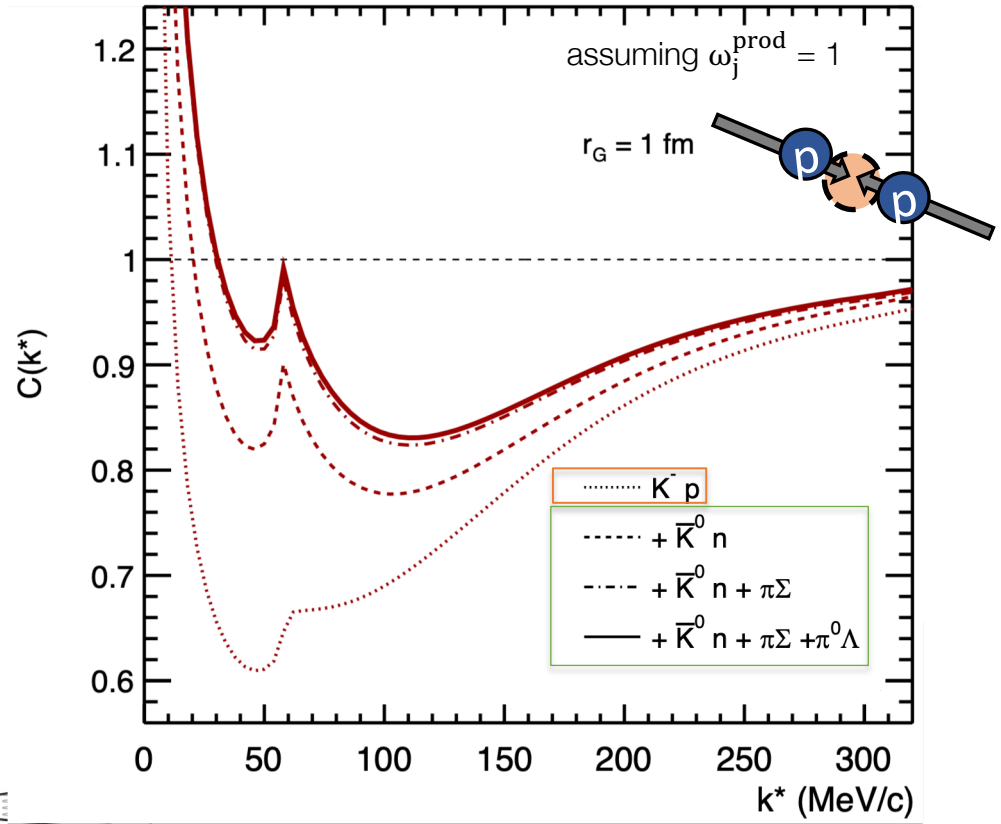
Can we shed light on the nature of this state with correlations?

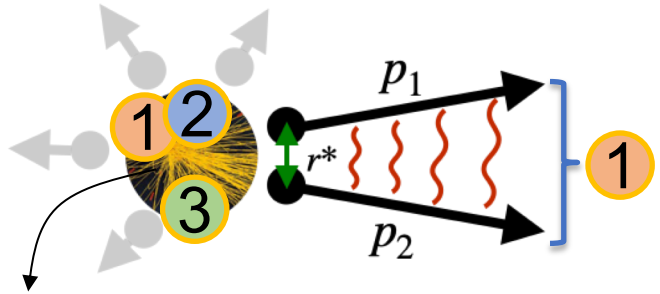
Coupled-channels dynamics in correlations

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

elastic
$1 \to 1$

inelastic
$2,3,\ldots \to 1$





Elastic/Inelastic channels

1 2

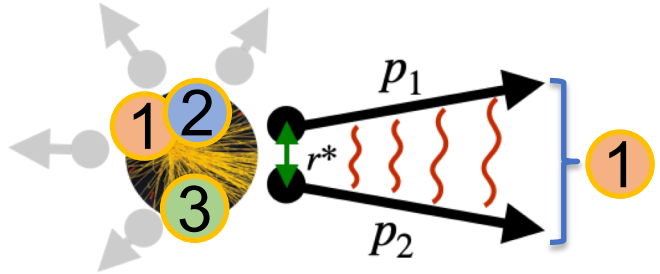
$\psi_1(\boldsymbol{k}_1, \boldsymbol{r})$ + $\psi_2(\boldsymbol{k}_2, \boldsymbol{r})$ + …

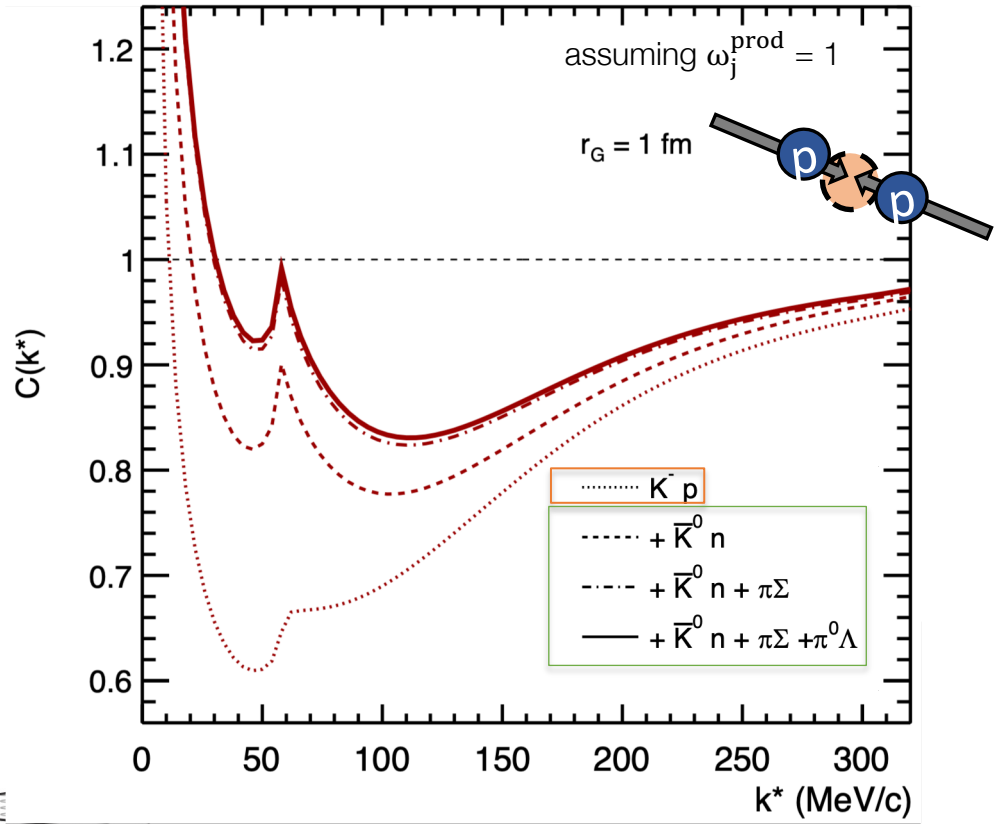
- Wavefunctions obtained in a coupled-channel approach
  - Above threshold: modify the shape of CF
    → cusp structure e.g.$\bar{K}^0$n
  - Below threshold: increase the strength of CF
    → shift upward of CF e.g.Σπ
- Conversion weights ω_j^{prod}
  - How many j pairs are produced as initial states?
  - Can be obtained in a data-driven way

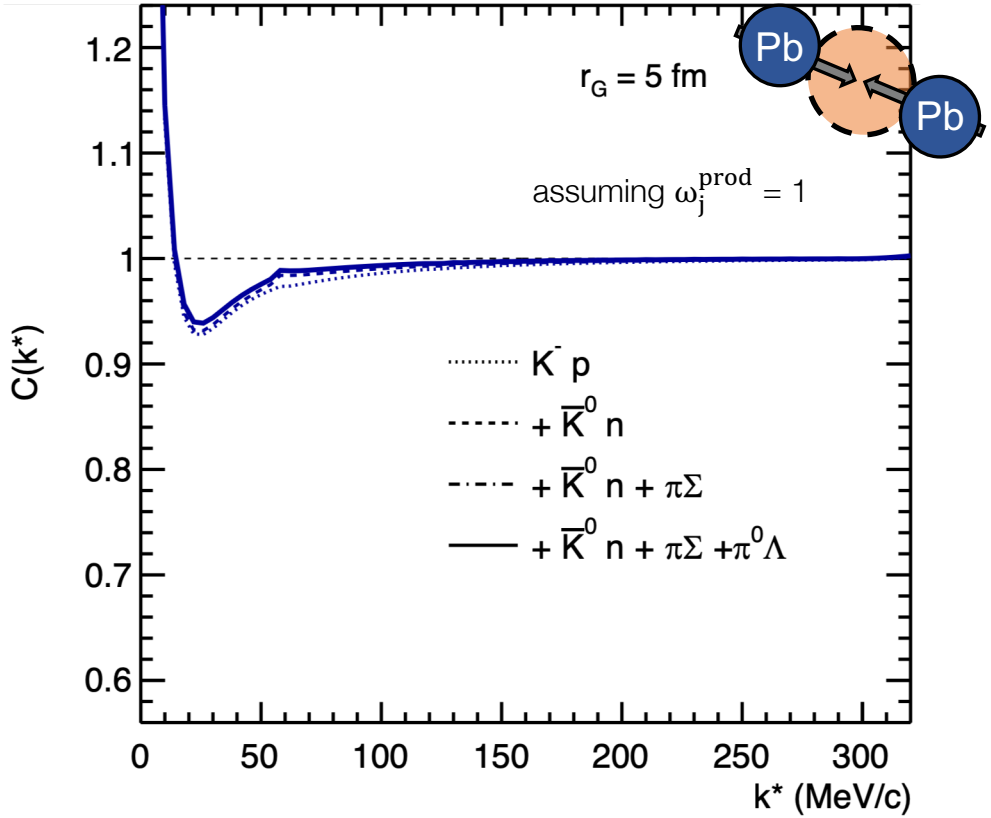
For more details: J. Haidenbauer NPA 981 (2019), Y. Kamiya et al. PRL 124 (2020)
L. Fabbietti, VMS, O. Vazquez Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)

Coupled-channels dynamics and source size

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







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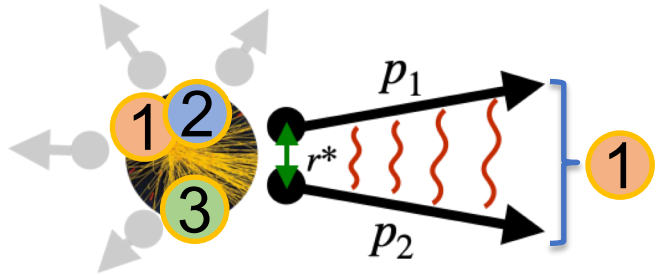
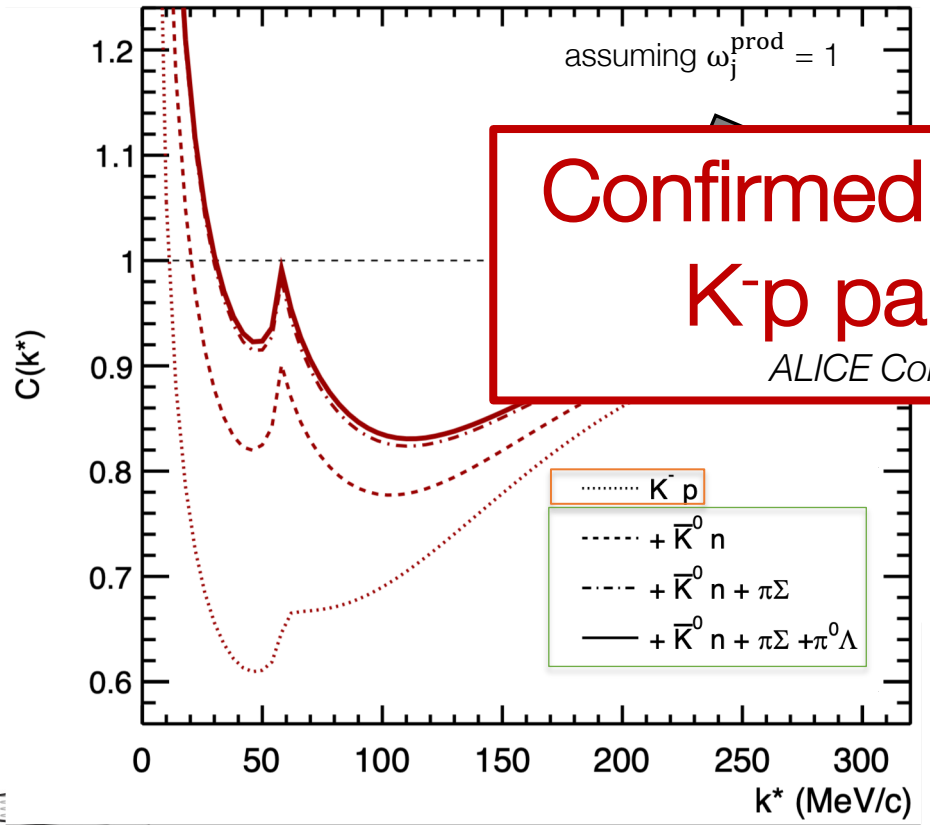
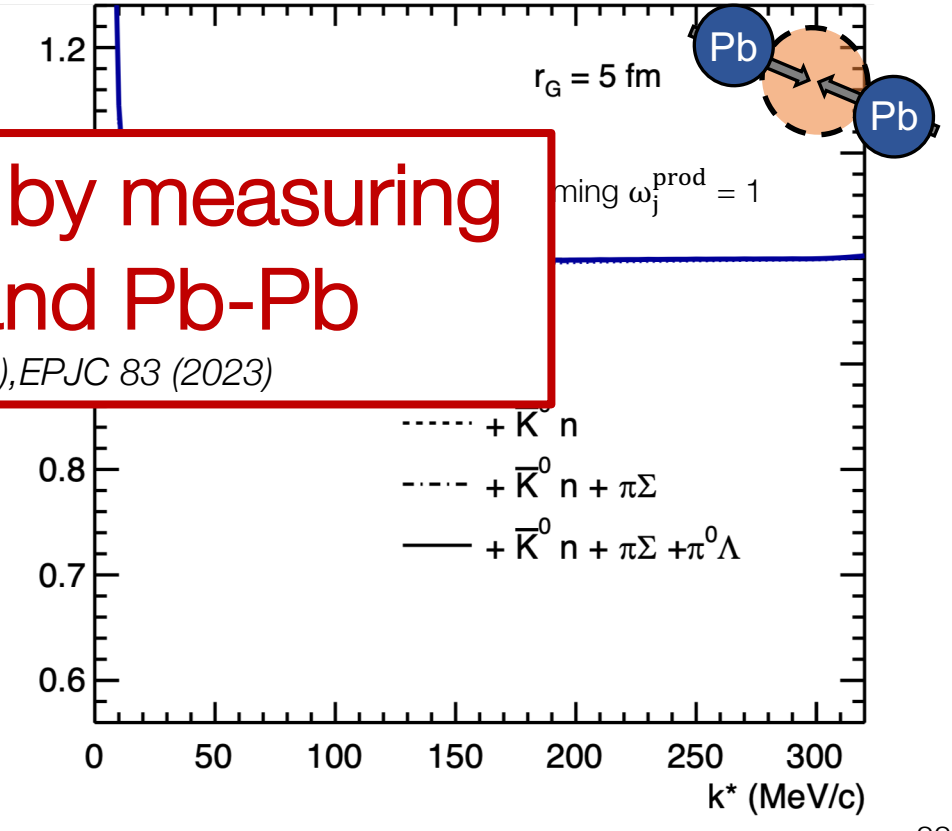




Confirmed experimentally by measuring K^-p pairs in pp,p-Pb and Pb-Pb

ALICE Coll. PRL 124 (2020), PLB 822 (2021),EPJC 83 (2023)



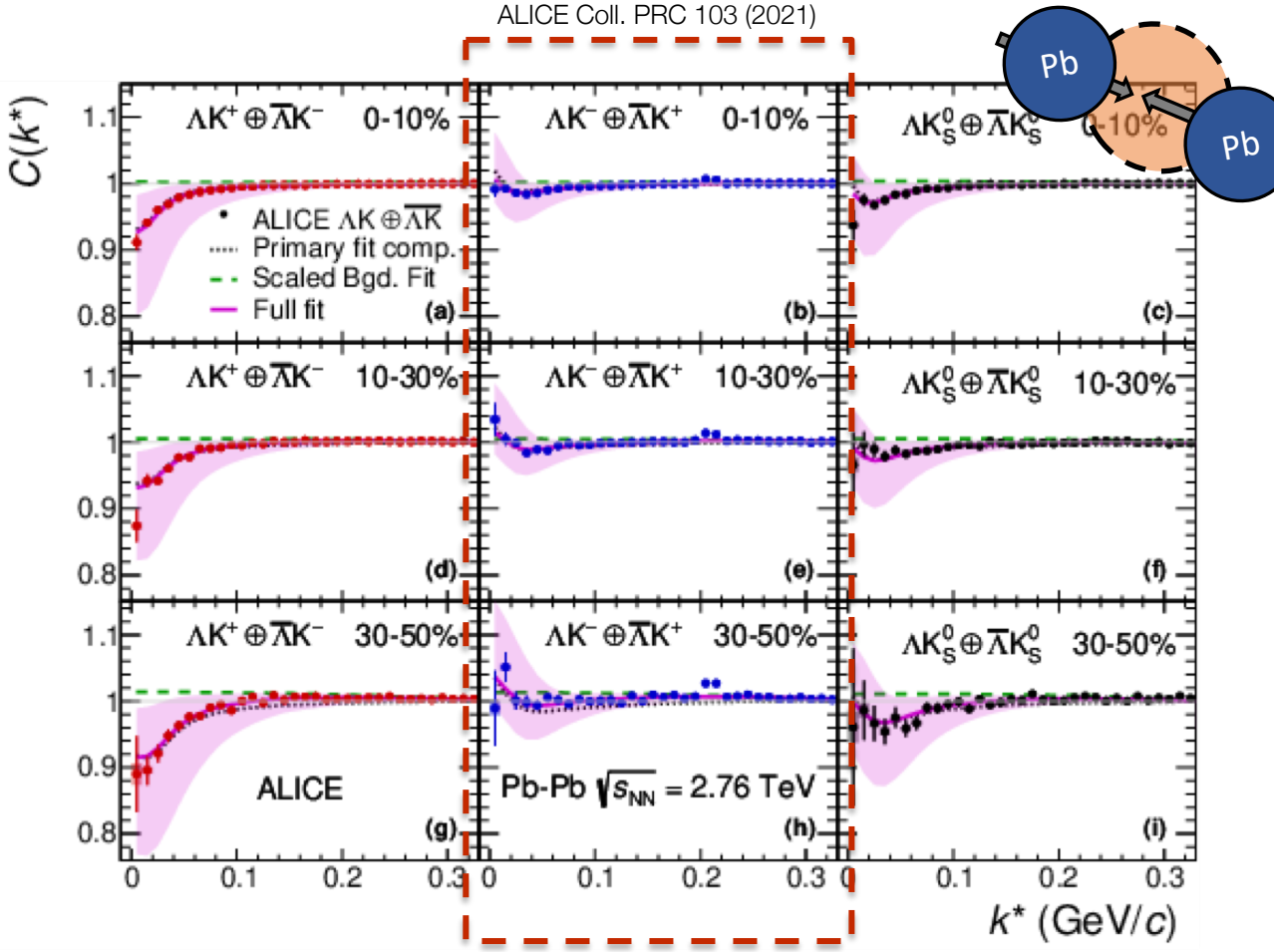
Accessing the ΛK̄ interaction with correlations

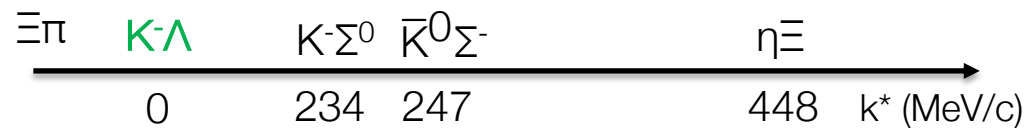
- Correlations in Pb-Pb
  - No particular cusps or structure visible
  - First measured scattering parameters available!

How does the correlation look like in pp collisions?

Presence of Ξ(1620)?

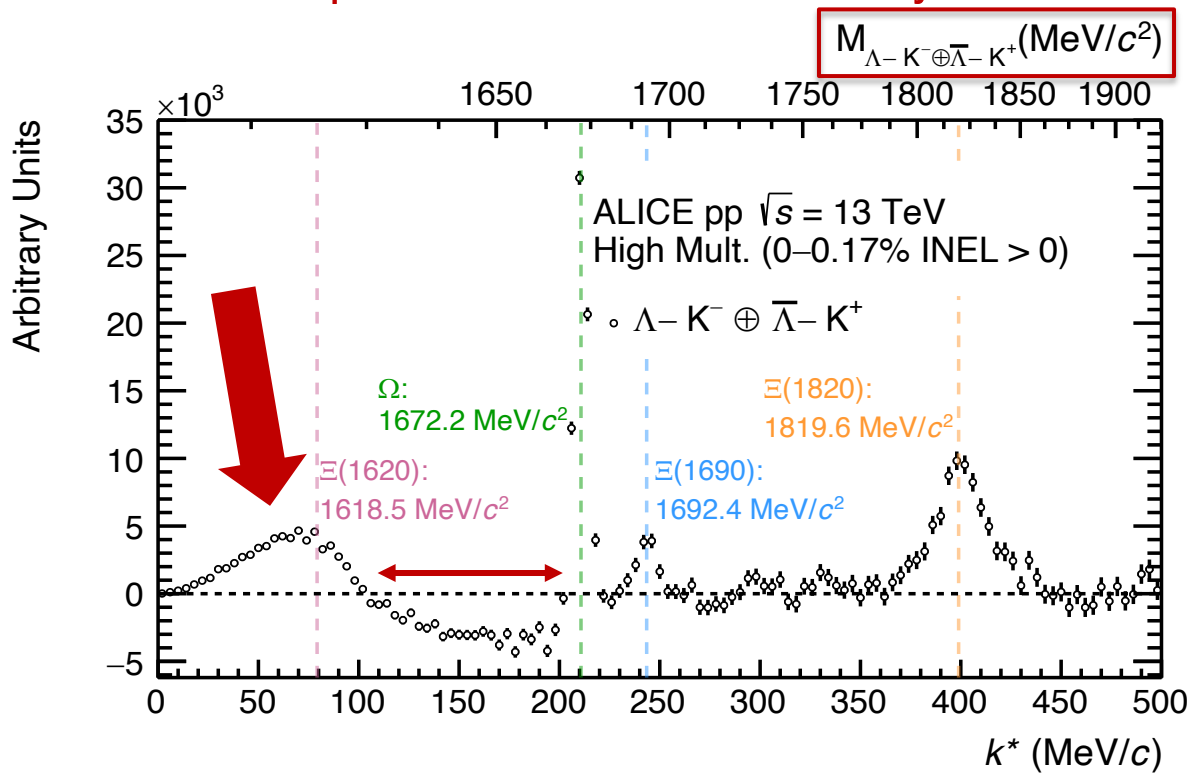
ALICE Coll. PRC 103 (2021)



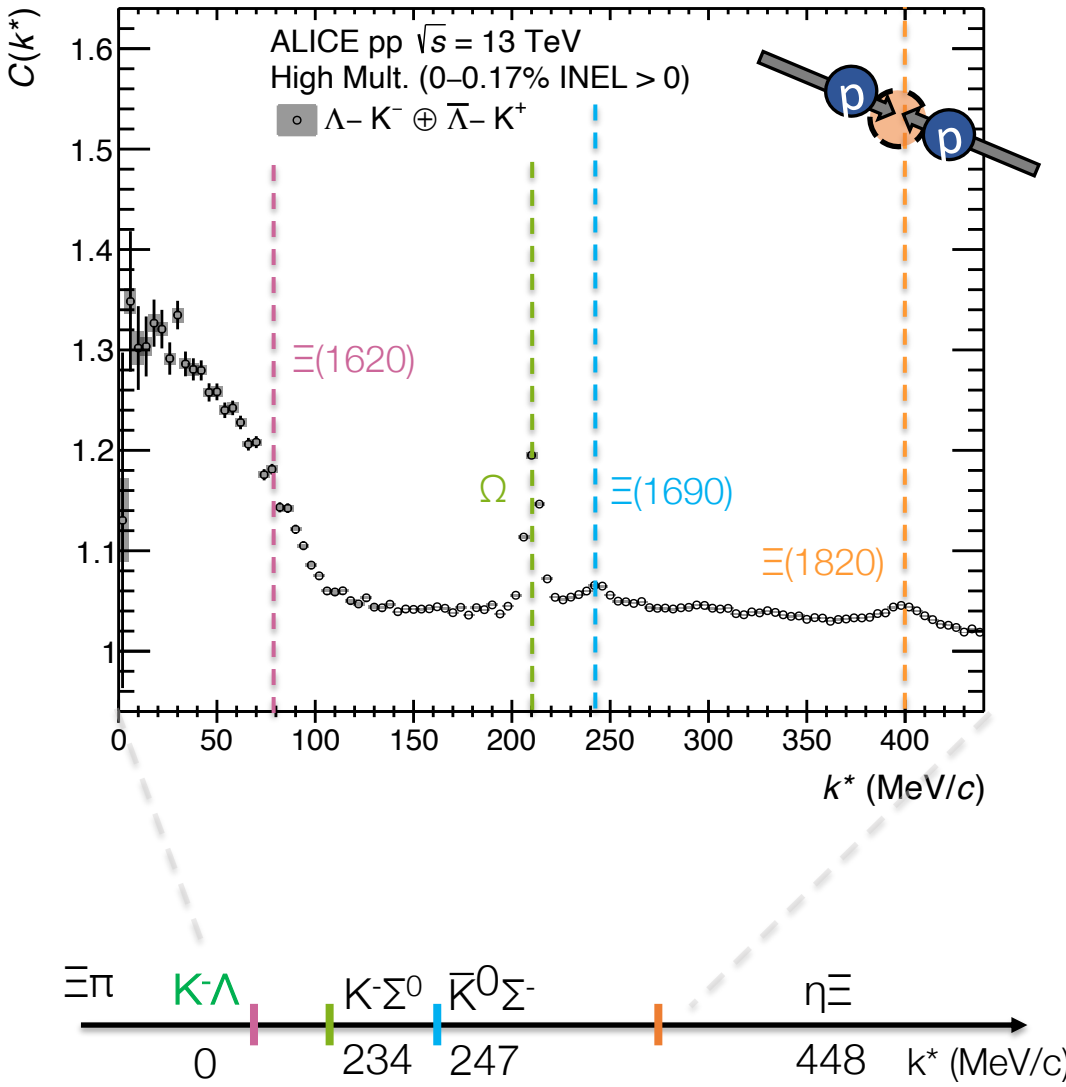


The ΛK⁻ correlation in pp collisions

- Several peak structures in the measured correlation
- Invariant mass from same and mixed event distributions used to build the correlation
  - Ξ(1620) just above the threshold
    → First experimental evidence of decay into ΛK⁻

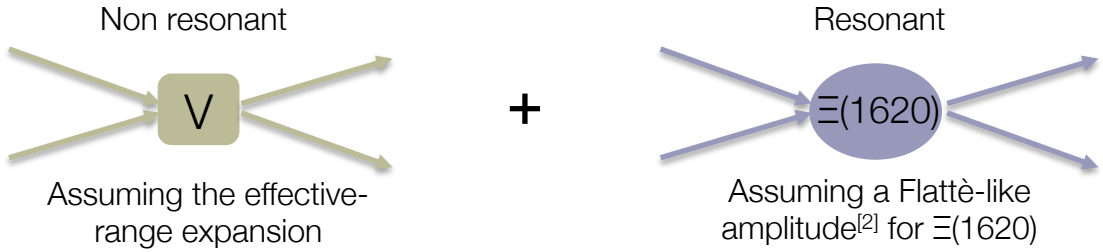


ALICE Coll. PLB 845 (2023) 138145



The ΛK⁻ correlation in pp collisions

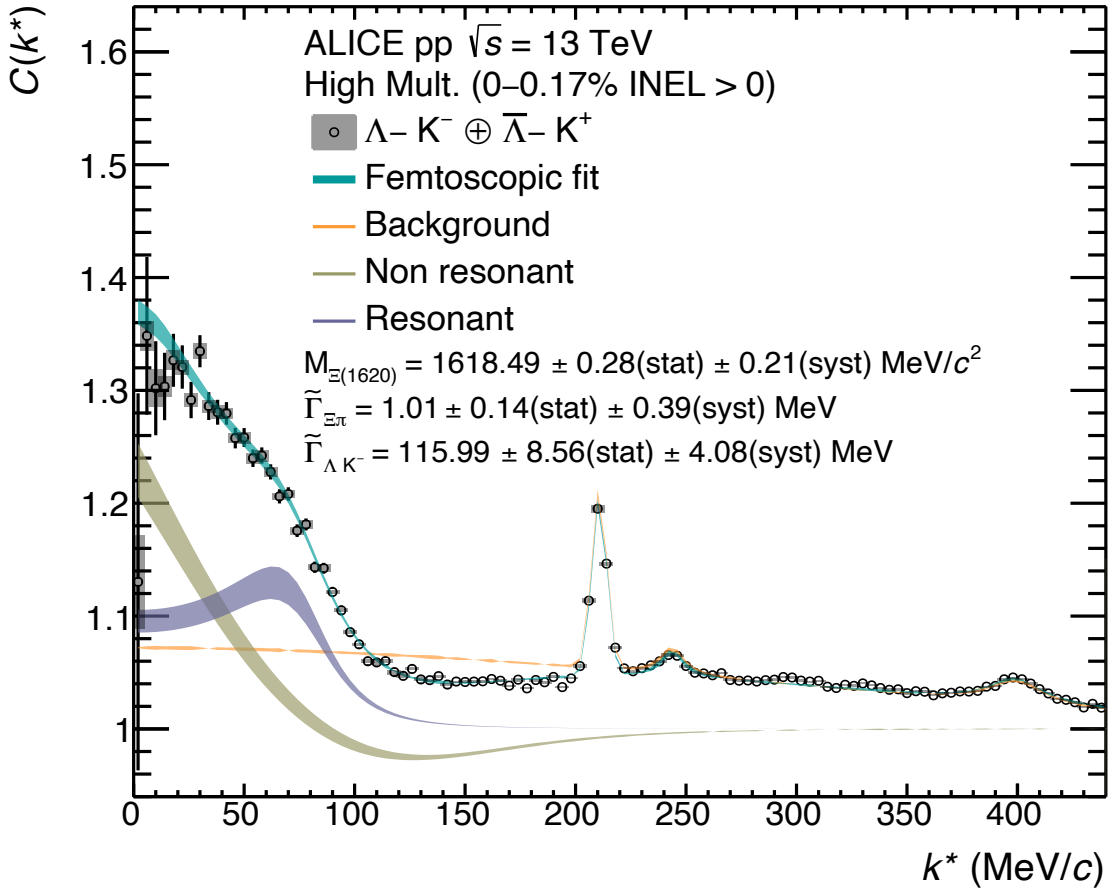
- Data modeled assuming effective scattering amplitude[1]



- **Ξ(1620) properties** and scattering parameters overall in agreement with Belle and Pb-Pb results
  - Indication of a large coupling of Ξ(1620) to ΛK^{-}

Can we use these femtoscopic data to constrain effective QCD models and investigate the Ξ(1620) nature?

ALICE Coll. PLB 845 (2023) 138145



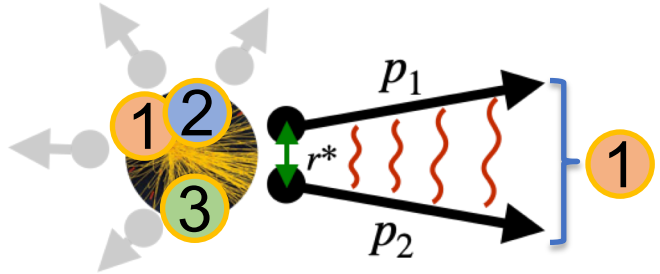
[1] R. Lednicky, V. Lyuboshits SJNP 35 (1982)
[2] F. Giacosa et al. EPJA 57 (2021), 12, 336

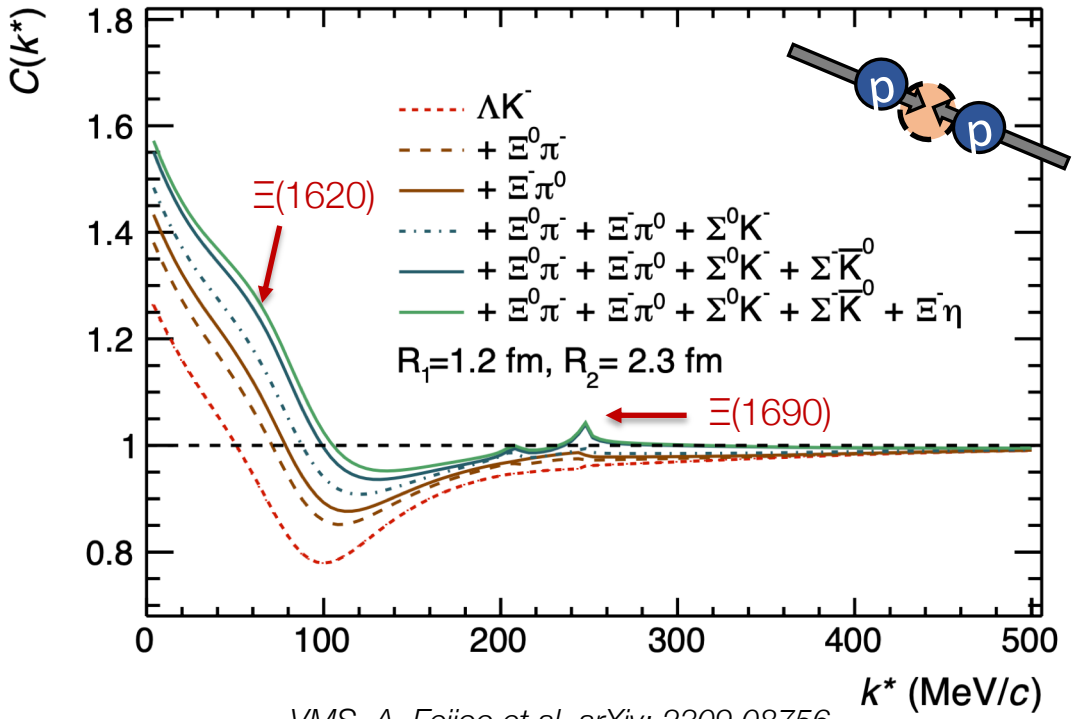
Constraining effective QCD lagrangians with correlations

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

elastic
1 → 1

inelastic
2,3,… → 1





VMS, A. Feijoo et al. arXiv: 2309.08756

Wavefunctions obtained in a coupled-channel approach

- State-of-the-art NLO effective lagrangian in UχPT
  A. Feijoo et al., PLB 841 (2023)

$$\mathcal{L}^{(1)}_{\phi B} = i\langle\bar{B}\gamma_\mu[D^\mu,B]\rangle - M_0\langle\bar{B}B\rangle - \frac{1}{2}D\langle\bar{B}\gamma_\mu\gamma_5\{u^\mu,B\}\rangle - \frac{1}{2}F\langle\bar{B}\gamma_\mu\gamma_5[u^\mu,B]\rangle\,,$$

$$\mathcal{L}^{(2)}_{\phi B} = b_D\langle\bar{B}\{\chi_+,B\}\rangle + b_F\langle\bar{B}[\chi_+,B]\rangle + b_0\langle\bar{B}B\rangle\langle\chi_+\rangle + d_1\langle\bar{B}\{u_\mu,[u^\mu,B]\}\rangle + d_2\langle\bar{B}[u_\mu,[u^\mu,B]]\rangle + d_3\langle\bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle\bar{B}B\rangle\langle u^\mu u_\mu\rangle\,.$$

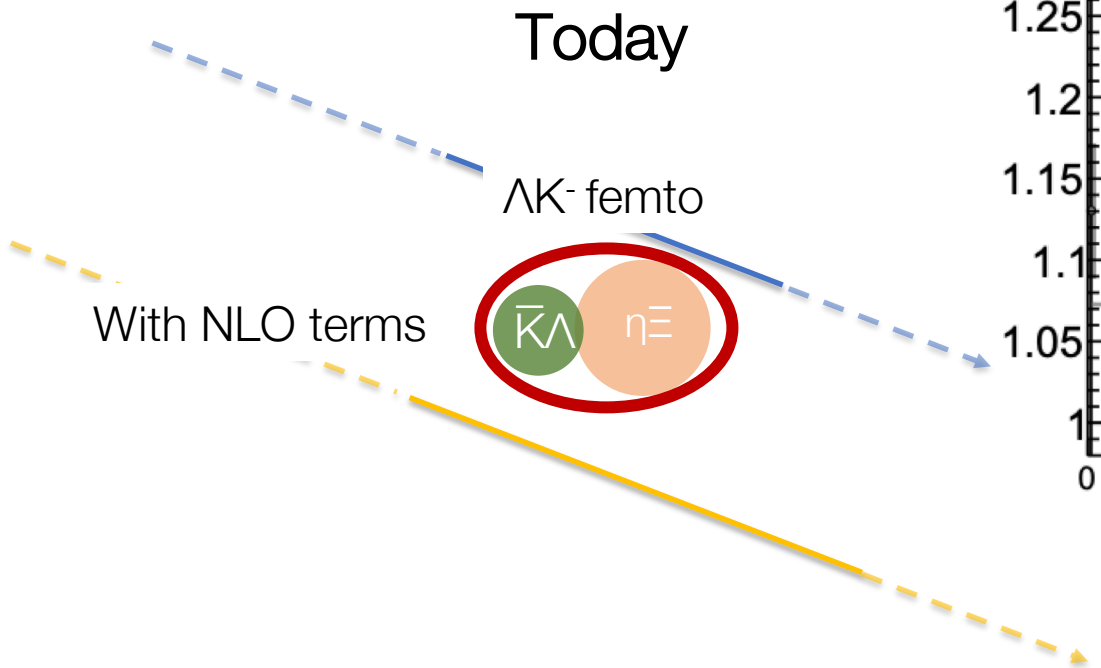
- Ξ(1620) and Ξ(1690) dynamically generated states

Conversion weights ω_j^{prod} and source studies

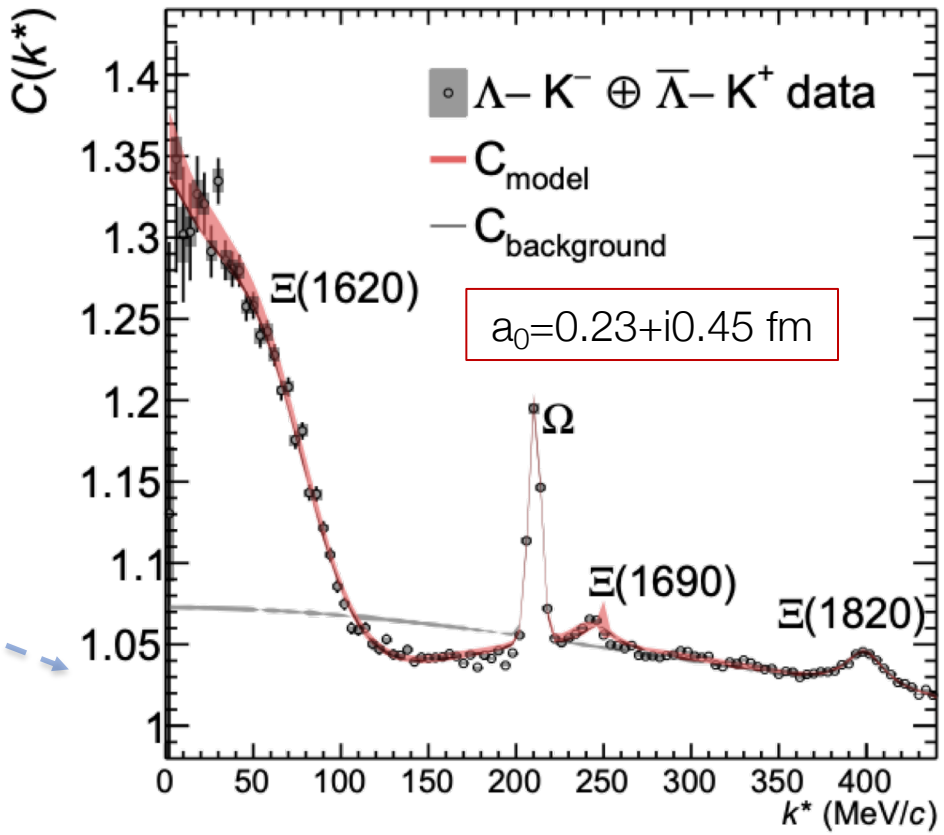
- Detailed data-driven study using thermal and transport models
  ALICE Coll. Eur.Phys.J.C 83 (2023), VMS, A. Feijoo et al. arXiv: 2309.08756

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



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

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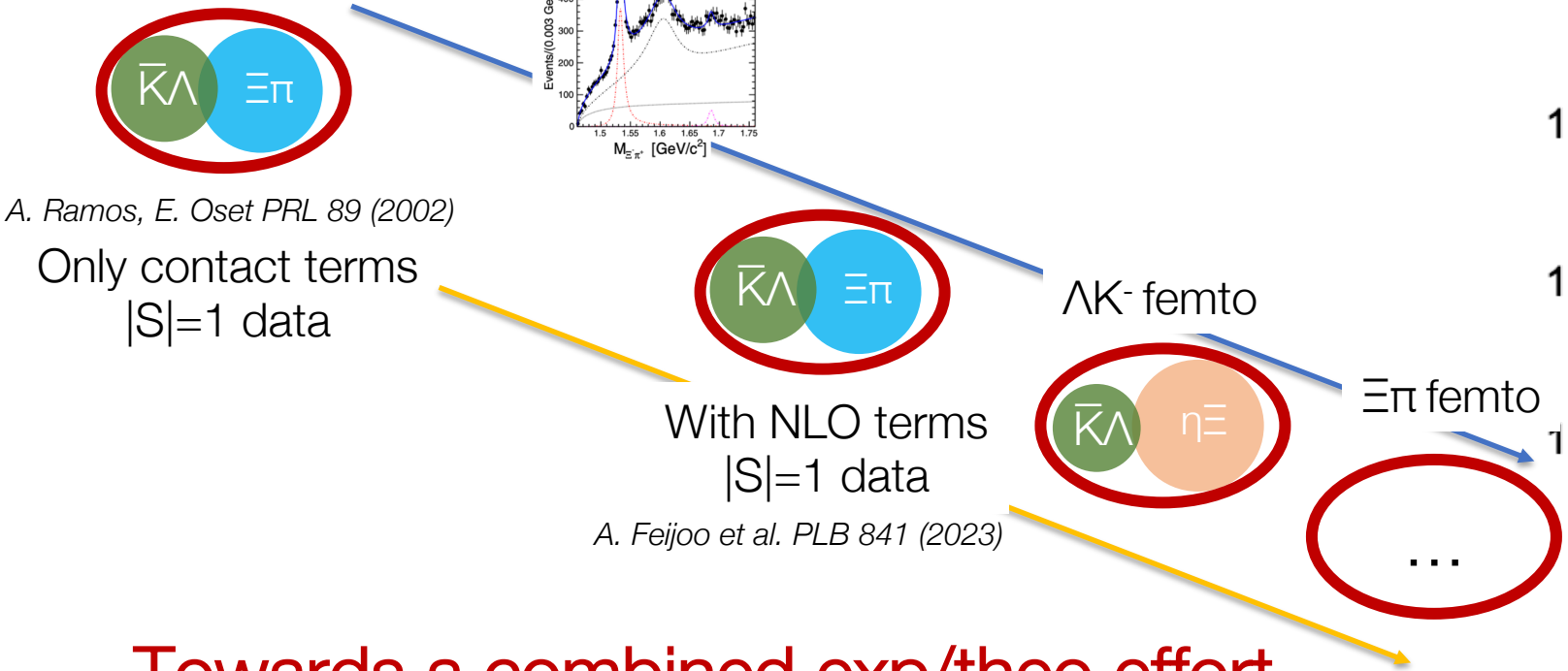
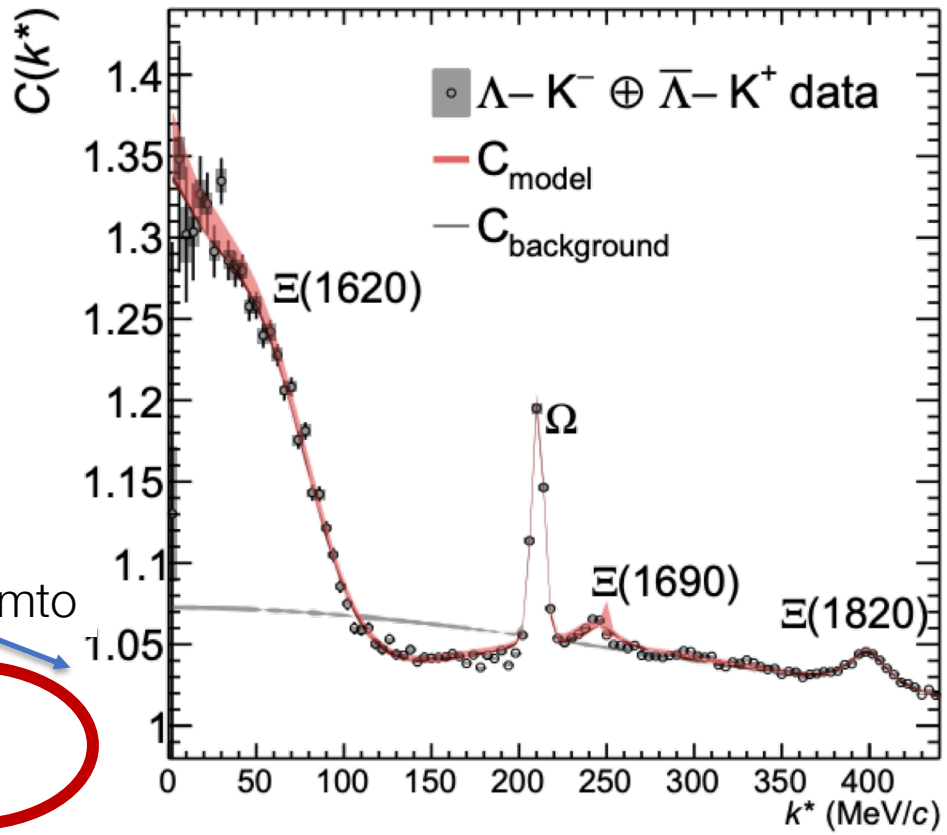


VMS, A. Feijoo et al. arXiv: 2309.08756

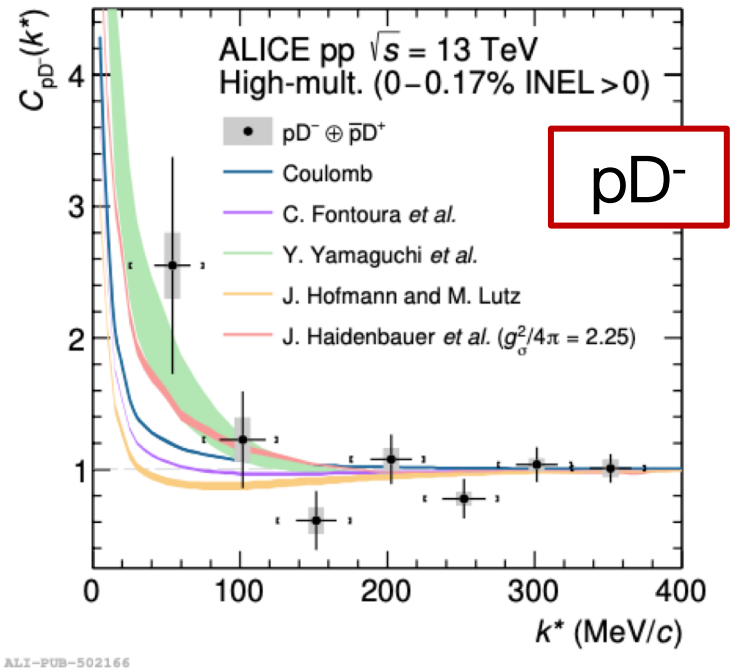


Towards a combined exp/theo effort to constrain this sector

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

Accessing the interaction between light and charm hadrons

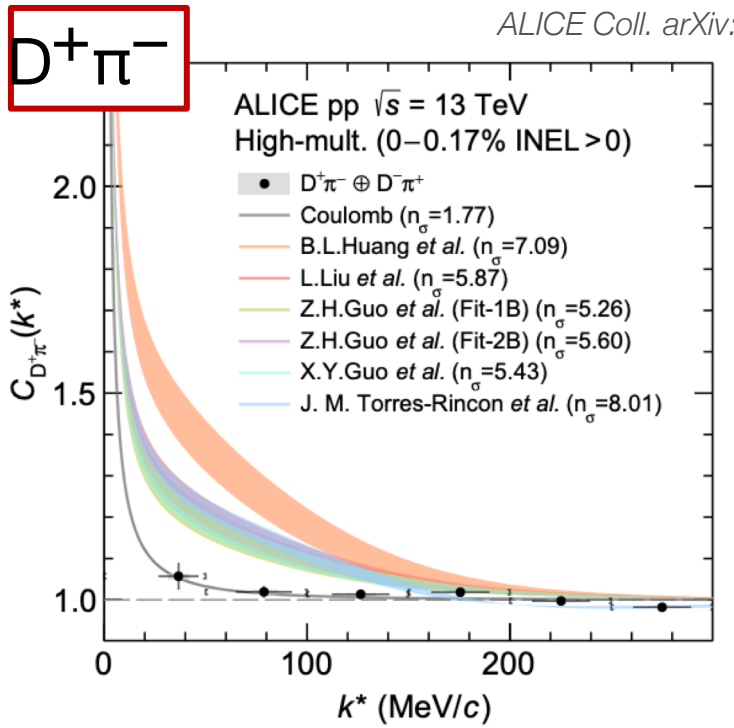
ALICE Coll. PRD 106 (2022), 5, 052010

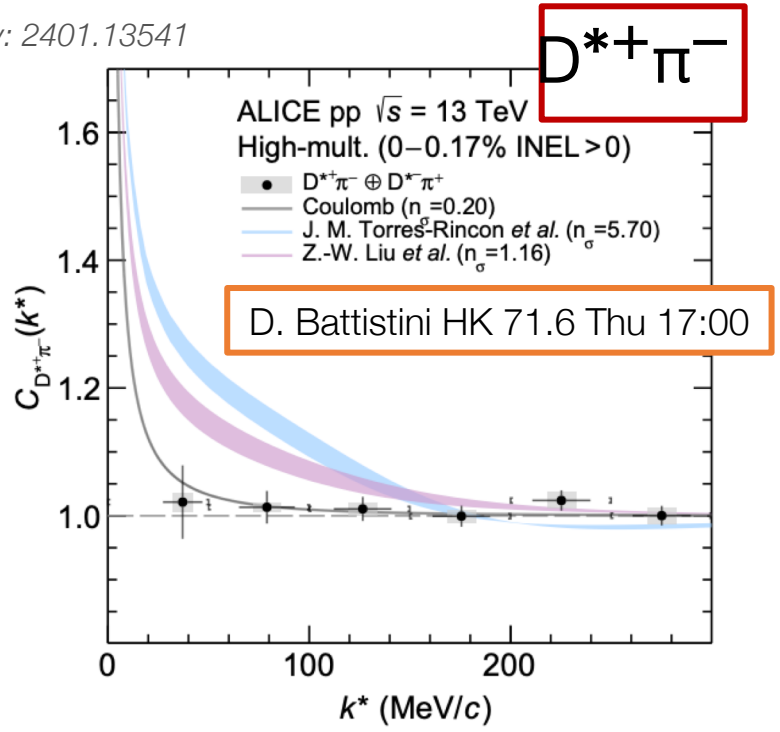


- First measurements of interaction between D(*) mesons and light hadrons
  - Several predictions of exotic states, crucial input for charm nuclei and heavy-flavor observables in heavy-ions
- Femtoscopy can be extended to the charm sector
  - More results to come with the LHC Run 3 and Run 4 statistics

Moving towards a charming future

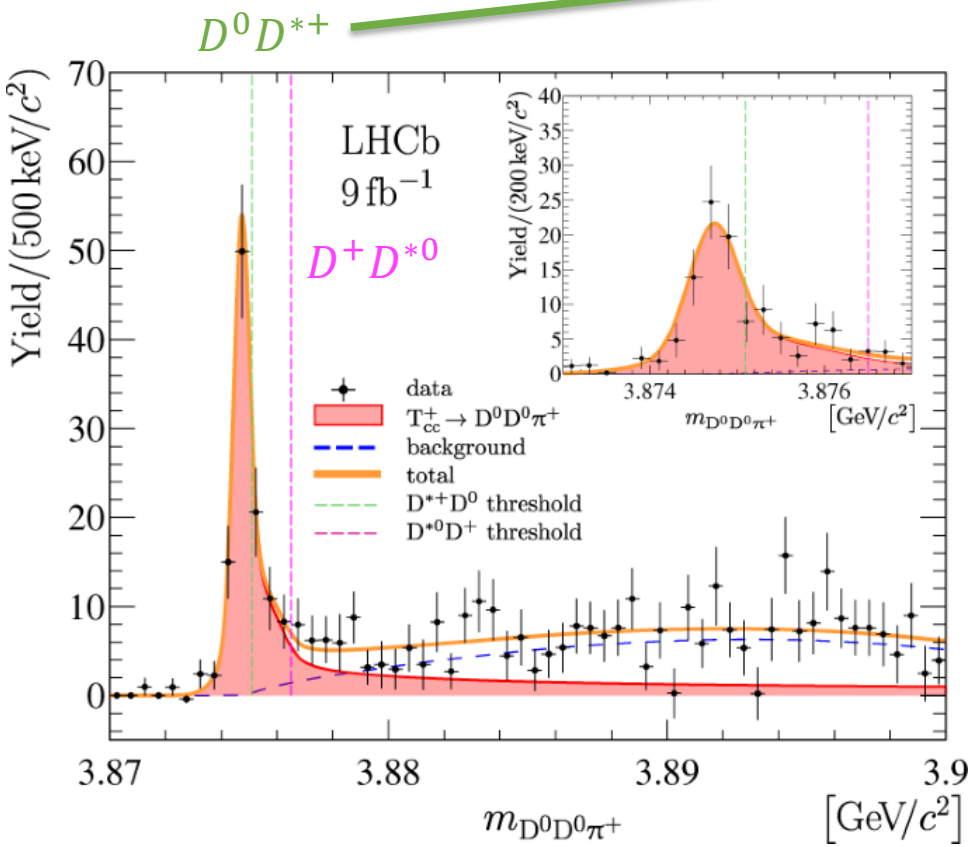
ALICE Coll. arXiv: 2401.13541





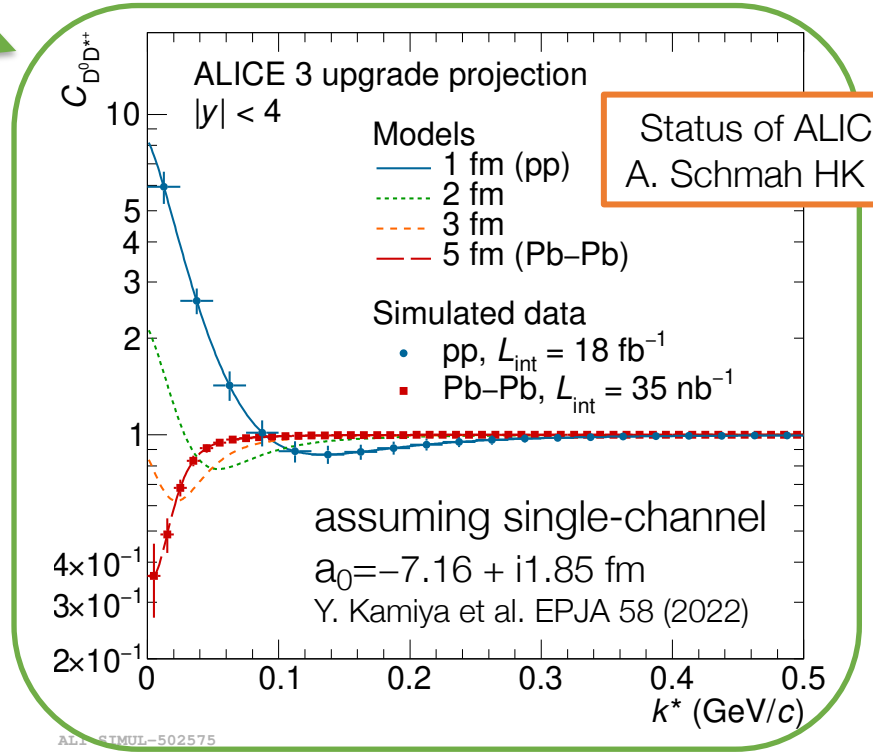
Correlations and exotic states for a charming future

- Exotic charm states as T_{cc}^{+} observed at LHCb
  - Possible molecular candidate



LHCb, Nature Physics 18 (2022), Nature Comm. 13 (2022)

- Investigate its nature with ALICE 3 in Run 5 and Run 6 (from 2035) via DD* correlations



Status of ALICE and ALICE 3
A. Schmah HK 59.3 Thu 12:00

ALICE 3 LOI, CERN-LHCC-2022-009

Future complementarity between spectroscopy and femtoscopy

Conclusions and outlooks

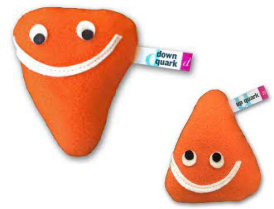
- **Femtoscopy** technique as a **complementary tool** to provide high-precision data on **hadron-hadron interactions to study exotic states**

- Access to strong interaction involving **strange** and **charm** hadrons
  - **most precise data** at low momenta available
  - input for **low-energy effective lagrangians** and test of **lattice potentials**

- **Many more correlations to come with on-going Run 3 and future LHC runs**

Femtoscopy DPG menu of the week

- B. Heybeck HK 23.4 Tue 16:45
- D. Mihaylov HK 57.2 Wed 18:00
- M. Korwieser HK 71.3, Thu 16:15
- D.F. Wang HK 71.4 Thu 16:30
- D. Battistini HK 71.6 Thu 17:00
- M. Lesch HK 57.4 Thu 17:15
- R. Del Grande HK 72.39 Thu 17:15
- G.Mantzaridis, J. Gonzalez HK. 72.52 Thu 17:15
- L. Serksnyte HK 72.38, Thu 17:15
- D. Melnichenko HK 72.41 Thu 17:15
- A. Riedel HK 72.37 Thu 17:15
- E. Chizzali HK 72.45 Thu 17:15
- B. Singh HK 72.51 Thu 17:15



Additional slides