Probing (Strong) interaction potentials with femtoscopy measurements in ALICE

Laura Fabbietti for the ALICE Collaboration

Technische Universität München

E62 - Dense and Strange Matter

Poster by **O. Vazquez Doce Tuesday**
'Femtoscopic studies on proton-Ξ and proton-Ω correlations in p-Pb and pp collisions with ALICE'

Talk by **J. Buxton on Thursday at 15:00**
'Λ-K Femtoscopy in Pb-Pb collisions at sqrt(s)=2.76 TeV with ALICE'

Outline

- Short Motivation
- The considered data set
- Correlation Function and CATS method
- Results for the following interactions:

$$K^+p,\ K^-p,\ pp,\ p\Lambda,\ p\Sigma^0,\ p\Xi^-,\ p\bar{\Omega}$$

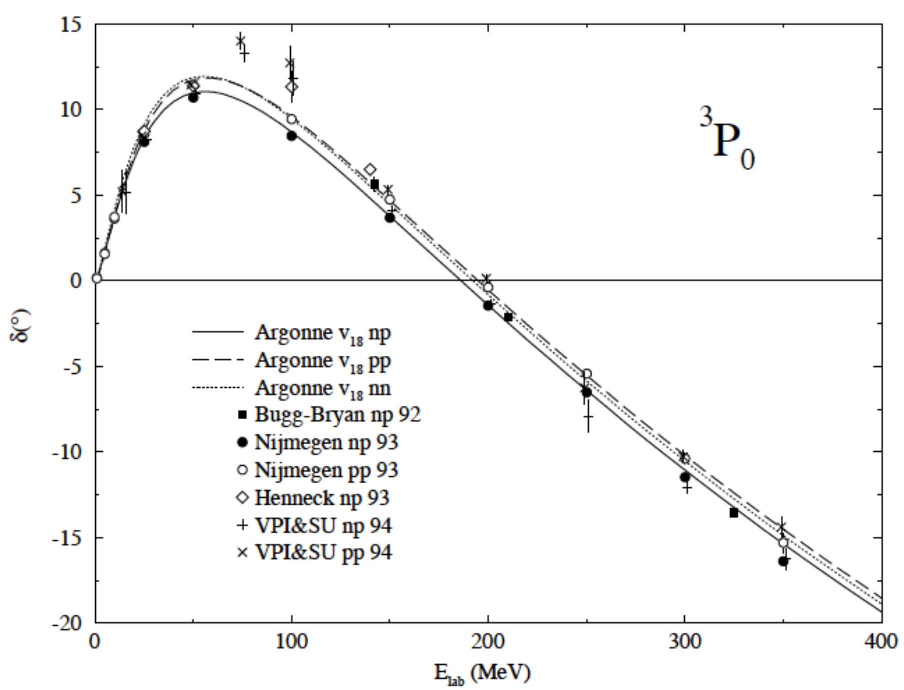
- Outlook

Can the LHC provide a precise testing of the strong interaction at distances around 1 fm?

Strong Interaction Among (Strange) Hadrons

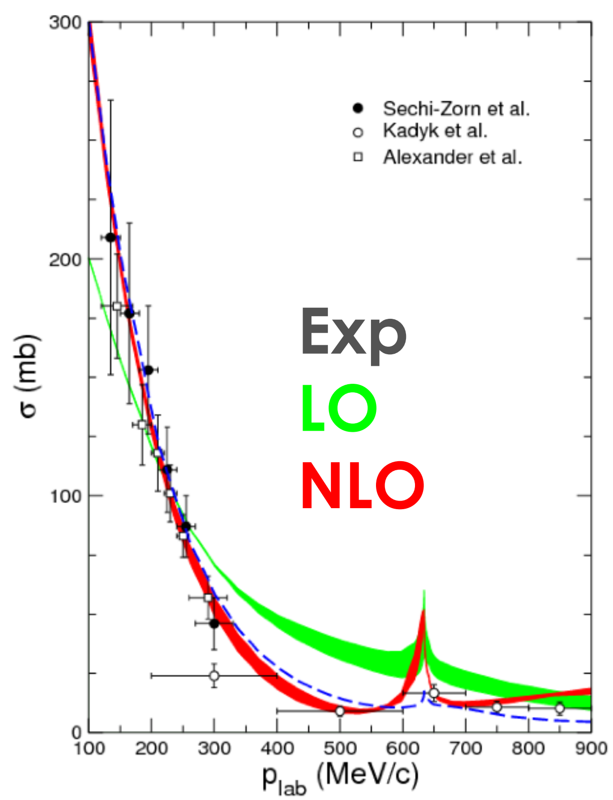
Normally studied with high precision via scattering experiments

$NN \to NN$



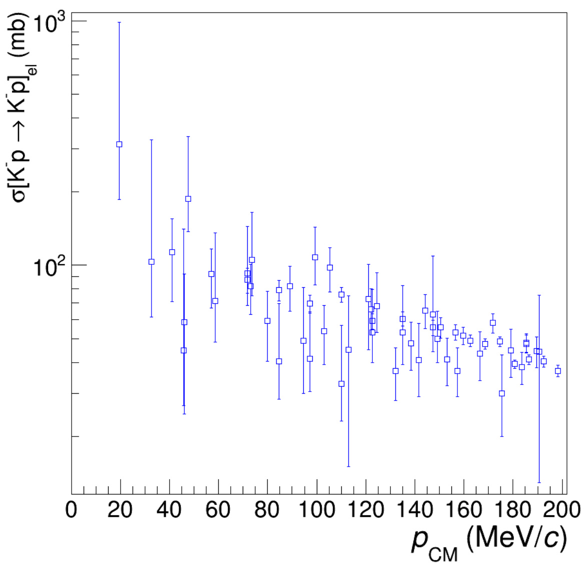
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla Phys.Rev. C51 (1995) 38-51 .

$\Lambda p \to \Lambda p$



LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

$K^- p \to K^- p$



M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

Theoretical Predictions for the Interactions

	Lattice (HAL-QCD)	Chiral Effective Field Theory	Meson-Exchange Models
General Properties	• **Quarks** and **gluons** are the **degrees of freedom** • Coupled channels are included • Allows for bound states • **Not fitted to scattering data** but with physical pion and kaon masses	• **Hadronic degrees of freedom** • Ordered scheme with **higher order loops** • Obeys SU(3) symmetry • Coupled channels included • Coupling constants **fitted to scattering data**	• **Hadronic degrees of freedom** • Phenomenological models with interactions **at tree level** • Obeys SU(3) symmetry • Coupled channel included • Some models do not allow for bound states • Coupling constants **fitted to scattering data**
Kp	✗	✓	✓
pp	✗	✓ (..N³LO..)	✓
$p\Lambda$	✗	✓ (NLO)	✓
$\Lambda\Lambda$	✓	✗	✓
$p\Sigma^0$	✗	✓ (NLO)	✓
$p\Xi^-$	✓	✓	✓
$p\Omega^-$	✓	✗	✓

Theoretical Predictions for the Interactions

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Kp	✗	✓	✓
pp	✗	✓	✓
$p\Lambda$	✗	✓ (NLO)	✓
$\Lambda\Lambda$	✓	✗	✓
$p\Sigma^0$	✗	✓ (NLO)	✓
$p\Xi^-$	✓	✓	✓
$p\Omega^-$	✓	✗	✓

The ALICE Data Set

We measure **pp**, **pΛ**, **ΛΛ**, **pΞ**, **pK**, **p**Σ , **p**Ω

Proton and Pion identification with TPC and TOF

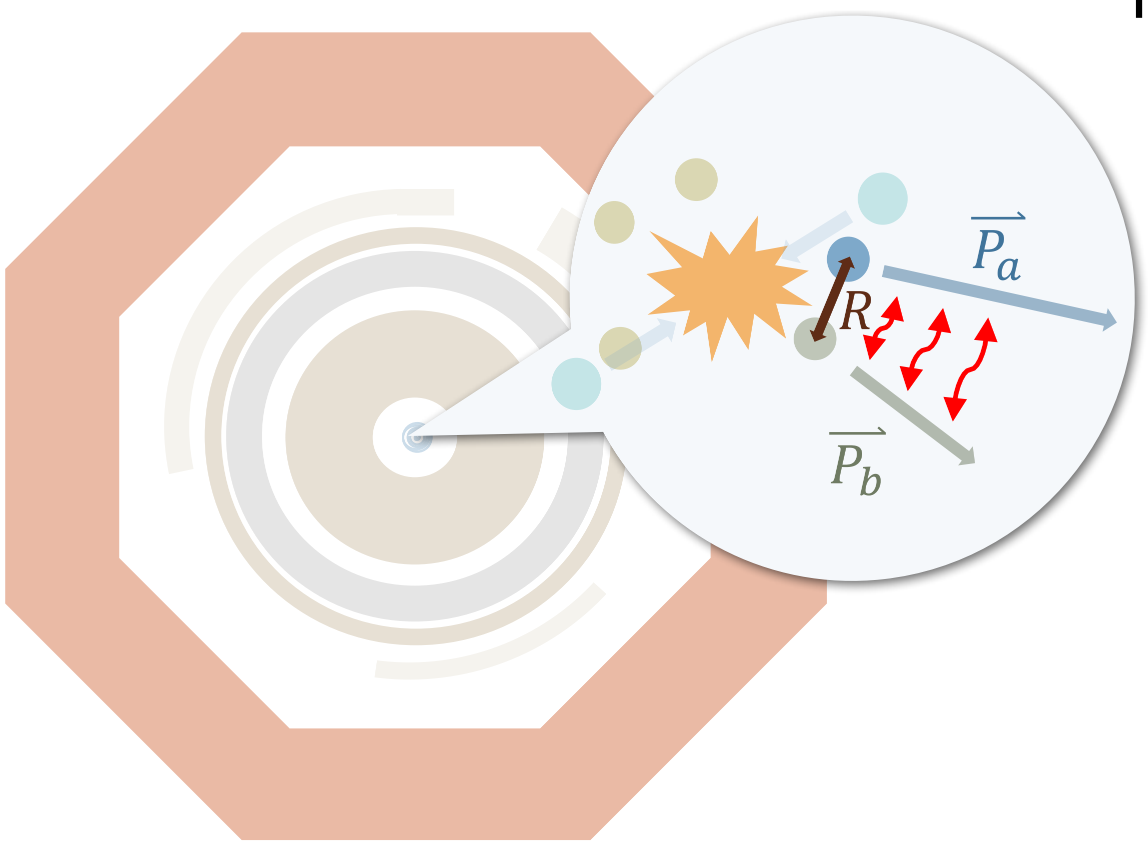
Reconstruction of hyperons

$\Lambda \rightarrow p\pi^-$ (BR ~ 64%)

$\Xi^- \rightarrow \Lambda\ \pi^-$ (BR ~ 100%)

$\Omega^- \rightarrow \Lambda K^- (BR\ 68\%)$

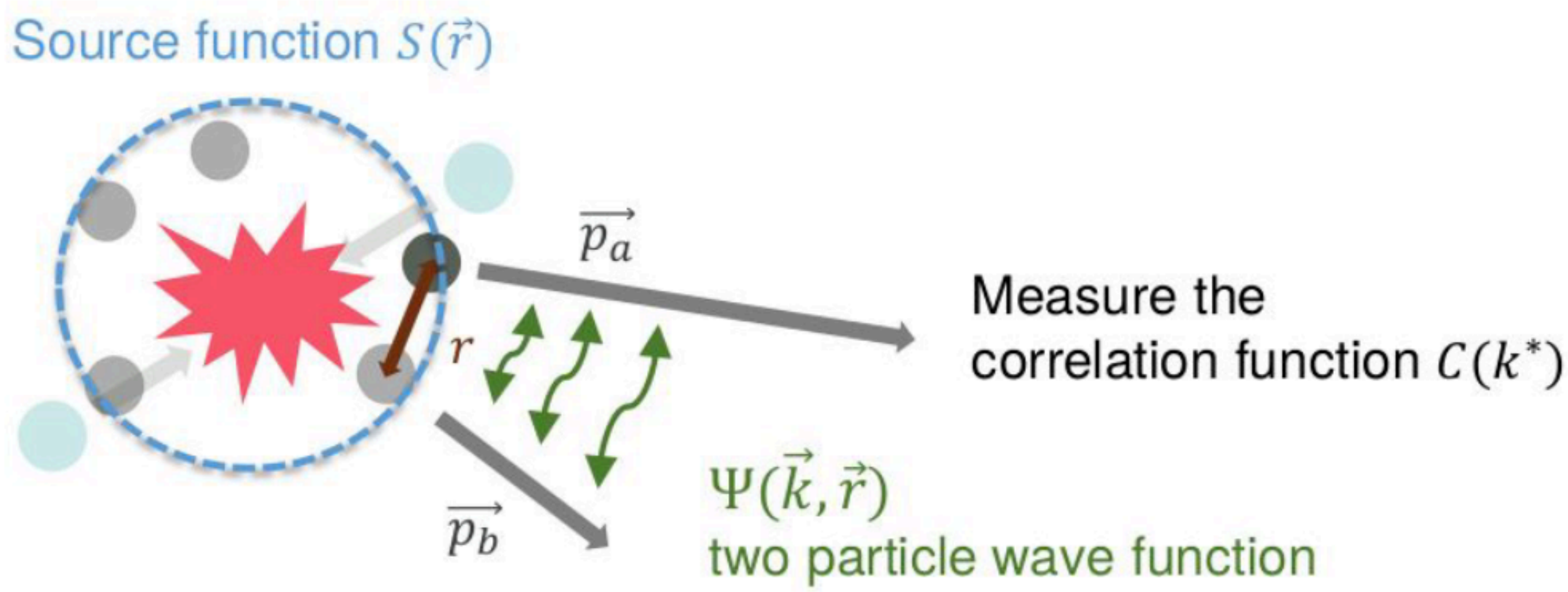
$\Sigma^0 \rightarrow \Lambda + \gamma$ (BR ~100%)



Datasets:

- pp 7 TeV: $3.4 \cdot 10^8$ MB Events
- pp 5 TeV: $10 \cdot 10^8$ MB Events
- pp 13 TeV: $15 \cdot 10^8$ MB Events
- p-Pb 5.02 TeV: $6.0 \cdot 10^8$ MB Events
- pp 13 TeV: $15 \cdot 10^8$ HM Events (0-0.072% INEL)

The Correlation Function



Experimental definition ***Theoretical definition***

$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{Same}}(k^*)}{N_{\mathrm{Mixed}}(k^*)} = \int S(\vec{r})\left|\Psi(\vec{k}^*,\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k^*\to\infty} 1$$

>1 : **Attractive** Interaction

<1: **Repulsive** Interaction

Relative distance / reduced momentum in the rest frame of the pair

The Correlation Function

D. Mihaylov (ALICE) WPCF19 slides

Experimental definition ***Theoretical definition***

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Relative distance / reduced momentum in the rest frame of the pair

Assumption of a '**common**' **source** for the **pp, pΛ, pΞ**, $\Lambda\Lambda$, pK$^+$, pK$^-$, pΣ and pΩ Correlation Function

The pp correlation is used to constrain the source, since both Coulomb and Strong interactions are very well known

The K$^+$p correlation is used to cross-check the pp benchmark independently since also for this channel the Coulomb and Strong interactions are known

CATS – Correlation Analysis Tool Using the Schrödinger Equation

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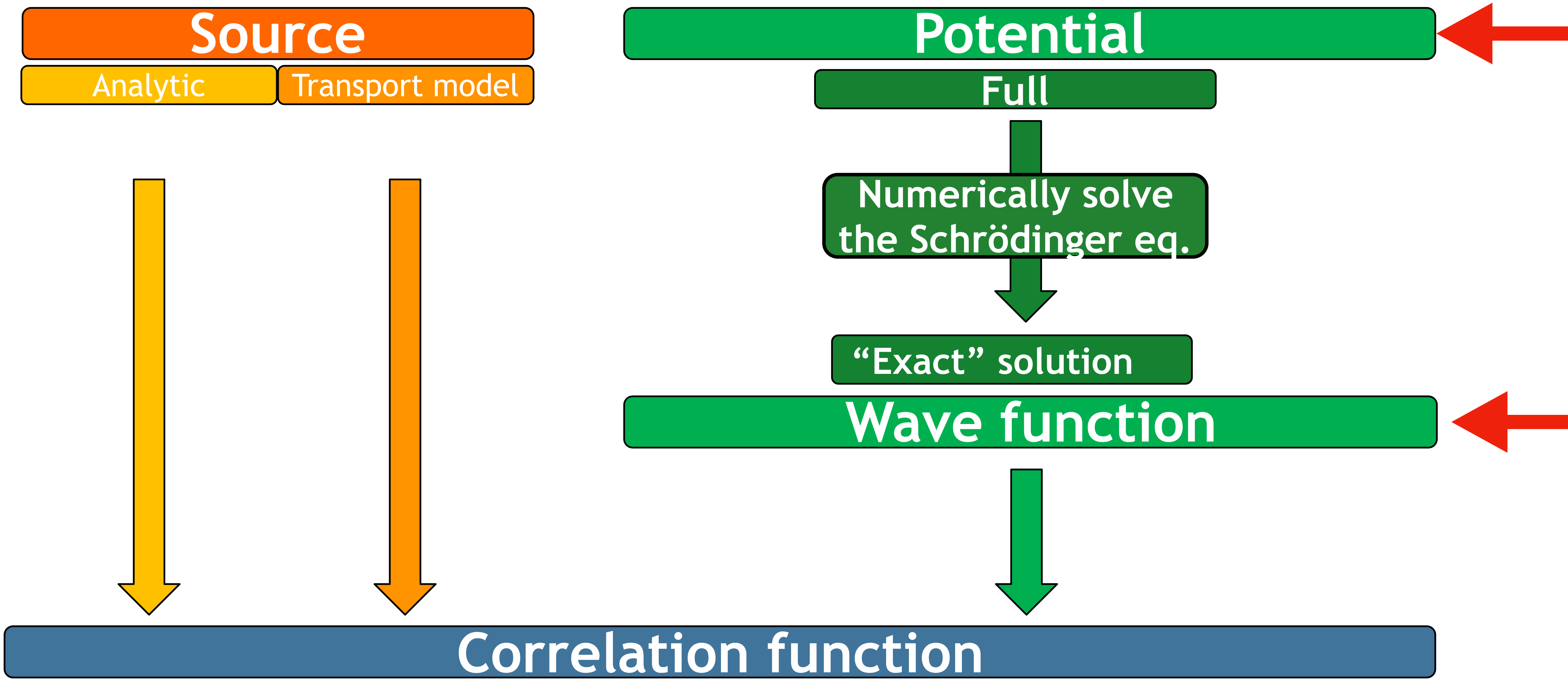
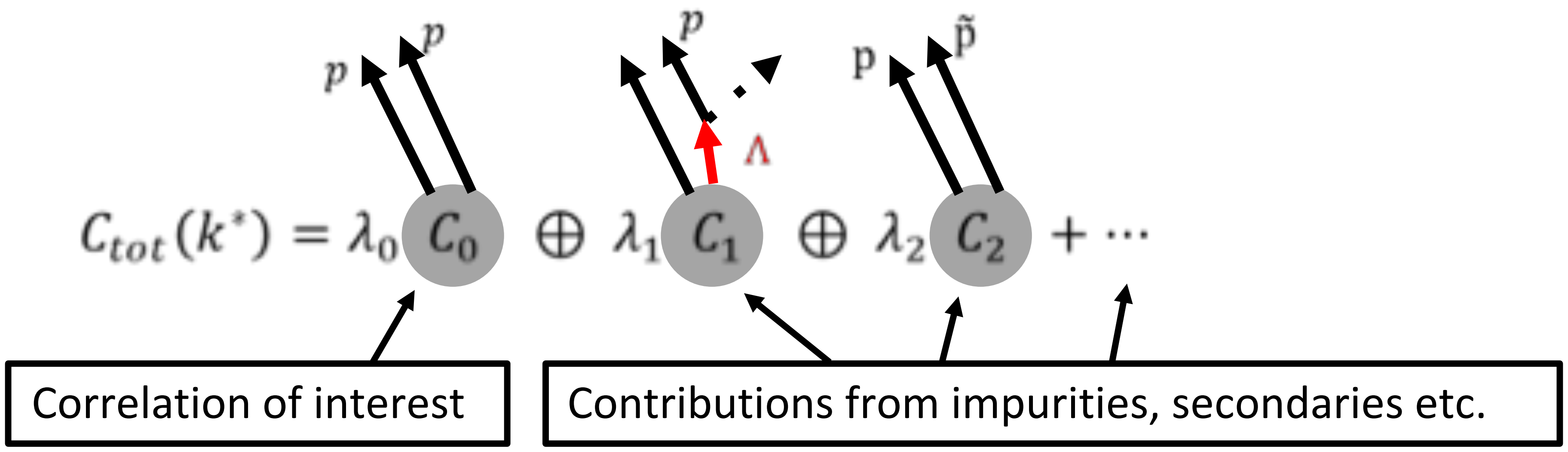
(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)



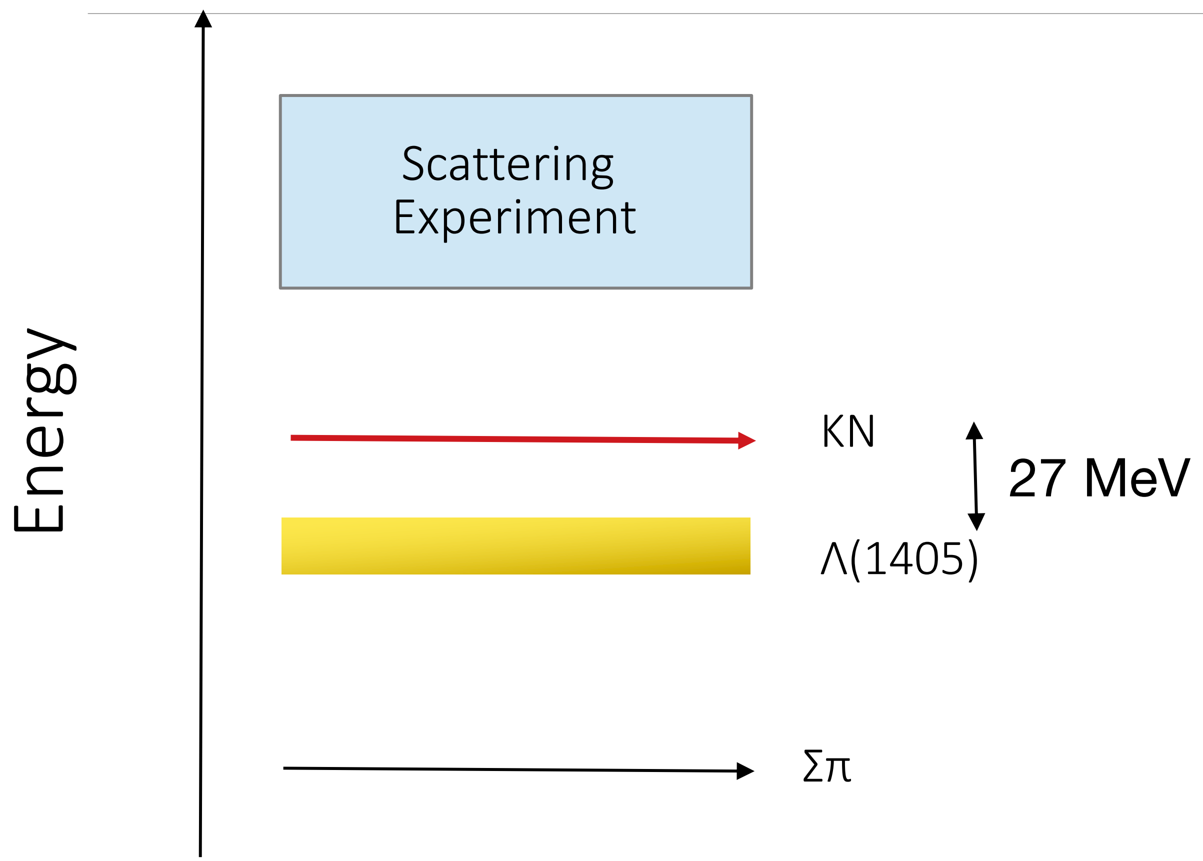
$$C(k) = \int S(\vec{r},k)|\psi(\vec{r},k)|^2\, d\vec{r} \xrightarrow{k\to\infty} 1$$

Decomposition of the Correlation Function



- Purities, fake fraction and material secondaries are determined either from simulations or template fits for single particles (Phys. Rev. C99 (2019) no.2, 024001)
- The contribution of weak decays is obtained from Montecarlo
- Resolution effects applied to the fit function

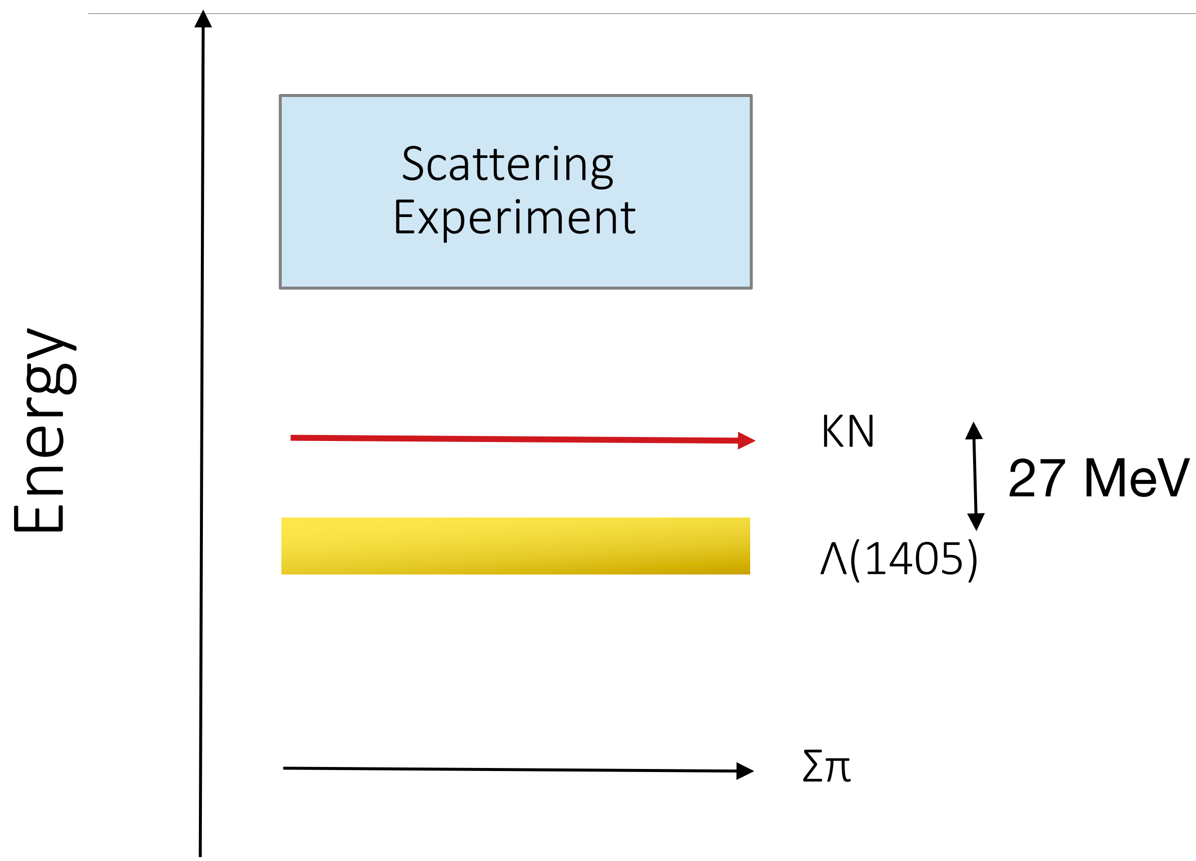
K^-p Interaction

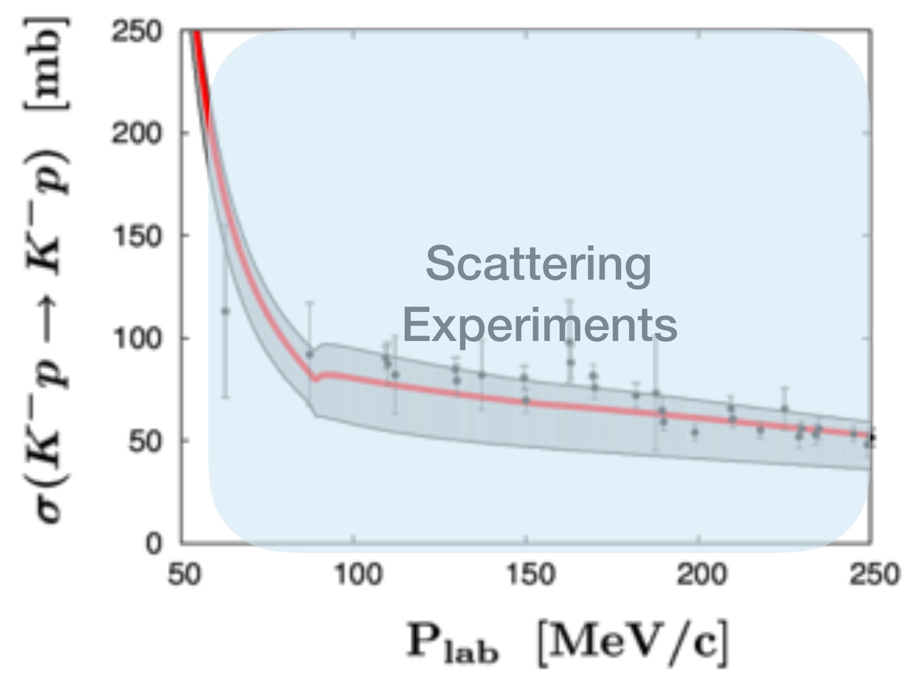


$\bar{K}N - \pi\Sigma$ form a molecular state : $\Lambda(1405)$

K^-p scattering data and kaonic hydrogen data are employed to constrain the amplitude also below the KN threshold

K-p Interaction





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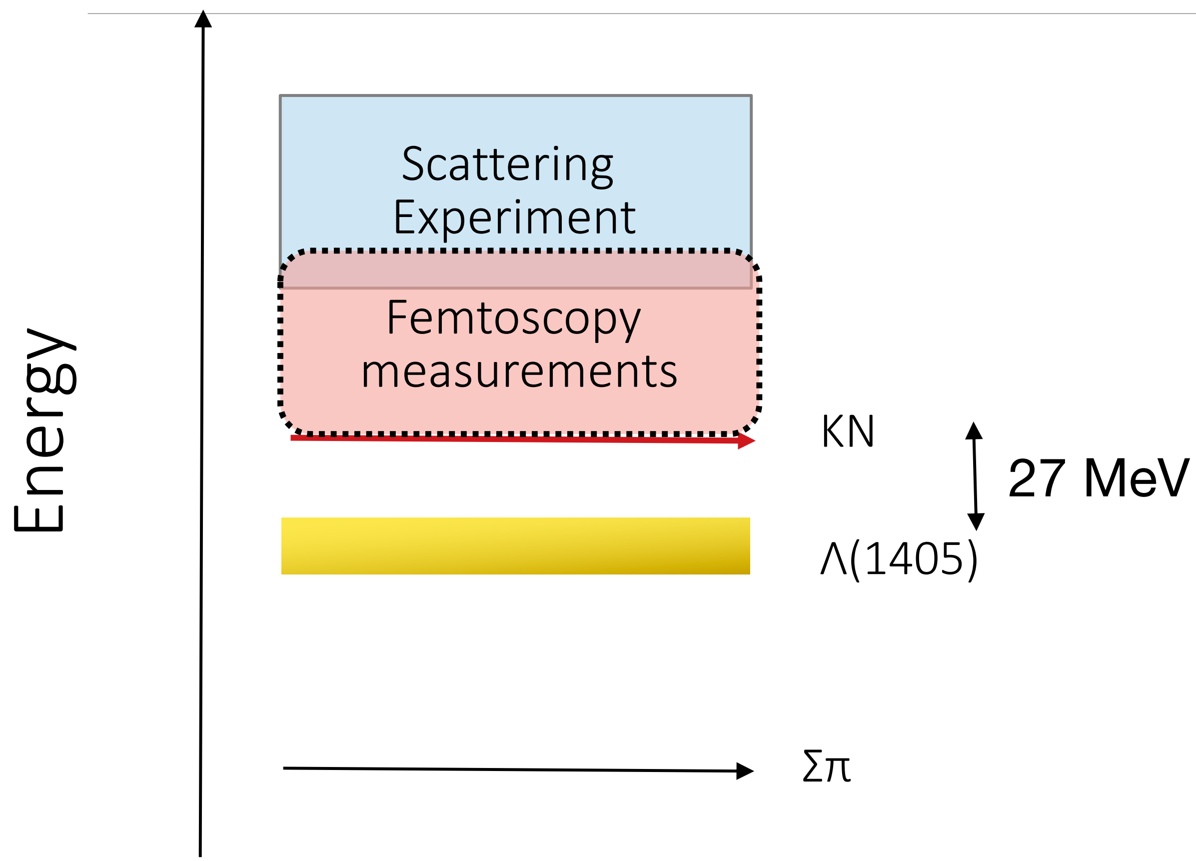

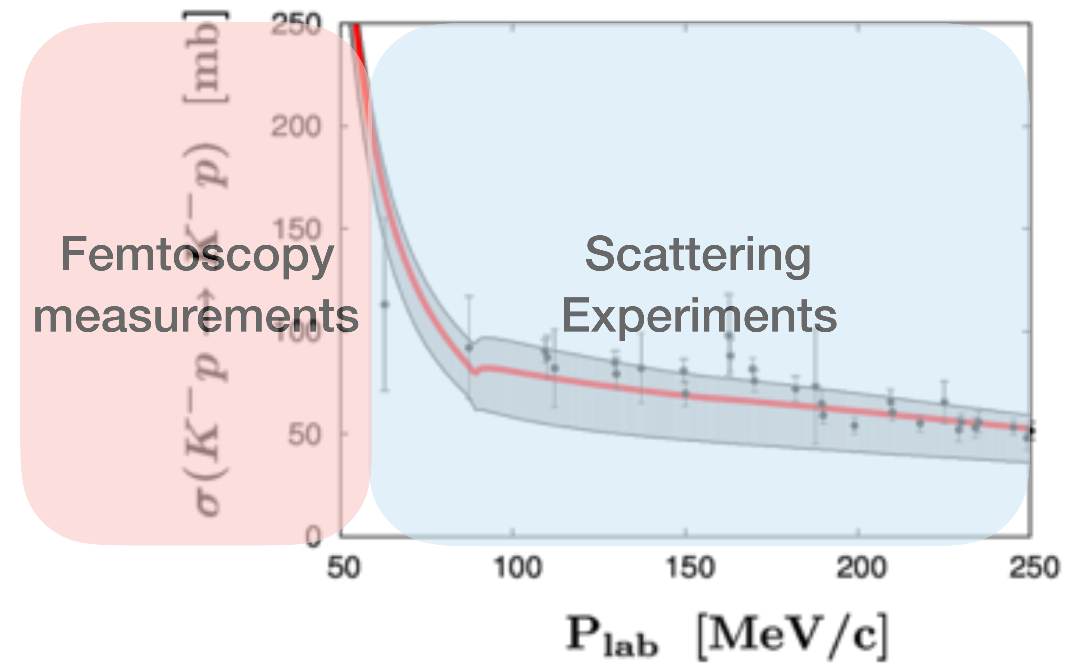

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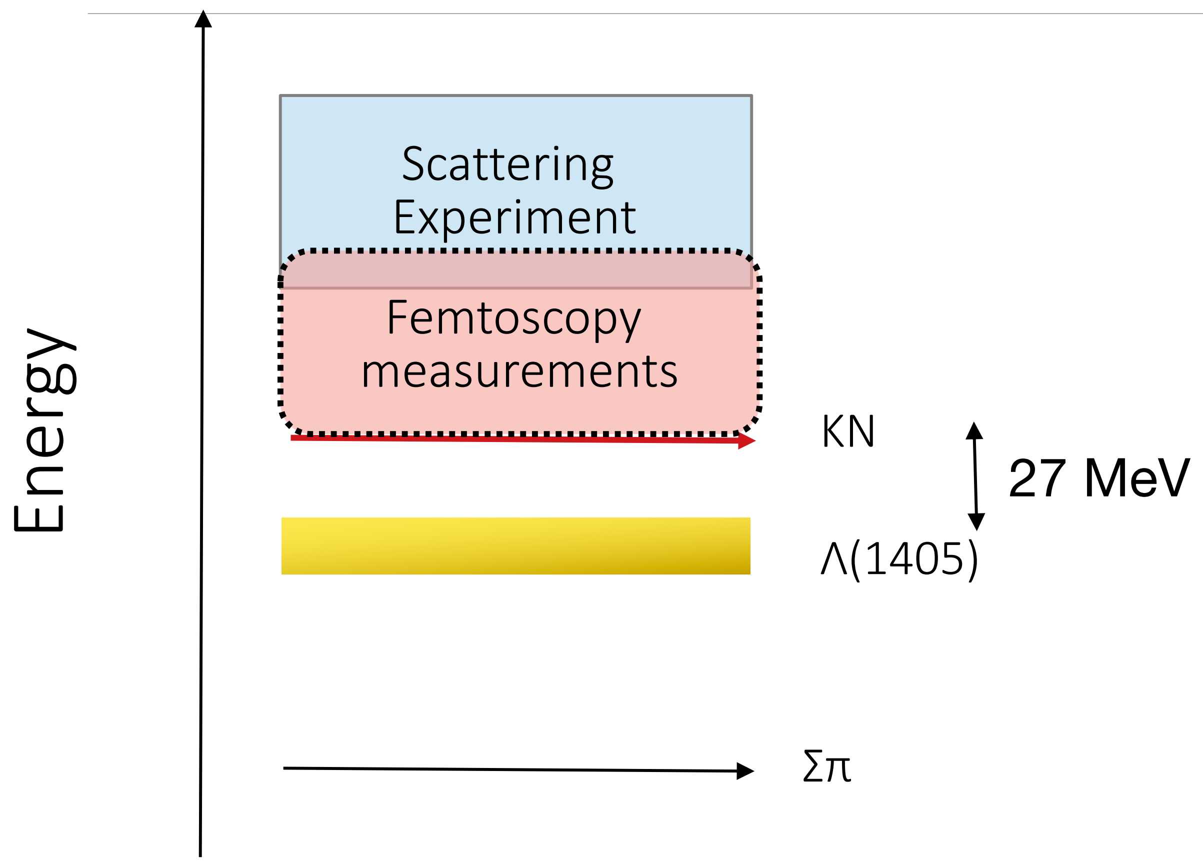

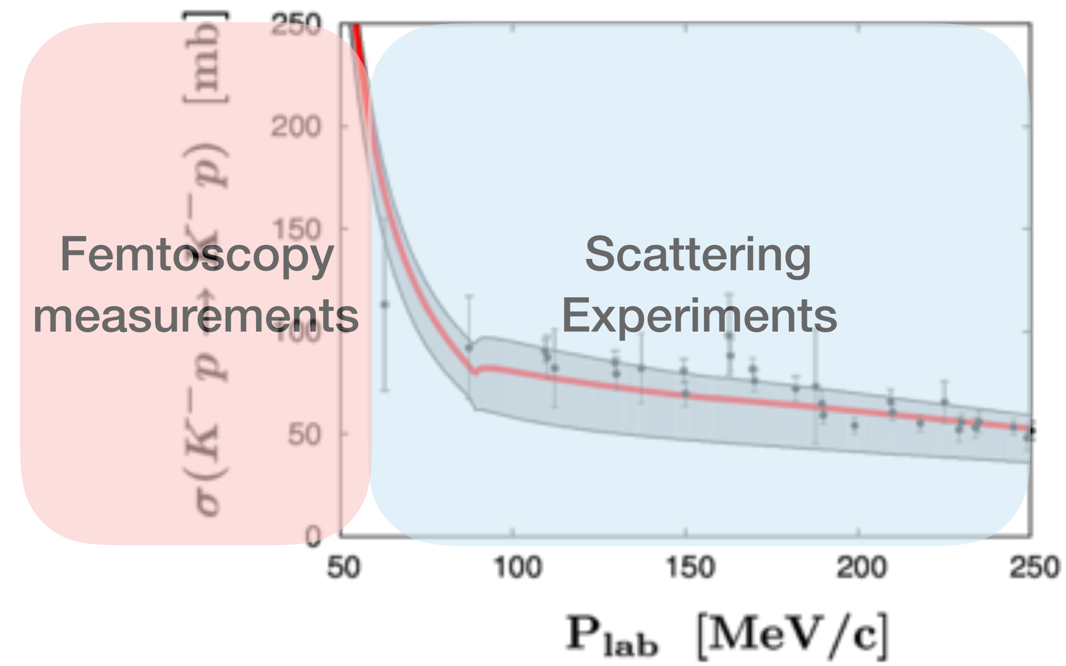

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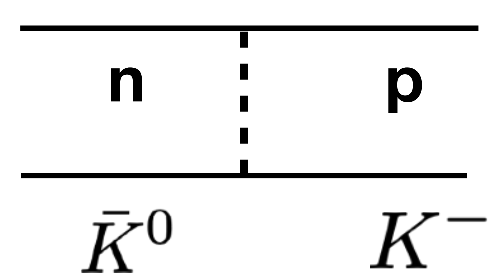
Coupled Channel Effects

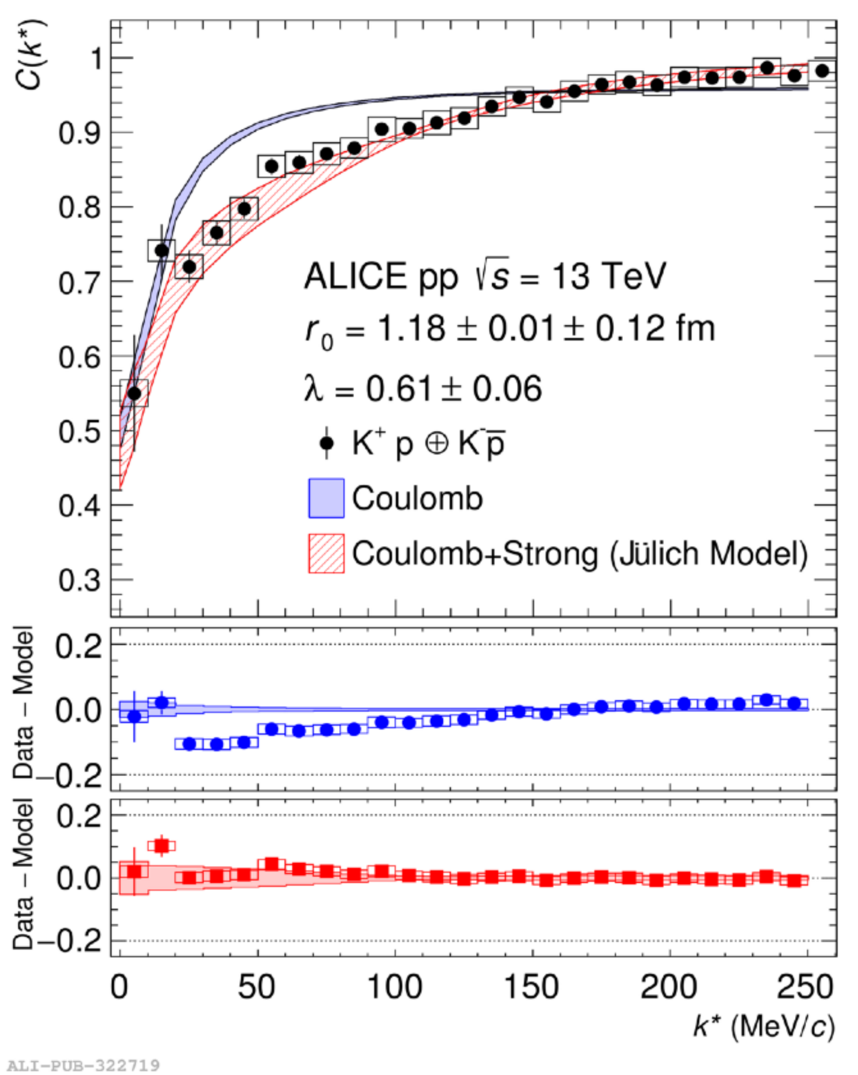


$$M(K^-p) + 5\,\mathrm{MeV} = M(n\bar{K}^0)$$

Results for pp 13 TeV MB

R. Lea (ALICE) WPCF19 slides

ALICE Collaboration, arXiv:1905.13470[nucl-ex]



Radius obtained from inclusive pp correlation
K^+p correlation used as a benchmark to study K^-p

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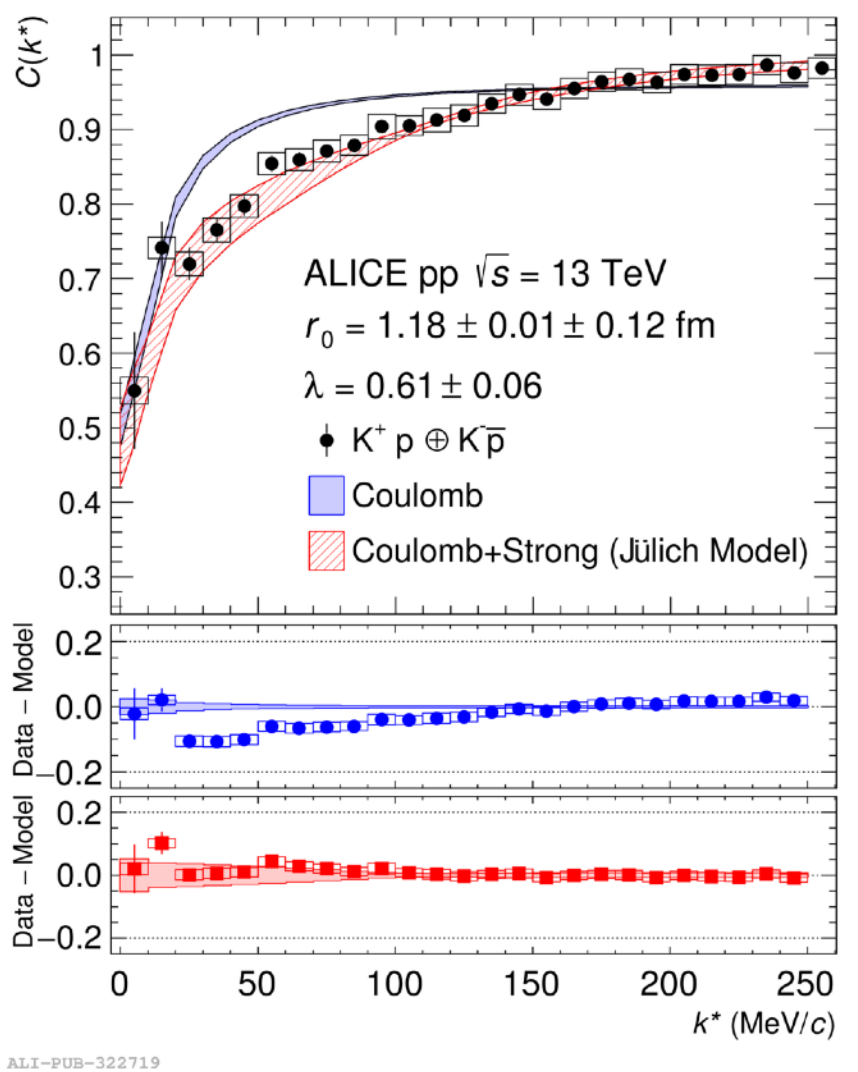

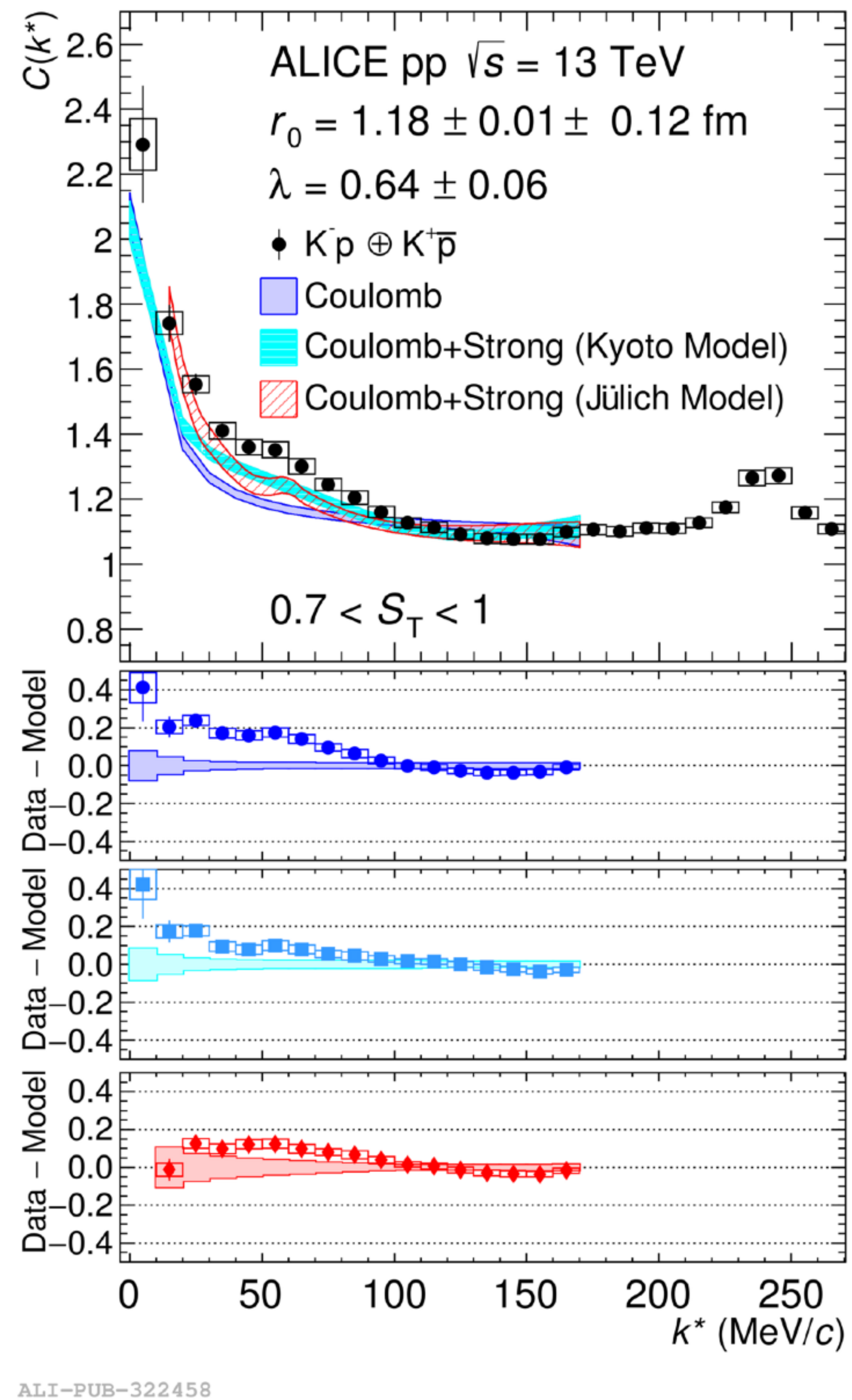

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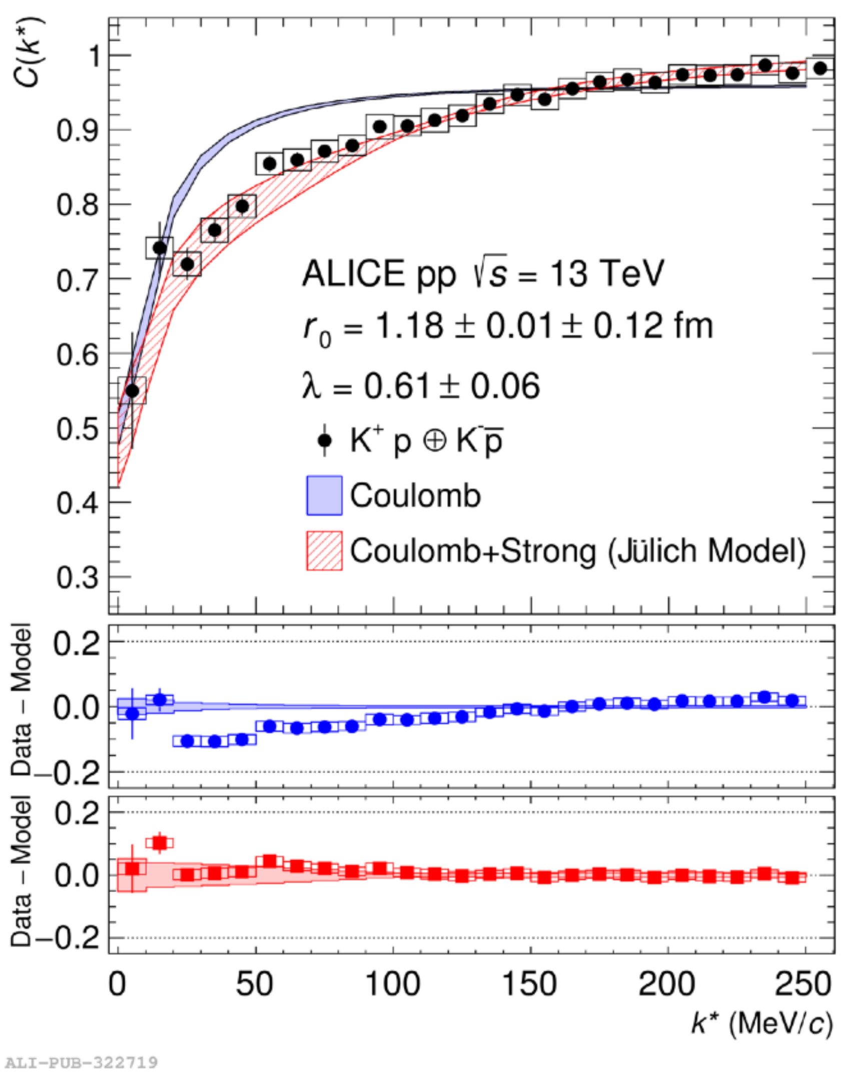
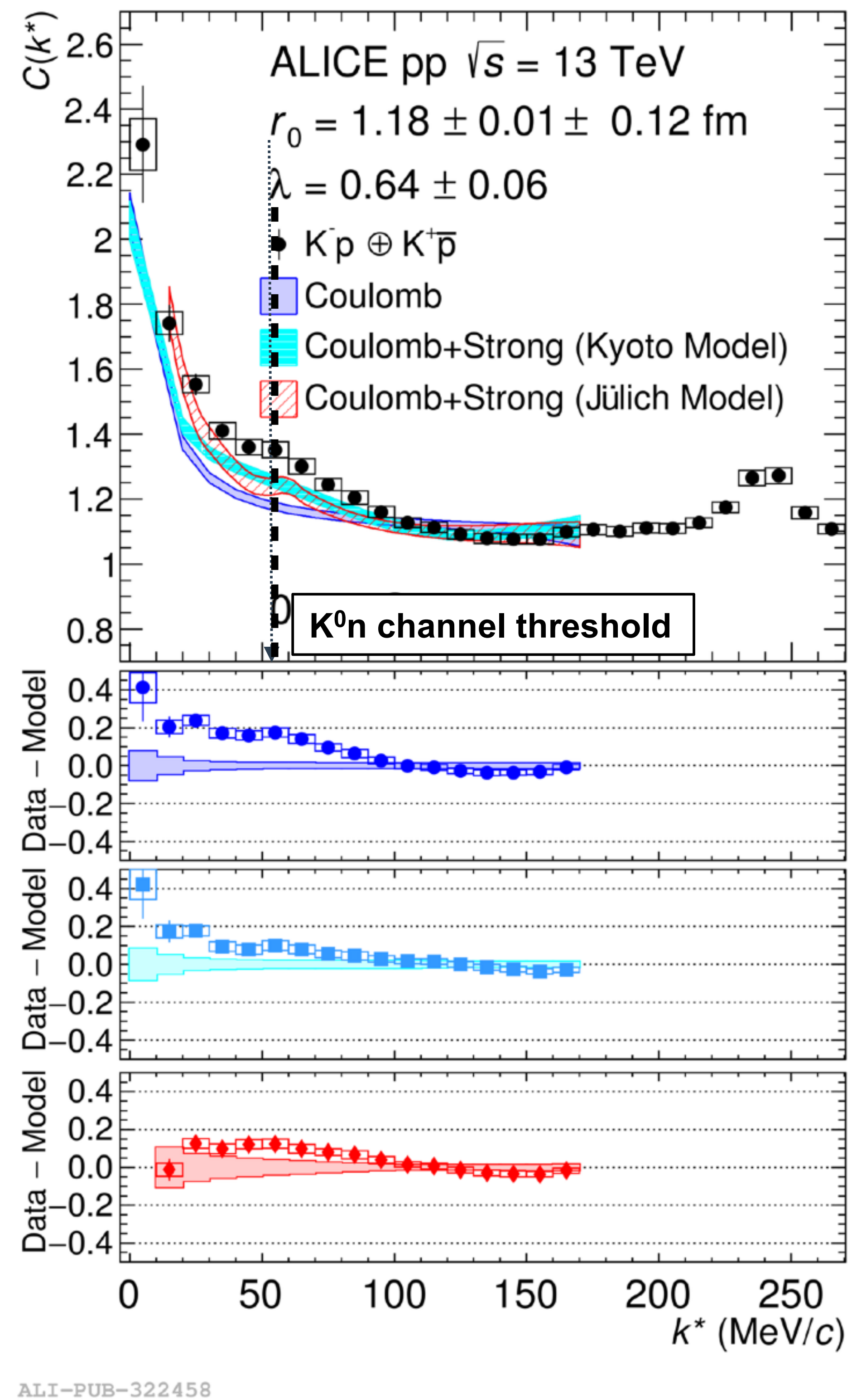




Radius obtained from inclusive pp correlation

K^+p correlation used as a benchmark to study K^-p

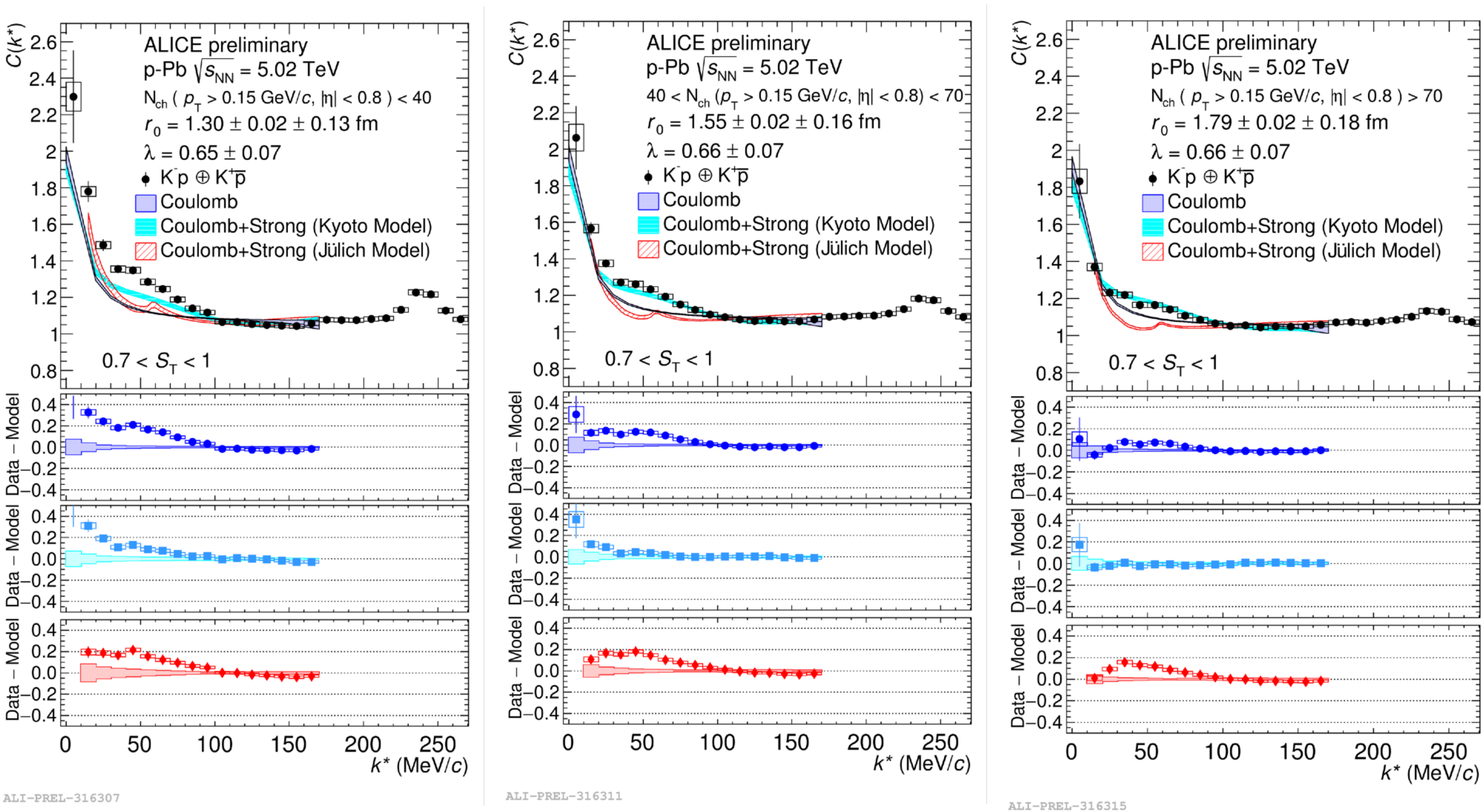
Observation of a bump close to the K^0n threshold→(58 MeV/*c* in the CM frame)

First experimental evidence of the opening of the K^0n isospin breaking channel

K-p Correlations for pPb 5 TeV

R. Lea (ALICE) WPCF19 slides

m<40 | 40<m<70 | m>70

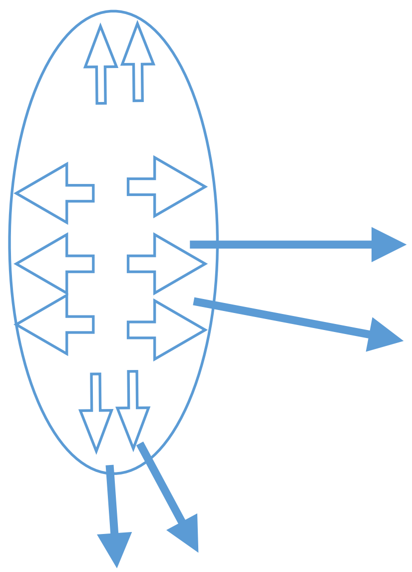


Interaction changes as a function of the particle distance

Model can now be tested/constrained in a more differential way

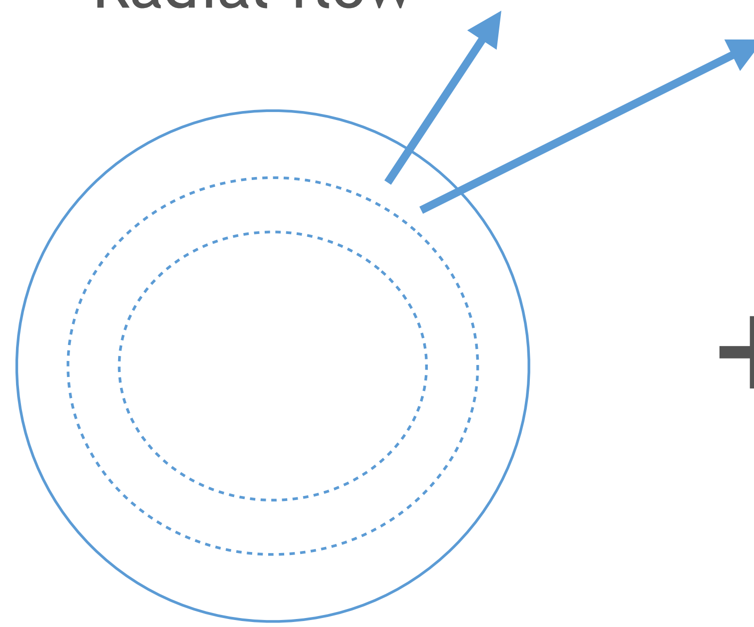
Small sources II: Collective Effects and Strong Resonances

Elliptic flow



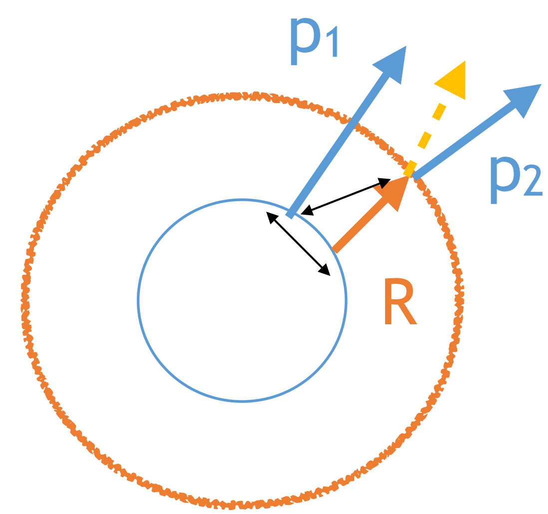
anisotropic pressure gradients within the source

Radial flow

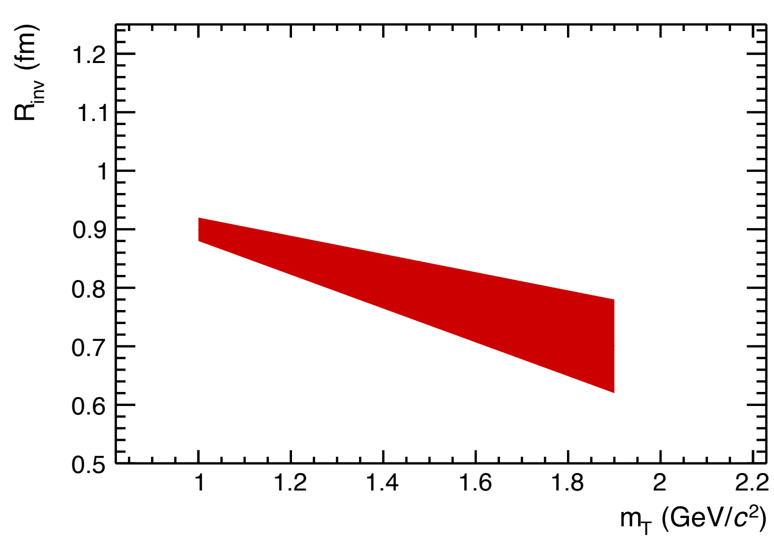


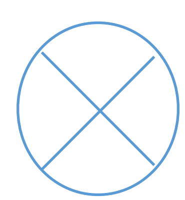
Expanding source with constant velocity
different effect on different masses

Strong decays of broad resonances



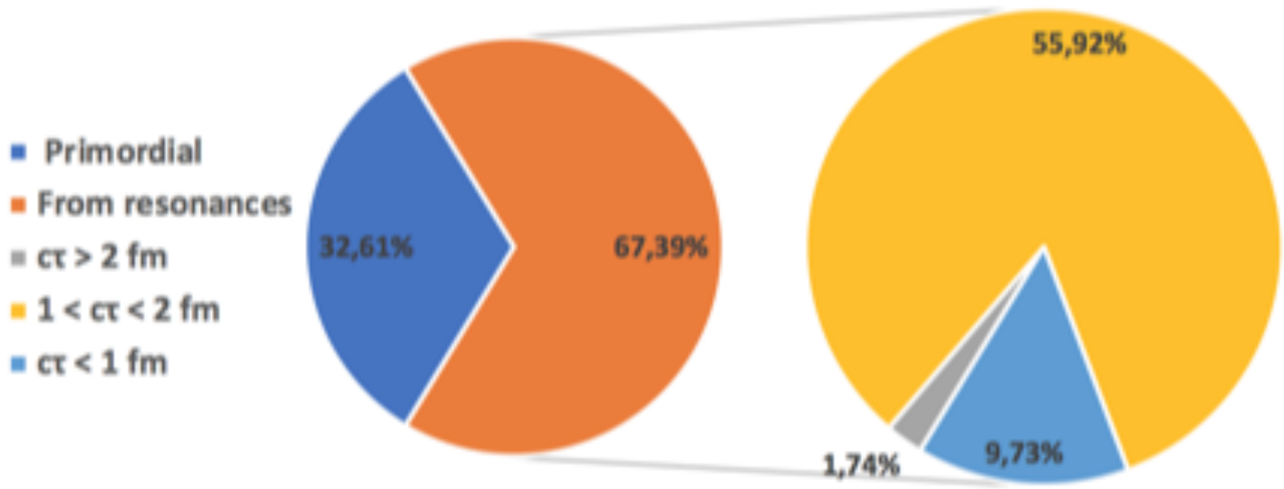
$p,\ \Lambda,\ \Xi,\ K$ are 'fed' by resonances with different masses and lifetimes





Strong decays of Specific resonances

pp Correlations for pp 13TeV HM



Gaussian 'Core' Common to all pairs
+ Exponential including the resonance decay width

Resonance yields evaluated with Statistical Hadronization Model in the canonical approach (Priv. Comm. With Prof. F. Becattini, see for details J.Phys. G38 (2011) 025002)

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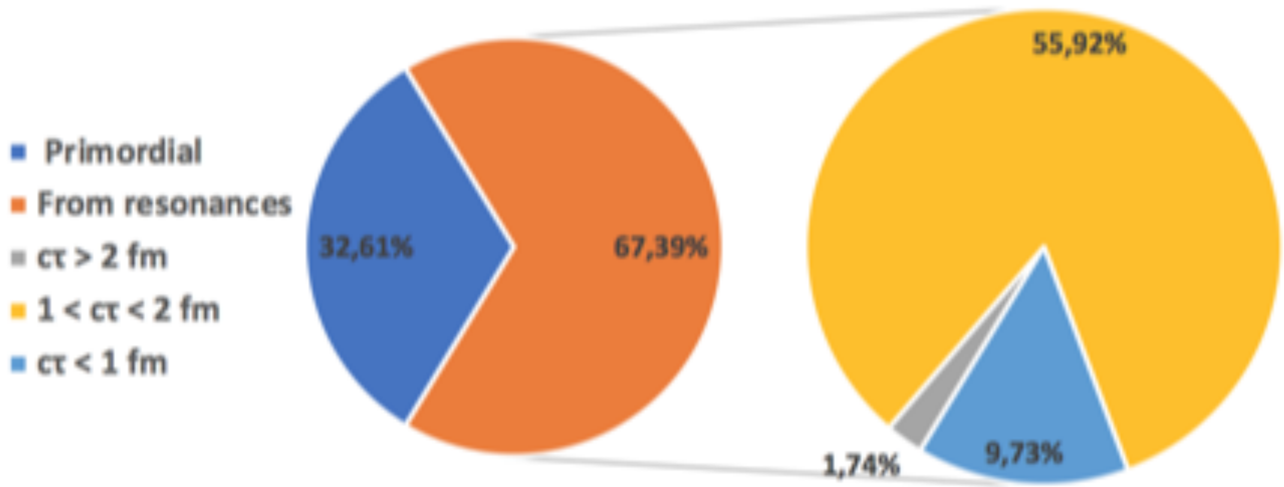

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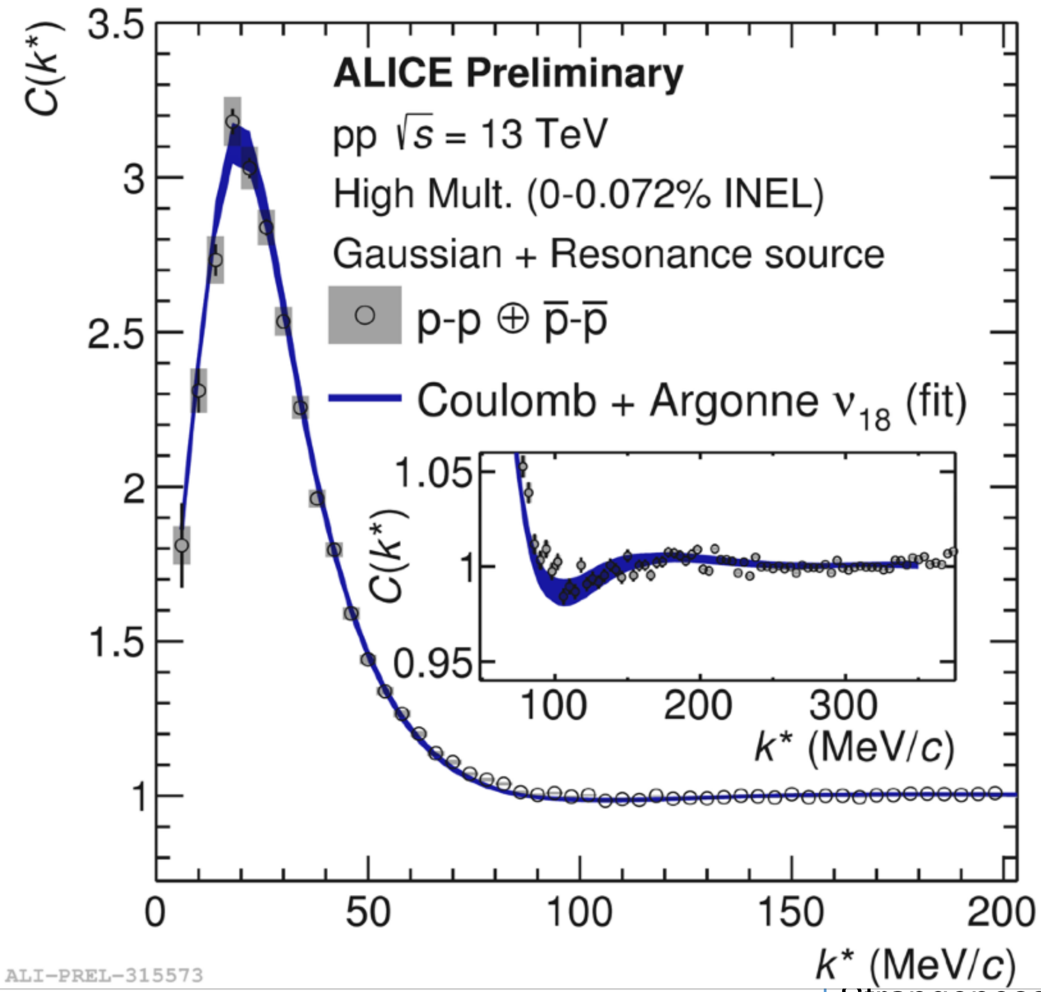
Fit with a 'core' Gaussian + Resonances

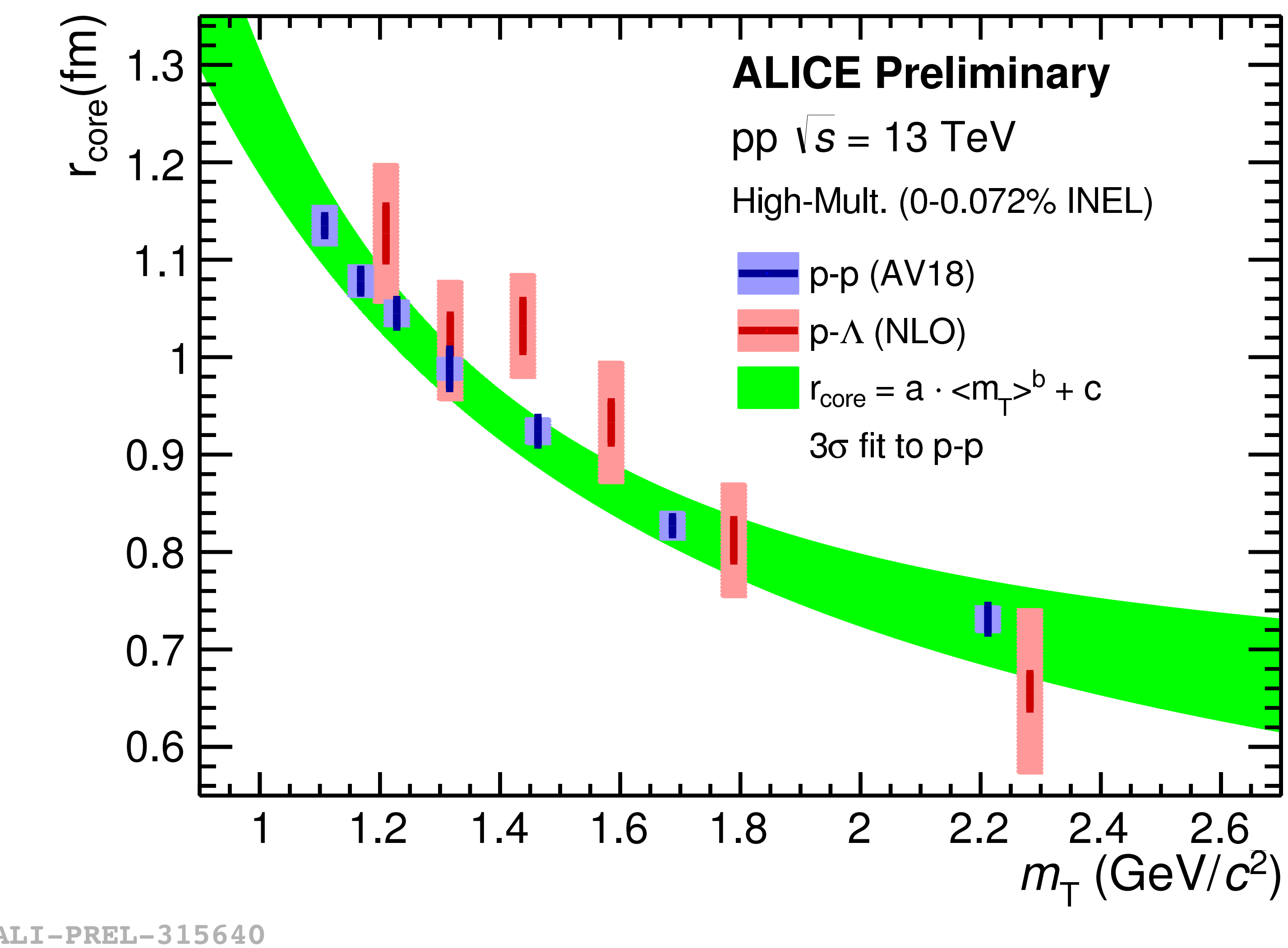


$$r_{Core} = 0.96\,\text{fm}$$
$$r_{Eff} = 1.28\,\text{fm}$$

m_T Dependence of the ‘Core’ Gaussian Radius

D. Mihaylov (ALICE) WPCF19 slides

Comparison of the Core Gaussian radius obtained for the pp and pΛ pairs including the strong decays (for p mainly Δ and for Λ mainly N*)



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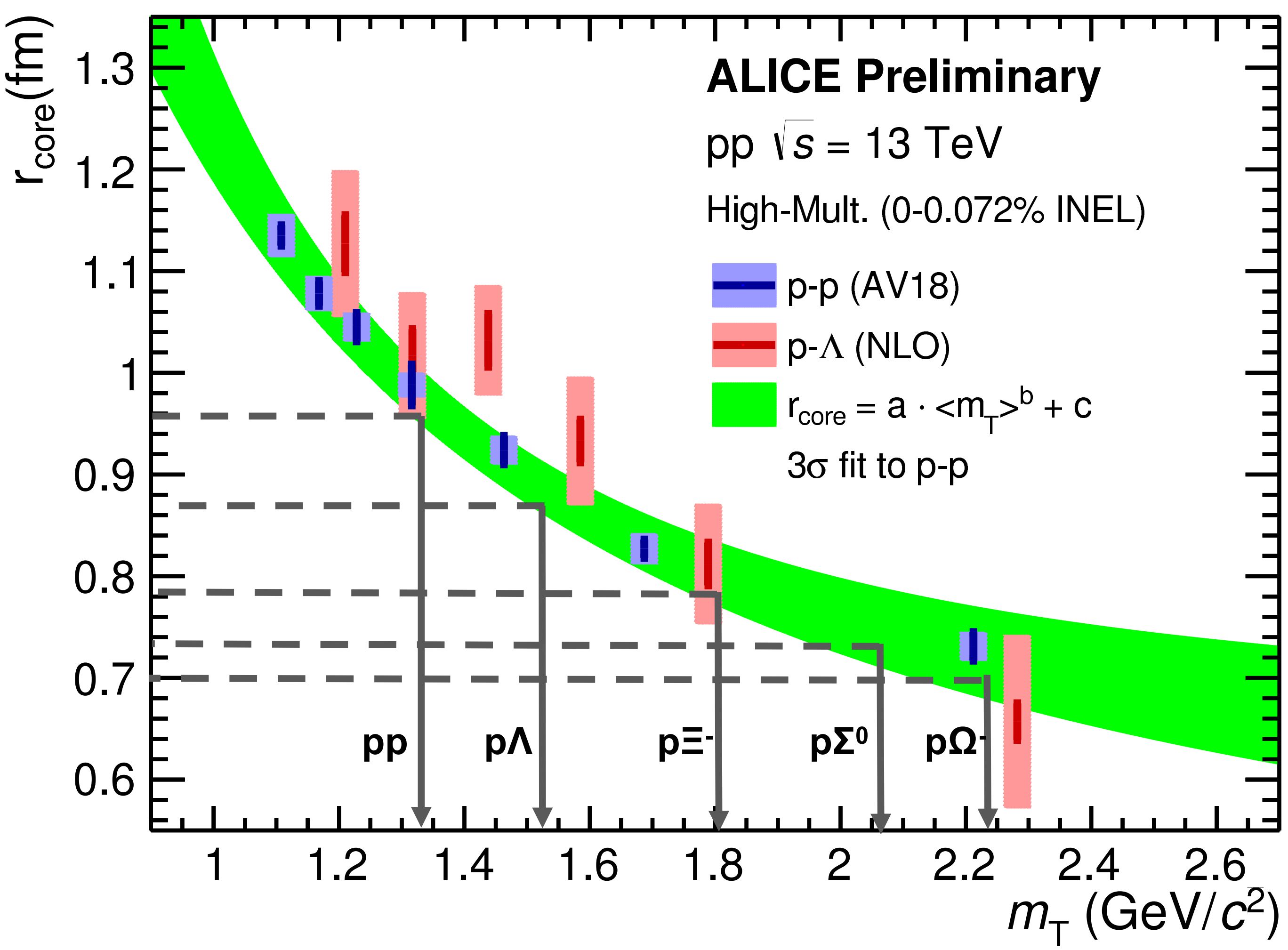

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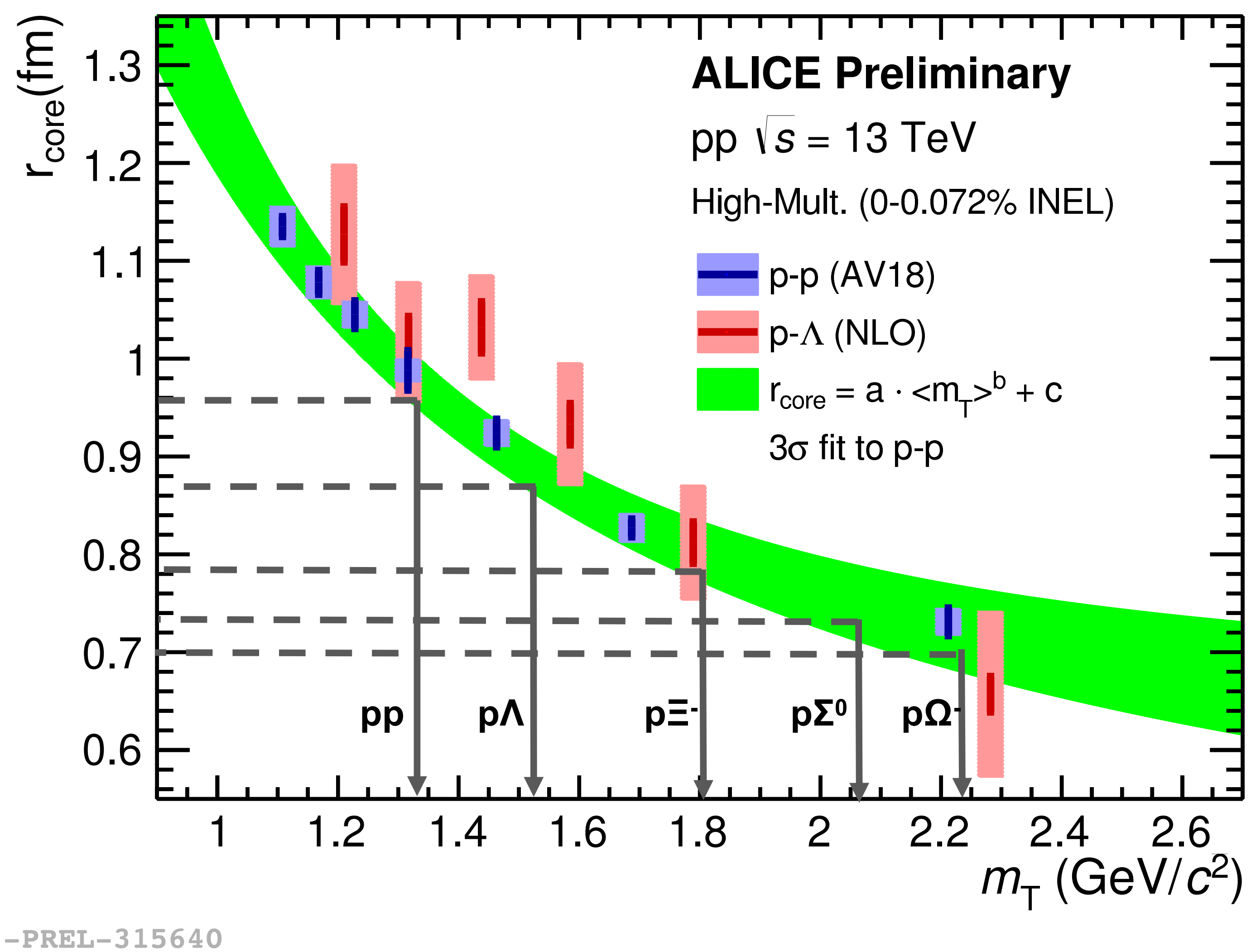

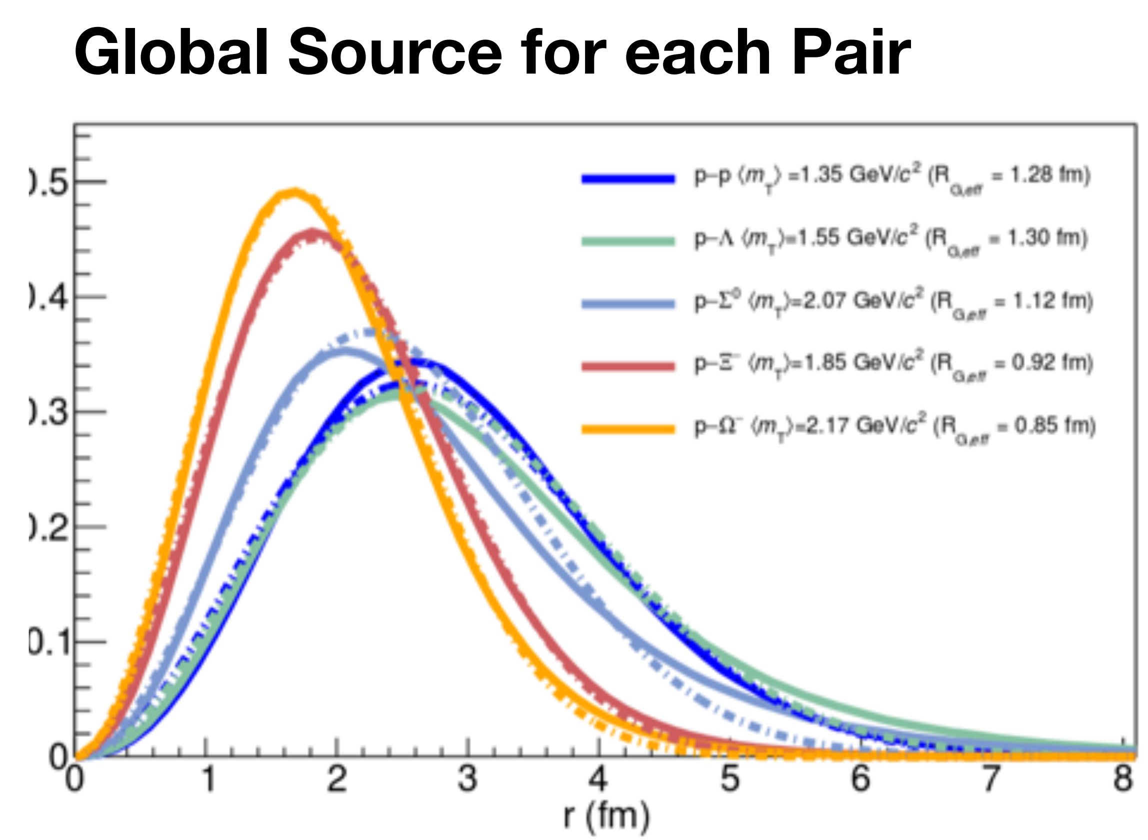

pΛ Correlations for pp 13TeV HM

LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
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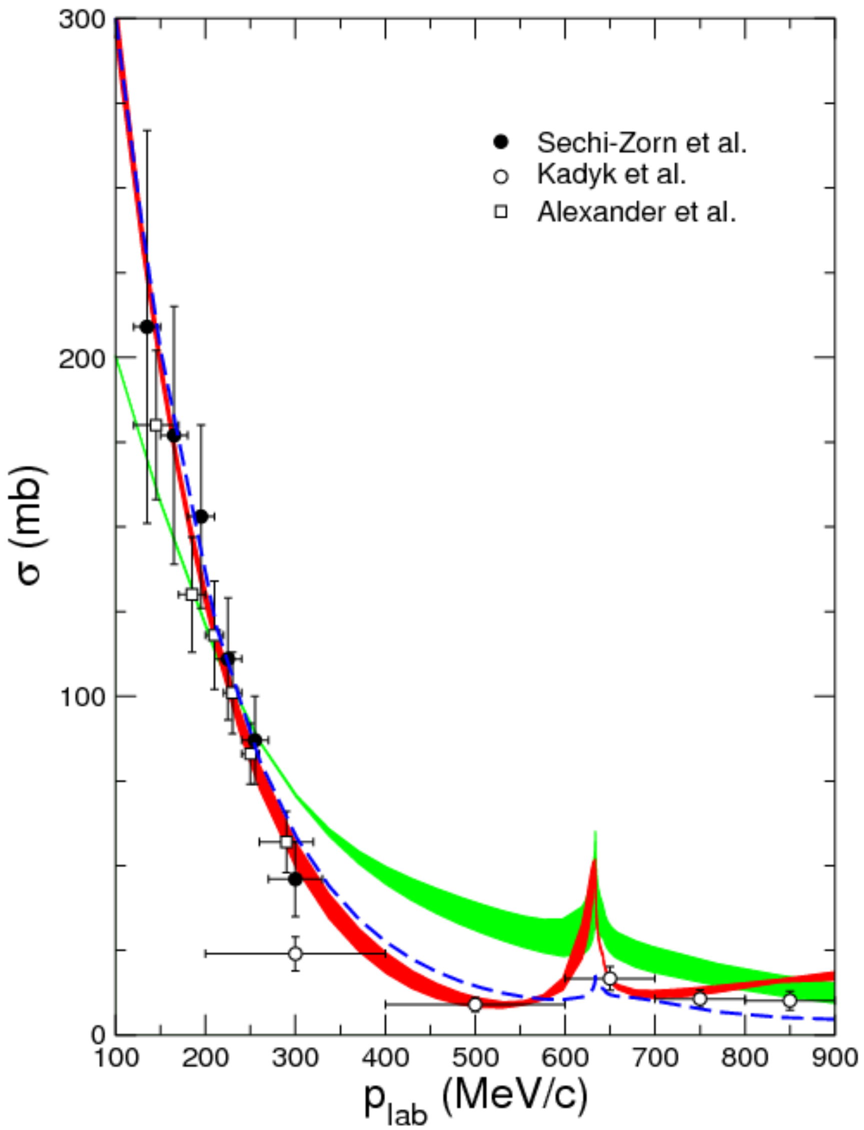
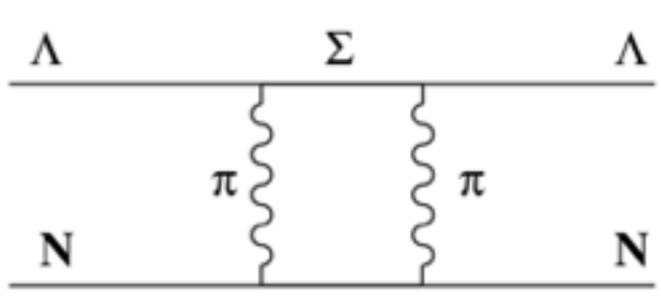


Scarse scattering data and no real experimental evidence of the Cusp due to the Coupling $\Sigma N <-> \Lambda N$



This coupling is responsible for the appearance of a repulsive short range component in the Λp interaction

pΛ Correlations for pp 13TeV HM

D. Mihaylov (ALICE) WPCF19 slides

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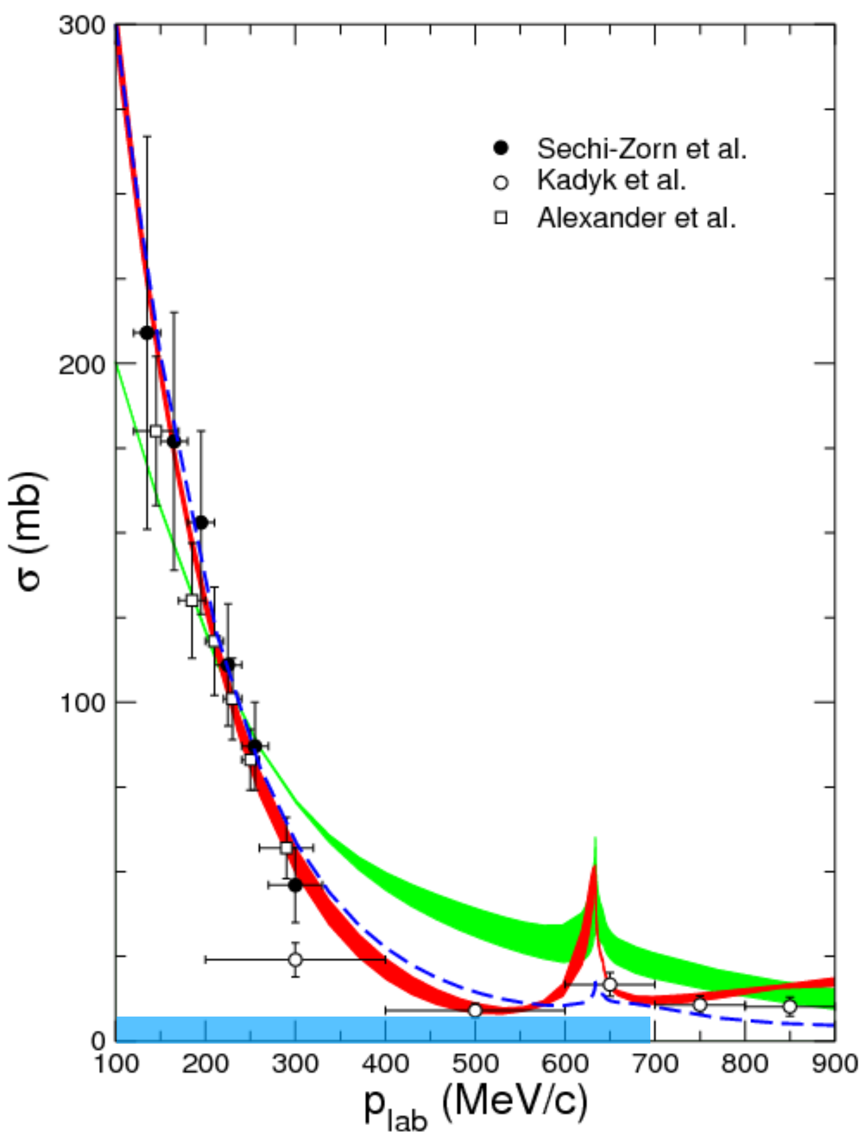
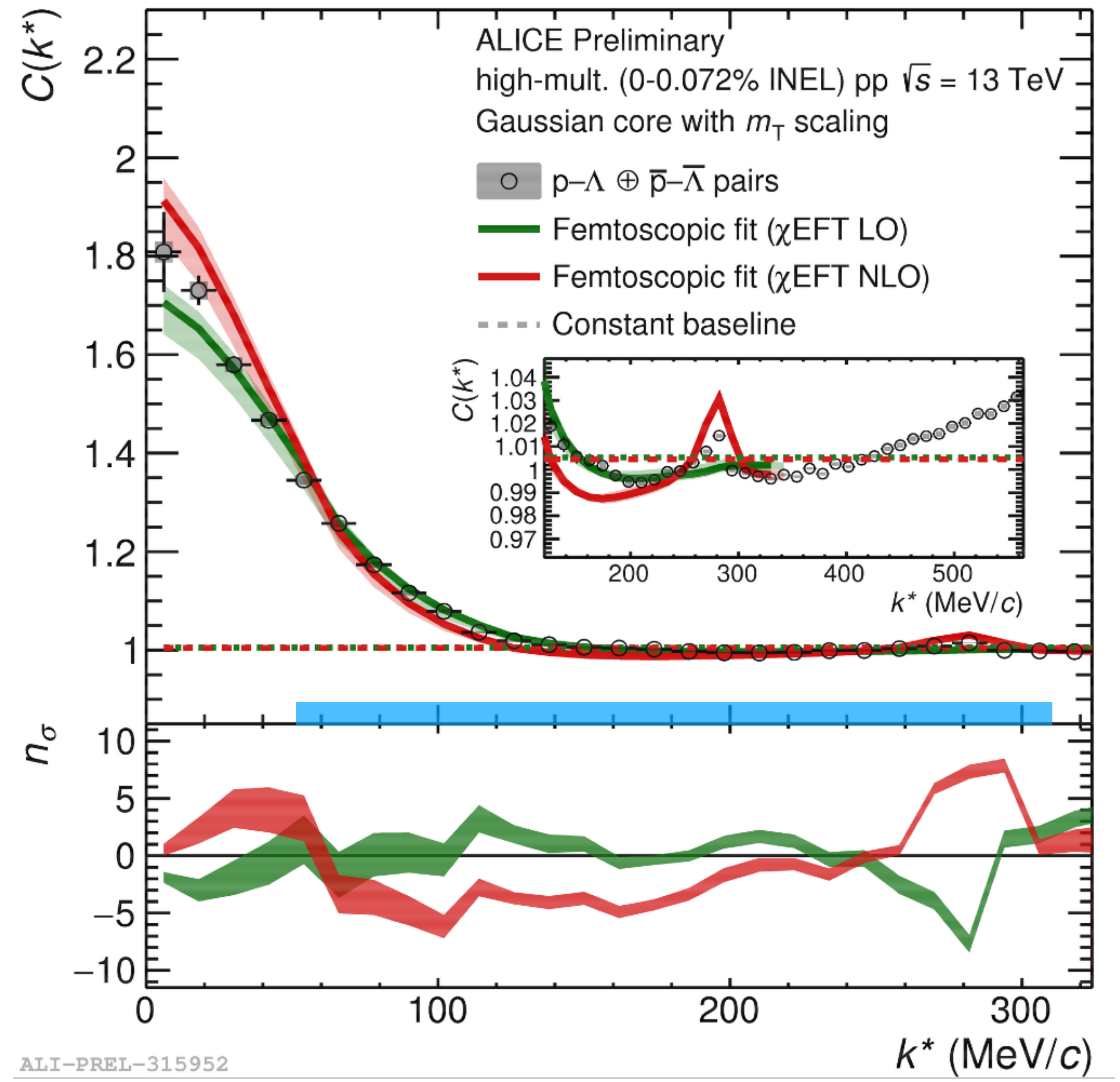
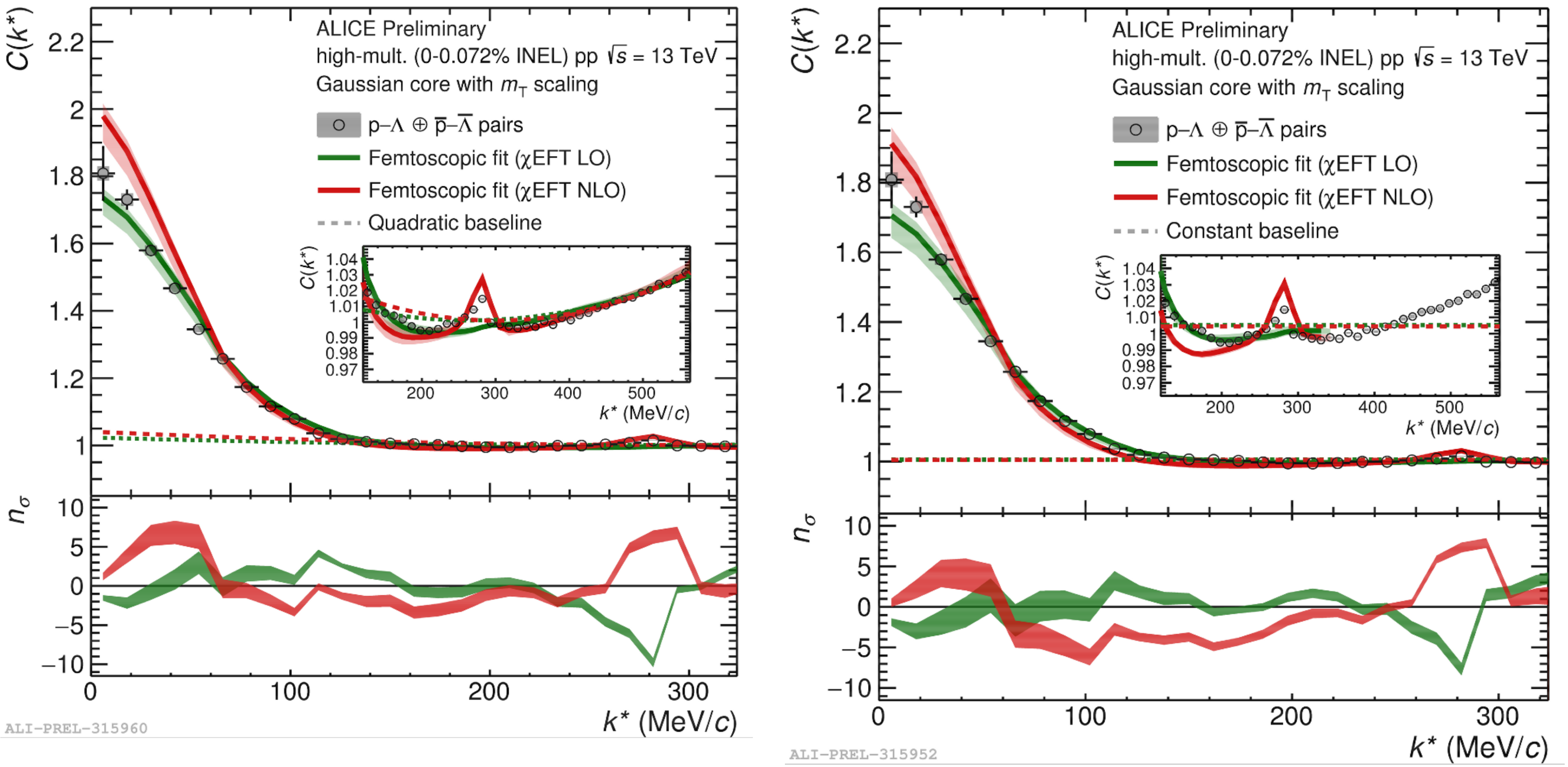




- **Extension of the kinematic range**
- **Much improved precision of the measurement**
- **Clear experimental evidence of the Cusp**

pΛ Correlations for pp 13TeV HM

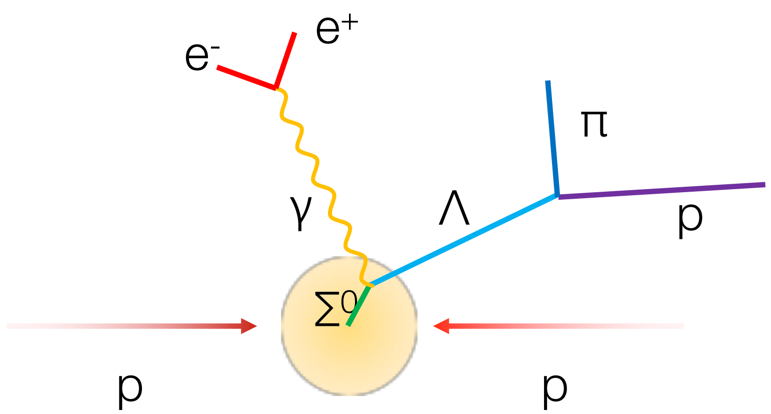
D. Mihaylov (ALICE) WPCF19 slides

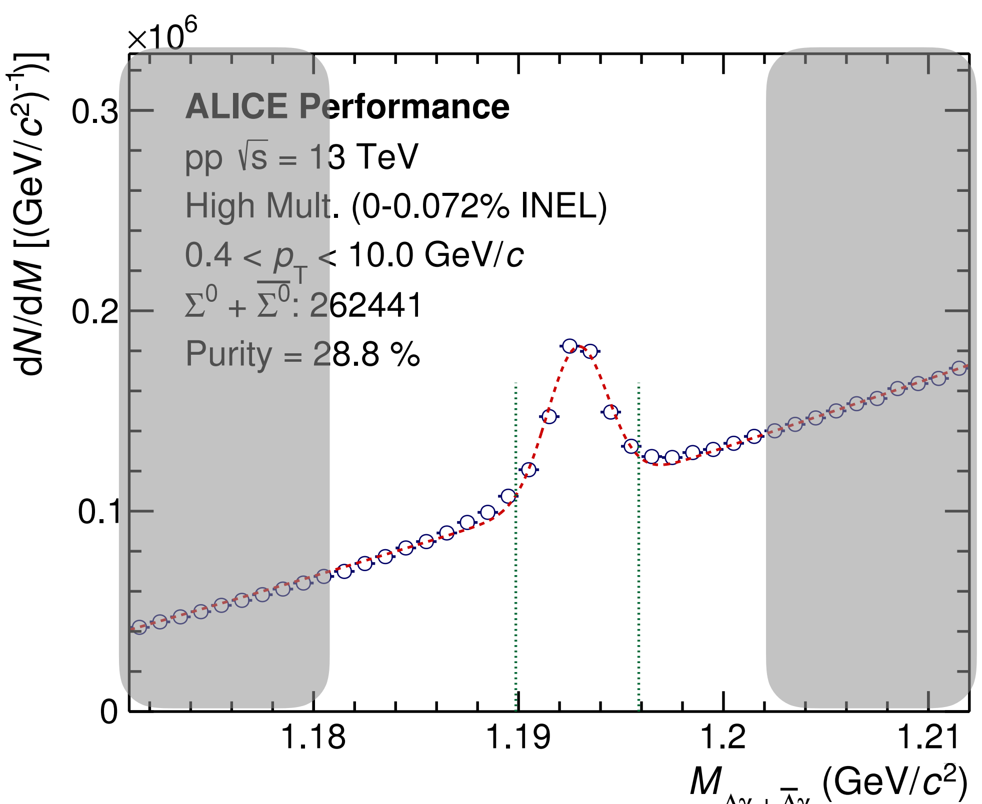


- **LO and NLO calculations of the interactions within xEFT fail to reproduce the data**

A. Mathis (ALICE) WPCF19 slides

$\Sigma^0 \to \Lambda\,\gamma$ (BR: almost 100 %)





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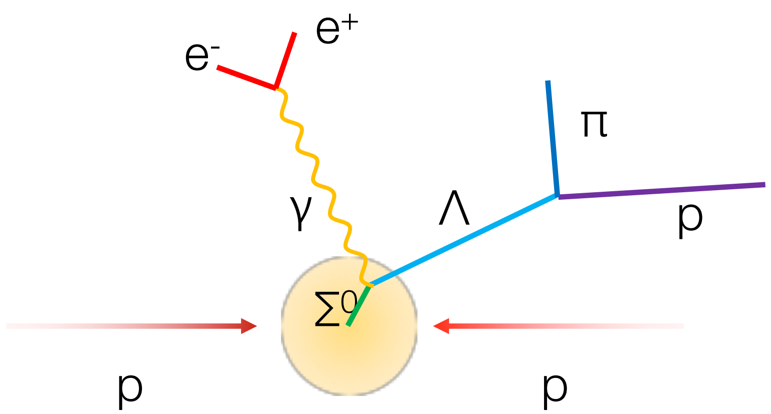
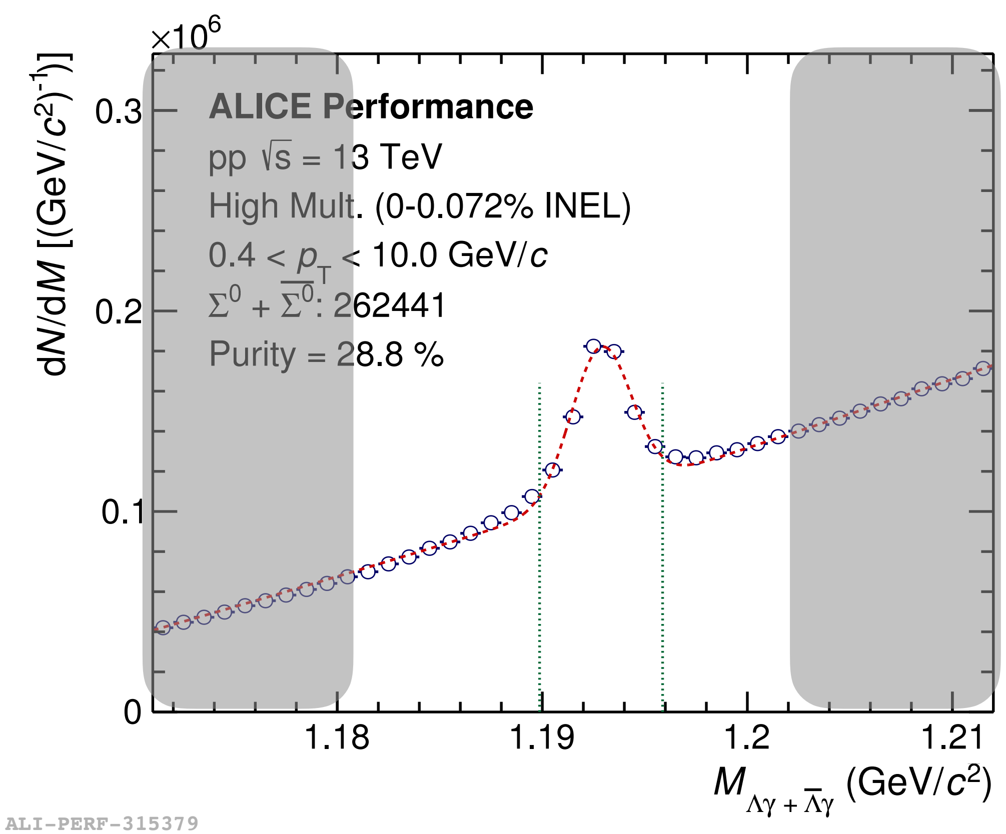
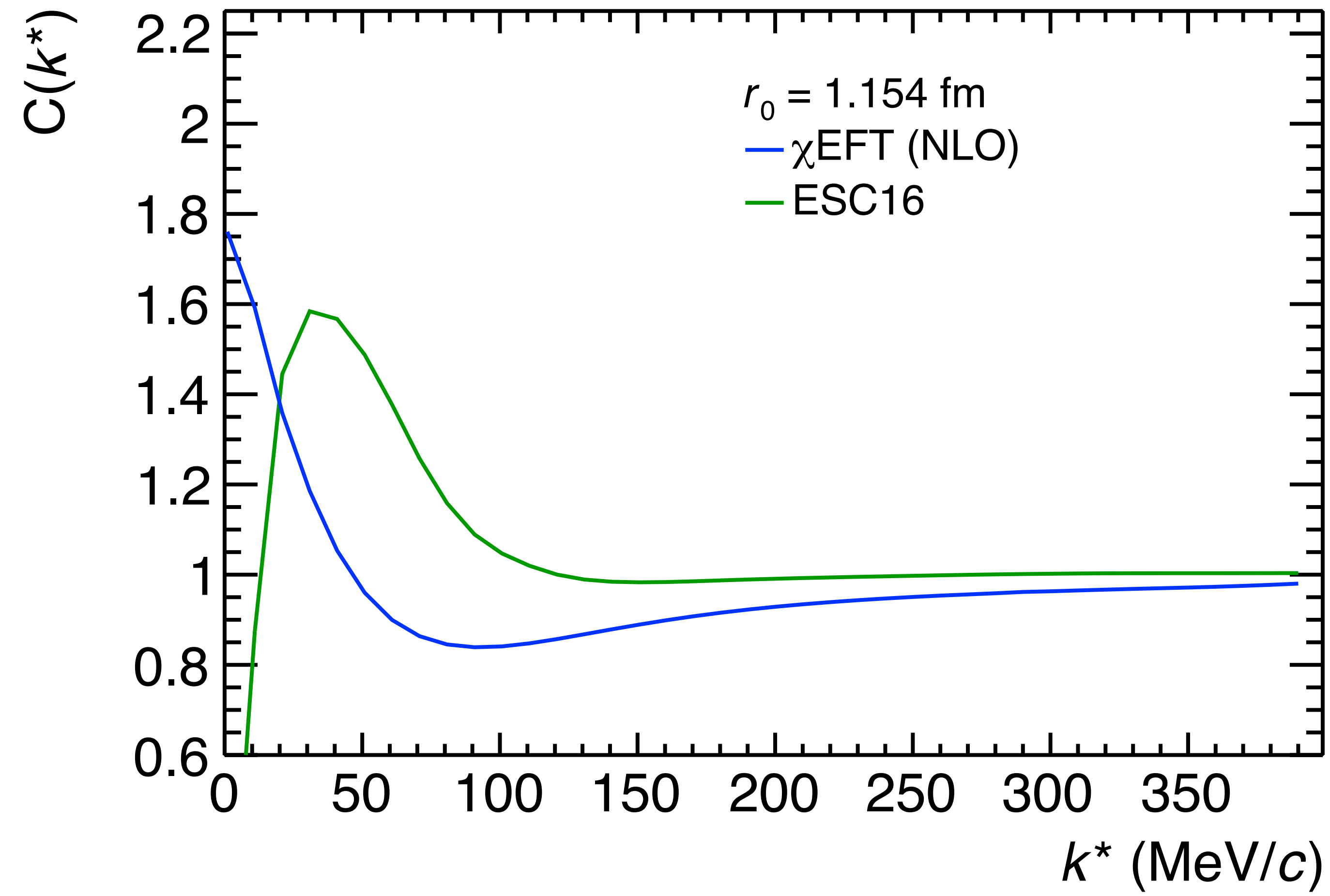
Σ^0 Selection and Theoretical Predictions

A. Mathis (ALICE) WPCF19 slides

$\Sigma^0 \rightarrow \Lambda\,\gamma$ (BR: almost 100 %)







χEFT at NLO J.Haidenbauer *et al.*, Nucl. Phys. A 915 (2013), 24.

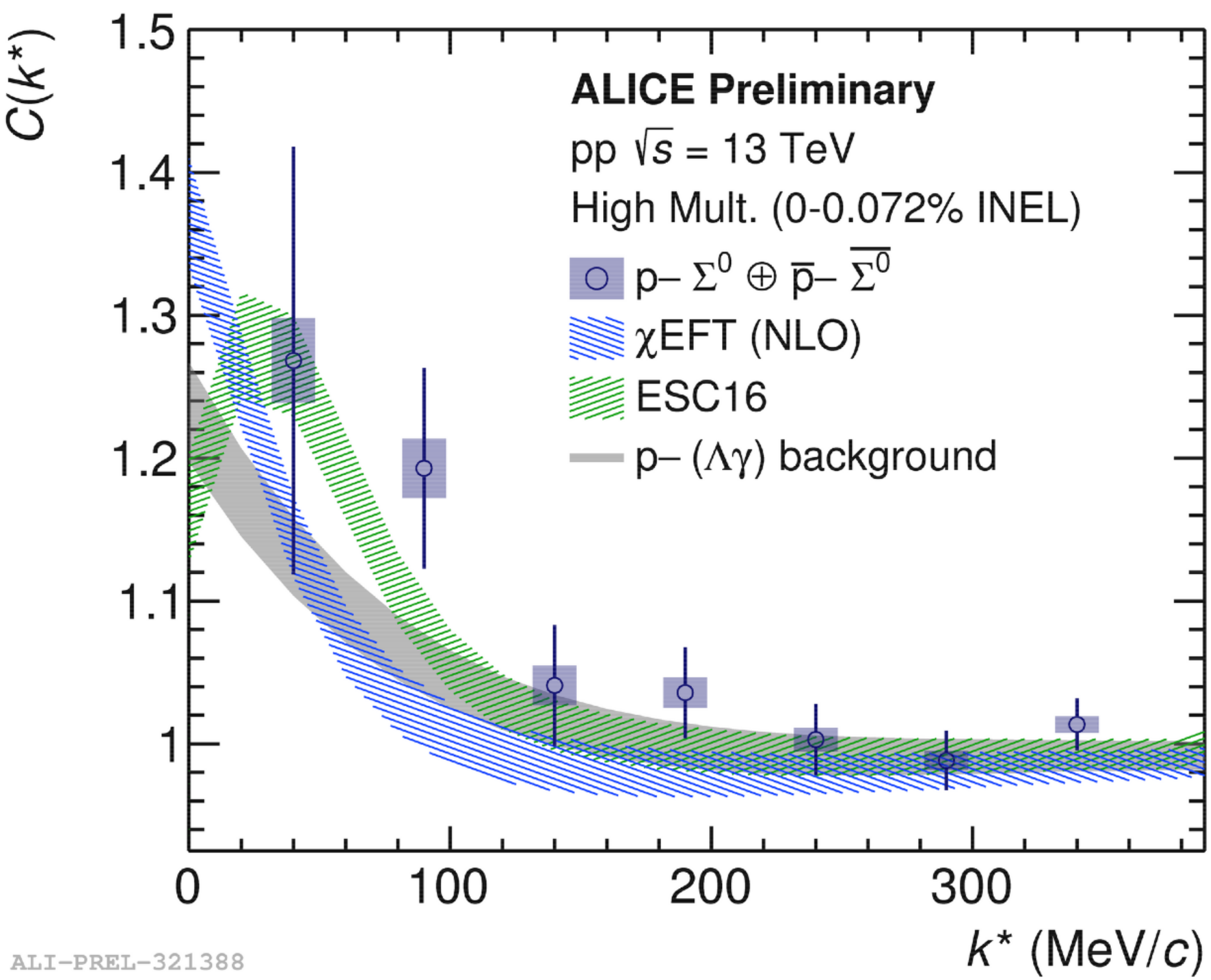
The p–Σ^0 wave function is used as an input to CATS

ESC16 M. M. Nagels, T. A. Rijken, and Y. Yamamoto, PRC 99 (2019) 044003.

The p–Σ^0 wave function is used as an input to CATS

$p\Sigma^0$ Correlations for pp 13TeV HM

A. Mathis (ALICE) WPCF19 slides

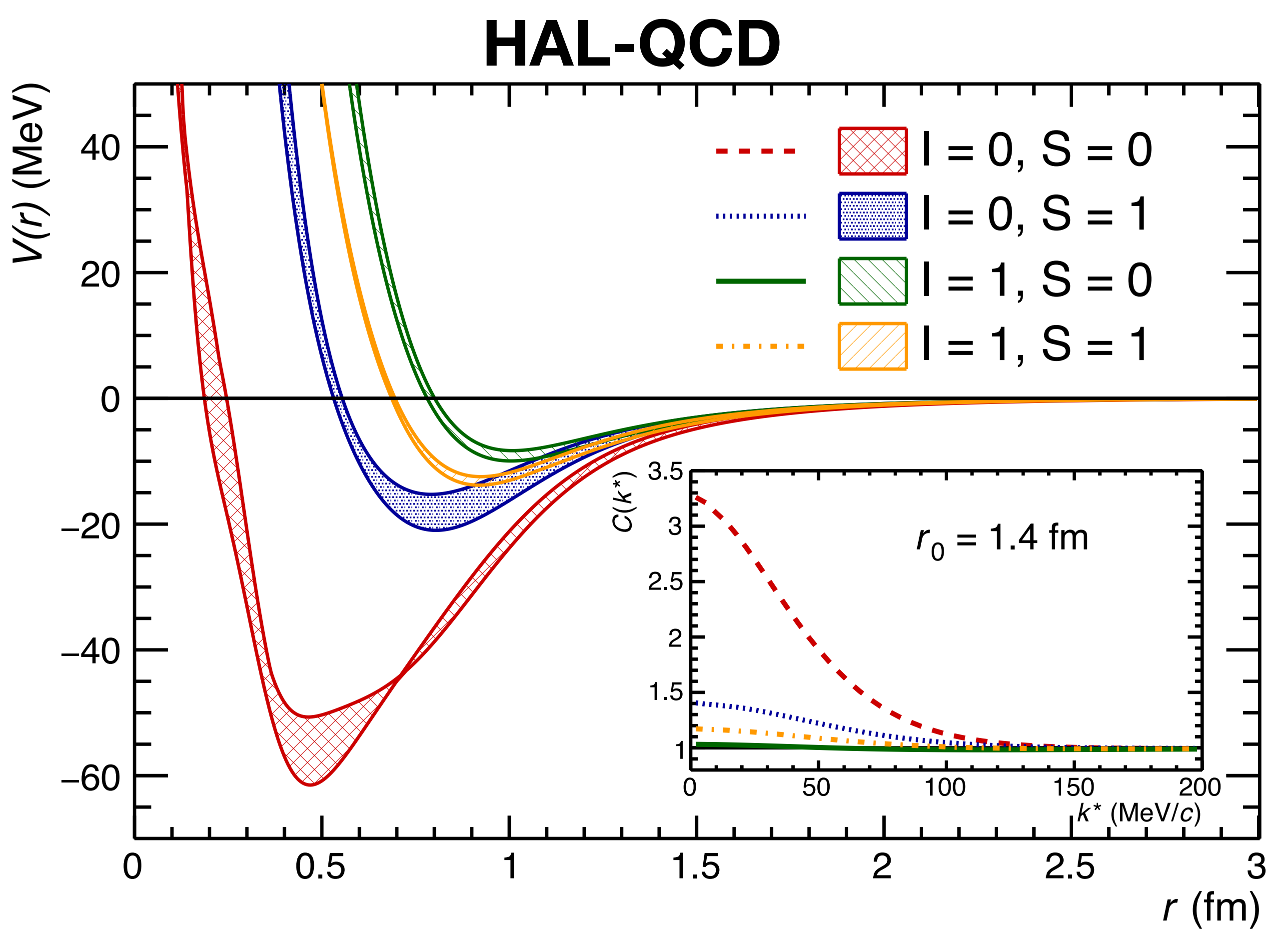


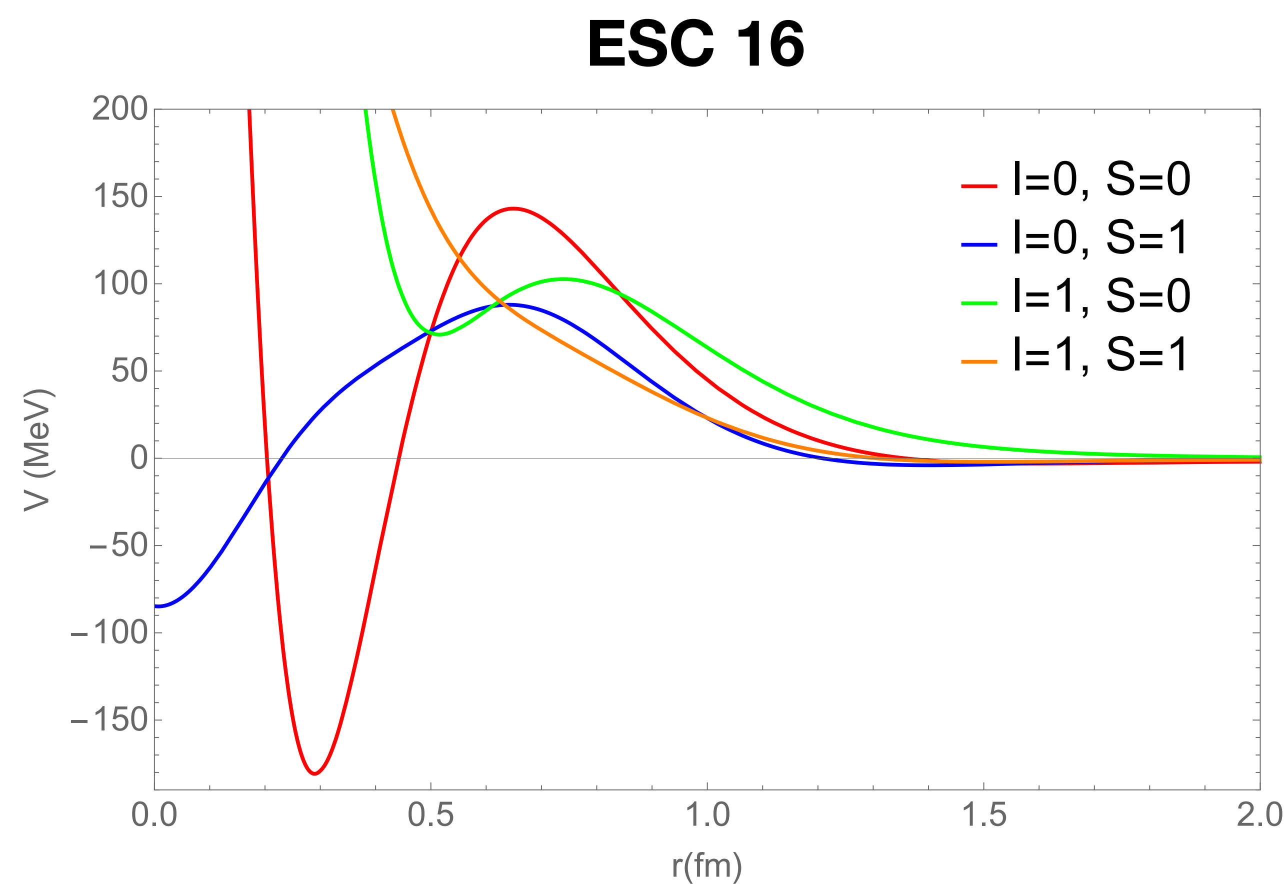
$$r_{Eff} = 1.15\,\mathrm{fm}$$

$p\Xi^-$ Interaction from LATTICE and ESC16 Model

B. Hohlweger (ALICE) WPCF19 slides

ALICE Collaboration, arXiv:1904.12198 [nucl-ex]
(Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)





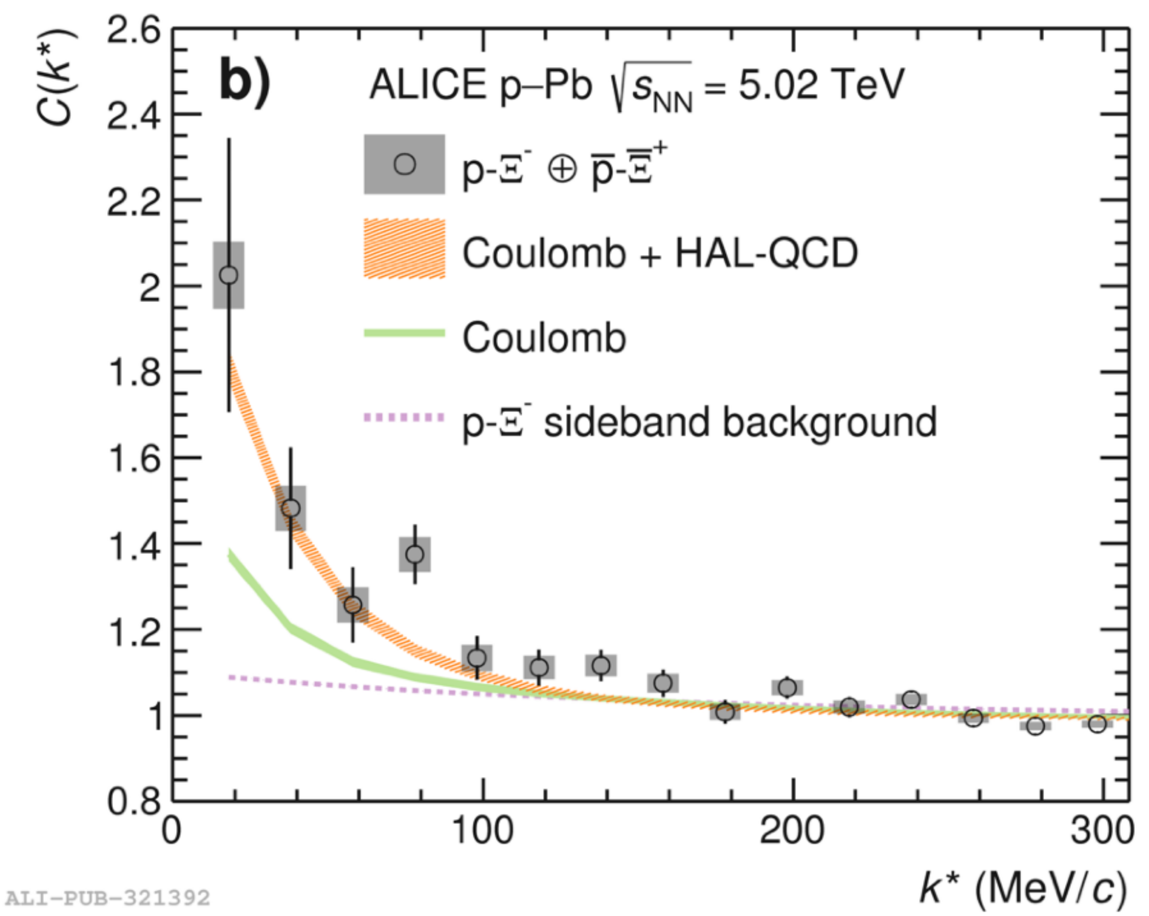
Each Potential can be converted in a correlation function via CATS and the total correlation function can be estimated

$$C(k^*) = \frac{1}{8}\left(C^{S=0}_{I=0} + C^{S=0}_{I=1}\right) + \frac{3}{8}\left(C^{S=1}_{I=0} + C^{S=1}_{I=1}\right)$$

$p\Xi^-$ Correlations for p-Pb 5 TeV and pp 13TeV HM

B. Hohlweger (ALICE) WPCF19 slides

ALICE Collaboration, arXiv:1904.12198 [nucl-ex]



$$r_0 = 1.4\,fm$$

Coulomb-only excluded at 4-5 σ level

HAL-QCD Correlation is compatible with the data

$p\Xi^-$ Correlations for p-Pb 5 TeV and pp 13TeV HM

B. Hohlweger (ALICE) WPCF19 slides

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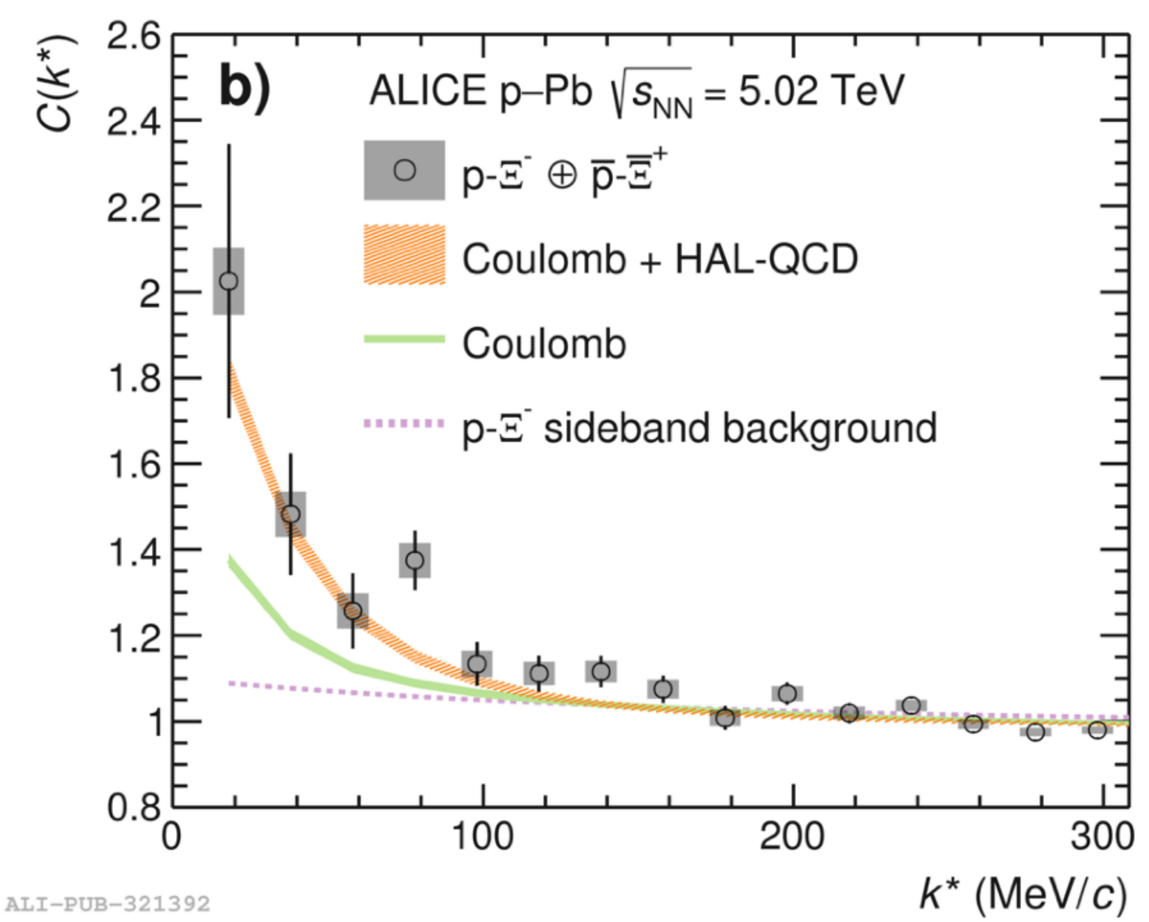
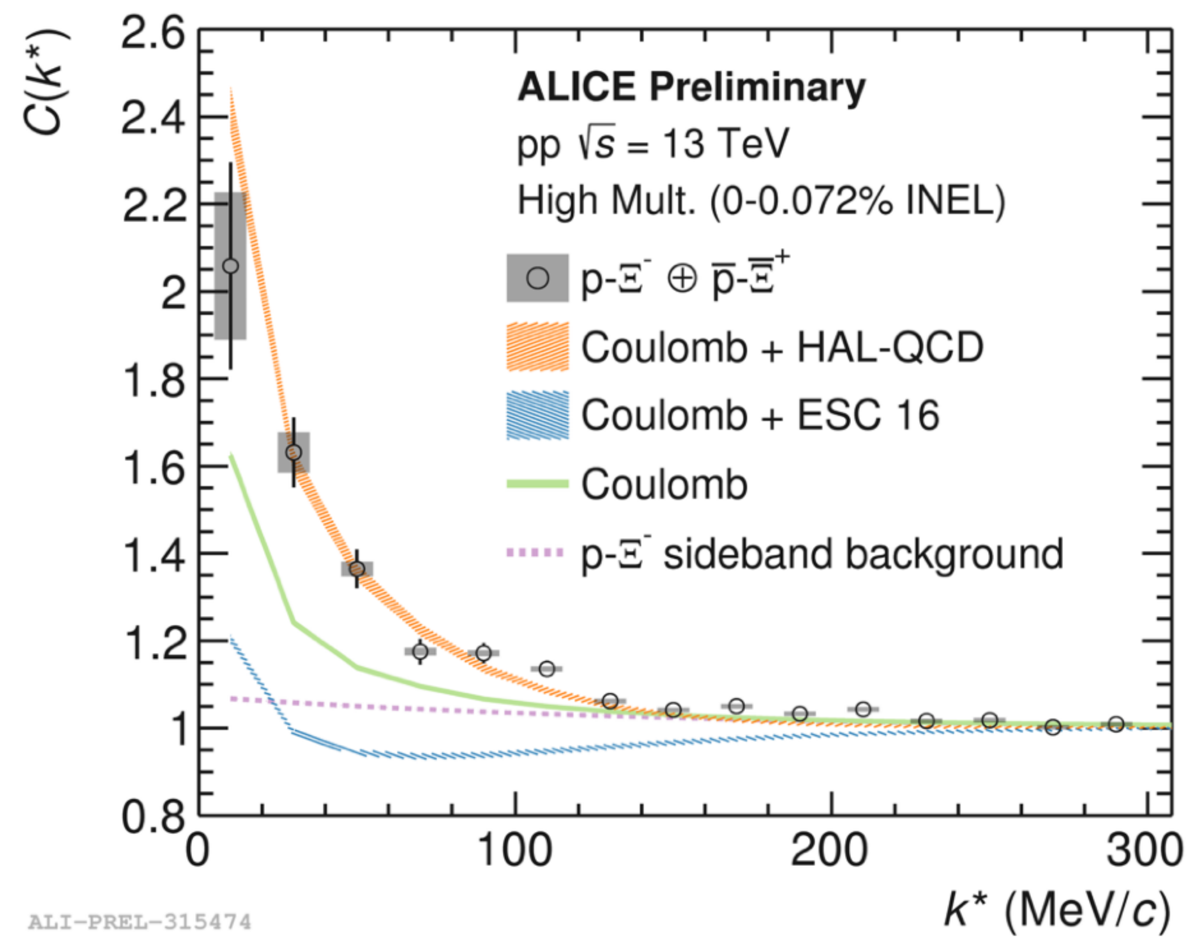




$$r_0 = 1.4\, fm$$

$$r_{EFF} = 0.93\, fm$$

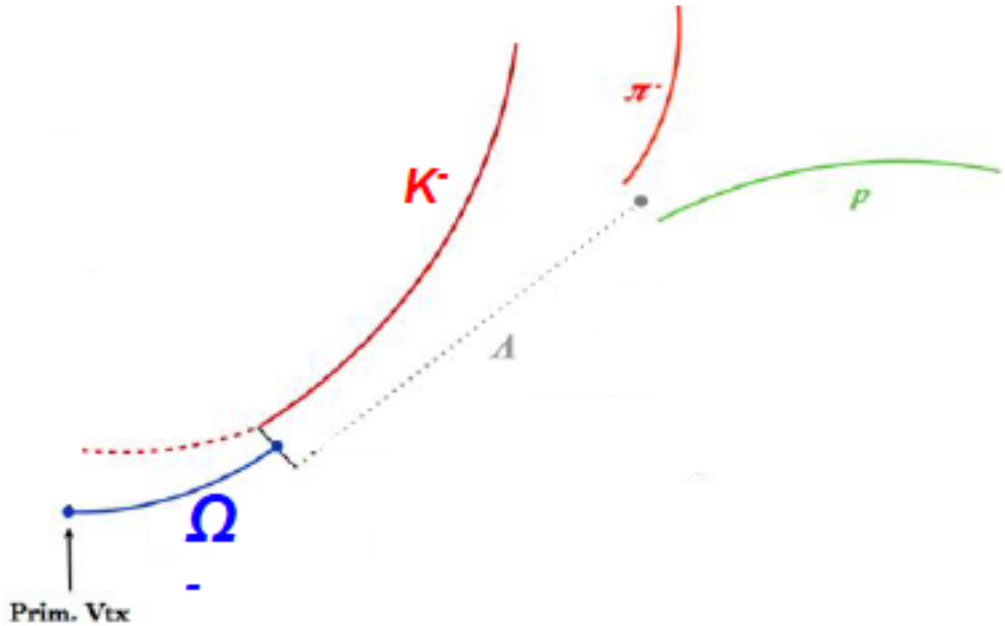
Coulomb-only excluded at 4-5 σ level
HAL-QCD Correlation is compatible with the data

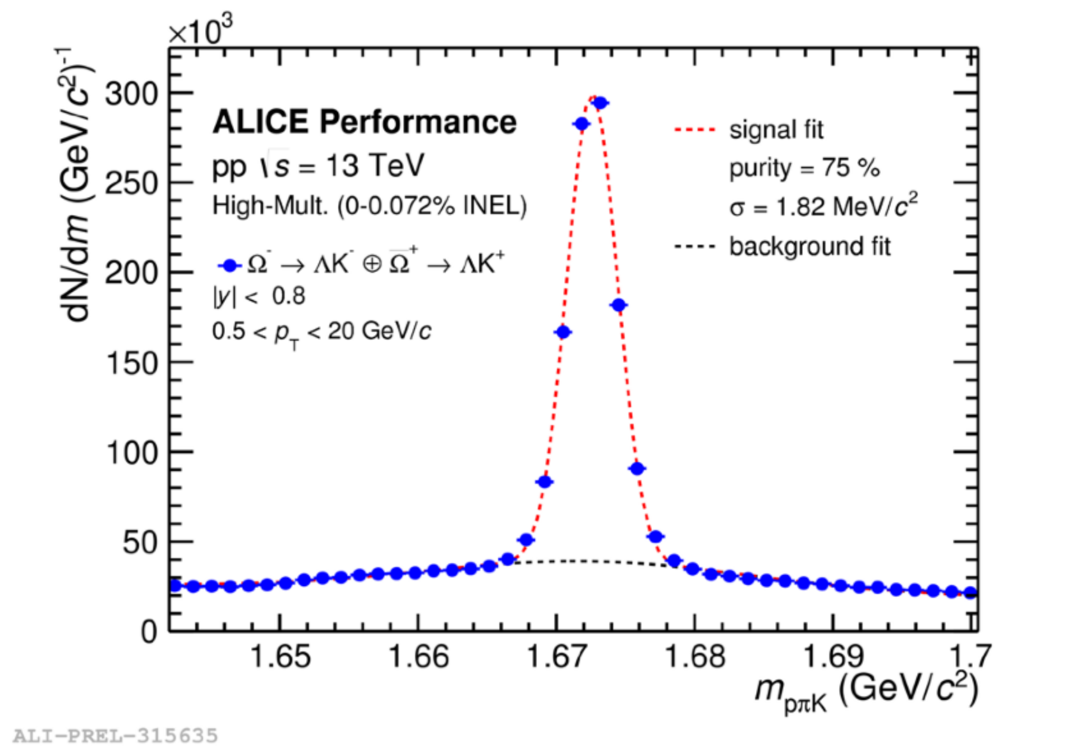
Coulomb only: > 5.7 σ
HAL-QCD Potential: (1.3-2.5) σ
ESC 16 Potential: > 18 σ

Visit the Poster by O. Vazquez Doce **Tonight**
Femtoscopic studies on proton-Ξ and proton-Ω correlations in p-Pb and pp collisions with ALICE

Ω^- Reconstruction and Theoretical Prediction

O.Vazquez Doce (ALICE) WPCF19 slides

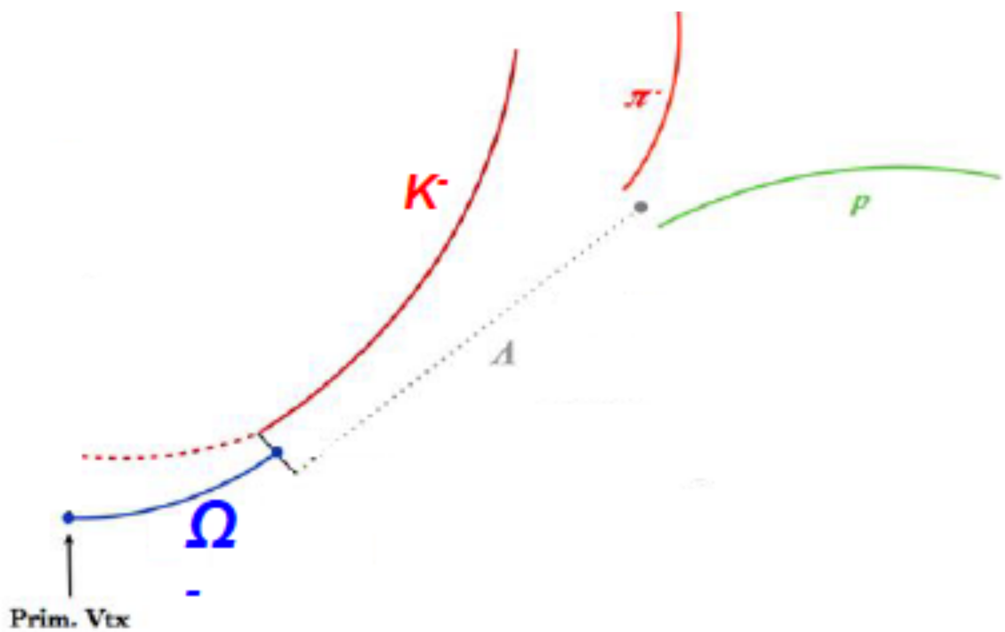


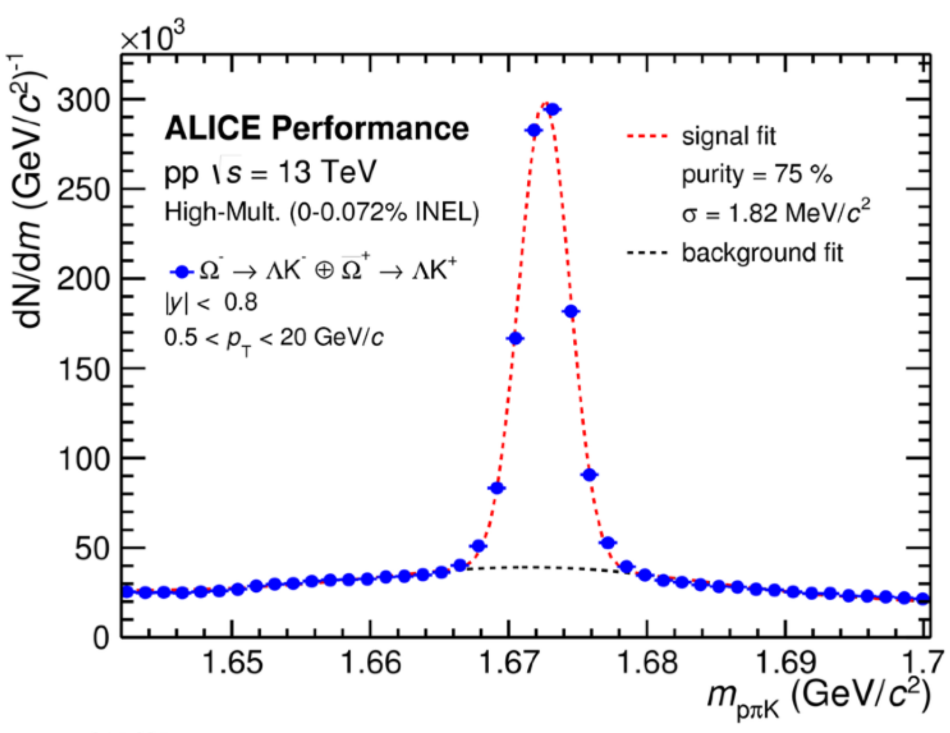


Signal = 1.2 x 10^6

Purity = 75%

Ω^- Reconstruction and Theoretical Prediction





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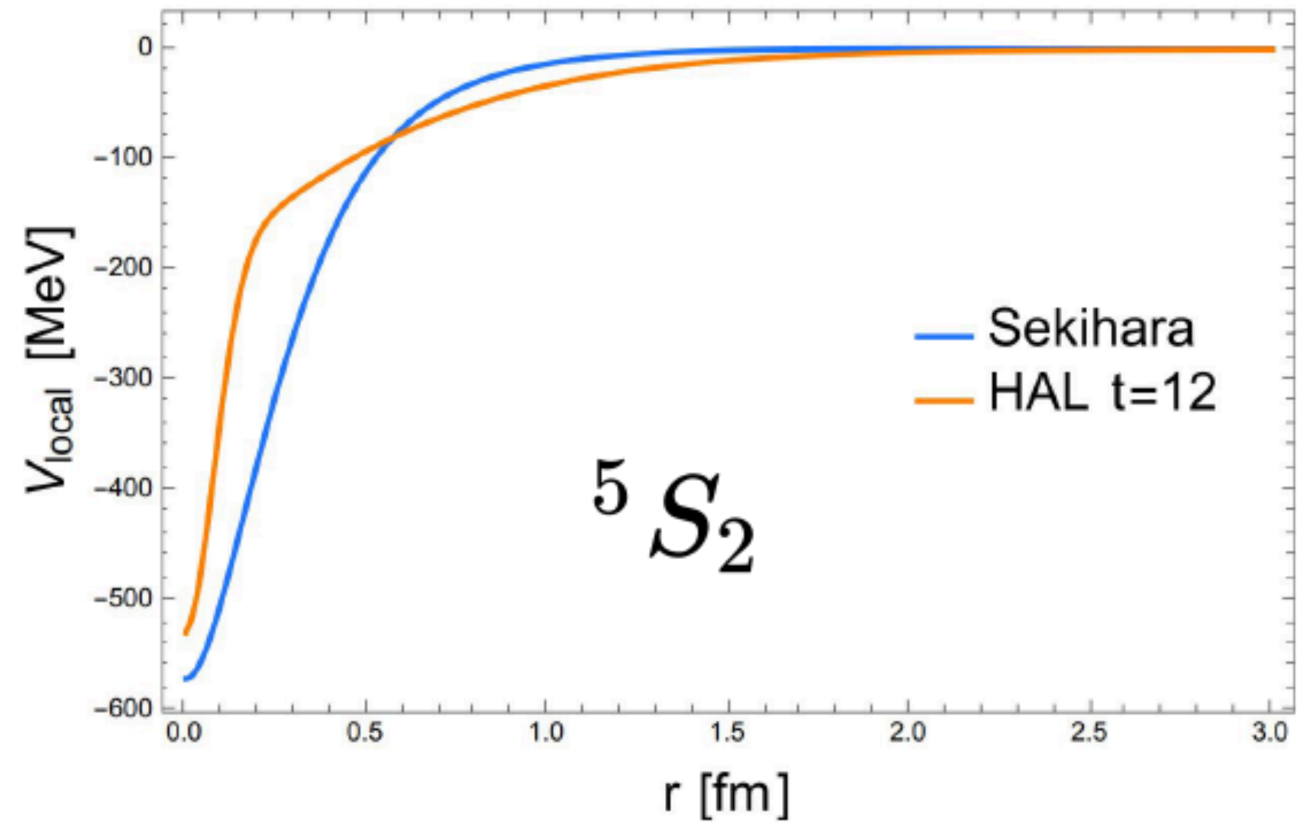
O.Vazquez Doce (ALICE) WPCF19 slides



Lattice HAL-QCD potential only for $^5S_2$ (with physical quark masses)

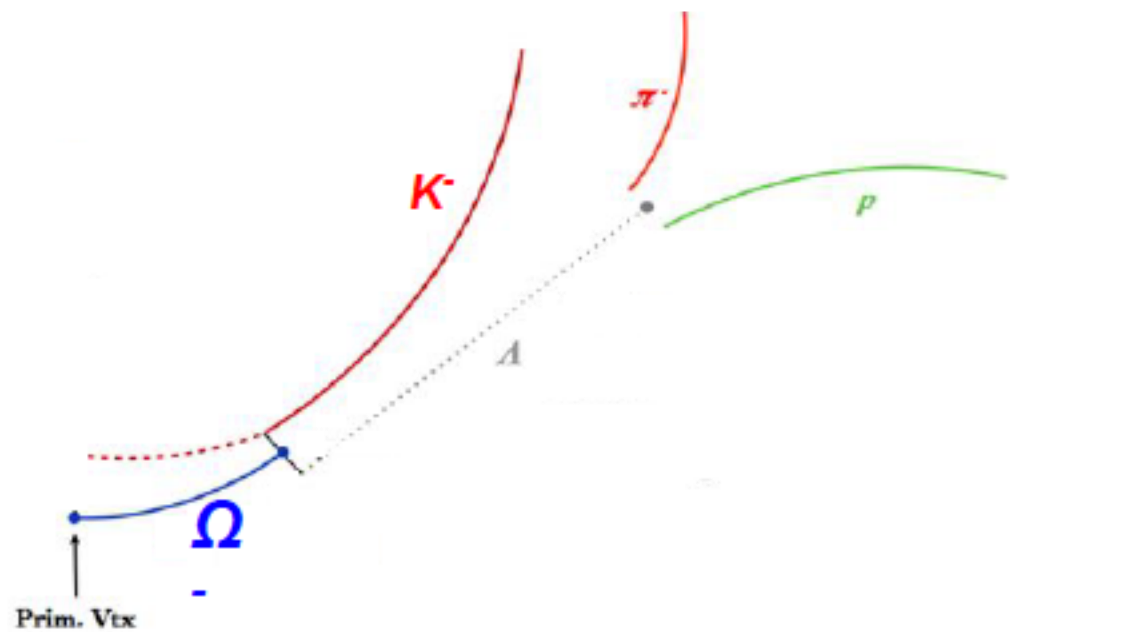
T. Iritami et al. arXiv:1810.03416

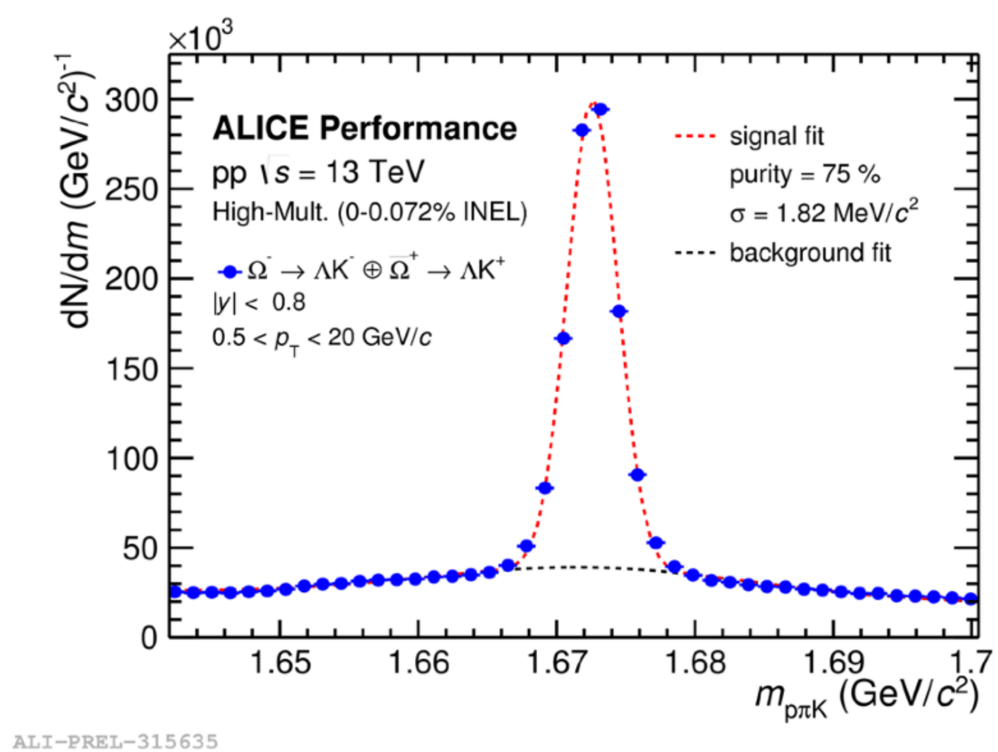
Sekihara: Meso-exchange model only for $^5S_2$

T. Sekihara et al., Phys. Rev.c C 98, 015205 (2018).

Ω^- Reconstruction and Theoretical Prediction

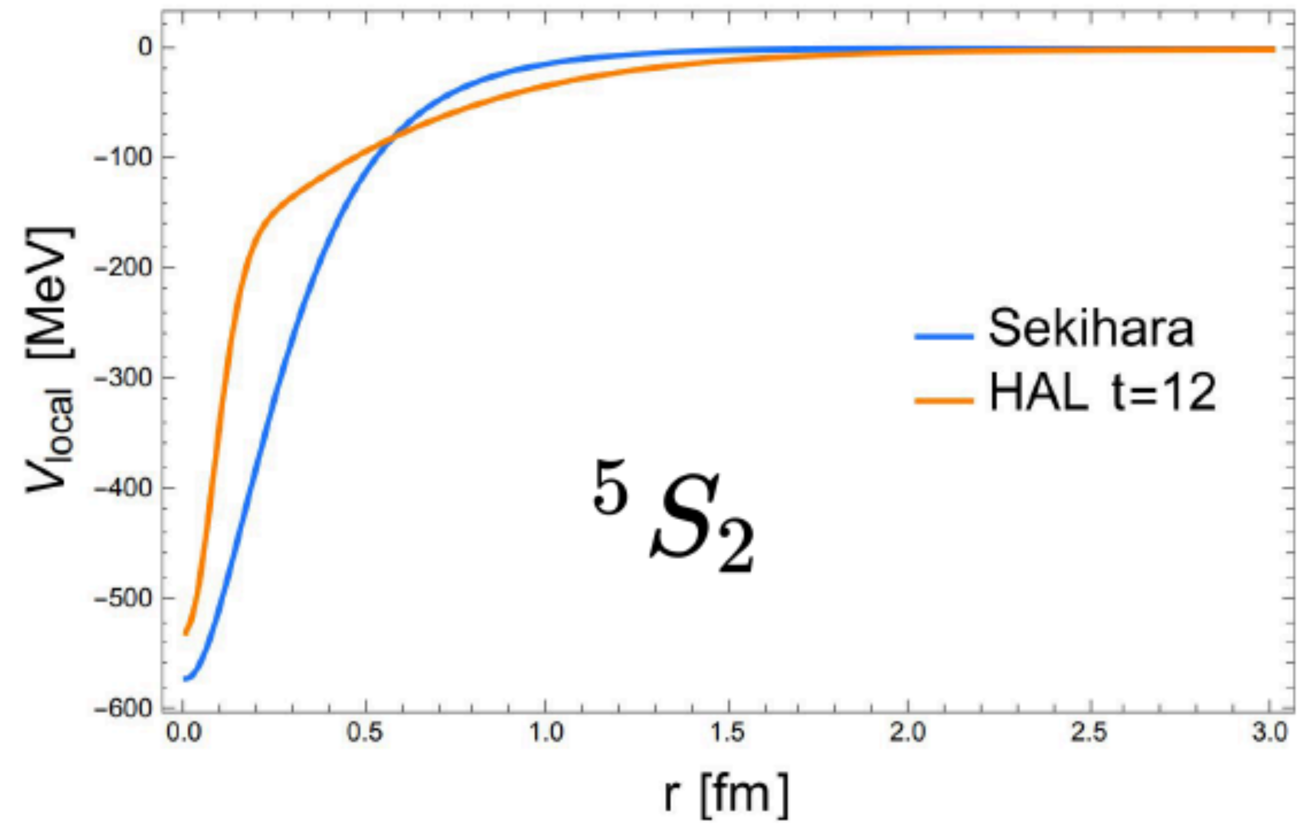
O.Vazquez Doce (ALICE) WPCF19 slides





Signal = 1.2×10^6

Purity = 75%



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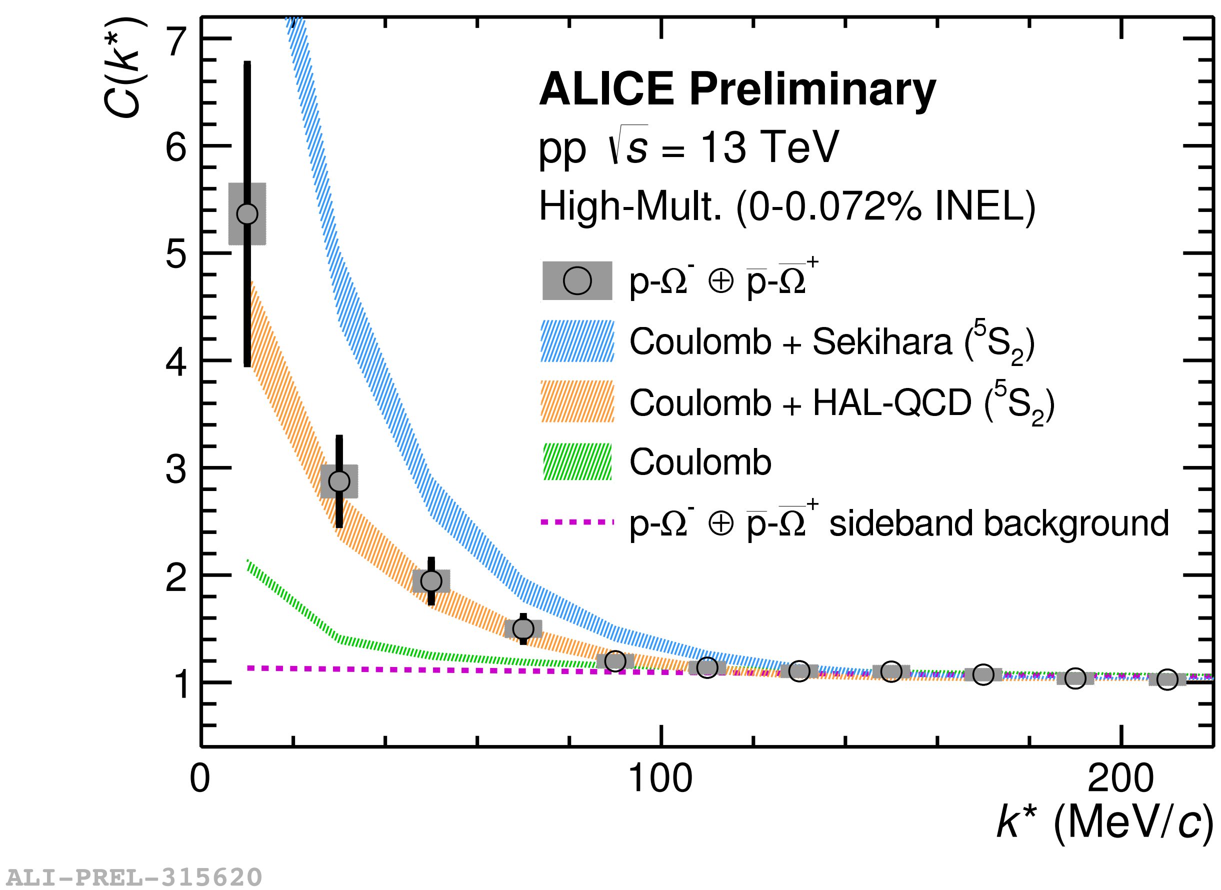
T. Sekihara et al., Phys. Rev.c C 98, 015205 (2018).

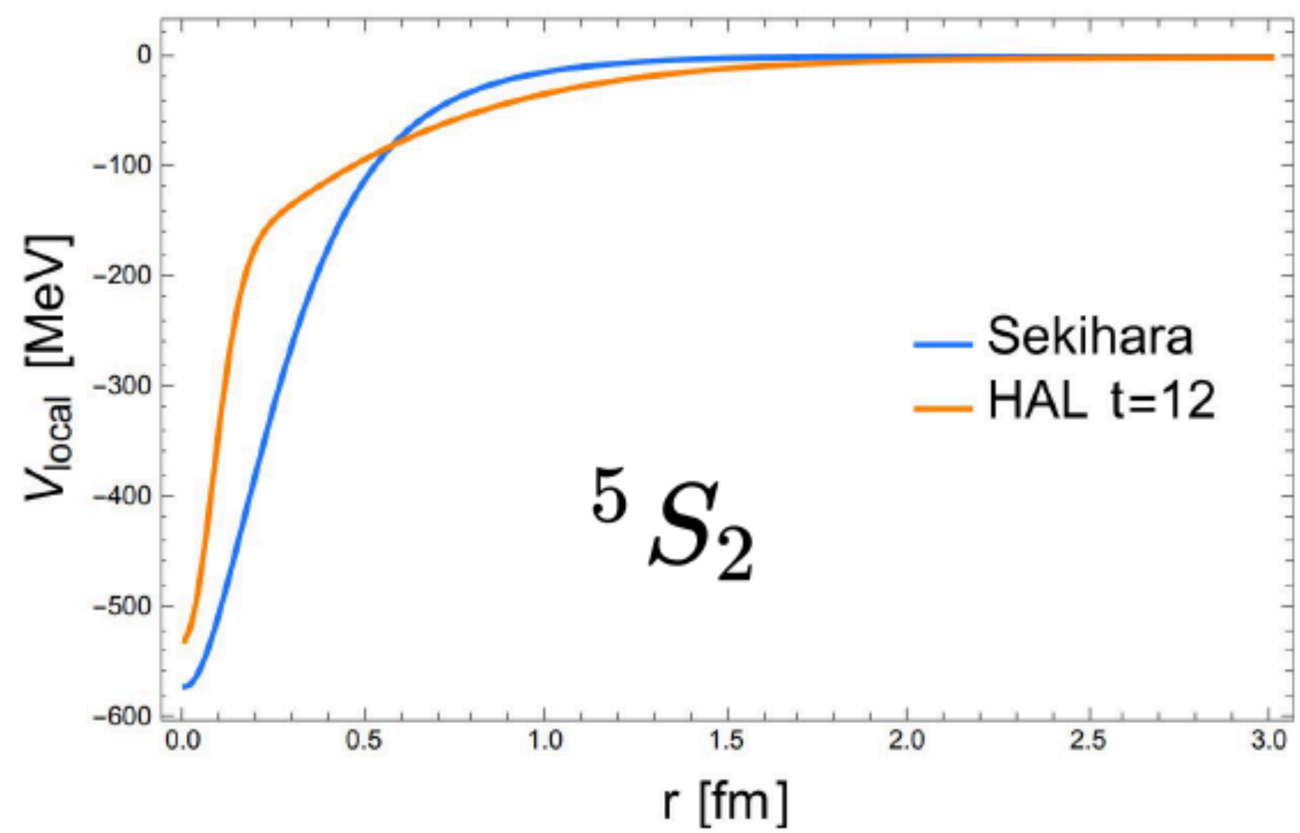
Model	NΩ binding energy
HAL-QCD	1.54 MeV/c^2
Sekihara	0.1 MeV/c^2

$p\Omega^-$ Correlations for pp 13TeV HM

O.Vazquez Doce (ALICE) WPCF19 slides

$$r_{EFF} = 0.85\, fm$$





Evidence of an attractive strong interaction
Strongly bound states?

Visit the Poster by O. Vazquez Doce **Tonight**
Femtoscopic studies on proton-Ξ and proton-Ω correlations in p-Pb and pp collisions with ALICE

Summary + Outlook

K^+p, K^-p, pp, $p\Lambda$, $p\Sigma^0$, $p\Xi^-$, $p\Omega$

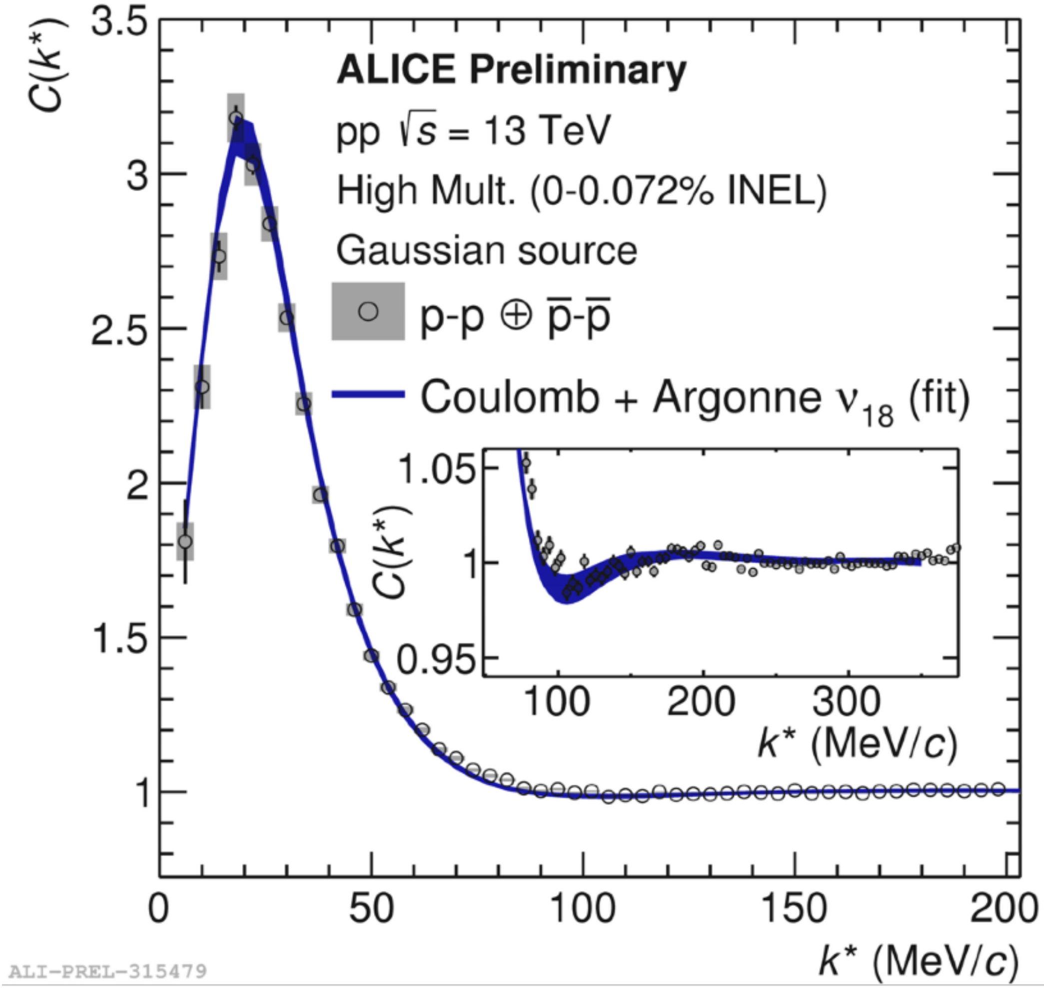
If these two body reactions were so-far poorly determined **how precise** can all the equations of state of dense neutron matter + strange hadrons be?

If the LHC provides a unique and precise testing of the strong interaction at distances lower than 1 fm **we mimic two-body interactions within dense matter.**

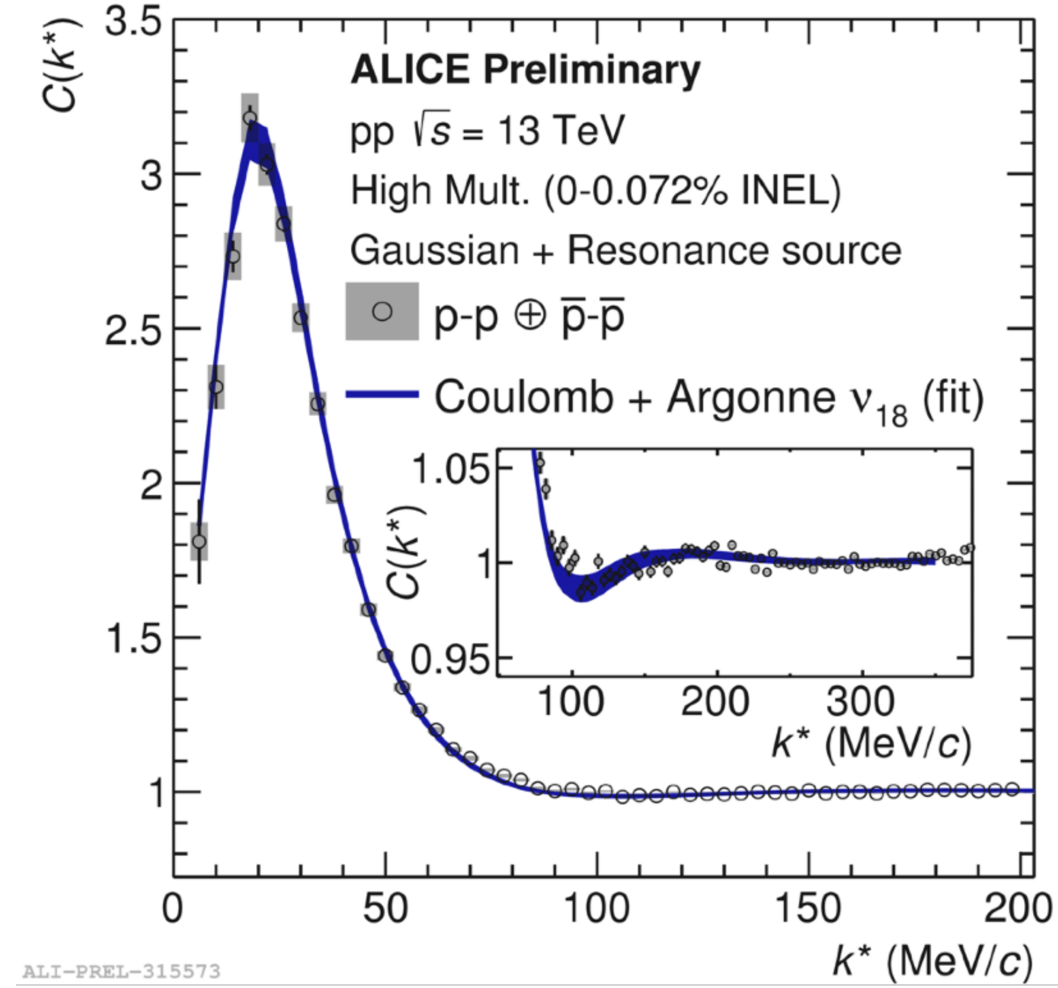
RUN3 and RUN4 will provide the possibility of carrying out more differential studies and also investigate three-body interactions.

Comparison Gaussian to Gaussian + Resonances

Fit with a simple Gaussian

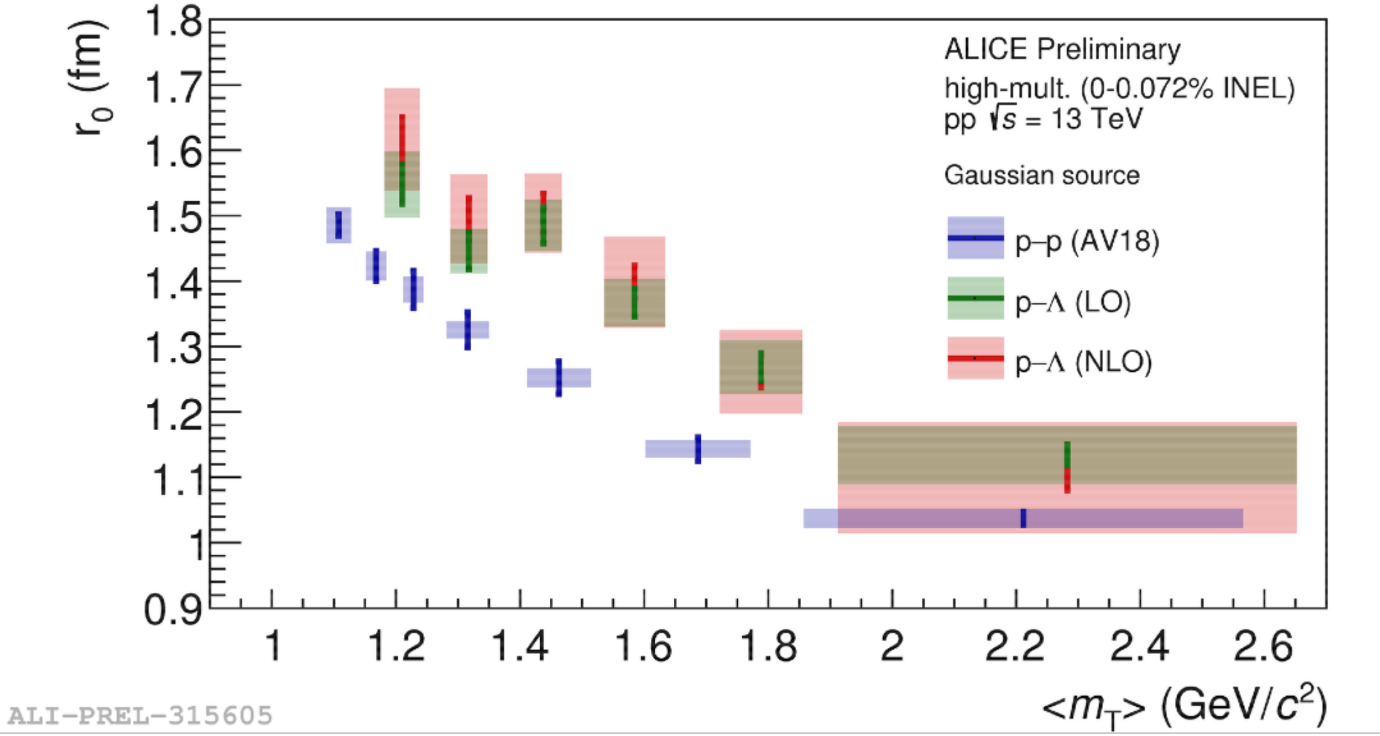


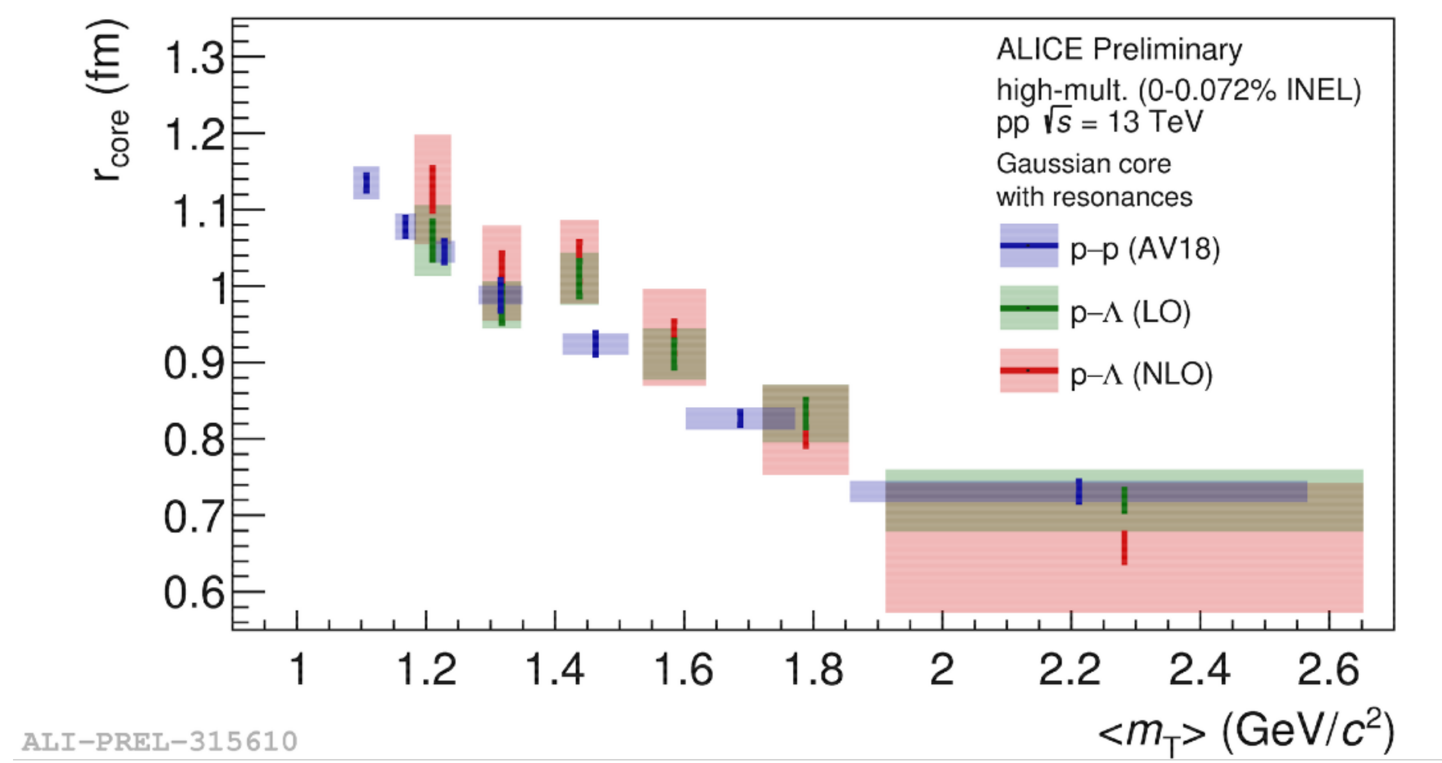
Fit with a 'core' Gaussian + Resonances



Independent Source Fit

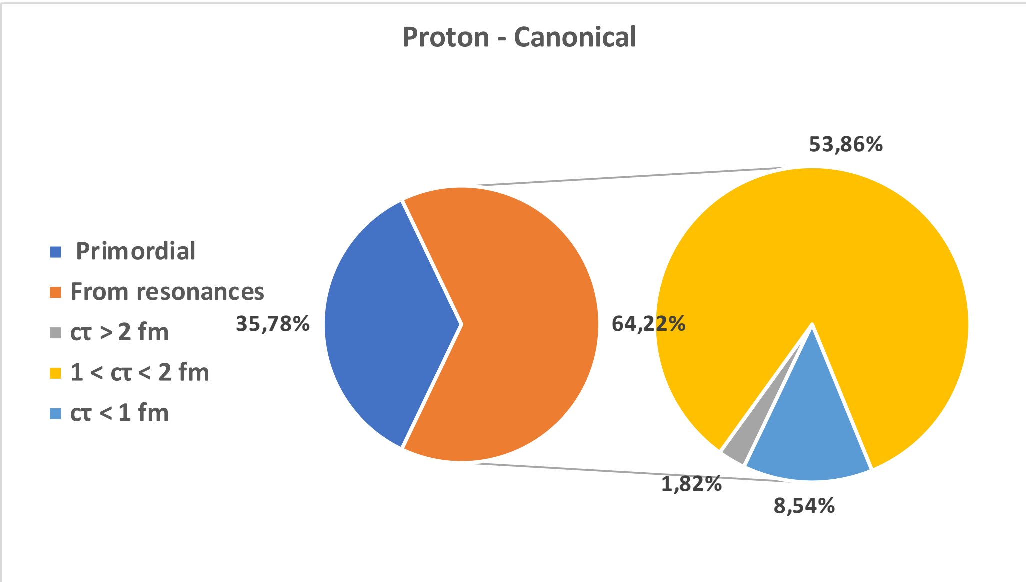
D. Mihaylov (ALICE) WPCF19 slides

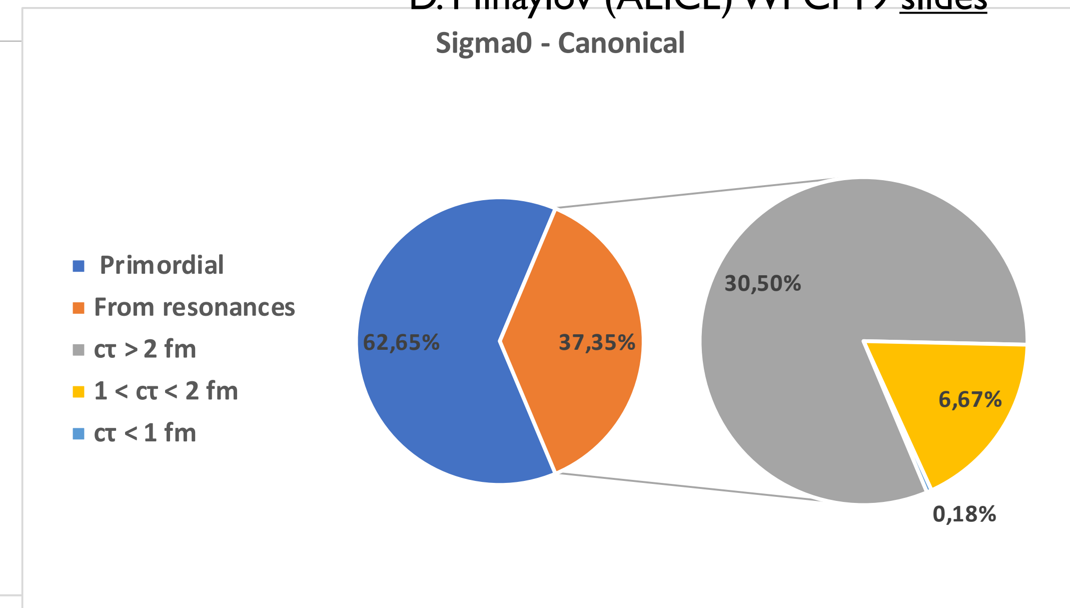


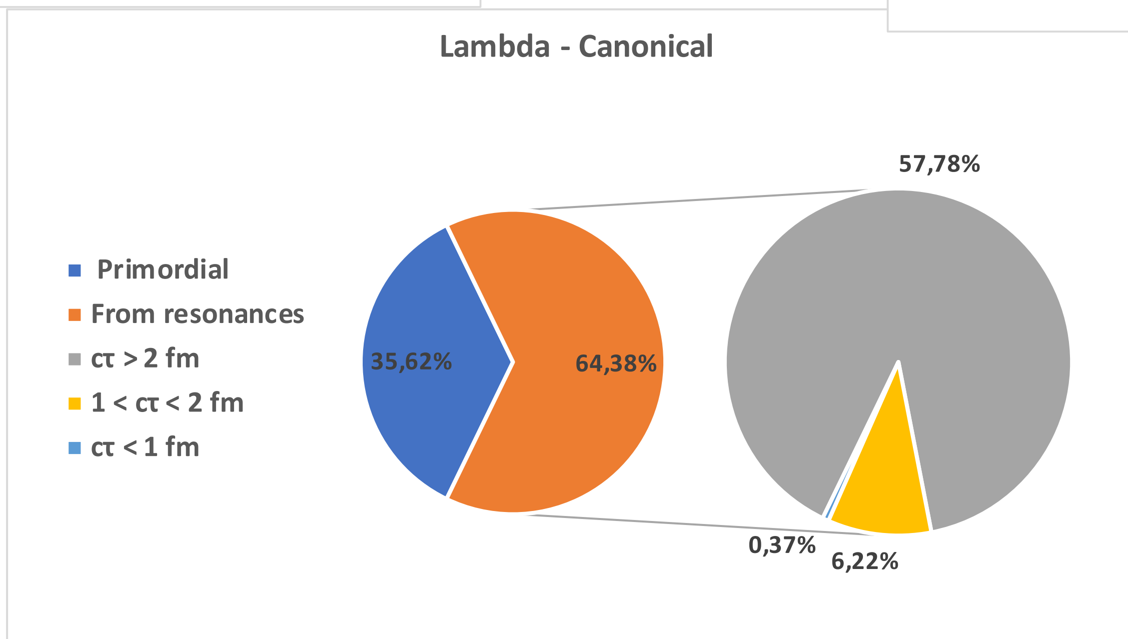


Contribution of Short-lived Resonances

D. Mihaylov (ALICE) WPCF19 slides







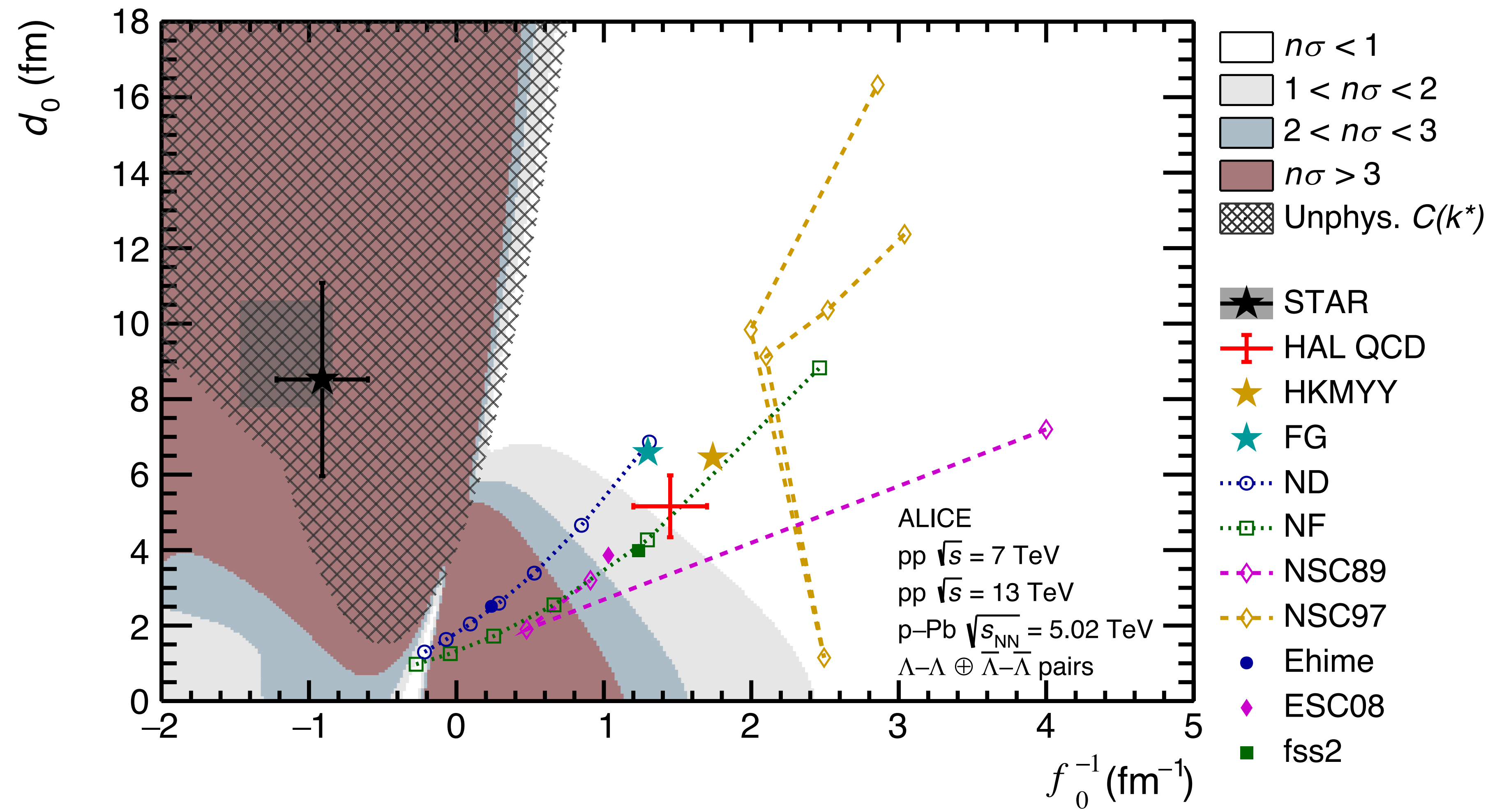
- For Ξ^- and Ω^- **no contributions**!
- Average mass and average cτ determined by the weighted average values of all resonances

Particle	M_{res} [MeV]	τ_{res} [fm]
p	1361.52	1.65
Λ	1462.93	4.69
Σ^0	1581.73	4.28

ΛΛ Exclusion Plot

A. Mathis (ALICE) WPCF19 slides

- Combination of all analyzed datasets
  - pp 7 & 13 TeV
  - p–Pb 5.02 TeV
- Test of the agreement between data and the prediction by the Lednický model in nσ
  - Under the hypothesis of a common, Gaussian source
  - Small source size limits the prediction power of the Lednický model

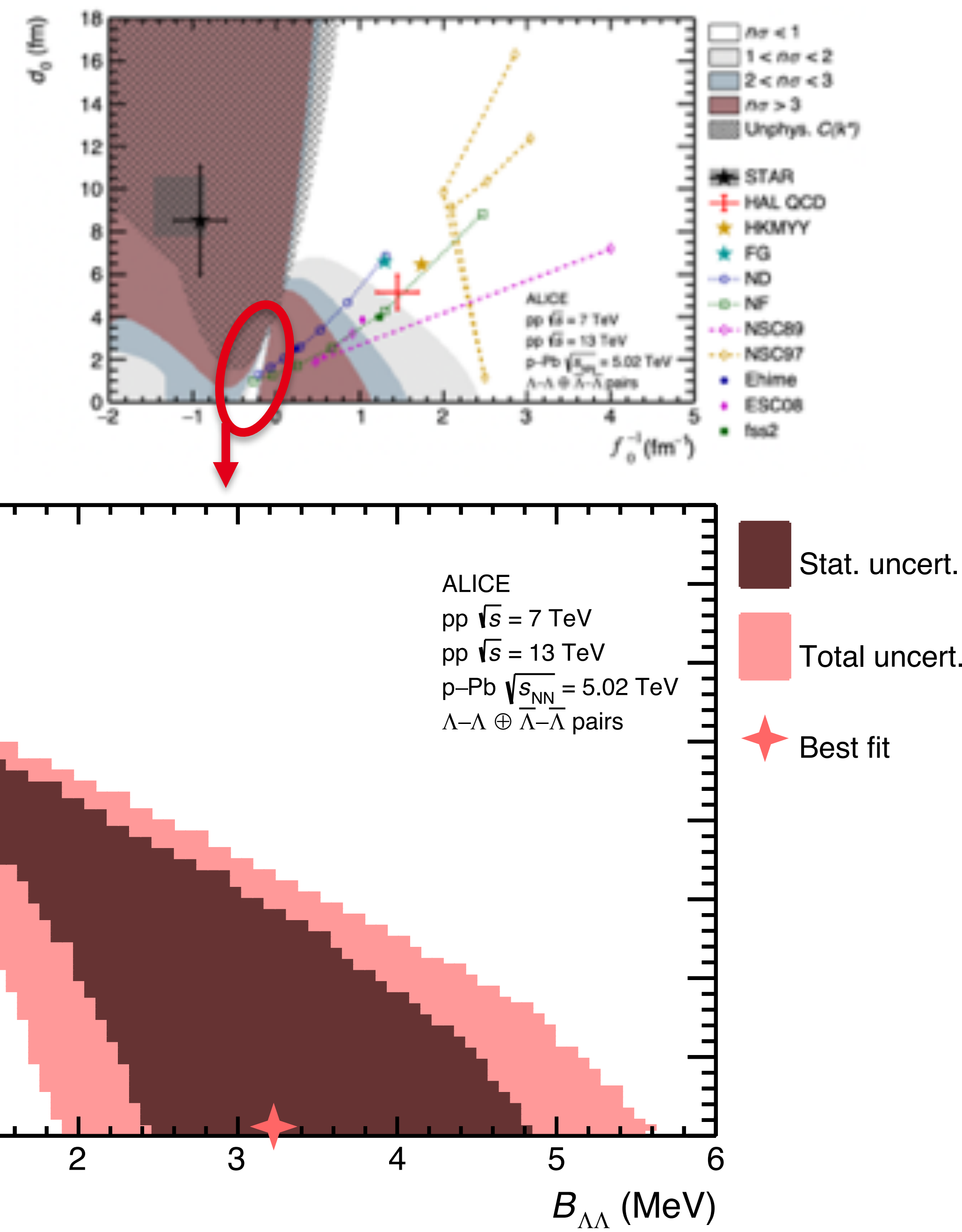


Upper Limit for the H-Dibaryon Binding Energy

A. Mathis (ALICE) WPCF19 slides

$$B_{\Lambda\Lambda} = \frac{1}{m_\Lambda d_0^2}\cdot\left(1-\sqrt{1+\frac{2d_0}{f_0}}\right)$$

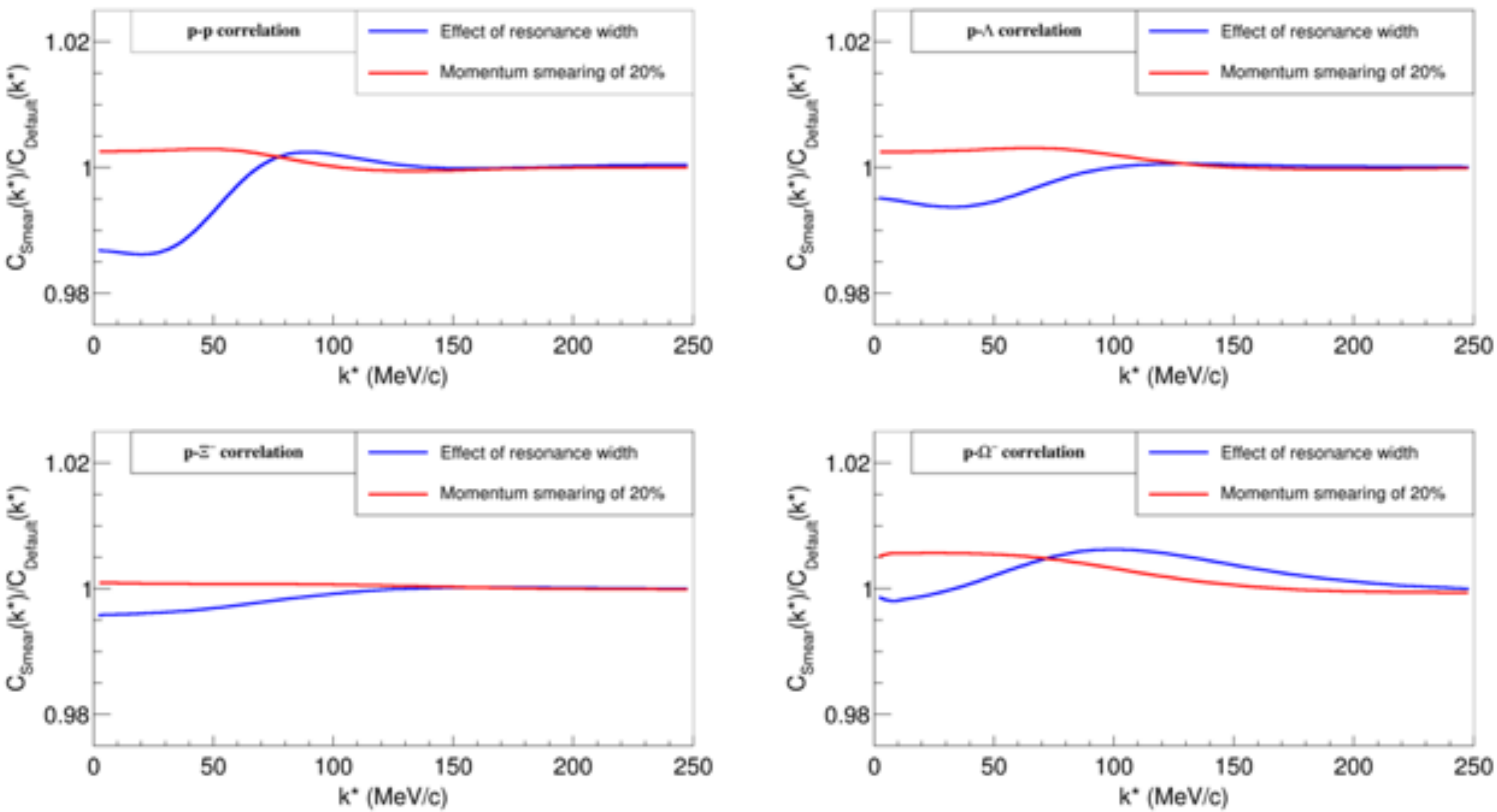
S. Gongyo et al., PRL 120 (2018) 212001.
P. Naidon and S. Endo, Rept. Prog. Phys. 80 (2017) 056001.



- H-Dibaryon: Tight constraints on the allowed binding energy
  - $B_{\Lambda-\Lambda} = 3.2^{+1.6}_{-2.4}\,(\text{stat.})^{+1.8}_{-1.0}\,(\text{syst.})$ MeV
  - More stringent than previous measurements
- For more details see arXiv:1905.07209

Effect of the smearing of Resonance Widths on the Source

D. Mihaylov (ALICE) WPCF19 slides



Different Version of the Lattice Calculations

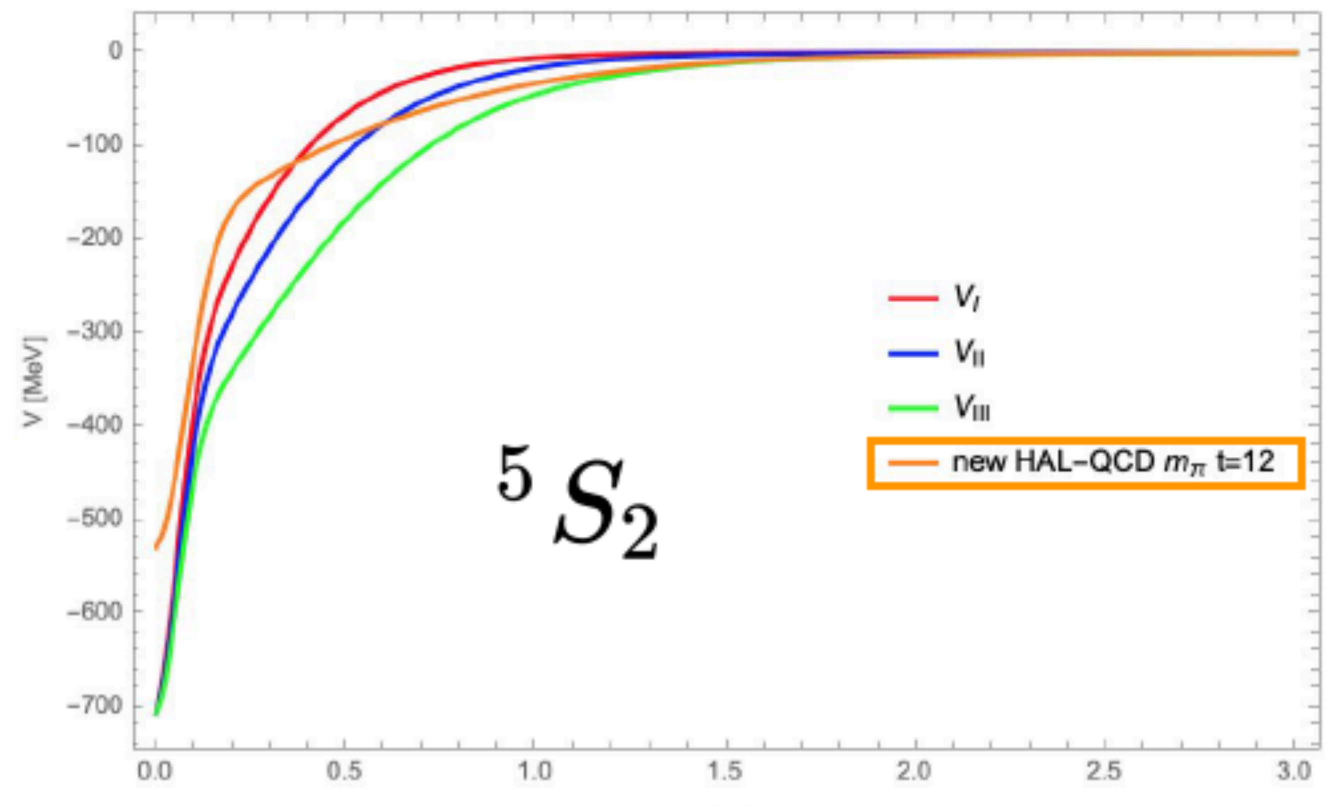
O.Vazquez Doce (ALICE) WPCF19 slides

- Based on Lattice calculations with heavy quark masses F. Etminan et al.(HAL QCD Collaboration),Nucl. Phys. A928,89(2014)
  - m_π = 875 MeV/c^2
  - m_K = 916 MeV/c^2
- Used in the STAR pΩ analysis in Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV
- Lattice calculations fitted by an attractive Gaussian core + an attractive tail, varying the range parameter at long distance (b_5)
  - V_{II}: best fit to Lattice calculations
  - V_I / V_{III}: weaker / stronger attraction

$$V(r) = b_1 e^{-b_2 r^2} + b_3(1 - e^{-b_4 r^2})(e^{-b_5 r}/r)^2$$

Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

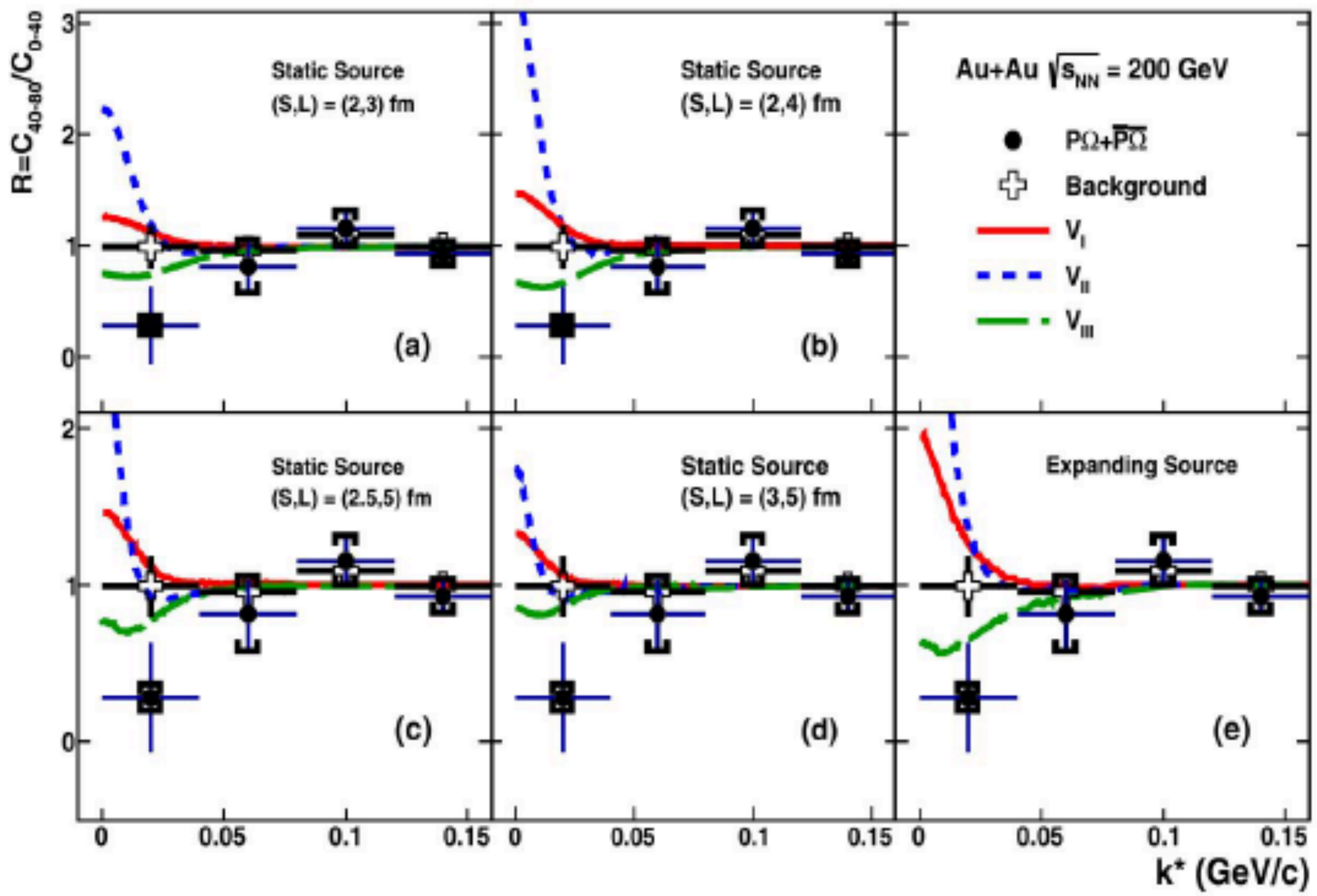
Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
$\mathbf{E_b}$ (MeV)	–	6.3	26.9
$\mathbf{a_0}$ (fm)	−1.12	5.79	1.29
$\mathbf{r_{eff}}$ (fm)	1.16	0.96	0.65



Recap of the STAR Results for pΩ^-

O.Vazquez Doce (ALICE) WPCF19 slides

- Study of the p-Ω^- correlation function in Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV STAR Collaboration. Phys. Lett. B790 (2019) 490-497
- Observable: ratio of the correlation function peripheral/central collisions.
- Comparison with Lattice QCD calculations (with large masses)



- Test different fits to Lattice QCD data (delivering **three different binding energies of the NΩ**):

Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

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[24] K. Morita, A. Ohnishi, F. Etminan, T. Hatsuda, Phys. Rev. C 94 (2016), 031901

STAR data favor V_{III}, with $\mathbf{E_b}$ **= 27 MeV**

3

Sensitivity of ALICE and STAR data

O.Vazquez Doce (ALICE) WPCF19 slides

- Expected correlation function from heavy quark Lattice QCD potentials
- **Smaller radius** source offers the ideal conditions to test the models
- **Better purity** of ALICE data increases the **sensitivity** of the test

purity 75% (ALICE)