



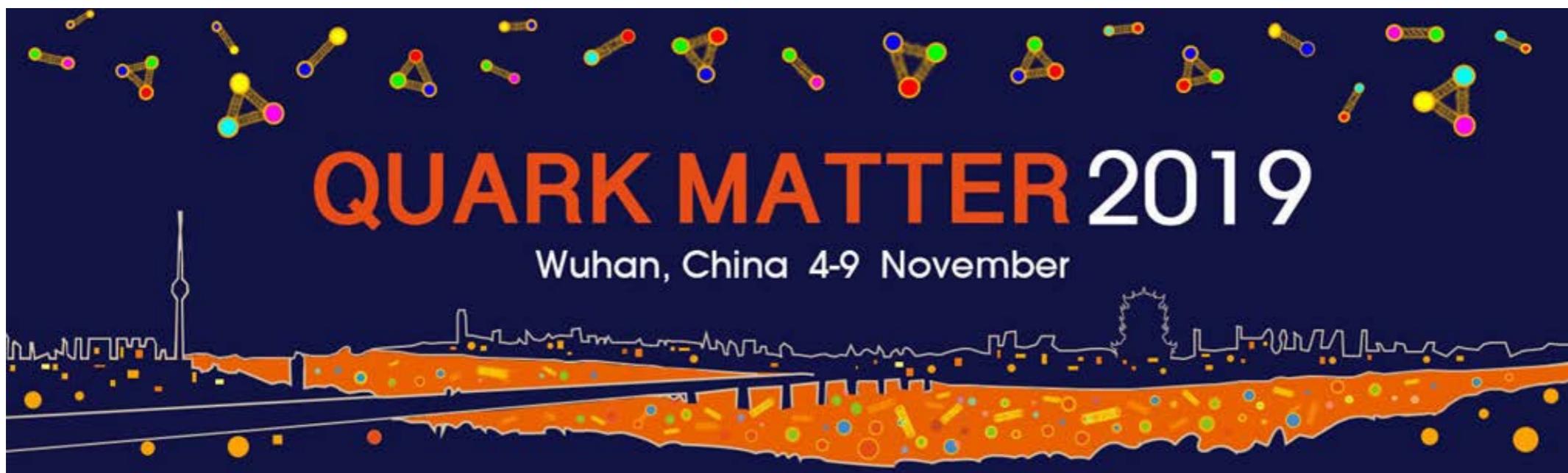
A new laboratory to study hadron-hadron interactions

Laura Fabbietti

Technische Universität München

E62 – Dense and Strange Matter

150 Jahre
culture of
excellence



Which Hadron-Hadron Interactions?

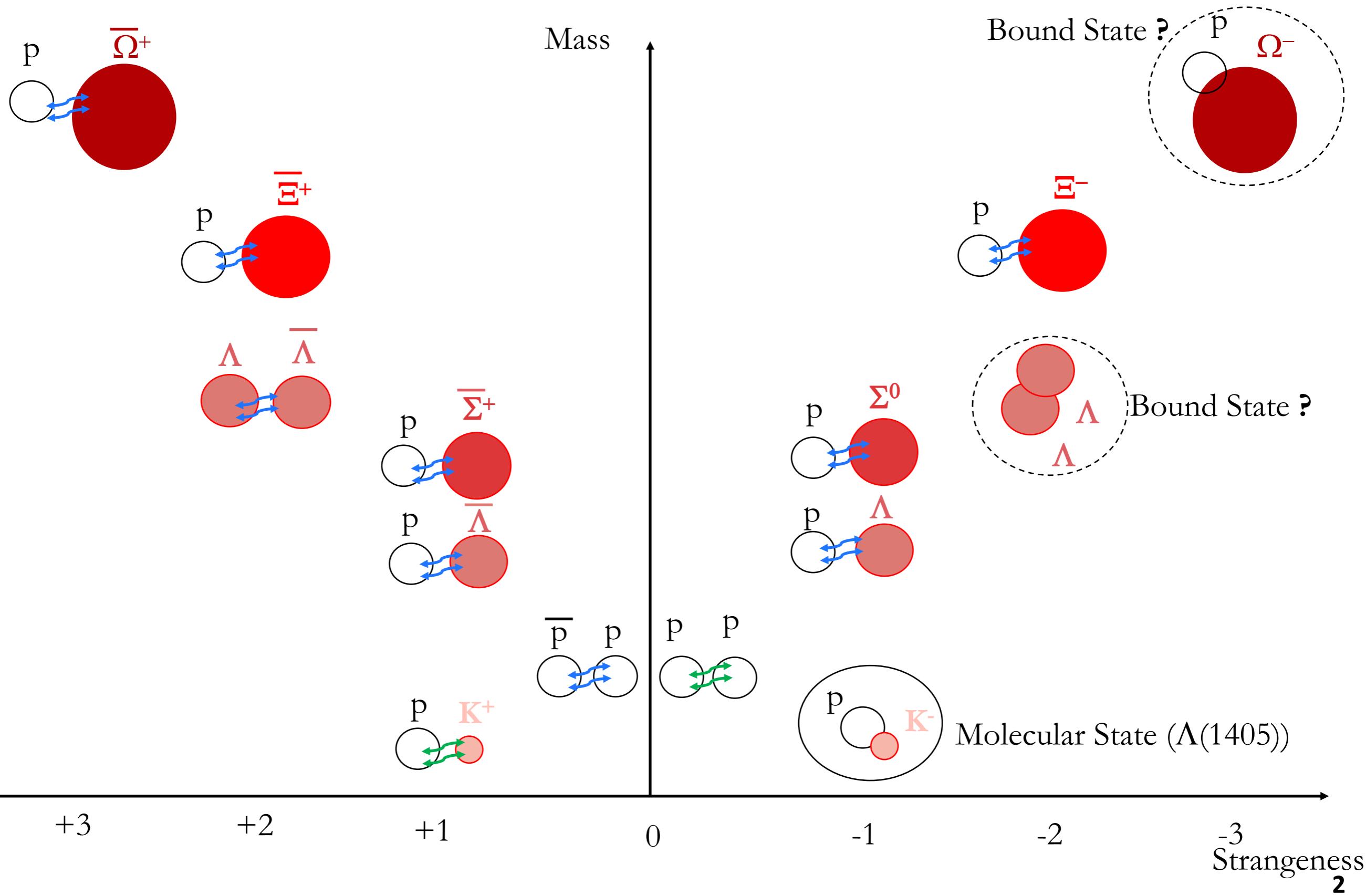
Why?

How to measure them in Ultrarelativistic Hadron collisions?

How precise are the obtained results?

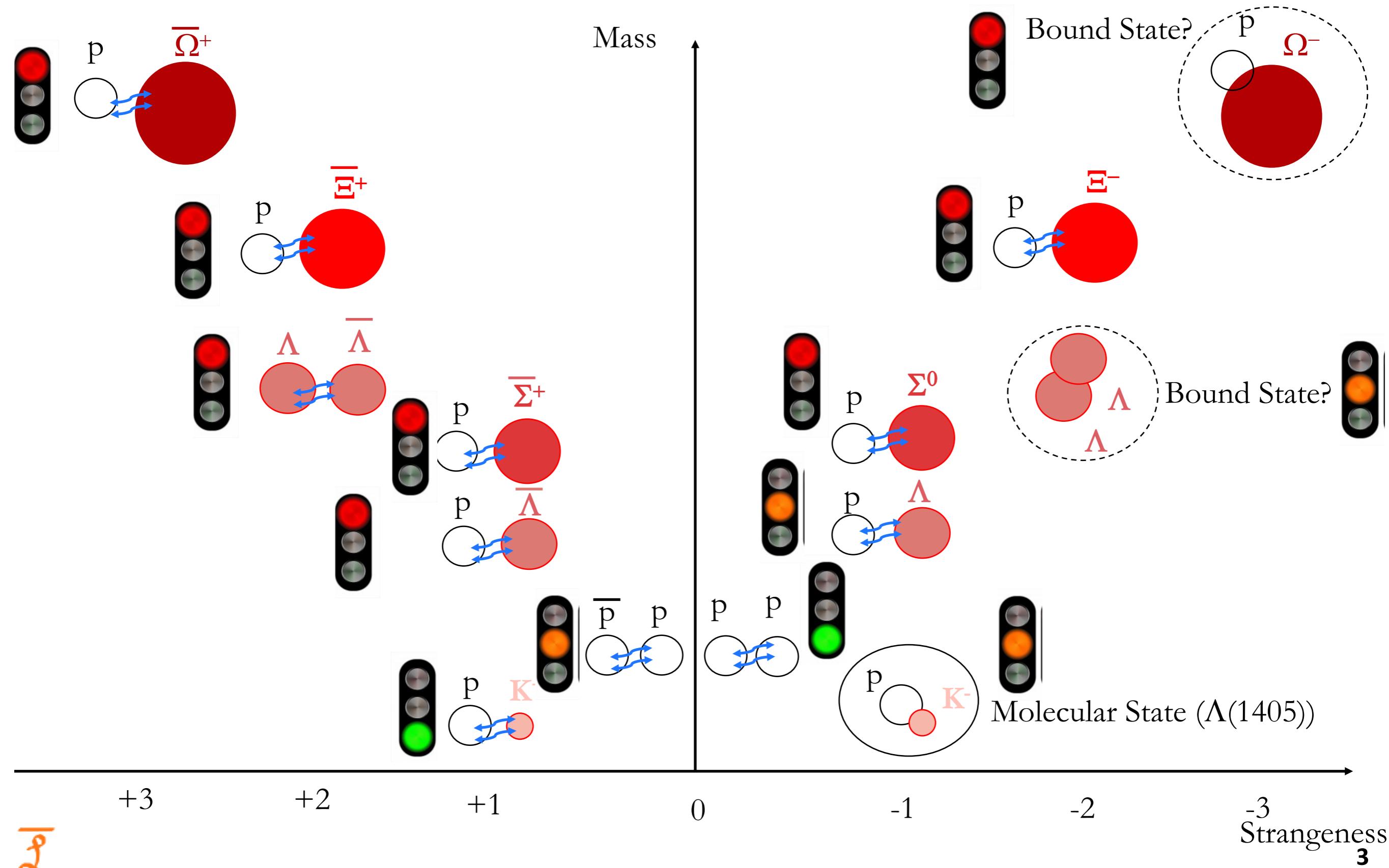


Hadron-Hadron Interactions within SU(3)





Hadron-Hadron Interactions within SU(3)





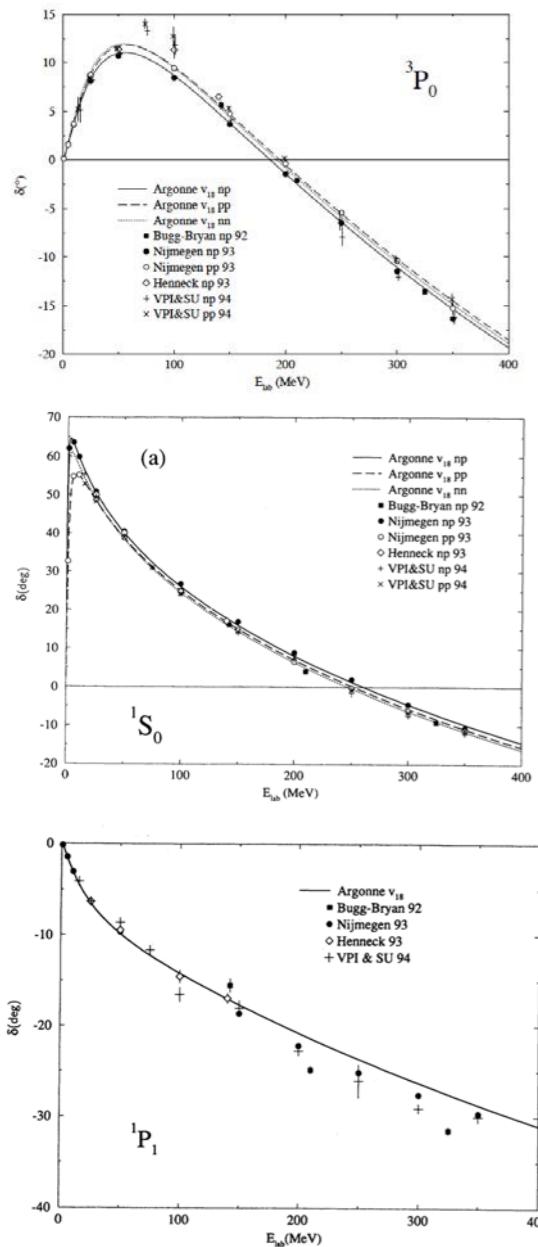
Why?

- Improved experiment **constraints** needed for low-energy QCD effective theories
- New developments in **Lattice** calculations for hadron-hadron interactions
- Search for **bound states**
- Physics of Neutron Stars: more precise **equation of state** of dense neutron-rich matter with strange content requires precise knowledge of the strong interaction

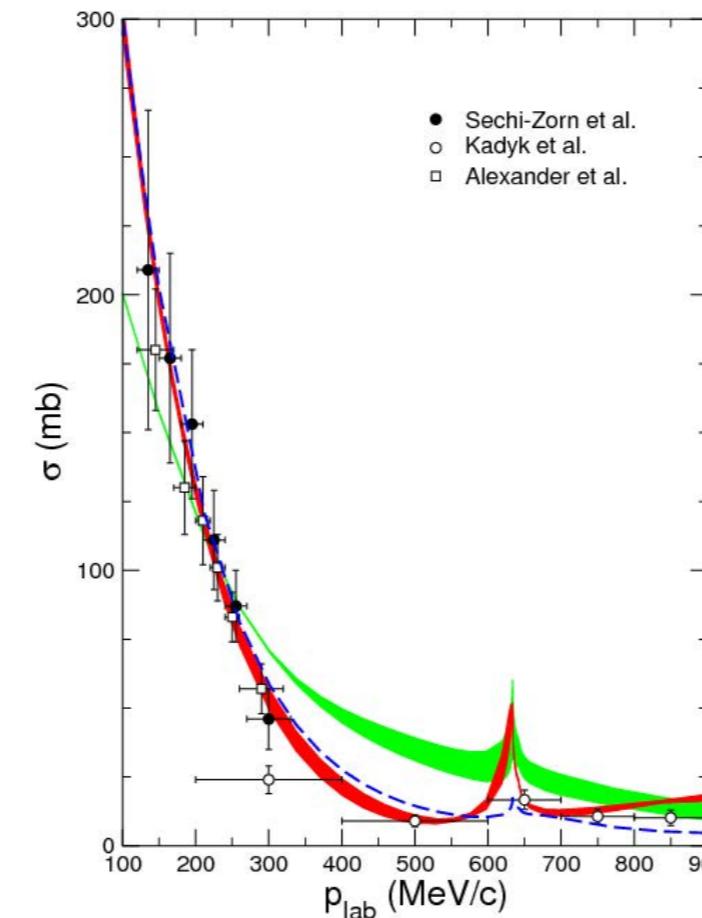
2-Body Interactions

Normally studied with high precision via scattering experiments

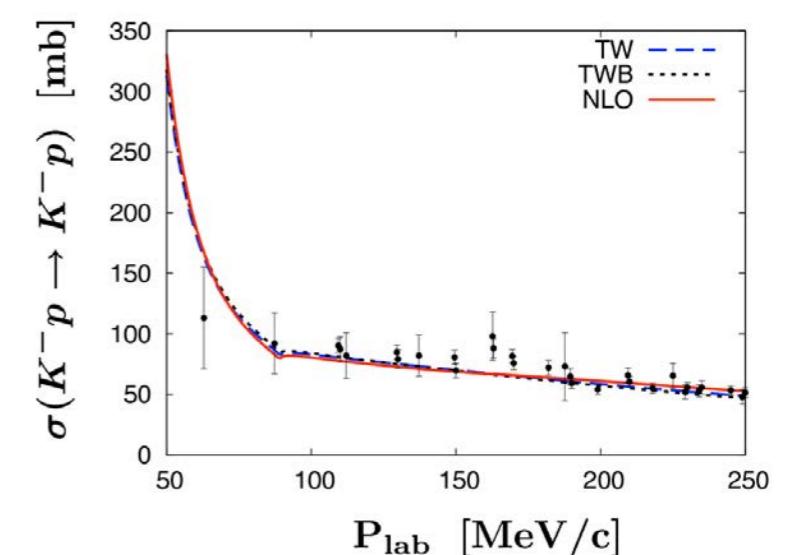
$$NN \rightarrow NN$$



$$\Lambda p \rightarrow \Lambda p$$



$$K^- p \rightarrow K^- p$$



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

Y. Ikeda et al., Nucl. Phys. A881, 98-114 (2012) .

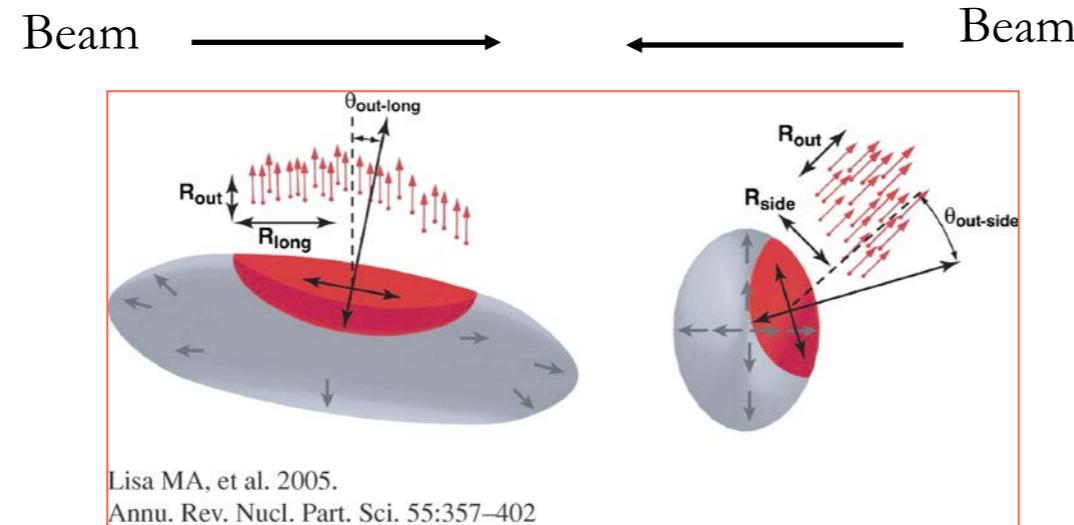
F. Eisele et al. Phys. Lett. B 37, 204-206 (1971)
G. Alexander et al., Phys. Rev. 173, 1452-1560 (1968)
B. Sechi-Zorn et al. Phys. Rev. 175, 1735-1740 (1968)

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

J. R. Bergervoet et al. Phys. Rev. C 41, 1435 (1990)

V.G.J. Stokes et al. Phys. Rev. C 48, 792 (1993)

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



Heavy Ion Collisions

Particle Source:

- Large Abundance of Hadrons composed of u, d, s quarks
- **Time evolution** of the fireball determines the particle source. QGP dynamics, initial state and collective effects
- Average intra-hadron distances of **3-5 fm**
- Different freeze-out times for hadrons?

ALICE Coll., Phys. Rev. C96, 064613 (2017)

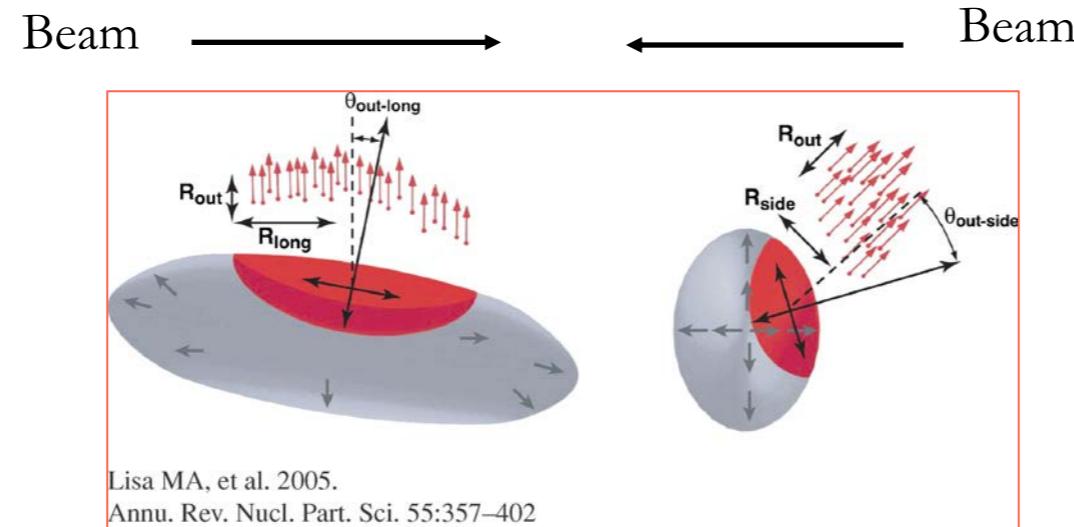
A. Kisiel Phys. Rev. C 98, 044909 (2018)

→ Kaons: 2.1 fm/c **delay** w.r.t. pions

pp and pPb Collisions

Particle Source:

- Less hadrons pro collisions
- No QGP formation, **less complex** time evolution?
- Average intra-hadrons distances of **1 fm?**
- Possible influence of collective effects also in small systems



Heavy Ion Collisions

Particle Source:

- Large Abundance of Hadrons composed of u, d, s quarks
- **Time evolution** of the fireball determines the particle source. QGP dynamics, initial state and collective effects
- Average intra-hadron distances of **3-5 fm**
- Different freeze-out times for hadrons?

ALICE Coll., Phys. Rev. C96, 064613 (2017)

A. Kisiel Phys. Rev. C 98, 044909 (2018)

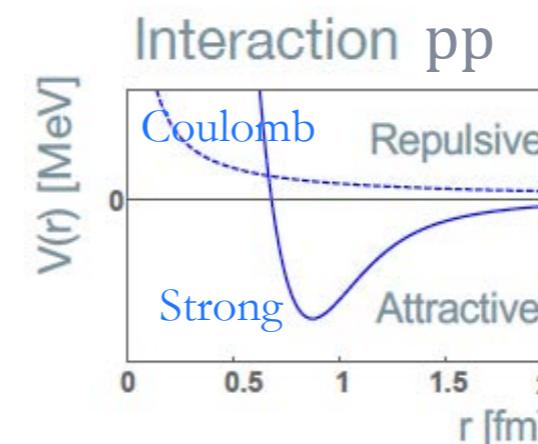
→ Kaons: 2.1 fm/c **delay** w.r.t. pions

-> Pioneering studies for interactions

pp and pPb Collisions

Particle Source:

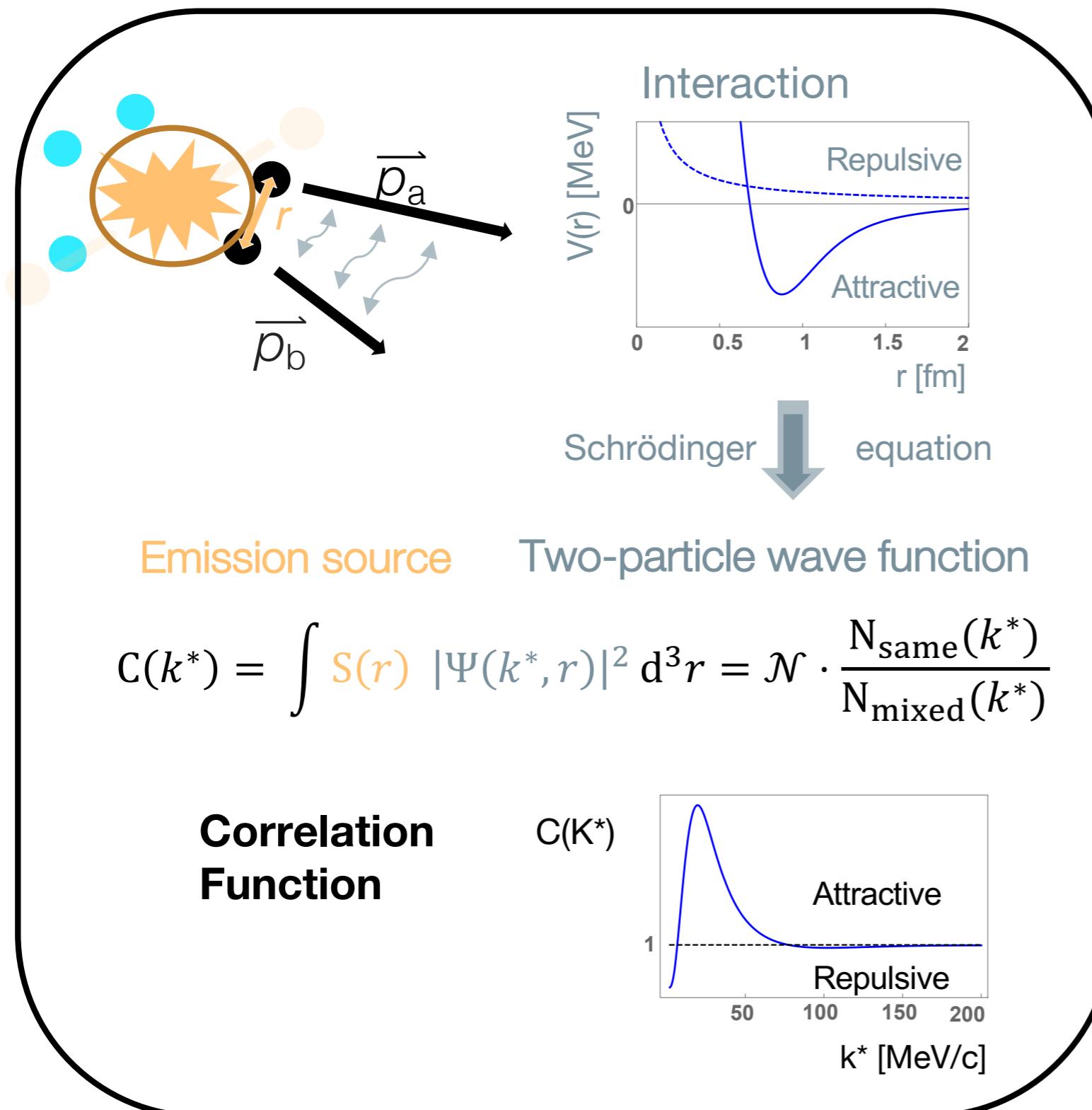
- Less hadrons pro collisions
- No QGP formation, **less complex** time evolution?
- Average intra-hadrons distances of **1 fm?**
- Possible influence of collective effects also in small systems



-> Small colliding systems could be useful to study the strong interaction

The Correlation Function

CATS: D.L.Mihaylov et al. Eur.Phys.J. C78, 394 (2018)



In pp and pPb collisions at the LHC:

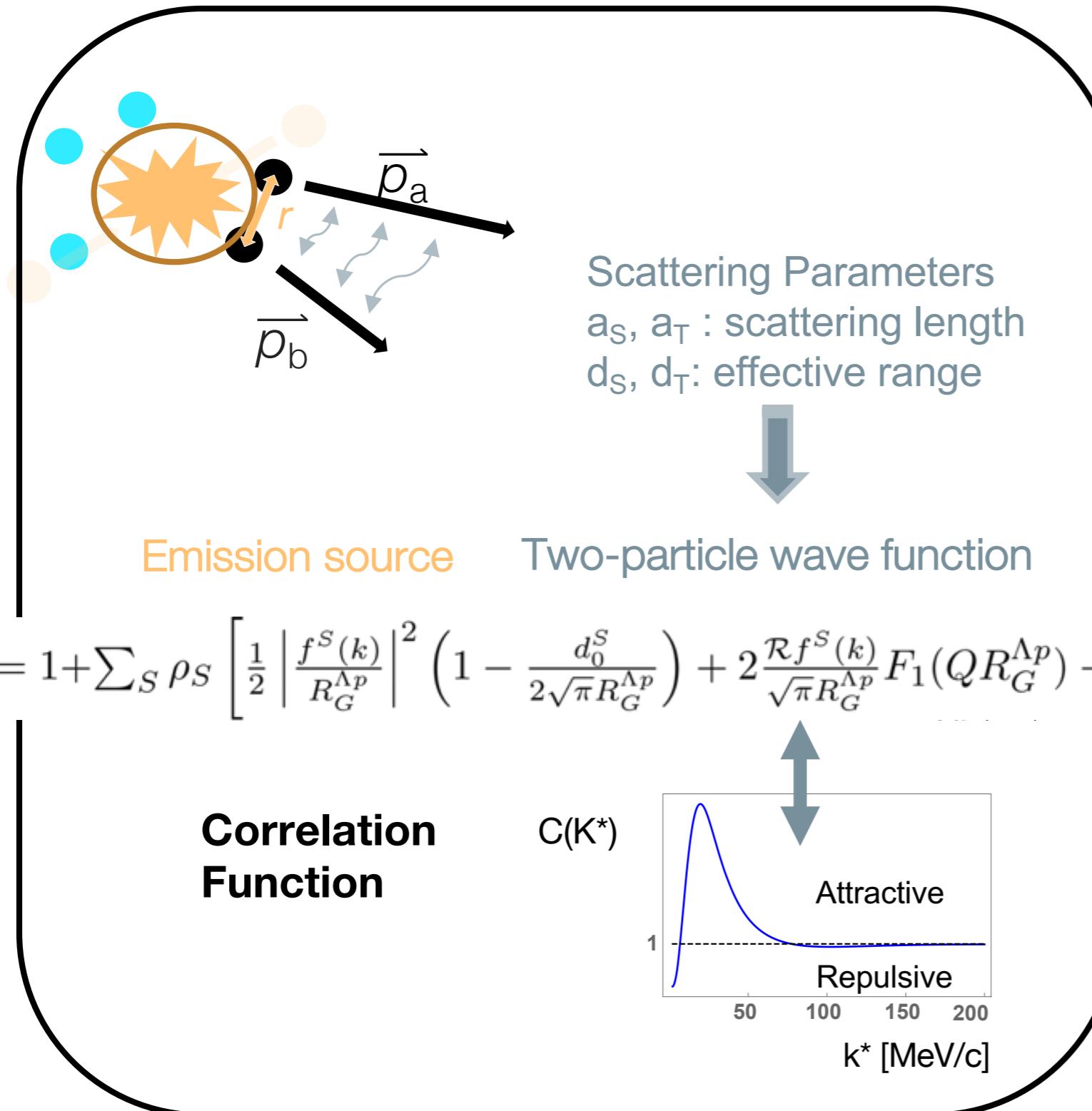
1D Emission source determined using the K^+p and pp correlations as **benchmarks**

K^+p : benchmark for $K-p$

pp : m_T -dependent source determination including decays of strong resonances, benchmark for Λp , $\Lambda\Lambda$, Σp , Ξp and Ωp

The Correlation Function

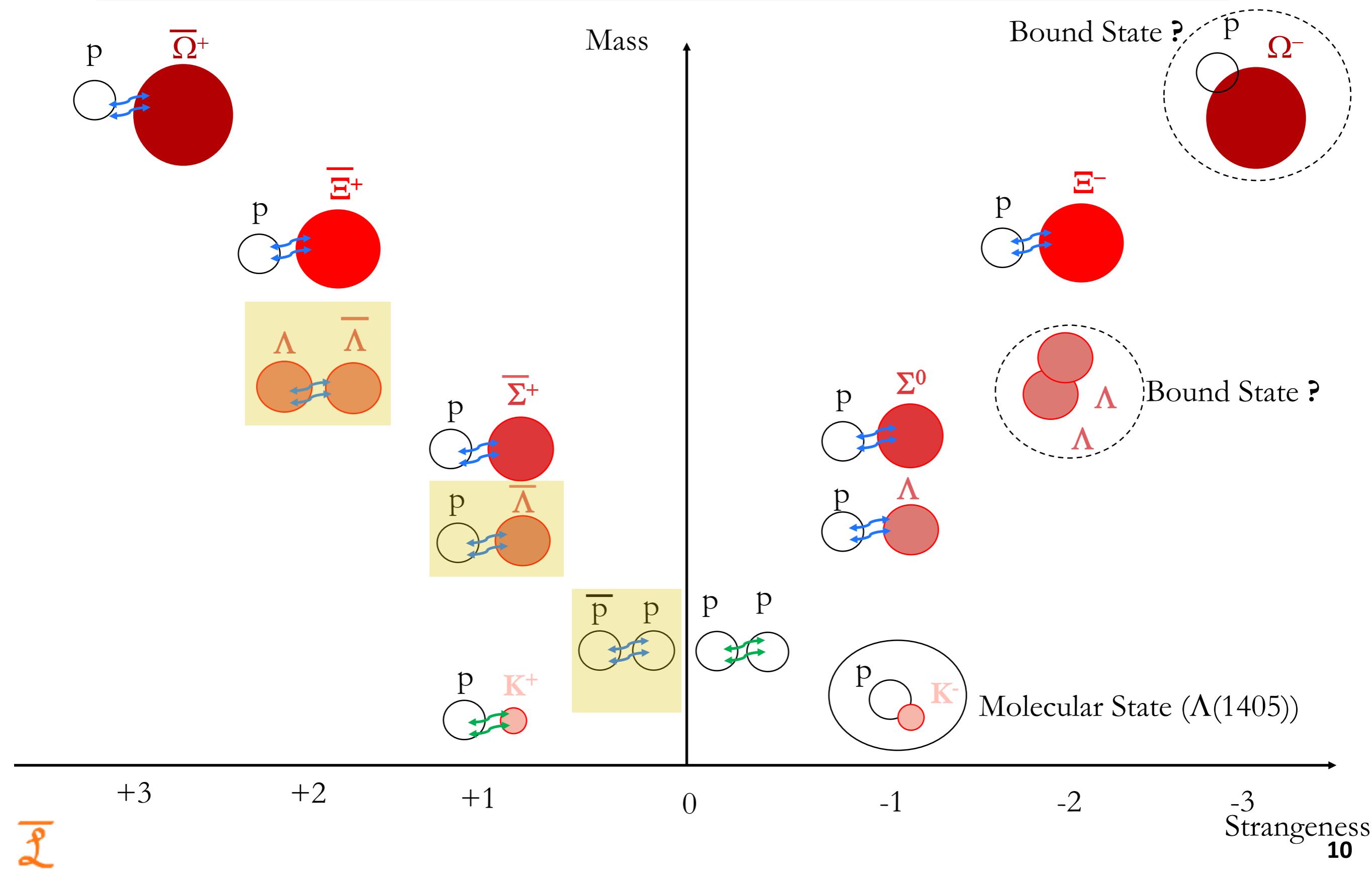
R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. 35, 770 (1982)



In Heavy Ion collisions:

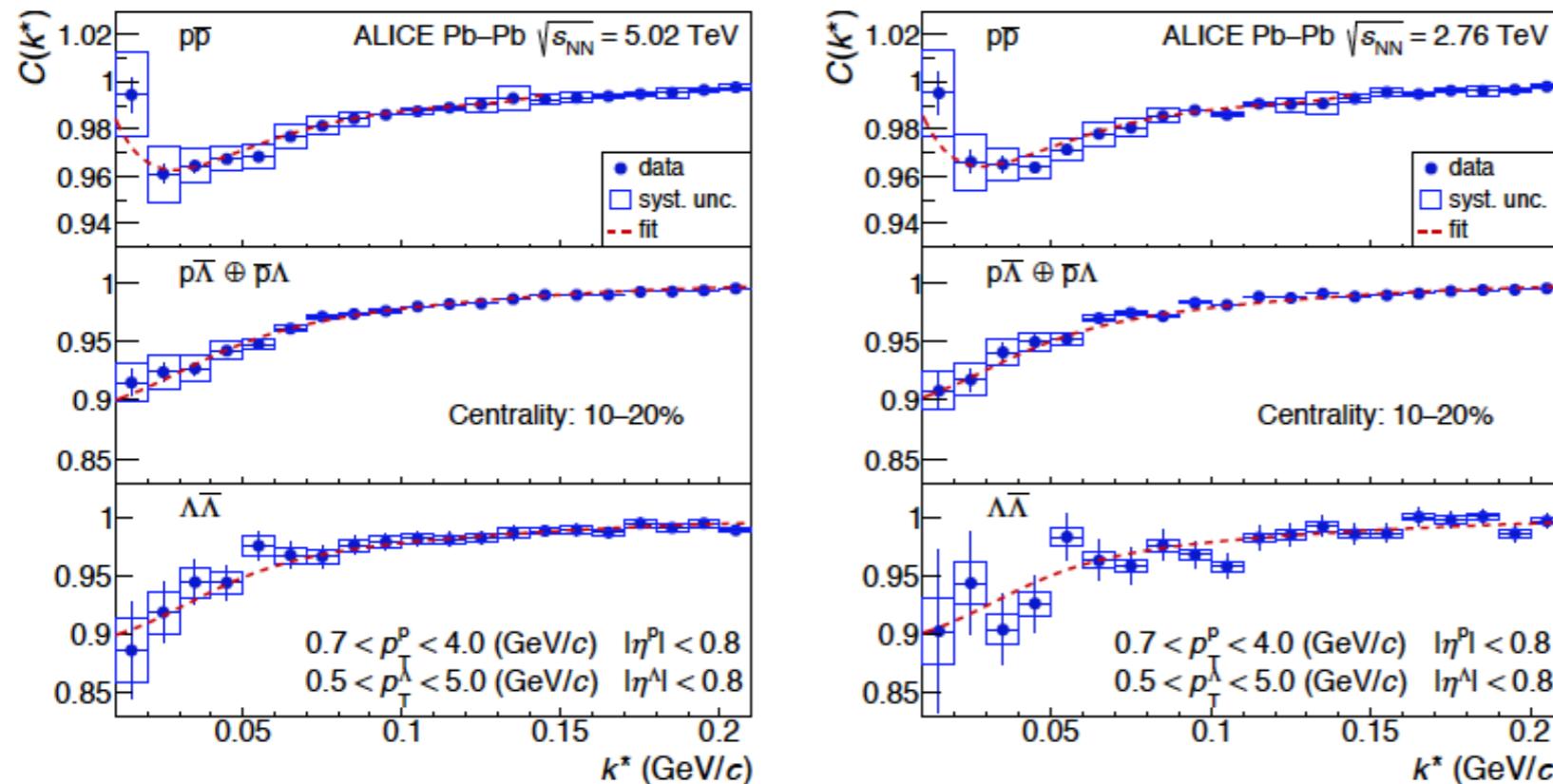
Analytical Formula used to fit the experimental correlation function with different source assumptions:

- 3D Gaussian Source
- 3D Expanding Source (Flow effects)
A. Kisiel et al., Phys. Rev. C73, 064902 (2006)
- 3D Levy Source
Phenix Coll., Phys. Rev. C97, 064911 (2018)



New Baryon-AntiBaryon Scattering Parameters

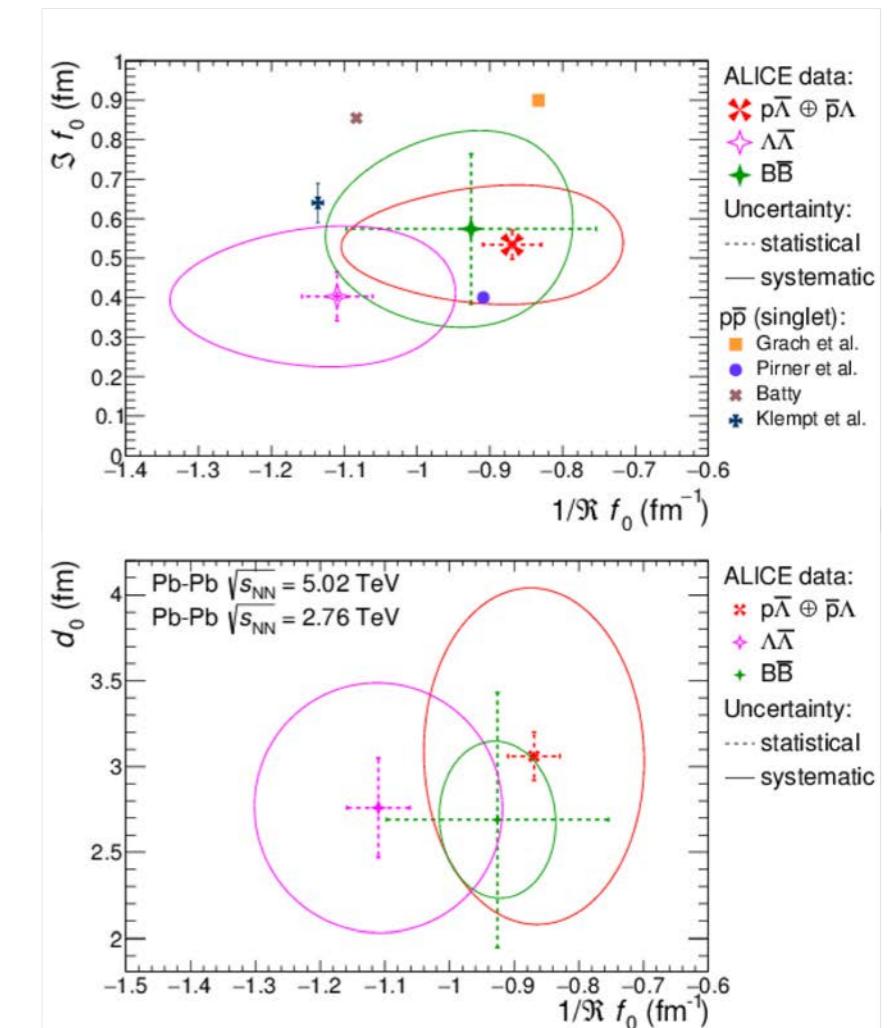
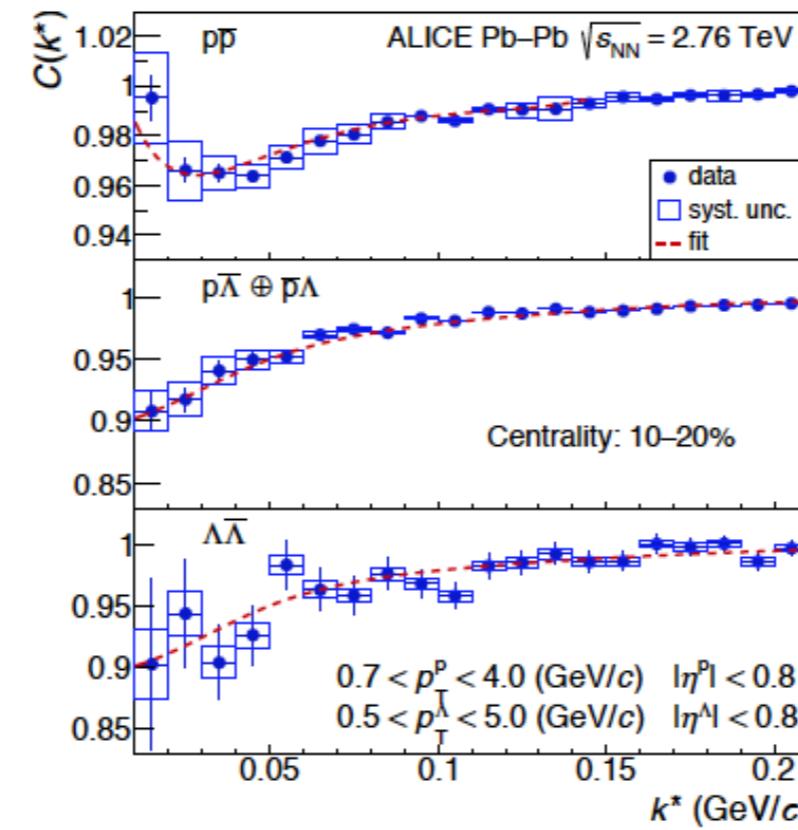
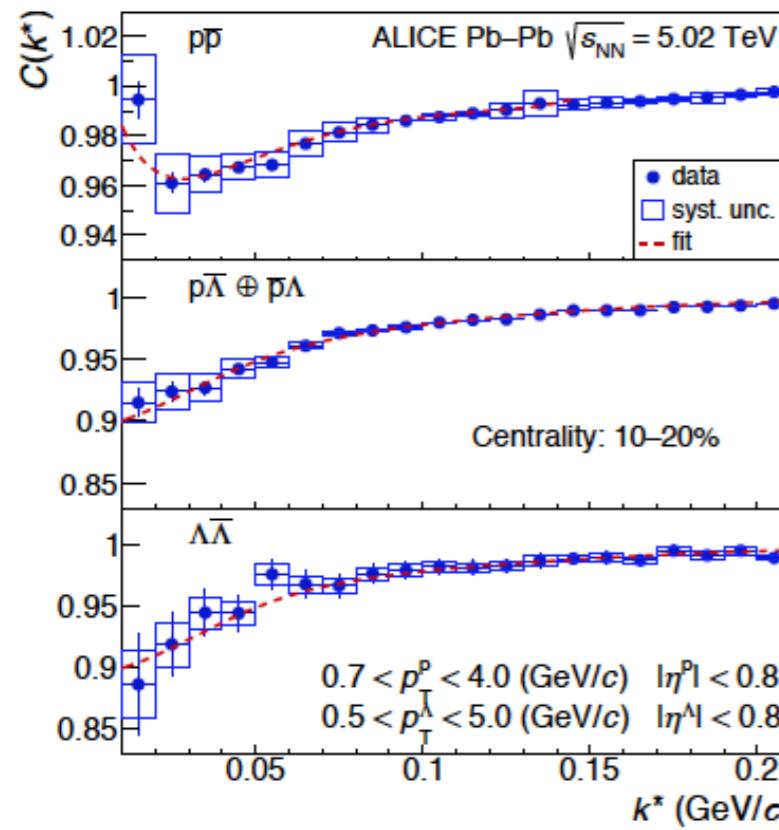
ALICE Coll., arXiv:1903.06149



- Lednicky Fit with static Gaussian Source
- Radius fixed by previous measurements
ALICE Coll., Phys. Rev. C 92 no. 5, 054908 (2015)
- Iterative procedure to account for all feed-down contribution
- Scattering parameter for $\bar{p}p$ taken from:
C. J. Batty, *Rept. Prog. Phys.* 52 (1989) 1165–1216.

New Baryon-AntiBaryon Scattering Parameters

ALICE Coll., arXiv:1903.06149



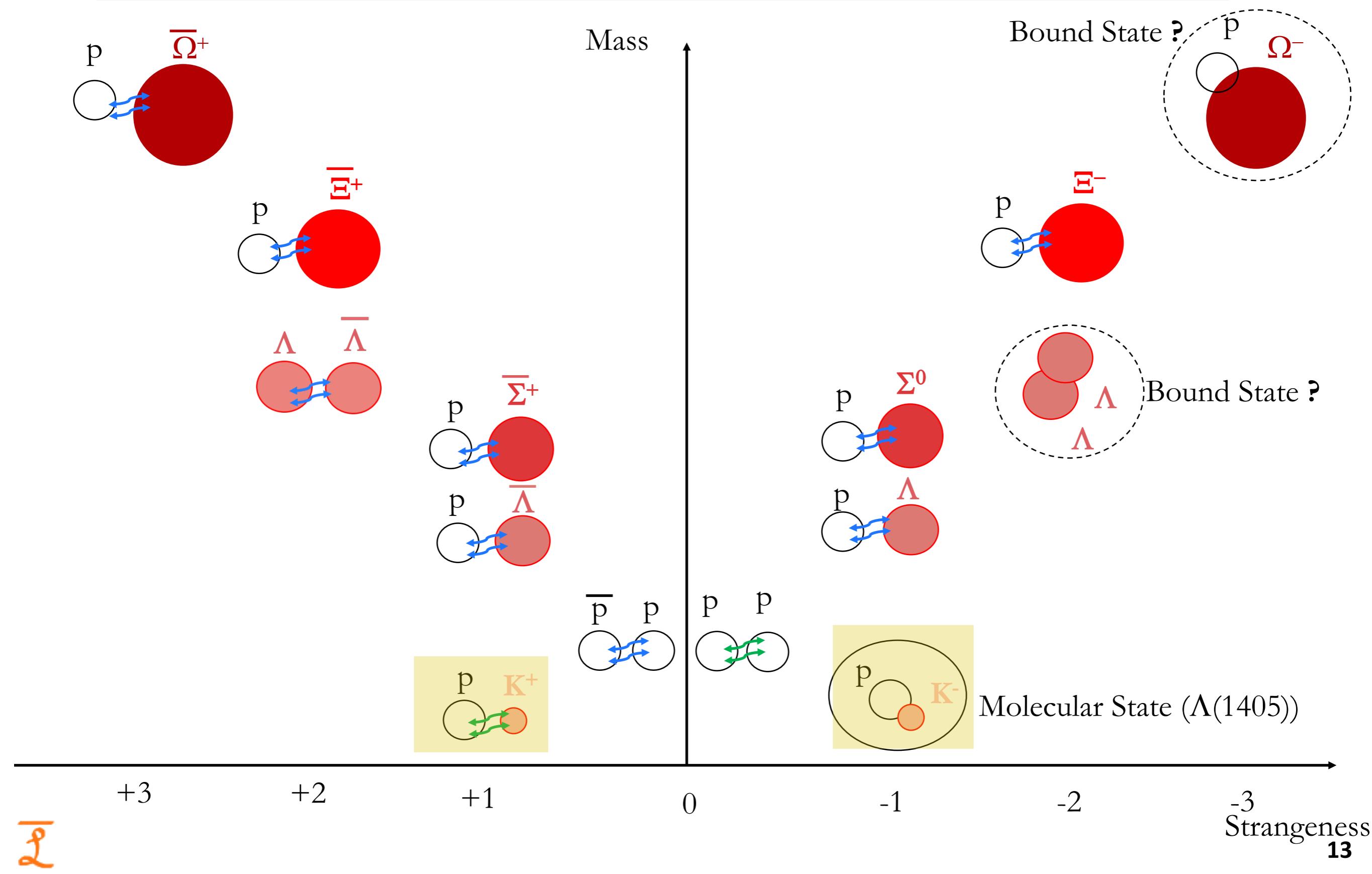
- Lednicky Fit with static Gaussian Source
- Radius fixed by previous measurements
ALICE Coll., Phys. Rev. C 92 no. 5, 054908 (2015)
- Iterative procedure to account for all feed-down contribution
- Scattering parameter for $\bar{p}p$ taken from:
C. J. Batty, *Rept. Prog. Phys.* 52 (1989) 1165–1216.

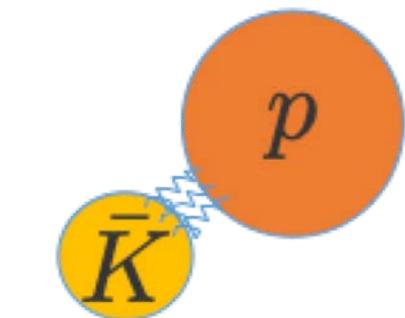
Large Imaginary Part:

→ Absorption

Negative real scattering parameter:

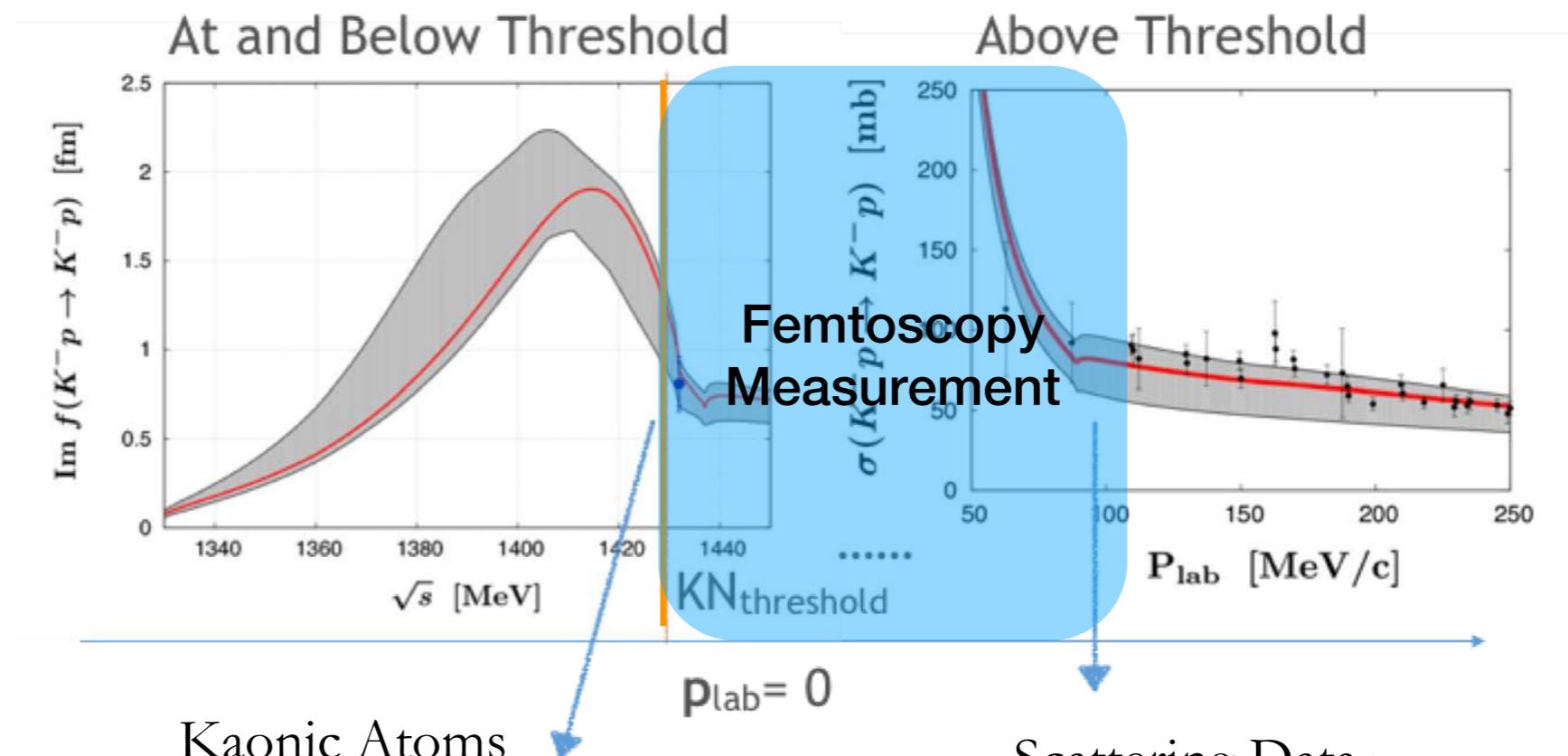
→ Repulsion, Fading-away of coupled channel or presence of a bound state





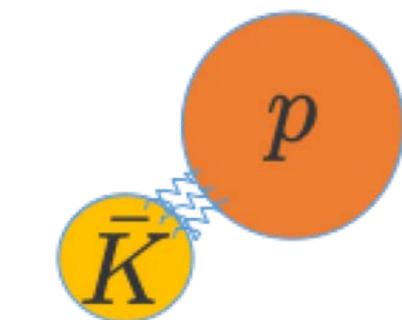
Bound state?
 $\Lambda(1405)$

Y. Ikeda et al., Nucl. Phys. A881 98-114 (2012)



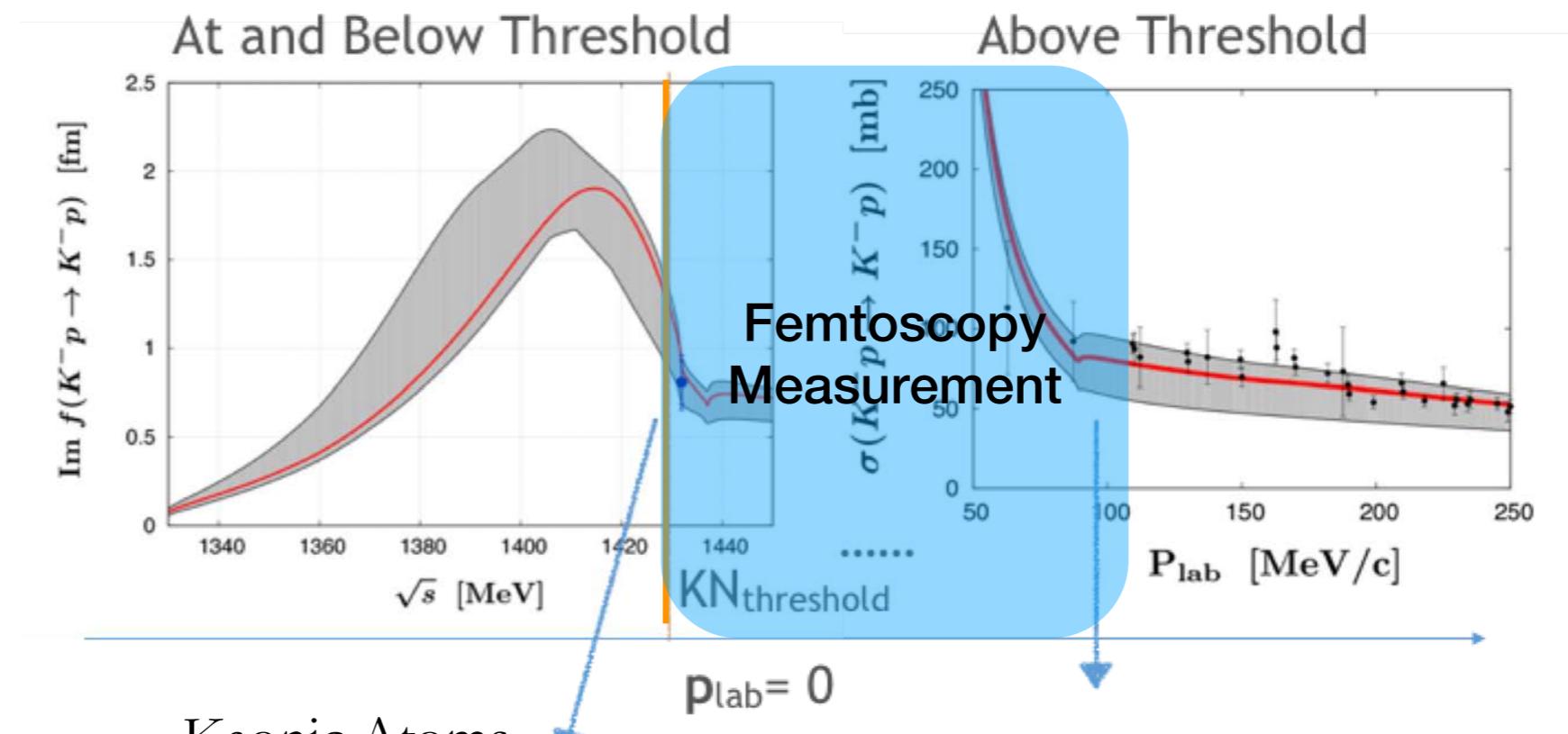
Siddharta Coll., Phys. Lett. B704 (2011)

G. S. Abrams et al., Phys. Rev. 139, B454-B457 (1965)



Bound state?
 $\Lambda(1405)$

Y. Ikeda et al., Nucl. Phys. A881 98-114 (2012)



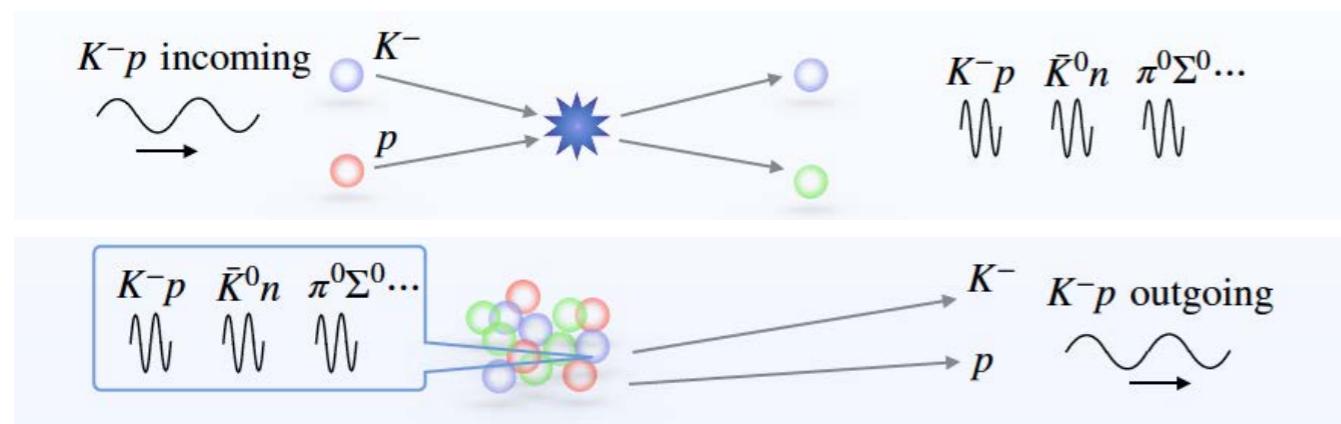
Kaonic Atoms

Siddharta Coll., Phys. Lett. B704 (2011)

Scattering Data

G. S. Abrams et al., Phys. Rev. 139, B454-B457 (1965)

Coupled-channel Interaction



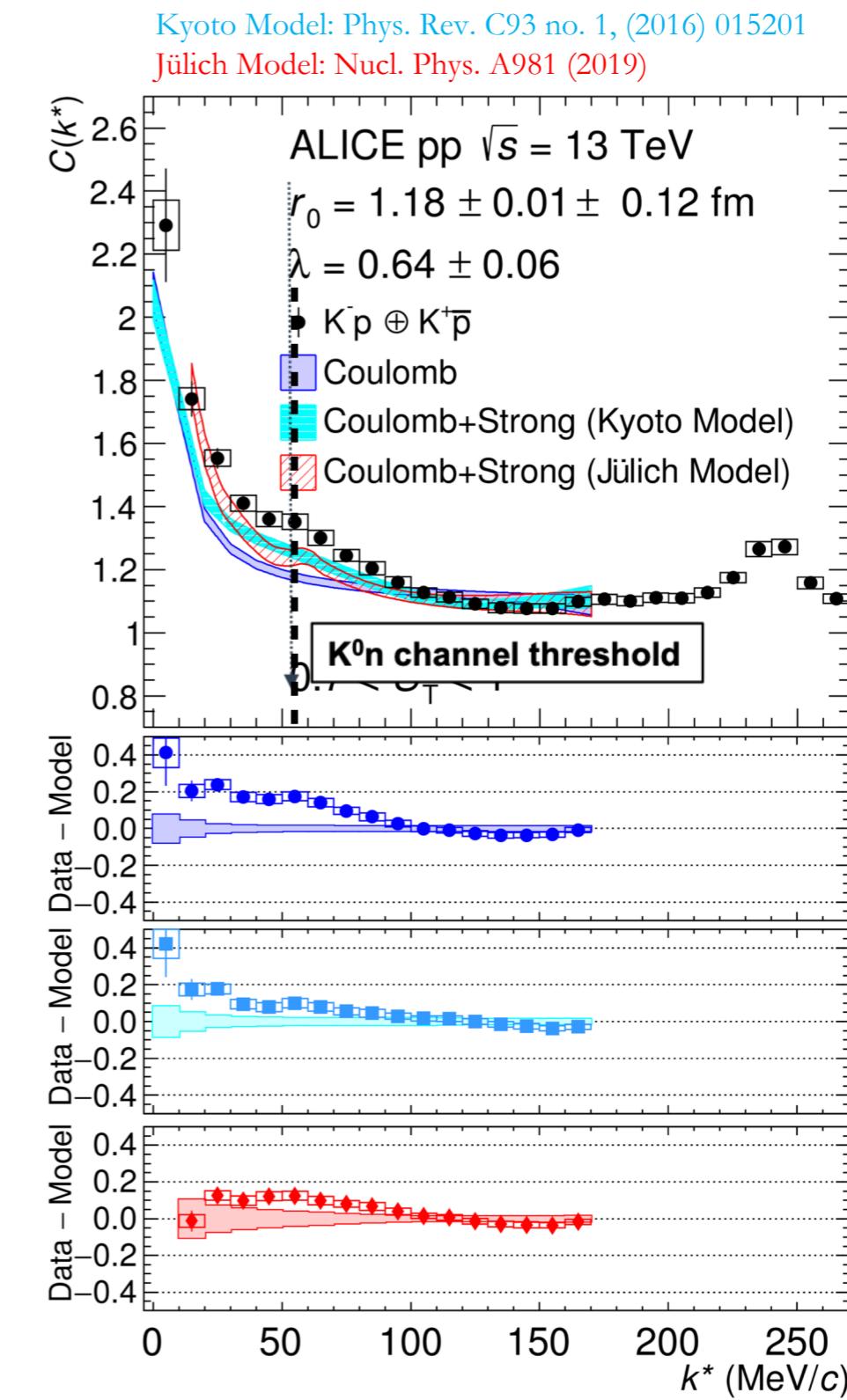
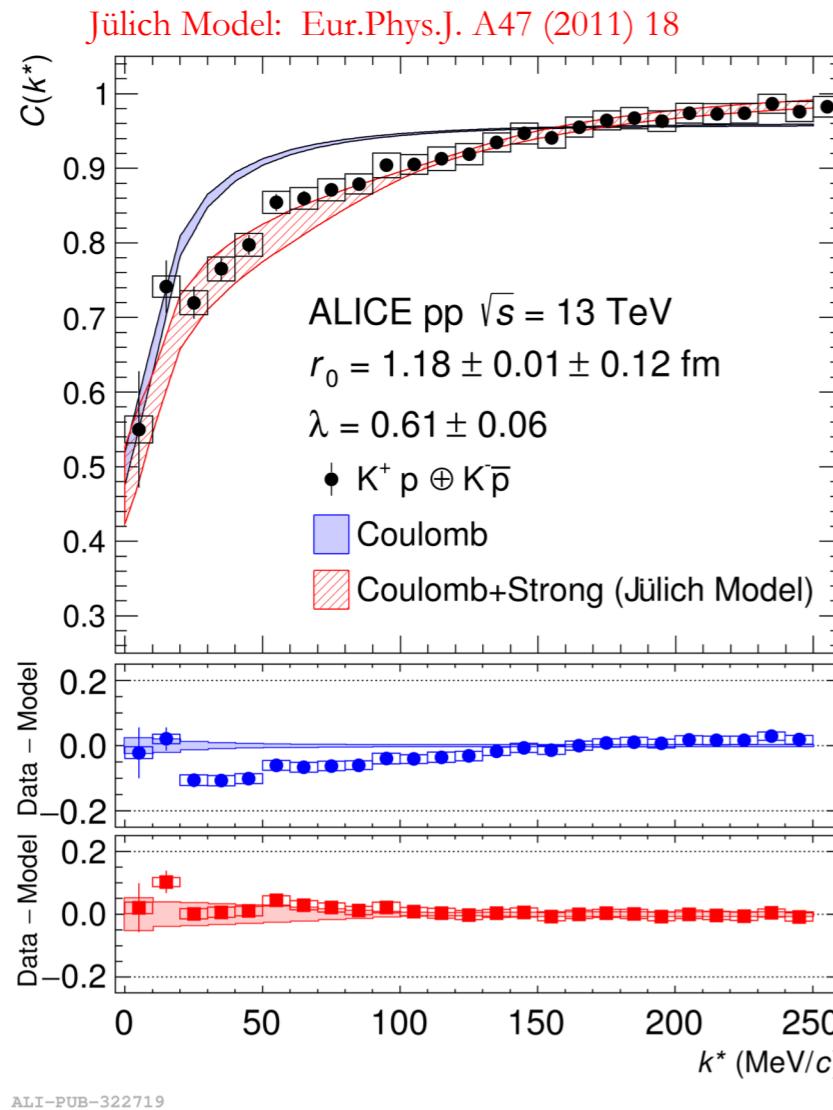
Courtesy Y. Kamiya

-> Since different initial states are produced at colliders, one can test **directly** the coupling

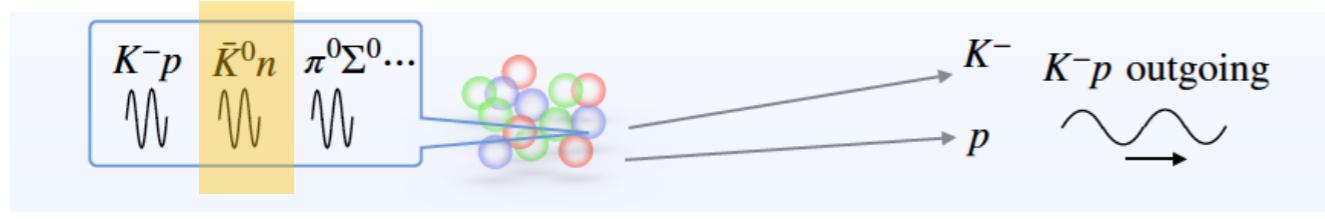


K⁻p Interaction: Results for pp 13 TeV MB

ALICE Collaboration, arXiv:1905.13470



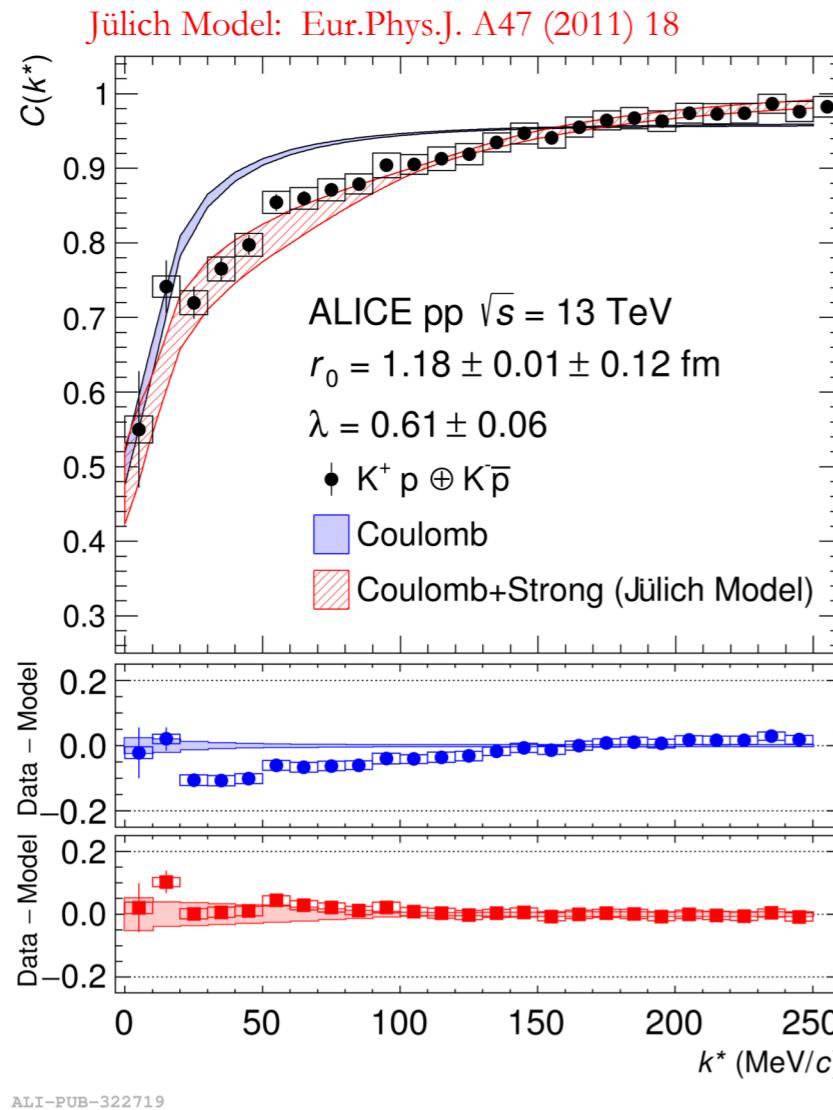
Radius obtained from inclusive pp correlation
K⁺p correlation used as a benchmark to study K⁻p



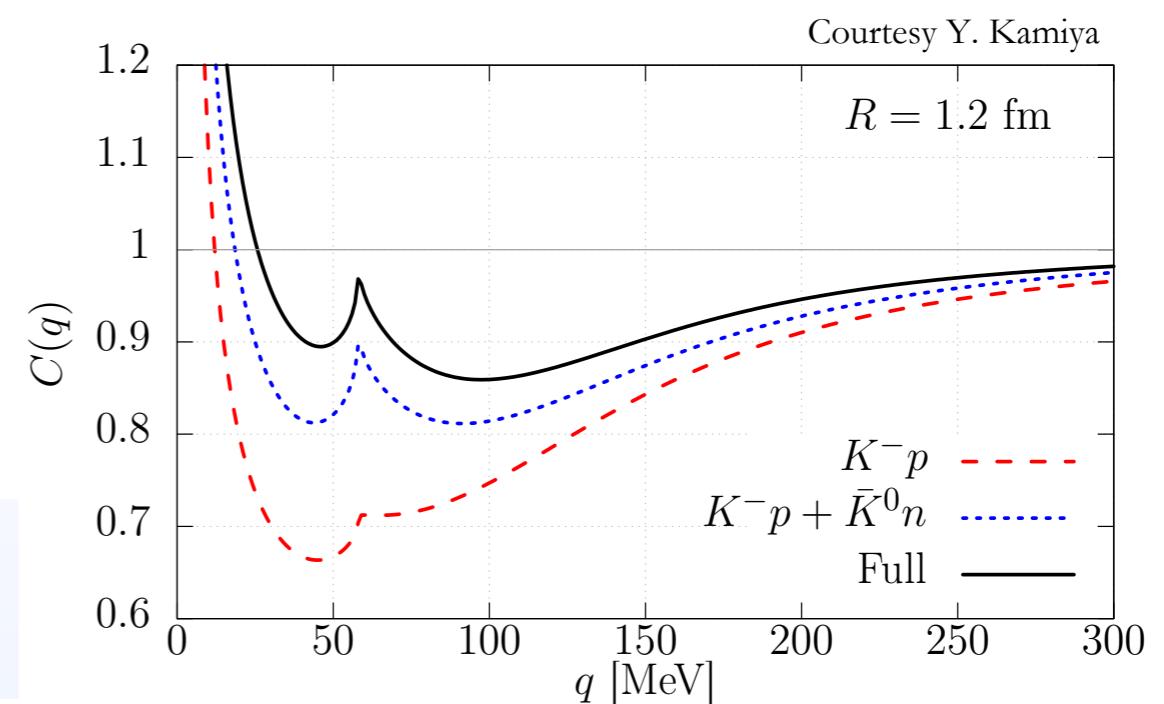
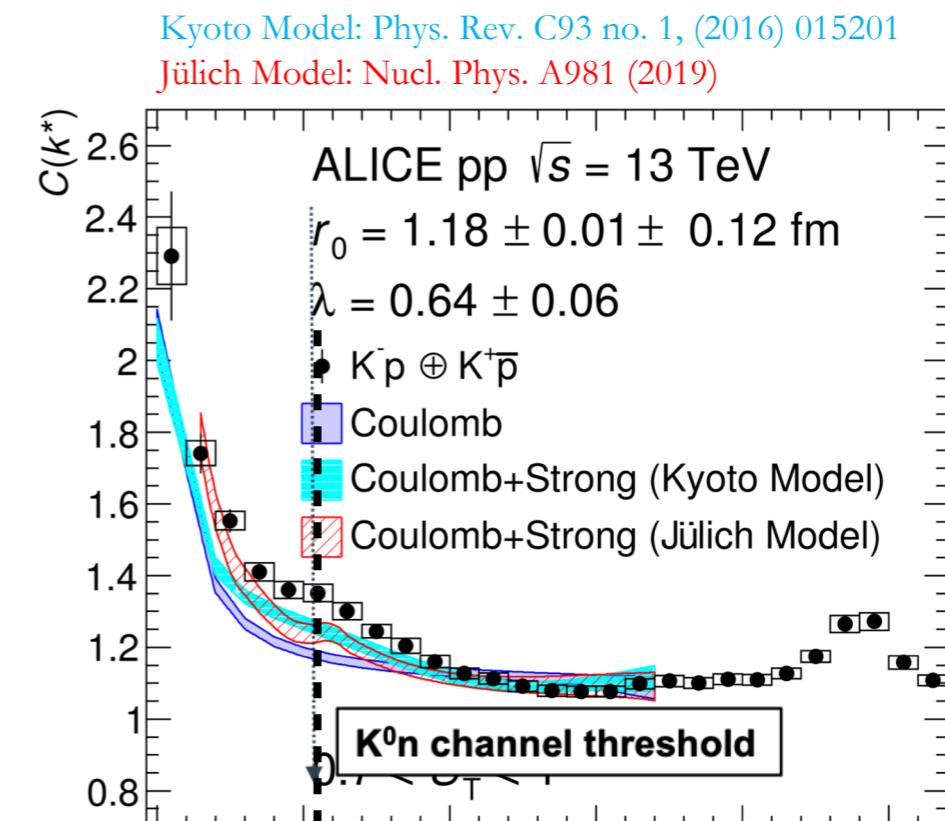
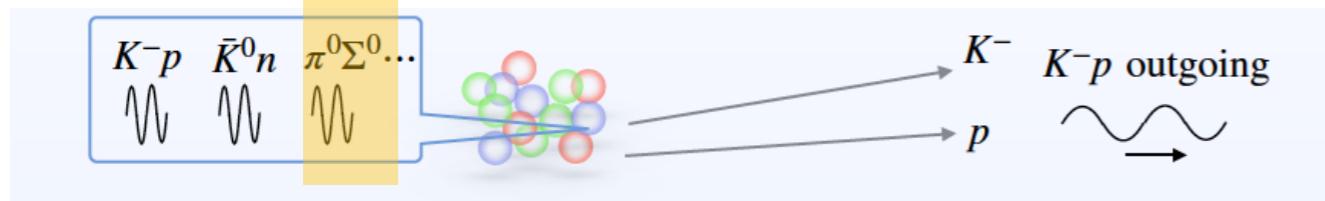


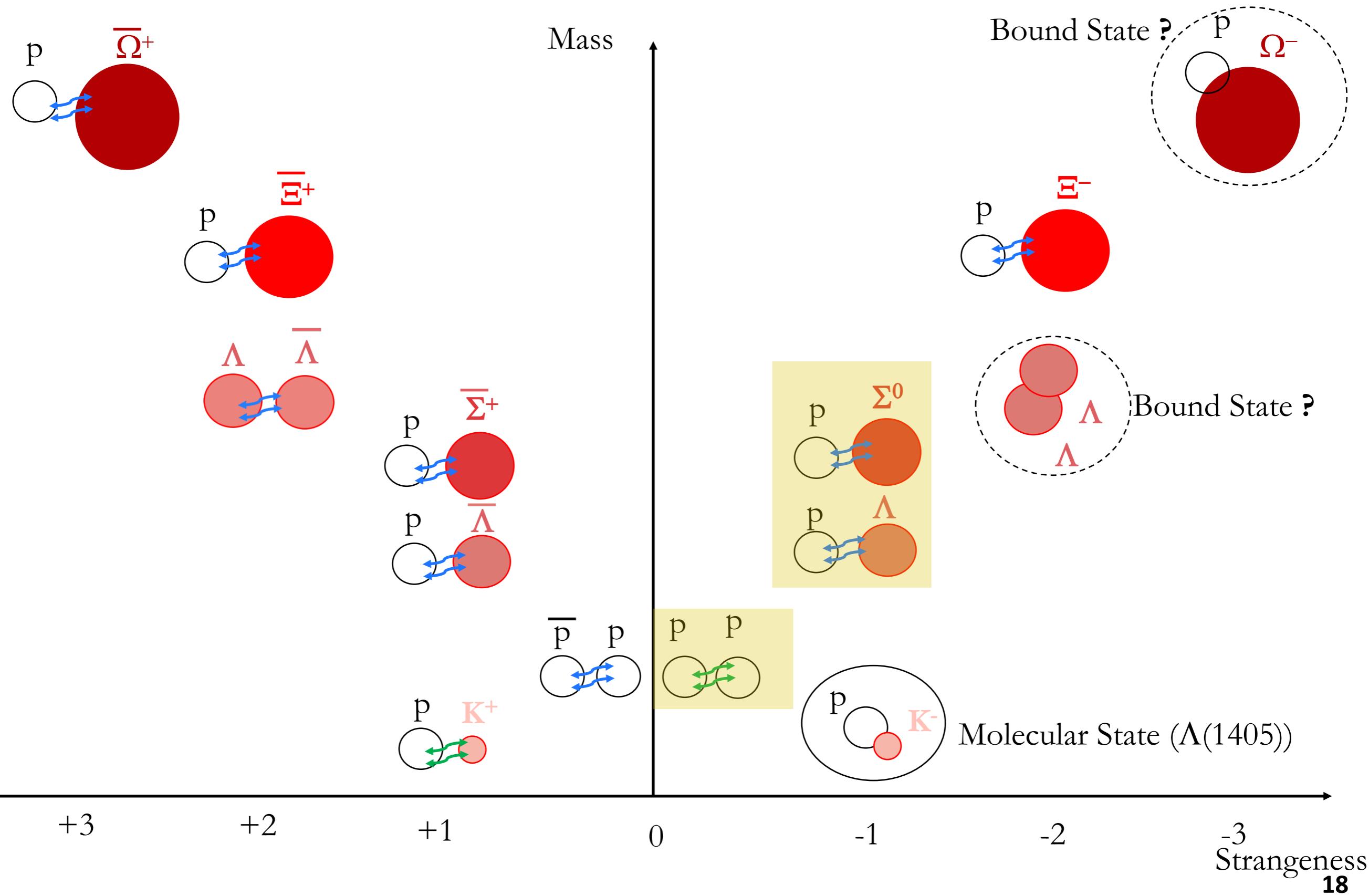
K⁻p Interaction: Results for pp 13 TeV MB

ALICE Collaboration, arXiv:1905.13470

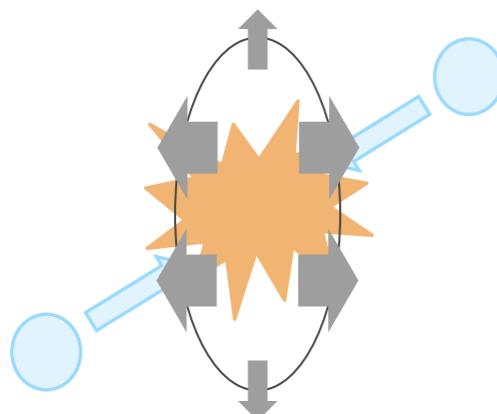


Radius obtained from inclusive pp correlation
K⁺p correlation used as a benchmark to study K⁻p

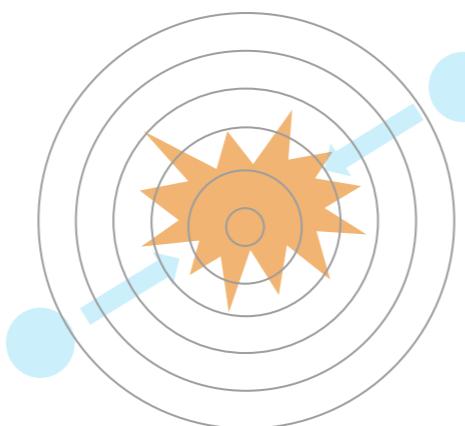




Elliptic flow



Radial flow

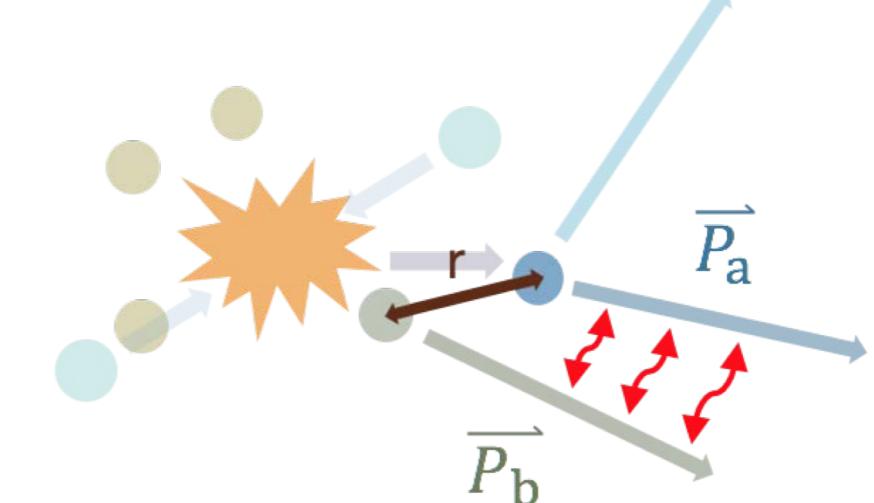


- Anisotropic pressure gradients within the source

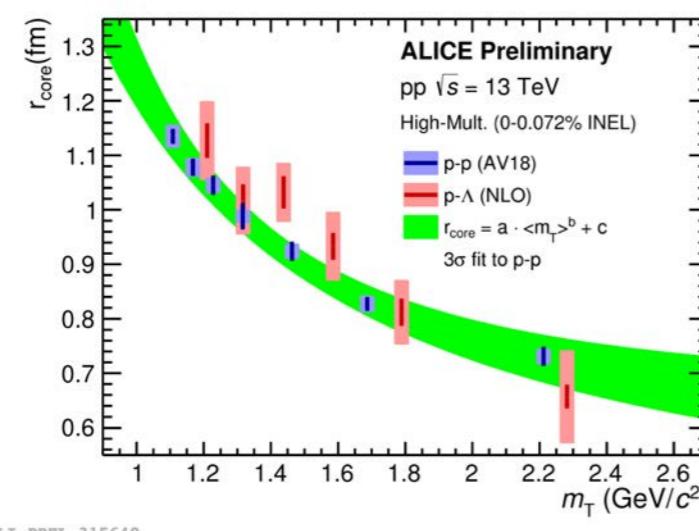
- Expanding source with constant velocity
- Different effect on different masses

Strong decays of broad resonances

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



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

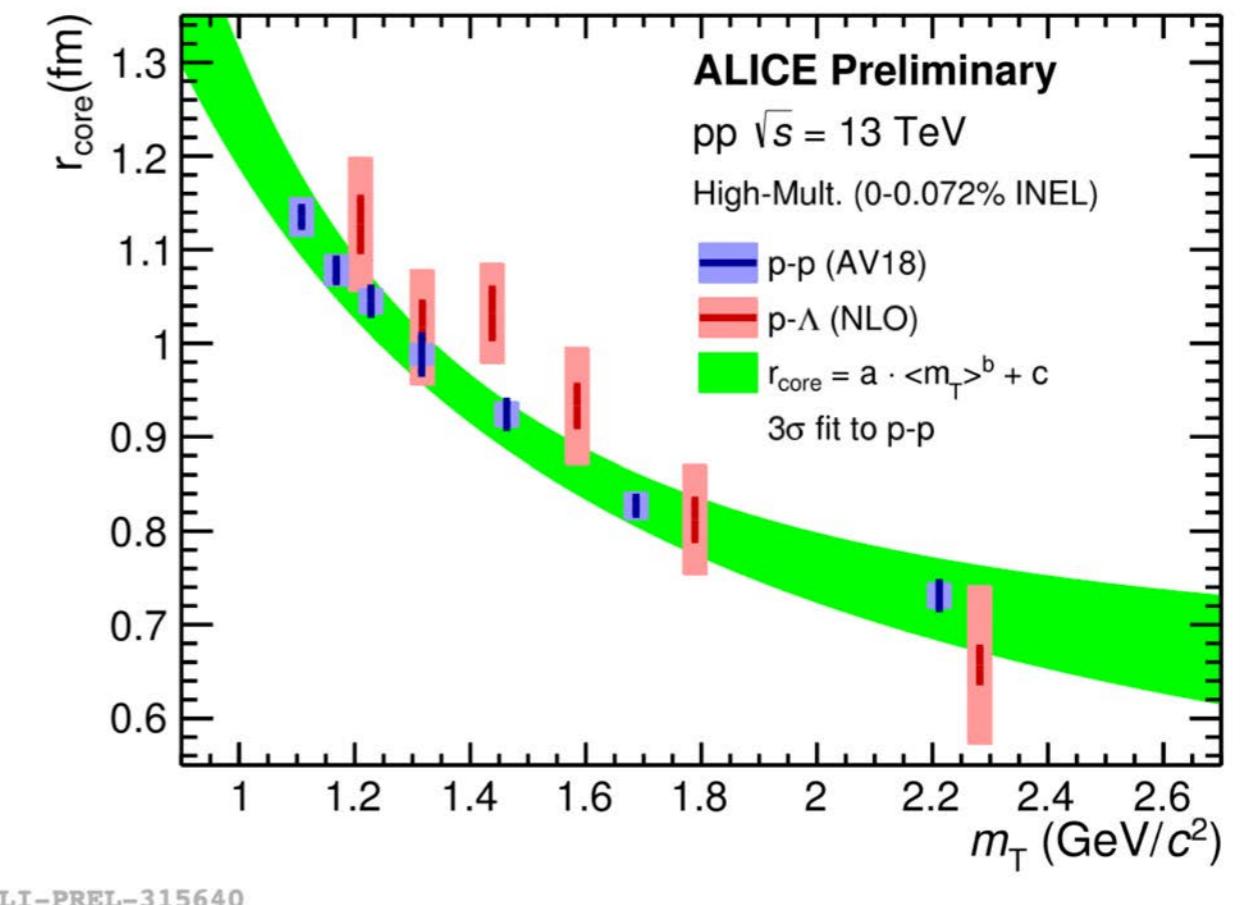
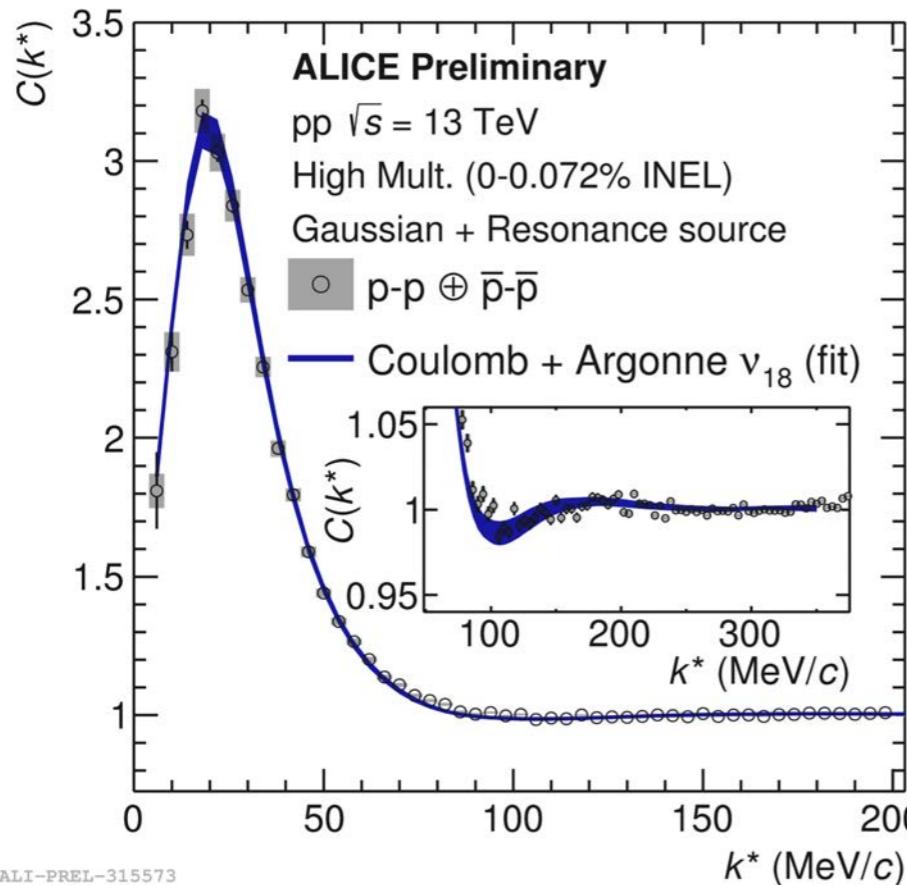


Strong decays of specific resonances

F. Becattini Priv. Comm. And J.Phys. G38 (2011) 025002.

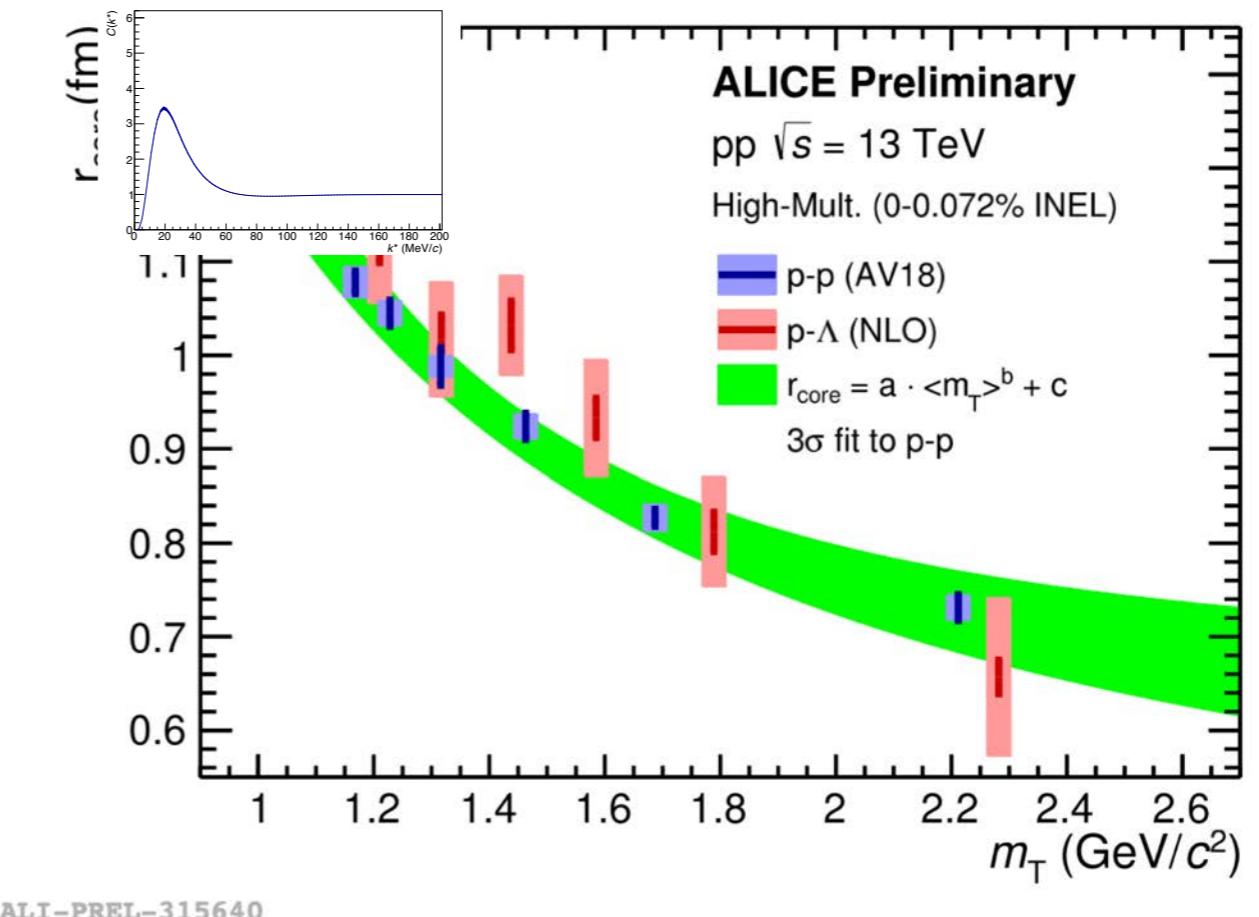
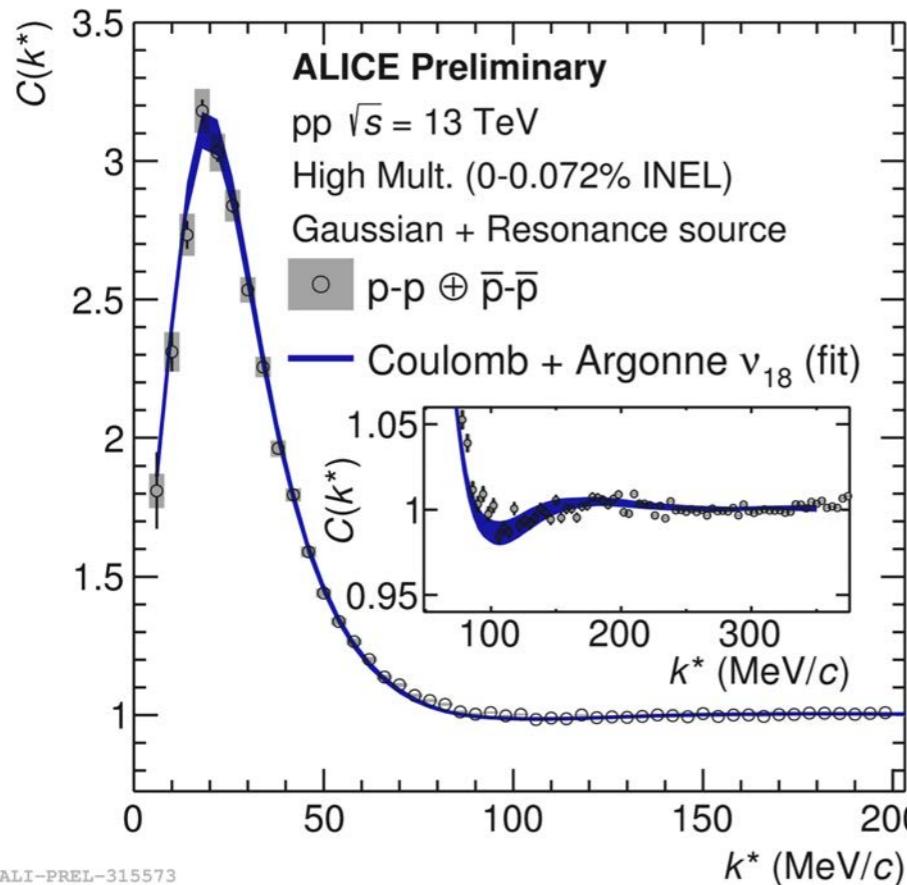
pp Correlations for pp 13TeV HM and Source

Fit with a ‘core’ Gaussian + Resonances



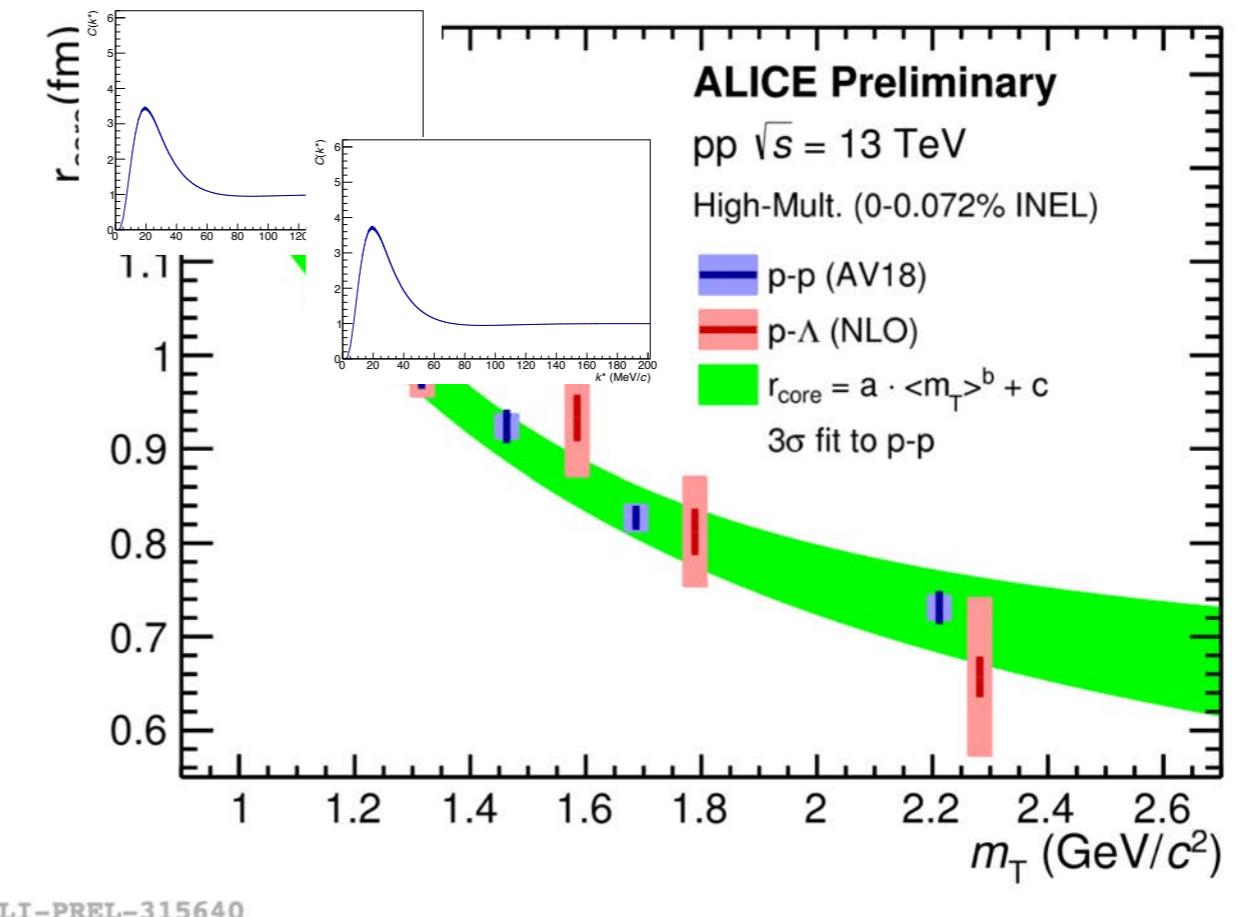
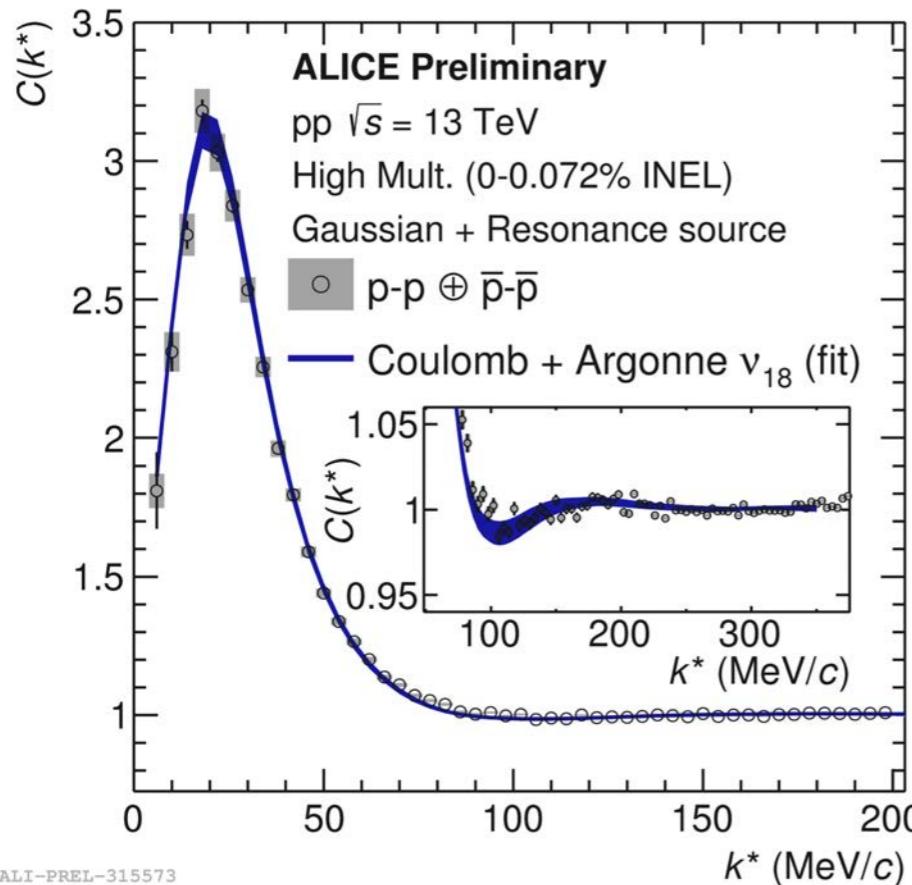
pp Correlations for pp 13TeV HM and Source

Fit with a ‘core’ Gaussian + Resonances



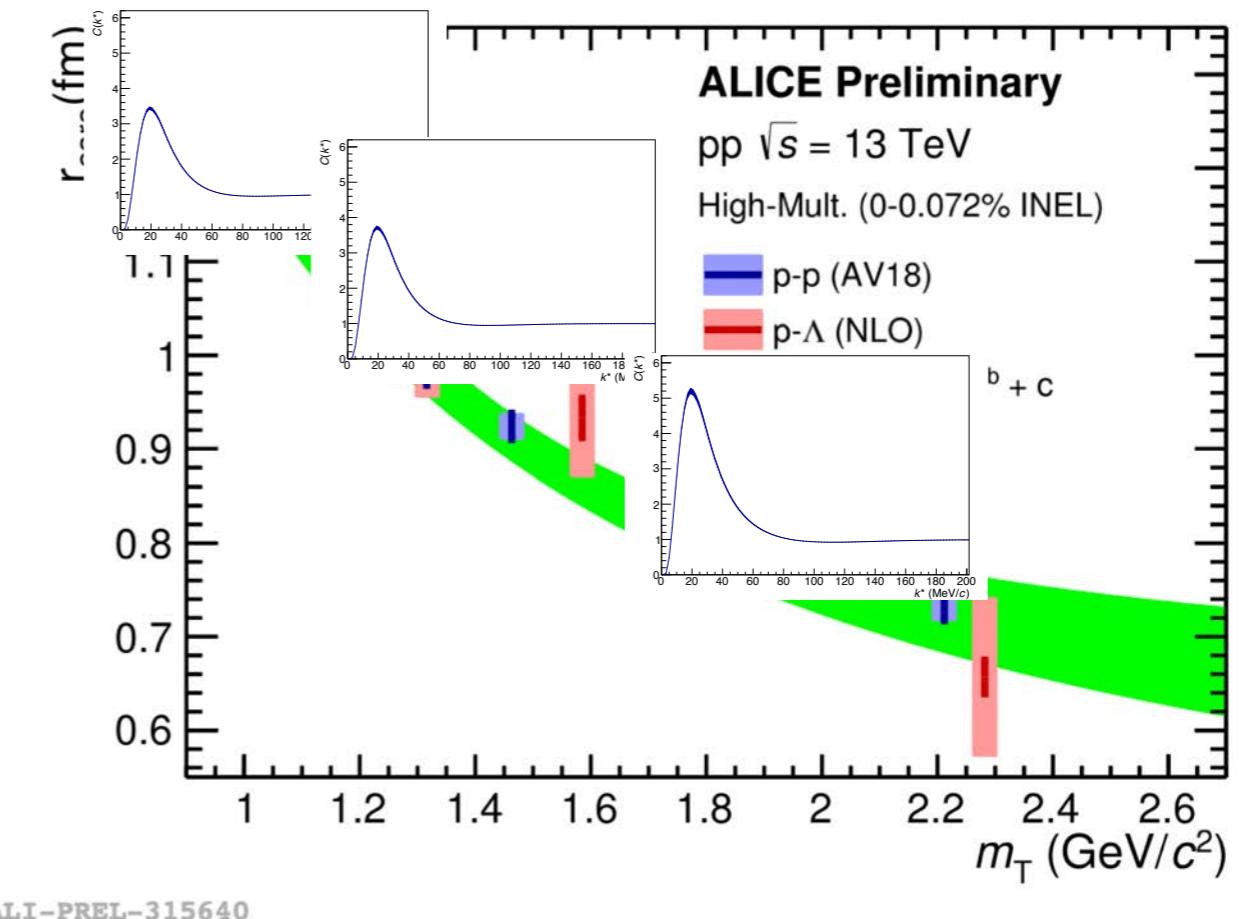
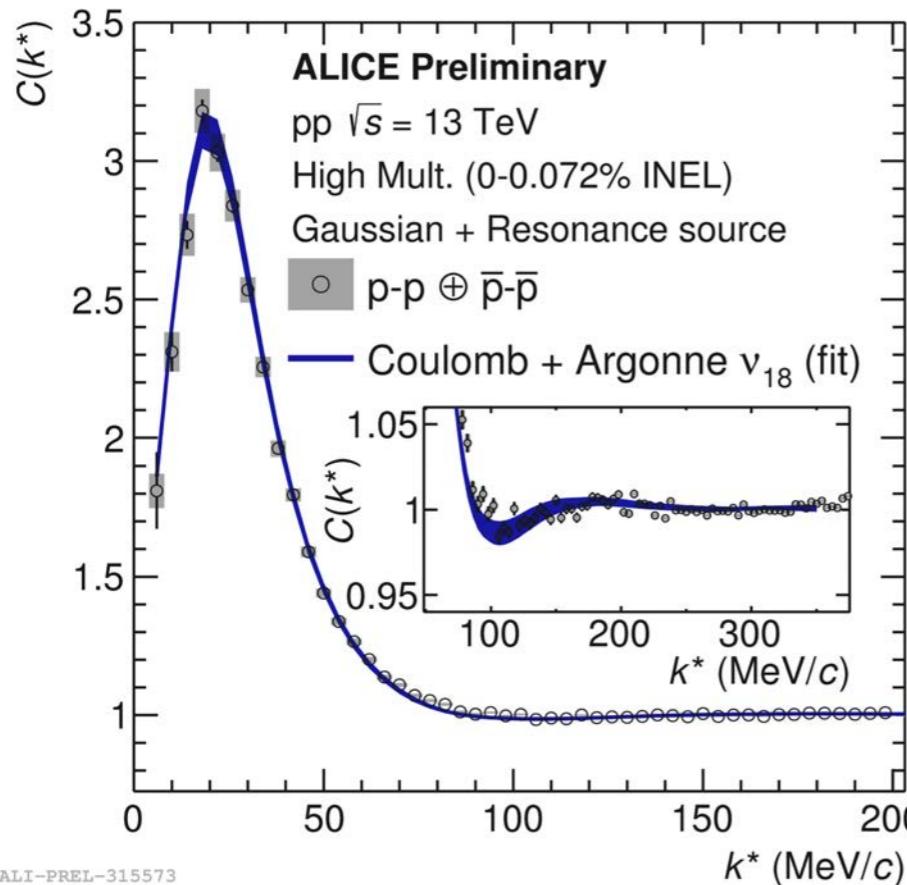
pp Correlations for pp 13TeV HM and Source

Fit with a ‘core’ Gaussian + Resonances



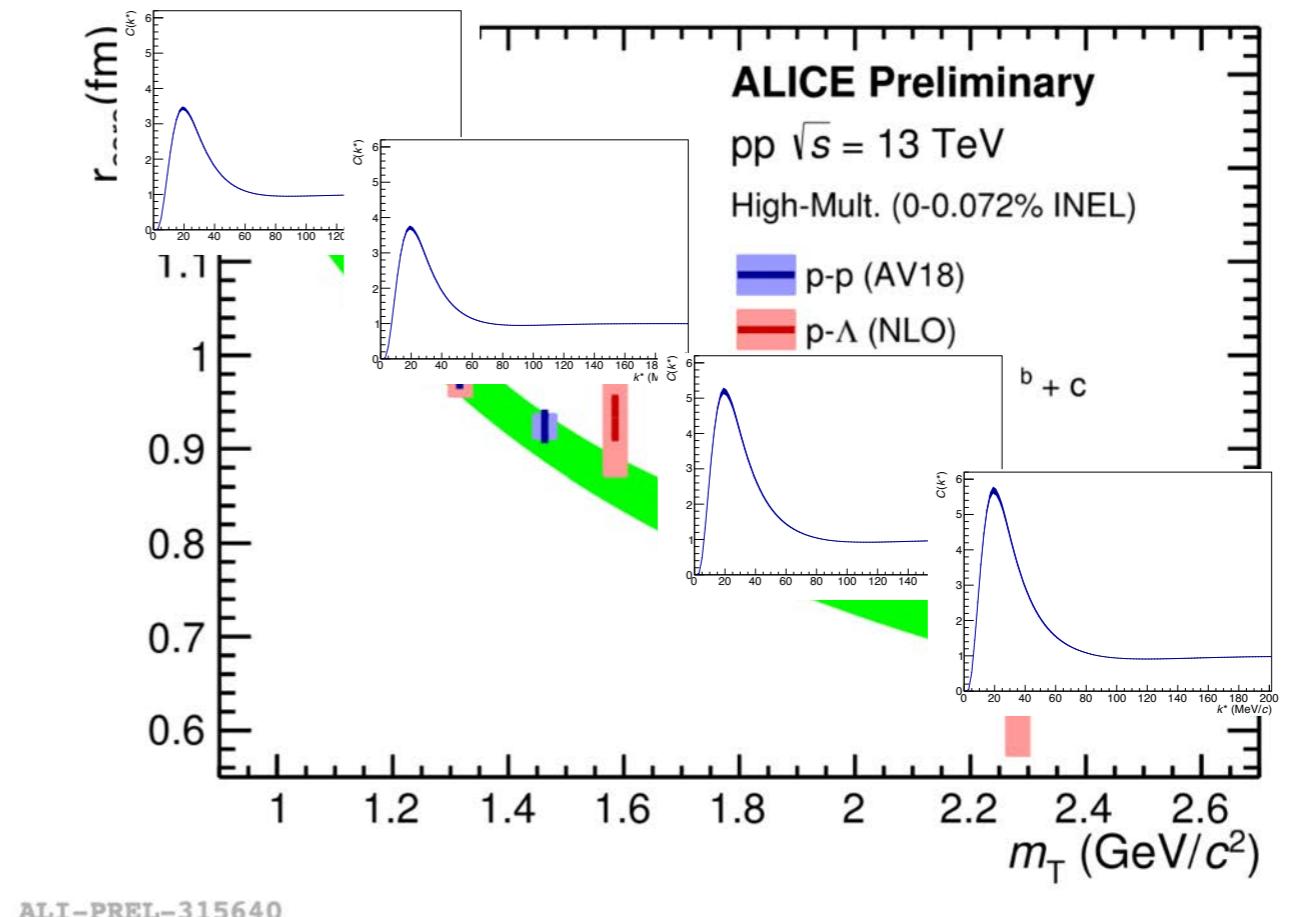
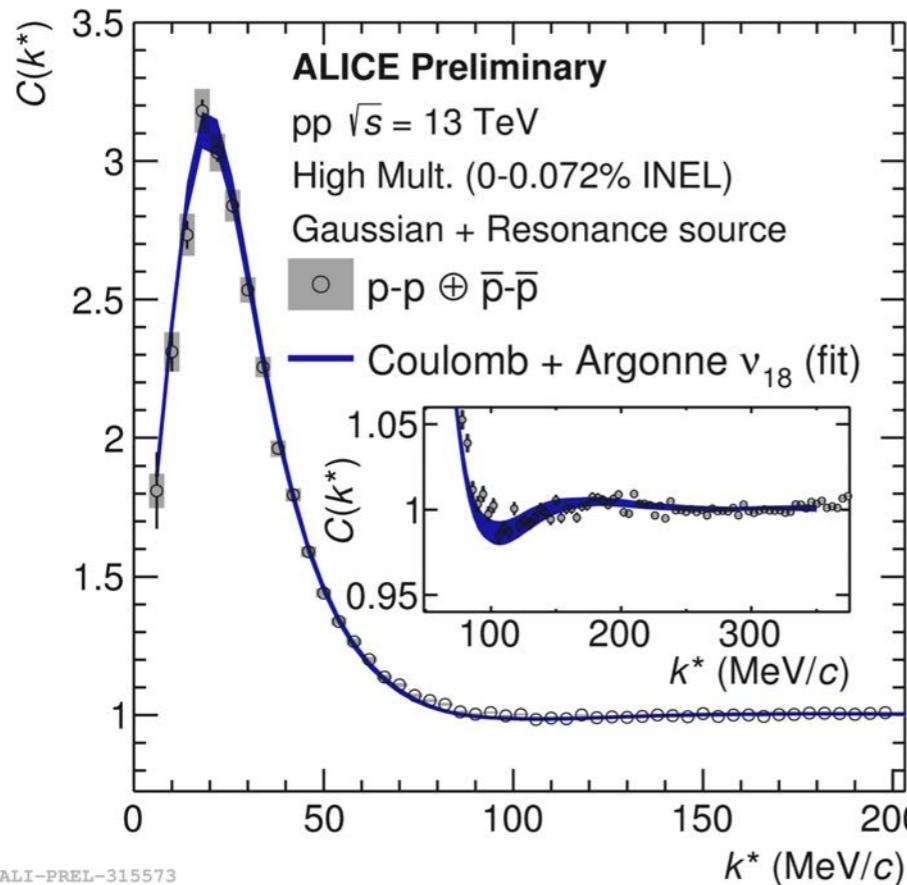
pp Correlations for pp 13TeV HM and Source

Fit with a ‘core’ Gaussian + Resonances



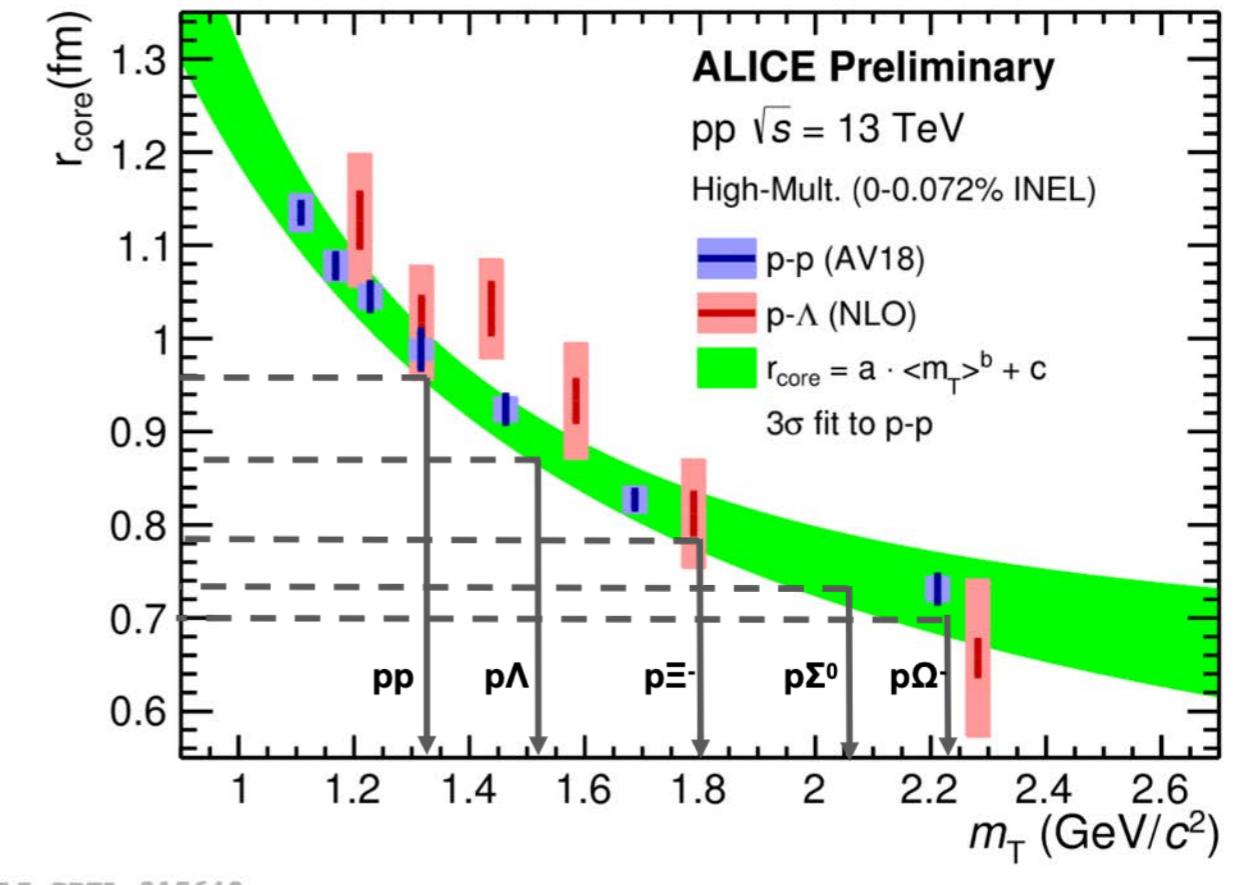
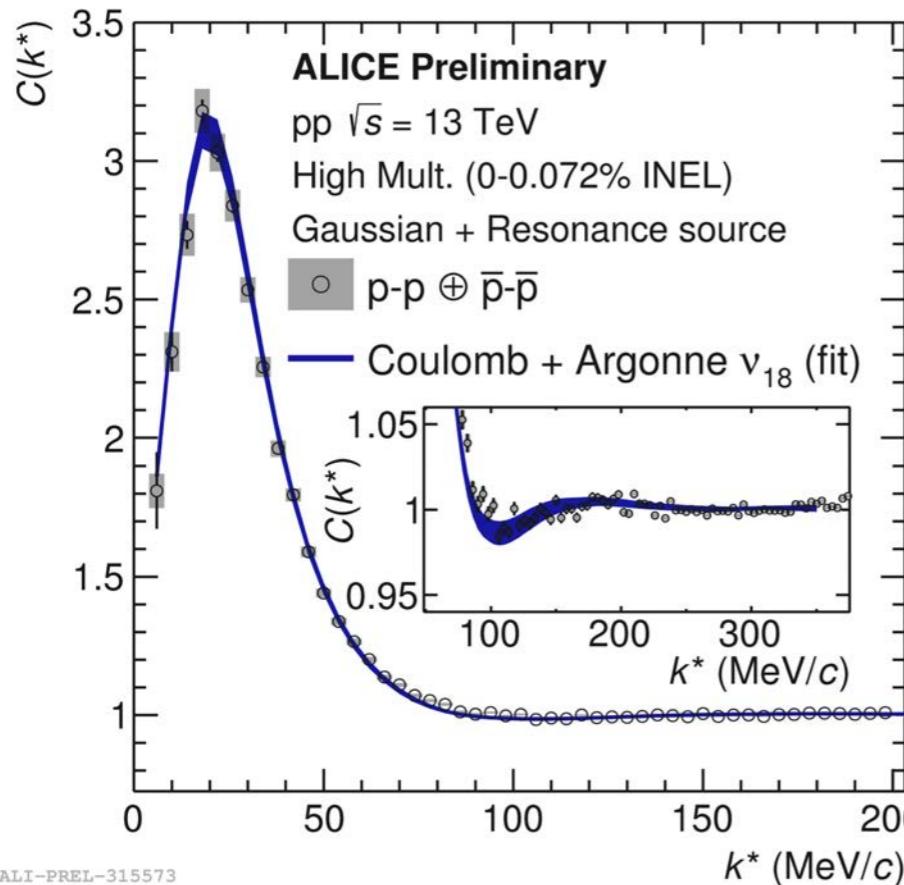
pp Correlations for pp 13TeV HM and Source

Fit with a ‘core’ Gaussian + Resonances



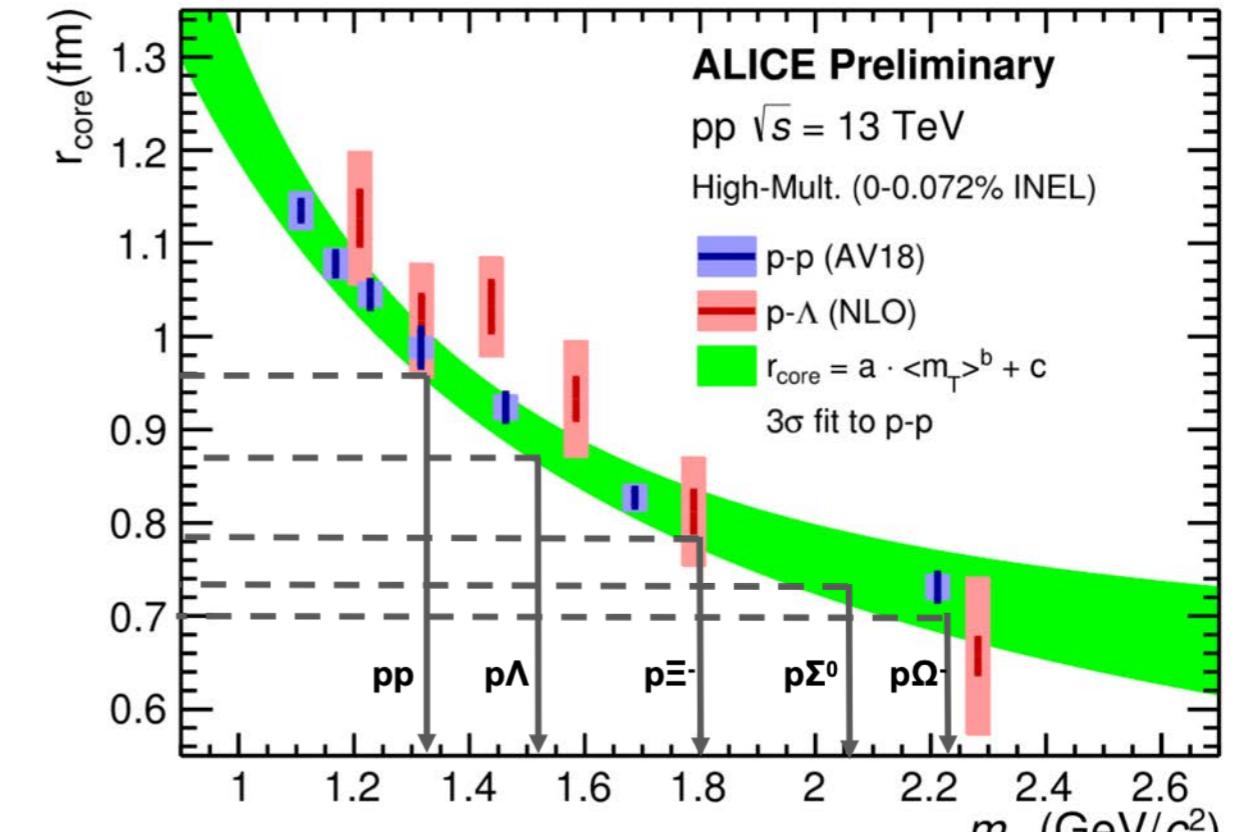
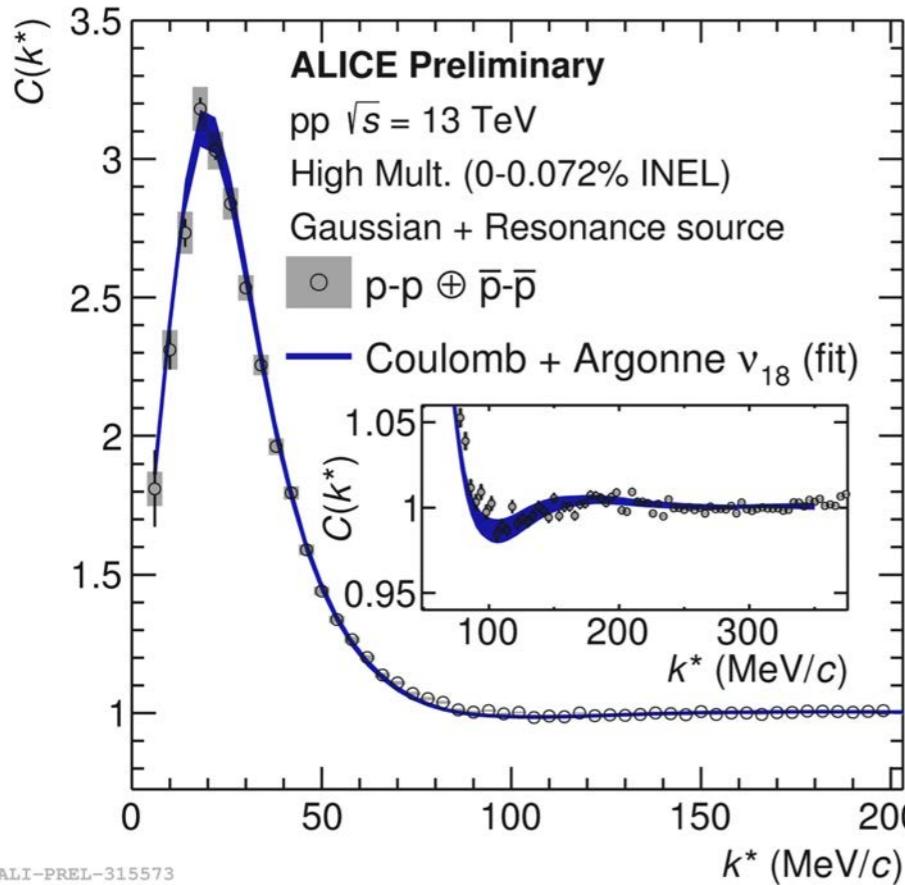
pp Correlations for pp 13TeV HM and Source

Fit with a ‘core’ Gaussian + Resonances

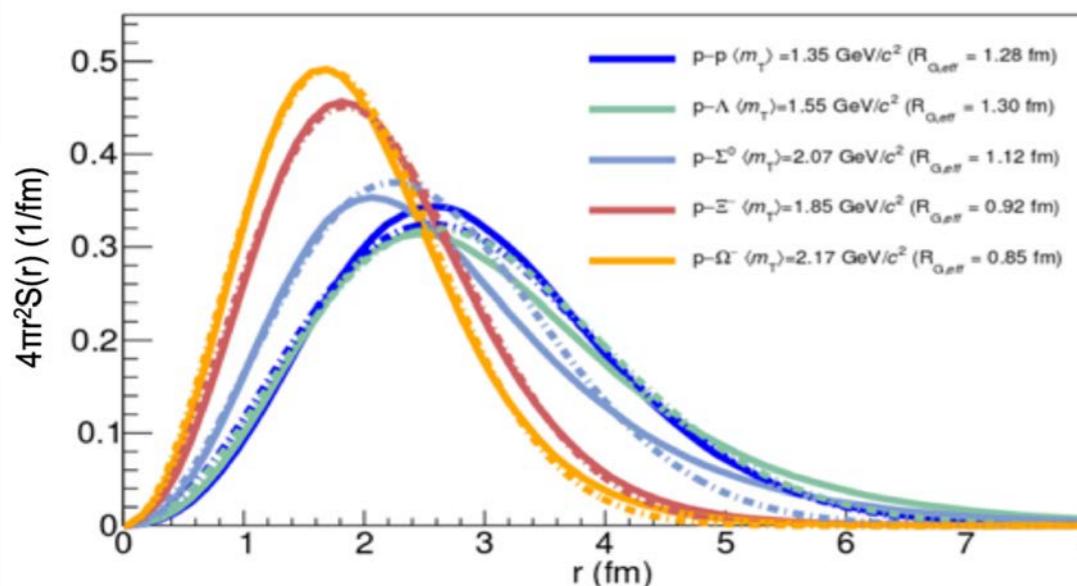


pp Correlations for pp 13TeV HM and Source

Fit with a ‘core’ Gaussian + Resonances



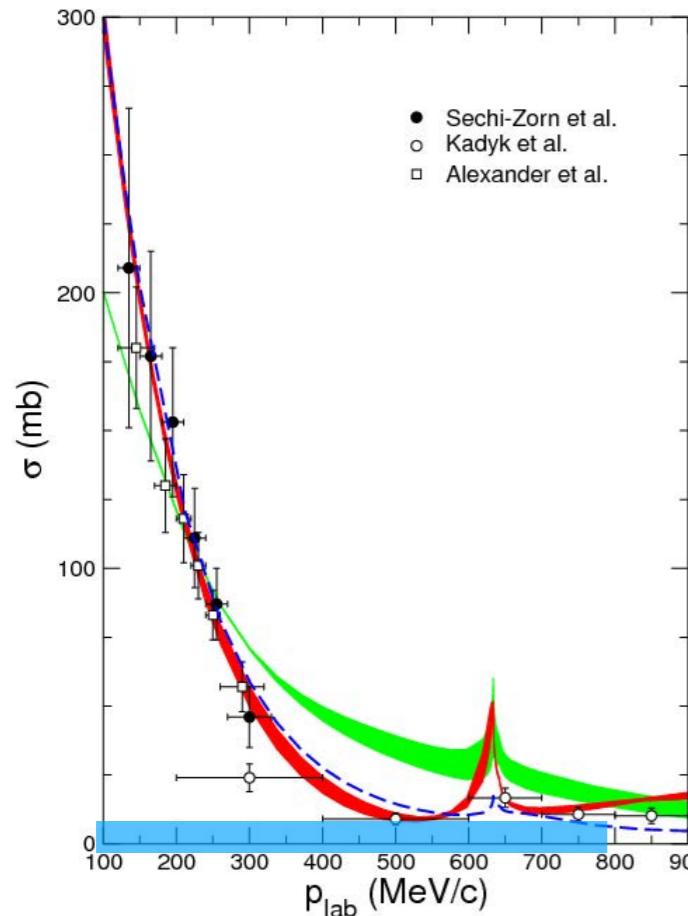
Global Source for each Pair



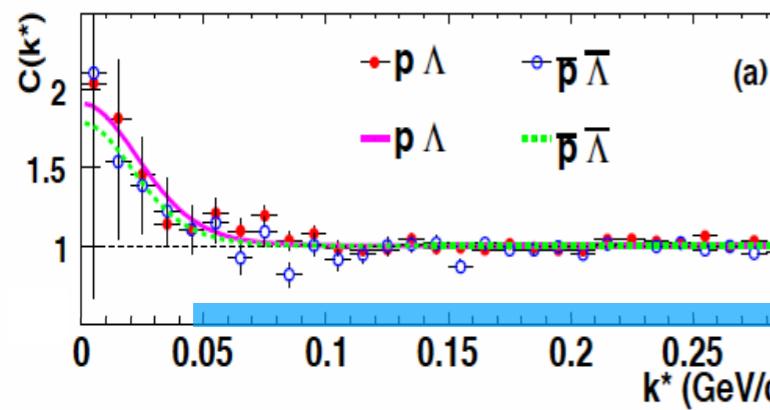
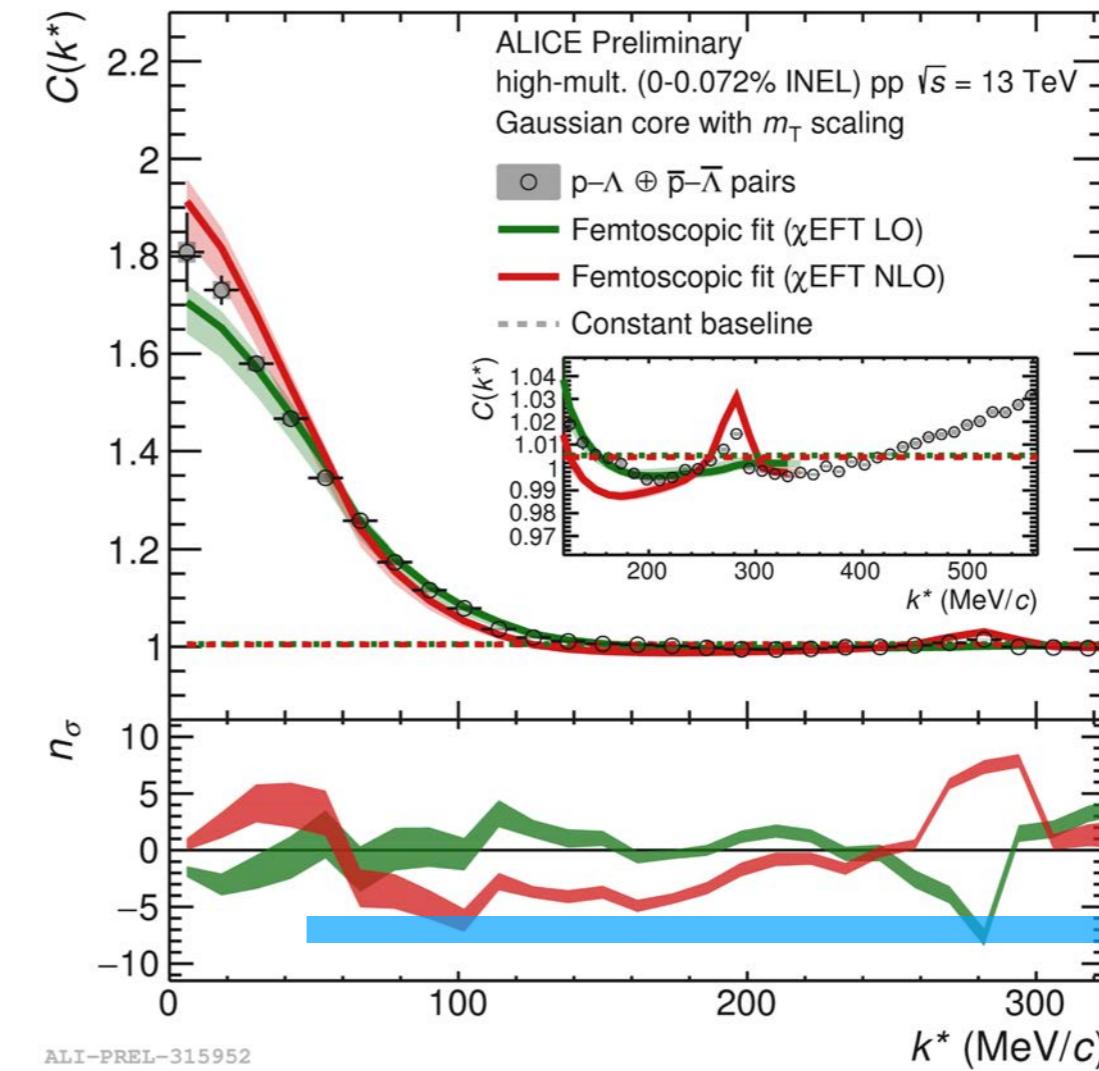
Pair	r_{Core} [fm]	r_{Eff} [fm]
pp	0.96	1.28
p Λ	0.88	1.3
p Σ^0	0.75	1.12
p Ξ^-	0.8	0.92
p Ω^-	0.73	0.85

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

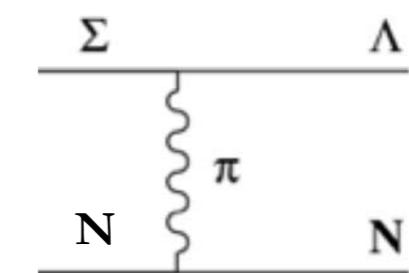
NLO: J. Haidenbauer, N. Kaiser et al., NPA 915, 24 (2013)



STAR Coll., Phys. Rev. C74, 064906 (2006)

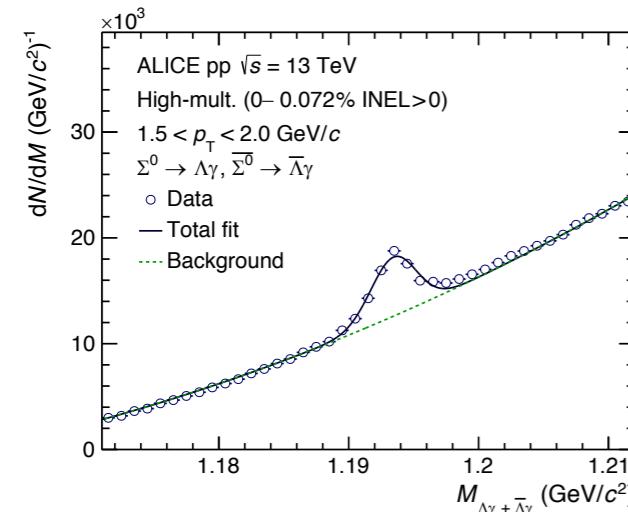
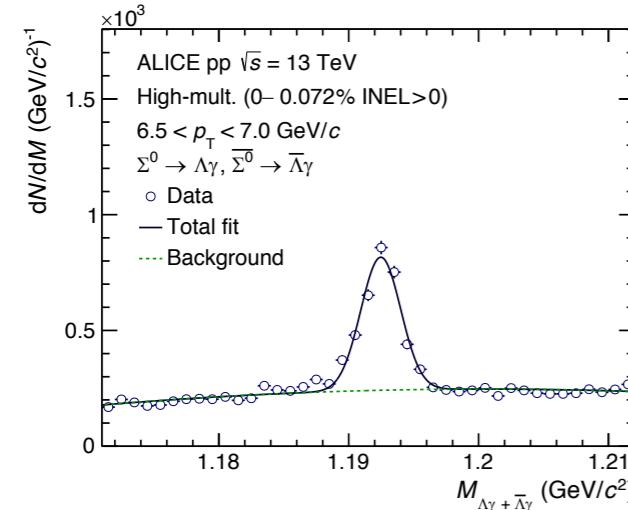
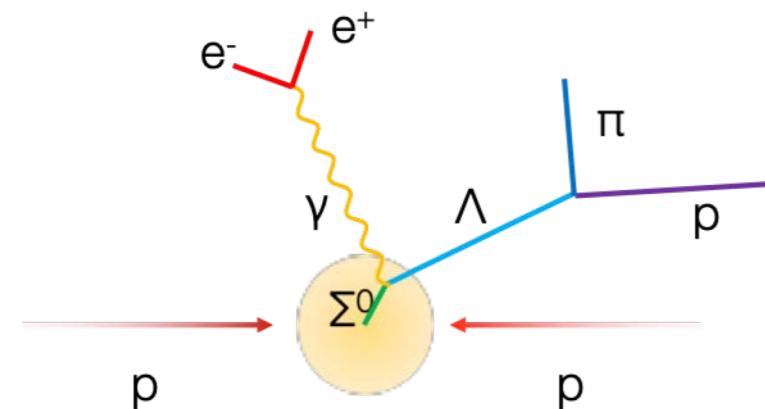


- Extension of the kinematic range
- Much improved precision of the measurement
- Clear experimental evidence of the Cusp



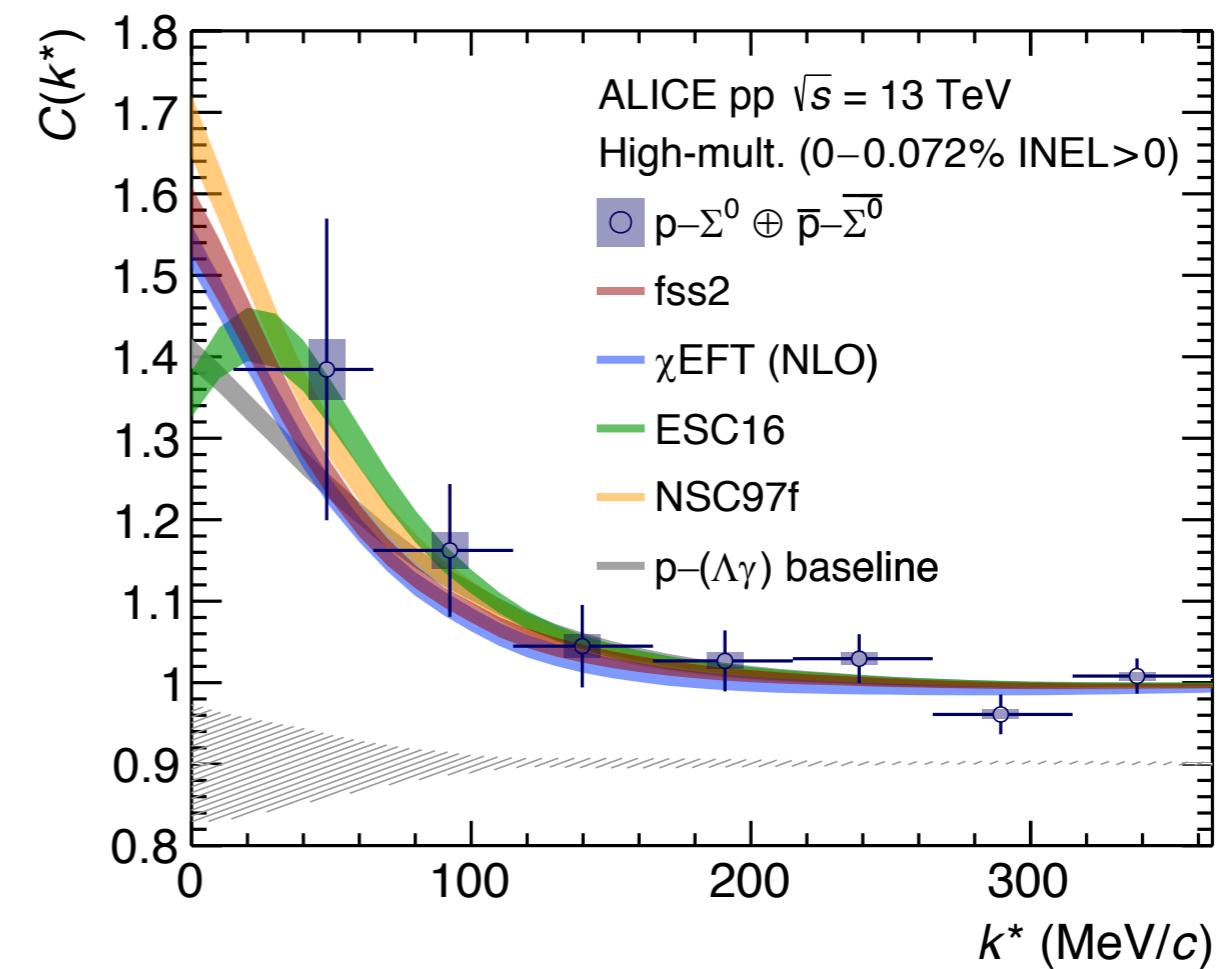
ALICE Coll., arXiv:1910.14407v1

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

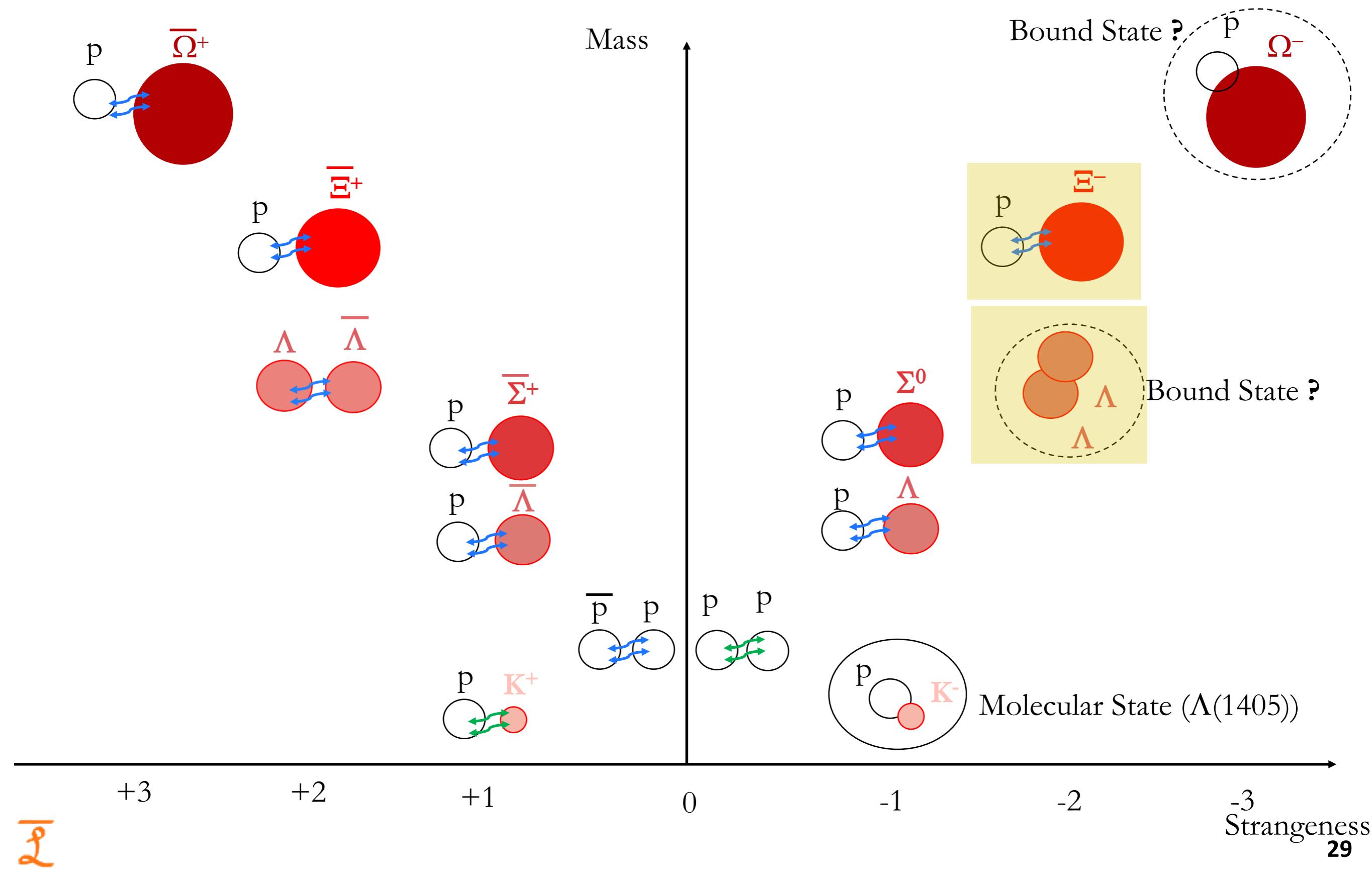


Models:

- J. Haidenbauer et. al, Nucl. Phys. A915 (2013) 24–58.
- T. A. Rijken et. al, Phys. Rev. C59 (1999) 21–40
- M. M. Nagels et. al, Phys. Rev. C99 (2019) 044003
- Y. Fujiwara et al., Prog. Part. Nucl. Phys. 58, 439–520 (2007)

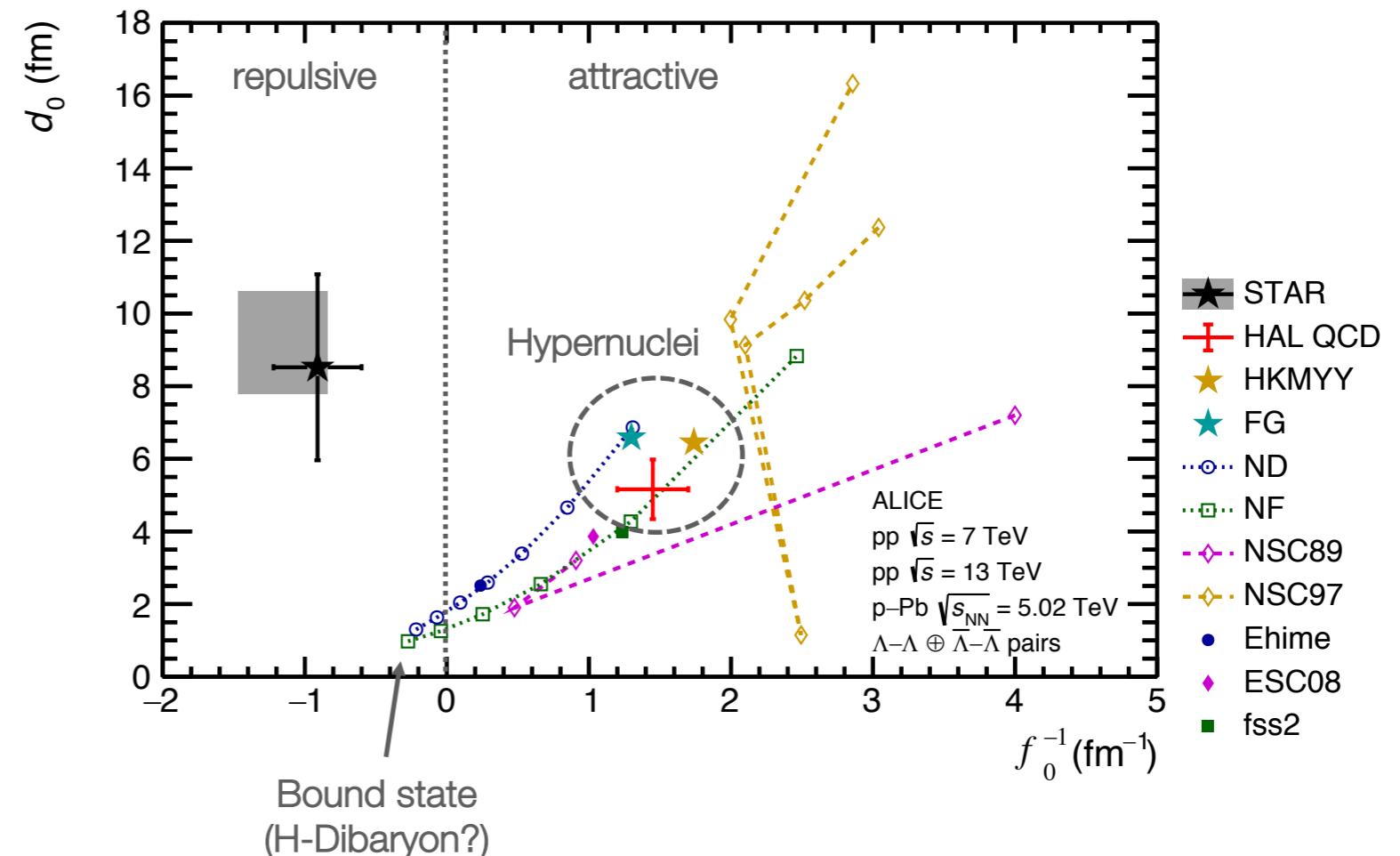


Data lay slightly above the baseline
RUN3-RUN4 will provide quantitative information



Theoretical models and experimental measurements cover a wide range in the scattering parameter phase space

- Measurement: STAR Collab., PRL 114 (2015) 022301.
- Models from K. Morita *et al.*, PRC 91 (2015) 024916.
- HAL QCD: K. Sasaki and T. Hatsuda (HAL QCD Collab.), private communication.

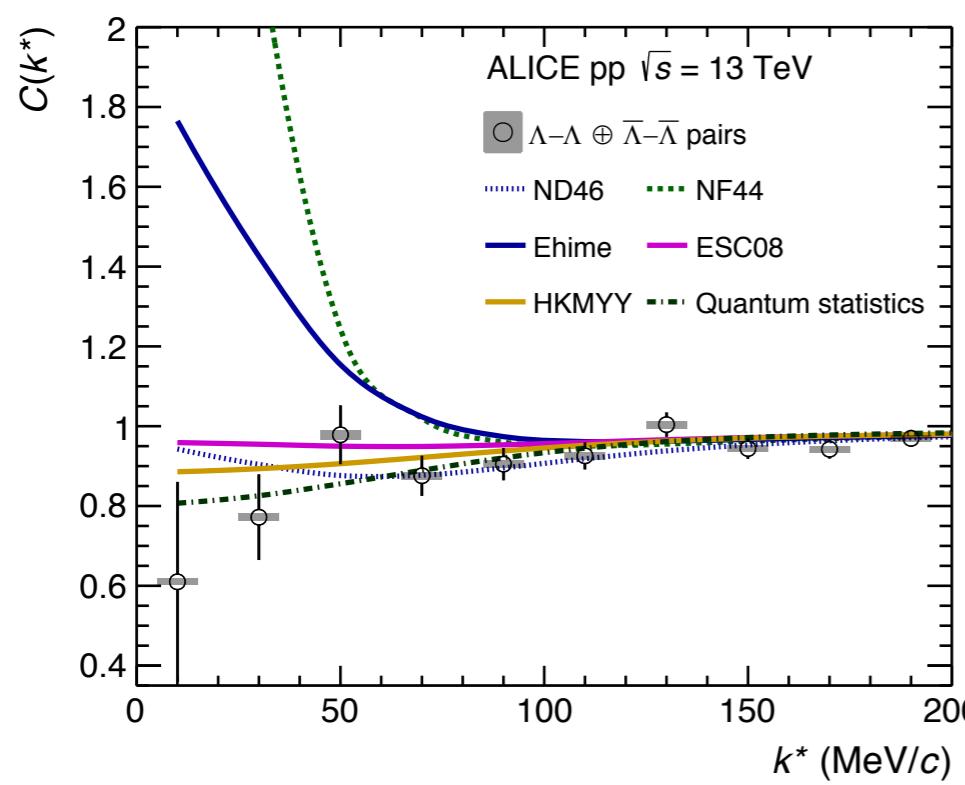
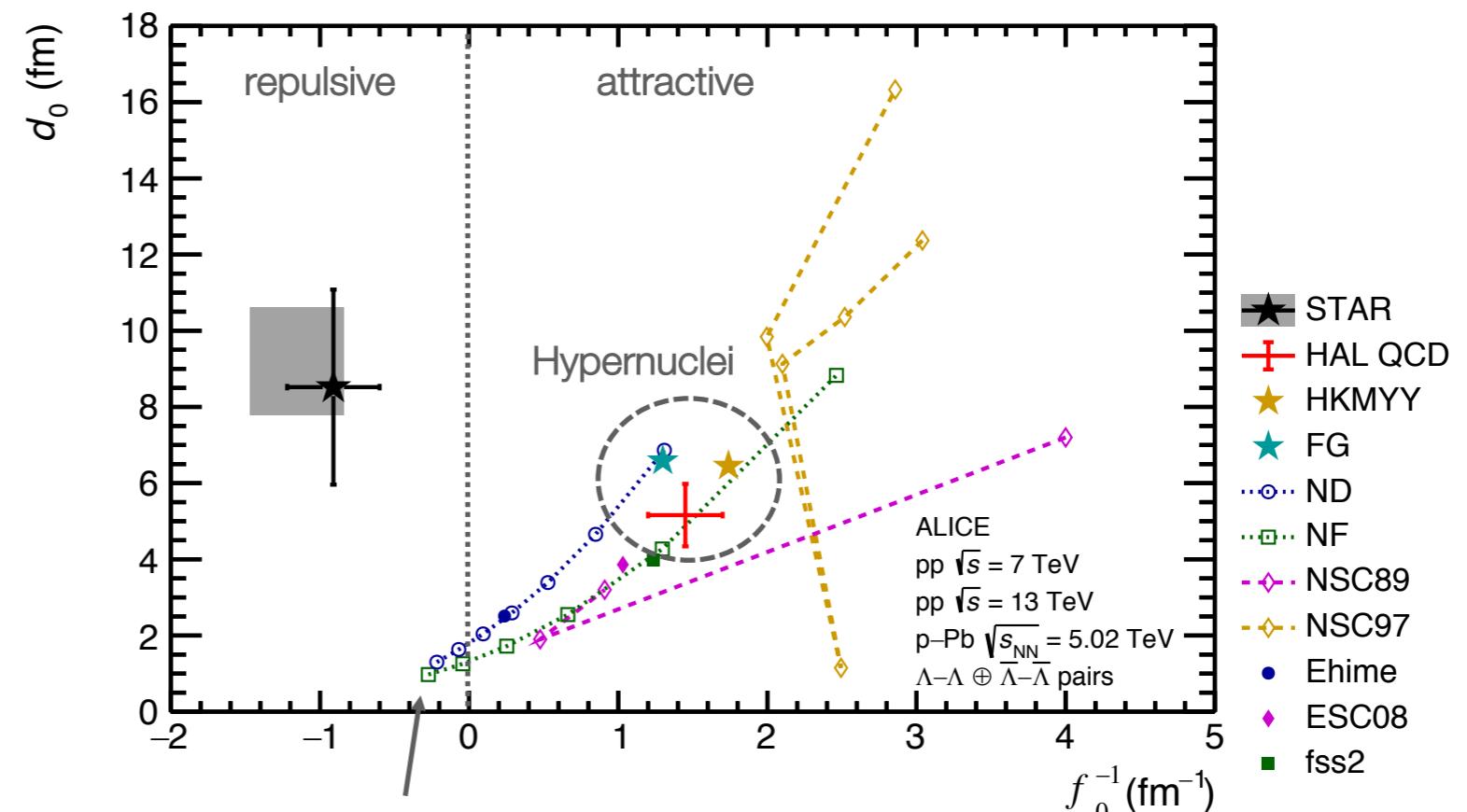


$\Lambda\bar{\Lambda}$ Interaction: the ALICE Measurement

ALICE Coll., Phys. Lett. B 797, 134822 (2019)

Theoretical models and experimental measurements cover a wide range in the scattering parameter phase space

- Measurement: STAR Collab., PRL 114 (2015) 022301.
- Models from K. Morita *et al.*, PRC 91 (2015) 024916.
- HAL QCD: K. Sasaki and T. Hatsuda (HAL QCD Collab.), private communication.

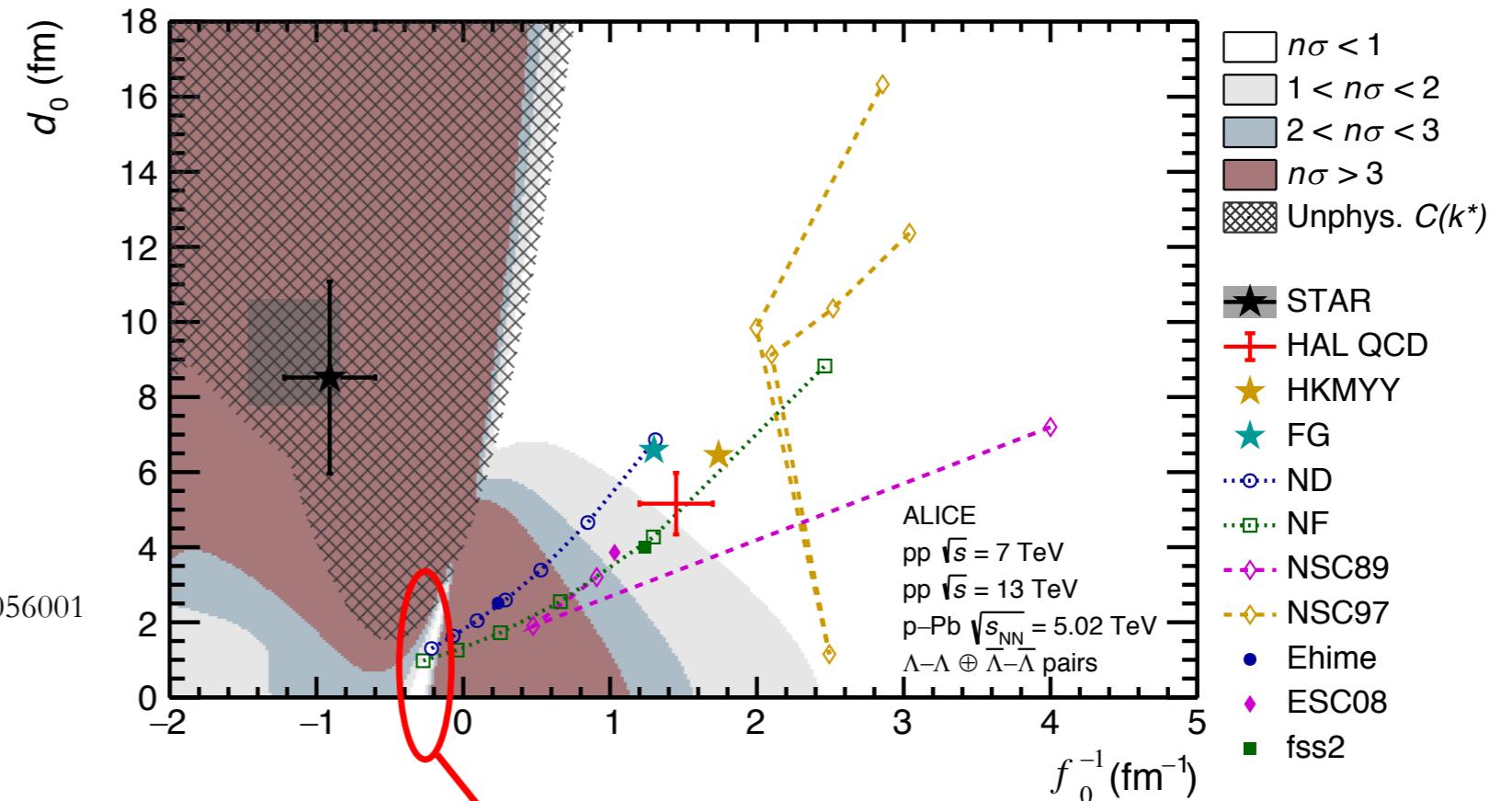


Strategy: Compute the pValue ($n\sigma$) w.r.t. the $\Lambda\bar{\Lambda}$ correlation function measured in pp 7 and 13 TeV and pPb 5 TeV for each d_0 and a_0 values seen in the upper plot using the Lednicky-formula

ALICE Coll., Phys. Lett. B 797, 134822 (2019)

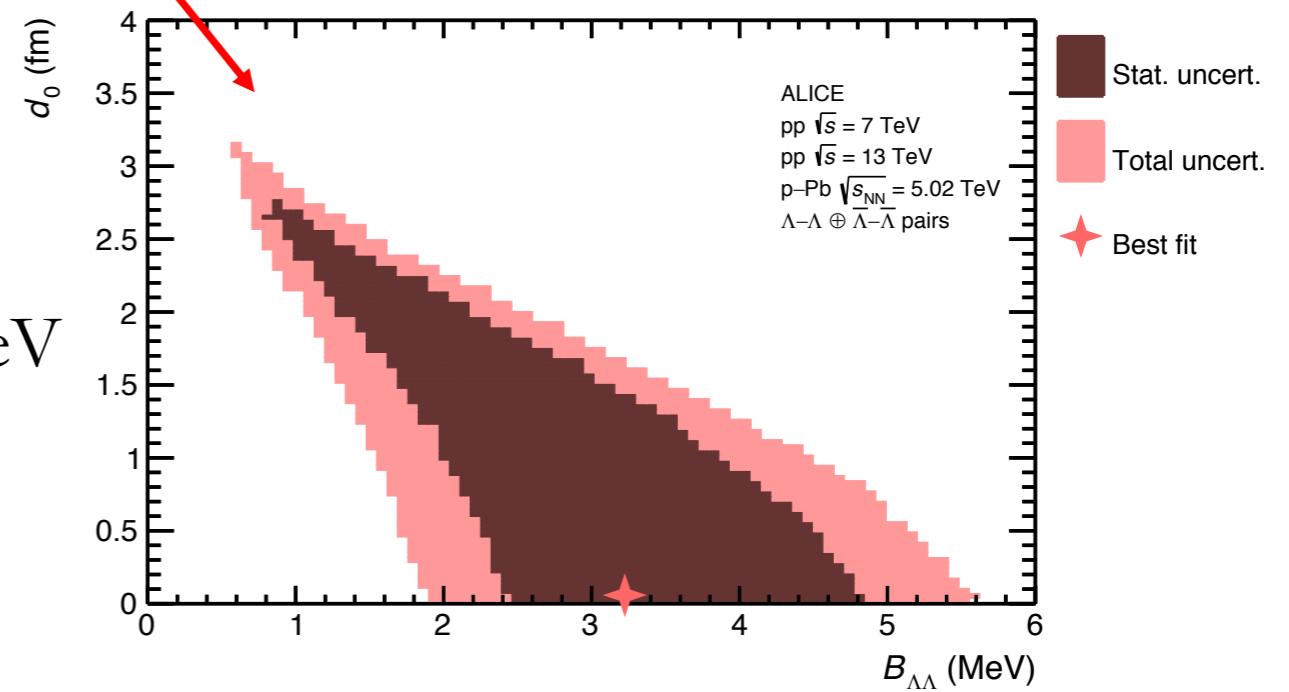
$$B_{\Lambda\bar{\Lambda}} = \frac{1}{m_\Lambda d_0^2} \cdot \left(1 - \sqrt{1 + \frac{2d_0}{f_0}} \right)$$

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



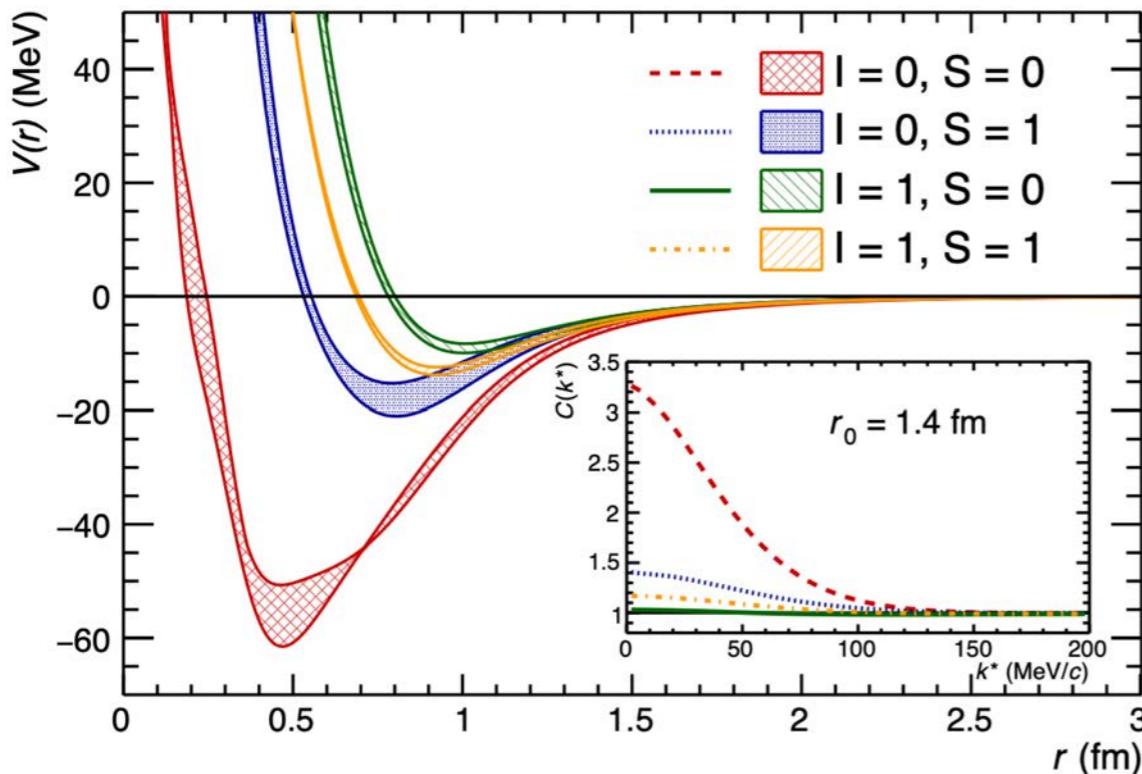
H-Dibaryon: tight constraints on the allowed binding energy

- $B_{\Lambda-\Lambda} = 3.2^{+1.6}_{-2.4}$ (stat.) $^{+1.8}_{-1.0}$ (syst.) MeV
- More stringent than previous measurements



T. Hatsuda et al., NPA967, 865 (2017); PoS Lattice2016, 116 (2016)

HAL-QCD Potential



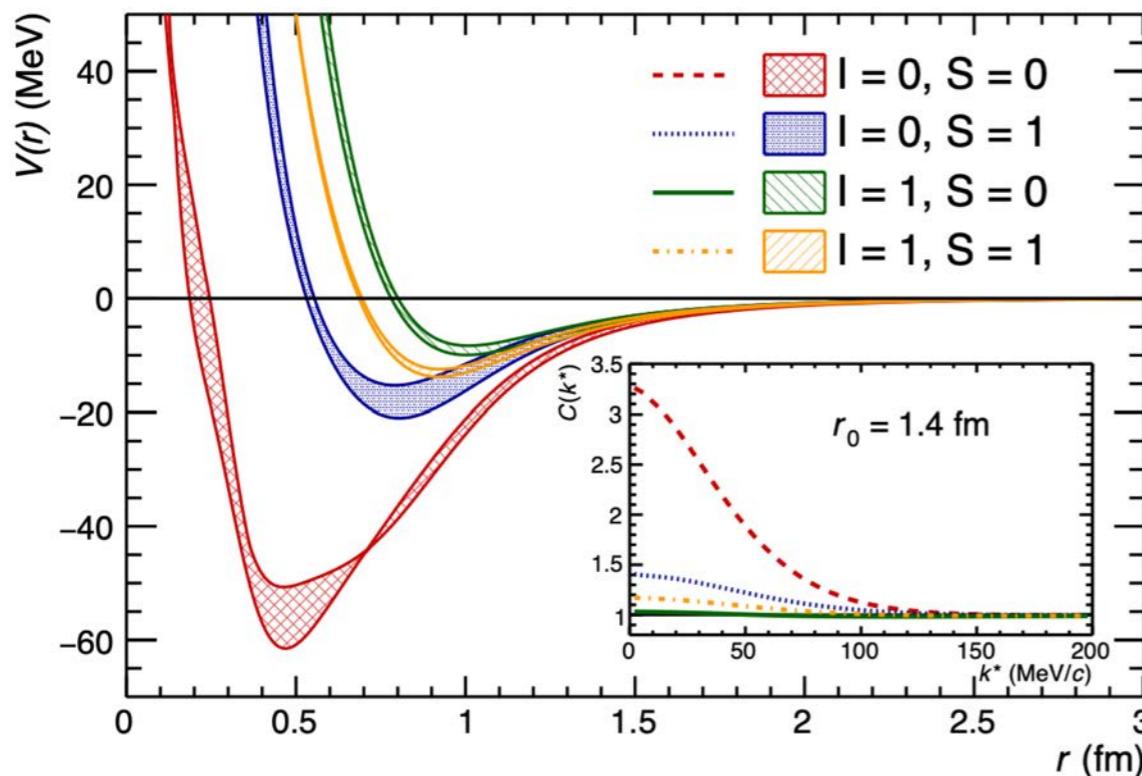
Each Potential can be converted in a correlation function via CATS and the total correlation function can be estimated

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

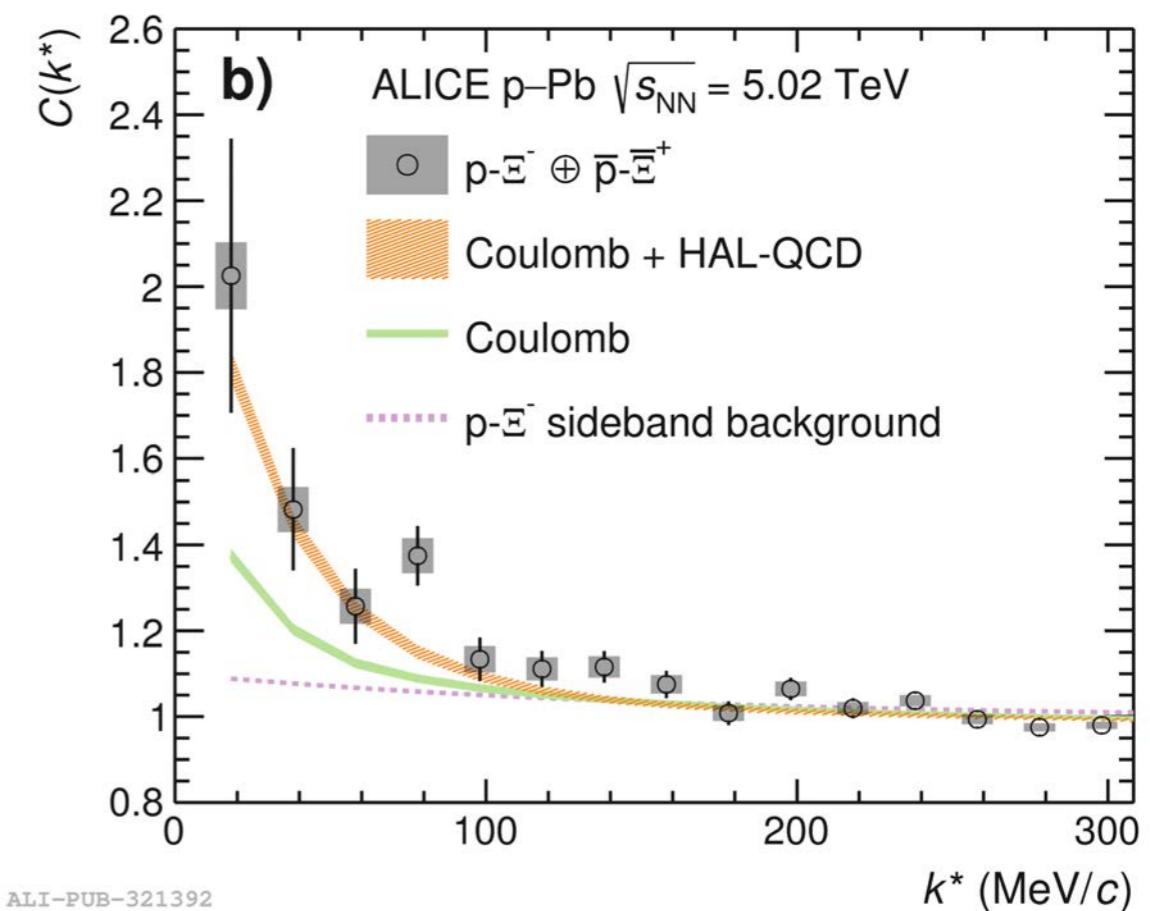
ALICE, Phys. Rev. Lett. 123, 112002 (2019)

T. Hatsuda et al., NPA967, 865 (2017); PoS Lattice2016, 116 (2016)

HAL-QCD Potential



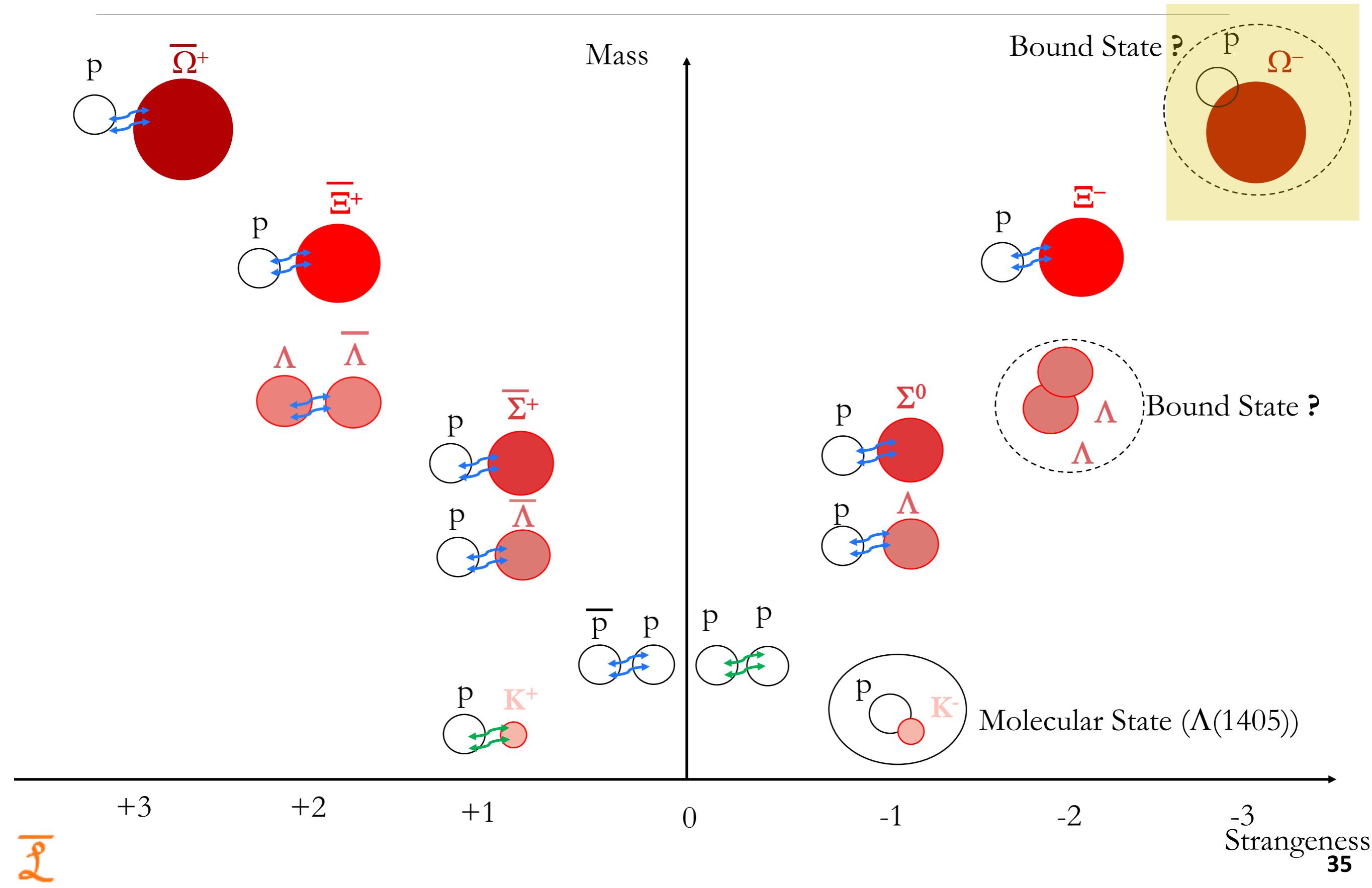
Correlation Function



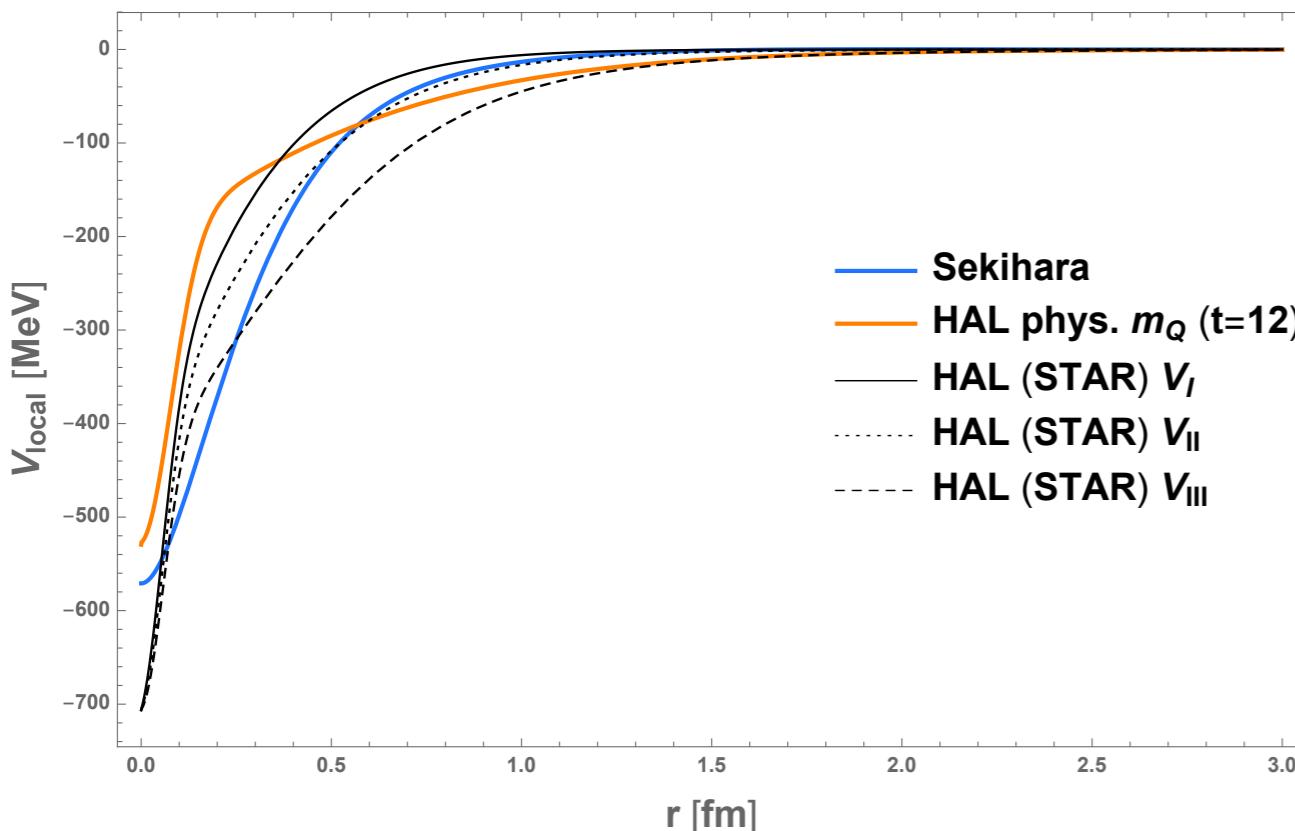
Each Potential can be converted in a correlation function via CATS and the total correlation function can be estimated

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

D. Mihaylov talk on Wednesday 6th Nov., 11:00 h
 -> New data from pp HM collisions at 13 TeV (ALICE).



$p\Omega^-$: Theoretical Predictions



Model	$p\Omega^-$ binding energy (strong interaction only)
HAL (STAR) VI	-
HAL (STAR) VII	6.3 MeV
HAL (STAR) VIII	24.8 MeV
HAL-QCD	1.54 MeV
Sekihara	0.1 MeV

— Older Lattice predictions (VIII-> $p\Omega^-$ Bound state with 28 MeV B.E.)

K. Morita et al. Phys. Rev. C 94 ,031901 (2016)

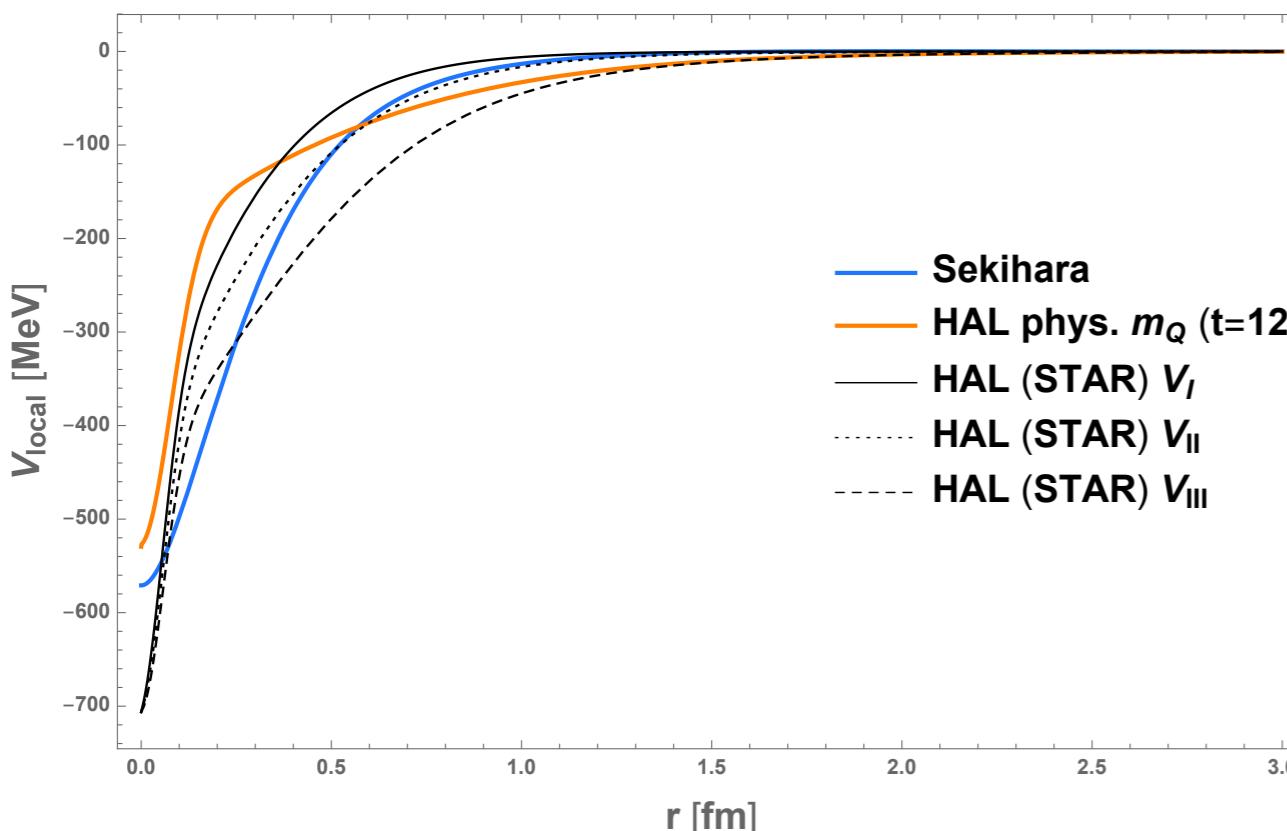
— Lattice HAL-QCD potential only for 5S_2 (with physical quark masses)

T. Iritami et al., Phys. Lett. B792, 284-289 (2019)

— Sekihara: Meson-Exchange Model

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

$p\Omega^-$: Theoretical Predictions



— Older Lattice predictions (VIII-> $p\Omega^-$ Bound state with 28 MeV B.E.)

K. Morita et al. Phys. Rev. C 94 ,031901 (2016)

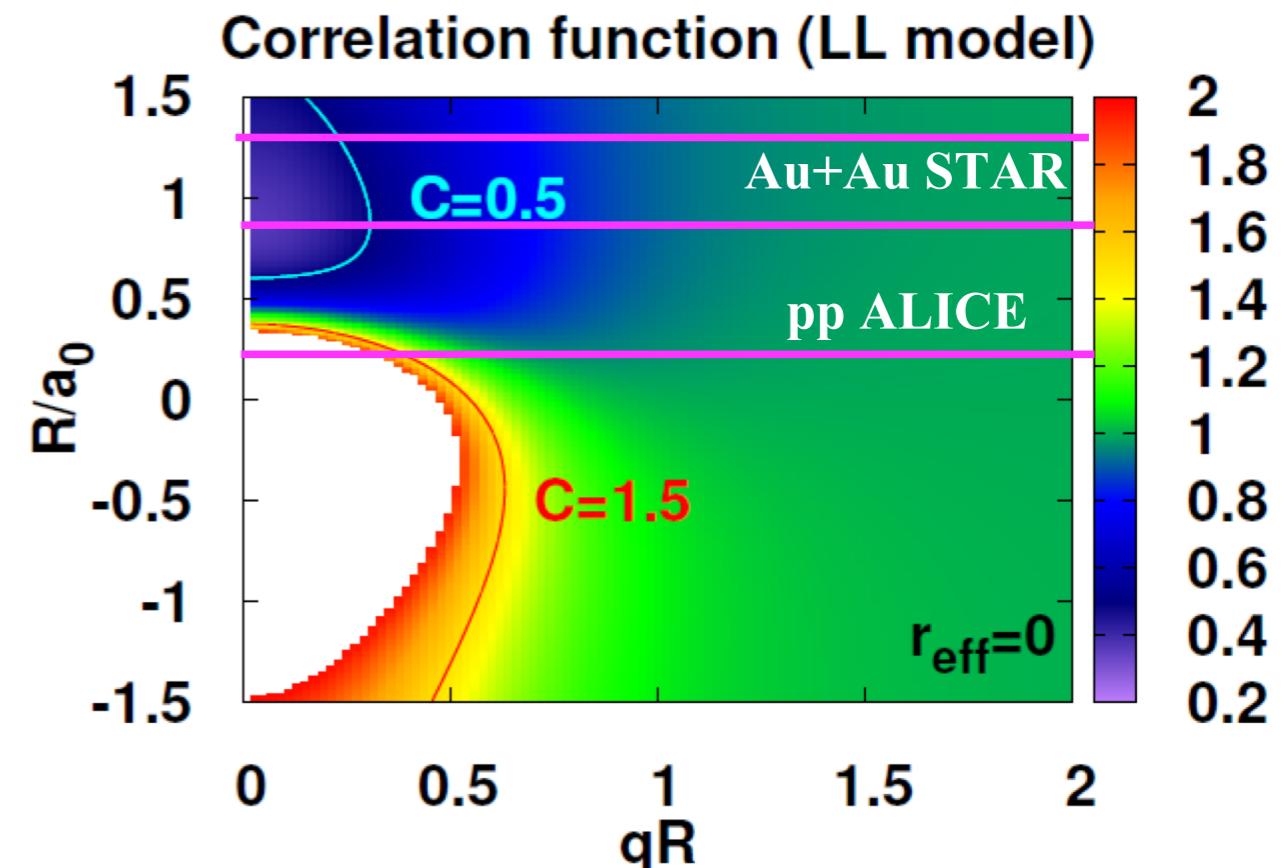
— Lattice HAL-QCD potential only for 5S_2 (with physical quark masses)

T. Iritami et al., Phys. Lett. B792, 284-289 (2019)

— Sekihara: Meson-Exchange Model

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

K. Morita et al., arXiv:1908.05414, Courtesy A. Ohnishi



$$a_0(p\Omega) \sim 3.4 \text{ fm}$$

$$R(\text{ALICE pp}) \sim 0.85 \text{ fm}, R(\text{STAR Au+Au}) \sim 2.5 - 5 \text{ fm}$$

The presence of a bound state would imply a variation of the correlation function from values about 1 for small distances to values below one for larger distances.

-> measurements of different colliding systems are necessary

$p\Omega^-$: the STAR Measurement in Au+Au @ 200 GeV

STAR Coll., Phys. Lett. B 790 (2019) 490-497

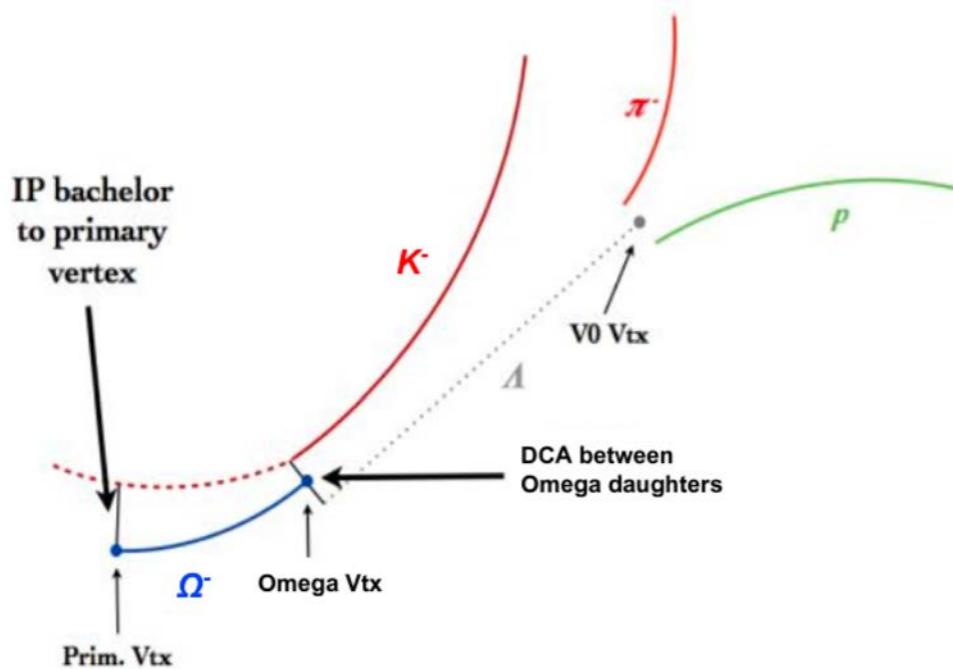
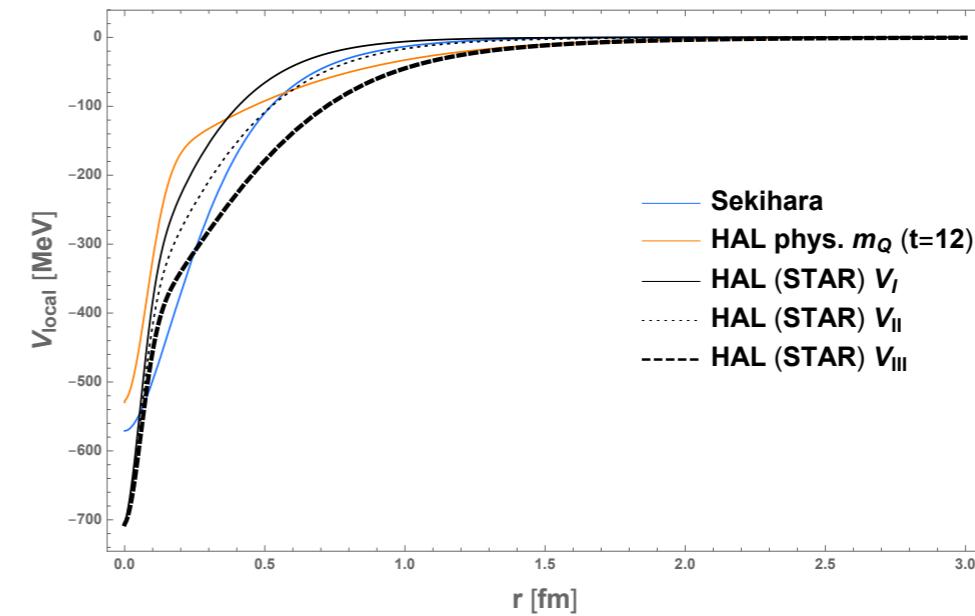
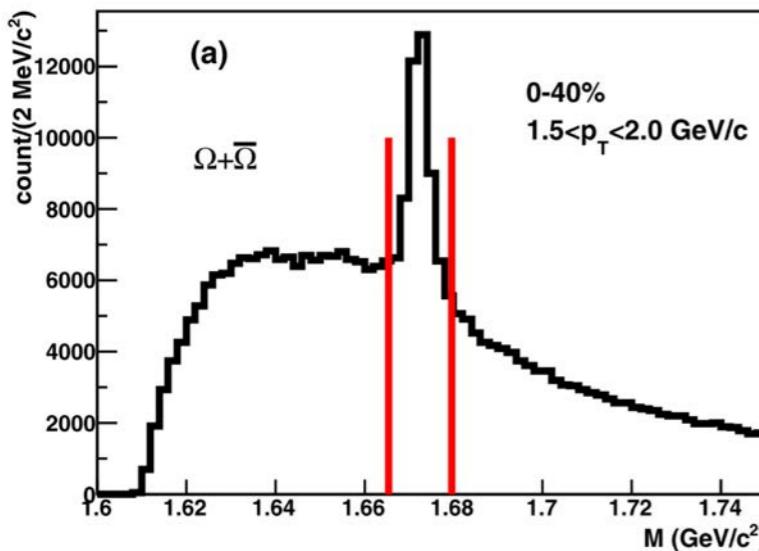
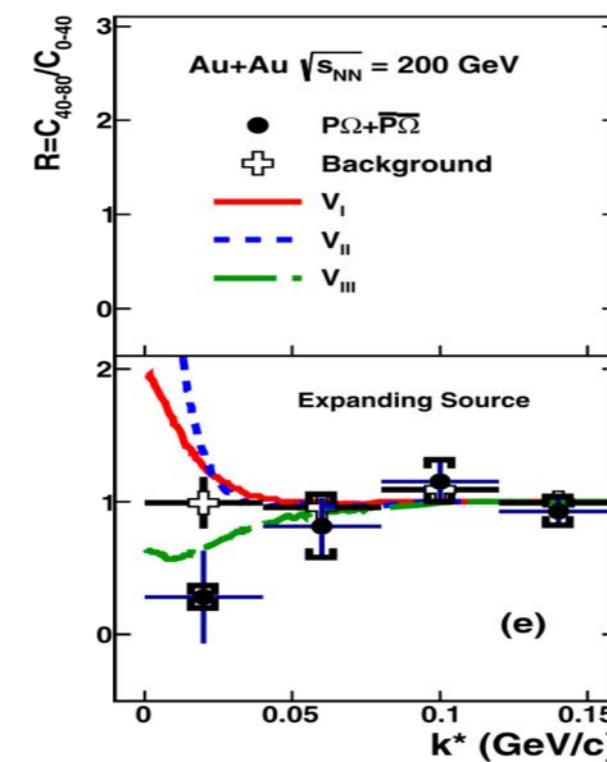


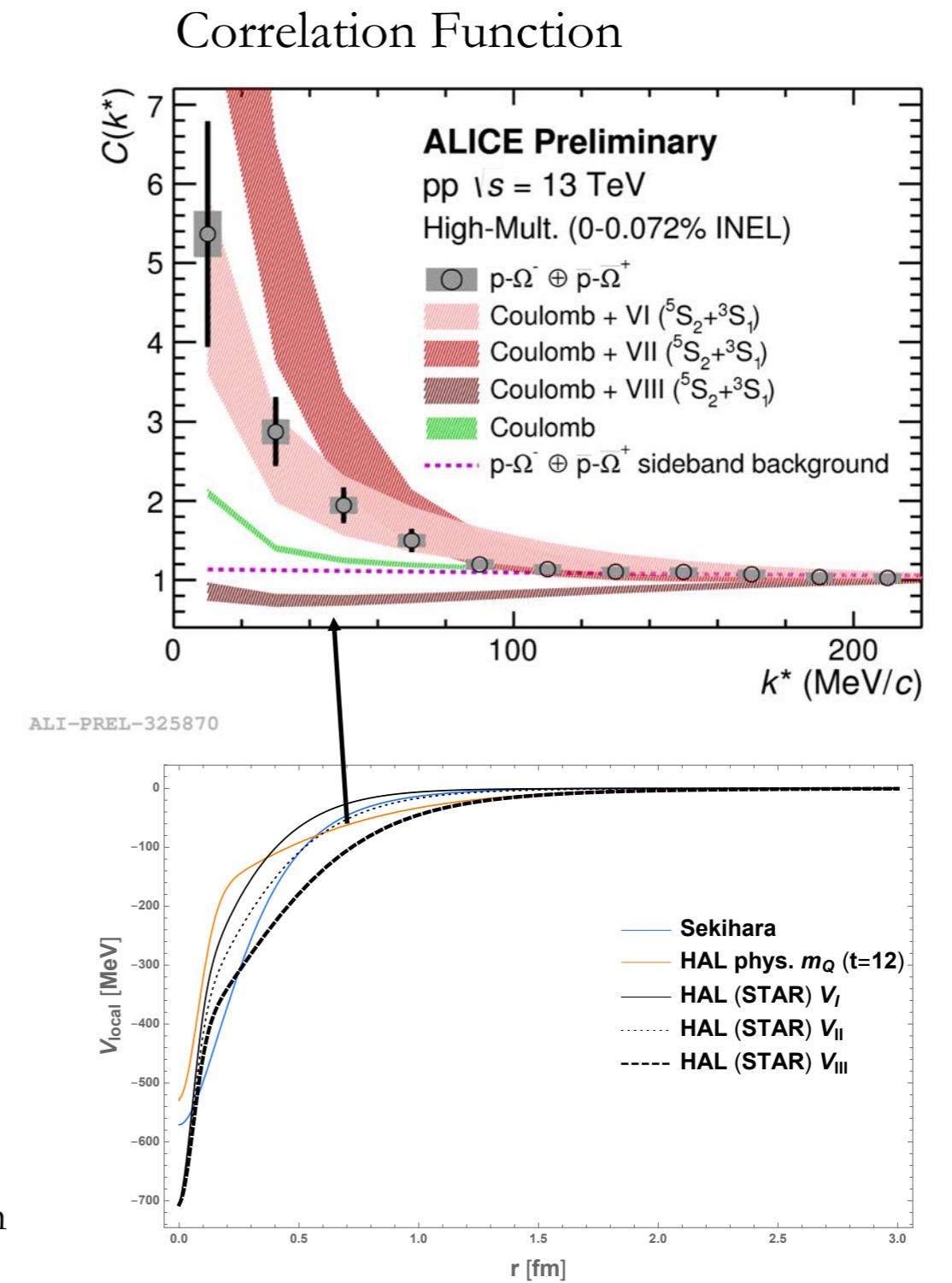
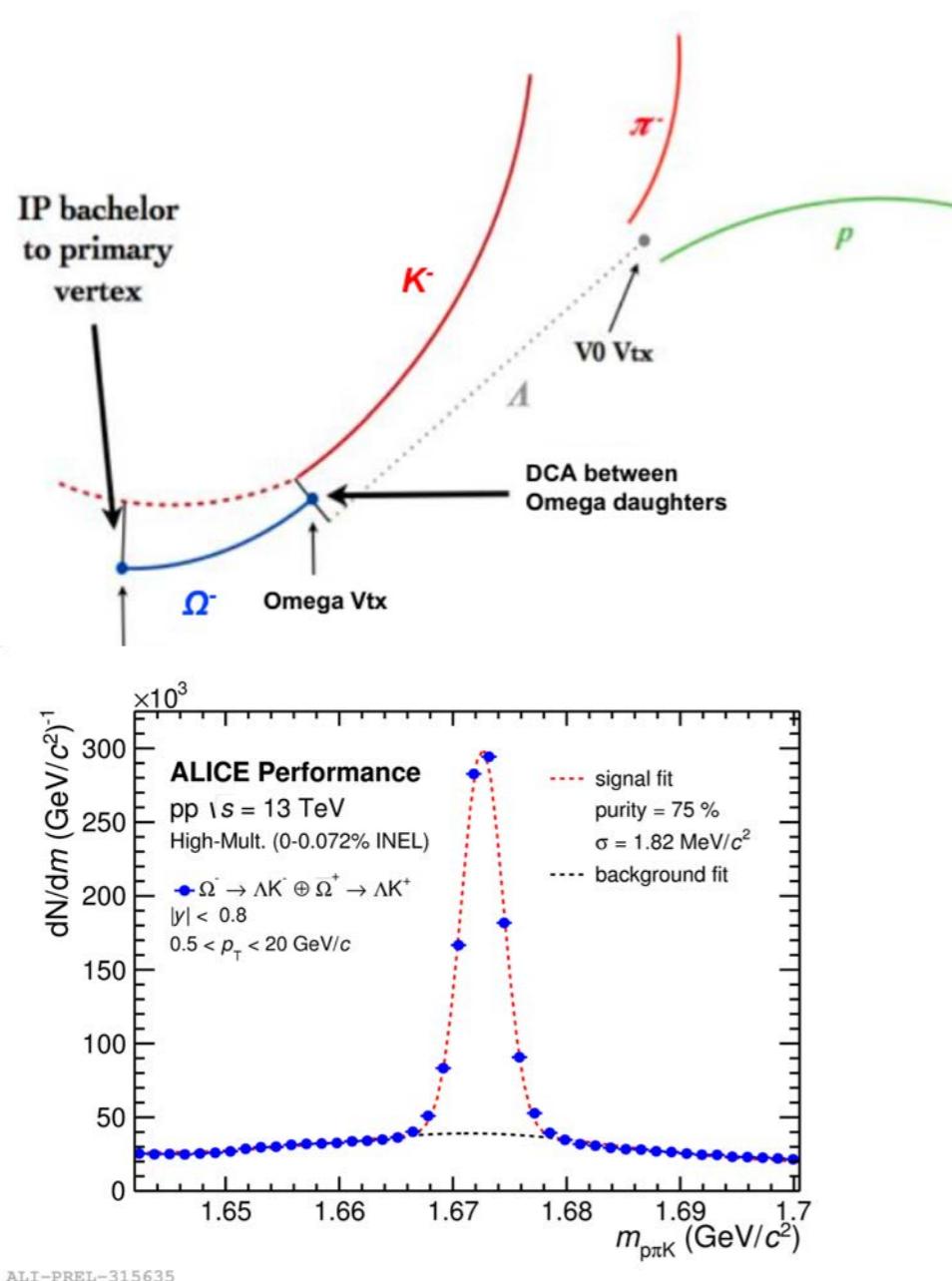
Fig. 2: Sketch of the Ω^- decay and identification.

Ratio of correlation functions



VIII most favoured B.E. = 26.9 MeV

$p\Omega^-$: the ALICE Measurement

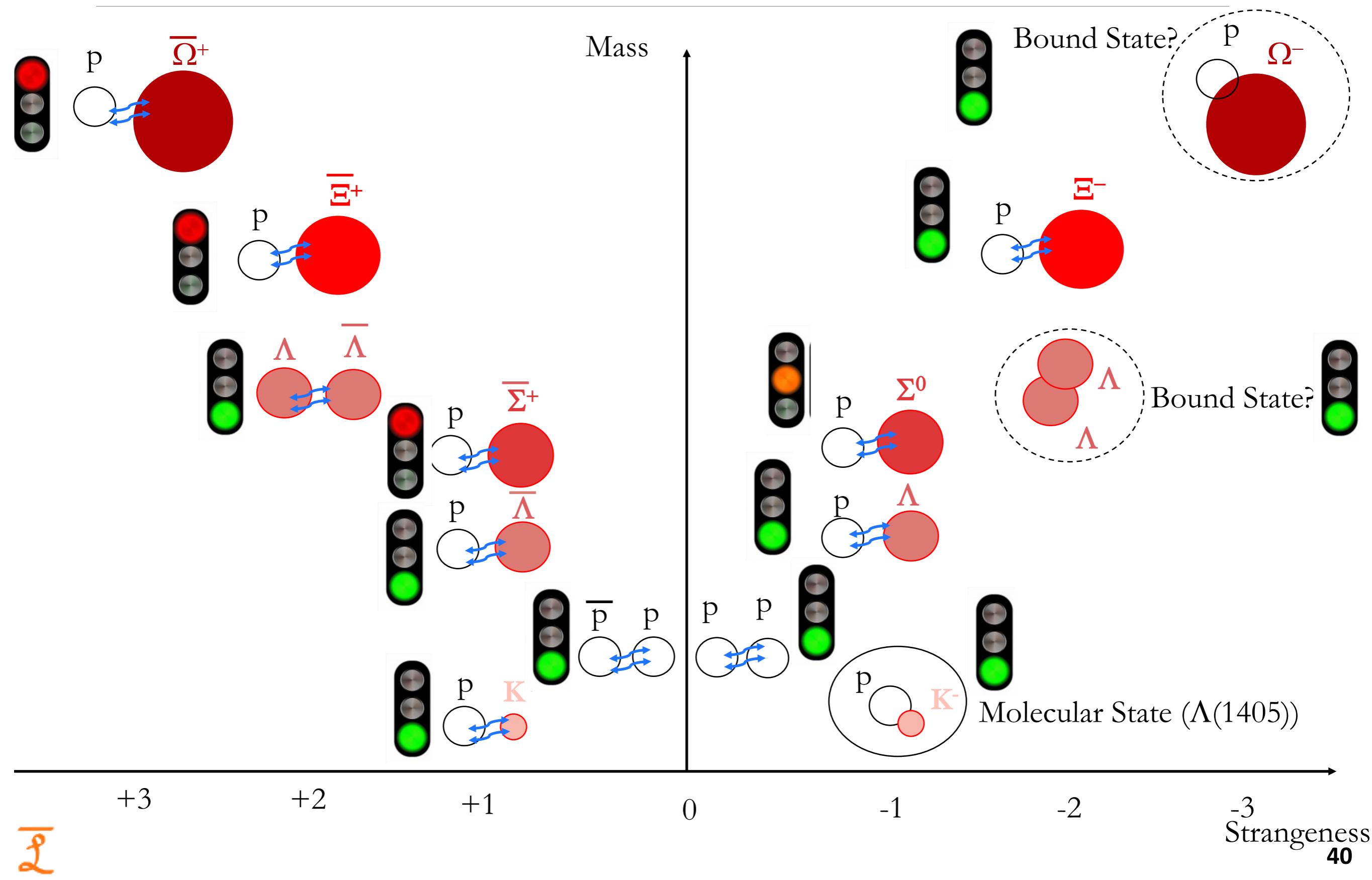


D. Mihaylov talk on Wednesday 6th Nov., 11:00 h
-> Comparison to state of the art caculations

VIII excluded — B.E. = 26.9 MeV



Hadron-Hadron Interactions within SU(3)





Some Considerations and Outlook

The LHC provides a unique and precise testing of the hadron-hadron interaction at distances lower than 1 fm.

Some measurements need a complementary approach in HIC and elementary collisions

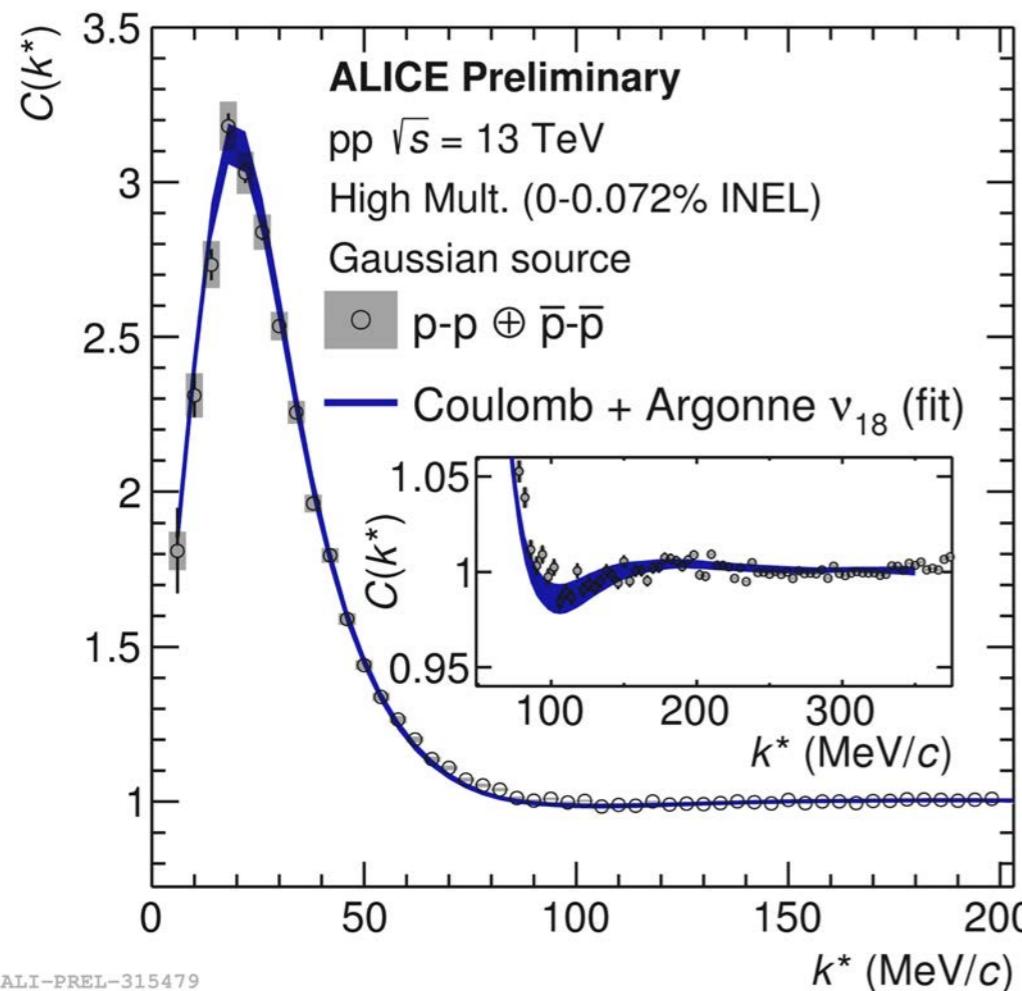
These interactions are necessary to compute reliable Equations of State

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

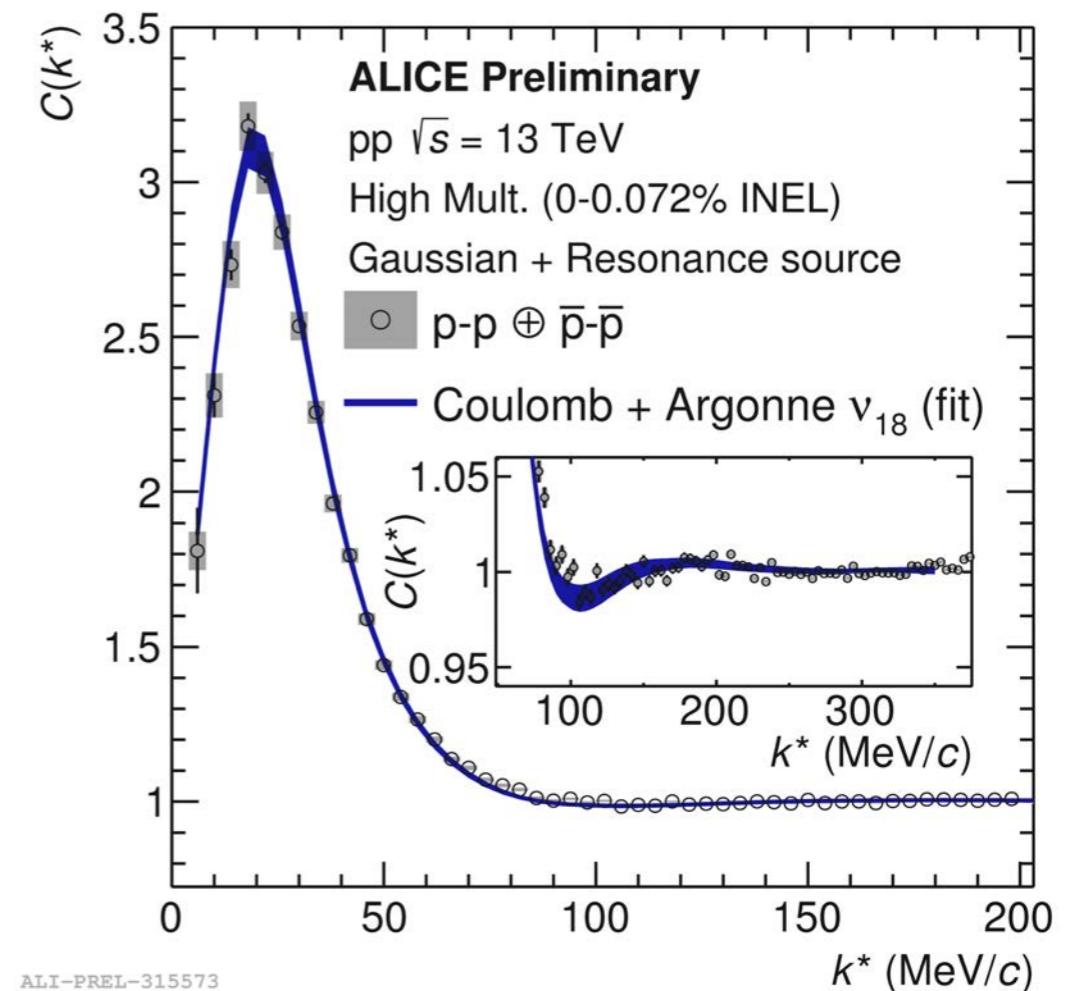
Ongoing Analyses : $p\phi$, $p\Sigma^+$, pd , Λd , $p\Xi^+$

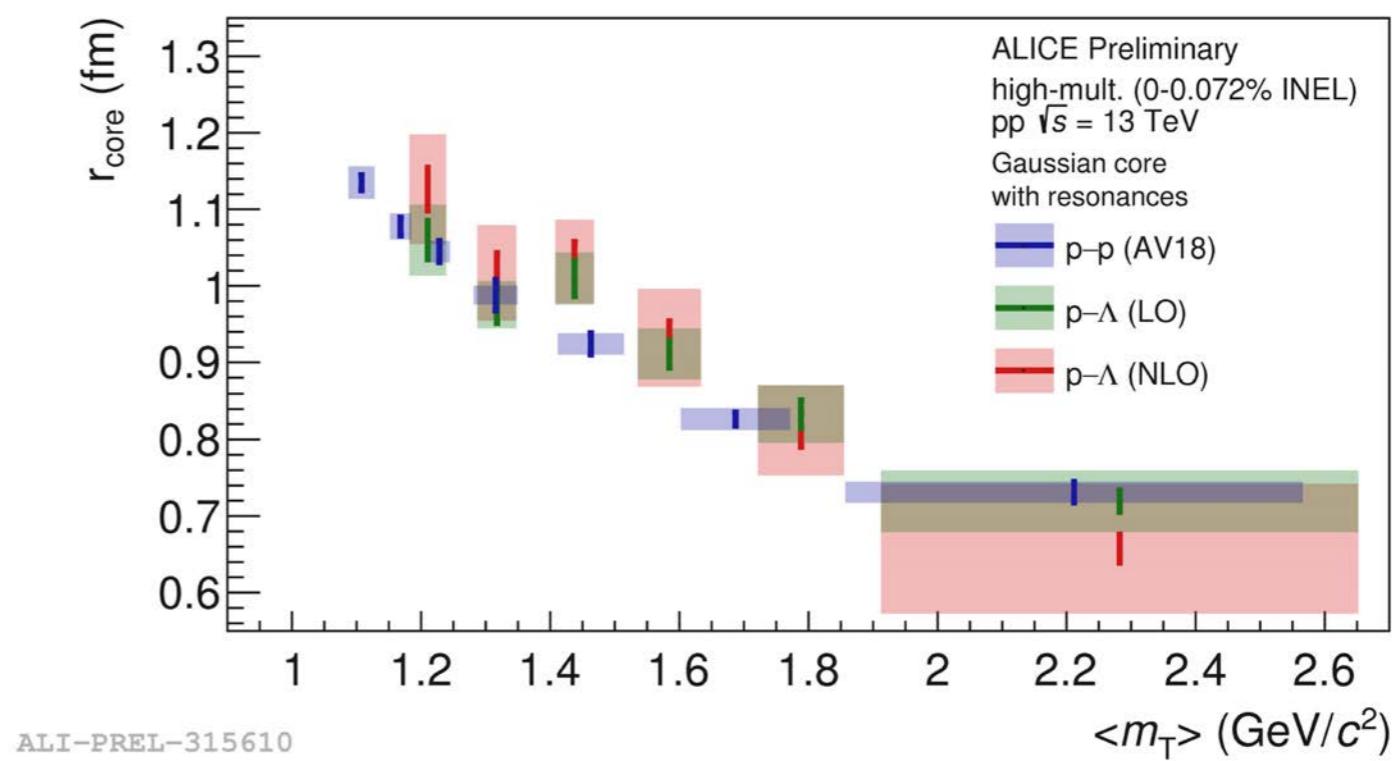
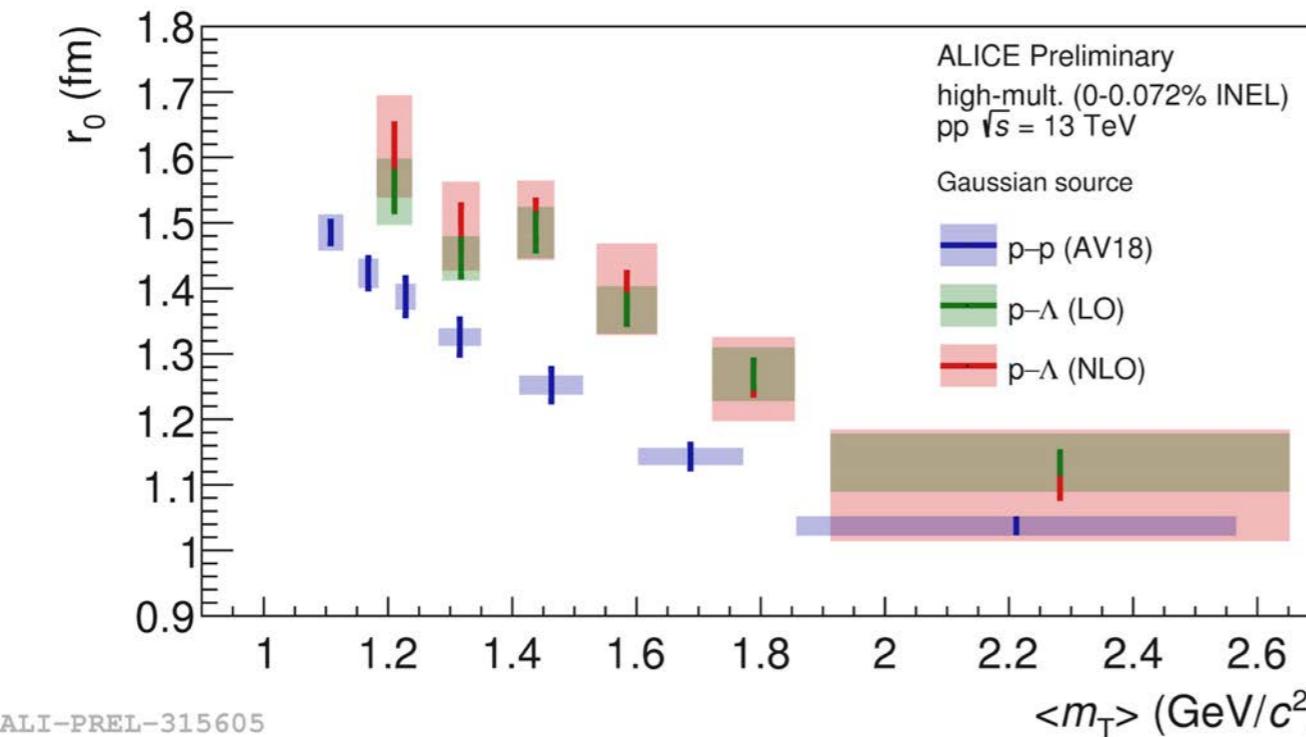
Future Analyses: $\Omega^-\Omega^-$ and Λpp

Fit with a simple Gaussian

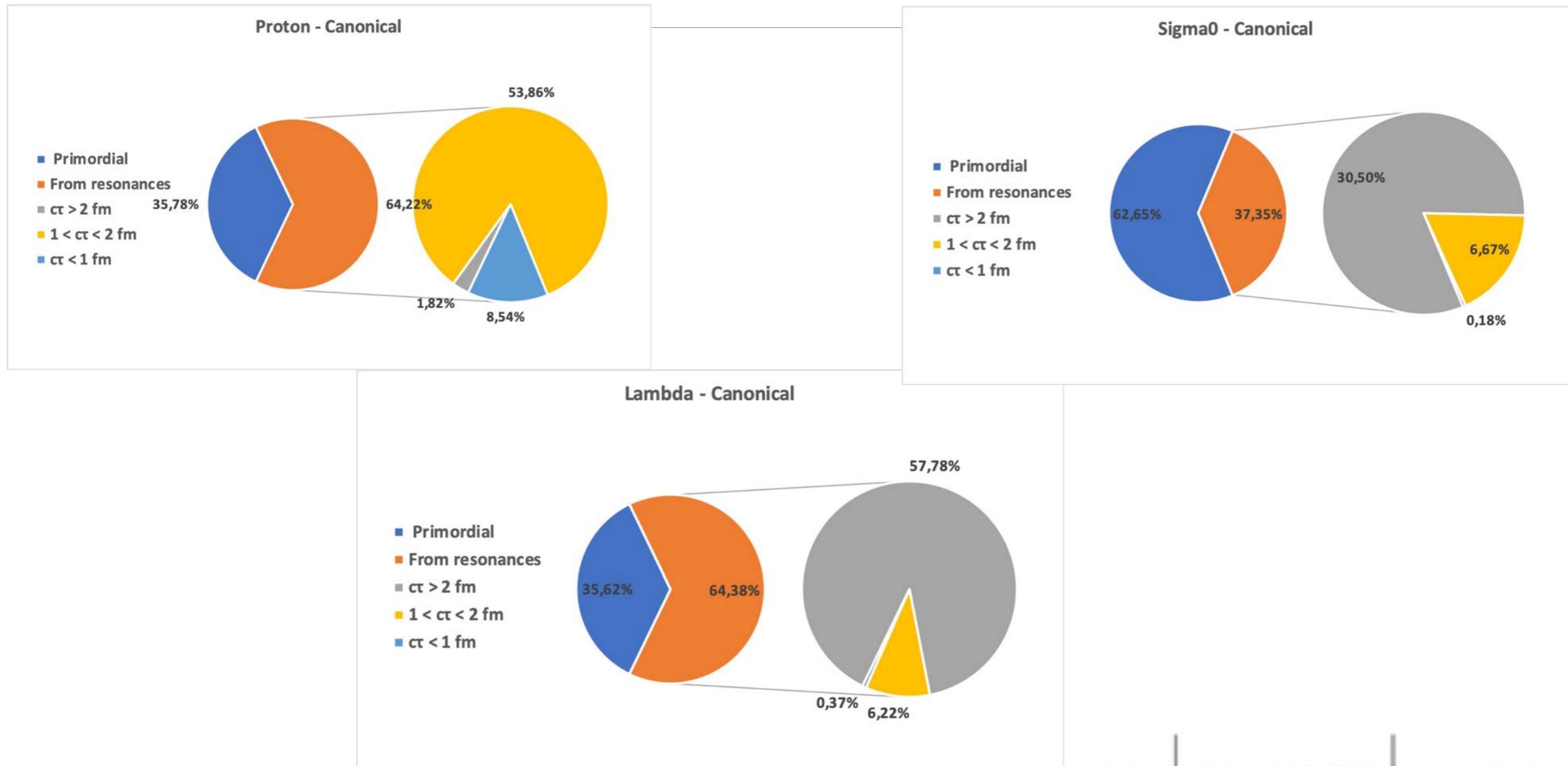


Fit with a ‘core’ Gaussian + Resonances





Contribution of Short-lived Resonances



- For Ξ^- and Ω^- no contributions!
- Average mass and average ct 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



Collective effects and strongly decaying resonances

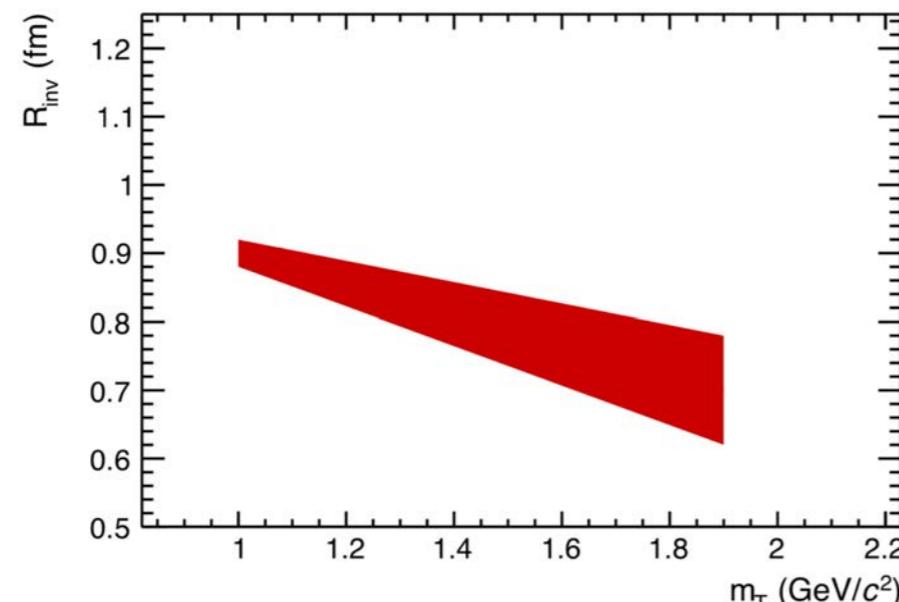
(An)isotropic flow

Gaussian core

+ Strongly decaying resonances



Exponential tail



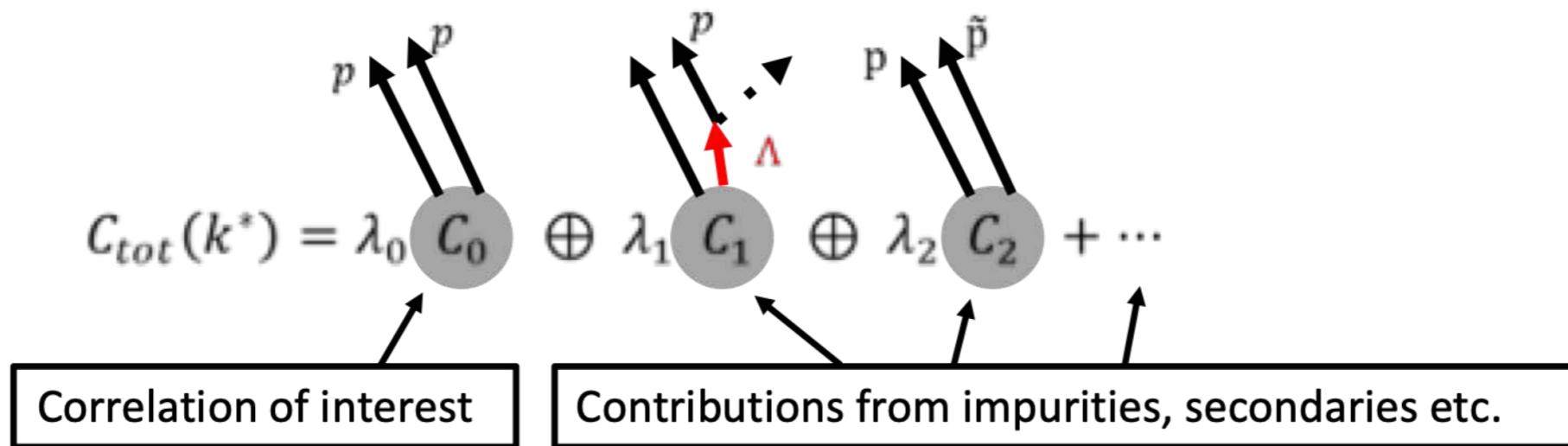
Particle	Primordial fraction	Resonances	
		$1 < c\tau < 2 \text{ fm}$	$c\tau > 2 \text{ fm}$
Proton	33 %	56 %	2 %
Lambda	35 %	8 %	58 %

Amount of resonances determined within the Statistical Hadronization Model in the canonical approach

Priv. Comm. with Prof. F. Becattini
[J.Phys. G38 \(2011\) 025002.](#)

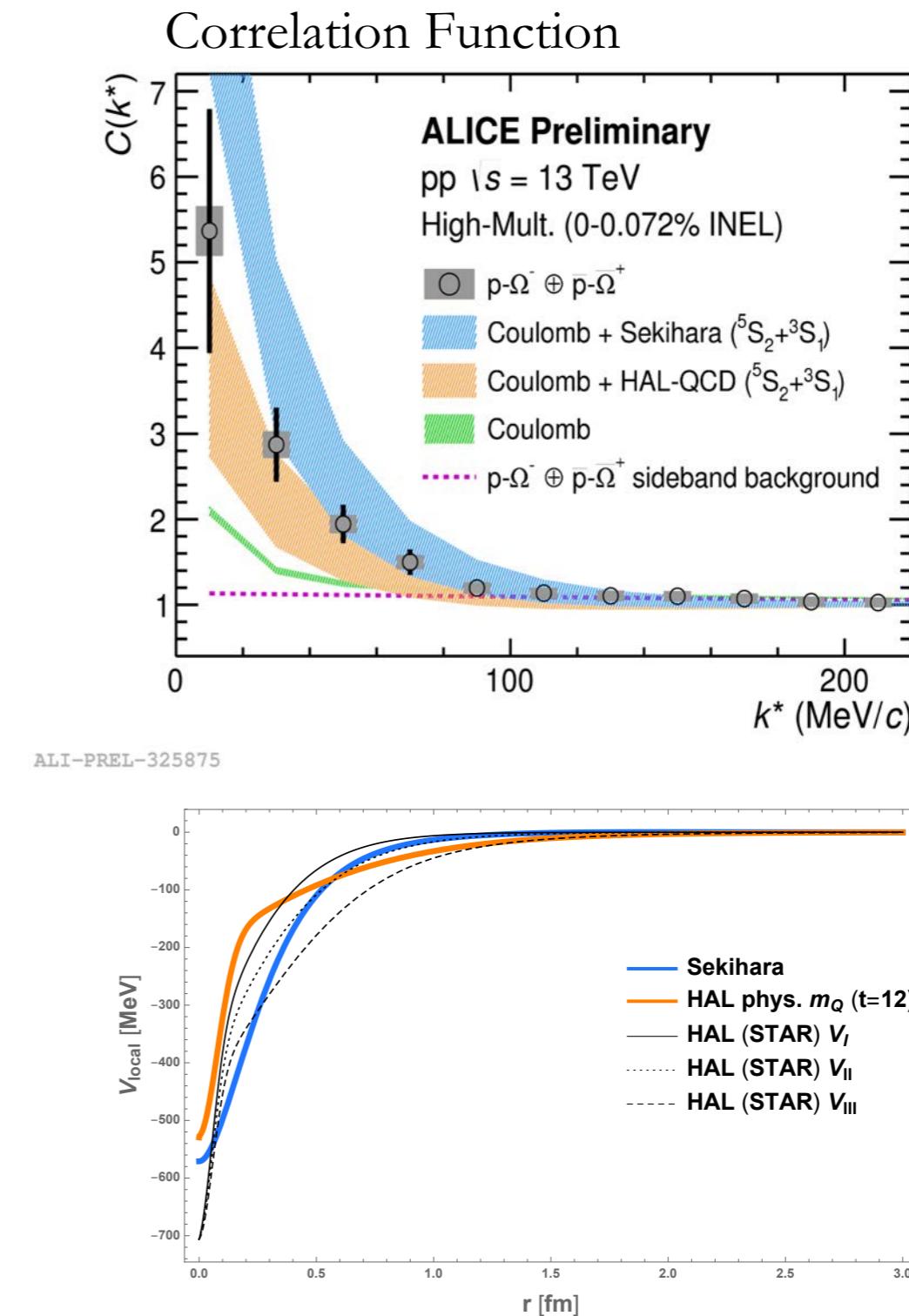
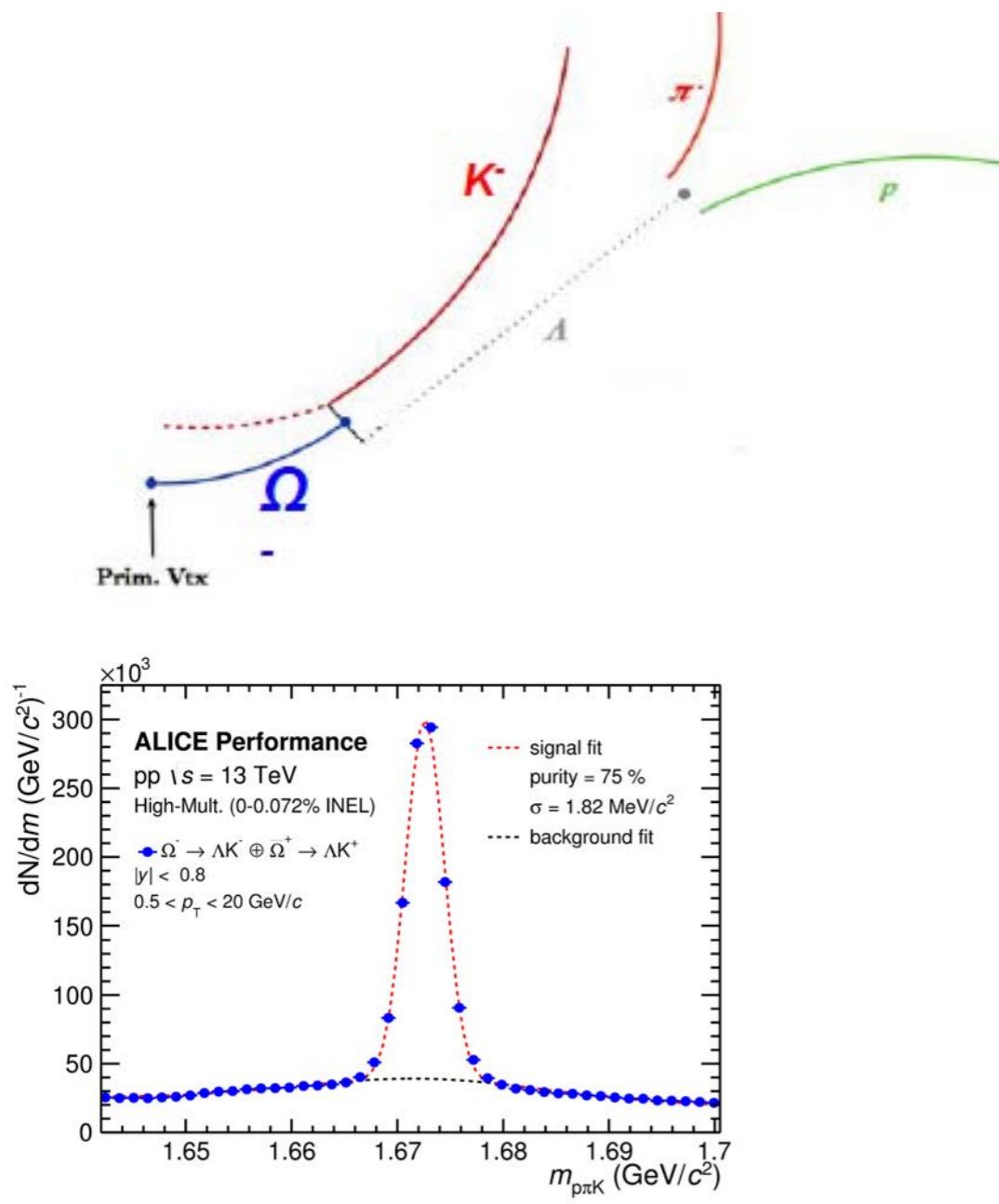
	Lattice (HAL-QCD)	Chiral Effective Field Theory	Meson-Exchange Models
General Properties	<ul style="list-style-type: none"> Quarks and gluons are the degrees of freedom Coupled channels are included Allows for bound states Not fitted to scattering data but with physical pion and kaon masses 	<ul style="list-style-type: none"> Hadronic degrees of freedom Ordered scheme with higher order loops Obeys SU(3) symmetry Coupled channels included Coupling constants fitted to scattering data 	<ul style="list-style-type: none"> 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	✗	✓ (..N ³ LO..)	✓
pΛ	✗	✓ (NLO)	✓
ΛΛ	✓	✗	✓
pΣ ⁰	✗	✓ (NLO)	✓
pΞ ⁻	✓	✓	✓
pΩ ⁻	✓	✗	✓

	Lattice (HAL-QCD)	Chiral Effective Field Theory	Meson-Exchange Models
General Properties	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Hadronic degrees of freedom Ordered scheme with higher order loops Obeys SU(3) symmetry Coupled channels included Coupling constants fitted to scattering data 	<ul style="list-style-type: none"> 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	X	✓	✓
pp	X	✓	✓
pΛ	X	✓ (NLO)	✓
ΛΛ	✓	X	✓
pΣ ⁰	X	✓ (NLO)	✓
pΞ ⁻	✓	✓	✓
pΩ ⁻	✓	X	✓



- Momentum and Tracking resolution are considered either in data corrections or in theoretical correlation functions
- 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 + Data is available

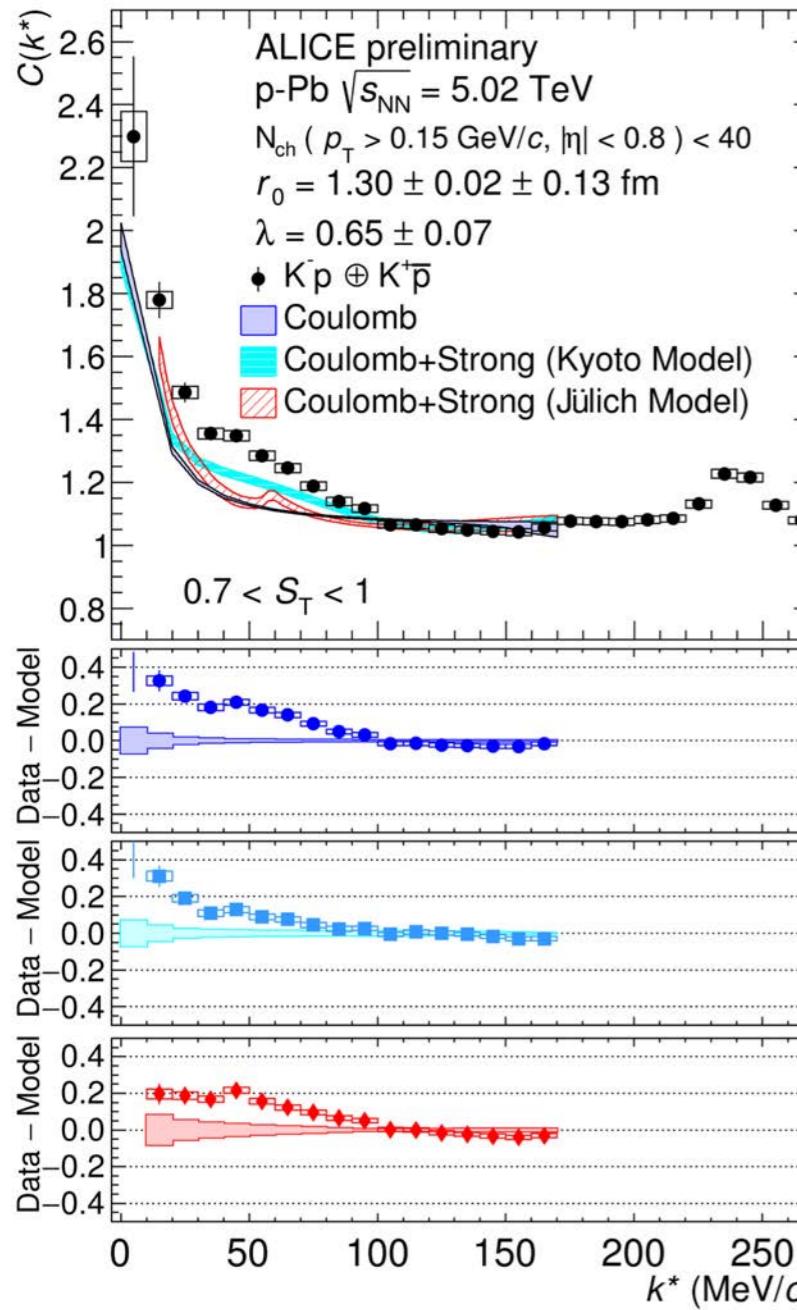
$p\Omega^-$: the ALICE Measurement





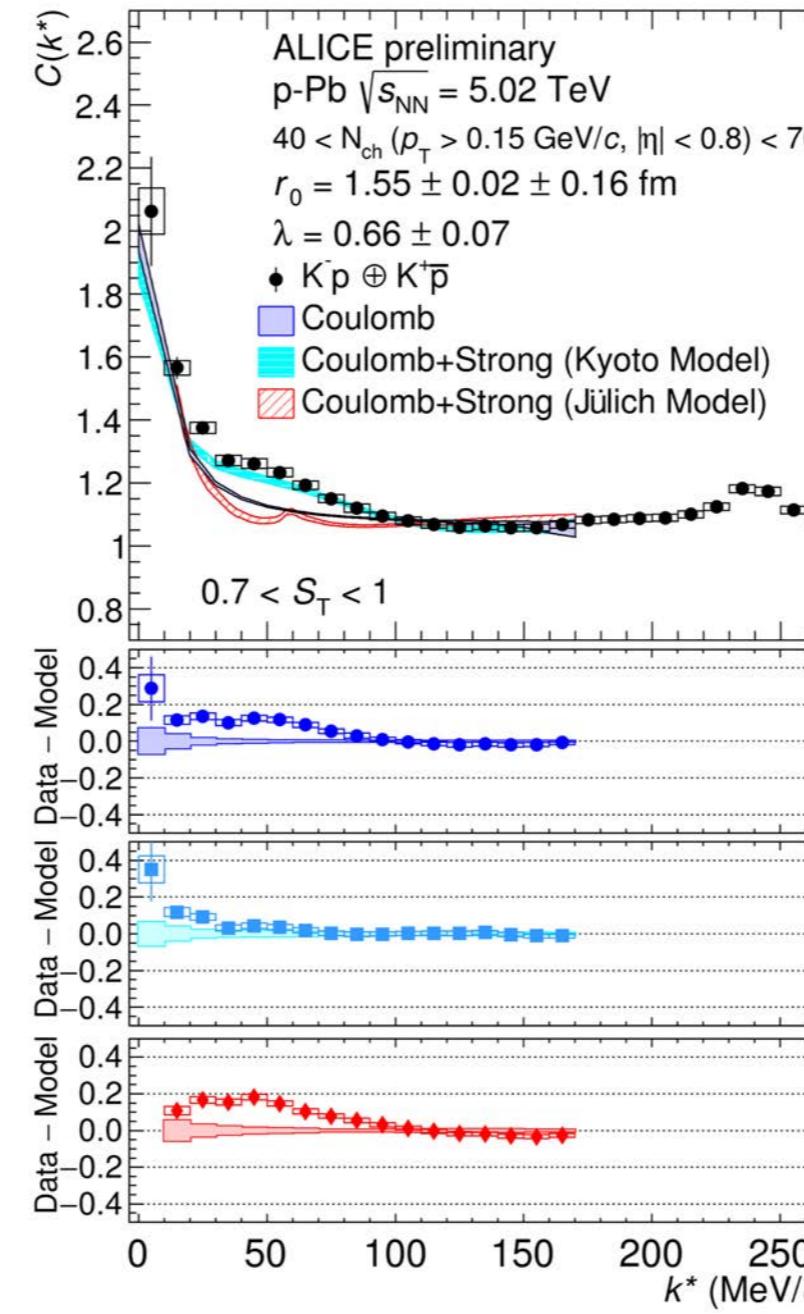
K-p Correlations for pPb 5 TeV

m<40



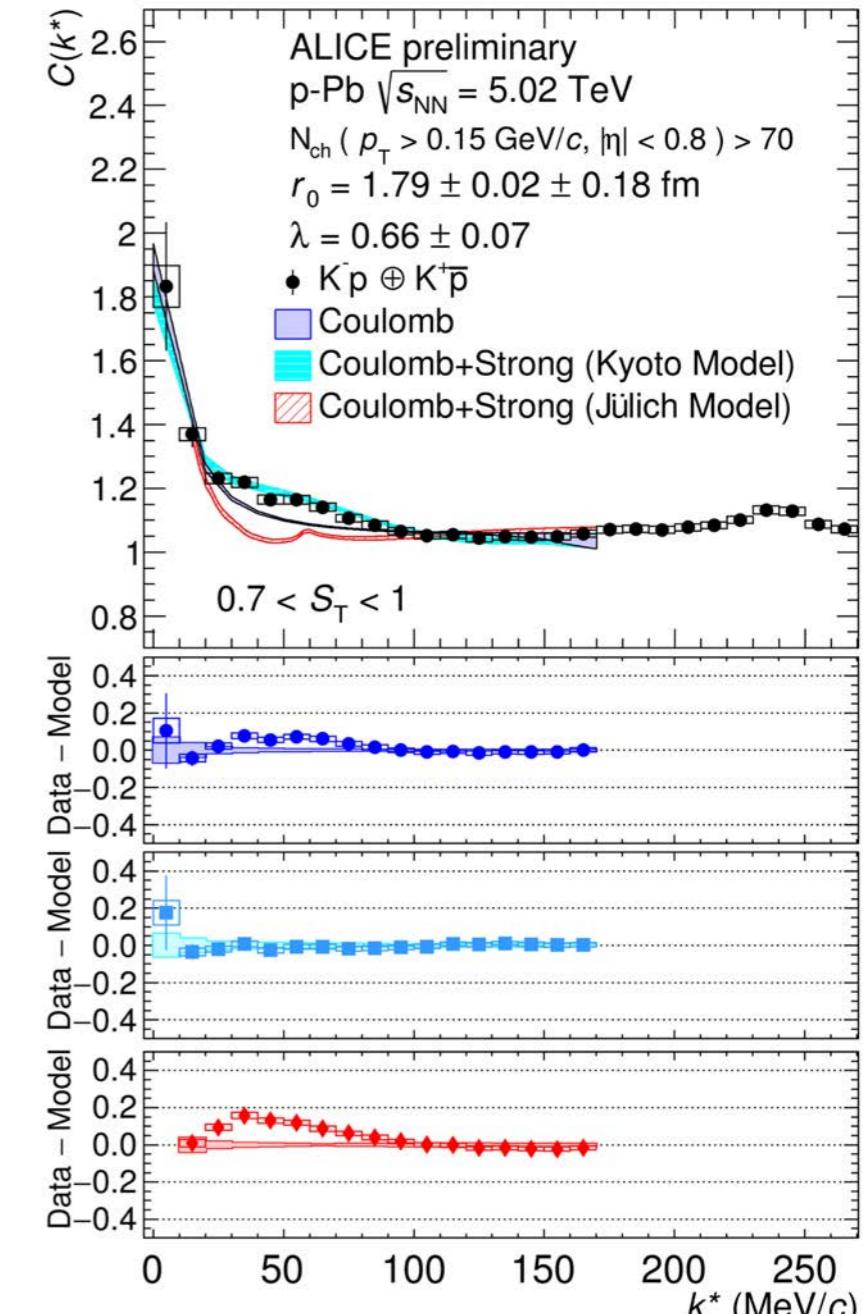
ALI-PREL-316307

40<m<70



ALI-PREL-316311

m>70



ALI-PREL-316315

Interaction changes as a function of the particle distance

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