PER ASPERA AD ASTRA: HOW INTERACTION MEASUREMENTS AT THE LHC CAN HELP UNDERSTANDING NEUTRON STARS

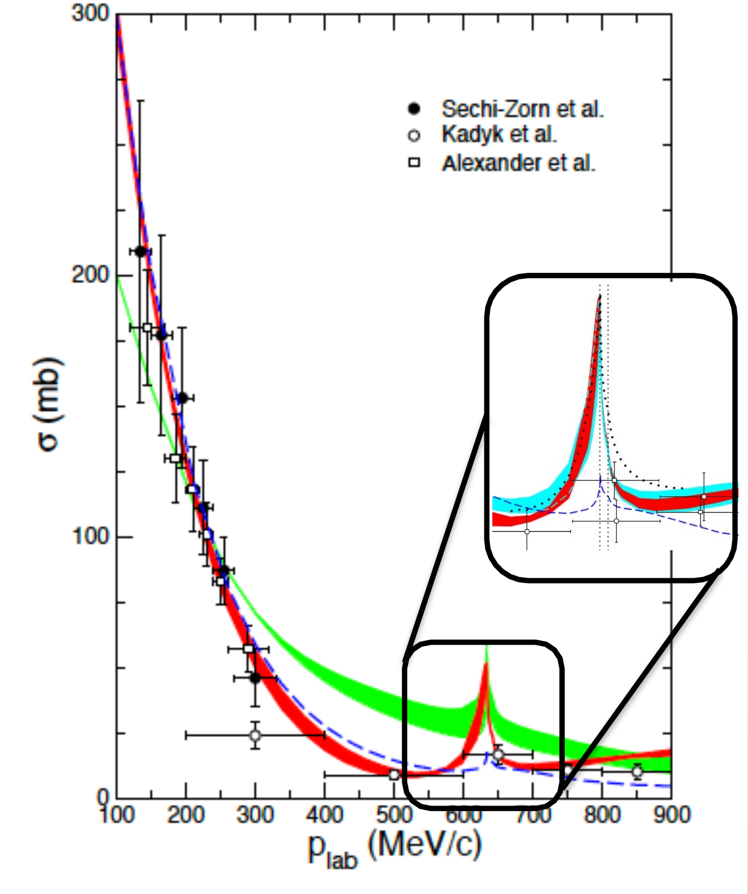
For Johanna’s birthday from Laura

EQUATION OF STATE OF DENSE BARYONIC MATTER

- Several approaches to evaluate the EoS
- One considers starting from two- and three-body baryonic interactions
- This family of EoS can currently not reliably be extrapolated to large baryonic densities ($\rho > 2\ \rho_0$)
- Several experimental techniques are or have been investigated in our field
  - Scattering experiments
  - Heavy ion collisions at (HADES, CBM)
  - Neutron skin studies (PREX, MREX, R3B)
  - Hypernuclei (JPARC, Hydra@R3B, ALICE, STAR)
  - ..
- **This talk is about studies of two- and thre-body interactions including nucleons and hyperons using the femtoscopy technique at the LHC.** Measurements were carried out by the ALICE collaboration
- Possible implications for the equation of state of dense baryonic matter and neutron stars will be discussed

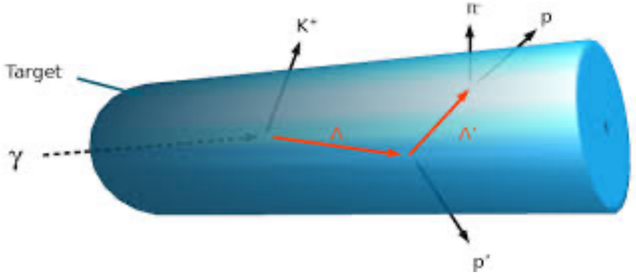
LANDSCAPE OF HYPERON-NUCLEON SCATTERING

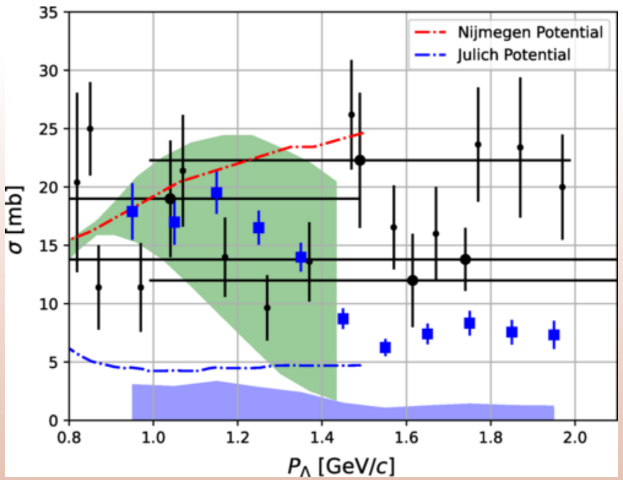
Scattering experiments CERN
Secondary Λ beam, p >100 MeV/c



Sechi-Zorn et al, Phys. Rev. **175** (1968) 1735.
Alexander et al. Phys. Rev. **173** (1968) 1452.
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

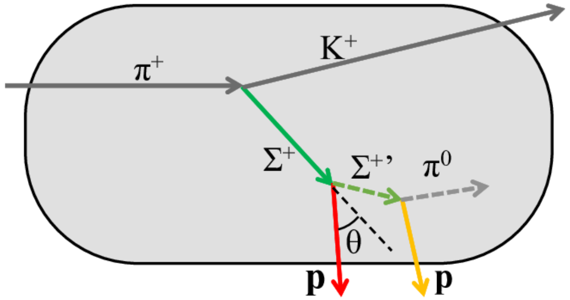
Λ production and tagging @JLAB
p > 800 MeV/c

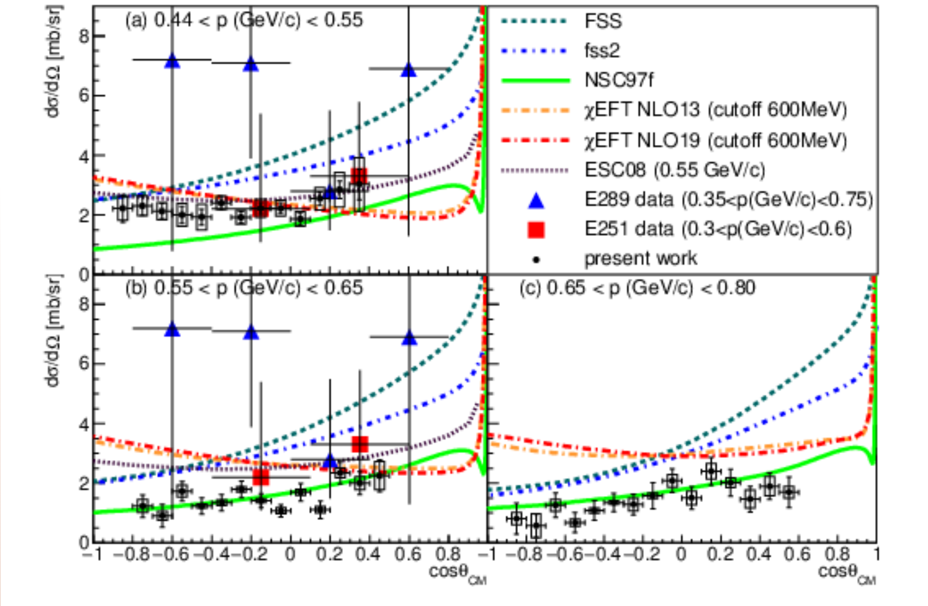




CLAS Coll. PRL 127 (2021)

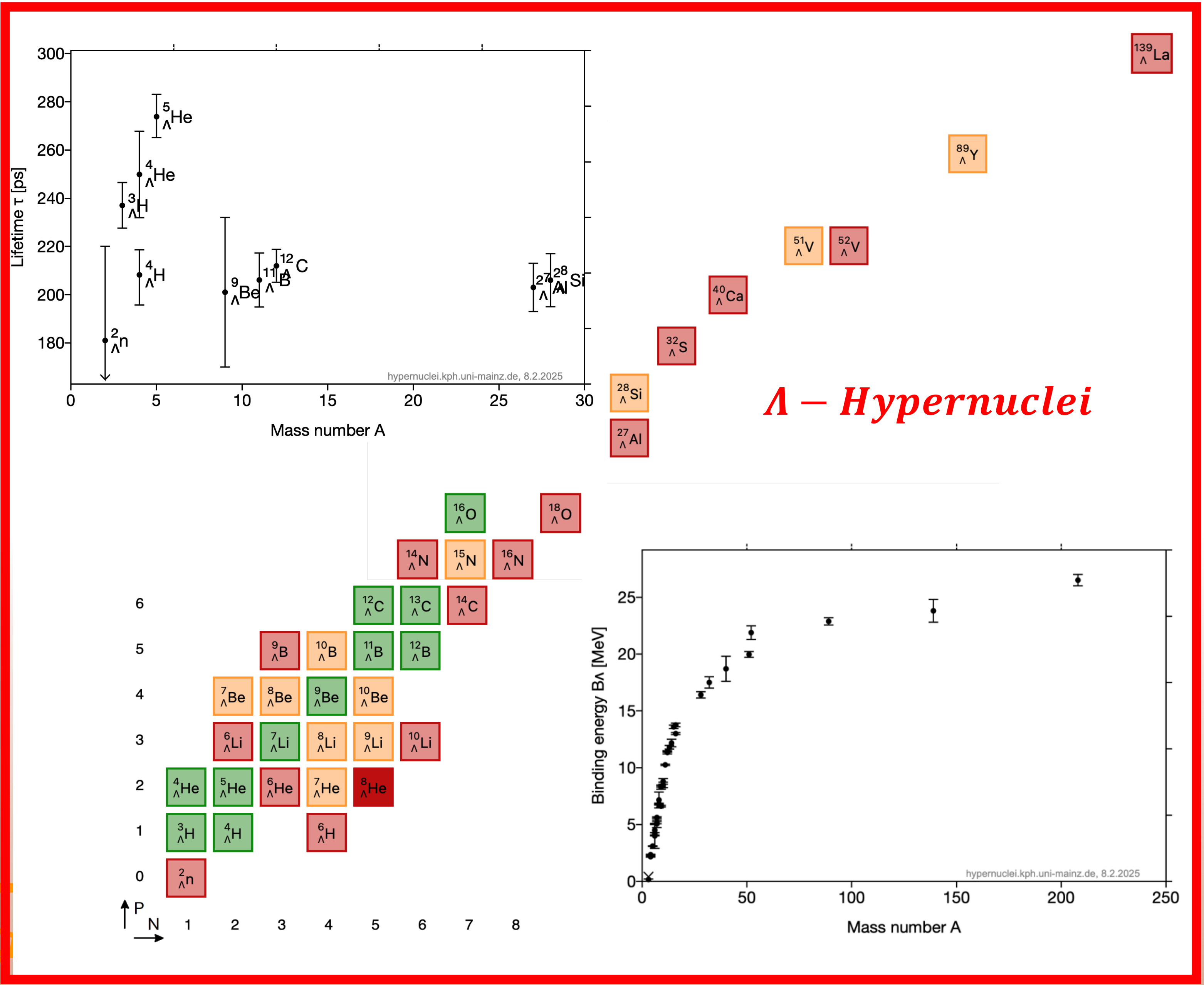
Σ^+ production and tagging @JPARC
p > 400 MeV/c

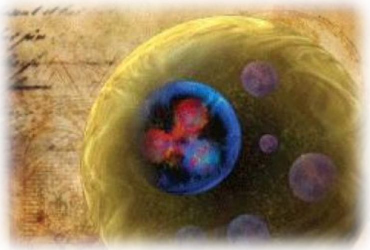




E40 Coll. PTEP 2022 (2022) 9, 093D01

LANDSCAPE OF HYPERNUCLEI MEASUREMENTS



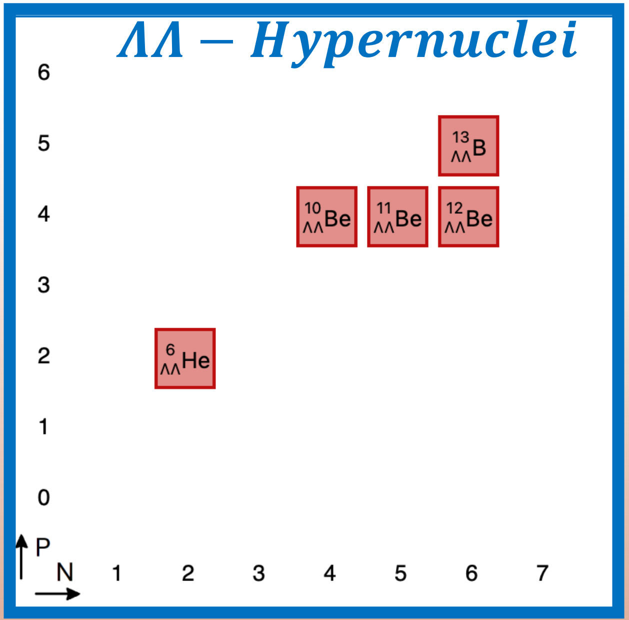


JPARC Experiments

- K-induced

Heavy Ion Experiments

- STAR, ALICE, Hydra, HADES, FOPI, CBM



HADRON INTERACTIONS WITH CORRELATIONS

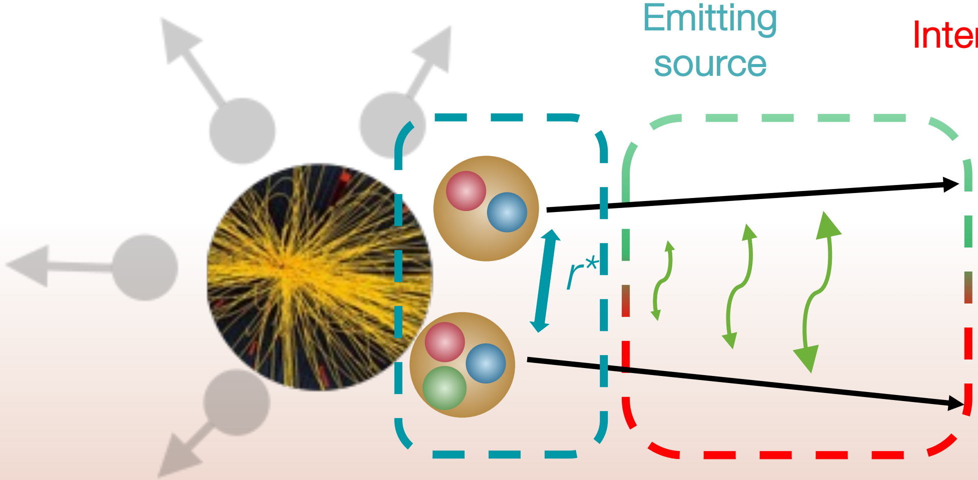
- Accessing hadronic final-state interaction with correlation functions measured in pp collisions

  M.Lisa, S. Pratt et al, ARNPS. 55 (2005), 357-402, LF, V. Mantonvani Sarti and O. Vazquez Doce ARNPS 71 (2021), 377-402

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

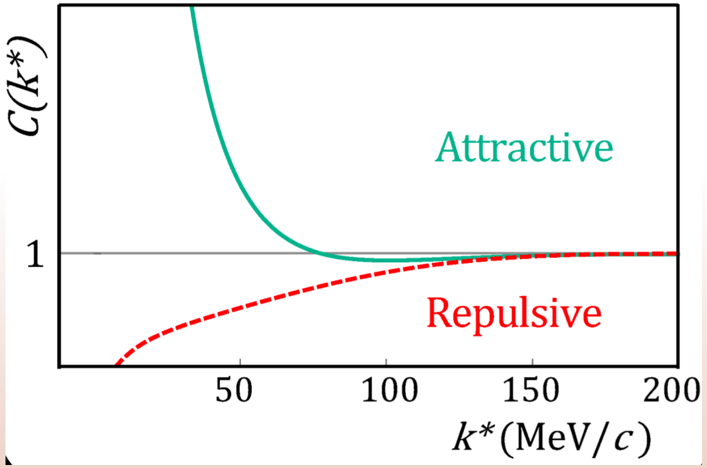
Emitting source

Interaction



r* ~1-2 fm

ALICE Coll. Nature 588 (2020) 232-238



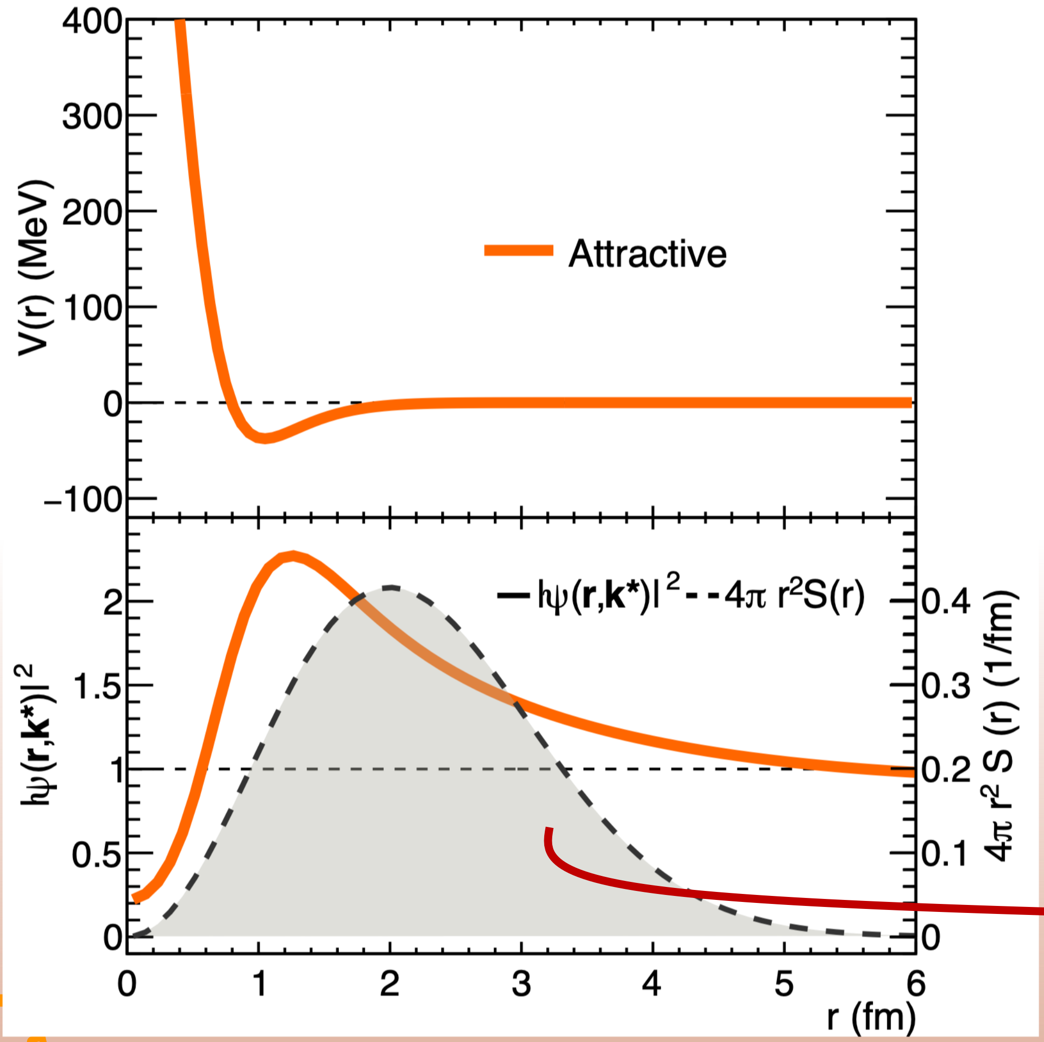
Correlation mapping 1-to-1 the nature of the interaction

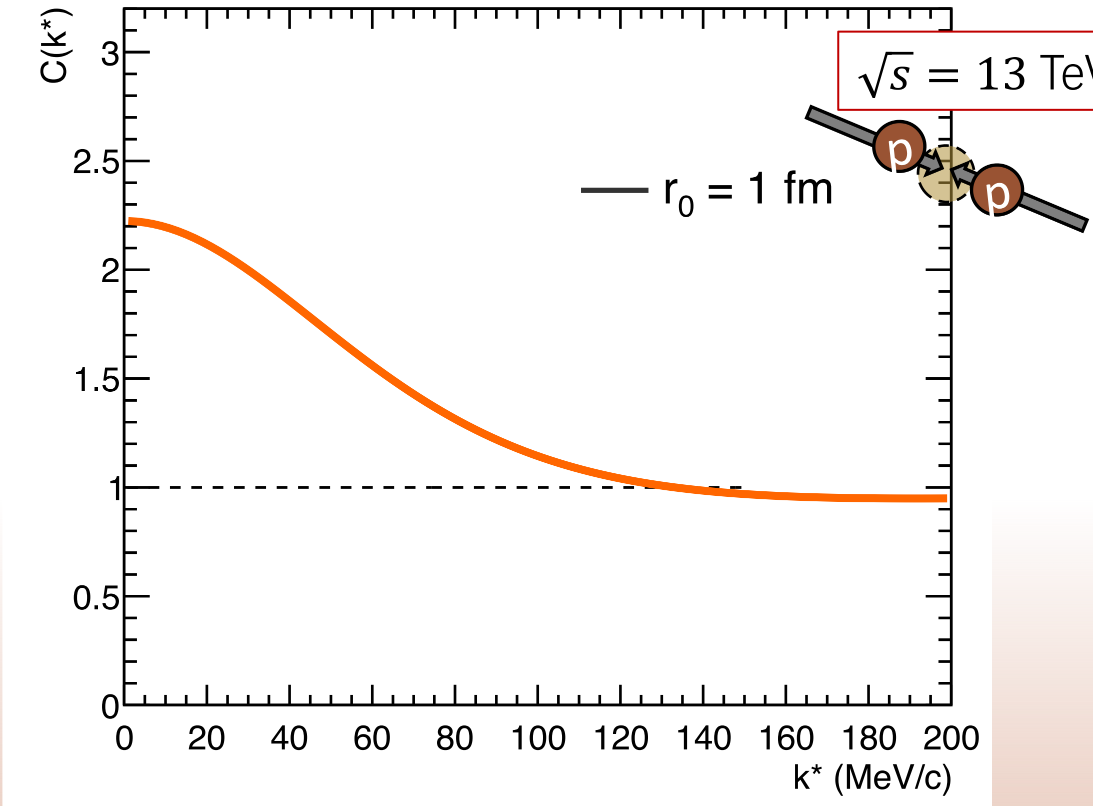
Courtesy VMS

FROM SMALL TO LARGE COLLIDING SYSTEMS

"What's inside the integral"

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





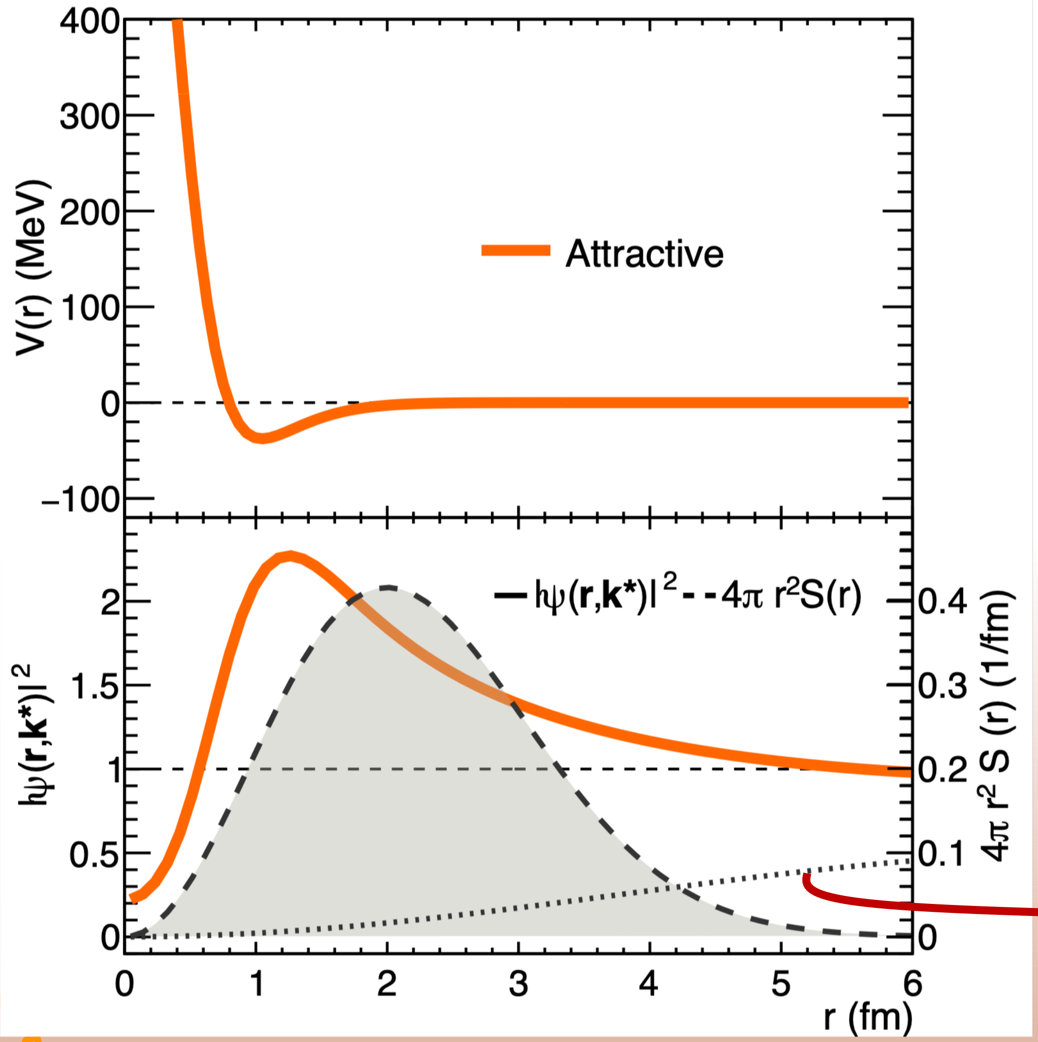
Accessing short-range dynamics in pp collisions

LF, V. Mantovani Sarti and O. Vazquez Doce ARNPS 71 (2021), 377-402

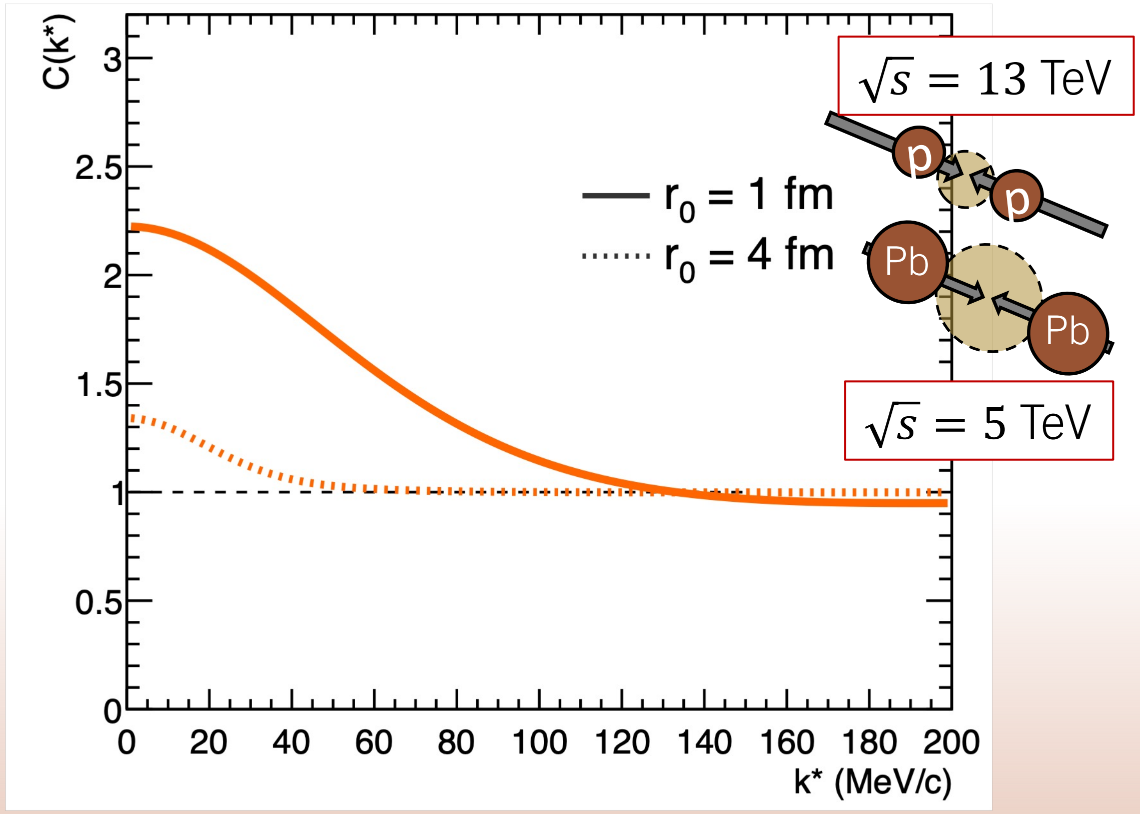
Courtesy VMS

FROM SMALL TO LARGE COLLIDING SYSTEMS

"What's inside the integral"



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



Decrease of signal strength for large source sizes

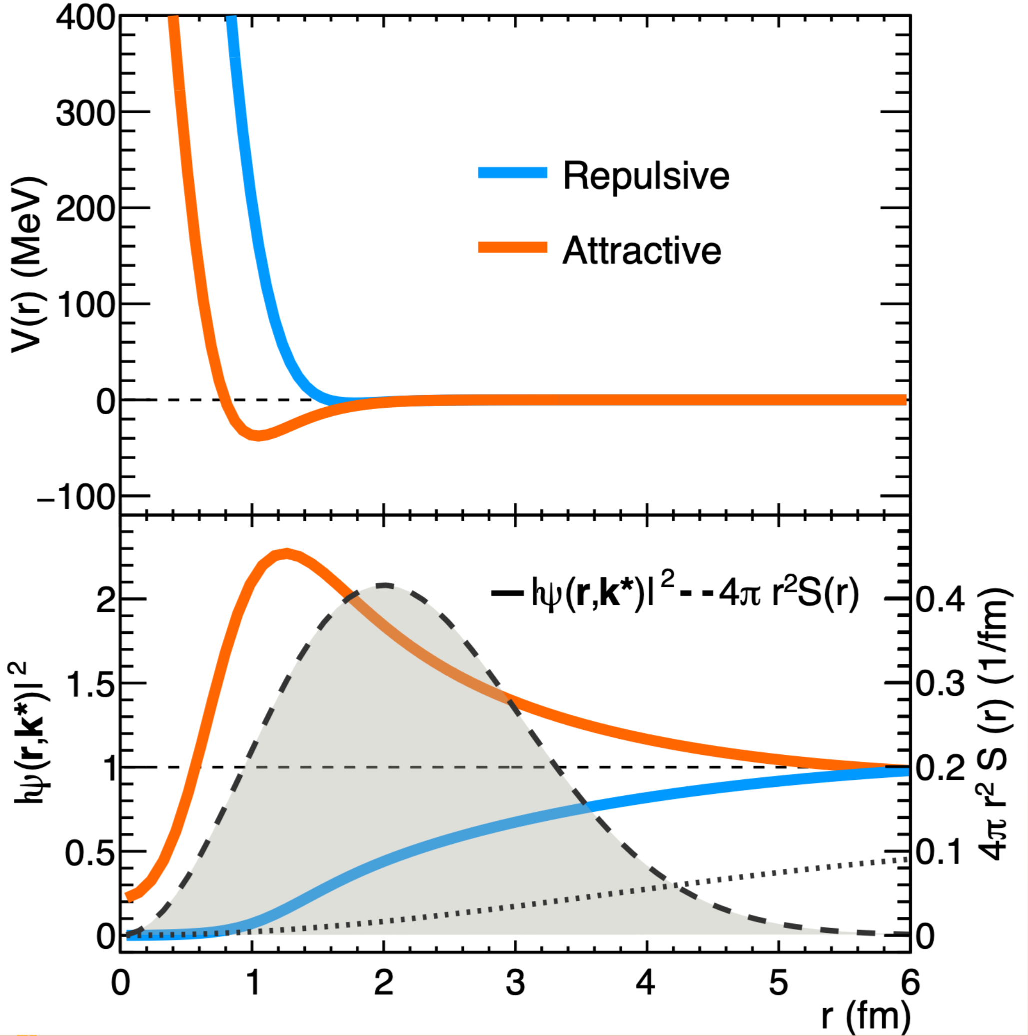
LF, V. Mantovani Sarti and O. Vazquez Doce ARNPS 71 (2021), 377-402

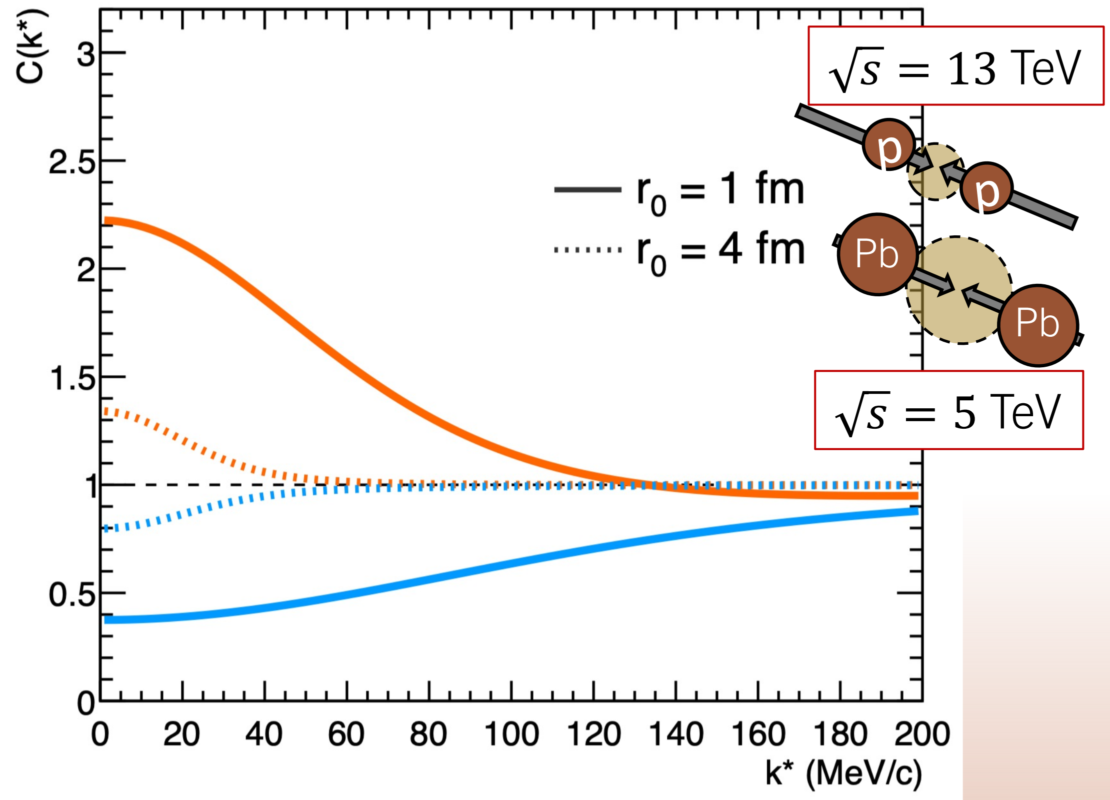
Courtesy VMS

FROM SMALL TO LARGE COLLIDING SYSTEMS

"What's inside the integral"

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





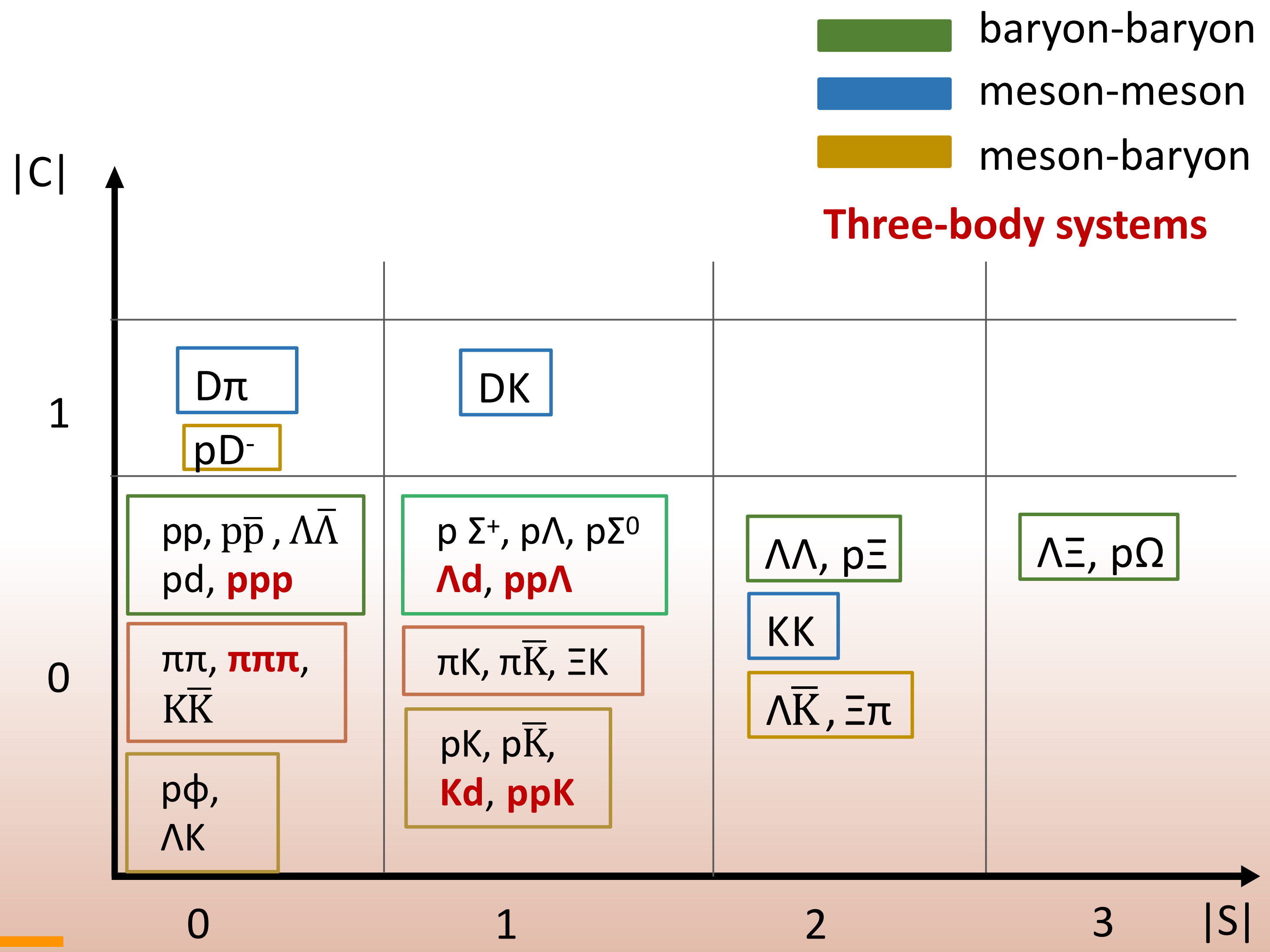
$C(k^*) \begin{cases} > 1 \\ < 1 \end{cases}$

Attractive (no BS)

Repulsive

Courtesy RDG

WHAT WAS MEASURED IN THE LAST 6 YEARS?



p-K: PRL 124 (2020) 9, 092301
PLB 822 (2021) 136708,
EPJC 83 (2023) 4, 340

p-p, p-Λ, Λ-Λ: PRC 99 (2019) 024001

Λ-Λ: PLB 797 (2019) 134822

p-Ξ⁻: PRL. 123 (2019) 112002

p-Ξ⁻, p-Ω⁻: Nature 588 (2020) 232–238

p-Σ⁰: PLB 805 (2020) 135419

p-ϕ: PRL 127 (2021) 172301

Baryon-Antibaryon: PLB 829 (2022) 137272

p-Λ: PLB 832 (2022) 137272

ΛΞ : PLB 844 (2023) 137223

D-p: PRD **106**, 052010 (2022)

p-p-p, p-p-Λ: EPJA 59 (2023) 7, 145

ppK: EPJA 59 (2023) 12, 298

D-π, D-K: PRD 110 (2024) 3, 032004

Λ -K: PL*B* 845 (2023) 138145

p-d, K-d: PRX 14 (2024) 3, 031051

Source studies: PLB 811 (2020) 135849
arXiv:2311.14527

ALICE DETECTOR

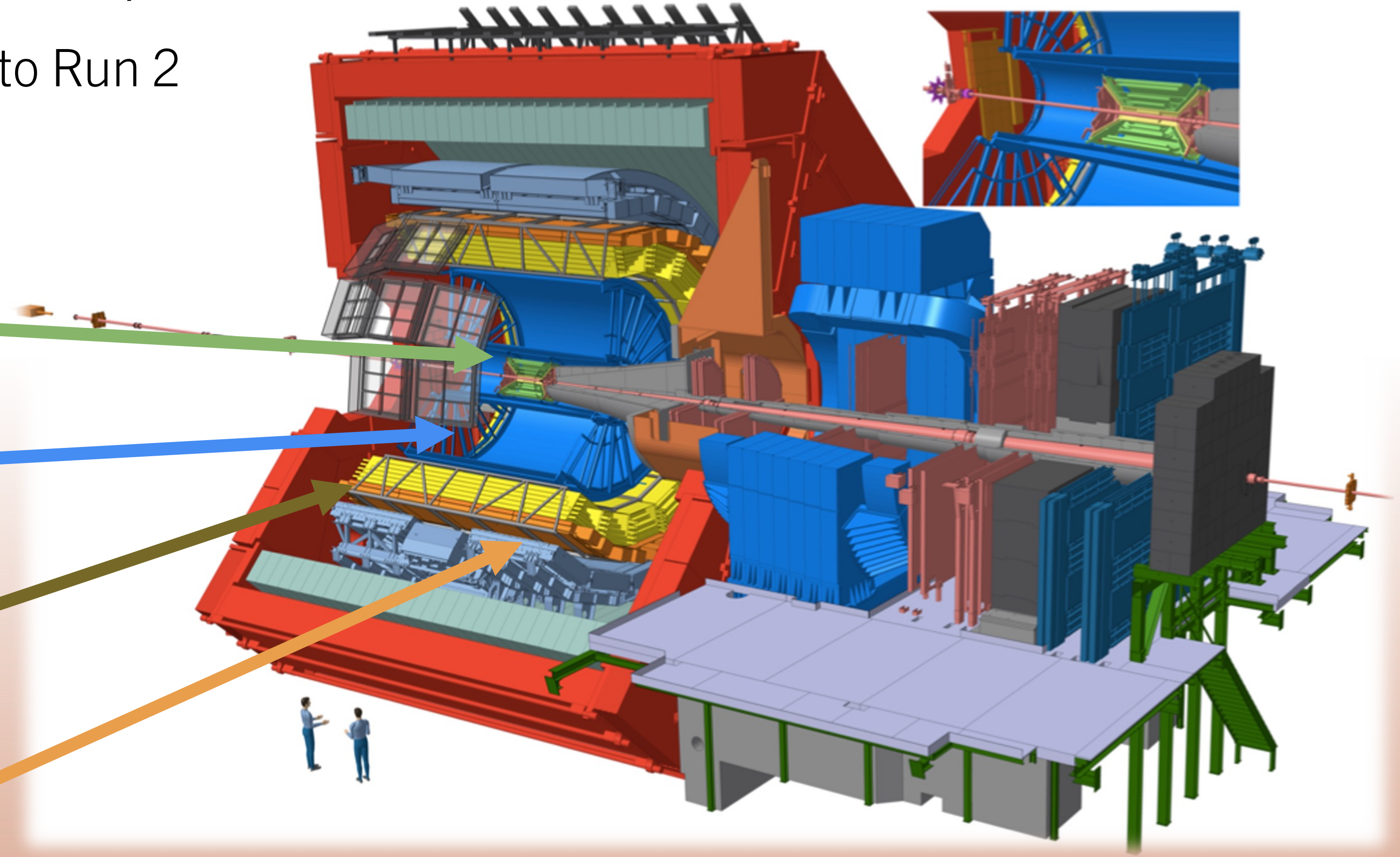
- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study (anti-)nuclei production and annihilation
- Results in this talk refer to pp HM at 13 TeV, Run2
- Major upgrade of the TPC (GEM read out) and ITS2
- Factor 100 in data taking rate w.r.t to Run 2
- Run 3 started in 2022-(2025)

Inner Tracking System
Tracking, vertex, PID (d*E*/dx)

Time Projection Chamber
Tracking, PID (d*E*/dx)

Transition Radiation Detector

Time Of Flight detector
PID (TOF measurement)



SOURCE FUNCTION IN PP COLLISIONS AT THE LHC

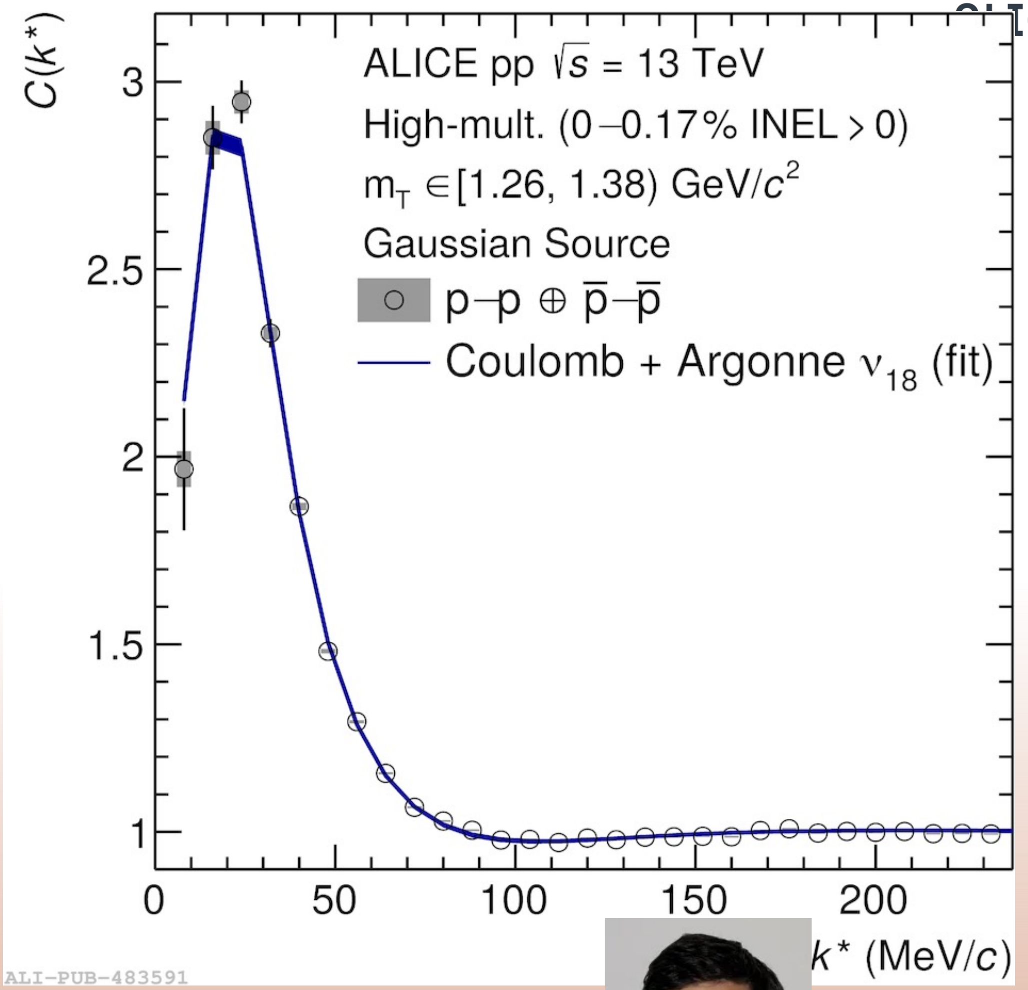
- Emitting source function anchored to p-p correlation function

$$\underset{\text{measured}}{C(k^*)} = \int S(\vec{r}\,) \underbrace{\left|\psi(\vec{k}^*, \vec{r}\,)\right|^2}_{\text{known interaction}} d^3\vec{r}$$

- Gaussian parametrization

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \times$$ Effect of short lived resonances (cτ ~ 1 fm)

ALICE Coll., PLB, 811 (2020), 135849



ALICE Coll., PLB, 811 (2020)

D.Mihaylov
TUM/Sofia Uni

SOURCE FUNCTION IN PP COLLISIONS AT THE LHC

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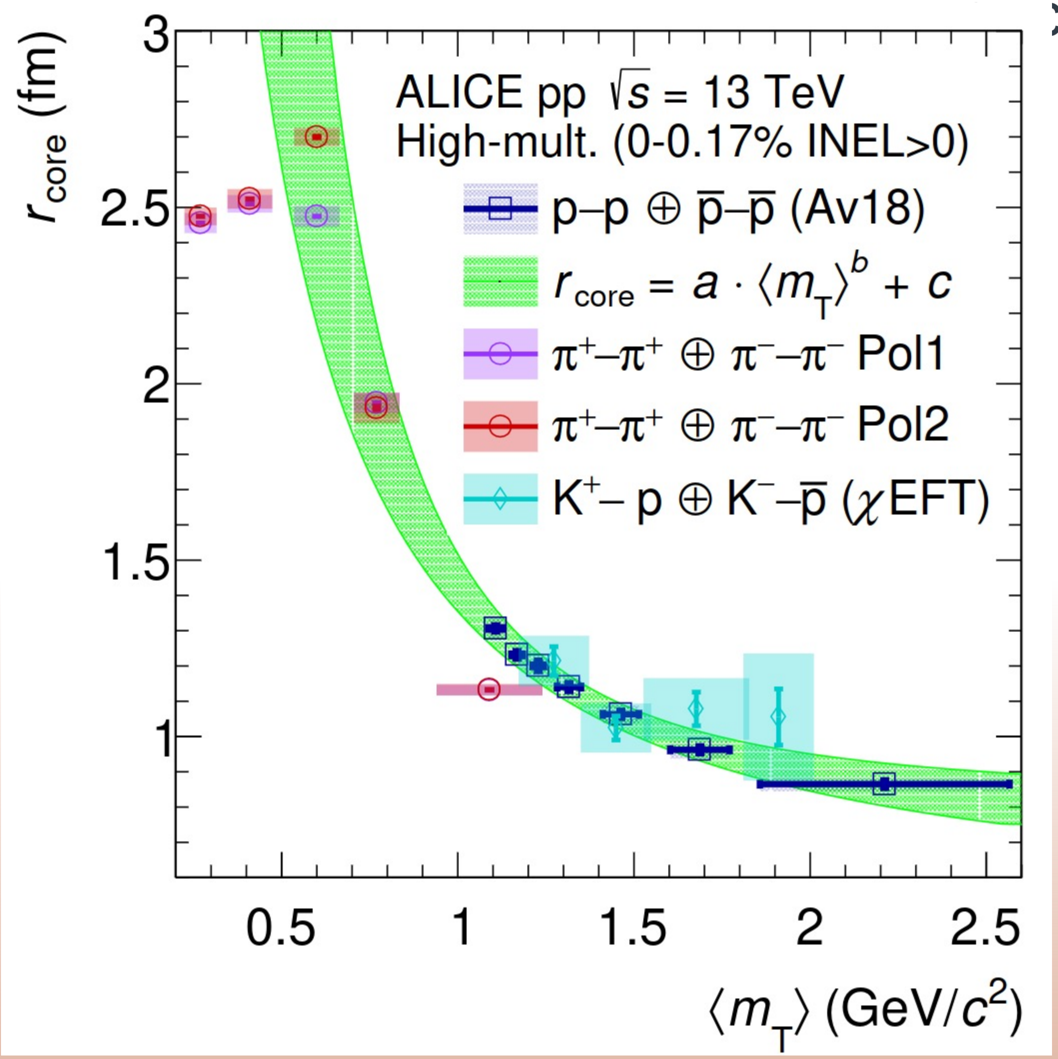
ALICE Coll., PLB, 811 (2020), 135849

- One universal source for all hadrons (cross-check with K⁺-p, π-π, p-Λ, p-π)

- Small particle-emitting source created in pp collisions at the LHC

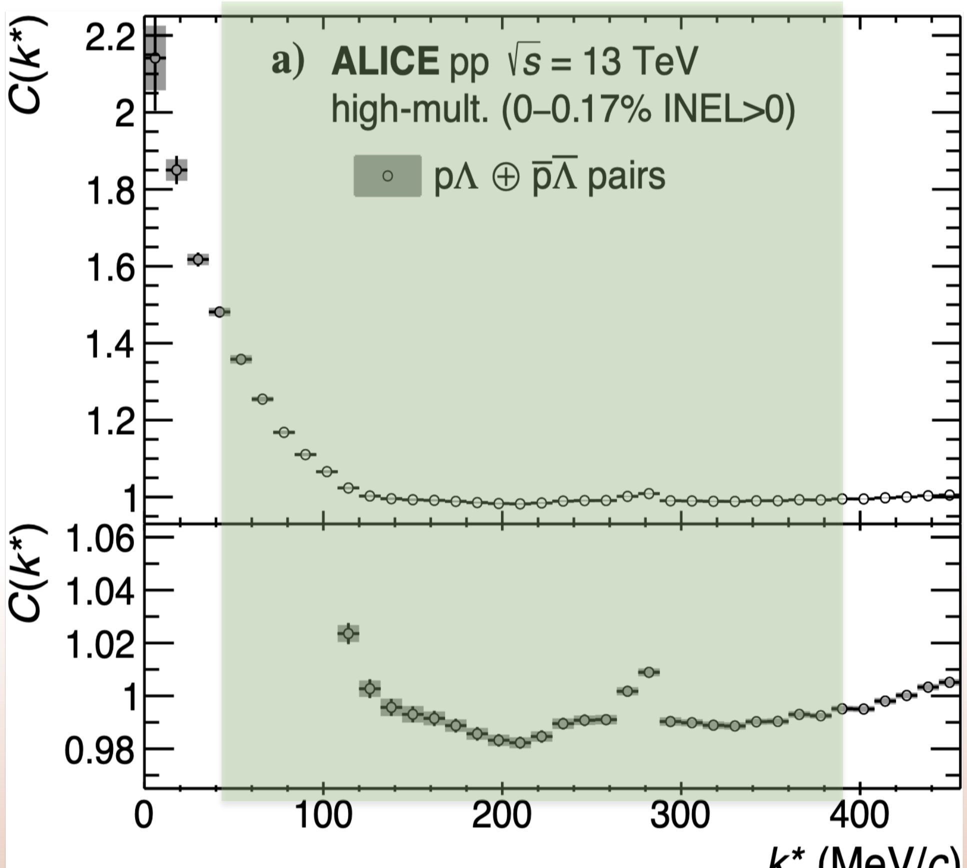
M. Korwieser
TUM



ALICE Coll., PLB, 811 (2020), 135849; ALICE Coll., arXiv:2311.14527

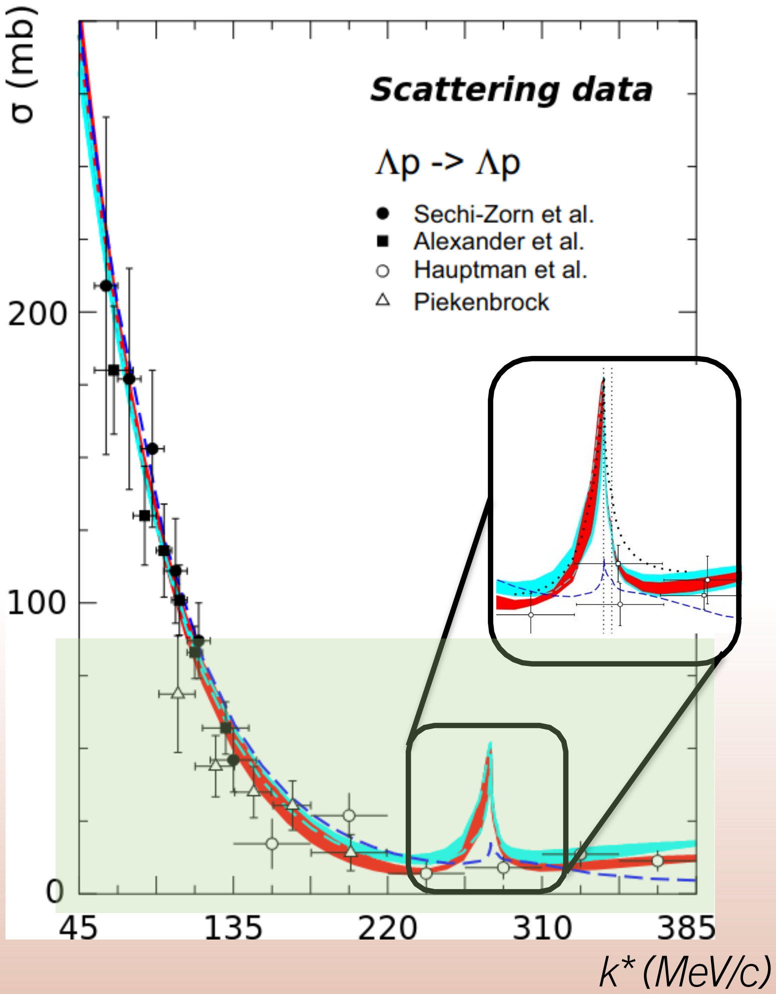
THE pΛ FEMTOSCOPY CORRELATION

$\sim 7 \cdot 10^5$ pΛ pairs with k*< 200 MeV/c



ALICE coll. PLB 833 (2022), 137272

- Measurement down to zero momentum
- Factor >20 improved precision (<1%)
- First experimental evidence of ΛN-ΣN opening in 2-body channel



NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

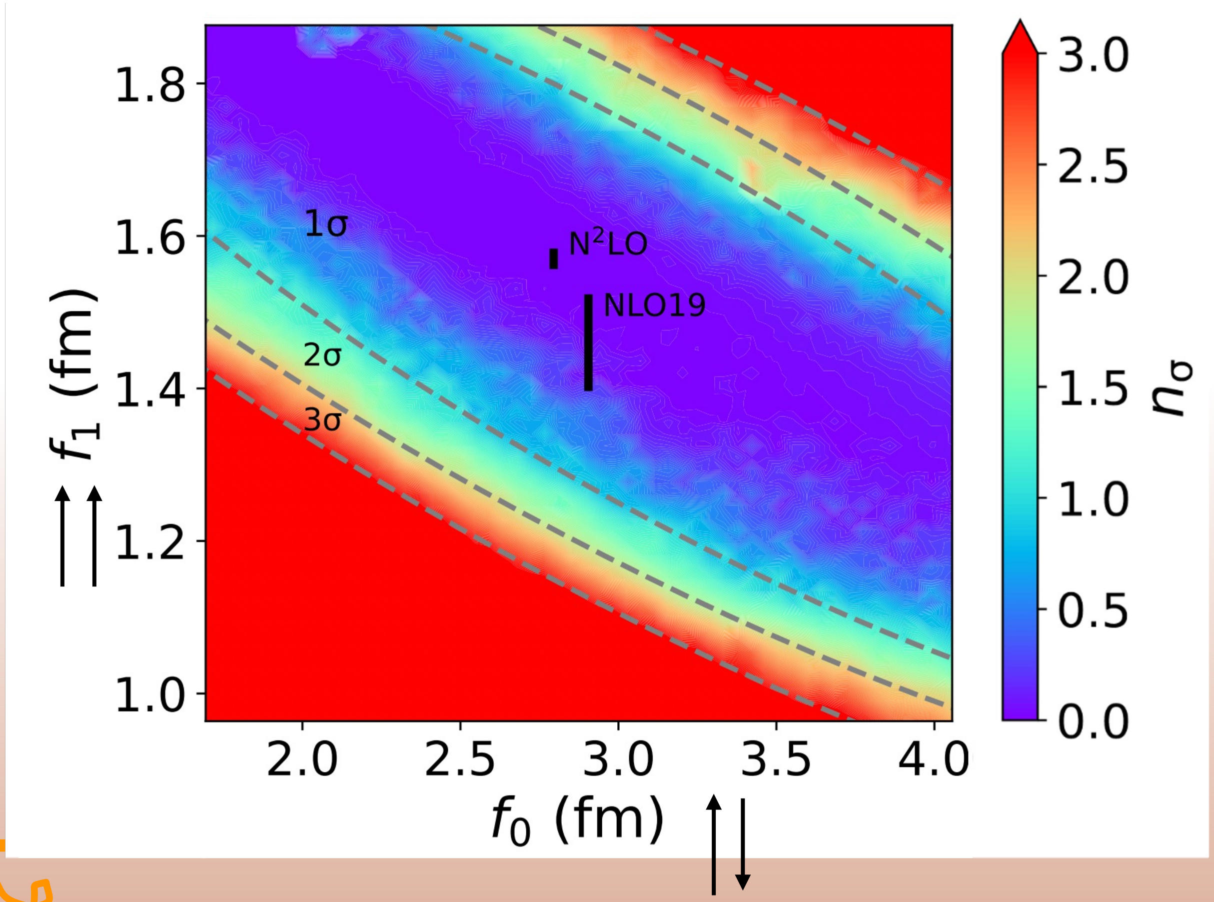
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

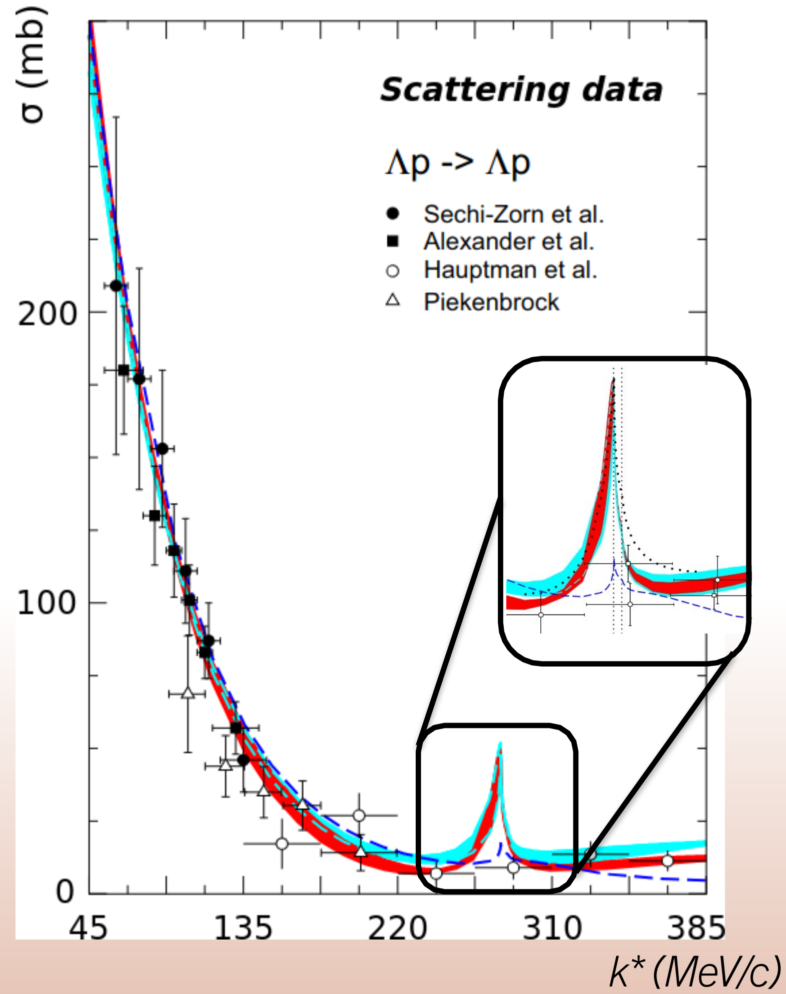
D.Mihaylov
TUM/Sofia Uni

PΛ SCATTERING PARAMETERS

- Spin-0 and Spin-1 scattering length from scattering data
- Agreement with N2LO and NLO19

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550





NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

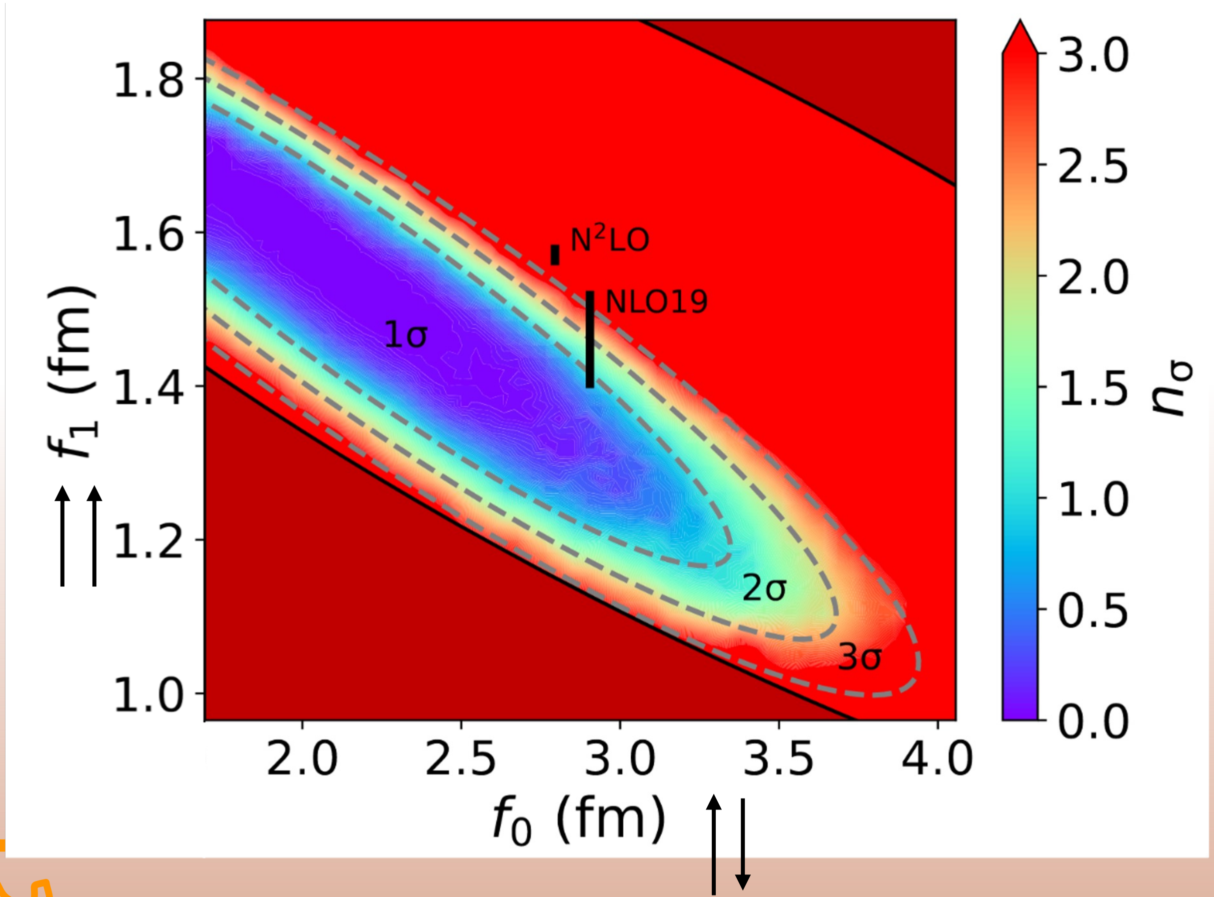
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

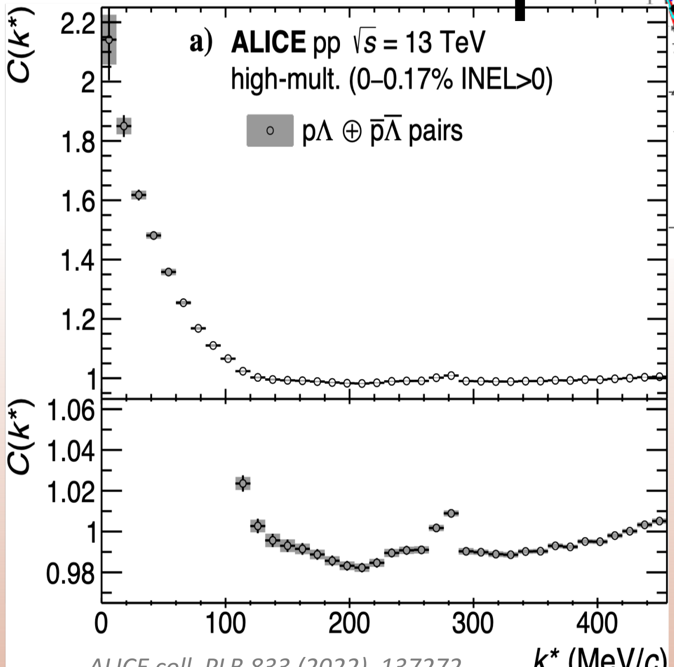
Courtesy RDG

FIRST SIMULTANEOUS FIT OF SCATTERING AND FEMTO DATA

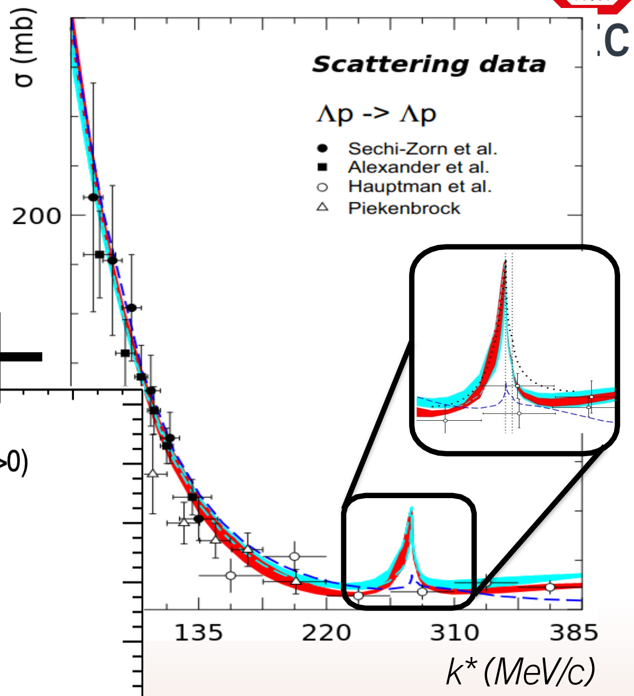
- <u>NEW</u>: combined analysis of femtoscopic and scattering data
- Less attractive ΛN interaction

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550

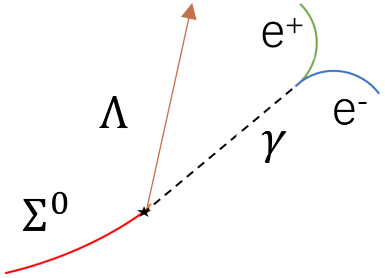


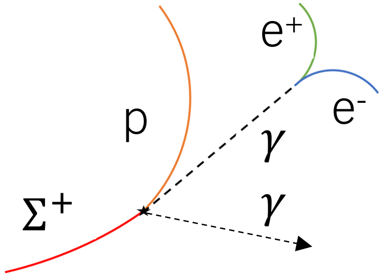


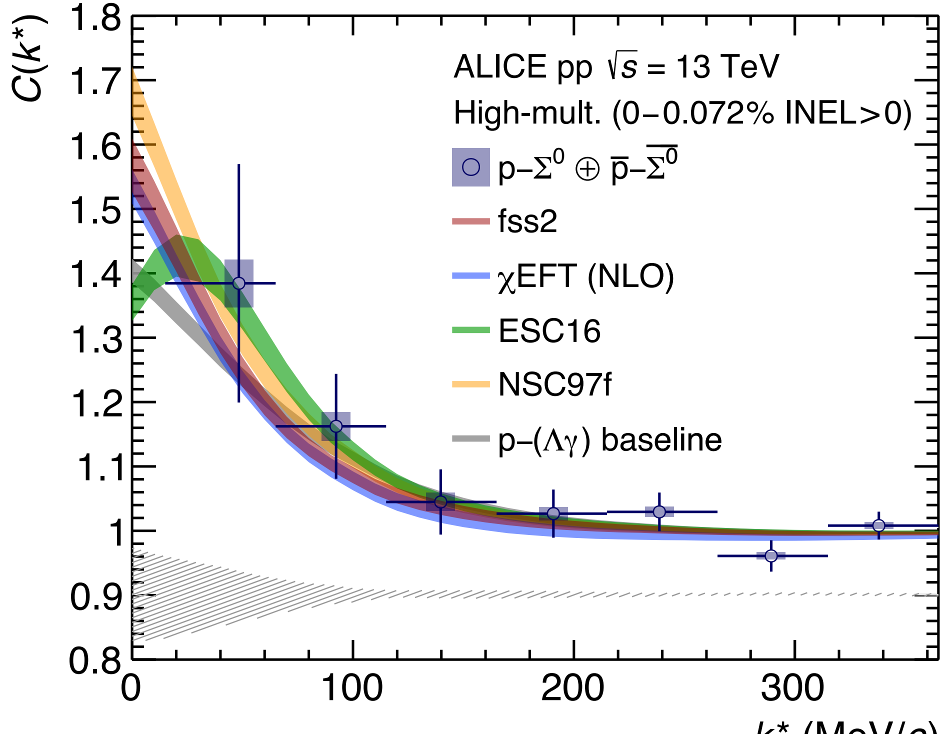
ALICE coll. PLB 833 (2022), 137272



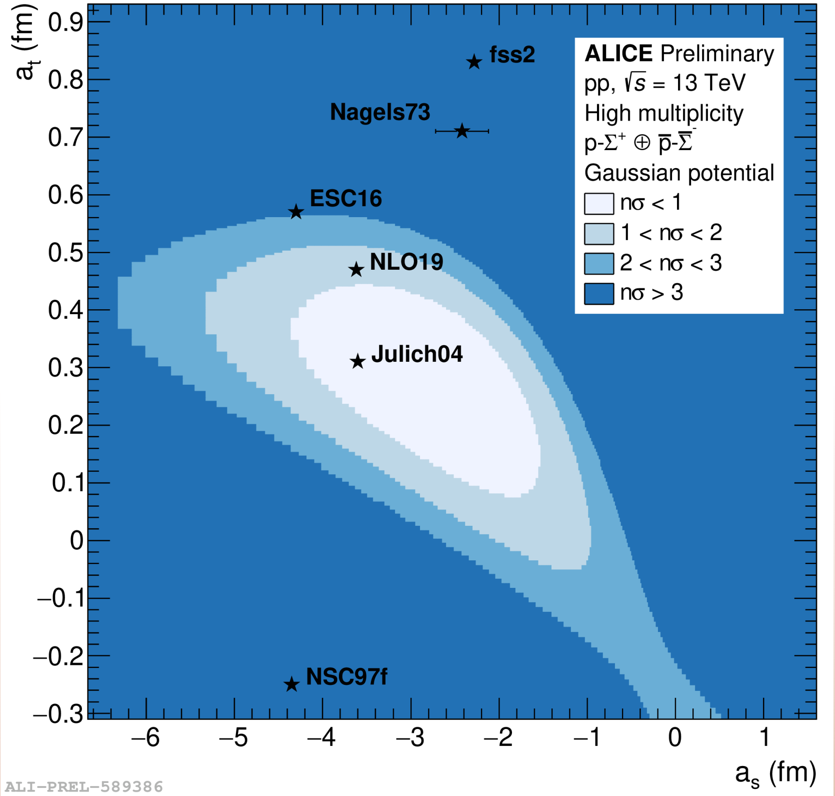
|S|=1: $p\Sigma^0$ AND $p\Sigma^+$







ALICE coll. PLB 805 (2020)



A. Mathis
TUM

B. Heybeck
Uni. Frankfurt

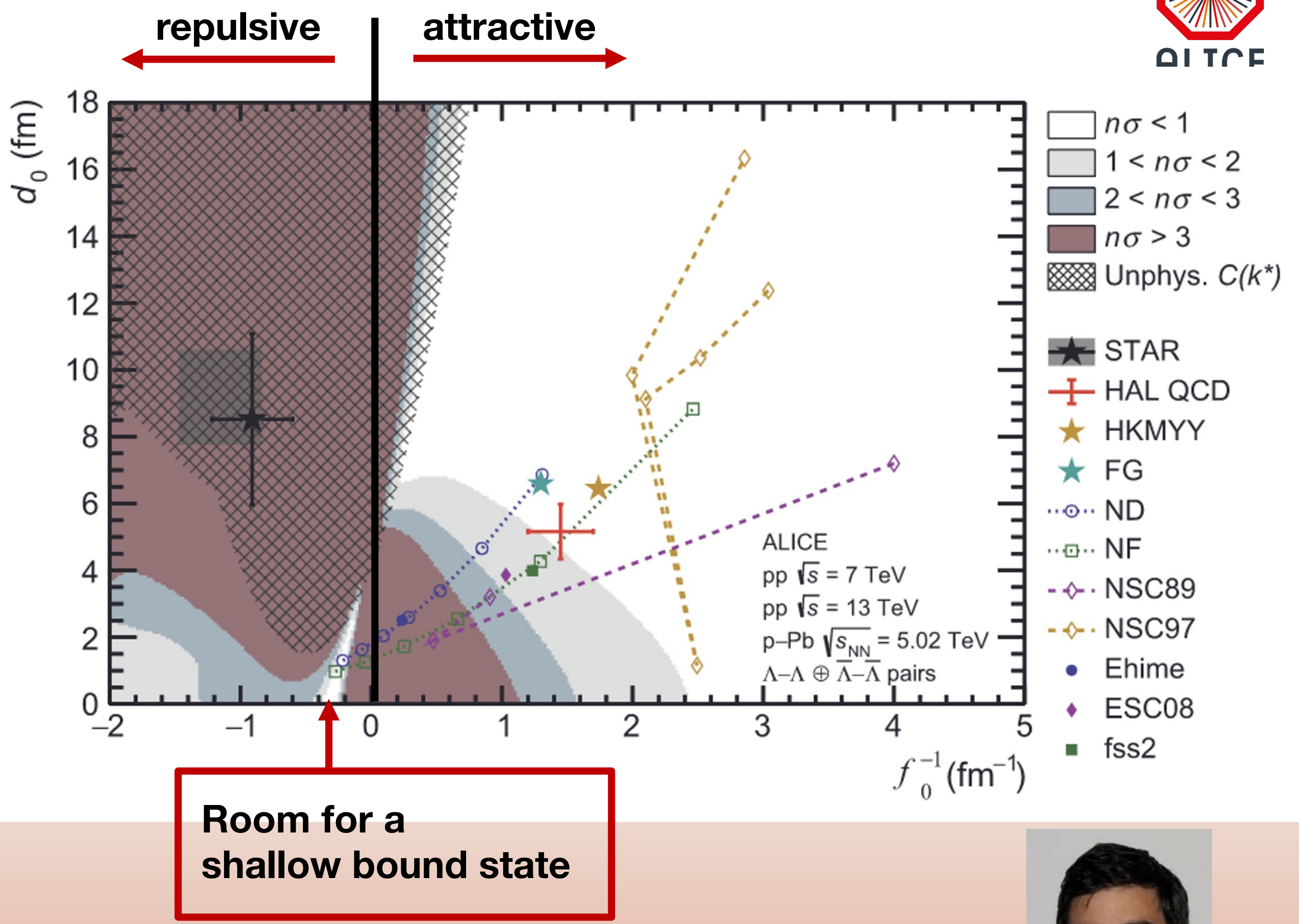
|S|=2 : ΛΛ SCATTERING PARAMETERS

- Important for existence of H-dibaryon
- ΛΛ correlation measured in pp MB 7, 13 TeV and p-Pb 5.02 TeV
- Scan in scattering parameter space (f_0^{-1}, d_0) and express agreement data/model in number of σ deviations

  Agreement with hypernuclei data and lattice predictions

- Most precise upper limit on the binding energy of the H-dibaryon

  $B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\text{stat})^{+1.8}_{-1.0}(\text{syst})$ MeV



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

D.Mihaylov
TUM/Sofia Uni

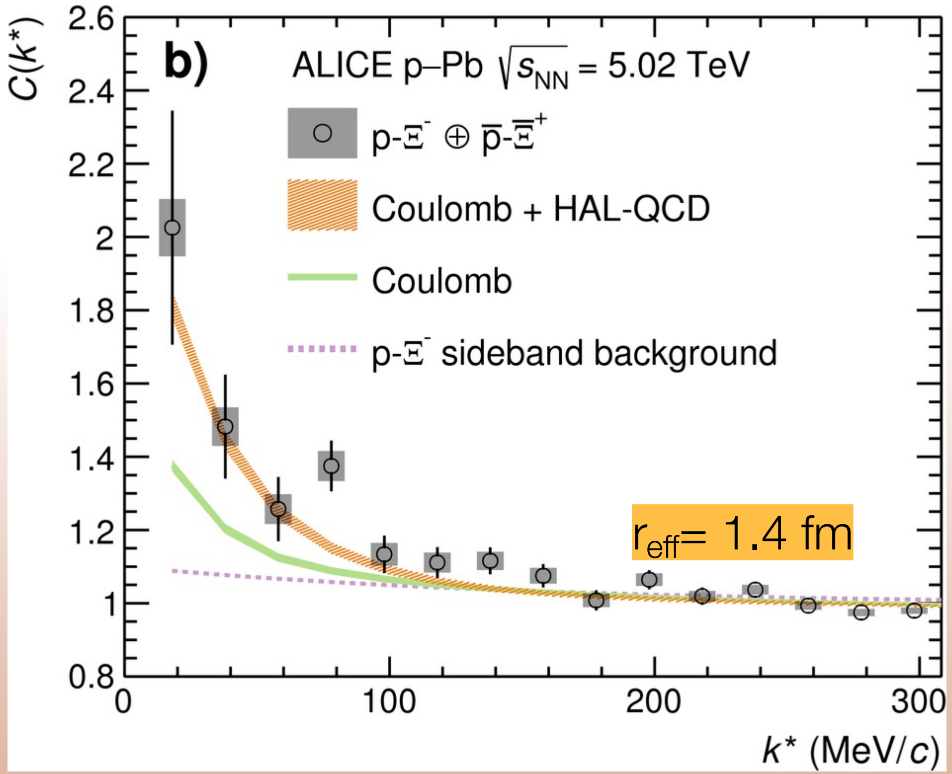
|S|=2: pΞ^- TEST LATTICE POTENTIALS

- Observation of the strong interaction beyond Coulomb
- Agreement with lattice calculations confirmed in pp and p-Pb colliding systems

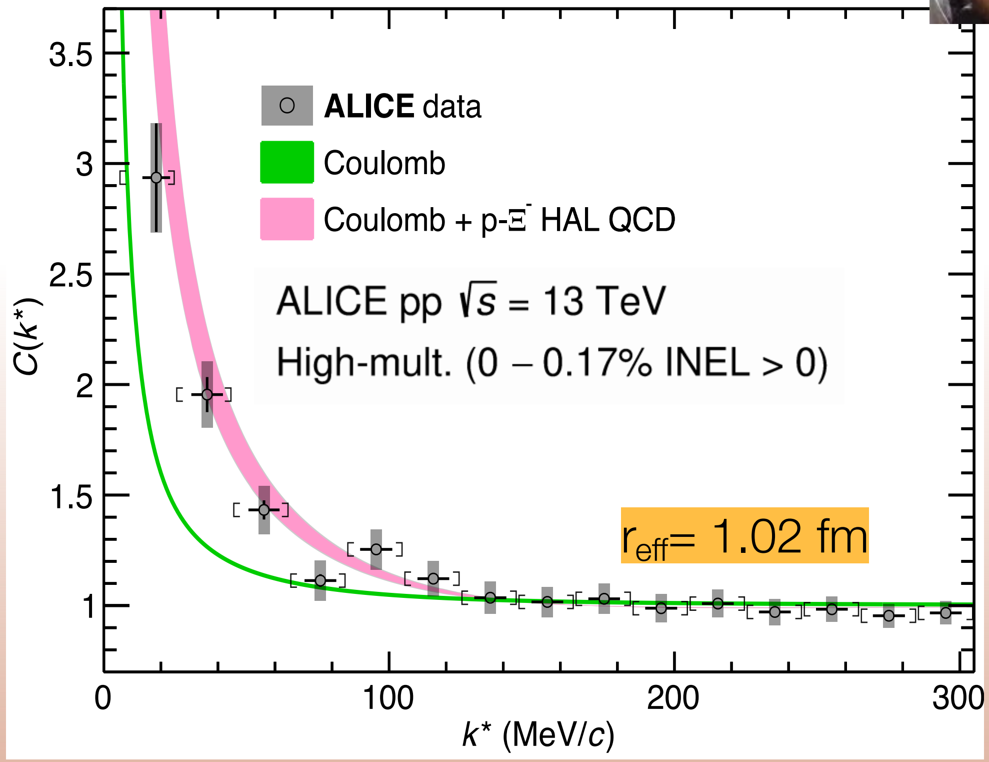
O. Vazquez-Doce
INFN Frascati

B. Holweger
TUM

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



ALICE Coll. Nature 588, 232–238 (2020)



(*) HAL QCD Coll., PoS INPC2016 (2016) 277

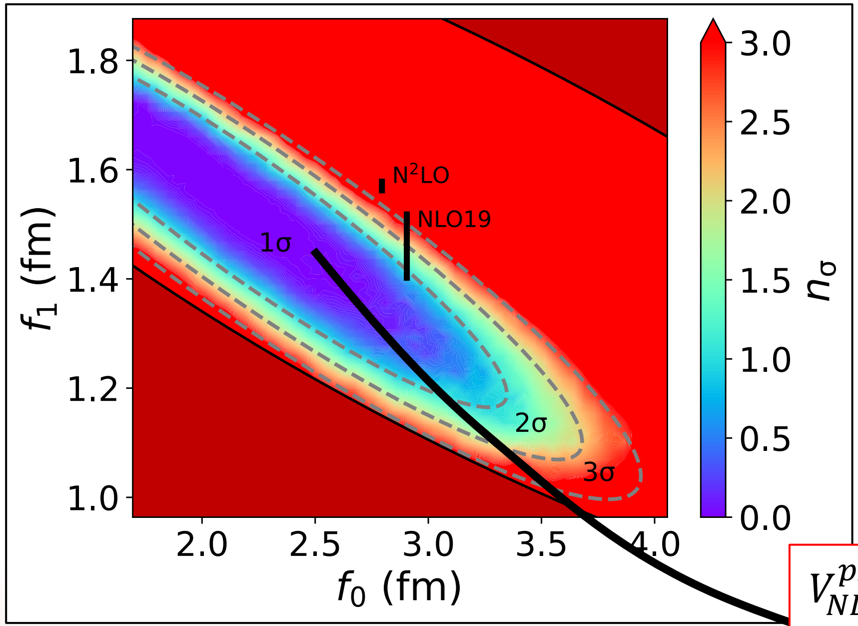
WHAT ABOUT NEUTRON STARS ?

Courtesy VMS

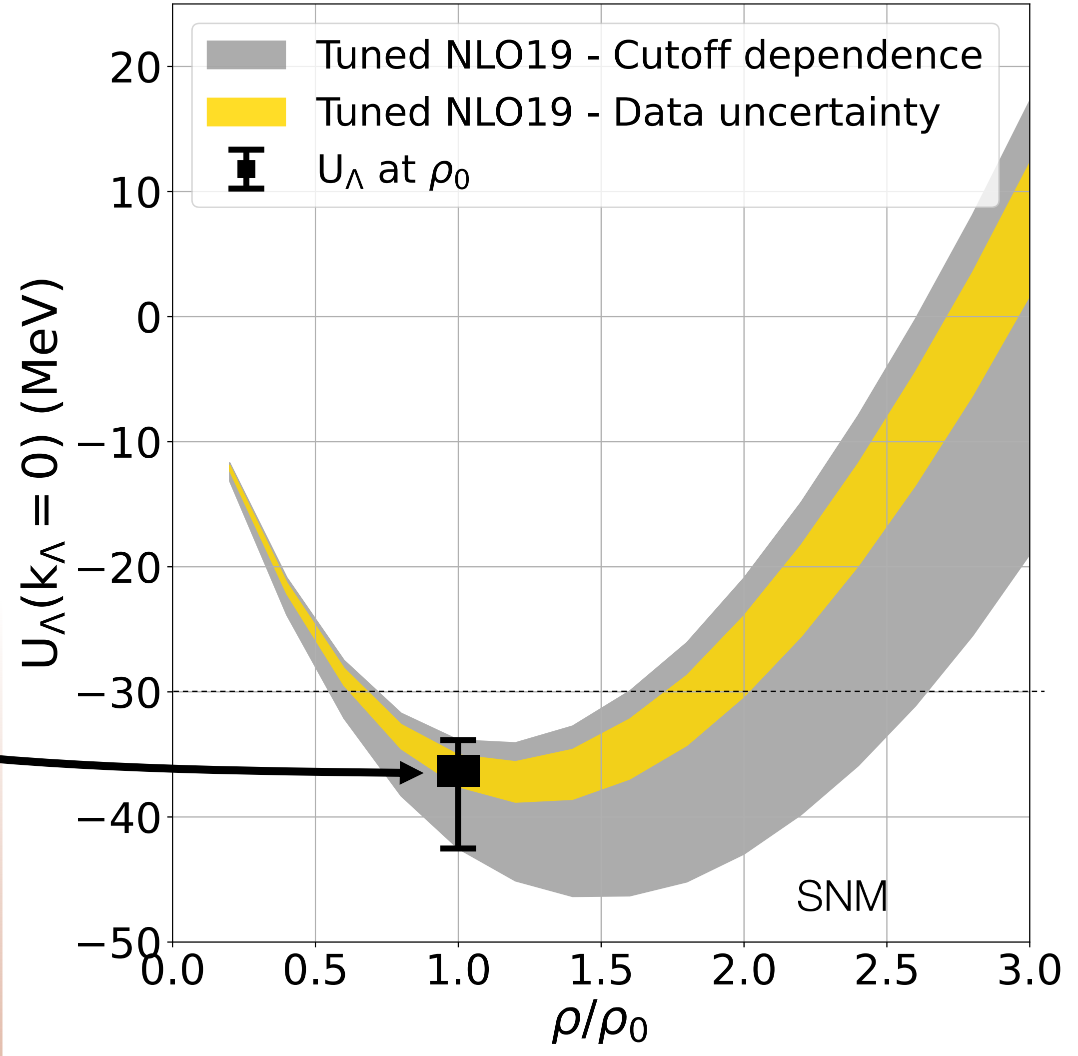
FROM SCATTERING PARAMETERS TO SINGLE PARTICLE POTENTIALS

D. Mihaylov, J. Haidenbauer and V. Mantonvani Sarti PLB 850 (2024) 138550

Combined fit



$V^{p\Lambda}_{NLO19}$ in mom. space via G-matrix approach



$$U_\Lambda^{2BF}(\rho_0) = -36.3 \pm 1.3(stat)^{+2.5}_{-6.2}(syst) \text{ MeV}$$

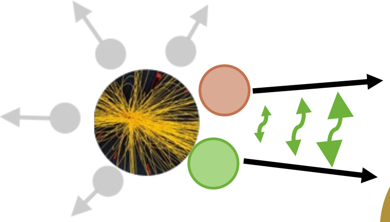
Quantitative estimate of repulsion from 3BF ΛNN at ρ_0 !

Courtesy VMS

A BOTTOM-UP APPROACH FOR A EOS WITH HYPERONS

Measured correlations by ALICE

pΛ (pΣ^0), pΞ, ΛΛ



Potentials in vacuum

Tuned NLO19 NΛ chiral potentials

ΛΛ, NΞ LQCD potentials

NN(AV18)+NNN ph.
K=160, 270 MeV from HIC

Le Fèvre et al. NPA 945 (2016)

I.Vidana, V. Mantovani Sarti, J. Haidenbauer, D. L. Mihaylov, LF arXiv:2412.12729v1

A BOTTOM-UP APPROACH FOR A EOS WITH HYPERONS

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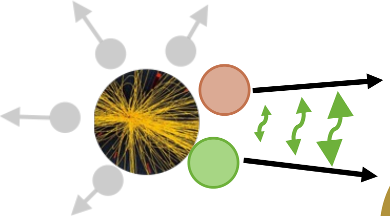


V. Mantovani Sarti
TUM

Potentials in vacuum

Tuned NLO19 NΛ chiral potentials

ΛΛ, NΞ LQCD potentials

J. Haidenbauer

NN(AV18)+NNN ph.
K=160, 270 MeV from HIC
Le Fèvre et al. NPA 945 (2016)

EoS with 2-body YN, YY

Mass vs Radius NSs

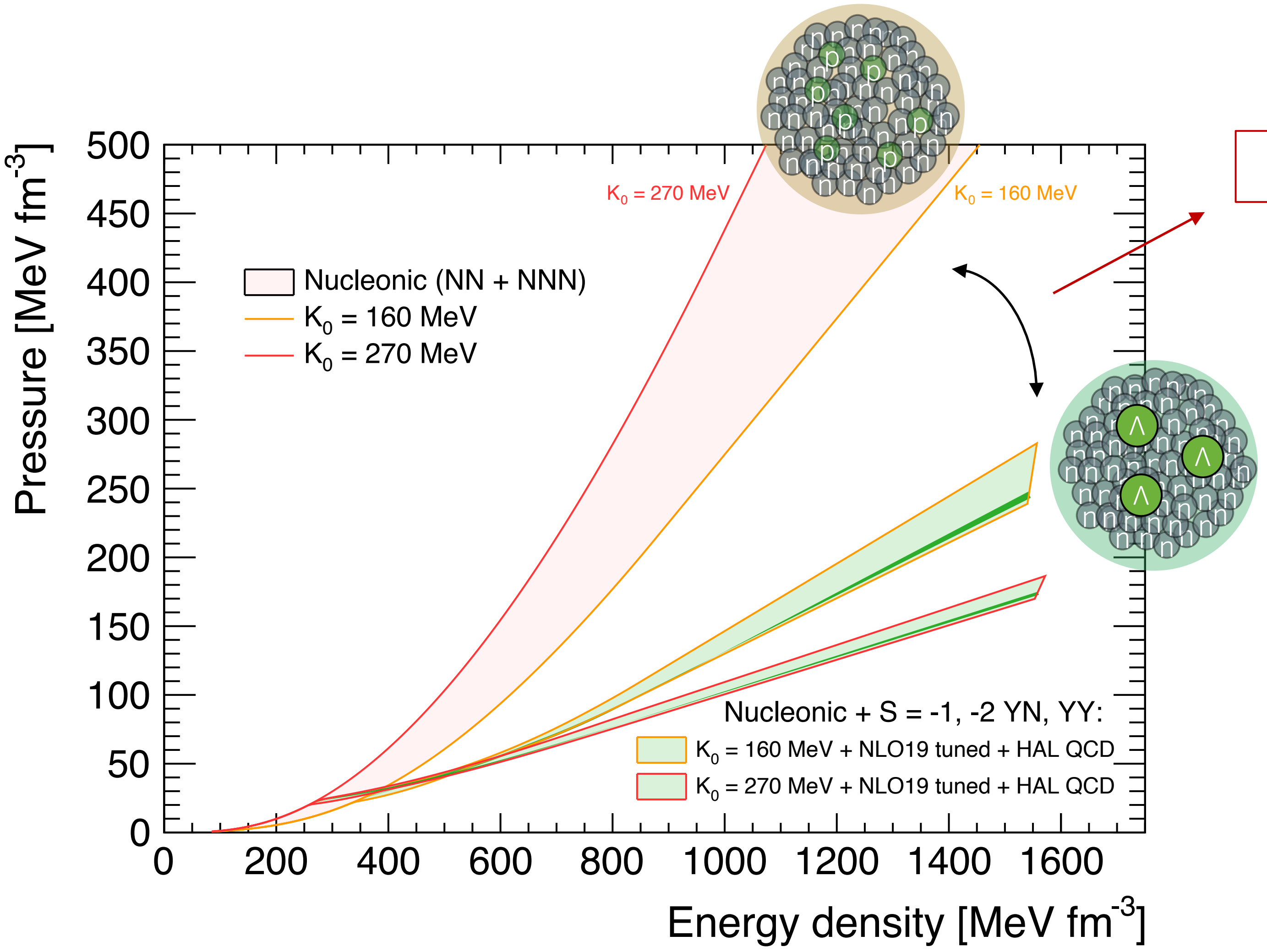
BB interactions at finite ρ

Brueckner-Hartree-Fock theory with detailed propagation of input uncertainties!!
Schulze et al. PLB 355 (1995)

I. Vidana
INFN Catania

I.Vidana, V. Mantovani Sarti, J. Haidenbauer, D. L. Mihaylov, LF arXiv:2412.12729v1

IMPACT ON NUCLEAR EOS AND NEUTRON STARS



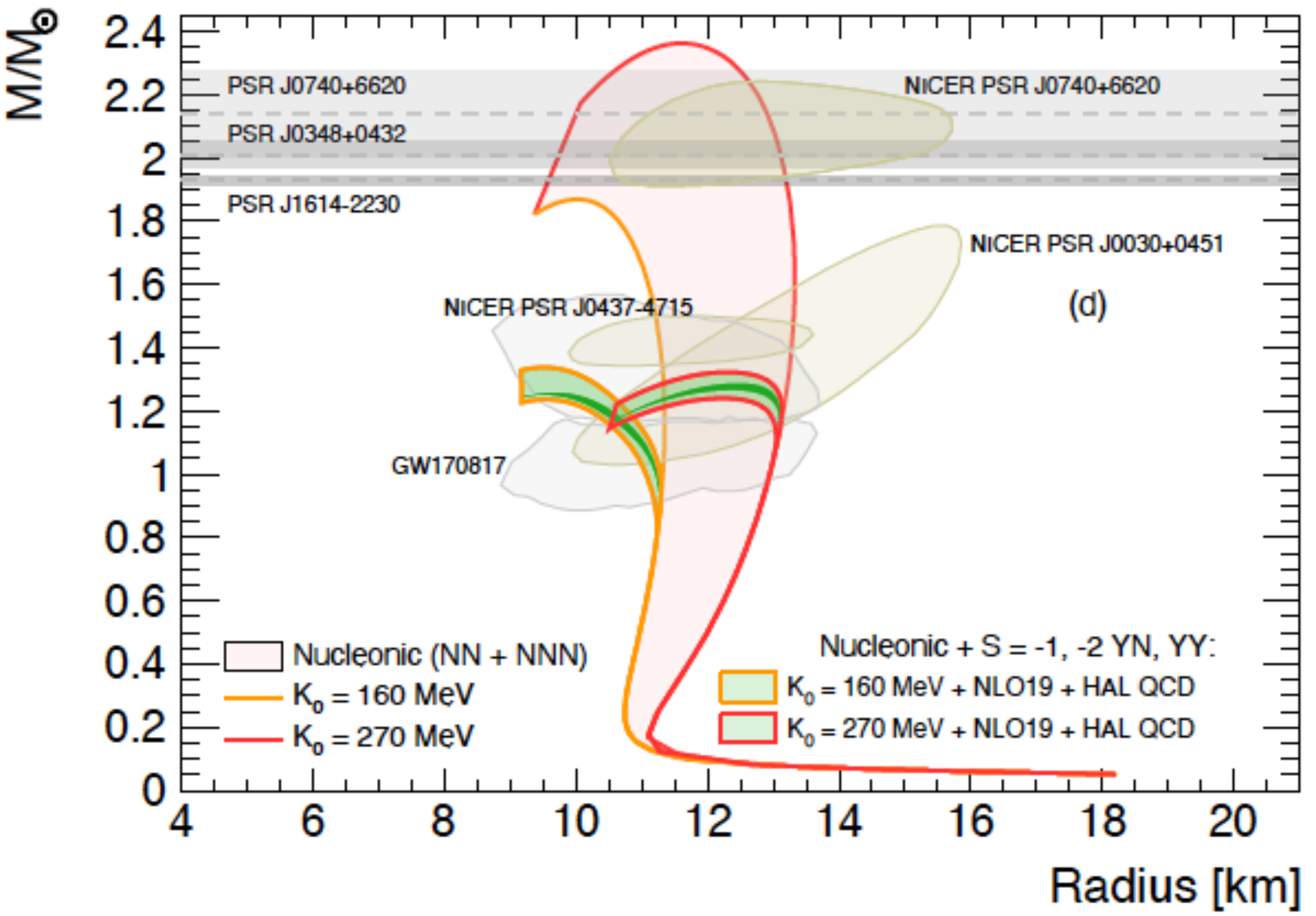
Inclusion of S=-1, -2 YN softens the EoS!

Light shade: theoretical uncertainty (cut-off)

Dark shade: experimental uncertainty (comb. fit scatt. + femto)

I.Vidana, V. Mantovani Sarti, J. Haidenbauer, D. L. Mihaylov, LF arXiv:2412.12729v1

IMPACT ON NUCLEAR EOS AND NEUTRON STARS



I.Vidana, V. Mantovani Sarti, J. Haidenbauer, D. L. Mihaylov, LF arXiv:2412.12729v1

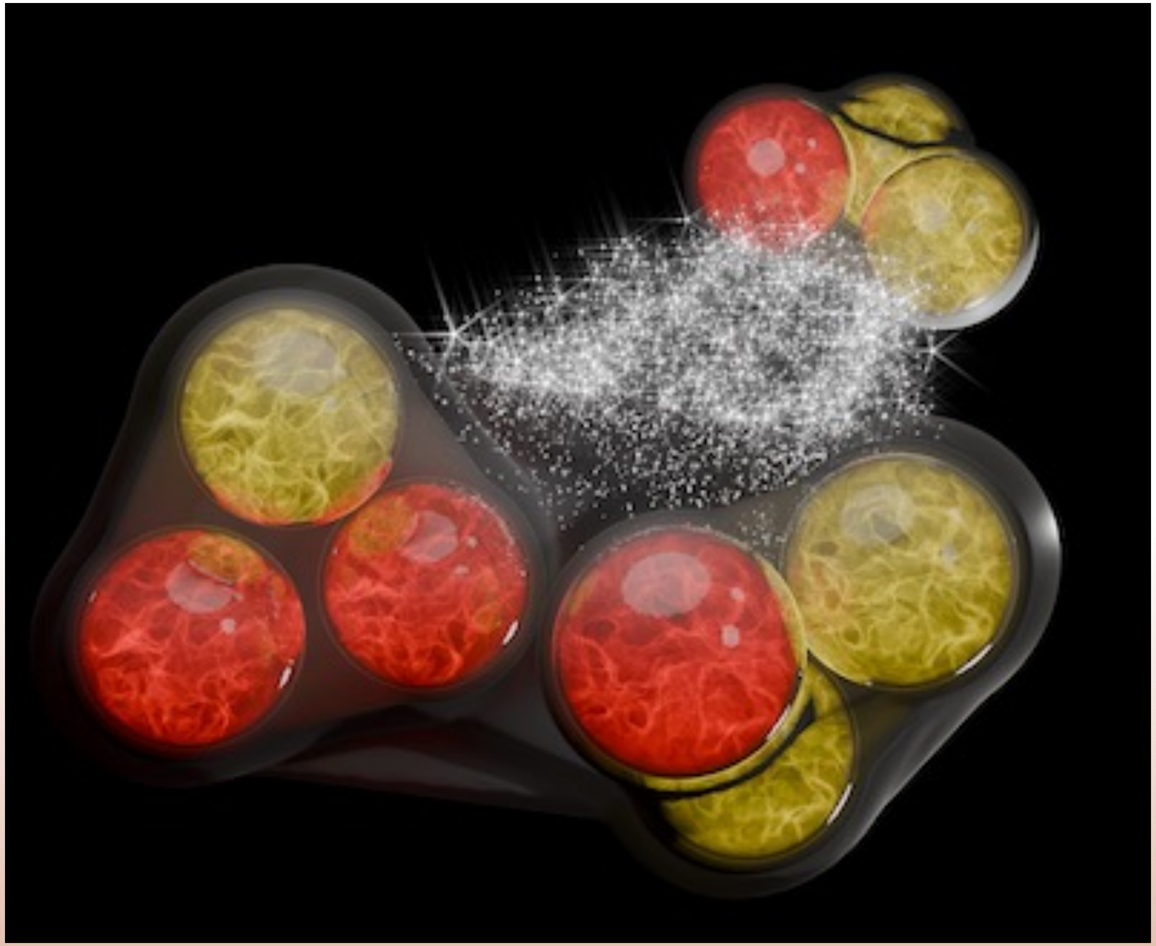
Upper limit of EoS with hyperons is too soft to reach 2M⊙

Additional repulsion among hadrons or new degree of freedom is needed

Three body hyperon nucleon interactions?

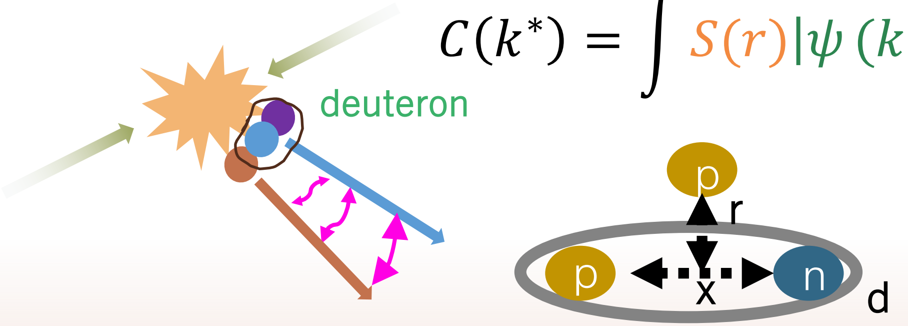
Axions in Neutron stars ?
K. Springmann et al. arXive:2410.10945

THREE BODY INTERACTION AT THE LHC

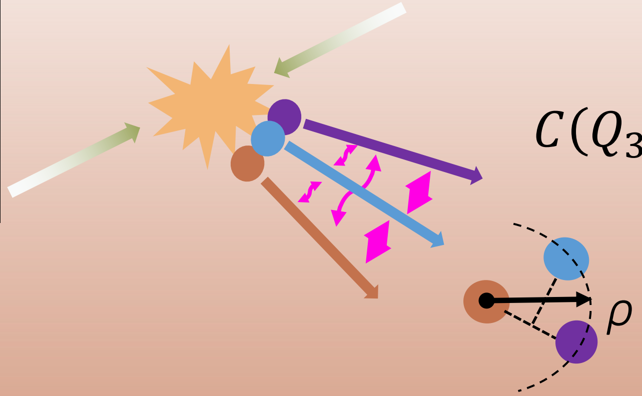


Two methods are currently studied

- Deuteron-baryon correlations
- Three-baryons correltions



$$C(k^*) = \int S(r)|\psi(k^*, r)|^2 \, 4\pi r^2 \, dr$$

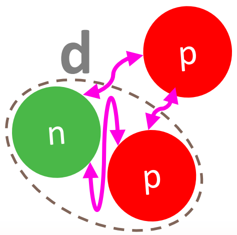


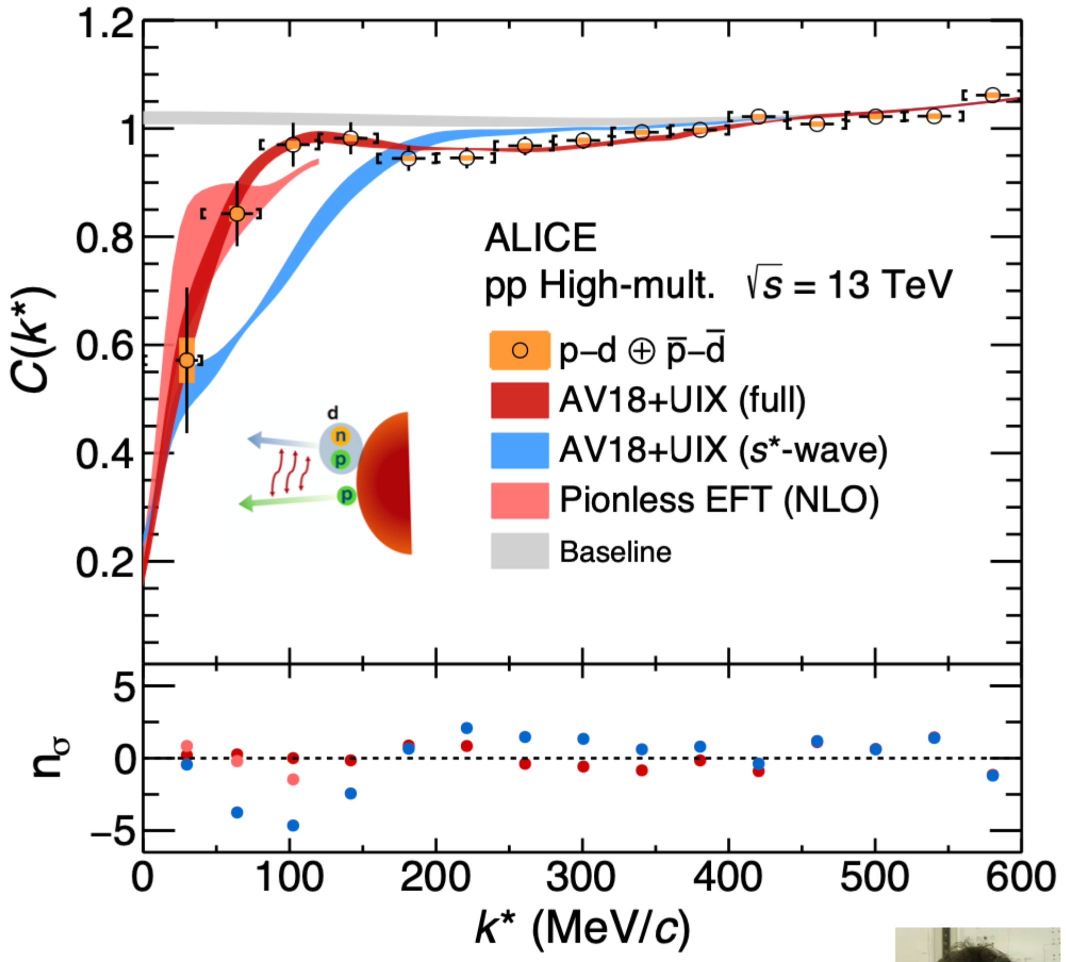
$$C(Q_3) = \int S(\rho)|\psi(Q_3, \rho)|^2 \rho^5 \, d\rho$$

$$Q_3 = \sqrt{-q_{ij}^2 - -q_{ik}^2 - q_{kj}^2}$$

NNN USING PROTON-DEUTERON CORRELATIONS

- Full three-body calculations are required (NN + NNN + Quantum Statistics)





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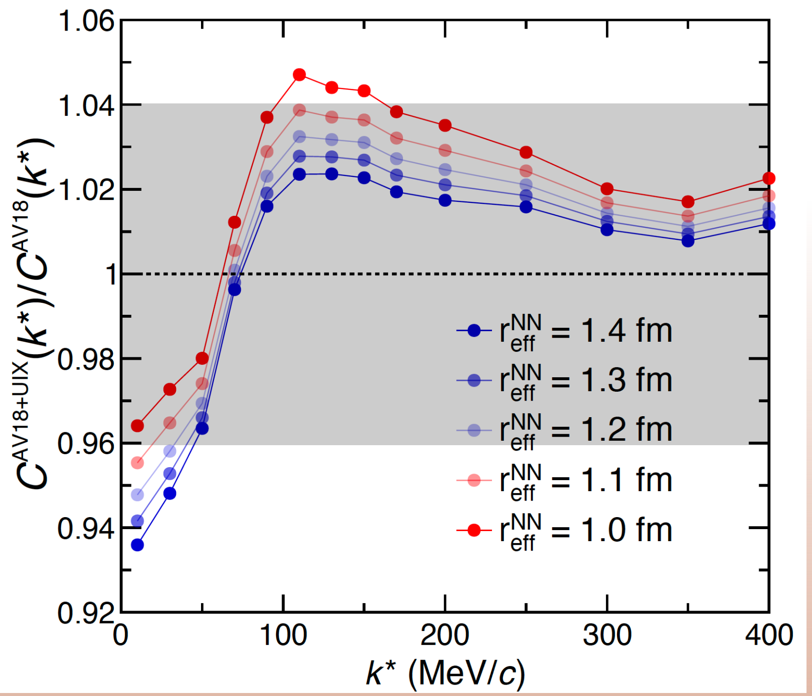
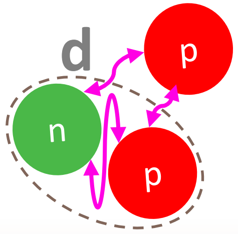
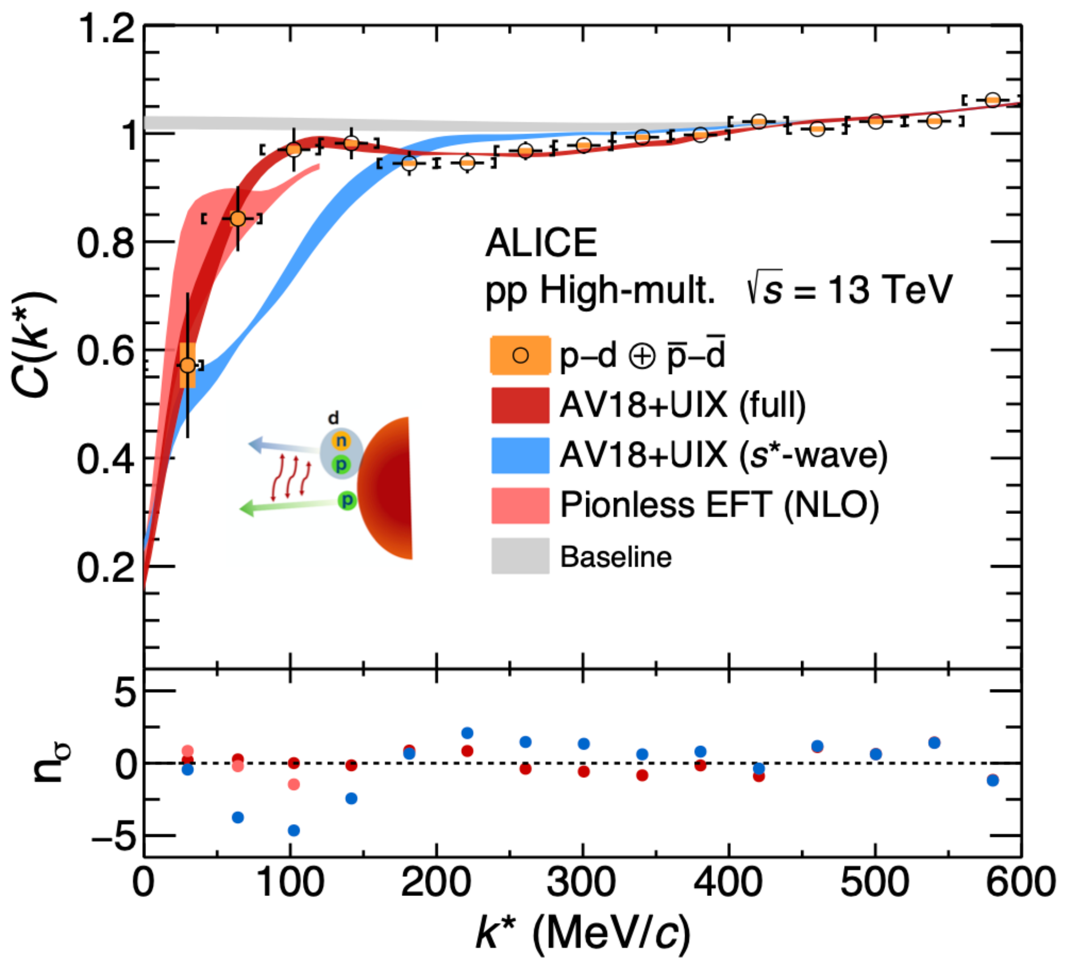
B. Singh
TUM

NNN USING PROTON-DEUTERON CORRELATIONS

- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics
- Sensitivity to three-body forces up to 5%







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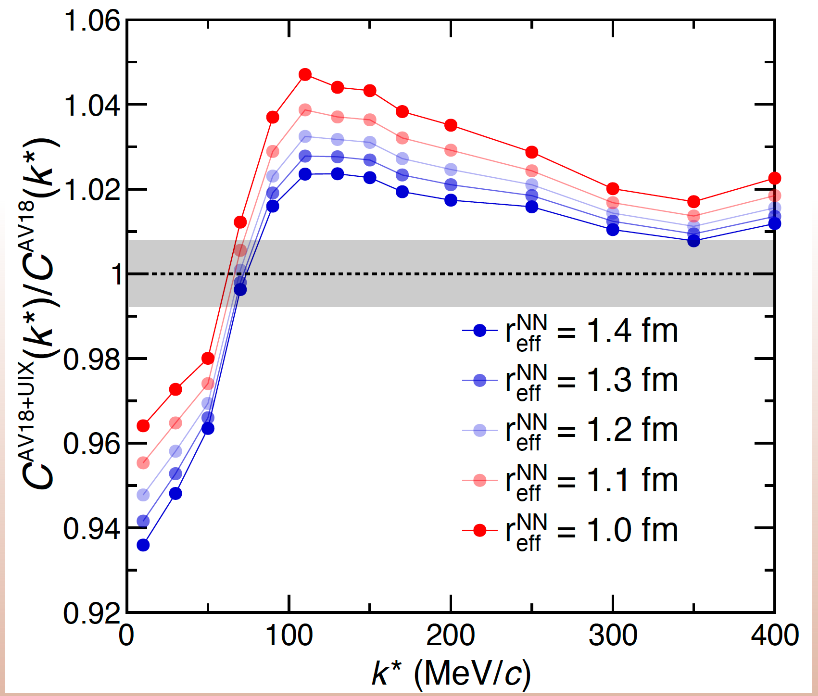
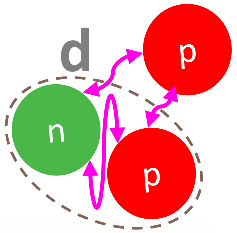
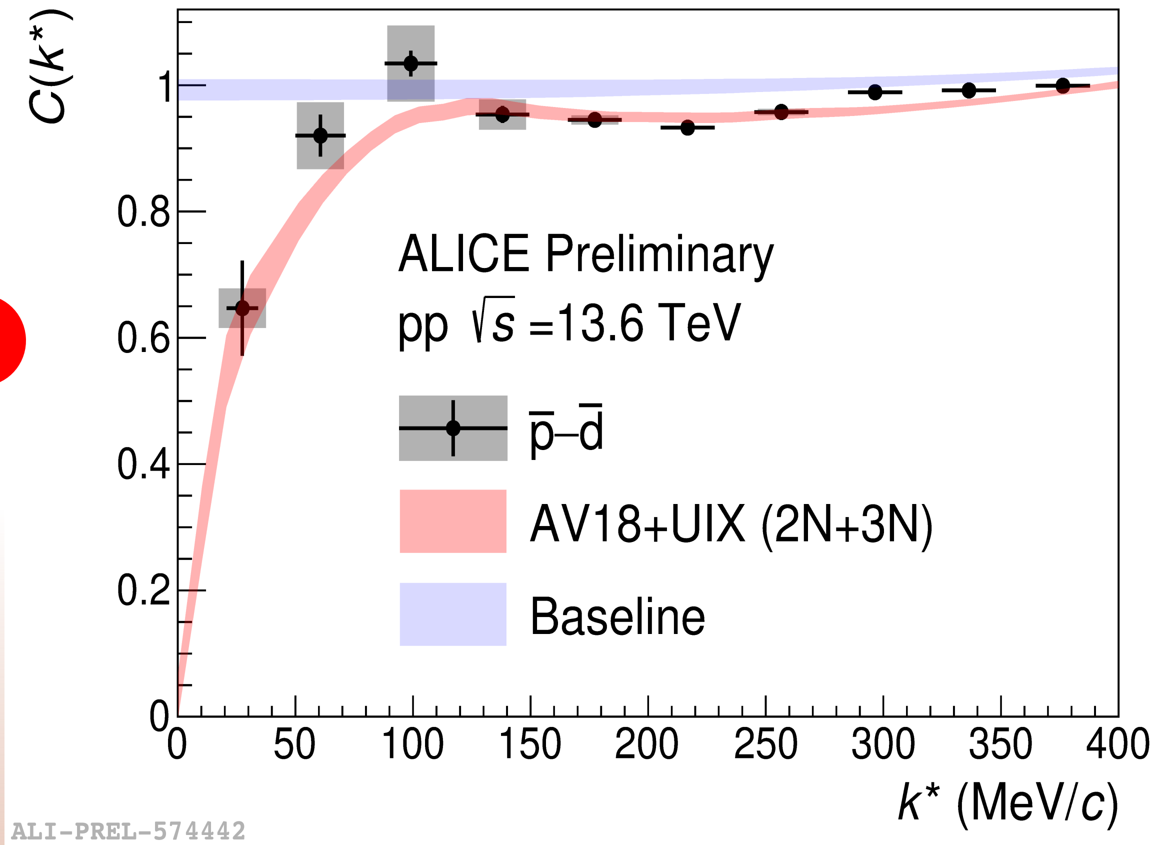
NNN USING PROTON-DEUTERON CORRELATIONS

- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics
- Sensitivity for Run 3 ~1%

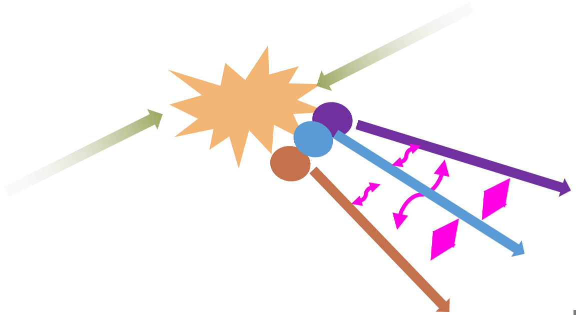






A. Riedel
TUM

PPΛ CORRELATION

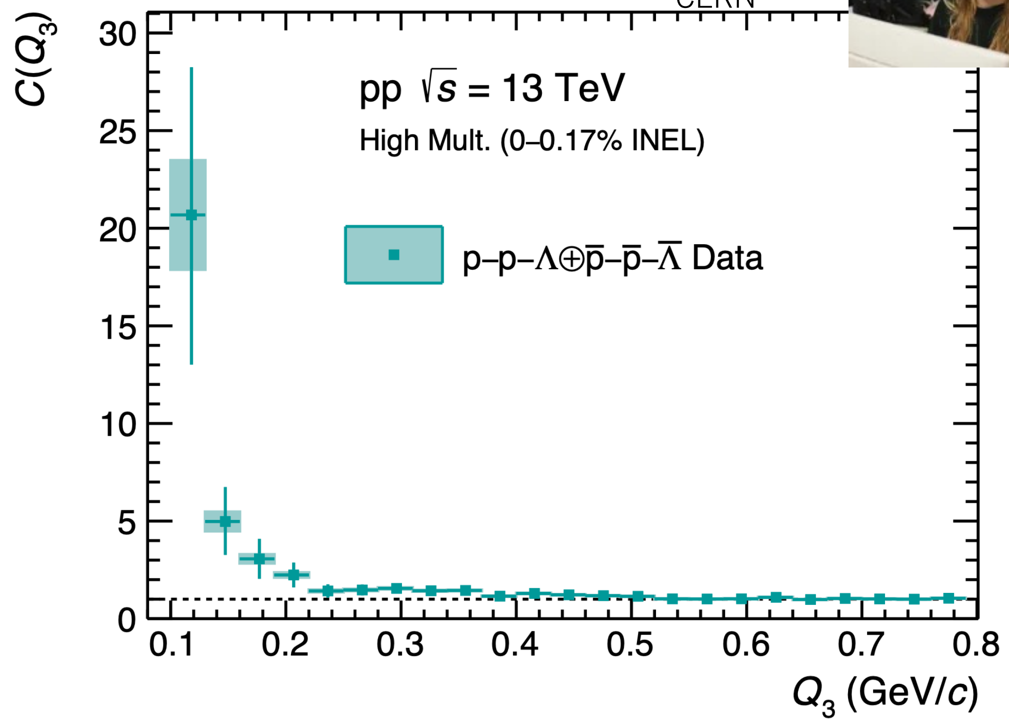


Run 2 data limited in statistics

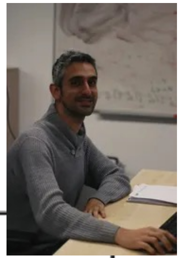
First calculation : → NΛ interaction from fit of scattering & femto data

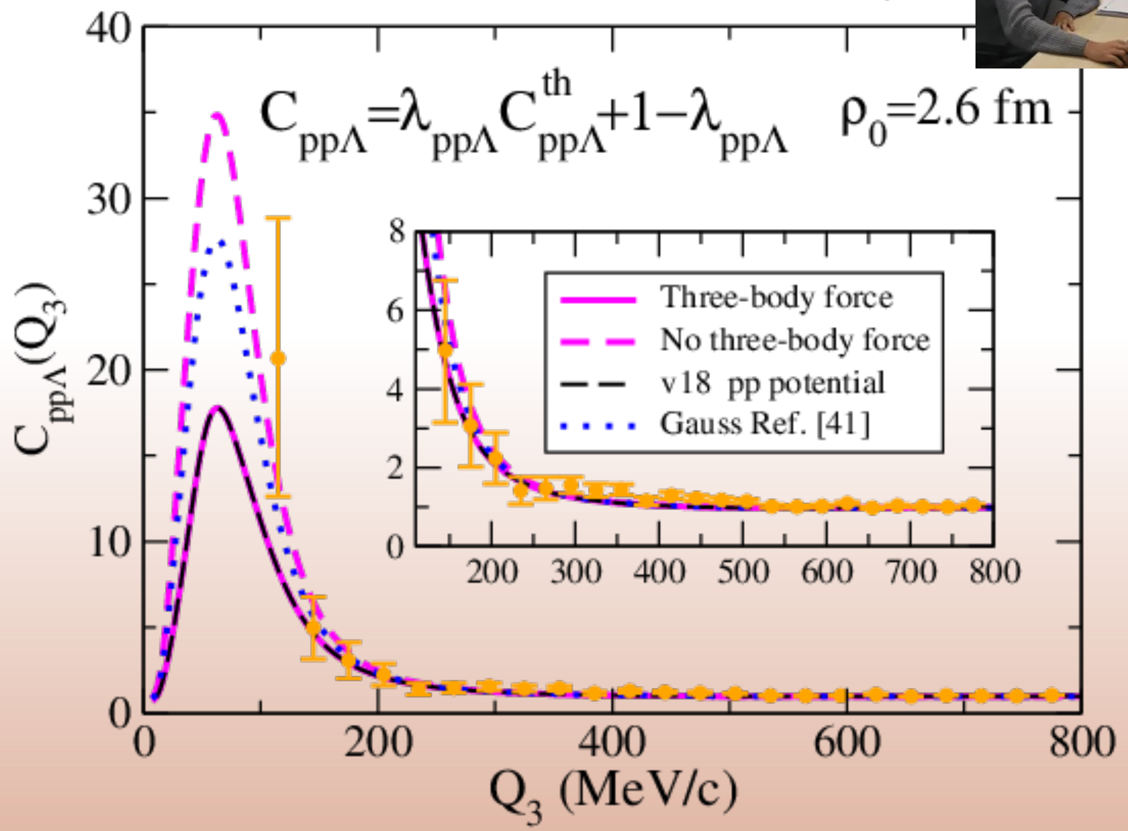
→ hypertrition BE reproduced with 2B interaction

L. Serksnyte
CERN



R. Del Grande
CTU Prague





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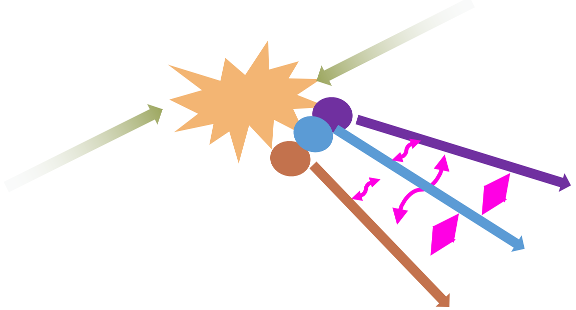
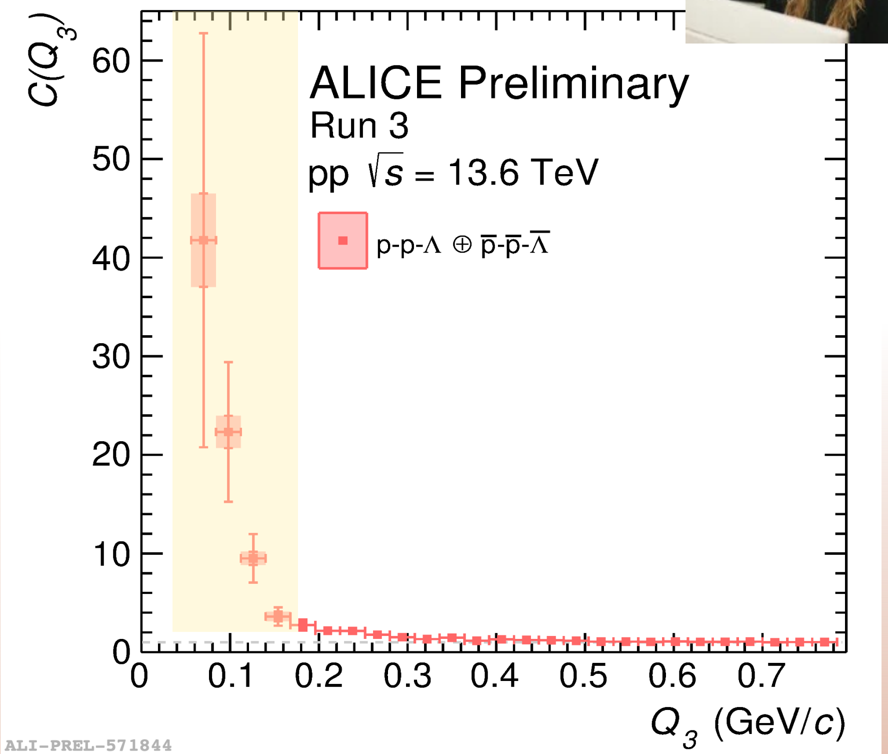
A. Kievsky and E. Garrido, Gattobigio, R. Del Grande, LF arXiv:2408.01750

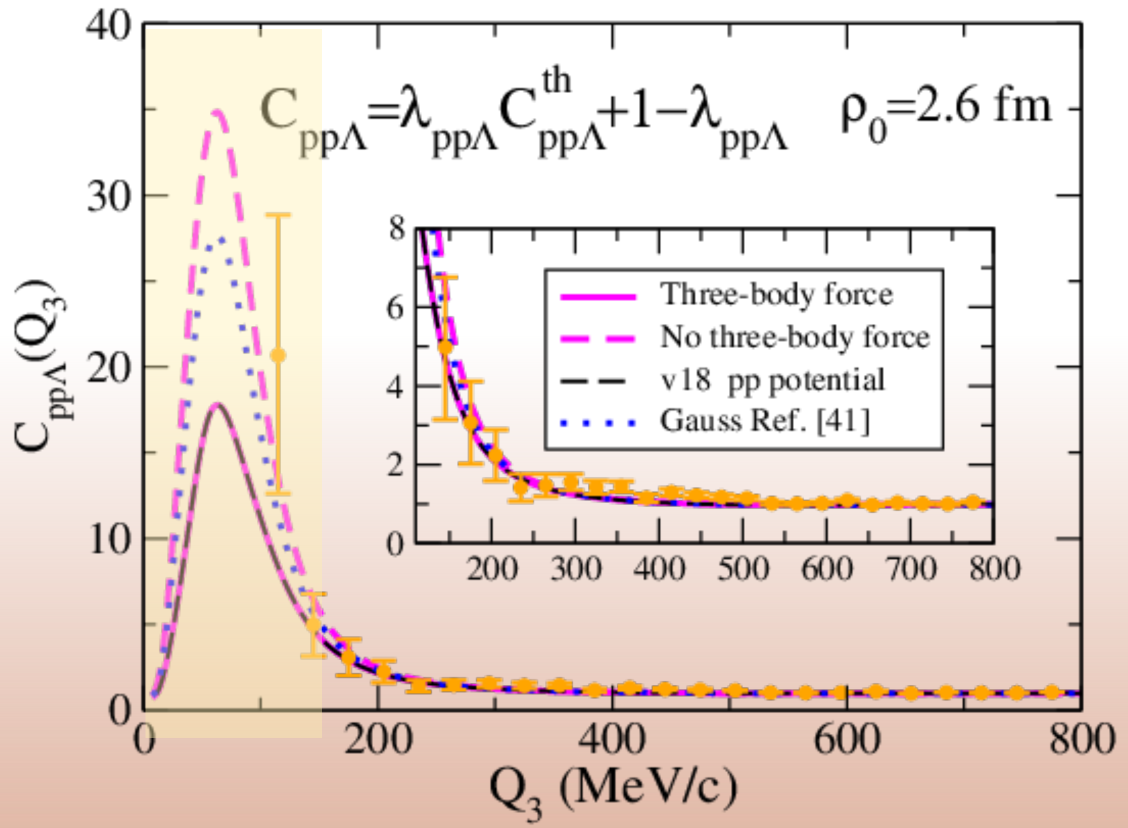
PPΛ CORRELATION



- Dedicated three body triggers for pp collisions at Run 3
- By the end of 2026 100 times more statistics

L. Serksnyte
CERN





A. Kievsky and E. Garrido, Gattobigio, R. Del Grande, LF arXiv:2408.01750

Only 2022 data!
Stay tuned for 2022-2024 results at QM2025

SUMMARY AND OUTLOOK

- Feasibility of high precision measurement for hadron-hadron interactions by means of the femtoscopy technique appied to pp and p-Pb collisions at the LHC has been demonstrated.
- Close collaboration with theoreticians in the interpretation of the correlation functions.
- New hyperon-nucleon scattering parameters haven been extracted and a new EoS for baryonic matter containing hyperons has been calculated. Experimental uncertainties on two-body interactions are propagated.
- The largest neutron star mass obtained with such an approach is still far from the heavist masses measured.
- The feasibility of the direct measurement of three body effects by means of three baryons correlation is undert study.

- The wonder of Run3 in numbers (2022-2024)

  pΛ pairs $k^* < 200$ MeV/c : 10^6 (Run2) - 10^7 (Run3)

  ppΛ triplets $Q_3 < 600$ MeV/c: 3500 (Run2) 135.000 (Run3)

Stay tuned for much more to be discovered.

‘If you can’t stand the heat you should stay out of the kitchen’
JS