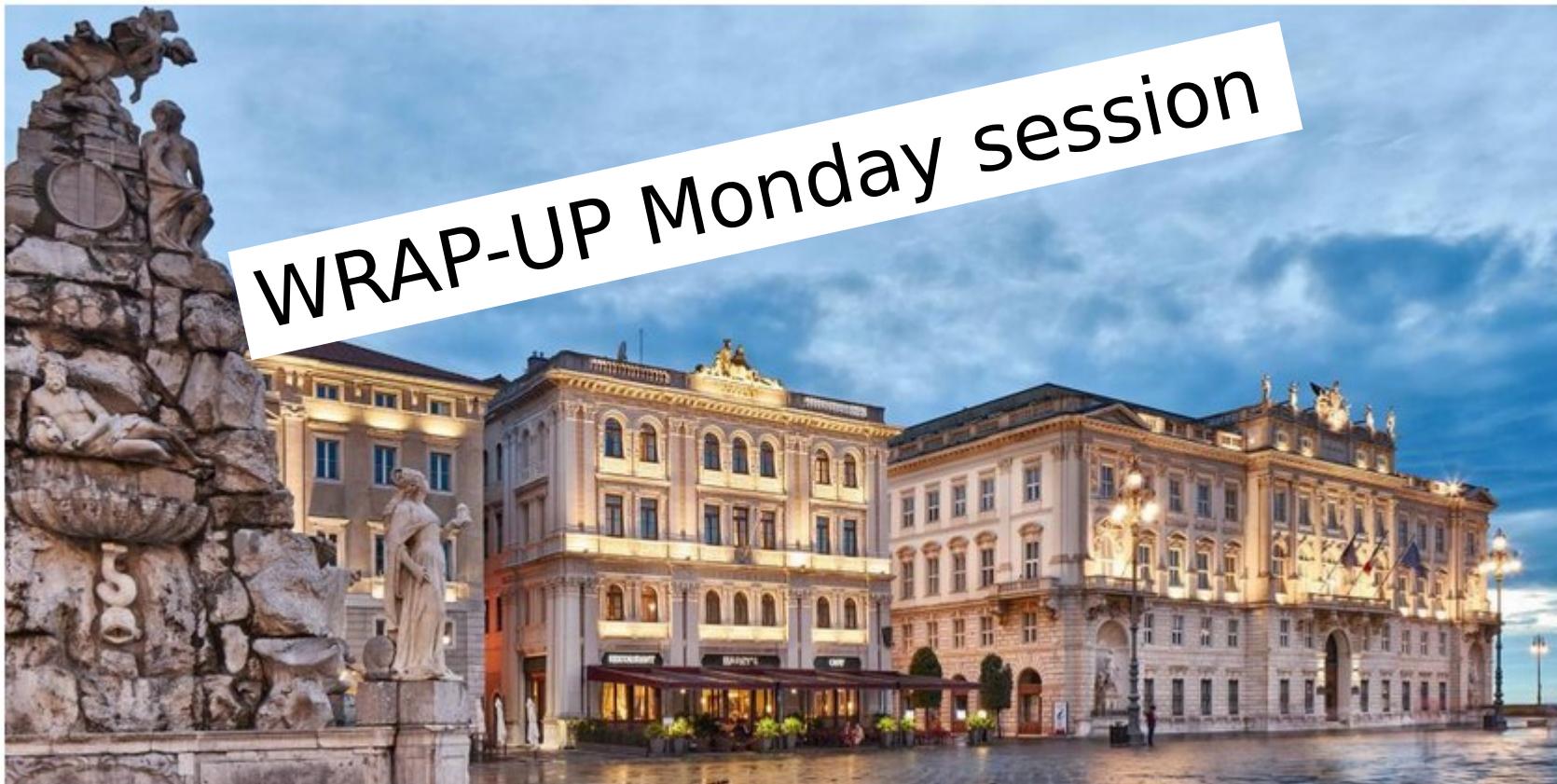




EMMI Workshop: Bound states and particle interactions in the 21st century

WRAP-UP Monday session



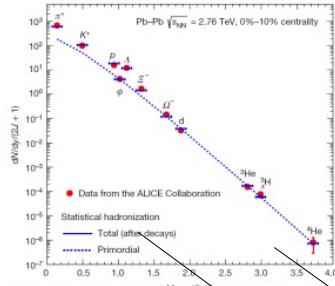
Production of bound states

Particle production mechanism

Statistical models (SHM)

- Hadrons emitted from a system in statistical and chemical equilibrium
 - $dN/dy \propto \exp(-m/T_{\text{chem}})$
 - $T_{\text{chem}} \approx 156 \text{ MeV}$

Pb-Pb $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}, 0\%-10\% \text{ centrality}$



From C.Pinto

ALICE

From H. Tamura

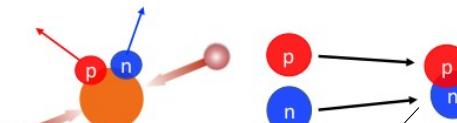


Meson / electron beam

Heavy ion collisions

Particle interactions

- (Anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state
 - Microscopic description



D. Lonardoni et al., PRL 114, 092301 (2015)

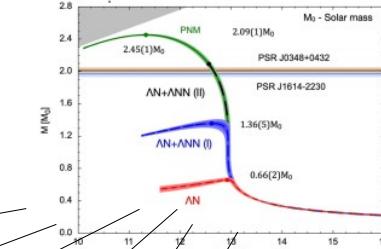
► STAR

HADES

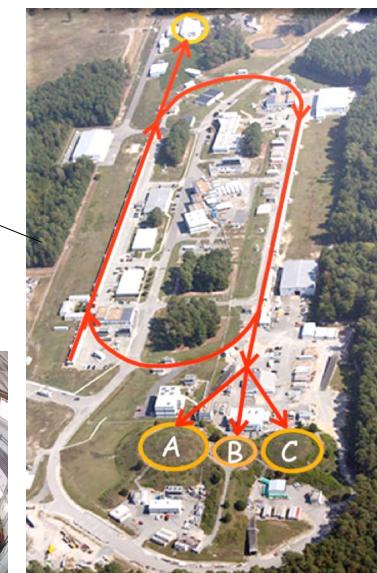
JPARC

Particle interactions

- Equation of state
 - Neutron stars
 - Exotic states (bound states, molecular states, coupled channels, ...)



From D. Watts



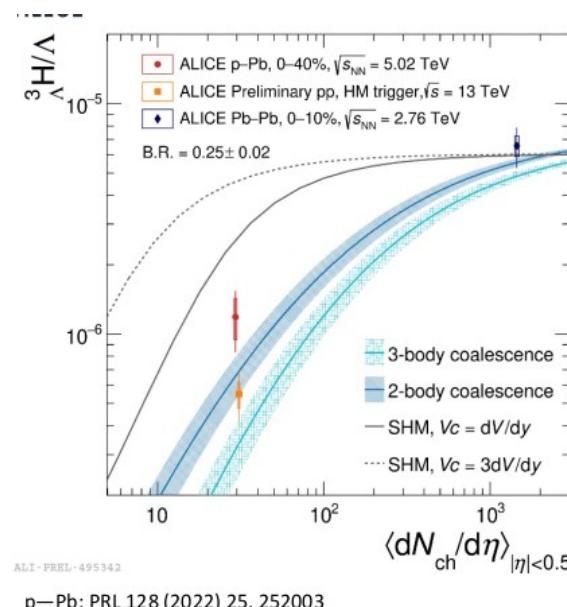
Sum-up from ALICE overview

Hypertriton lifetime

From C.Pinto

- Most precise measurement
- Compatible with latest ALICE and STAR measurements
- Models predicting a lifetime close to the free Λ one are favoured
- Strong hint that hypertriton is weakly bound, but B_Λ is still needed to solve the puzzle

$$\tau = [253 \pm 11 \text{ (stat.)} \pm 6 \text{ (syst.)}] \text{ ps}$$



p—Pb: PRL 128 (2022) 25, 252003

- **Pb—Pb collisions:**
 - small difference between the predictions from SHM and coalescence
- **pp and p—Pb collisions:**
 - large separation between production models
 - **measurements are in good agreement with 2-body coalescence**
 - tension with SHM at low charged-particle multiplicity density
 - configuration with $V_c = 3dV/dy$ is excluded by more than 6σ

Coalescence quantitatively describes the 3H suppression in small systems
> the nuclear size matters at low charged-particle multiplicity

Hypertriton binding energy

- From the mass measurement to B_Λ

$$B_\Lambda = M_\Lambda + M_d - M_{^3\Lambda H}$$

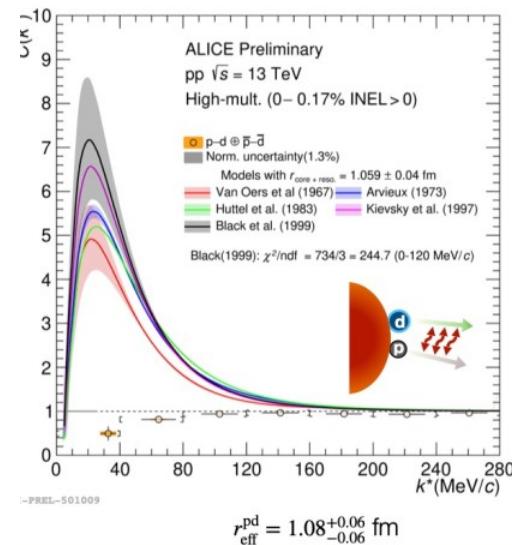
$$B_\Lambda = [72 \pm 63 \text{ (stat.)} \pm 36 \text{ (syst.)}] \text{ keV}$$

Theoretical predictions
---- NPB47 (1972) 109-137 — PRC77 (2008) 027001

Sum-up from ALICE overview

p-d correlations in pp collisions

From C.Pinto

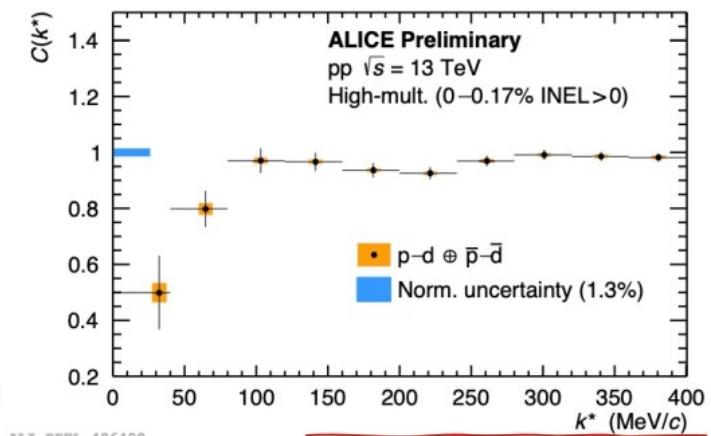
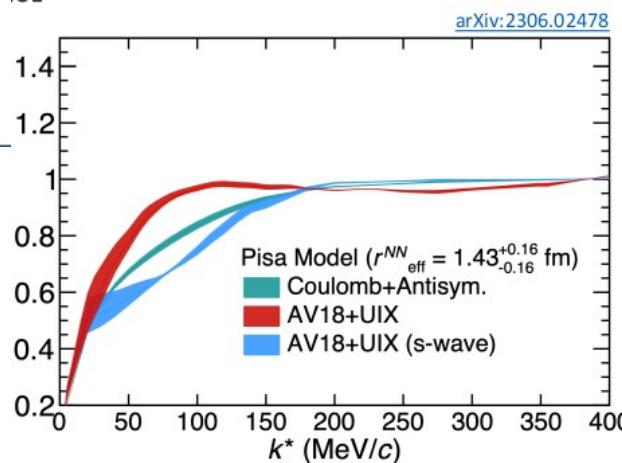


- Data compared with models that describe strong-interaction treating d as a point-like particle
- Models very different from the measurement at low k^*
 - the composite nature of d cannot be neglected
 - Short-range interaction must be treated properly

Sensitivity to the dynamics of the three-body
p-(p-n) system

p-d correlations in pp collisions

13



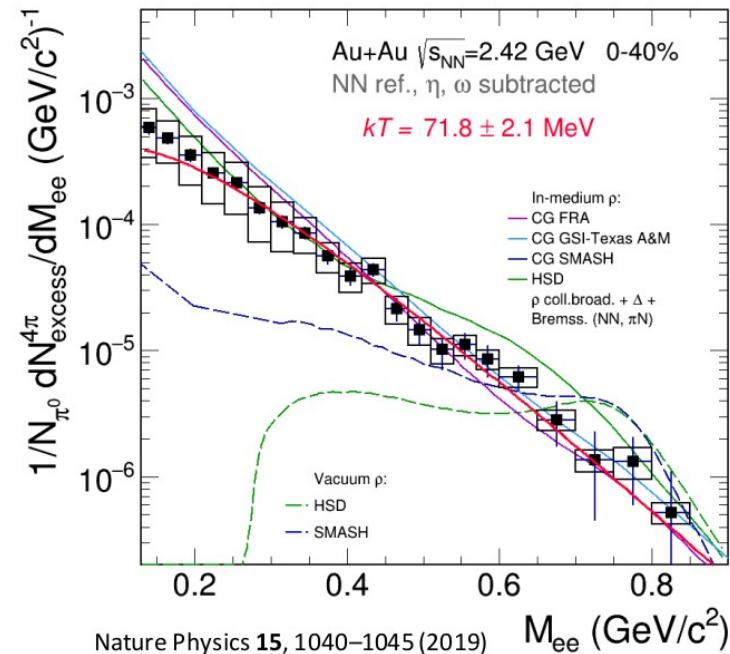
3-body calculations done by PISA theory group: M. Viviani, A. Kievsky and L. Marcucci
 → Model calculation qualitatively reproduces the data
 → The p-d correlation is affected by two + three-body p-p-n interactions!
 → Data sensitive to the higher order partial waves

This paves the way to 3-body systems interactions measurements (hadron-deuteron systems)
 → Λ instead of p (${}^3\text{H}$)
 → ALICE Run3

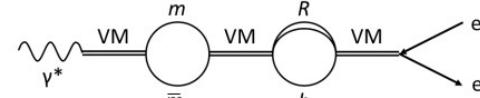
Sum-up from HADES overview

Dilepton Excess Radiation from Au+Au

From S. Spies



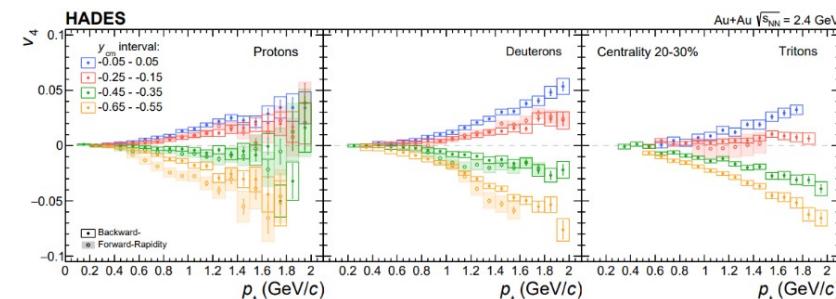
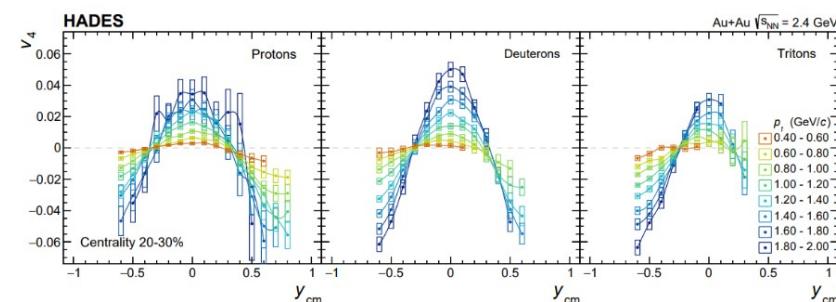
Nature Physics 15, 1040–1045 (2019)



- Excess Radiation in heavy-ion reactions properly described by Coarse Graining approach – VDM justified!

Flow (Au+Au)

- High precision measurement of Proton, Deuteron and Triton flow coefficients up to v_4
Eur.Phys.J.A 59 (2023) 4, 80
- Wide ranges in rapidity and transverse momentum covered
- Important input to model calculations to constrain of EoS of compressed baryonic matter
- Ag+Ag data under analysis

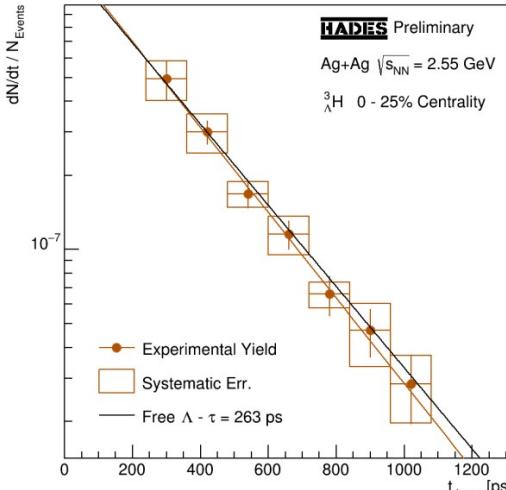


Eur.Phys.J.A 59 (2023) 4, 80

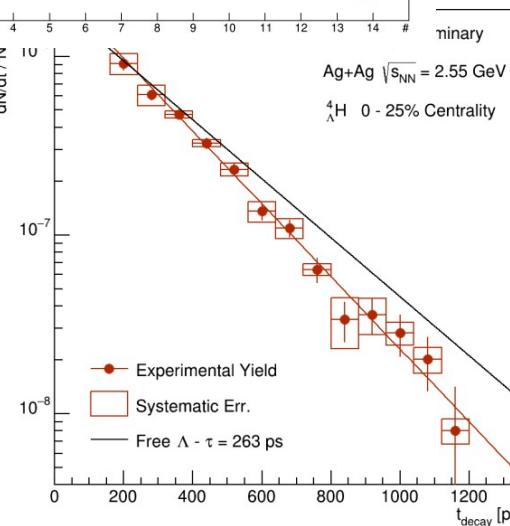
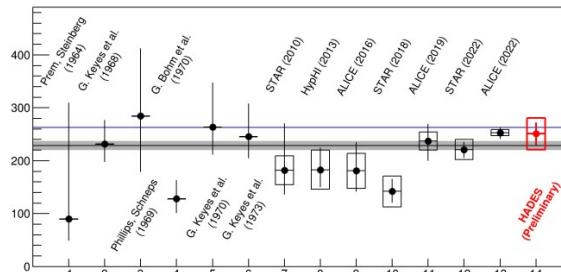
Sum-up from HADES overview

${}^3\Lambda$ Two-Body Decay: ${}^3\Lambda \rightarrow {}^3\text{He} + \pi^-$

From S. Spies

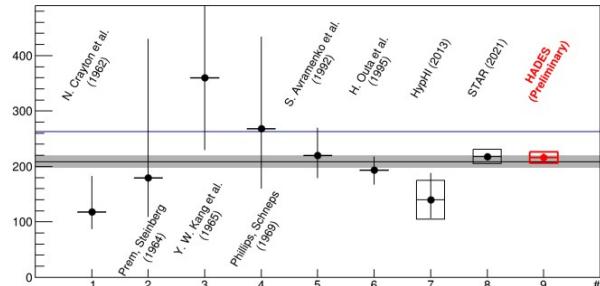


- ${}^3\Lambda$ lifetime measurement contributing to resolving the ${}^3\Lambda$ lifetime puzzle
- Lifetime of $(251 \pm 21_{\text{stat}} \pm 30_{\text{sys}}) \text{ ps}$ compatible with free Λ lifetime measured
- Further systematic uncertainty analyses ongoing

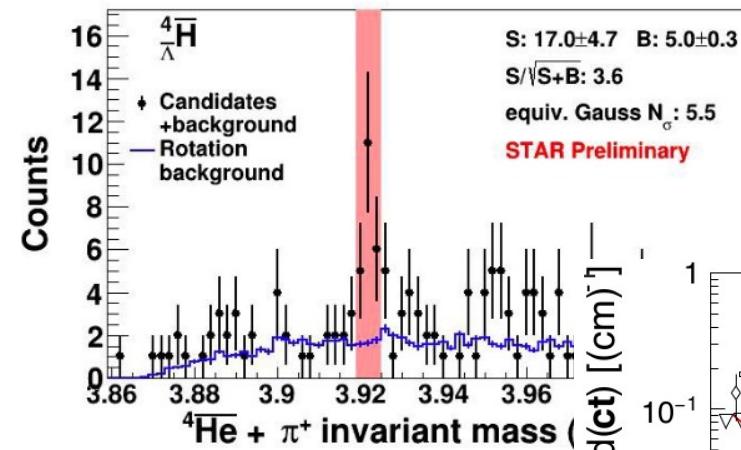
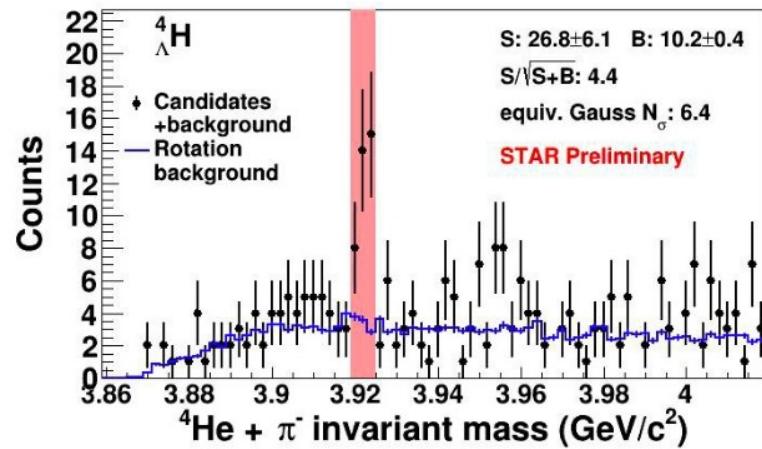


Decay: ${}^4\Lambda \rightarrow {}^4\text{He} + \pi^-$

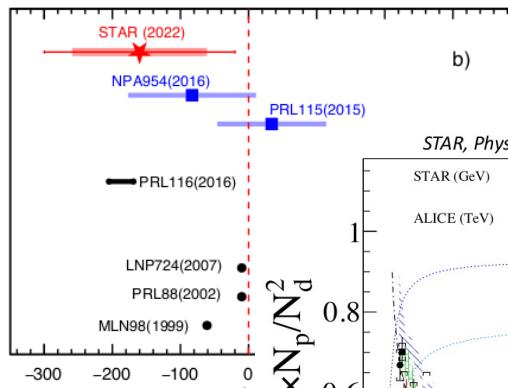
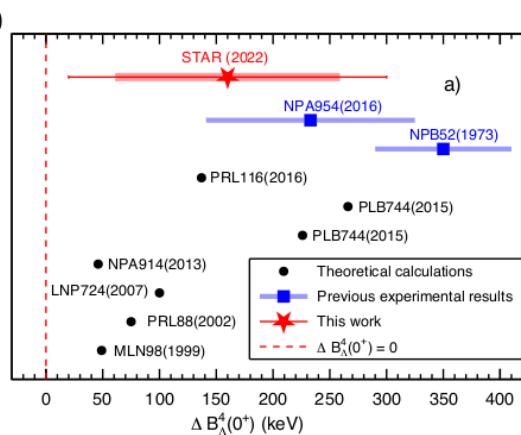
- ${}^4\Lambda$ lifetime measurement contribution to world data
- Lifetime of $(216 \pm 7_{\text{stat}} \pm 10_{\text{sys}}) \text{ ps}$ compatible with earlier measurements measured
 - $\gg 4.85\sigma$ deviation to free Λ lifetime
- Further systematic uncertainty analyses ongoing



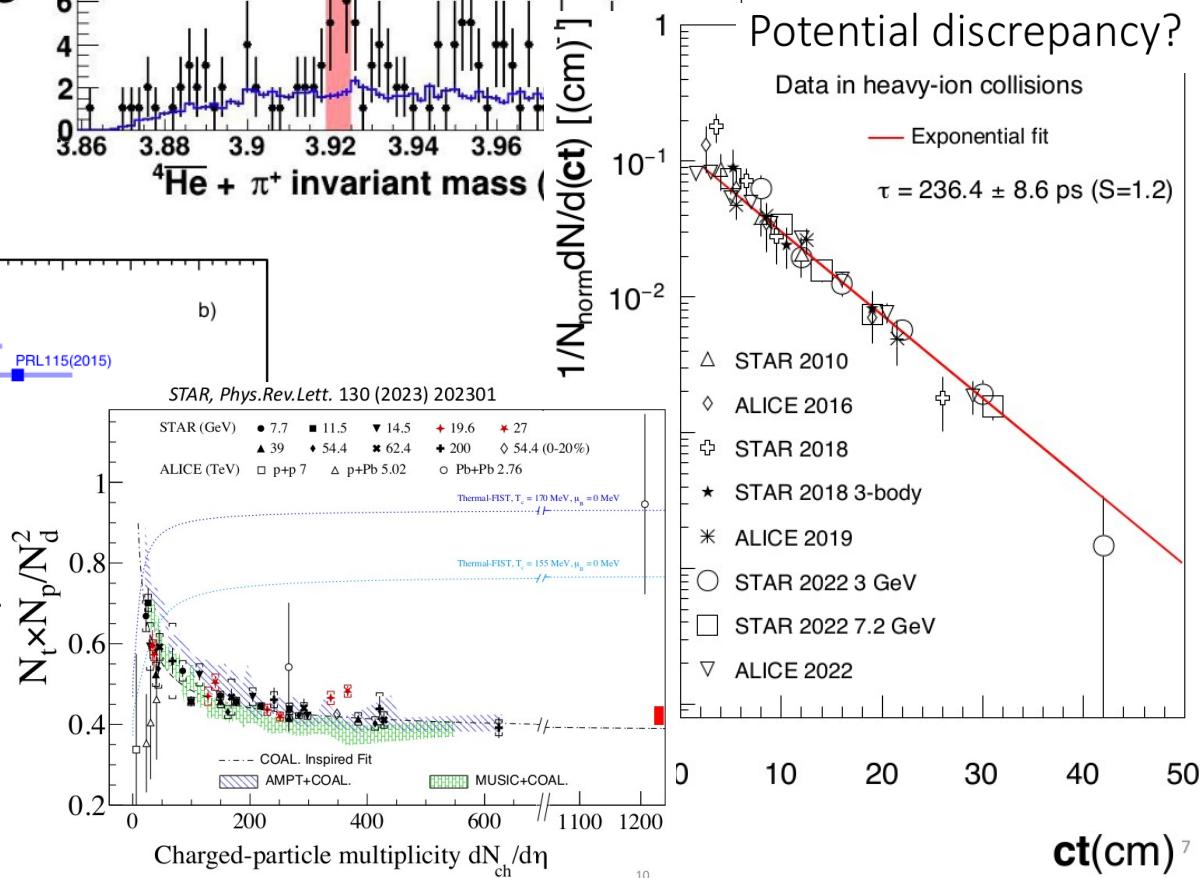
Sum-up from STAR overview



From Z. Xu



CSB \rightarrow small and symmetric ΔB



Charged-particle multiplicity $dN_{\text{ch}}/d\eta$

10

$ct(\text{cm})^7$

Sum-up from STAR overview

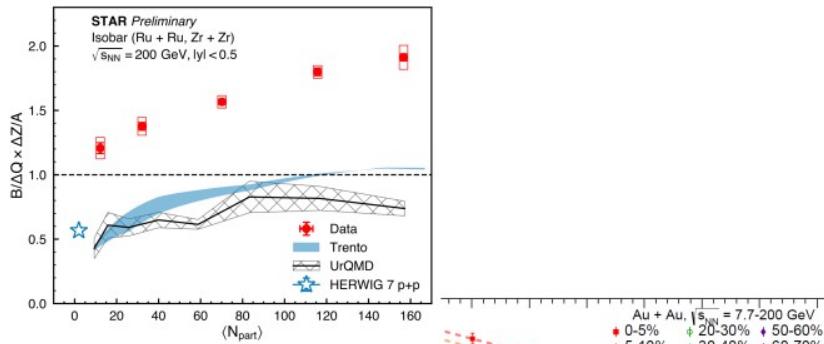
Three approaches toward tracking the origin of the baryon number

From Z. Xu

1. STAR Method:

Charge (Q) stopping vs baryon (B) stopping:
if valence quarks carry Q and B,
 $Q=B$ at middle rapidity

$$B/Q=2$$



2. Kharzeev-STAR Method:

If gluon topology (J) carries B as one unit, it should show scaling according to

Regge theory

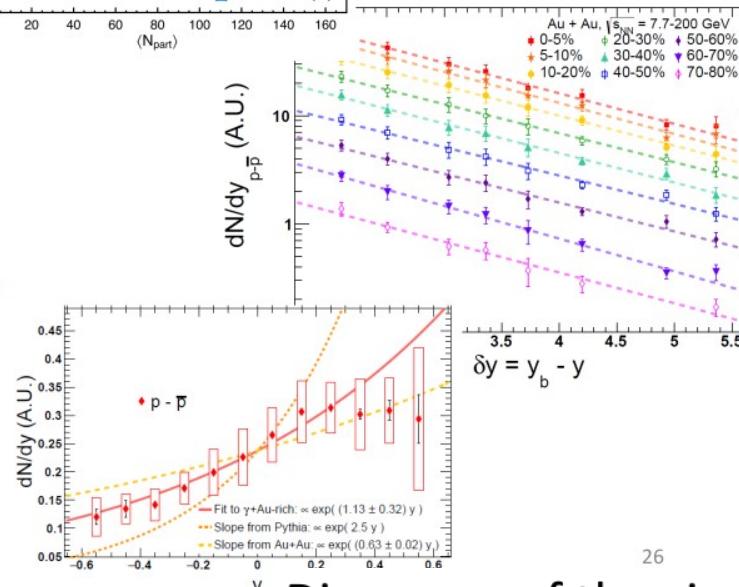
$$\alpha_B = 0.61$$

$$p = \sim e^{-\alpha_B y}$$
$$\alpha_B \sim 0.5$$

3. Artru Method:

In $\gamma+Au$ collision, rapidity asymmetry can reveal the origin

$$\alpha_B(A+A) = 0.61 < \alpha_B(\gamma+A) = 1.1 < \alpha_B(\text{PYTHIA})$$



26

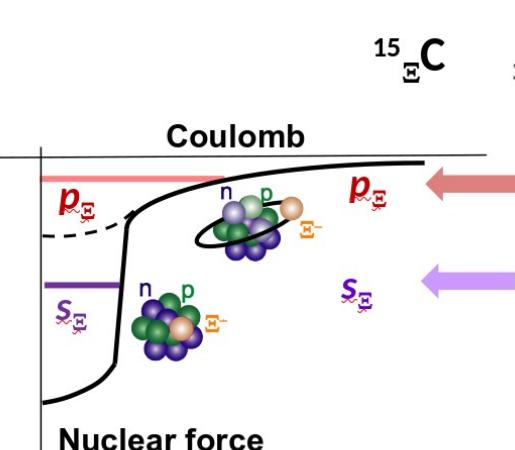
Discovery of the simplest QCD topology: the baryon gluon junction 21

Sum-up from J-PARC overview

From H. Tamura

**BB int. in matter: much different from those in free space
strong density dependence**

Observation of p - and s -state Ξ hypernucleus (?)

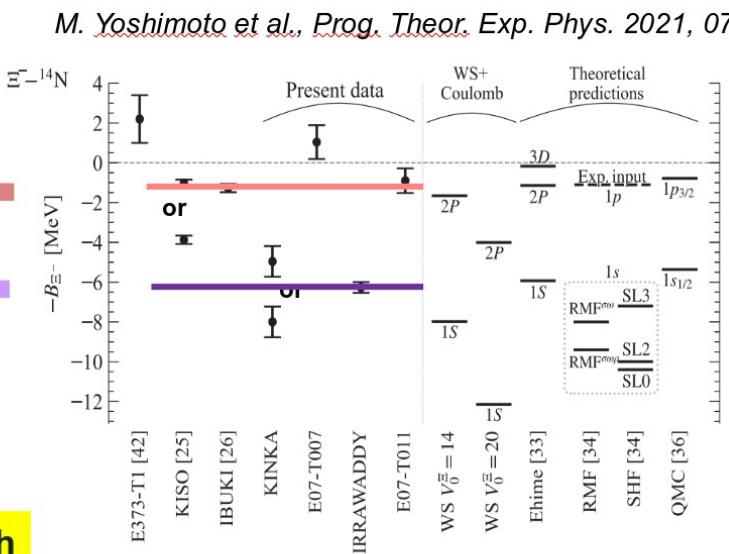


Mystery on $\Xi N \Xi \Lambda \Lambda$ strength

Nijmegen SC models: Ξ absorption mainly from 3D orbit. 4%-0.3% from 2P orbit (T. Koike)

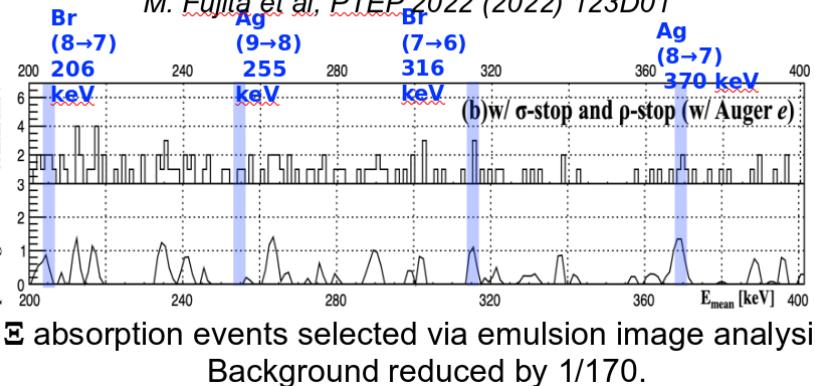
HAL QCD: ~ 1/10 of NSC \rightarrow 2P absorption comparable to 3D, but 1S absorption still negligible

$m(\Xi^-) - m(\Xi^0) = 6.9$ MeV \Rightarrow $p(\Xi^0)$ state via $\Xi^- - \Xi^0$ mixing? (Gal-Friedman, PLB 837 (2023) 137669)



Ξ^- atomic X-rays (E07, E03)

E07 "Reaction-Xray-Emulsion" triple-coinc. hybrid method
M. Fujita et al., PTEP 2022 (2022) 123D01



Sum-up from J-PARC overview

Structure of baryons in matter: could be different from those in free space

From H. Tamura

Experimental Plans

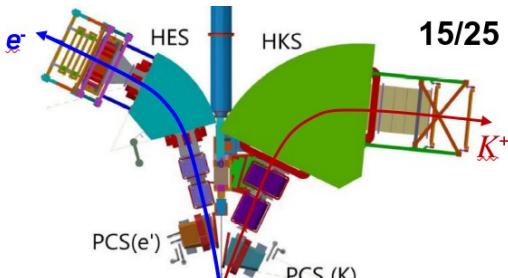
JLab

@Hall C

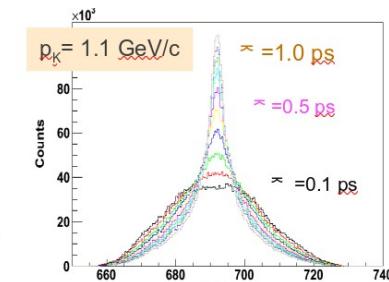
E12-15-008: $^{40,48}\text{Ca}(e,e'K^+)$ $^{40,48}\Lambda\text{K}$

E12-18-013: $^{208}\text{Pb}(e,e'K^+)$ $^{208}\Lambda\text{Ti}$

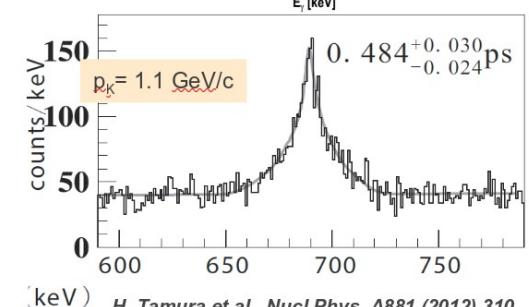
T=1 ΔNN force $\Rightarrow \Delta nn$ force in NS



Λ 's magnetic moment in a nucleus



19/2



H. Tamura et al., Nucl.Phys. A881 (2012) 310

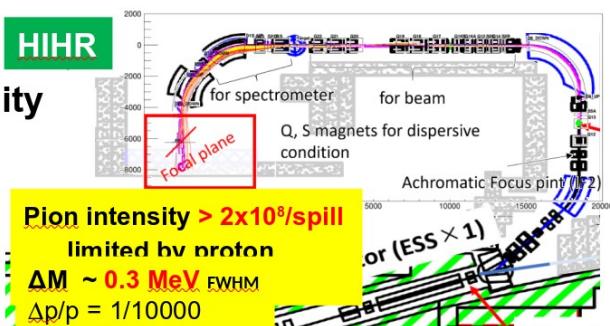
$$\text{Stat. error} \Rightarrow \frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|} \sim 3\%$$

$$\Delta\tau/\tau = 6\%$$

J-PARC @HIHR line at the extended Hadron Facility

HIHR

P84: $(\pi^+, K^+) \dots ^{12}\Lambda\text{C}, ^{28}\Lambda\text{Si}, ^{40}\Lambda\text{Ca},$
 $^{51}\Lambda\text{V}, ^{89}\Lambda\text{Y}, ^{139}\Lambda\text{La}, ^{208}\Lambda\text{Pb}$
 $\Delta M < 400 \text{ keV (FWHM)}$



Possibilities on neutron star core

J-PARC
determines
this strength

repulsive
strong
weak
0

Described in hadron level
Hyperons do not appear
or
Hyperons partly appear

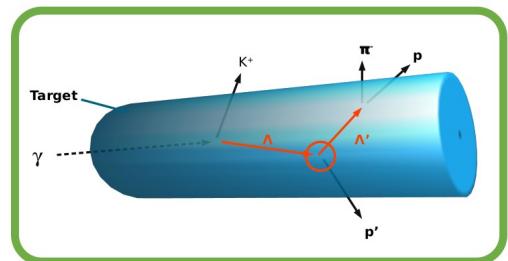
Cannot be explained in hadron level
Quark matter appears (hybrid star)

Sum-up CLAS YN interaction study

From D. Watts

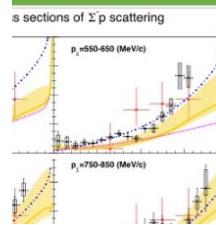
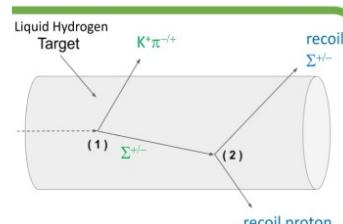
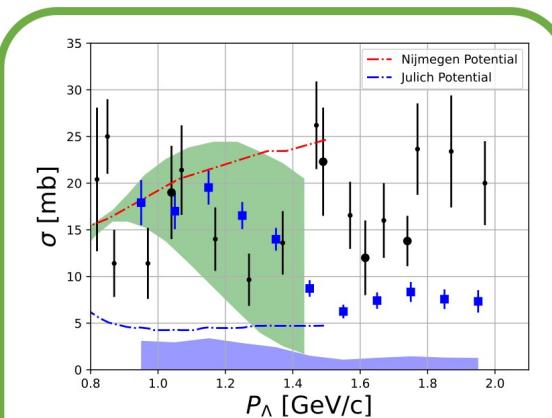
Work in progress - Σp Elastic Scattering

Λp Elastic Scattering

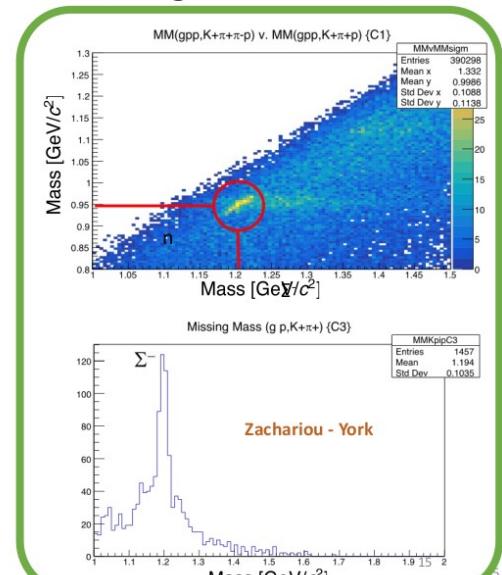


- Cross section determination challenging
- Need careful account of detector acceptance, efficiency

(see paper for details)

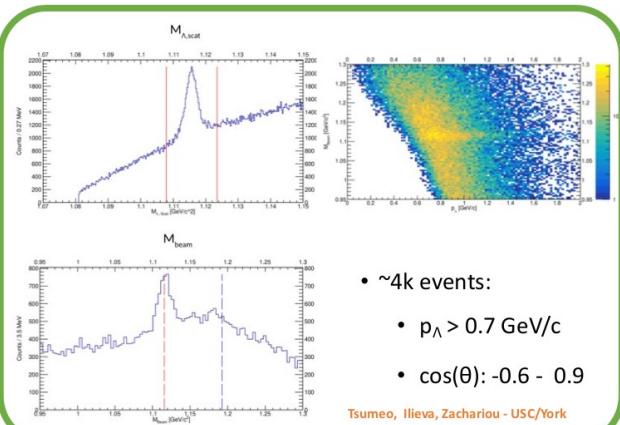


Overlap with recent JPARC, extend momentum range



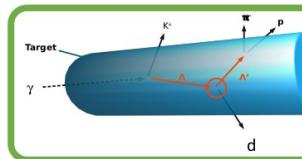
Zachariou - York

Work in progress: Λd elastic scattering



- ~4k events:
- $p_\Lambda > 0.7$ GeV/c
- $\cos(\theta): -0.6 - 0.9$

Tsumeo, Ilieva, Zachariou - USC/York



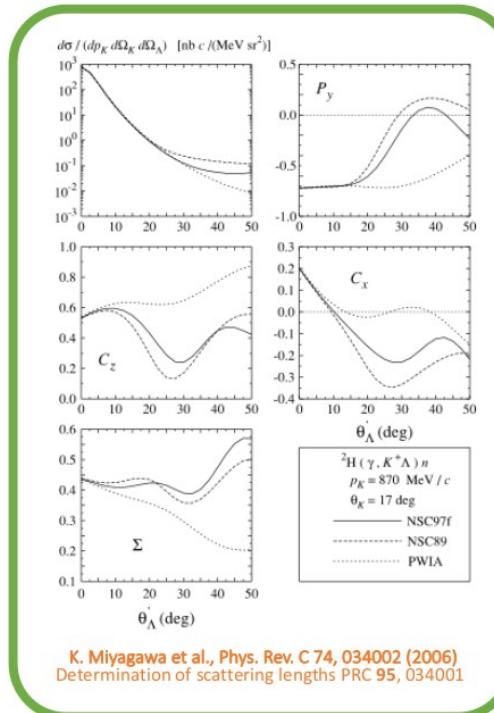
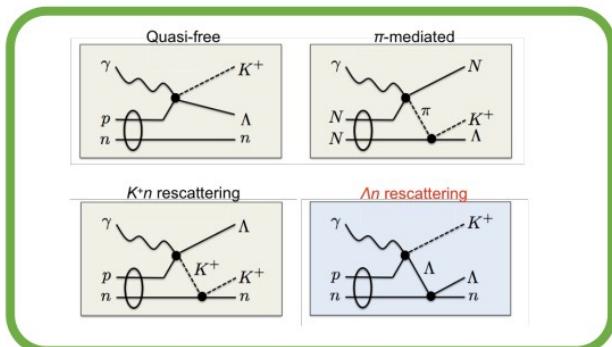
045204

Sum-up CLAS YN interaction

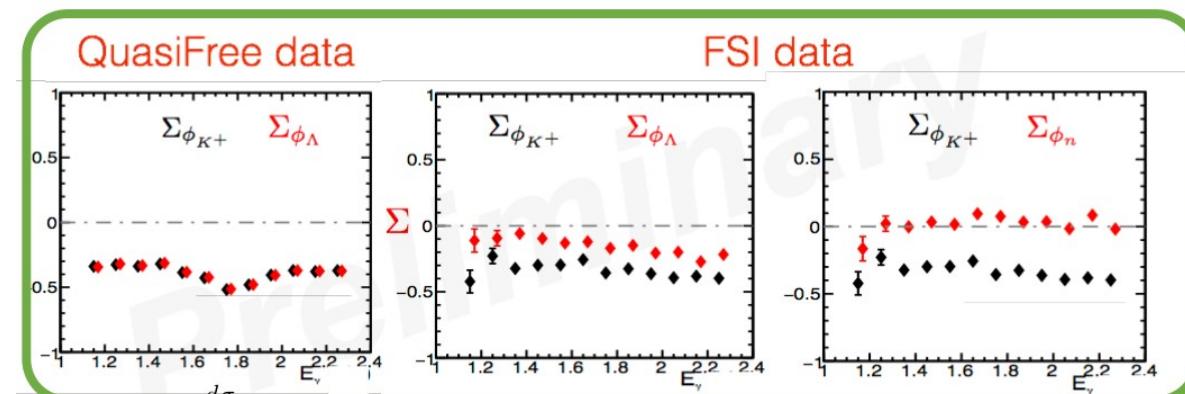


Polarisation Observables Λn

- Rescattering of hyperons in FSI -> powerful info
- YN potentials (NSC97F and NSC89) both give correct BE (e.g hypertriton) -> but degeneracy broken in polarisation observables!



From D. Watts



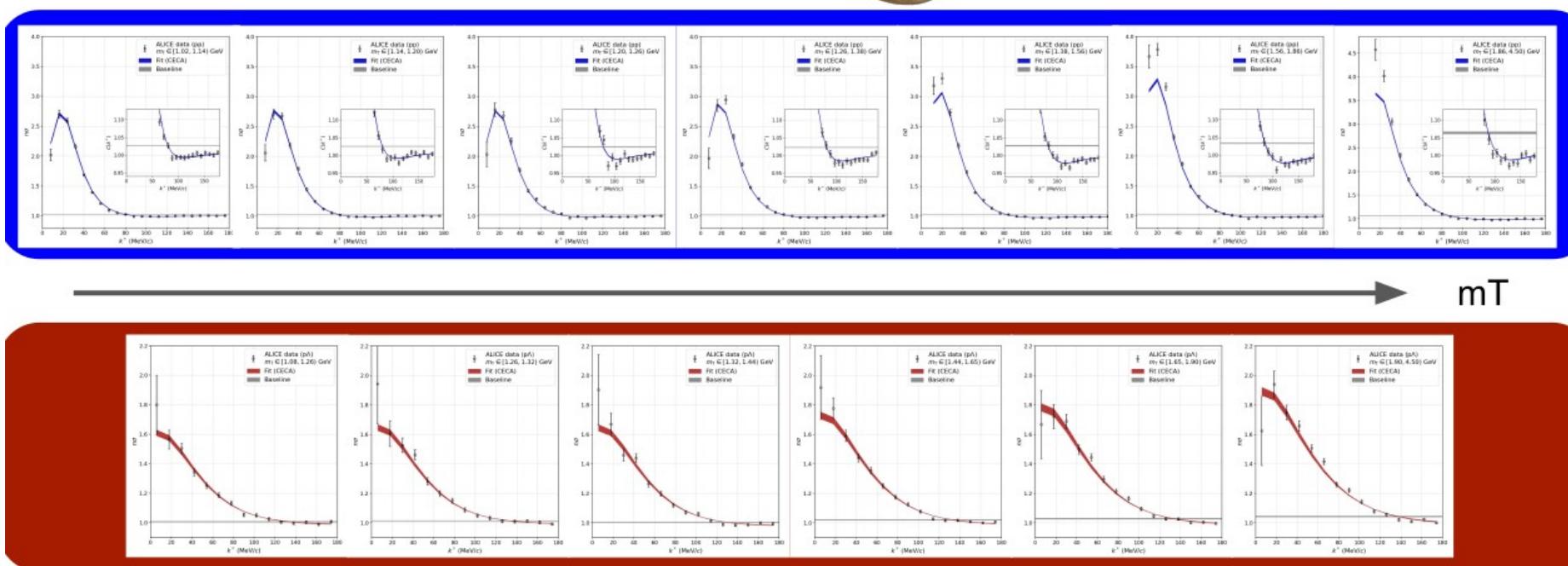
Sum-up hadron-hadron scattering @ LHC



ALICE data + CECA

One source to rule them all

From D. Mihaylov



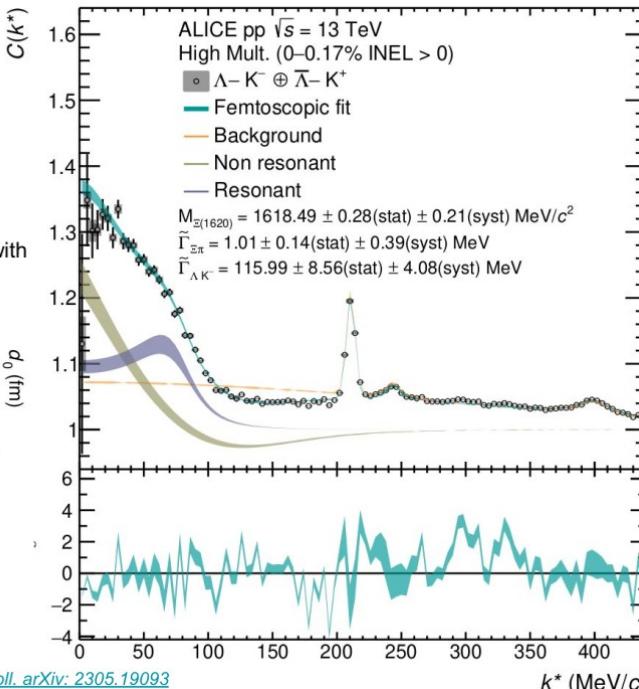
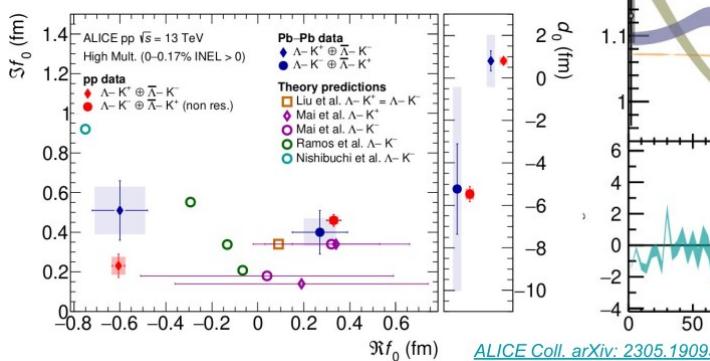
- pp interaction: fixed to the Argonne v18 potential [Phys. Rev. C, 51:38–51, 1995](#)
- p Λ interaction: Usmani potential, short-range repulsive core fitted [Phys. Rev. C, 29:684–687, 1984](#)
- **A combined fit of the mT differential pp and p Λ correlations!**

32

Sum-up hadron-hadron scattering @ LHC

TUM ΛK^- correlations
Results

- Indication of a large coupling of $\Xi(1620)$ to ΛK^-
 $M_{\Xi(1620)} = 1618.49 \pm 0.28(\text{stat}) \pm 0.21(\text{syst})$
- Non-resonant scattering parameters in agreement with ALICE Pb-Pb results
PRC 103 (2021), 5, 055201



From D. Mihaylov

— Constraining the theory

$$C(k^*)_{CC} = \int S(r^*) |\Psi(\vec{k}^*, \vec{r}^*)|^2 d^3 r^* + \sum_j \omega_j \int S_j(r^*) |\Psi_j(\vec{k}^*, \vec{r}^*)|^2 d^3 r^*$$

Elastic $\Lambda K^- \rightarrow \Lambda K^-$

Inelastic $\Xi\pi, \bar{\Sigma}K, \Xi\eta \rightarrow \Lambda K^-$

Fit LECs and SCs to the measured ALICE ΛK^- correlation

How does the $\Xi(1620)$ pole scenario look like?

Pole 3: Poles, couplings and compositeness for model WT+NLO

$0^- \oplus \frac{1}{2}^+$ interaction in the $(I, S) = (0, -2)$ sector

$M = 1615.46$ MeV

$\Gamma = 20.92$ MeV

$(-, -, +, +) \rightarrow$ pole

$ g_i $	$ g_i^2 dG/dE $
$\pi\Xi(1456)$	0.631
$\bar{K}\Lambda(1611)$	0.919
$\bar{K}\Sigma(1689)$	2.15
$\eta\Xi(1866)$	2.75

$M = 1687.69$ MeV

$\Gamma = 17.16$ MeV

$(+, +, -, +) \rightarrow$ virtual

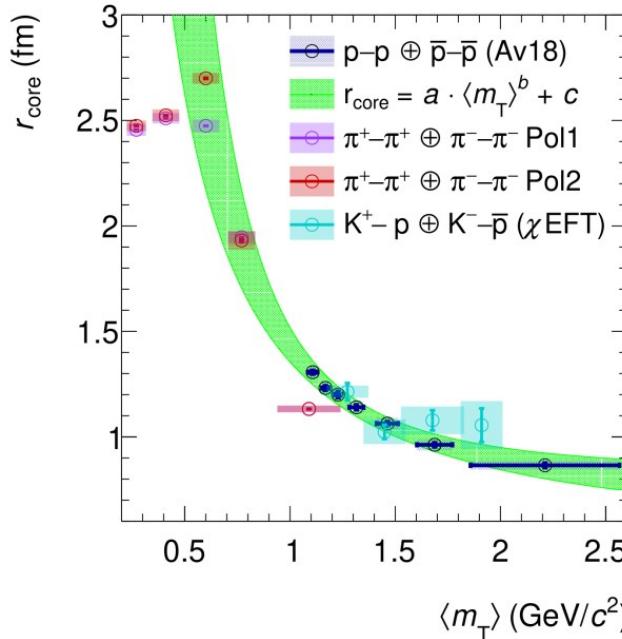
$ g_i $	$ g_i^2 dG/dE $
$\pi\Xi(1456)$	0.581
$\bar{K}\Lambda(1611)$	0.576
$\bar{K}\Sigma(1689)$	1.54
$\eta\Xi(1866)$	0.727

$\Xi(1620)$ pole
Mainly molecular nature composed of $\bar{K}\Sigma$
NEW PARADIGM!

$\Xi(1690)$ pole
Virtual state
Mainly coupled to $\bar{K}\Sigma$

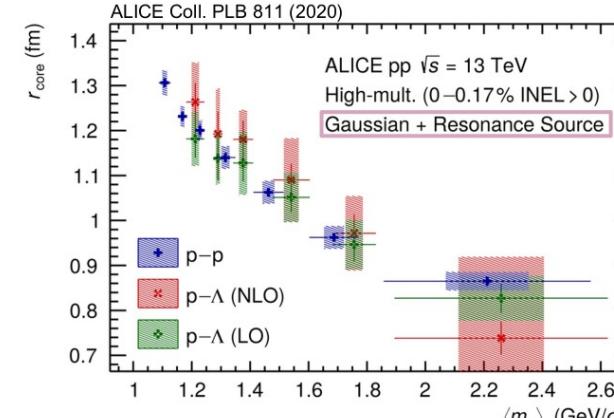
Sum-up common particle-

 r_{core} compared to previous results in HM pp 13 TeV



- $p-p$ taken from PLB 811 2020
- Parameterization and extrapolation of the r_{core} dependence
- $\pi-\pi$ from this analysis
- $K^+ - p$ from this analysis
- For m_T above 0.4 GeV/ c^2 good agreement with parametrization
→ Evidence for a common source for all mesons and baryons in HM pp at 13 TeV

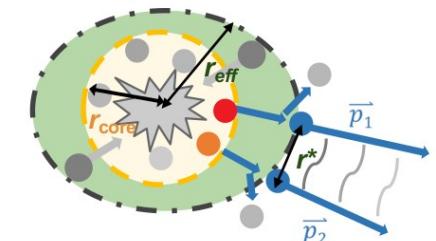
wieser@tum.de



Access smaller m_T by studying $\pi-\pi$ and meson-baryon correlations with $K^+ - p$

From M. Korwieser

- Common scaling is restored by accounting for **non-gaussian** contributions
→ Motivates the assumption of a universal particle source for baryons
- How well does the source resonance model (RSM) perform for mesons?
Is the scaling different?



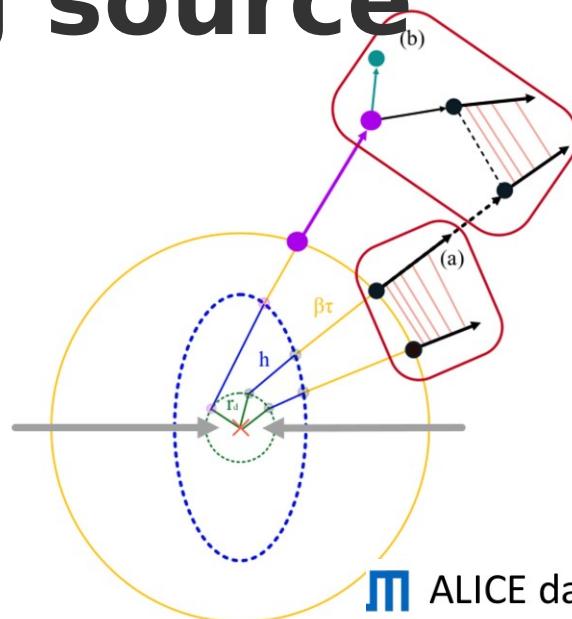
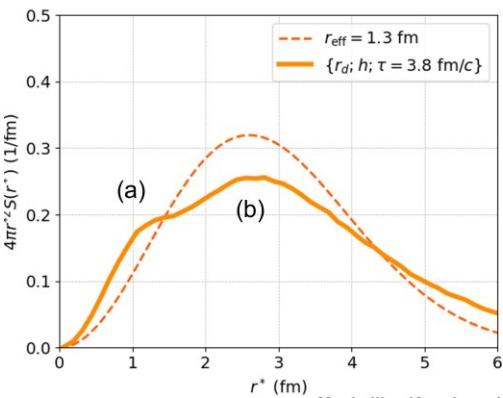
Sum-up common particle-emitting source



CECA: The common source

An example for pp pairs

- Decay short-lived resonances and group the final particles into pairs, after equalizing their time.
N.B. 2/3 of the protons stem from resonances!



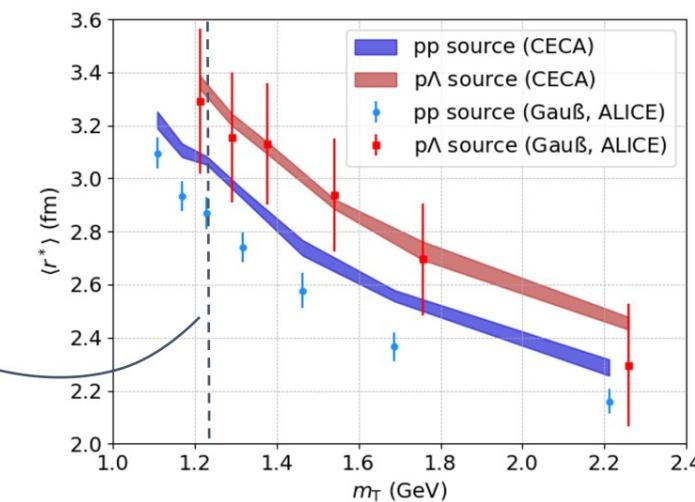
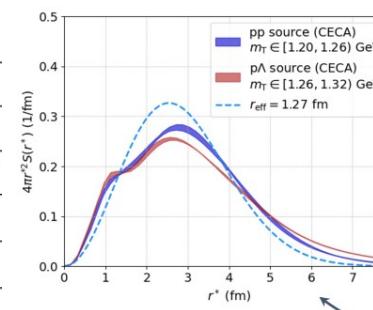
From M. Korwieser

ALICE data + CECA: Source distribution m_T scaling

ALICE data + CECA: Results of $p\Lambda$ fit

	Usmani	Usmani (NLO19)	Usmani (Fit)
χ^2	-	473	371
d (fm)	-	0.288 ± 0.013	0.176 ± 0.005
h_T (fm)	-	$3.23^{+0.05}_{-0.30}$	$2.68^{+0.06}_{-0.04}$
τ (fm/c)	-	$3.26^{+0.16}_{-0.04}$	$3.76^{+0.05}_{-0.03}$
f_0 (fm)	2.88	2.88	2.88
f_1 (fm)	1.66	1.41	1.15 ± 0.07

Femtoscopic data prefer reduced strong interaction strength in 3S_1

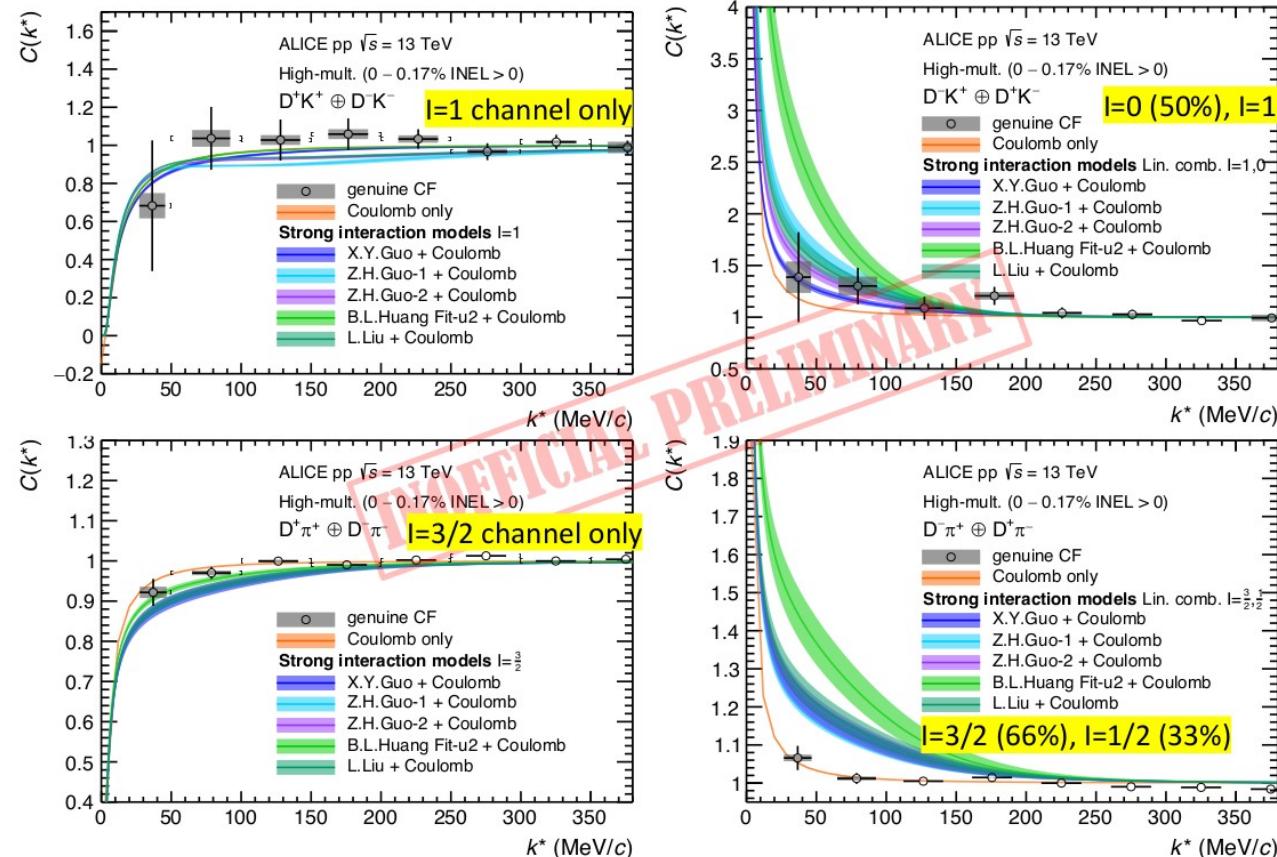


Sum-up D-hadron interactions

D π and DK interaction



- Model correlation functions obtained from Gaussian-type potential, tuned to reproduce scattering lengths
- Change from isospin basis (theory) to charge basis (experiment)

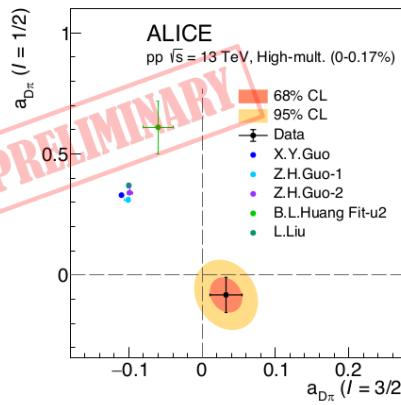
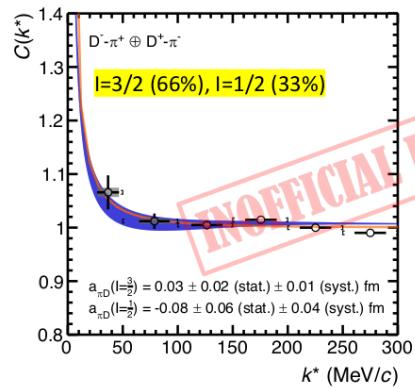
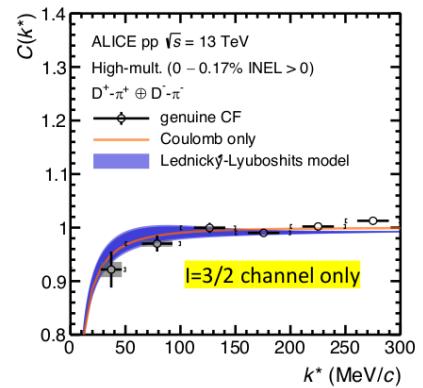


L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13

Sum-up D-hadron interactions

D π correlation function fit

From E. Chizzali



- $D^+\pi^+$ and $D^+\pi^-$ share $I=3/2$ scattering length \rightarrow simultaneous fit with Lednický-Lyuboshits model

R. Lednický and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53 (1982) 770

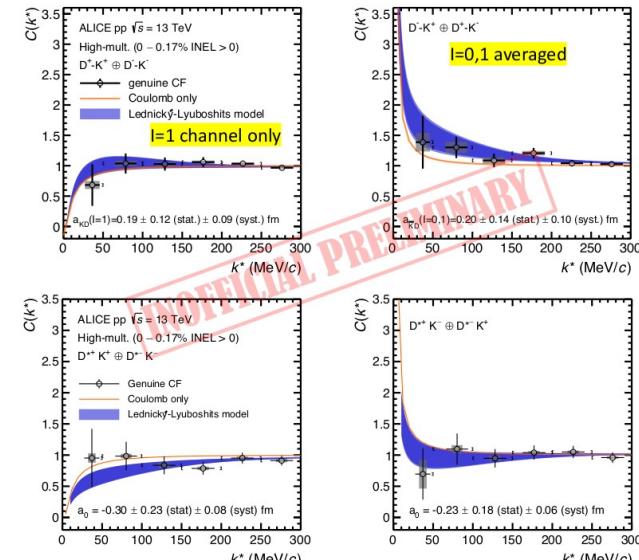
- Vanishing values indicate small rescattering in hadronic phase of HIC
- Deviation from theory prediction in both isospins

D/D*-K correlation function fit

- D^+K^+ and D^+K^- fitted individually with Lednický-Lyuboshits formula

R. Lednický and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53 (1982) 770

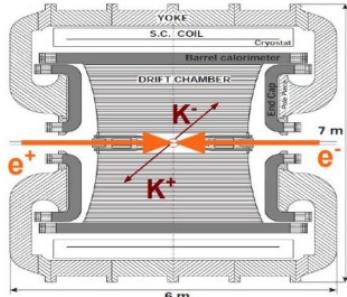
- Poor statistics
- Scattering parameters vanish within uncertainties



Strong interaction found to be shallow \rightarrow Data compatible with Coulomb-only hypothesis

Sum-up $\bar{K}N$ interaction

AMADEUS: Inelastic cross sections at $p=98$ MeV

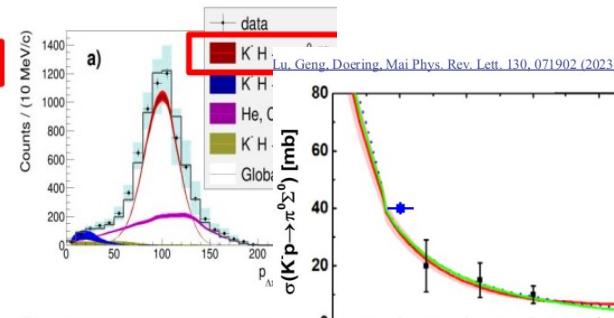
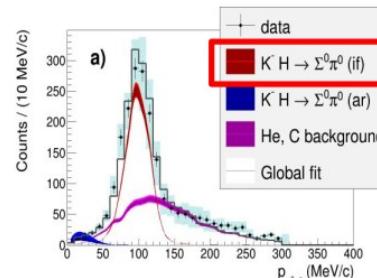


- KLOE at Daøne e^+e^- collider: ϕ factory \Rightarrow Kaon beam of ~ 120 MeV
- Drift chamber of KLOE used as active target (90% ${}^4\text{He}$, 10% C_4H_{10})

First Simultaneous $K^- p \rightarrow (\Sigma^0/\Lambda) \pi^0$ Cross Sections Measurements at 98 MeV/c

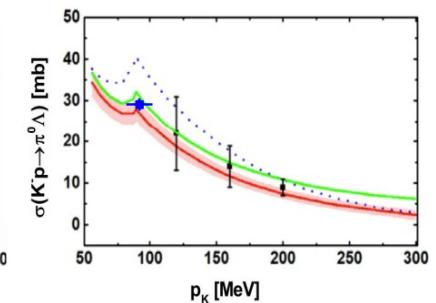
AMADEUS Collaboration, arXiv:2210.10342 [nucl-ex]. Submitted to PRL.

- $\sigma_{K^- p \rightarrow \Sigma^0 \pi^0} = 42.8 \pm 1.5(\text{stat.})^{+2.4}_{-2.0}(\text{syst.}) \text{ mb}$
- $\sigma_{K^- p \rightarrow \Lambda \pi^0} = 31.0 \pm 0.5(\text{stat.})^{+1.2}_{-1.2}(\text{syst.}) \text{ mb.}$

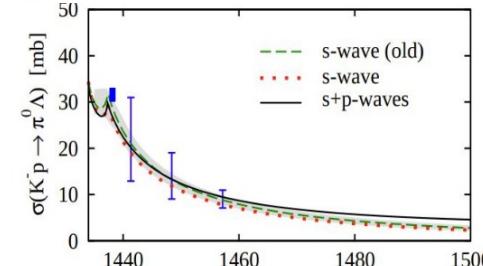
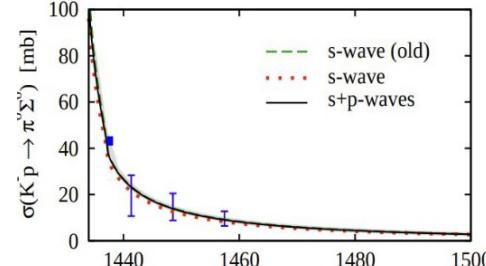
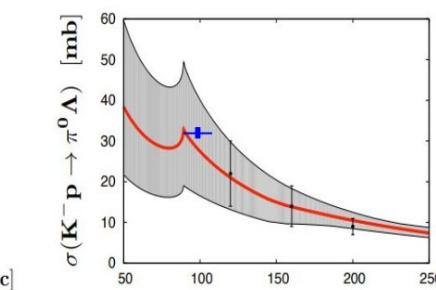


From O. Doce

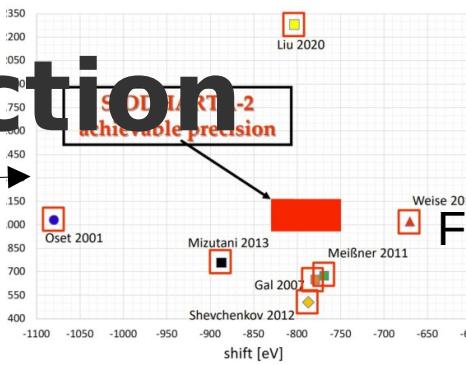
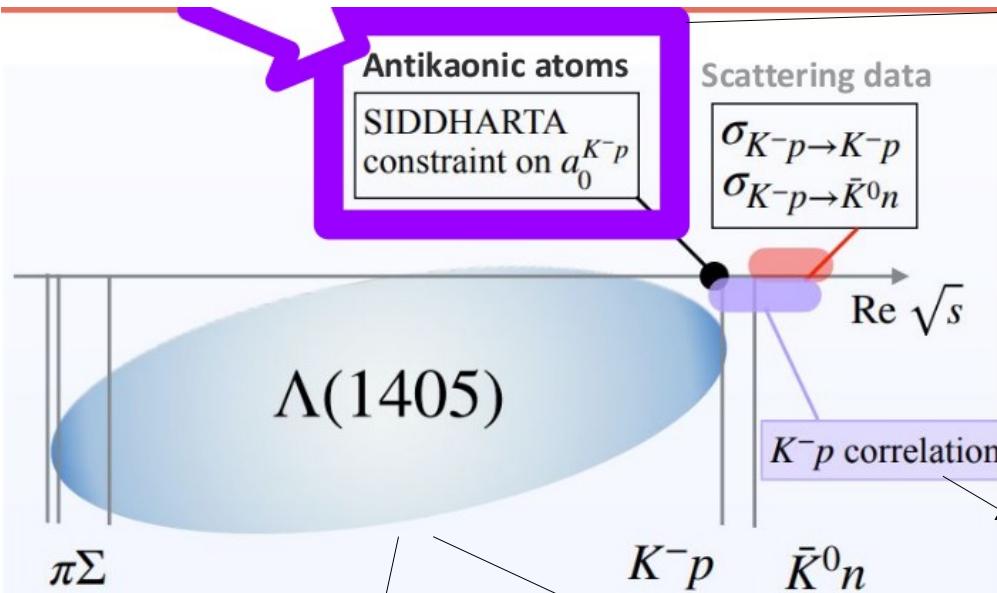
New AMADEUS data arXiv:2210.1034



New AMADEUS data arXiv:2210.10342 [nucl-ex]



Sum-up $\bar{K}N$ interaction



From O. Doce

$\bar{K}p$ Femtoscopy with ALICE

Correlation function with coupled channels:

$$C_{\bar{K}p}(k^*) = \int d^3r^* S_{\bar{K}p}(r^*) |\psi_{\bar{K}p}(k^*, r^*)|^2 + \sum_j \omega_j \int d^3r^* S_j(r^*) |\psi_j(k^*, r^*)|^2$$

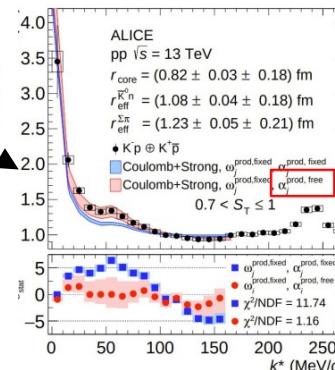
\downarrow

$$\omega_j = \alpha_j \times \omega_j^{\text{prod}}$$

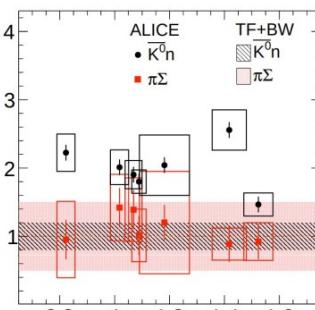
$\omega_j^{\text{prod}} = \text{production yields (thermal model)}$
+ production p_T spectrum (blast-wave)
+ pair kinematics

⇒ Quantitative test of coupled channels in the theory

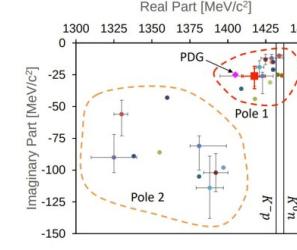
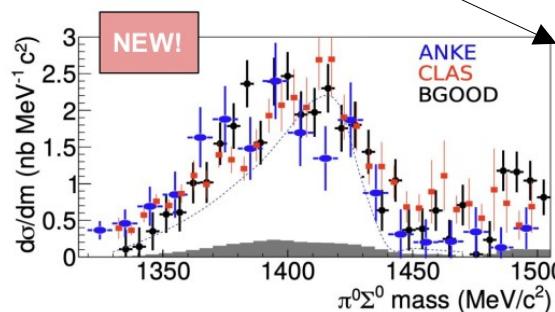
ALICE coll. Eur.Phys.J.C 83 (2023) 4, 340



The model does not reproduce the strength of the anti K^0 -n channel! ⇒



$\Lambda(1405)$ with J-PARC E31 data



⇒ Higher pole ~1420 MeV well constrained
Lower pole: large differences in predictions.

New data:

- photo-production: BGOOD ⇒ G. Scheluchin et al., Phys. Lett. B833, 137375 (2022)
- J-PARC E31: $d(K^-, n)\pi$ reaction J-PARC E31 Coll. Phys Lett B 837 137687 (2023)
- (Preliminary) GlueX photoproduction arXiv:2209.06230v1 [nucl-ex]

Done for today !