Wrap-Up of Thursday

EMMI-Workshop on
“Anti-matter, hyper-matter and exotica production at the LHC”
Wrocław, Dec. 2019

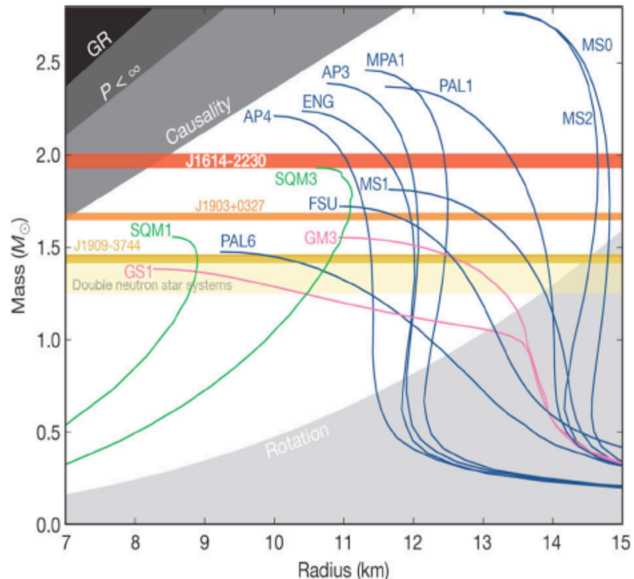
Christoph Blume
Goethe-University of Frankfurt
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Neutron Star Challenges: Mass and Radius

Constraint from observation of $2M_\odot$ NS

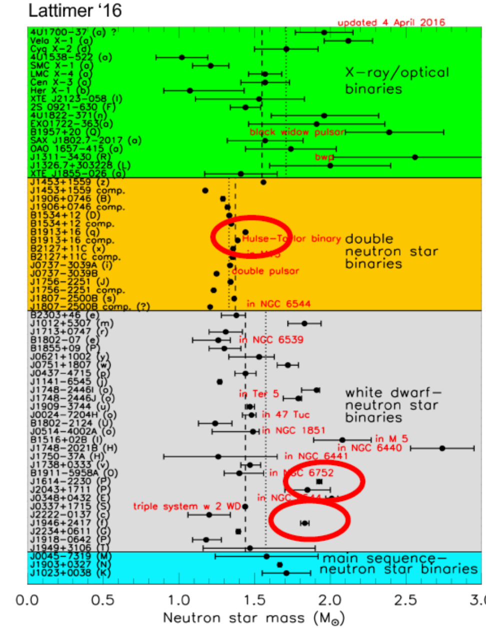
Simultaneous measurements of mass and radius needed → NICER

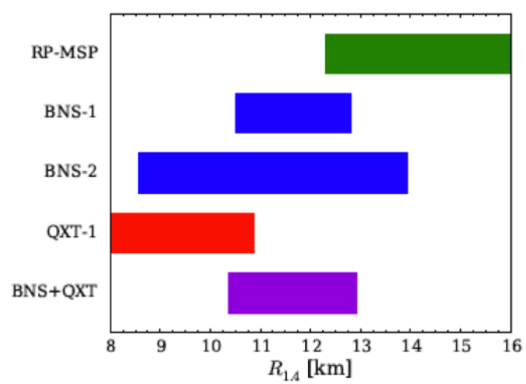
<u>But</u>: some information via GW-signal from NS-merger



Ozel et al '16

Lattimer '16





GW170817

using tidal deformability sets constraints on

$M_{max} \lesssim 2.2\ M_\odot$

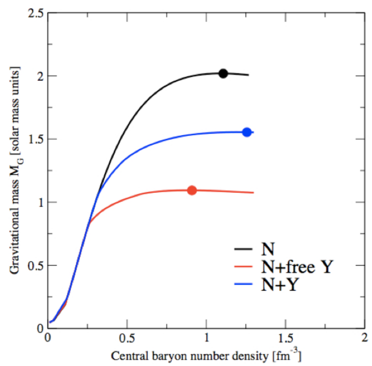
Margalit and Metzger '17, Rezzolla, Most and Weih '18,..

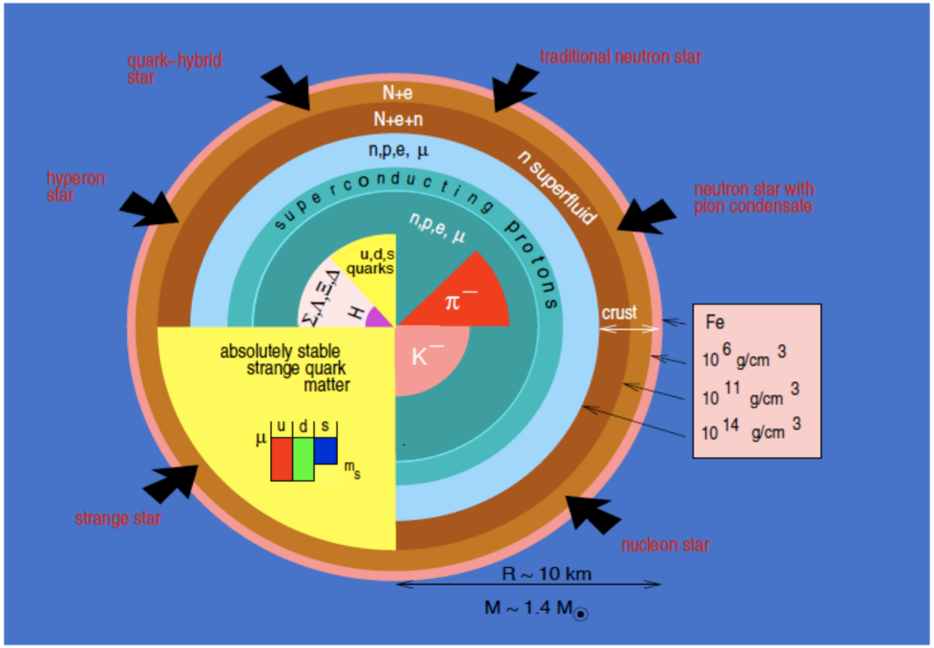
$9\text{-}10\ \text{Km} \lesssim R_{1.4M_\odot} \lesssim 13\ \text{Km}$

Annala et al '18, Kumar et al '18, Abbott et al '18, Fattoyev et al '18, Most et al '18, Lim et al '18, Raithel et al '18, Burgio et al '18, Tews et al '18, De et al '18, Abbott et al '18,

Neutron Star Challenges: Hyperon Puzzle

Hyperons should appear
as density increases
→ EOS softens
→ Cannot reach $2M_\odot$ NS





What EOS are possible?

- 3-body forces between Ys
- Stiffer YN and YY interactions, repulsion
- Move onset of Y appearance, phase transition to deconfined matter

Information on YY and YN interaction needed

- Experiment: hypernuclei, correlations, scattering data
- Theory: chiral effective theory, Nijmegen ESC16 model, NPLQCD

Equation-Of-State

Phenomenological model based on FSU2 model

Chen and Piekariewicz '12

$$\mathcal{L} = \sum_b \mathcal{L}_b + \mathcal{L}_m + \sum_{l=e,\mu} \mathcal{L}_l,$$

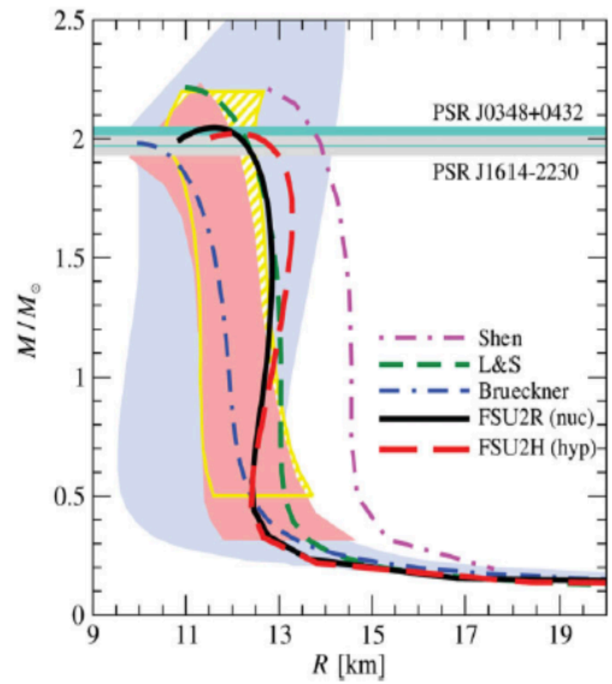
$$\mathcal{L}_b = \bar{\Psi}_b (i\gamma_\mu \partial^\mu - q_b \gamma_\mu A^\mu - m_b + g_{\sigma b}\sigma - g_{\omega b}\gamma_\mu \omega^\mu - g_{\phi b}\gamma_\mu \phi^\mu - g_{\rho b}\gamma_\mu \vec{I}_b \vec{\rho}^{\,\mu})\Psi_b,$$

$$\mathcal{L}_l = \bar{\psi}_l (i\gamma_\mu \partial^\mu - q_l \gamma_\mu A^\mu - m_l)\psi_l,$$

$$\begin{aligned}\mathcal{L}_m = {} & \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2}m_\sigma^2 \sigma^2 - \frac{\kappa}{3!}(g_{\sigma N}\sigma)^3 - \frac{\lambda}{4!}(g_{\sigma N}\sigma)^4 \\ & - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2 \omega_\mu \omega^\mu + \frac{\zeta}{4!}(g_{\omega N}\omega_\mu \omega^\mu)^4 \\ & - \frac{1}{4}\vec{R}^{\mu\nu}\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2 \vec{\rho}_\mu \vec{\rho}^{\,\mu} + \Lambda_\omega g_{\rho N}^2 \vec{\rho}_\mu \vec{\rho}^{\,\mu} g_{\omega N}^2 \omega_\mu \omega^\mu \\ & - \frac{1}{4}P^{\mu\nu}P_{\mu\nu} + \frac{1}{2}m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}, \end{aligned} \qquad (2)$$

stiffening of EoS at $n >> n_0$: small ζ implies stiff EoS at $n >> n_0$

modify density dependence of E_{sym} at 1-2n_0: small Λ_w implies stiff EoS at $\sim n_0$



FSU2R: Good agreement with heavy-ion data

Description of nuclear properties at saturation densities

(energies, charge radii, symm. energy, ^{208}Pb skin thickness)

FSU2H: Hyperons included, parameters (ζ and Λ_w) adjusted

Both EOS can satisfy $M > 2M_\odot$ and $R \lesssim 13$ km

Laura Tolós

Equation-Of-State

Neutrino emission processes:

- Fast neutrino reactions:

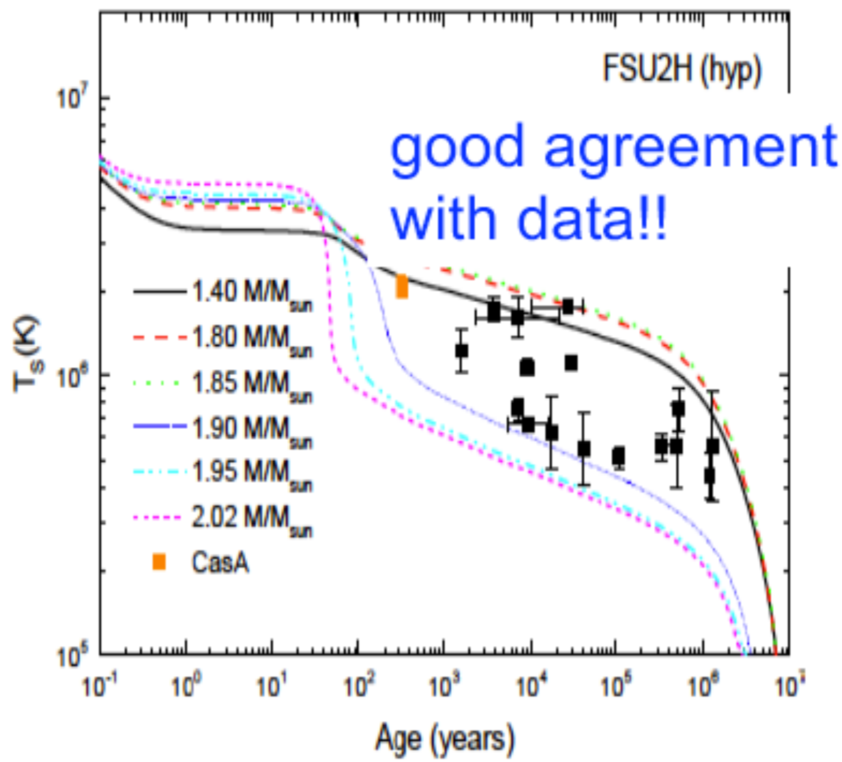
direct URCA process
only in inner core and have density thresholds

$$n \rightarrow p + e^- + \bar{\nu}_e \; ; \; p + e^- \rightarrow n + \nu_e$$
$$Y \rightarrow (Y, N) + e^- + \bar{\nu}_e$$

- Slow neutrino reactions:

modified URCA process & NN bremsstrahlung
everywhere in core, particularly in outer core (low-mass stars)

$$N + p + e^- \rightarrow N + n + \nu_e$$
$$N + n \rightarrow N + p + e^- + \bar{\nu}_e$$
$$N + N \rightarrow \nu\bar{\nu}$$



Low-mass stars ($M\sim1.4\ M_\odot$): soft/stiff nuclear symmetry implies slow/fast cooling

High-mass stars ($1.8\text{-}2\ M_\odot$): stiffer EoS implies lower central densities and, thus, slower cooling

Hyperons in medium to heavy mass stars speed up the cooling due to reduction of neutron fraction

Nucleon pairing helps further

LT, Centelles, Ramos, Astrophys. J. 834 (2017) 3
LT, Centelles, Ramos, Publ. Astron. Soc. Austral. 34 (2017) e065
Negreiros, LT, Centelles, Ramos, Dexheimer, Astrophys. J. 863 (2018) 104

Laura Tolós

Hyperon Puzzle: NNΛ-Force

EPJA 55, 207 (2019)

- ✧ Study of the effects of NNΛ force on neutron stars

  To such end EoS & NS structure derived within the BHF approach using:

  - NN at N^3LO in χEFT including Δ isobar in intermediate states of NN scattering
  - NNN at N^2LO in χEFT
  - NΛ from meson-exchange (Nijmegen group). Weak point of the work
  - NNΛ derived by the Juelich-Munich-Bonn group in χEFT at N^2LO

- ✧ Inclusion of NNΛ force improves description of heavy hypernuclei
- ✧ Inclusion of NNΛ force leads to an EoS stiff enough such that he resulting NS maximum mass is compatible with current observations **but the model contains only N, leptons & Λ's**
- ✧ We have **NOT SOLVED** the hyperon puzzle **but have taken an additional step towards its solution**

Isaac Vidaña

Hyperon Puzzle: NNΛ-Force

Improves description of hypernuclei ($^{91}_{\Lambda}$Zr and $^{209}_{\Lambda}$Pb)

Λ separation energy in $^{41}{}_{\Lambda}$Ca, $^{91}{}_{\Lambda}$Zr & $^{209}{}_{\Lambda}$Pb

	$^{41}_{\Lambda}$Ca	$^{91}_{\Lambda}$Zr	$^{209}_{\Lambda}$Pb
NSC97a	23.0	31.3	38.8
NSC97a+NNΛ$_1$	14.9	21.1	26.8
NSC97a+NNΛ$_2$	13.3	19.3	24.7
NSC97e	24.2	32.3	39.5
NSC97e+NNΛ$_1$	16.1	22.3	27.9
NSC97e+NNΛ$_2$	14.7	20.7	26.1
Exp.	18.7(1.1)*	23.6(5)	26.9(8)

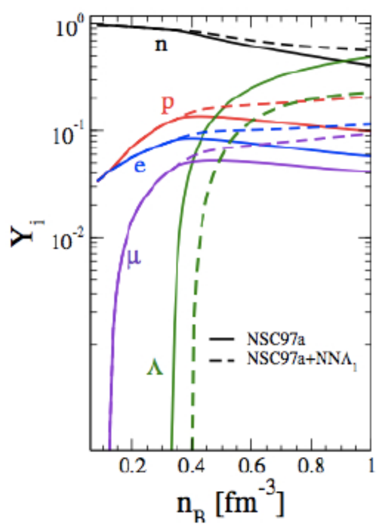
Repulsion due to NNΛ force

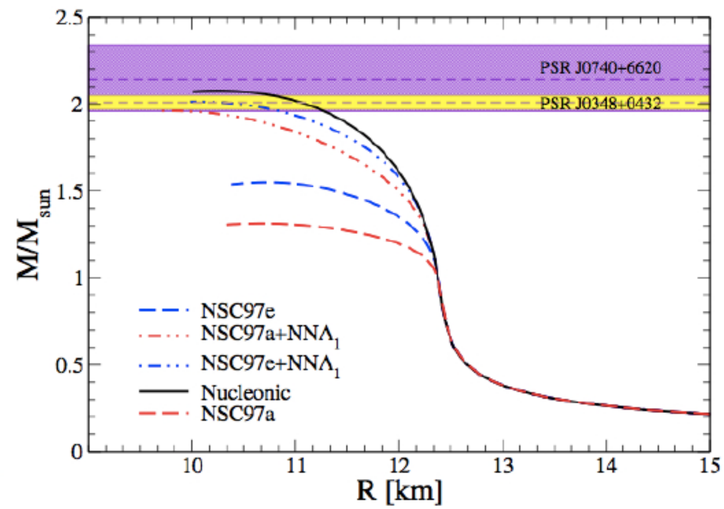
- Shifts onset of Λ to higher baryon density
- Reduction of amount of Λ at large n_B

Compatible with $2M_{\odot}$

Caveat: other hyperons ignored

Isaac Vidaña





YN-Interaction in Chiral Effective Field Theory

NLO interaction from 2019

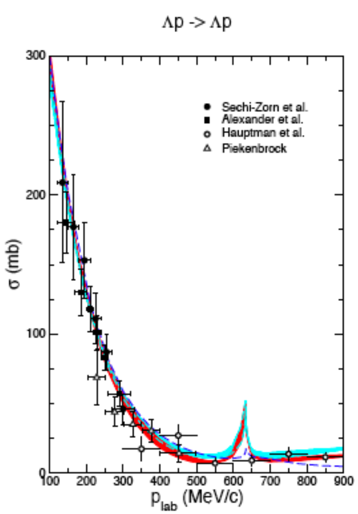
J.H., U.-G. Meißner, A. Nogga, arXiv:1906.11681

explore those correlations between the LO and NLO LECs

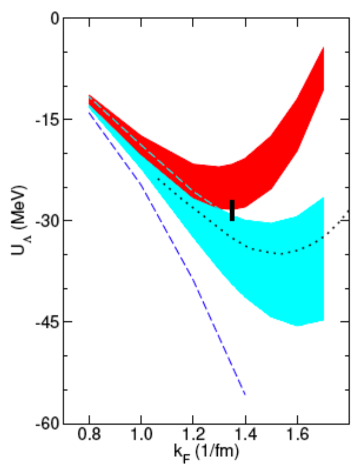
explore consequences for the YN interaction, for light hypernuclei, and for in-medium properties of the Λ and Σ hyperons

reduce correlations by taking over 2 (NLO) LECs from the NN sector, fixed from the $^1S_0$ and $^3S_1$ NN phase shifts

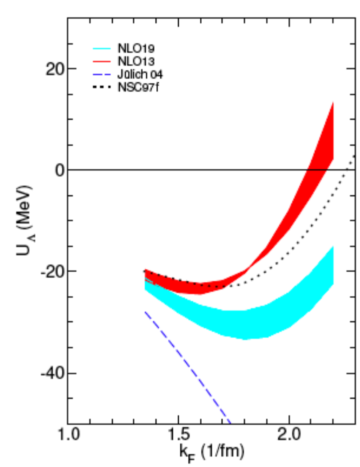
decision is somewhat arbitrary - but in line with the power counting up to NLO:
SU(3) symmetry in the NLO LECs
SU(3) symmetry breaking in the LO LECs due to $m_\pi - m_K$ mass difference



symmetric nuclear matter



neutron matter



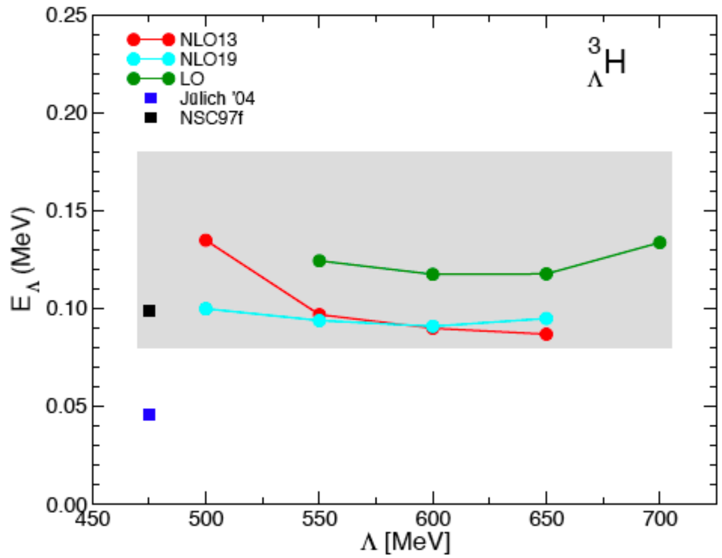
NLO13: J.H., S. Petschauer, et al., NPA 915 (2013) 24
NLO19: J.H., U.-G. Meißner, A. Nogga, arXiv:1906.11681
Jülich '04: J.H., U.-G. Meißner, PRC 72 (2005) 044005
Nijmegen NSC97f: T.A. Rijken et al., PRC 59 (1999) 21

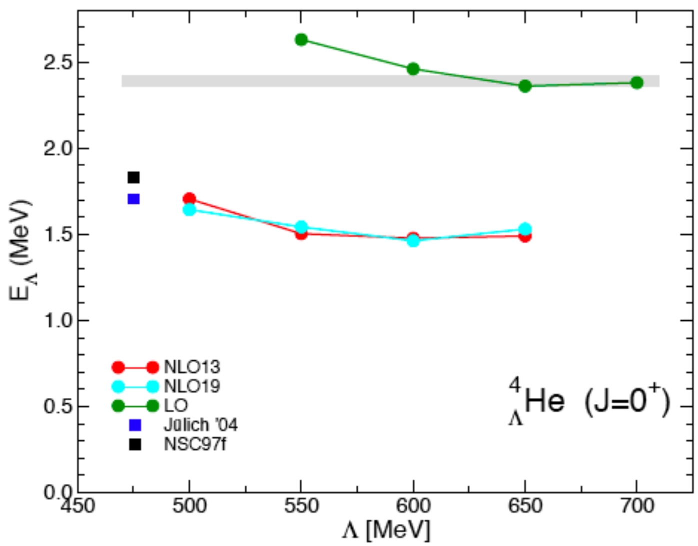
Contributions from three-body forces missing!

Johann Haidenbauer

YN-Interaction in Chiral Effective Field Theory

Results for Λ-separation-energies (dependence on cutoff-energy)





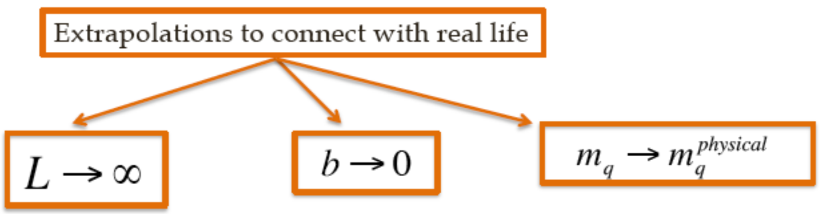
- $S = -1$: Excellent results at next-to-leading order (NLO)
  Λp, ΣN low-energy data are reproduced with a quality comparable to phenomenological models
- Strength of the ΛN-ΣN transition potential (Λ-Σ conversion) is not an observable
  Λ-Σ conversion and 3BFs are interrelated in few- and many body applications
- $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He ... effects of three-body forces should be small
  needs to be quantified/confirmed by explicit inclusion of 3BFs
- nothing speaks against a somewhat larger binding energy of $^{3}_{\Lambda}$H!

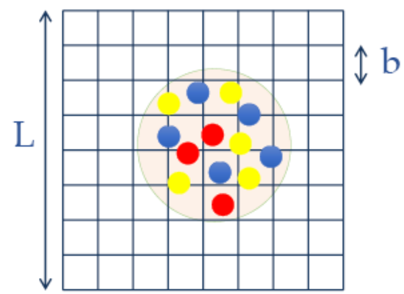
Johann Haidenbauer

NPLQCD Calculations

Connection to fundamental theory (QCD)

Extrapolation to physical situation quite involved



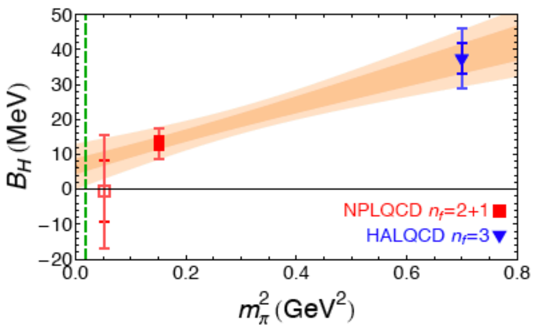


$L >>$ relevant scales $>> b$

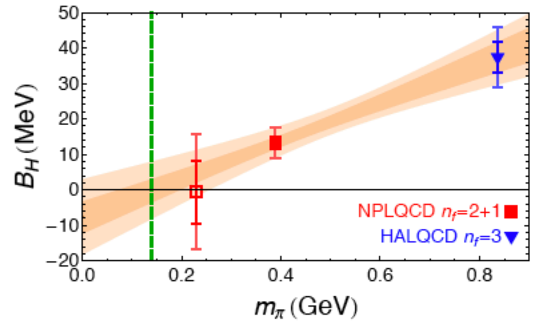
$$\left(\frac{1}{L} << m_\pi << \Lambda_\chi << \frac{1}{b}\right)$$

$$b << M_N^{-1}$$

Extrapolate to physical results:
Use of Effective Field Theory



$$B_H(m_\pi) = B_0 + d_1 m_\pi^2$$
$$B_H^{\rm quadratic} = 7.4 \pm 2.1 \pm 5.8\,{\rm MeV}$$



$$B_H(m_\pi) = \tilde{B}_0 + c_1 m_\pi$$
$$B_H^{\rm linear} = -0.2 \pm 3.3 \pm 7.3\,{\rm MeV}$$

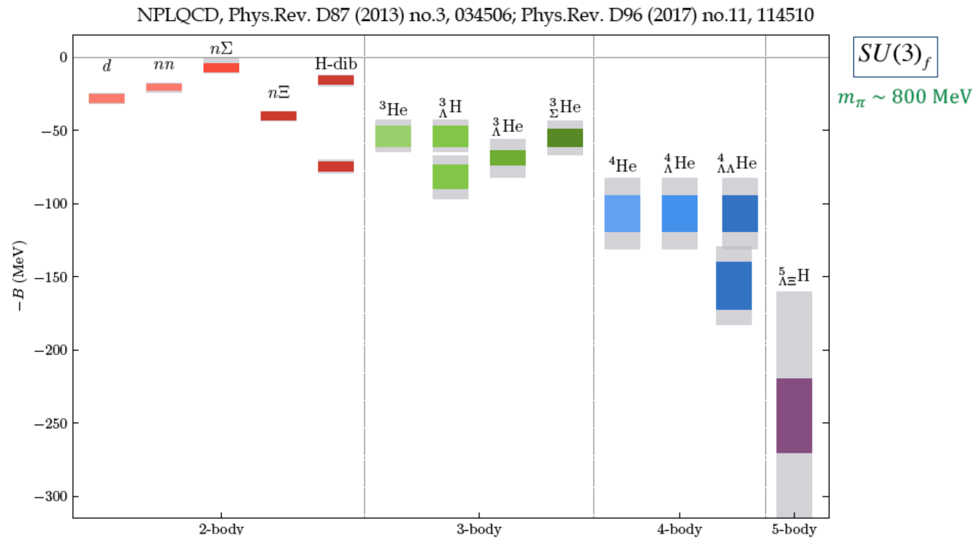
Mod. Phys. Lett. A **26**, 2587 (2011)

Assumpta Parreño

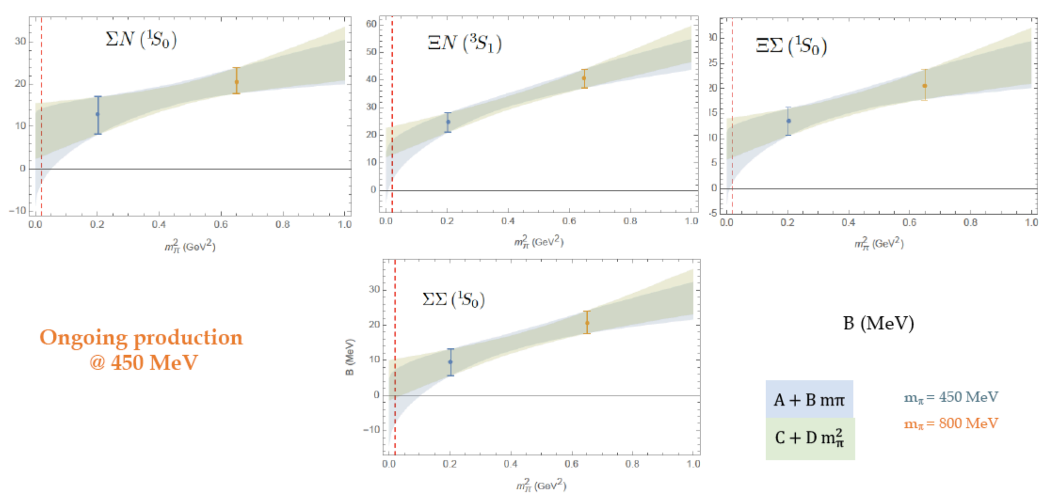
NPLQCD Calculations

Work in progress!

Extrapolation to physical pion mass being refined
→ Results will still change



STRANGE CHANNELS. PRELIMINARY



Assumpta Parreño

Baryon-Baryon-Correlations with ESC16*

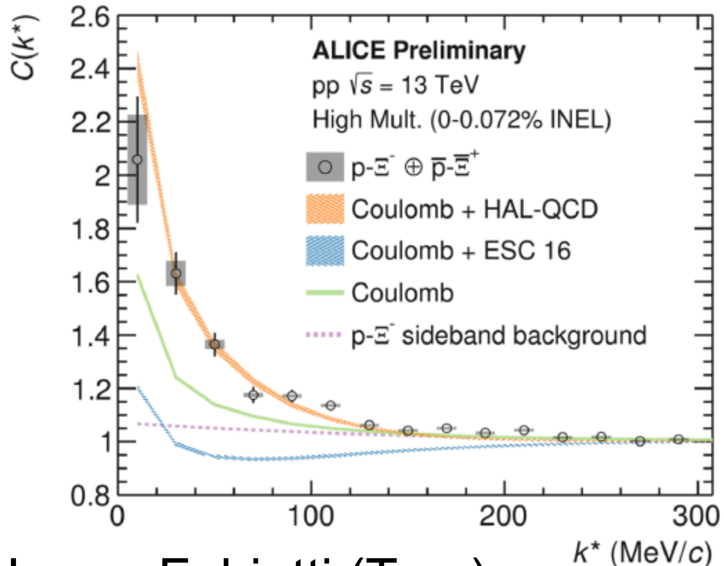
ESC16*: ESC16 $\oplus$ New Two-body Forces!?

- ESC16 Two-body forces incomplete, fail to explain:

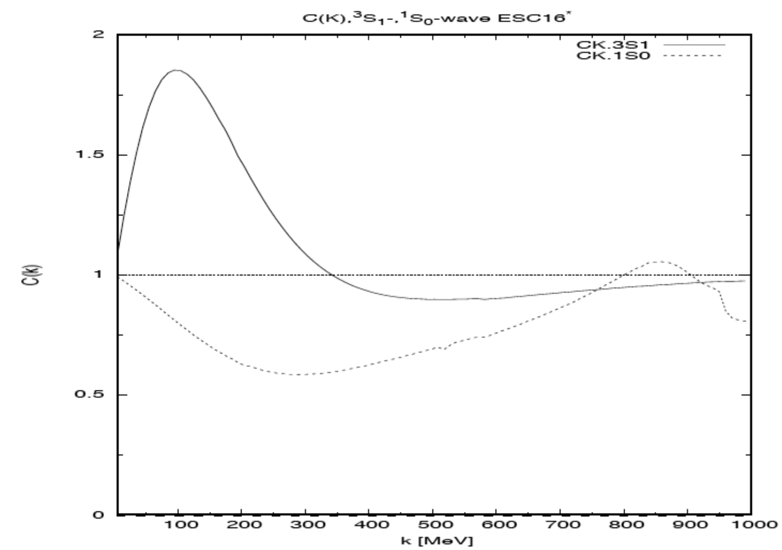
1. U_Σ: $\Sigma^+ p$: SU(3)+X-sections $\rightarrow$ limit on two-body repulsion
   $\Rightarrow$ problem to obtain large $U_\Sigma \approx +15$ MeV.
2. U_Ξ: Small ΞN scattering X-sections: how to obtain $U_\Xi \approx -14$ MeV?
   How to accomodate the Nakazawa et al Ξ-hypernuclei,
   produced by (K^-, K^+)-reactions with ${}^{12}C, {}^{16}O, {}^{14}N$?
3. N-star: How to avoid softening of EoS for neutron star matter
   with hyperons, the so-called "hyperon-puzzle"?
4. $C_{\Xi^- p}$-correlation (Fabietti talk)

Thomas Rijken

Baryon-Baryon-Correlations with ESC16*



Laura Fabietti (Tue.)



$\Xi^- p$-correlations, U_Ξ, U_Σ: Problem for ESC(16 etc)-models!,

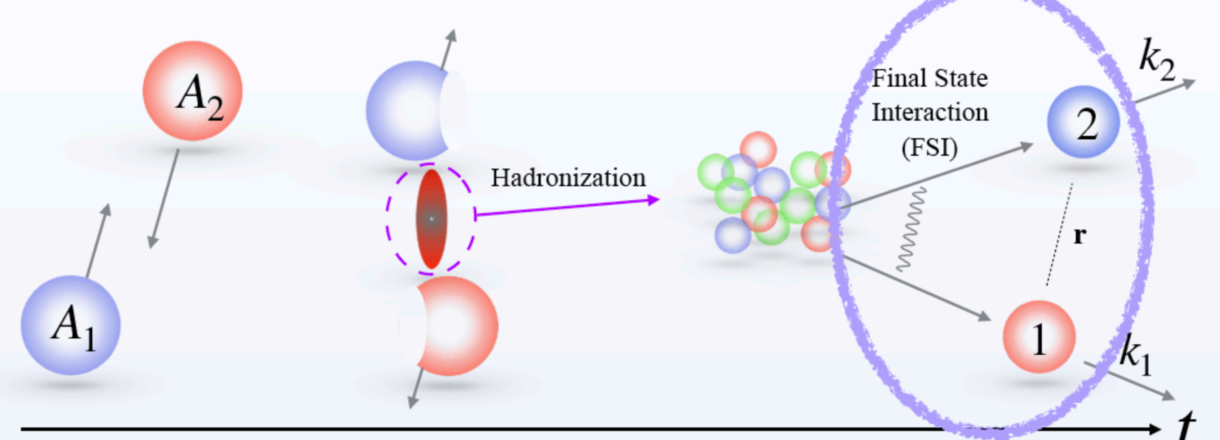
ALICE-correlations $C_{\Xi^- p}(k)$: ESC16-model is incomplete!
Additional (SU(3)-symmetric) needed!

ESC16*: SU(3)-invariant extension ESC16-model: succesful!

Thomas Rijken

K⁻ p Correlations

- High energy nuclear collision and FSI



- Hadron-hadron correlation
  - Koonin-Pratt formula : S.E. Koonin, PLB 70 (1977); S. Pratt et. al. PRC 42 (1990)

$$C(\mathbf{q}) \simeq \int d^3\mathbf{r}\ S(\mathbf{r})\,|\varphi^{(-)}(\mathbf{q},\mathbf{r})|^2$$

$$\mathbf{q} = (m_2\mathbf{k}_1 - m_1\mathbf{k}_2)/(m_1+m_2)$$

$S(\mathbf{r})$: Source function

$\varphi^{(-)}(\mathbf{q},\mathbf{r})$: Relative wave function

- Depends on …
  - Interaction (strong and Coulomb)
  - quantum statistics (Fermion, boson)

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$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S_{K^-p}(\mathbf{r})\left[|\varphi^{C,\mathrm{full}}(\mathbf{q};\mathbf{r})|^2 - |\phi_0^C(qr)|^2 + |\psi_{K^-p}^{C,(-)}(q;r)|^2\right] + \sum_{j\neq i}\omega_j \int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\psi_j^{C,(-)}(q;r)|^2$$

Free Coulomb wave ($l \geq 1$ waves)

Scattering s-wave function with Coulomb int.

Coupled-channel source contribution

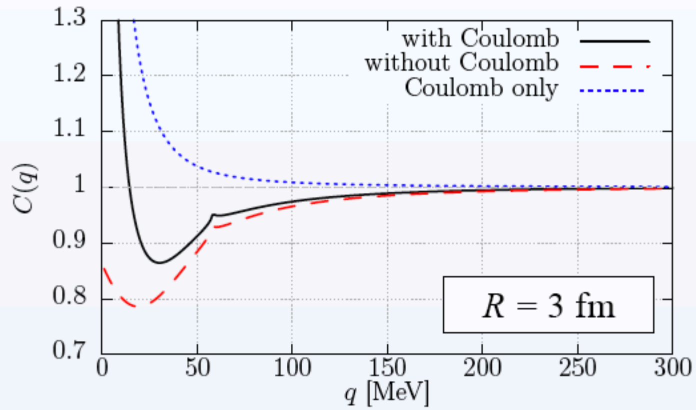
Yuki Kamiya

K^- p Correlations

Kyoto Model Ohnishi et al. NPA 954 (2016)
Cho, et al., PPNP 95 (2017)

- Interaction: Based on Chiral SU(3) dynamics
  Ikeda, Hyodo, Weise, NPA881 (2012)

Current study with $K^-p + \bar{K}^0 n$



- $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channel potential
- *Full* outgoing boundary condition

$$\psi \to \frac{1}{2iqr}[e^{iqr} - \mathcal{S}^{\dagger}_{K^-pK^-p} e^{-iqr}] e_{K^-p} - \sqrt{\frac{\mu_{K^-p} q}{\mu_{\bar{K}^0 n} q_{\bar{K}^0 n}}} \mathcal{S}^{\dagger}_{K^-p\bar{K}^0 n} e^{-iq_{\bar{K}^0 n} r} e_{\bar{K}^0 n}$$

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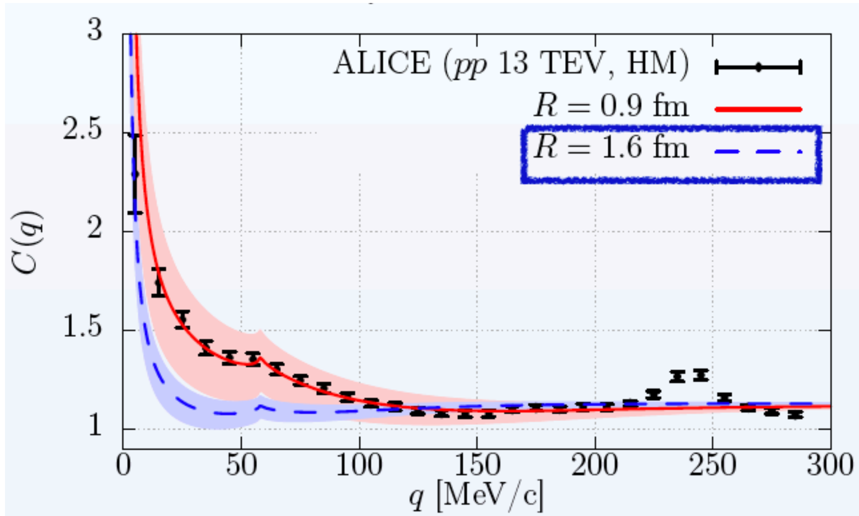


→ Good agreement with ALICE data

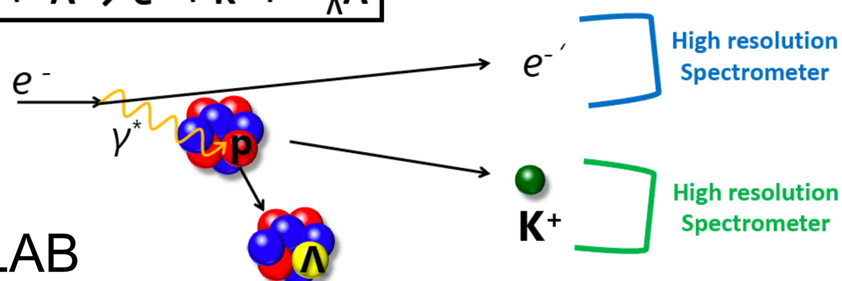
==> • Coupling to decay channels are not negligible

• Boundary condition should be taken carefully

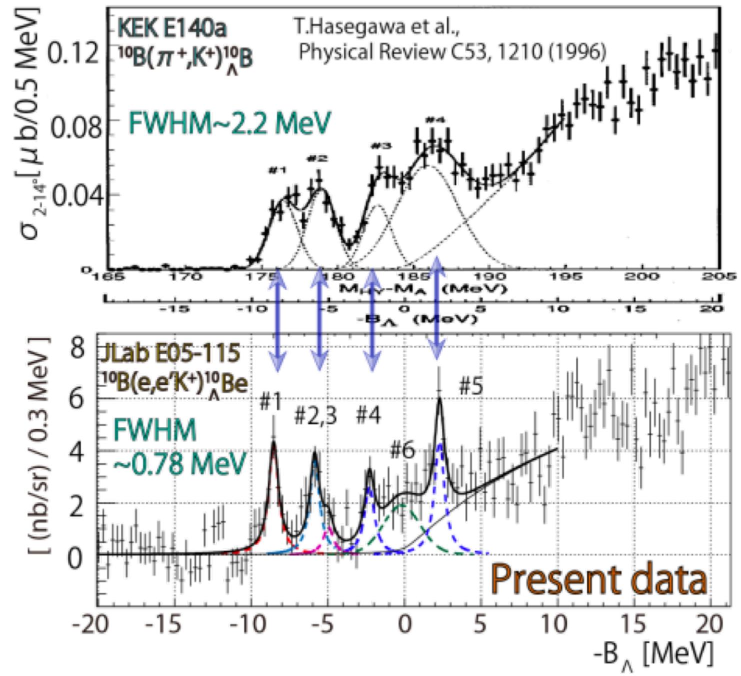
Yuki Kamiya

Spectroscopy of Hypernuclei

$e^- + {}^{Z}A \rightarrow e^{-\prime} + K^+ + {}^{Z-1}_{\Lambda}A$



JLAB



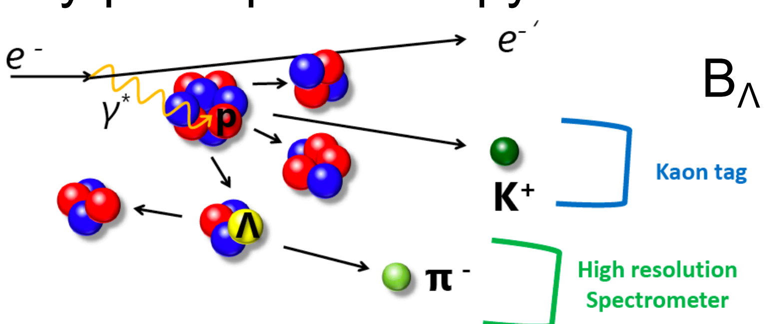
High resolution (sub MeV)

high quality primary electron beams, less stuff target

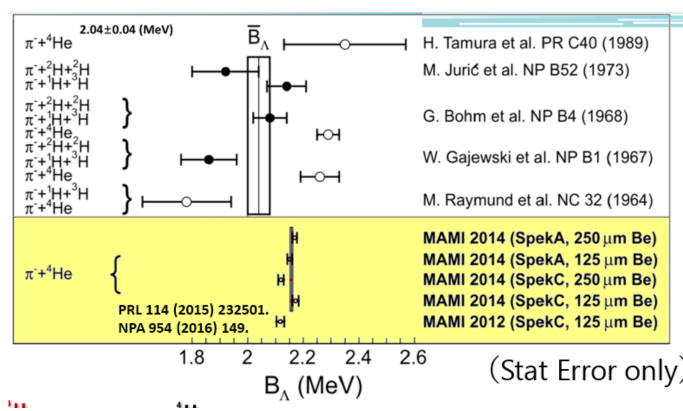
High Accuracy (100 ~ a few 100 keV)

Absolute calibration with Λ & Σ masses

Decay-pion spectroscopy at MAMI



B_Λ of ${}^4_\Lambda H$



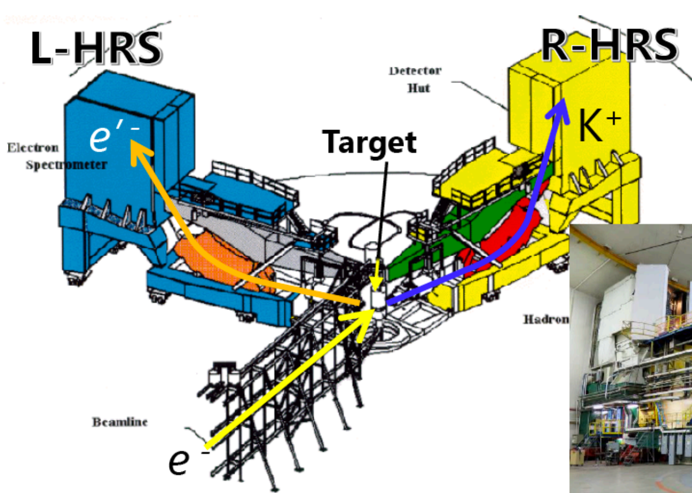
(Stat Error only)

Sho Nagao

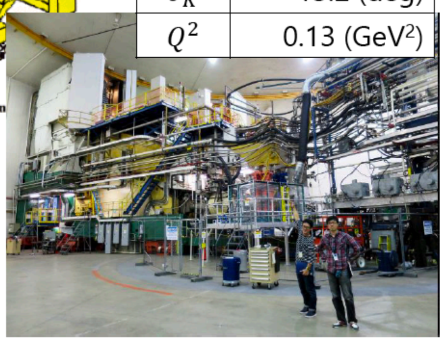
Search for Bound nnΛ-State

Evidence from HypHI experiment
Theory: unbound or resonance

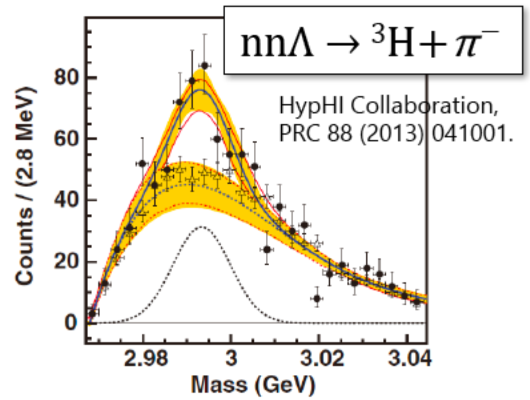
New experiment at CEBAF



E_e	4.319 (GeV)
$p_{e'}$	2.180 (GeV/c)
p_K	1.823 (GeV/c)
$\theta_{e'}$	13.2 (deg)
θ_K	13.2 (deg)
Q^2	0.13 (GeV^2)

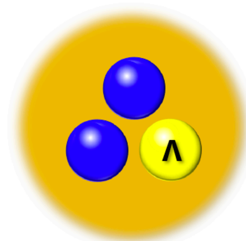


2-HRS system (standard equipment) at Hall-A.



$\tau = 190^{+47}_{-35}$ ps

Search for nnΛ state
(JLab E12-17-003)

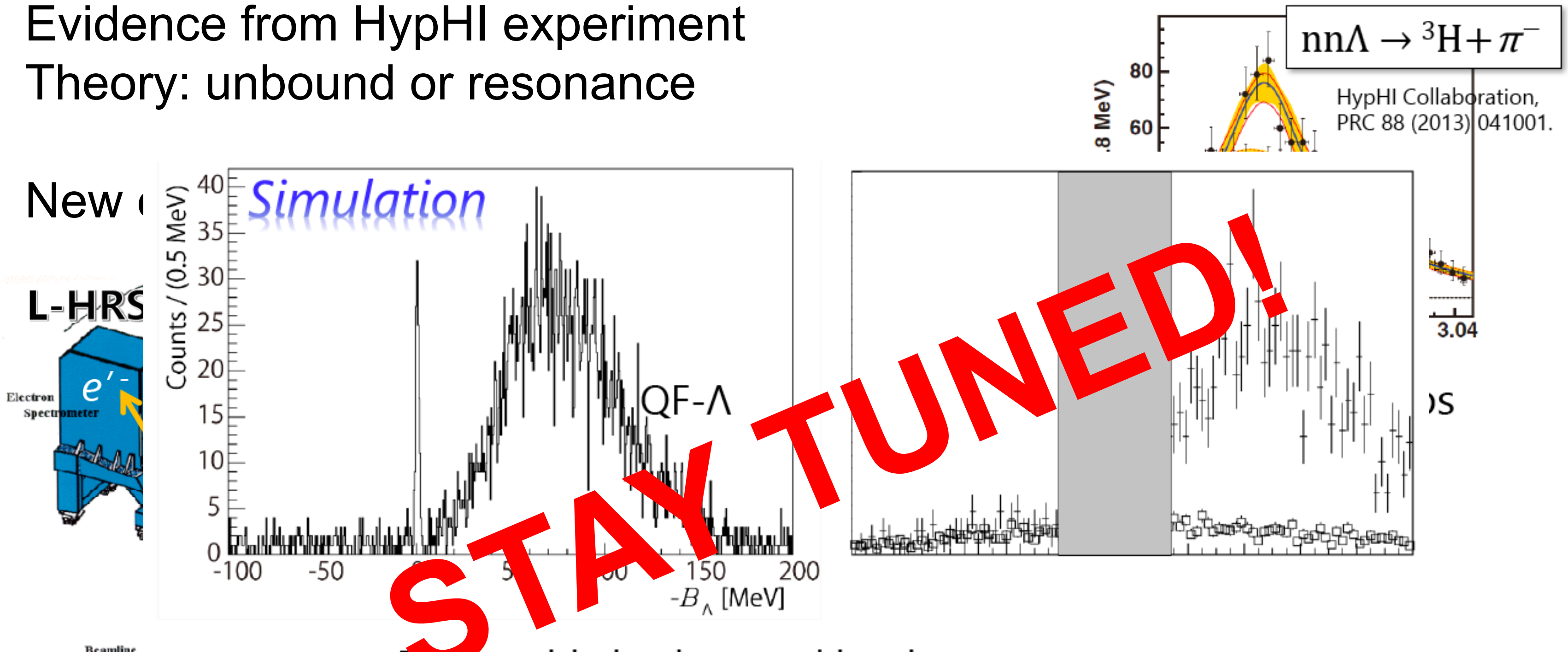


Sho Nagao

Search for Bound nnΛ-State

Evidence from HypHI experiment
Theory: unbound or resonance

New (



Reasonable background level.
Comparable QF events with simulation.
Obtain Re (and Im) if a peak would be observed.
Analysis of E12-15-008 in progress.

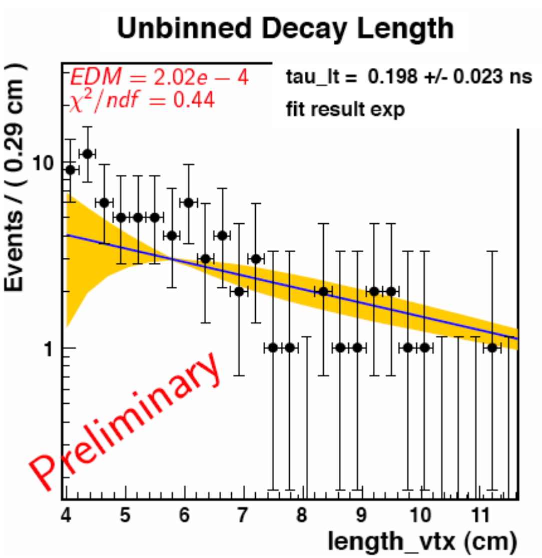
Sho Nagao

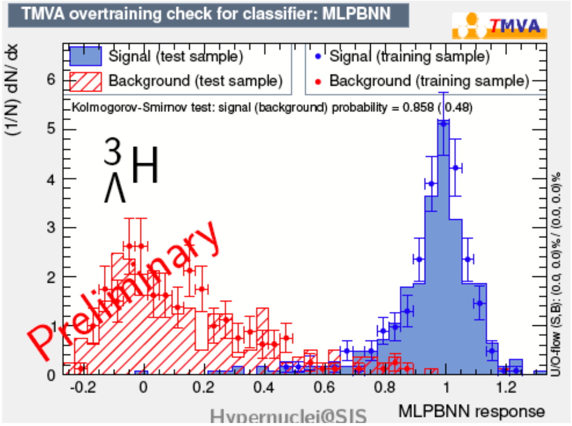
Hypernuclei with Ion Beams: HypHI

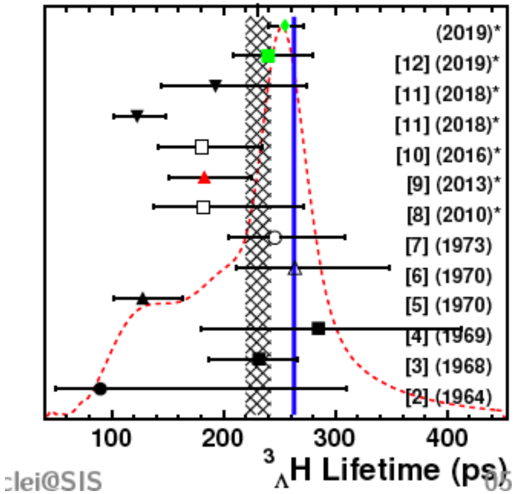
Applying ML discrimination for ${}^{3}_{\Lambda}H$ lifetime :

- Preliminary statistical error: $198\ ^{+25}_{-21}$ ps
- Need more detailed analysis before publishing.

$^{6}Li + {}^{12}C$ at 2*A* GeV



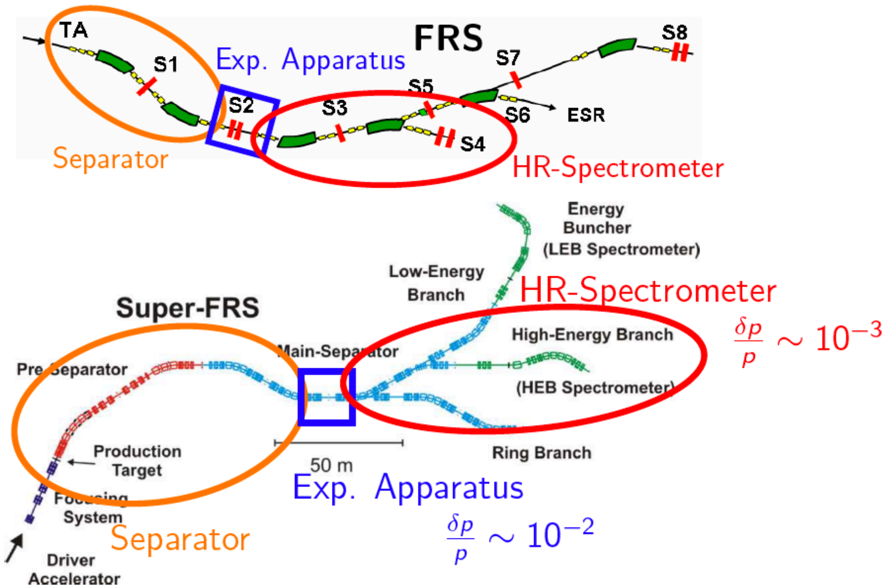


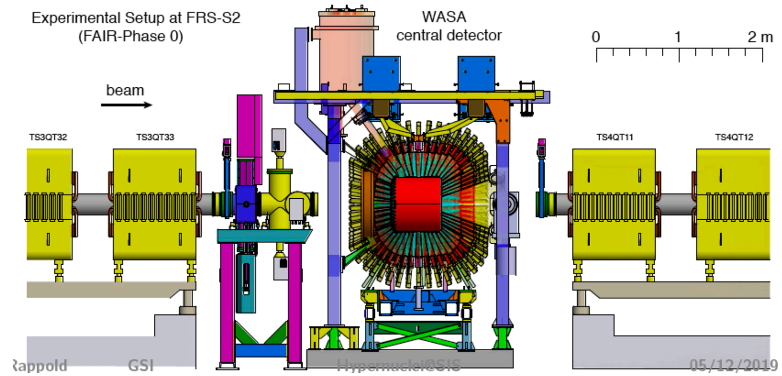


But: latest ALICE result
very close to free Λ lifetime

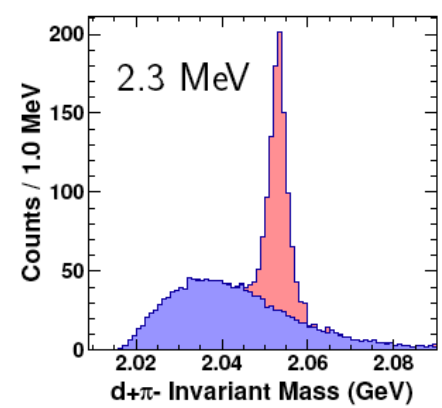
Christophe Rappold

Hypernuclei with Ion Beams: Future Projects





$^{3}_{\Lambda}n \rightarrow d + \pi^-$



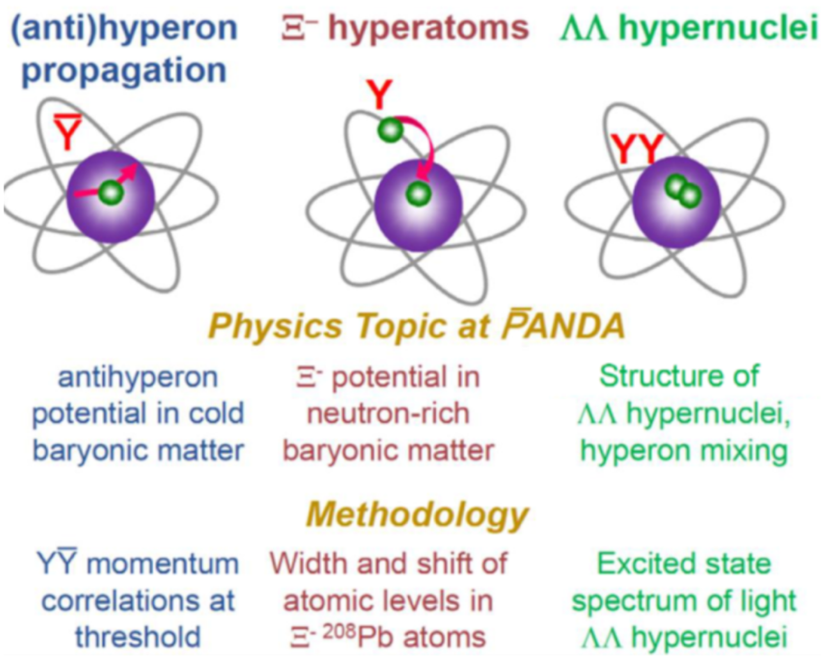
$^{3}_{\Lambda}n \longrightarrow t + \pi^-$

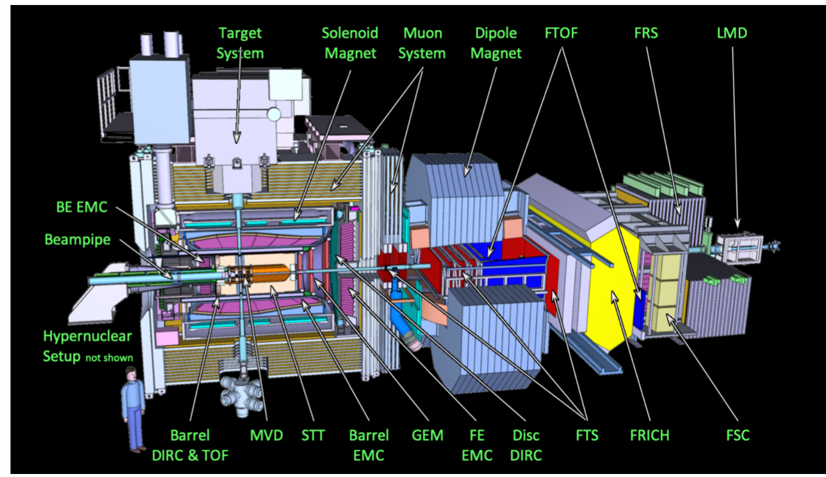
$\longrightarrow d + n + \pi^-$

- in near future at FRS (FAIR Phase 0):
  - $\Rightarrow$ Possibility to confirm or not the existence of $^{3}_{\Lambda}n$ via $d+\pi^-$
  - Improve $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ mass resolution + Lifetime
- in future at SuperFRS:
  - Study proton and neutron-rich hypernuclei possible
    Unknown: $^{8}_{\Lambda}Be$, $^{16}_{\Lambda}C$, $^{9}_{\Lambda}Li$, $^{11}_{\Lambda}Be$, $^{13}_{\Lambda}B$
- Unique opportunity with HIAF - China for exotic hypernuclei & multi-hypernuclear object

Christophe Rappold

Physics with Hyperons at PANDA





Josef Pochodzalla

Antihyperons in Nuclei at PANDA

Motivation: create dense, cold nuclear matter by implanting an anti-baryon

Curiosity

- Antiprotons in (cold) nuclei reasonably well known
  BUT: Nothing is known about antihyperons in nuclei
- (Only) PANDA can do it
- Simple experiment

Antibaryon production important probe for RHIC

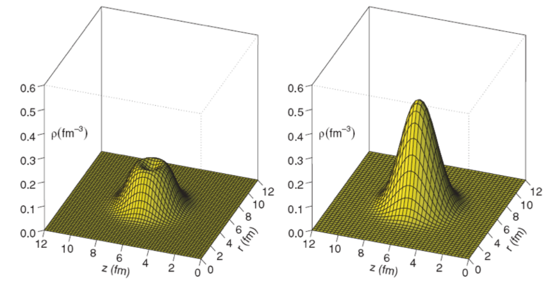
- Transport models important tool
- Antibaryons are usually treated superficially

Probe of short-range multi-body interaction

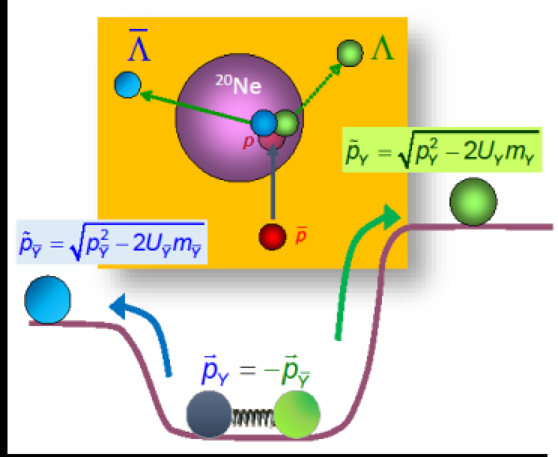
- Complements baryon-antibaryon FSI studies
- Baryonic environment (no pions)
- Possibly neutron rich

➢ The high production rate at PANDA makes this measurement an ideal topic for day-one of PANDA

➢ Extension to other YY pairs possible



nucleon density in the ^{16}O nucleus (left) and in the bound $\bar{p} + {}^{16}$O system (right)
I. N. Mishustin, L. M. Satarov, T. J. Bürvenich, H. Stöcker, and W. Greiner
PHYSICAL REVIEW C **71**, 035201 (2005)



Josef Pochodzalla


Enjoy the dinner!