HADRON2019

Guilin, August 16-21, 2019

Status and future perspectives of hypernuclear physics

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OUTLINE

- Introduction to Strangeness Nuclear Physics
- S=-1 systems
- S=-2 systems
- Summary

STRANGENESS

- Nakano-Nishijima-Gell-Mann Formula: $Q=I_3+(B+S)/2$
    - S is conserved in strong interaction, but not in weak interaction
- Role of Strangeness in Hadron spectroscopy
    - constituent quark mass : $m_u \sim m_d = 330\ \mathrm{MeV}/c^2$, $m_s \sim 500\ \mathrm{MeV}/c^2$
- Role of Strangeness in Dense Matter
    - nuclear matter (S=0) ⇔ hyperonic matter (S=-∞)

nobelprize.org

cerncourier.com

HYPERON PUZZLE

Core of Neutron Star (NS)

||

Test ground of High Density Matter

Nuclear Many-Body Theory

Hypernuclear Data

ΔE=1 MeV

YN Scattering Data

Limited statistics

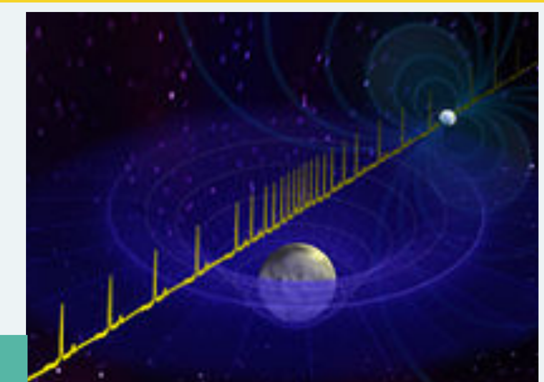
Hyperon Puzzle !

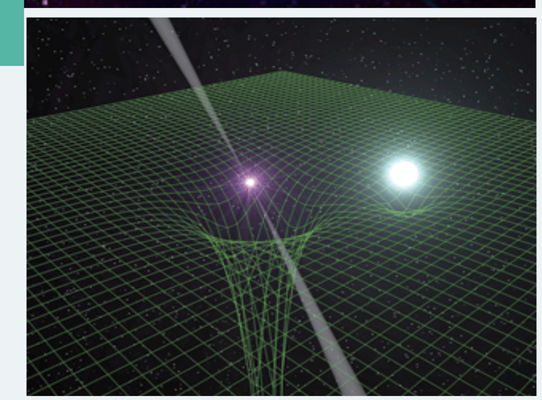
$M_{max}<1.5M_\odot$

?

$M_{max}>2M_\odot$

Observation of $2M_\odot$ NS



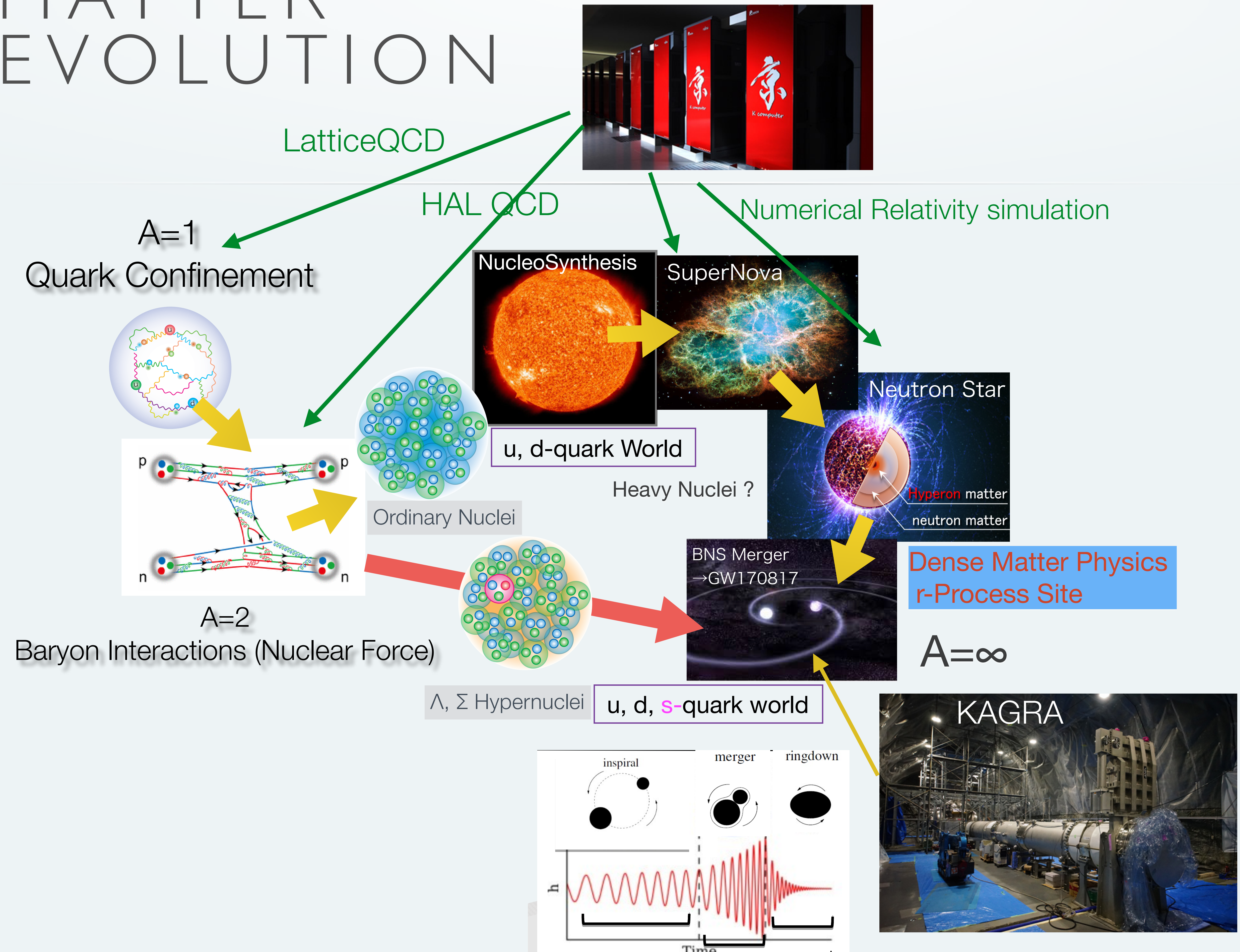


Nature 467 (2010) 1081-83.
Science 340 (2013) 6131.

Hyperons should appear !

Astronomical Observation challenges the Standard Nuclear Physics.

MATTER EVOLUTION



FACILITIES FOR SNP

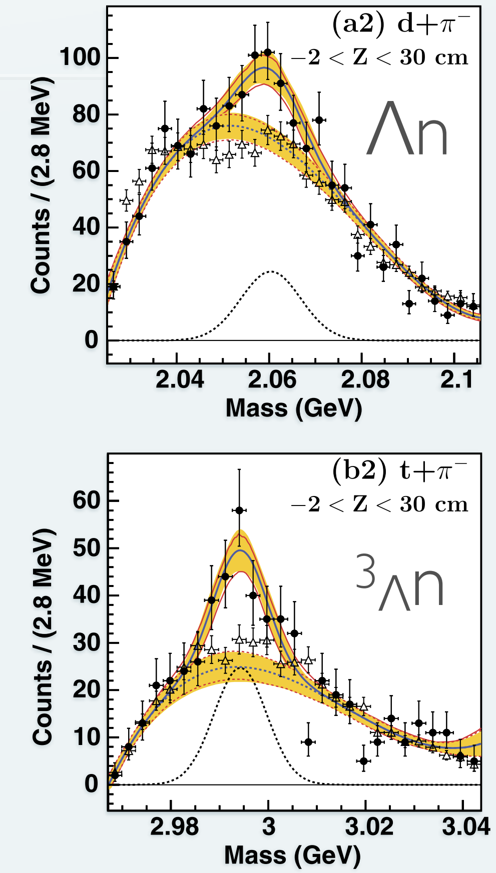
- J-PARC ; highest intensity K^- beams, (K^-,π^-), (K^-, K^+)
- JLab ; high resolution $(e, e'K^+)$ spectroscopy (ΔE=0.1~0.3 MeV)
- Mainz ; $(e, e'K^+)$, decay π spectroscopy (ΔE<0.1 MeV)
- GSI : hyper fragments production, π beam
- RHIC STAR & LHC ALICE : "Femtoscopy", Anti-hypernuclei, Lifetime for hyper fragments
- FAIR ; p-bar

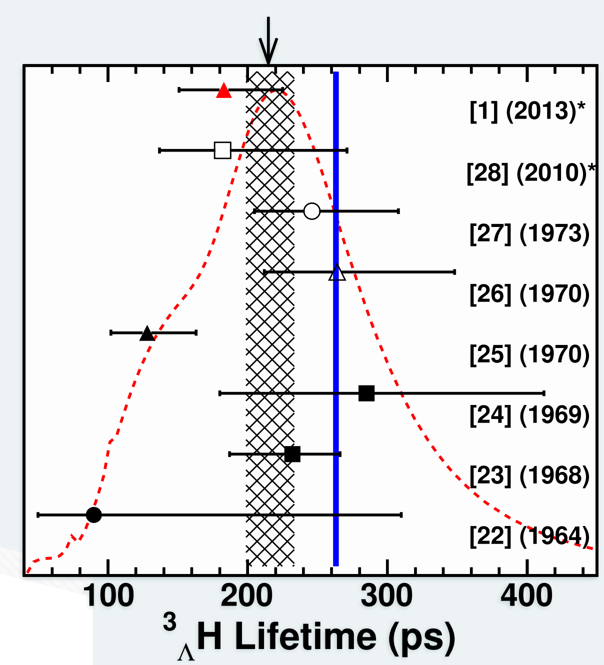
S = -1 SYSTEMS

WE THOUGHT WE'VE ESTABLISHED …

- Λ-hypernuclei : $^{3}_{\Lambda}H$, …, $^{208}_{\Lambda}Pb$
  - U_{Λ}= -29±1 MeV (attractive)
- Only one $^{4}_{\Sigma}He$
  - U_{Σ}> +20-30 MeV (repulsive)
- $^{6}_{\Lambda\Lambda}He$, $\Delta B_{\Lambda\Lambda}$=0.7 MeV (weakly attractive)

- Λn, $^{3}_{\Lambda}n$; bound ?
- Short Lifetime of $^{3}_{\Lambda}H$

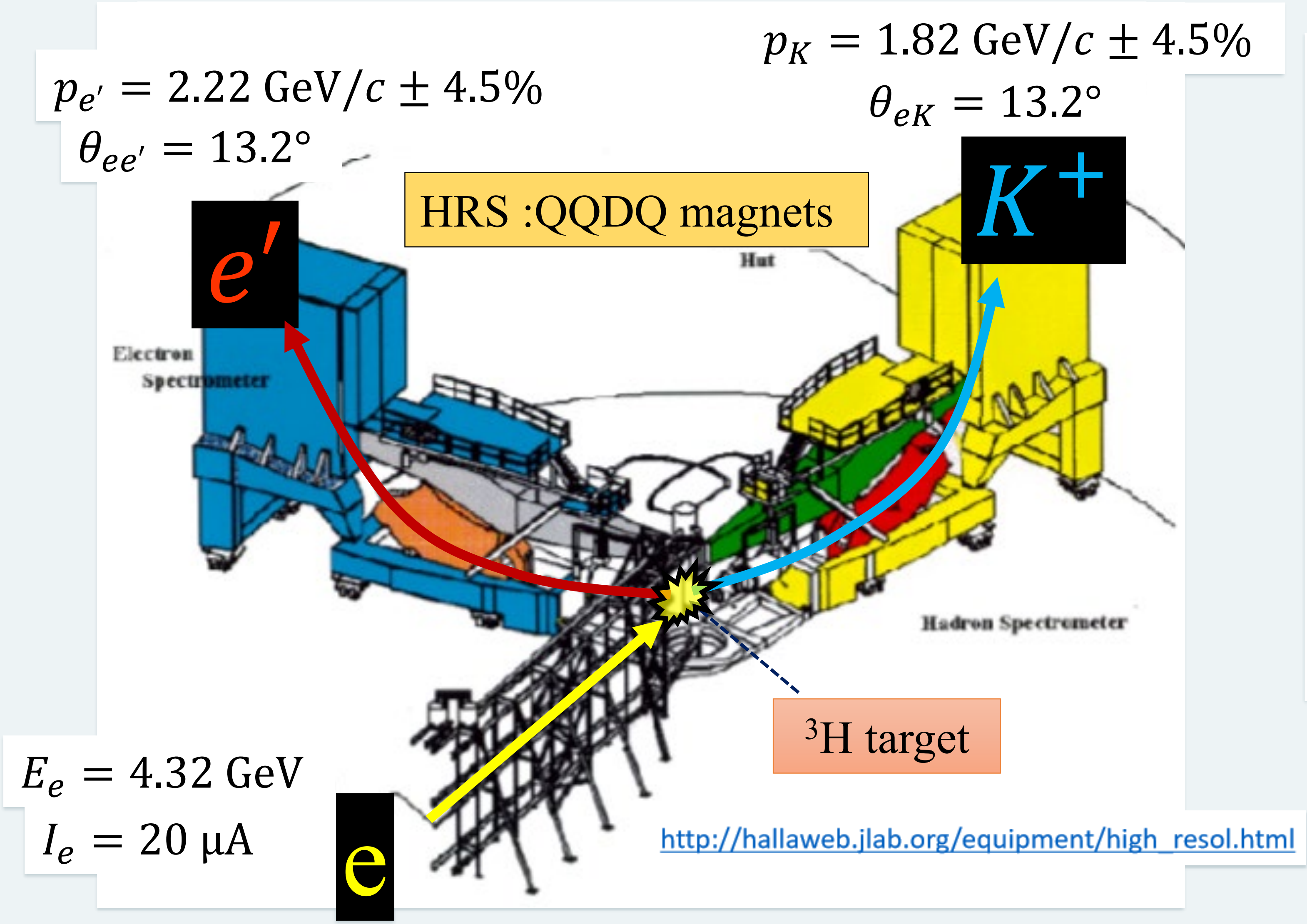


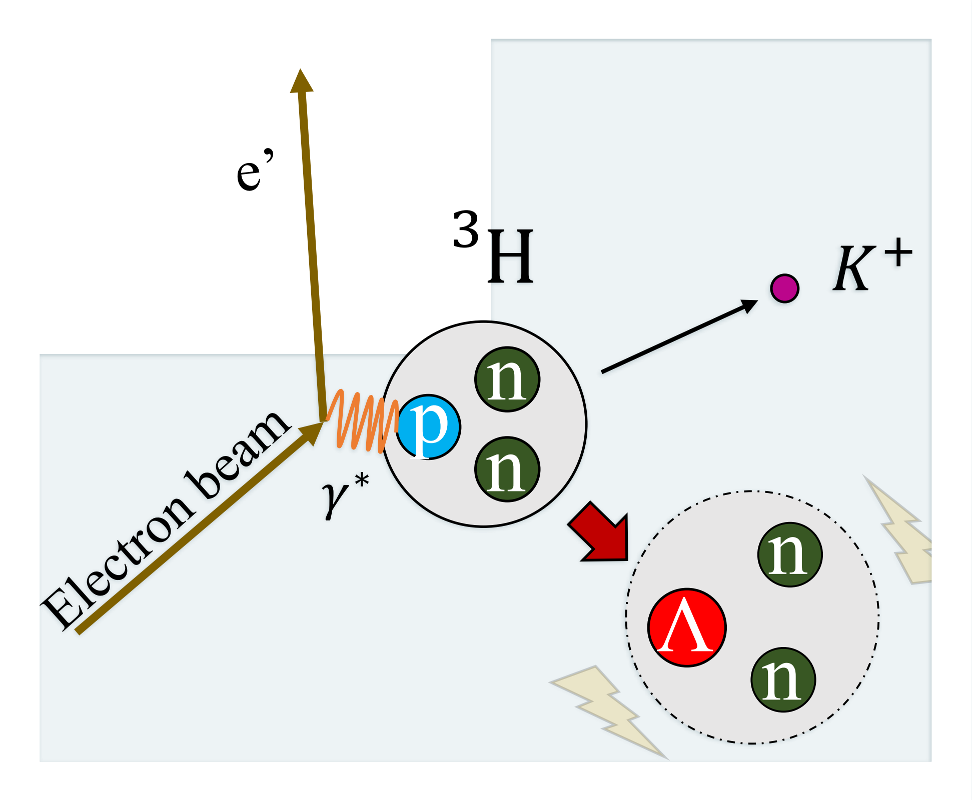


C.Rappold et al., PRC 88 (2013) 041001R

SEARCH FOR $^{3}{}_{\Lambda}n$

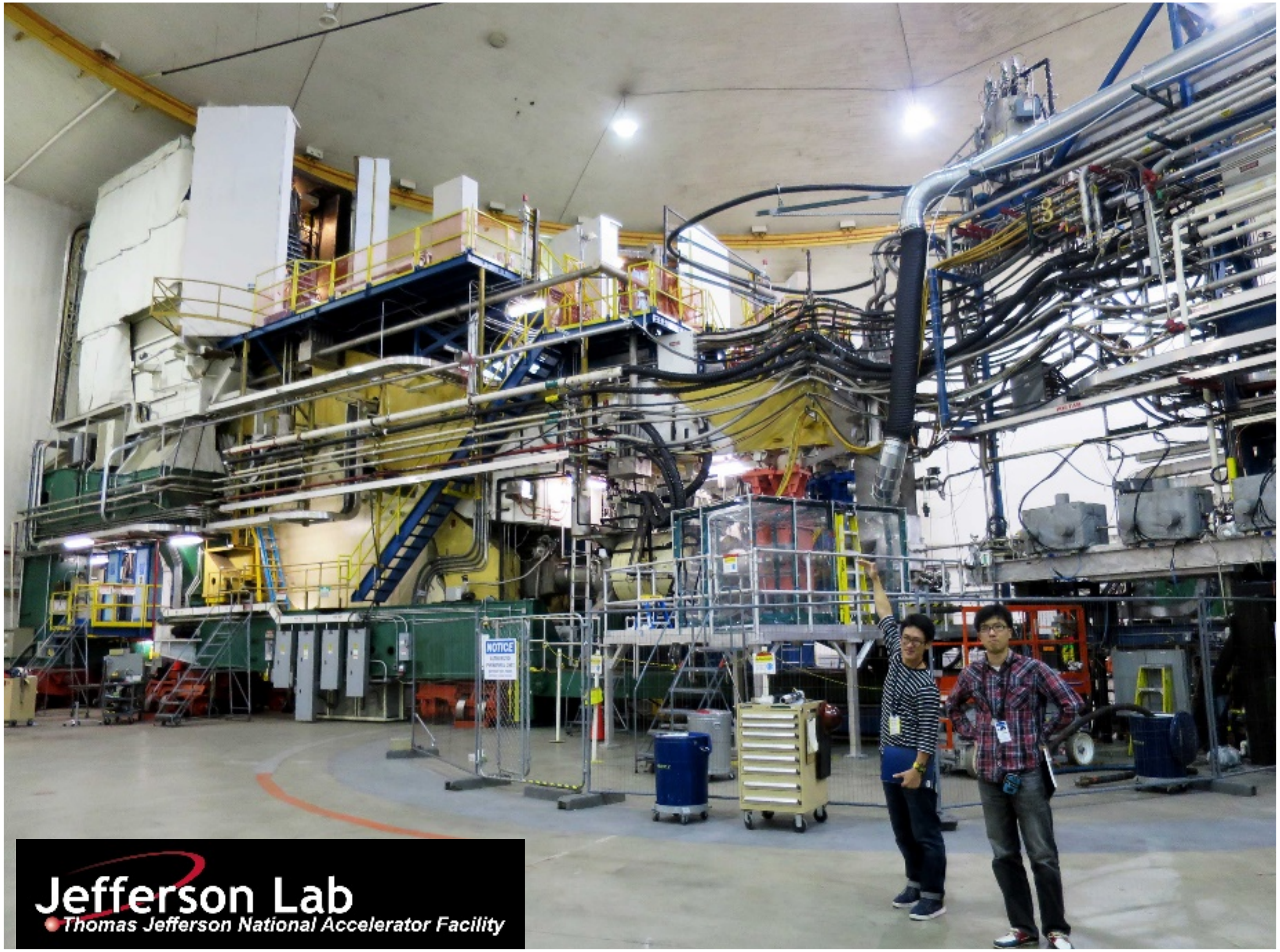
JLab E12-17-003





Liguang Tang's Talk

Data Taking : Oct 30 - Nov 25, 2018.



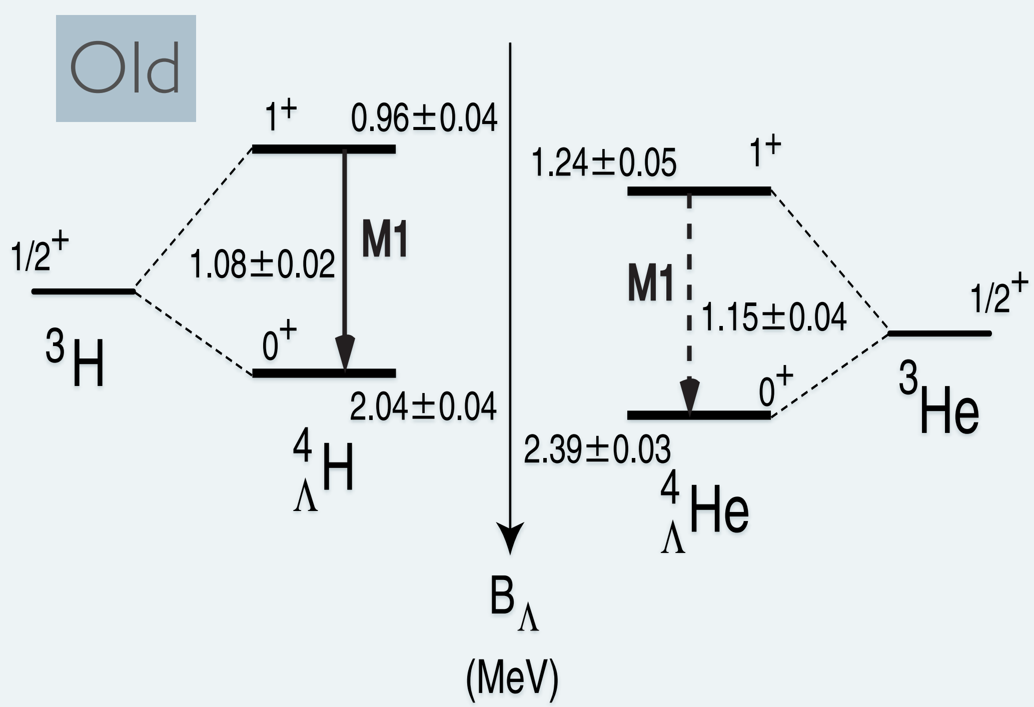
CHARGE-SYMMETRY BREAKING IN 4-BODY SYSTEMS

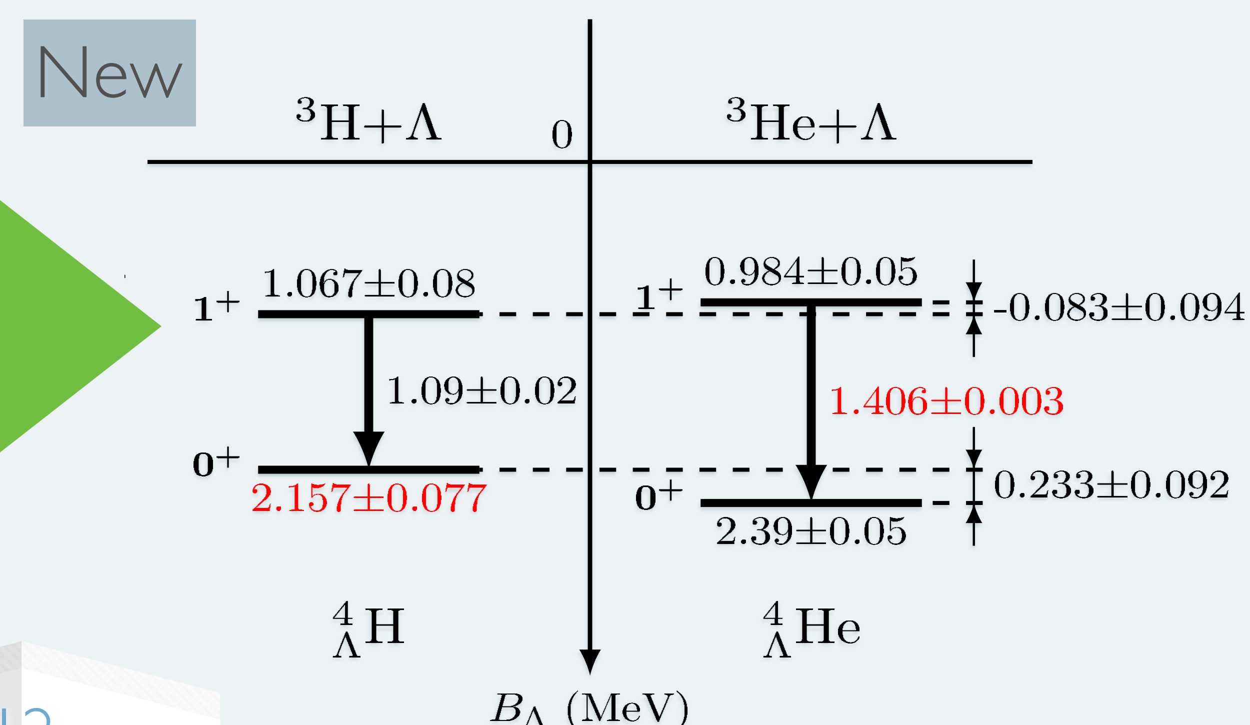
- ${}^{4}_{\Lambda}$He - ${}^{4}_{\Lambda}$H (Update)
  - New measurement of B(${}^{4}_{\Lambda}$H)=2.157±0.077 MeV by MAMI A1.

    PRL 114 (2015) 232501.

    NPA 954 (2016) 149.
  - New measurement of ΔB(${}^{4}_{\Lambda}$He) at J-PARC.

    PRL 115 (2015) 222501.
    - Eγ(M1)=1.406±0.002±0.002 MeV

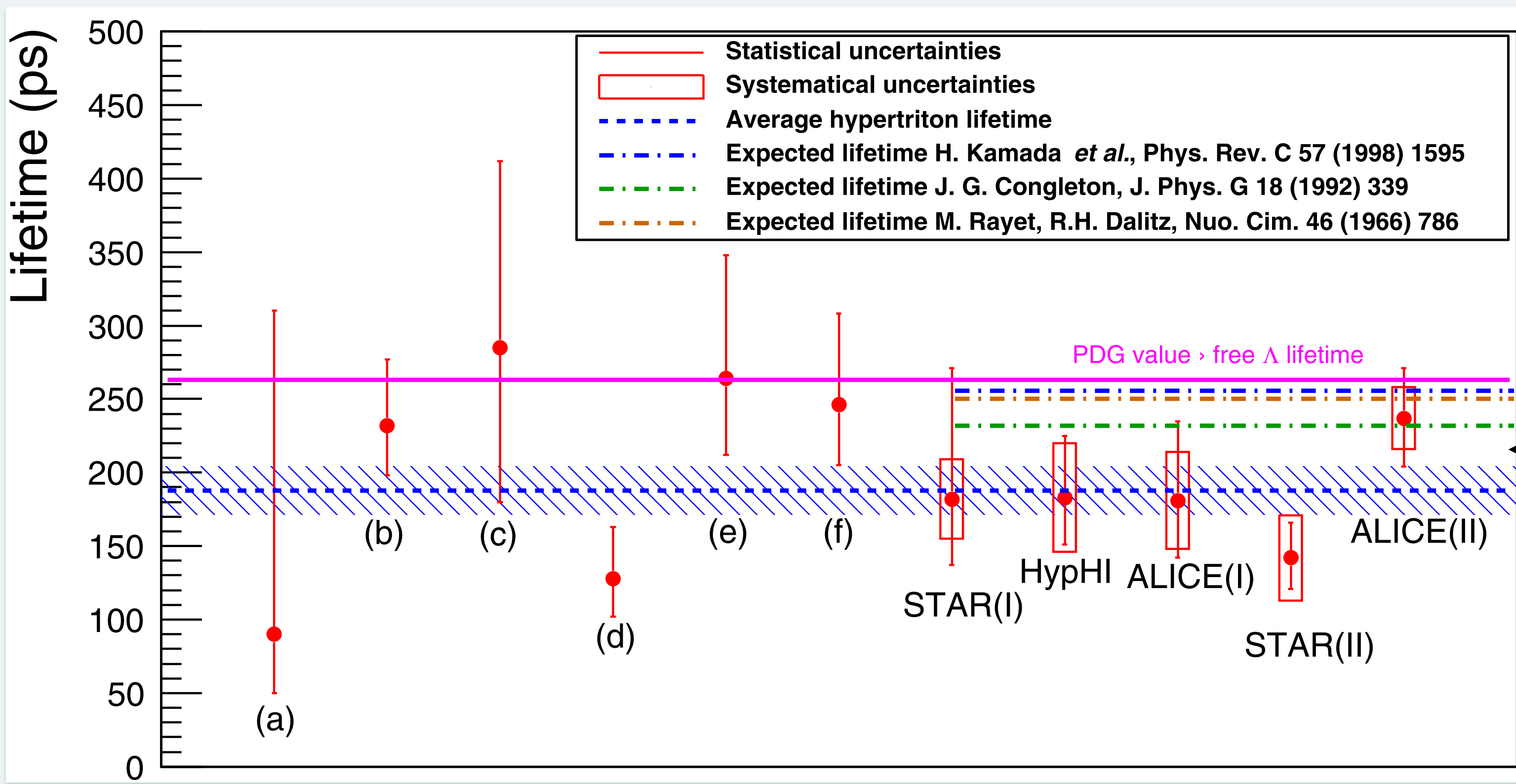




$^{3}{}_{\Lambda}$H LIFETIME

Loosely-bound p-n-Λ, B_{Λ}~0.1 MeV

$\tau(^{3}{}_{\Lambda}H) \sim \tau_{\Lambda}$?



A. Gal, H. Garcilazo PLB 791 (2019) 48.

Fig. 1. Measured $^{3}_{\Lambda}$H lifetime values in chronological order, with (a)–(f) from emulsion and bubble-chamber measurements [3–8], and from recent relativistic heavy ion experiments: STAR(I) [9], HypHI [10], ALICE(I) [11], STAR(II) [12], ALICE(II) [13], see text. We thank Benjamin Dönigus for providing this figure [14].

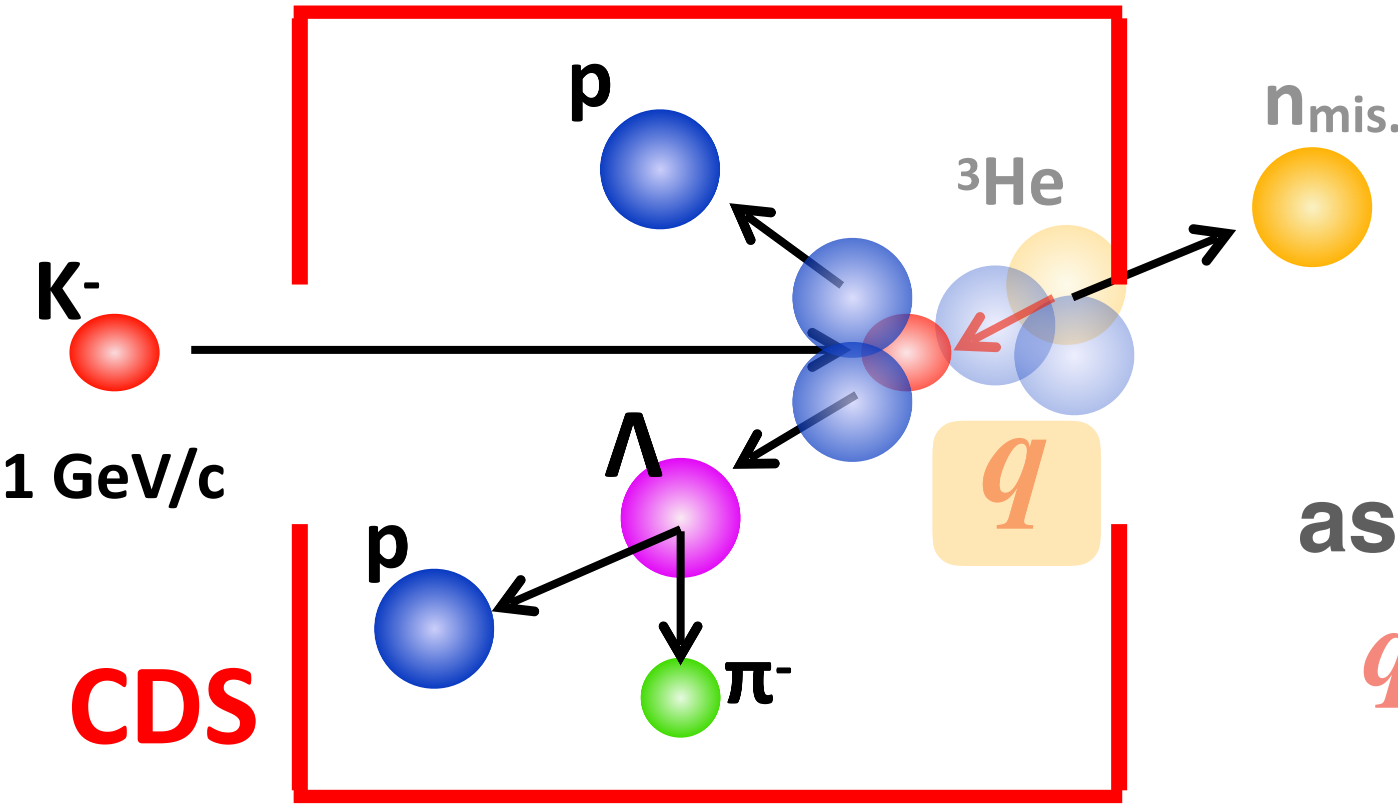
Pion FSI (attractive) shorten the life time $(0.81 \pm 0.02)\tau_{\Lambda}$

Exclusive: Λ p n

simplest final state

3 baryon w/ strangeness

E15



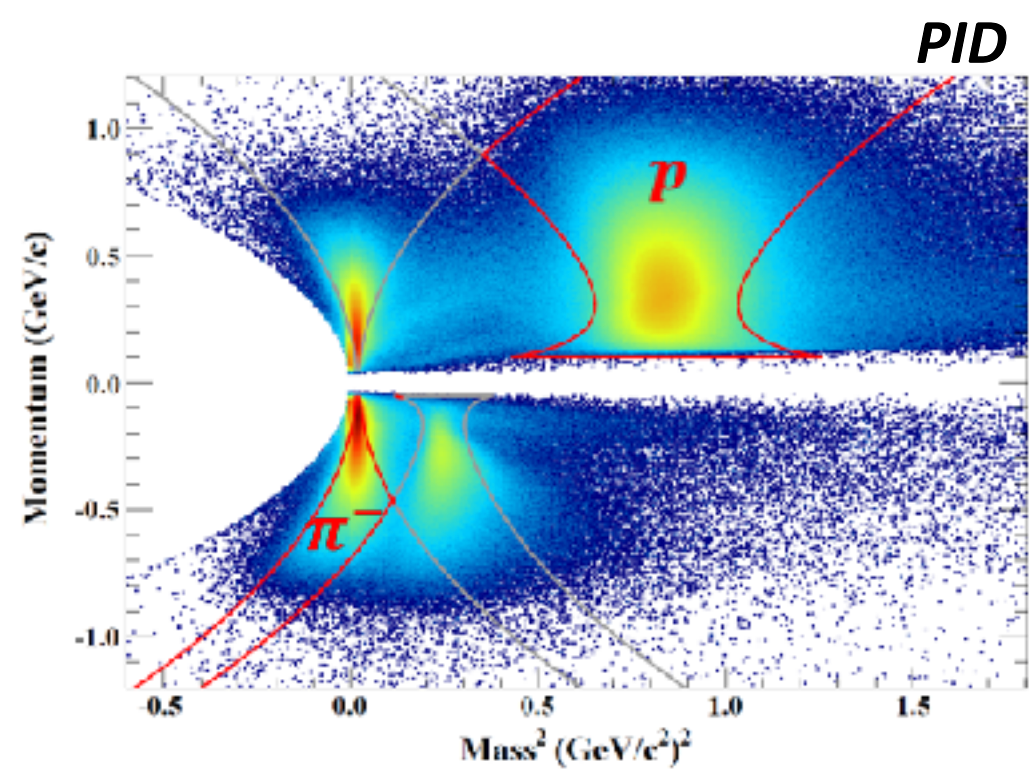
assuming KN→KN

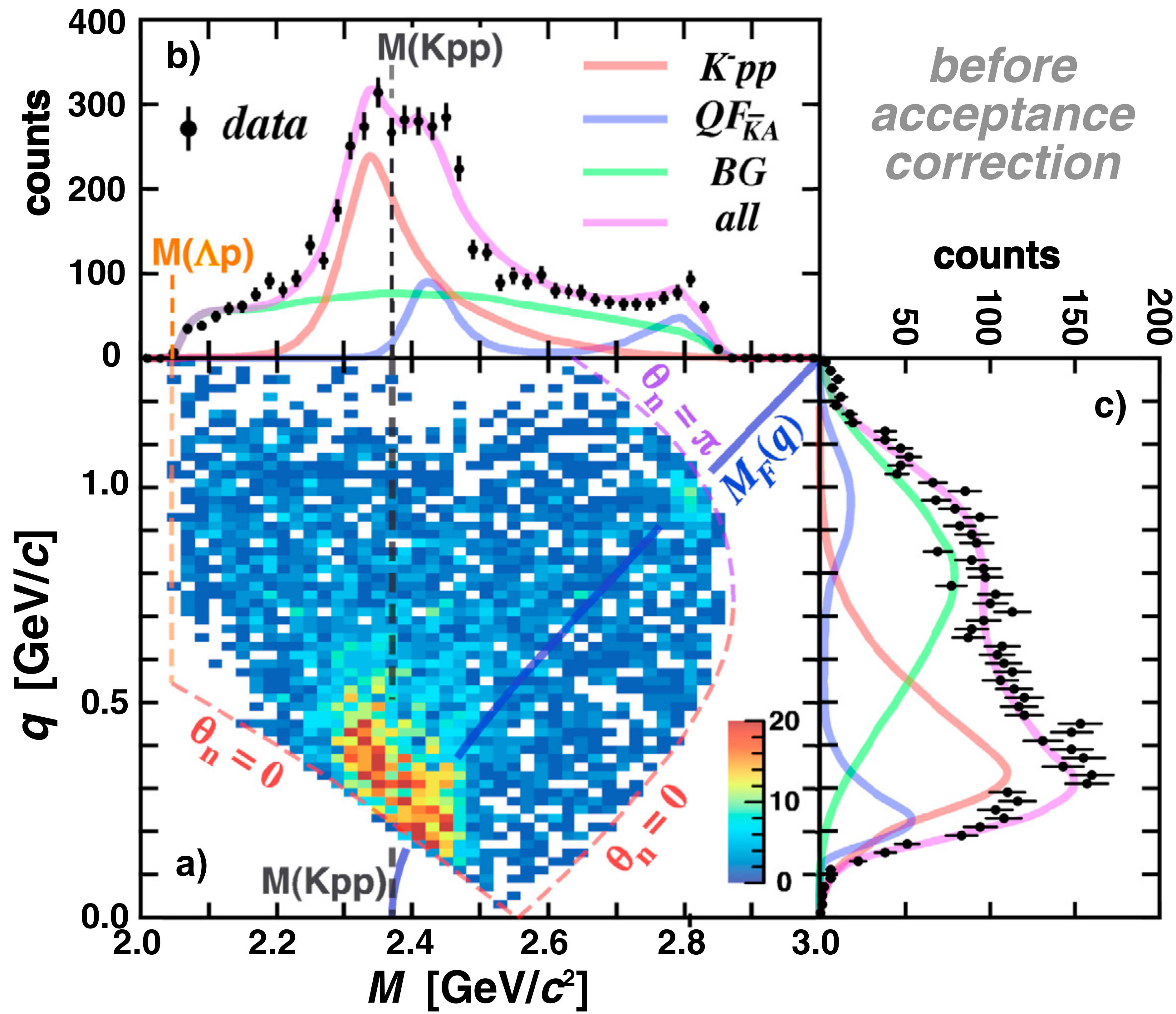
q: virtual kaon momentum

$$K^- + {}^3He \to (\Lambda + p) + n$$

$M_{\Lambda p}$

Λpn final state w/ 4-momentum conservation



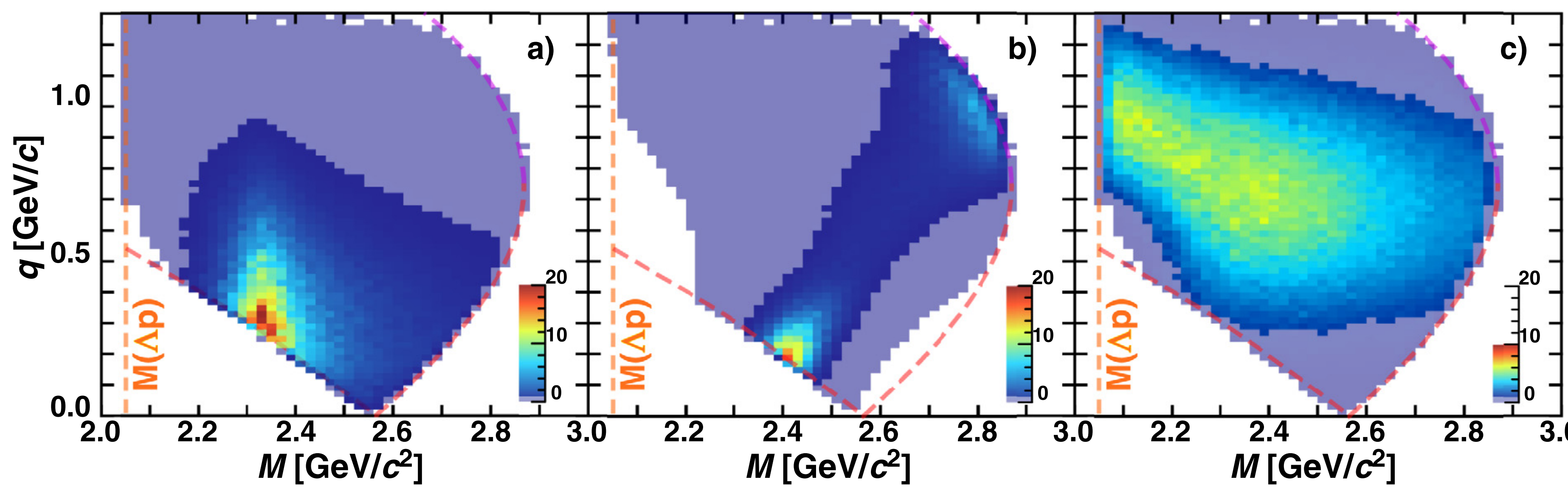


before acceptance correction

CAPLINE HEADER ELEMENT

THREE PROCESSES CONSIDERED

Simulation



K^-pp :

$K^-\,{}^3He \to (K^-pp)+n$,

$(K^-pp) \to \Lambda p$

QF_{KA}:

$K^-\text{“}n\text{”} \to n\text{“}K\text{”}$,

$\text{“}K\text{”}+\text{“}pp\text{”} \to \Lambda p$

$3N_{abs}$:

$K^-\,{}^3He \to \Lambda pn$

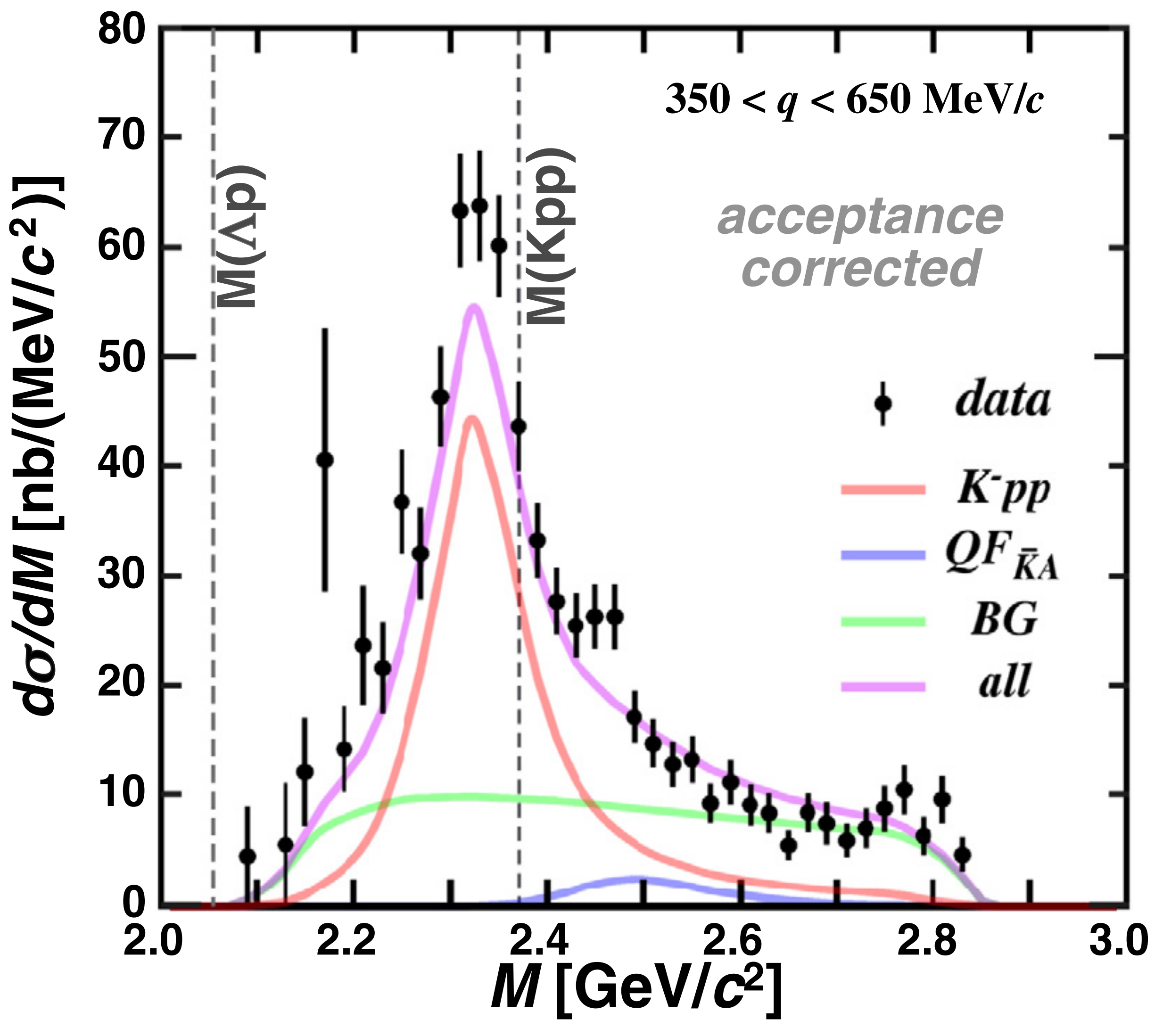
$$f_{\{Kpp\}} = \frac{C_{Kpp}\,(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2}\exp\left(-\left(\frac{q}{Q_{Kpp}}\right)^2\right)$$

$$\mathscr{E}(M,q)\times\rho_3(M,q)$$

Fit result for K⁻pp

q: 350 ~ 650 MeV/c

- B_{Kpp}=46±3+3/-6 MeV
- Γ_{Kpp}=115±7+10/-20 MeV
- Q_{Kpp}=381±14+57/-0 MeV
- σ•Br=11.8±0.4+0.2/-1.7 μb

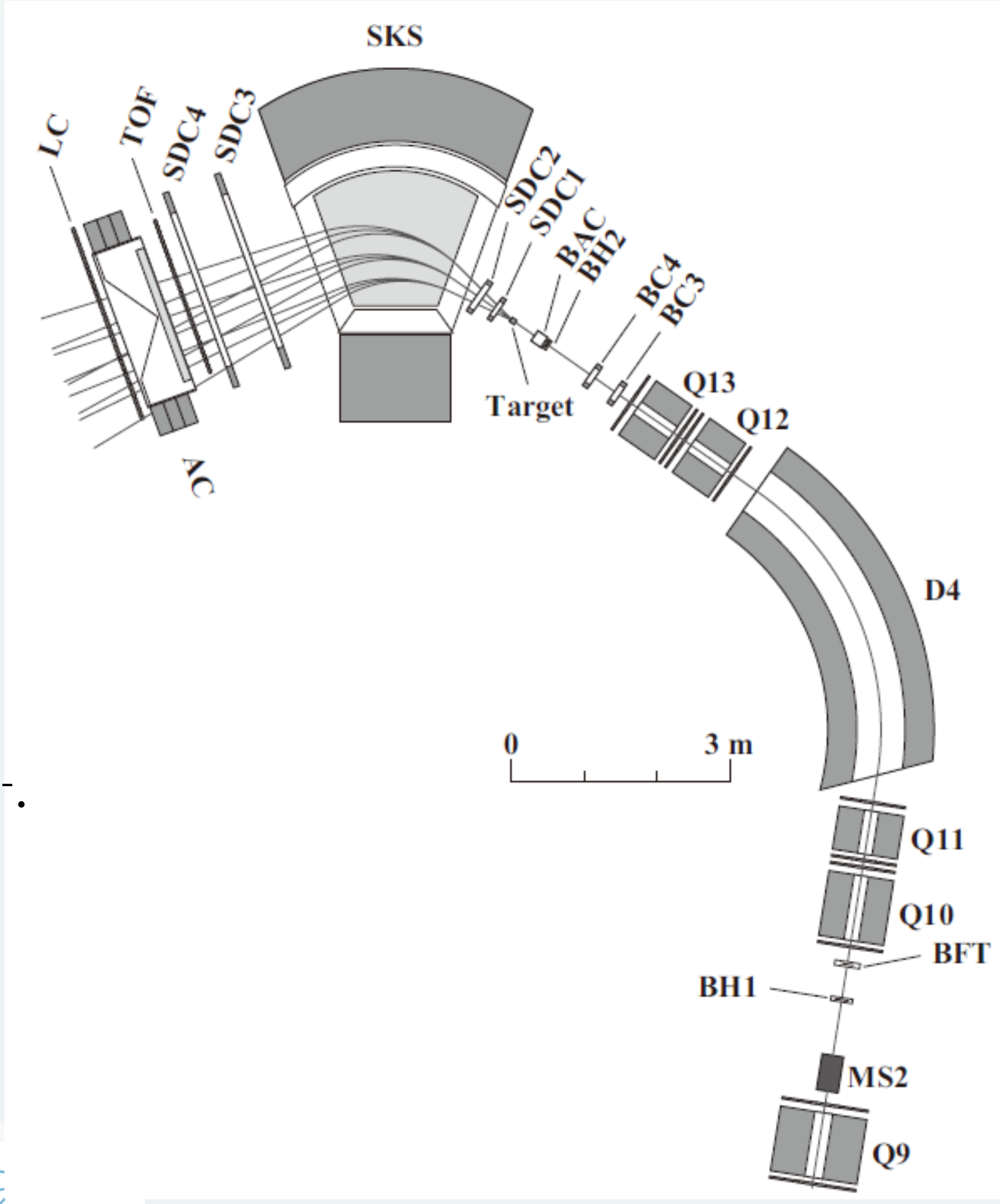


S=-2 SYSTEMS

J-PARC E05

Search for a Ξ-hypernucleus

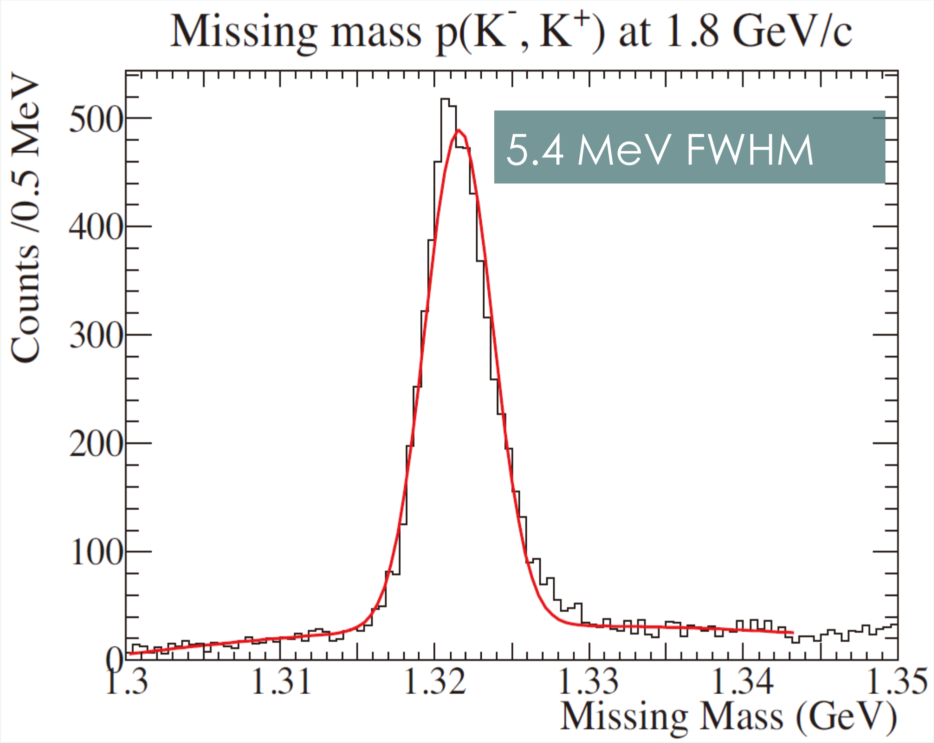
- $^{12}C(K^-,K^+)$ at 1.8 GeV/c
  - 26-Oct-2015 ~ 19-Nov-2015
  - K^- intensity : 6×10^5 K^- / spill
  - (5.52 seconds cycle) @ 39 kW
  - 9.36 g/cm^2 ^{nat}C; 10 days
  - 9.54 g/cm^2 CH_2; 2 days
- E05 Setup
  - $\Delta\Omega$ = 110 msr, $\Delta p/p_{SKS} = 3 \times 10^{-3}$.
  - ΔE = 5.4 MeV(FWHM) for $K^-p \rightarrow K^+\Xi^-$.
  - Best performance for the (K^-,K^+) reaction

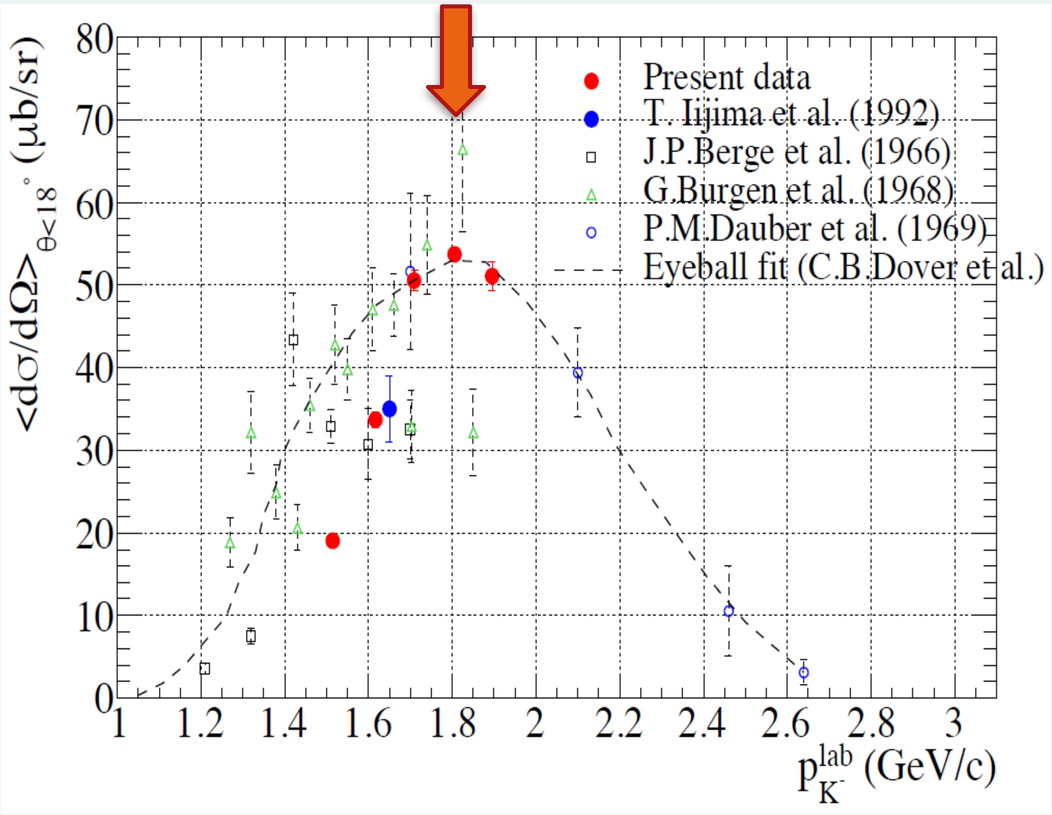


$P(K^-, K^+)\Xi^-$

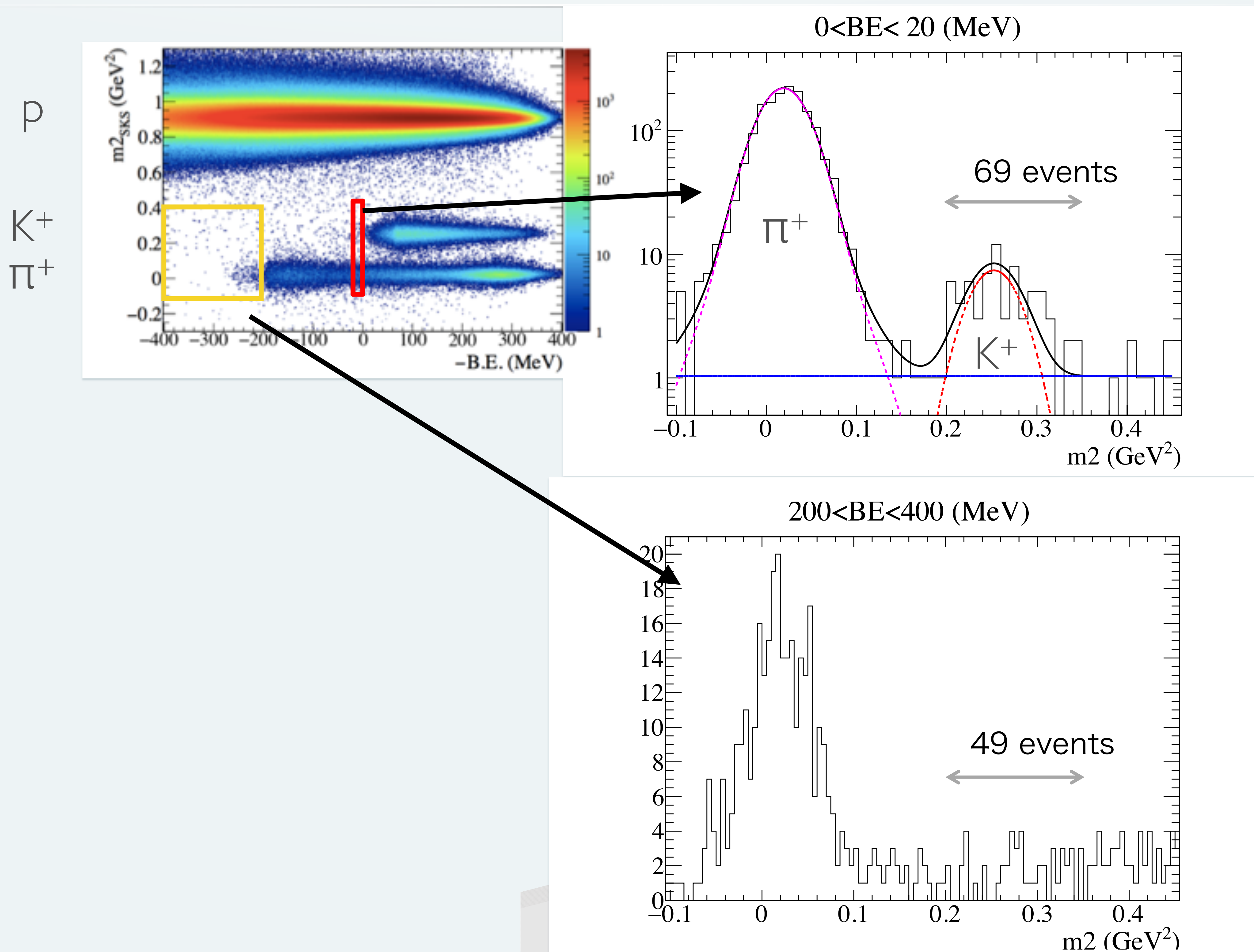
CH2 target

Max. at 1.8 GeV/c

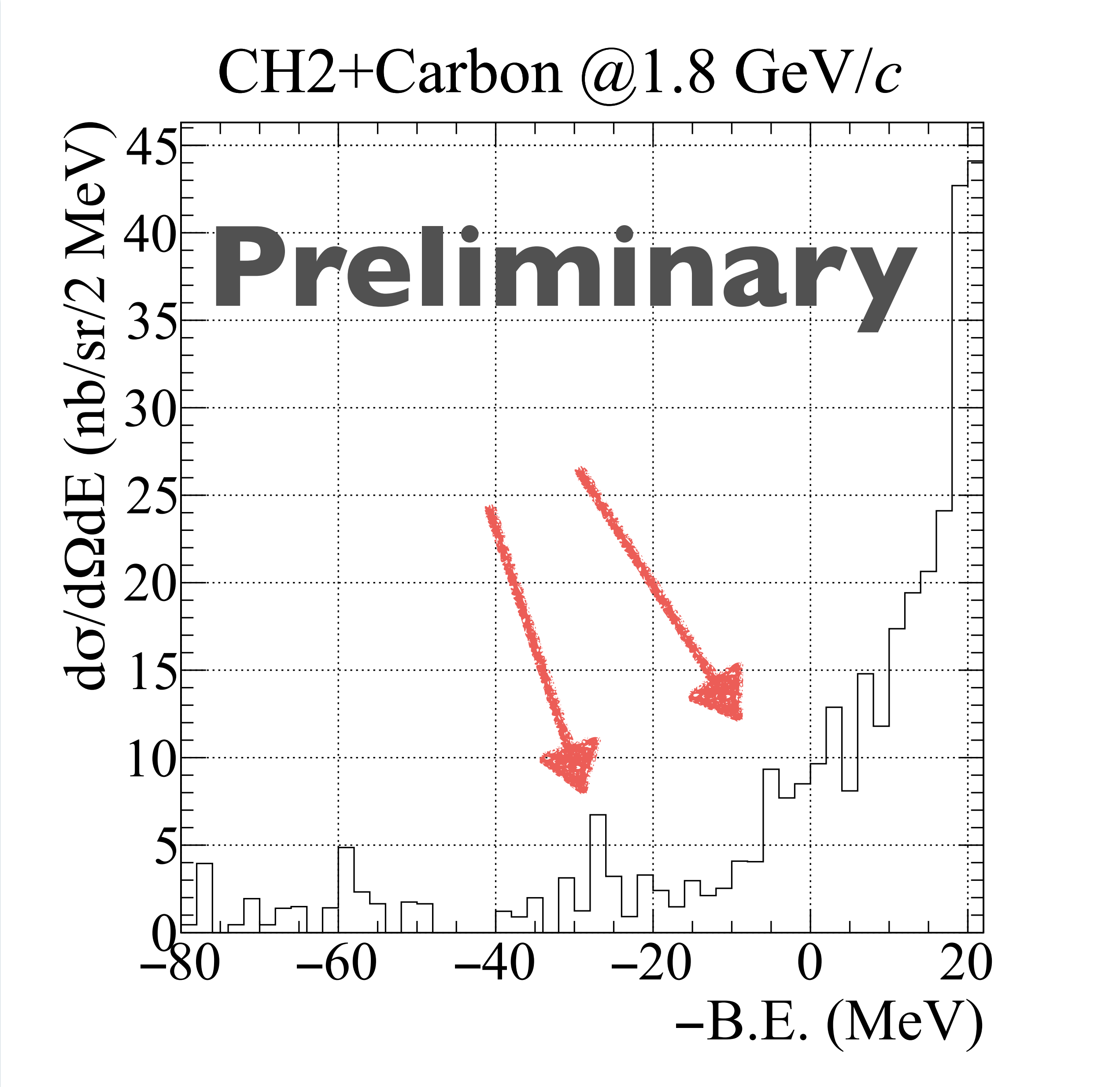




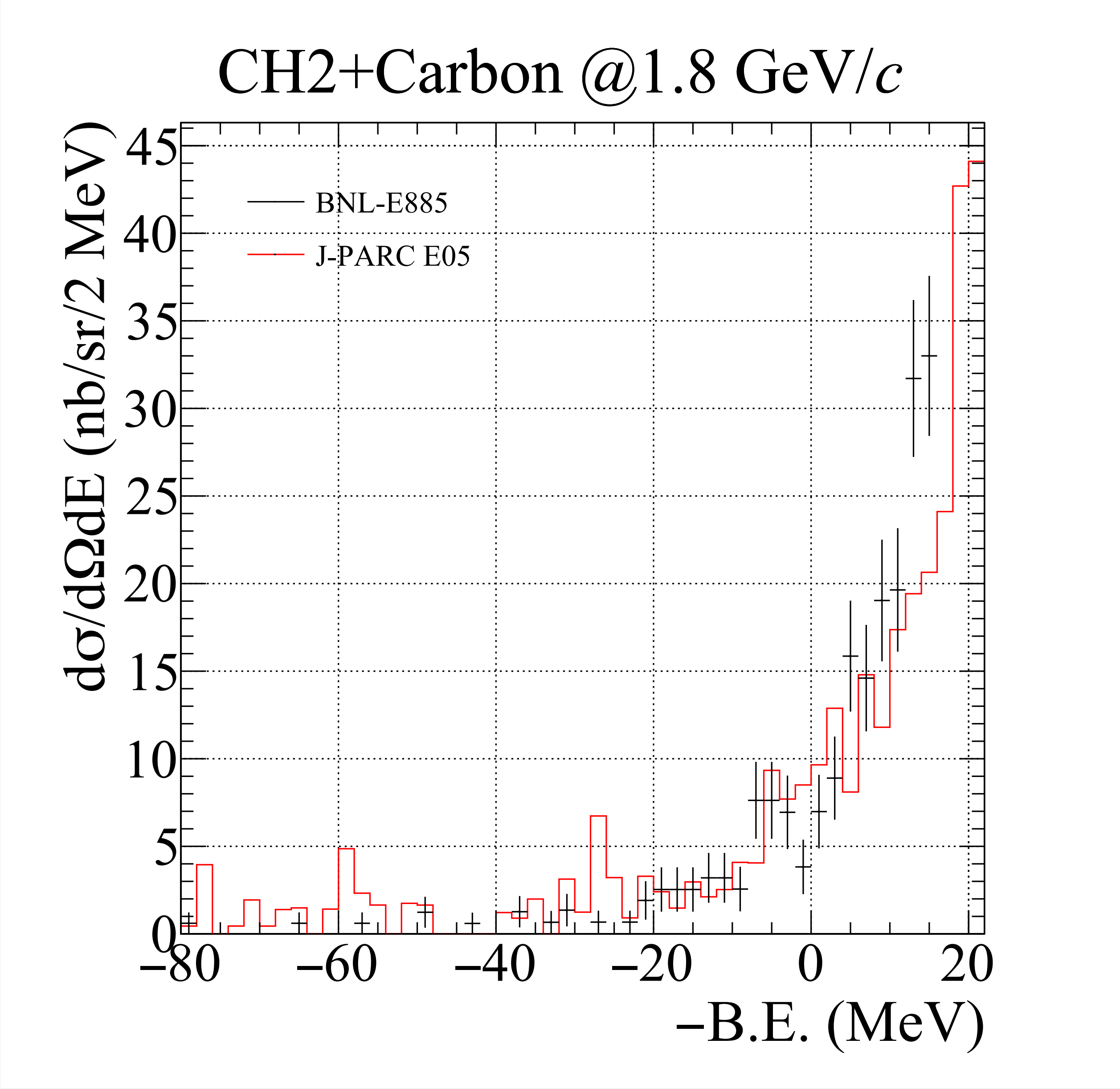
PID: BOUND REGION



Θ<14 deg.



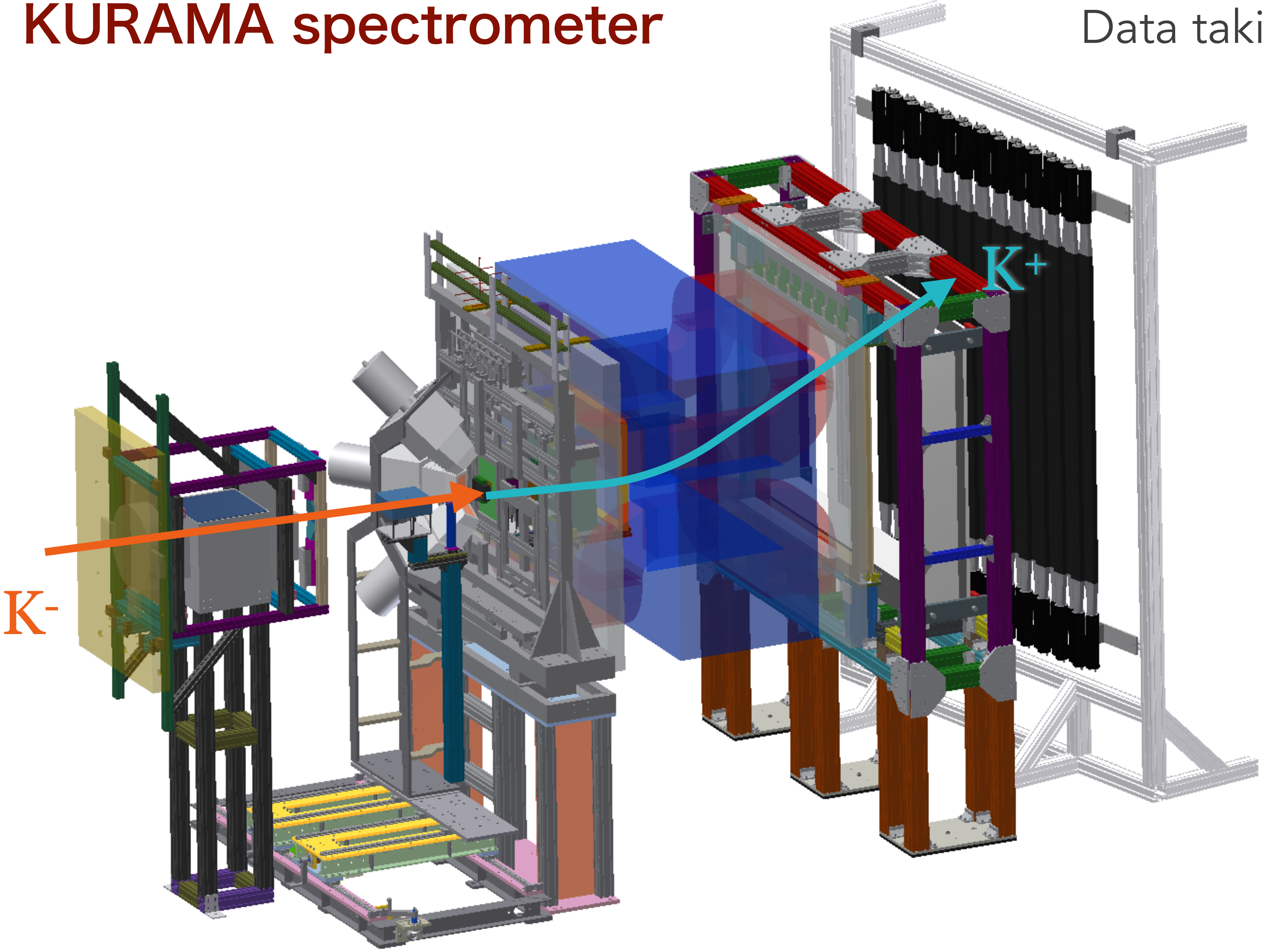
BNL E885 vs. E05

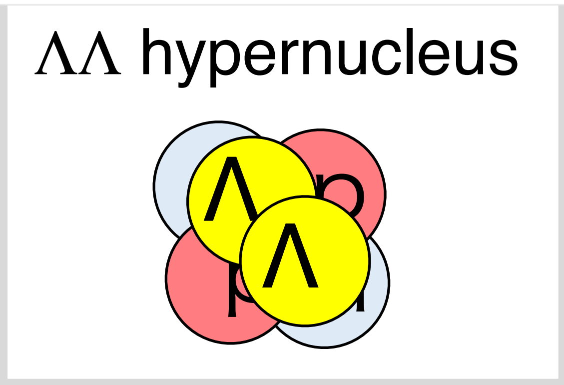


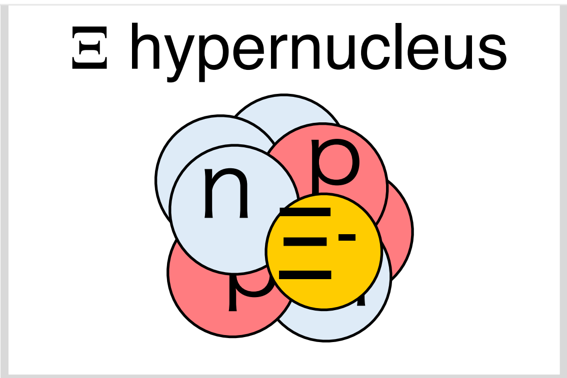
J-PARC E07 Systematic study of double strangeness nuclei with Hybrid emulsion method

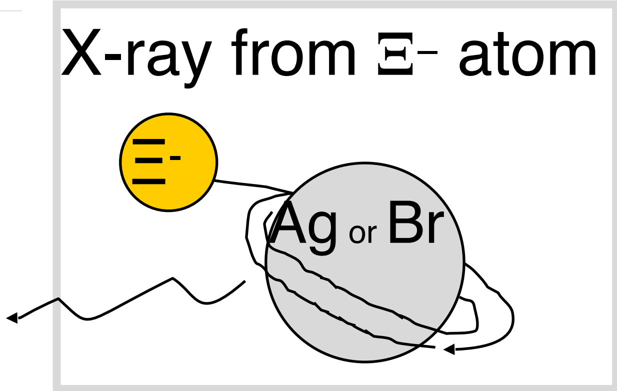
KURAMA spectrometer

Data taking in 2016 and 2017







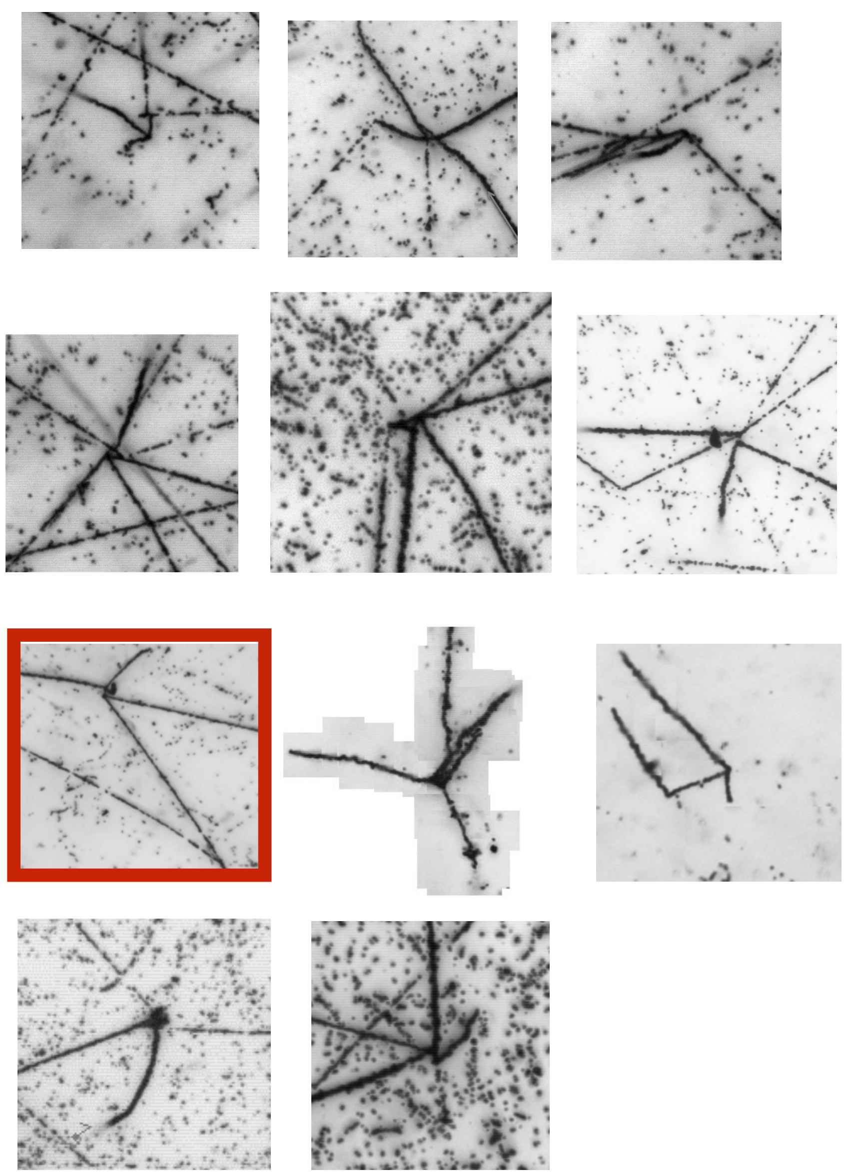


2019 May

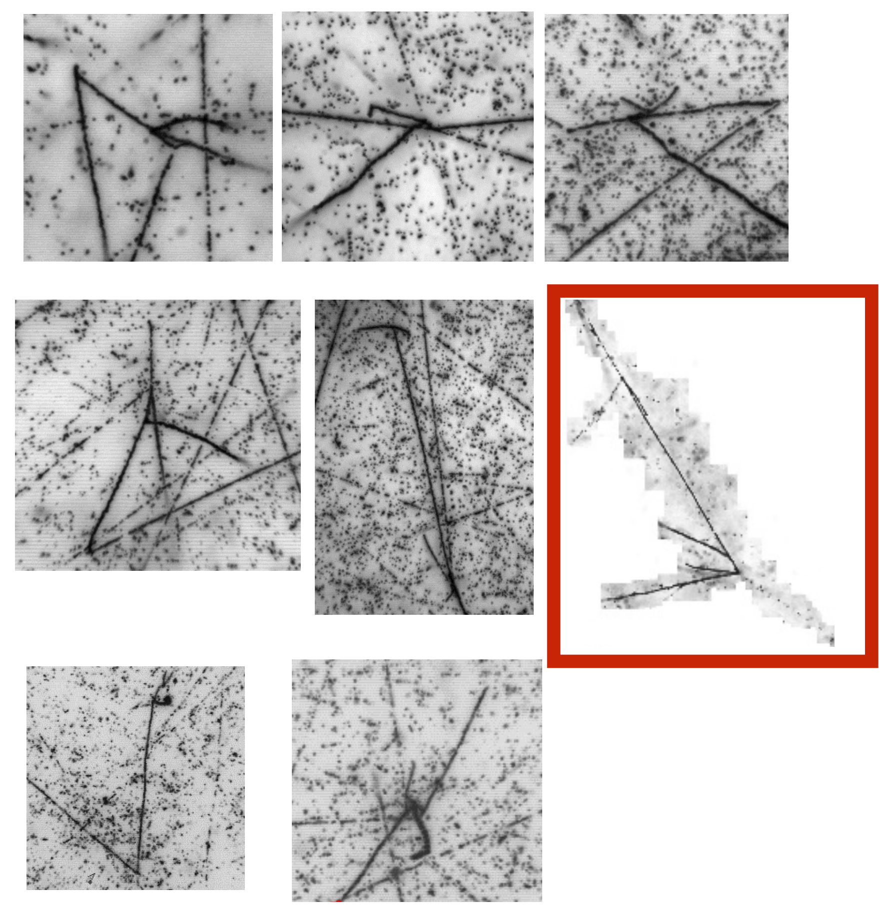
So far, 70% of emulsion sheets has been scanned at least once.

	KEK-PS E373	E07 (current)	
Ξ^- stop with nuclear fragment	430	1.6k	(1.6k/430 = 3.8)
S=-2 system	9	26	

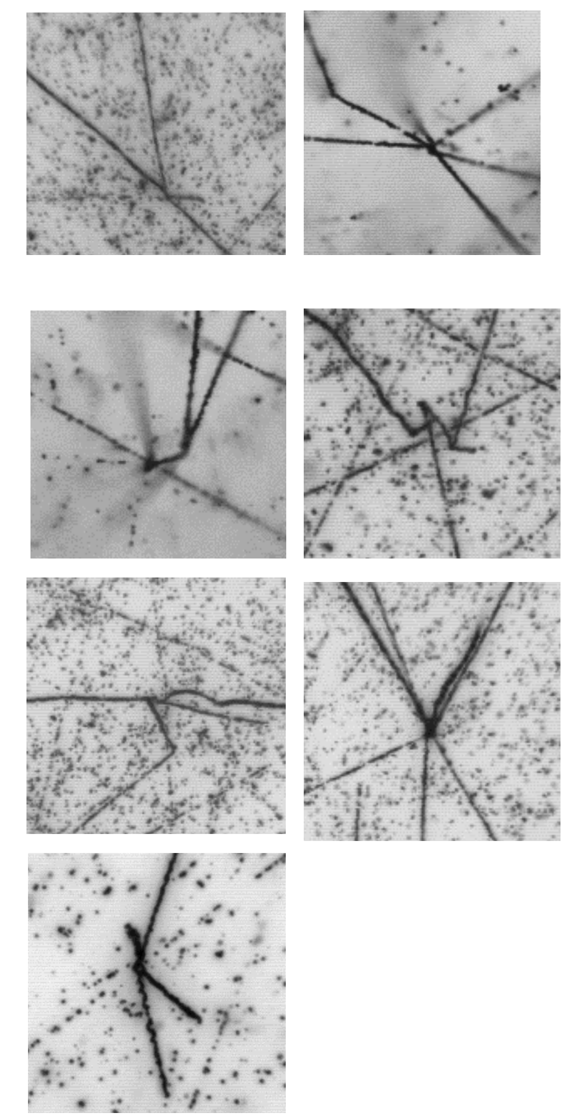
11 double Lambda events



8 twin events

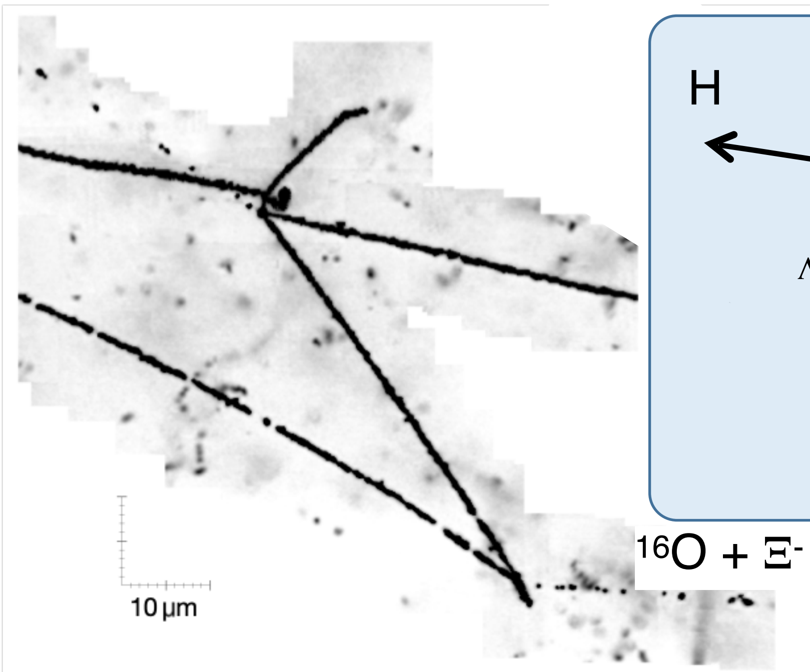


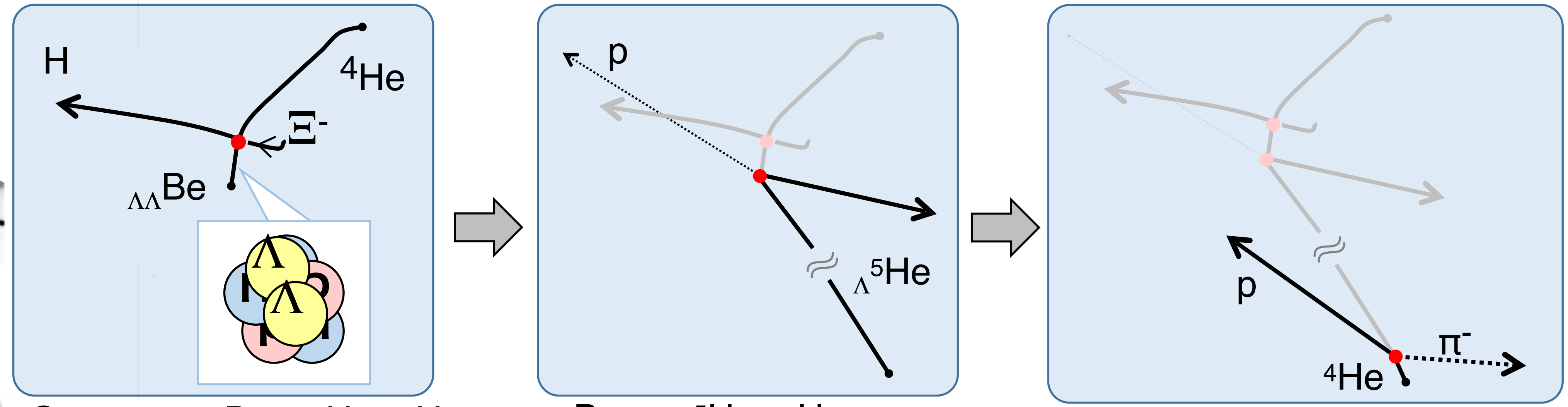
7 others



Double-Λ Hypernucleus MINO event

H. Ekawa et al.,Prog. Theor. Exp. Phys. 2019, 021D02



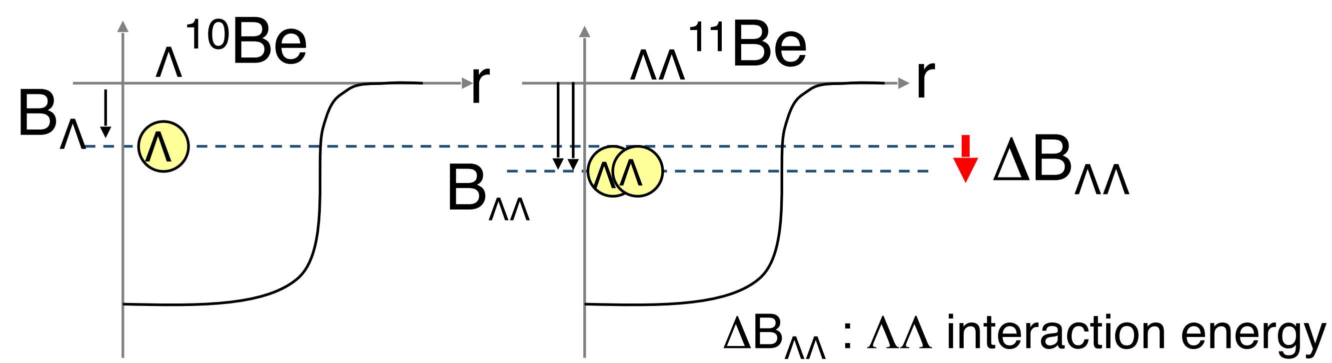


$^{16}O + \Xi^- \rightarrow {}_{\Lambda\Lambda}Be + {}^4He + H$

${}_{\Lambda\Lambda}Be \rightarrow {}_{\Lambda}{}^5He + H + p + xn$

${}_{\Lambda}{}^5He \rightarrow {}^4He + p + \pi^-$

$$^{16}\mathrm{O} + \Xi^- \rightarrow ({}^{10}_{\Lambda\Lambda}\mathrm{Be},\ {}^{11}_{\Lambda\Lambda}\mathrm{Be},\ {}^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_\Lambda\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$



$\Delta B_{\Lambda\Lambda}$: $\Lambda\Lambda$ interaction energy

$M(^9Be) + M_\Lambda - B_\Lambda$

$M(^9Be) + 2M_\Lambda - B_{\Lambda\Lambda}$

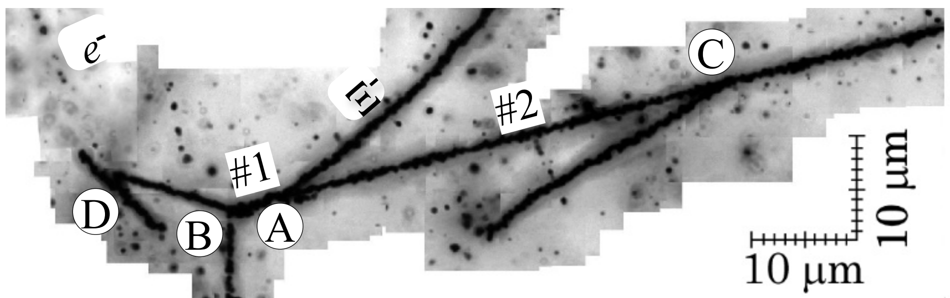
Possible interpretations	$B_{\Lambda\Lambda}$ [MeV].	$\Delta B_{\Lambda\Lambda}$ [MeV]	kinematic fitting χ^2	p-value[%]
$\Xi^- + {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{10}Be + {}^4He + t$	15.05 +- 0.11	1.63 +- 0.14	11.5	0.9
$\Xi^- + {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{11}Be + {}^4He + d$	19.07 +- 0.11	1.87 +- 0.37	7.3	6.4
$\Xi^- + {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{12}Be^* + {}^4He + p$	13.68 +- 0.11 + E_{ex}	-2.7+- 1.0 + E_{ex}	11.3	1.0

${}_{\Lambda\Lambda}{}^{11}Be$ is most probable by kinematic fittng χ^2 (DOF=3)

Deeply bound Ξ^--^{14}N systems

0.174 MeV:3D atomic state
Prog. Theor. Phys. 105 (2001) 627.

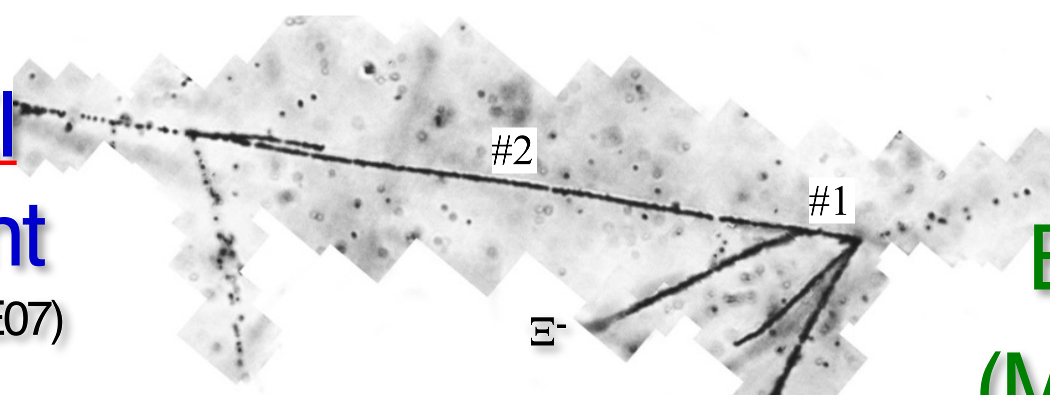
KISO event
(KEK-E373)



E.Hiyama, K. Nakazawa, Annu. Rev. Nucl. Part. Sci. 2018.68.131

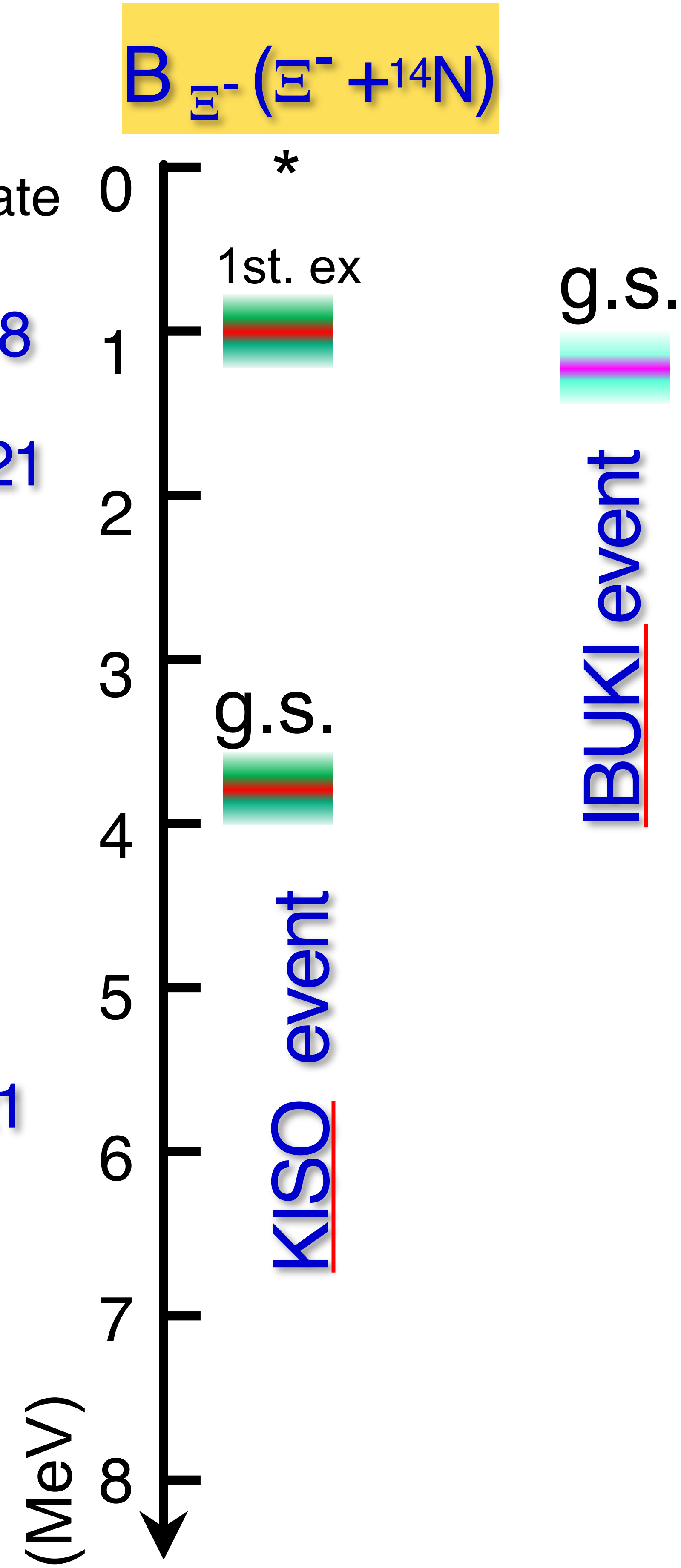
B_{Ξ^-} 1.03 ± 0.18 or 3.87 ± 0.21 (MeV)

IBUKI event
(J-PARC E07)



S. Hayakawa, PhD thesis (2019) Osaka Univ., Unpublished

B_{Ξ} 1.27 ± 0.21 (MeV)



* Multiple candidates of Ξ hypernucleus with B_{Ξ^-} beyond 3D atomic level in Ξ^--^{14}N systems
* We expect more examples through further analysis in E07.

FEMTOSCOPY @ ALICE

- Two-particle correlations $C(\vec{p}_1, \vec{p}_2) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)}.$
  - p-p → Source size r_0 → Strong Interaction Information on other hadron pairs
  - p-Ξ^- arXiv:1904.12198 [nucl-ex]
  - Λ-Λ arXiv: 1905.07209 [nucl-ex]

two-particle emitting source

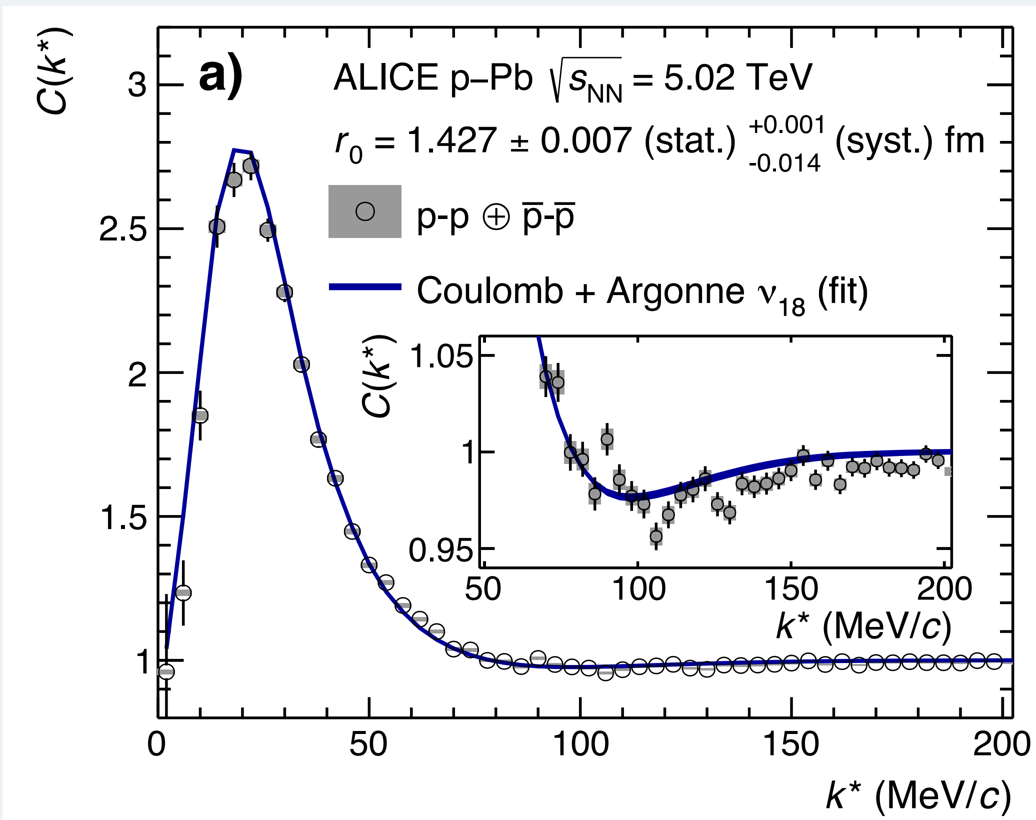
$$C(k^*) = \int S(r) \mid \Psi(\vec{k}^*, \vec{r}) \mid^2 \mathrm{d}^3 r \xrightarrow{k^* \to \infty} 1,$$

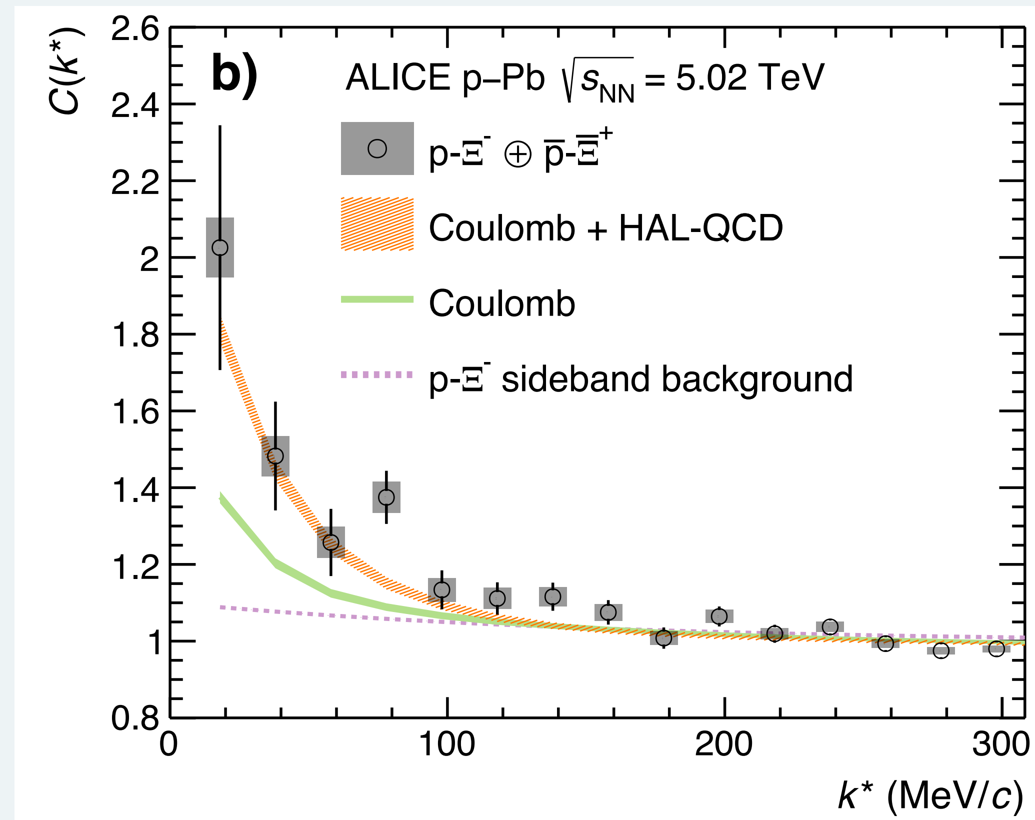
$P - \Xi^-$

k*〈200 MeV/c

p-p; AV_{18}

$3.3\mathrm{x}10^3(2.6\mathrm{x}10^3) p - \Xi^-(\bar{p} - \bar{\Xi}^+)$





$574\mathrm{x}10^3(412\mathrm{x}10^3)$p-p$(\bar{p} - \bar{p})$

source size r_0 : fit parameter

$r_0 = 1.427 \pm 0.007(stat.)^{0.001}_{-0.0014}(syst.)$ fm, $\chi^2/ndf = 1.42$

Λ - Λ

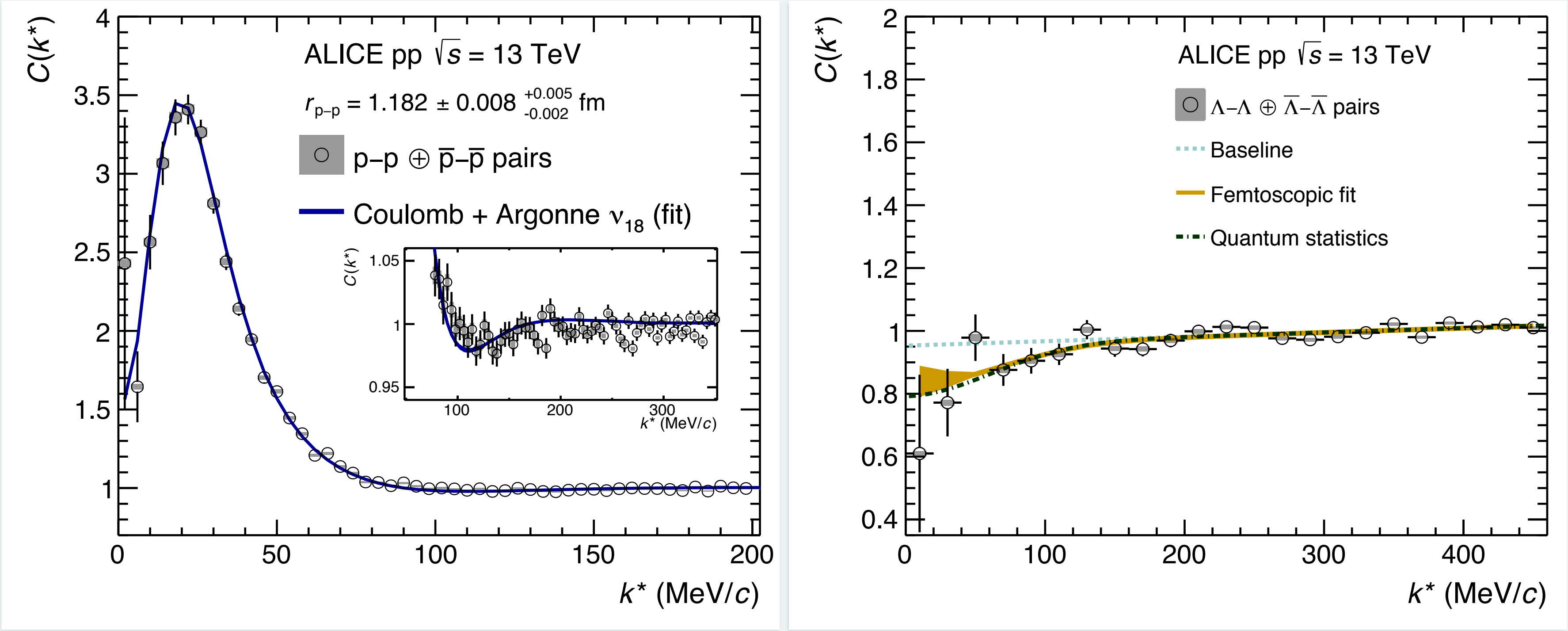


Fig. 1: Results for the fit of the pp data at $\sqrt{s} = 13$ TeV. The p–p correlation function (left panel) is fitted with CATS (blue line) and the Λ–Λ correlation function (right panel) is fitted with the Lednický model (yellow line). The dashed line represents the linear baseline from Eq. 5, while the dark dashed-dotted line on top of the Λ–Λ data shows the expected correlation based on quantum statistics alone.

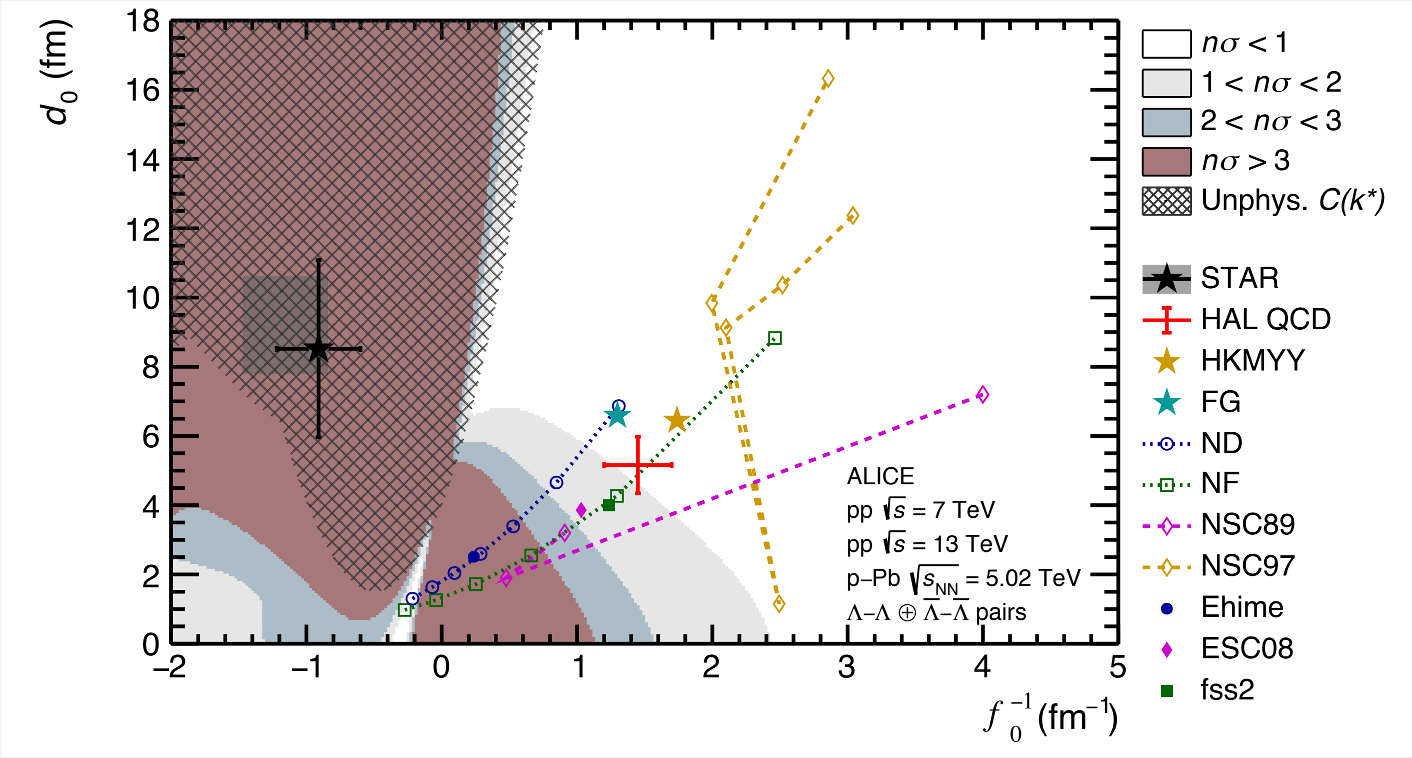


Fig. 3: Exclusion plot for the Λ–Λ scattering parameters obtained using the Λ–Λ correlations from pp collisions at $\sqrt{s} = 7$ and 13 TeV as well as p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The different colors represent the confidence level of excluding a set of parameters, given in $n\sigma$. The black hashed region is where the Lednický model produces an unphysical correlation. The two models denoted by colored stars are compatible with hypernuclei data, while the red cross corresponds to the preliminary result of the lattice computation performed by the HAL QCD collaboration. For details regarding the region at slightly negative f_0^{-1} and $d_0 < 4$, compatible with a bound state, refer to Fig. 4.

SUMMARY

- **New era of Dense Matter Physics**
  - Gravitational Wave from Binary Neutron Star merger events
- Revisit S=-1 systems
- Neutron-rich(neutral) hypernuclei ; nnΛ, nΛ !?
- ${}^{4}_{\Lambda}$He γ-ray is measured in high precision. CSB has been confirmed.
- $K^{-}pp$ signals are observed in E15
- Dawn of S=-2 spectroscopy
- E05 observed a Ξ hyper nucleus and a double Λ excited state.
- E07 completed the emulsion exposure in 2017; New events for ${}_{\Lambda\Lambda}$Be and Ξ^{-}-^{14}N.
- Femtoscopy : p-Ξ, Λ-Λ.