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Search for the simplest kaonic bound state K⁻pp via ^{3}He(K⁻,n) reaction at J-PARC

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RIKEN / TokyoTech
for E15 collaboration

RIKEN

RIKEN NISHINA CENTER

Subject for discussion: J-PARC E15

Strong $\bar{K}N$ attraction! $\Lambda(1405)$ = K^-p bound state?

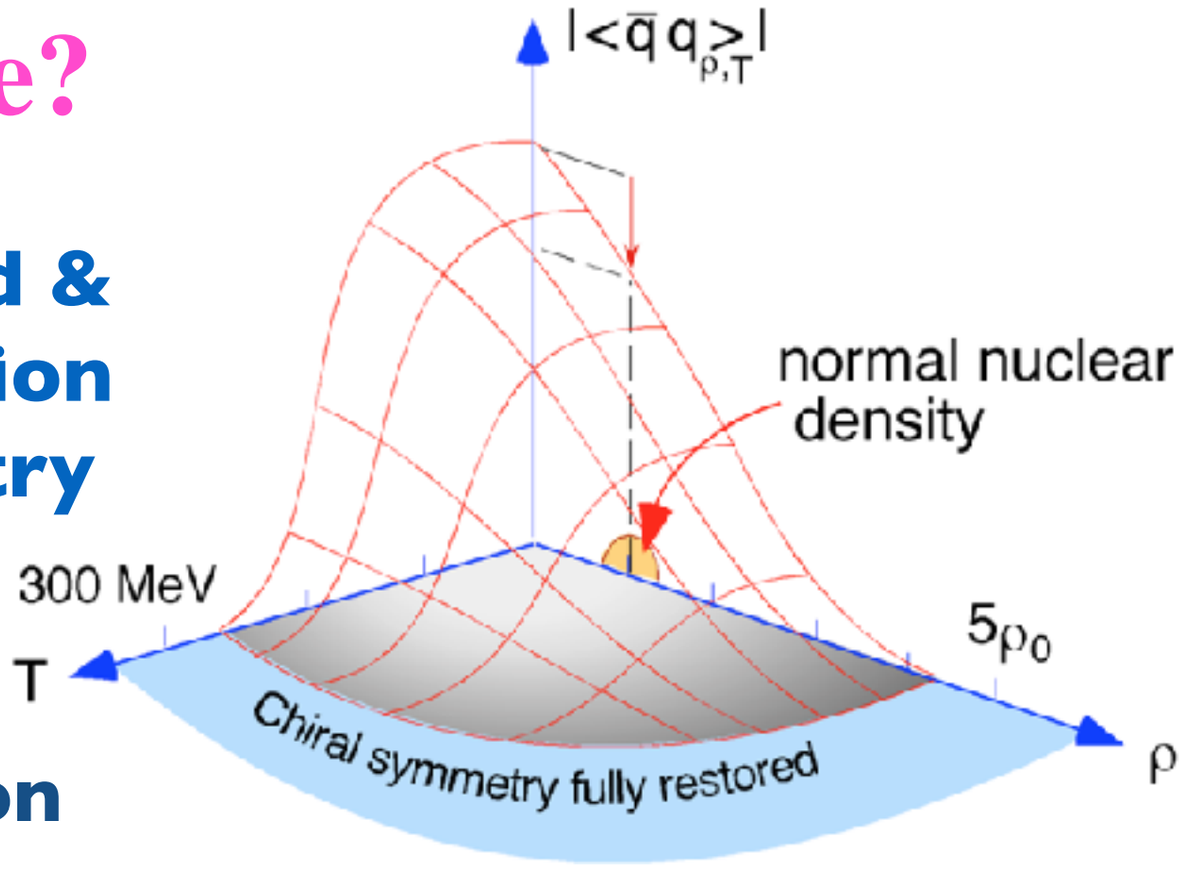
→ excellent introduction by Dr. Laura Tolós

Key questions :

- Can kaon (boson) be a member of nuclei?
- Kaon properties change in nuclear media?
- Size of Kaon bound state?

Could be a good probe for cold & dense QCD, to study the relation of hadron mass and χ-symmetry

<q̄q> as QCD-Higgs condensation

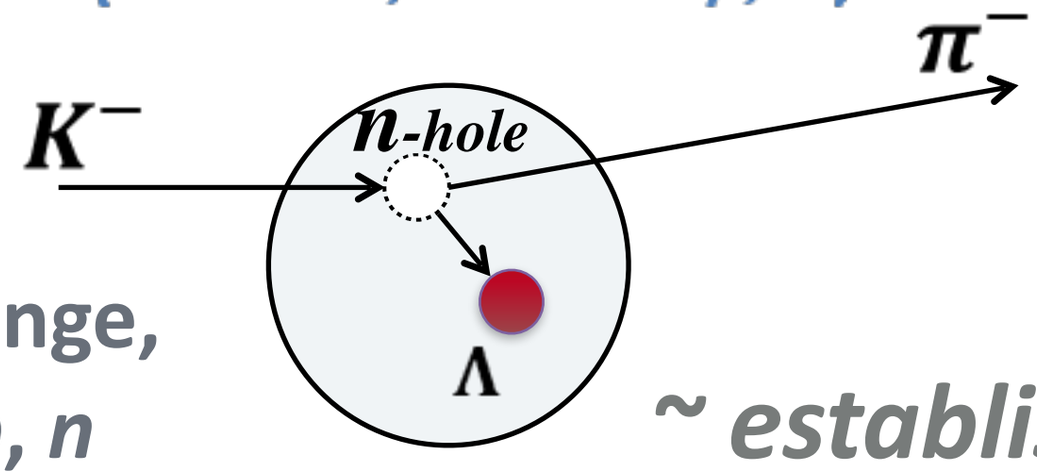


Can “boson” be a constituent of “matter”?

Hyper-nucleus

Λ : 3-quark baryon (Fermion, same as *p, n*)

$$K^- + n \rightarrow \Lambda + \pi^-$$
$$(\bar{u}s)\quad (udd)\ (uds)\ (\bar{u}d)$$



existence might not that strange,
because it is Fermion like *p, n*

~ established

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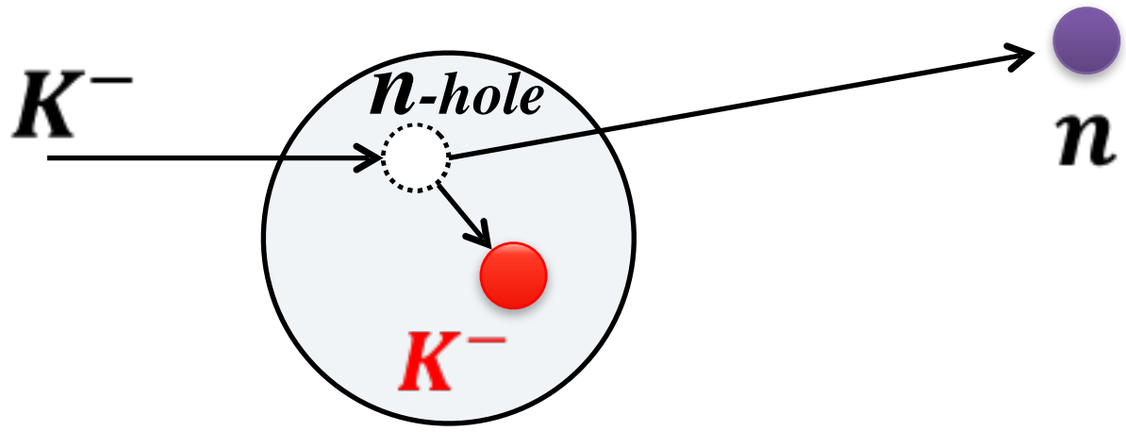
anti Kaon-nucleus

New Paradigm

Can anti-quark $\bar{u}$ “survive” in a nucleus?

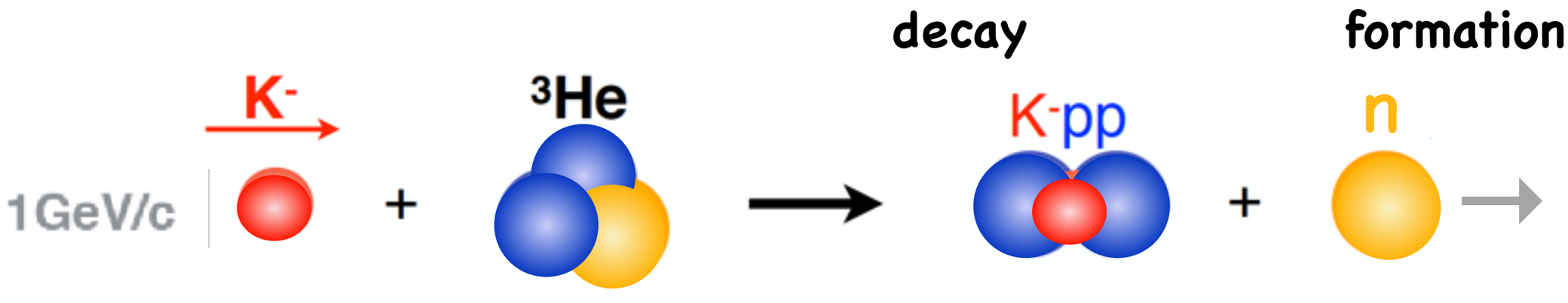


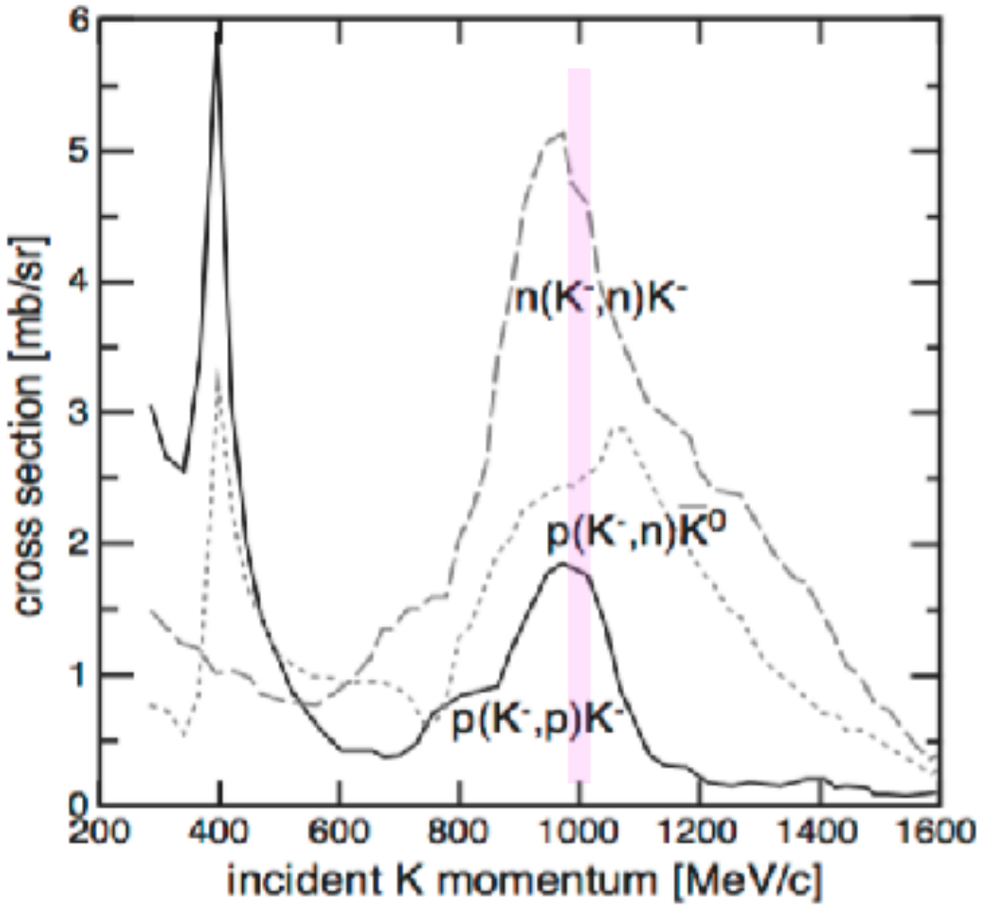
K : $(\bar{u}s)$ meson (Boson, like π, *but strongly attractive*)

$$K^- + n \rightarrow K^- + n$$
$$(\bar{u}s)\quad (udd)\ (\bar{u}s)\quad (udd)$$

Can we make “meson” as a
member of “nuclear matter”?

E15 1st





q_K is as small as 200 MeV/c

large sticking is expected

Published E15^{1st} data

PTEP

Prog. Theor. Exp. Phys. 2015, 061D01 (11 pages)
DOI: 10.1093/ptep/ptv076

^{3}He(K$^-$, n) — semi-inclusive

Letter

Search for the deeply bound $K^- pp$ state from the semi-inclusive forward-neutron spectrum in the in-flight K^- reaction on helium-3

J-PARC E15 Collaboration
T. Hashimoto[1,*,†], S. Ajimura[2], G. Beer[3], H. Bhang[4], M. Bragadireanu[
M. Cargnelli[8], S. Choi[4], C. Curceanu[9], S. Enomoto[2], D. Faso[6,7], H. Fuj
Y. Fujiwara[1], T. Fukuda[11], C. Guaraldo[9], R. S. Hayano[1], T. Hiraiwa[2], N
M. Iliescu[9], K. Inoue[13], Y. Ishiguro[10], T. Ishikawa[1], S. Ishimoto[12], K. I
M. Iwai[12], M. Iwasaki[14,15], Y. Kato[14], S. Kawasaki[13], P. Kienle[16,‡], H.
J. Marton[8], Y. Matsuda[17], Y. Mizoi[11], O. Morra[6], T. Nagae[10], H. Noum
H. Ohnishi[14,2], S. Okada[14], H. Outa[14], K. Piscicchia[9], M. Poli Lener[9],
A. Romero Vidal[9], Y. Sada[10], A. Sakaguchi[13], F. Sakuma[14], M. Sato[14],
M. Sekimoto[12], H. Shi[9], D. Sirghi[9,5], F. Sirghi[9,5], S. Suzuki[12], T. Suzuk
H. Tatsuno[1], M. Tokuda[15], D. Tomono[10], A. Toyoda[12], K. Tsukada[18],
O. Vazquez Doce[9,19], E. Widmann[8], T. Yamaga[13], T. Yamazaki[1,14], H.
Q. Zhang[14], J. Zmeskal[8]

PTEP

Prog. Theor. Exp. Phys. 2016, 051D01 (11 pages)
DOI: 10.1093/ptep/ptw040

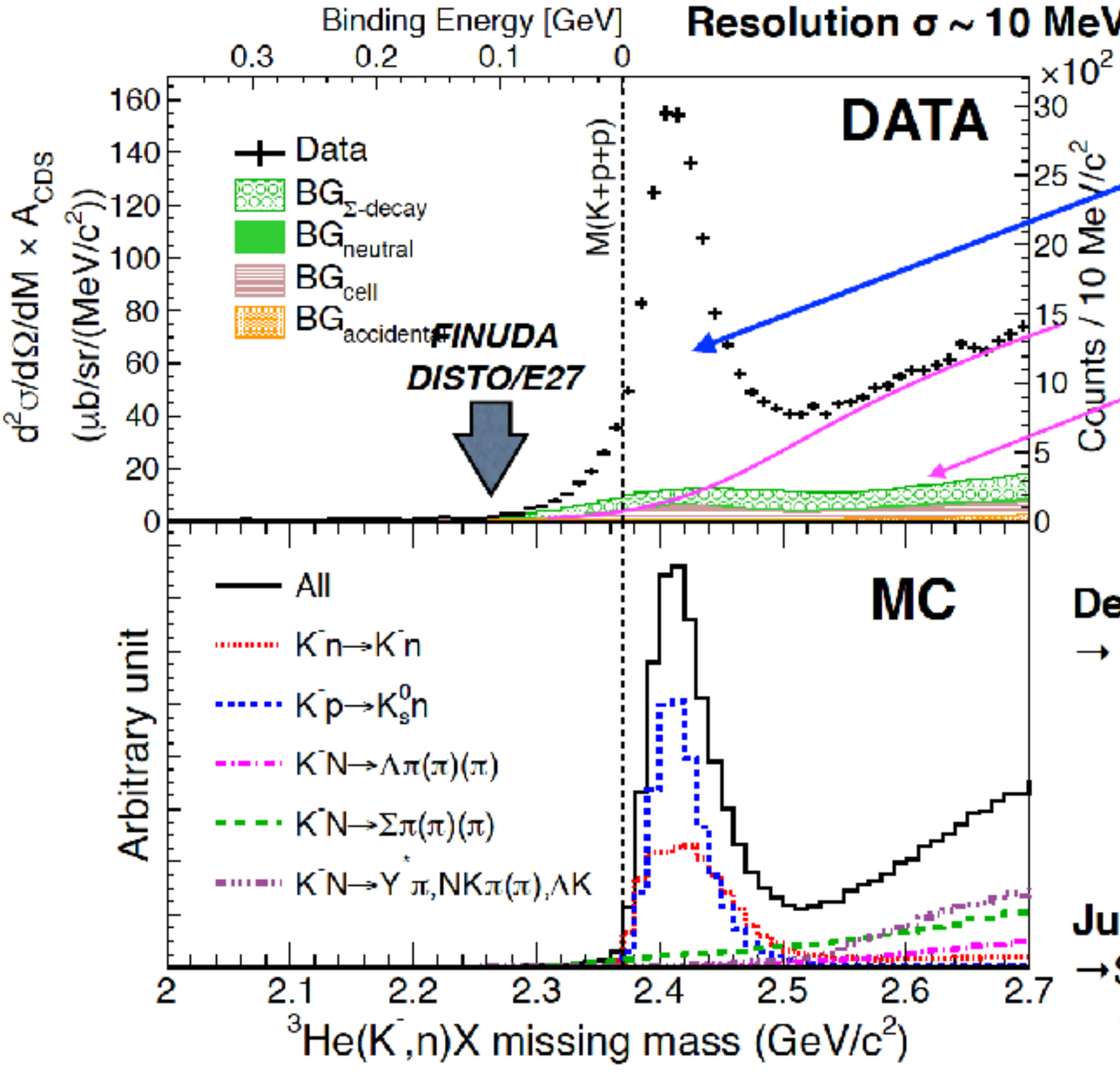
^{3}He(K$^-$, Λp) n — exclusive

Letter

Structure near the $K^- + p + p$ threshold in the in-flight $^3\mathrm{He}(K^-, \Lambda p)n$ reaction

J-PARC E15 Collaboration
Y. Sada[1,*], S. Ajimura[1], M. Bazzi[2], G. Beer[3], H. Bhang[4], M. Bragadireanu[5], P. Buehler[6], L. Busso[7,9], M. Cargnelli[6], S. Choi[4], C. Curceanu[2], S. Enomoto[8], D. Faso[7,9], H. Fujioka[10], Y. Fujiwara[11], T. Fukuda[12], C. Guaraldo[2], T. Hashimoto[13], R. S. Hayano[11], T. Hiraiwa[1], M. Iio[8], M. Iliescu[2], K. Inoue[1], Y. Ishiguro[10], T. Ishikawa[11], S. Ishimoto[8], T. Ishiwatari[6], K. Itahashi[13], M. Iwai[8], M. Iwasaki[13,14], Y. Kato[13], S. Kawasaki[15], P. Kienle[†,16], H. Kou[14], Y. Ma[13], J. Marton[6], Y. Matsuda[17], Y. Mizoi[12], O. Morra[7], T. Nagae[10], H. Noumi[1], H. Ohnishi[13,1], S. Okada[13], H. Outa[13], K. Piscicchia[2], A. Romero Vidal[2], A. Sakaguchi[15], F. Sakuma[13], M. Sato[13], A. Scordo[2], M. Sekimoto[8], H. Shi[2], D. Sirghi[2,5], F. Sirghi[2,5], K. Suzuki[6], S. Suzuki[8], T. Suzuki[11], K. Tanida[18], H. Tatsuno[19], M. Tokuda[14], D. Tomono[1], A. Toyoda[8], K. Tsukada[20], O. Vazquez Doce[2,21], E. Widmann[6], B. K. Wuenschek[6], T. Yamaga[15], T. Yamazaki[11,13], H. Yim[22], Q. Zhang[13], and J. Zmeskal[6]

Forward neutron semi-inclusive spectrum



Quasi-elastic

$K^- + {}^3He \rightarrow K^0 + d_s + n$

$K^- + {}^3He \rightarrow K^- + 2p_s + n$

Hyperon decay

$K^- + {}^3He \rightarrow Y + \pi(\pi)(\pi) + 2N_s$

$Y \rightarrow n + \pi$

Deep-bound region

→ No significant peak
set upper limit:
a few hundreds ub/sr
= a few % of quasi-elastic K

Just below the threshold

→Significant yield ~ 1 mb/sr
should include quasi-free Λ(1405)

Λp invariant mass with a missing neutron

Resolution σ ~ 10 MeV/c² @ threshold

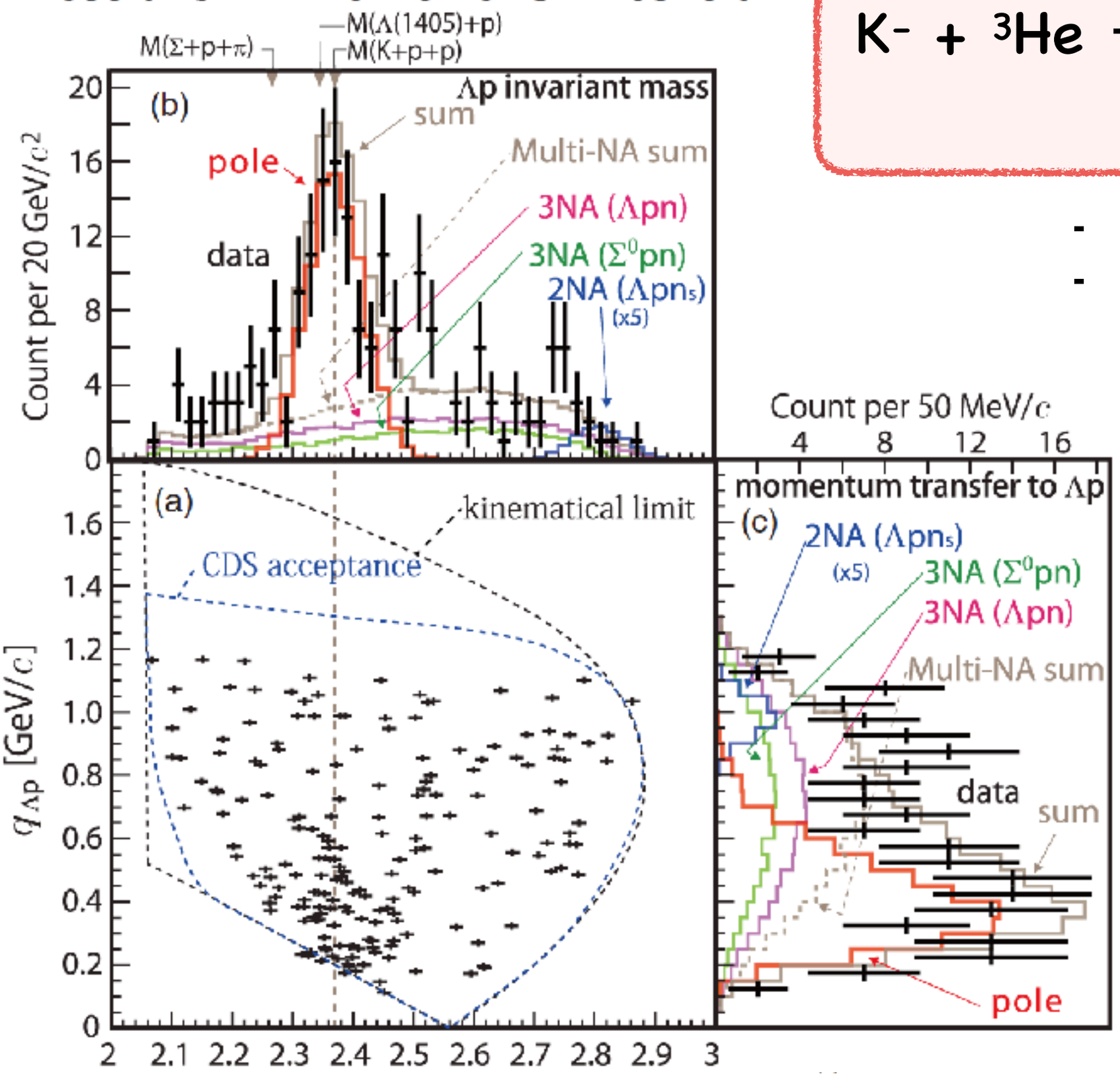
$$K^- + {}^3He \rightarrow (K^- p p) + n$$
$$\rightarrow (\Lambda + p) + n$$

- **s-wave Breit-Wigner pole**
- **w/ Gaussian form-factor**

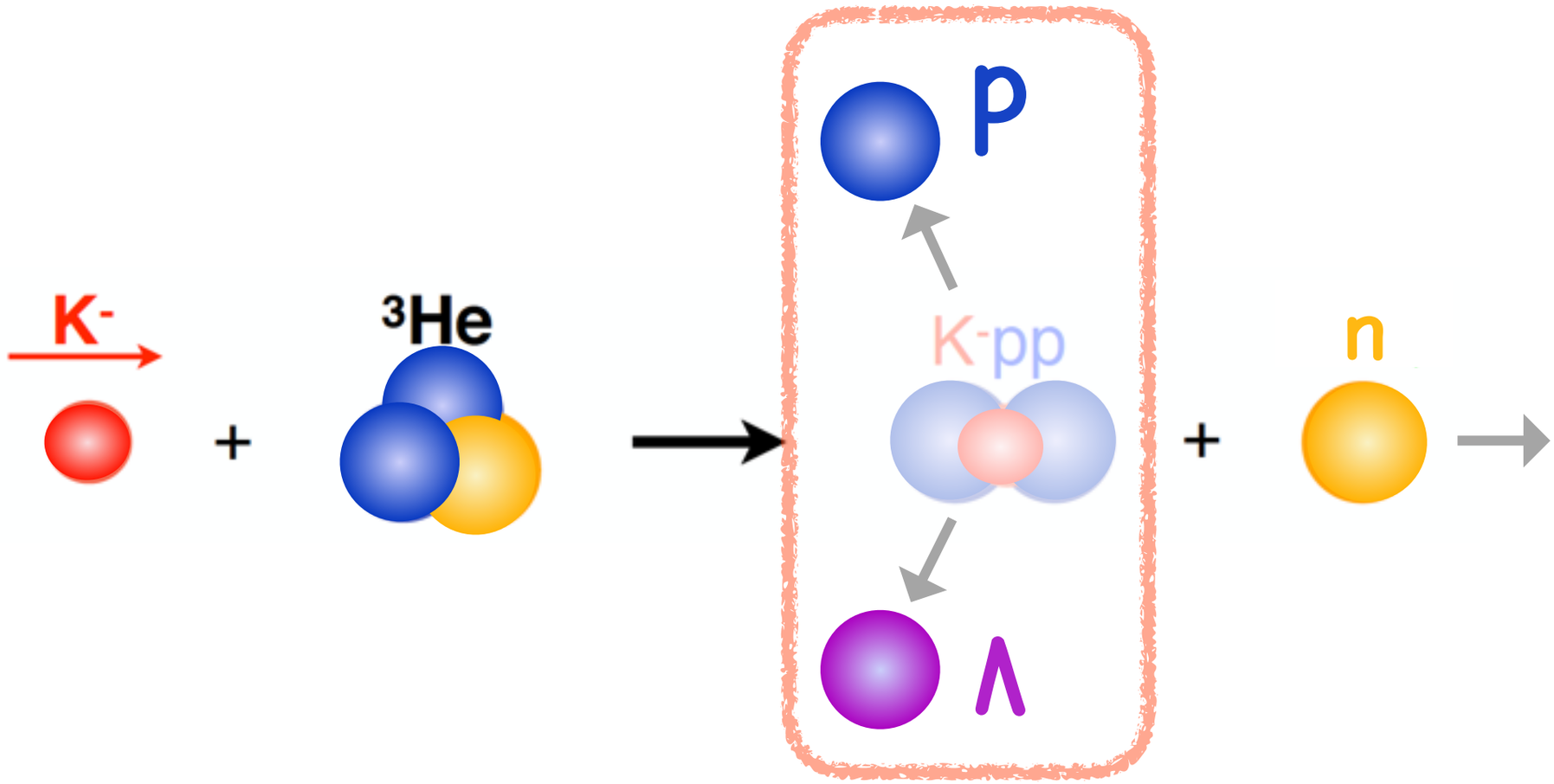
$$\frac{d^2\sigma}{dM\,dq} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M-M_X)^2+(\Gamma_X/2)^2} \times \left|exp\left(-\frac{q^2}{2Q_X^2}\right)\right|^2$$

$$B_X \sim 15\ \mathrm{MeV}$$
$$\Gamma_X \sim 100\ \mathrm{MeV}$$
$$Q_X \sim 400\ \mathrm{MeV}$$

Compact state?



E15 2nd



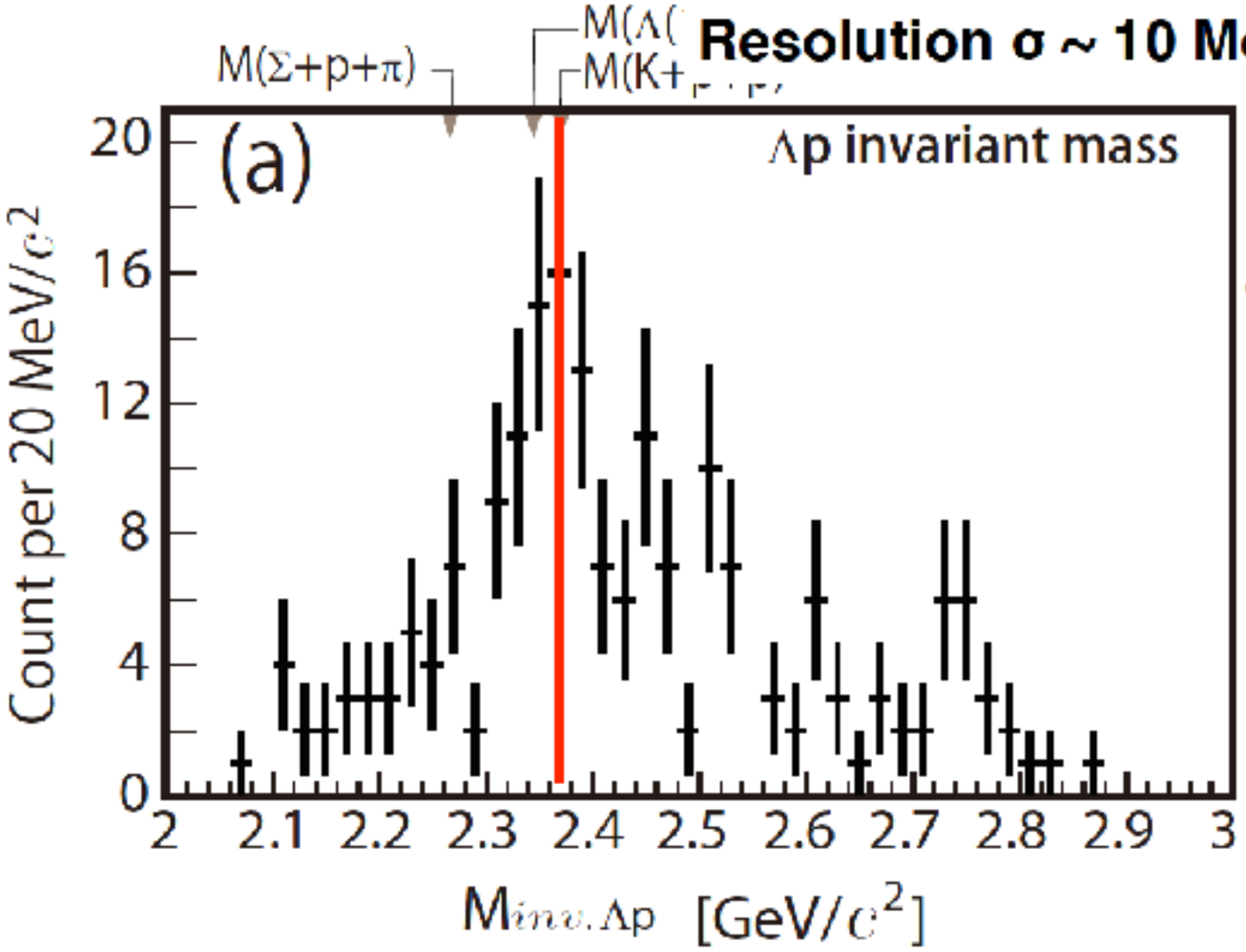
$K^- + {}^3He \rightarrow (\Lambda + p) + n$

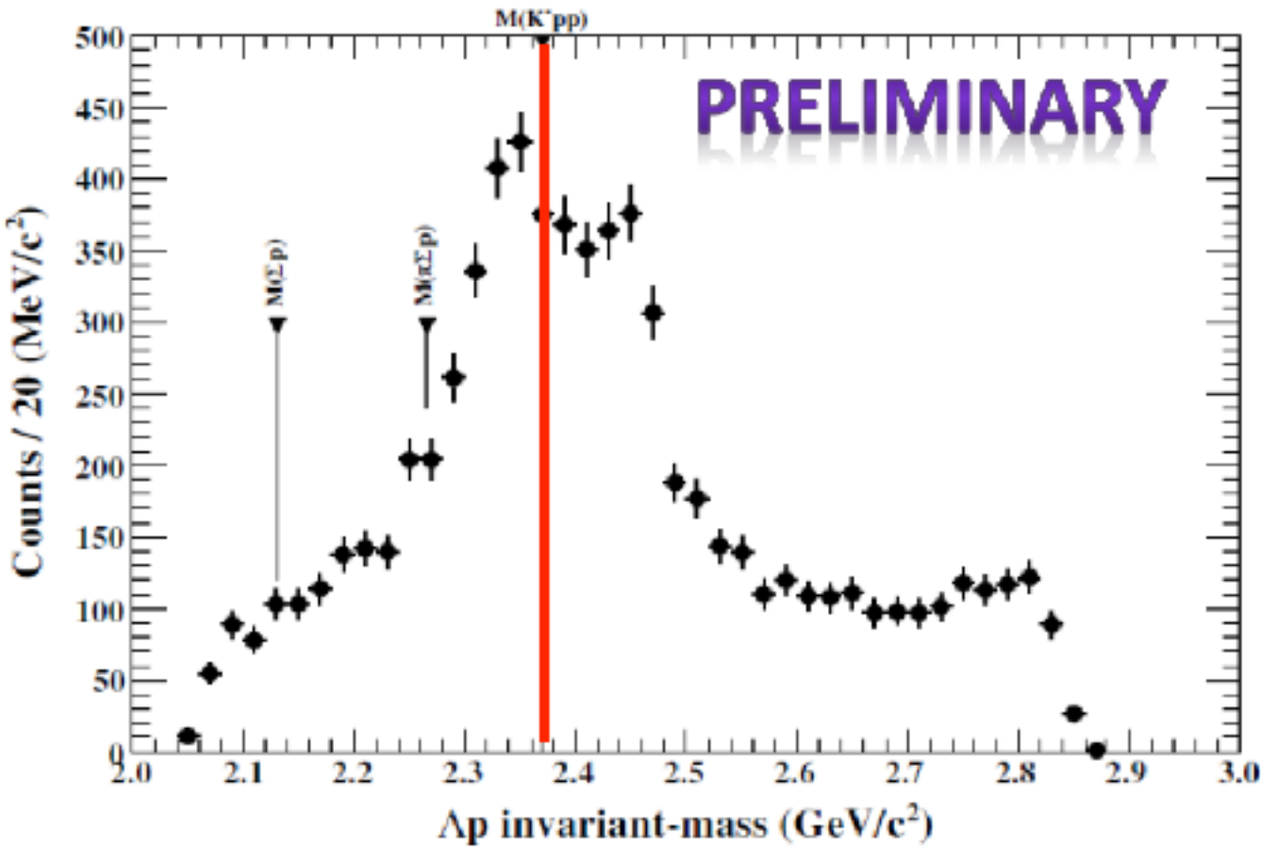
~ 30 times for Λpn channel

Comparison between E15[1st] & E15[2nd]

1st → **2nd**

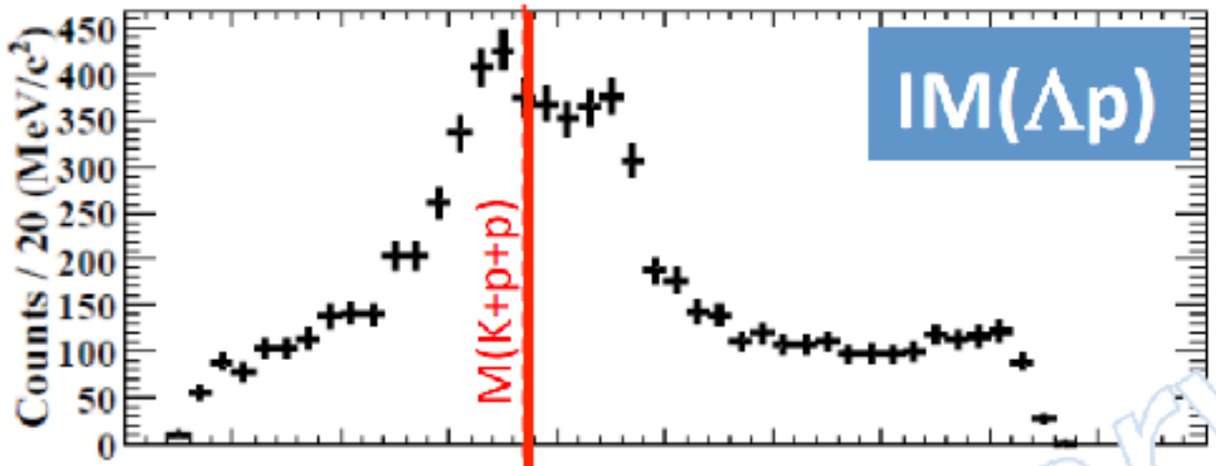
Resolution σ ~ 10 MeV/c² @ threshold

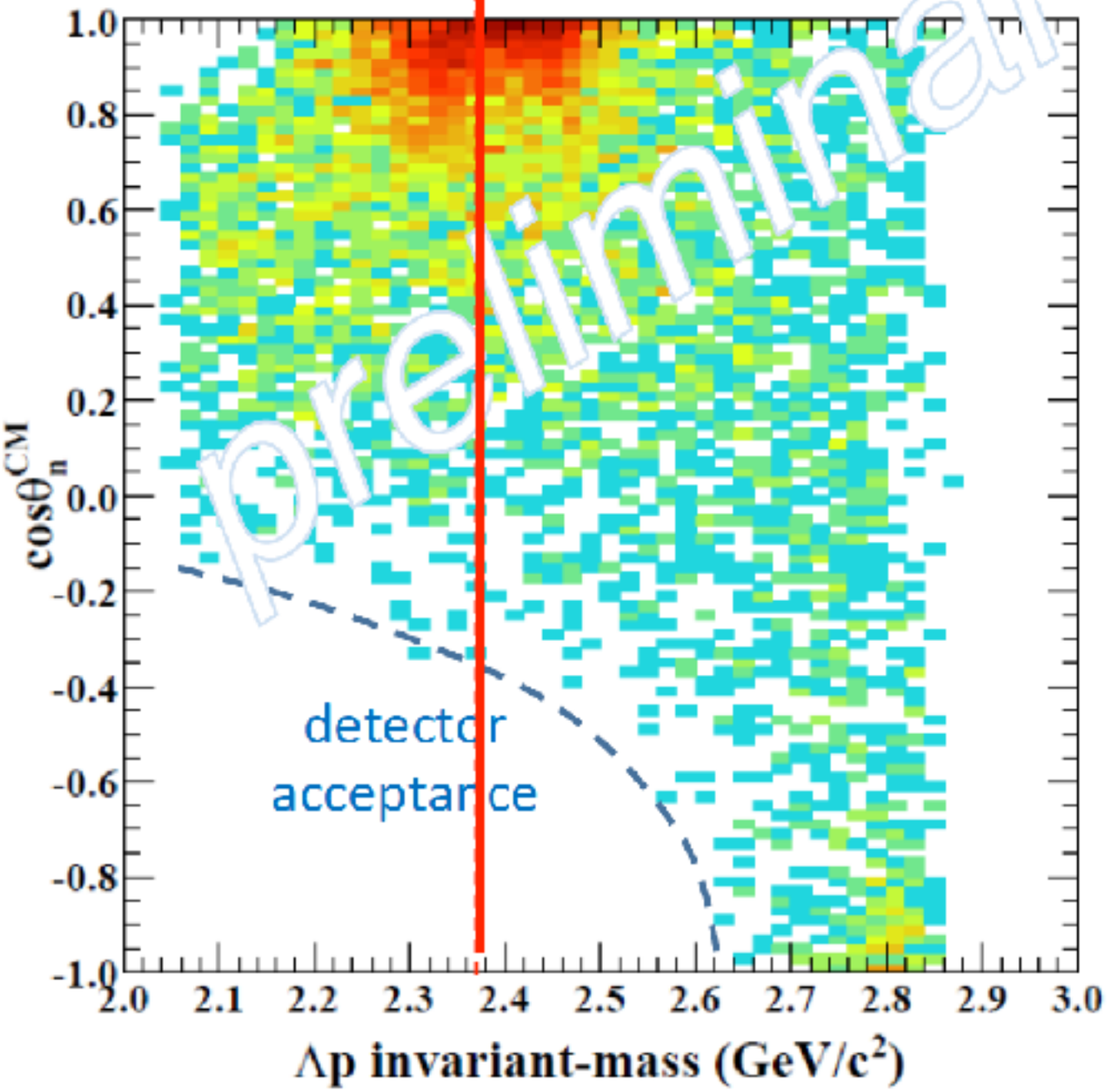




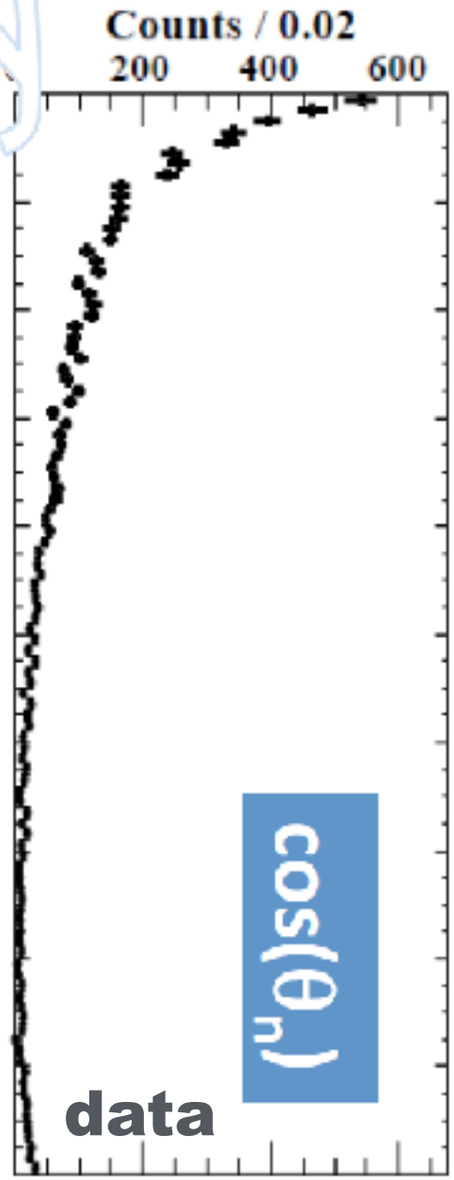
- **x 30 data for Λp(n) final state**
  - x 7 beam + dedicated trigger (requires > 3 hits on CDH)

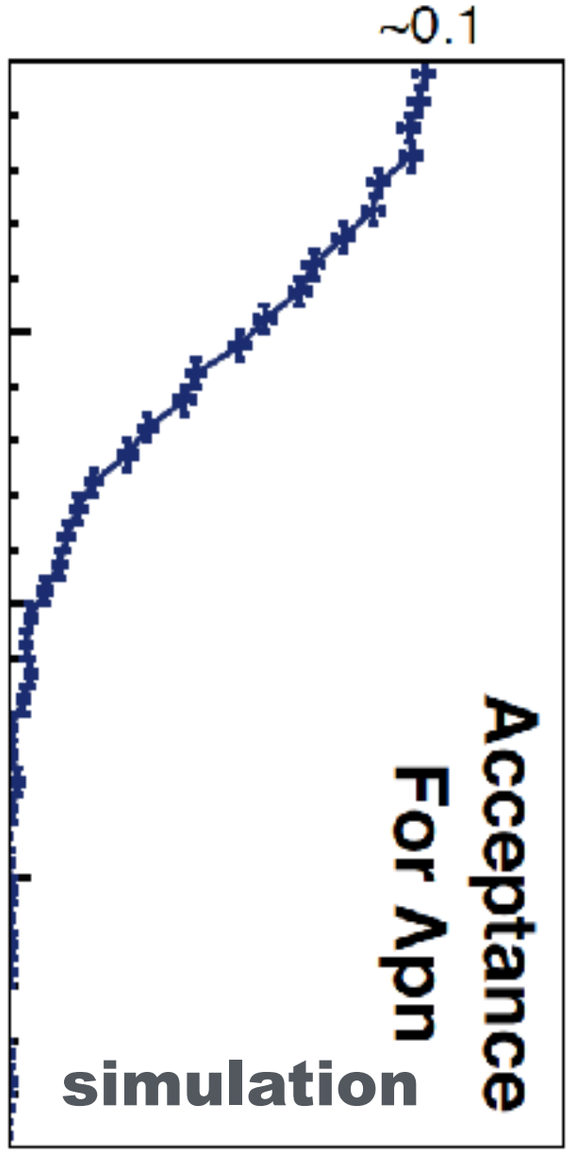
Reaction angle: $\cos\theta_n$



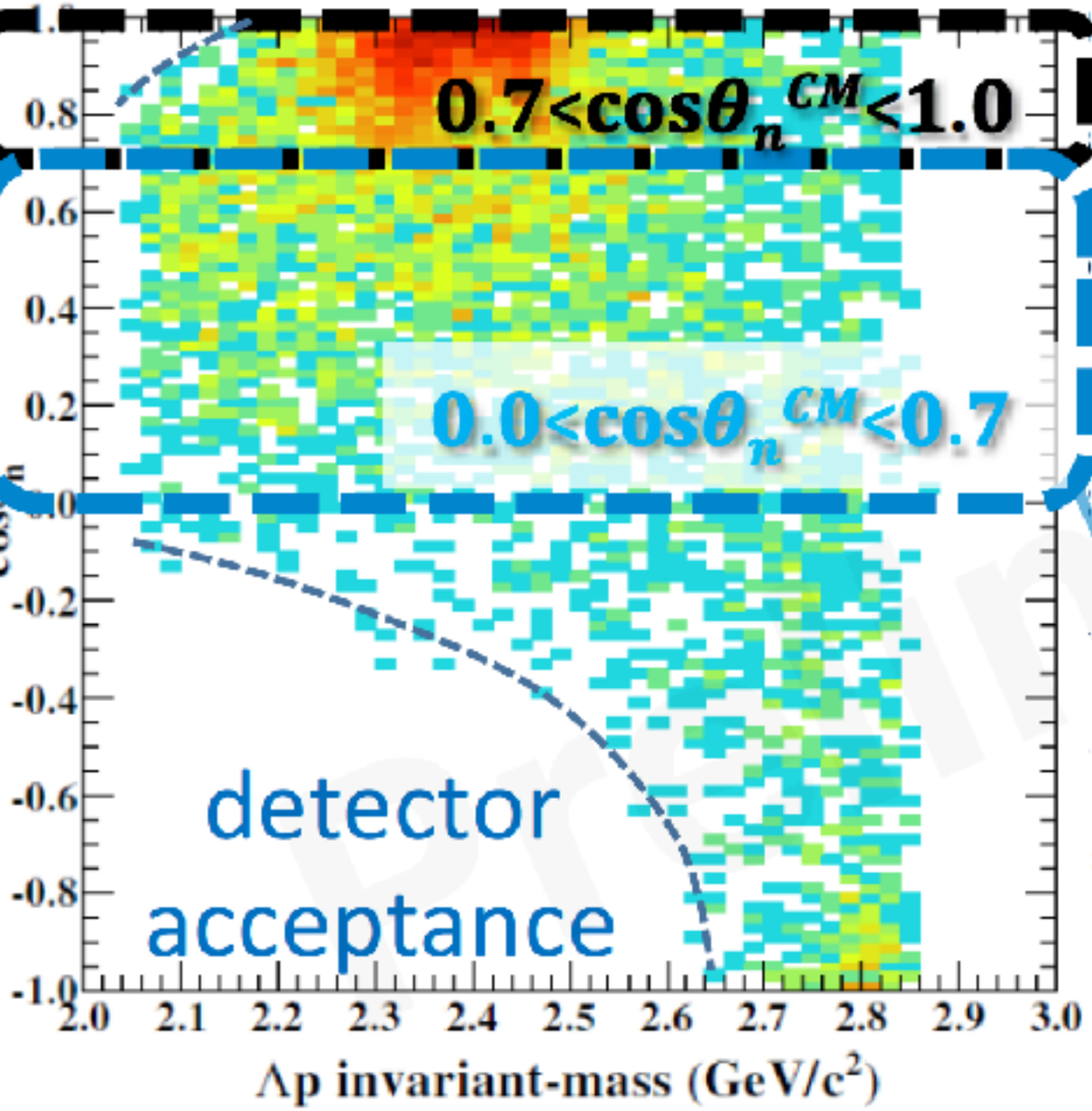


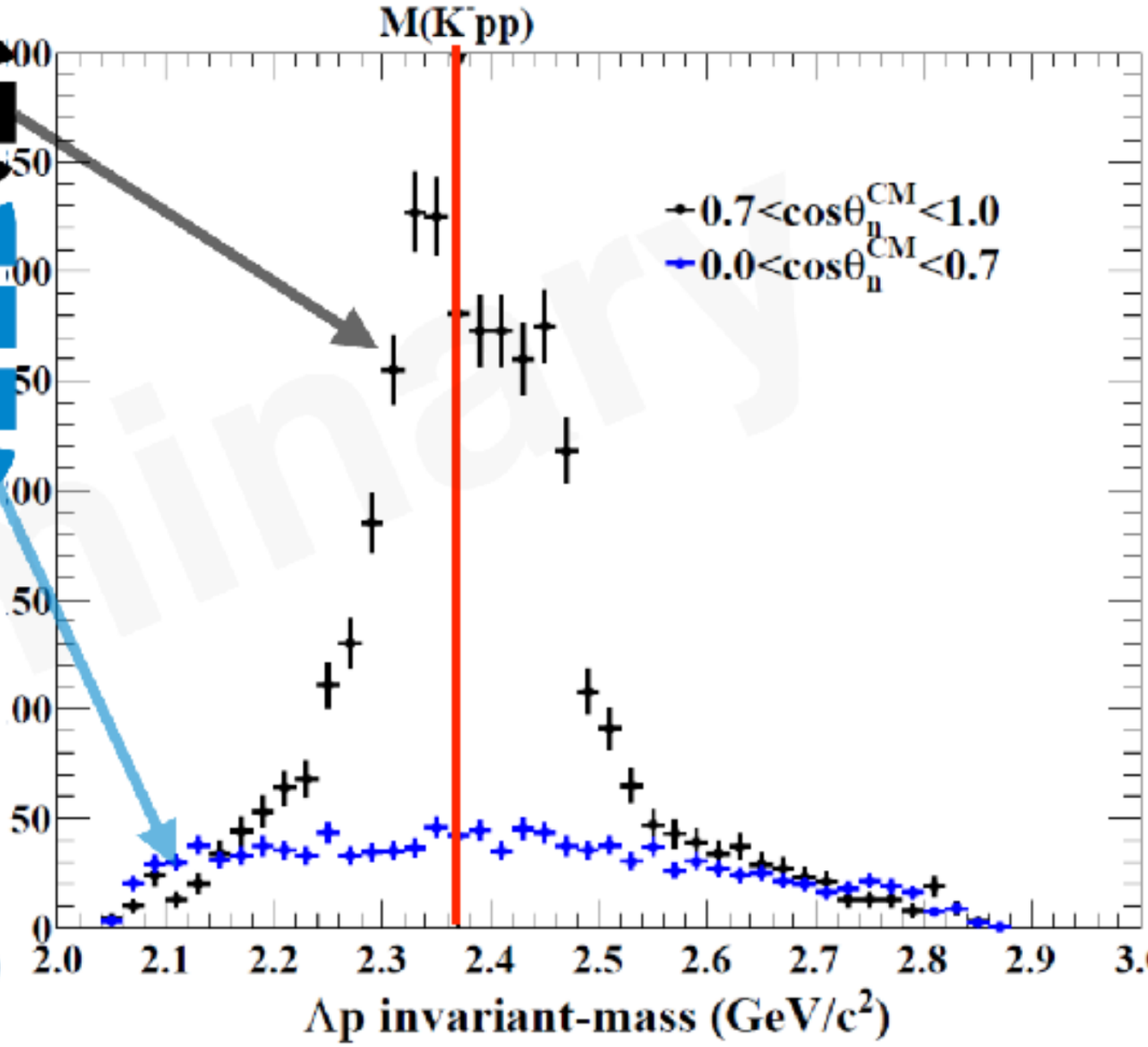
Larger dataset allow us
to perform detailed systematic study.
i.e., **angular dependence** etc.





Reaction angle dependence: $\cos\theta_n$





- **Structure around the threshold prefers the forward neutron**
- **Events widely spread to the phase space in the other region**
  - Point-like three nucleon absorption? 2 NA relatively weak.

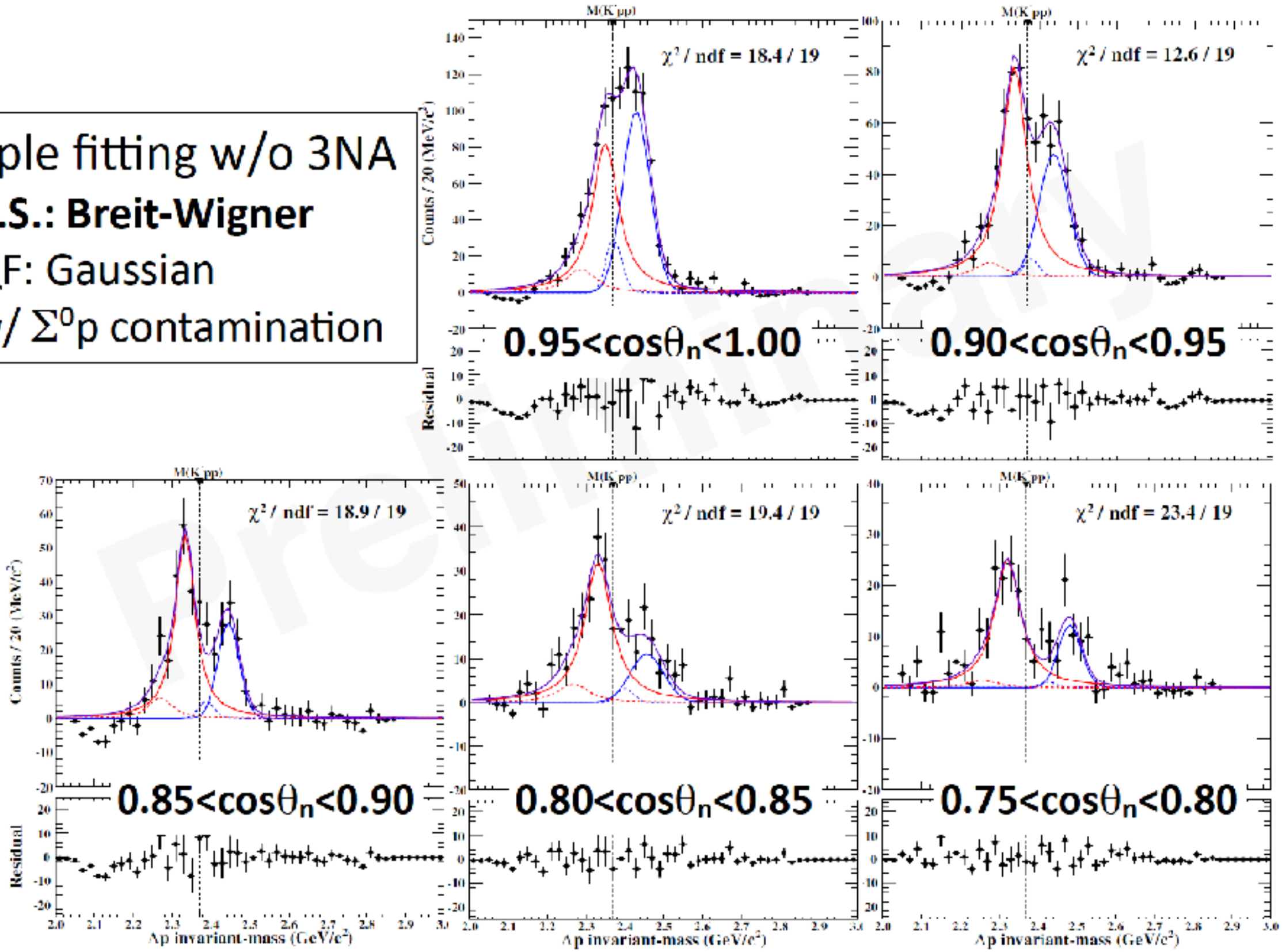
Slice by reaction angle: $\cos\theta_n$

Simple fitting w/o 3NA

B.S.: Breit-Wigner

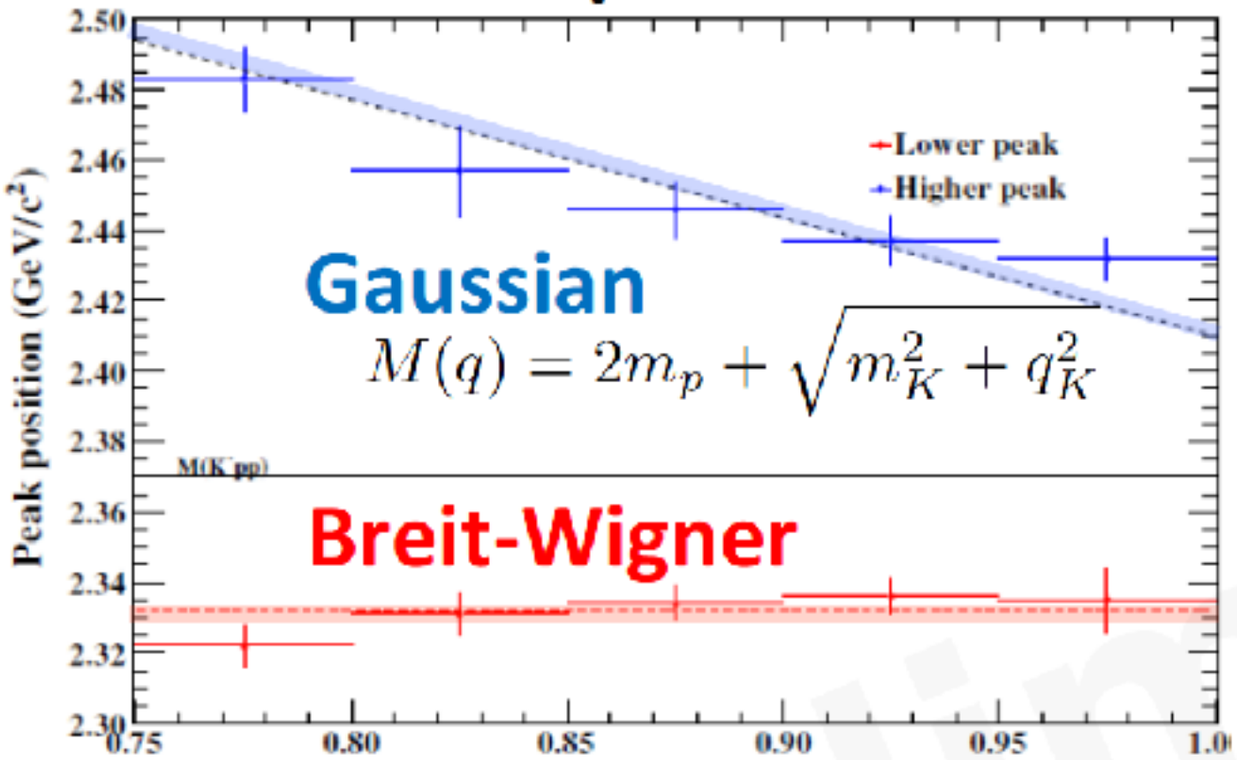
QF: Gaussian

w/ $\Sigma^0 p$ contamination

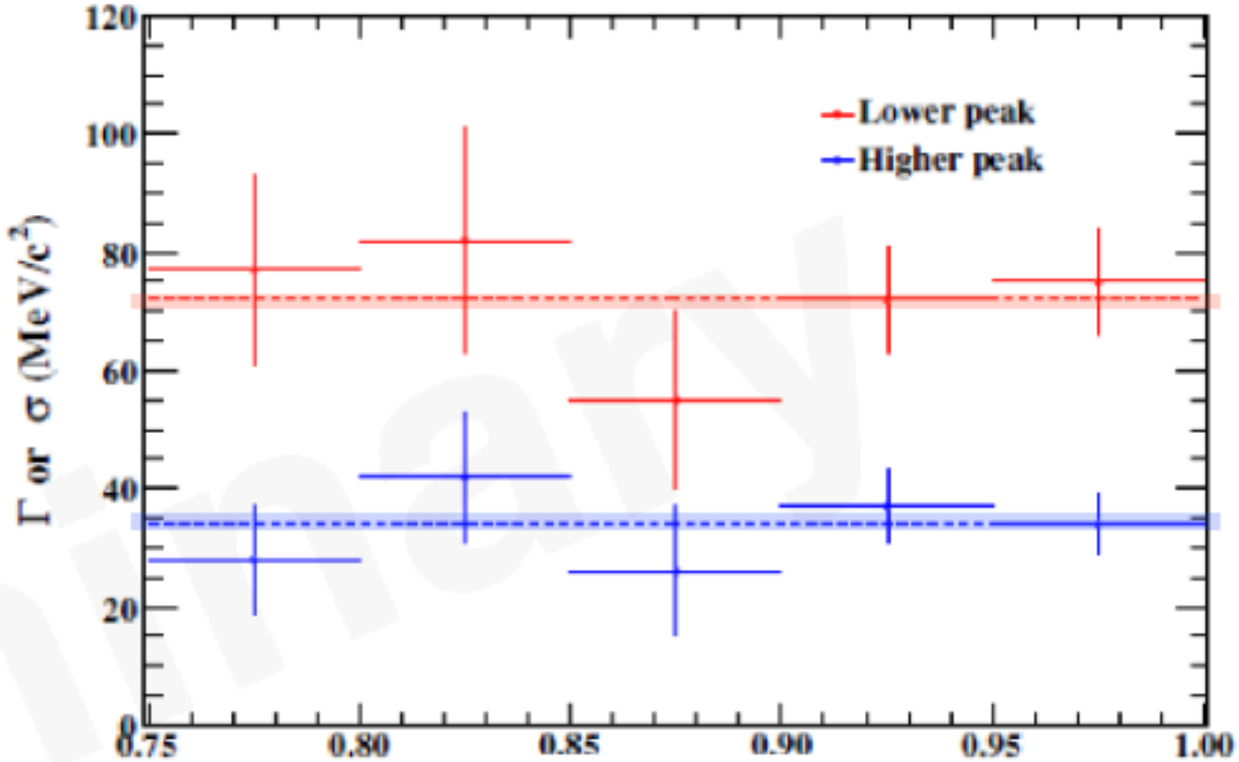


Two structures

Peak position



Width



Above M(K-pp): QE + IC

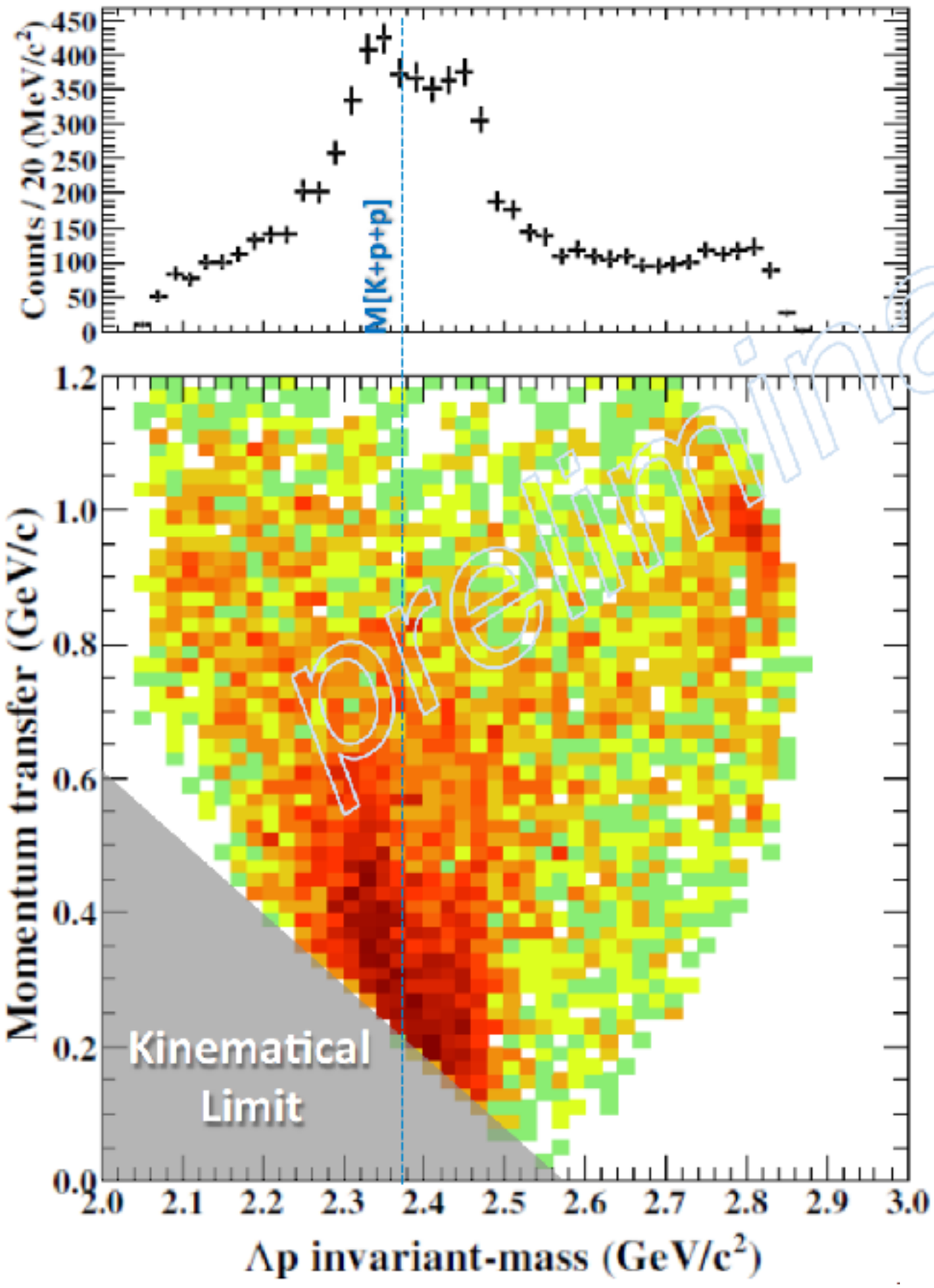
peak shift by recoil kaon energy

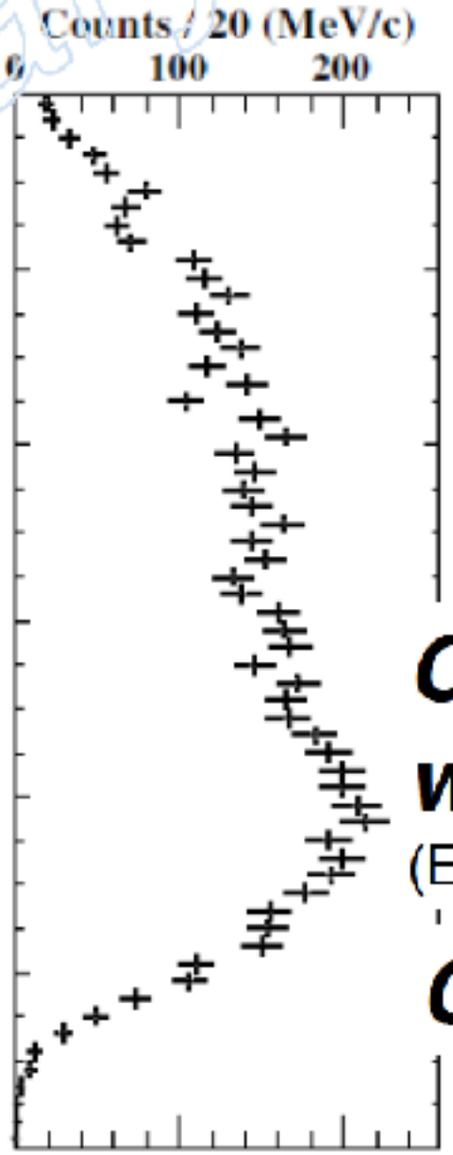
Below M(K-pp): Bound state!

peak is independent to $\cos\theta_n$

(~ momentum transfer)

Momentum transfer



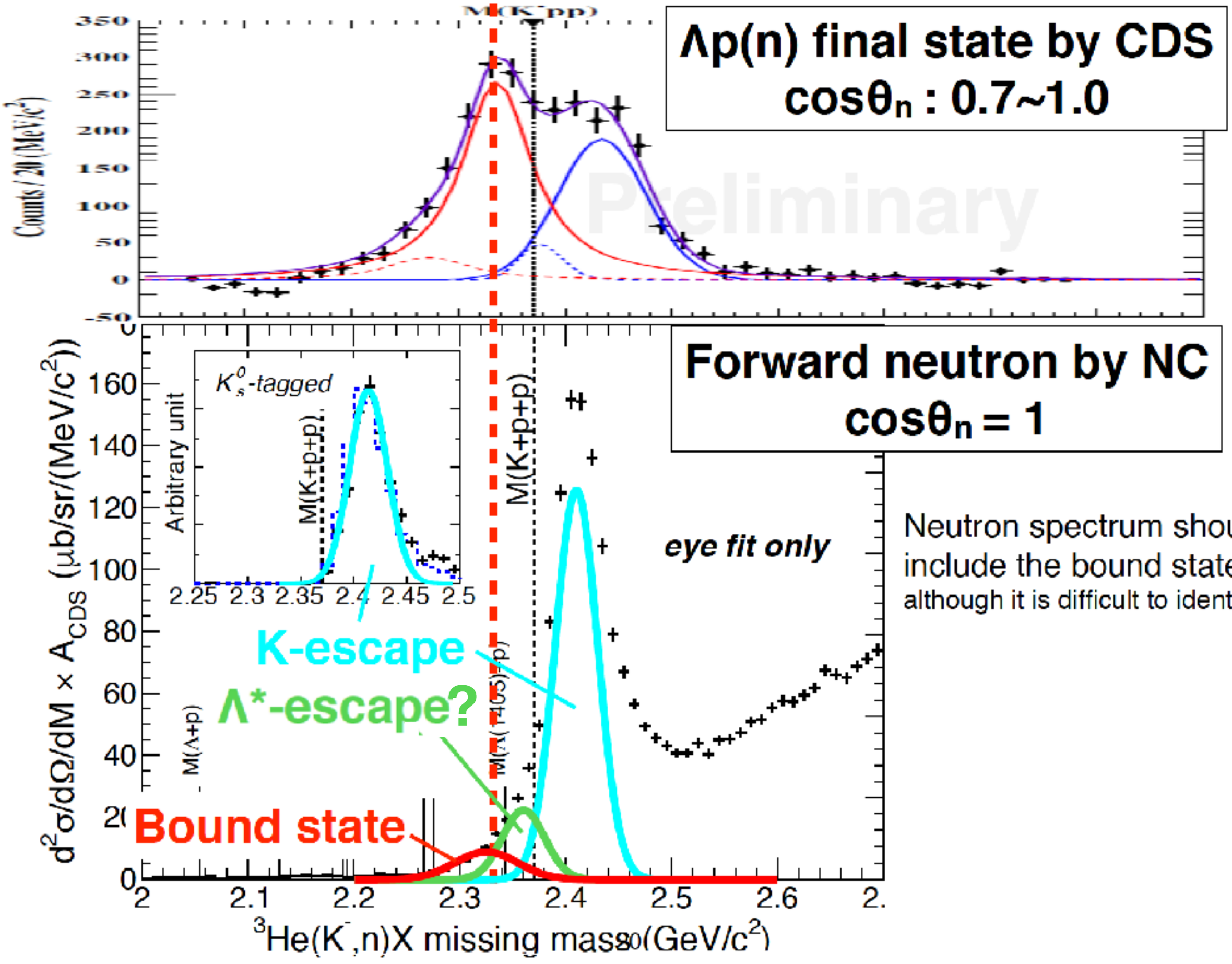


Momentum transfer
Reaches ~ **600 MeV/c**
for sub-threshold structure

Consistent with E15[1st]

(E15[1st] includes unbound region)

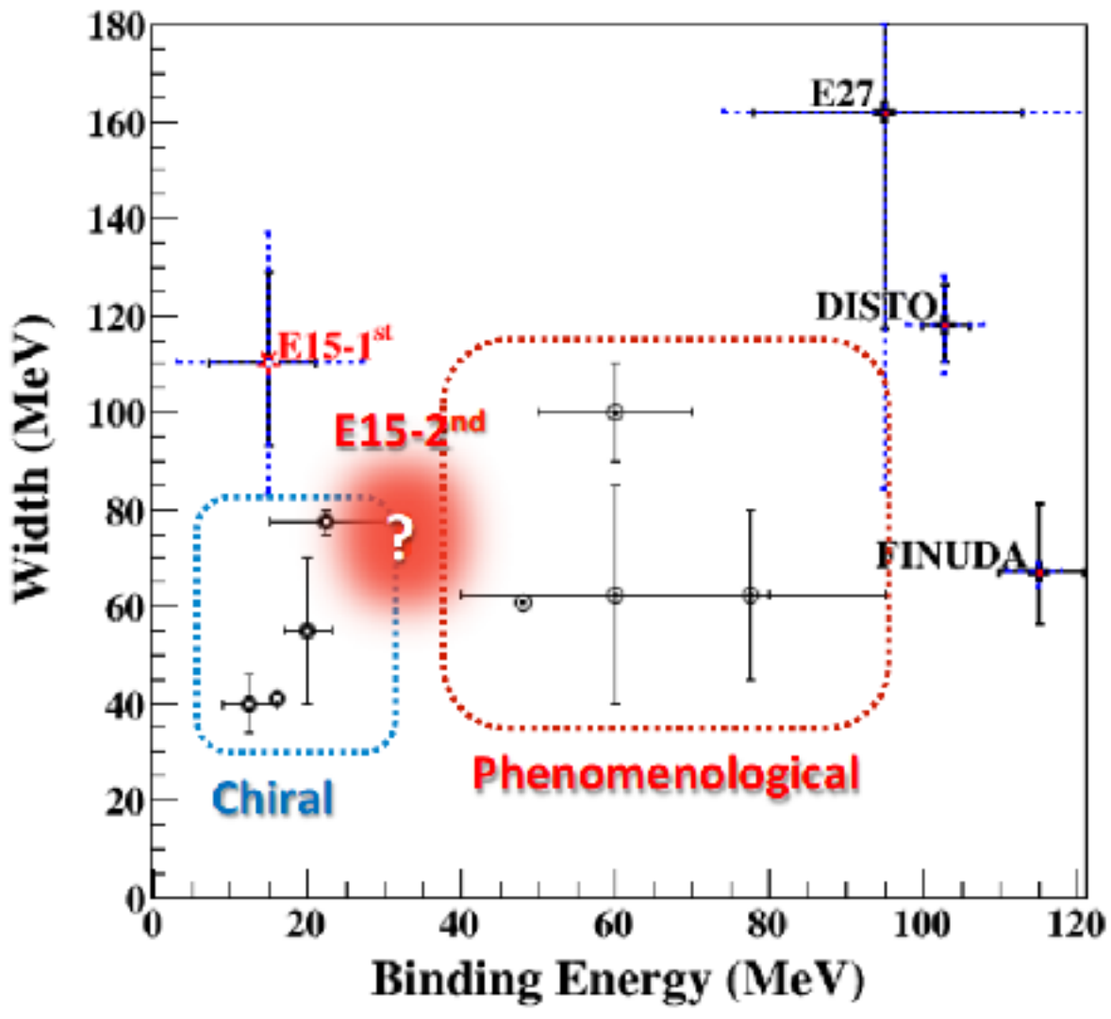
Compact state !?


Λp(n) final state by CDS
cosθn : 0.7~1.0
Preliminary
Forward neutron by NC
cosθn = 1
Neutron spectrum should include the bound state,
although it is difficult to identify…
eye fit only
K-escape
Λ*-escape?
Bound state
K0s-tagged
Counts / 20 (MeV/c2)
d2σ/dΩ/dM × ACDS (μb/sr/(MeV/c2))
3He(K-,n)X missing mass (GeV/c2)
M(K+pp)
M(K+p+p)
M(Λ+p)
Arbitrary unit

Summary

- **J-PARC E15: "K⁻pp" search in the ^{3}He(K⁻,n) reaction**

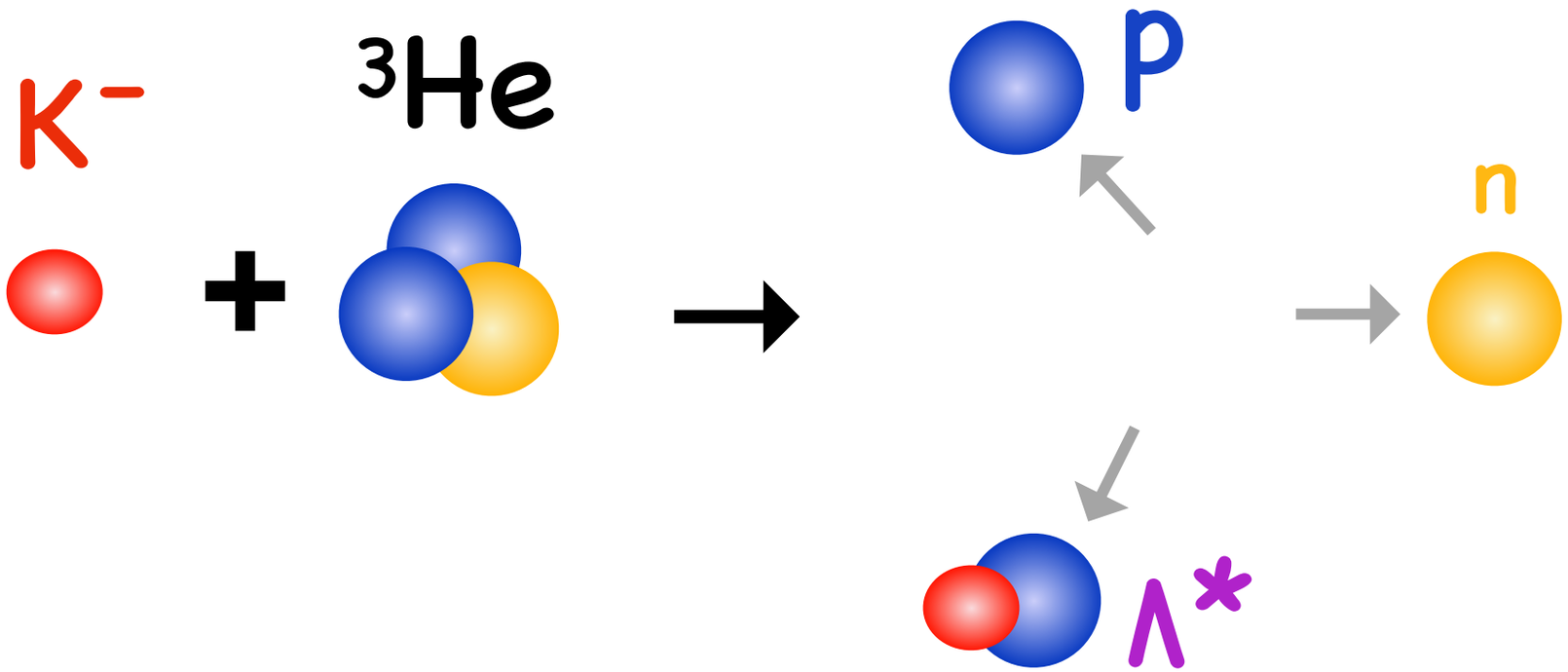
- **Λp spectrum with a larger data set obtained in 2015**
  - Above the M(K⁻pp) threshold
    - Peak shifts against $\cos\theta_n$ / q_K
    - Quasi-elastic + Internal conversion
  - Below the M(K⁻pp) threshold
    - q_K-independent peak → bound state !
    - Could be a compact state
      ← momentum transfer distribution
  - Consistent with
    forward neutron spectrum



Physics to come

Λ^* in vacuum

or K-pp decay



What is the structure found in E15[1st] data?

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

$\rightarrow (\ \Lambda + p\ ) + n$

$\rightarrow (\ p\pi^- + p\ ) + n$

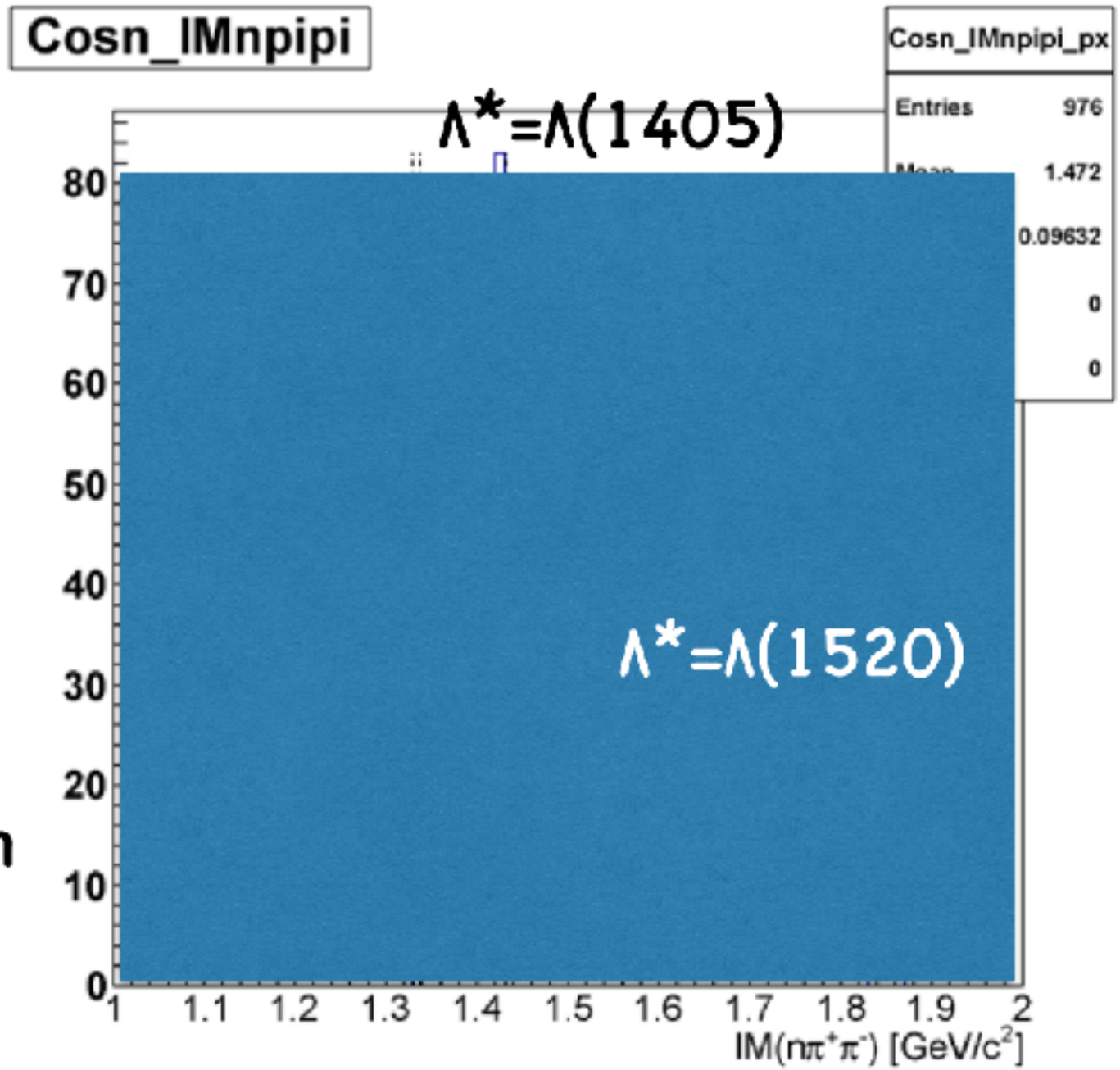
$K^- + {}^3He \rightarrow (\ \Lambda^* + p\ ) + n$

$\rightarrow (\ \Sigma^{\pm}\pi^{\mp} + p\ ) + n$

$\rightarrow (\ n\ \pi^{\pm}\pi^{\mp} + p\ ) + n$

$T = 0$ dominant

large Λ^* yield (4-hold coin. w/ neutron)



invariant mass of Λ^*

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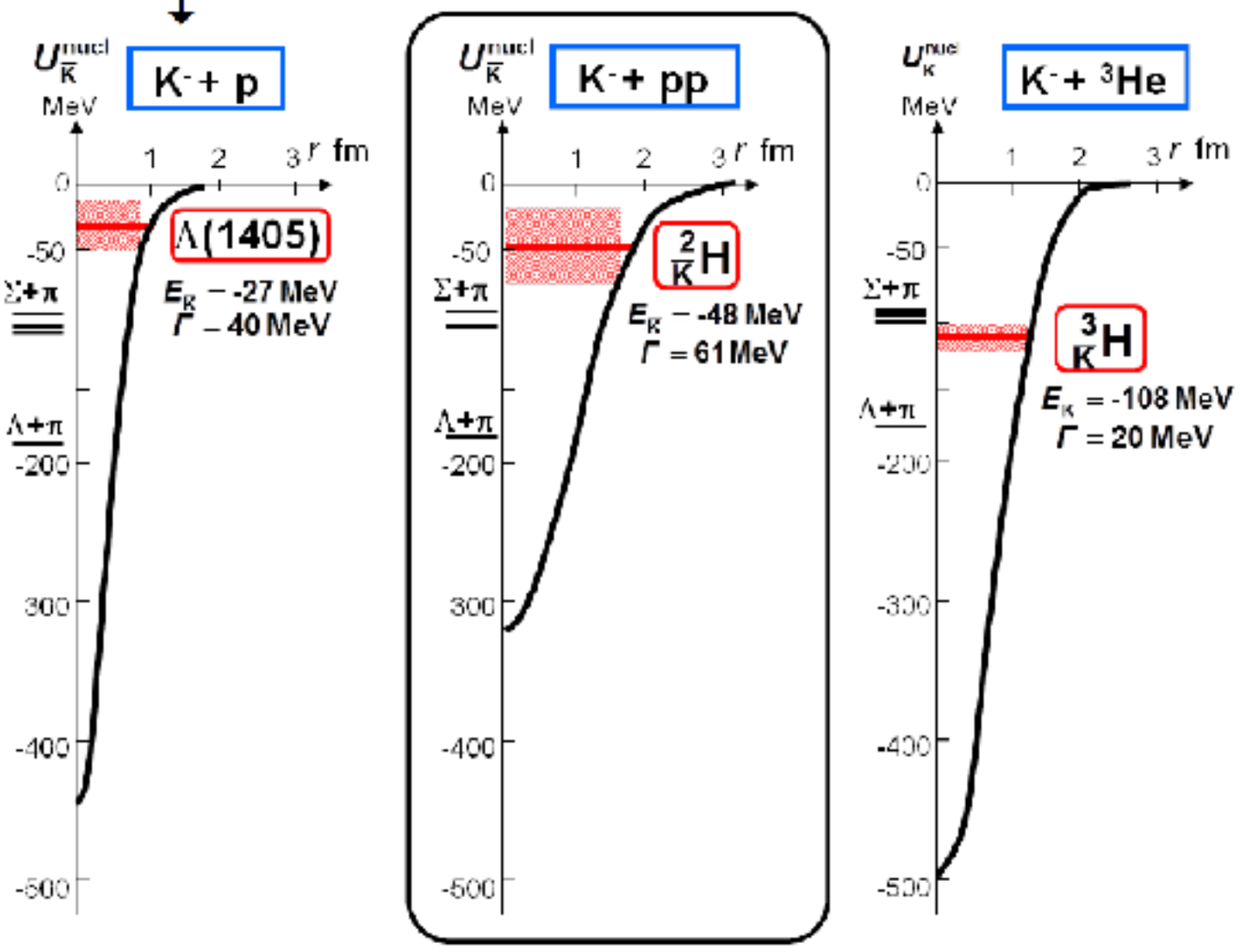
Kaonic nuclear bound state

Could be a good probe for dense & cold QCD

Assumption

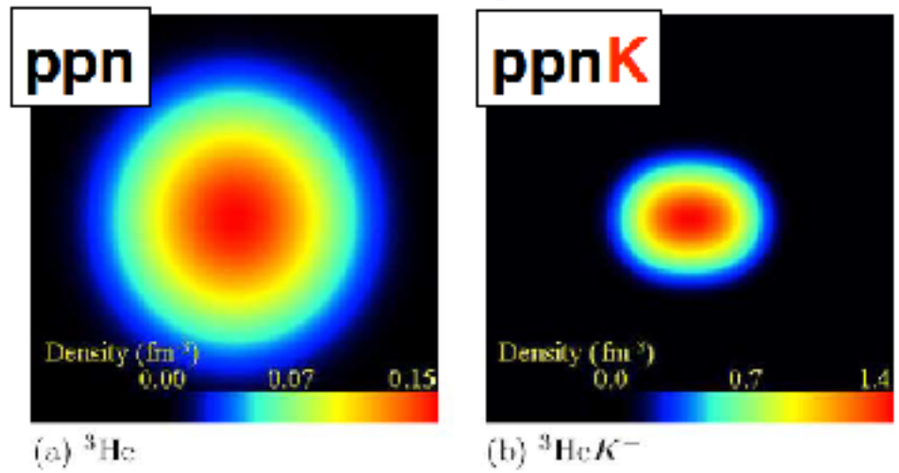


1.Y. Akaishi and T. Yamazaki. *Phys. Rev. C* **65**, 044005 (2002).
2.T. Yamazaki and Y. Akaishi. *Physics Letters B* **535**, 70–76 (2002).

the lightest kaonic nucleus

"K-pp" : $[K^{bar}(NN)_{I=1,S=0}]_{I=1/2}$, $J^{\pi}=0^{-}$

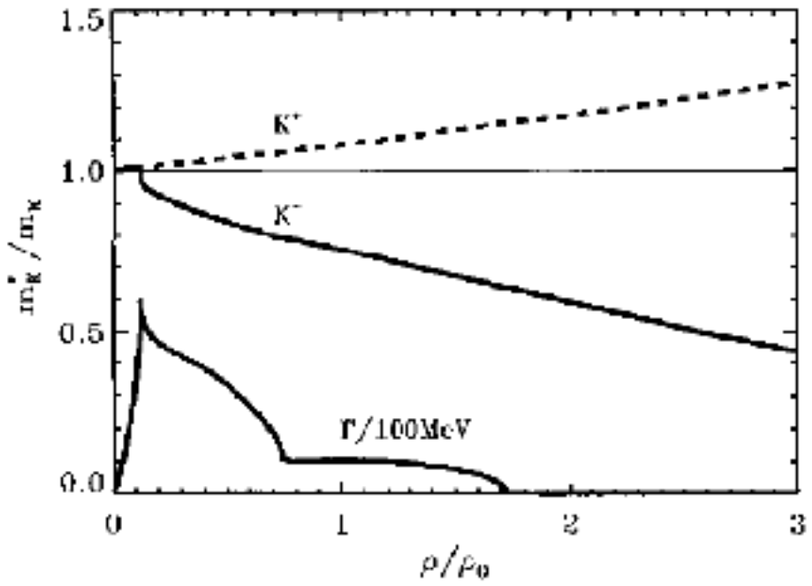
dense nuclei are predicted



(a) ^{3}He (b) ^{3}HeK^{-}

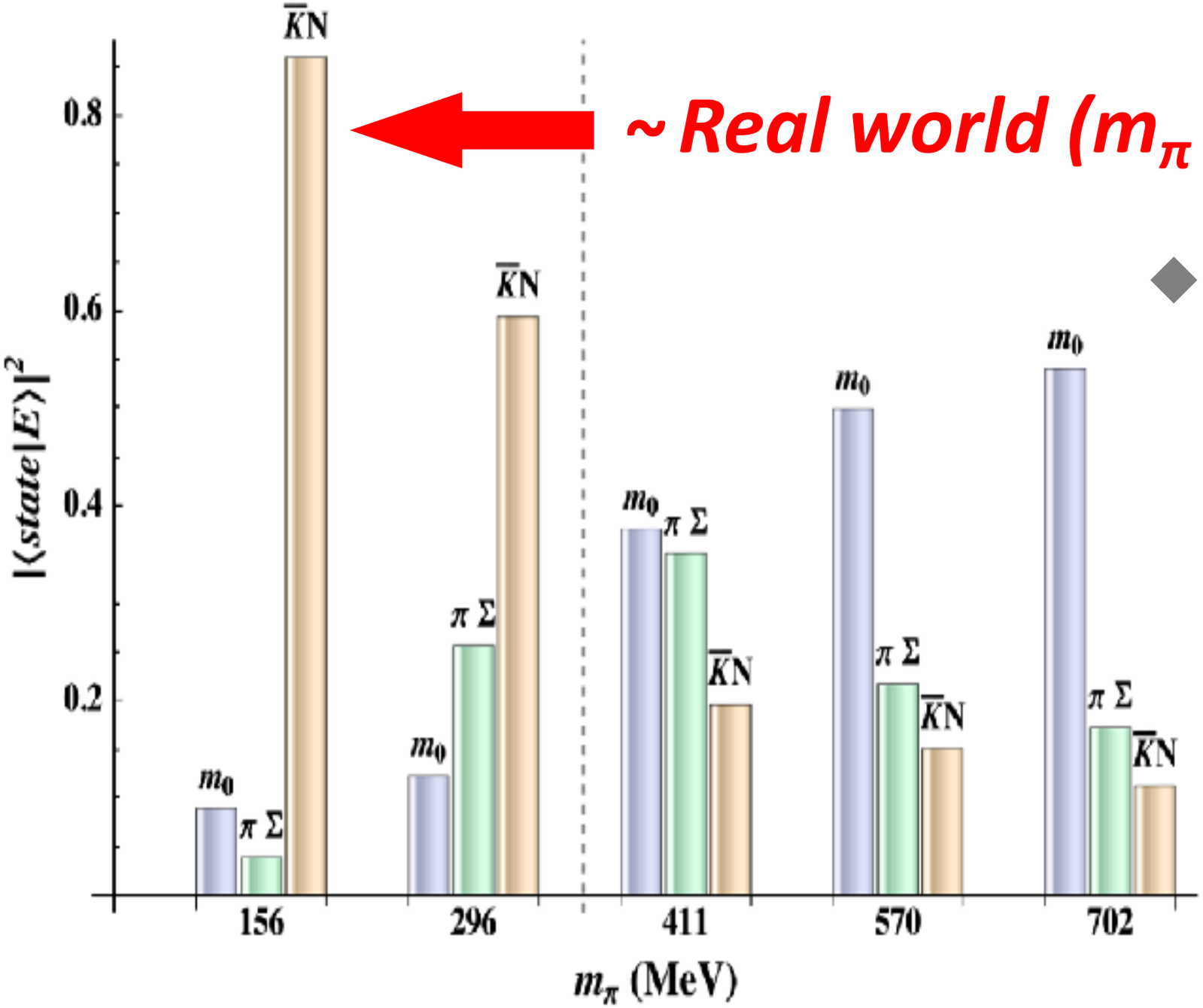
A. Dote, H. Horiuchi, Y. Akaishi and T. Yamazaki, Phys. Lett. B 590 (2004) 51

Kaon mass in nuclear medium?



1.T. Waas *et al. Physics Letters B* **379**, 34–38 (1996).

$\Lambda(1405)$ structure from Lattice QCD calculation



~ *Real world (m_π = 140 MeV/c²)*

- **Recent Lattice QCD supports,**

$$\Lambda(1405) = p - K^-$$

$$= (uud)\text{-}(\bar{u}s)$$

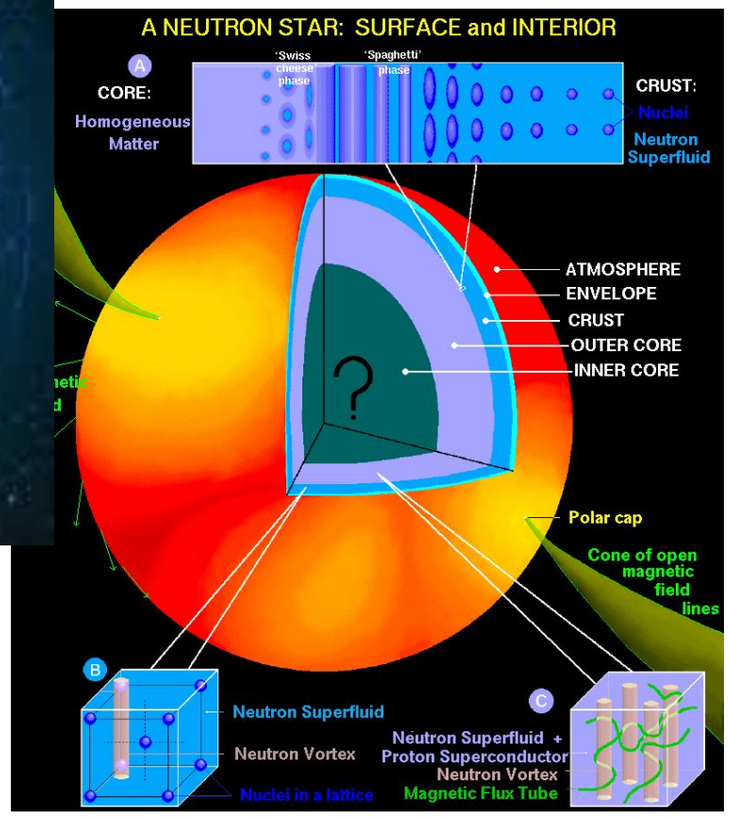
J.M.M. Hall et al., Phys. Rev. Lett. 114(2015)132002.

Particle fraction in dense nuclear matter – a possibility –

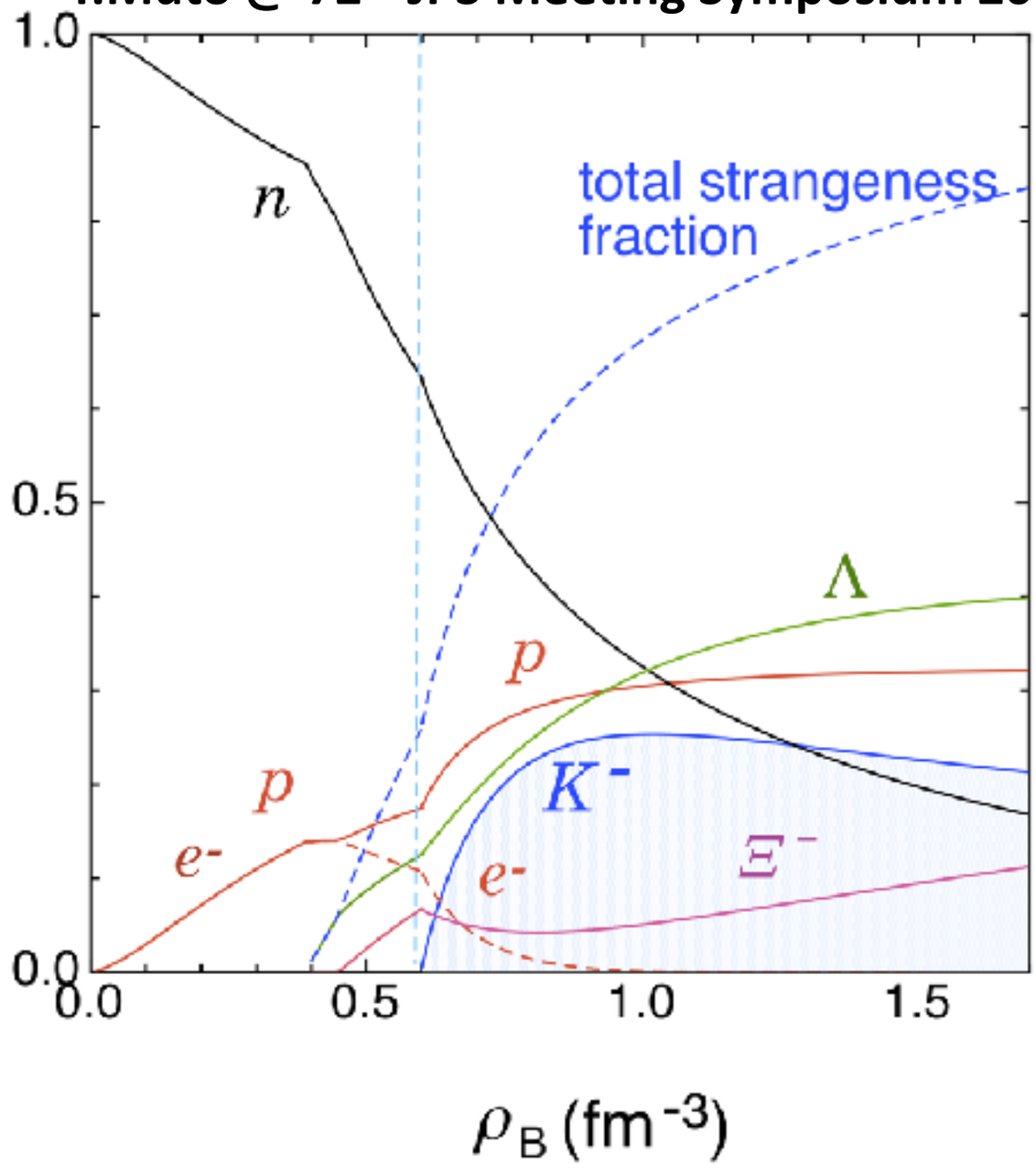
Does kaon can be born spontaneously in star matter?

EOS might be too soft…

http://pl.wikipedia.org/wiki/Gwiazda_neutronowa#mediaviewer/File:Chandra-crab.jpg



T.Muto @ 72th JPS Meeting Symposium 2017



What is the structure found in E15[1st] data?

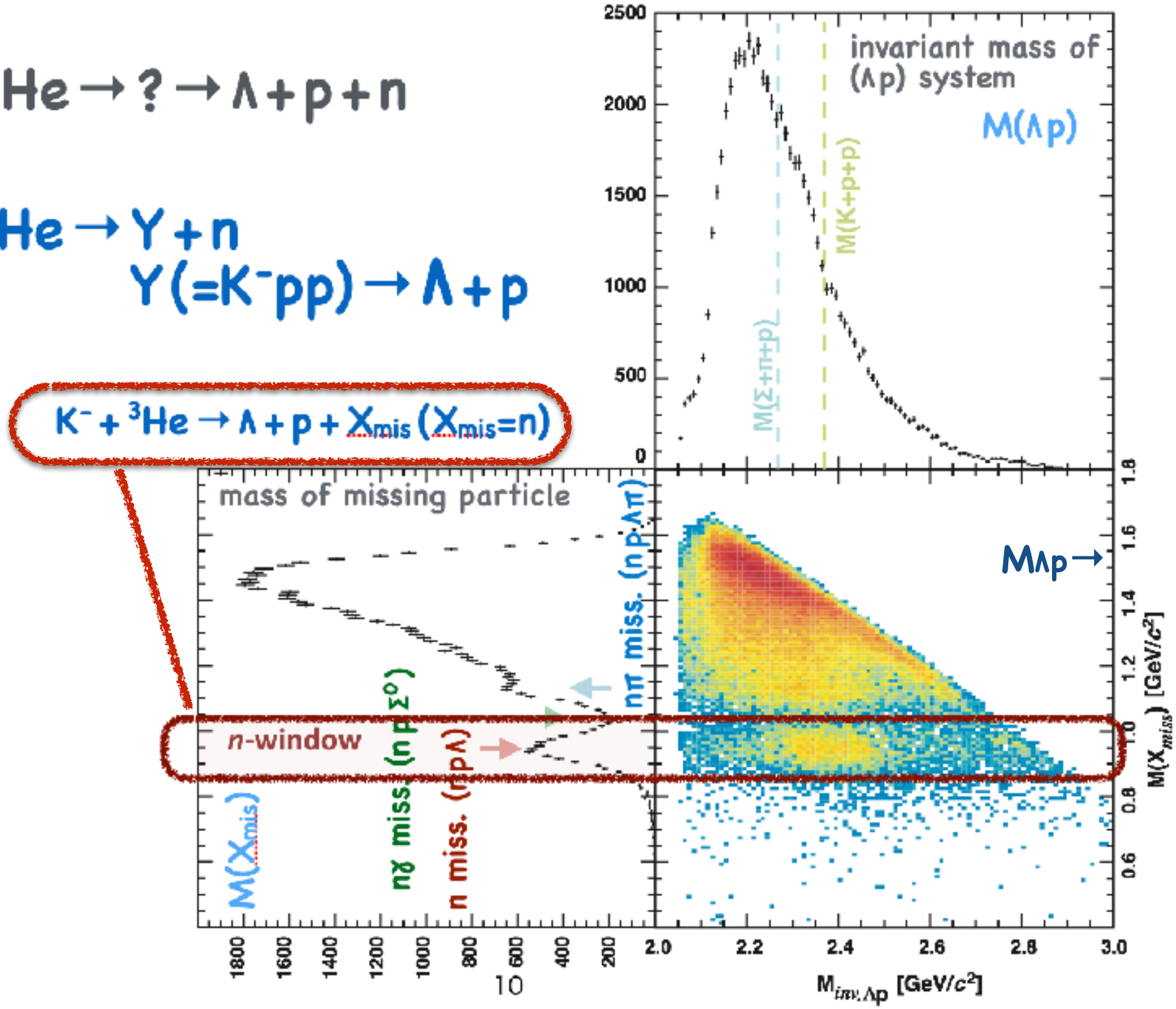
Improving statistics via E15[2nd] data

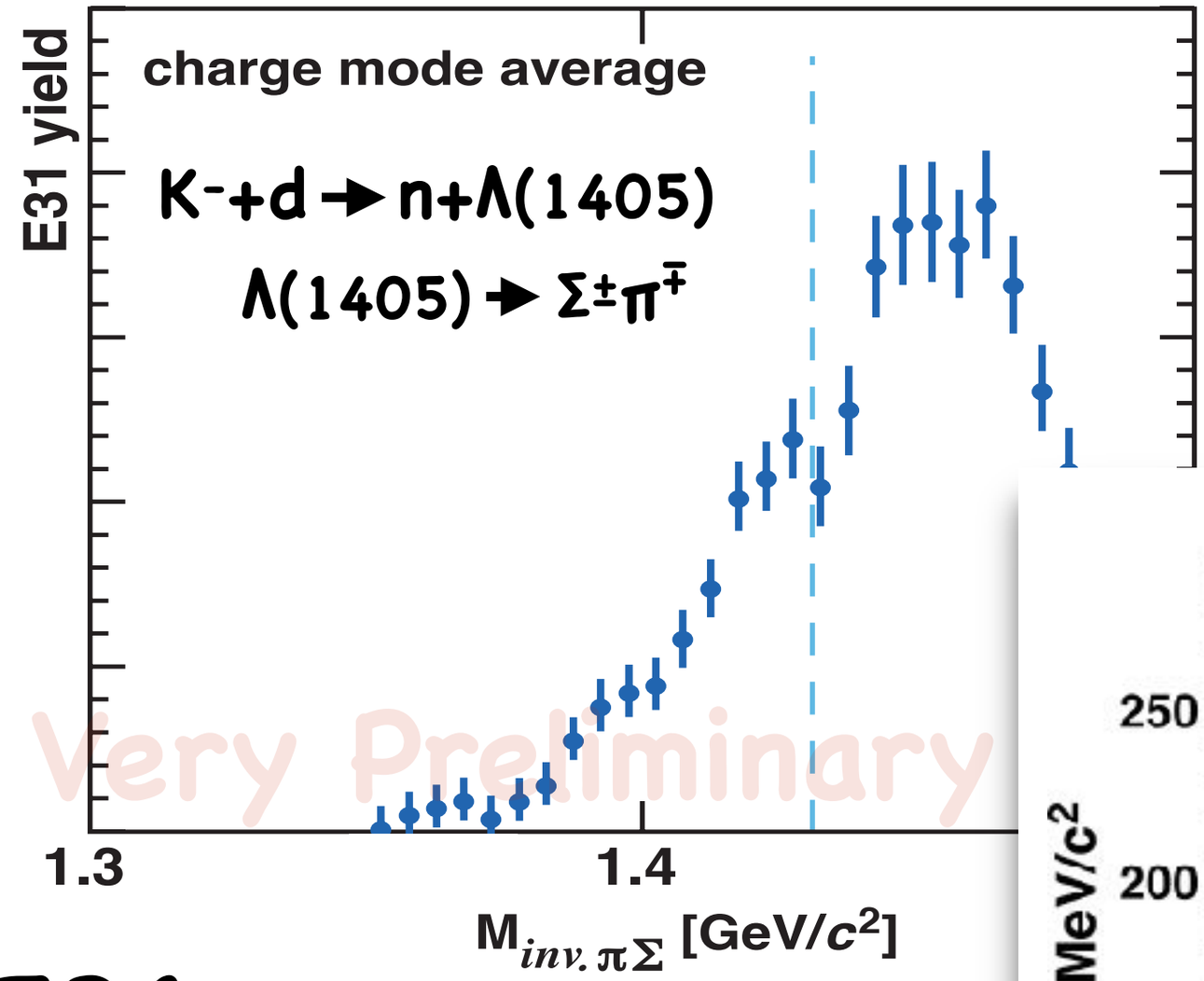
$K^- + {}^3He \rightarrow ? \rightarrow \Lambda + p + n$

$K^- + {}^3He \rightarrow Y + n$

$Y(=K^-pp) \rightarrow \Lambda + p$

$K^- + {}^3He \rightarrow \Lambda + p + X_{mis}\ (X_{mis}=n)$





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E31:

$K^-+d \rightarrow n+\Lambda(1405)$

$\Lambda(1405) \rightarrow \Sigma^{\pm}\pi^{\mp}$