Search for the Kaonic Bound State $K^{bar}NN$ at J-PARC

via Λp and $\pi\Sigma p$ decay channels

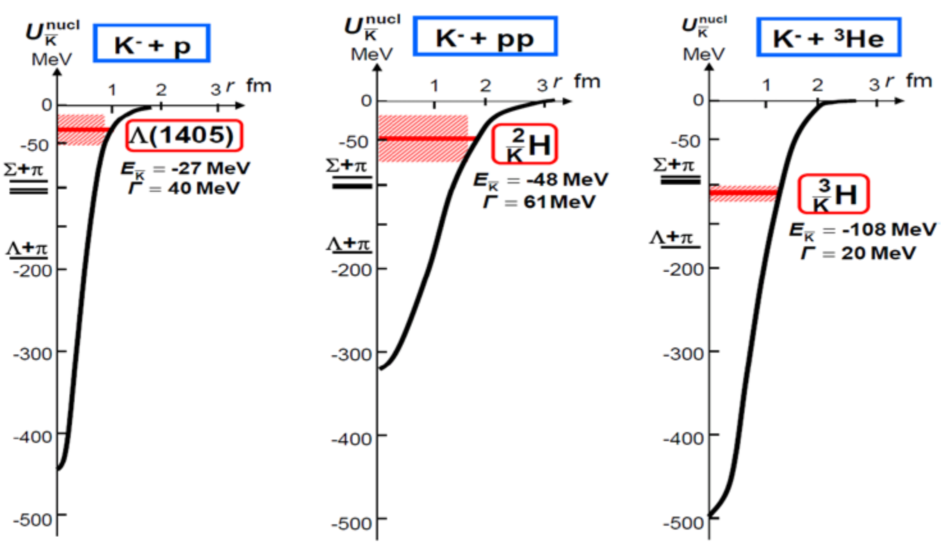
F. Sakuma, RIKEN

on behalf of the J-PARC E15 collaboration

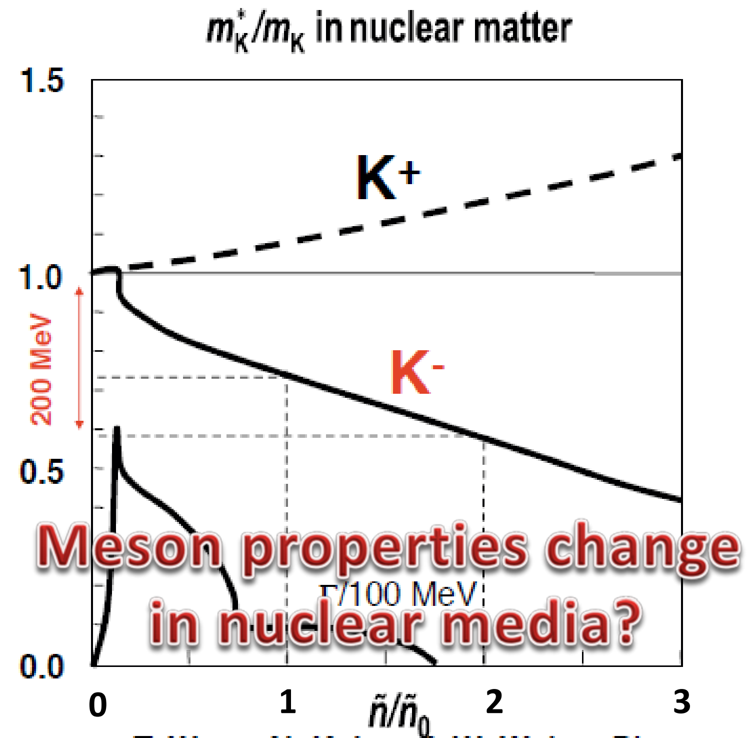
MESON2018, June 7-12, 2018, KRAKÓW, POLAND

Kaonic Nuclei

- Bound states of nucleus and anti-kaon
- Predicted as a consequence of **attractive $K^{bar}N$ interaction in I=0**



Y.Akaishi & T.Yamazaki, PLB535, 70(2002).

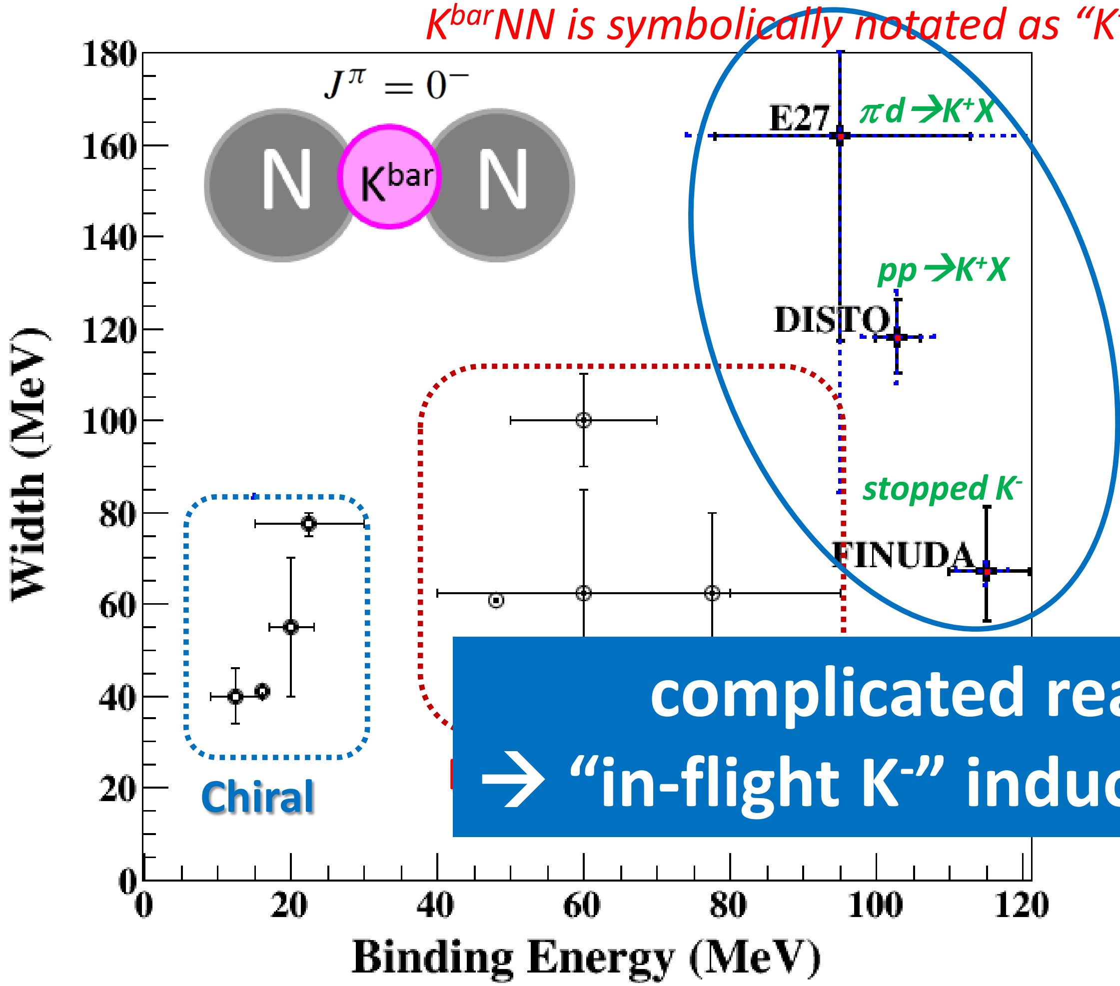


T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

- Will provide new insight on $K^{bar}N$ interaction in media

Present Status of $K^{bar}NN$ = “$K^{-}pp$”

$K^{bar}NN$ is symbolically notated as “$K^{-}pp$” in this talk



complicated reactions
→ “in-flight K^{-}” induced reaction

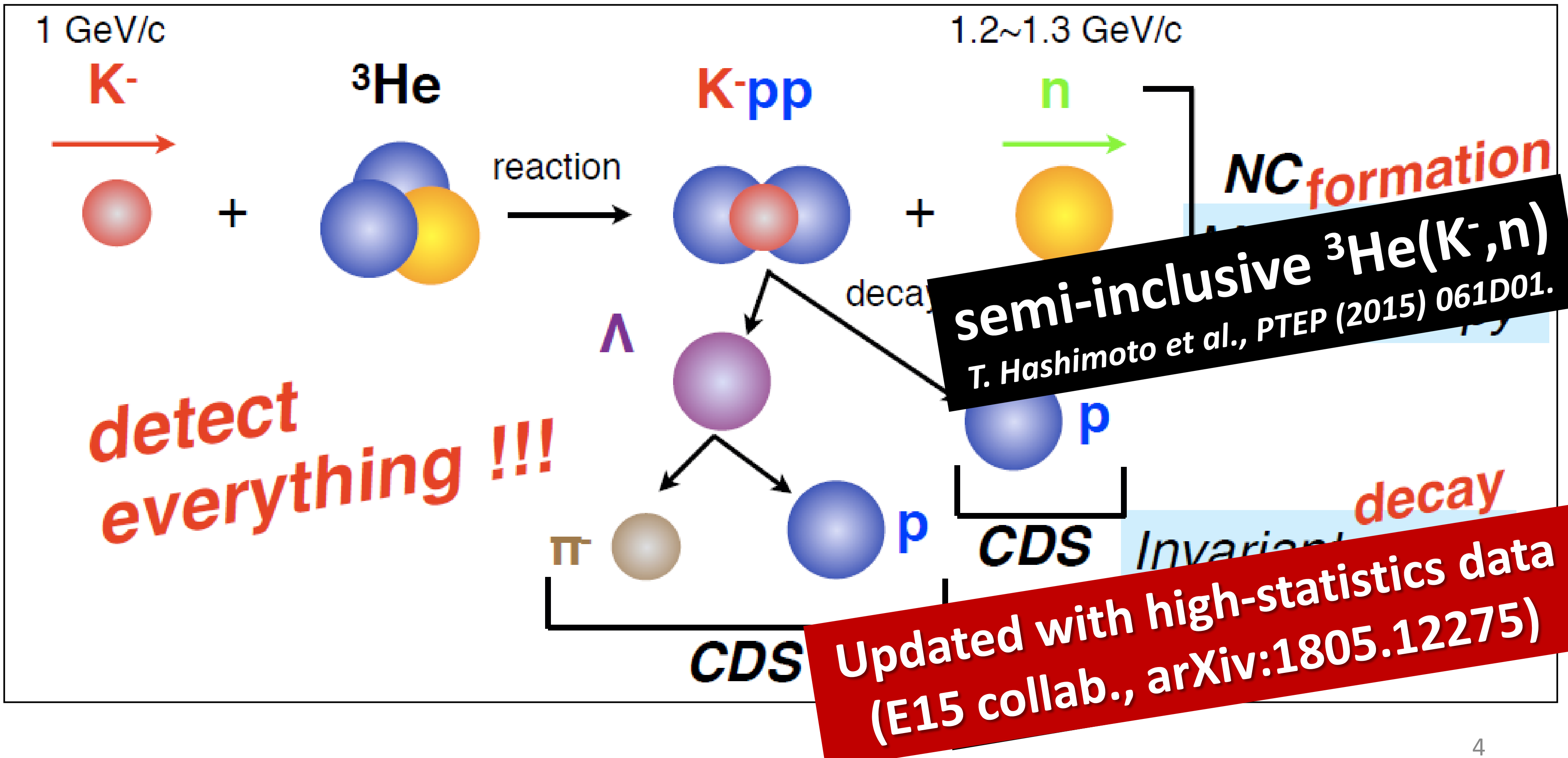
Upper limits were also obtained:

- **LEPS@SPring8 [Inclusive $d(\gamma, K^{+}\pi^{-})X$]**
- **HADES@GSI [Exclusive $pp \rightarrow p\Lambda K^{+}$]**

J-PARC E15 Experiment

- ^{3}He(*in-flight* K$^-$,n) reaction @ 1.0 GeV/c

2NA processes and Y decays can be discriminated kinematically



“K^-pp” in ^{3}He(K^-,Λp)n

“K^-pp”, a $\overline{K}$-Meson Nuclear Bound State, Observed in ^{3}He(K^-, Λp)n Reactions

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

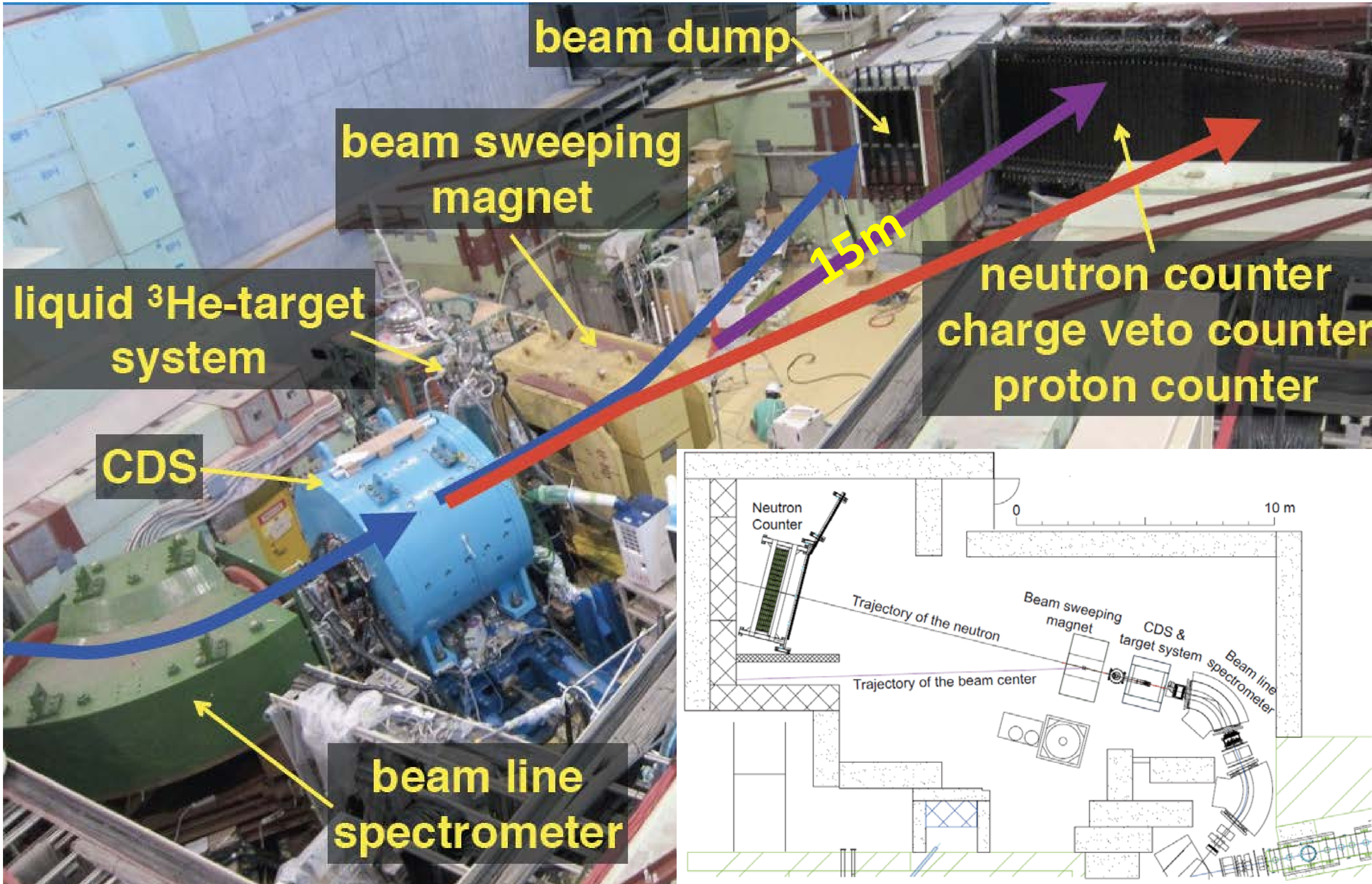
[1] *Osaka University, Osaka, 567-0047, Japan*
[2] *RIKEN, Wako, 351-0198, Japan*
[3] *University of Victoria, Victoria BC V8W 3P6, Canada*
[4] *Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria*
[5] *Seoul National University, Seoul, 151-742, South Korea*
[6] *National Institute of Physics and Nuclear Engineering - IFIN HH, Bucharest - Magurele, Romania*
[7] *INFN Sezione di Torino, 10125 Torino, Italy*
[8] *Università di Torino, Torino, Italy*
[9] *Laboratori Nazionali di Frascati dell' INFN, [illegible]00044 Frascati, Italy*
[10] *High Energy Accelerator Research [illegible] (KEK), Tsukuba, 305-0801, Japan*
[11] *Tokyo Institute of Technology, Tokyo, [illegible]52-8551, Japan*
[12] *The University of Tokyo, Tokyo, 11[illegible]0033, Japan*
[13] *Osaka Electro-Communication University, Osaka, 572-8530, Japan*
[14] *Japan Atomic Energy Agency, Ibaraki 319-1195, Japan*
[15] *Kyoto University, Kyoto, 606-8502, Japan*
[16] *Technische Universität München, D-85748, Garching, Germany*
[17] *Tohoku University, Sendai, 982-0826, Japan and*
[18] *Lund University, Lund, 221 00, Sweden*

(J-PARC E15 Collaboration)

We observed a distinct resonance peak in the Λp invariant-mass spectrum of ^{3}He(K^-, Λp)n, well below the mass threshold of $M(K^-pp)$. By selecting a relatively large momentum-transfer region $q = 350 \sim 650$ MeV/c, one can clearly separate the resonance peak from the quasi-free process, $\overline{K}N \to \overline{K}N$ followed by the non-resonant absorption by the two spectator-nucleons $\overline{K}NN \to \Lambda N$. We found that the simplest fit to the observed peak gives us a Breit-Wigner pole at $B_{Kpp} = 47 \pm 3\,(stat.)\,^{+3}_{-6}\,(sys.)$ MeV having a width $\Gamma_{Kpp} = 115 \pm 7\,(stat.)\,^{+10}_{-9}\,(sys.)$ MeV, and the S-wave Gaussian reaction form-factor parameter $Q_{Kpp} = 381 \pm 14\,(stat.)\,^{+57}_{-0}\,(sys.)$ MeV/c, as a new form of the nuclear bound system with strangeness – “K^-pp”.

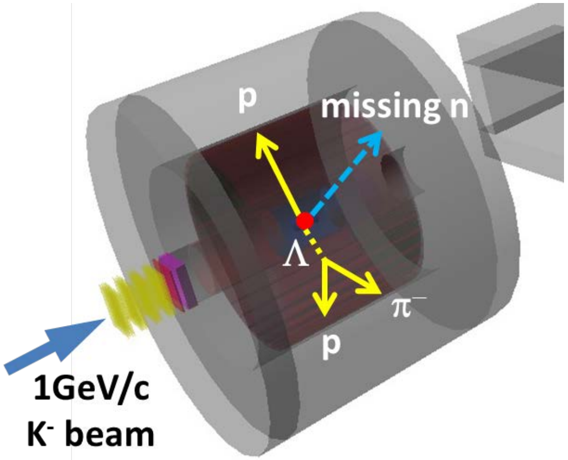
Since the prediction of the π-meson by Yukawa [1], there has been a long-standing question as to whether a mesonic nuclear bound state exists. Mesons are introduced as mediators between nucleons to confine them in vacuum one needs energy m to produce them. If a mesonic nuclear bound state exists, it will form a quantum state at an energy E_M below m whose binding energy $B_M = m - E_M$. Many mesons have been examined

Experimental Setup @ K1.8BR

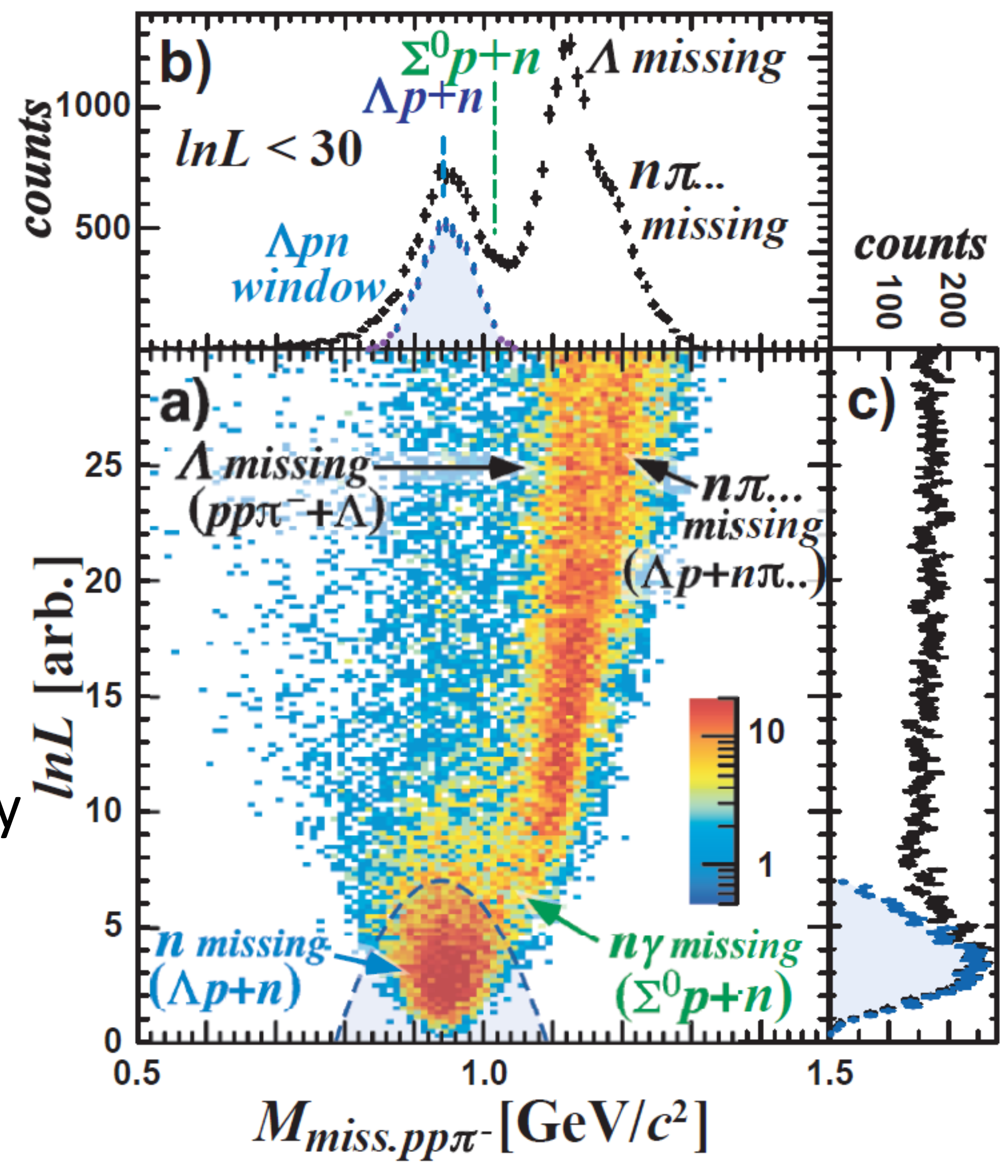


K. Agari et. al., PTEP 2012, 02B011

^{3}He + K$^-$ → Λ p n Selection



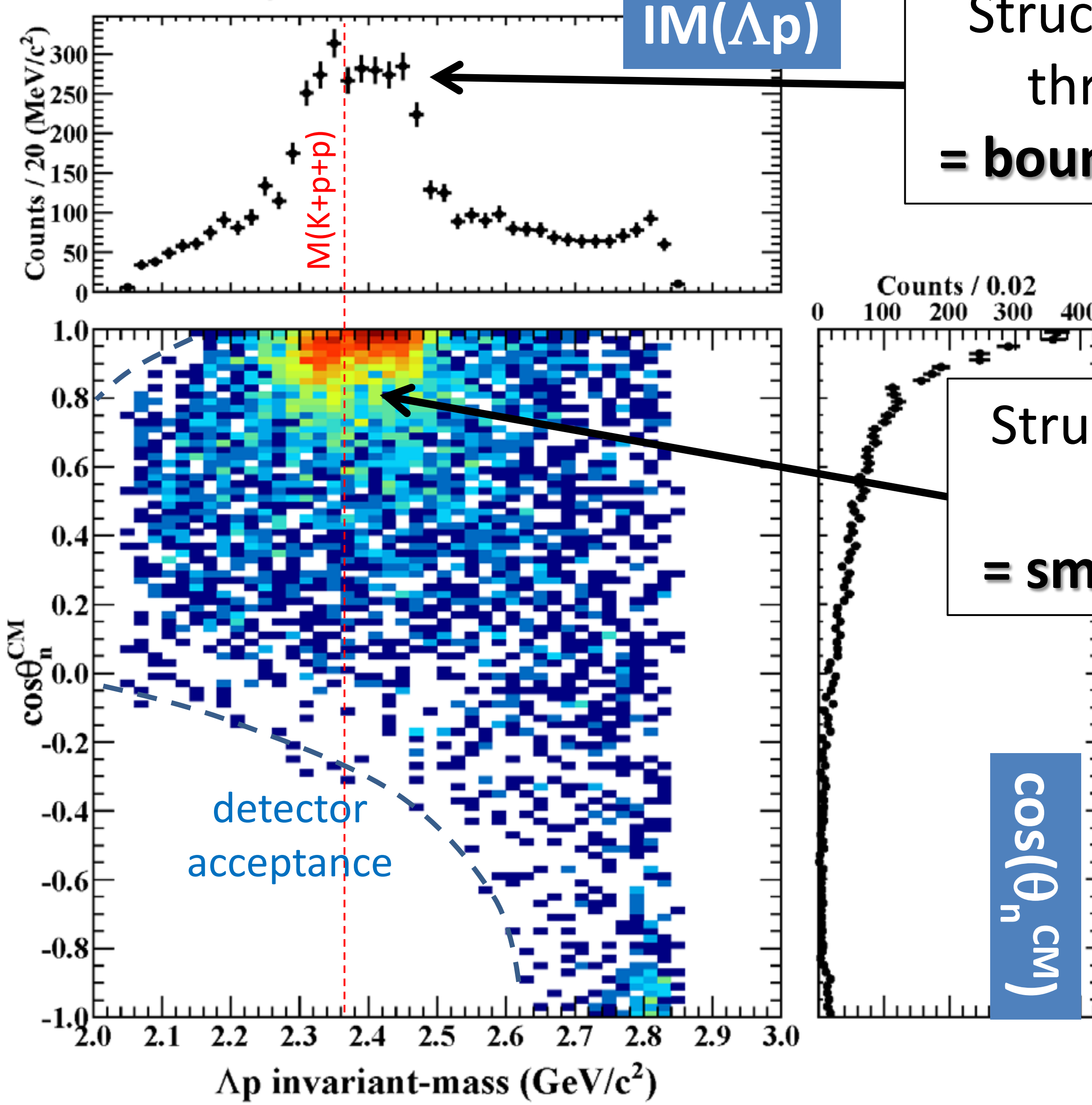
E15 collab., arXiv:1805.12275



- Λ→π$^-$p and p are detected with CDS
  - A missing neutron is identified by missing-mass of ^{3}He(K$^-$,Λp)n
- Λpn$_{miss}$ events are selected by log-likelihood method (*ln*L)
  - distance-of-closest-approach for each vertex
  - kinematical constraint

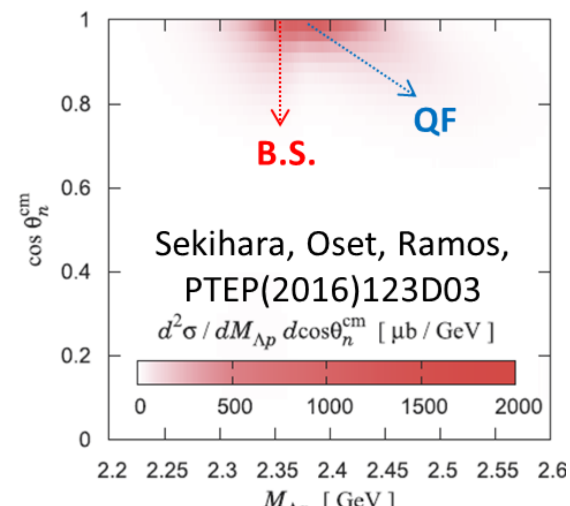
IM(Λp) vs. cos(θ_n^{CM})

E15 collab., arXiv:1805.12275



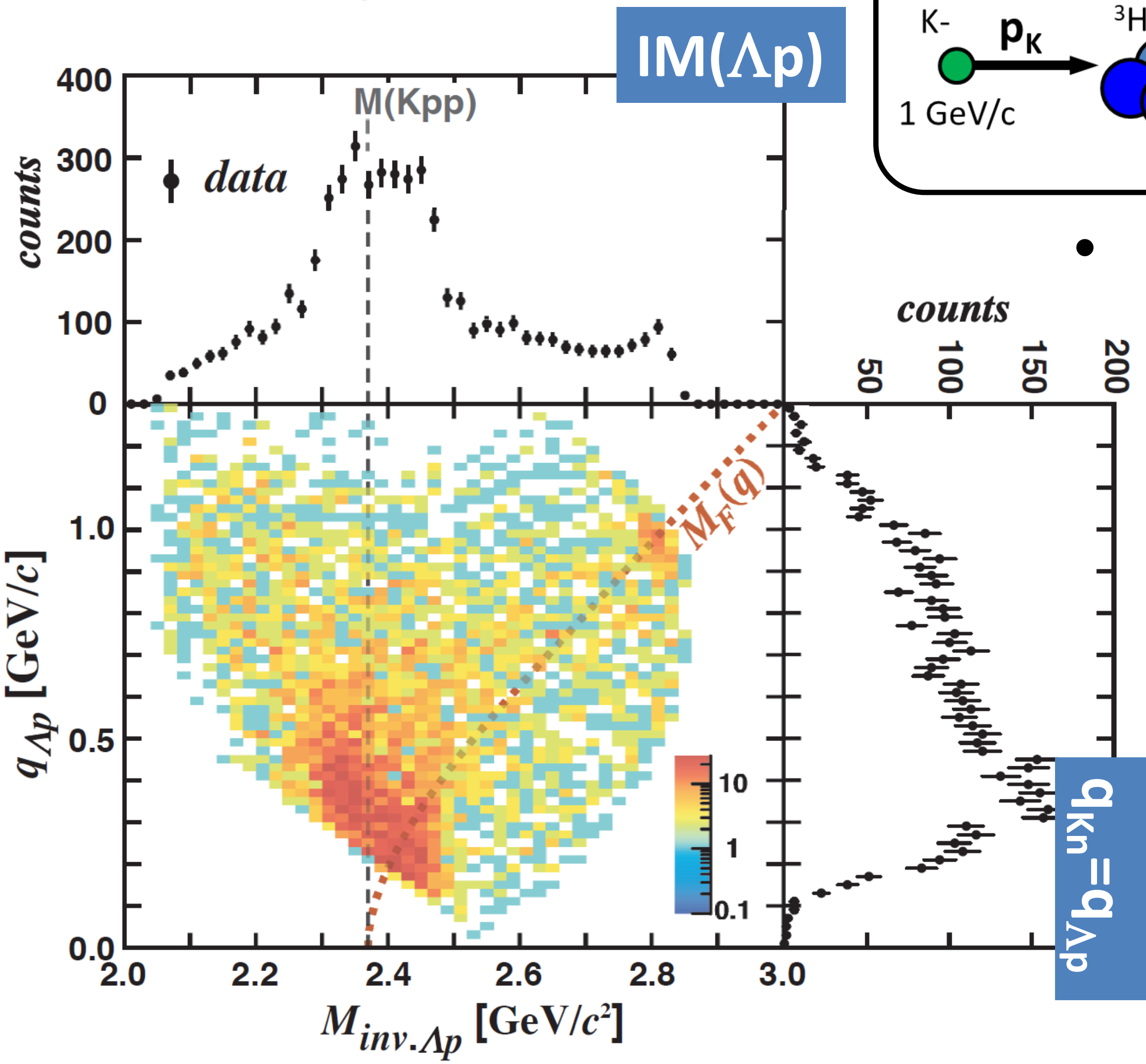
Structures around the K⁻pp threshold can be seen
= bound-state + quasi-elastic

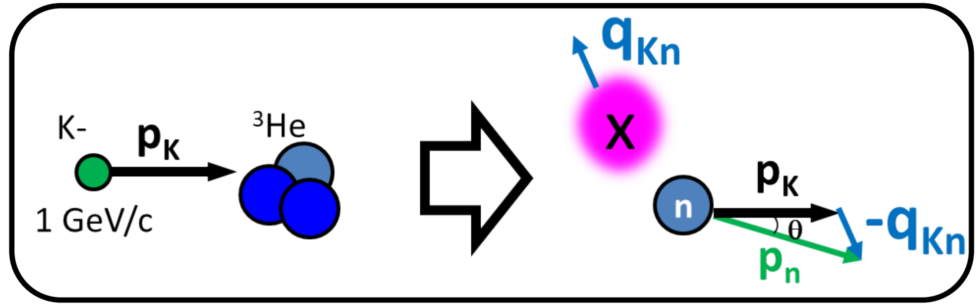
Structures are concentrated in forward-n region
= small momentum-transfer



IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275

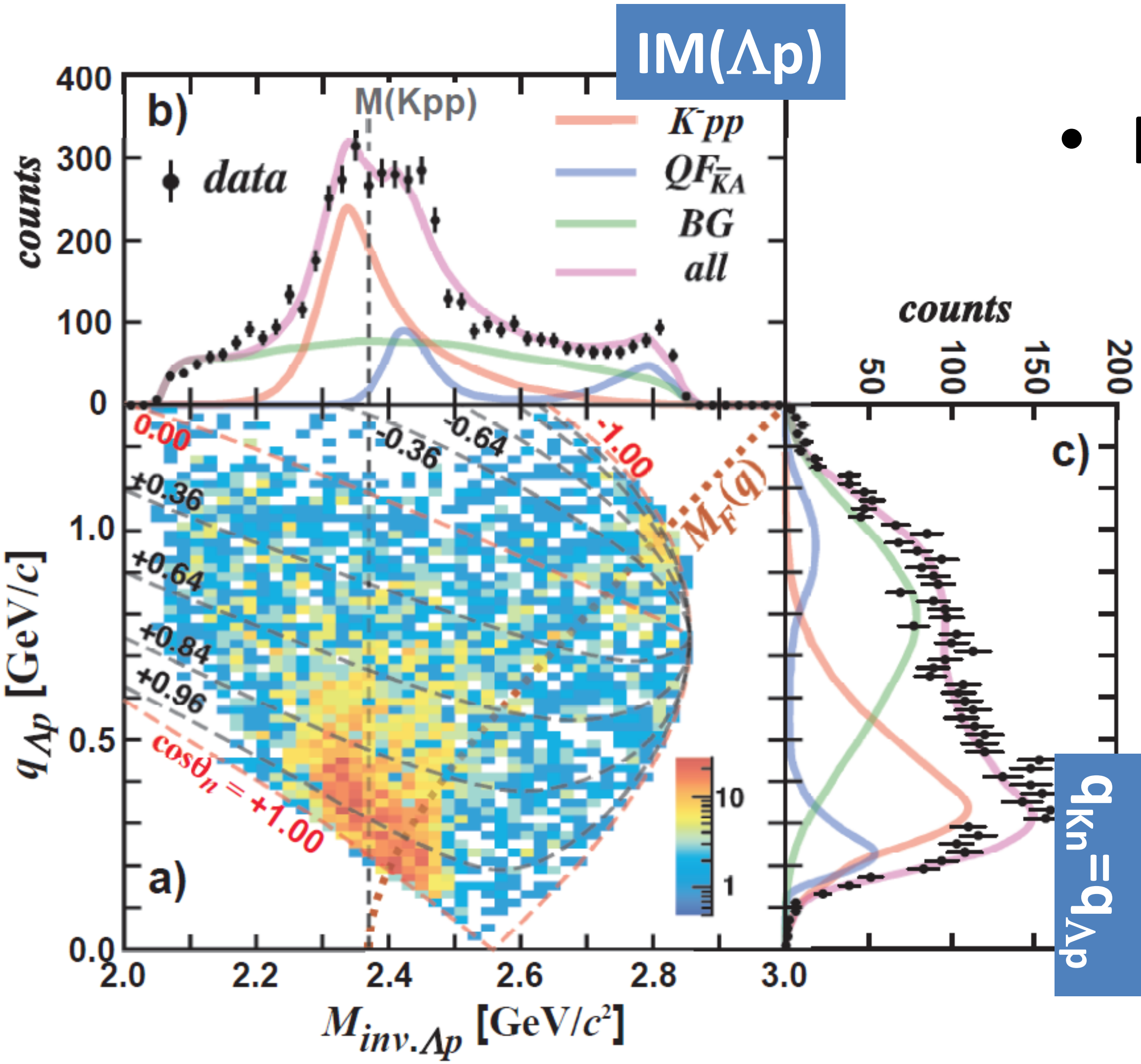




- Seems to consist of 3 components
  - **Bound state**
    - centroid NOT depend on q_{Kn}
  - **Qasi-elastic K^- abs.**
    - centroid depends on q_{Kn}
  - **Background**
    - Broad distribution

IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275



** We conduct the fitting in each 2D bin*

- Fit with 3 components
  - **Bound state**
    - **centroid NOT depend on q_{Kn}**
    - BW*(Gauss form-factor)

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

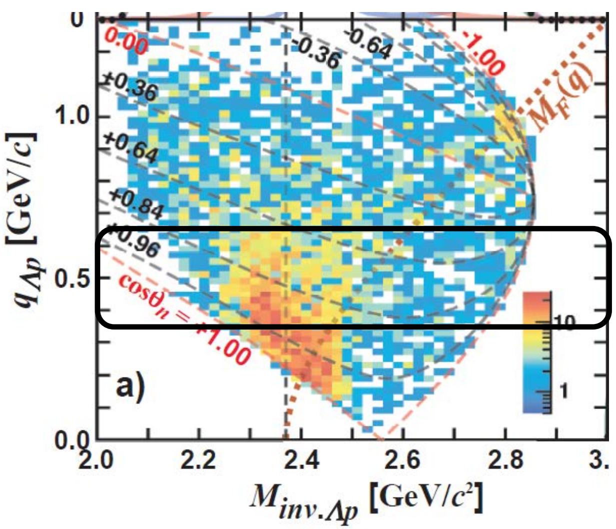
  - **Qasi-elastic K^- abs.**
    - **centroid depends on q_{Kn}**
    - Followed by Λp conversion
  - **Background**
    - Broad distribution

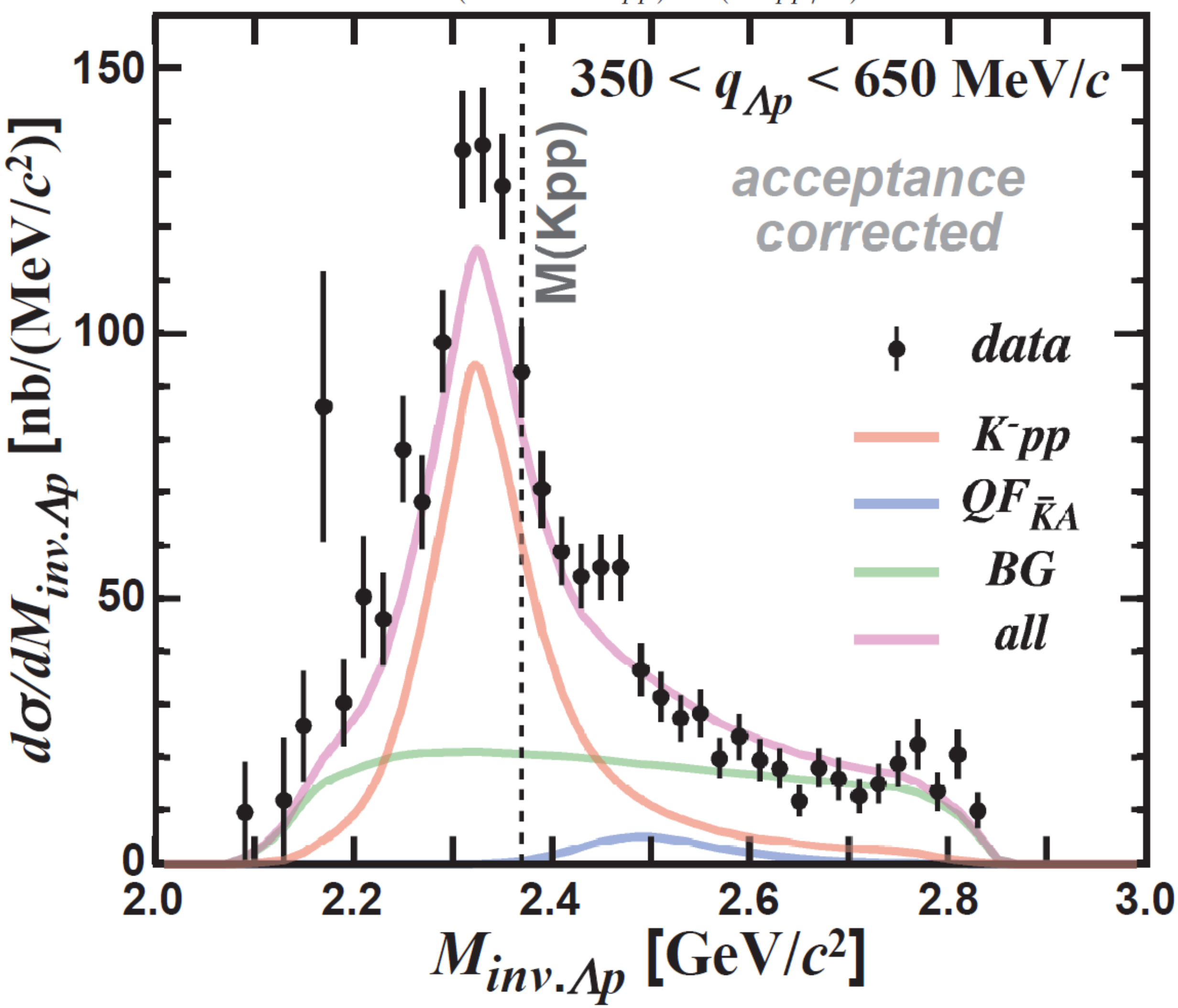
“K⁻pp” Bound-State

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

Select $0.35<q_{Kn}<0.65$ GeV/c

- BS and QF are well separated

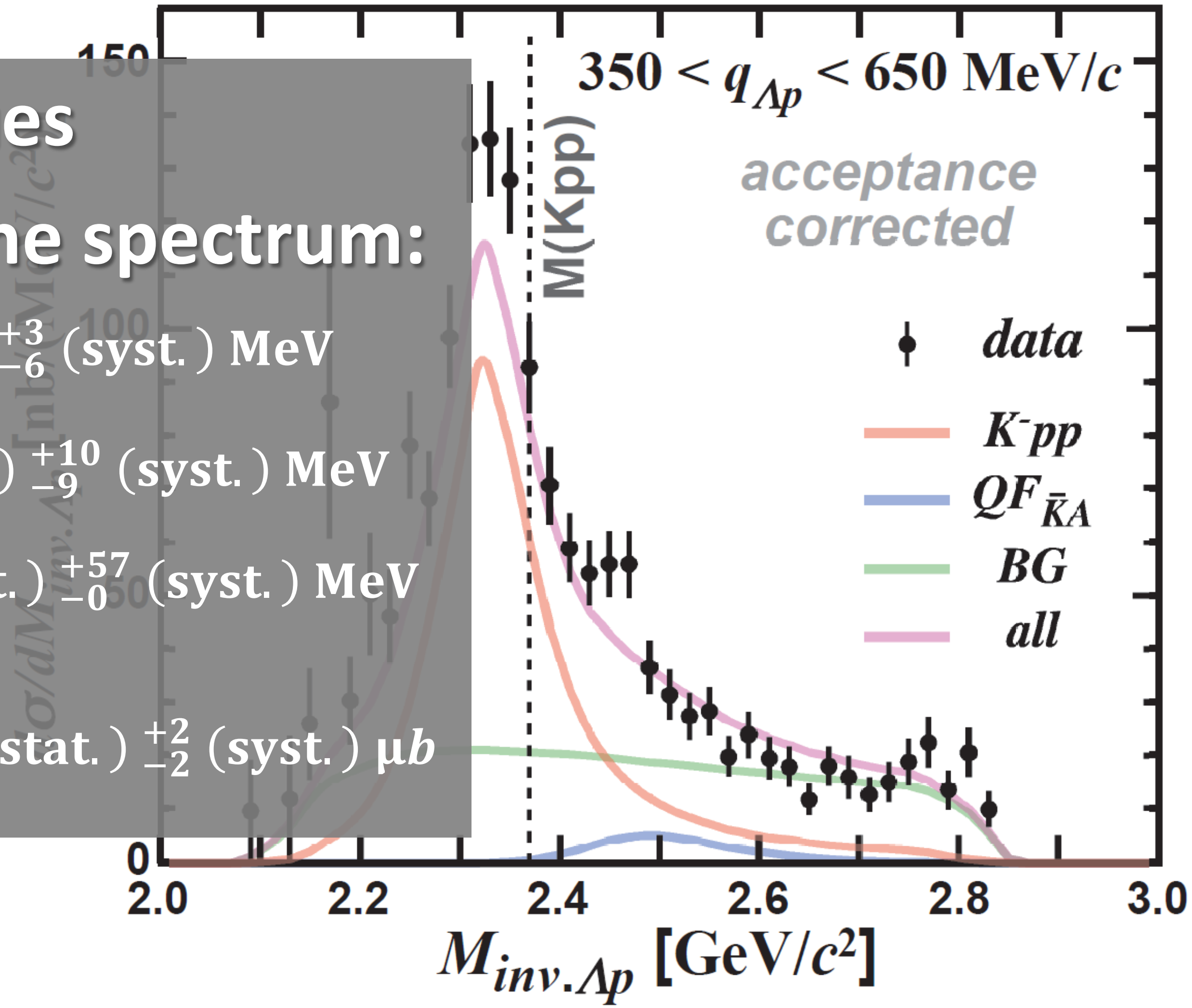




E15 collab., arXiv:1805.12275

“K⁻pp” Bound-State

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



Fit values that reproduce the spectrum:

$B_{\text{"Kpp"}} = 47 \pm 3\,(\text{stat.})\,^{+3}_{-6}\,(\text{syst.})$ MeV

$\Gamma_{\text{"Kpp"}} = 115 \pm 7\,(\text{stat.})\,^{+10}_{-9}\,(\text{syst.})$ MeV

$Q_{\text{"Kpp"}} = 381 \pm 14\,(\text{stat.})\,^{+57}_{-0}\,(\text{syst.})$ MeV

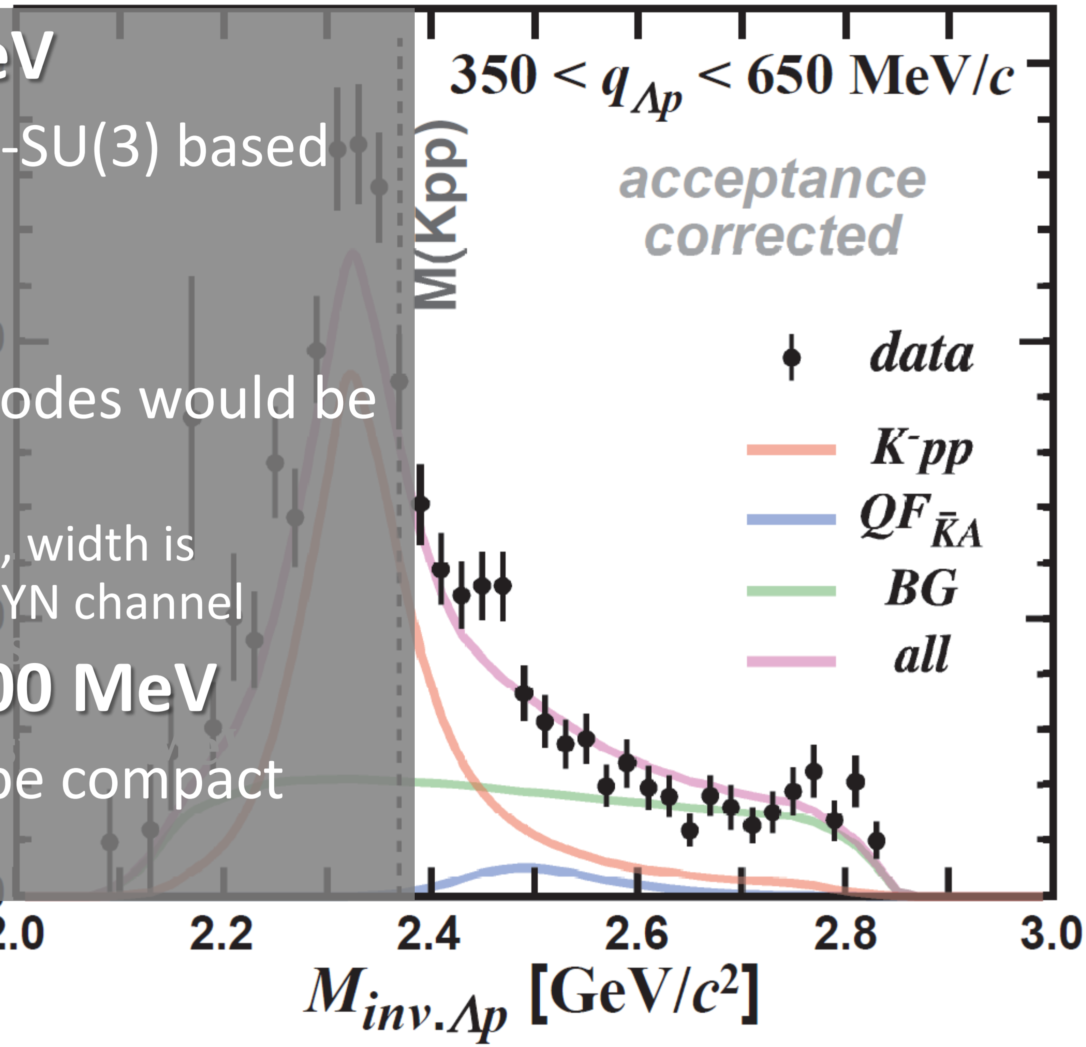
at below the $M(K^{-}pp)$
$\sigma_{\text{"Kpp"}} \cdot Br_{\Lambda p} = 15 \pm 1\,(\text{stat.})\,^{+2}_{-2}\,(\text{syst.})\ \mu b$

E15 collab., arXiv:1805.12275

“K⁻pp” Bound-State

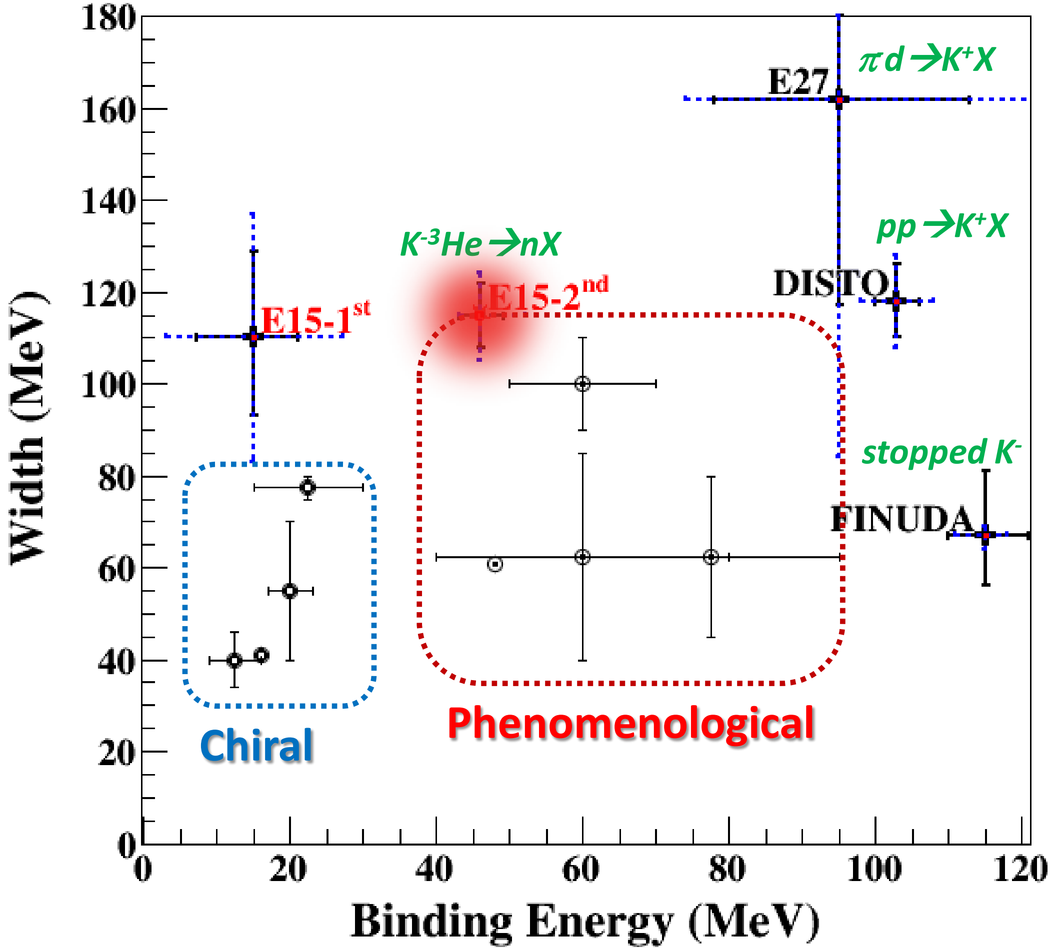
$$f_{\{Kpp\}}(M,q) = \frac{A_{Kpp}\ (\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2}\ e^{-\left(\frac{q}{Q_{Kpp}}\right)^2},$$

- **Binding energy: ~50 MeV**
  - Much deeper than chiral-SU(3) based theoretical predictions
- **Width: ~100 MeV**
  - Non-meonic YN decay modes would be dominant
    - in theoretical calculations, width is evaluated with mesonic πYN channel
- **S-wave form factor: ~400 MeV**
  - $K^- + {}^3$He reaction would be compact (~0.5 fm)



E15 collab., arXiv:1805.12275

Present Status of "K⁻pp"

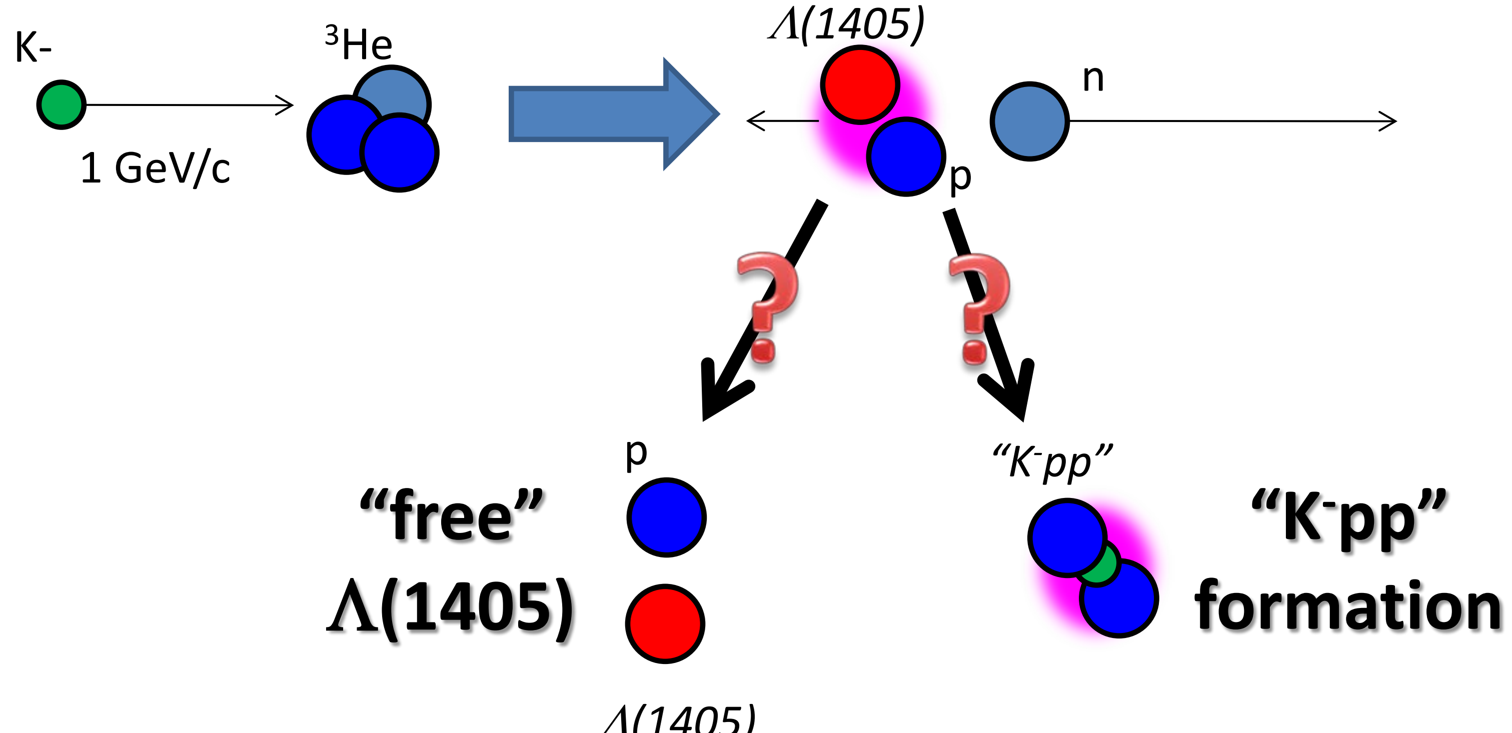


For further understandings:

✓ Λ(1405) production → Λ*N doorway

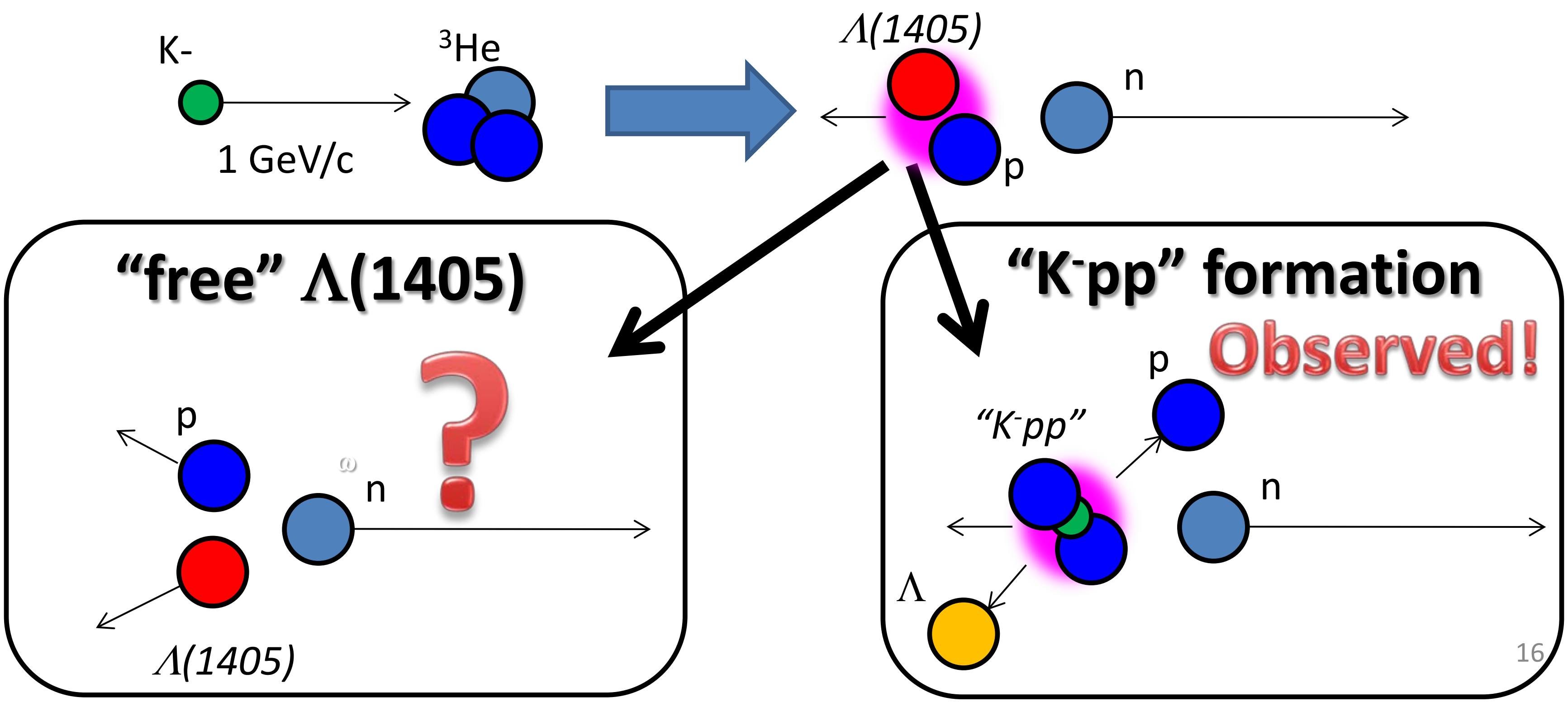
✓ πΣN decay channel → new info. of $K^{bar}NN$

$\Lambda(1405)$ in $^3He(K^-,\pi\Sigma p)n$



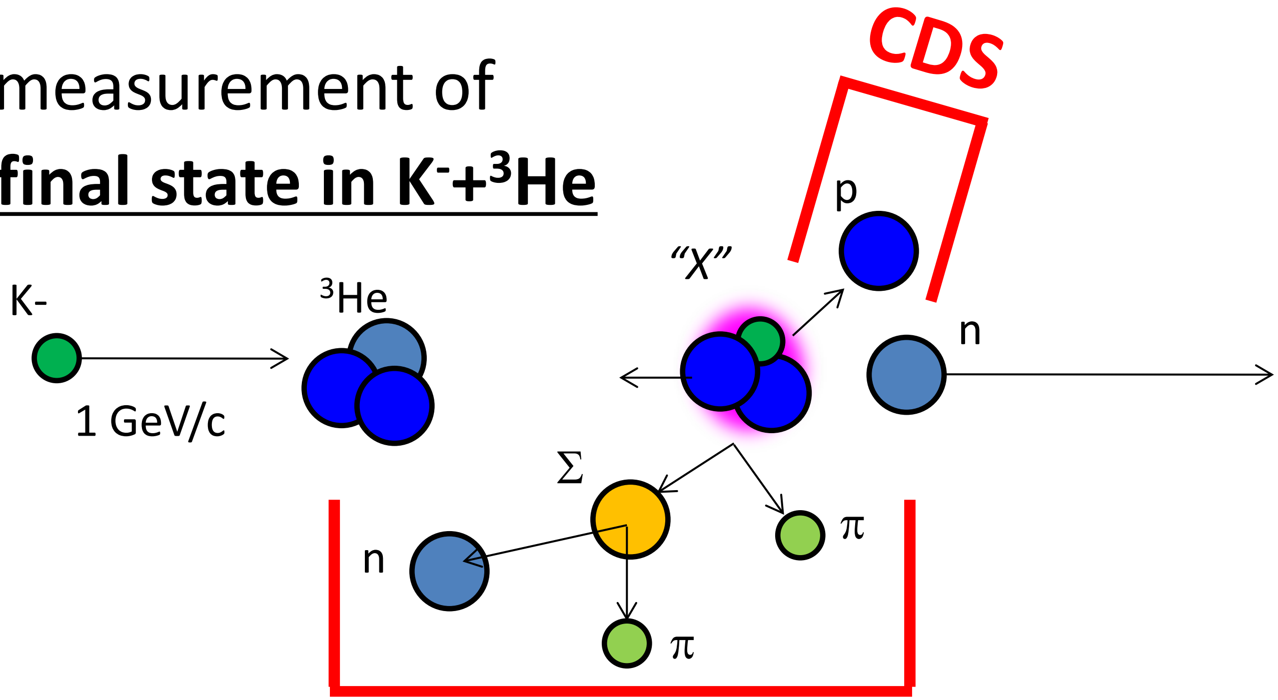
Λ(1405)p and "K⁻pp"

- Theoretically, "K⁻pp" is expected to be produced via **<u>Λ(1405)+p→"K⁻pp" door-way process</u>**
  - comparison between Λ(1405)p and "K⁻pp" production would give us an important information



$K^{-}\ {}^{3}He \rightarrow \pi\Sigma pn$ @ E15

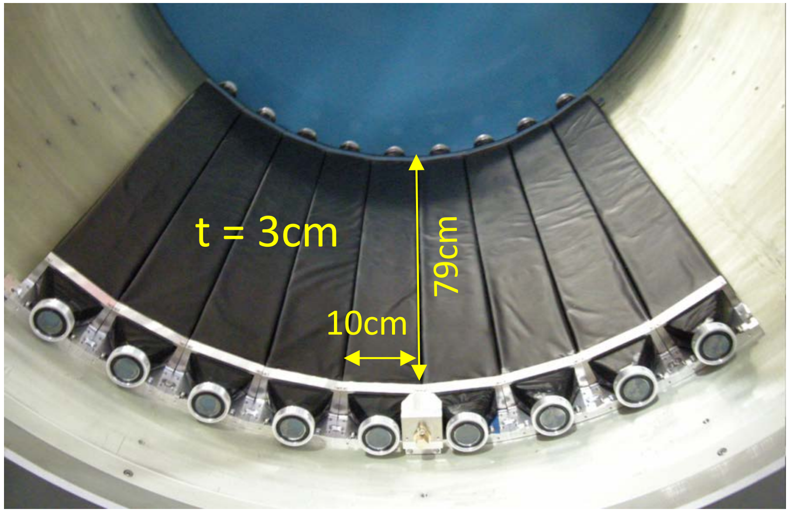
- Exclusive measurement of **$\pi^{\pm}\Sigma^{\mp}pn$ final state in $K^{-}+{}^{3}He$**



- **Experimental challenge** of neutron detection with thin scintillation counter (t=3cm)

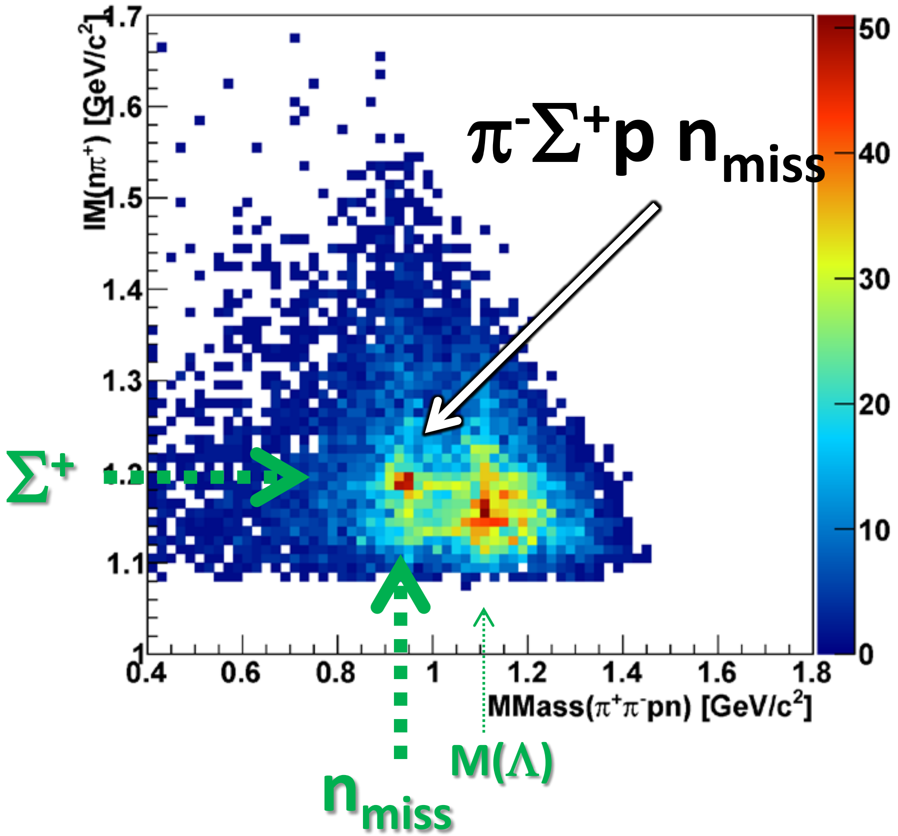
n detection efficiency ~ 3%

CDS

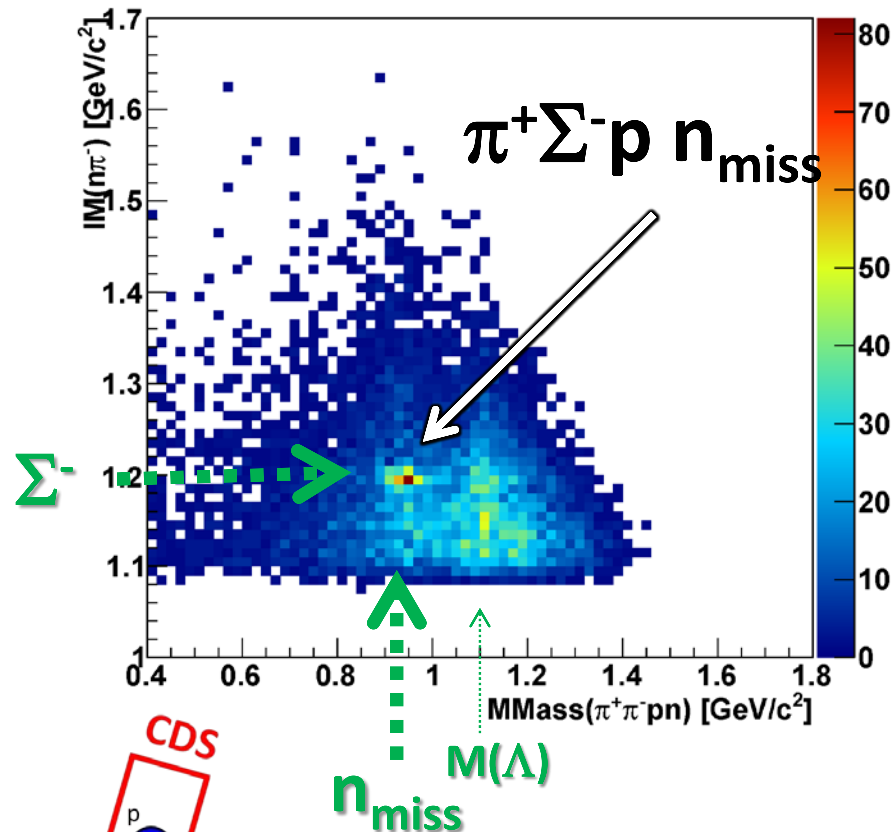


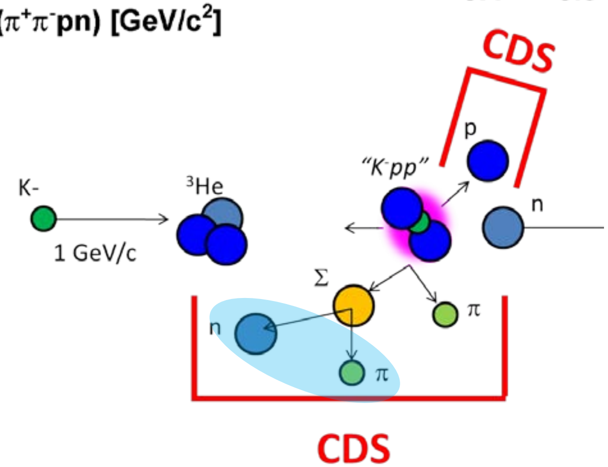
$\pi\Sigma pn$ Events

$IM(n\pi^+)$ vs $MM(\pi^+\pi^-pn)$



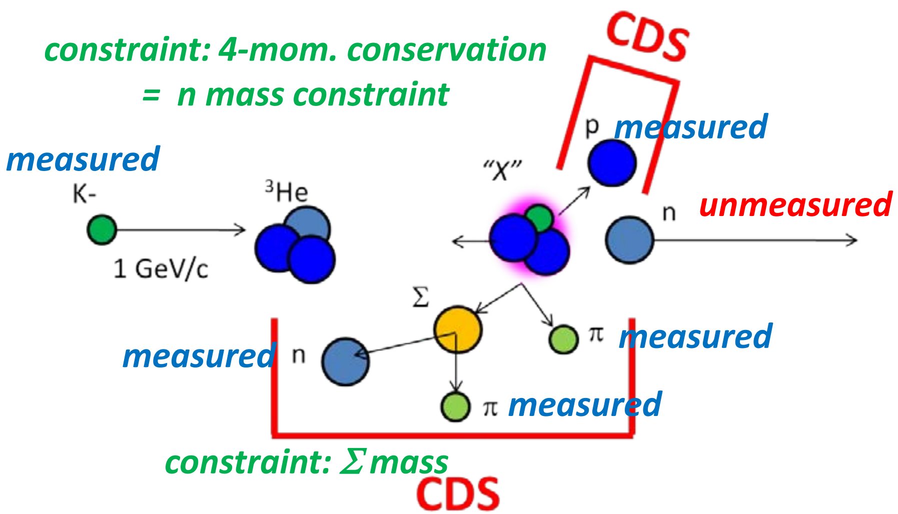
$IM(n\pi^-)$ vs $MM(\pi^+\pi^-pn)$

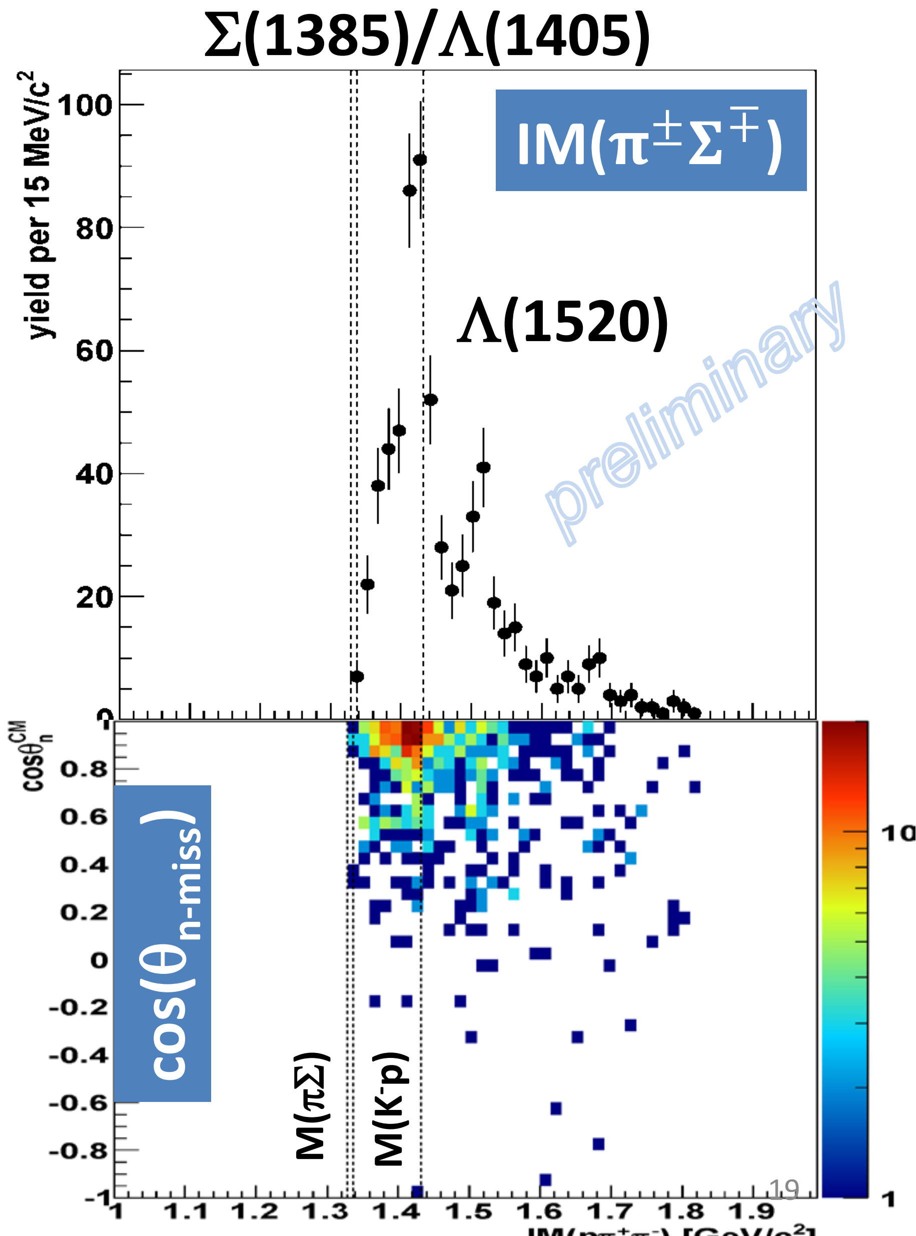




IM(πΣ) vs. cos(θ_n^{CM})

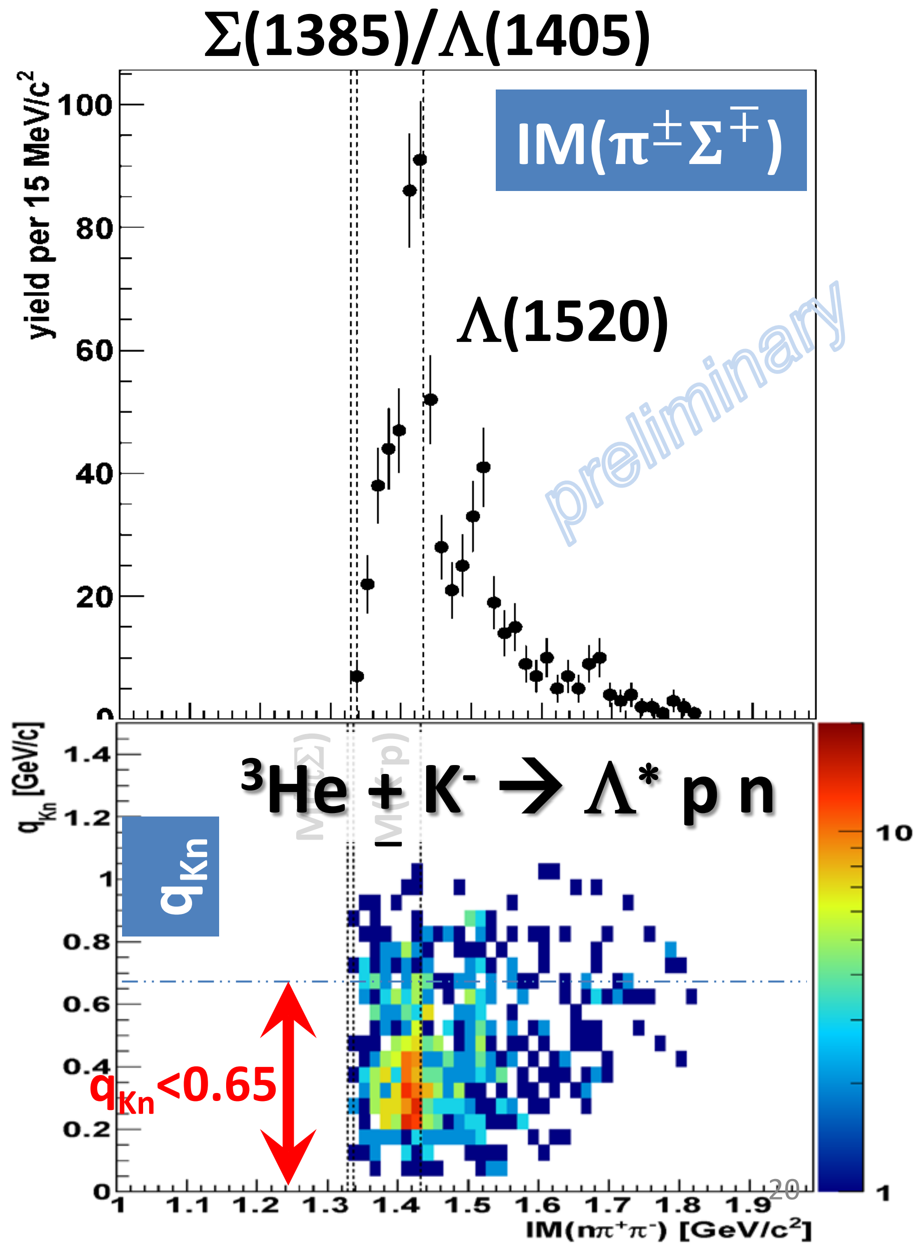
- $\pi^{\pm}\Sigma^{\mp}$ events are separated using kinematical-fit
  - Constraints:
    - M(Σ→nπ)
    - 4-momentum conservation
  - Event selection by χ^2 probability (0.01<p)



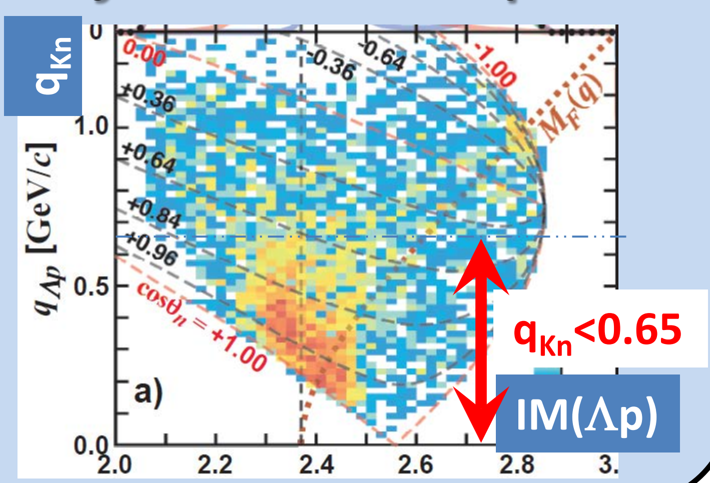


IM(πΣ) vs. Momentum Transfer q_{Kn}

- **To compare "K^-pp" and Λ^* production CS's, we select q_{Kn}<0.65 GeV/c region**
  - "K^-pp" and Λ^* signals can be seen in this region



***cf.* $^3He + K^- \rightarrow \Lambda\ p\ n$**



Y^* CS (q_{Kn}<0.65)

$\Lambda(1405)$

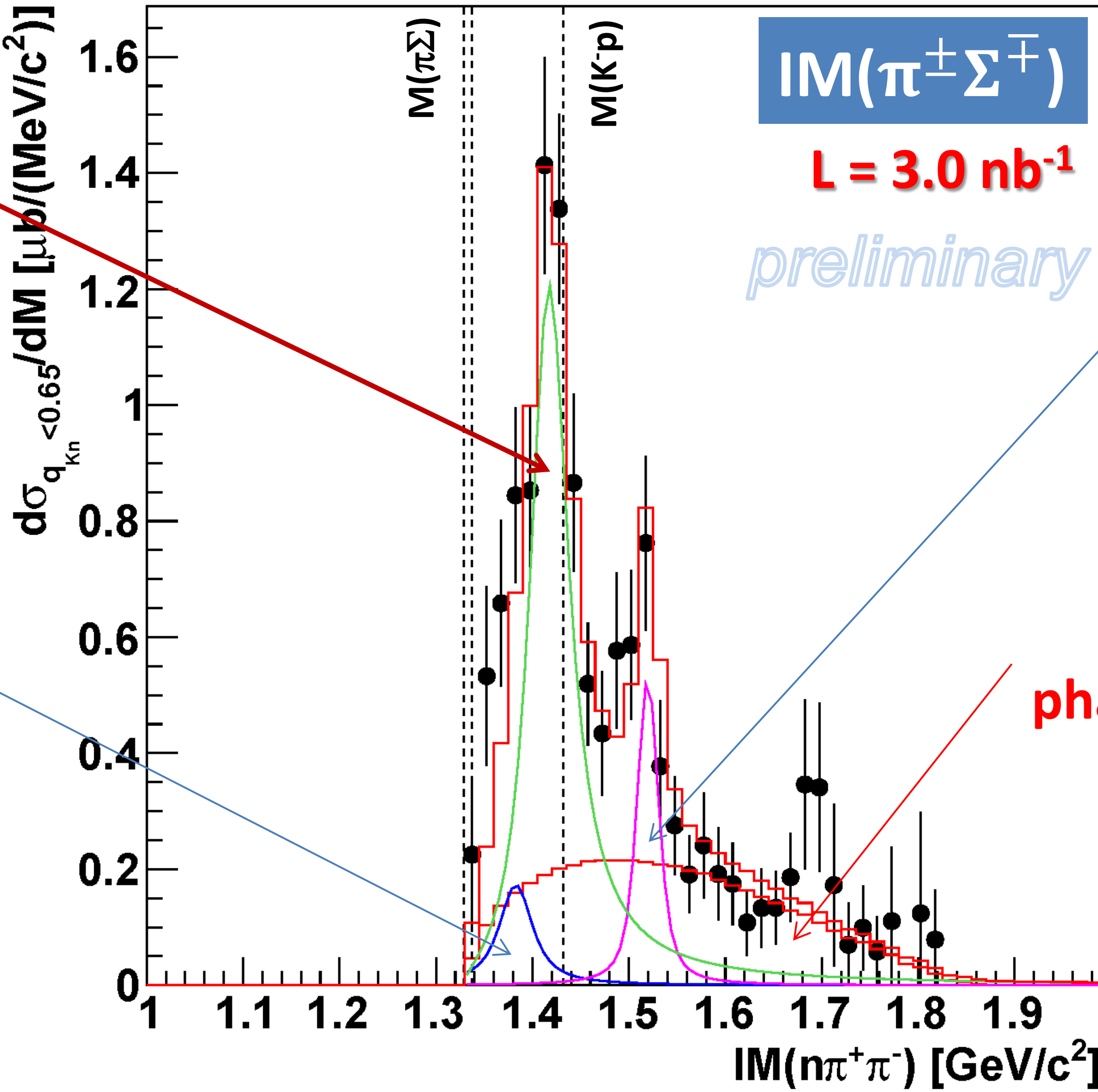
~ 130-140 μb

Flatté param.:

m_R ~ 1418 MeV/c

$g_{\pi\Sigma}$ ~ 1.9E-1

g_{KN} ~ 1.7E-2



$\Lambda(1520)$

~ 70 μb

$\pi\Sigma pn$

phases-space

$\Sigma^0(1385)$

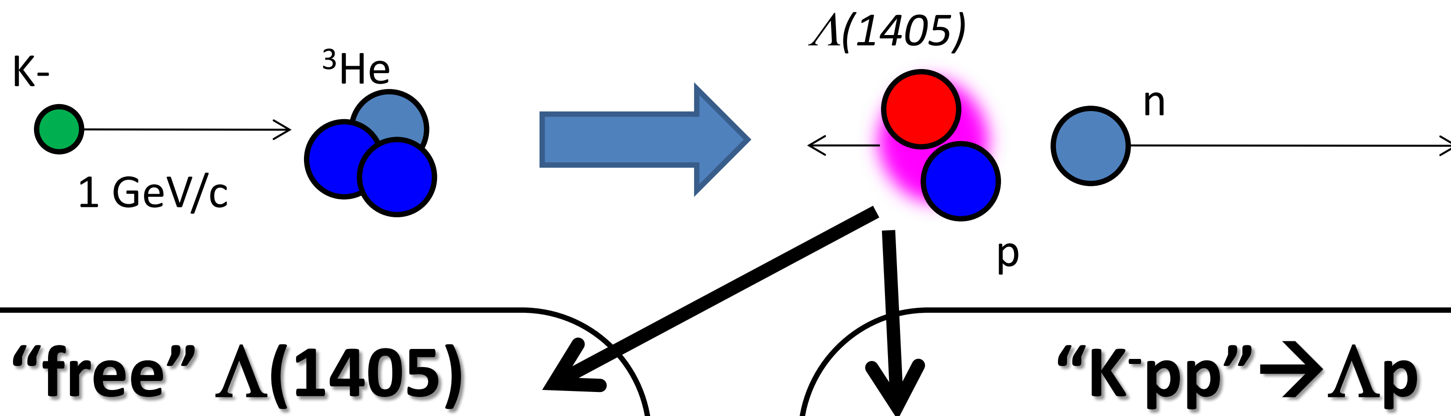
~ 40-80 μb

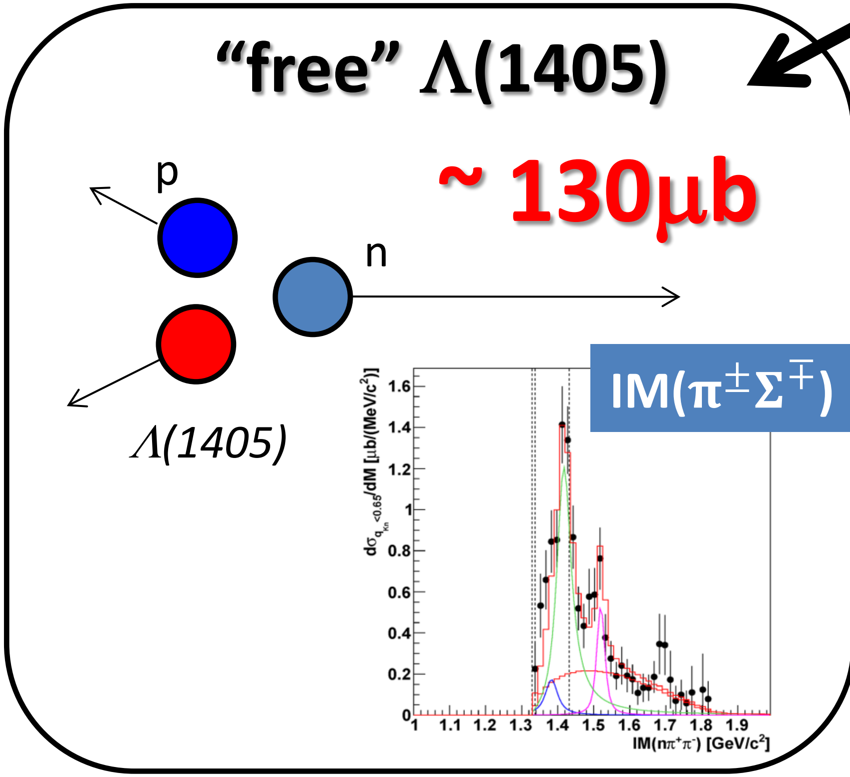
[evaluated from

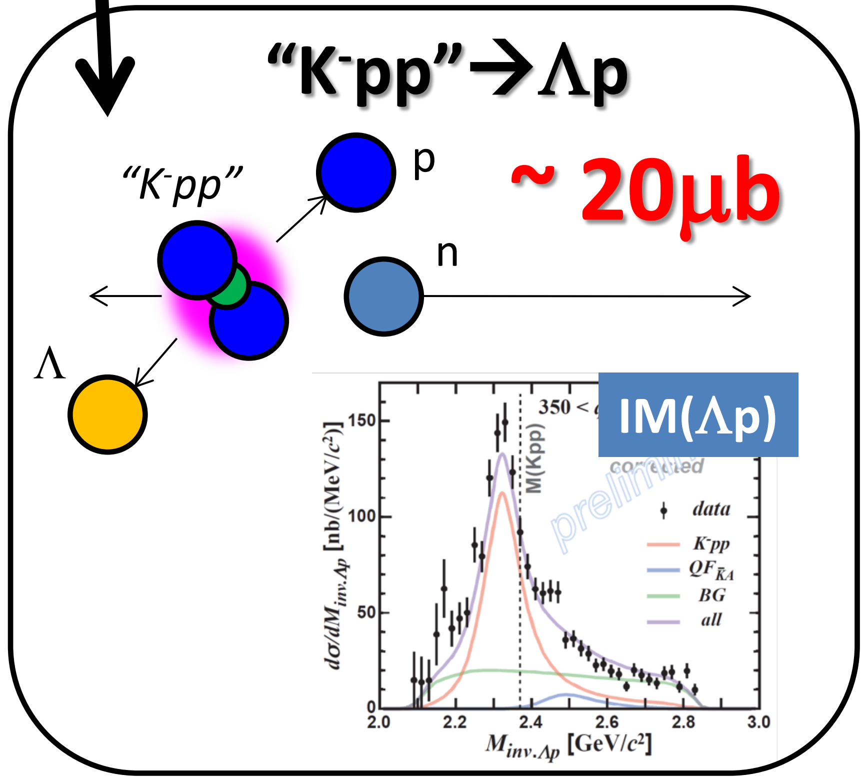
$\Sigma^+(1385) \rightarrow \pi^+\Lambda$

measurement]

Production of Λ(1405)p and "K^-pp"







Large CS of Λ^* compared to "K^-pp" formation

“K^-pp” in $^3He(K^-,\pi\Sigma p)n$

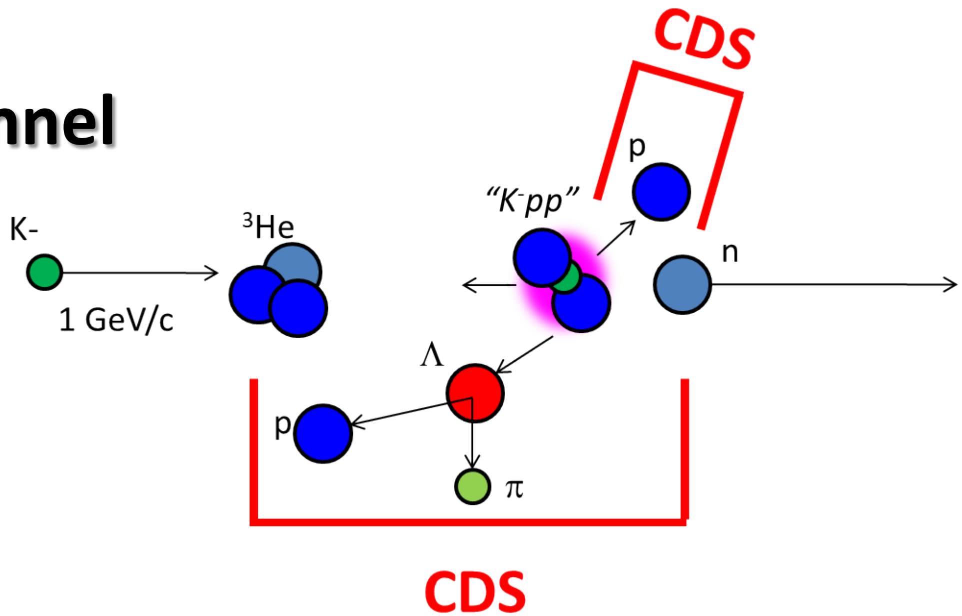
Search for “K^-pp” → $\pi\Sigma N$ decay channel

Two Decay Mode of “K$^-$pp”

1. “K$^-$pp” search via Λp channel

→ Non-mesonic channel

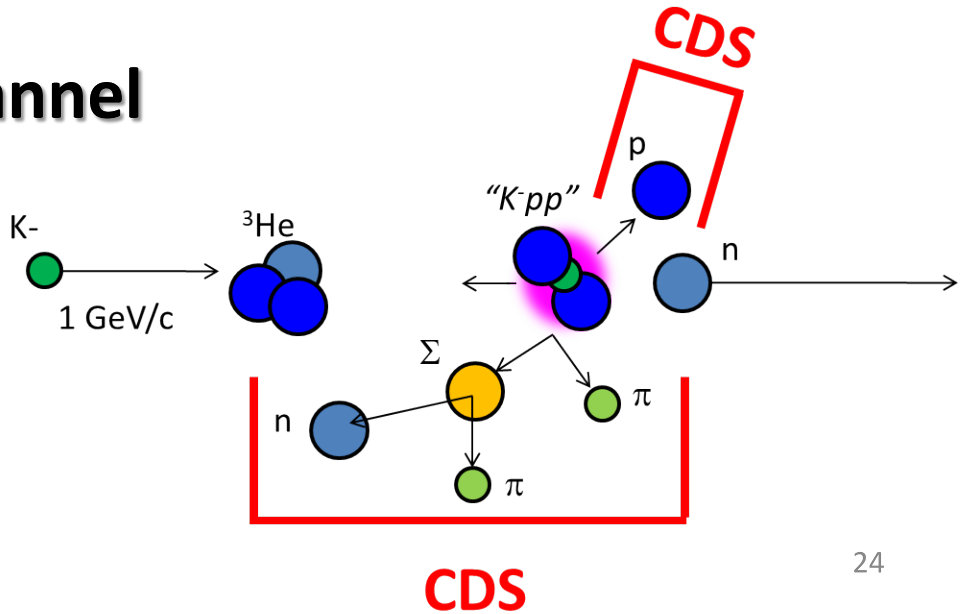
FINUDA/DISTO/E27/E15…



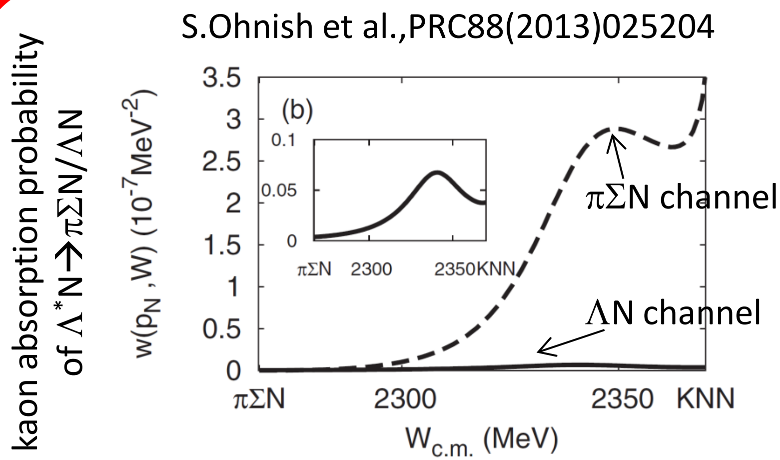
2. “K$^-$pp” search via πΣp channel

→ Mesonic channel

NO measurement so far



Two Decay Mode of "K⁻pp"

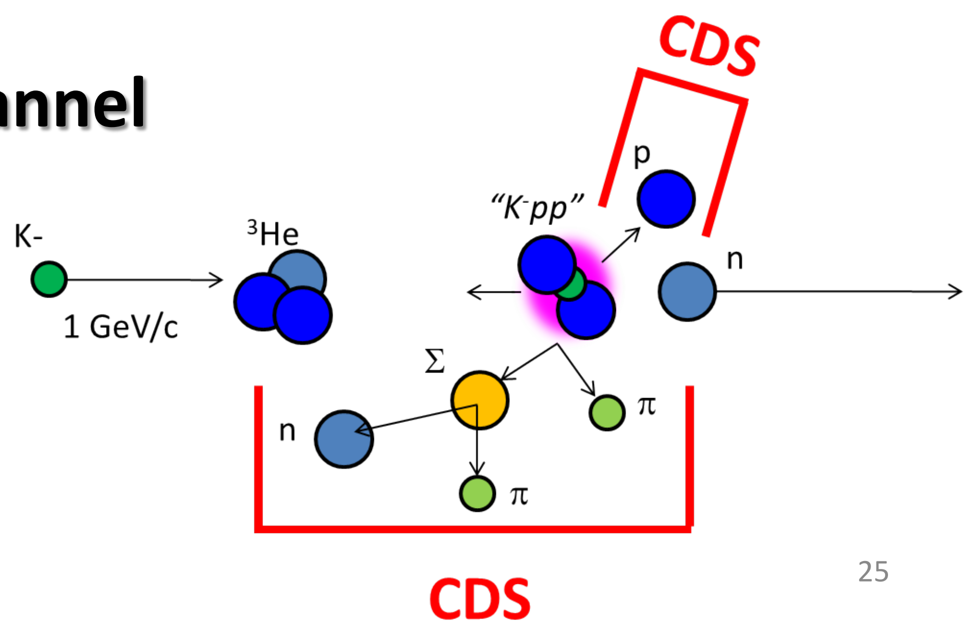


Theoretically, πΣN decay is expected to be the dominant channel

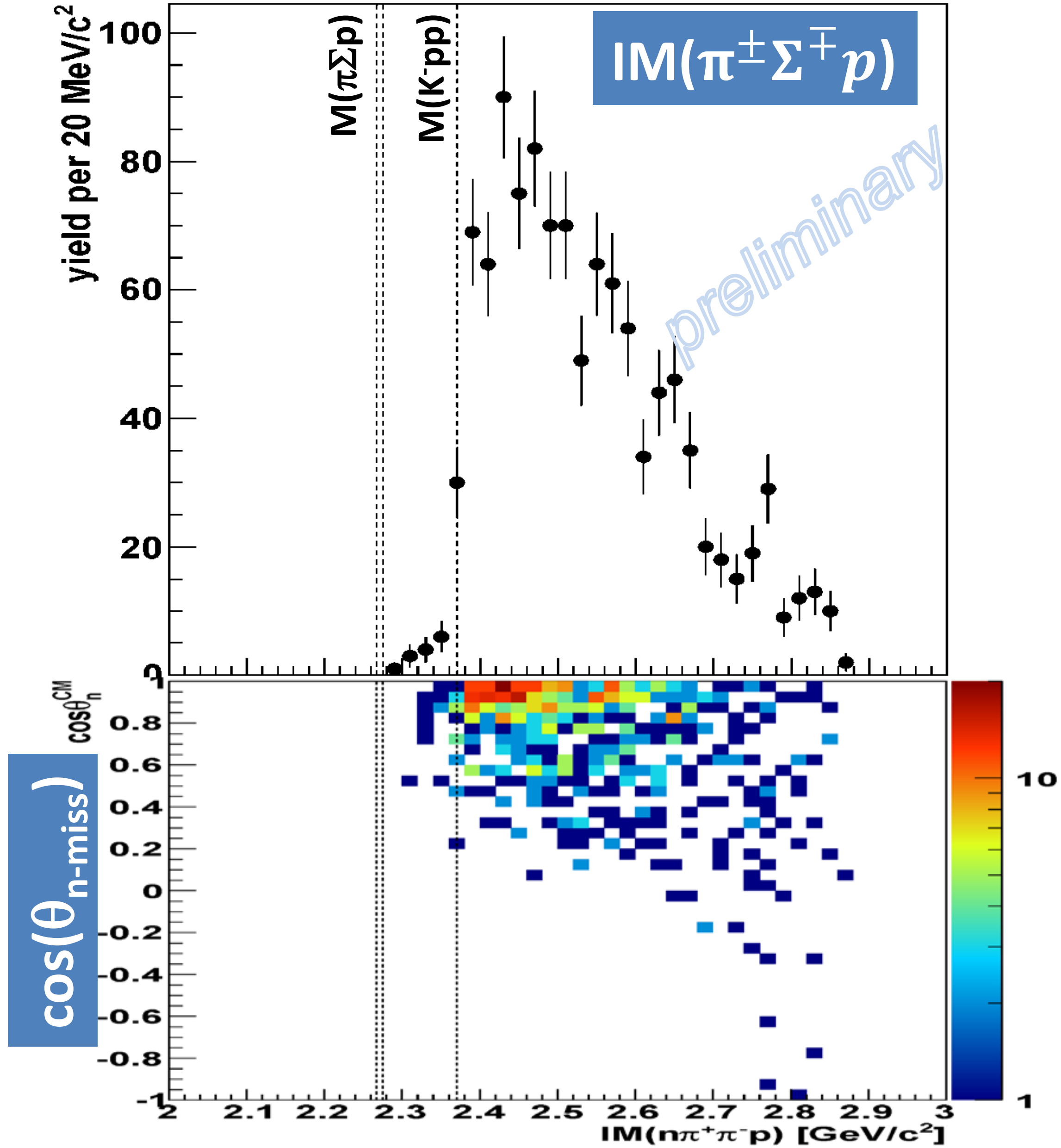
2. "K⁻pp" search via πΣp channel

→ Mesonic channel

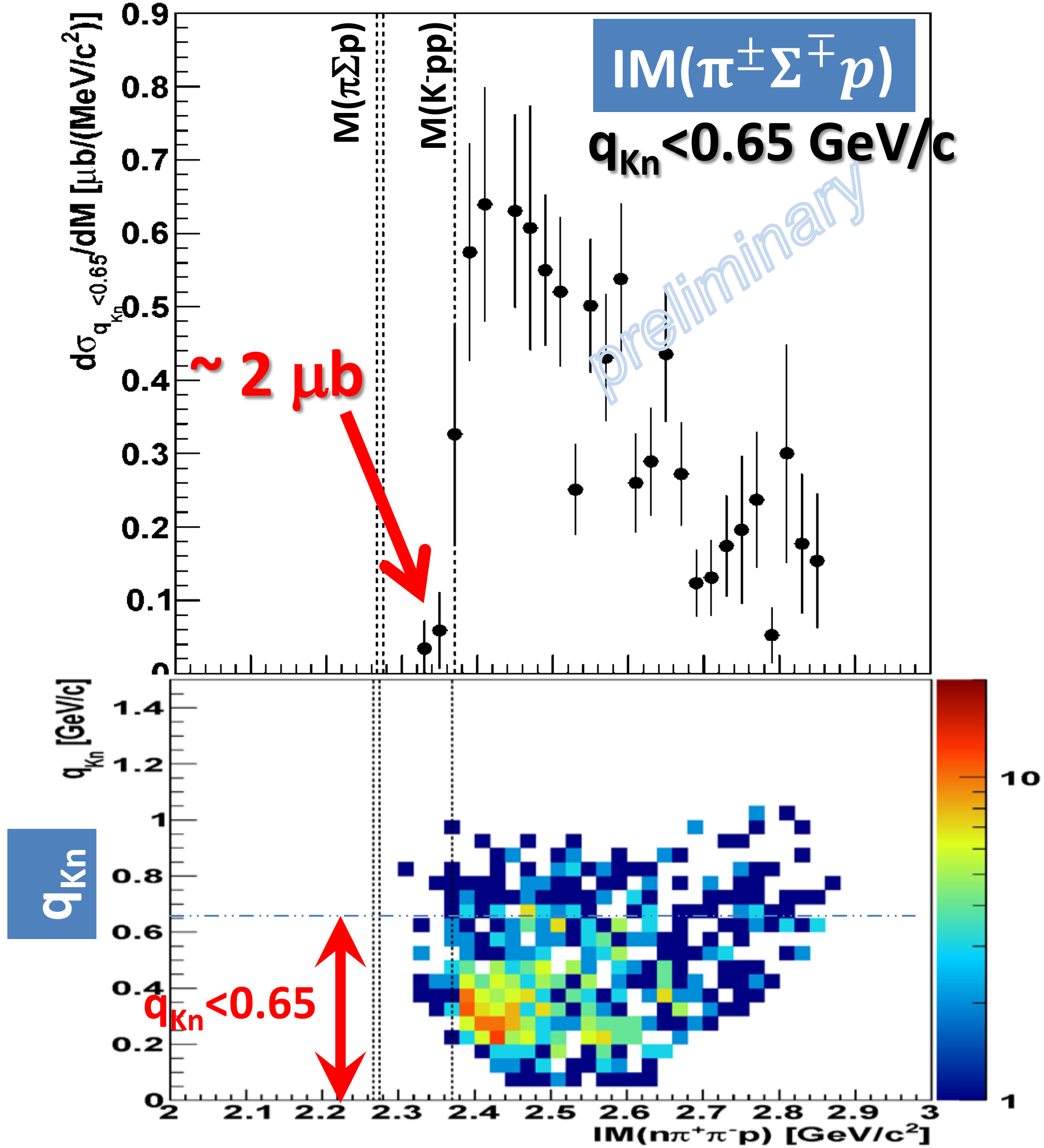
NO measurement so far

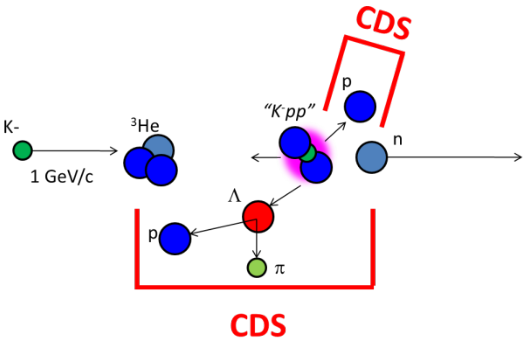


IM($\pi\Sigma p$) vs. cos(θ_n^{CM})

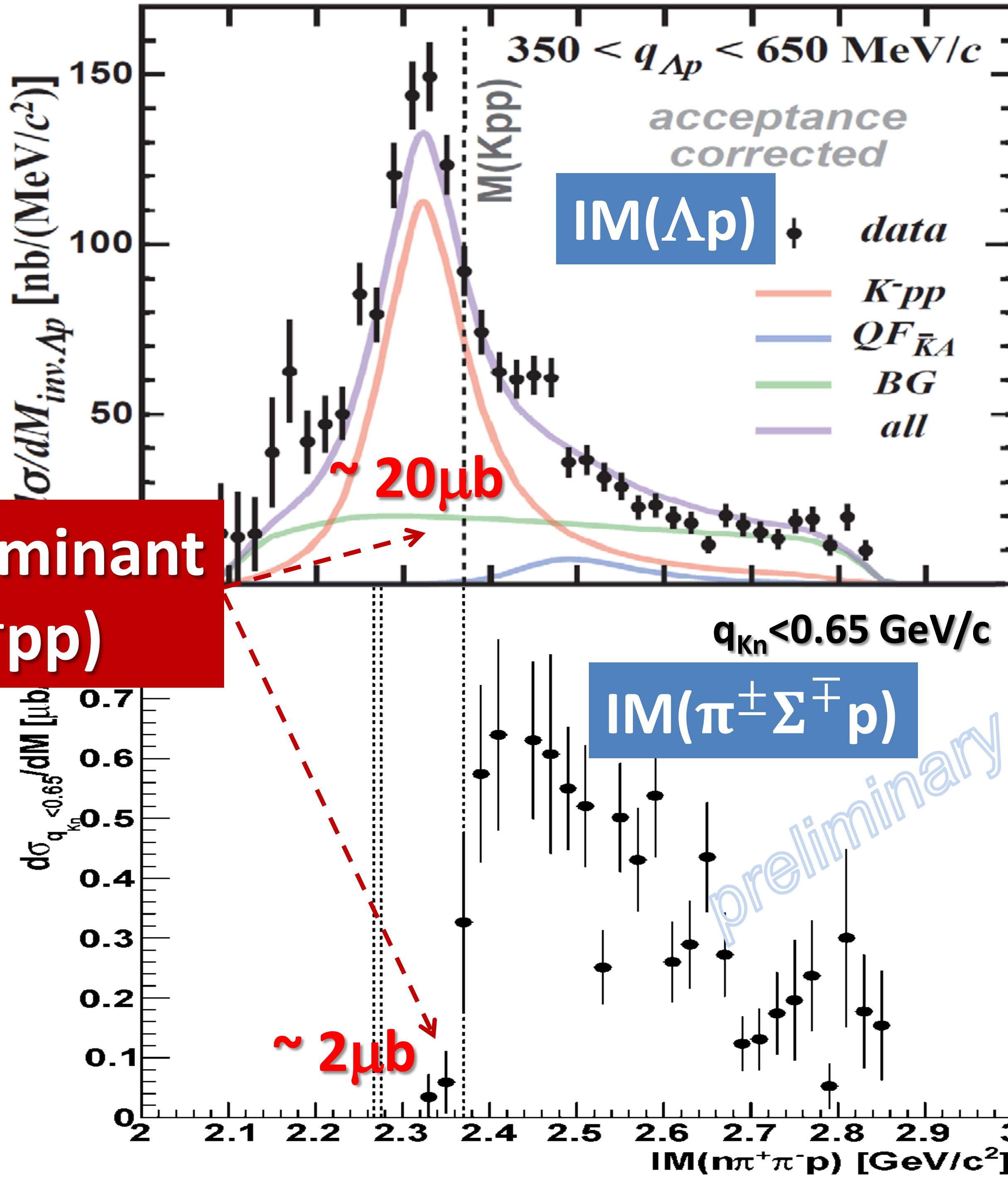


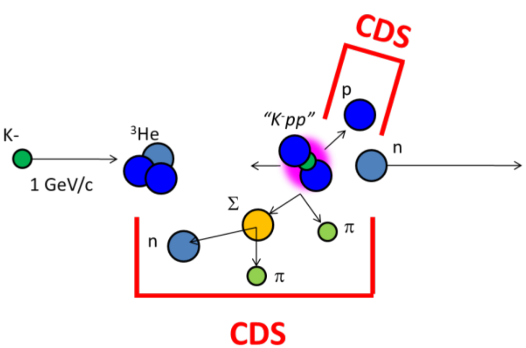
IM(πΣp) vs. Momentum Transfer q_{Kn}



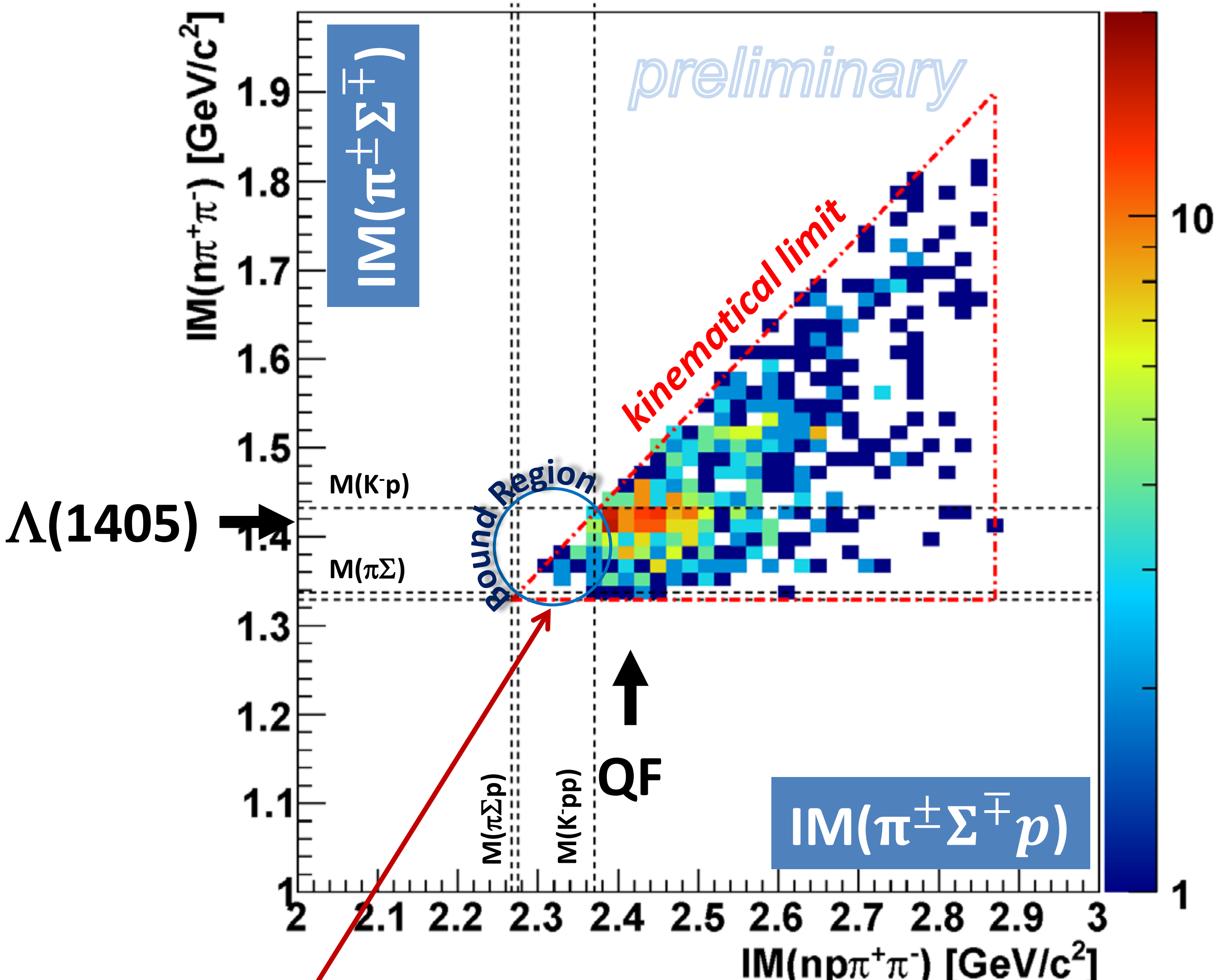


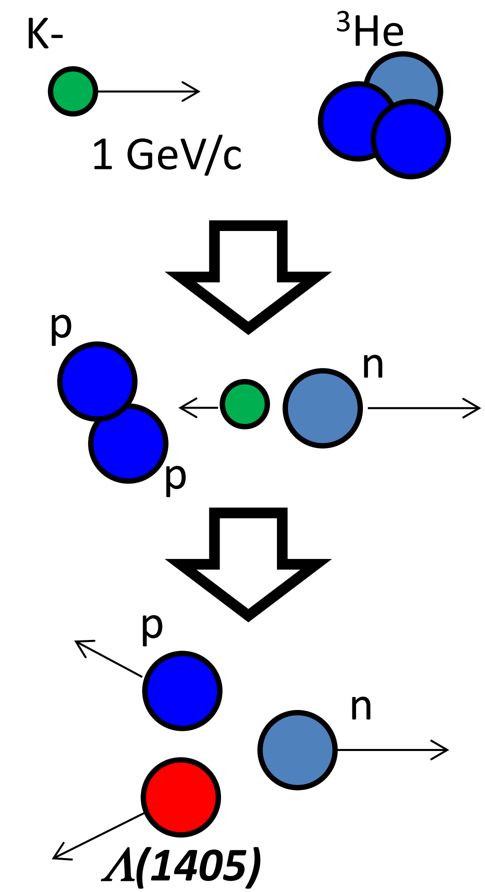
Λp decay is dominant below M(K⁻pp)





IM($\pi^{\pm}\Sigma^{\mp}$) vs. IM($\pi^{\pm}\Sigma^{\mp}p$)



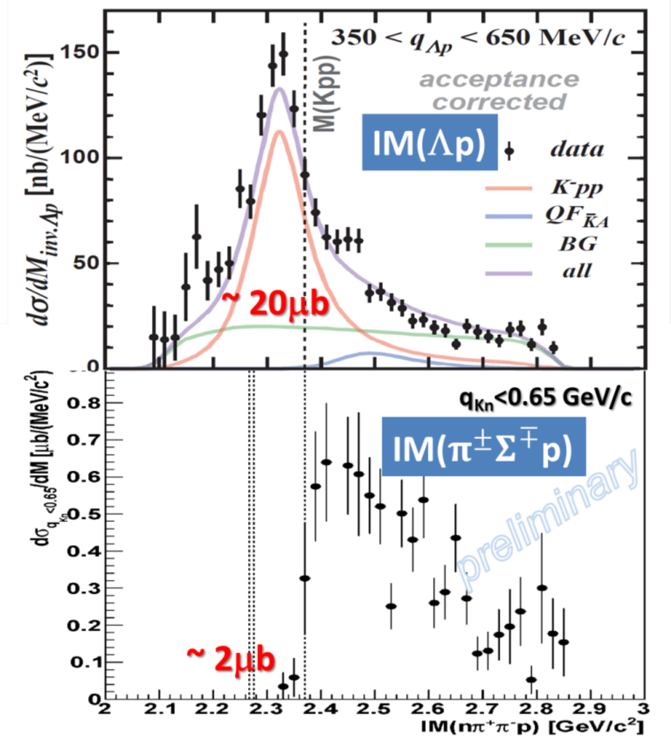


Small phase-space of "K⁻pp"→πΣN

Conclusions

- **We have observed a resonance peak below the K^-pp threshold in $^3He(K^-,\Lambda p)n$, "K^-pp"**
  - Binding energy: ~50 MeV
  - Width: ~100 MeV
  - S-wave form factor: ~400 MeV

  ← E15 collab., arXiv:1805.12275



- **$\Lambda(1405)$ was clearly observed in $\pi^\pm\Sigma^\mp p\ n_{miss}$ final state**
  - Large CS of Λ^*compared to "K^-pp" formation

  ← need theoretical feedbacks

- **Weak structure below the K^-pp threshold is seen in IM($\pi^\pm\Sigma^\mp p$)**
  - Non-meonic YN decay modes would be dominant

  ← need further investigation of "K^-pp" → $\pi\Sigma N$

What we have to do next

- **More quantitative studies of the "K^-pp"**
  - J^P
    - Angular distributions are consistent with a $J^P=0^-$ assumption in current statistics
  - $\pi\Sigma p$ decay mode
    - Due to phase-space, or, detector acceptance(?)

- **Series of the kaonic nuclei searches:**
  - "K^-ppn" via [K^- + ^4He], "K^-ppnn/K^-pppnn" via [K^- + ^6Li], etc.
  - "K^-K^-pp" via [p^{bar} + ^3He annihilation]

We need a 4π detector system with γ/n sensitive detectors

Thank You!

J-PARC E15 Collaboration

S. Ajimura[a], H. Asano[n], G. Beer[b], C. Berucci[f], H. Bhang[c], M. Bragadireanu[e], P. Buehler[f], L. Busso[g,h], M. Cargnelli[f], S. Choi[c], C. Curceanu[d], S. Enomoto[o], H. Fujioka[m], Y. Fujiwara[k], T. Fukuda[l], C. Guaraldo[d], T. Hashimoto[u], R. S. Hayano[k], T. Hiraiwa[a], M. Iio[o], M. Iliescu[d], K. Inoue[a], Y. Ishiguro[j], T. Ishikawa[k], S. Ishimoto[o], K. Itahashi[n], M. Iwai[o], M. Iwasaki[m,n*], K. Kanno[k], K. Kato[j], Y. Kato[n], S. Kawasaki[i], P. Kienle[†p], H. Kou[m], Y. Ma[n], J. Marton[f], Y. Matsuda[q], Y. Mizoi[l], O. Morra[g], T. Nagae[j$], H. Noumi[a], H. Ohnishi[w], S. Okada[n], H. Outa[n], K. Piscicchia[d], Y. Sada[a], A. Sakaguchi[i], F. Sakuma[n], M. Sato[o], A. Scordo[d], M. Sekimoto[o], H. Shi[d], K. Shirotori[a], D. Sirghi[d,e], F. Sirghi[d,e], K. Suzuki[f], S. Suzuki[o], T. Suzuki[k], K. Tanida[u], H. Tatsuno[v], M. Tokuda[m], D. Tomono[a], A. Toyoda[o], K. Tsukada[r], O. Vazquez Doce[d,p], E. Widmann[f], T. Yamaga[n], T. Yamazaki[k,n], H. Yim[t], Q. Zhang[n], and J. Zmeskal[f]

(a) Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan
(b) Department of Physics and Astronomy, University of Victoria, Victoria BC V8W 3P6, Canada
(c) Department of Physics, Seoul National University, Seoul, 151-742, South Korea
(d) Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy
(e) National Institute of Physics and Nuclear Engineering - IFIN HH, Romania
(f) Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria
(g) INFN Sezione di Torino, Torino, Italy
(h) Dipartimento di Fisica Generale, Universita' di Torino, Torino, Italy
(i) Department of Physics, Osaka University, Osaka, 560-0043, Japan
(j) Department of Physics, Kyoto University, Kyoto, 606-8502, Japan
(k) Department of Physics, The University of Tokyo, Tokyo, 113-0033, Japan
(l) Laboratory of Physics, Osaka Electro-Communication University, Osaka, 572-8530, Japan
(m) Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan
(n) RIKEN Nishina Center, RIKEN, Wako, 351-0198, Japan
(o) High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
(p) Technische Universität München, D-85748, Garching, Germany
(q) Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, 153-8902, Japan
(r) Department of Physics, Tohoku University, Sendai, 980-8578, Japan
(s) Excellence Cluster Universe, Technische Universität München, D-85748, Garching, Germany
(t) Korea Institute of Radiological and Medical Sciences (KIRAMS), Seoul, 139-706, South Korea
(u) ASRC, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
(v) Department of Chemical Physics, Lund University, Lund, 221 00, Sweden
(w) Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan