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

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

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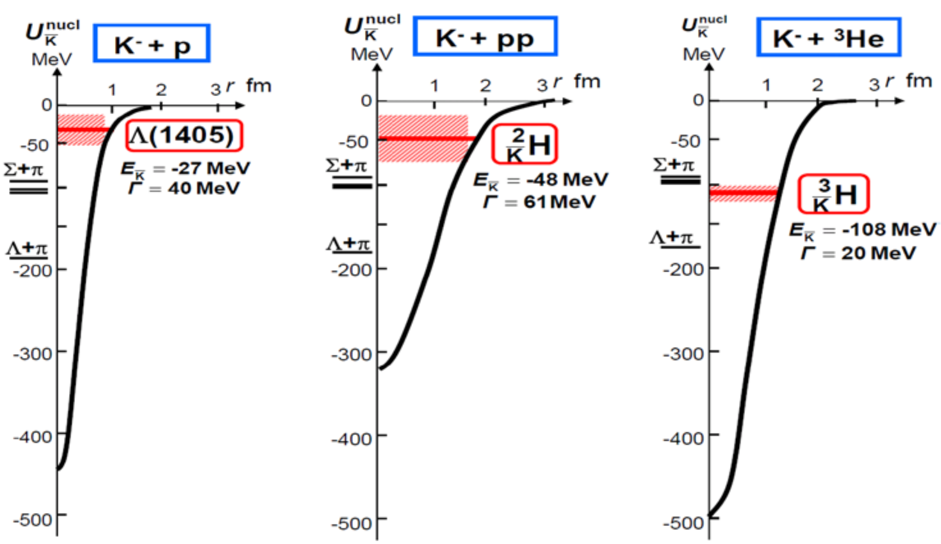
on behalf of the J-PARC E15 collaboration

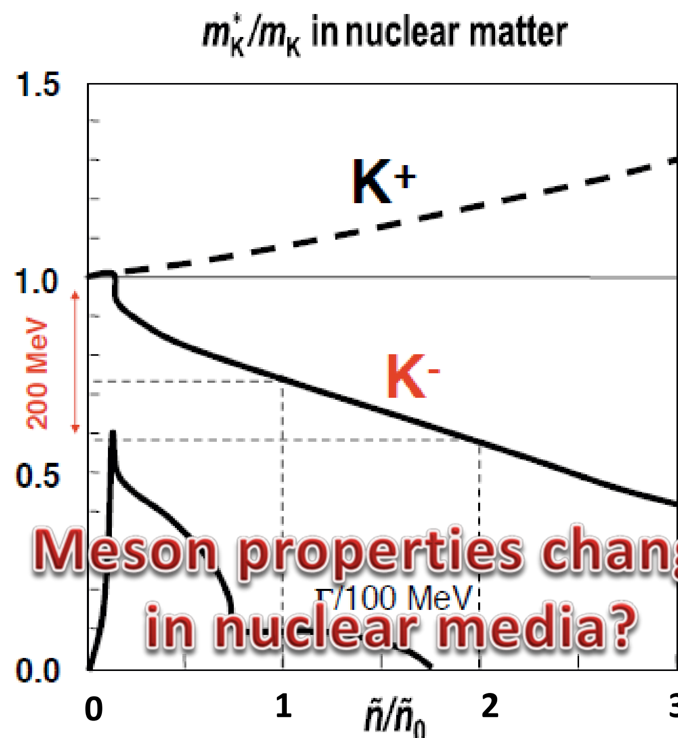
MESON2018, June 7-12, 2018, KRAKÓW, POLAND

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).



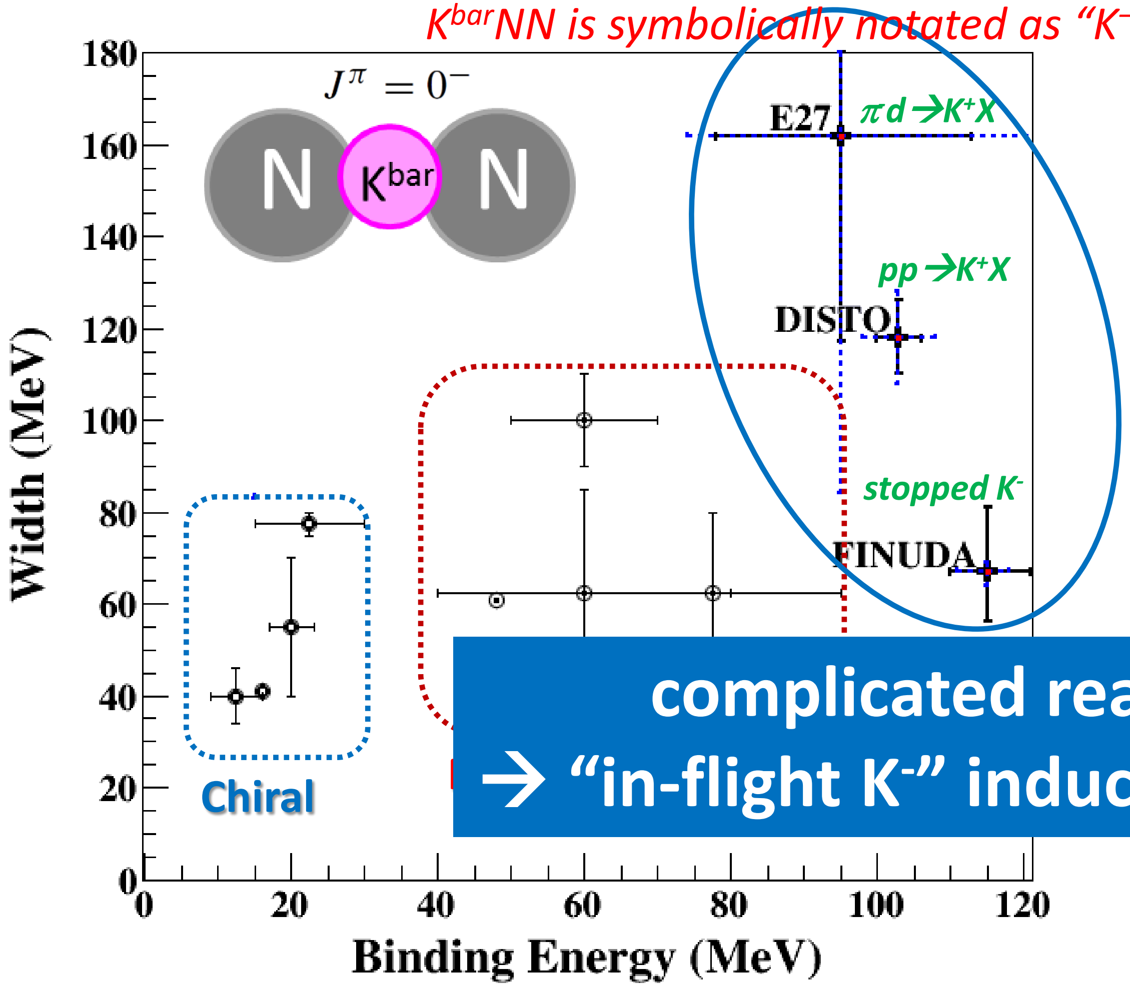
Meson properties change in nuclear media?

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

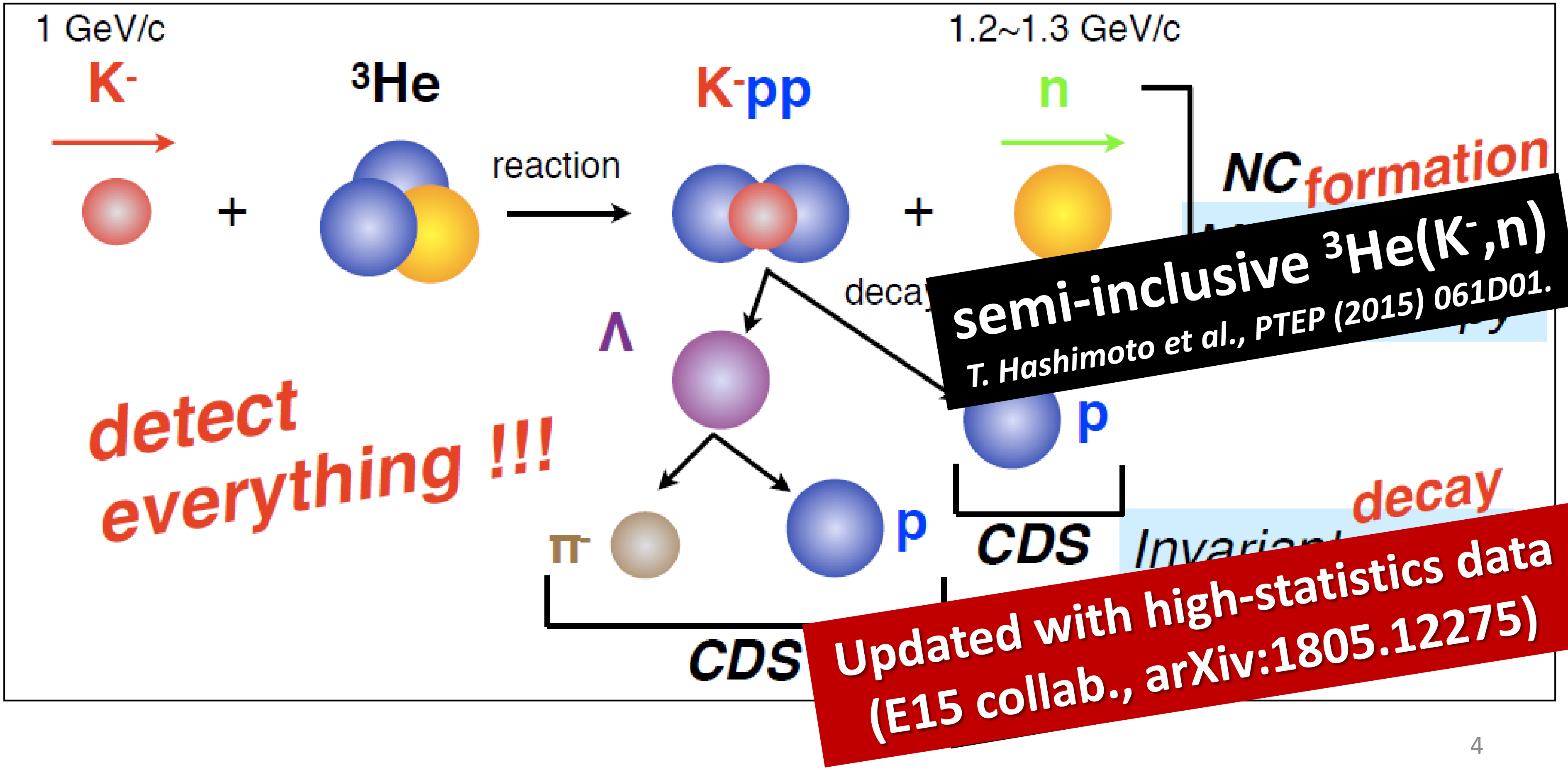
Upper limits were also obtained:

- **LEPS@SPring8 [Inclusive d(γ, $K^+\pi^-$)X]**
- **HADES@GSI [Exclusive pp→pΛK^+]**

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]

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[6] *National Institute of Physics and Nuclear Engineering - IFIN HH, Bucharest - Magurele, Romania*
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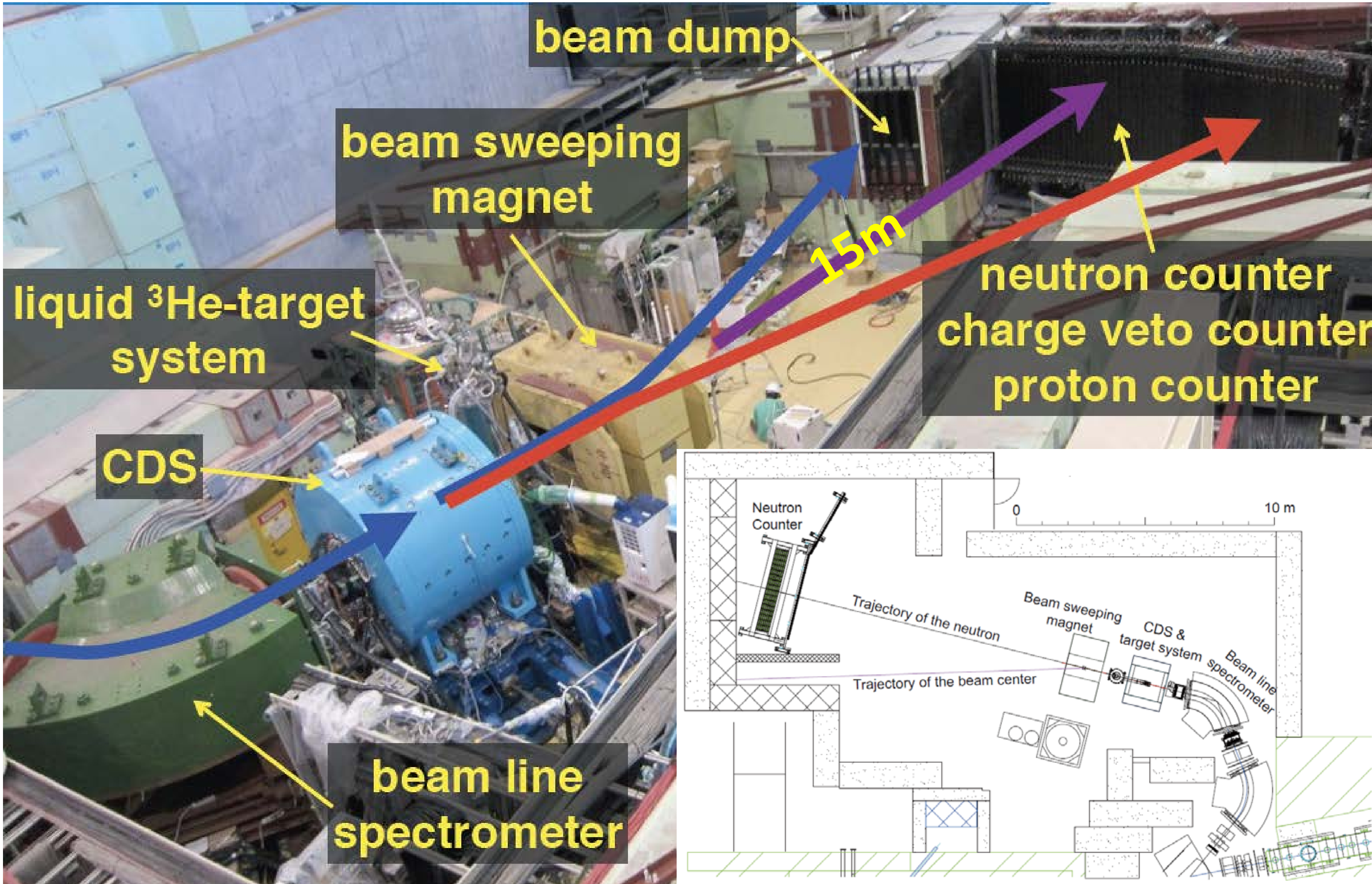
[10] *High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan*
[11] *Tokyo Institute of Technology, Tokyo, 152-8551, Japan*
[12] *The University of Tokyo, Tokyo, 113-0033, Japan*
[13] *Osaka Electro-Communication University, Osaka, 572-8530, Japan*
[14] *Japan Atomic Energy Agency, 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”.

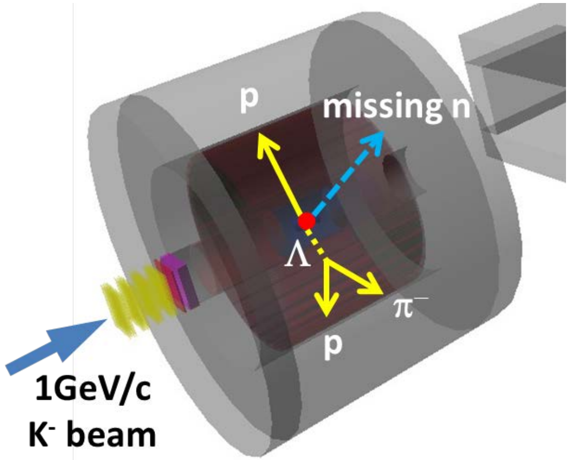
Since the prediction of the π-meson by Yukawa [1], there has been a long-standing question as to whether a mesonic nuclear bound state exists. Mesons are introduced as mediators between nucleons to confine them in vacuum one needs energy m to produce them. If a mesonic nuclear bound state exists, it 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

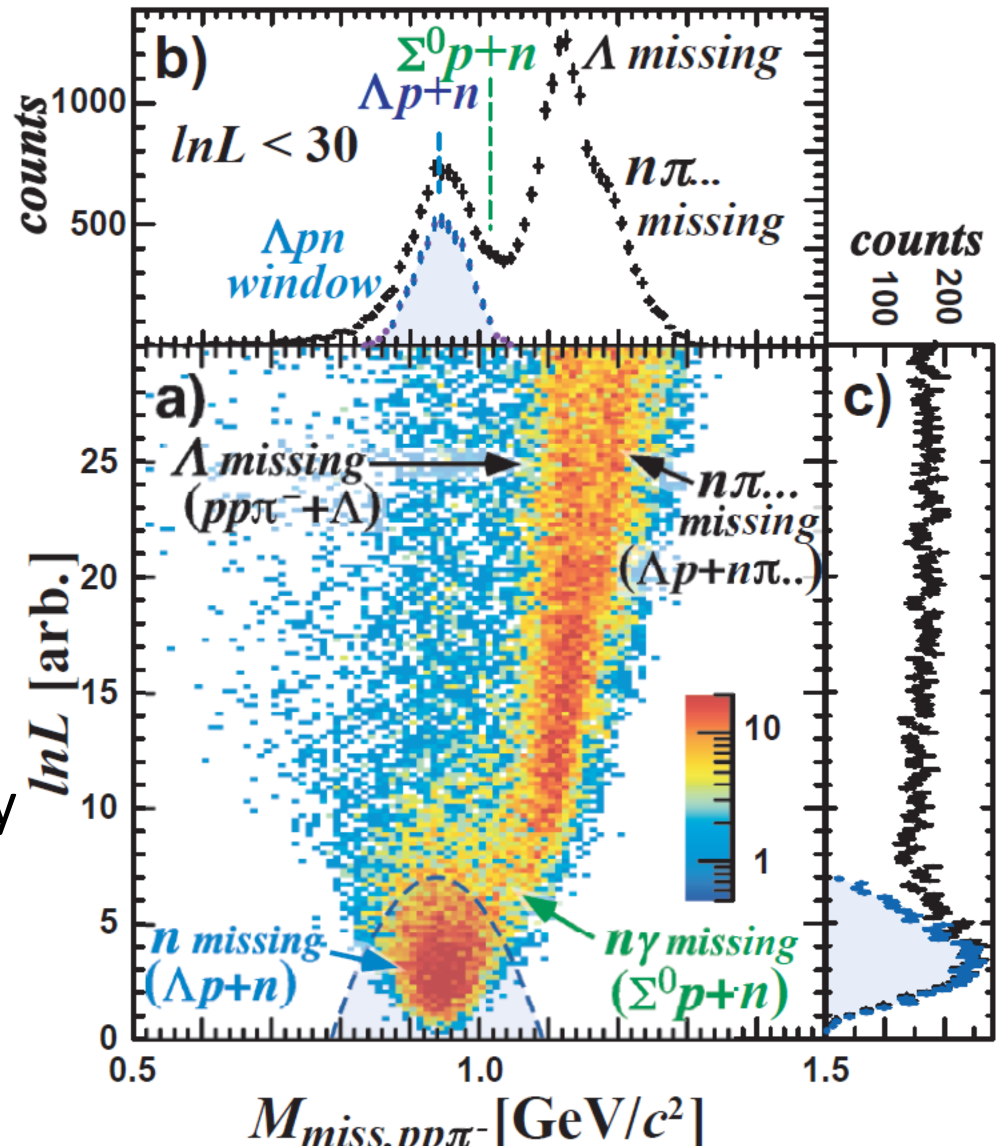


K. Agari et. al., PTEP 2012, 02B011

^{3}He + K$^-$ → Λ p n Selection



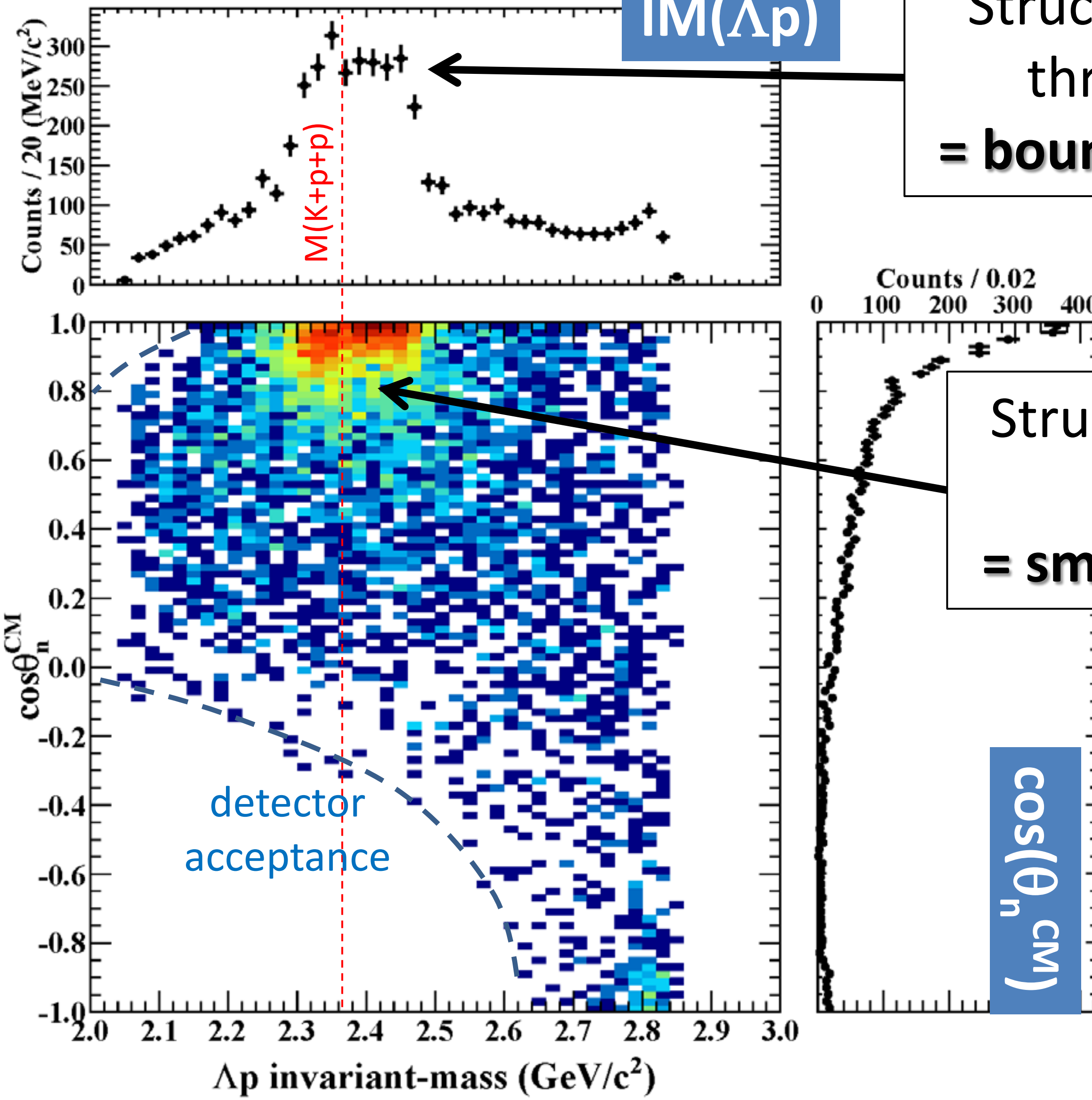
E15 collab., arXiv:1805.12275



- 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

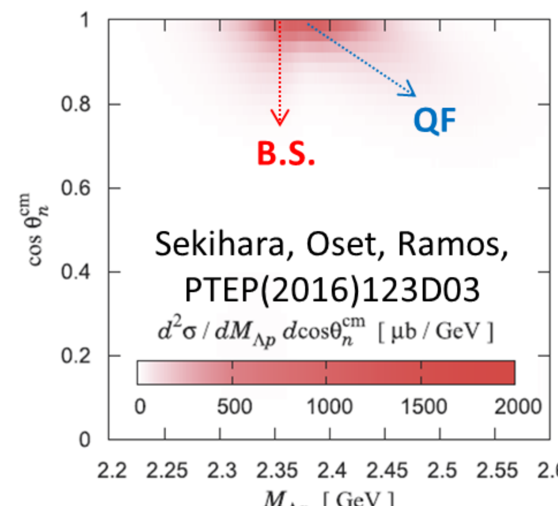
IM(Λp) vs. cos(θ_n^{CM})

E15 collab., arXiv:1805.12275



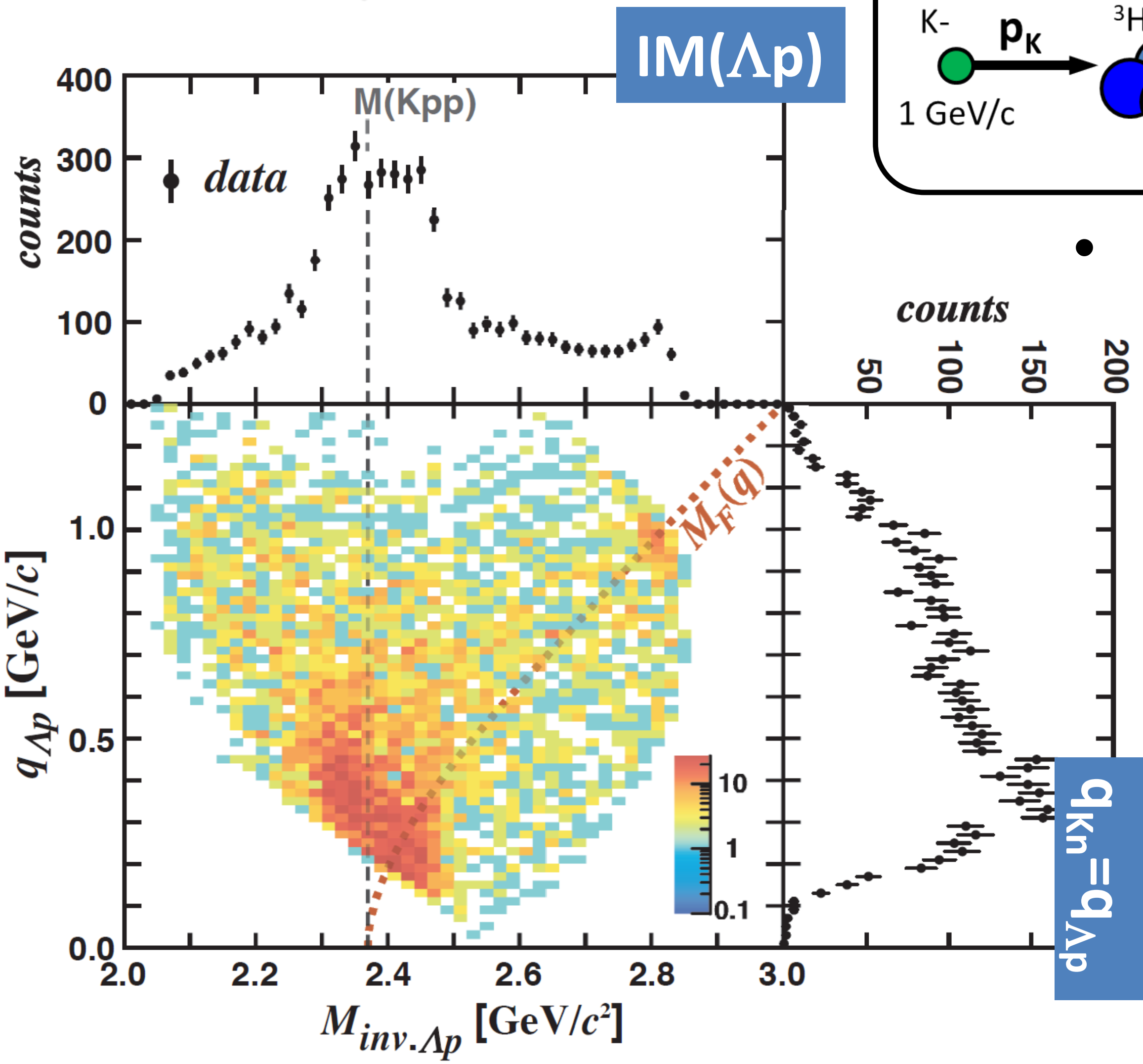
Structures around the K⁻pp threshold can be seen
= bound-state + quasi-elastic

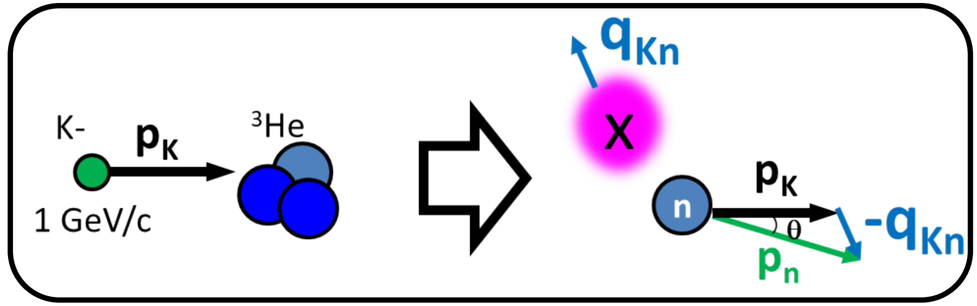
Structures are concentrated in forward-n region
= small momentum-transfer



IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275

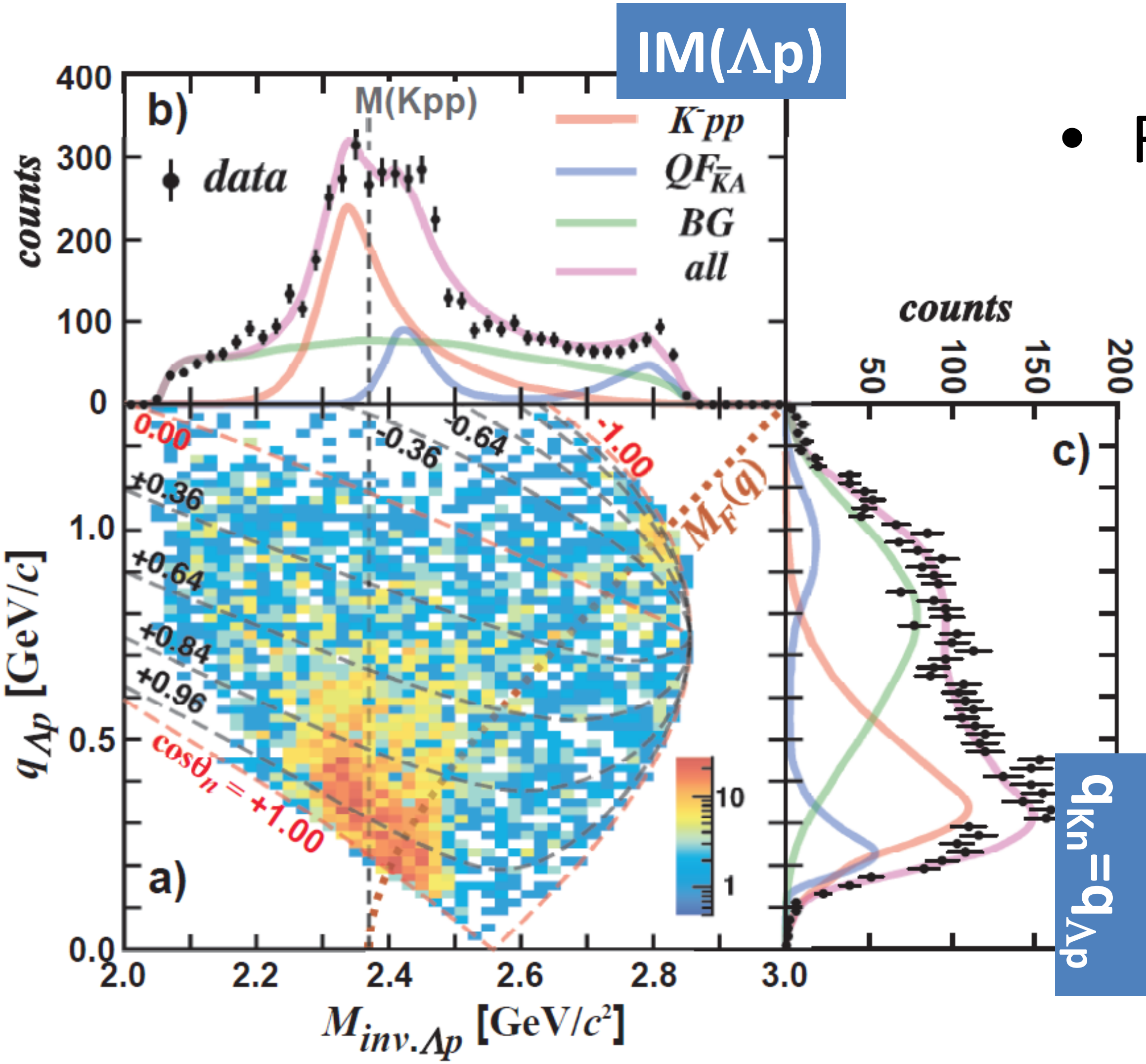




- Seems to consist of 3 components
  - **Bound state**
    - centroid NOT depend on q_{Kn}
  - **Qasi-elastic K⁻ abs.**
    - centroid depends on q_{Kn}
  - **Background**
    - Broad distribution

IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275



- 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

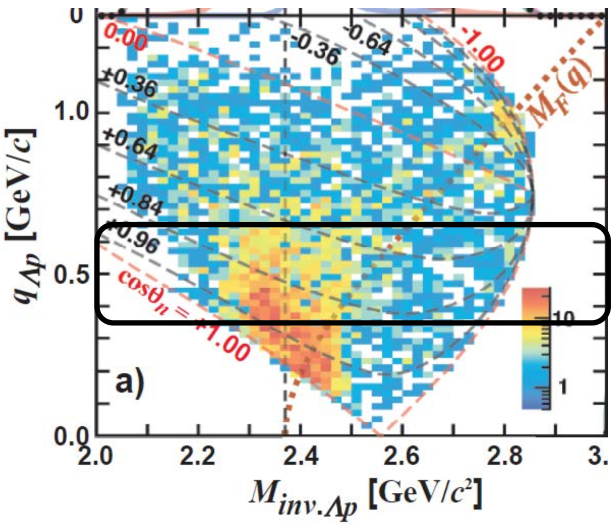
** We conduct the fitting in each 2D bin*

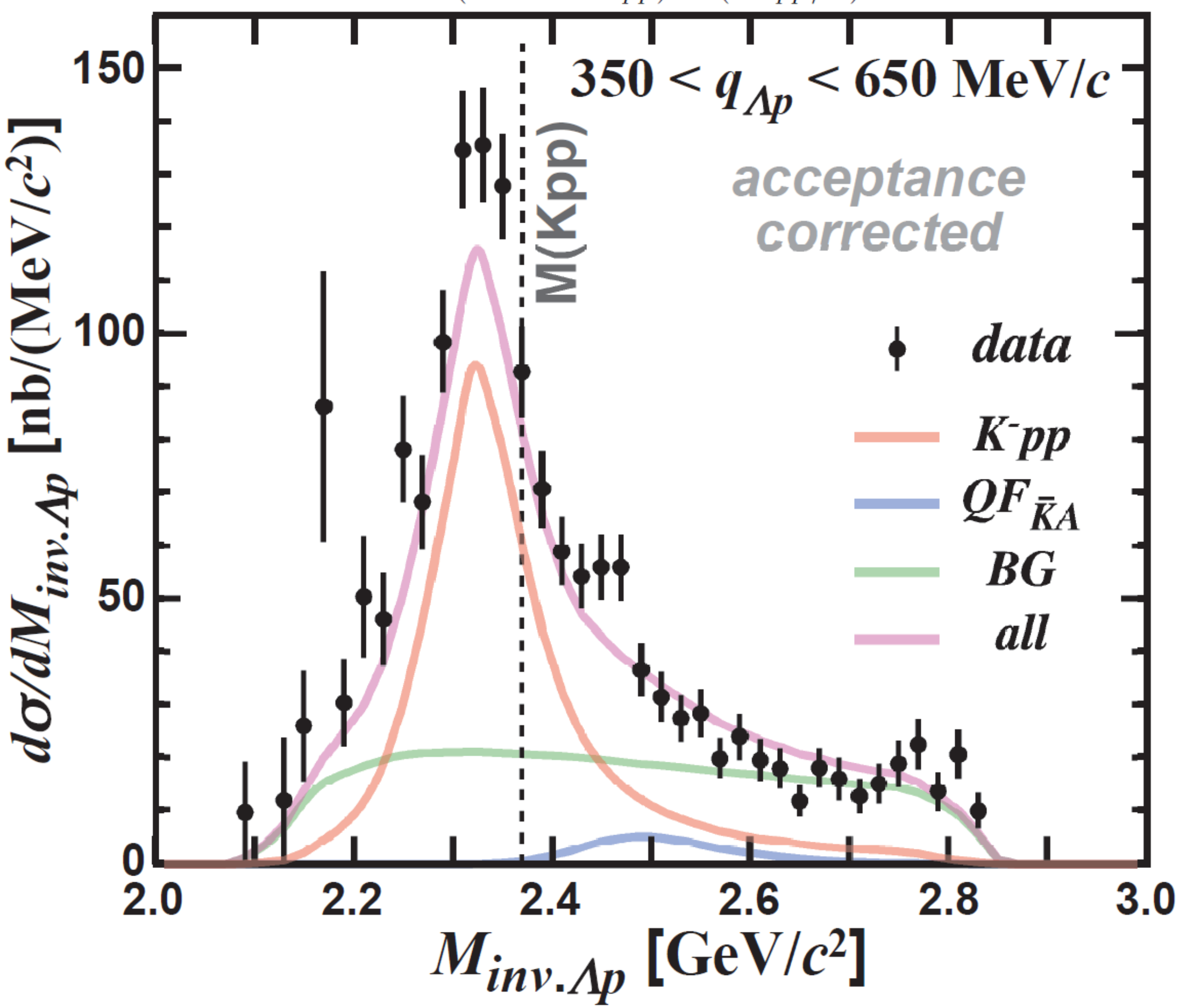
“K⁻pp” Bound-State

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

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

- BS and QF are well separated

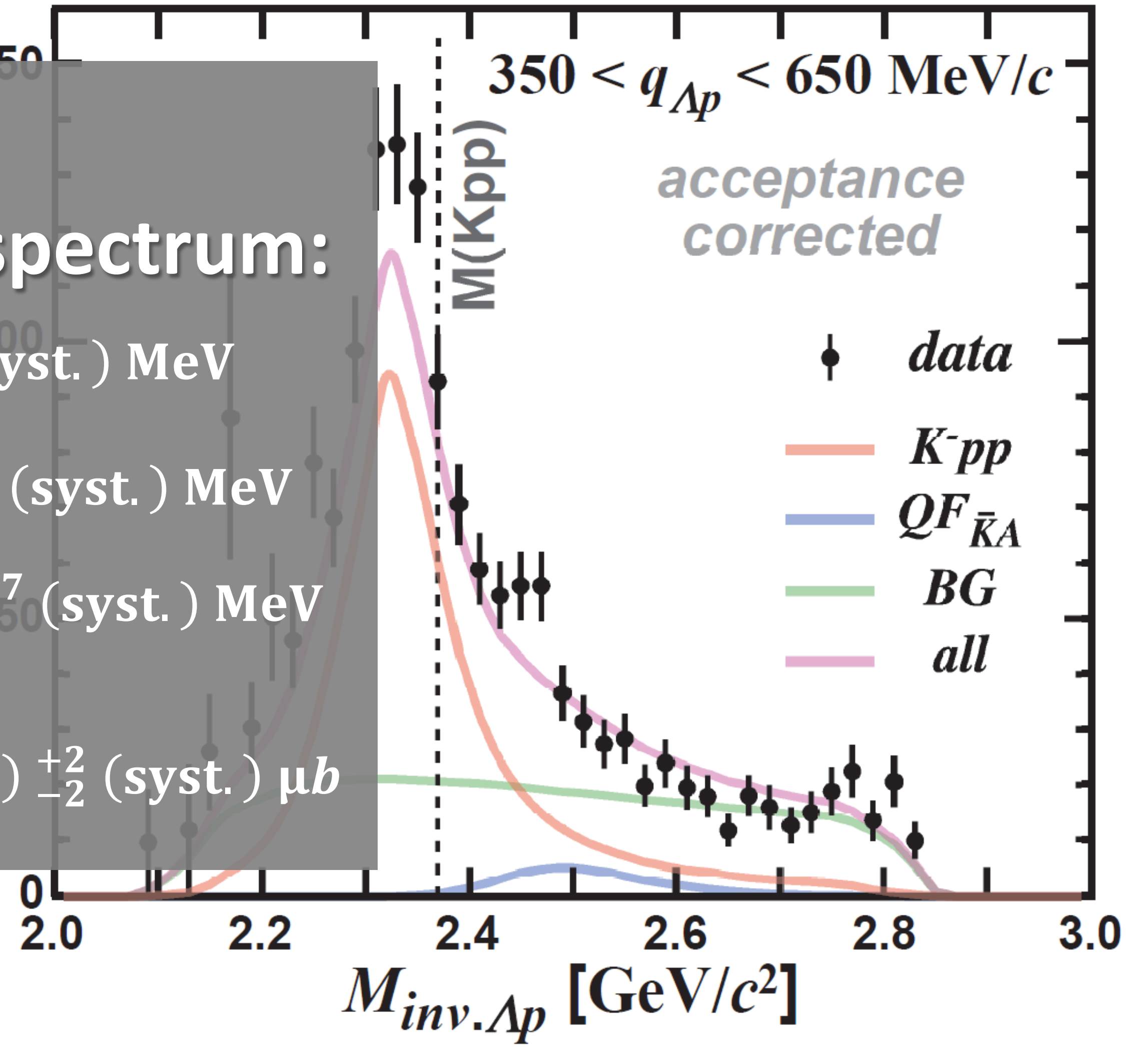




E15 collab., arXiv:1805.12275

“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:

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

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

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

at below the $M(K^{-}pp)$

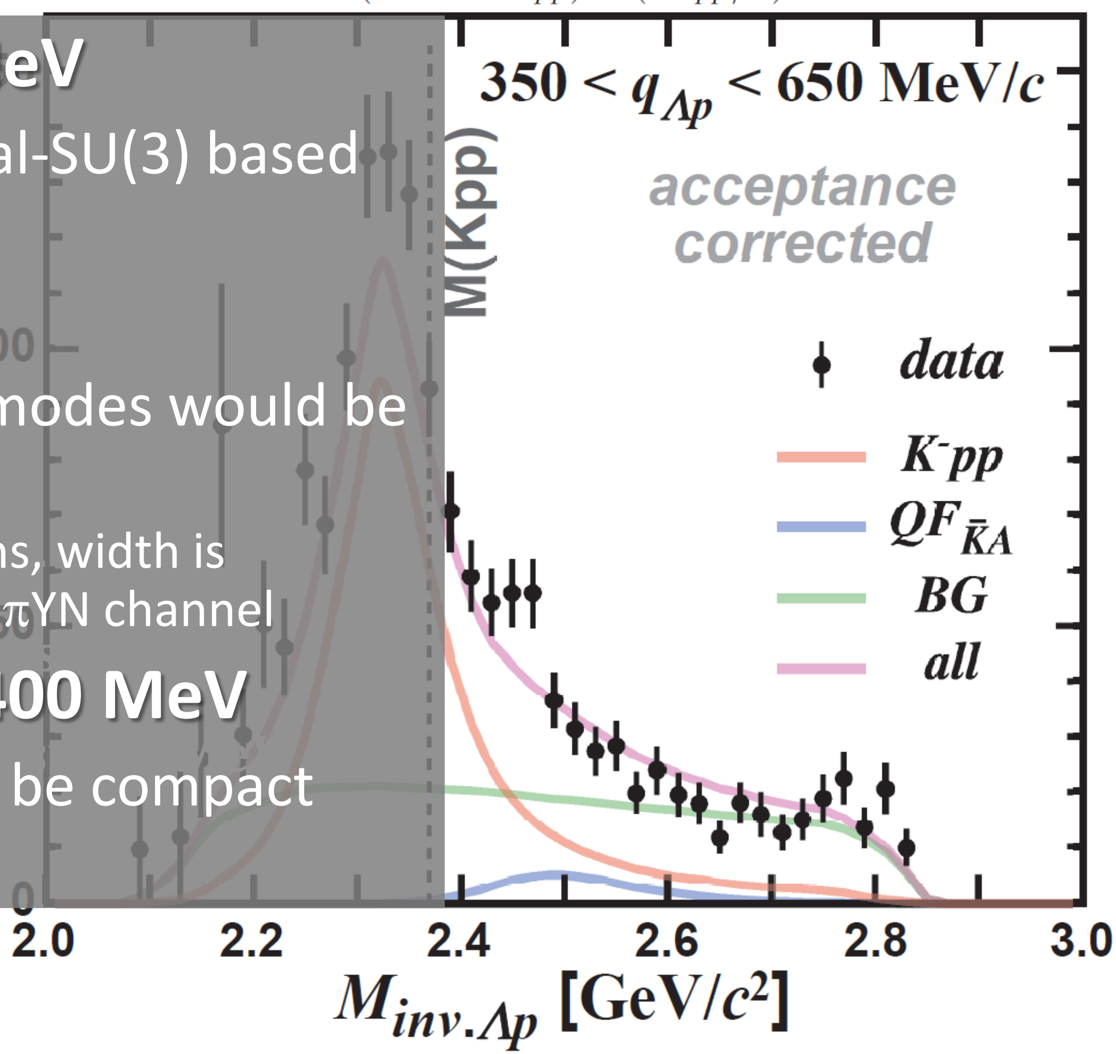
$\sigma_{“Kpp”} \cdot Br_{\Lambda p} = 15 \pm 1\,(\text{stat.})\,^{+2}_{-2}\,(\text{syst.})\ \mu b$

E15 collab., arXiv:1805.12275

“K⁻pp” Bound-State

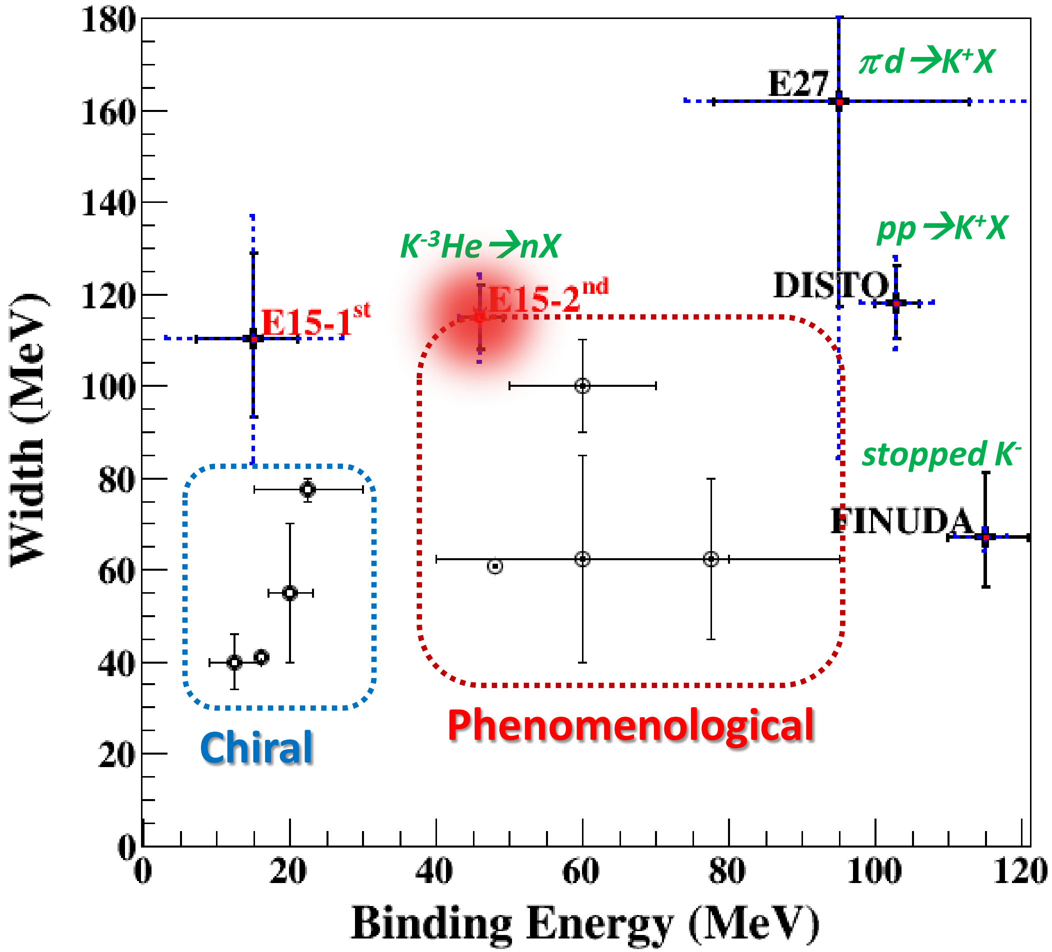
$$f_{\{Kpp\}}(M,q) = \frac{A_{Kpp}\,(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2}\, e^{-\left(\frac{q}{Q_{Kpp}}\right)^2},$$

- **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

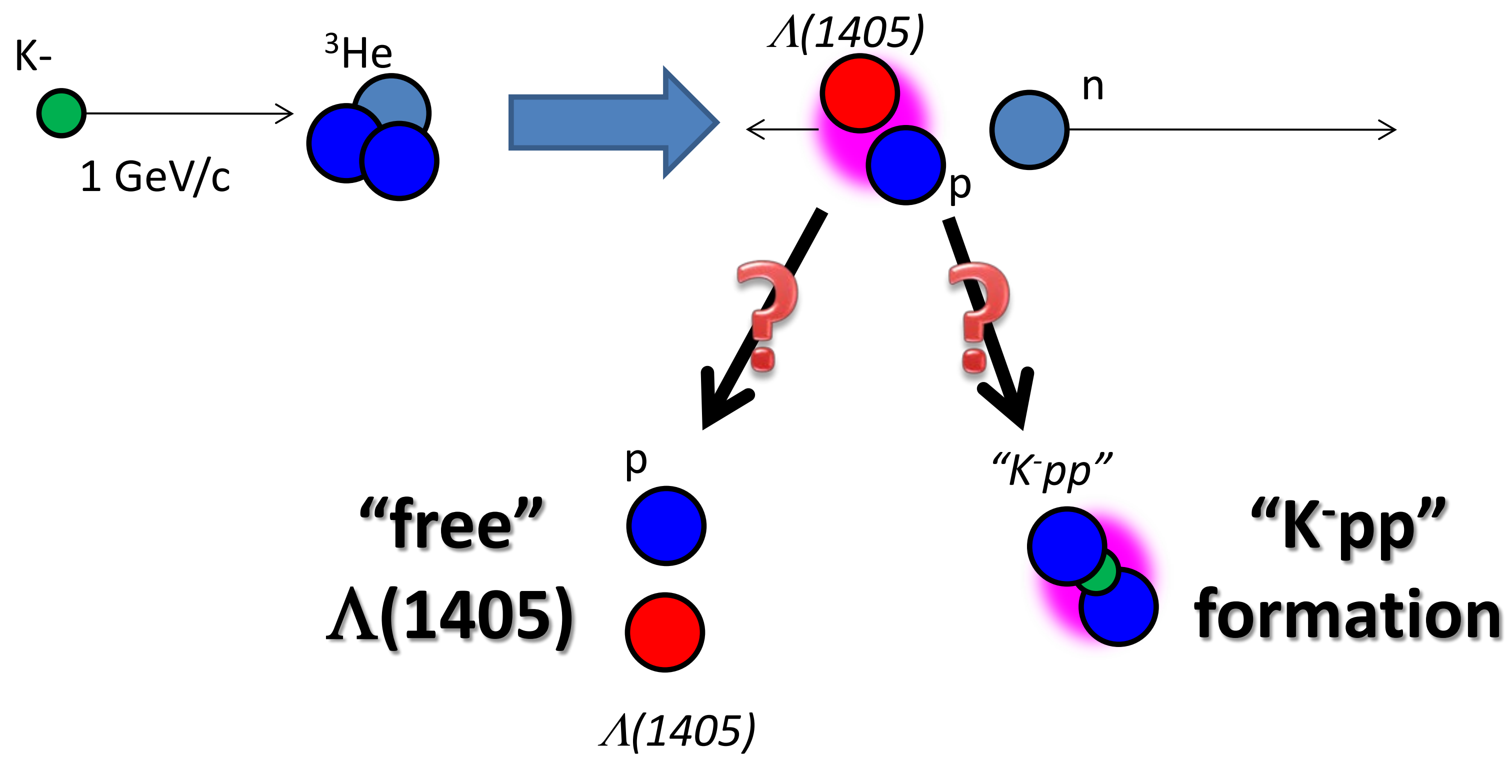
Present Status of "K⁻pp"



For further understandings:

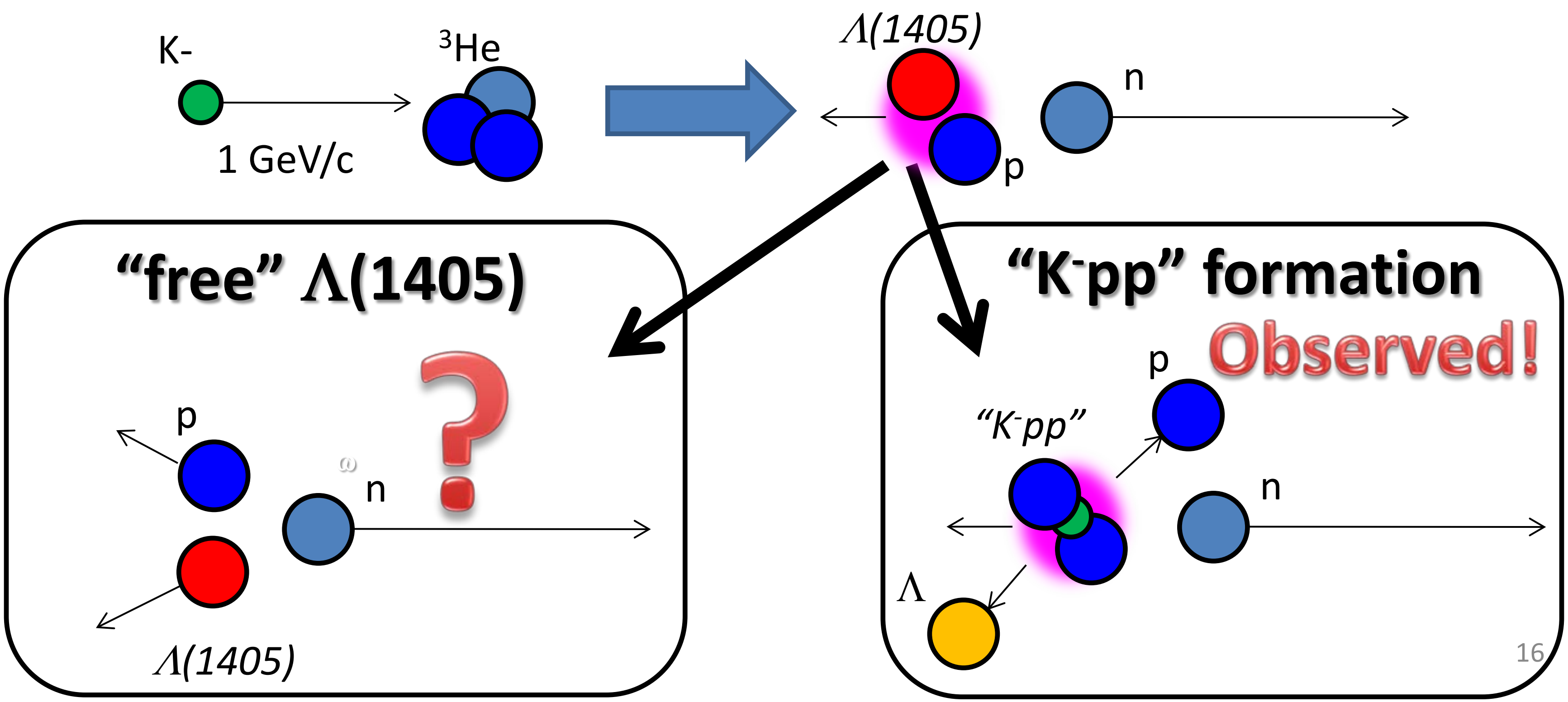
- ✓ Λ(1405) production → Λ*N doorway
- ✓ πΣN decay channel → new info. of K^{bar}NN

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



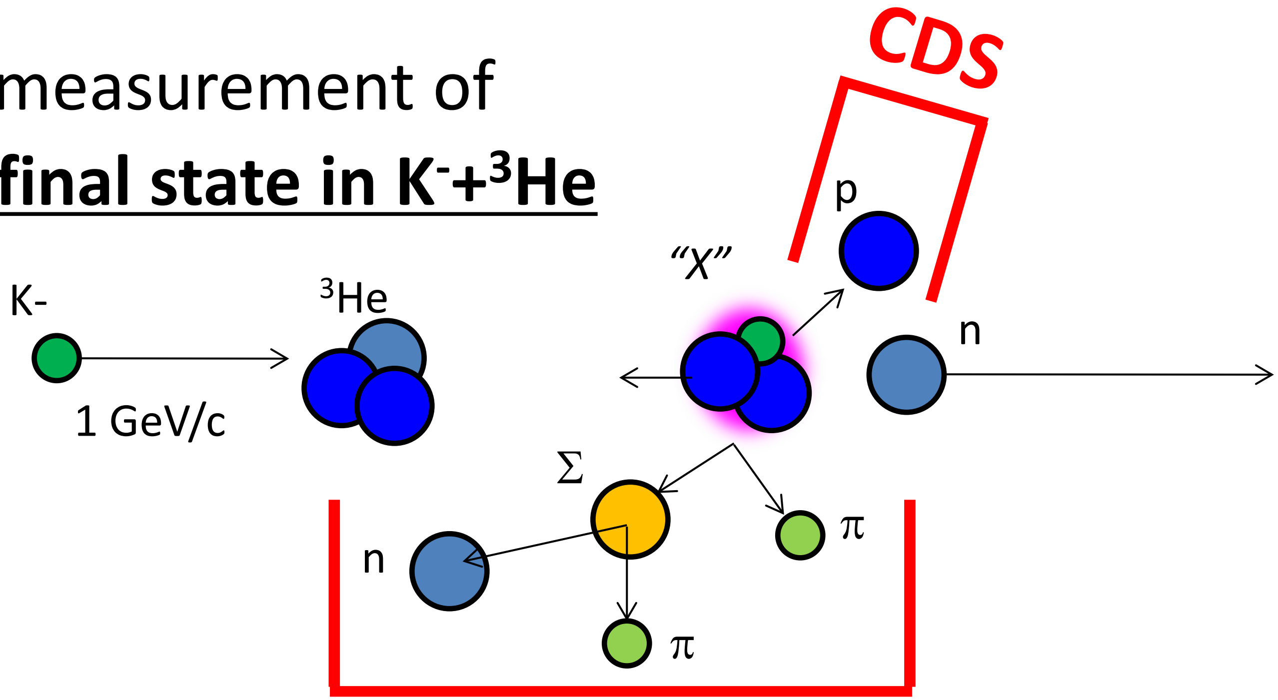
Λ(1405)p and "K⁻pp"

- 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



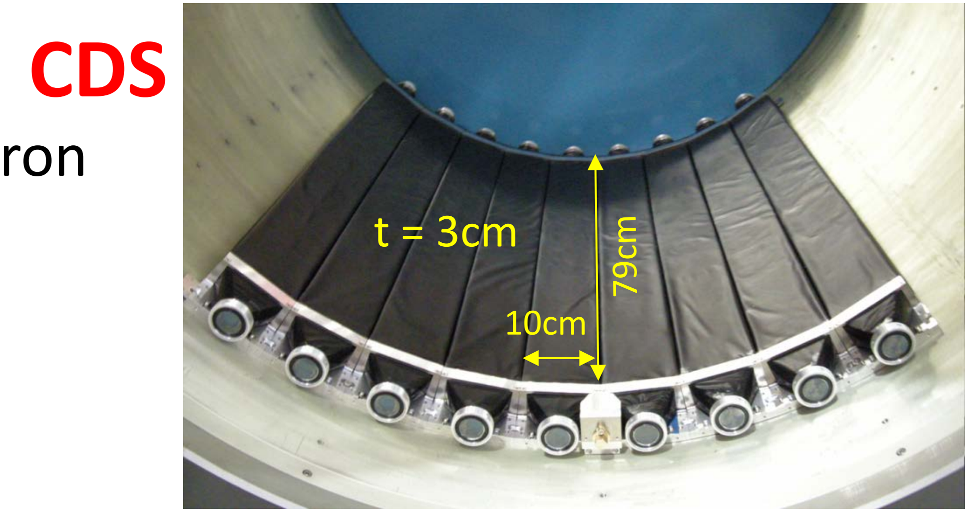
$K^- \, {}^3He \rightarrow \pi\Sigma pn$ @ E15

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

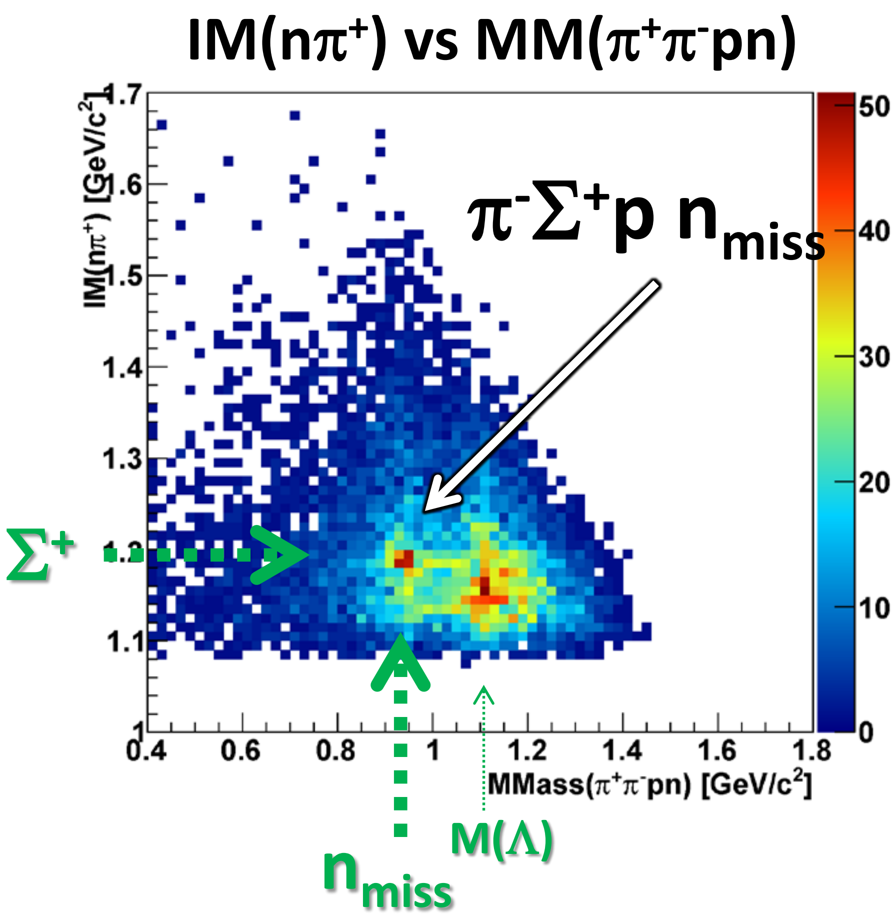


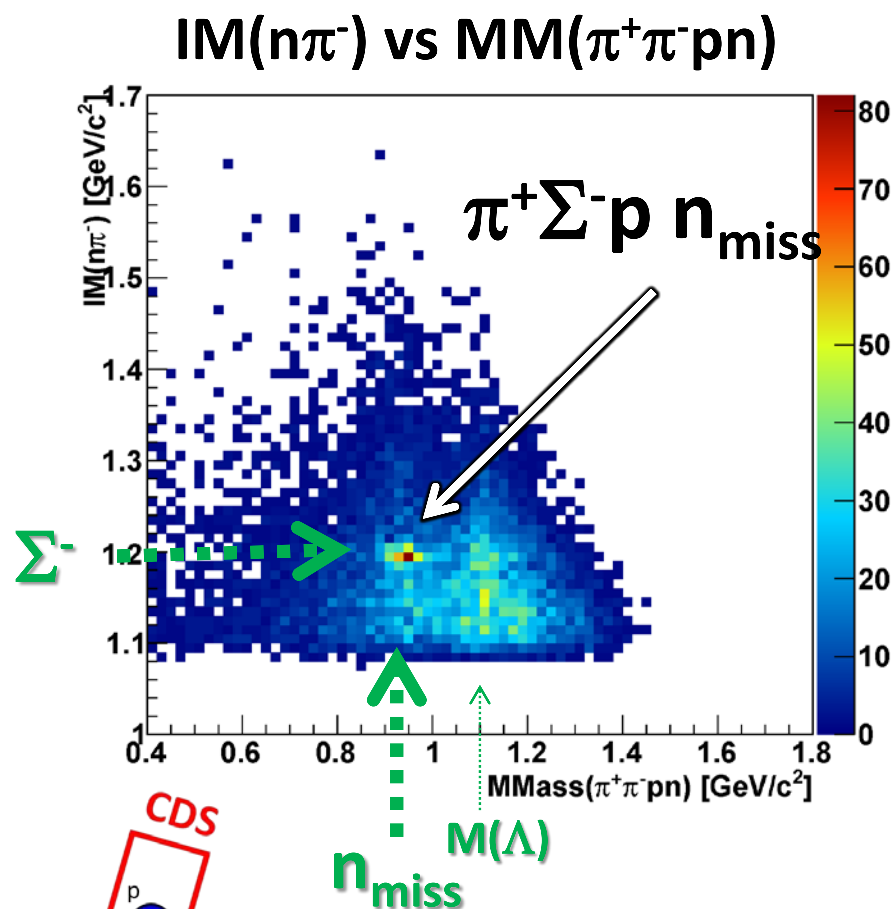
- **Experimental challenge** of neutron detection with thin scintillation counter (t=3cm)

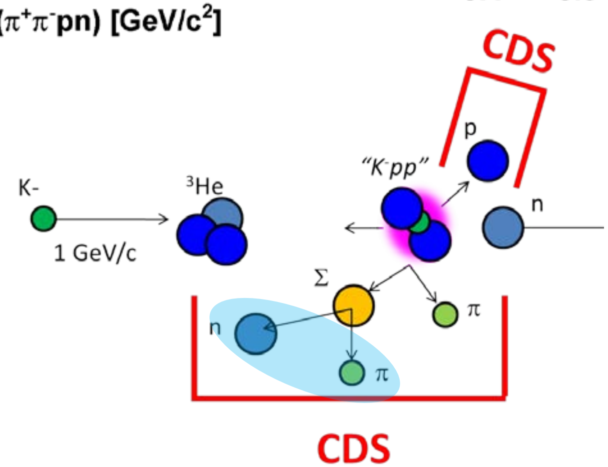
  n detection efficiency ~ 3%



πΣpn Events

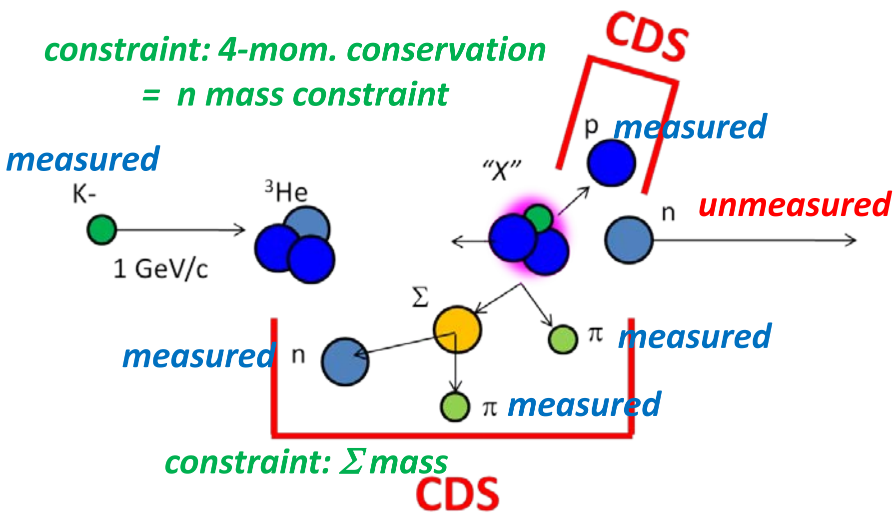

IM(nπ+) vs MM(π+π-pn)
π-Σ+p nmiss
Σ+
nmiss
M(Λ)
IM(nπ+) [GeV/c2]
MMass(π+π-pn) [GeV/c2]

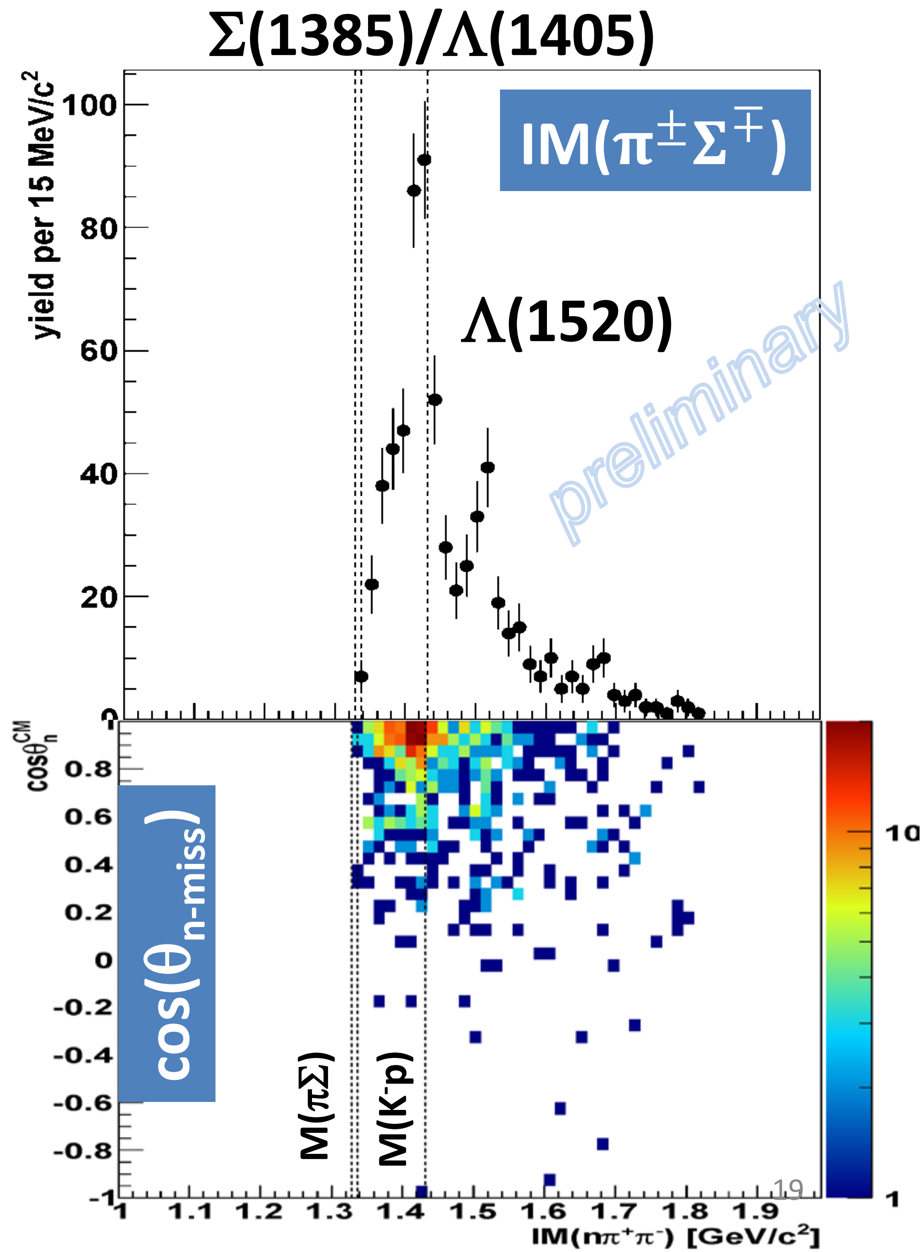

IM(nπ-) vs MM(π+π-pn)
π+Σ-p nmiss
Σ-
nmiss
M(Λ)
IM(nπ-) [GeV/c2]
MMass(π+π-pn) [GeV/c2]


CDS
K-
1 GeV/c
3He
"K-pp"
p
n
Σ
π
n
π
CDS

IM($\pi\Sigma$) vs. cos(θ_n^{CM})

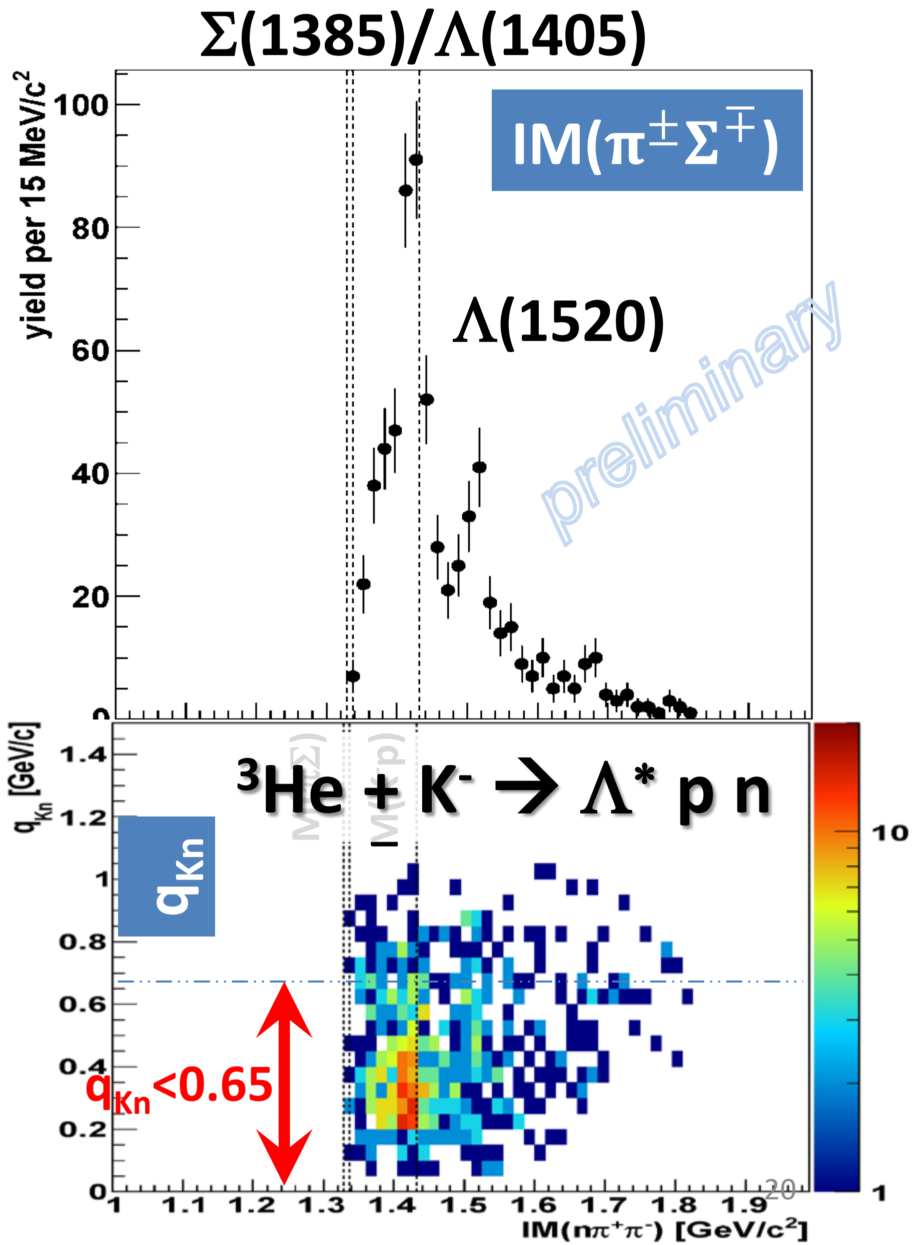
- $\pi^{\pm}\Sigma^{\mp}$ **events are separated using kinematical-fit**
  - Constraints:
    - M($\Sigma \rightarrow n\pi$)
    - 4-momentum conservation
  - Event selection by χ^2 probability (0.01<p)

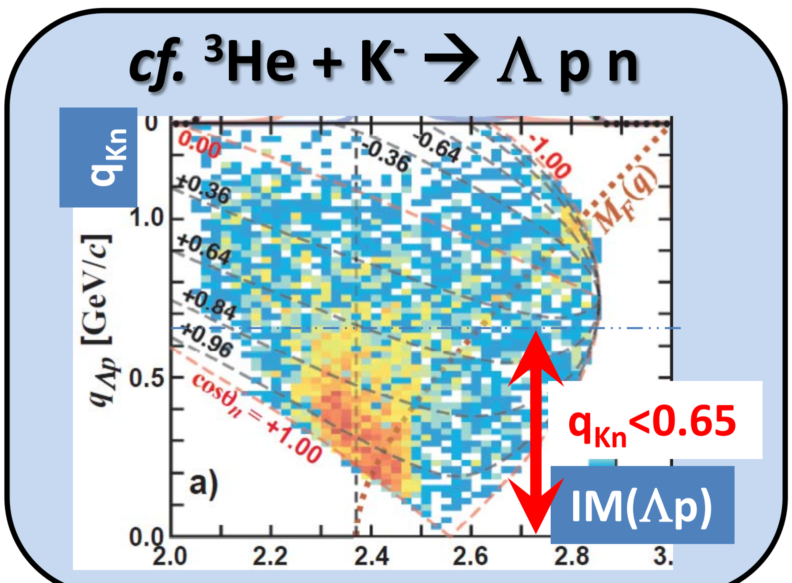




IM(πΣ) vs. Momentum Transfer q_{Kn}

- **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





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

Λ(1405)

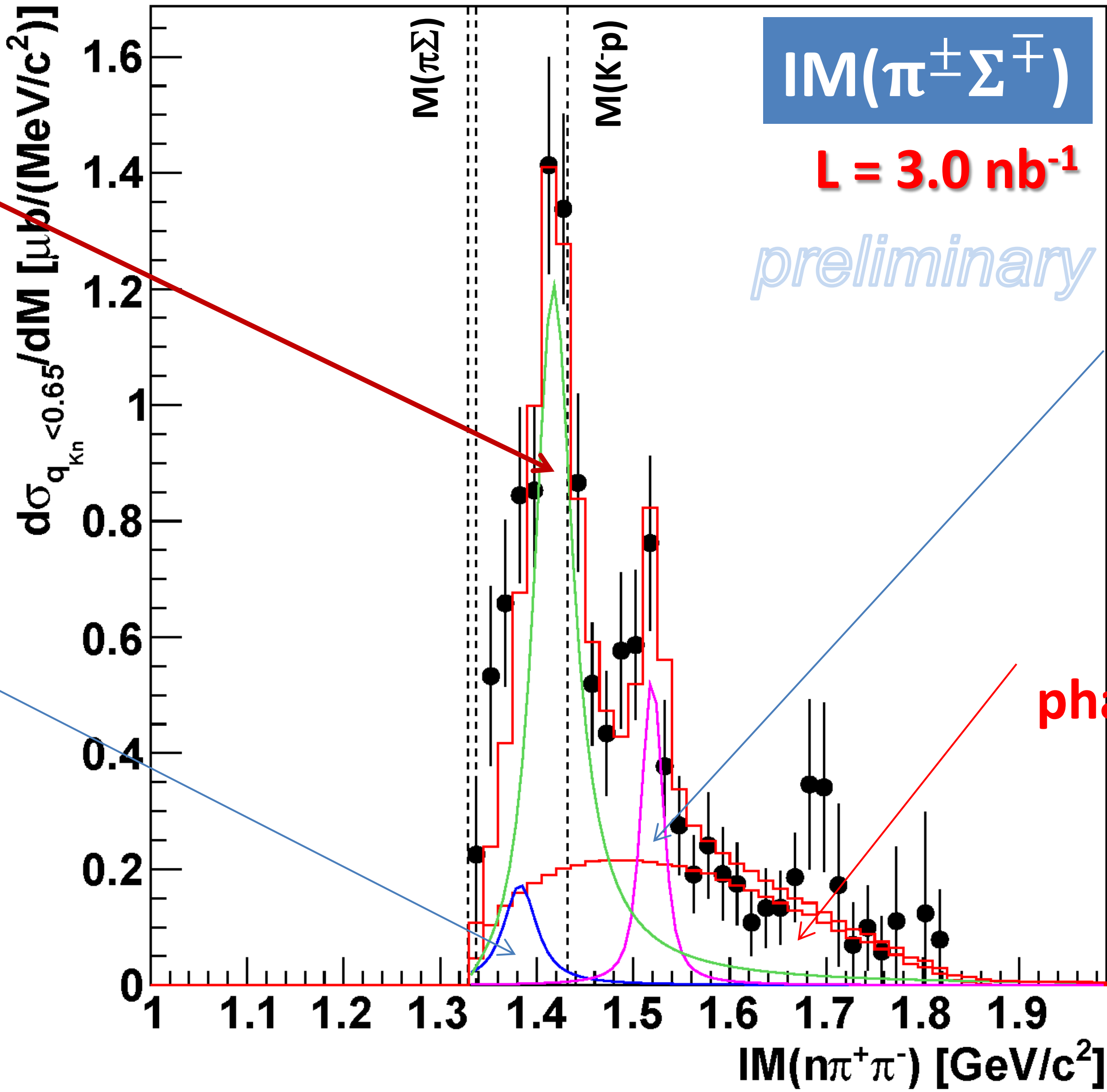
~ 130-140 μb

Flatté param.:

m_R ~ 1418 MeV/c

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

g_{KN} ~ 1.7E-2



Λ(1520)

~ 70 μb

πΣpn

phases-space

Σ^0(1385)

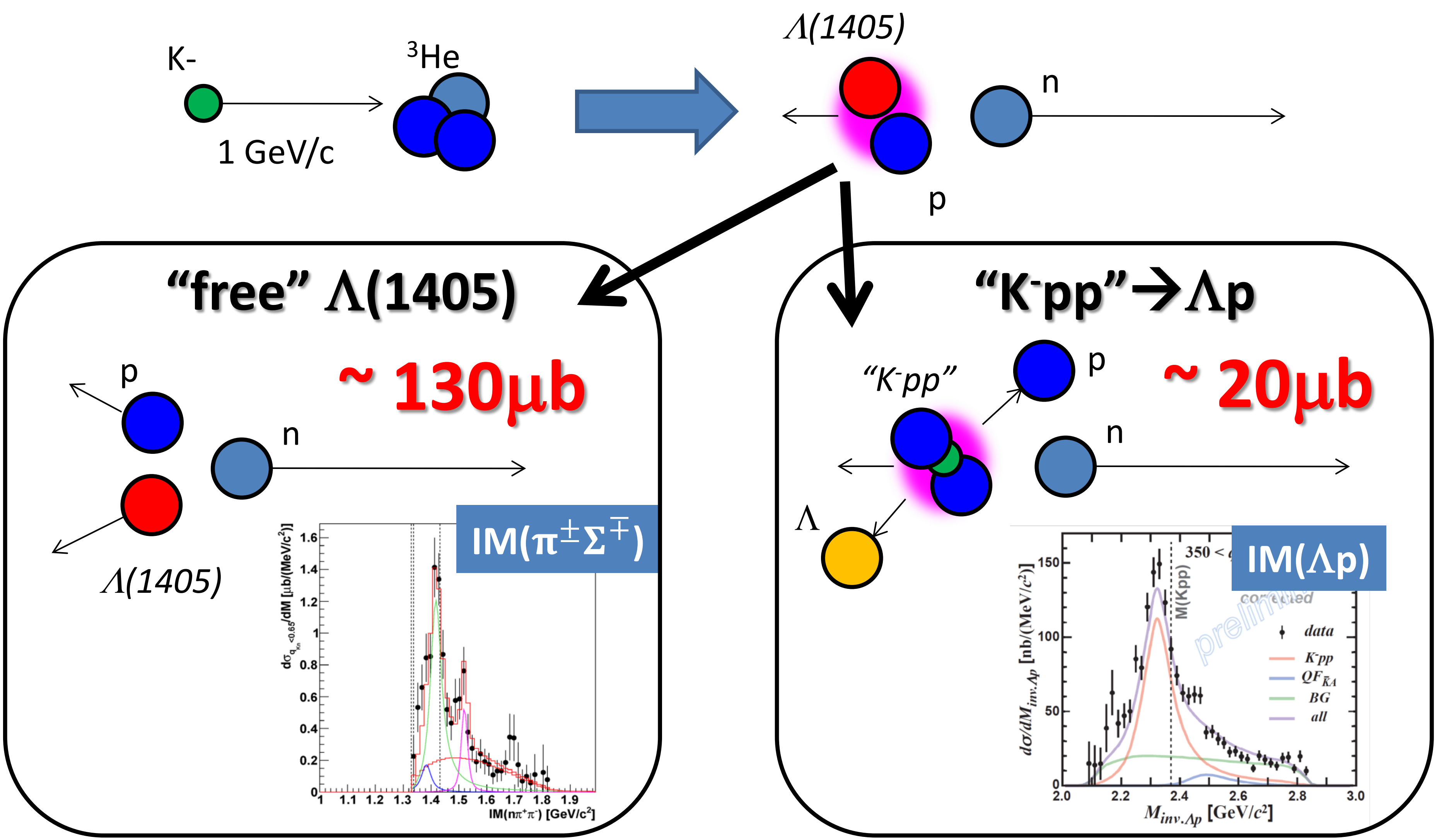
~ 40-80 μb

[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 $^3He(K^-,\pi\Sigma p)n$

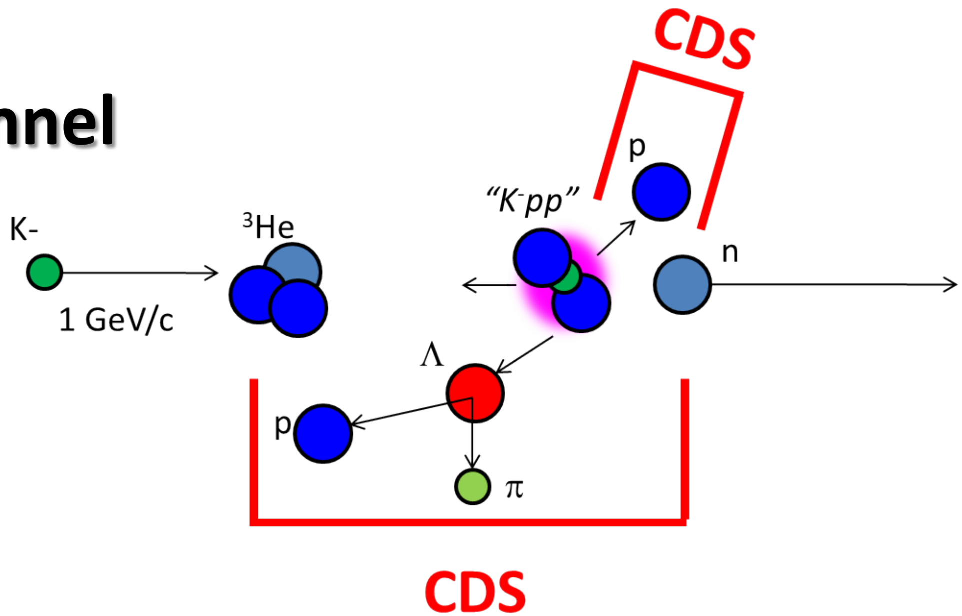
Search for "K^-pp" → $\pi\Sigma N$ decay channel

Two Decay Mode of "K⁻pp"

1. "K⁻pp" search via Λp channel

→ Non-mesonic channel

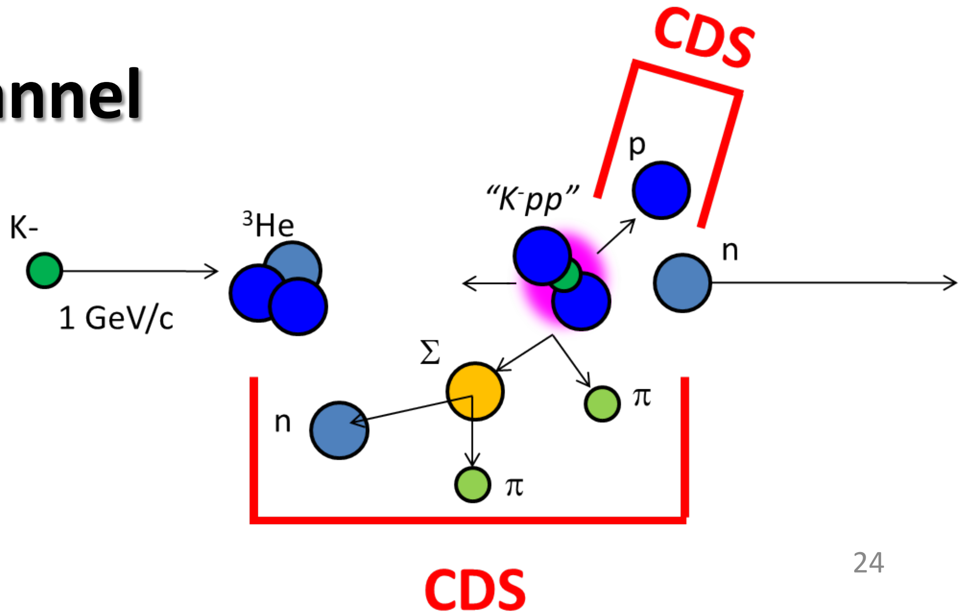
FINUDA/DISTO/E27/E15...



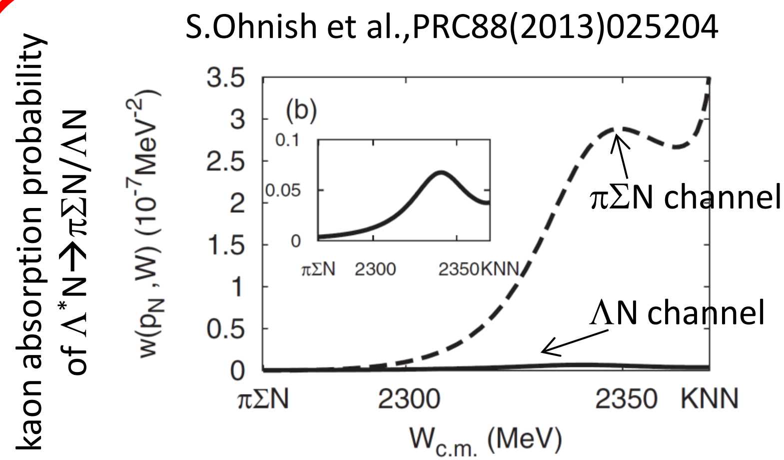
2. "K⁻pp" search via πΣp channel

→ Mesonic channel

NO measurement so far



Two Decay Mode of "K⁻pp"

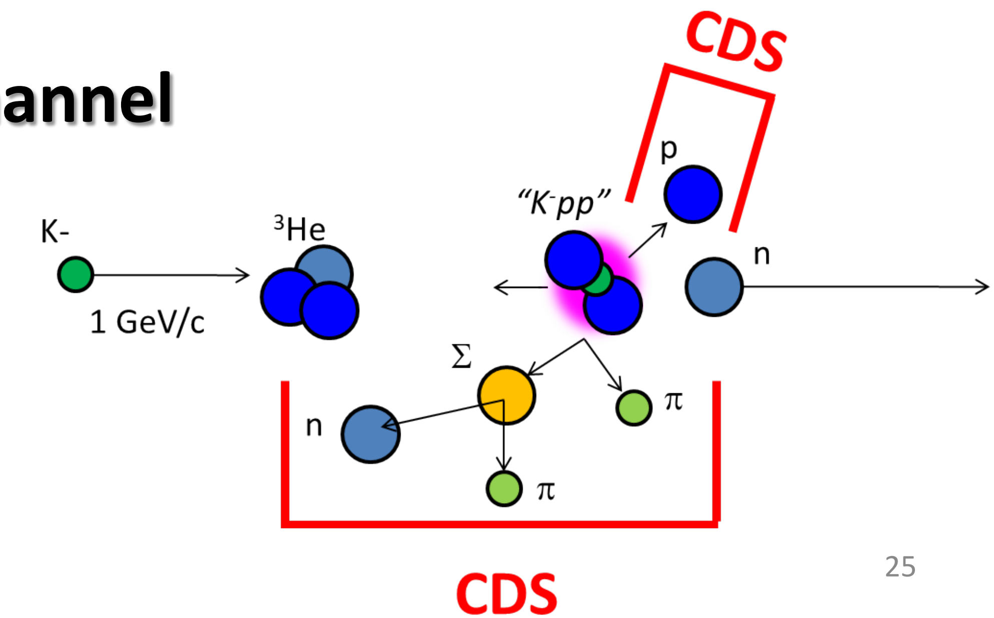


Theoretically,
πΣN decay is expected to be the dominant channel

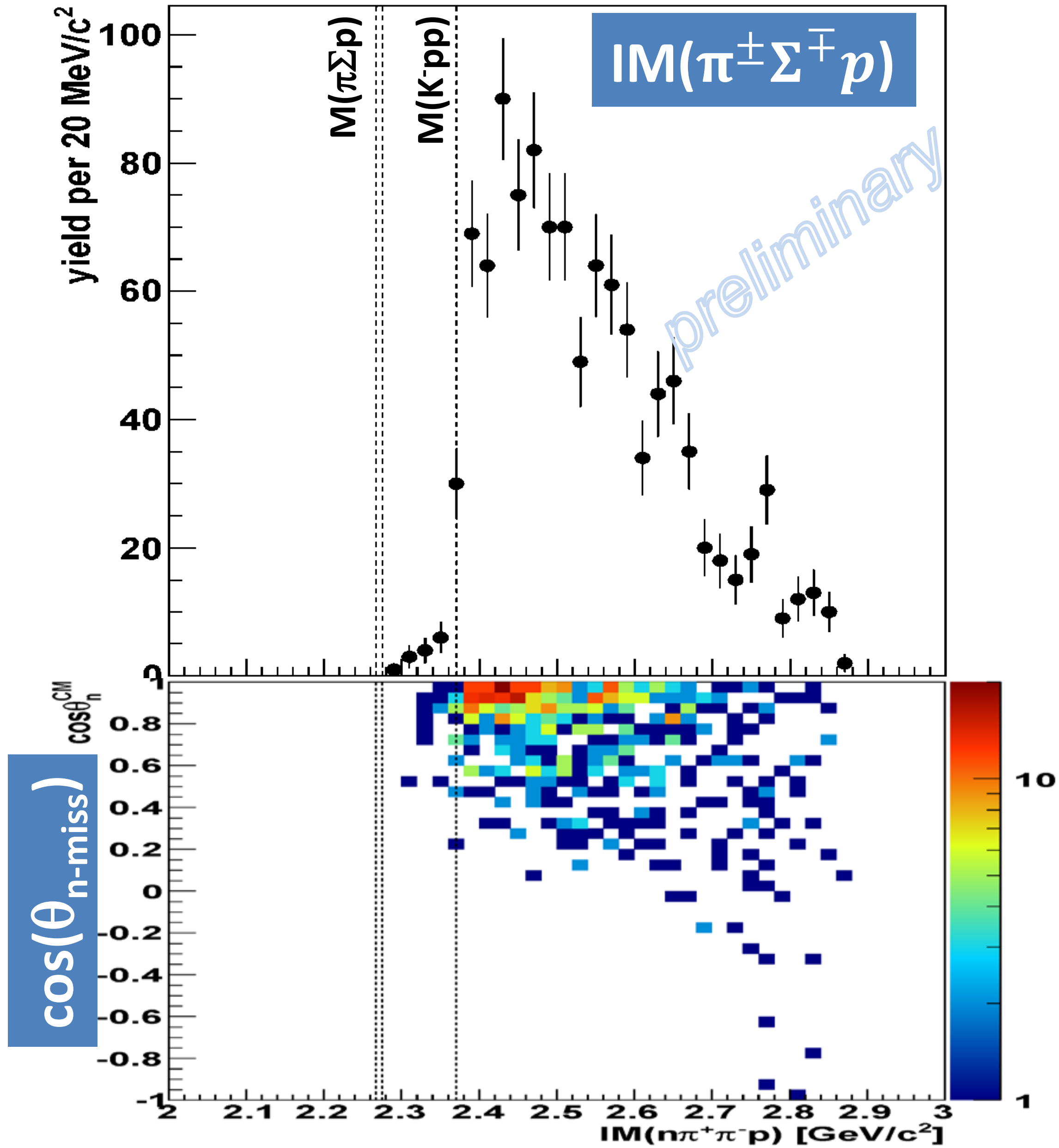
2. "K⁻pp" search via πΣp channel

→ Mesonic channel

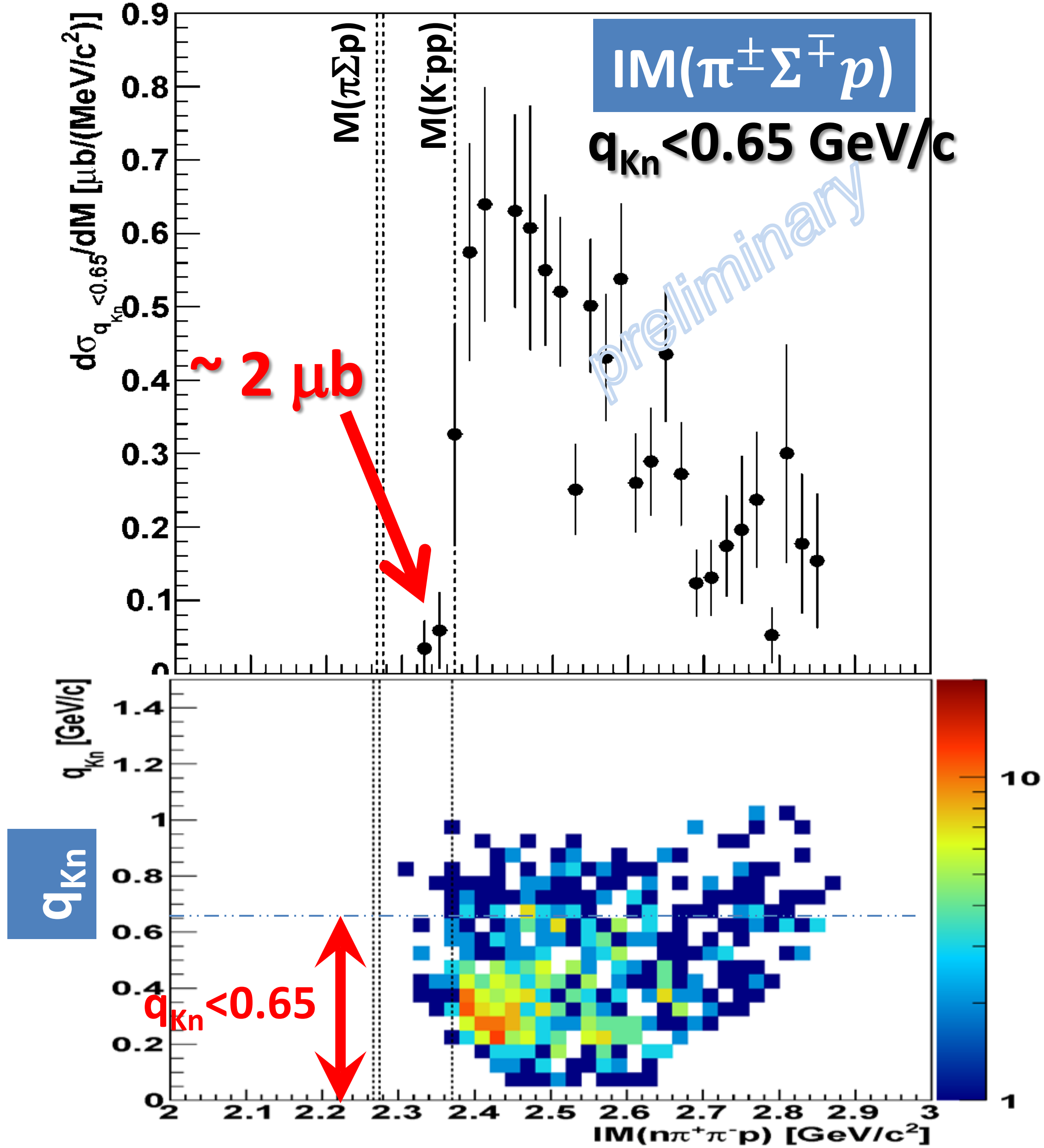
NO measurement so far

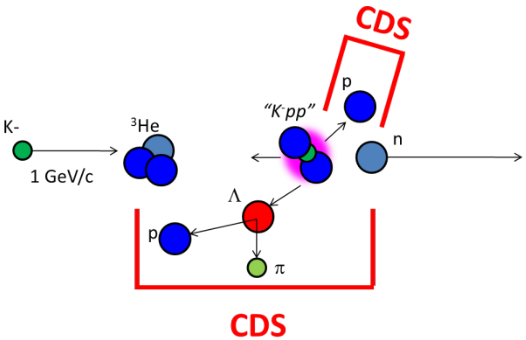


IM(πΣp) vs. cos(θ_n^{CM})

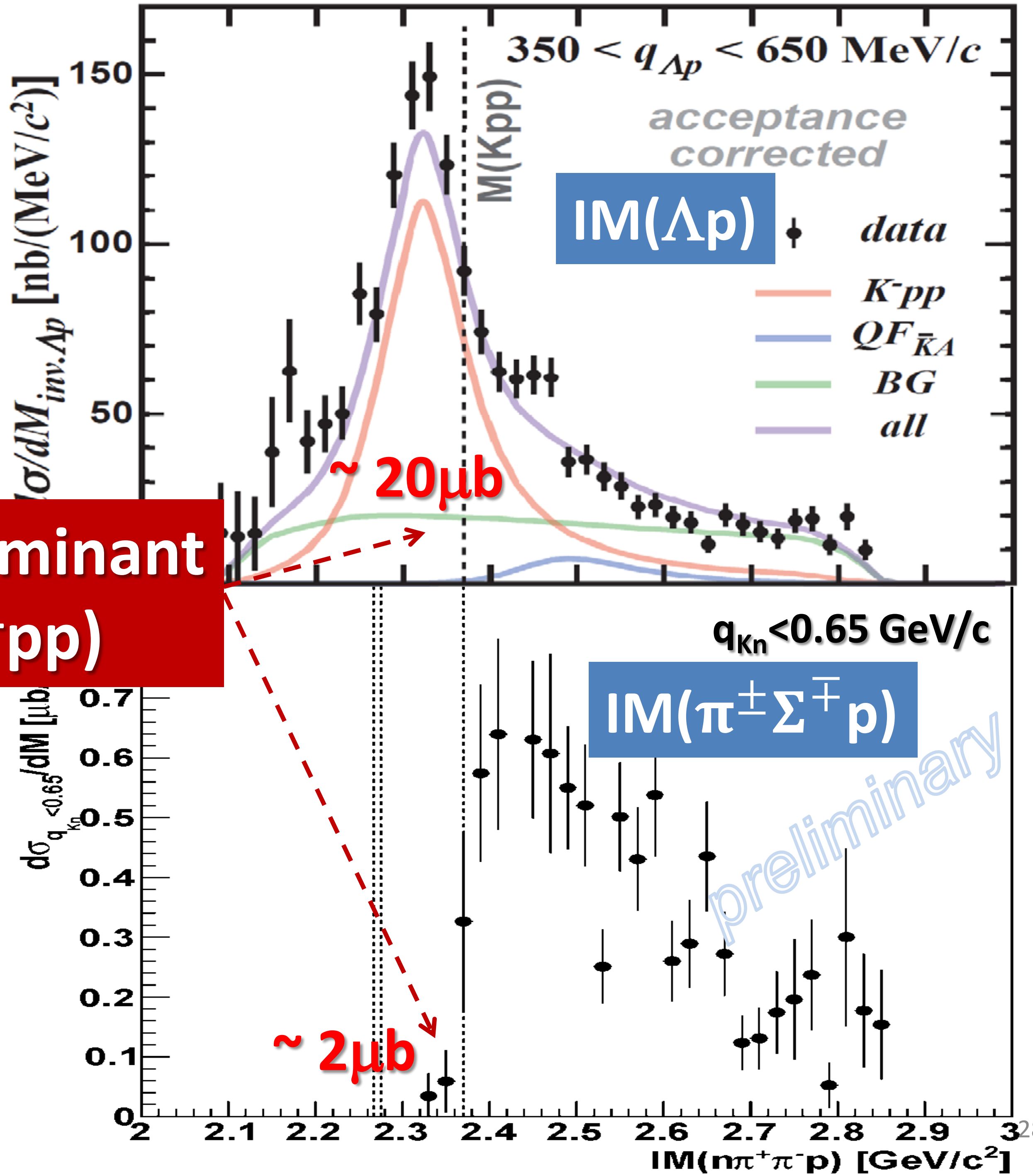


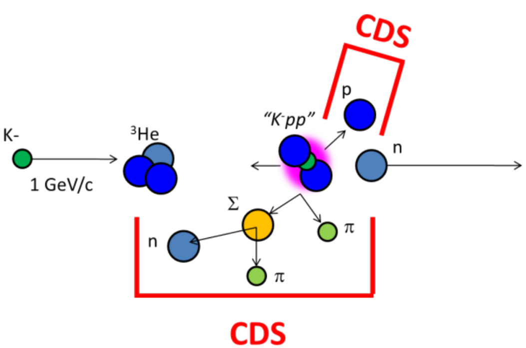
IM($\pi\Sigma$p) vs. Momentum Transfer q_{Kn}



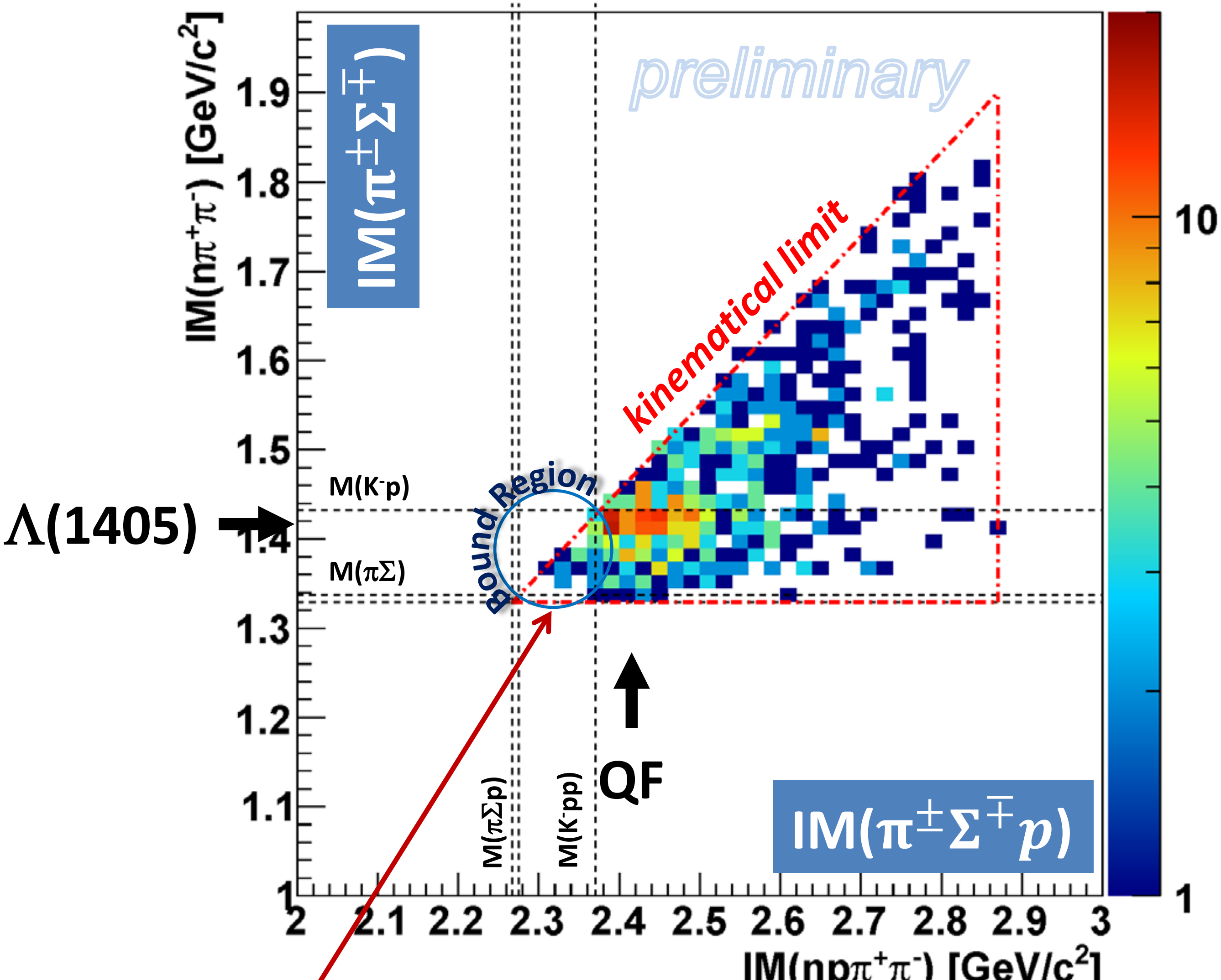


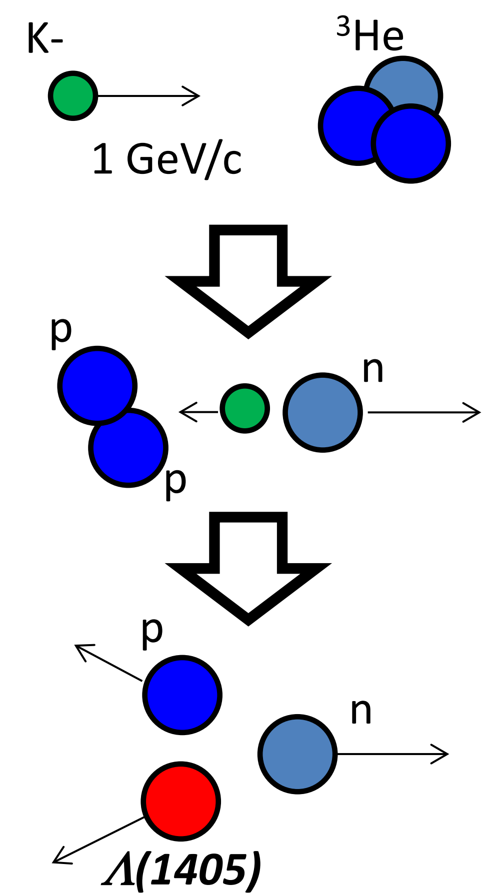
Λp decay is dominant below M(K⁻pp)





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





Small phase-space of "K⁻pp"→πΣN

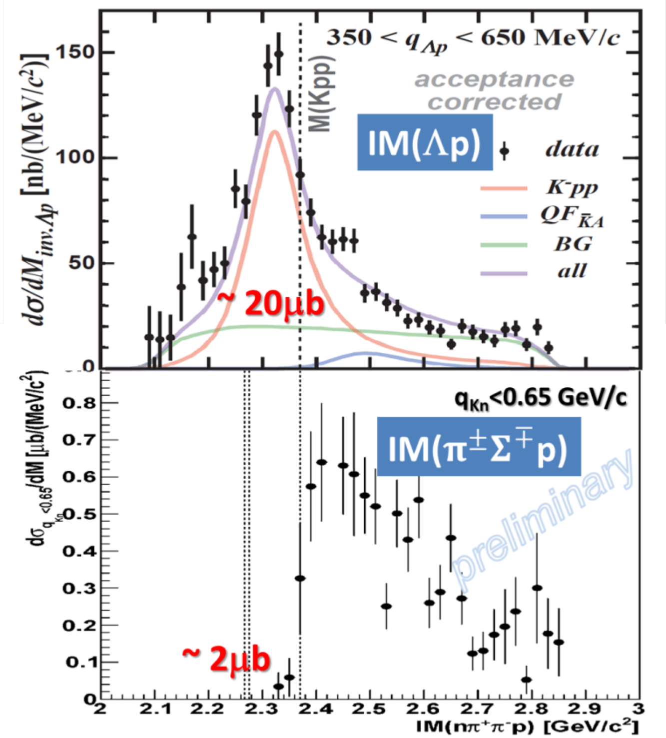
Conclusions

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

  ← E15 collab., arXiv:1805.12275

- **Λ(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" → πΣN

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

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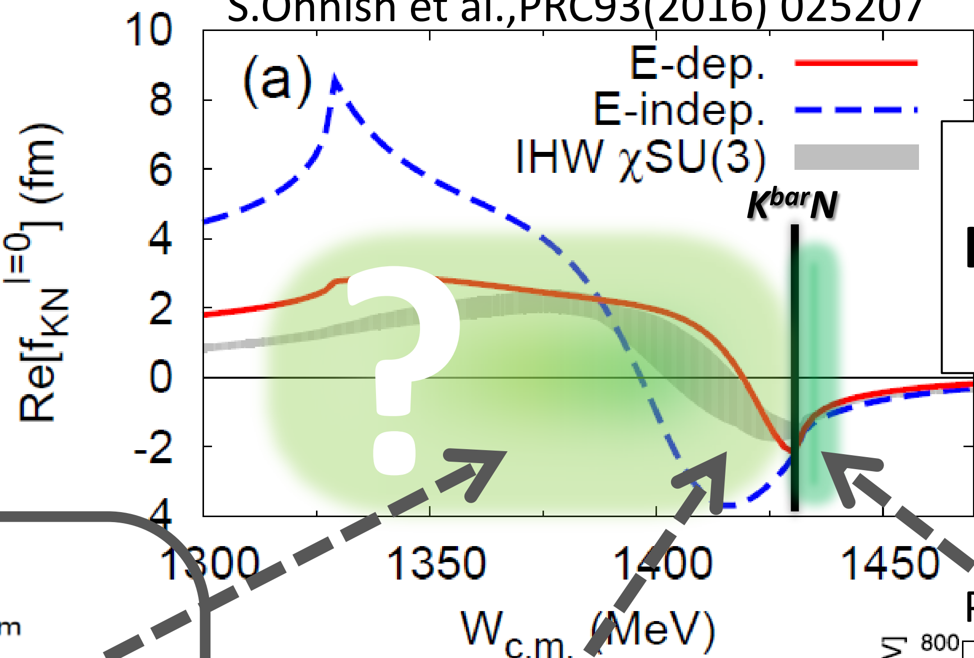
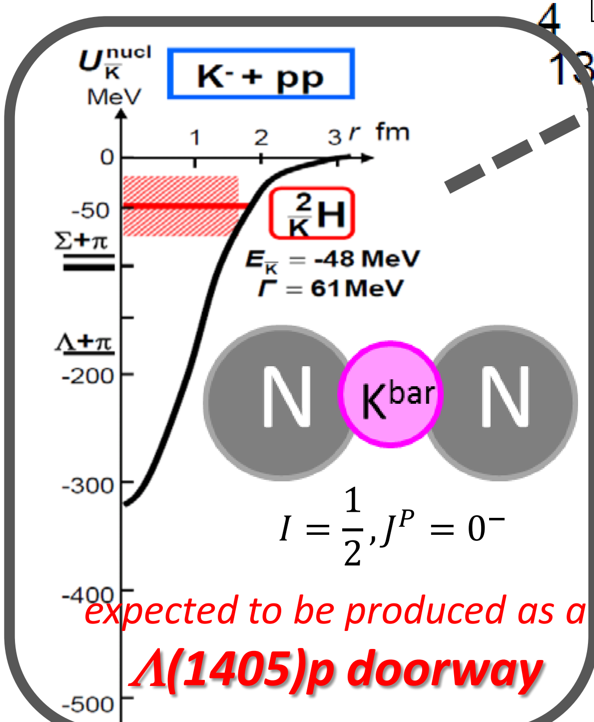
Spares

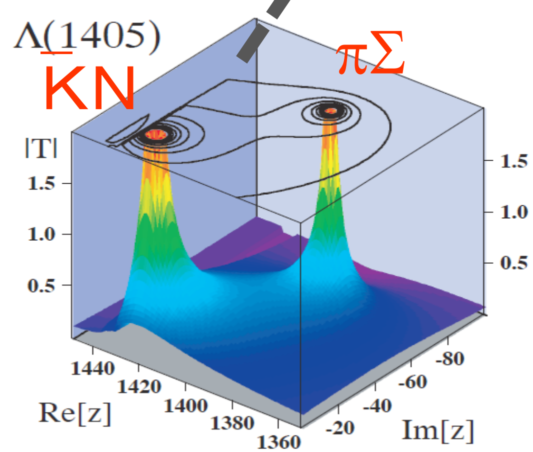
$K^{bar}N$ interaction - A good probe for low-energy QCD

S.Ohnish et al.,PRC93(2016) 025207



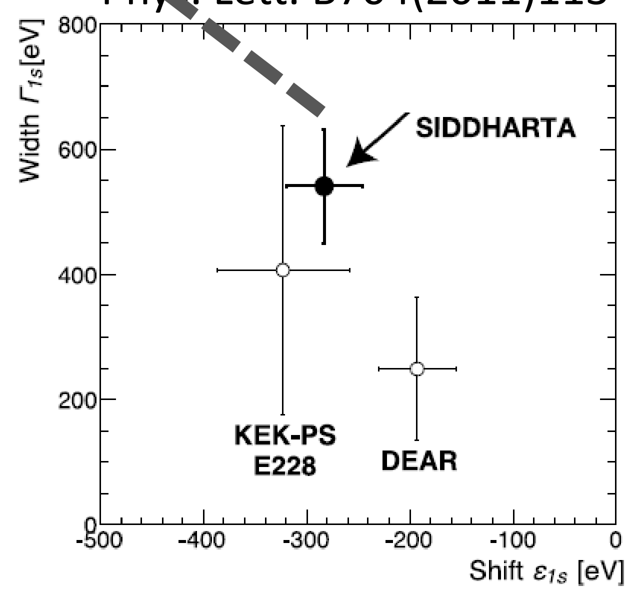
Calculation on $K^{bar}N$ amplitude in I = 0





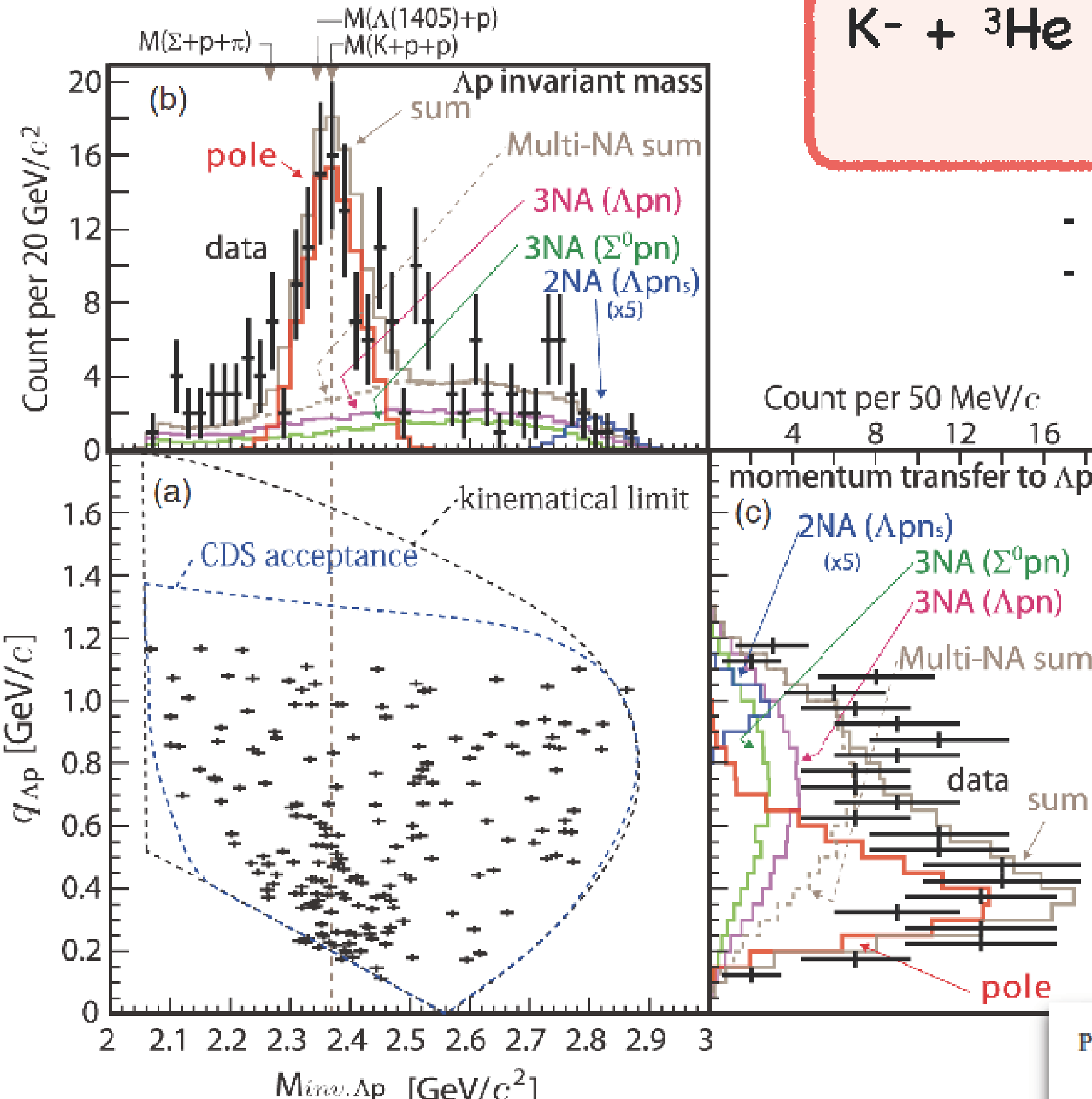
ChU model, T. Hyodo

M. Bazzi et al., (SIDDHARTA Coll.), Phys. Lett. B704(2011)113



Forward $n_{mis.}$ + Λ p @ E15[1st]

Resolution σ ~ 10 MeV/c² @ threshold



K⁻ + ³He → (K⁻ p p) + n

→ (Λ + 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 MeV

$\Gamma_X \sim$ 100 MeV

$Q_X \sim$ 400 MeV

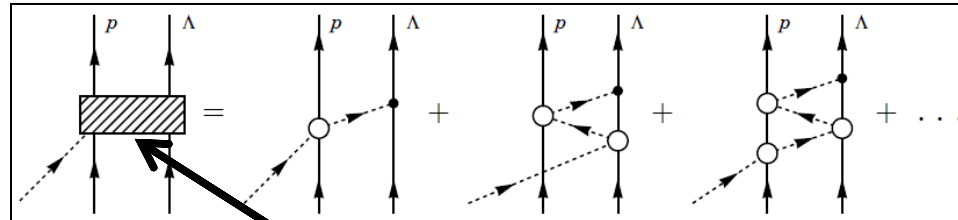
Compact state?

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

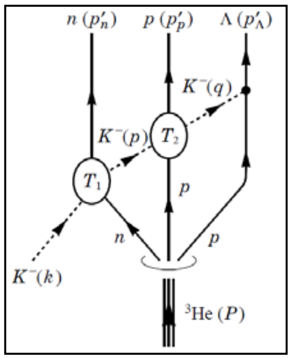
A Theoretical Interpretation of E15

Sekihara, Oset, Ramos, arXiv:1607.02058

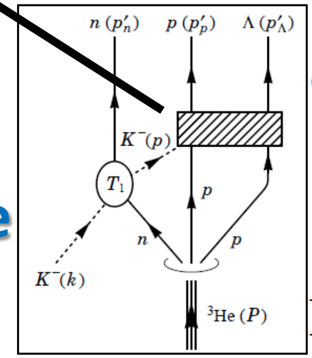
Chiral unitary approach



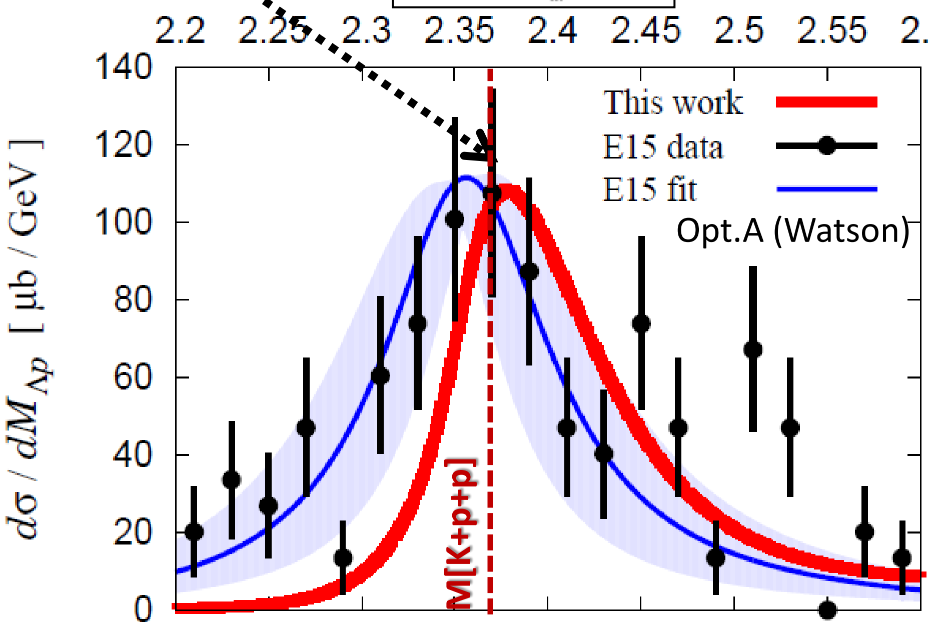
Uncorrelated Λ(1405)p state

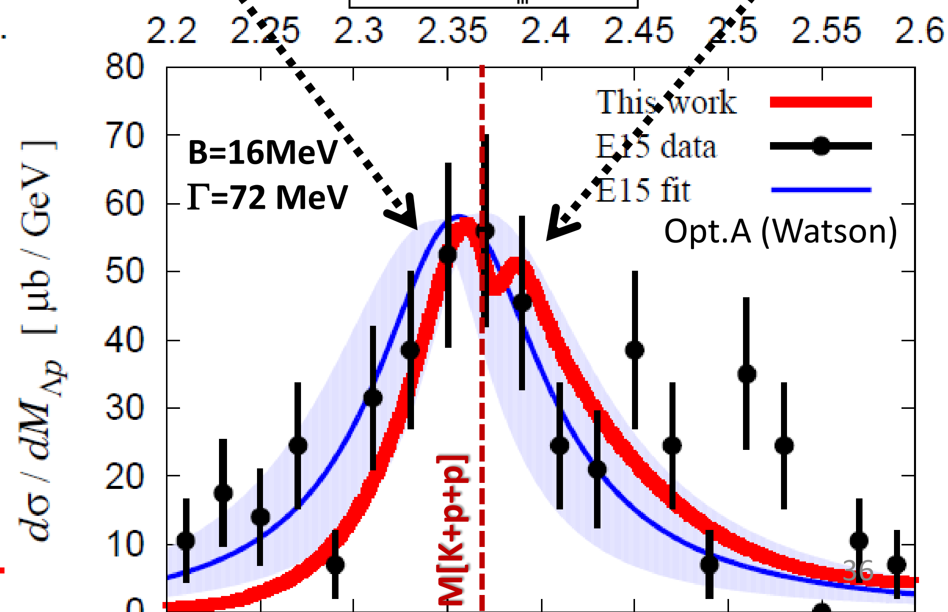


K^{bar}NN bound-state



quasi-elastic kaon scattering





$K^{bar}NN$ or NOT? --- Other Possibilities

A structure near $K^{bar}NN$ threshold

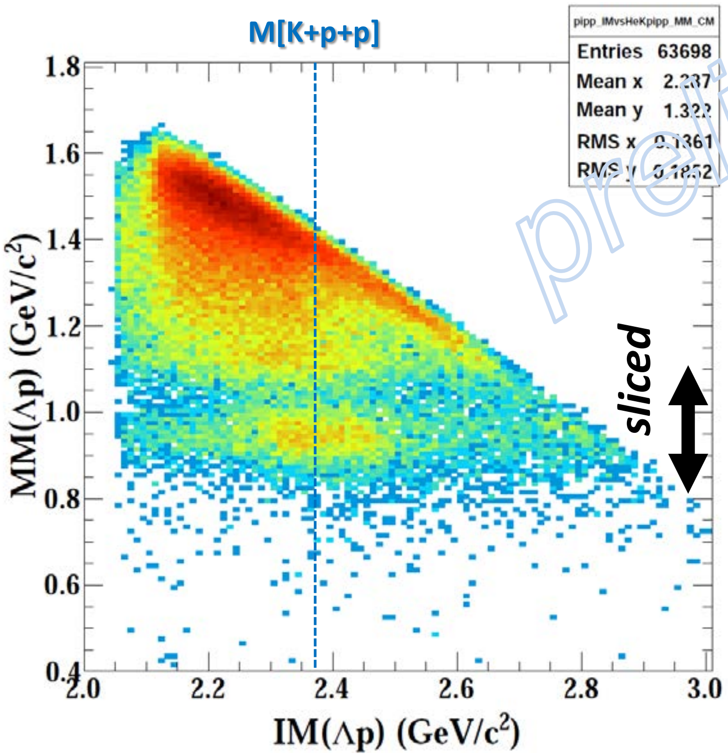
- **Λ(1405)N bound state** — T. Uchino et al., NPA868(2011)53.
  - loosely-bound system, I=1/2, $J^{\pi}=0^{-}$
  - various decay modes, $\Lambda N/\Sigma N/\pi\Sigma N$

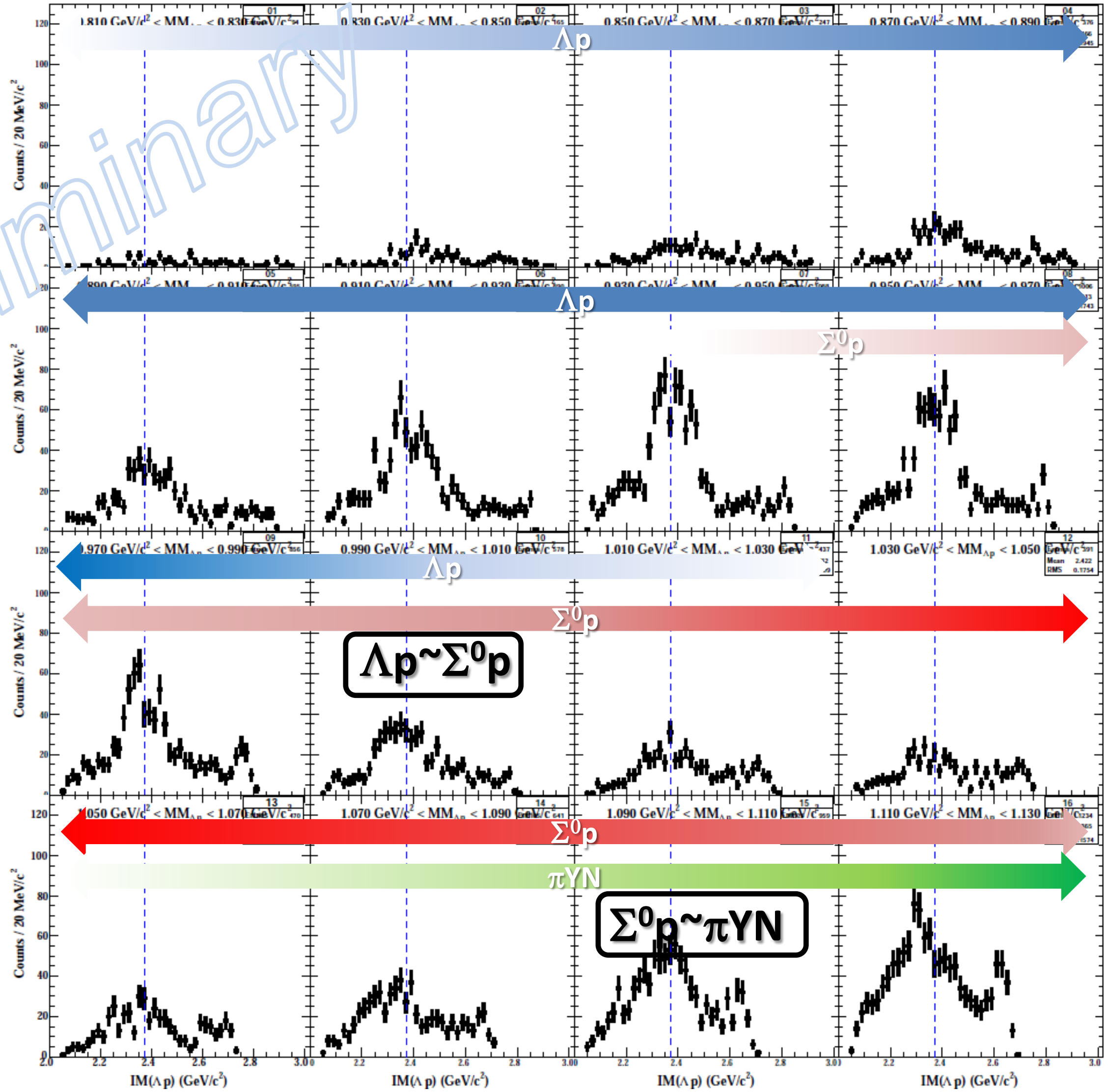
A structure near $\pi\Sigma N$ threshold

- **$\pi\Lambda N$-$\pi\Sigma N$ dibaryon** — H. Garcilazo, A. Gal, NPA897(2013)167.
  - structure near $\pi\Sigma N$ threshold
  - I=3/2, $J^{\pi}=2^{+}$ → no Λp decay (I=1/2)?
- **Double-pole $K^{bar}NN$** — A. Dote, T. Inoue, T. Myo, PTEP (2015) 043D02.
  - loosely-bound $K^{bar}NN$, &
  - broad resonance near the $\pi\Sigma N$ threshold → $\pi\Sigma N$ decay
- **Partial restoration of Chiral symmetry**
  - enhancement of the $K^{bar}N$ interaction in dense nuclei

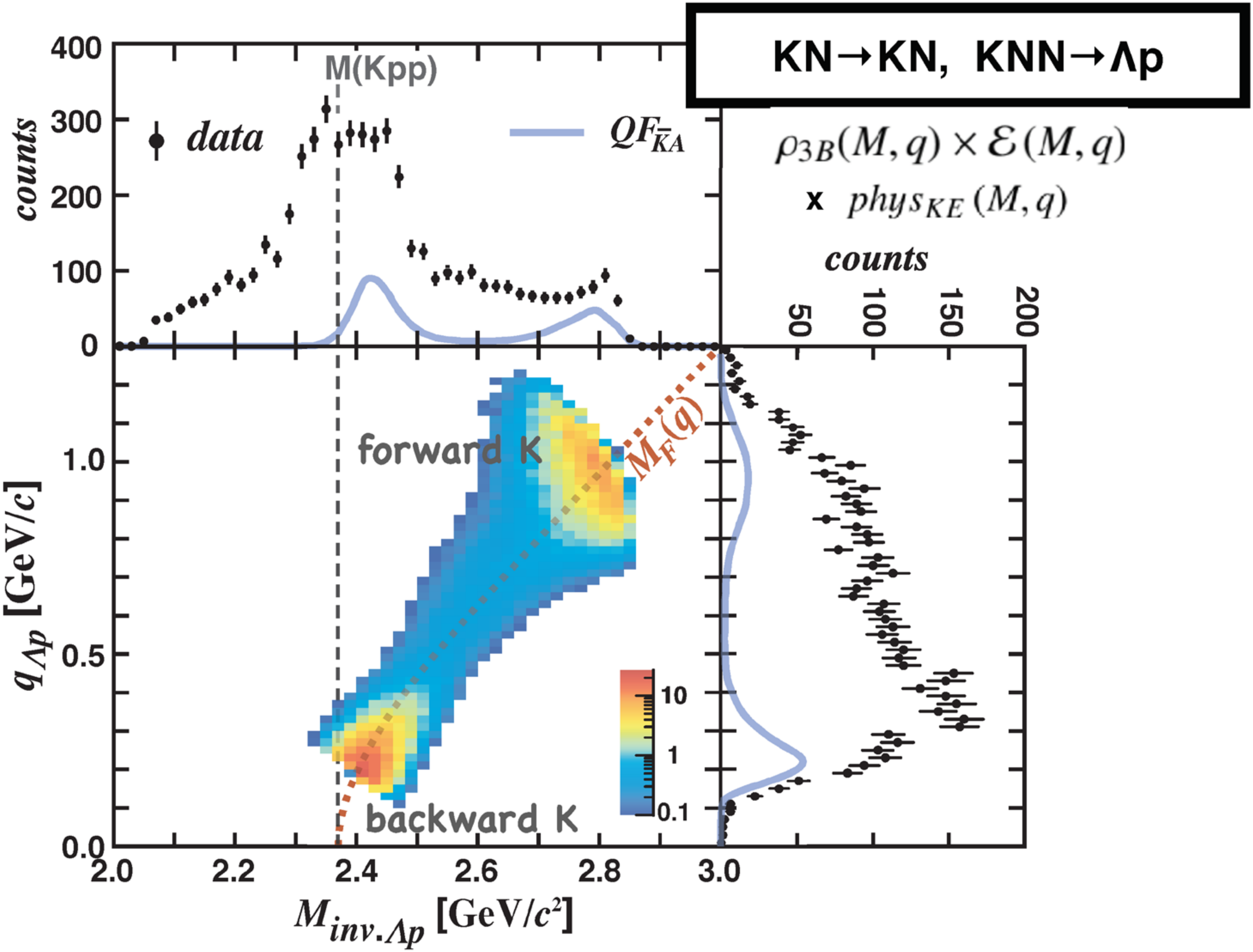
S. Maeda, Y. Akaishi, T. Yamazaki, Proc. Jpn. Acad., B89(2013)418.

$^{3}He(K^{-},\Lambda p)n$: Decay Channel

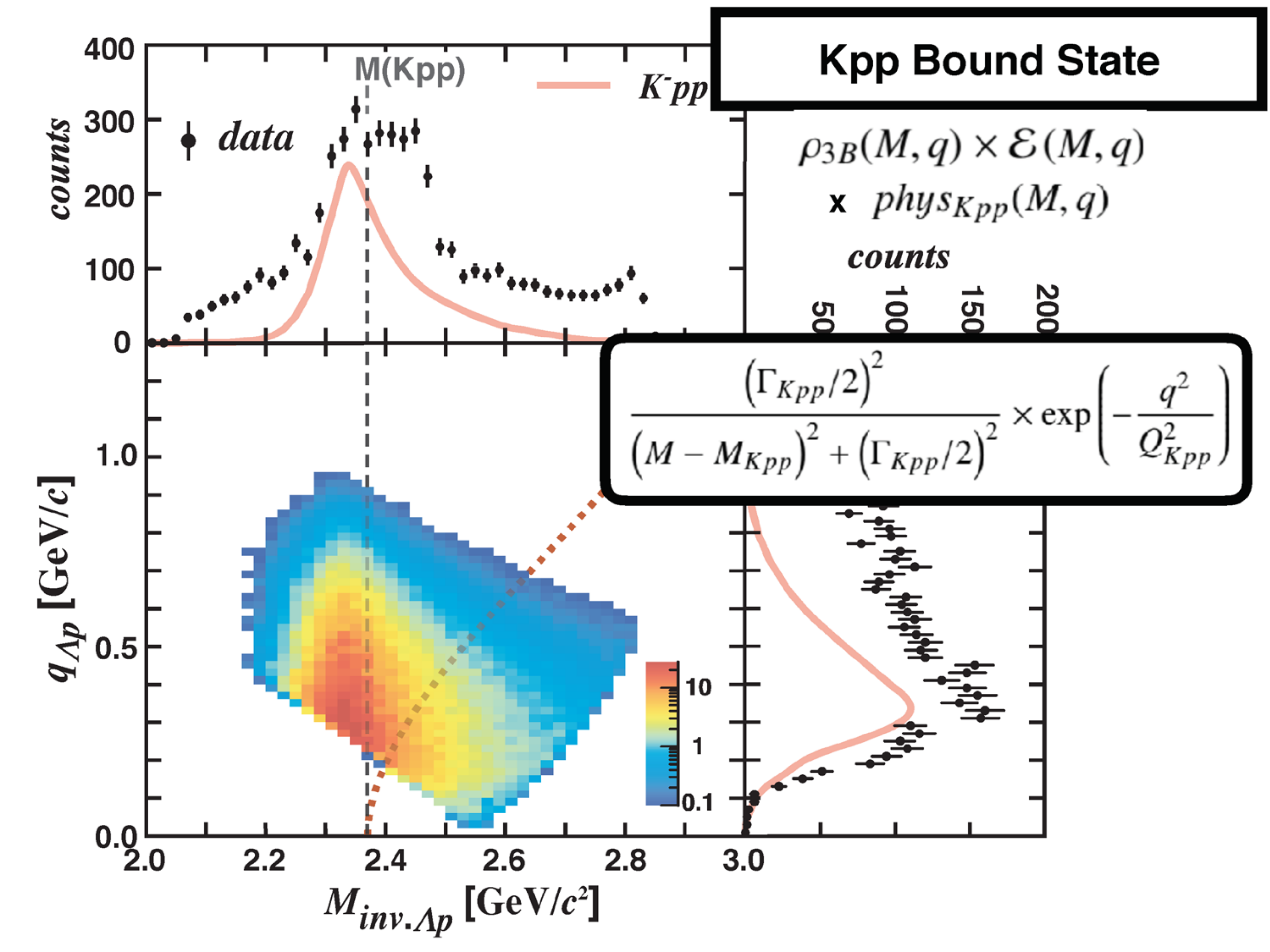


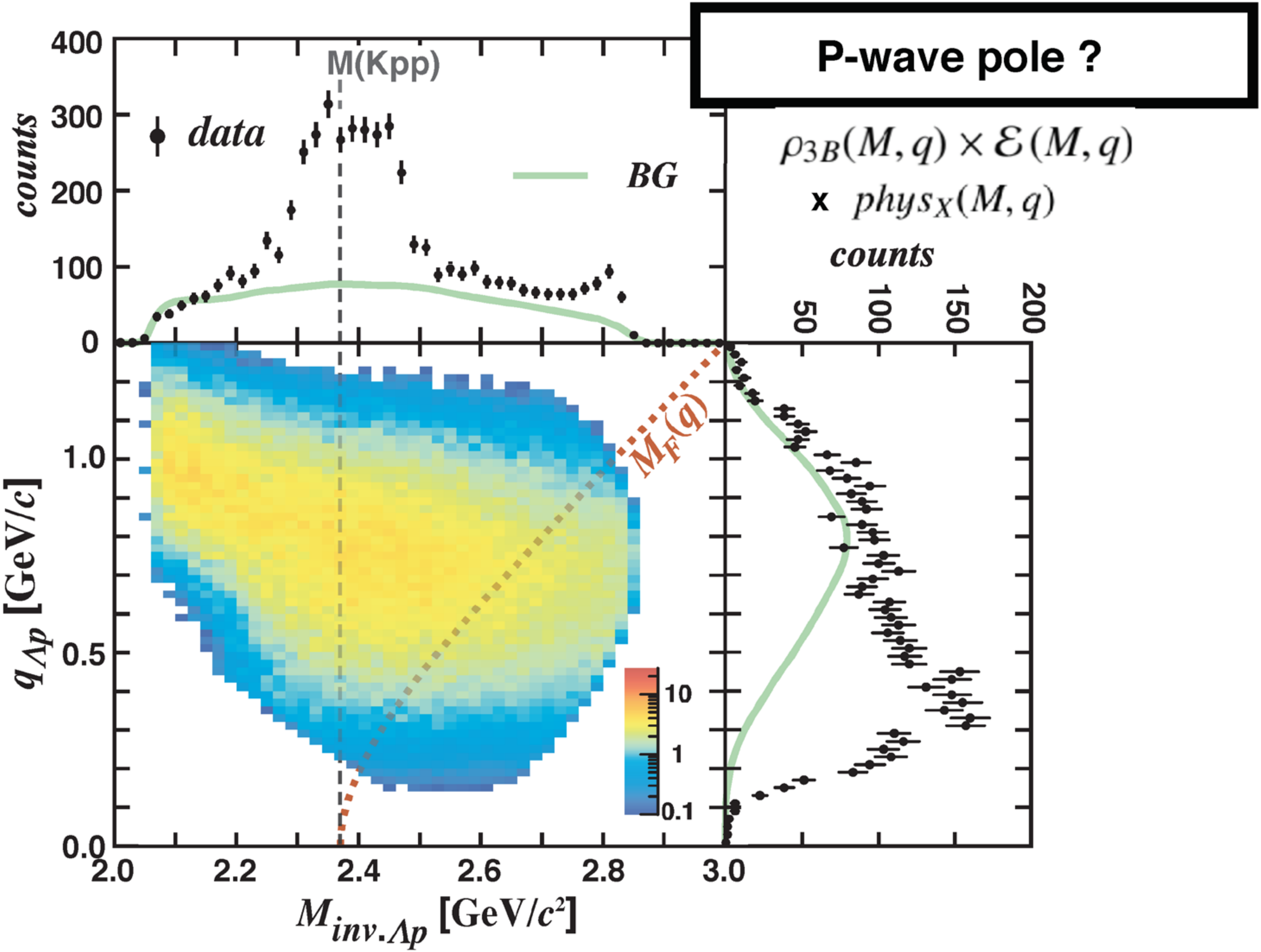


$\Gamma(\Lambda p) > \Gamma(\Sigma^0 p)$!?

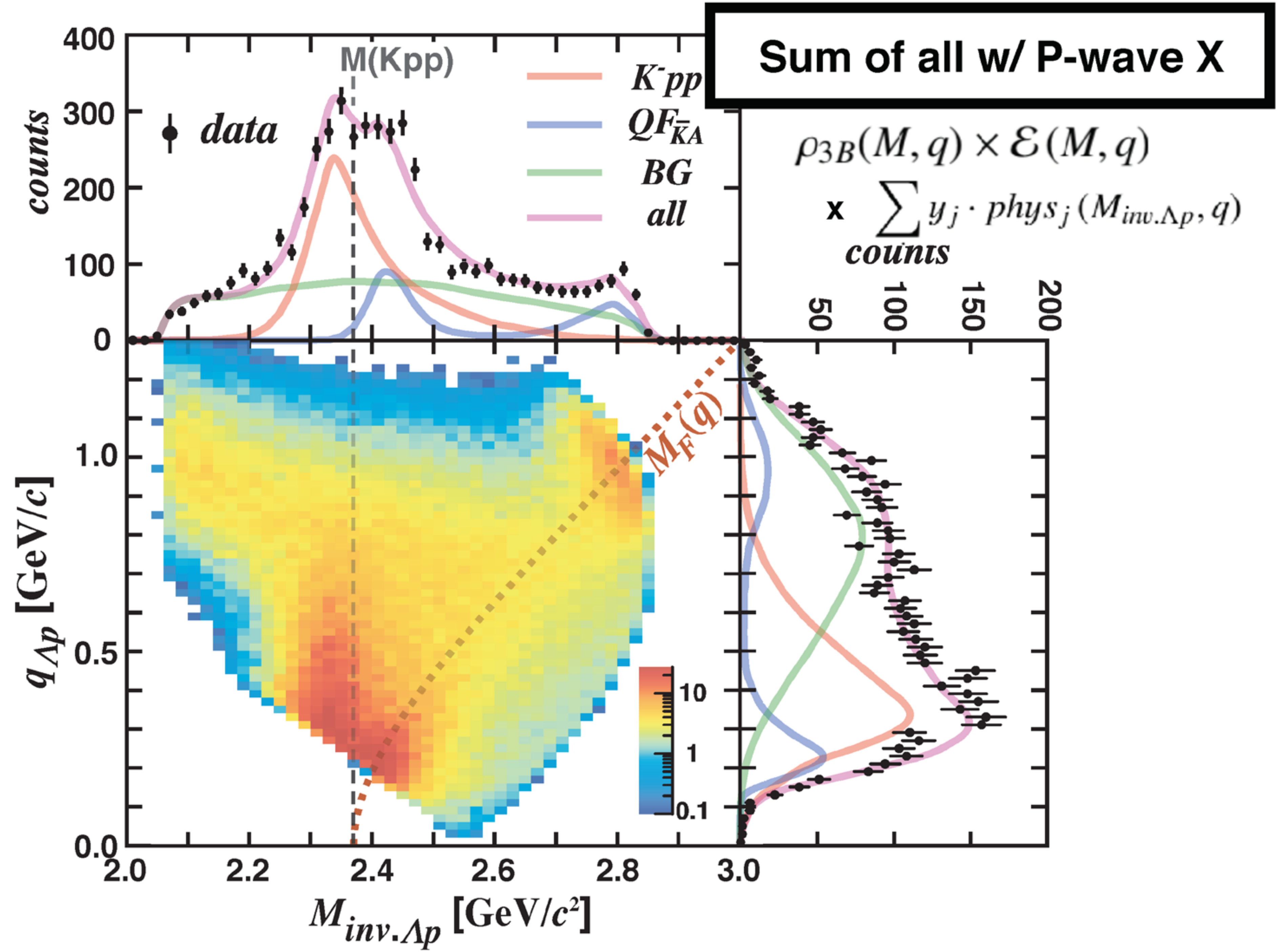


KN→KN, KNN→Λp
M(Kpp)
data
$QF_{\bar{K}A}$
$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$
x $phys_{KE}(M,q)$
counts
counts
forward K
backward K
$M_F(q)$
$q_{\Lambda p}$ [GeV/c]
$M_{inv.\Lambda p}$ [GeV/c^2]


Kpp Bound State
M(Kpp)
data
K⁻pp
counts
400
300
200
100
0
$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$
x $phys_{Kpp}(M,q)$
counts
50
100
150
200
$\frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$
$q_{\Lambda p}$ [GeV/c]
1.0
0.5
0.0
10
1
0.1
2.0
2.2
2.4
2.6
2.8
3.0
$M_{inv.\Lambda p}$ [GeV/c^2]



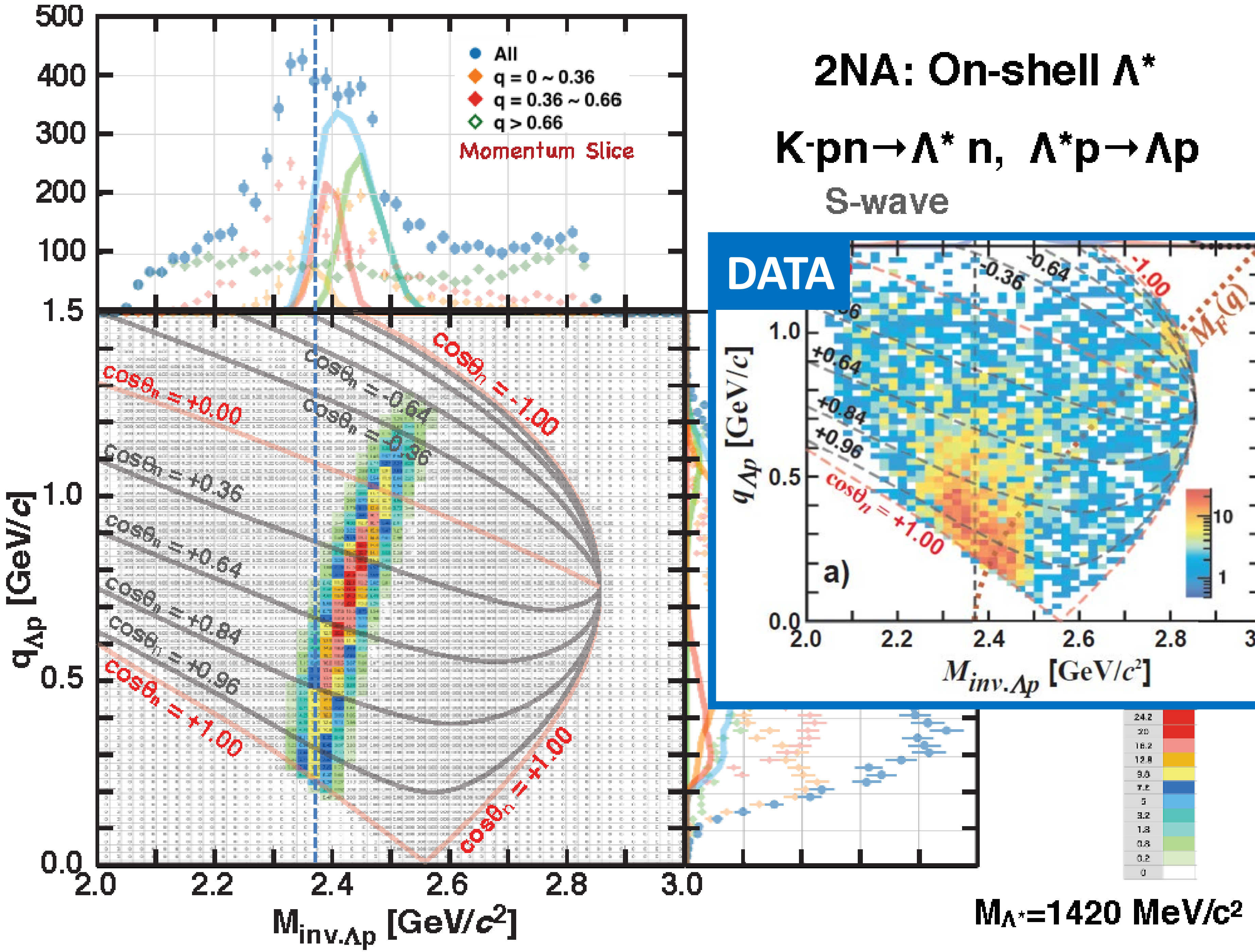
P-wave pole ?
M(Kpp)
data
BG
counts
$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$
x $phys_X(M,q)$
counts
50
100
150
200
400
300
200
100
0
1.0
0.5
0.0
2.0
2.2
2.4
2.6
2.8
3.0
$M_F(q)$
10
1
0.1
$q_{\Lambda p}$ [GeV/c]
$M_{inv.\Lambda p}$ [GeV/c^2]


Sum of all w/ P-wave X
M(Kpp)
data
K⁻pp
$QF_{\bar{K}A}$
BG
all
counts
$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$
x $\sum y_j \cdot phys_j(M_{inv.\Lambda p}, q)$
$M_F(q)$
$q_{\Lambda p}$ [GeV/c]
$M_{inv.\Lambda p}$ [GeV/c²]
400
300
200
100
0
1.0
0.5
0.0
2.0
2.2
2.4
2.6
2.8
3.0
50
100
150
200
10
1
0.1

2NA: On-shell Λ*

$K^-pn \rightarrow \Lambda^* n$, $\Lambda^* p \rightarrow \Lambda p$

S-wave

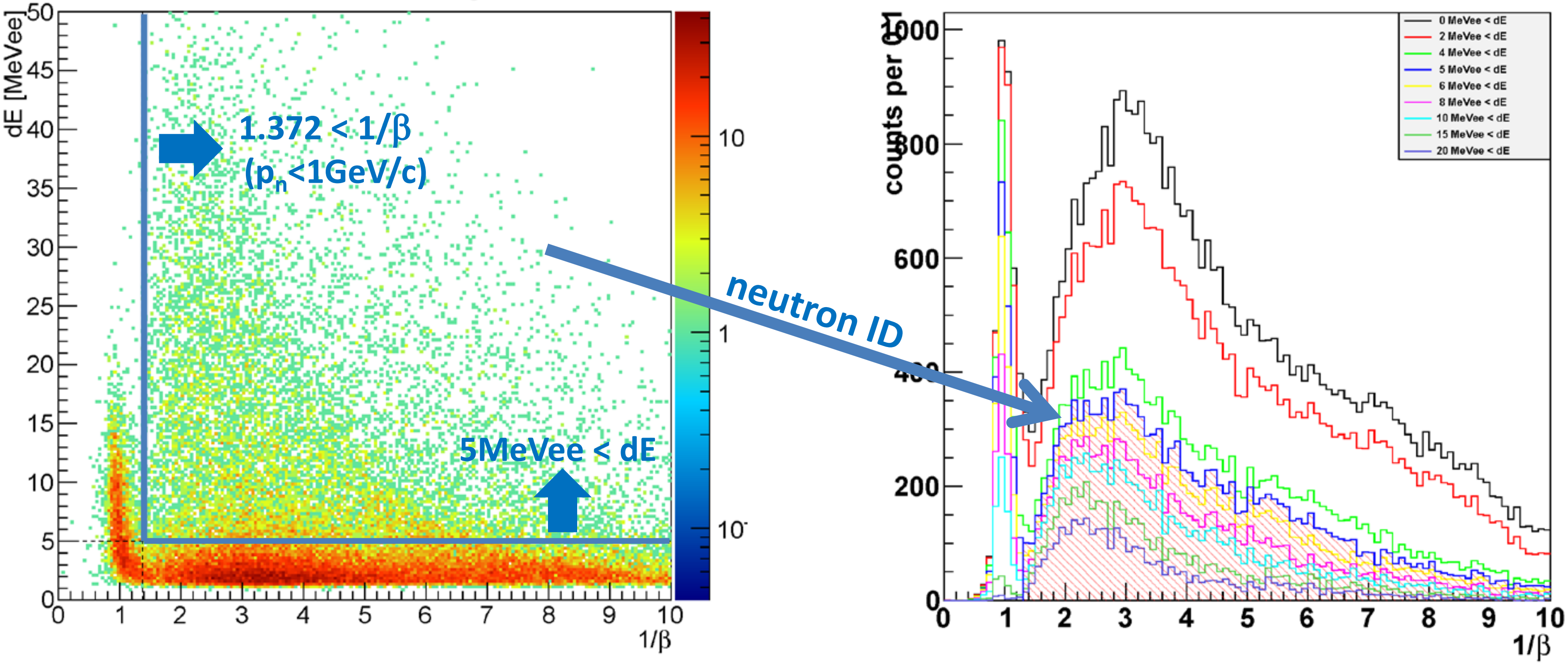


M_{Λ^*}=1420 MeV/c²

Neutron ID with CDS

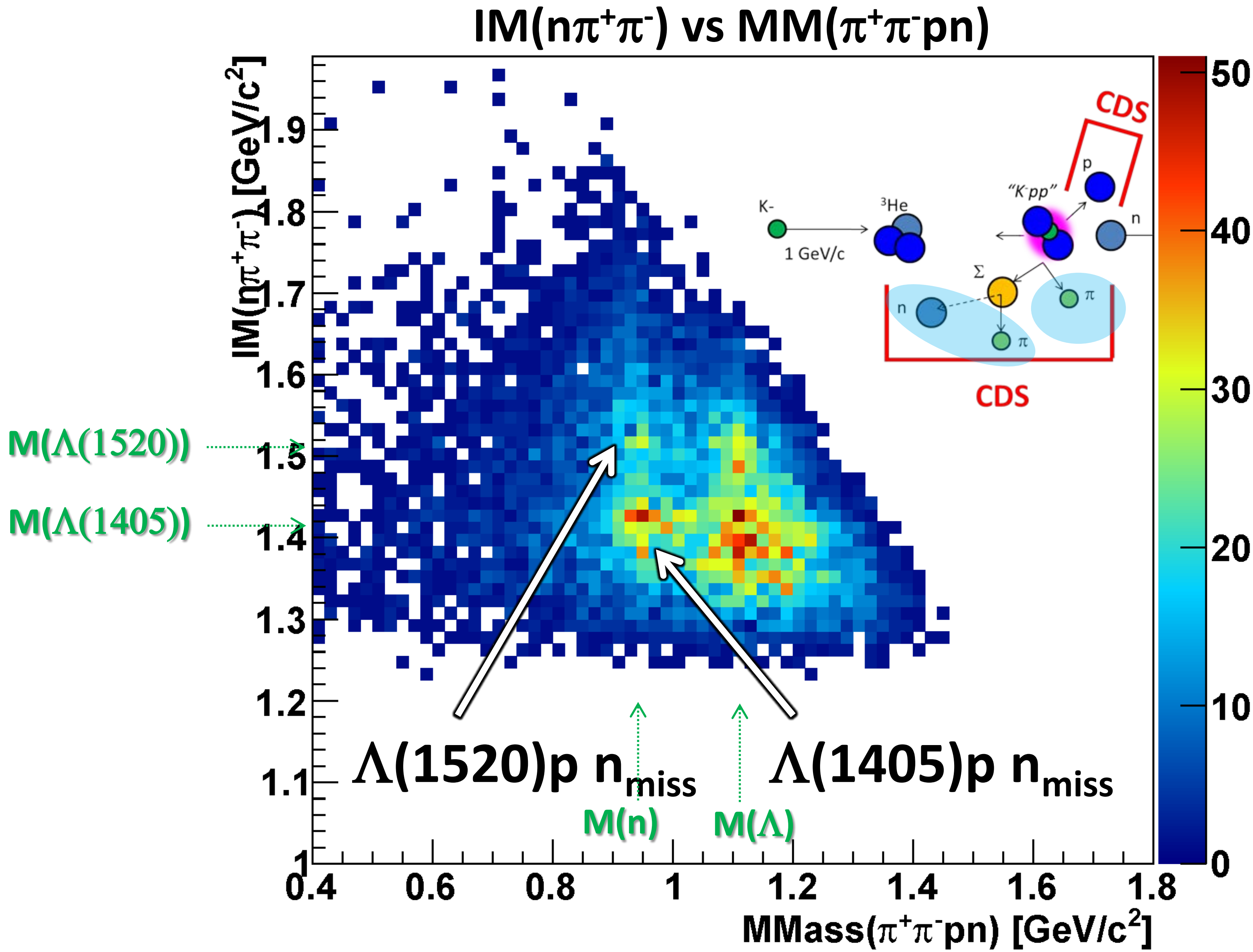
- $\pi^+\pi^- p$ events (3 tracks) in CDS with 4 CDH hits are selected
- a CDH hit with CDC-veto (outer-layer) is applied to identify the "neutral hit"

dE vs. 1/β | **dE-cut dependence**

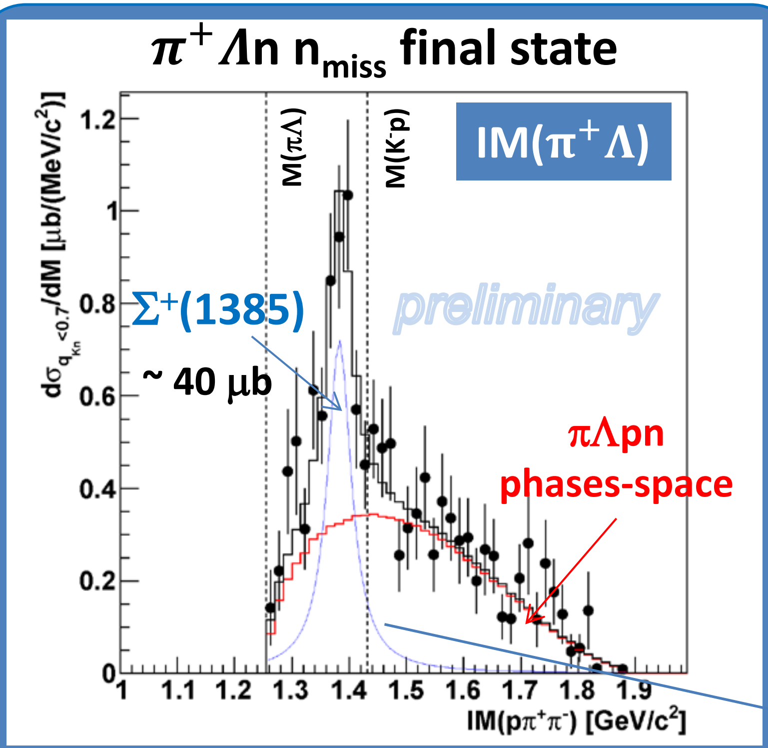


Neutron can be identified with CDS

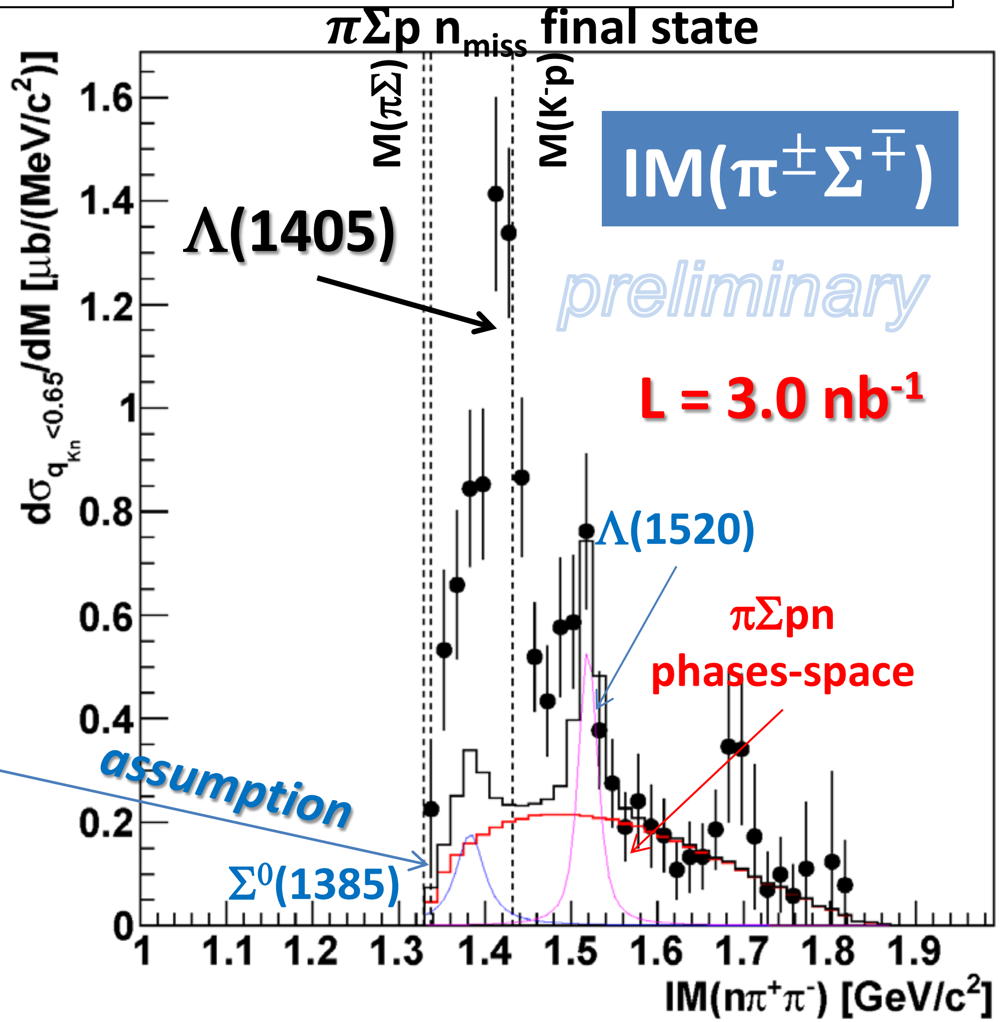
Λ^{*}pn Events



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

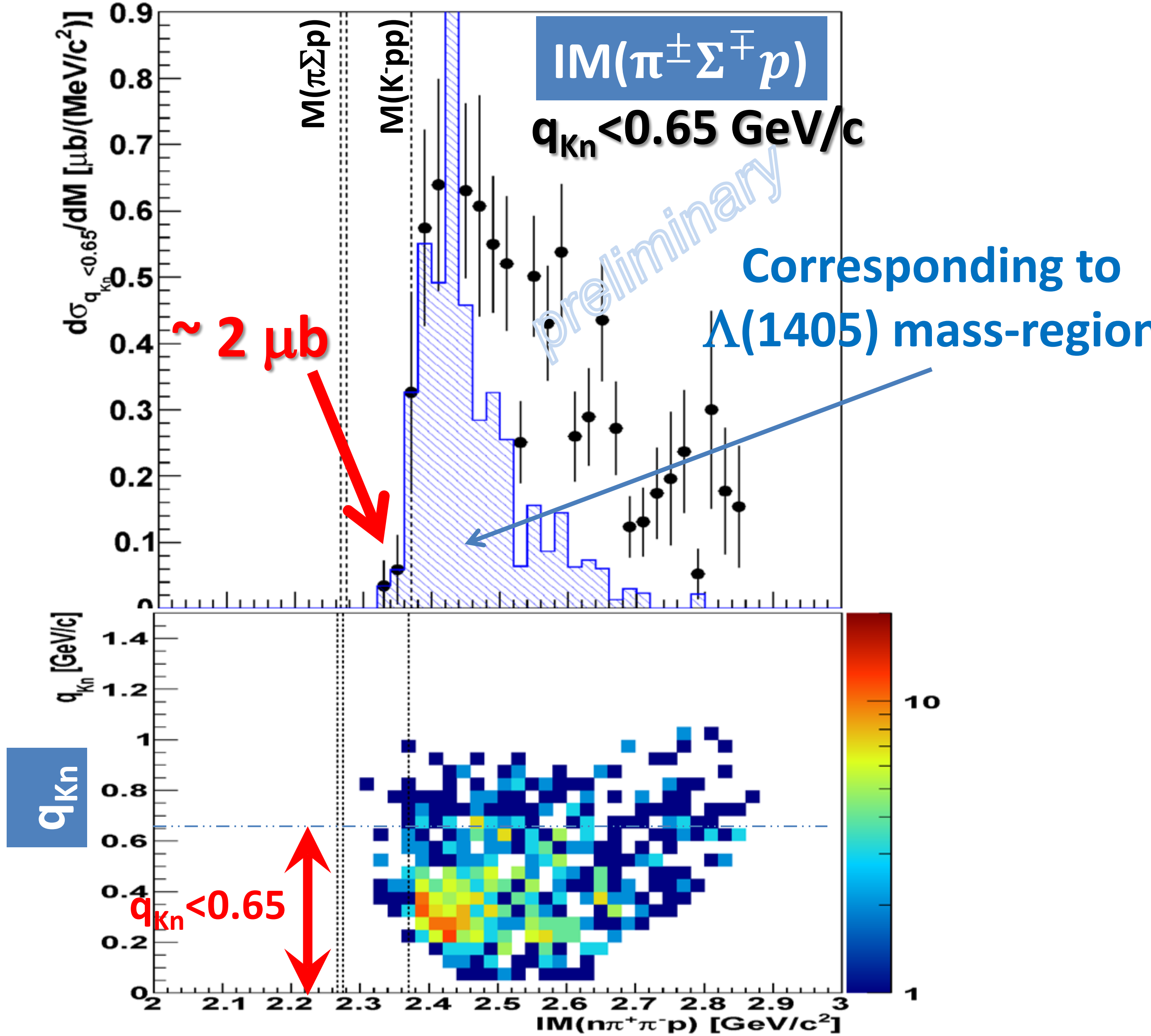


we assume Σ^0(1385) CS at 1.0 GeV/c to be:
$\sigma(\Sigma^{*0})$ ~ 1-2*$\sigma(\Sigma^{*+})$



K^- + ^{3}He → **Σ^0(1385)** + p + n: ~ 40-80 μb (assumption)
K^- + ^{3}He → **Λ(1405)** + p + n: ~ 130 μb
K^- + ^{3}He → **Λ(1520)** + p + n: ~ 70 μb

IM(πΣp) vs. Momentum Transfer q_{Kn}



Detector Acceptance: Λp vs. πΣp

- **Detector acceptance is different between Λp and πΣp**
  - At $\cos\theta_n$~1:
    - Λp: flat acceptance
    - πΣp: limited acceptance below the threshold