K^{bar}-Nuclear Bound State at J-PARC

F. Sakuma, RIKEN

on behalf of the J-PARC E15 collaboration

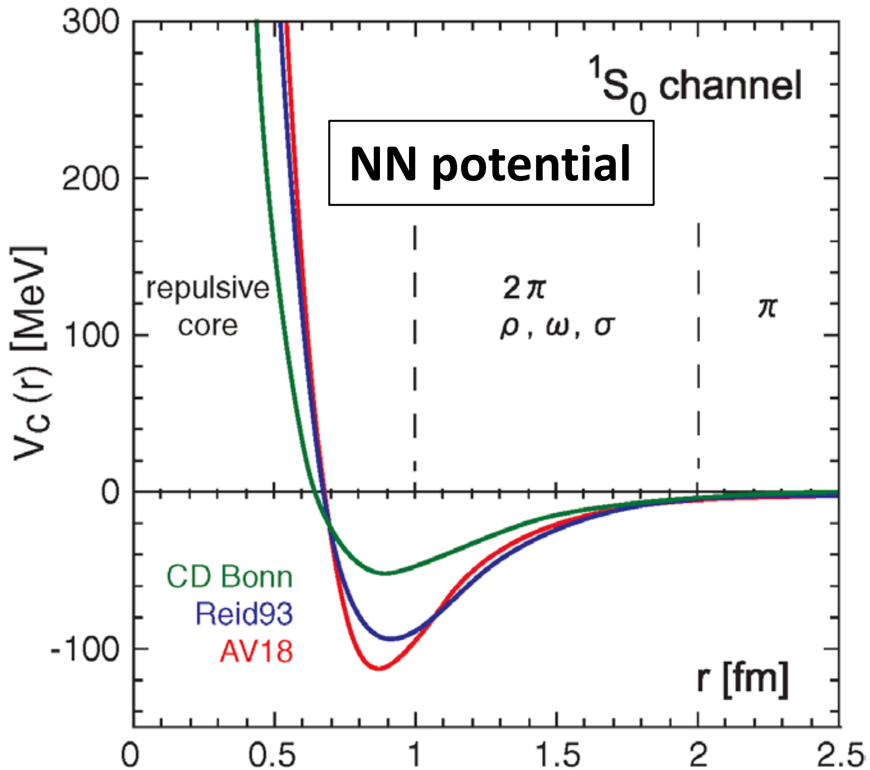
NN2018 SAITAMA, JAPAN NUCLEUS-NUCLEUS COLLISIONS

"13th International Conference on Nucleus-Nucleus Collisions (NN2018)"

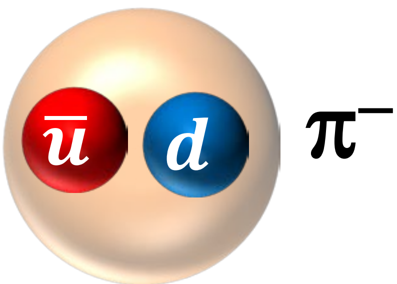
Dec. 4(Tue.)-8(Sat.), 2018 in Omiya, Saitama, Japan

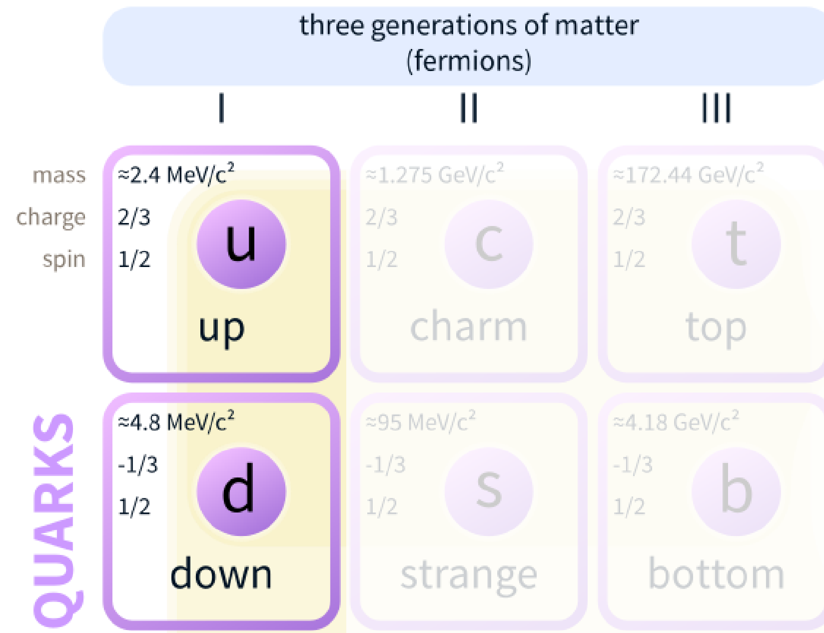
Meson-Baryon Interaction

- ***"virtual"*** light mesons
  - play an important role in a nucleus as **"glue"**



PRL99(2007)022001.





Wikipedia

Meson-Baryon Interaction

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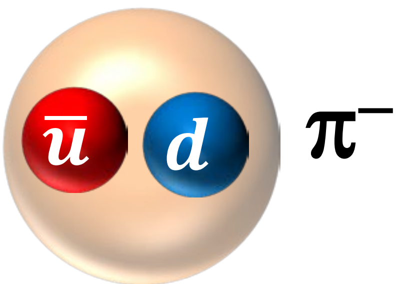
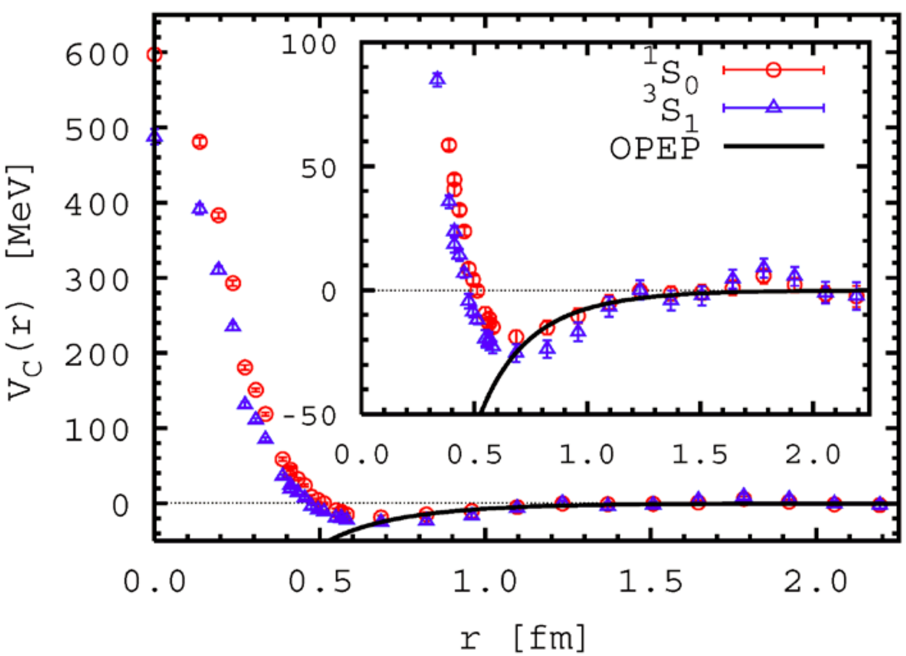
  - play an important role in a nucleus as **"glue"**



LQCD calculation



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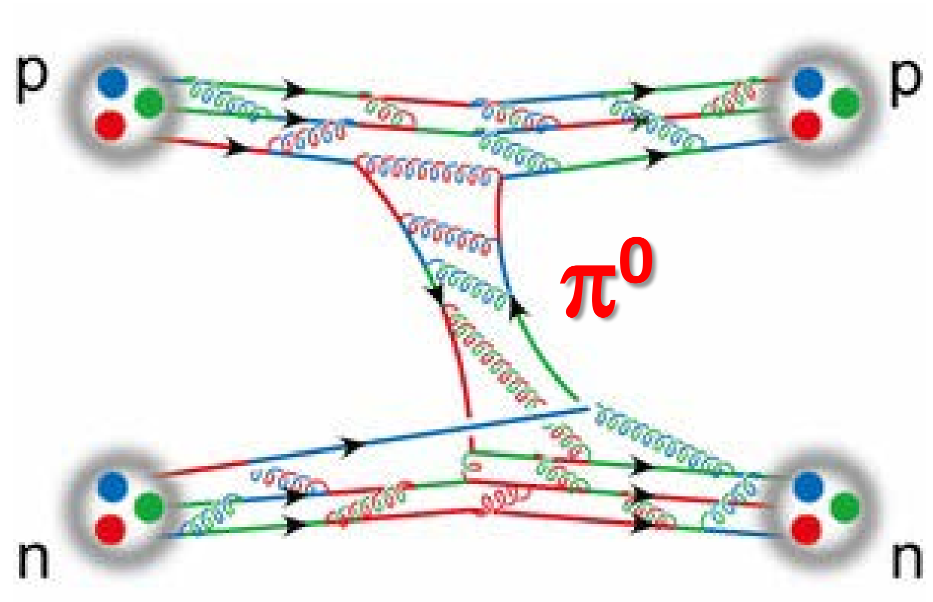
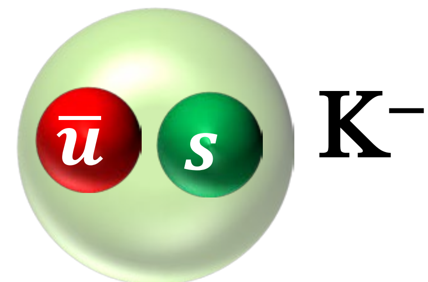
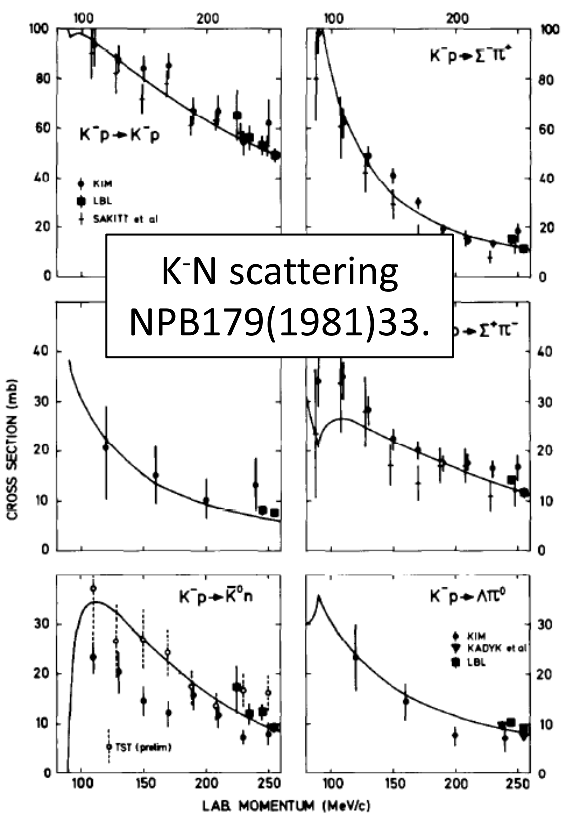


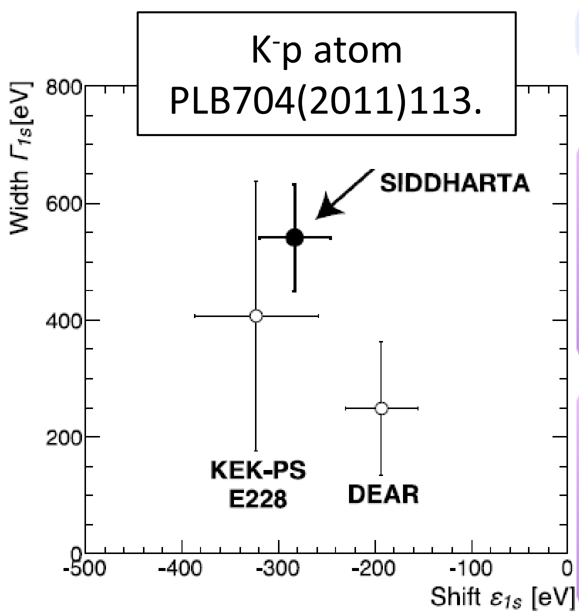
K⁻ Meson in Nucleus?

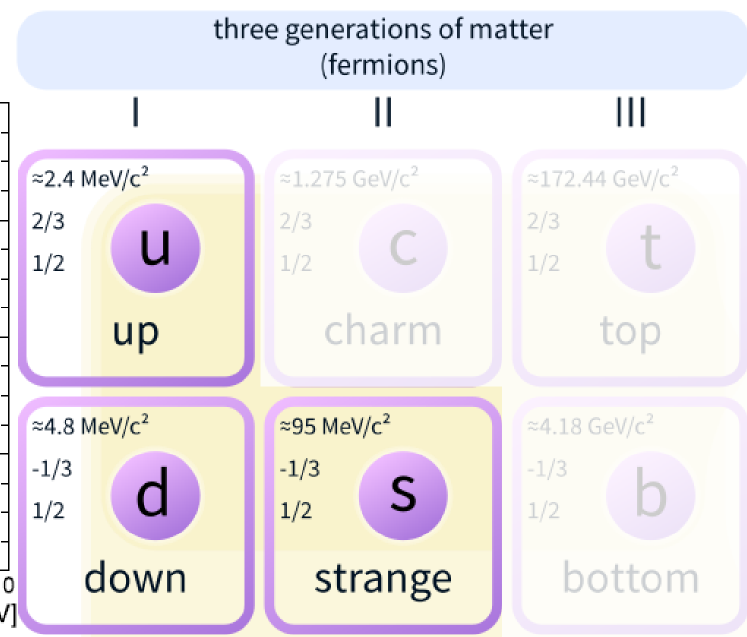
- **Lightest S=-1 meson, K⁻**
  - K^{bar}-N interaction:

    strongly attractive in I=0









Wikipedia

K⁻ Meson in Nucleus?

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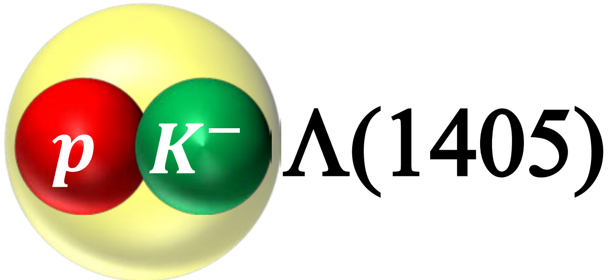
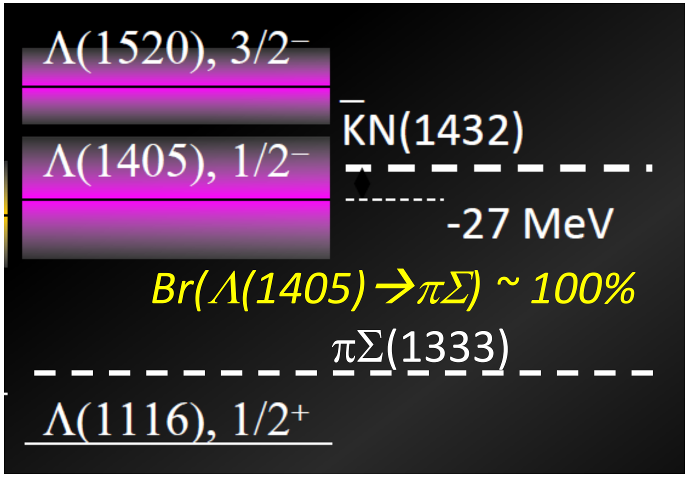
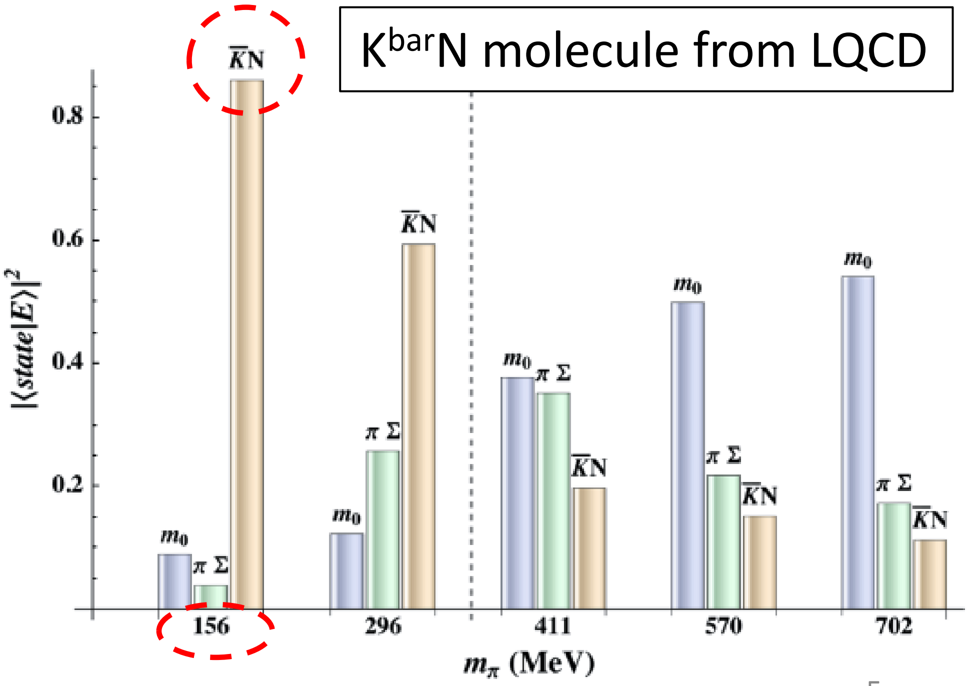


- **Λ(1405)**
  - considered as a $K^{bar}N$ molecular state





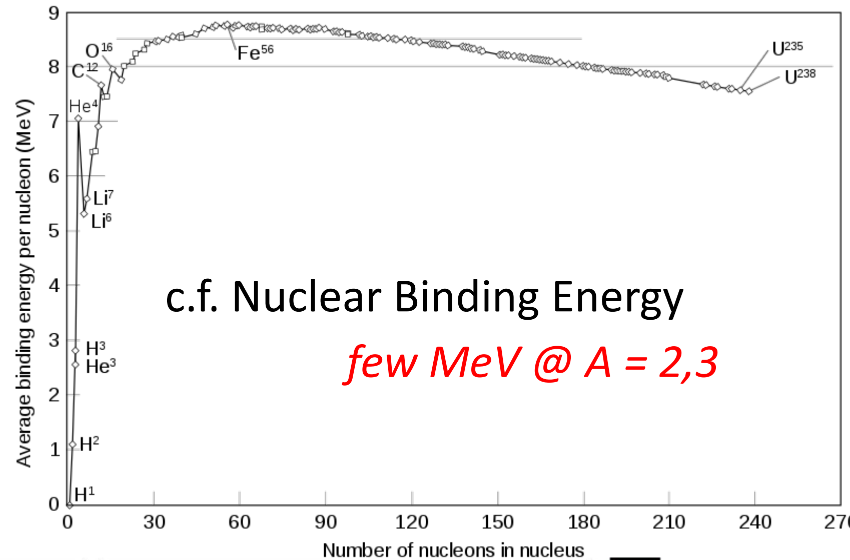
PRL114(2015)132002.

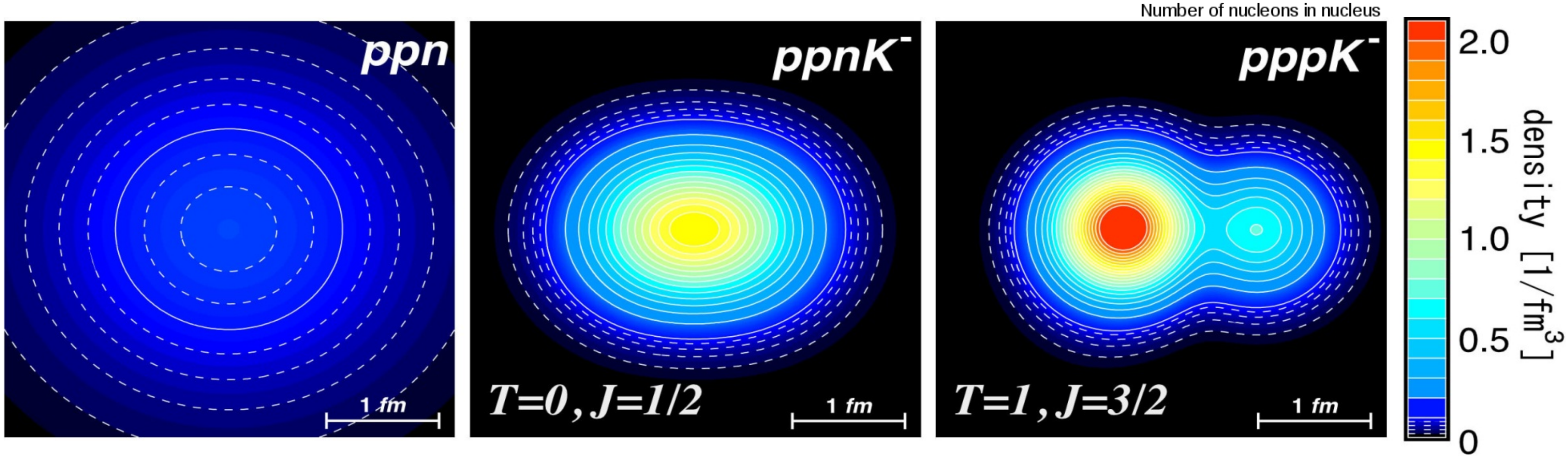
K^{bar}-Nuclear Bound State

Predicted from **attractive $K^{bar}N$ interaction in I=0**

Kaonic Nuclei	Binding Energy [MeV]	Width [MeV]	Central Density
$K^{-}p$	27	40	**$3.5\rho_0$**
$K^{-}pp$	48	61	**$3.1\rho_0$**
$K^{-}ppp$	97	13	**$9.2\rho_0$**
$K^{-}ppn$	118	21	**$8.8\rho_0$**

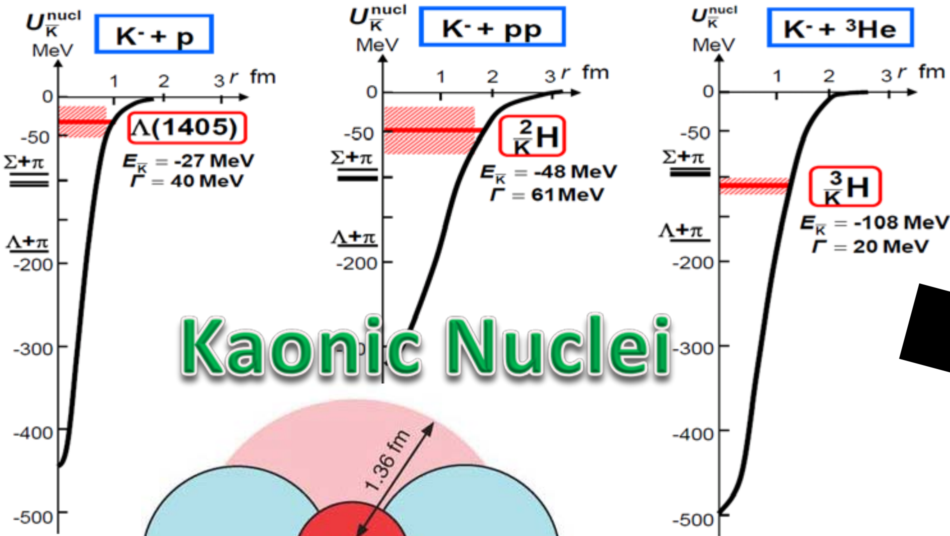
Y.Akaishi and T.Yamazaki, PRC65(2002)044005.
A. Dote et al. PRC70(2004)044313. etc.



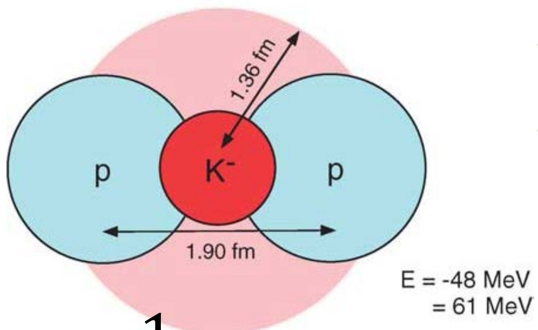


K^{bar}-Nuclear Bound State

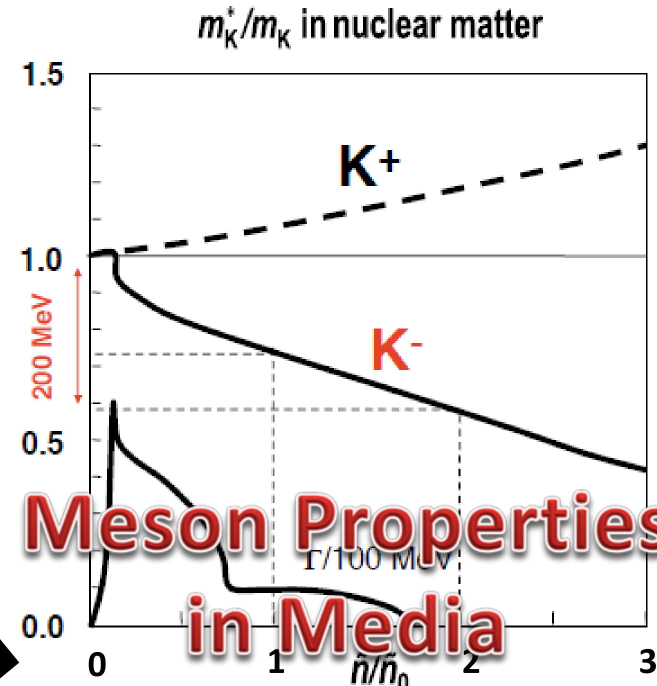
Y.Akaishi & T.Yamazaki, PLB535, 70(2002).



Kaonic Nuclei

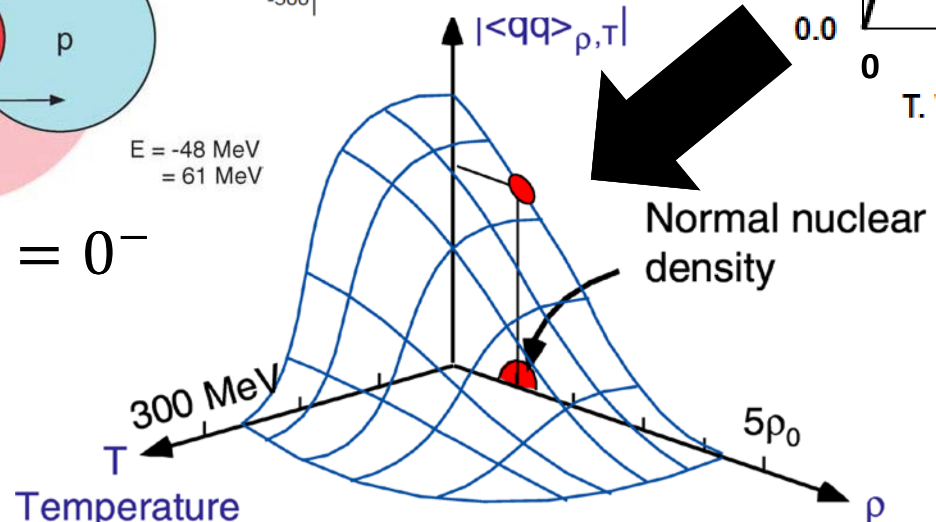


$$I = \frac{1}{2}, J^P = 0^-$$



Meson Properties in Media

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

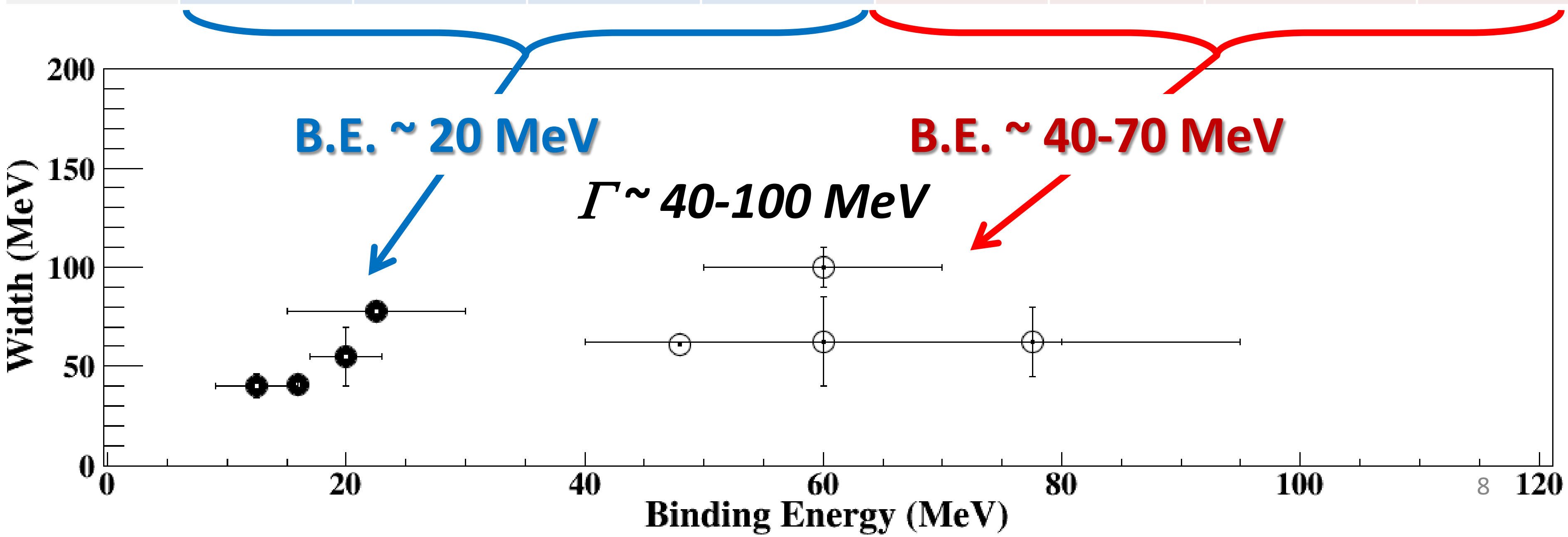


W.Weise NPA553, 59 (1993).

Chiral Symmetry ≡ Origin of the QCD Mass

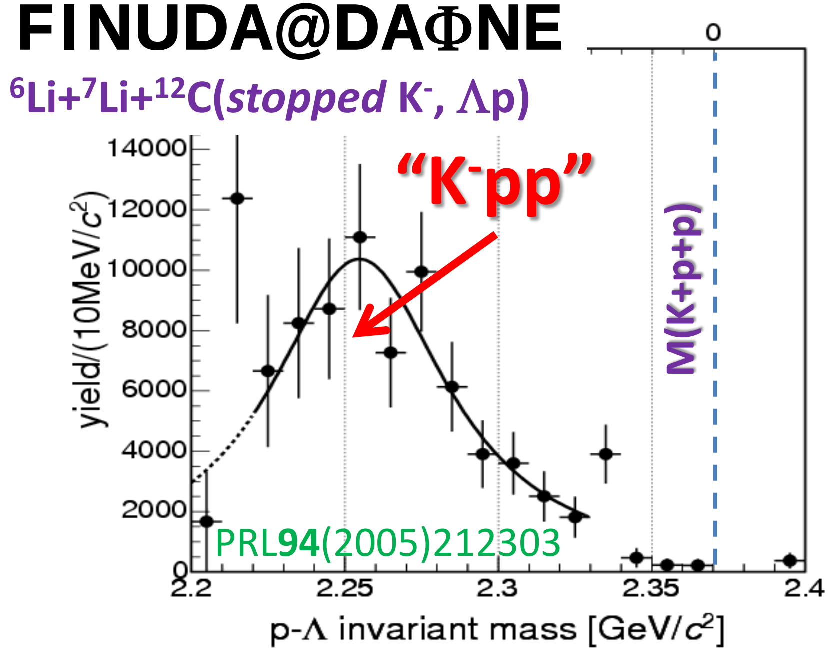
Theoretical Calculations on "K⁻pp"

$K^{bar}N$ int.	Chiral SU(3) (energy dependent)				Phenomenological (energy independent)			
Method	Variational		Faddeev		Variational		Faddeev	
	Barnea, Gal, Liverts	Dote, Hyodo, Weise	Ikeda, Kamano, Sato	Bayar, Oset	Yamazaki, Akaishi	Wyceck, Green	Shevchenko, Gal, Mares	Ikeda, Sato
B (MeV)	**16**	**17-23**	**9-16**	**15-30**	**48**	**40-80**	**50-70**	**60-95**
Γ (MeV)	**41**	**40-70**	**34-46**	**75-80**	**61**	**40-85**	**90-110**	**45-80**



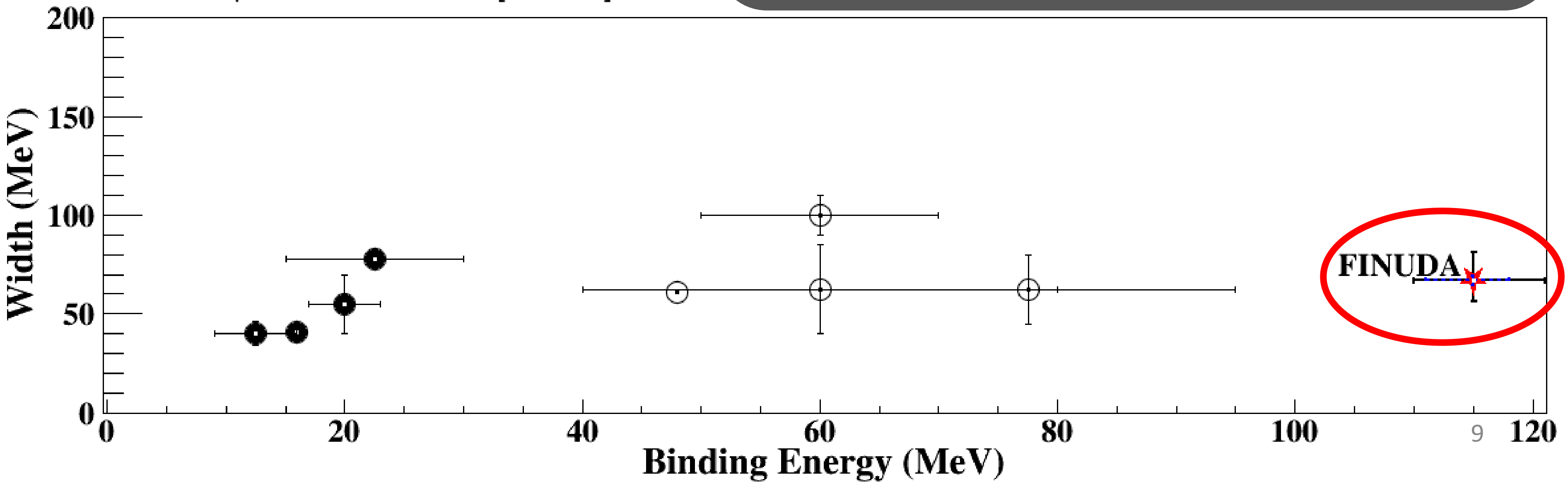
"K^-pp" Search via Stopped-K^-

FINUDA@DAΦNE



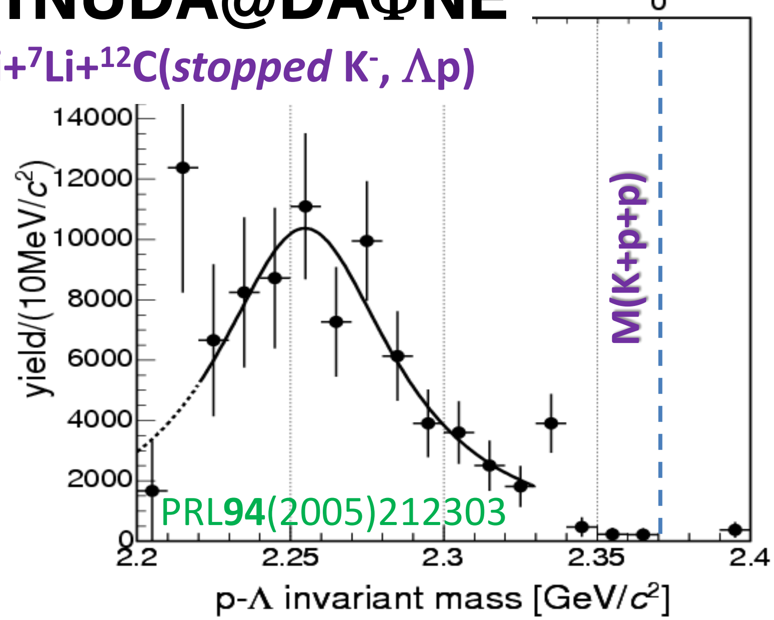
- **multi-nucleon absorption processes followed by FSI?**
  - PRC74(2006)025206
  - PRC82(2010)034608

$$K^- + {}^{A}_{Z}N \rightarrow (K^- + \text{"}pp\text{"}) + {}^{A-2}_{Z-2}N$$
$$\rightarrow \Lambda + p + {}^{A-2}_{Z-2}N \quad \textbf{(2NA)}$$
$$\rightarrow (\Lambda + \text{"}n\text{"}) + p + {}^{A-3}_{Z-2}N$$
$$\rightarrow \Lambda + p + n + {}^{A-3}_{Z-2}N \quad \textbf{(FSI)}$$

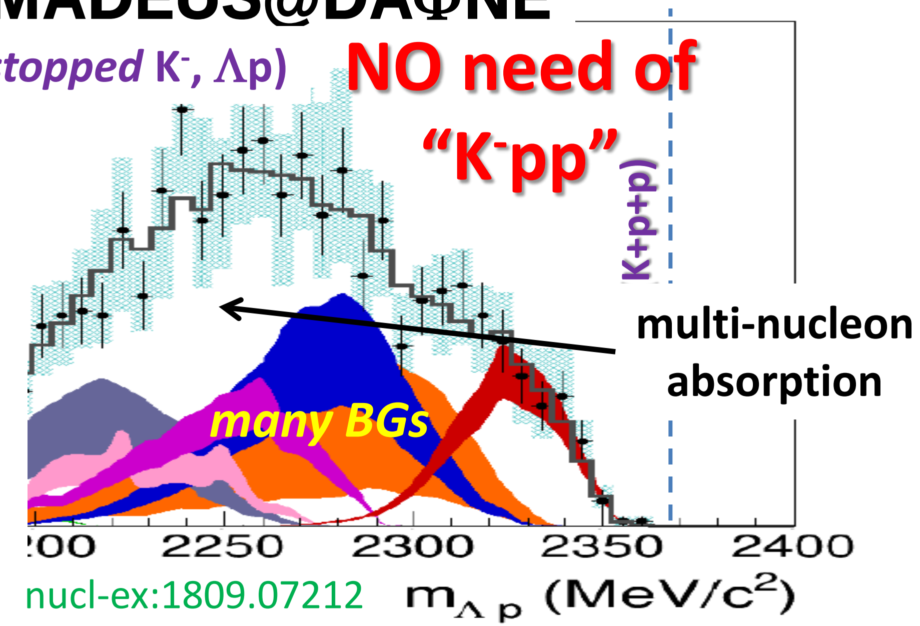


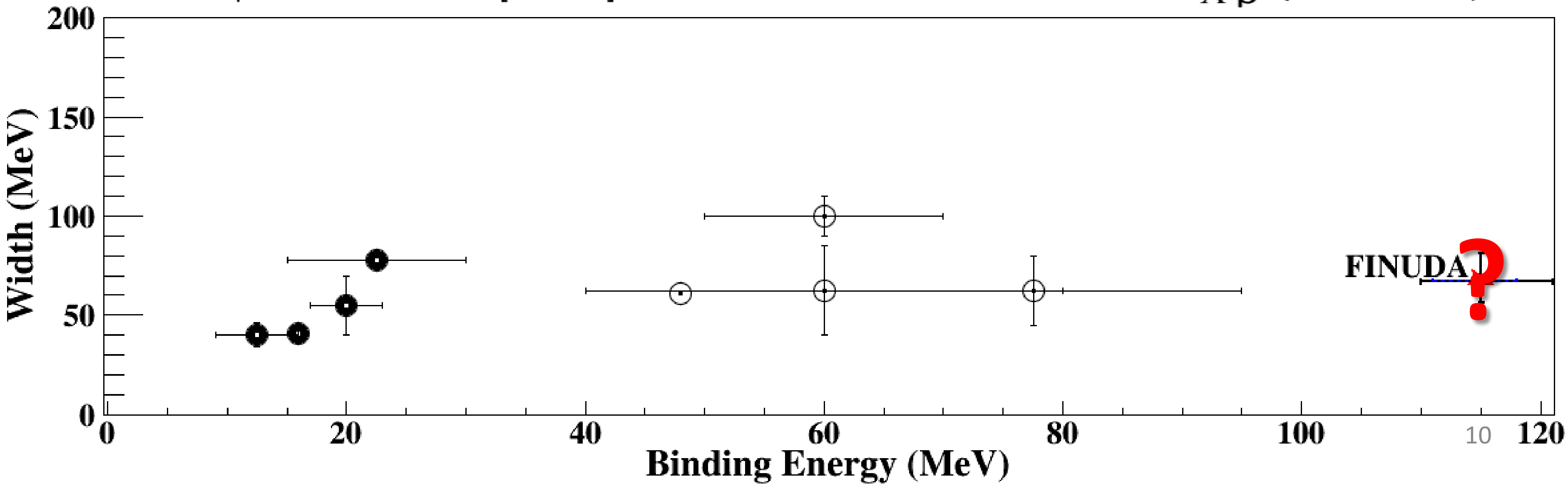
“K⁻pp” Search via Stopped-K⁻

FINUDA@DAΦNE



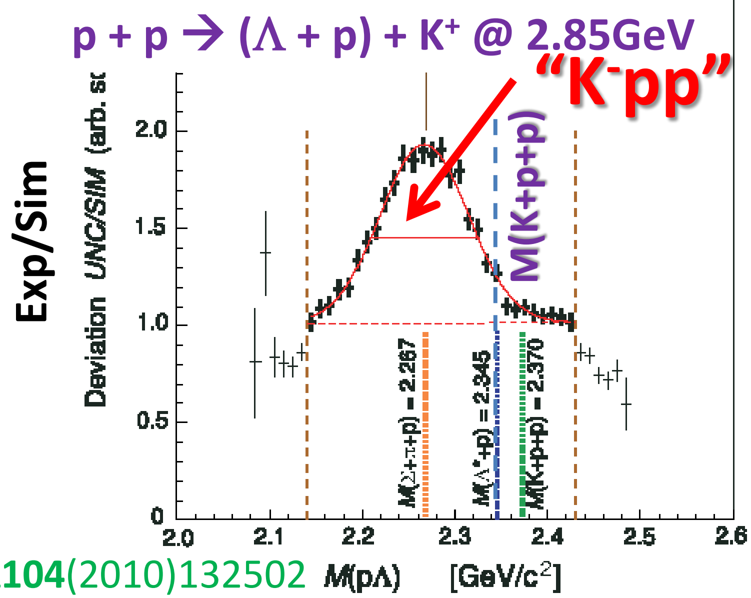
AMADEUS@DAΦNE





"K⁻pp" Search via pp Collision

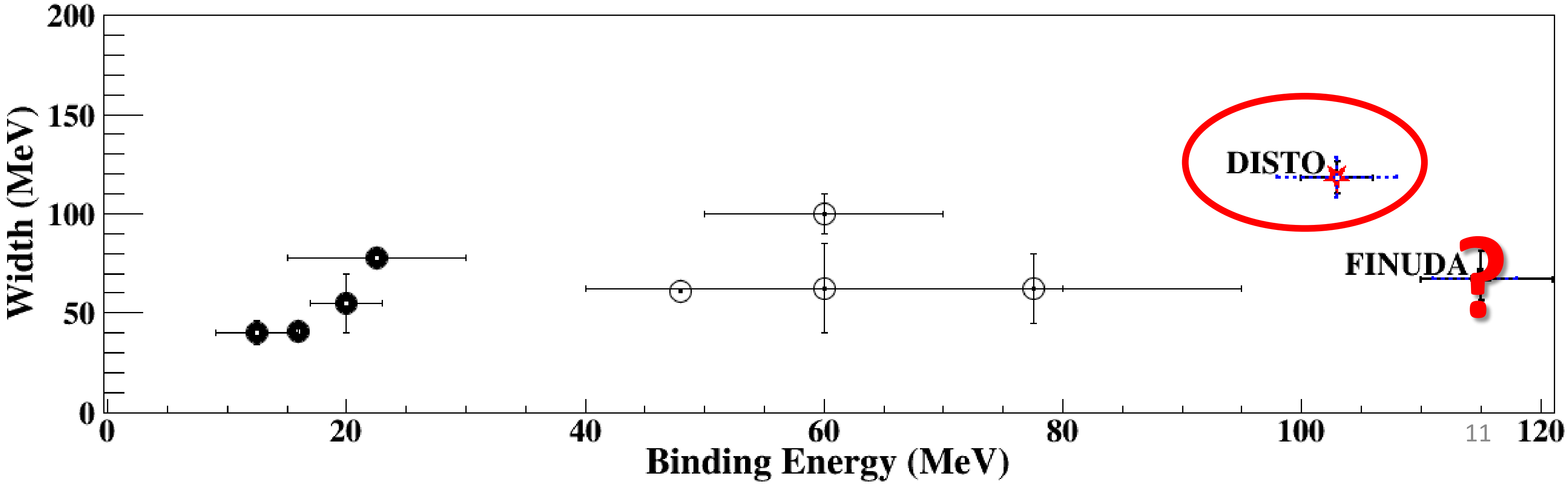
DISTO@SATURNE



PRL**104**(2010)132502

- contribution of $N^{*+} \to \Lambda K^+$?
  - PRC92(2015)044002

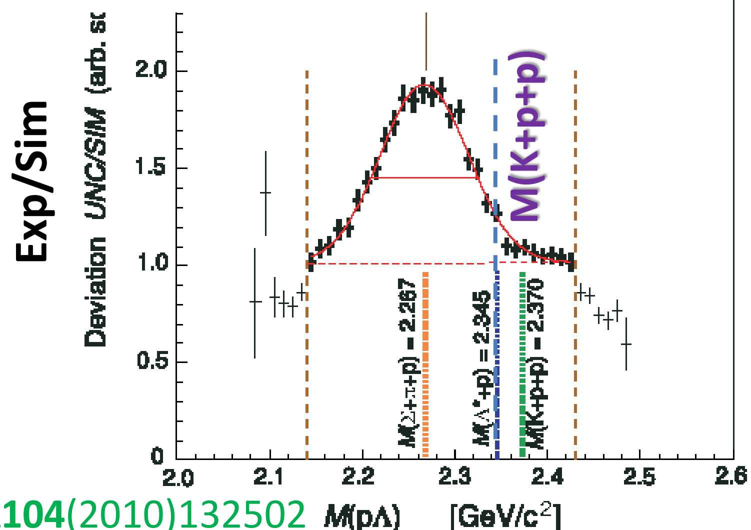
$$p + p \to p + N^{*+}$$
$$\to \boldsymbol{p + \Lambda} + K^+$$



“K⁻pp” Search via pp Collision

DISTO@SATURNE

$p + p \rightarrow (\Lambda + p) + K^+$ @ 2.85GeV

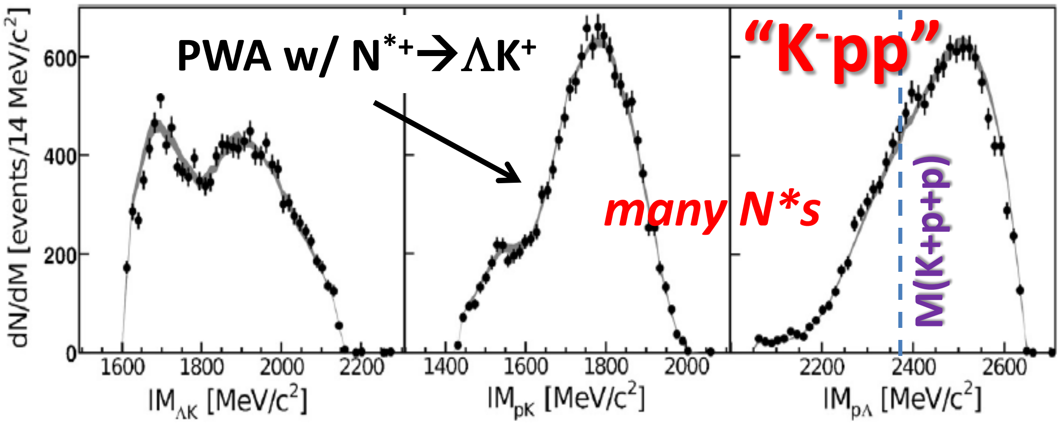


PRL**104**(2010)132502

HADES@GSI

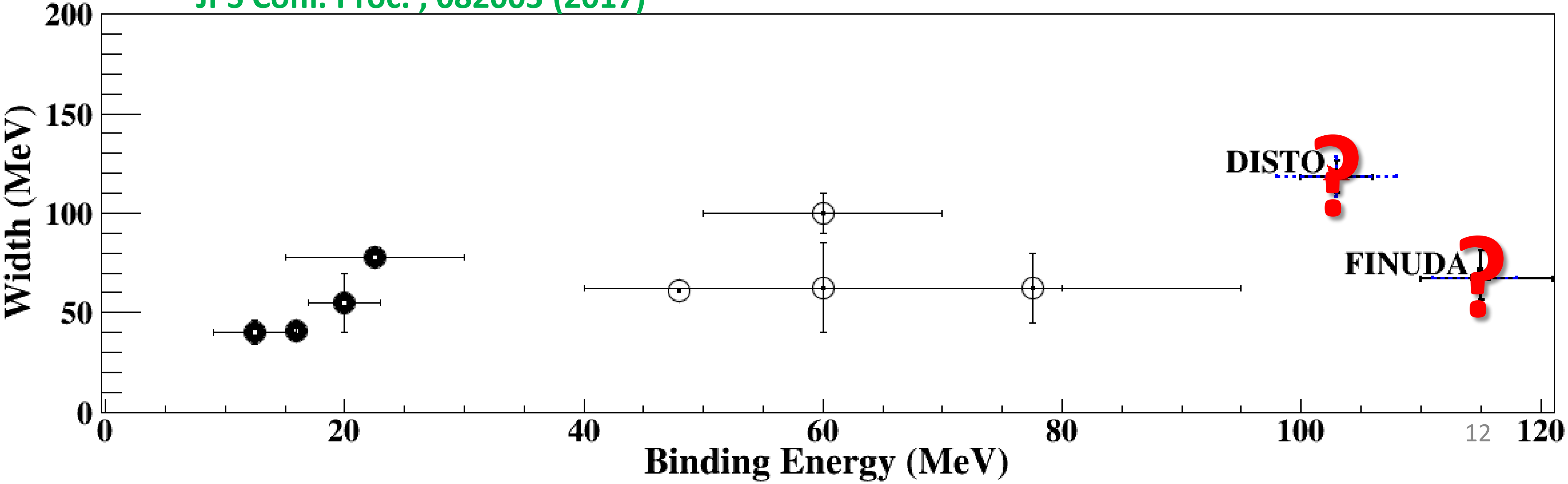
$p + p \rightarrow (\Lambda + p) + K^+$ @ 3.5GeV

NO need of “K⁻pp”

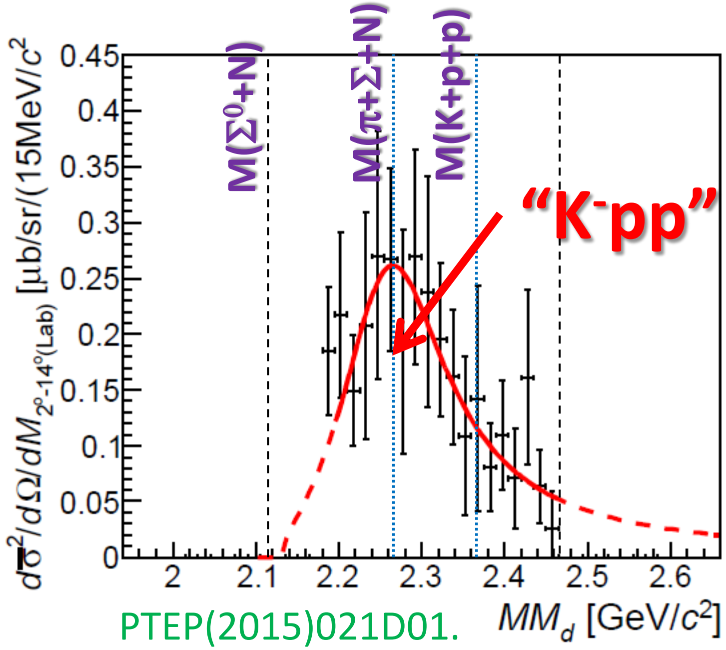


PLB**742**(2015)242

JPS Conf. Proc. , 082003 (2017)



"K⁻pp" Search via $d(\pi^+, K^+)X$



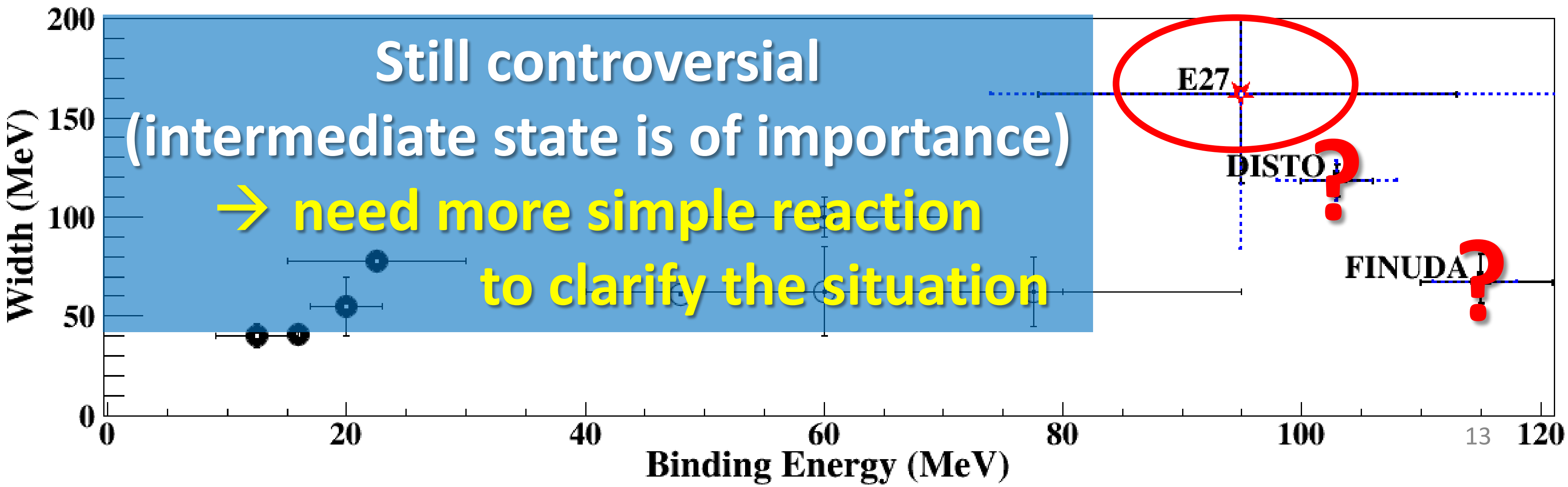
PTEP(2015)021D01.

E27@J-PARC

$d(\pi^+, K^+)\Sigma^0 p$ @ 1.69 GeV/c

- need more statistics and wide acceptance detector

$$\pi^+ + d \rightarrow \Sigma^0 + K^+ + p_{spect} \quad \text{(QF)}$$
$$\rightarrow (\Sigma^0 + "p") + K^+$$
$$\rightarrow \Sigma^0 + \boldsymbol{p} + K^+ \quad \text{(FSI)}$$

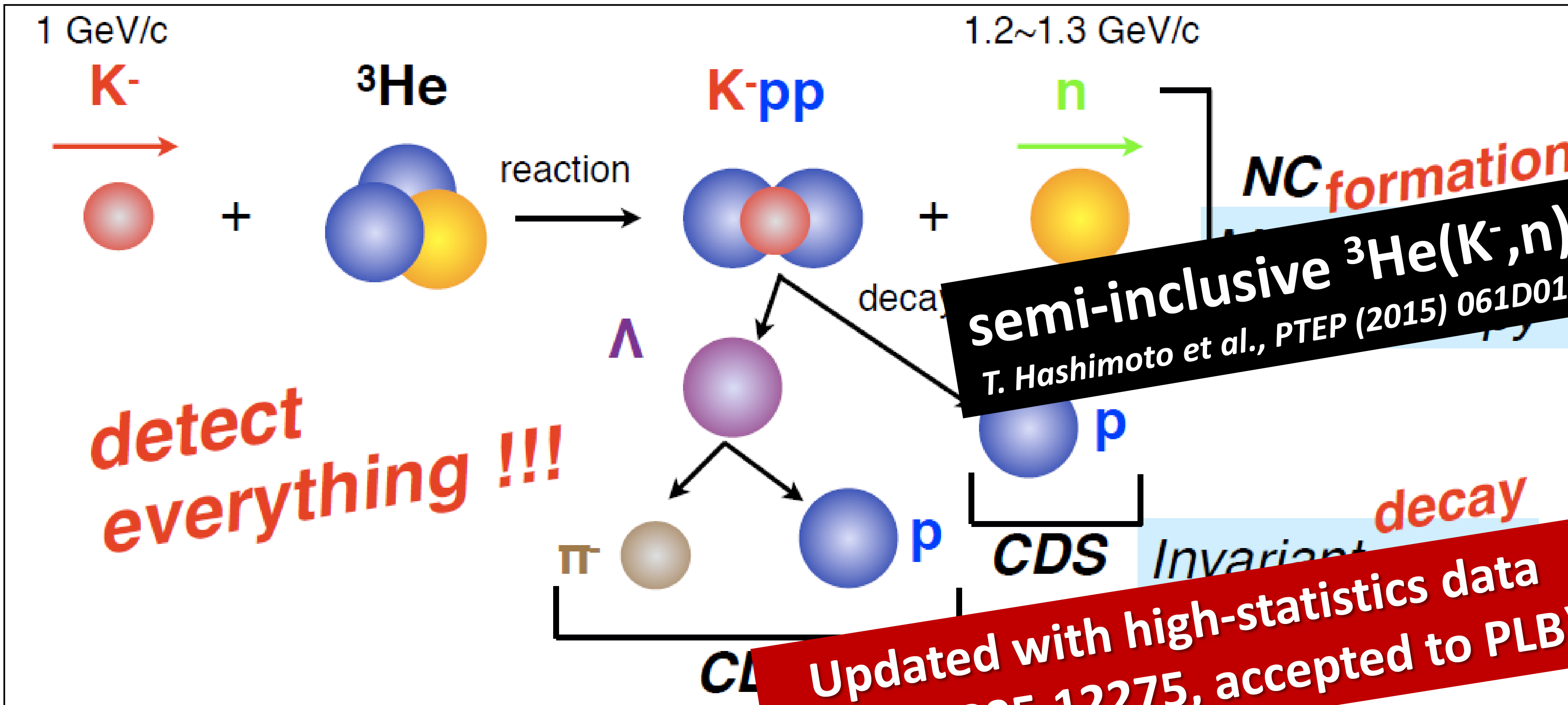


Still controversial
(intermediate state is of importance)
→ need more simple reaction
to clarify the situation

J-PARC E15 Experiment

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

2NA and Y decays can be discriminated kinematically

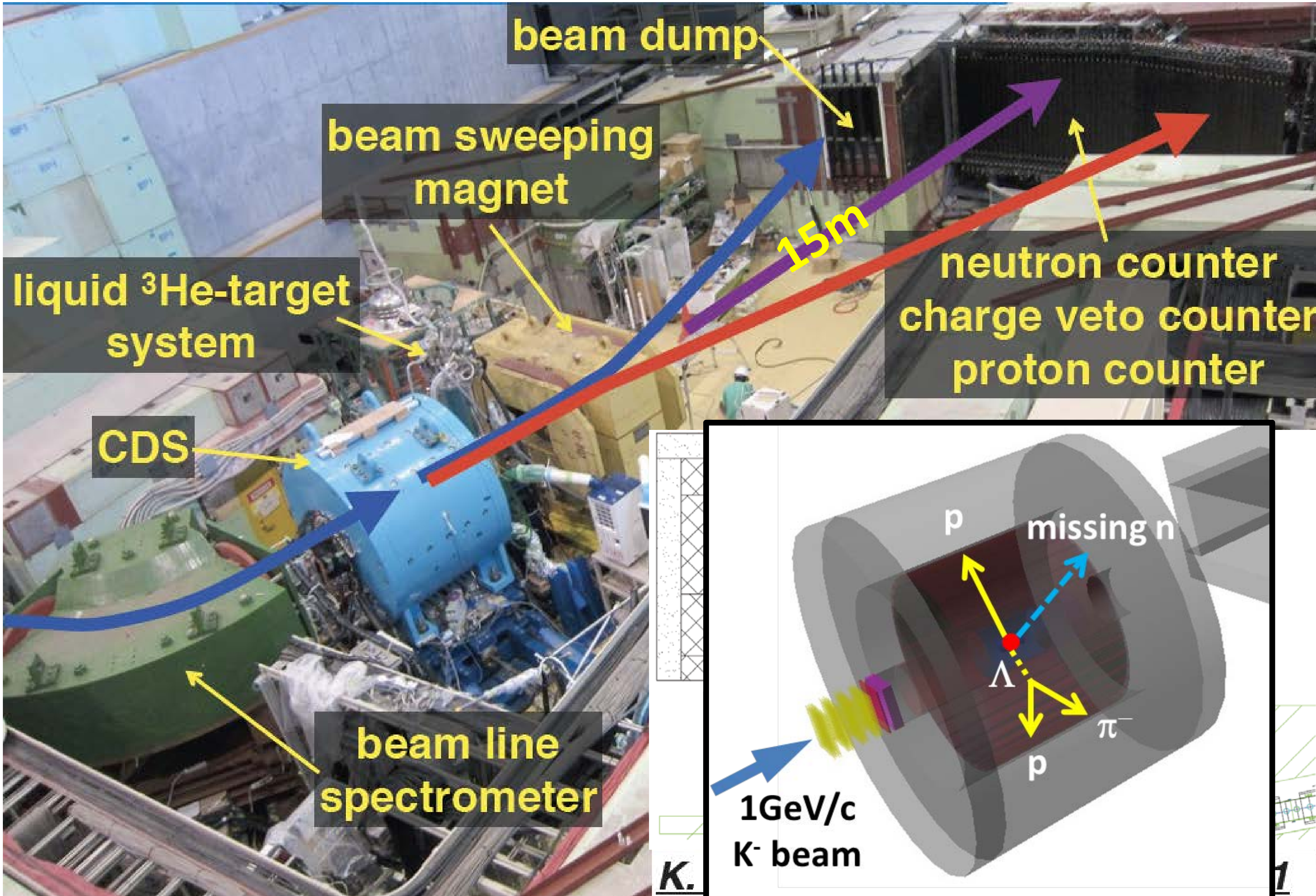


semi-inclusive ^{3}He(K^{-},n)

T. Hashimoto et al., PTEP (2015) 061D01.

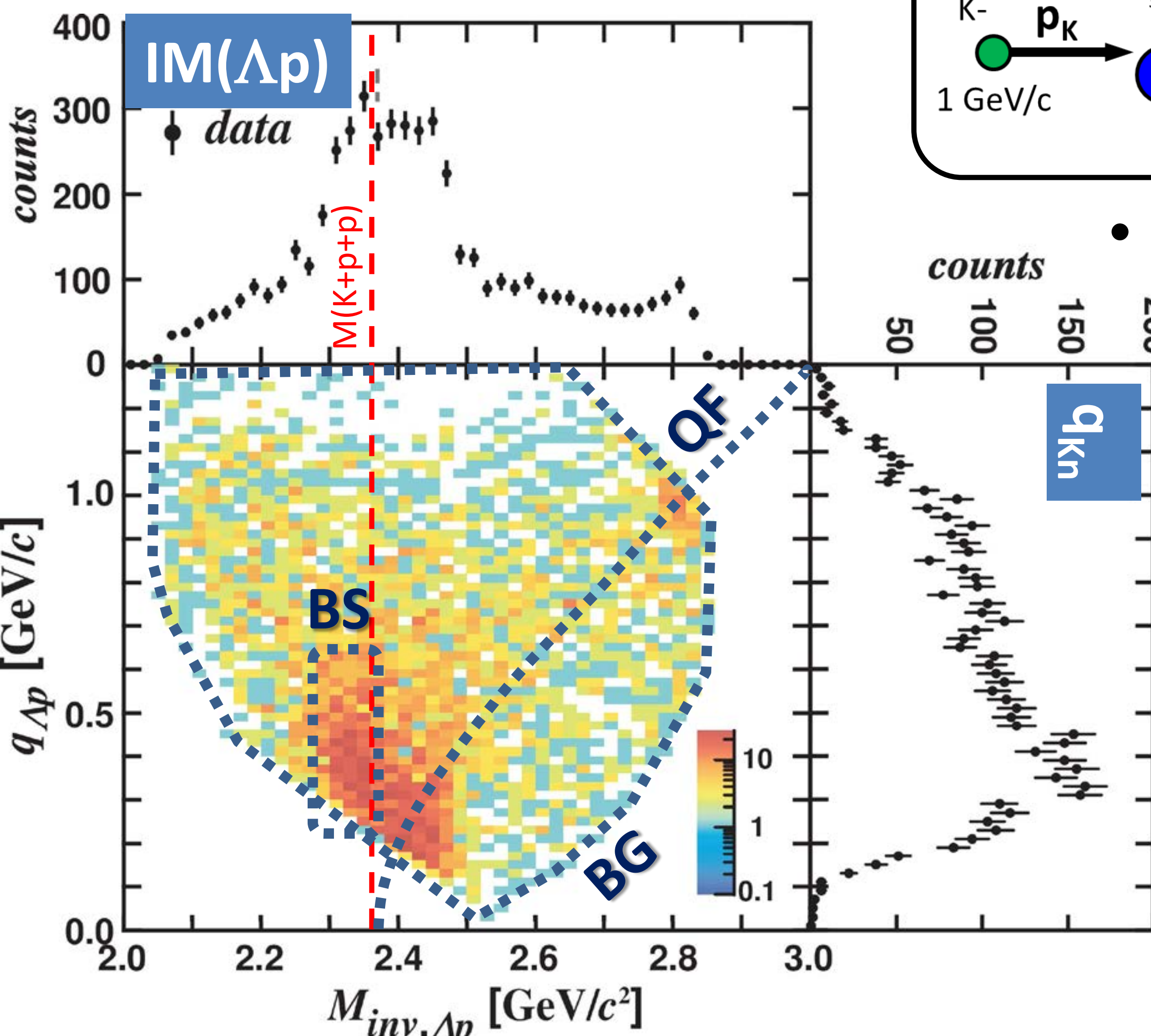
Updated with high-statistics data (arXiv:1805.12275, accepted to PLB)

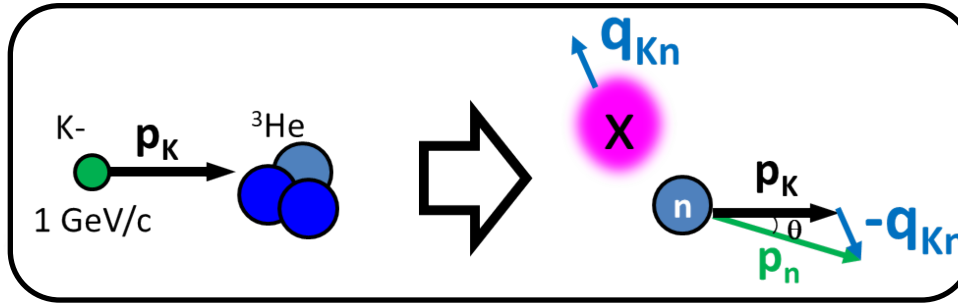
Experimental Setup @ K1.8BR



IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275

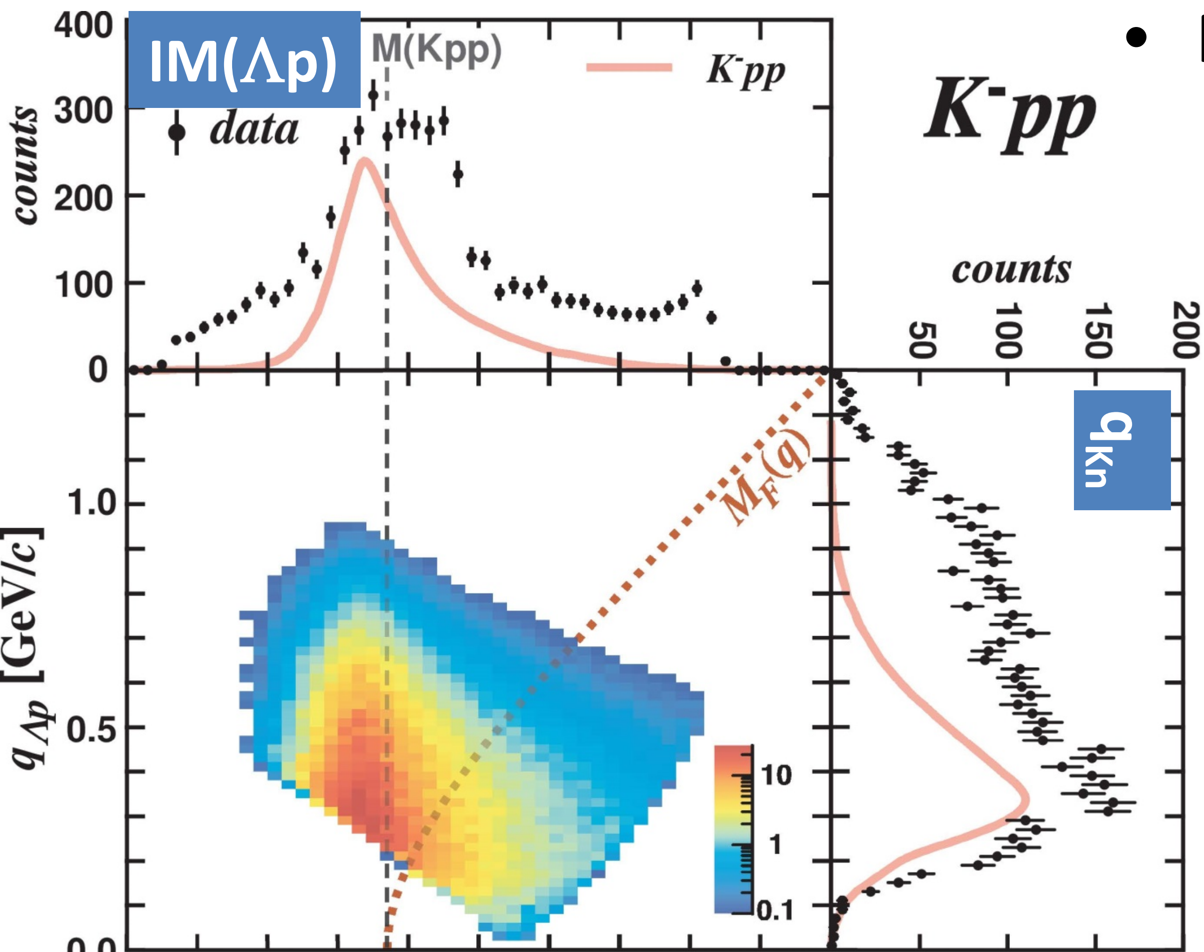




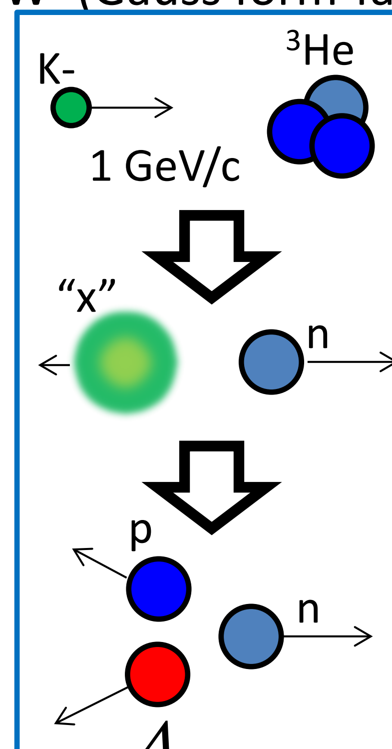
- Can be interpreted as 3 components
  - **Bound state**
    - centroid DOES NOT depend on q_{Kn}
  - **Quasi-elastic K^- abs.**
    - centroid depends on q_{Kn}
  - **Background**
    - Broad distribution

IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275



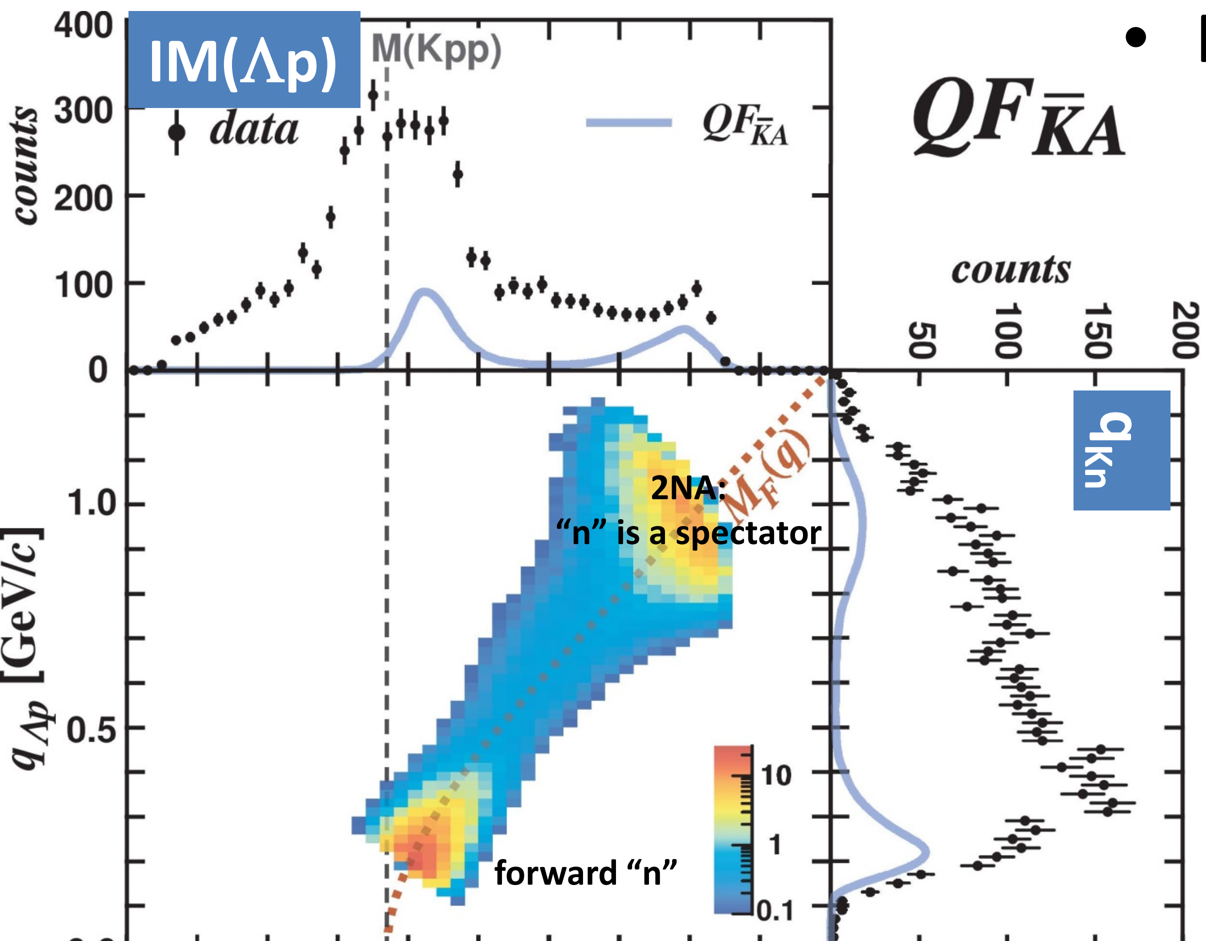
- Fit with 3 components
  - **Bound state**
    - **centroid DOES NOT depend on q_{Kn}**
    - BW*(Gauss form-factor)



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

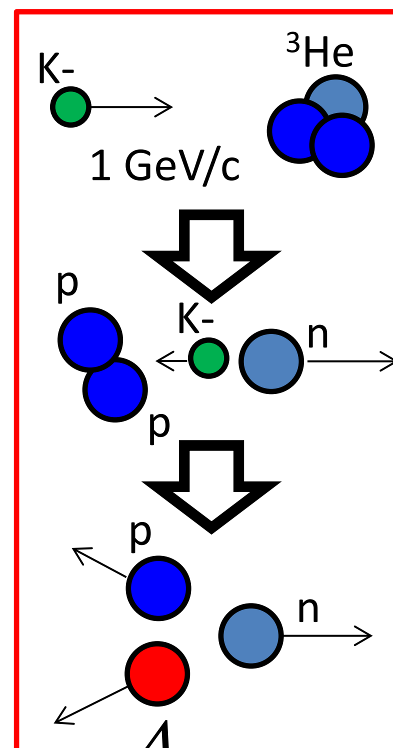
IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275



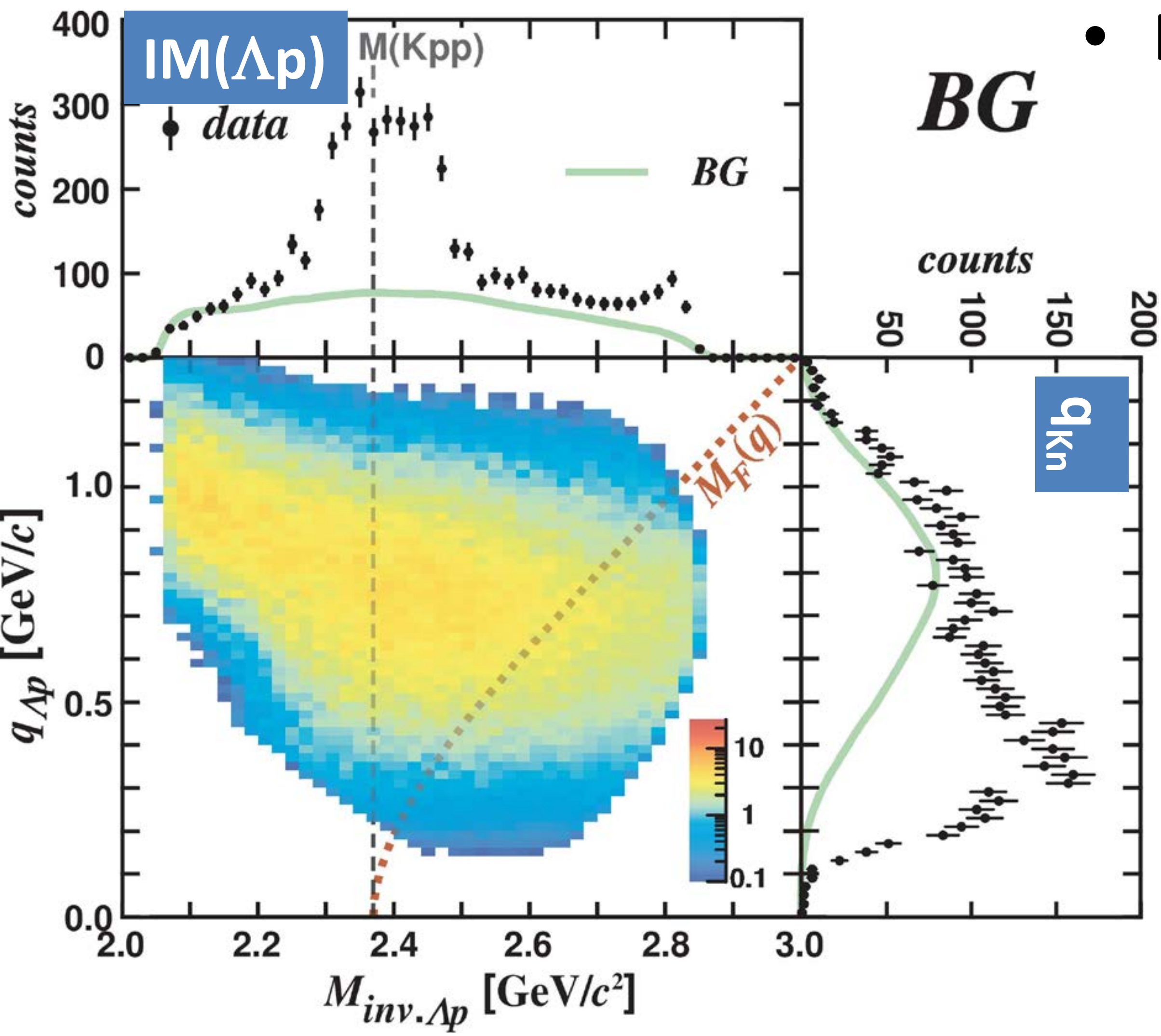
$$M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N\sqrt{m_K^2 + q^2}},$$

- Fit with 3 components
  - <u>**Quasi-elastic K⁻ abs.**</u>
    - **centroid depends on q_{Kn}**
    - Followed by Λp conversion

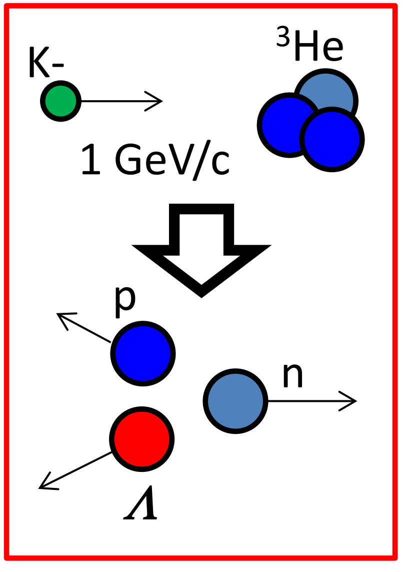


IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275

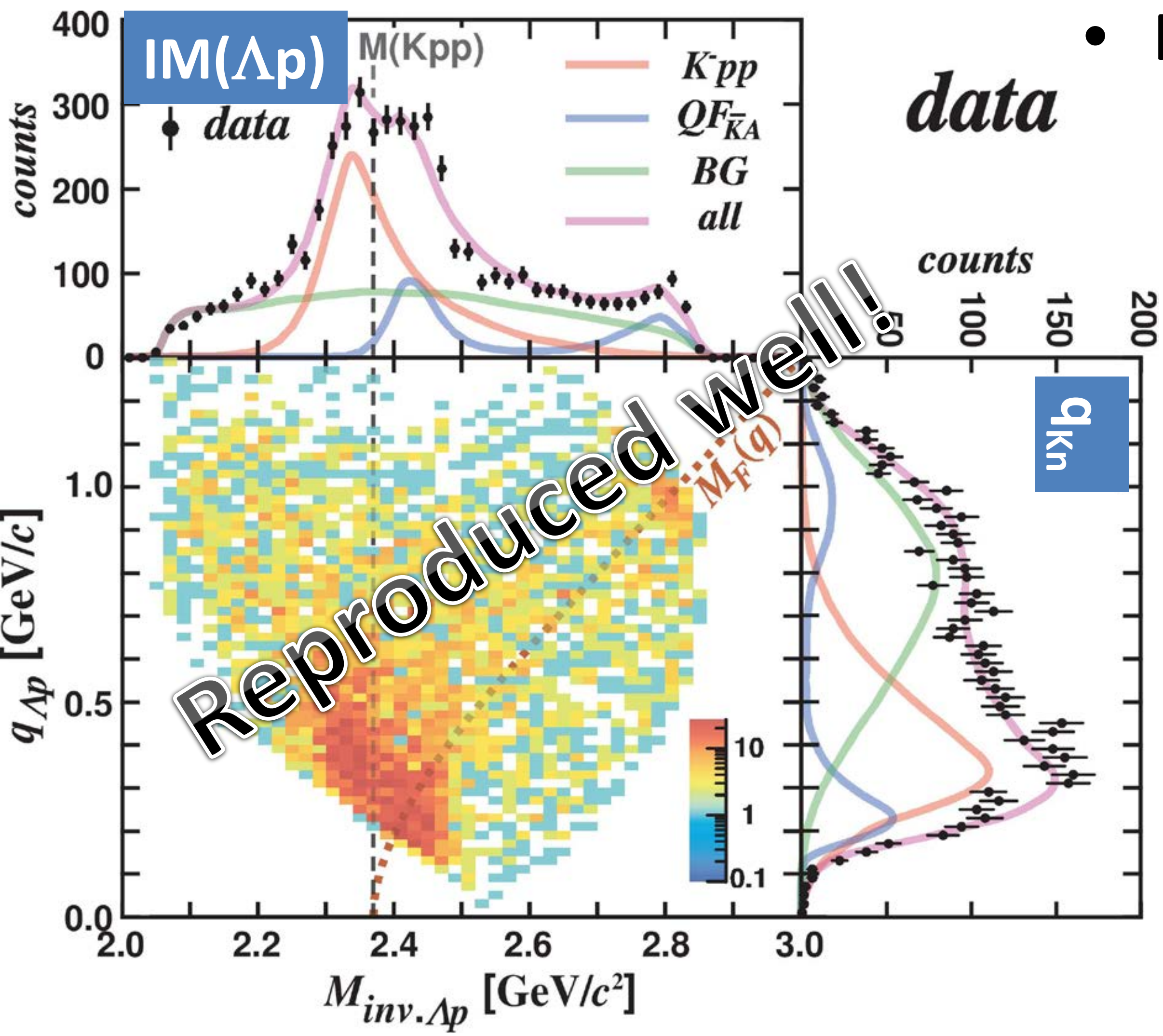


- Fit with 3 components
  - **Background**
    - Broad distribution



IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., arXiv:1805.12275



- Fit with 3 components
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$$M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N\sqrt{m_K^2+q^2}},$$

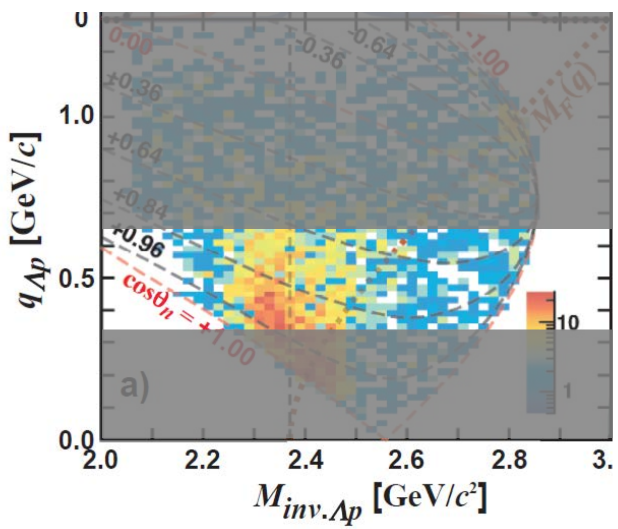
  - **Background**
    - Broad distribution

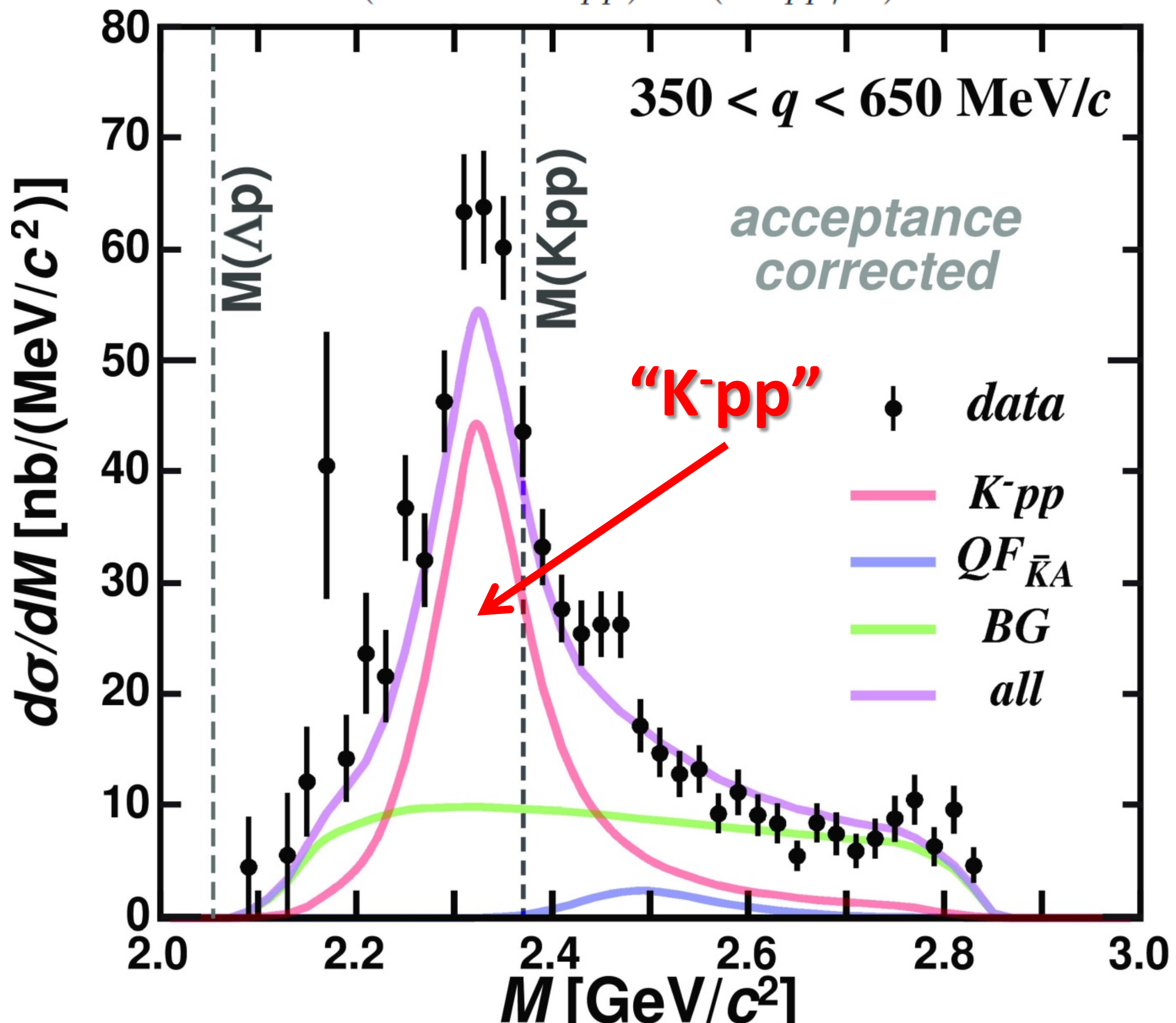
"K⁻pp" Bound-State

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

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

- BS and QF are well separated





E15 collab., arXiv:1805.12275

“K⁻pp” Bound-State

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

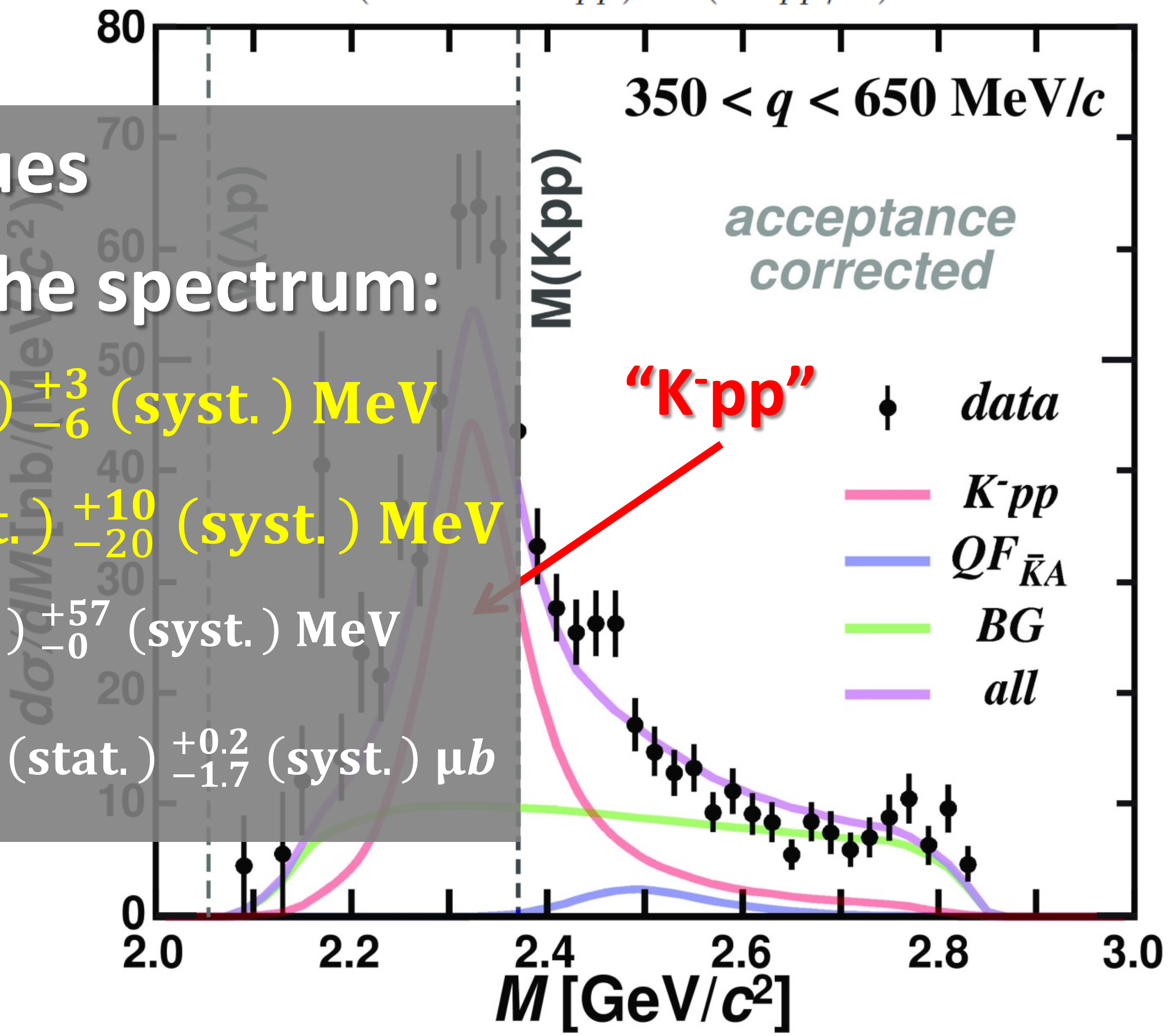
Fit values that reproduce the spectrum:

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

$\Gamma_{\text{"Kpp"}} = 115 \pm 7\,(\text{stat.})\,^{+10}_{-20}\,(\text{syst.})\ \text{MeV}$

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

$\sigma_{\text{“Kpp”}} \cdot Br_{\Lambda p} = 11.8 \pm 0.4\,(\text{stat.})\,^{+0.2}_{-1.7}\,(\text{syst.})\ \mu b$

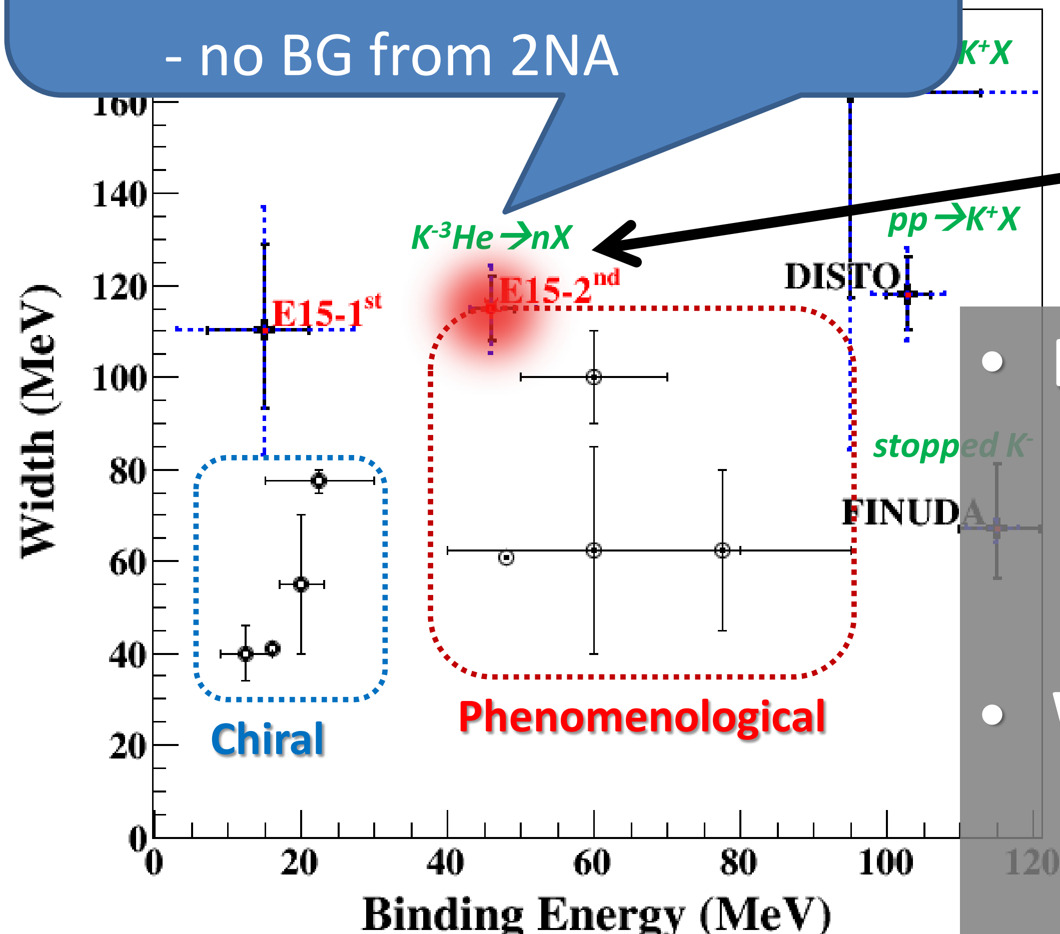


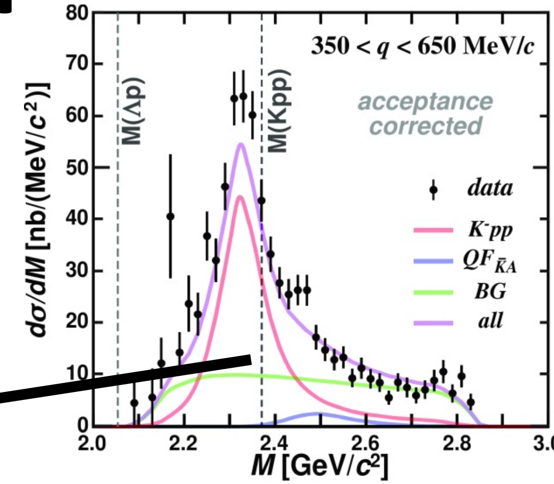
E15 collab., arXiv:1805.12275

Observed "K⁻pp"

the most reliable observation

- simple reaction
- exclusive measurement
- no BG from 2NA



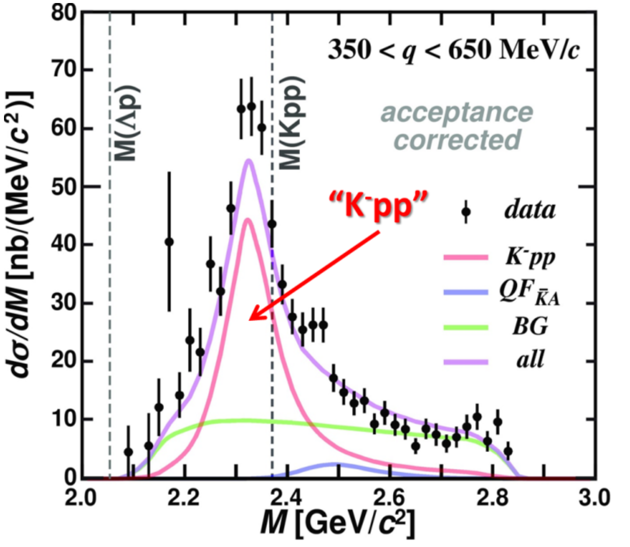


- **Binding energy: ~50 MeV**
  - Much deeper than chiral-SU(3) based theoretical predictions
- **Width: ~100 MeV**
  - Seems to be larger than theoretical calculations

Conclusion I

- **We observed the "K⁻pp" bound state in ^{3}He(K$^-$,Λp)n**
  - Binding energy: ~50 MeV
  - Width: ~100 MeV

← arXiv:1805.12275, accepted to PLB

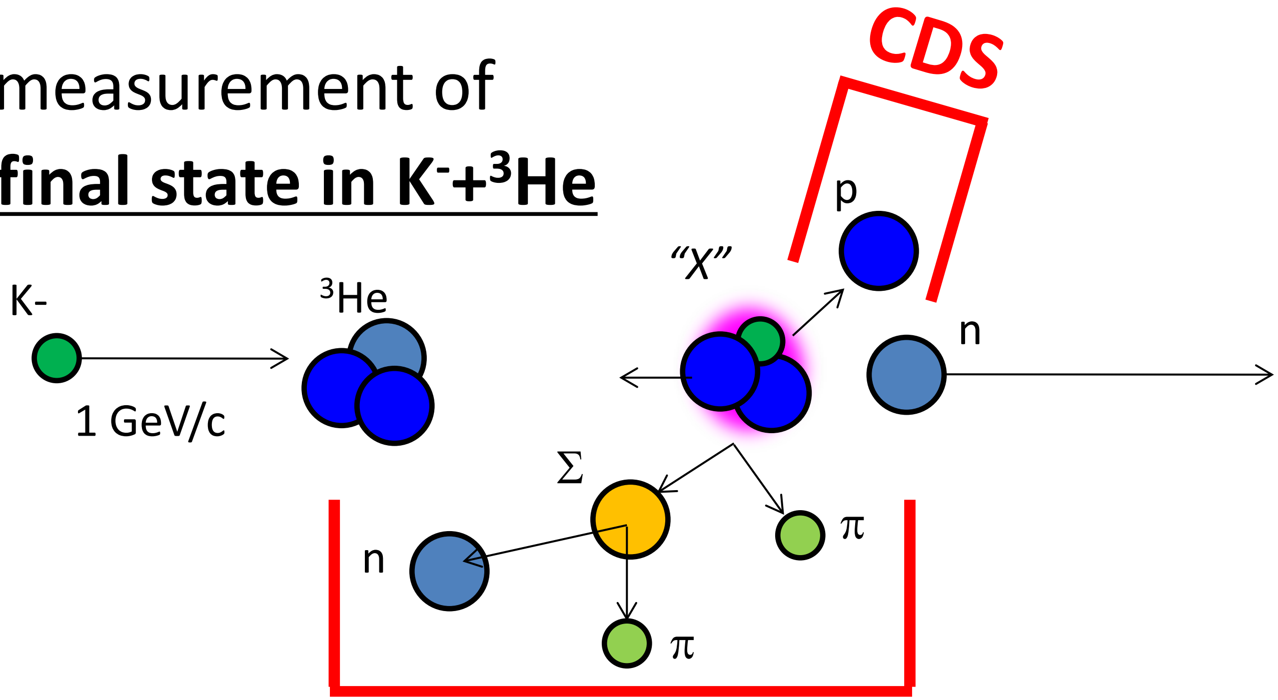


We need further understandings

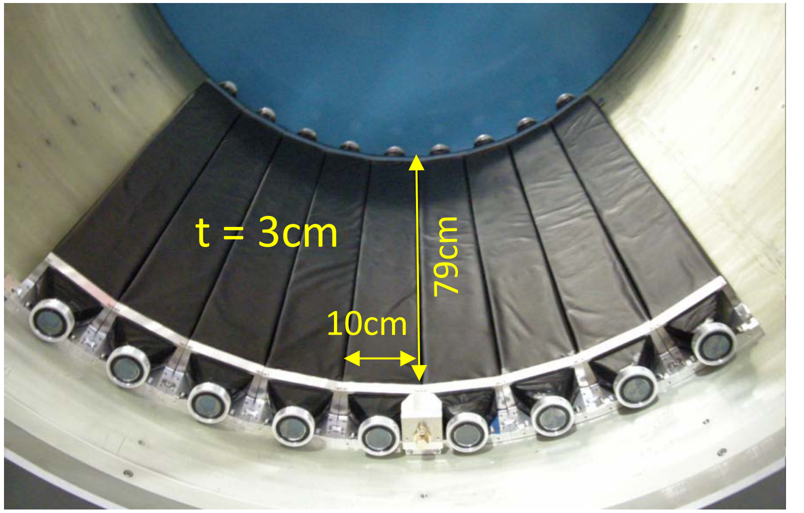
- **Spin/Parity of the "K⁻pp"**
  - *New 4π detector system is needed* ← ***Future plan***
- **Other decay channels** $K^- \, {}^3He \rightarrow \pi\Sigma pn$
  - **<u>$\pi\Sigma$N mesonic decay</u>** is theoretically expected to be the dominant channel
    - Only YN non-mesonic decays were reported
- **Reaction mechanism**
  - Relation between Λ(1405) & "K⁻pp"
    - Λ(1405) has been considered as **<u>"K⁻p"</u>**
    - Theoretically, "K⁻pp" is expected to be produced via **<u>Λ(1405)+p→"K⁻pp" door-way process</u>**

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

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



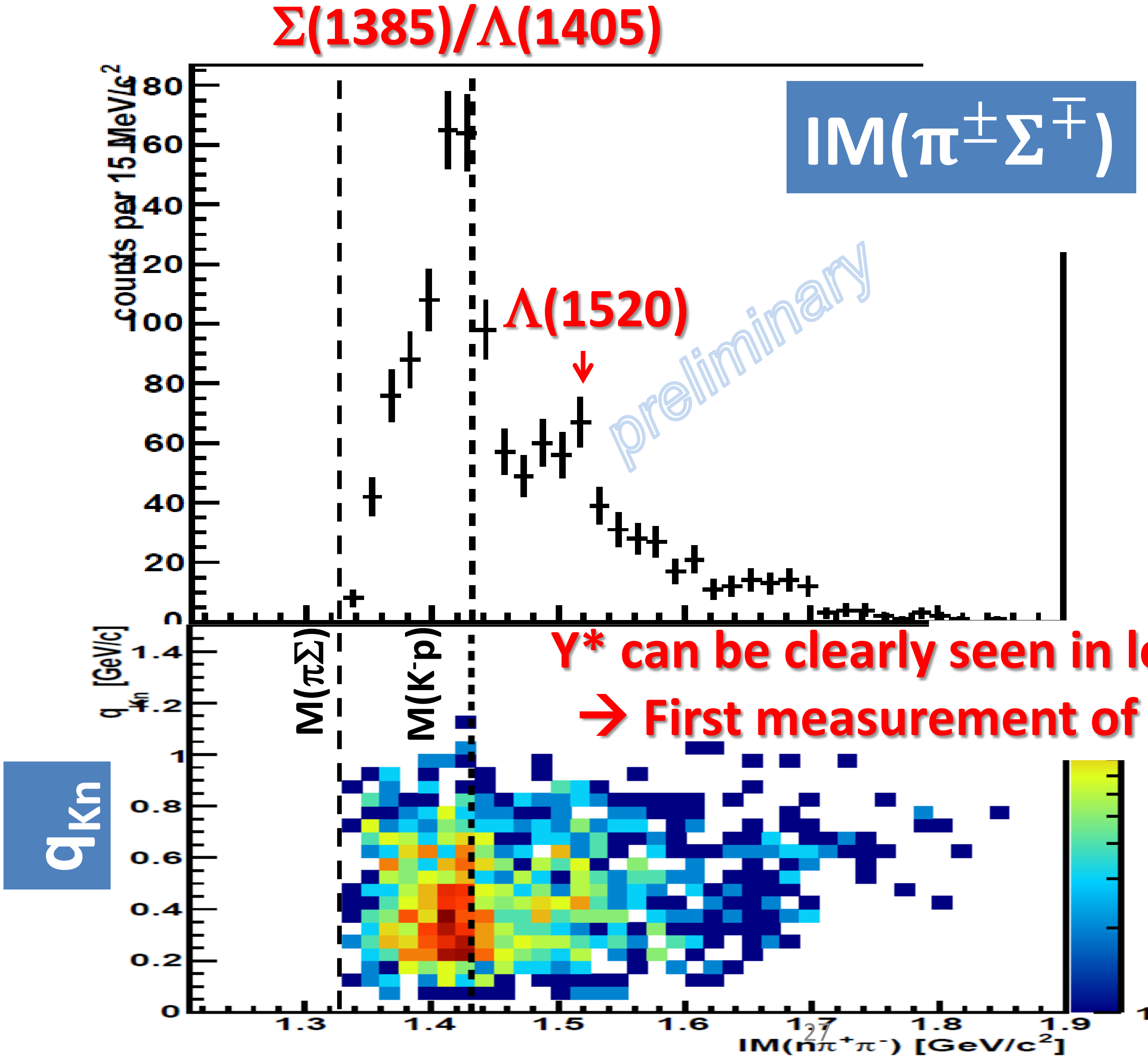
CDS



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

n detection efficiency ~ 3-10%

IM($\pi^{\pm}\Sigma^{\mp}$) in $\pi^{\pm}\Sigma^{\mp}pn$ Final State



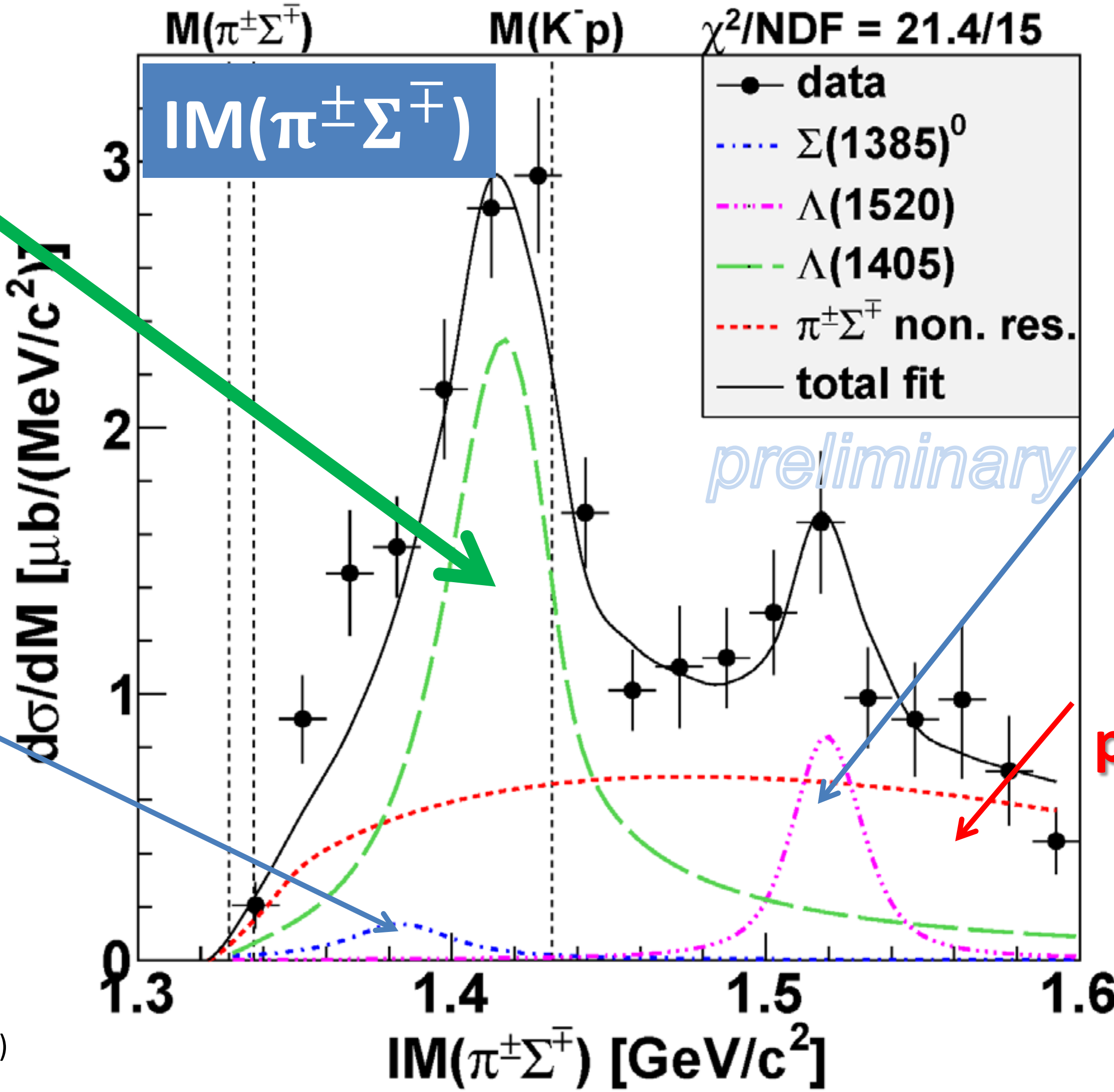
Y* can be clearly seen in low q_{Kn}

→ First measurement of Y* in K^{-3}He

Λ(1405)pn CS

0.2<$\cos\theta_n^{CM}$

Λ(1405)
~ 240 μb
Fit w/ Flatté:
Re(z) ~ 1415 MeV
-Im(z) ~ 20 MeV



Λ(1520)
~ 100 μb

πΣpn phases-space

Σ⁰(1385)
~ 40-80 μb
[evaluated from Σ+/-(1385)→π+/-Λ measurement]
(Σ(1385)→πΛ/πΣ : 87.0/11.7%)

Λ(1405)pn CS

$0.2<\cos\theta_n^{CM}$

Λ(1405)

~ 240 μb

Fit w/ Flatté:

Re(z) ~ 1415 MeV

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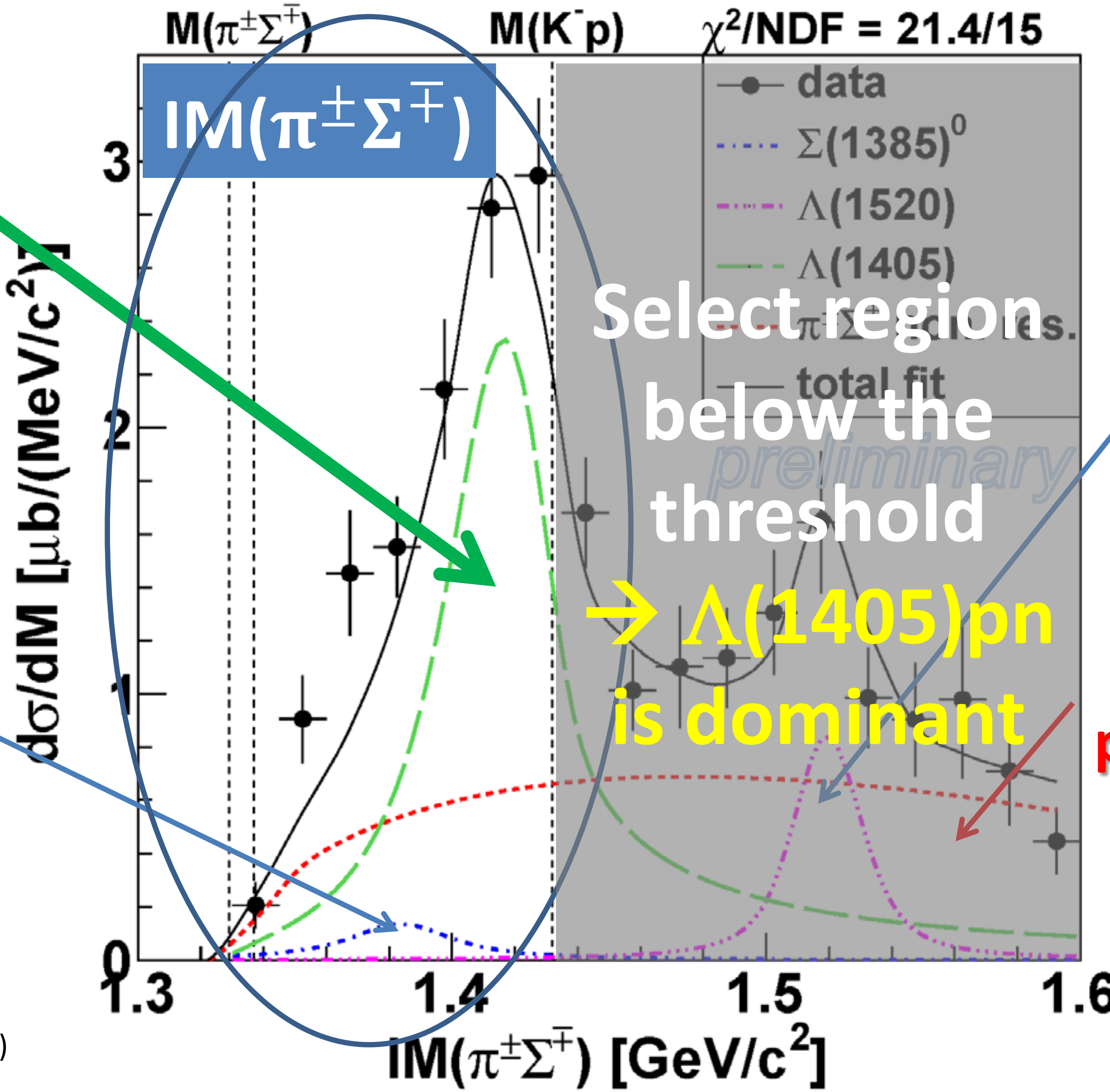


Λ(1520)

~ 100 μb

πΣpn phases-space

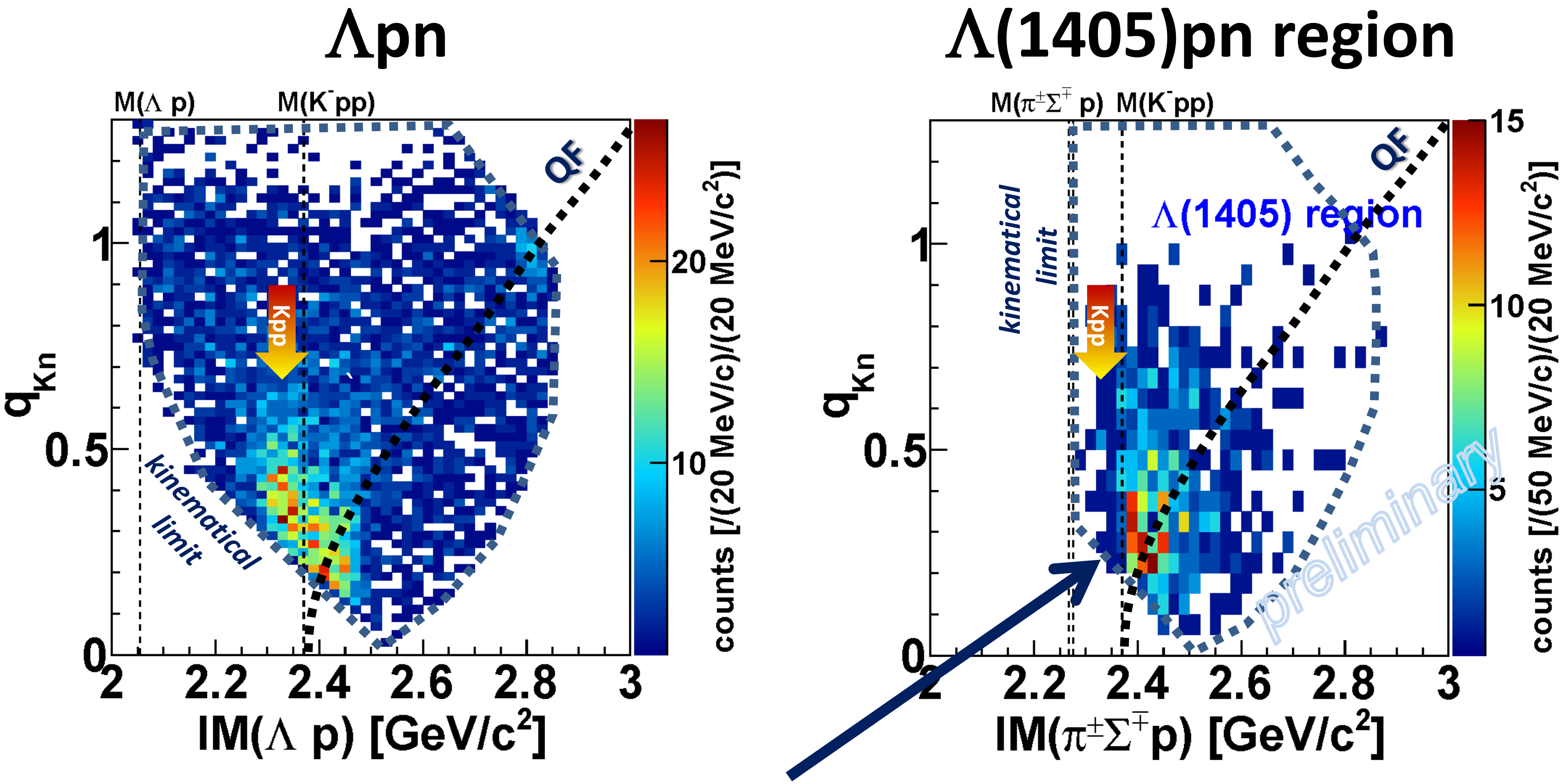
$\Sigma^0(1385)$

~ 40-80 μb

[evaluated from $\Sigma^{+/-}(1385)\rightarrow\pi^{+/-}\Lambda$ measurement]

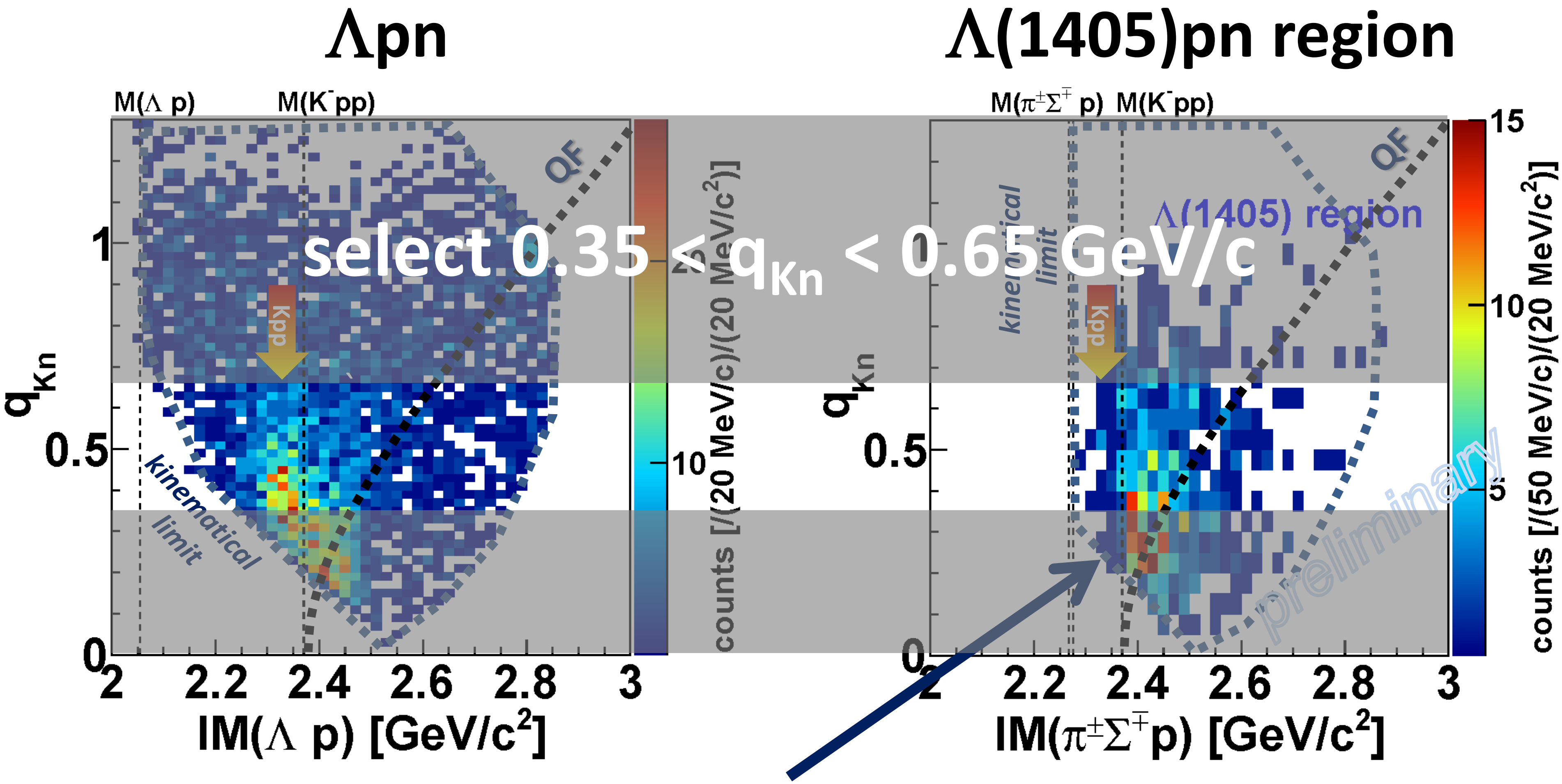
($\Sigma(1385)\rightarrow\pi\Lambda/\pi\Sigma$: 87.0/11.7%)

Comparison of Λpn & Λ(1405)pn



- **No clear structure below M(Kpp) in the IM(πΣp)**
- **QF followed by Λ(1405)p is dominant**

Comparison of Λpn & Λ(1405)pn



- **No clear structure below M(Kpp) in the IM(πΣp)**
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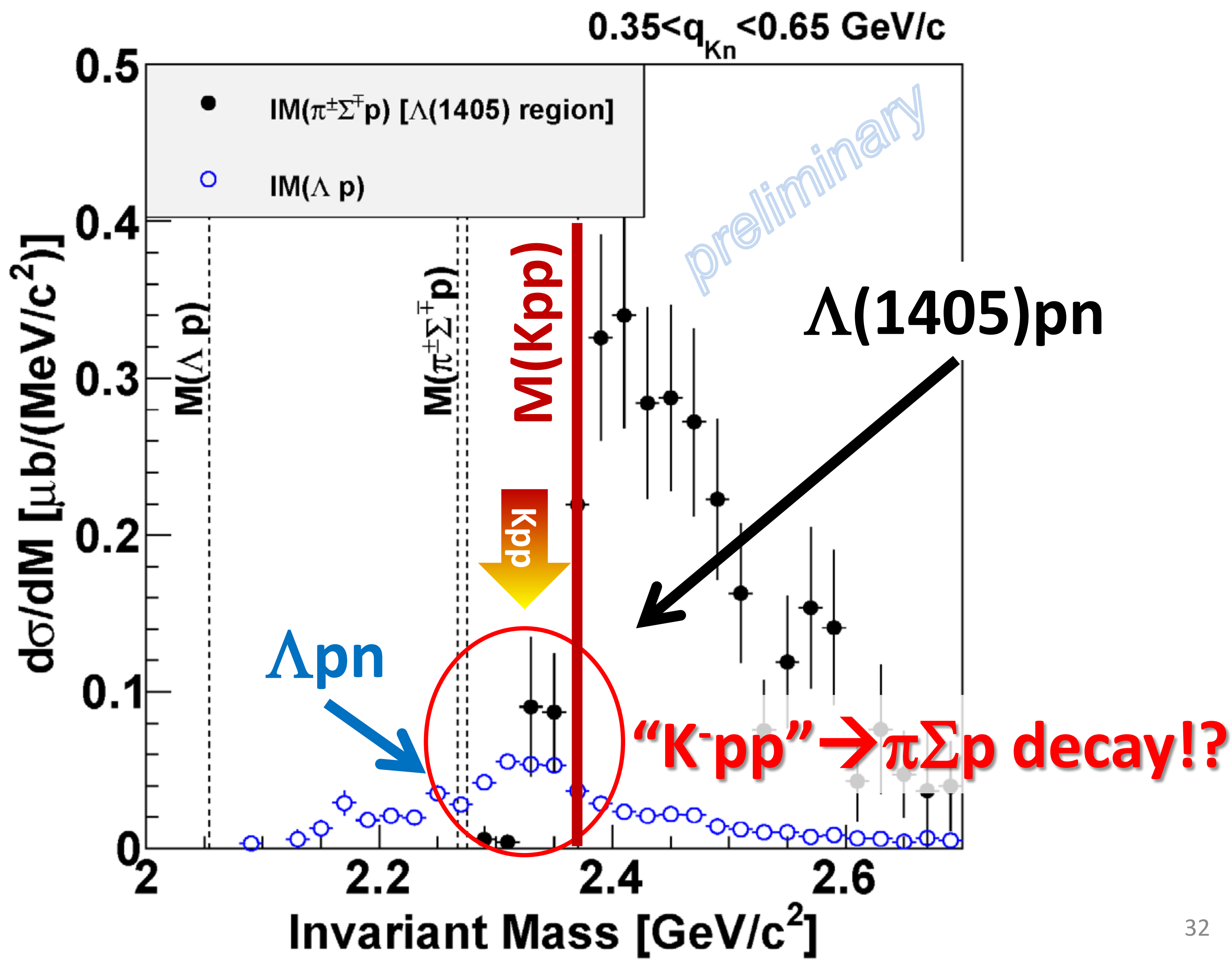
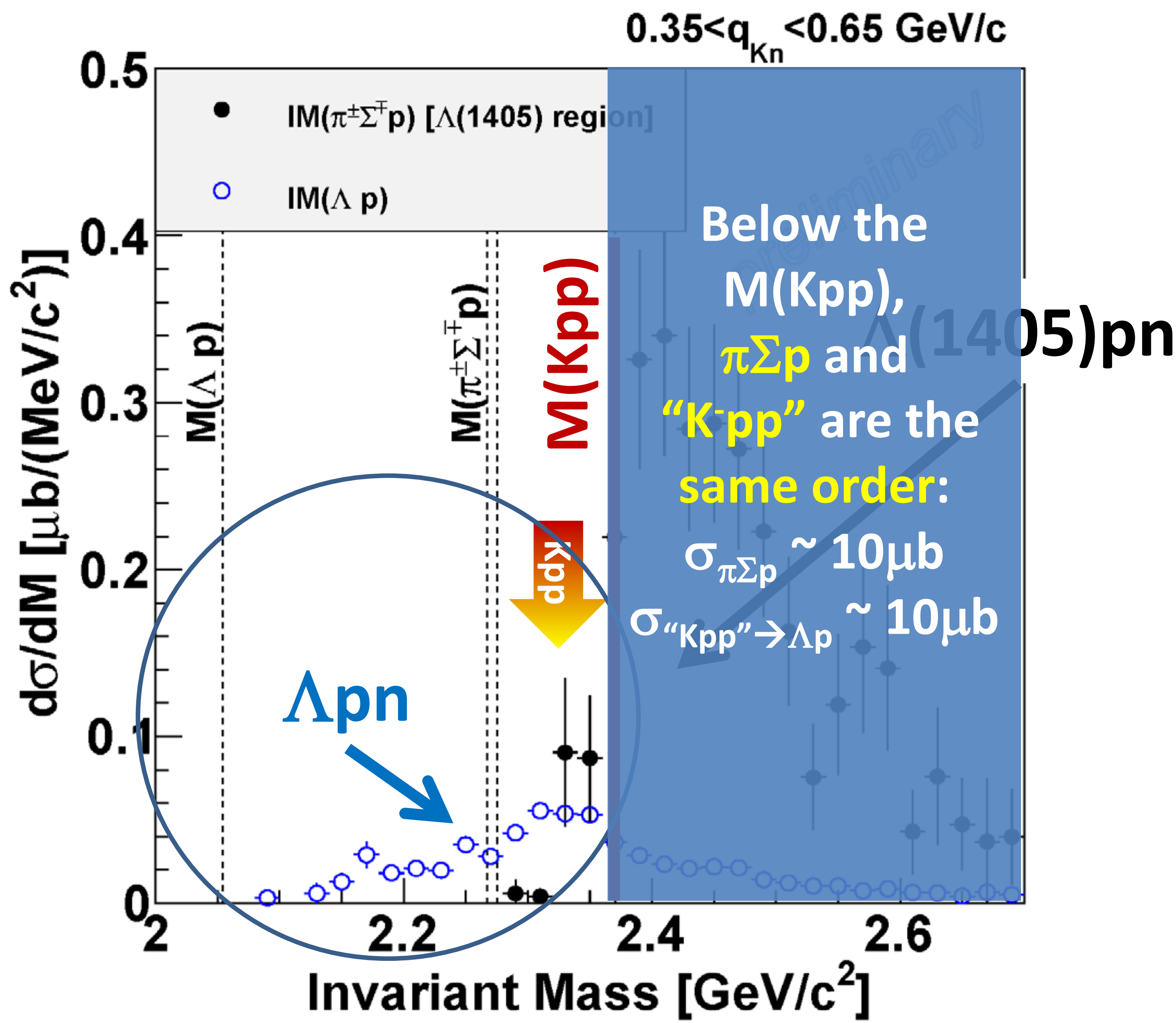
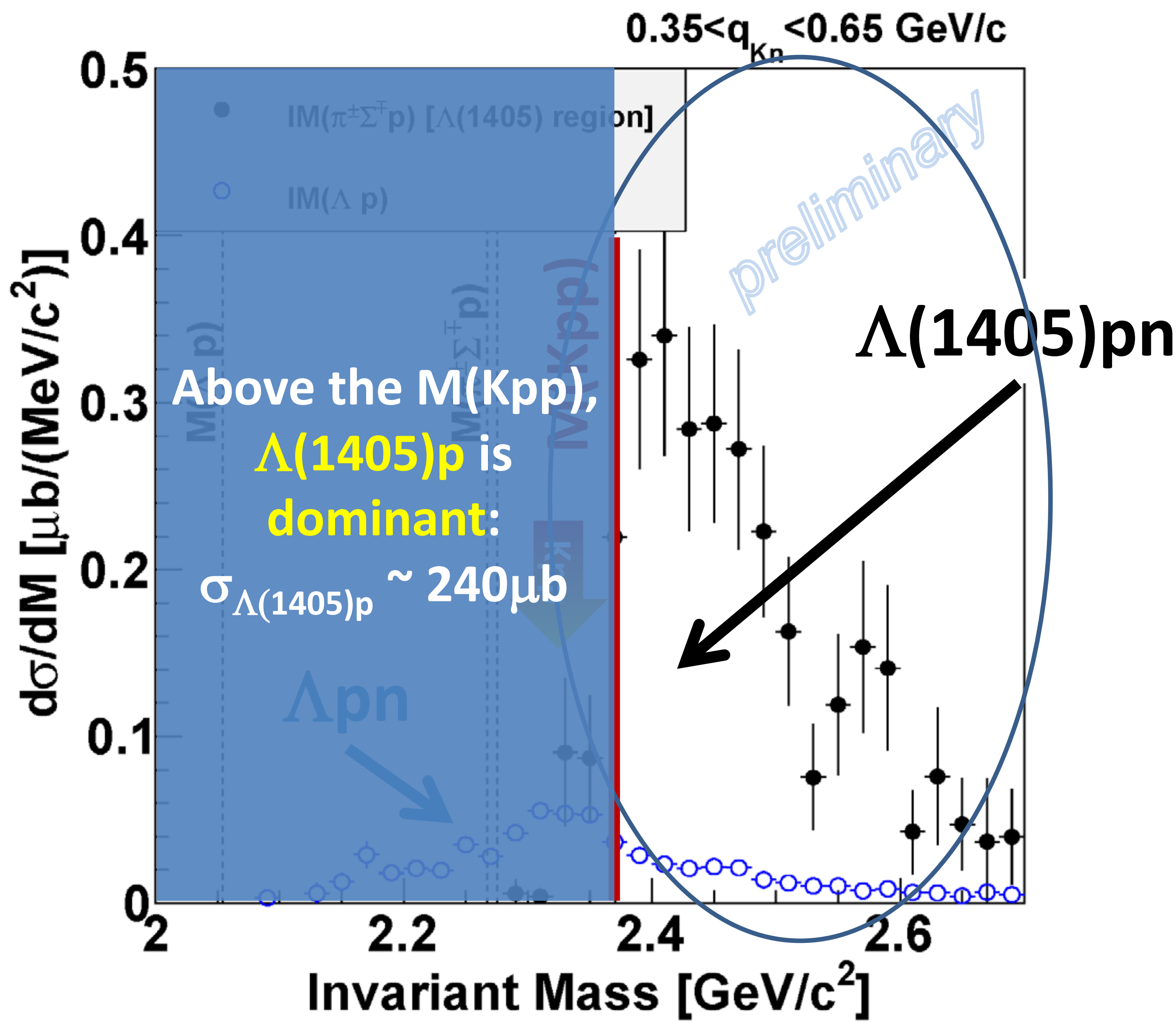
Comparison of Λpn & Λ(1405)pn



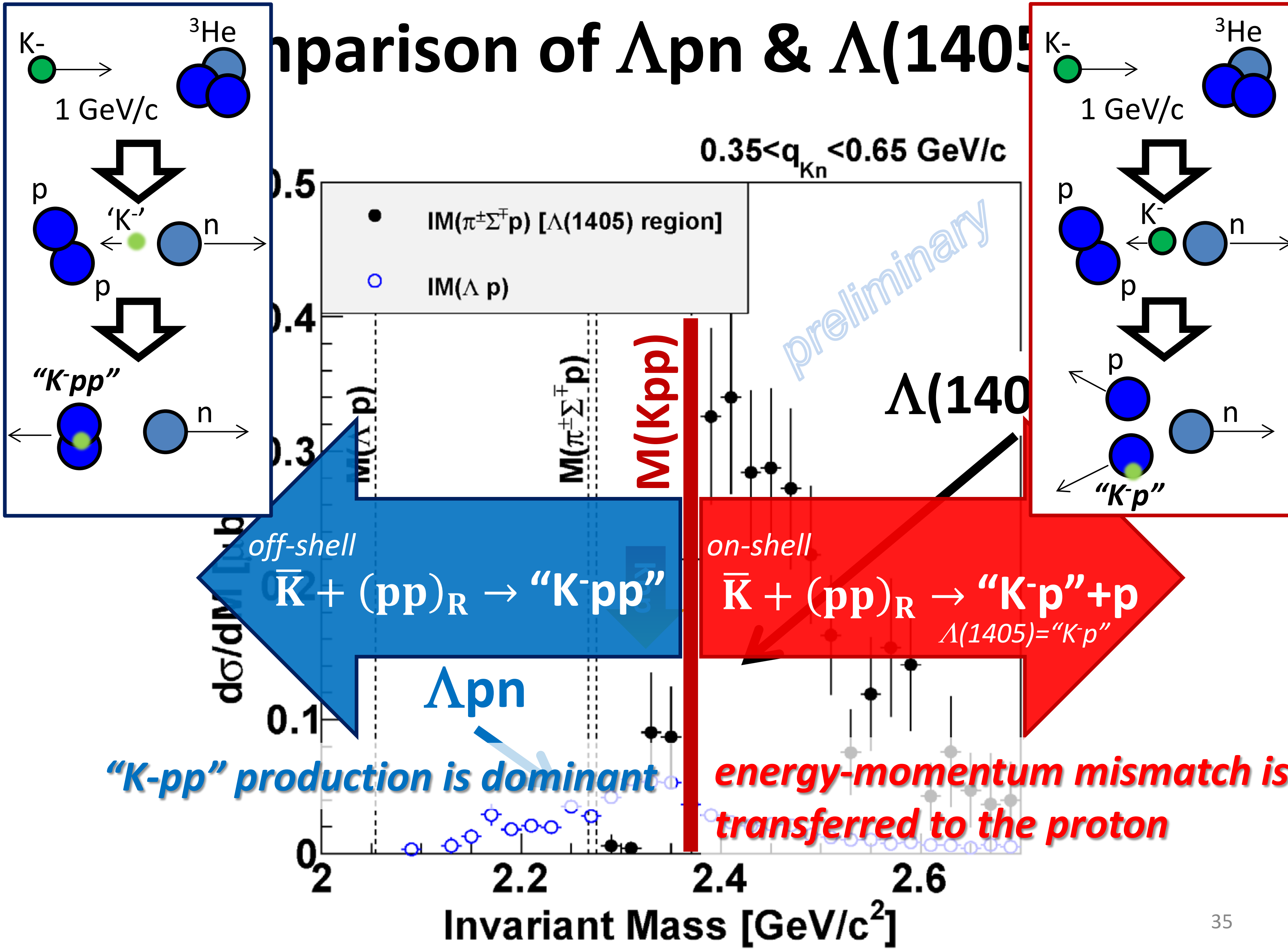
Comparison of Λpn & Λ(1405)pn



Comparison of Λpn & Λ(1405)pn



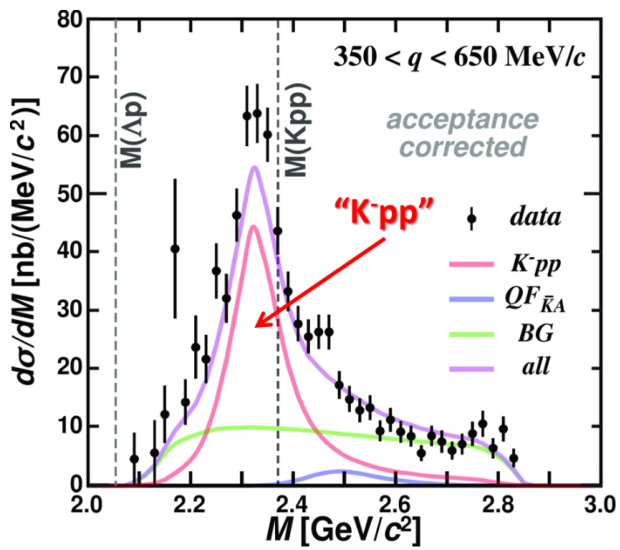
…nparison of Λpn & Λ(1405…



Conclusion II

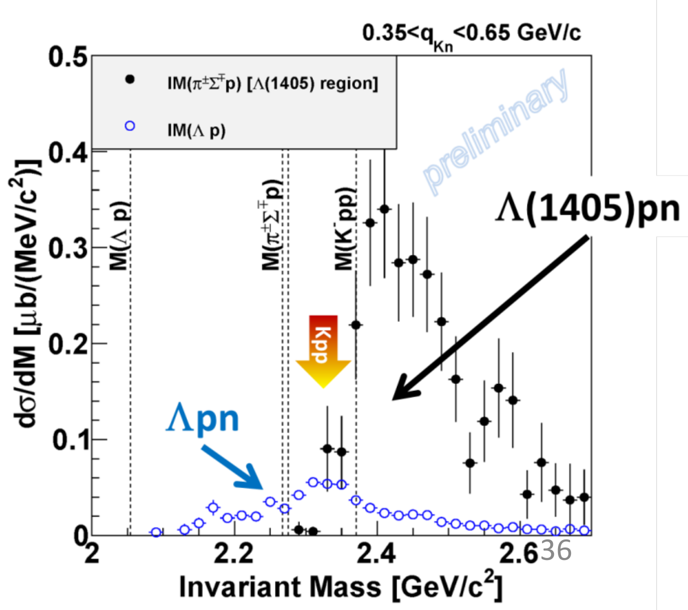
- **We observed the "$K^{-}pp$" bound state in $^{3}He(K^{-},\Lambda p)n$**
  - Binding energy: ~50 MeV
  - Width: ~100 MeV

← arXiv:1805.12275, accepted in PLB



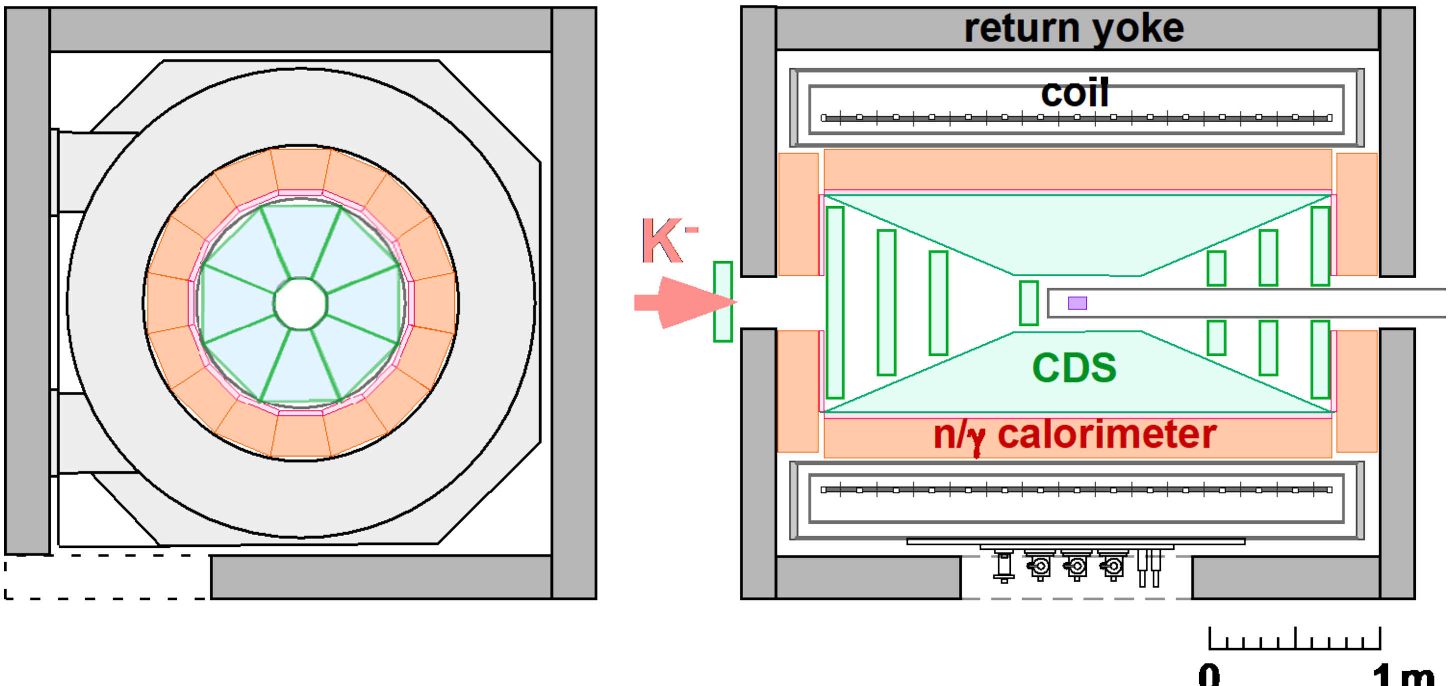
- **We found large CS of the $\Lambda(1405)p$ formation compared to the "$K^{-}pp$"**
  - quite important measurement for the production mechanism of the "$K^{-}pp$"

← paper in preparation



What we have to do next

- **More quantitative studies of the "K⁻pp"**
  - **J^P** and **other decay modes**
- **Study of other kaonic nuclei:**
  - Single: **"K⁻ppn"** via [K^- + ^{4}He], **"K⁻ppnn/K⁻pppnn"** via [K^- + ^{6}Li]
  - Double: **"K⁻K⁻pp"** via [p^{bar} + ^{3}He]



Need the new 4π detector 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]

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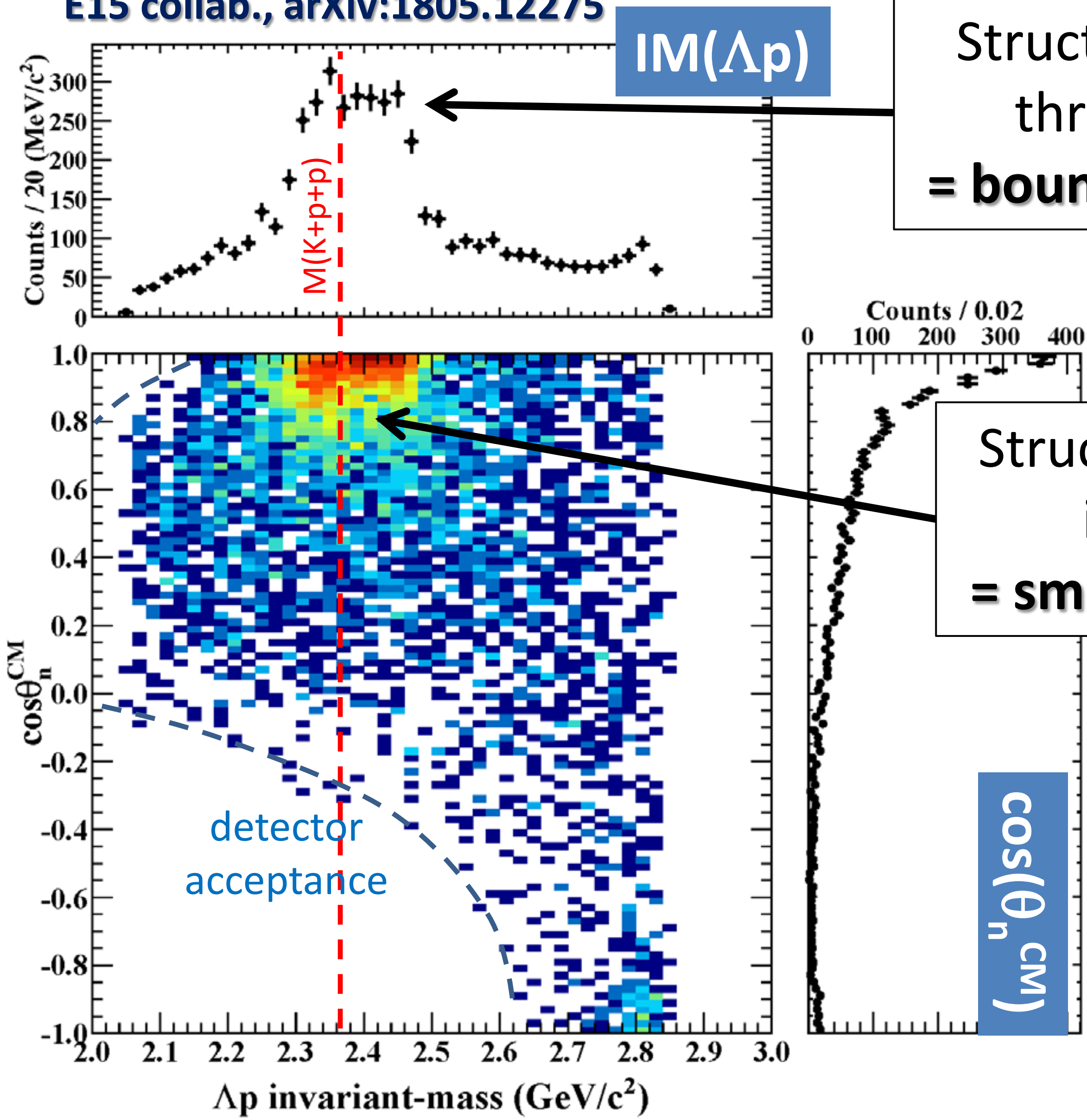
Spares

IM(Λp) vs. cos(θ_n^{CM})

E15 collab., arXiv:1805.12275

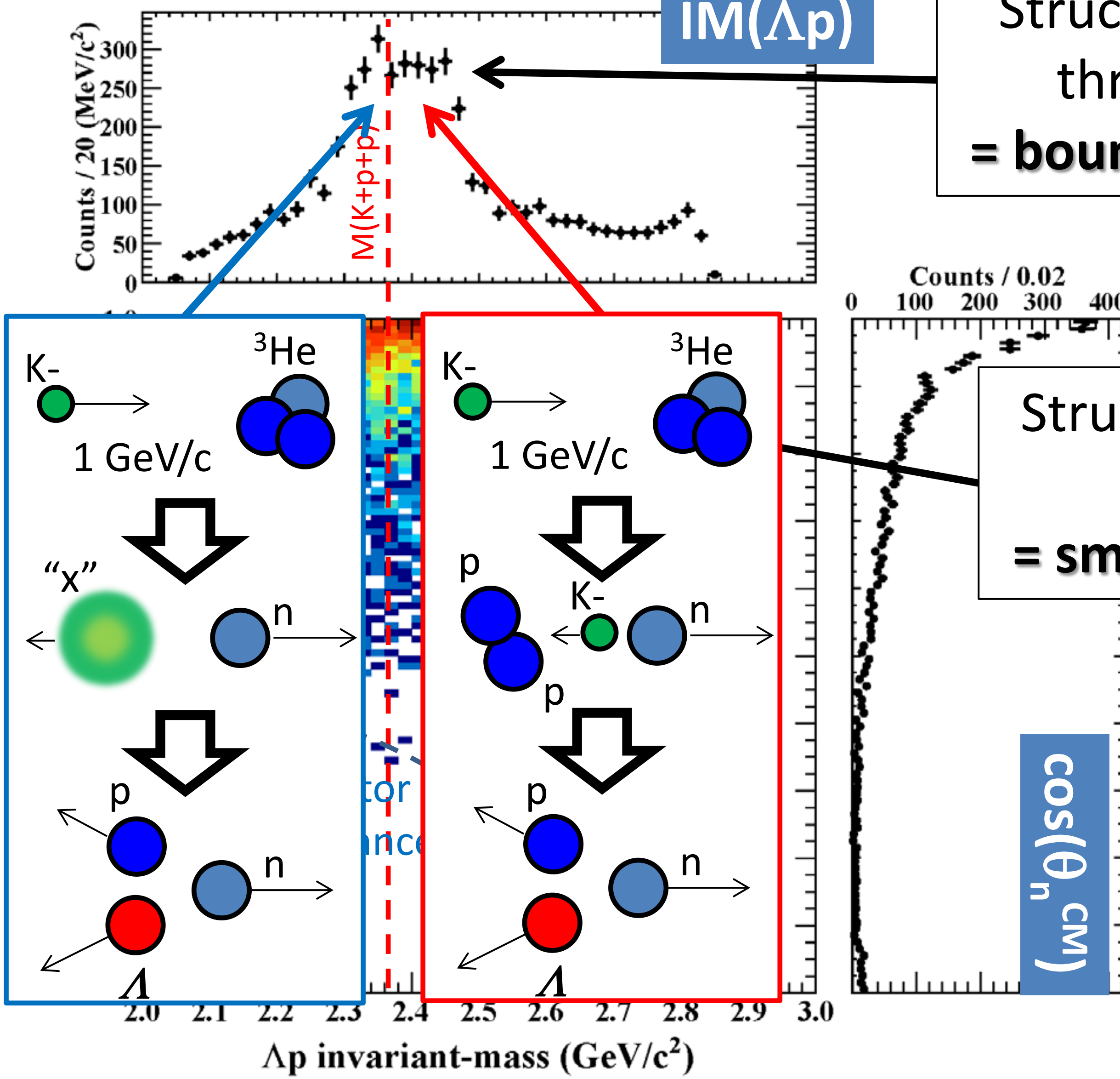


Structures around the K⁻pp threshold can be seen
= bound-state + quasi-elastic

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

IM(Λp) vs. cos(θ_n^{CM})

E15 collab., arXiv:1805.12275



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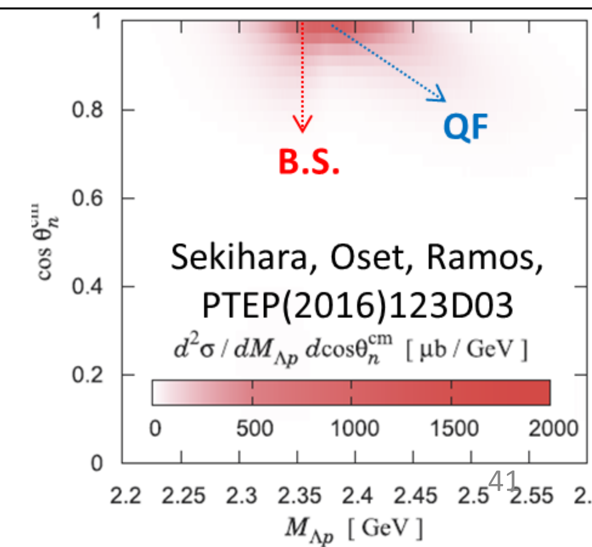


$K^{bar}NN$ or NOT? --- Other Possibilities

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, ΛN/ΣN/$\pi\Sigma$N

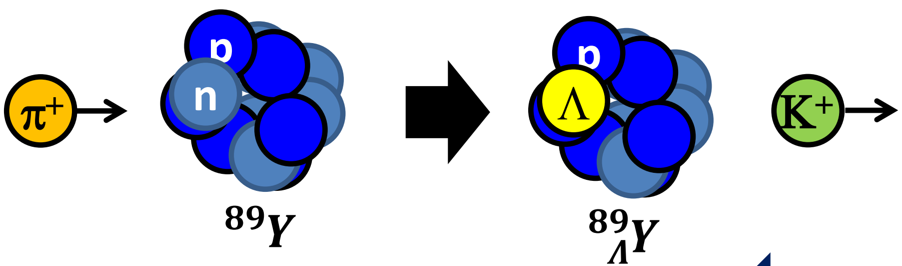
A structure near $\pi\Sigma$N threshold

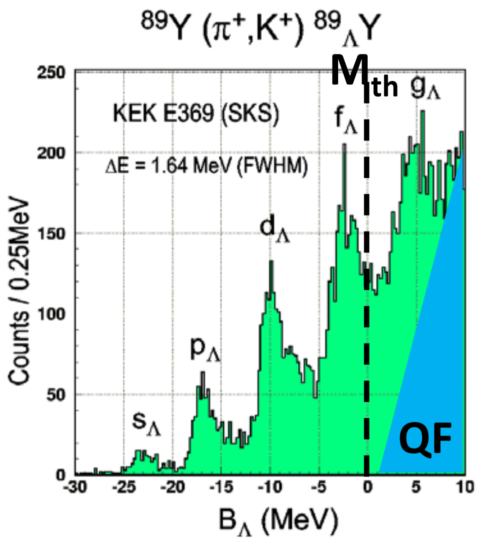
- **$\pi\Lambda$N-$\pi\Sigma$N dibaryon** H. Garcilazo, A. Gal, NPA897(2013)167.
  - structure near $\pi\Sigma$N threshold
  - I=3/2, $J^{\pi}=2^{+}$ → no Λp decay (I=1/2)?
- **Double-pole $K^{bar}NN$** A. Dote, T. Inoue, T. Myo, PTEP (2015) 043D02.
  - loosely-bound $K^{bar}NN$, &
  - broad resonance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

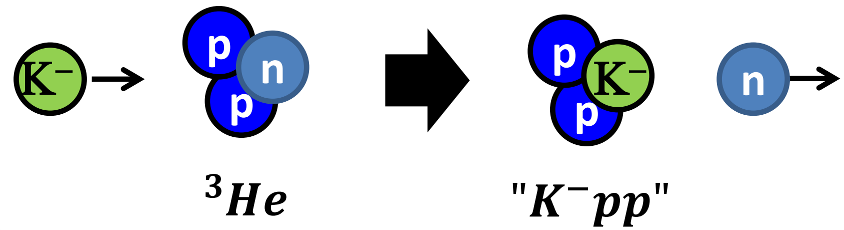
Interpretation as the "K⁻pp"

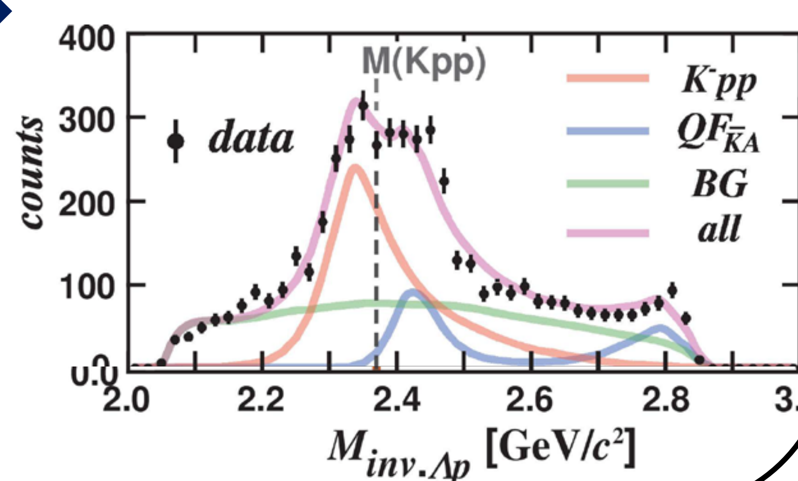
Λ-hypernuclei





"K⁻pp" @ E15





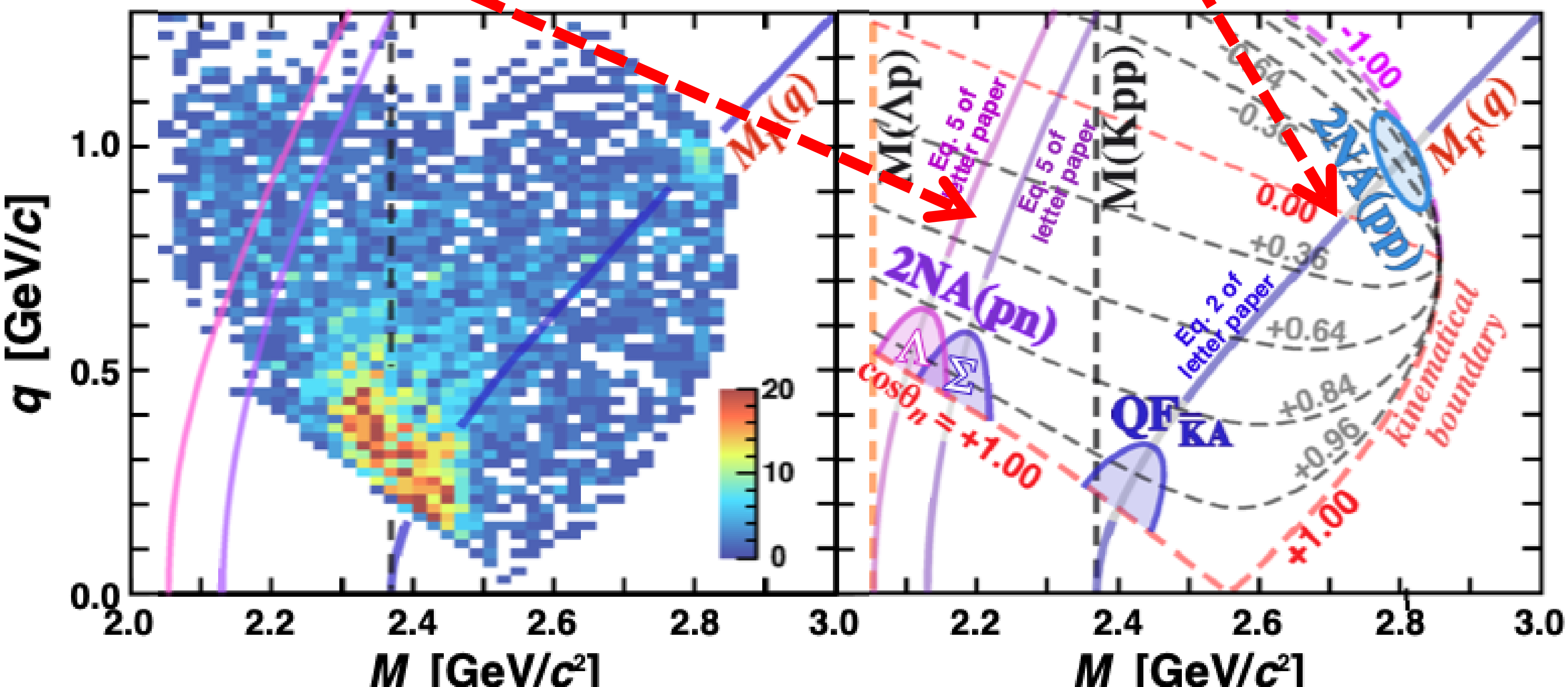
Bound state and QF can be seen clearly

- On the analogy of the formation of Λ-hypernuclei, **the observed bump structure would be the "K⁻pp"**

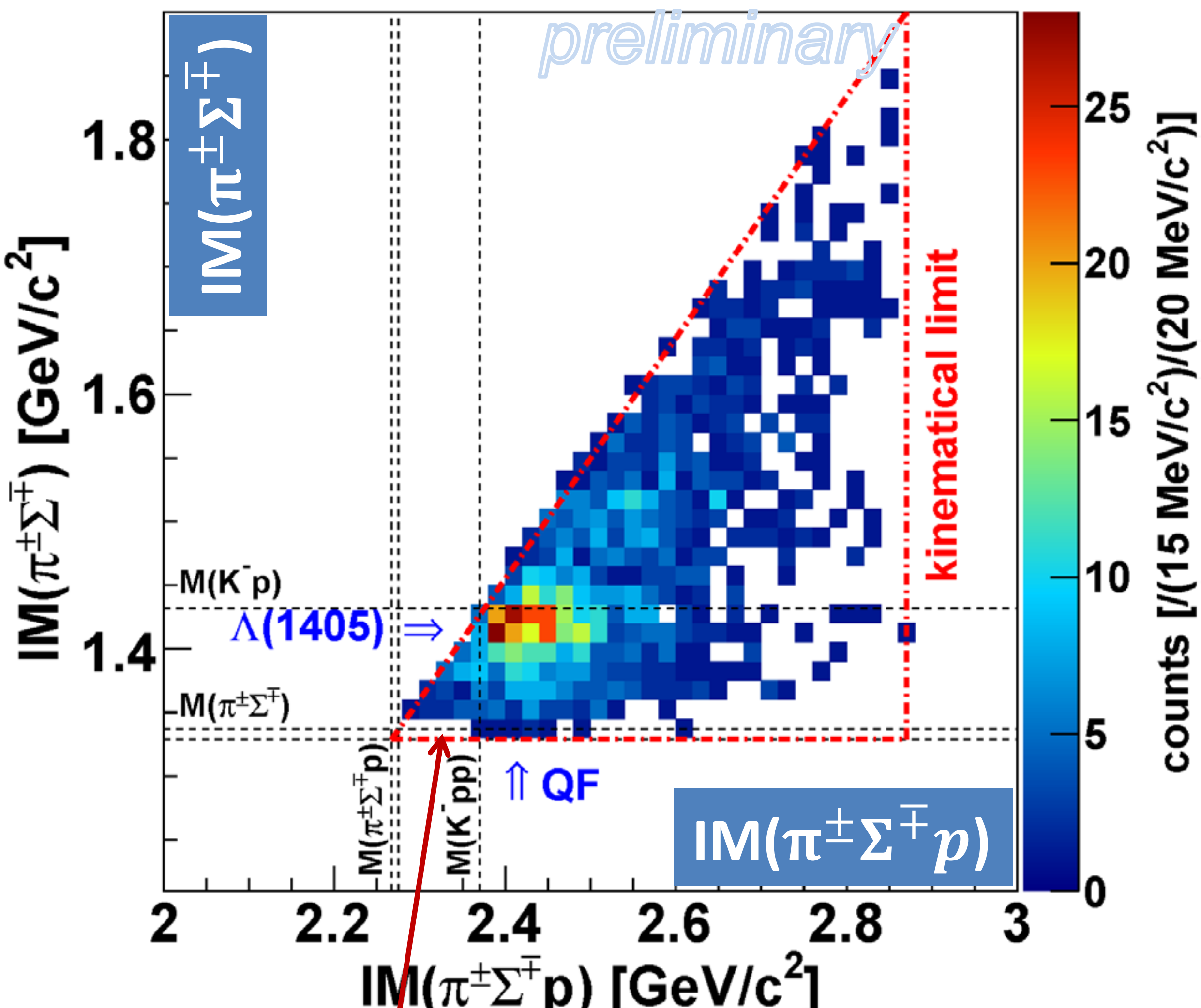
BG: 2NA followed by FSI

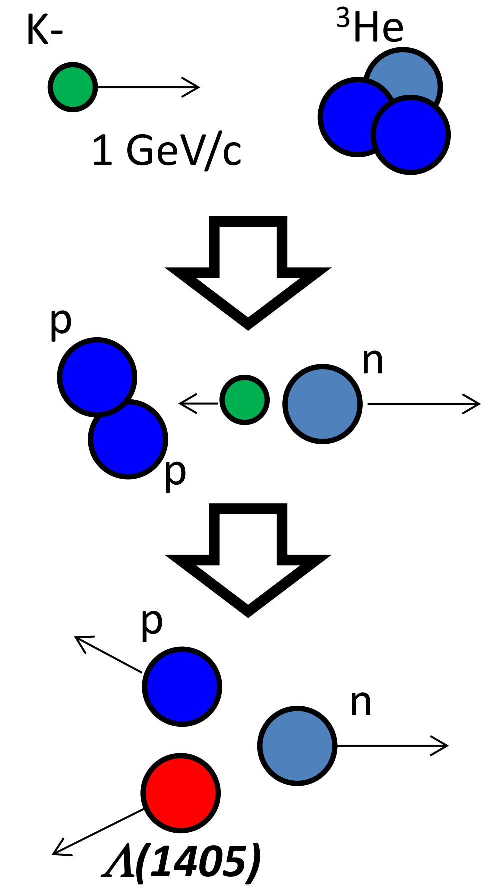
$K^- + {}^3He \to (K^- + "pn") + p_{spect}$
$\to Y + n + p_{spect}$ **(2NA)**
$\to (Y + "p") + n$
$\to \Lambda + p + n$ **(FSI)**

$K^- + {}^3He \to (K^- + "pp") + n_{spect}$
$\to Y + p + n_{spect}$ **(2NA)**
$\to (Y + "n") + p$
$\to \Lambda + p + n$ **(FSI)**



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

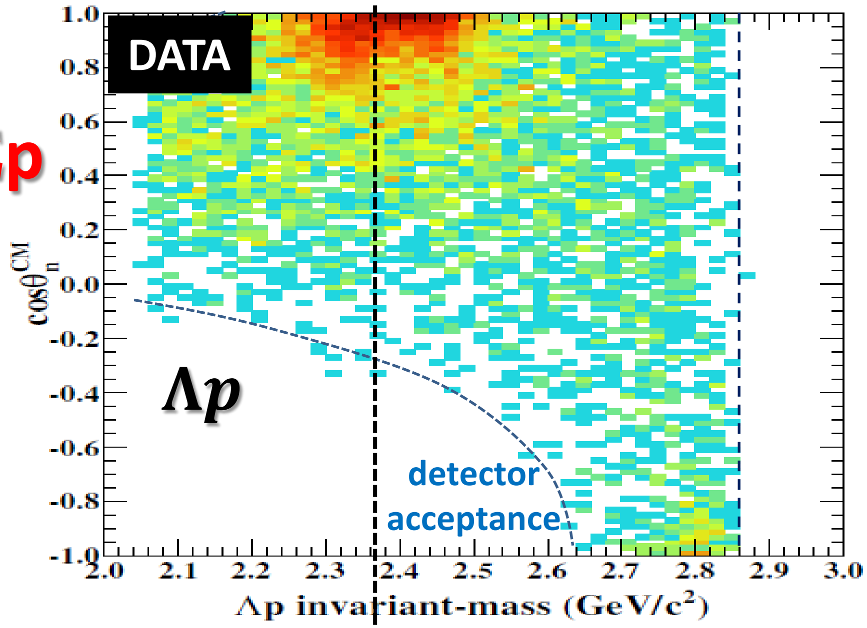


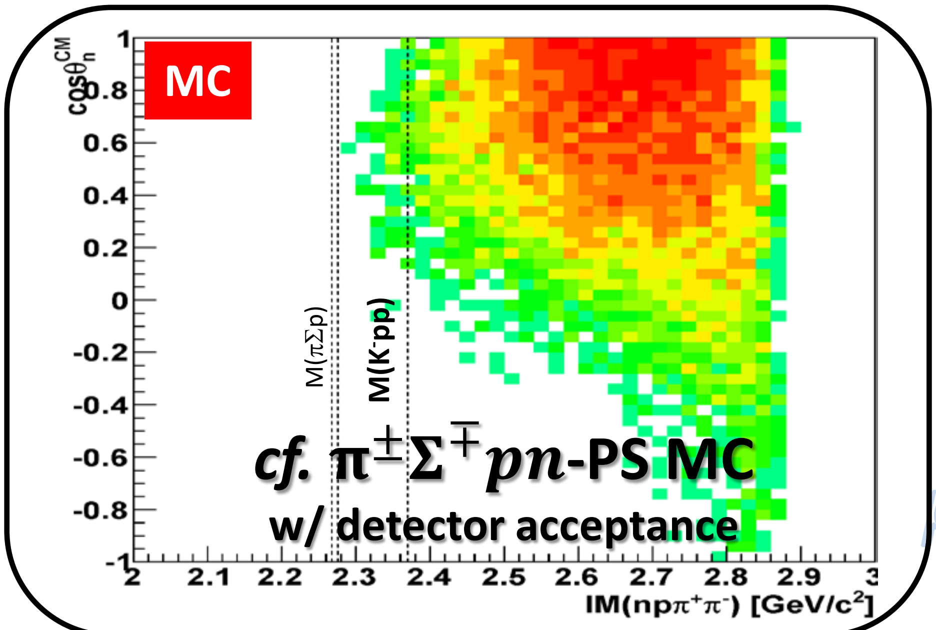


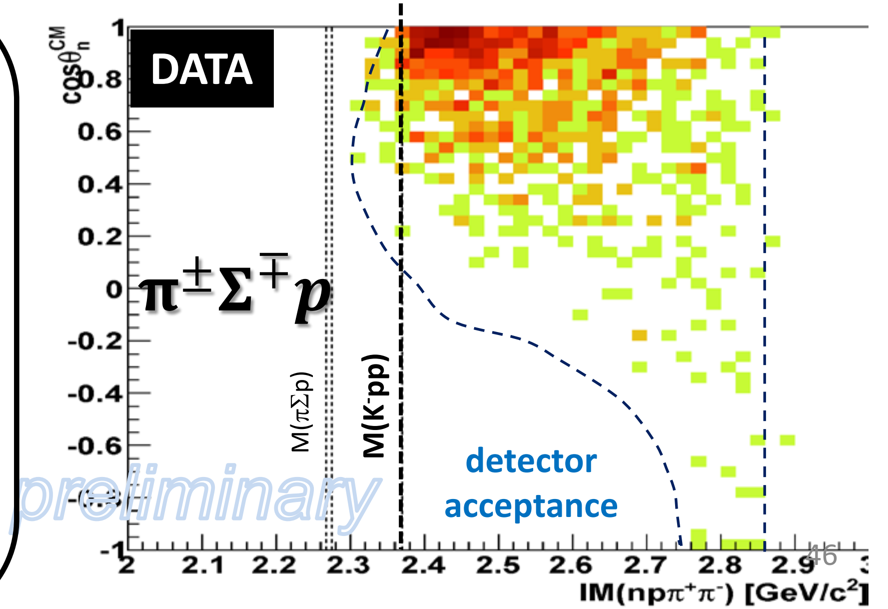
Small phase-space of "K$^-$pp"→πΣN

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



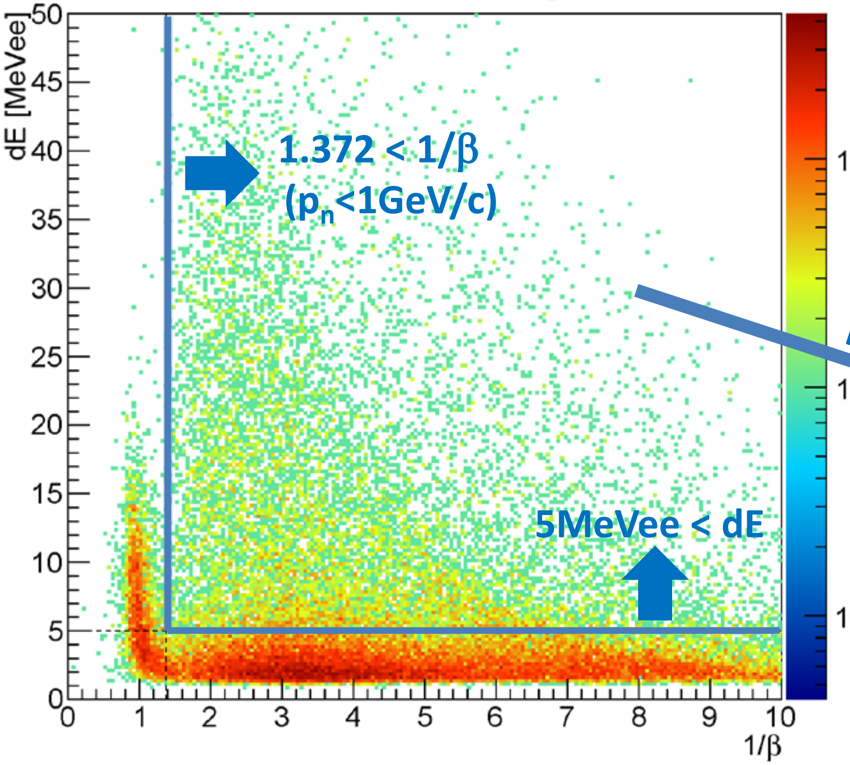




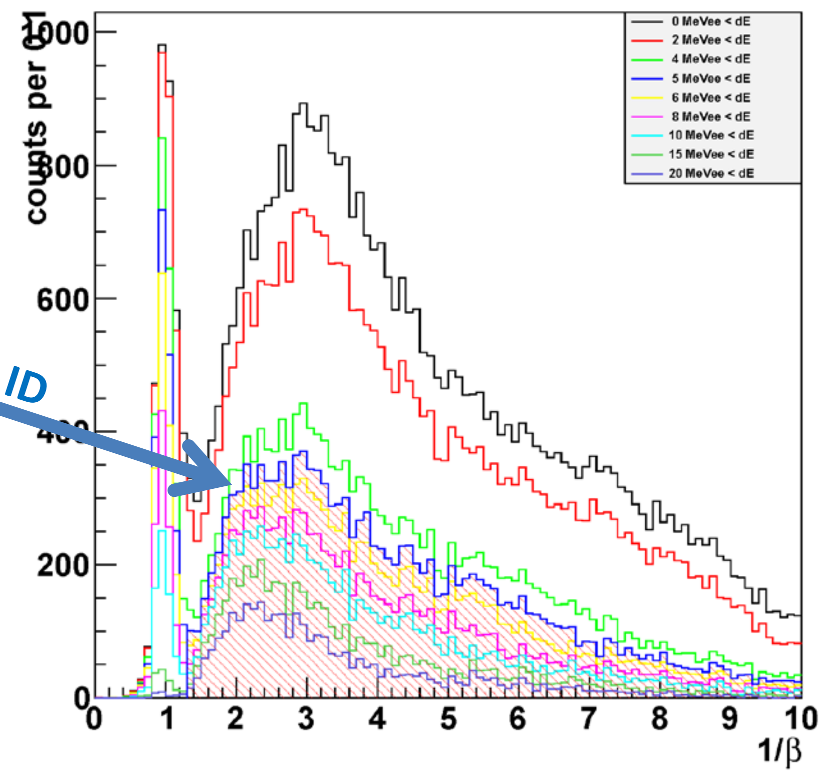
Neutron ID with CDS

- $\pi^+\pi^-p$ 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

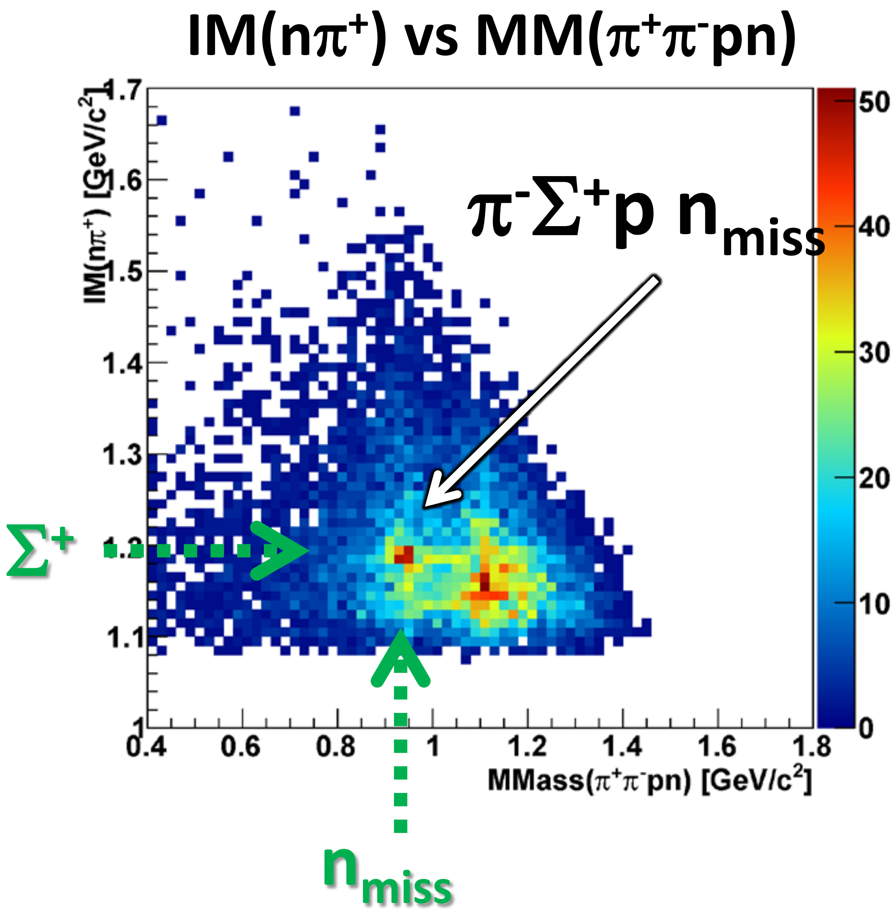


dE-cut dependence

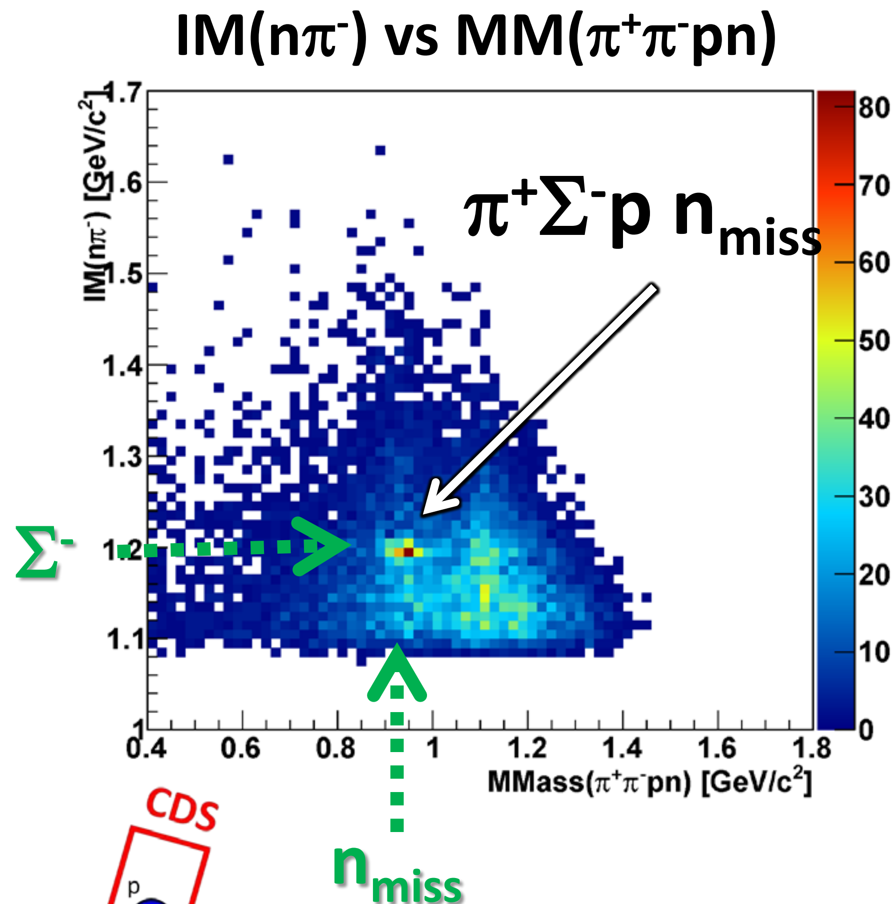


Neutron can be identified with CDS

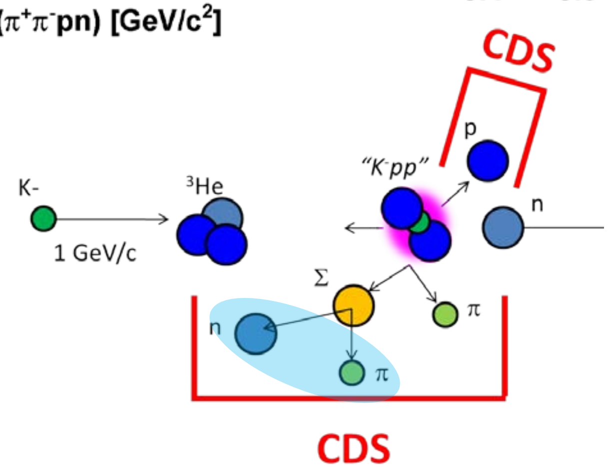
πΣpn Events



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



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

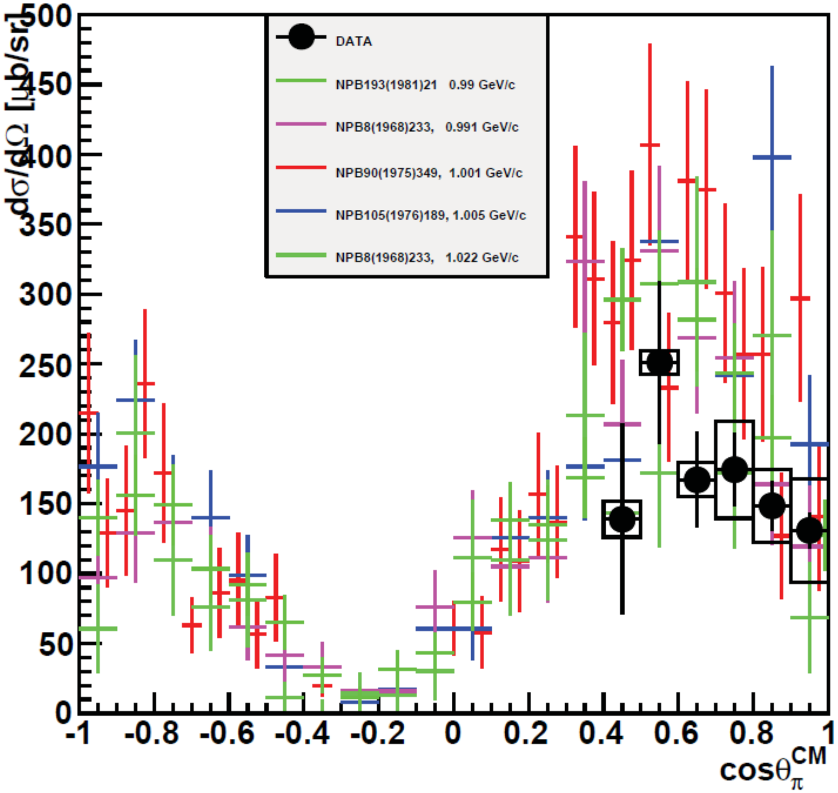


CDS
K-
1 GeV/c
3He
"K-pp"
p
n
Σ
π
n
π
CDS

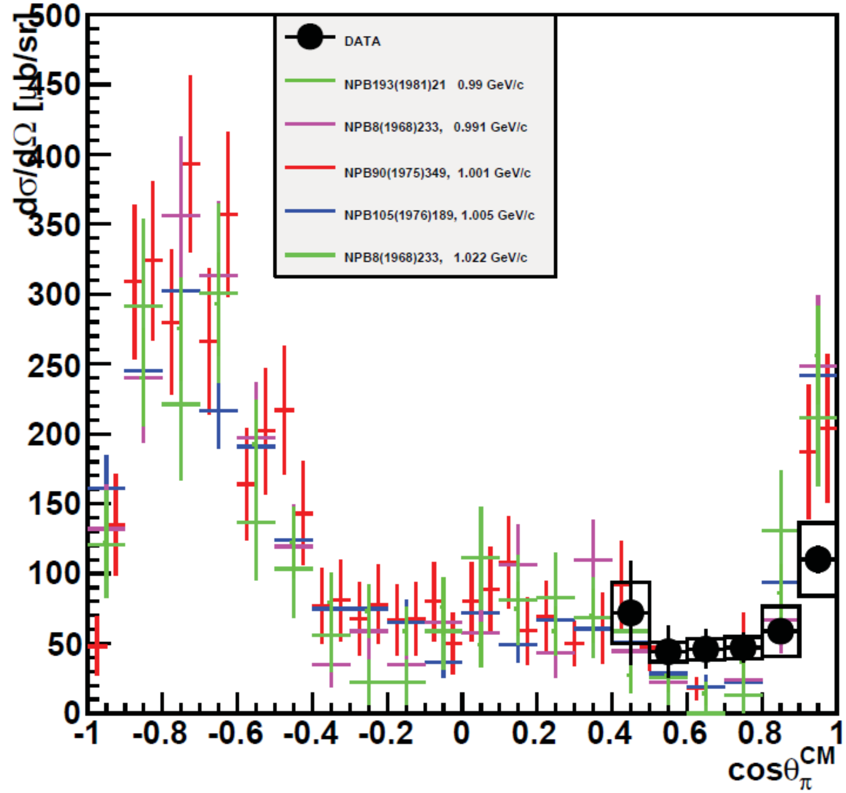
$K^{-}p \rightarrow \Sigma^{+}\pi^{-}/\Sigma^{-}\pi^{+}$ Cross Section

* Error box represents systematic error

$\Sigma^{+}\pi^{-}$

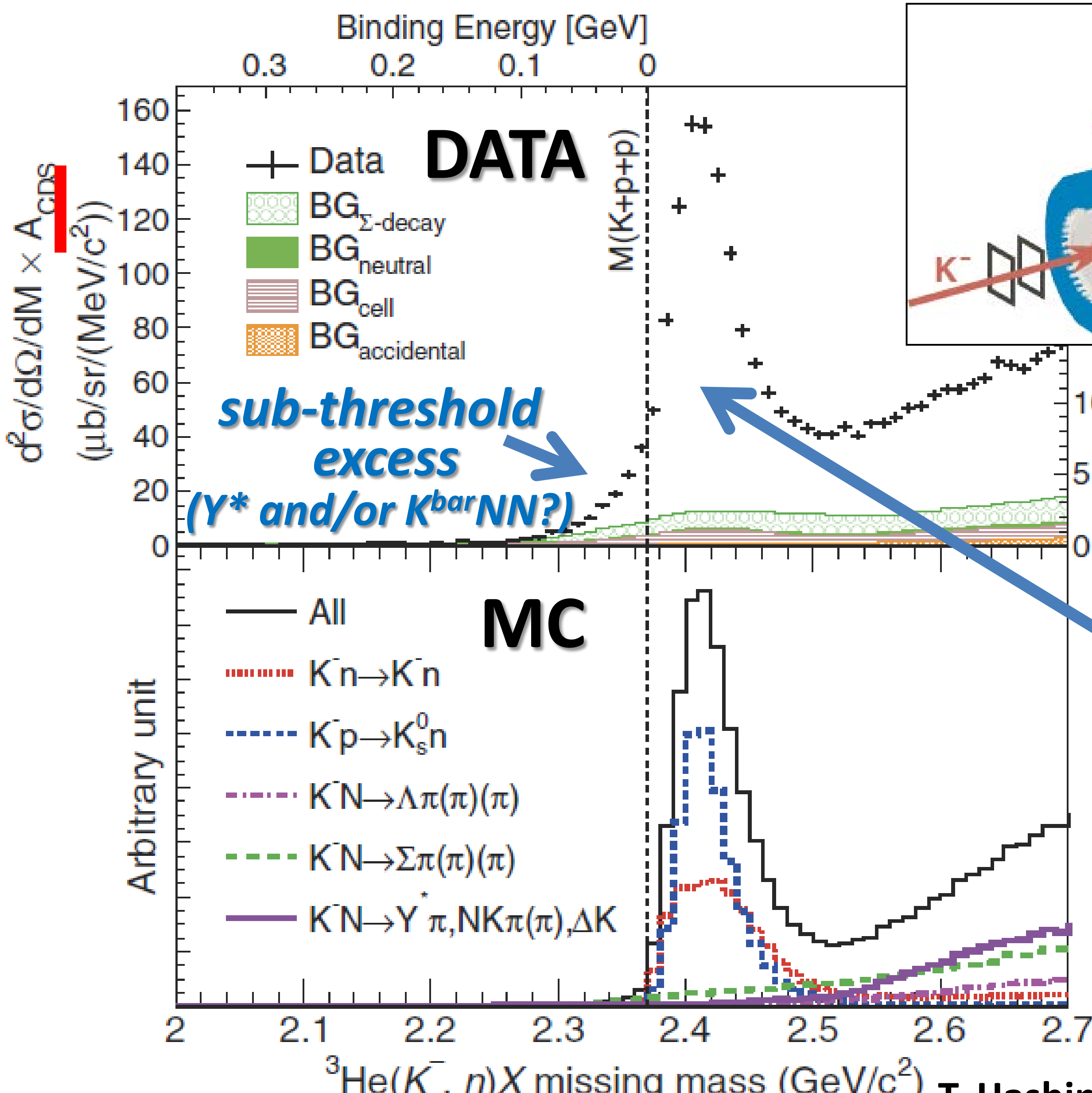


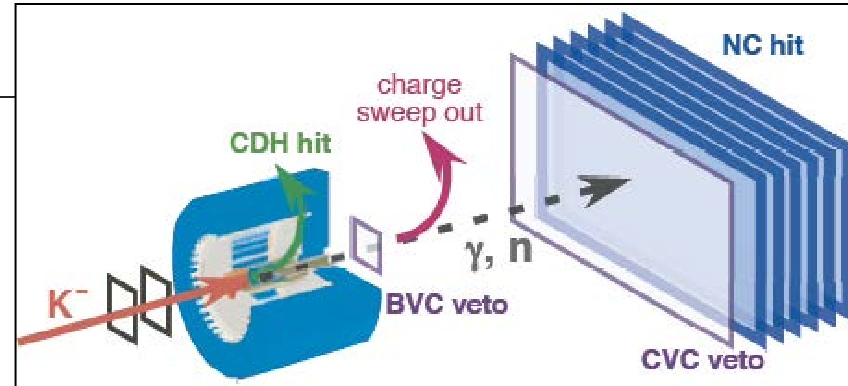
$\Sigma^{-}\pi^{+}$



consistent with the references

Semi-Inclusive $^3He(K^-,n)X$





Quasi Elastic

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

$d\sigma/d\Omega_{\theta=0deg}$ ~ 6mb/sr

Charge-Exchange

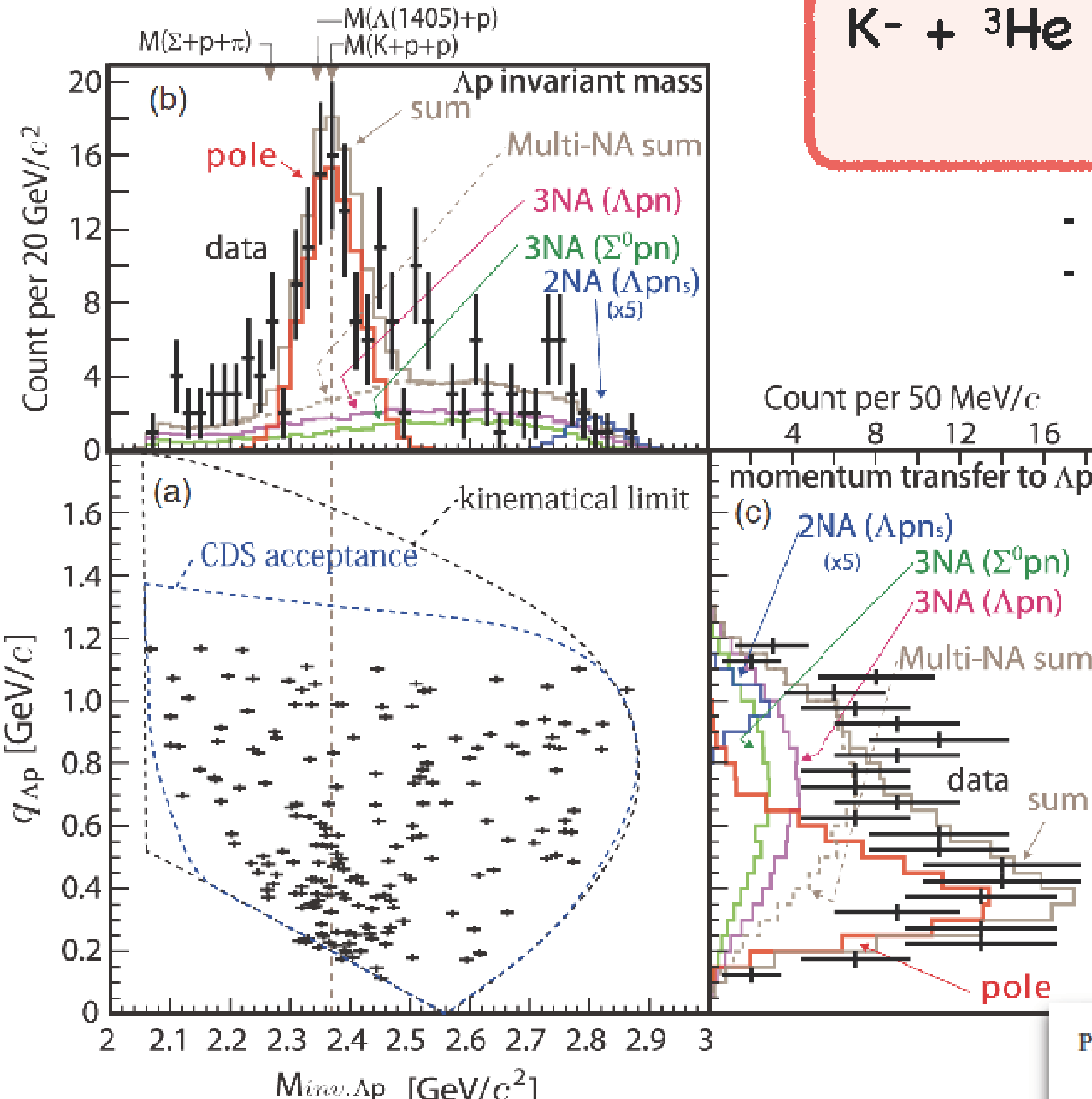
$K^- + {}^3He \rightarrow K^0 + \mathbf{n} + d_s$

$d\sigma/d\Omega_{\theta=0deg}$ ~ 11mb/sr

T. Hashimoto et al., PTEP (2015) 061D01.

Forward $n_{mis.}$ + Λ p @ E15[1st]

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 MeV

$\Gamma_X \sim$ 100 MeV

$Q_X \sim$ 400 MeV

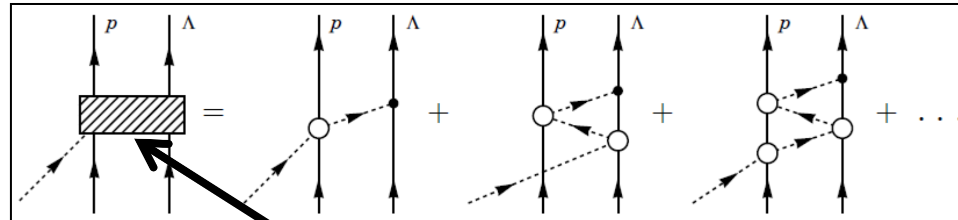
Compact state?

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

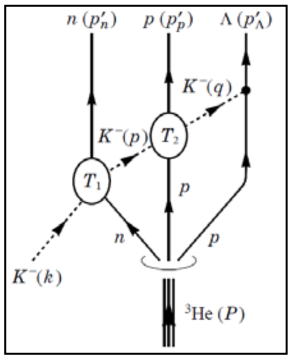
A Theoretical Interpretation of E15

Sekihara, Oset, Ramos, arXiv:1607.02058

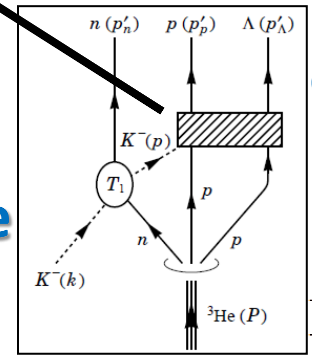
Chiral unitary approach



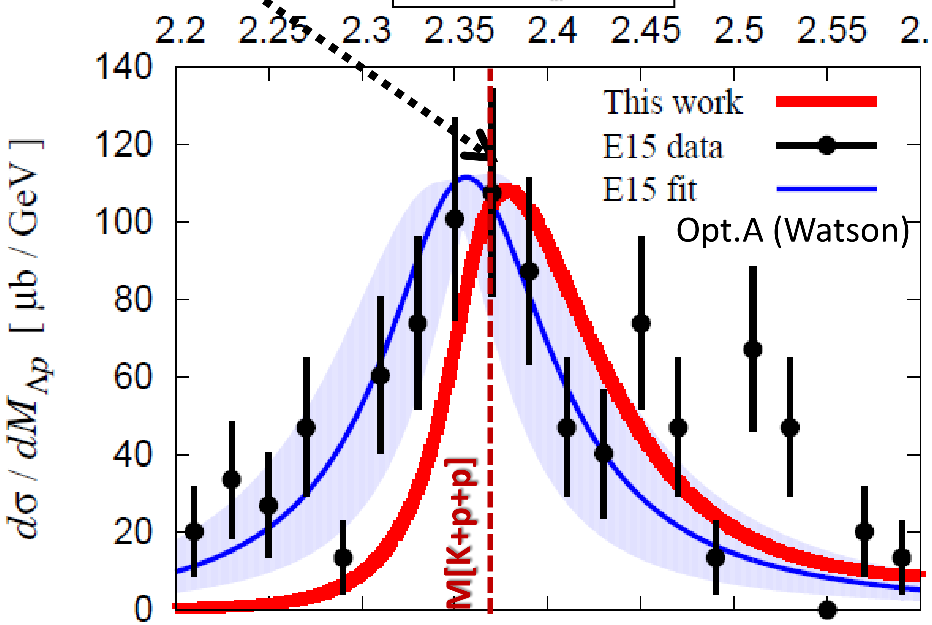
Uncorrelated Λ(1405)p state

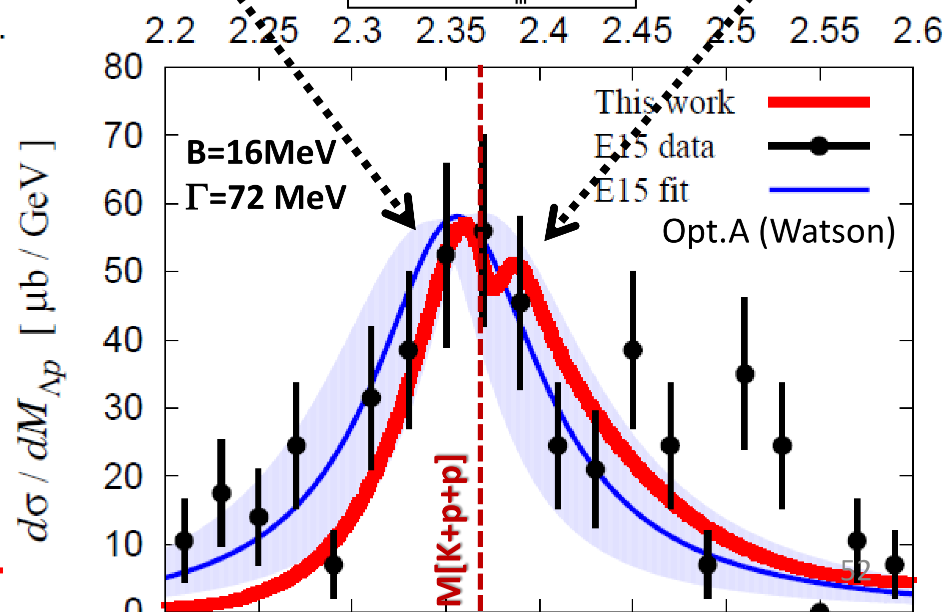


K^{bar}NN bound-state

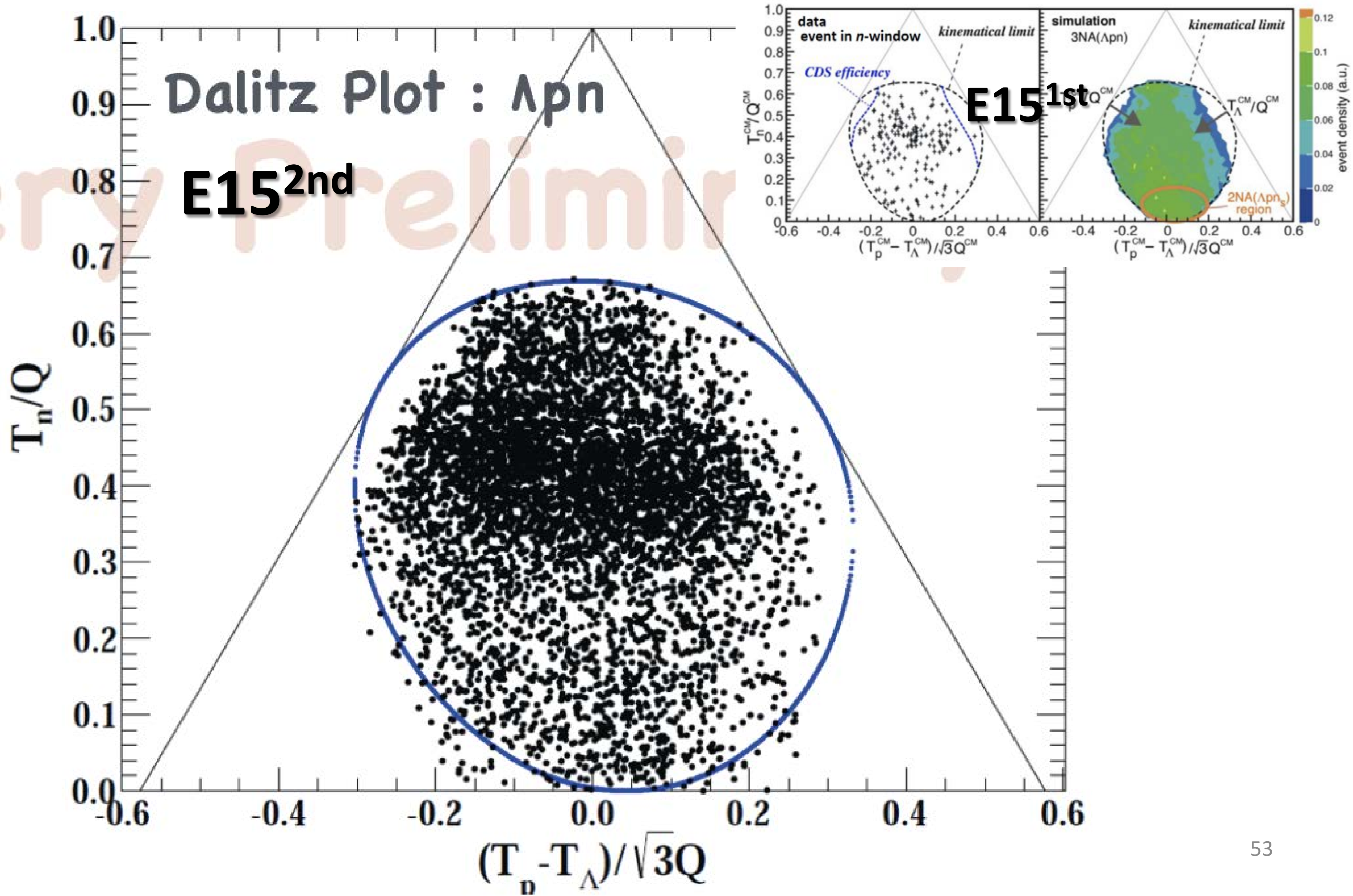


quasi-elastic kaon scattering



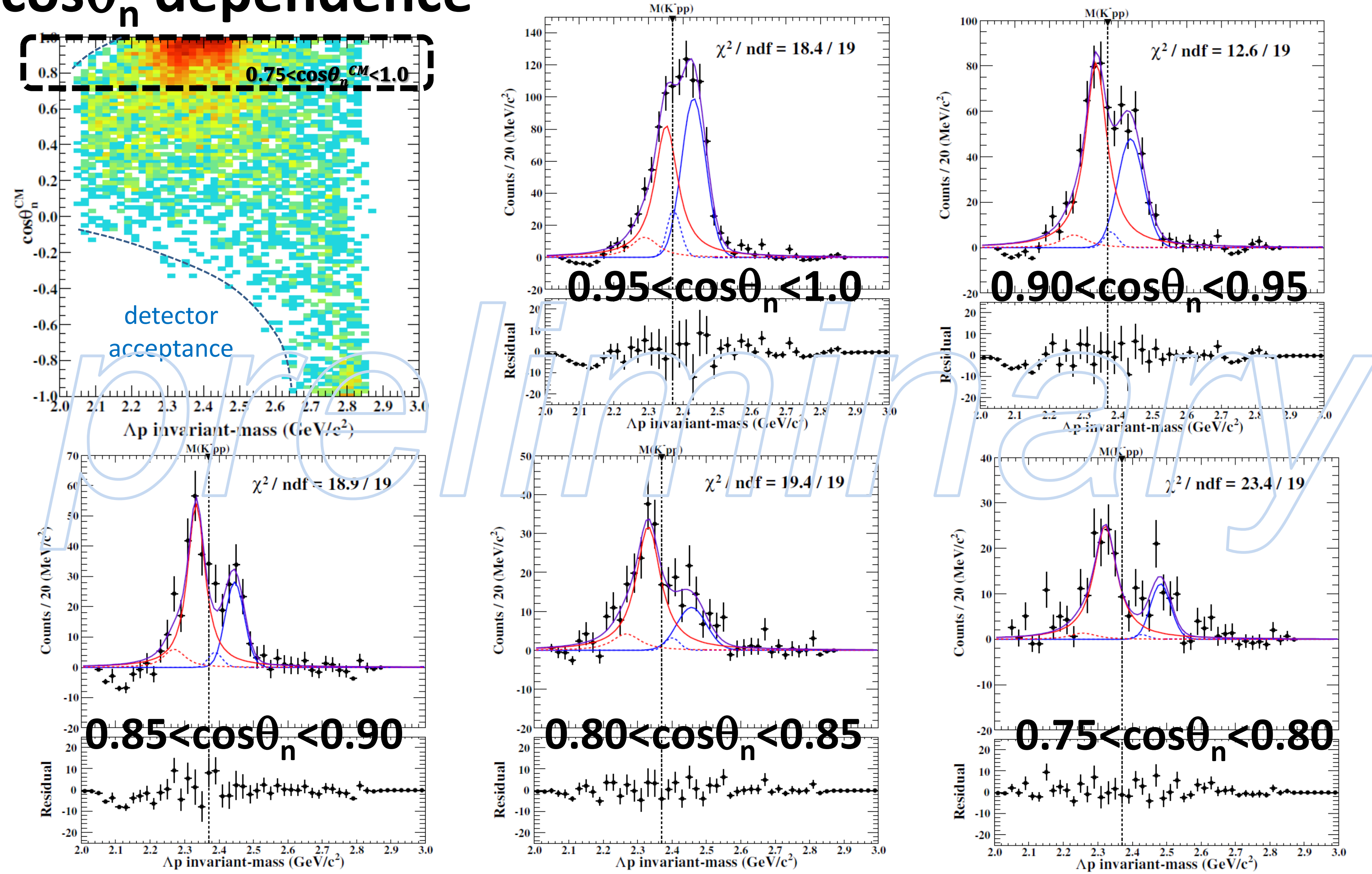


Exclusive $^3He(K^-,\Lambda p)n$



Results of $^{3}He(K^{-},\Lambda p)n$ [E15-2nd]

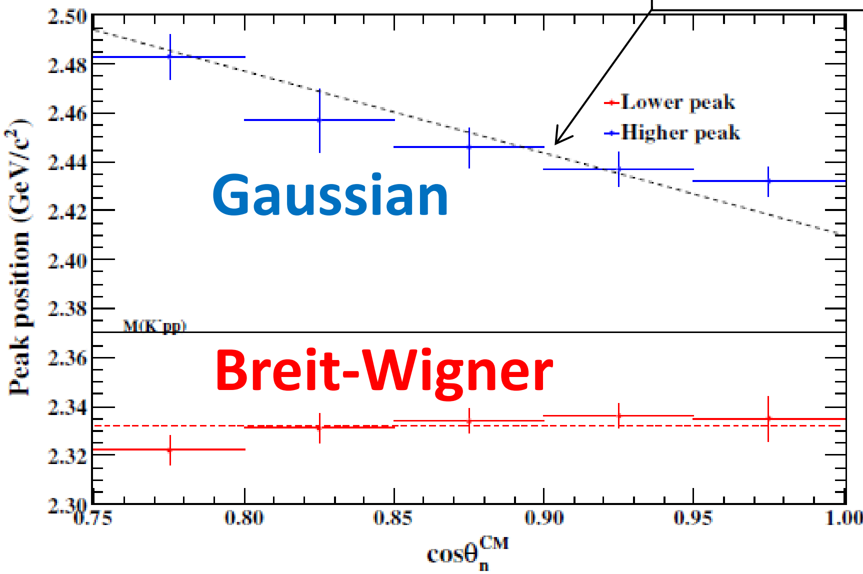
$\cos\theta_n$ dependence



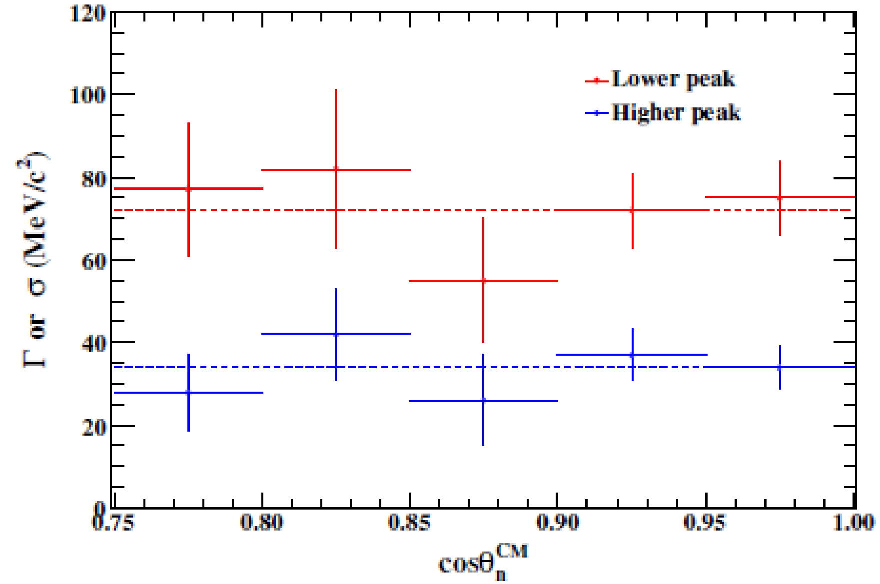
Results of $^3He(K^-,\Lambda p)n$ [E15-2nd]

Peak position

$$M_{QF} = M_{K^-pp} + \frac{q^2}{2M_{K^-}}$$



Width



- **Above M(K-pp):**
  - peak shift by recoil kaon energy
- **Below M(K-pp):**
  - peak is independent to $\cos\theta_n$ (~ momentum transfer)
- **Similar tendency as a theoretical calc., but QF seems to be originated from recoil kaon**