K^-pp Bound System at J-PARC

F. Sakuma, RIKEN

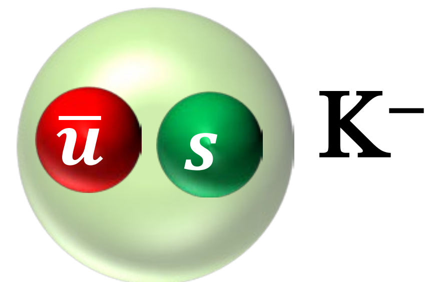
on behalf of the J-PARC E15 collaboration

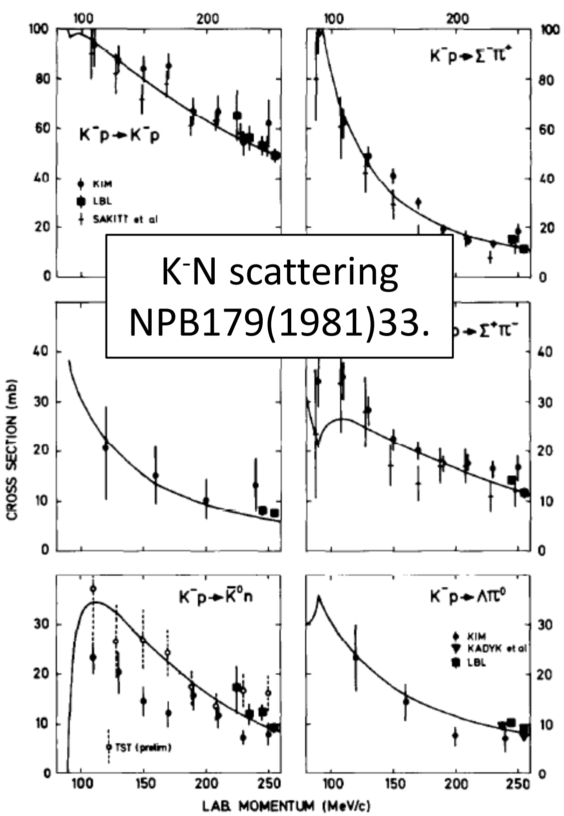
"The 15th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon, MENU-2019"
Carnegie Mellon University, Pittsburgh Pennsylvania
June 2 to June 7, 2019

Meson in a Nucleus?

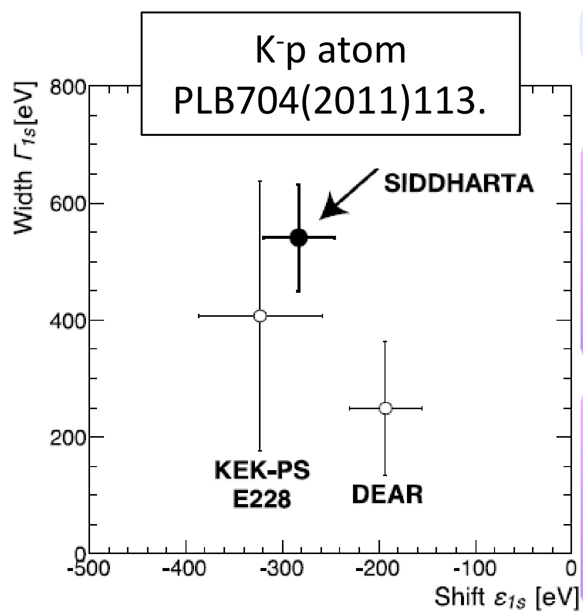
- **Lightest S=-1 meson, K^-**
  - K^{bar}-N interaction:

    strongly attractive in I=0

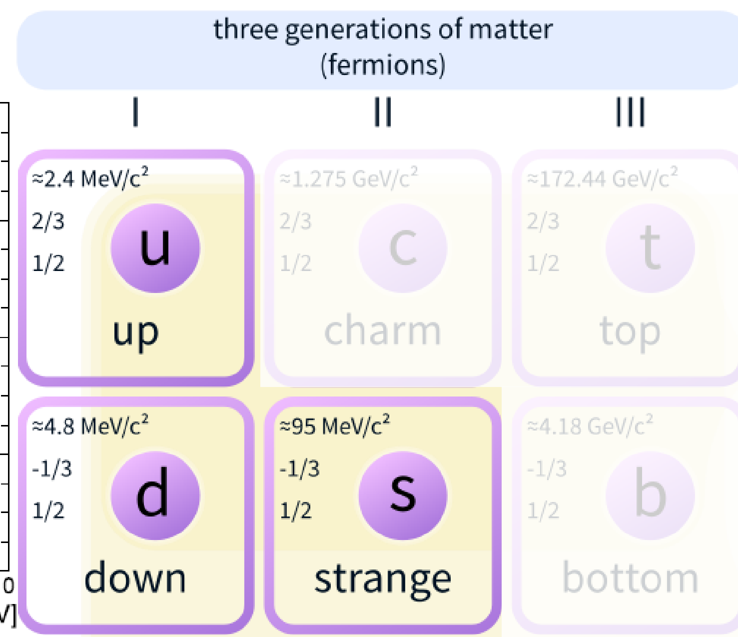




K^-N scattering
NPB179(1981)33.



K^-p atom
PLB704(2011)113.



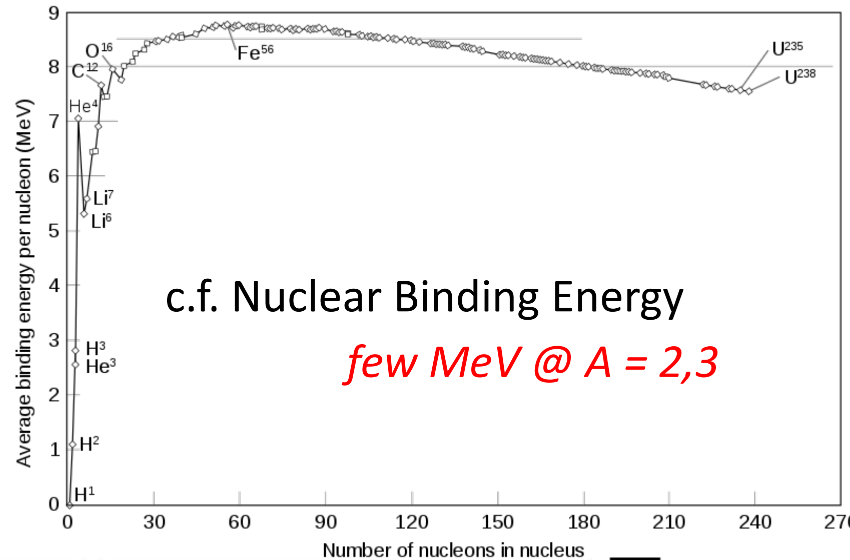
Wikipedia

K^{bar}-Nuclear Bound State

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

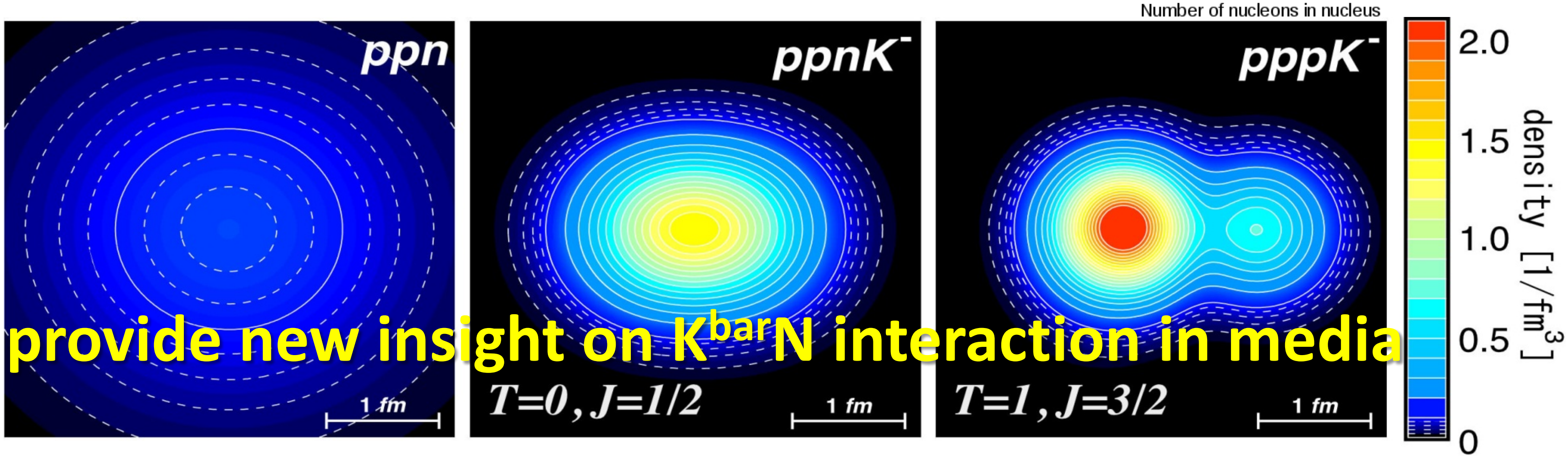
Kaonic Nuclei	Binding Energy [MeV]	Width [MeV]
Λ(1405) = K^-p	27	40
K^-pp	48	61
K^-ppp	97	13
K^-ppn	118	21

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



c.f. Nuclear Binding Energy

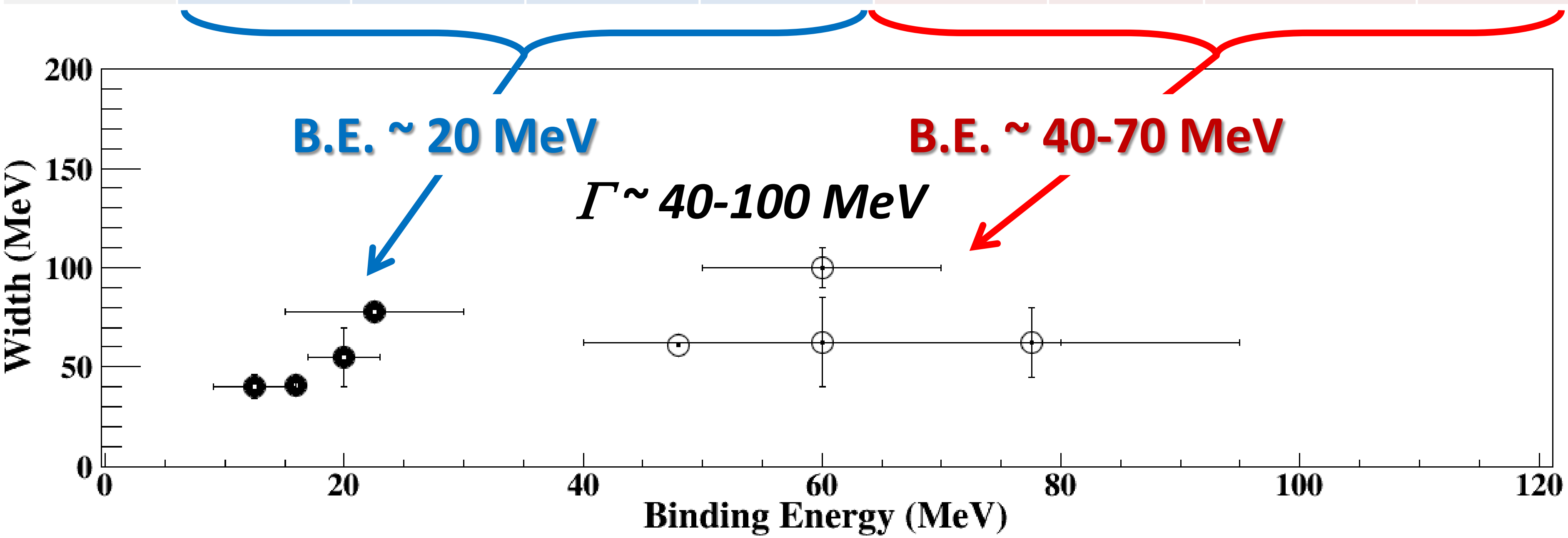
few MeV @ A = 2,3



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

Theoretical Calculations on "K$^-$pp"

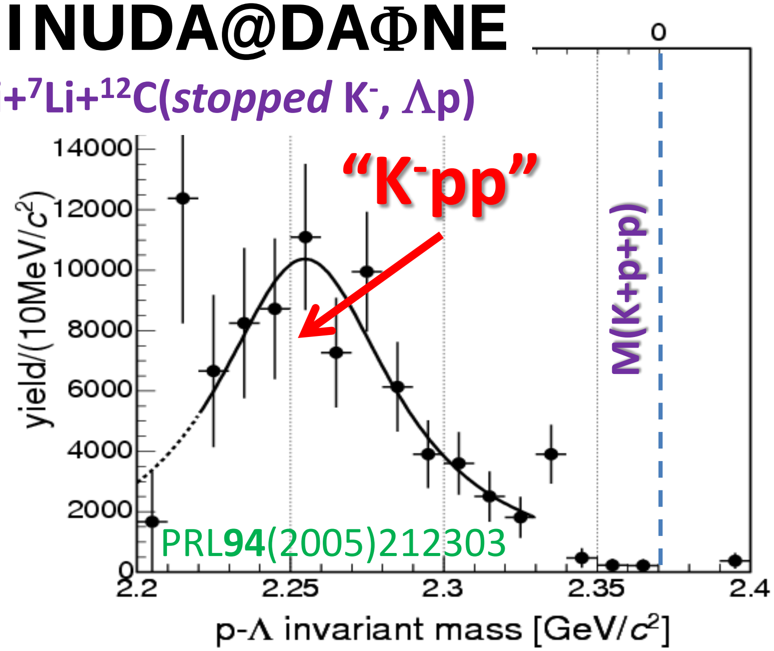
$K^{bar}N$ int.	Chiral SU(3) (energy dependent)				Phenomenological (energy independent)			
Method	Variational		Faddeev		Variational		Faddeev	
	Barnea, Gal, Liverts	Dote, Hyodo, Weise	Ikeda, Kamano, Sato	Bayar, Oset	Yamazaki, Akaishi	Wyceck, Green	Shevchenko, Gal, Mares	Ikeda, Sato
B (MeV)	16	17-23	9-16	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

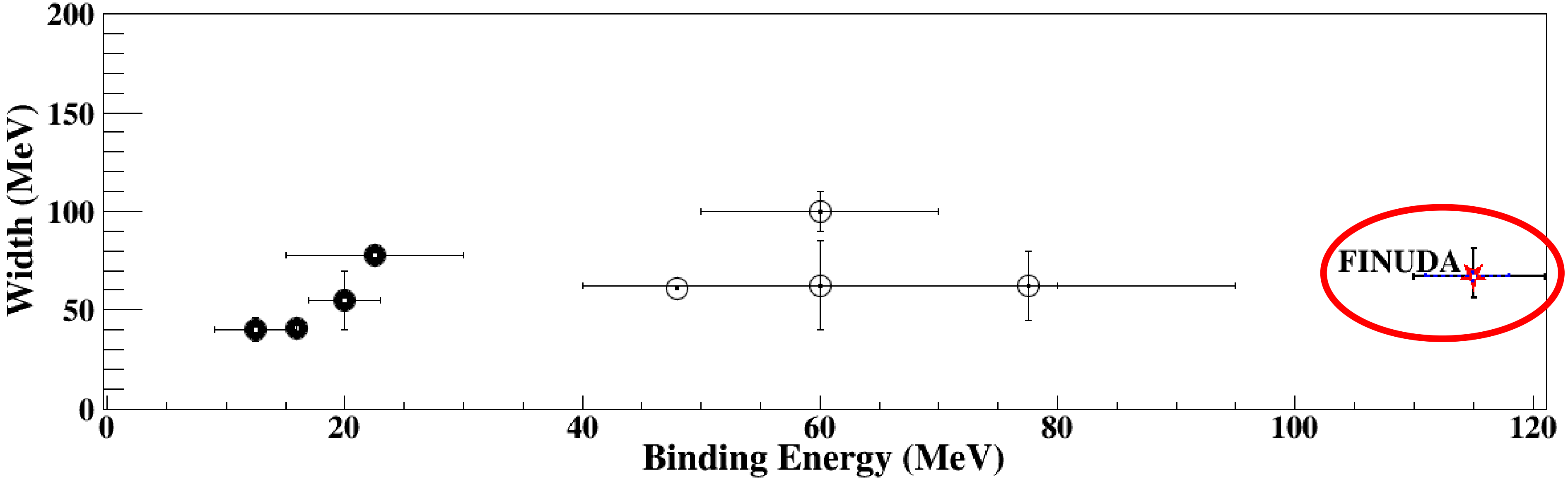


"K⁻pp" Search via Stopped-K⁻

FINUDA@DAΦNE

$^{6}Li+^{7}Li+^{12}C$(*stopped* K^-, Λp)





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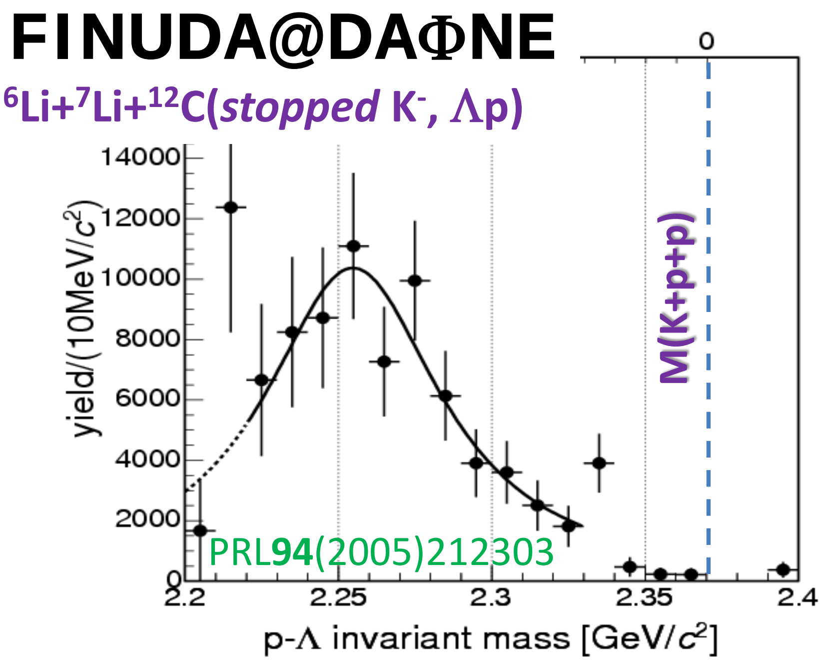
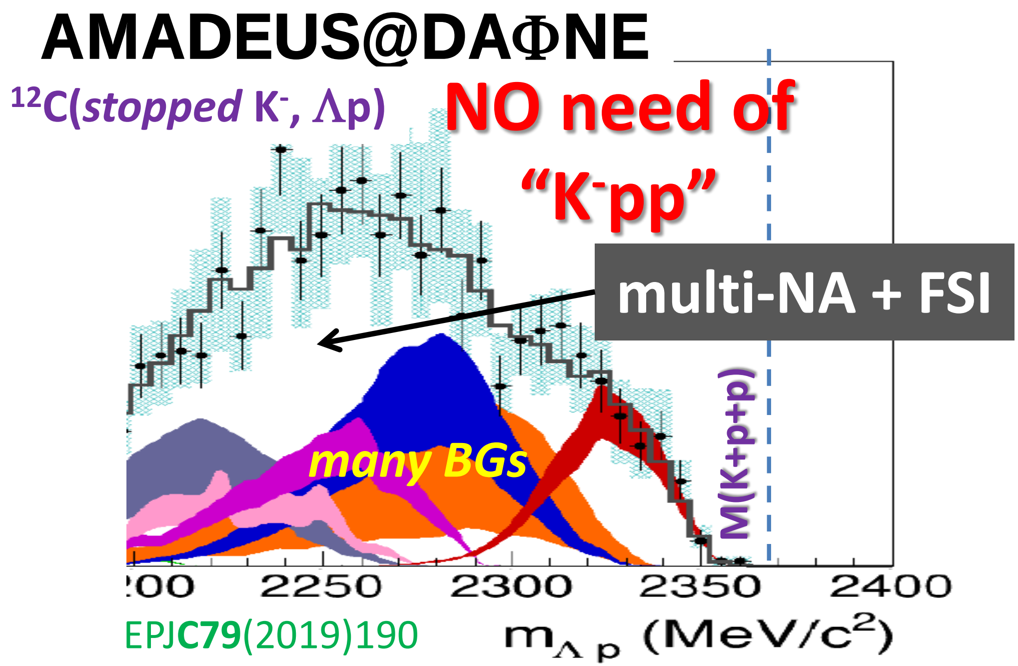
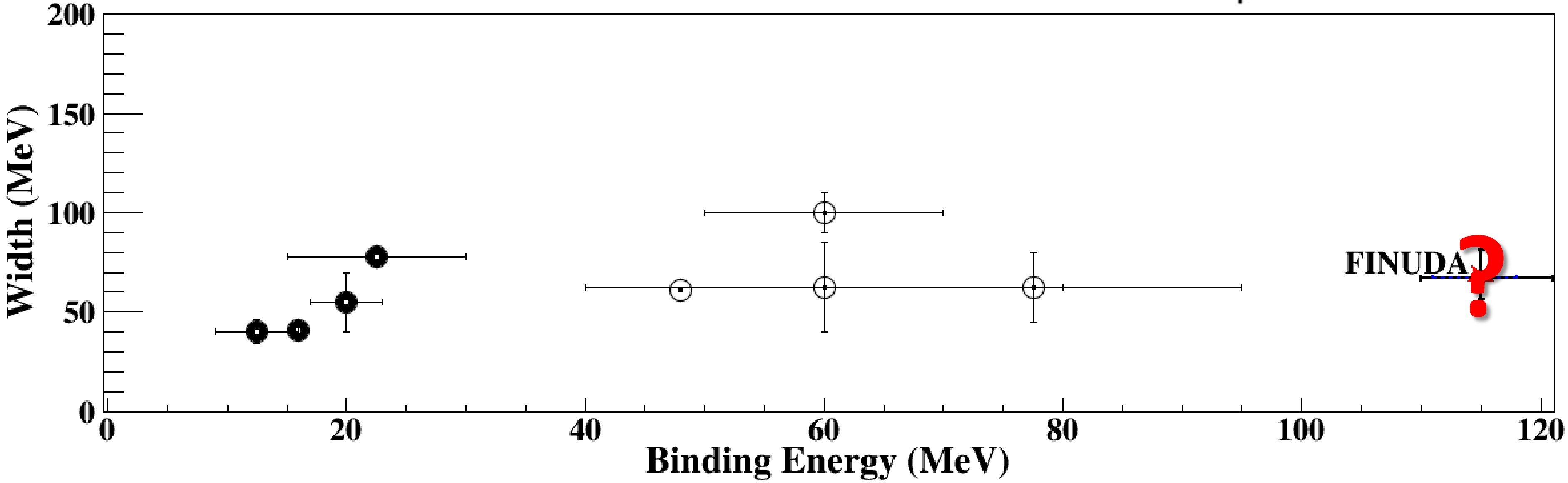
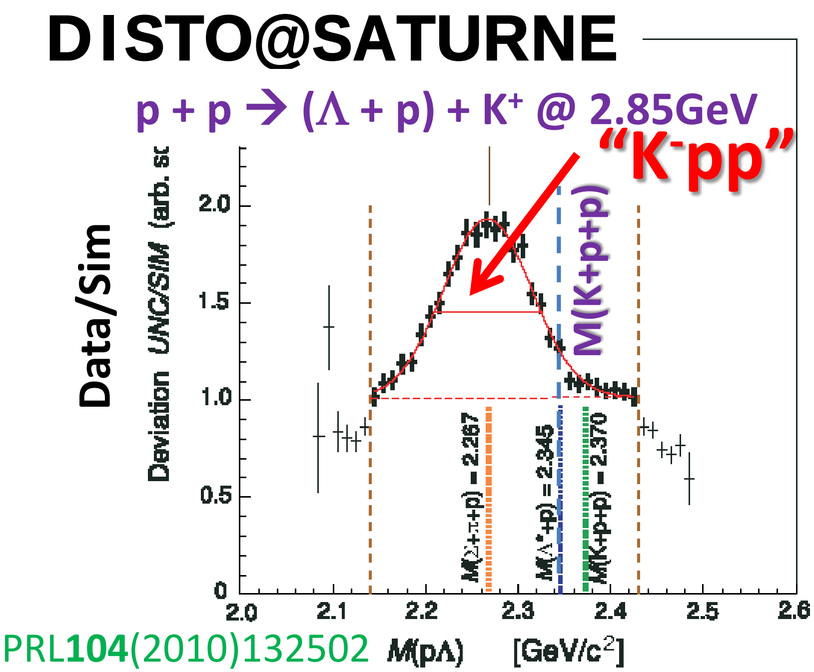
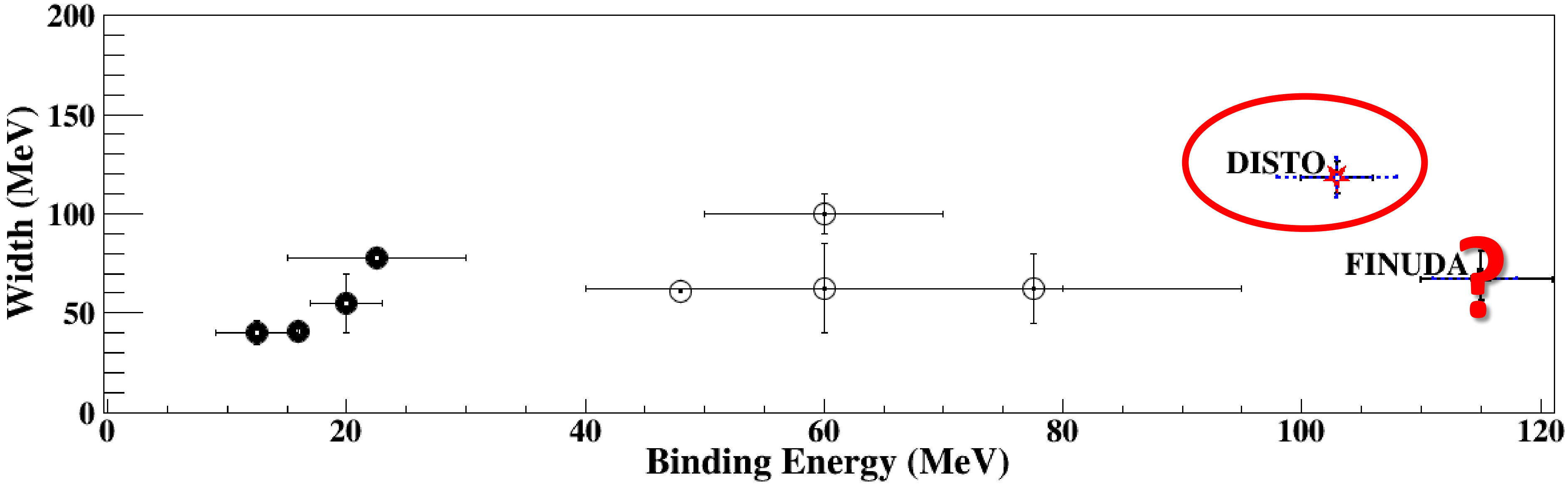






"K$^-$pp" Search via pp Collisions

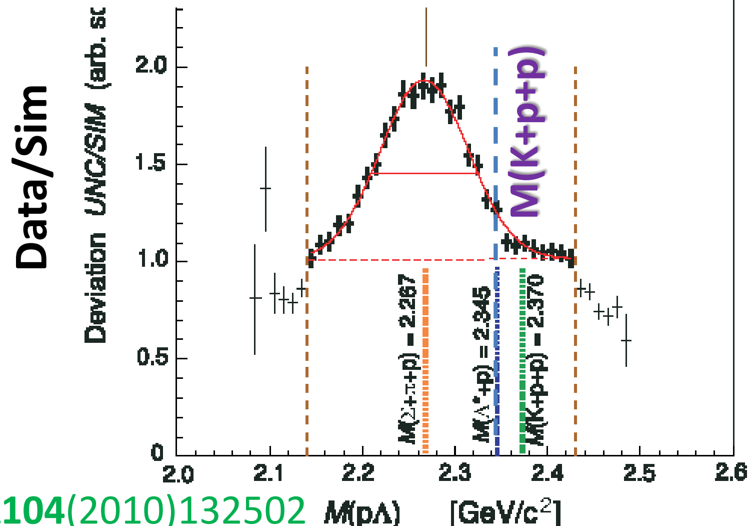




“K⁻pp” Search via pp Collisions

DISTO@SATURNE

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

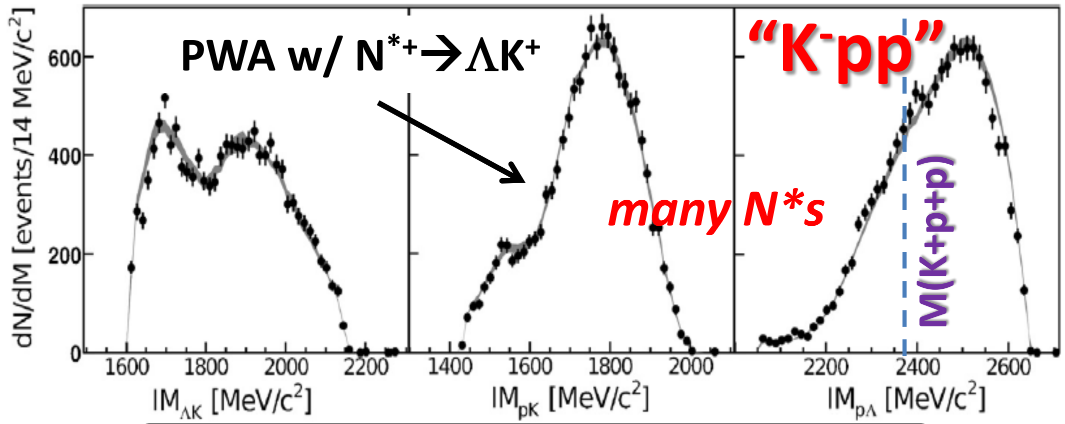


PRL**104**(2010)132502
JPS Conf. Proc. , 082003 (2017)

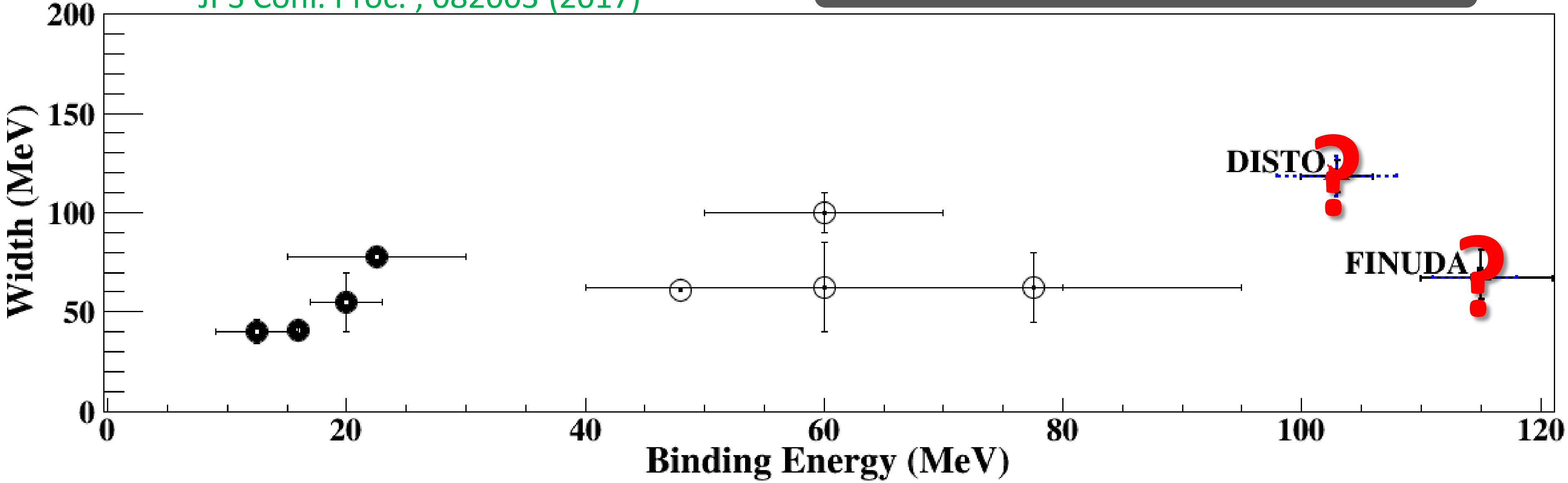
HADES@GSI

PL**B742**(2015)242

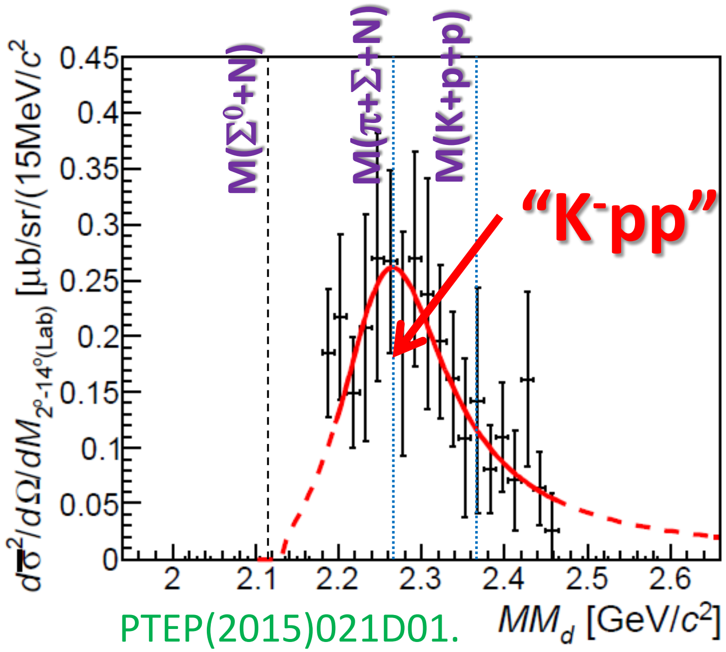
$p + p \rightarrow (\Lambda + p) + K^+$ @ 3.5GeV **NO need of**



$$p + p \rightarrow p + N^{*+} \rightarrow p + \Lambda + K^+$$

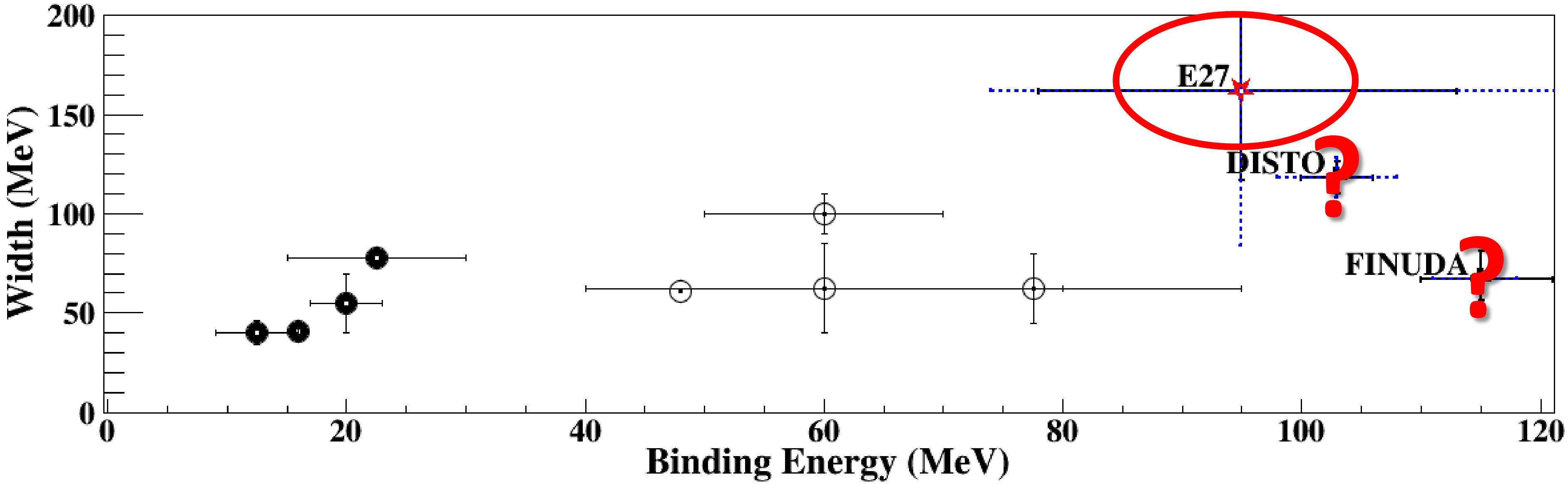


"K⁻pp" Search via $d(\pi^+,K^+)X$



PTEP(2015)021D01.

E27@J-PARC $d(\pi^+, K^+)\Sigma^0 p$ @ 1.69 GeV/c



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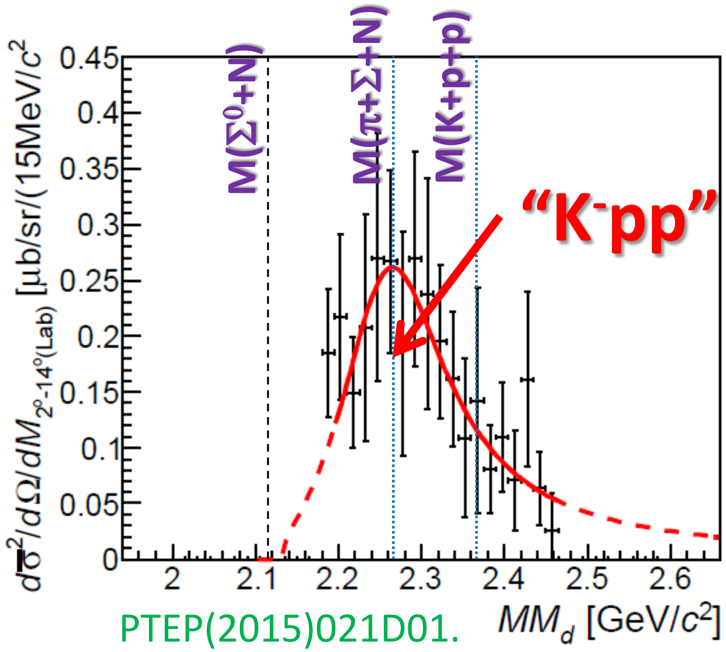
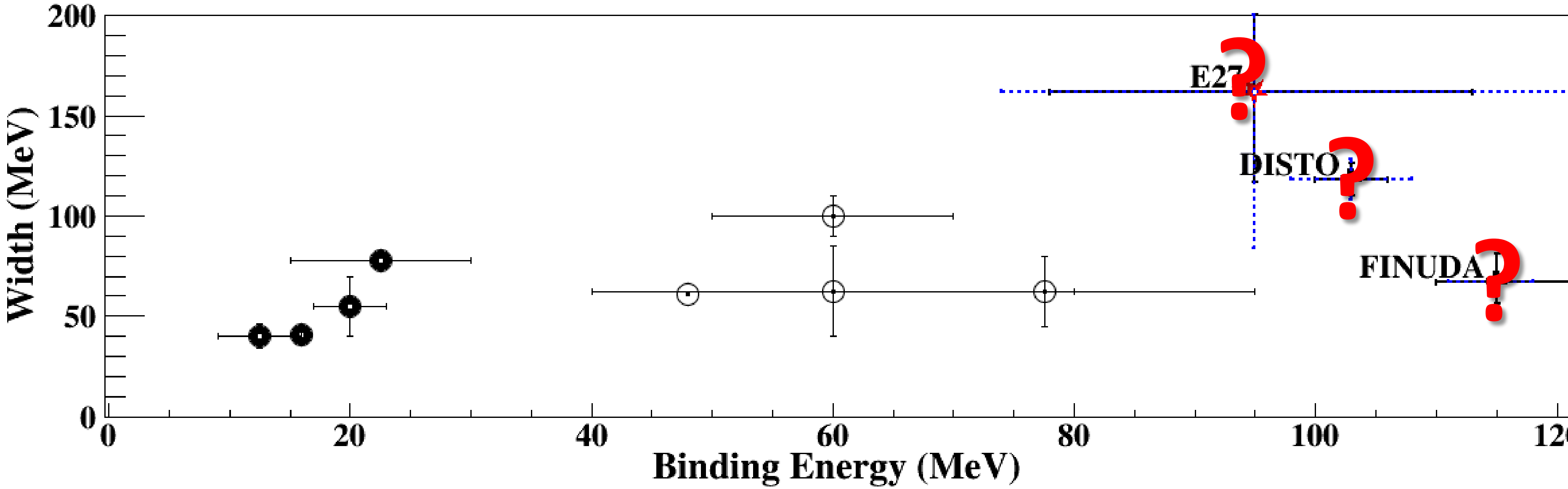


PTEP(2015)021D01.

E27@J-PARC $d(\pi^+, K^+)\Sigma^0 p$ @ 1.69 GeV/c

- **need to be confirmed with more statistics and a wide acceptance detector**

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

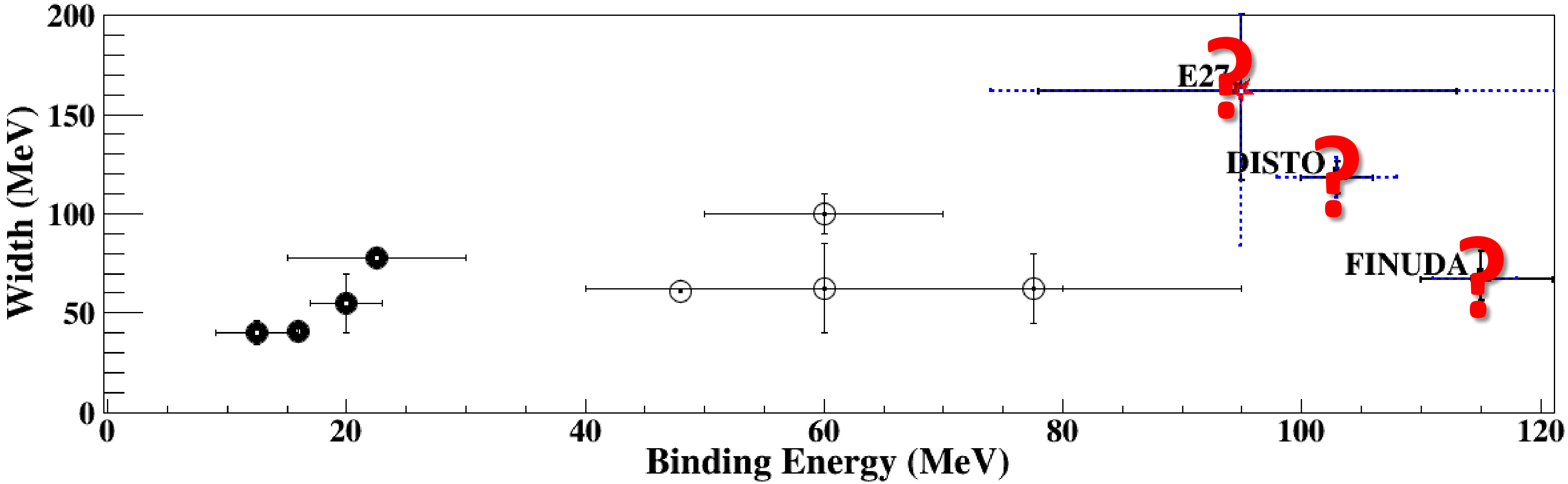


“K^-pp” Search WAS Controversial..

What we have learned from previous experiments:

- Intermediate state is of importance
- Should use more simple reaction
- Exclusive measurement is a key

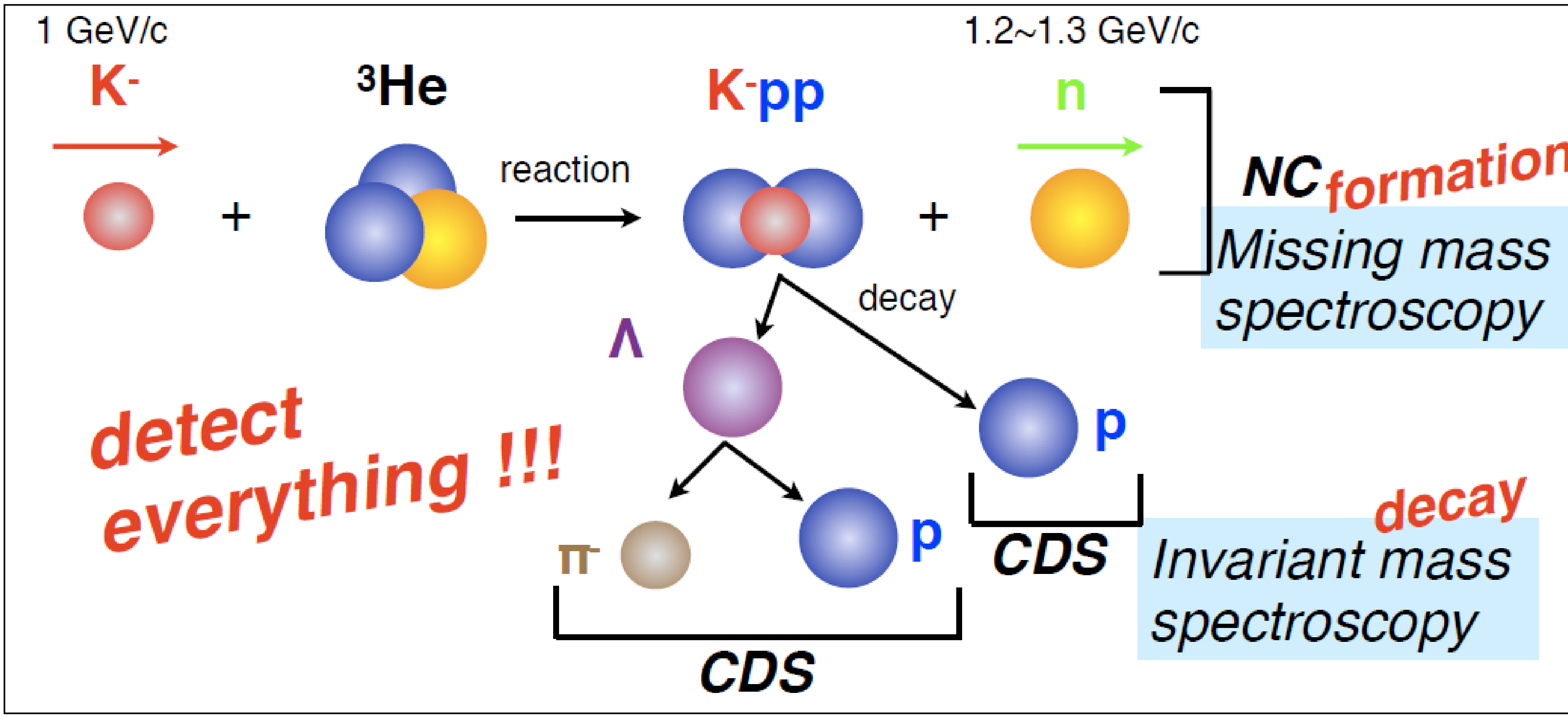
→ J-PARC E15 experiment



J-PARC E15 Experiment

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

2NA and Y decays can be discriminated kinematically



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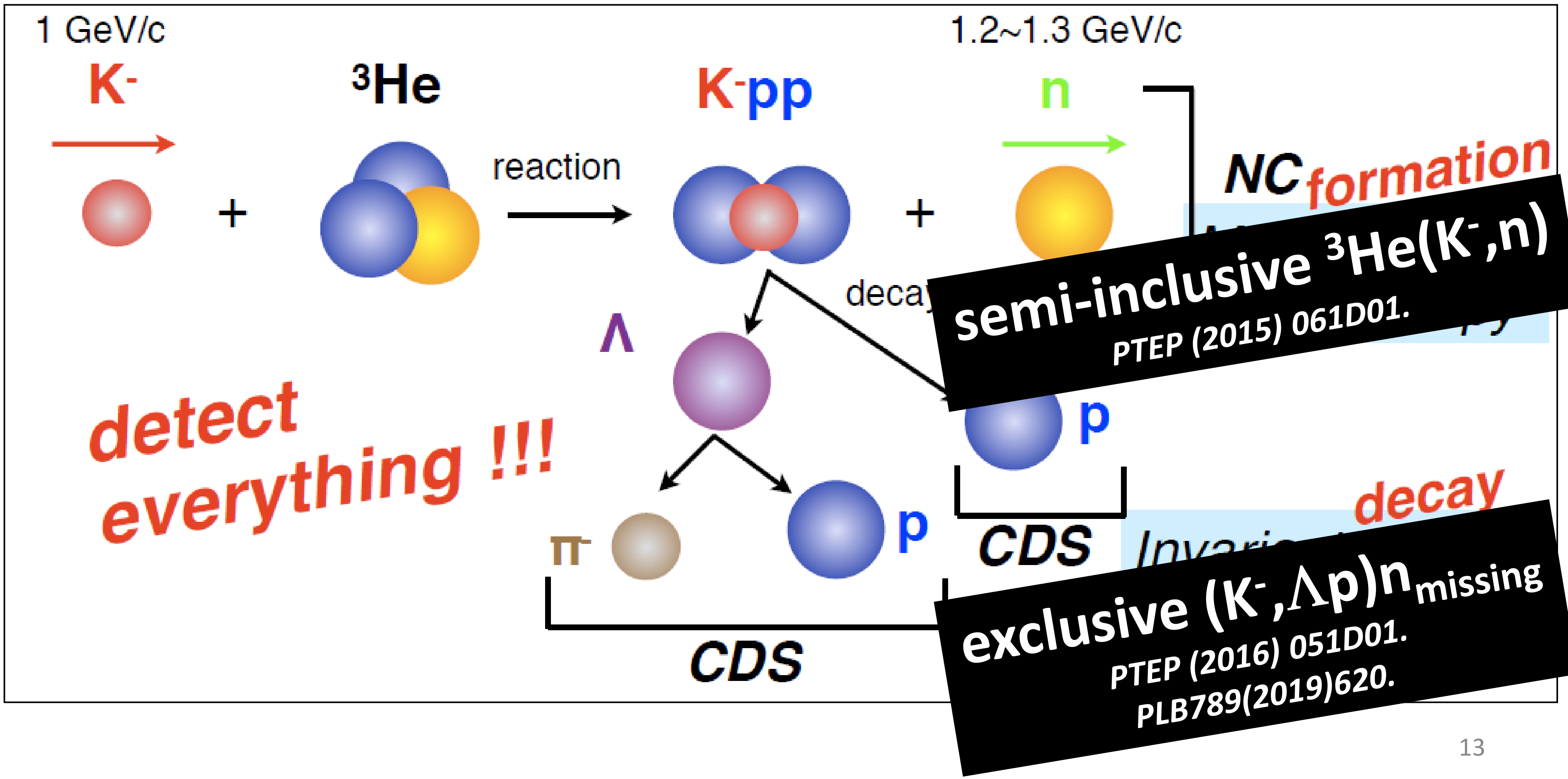
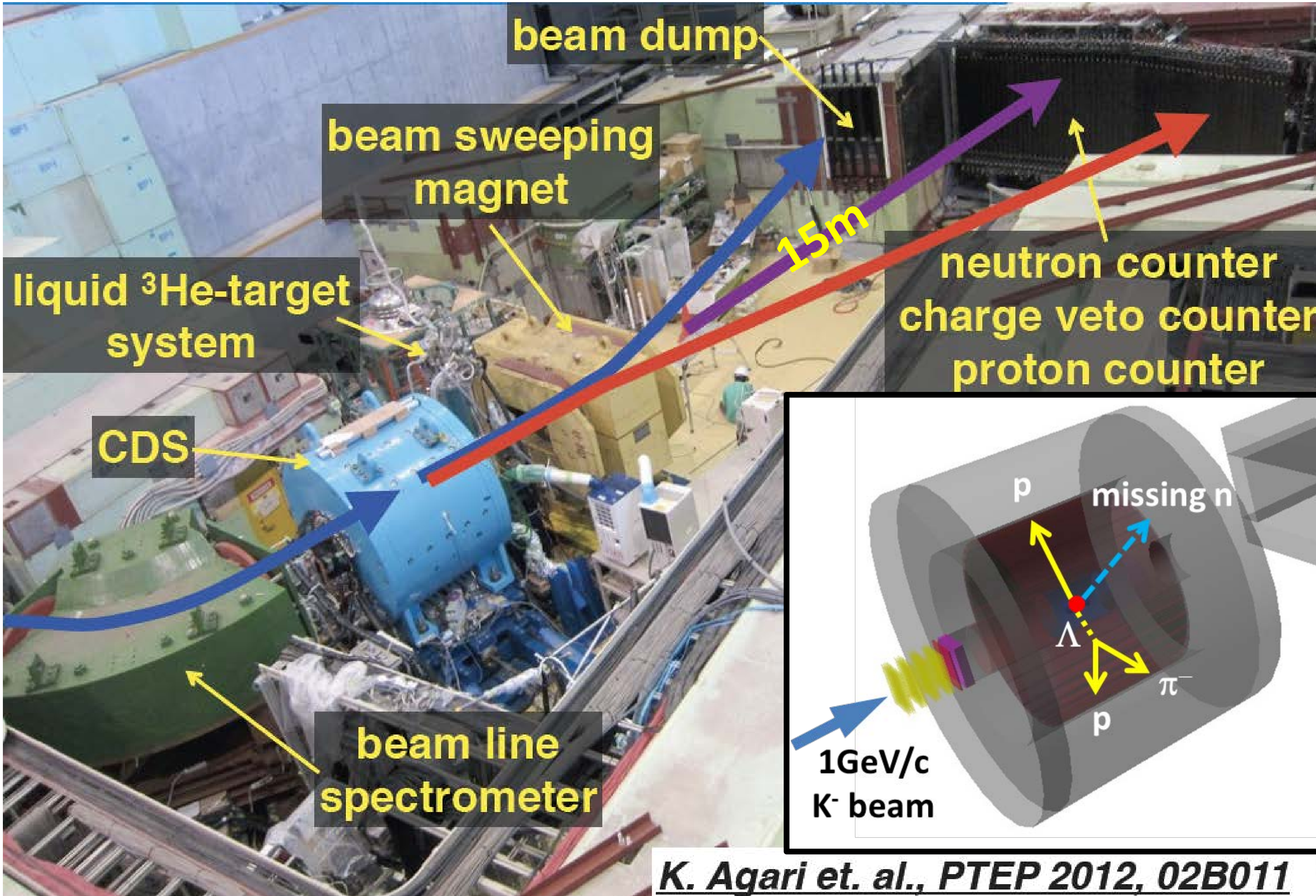
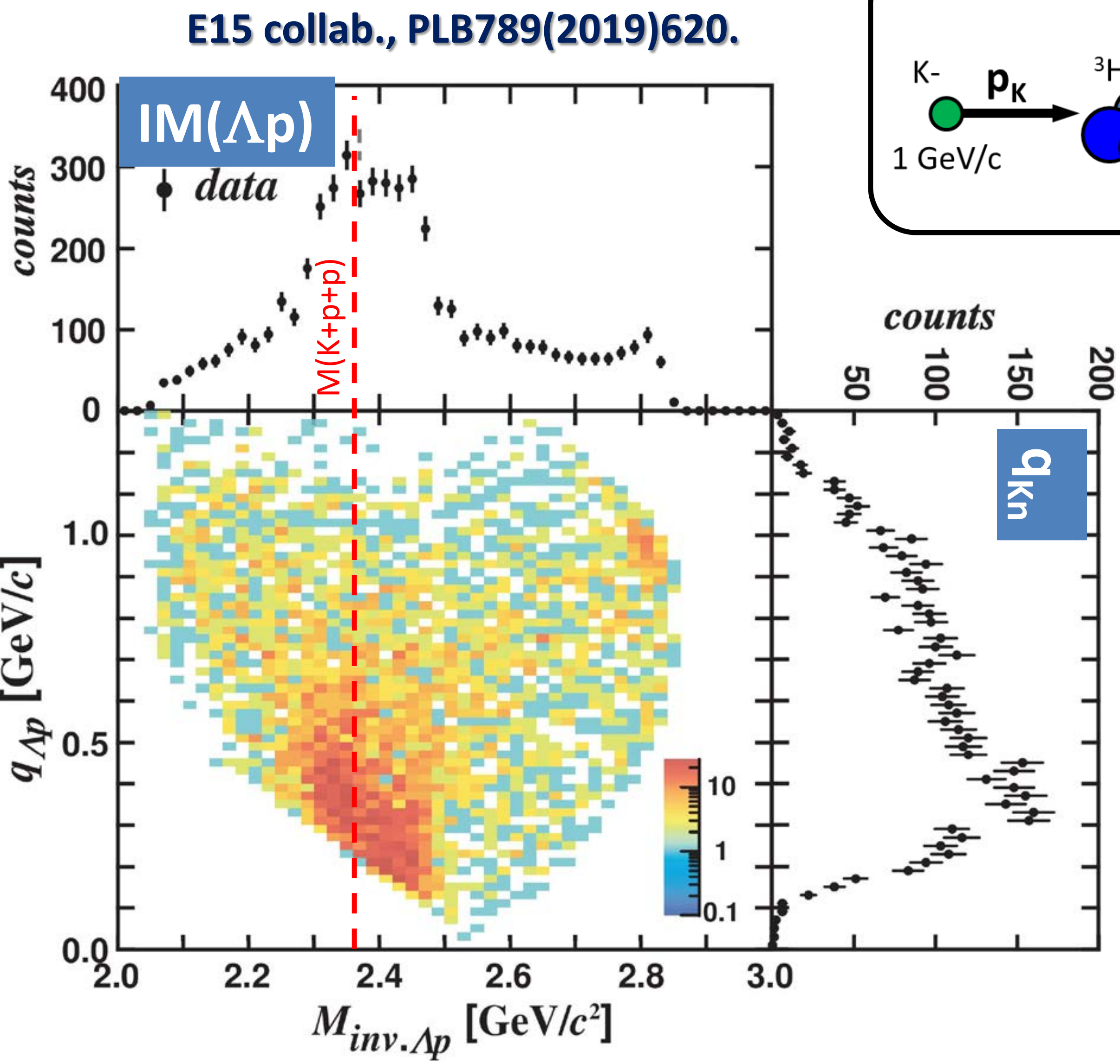


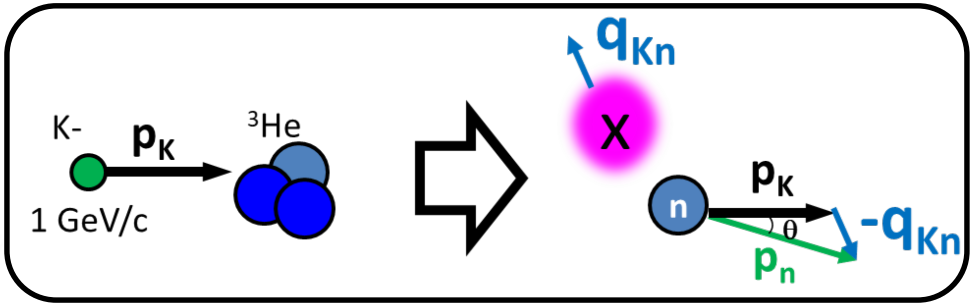
Experimental Setup @ K1.8BR



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

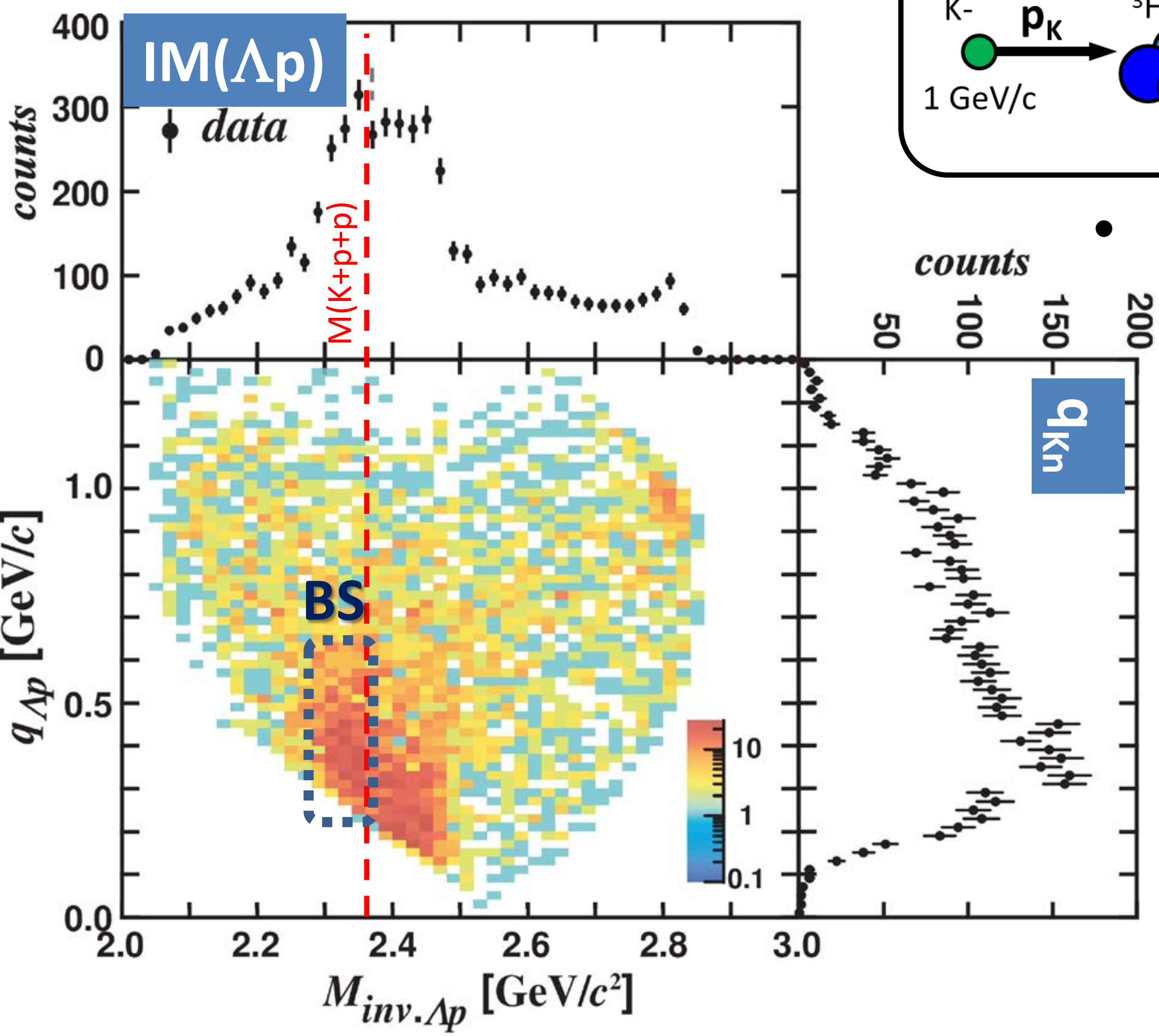
IM(Λp) vs. Momentum Transfer q_{Kn}

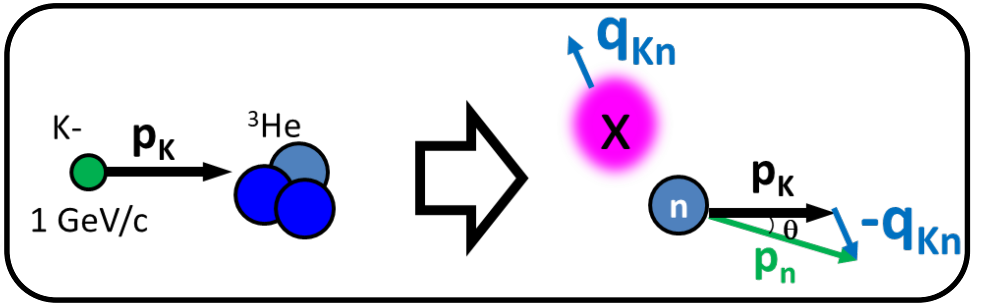




IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., PLB789(2019)620.





- Can be interpreted as 3 components
  - Bound state
    - centroid DOES NOT depend on q_{Kn}

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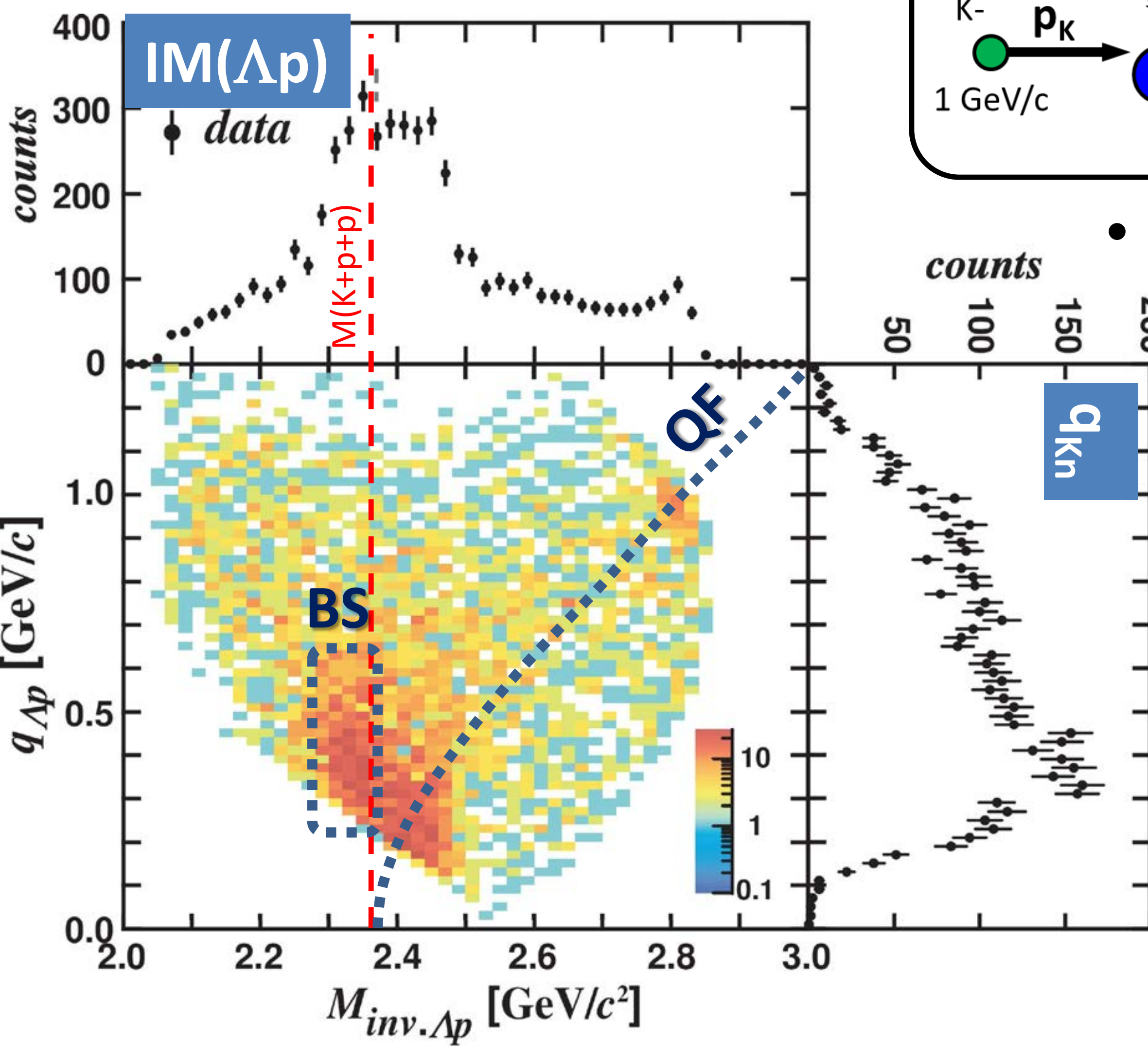

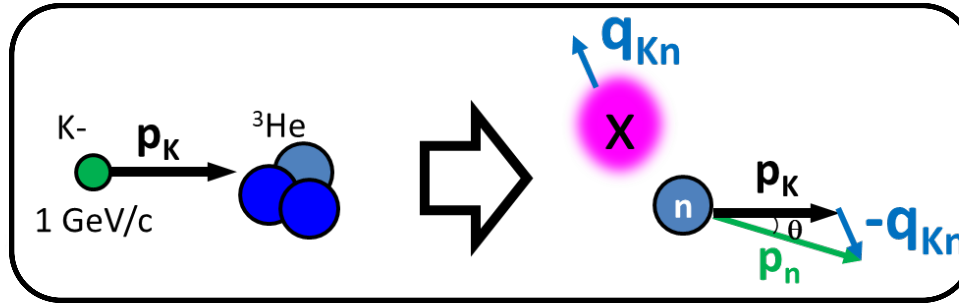

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    - centroid depends on q_{Kn}

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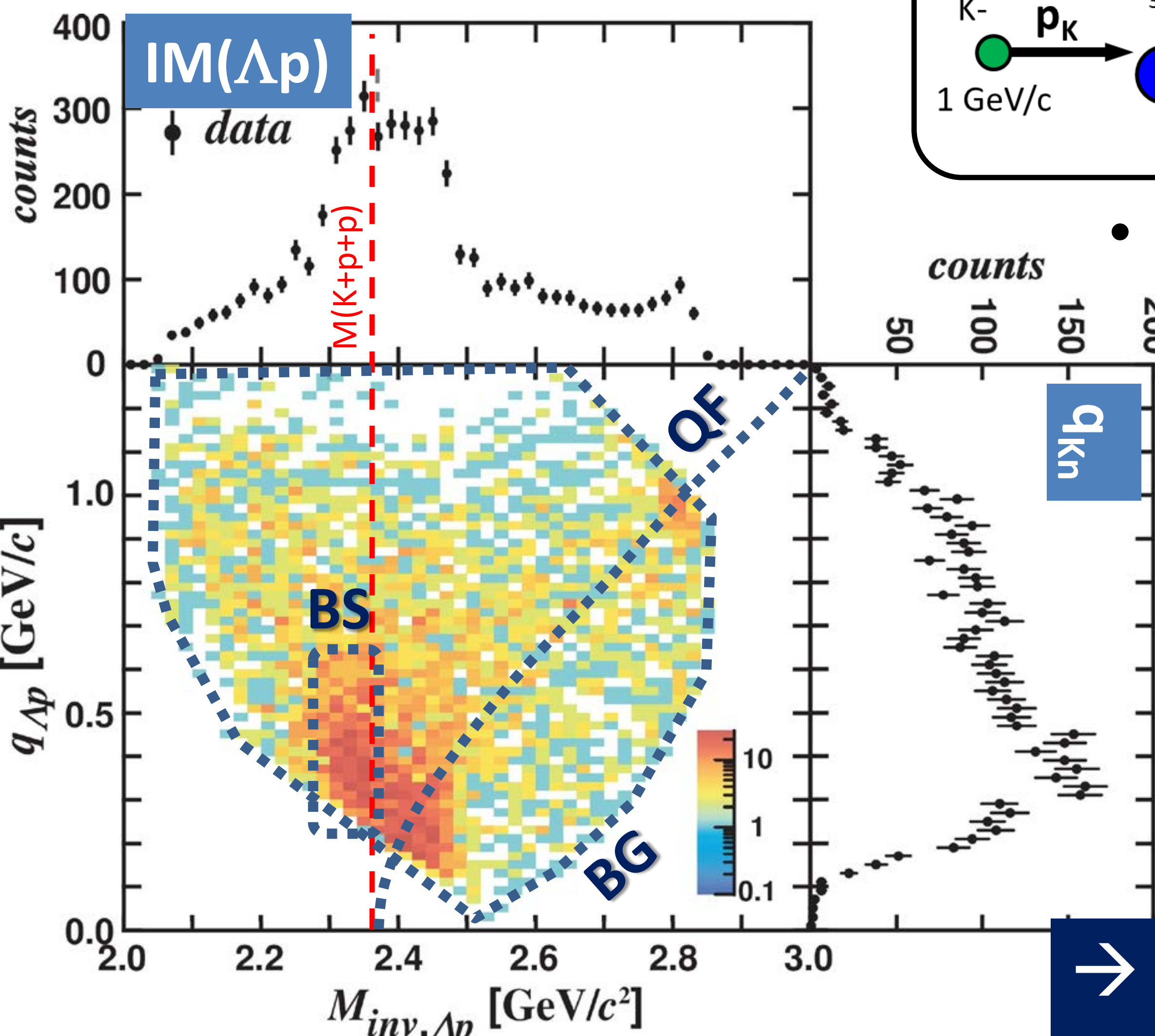
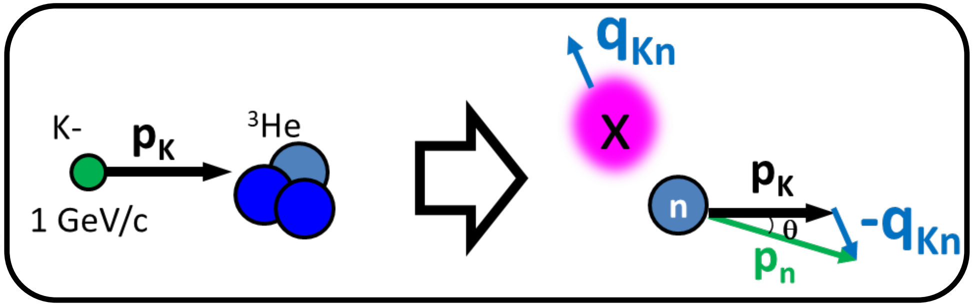


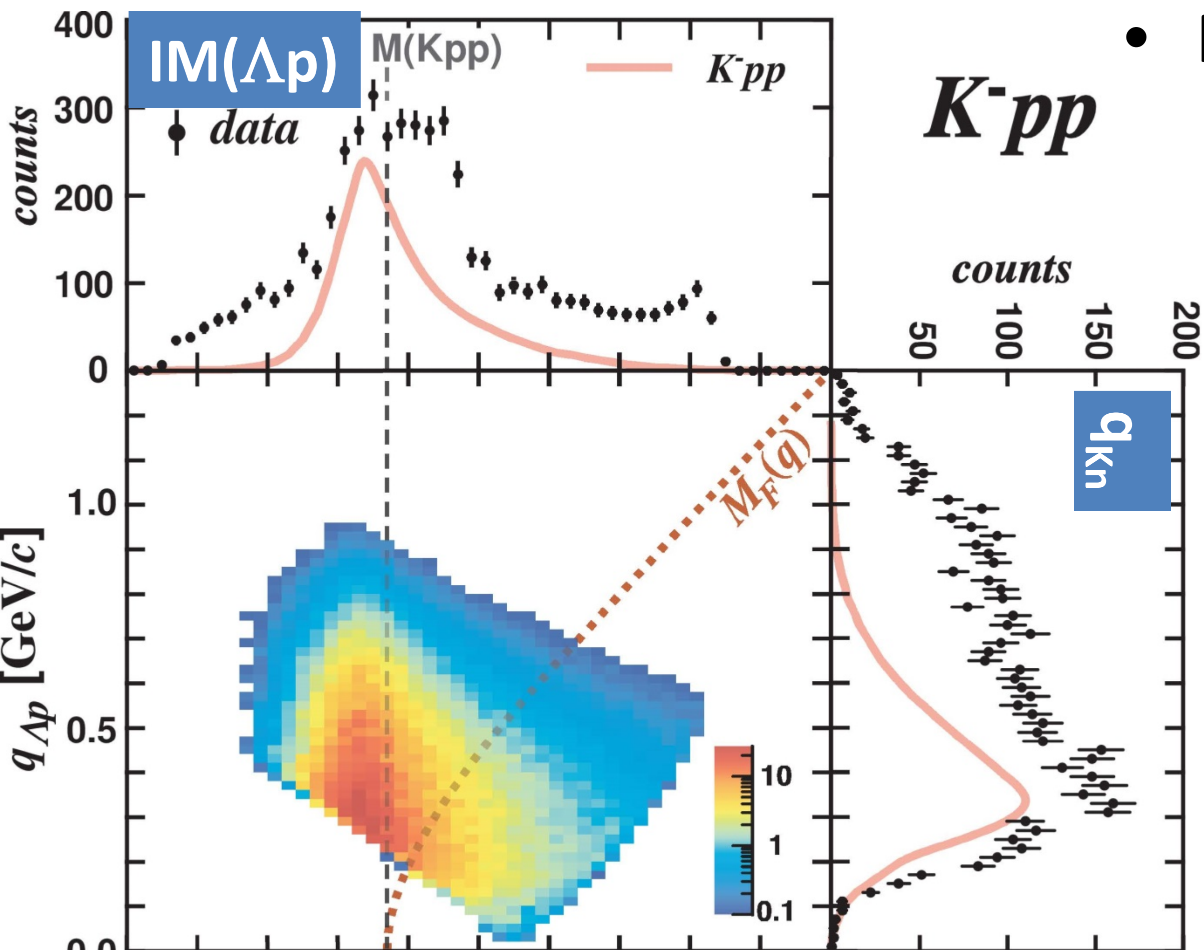


- Can be interpreted as 3 components
  - **<u>Bound state</u>**
    - centroid DOES NOT depend on q_{Kn}
  - **<u>Quasi-elastic K⁻ abs.</u>**
    - centroid depends on q_{Kn}
  - **<u>Background</u>**
    - Broad distribution

→ Fit the spectrum with 3 components

IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., PLB789(2019)620.



- Fit with 3 components
  - **Bound state**
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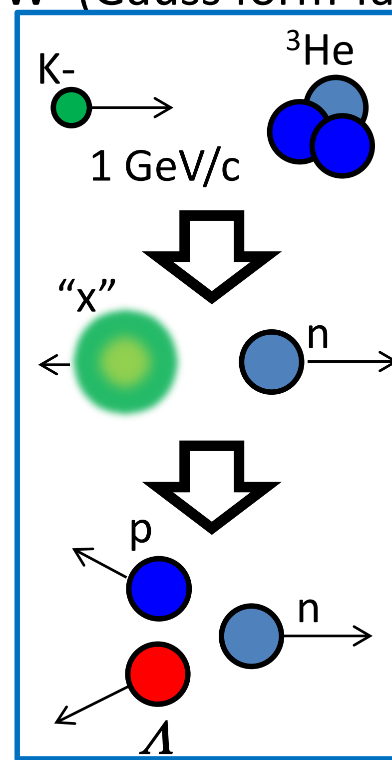
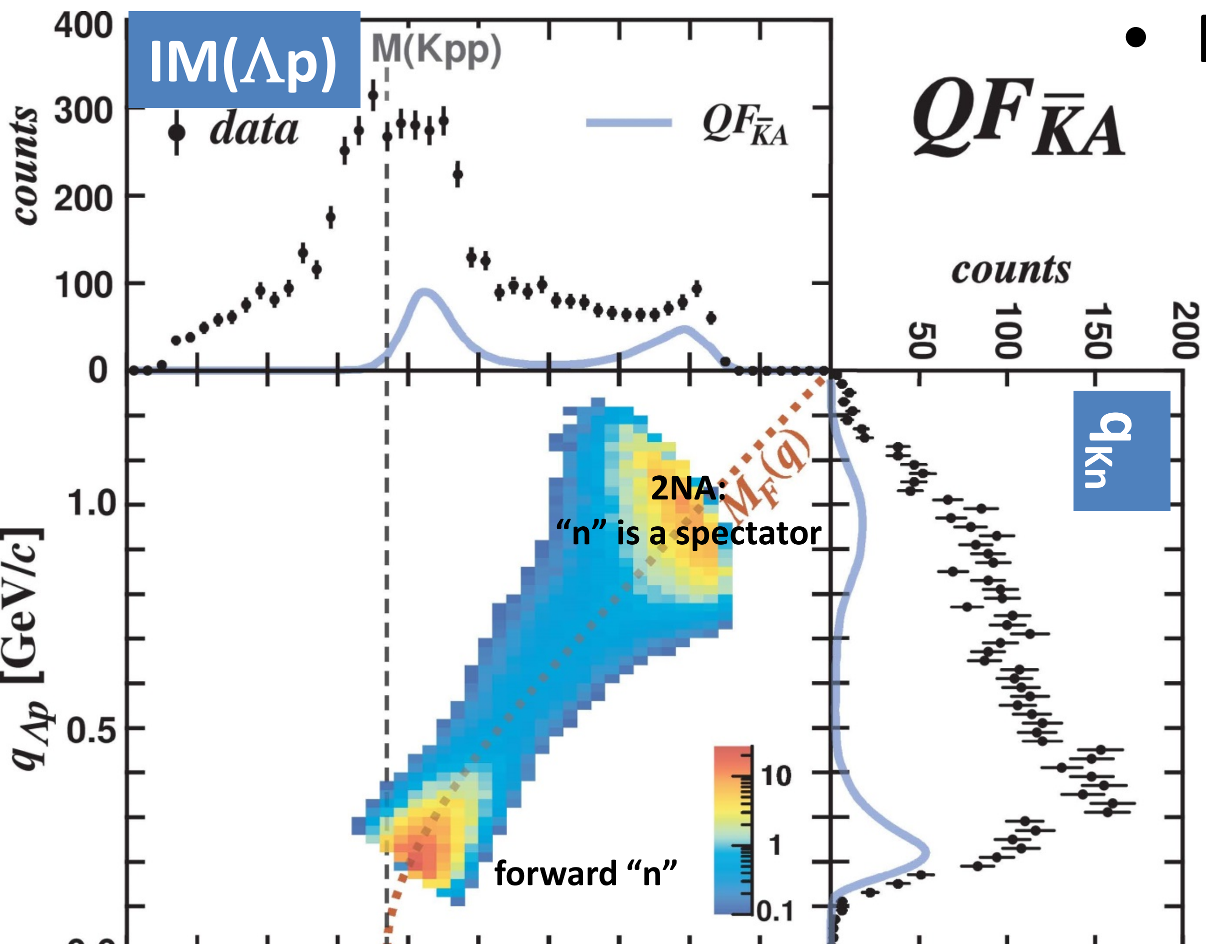
    - BW*(Gauss form-factor)



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

IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., PLB789(2019)620.



- Fit with 3 components
  - **Quasi-elastic K⁻ abs.**
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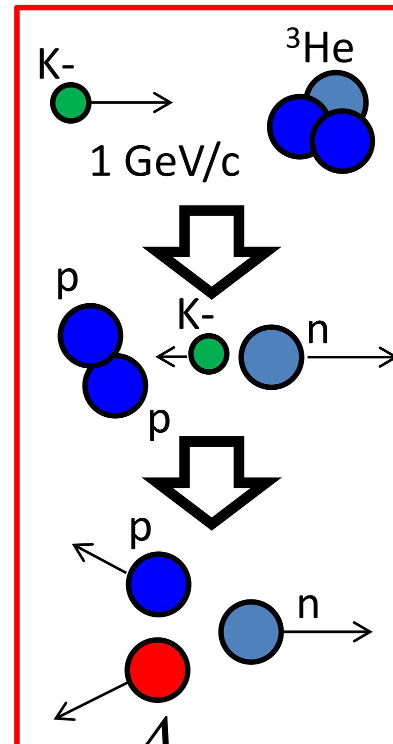
    - Followed by Λp conversion



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

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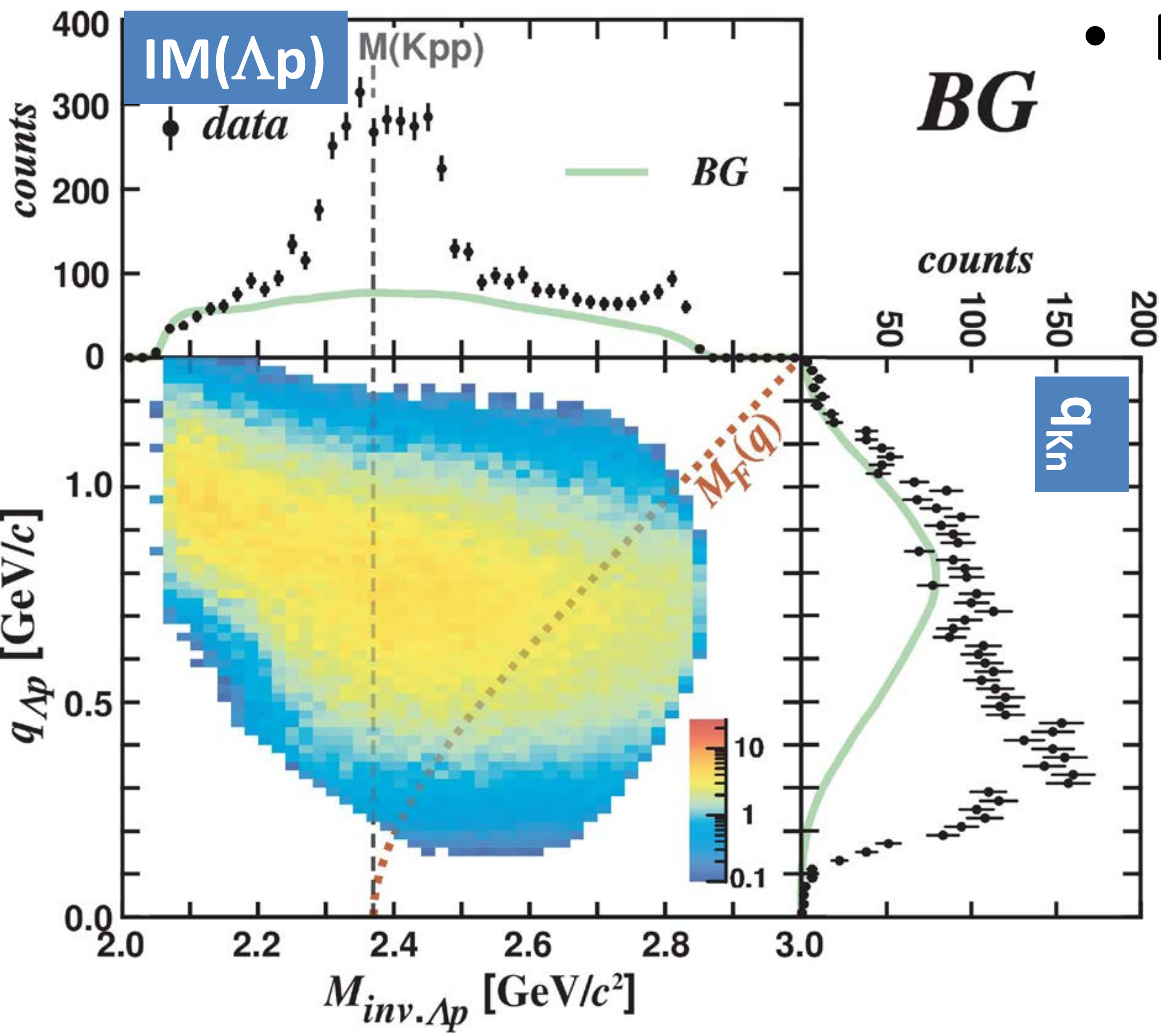

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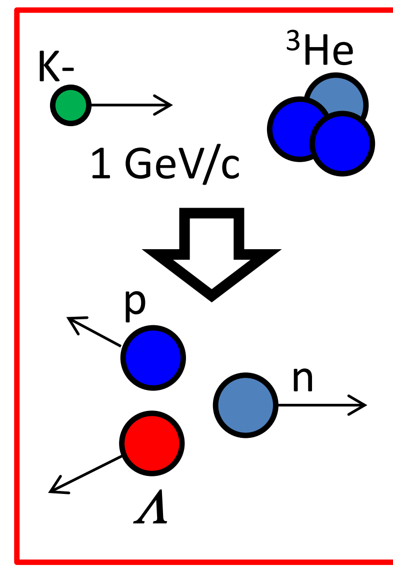

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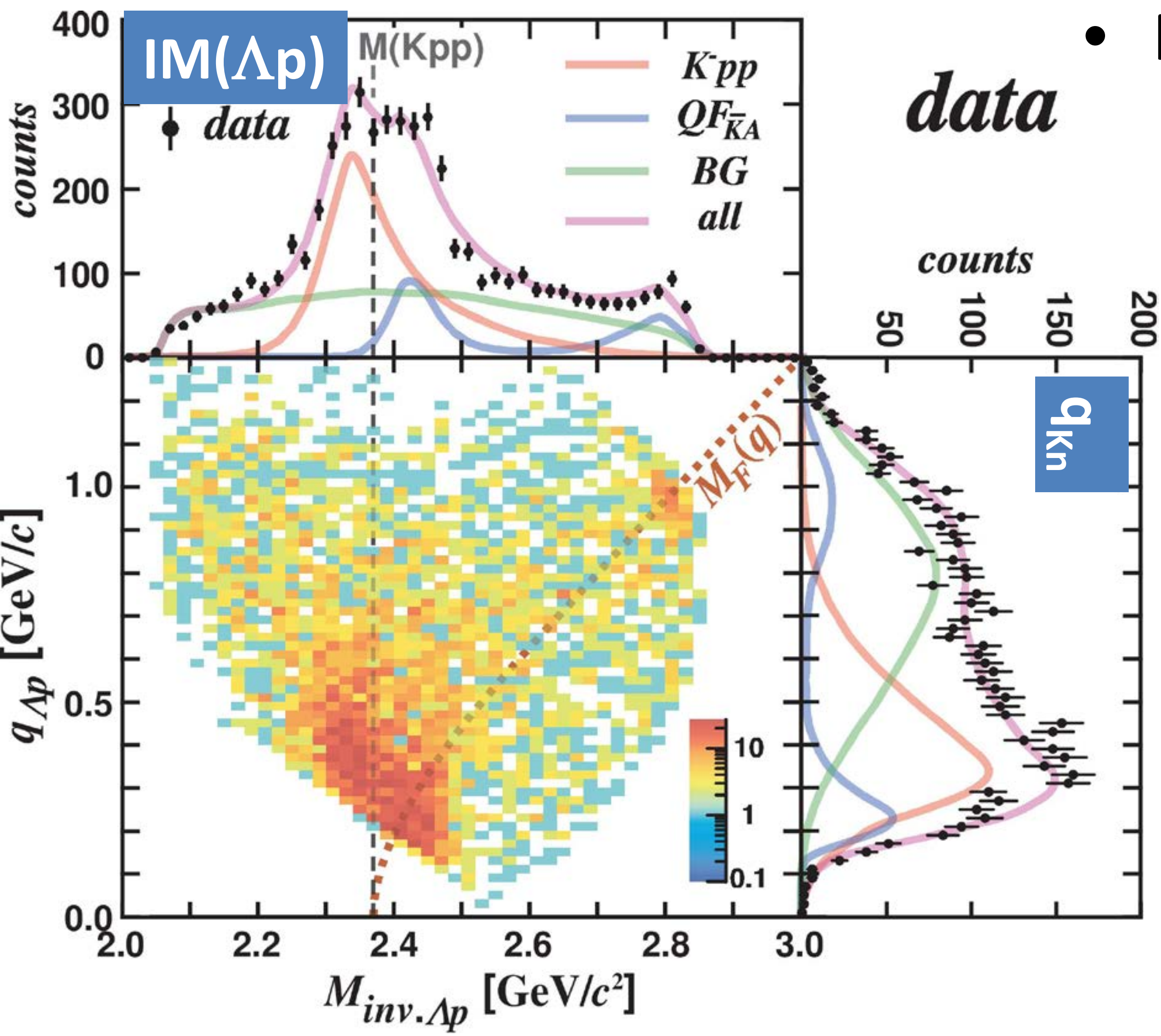

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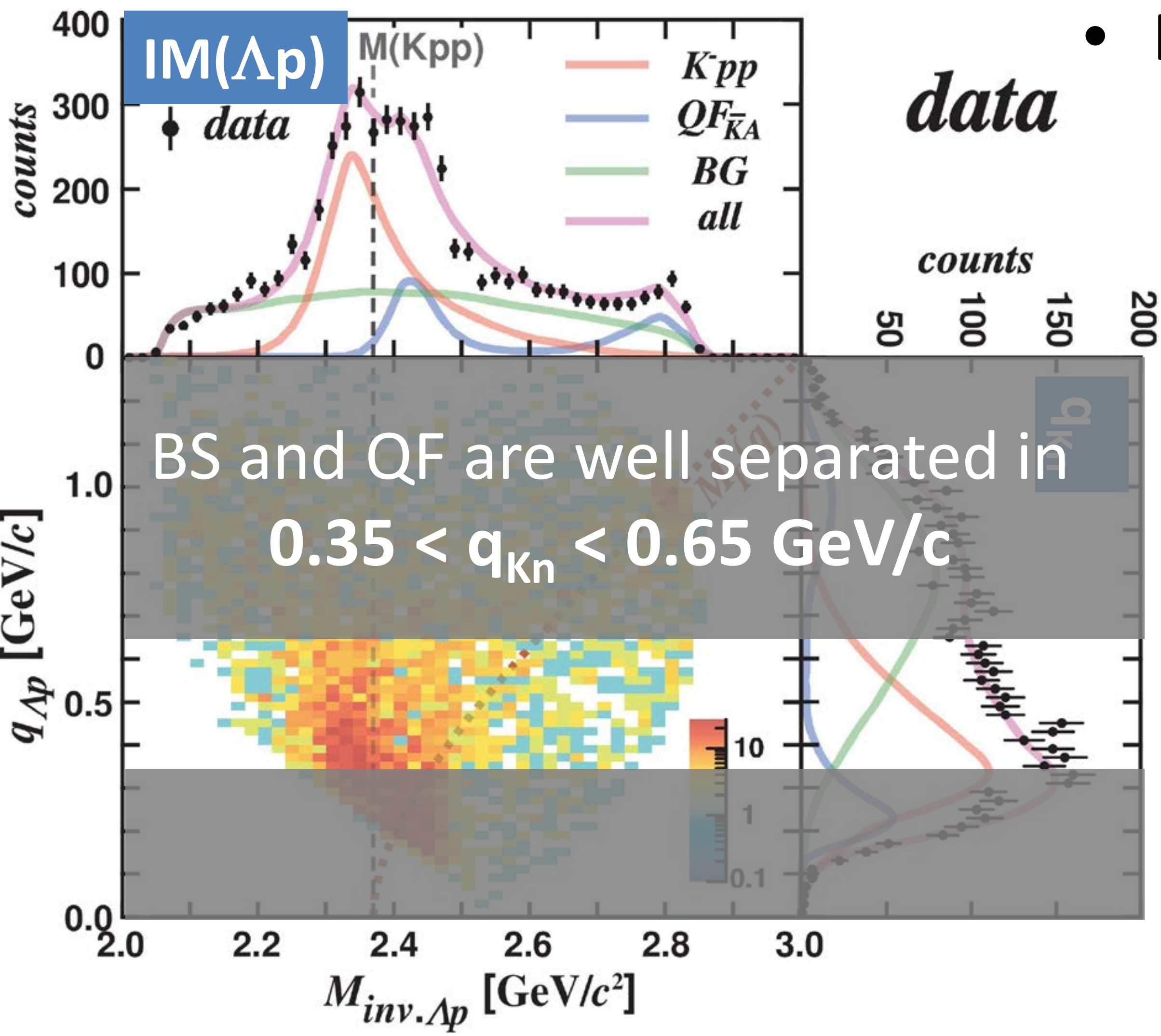

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“K⁻pp” Bound-State

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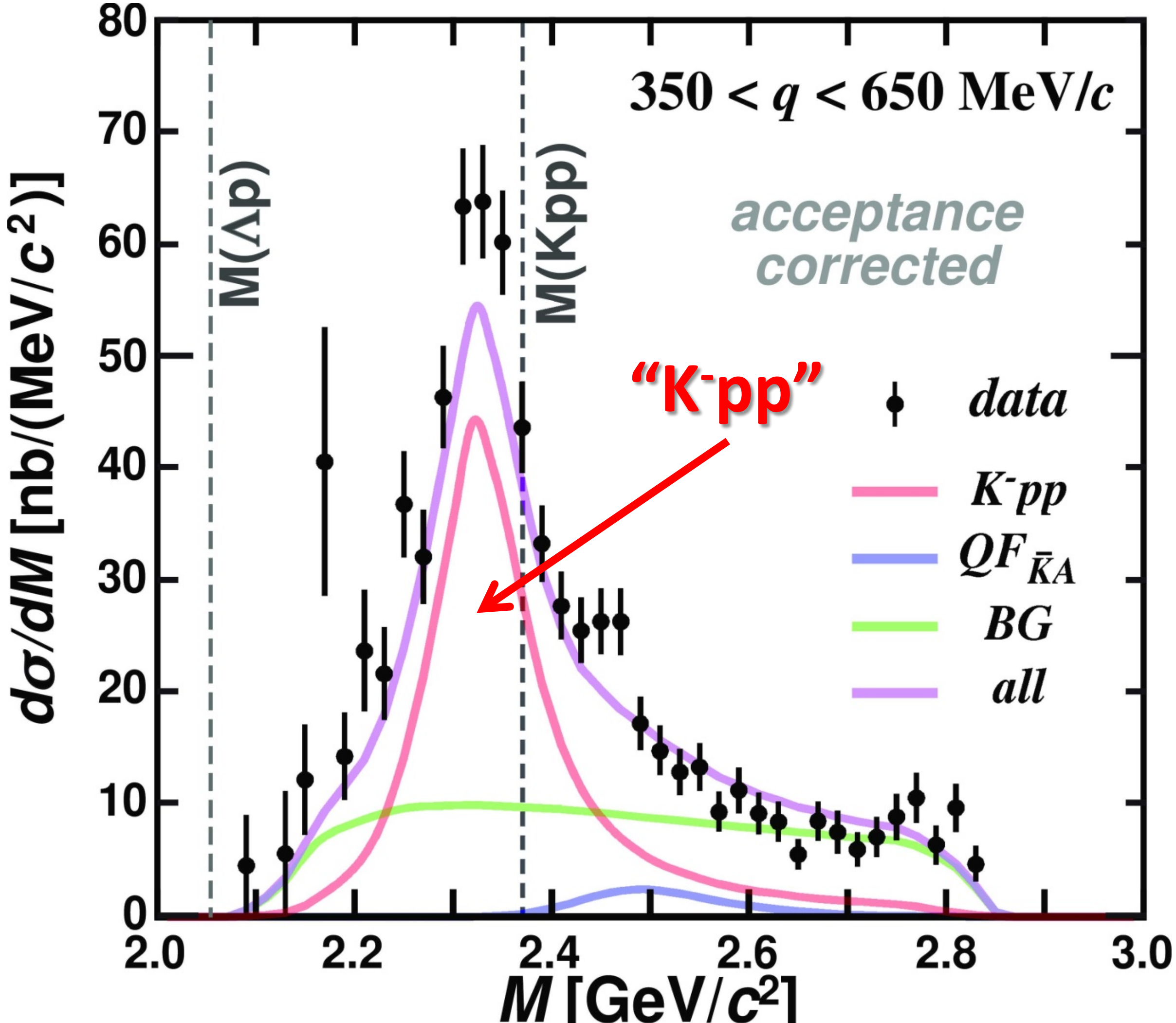
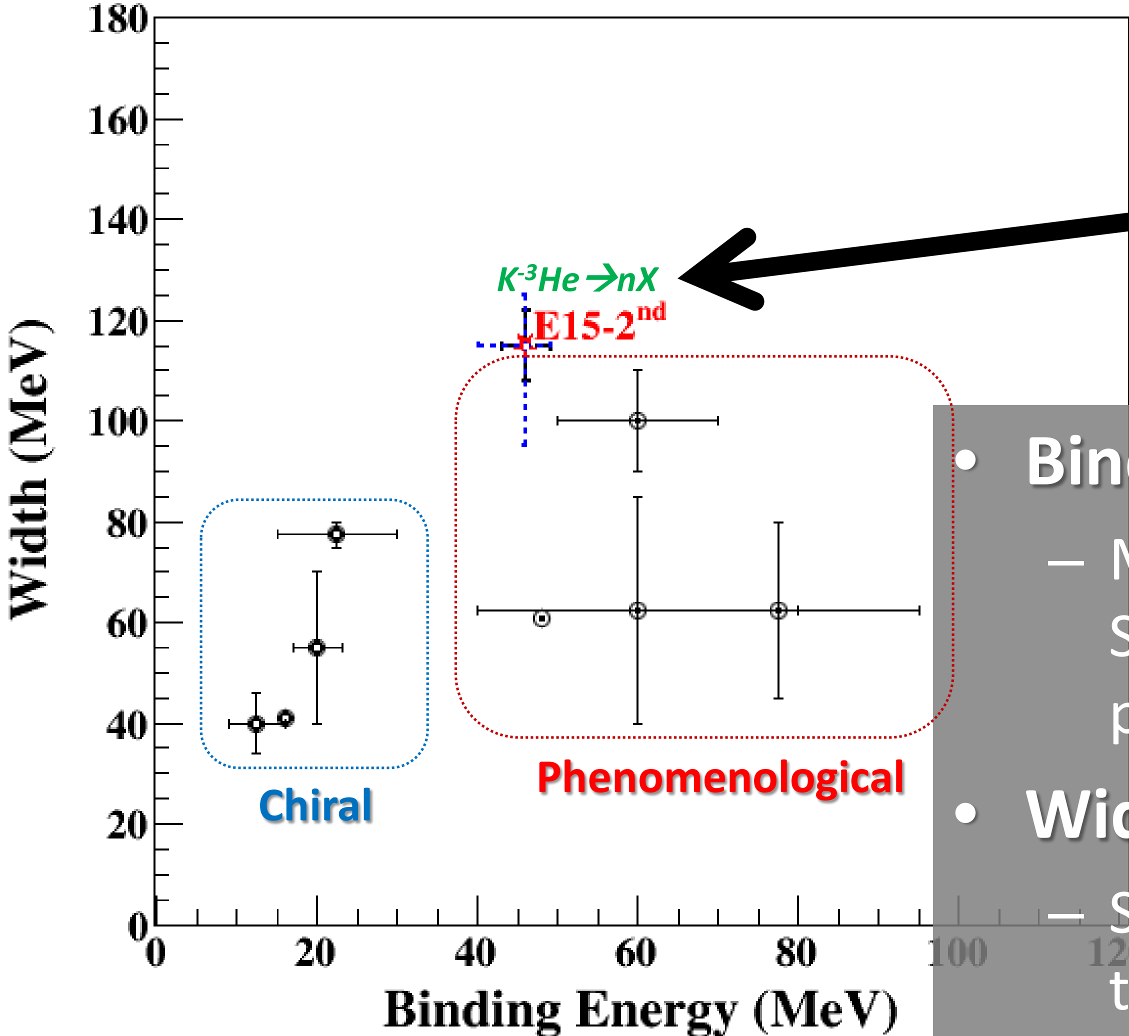
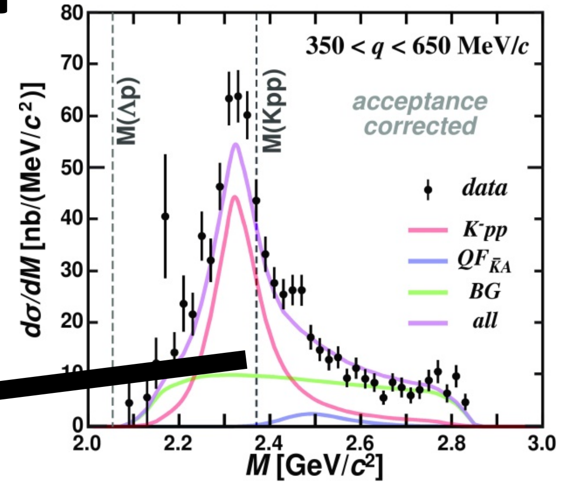


E15 collab., PLB789(2019)620.

Observed "K⁻pp"



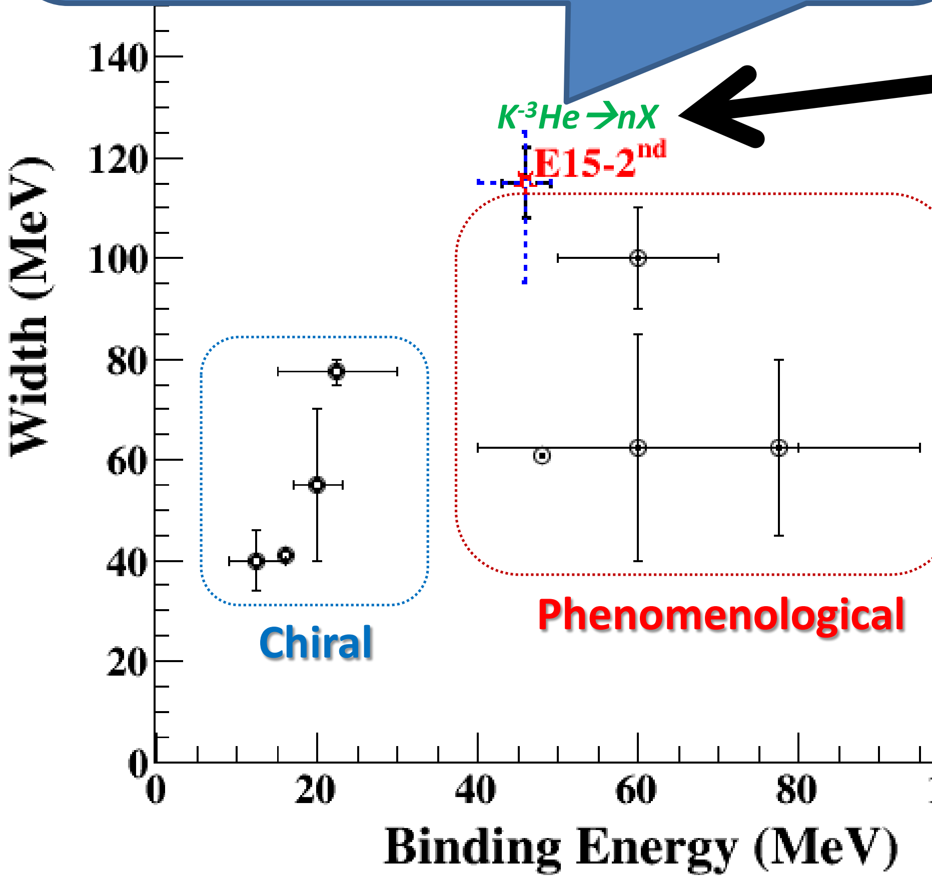


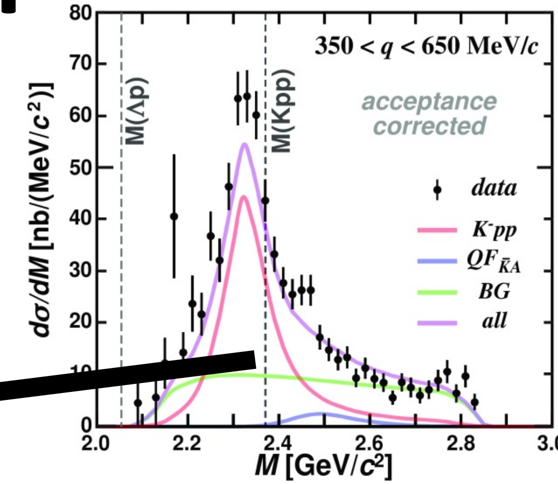
- **Binding energy: ~50 MeV**
  - Much deeper than chiral-SU(3) based theoretical predictions
- **Width: ~100 MeV**
  - Seems to be larger than theoretical calculations (mesonic πY decays only)

Observed "K⁻pp"

the most reliable observation

- simple K- induced reaction
- exclusive measurement
- good BG separation from 2NA





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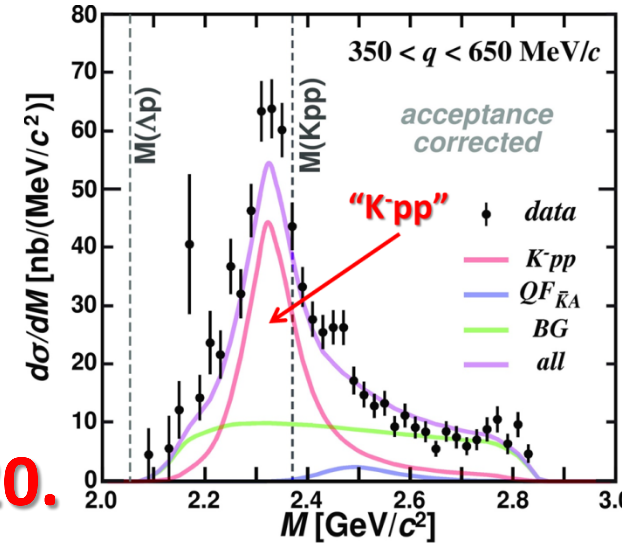
Conclusion I

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

← E15 collaboration, PLB789(2019)620.



We need further understanding

- **Spin/Parity of the "$K^{-}pp$"**
  - *New 4π detector system is needed* **← *Future plan***

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- **Reaction mechanism**
  - Relation between Λ(1405) & "K^-pp"
    - Λ(1405) has been considered as **"K^-p"**
    - Theoretically, "K^-pp" is expected to be produced via **Λ(1405)+p→"K^-pp" door-way process**

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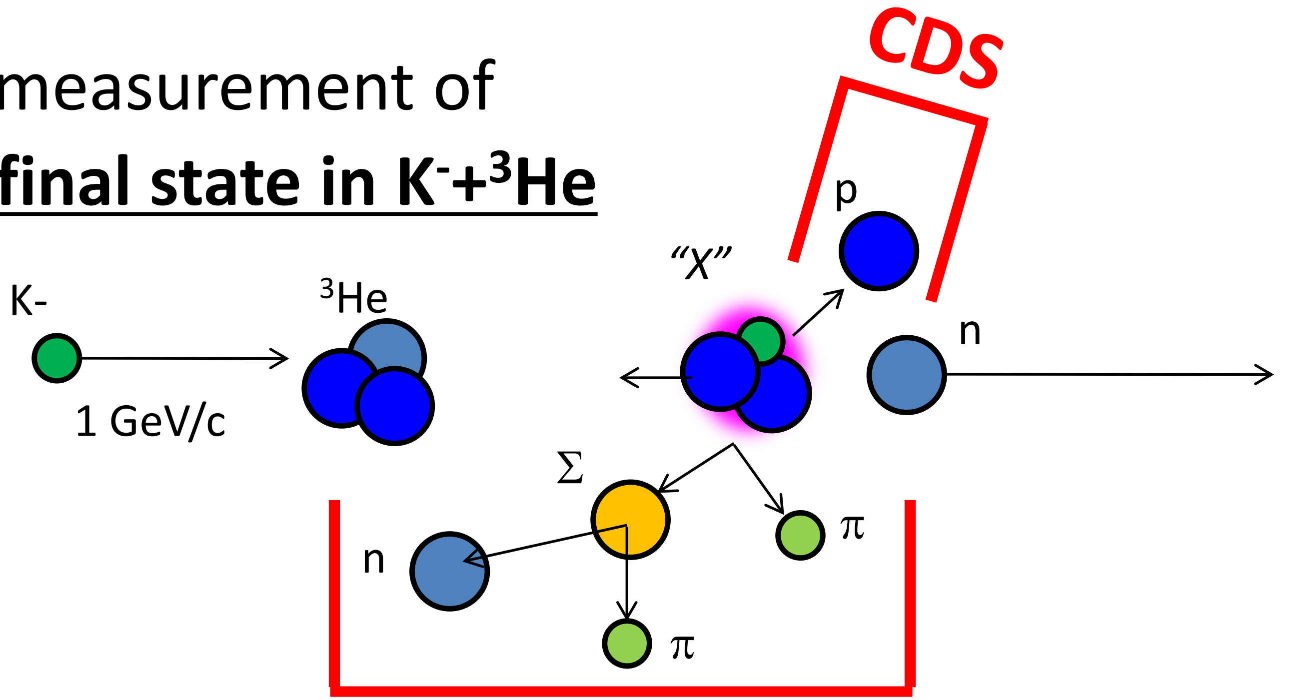
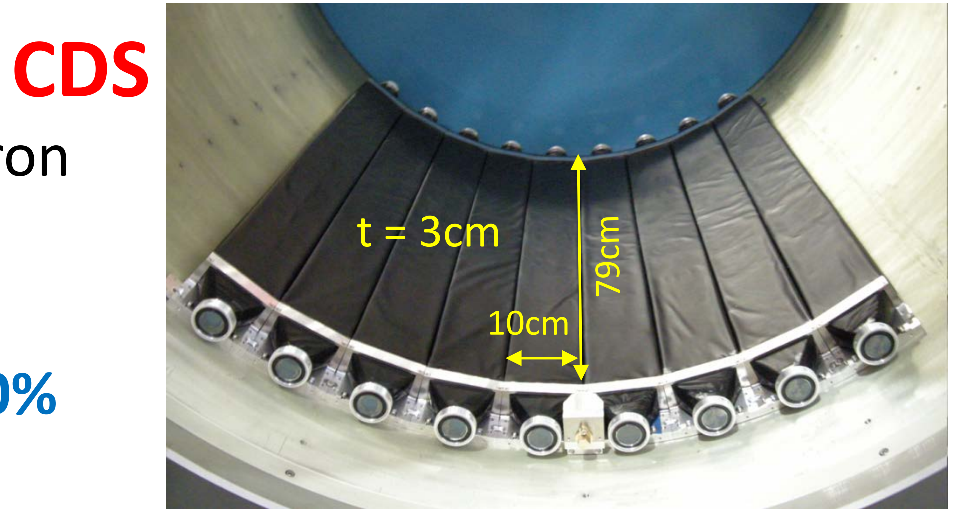
- **Other decay channels** **$K^{-}\ {}^{3}He \rightarrow \pi\Sigma pn$**
  - **<u>$\pi\Sigma N$ mesonic decay</u>** is theoretically expected to be the dominant channel
    - Only YN non-mesonic decays were reported
- **Reaction mechanism**
  - Relation between $\Lambda(1405)$ & "$K^{-}pp$"
    - $\Lambda(1405)$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

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

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



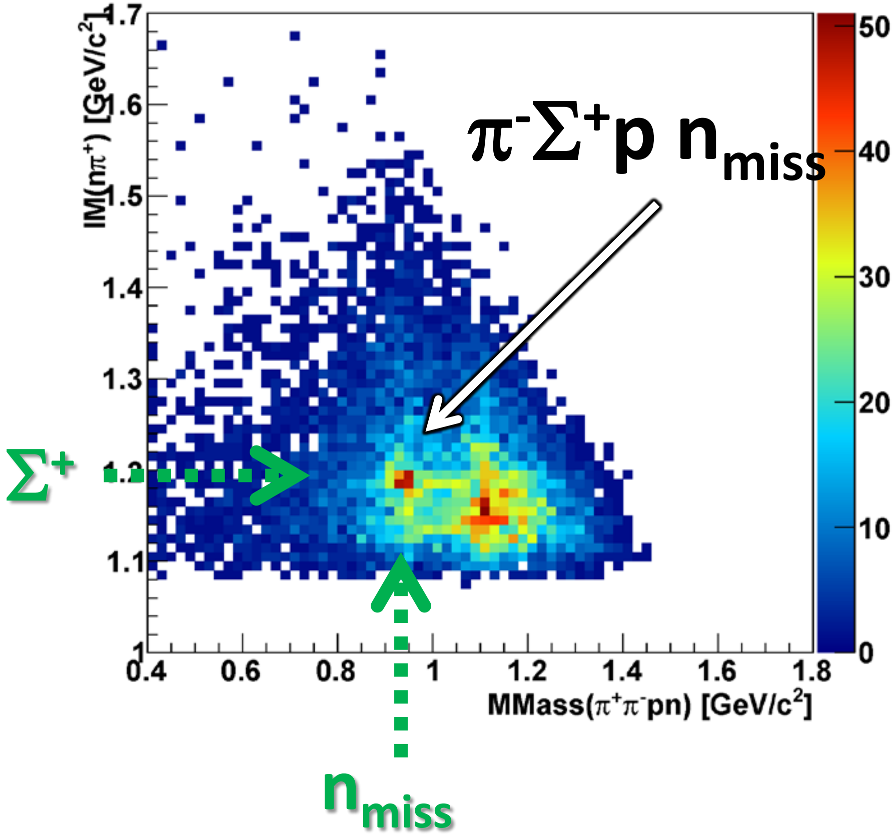


- **Experimental challenge** of neutron detection with thin scintillation counter (t=3cm)

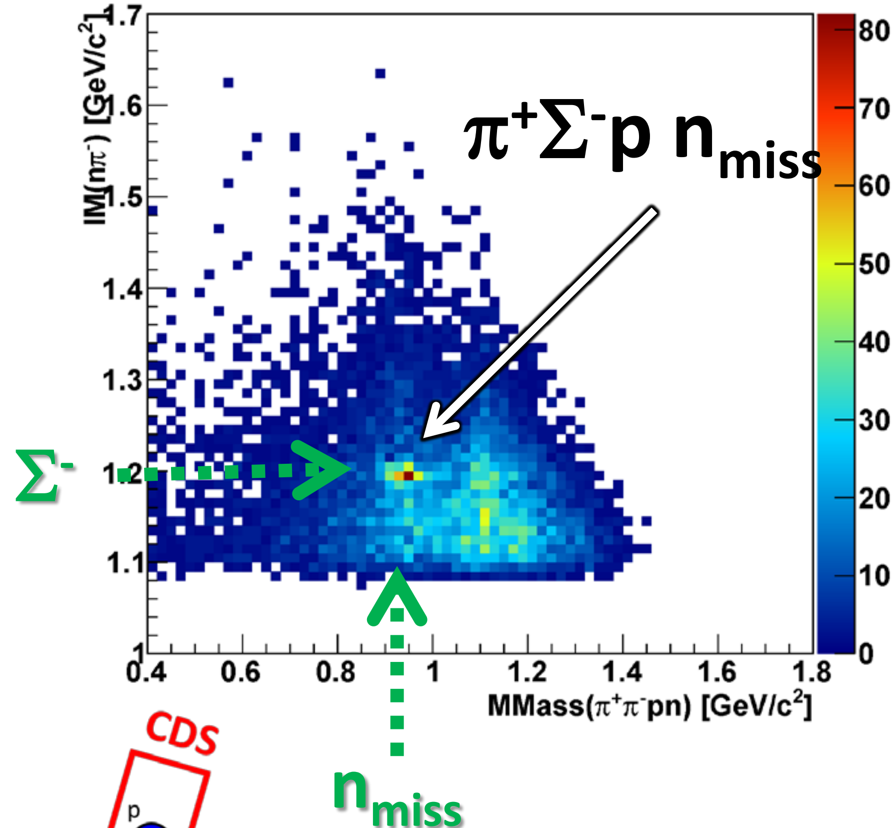
n detection efficiency ~ 3-10%

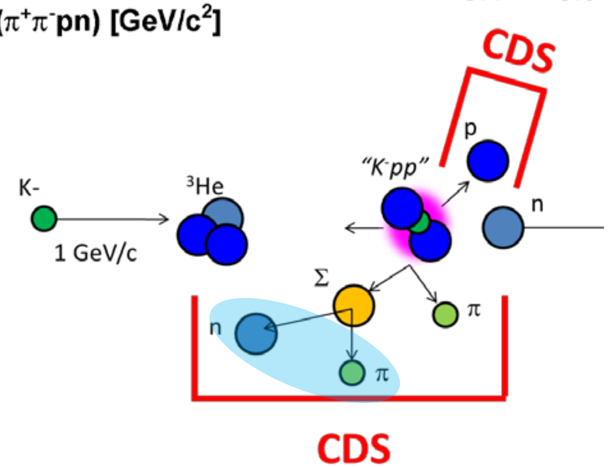
$\pi\Sigma$pn Events

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

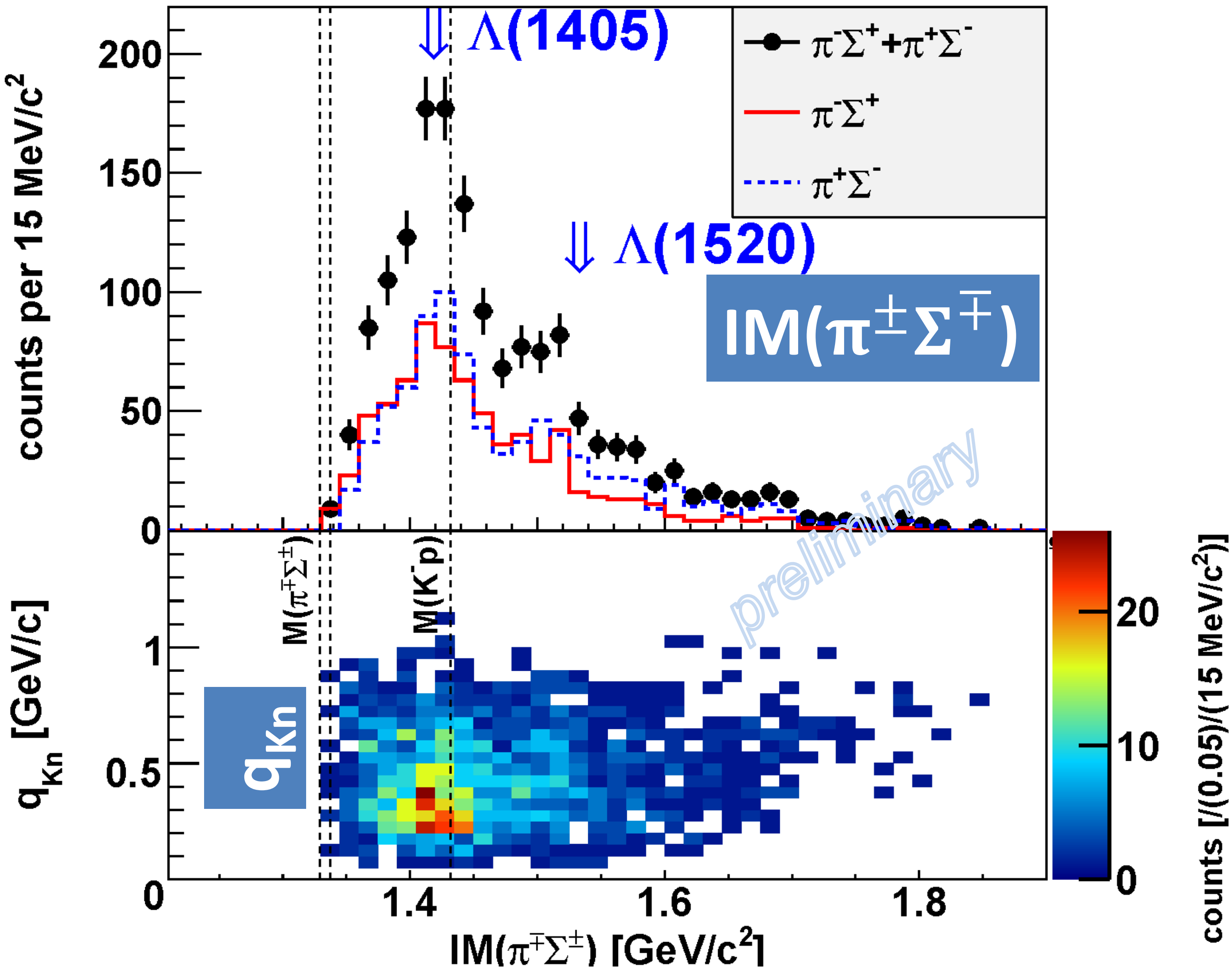


IM($n\pi^-$) vs MM($\pi^+\pi^-$pn)





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



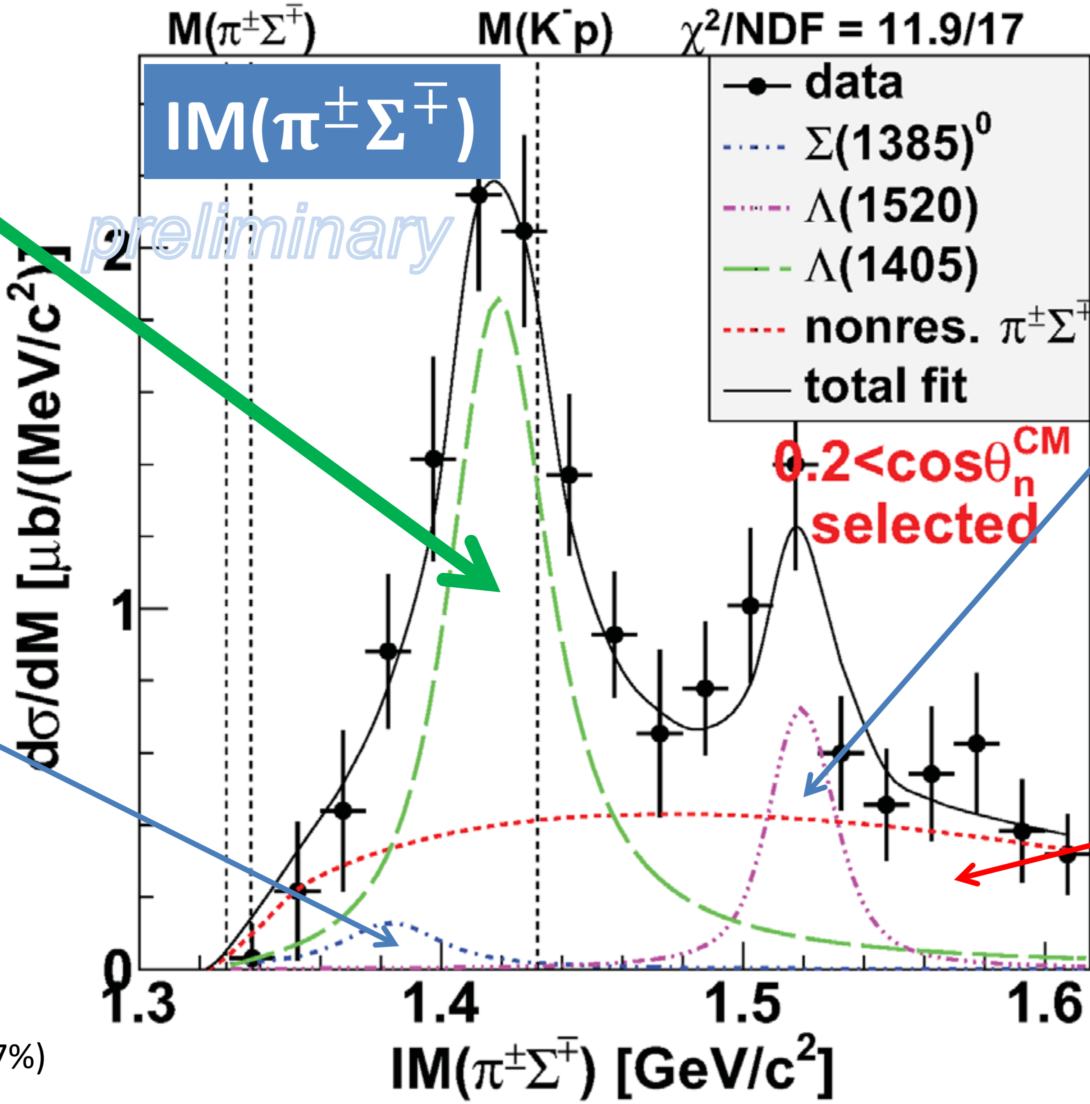
Λ(1405) can be clearly seen in low q_{Kn}

$Y^{*}pn$ Final State

Λ(1405)

~ 150 μb

Fit w/ Flatté formula:
Re(z) ~ 1420 MeV
-Im(z) ~ 15 MeV



Λ(1520)

~ 100 μb

πΣpn non-resonant

Σ⁰(1385)

~ 20-100 μb

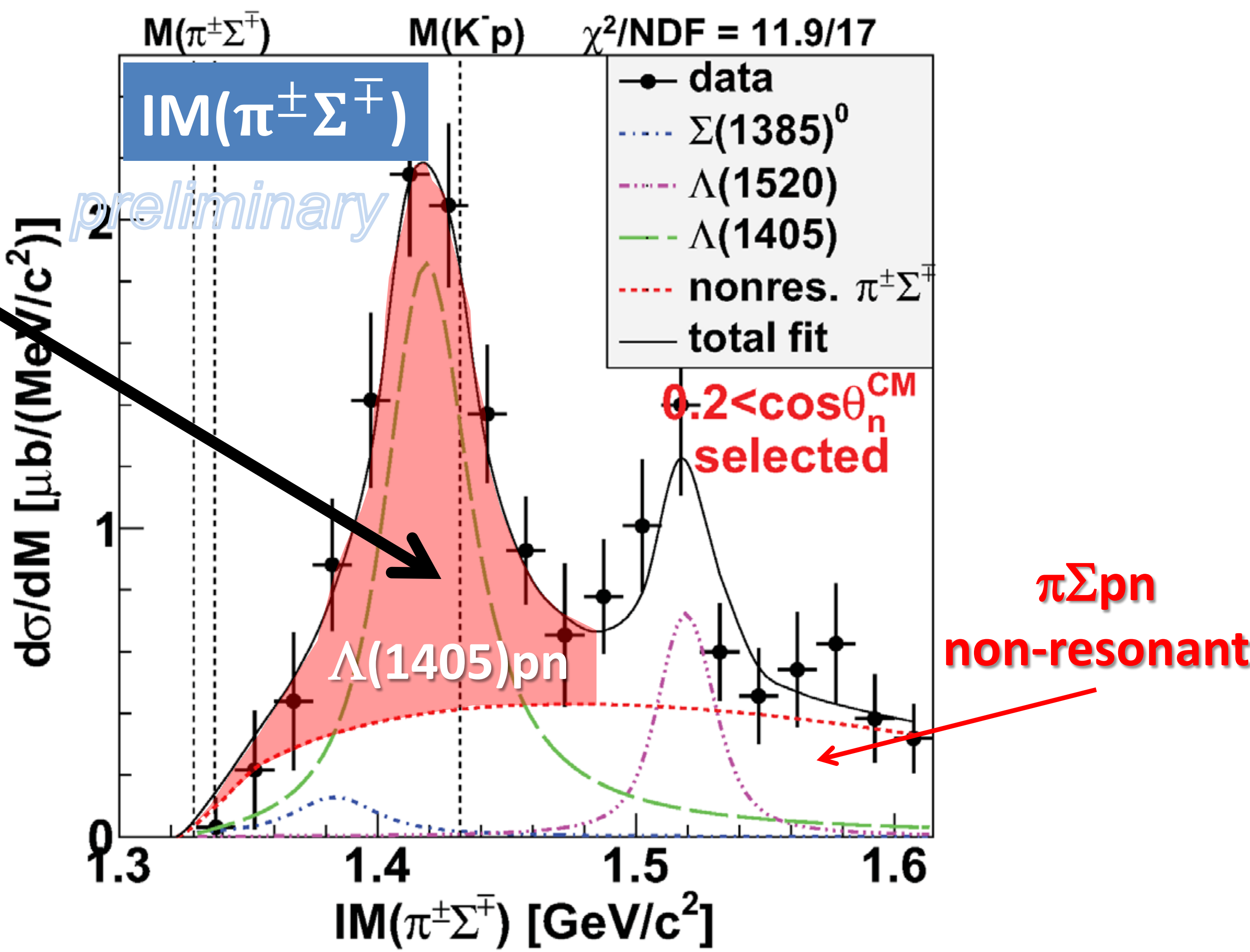
[evaluated from $\Sigma^{+/-}(1385) \to \pi^{+/-}\Lambda$ measurement]

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

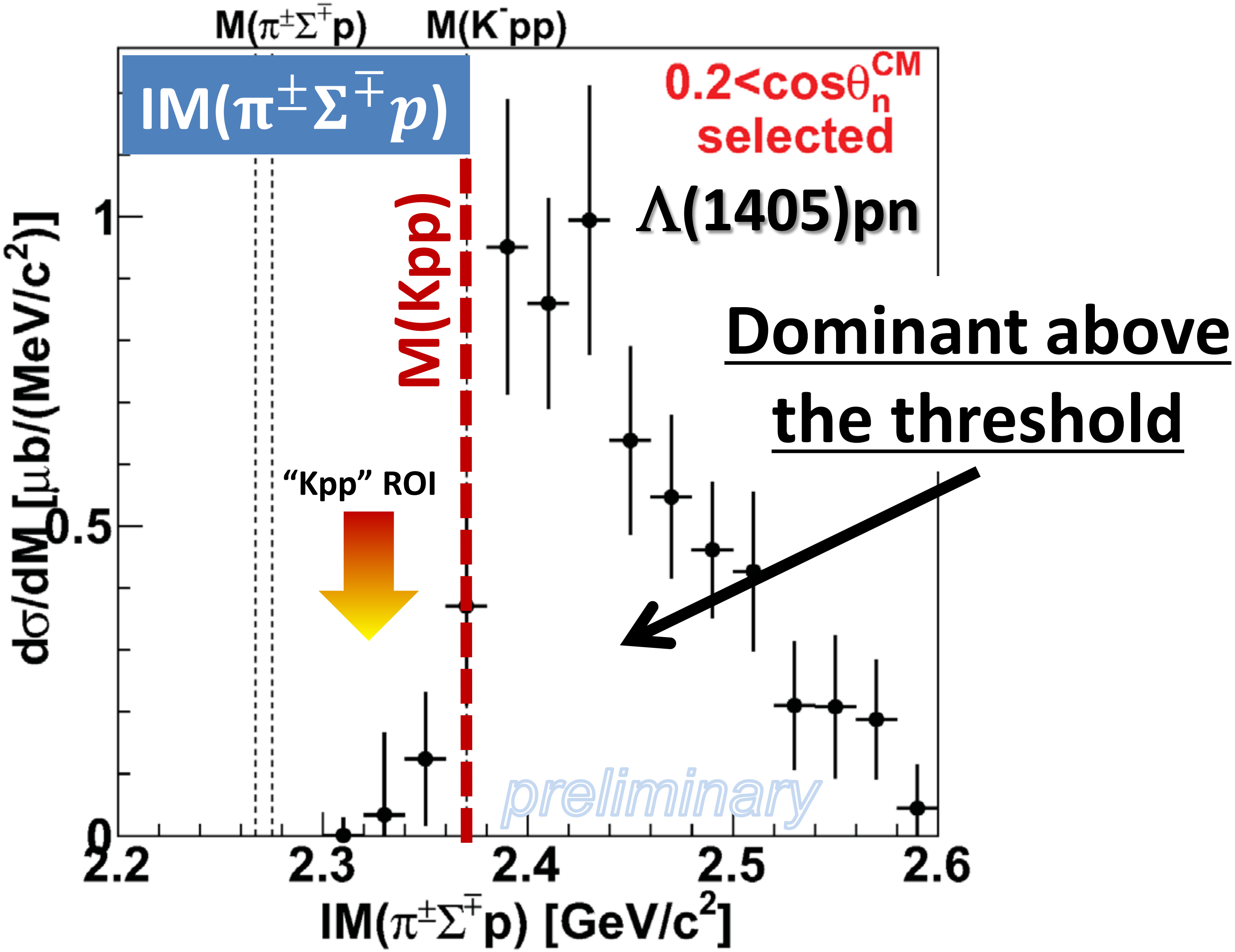
$\Lambda(1405)$pn Final State Selection

Select $\Lambda(1405)$pn final state

- Below $\Lambda(1520)$
- Small contribution from $\Sigma(1385)$



IM($\pi\Sigma$p) in Λ(1405)pn Final State

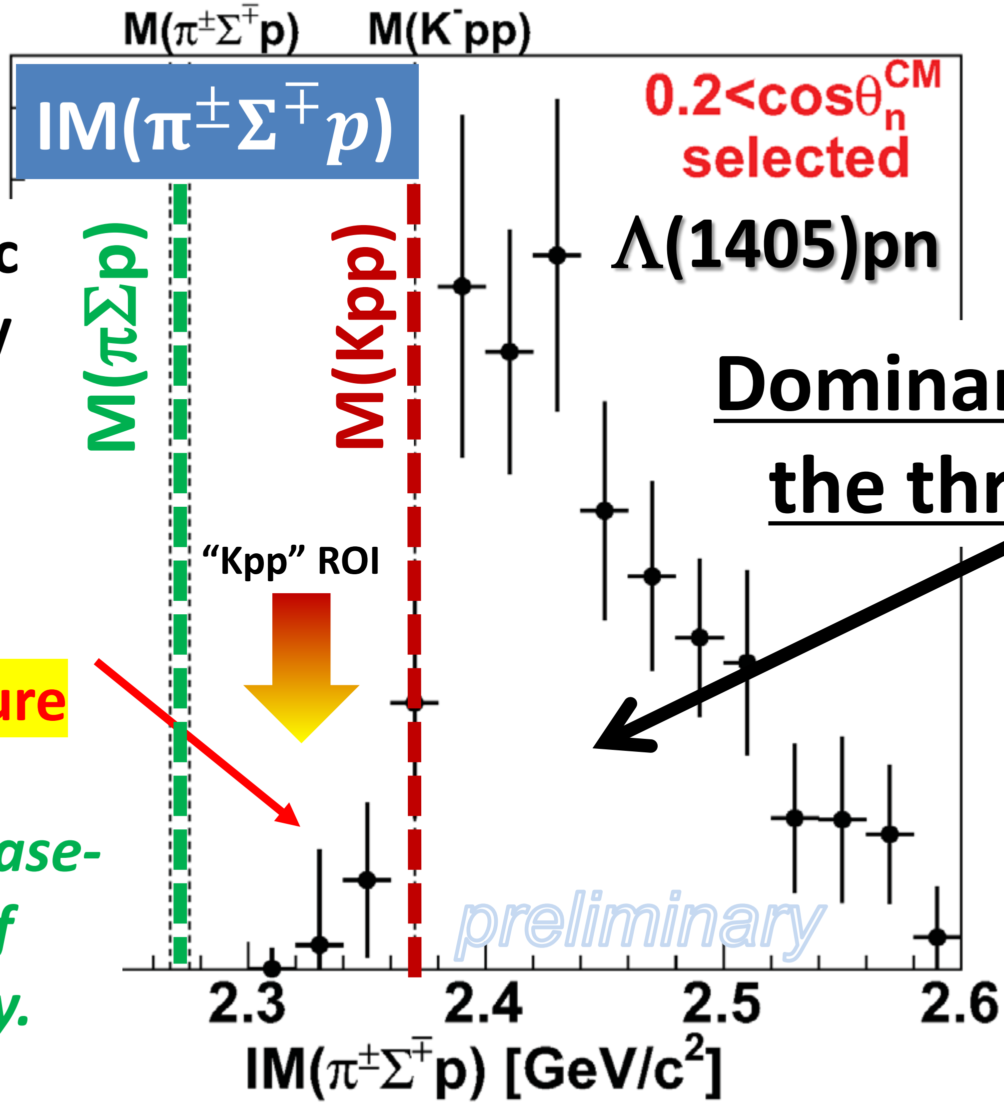


IM(πΣp) in Λ(1405)pn Final State

"Kpp"→πΣN mesonic decay is theoretically expected to be the dominant channel

BUT, statistically, NO significant structure

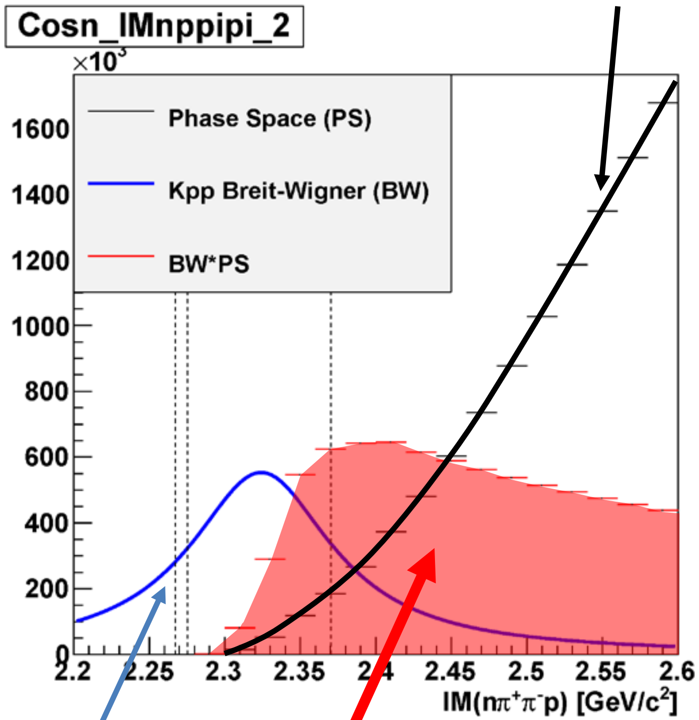
This will be due to phase-space limitation of "K⁻pp"→πΣN decay.



Dominant above the threshold

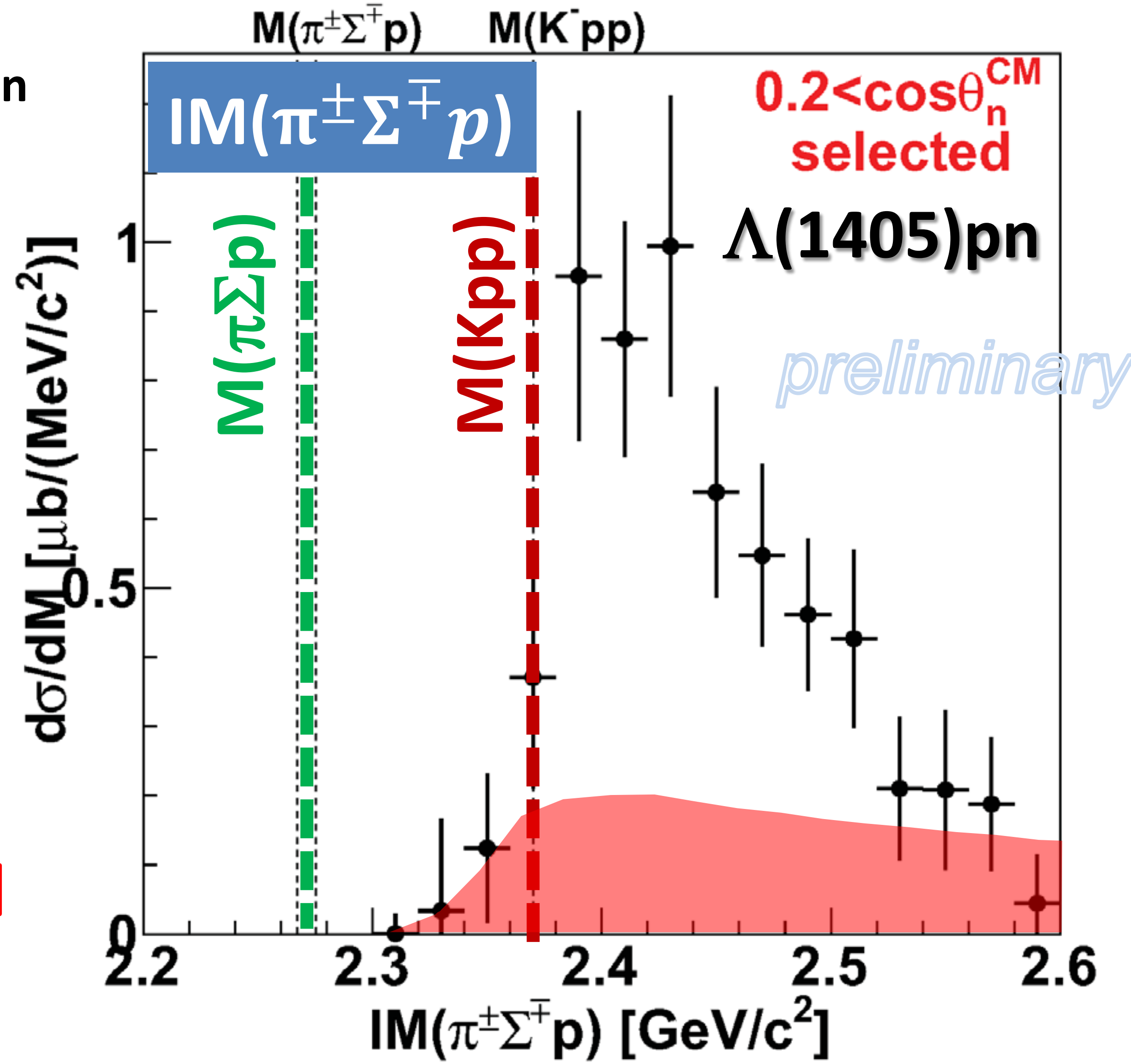
PS Limitation of “K⁻pp”→πΣp Decay

Phase space of πΣpn

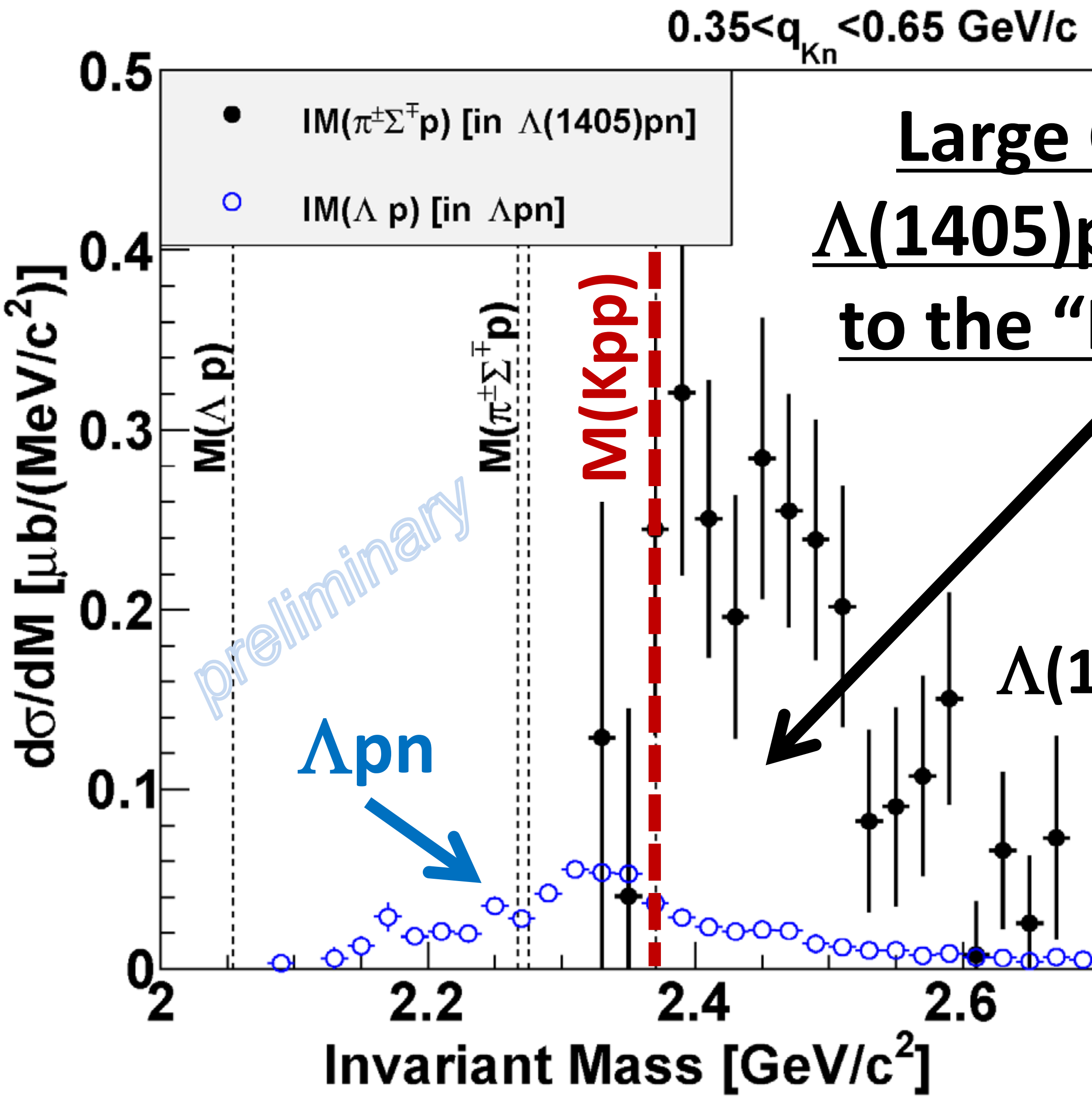


[BW] * [phase space]

Kpp BW obtained with Λp

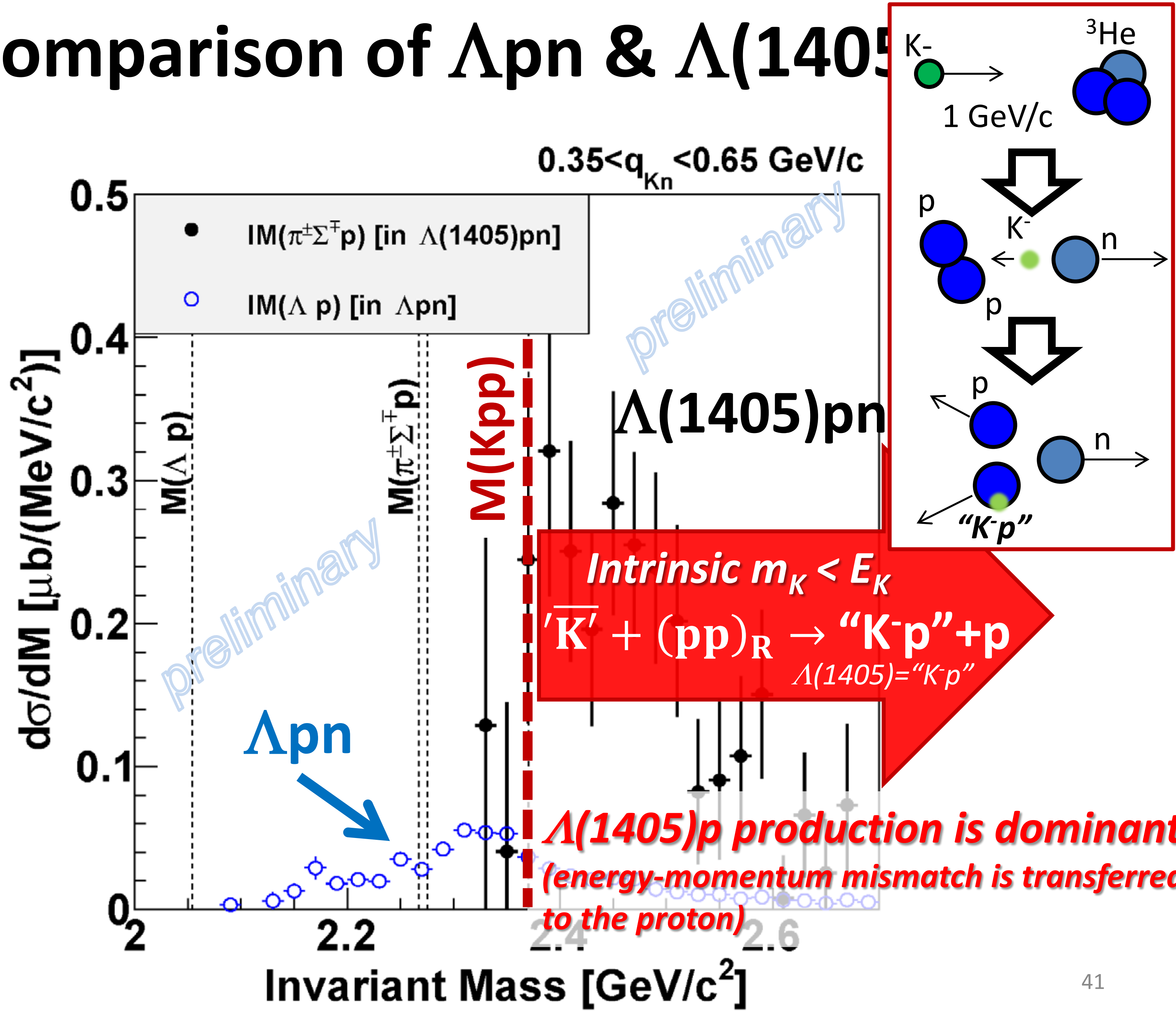


Comparison of Λpn & Λ(1405)pn

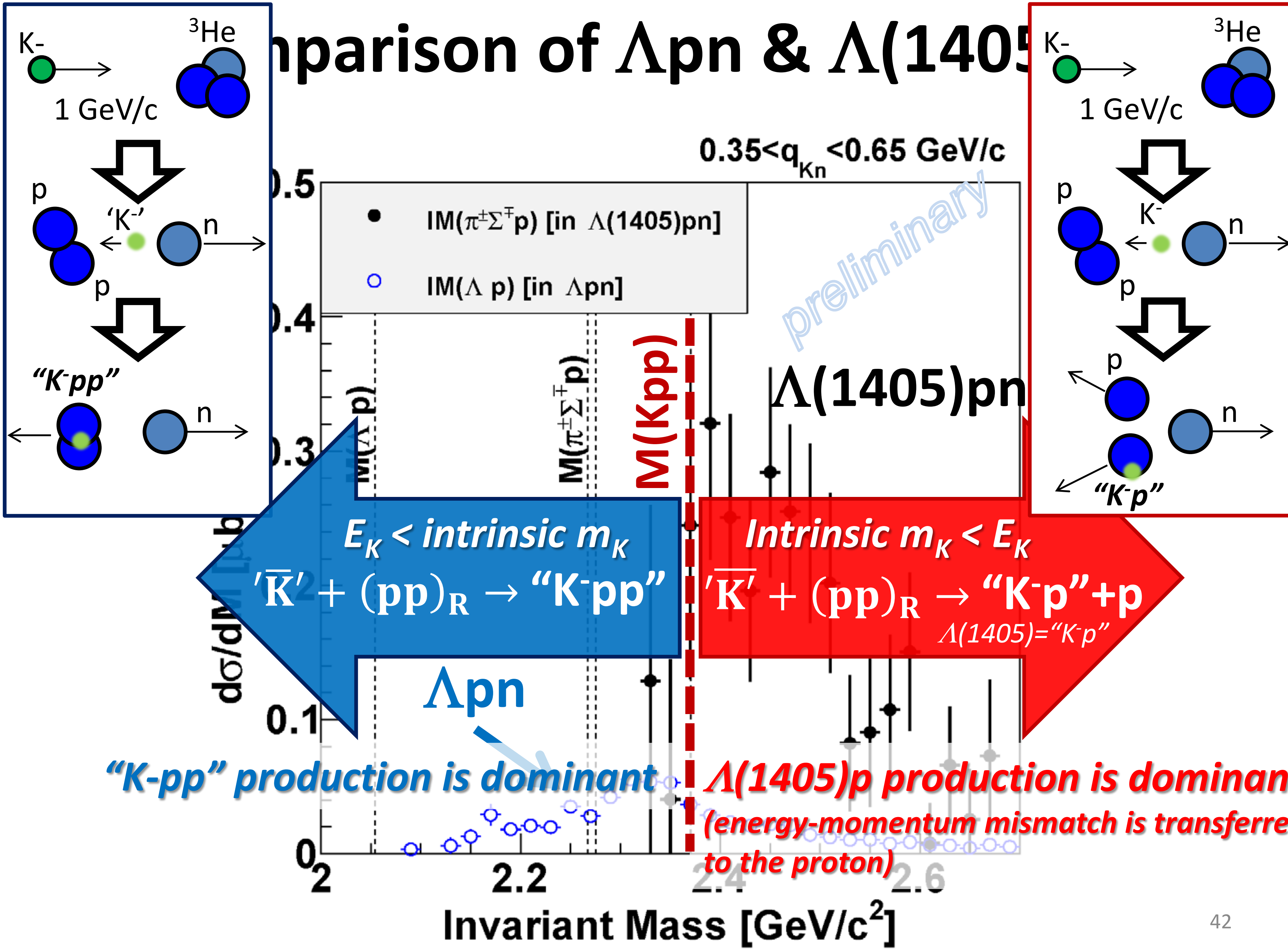


Large CS of the Λ(1405)p compared to the "K⁻pp"→Λp

Comparison of Λpn & Λ(1405



nparison of Λpn & Λ(1405



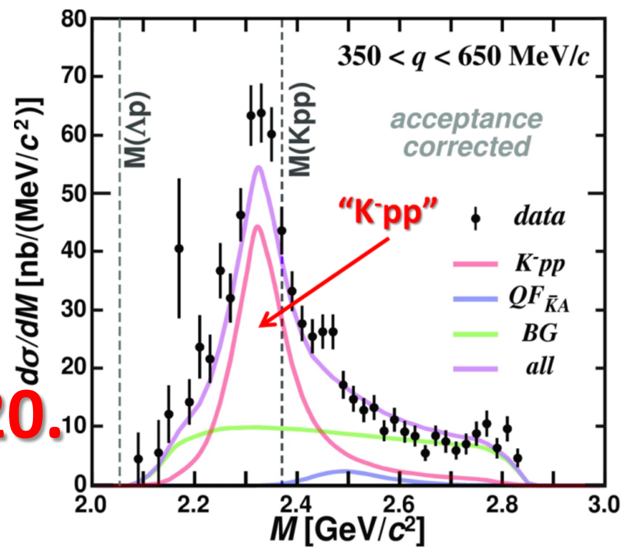
"K-pp" production is dominant

Λ(1405)p production is dominant
(energy-momentum mismatch is transferred to the proton)

Conclusion II

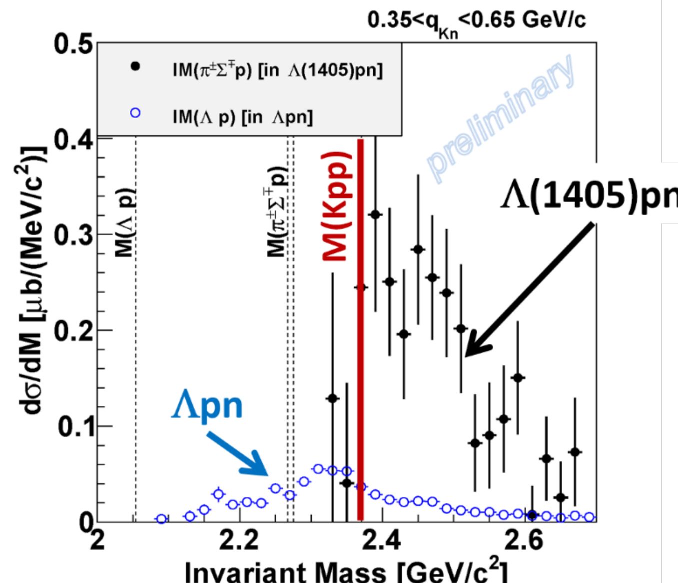
- **We observed the "K⁻pp" bound state in $^3He(K^-,\Lambda p)n$**
  - Binding energy: ~50 MeV
  - Width: ~100 MeV

← E15 collaboration, PLB789(2019)620.

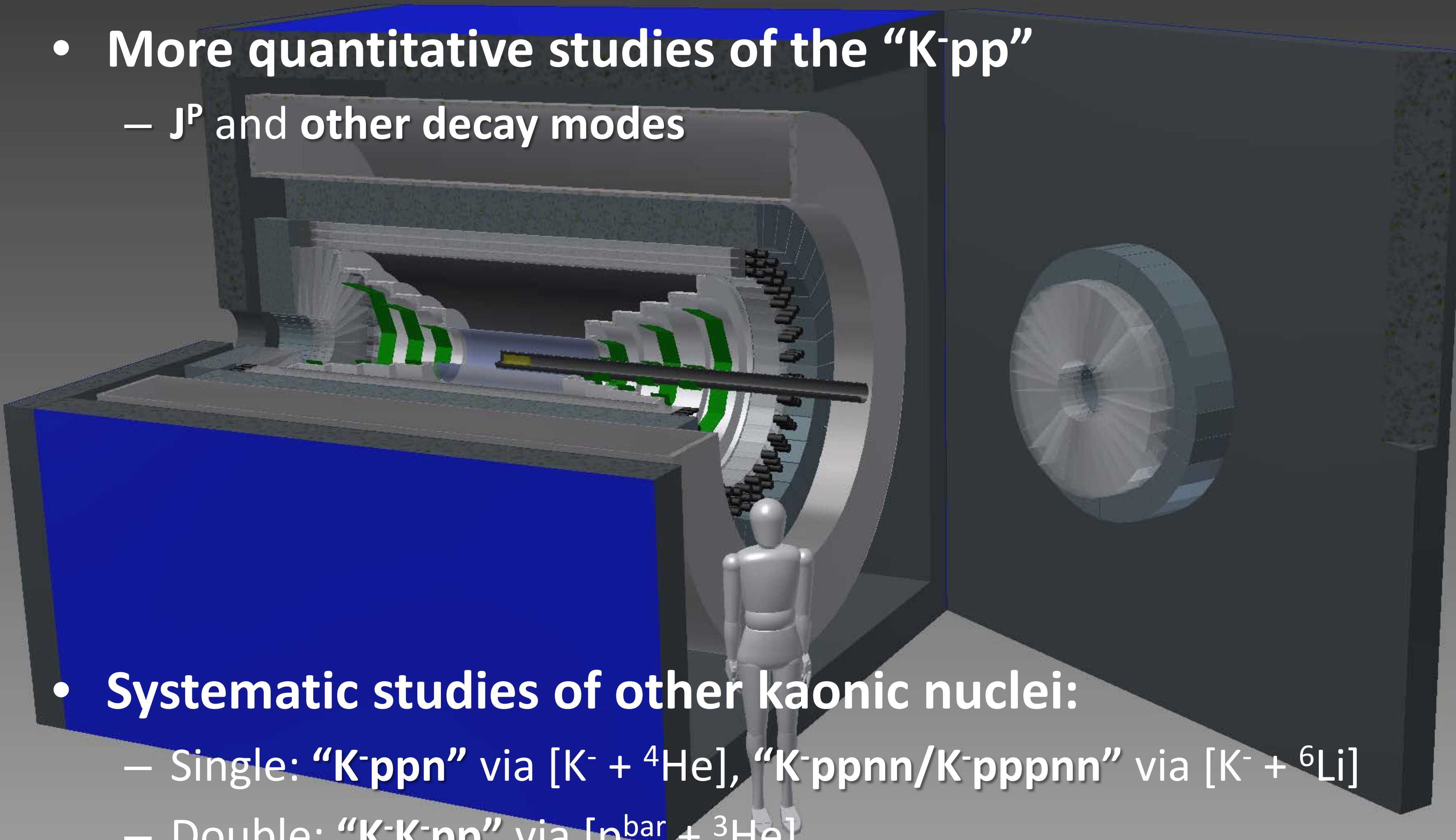


- **We found large CS of the Λ(1405)p formation compared to the "K⁻pp"**
  - quite important information on the production mechanism of the "K⁻pp"

← paper in preparation



Need further investigation



- **More quantitative studies of the "K^-pp"**
  - **J^P** and **other decay modes**
- **Systematic studies 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]

A new 4π detector with γ/n sensitive detectors is required

Thank You!

J-PARC E15 Collaboration

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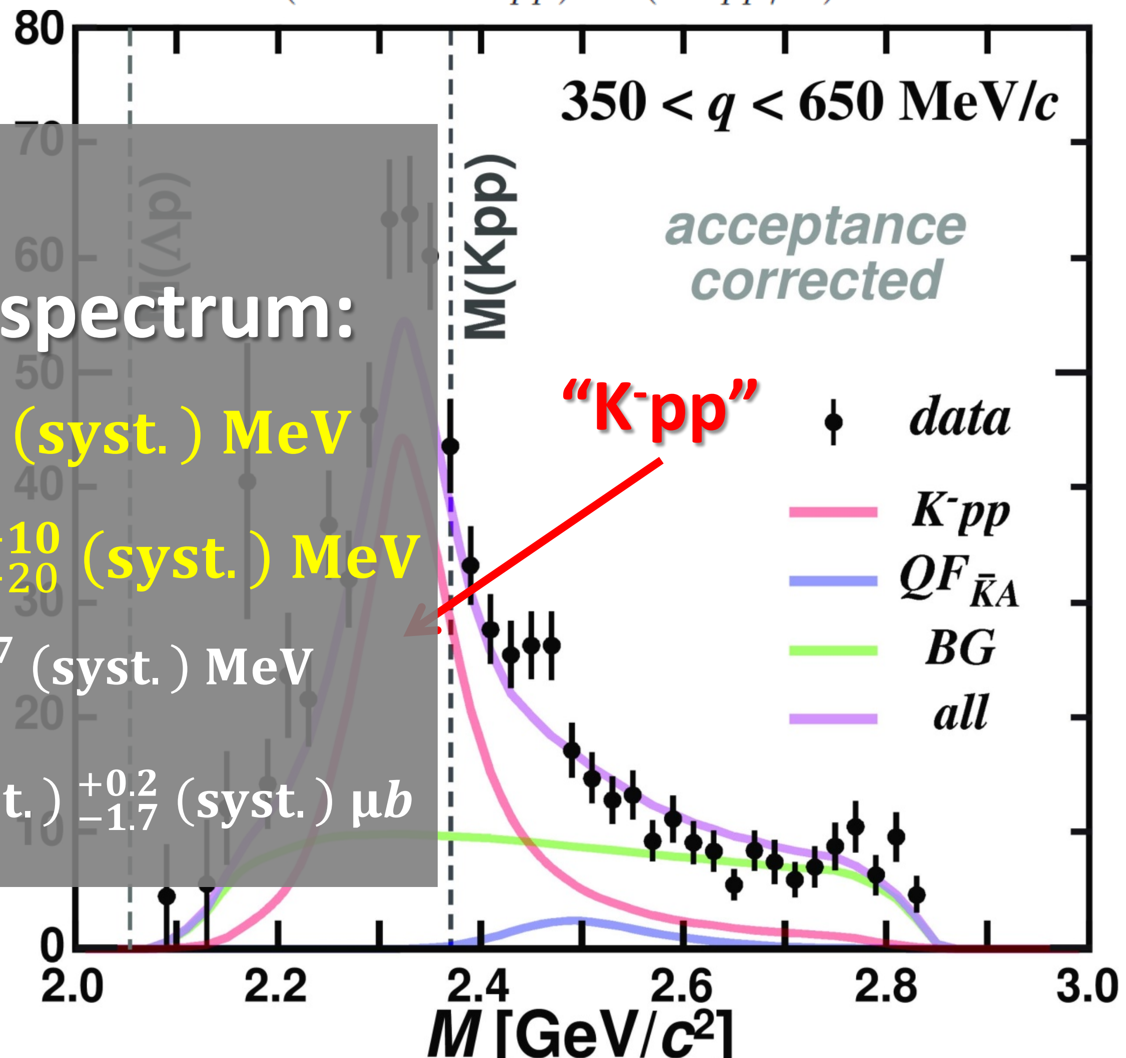
Spares

“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

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

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

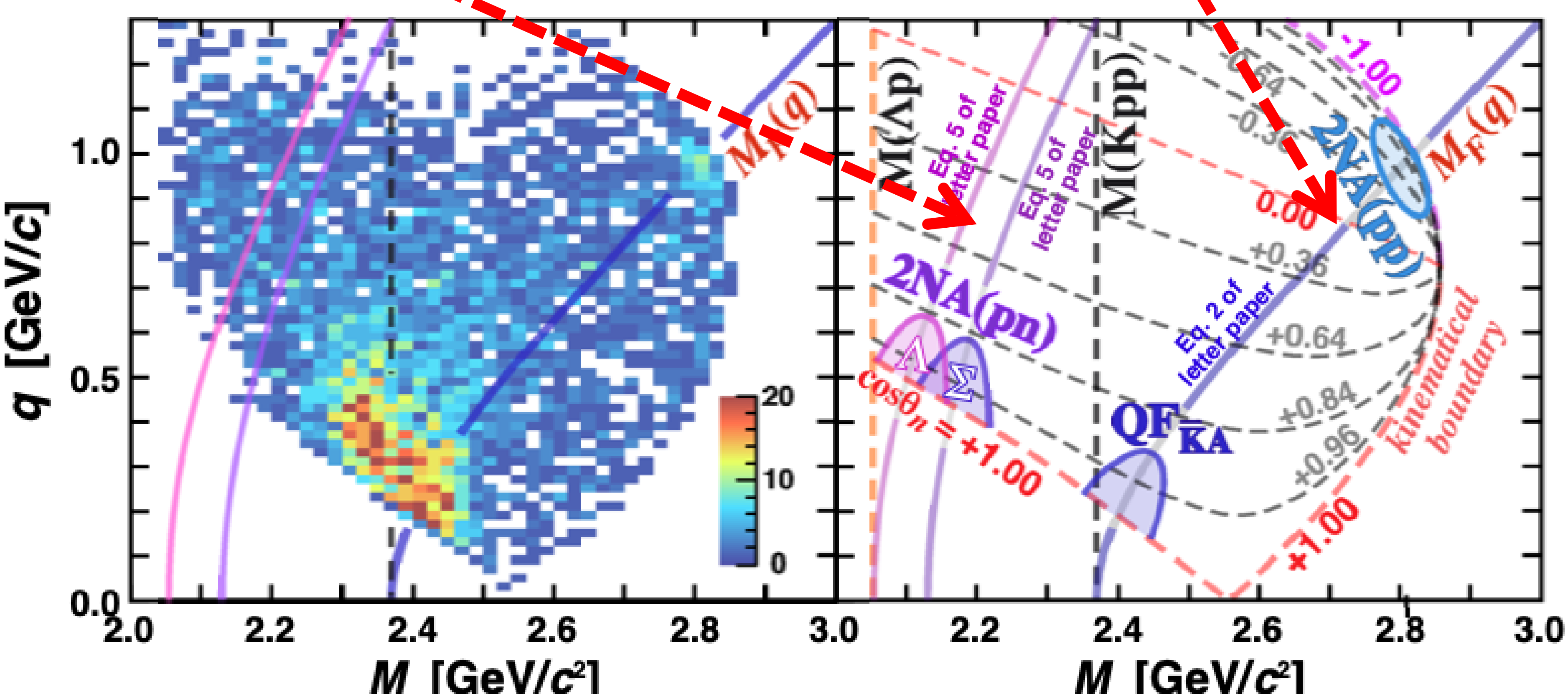
$\sigma_{\text{“Kpp”}} \cdot Br_{\Lambda p} = 11.8 \pm 0.4\,(\text{stat.})\,^{+0.2}_{-1.7}\,(\text{syst.})\ \mu b$

E15 collab., PLB789(2019)620)

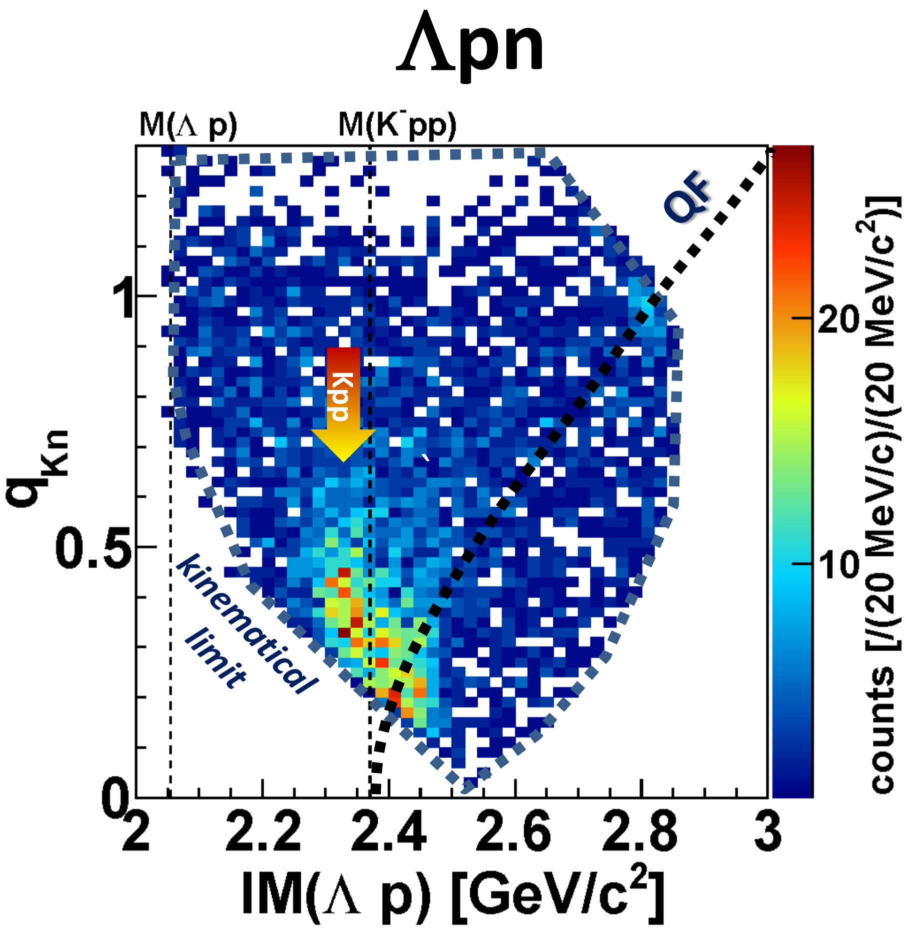
BG: 2NA followed by FSI

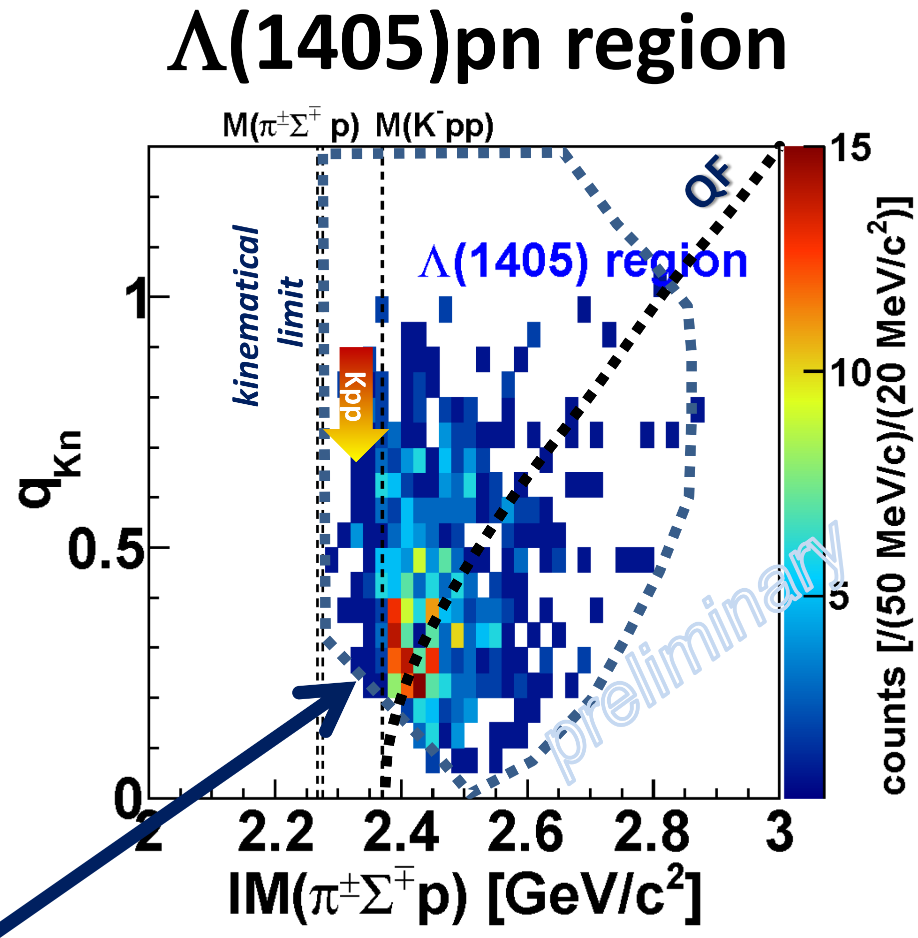
$$K^- + {}^3He \rightarrow (K^- + "pn") + p_{spect}$$
$$\rightarrow Y + n + p_{spect} \quad \textbf{(2NA)}$$
$$\rightarrow (Y + "p") + n$$
$$\rightarrow \Lambda + p + n \quad \textbf{(FSI)}$$

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



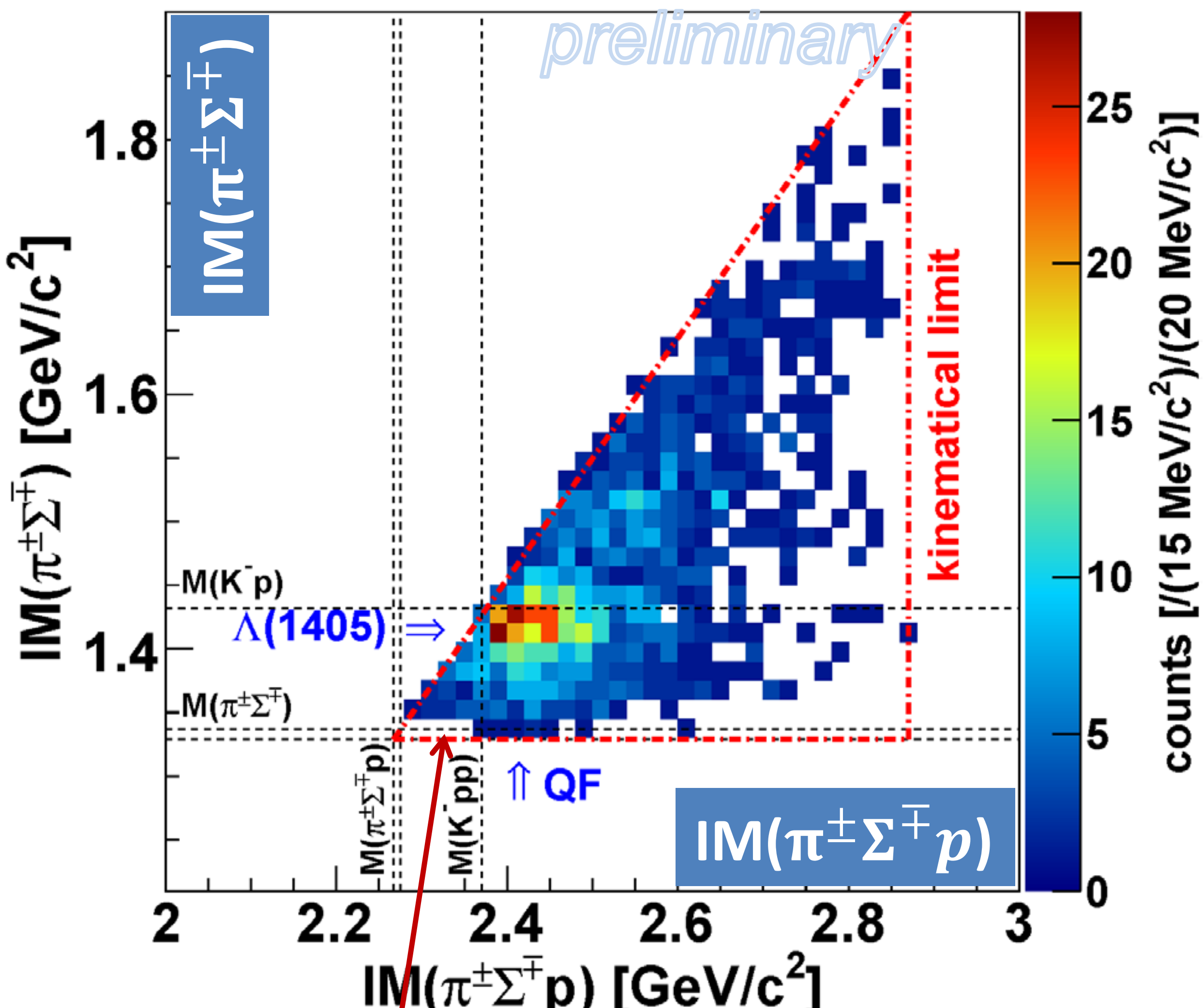
Comparison of Λpn & Λ(1405)pn

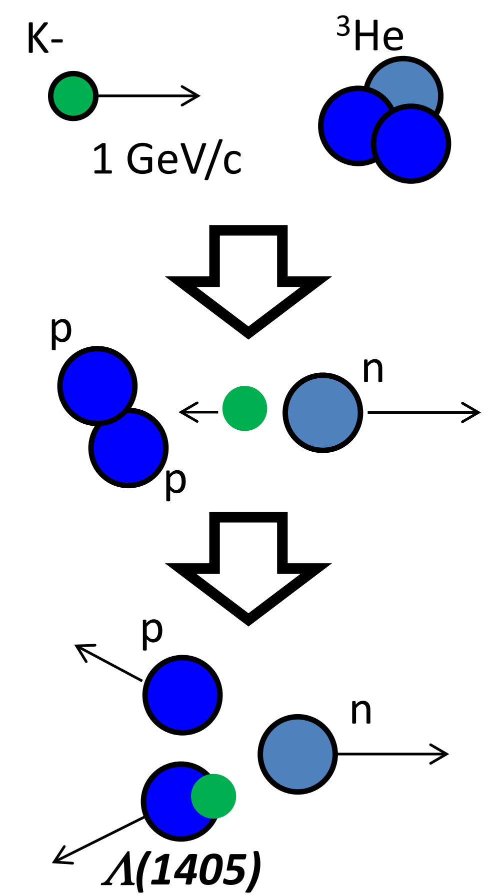




- **No clear structure below M(Kpp) in the IM(πΣp)**
- **QF followed by Λ(1405)p is dominant**

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

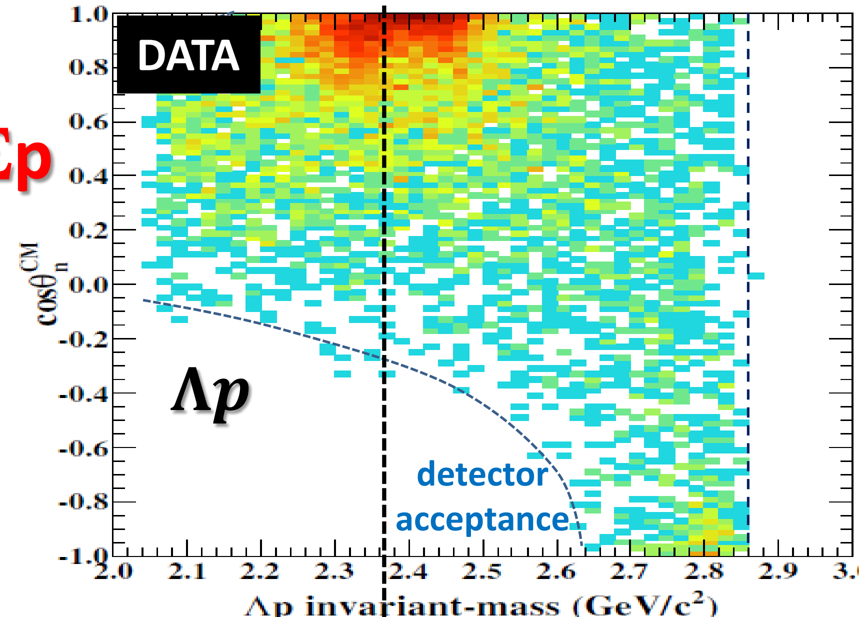


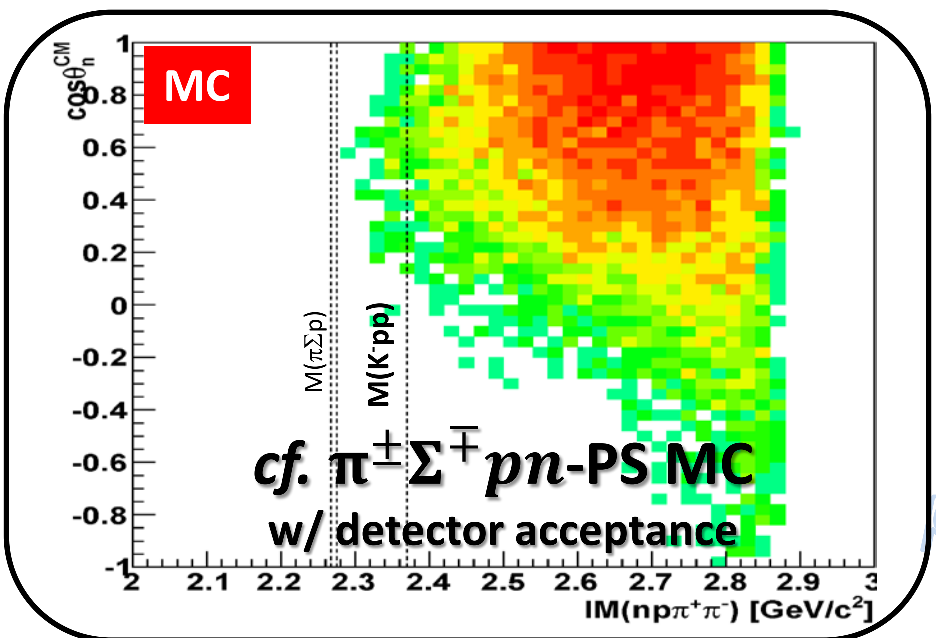


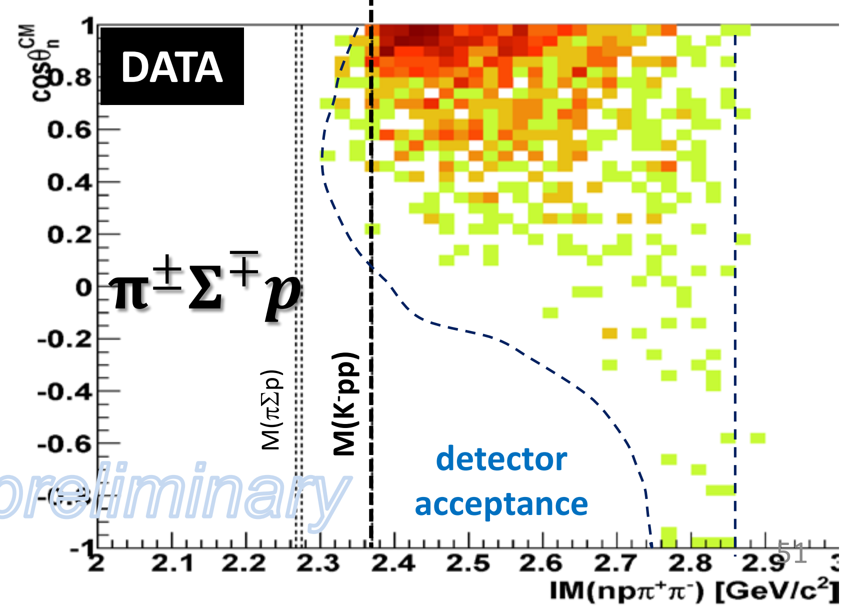
Small phase-space of "K⁻pp"→πΣN

Detector Acceptance: Λp vs. $\pi\Sigma p$

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



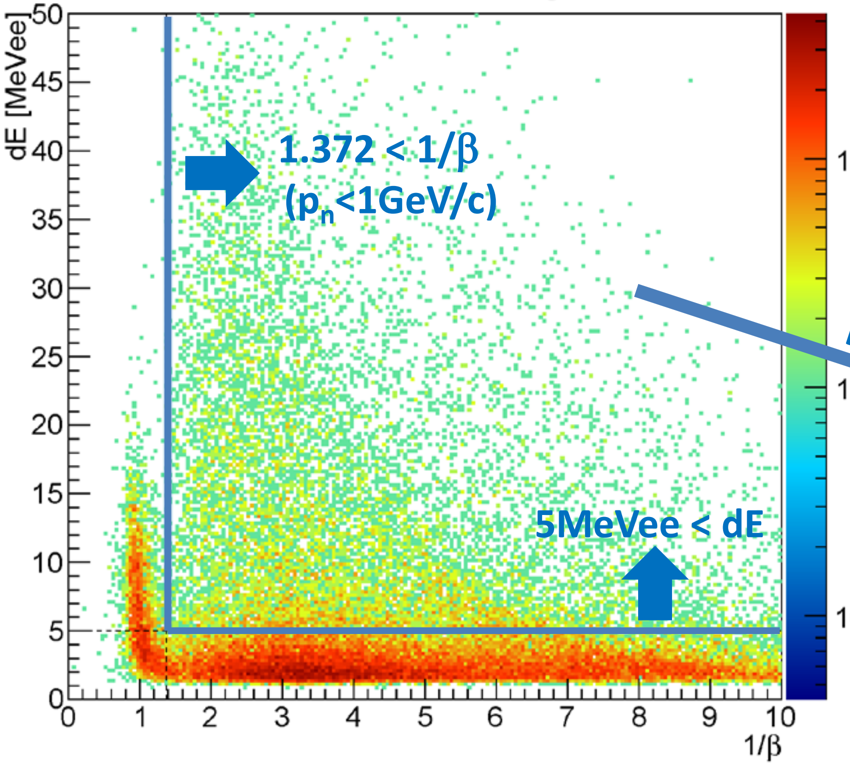




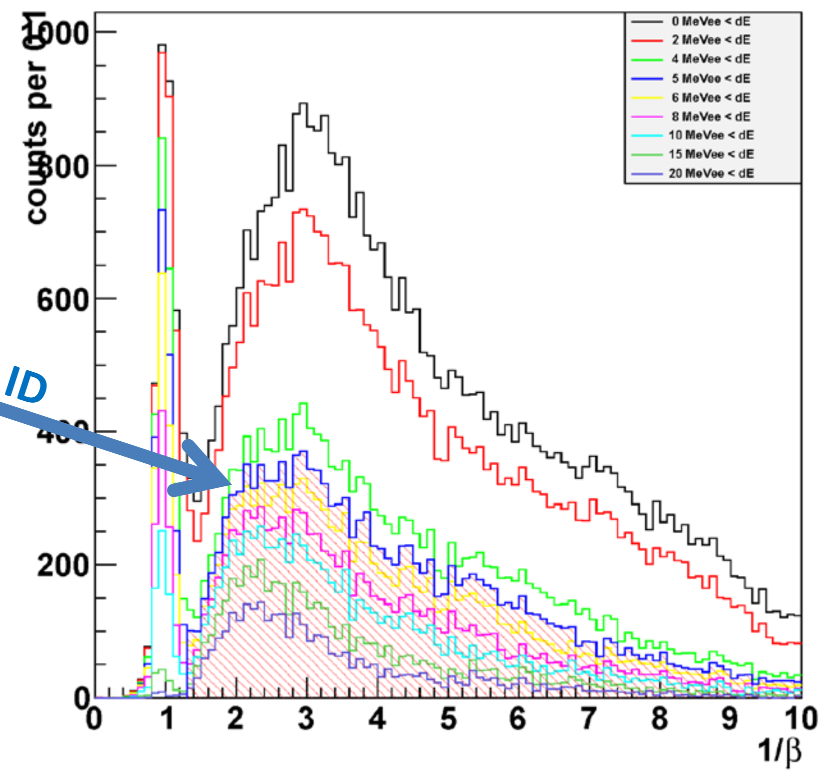
Neutron ID with CDS

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

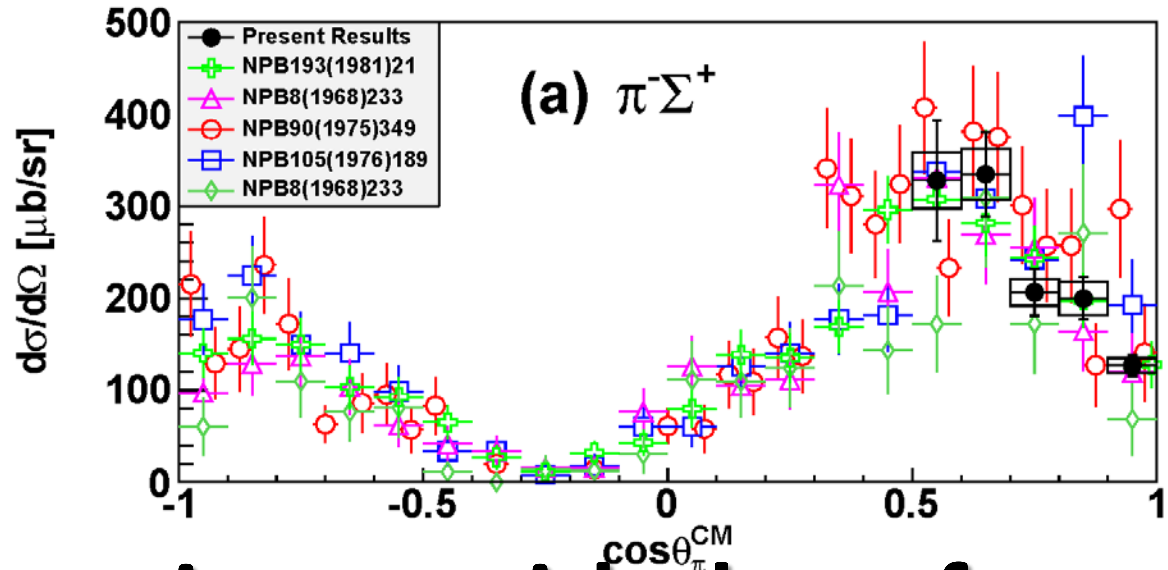


dE-cut dependence

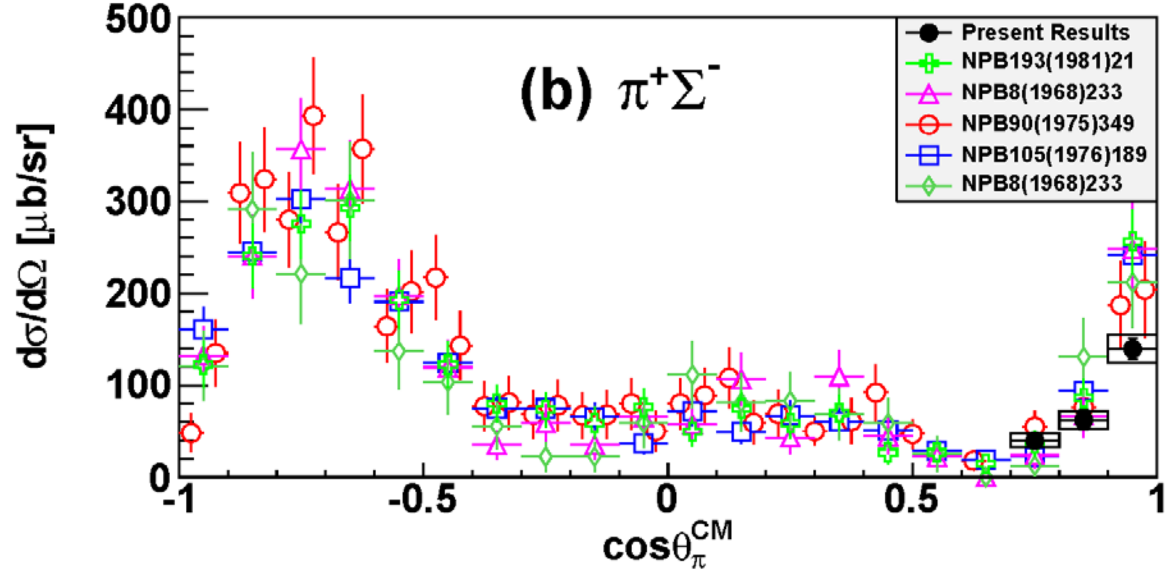


Neutron can be identified with CDS

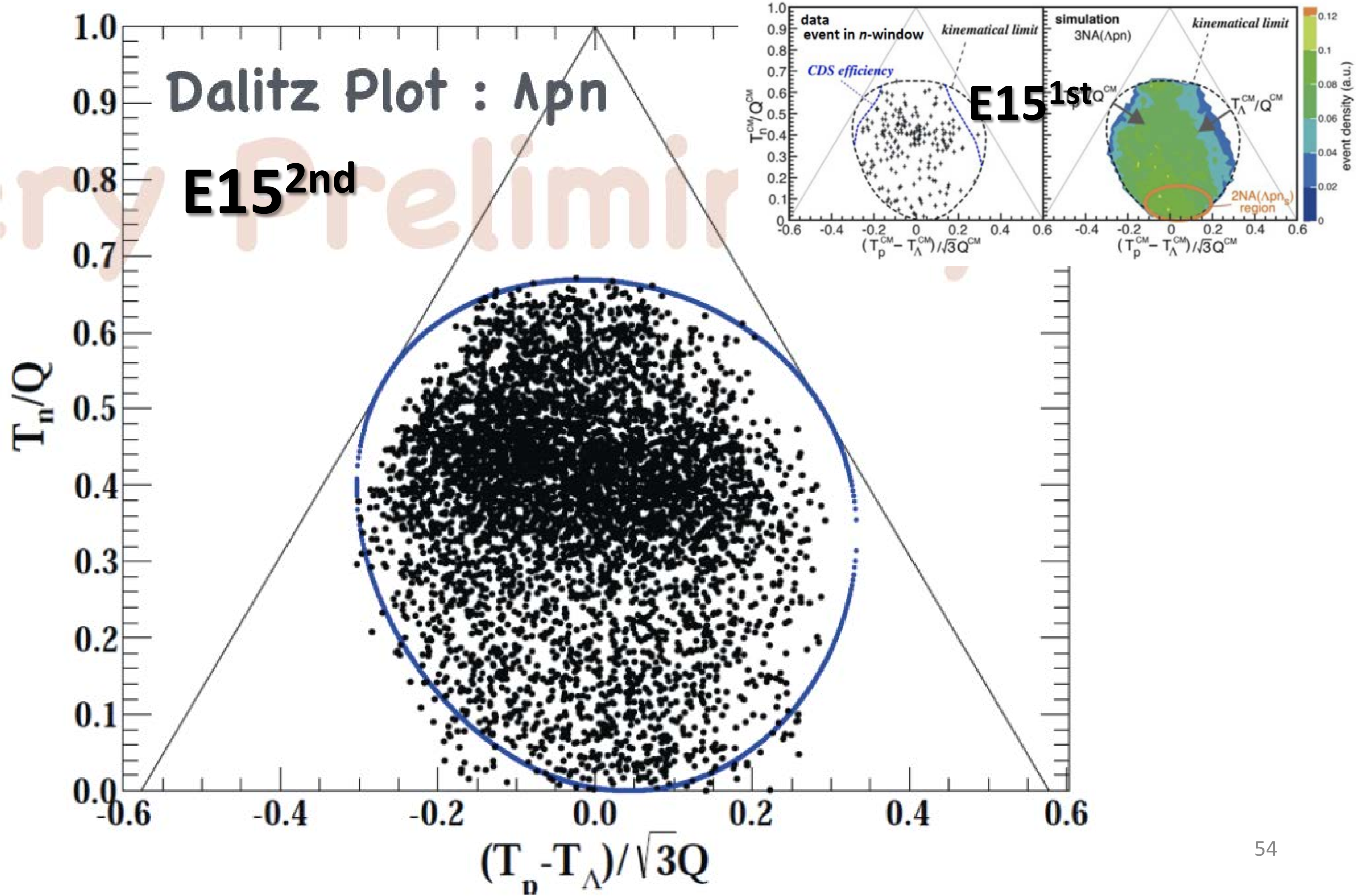
$K^-p \rightarrow \Sigma^+\pi^- / \Sigma^-\pi^+$ Cross Section



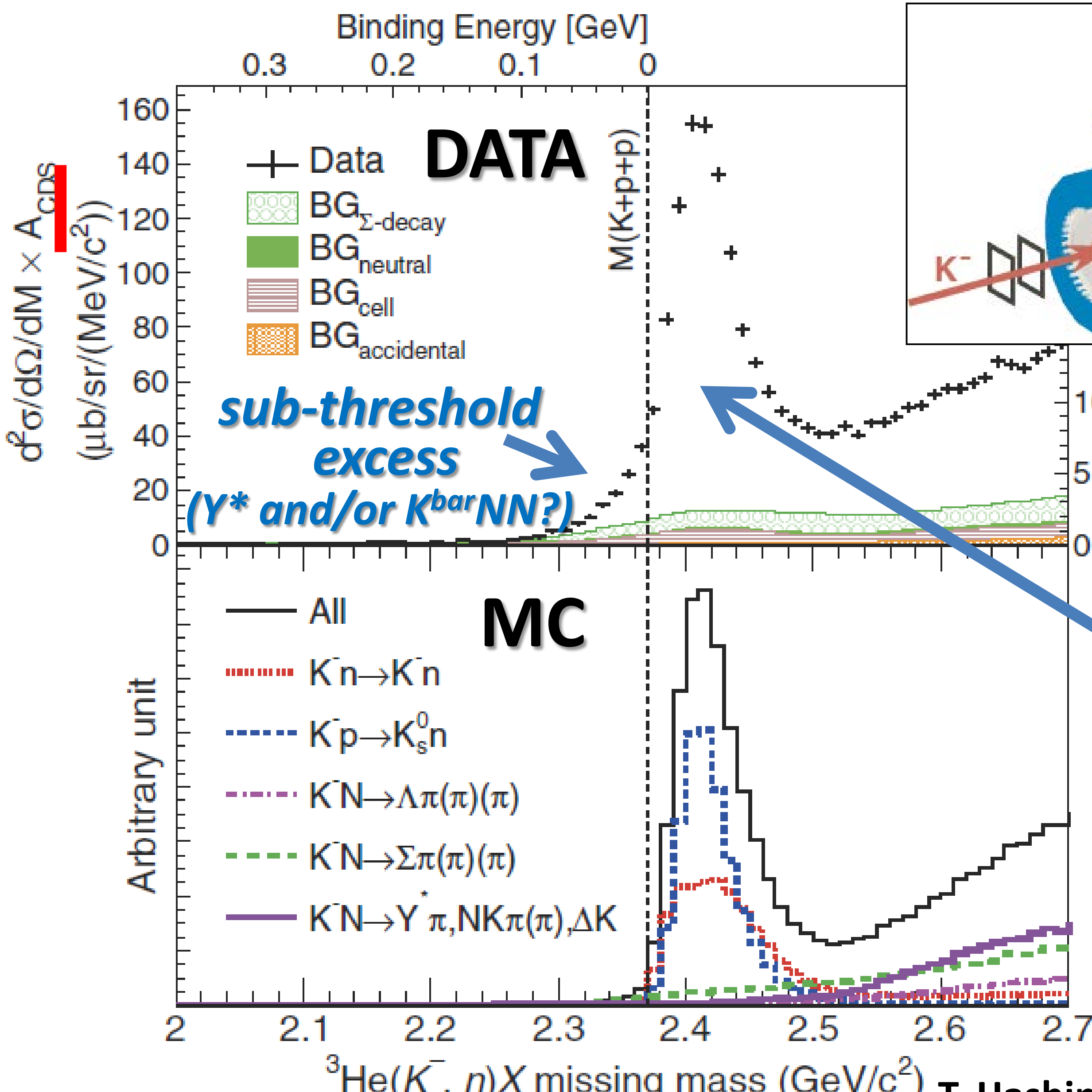
consistent with the references

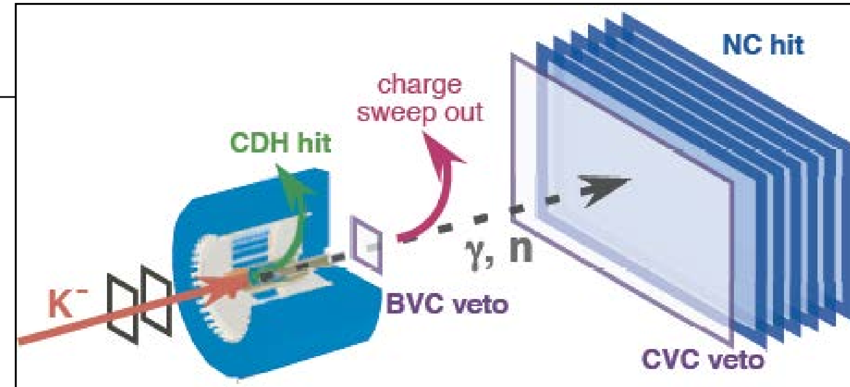


Exclusive $^3He(K^-,\Lambda p)n$



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

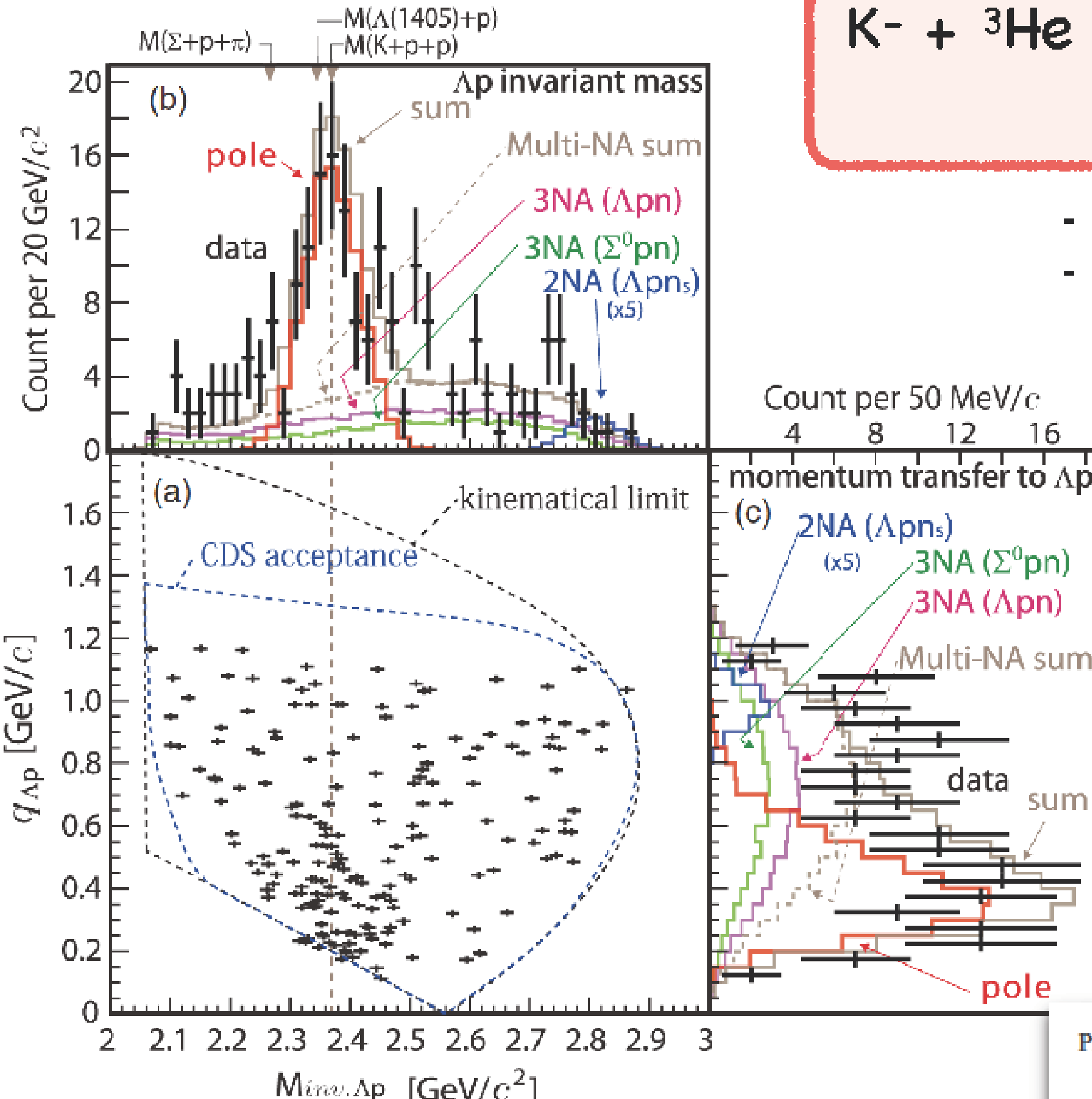
$K^- + {}^3He \rightarrow K^0 + \mathbf{n} + d_s$

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

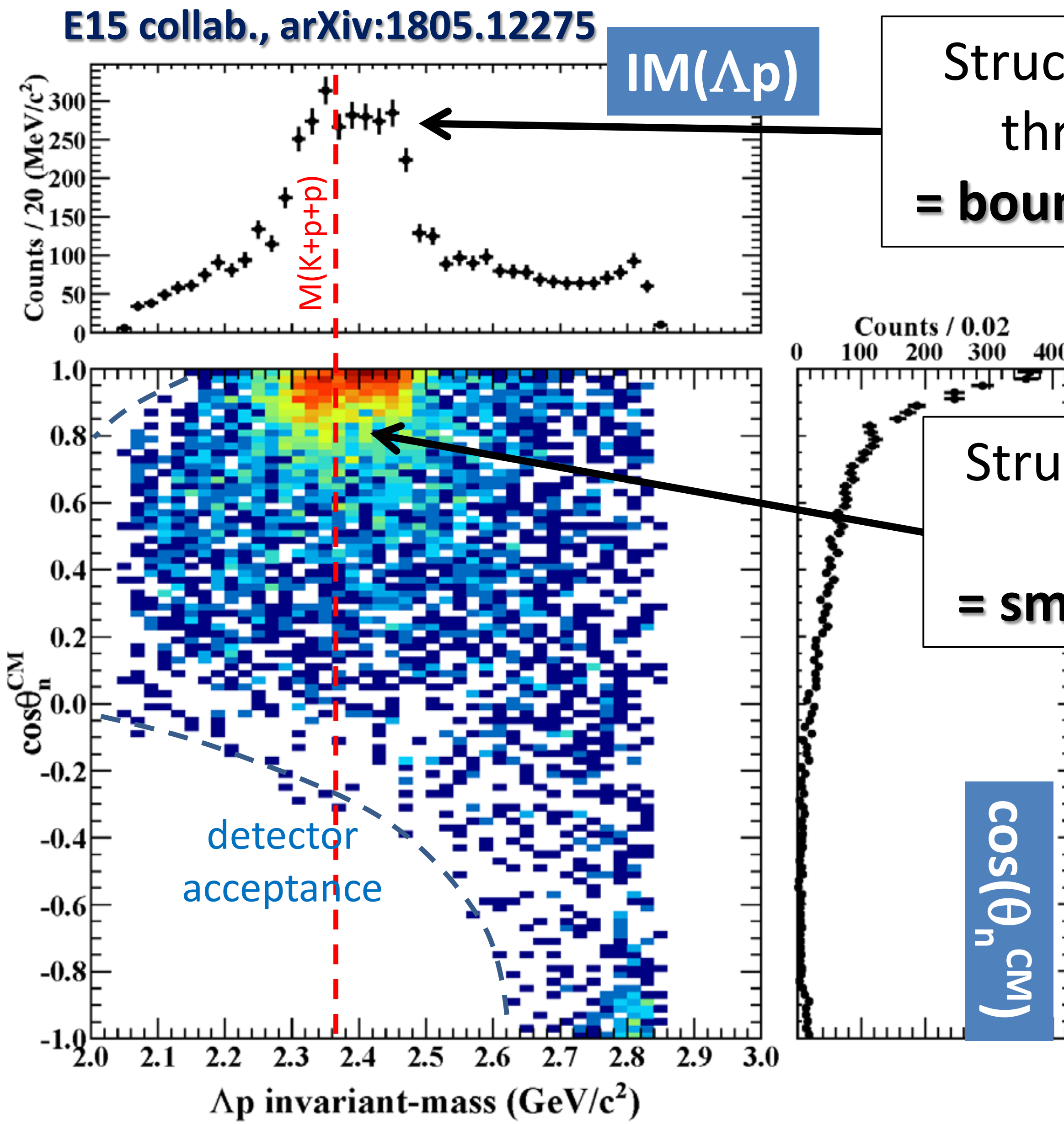
$\Gamma_X \sim$ 100 MeV

$Q_X \sim$ 400 MeV

Compact state?

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

IM(Λp) vs. cos(θ_n^{CM})

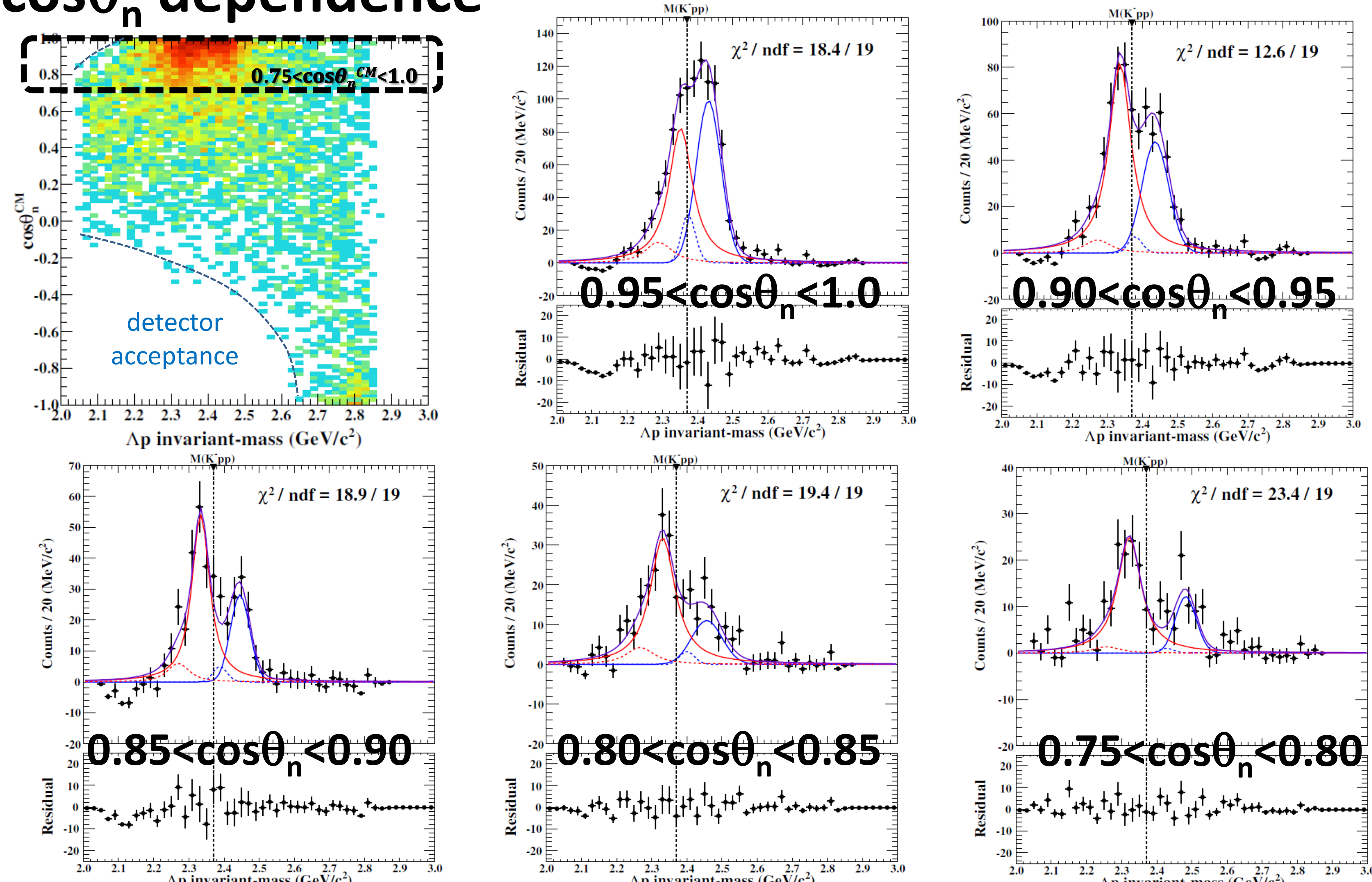


Structures around the K⁻pp threshold can be seen
= bound-state + quasi-elastic

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

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

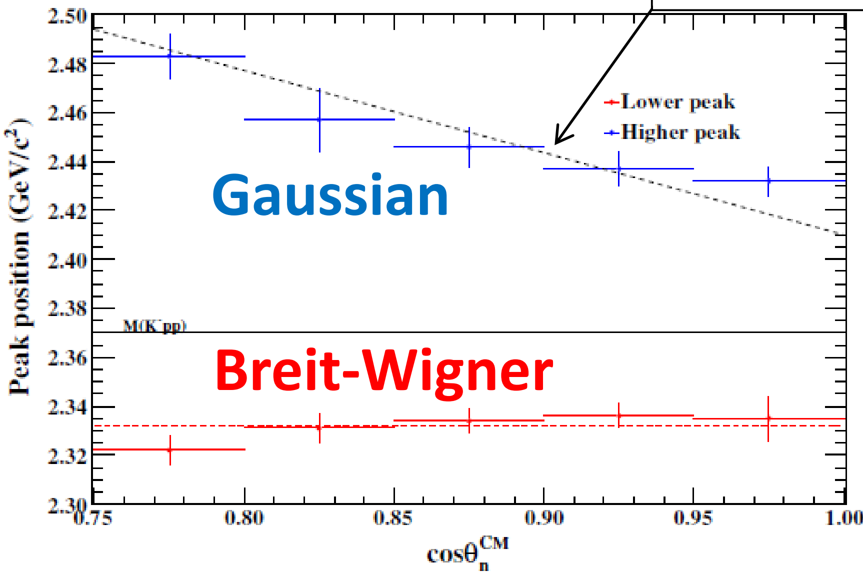
$\cos\theta_n$ dependence



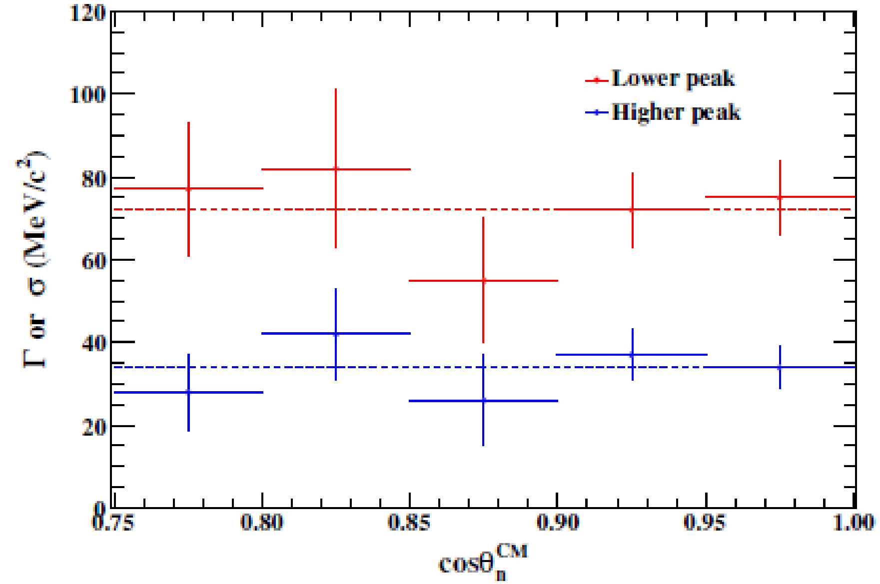
Results of ^{3}He(K$^-$,Λp)n [E15-2nd]

Peak position

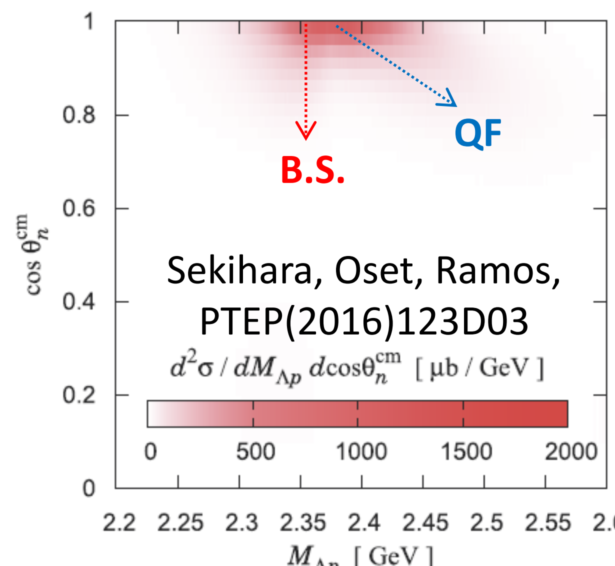
$$M_{QF} = M_{K^- pp} + \frac{q^2}{2M_{K^-}}$$



Width



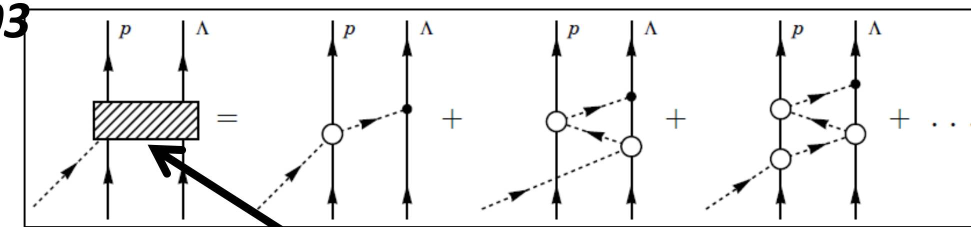
- **Above M(K-pp):**
  - peak shift by recoil kaon energy
- **Below M(K-pp):**
  - peak is independent to cosθ_n (~ momentum transfer)
- **Similar tendency as a theoretical calc., but QF seems to be originated from recoil kaon**



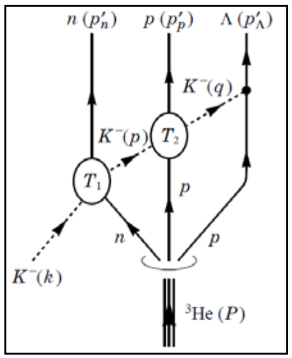
A Theoretical Interpretation of E15

Sekihara, Oset, Ramos, PTEP(2016)123D03

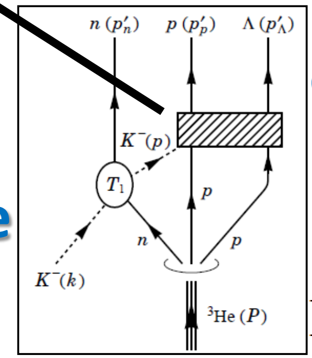
Chiral unitary approach



Uncorrelated Λ(1405)p state



K^bar NN bound-state



quasi-elastic kaon scattering