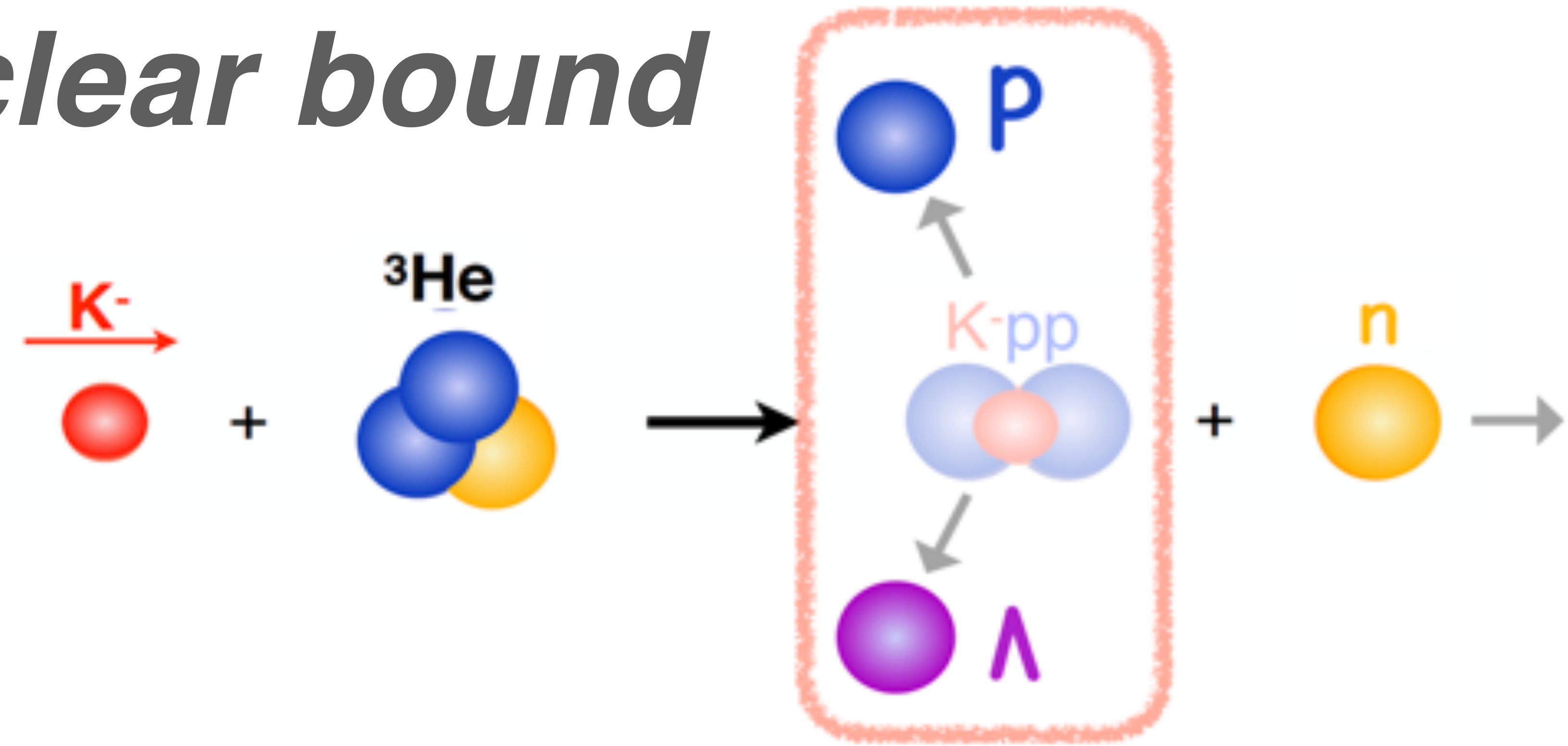
K中間子と原子核

K-meson and nuclei

Based on E15: Search for kaonic nuclear bound state



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

岩崎雅彦

理化学研究所　中間子科学研究室

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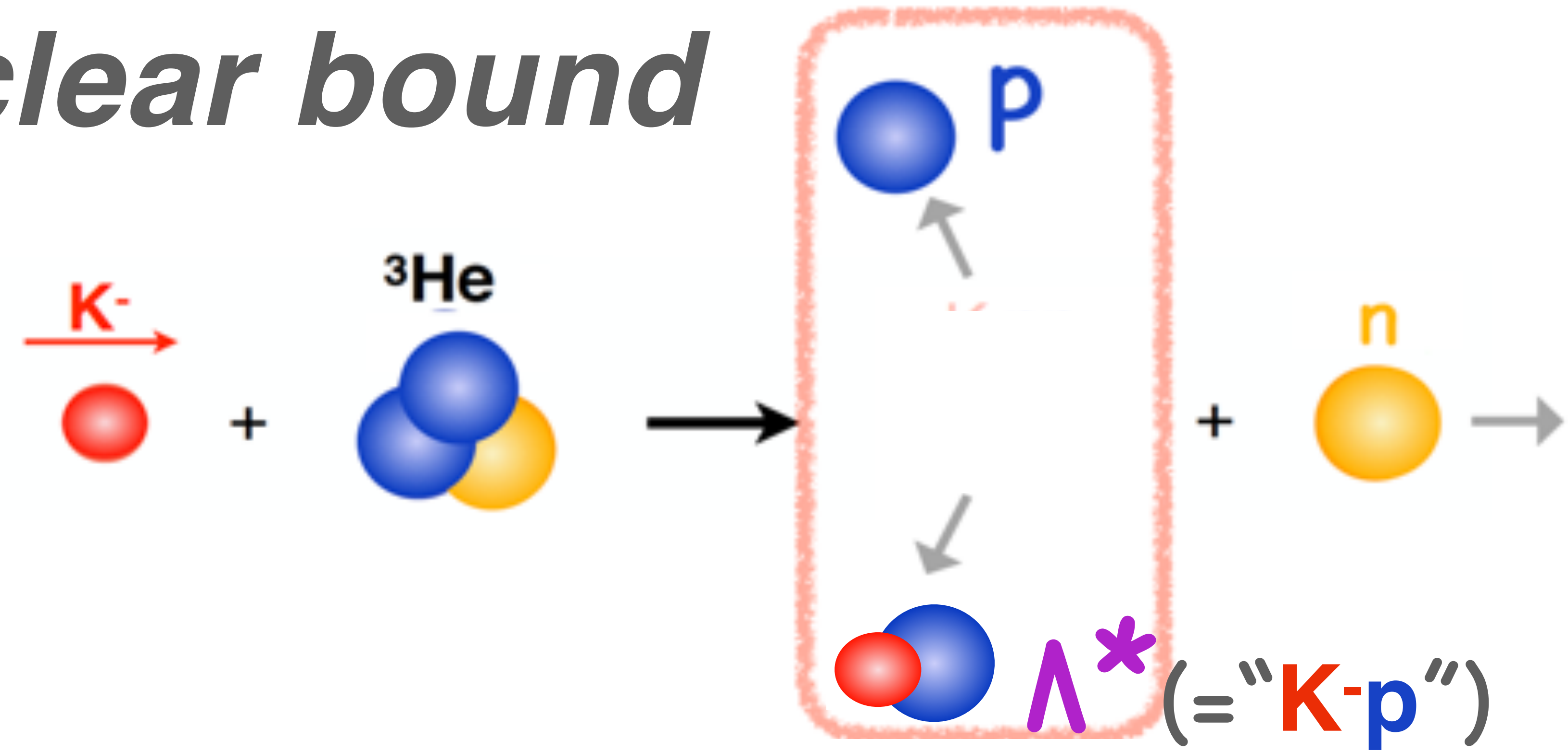
Based on E15: Search for kaonic nuclear bound state



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

$$\rightarrow (\Sigma\pi) + p + n$$

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Notification & apology

— Most of the spectra are still preliminary

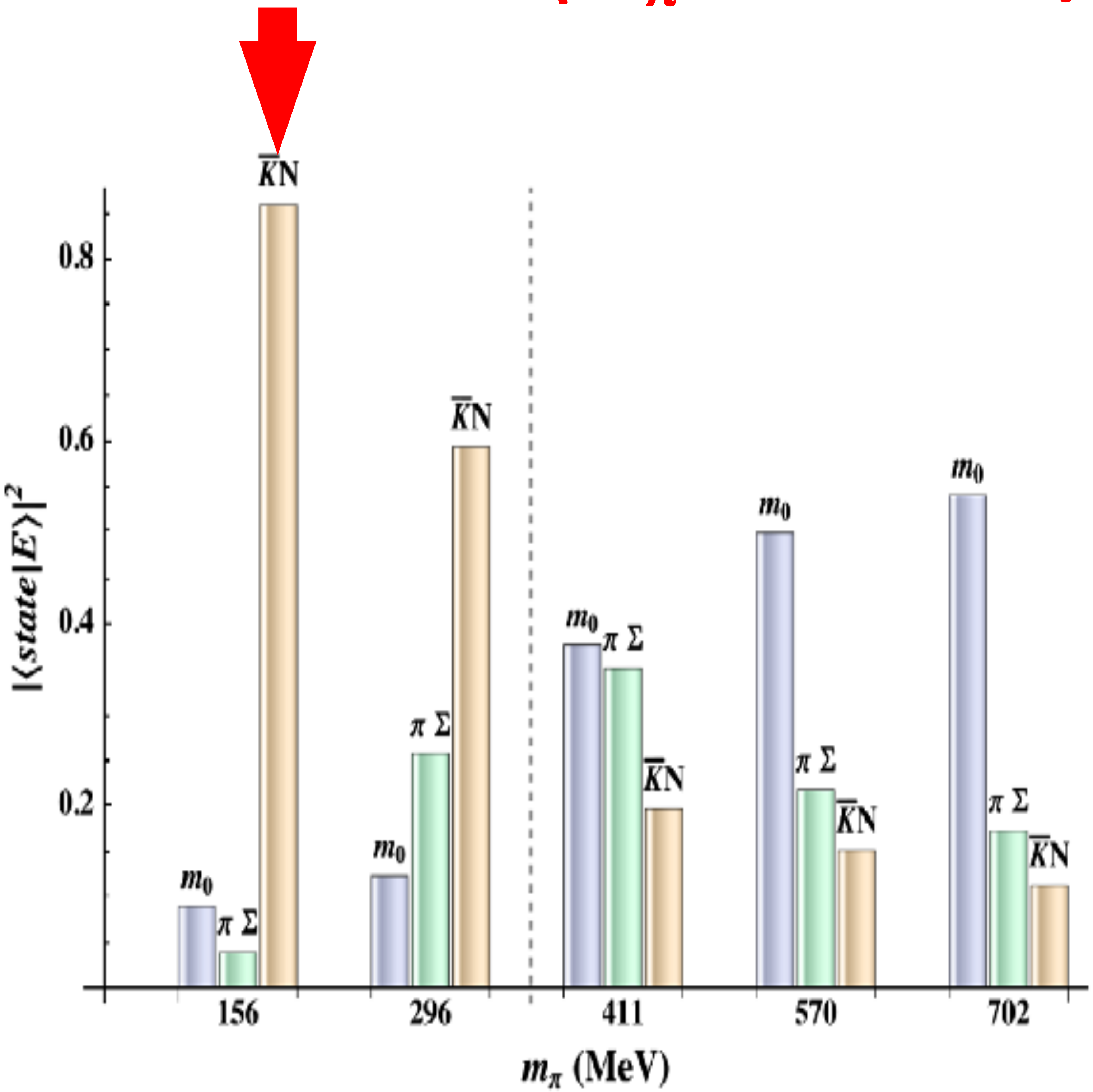
no definitive numbers,

although it is very close to the final

Please be aware three points in this talk

$\Lambda(1405)$ (Λ^*) in Lattice-QCD

~Real world (m_π = 140 MeV/c²)



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

- Recent Lattice QCD supports,

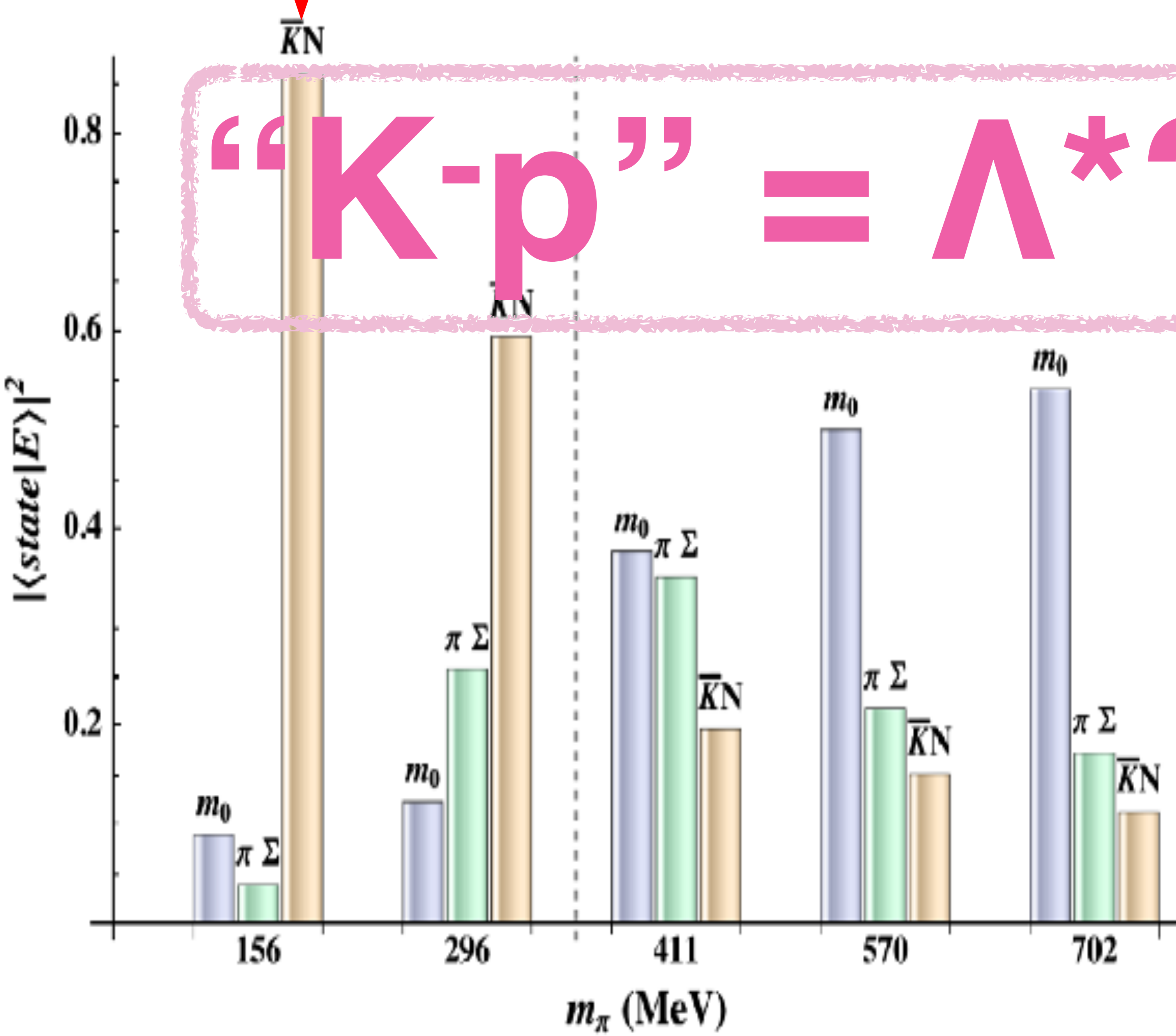
$$\Lambda(1405) = p - K^-$$

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

then, one can embed K into nucleus

Λ(1405) (Λ*) in Lattice-QCD

~ *Real world (m_π = 140 MeV/c^2)*



"K⁻p" = Λ*?

- **Recent Lattice QCD supports,**

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

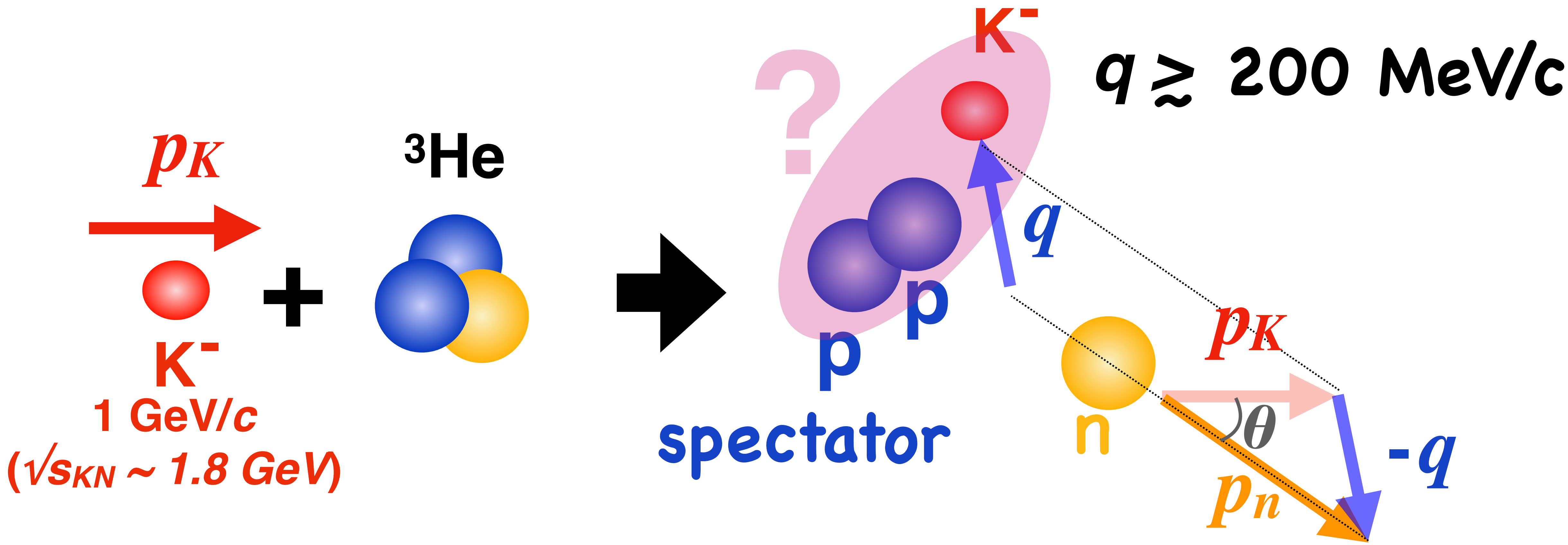
$$= (uud)\text{-}(\bar{u}s)$$

then, one can embed K into nucleus

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

Kinematics when $M_{inv.}$"?" is known

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



opening angle

$q \longleftrightarrow \theta$ unique for given $M_{inv.}$"?"

momentum transfer

How we can learn physics from event distributions?

5 kinematical parameters for $\Lambda p n$ final state (including $\Lambda \rightarrow p\pi$ decay)

resonance

$$K^- + {}^3\mathrm{He} \rightarrow R + n \quad \& \quad R \rightarrow \Lambda + p$$

ejectile

How R is formed:

$M_{inv.\Lambda p}$: mass pole position

q : momentum transfer to $M_{inv.\Lambda p}$ ($\cos\theta_n$)

How R is decay to Λp:

$\cos\theta_{q\rightarrow p\Lambda}$: angle between *q* and *Λp decay axis*

$\eta_{Kn\_\Lambda p}$: *angle between K-n plane and Λ-p plane*

How R can polarize Λ:

$\cos\theta_{\Lambda\rightarrow p\pi}$: Λ polarization

How we can learn physics from event distributions?

5 kinematical parameters for Λpn final state (including Λ→pπ decay)

resonance

$$K^- + {}^3\mathrm{He} \rightarrow R + n \quad \& \quad R \rightarrow \Lambda + p$$

ejectile

How R is formed:

$M_{inv.\Lambda p}$: mass pole position

q : momentum transfer to $M_{inv.\Lambda p}$ ($\cos\theta_n$)

How R is decay to Λp:

$\cos\theta_{q\rightarrow p\Lambda}$: angle between q and Λp *decay axis*

$\eta_{Kn\_\Lambda p}$: *angle between K-n plane and Λ-p plane*

How R can polarize Λ:

$\cos\theta_{\Lambda\rightarrow p\pi}$: Λ polarization

integrated out for S-wave

Please be aware three points in this talk

$\boxed{\text{“}K^{-}p\text{”} \sim \Lambda^{*}}$

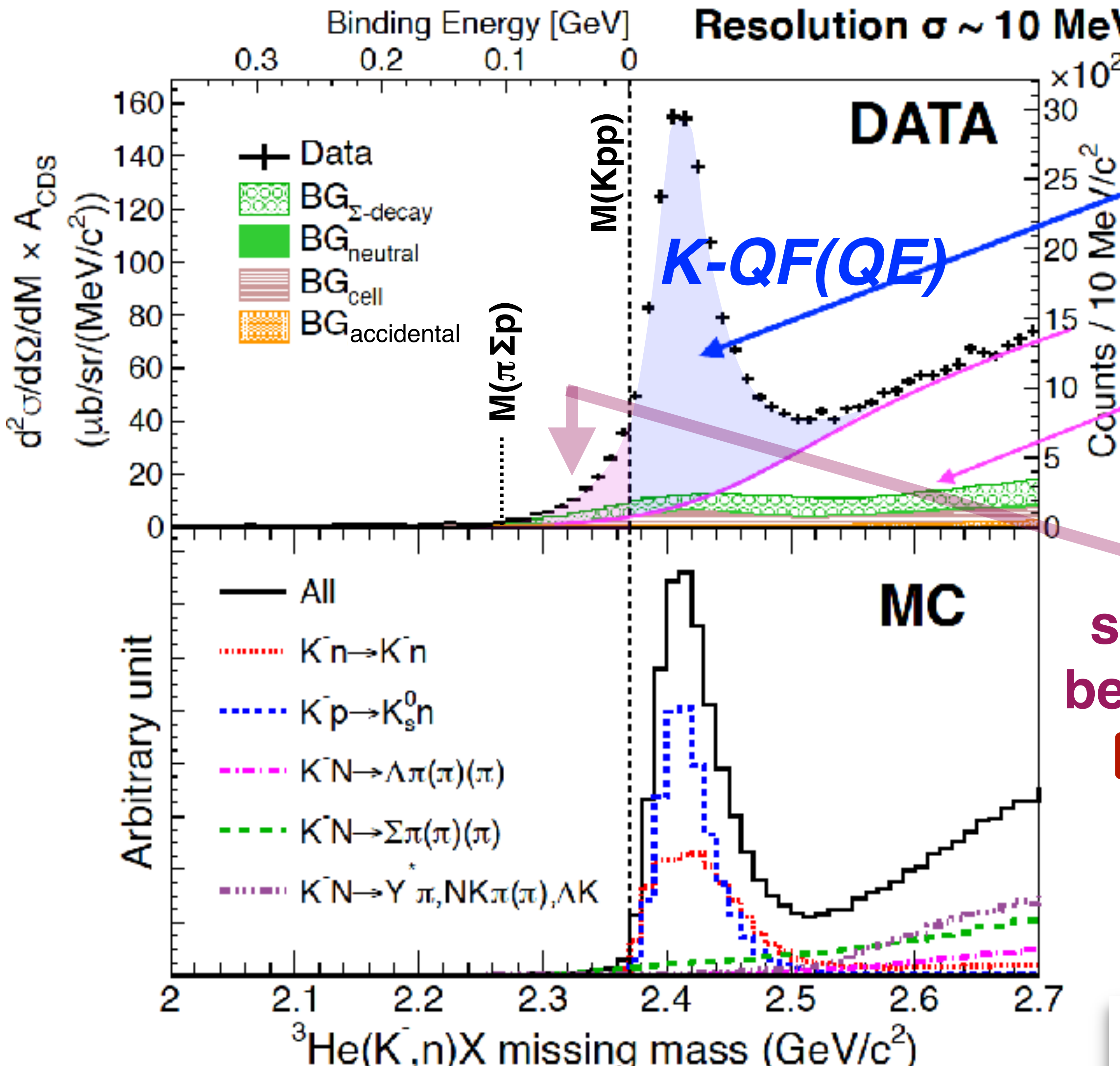
$q \longleftrightarrow \theta$ unique for given $M_{inv.}$“?”

$\boxed{f(M_{inv.\Lambda p}, q_{\Lambda p})}$

Previous experiments E15^{1st}

Forward n semi-inclusive

Resolution σ ~ 10 MeV/c² @ threshold



Quasi-elastic

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

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

Hyperon decay

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

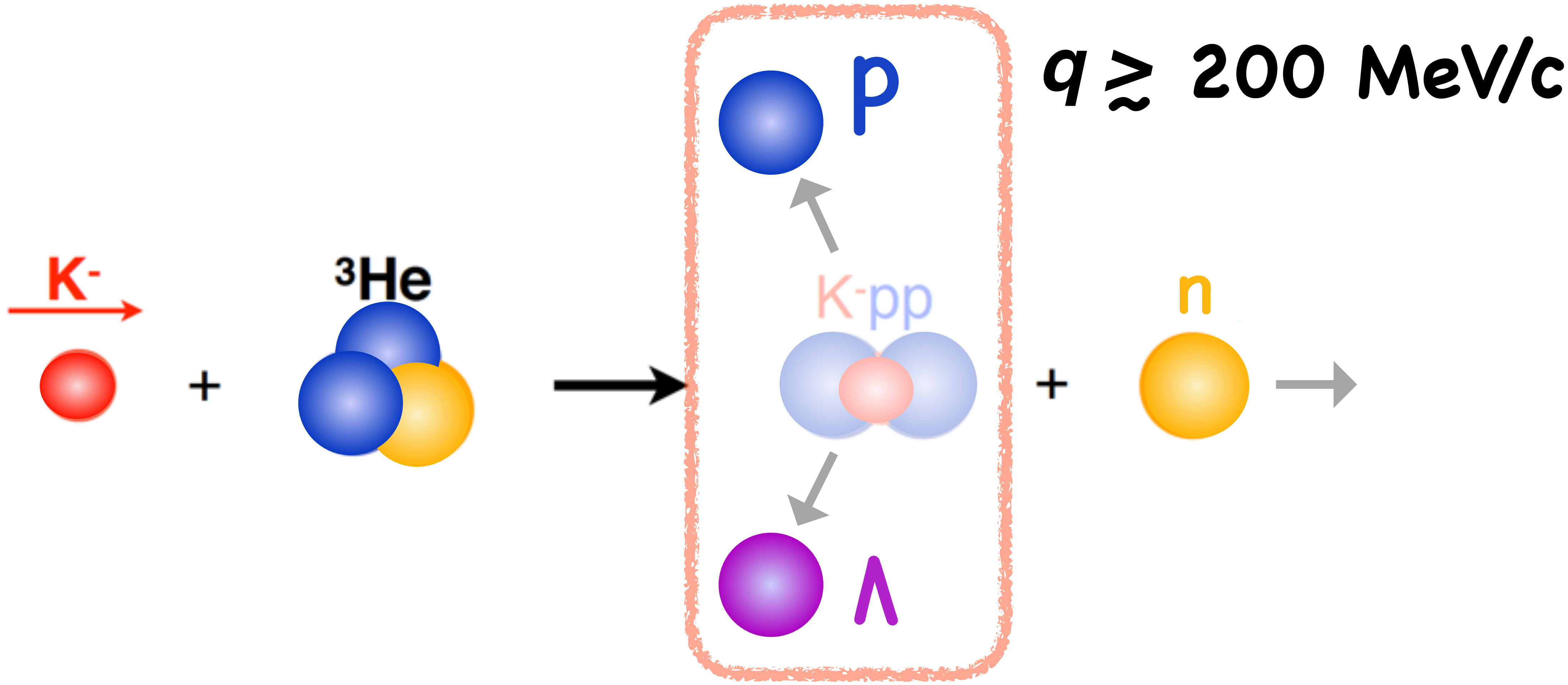
$Y \rightarrow n + \pi$

significant yield ~ 1 mb/st below the threshold M(Kpp)

How they produced?

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

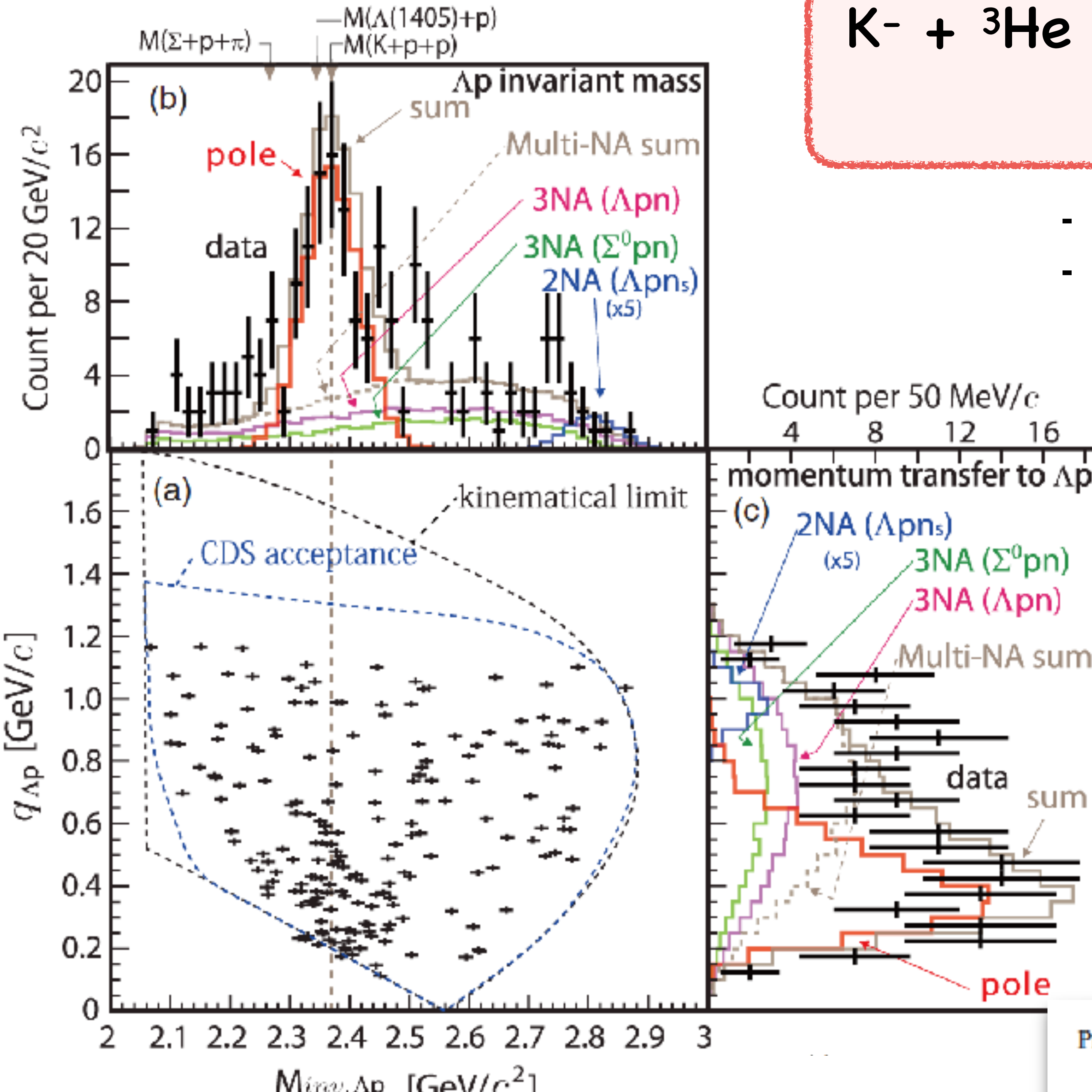
Forward $n_{mis.}$ + Λ p



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

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

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

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

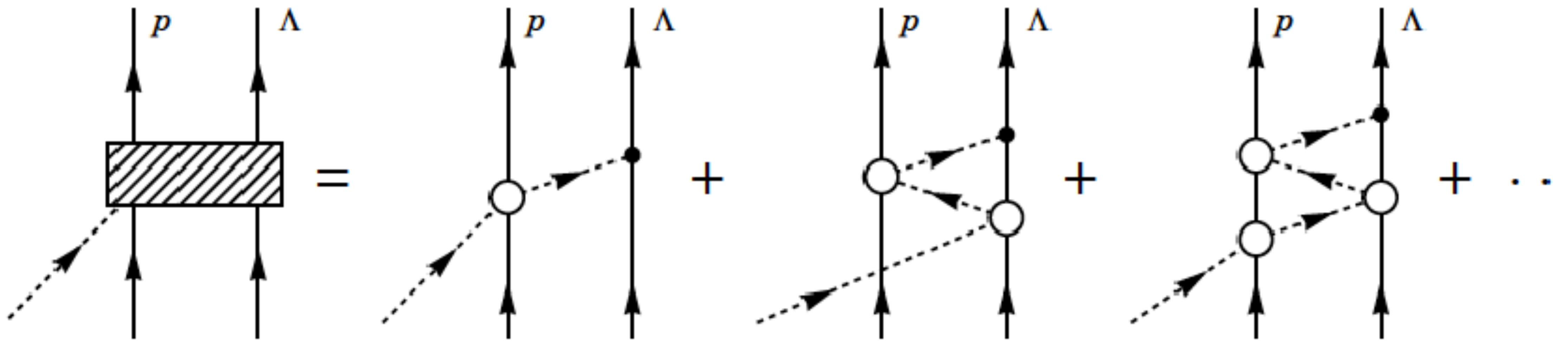
Compact state?

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

Forward $n_{mis.}$ + Λp vs. theory

Sekihara-Oset-Ramos

Structure can be explained with quasi-elastic K scattering & Kpp @ x-UM?



Sekihara Oset Ramos

PTEP

Prog. Theor. Exp. Phys. 2016, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166

On the structure observed in the in-flight ^{3}He(K^-, Λp)n reaction at J-PARC

Takayasu Sekihara[1,*], Eulogio Oset[2], and Angels Ramos[3]

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[2]Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apdo. 22085, 46071 Valencia, Spain
[3]Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain
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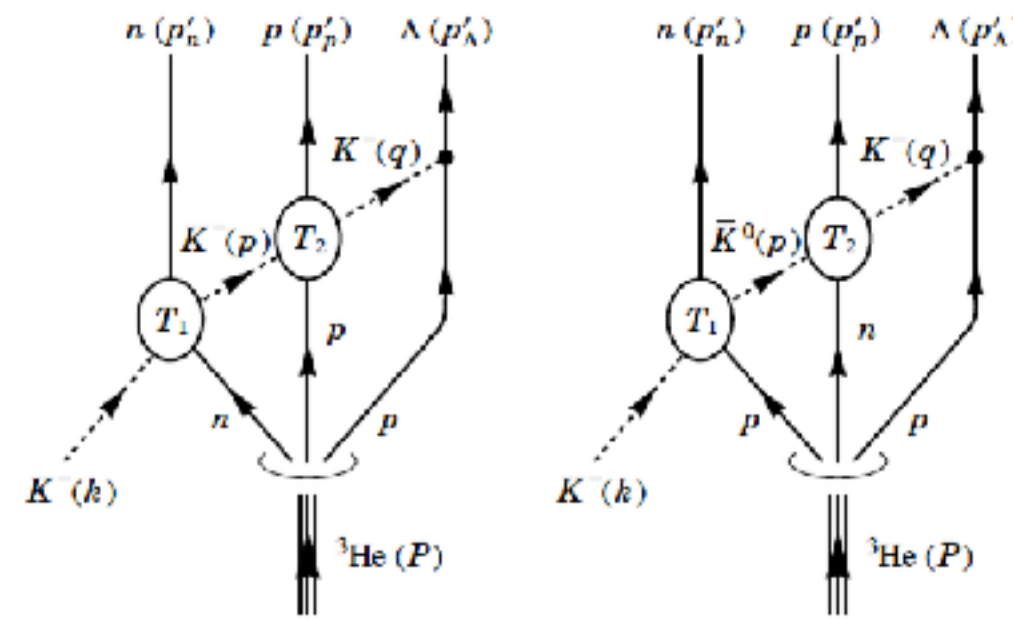
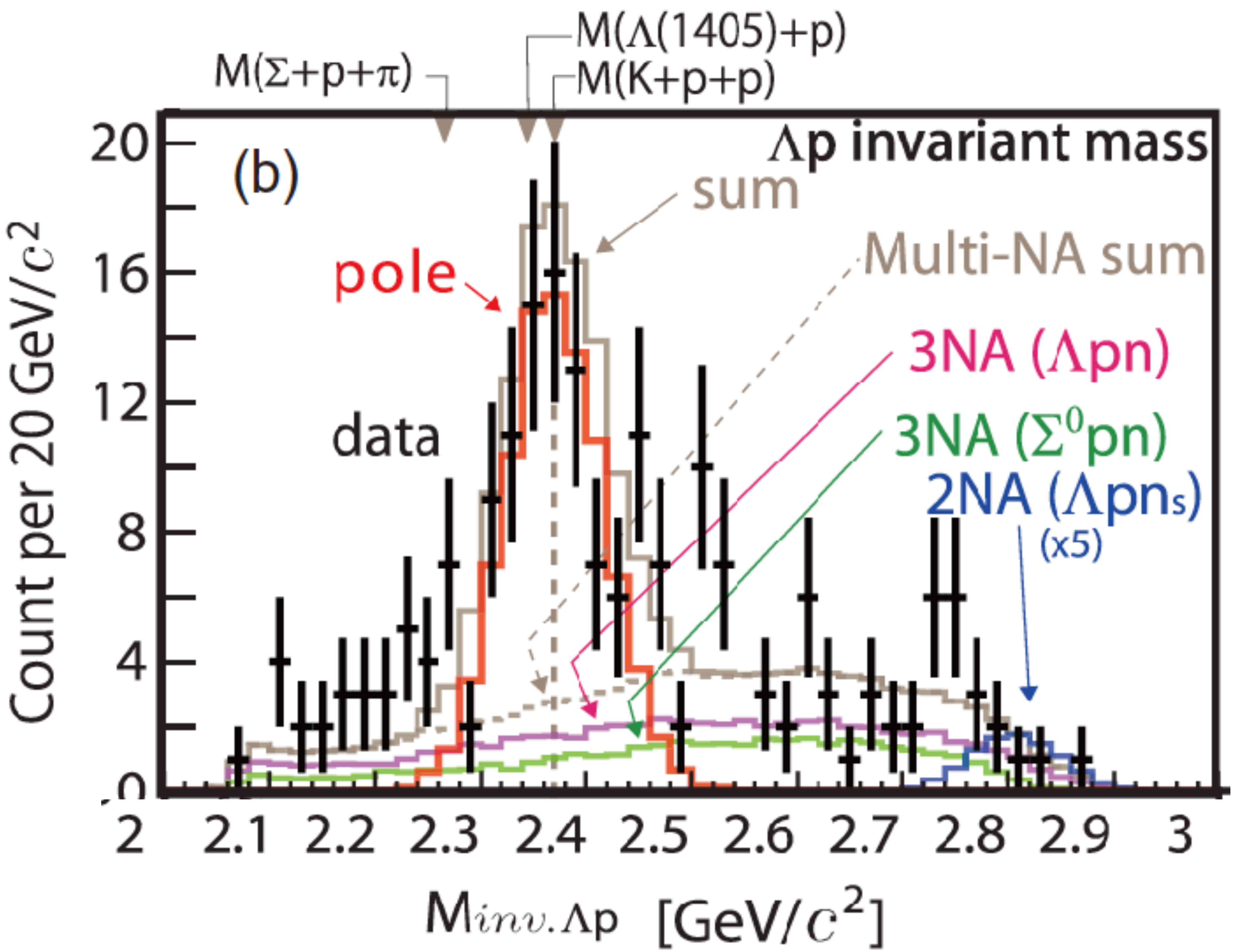
Received July 11, 2016; Revised October 7, 2016; Accepted October 15, 2016; Published December 30, 2016



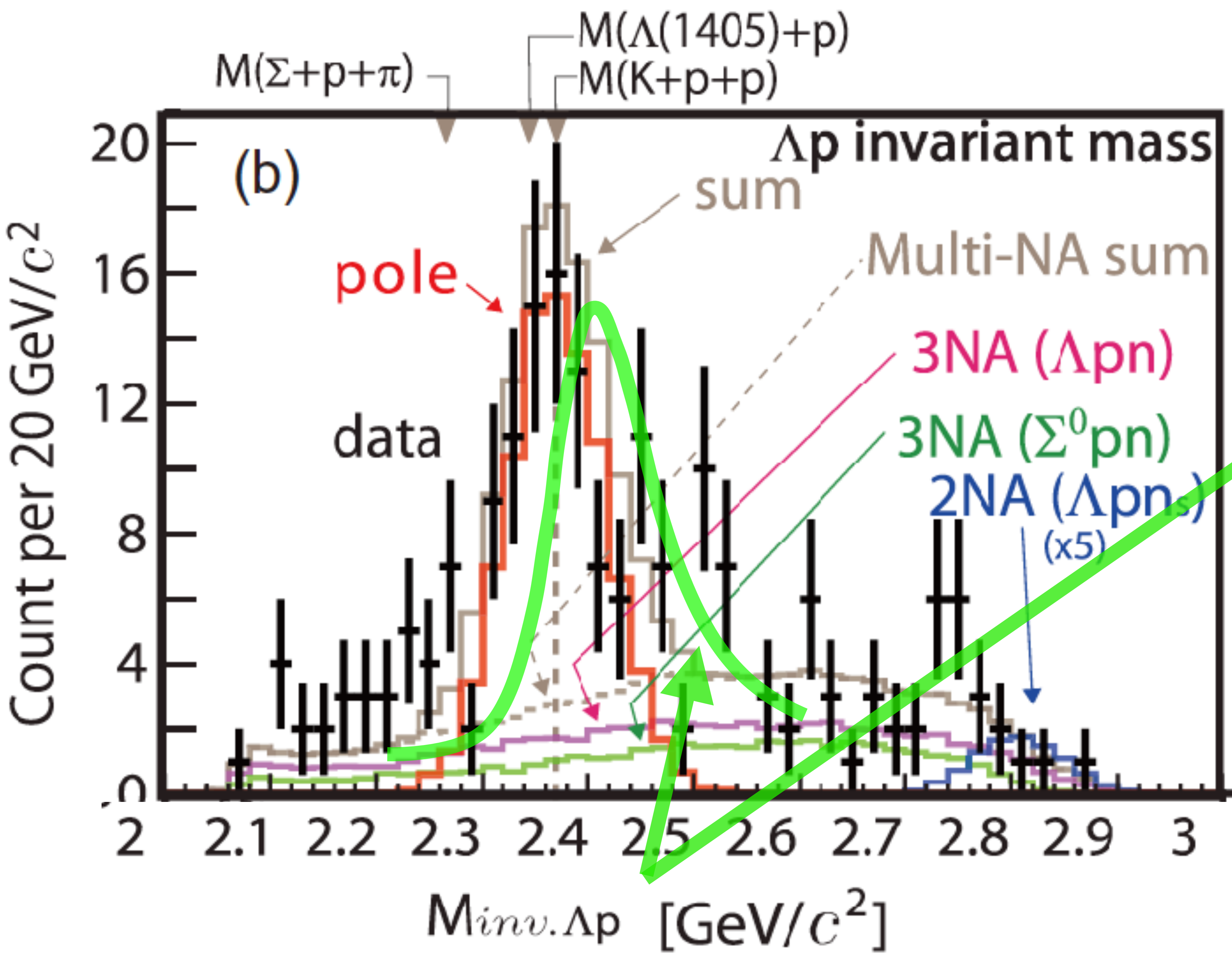
Forward $n_{mis.}$ + Λp



Forward $n_{mis.}$ + Λp vs. theory

Sekihara-Oset-Ramos

Prog. Theor. Exp. Phys. **2016**, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166



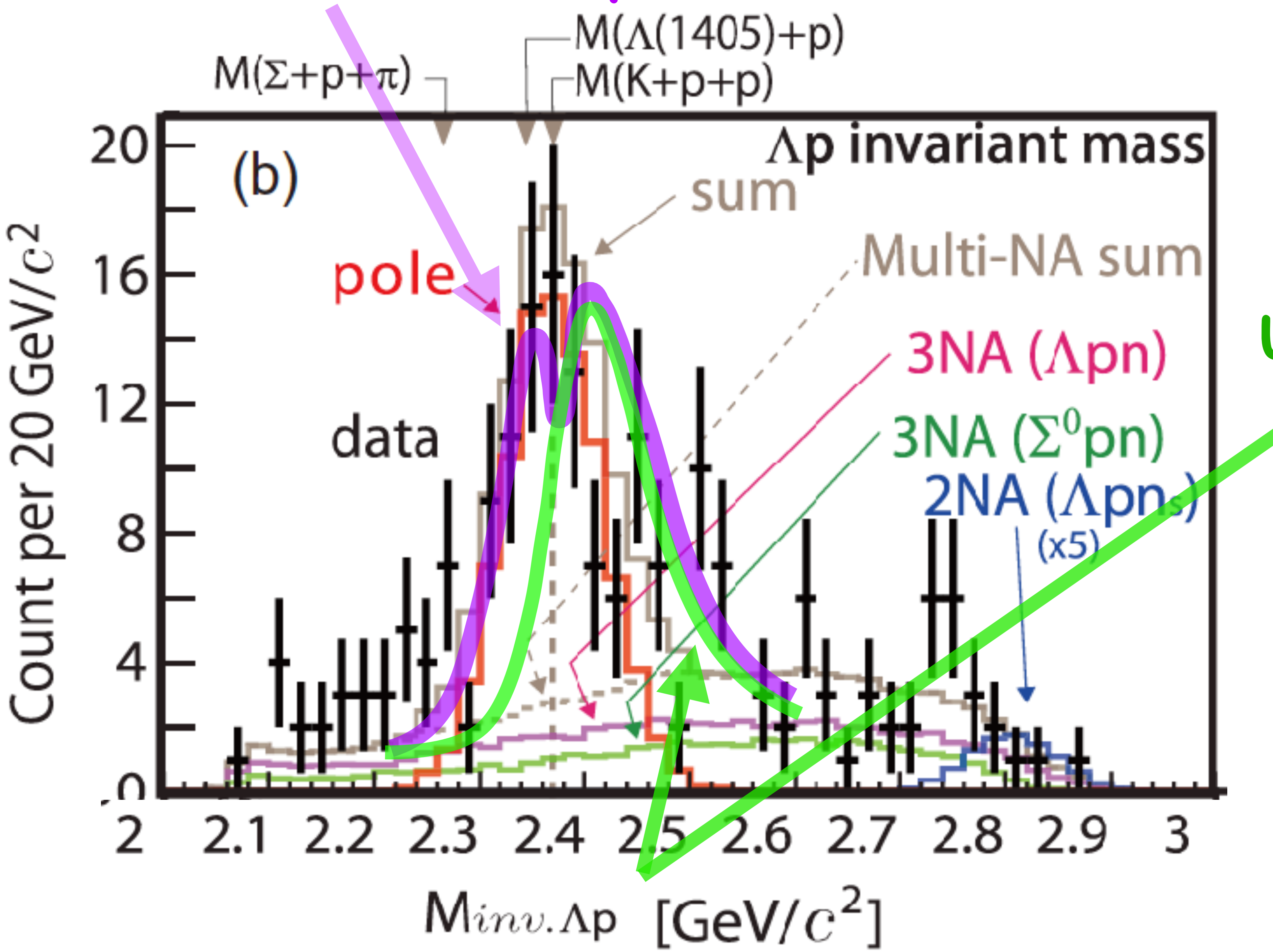
Uncorrelated Λ*p only

Forward $n_{mis.}$ + Λp vs. theory

Sekihara-Oset-Ramos

Prog. Theor. Exp. Phys. **2016**, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166

"Kpp"
+ Uncorrelated Λ*p



Uncorrelated Λ*p only

Forward $n_{mis.}$ + Λp vs. theory

Sekihara–Oset–Ramos

Prog. Theor. Exp. Phys. **2016**, 123D03 (27 pages)
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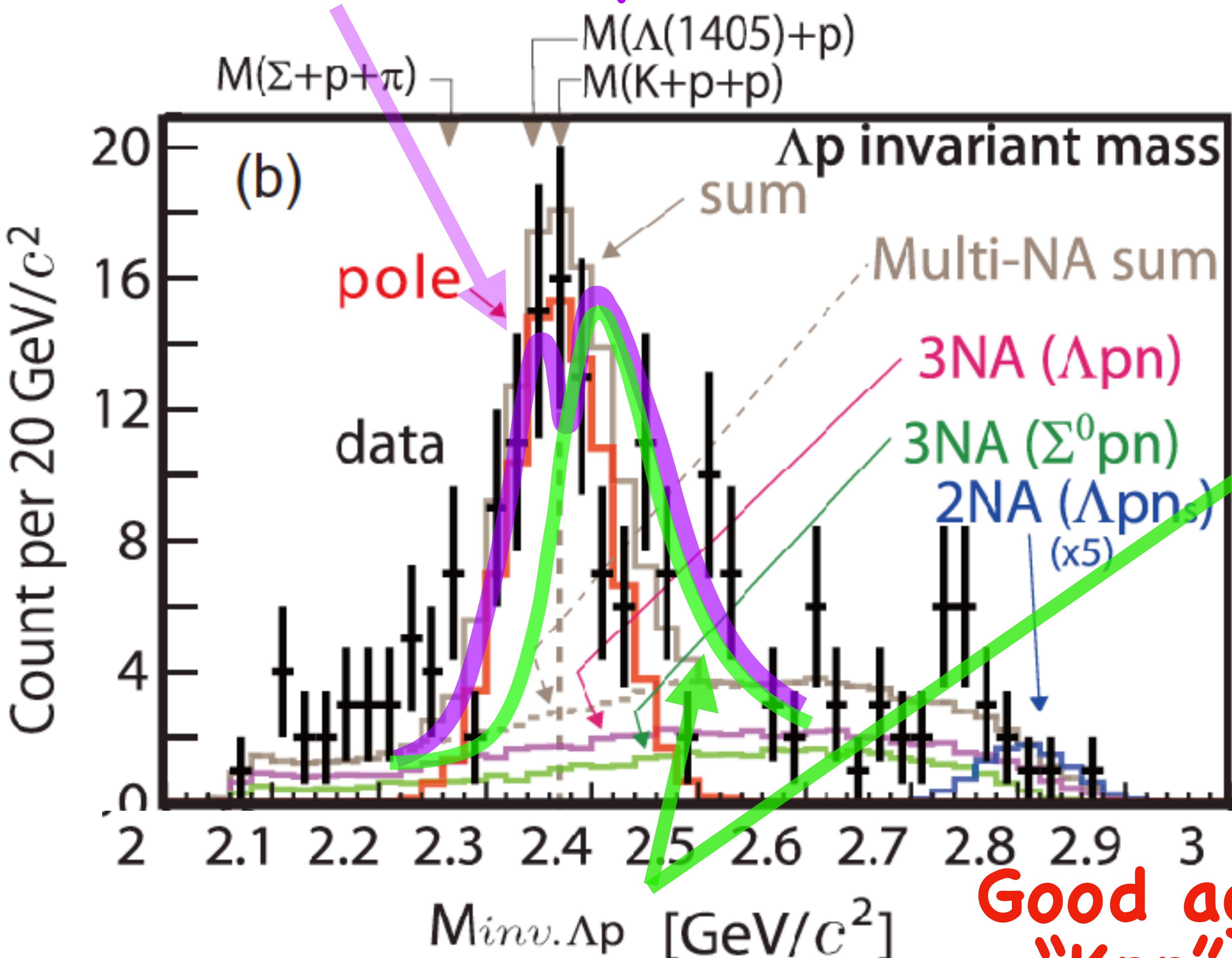
"Kpp"
+ Uncorrelated Λ*p



Uncorrelated
Λ*p only

Good agreement! for
"Kpp" + uncr. Λ*p

T. Yamaga

Higher statistics @ E15^{2nd}

Forward $n_{mis.}$ + $(\Lambda\ p)_{CDS}$

T. Yamaga

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

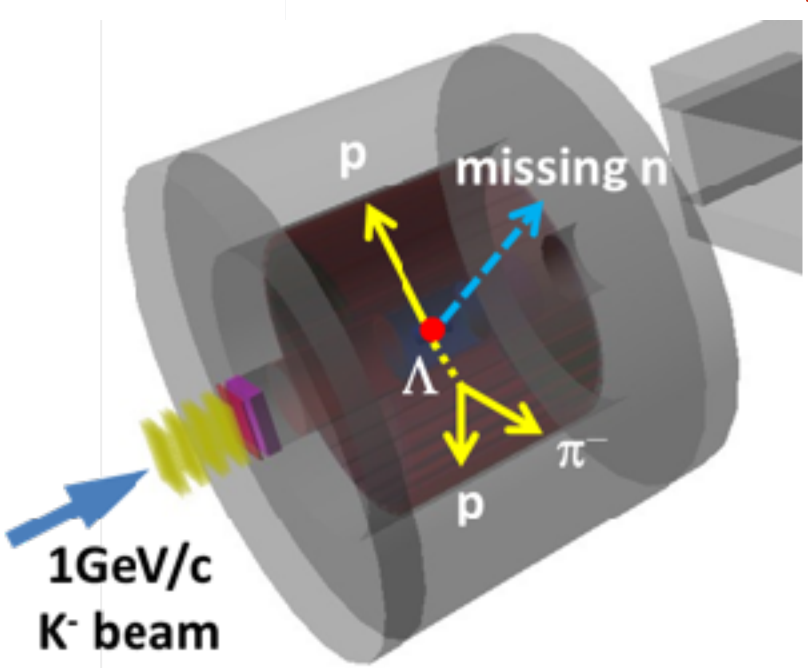
Improving statistics via E15[2nd] data

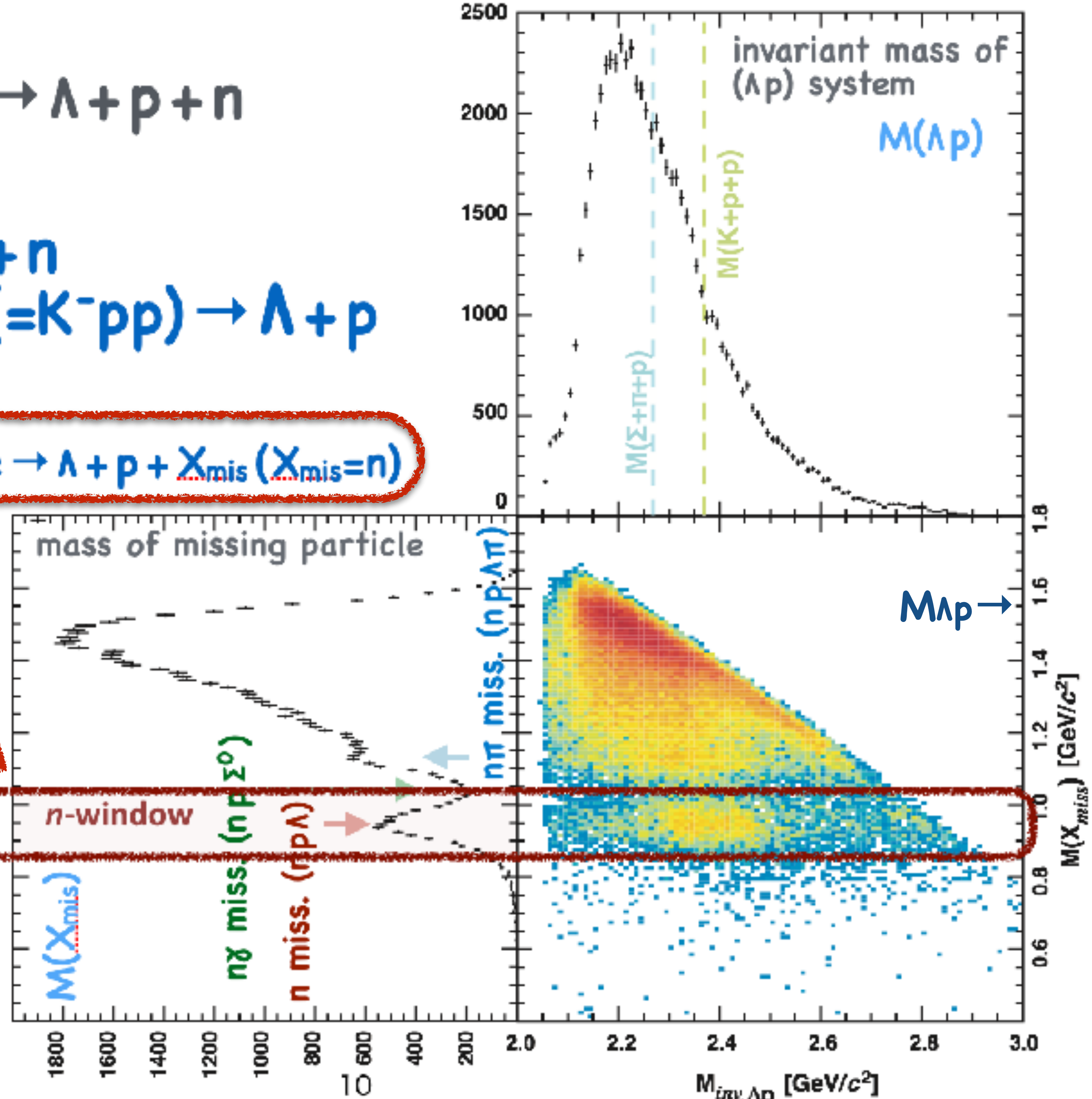
$K^- + {}^3He \rightarrow ? \rightarrow \Lambda + p + n$

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

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

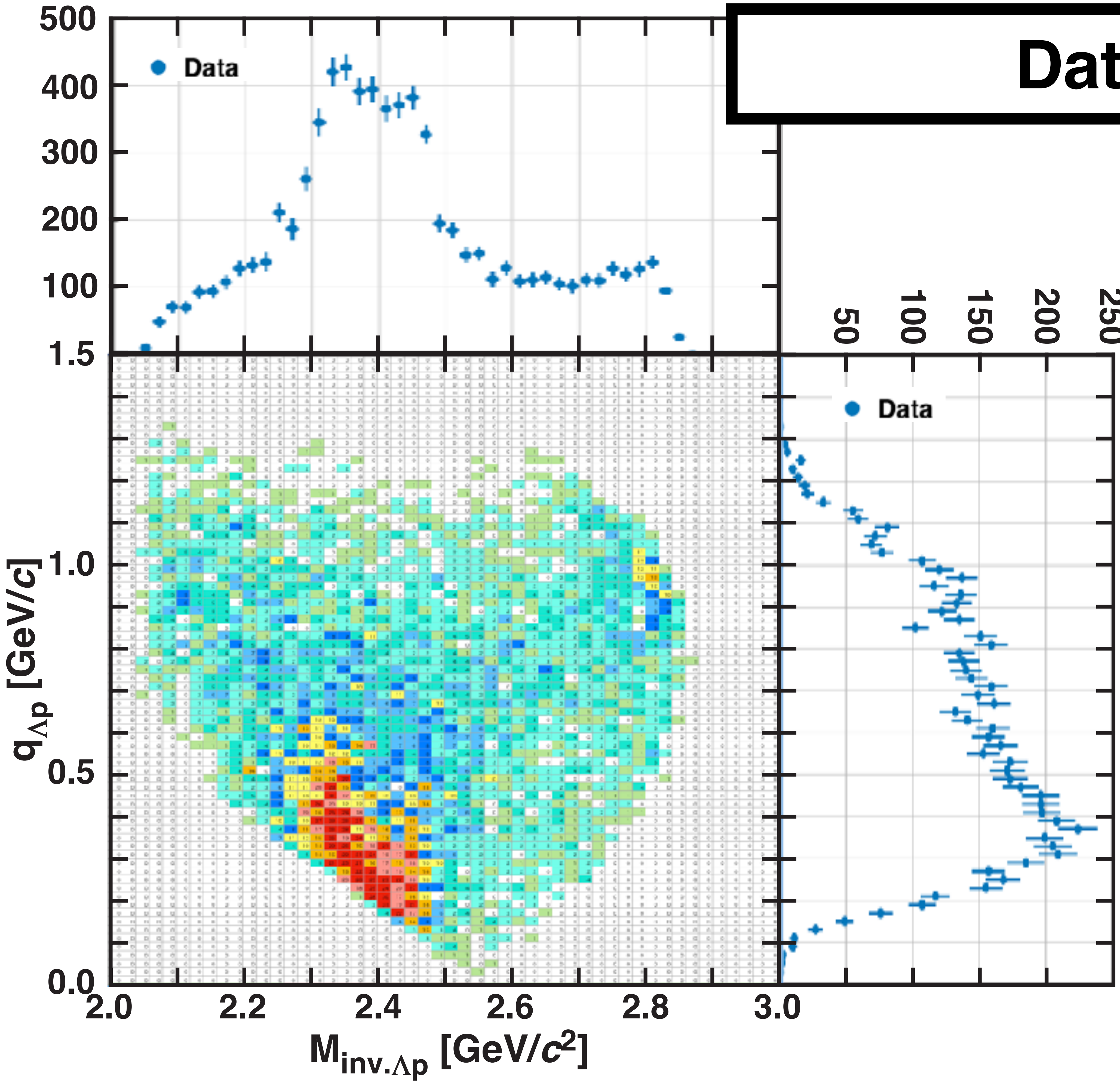
$K^- + {}^3He \rightarrow \Lambda + p + X_{mis}\ (X_{mis}=n)$

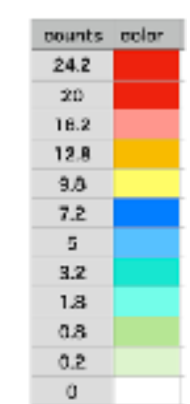




Data

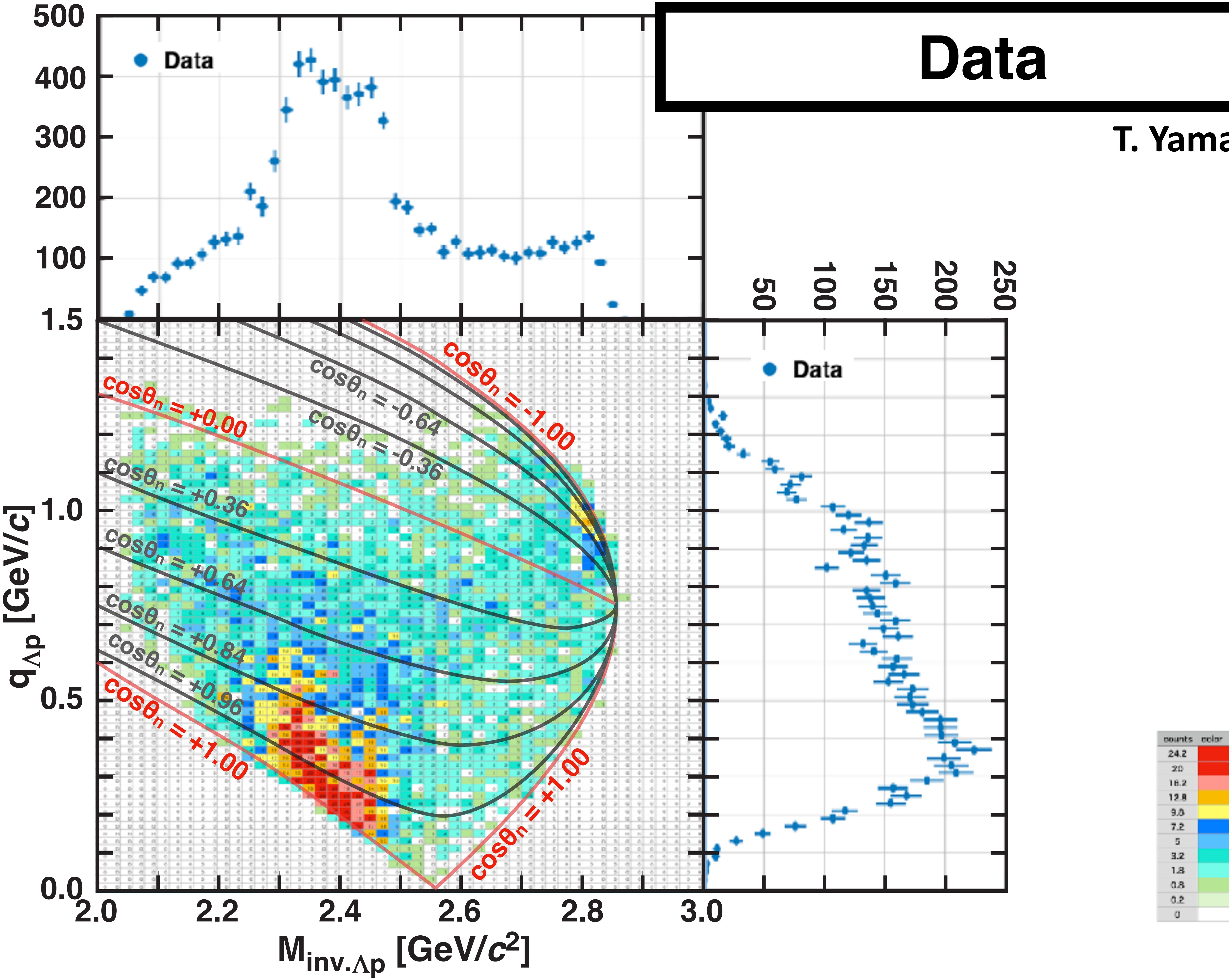
T. Yamaga





Data

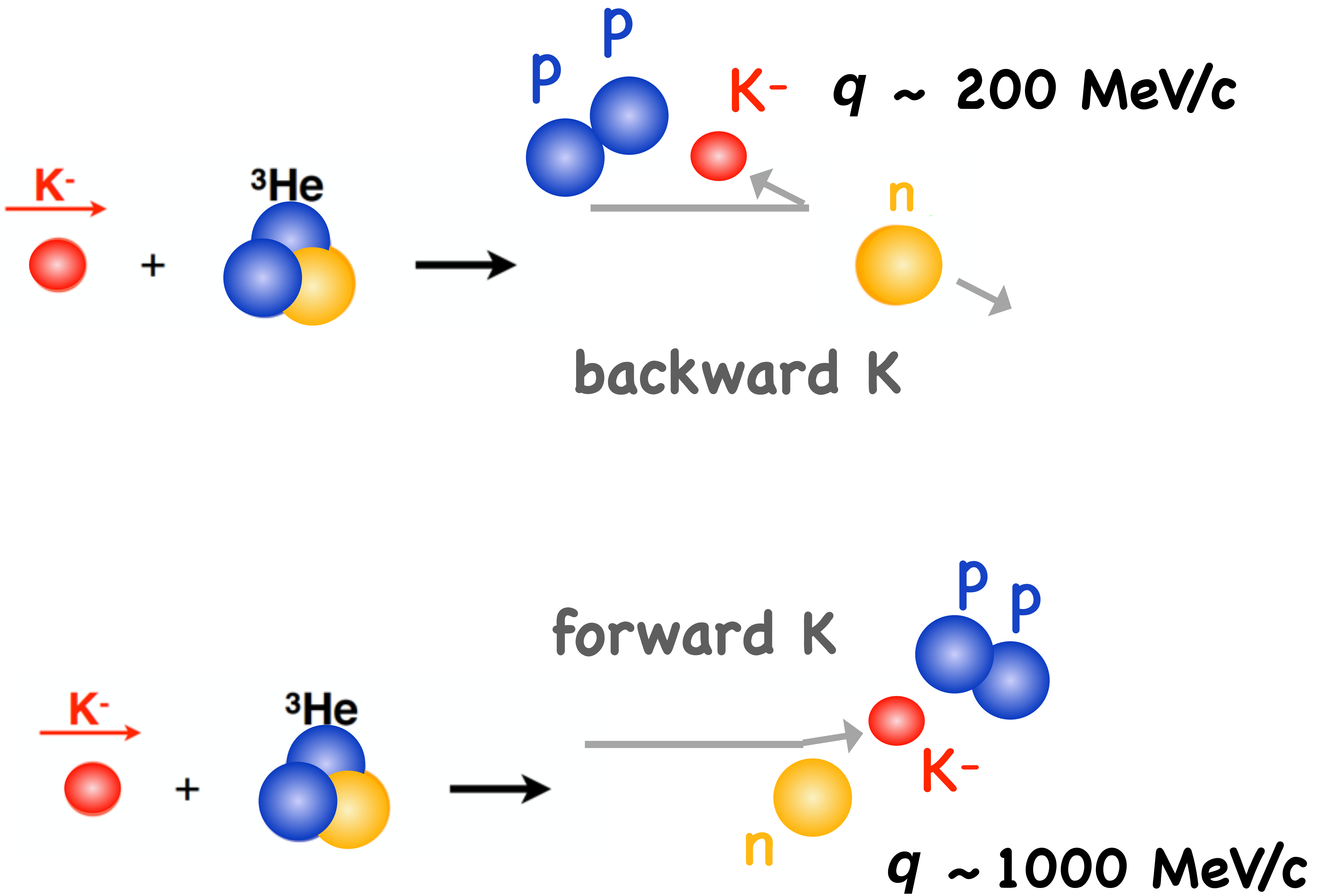
T. Yamaga



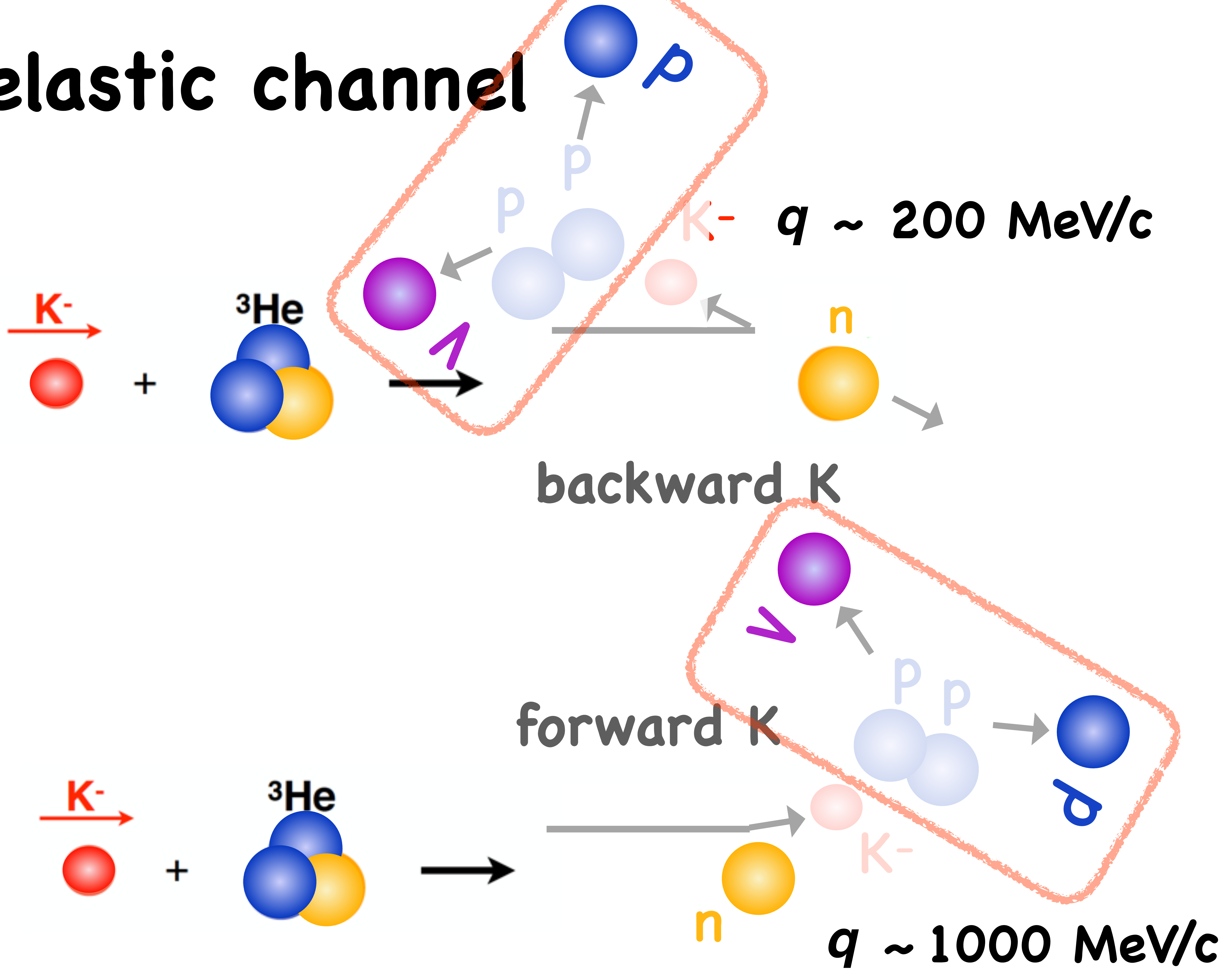
Astonished because $M_{inv.\Lambda p}$ spectra looks qualitatively similar to Sekihara-Oset-Ramos

Let's see in more detail

$\bar{K}$ elastic channel

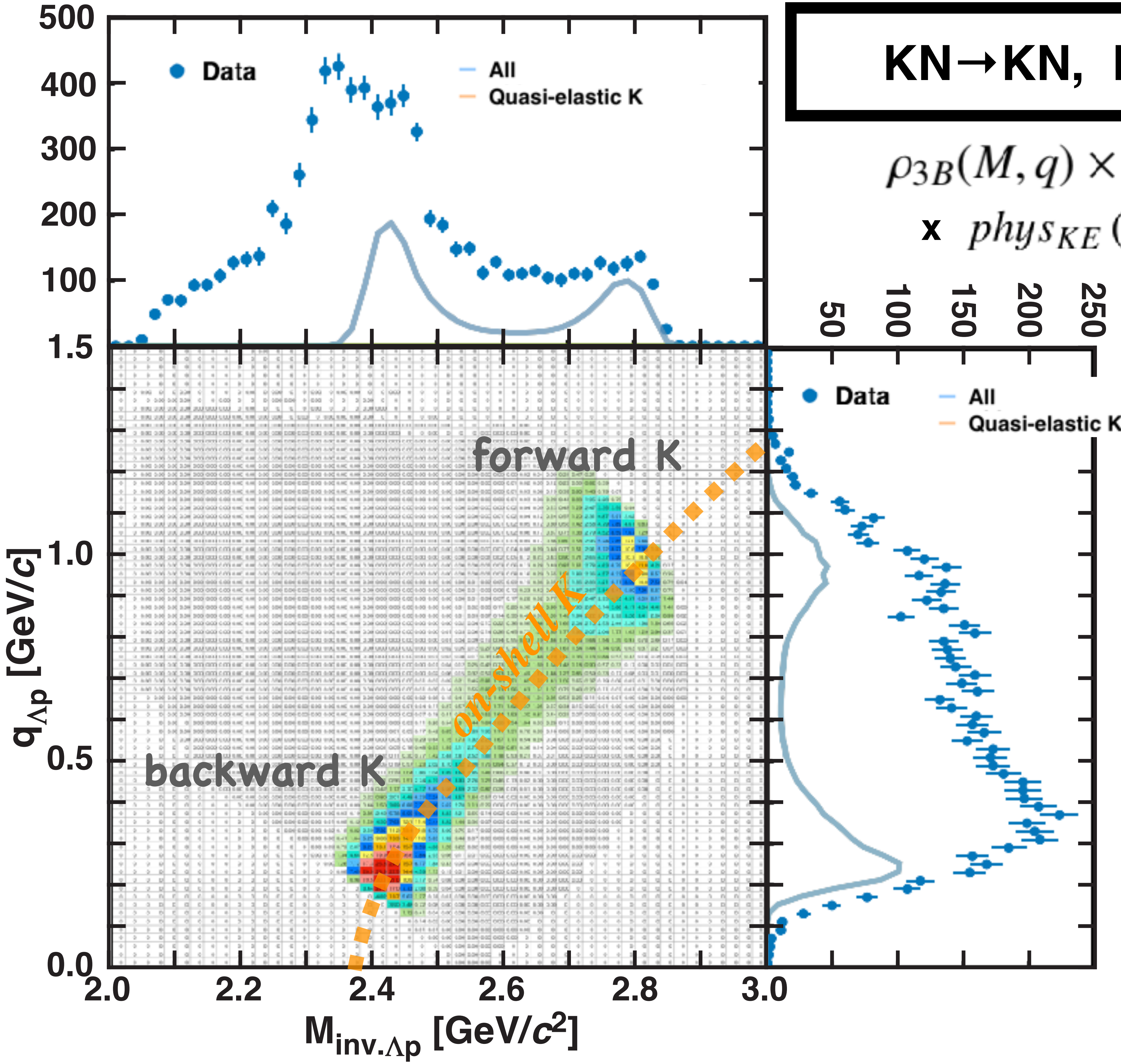


$\bar{K}$ elastic channel

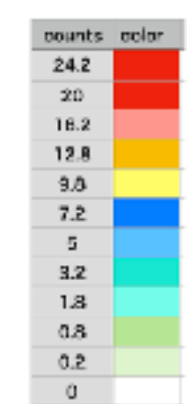


KN→KN, KNN→Λp

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$
$$\mathbf{x}\;\; phys_{KE}(M,q)$$



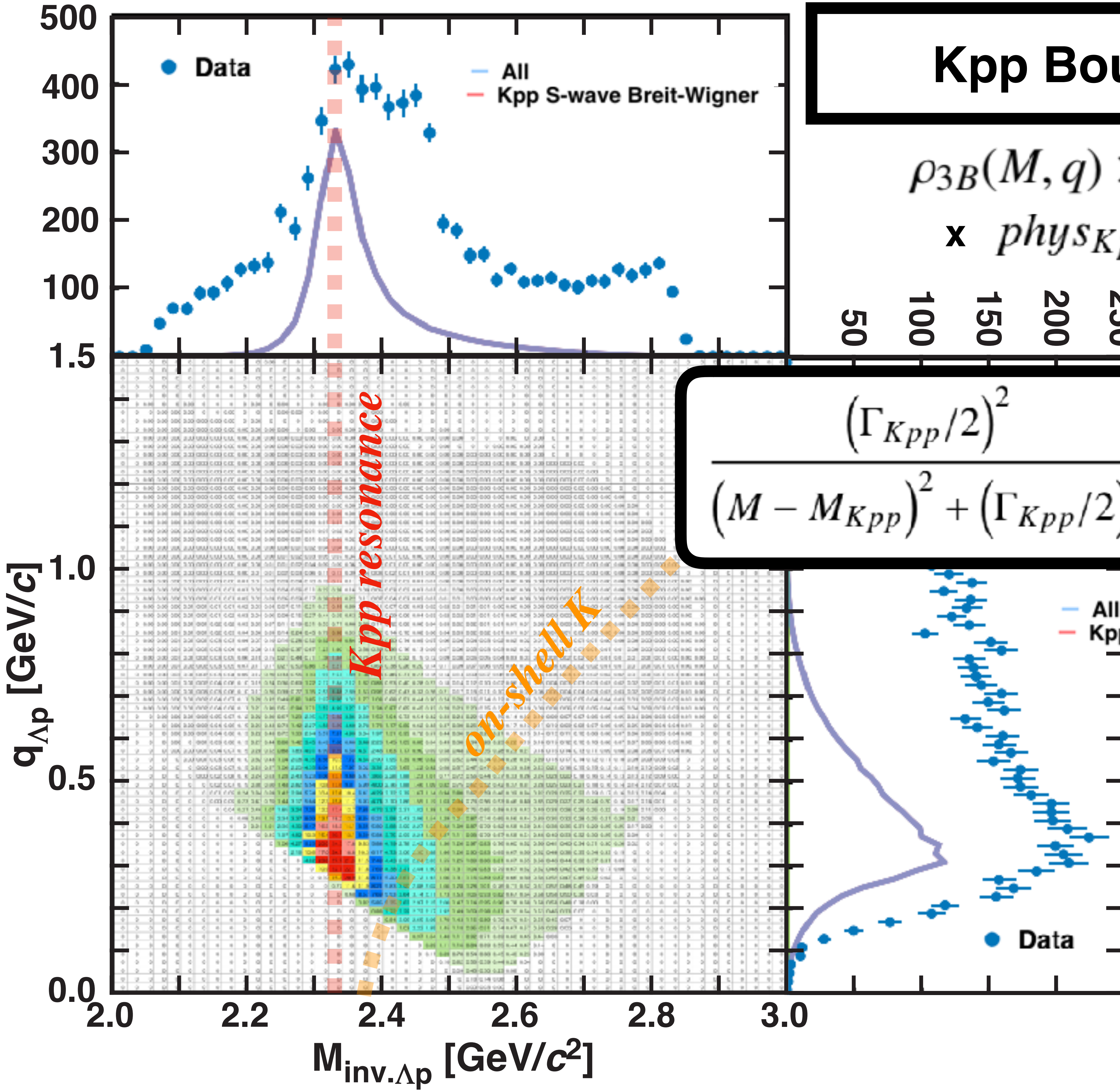
8 parameters



Kpp Bound State

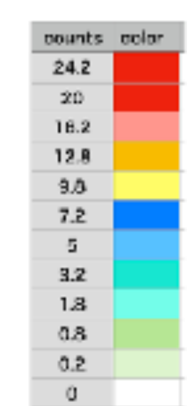
$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$

$$\times \quad phys_{Kpp}(M,q)$$



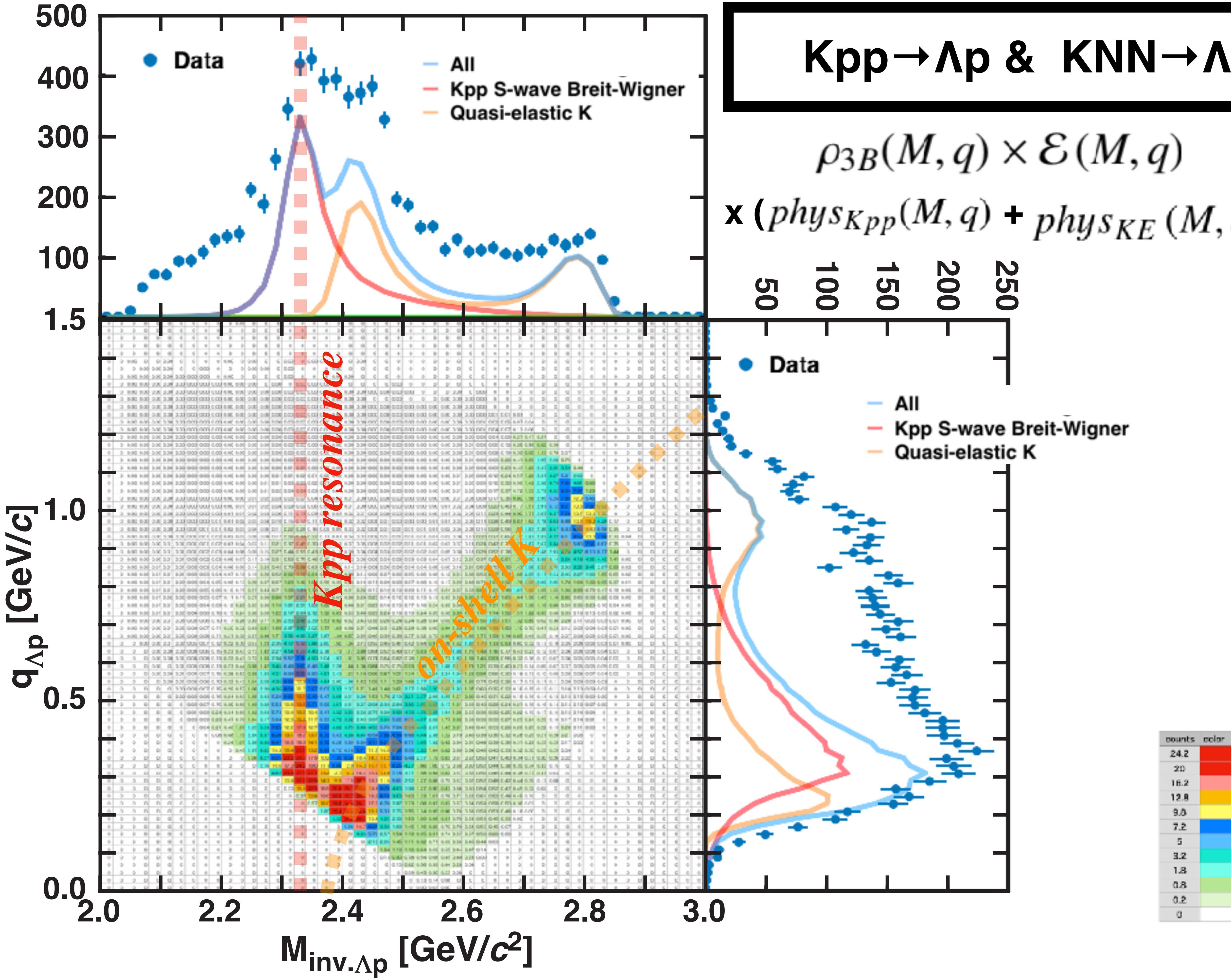
$$\frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

4 parameters

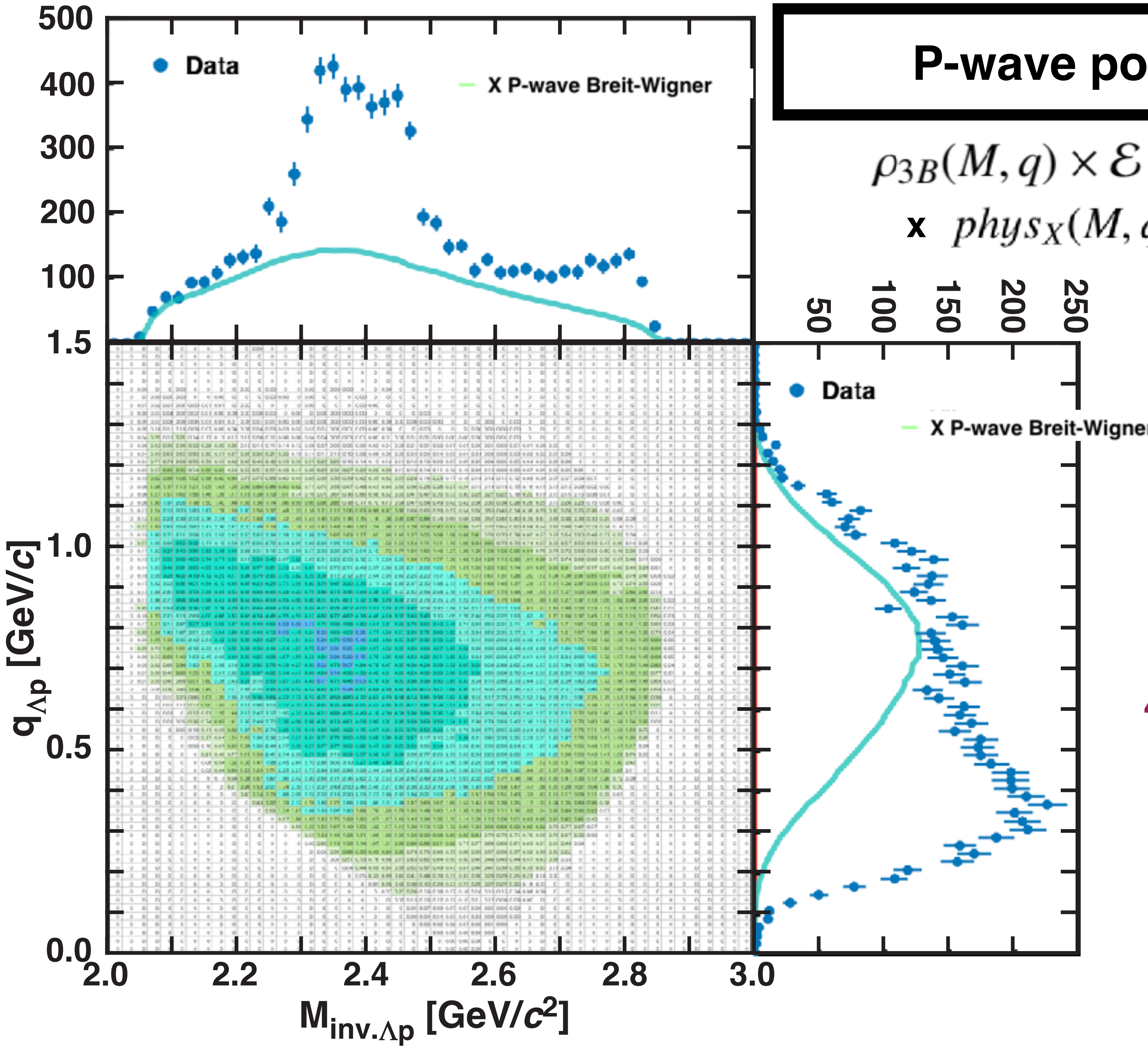


Kpp→Λp & KNN→Λp

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$
$$\times \left(phys_{Kpp}(M,q) + phys_{KE}(M,q) \right)$$



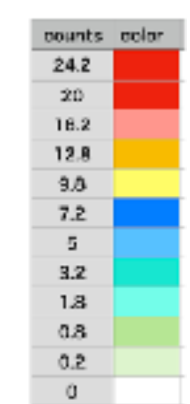
P-wave pole ?



$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$

$$\times \quad phys_X(M,q)$$

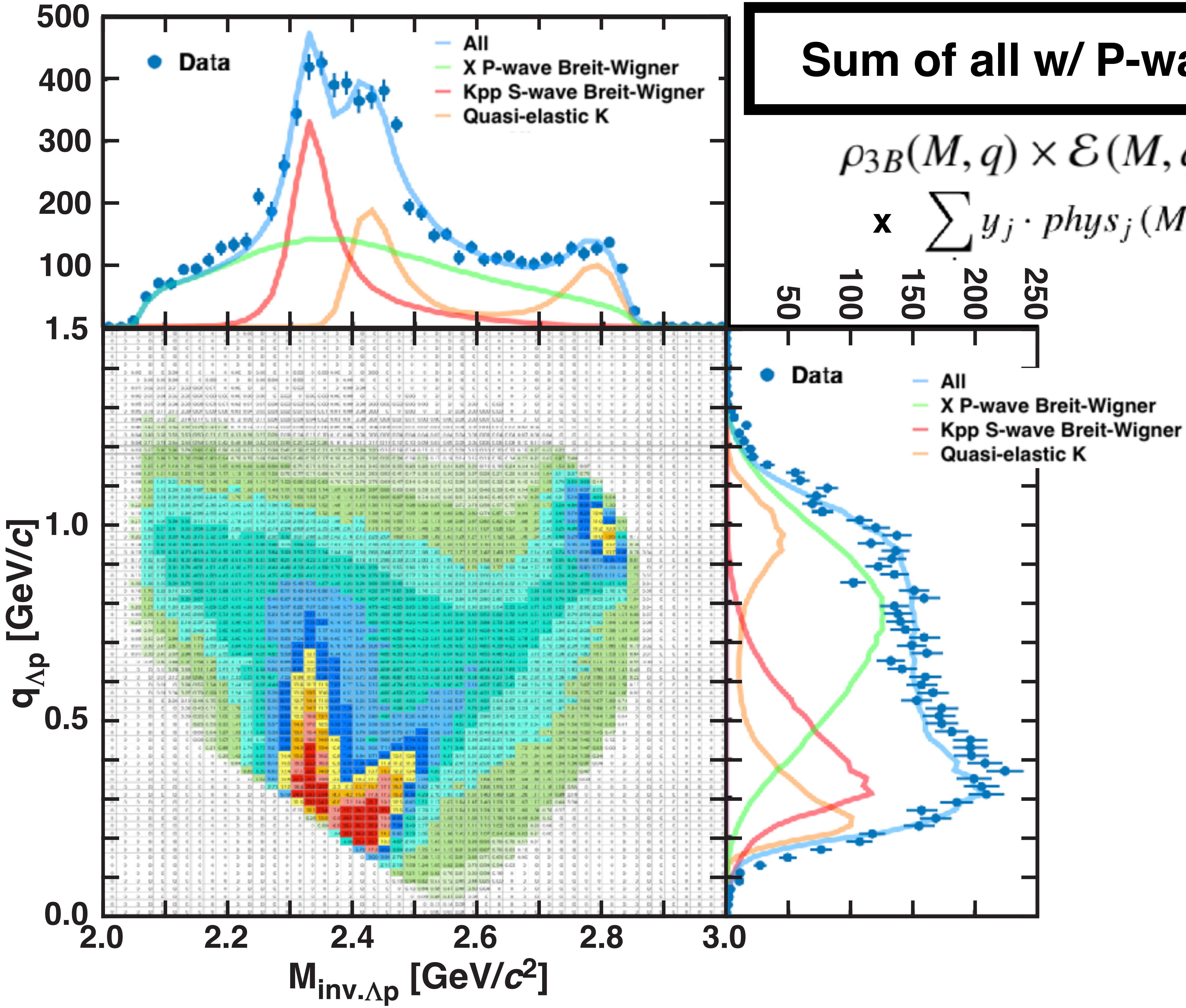
4 parameters

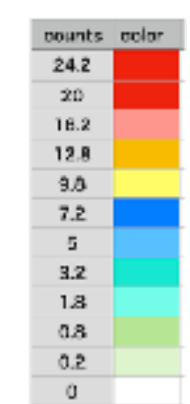


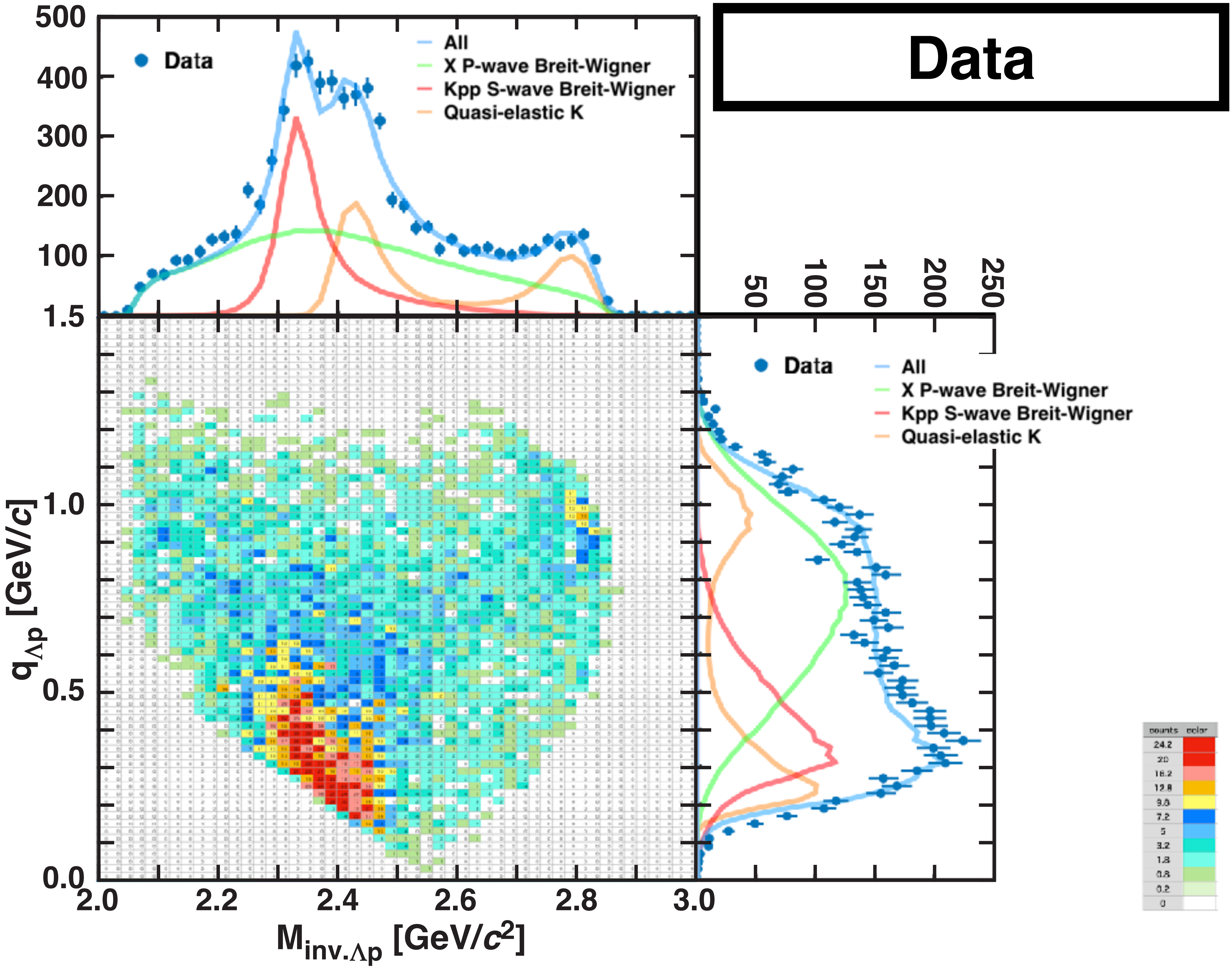
Sum of all w/ P-wave X

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$

$$\times \sum y_j \cdot phys_j(M_{inv.\Lambda p}, q)$$



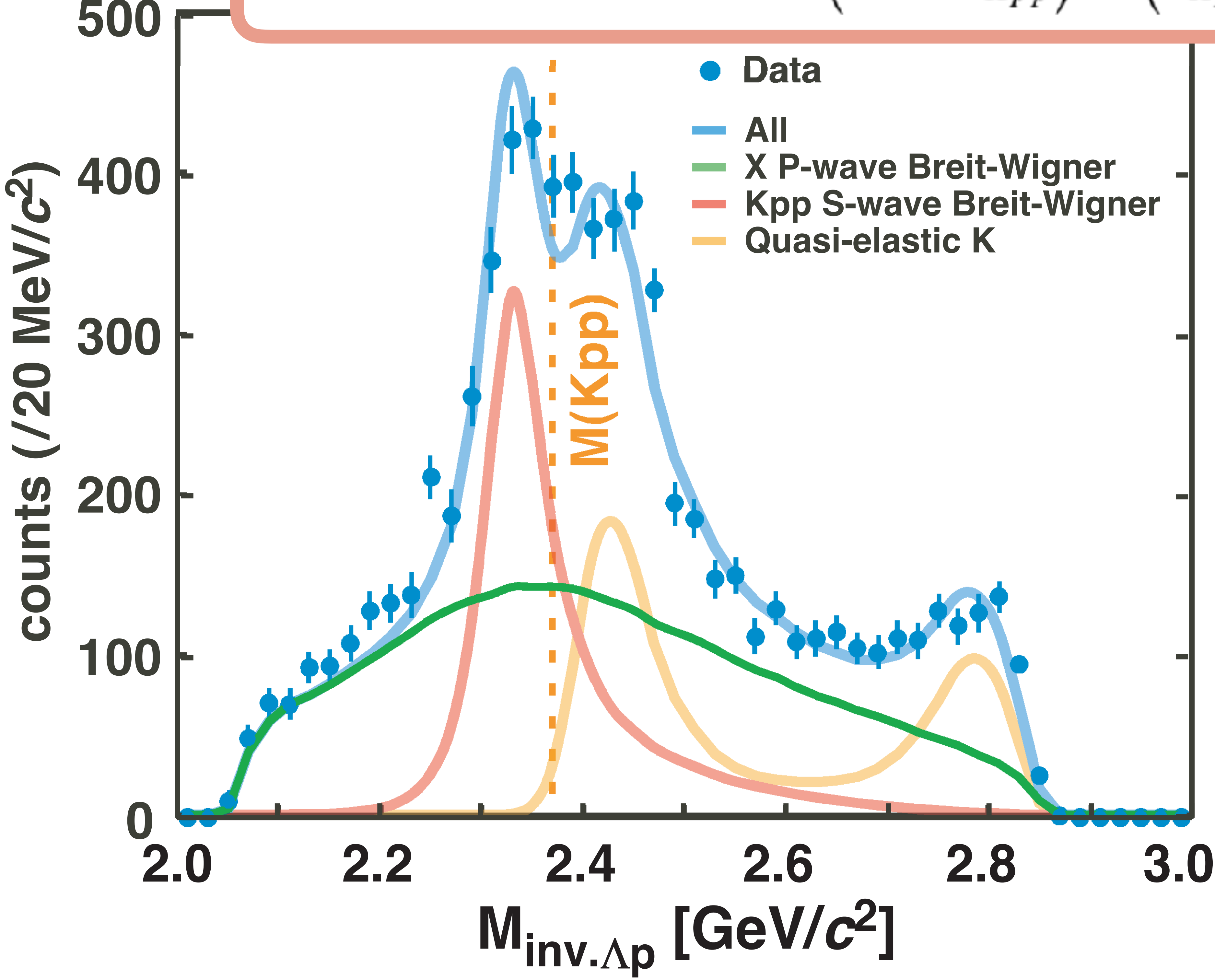




Data
Data
All
X P-wave Breit-Wigner
Kpp S-wave Breit-Wigner
Quasi-elastic K
500
400
300
200
100
1.5
1.0
0.5
0.0
2.0
2.2
2.4
2.6
2.8
3.0
50
100
150
200
250
$M_{inv.\Lambda p}$ [GeV/c^2]
$q_{\Lambda p}$ [GeV/c]
Data
All
X P-wave Breit-Wigner
Kpp S-wave Breit-Wigner
Quasi-elastic K

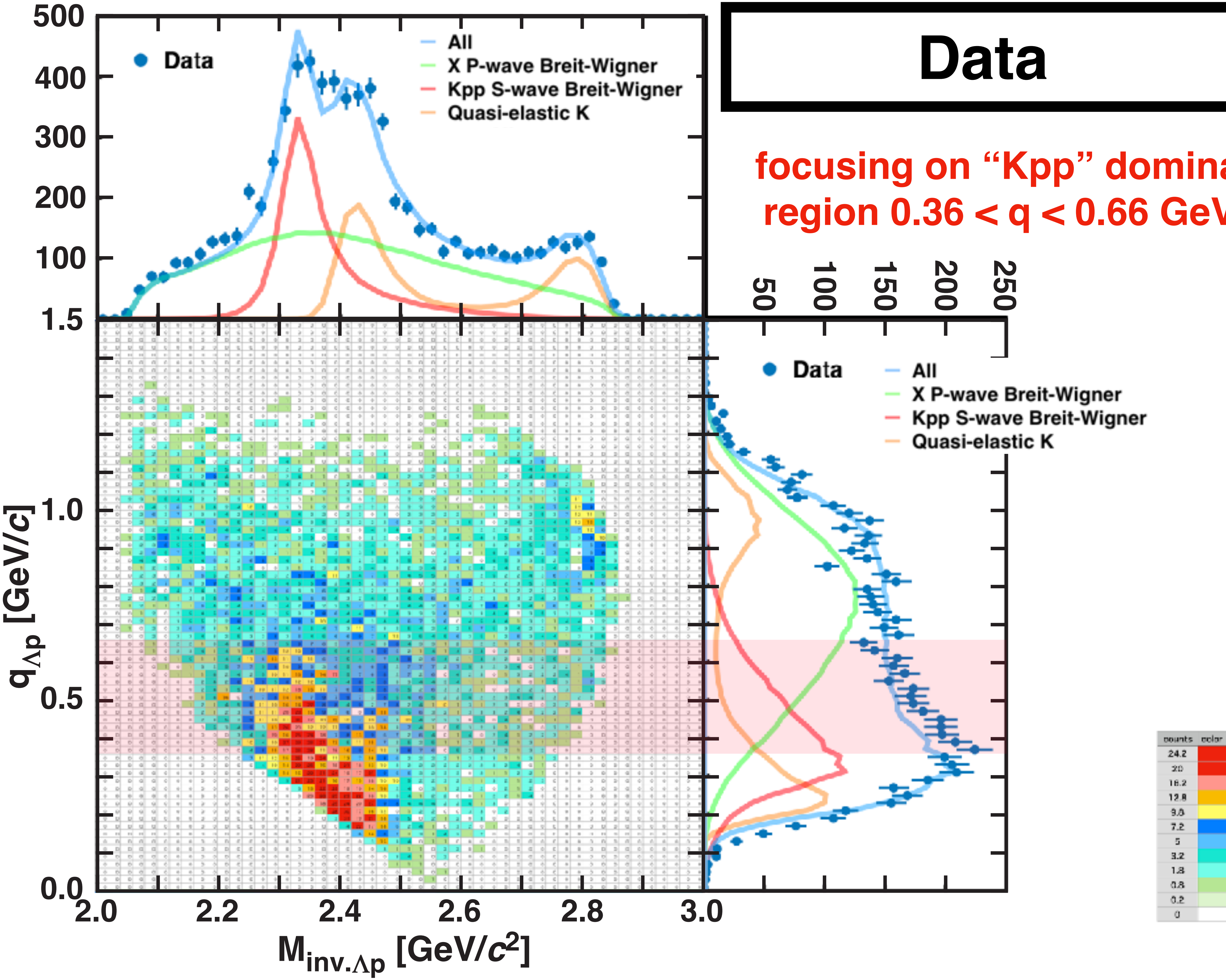
$M_{inv.\Lambda p}$ $n_{mis.}$ + Λ p

$$\rho_{3B}(M,q)\times\mathcal{E}(M,q)\times\frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M-M_{Kpp}\right)^2+\left(\Gamma_{Kpp}/2\right)^2}\times\exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$



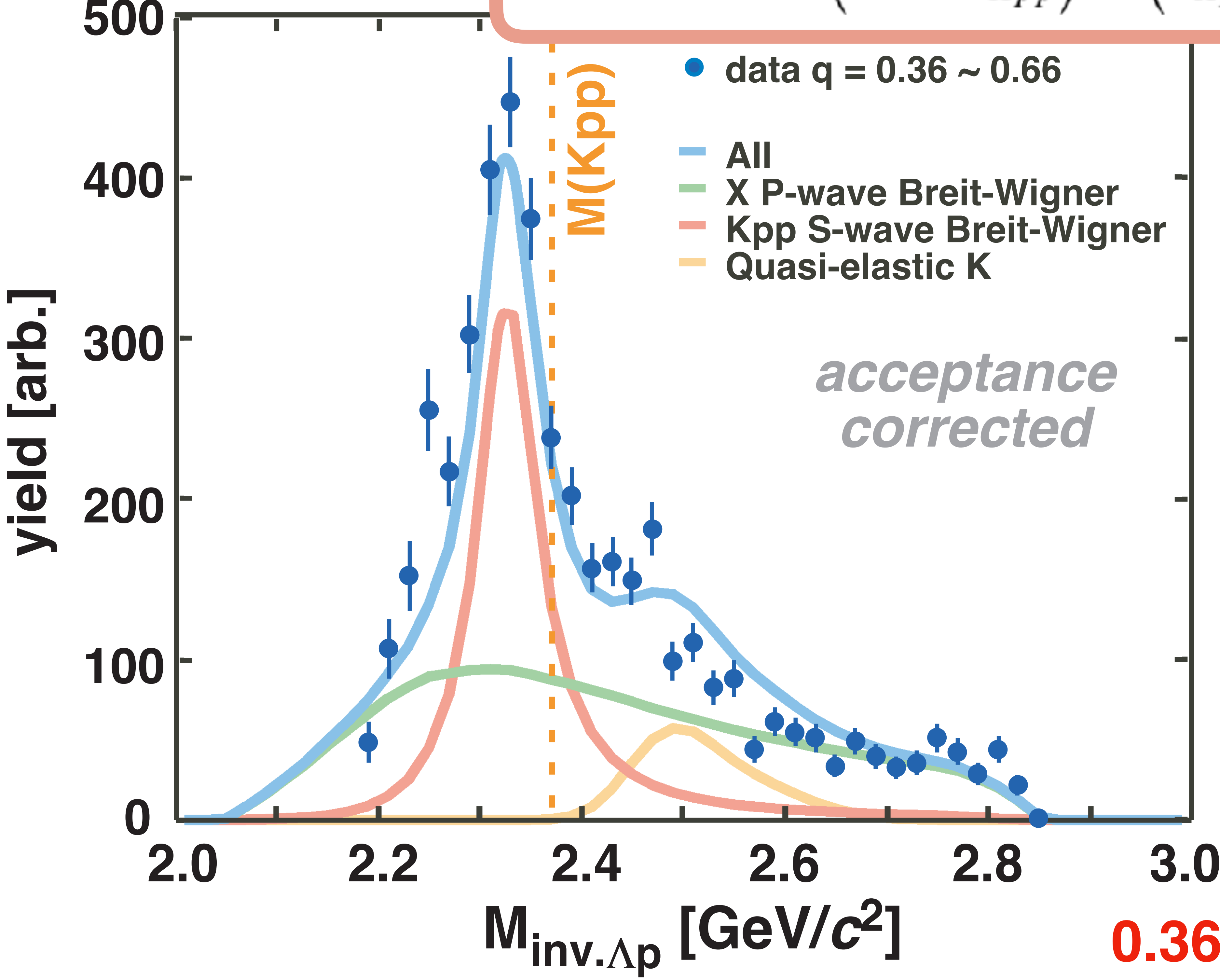
Data

focusing on “Kpp” dominant region 0.36 < q < 0.66 GeV/c



$M_{inv.\Lambda p}$ q-selected $n_{mis.}$ + Λ p

$$\rho_{3B}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$



0.36 < q < 0.66 GeV/c

conclusion A:

Definitive peak observed below M(Kpp)

"Kpp", K-QE, broad(?)

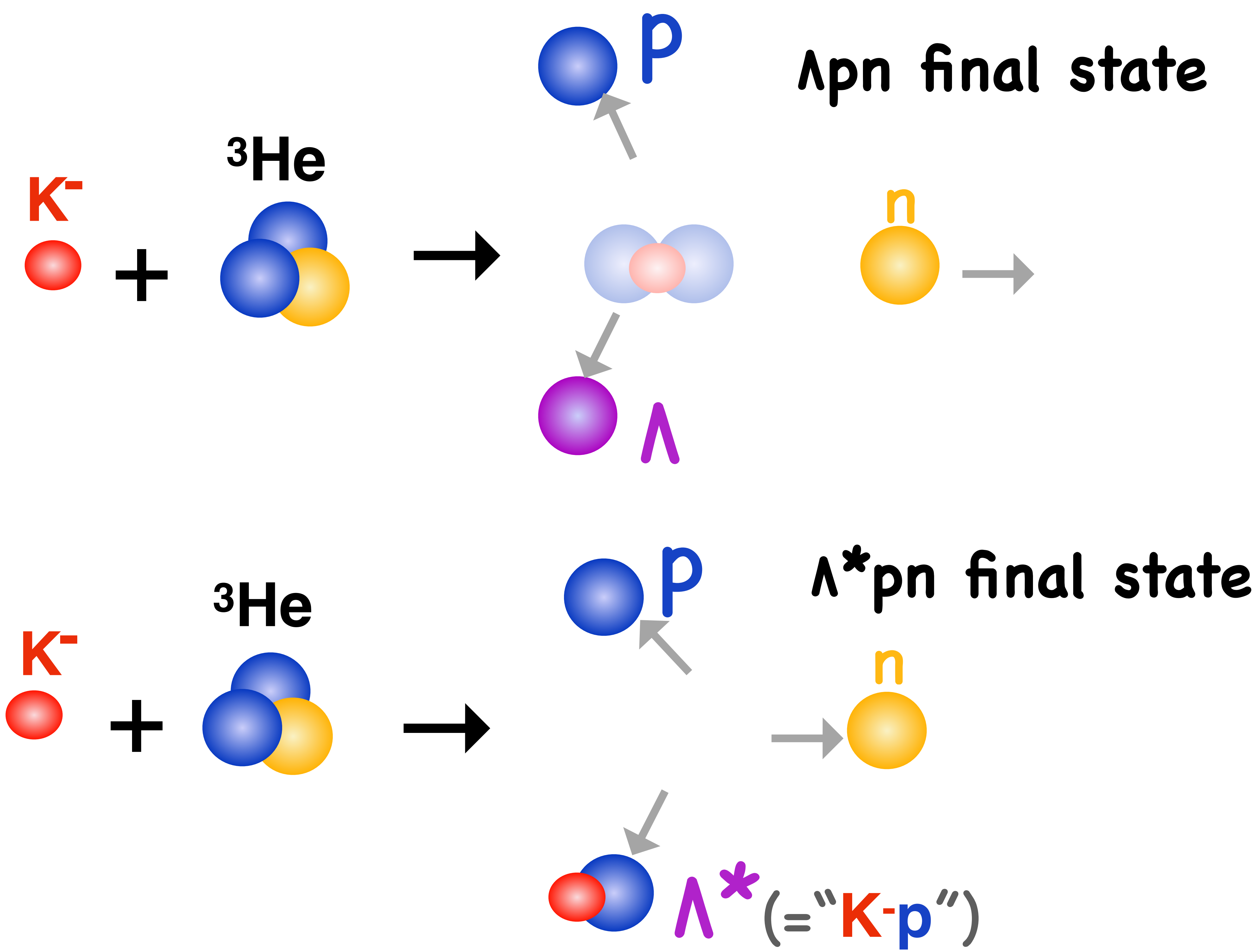
Three physical processes in Λpn final state

Higher statistics @ E15^{2nd}

Forward $n_{mis.}$ + $(\Lambda^* \ p)_{CDS}$

F. Sakuma

Where Λ* goes?

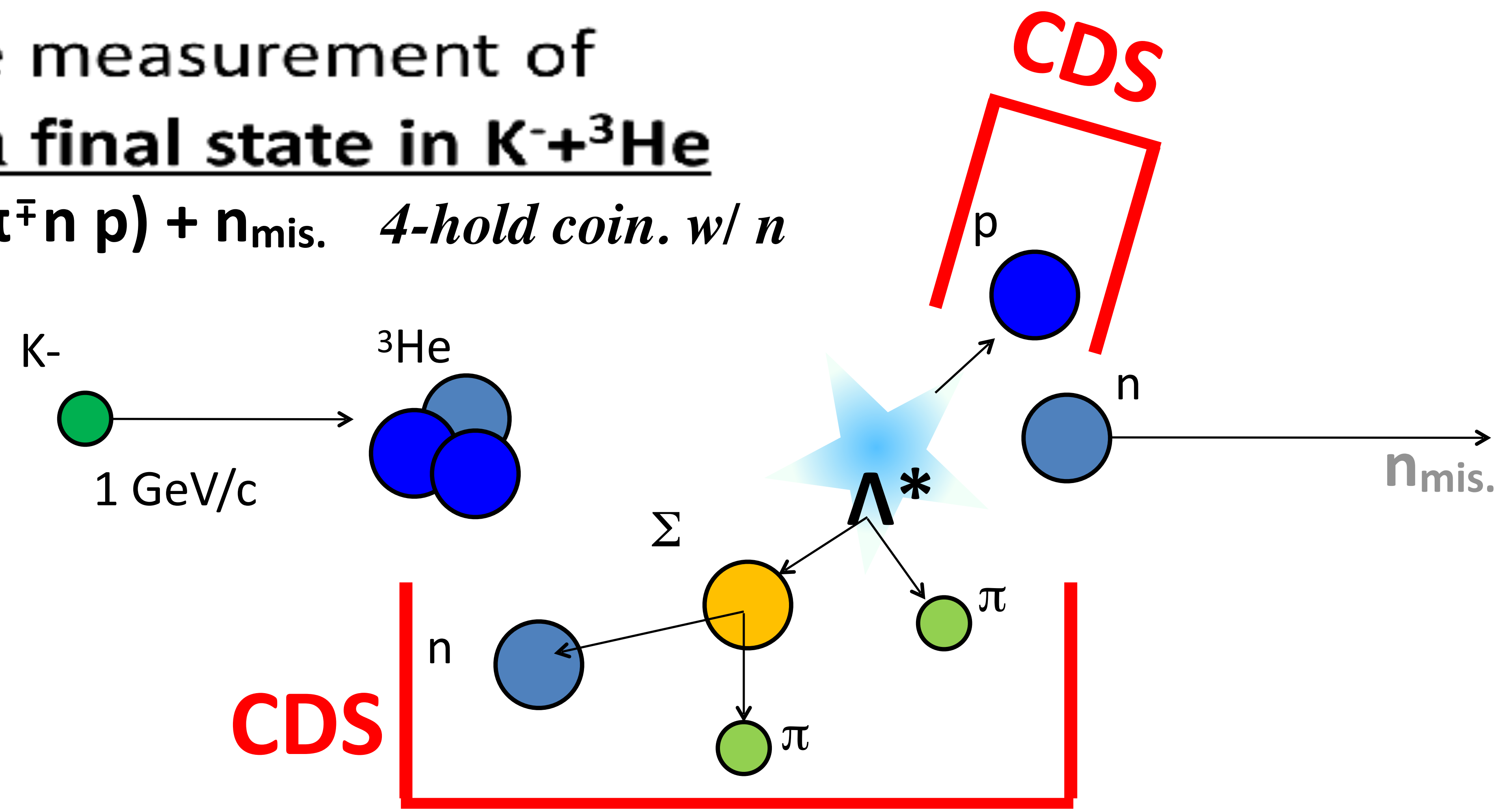


K^- ^3He → Λ*pn @ E15

F. Sakuma

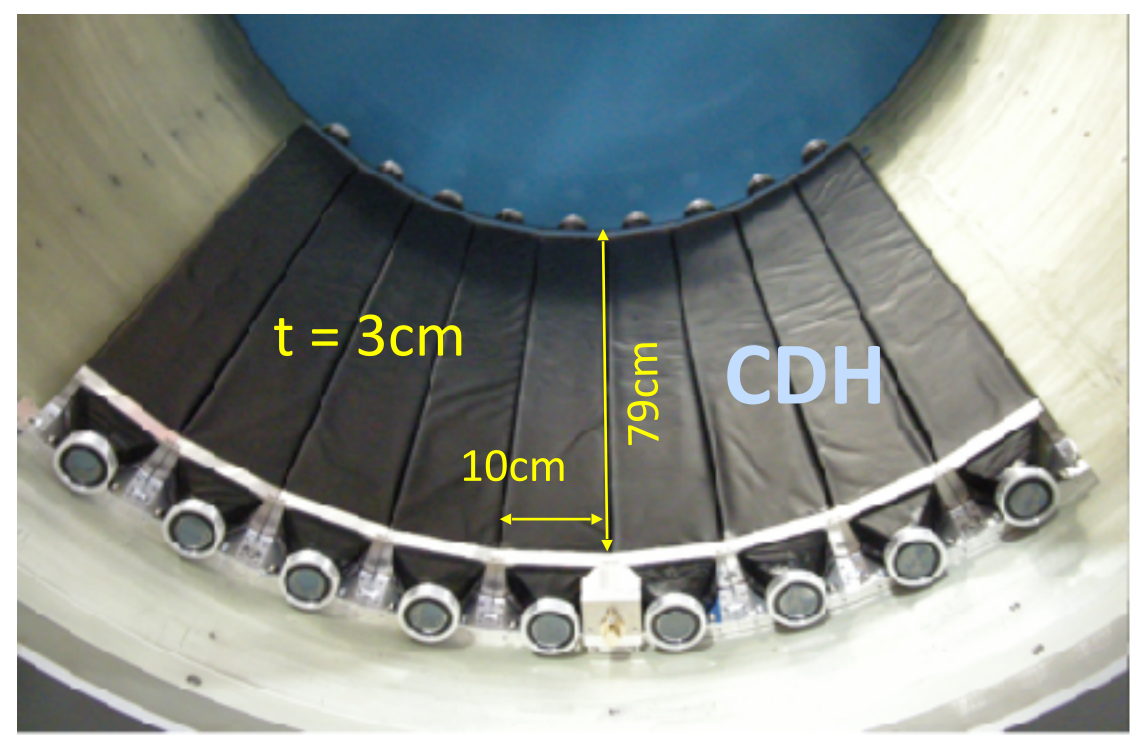
- Exclusive measurement of
  <u>**$\pi^\pm\Sigma^\mp$pn final state in K^-+^{3}He**</u>

  ($\pi^\pm \pi^\mp$n p) + $n_{mis.}$ ***4-hold coin. w/ n***



- <u>**Experimental challenge**</u>: neutron detection with plastic counter (t=3cm)

  n detection efficiency on CDH ~ 3%
  solid angle of CDH ~ 60%



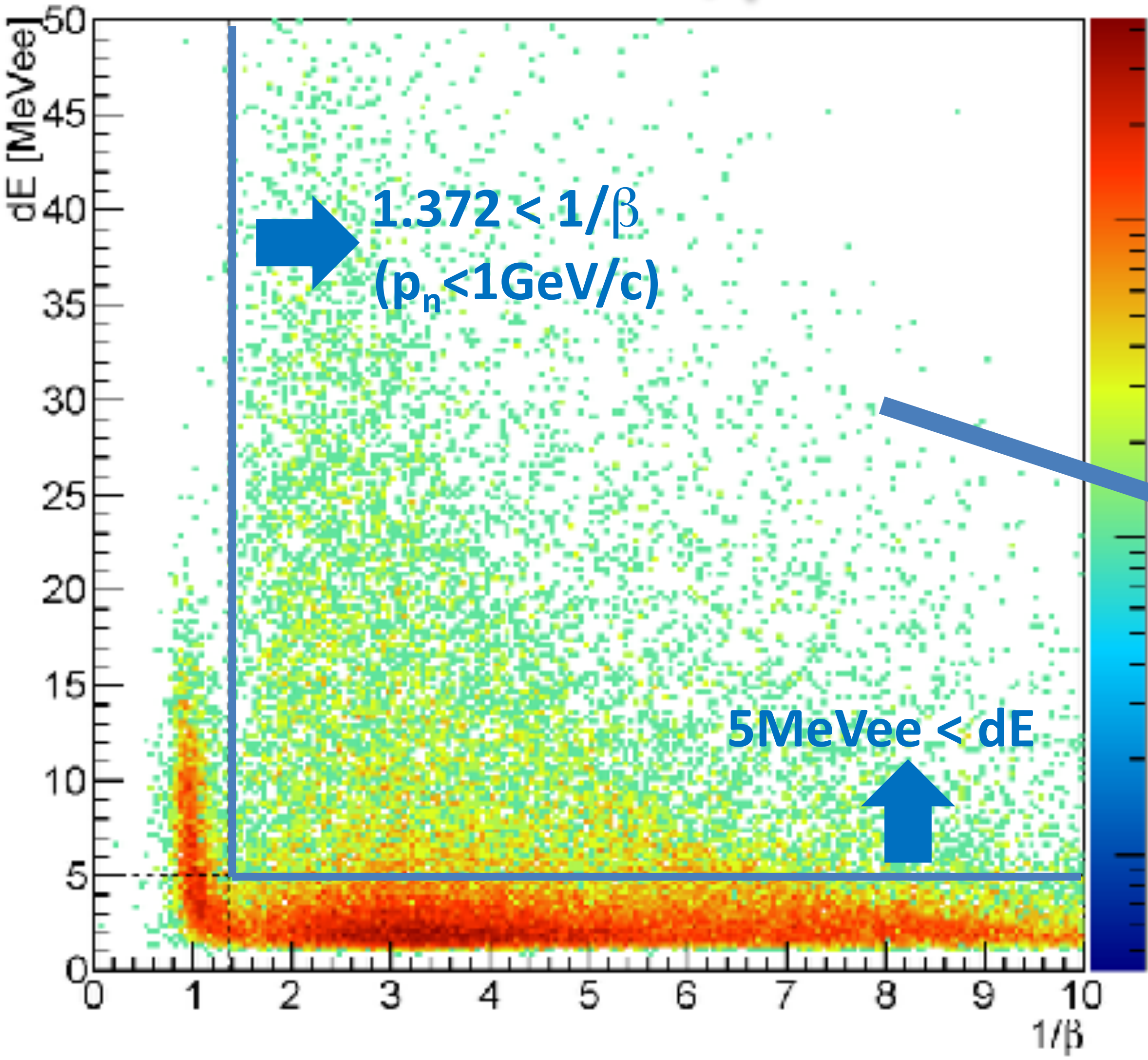
x 55 more difficult than Λpn

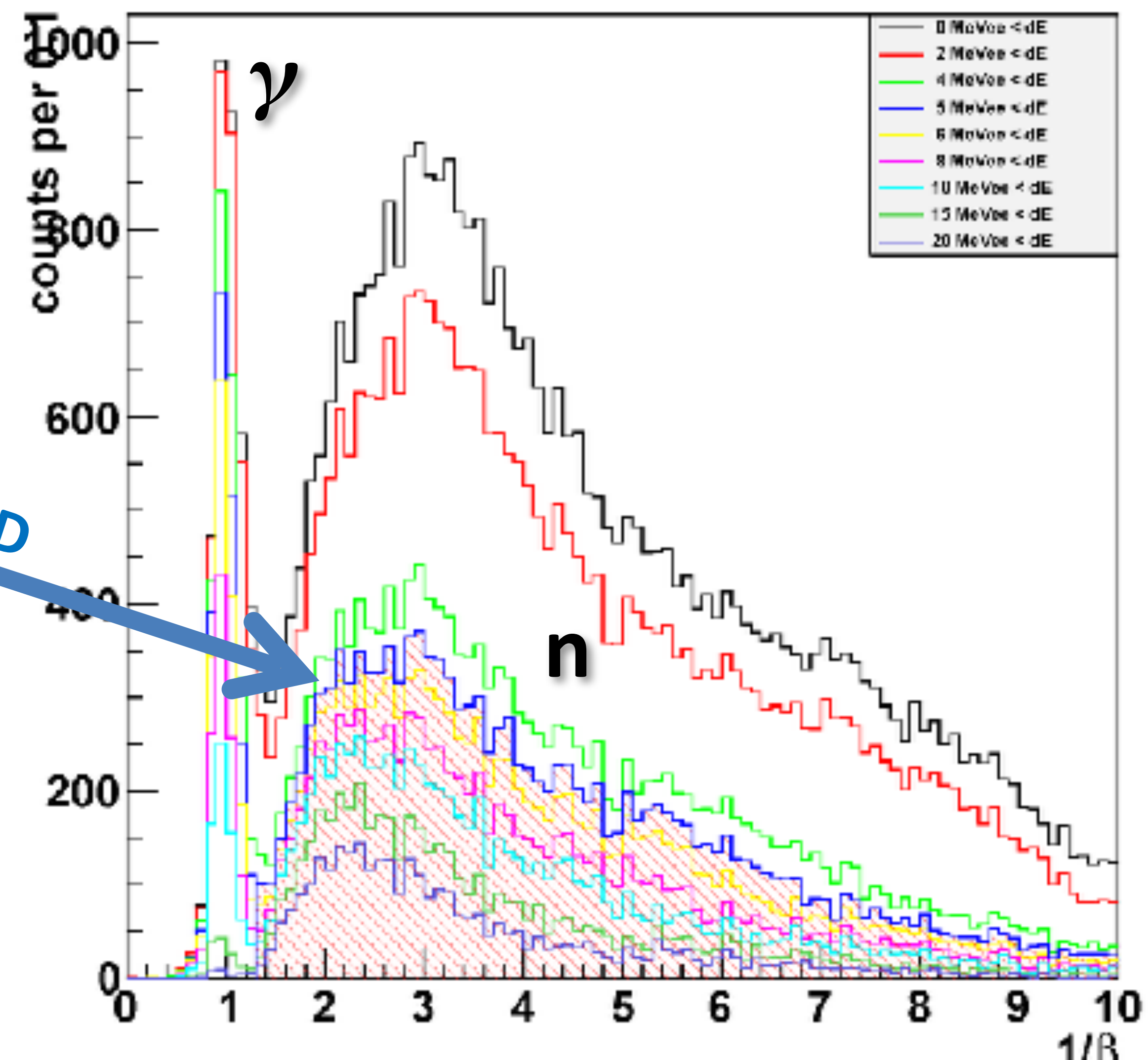
($pp\pi^-$) + $n_{mis.}$ ***3-hold coin.***

Neutron ID with CDH

F. Sakuma

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



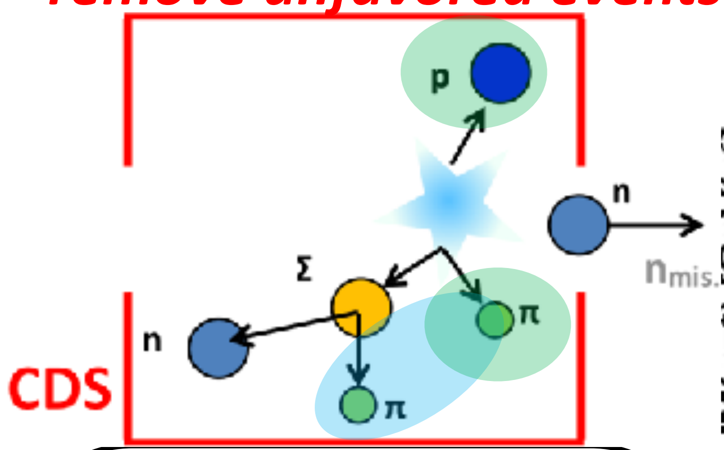


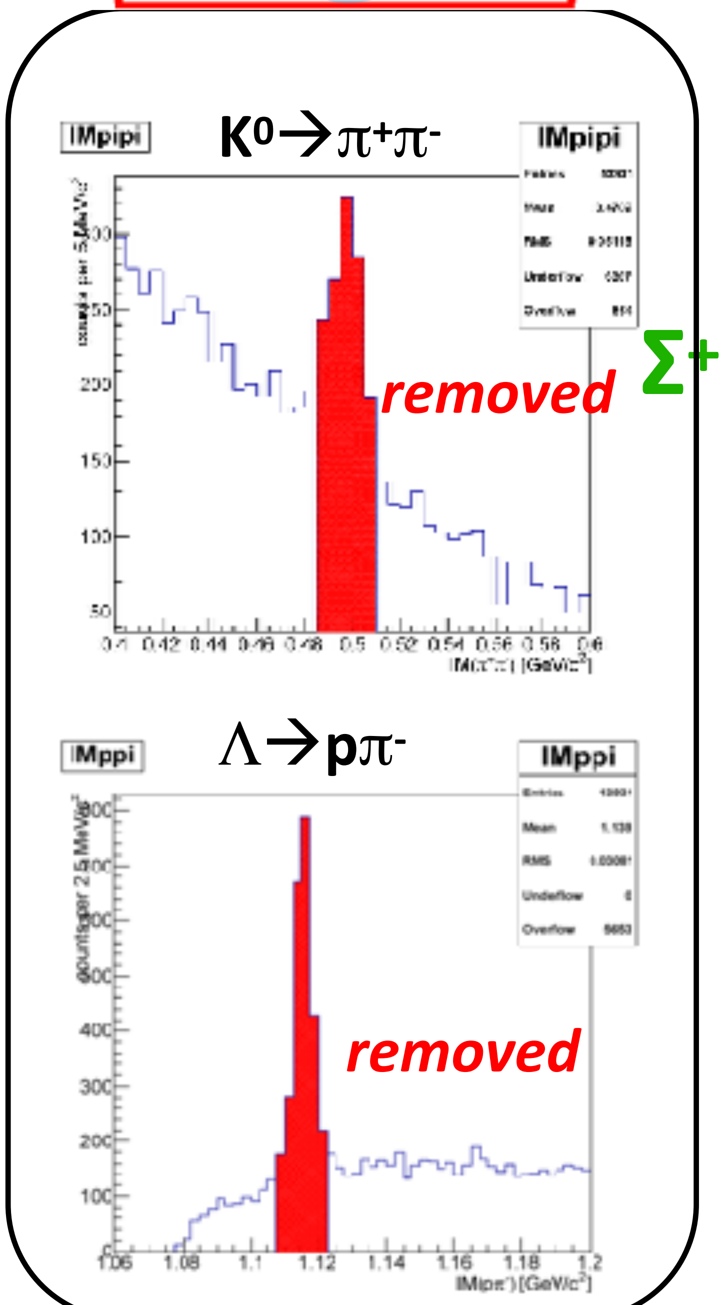
Neutron clearly identified by CDH

$\pi\Sigma pn$ Events

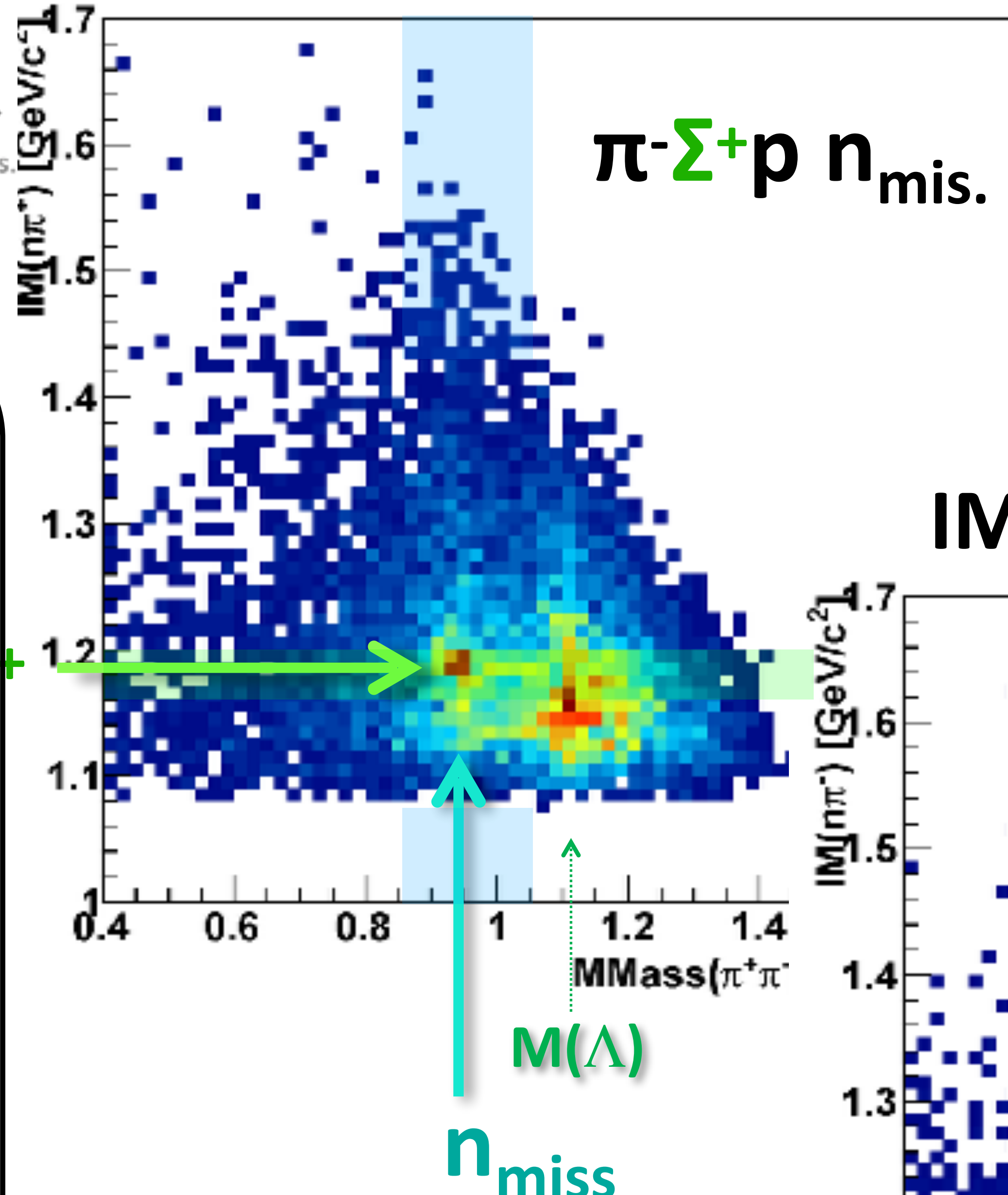
F. Sakuma

remove unfavored events

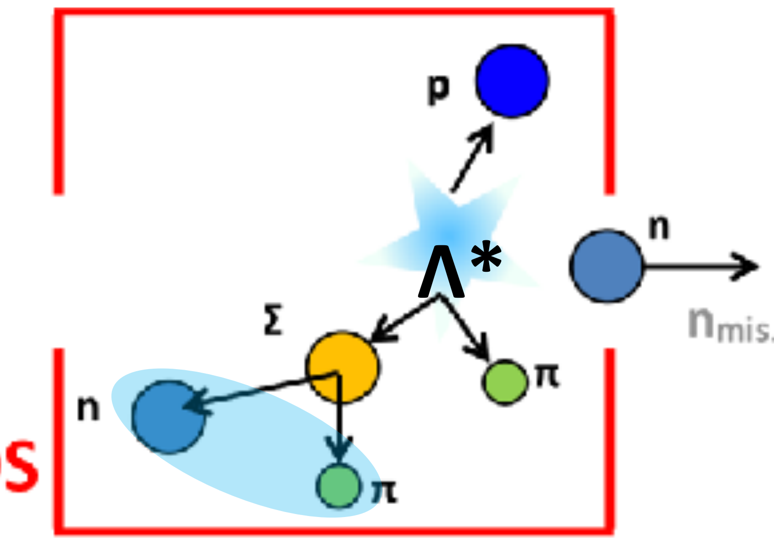




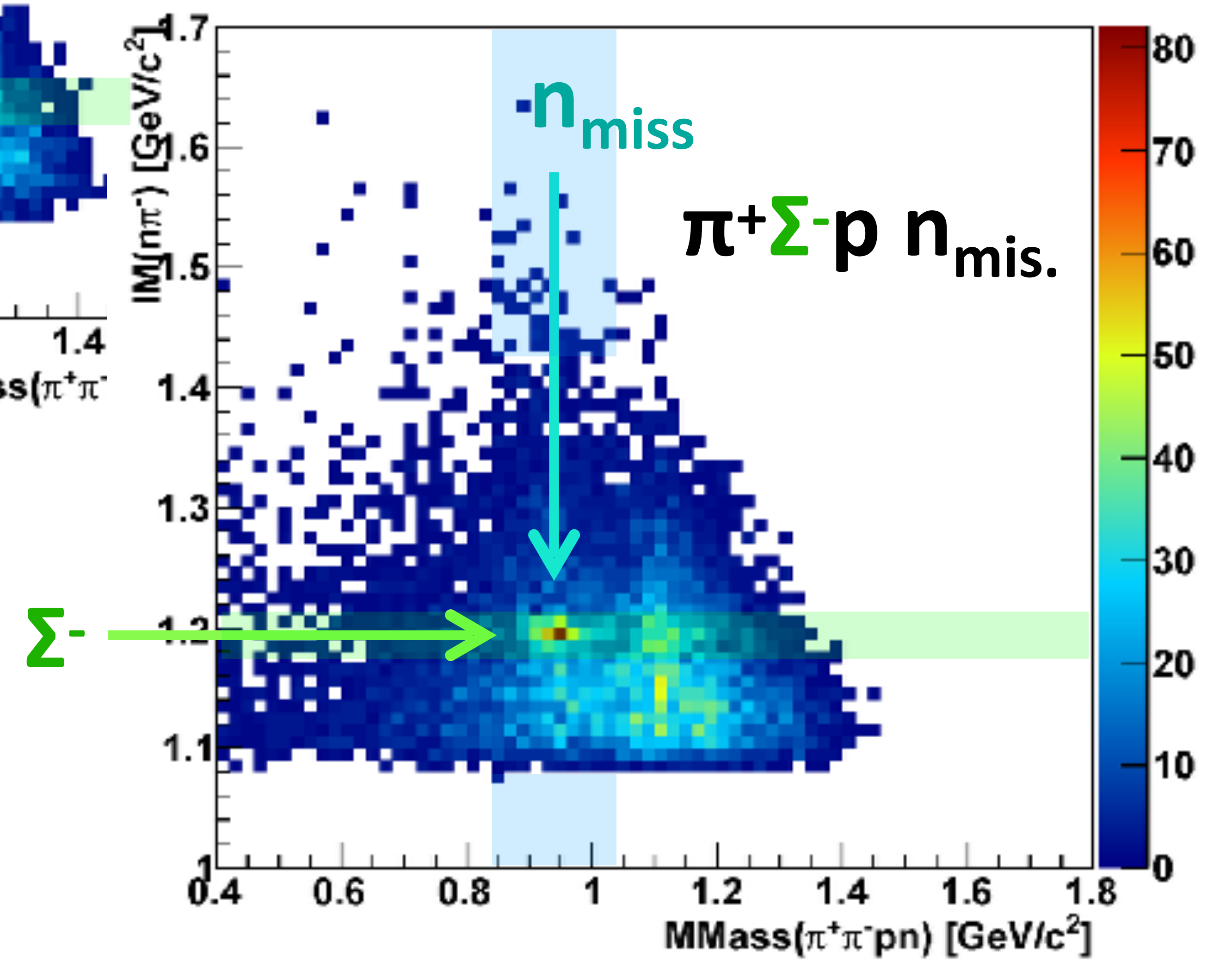
IM($n\pi^+$) vs MM($\pi^+\pi^- pn$)



Σ identification



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



F. Sakuma

$\Lambda^*(\pi\Sigma)pn$ Events

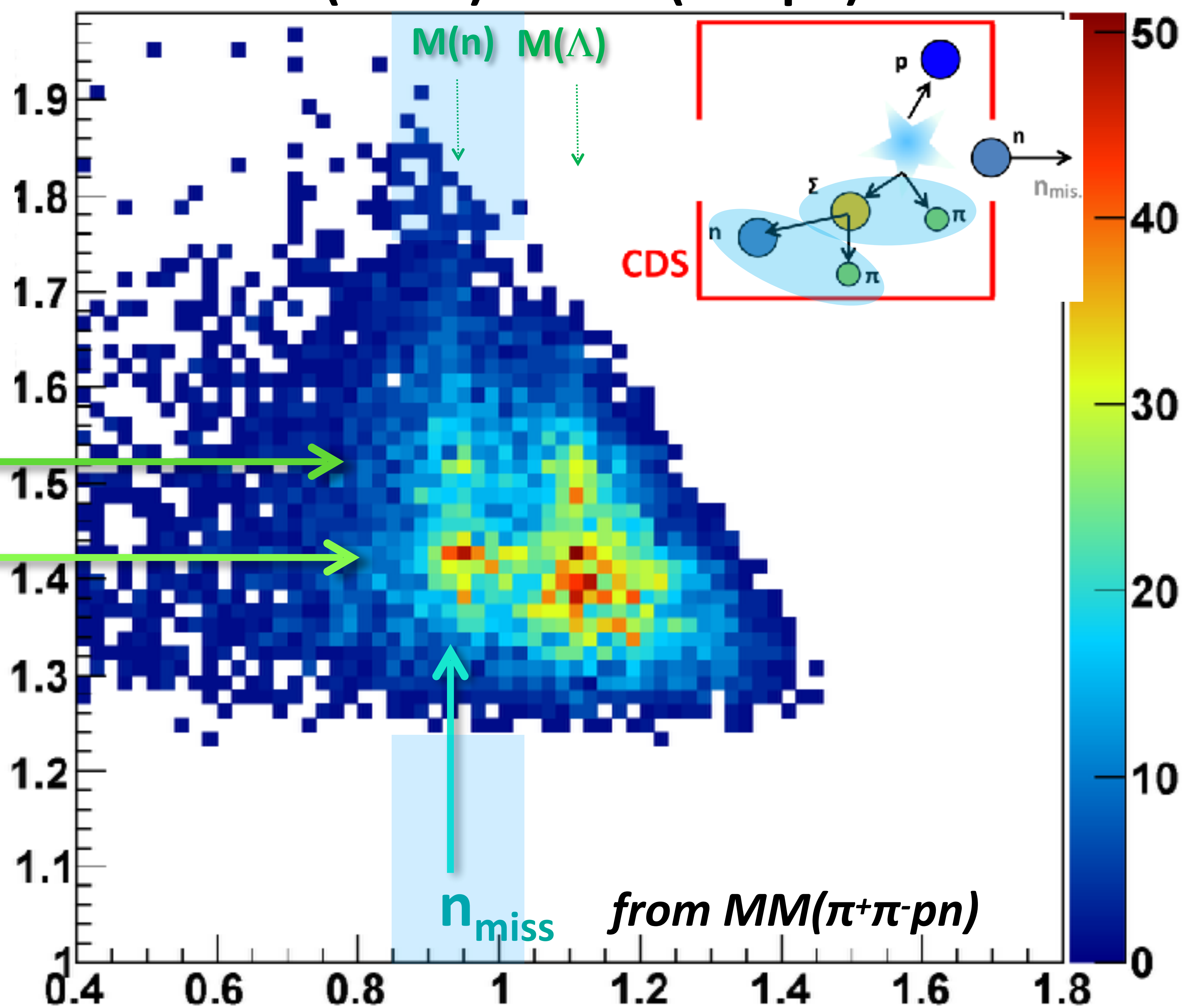
IM($n\pi^+\pi^-$) vs MM($\pi^+\pi^- pn$)

Λ^* mass

(*by* $\pi^+(\pi^- n)$ *or* $\pi^-(\pi^+ n)$)

$\Lambda(1520)$

$\Lambda(1405)$



missing mass (*by* $\pi^+\pi^- np$)

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Λ*(πΣ)p*n* final state [by πΣ invariant mass]

Event Selection

Missing n:

$0.85 < MM(\pi^+\pi^- pn) < 1.03$ GeV/c^2

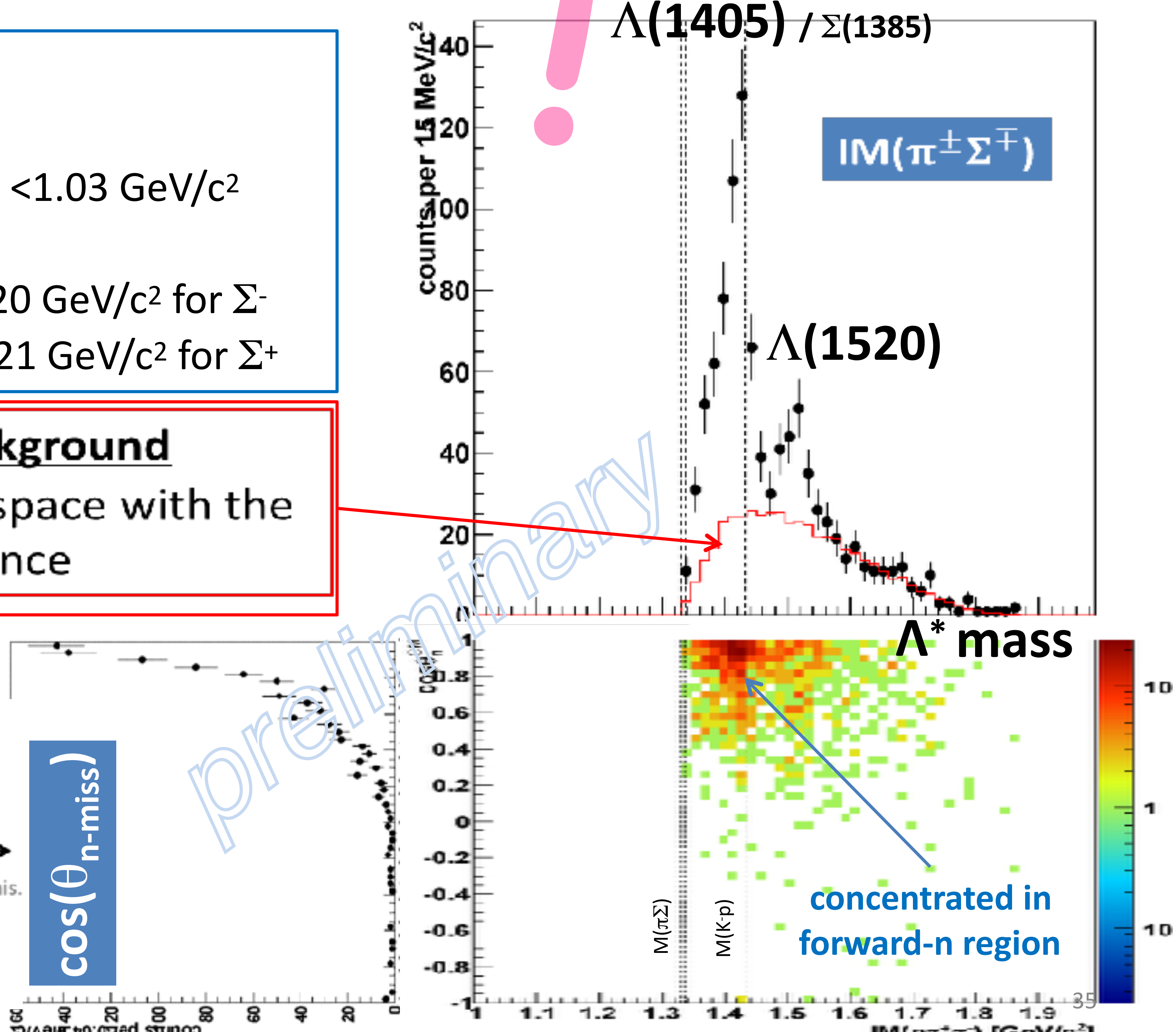
Σ mass:

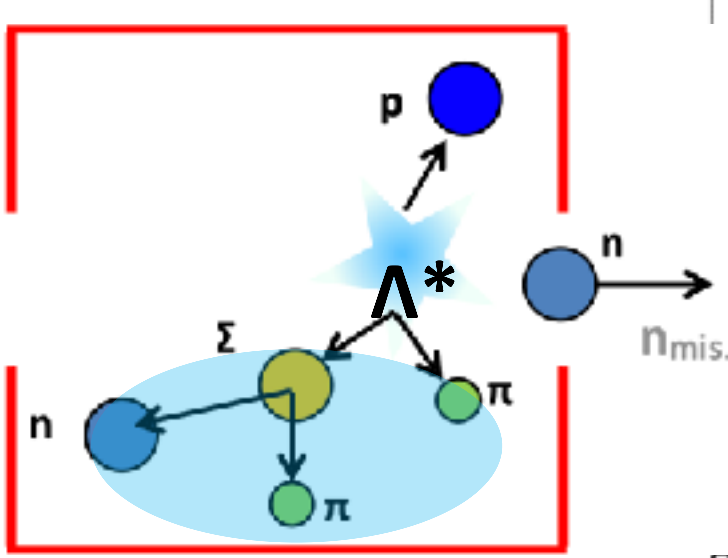
$1.18 < IM(n\pi^-) < 1.20$ GeV/c^2 for Σ^-

$1.19 < IM(n\pi^+) < 1.21$ GeV/c^2 for Σ^+

"Simple" PS-Background

$\pi^\pm\Sigma^\mp pn$ phase-space with the detector acceptance





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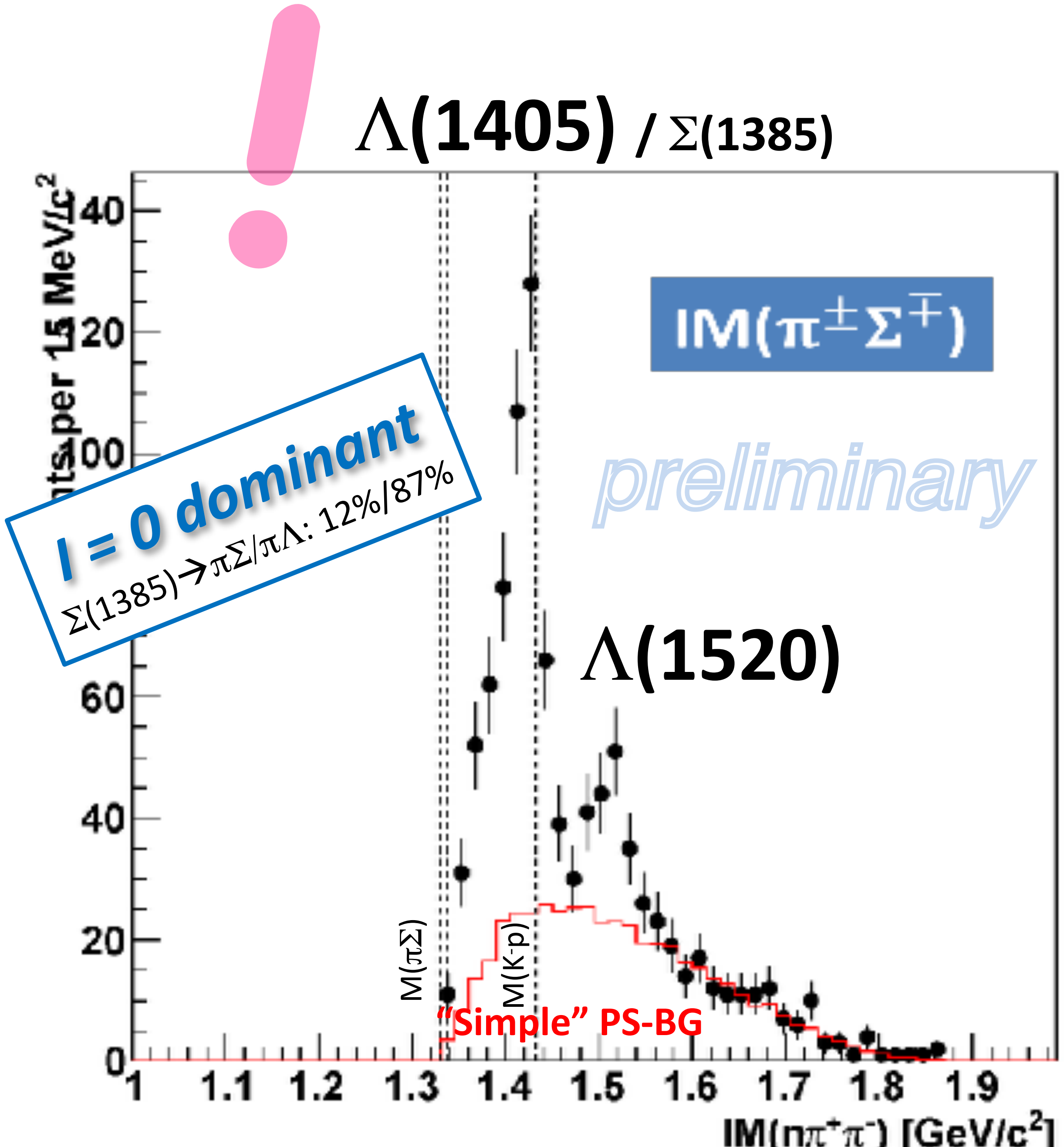
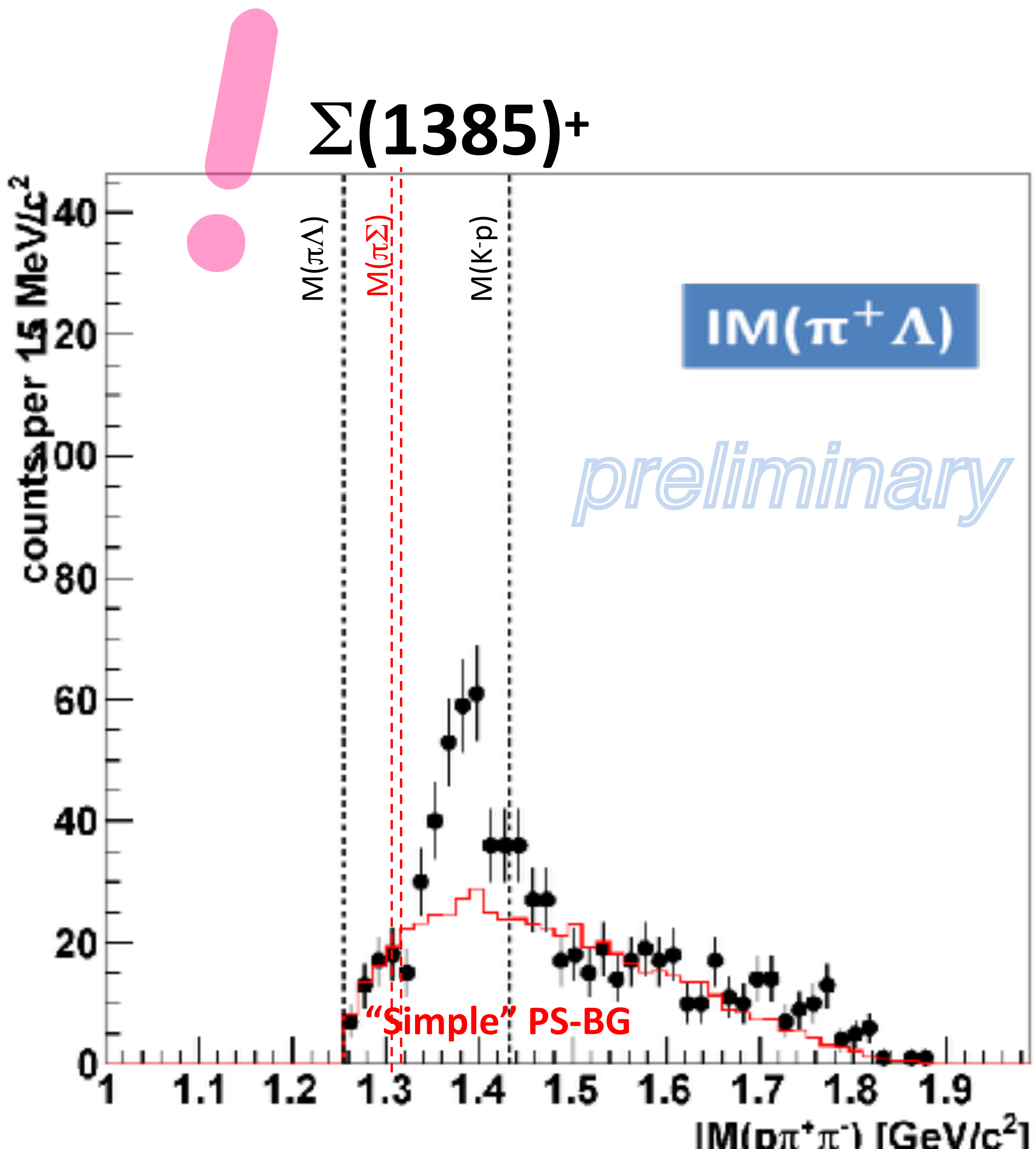
$\Lambda^*(\pi\Sigma)pn$ *vs.* $\Sigma^*(\pi^+\Lambda)nn$



I =0 and 1 mode

Λ* mass



I = 1 mode

Σ* mass

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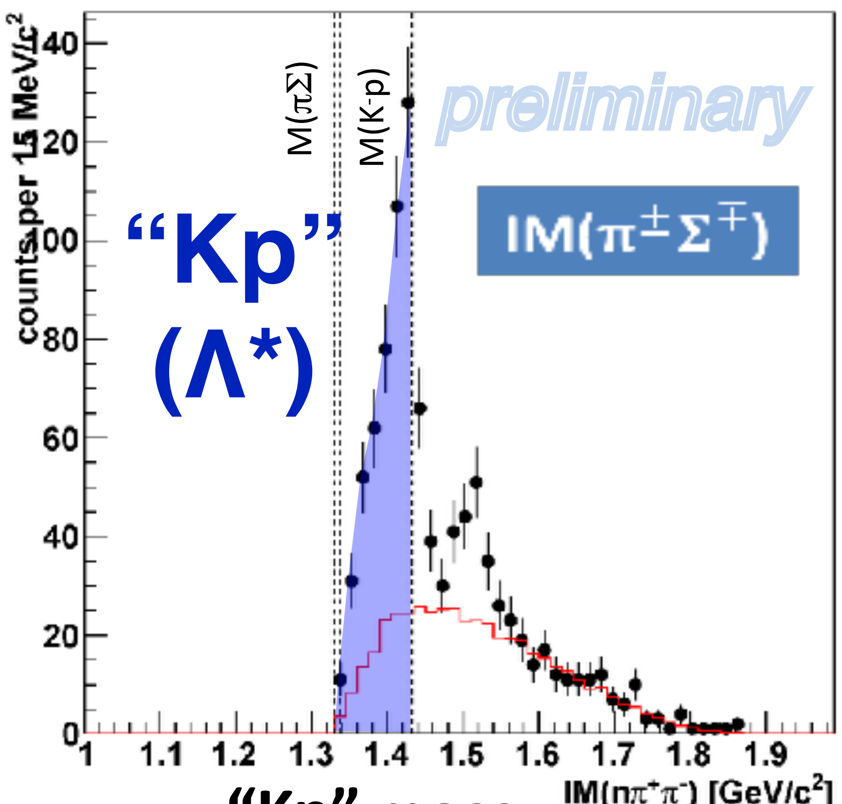
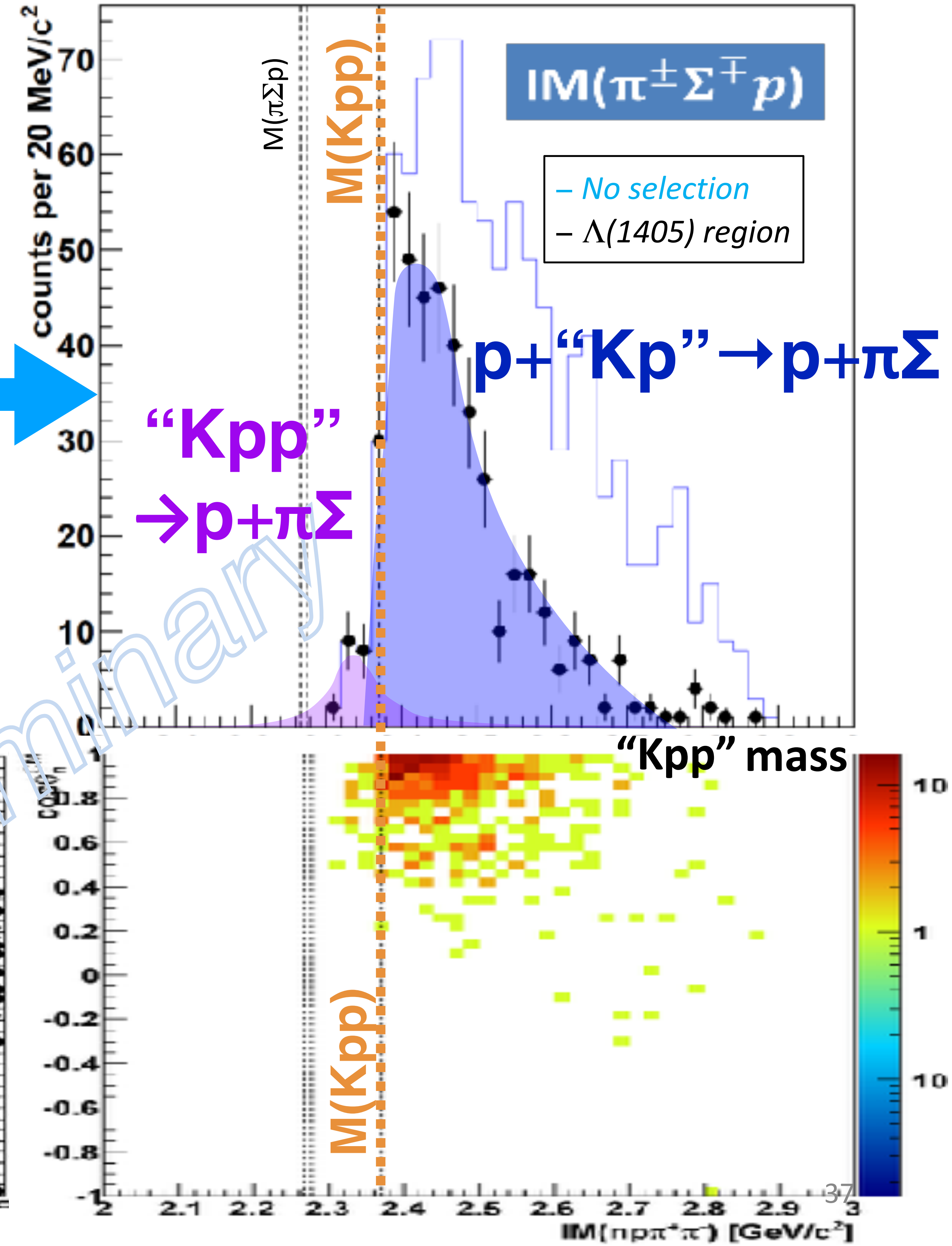
$\Lambda^* \rightarrow \pi\Sigma$ decay of Λ^*p*n* events

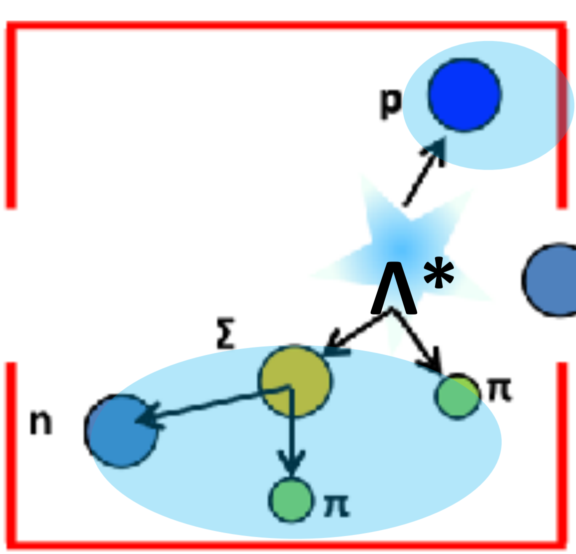
Λ(1405) region is selected

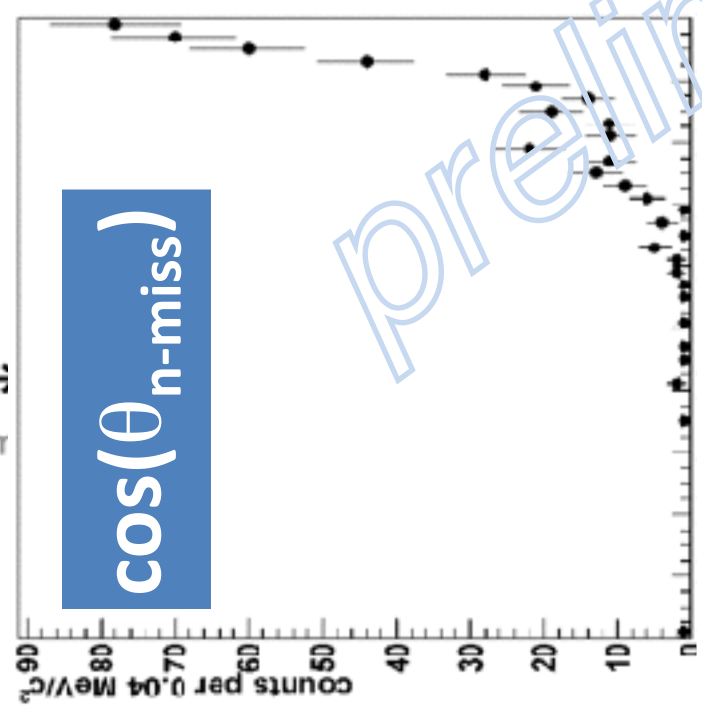
[$IM(n\pi^+\pi^-)<M(K^-p)$]



"Kp" mass







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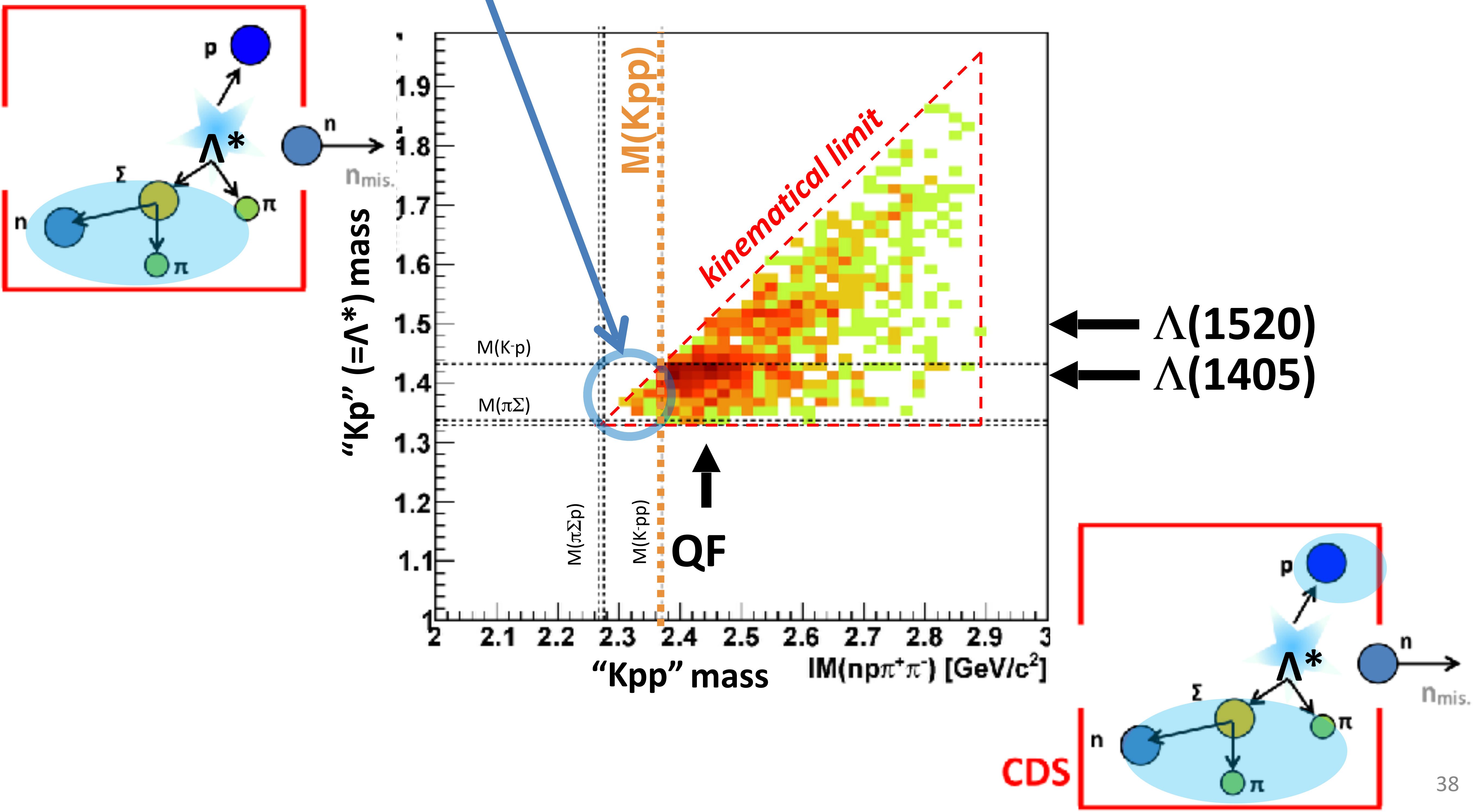
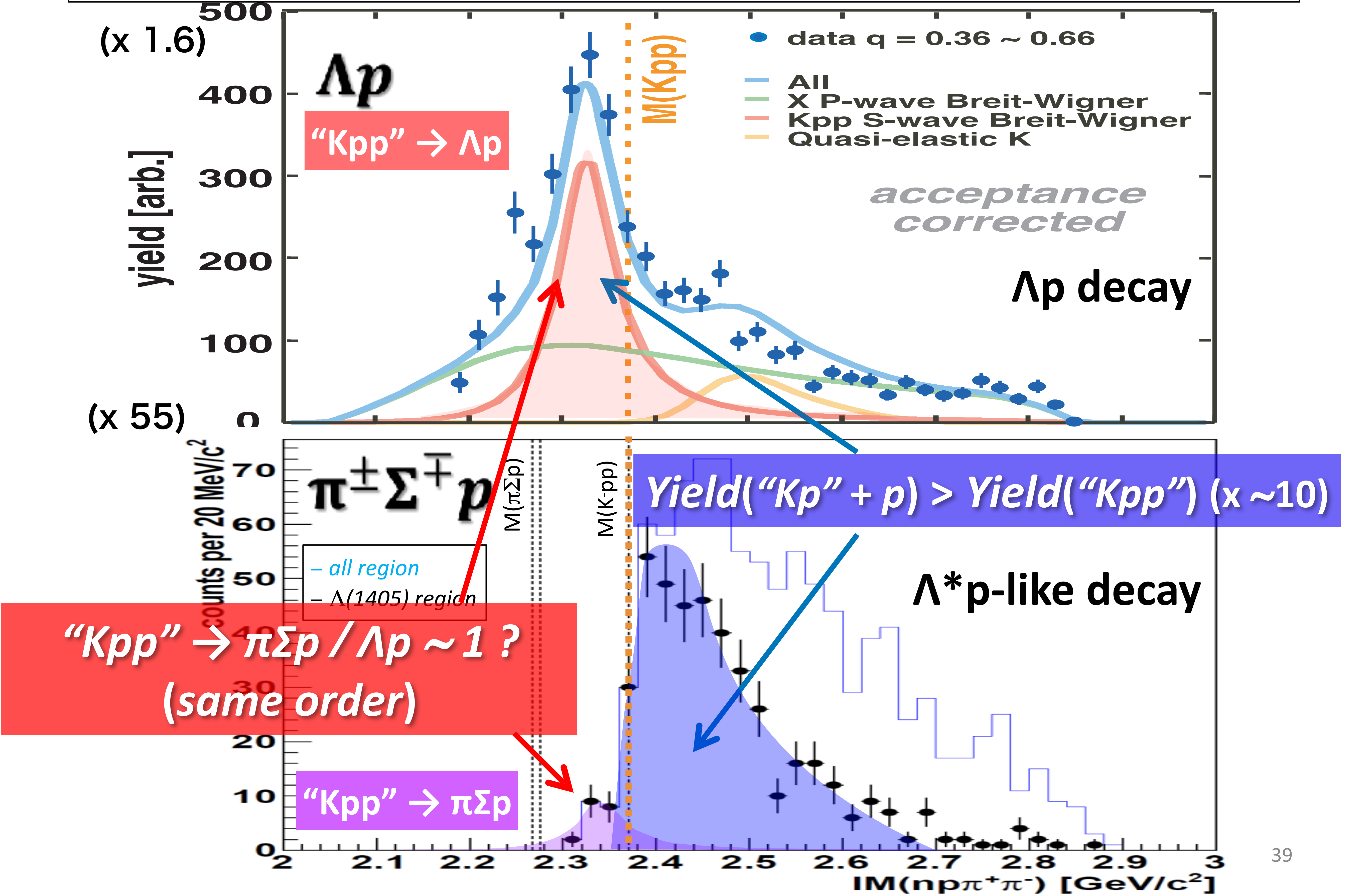
Why $p\Lambda^* \rightarrow \pi\Sigma p$ decay is relatively weak?

small phase-space for "K-pp"→πΣN



Λp vs. πΣp

F. Sakuma



$K^- \, {}^3He \rightarrow \Lambda p + n$ — 3 branches

— $\bar{K}N \rightarrow \bar{K}N$ & $\bar{K}NN \rightarrow \Lambda N$ K-QE + incoherent abs.

— "Kpp" + n & "Kpp" → Λp S-wave

— "X" + n & "X" → Λp P-wave?

$K^- \, {}^3He \rightarrow \Lambda^* p + n$ — Λ* is not a doorway to "Kpp"

— "Kp" + p + n *Yield*("*Kp*" + *p*) > *Yield*("*Kpp*") (x ~10)

"Kp" is more efficiently formed by kicking out p

— "Kpp" + n & "Kpp" → πΣp / Λp ~ 1

Λ*-like decay branch of "Kpp" is similar to YN

$$K^- \, {}^3He \rightarrow \frac{\text{“Kp”} + p + n}{\text{“Kpp”} + n} \sim 10$$

"Kp" & "Kpp"

— seems to be exclusive

Is it mesonic nuclear bound state?

	Kaonic nuclei Kpp		Λ* p resonance Λ* hypernucleus		Hypernuclei: hyperon bound system	
below threshold	M(K+p+p)	yes	slightly below M(Λ*+p)	maybe?	M(Λ+#p+#n)	yes
Theoretical support for existence of pole	Chi.U + Phenomenological	yes	none?	not yet	phenomenological	yes
B.W. pole well separated from threshold	similar to Σ hypernucleus	yes	slightly below M(Λ*+p)	maybe not	weak decay only for Λ while $\Gamma_\Sigma \gg \Gamma_\Lambda$	yes
decay channel open only in nuclei	none-mesonic: Kpp → Λ+p	yes & strong	none-mesonic: Λ*N→ NN	yes but relatively weak	none-mesonic-weak: ΛN→ NN	strong for heavy nuclei
branch suppression of mesonic decay as in vacuum	mesonic: Kpp → Σ π p	yes much weaker	mesonic-weak-decay: Λ* → Σ π	no	mesonic-weak-decay: Λ → p π	yes / weak in heavy nuclei
none-resonant reaction channel above threshold	quasi-elastic K: KN → KN & Kpp → Λ+p	yes	KNN → Λ*N & Λ*p → Λ+p	N.A.	quasi-free : KN → Λ π	yes
Reaction form factor	~ 400 MeV/c :	compact?	N.A.	N.A.	~ 200 MeV/c :	~ nuclei size
variety	Kpp the first	1	N.A.	N.A.	from A = 3 ~	many

most likely, it is.

conclusion B:

"Kp" (=Λ^*) formation observed clearly

in K^- ^{3}He reaction

"Kp" and "Kpp" are produced rather exclusively

We are preparing the paper
of the observation of
— masons in nuclei —

other channels come shortly

Asano: $K^- \, d \rightarrow$ "Kp" $+ n \rightarrow (\Sigma\pi)_{CDS} + n_{mis.}$

q-dependence study : size of resonance?

Hashimoto: $K^- \, d \rightarrow$ "Kpp" $+ \pi^- \rightarrow (\Lambda p)_{CDS} + \pi^-$

parasitic to E31 with forward π^- :
inverse kinematics of E27

other channels of interest

$K^{-}\ {}^{4}He \rightarrow$ "Kppn" $+\ n \rightarrow \Lambda pn + n$

$K^{-}\ {}^{6}Li \rightarrow$ "K$p\alpha$" $+\ n \rightarrow \Lambda\alpha + n$

improve efficiency, especially for n & γ

The E15 Collaborations

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