https://doi.org/10.1016/j.physletb.2018.12.058

ARTICLE IN PRESS
JID:PLB AID:34351 /SCO Doctopic: Experiments [m5Gv1.3; v1.250; Prn:8/01/2019; 5:02] P.1 (1-6)
Physics Letters B ••• (••••) •••–•••
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E15 [K1.8BR]

"K^-pp", a $\overline{K}$-meson nuclear bound state, observed in ^{3}He(K^-, Λp)n reactions

J-PARC E15 collaboration, S. Ajimura[a], H. Asano[b], G. Beer[c], C. Berucci[d], H. Bhang[e], M. Bragadireanu[f], P. Buehler[d], L. Busso[g,h], M. Cargnelli[d], S. Choi[e], C. Curceanu[i], S. Enomoto[j], H. Fujioka[k], Y. Fujiwara[l], T. Fukuda[m], C. Guaraldo[i], T. Hashimoto[n], R.S. Hayano[l], T. Hiraiwa[a], M. Iio[j], M. Iliescu[i], K. Inoue[a], Y. Ishiguro[o], T. Ishikawa[l], S. Ishimoto[j], K. Itahashi[b], M. Iwasaki[b,k,*], K. Kanno[l], K. Kato[o], Y. Kato[b], S. Kawasaki[a], P. Kienle[p,1], H. Kou[k], Y. Ma[b], J. Marton[d], Y. Matsuda[l], Y. Mizoi[m], O. Morra[g], T. Nagae[o], H. Noumi[a], H. Ohnishi[q,b], S. Okada[b], H. Outa[b], K. Piscicchia[i], Y. Sada[a], A. Sakaguchi[a], F. Sakuma[b,*], M. Sato[j], A. Scordo[i], M. Sekimoto[j], H. Shi[i], K. Shirotori[a], D. Sirghi[i,f], F. Sirghi[i,f], K. Suzuki[d], S. Suzuki[j], T. Suzuki[l], K. Tanida[n], H. Tatsuno[r], M. Tokuda[k], D. Tomono[a], A. Toyoda[j], K. Tsukada[q], O. Vazquez Doce[i,p], E. Widmann[d], T. Yamaga[b,a,*], T. Yamazaki[l,b], Q. Zhang[b], J. Zmeskal[d]

A Search for deeply-bound kaonic nuclear states by in-flight ^{3}He(K$^-$,n) reaction

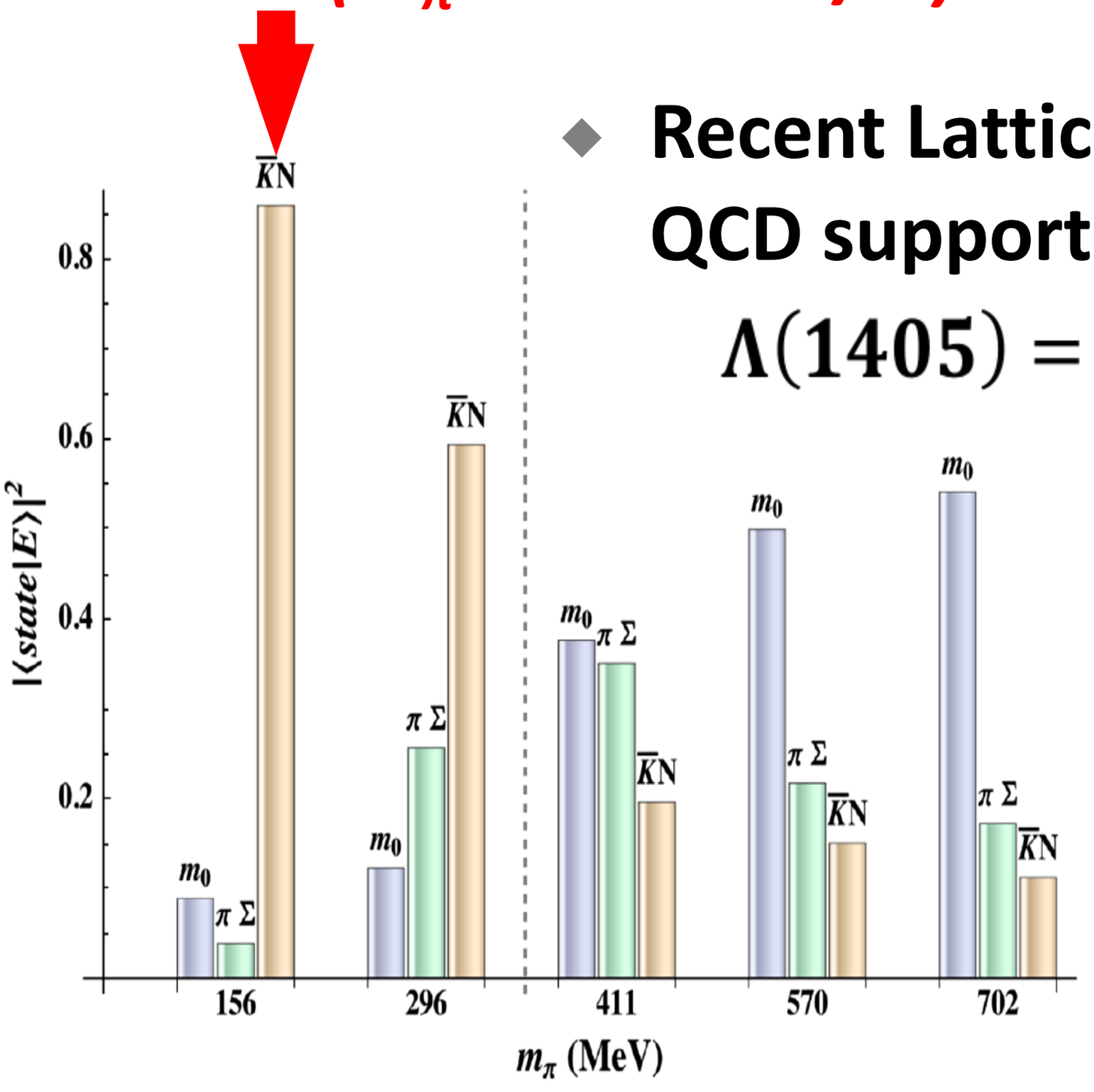
for J-PARC E15 collaboration

M. Iwasaki

RIKEN
Cluster for Pioneering Research
Meson Science Lab.

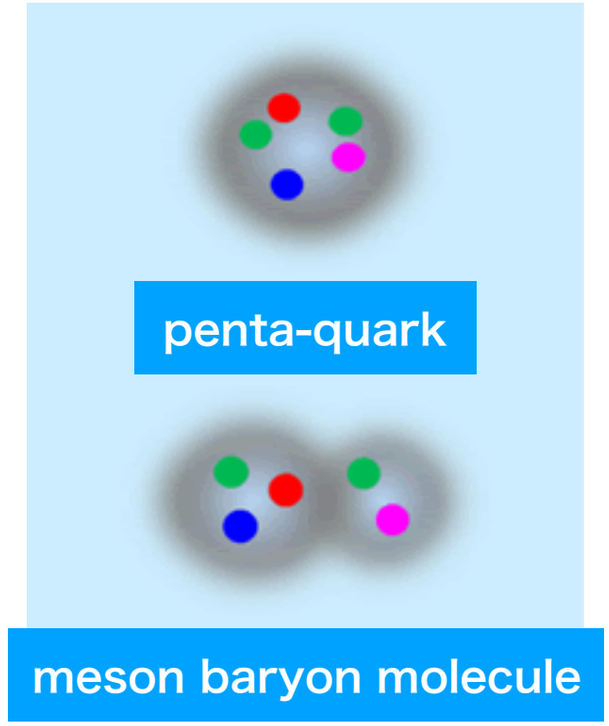
Λ(1405) (Λ*) in Lattice-QCD

~ Real (m_π = 140 MeV/c^2)



- **Recent Lattice QCD supports,**

$$\Lambda(1405) = p - K^- = (uud)\text{-}(\bar{u}s)$$

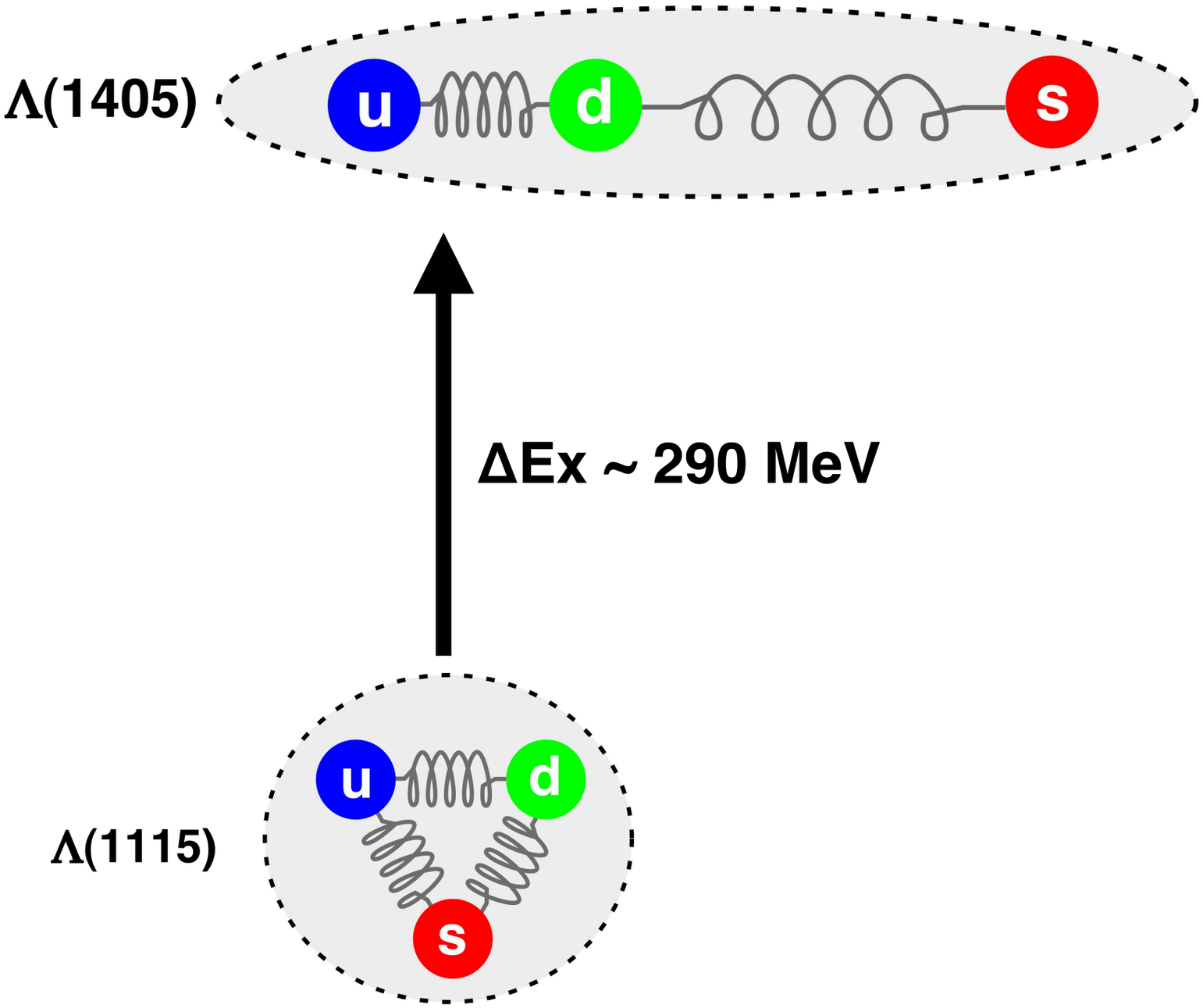


then, one can embed K into nucleus

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

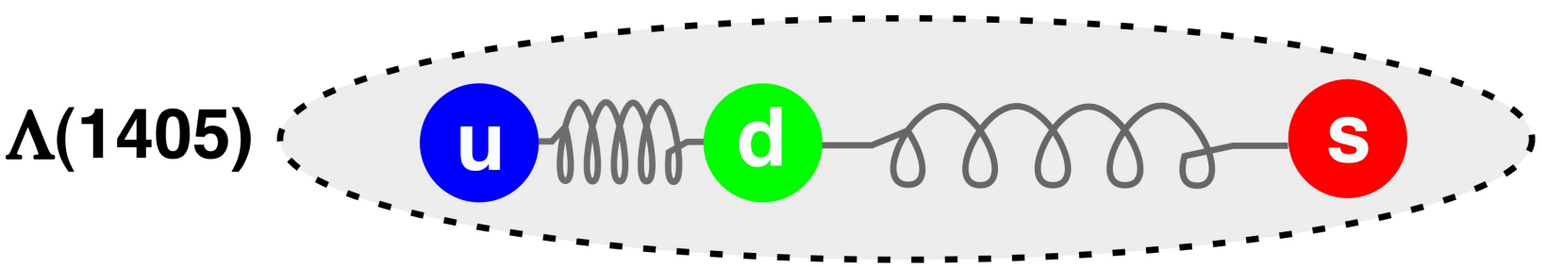
From Λ(1405) to kaonic nuclei

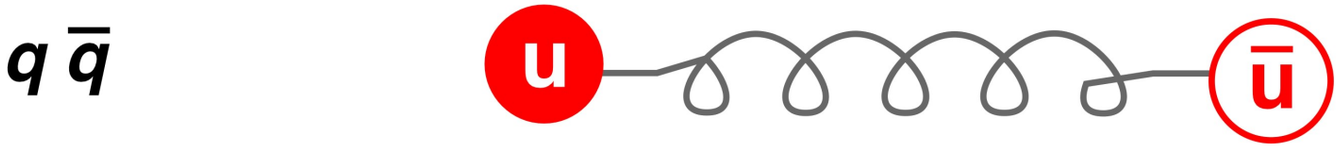
Is it an excited state of *uds* : Λ(1115)?



From Λ(1405) to kaonic nuclei

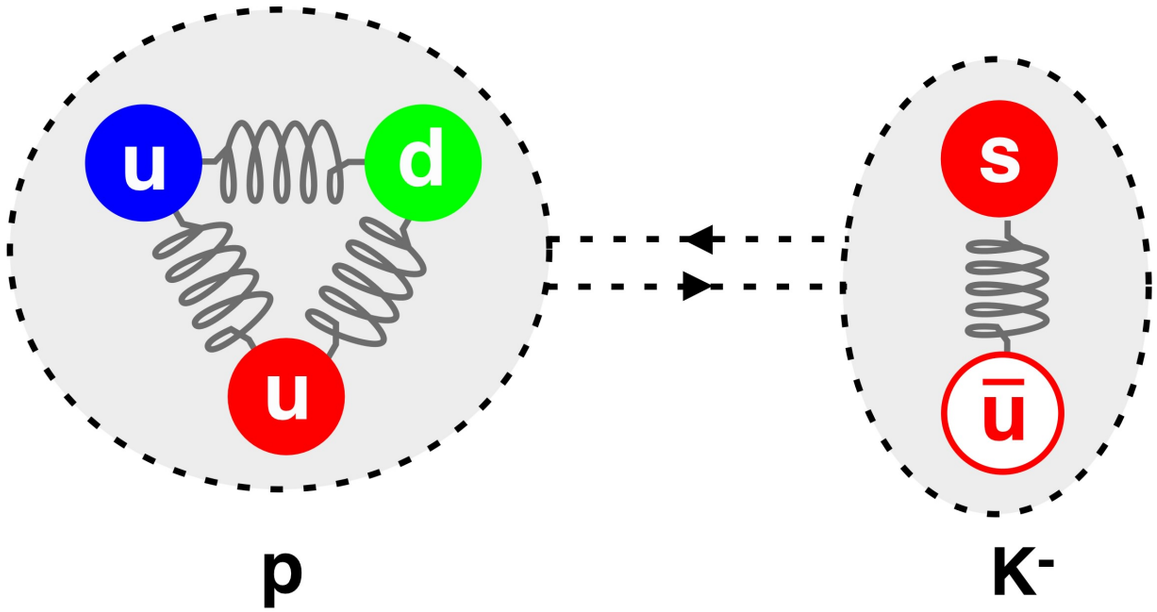
with $\bar{q}q$ (χ-condensate) in vacuum





From Λ(1405) to kaonic nuclei

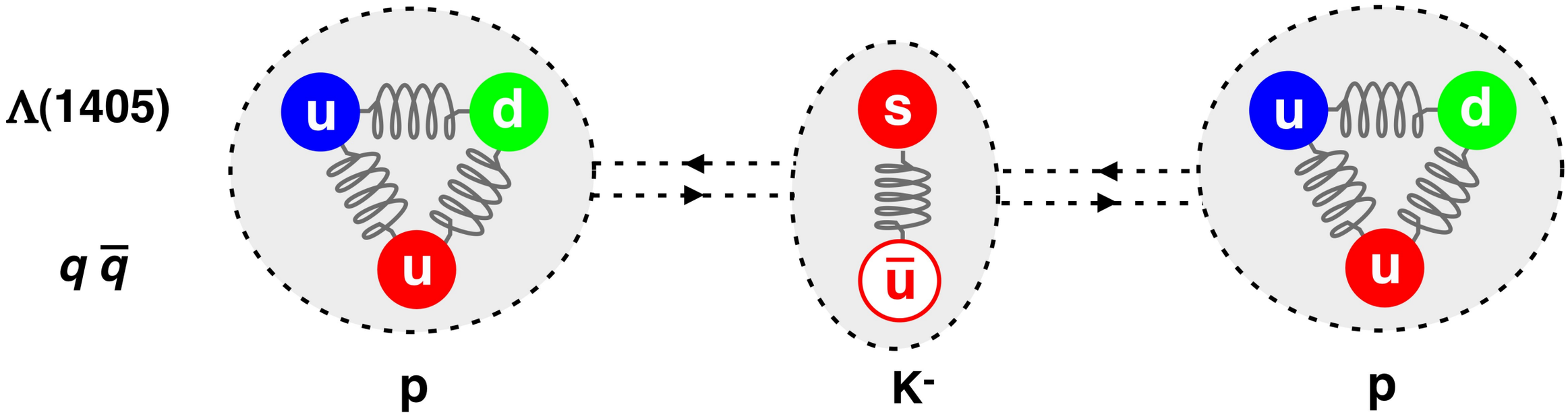
two color-singlet objects : p ≡ K^-



$M(pK^-) = 1432\ \mathrm{MeV}/c^2$ $\quad B_{Kp} \sim 25\ \mathrm{MeV}$

From Λ(1405) to kaonic nuclei

kaonic nucleus “Kpp”



$M(pK^-) = 1432\ \mathrm{MeV}/c^2$

$M(ppK^-) = 2370\ \mathrm{MeV}/c^2$

$M_{Kpp} \sim 2320\ \mathrm{MeV}/c^2$

$B_{Kpp} \sim 50\ \mathrm{MeV}$

$\Gamma_{Kpp} \sim 100\ \mathrm{MeV}$

observed

More studies w/ upgraded setup

Subject for discussion:

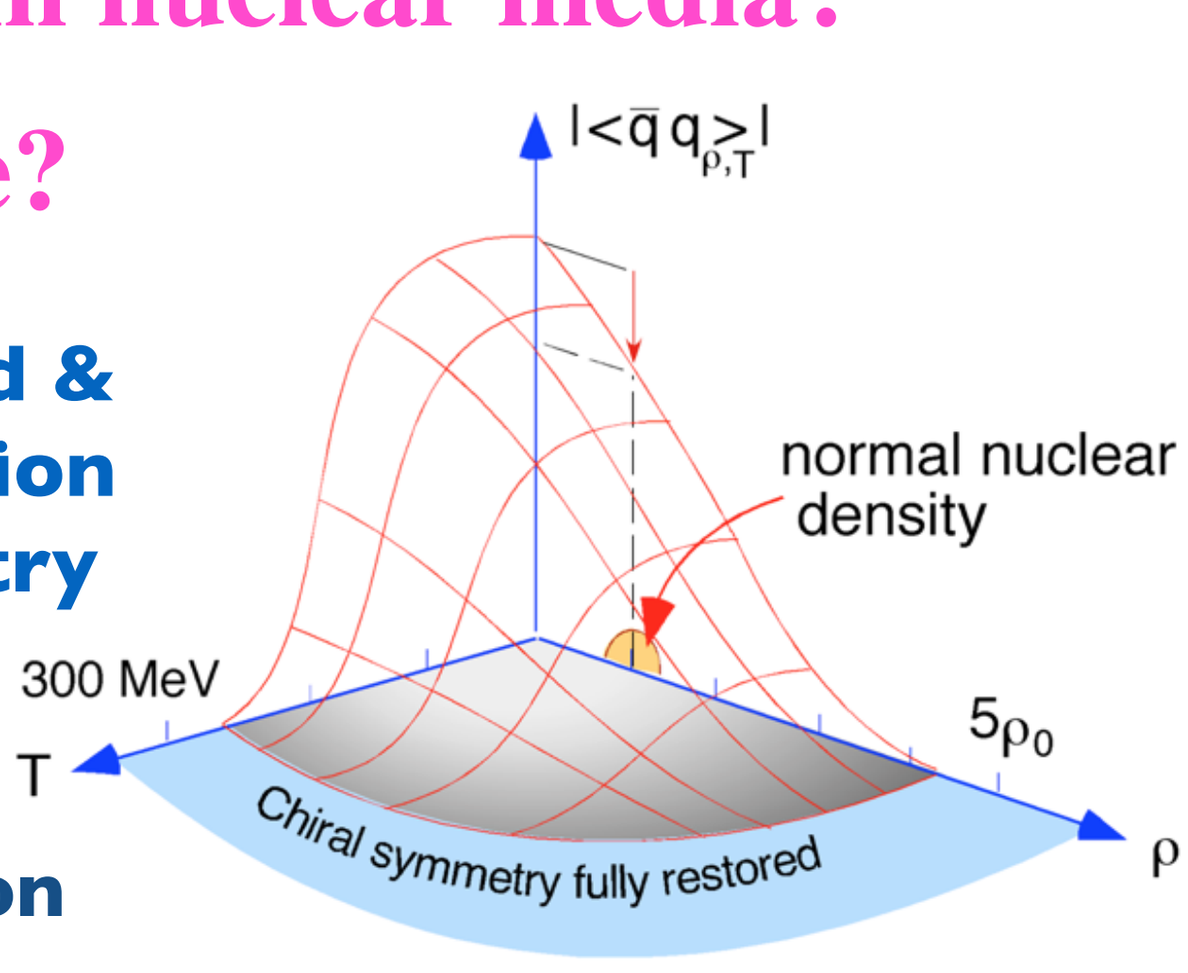
Strong $\bar{K}N$ attraction! $\Lambda(1405) = K^- p$ bound state

Key questions :

- How hadrons are confined in nuclei?
- Kaon(mason) property in nuclear media?
- Size of kaon bound state?

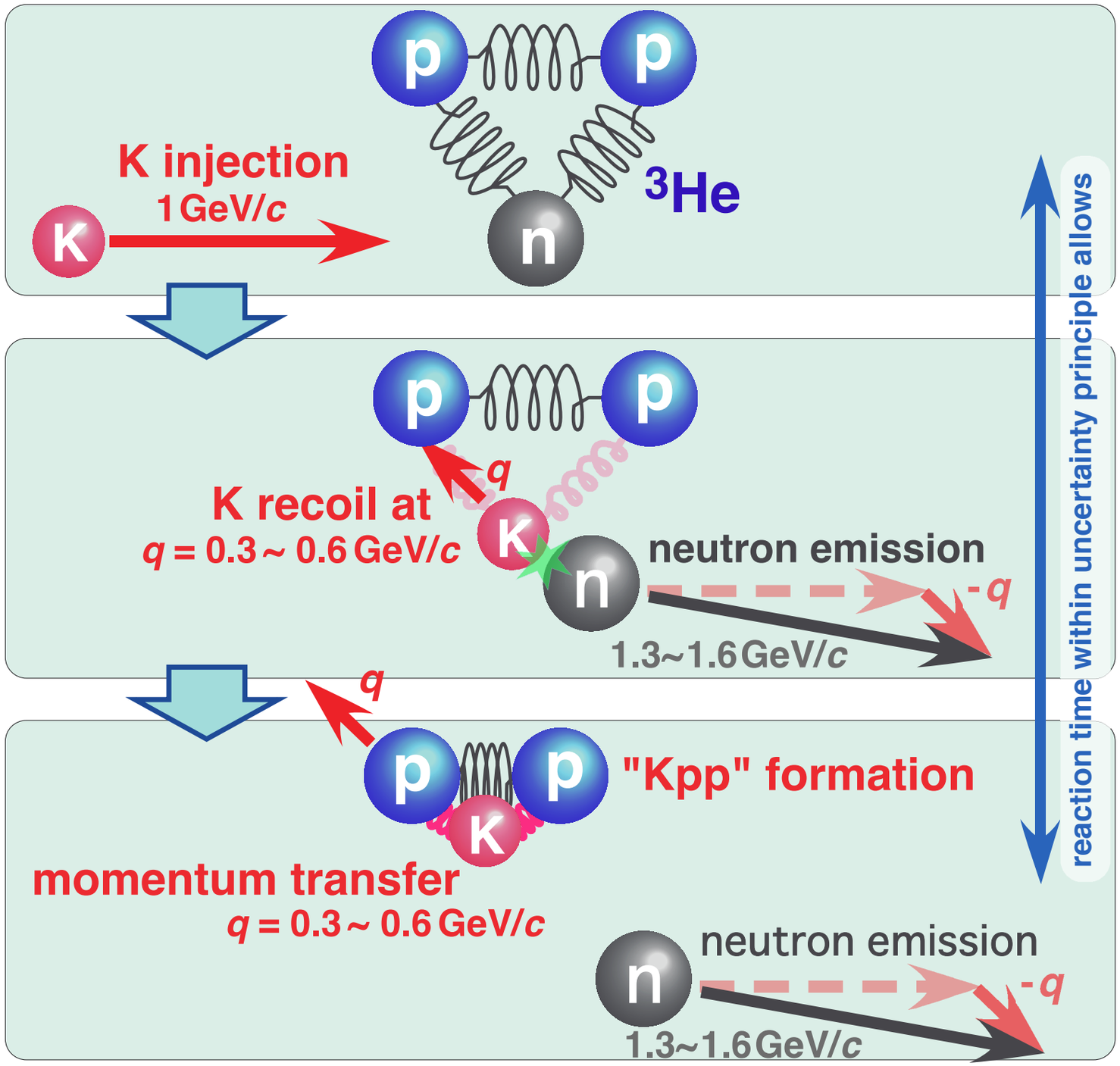
Could be a good probe for cold & dense QCD, to study the relation of hadron mass and χ-symmetry

<q̄q> as QCD-Higgs condensation

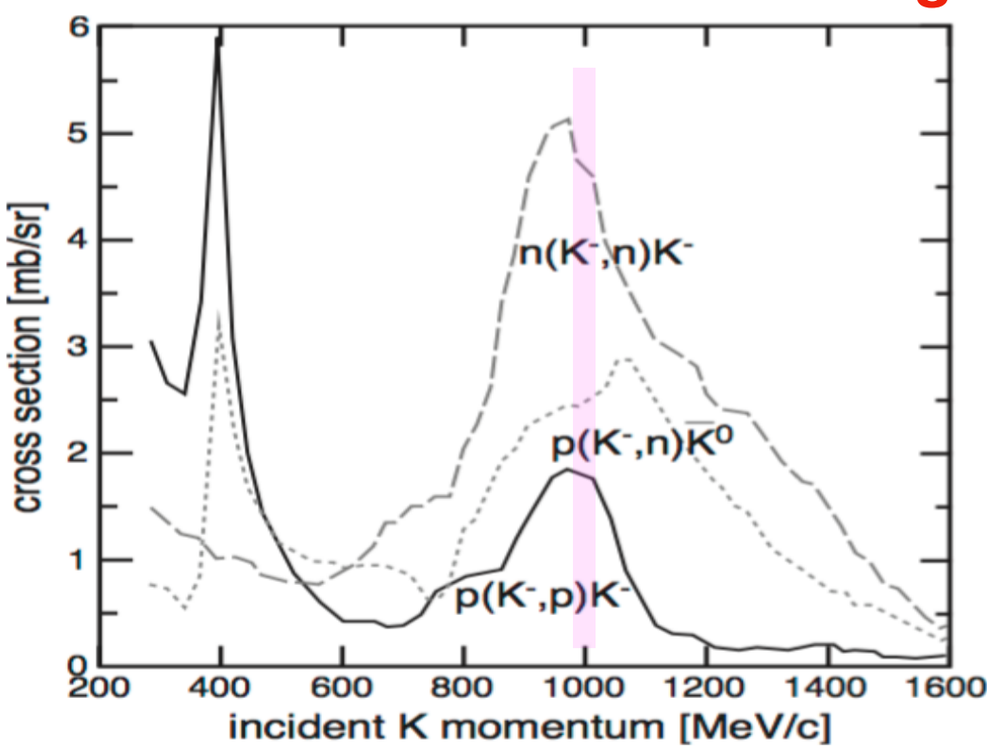


“Kpp” bound state via ^{3}He(K^-, n) reaction

K^- + pp →“Kpp” is impossible
may study only above M(Kpp)



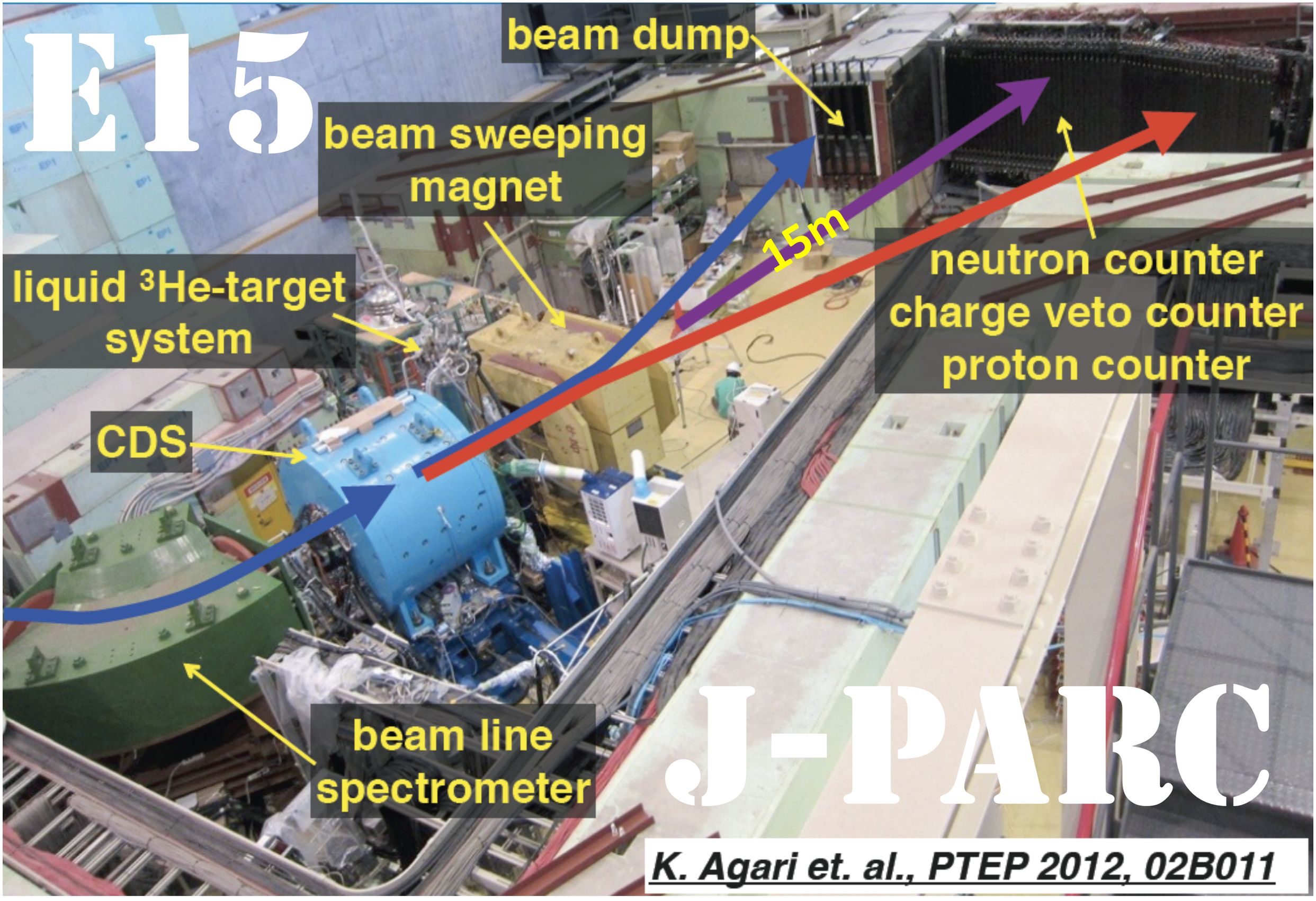
KN→KN backward scattering



when K is in off-shell

$$E_K^2 - q^2 < m_K^2$$

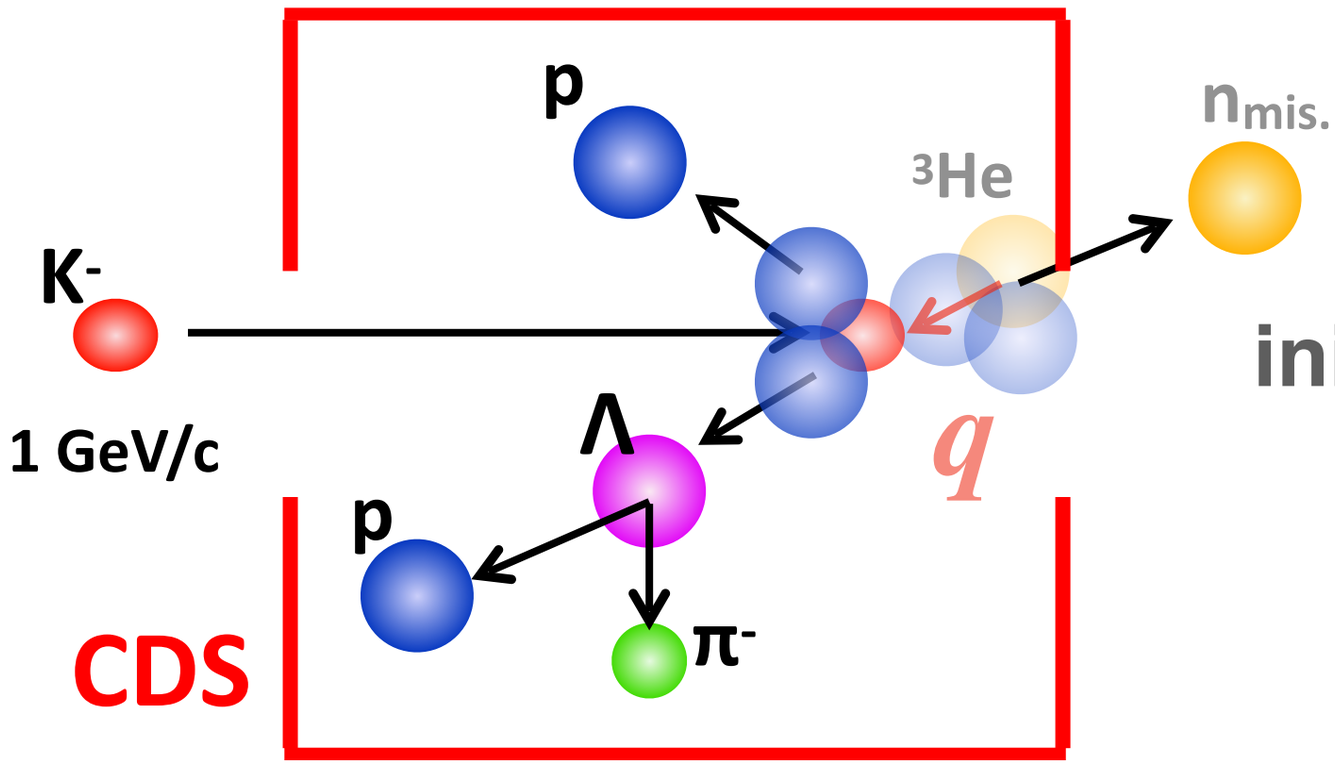
“Kpp” can be formed


E15
beam dump
beam sweeping magnet
liquid ³He-target system
CDS
beam line spectrometer
15m
neutron counter
charge veto counter
proton counter
J-PARC
K. Agari et. al., PTEP 2012, 02B011

Exclusive: Λ p n

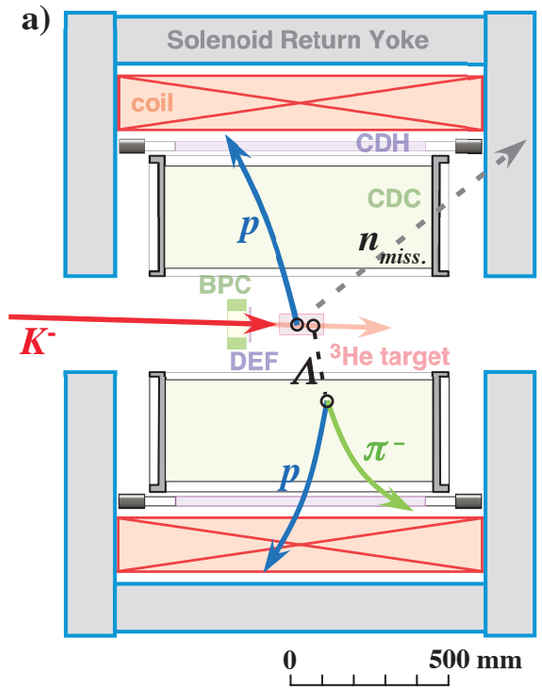
simplest final state

3 baryon w/ strangeness



initiated by KN→KN

q: virtual kaon momentum



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

- E15^{2nd}

before acceptance correction

b)

data

$QF_{\bar{K}A}$

M(Λp)

M(Kpp)

counts

400

300

200

100

0

c)

counts

50

100

150

200

a)

M(Kpp)

$\theta_n = \pi$

$\theta_n = 0$

$\theta_n = 0$

20

10

0

q [GeV/*c*]

1.0

0.5

0.0

2.0

2.2

2.4

2.6

2.8

3.0

M [GeV/c^2]

after acceptance correction

q [GeV/c]

1.0

0.5

0.0

2.0

2.2

2.4

2.6

2.8

3.0

M [GeV/c^2]

$\theta_n = \pi$

$\theta_n = 0$

$\theta_n = 0$

$M_F(q)$

M(Kpp)

>5

4

3

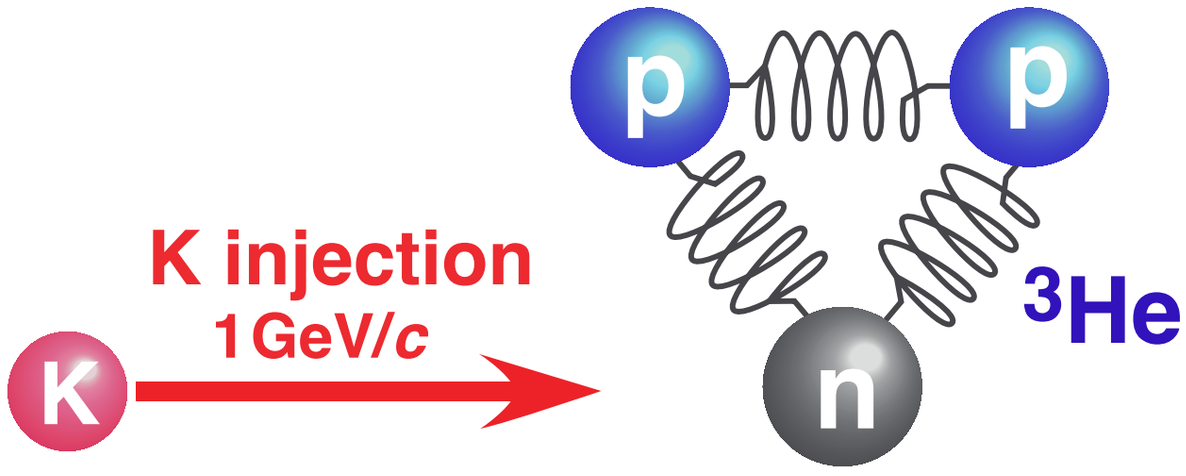
2

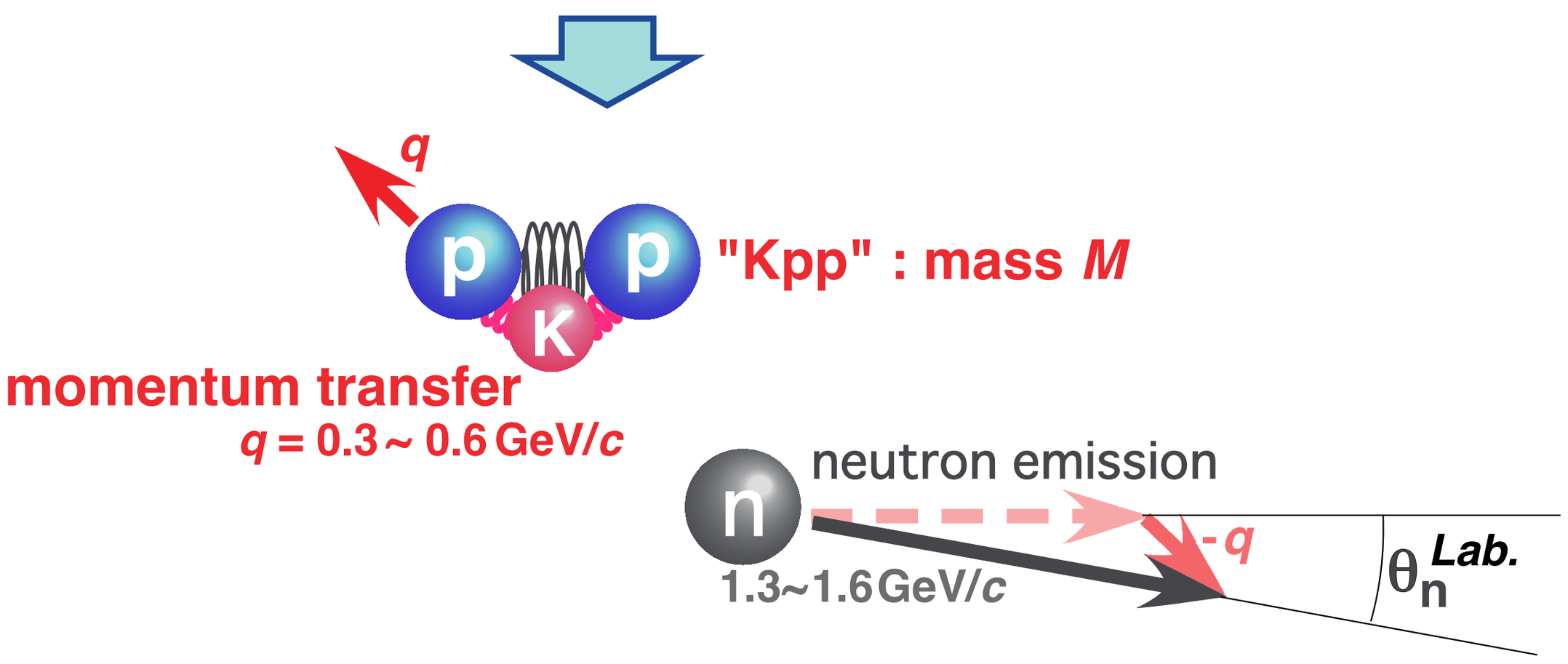
1

0

M & *q* defines kinematics ⟷ (or *M* & θ_n)

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



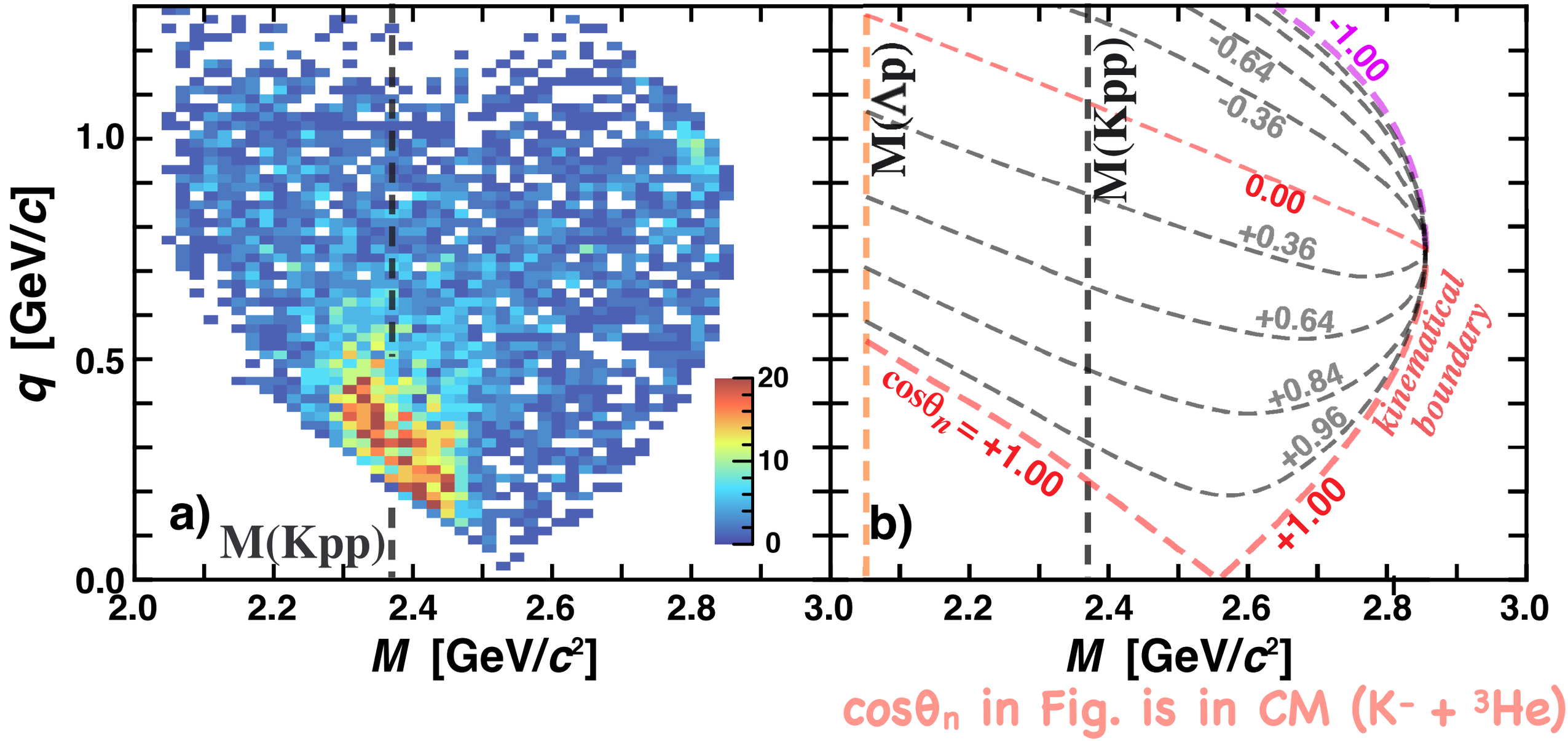


M & *q* defines kinematics ⟷ (or *M* & θ_n)

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

$$\tan\theta_n^{Lab.} = \frac{-q\sin\theta}{p_K - q\cos\theta}$$

$$\begin{pmatrix}\sqrt{m_K^2+p_K^2}\\ p_K\\ 0\end{pmatrix} + \begin{pmatrix}M_{^3\mathrm{He}}\\ 0\\ 0\end{pmatrix} = \begin{pmatrix}\sqrt{M^2+q^2}\\ q\cos\theta\\ q\sin\theta\end{pmatrix} + \begin{pmatrix}\sqrt{m_n^2+p_K^2-2p_K q\cos\theta+q^2}\\ p_K - q\cos\theta\\ -q\sin\theta\end{pmatrix}$$

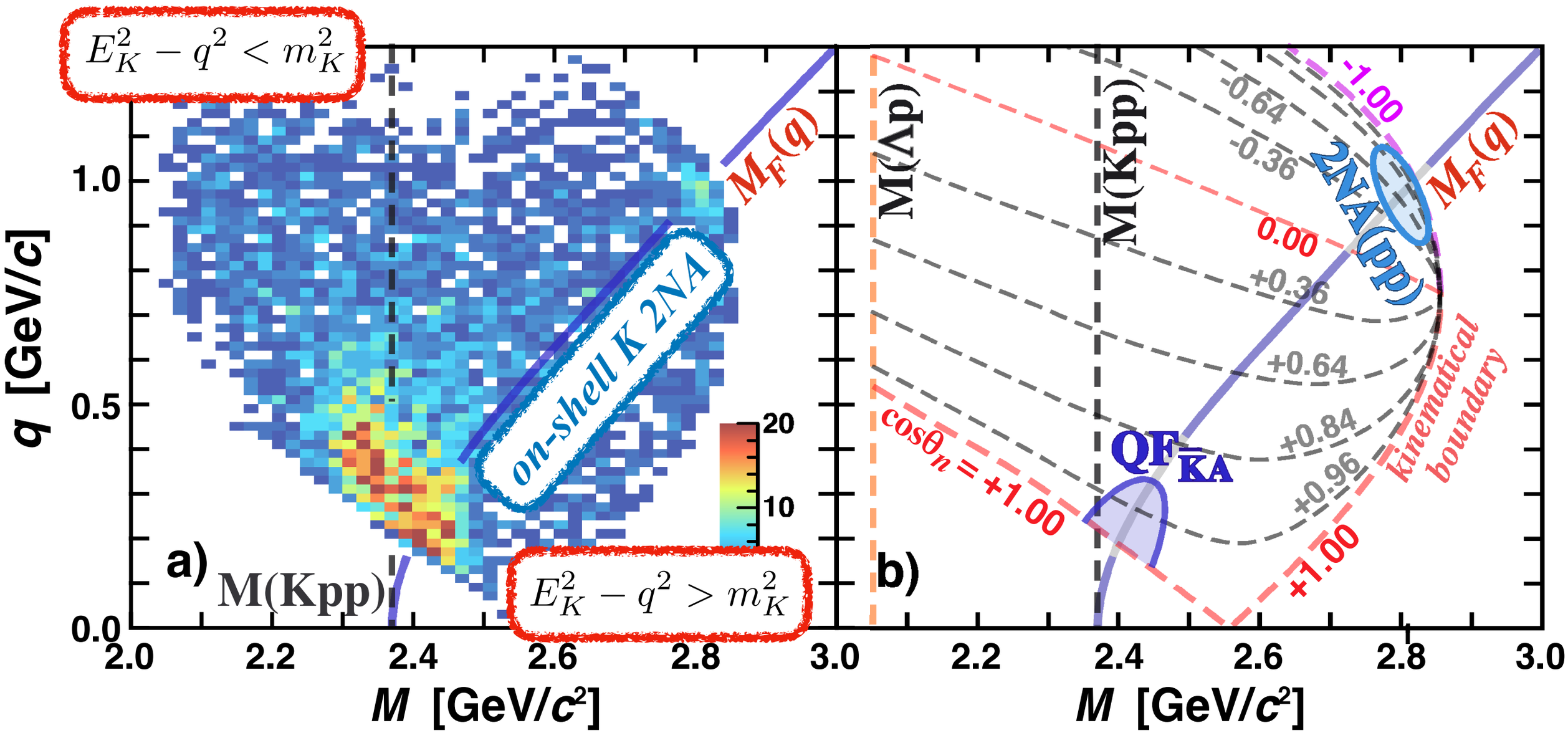


cosθn in Fig. is in CM (K^- + ^{3}He)

$QF_{\bar{K}A}$: $K^- + N \rightarrow \bar{K} + n$

$\bar{K} + N_s + N_s \rightarrow F\ (= \Lambda + p)$ *back scattered K*

$$\begin{pmatrix} \sqrt{m_K^2 + q^2} \\ q \end{pmatrix} + \begin{pmatrix} m_N \\ 0 \end{pmatrix} + \begin{pmatrix} m_N \\ 0 \end{pmatrix} = \begin{pmatrix} \sqrt{M_F^2 + q^2} \\ q \end{pmatrix}$$



Exclusive: Λ p n

"Kpp" seen

Quasi-free kaon absorption (QF_{KA})

$K^- + N \rightarrow \bar{K} + n \qquad \bar{K} + N_s + N_s \rightarrow \Lambda + p$

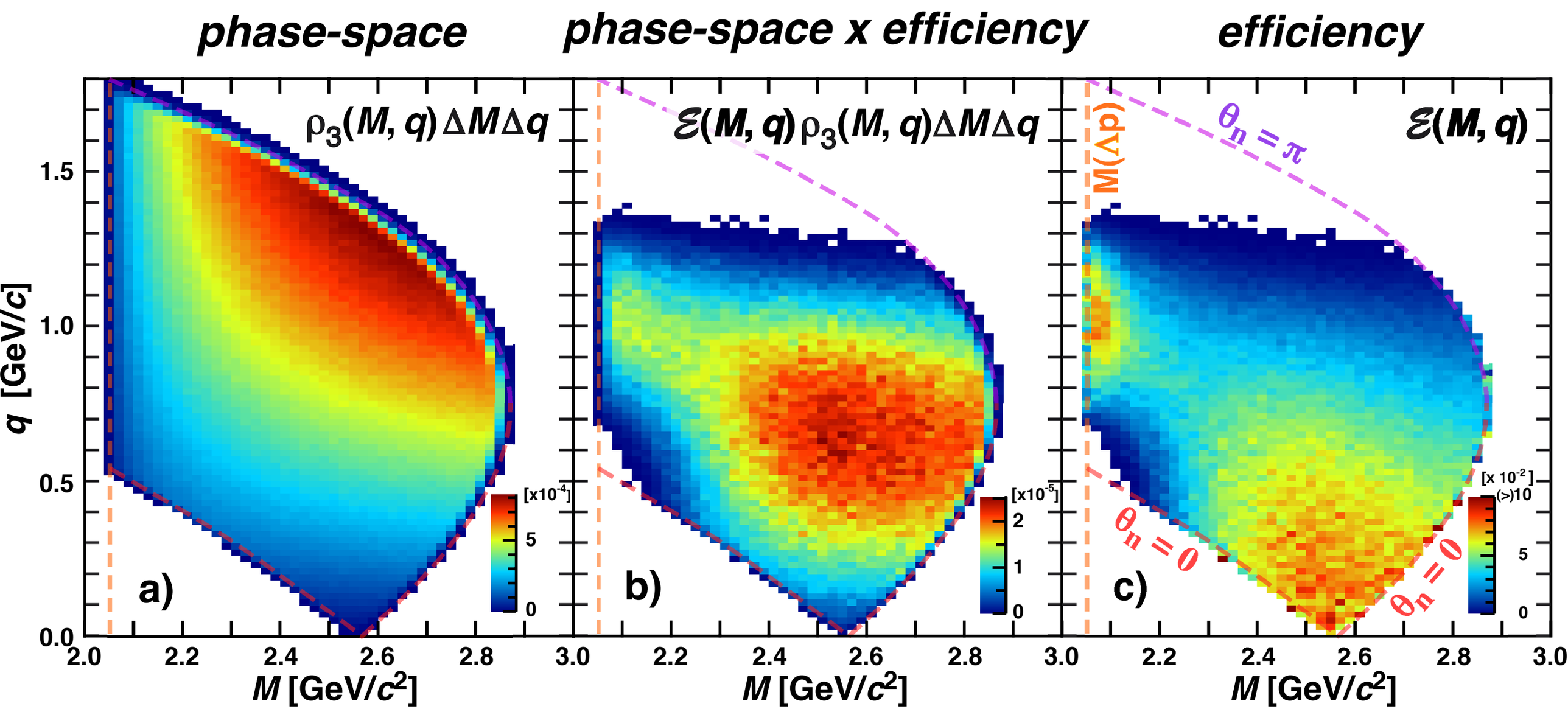
Forward QF_{KA} [or Kaon direct 2NA (pp)]

$K^- + p + p \rightarrow \Lambda + p$

What happens if you see

point-like $K^- + {}^3He \rightarrow \Lambda + p + n$ reaction

$\propto$ *phase-space*

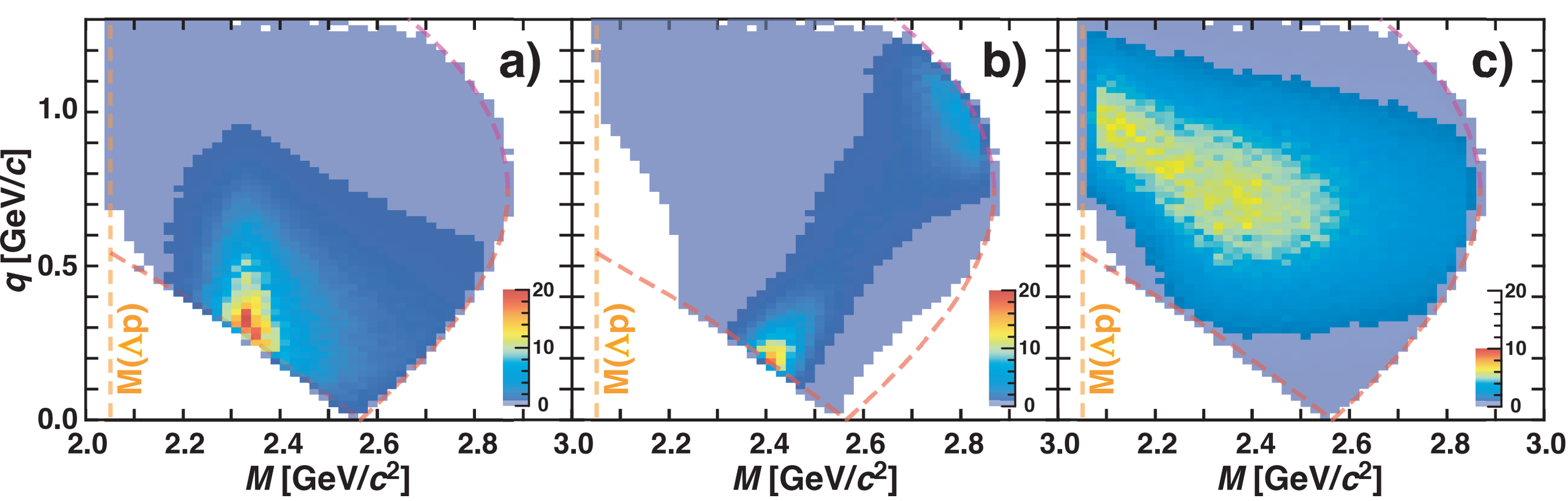


weak yield of "Kpp" at θ_n=0 is due to the phase volume

We introduce three model functions to fit

$$\mathcal{E}(M,q) \times \rho_3(M,q) \times phys_X(M,q)$$

detector efficiency	Λpn 3-body phase space	physics process
"Kpp"	**$QF_{\bar{K}A}$**	**broad(BG)**
KN→KN, KNN→"Kpp"	KN→KN, KNN→Λp	K ^{3}He→Λpn ?



- E15^{2nd}

b)

I I(Kpp)

data

K^-pp

$QF_{\bar{K}A}$

BG

all

before acceptance correction

counts

M(Λp)

counts

50 100 150 200

c)

$M_F(q)$

$\theta_n = 0$

$\theta_n = 0$

$\theta_n = 0$

a)

M(Kpp)

20 10 0

q [GeV/*c*]

0.0 0.5 1.0

2.0 2.2 2.4 2.6 2.8 3.0

M [GeV/c^2]

- E15^{2nd}

b)

I I(Kpp)

data

K^-pp

$QF_{\bar{K}A}$

BG

all

before acceptance correction

counts

M(Λp)

counts

c)

$\theta_n = \pi$

$M_F(q)$

$\theta_n = 0$

$\theta_n = 0$

a)

M(Kpp)

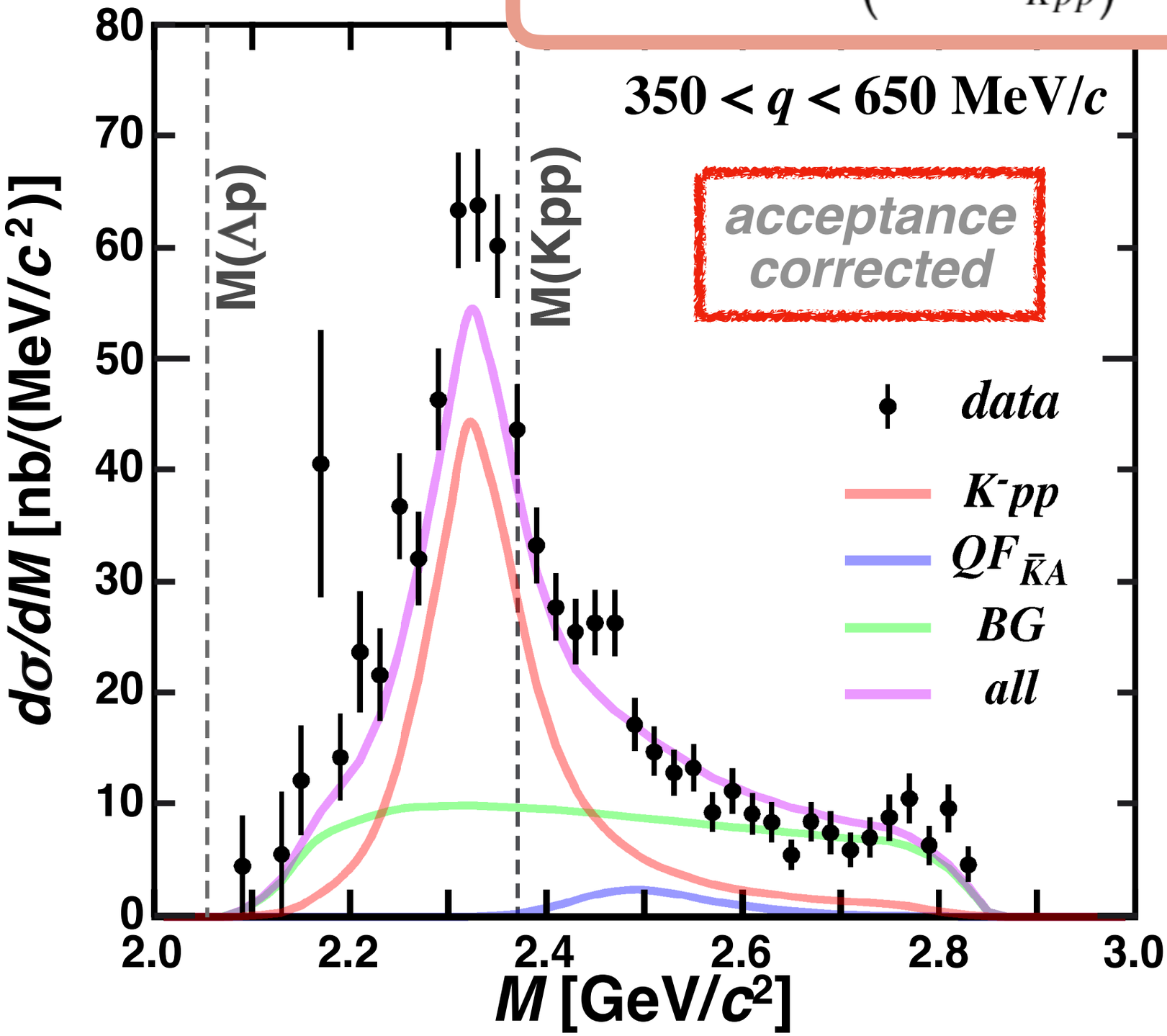
q [GeV/*c*]

M [GeV/c^2]

momentum transferred

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

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



$\sigma_M(\Lambda p) \sim 10$ MeV/c²

after acceptance correction

$E_K^2 - q^2 < m_K^2$

$\theta_n = \pi$

$M_F(q)$

$\theta_n = 0$

M(Kpp)

$E_K^2 - q^2 > m_K^2$

>5
4
3
2
1
0

1.0
0.5
0.0

2.0
2.2
2.4
2.6
2.8
3.0

q [GeV/c]

M [GeV/c^2]

conclusion A:

Definitive peak observed

B_{Kpp} ~50 MeV, Γ_{Kpp} ~100 MeV, Q_{Kpp} ~400 MeV/c

arXiv:1805.12275

Three physical processes in Λpn final state

"Kpp", $QF_{\bar{K}A}$, broad(BG)

("Kpp" is consistent with S-wave)

Λ* by K⁻ reaction?

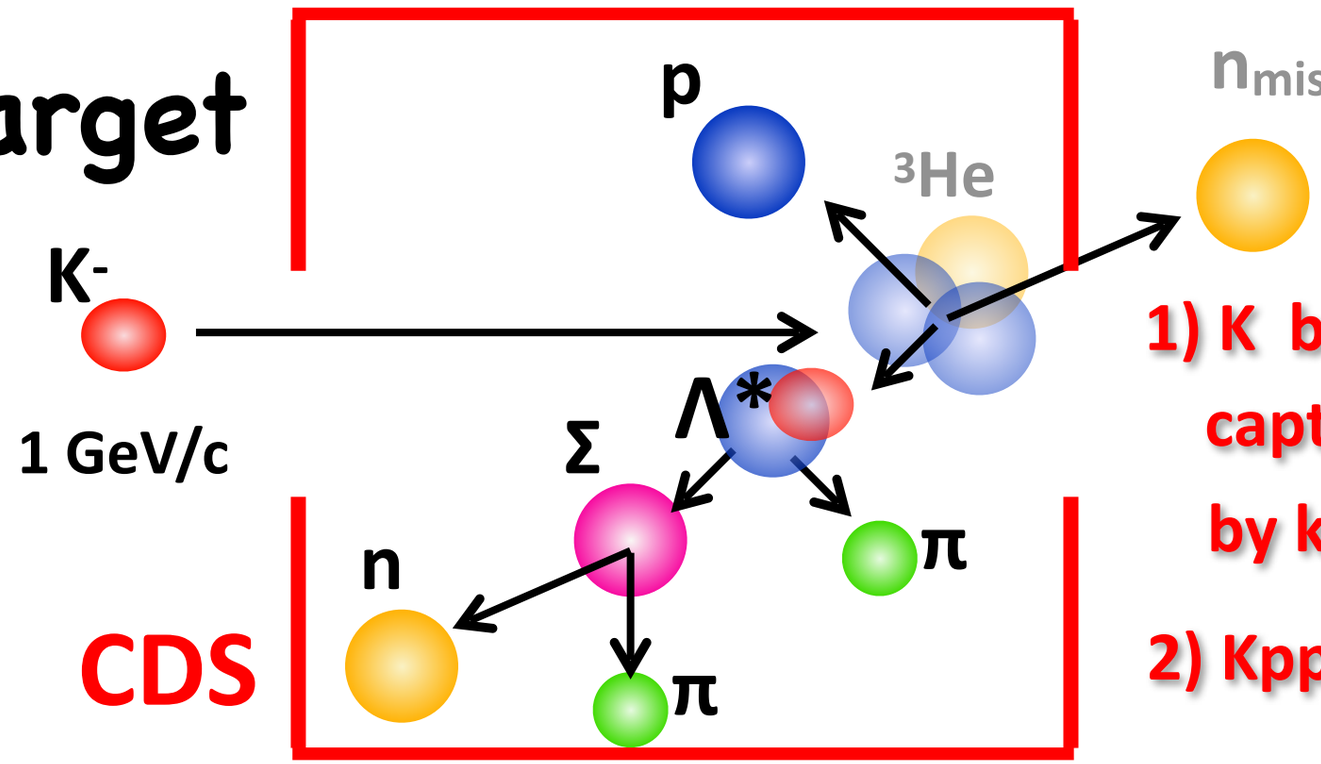
E15

paper will come soon

Λ*pn final state

see Appendix

³He target

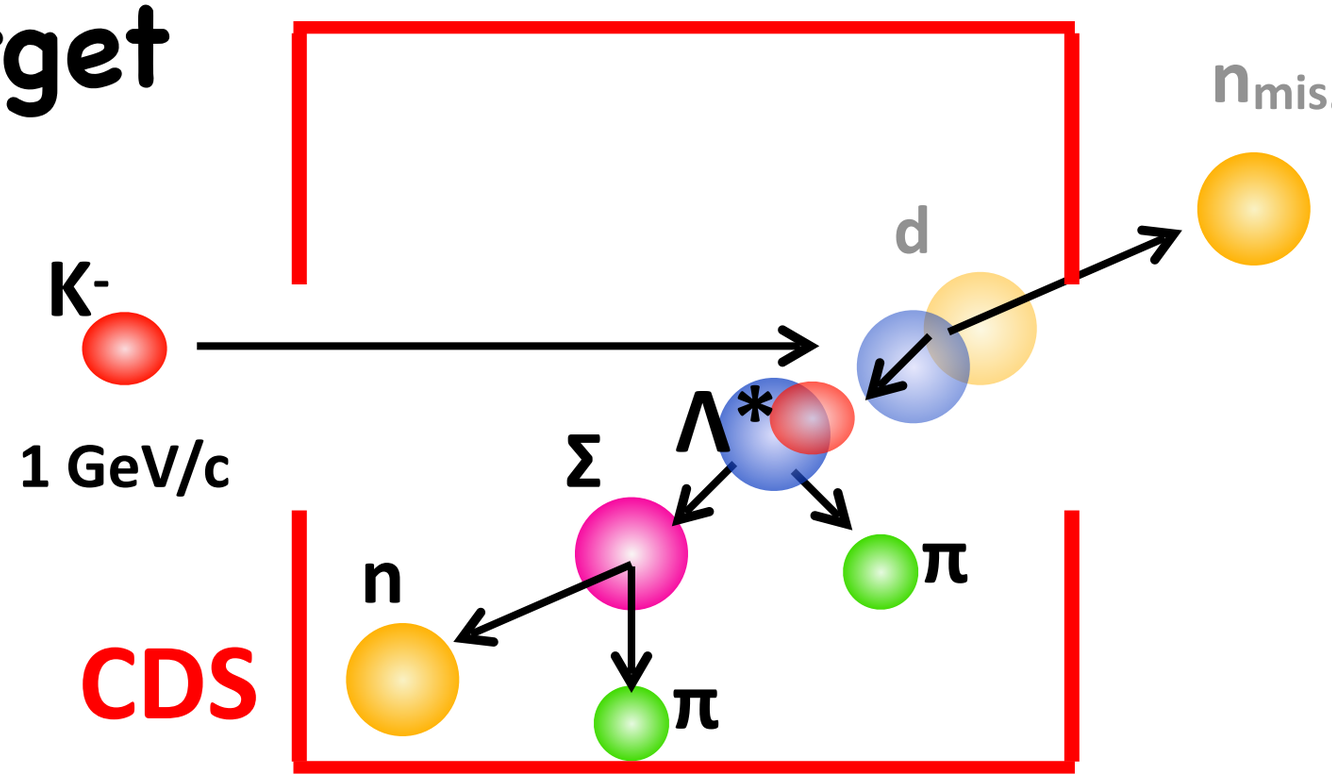


1) K bck. scattered with E excess
capture a proton to form "Kp" (Λ*)
by kicking out another proton

2) Kpp major decay channel YN
cf. Λ* → πΣ

---

d target



E31

How will it look like?

Λ*n final state

still preliminary

A quest for the “Kp” (=Λ(1405)) bound state via d(K^-, n) reaction, J-PARC E31 experiment

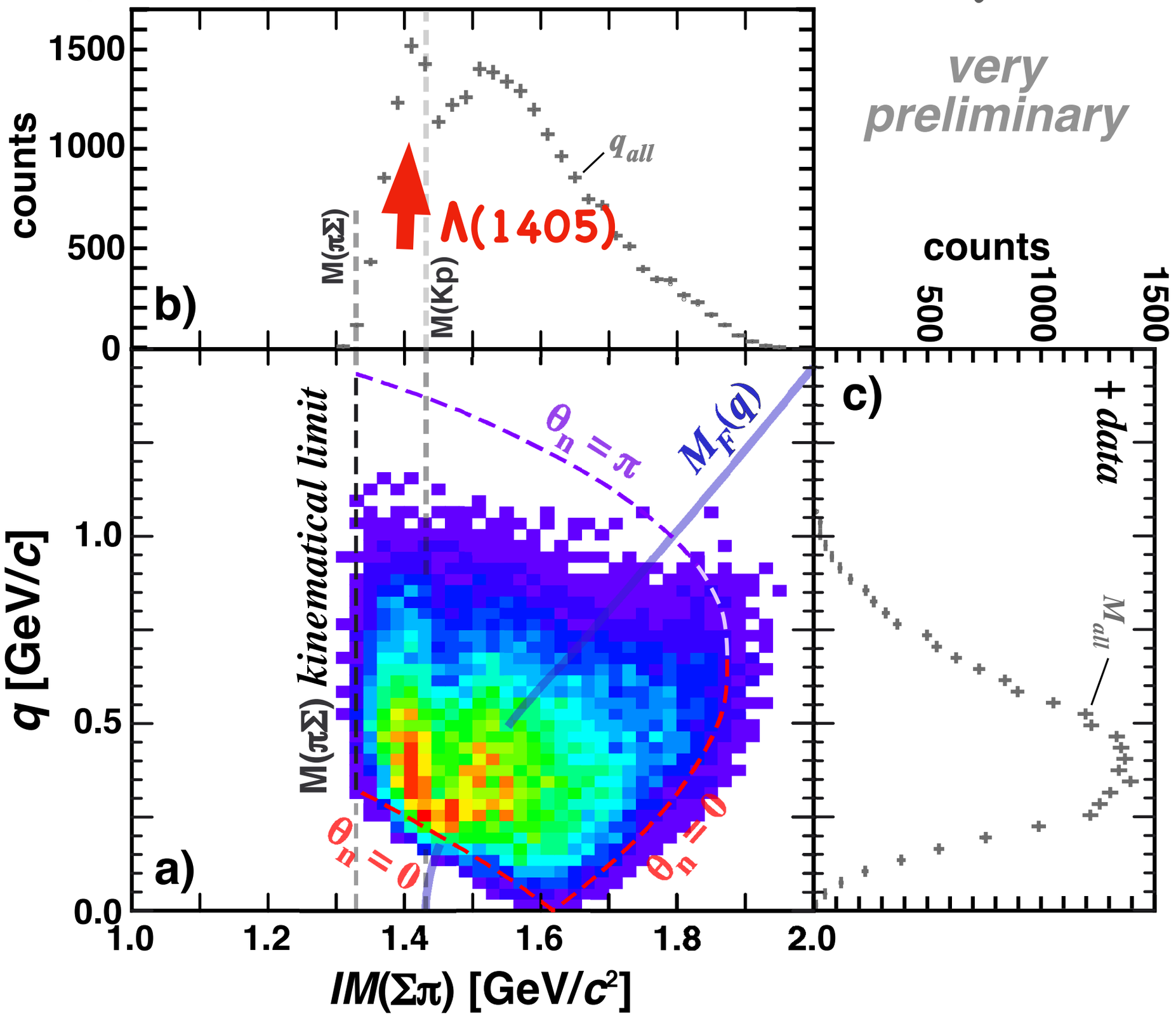
spokesperson: Hiroyuki Noumi

convincing & consistent data with E15

The last piece of the Jigsaw puzzle

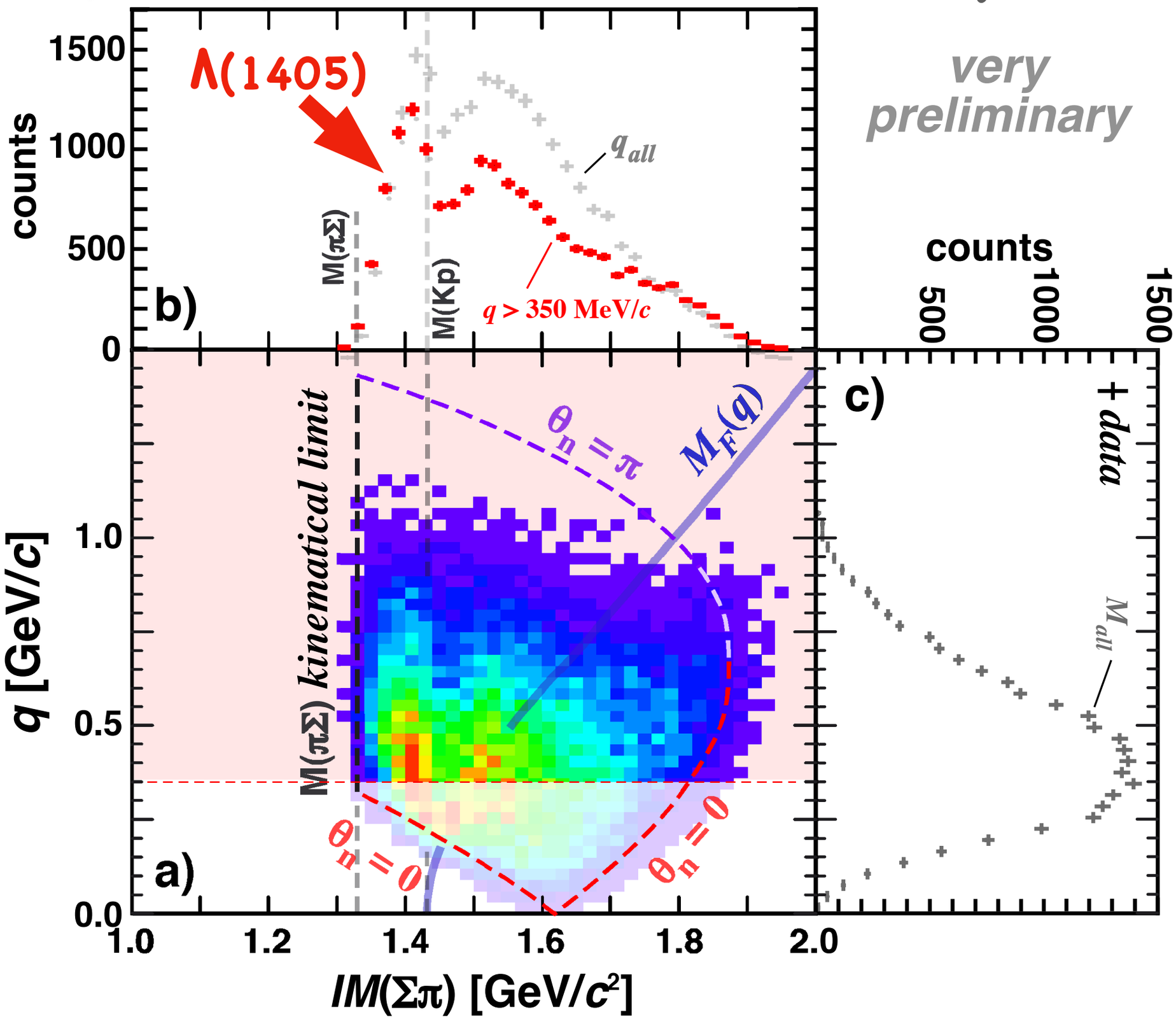
Λ(1405)n final state

Λ(1405) → π⁺Σ⁻ / π⁻Σ⁺ decay modes



Λ(1405)n final state

Λ(1405) → π⁺Σ⁻ / π⁻Σ⁺ decay modes



conclusion B:

Λ* formation observed clearly via the K+p channel

Distribution is very similar to "Kpp"

E15 and E31 are consistent
Strongly suggesting Λ* = "Kp"

WHAT SHALL WE DO NEXT?

We wish to extend E15 (another ~90%), if J-PARC can provide an order larger proton intensity soon, as it is originally planned before.

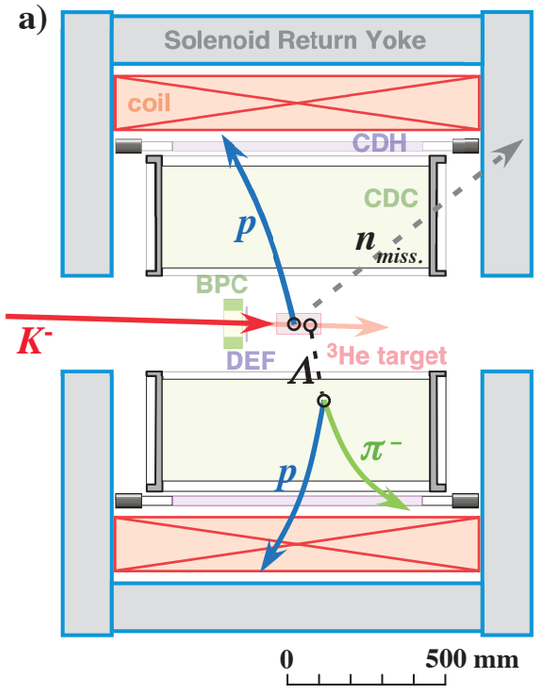
If it is not the case, it is time to think about major detector upgrade.

Objectives: *spin / parity / energy / size ...*

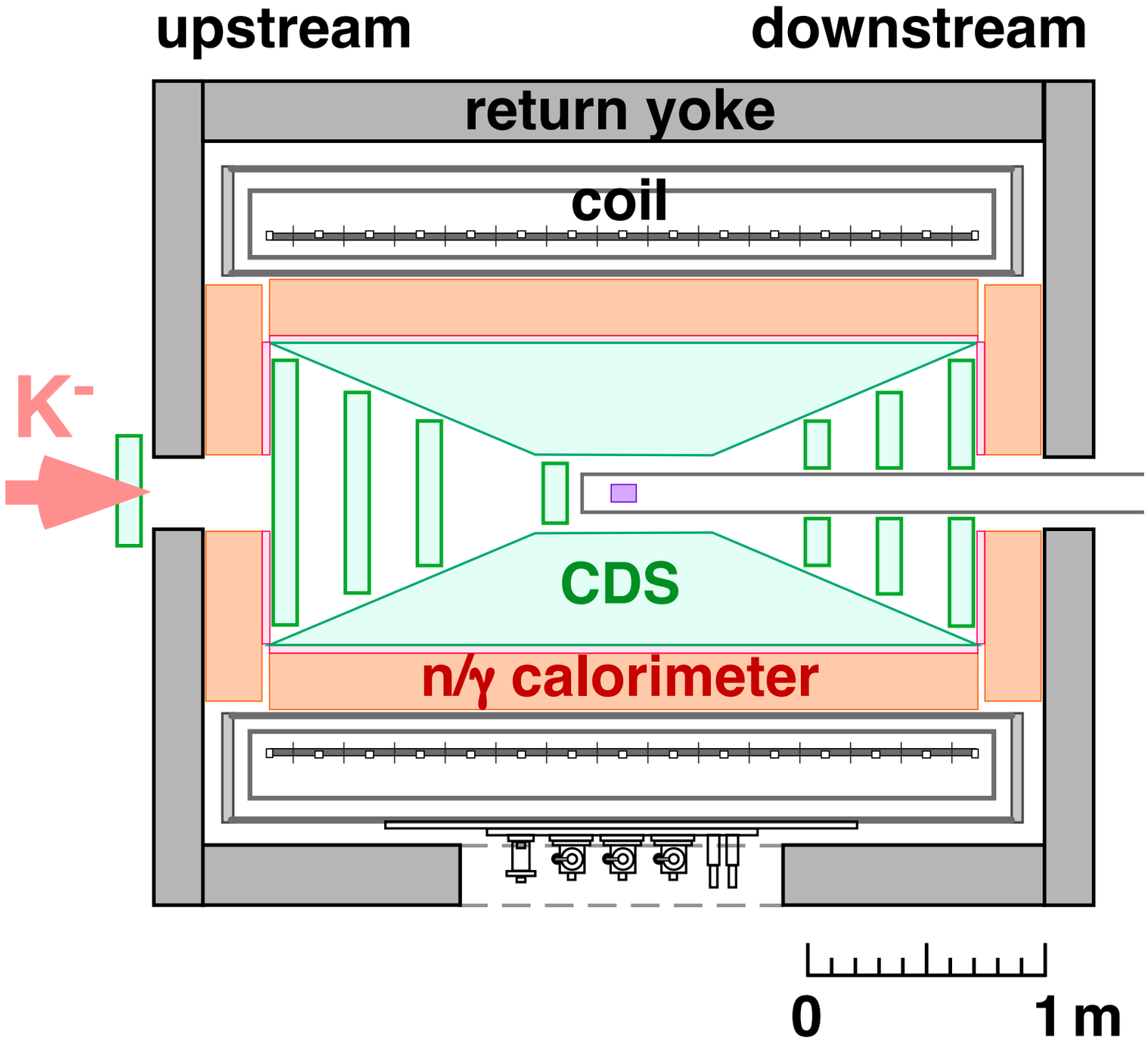
Kp, Kpp, Kppn, KKpp ...

with γ/n detection capability in CDS

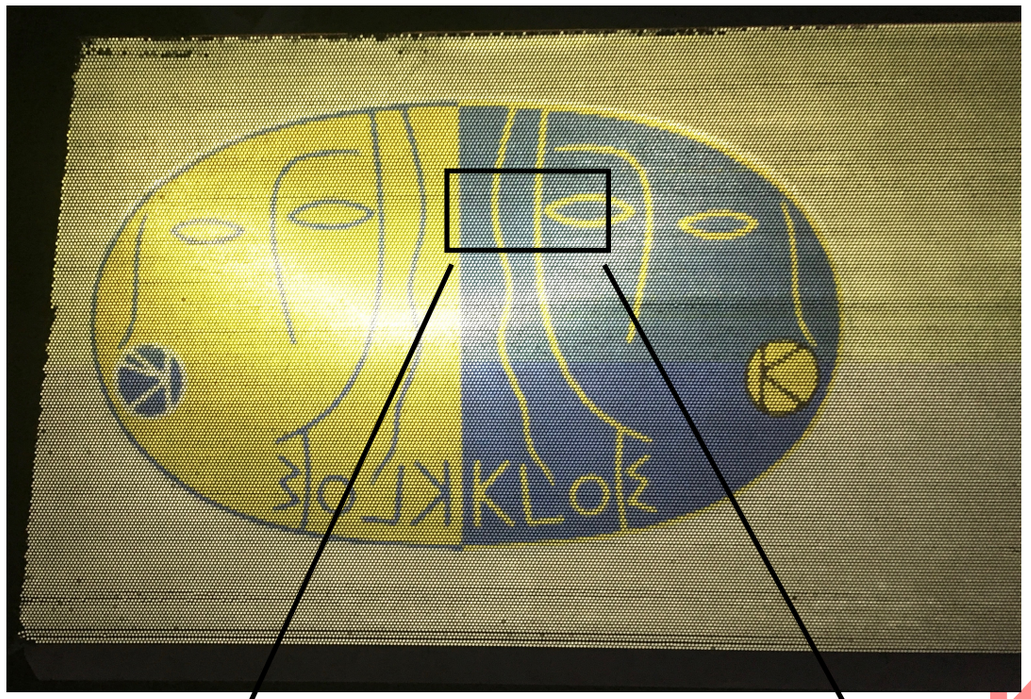
present E15

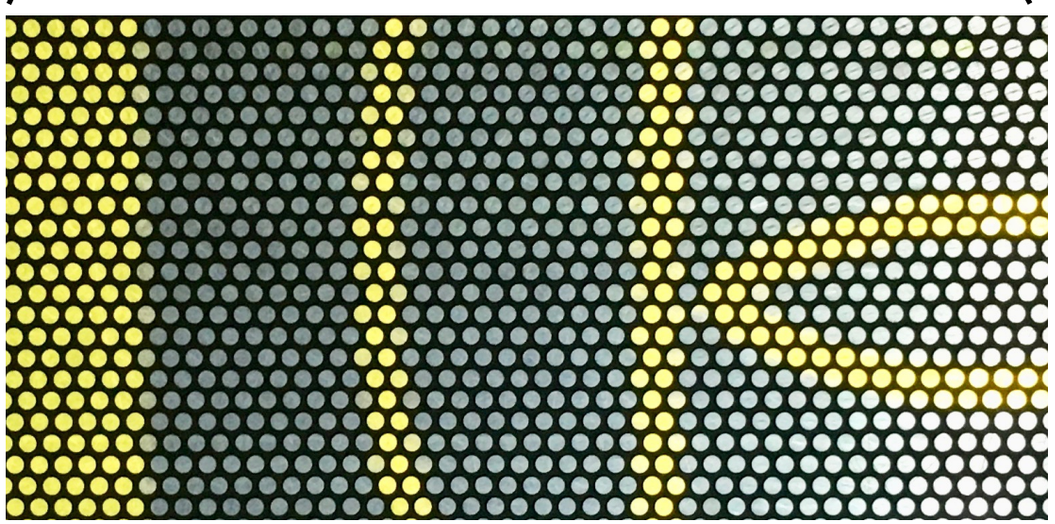


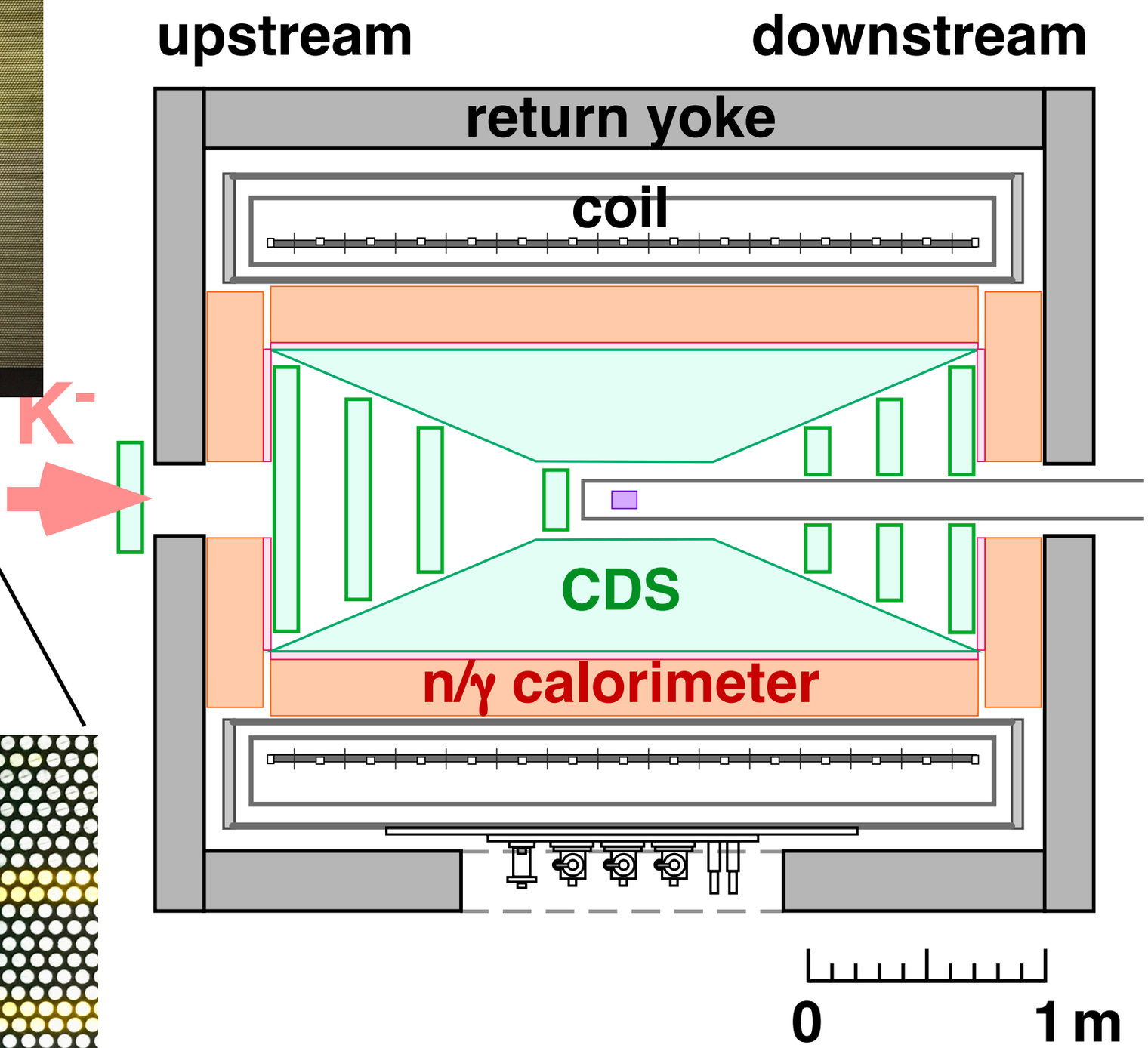
upgrade plan



upgrade plan







Summary

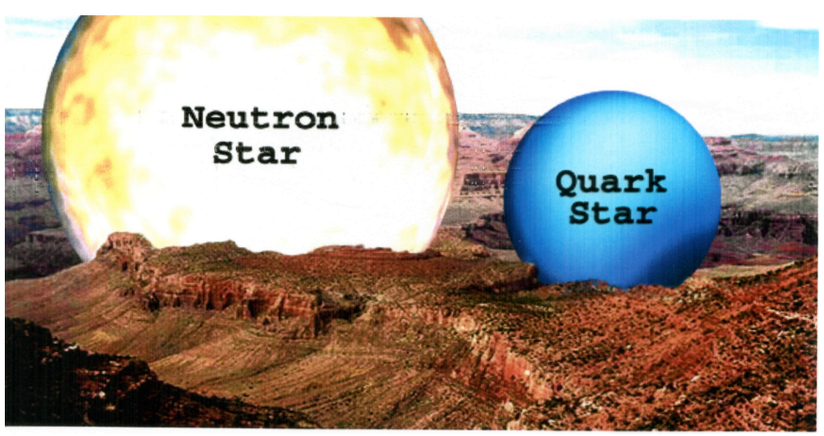
future to go

E15: $K^- + {}^3He \rightarrow (\Lambda + p) + n$

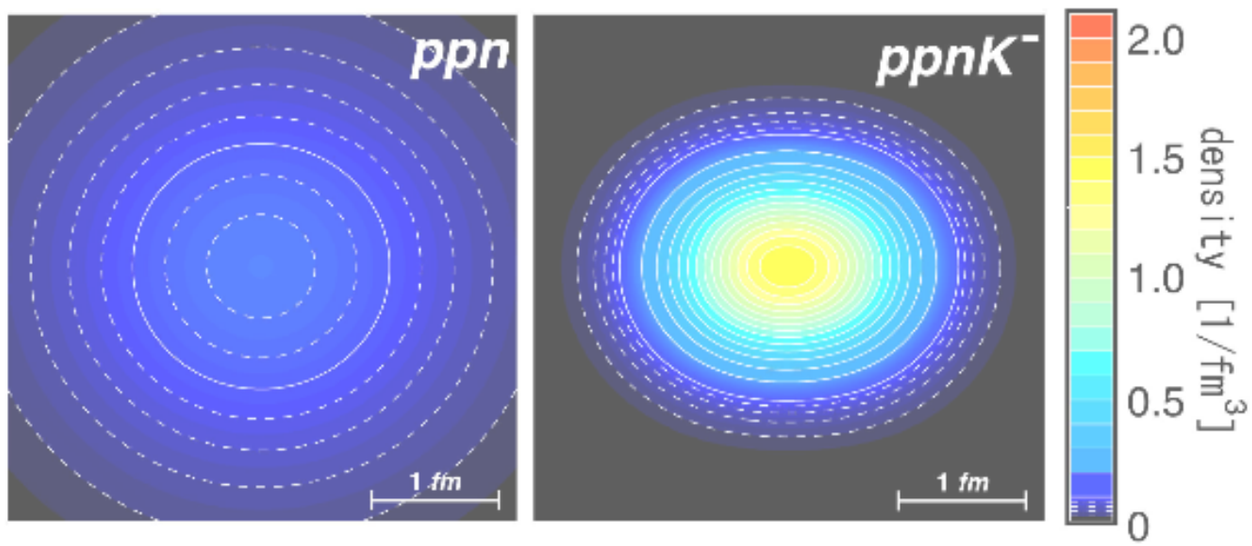
convincing Kpp signal obtained

systematic study on light kaonic nuclei

compact deep nuclear bound system ?



Dote et al., PLB 590 (2004) 51



The E15 Collaborations

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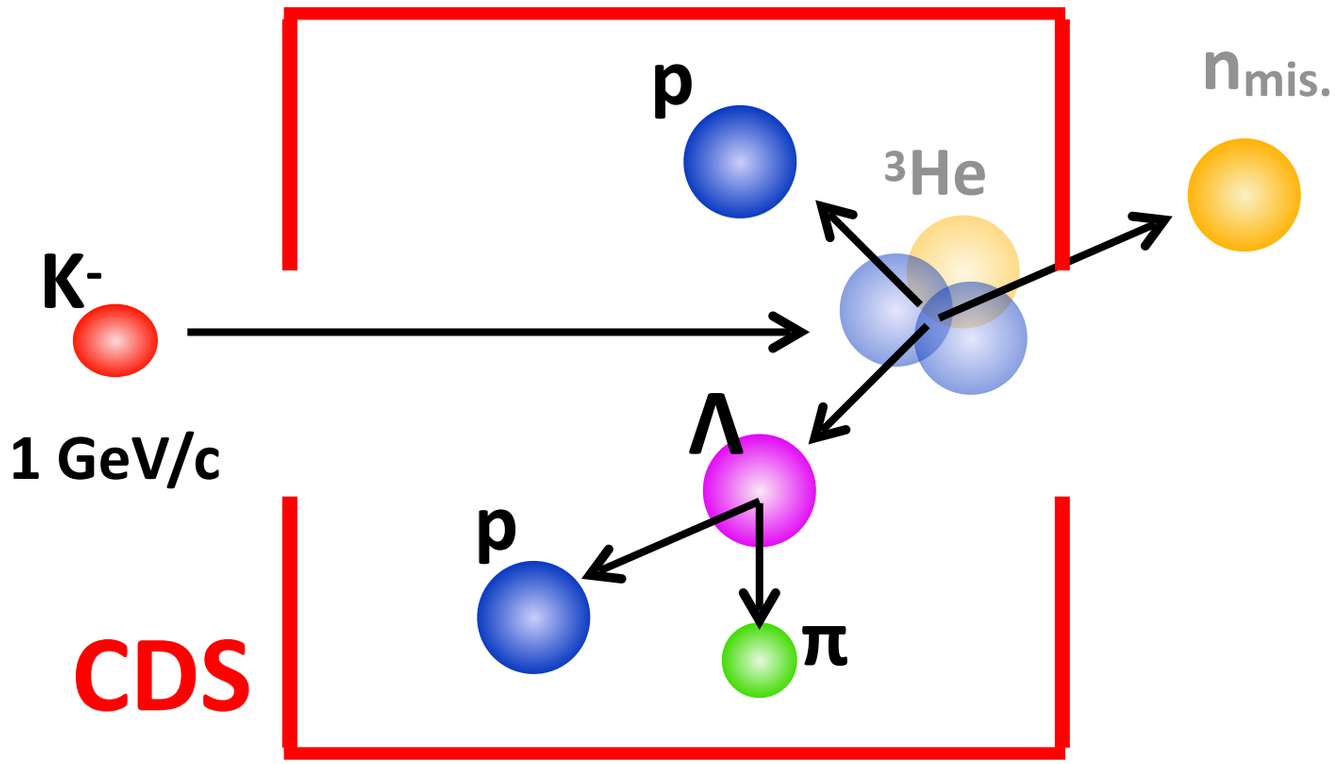
(J-PARC E15 Collaboration)

Appendix

Where is Λ*?

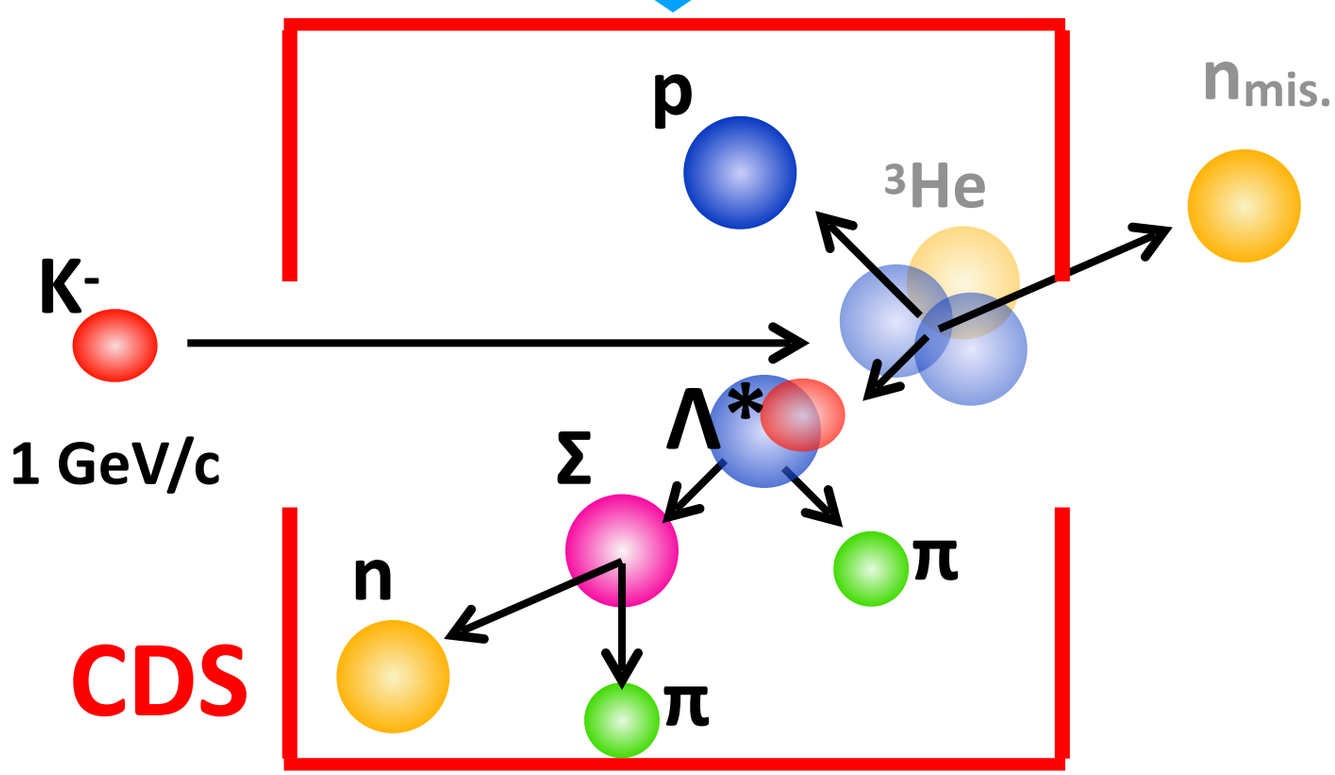
We started study assuming Λ(1405) = "K-p" bound state



if "K-pp" is formed

Λpn final state

arXiv:1805.12275



"K-p" must be formed

Λ*pn final state

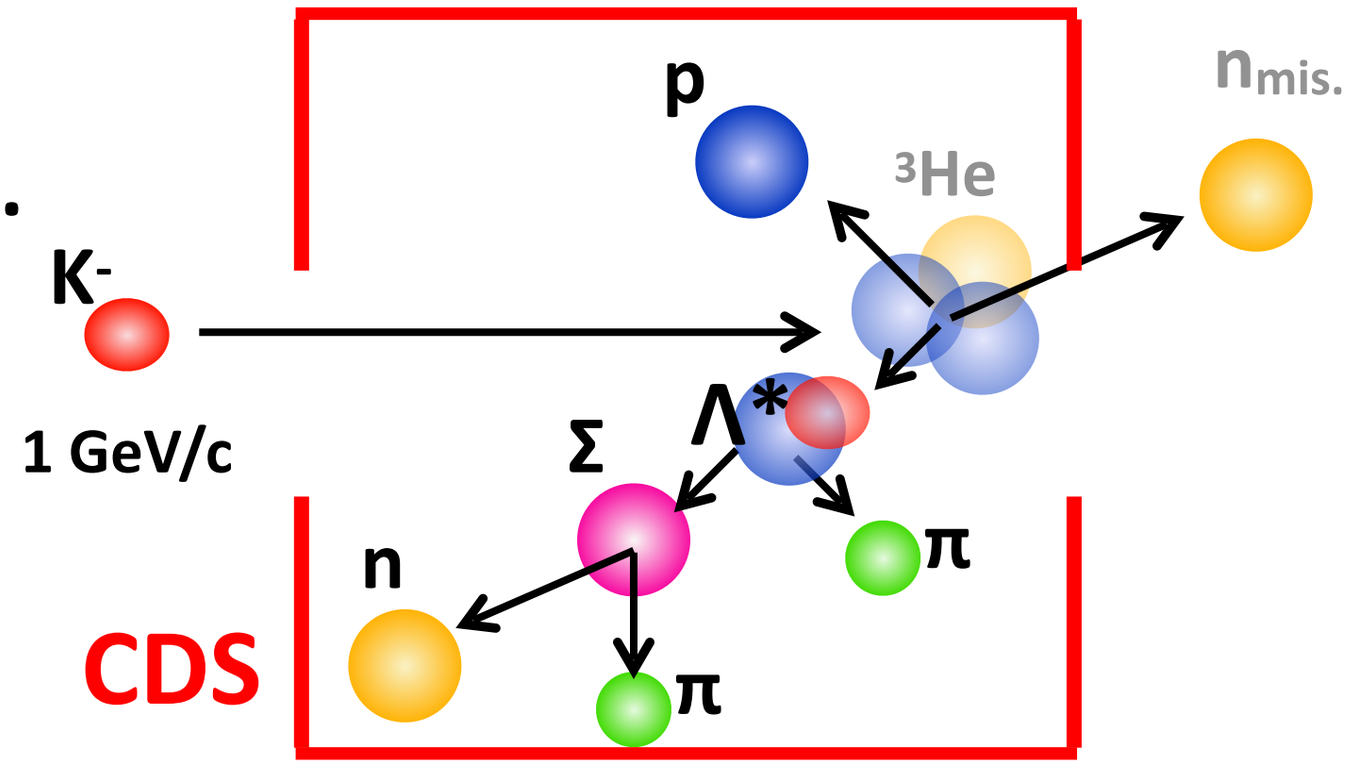
all preliminary

K^- $^3He \rightarrow \Lambda^* pn$ @ E15

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

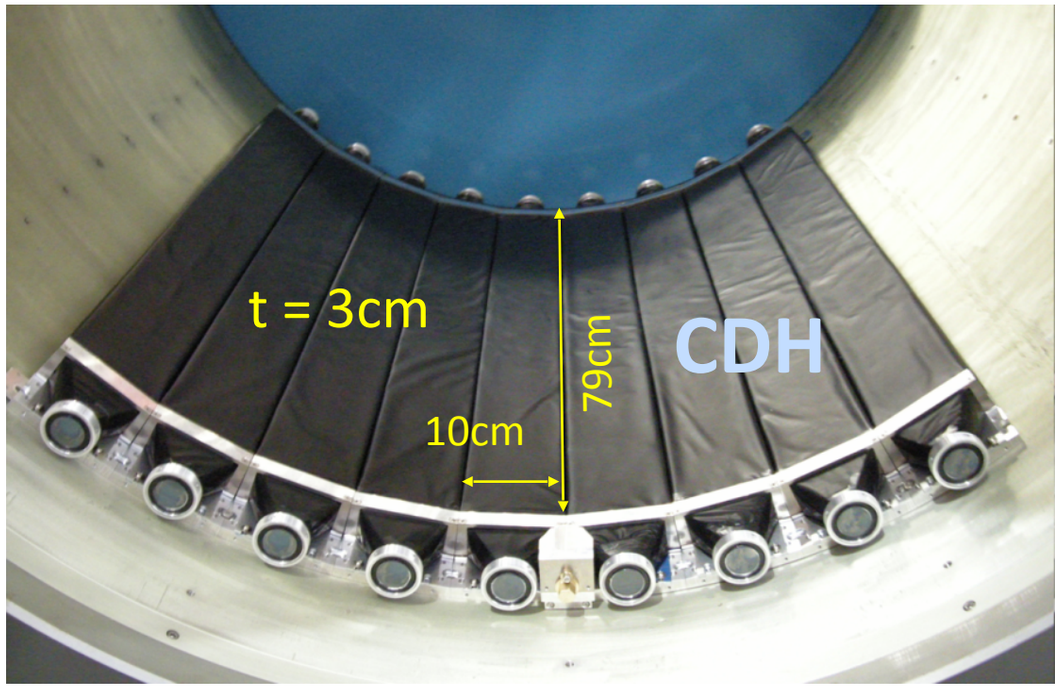
$(\pi^{\pm}\pi^{\mp}n\ p) + n_{mis.}$

4-hold coin. w/ n-missing



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

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



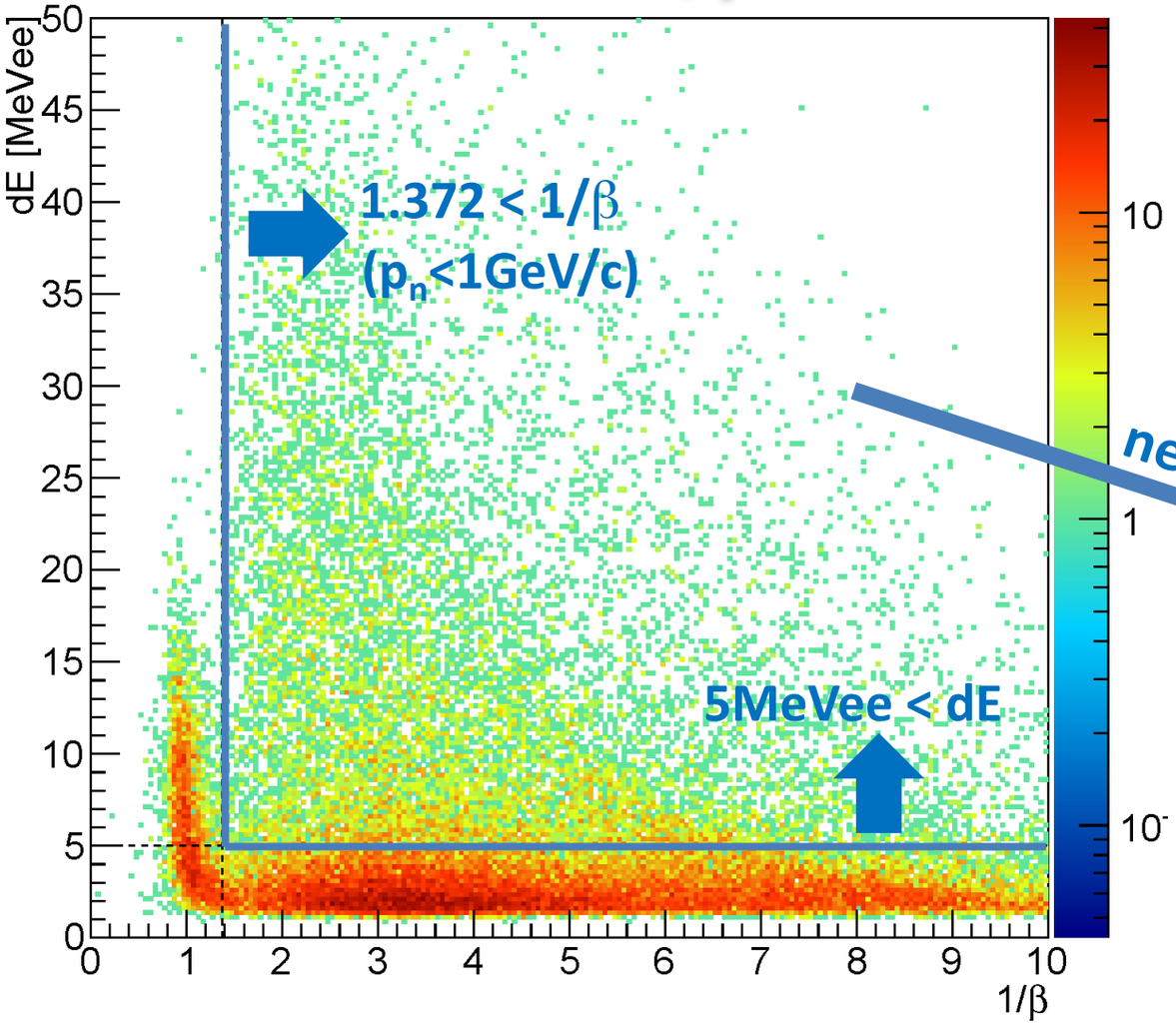
x 55 more difficult than Λpn

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

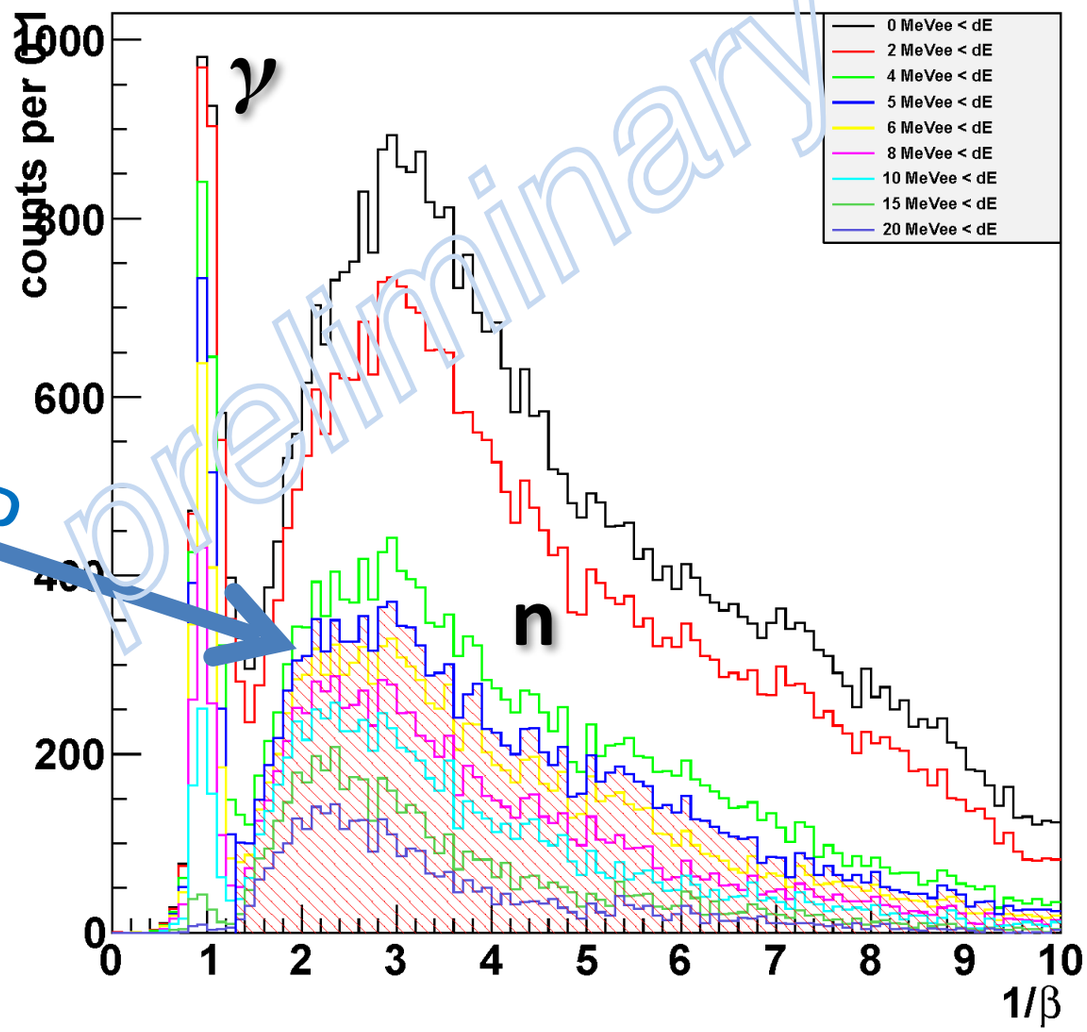
Neutron ID with CDH

- $\pi^+\pi^-$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



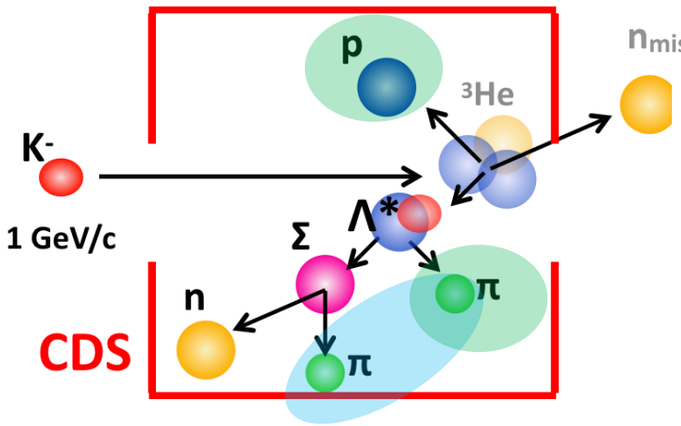
dE-cut dependence

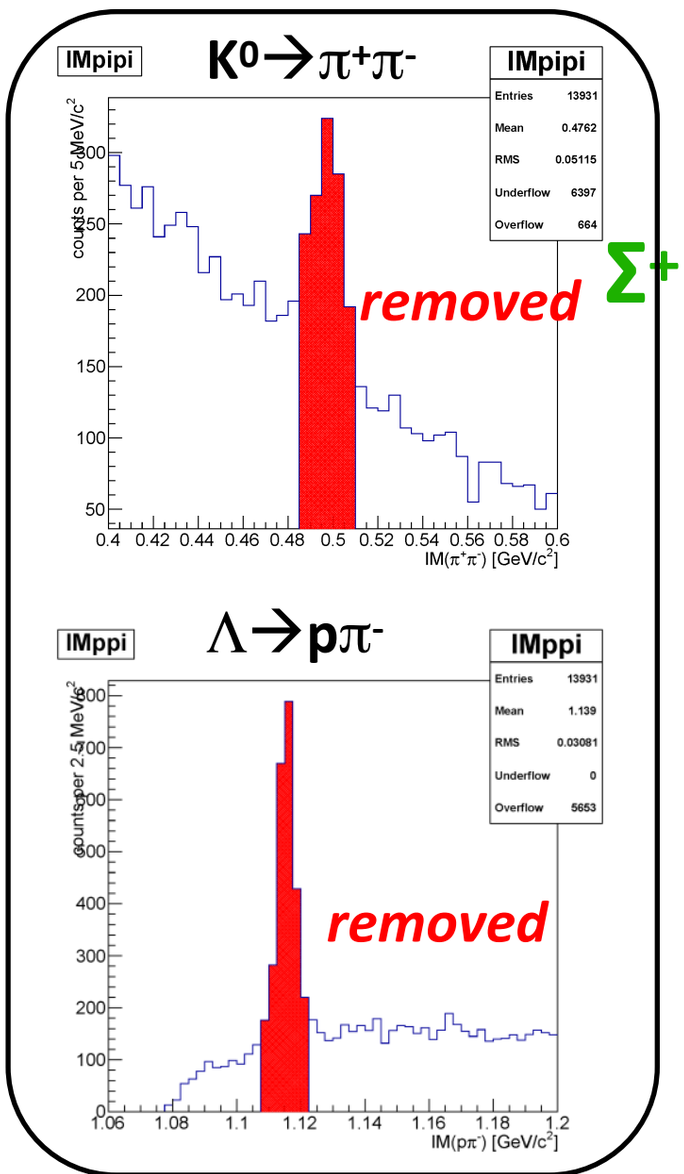


Neutron clearly identified by CDH

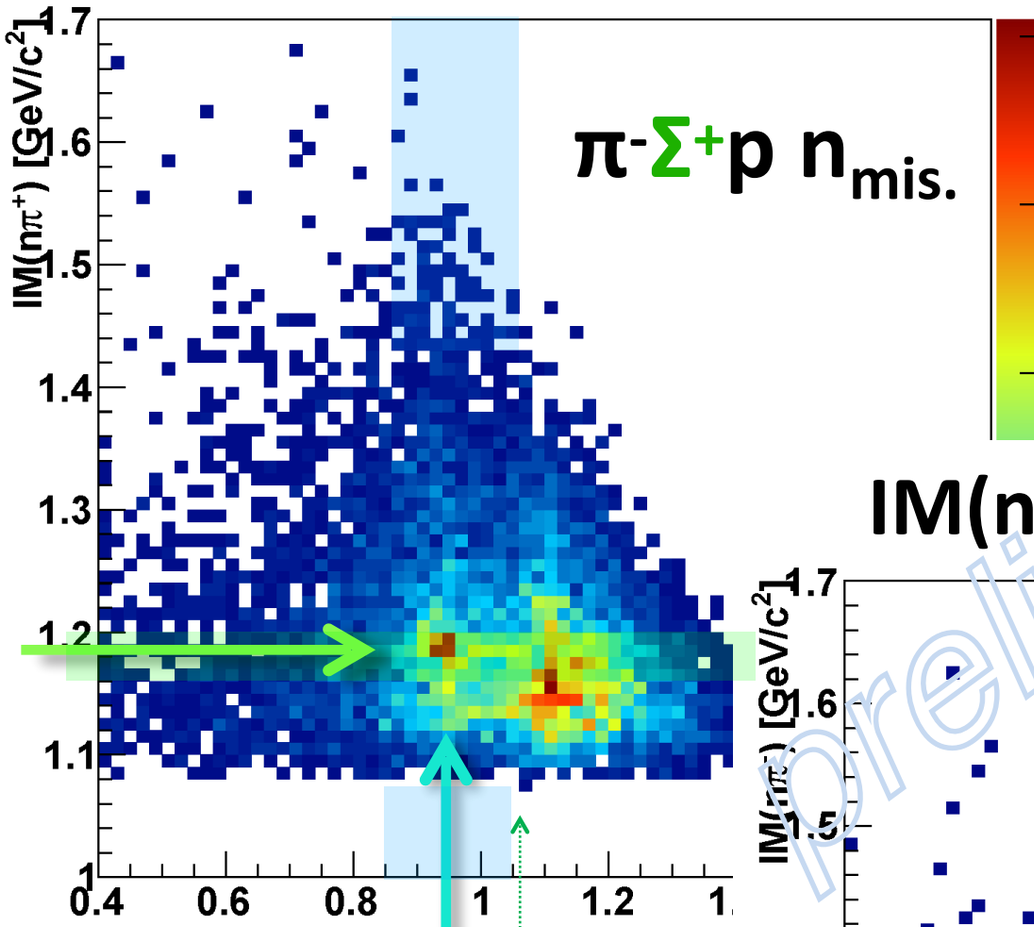
ππnp*n*→π**Σ**p*n*

remove unfavored events

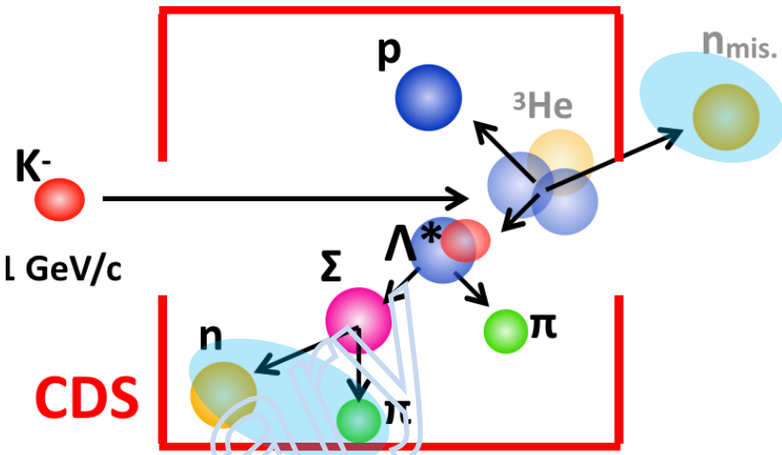




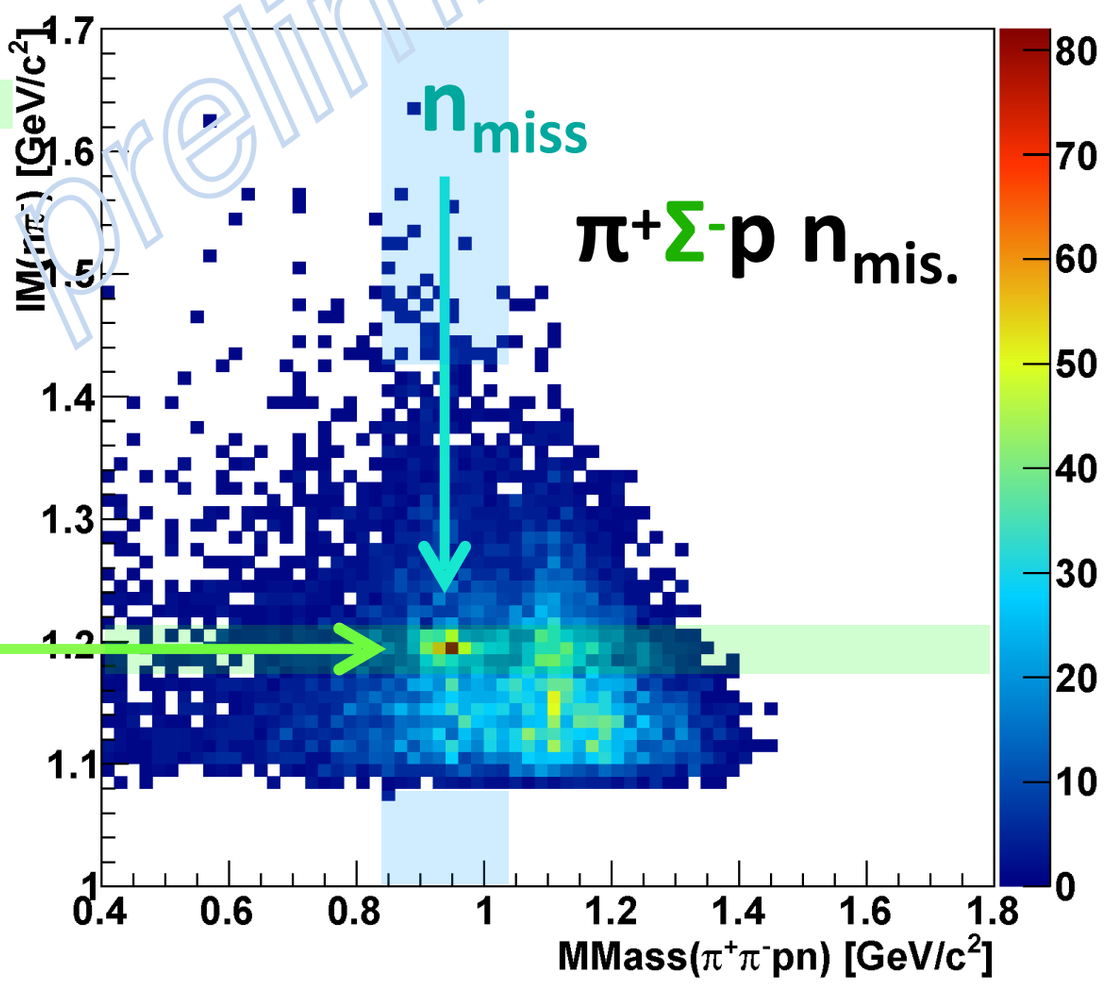
IM(nπ⁺) vs MM(π⁺π⁻pn)



Σ identification



IM(nπ⁻) vs MM(π⁺π⁻pn)



Λ*(πΣ)p*n* final state

Event Selection

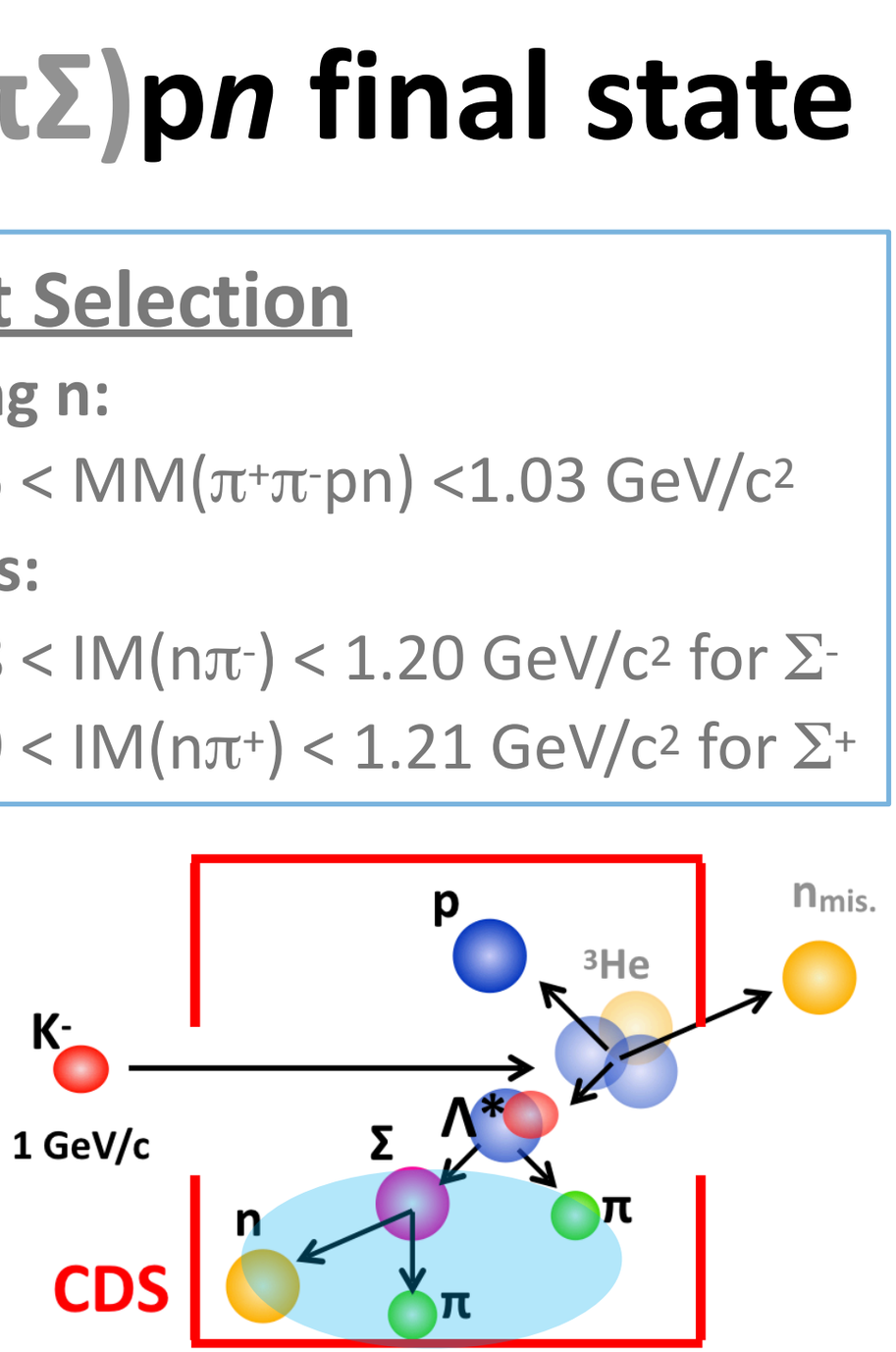
Missing n:

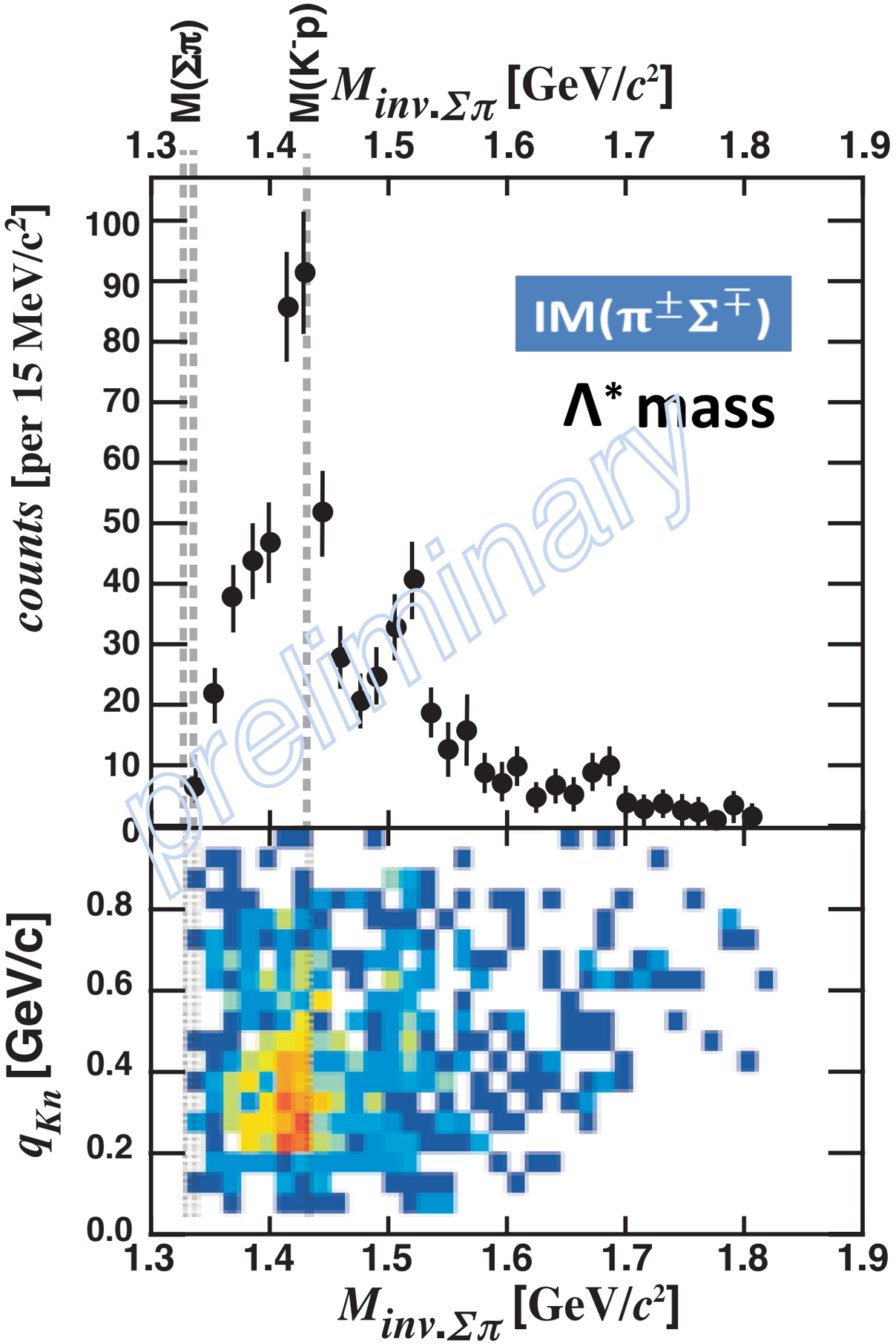
$0.85 < MM(\pi^+\pi^-pn) < 1.03$ GeV/c²

Σ mass:

$1.18 < IM(n\pi^-) < 1.20$ GeV/c² for Σ^-

$1.19 < IM(n\pi^+) < 1.21$ GeV/c² for Σ^+





Y* Cross Section (q_{Kn}<0.65 GeV/c)

$\Lambda(1405)$

~ 130-140 μb

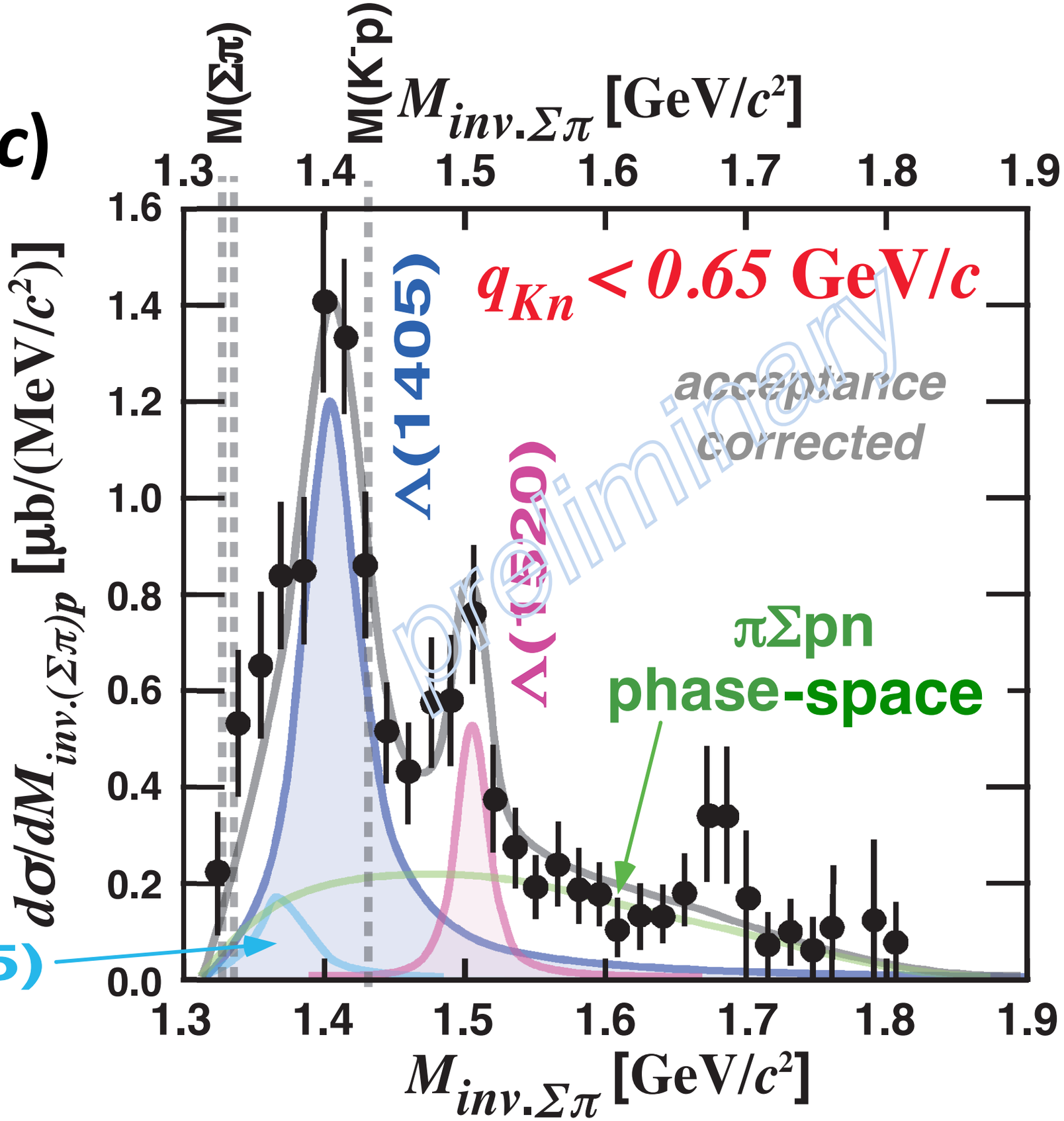
z_R ~ 1415 - 19 *i* MeV/c

$g_{\pi\Sigma}$ ~ 0.29

g_{KN} ~ 0.1

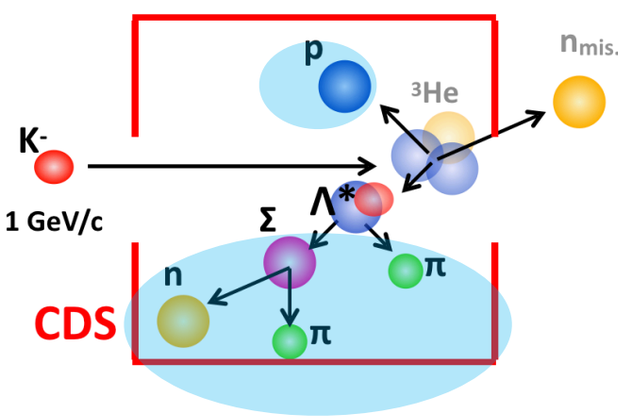
~ 40-80 μb
[evaluated from $\Sigma^+(1385)\rightarrow\pi^+\Lambda$ measurement]

$\Sigma^0(1385)$

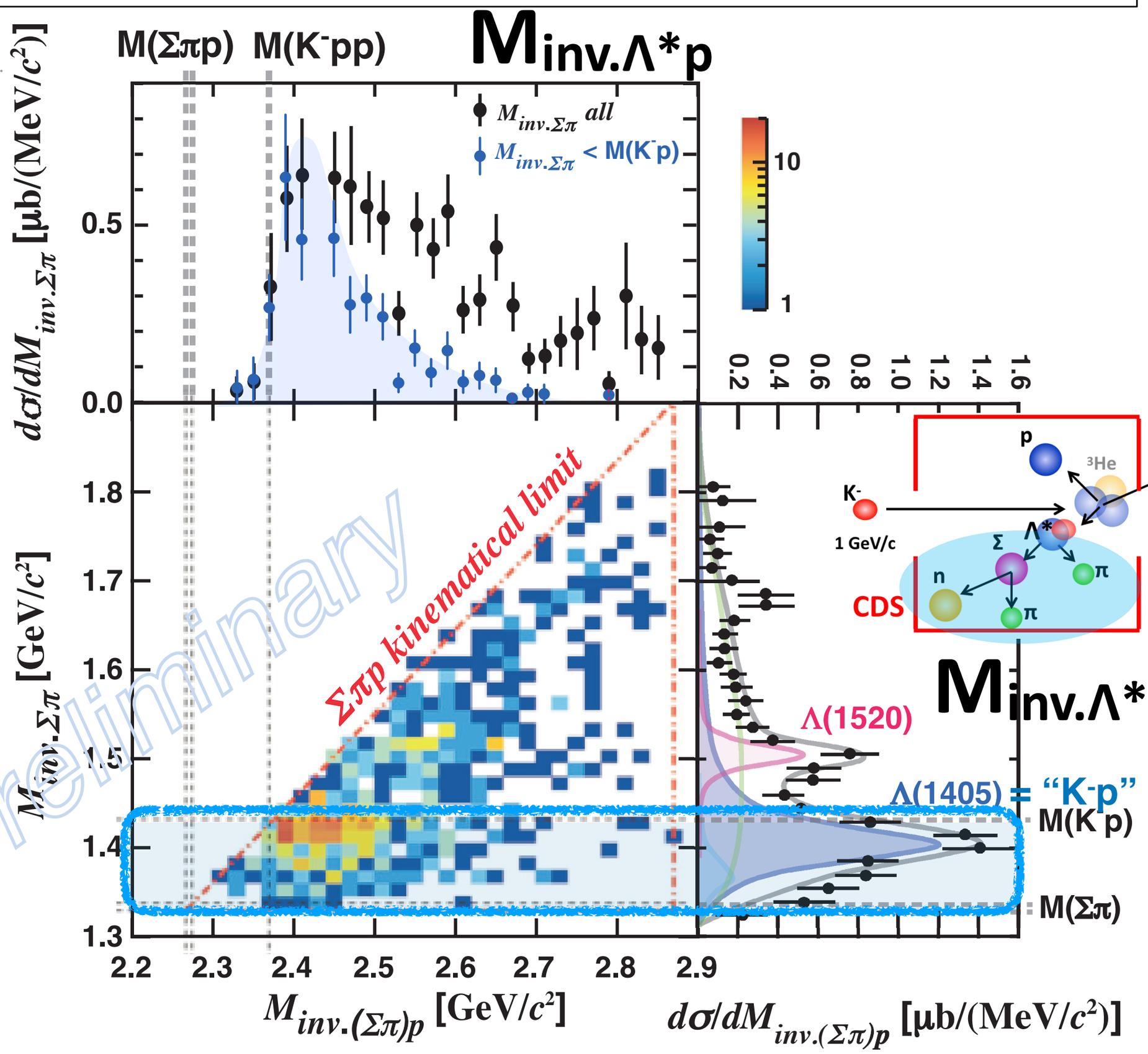


Λ(1405) strength sharply drops at M(Kp)

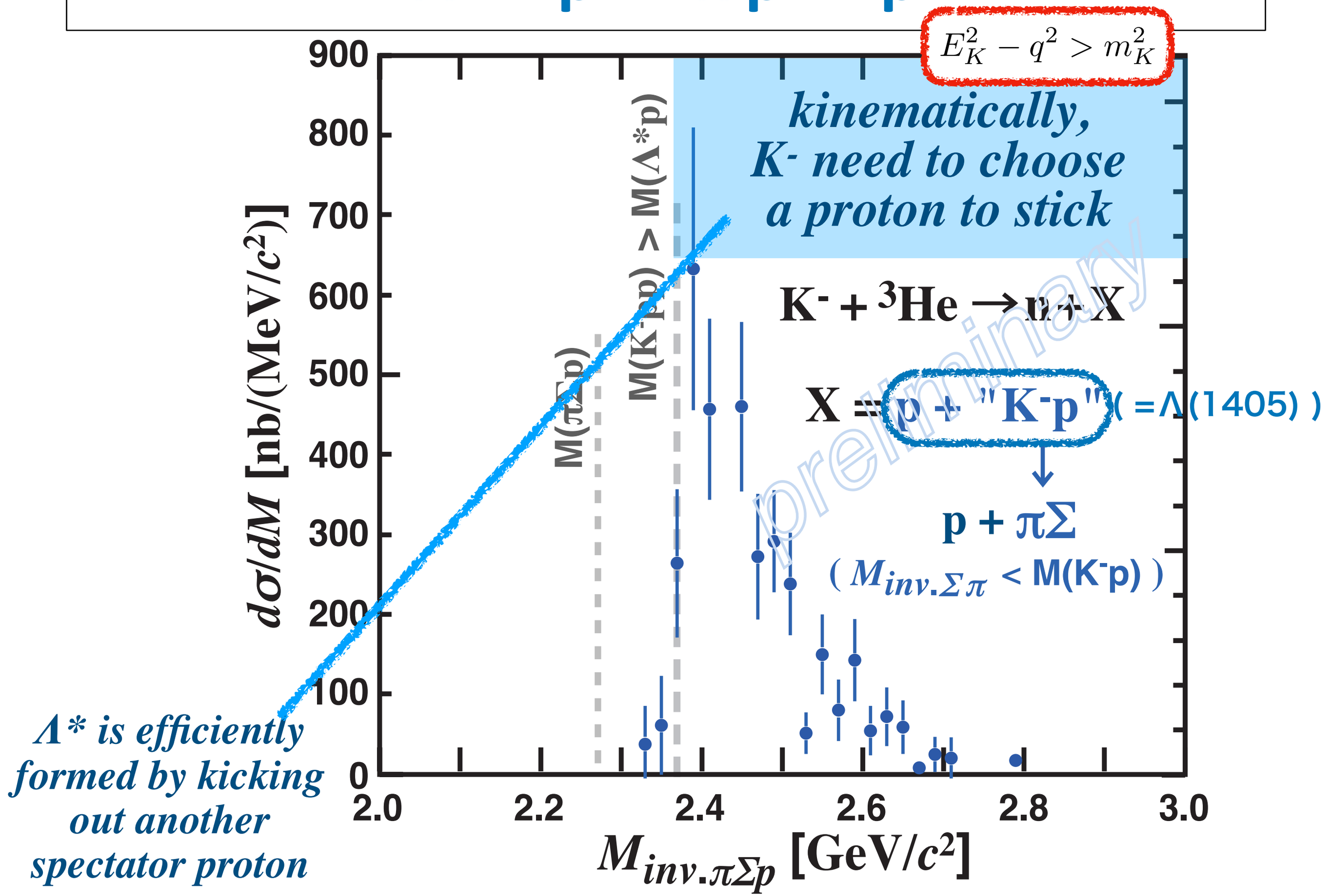
$M_{inv.\Lambda^*p}$ - *vs* - $M_{inv.\Lambda^*}$ ($\Lambda^* \rightarrow \pi\Sigma$)



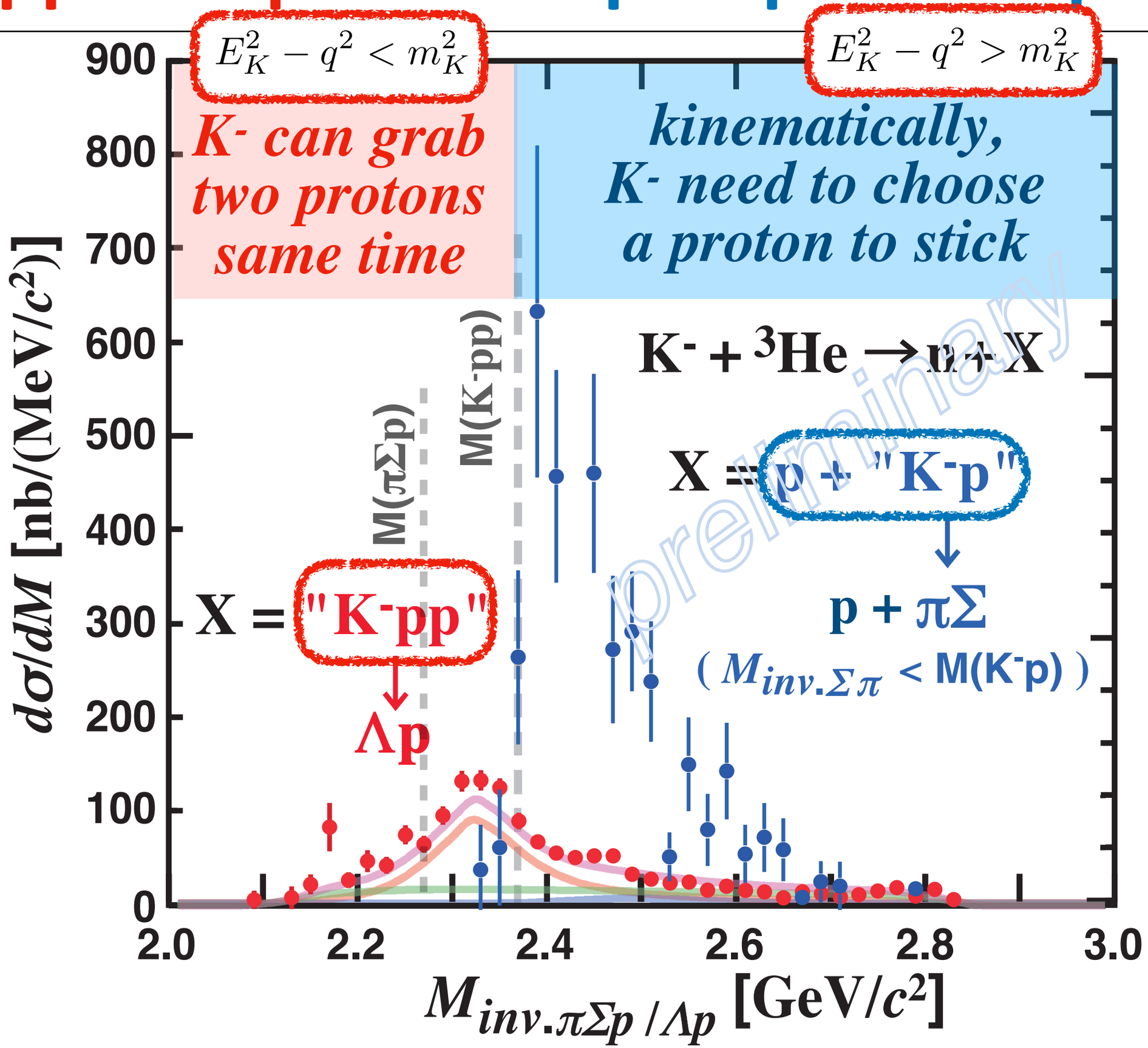
$M_{inv.\Lambda^*p}$



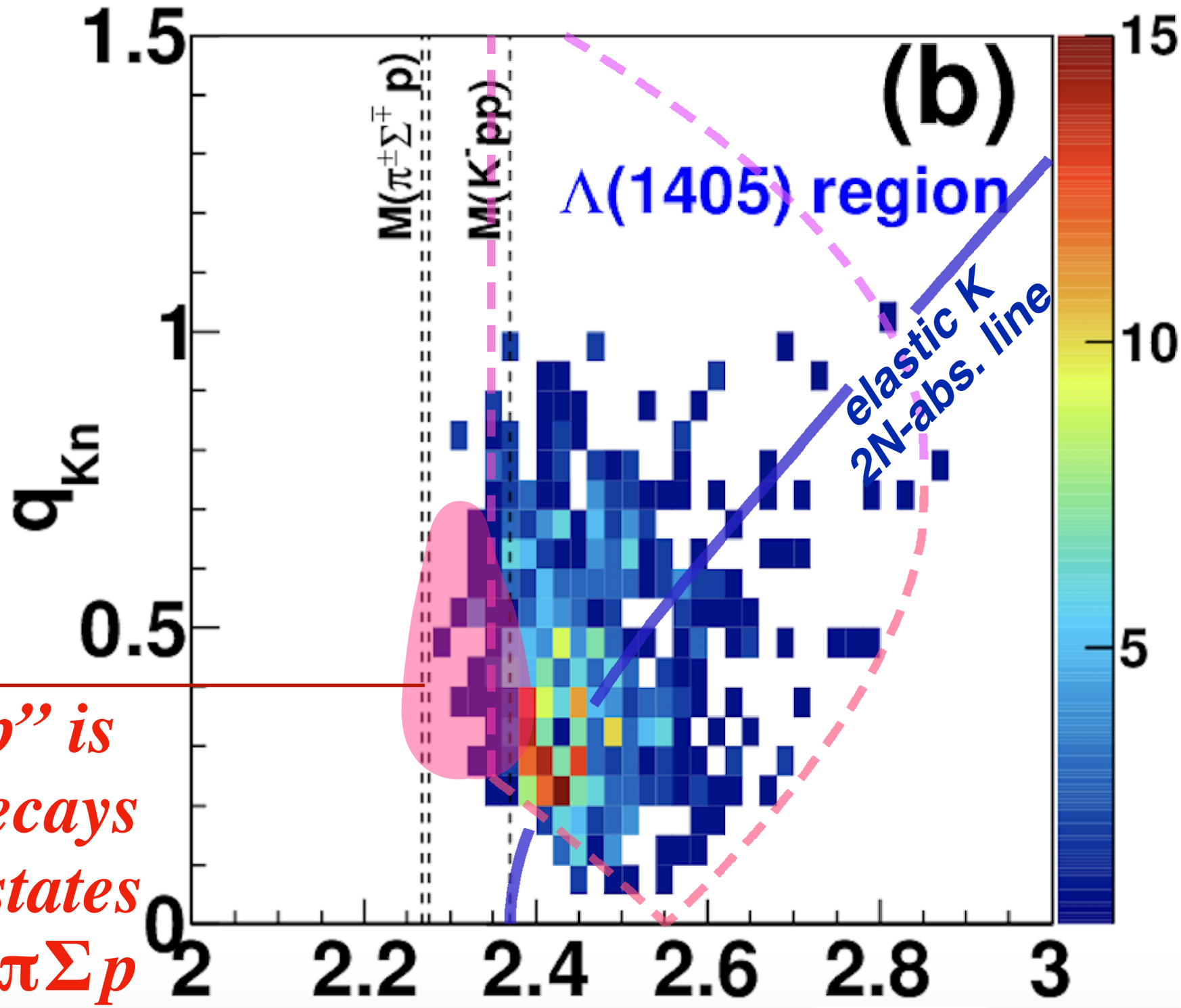
Λ* + p = "K⁻p" + p


$E_K^2 - q^2 > m_K^2$
kinematically,
K⁻ need to choose
a proton to stick
K⁻ + ³He → n + X
X = p + "K⁻p" (=Λ(1405))
p + πΣ
($M_{inv.\Sigma\pi}$ < M(K⁻p))
M(K⁻pp) > M(Λ*p)
M(πΣp)
preliminary
Λ* is efficiently
formed by kicking
out another
spectator proton
$d\sigma/dM$ [nb/(MeV/c^2)]
$M_{inv.\pi\Sigma p}$ [GeV/c^2]
900
800
700
600
500
400
300
200
100
0
2.0
2.2
2.4
2.6
2.8
3.0

"K⁻pp" → Λp - *vs* - "K⁻p" + p → πΣ + p



M vs *q* for Λ(1405) p n final state



When "Kpp" is formed, it decays to YN final states rather than πΣp

IM(πΣp) = IM(Λ(1405) p)

conclusion C:

"Kp" (=Λ*) formation observed

with sharp drop at **M(Kp)**

reaction summary:

$E_K^2 - q^2 > m_K^2$

n + "K⁻ p" + p → (Λ*) → n + Λ + p *weakly by FSI*

n + (π + Σ)⁰ + p

K⁻ + ³He → ---------- **M(Kpp)**

$E_K^2 - q^2 < m_K^2$

n + "K⁻ pp" → n + Λ + p

virtual "K⁻" energy controls the reaction branch

"Kpp" seems more like 'Kpp' rather than 'Λ*p' hypernucleus

consistent picture w/ "K⁻p" & "K⁻pp"