International Conference on Exotic Atoms and Related Topics and conference on Low Energy Antiprotons (EXA/LEAP 2024)

Prospect of Hadronic-Molecule / Cluster with Strangeness

- via the detailed study of the kaonic nucleus -

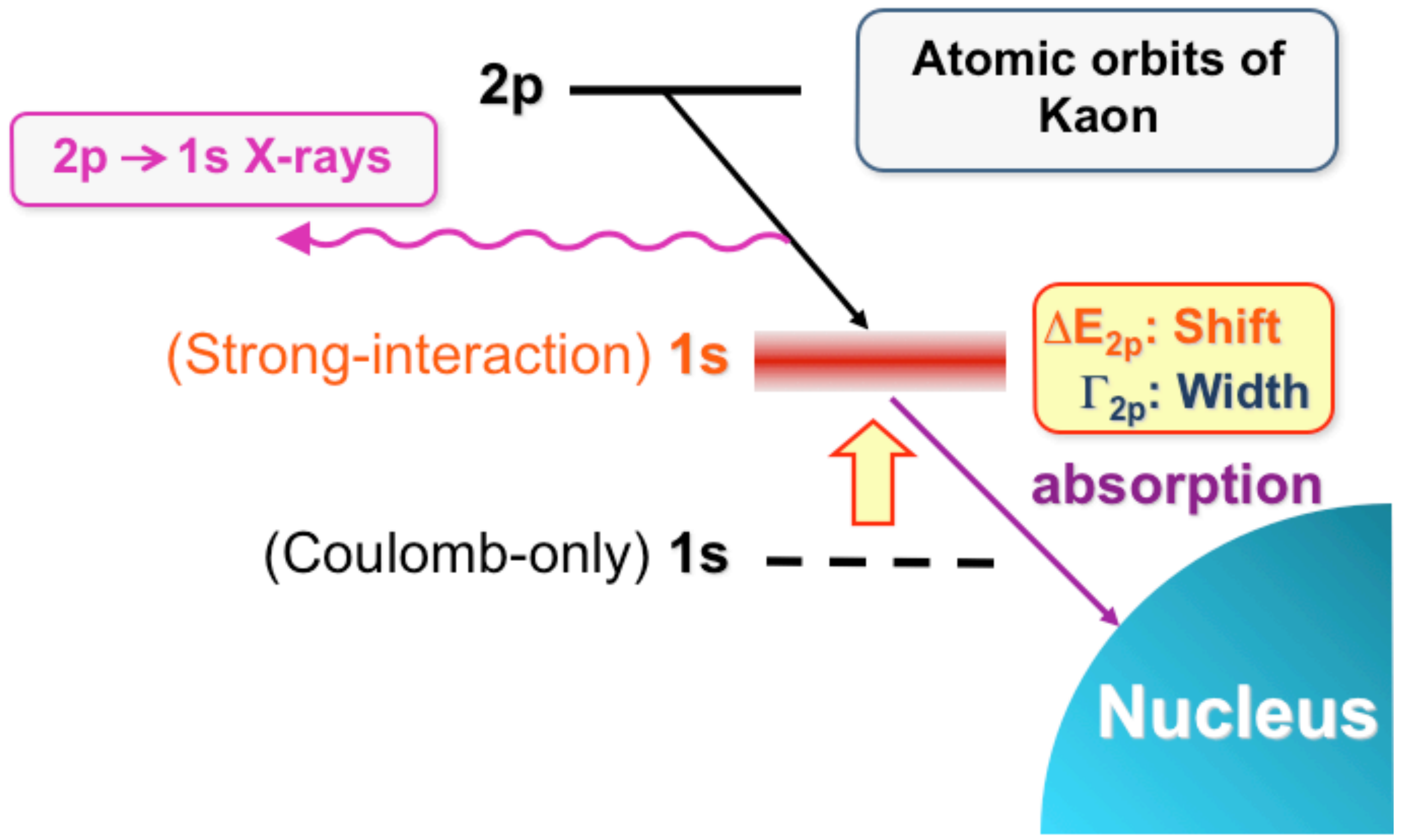
– 28 / 08 / 2024 –

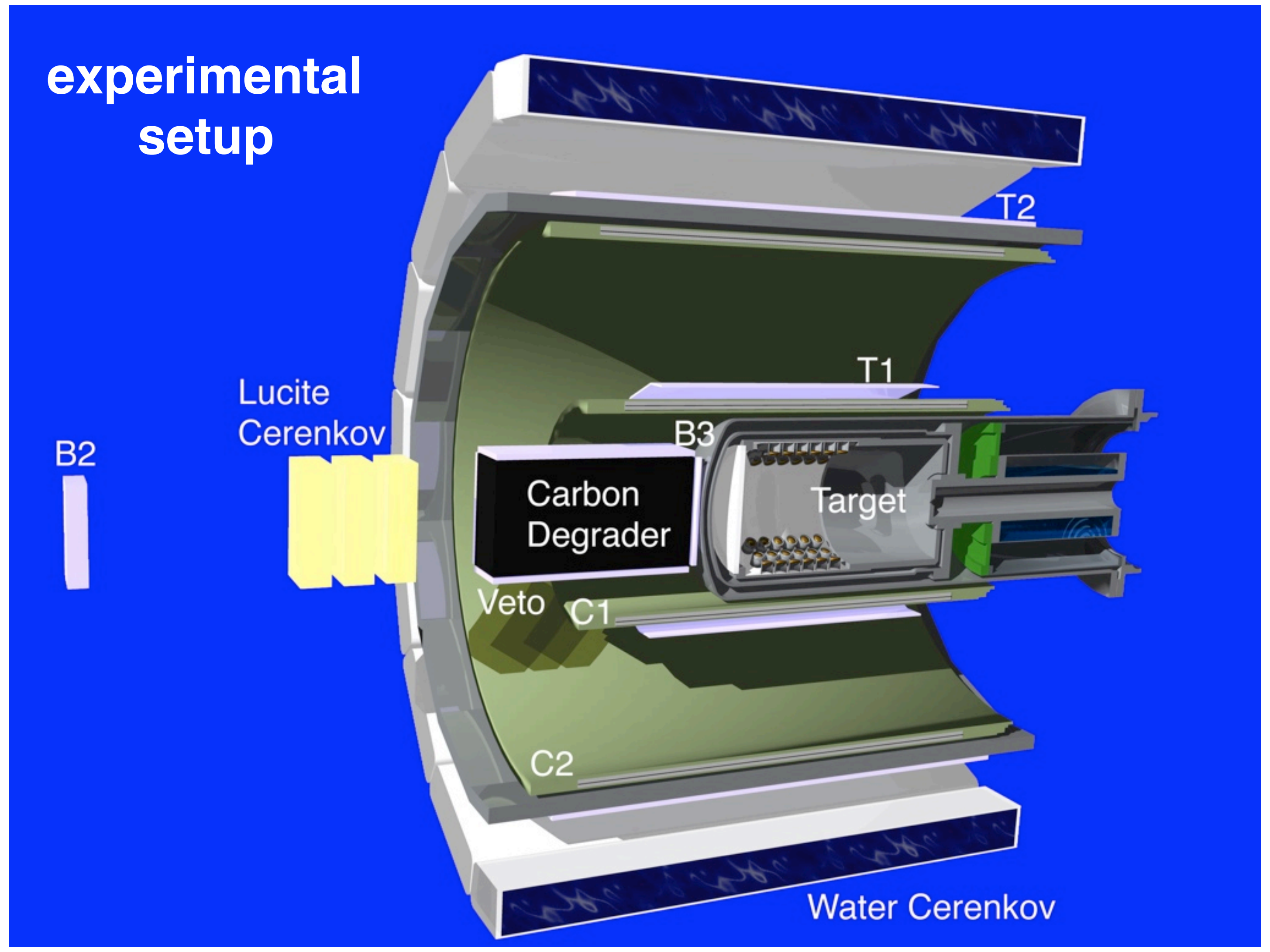
M. Iwasaki / RIKEN

$\bar{K}N$ interaction study via Kaonic atom

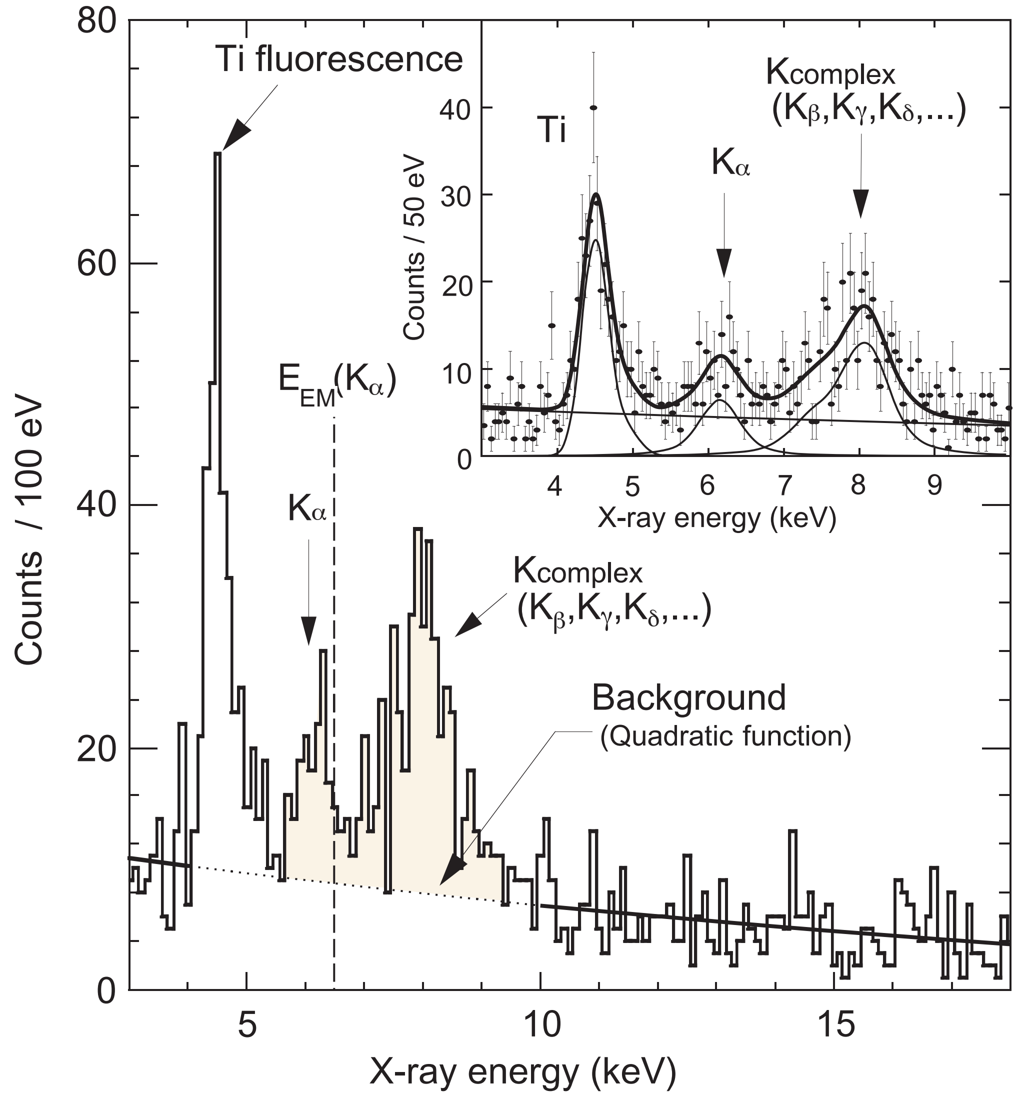
Succeeded in Kaonic Hydrogen x-ray Measurement

KpX experiment at KEK in 1997:





KpX: *obtained X-ray spectrum*



The European Physical Journal C

Volume 15 · Number 1-4 · 2000

THE Λ(1405)

Revised March 1998 by R.H. Dalitz, Oxford University

....

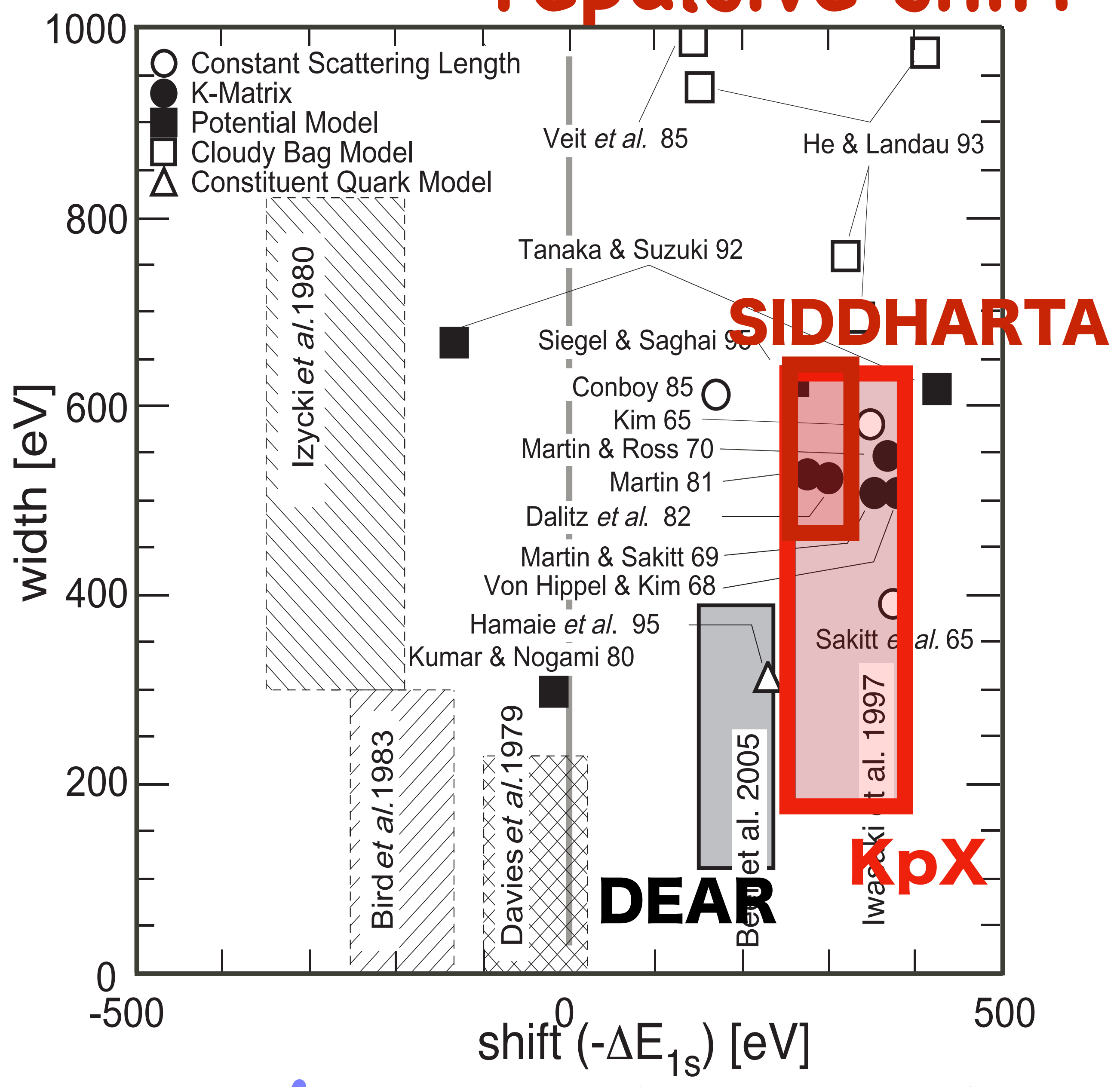
From the measurement of $2p - 1s$ x rays from kaonic-hydrogen, the energy-level shift ΔE and width Γ of its 1s state can give us two further constraints on the $(\bar{\Sigma}\pi, NK)$ system, at an energy roughly midway between those from the low-energy hydrogen bubble chamber studies and those from qR($\Sigma\pi$) observations below pK⁻ threshold. IWASAKI 97 have reported the first convincing observation of this x ray, with a good initial estimate:

$$\Delta E - i\Gamma/2 = (-323 \pm 63 \pm 11) - i(204 \pm 104 \pm 50) \text{ eV}. \quad (2)$$

the errors here encompass about half of the predictions made following various analyses and/or models for the in-flight K^-p and sub-threshold qR($\Sigma\pi$) data. Better measurements will be needed to discriminate between the analyses and predictions. ...., perhaps from the DAΦNE storage ring at Frascati, information vital for our quantitative understanding of the $(\Sigma\pi, NK)$ system in this region. .....

Kaonic hydrogen puzzle was resolved!

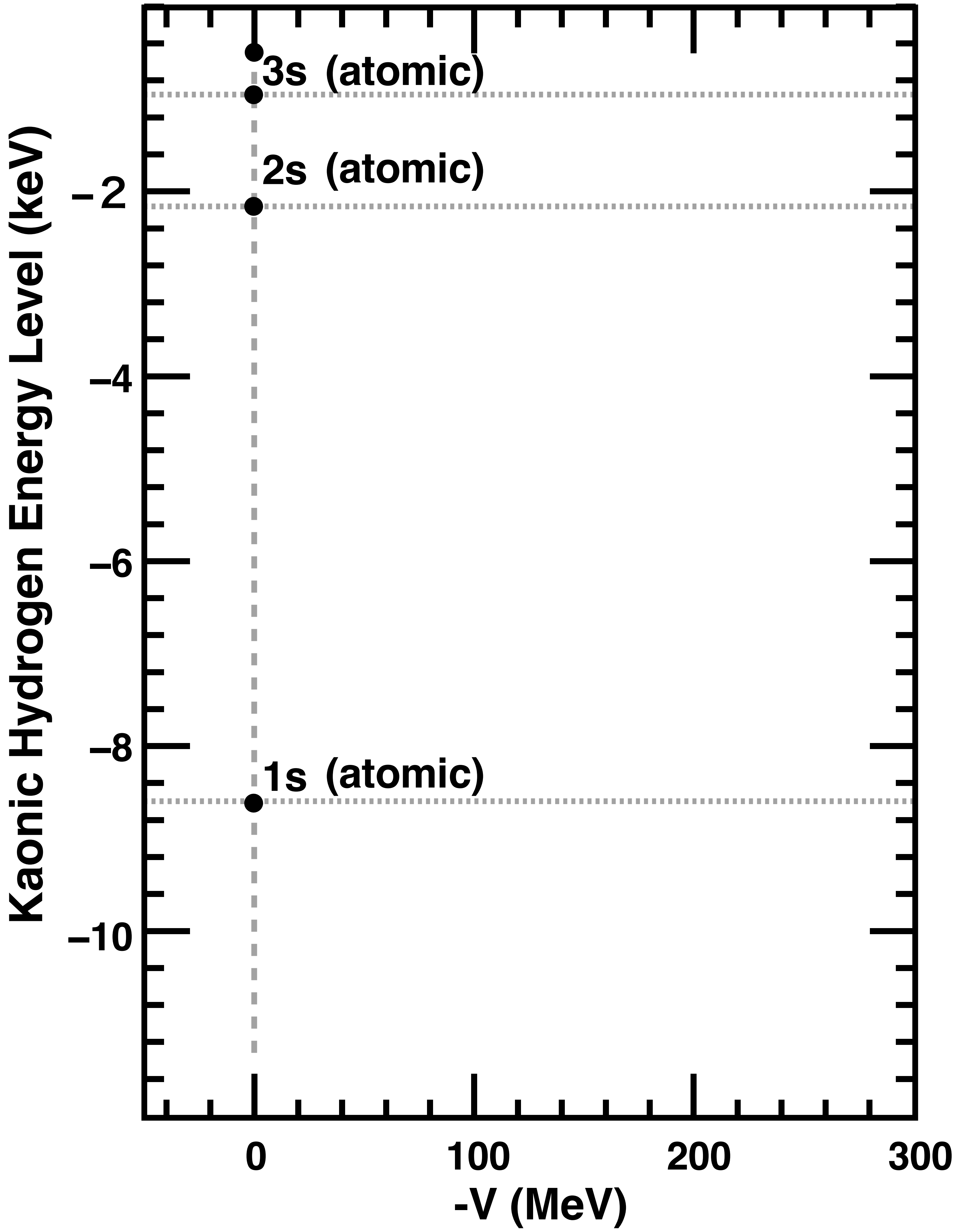
repulsive shift



What's next in physics?

Observed Shift was REPULSIVE!

Is $\overline{K}N$ interaction repulsive? → *Let's study how atomic level shifts depending on $\bar{K}N$ interaction.*



Without $\bar{K}N$ interaction ($V_{\bar{K}N} = 0, W_{\bar{K}N} = 0$), Coulomb potential forms $K^{-}p$ atomic levels.

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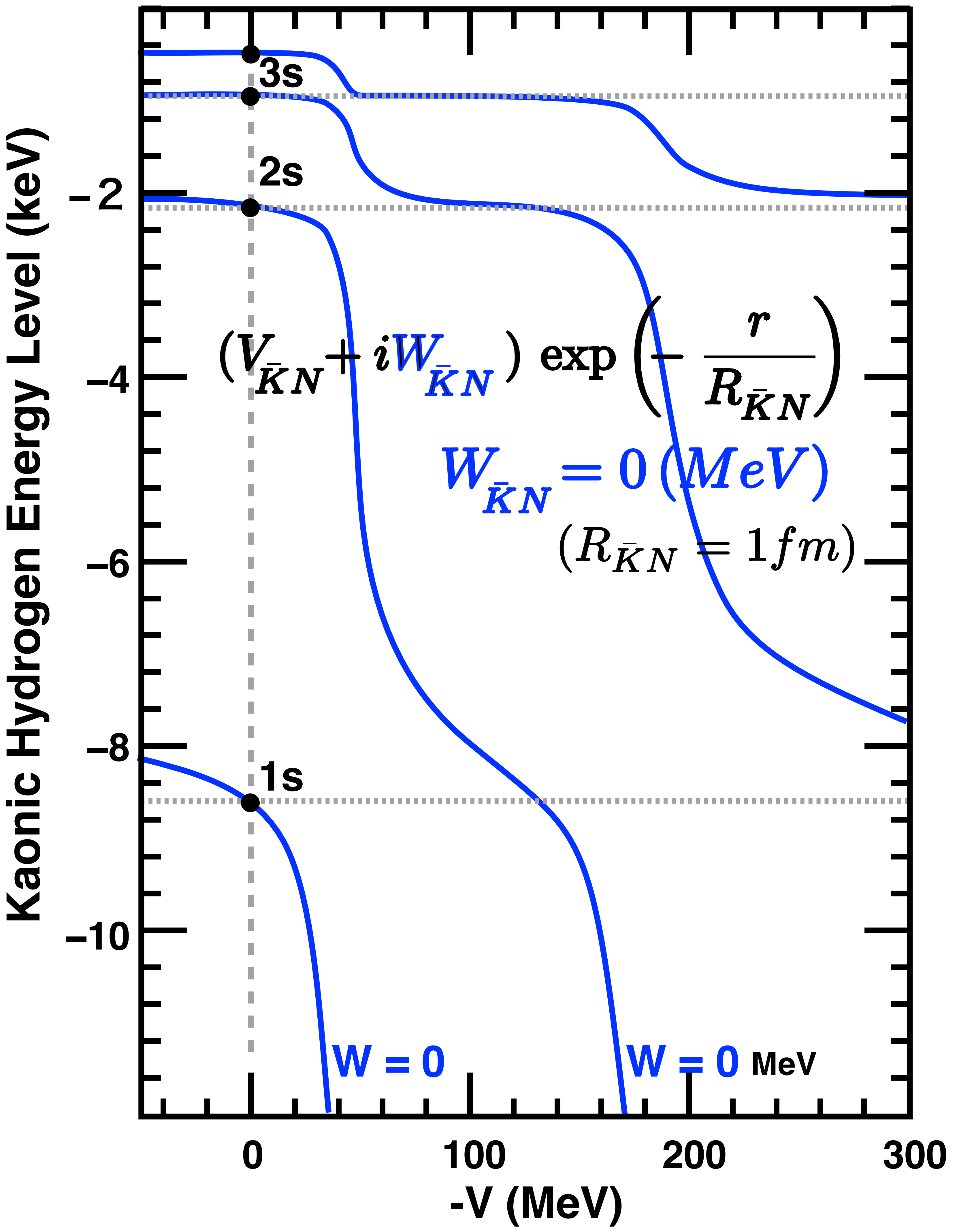
Coulomb + $\overline{\mathrm{K}}$N interaction



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Each atomic level shifts downward as a function of $-V_{\bar{K}N}$ (at $W_{\bar{K}N} = 0$) in a step-like function, and atomic 1s change its nature to be a nuclear ground state.

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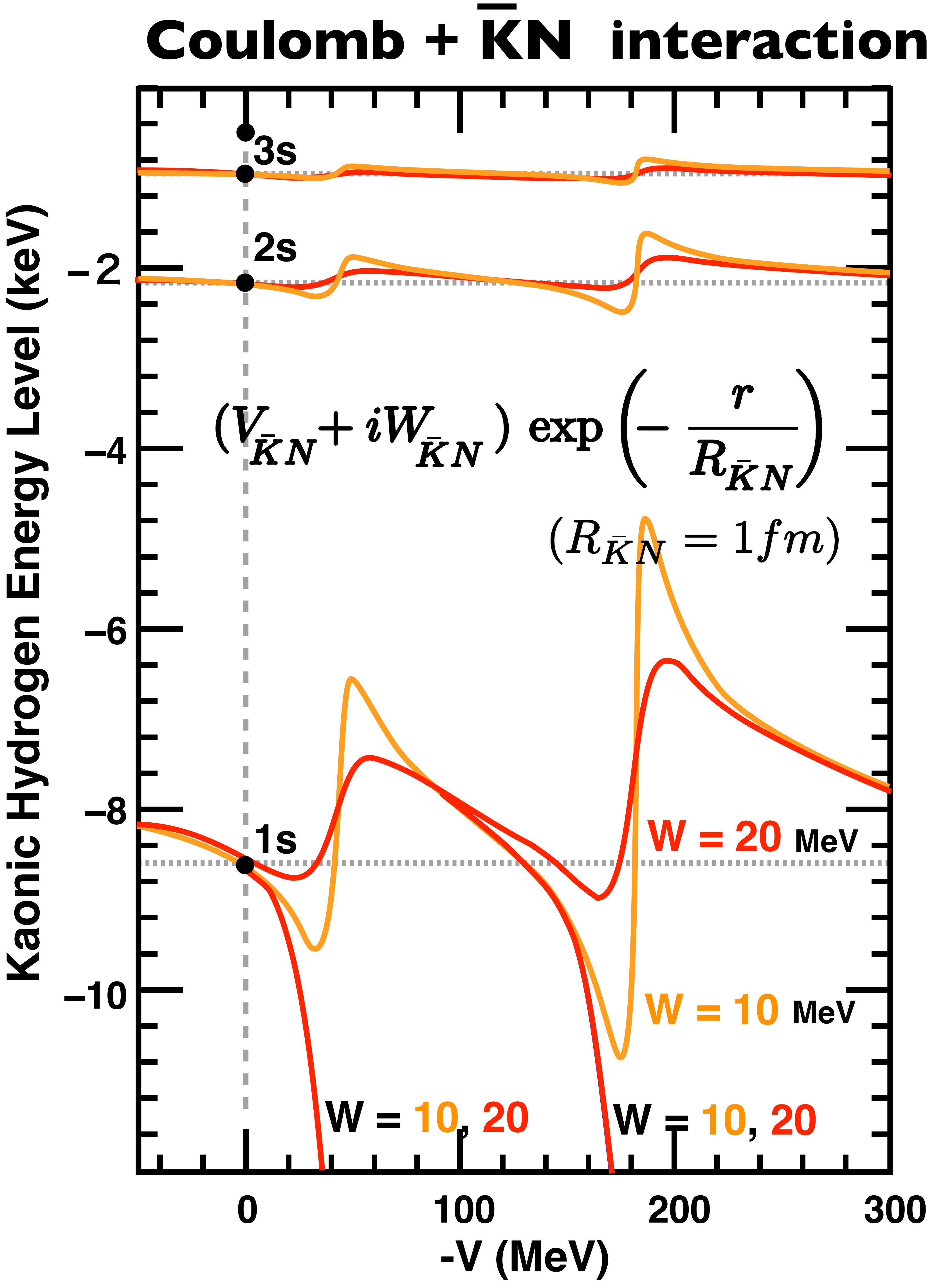

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When switching on the absorption part $W_{\bar{K}N}$, a level crossing happens and connects to another level.

As a result, a wiggling pattern appears in energy levels (red lines), and the nuclear bound state is branched and separated from the atomic ground state.

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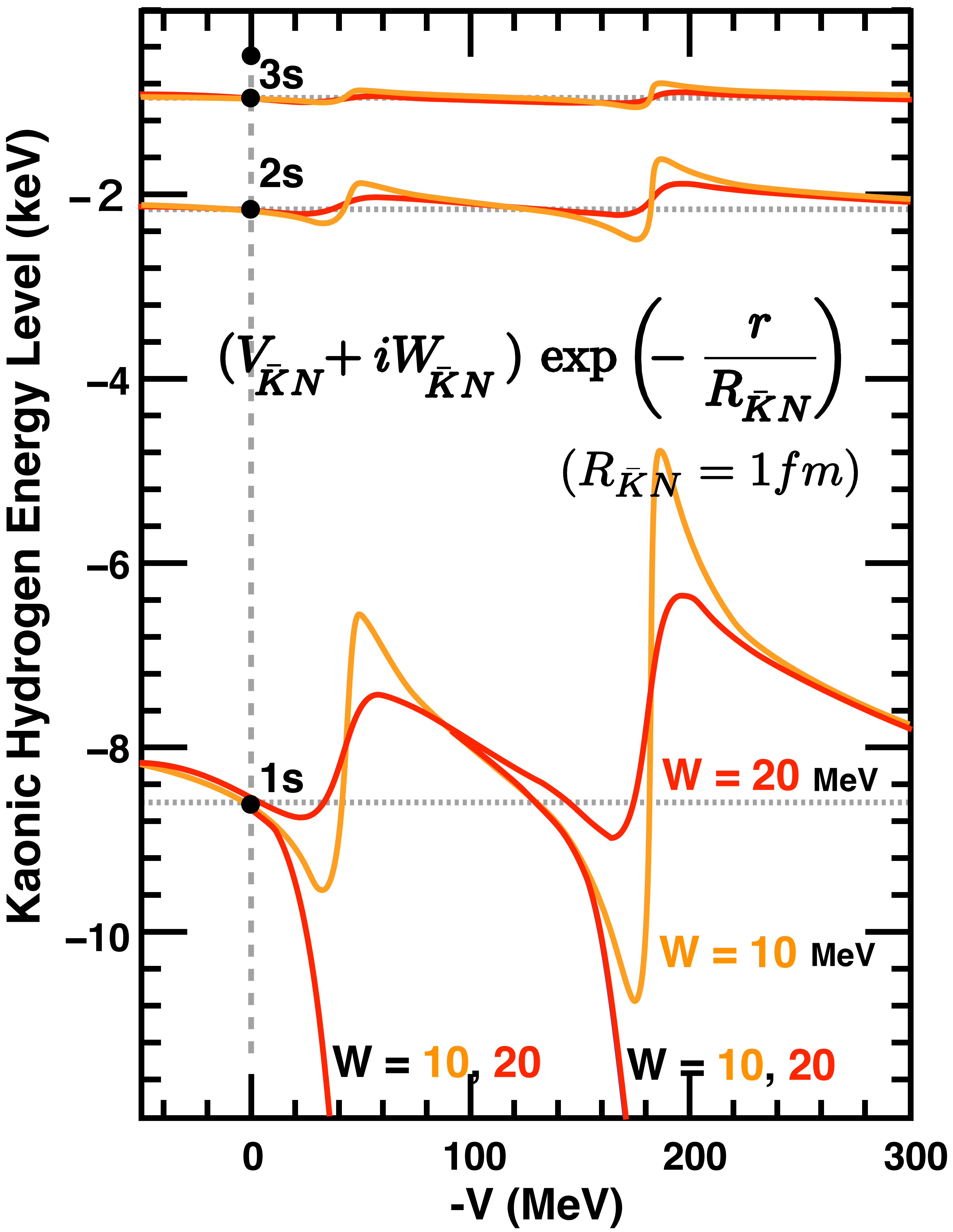
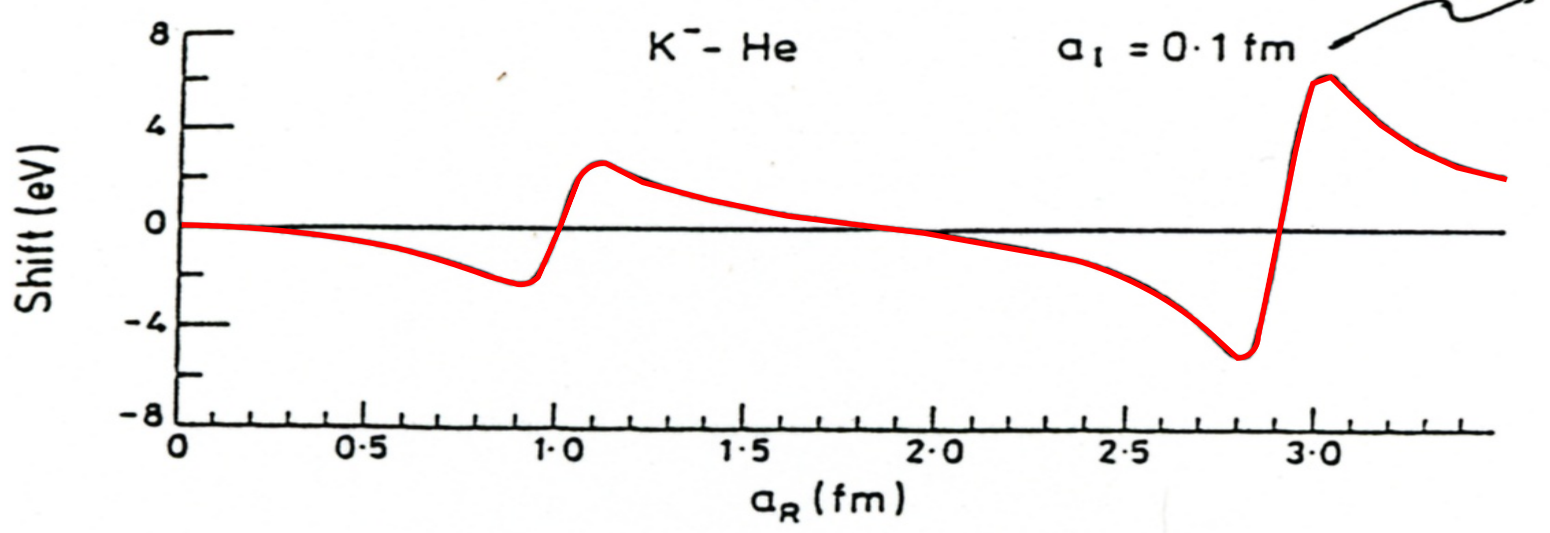


$W_0 = -277$ MeV fm^{-1} $\times\ \bar{a} = -30$ MeV



Theoretical calculations for realistic $\bar{K}N$ interaction

R. Seki, Phys. Rev. C5 (1972) 1196

S. Baird et al., Nucl. Phys. A392 (1983) 297

C.J. Batty, Nucl. Phys. A508 (1990) 89c

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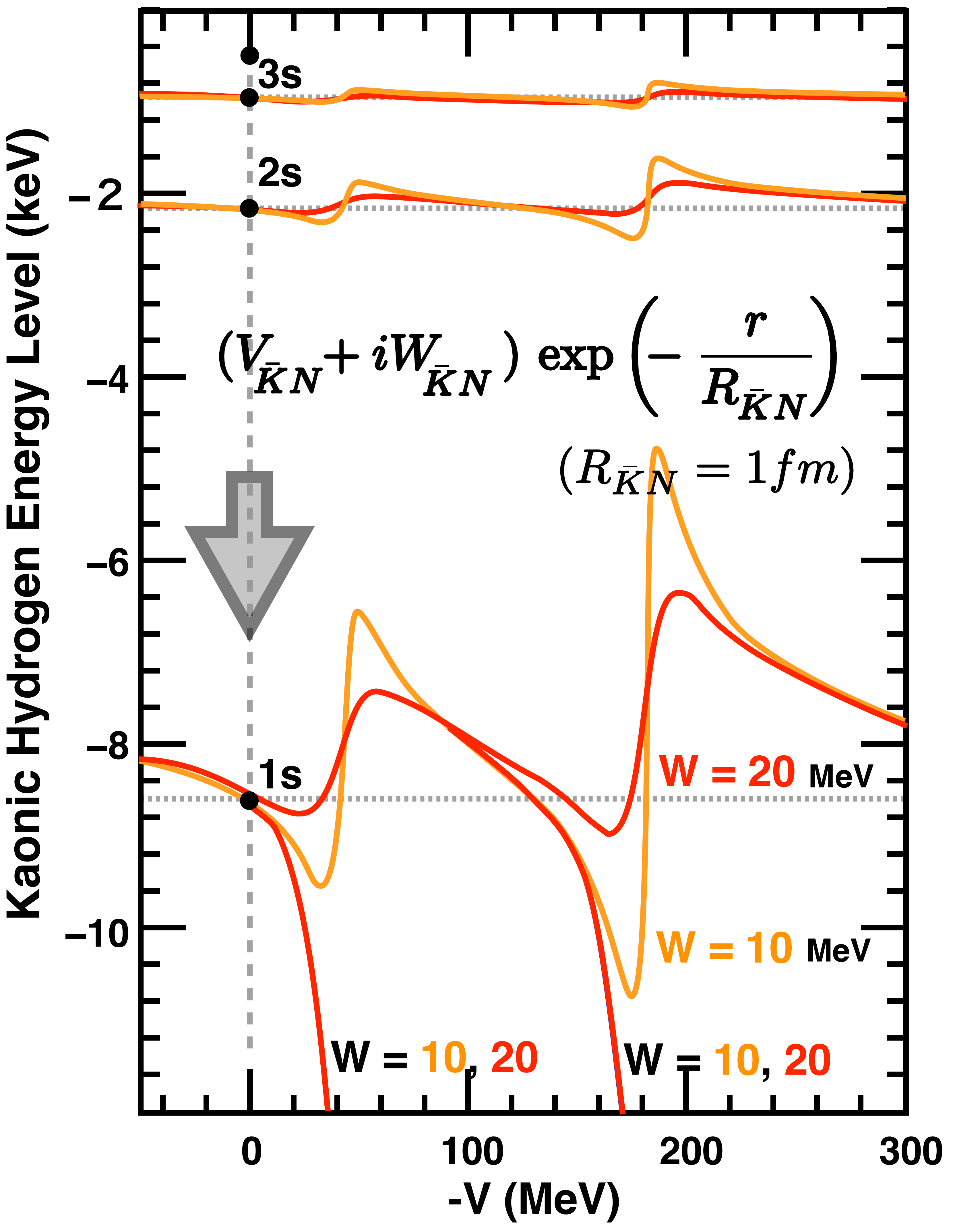

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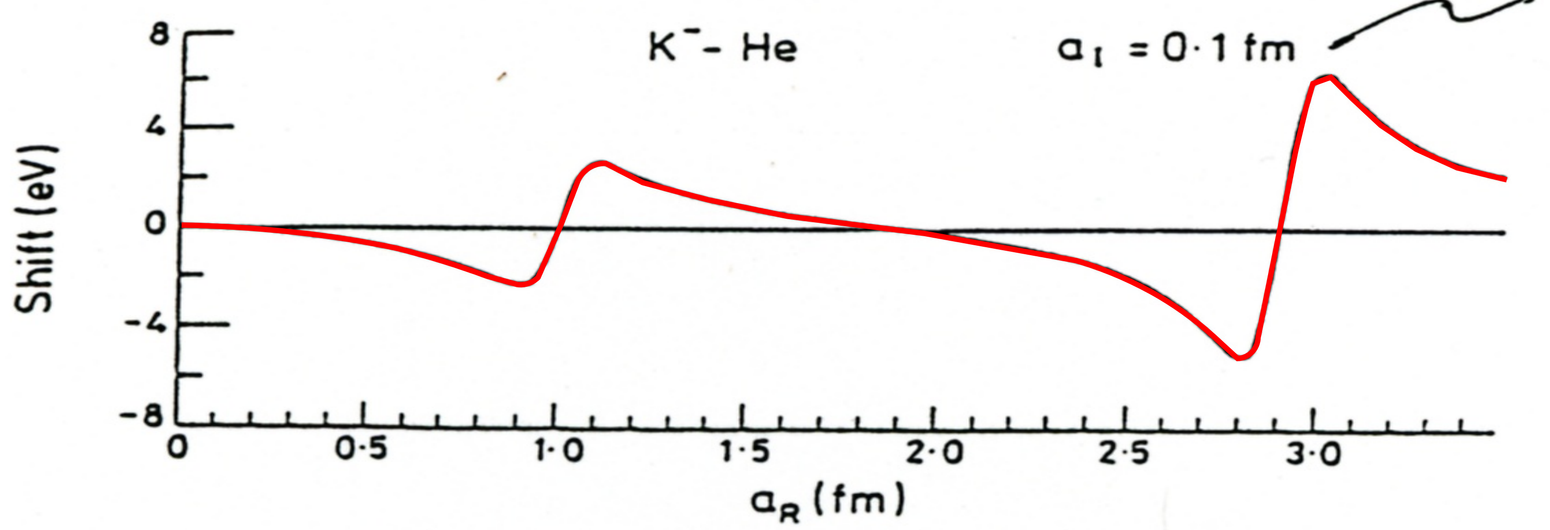

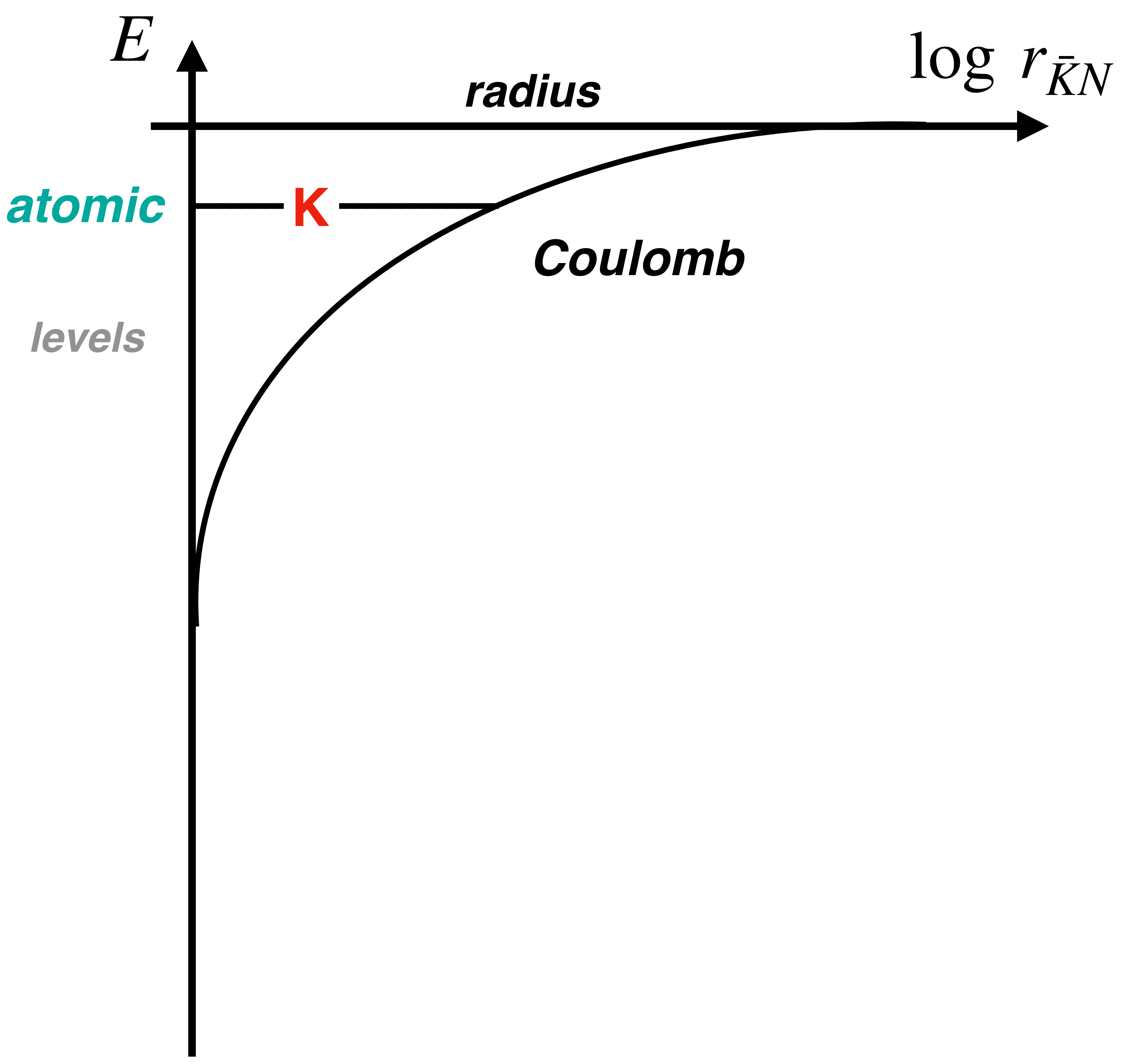

Illustrative Animation

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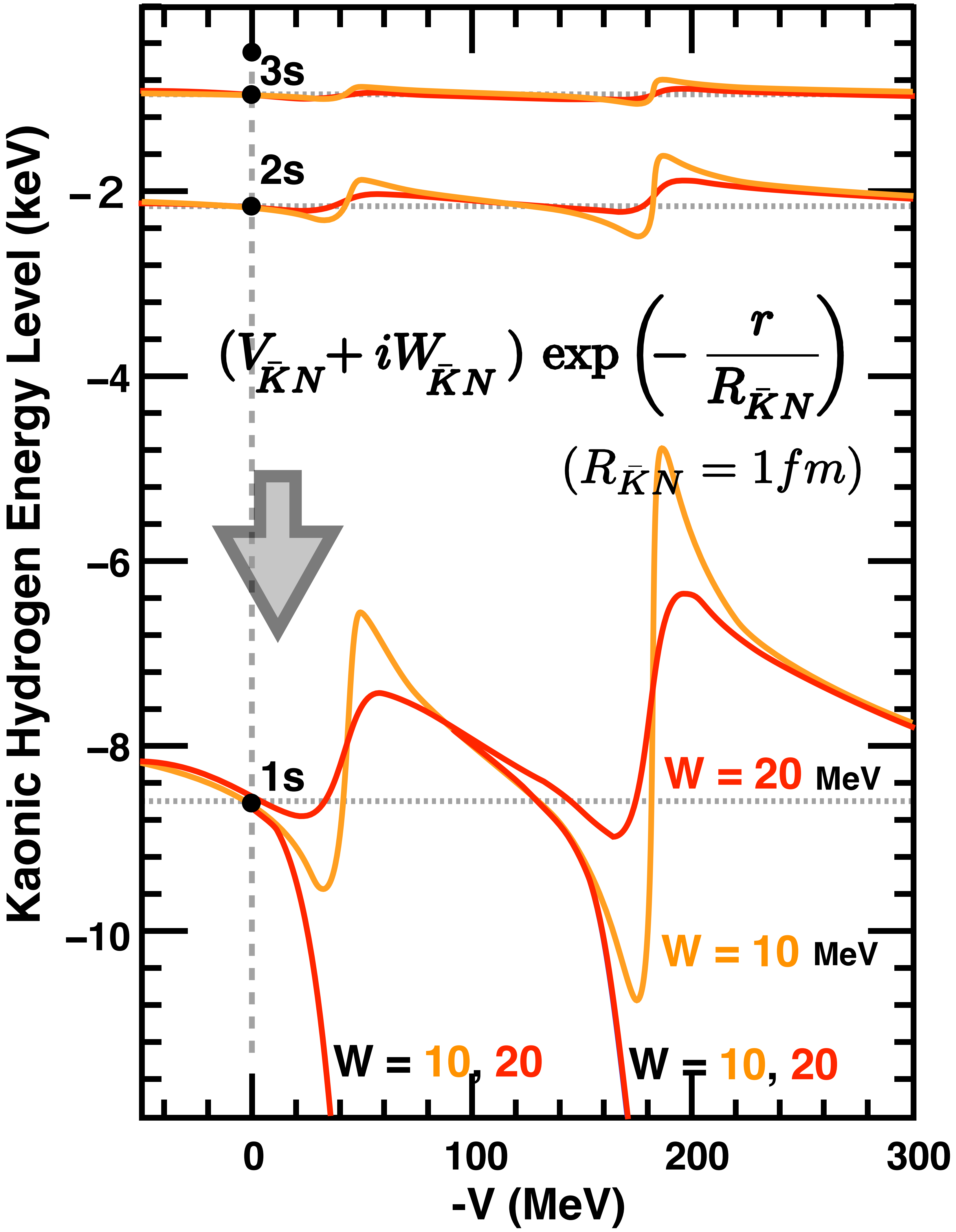

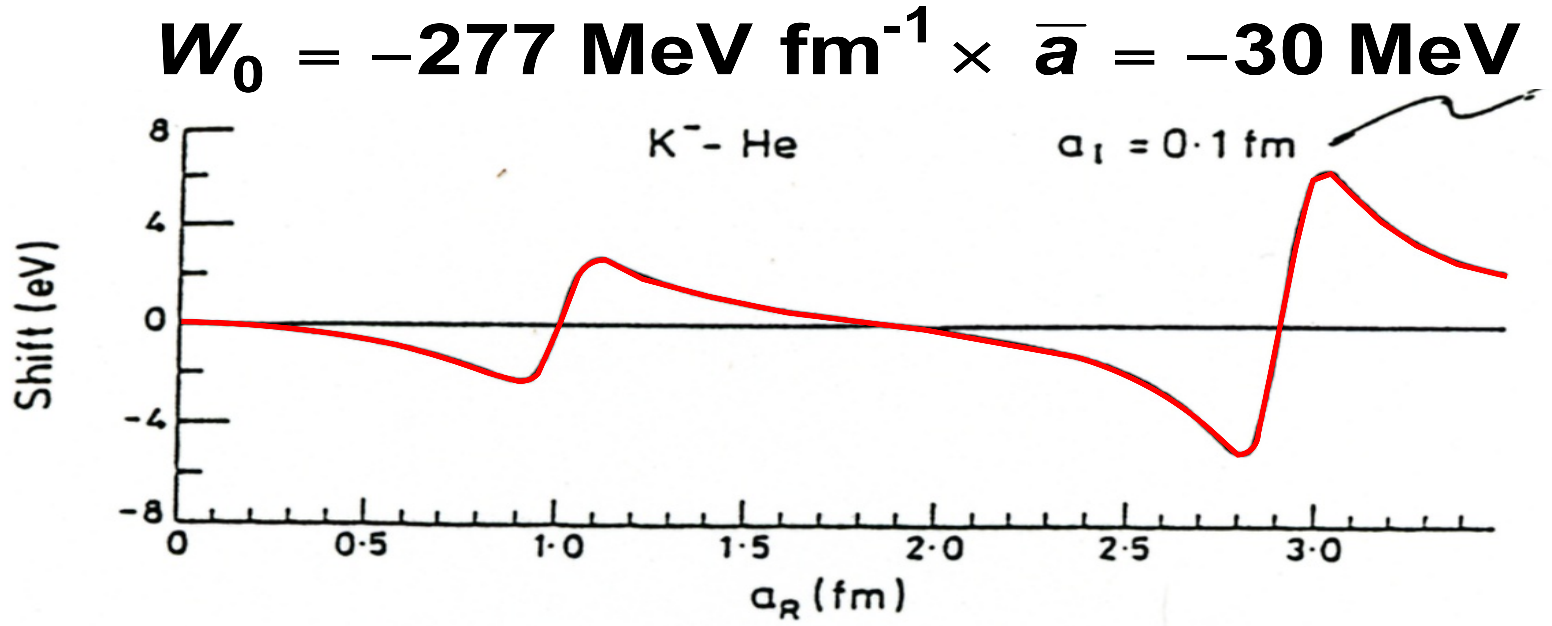

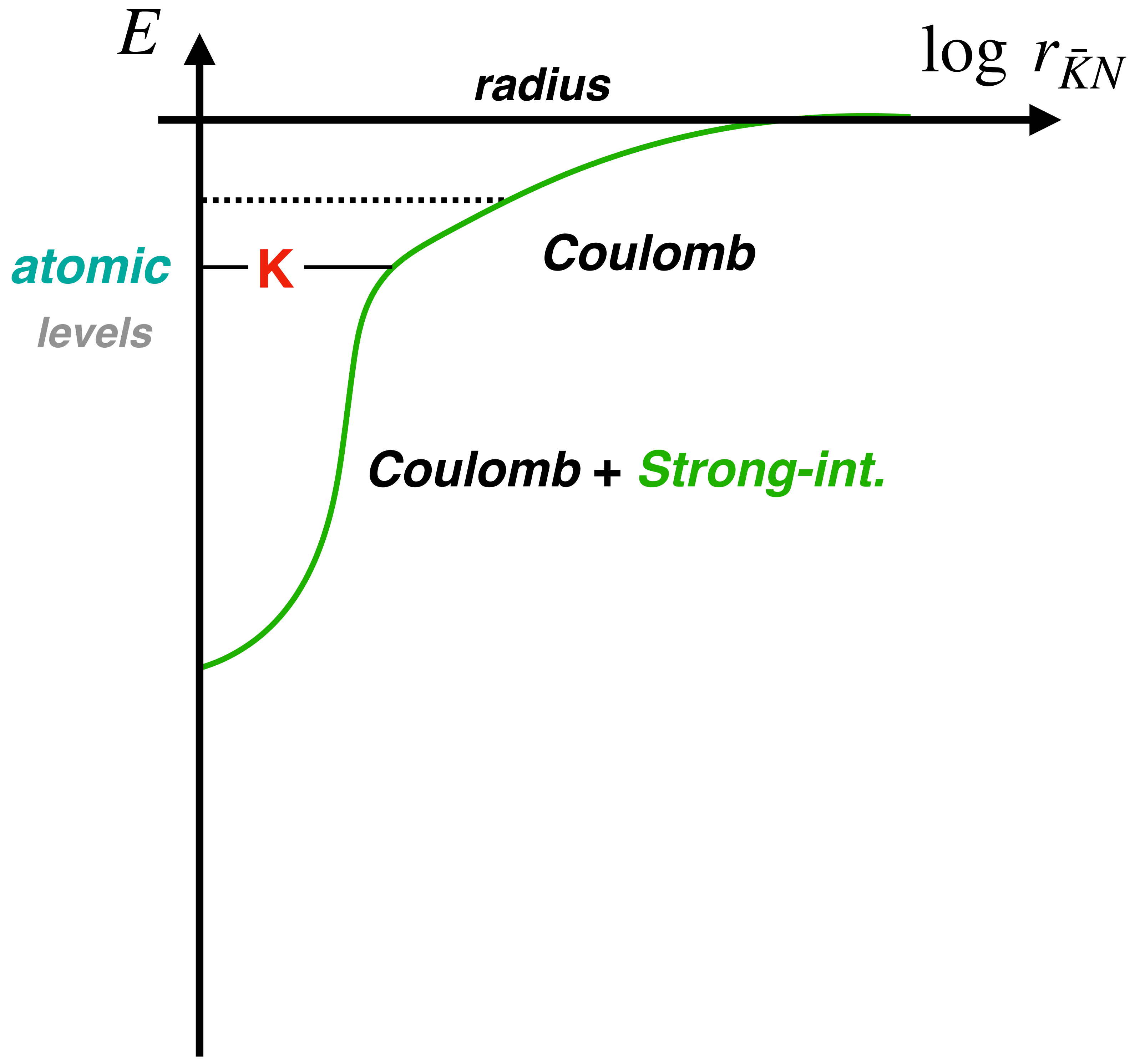

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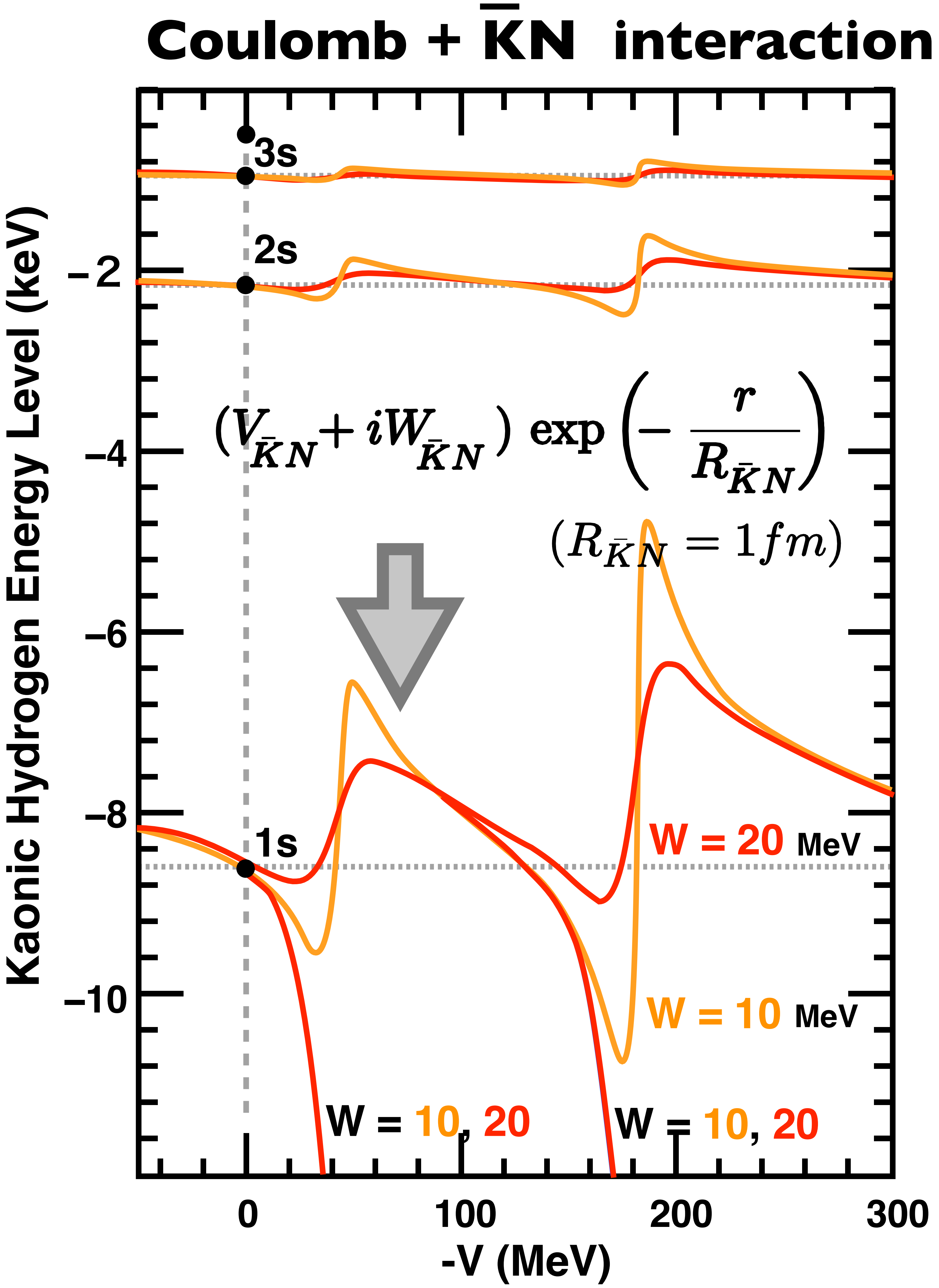

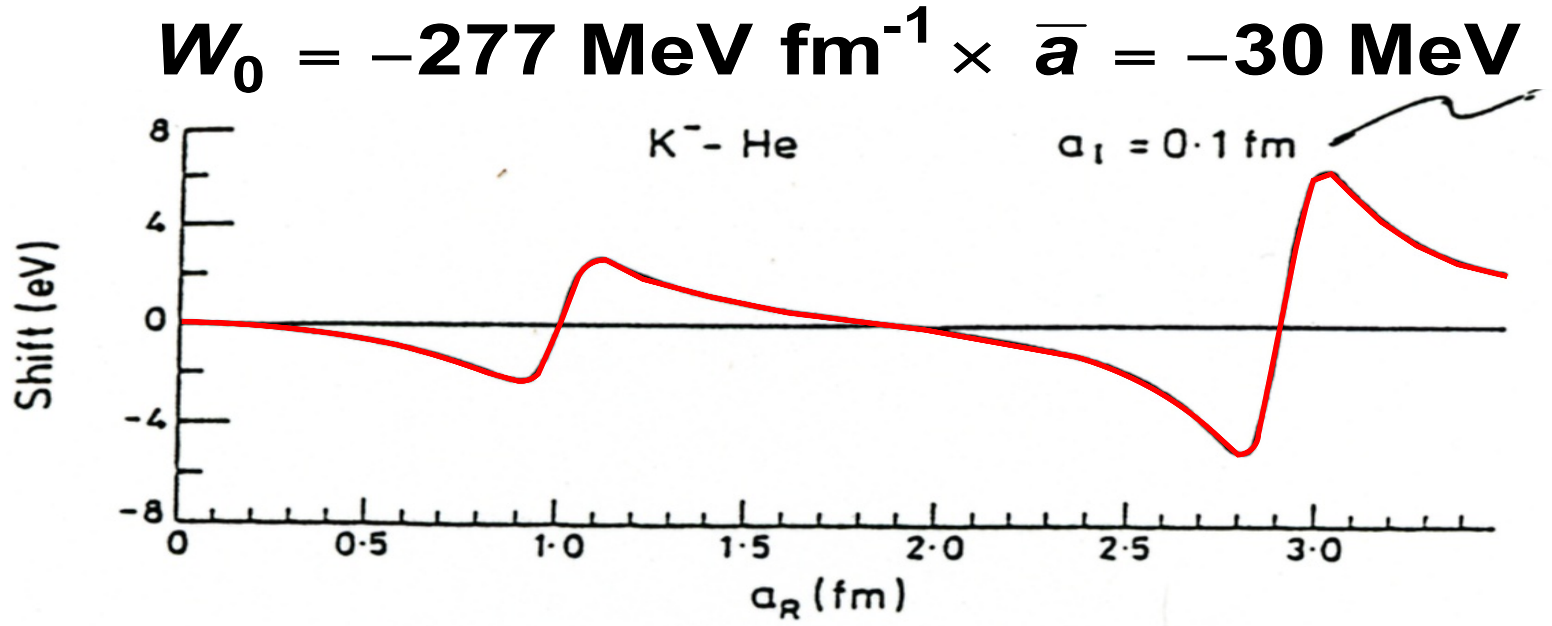

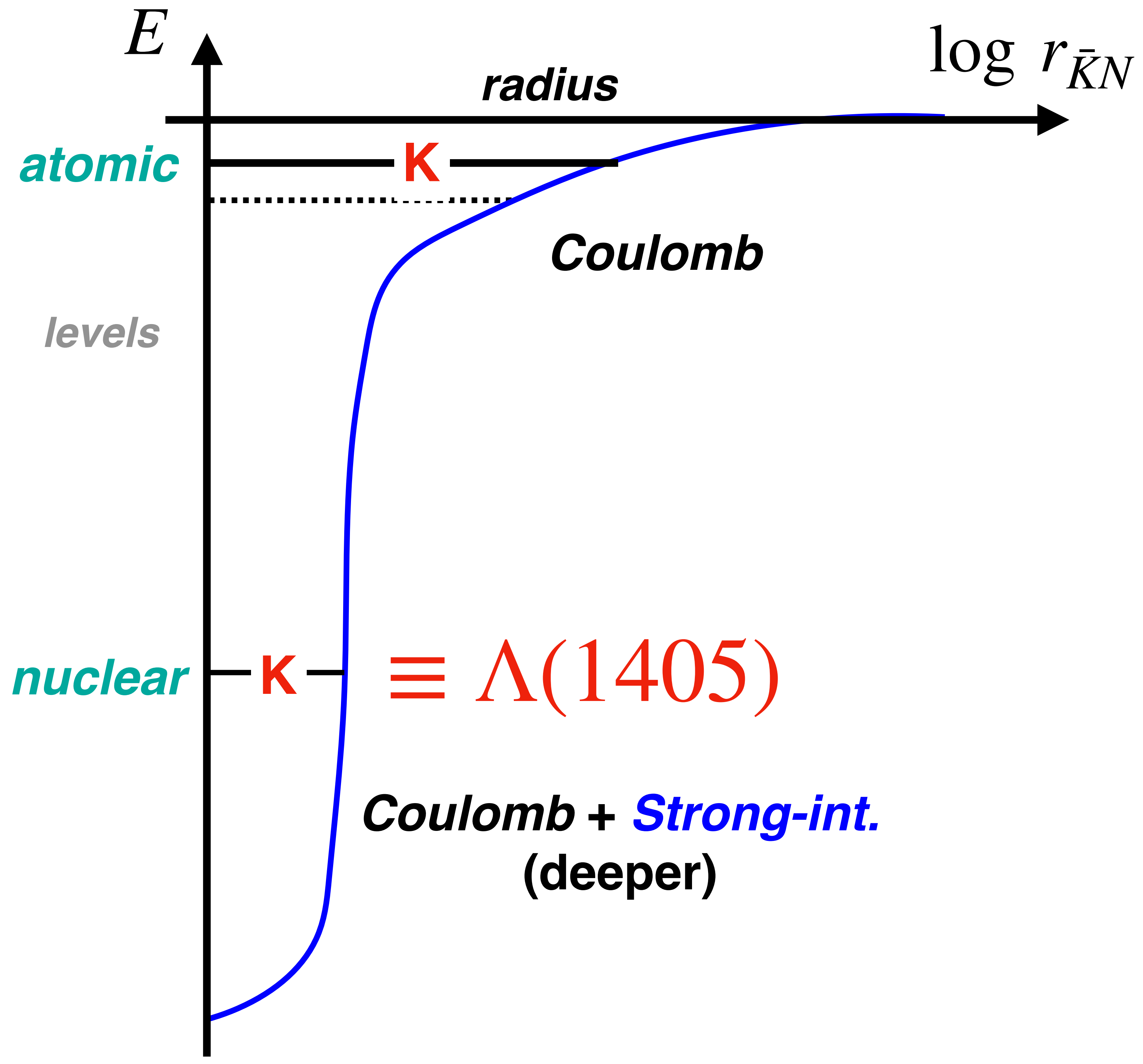

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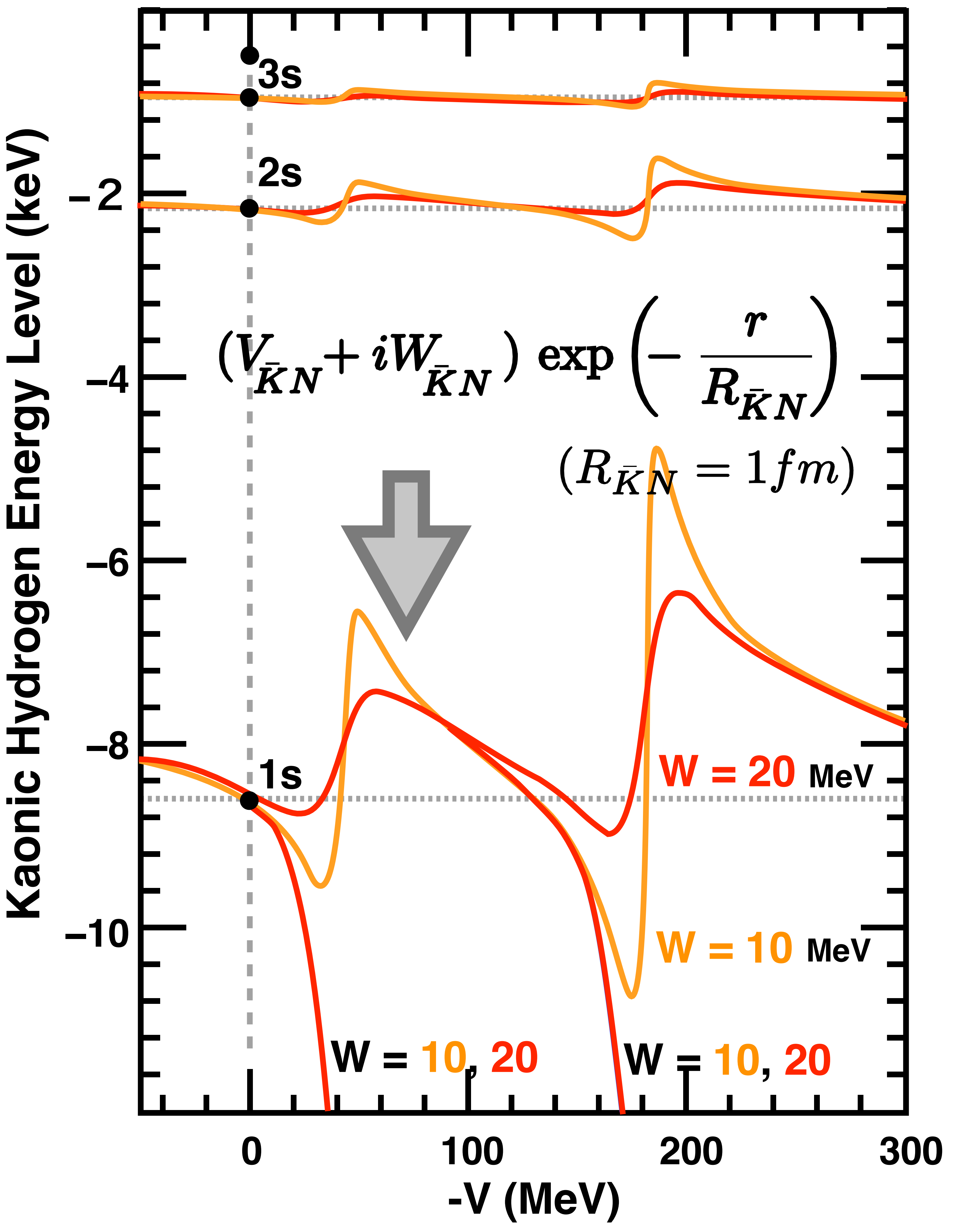

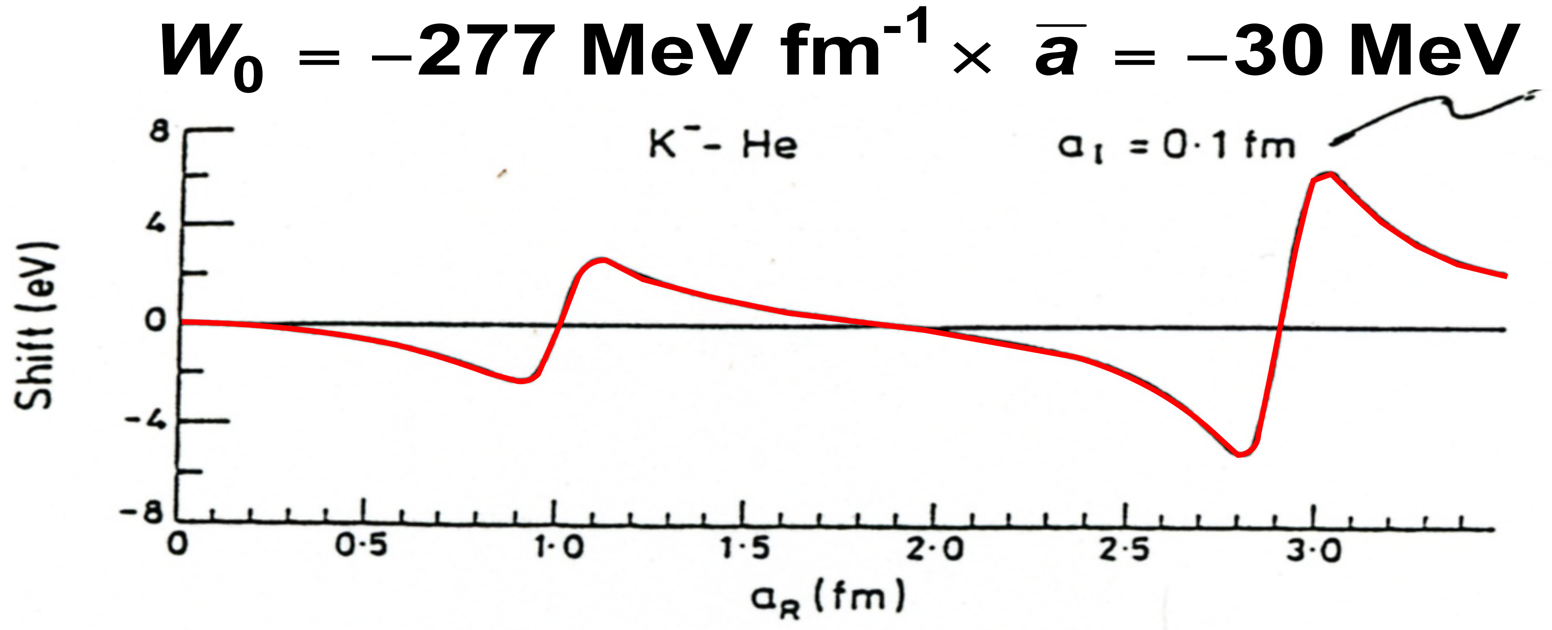

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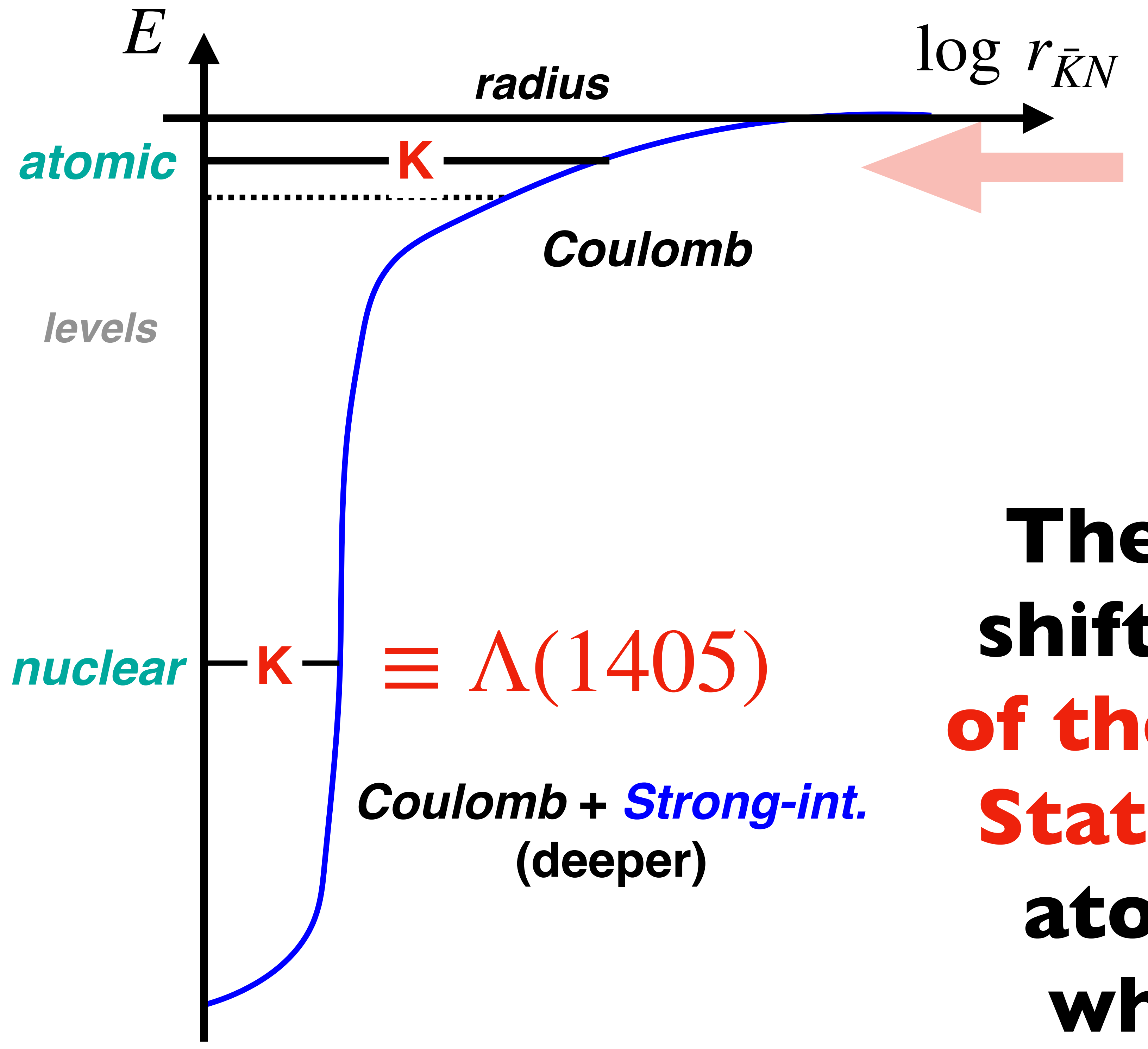


repulsive shift of atomic 1s

Illustrative Animation

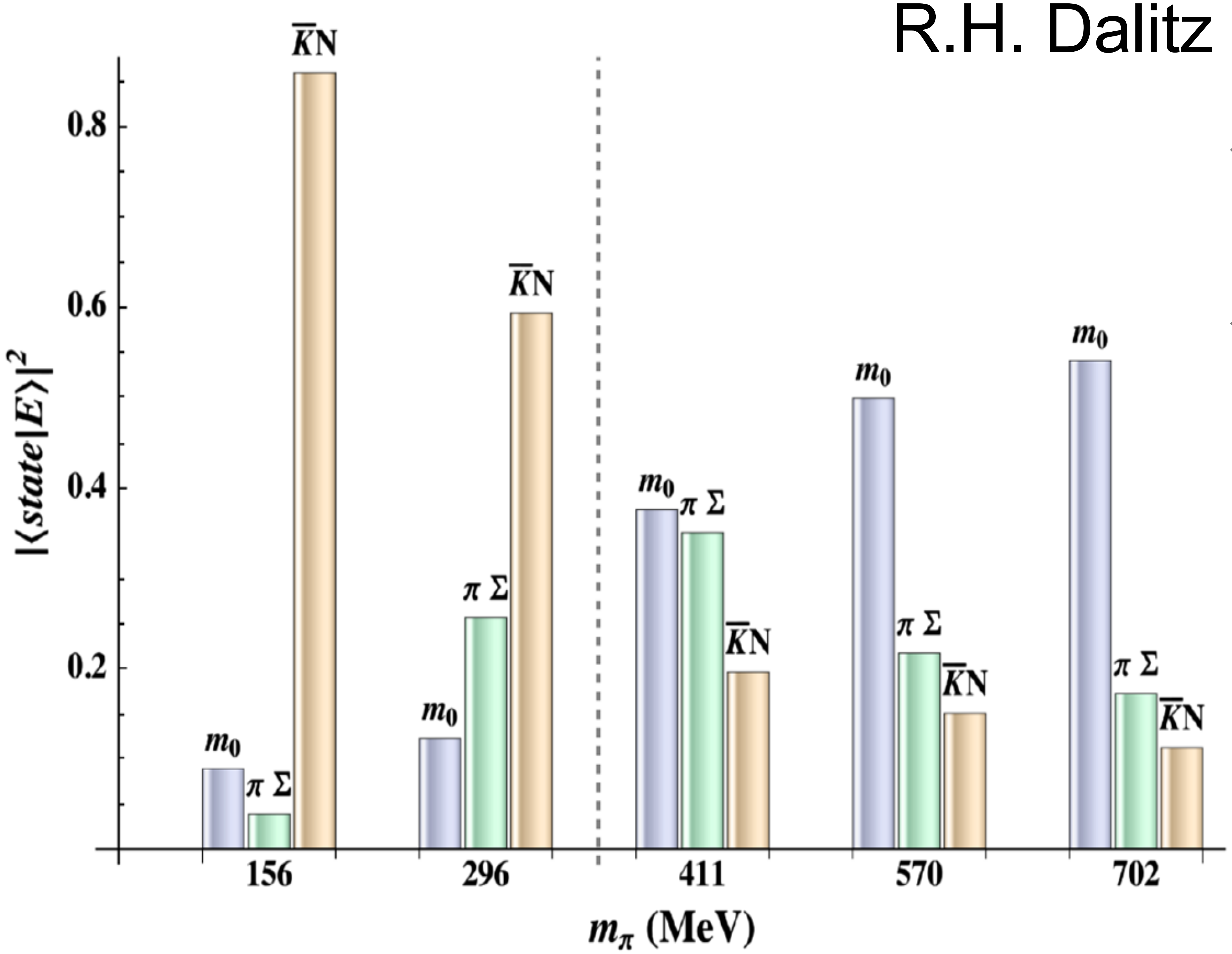
The sign flip of the energy shift suggests the existence of the Kaonic Nuclear Bound State because the repulsive atomic shift appears only when the bound state is formed!

As a candidate of K^-p bound state, Λ(1405) is the most natural

- Is it quark excited state of Λ baryon (*qqq*)?

Λ(1405) = $\bar{K}N$ … a "molecule-like hadron composite"

R.H. Dalitz and S.F. Tuan, Ann. Phys., 3, 307 (1960)

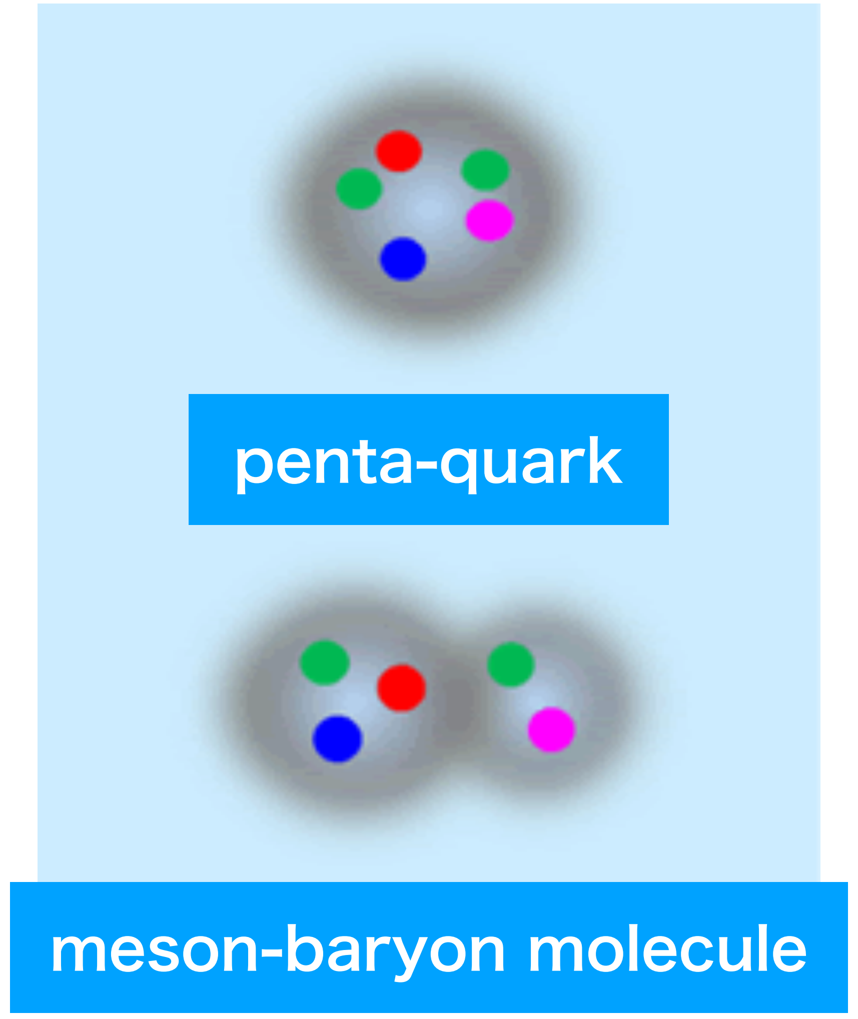


- **supported by kaonic hydrogen data**

  Phys. Rev. Lett., 78, 3067 (1997)

- **supported by Lattice QCD**

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



why not $\bar{K}NN$?

forming a nuclear bound state

Search for $\bar{K}NN$ bound state

T. Hashimoto, S. Ajimura, G. Beer, PTEP (2015) ptep/ptv076.

S. Ajimura, H. Asano, G. Beer et al. Phys. Lett. B789 (2019) 620.

T.Yamaga, S. Ajimura, H. Asano et al. Phys. Rev. C102 (2020) 044002.

Basic understanding of nuclei

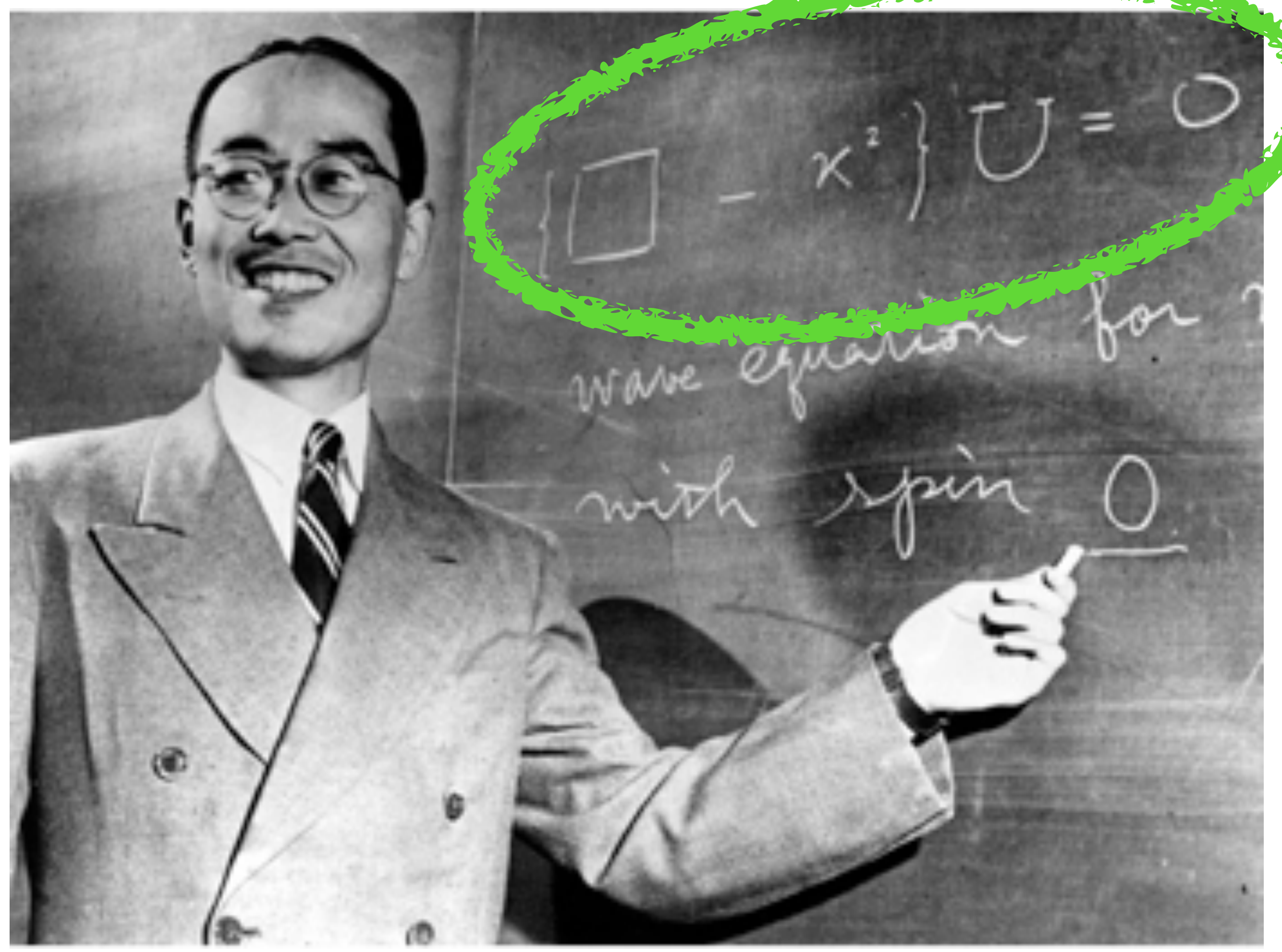
- Nuclei consist of nucleons bound by nuclear force

nucleons (*N*): *qqq* ← meson: $\bar{q}q$ →

q = *u* or *d* | Fermion: Pauli exclusion | Boson: particles can share a quantum state

Z [e]	ist	2nd	3rd
$+\frac{2}{3}$	*u*	*c*	*t*
$-\frac{1}{3}$	*d*	*s*	*b*

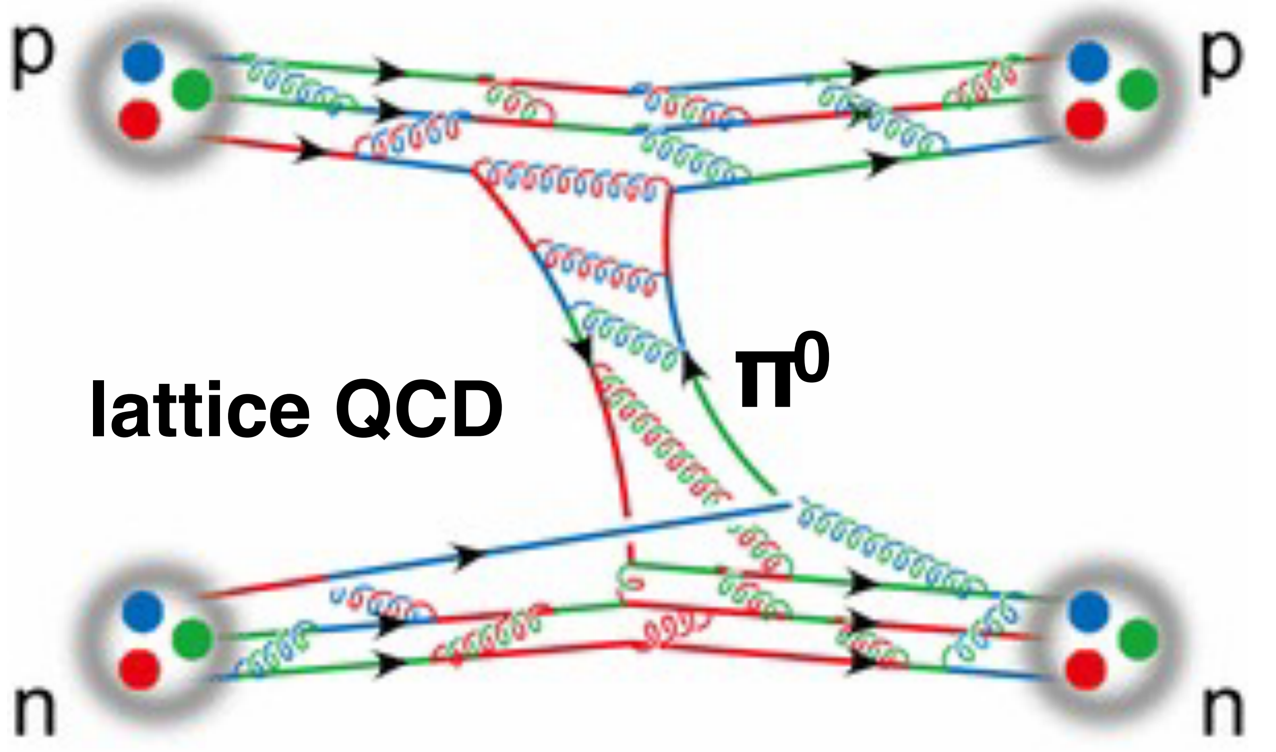
quark flavor



Yukawa Theorem tells：

- in nuclei, mesons are virtual particles and form nuclear potential
- in vacuum, mesons are real particles having own intrinsic masses

$$\phi \propto \frac{1}{r}\exp(-mr)$$



Beyond Conventional Understanding

Long standing question：

Can meson be a constituent particle forming nuclei?

— Can meson form a quantum state as a particle ? —

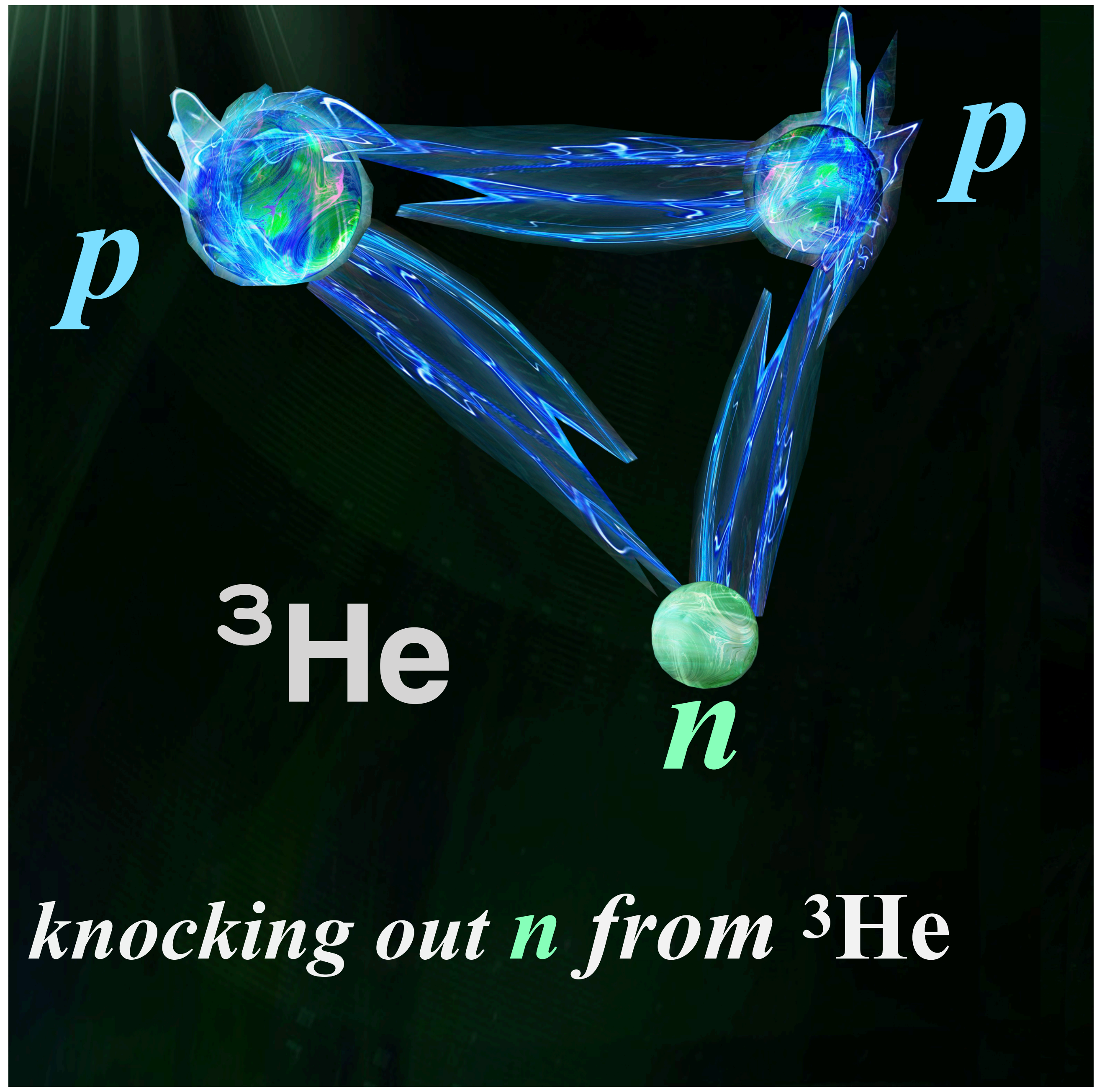
... in the case of K-meson ...

$\bar{K}$ ($\bar{q}s$) forms a bound state with two nucleons → **totally new probe (impurity) to study inside nuclei**

$\bar{K}$ meson (K^- : $\bar{u}s$, $\bar{K}^0$: $\bar{d}s$)

J-PARC E15: "K^-pp" Exploration

K^- + ^{3}He (ppn)



(K^- + pp) + n

substitute n in ^{3}He by K^-

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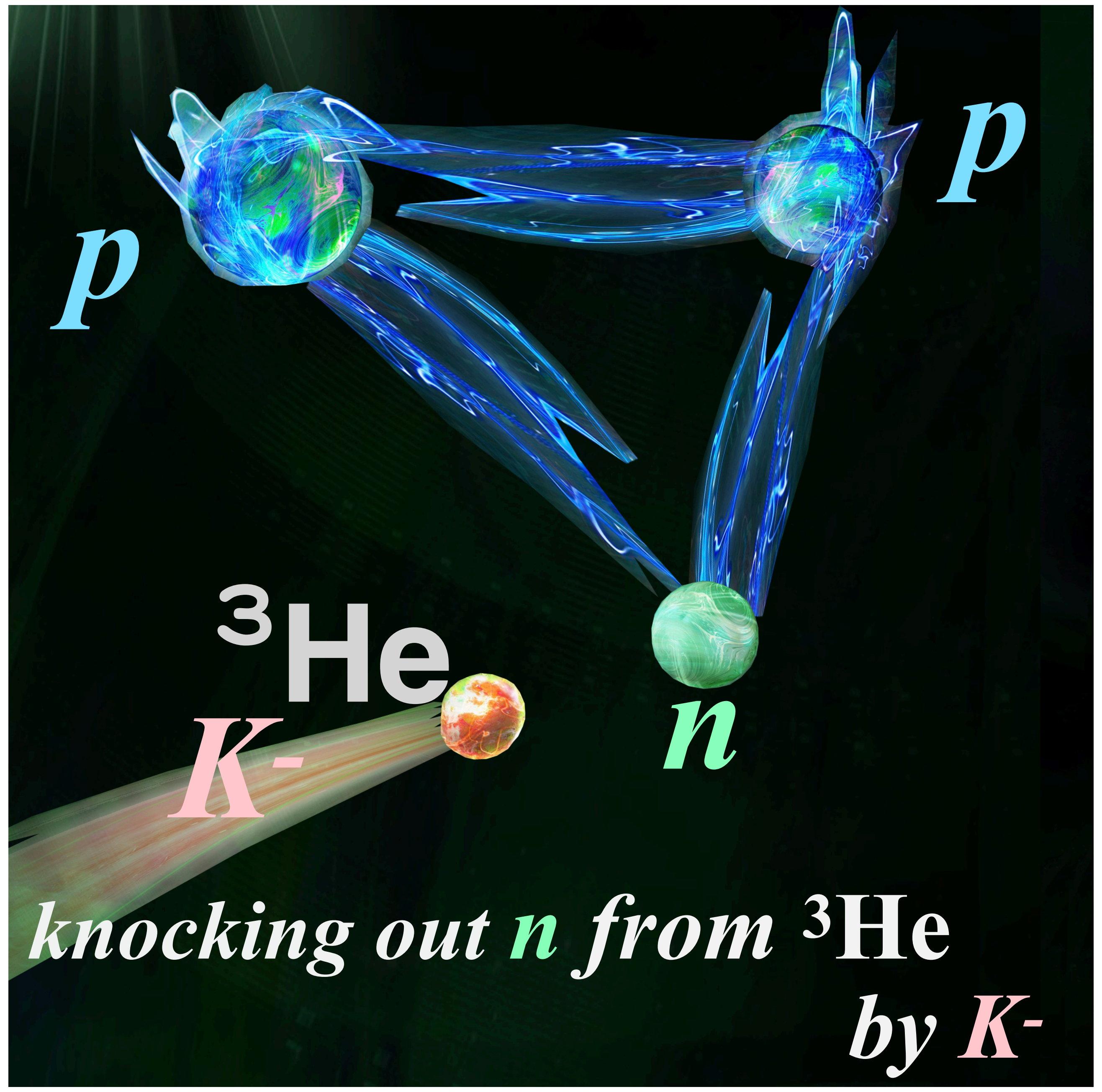

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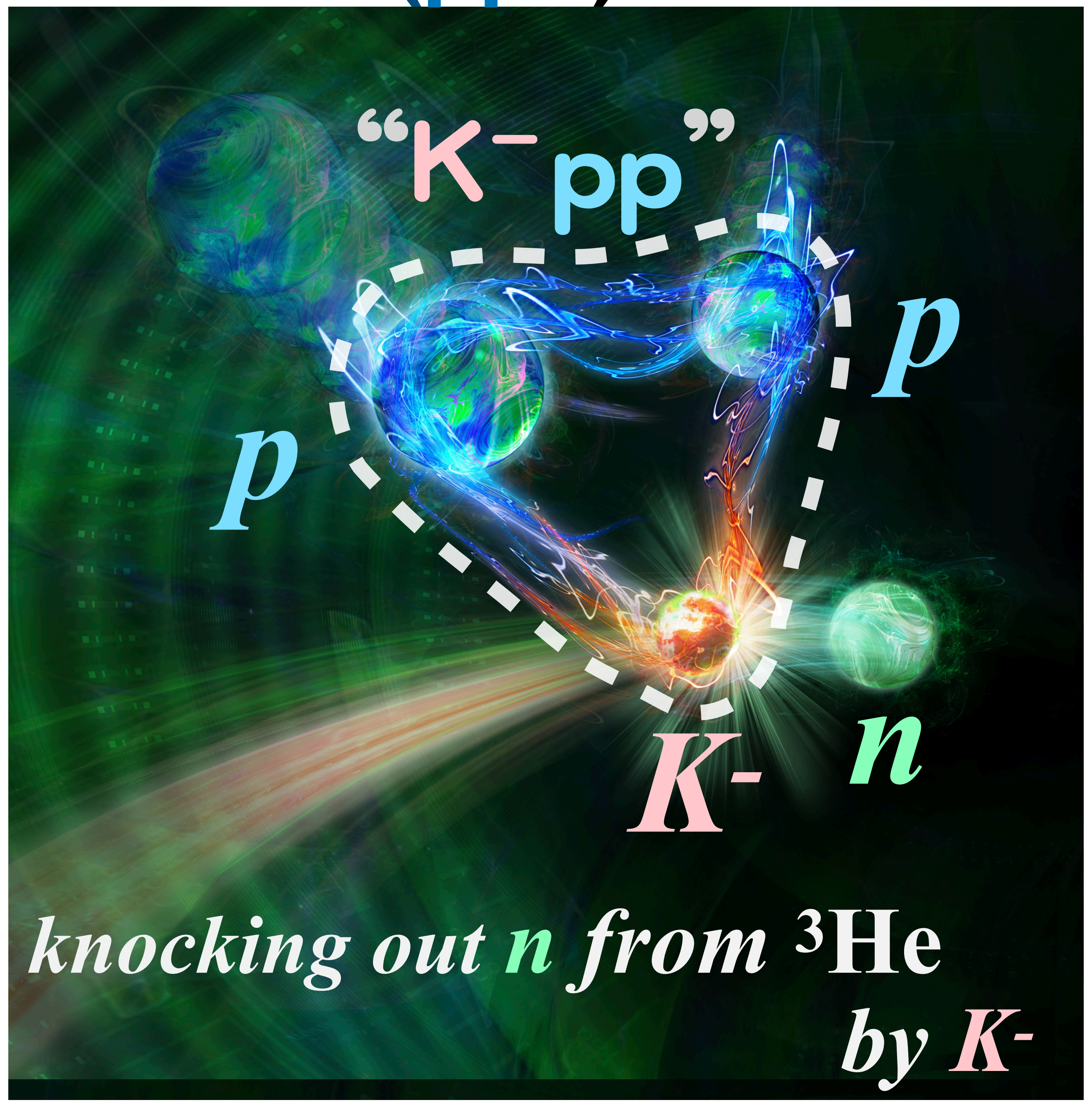

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substitute n in ^{3}He by K^-

If "K^-pp" exits, a peak will be formed in invariant mass spectrum below M(K^-pp)

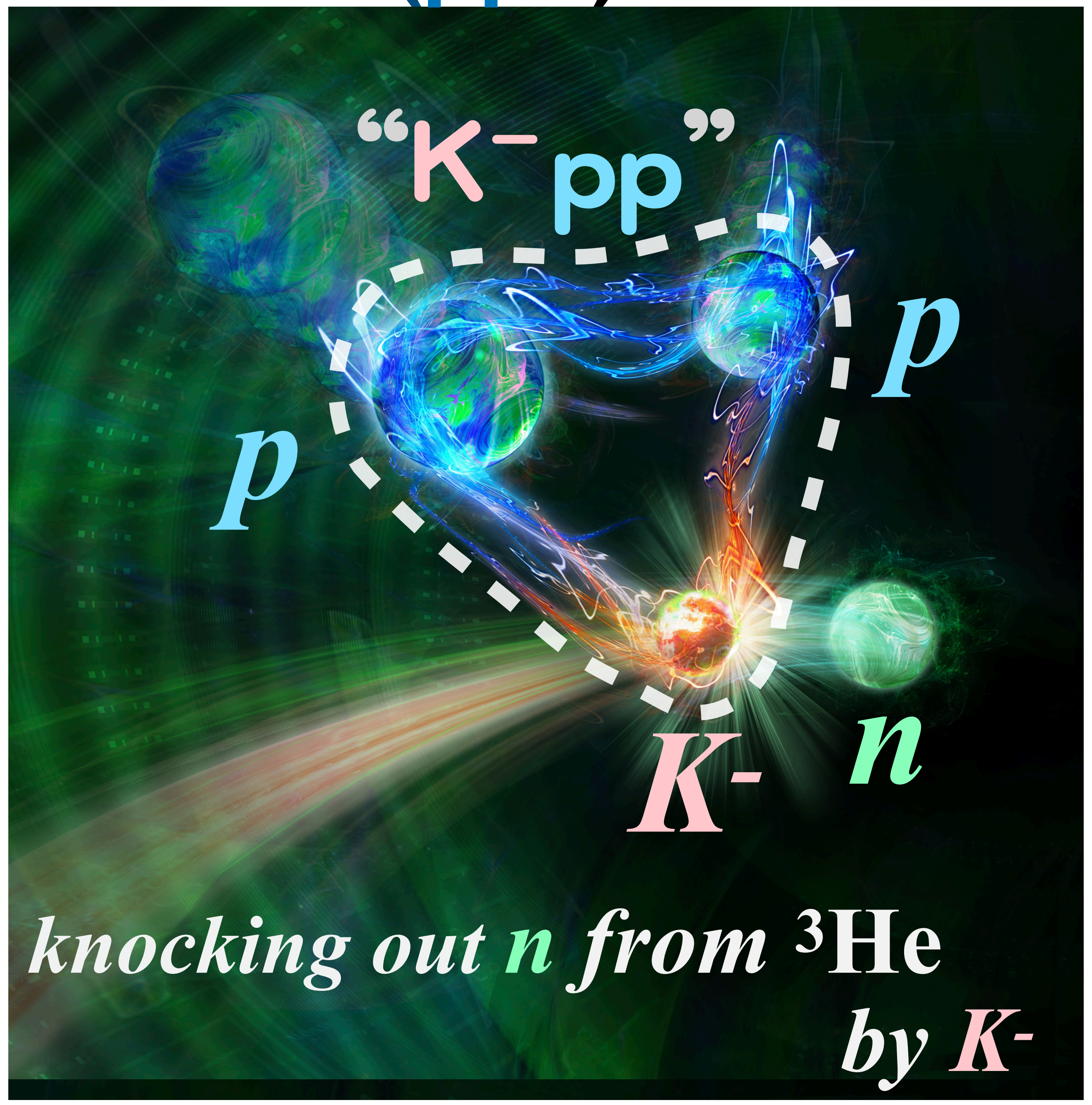
$$M(K^- pp) \equiv m_{K^-} + 2m_p$$

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

: formation

J-PARC E15: “K^-pp” Exploration

K^- + ^{3}He (ppn)



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$$M(K^-pp) \equiv m_{K^-} + 2m_p$$

kinematically identified

K^- + ^{3}He → (K^- + pp) + n : formation

(K^- + pp) → Λ + p : decay (*M, q*)

identified as charged particles

select K^- + ^{3}He → (Λ+p)+n events,
analyze *invariant mass M* of (K^- + pp)-system
and *momentum transfer q* to the system

provides multi-dimensional kinematical information

Λp $+n$ events on (*M*, *q*)-plane

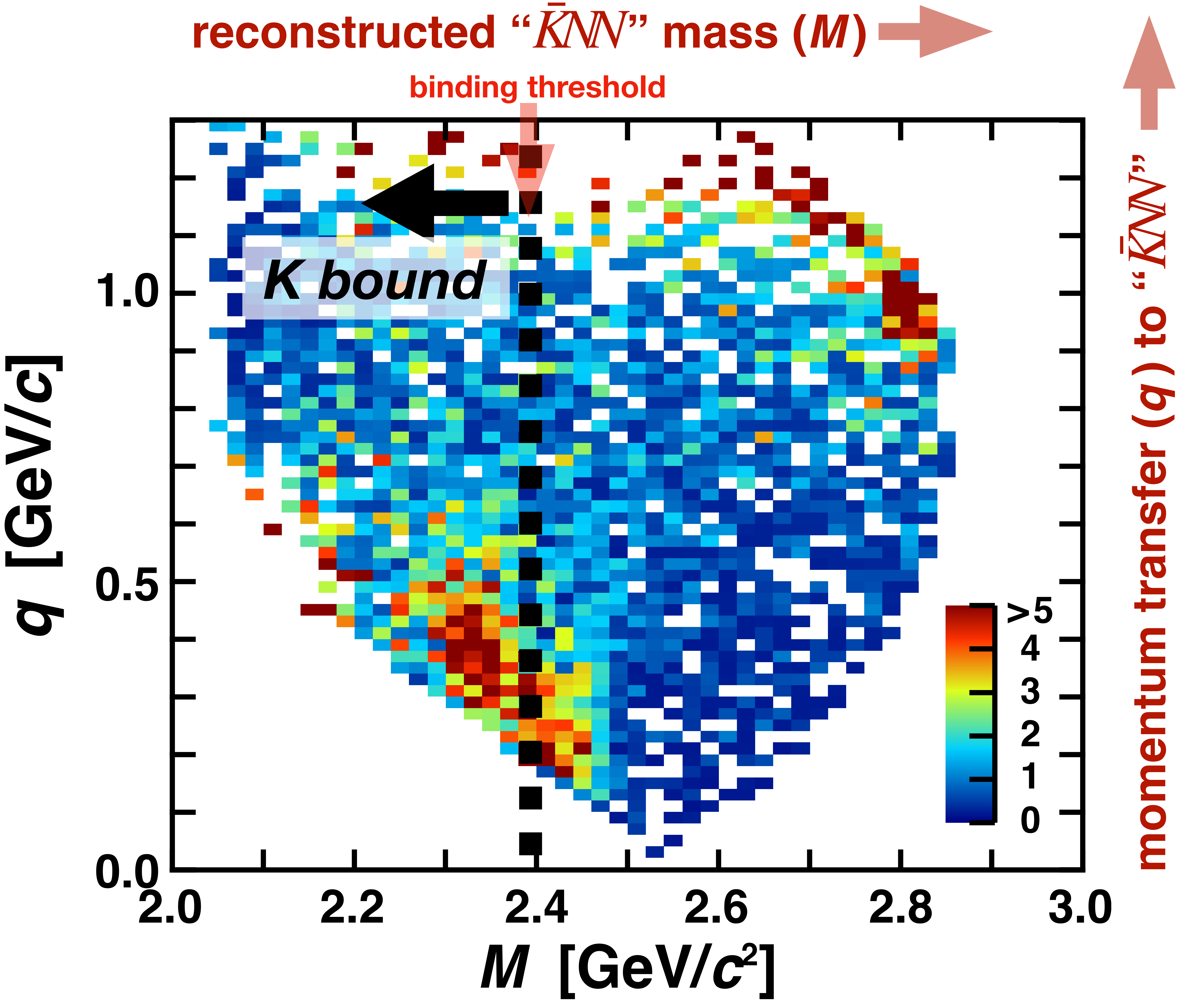
q-distribution: system size

— high-*q* capture happens if the system is compact —

M-distribution: binding energy & absorption width

—sensitive to $\bar{K}N$ interaction —

Acceptance corrected event distribution on (M, q)



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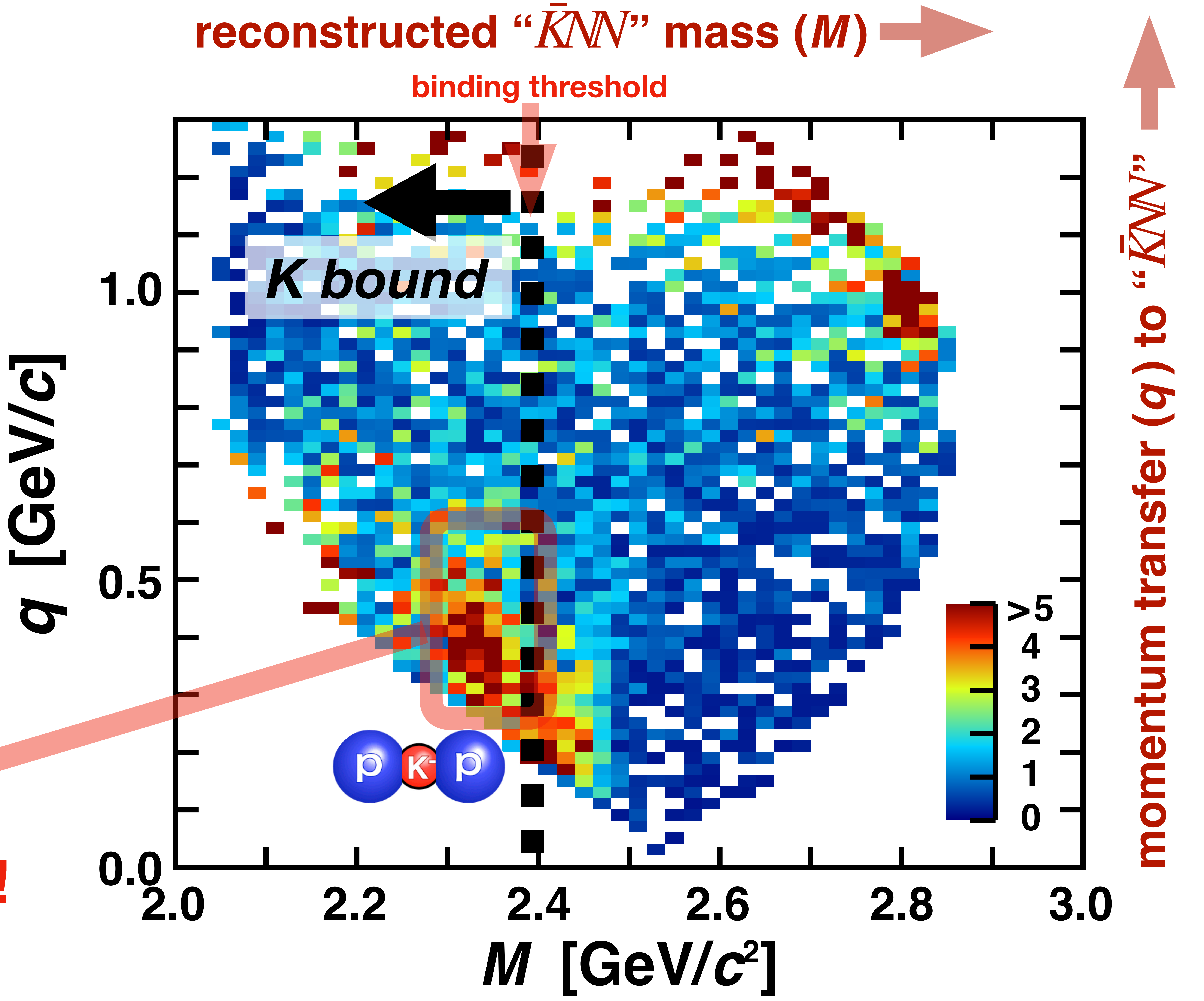

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— sensitive to $\bar{K}N$ interaction —

The K^-pp signal is clearly seen on (M, q)-plane!

— relatively deep and wide, and extended to high-*q* region —

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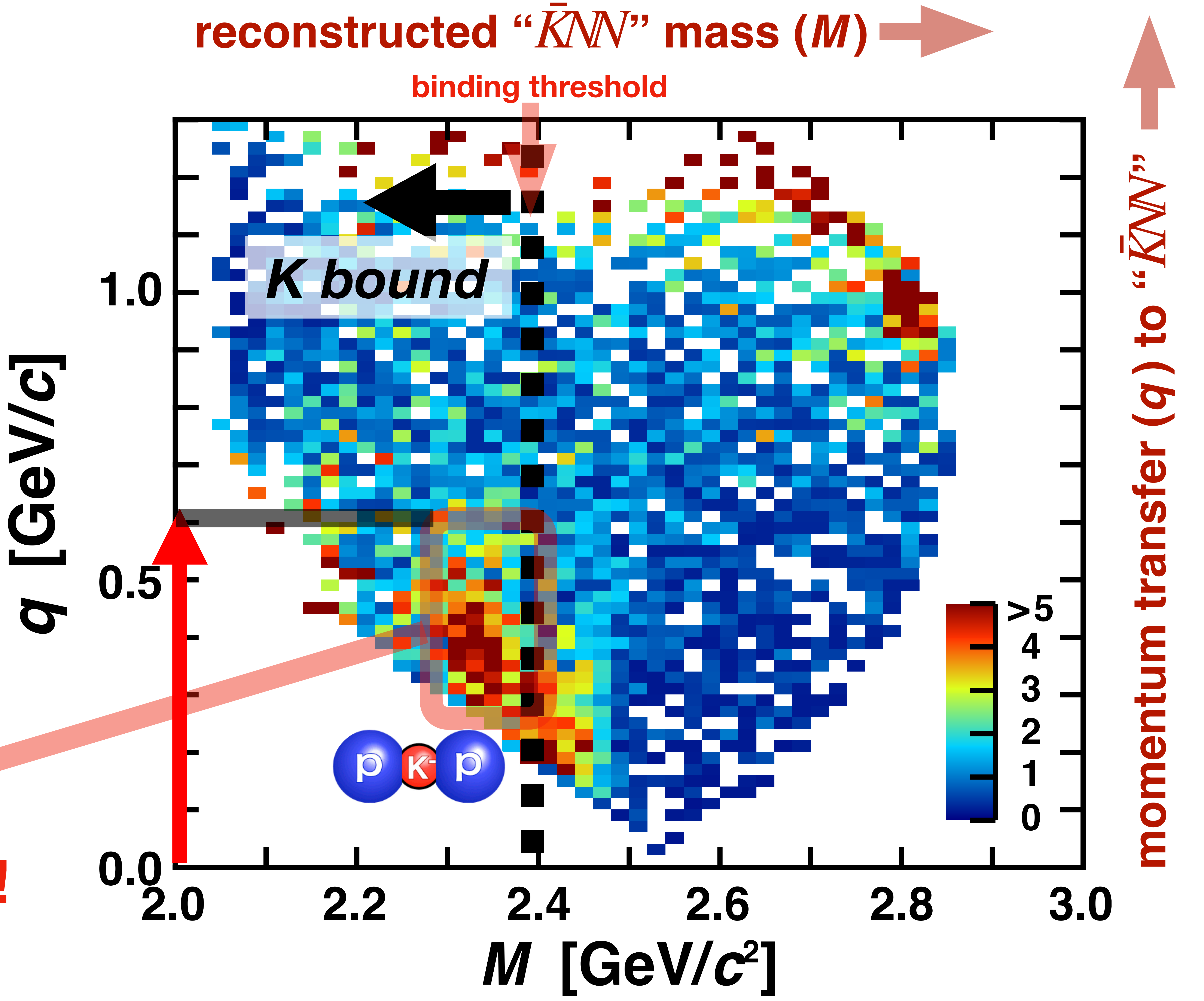

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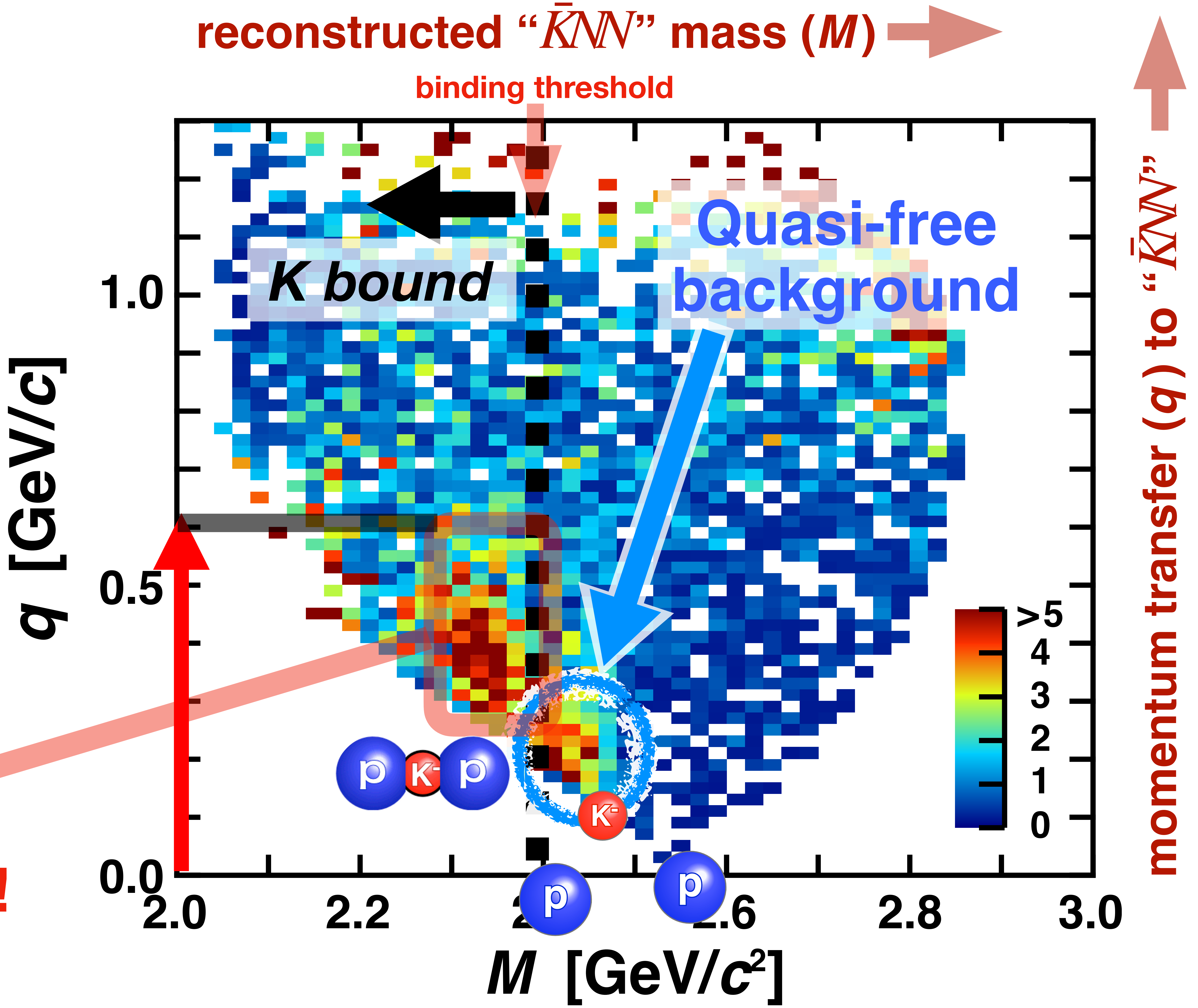
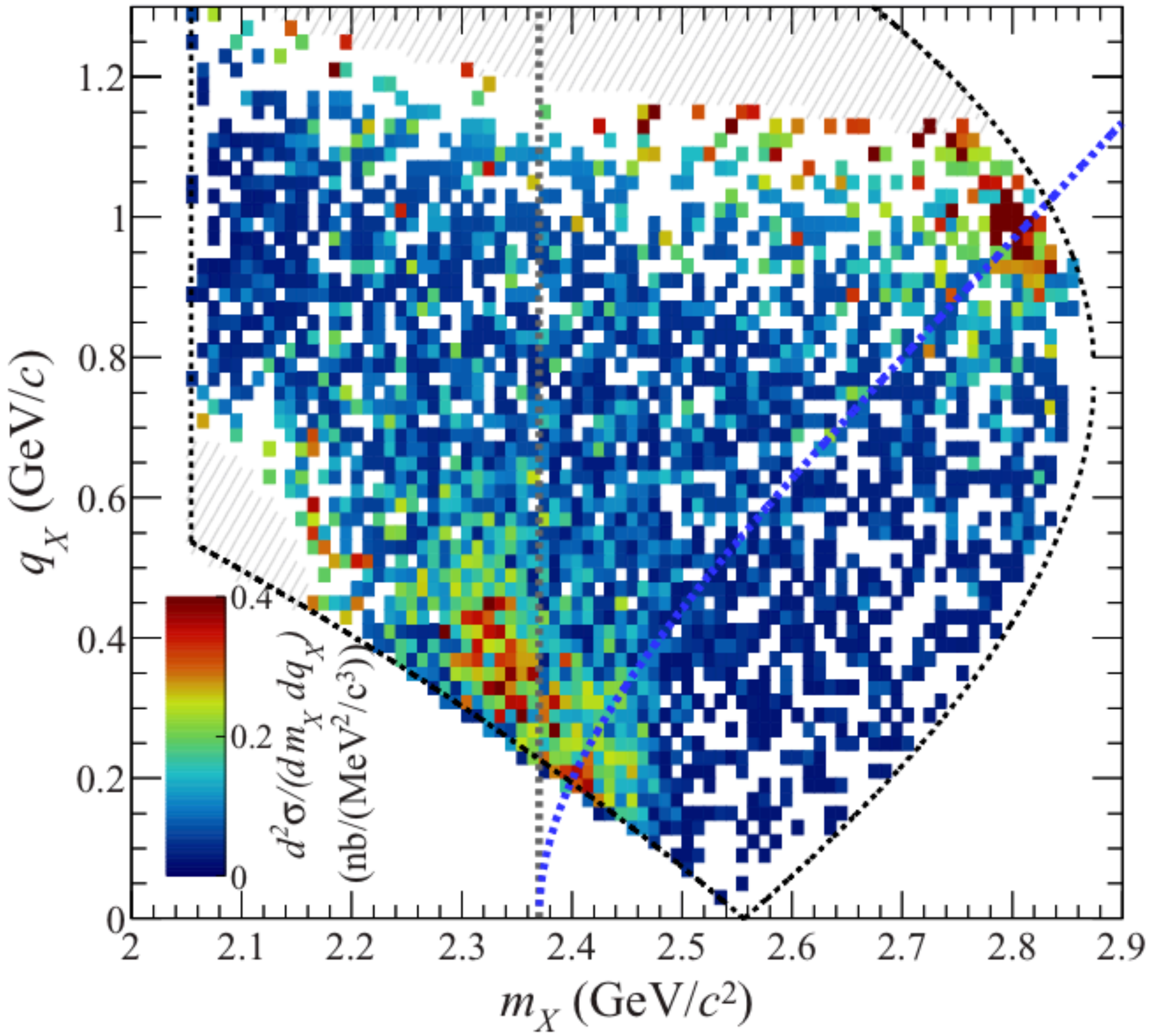


$\Lambda p + n_{\text{miss}}$

Phenomenological model fitting function in (m, q)-plane

ρ : Lorentz-invariant phase-space

$$f_{\bar{K}NN}(m,q) \times \rho_{\{\Lambda pn\}}(m,q) \quad f_{QF\text{-}\bar{K}}(m,q) \times \rho_{\{\Lambda pn\}}(m,q)$$



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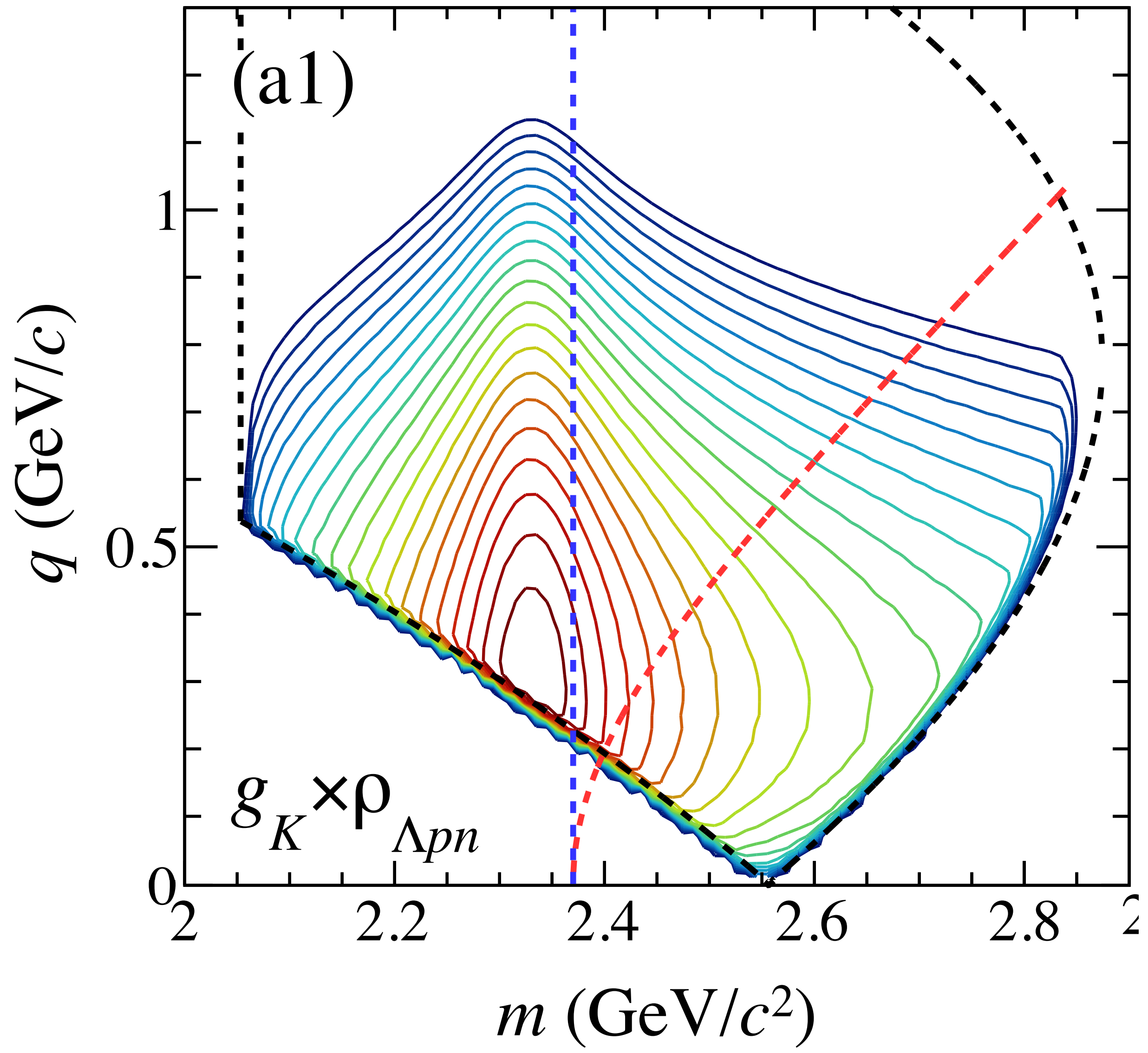
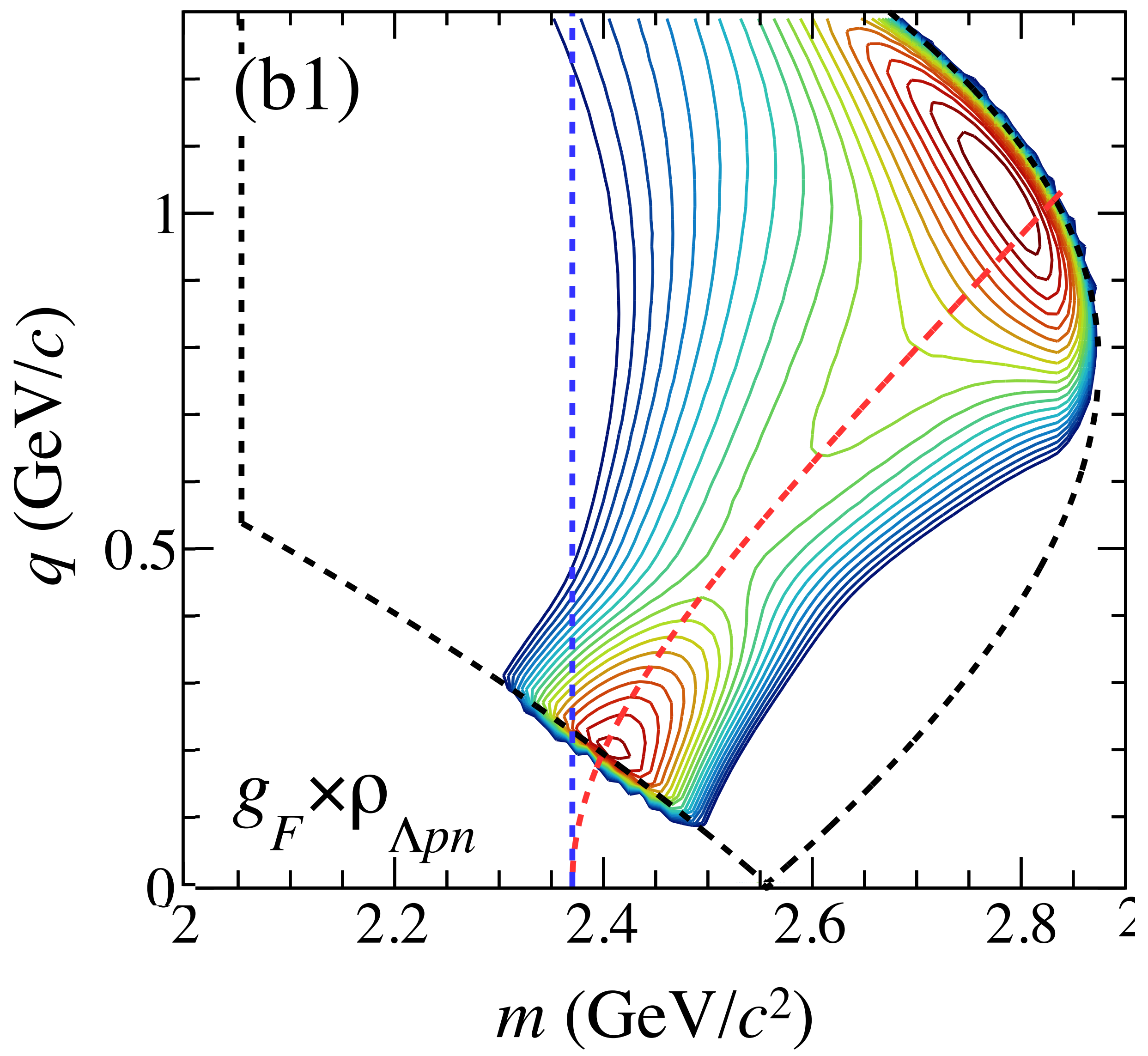
$\bar{K}NN$ production



+

QF-$\bar{K}$ absorption



$f_{\bar{K}NN}(m,q)$: $B.W.(m) \times$ *form factor*(q)

$f_{QF\text{-}\bar{K}}(m,q)$: *phenomenological*

PWIA based interpretation

(plane wave impulse approximation)

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

Differential cross section

PWIA based interpretation

(plane wave impulse approximation)

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Differential cross section

Lorentz invariant phase space (Λpn)

PWIA based interpretation

(plane wave impulse approximation)

— from time integral —

B.W. / Lorentzian

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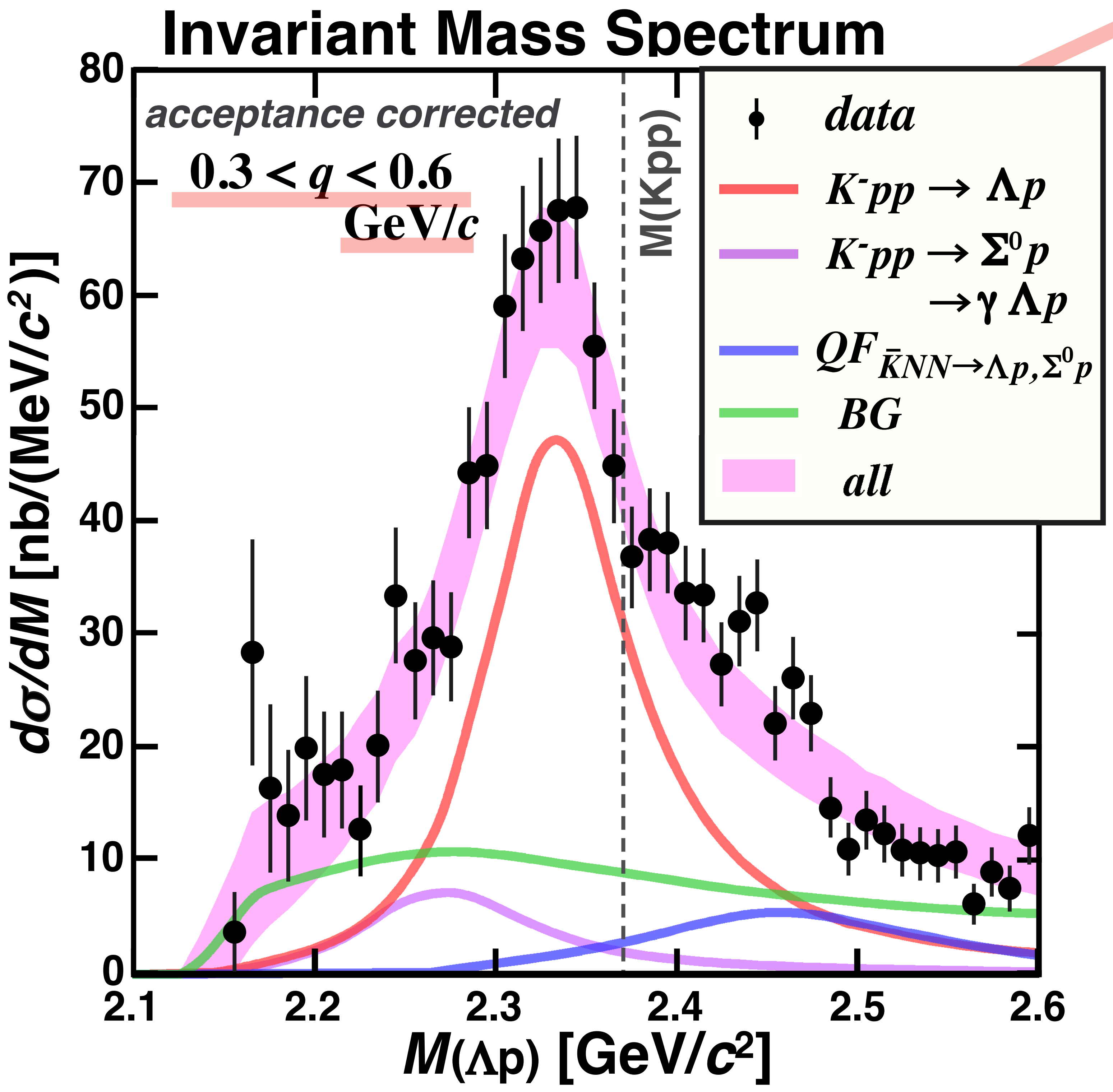
Differential cross section

Lorentz invariant phase space (Λpn)



strong binding ($\bar{K}$N attraction)

$B_{Kpp} \sim 40$ MeV, $\Gamma_{Kpp} \sim 100$ MeV

PWIA based interpretation

(plane wave impulse approximation)

— from time integral — — from space integral —

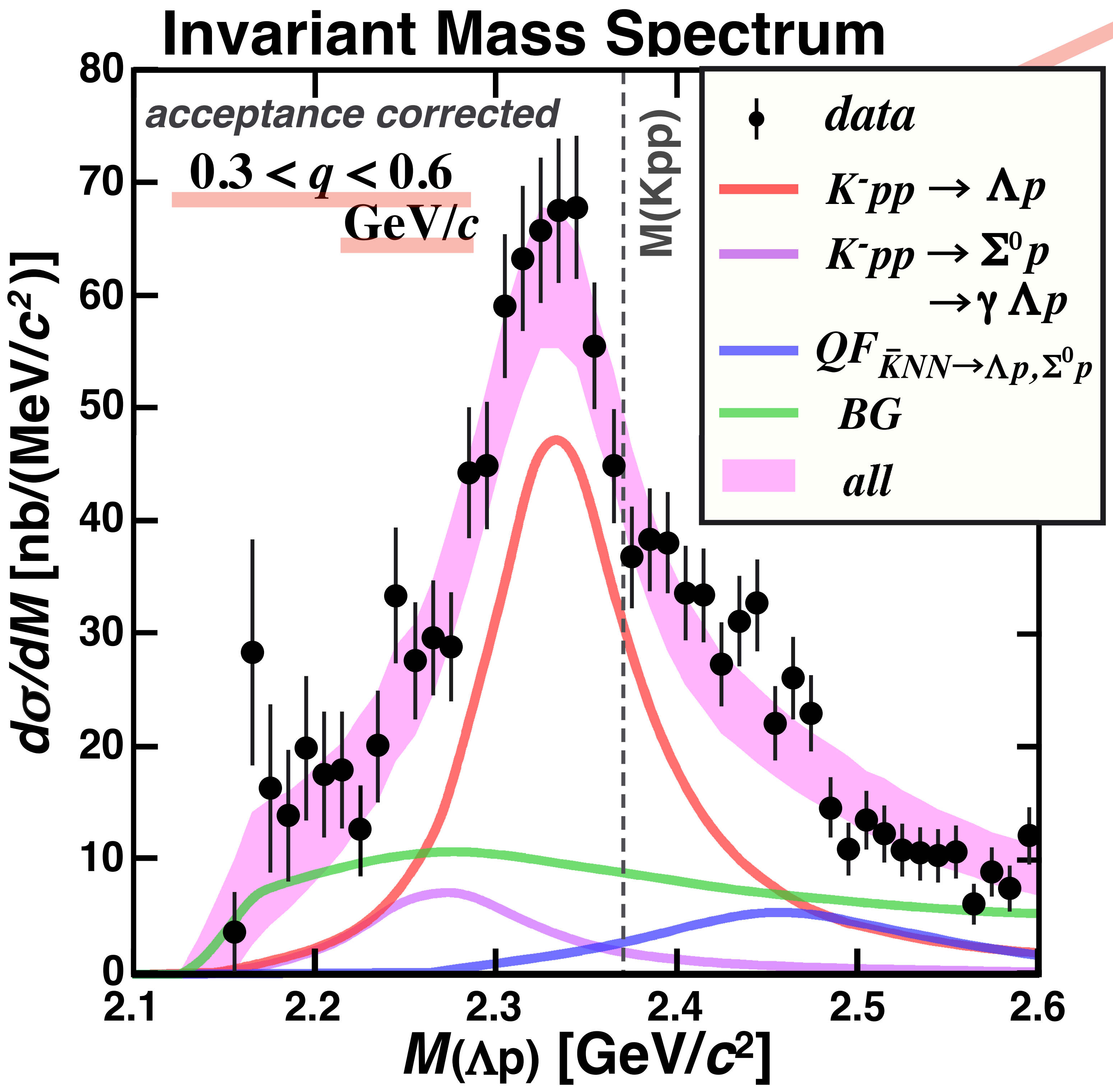
B.W. / Lorentzian — Gaussian form factor / structure factor

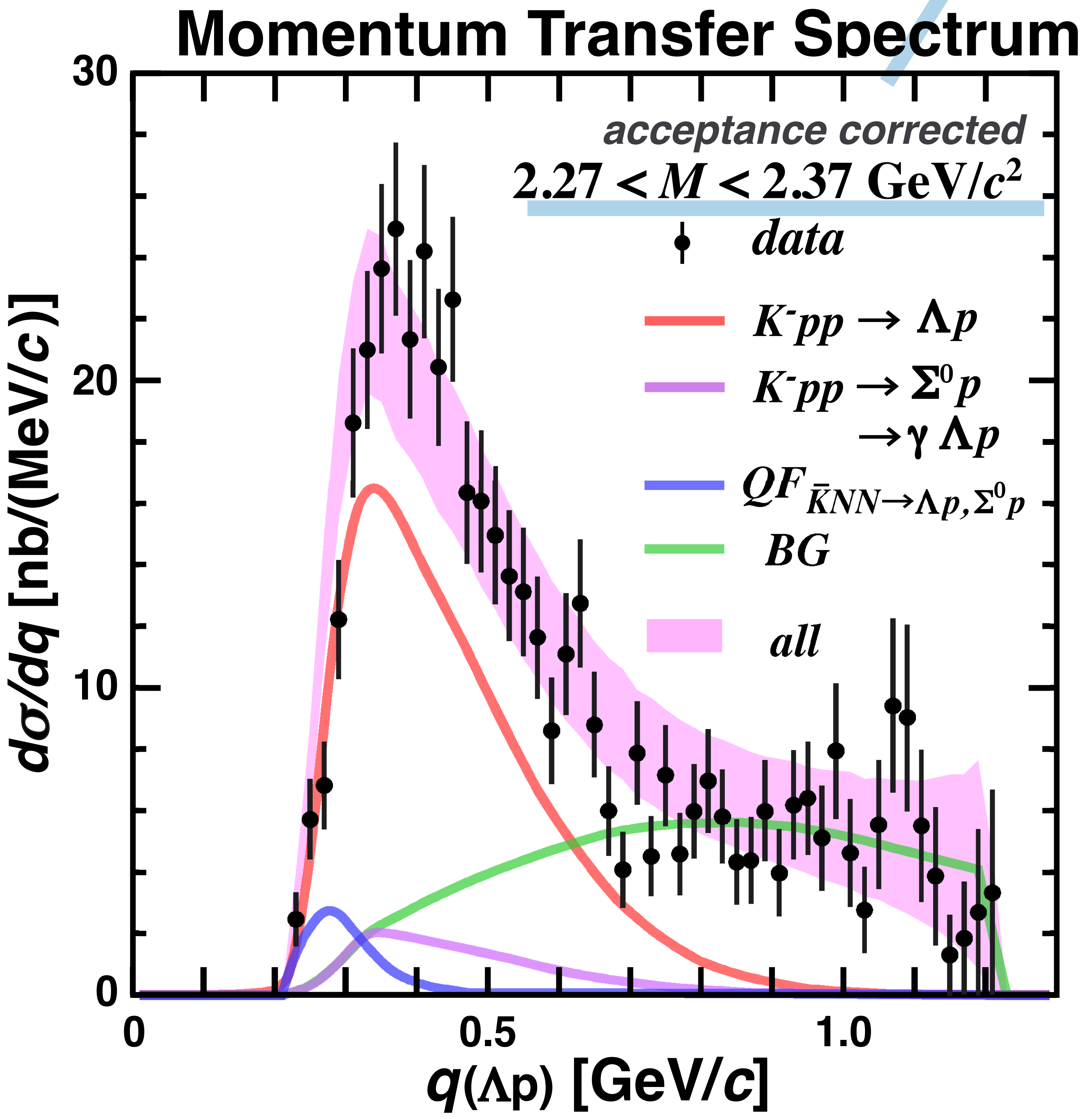
$$\sigma(M, q) \propto \rho_{3B}(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

Differential cross section

Lorentz invariant phase space (Λpn)

Fourier Transformation of S-wave Harmonic Oscillator (HO) — from spatial integral —





strong binding ($\bar{K}N$ attraction)

wide momentum width

$B_{Kpp} \sim 40$ MeV, $\Gamma_{Kpp} \sim 100$ MeV

$Q_{Kpp} \sim 400$ MeV/c

PWIA based interpretation

(plane wave impulse approximation)

— from time integral — — from space integral —

B.W. / Lorentzian

Gaussian form factor / structure factor

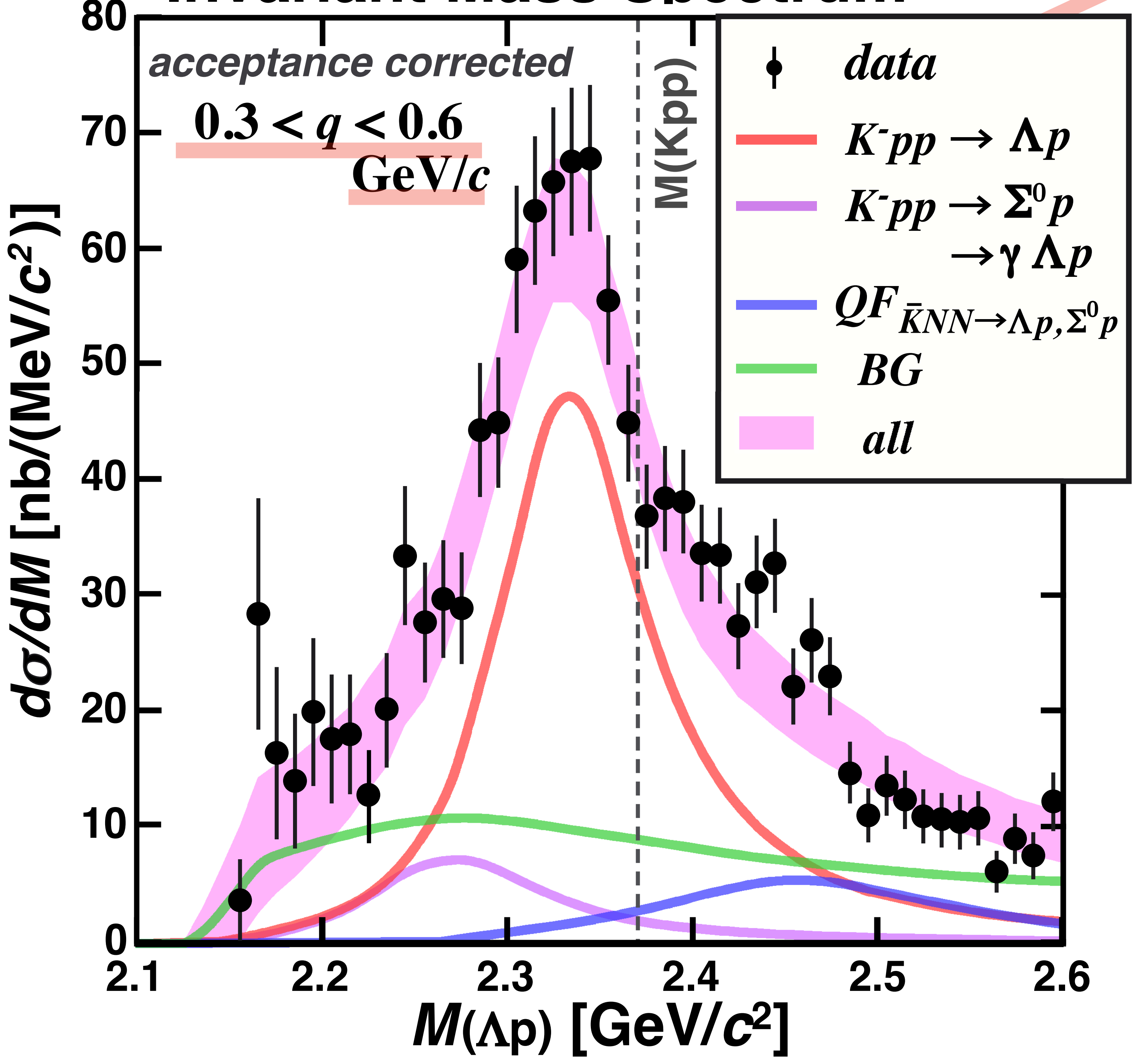
$$\sigma(M, q) \propto \rho_{3B}(M, q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

Differential cross section

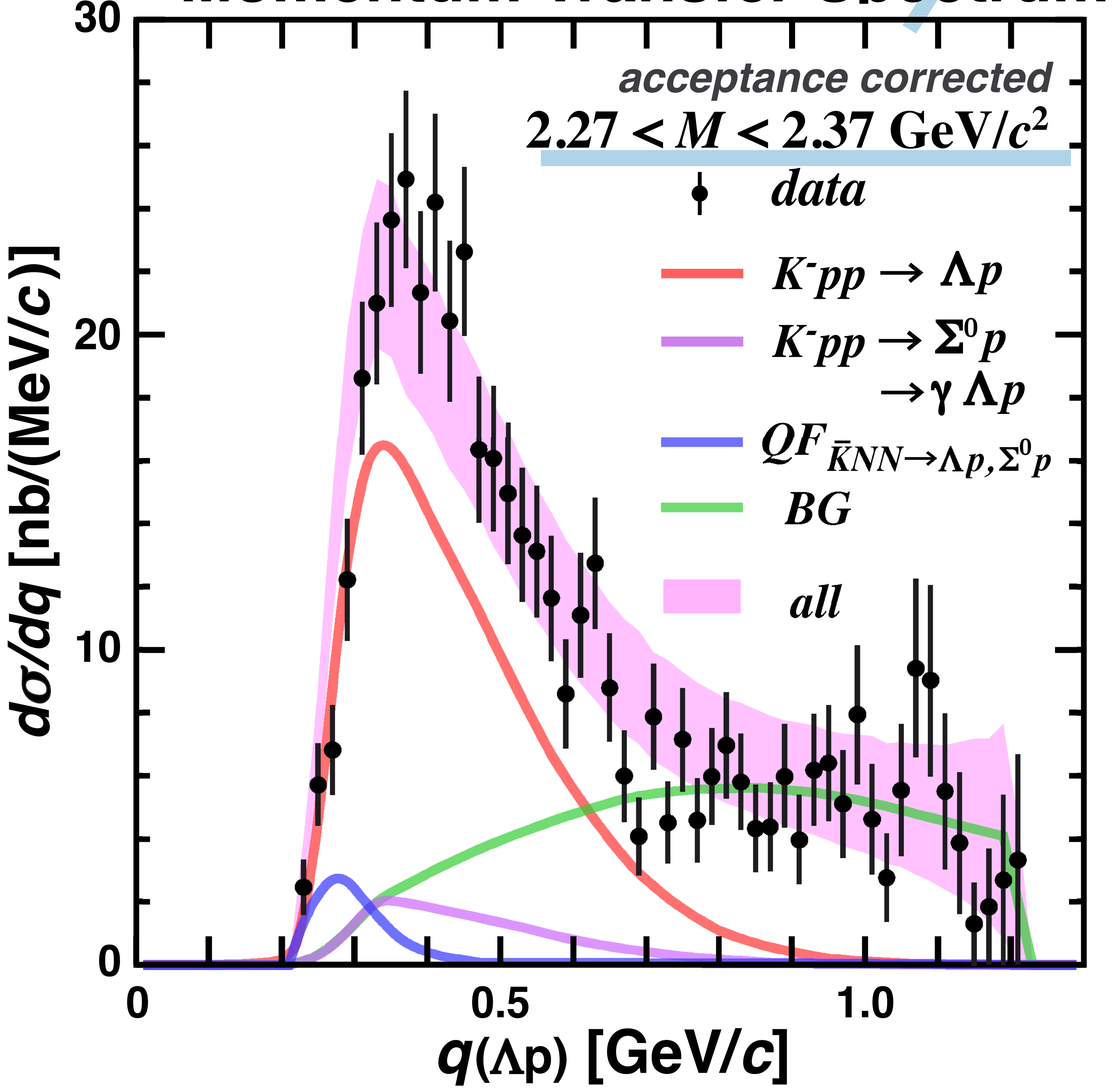
Lorentz invariant phase space (Λpn)

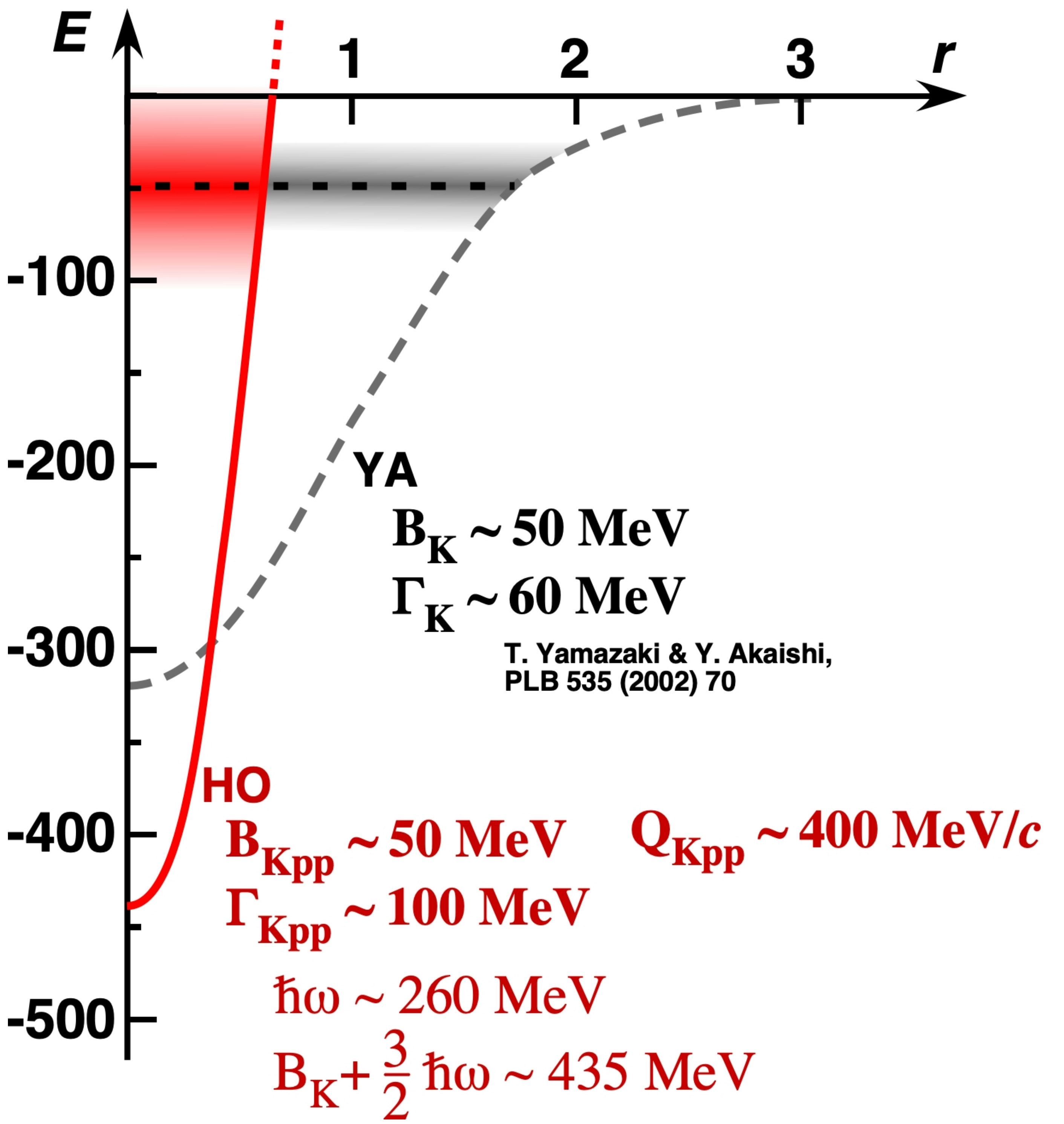
Fourier Transformation of S-wave Harmonic Oscillator (HO) — from spatial integral —

Invariant Mass Spectrum



Momentum Transfer Spectrum





strong binding (K̄N attraction)

$B_{Kpp} \sim 40$ MeV, $\Gamma_{Kpp} \sim 100$ MeV

wide momentum width

$Q_{Kpp} \sim 400$ MeV/c

… could be quite compact …

($R_{Kpp} \sim 0.6$ fm (H.O.))

Mesonic Decay Modes of $\bar{K}NN$

T. Yamaga et.al., Phys. Rev. C 110, 014002 (2024)

- Mesonic decays will give us further information on $\bar{K}NN$
  - ✓ internal structure
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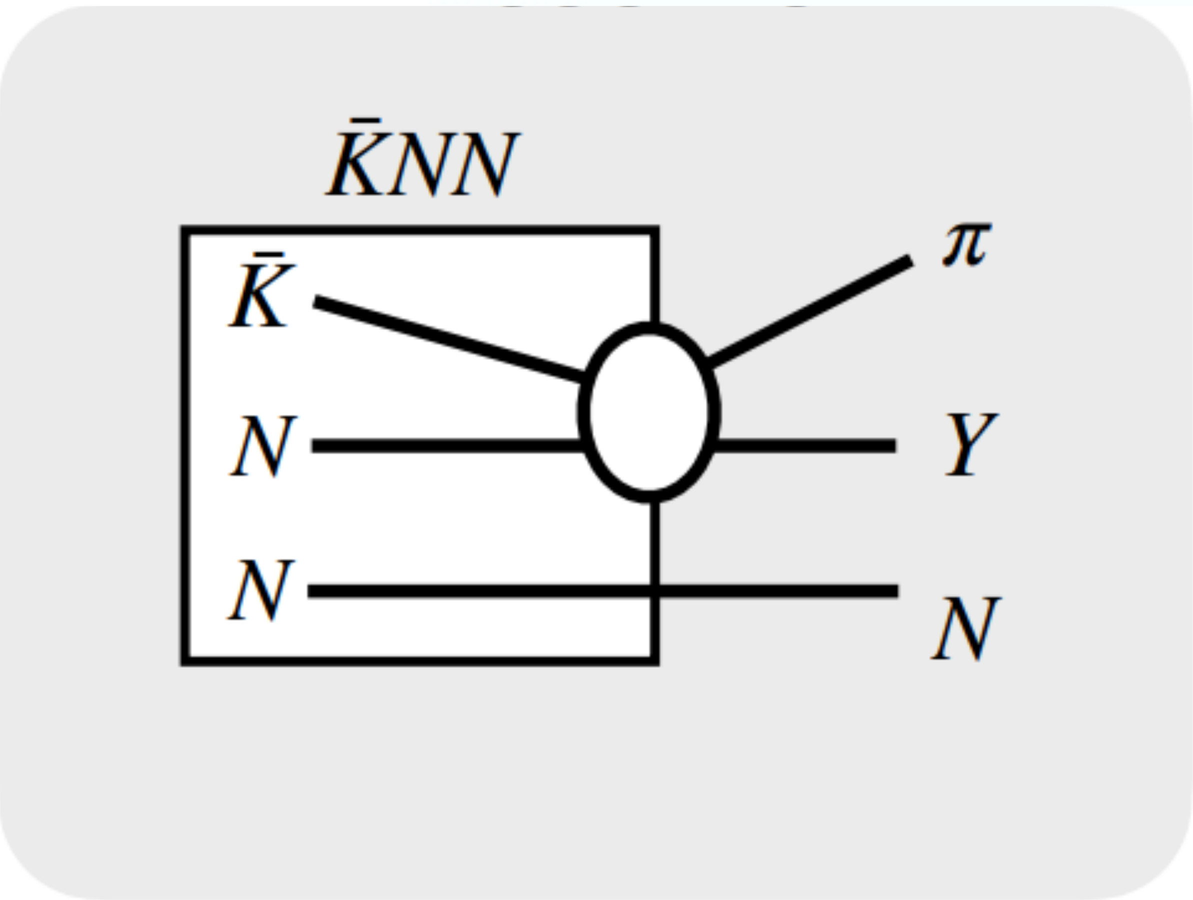
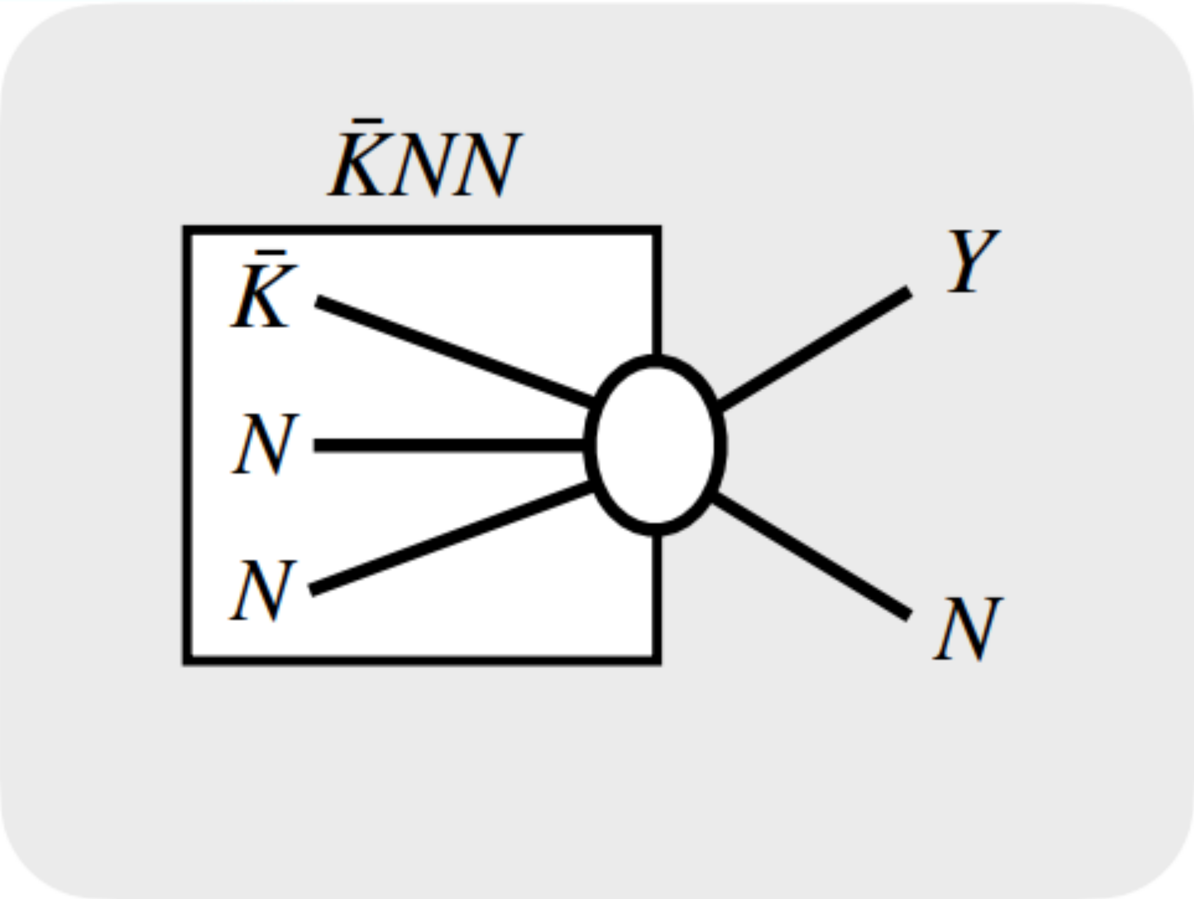
Mesonic



1N absorption

Non-mesonic



2N absorption

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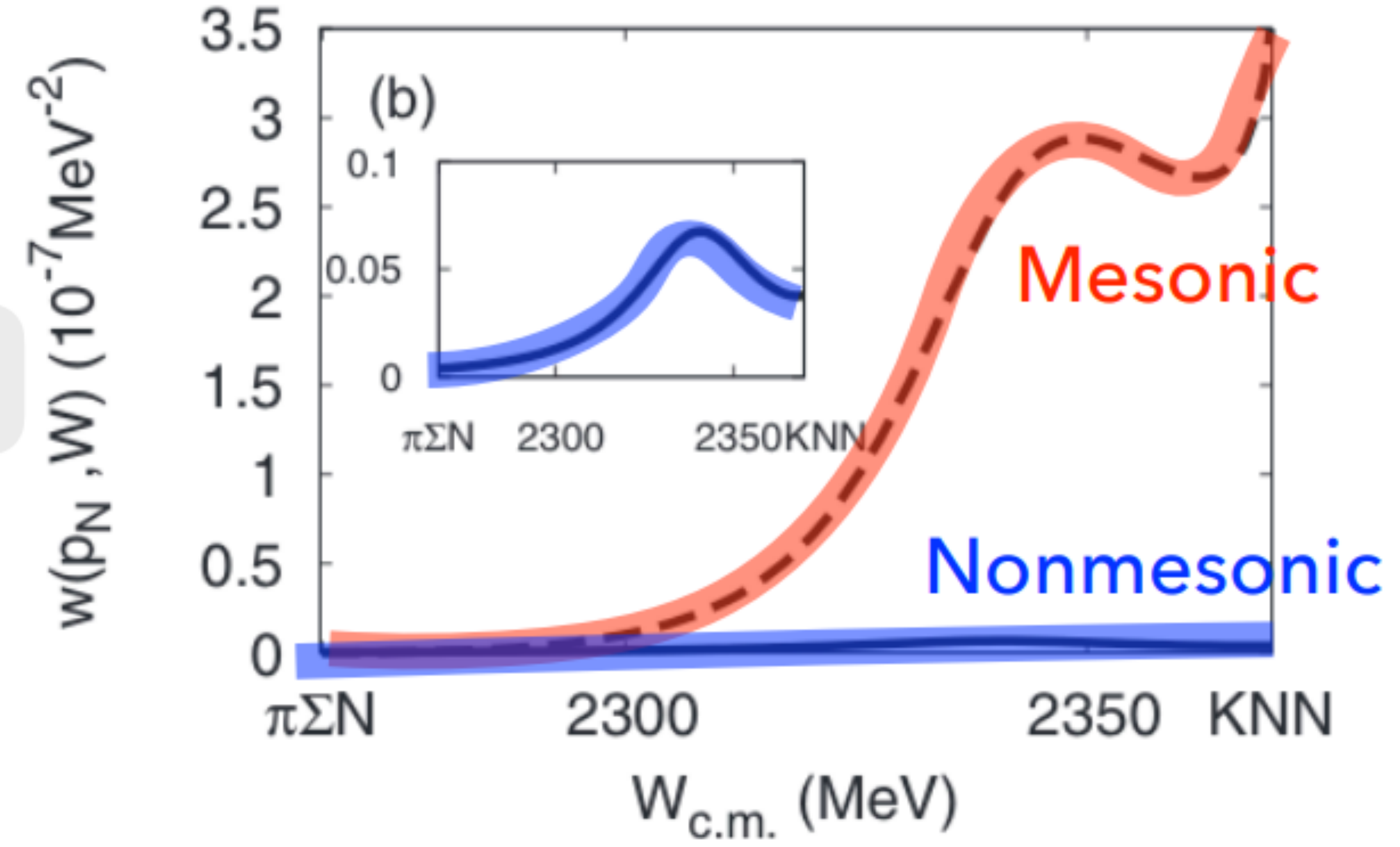
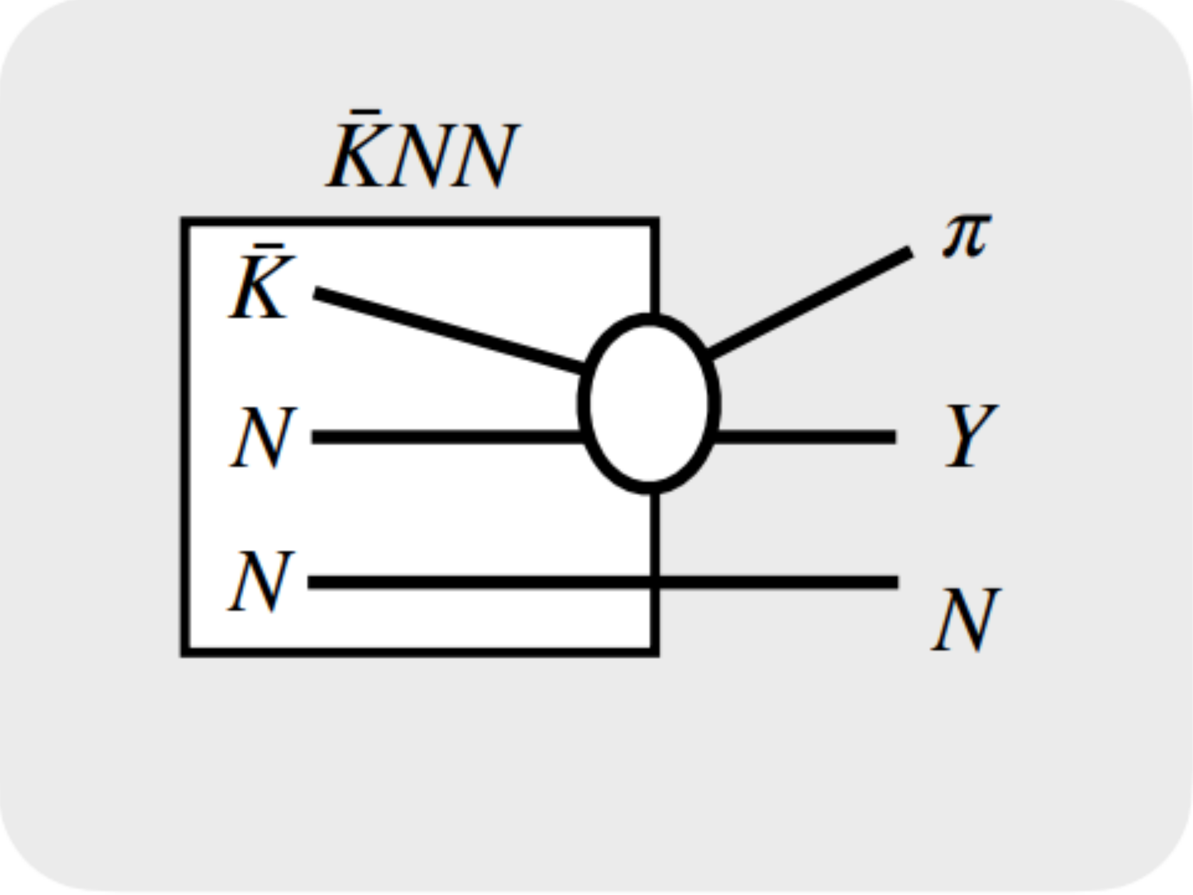
S. Ohnishi, et al., Phys. Rev. C 88 (2013) 025204.

$$\Gamma_{YN} \ll \Gamma_{\pi YN}$$



Mesonic



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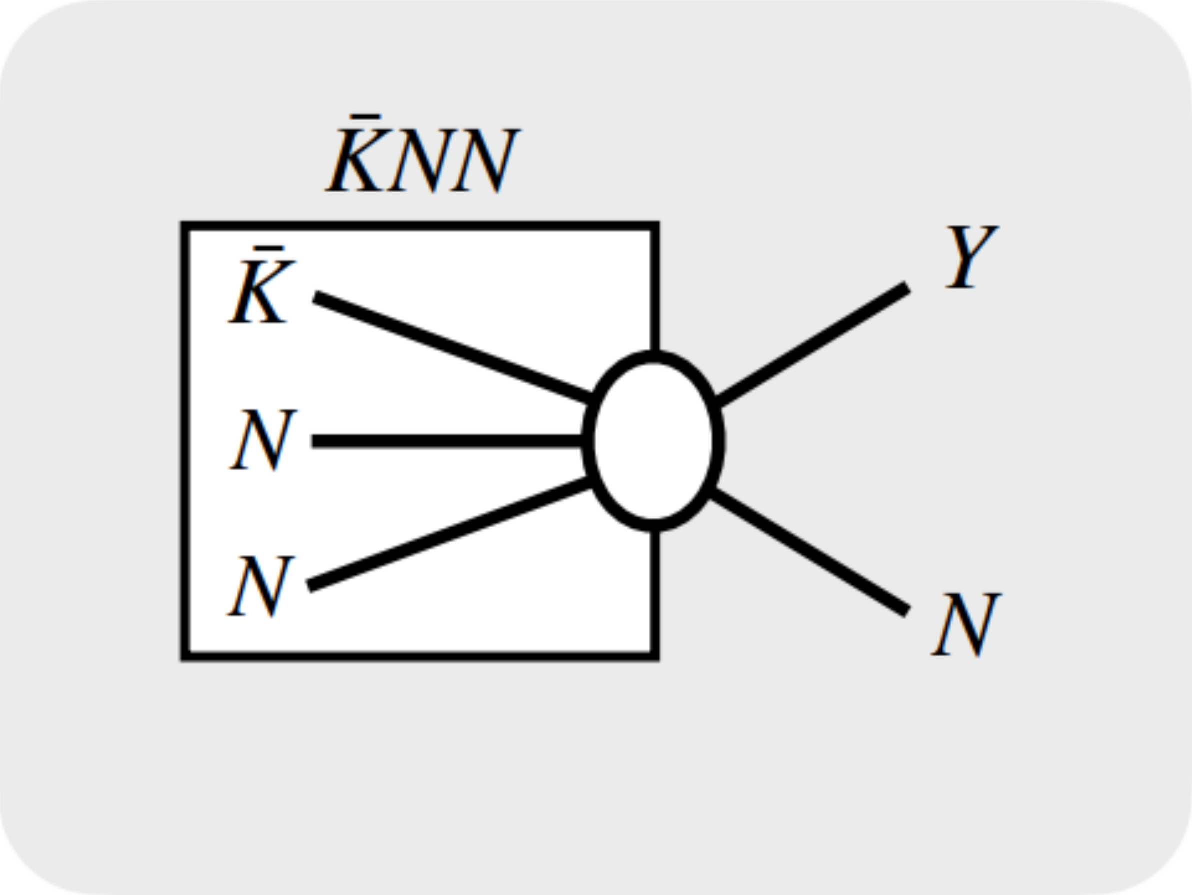

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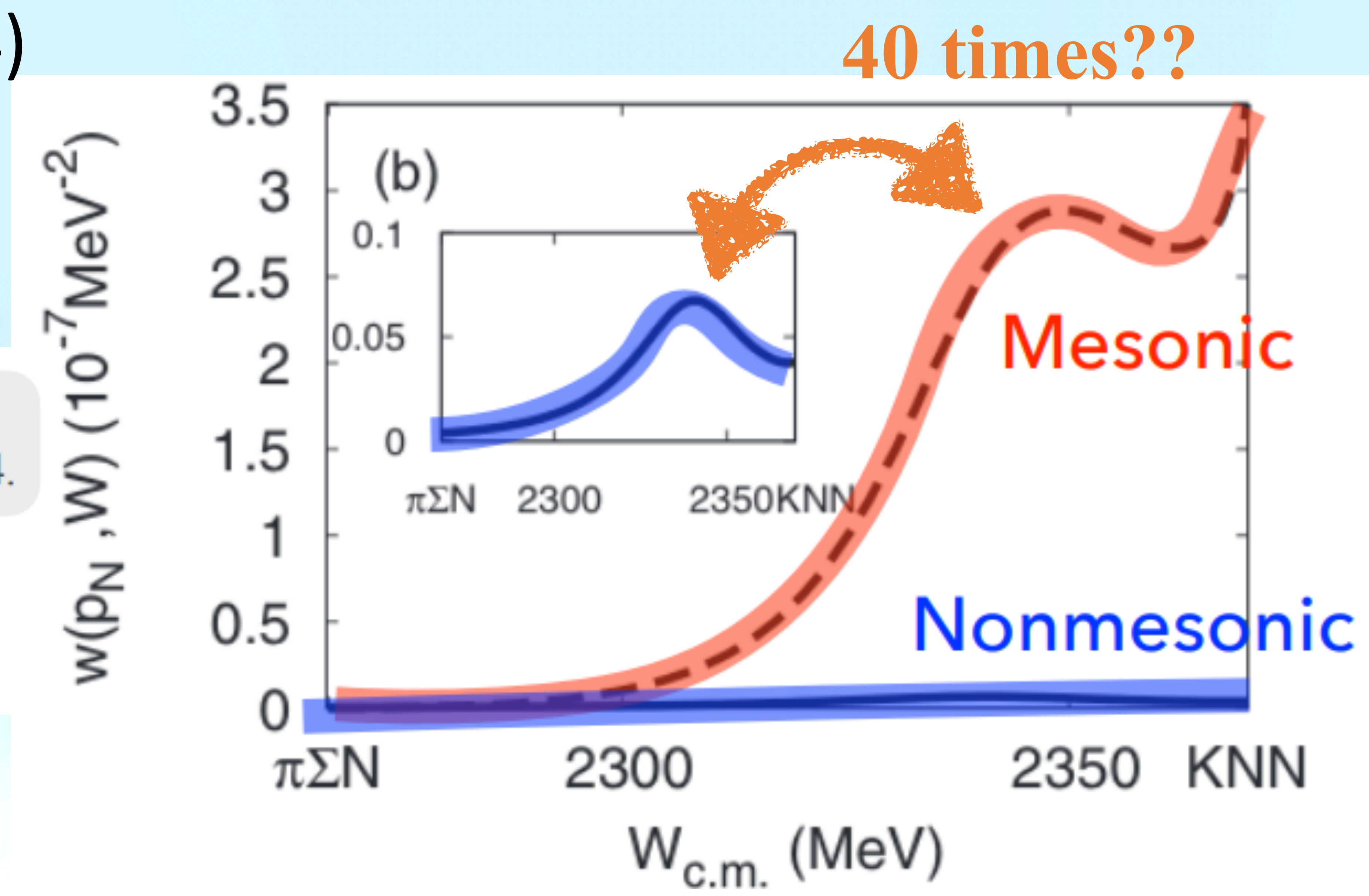
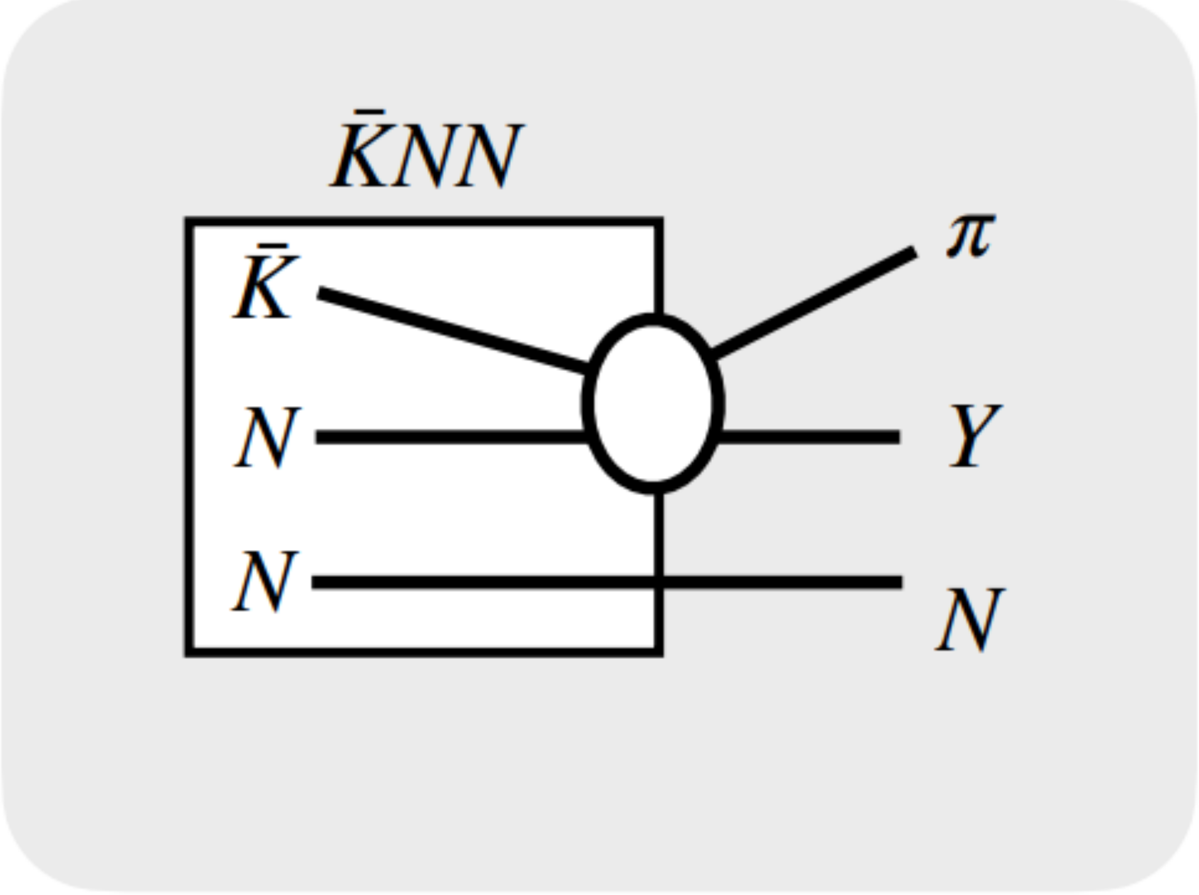


Mesonic



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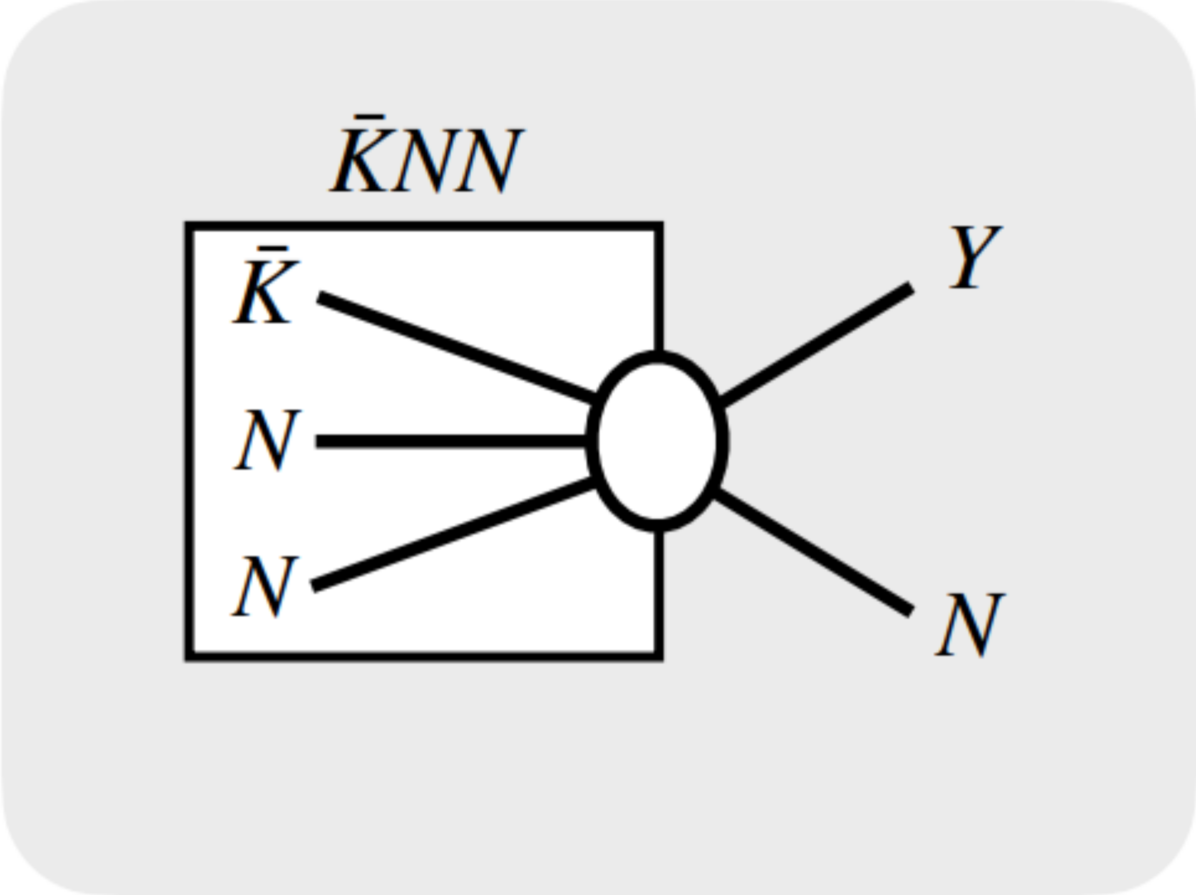

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  - ✓ density of the state

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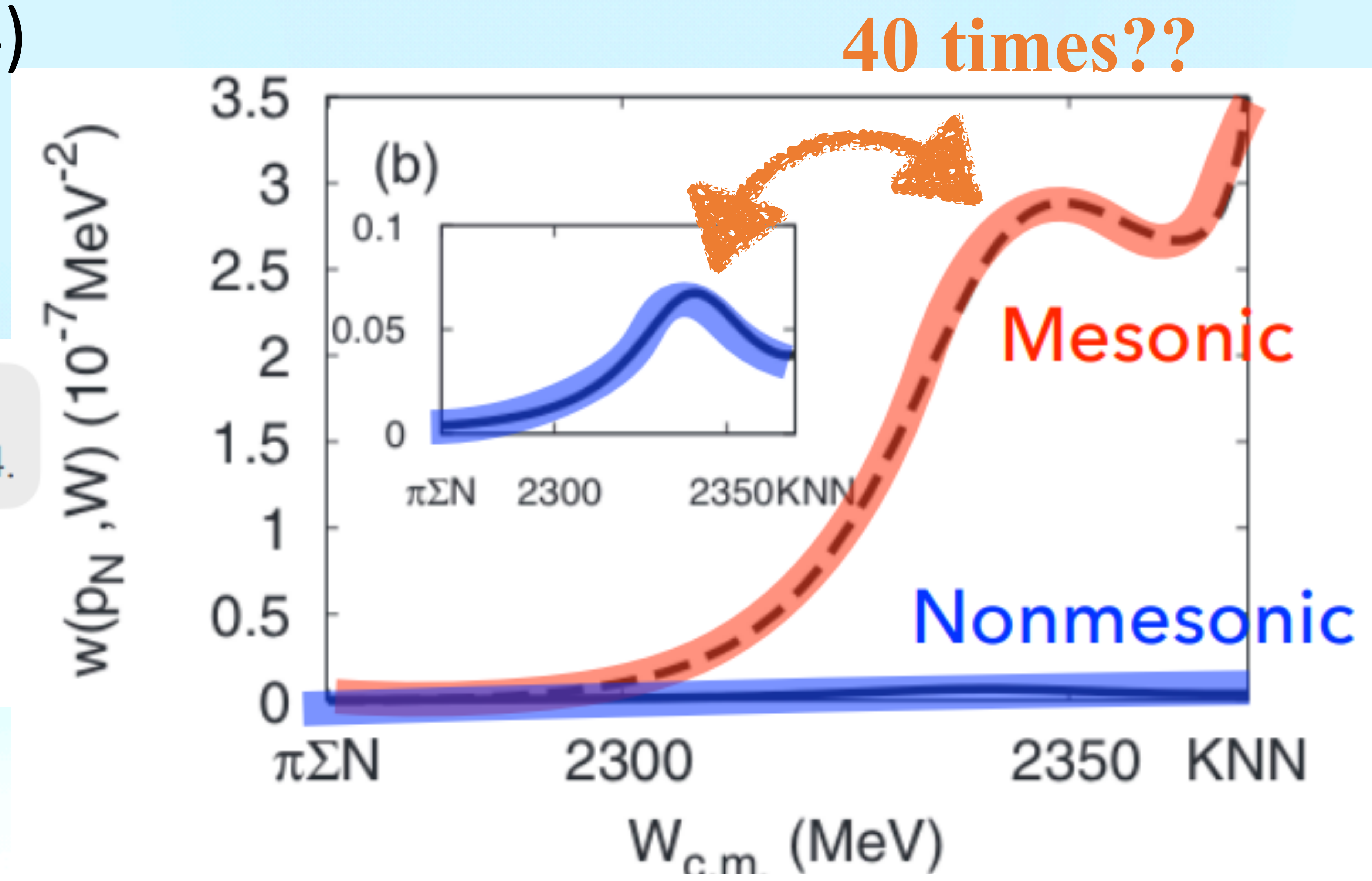

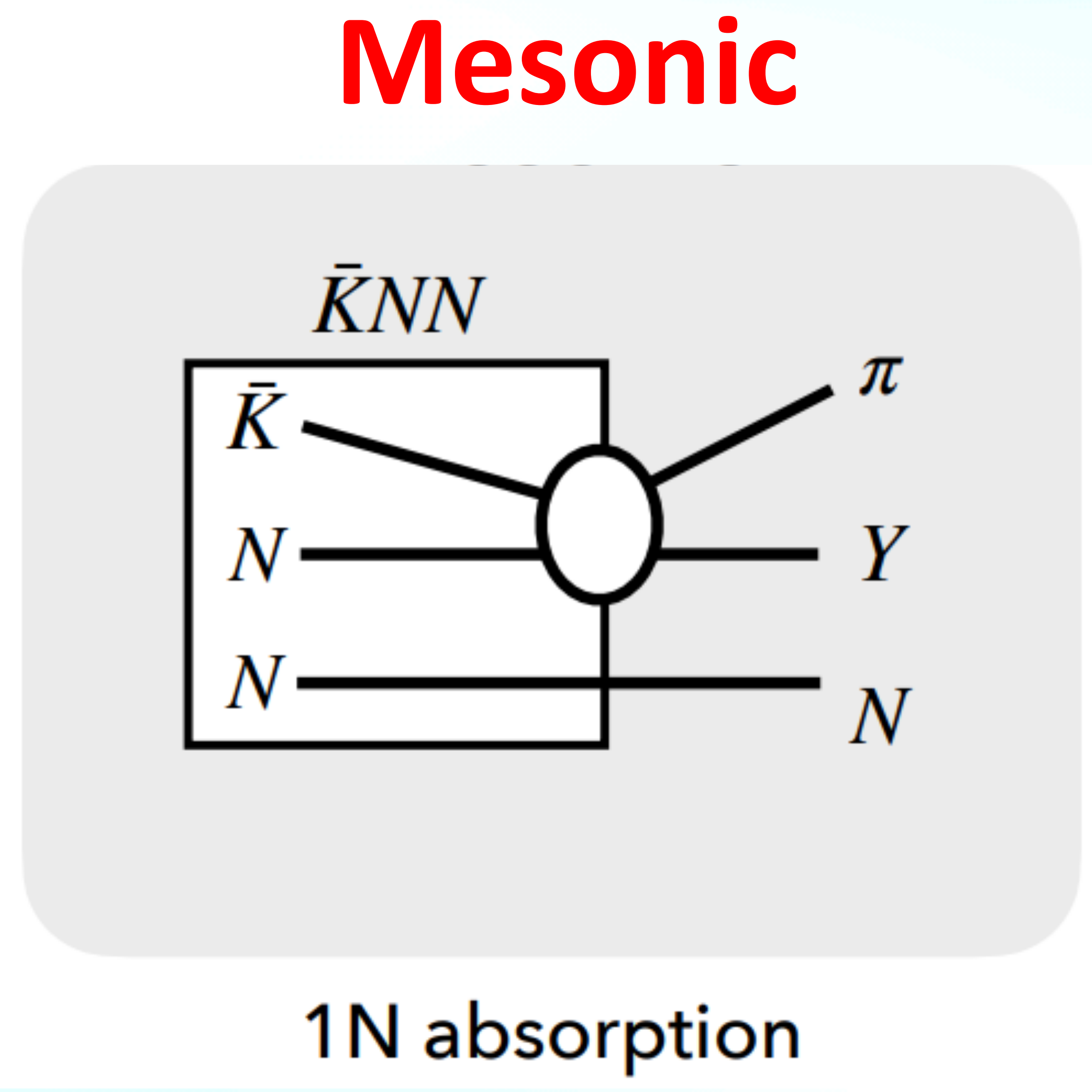

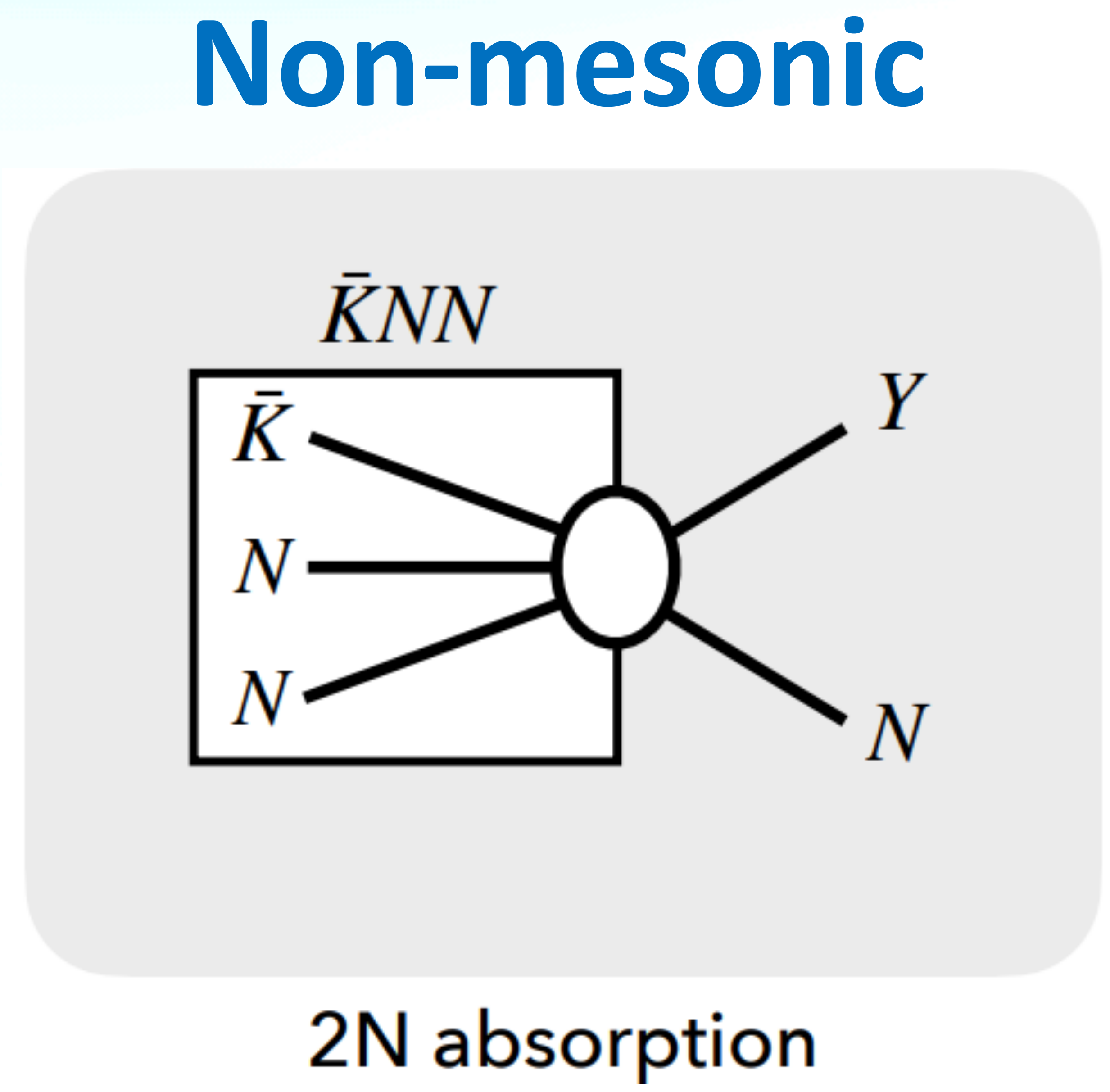

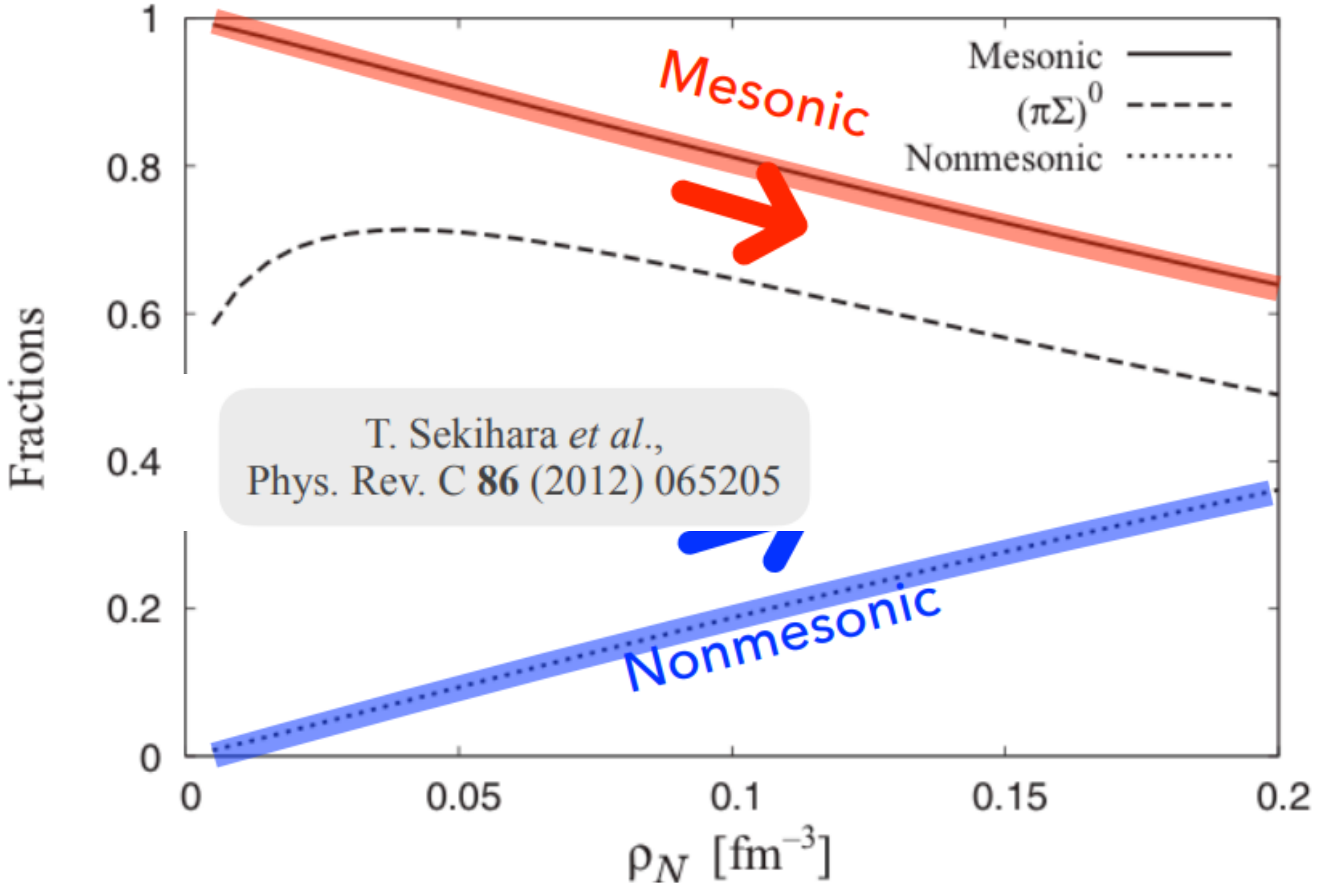

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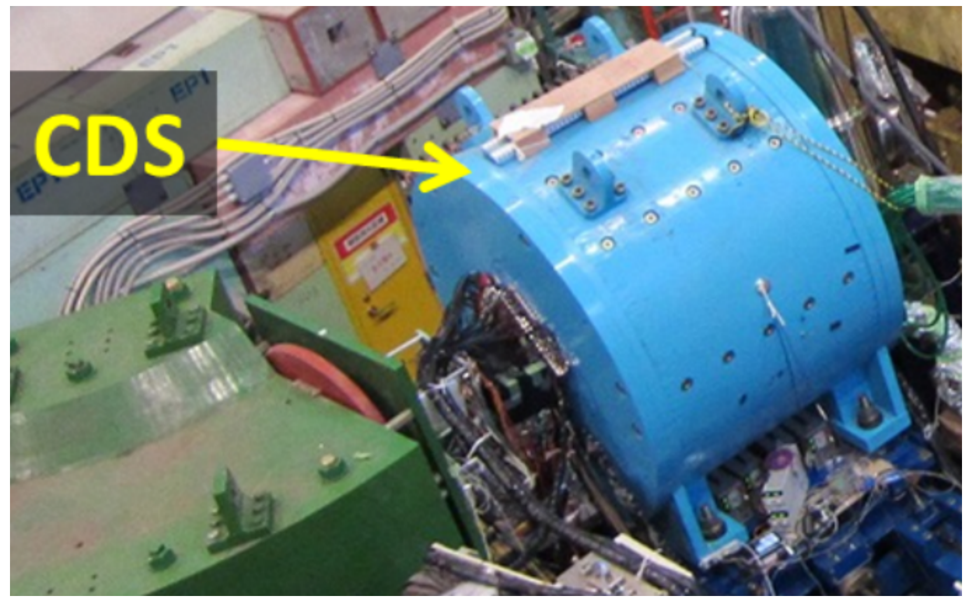
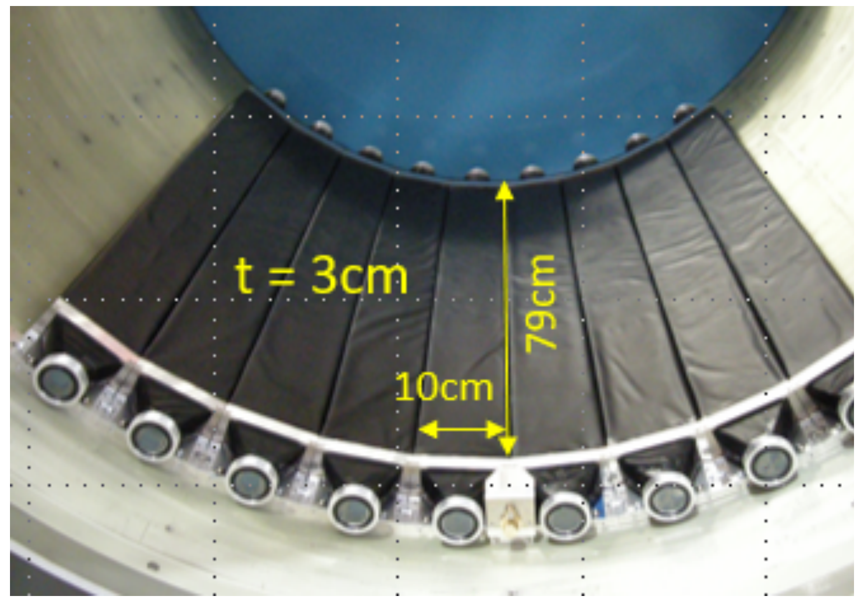
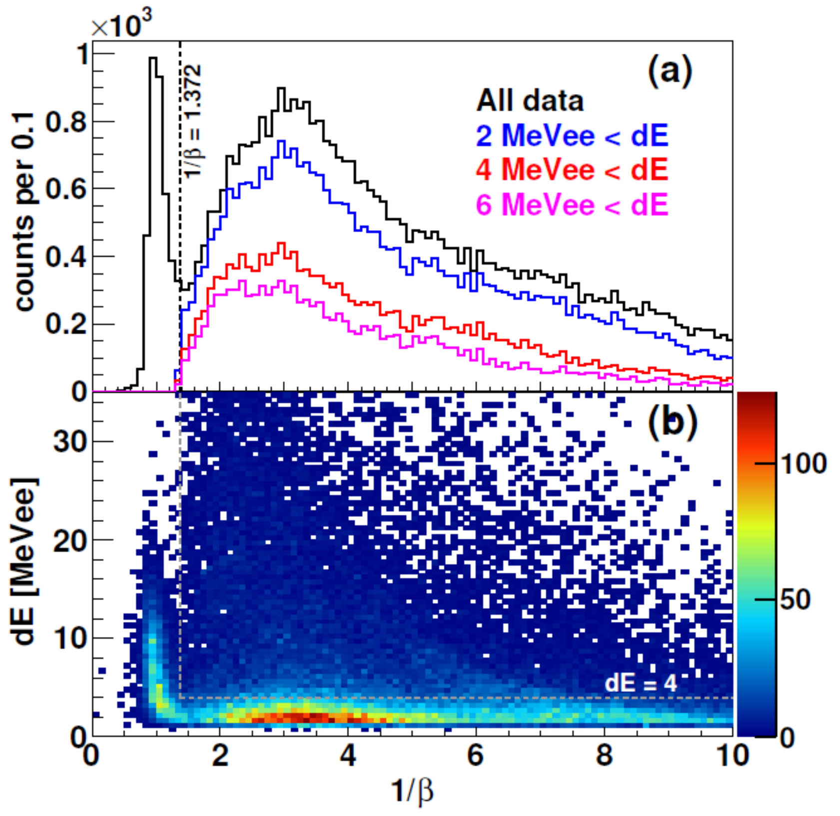
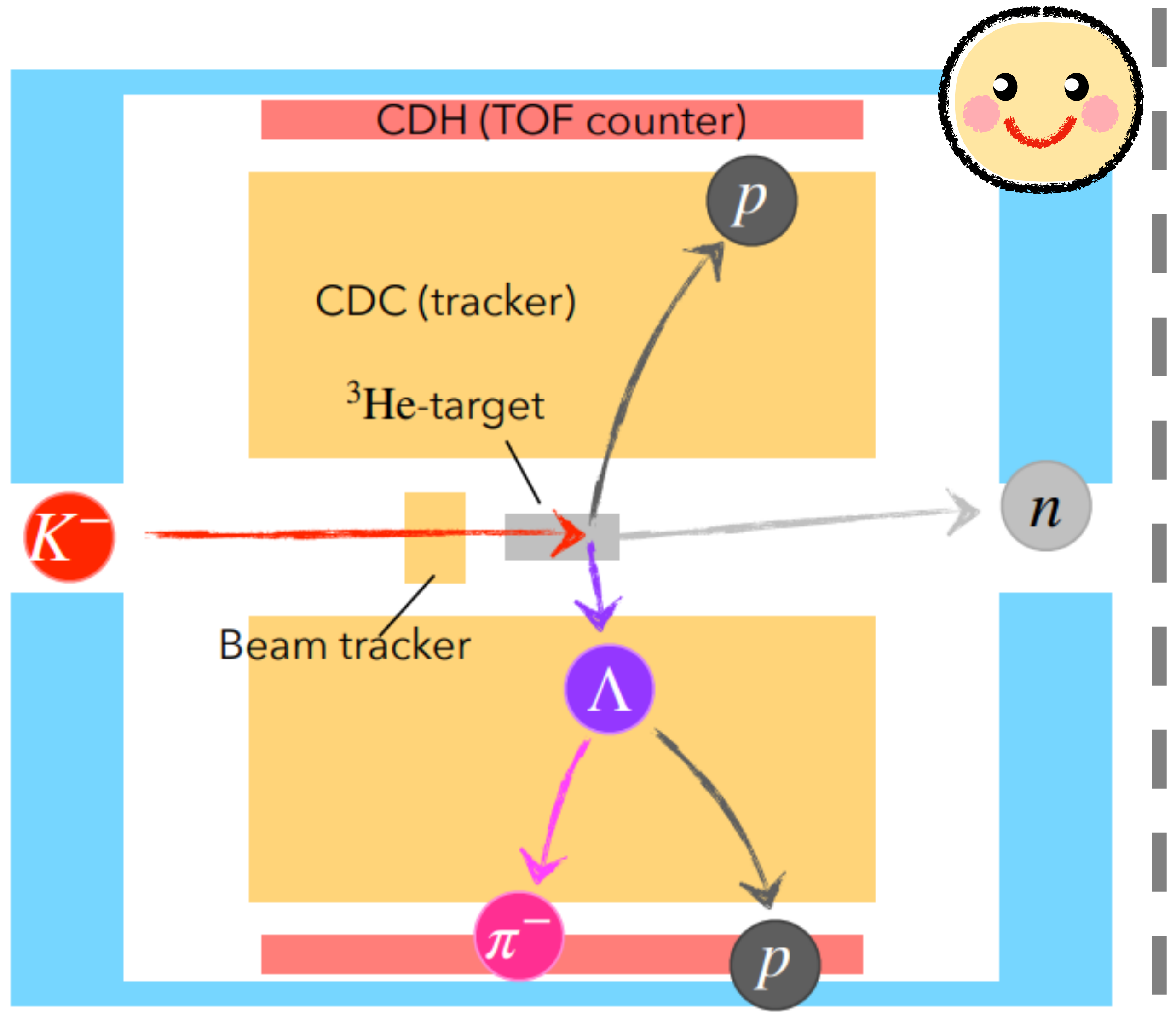
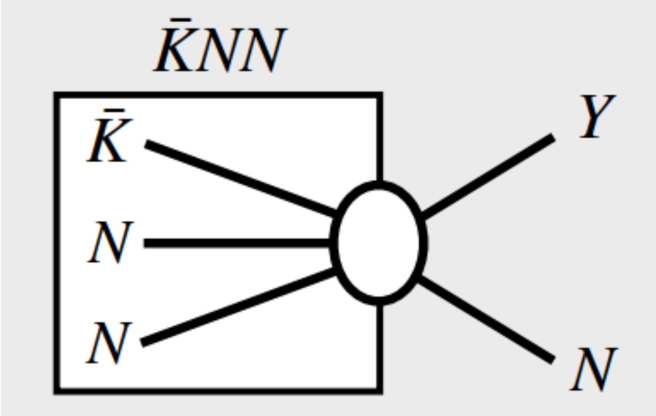




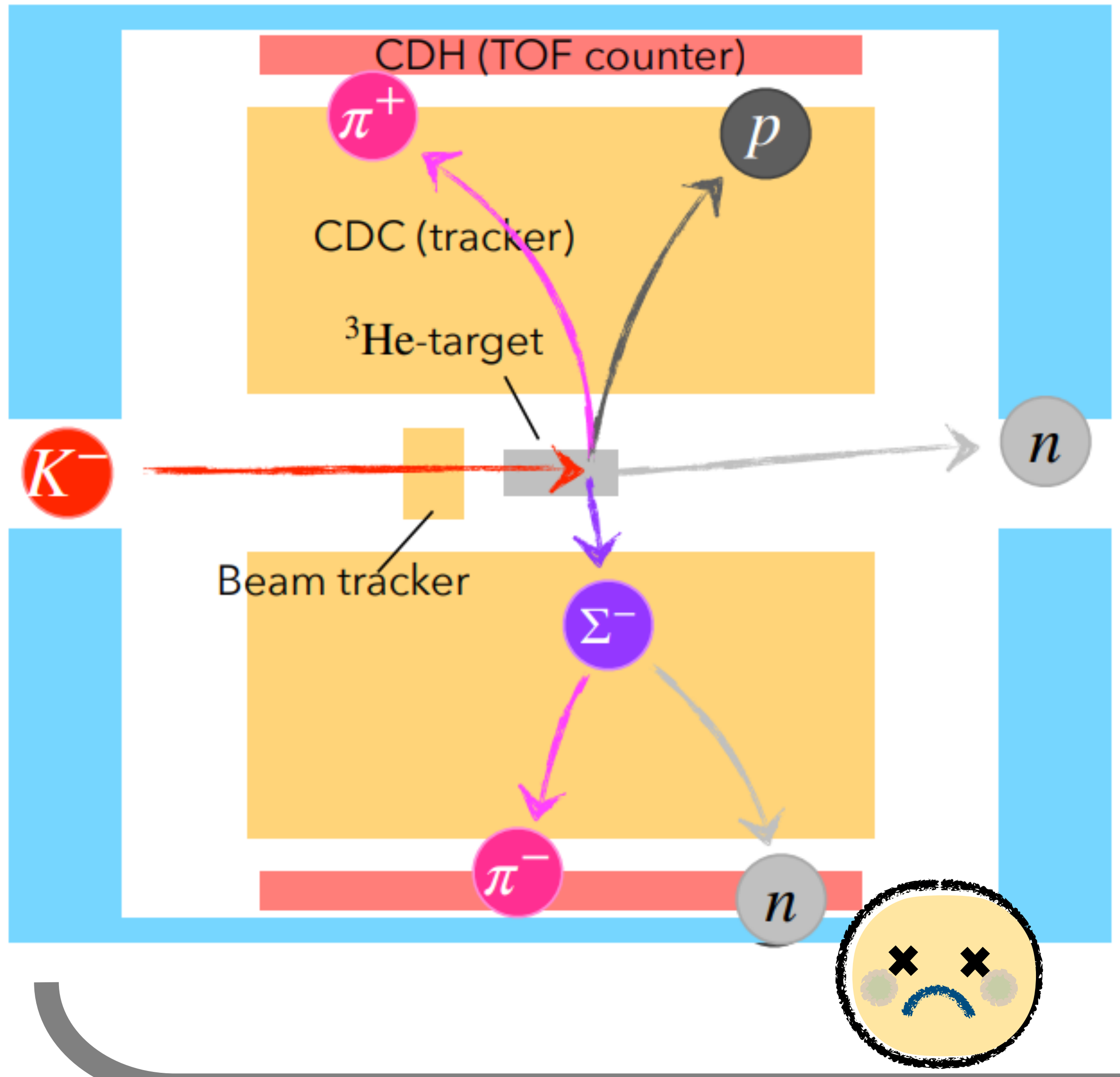


$$"K^-pp" \to \Lambda p$$





$$"K^-pp" \to \pi^\pm\Sigma^\mp p$$



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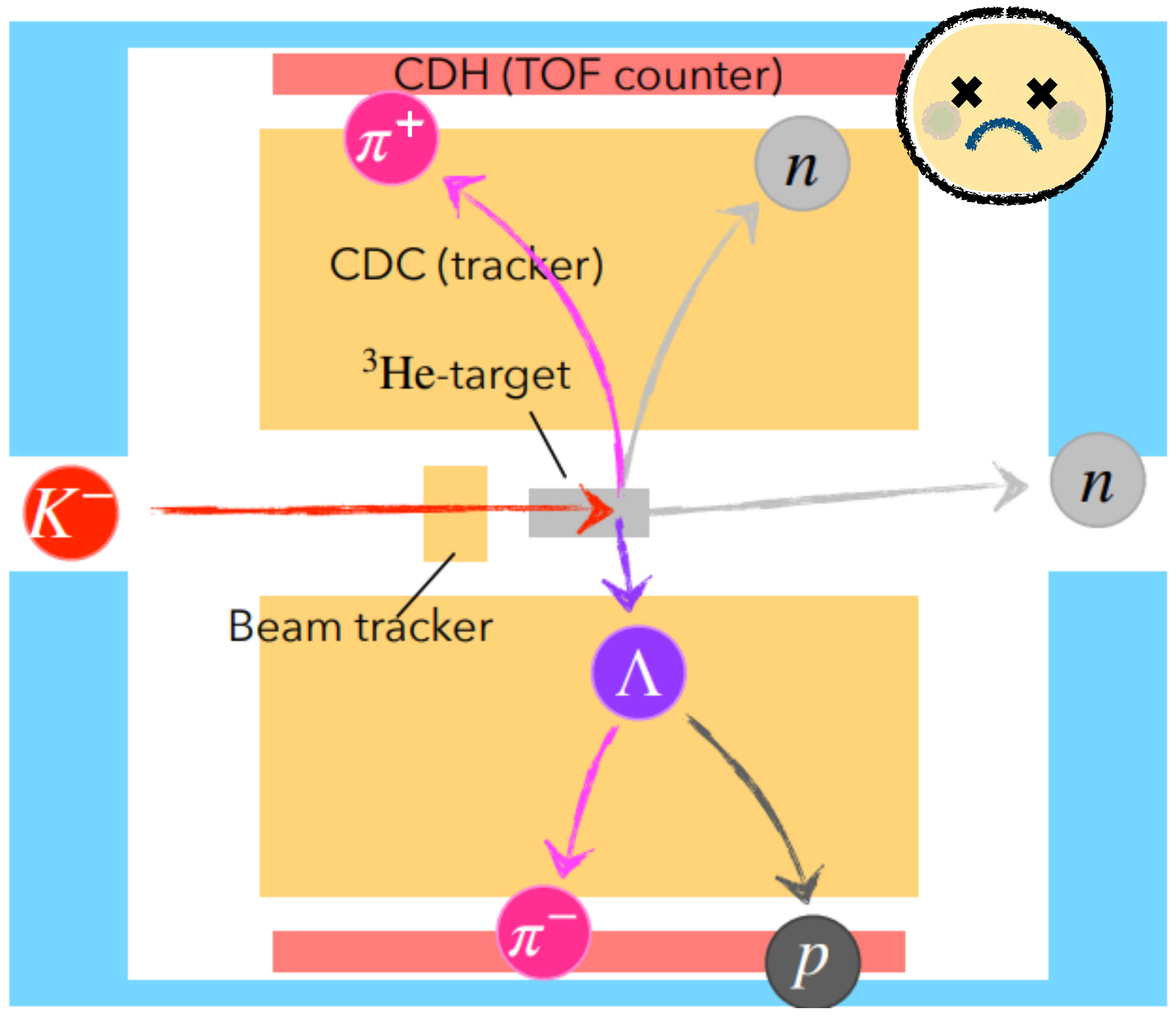

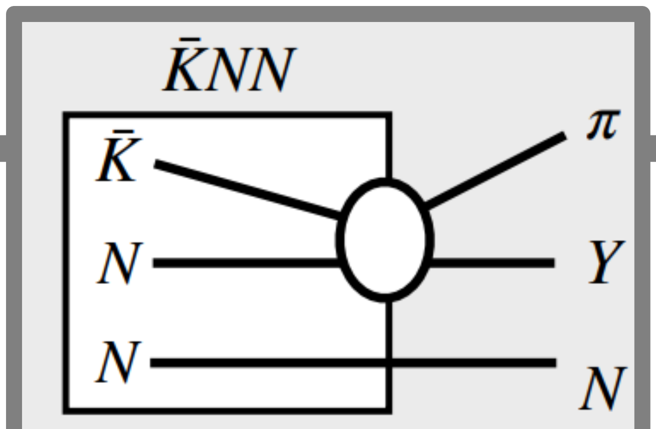

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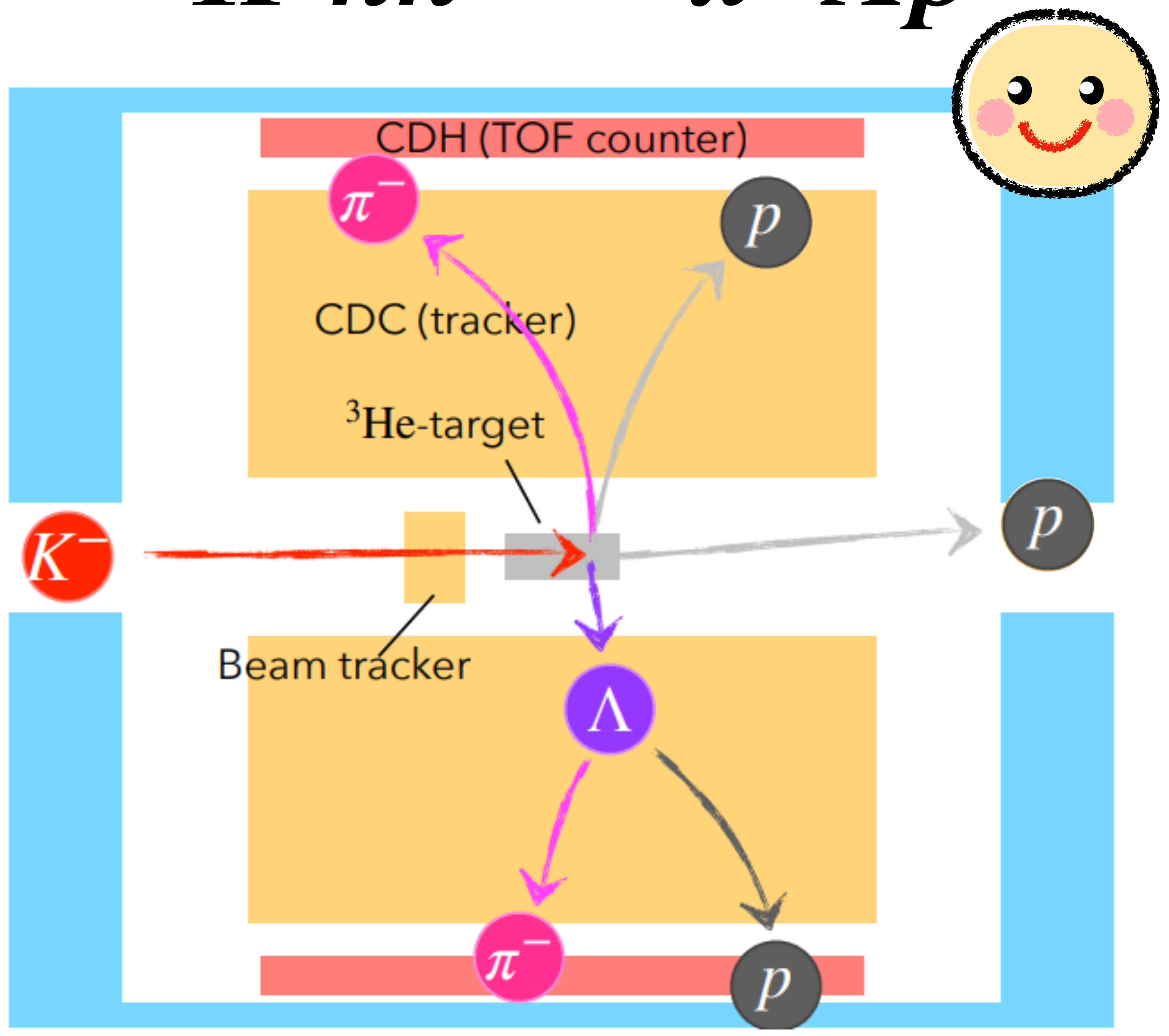

Plane Wave Impulse Approximation

Fit with PWIA

Phase space

Momentum term from spatial integral

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

Energy term (BW type) from time integral

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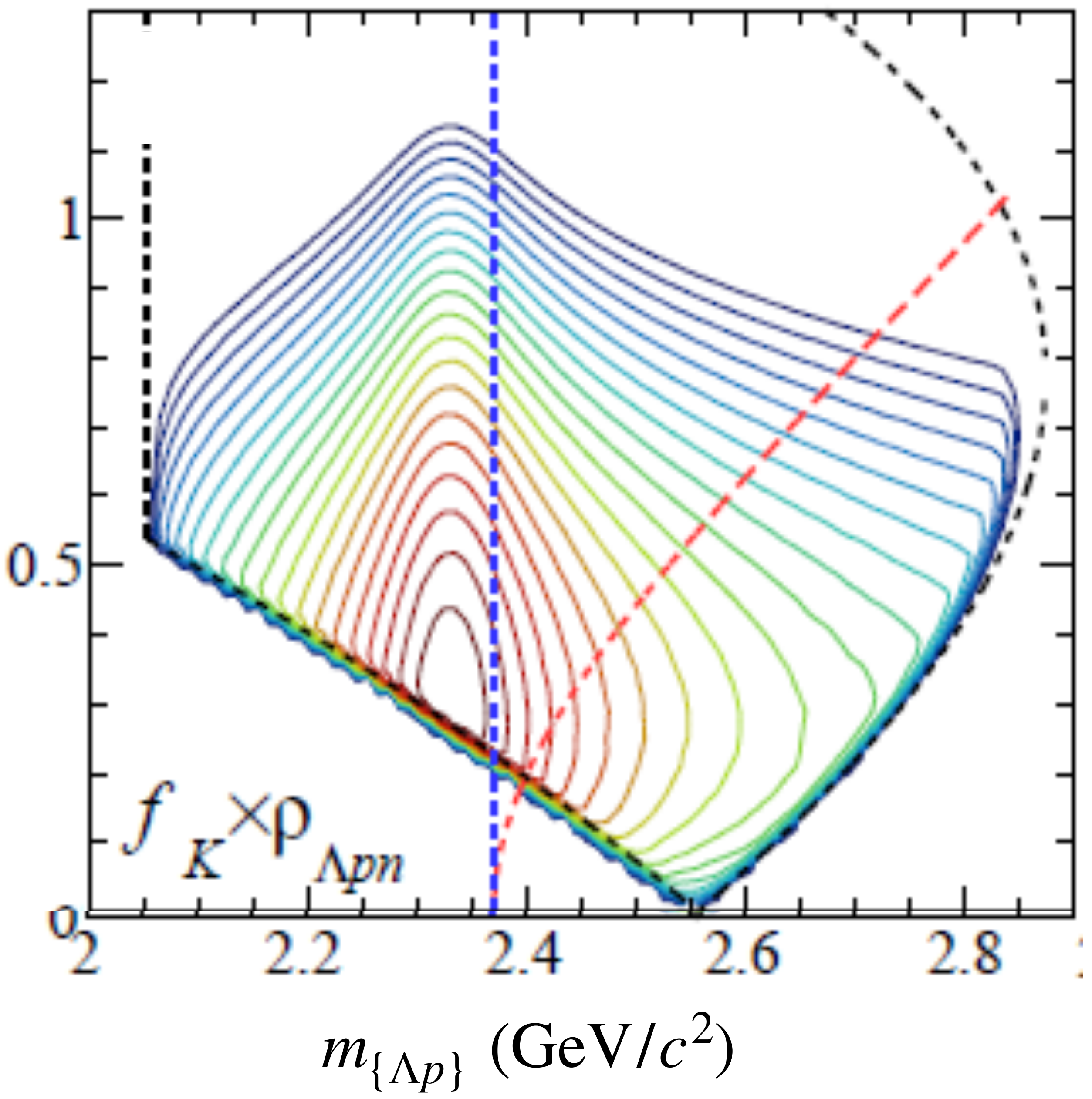

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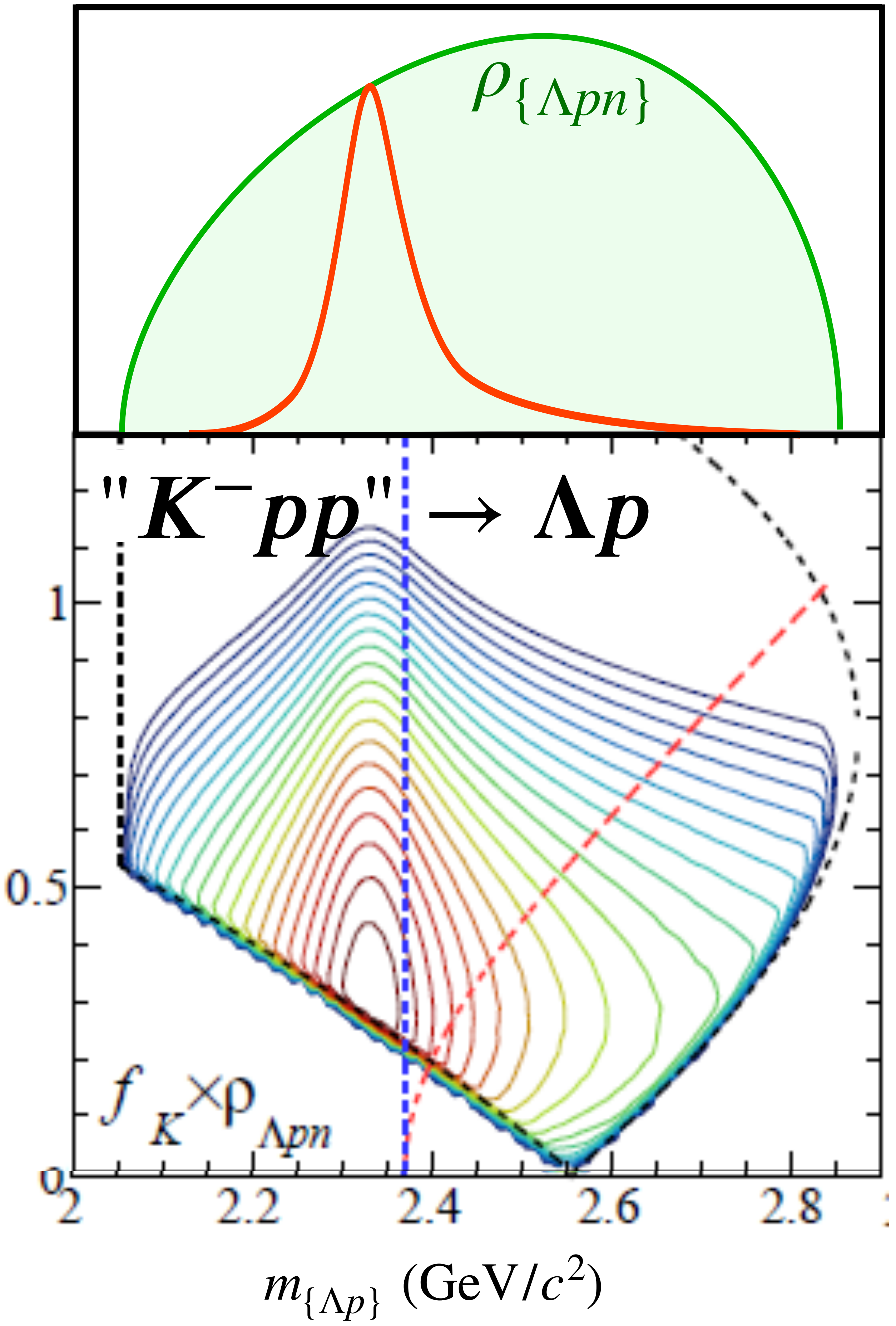

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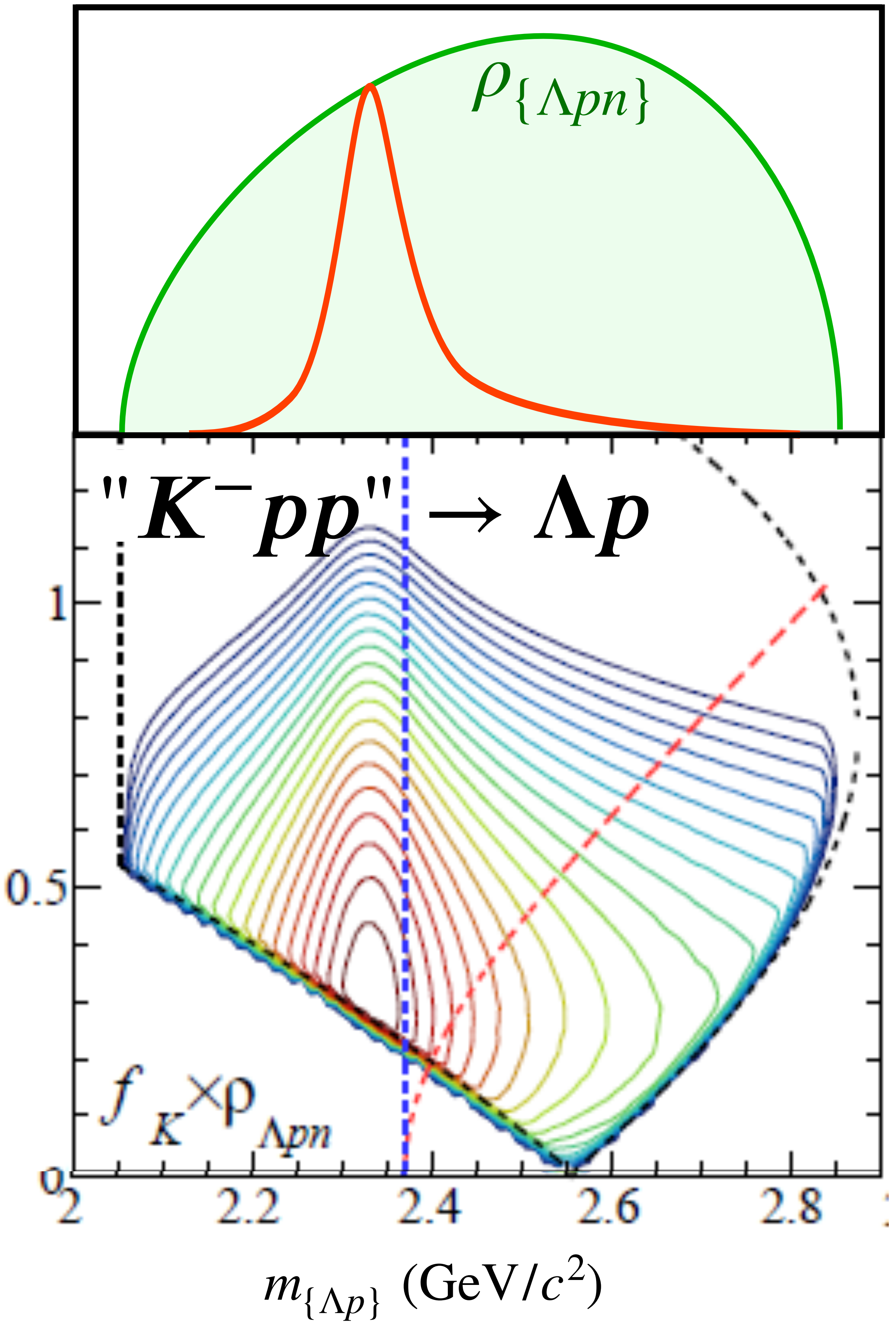
Energy term (BW type) from time integral

Mesonic decay suppression / spectral modification happens, due to the Phase Space Difference!



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1) *mass threshold* $m_{\{\pi\Lambda p\}} \in [m_\Lambda + m_p,\ E^*_{\{K\,^3\mathrm{He}\}} - m_n] \rightarrow [m_\pi + m_Y + m_N,\ E^*_{\{K\,^3\mathrm{He}\}} - m_N]$

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Thus, the peak structure is difficult to be detected in the $K^- + {}^3\mathrm{He} \rightarrow \{\pi YN\} + N'$ ***reaction dynamics.***

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Thus, the peak structure is difficult to be detected in the $K^- + {}^3\mathrm{He} \rightarrow \{\pi YN\} + N'$ ***reaction dynamics.***

Therefore, we focus on the test whether the mass spectra are consistent with the $K^- + {}^3\mathrm{He} \rightarrow \{\Lambda p\} + n'$ ***reaction dynamics.***

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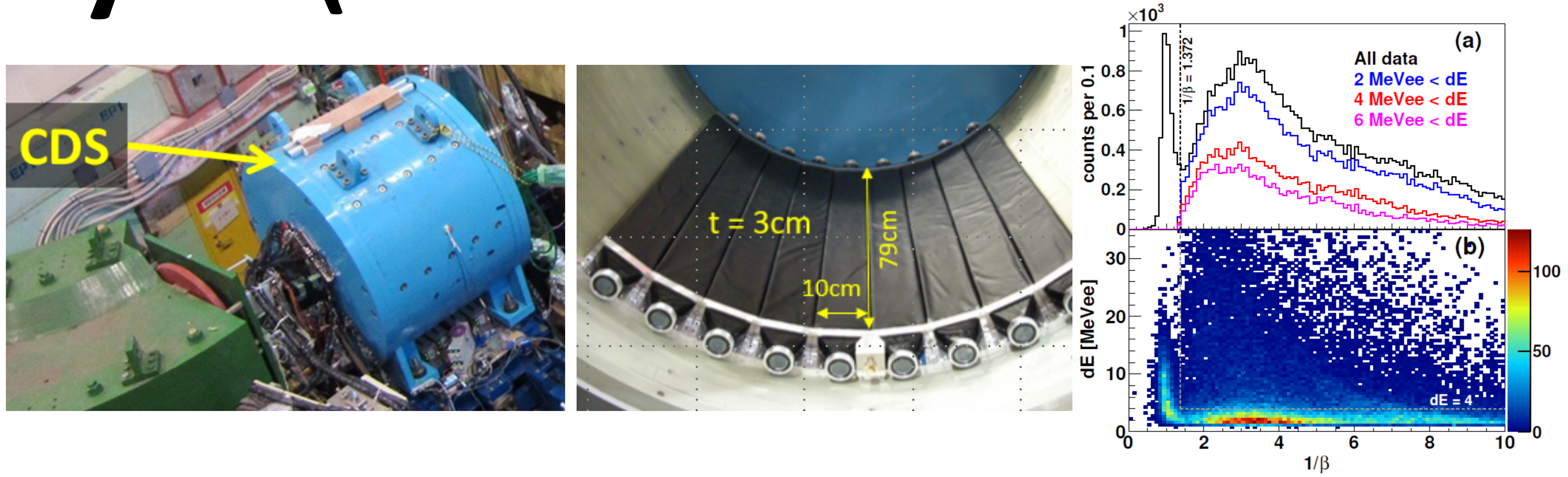

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Fit the 1D spectra in 0.3<q<0.6 with the same model func.

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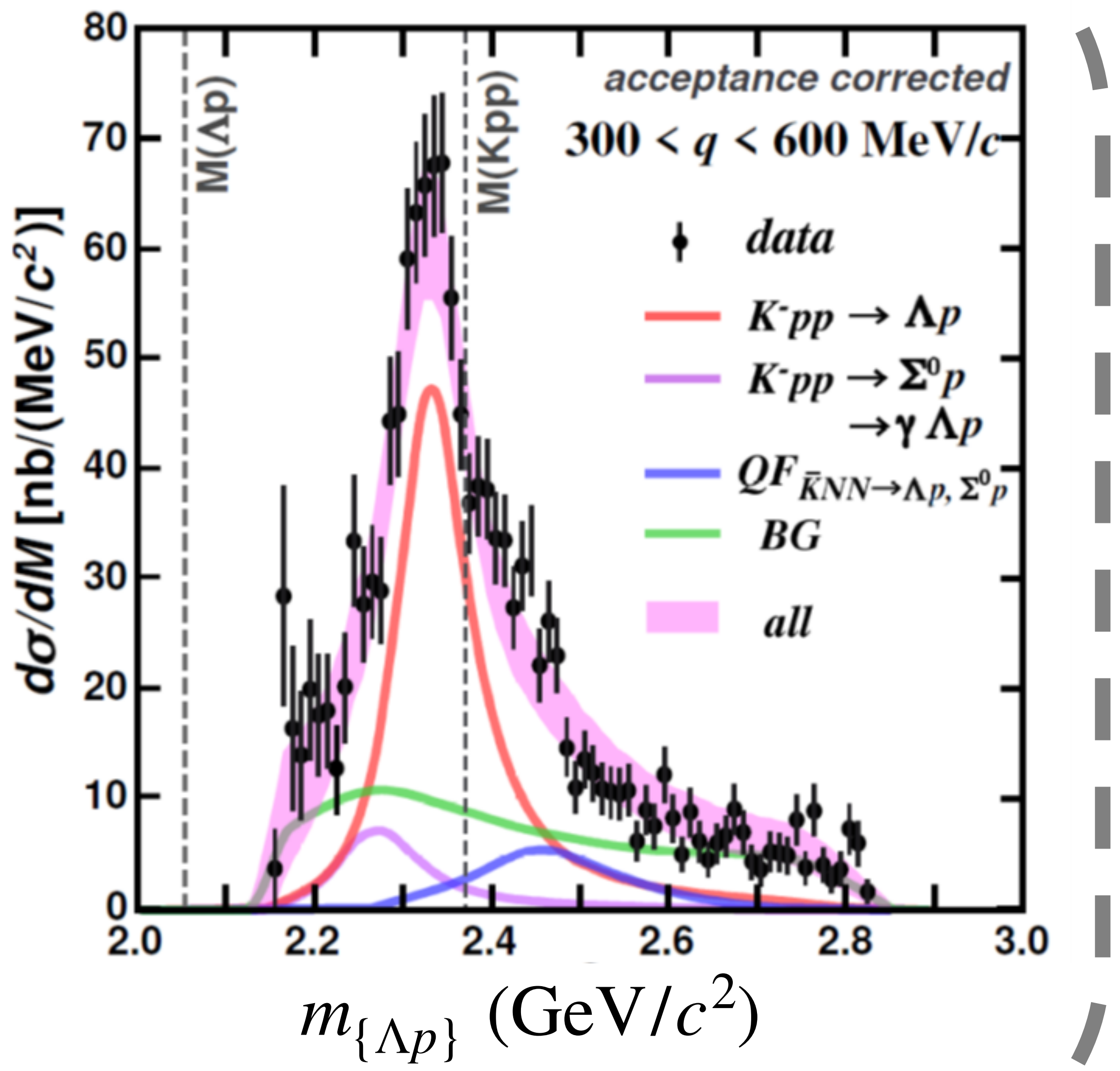
$K^- + {}^3\mathrm{He} \rightarrow$ "K^-pp" $+ n'$

$K^- + {}^3\mathrm{He} \rightarrow$ "$\bar{K}^0 nn$" $+ p'$

"K^-pp" $\rightarrow \Lambda p$



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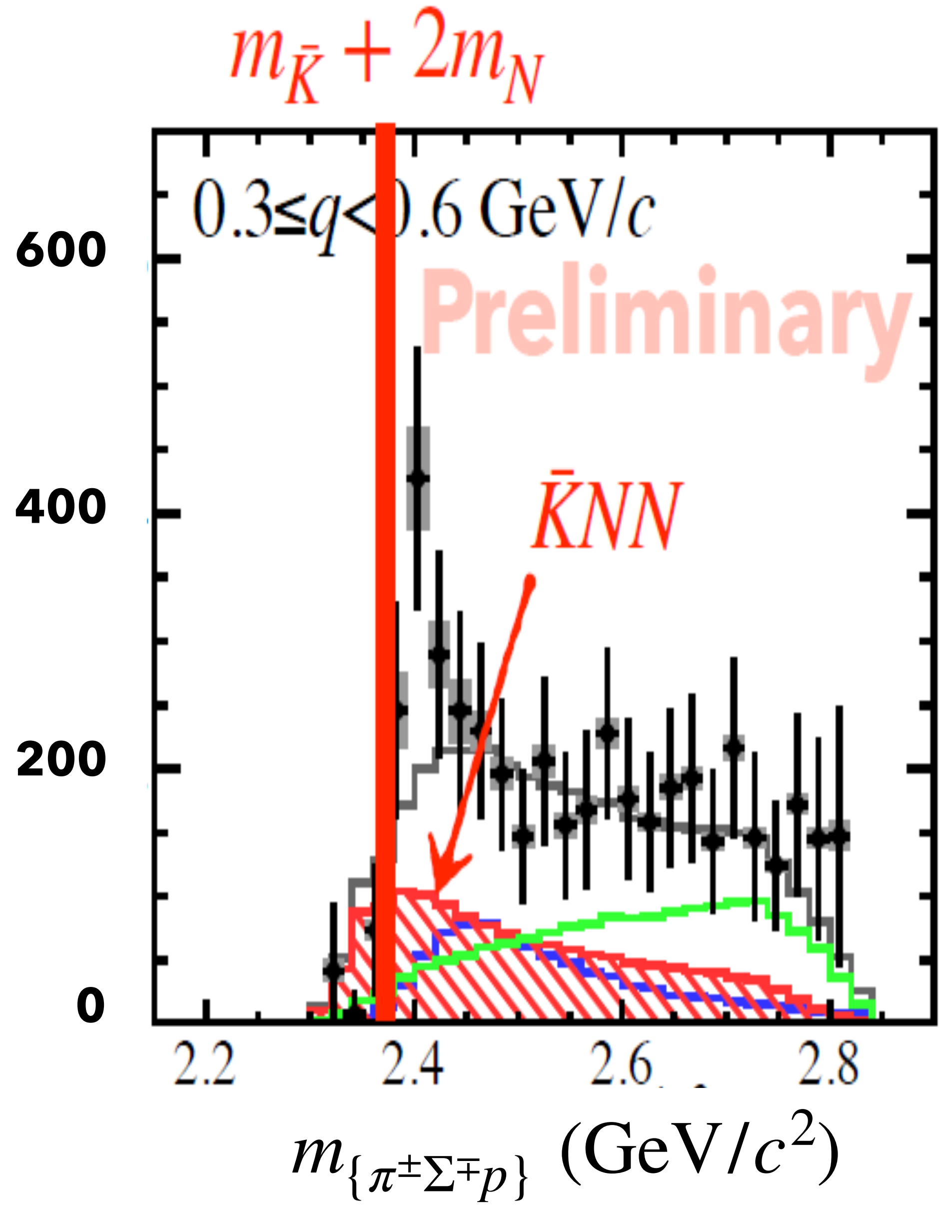

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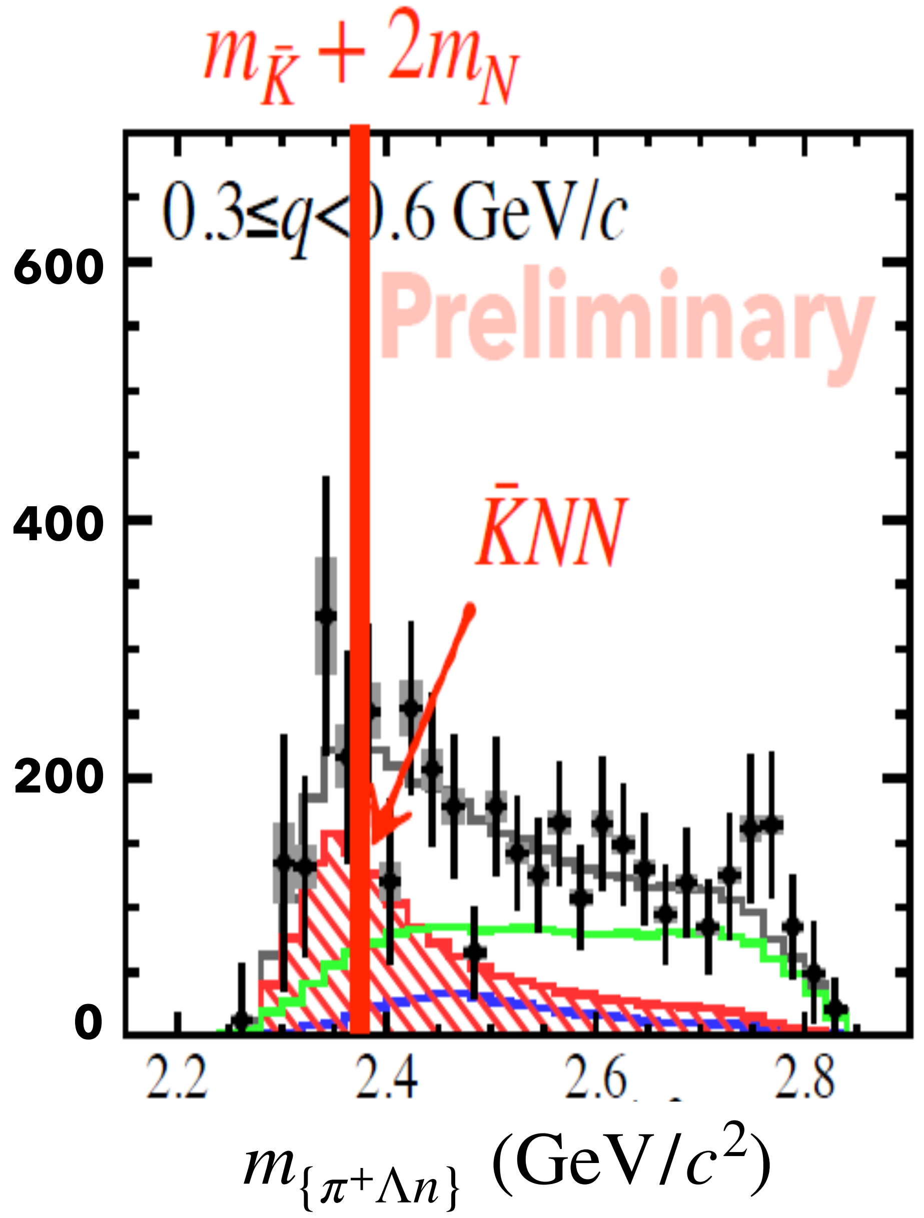

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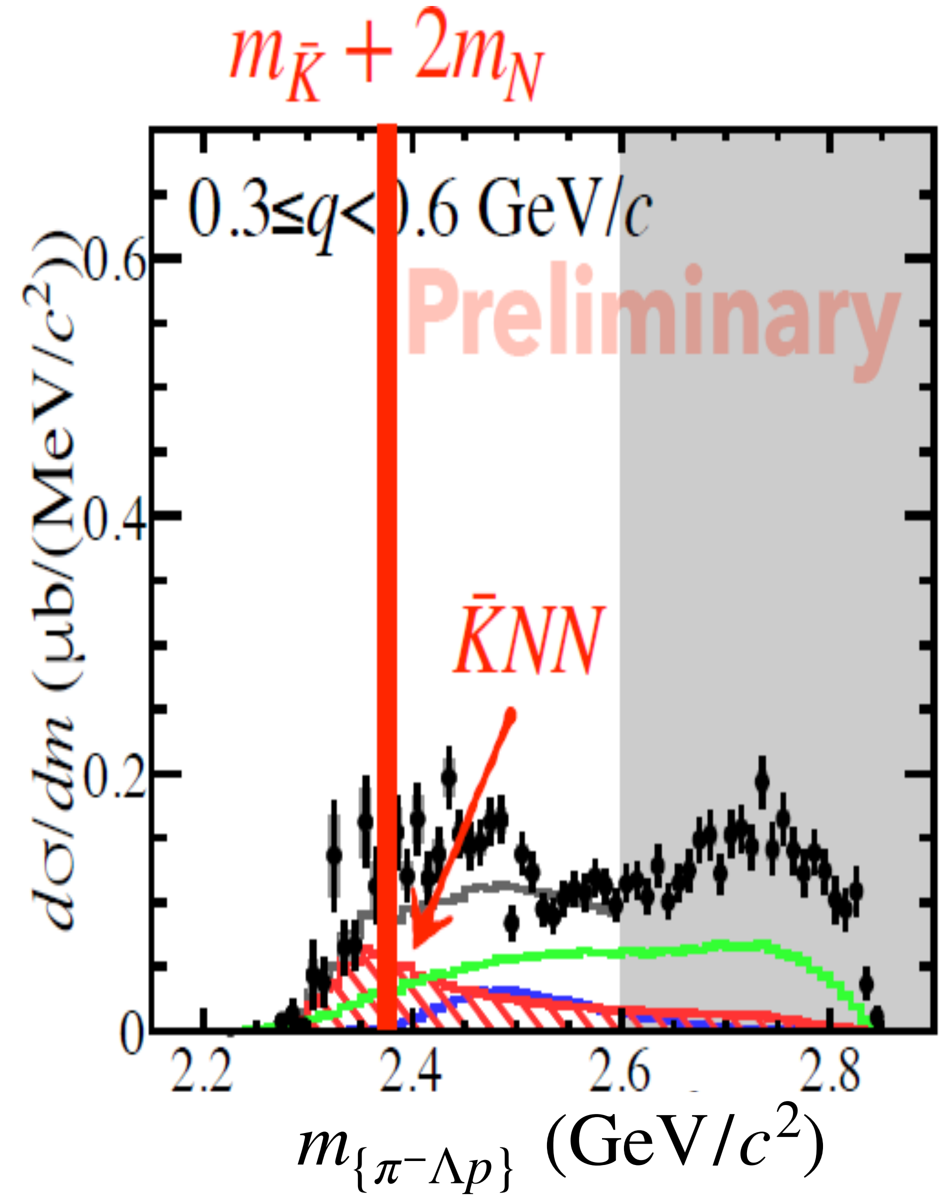

With the model func., the spectra are consistently explained.

T.Yamaga et.al., Phys. Rev. C 110, 014002 (2024) arXiv:2404.01773 [nucl-ex]

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$"K^- pp" \rightarrow \Lambda p$

$\sigma^{tot}_{\bar{K}NN} \times Br\ (\mu b) =$

$9.3 \pm 0.8^{+1.4}_{-1.0}$ **[all]**

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- $\Gamma_{\pi^+\Lambda n}/\Gamma_{\pi^-\Lambda p} \sim 2$: if we assume $Br_{\{K^-pp\}\to\pi^+\Lambda p}/Br_{\{\bar{K}^0nn\}\to\pi^-\Lambda p} \approx 1$ & $\sigma_{\{K^-pp\}}/\sigma_{\{\bar{K}^0nn\}} \approx 2$

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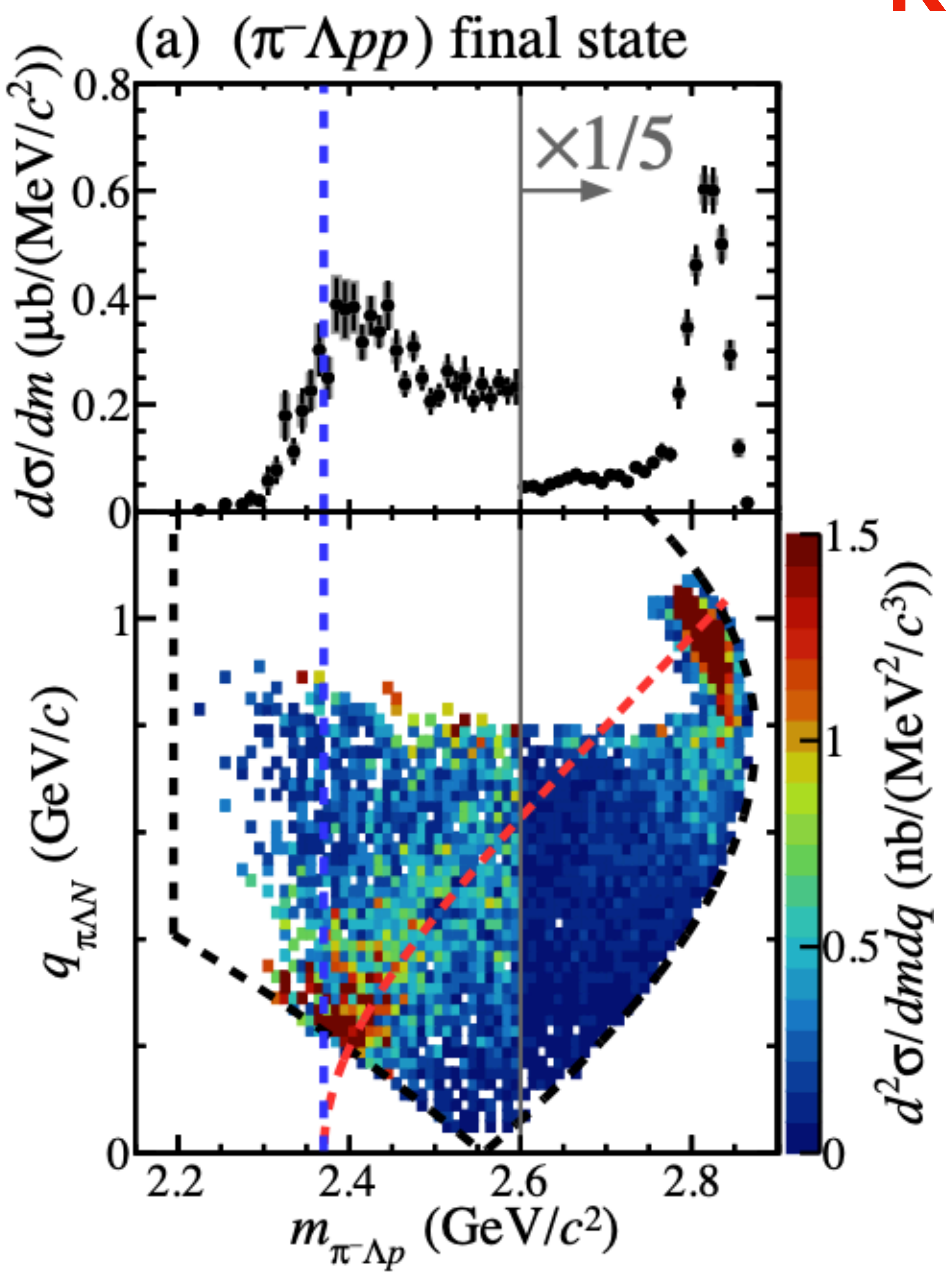
$I_{\bar{K}N} = 1$

Mesonic decay branch of $\bar{K}^0 nn$?



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

$((\pi^- \Lambda)+p) \rightarrow \pi^- \Lambda + p$

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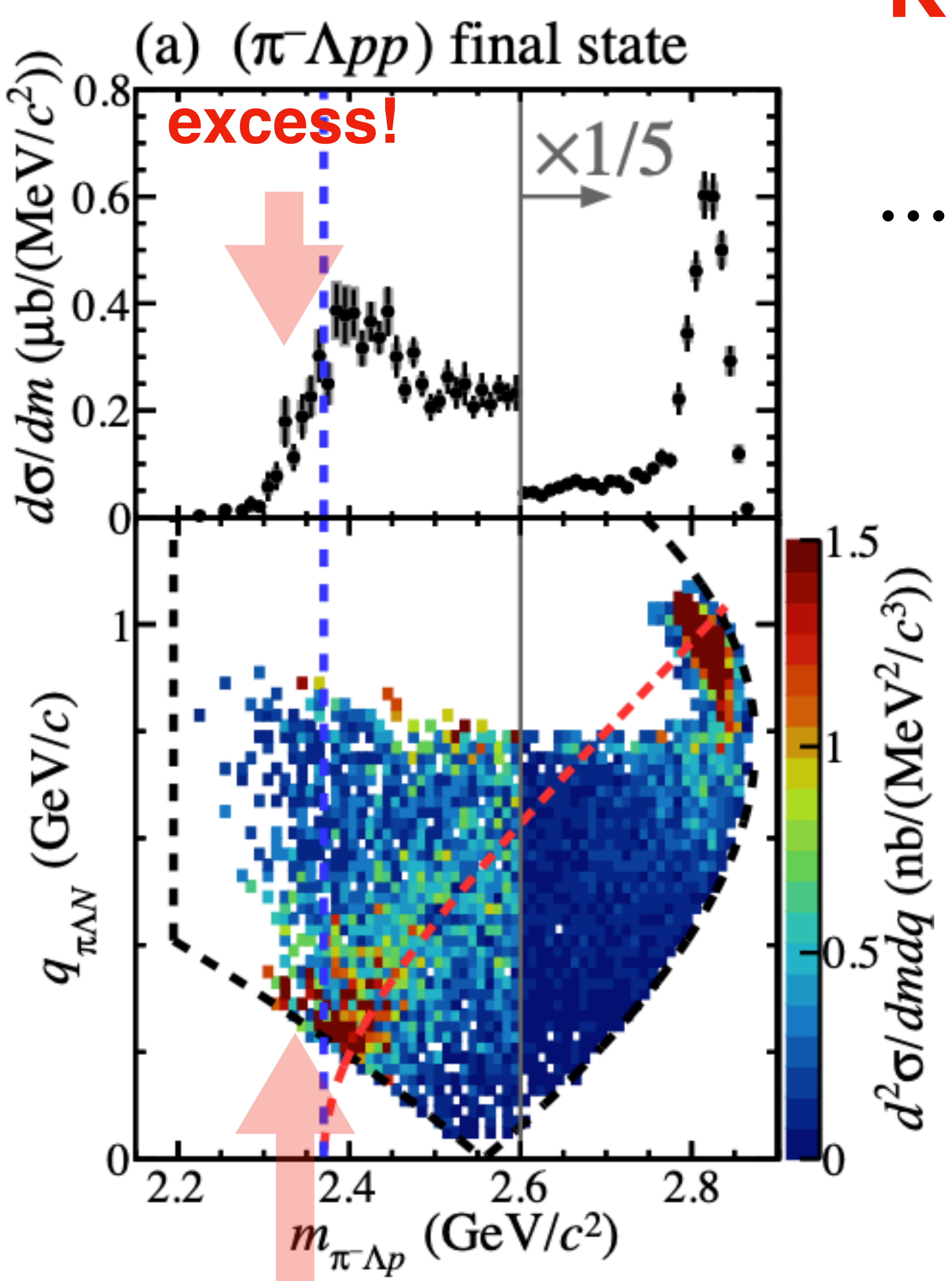

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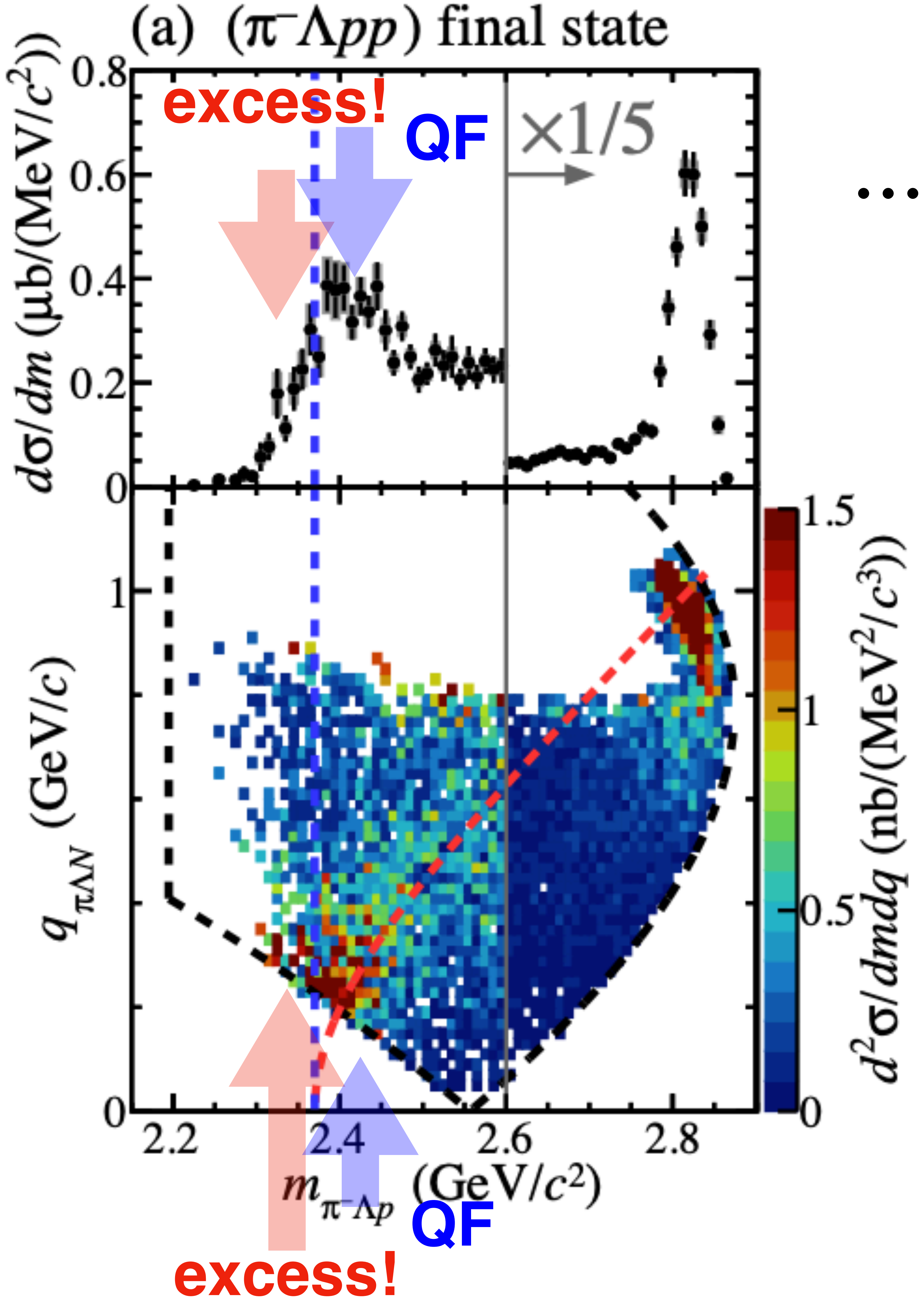

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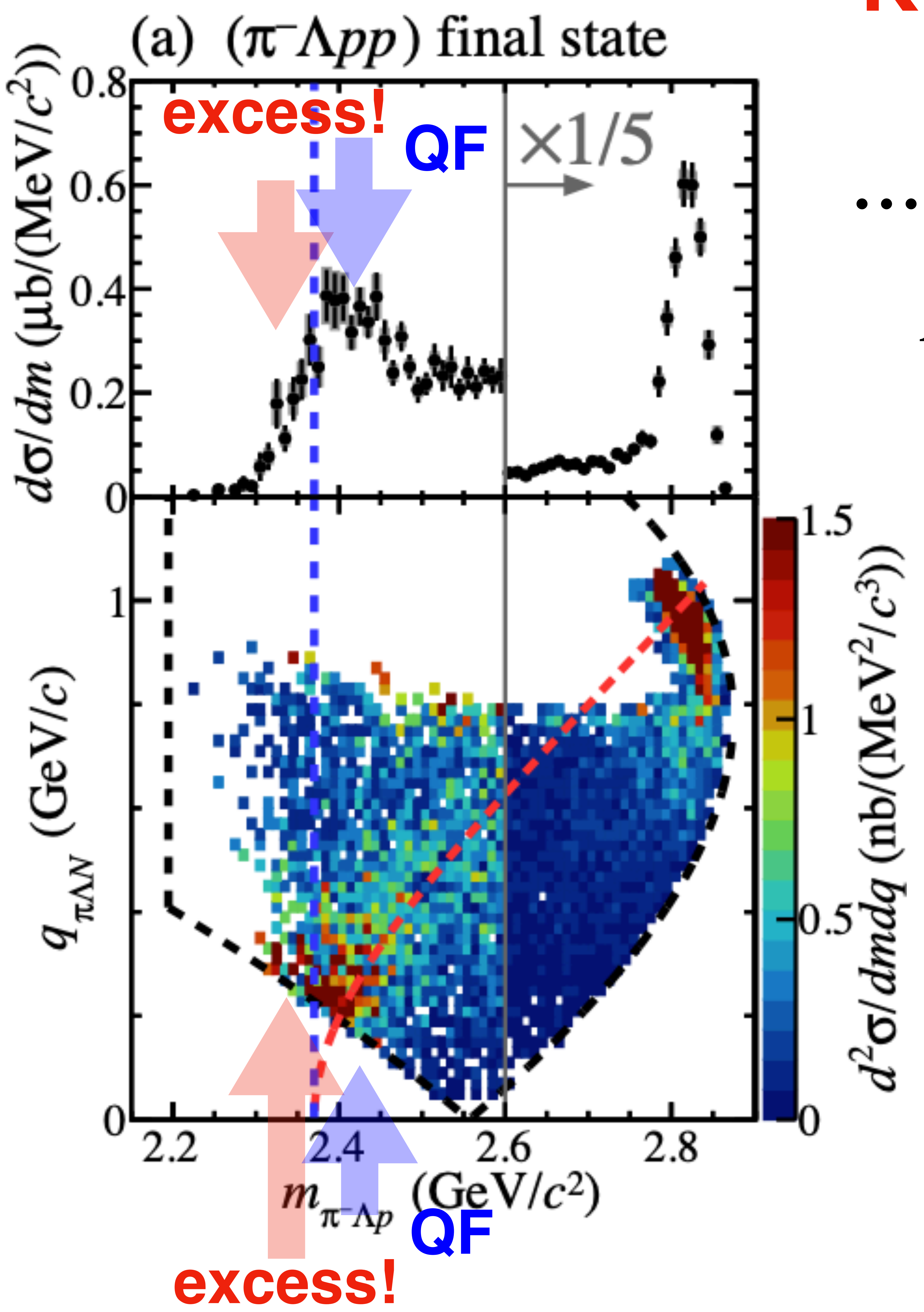

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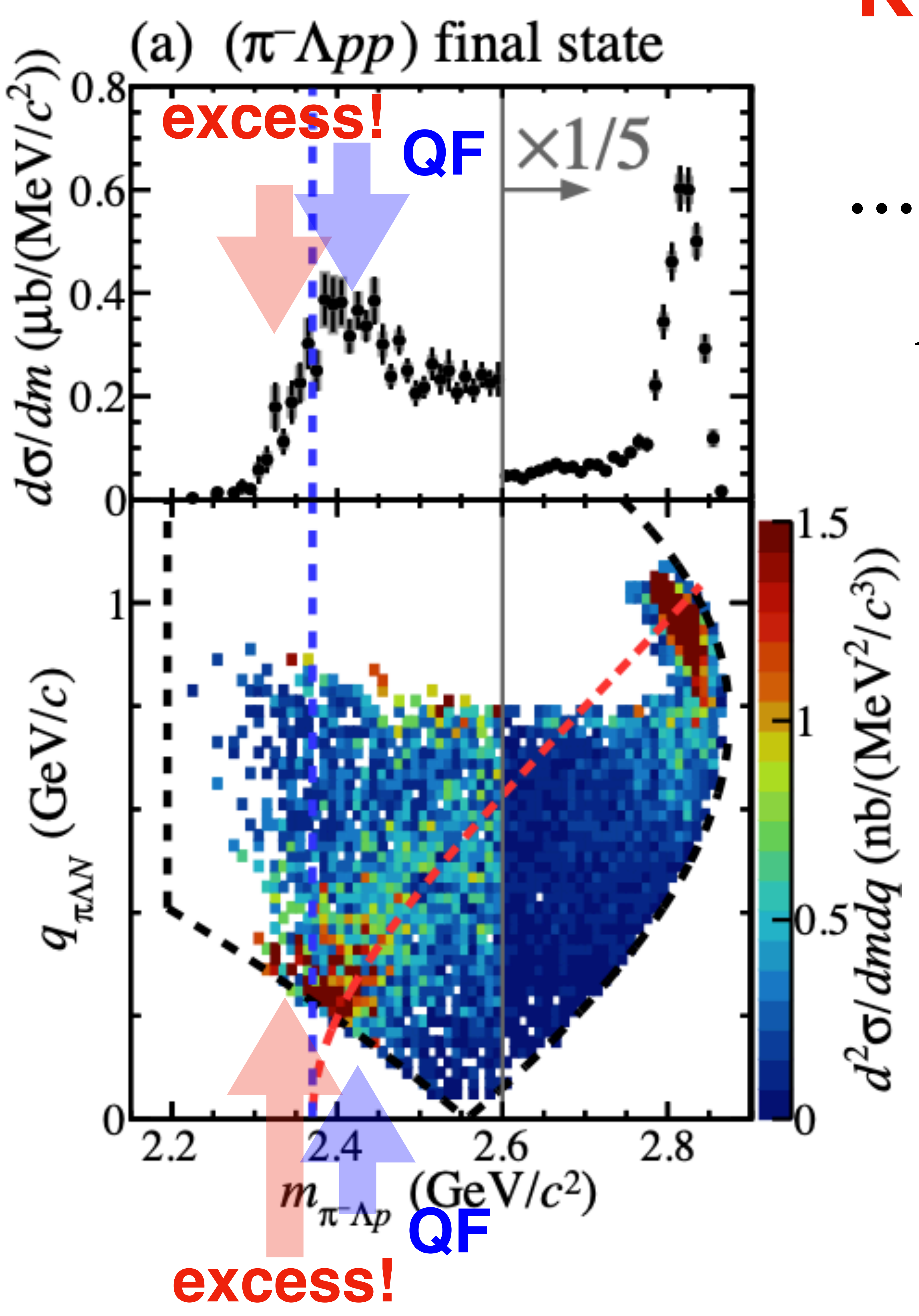

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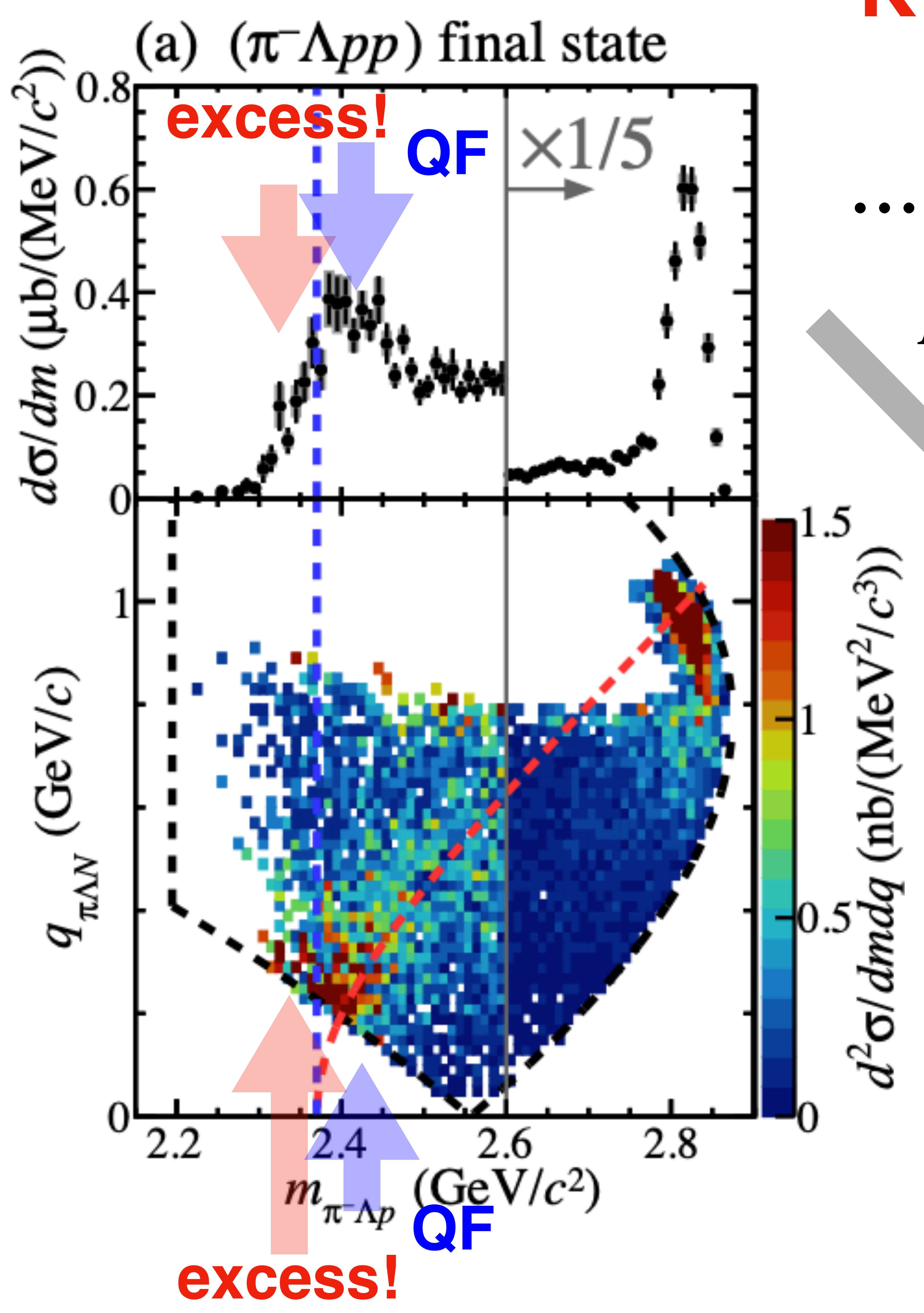

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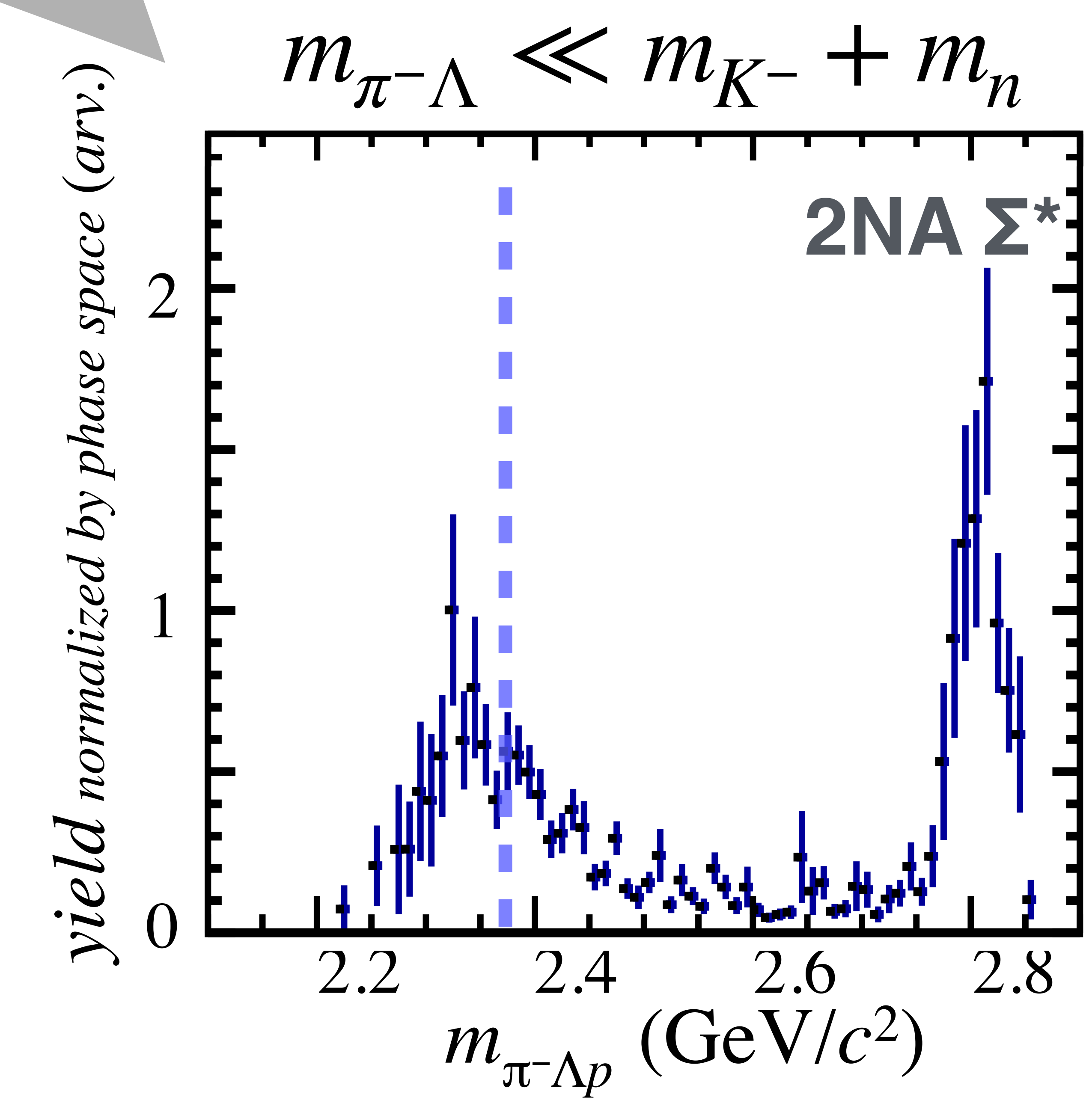

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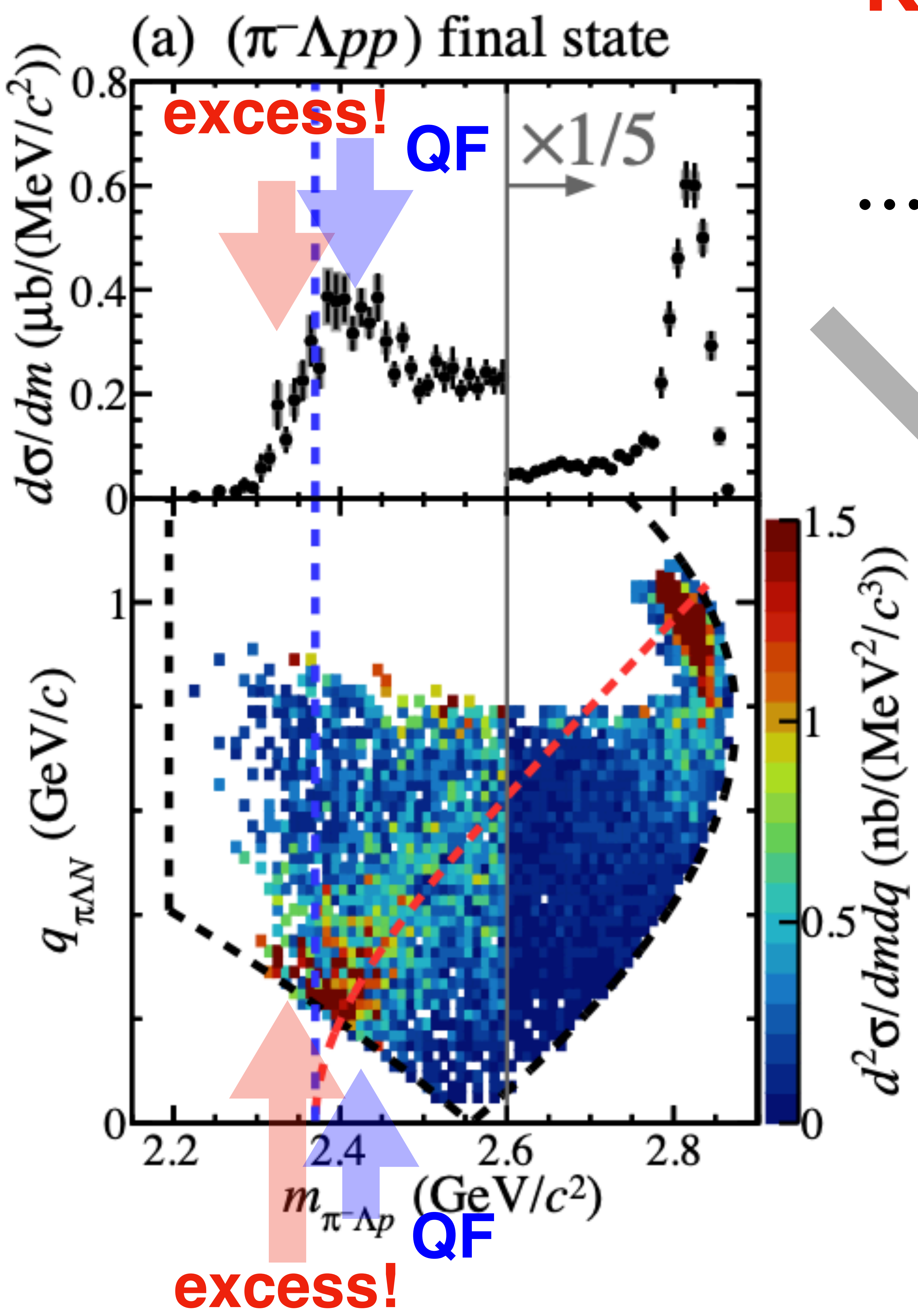

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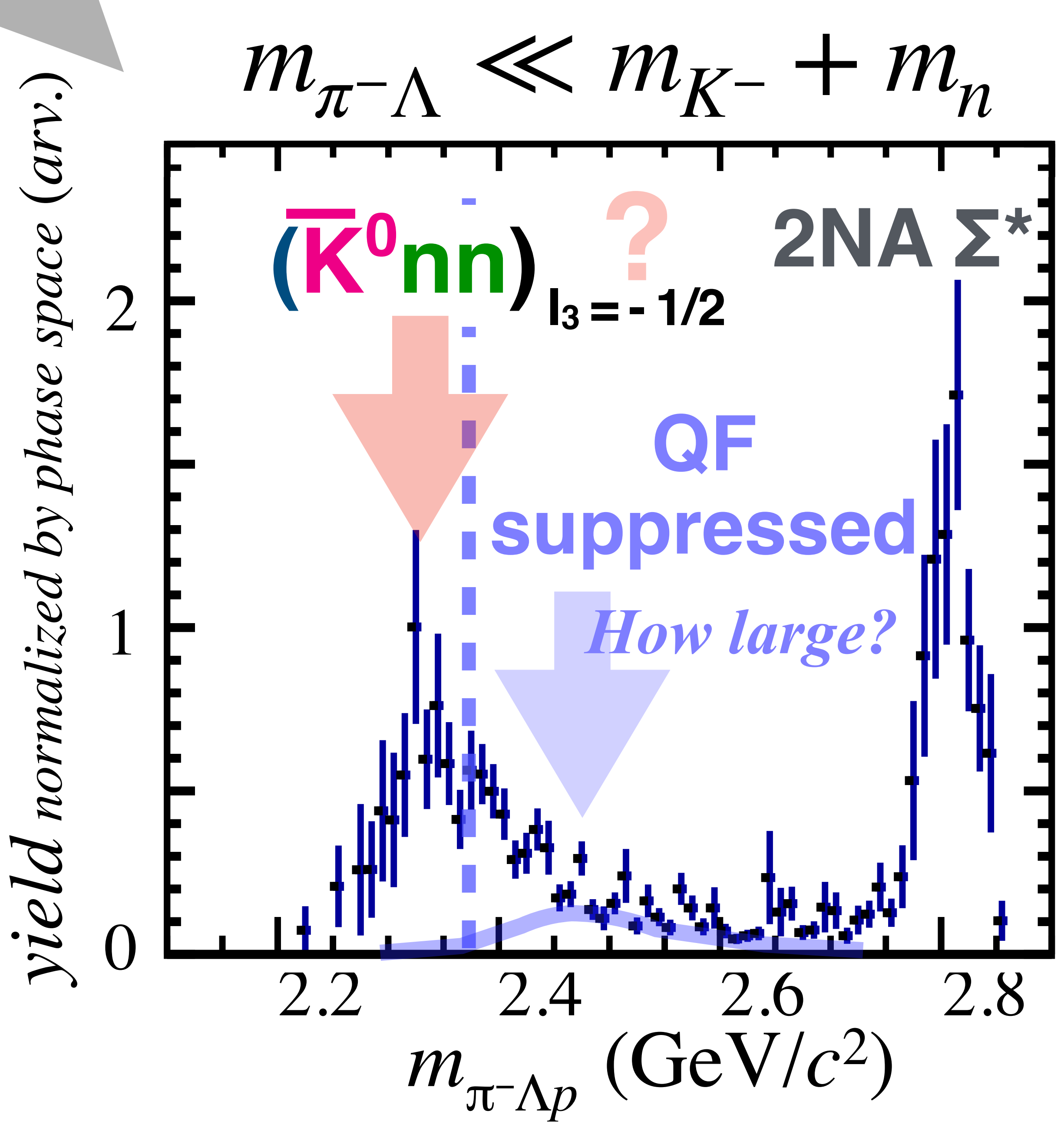

Why don't we normalize it by the Phase Space? It is very promising, but needs further verification.

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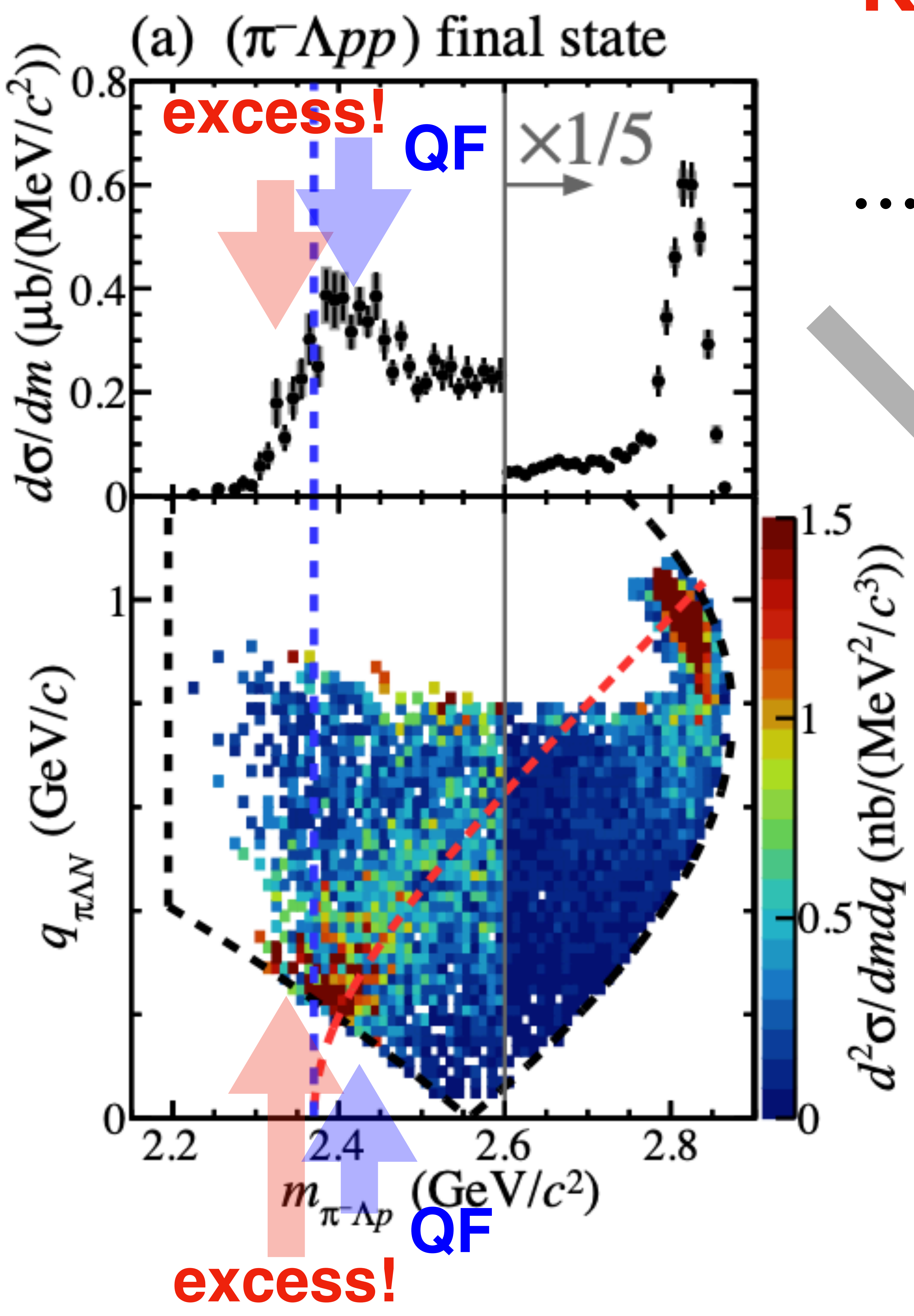

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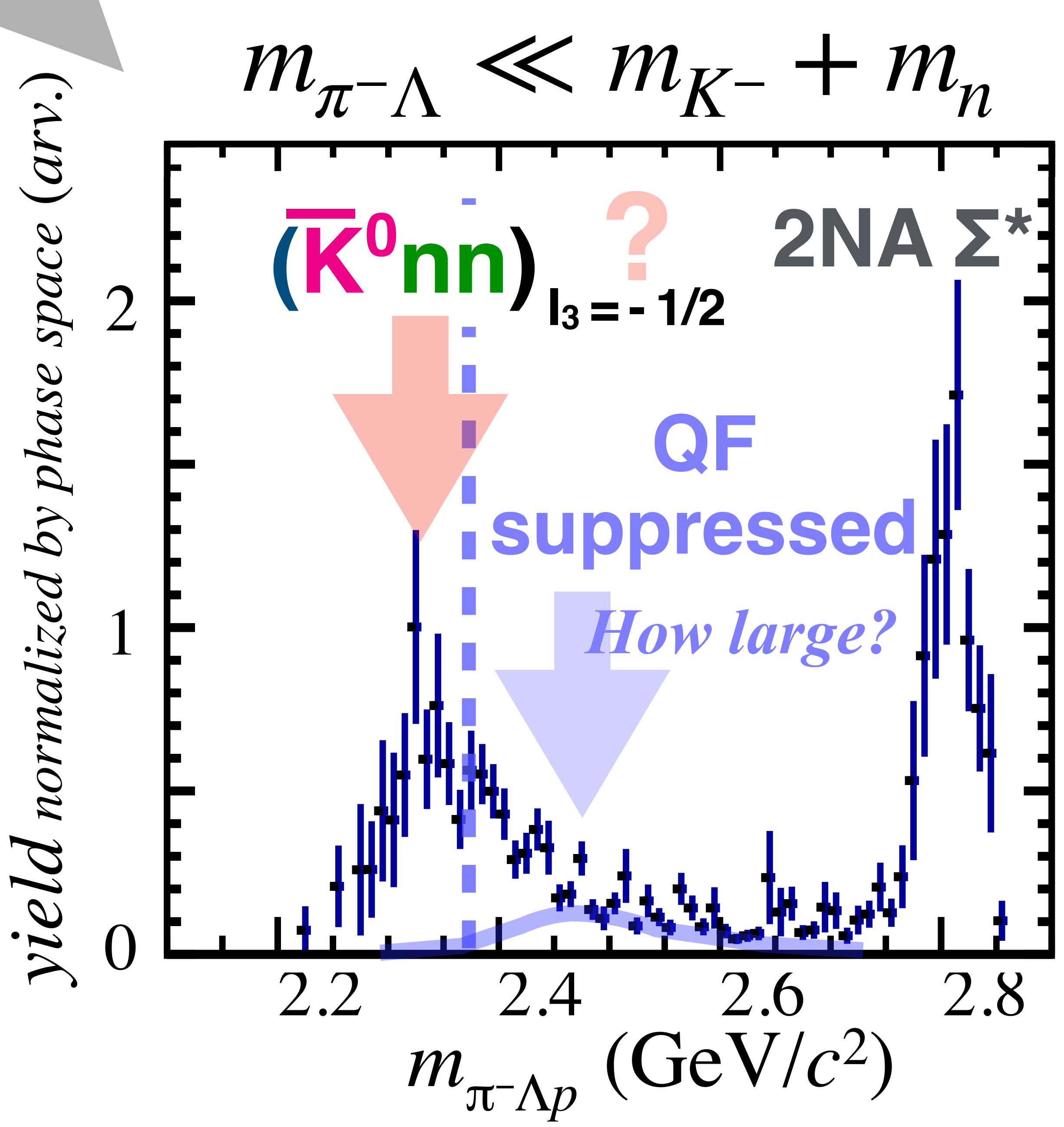

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$(K^- + np) \rightarrow \Lambda + n$

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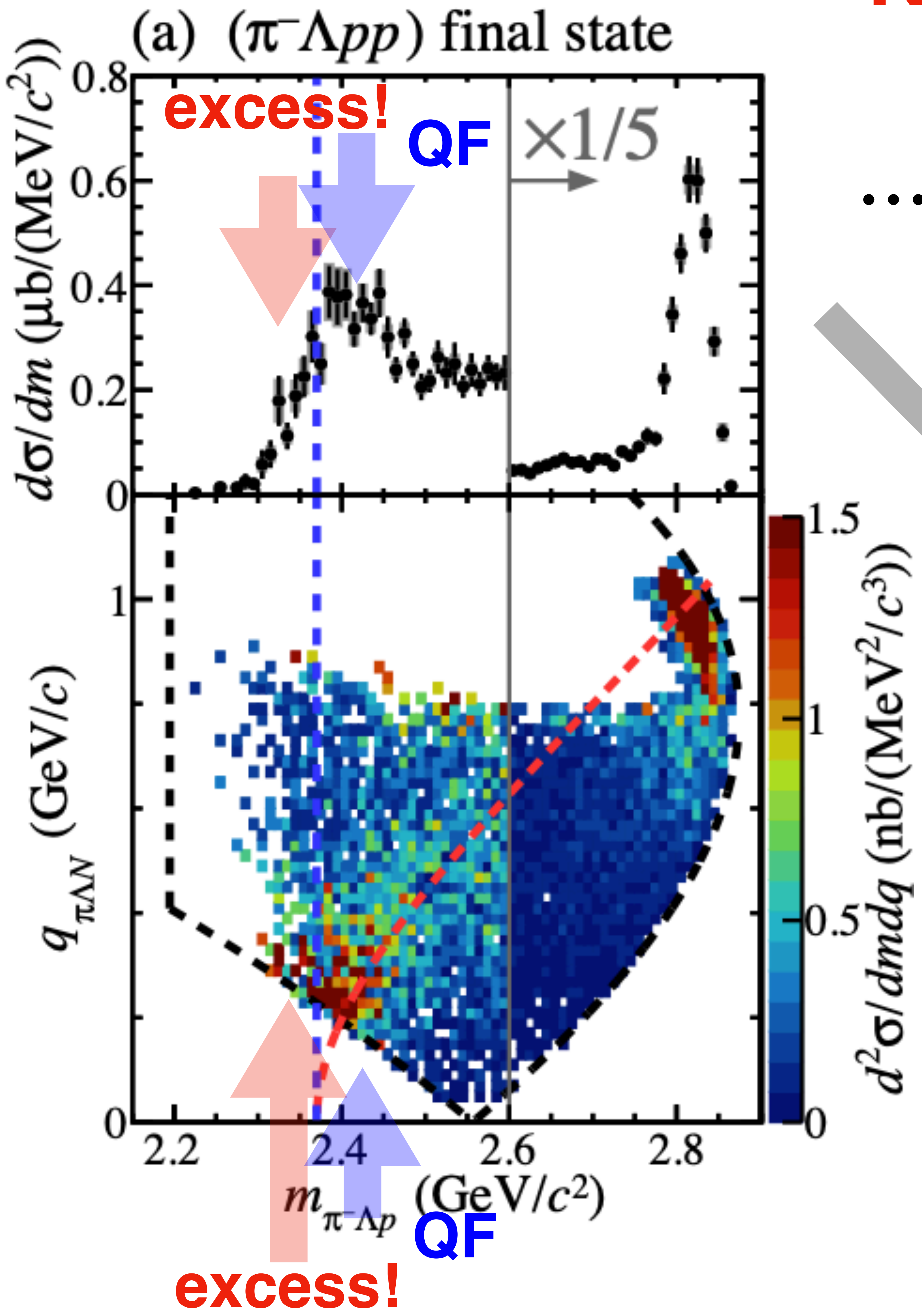

K⁻ + ³He → ((K⁻ + n)p) + p

((π⁻ Λ)+p) → π⁻ Λ + p

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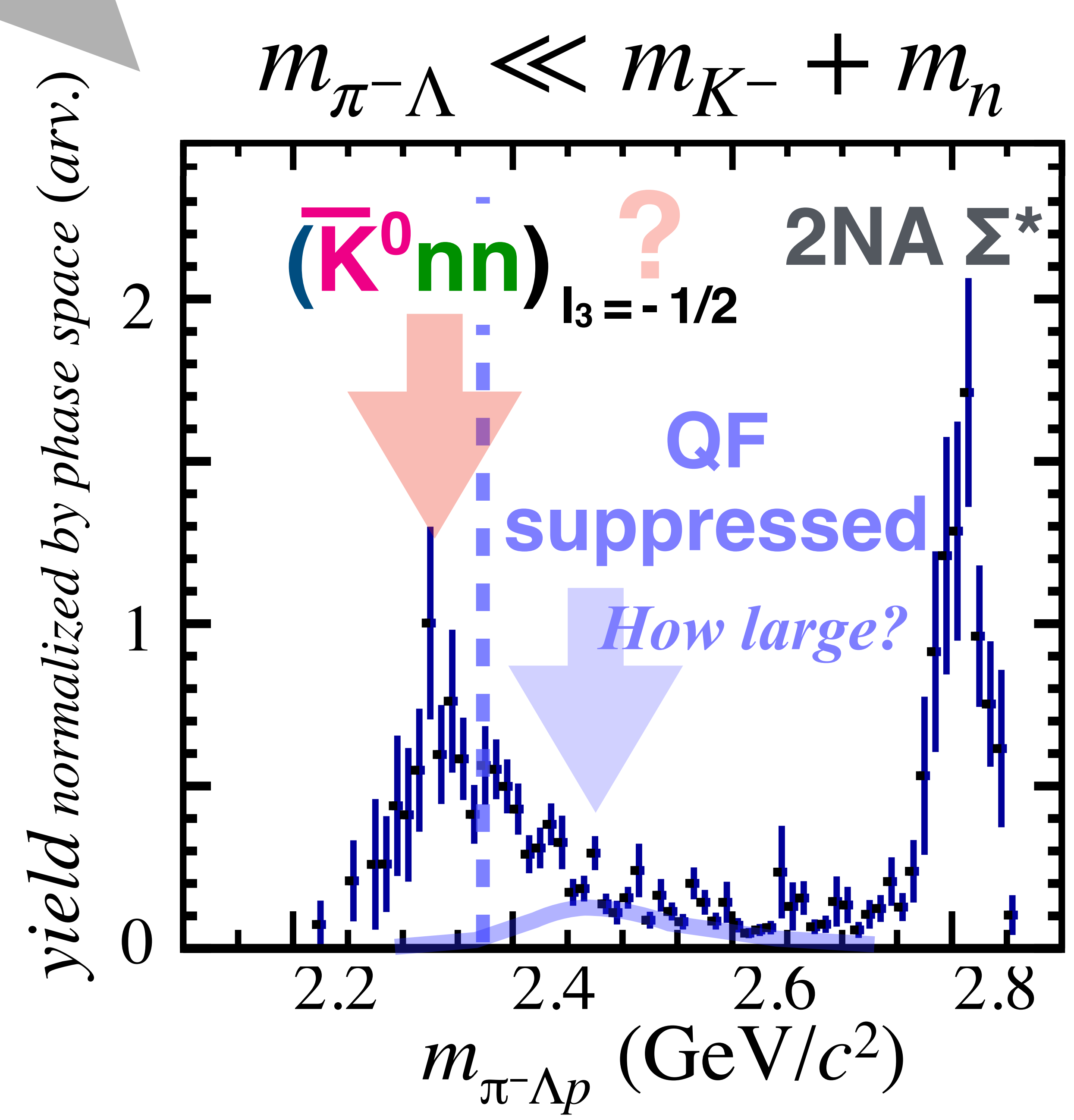

Why don't we normalize it by the Phase Space? It is very promising, but needs further verification.

K⁻ + ³He → (K⁻ + np) + p

(K⁻ + np) = $(\bar{K}^0 nn)_{I_3 = -1/2}$ → Λ + n

K⁻ + ³He → (K⁻ + pp) + n

(K⁻ + pp) = $(K^- pp)_{I_3 = +1/2}$ → Λ + p

Further analysis on other data

Signal of $\bar{K}NNN$?

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

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

$\Rightarrow$

$K^- + {}^4He \rightarrow (K^- + ppn) + n$

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

Preliminary data analysis for $\bar{K}NNN$ formation study utilizing ${}^4_\Lambda\mathrm{He}$ lifetime measurement via $K^- + {}^4\mathrm{He} \rightarrow \pi^0 + {}^4_\Lambda\mathrm{He}$ reaction giving us a very interesting result

… Analyzed by T.Hashimoto

Further analysis on other data

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~ 600 MeV/c

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spectator

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K⁻ + ^{4}He → (K⁻ + ppn) + n
(K⁻ + p(pn)) → Λ+(pn)

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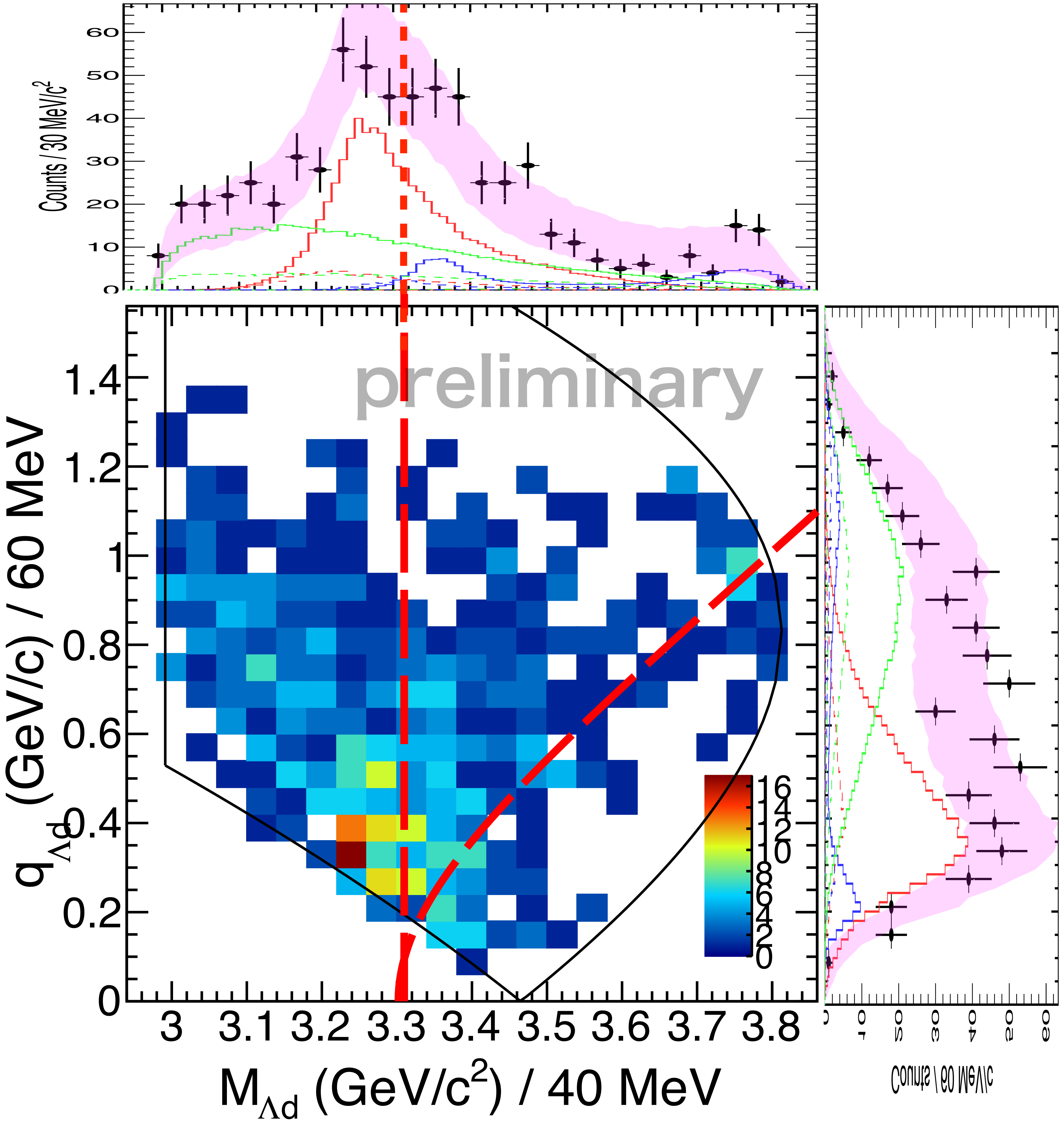
… Analyzed by T.Hashimoto

K^- $^4He \to \{\Lambda d\} + n$ Analysis (with the T77 Data)

Promising signal is observed!



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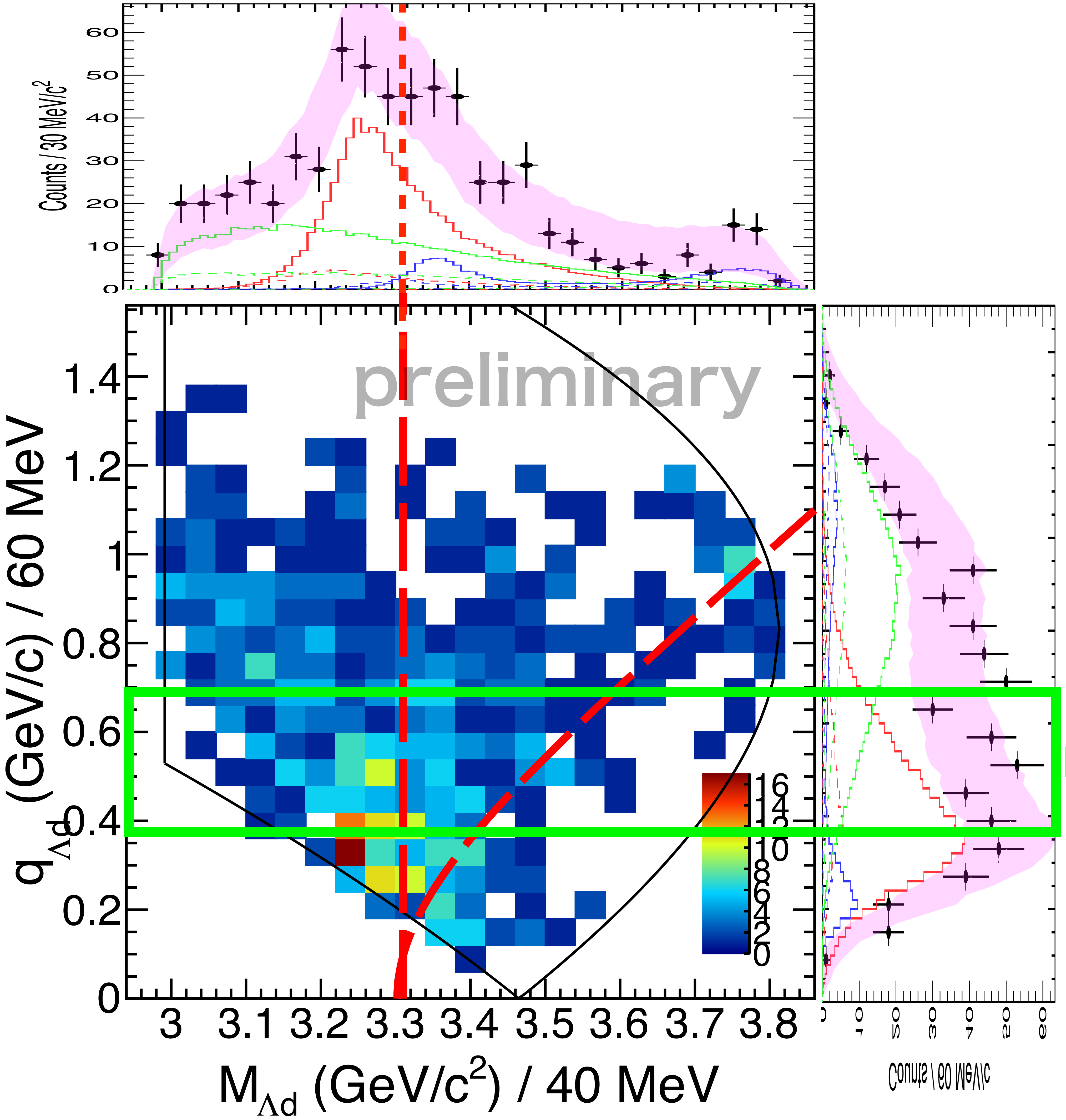
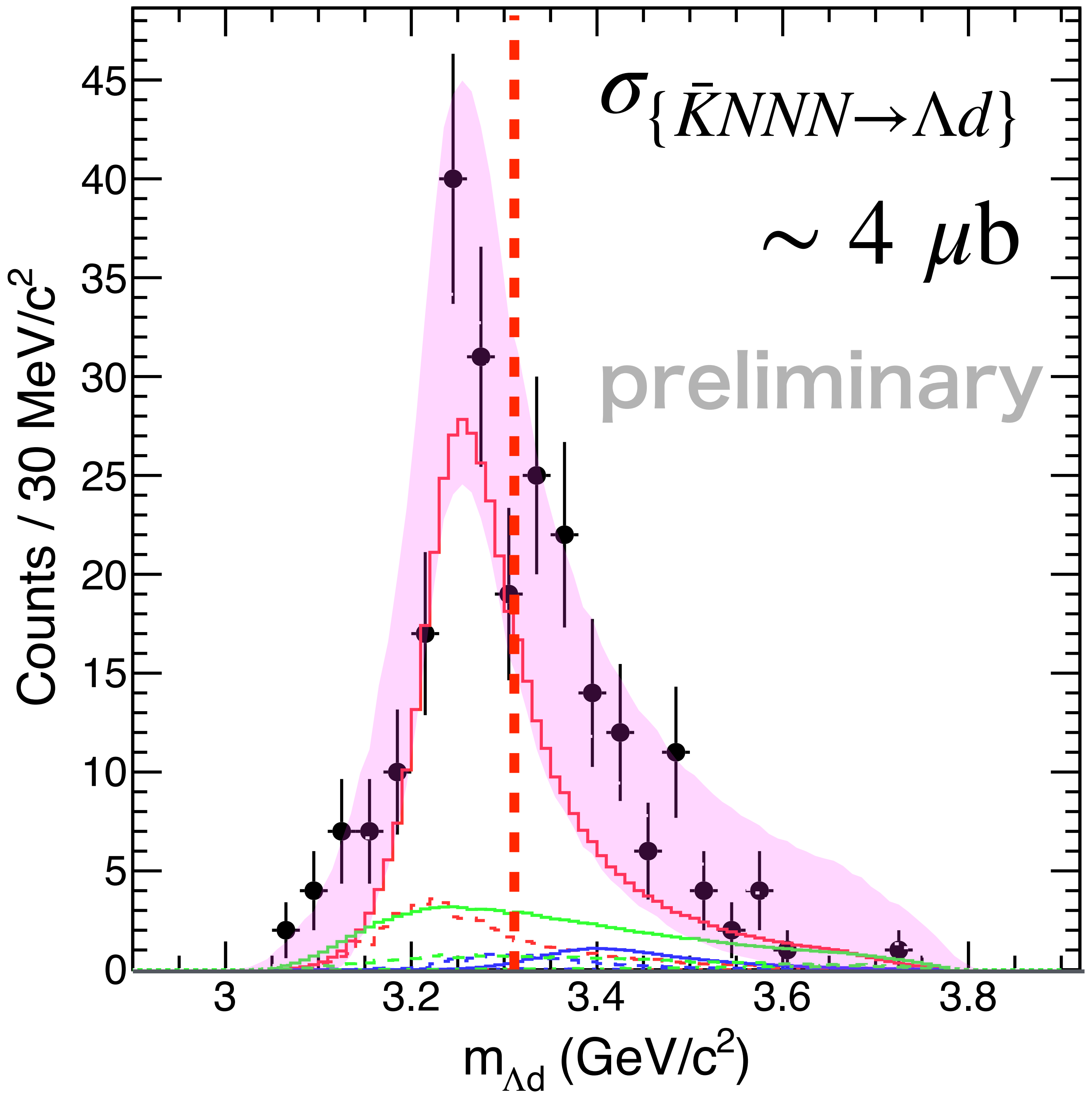


$0.3 < q_{\Lambda d} < 0.6$ GeV/c window



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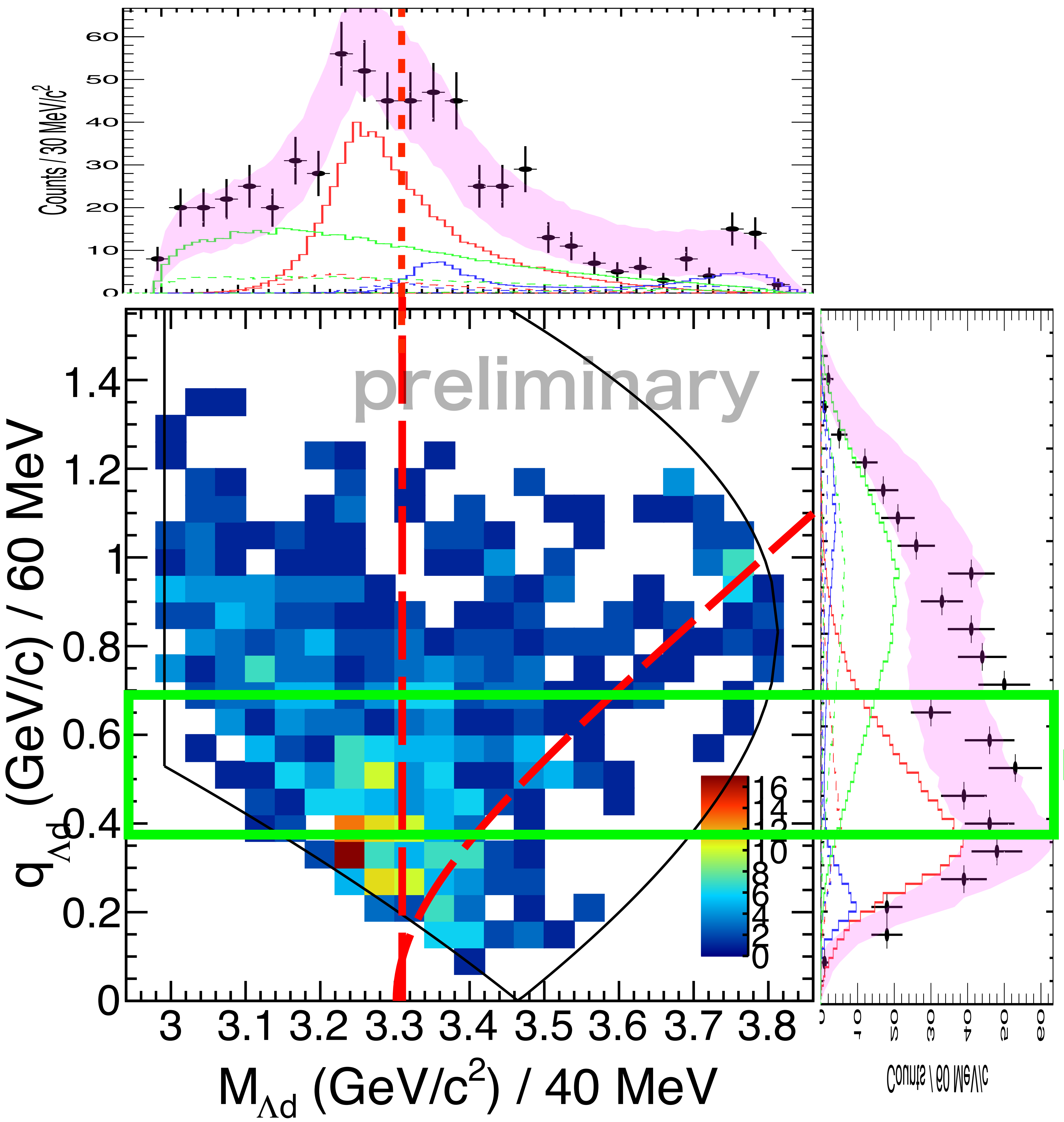
Promising signal is observed! *1) It suggests kaonic nuclei exist more universally, not just in cases like K^-pp.*



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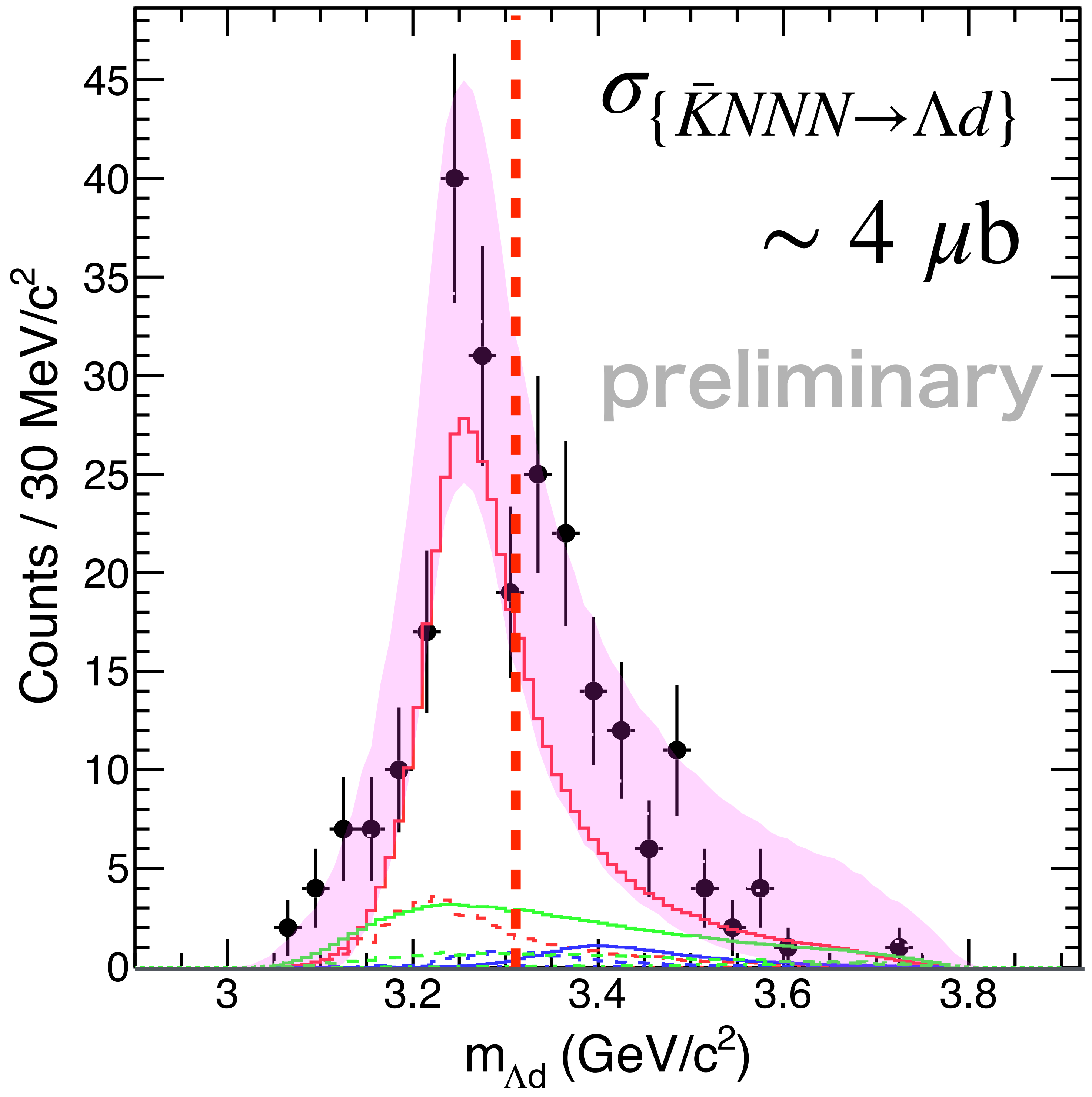
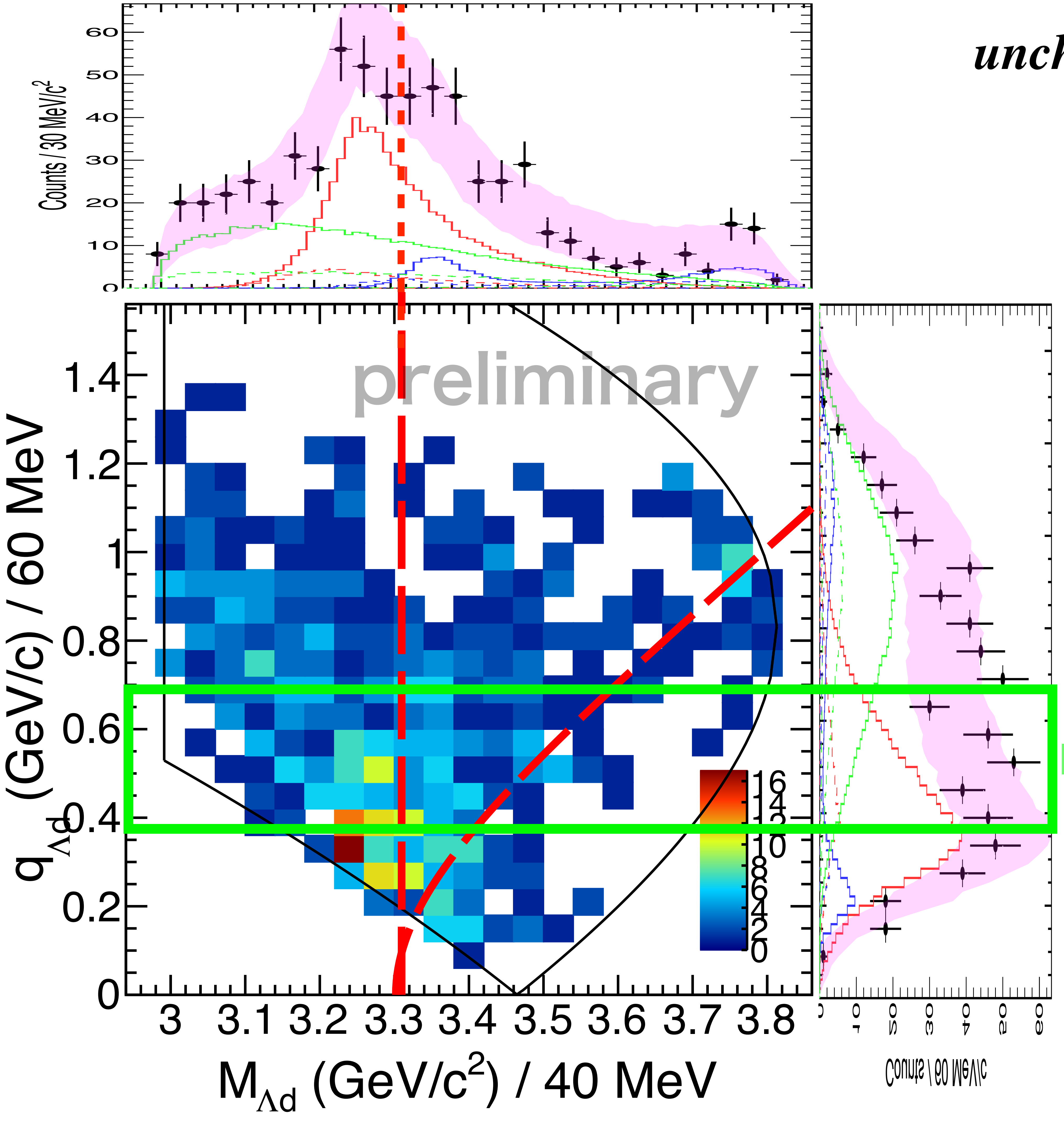


$K^{-}\,{}^4He \rightarrow \{\Lambda d\} + n$ Analysis (with the T77 Data)

Promising signal is observed!

1) *It suggests kaonic nuclei exist more universally, not just in cases like $K^{-}pp$.*
2) *Despite more nucleons absorbing the K meson, the width remains unchanged, suggesting a near plateau.*



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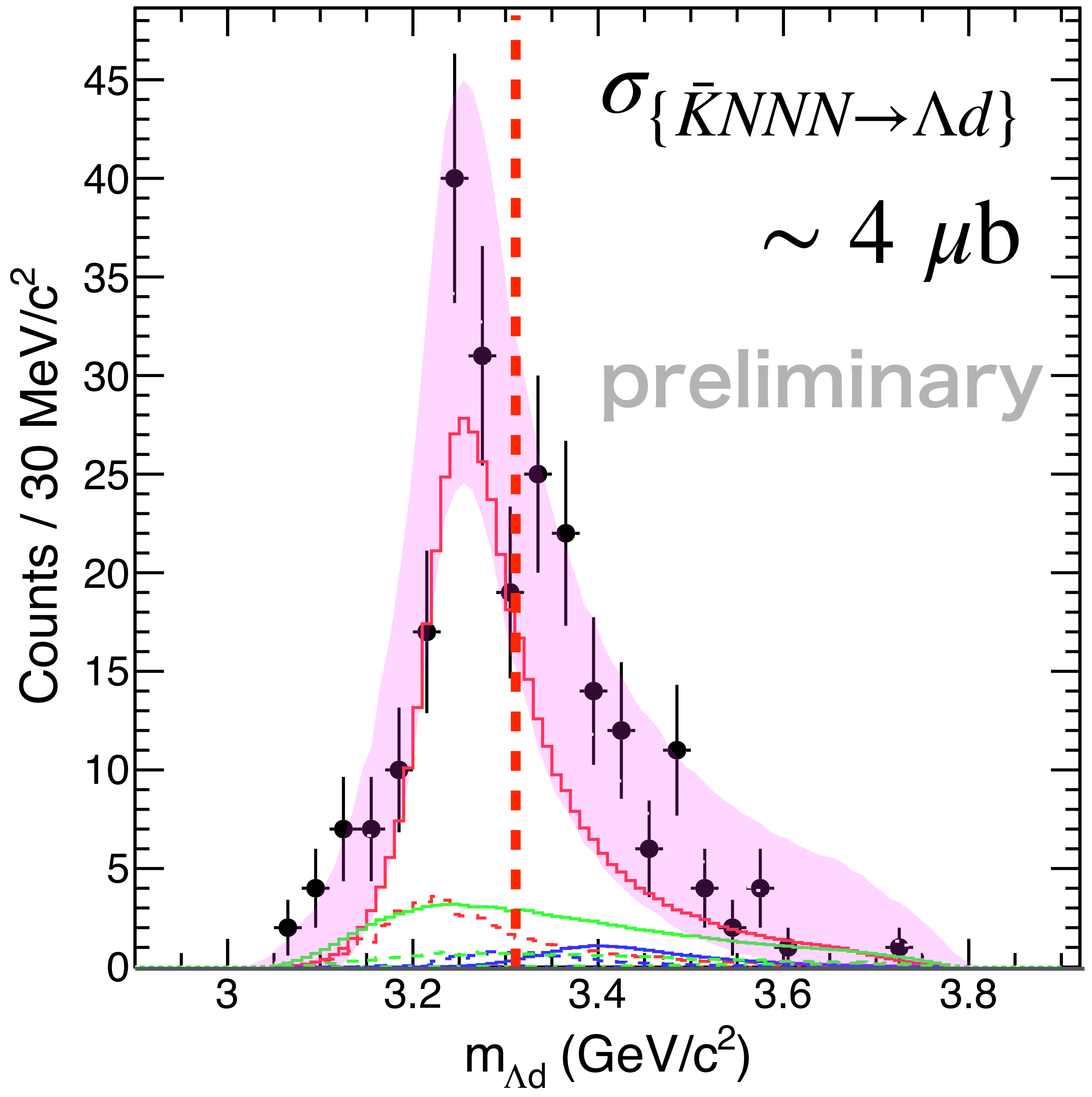

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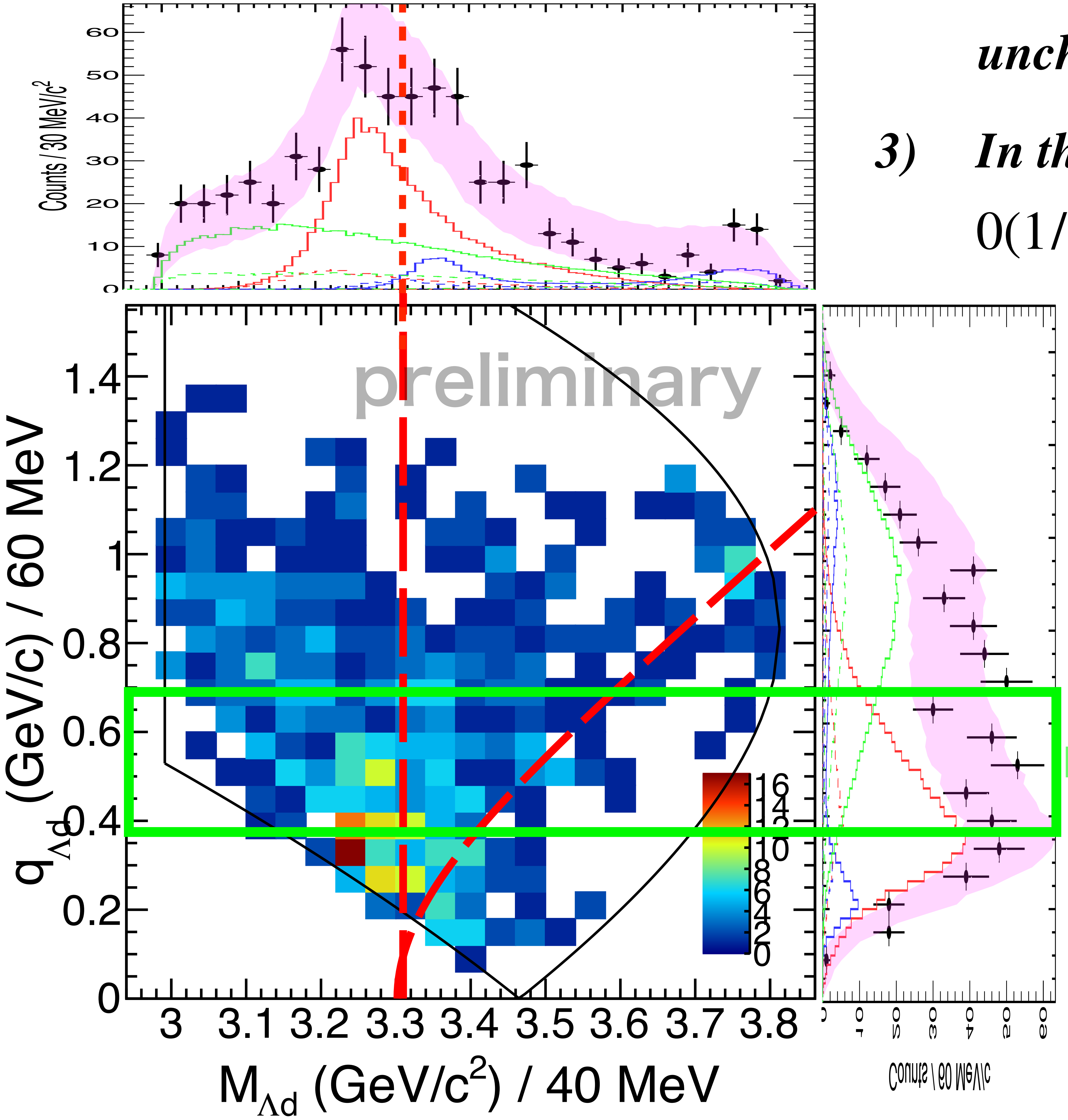
Promising signal is observed!

1) *It suggests kaonic nuclei exist more universally, not just in cases like K^-pp.*
2) *Despite more nucleons absorbing the K meson, the width remains unchanged, suggesting a near plateau.*
3) *In the case of K^-ppn, isospin and spin-parity $I(J^P)$, has been fixed to be $0(1/2^-)$ with high certainty through Λp decay.*



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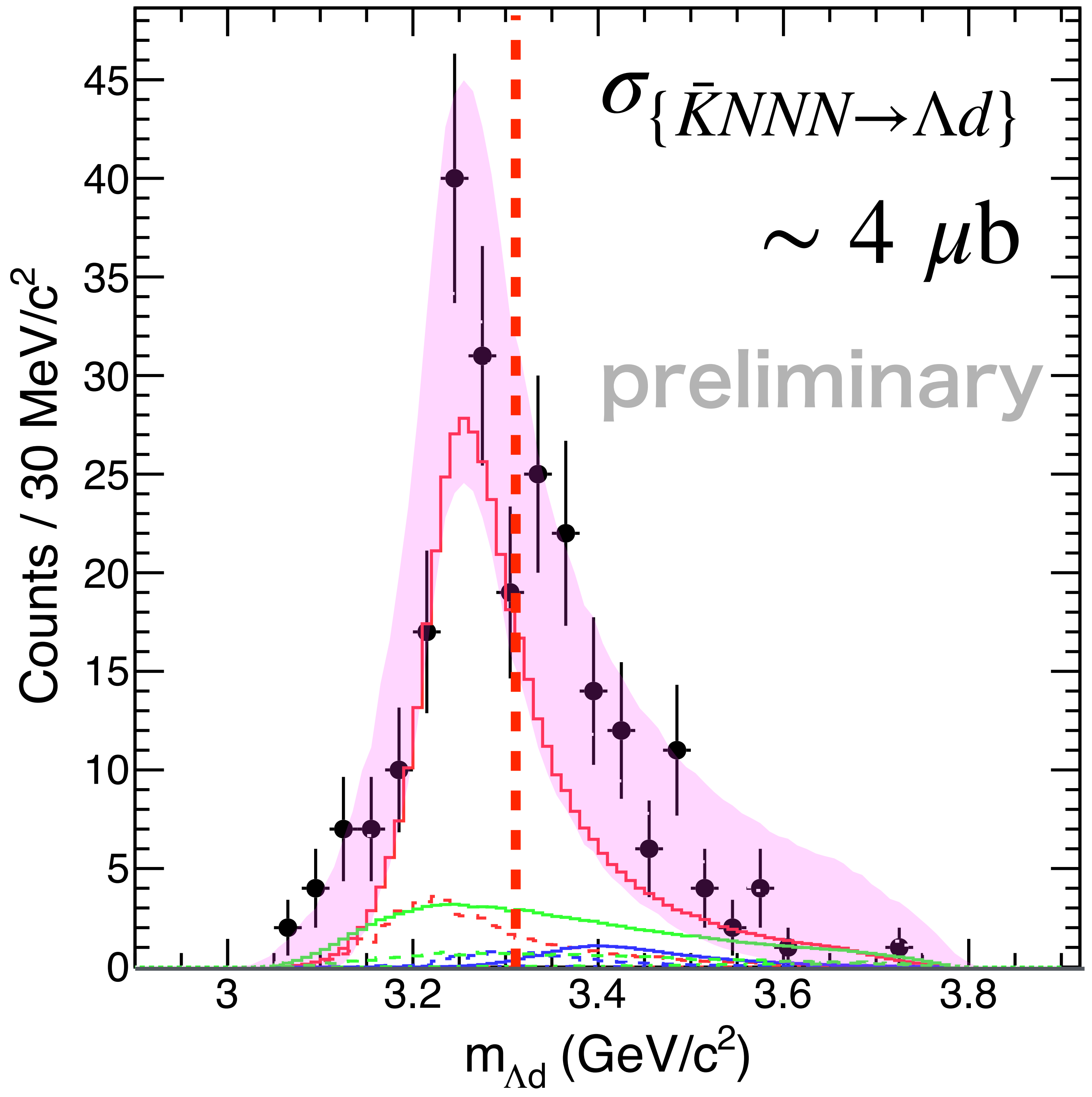

I(J^P) of X in $K^- \, ^4He \rightarrow X + n$

What is the I(J^P) of the observed state? := 0($1/2^-$)

➢ Λpn would be the major decay mode (relatively easily identified in this channel)

1. <u>"X"→Λd decay mode is unique evidence of **$I_{"X"}$ = 0**</u>

- I(J^P) : Λ = 0($1/2^+$), d = 0(1^+), K^- = 1/2(0^-), ^{3}He = 1/2($1/2^+$) , ^{4}He = 0(0^+)

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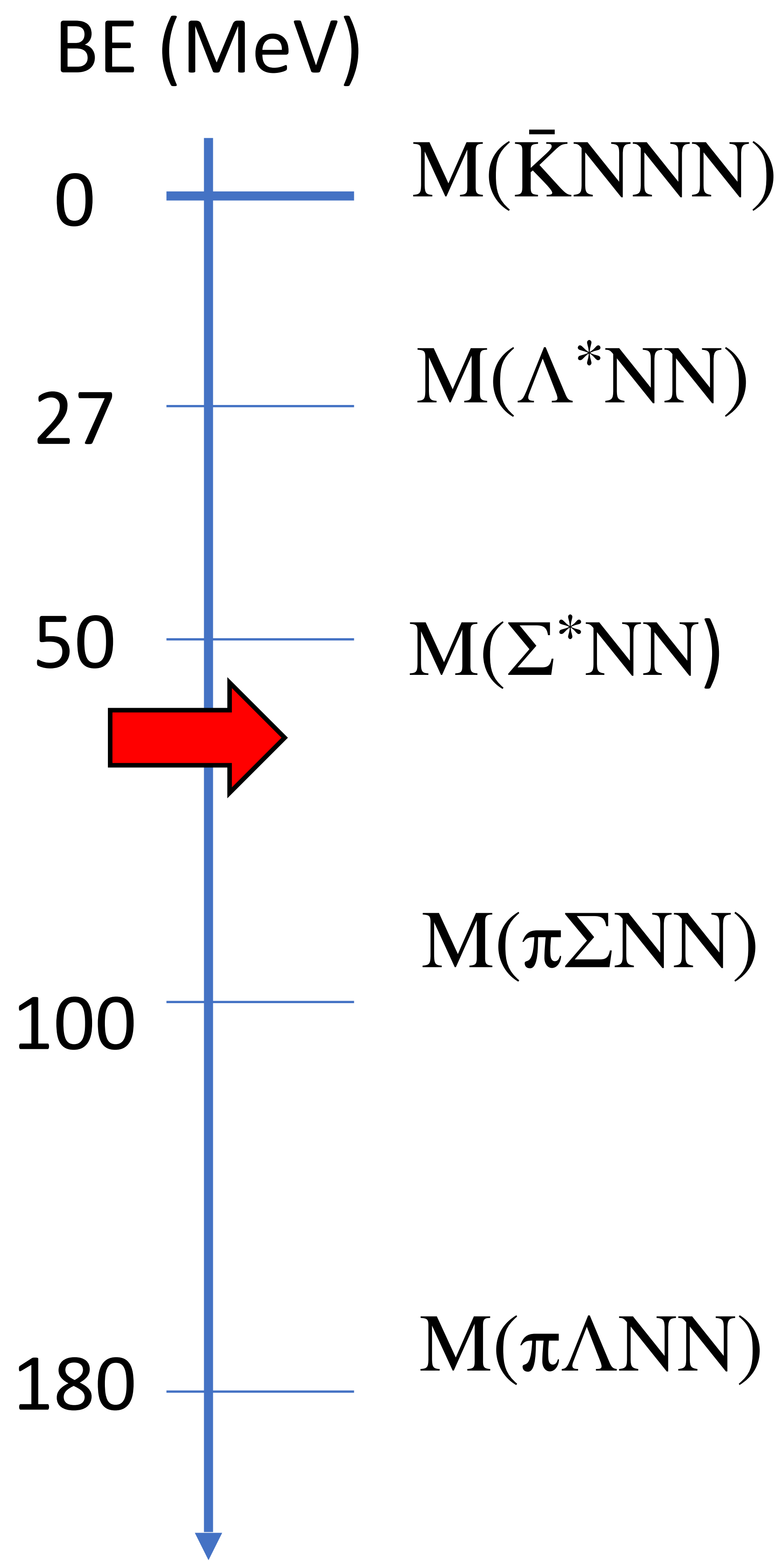
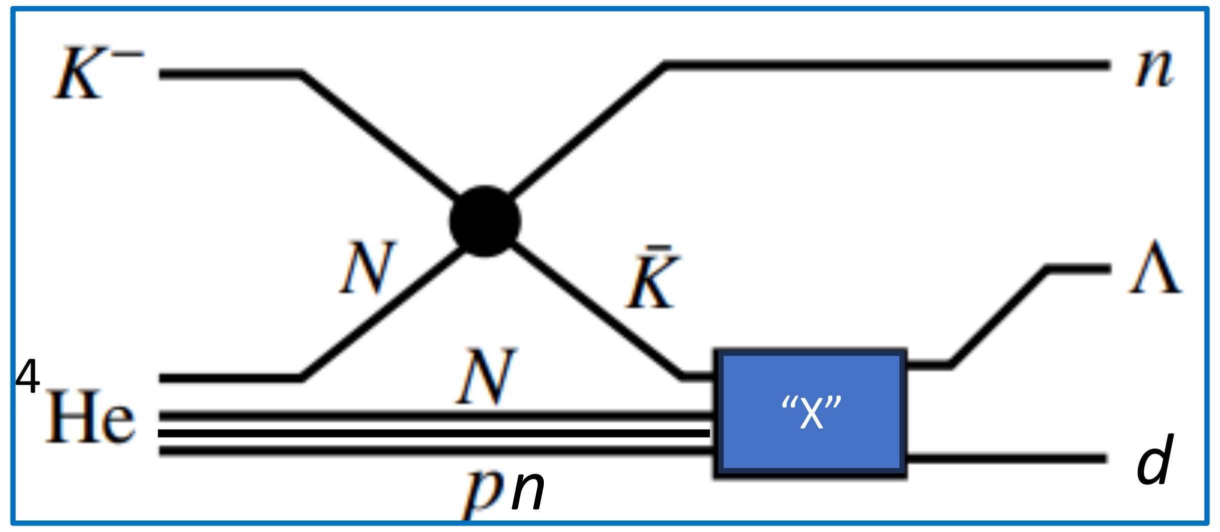
1. **“X”→Λd decay mode is unique evidence of $I_{\text{“X”}}$ = 0**
   - I(J^P) : Λ = 0(1/2⁺), d = 0(1⁺), K^- = 1/2(0⁻), ^{3}He = 1/2(1/2⁺) , ^{4}He = 0(0⁺)
2. **If “X”=“K^-ppn”, then J would be J_{K^-ppn} = 1/2**, because J_{NNN} must be 1/2 (two nucleons out of three are identical).
   - **Most likely, it is “X”=“K^-ppn”,** in which $\bar{K}$’s isospin anti-parallel coupling with *NNN* [I(J) = 1/2(1/2)] in S-wave
   - **Difficult to interpret as *Σ*NN***: 1) spin/isospin of NN [I(J) = 1(0)] part must flip to form deuteron [I(J) = 0(1)] without breaking the NN pair, while 2) the energy release of ***Σ*N* → *ΛN*** is much bigger than the binding energy of *d.*





Size of $\bar{K}NNN$ via Data?

One nucleon $\bar{K}$ absorption ($1N_{\bar{K}A}$):

$K^- + {}^4He \rightarrow ((K^- + n)pp) + n$

$((\pi^- \Lambda) + pp) \rightarrow \pi^- \Lambda + pp$

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The ratio of the three nucleon processes would be sensitive to the core size.

1N$_{\bar{K}A}$: 2N$_{\bar{K}A}$: 3N$_{\bar{K}A}$ ~ $\rho_N : \rho_N^2 : \rho_N^3$?

Theoretical inputs are needed.

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spectators
$p_F \sim 140$ MeV/c

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Normal core: ~ 600 MeV/c

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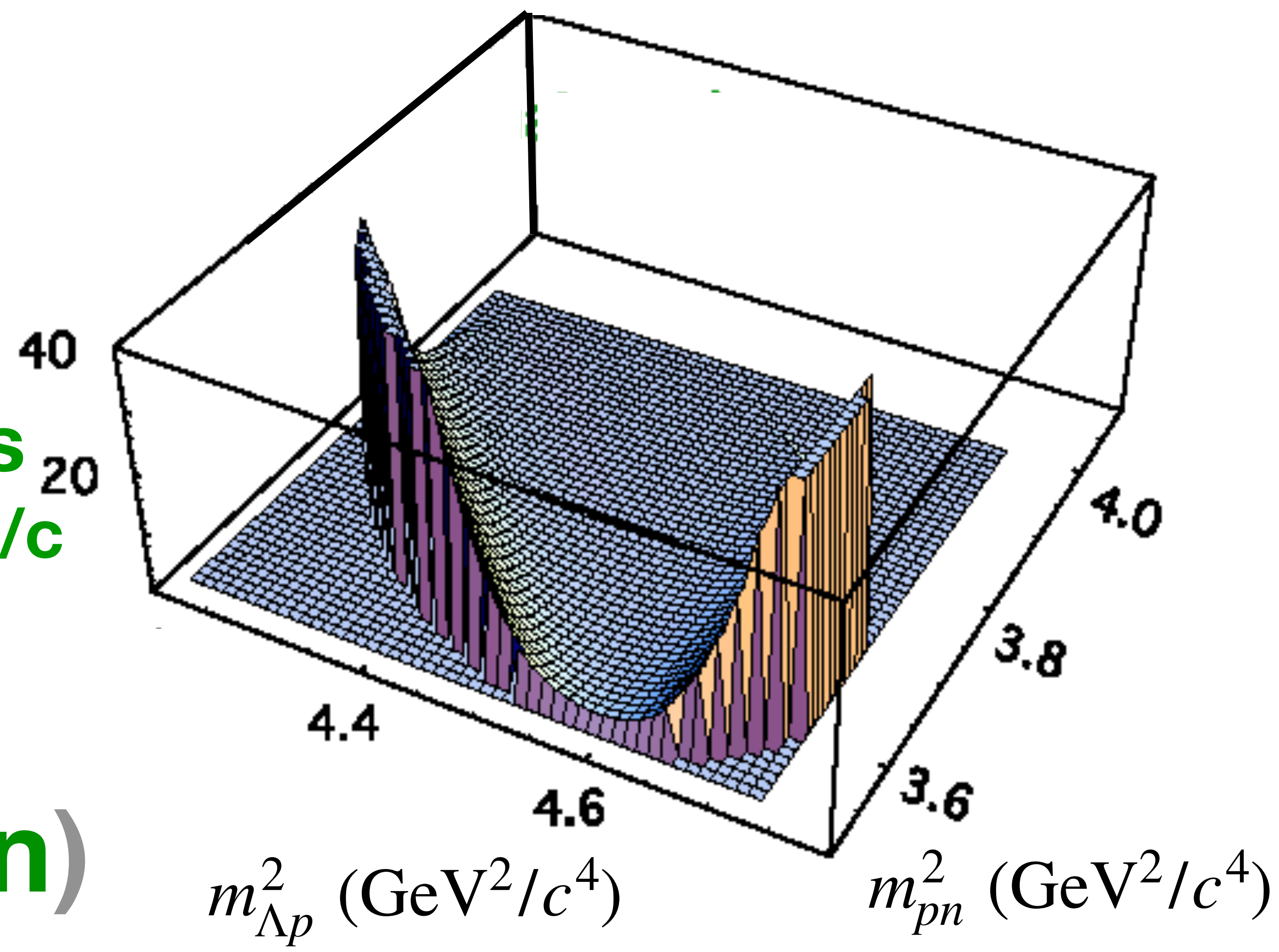
Dalitz plots

Normal core:



P. Kienle, Y. Akaishi, T. Yamazaki: Phys. Lett. B 632 (2006) 187

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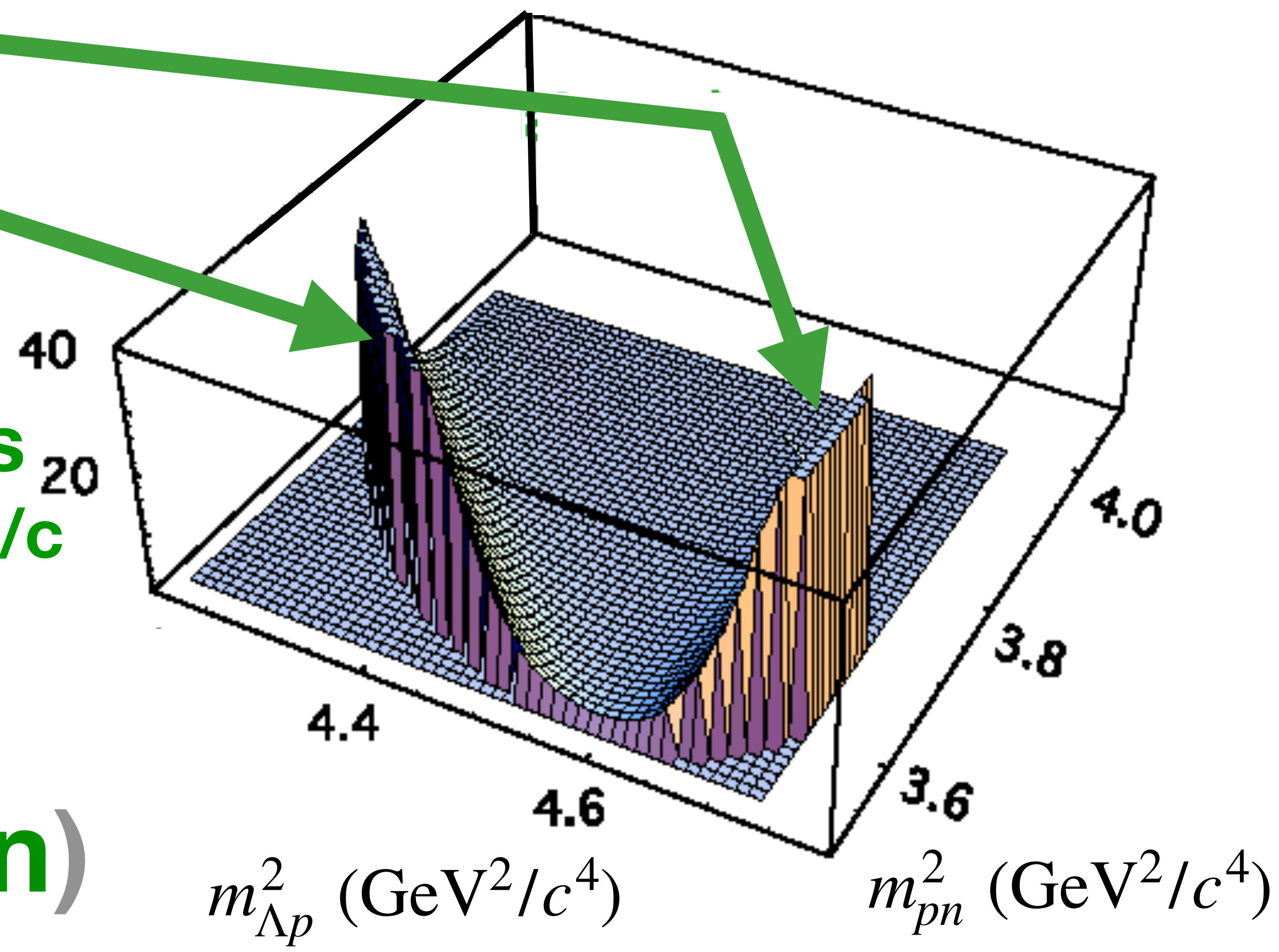

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$((K^- + pp)n) \rightarrow (\Lambda+p)+n$

$((K^- + pn)p) \rightarrow (\Lambda+n)+p$

Compact core: roughly ~ 470 MeV/c

Normal core: ~ 600 MeV/c

spectators p_F ~ 140 MeV/c

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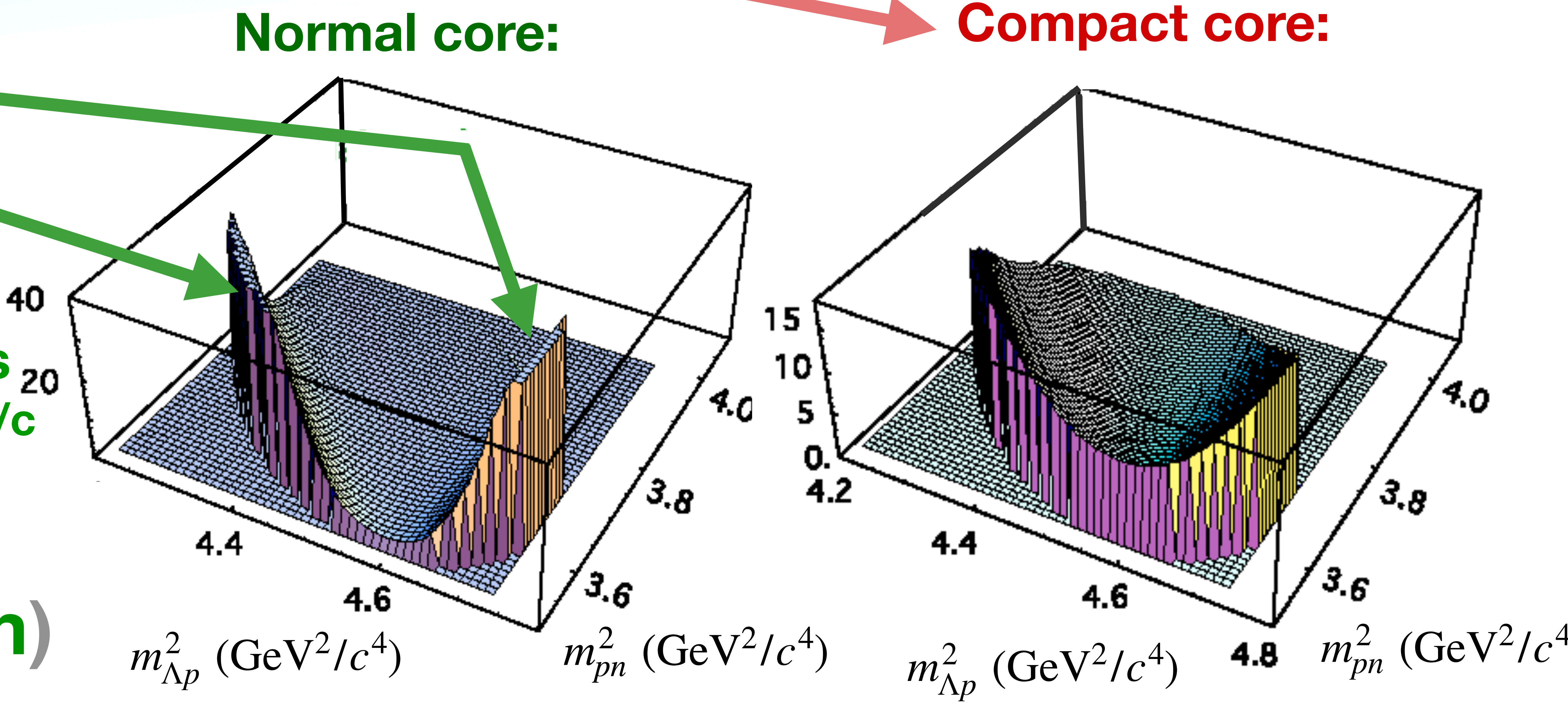


P. Kienle, Y. Akaishi, T. Yamazaki: Phys. Lett. B 632 (2006) 187

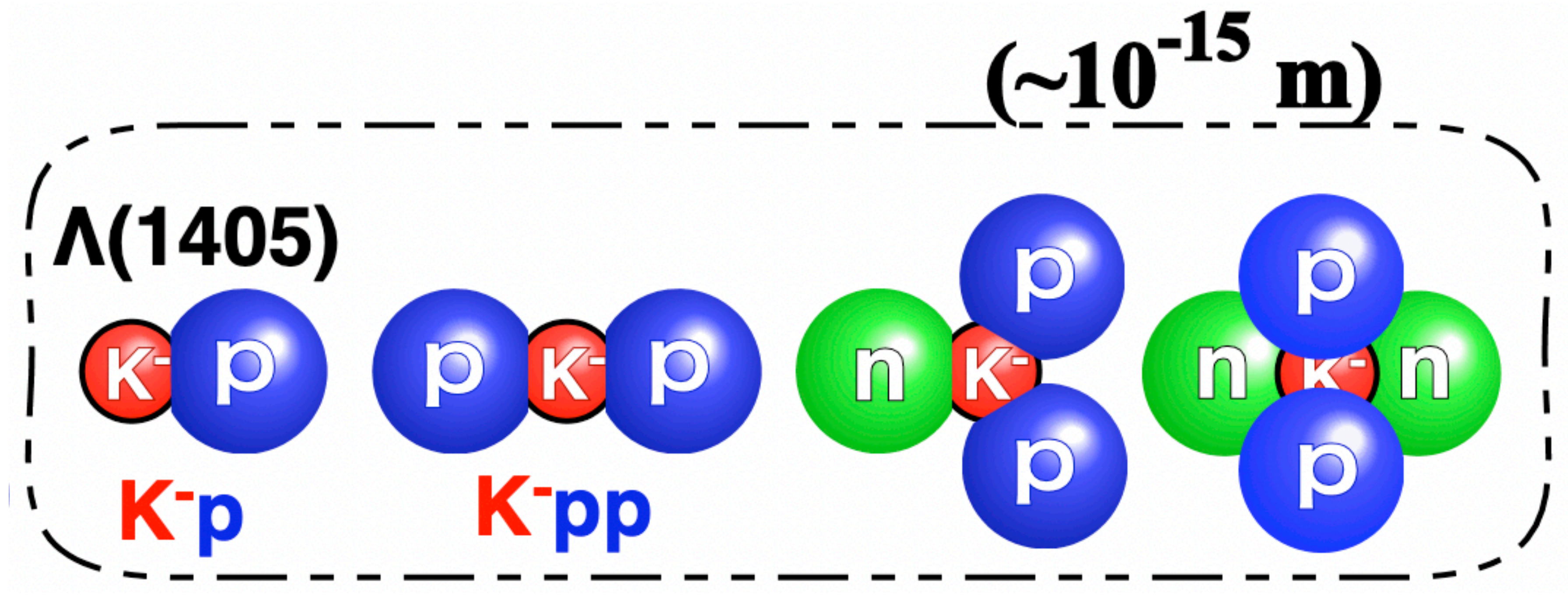
Toward next generation research — New Spectrometer —

Does Isospin-partner $(\bar{K}^0 nn)_{I_3=-1/2}$ exist?

Are kaonic nuclei really compact?

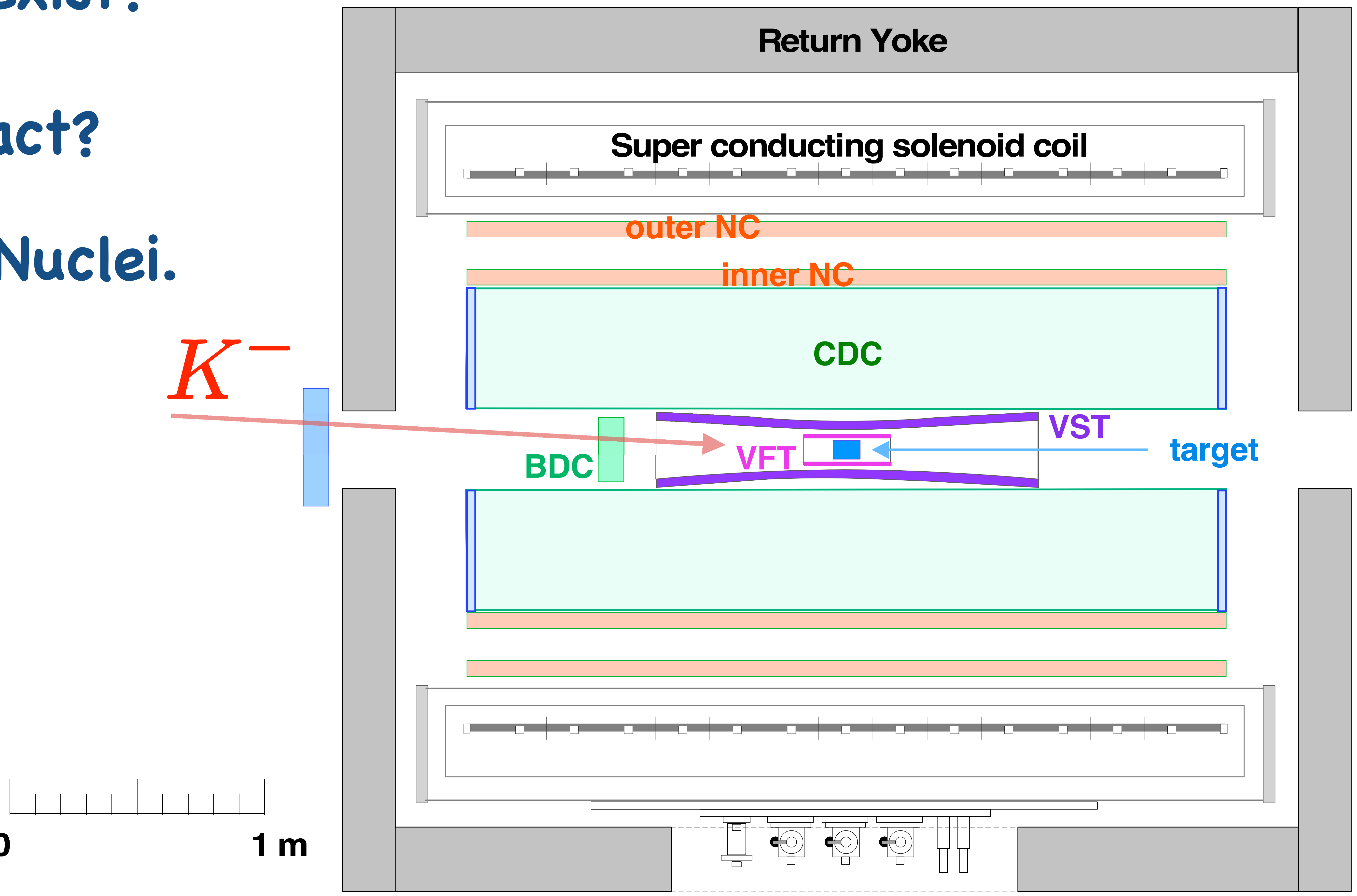
Theoretical exploration of Kaonic Nuclei.

for the systematic study on



molecule-like hadronic nuclear cluster

"Does it have a unique shape like a chemical molecule?"



... *Construction is in progress, led by F. Sakuma*

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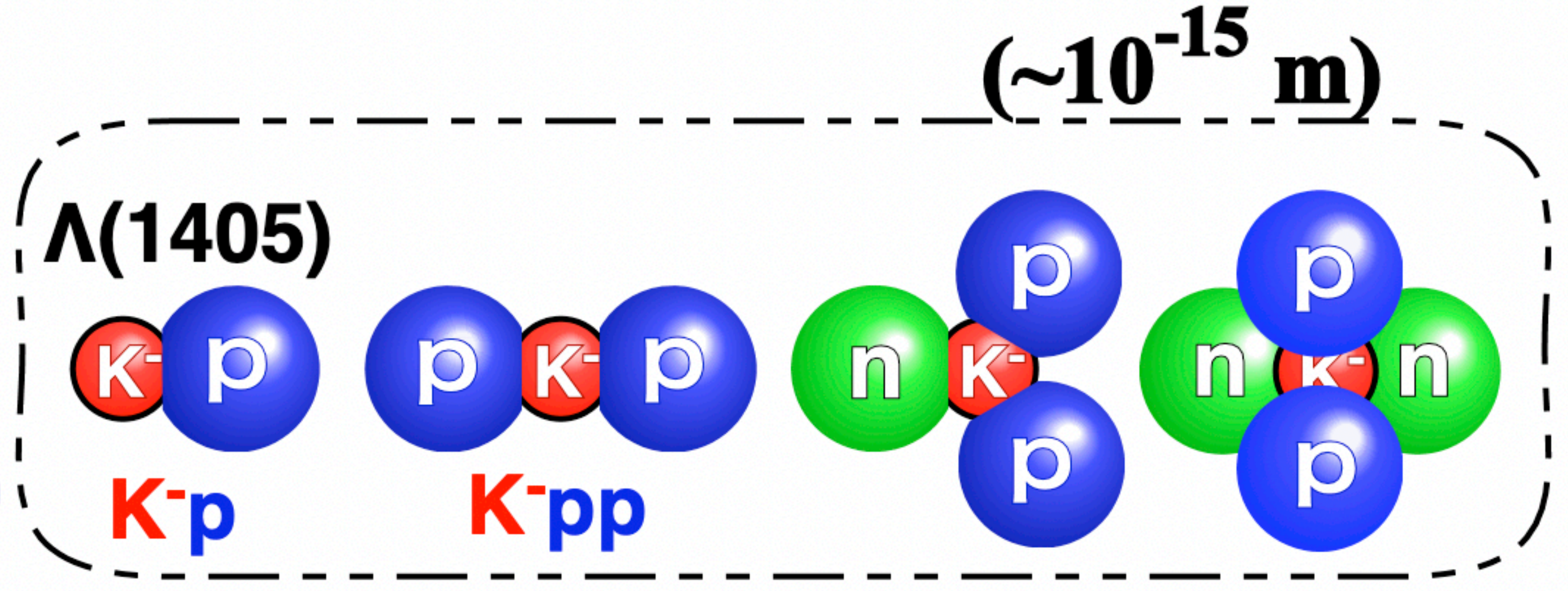
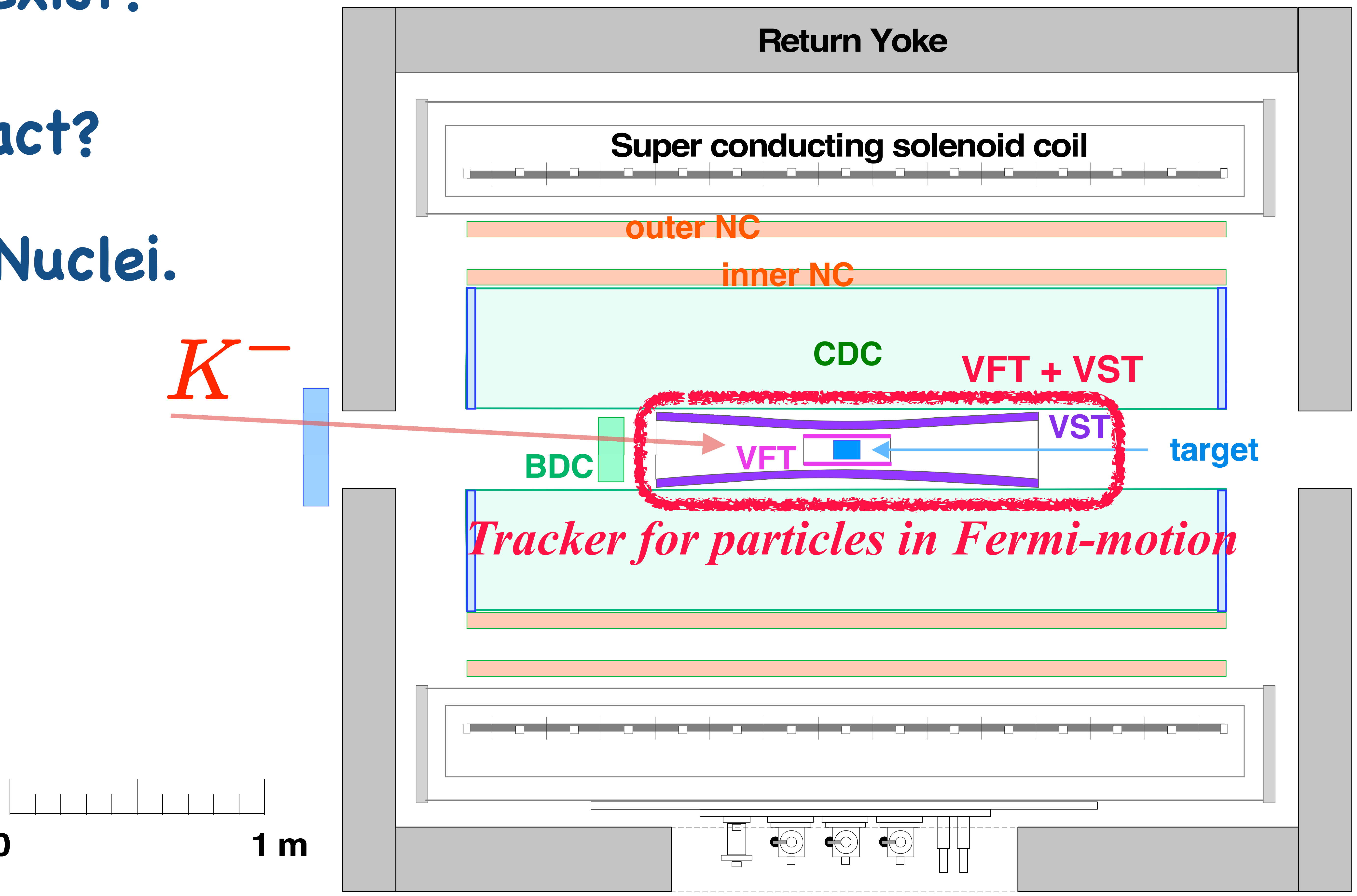
Theoretical exploration of Kaonic Nuclei.

for the systematic study on



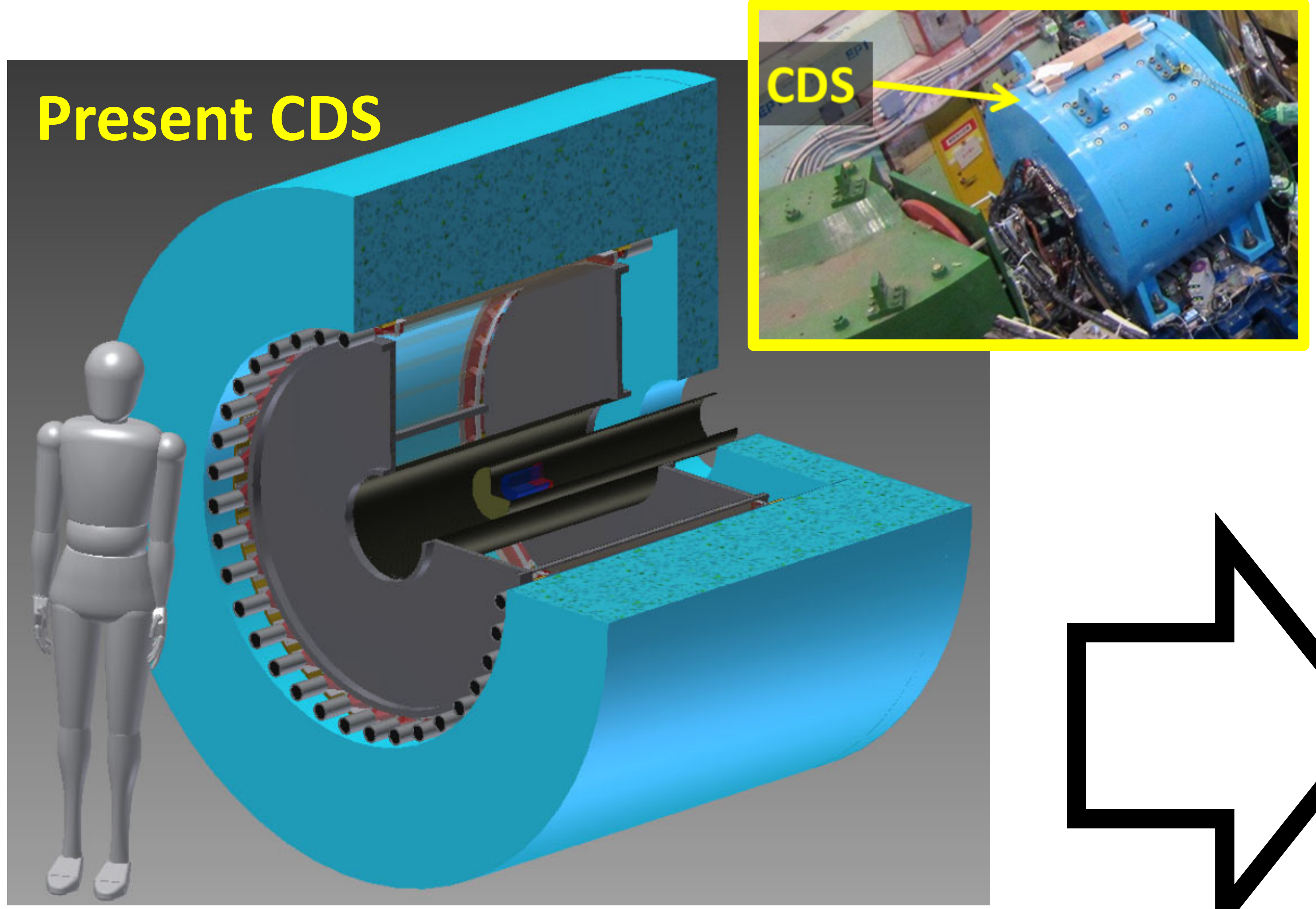
molecule-like hadronic nuclear cluster

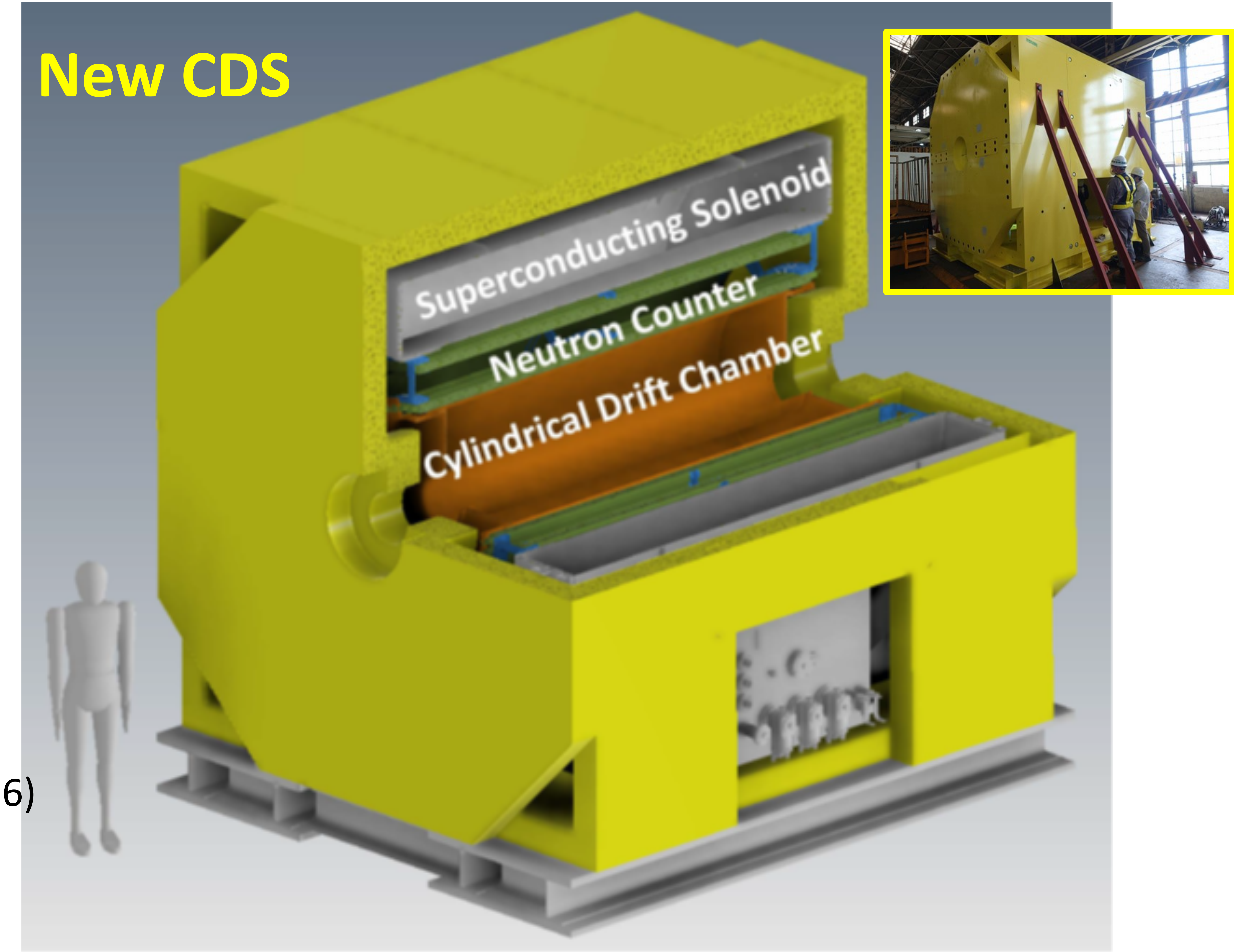
"Does it have a unique shape like a chemical molecule?"



... Construction is in progress, led by F. Sakuma

New Cylindrical Detector System (CDS)



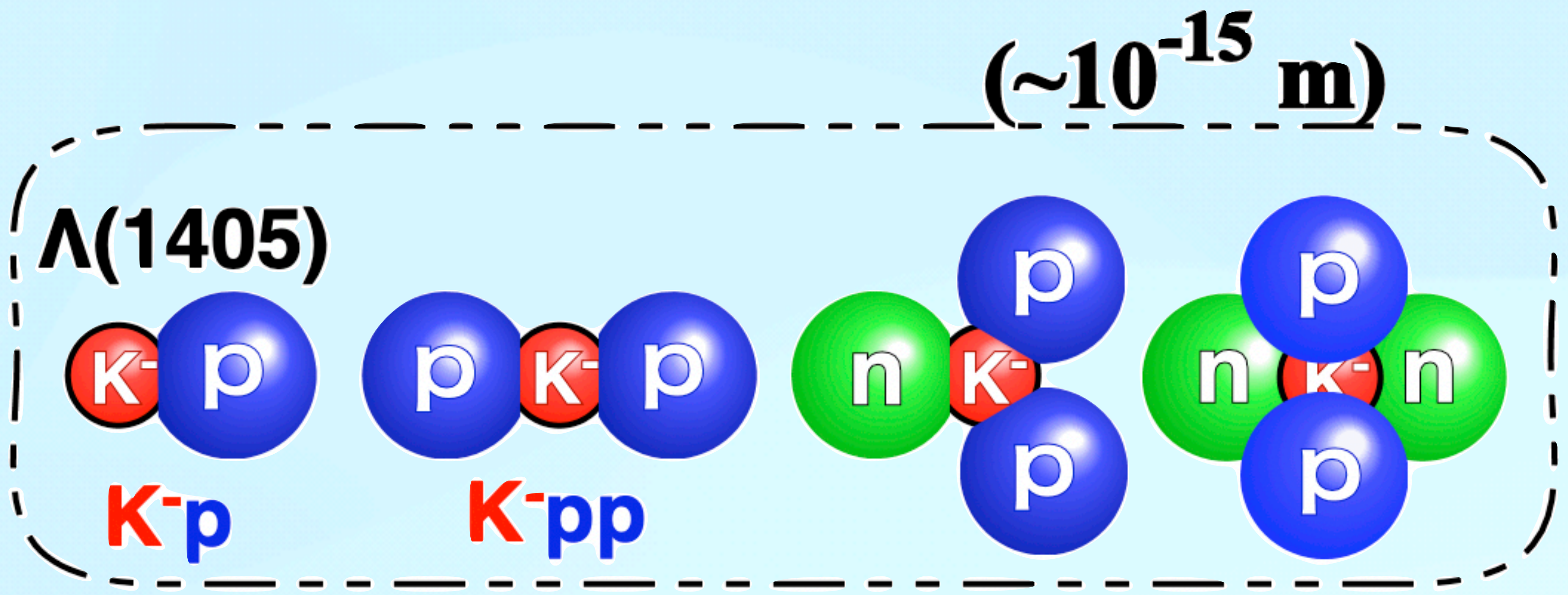


√**Solid angle: x1.6** (59% → 93%)

√**Neutron eff.: x7** (3% → 12%x1.6)

With new spectrometer, we will conduct

— a systematic study on light kaonic nuclei —

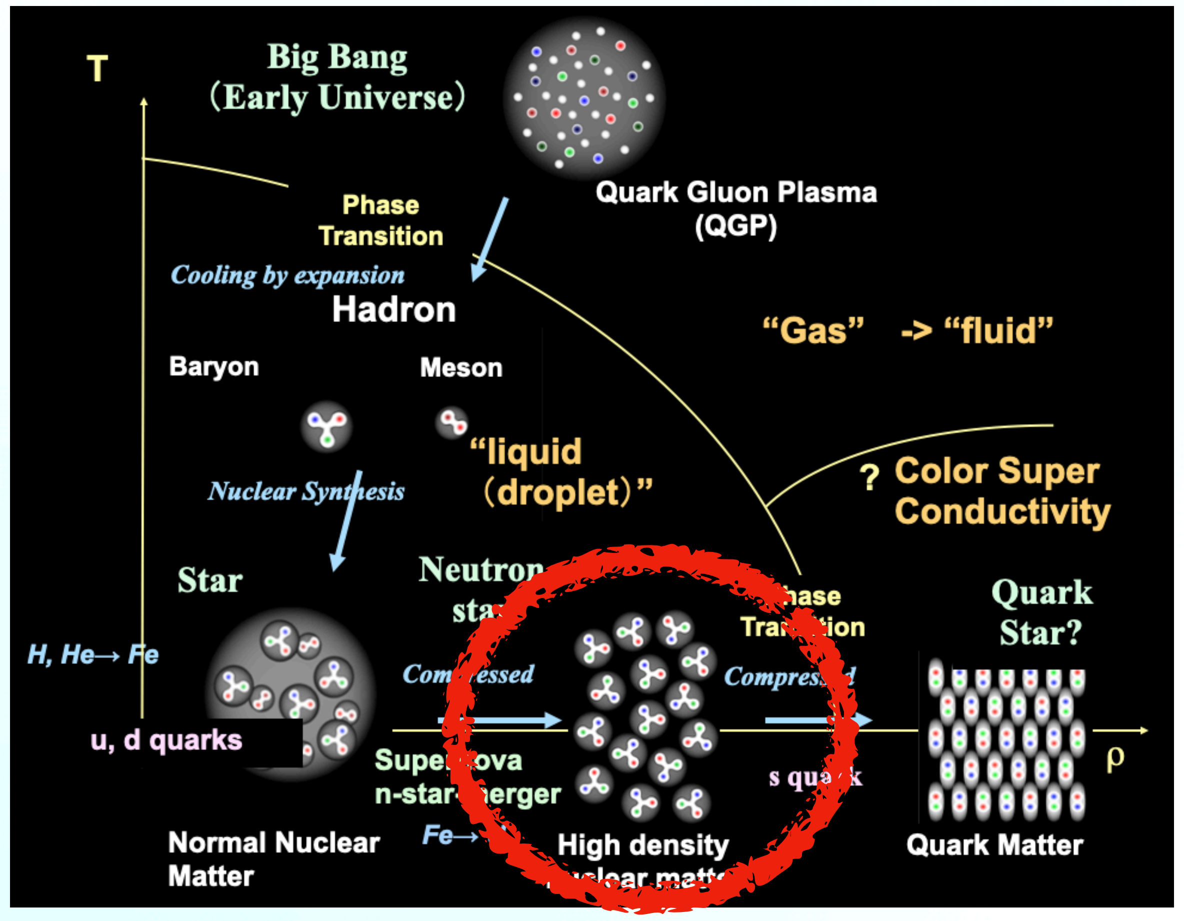


"Does it have a unique shape like a chemical molecule?"

molecule-like hadronic nuclear cluster

By establishing the $I(J^P)$, presence of "K^- nn" — a Charge Mirror State of "K^- pp" — and the Detailed Study of Three-Nucleon Kaon Nuclear Bound State as new starting points, we aim to open the door to research on high-density nuclear matter.

How hadron mass is generated?



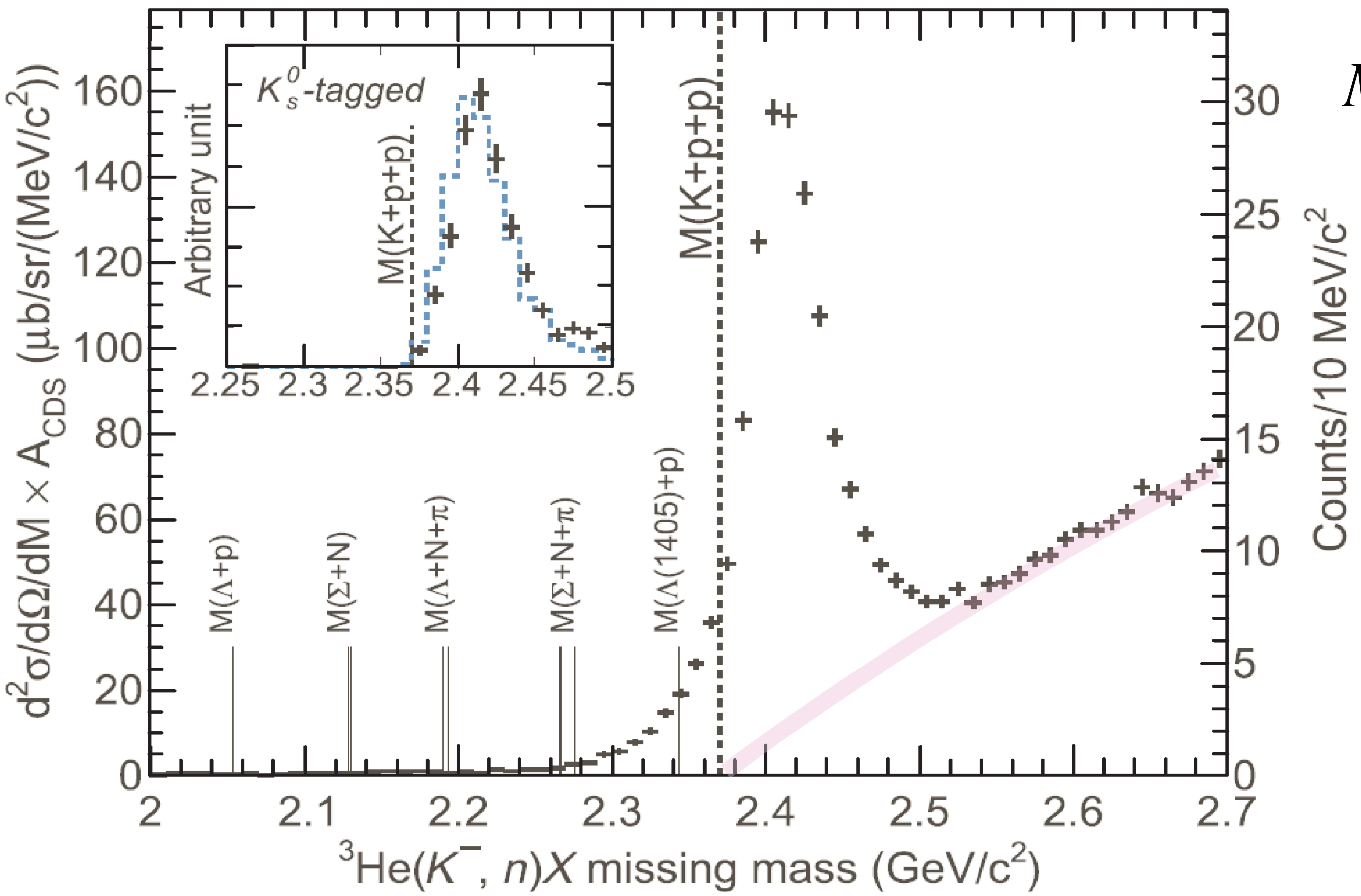
Physics at high density?

Hannes truly enjoyed his time in Japan, immersing himself in the physics research and embracing new experiences with enthusiasm. As our field evolves, the need for long-term projects and collaborative efforts across multiple disciplines has become increasingly vital. Inspired by Hannes's passion for discovery, I am committed to continuing this valuable research and building on what we've accomplished together. I would like to extend an invitation to anyone interested in embarking on new collaborations. Together, we can explore new frontiers in physics and create truly remarkable Hadronic-Molecule Study — Kaonic Nuclear Bound State. If you share this vision, I encourage you to join us in this exciting journey!

Thank you for your attention!

^{3}He(K^-, n_{NC})X — semi-inclusive

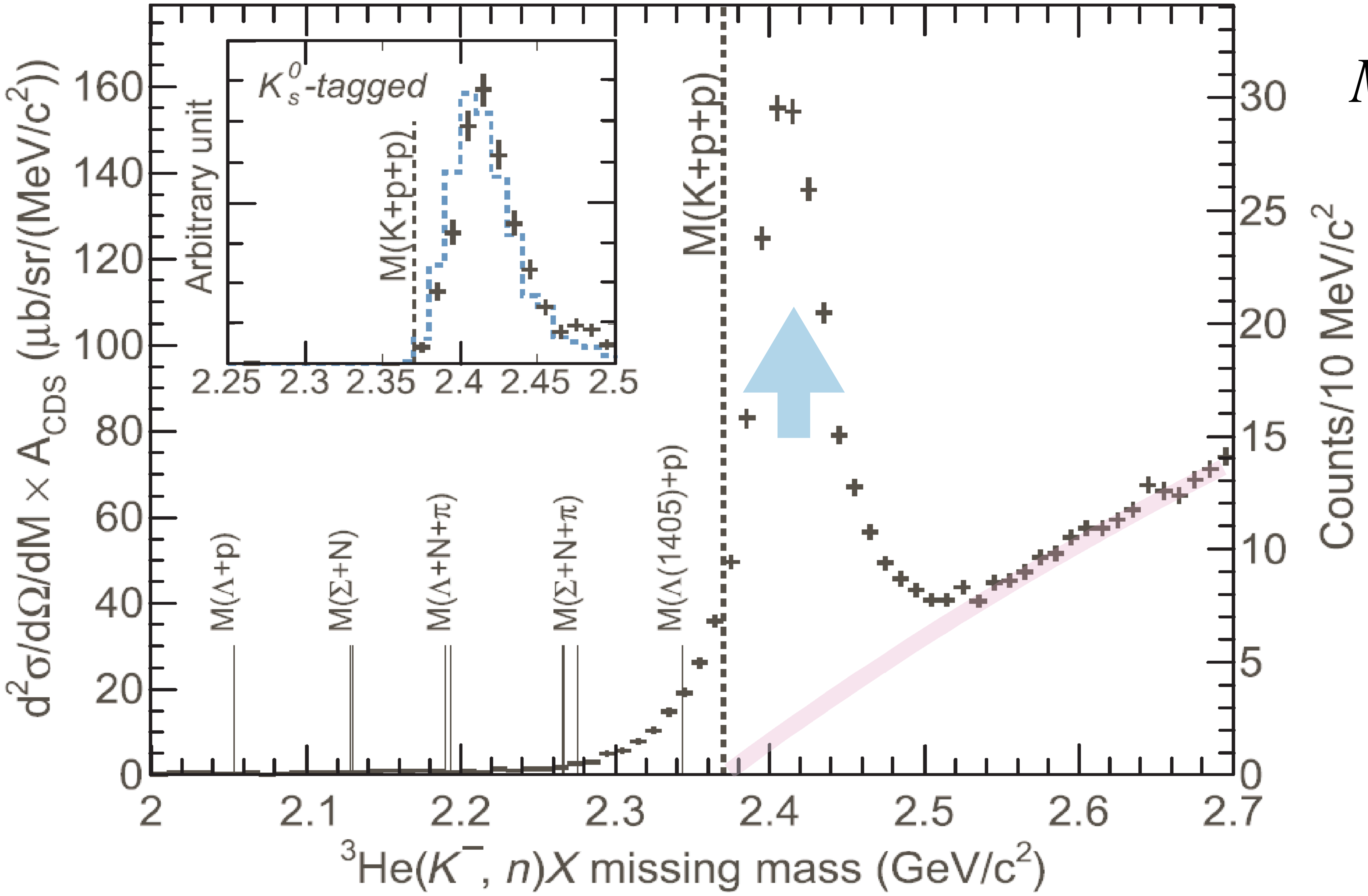
$$K^- + {}^3\text{He} \to (\bar{K} + NN) + n'$$



$M(K^- pp) \sim 2.37$ GeV$/c^2$

$^3He(K^-, n_{NC})X$ — semi-inclusive

$$K^- + {}^3\text{He} \rightarrow (\bar{K} + NN) + n'$$

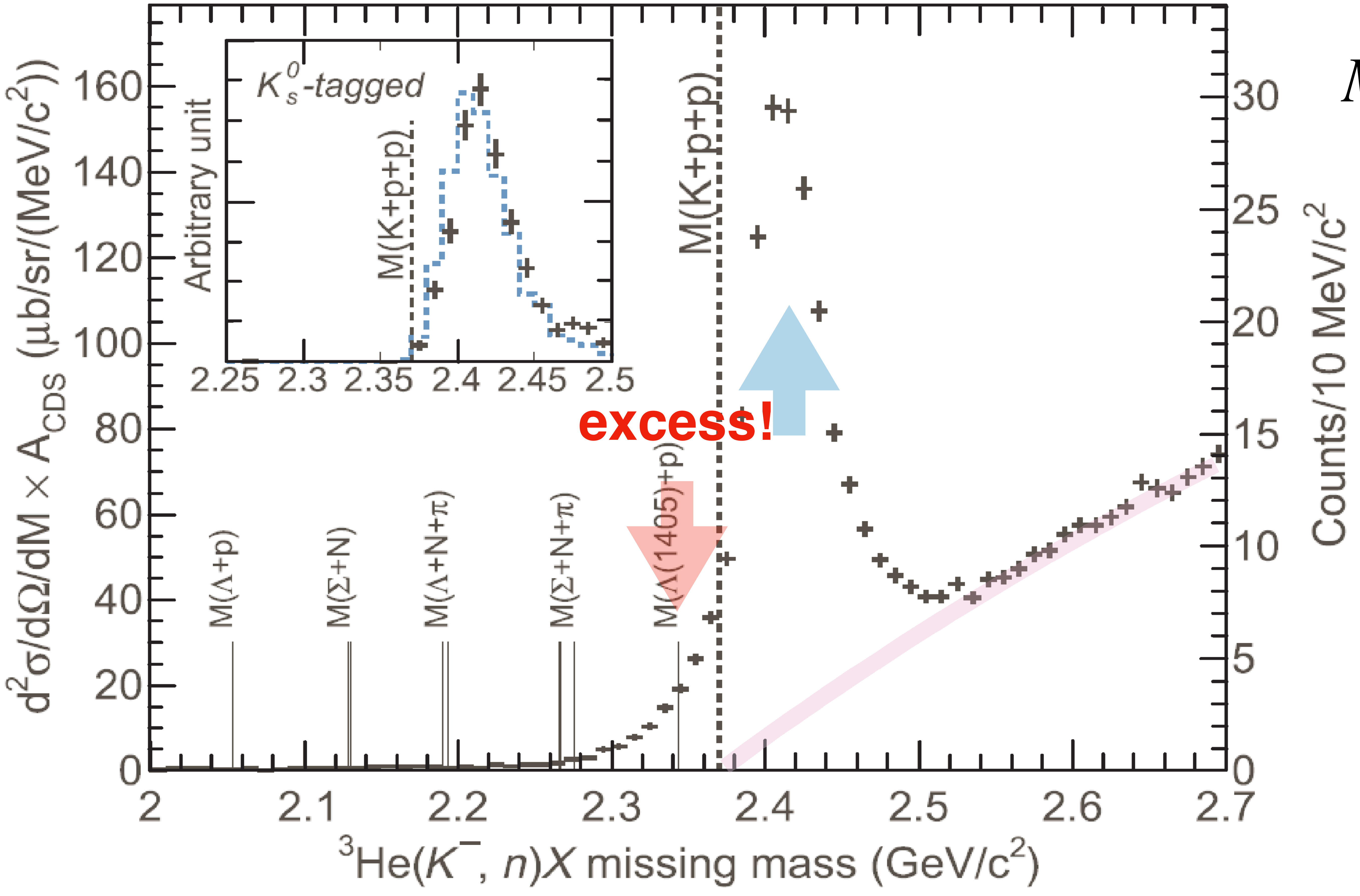


$M(K^-pp) \sim 2.37\ \text{GeV}/c^2$

A nucleon knockout reaction $K^-N \rightarrow \bar{K}n'$ is the dominant reaction process

^{3}He(K$^-$, n$_{NC}$)X — semi-inclusive

$$K^- + {}^3\text{He} \to (\bar{K} + NN) + n'$$



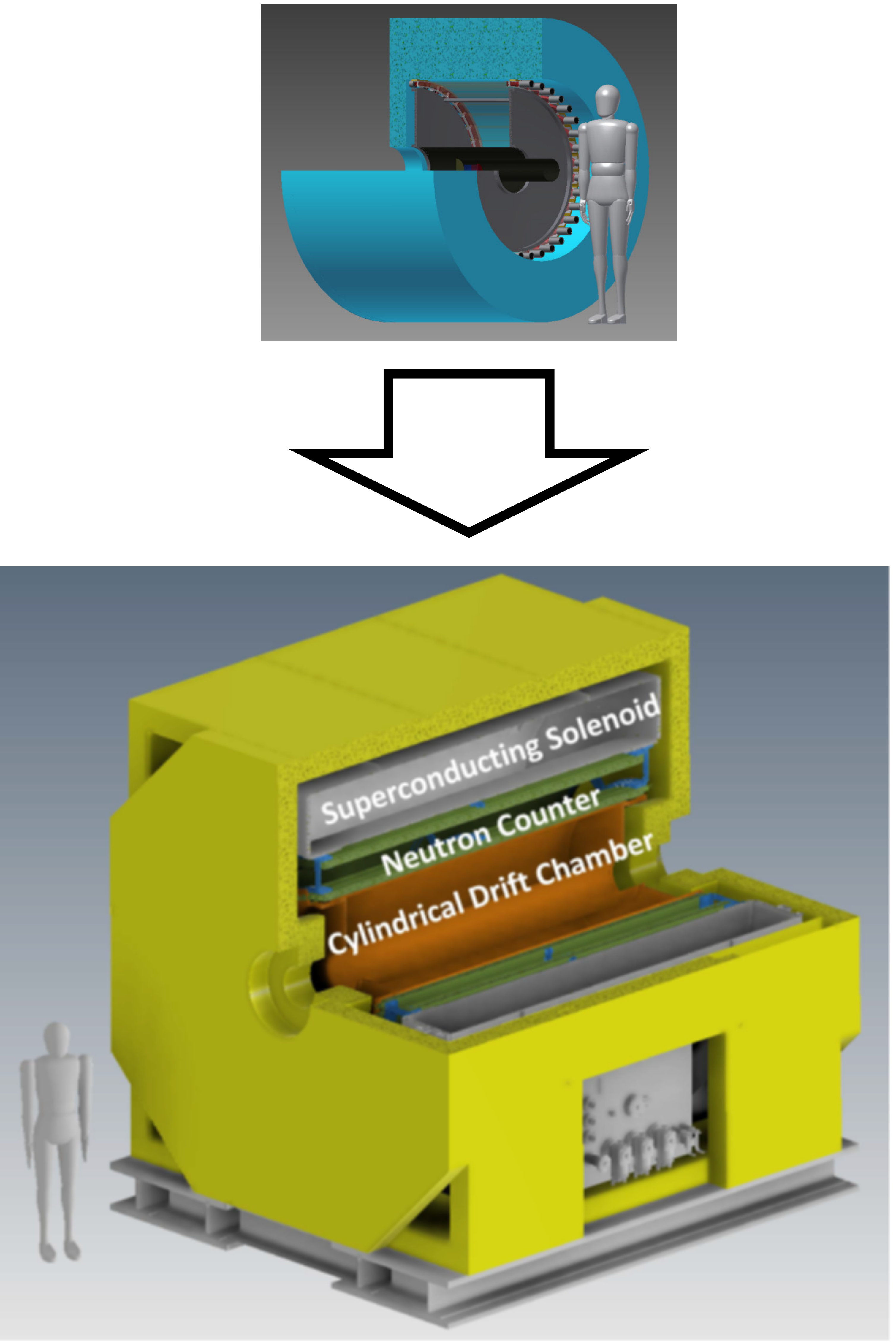
$M(K^-pp) \sim 2.37\ \text{GeV}/c^2$

How to study excess:

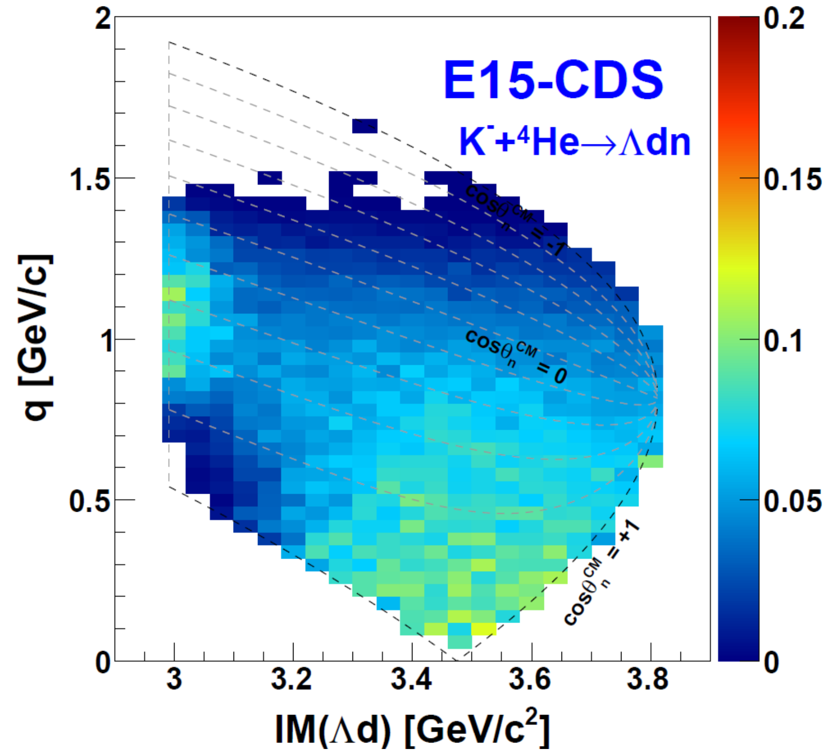
$\bar{K} + NN \to \Lambda p$ happens only when all the particles are in the strong interaction range, because of energy-momentum mismatch

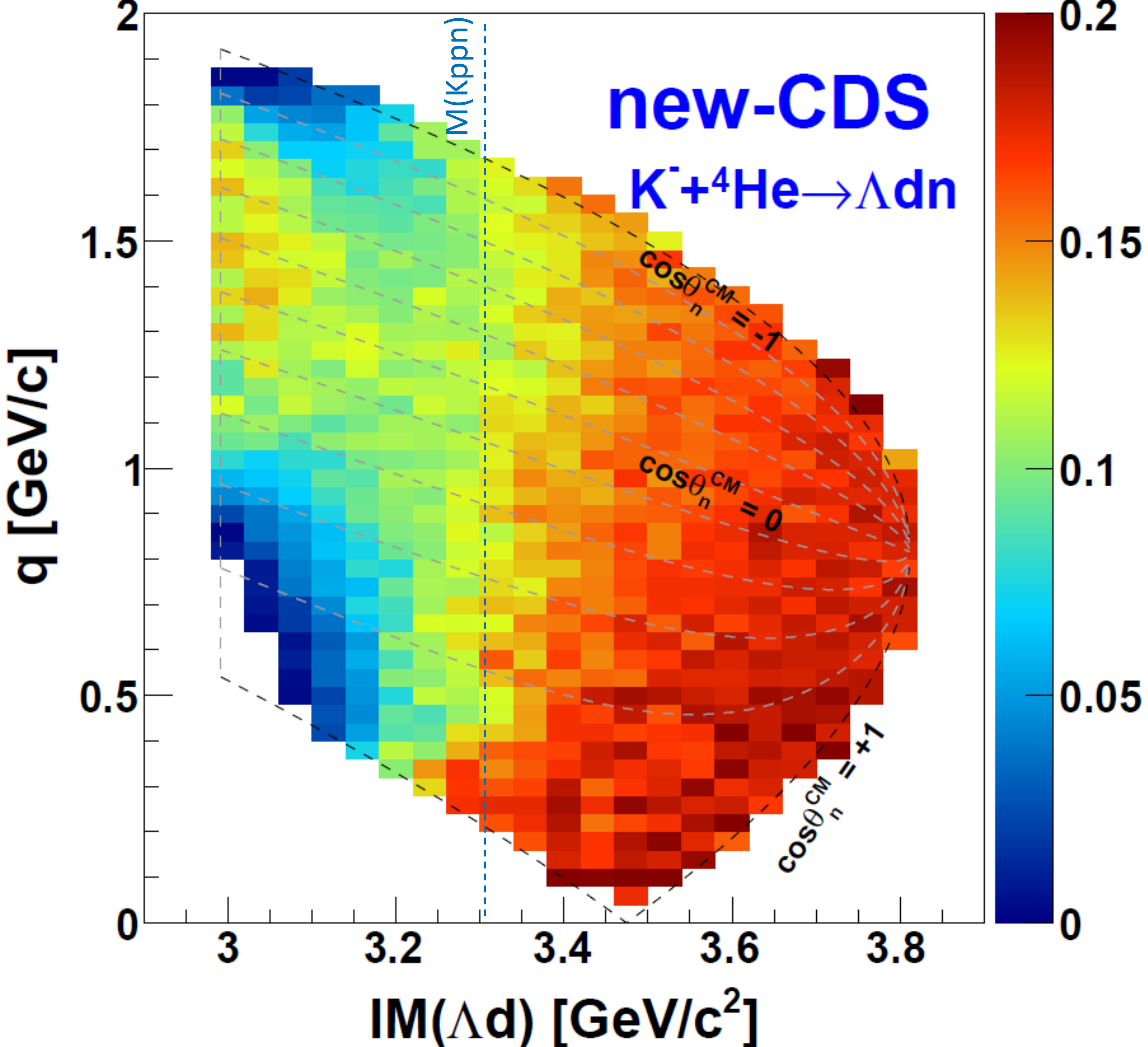
A nucleon knockout reaction $K^-N \to \bar{K}n'$ is the dominant reaction process

Acceptance for K^{-} ^{4}He reaction

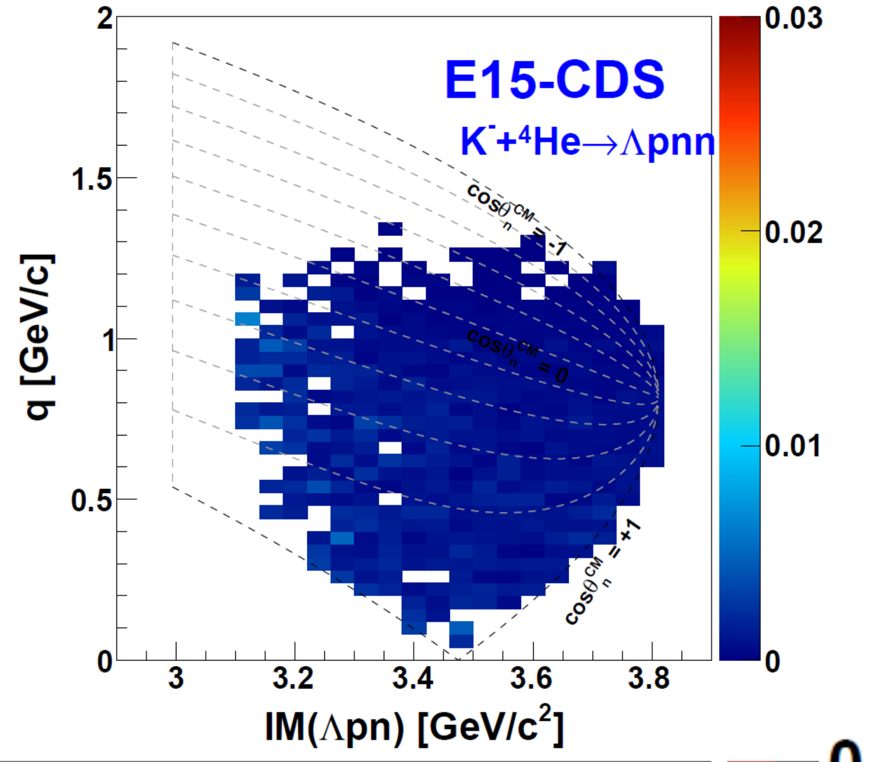


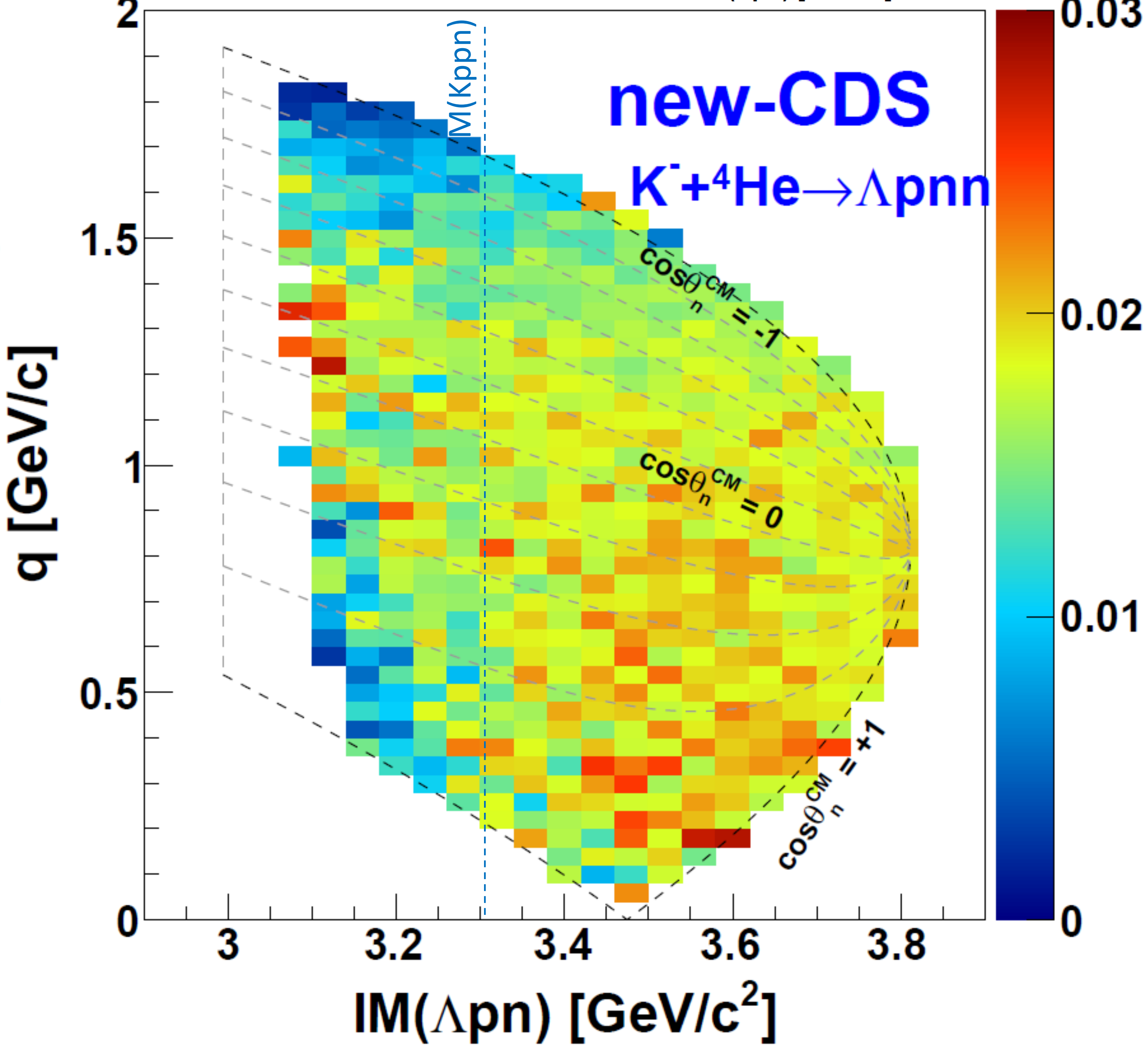
Λd in CDS





Λpn in CDS





Possible I(J^P) ?

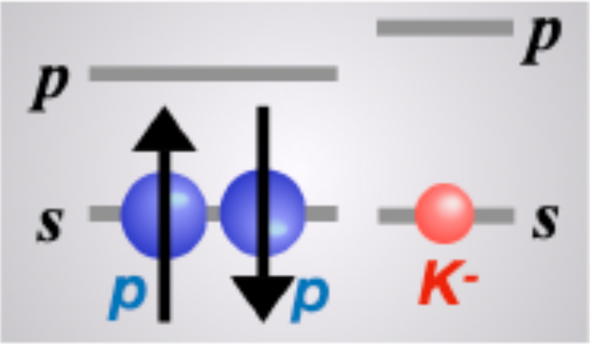
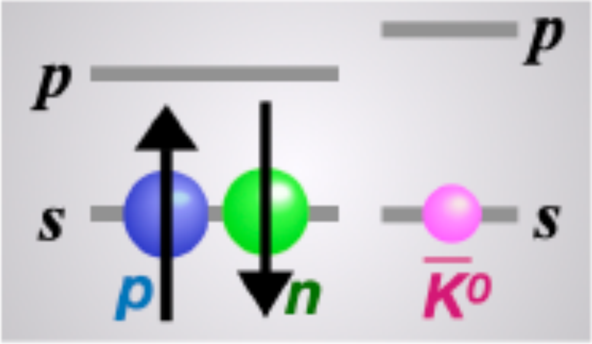
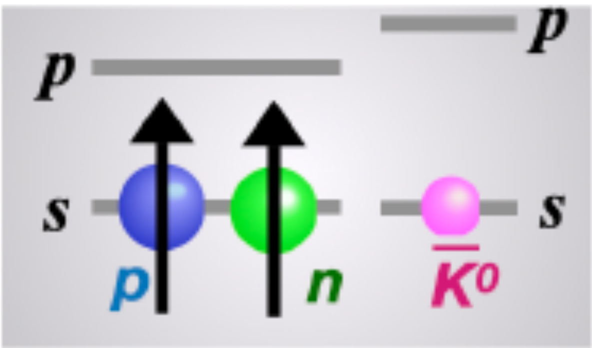
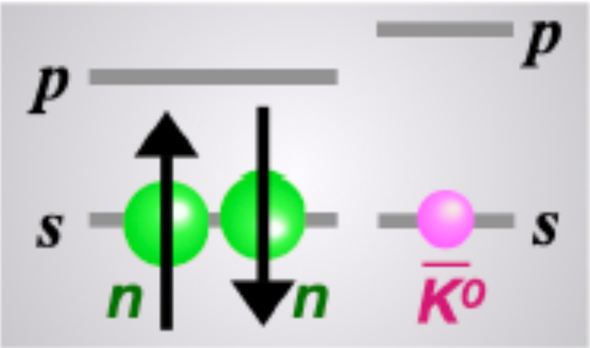
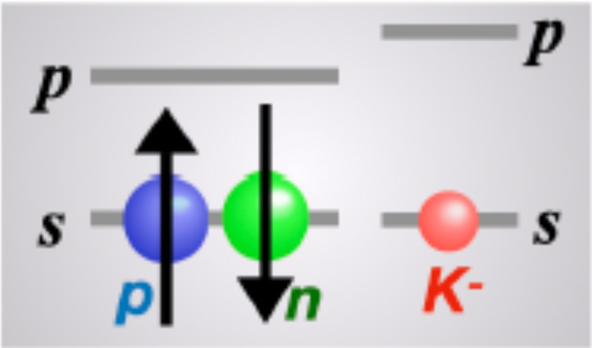
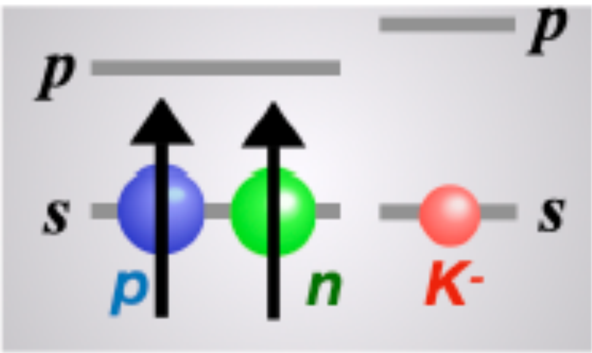
$\bar{K}NN$: $J^P = 0^-$, $I = 1/2$: $I_{NN} = 1$, $S_{NN} = 0$, $L_{\bar{K}} = 0$

nucleon isospin symmetric (I_{NN} = 1) and spin anti-symmetric (S_{NN} = 0)

$\bar{K}NN$: $J^P = 1^-$, $I = 1/2$: $I_{NN} = 0$, $S_{NN} = 1$, $L_{\bar{K}} = 0$

nucleon isospin anti-symmetric (I_{NN} = 0) and spin symmetric (S_{NN} = 1)

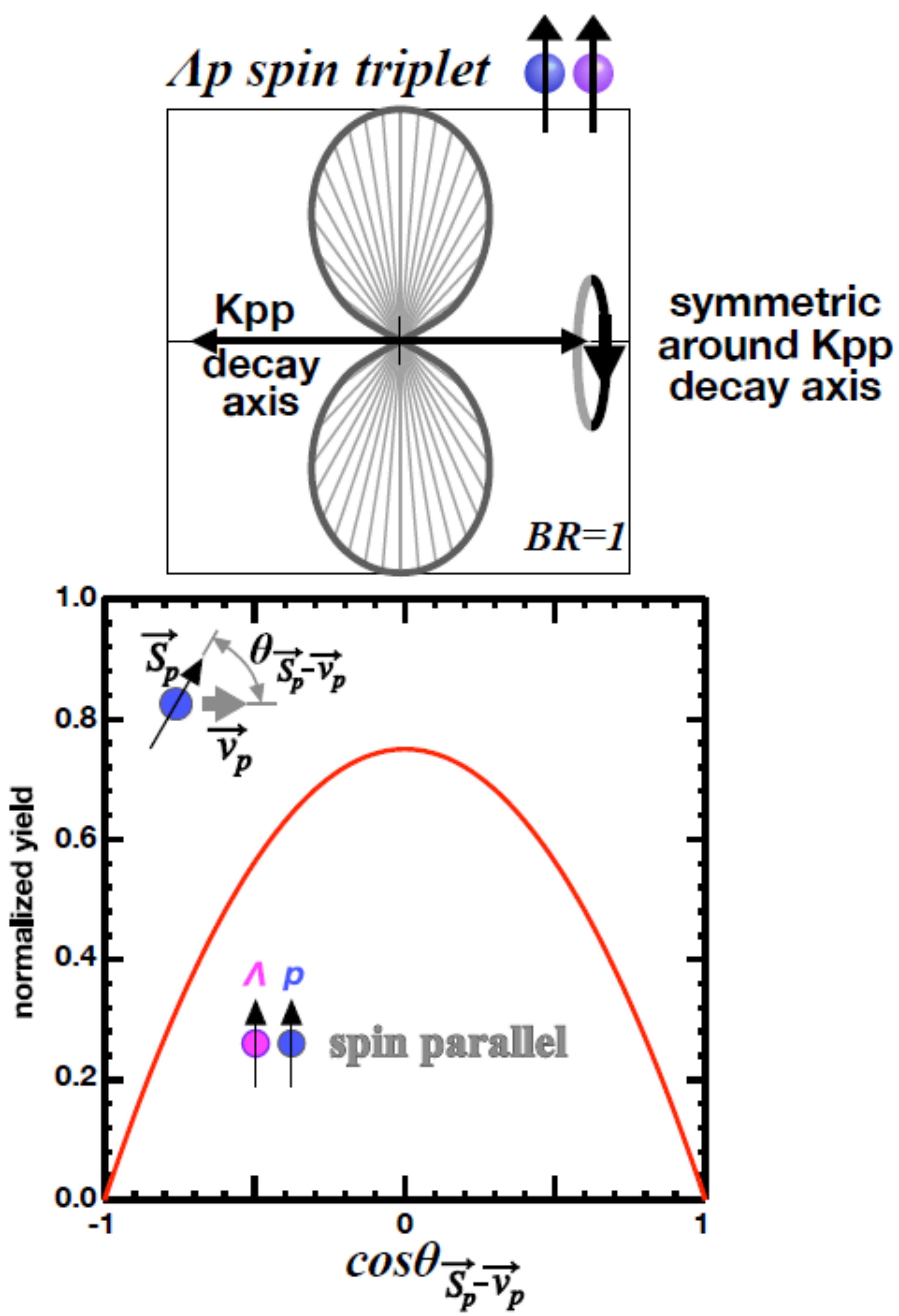
"K^-pp" $\rightarrow \Lambda p$ requires $I = 1/2$, presence of kaon requires negative parity, and the Λp dacay must be in P-wave due to the negative parity

$I(\bar{K}NN)\,/\,J^P(\bar{K}NN)$	$(1/2)\,/\,(0^-)$	$(1/2)\,/\,(1^-)$
NN symmetry	$I(NN) = 1,\ S(NN) = 0$	$I(NN) = 0,\ S(NN) = 1$
"K^-pp" $I_3(\bar{K}NN) = +\frac{1}{2}$	 +  $-\sqrt{\frac{1}{3}}\left(\sqrt{2}K^-pp + \bar{K}^0\frac{pn+np}{\sqrt{2}}\right)\otimes\left(\frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}\right)$	 $\bar{K}^0\frac{(pn-np)}{\sqrt{2}}\otimes\left(\uparrow\uparrow, \frac{\uparrow\downarrow + \downarrow\uparrow}{\sqrt{2}}, \downarrow\downarrow\right)$
"$\bar{K}^0nn$" $I_3(\bar{K}NN) = -\frac{1}{2}$	 +  $-\sqrt{\frac{1}{3}}\left(\sqrt{2}\bar{K}^0nn + K^-\frac{pn+np}{\sqrt{2}}\right)\otimes\left(\frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}\right)$	 $-K^-\frac{(pn-np)}{\sqrt{2}}\otimes\left(\uparrow\uparrow, \frac{\uparrow\downarrow + \downarrow\uparrow}{\sqrt{2}}, \downarrow\downarrow\right)$
$\bar{K}N$ coupling	$\frac{\lvert I_{\bar{K}N} = 0\rvert^2}{\lvert I_{\bar{K}N} = 1\rvert^2} = \frac{3}{1}$	$\frac{\lvert I_{\bar{K}N} = 0\rvert^2}{\lvert I_{\bar{K}N} = 1\rvert^2} = \frac{1}{3}$
$\frac{\sigma_{\bar{K}^0nn}}{\sigma_{K^-pp}}$	$0.13 \sim 0.15$	~ 0.75

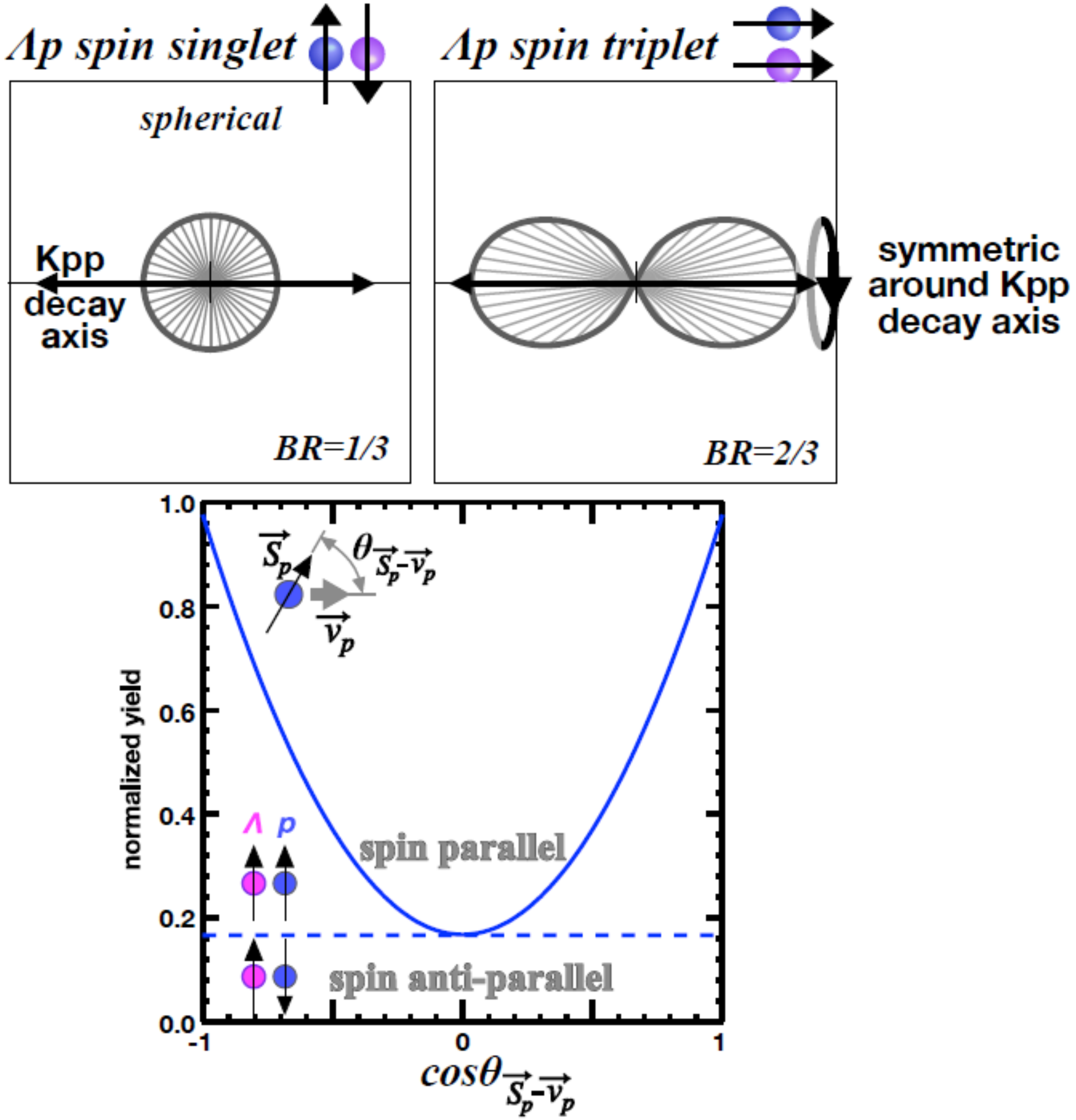
Λp decay axis and spin axis of $\bar{K}NN$ J^P

spin axis distribution referring to the decay axis

$\bar{K}NN$: $J^P = 0^-$, $I = 1/2$: $I_{NN} = 1$, $S_{NN} = 0$, $L_{\bar{K}} = 0$



$\bar{K}NN$: $J^P = 1^-$, $I = 1/2$: $I_{NN} = 0$, $S_{NN} = 1$, $L_{\bar{K}} = 0$

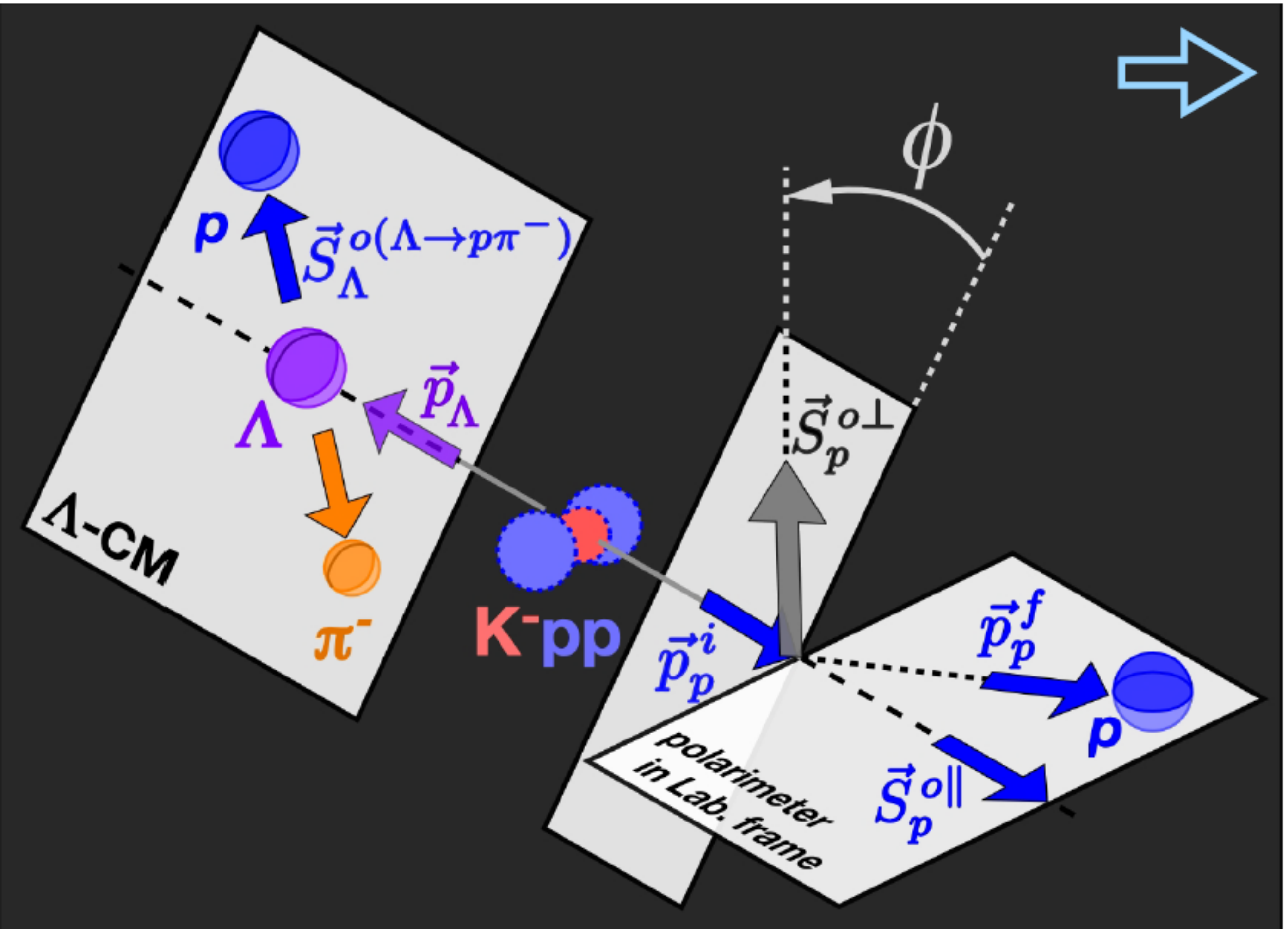


How to measure spin-spin correlation

– spin asymmetry measurement using $\Lambda \to p\pi^-$ & p-C(H) scattering–

p-C(H) scattering sensitive only on ϕ asymmetry

$\vec{S}_\Lambda^{o(\Lambda\to p\pi^-)} \approx \vec{v}_p^{(\Lambda\to p\pi^-)} (in\ \Lambda\text{–}CM)$



$$N(\phi)\,d\phi \propto (1 + r\cdot\alpha_{\Lambda p}\cos\phi)\,d\phi$$

r : scaling factor

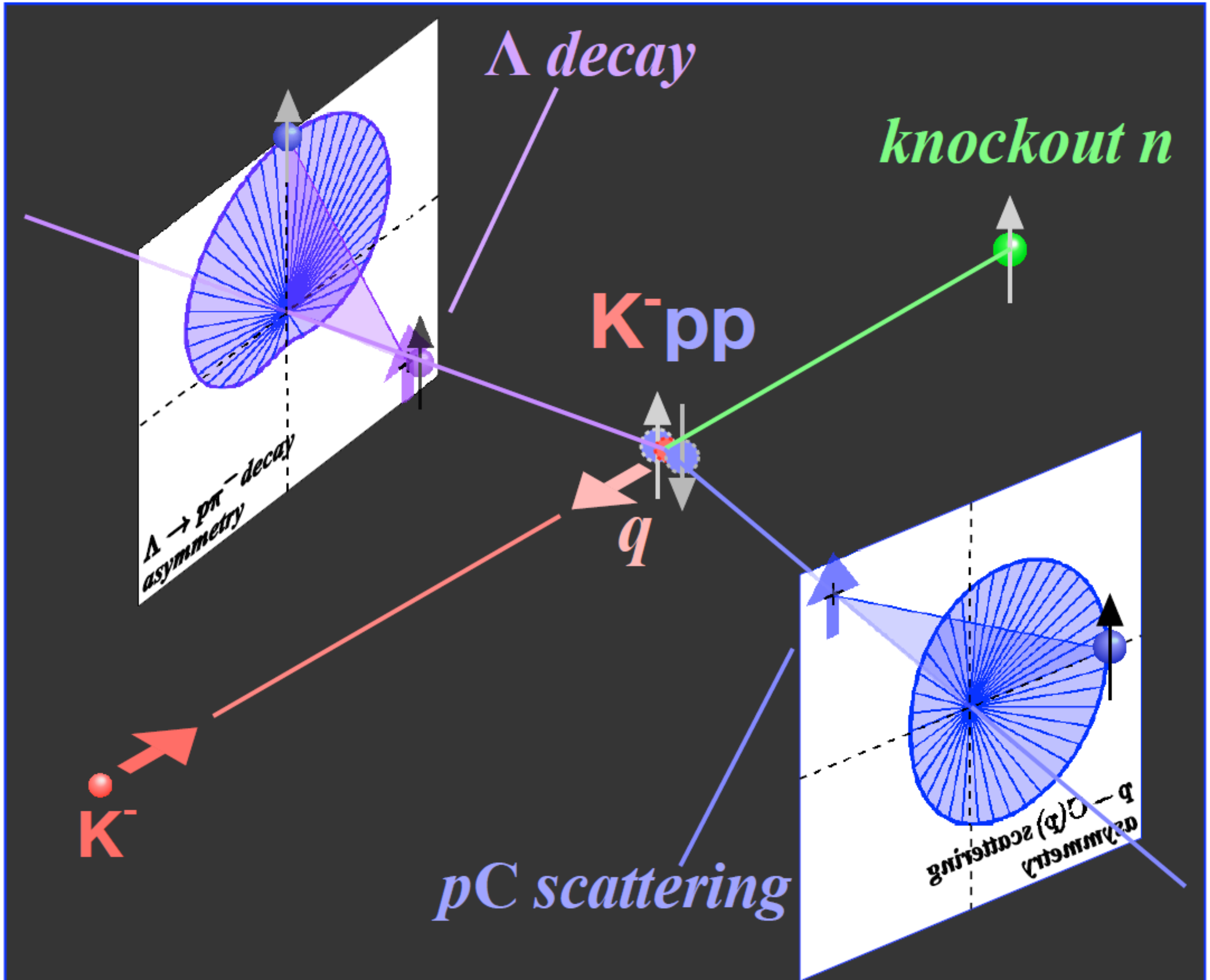
$$r = A_\Lambda \cdot A_{pC} \cdot \vec{S}\cdot\vec{S}^{\parallel} \cdot c_{conv}$$

A_Λ : Λ asymmetry parameter

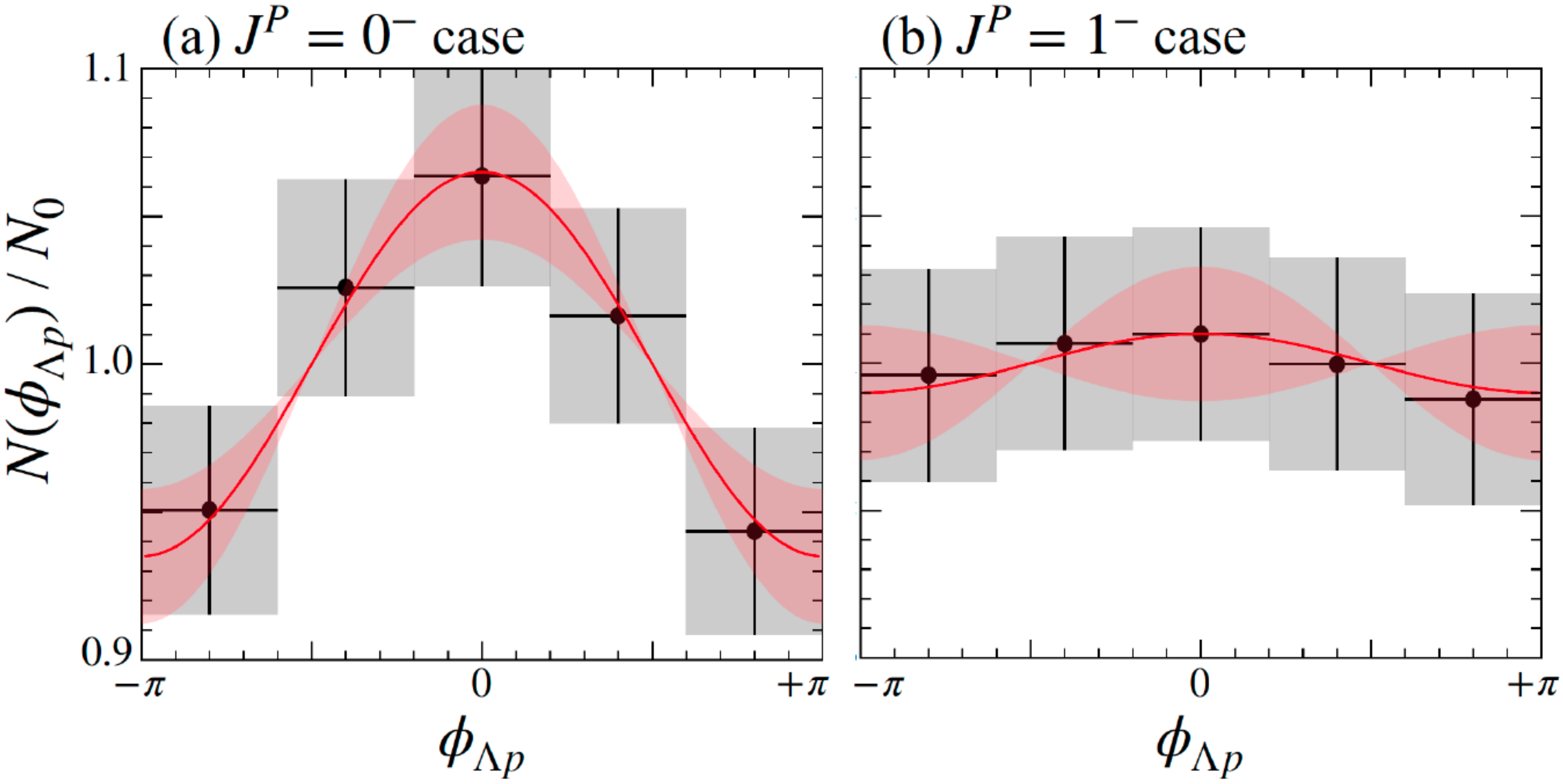
A_{pC} : proton spin-analyzing-power on carbon (and on p)

$\vec{S}\cdot\vec{S}^{\parallel}\ (\equiv \vec{S}_p\cdot\vec{S}_p^{\parallel})$: spin sensitivity referring to motional axis

c_{conv} : convolution coefficient between two asymmetries


Λ decay
knockout n
K⁻pp
Λ → pπ⁻ decay asymmetry
q
K⁻
pC scattering

Λp spin-spin asymmetry



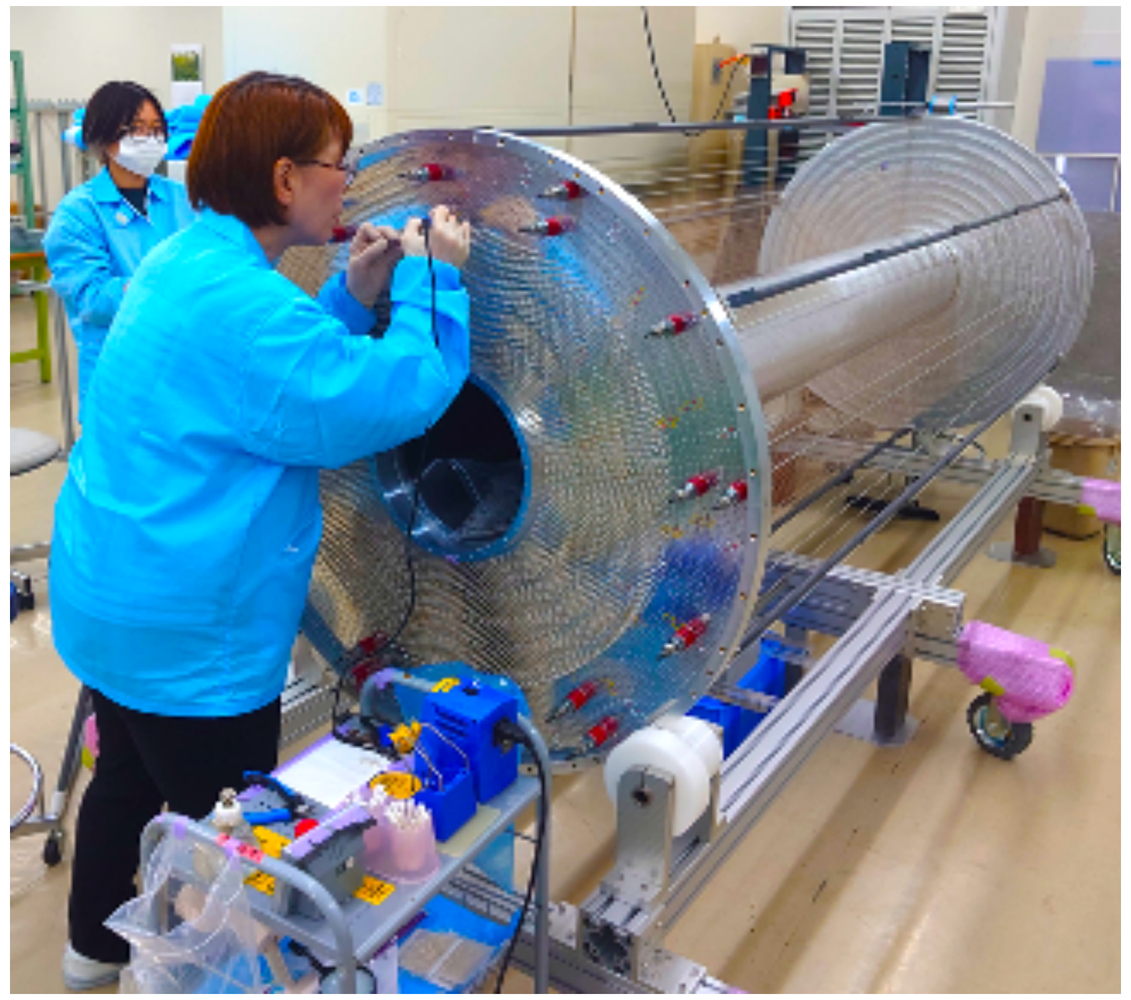
New Spectrometer under construction

Preparation of planned devices / detectors

under construction

Return Yoke

Super-conducting Solenoid Coil



Cylindrical Drift Chamber (CDC)

New Spectrometer under construction

Preparation of planned devices / detectors

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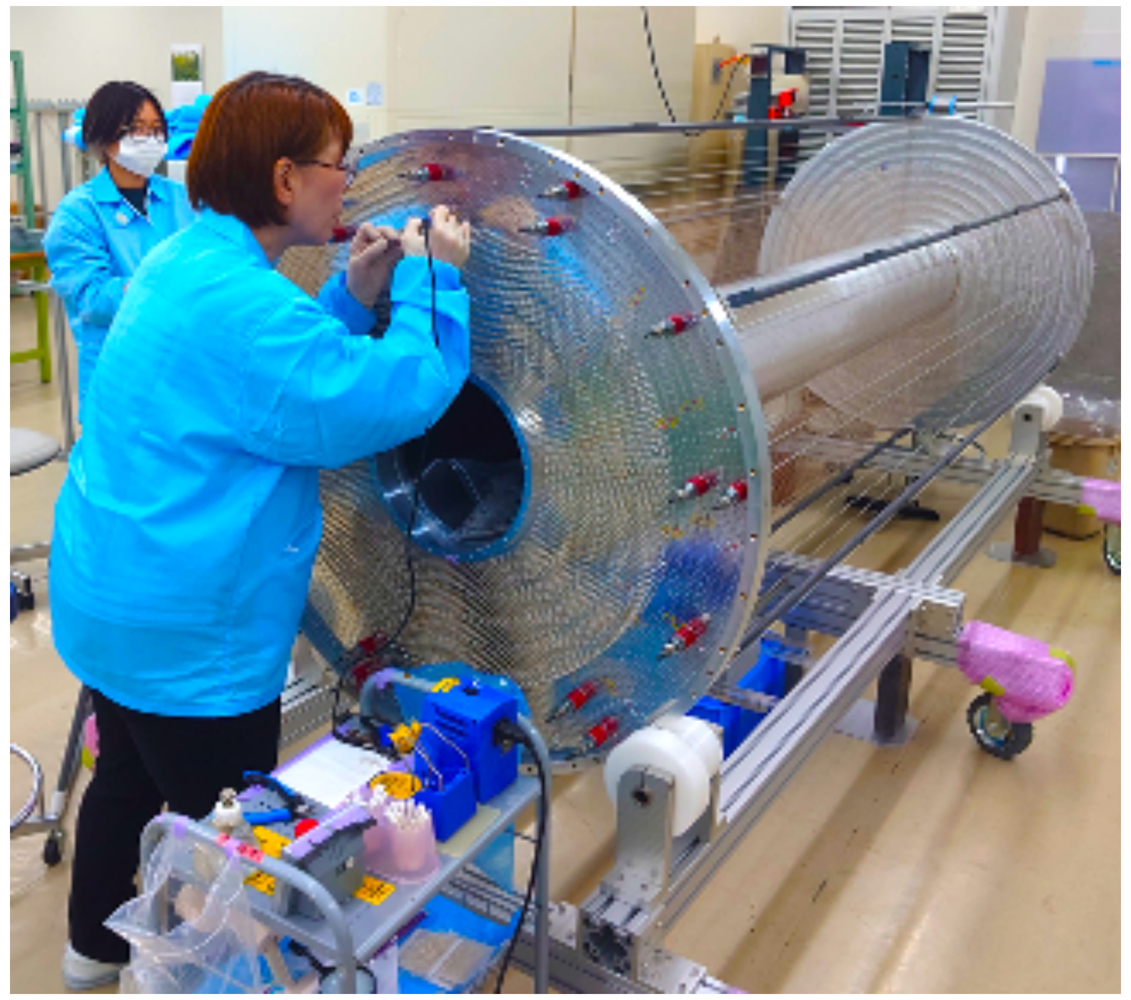
Super-conducting Solenoid Coil

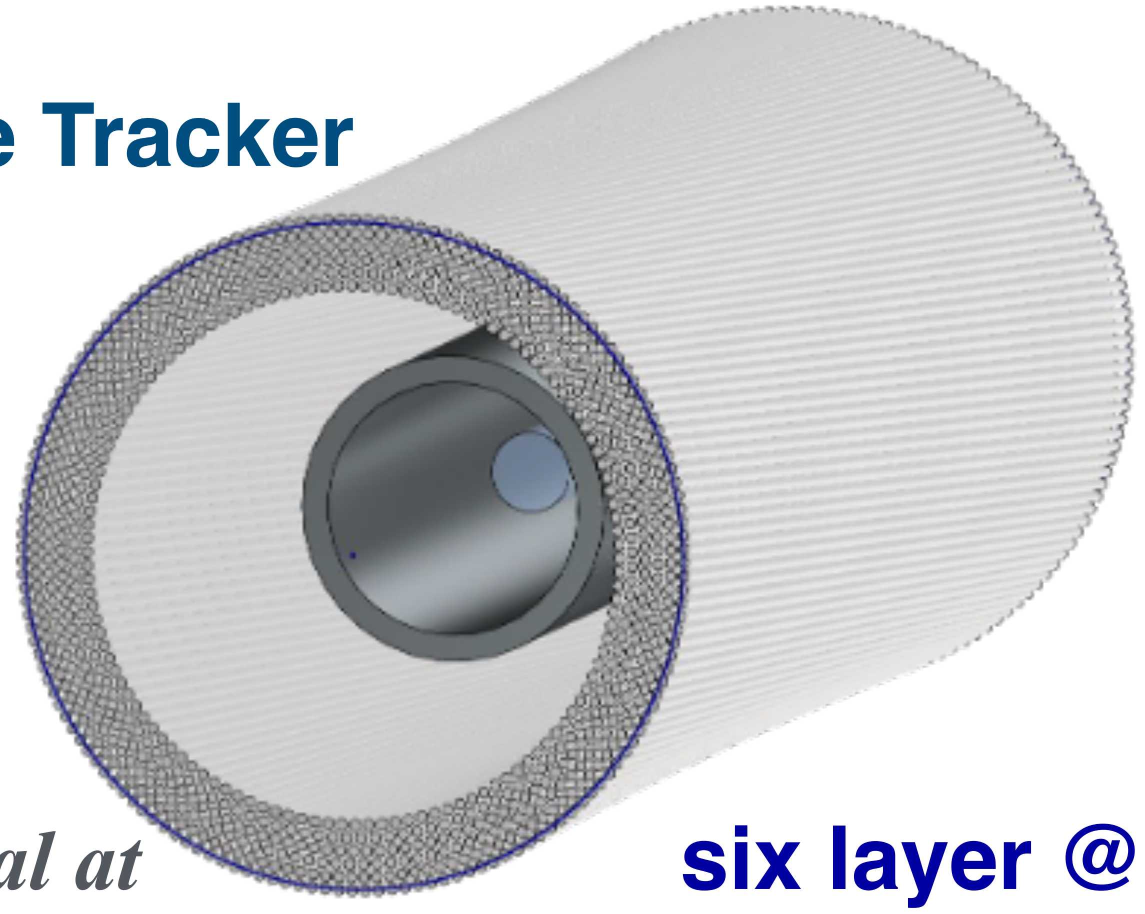


Cylindrical Drift Chamber (CDC)

Additional detectors to improve

To detect the proton in Fermi-motion
& to drastically improve vertex resolution (Λ/Σ⁰ separation)

Vertex Straw-tube Tracker (VST)

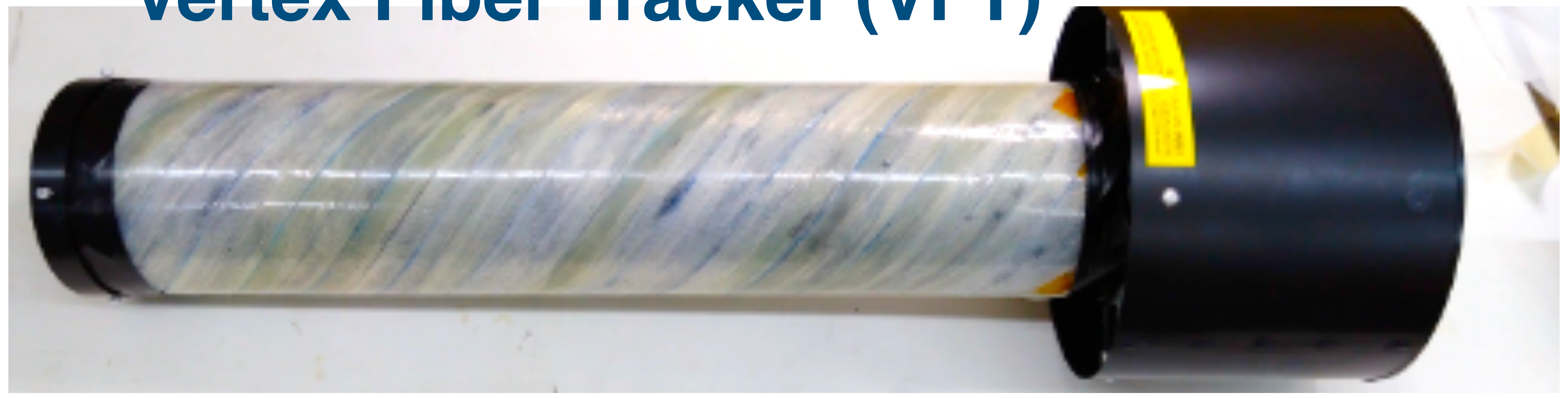


Currently, J. Zmeskal at SMI is applying for funding.

six layer @ crossing angle ± 6°

Constructed by T.Hashimoto

Vertex Fiber Tracker (VFT)



doble layer @ crossing angle ± 45°

Superconducting Solenoid Magnet

- Same design as “the detector solenoid magnet” for COMET-I

being constructed in cooperation with the J-PARC Cryogenics Section

- 3.3m x 3.3m x 3.9m, ~108t in total
- Max. field of 1.0T @ center
  - 189A – 10V
- NbTi/Cu SC wire, 98km in total
- **Conduction-cooling with GM*3**
- Semi-active quench-back system
- **Will be completed in FY2024**

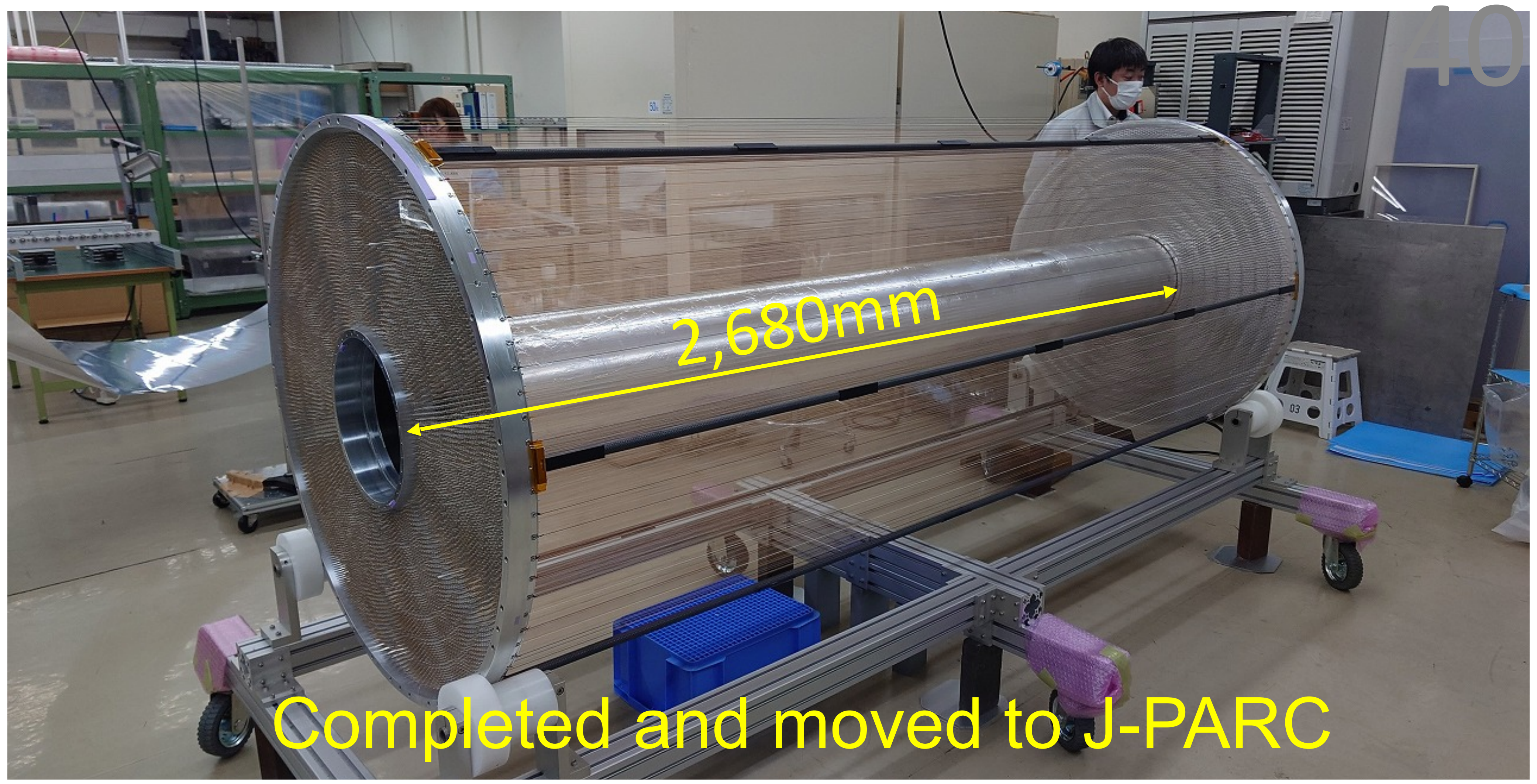
SHI FA-50 (air cooling)

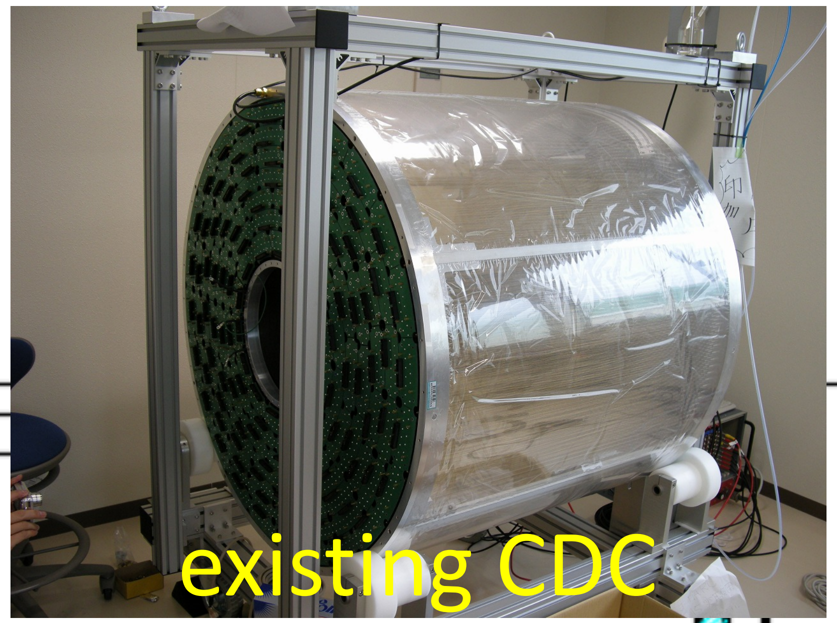
RDE-418D4

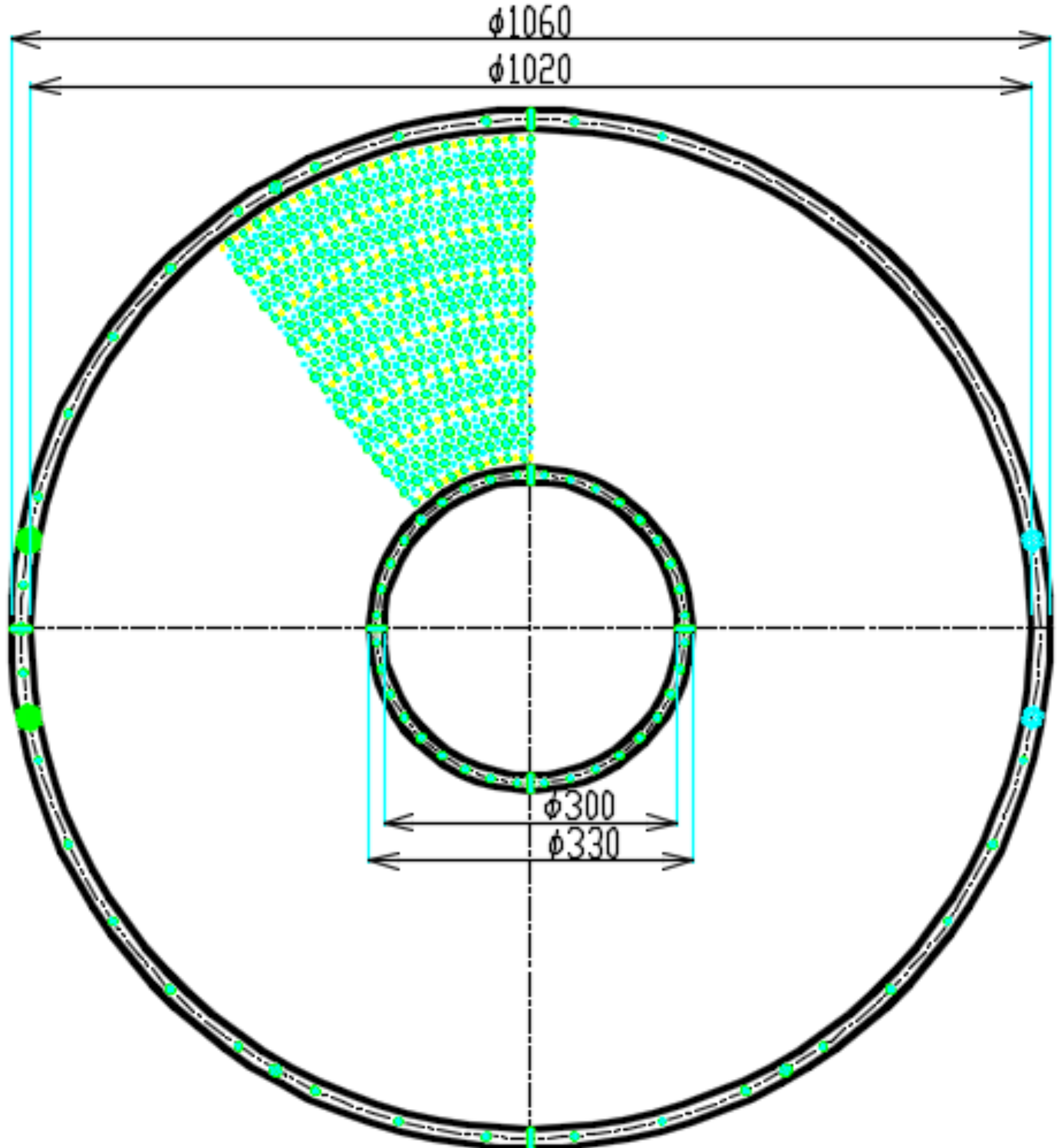
Cylindrical Drift Chamber (CDC)

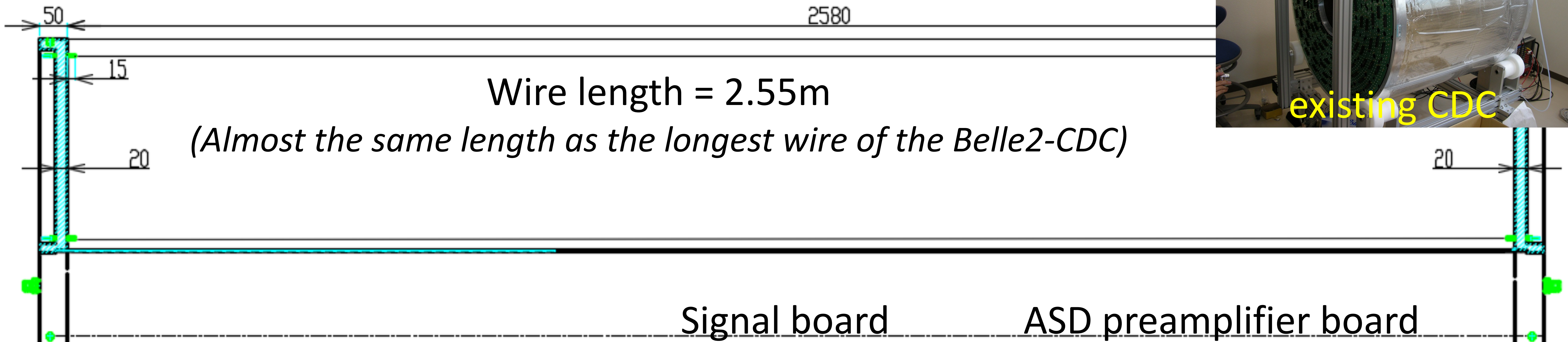
- 3 times the length of the existing CDC
  - Gas: Ar/CO_2=90/10
- The same design of the present end-cap
- Readout systems are reused

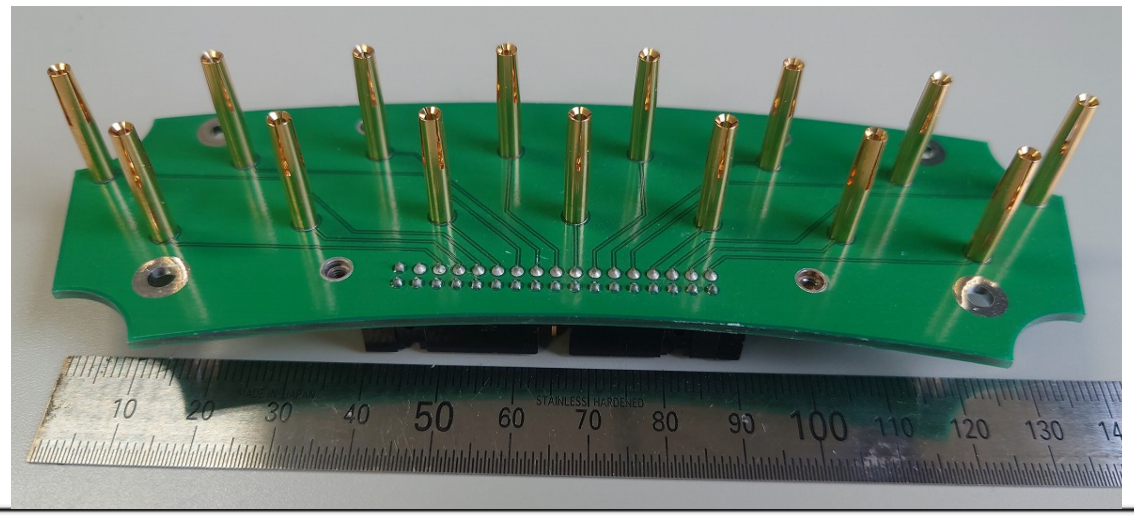
Completed this month, and commissioning will soon start @ J-PARC



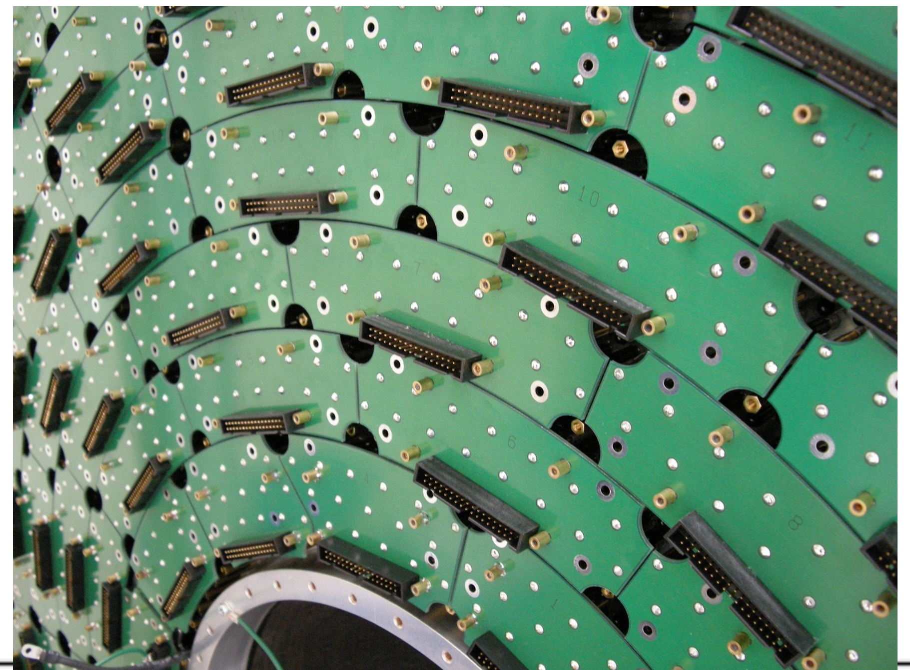




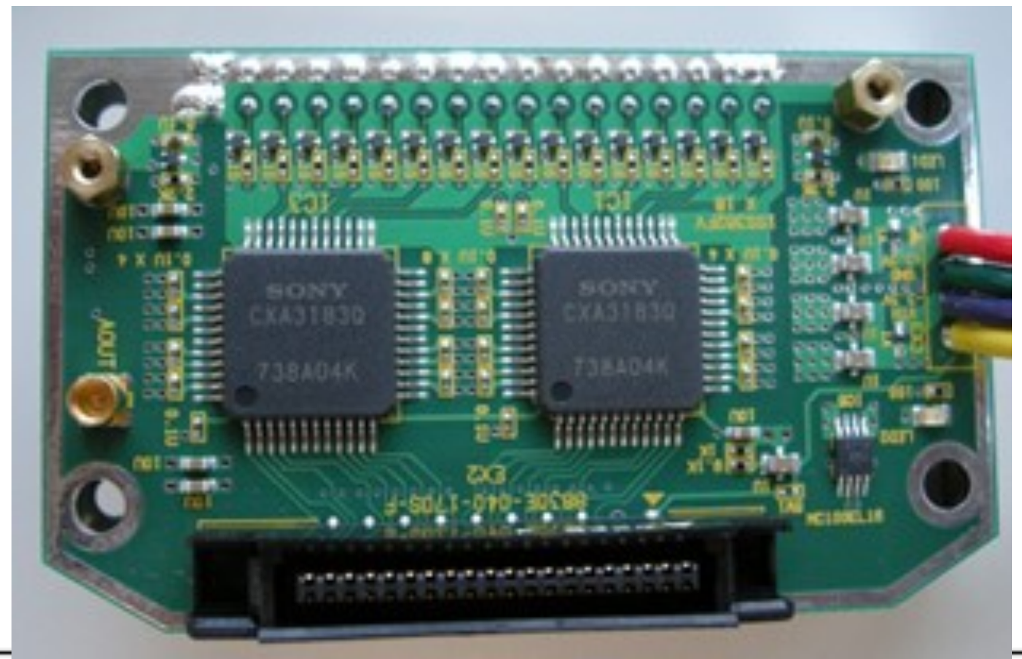




Signal board

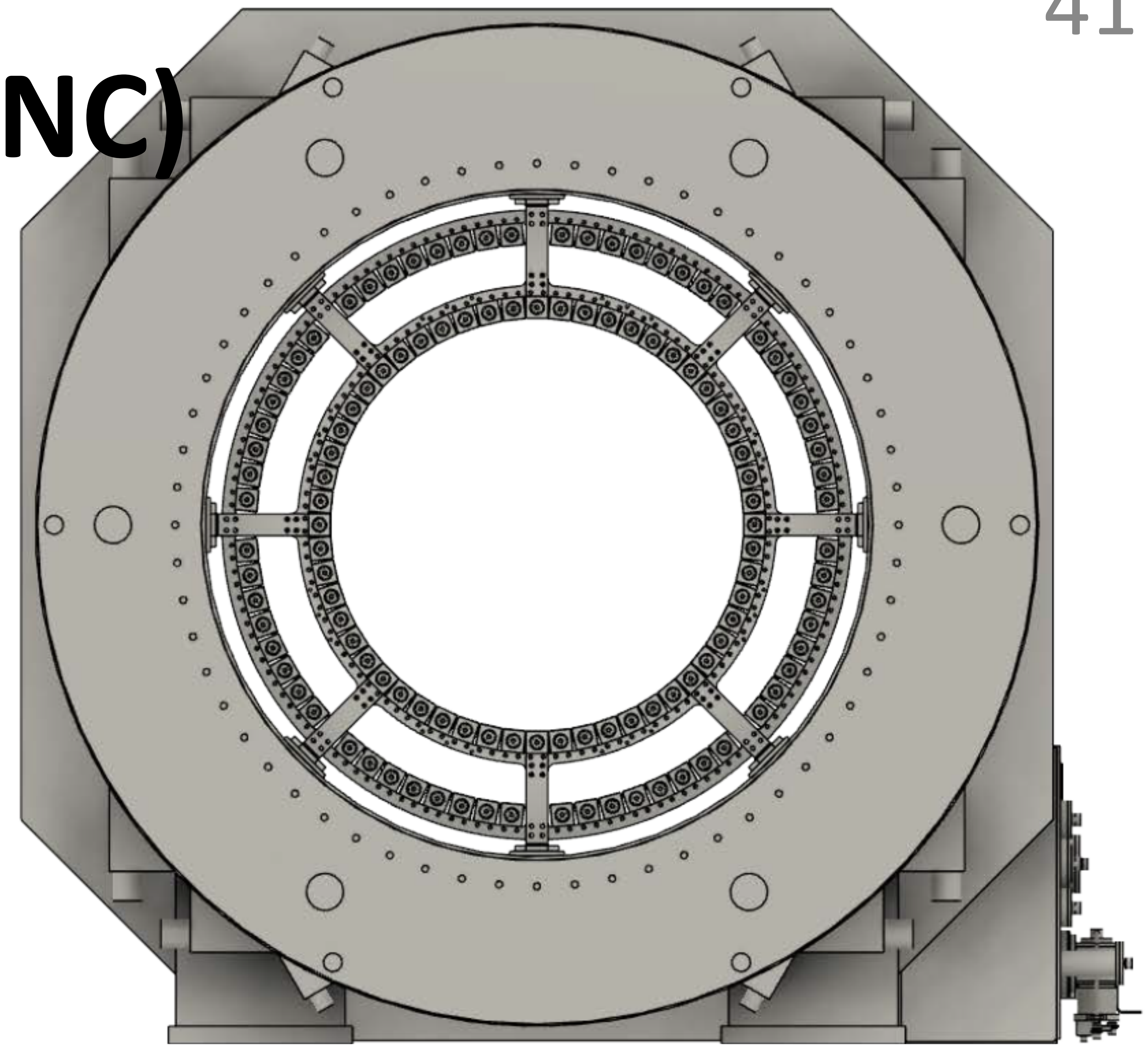


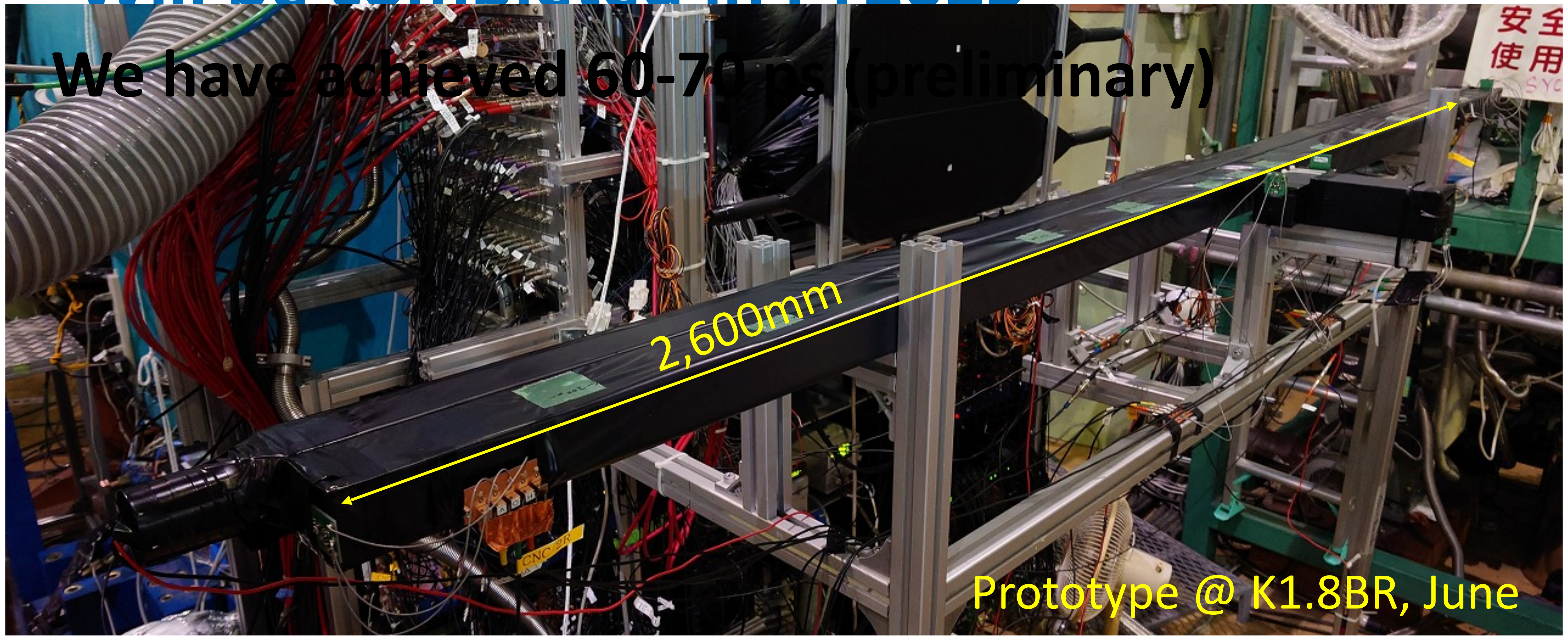
ASD preamplifier board



Cylindrical Neutron Counter (CNC)

- scintillator array: 2 layers, 12cm thickness
- Neutron detection efficiency of 12~36%
- 56+80=136 modules
  - ELJEN EJ-200: (T)60mm, (W)60mm, (L)3,000mm
- 1.5-inch FM-PMT [H8409(R7761)] & MPPC array [S13361-6050AE-04]
- **Will be completed in FY2025**

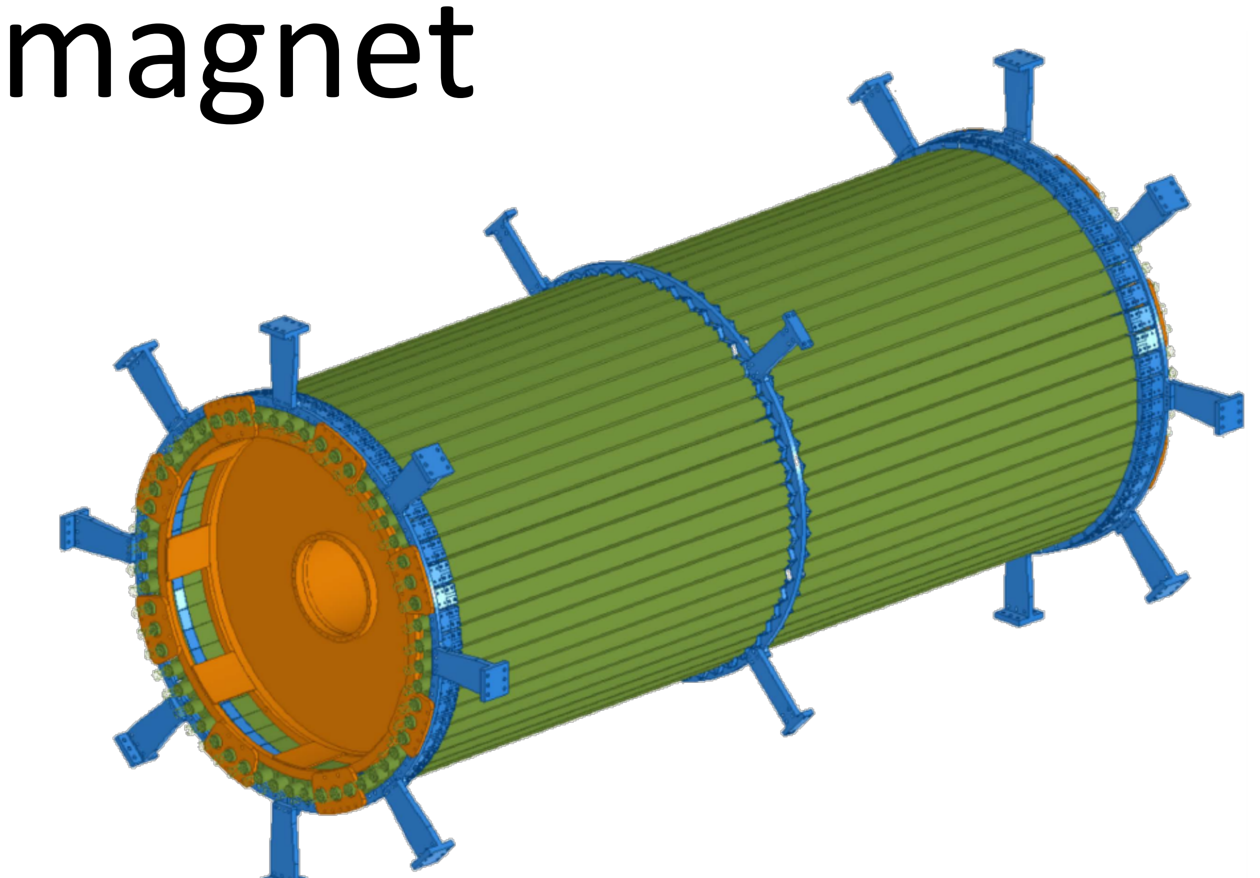


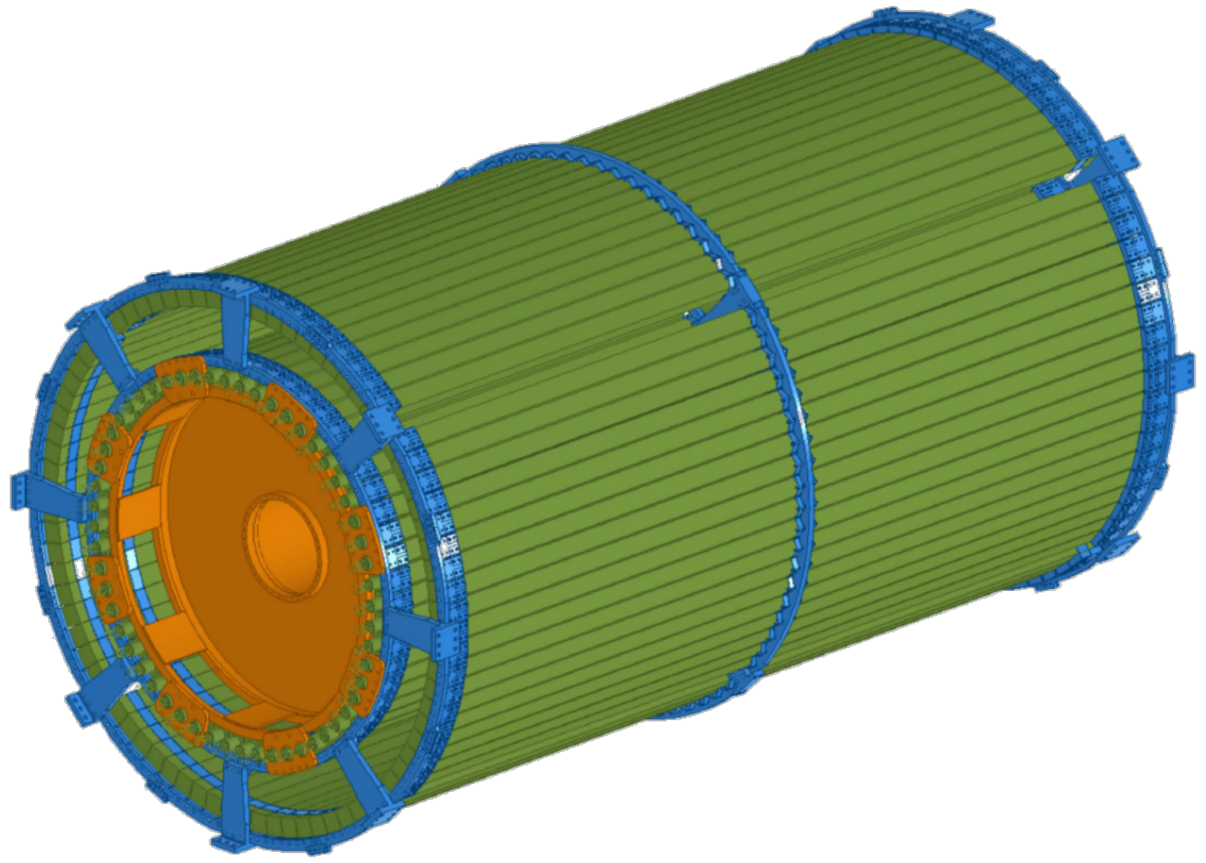


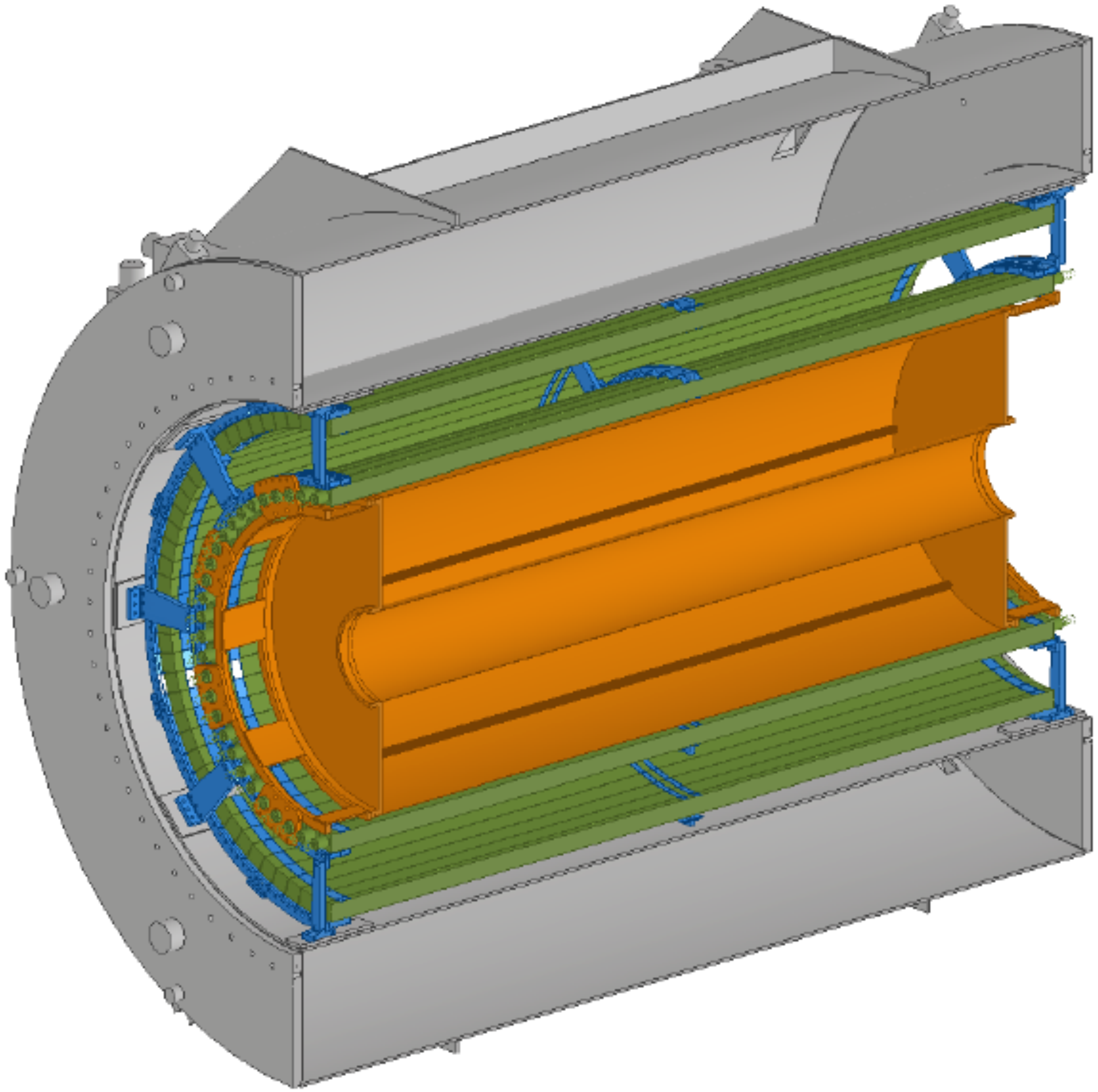
136 scintillators in total
- 56 segments @ r548~608mm
  - ➢ 112 FM-PMTs
- 80 segments @ r780~840mm
  - ➢ 160 MPPC-arrays

Support Structure

- CNC is supported at upstream, downstream and middle position
  1. pillars are mounted on the inner cylinder of the magnet
  2. ring structures are installed on the pillars
  3. each module is mounted on the ring structures
- CDC is installed by inserting a long frame bar into the center of the CDC and magnet





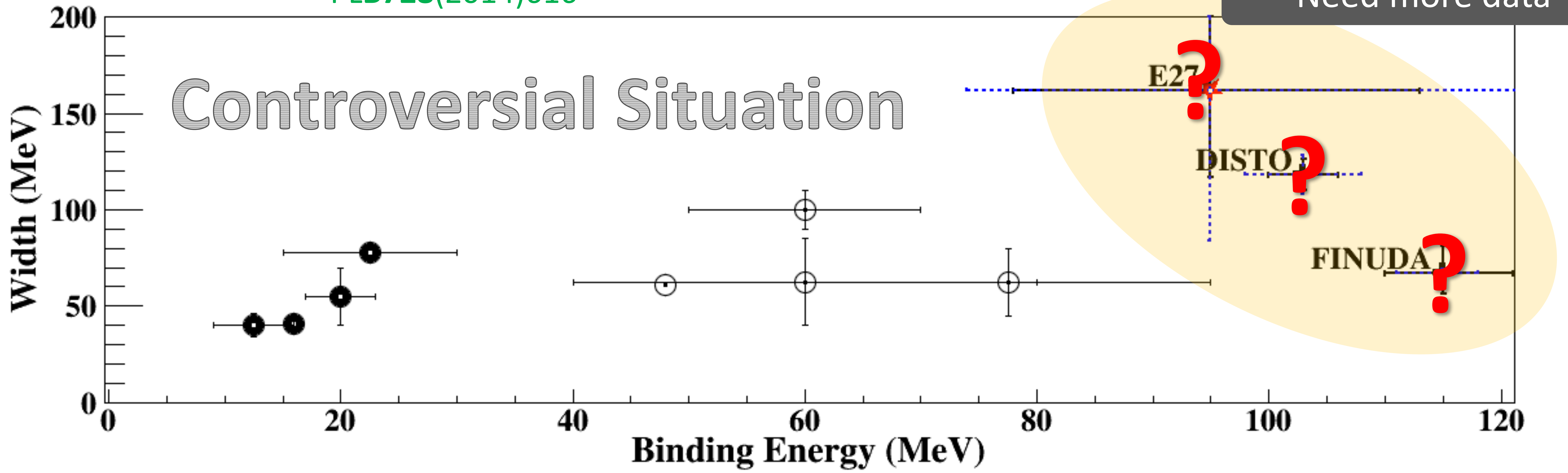


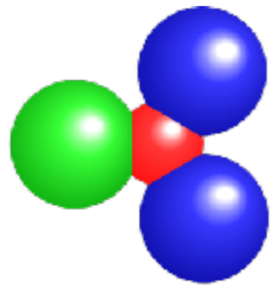
Will be prepared in FY2025-26

Summary of Experimental Status

Negative results		***Positive results***
AMADEUS@DAΦNE $^{12}C(K^-_{stopped}, \Lambda p)$ EPJ**C79**(2019)190	⟷	**FINUDA@DAΦNE** PRL**94**(2005)212303 $^{6}Li/^{7}Li/^{12}C(K^-_{stopped}, \Lambda p)$ Multi-NA processes?
HADES@GSI p + p → (Λ + p) + K^+ @ 3.5GeV PL**B742**(2015)242	⟷	**DISTO@SATURNE** PRL**104**(2010)132502 p + p → (Λ + p) + K^+ @ 2.85GeV Intermediate $N^* \rightarrow \Lambda K^+$?
LEPS@SPring-8 d(γ, $\pi^- K^+$)X @ 1.5-2.4 GeV PL**B728**(2014)616	⟷	**E27@J-PARC** PTEP(2015)021D01. d(π^+, K^+)Σ^0p @ 1.69 GeV/c

Need more data

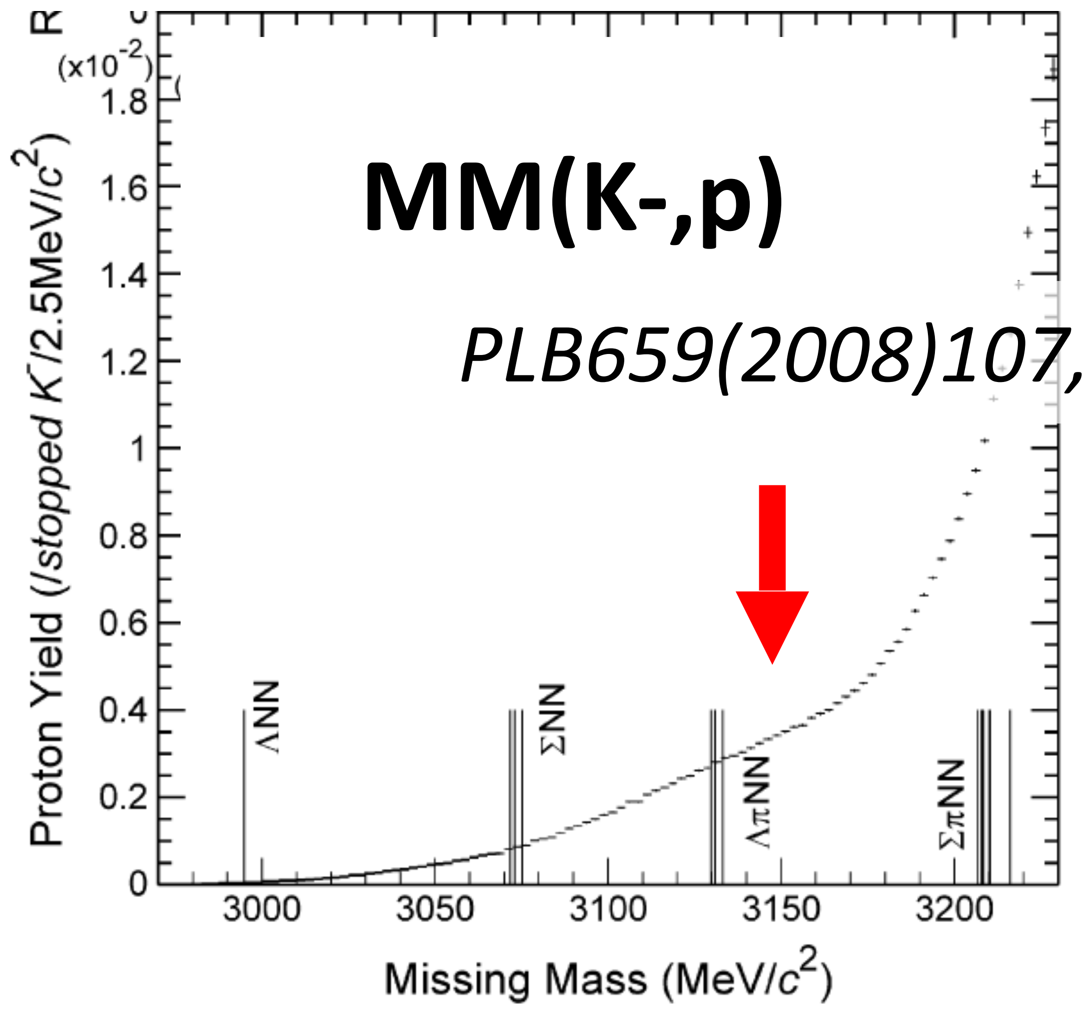


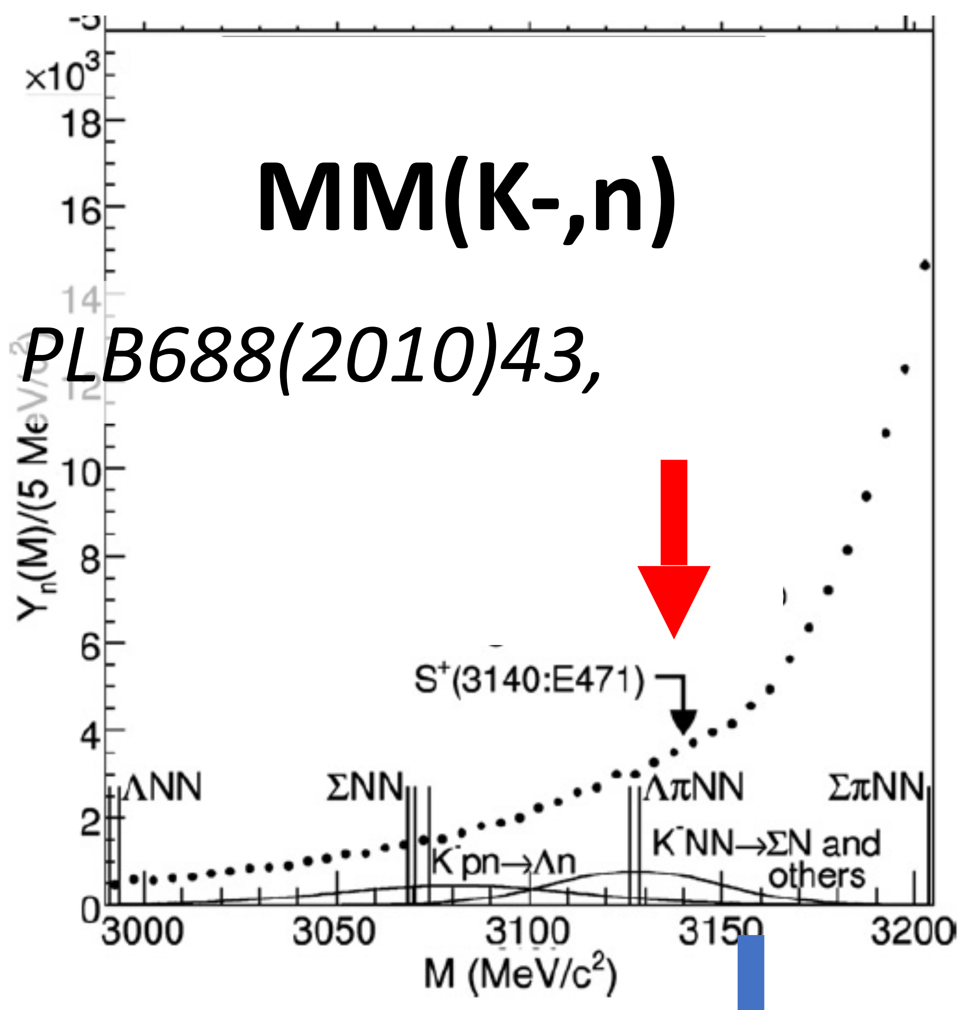


$\bar{K}NNN$ Searches so far

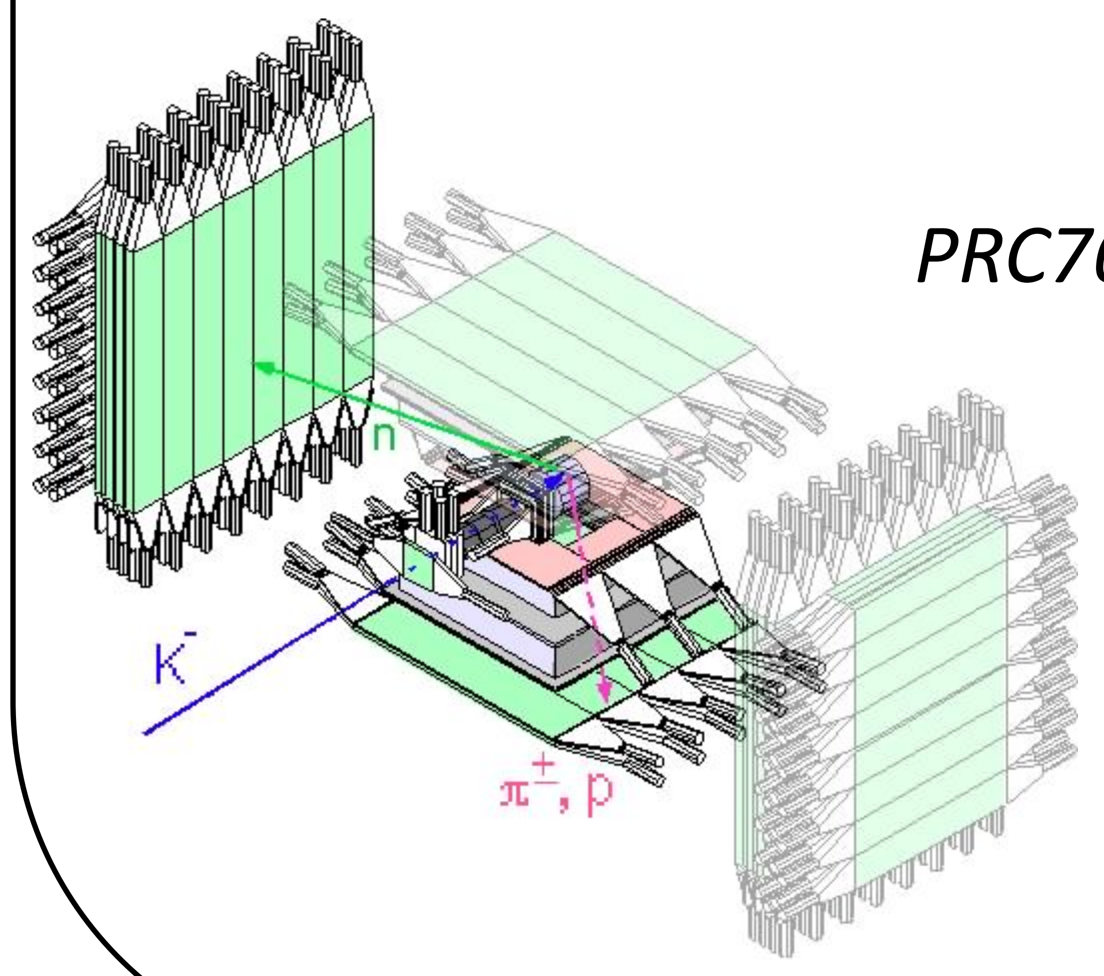
E471/E549@KEK

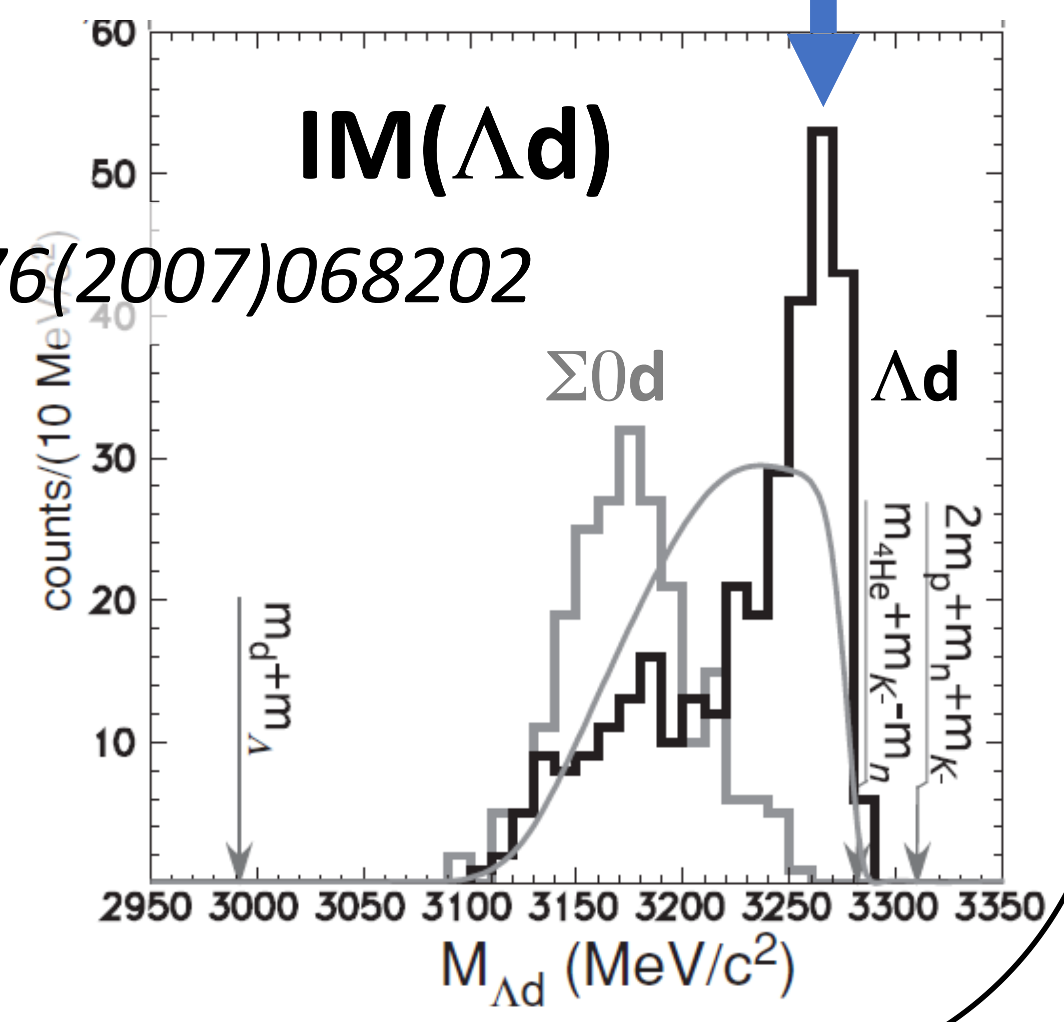
^{4}He(stopped-K$^-$,p/n/Yd)





PLB659(2008)107, PLB688(2010)43,

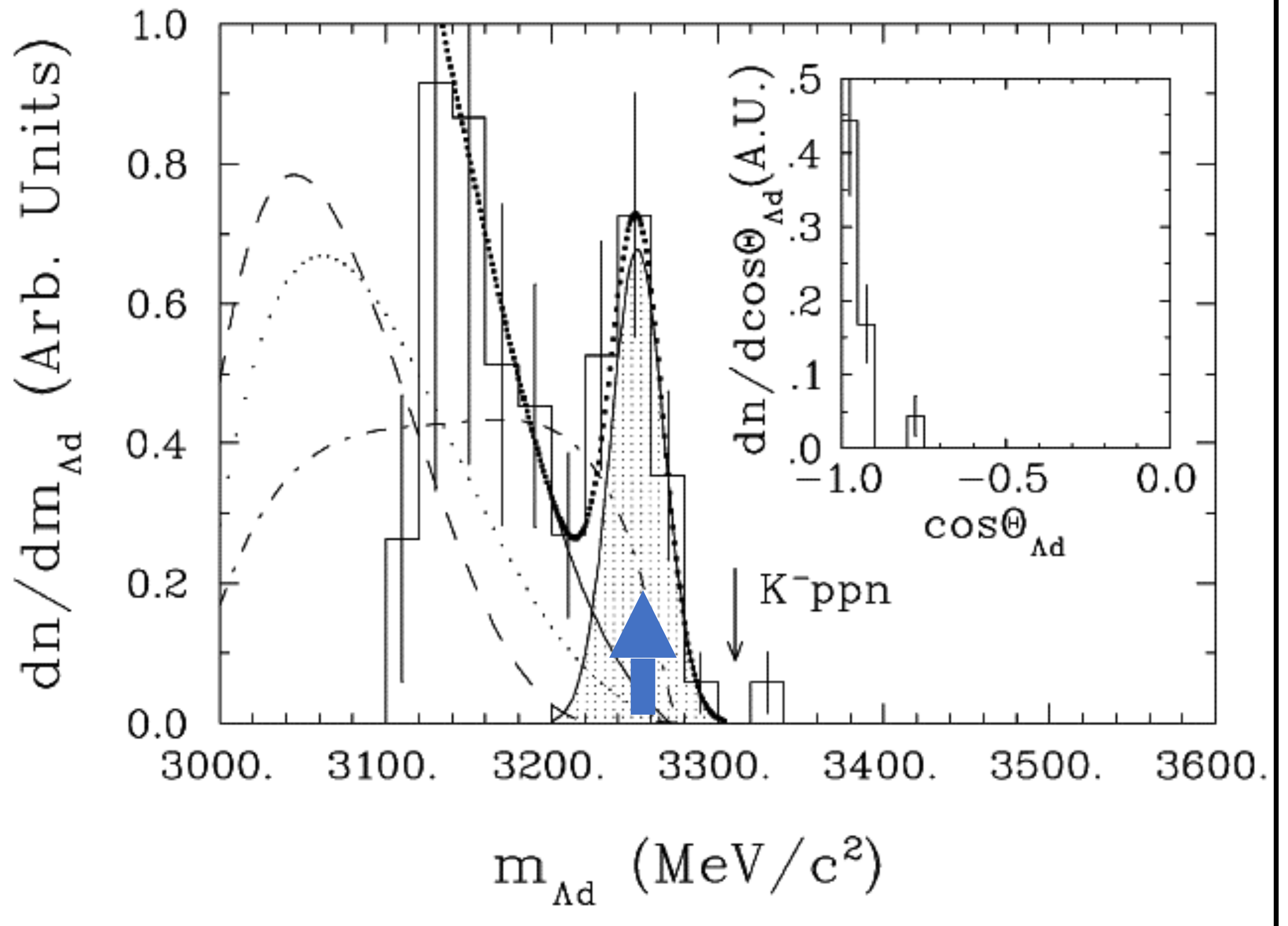




PRC76(2007)068202

FINUDA@DAΦNE

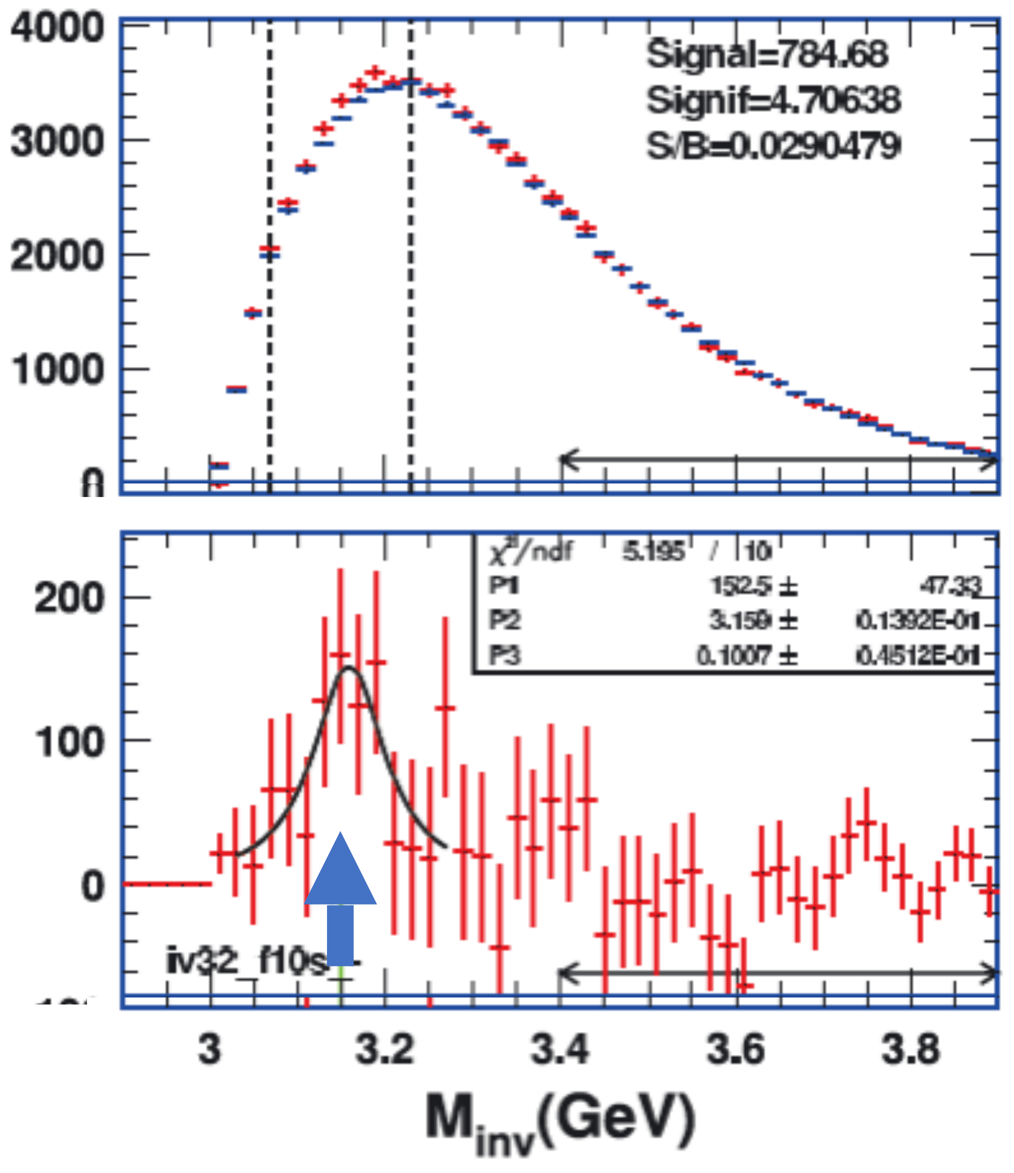
Li/C(stopped-K$^-$,Λd)



PLB654(2007)80

FOPI@GSI

Λd in Ni+Ni



EXA05 Conference (2005)

No conclusive results.

multi-N absorption in stopped-K reaction makes interpretation difficult

The detail can be found:

— in a review —

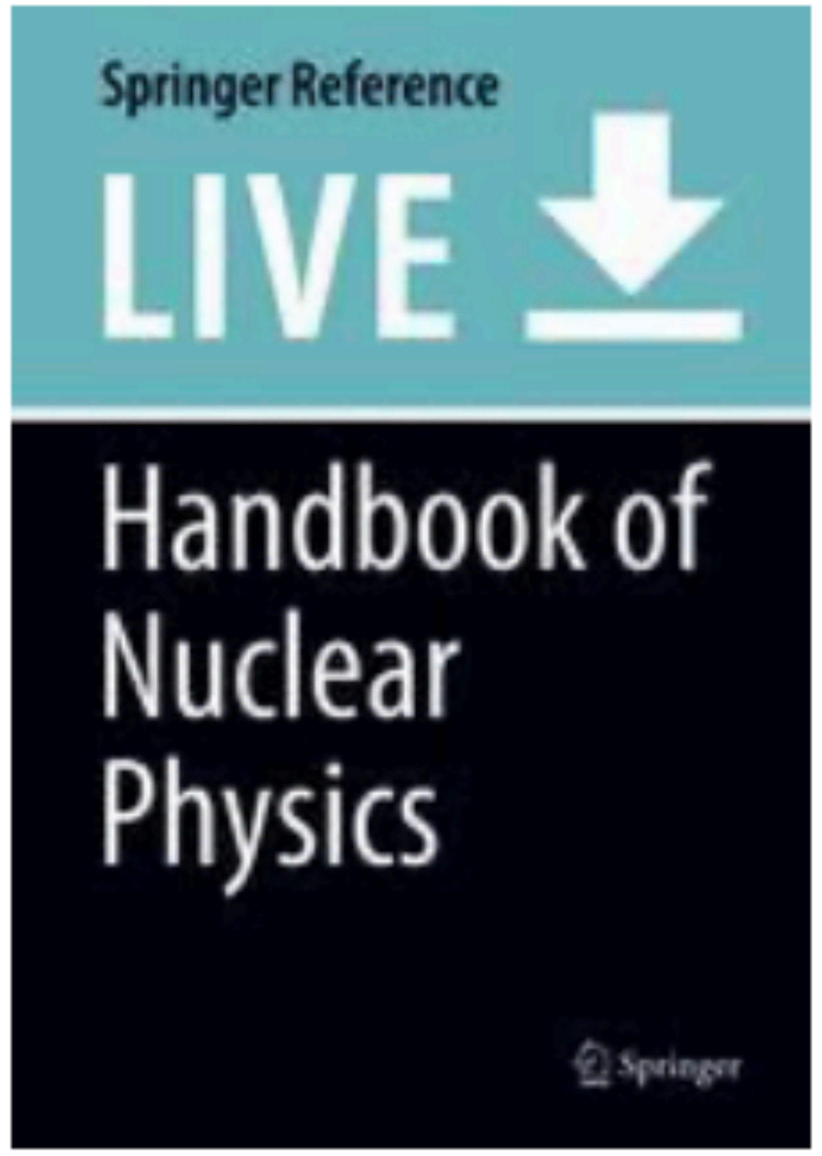
$\bar{K}N$ interaction study via kaonic atom

Search for $\bar{K}NN$ nuclear bound state as a natural extension of $\Lambda(1405) \equiv \bar{K}N$

Recent results on $\bar{K}$ bound state

This is a fee-based literature.

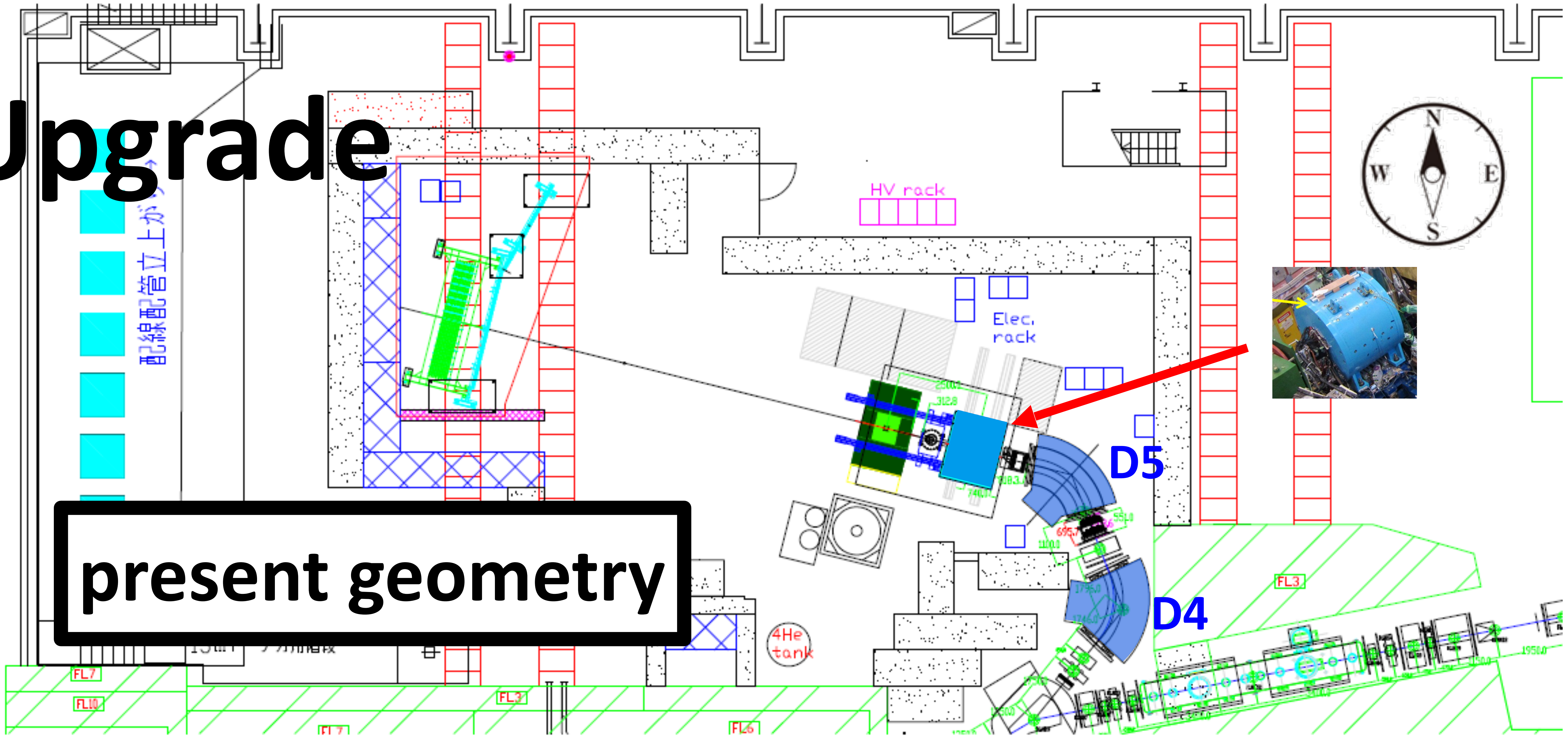
Kaonic Nuclei from the Experimental Viewpoint



Iwasaki, M. (2022).
Kaonic Nuclei from the Experimental Viewpoint.
In: Tanihata, I., Toki, H., Kajino, T. (eds)
Handbook of Nuclear Physics . Springer, Singapore.
https://doi.org/10.1007/978-981-15-8818-1_37-1

https://link.springer.com/referenceworkentry/10.1007/978-981-15-8818-1_37-1

Proposed K1.8BR Upgrade



- **Shortened beam line to enhance Kaon yield**

Shorten the beam line (~2.5m) by removing the final D5 magnet

with π/K ratio ~ 2

Relative beam-line length (m)	@ D5	@ D4
Present CDS	0	-3.7
New CDS	+1.2	**-2.5**

➢ K- yield increases by **~ 1.4 times @ 1.0 GeV/c**

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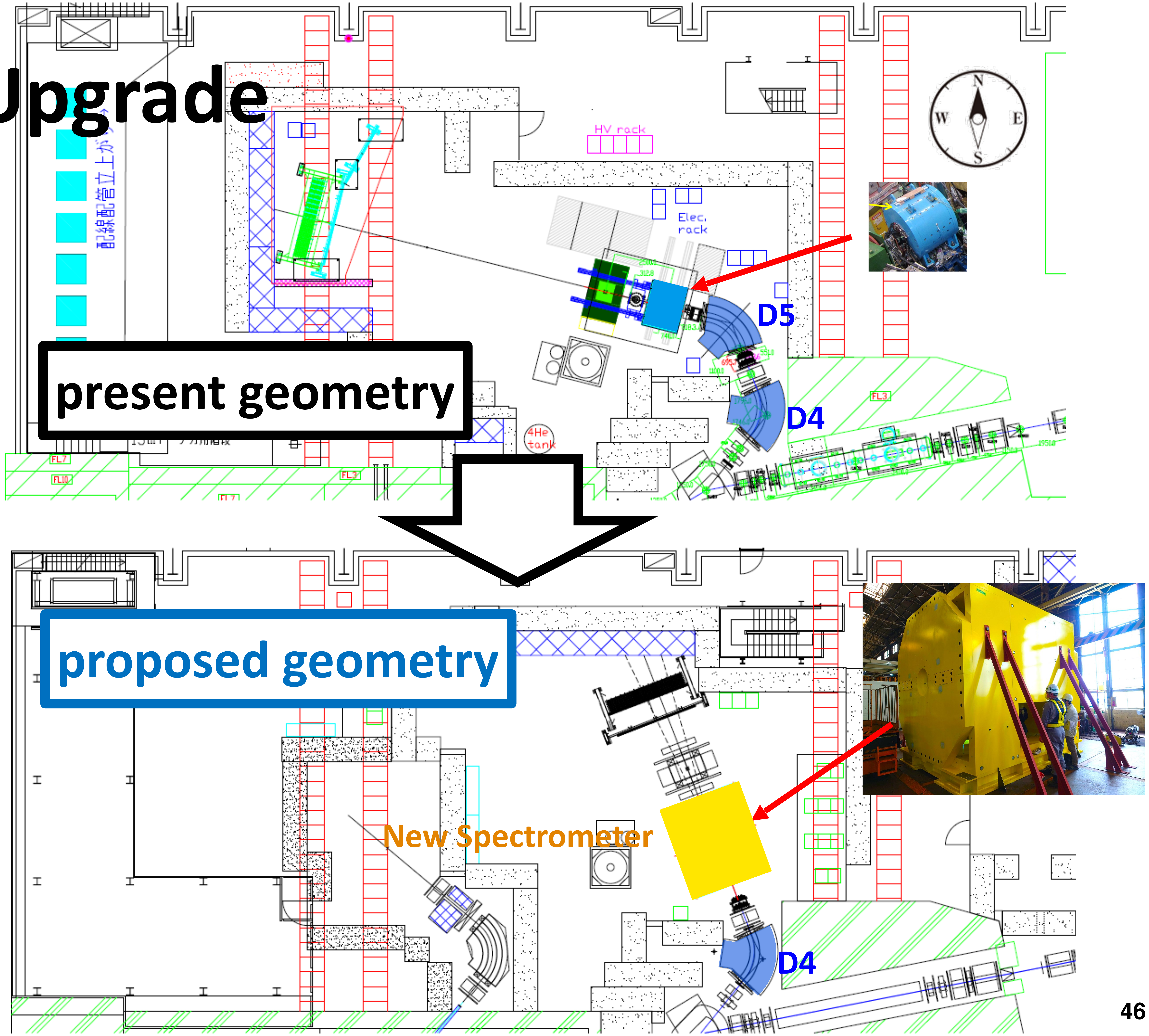
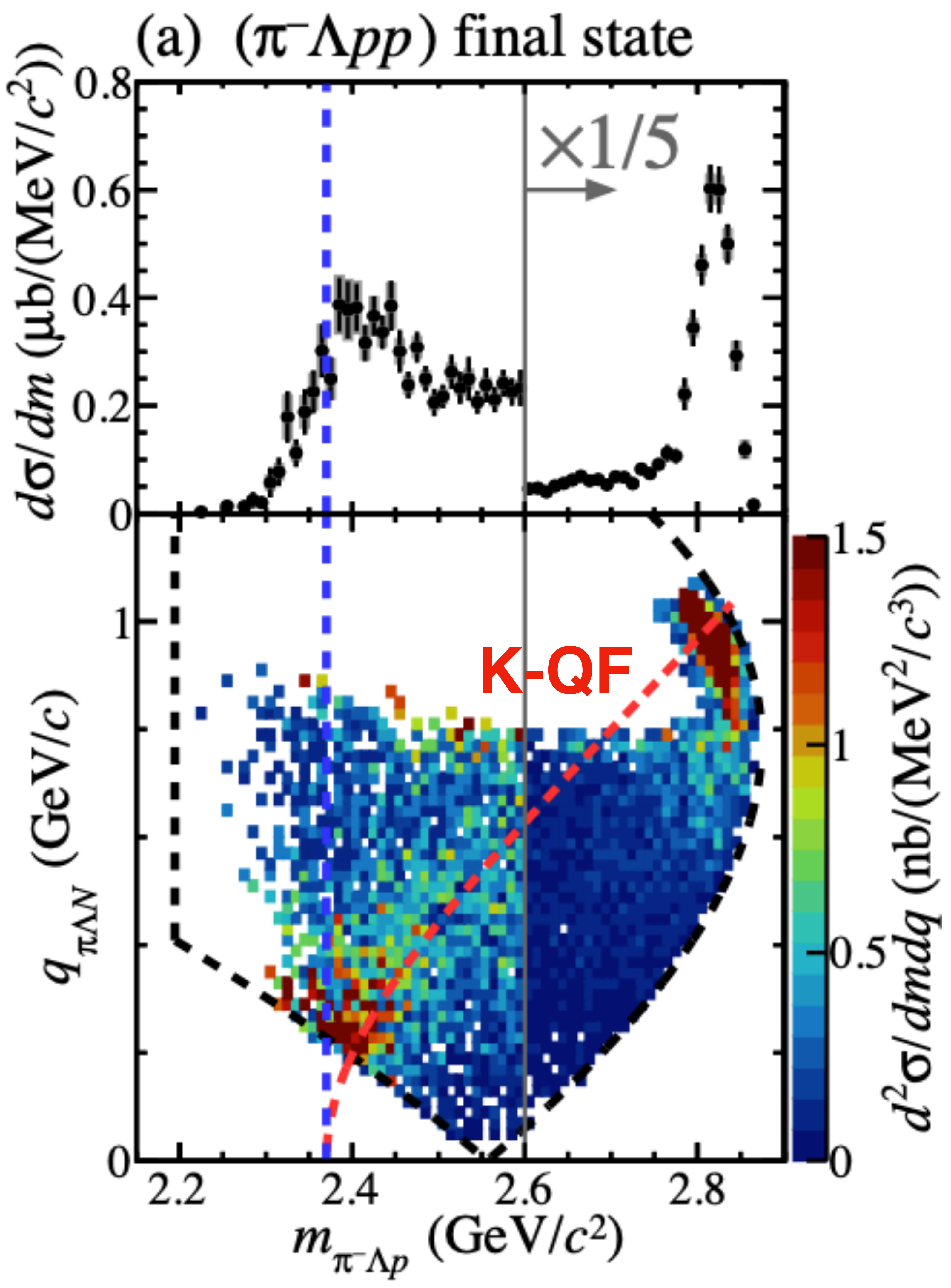
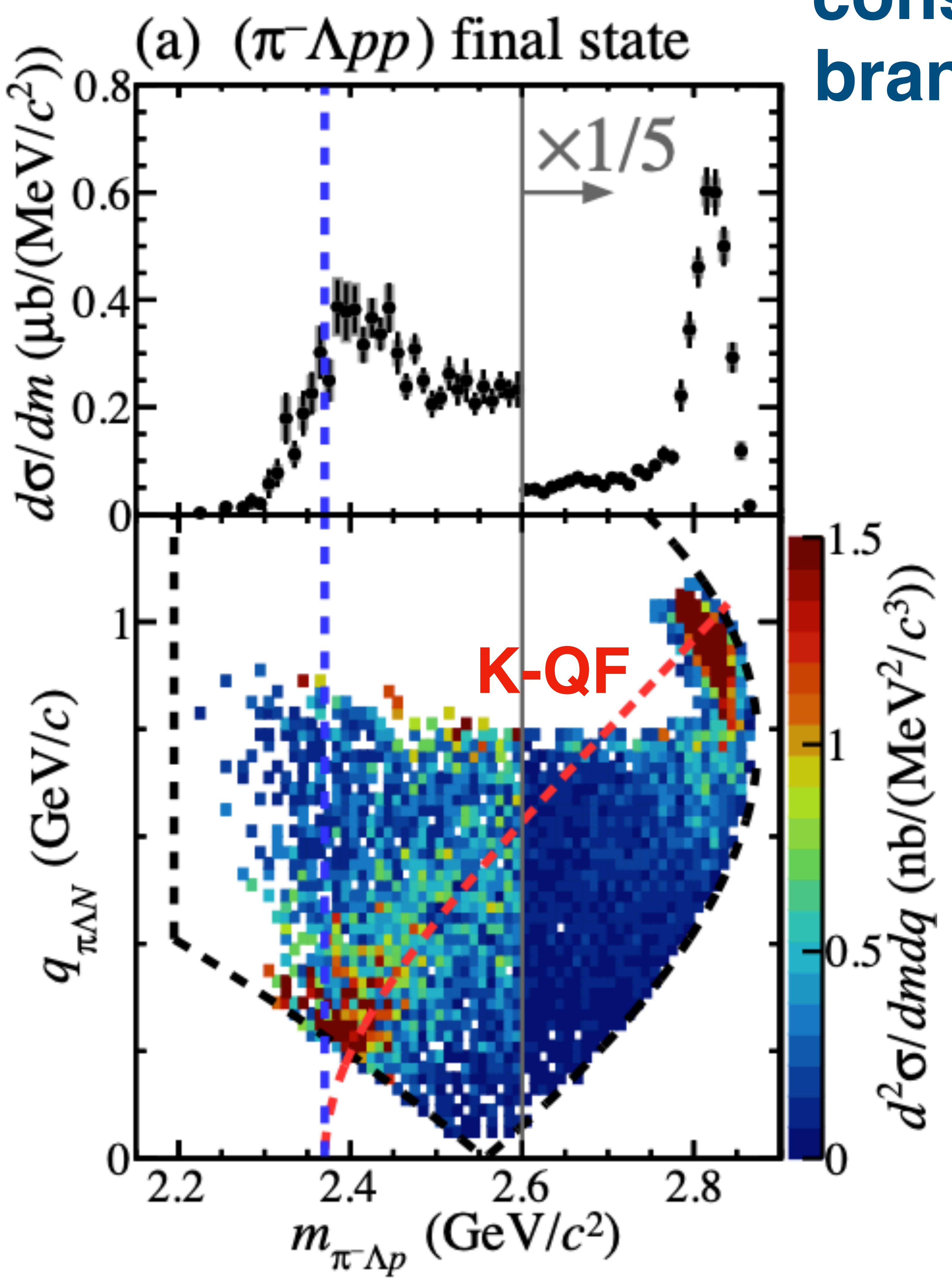


$K^- + {}^3He \rightarrow (\pi^-\Lambda p) + p$ reaction



… *analyzed by T. Yamaga*

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



consistent with $K^- + {}^3He \rightarrow \Lambda pn$ reaction
branch seems to be oder bigger

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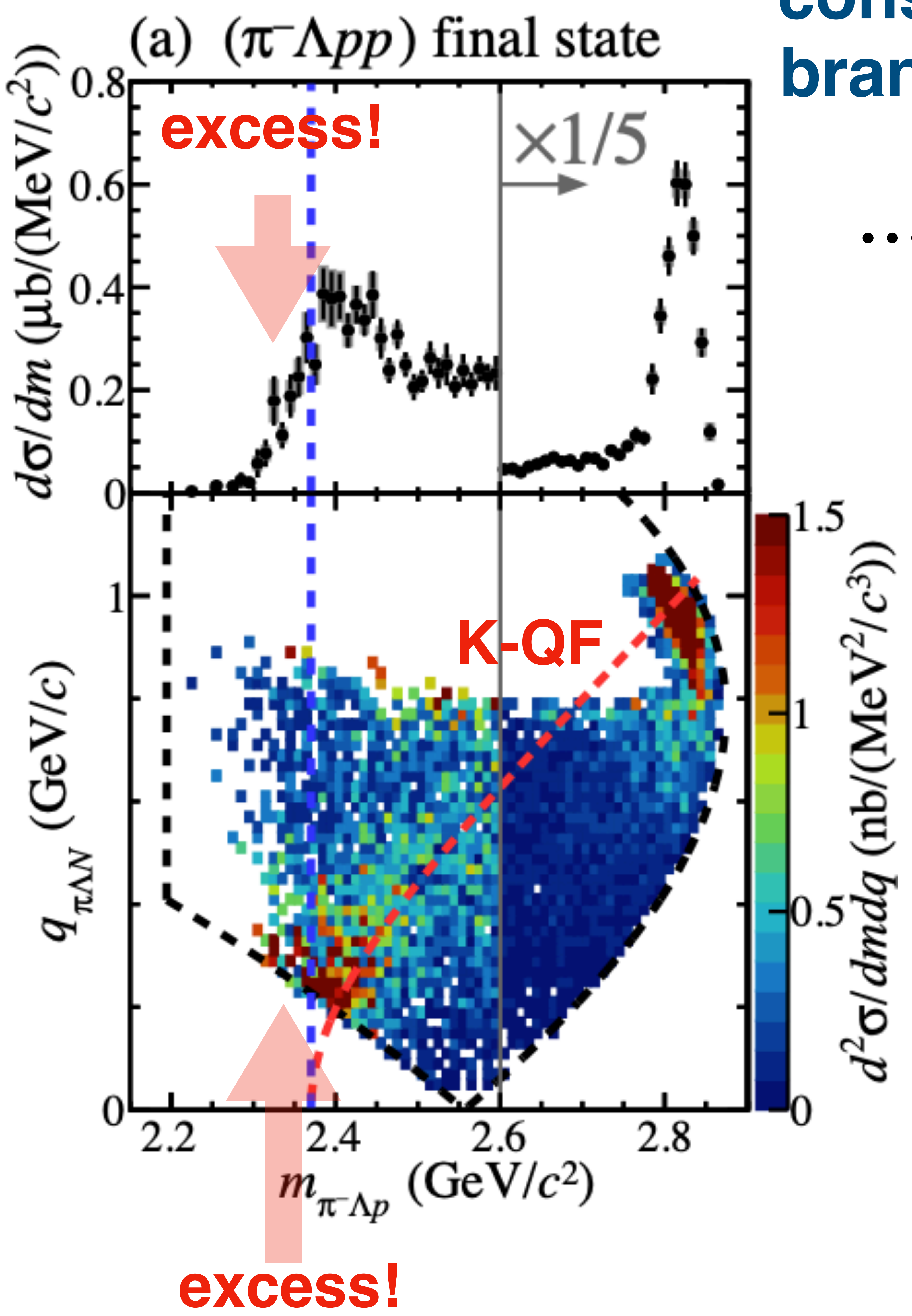
$K^- + {}^3He \rightarrow (\pi^-\Lambda p) + p$ reaction



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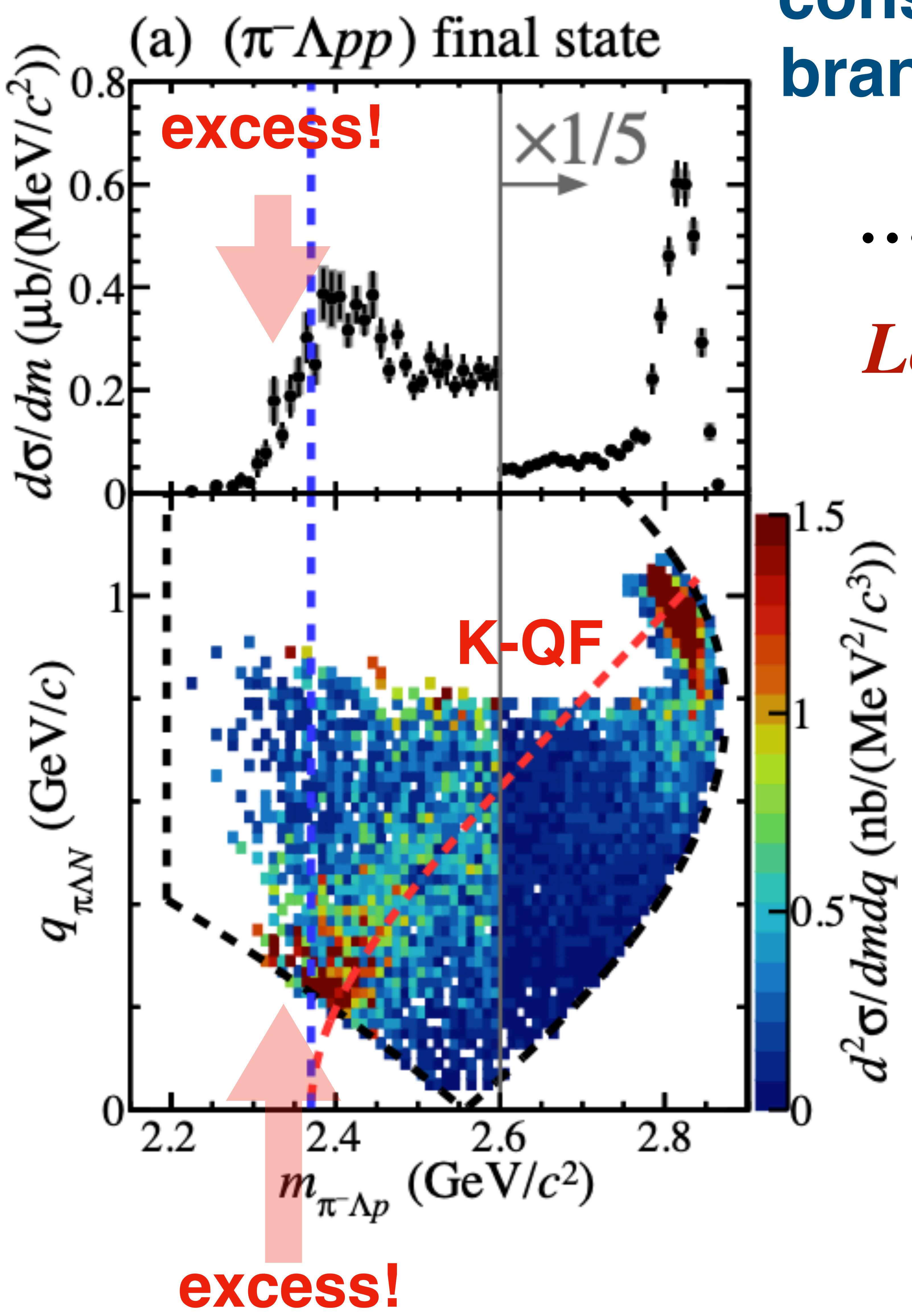
K⁻ + ³He →(π⁻Λp)+p reaction



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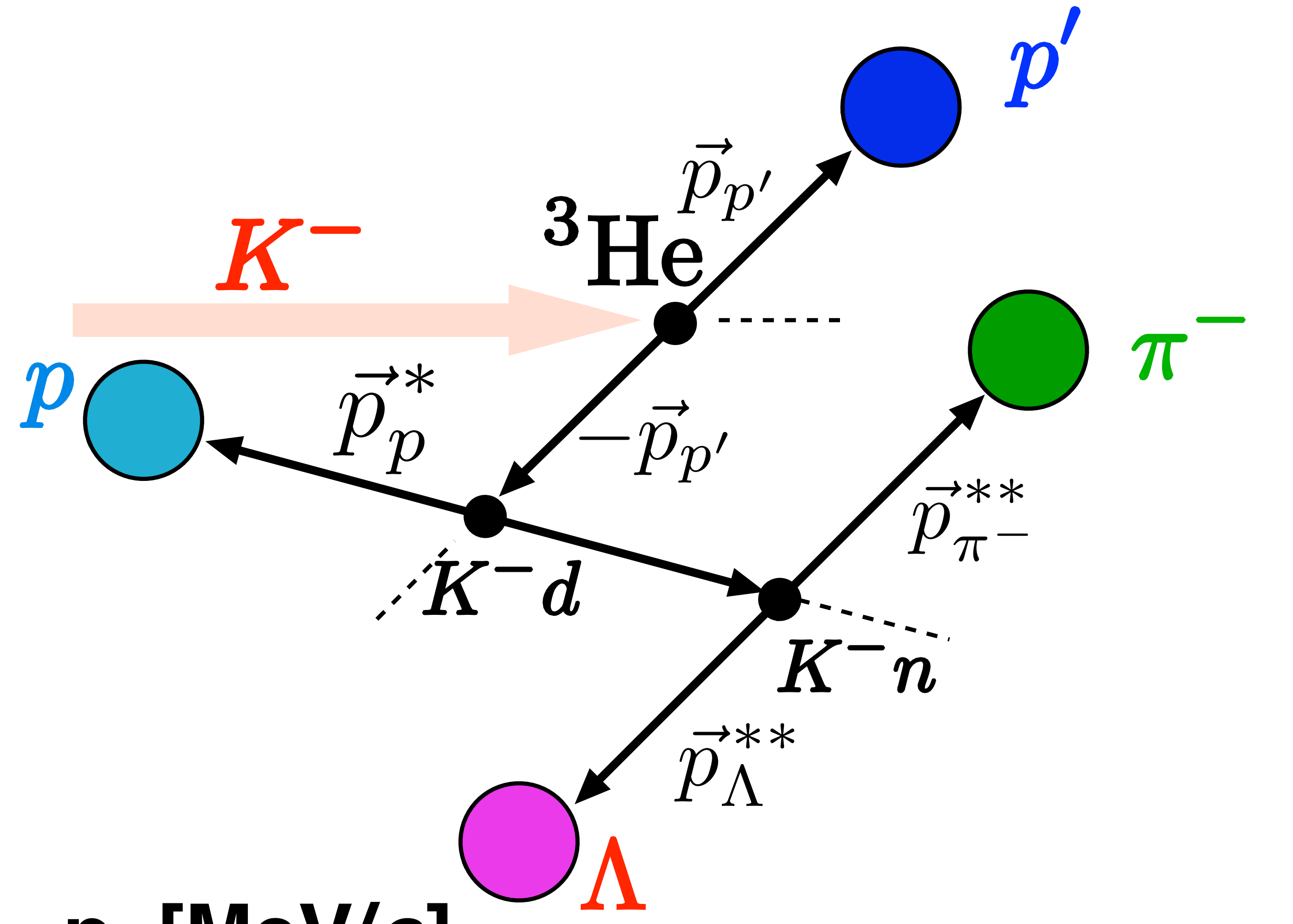

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Let's normalize event density by 4-body phase space

The normalization by 4-body phase space, i.e., final-state-density

$$\rho_{(\pi^-\Lambda pp')} = \frac{d^2N_{(\pi^-\Lambda pp')}}{dm_{\{\pi^-\Lambda p\}}\, dm_{\{\pi^-\Lambda\}}}$$

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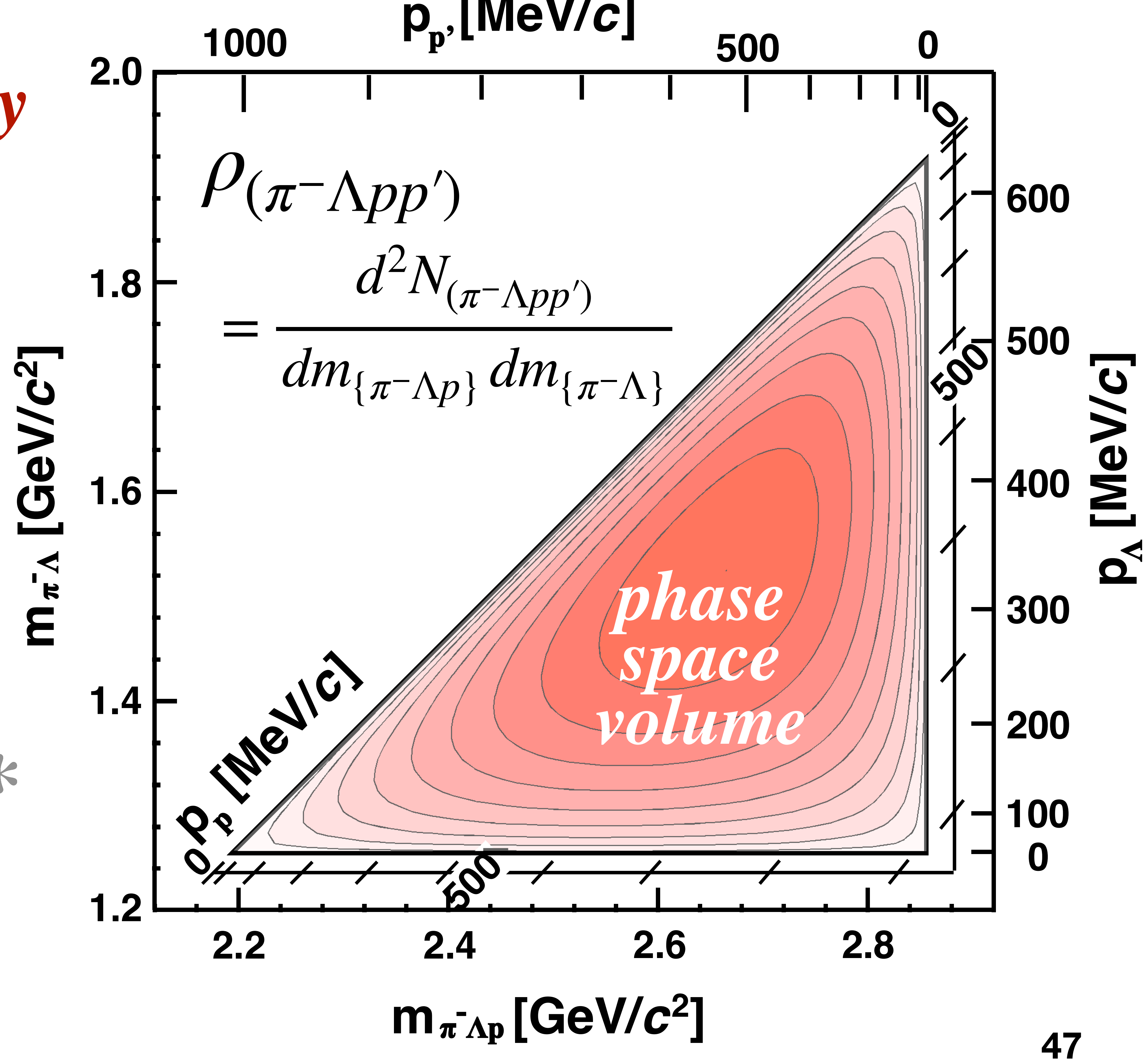

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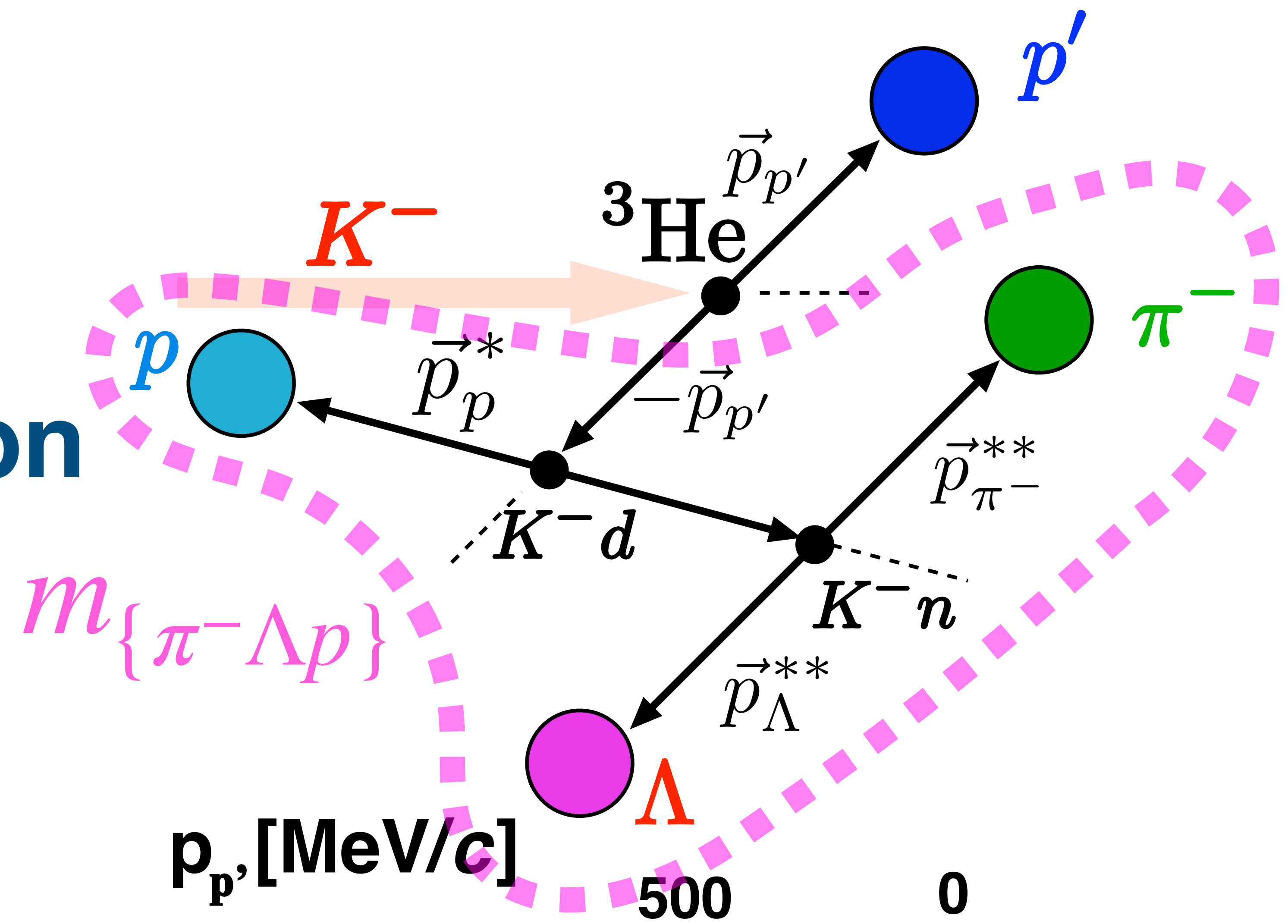

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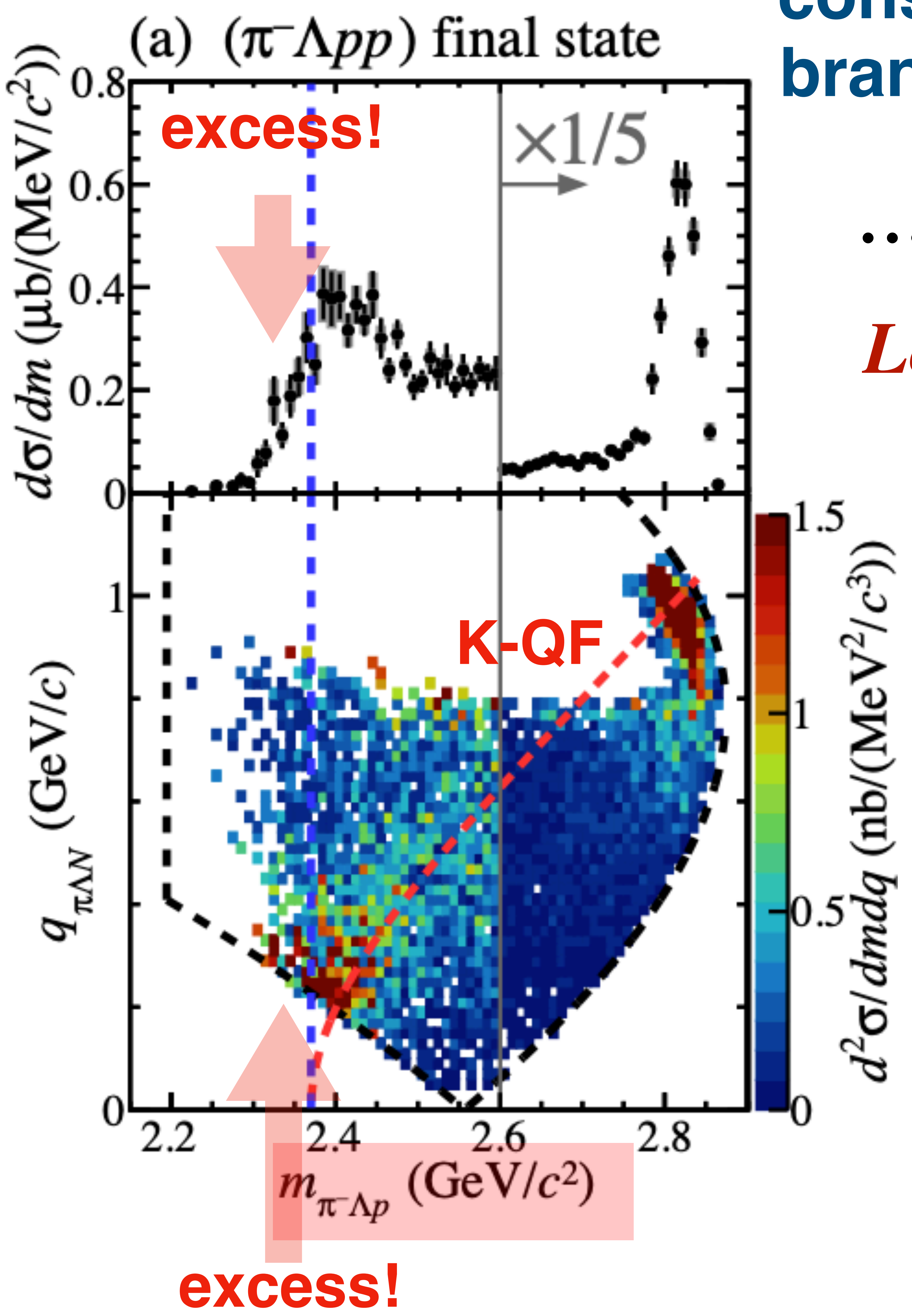

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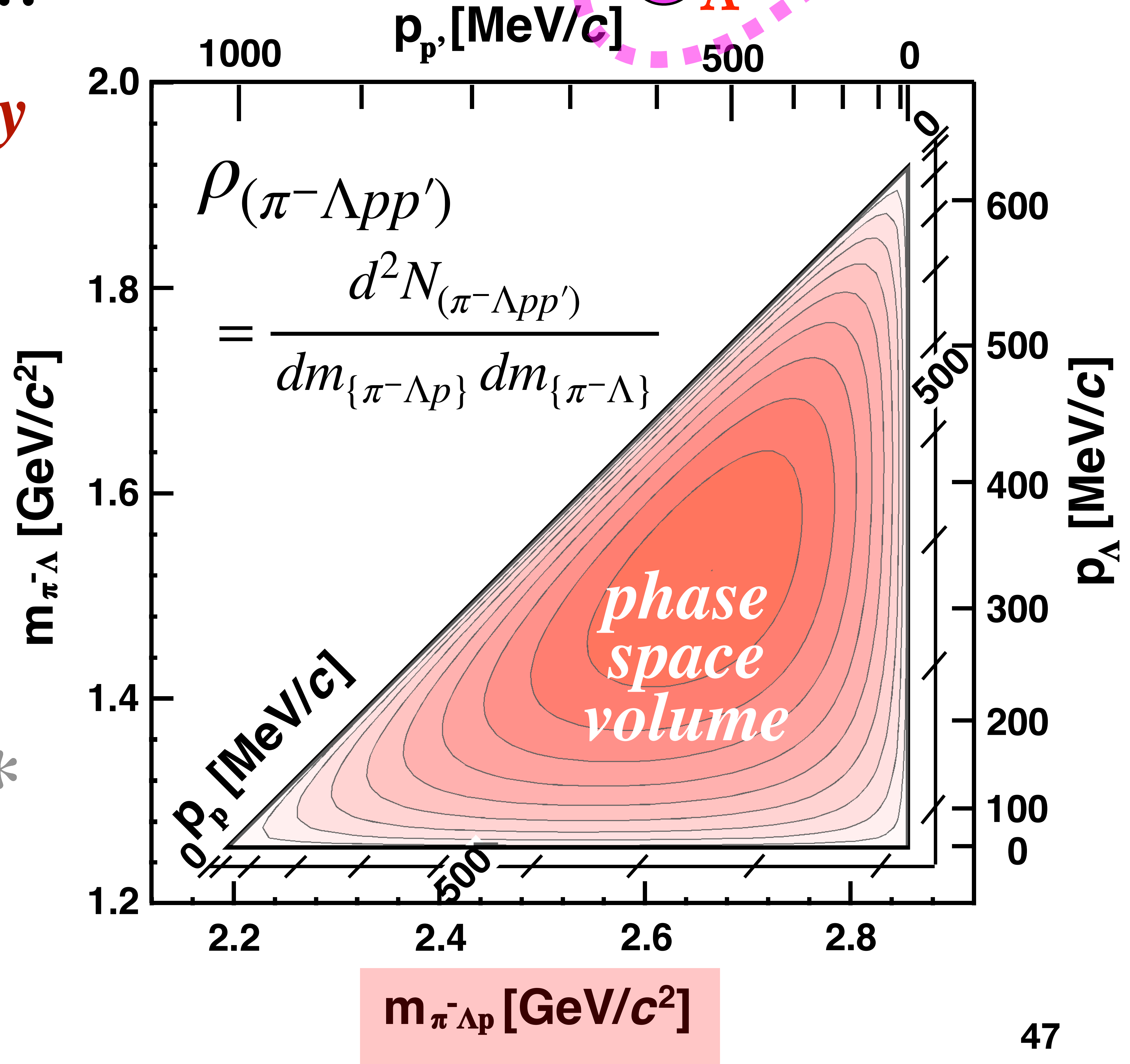

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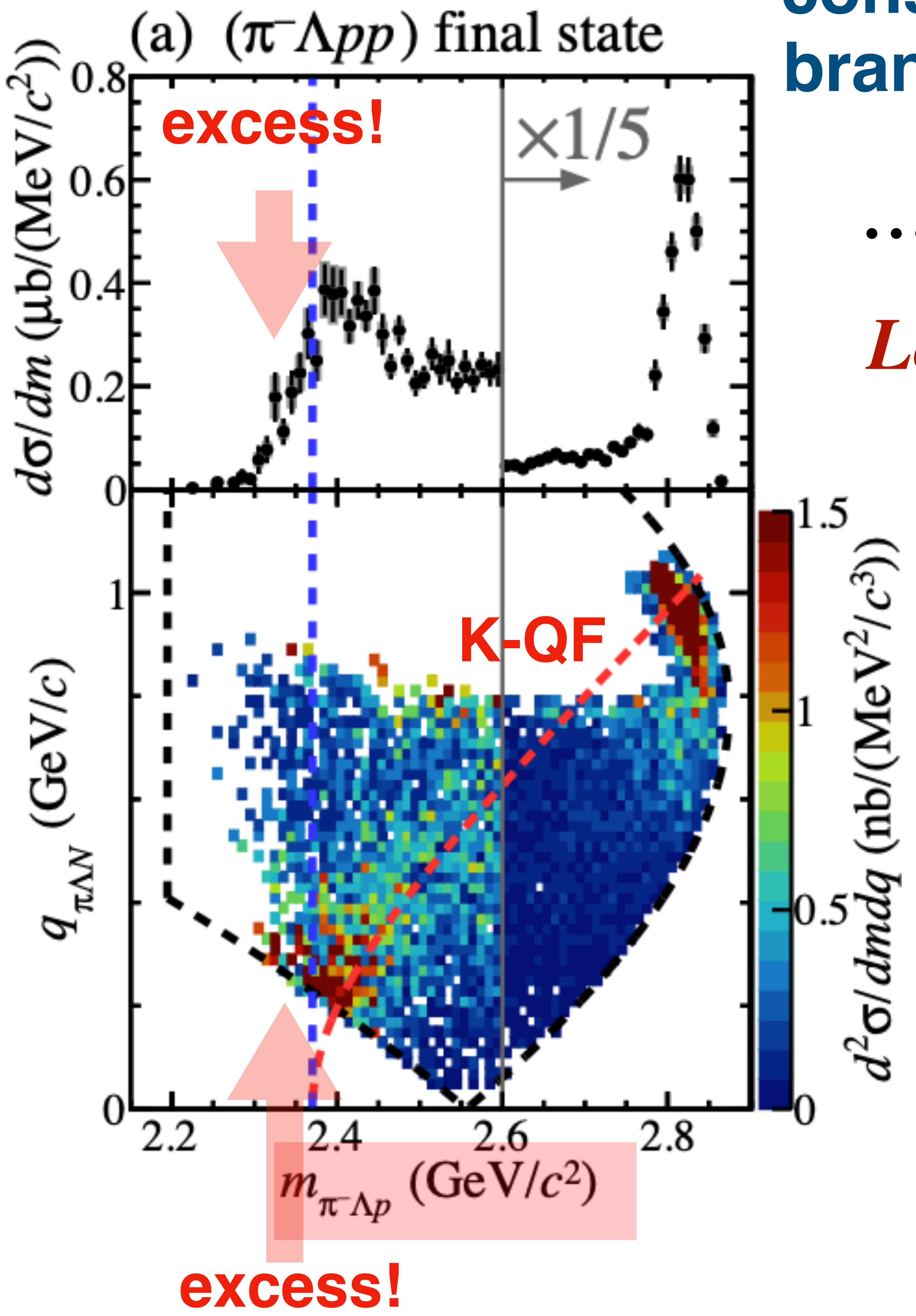
$K^- + {}^3He \rightarrow (\pi^- \Lambda p) + p$ reaction



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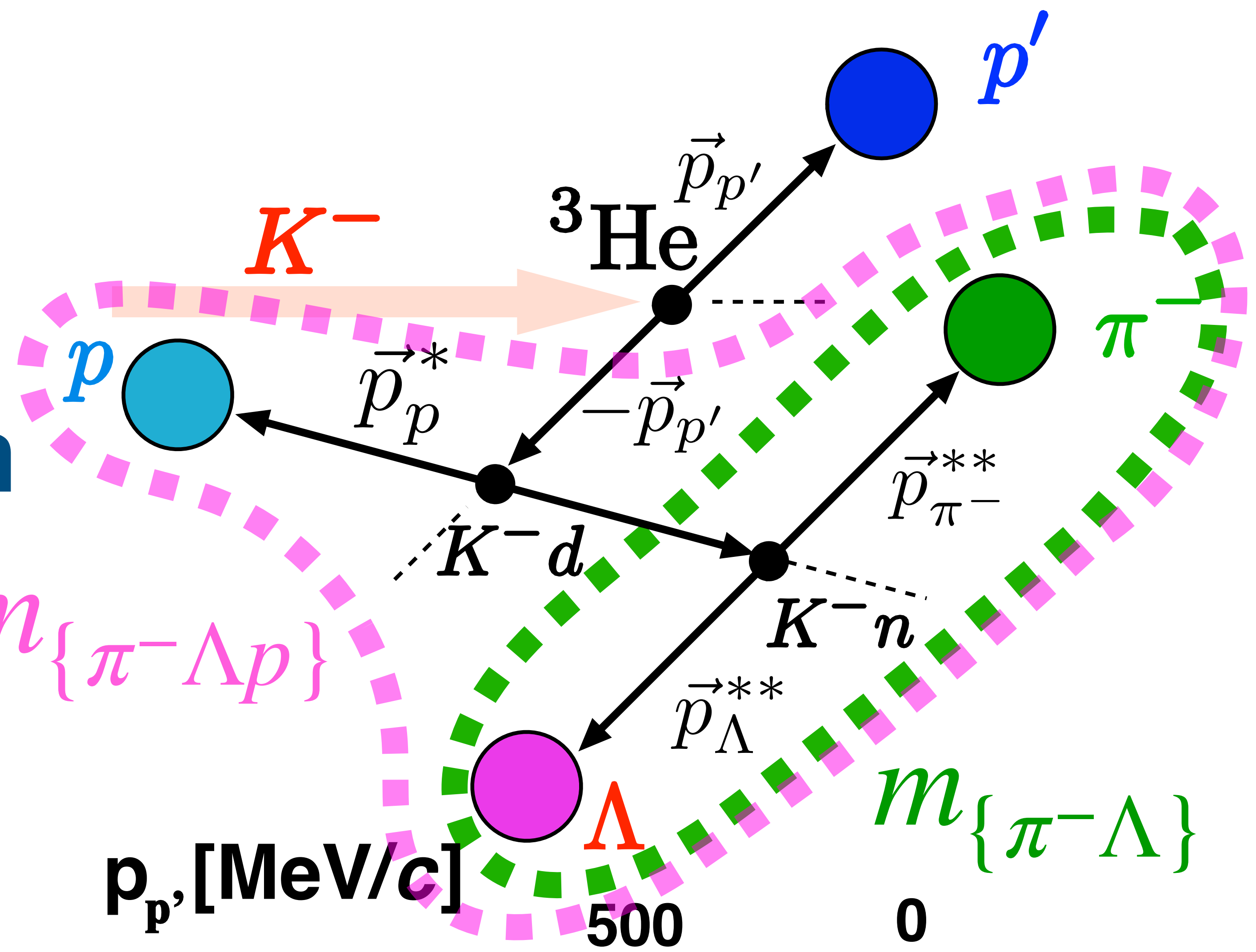

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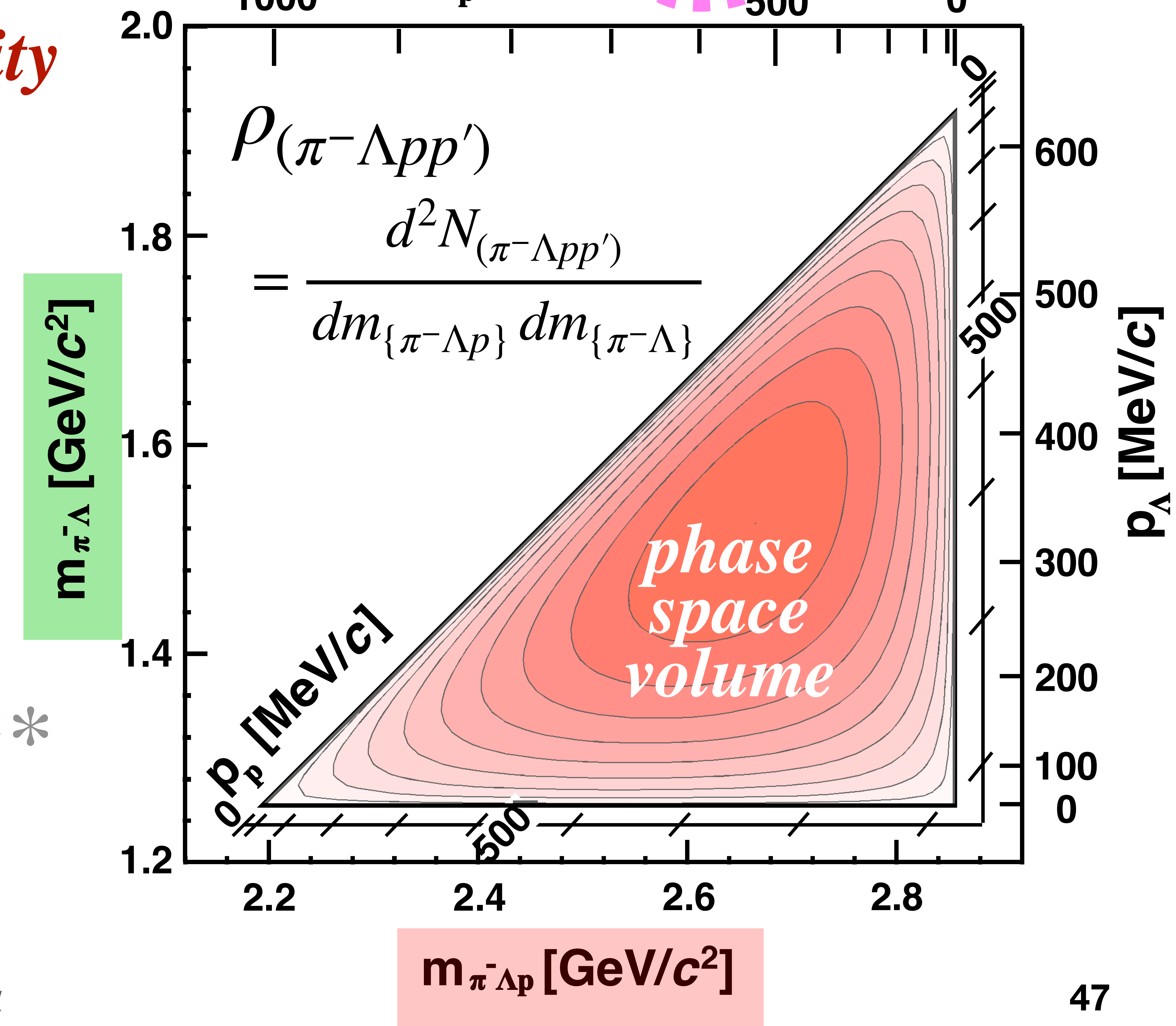

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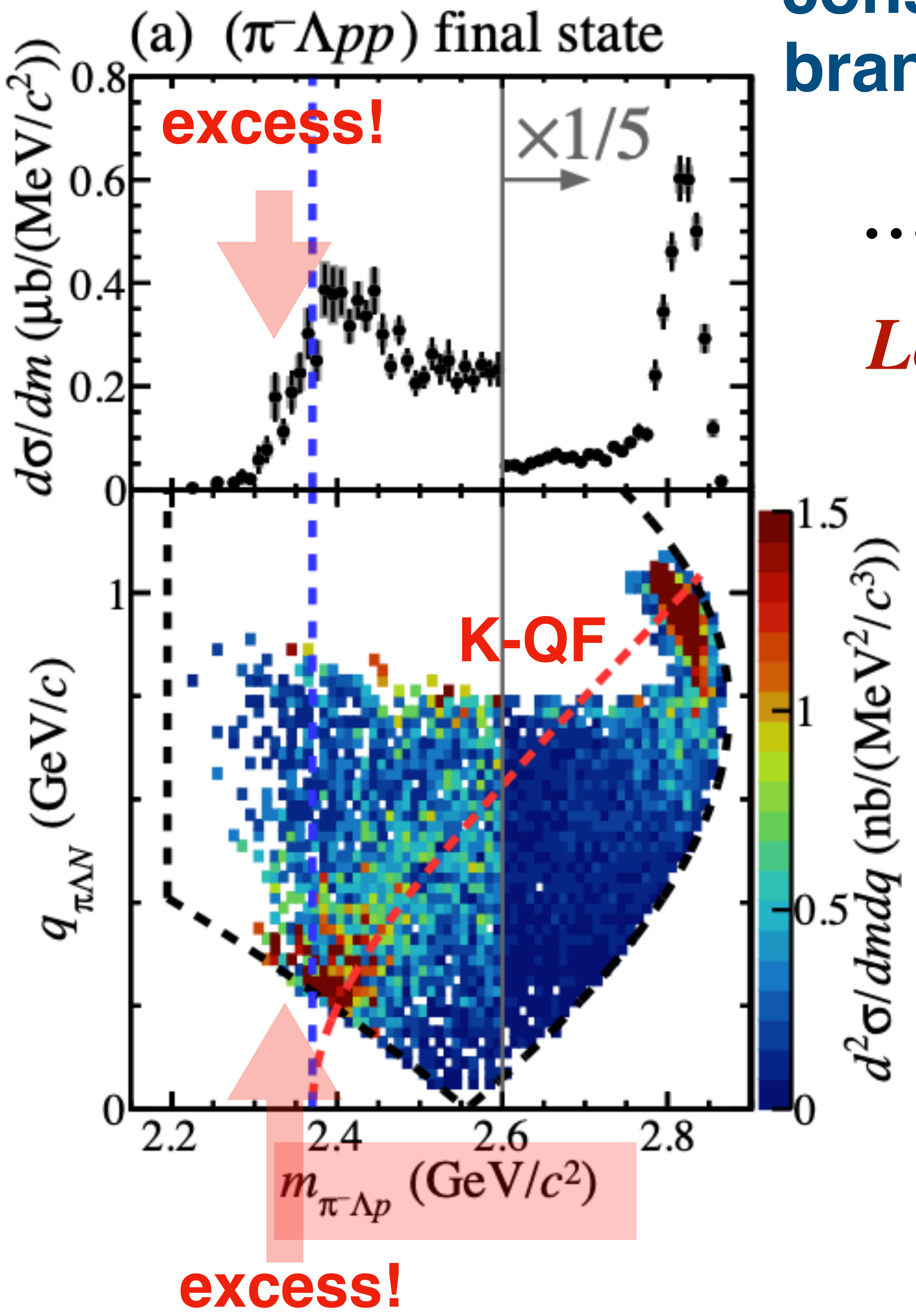

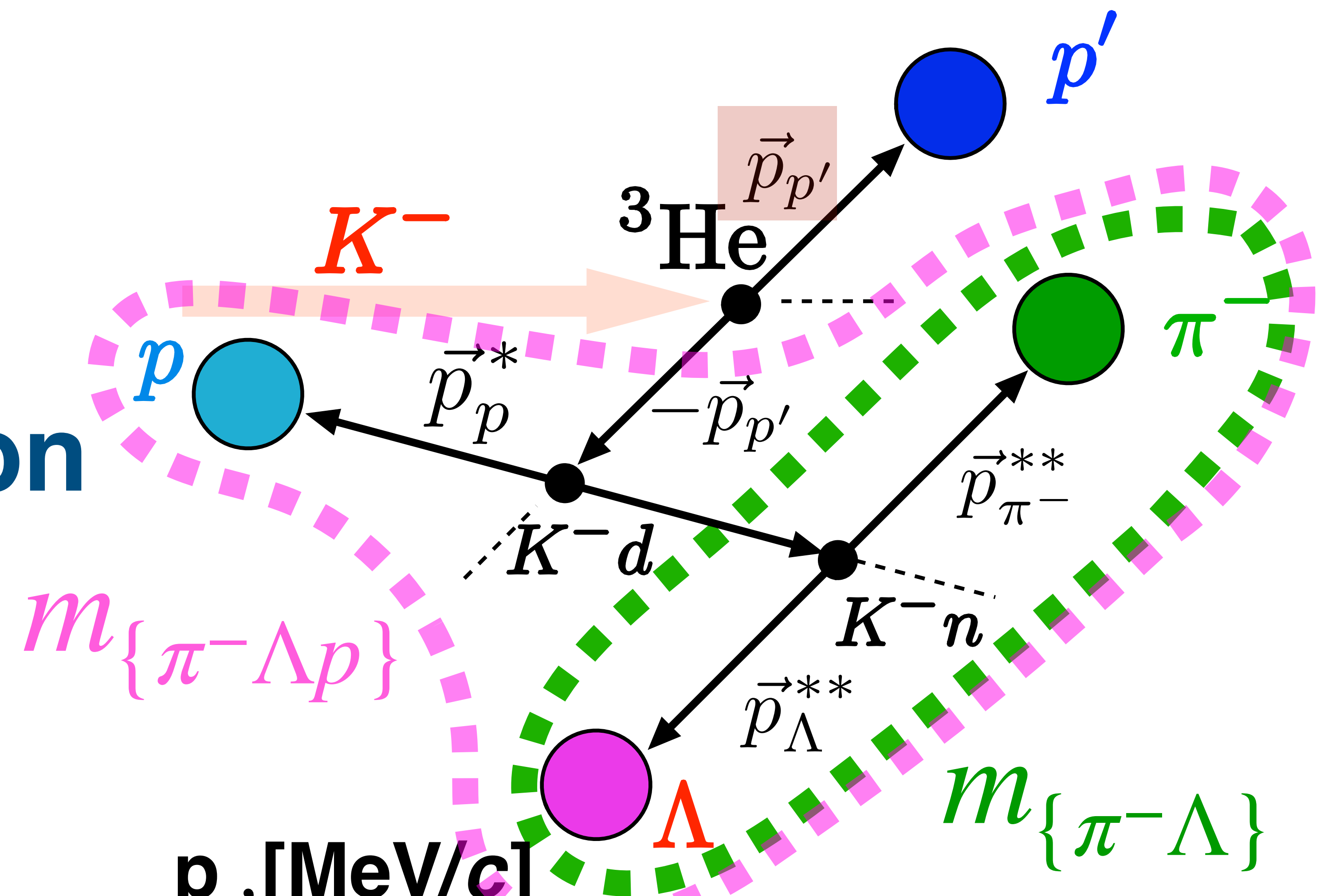

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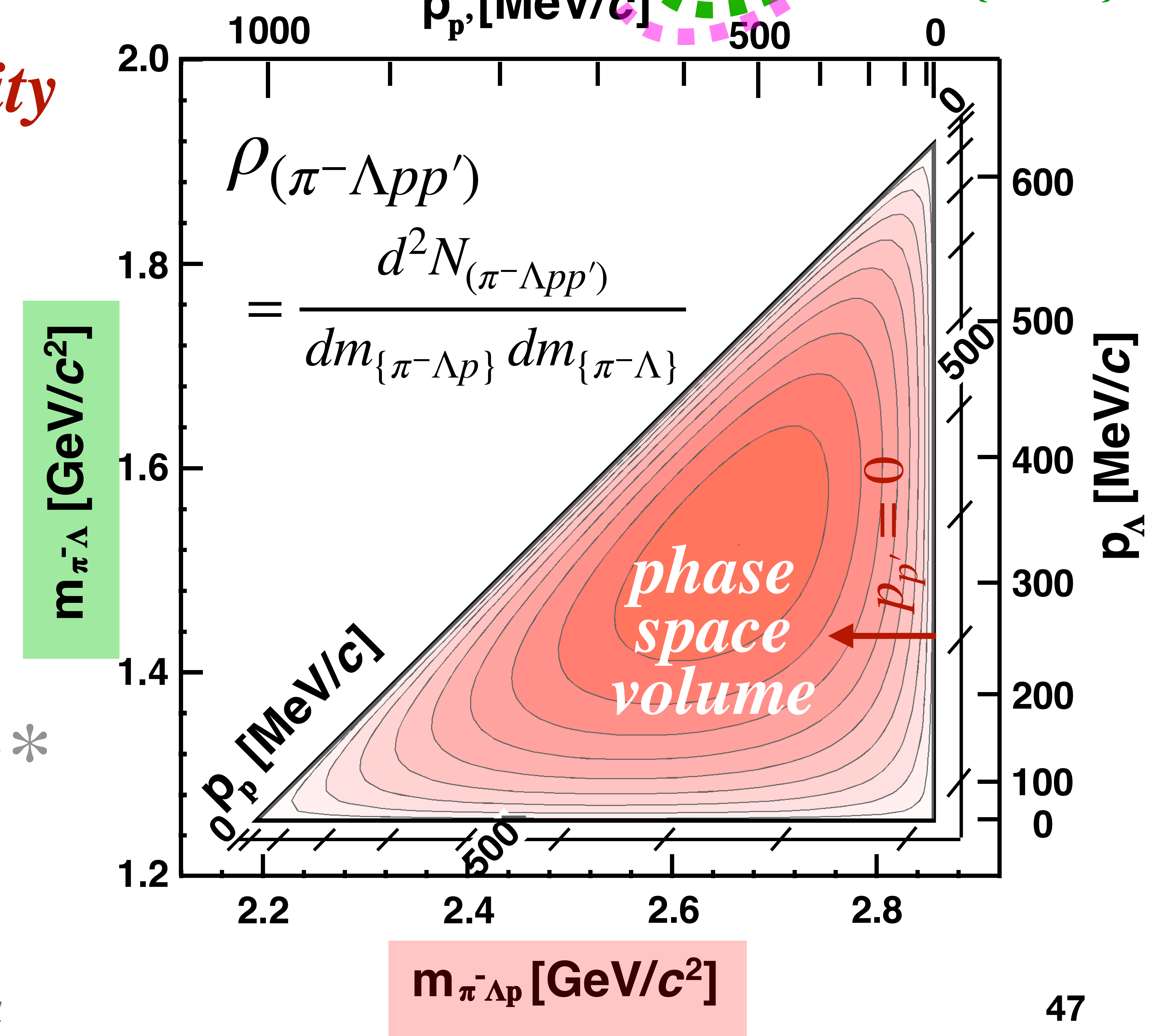

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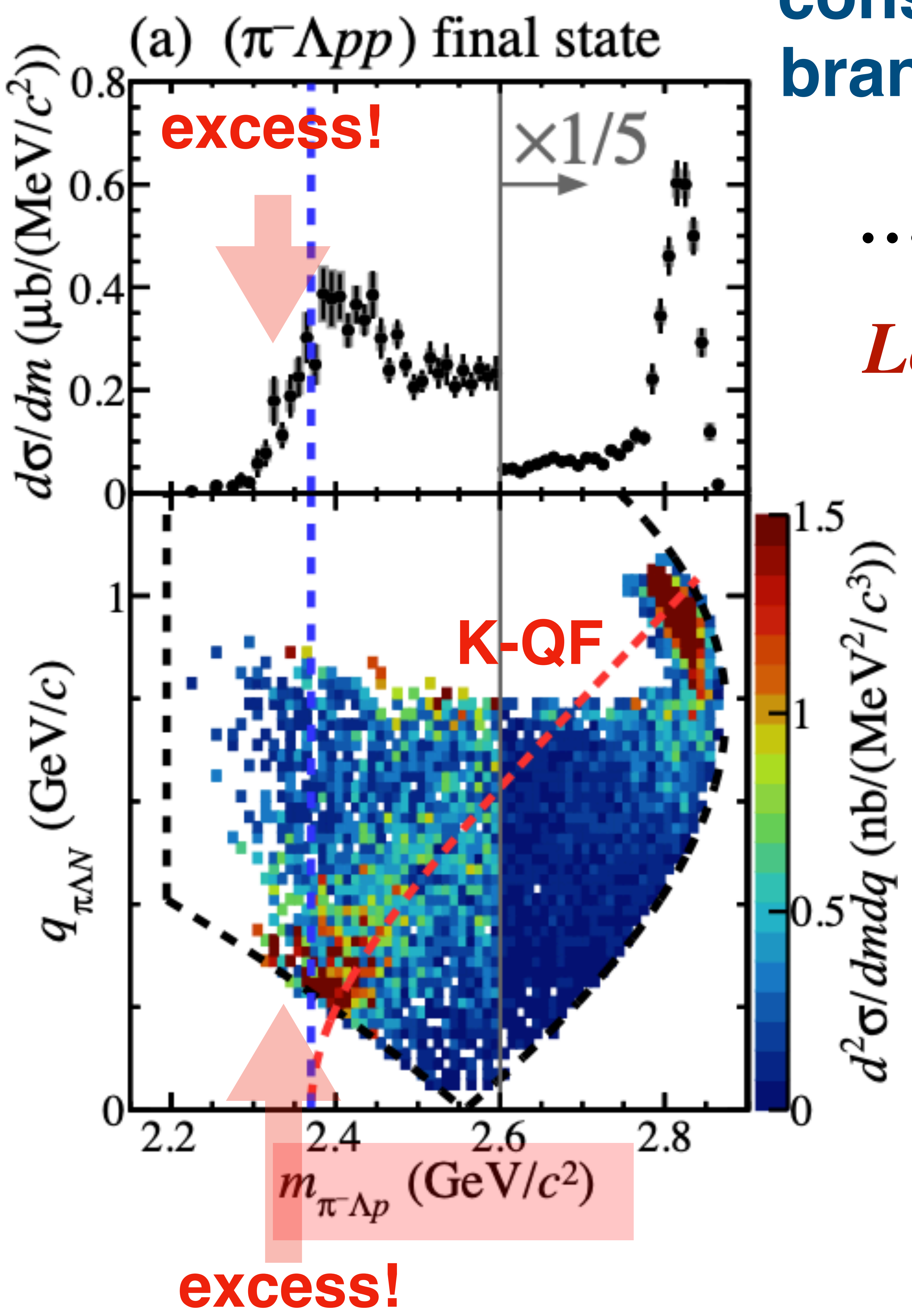

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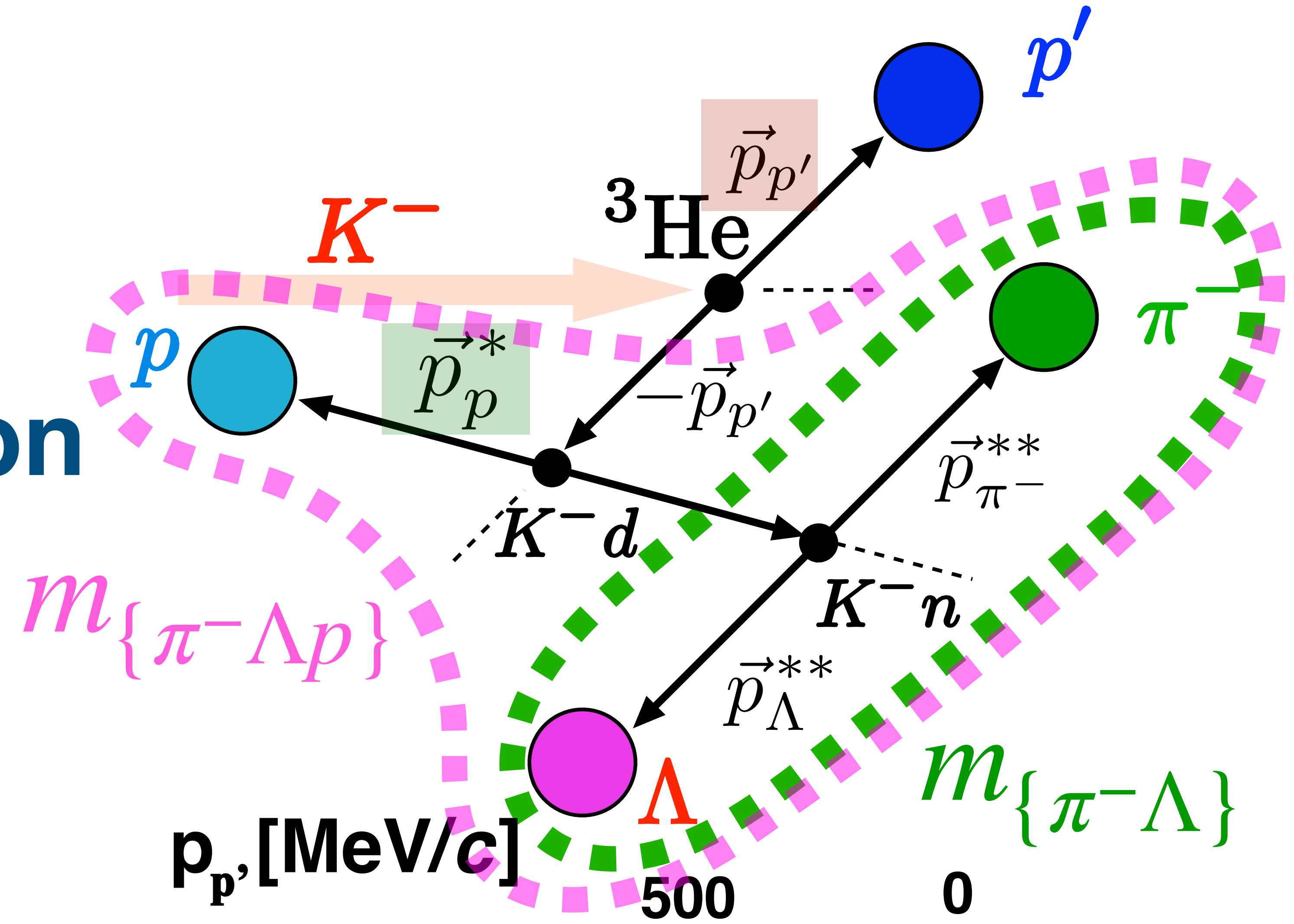

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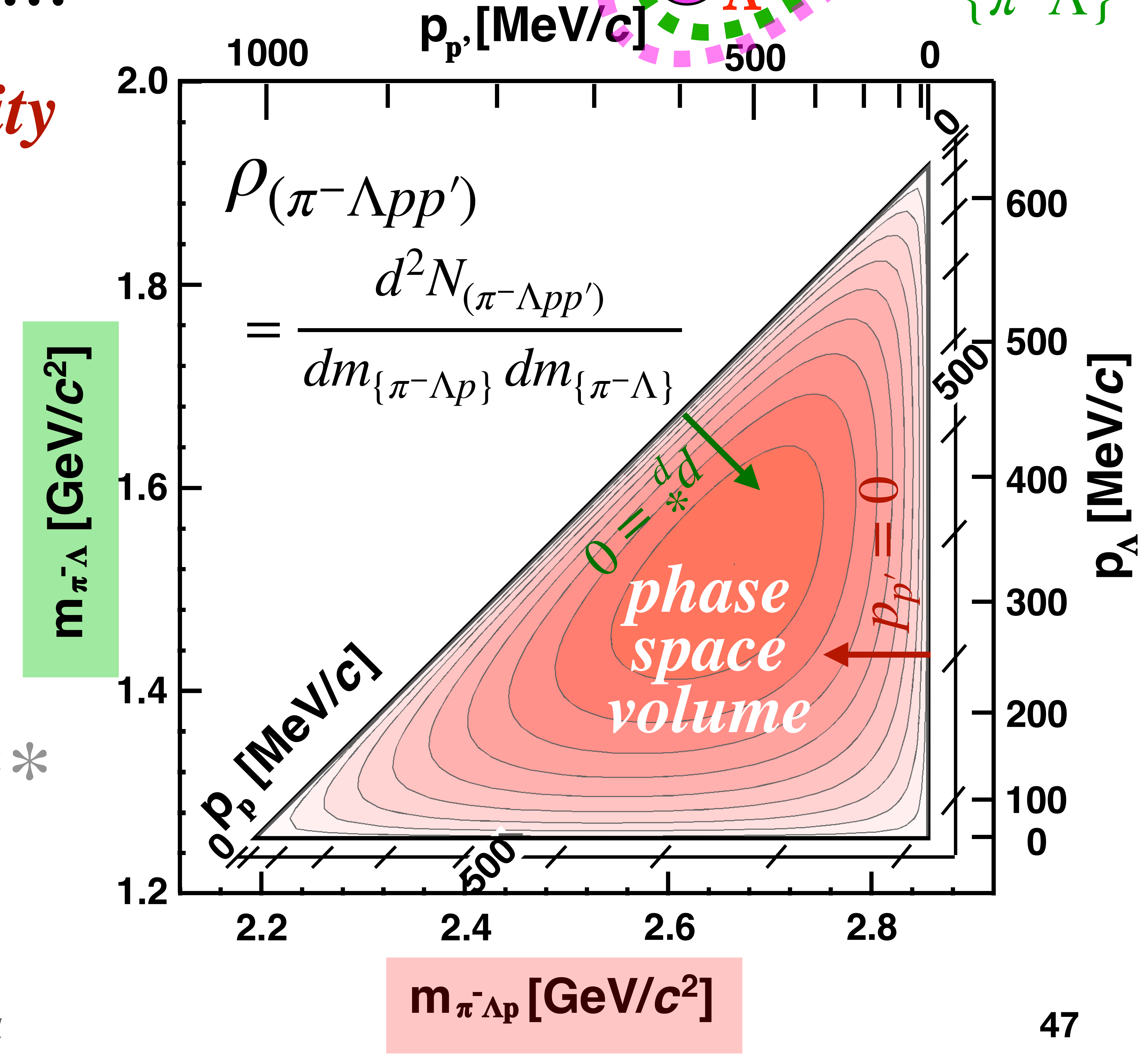

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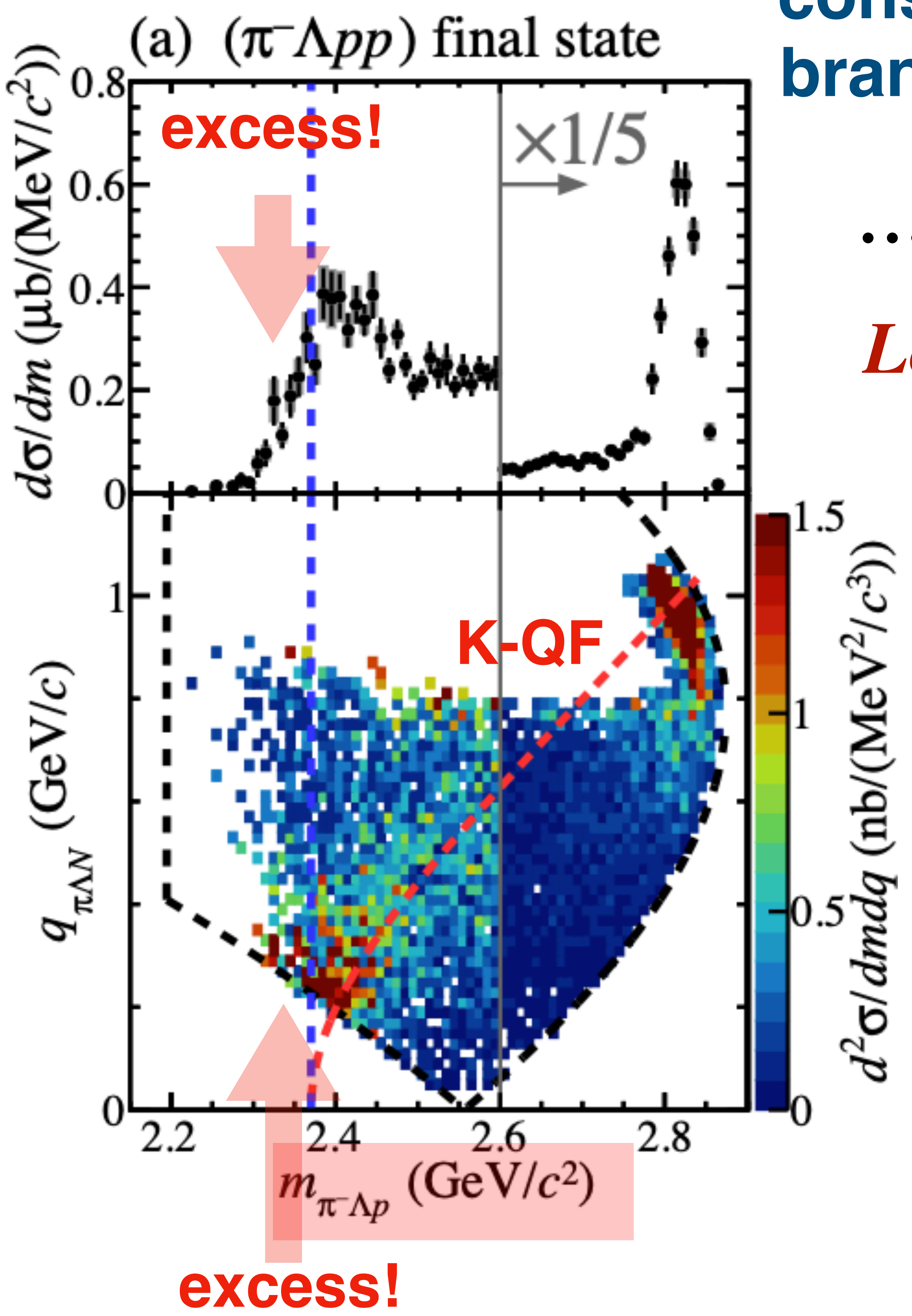

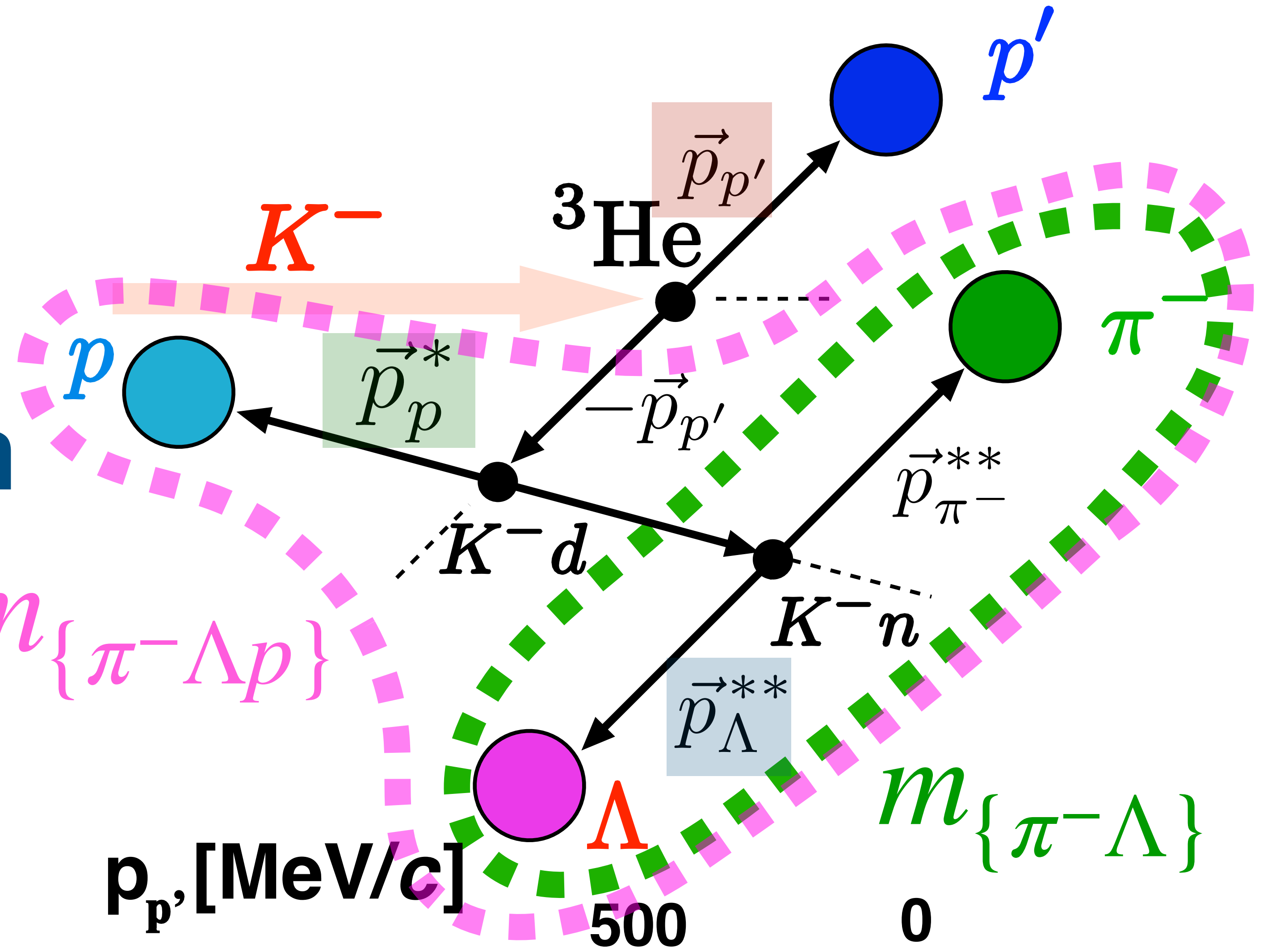

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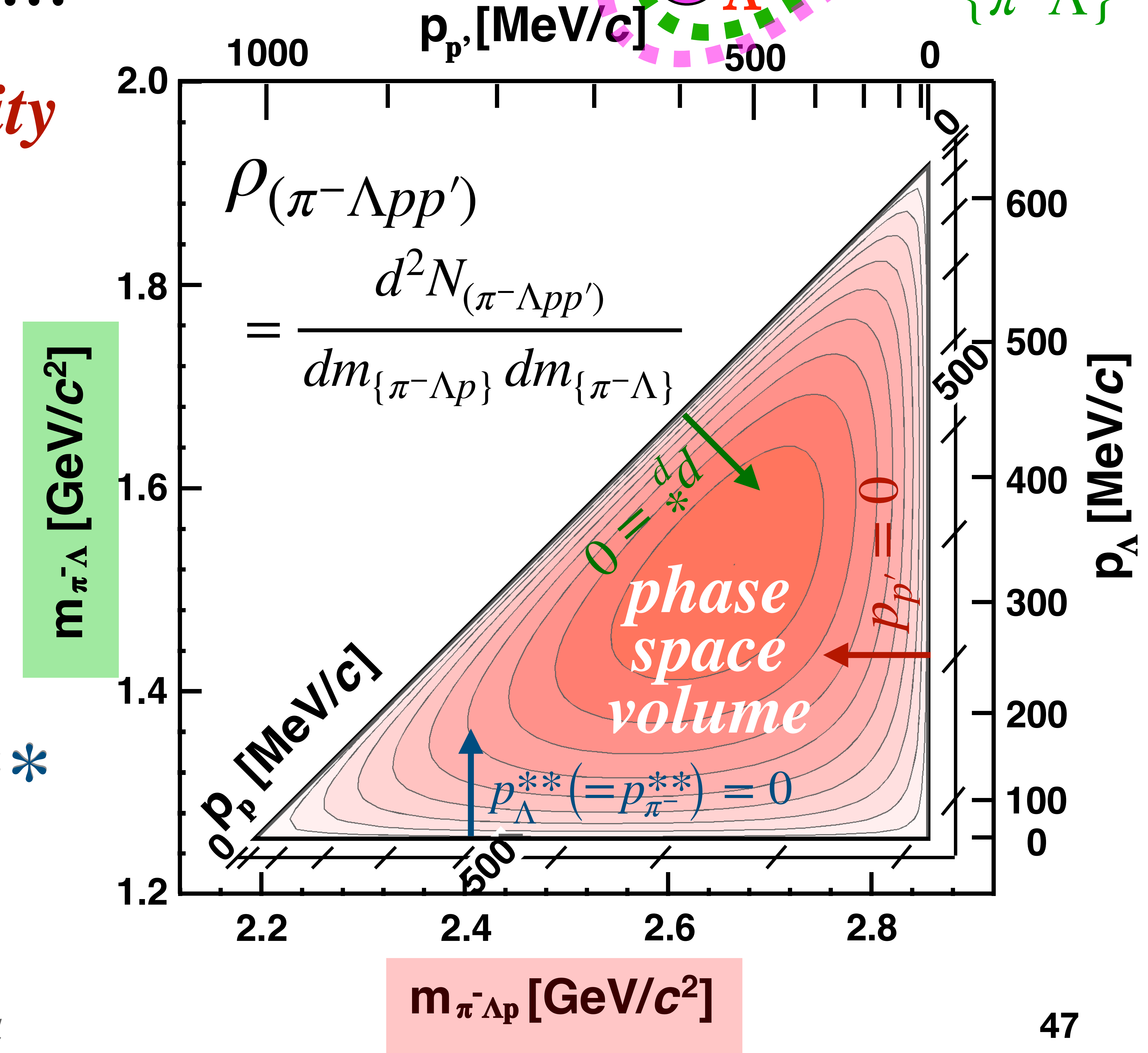

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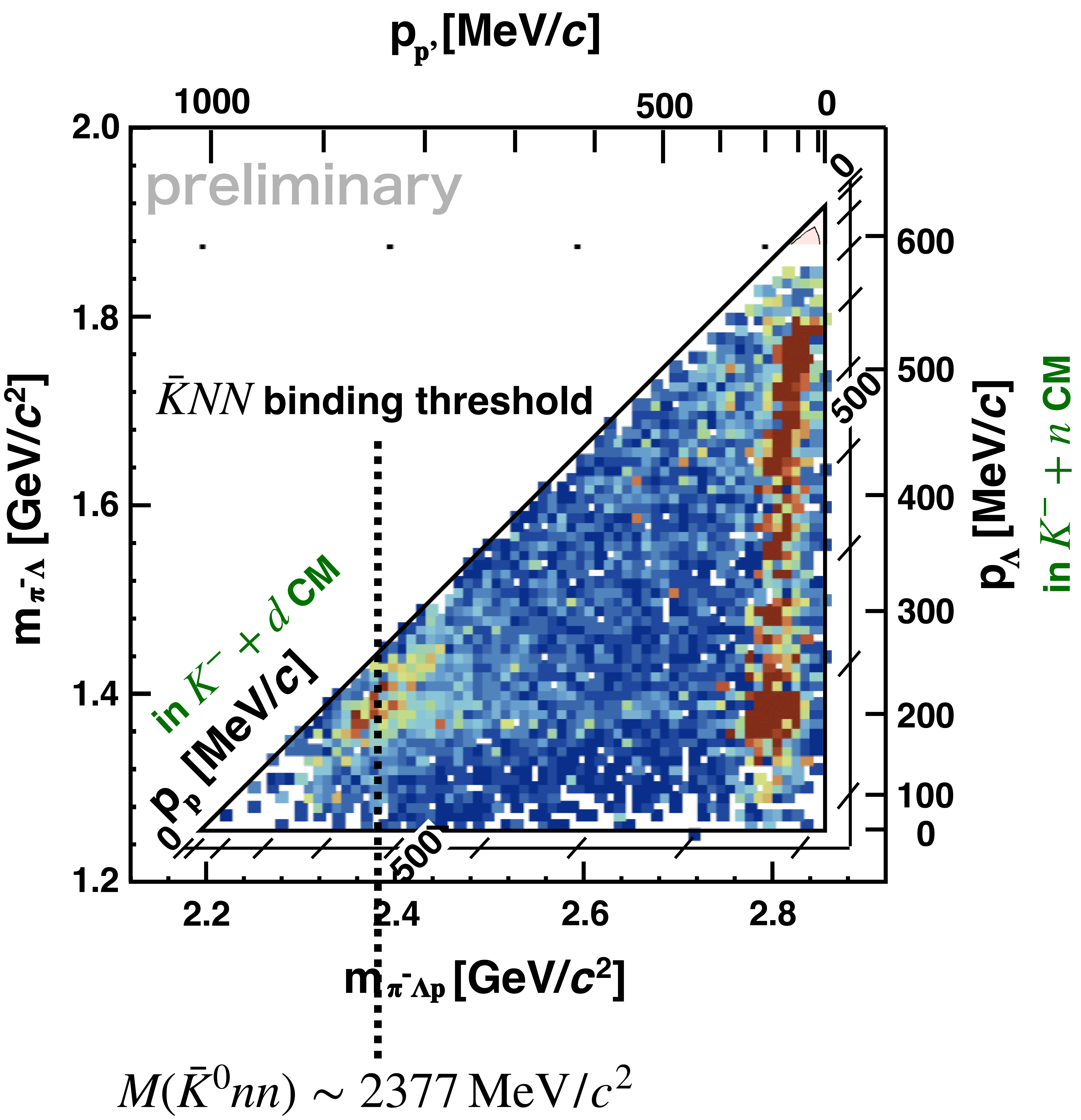

p$_{p'}$ [MeV/c]
1000
500
0
2.0
1.8
1.6
1.4
1.2
preliminary
$\bar{K}NN$ binding threshold
in $K^- + d$ CM
p$_p$ [MeV/c]
600
500
400
300
200
100
0
p$_\Lambda$ [MeV/c]
in $K^- + n$ CM
2.2
2.4
2.6
2.8
m$_{\pi^-\Lambda p}$ [GeV/c^2]
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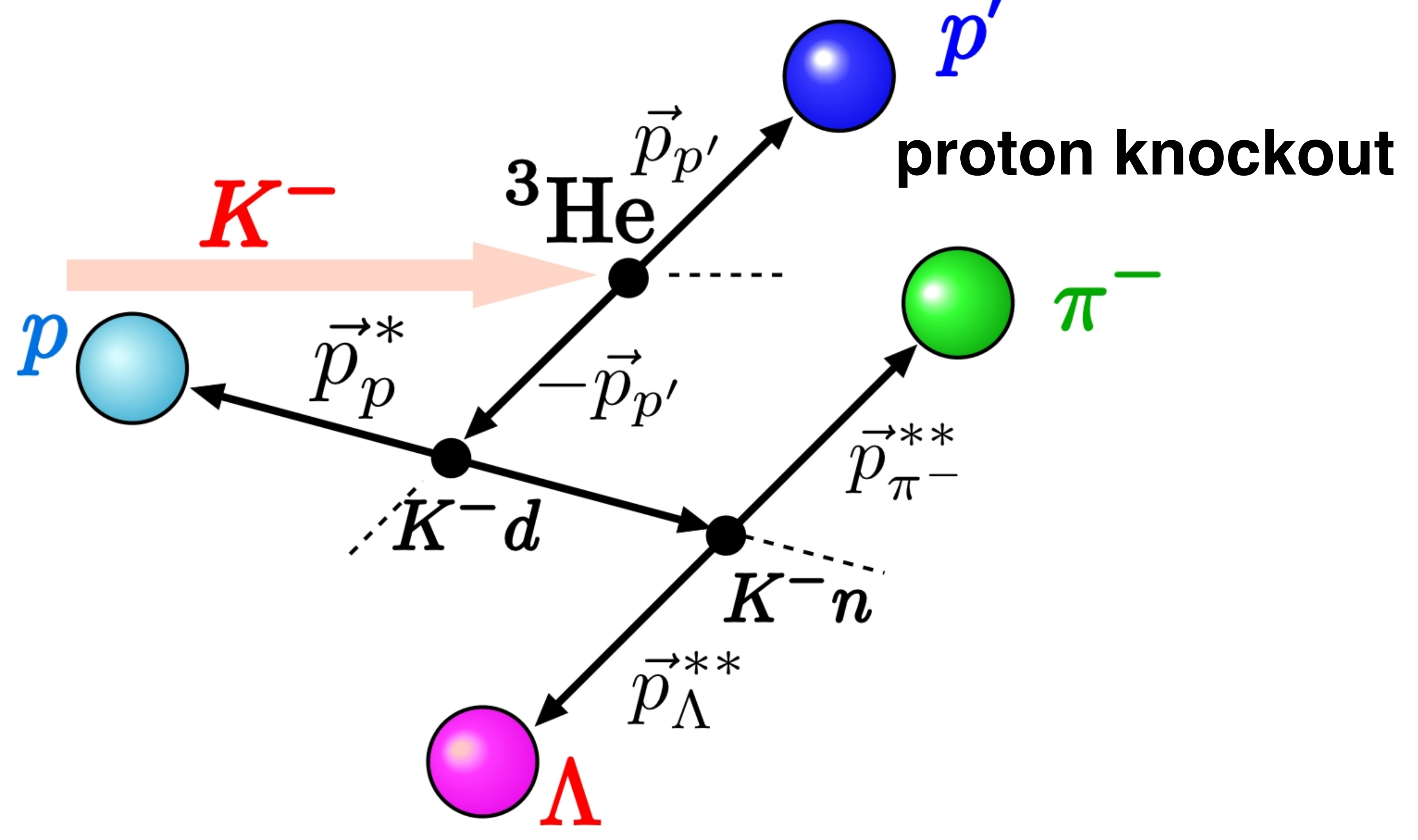
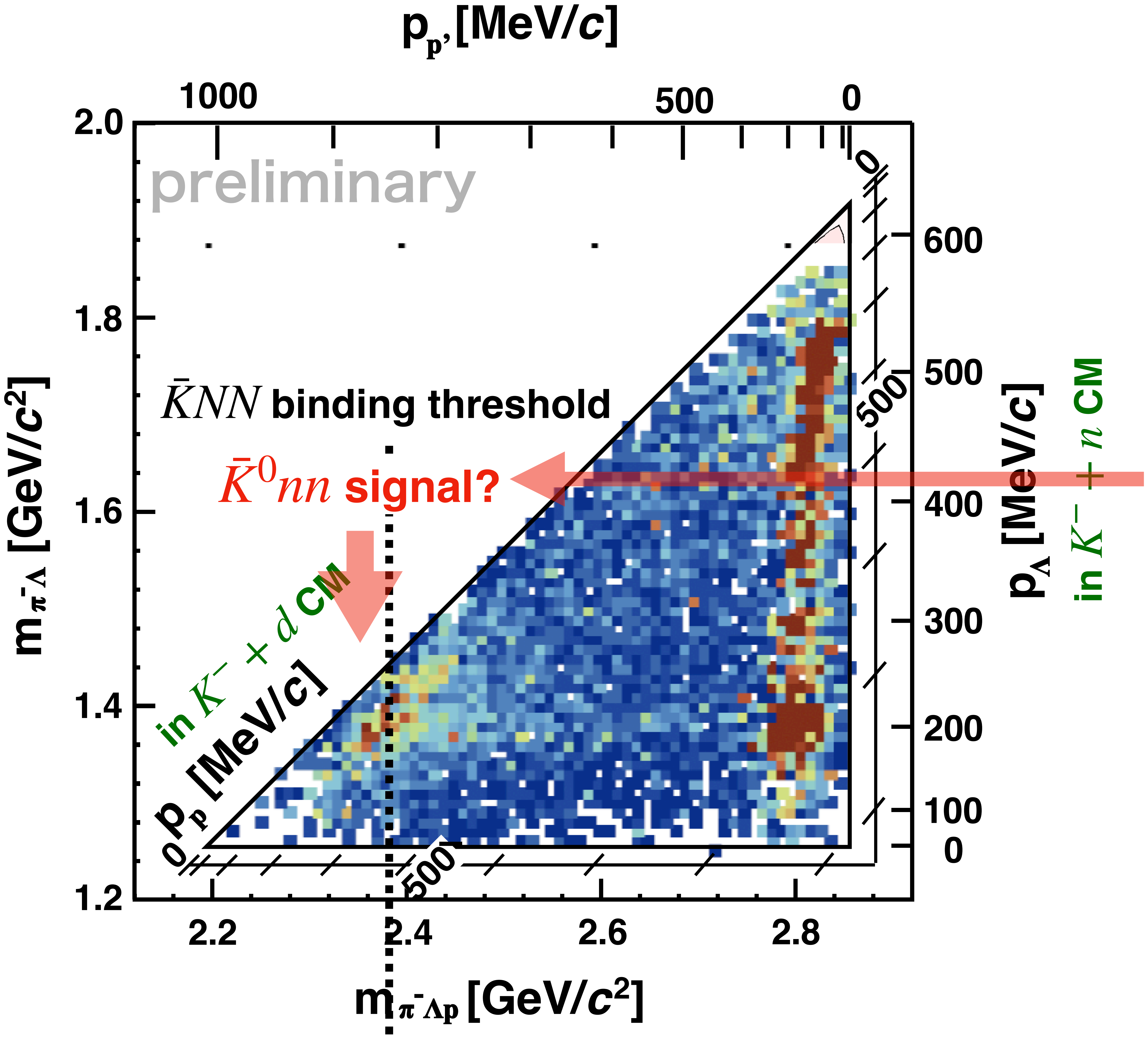
$M(\bar{K}^0 nn) \sim 2377\,\mathrm{MeV}/c^2$



K^-
^{3}He
p'
$\vec{p}_{p'}$
proton knockout
p
$\vec{p}^*_p$
$-\vec{p}_{p'}$
π^-
$\vec{p}^{**}_{\pi^-}$
$K^- d$
$K^- n$
$\vec{p}^{**}_\Lambda$
Λ



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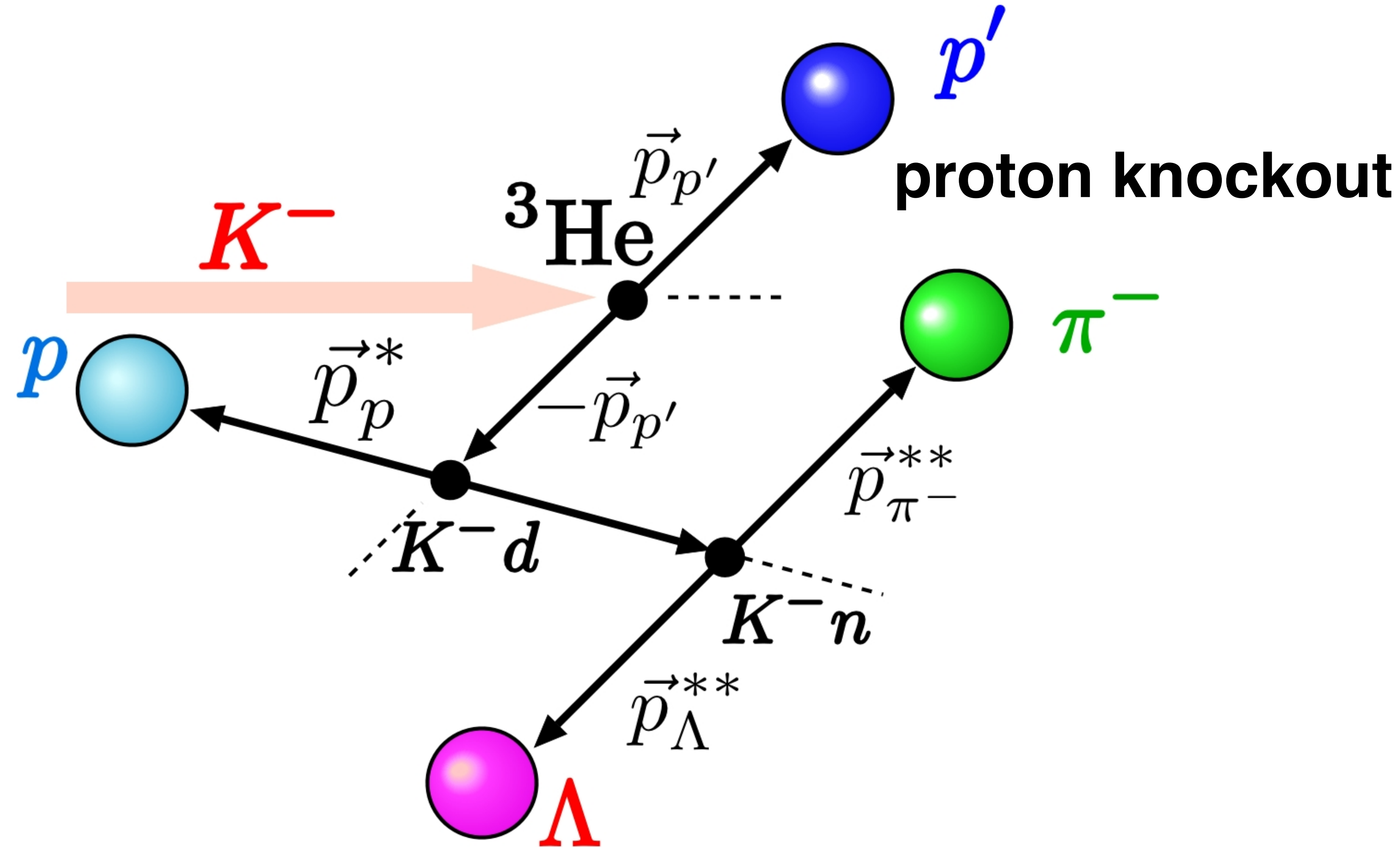
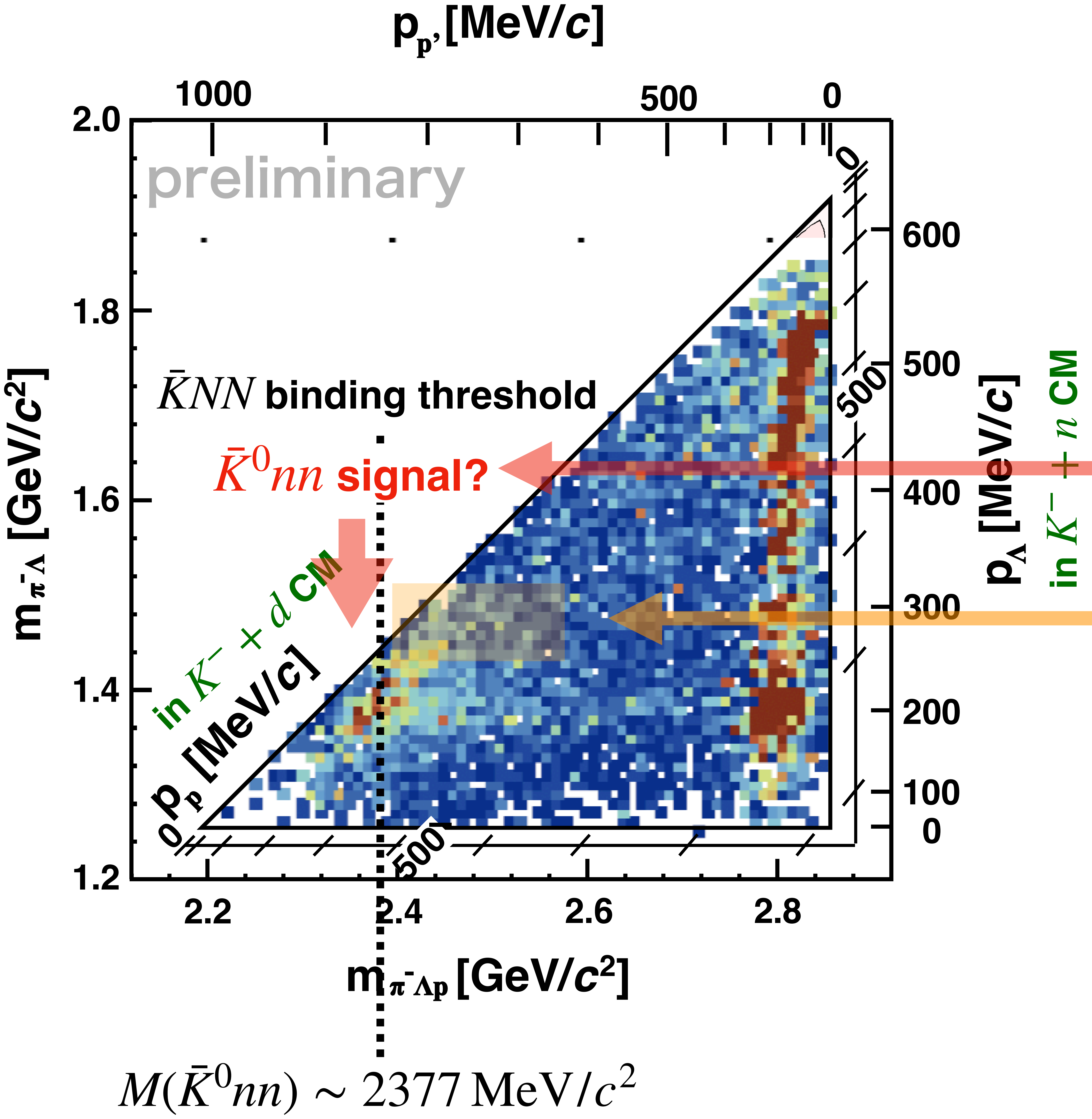
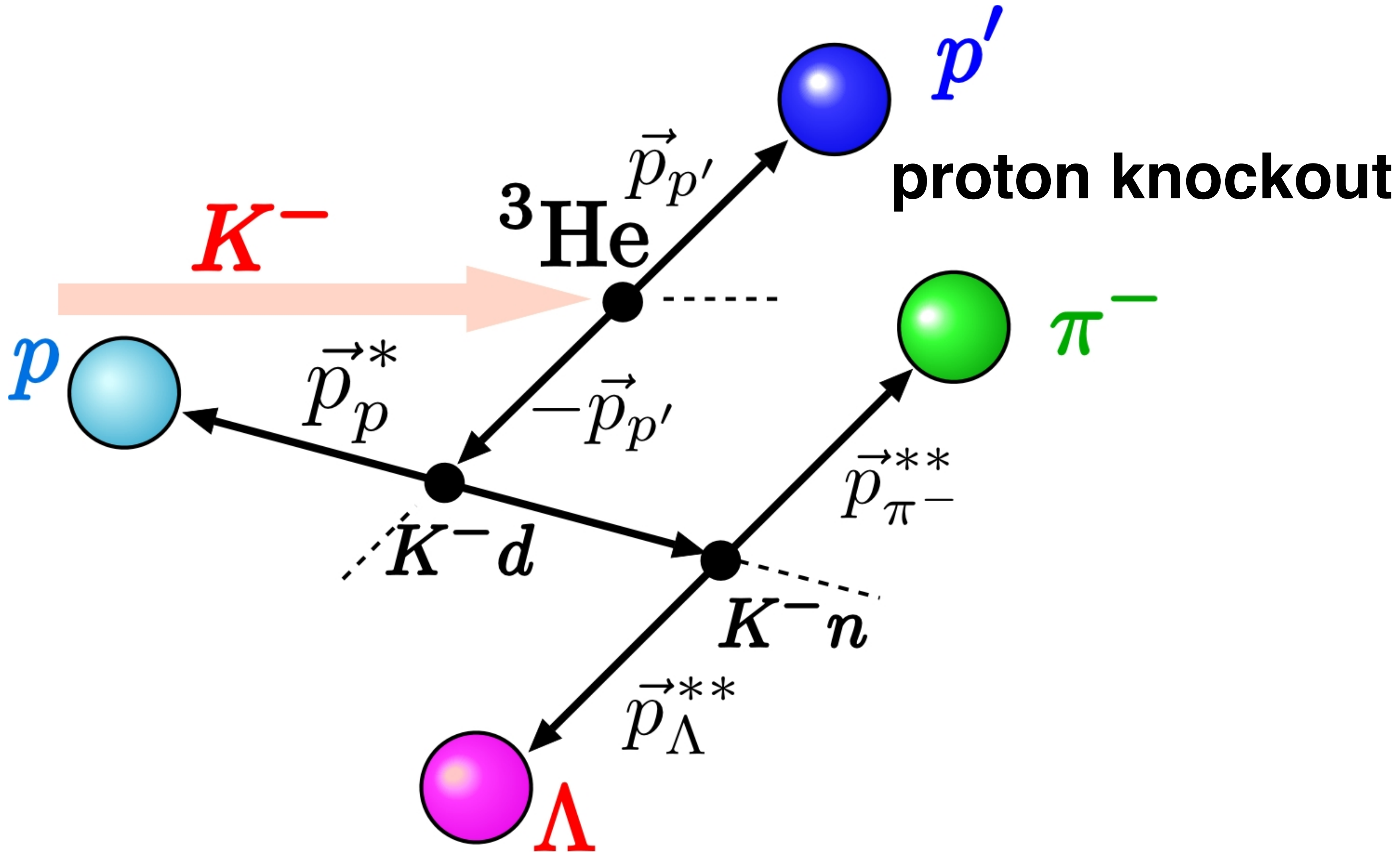


$\bar{K}^0nn$ signal-like event concentration below $\bar{K}$-bound threshold is seen?

— *twice more data become available in April* —





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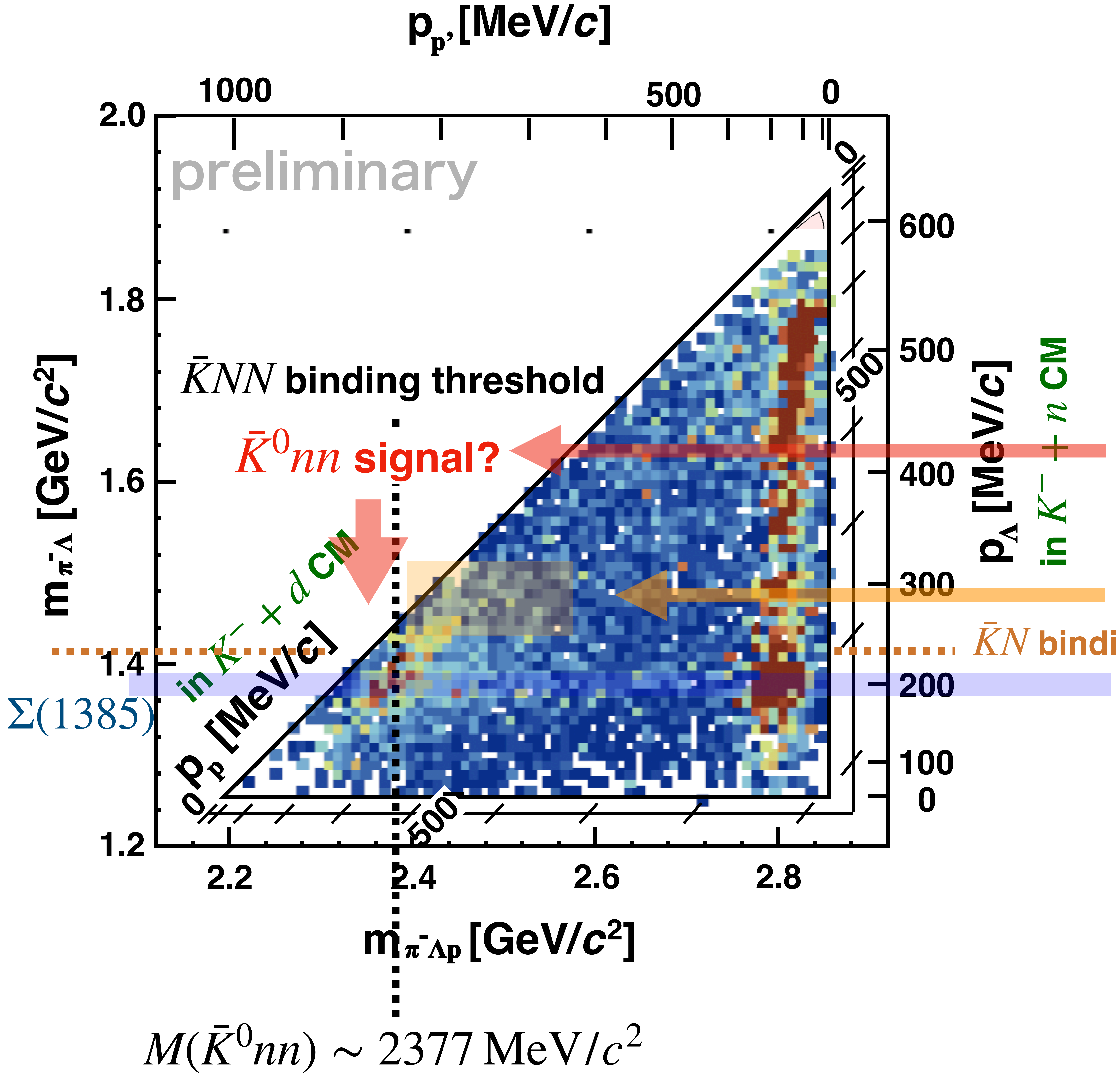
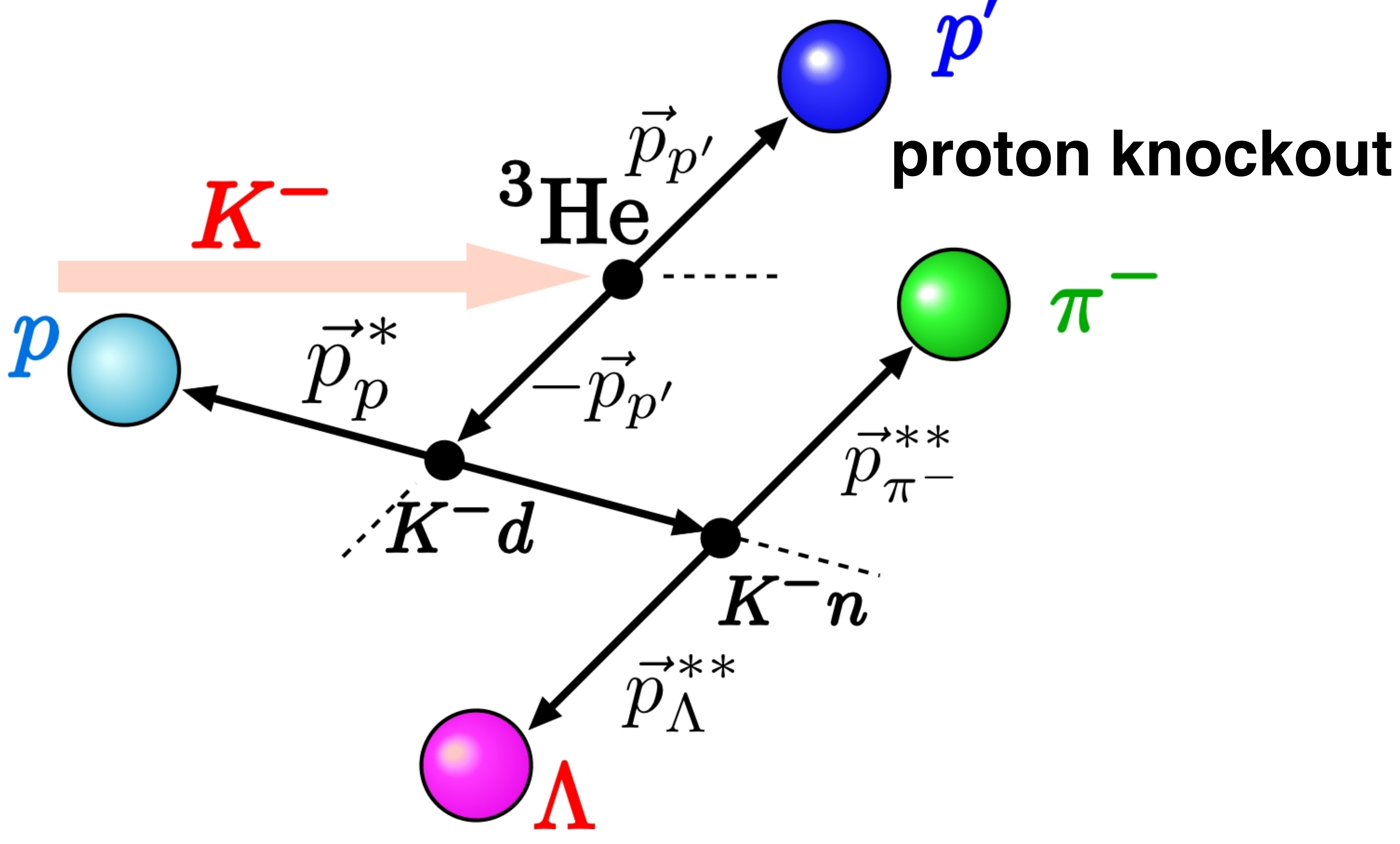
QF-K induced reaction?





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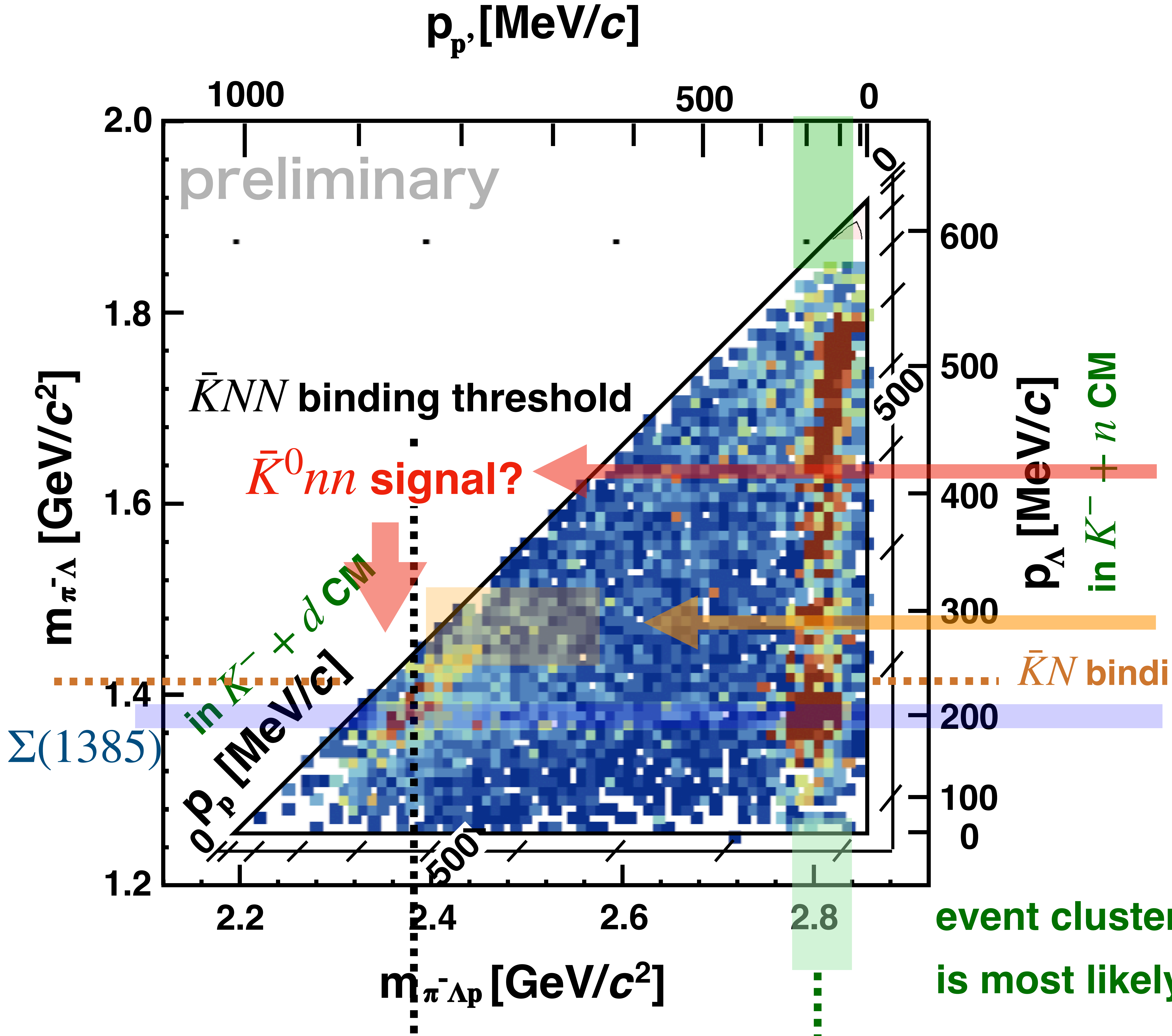

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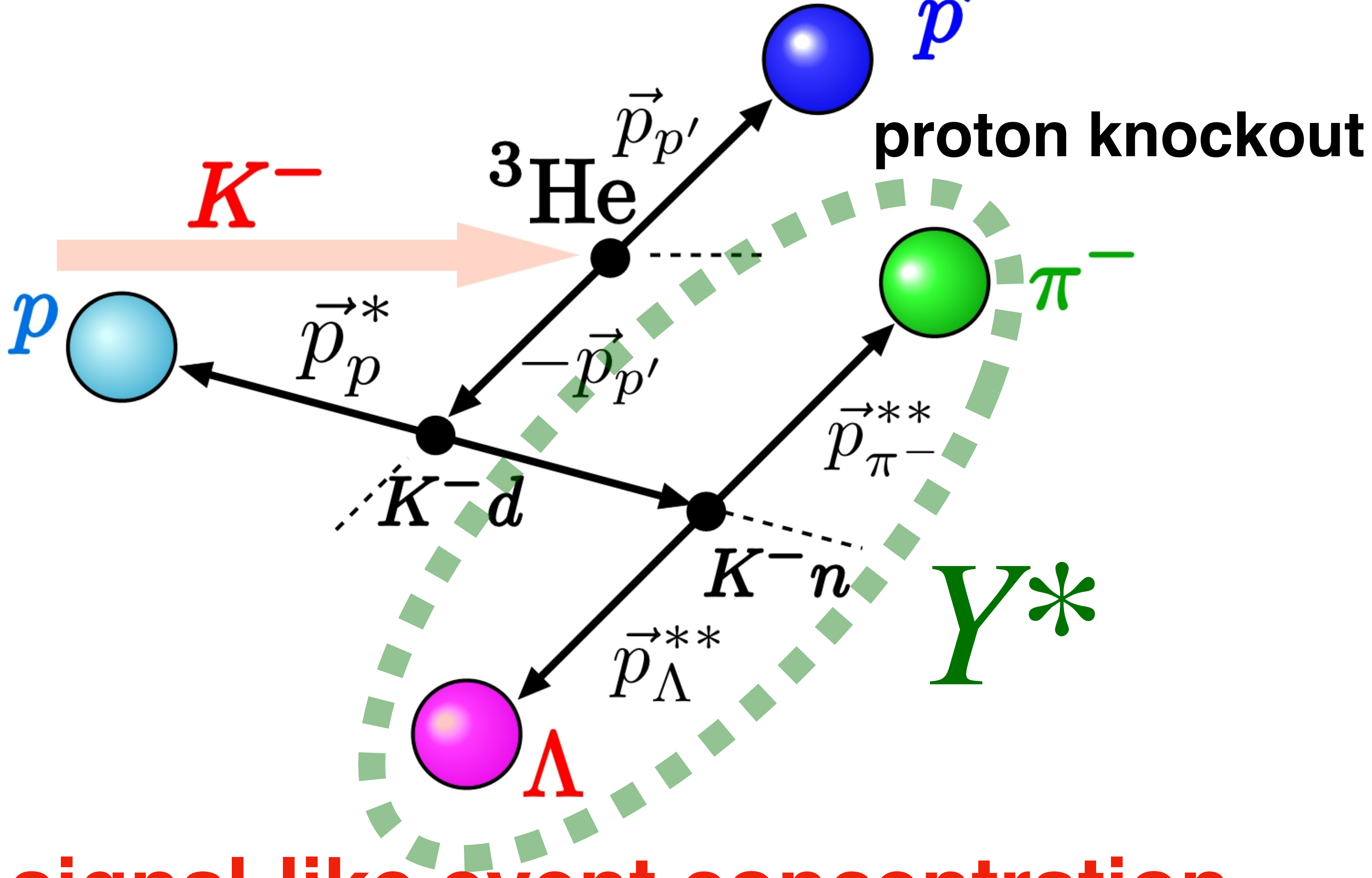

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event cluster at $m_{\pi^-\Lambda p} \sim \sqrt{s_{K^-d}} \approx 2.83\,\mathrm{GeV}$ is most likely ...

2NA: $K^-d \rightarrow Y^*p$ reaction leaving p' as a spectator

— K^- seems to be sensitive to the deuteron cluster in ^{3}He —