The history and future of hadronic-molecule/cluster with strangeness

Experimental point of view toward revolutionary Nuclear Study via revealing Internal Structure of hadronic-molecule

M. Iwasaki

from **RIKEN**
Cluster of Pioneering Research
Nishina Center

contents:

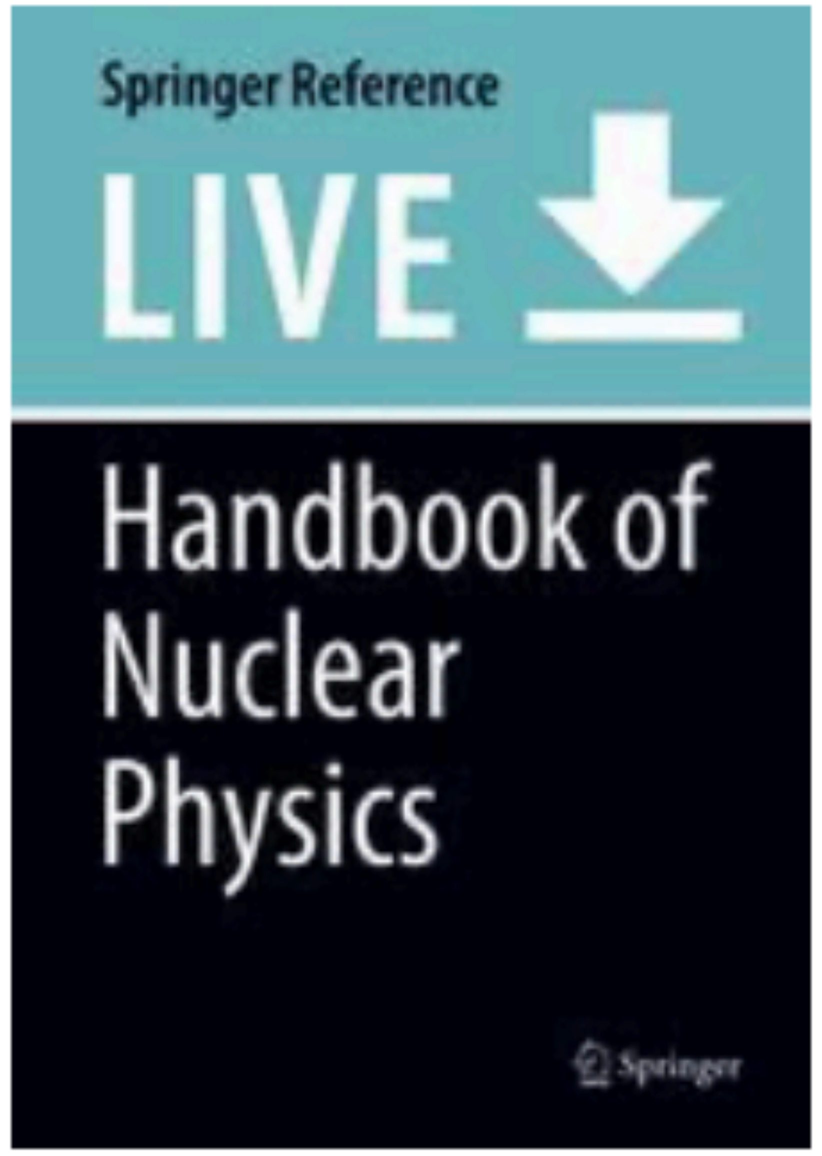
$\bar{K}N$ interaction study via kaonic atom

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

Future direction for $\bar{K}$ (ϕ) bound state study

https://doi.org/10.1007/978-981-15-8818-1_37-1



Kaonic Nuclei from the Experimental Viewpoint

Research on kaonic nuclear bound states is a completely new field. This nuclear system consists of

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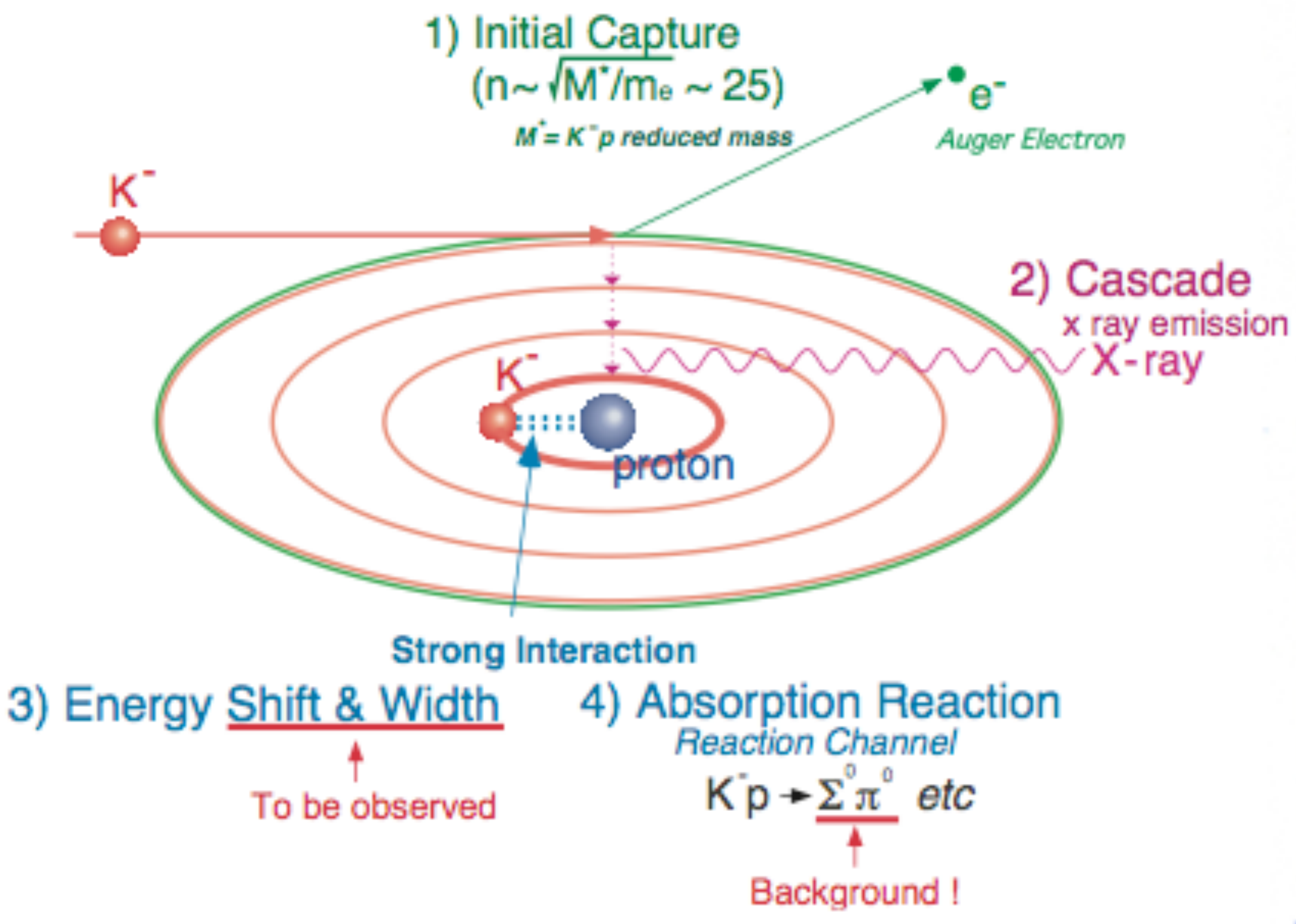
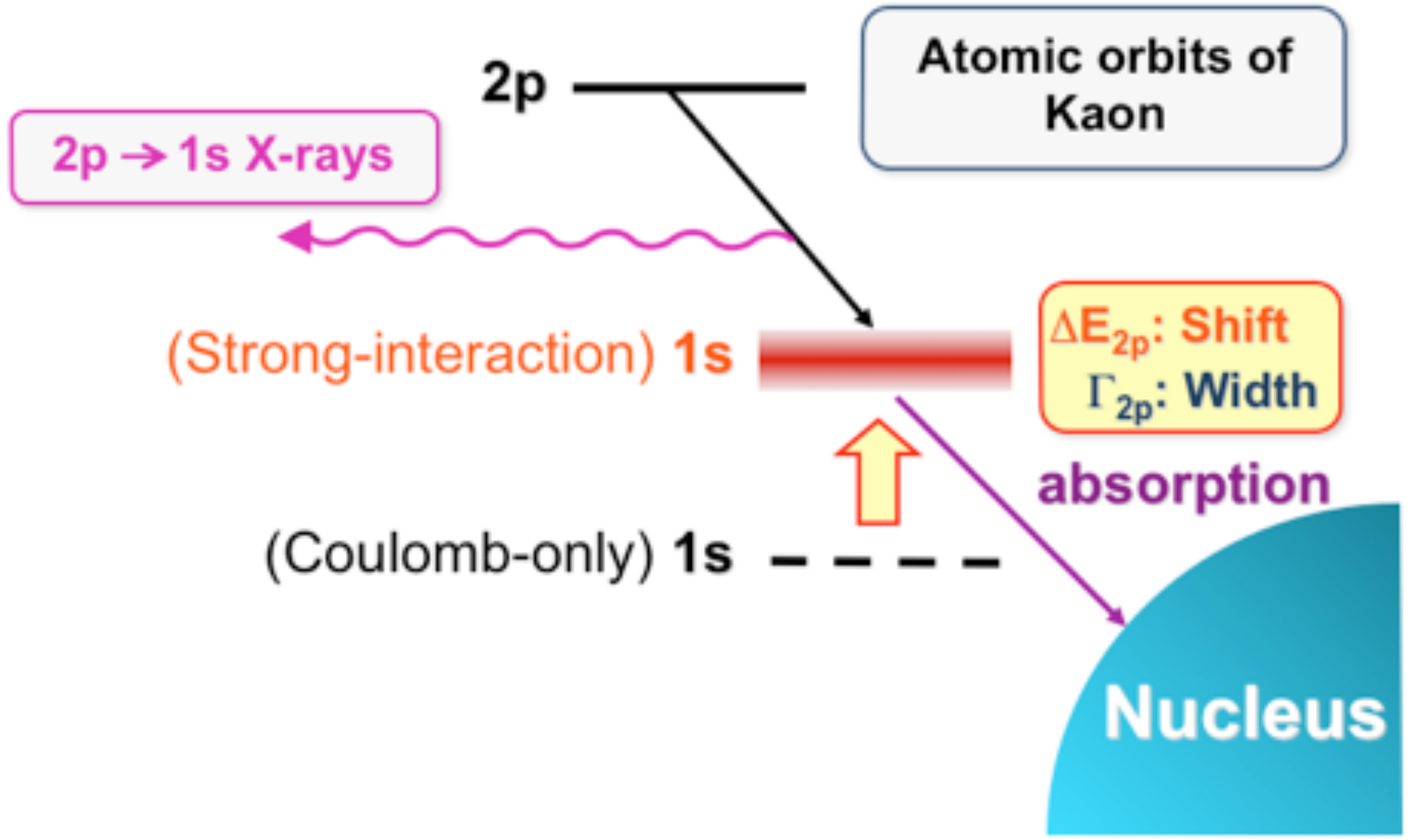
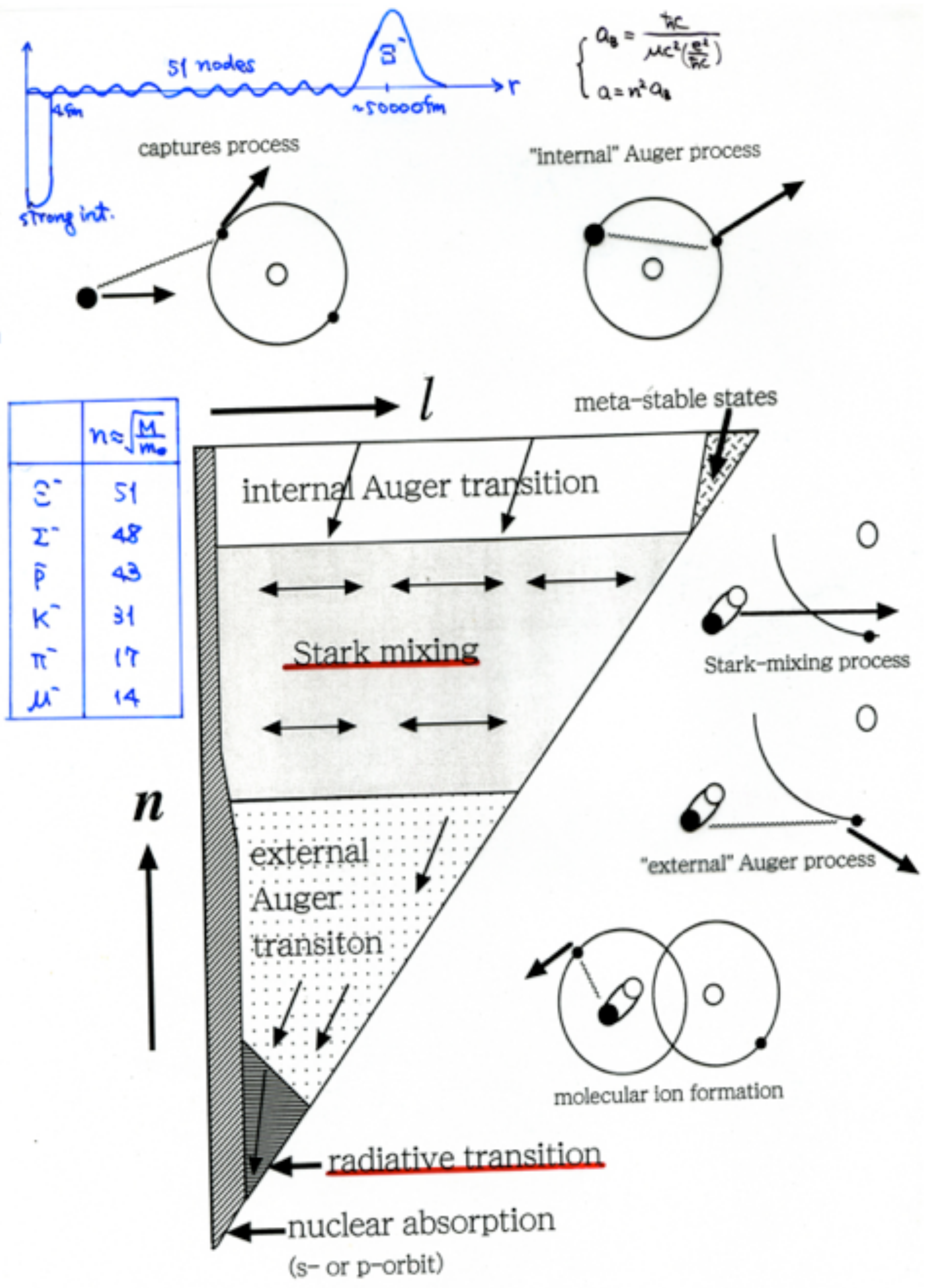
kaonic hydrogen formation

Kaonic Atom Formation





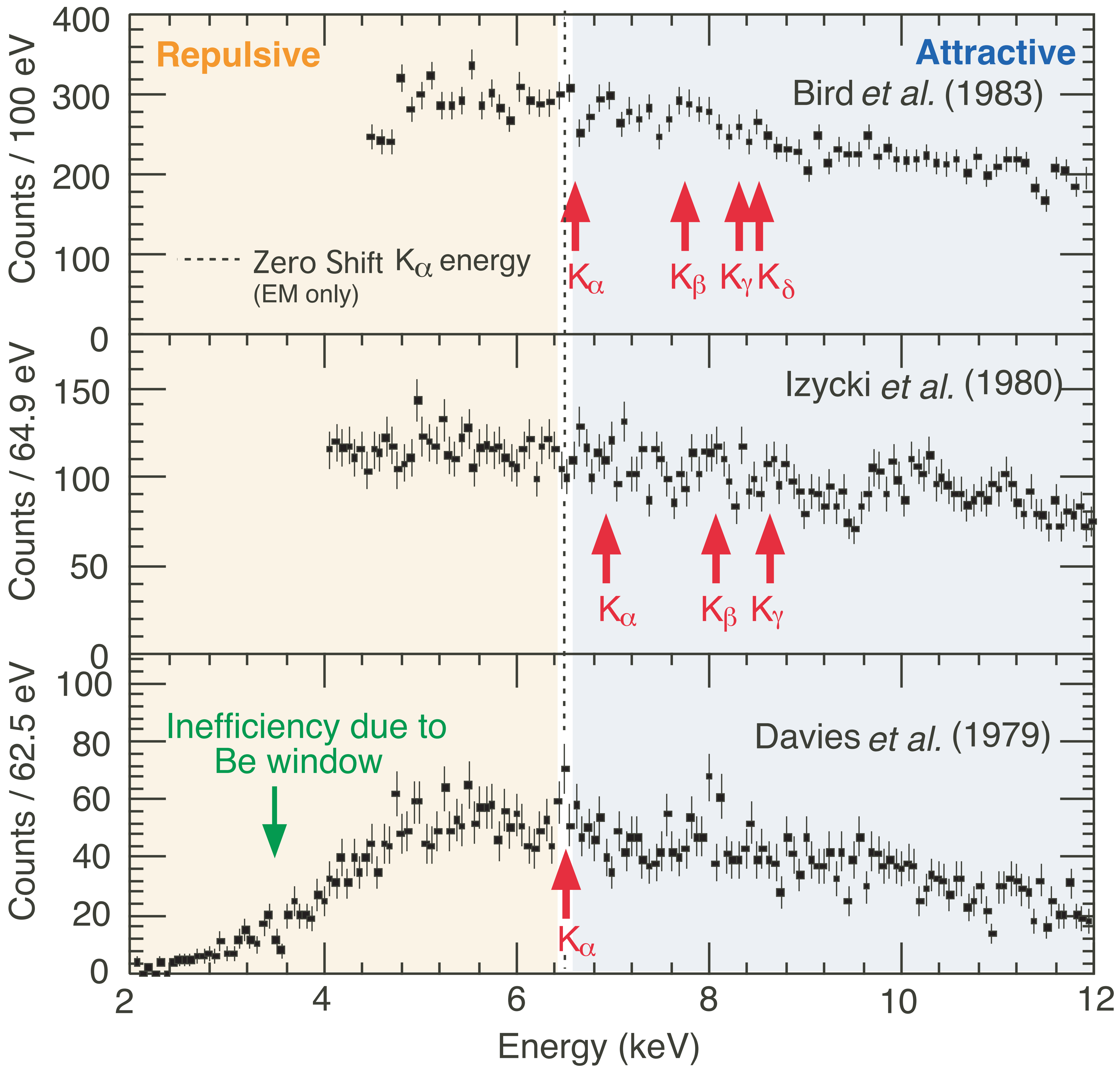


	$n \approx \sqrt{\frac{M}{m_e}}$
Ξ^-	51
Σ^-	48
$\bar{p}$	43
K^-	31
π^-	17
μ^-	14

Kaonic hydrogen atom (pre-history)

Dalitz and Yazaki's naive question:

"Why you cannot resolve kaonic hydrogen puzzle?"



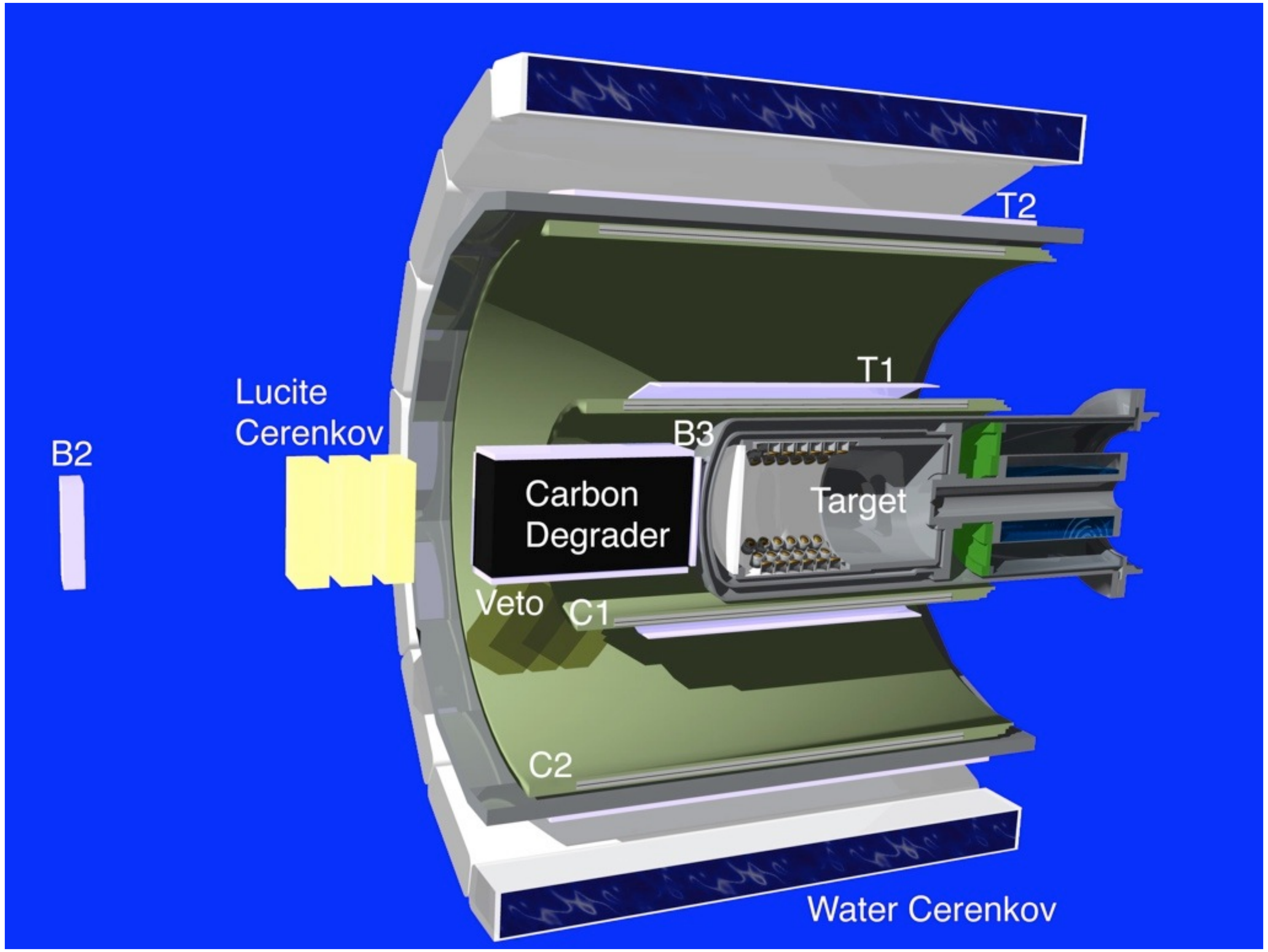
Small Signal
- Stark
- Low Hydrogen Density

Huge Background
- Absorption Reaction
- Decay in Flight

nuclear physics (pre-history)

How to approach kaonic hydrogen puzzle?

- Gas Target   Stark Free
- Si(Li) in Hydrogen Gas



nuclear physics (pre-history)

How to approach kaonic hydrogen puzzle?

- Background Free

gaseous target / final state tagging / stop K selection / fiducial cut

Reaction	Produced Particles	Branching Ratio	$\pi/\mu/e$ Multiplicity ($>$ 150 MeV/c)	γ Multiplicity
		Free Decay of K^-		
$\mu^-\nu$	$\mu^-\nu$	63.5 %	1	0
$\pi^-\pi^o$	$\pi^-2\gamma$	21.2 %	1	2
$\pi^-\pi^-\pi^+$	$\pi^-\pi^-\pi^+$	5.59 %	0	0
$e^-\pi^o\nu$	$e^-2\gamma$	4.82 %	1	2
$\mu^-\pi^o\nu$	$\mu^-2\gamma$	3.18 %	1	2
$\pi^-\pi^o\pi^o$	$\pi^-4\gamma$	1.73 %	0	4
		K^-p Reaction		
$\Sigma^+\pi^-$	$\pi^-2\gamma p$	10 %	1	2
$\Sigma^+\pi^-$	$\pi^-\pi^+n$	10 %	2	0
$\Sigma^-\pi^+$	$\pi^+\pi^-n$	46 %	2	0
$\Sigma^o\pi^o$	$\pi^-3\gamma p$	18 %	0	3
$\Sigma^o\pi^o$	$5\gamma n$	10 %	0	5
$\Lambda\pi^o$	$\pi^-2\gamma p$	4 %	0	2
$\Lambda\pi^o$	$4\gamma n$	2 %	0	4

nuclear physics (pre-history)

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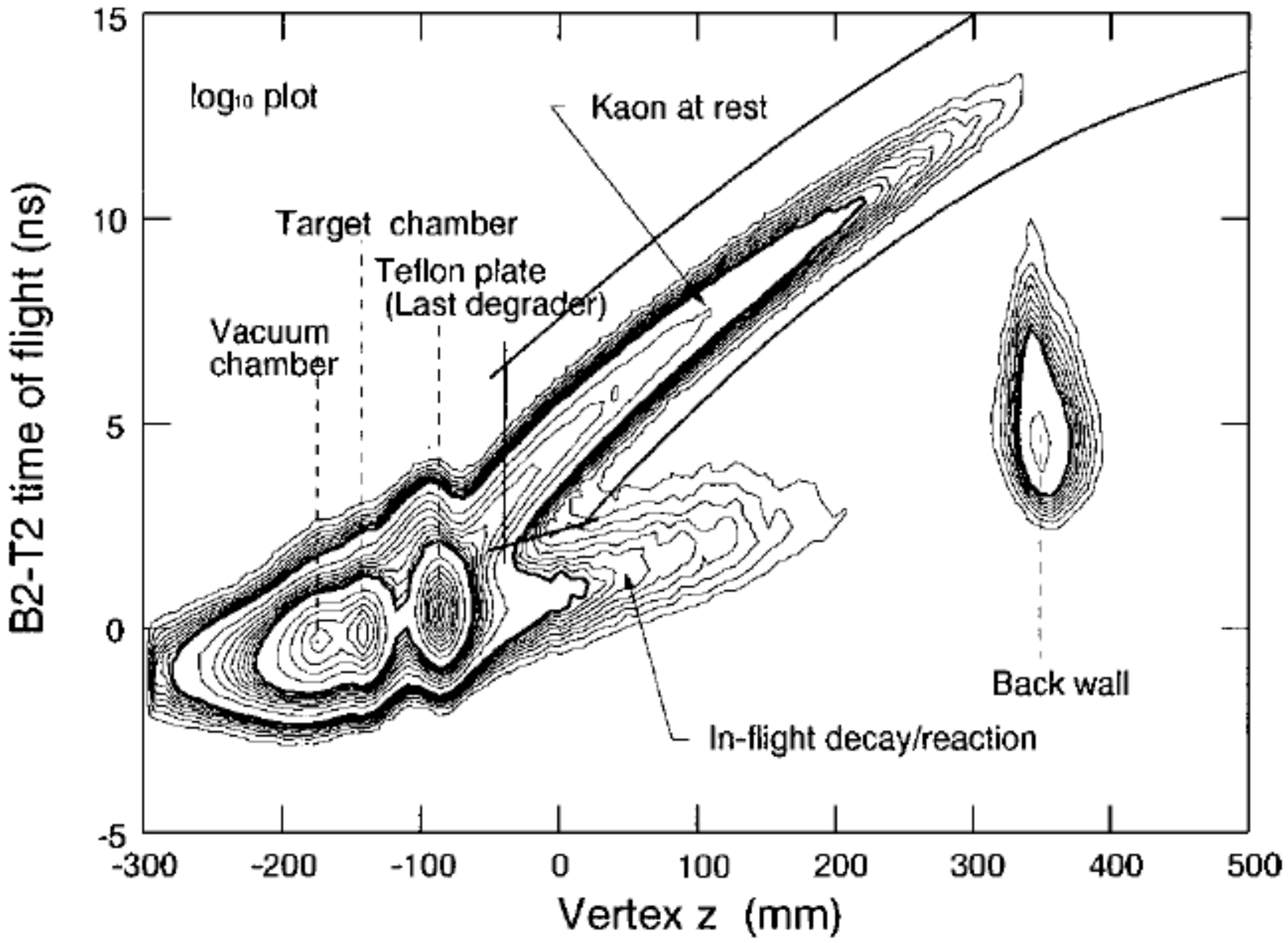

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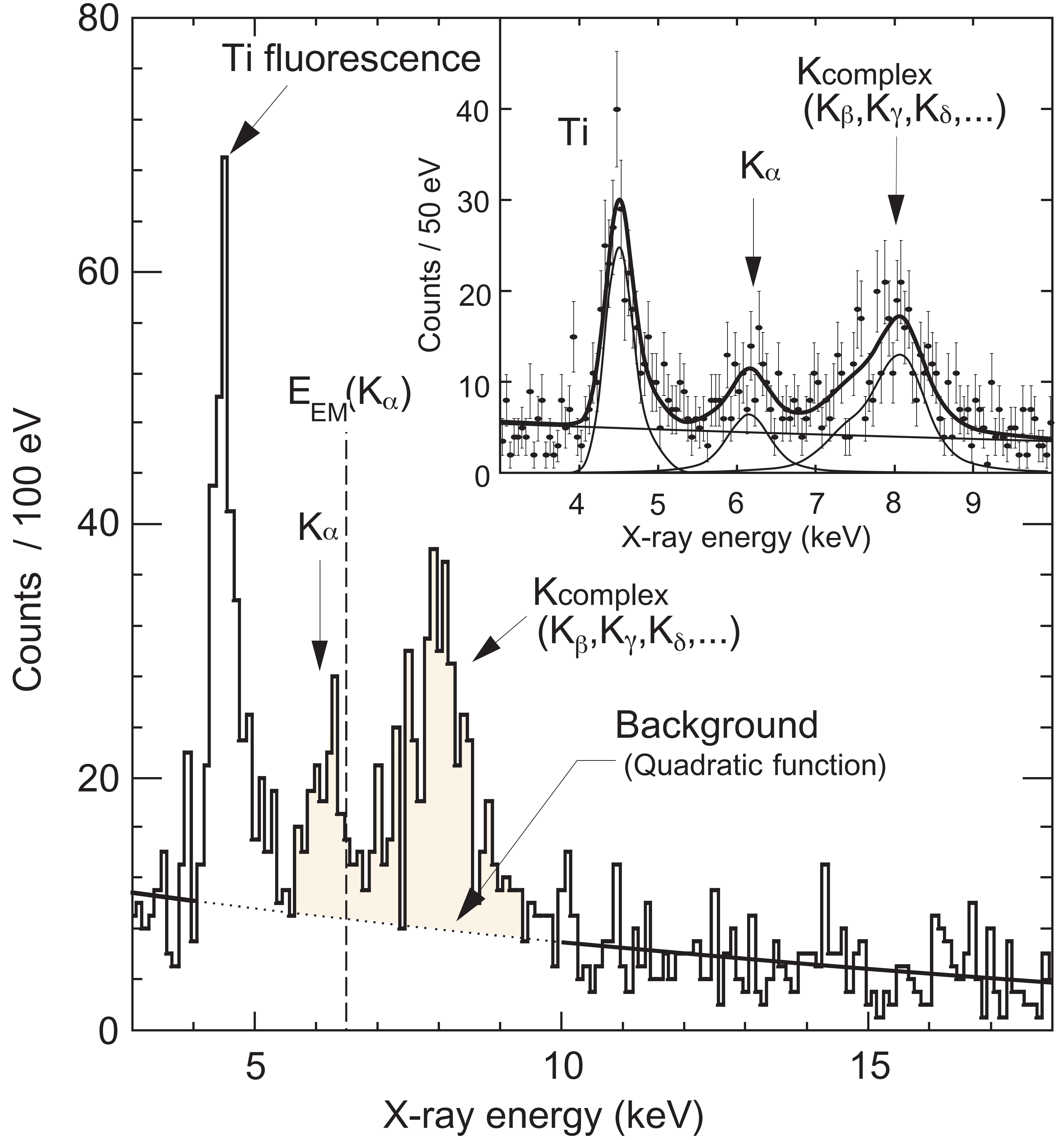
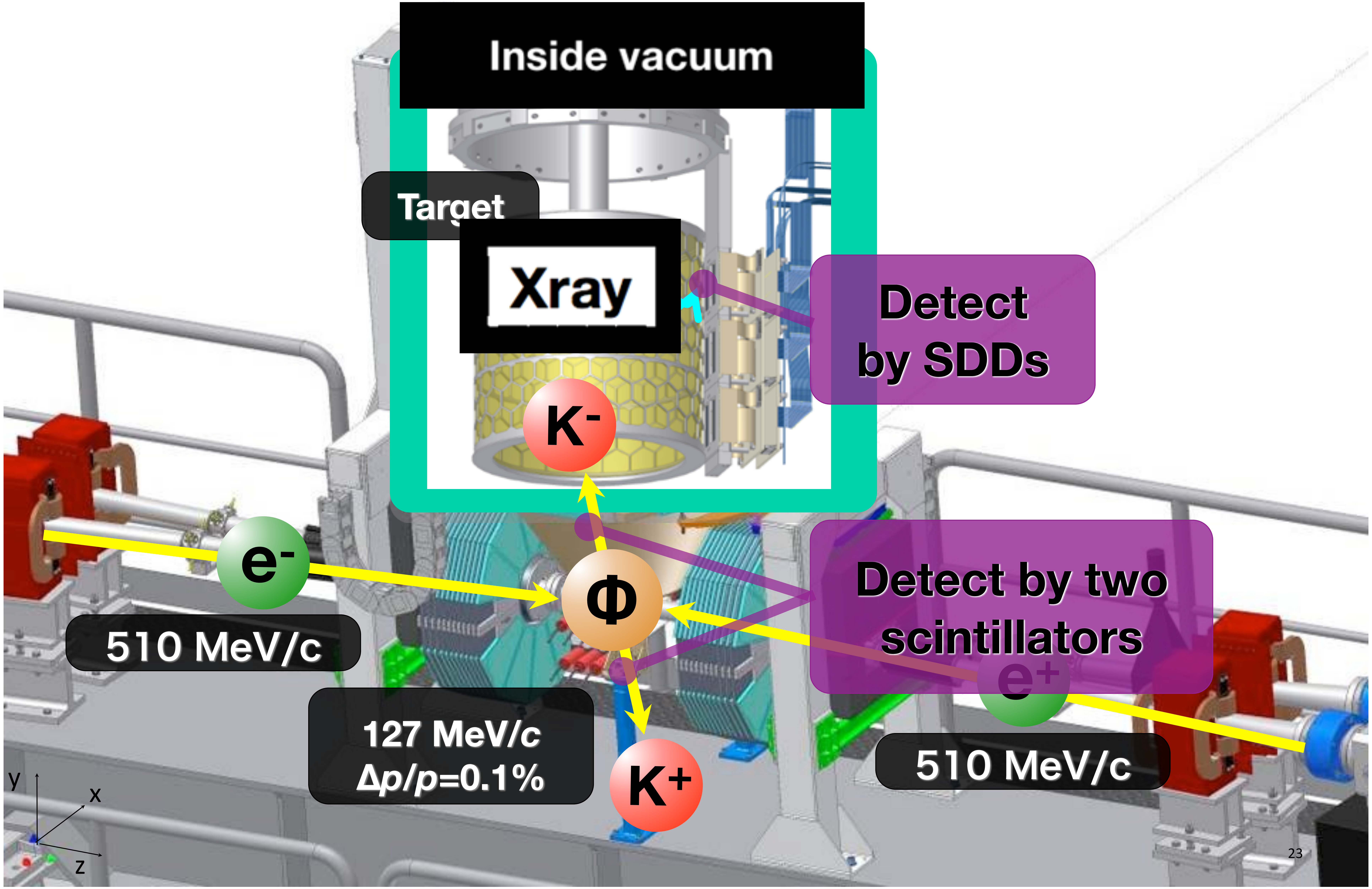
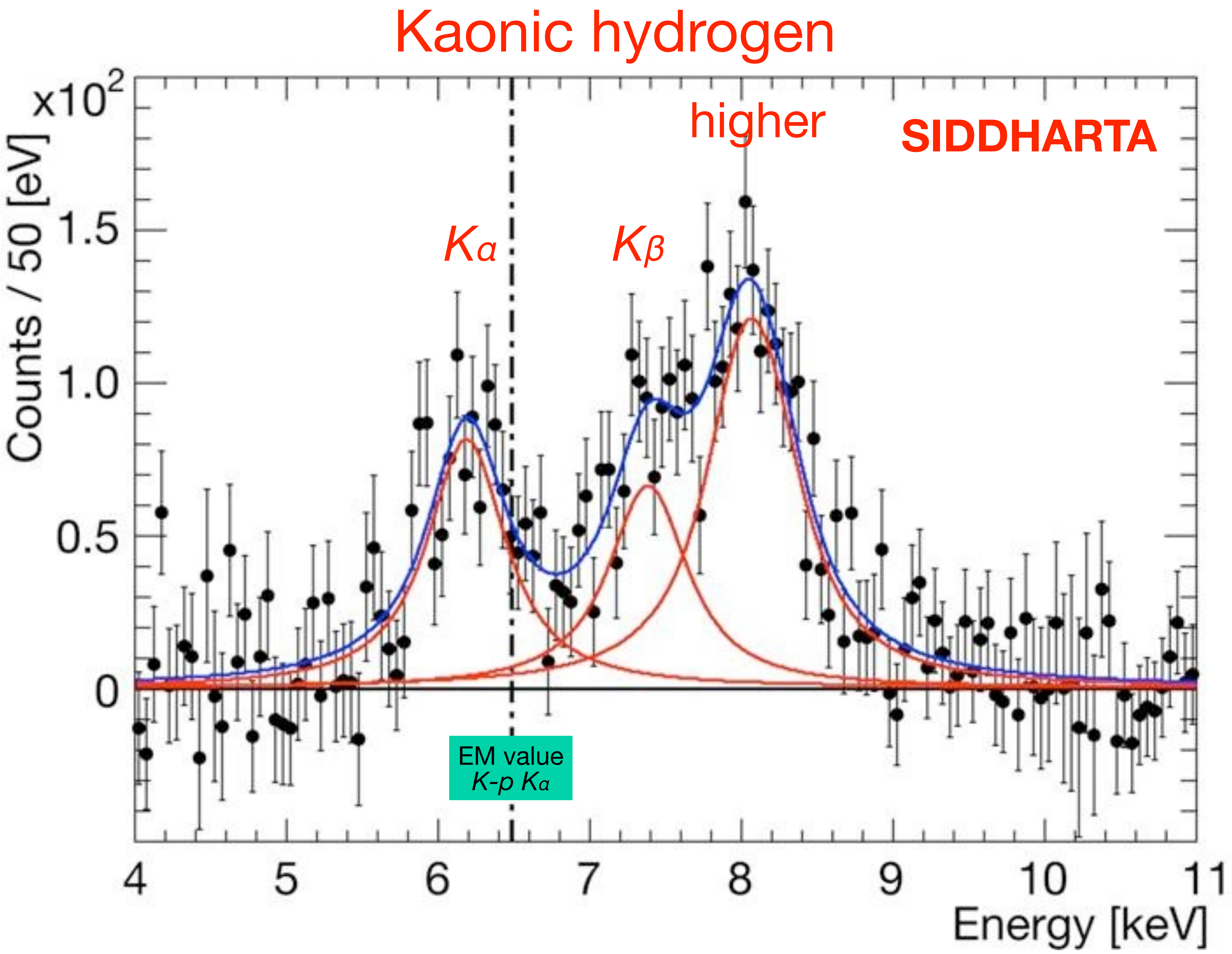


SIDDHARTA setup at DAΦNE



Residuals of K-p x-ray spectrum after subtraction of fitted background

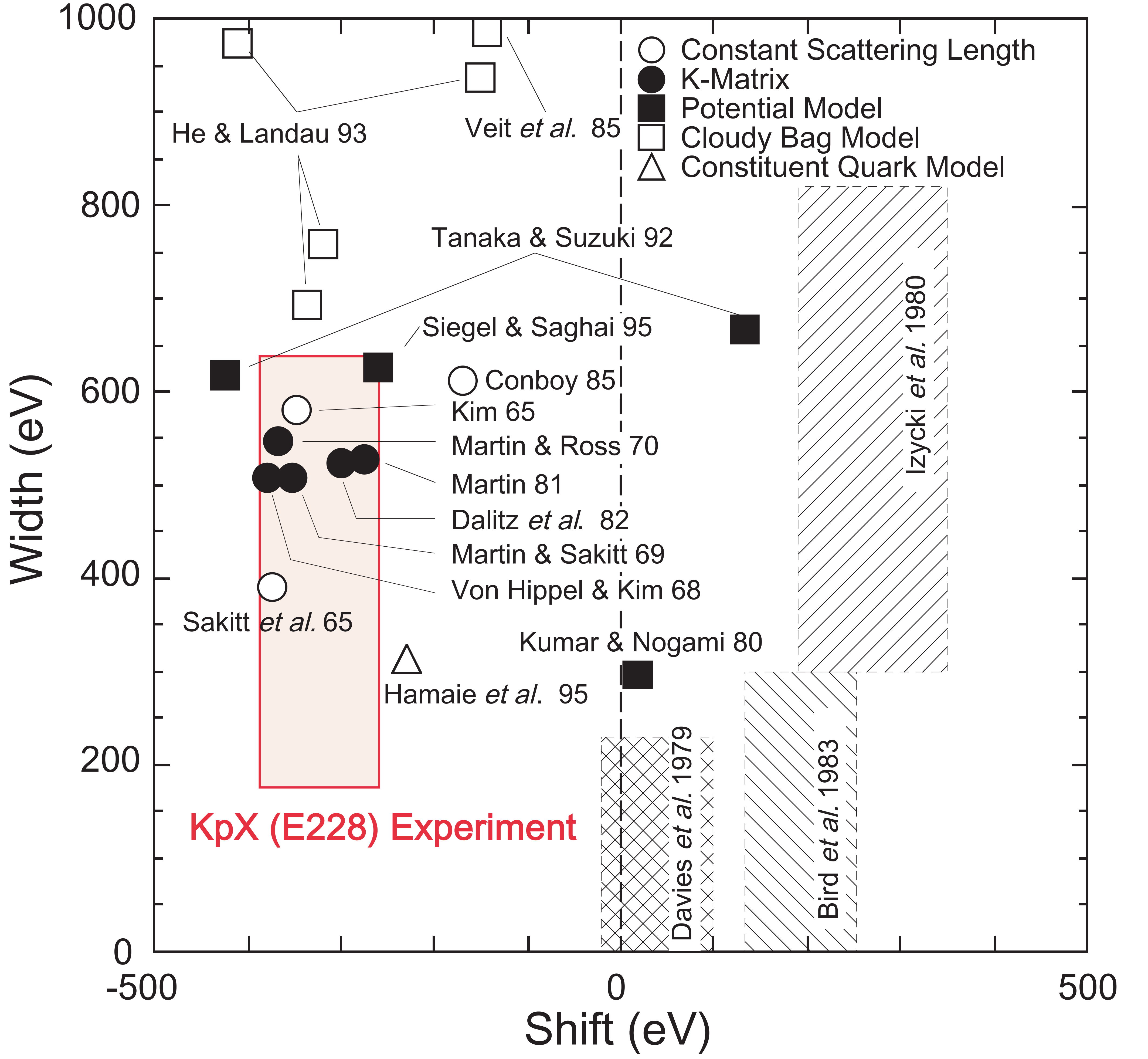


KAONIC HYDROGEN results

$$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV}$$
$$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV}$$

upward (repulsive) shift

downward (attractive) shift



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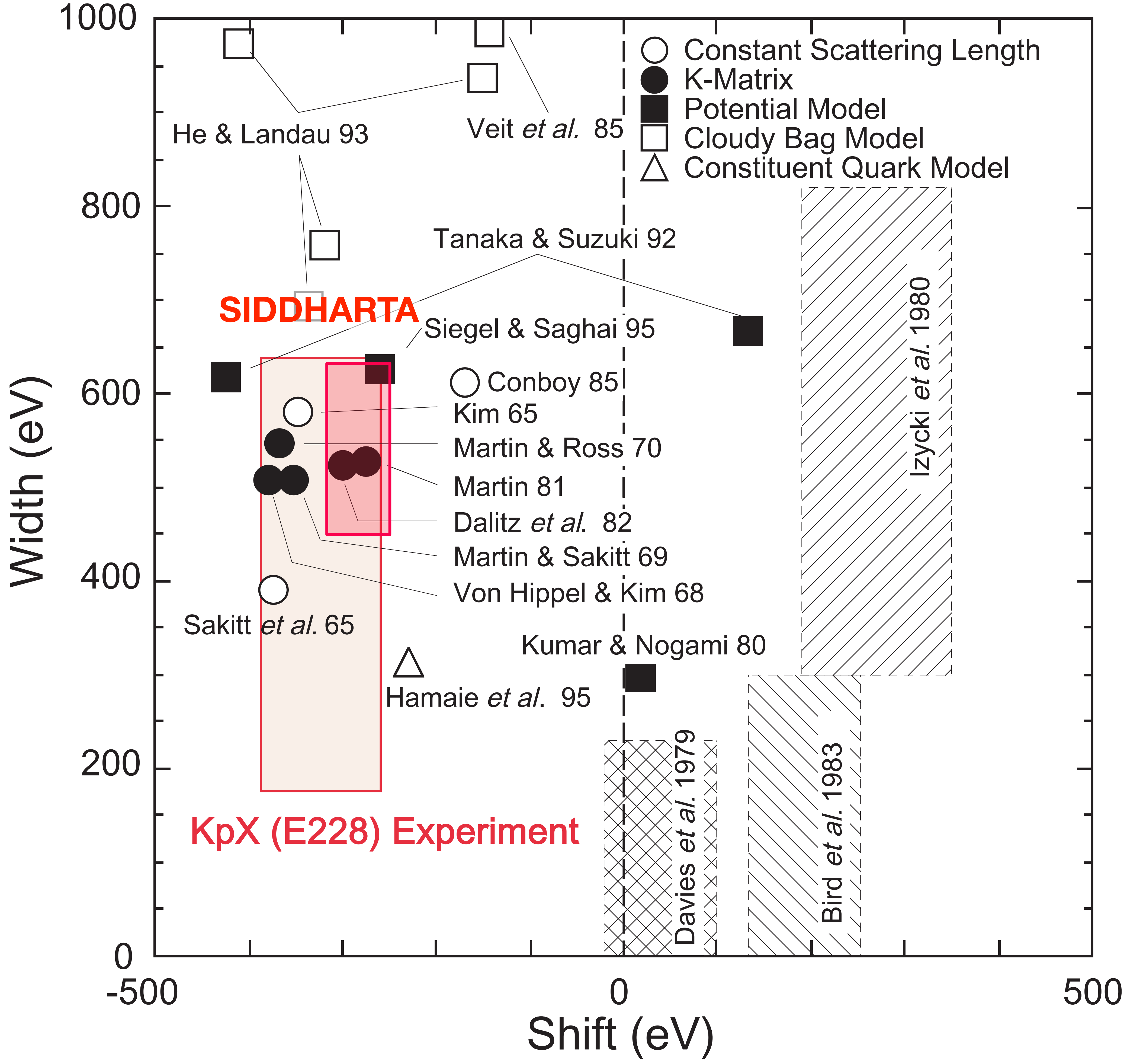
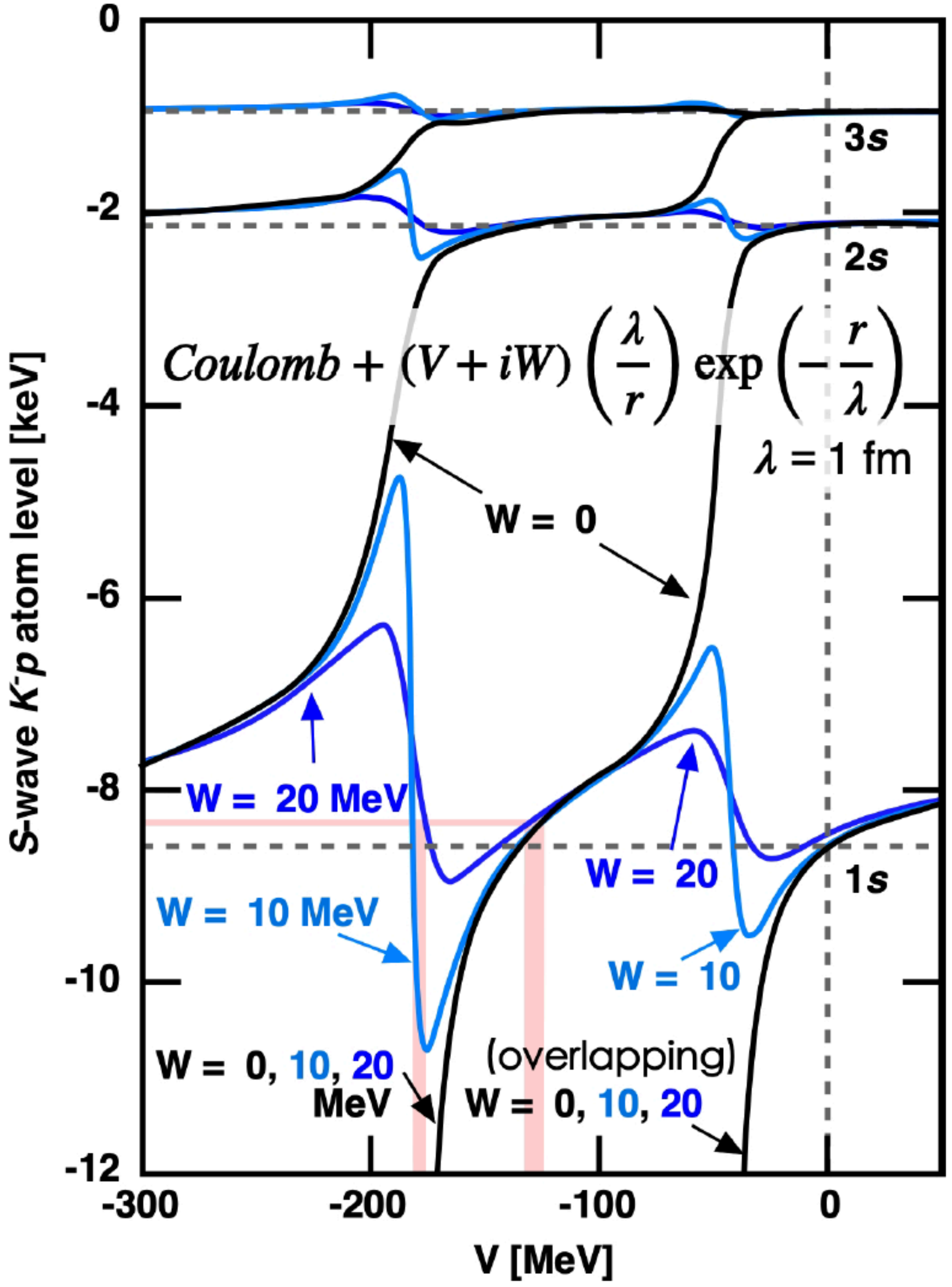


Dose $\overline{K}N$ interaction repulsive?



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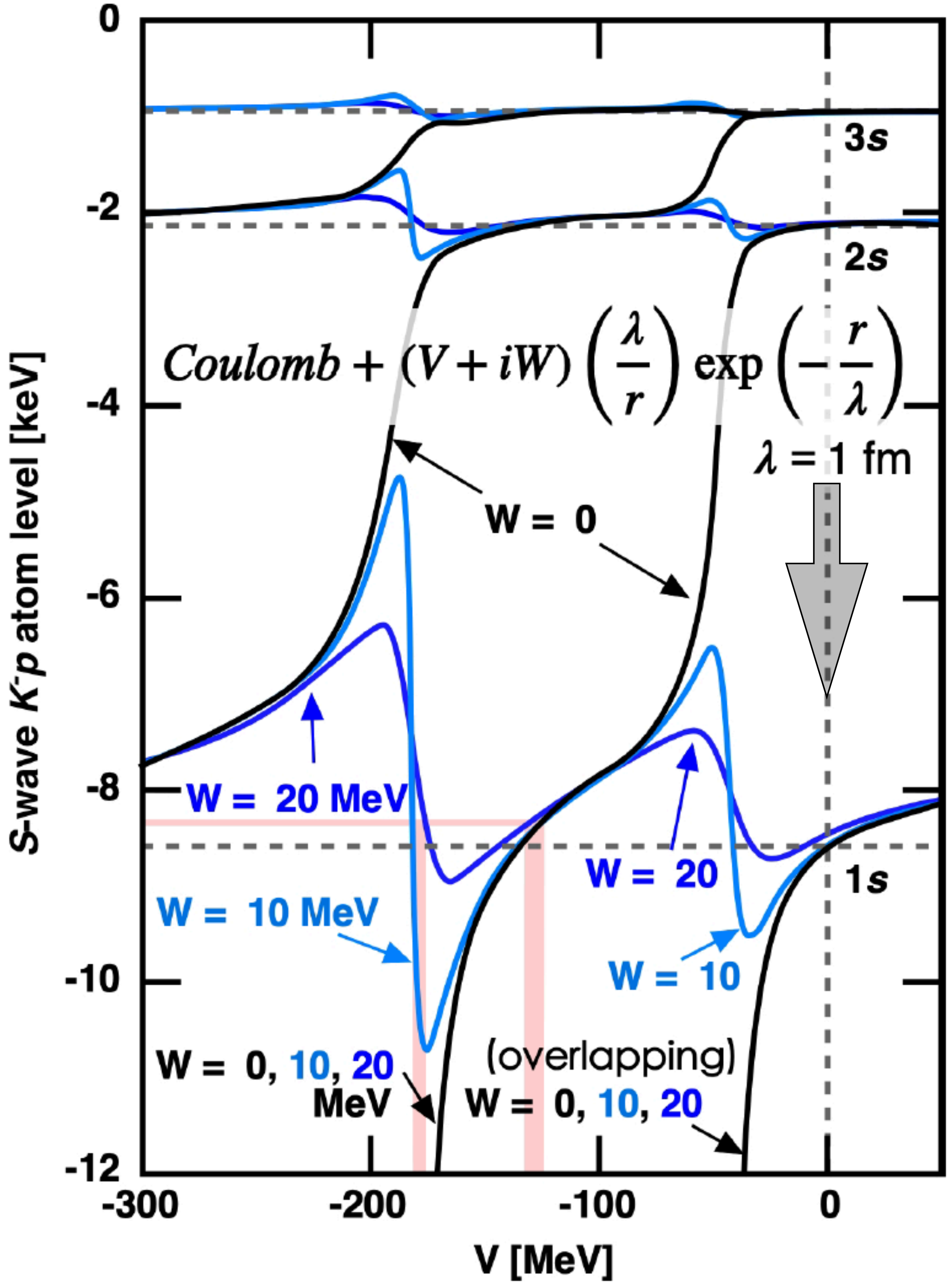

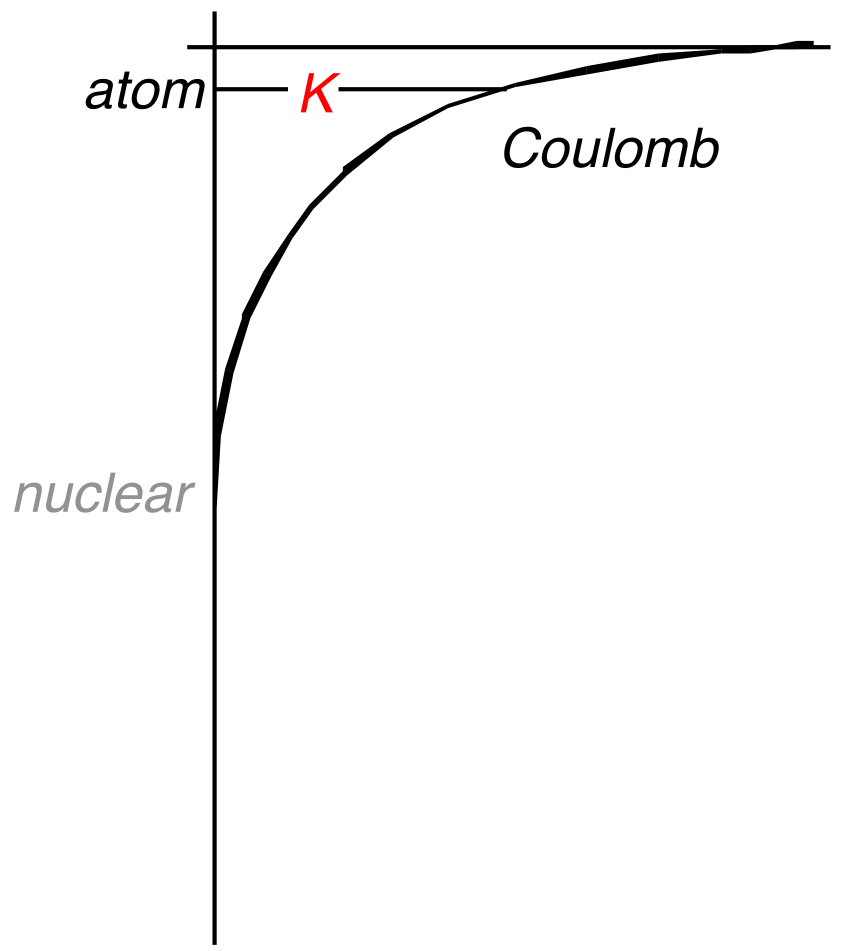

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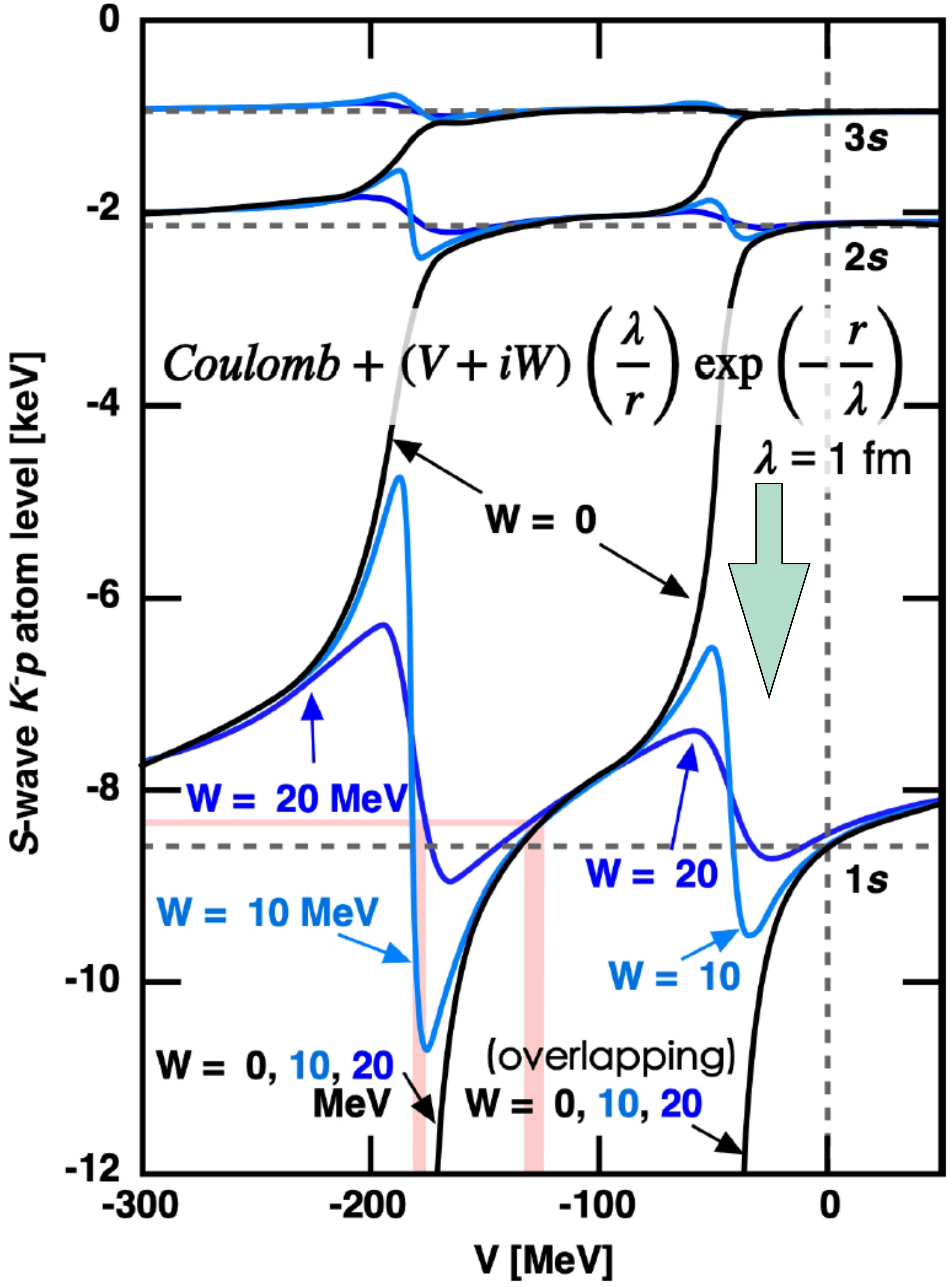

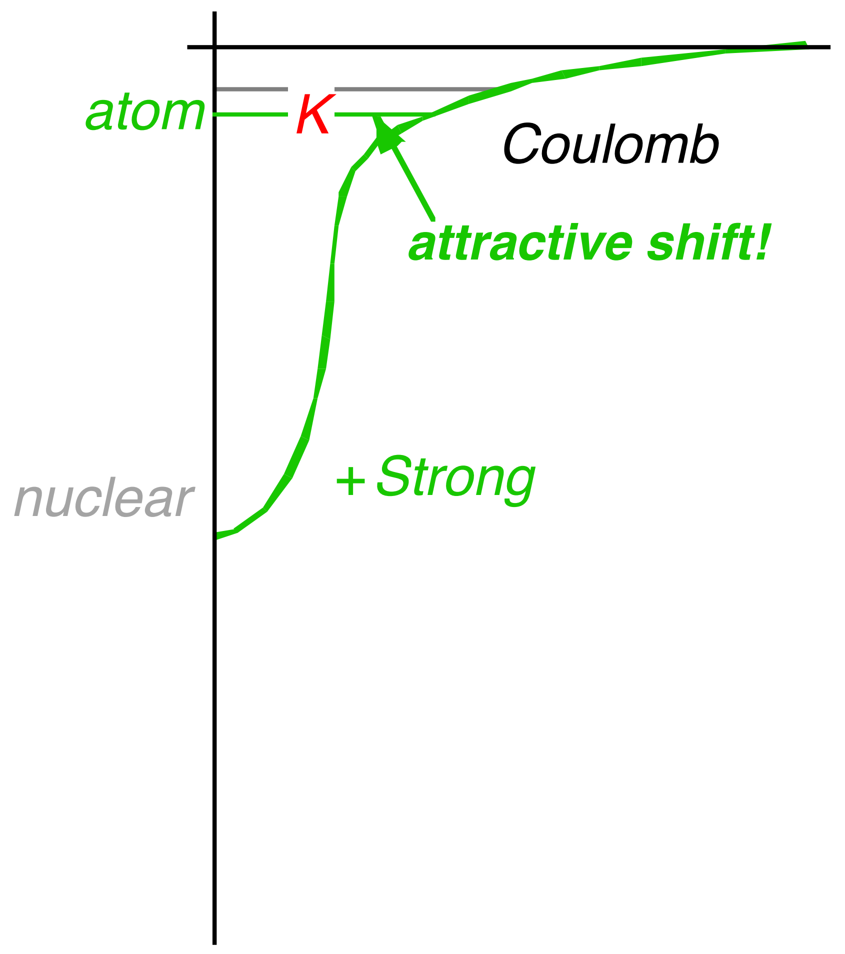

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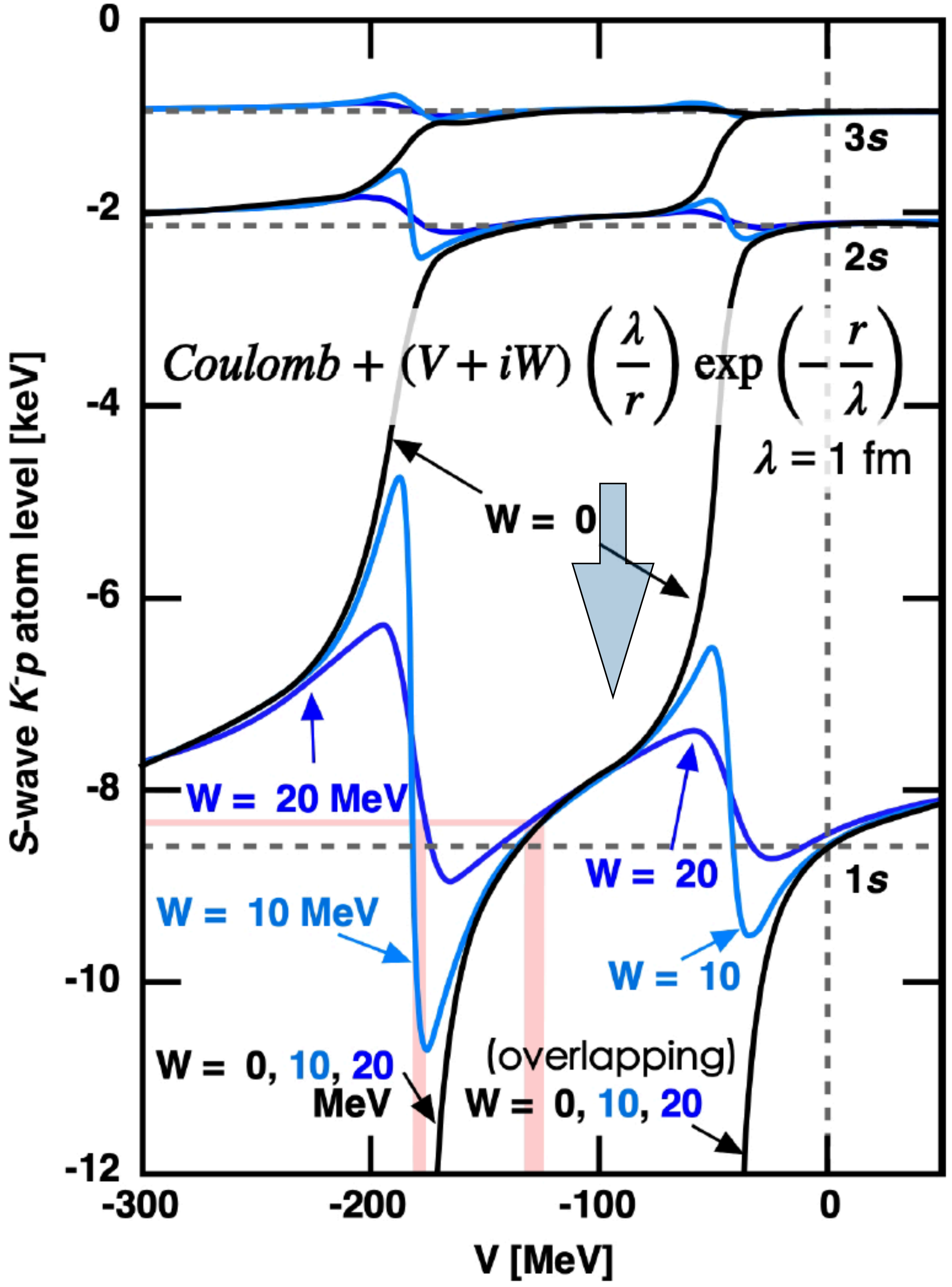

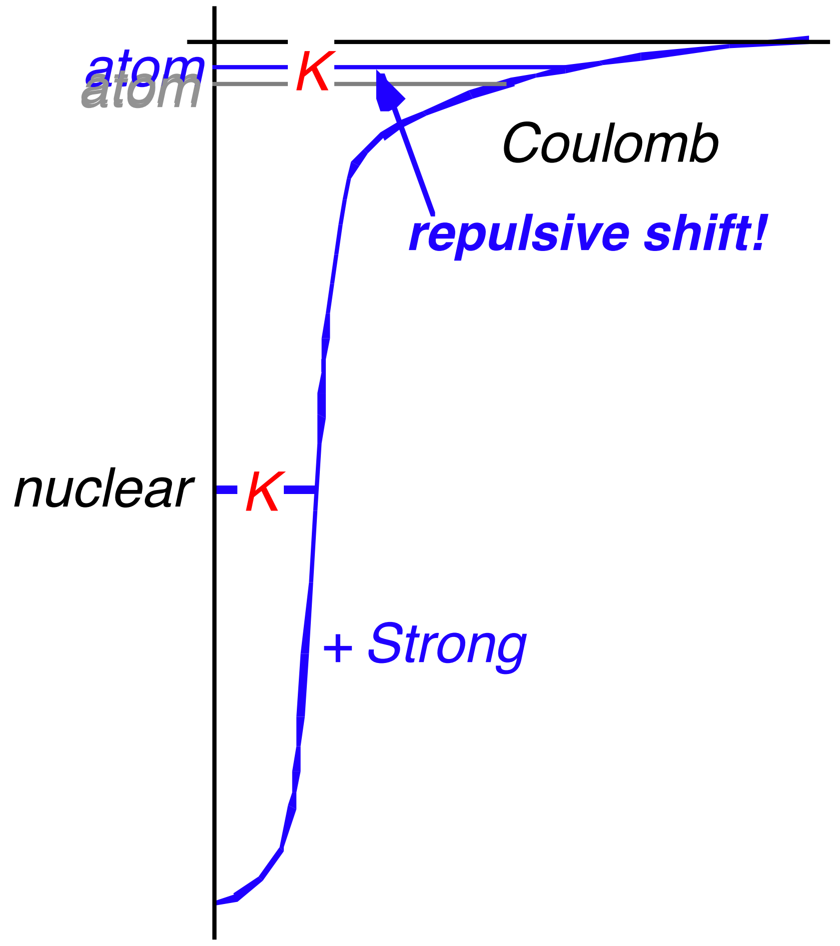

Very strongly attractive so as to form bound state!

$\bar{K}N \equiv \Lambda(1405)$

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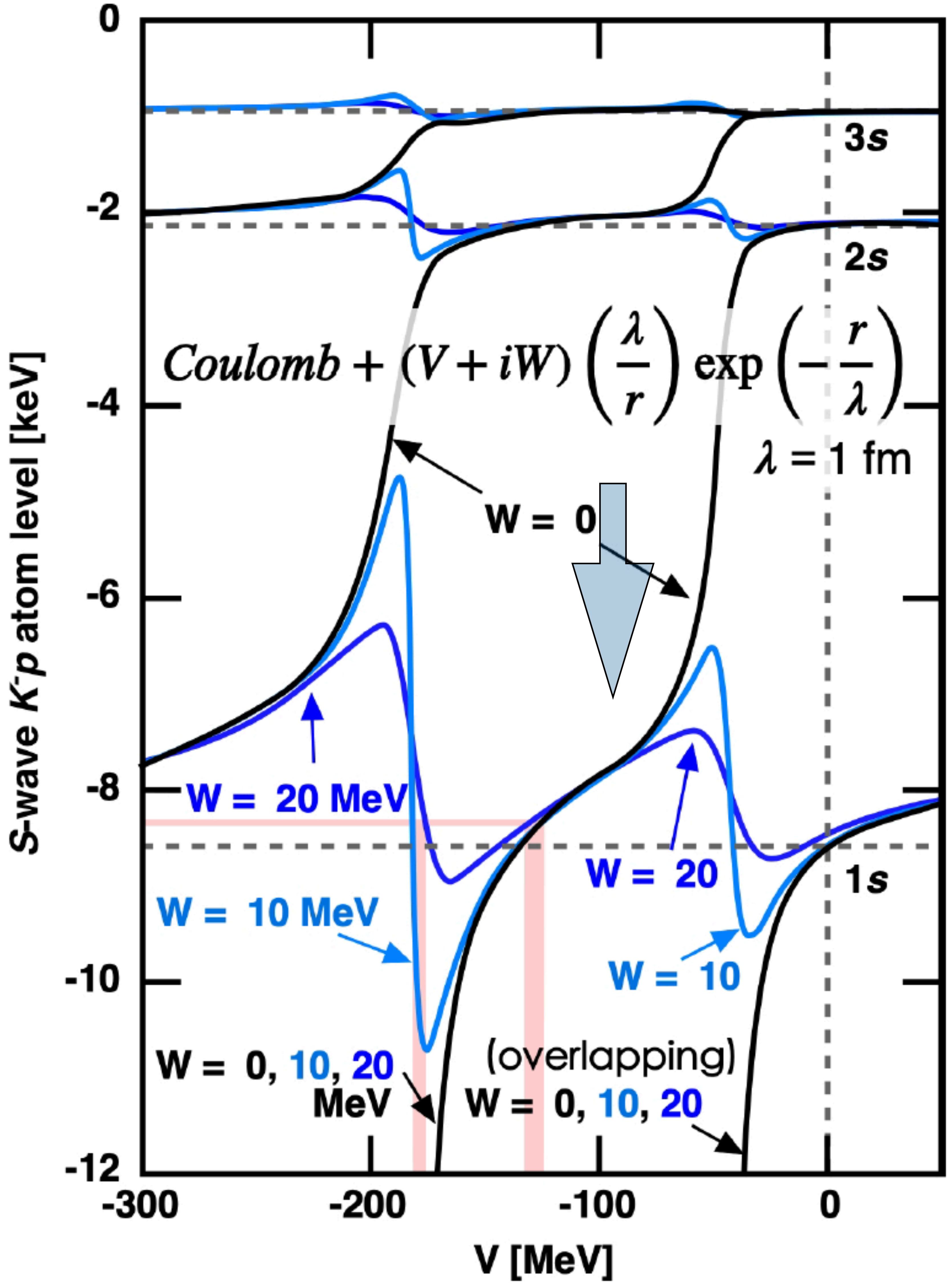
R. Seki, Phys. Rev. C5 (1972) 1196

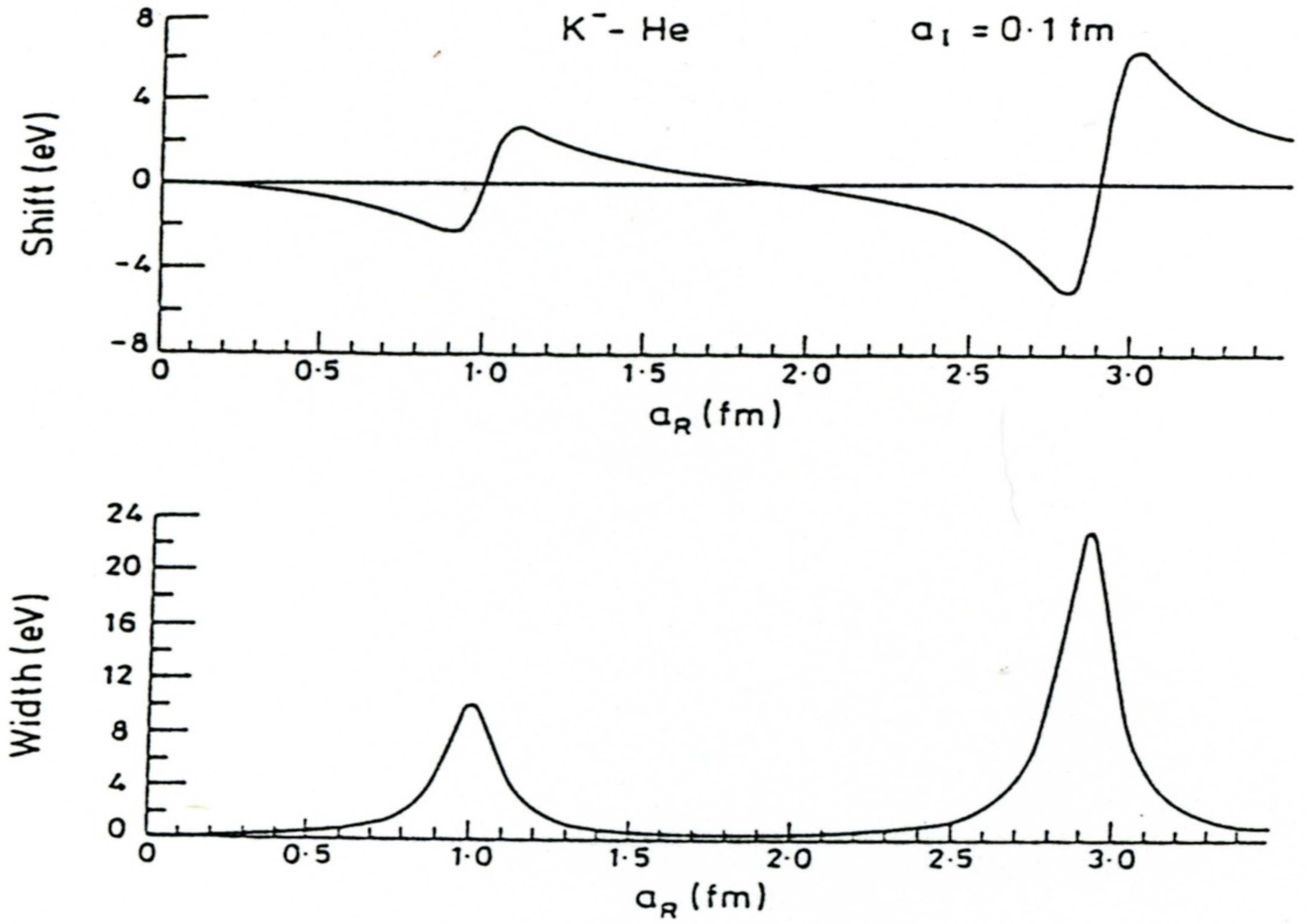
S. Baird et al., Nucl. Phys. A392 (1983) 297

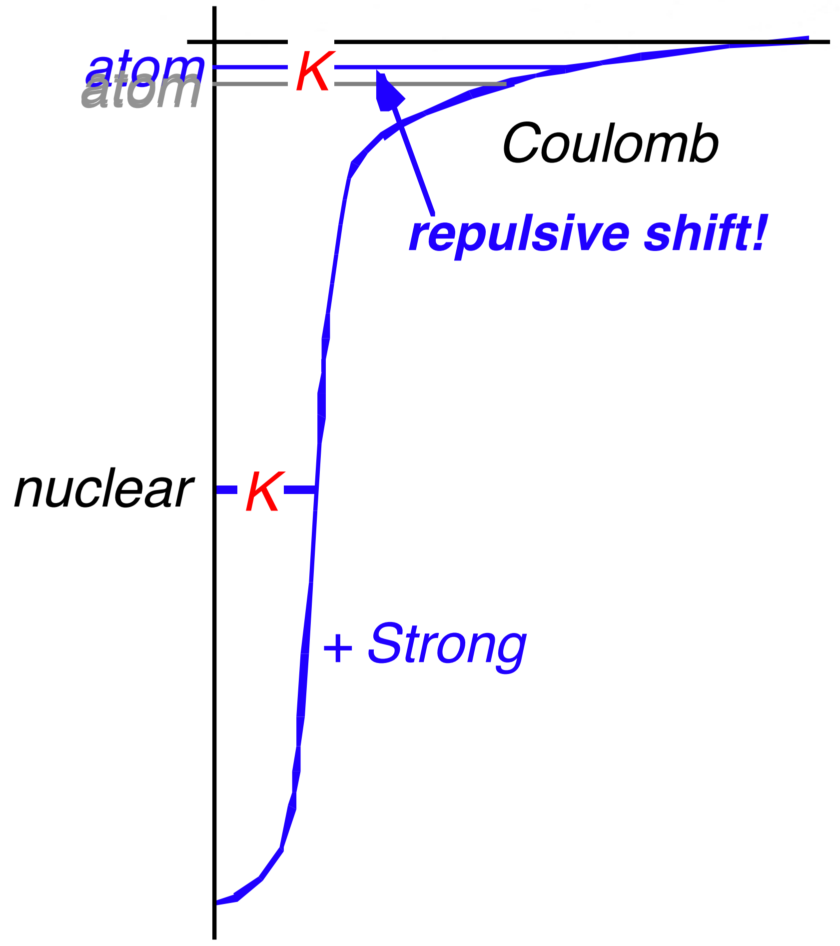
C.J. Batty, Nucl. Phys. A508 (1990) 89c

Repulsive shift means possible $\bar{K}N$ bound state



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





Very strongly attractive so as to form bound state!

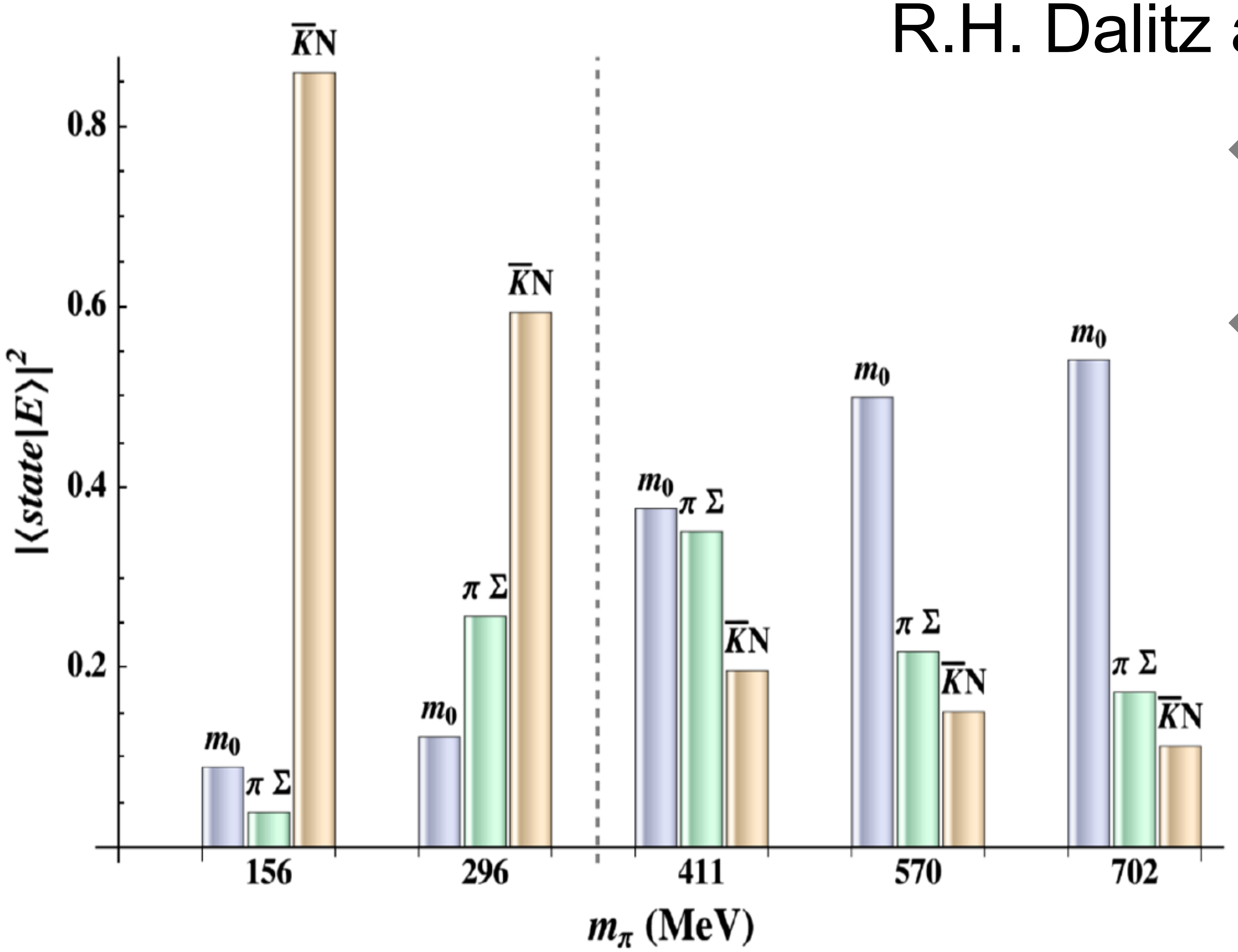
$\bar{K}N \equiv \Lambda(1405)$

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"

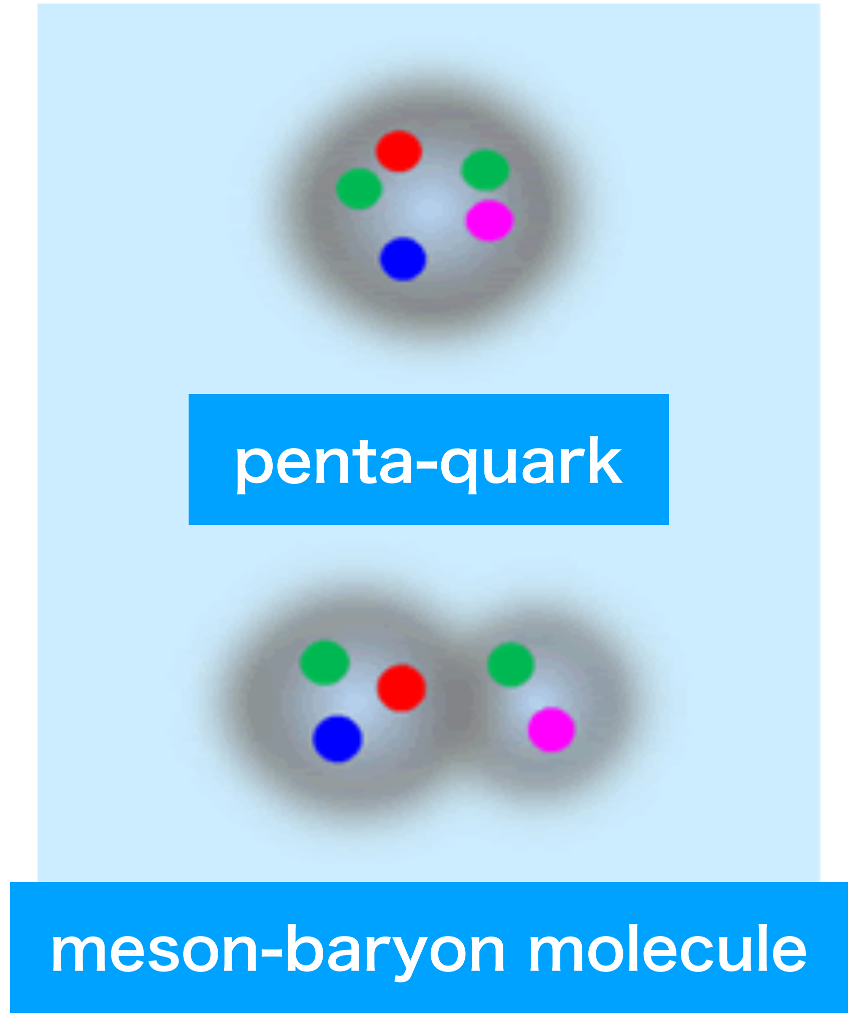
R.H. Dalitz and S.F. Tuan, Ann. Phys., 3, 307 (1960)



- **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.

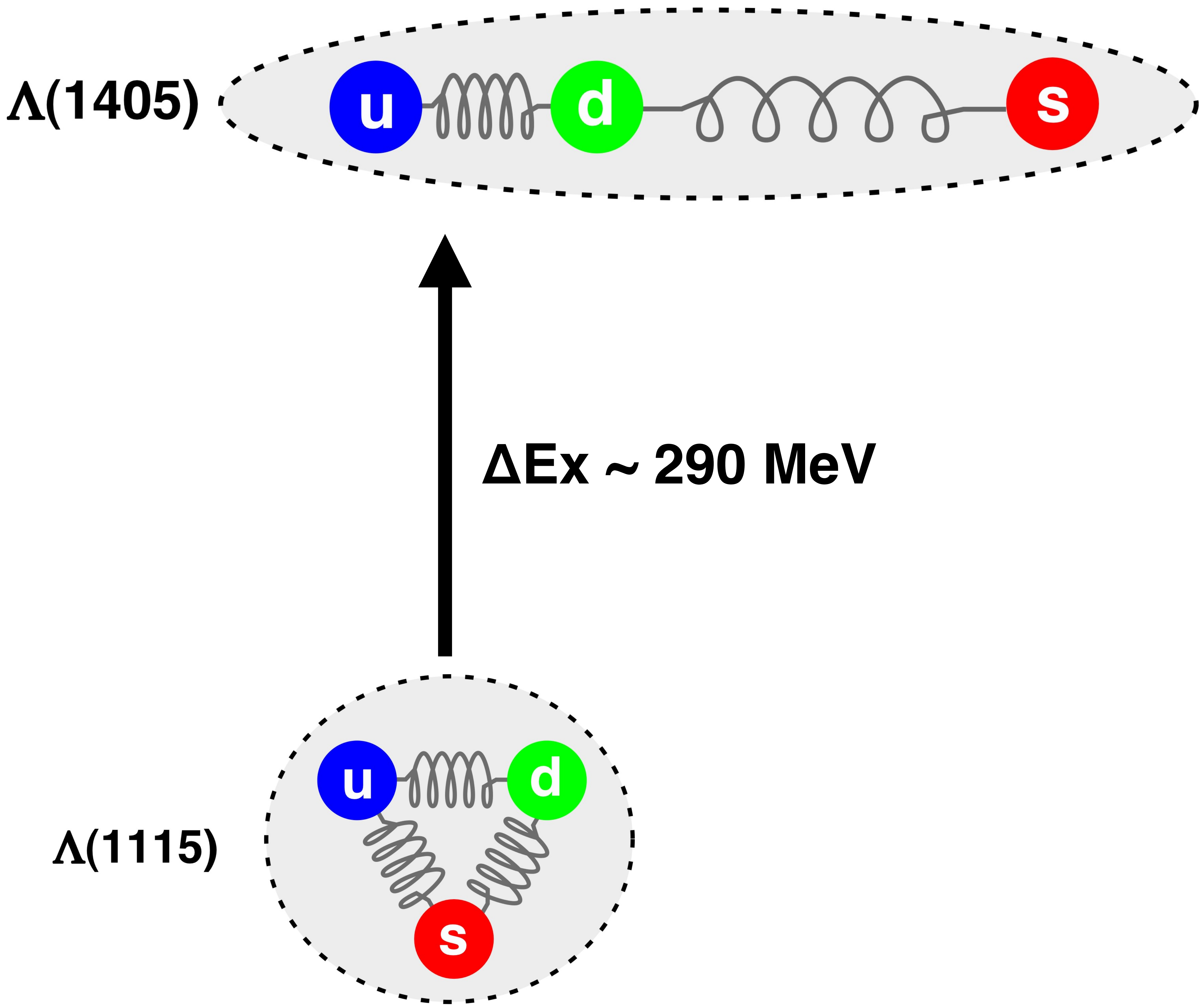


why not $\bar{K}NN$?

forming a nuclear bound state

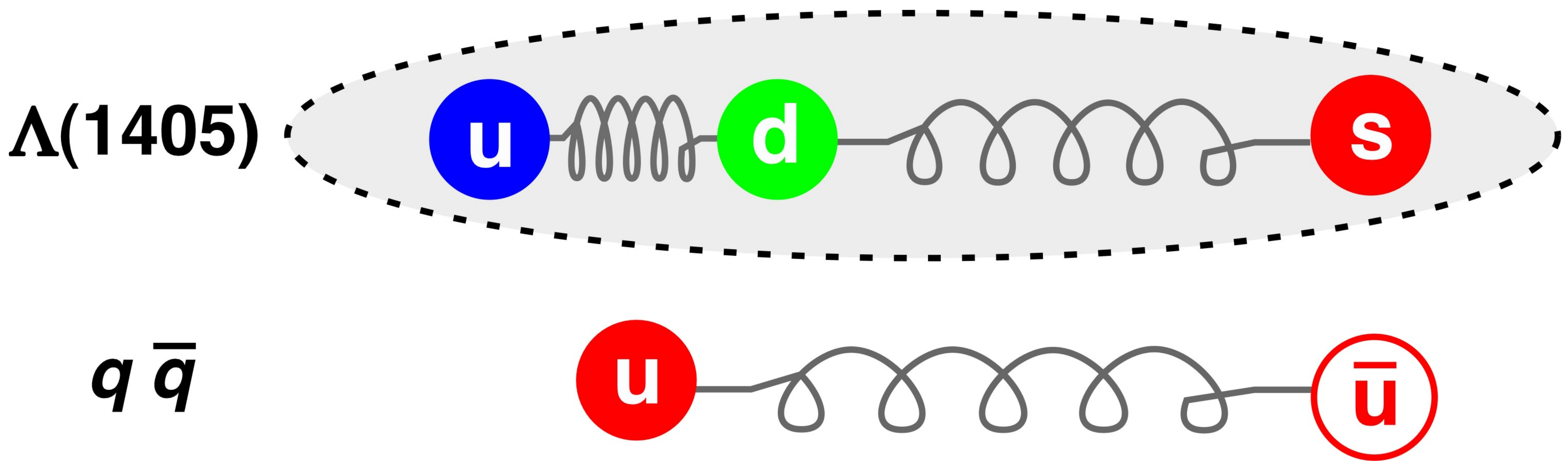
From Λ(1405) to kaonic nuclei

Is Λ(1115) an excited state of *uds*?



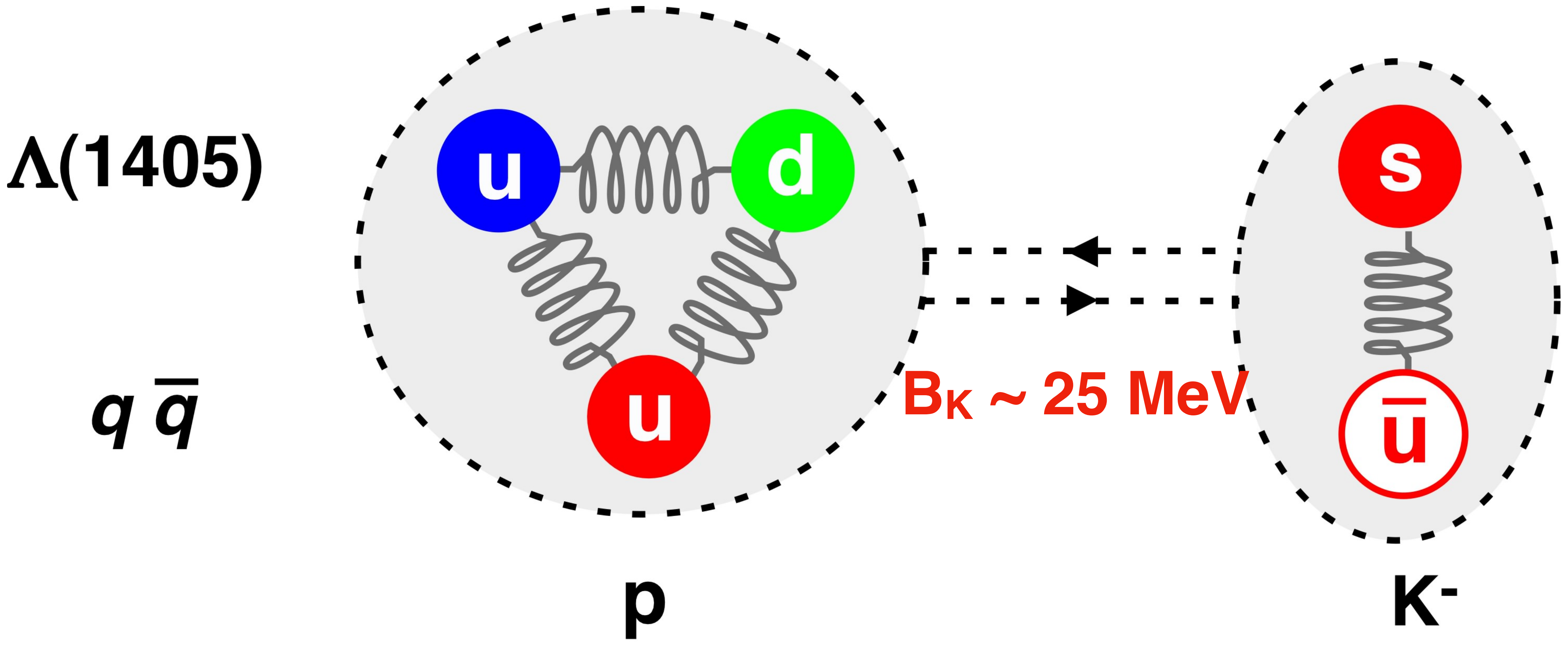
From Λ(1405) to kaonic nuclei

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



From Λ(1405) to kaonic nuclei

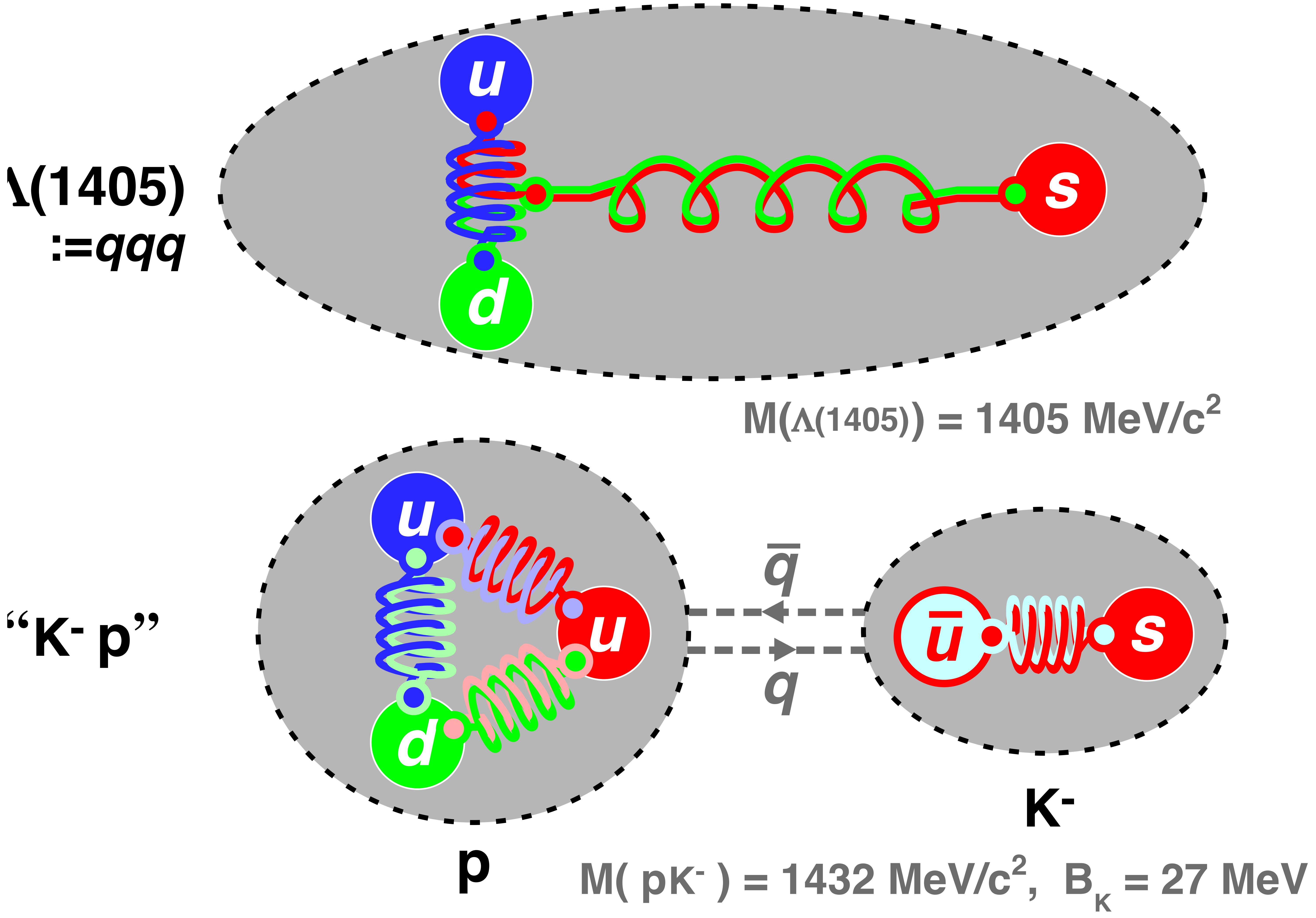
two color-singlet objects bound by meson exchange : p = K⁻



M(pK⁻) = 1432 MeV/c²

$\Lambda(1405)$ is the most natural candidate as for the $K^{-}p$ bound state due to the strong interaction, which locates far below the Coulomb bound state (atomic states).

Is Λ(1405) be a *qqq* or meson-baryon composite?



Λ(1405) is on-site of "hadronization", where the system captures $\bar{q}q$ from vacuum

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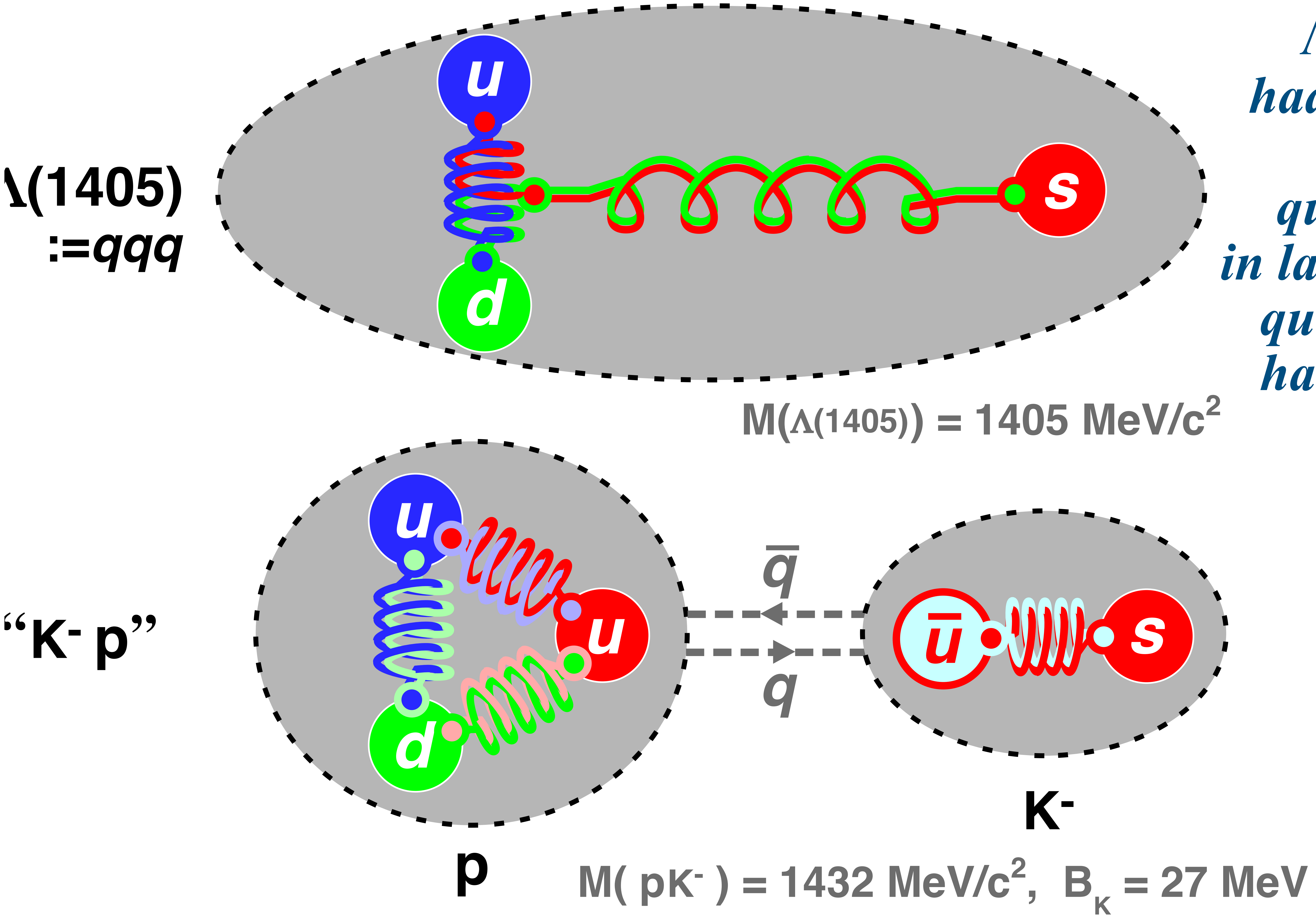

Λ(1405) can be molecule-like hadron cluster composed of "$K^- p$" or in between the quark- and/or hadron-composite in lattice-QCD

quark-composite: ~10%

hadron-composite: ~90%

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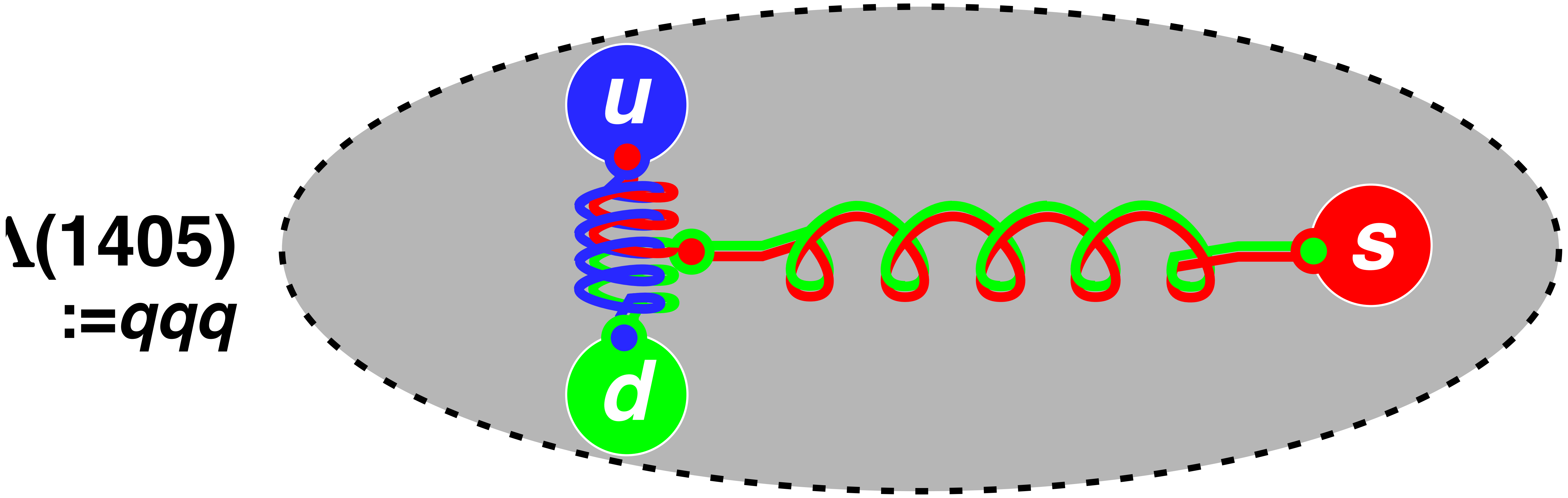

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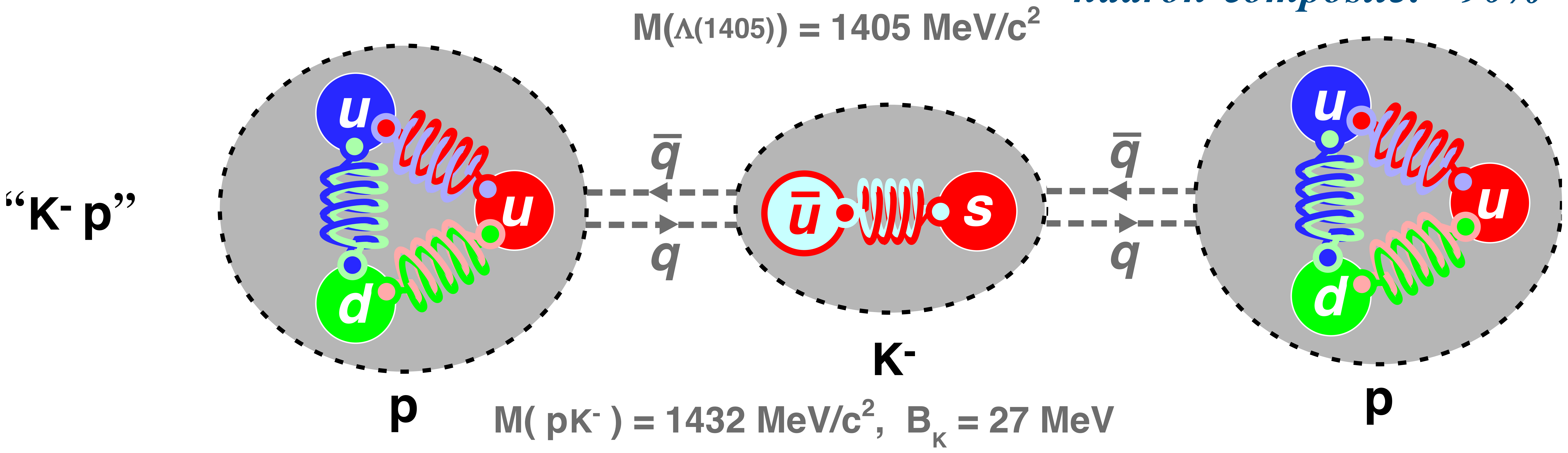

Then you may put one more proton …

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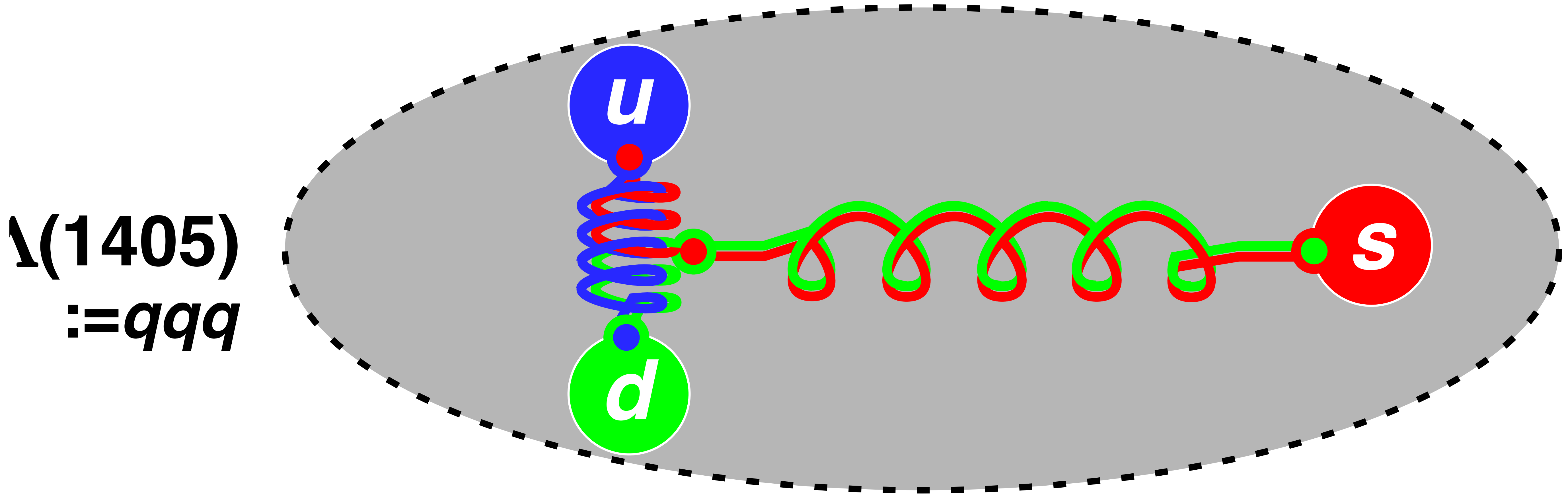

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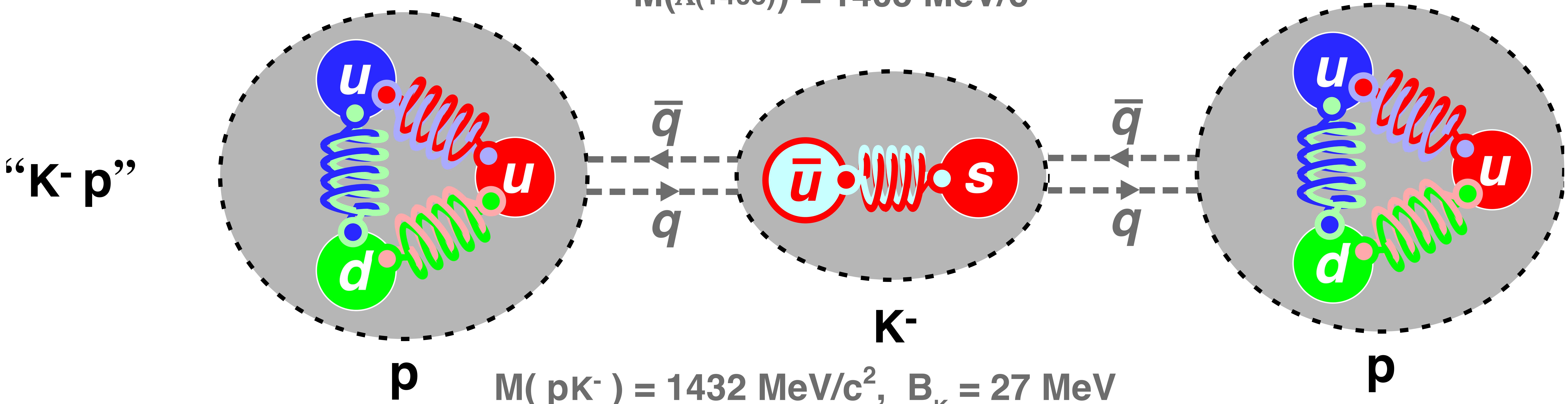
M(Λ(1405)) = 1405 MeV/c^2



M(pK^-) = 1432 MeV/c^2, B_K = 27 MeV

Λ(1405) is on-site of "hadronization", where the system captures $\bar{q}q$ from vacuum

Then you may put one more proton …

"K^-pp" may exist

contents:

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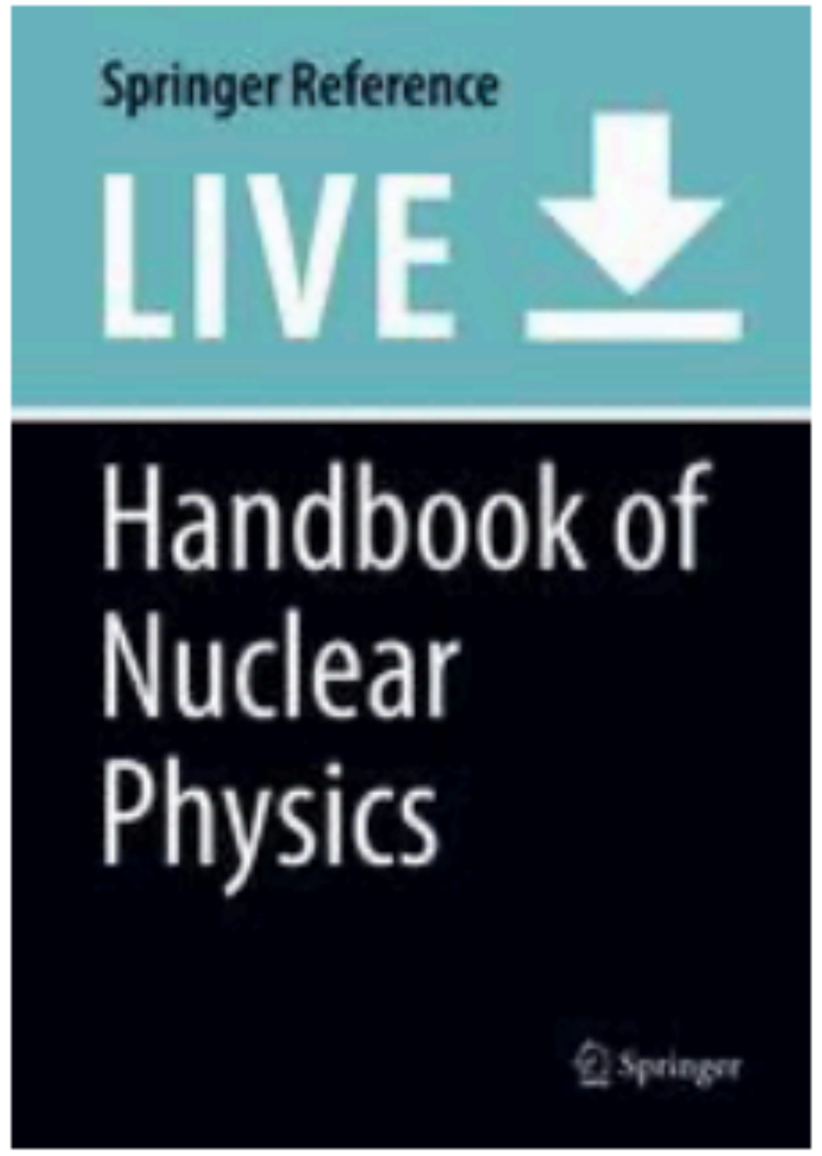

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Basic understanding of nuclei

- Nuclei consist of nucleons bound by nuclear force

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

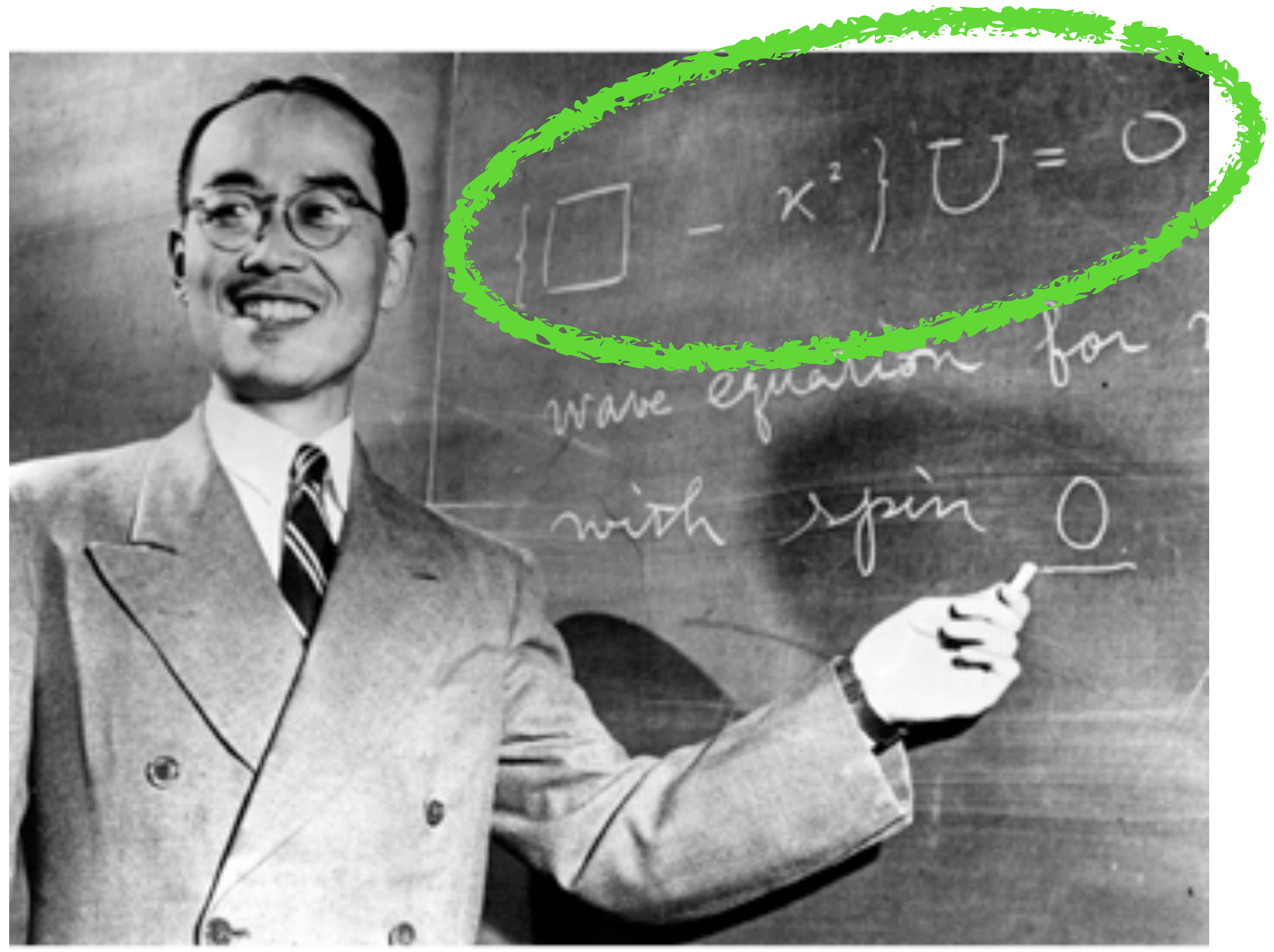
q = *u* or *d*

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*

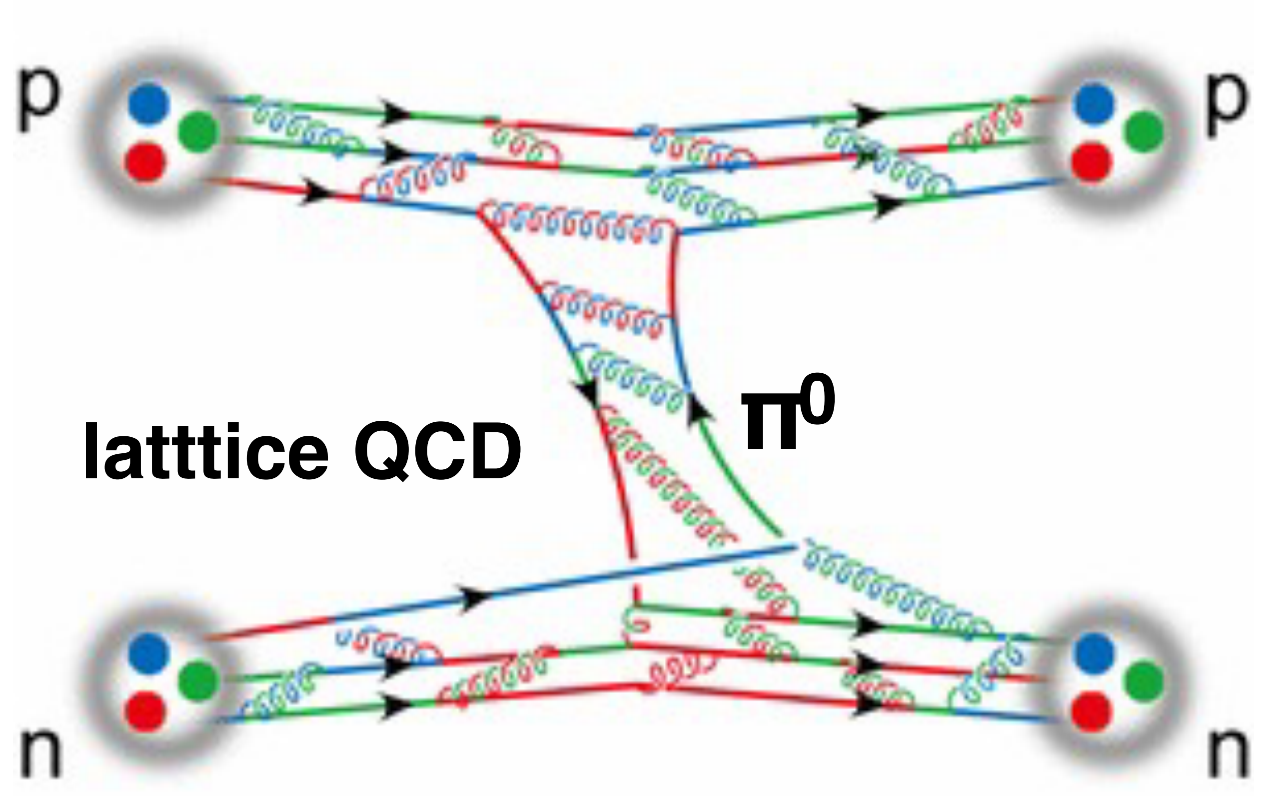
quark flavor



Yukawa Theorem tells：

- in nuclei, mesons are virtual particles and form nuclear potential

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



latttice QCD

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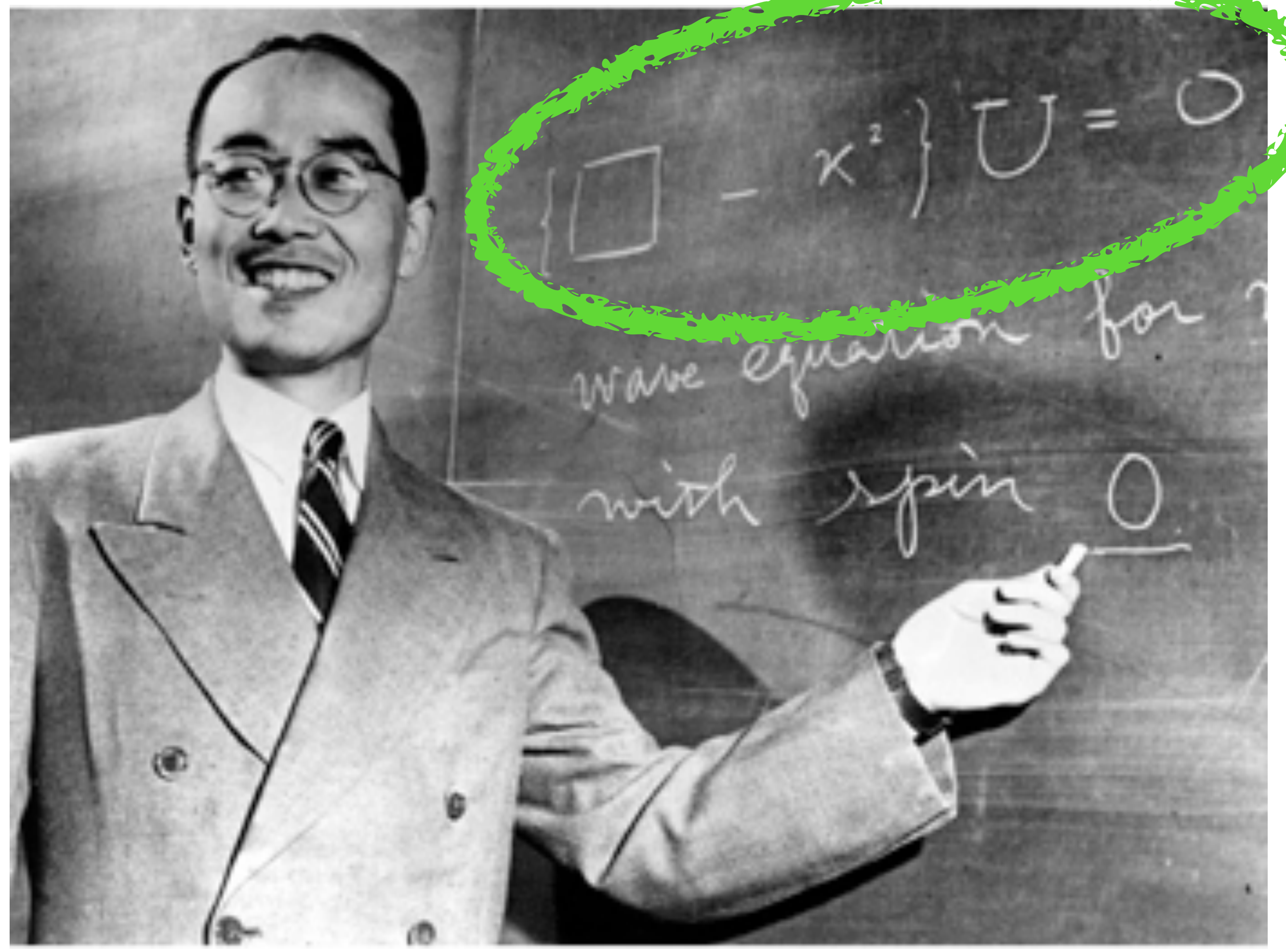

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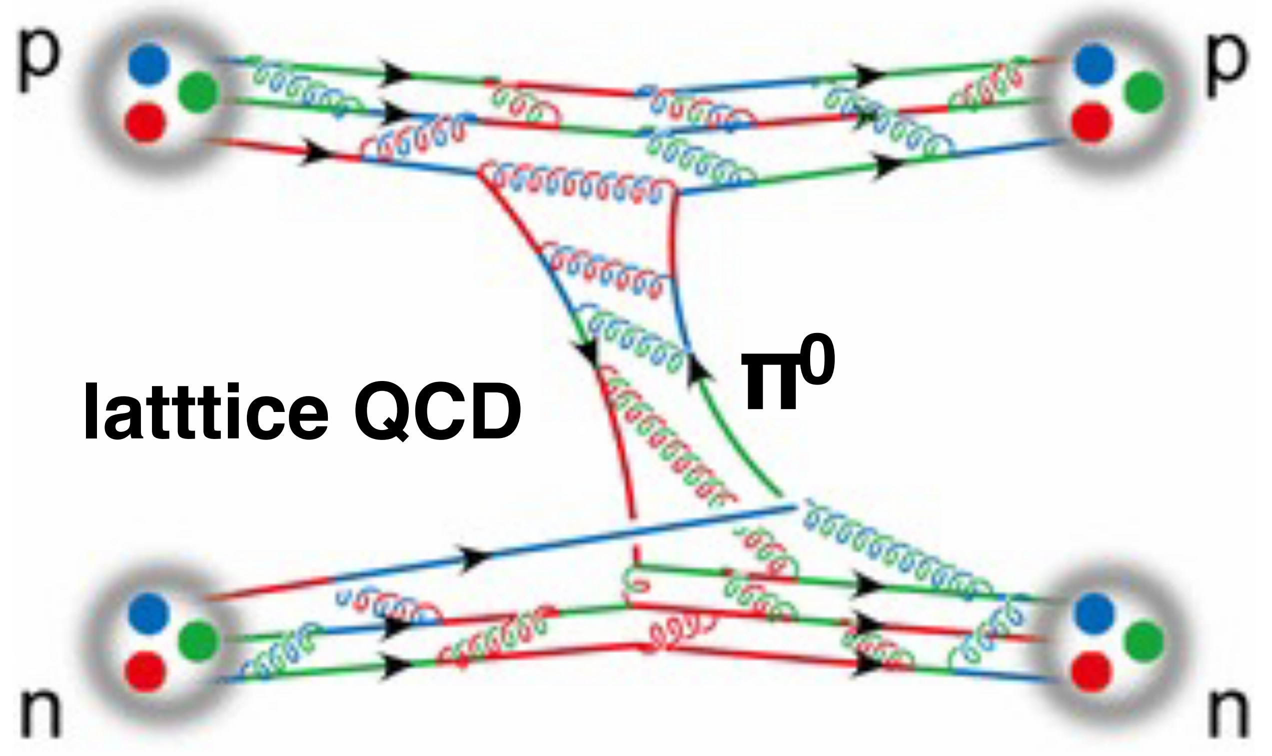

Long standing question：

Can meson be a constituent particle forming nuclei?

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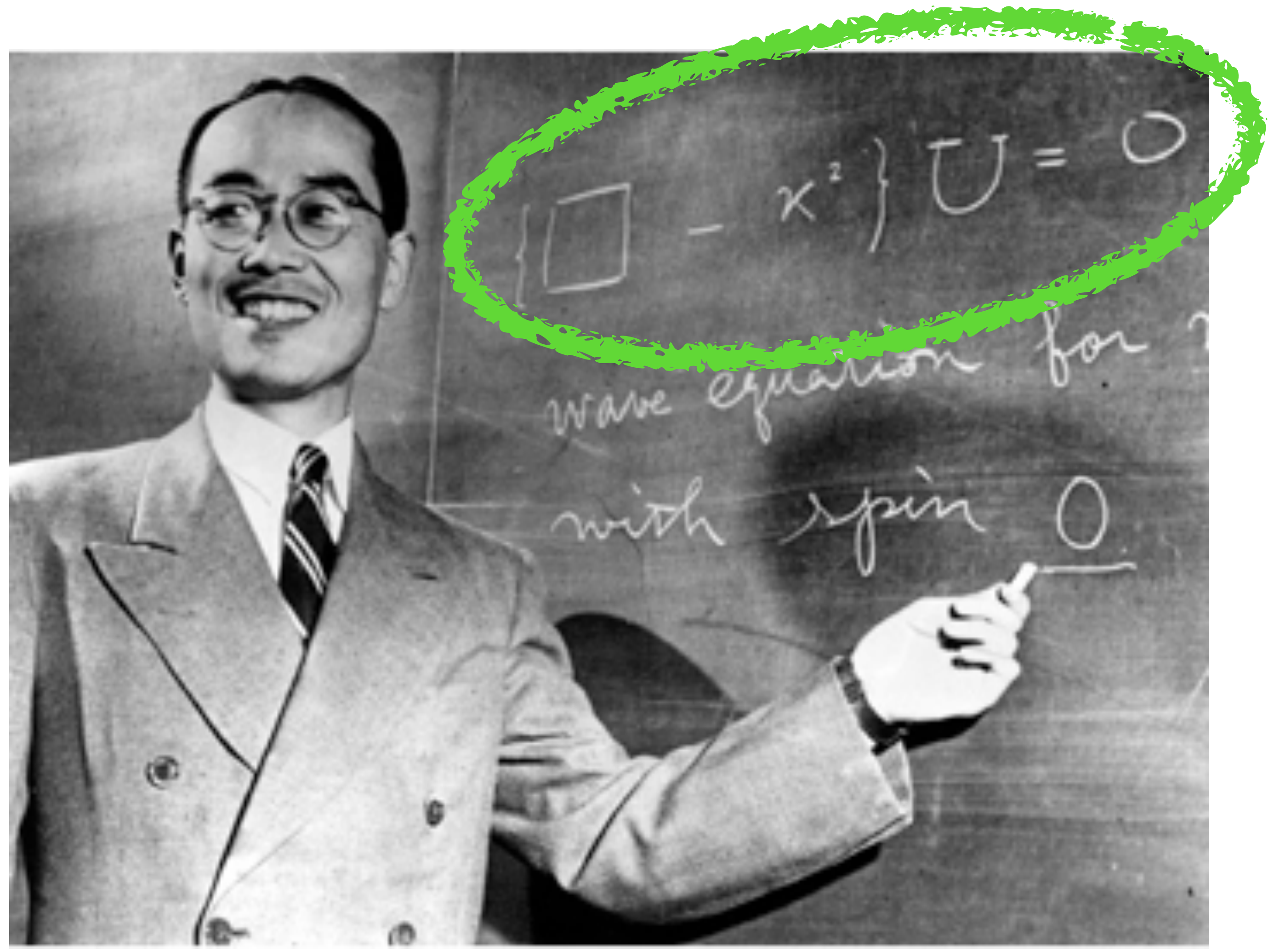

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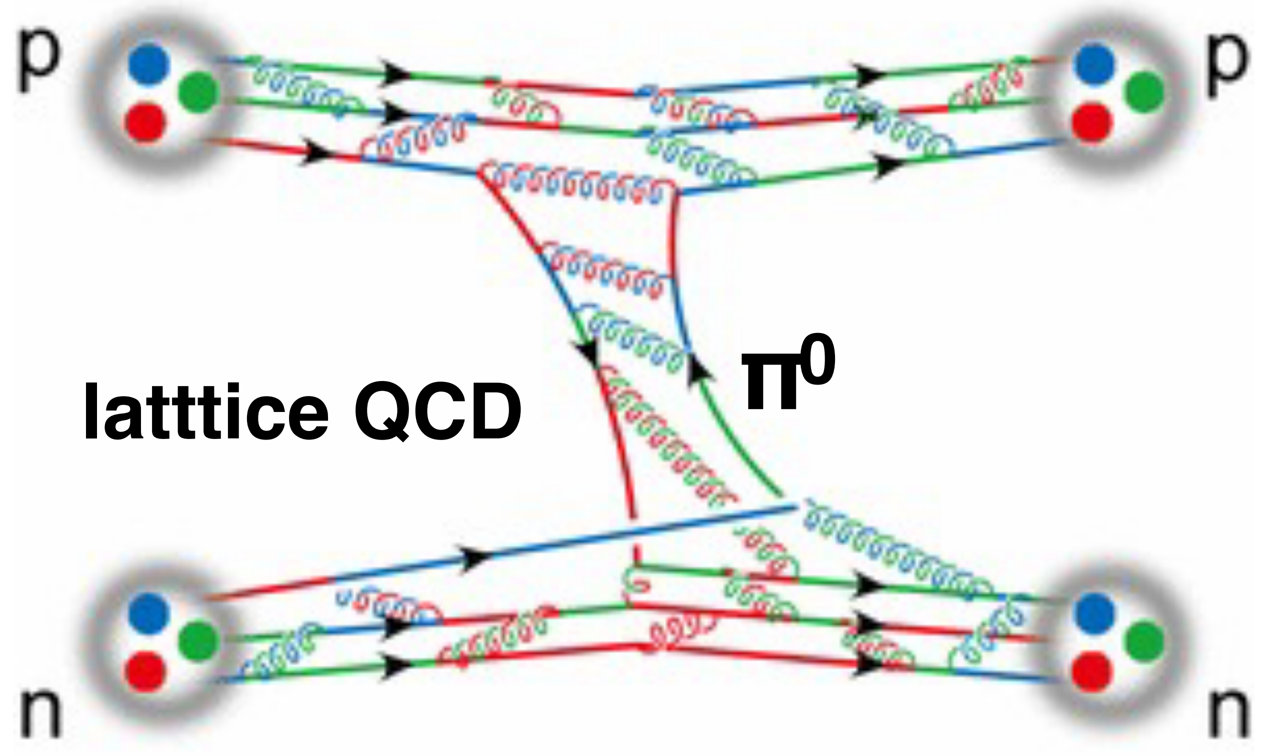

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… finally resolved as …

$\bar{K}$ ($\bar{q}s$) forms a bound state with two nulceons

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

Basic understanding of nuclei

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nucleons (N): qqq ⟵ meson: $\bar{q}q$ ⟶

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

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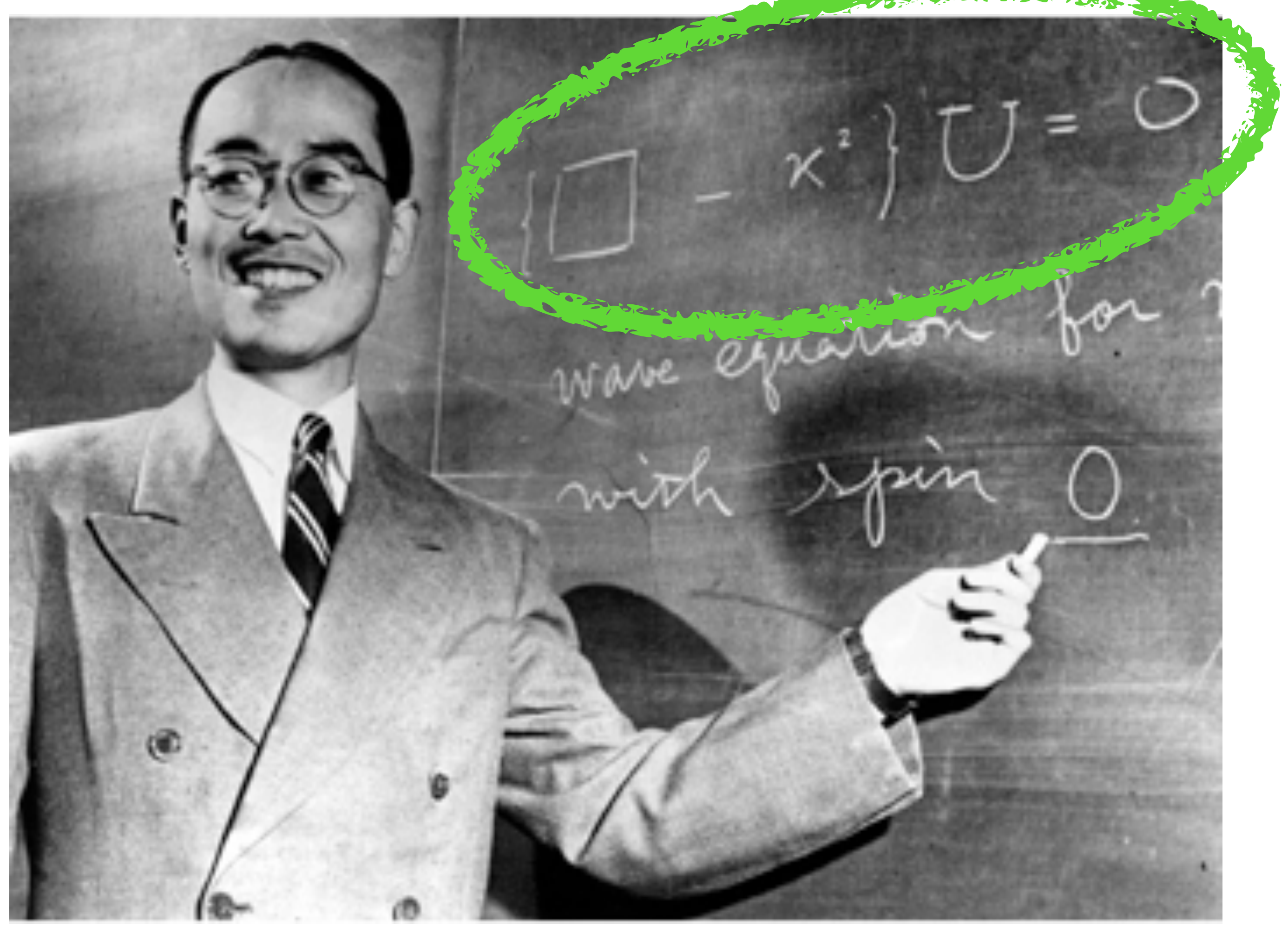

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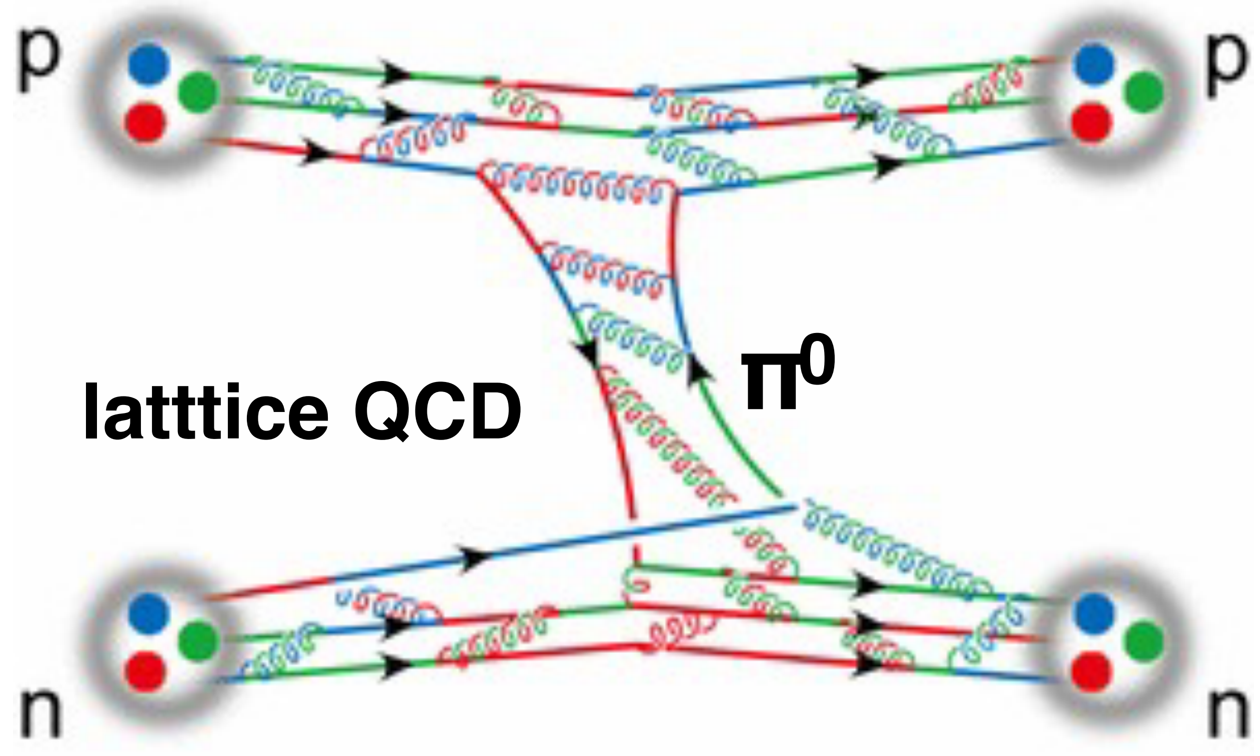

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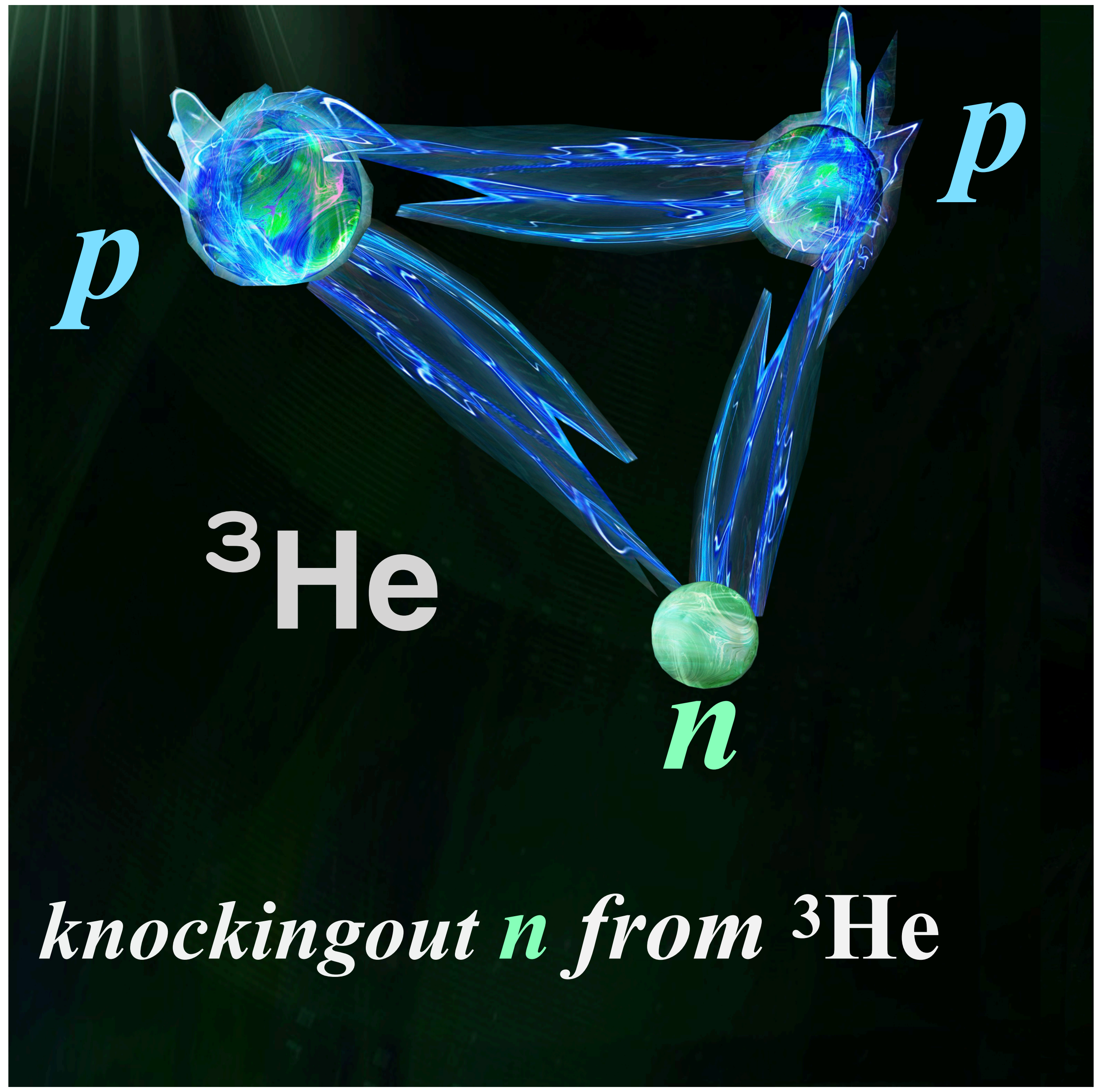
$\bar{K}$ meson (K^- : $\bar{u}s$, $\bar{K}^0$: $\bar{d}s$)

J-PARC E15: “K^-pp” Exploration Research

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



(K^- + pp) + n

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

@ 1 GeV/c

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

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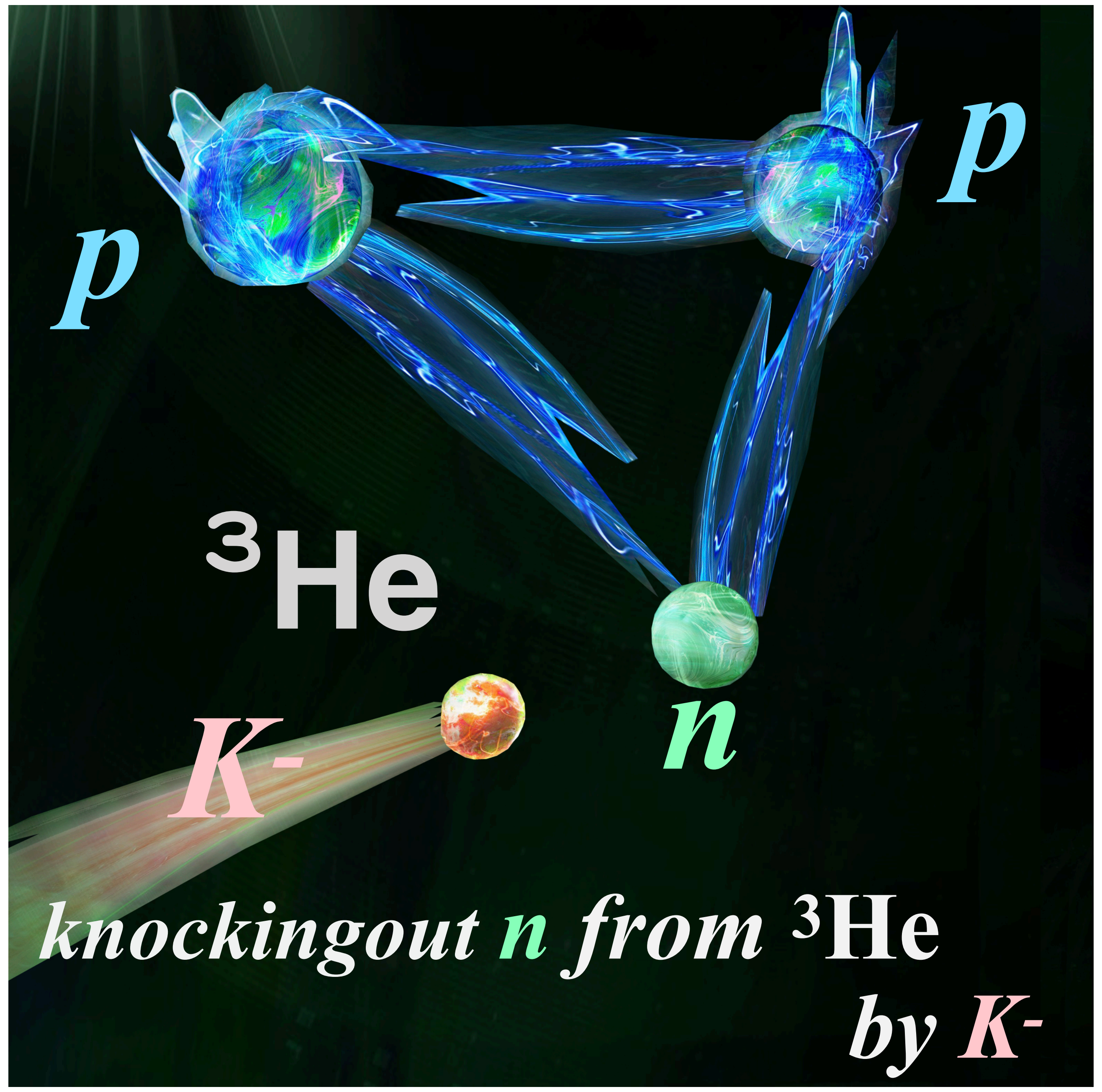

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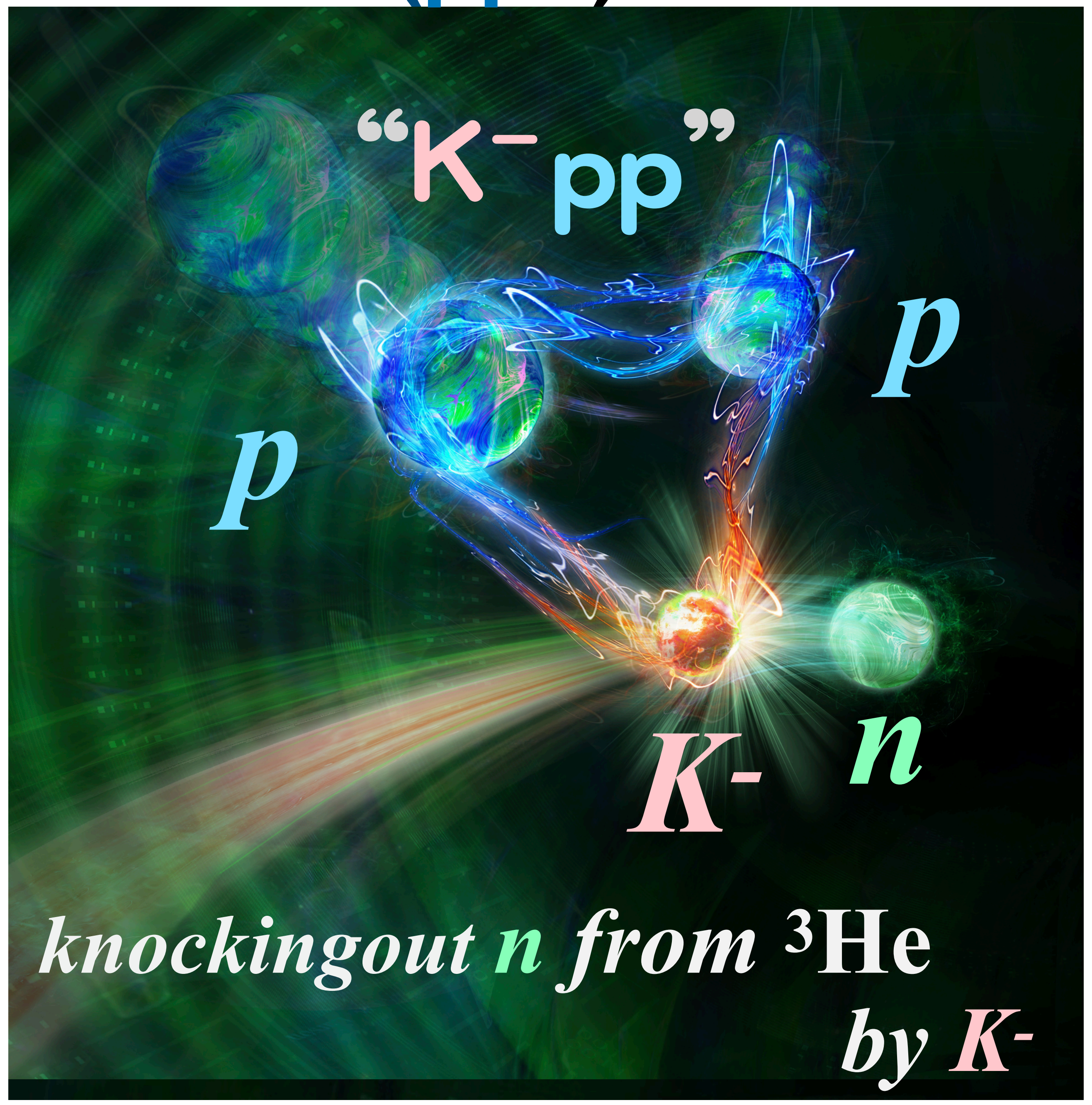

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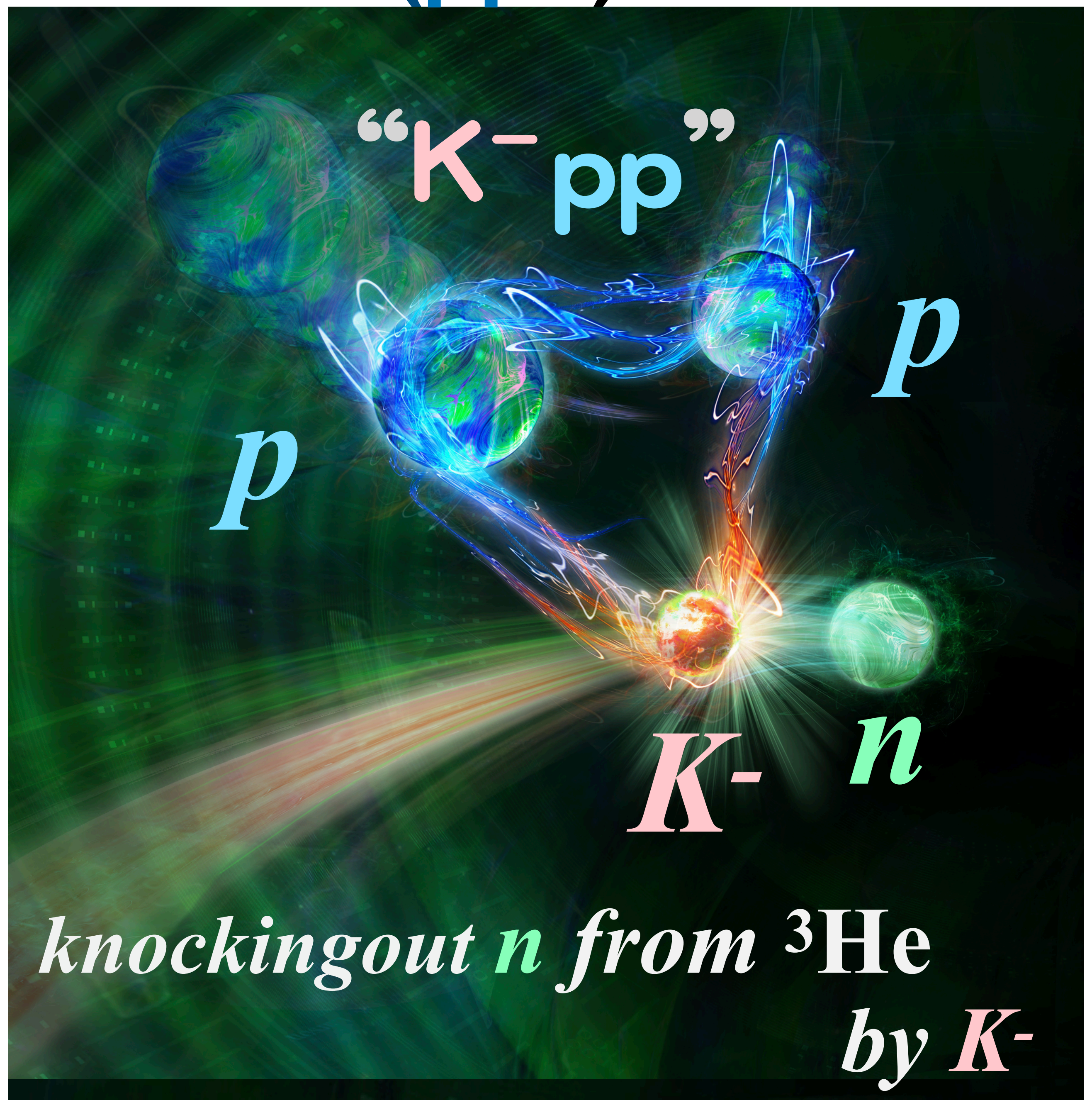
$K^- + {}^3He \rightarrow (K^- + pp) + n$: formation

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

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



$(K^- + pp) + n$

substitute n in ^3He by K^-

@ 1 GeV/c

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

strong $\bar{K}N$ attraction?

"K^-pp" bound state? / compact system?

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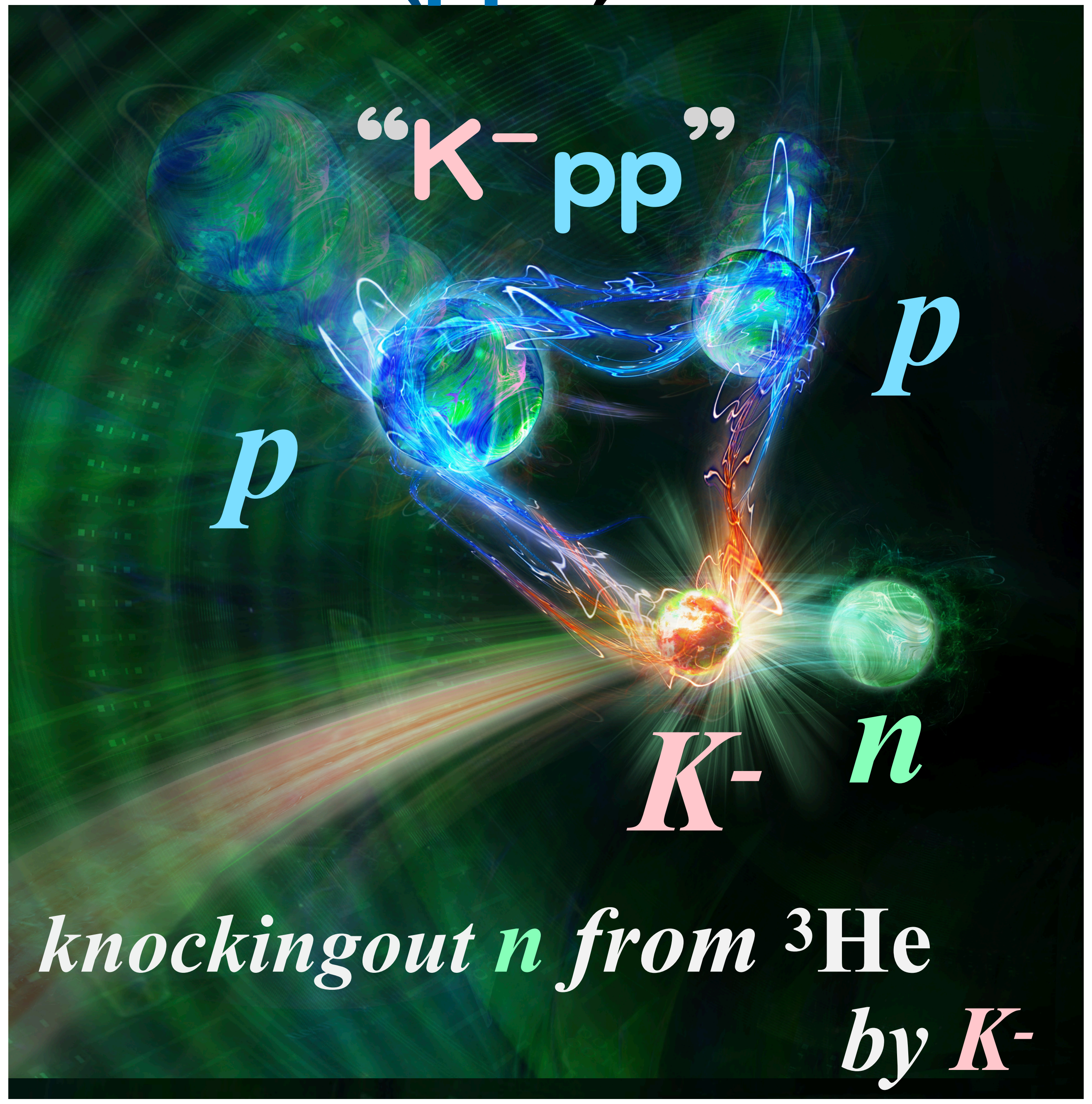

(K^- + pp) + n

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

@ 1 GeV/c

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

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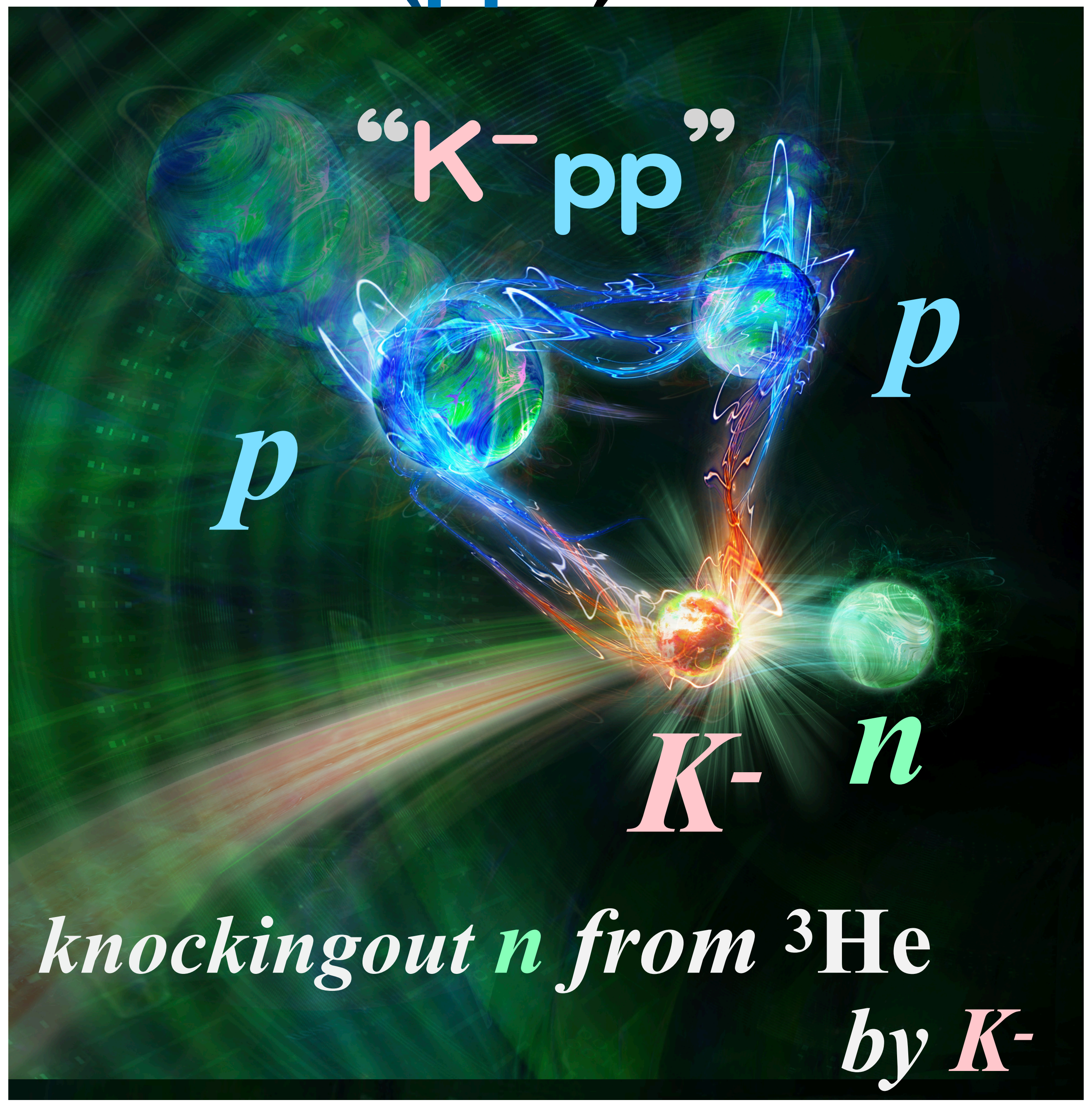

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K^- + ^{3}He → (K^- + pp) + n : formation

(K^- + pp) → Λ + p : decay (M, q)

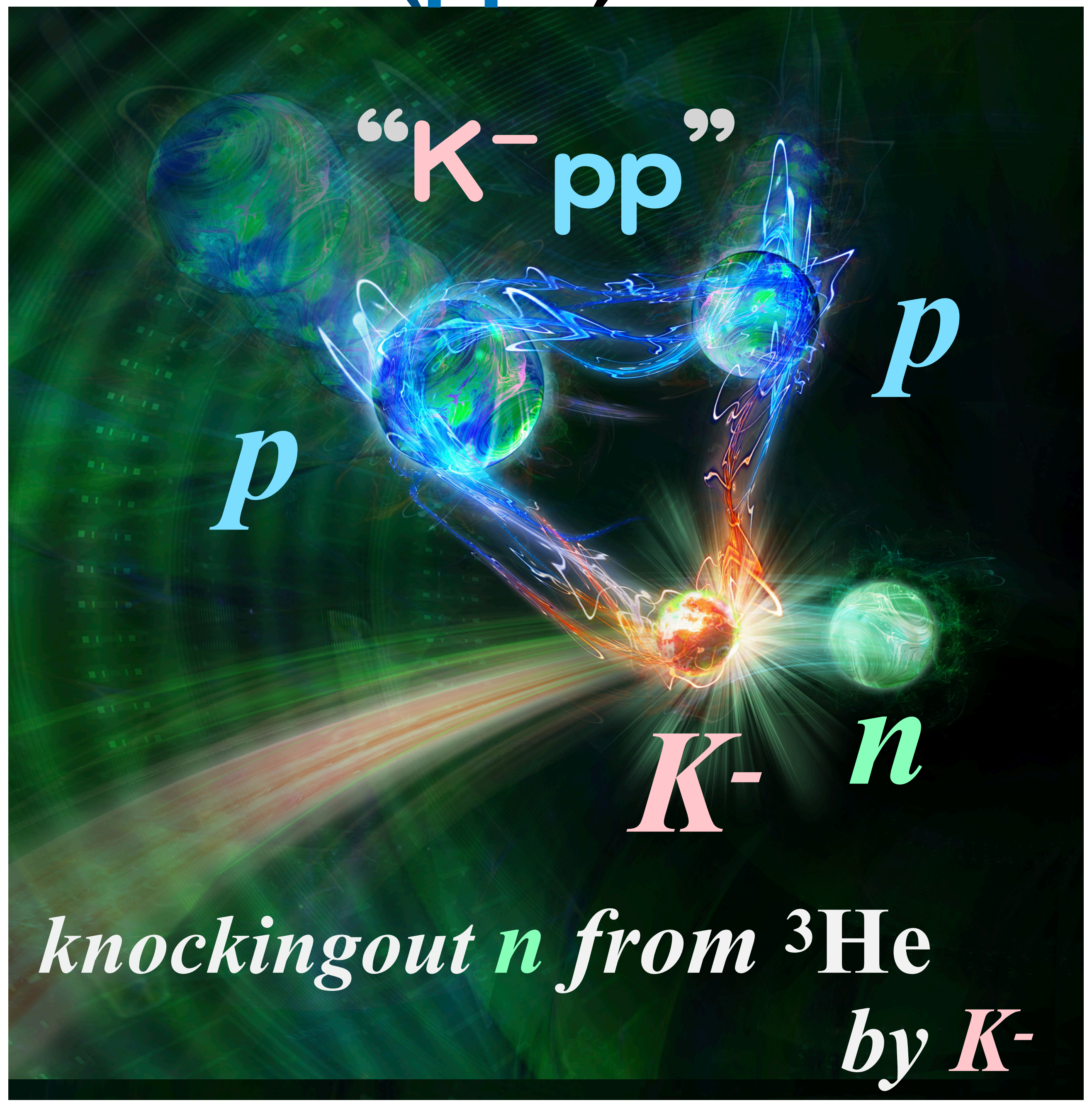
only when all the particles are in the strong interaction range

strong $\bar{K}N$ attraction?

"K^-pp" bound state? / compact system?

J-PARC E15: "K⁻pp" Exploration Research

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



(K⁻ + pp) + n

substitute n in ³He by K⁻

@ 1 GeV/c

strong $\bar{K}N$ attraction?

"K⁻pp" bound state? / compact system?

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

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

final state particles

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

$(K^- + pp) \rightarrow \Lambda + p$: decay (*M*, *q*)

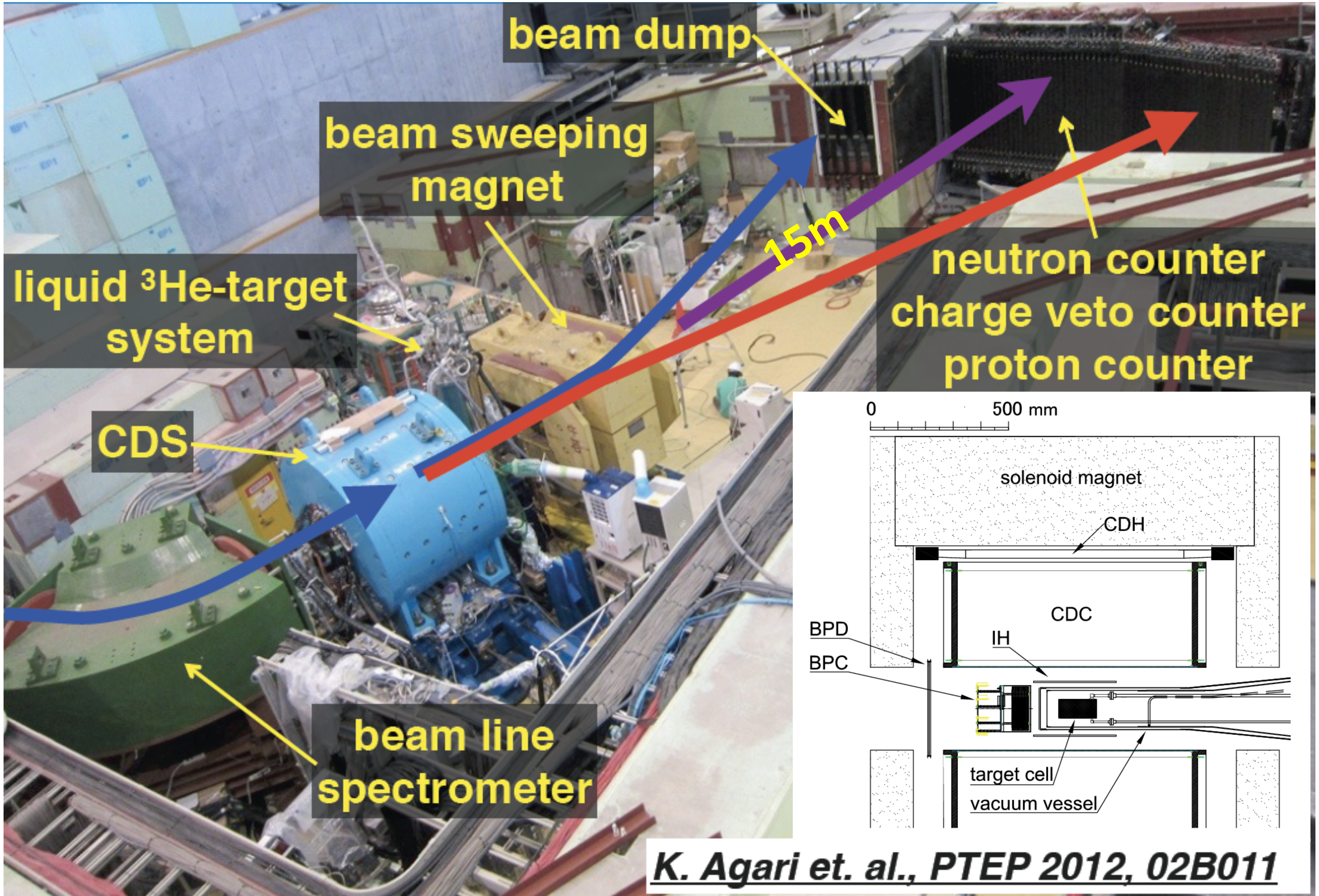
only when all the particles are in the strong interaction range

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

analyze *invariant mass M* of (K⁻ + pp)-system

and *momentum transfer q* to the system

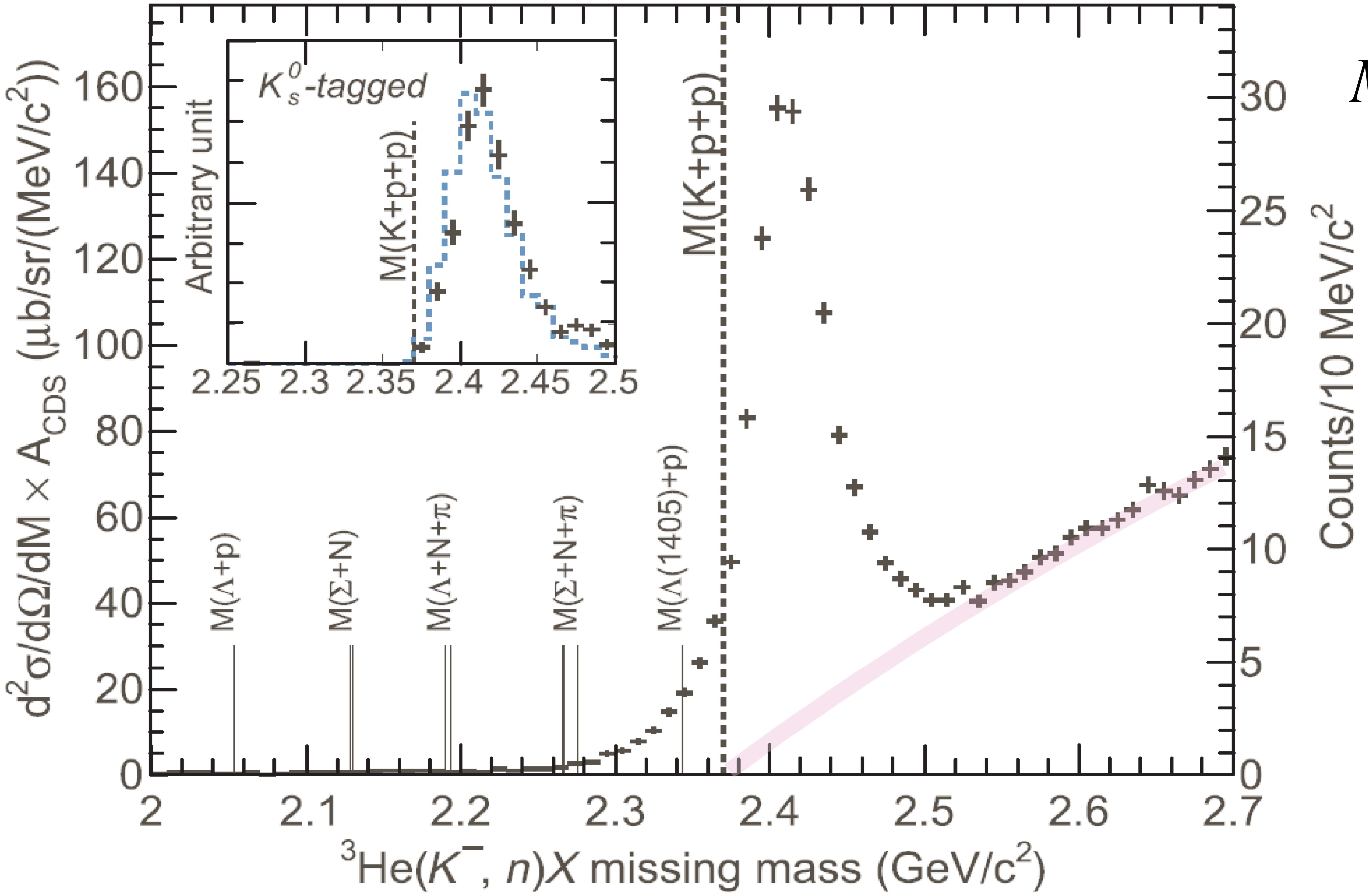
Experimental Setup for E15



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

$^3He(K^-, n_{NC})X$ — semi-inclusive

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



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

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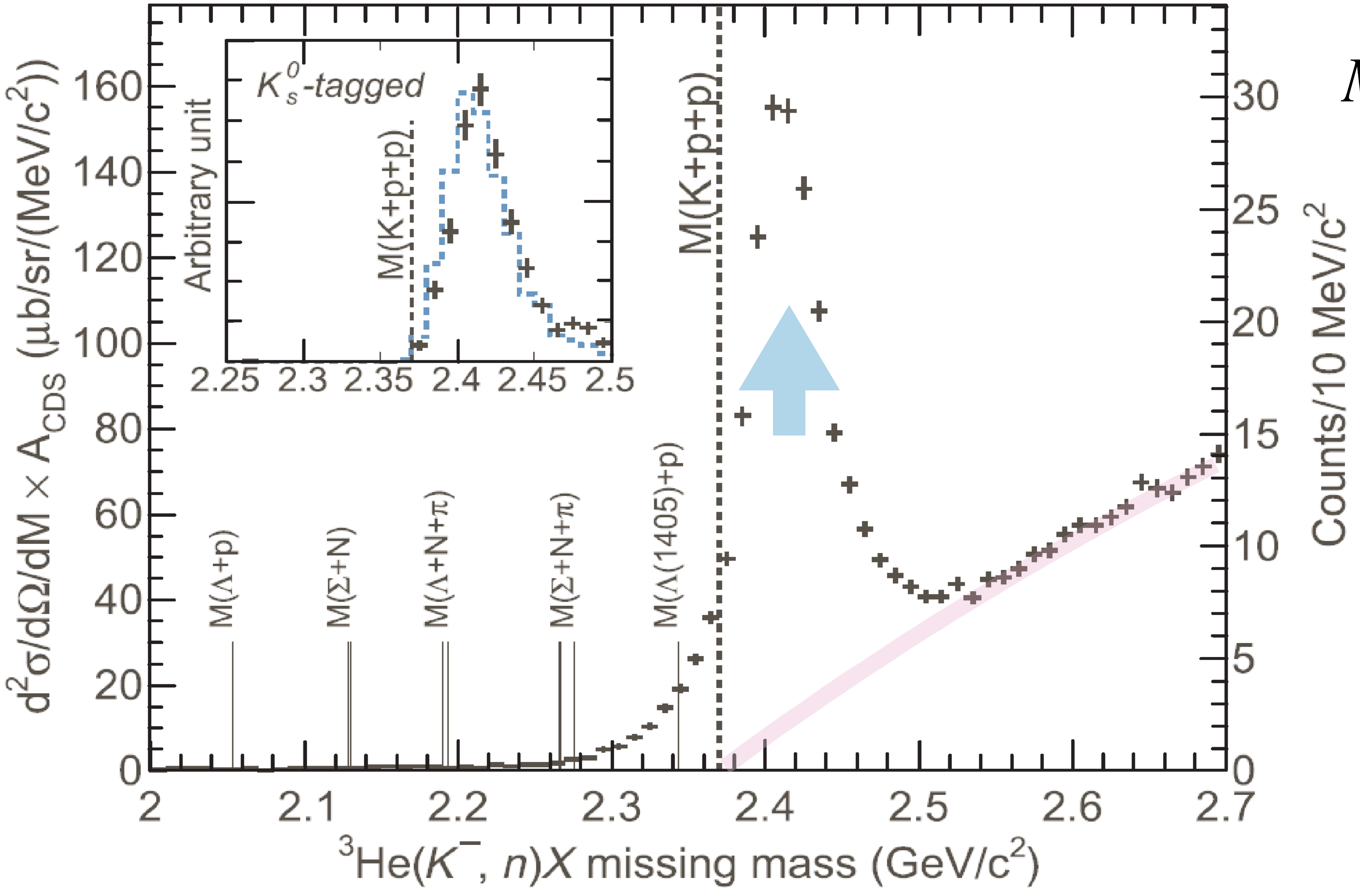

$M(K^-pp) \sim 2.37\ \mathrm{GeV}/c^2$

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

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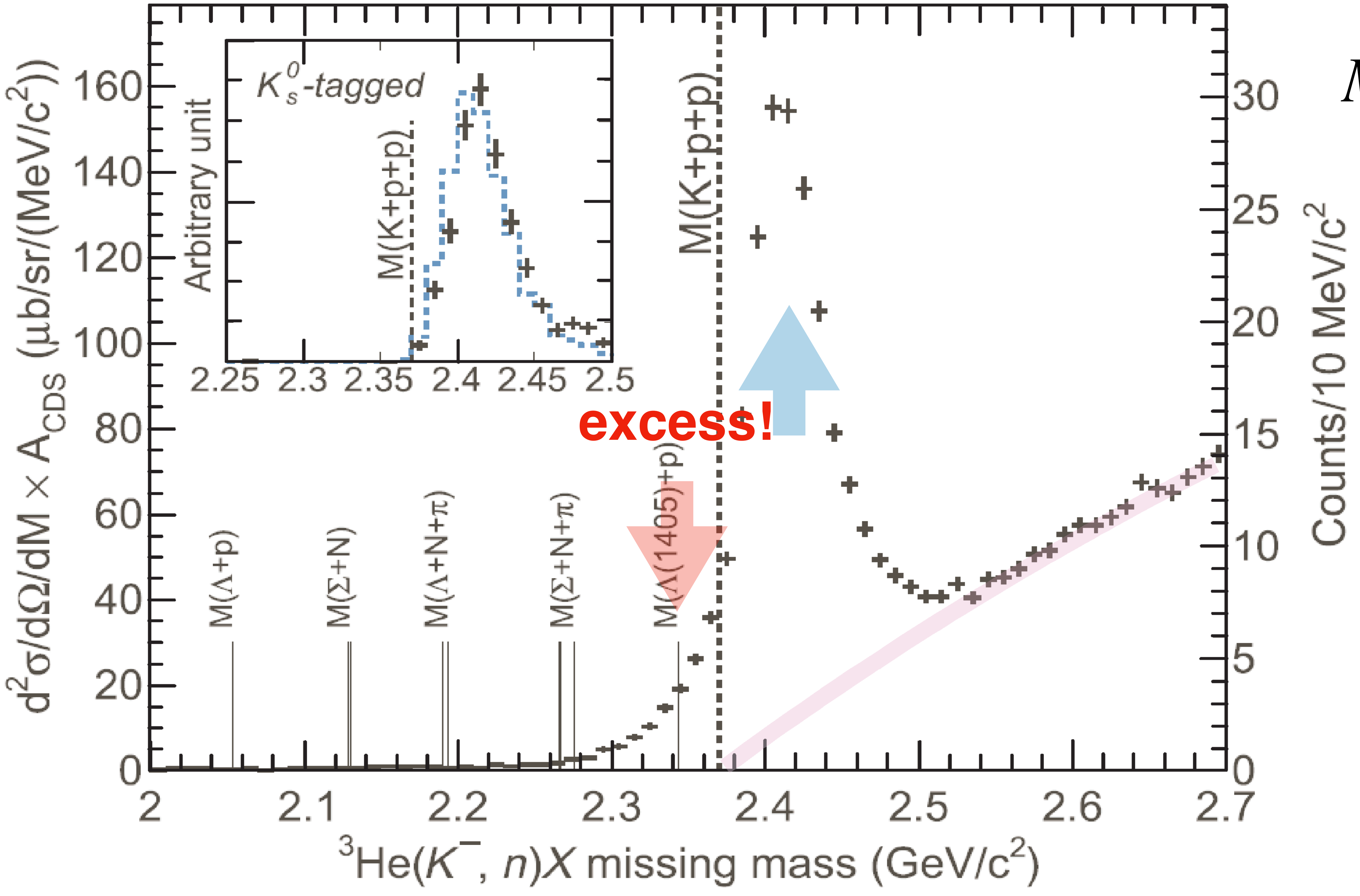


$M(K^-pp) \sim 2.37$ GeV$/c^2$

How to study excess:

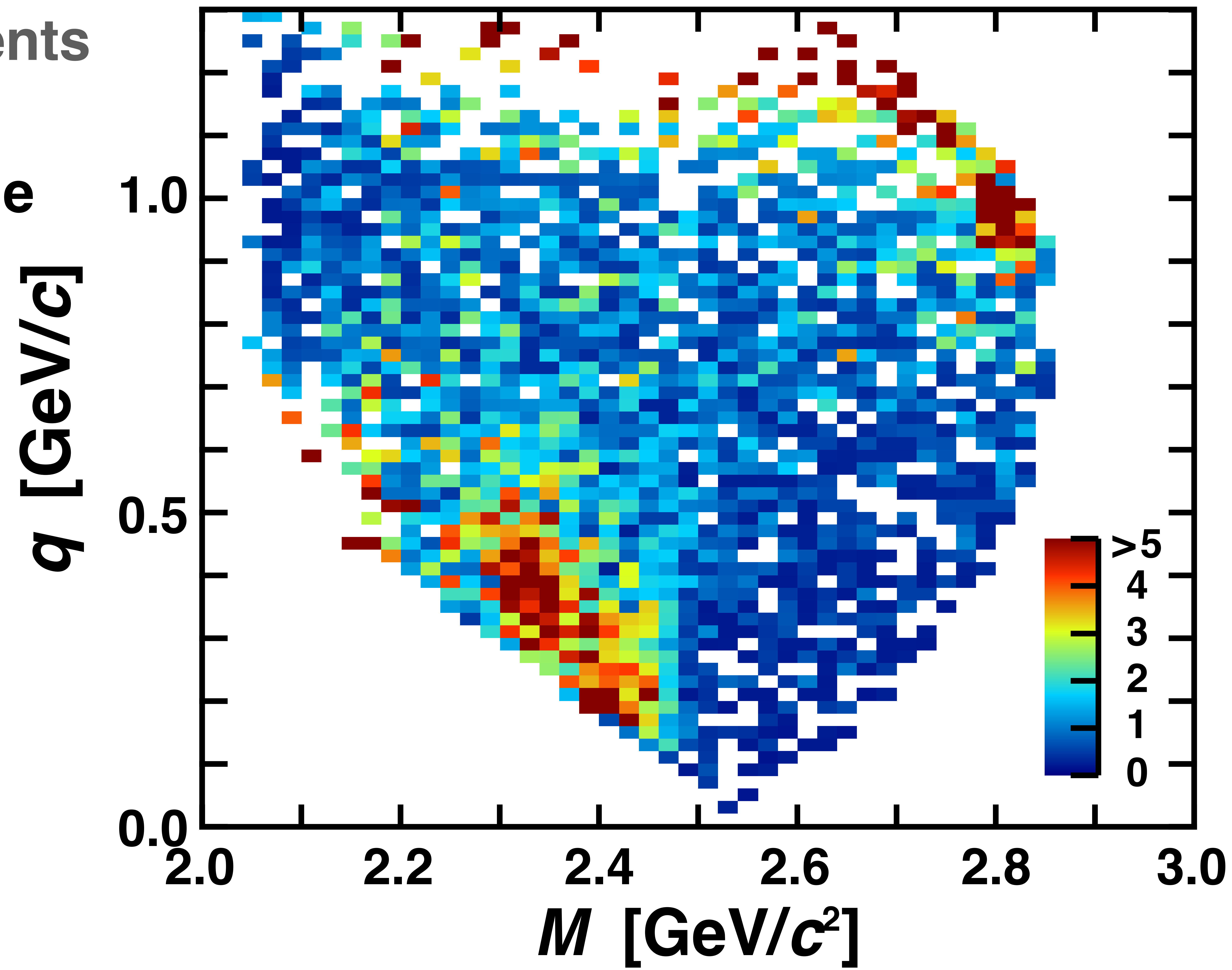
$\bar{K} + NN \to \Lambda p$ **happens only when all the particles are in the strong interaction range, because of energy-momentum mismatch**

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

Λp $+n$ events

on (*M*, *q*)-plane

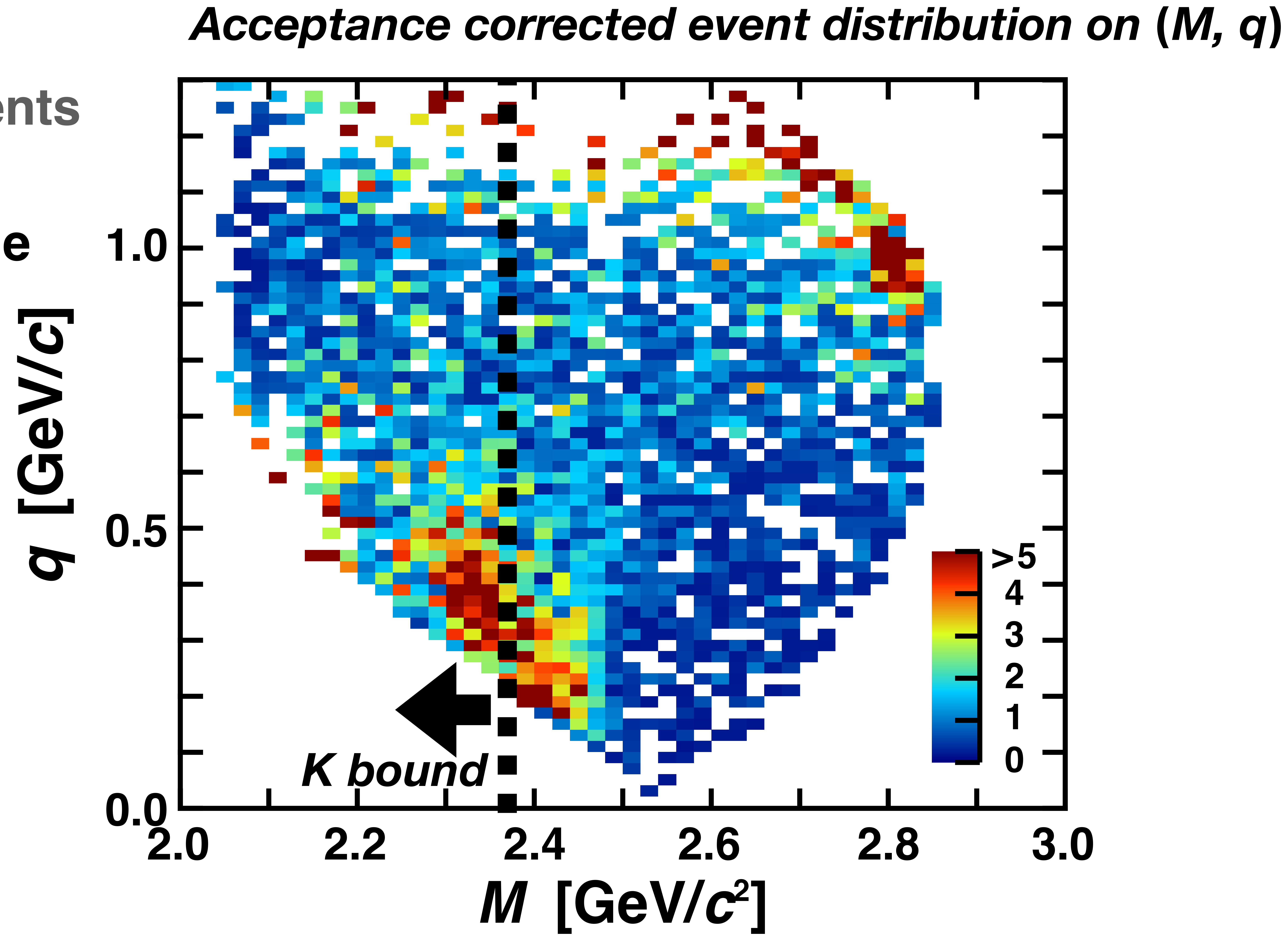
Acceptance corrected event distribution on (M, q)



z-axis is in [nb] per (20MeV/c x 20 MeV/c²)

Λp $+n$ events

on (*M*, *q*)-plane

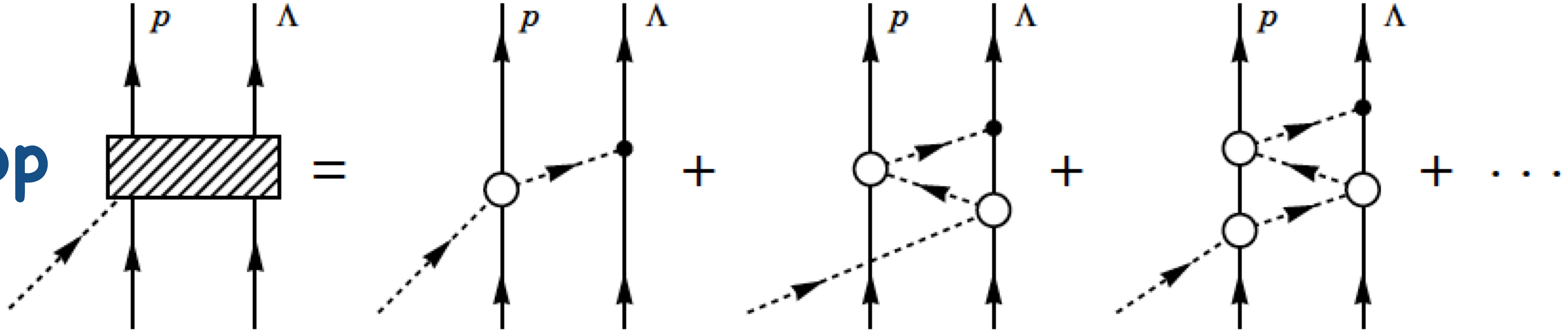


z-axis is in [nb] per (20MeV/c x 20 MeV/c²)

Λp + $n_{mis.}$ vs. theory

Theory helps a lot to understand Λp invariant mass spectrum, but still not compatible in large-q distribution

Kpp



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

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*E-mail: sekihara@post.j-parc.jp

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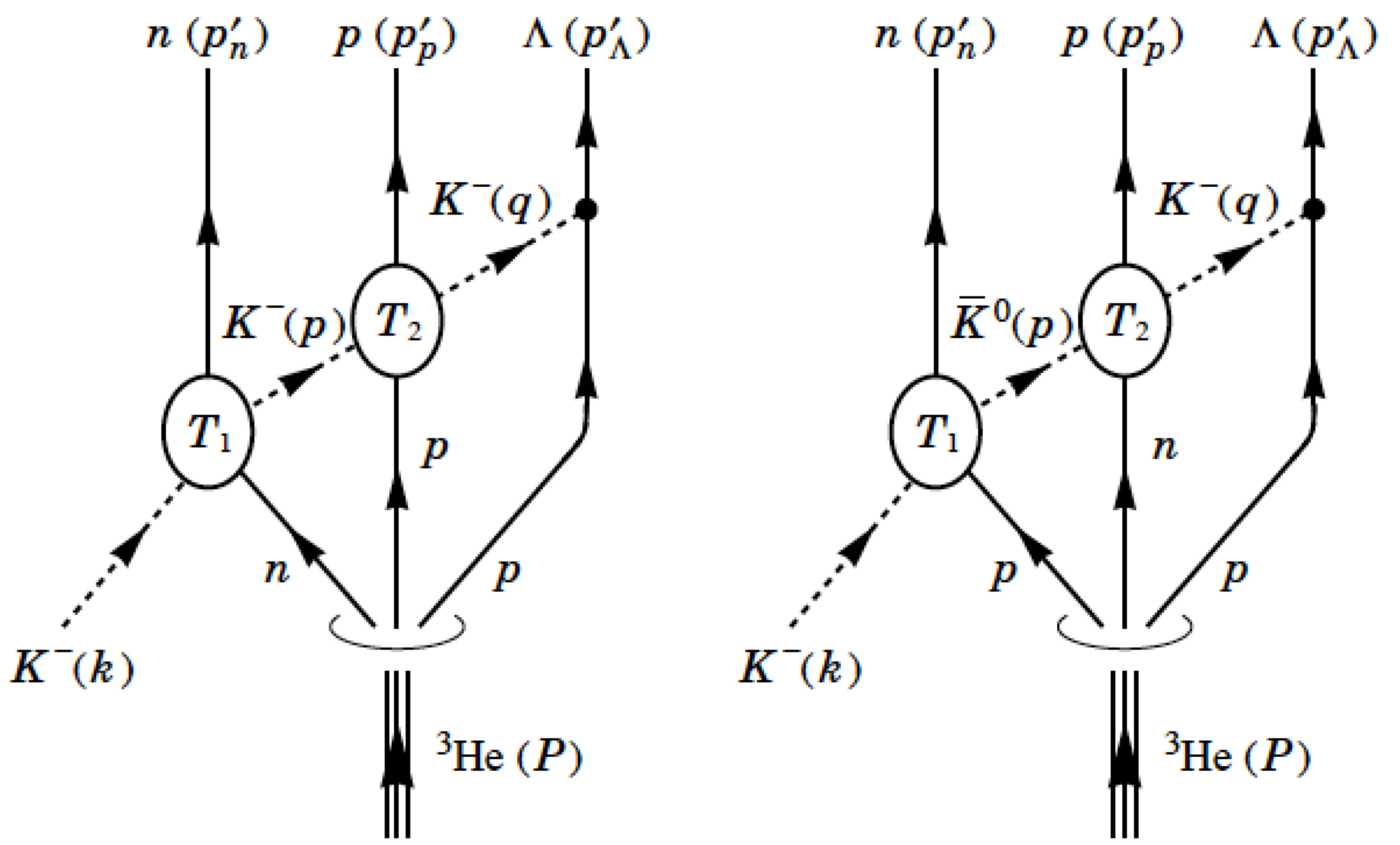


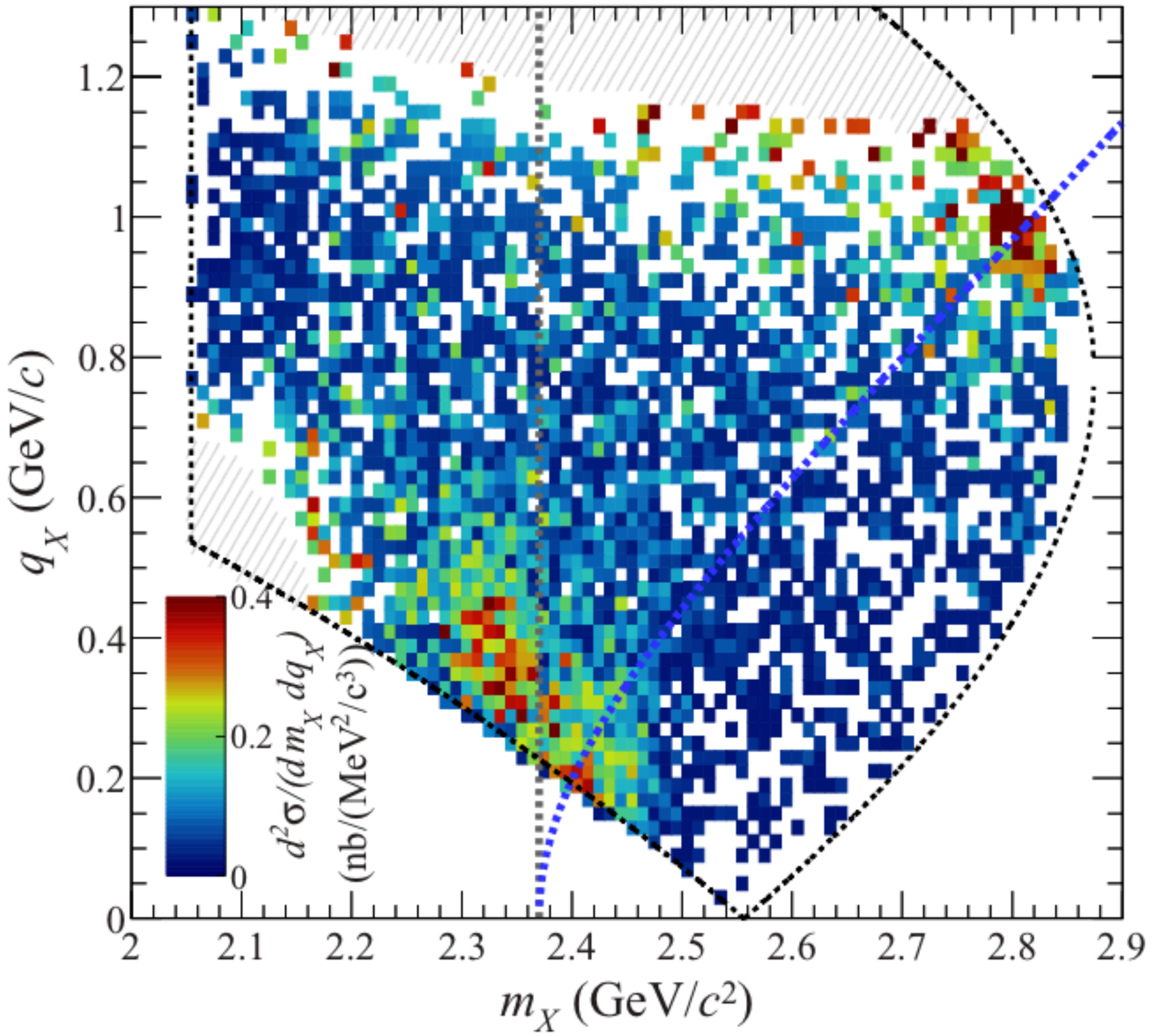
QF$\bar{K}$A

$\Lambda p + n_{miss}$

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

ρ : Lorentz-invariant phase-space

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



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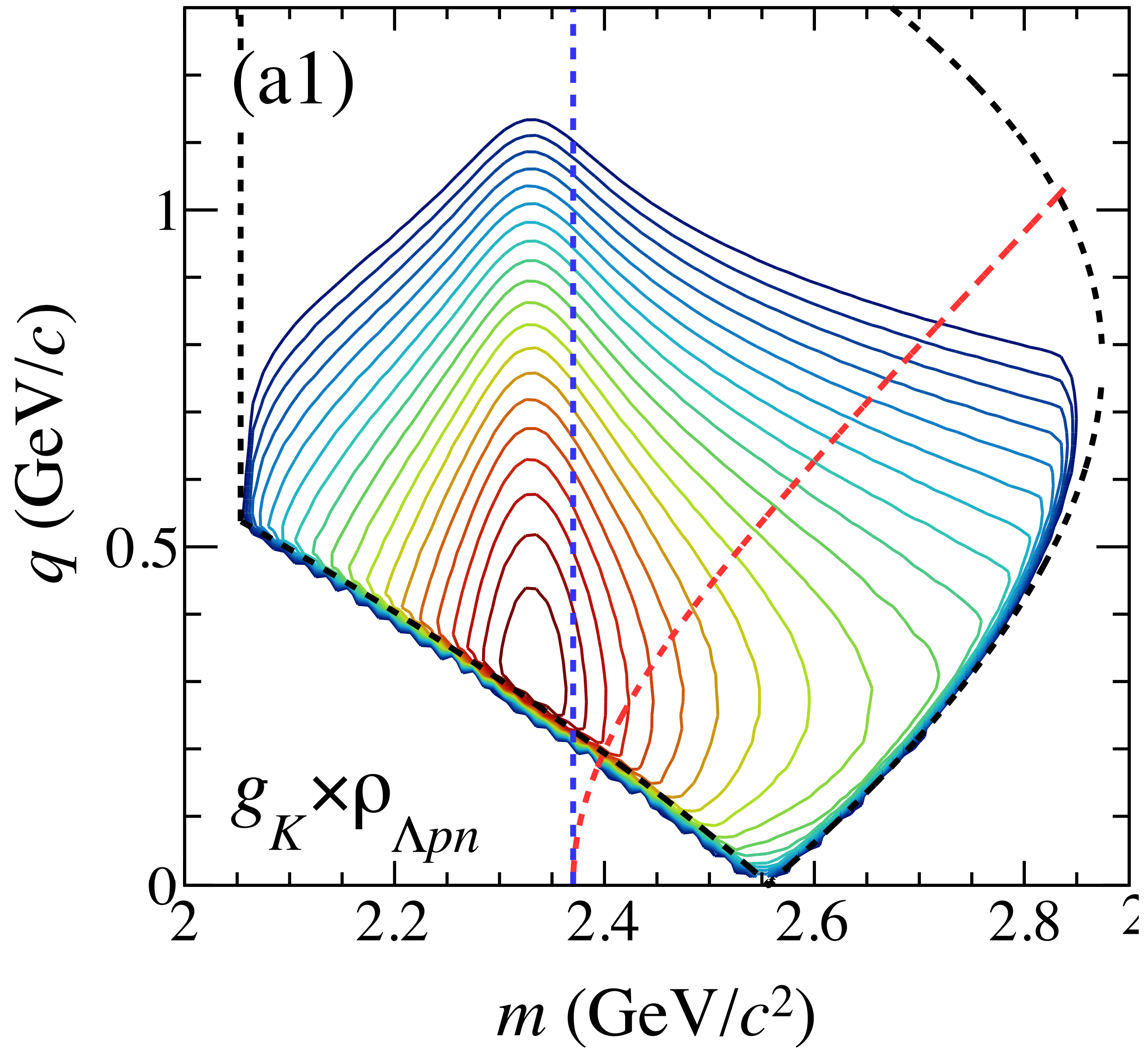
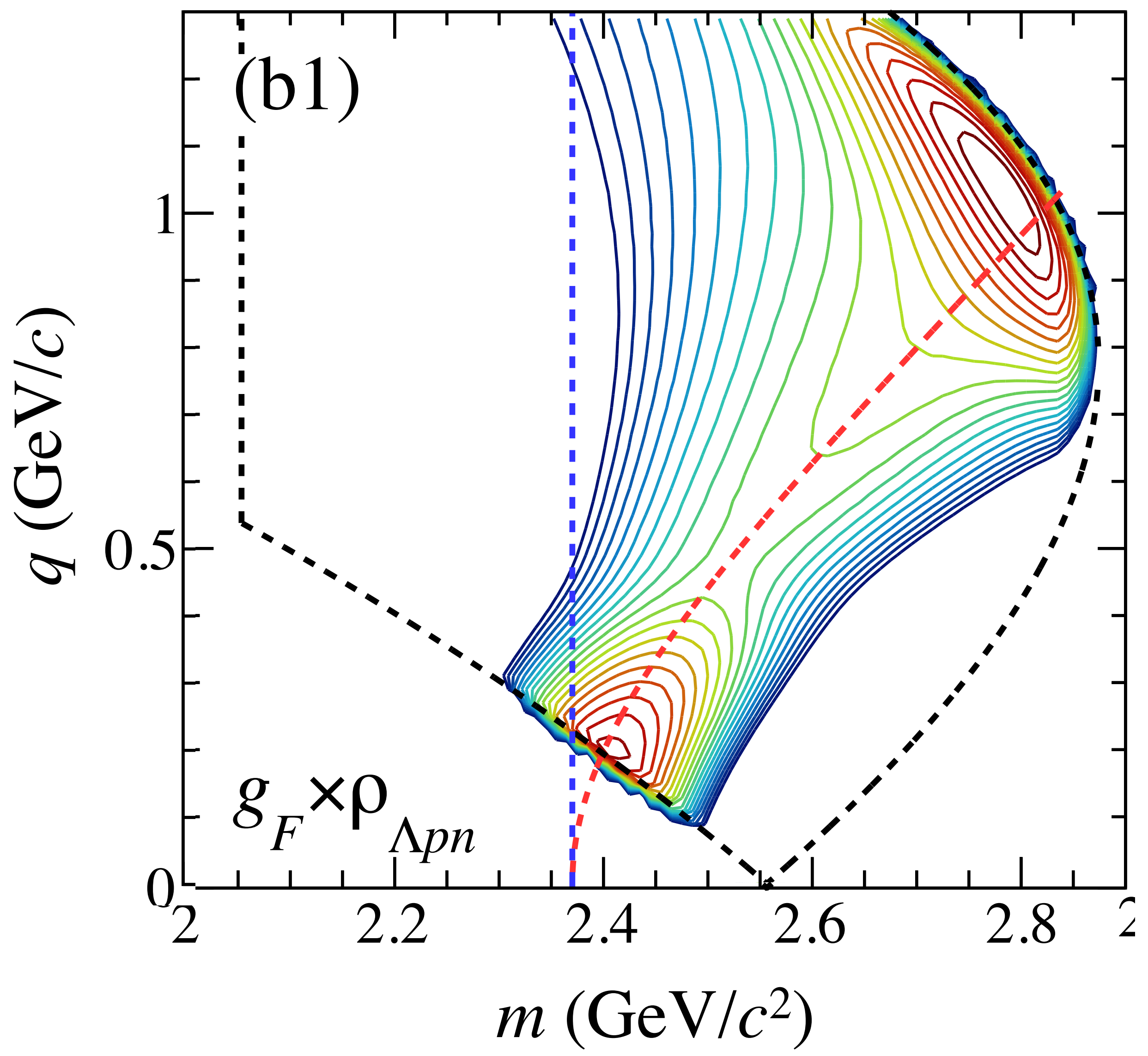
$\bar{K}NN$ production



+

QF-$\bar{K}$ absorption



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

$f_{QF\text{-}\bar{K}}(m,q)$: *quasi-free (on mass-shell) K abs.*

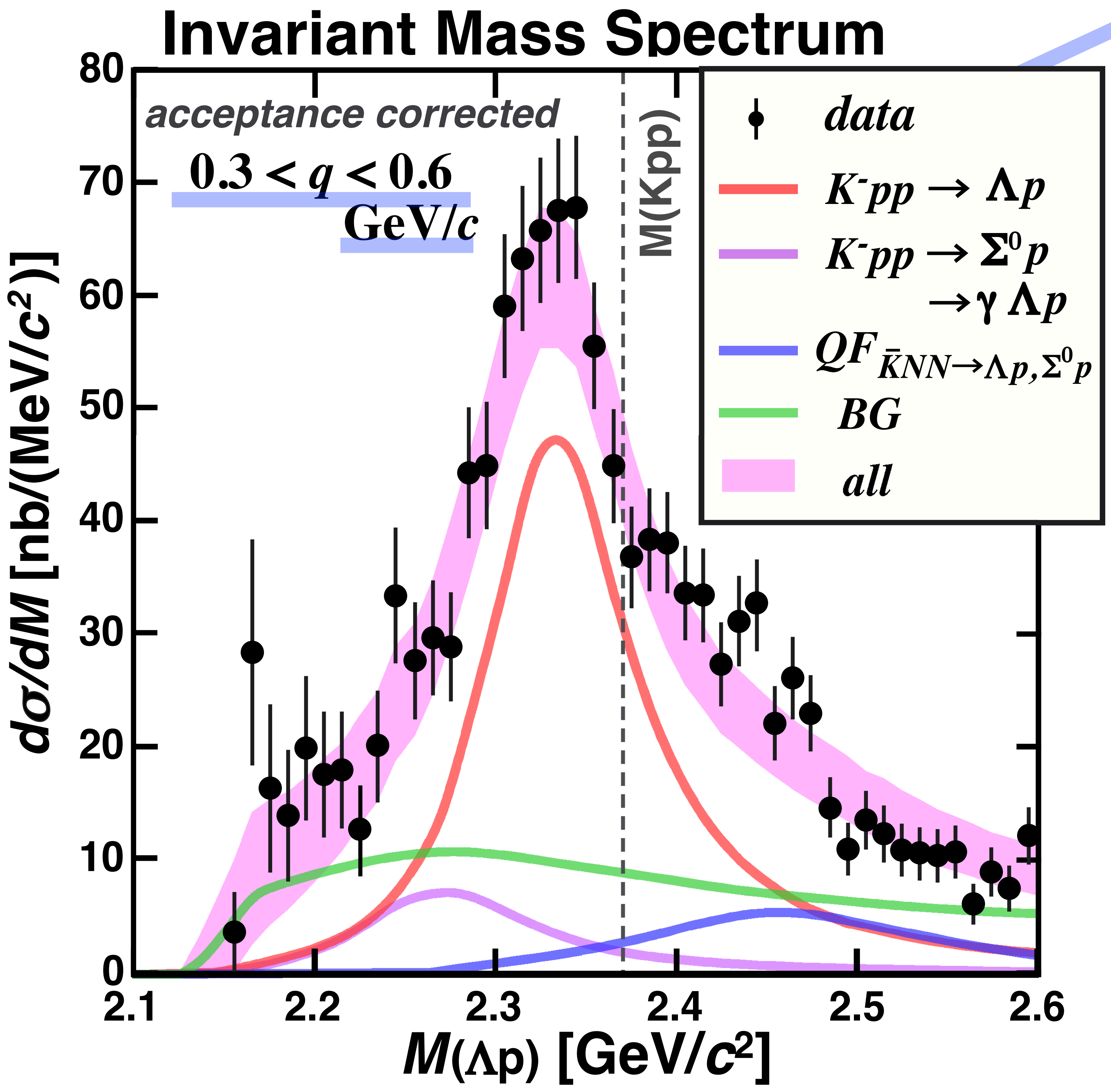
PWIA based interpretation

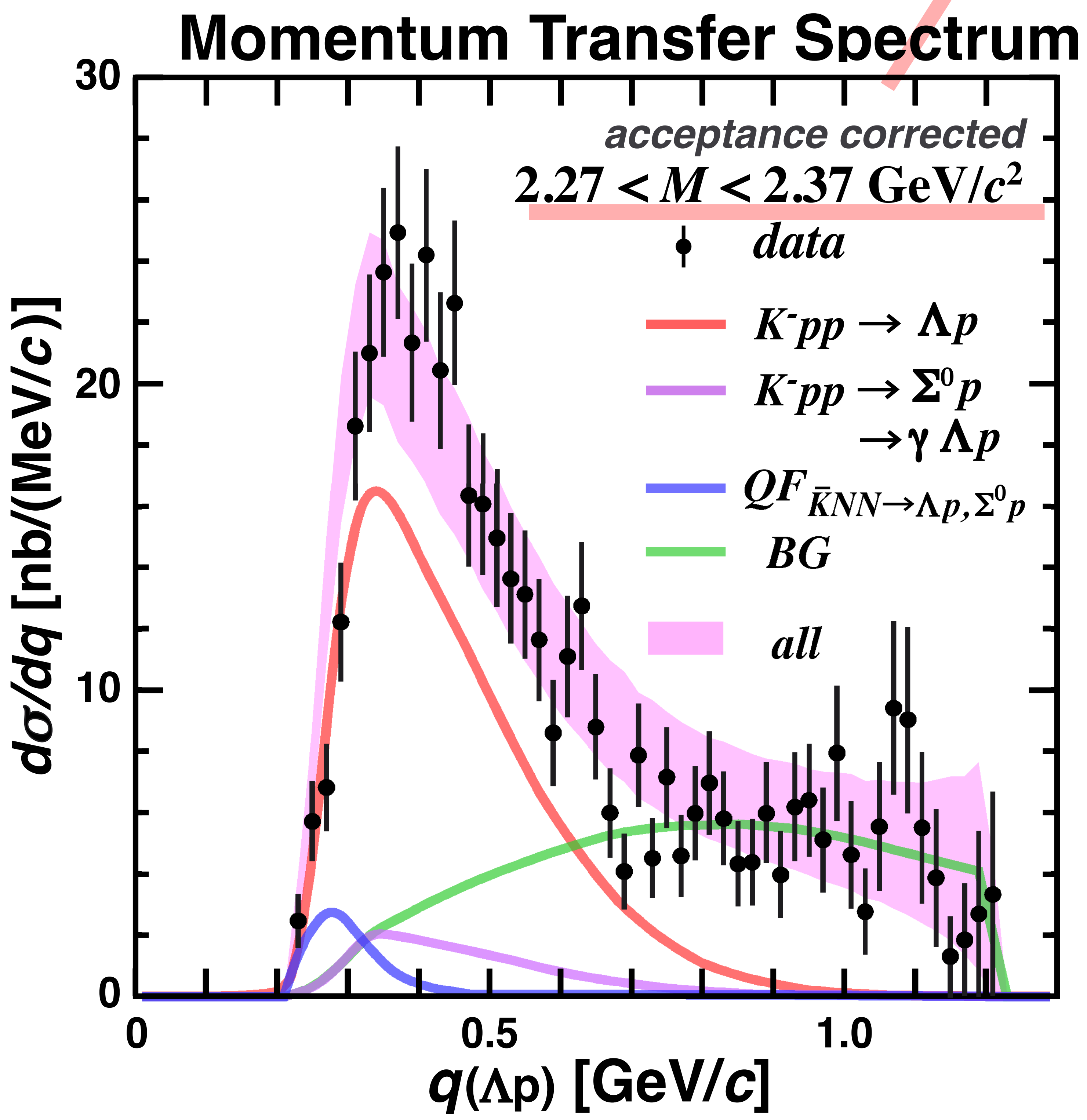
(plane wave impulse approximation)

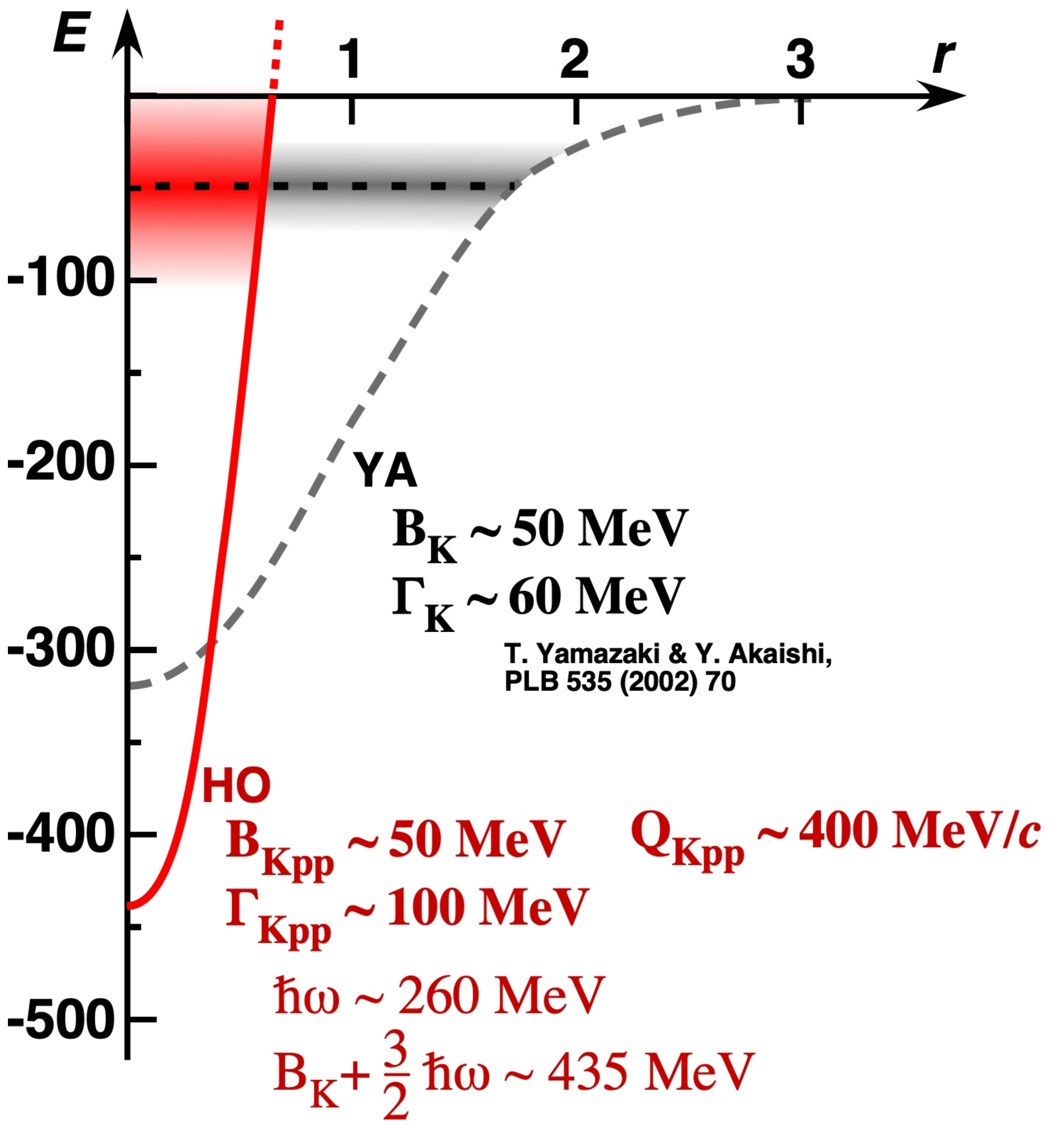
B.W. / Lorentzian — form factor / structure factor

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

Differential cross section — Lorentz invariant phase space (Λpn)







strong binding ($\bar{K}N$ attraction) — wide momentum width — … could be quite compact …

$B_{Kpp} \sim 40$ MeV, $\Gamma_{Kpp} \sim 100$ MeV — $Q_{Kpp} \sim 400$ MeV/c — ($R_{Kpp} \sim 0.6$ fm (H.O.))

contents:

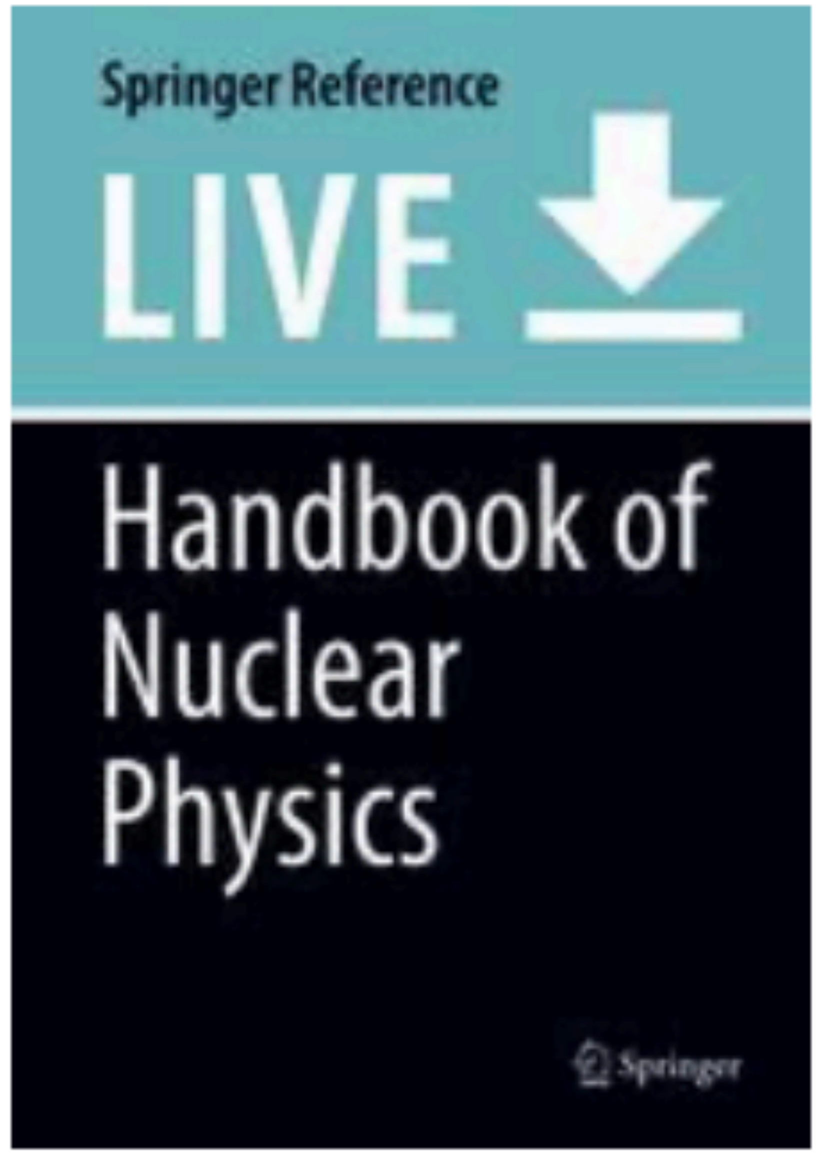
$\bar{K}N$ ***interaction study via kaonic atom***

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***

Future direction for $\bar{K}$ ***(***ϕ***) bound state study***

https://doi.org/10.1007/978-981-15-8818-1_37-1



Kaonic Nuclei from the Experimental Viewpoint

Research on kaonic nuclear bound states is a completely new field. This nuclear system consists of

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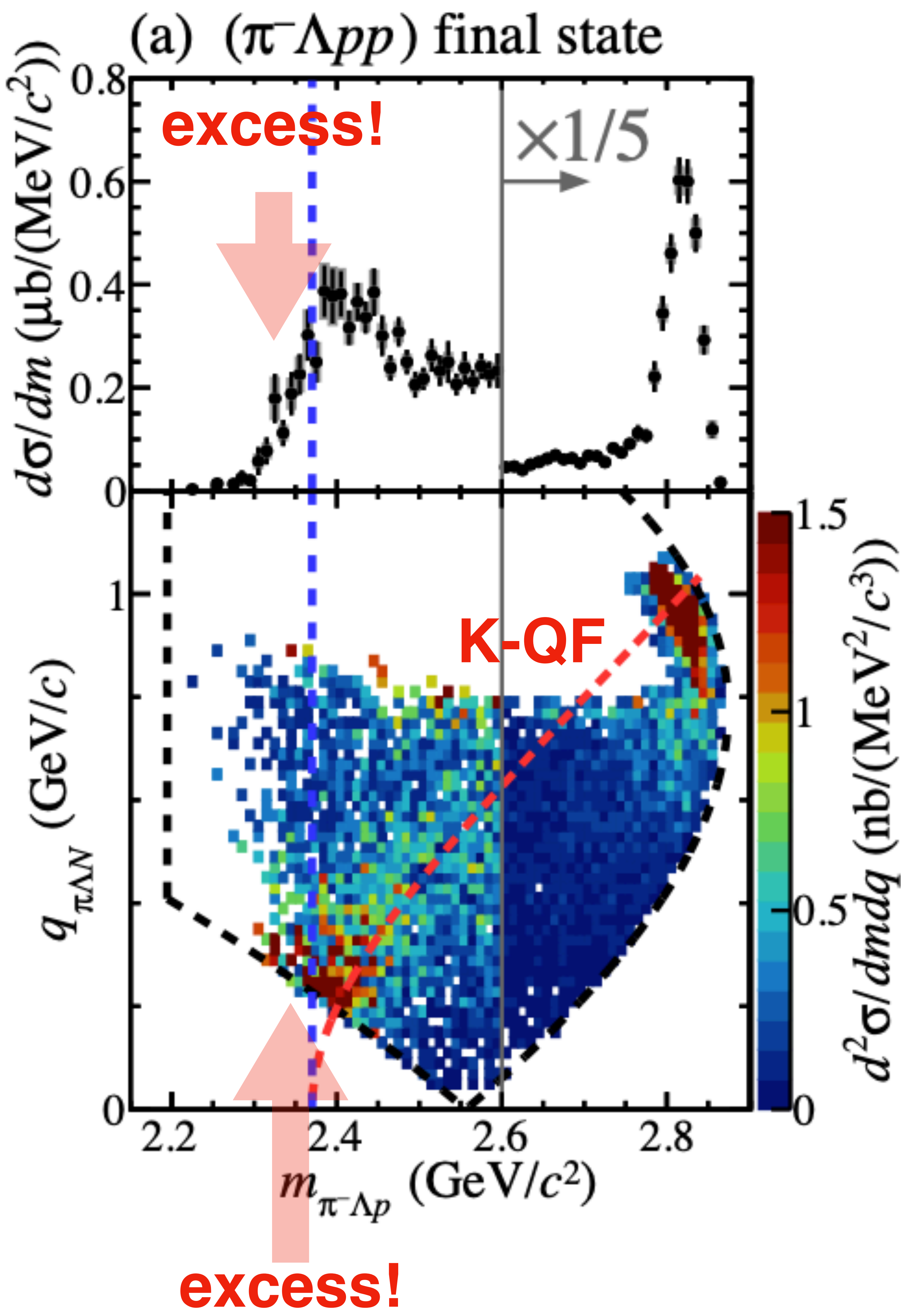
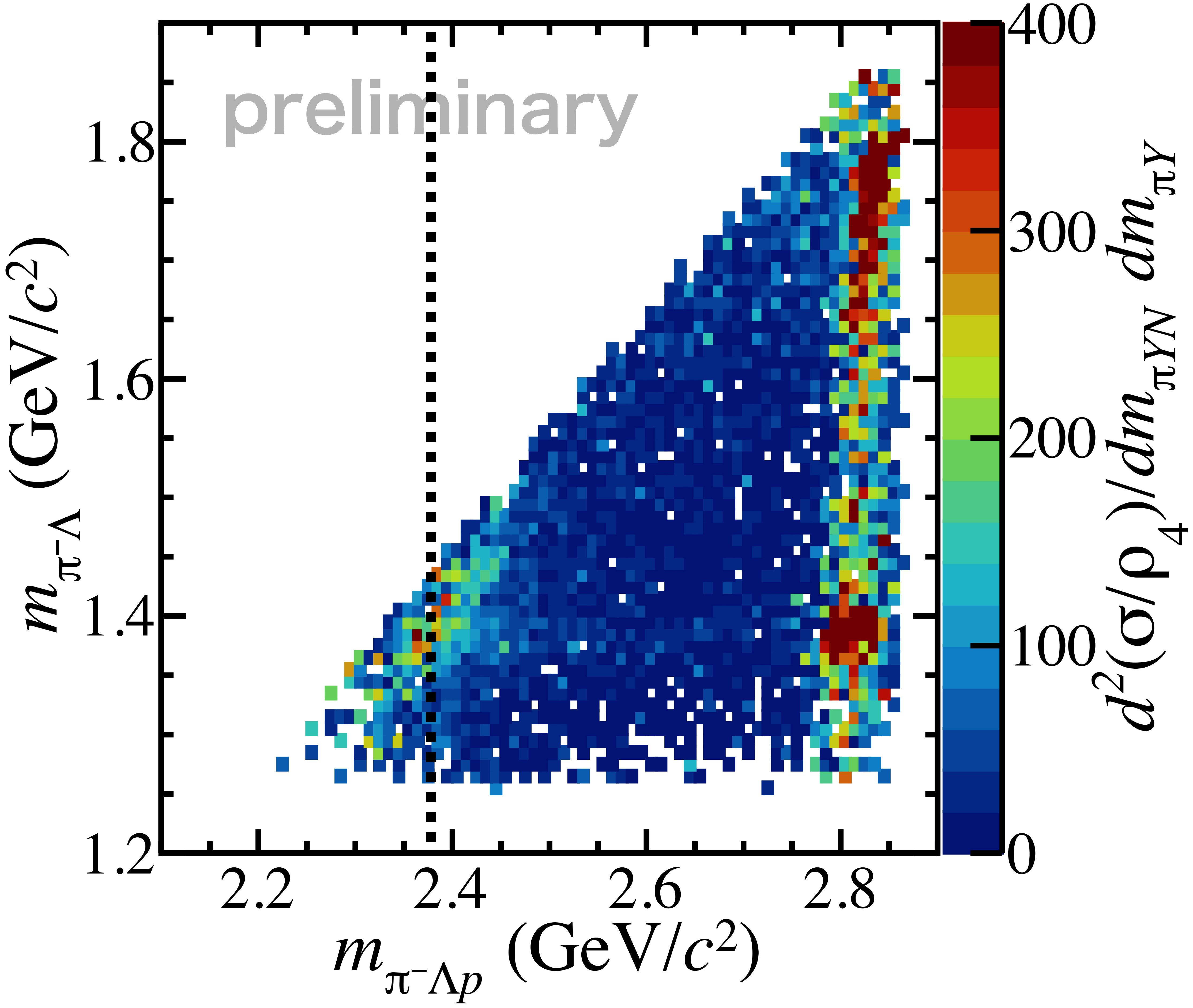
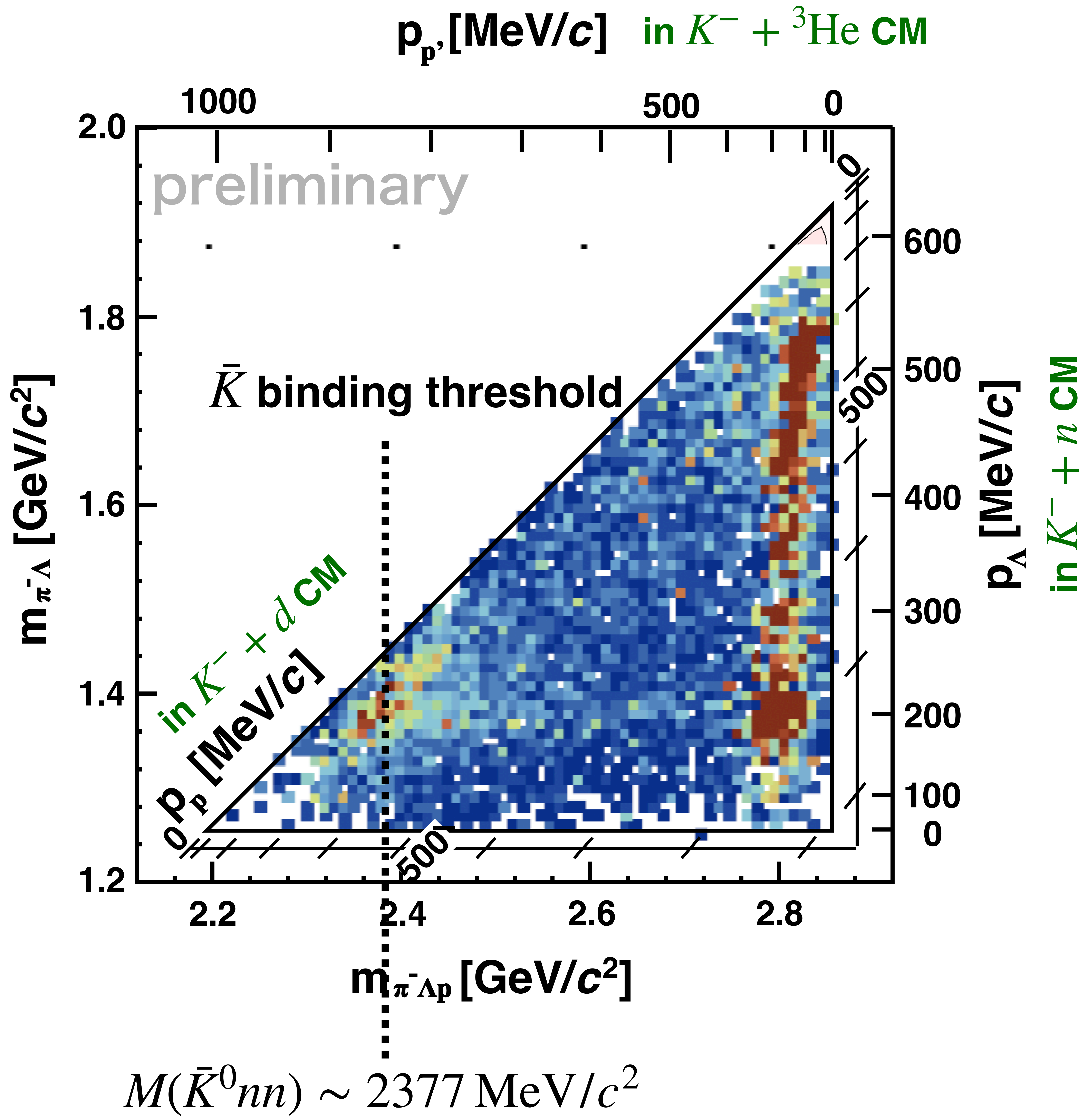
$K^- + {}^3He \rightarrow \pi^-\Lambda pp$ reaction

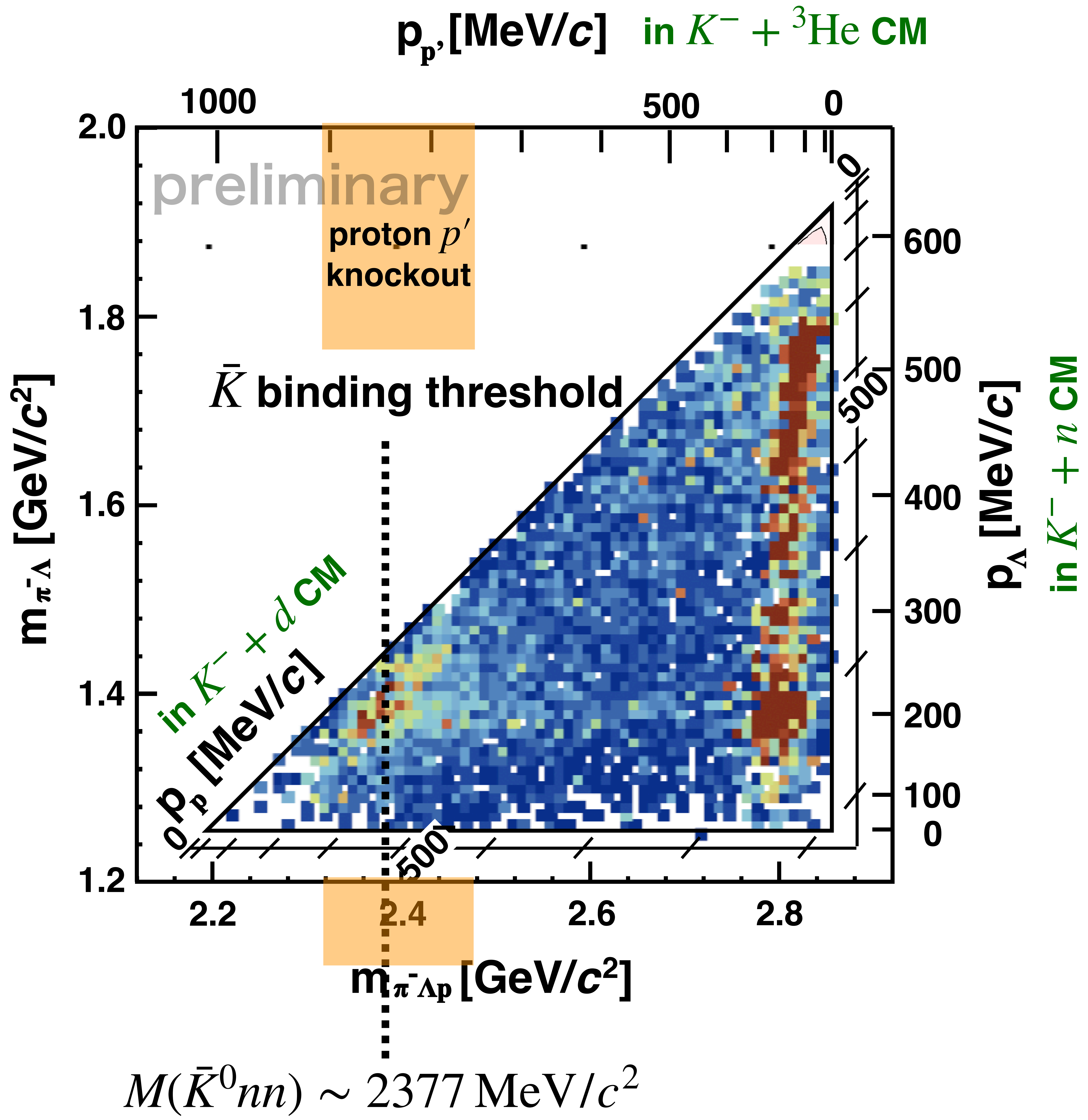
… T. Yamaga's talk



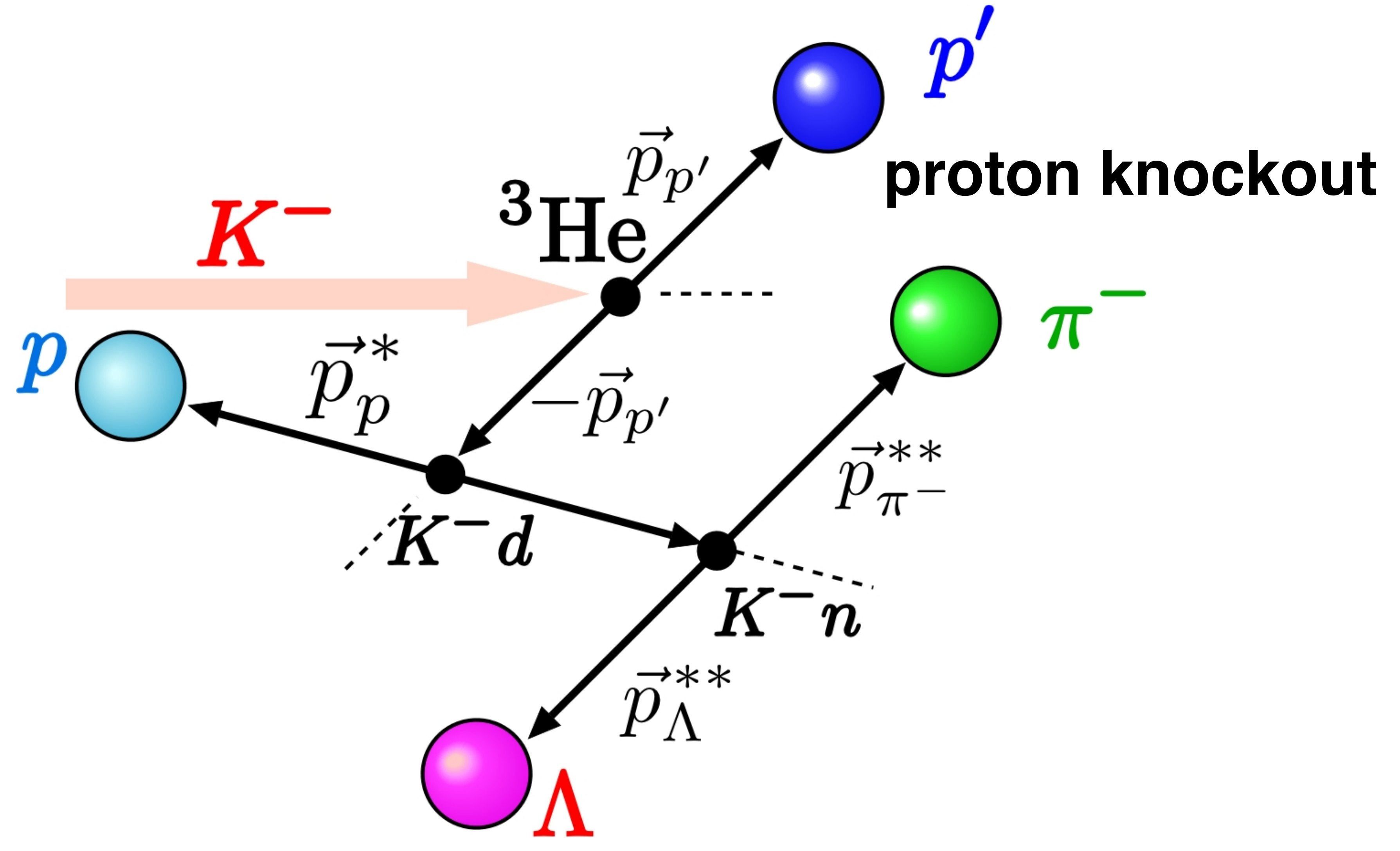
normalized by 4-body phase space



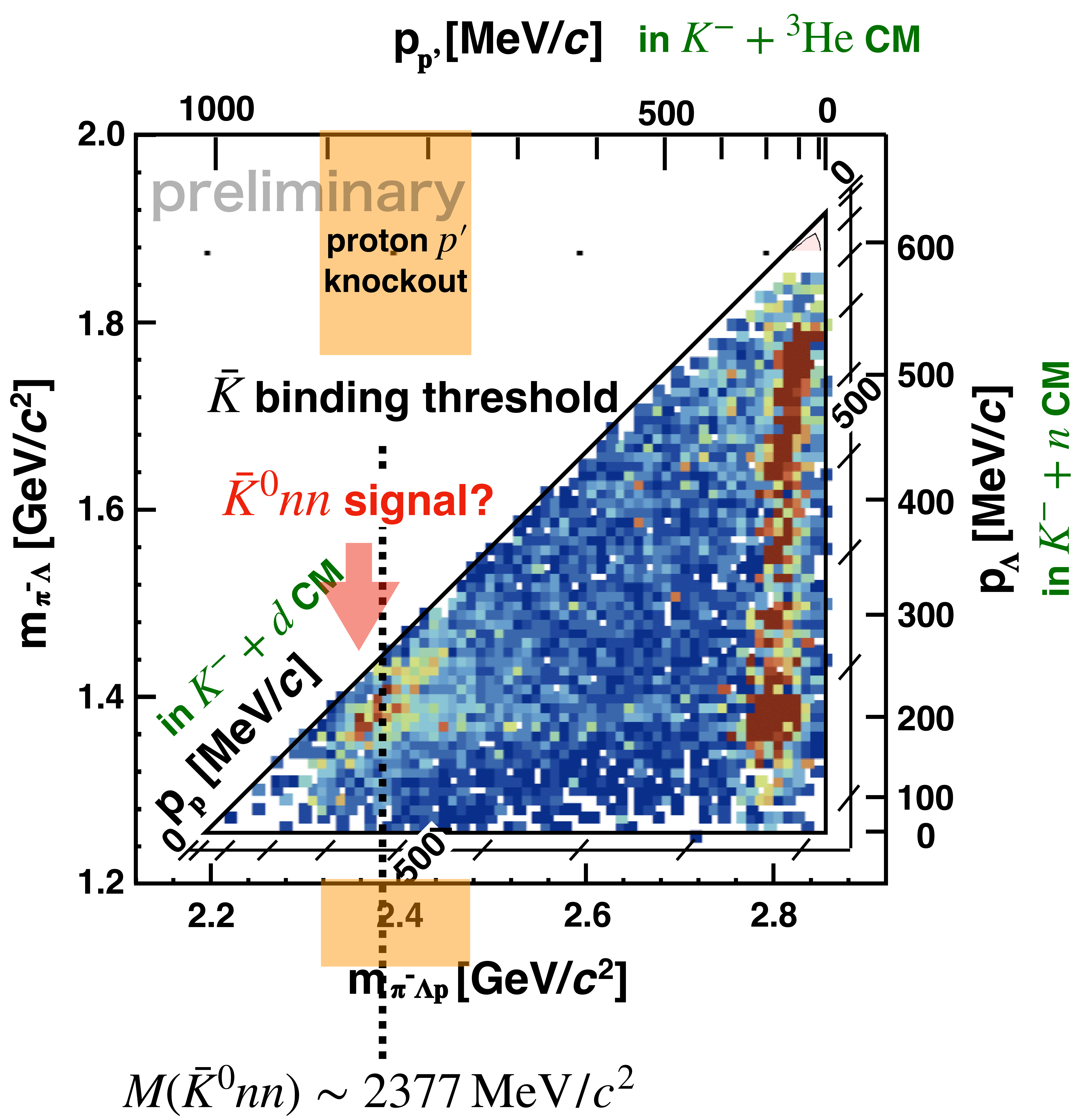

p_p,[MeV/c] in $K^- + {}^3$He CM
1000
500
0
2.0
1.8
1.6
1.4
1.2
preliminary
$\bar{K}$ binding threshold
$m_{\pi^-\Lambda}$ [GeV/c^2]
in $K^- + d$ CM
p_p [MeV/c]
0
500
600
500
400
300
200
100
0
p_Λ [MeV/c]
in $K^- + n$ CM
2.2
2.4
2.6
2.8
$m_{\pi^-\Lambda p}$ [GeV/c^2]
$M(\bar{K}^0 nn) \sim 2377$ MeV/c^2

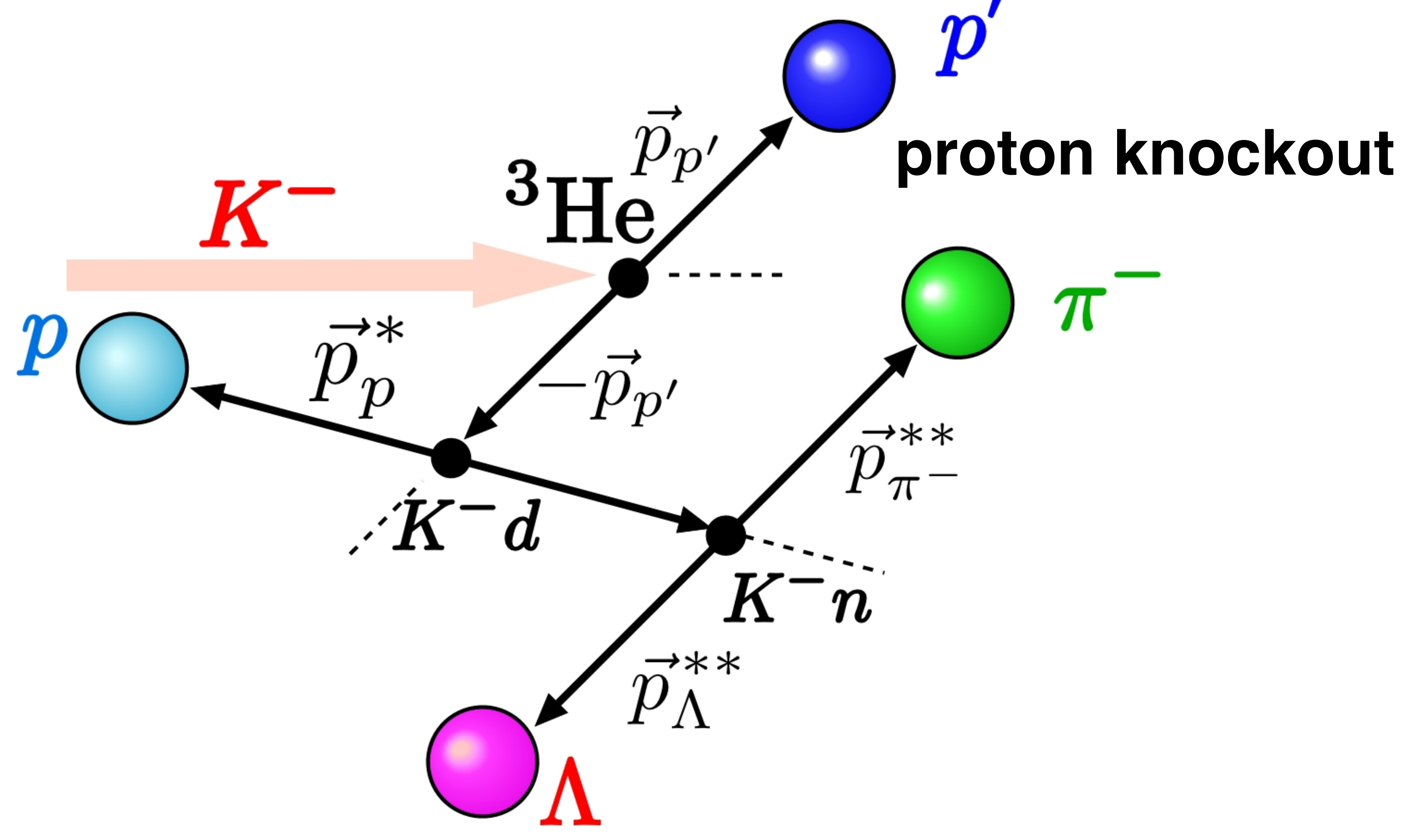


p_p' [MeV/c] in K⁻ + ³He CM
1000
500
0
2.0
1.8
1.6
1.4
1.2
preliminary
proton p′ knockout
K̄ binding threshold
m_π⁻Λ [GeV/c²]
in K⁻ + d CM
p_p [MeV/c]
p_Λ [MeV/c] in K⁻ + n CM
600
500
400
300
200
100
0
2.2
2.4
2.6
2.8
m_π⁻Λp [GeV/c²]
M(K̄⁰nn) ~ 2377 MeV/c²

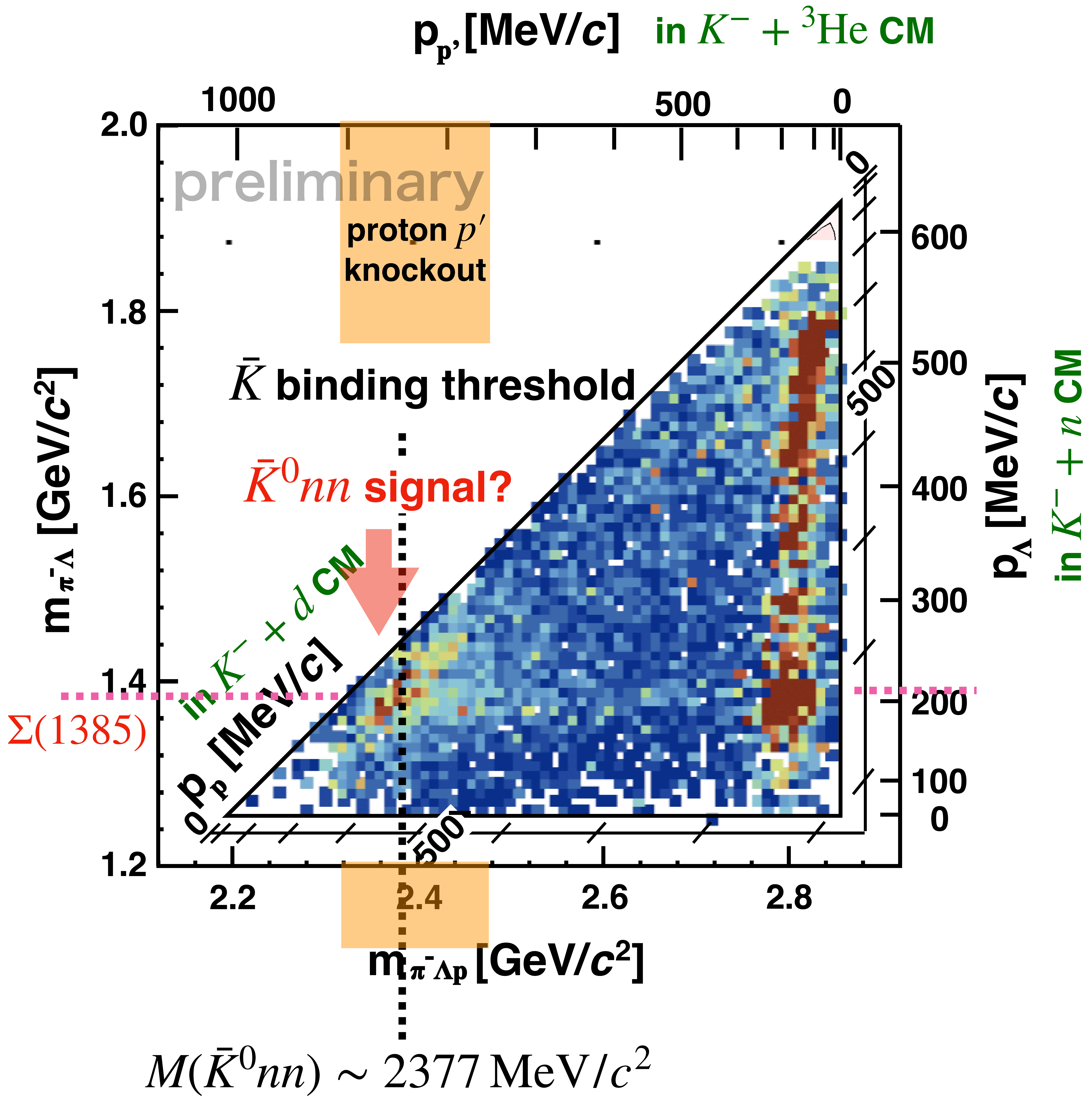


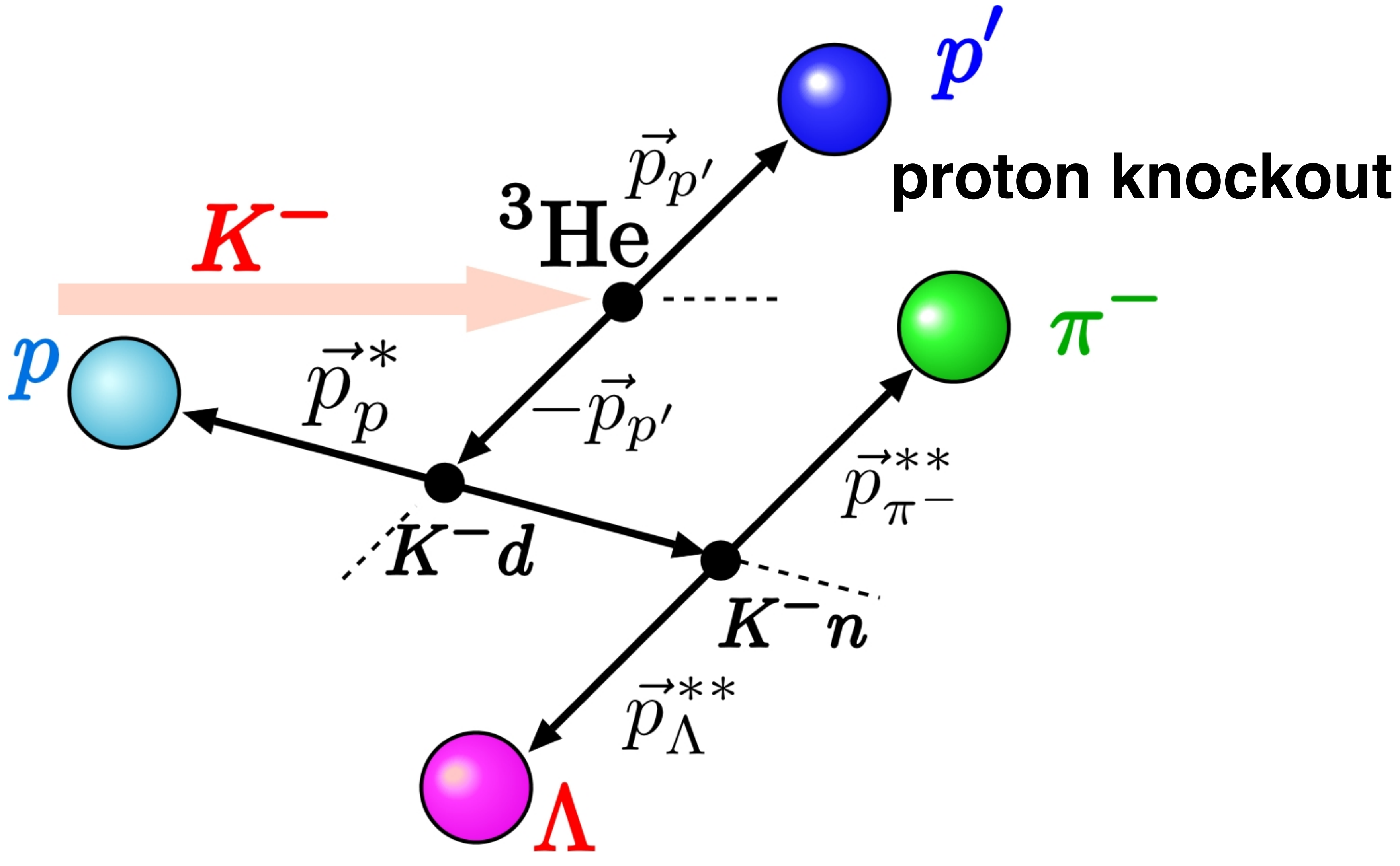
K⁻
³He
p′
proton knockout
π⁻
p
K⁻d
K⁻n
Λ





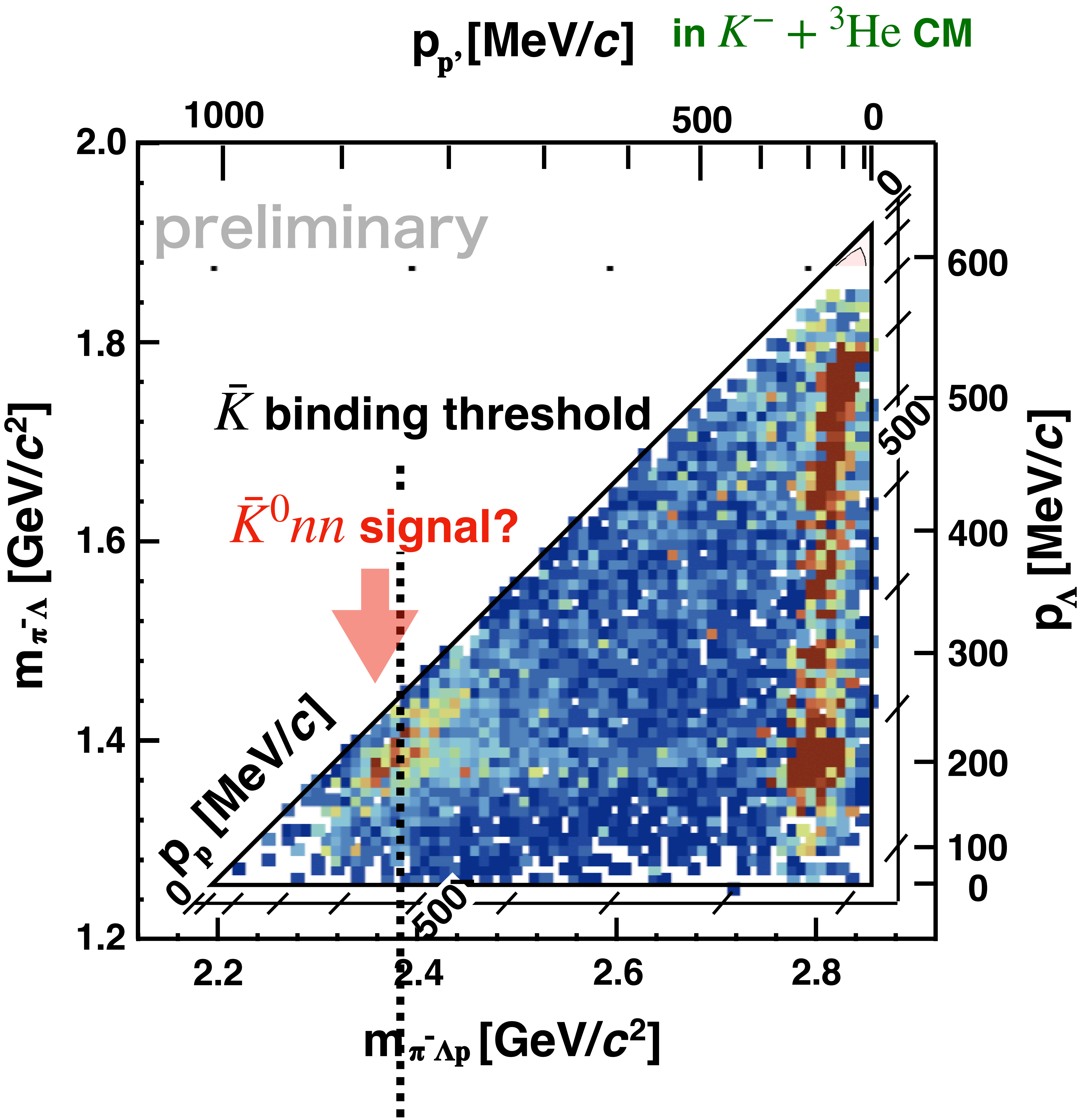
$\bar{K}^0nn$ **signal-like event concentration below $\bar{K}$-bound thereshold is observed again, although the statistics is not sufficient.**





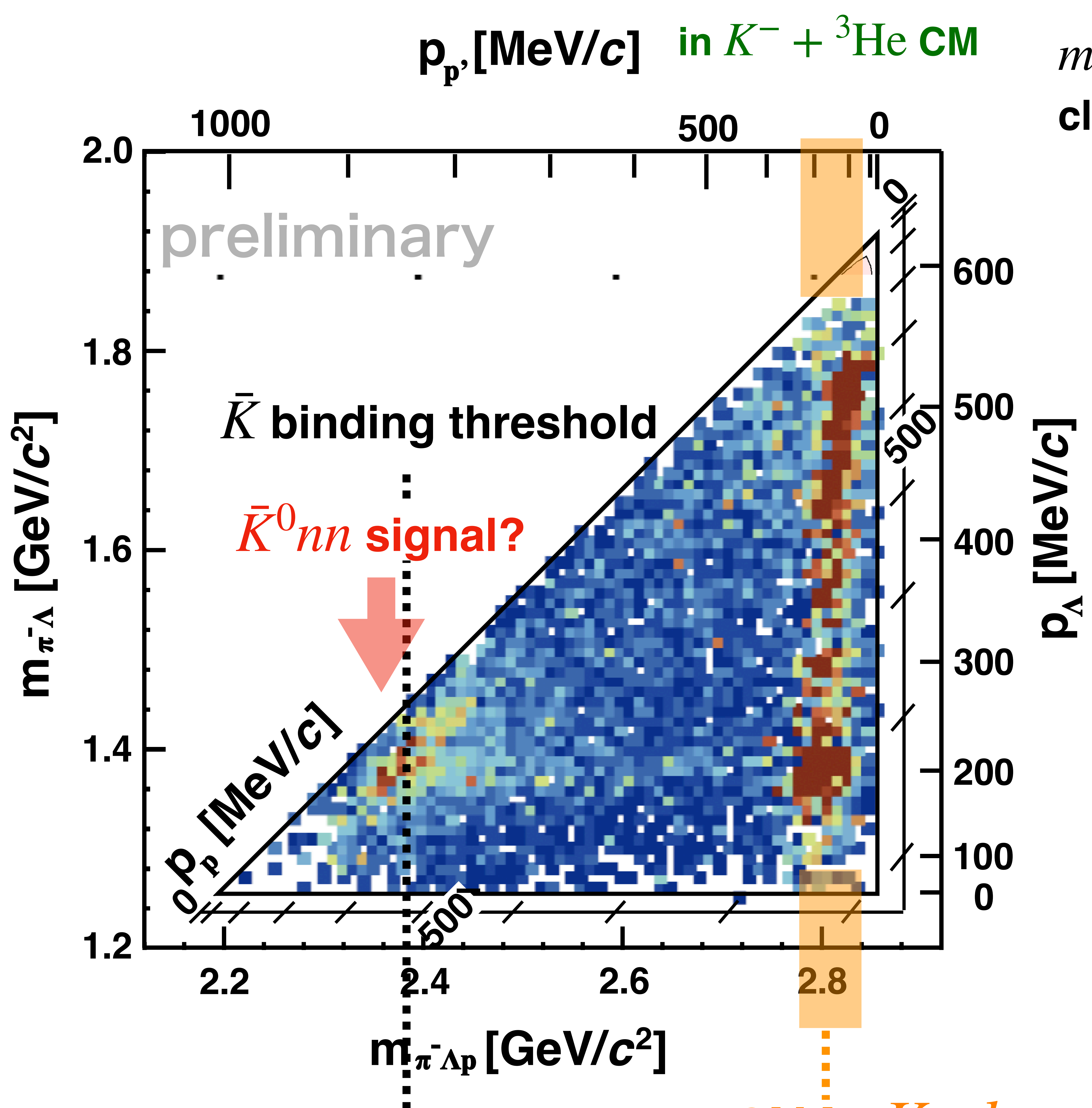
$\bar{K}^0nn$ signal-like event concentration below $\bar{K}$-bound thereshold is observed again, although the statistics is not sufficient.

$\Sigma(1385)$ contribution is not negligible compared to $(\Lambda p) + n$ final state.

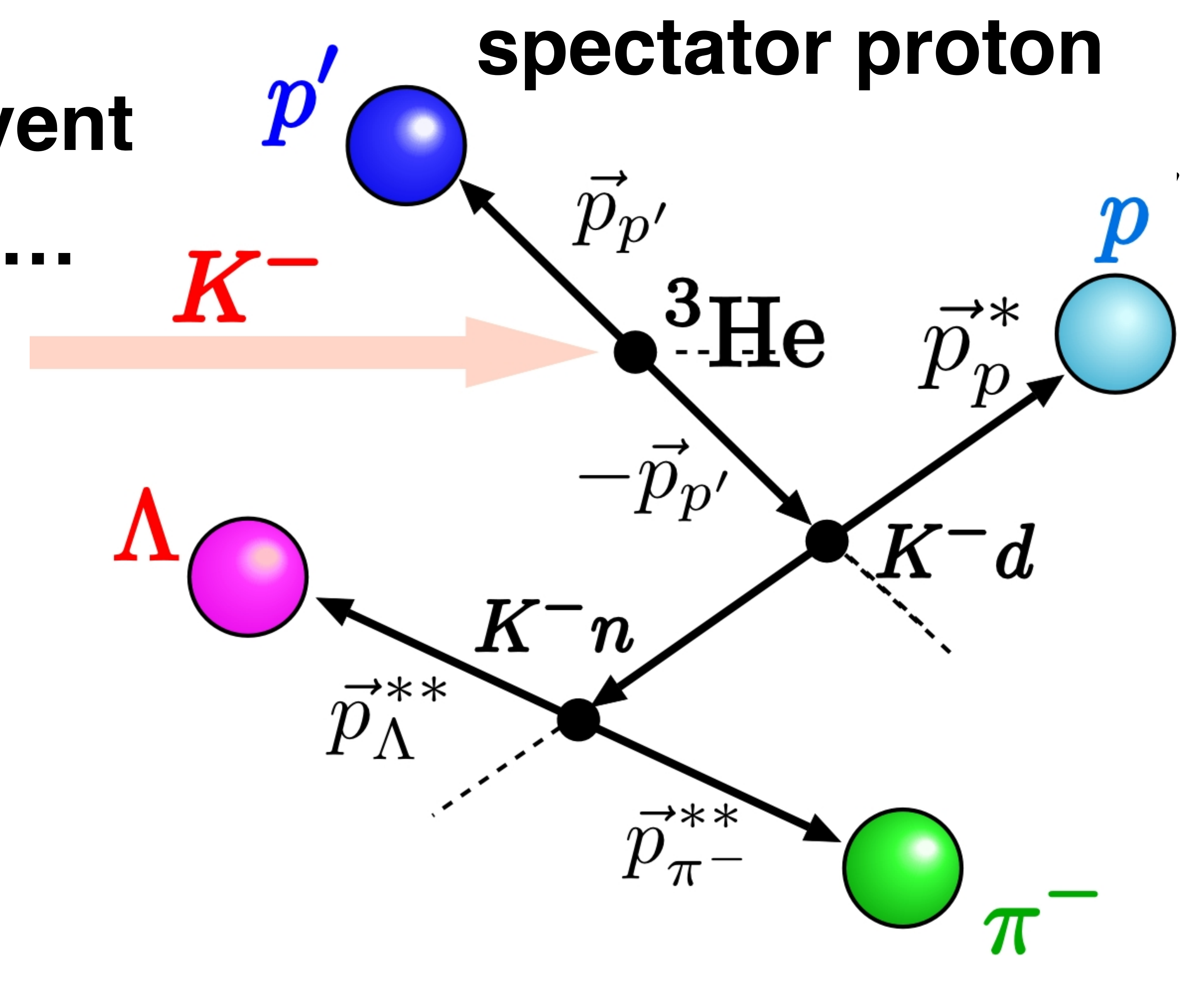


$M(\bar{K}^0 nn) \sim 2377\,\mathrm{MeV}/c^2$

p''



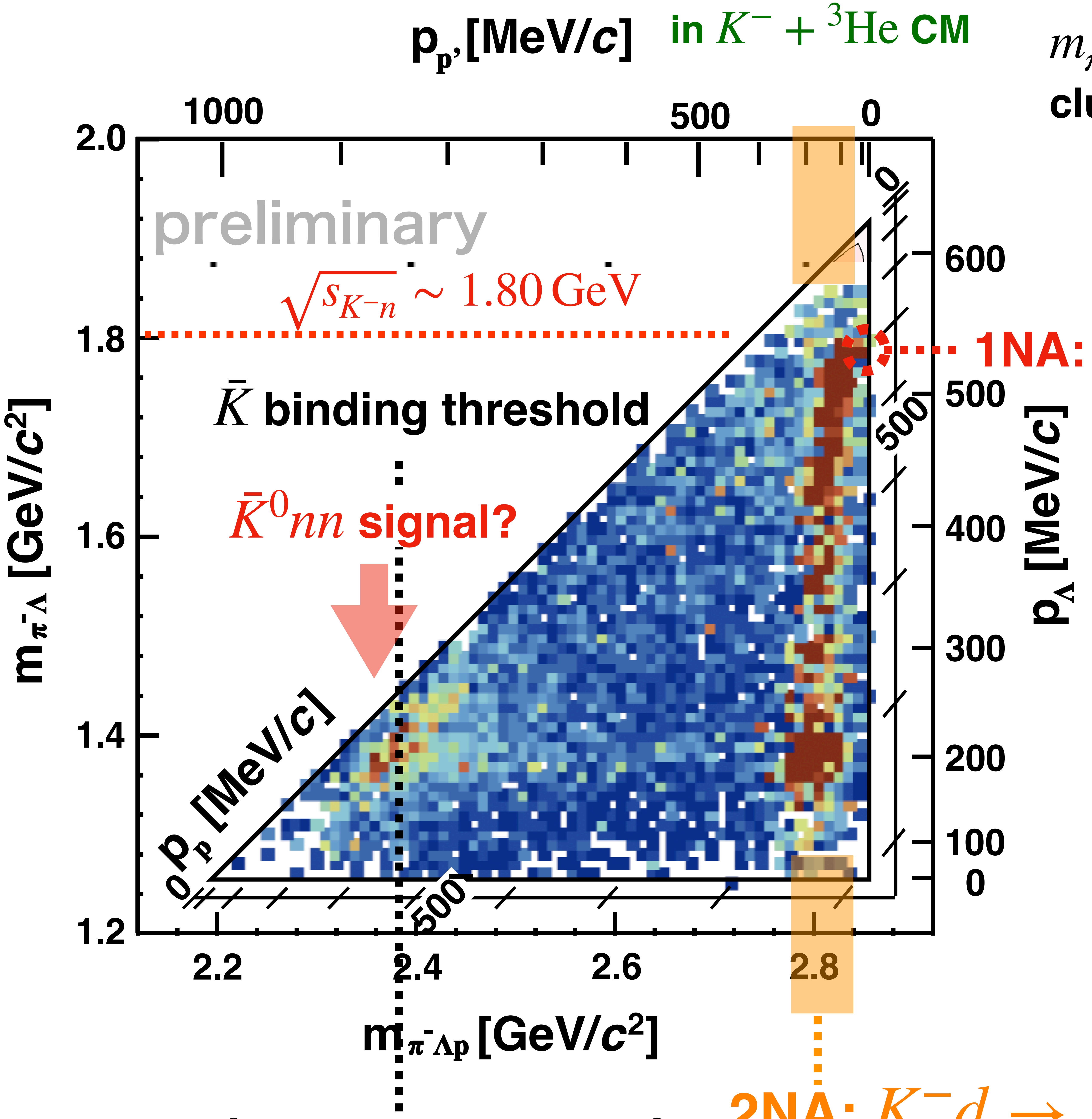
$m_{\pi^-\Lambda p} \sim 2.83\,\mathrm{GeV}$ event cluster is most likely …



$M(\bar{K}^0nn) \sim 2377\,\mathrm{MeV}/c^2$

2NA: $K^-d \rightarrow \Lambda\pi^-p$ region $\sqrt{s_{K^-d}} \sim 2.83\,\mathrm{GeV}$

with a spectator proton



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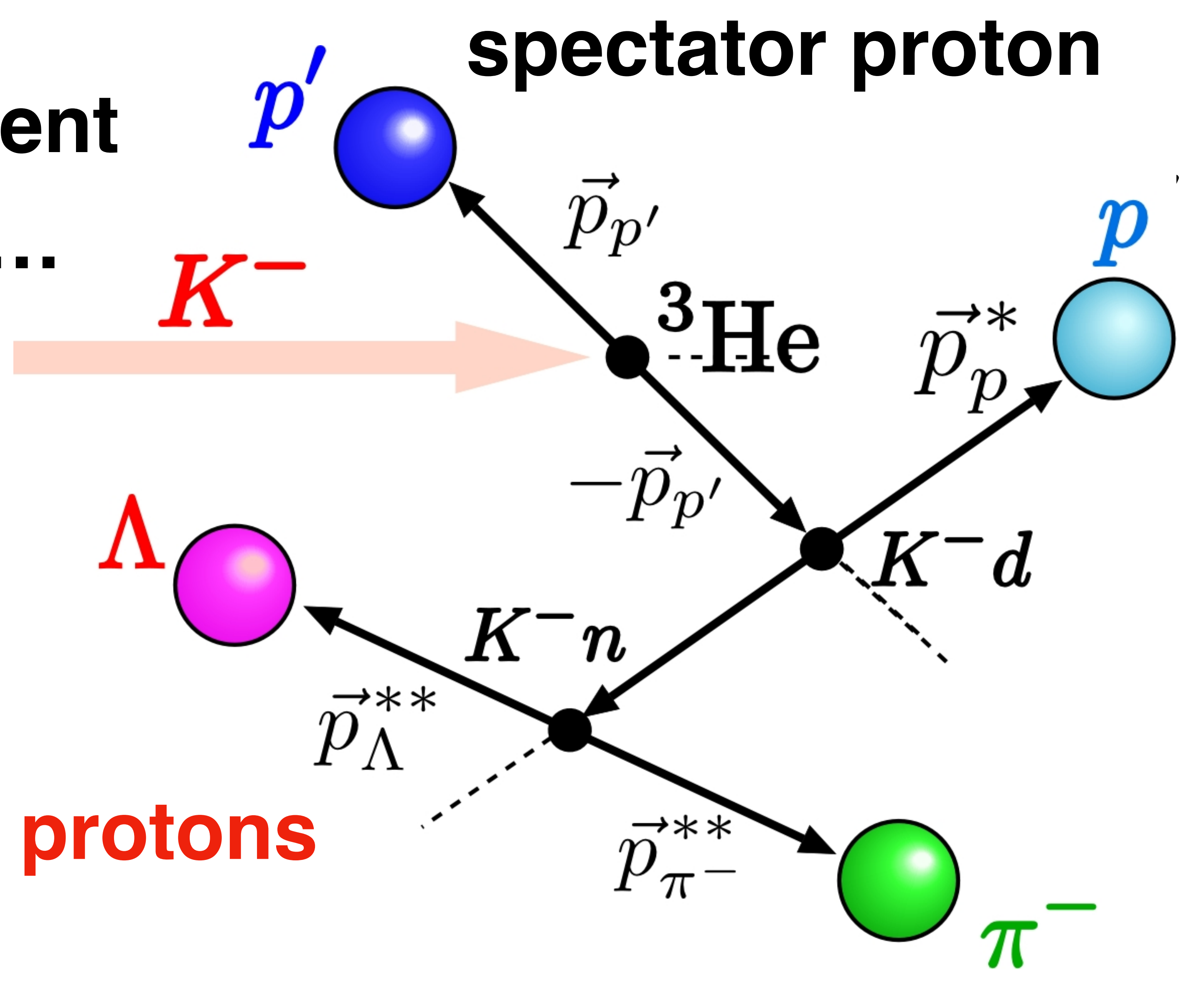


1NA: $K^-n \rightarrow \Lambda\pi^-$

with two spectator protons

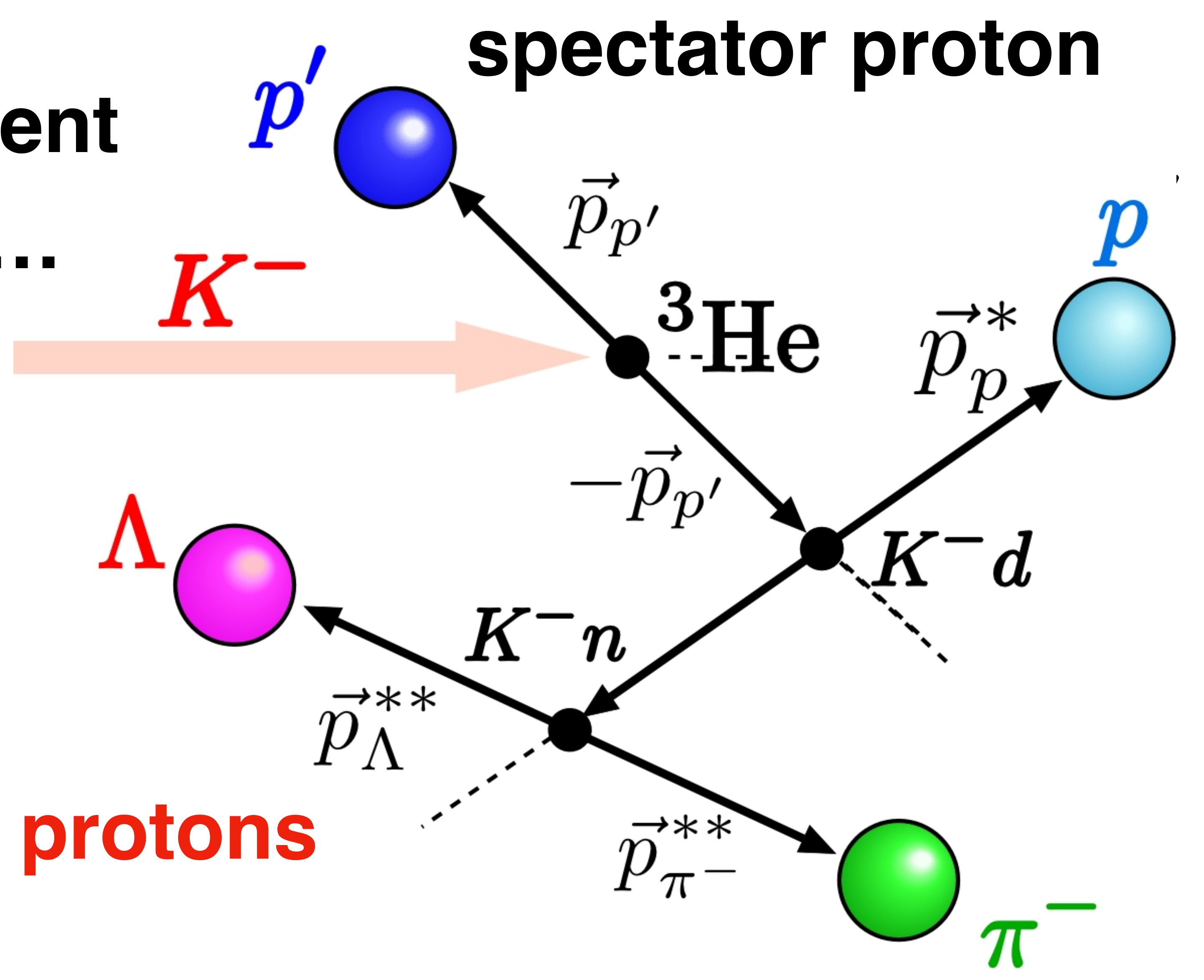
$M(\bar{K}^0 nn) \sim 2377\,\mathrm{MeV}/c^2$

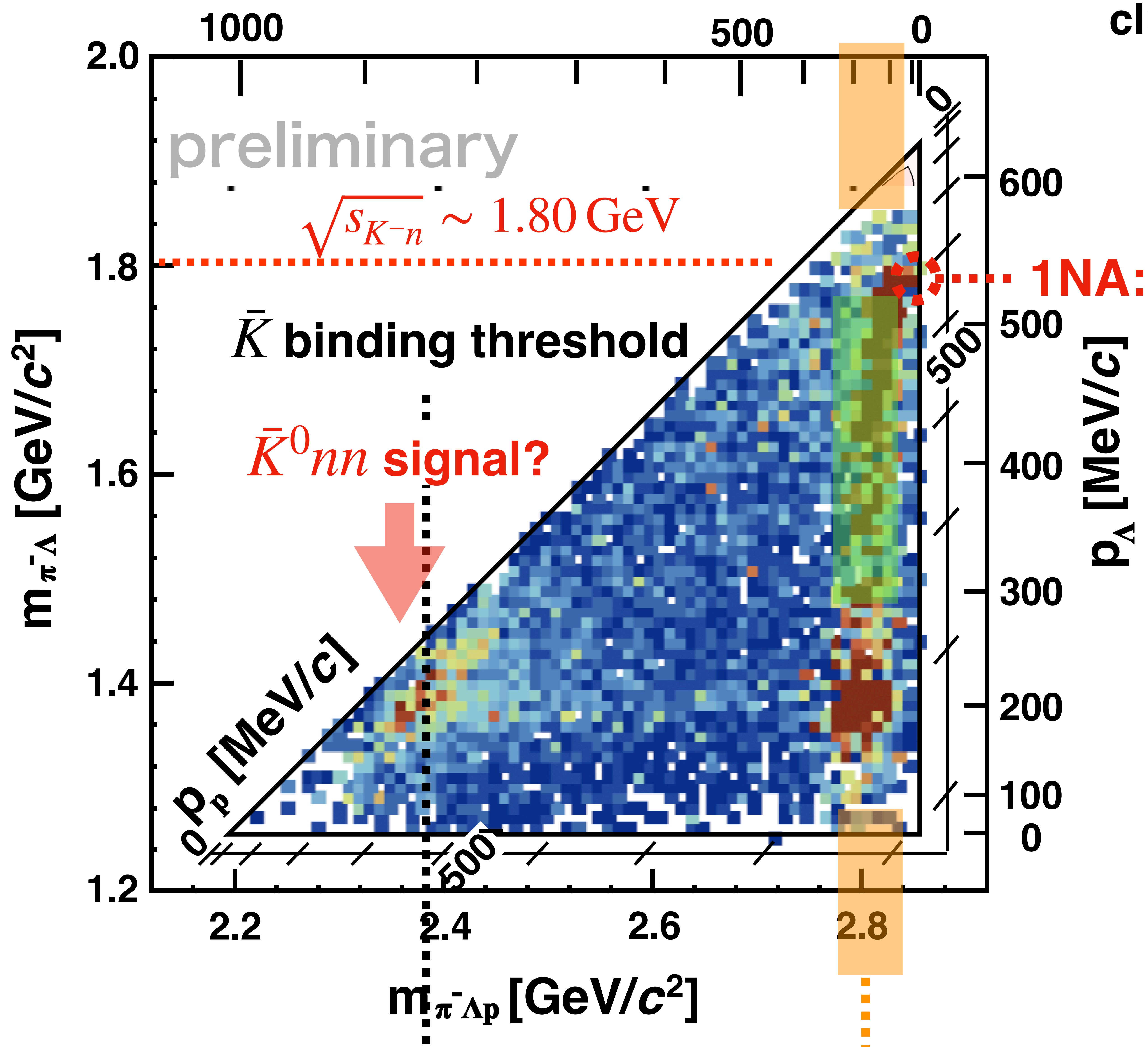
2NA: $K^-d \rightarrow \Lambda\pi^- p$ region

with a spectator proton

$\sqrt{s_{K^-d}} \sim 2.83\,\mathrm{GeV}$

$m_{\pi^-\Lambda p} \sim 2.83\,\mathrm{GeV}$ **event cluster is most likely …**





1NA: $K^-n \to \Lambda\pi^-$

with two spectator protons

2 step 2NA: $K^-p \to K^{-'}p''$ **kaon knockout p in d**

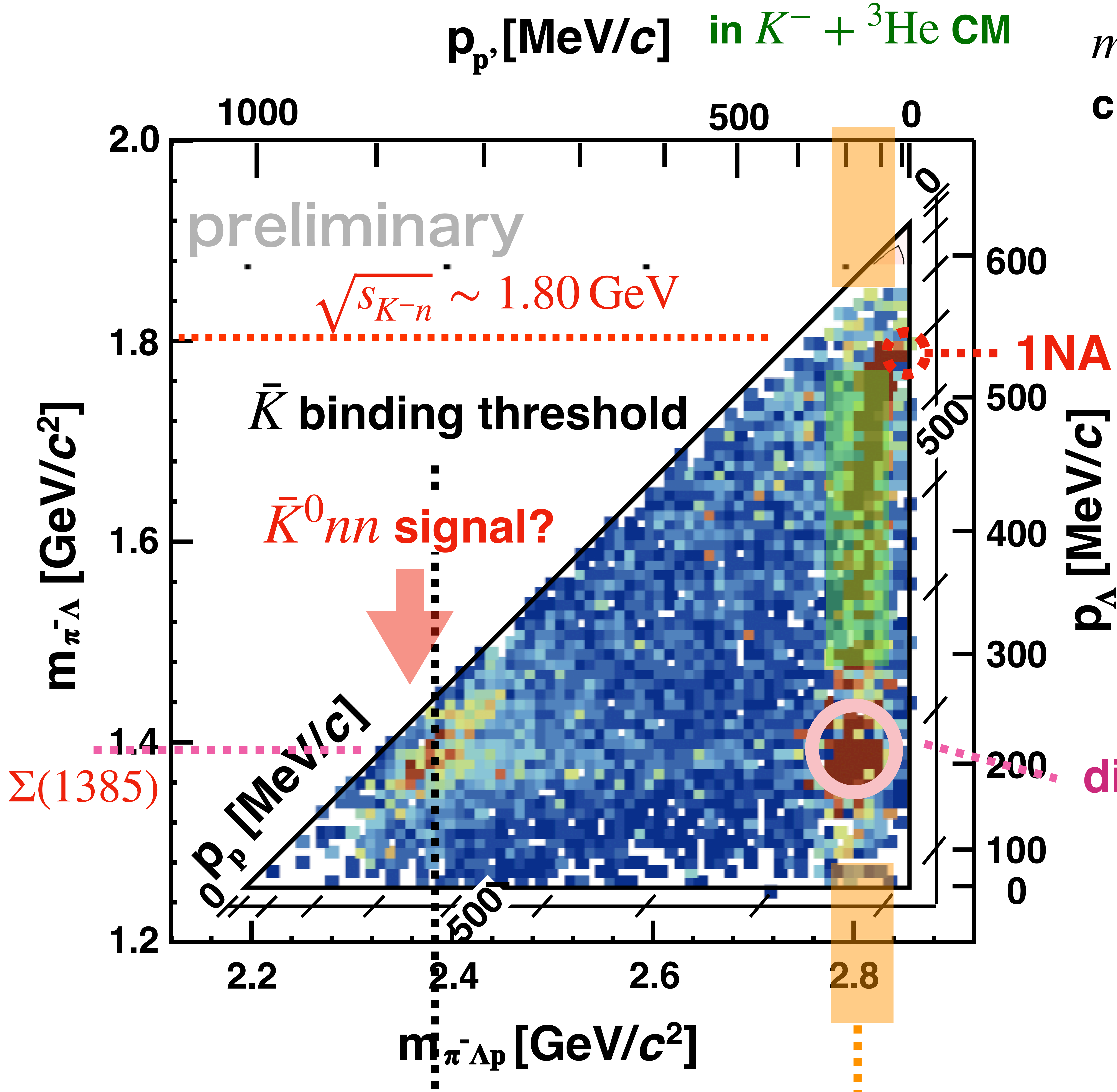
+ $K^{-'}n \to \Lambda\pi^-$ **QF-K react with n in d**

p'' **momentum in** K^-d **CM** $\approx 400 \sim 750\,\mathrm{MeV}/c$

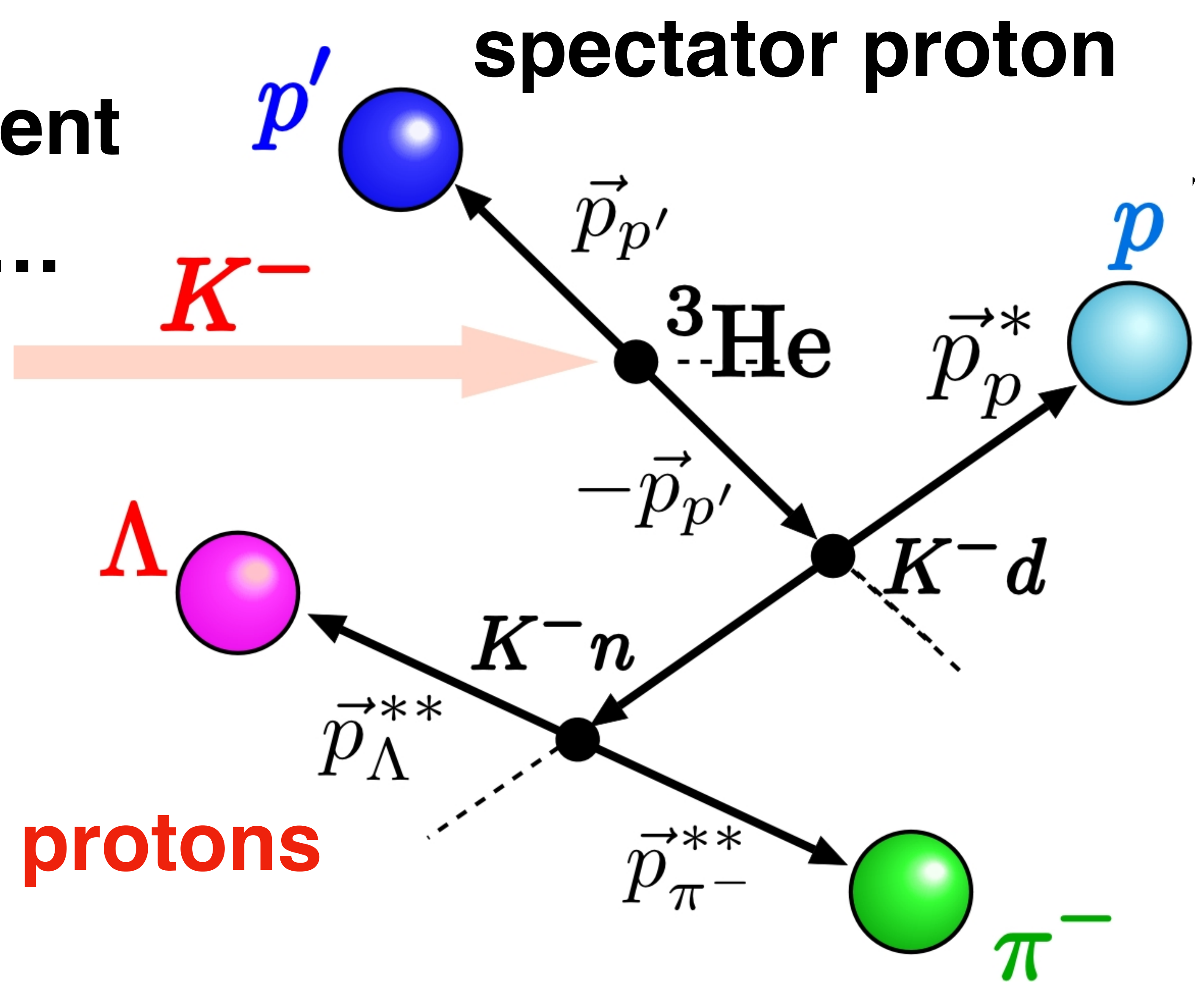
$M(\bar{K}^0 nn) \sim 2377\,\mathrm{MeV}/c^2$

2NA: $K^-d \to \Lambda\pi^-p$ **region** $\sqrt{s_{K^-d}} \sim 2.83\,\mathrm{GeV}$

with a spectator proton



$m_{\pi^-\Lambda p} \sim 2.83\,\mathrm{GeV}$ **event cluster is most likely …**



1NA: $K^-n \to \Lambda\pi^-$
with two spectator protons

2 step 2NA: $K^-p \to K^{-'}p''$ kaon knockout p in d
+ $K^{-'}n \to \Lambda\pi^-$ QF-K react with n in d
p'' **momentum in K^-d CM** $\approx 400 \sim 750\,\mathrm{MeV}/c$

direct 2NA: $K^-d \to \Sigma^-(1385)\,p''$
d **: short-range pn-pair … with a spectator proton p'**
$\leftarrow\Sigma^*\ p''\rightarrow$ **@ 770 MeV/c**

$M(\bar{K}^0nn) \sim 2377\,\mathrm{MeV}/c^2$

2NA: $K^-d \to \Lambda\pi^-p$ region $\sqrt{s_{K^-d}} \sim 2.83\,\mathrm{GeV}$
with a spectator proton

Comments on π⁻Λpp reaction

Hint of $\bar{K}^0 nn$ (isospin partner of $K^- pp$) is given

statistically insufficient to conclude, though

The 2NA (two-nucleon absorption) reaction induced by K mesons is of interest regarding short-range pn-pair correlation in nuclei.

strong $m_{\pi^-\Lambda p} \approx \sqrt{s_{K^-d}} \sim 2.83\,\mathrm{GeV}$ is seen, but not in $m_{\pi^+\Lambda n} \approx \sqrt{s_{K^-pp}}$ nor in $m_{\pi^\pm\Sigma^\mp n}$, which may suggest much weaker short-range pp-pair correlation in $^3\mathrm{He}$ nuclei

what we are working on … II

Signal of $\bar{K}NNN$

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

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

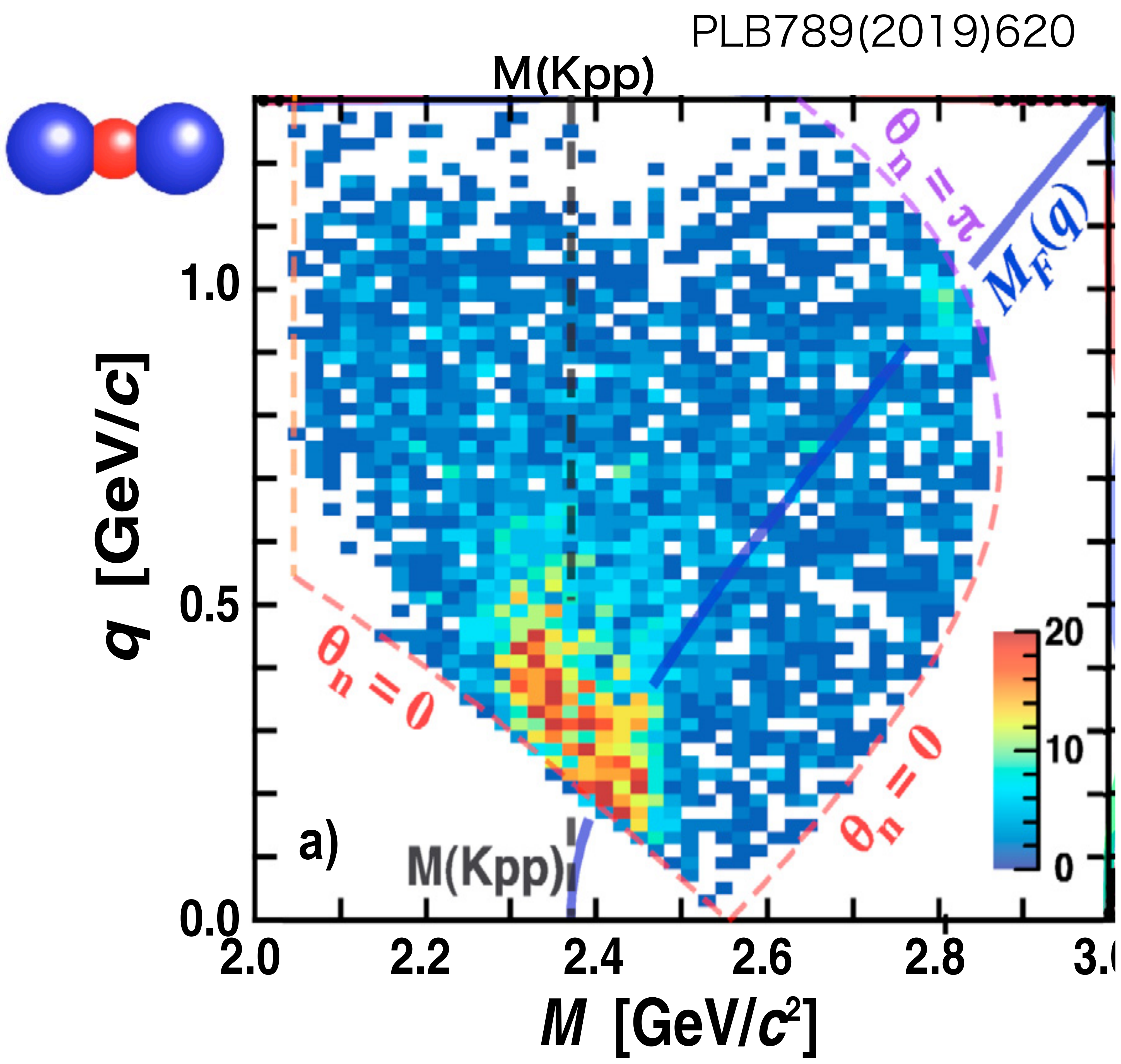
➡

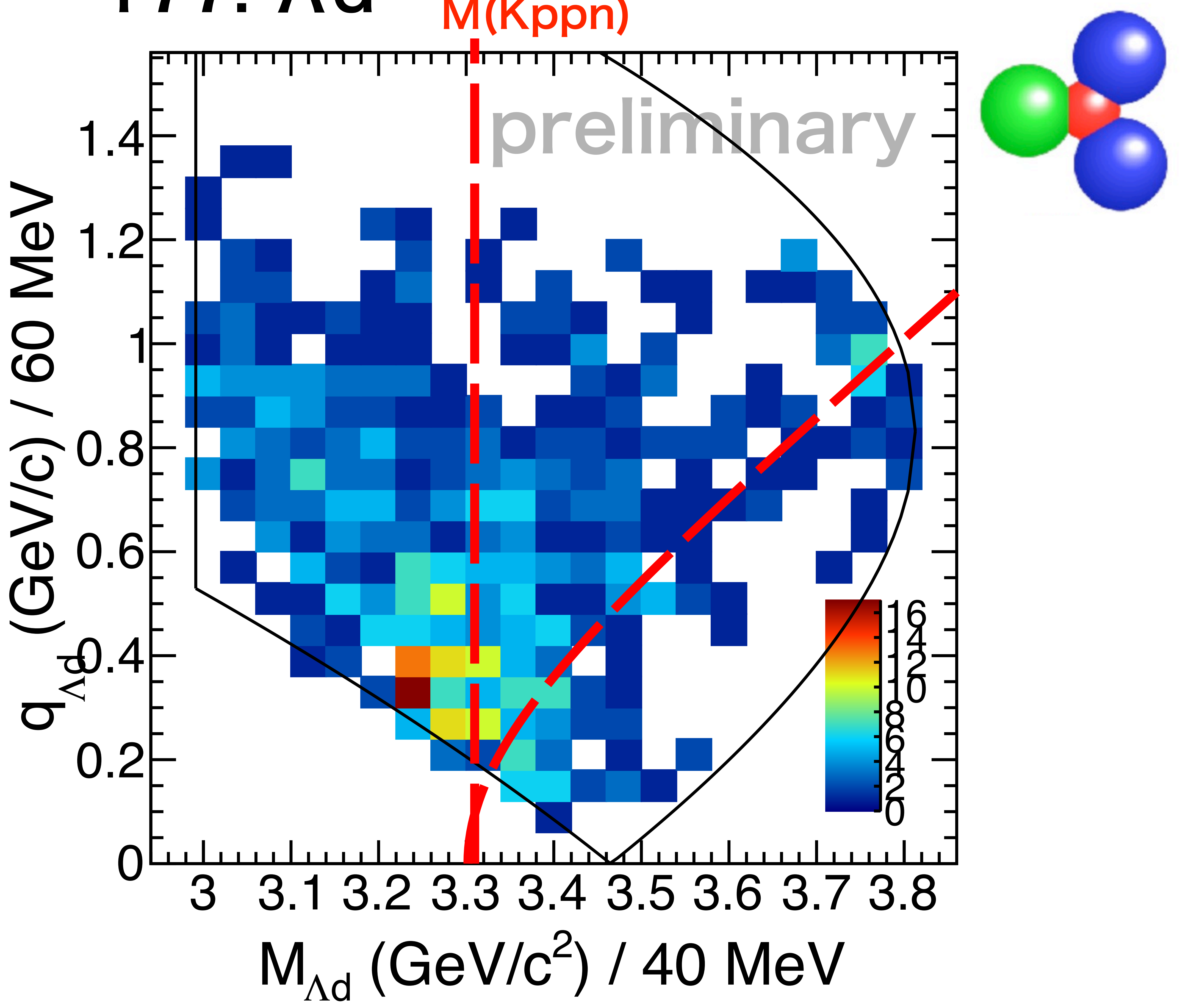
$K^- + {}^4He \rightarrow (K^- + ppn) + n$

$(K^- + ppn) \rightarrow \Lambda + d$

… T. Hashimoto

E15: Λp Preliminary Λd result





- Two disributions are quite similar
- structure below the threshold, QF-K, and broad background

Summary of present status

- $\bar{K}NN,\ I_3 = +\dfrac{1}{2}$ **identified in** $\bar{K}NN \to \Lambda p$ **analysis**

  Phys. Lett. B789, 620-625 (2019)

  Phys. Rev. C102, 044002 (2020)

- $\bar{K}NN \to \pi Y p$ **decay dominance** $Br_{\pi Y p} > 10 \times Br_{\Lambda p}$

  … T. Yamaga's talk

- $\bar{K}NN,\ I_3 = -\dfrac{1}{2}$ **hint in** $\bar{K}NN \to \pi^- \Lambda p$ **spectrum**

- $\bar{K}NNN,\ I = 0$ **identified in** $\bar{K}NNN \to \Lambda d$ **analysis**

  … T. Hashimoto's talk

- $\bar{K}$ **nuclear bound state becomes more solid**

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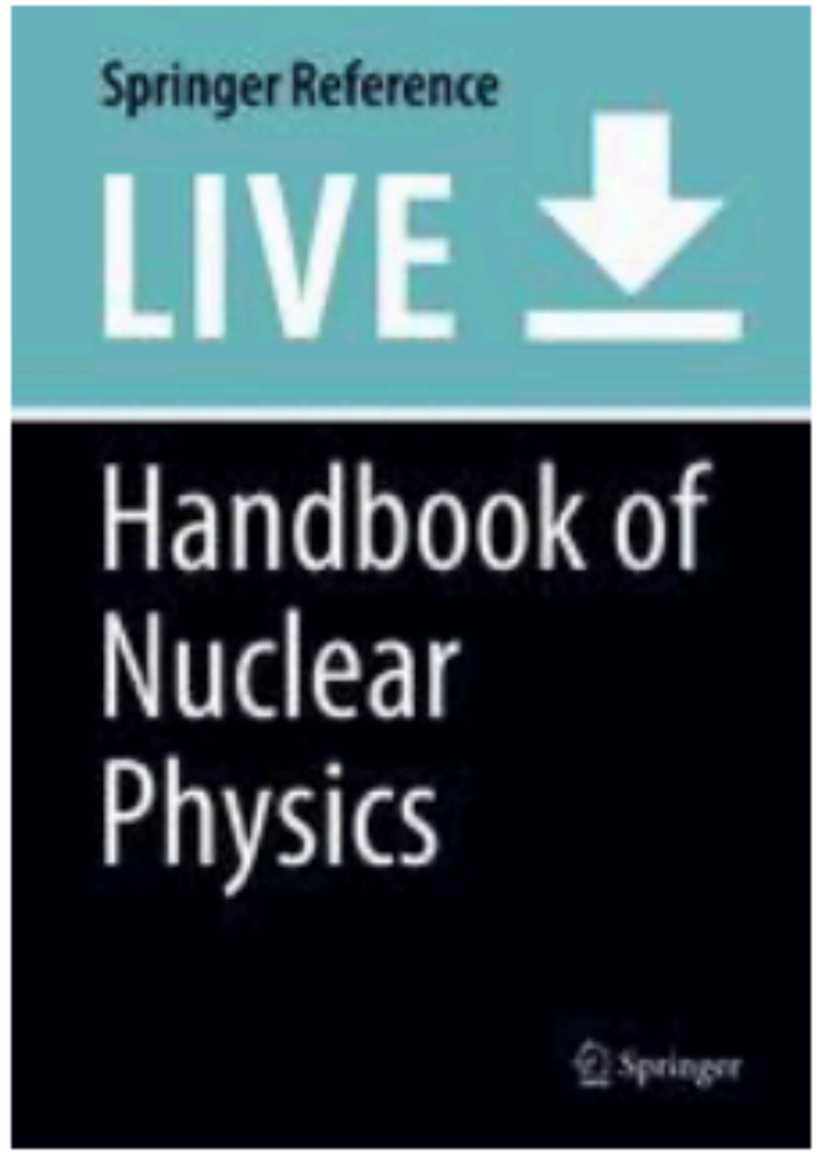


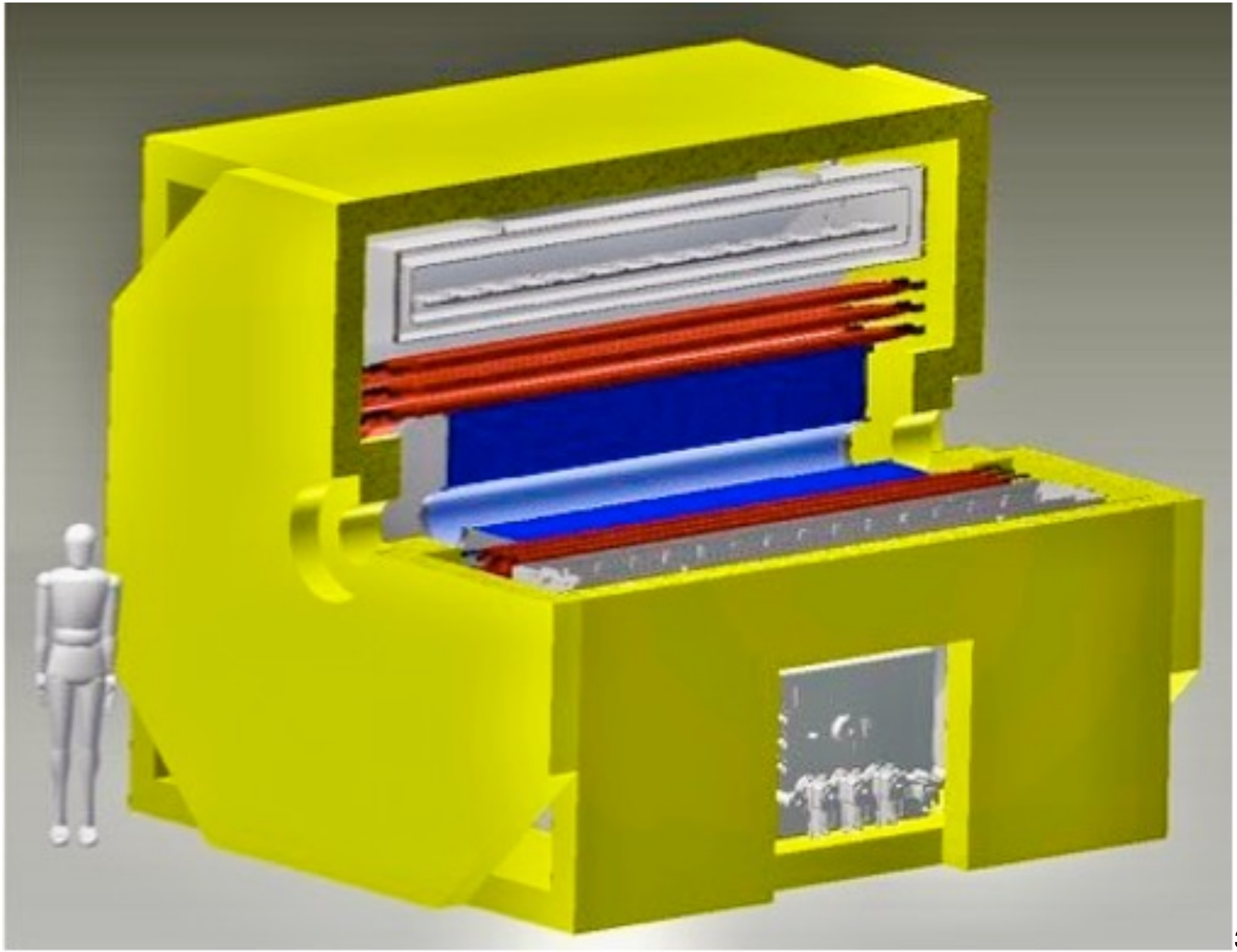
Kaonic Nuclei from the Experimental Viewpoint

Research on kaonic nuclear bound states is a completely new field. This nuclear system consists of

doi.org

Toward systematic study and J^P (spin-parity) study

the nature of



… *F. Sakuma*

Toward systematic study and J^P (spin-parity) study

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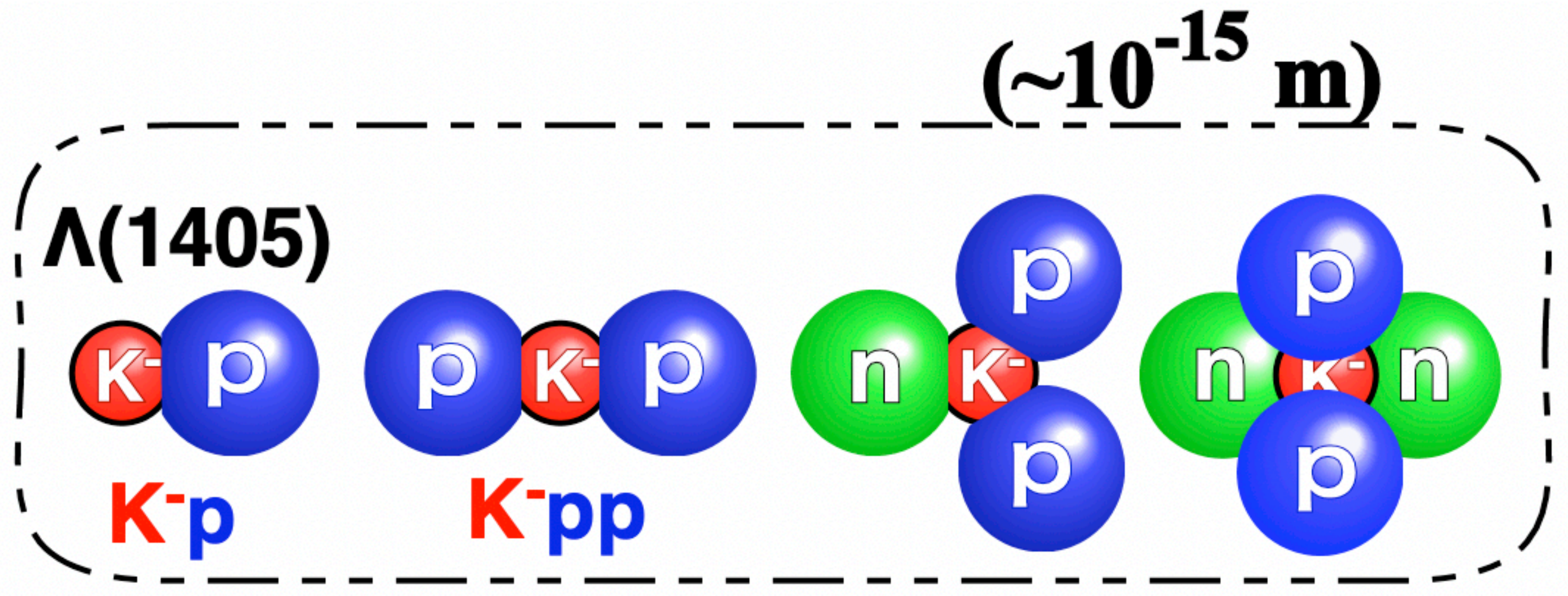
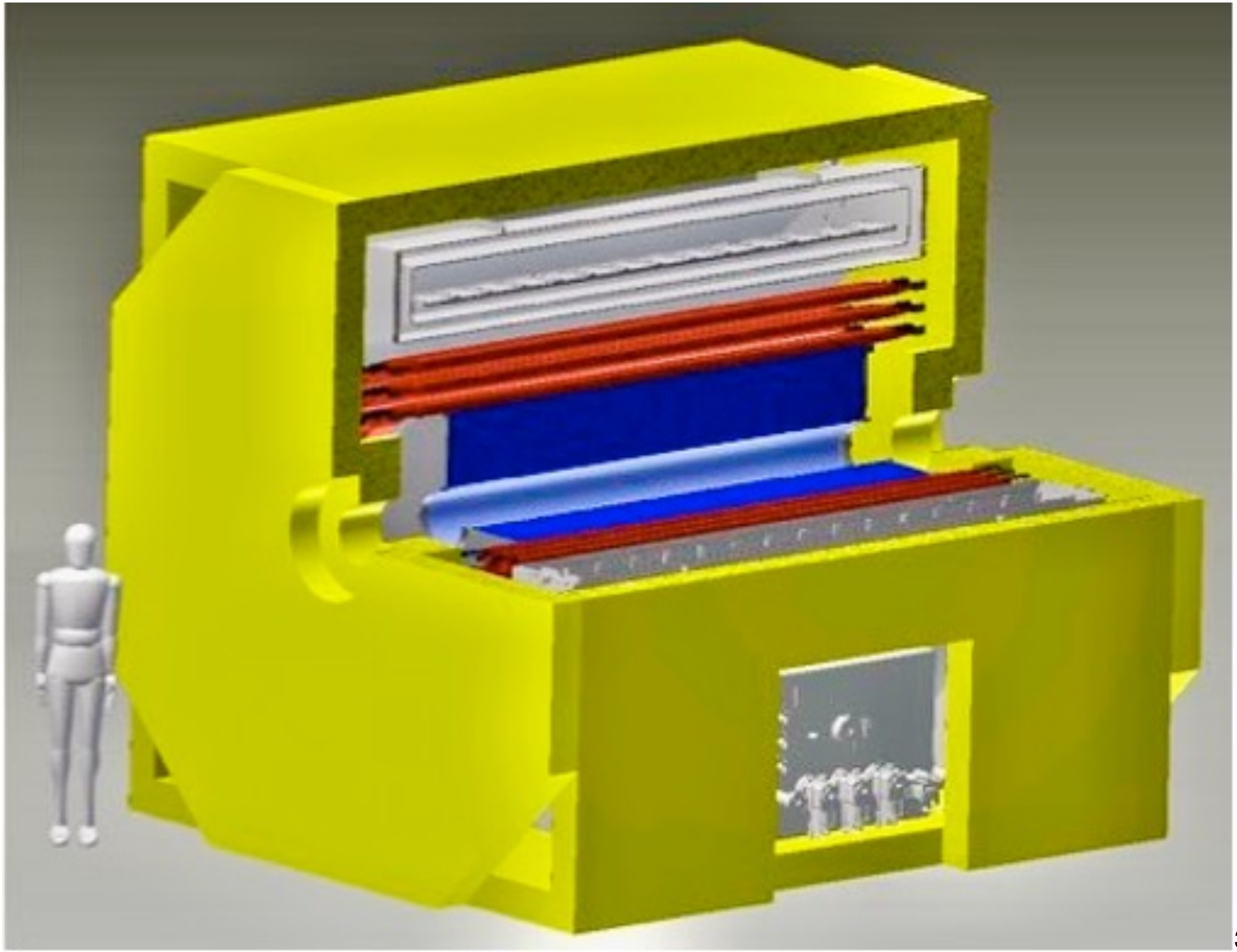




… F. Sakuma

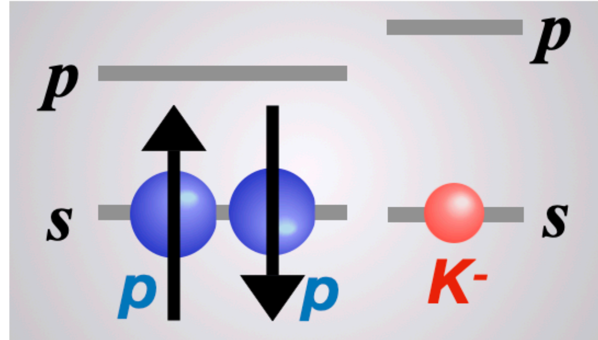
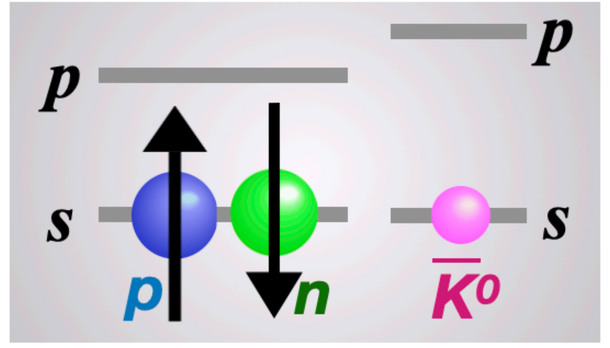
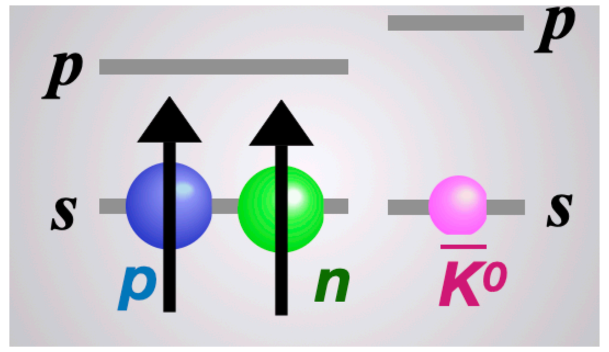
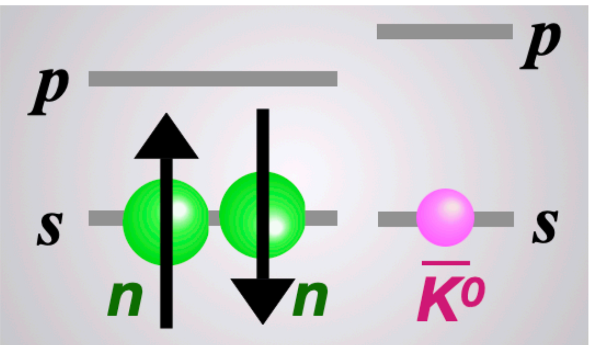
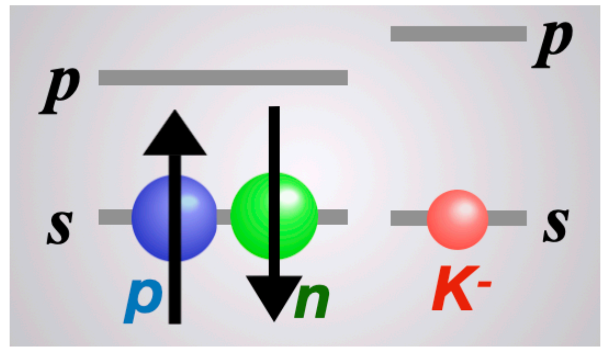
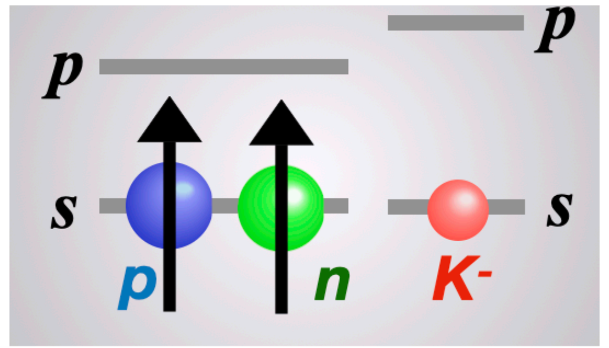
Possible I(J^P) ?

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

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 ($S_{NN} = 1$)

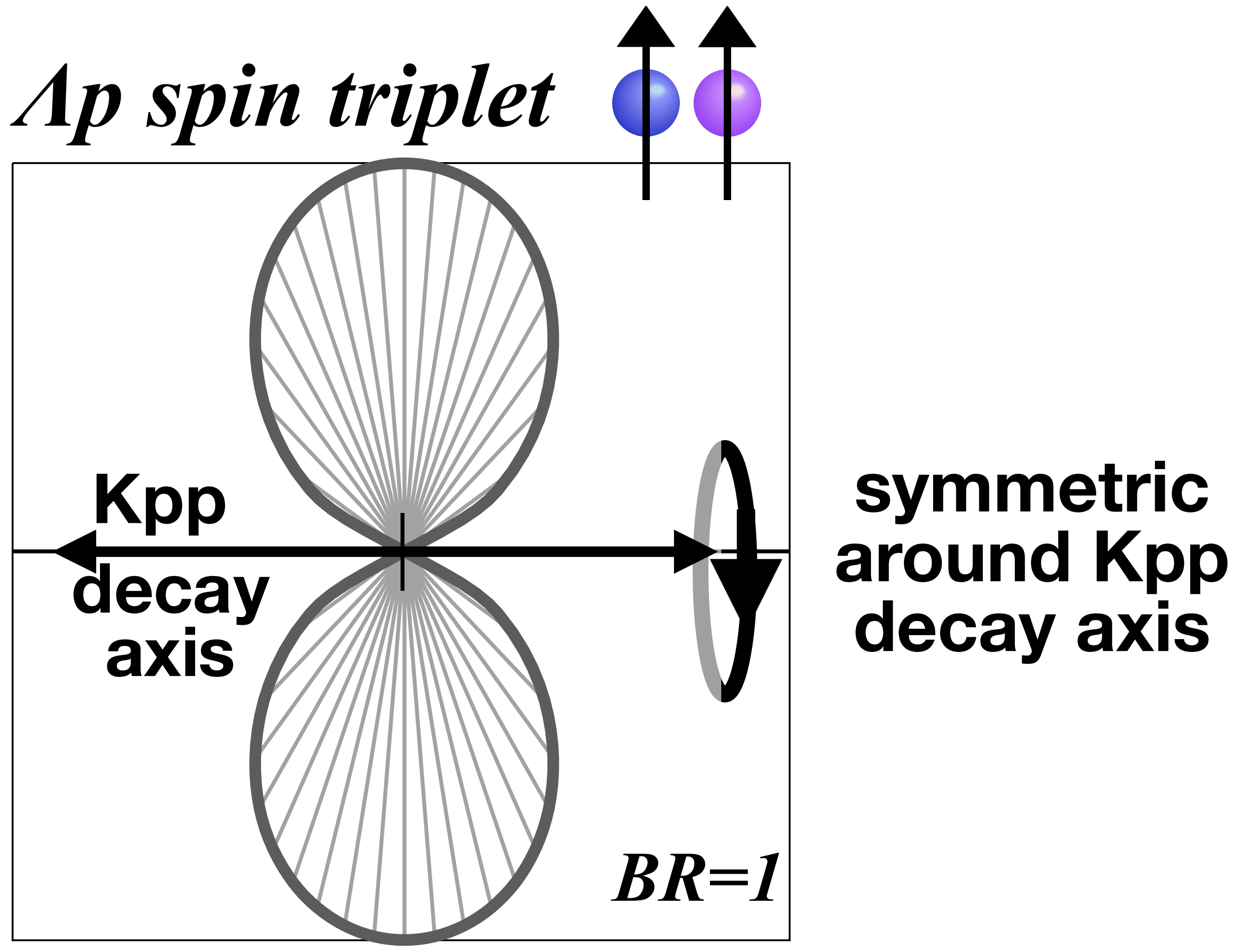
$I(\bar{K}NN)$ / $J^P(\bar{K}NN)$	(1/2) / (0$^-$)	(1/2) / (1$^-$)
NN symmetry	$I(NN) = 1,\ S(NN) = 0$	$I(NN) = 0,\ S(NN) = 1$
“K^-pp” $I_3(\bar{K}NN) = +\frac{1}{2}$	 +  $-\sqrt{\frac{1}{3}}\left(\sqrt{2}K^-pp + \bar{K}^0\frac{pn+np}{\sqrt{2}}\right)\otimes\left(\frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}\right)$	 $\bar{K}^0\frac{(pn-np)}{\sqrt{2}}\otimes\left(\uparrow\uparrow, \frac{\uparrow\downarrow + \downarrow\uparrow}{\sqrt{2}}, \downarrow\downarrow\right)$
“$\bar{K}^0nn$” $I_3(\bar{K}NN) = -\frac{1}{2}$	 +  $-\sqrt{\frac{1}{3}}\left(\sqrt{2}\bar{K}^0nn + K^-\frac{pn+np}{\sqrt{2}}\right)\otimes\left(\frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}\right)$	 $-K^-\frac{(pn-np)}{\sqrt{2}}\otimes\left(\uparrow\uparrow, \frac{\uparrow\downarrow + \downarrow\uparrow}{\sqrt{2}}, \downarrow\downarrow\right)$
$\bar{K}N$ 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

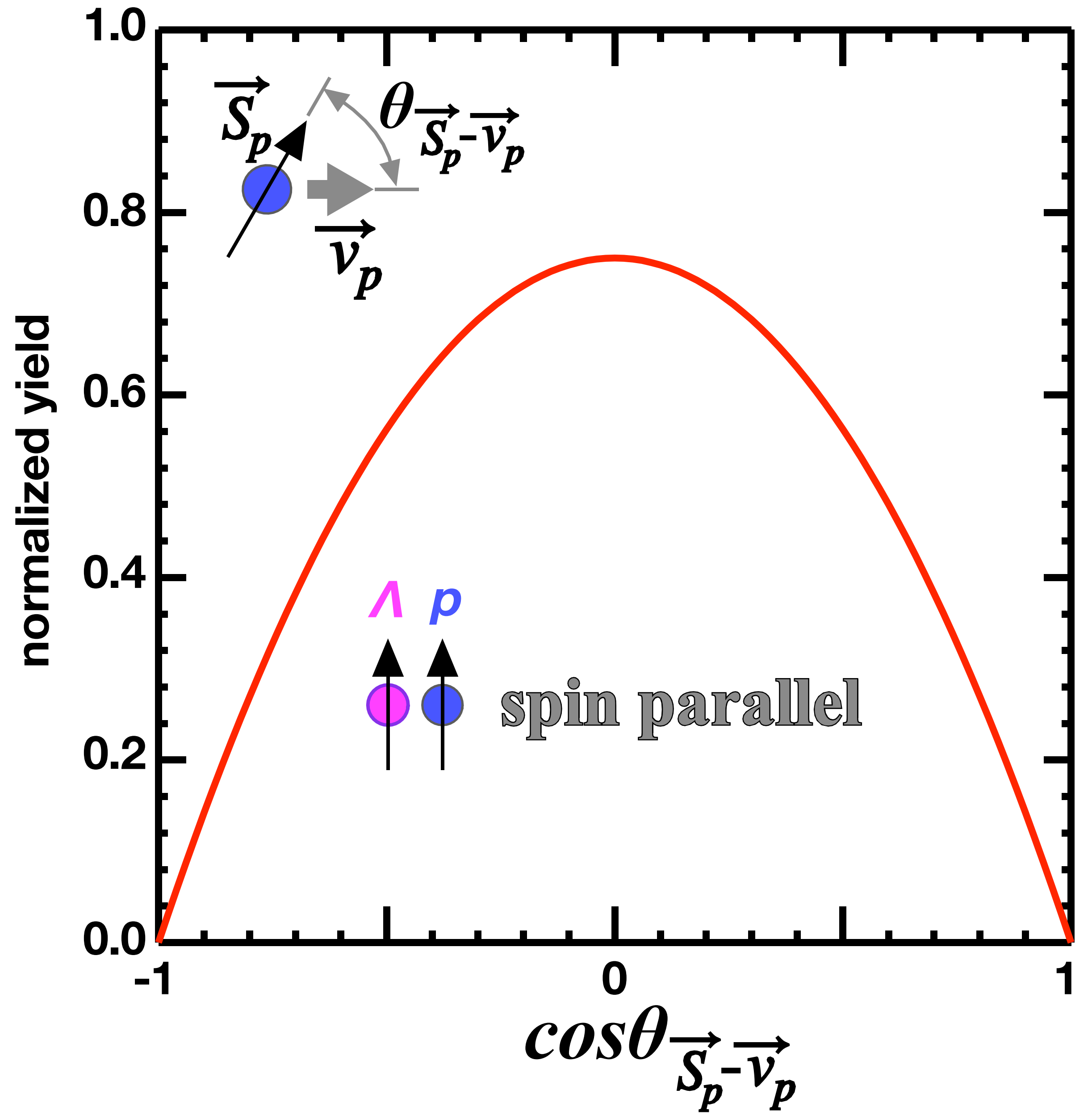
“K^-pp” $\to \Lambda p$ requires $I = 1/2$, presence of kaon requires negative parity, and the Λp dacay must be in P-wave due to the negative parity

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

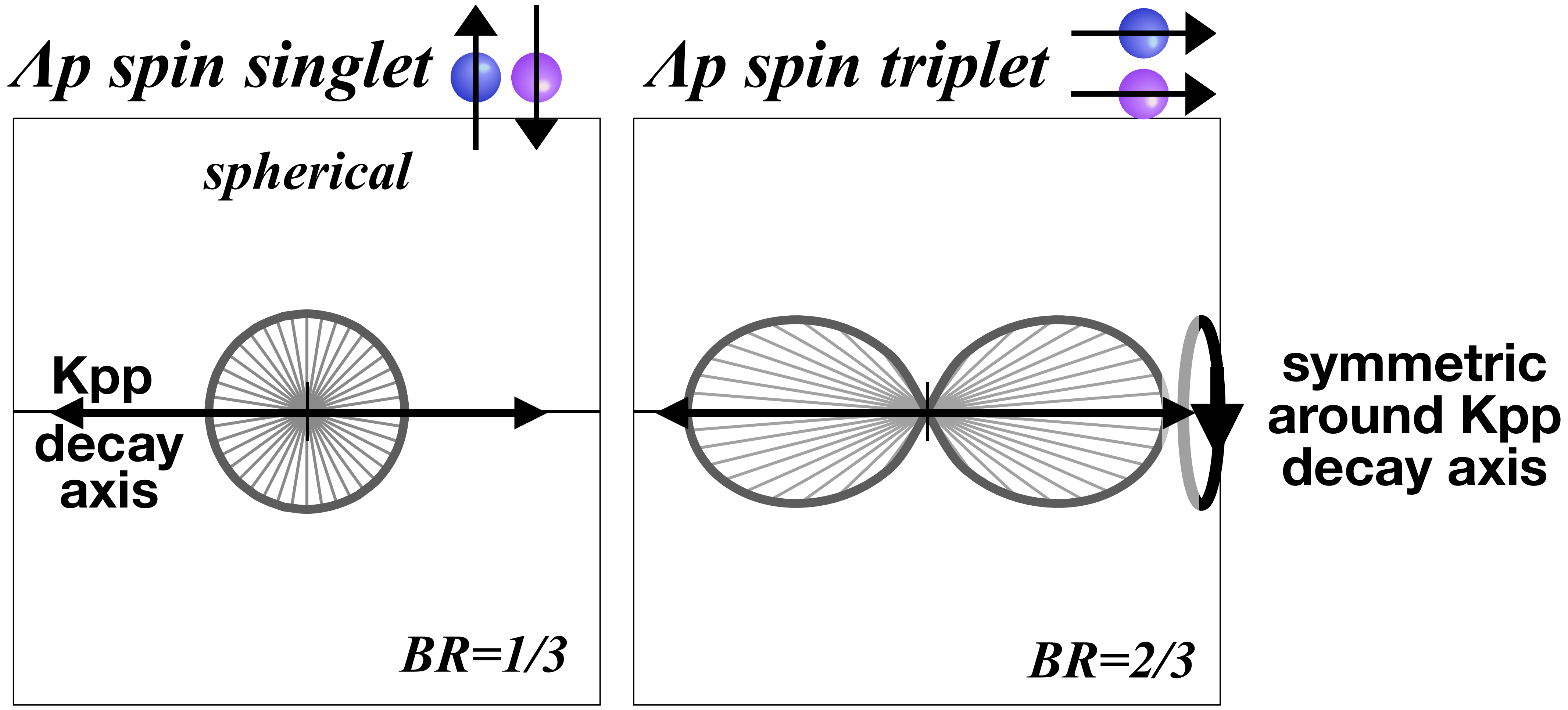
spin axis distribution referring to the decay axis

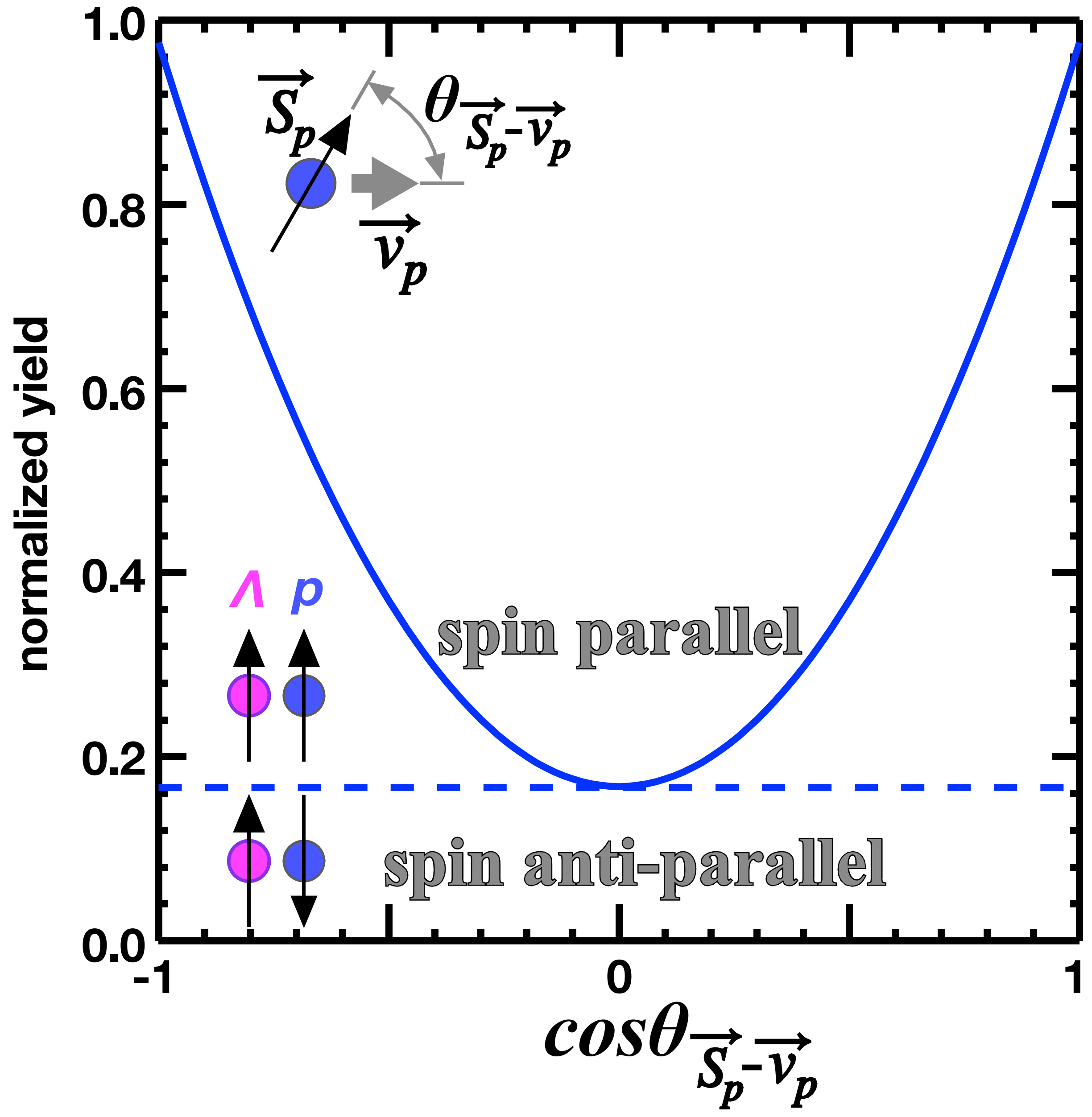
$\bar{K}NN$: $J^P = 0^-$, $I = 1/2$: $I_{NN} = 1$, $S_{NN} = 0$, $L_{\bar{K}} = 0$





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



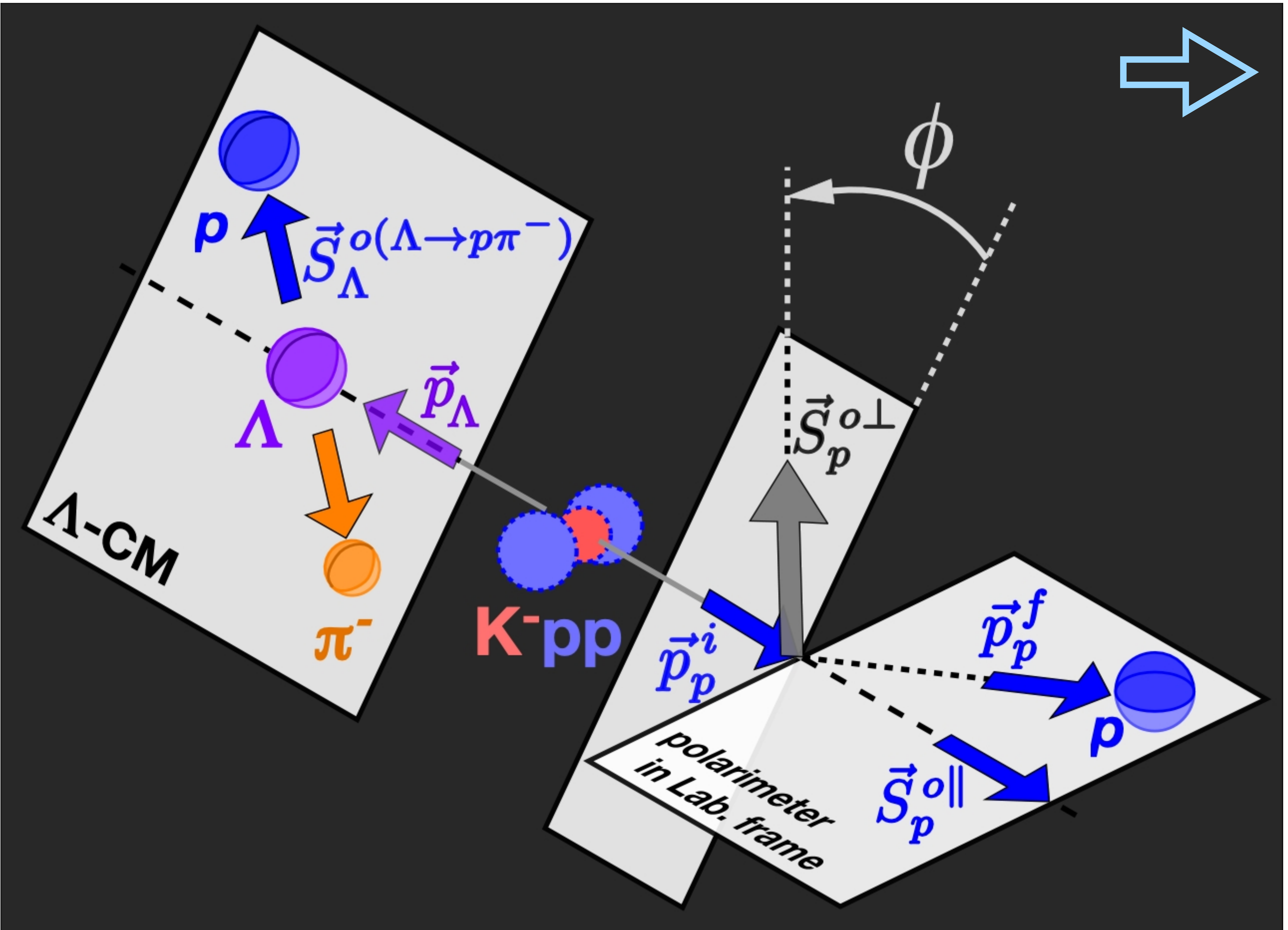


How to measure spin-spin correlation

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

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

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



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

r : scaling factor

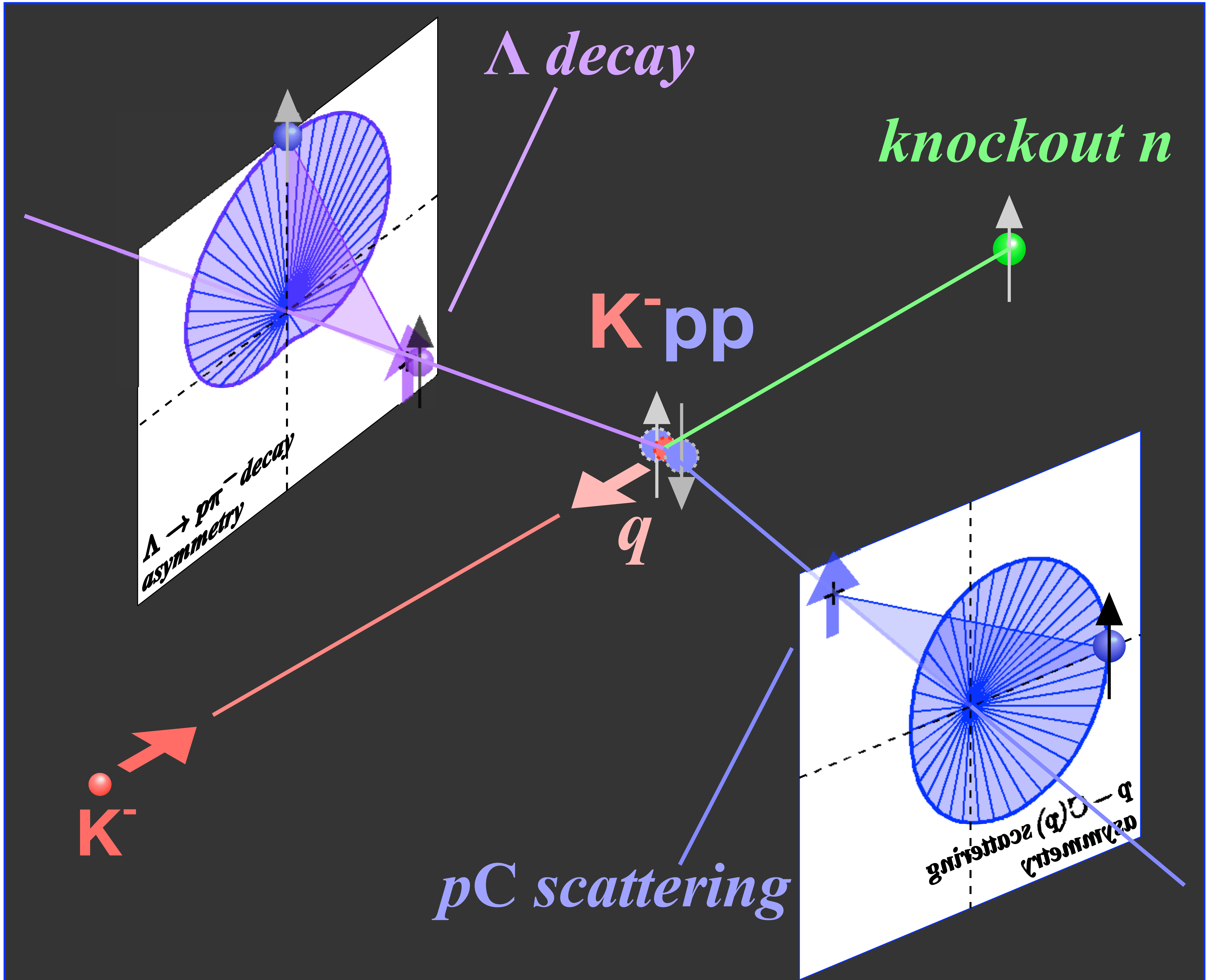
$$r = A_\Lambda \cdot A_{pC}\cdot \vec{S}\cdot\vec{S}^{\parallel}\cdot c_{conv}$$

A_Λ : Λ asymmetry parameter

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

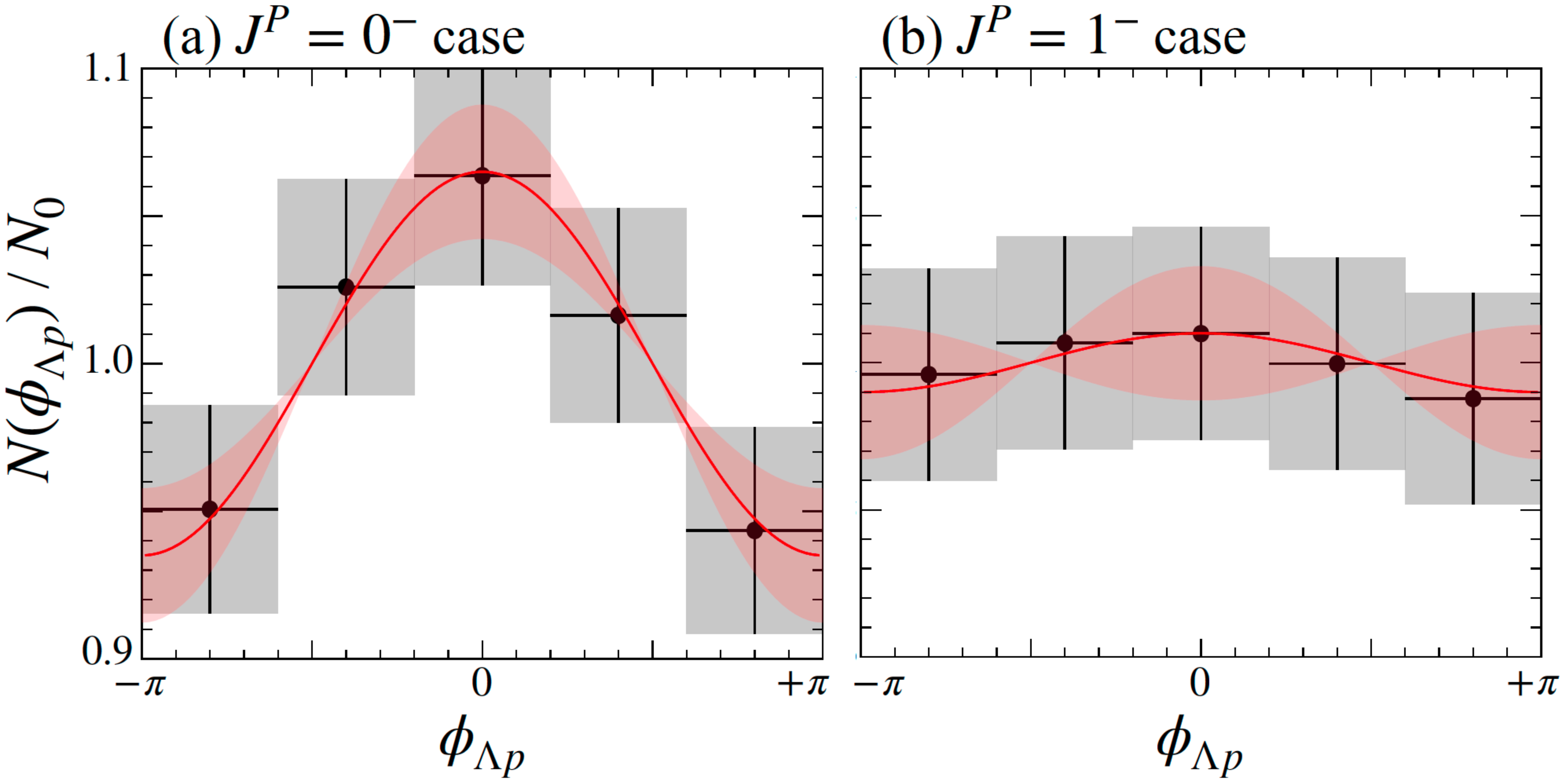
$\vec{S}\cdot\vec{S}^{\parallel}$ ($\equiv \vec{S}_p\cdot\vec{S}_p^{\parallel}$) : spin sensitivity referring to motional axis

c_{conv} : convolution coefficient between two asymmetries

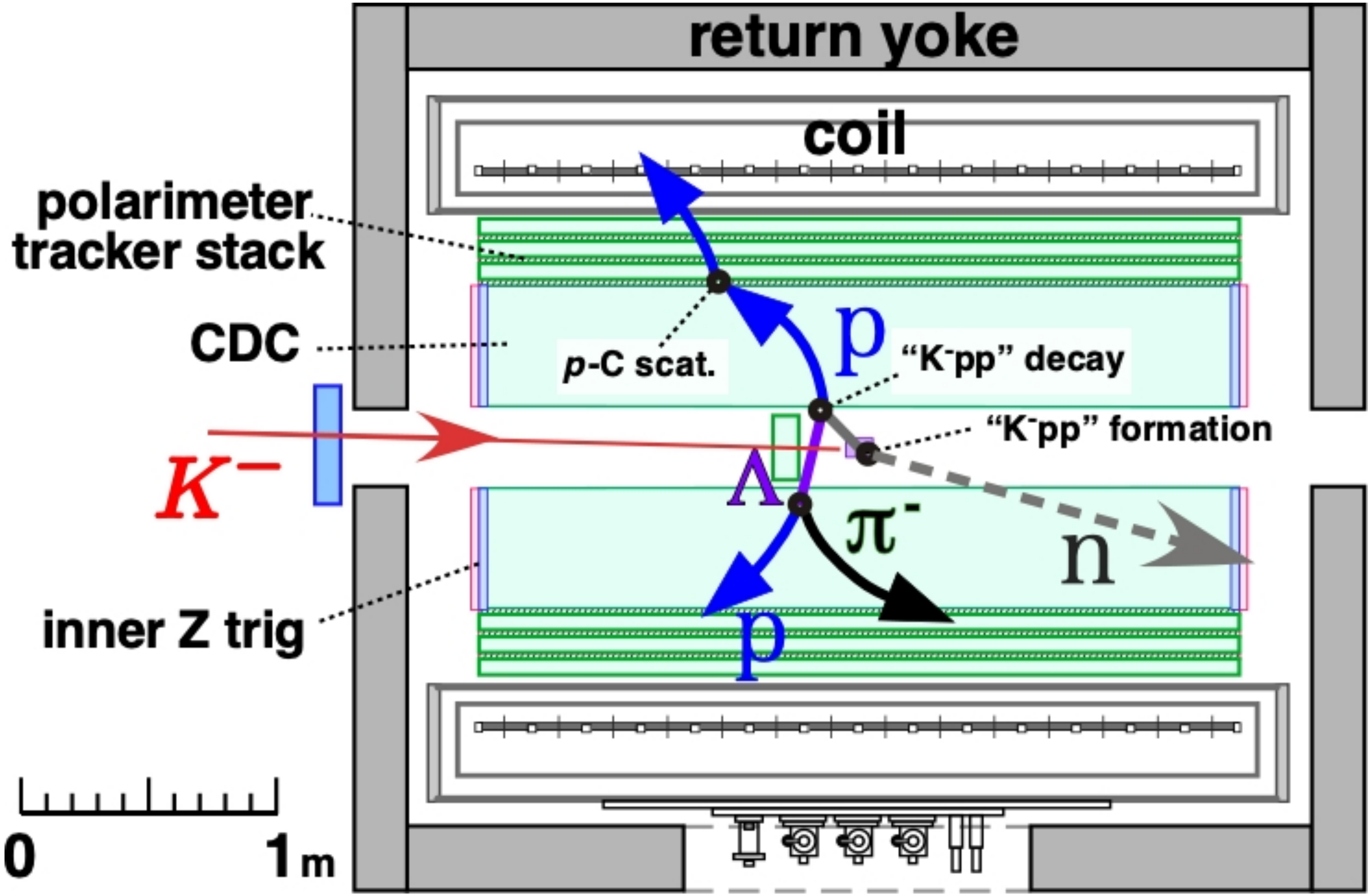


Λ decay
knockout n
K⁻pp
q
K⁻
pC scattering
Λ → pπ⁻ decay
asymmetry

Λp spin-spin asymmetry



Toward J^P (spin・parity) study of K^-pp with ^3He target



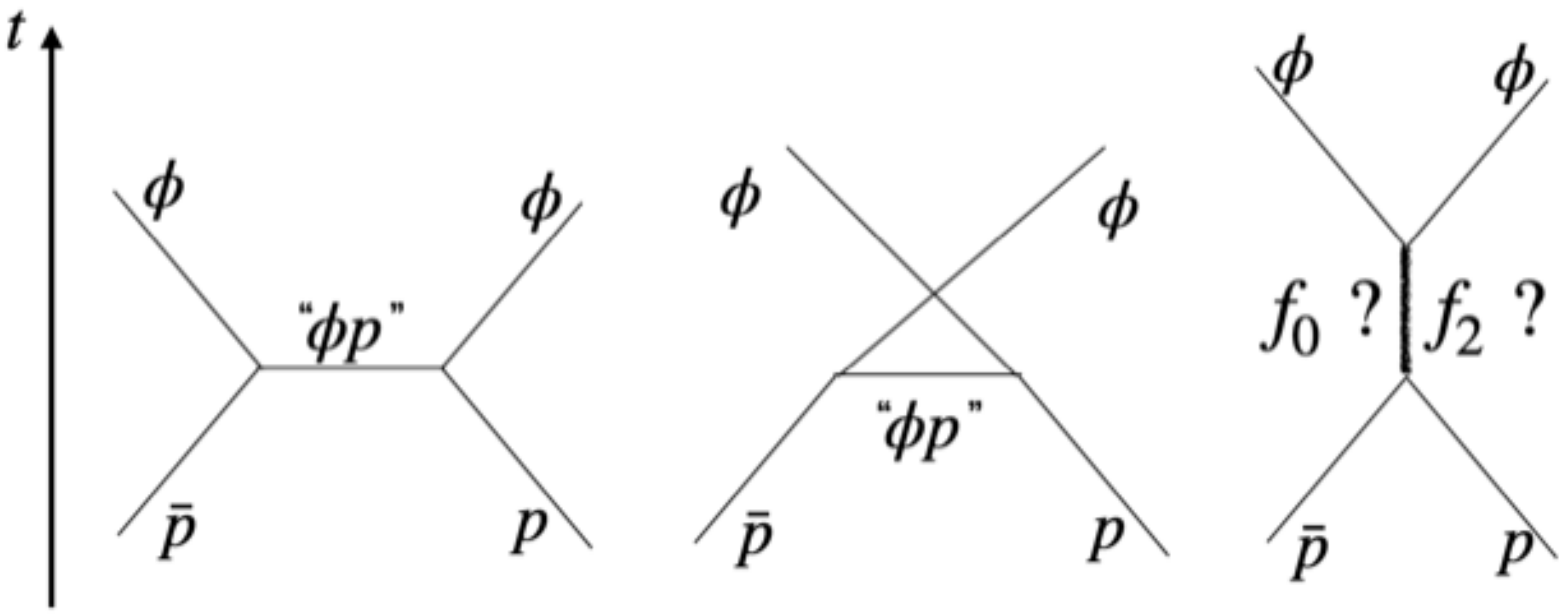
Another extension:

ϕN bound state ?

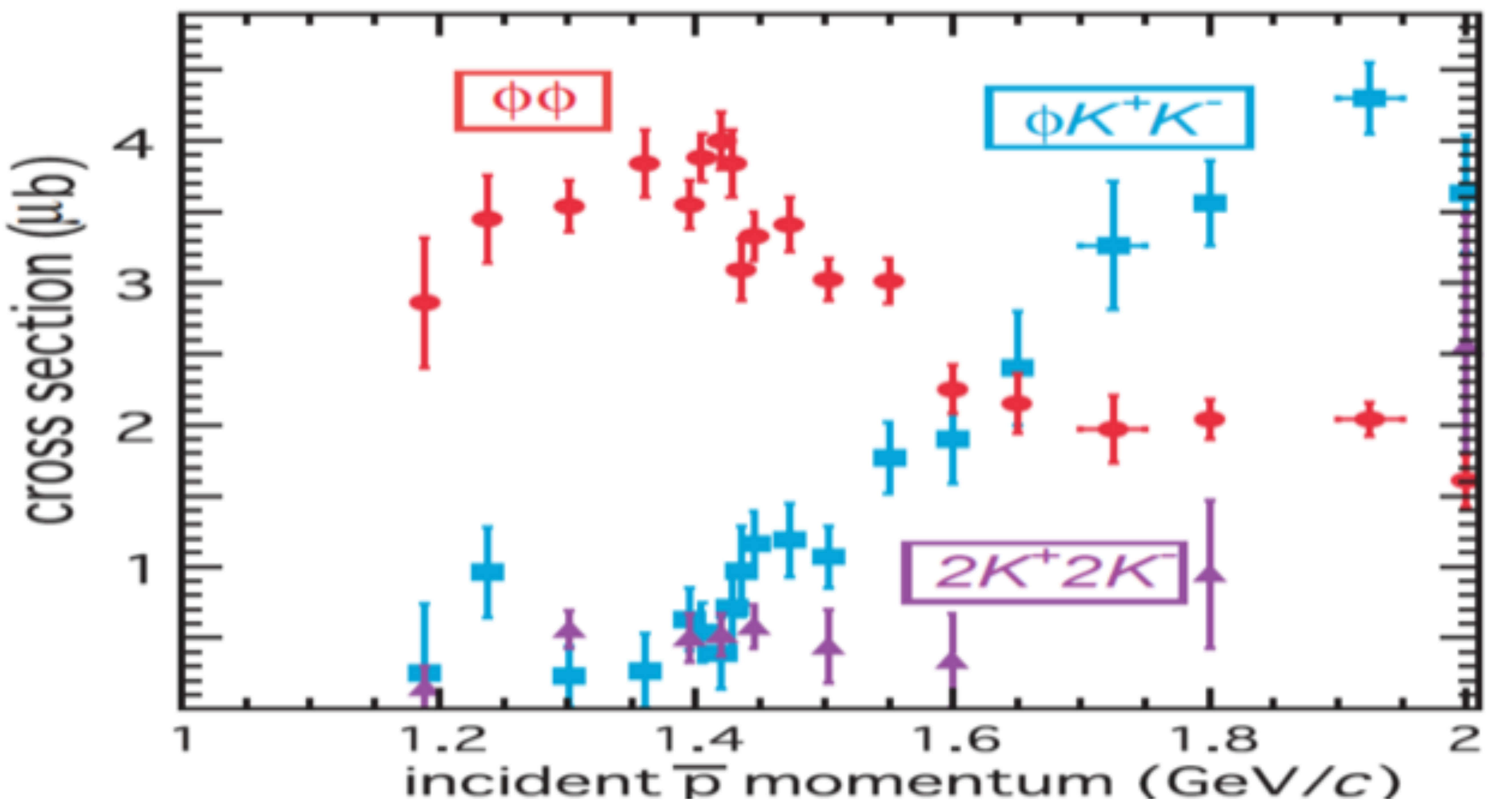
arXiv:2212.12690

Evidence of a p–ϕ bound state

Emma Chizzali[a,b,*], Yuki Kamiya[c,d,**], Raffaele Del Grande[b], Takumi Doi[d], Laura Fabbietti[b], Tetsuo Hatsuda[d], and Yan Lyu[d,e]

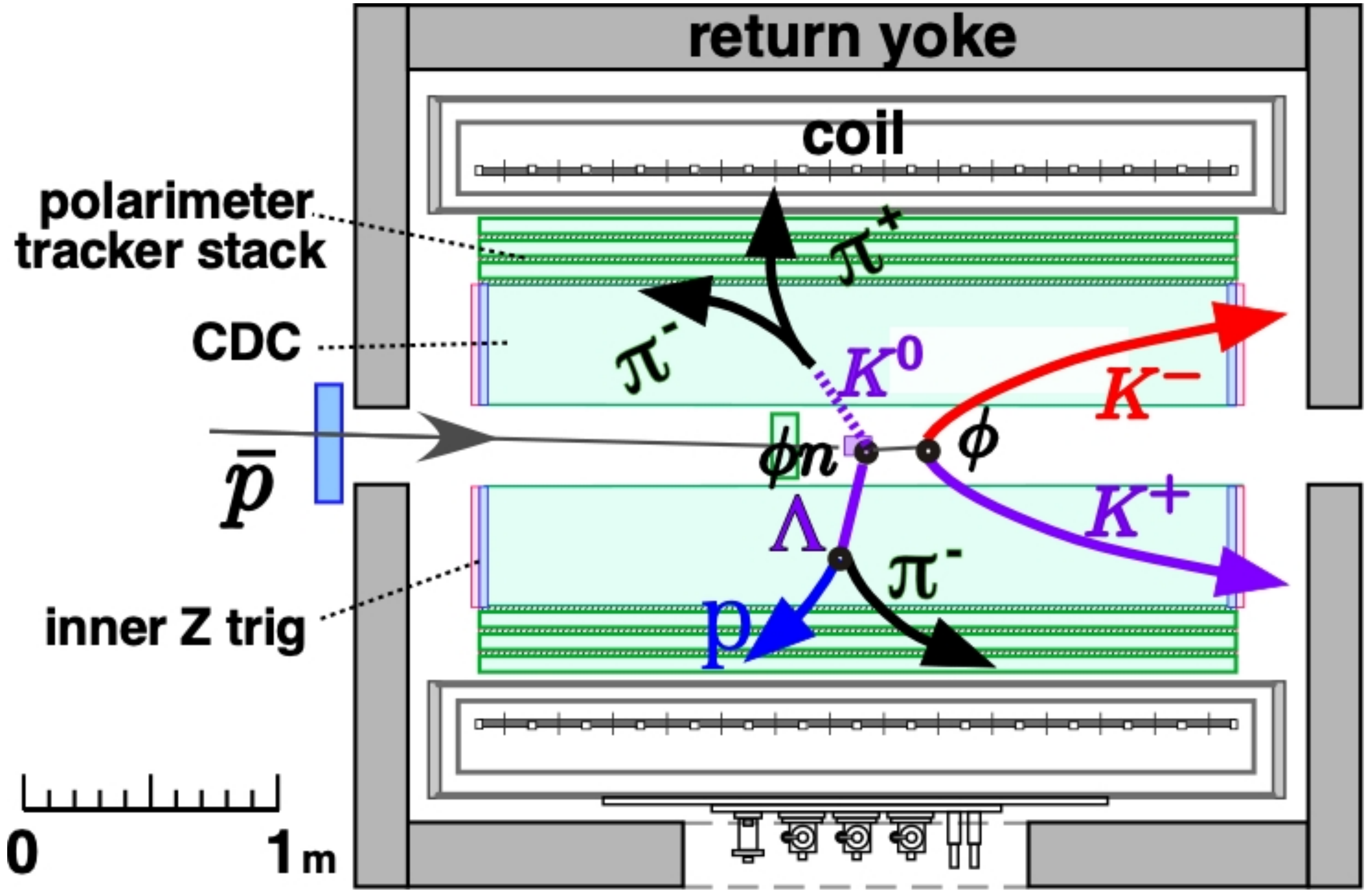


The possibility of the existence of a ϕN bound state ($J = 1/2$) as a novel molecular hadron cluster has been pointed out by T. Hatsuda et al. This is consistent with $\phi\phi$ dominance near the production threshold of the $\bar{p}p$ reaction channel.



ϕN signal might be found in J/Ψ decay?

If exist, nuclear ϕ bound states search is of interest



... *H. Onishi*

Summary

At present, it is crucial to systematically investigate the properties of various molecule-like hadron clusters (such as quantum energy and spin-parity) to better understand the hadron cluster — $\bar{K}N$, $\bar{K}NN$, $\bar{K}NNN$, … and possibly ϕ as well to understand the hadronization in detail. (cf. quark-hadron cross over)

Even if the ϕN bound state does not exist, strong attraction between ϕN suggests the possible existence of multi-nucleon bound states like ϕNN, ϕNNN, …

Using a new spectrometer system, we aim to investigate the properties of these molecule-like hadronic clusters with multiple nucleons ($A \geq 2$) in the future.

Theoretical progress is another key to fully understand the molecule-like hadronic clusters