Strangeness Physics

Ryugo S. Hayano, U. Tokyo

THE UNIVERSITY OF TOKYO

Strangeness Physics

at **FAIR**
in conjunction with the J-PARC program

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Outline

1. Why strangeness?

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2. What to study experimentally?

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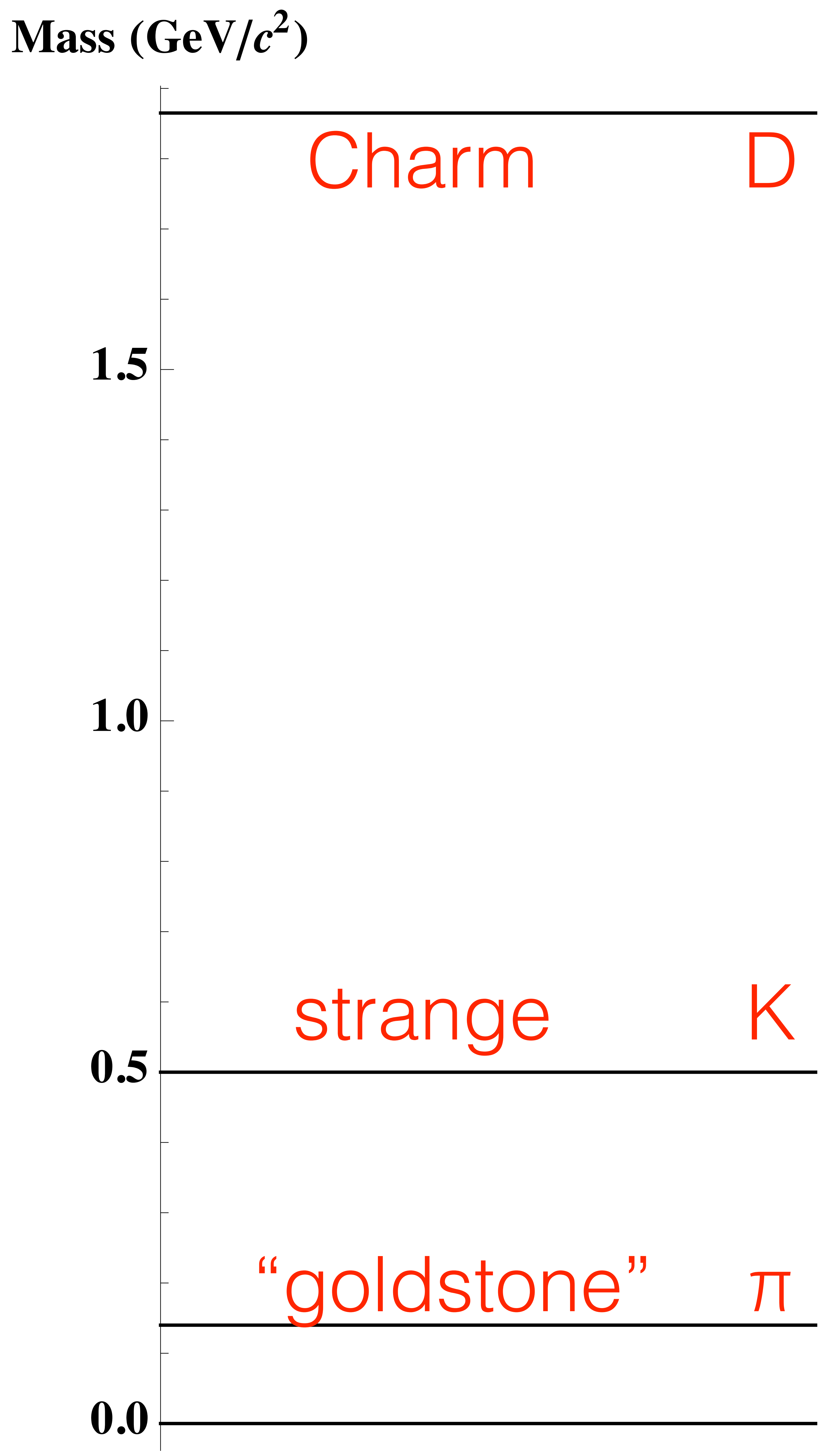
5. Hypernuclei and J-PARC program
6. Hidden strangeness at FAIR
7. Open strangeness at FAIR

1

Why strangeness?

Why strangeness?

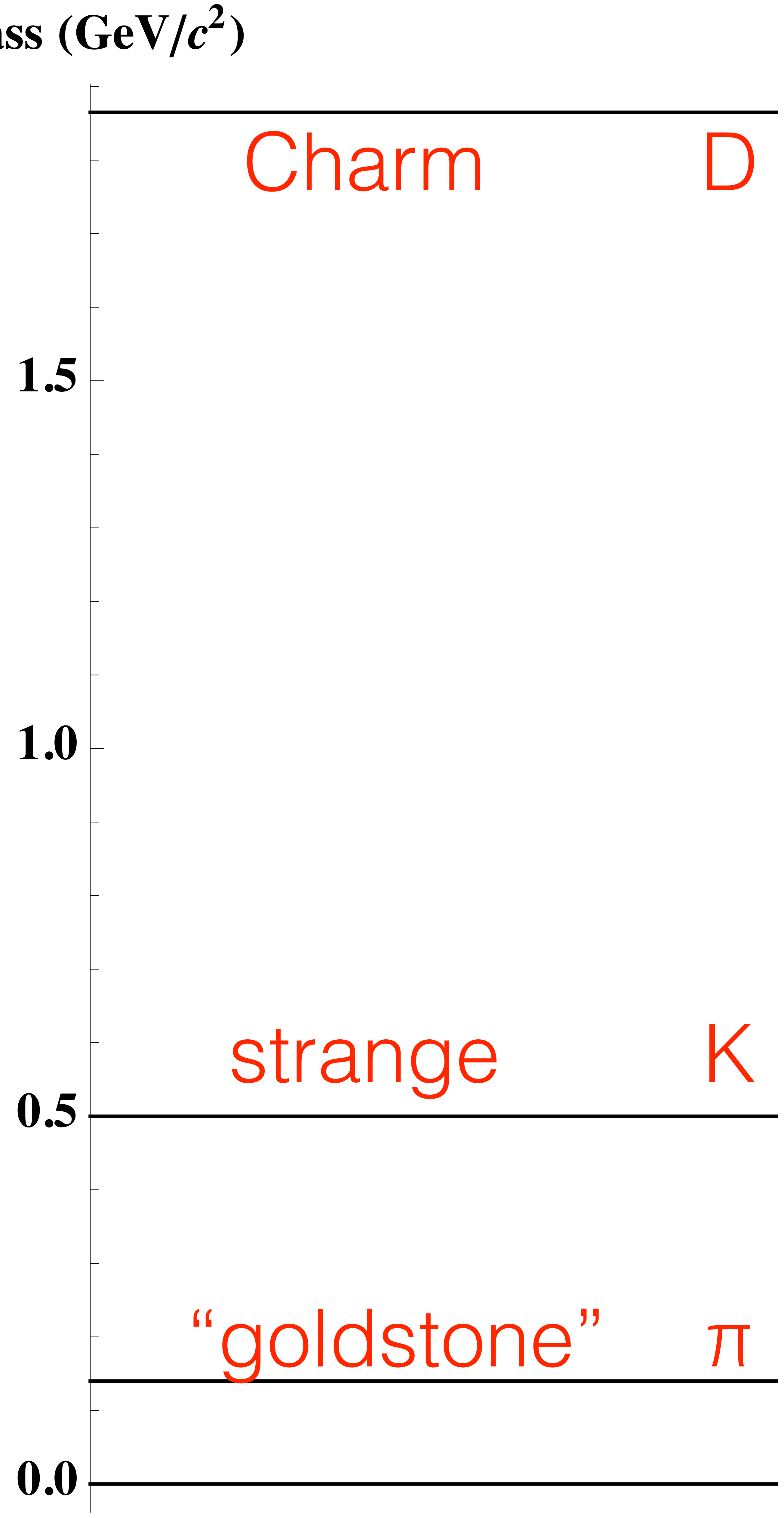
Spontaneous and explicit chiral symmetry breaking in low-energy QCD


Mass (GeV/c^2)
Charm D
1.5
1.0
strange K
0.5
"goldstone" π
0.0

Strange quarks: not “light”, not “heavy”

spontaneous and explicit chiral symmetry breaking in low-energy QCD

Weise



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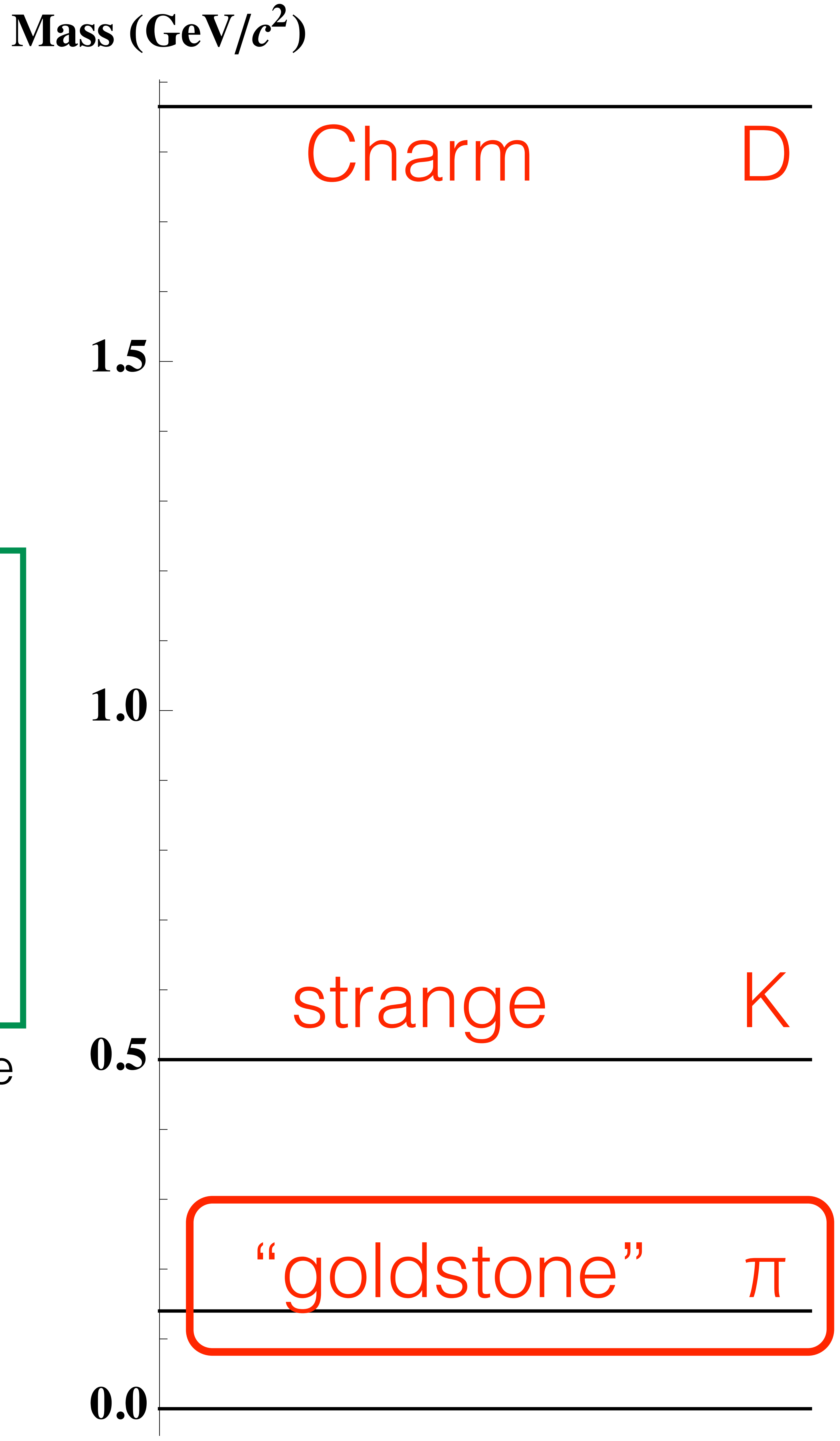
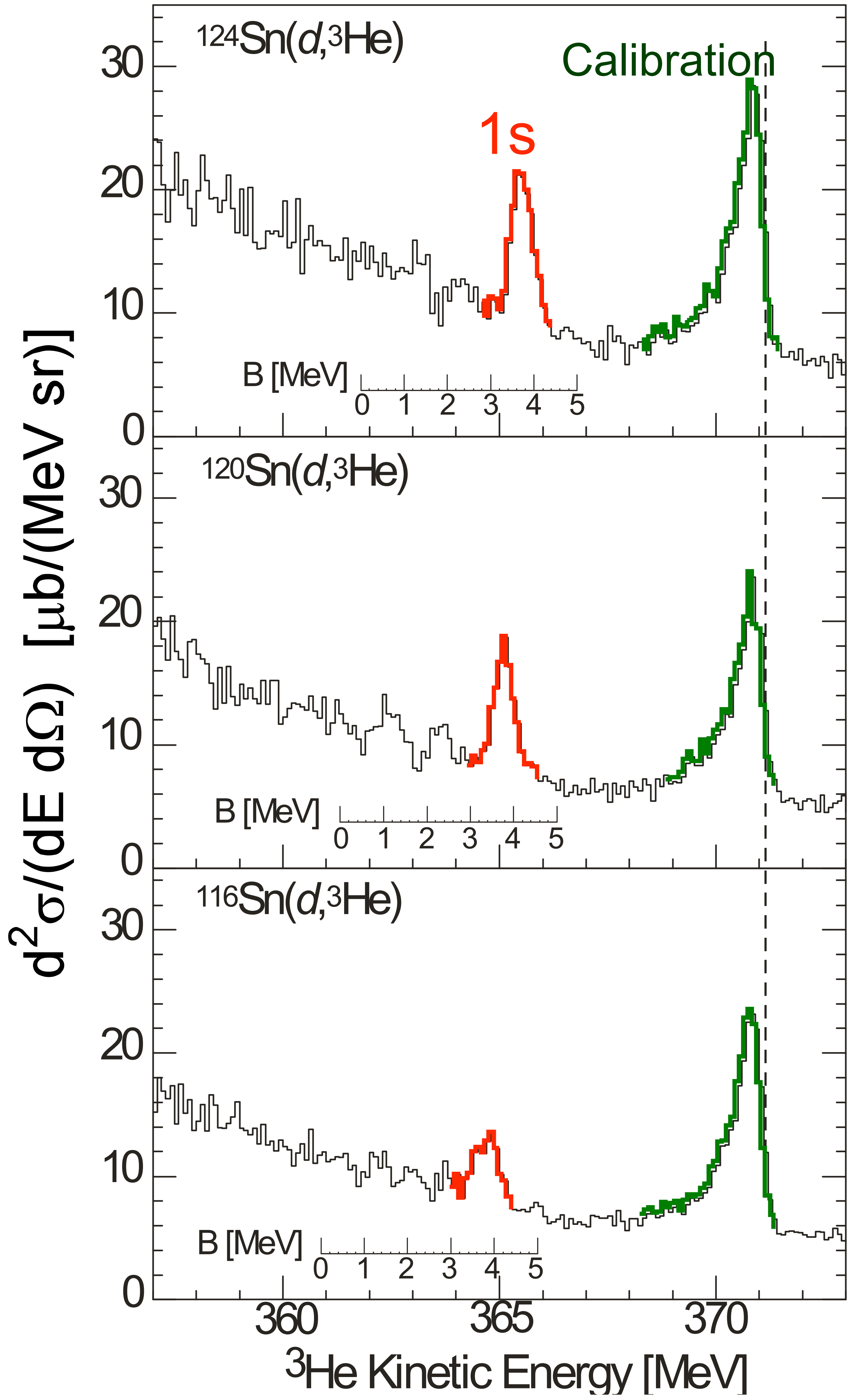
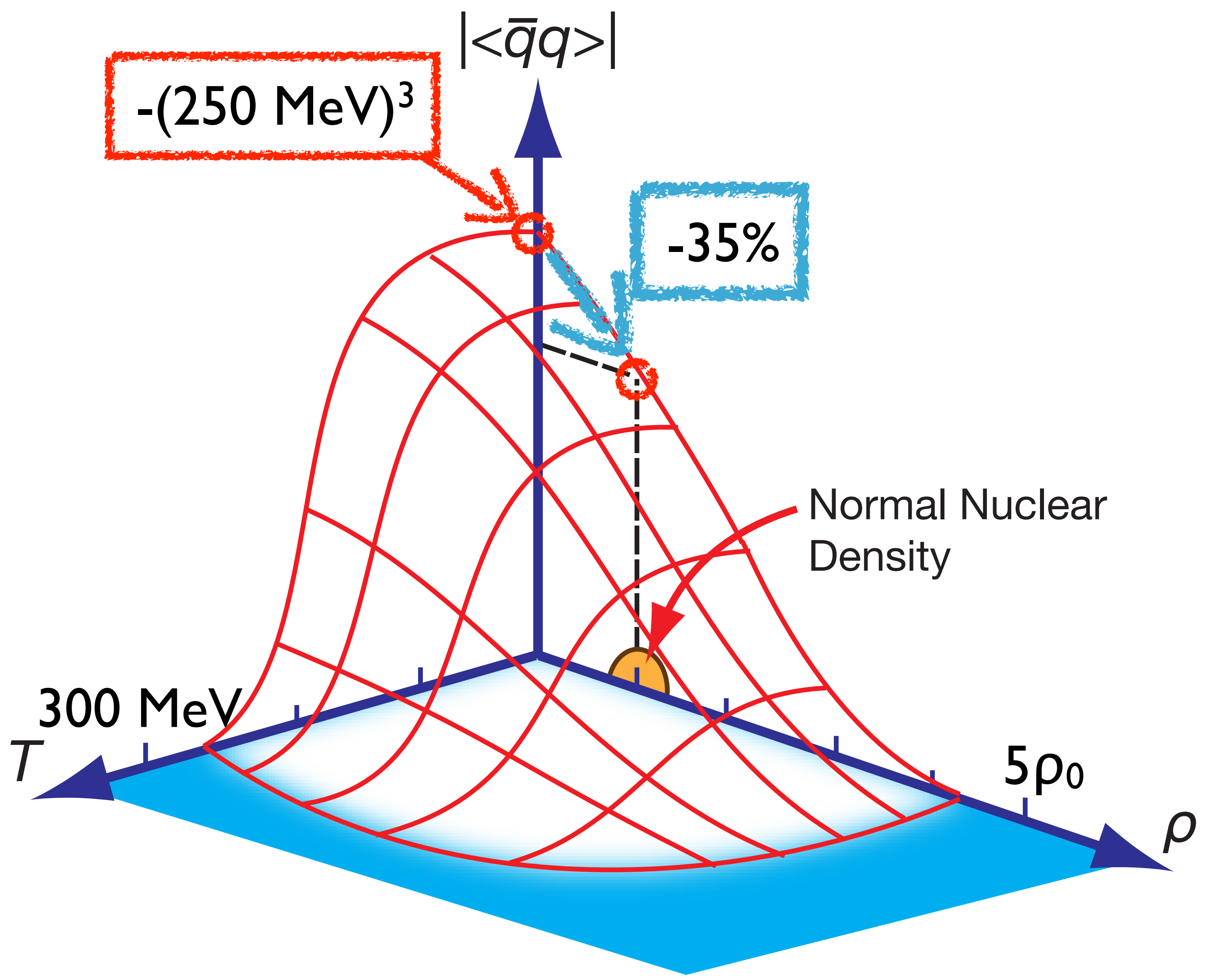
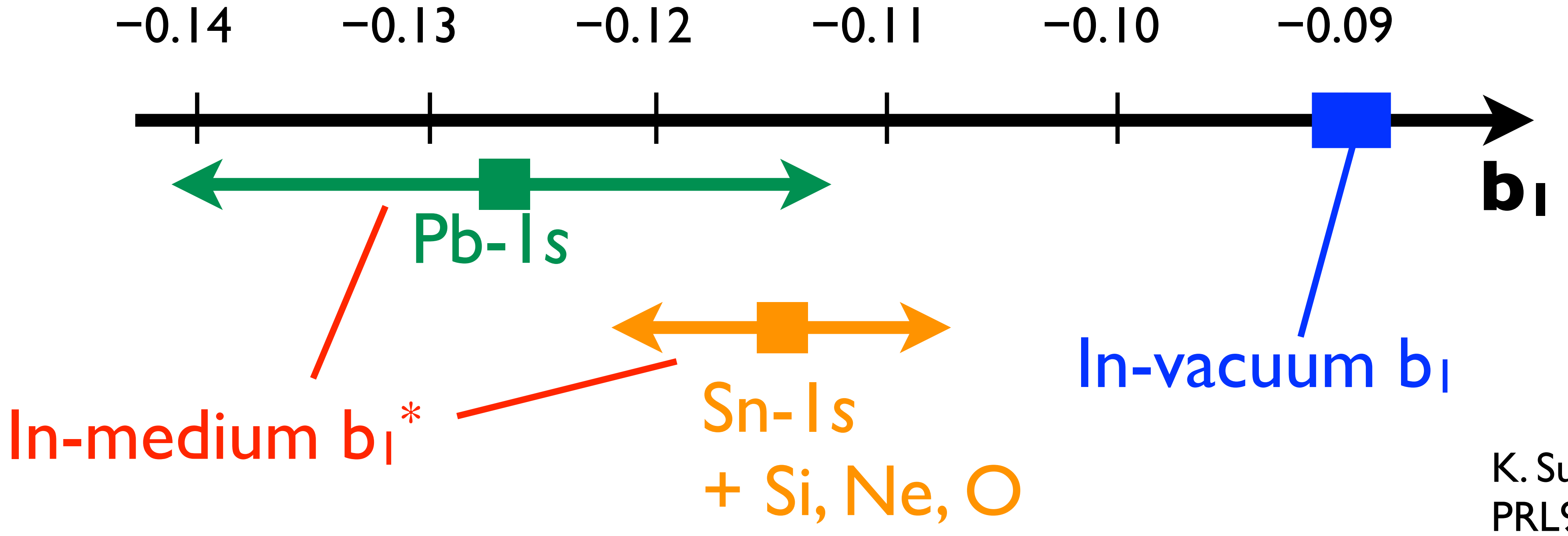


π in nuclei - pioneered at FRS





$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \approx \frac{b_1^{\mathrm{free}}}{b_1(\rho)}$$



K. Suzuki et al., PRL92(04)072302.

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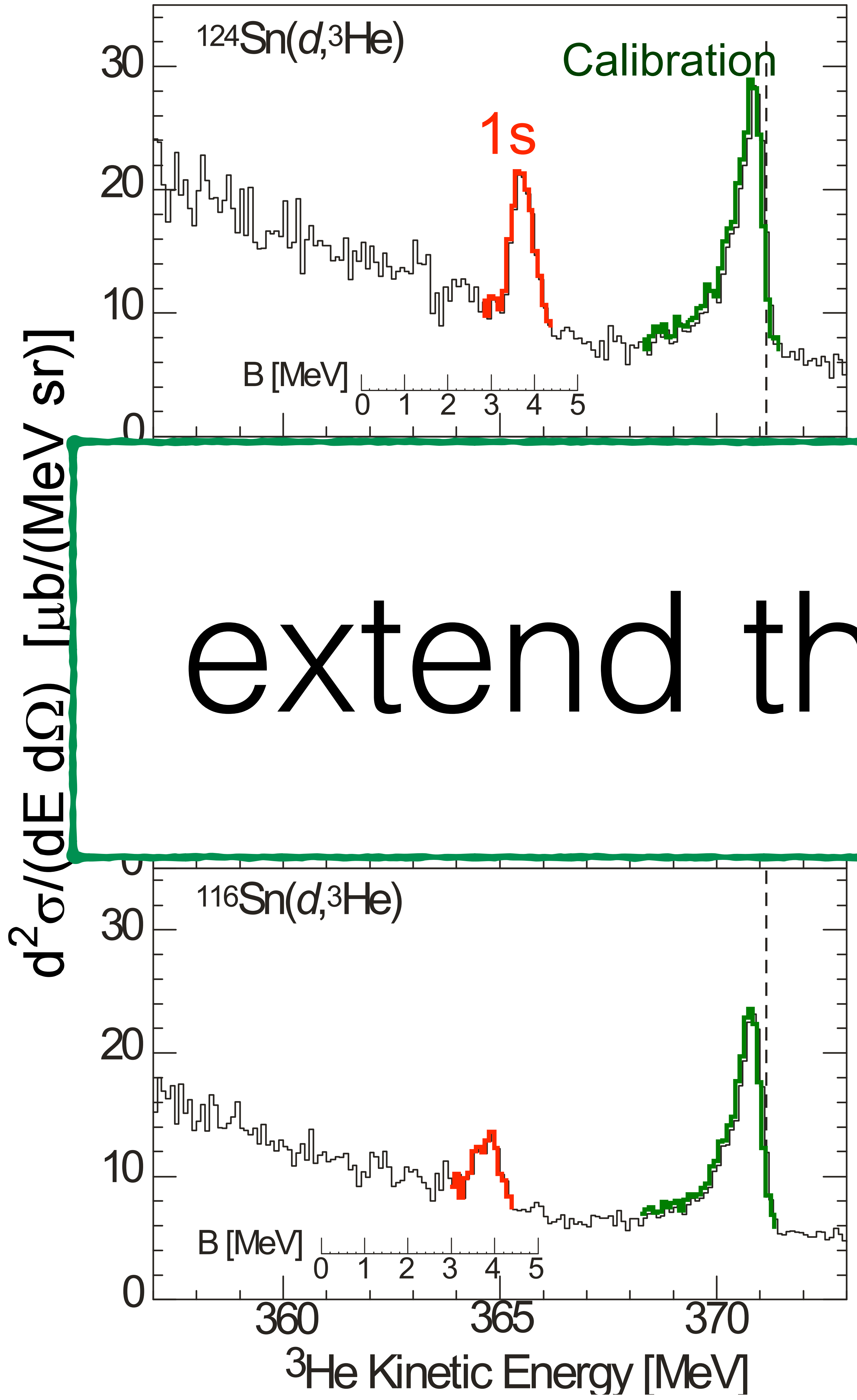
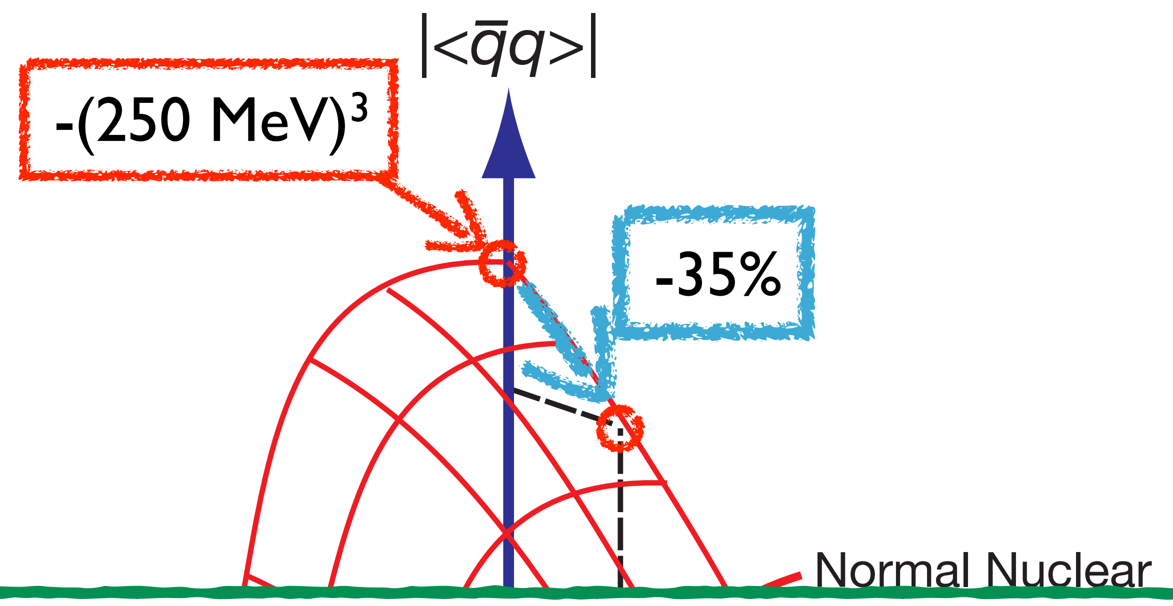
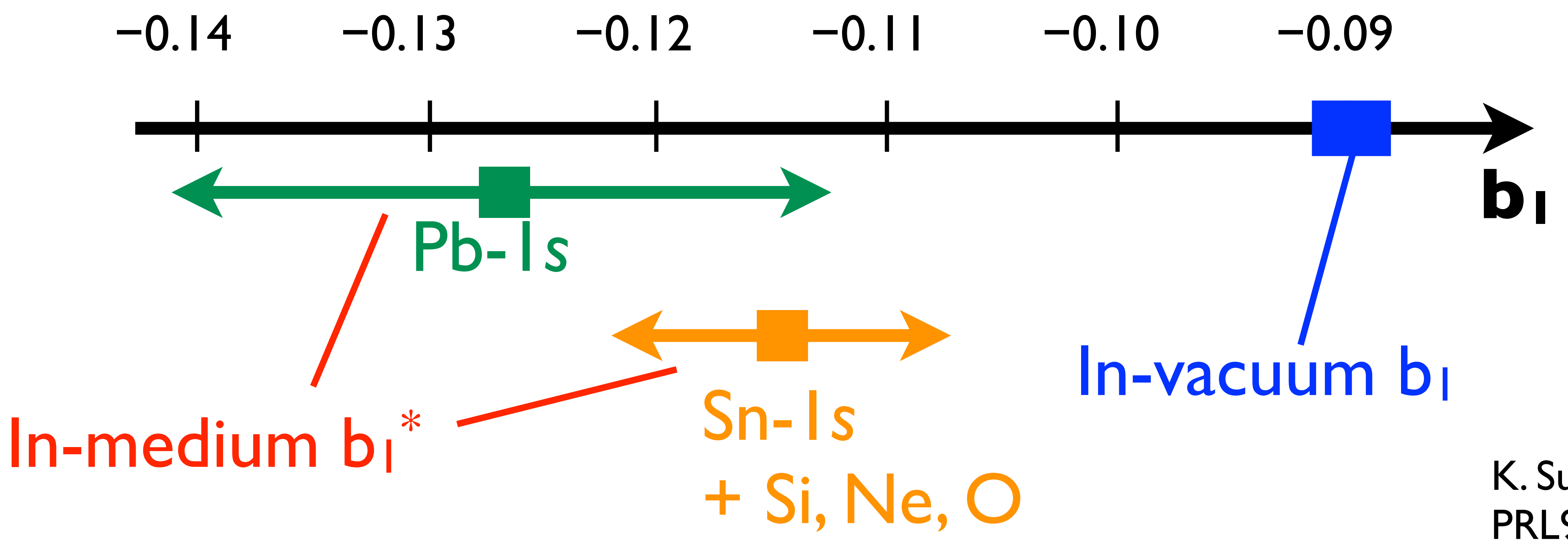




$$\frac{\langle \bar{q}q \rangle_\rho}{\ldots} \simeq \frac{b_1^{\text{free}}}{\ldots \rho)}$$

extend this to other PS mesons



K. Suzuki et al., PRL92(04)072302.

Why strangeness?

Spontaneous and explicit chiral symmetry breaking in low-energy QCD

- $\bar{K}N$ interaction
- In-medium hadrons e.g., mass, magnetic moment, …?
- $\bar{K}NN$?

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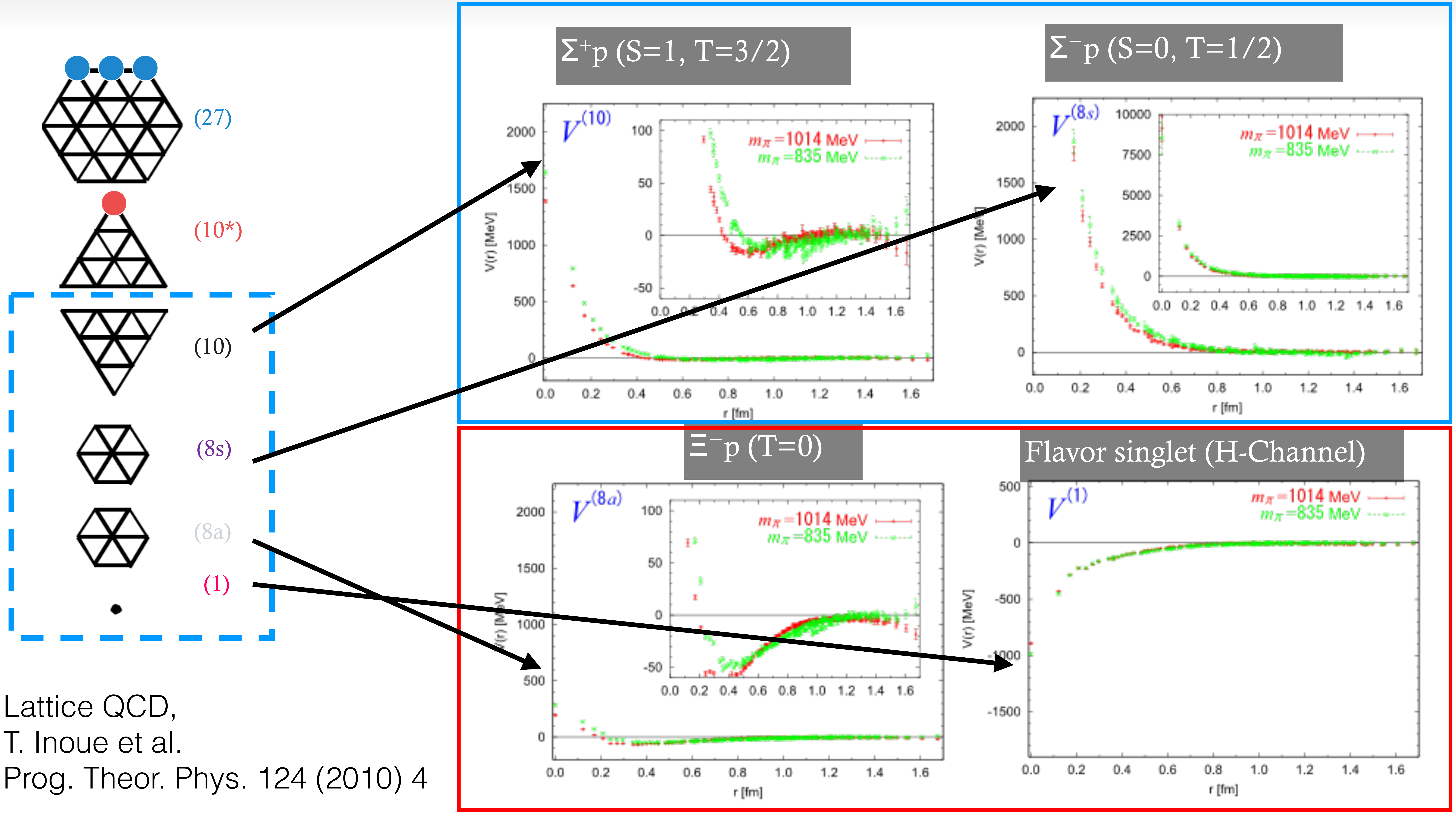
Baryon-baryon interaction

- 3-body force ΛNN
- the origin/nature of repulsive core

Lattice QCD

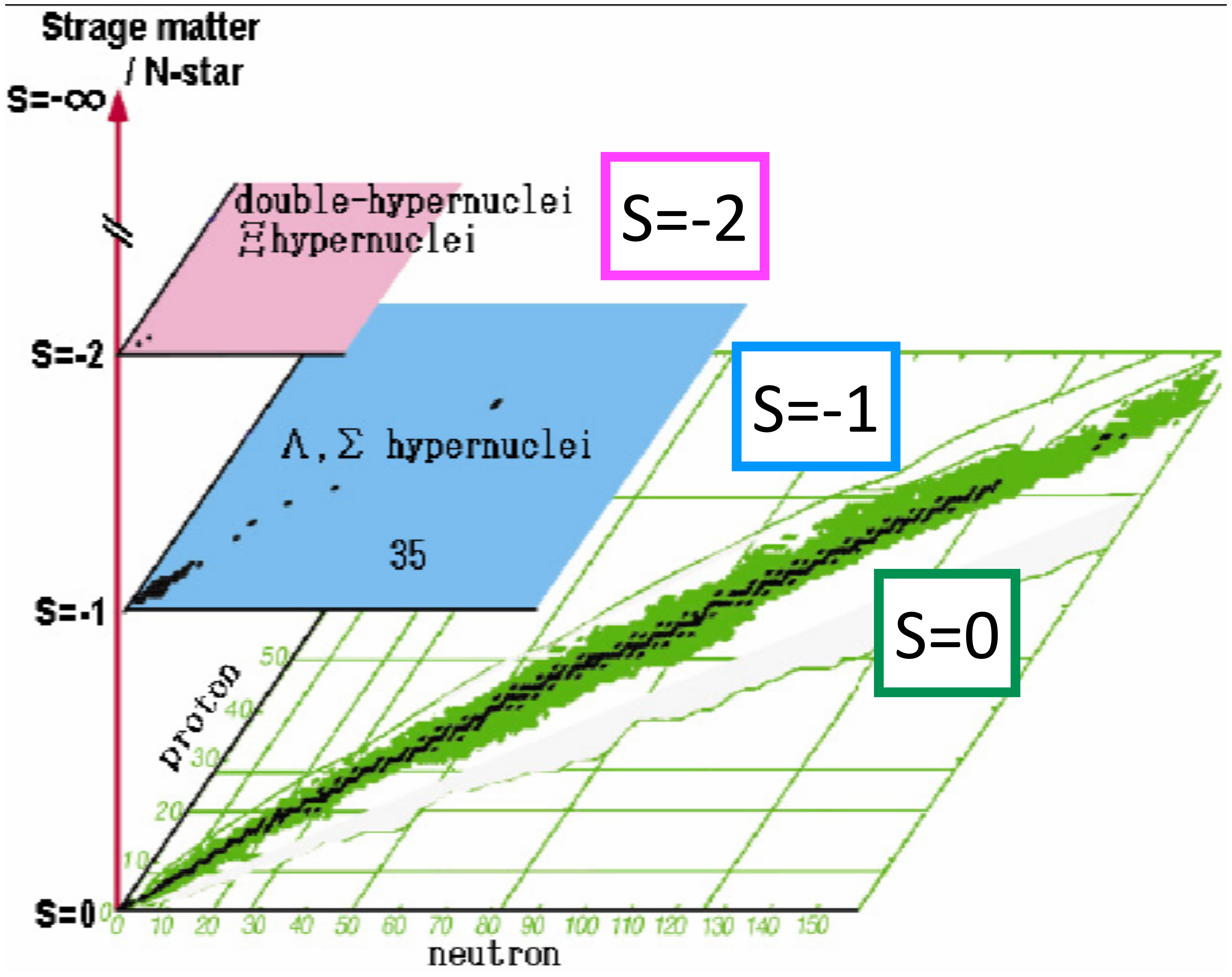


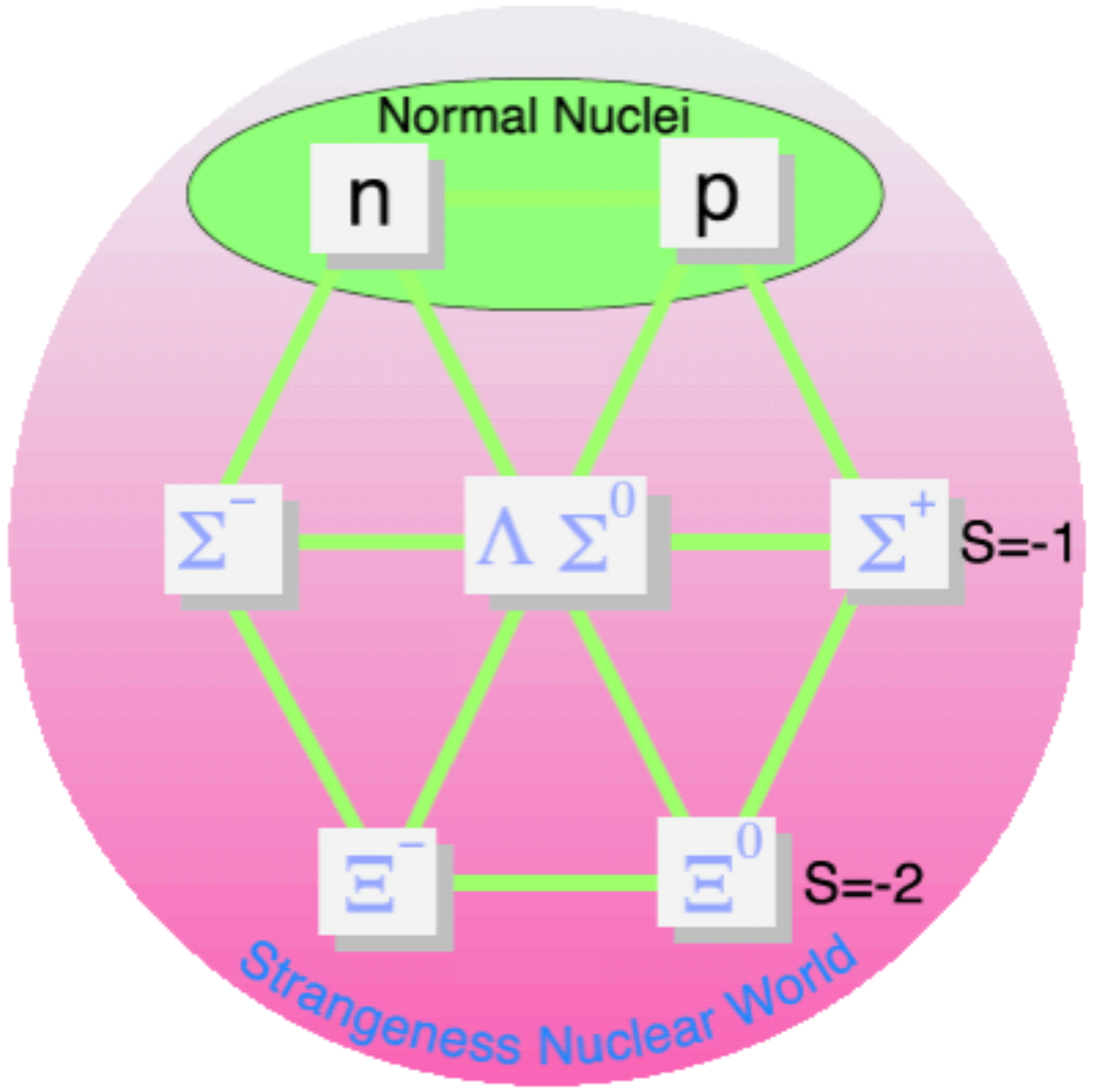
Strong repulsive core

Weak or attractive core

Lattice QCD,
T. Inoue et al.
Prog. Theor. Phys. 124 (2010) 4

Baryon-baryon interaction SU(3)





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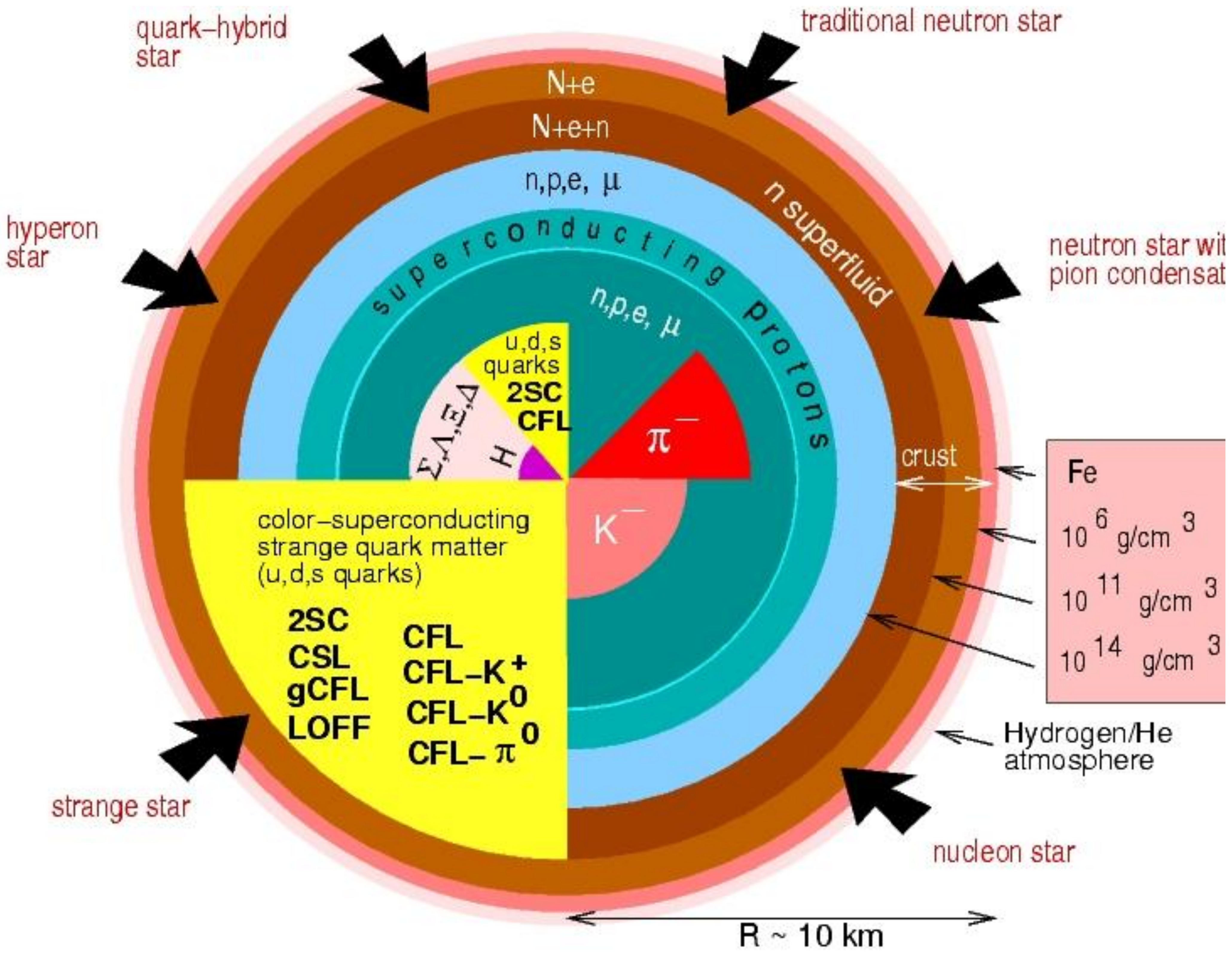
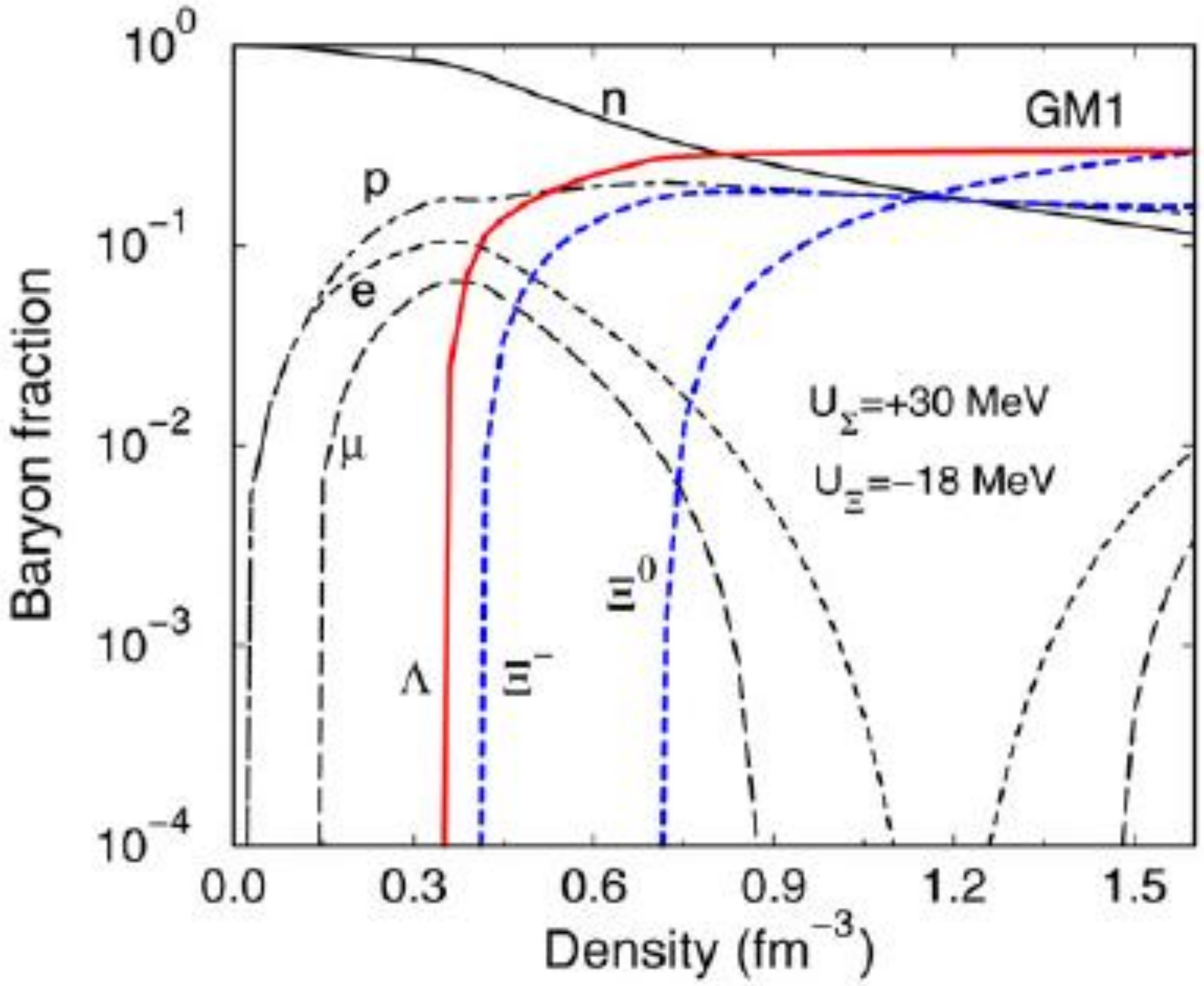
Role of **strangeness** in dense baryonic matter?

Is this picture consistent with the ~2 M⊙ neutron star?





J. Schaffner-Bielich, Nucl. Phys. A 804, 309 (2008).

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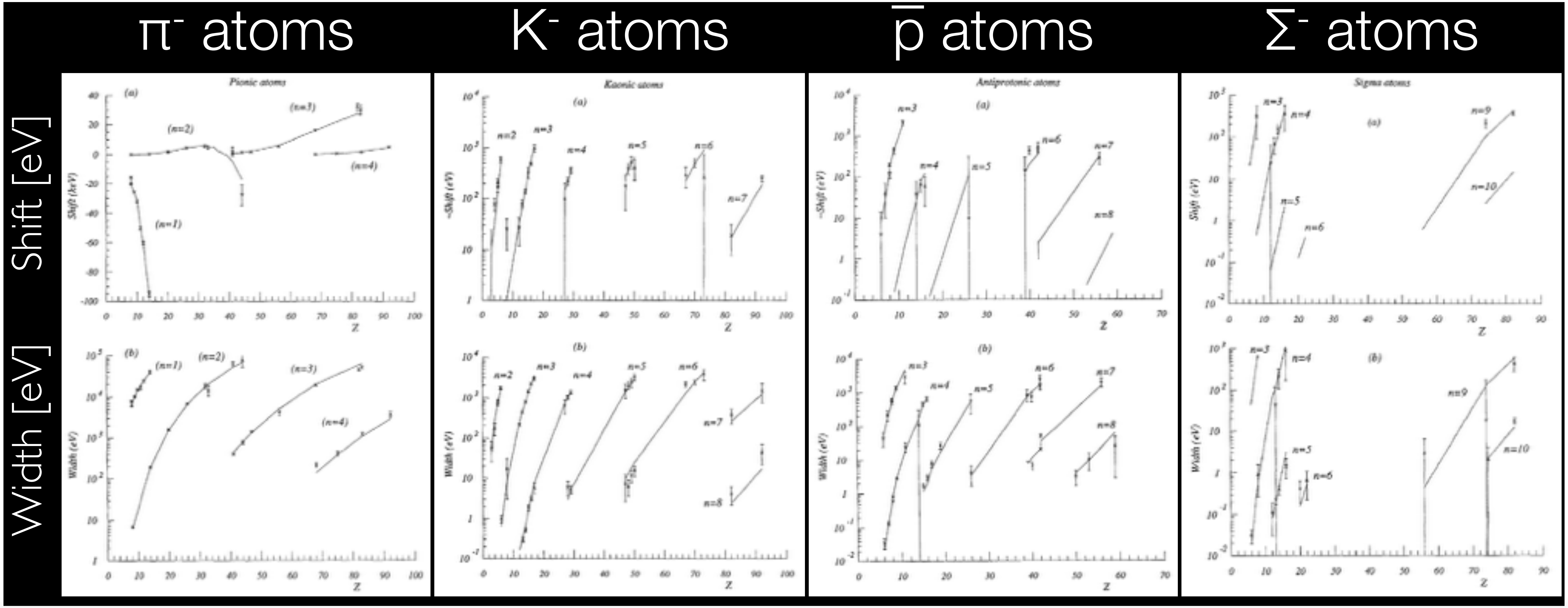
What to study experimentally?

Strange atoms scattering length at threshold

- K^- atom ← room to improve
- Σ^- atom
- Ξ^- atom ← NEW (J-PARC & FAIR)

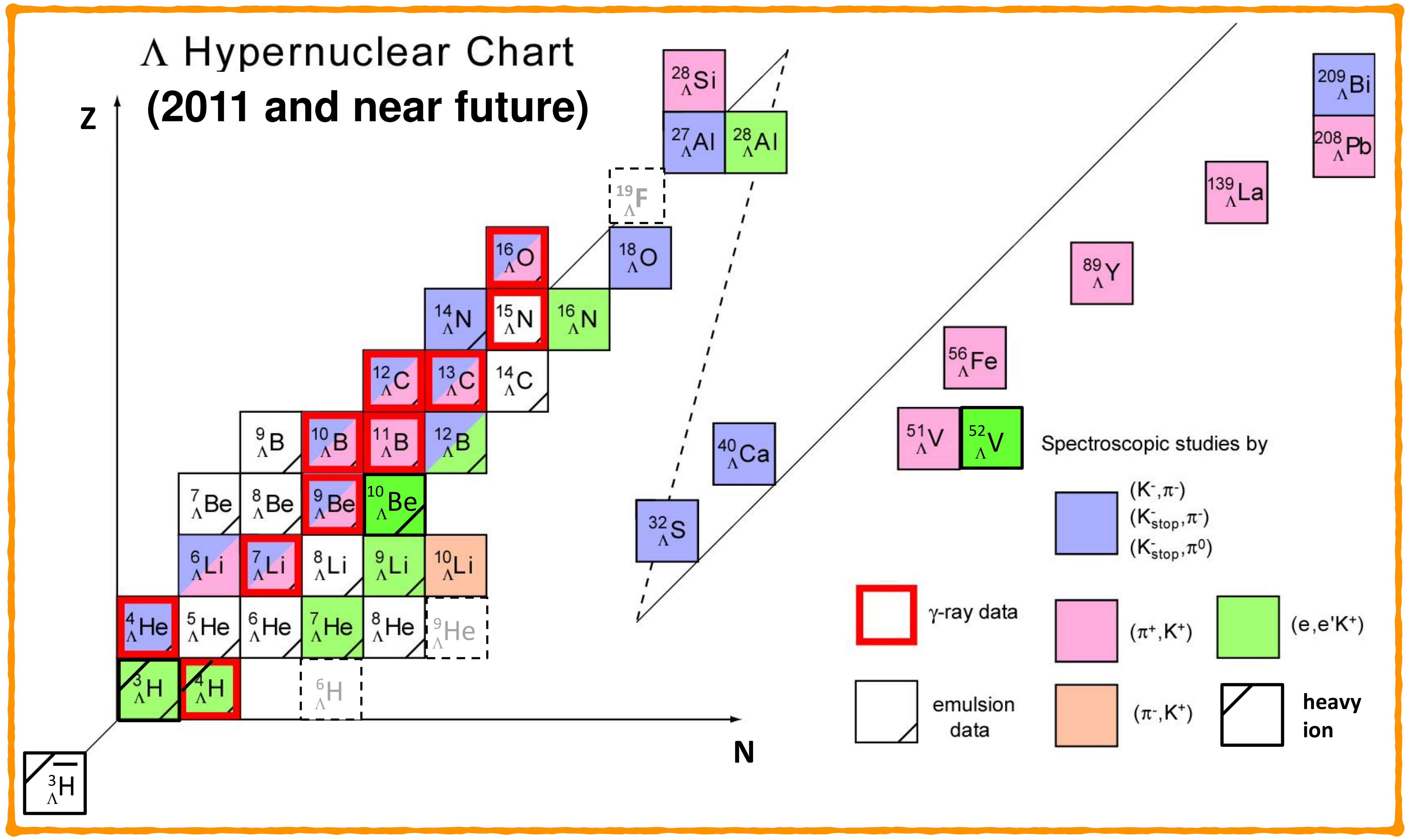
C.J. Batty, E. Friedman, A. Gal, Physics Reports 287 (1997) 385 - 445



Hypernuclei missing mass, inv. mass, γ-ray, weak-decay

- S=-1 (π^+K^+, $K^-\pi^-$, π^-K^+, ee'K^+, $\bar{p}$-induced, HI-induced…)

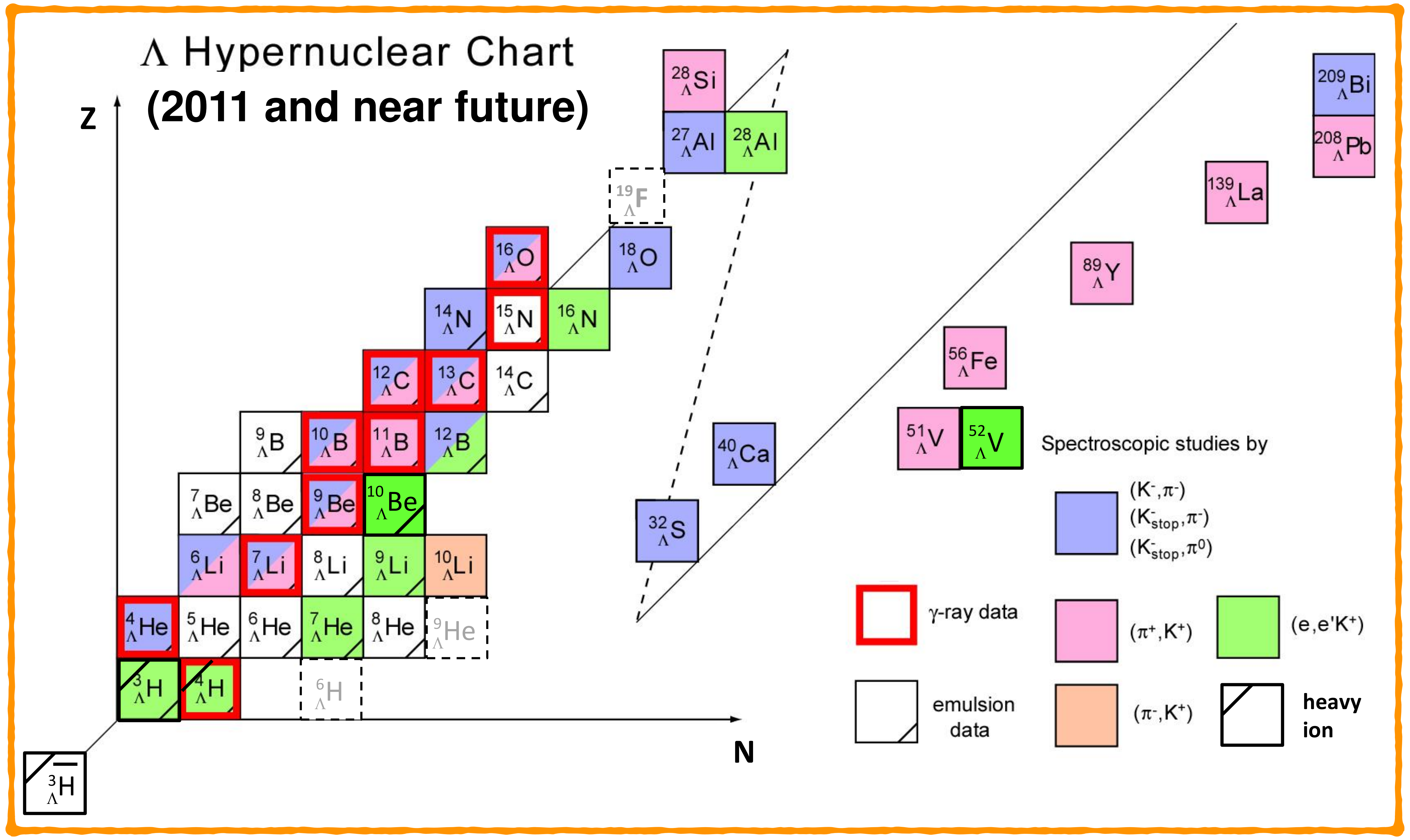
S=-1



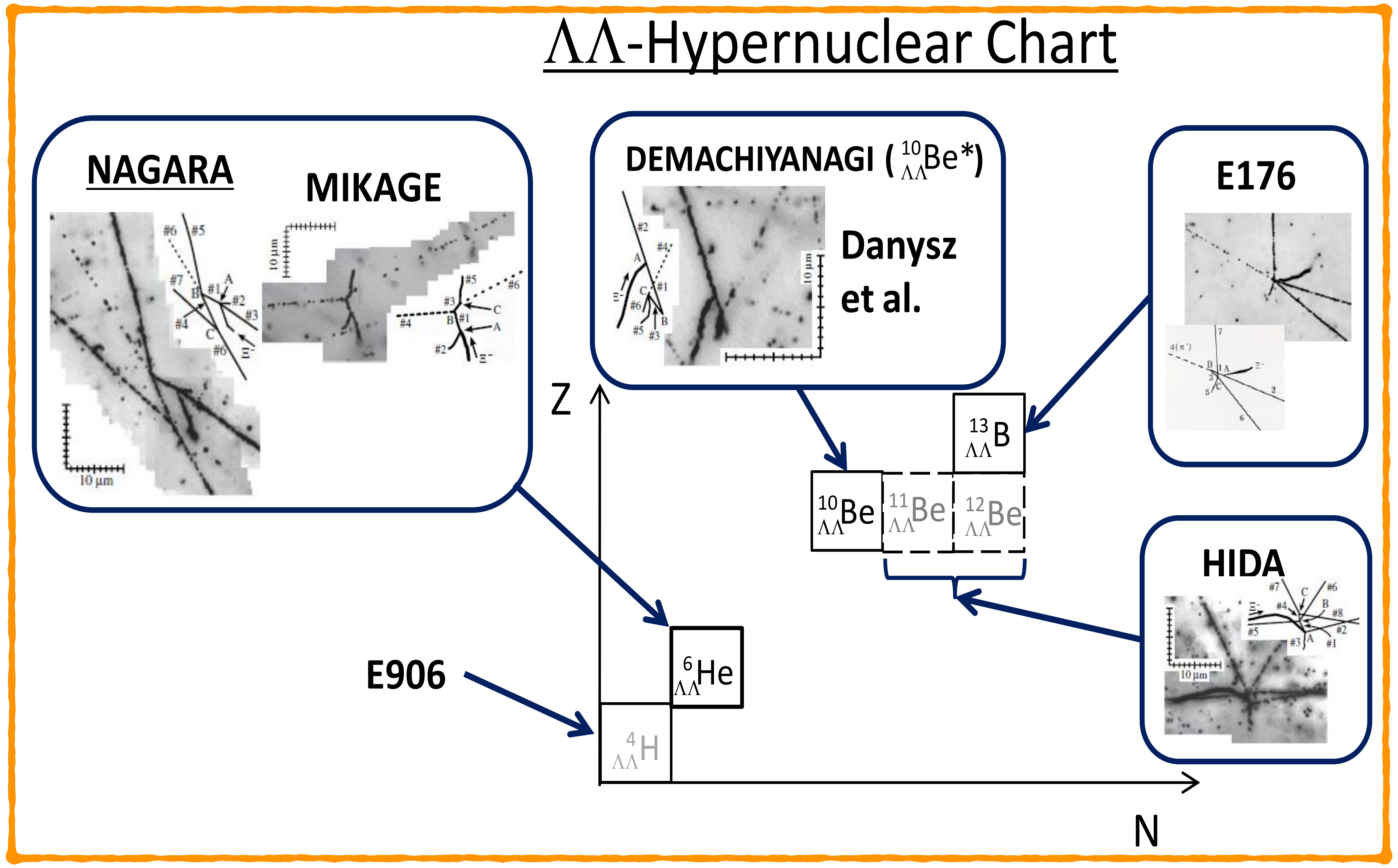
Hypernuclei missing mass, inv. mass, γ-ray, weak-decay

- S=-1 (π^+K^+, $K^-\pi^-$, π^-K^+, ee'K^+, $\bar{p}$-induced, HI-induced…)
- S=-2 (K^-K^+, $\bar{p}$-induced, HI-induced…)

S=-1



S=-2



Hidden strangeness

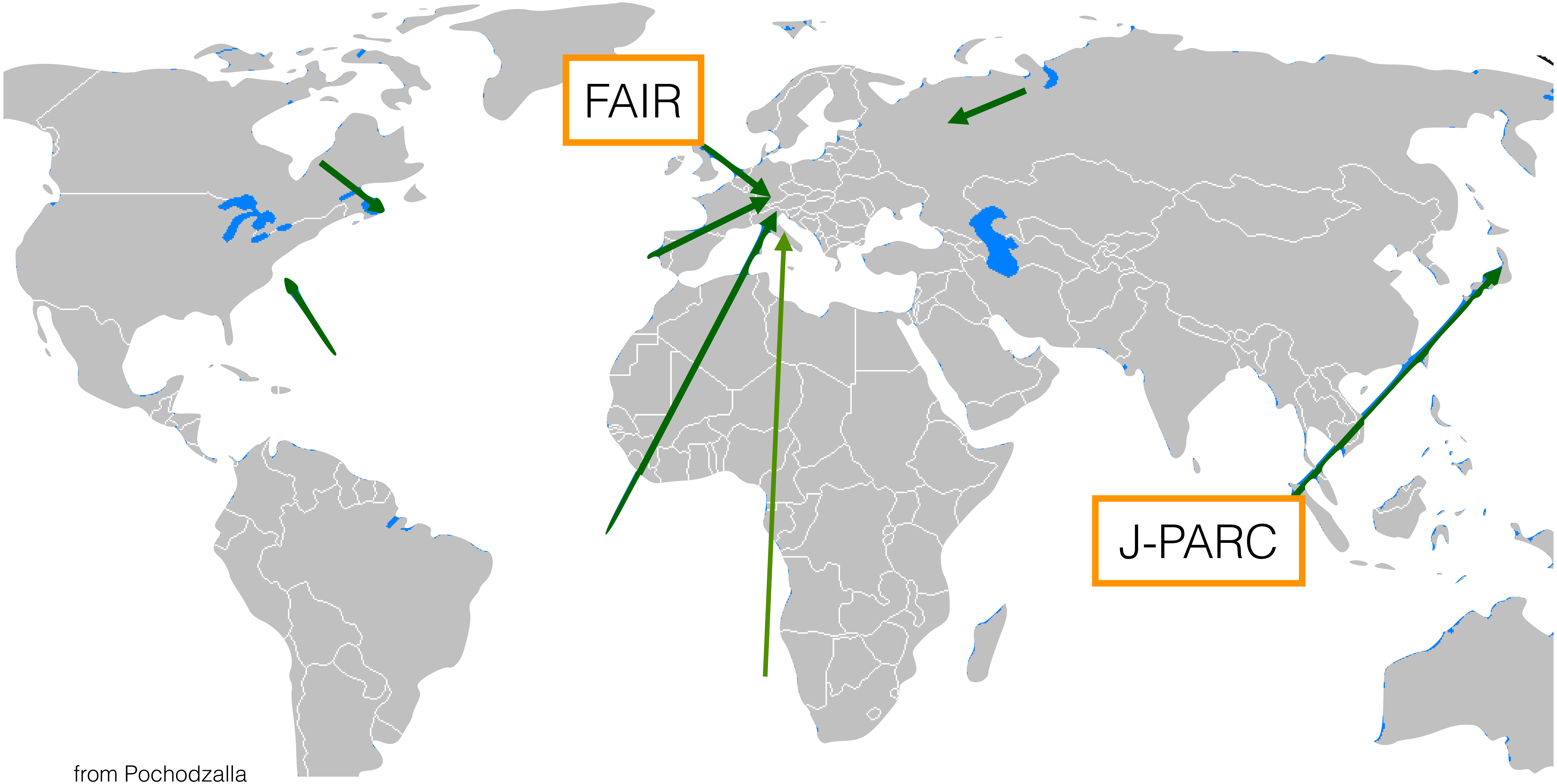
- η, η', … meson in nuclei

Exotica

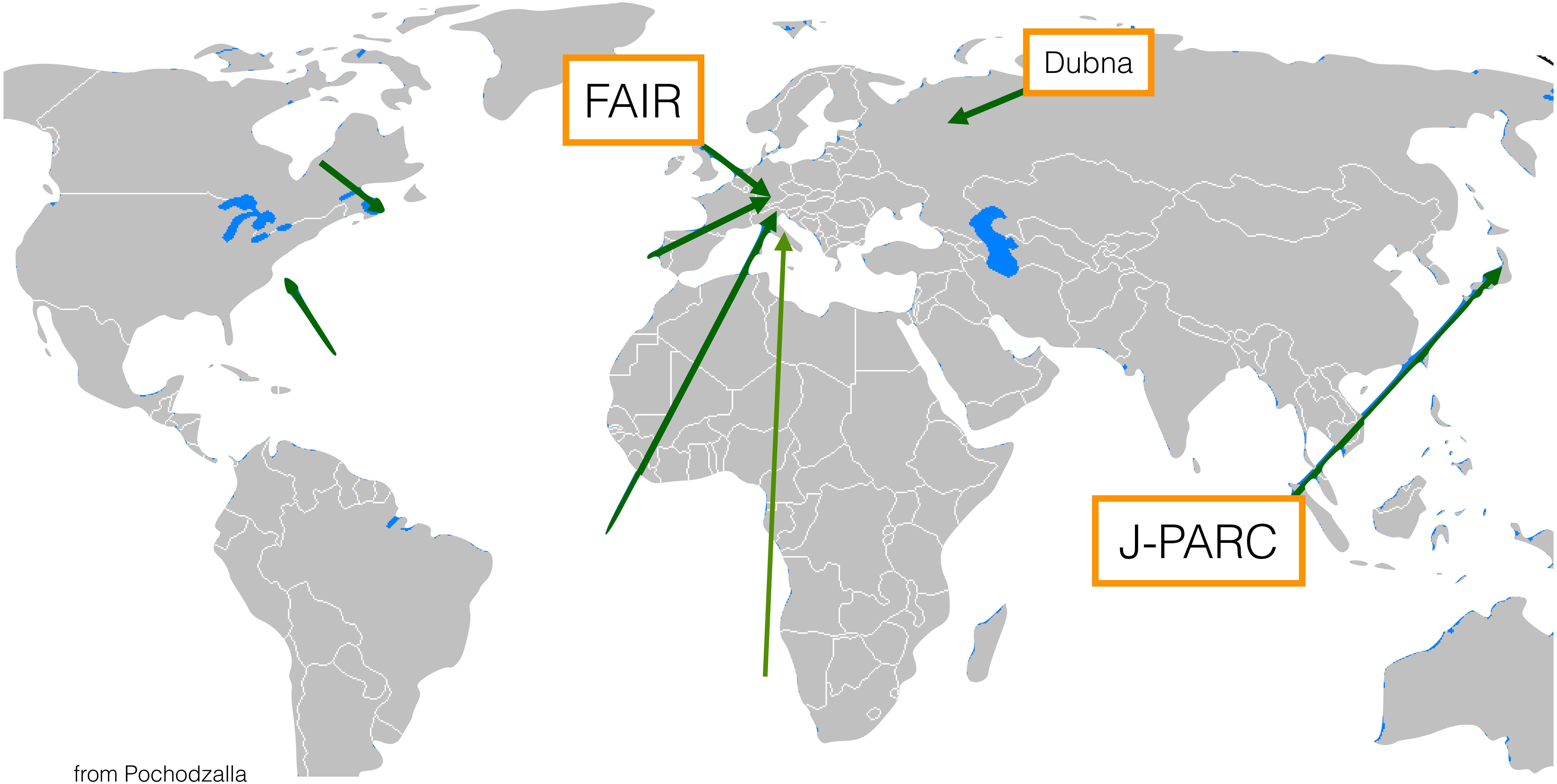
- $\bar{K}NN$, $\bar{K}\bar{K}NN$, …
- anti-hyperon in nuclei

3

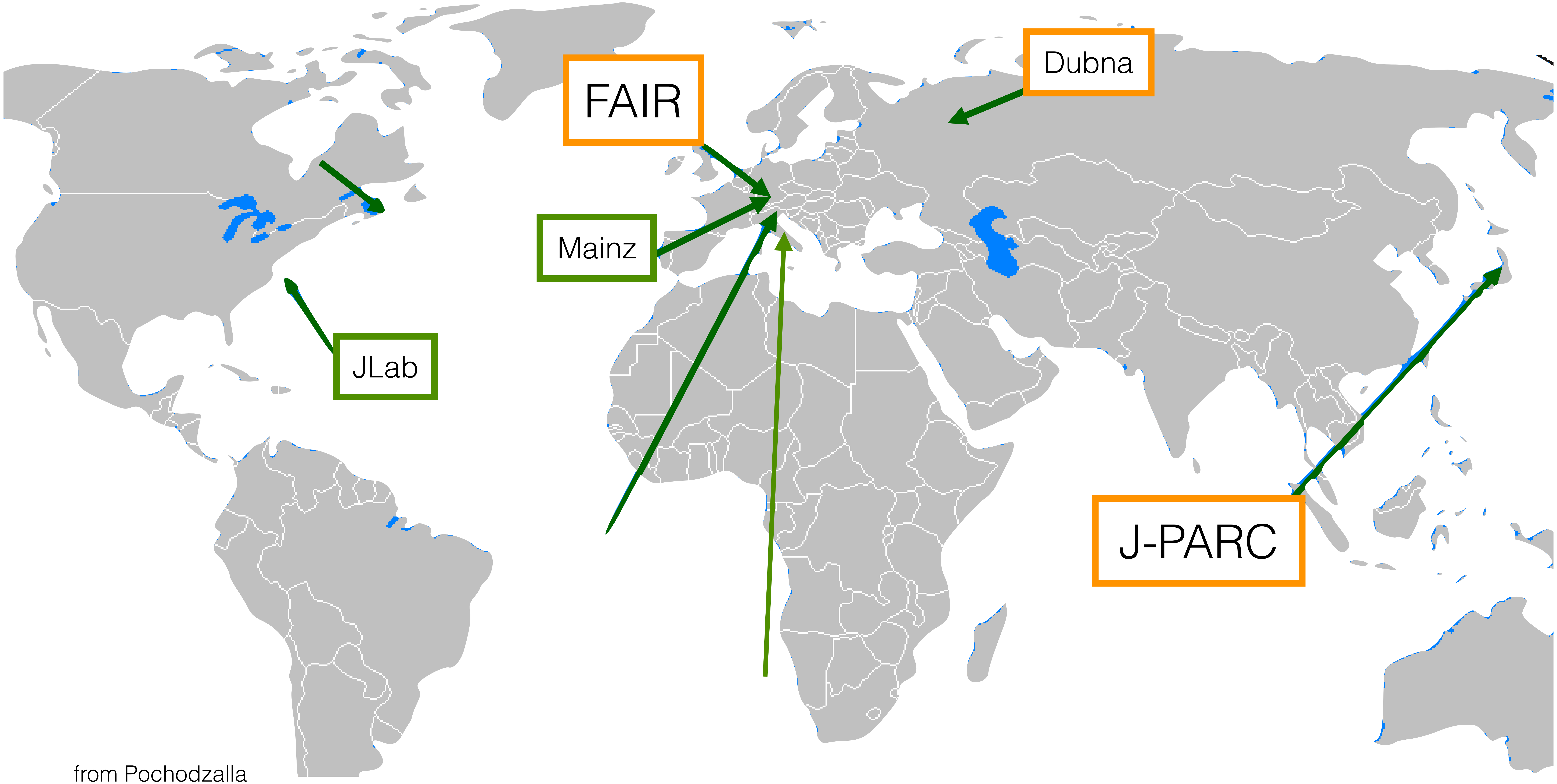
Facilities



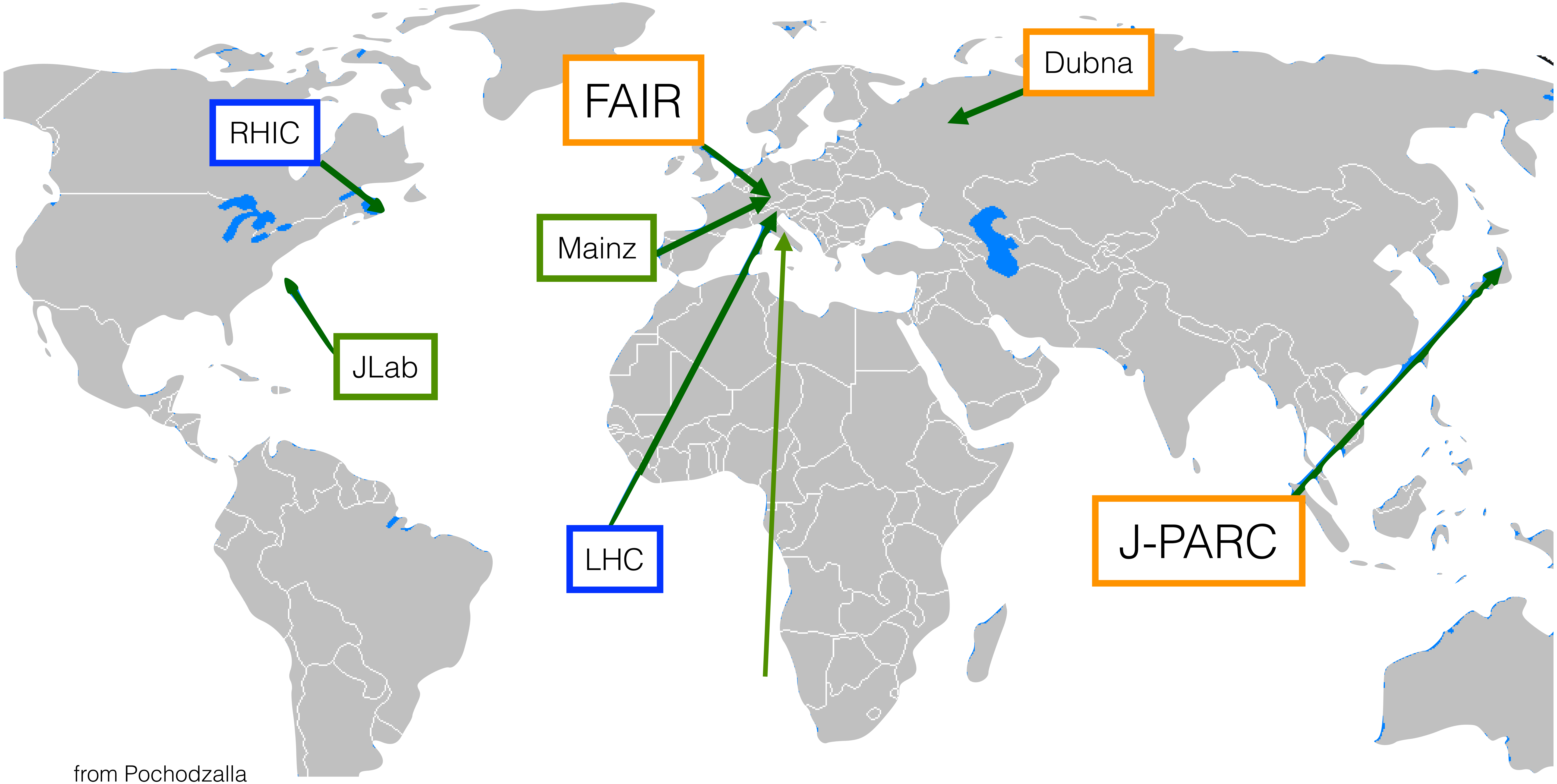
from Pochodzalla



from Pochodzalla



from Pochodzalla



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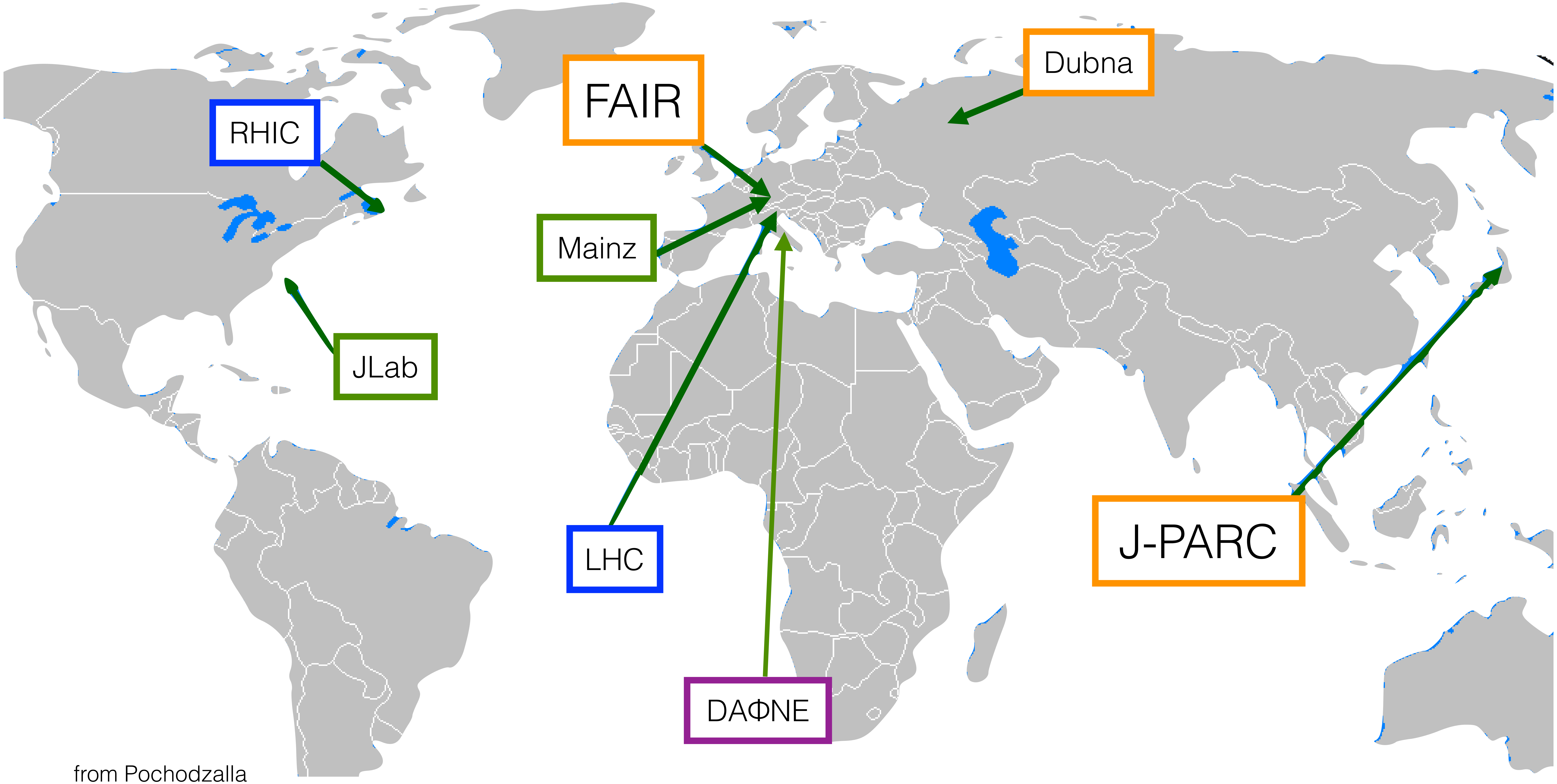

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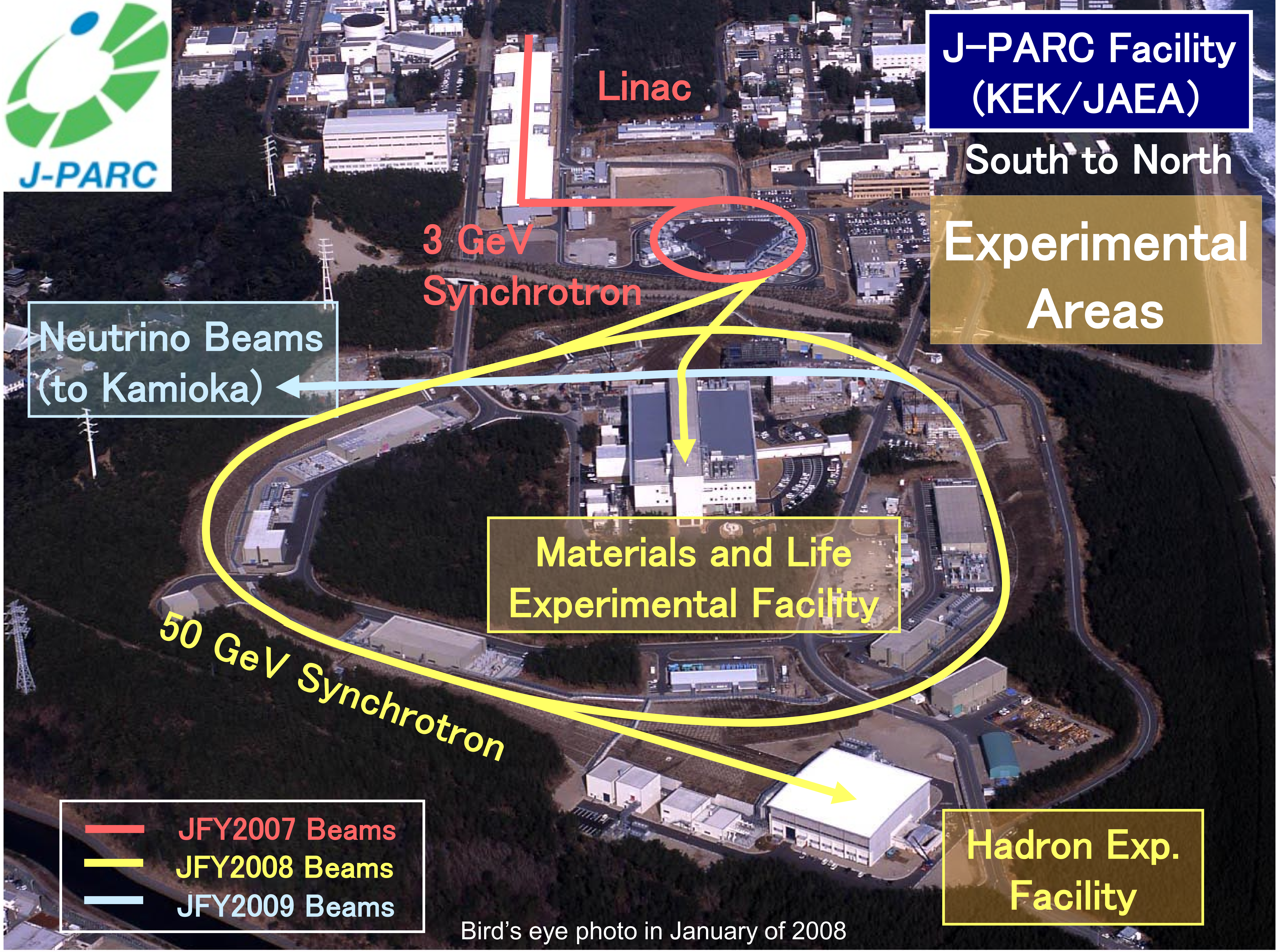
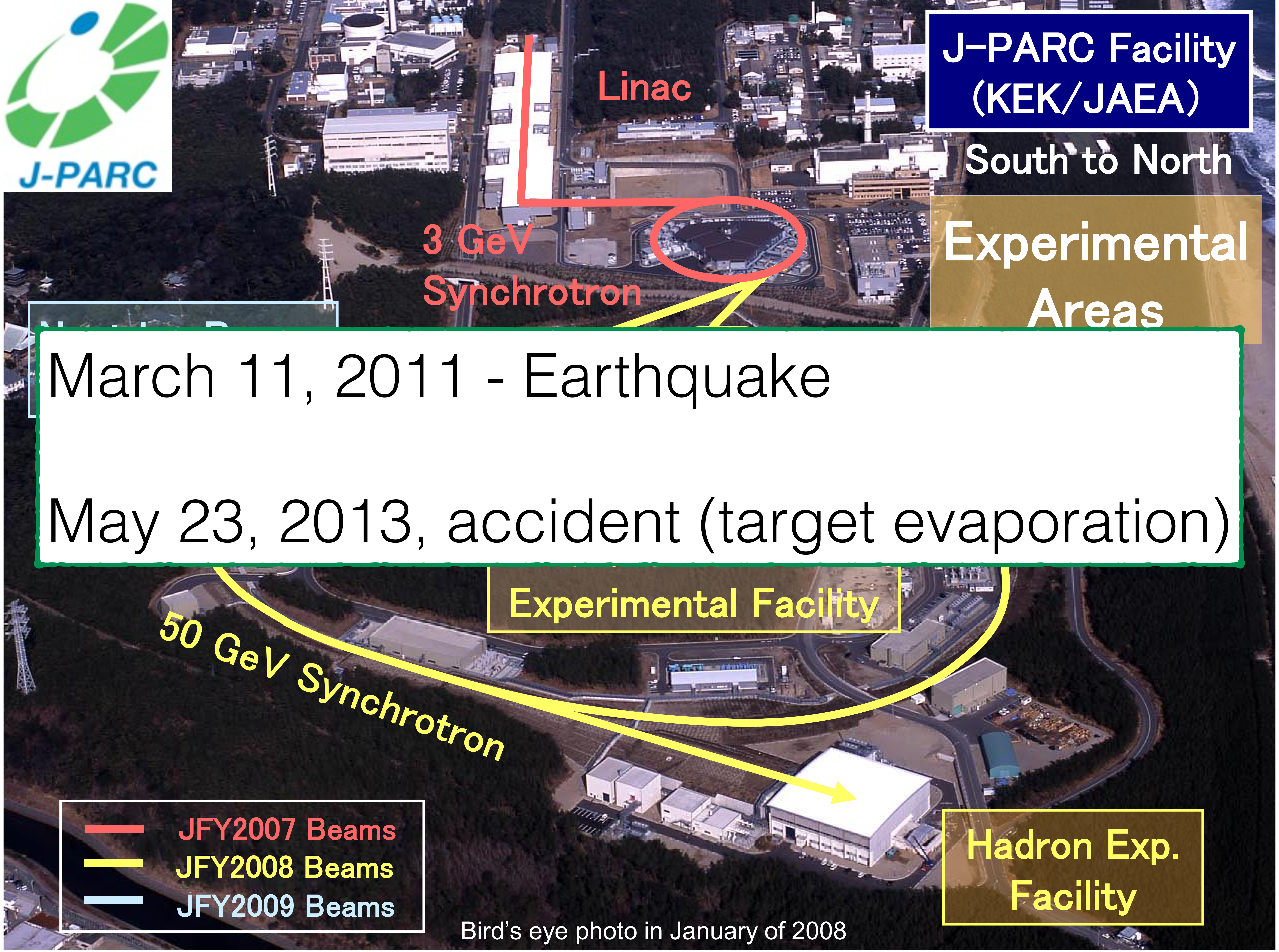

J-PARC
J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Experimental
Areas
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
50 GeV Synchrotron
Hadron Exp.
Facility
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008



Bird's eye photo in January of 2008

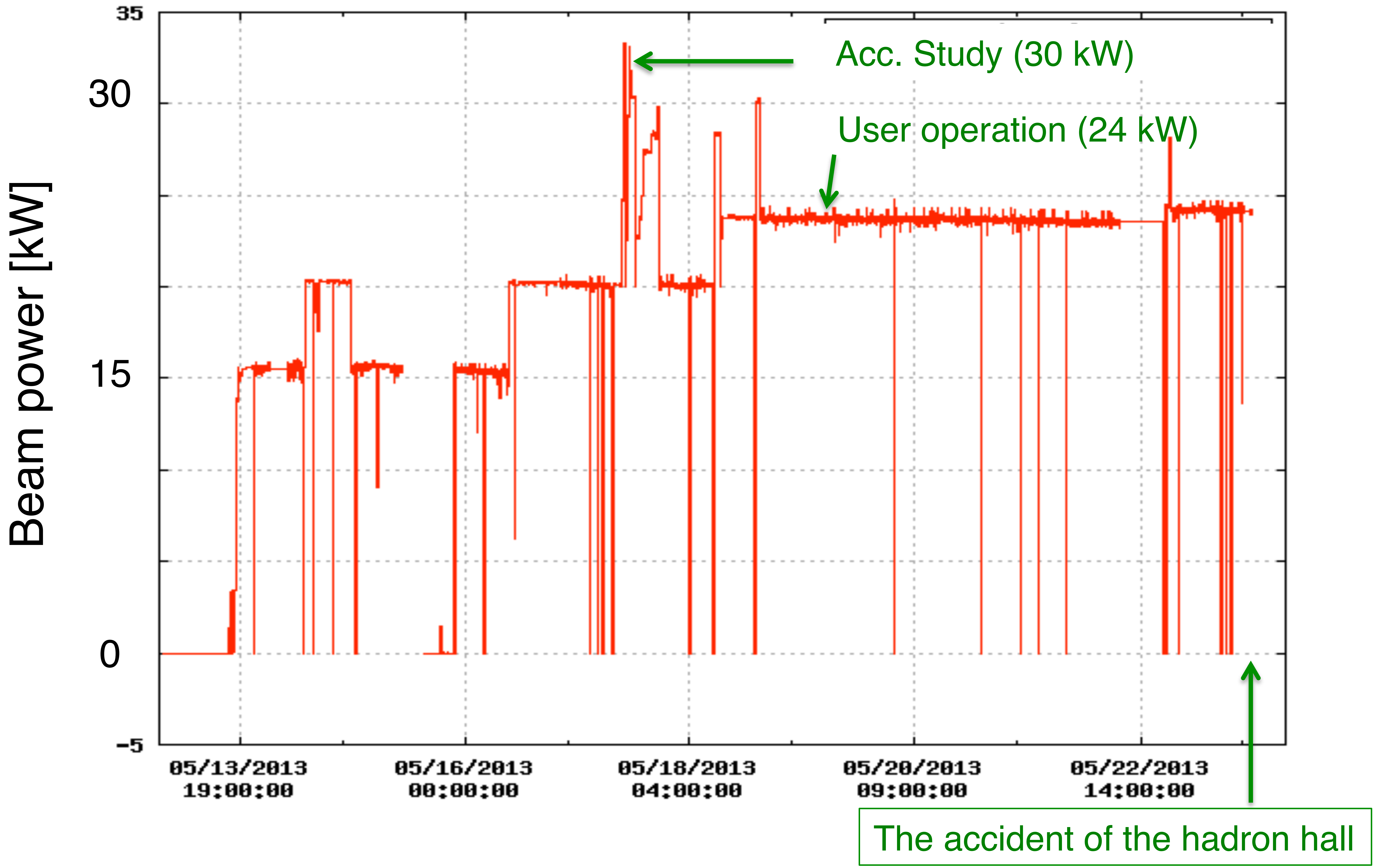
March 11, 2011 - Earthquake

May 23, 2013, accident (target evaporation)

Beam power of SX operation in May of 2013.

koseki, J-PARC

The maximum delivered power before May of 2013: 15 kW



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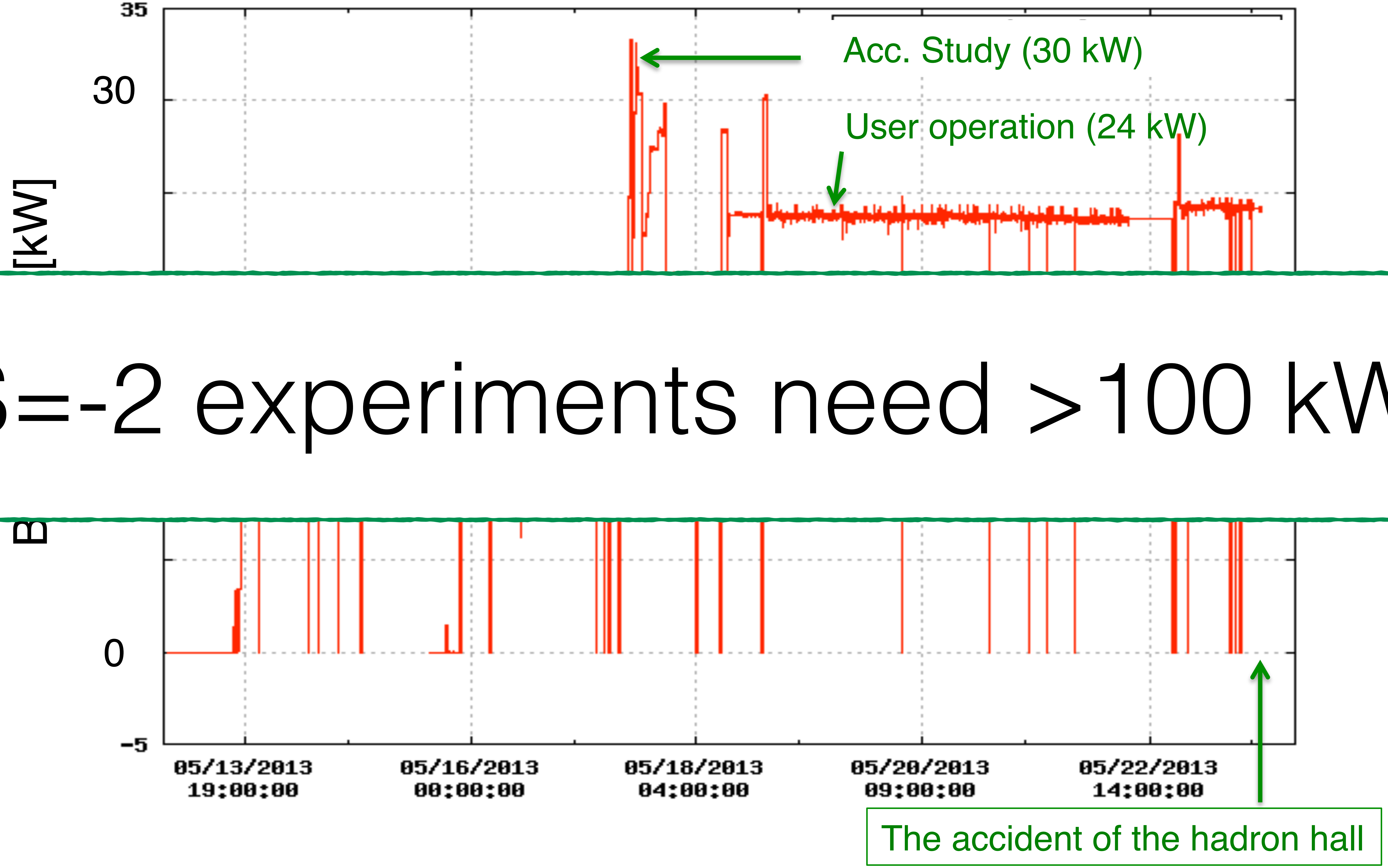
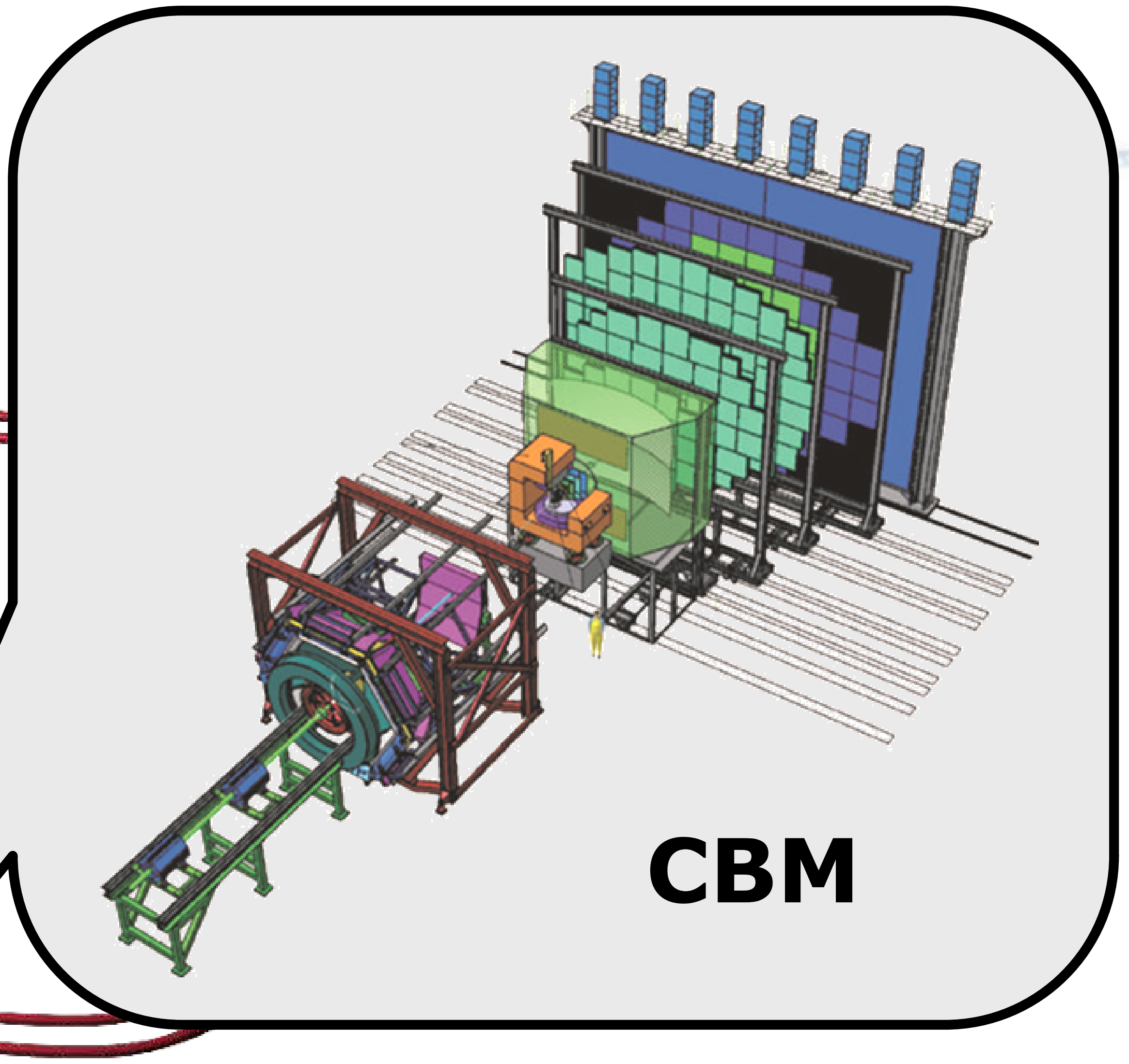


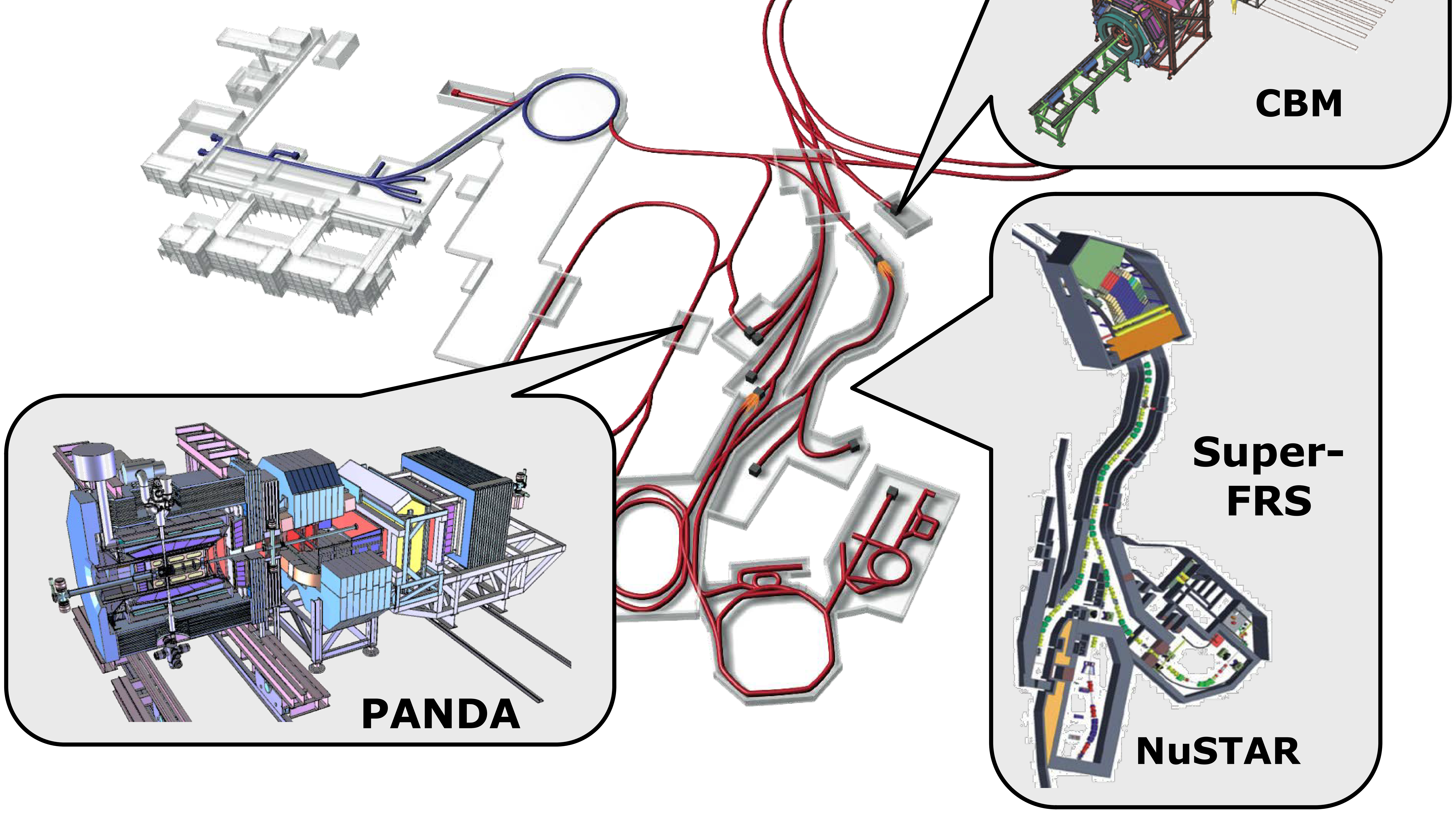
S=-2 experiments need >100 kW

koseki, J-PARC

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial)	150	200	200 - 240	200 –300 (400)			750
SX power [kW] (study/trial)	3 (10)	10 (20)	25 (30)	20-50			100
Cycle time of main magnet PS	3.04 s	2.56 s	2.48 s				1.3 s
New magnet PS for high rep.		R&D			Manufacture installation/test		
Present RF system	Install. #7,8	Install. #9					
New high gradient rf system		R&D		Manufacture installation/test			
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system	Inj. kicker	Kicker PS improvement, Septa manufacture /test					
FX system		Kicker PS improvement, LF septum, HF septa manufacture /test					
SX collimator / Local shields	SX collimator					Local shields	
Ti ducts and SX devices with Ti chamber		SX septum endplate	Beam ducts	Beam ducts ESS			

“Strangeness”-capable facilities





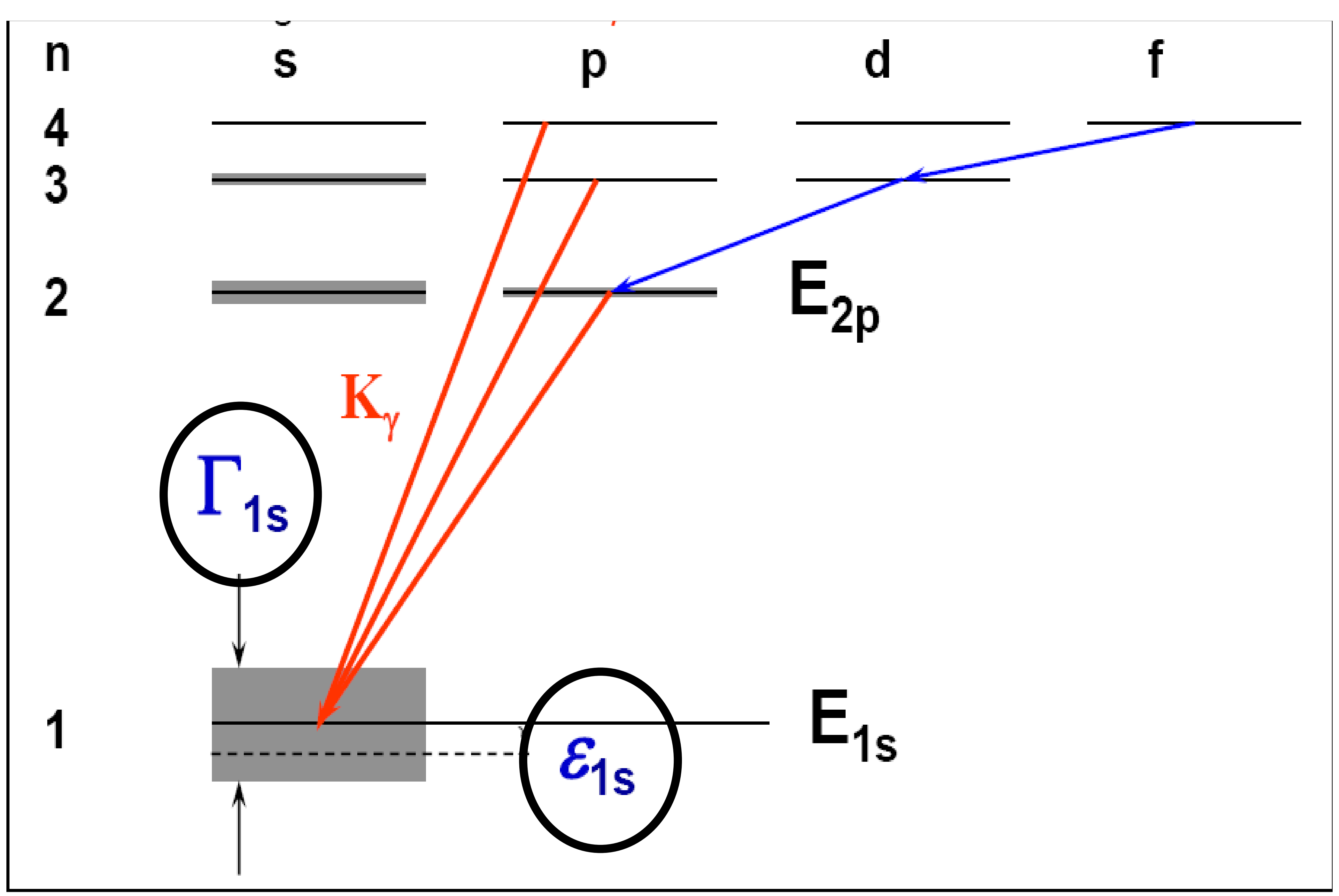
from Pochodzalla

4

Strange atoms

Kaonic atom ($\bar{K}N$ at threshold)

strong-interaction shift and width



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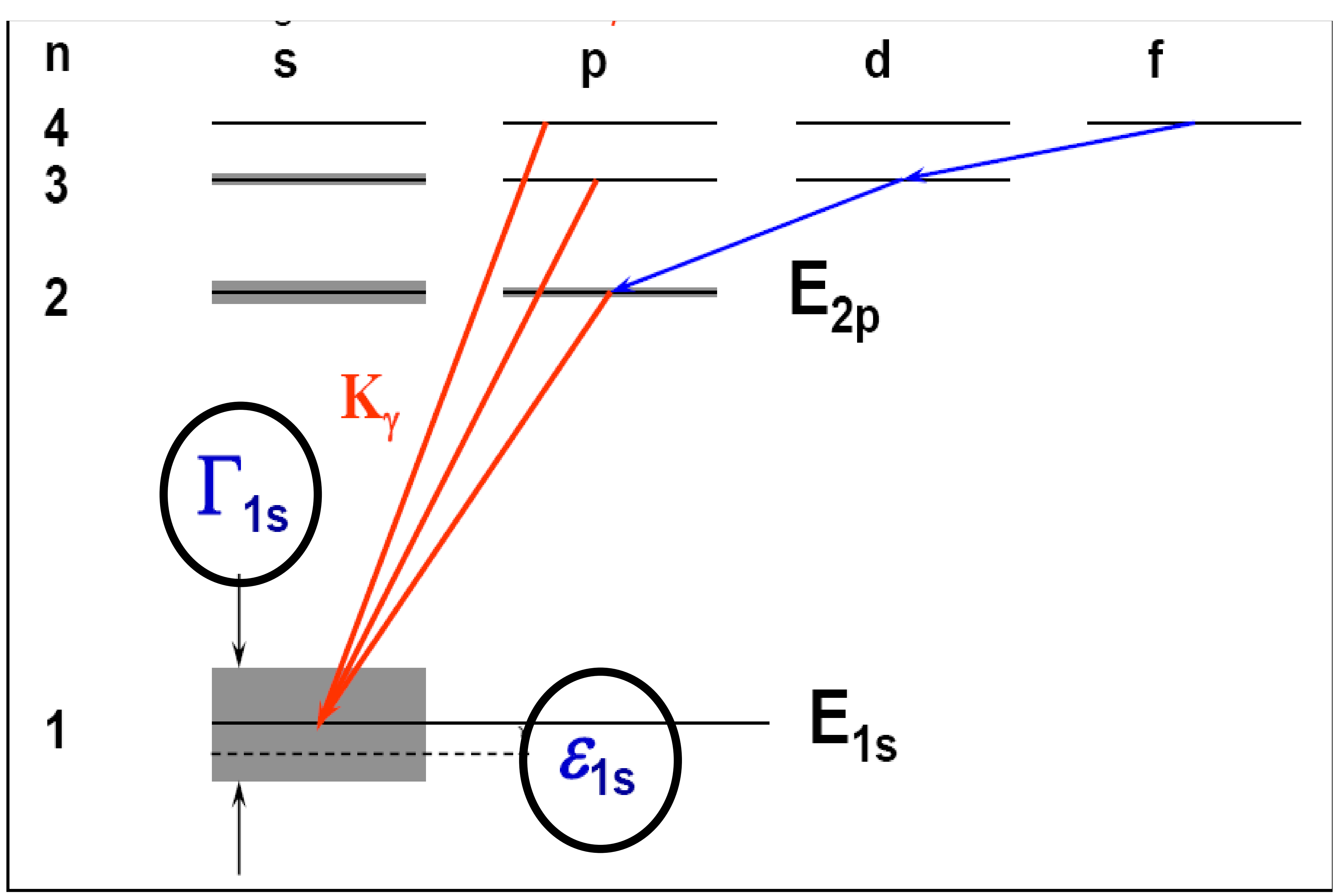
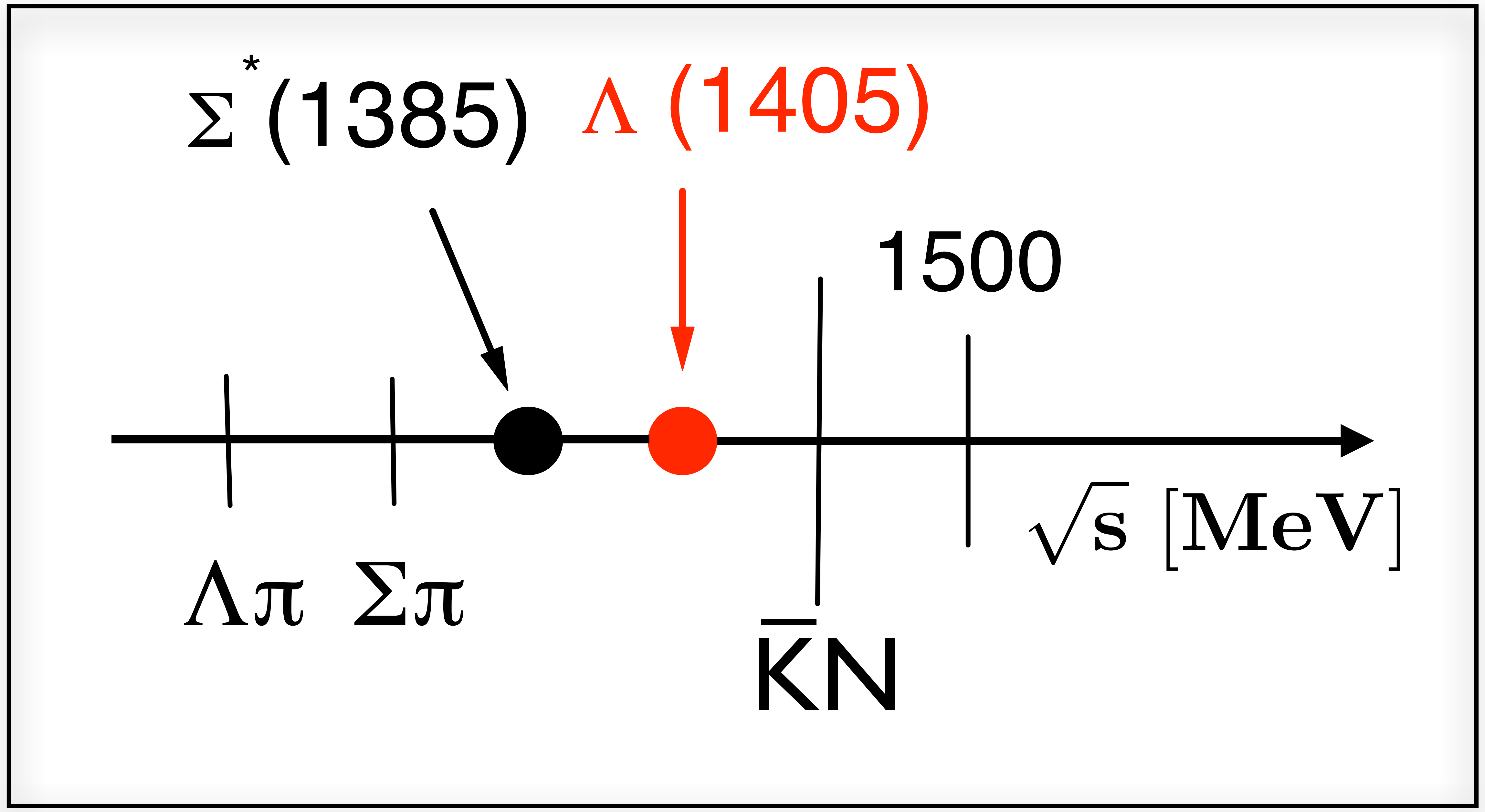
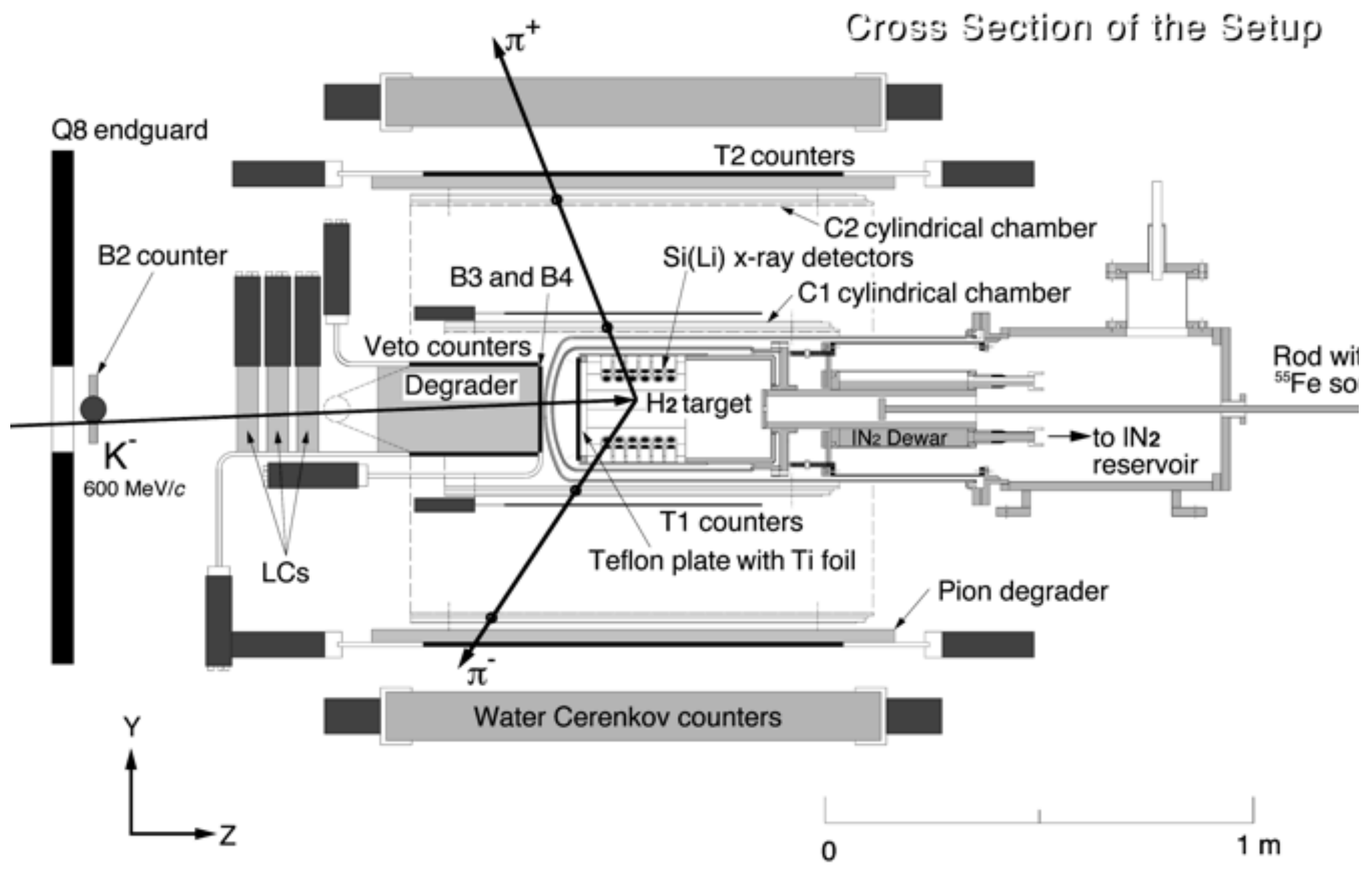
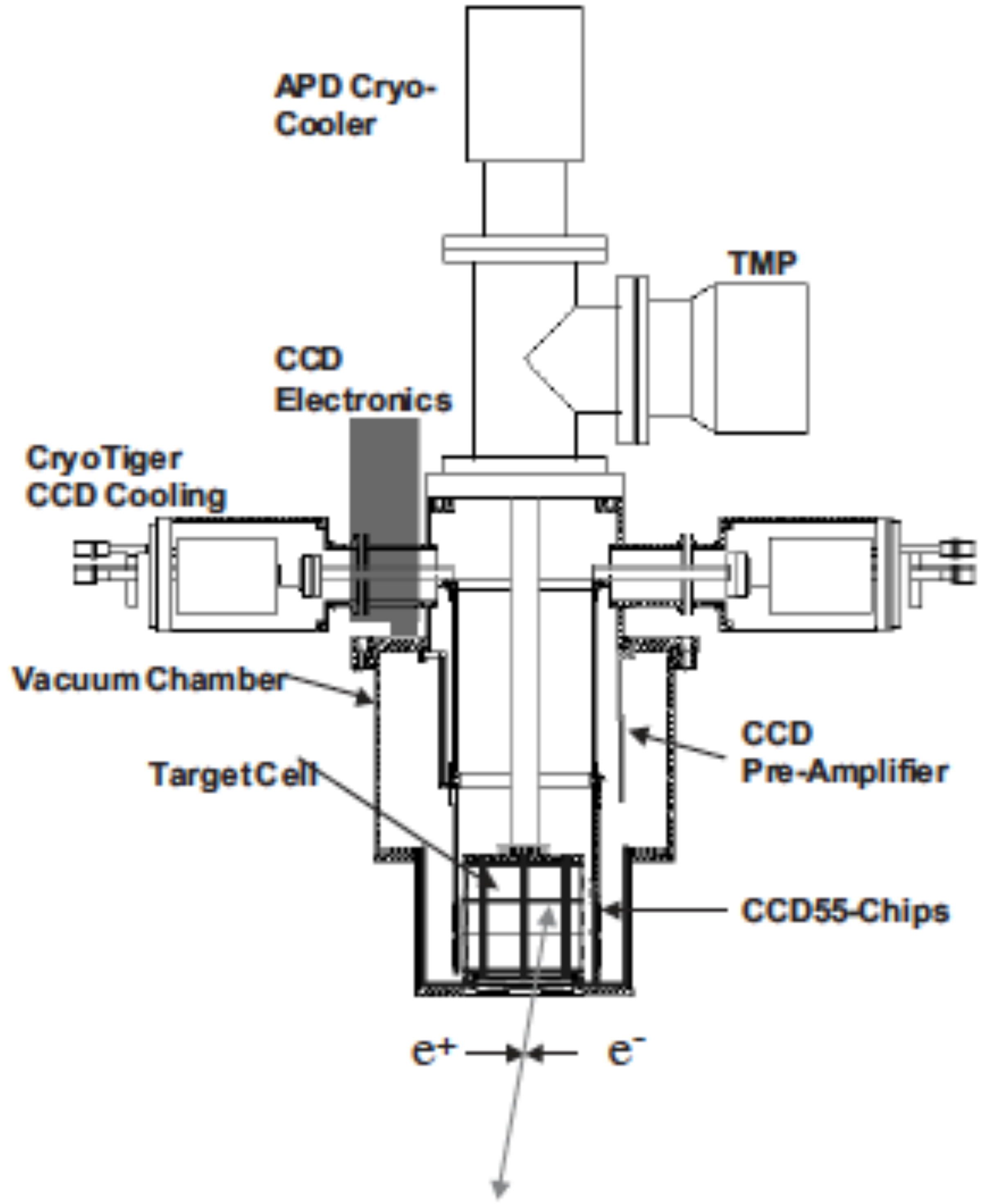


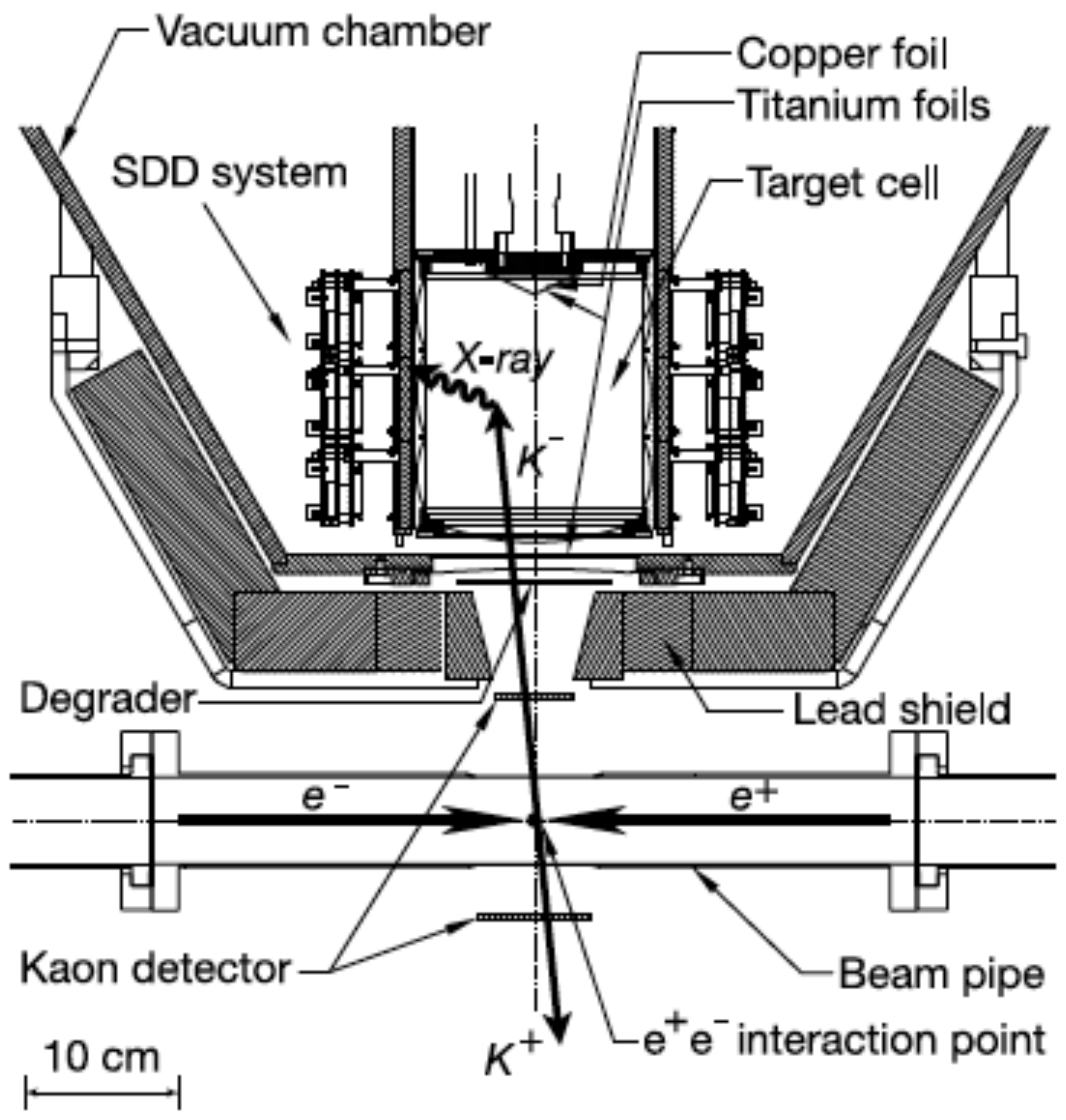
Λ(1405) below the threshold
K-p interaction : attractive
x-ray shift : repulsive



K⁻p x-ray - 1997-2011



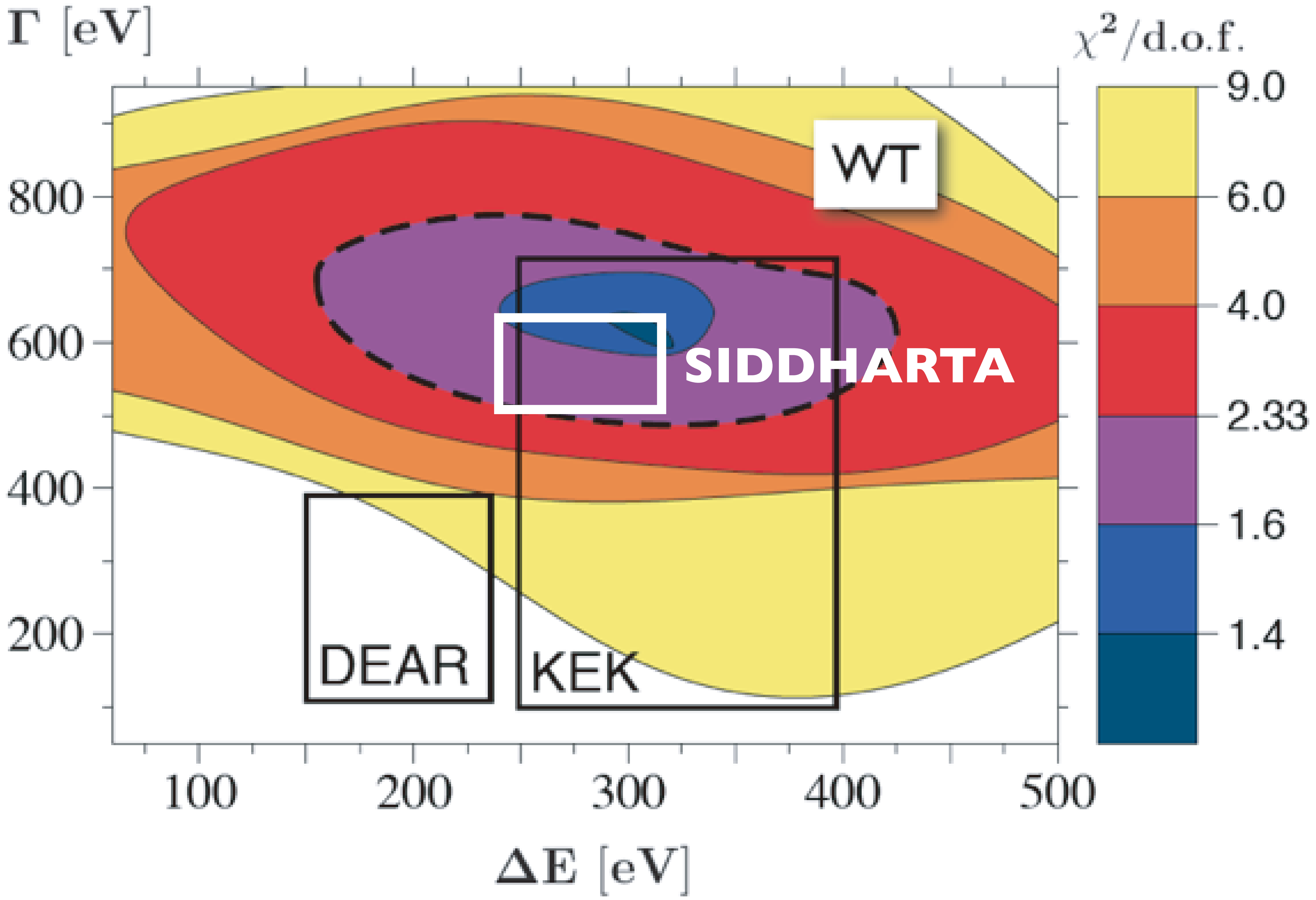




KpX, PRL1997
KEK (K beam)
Gas target
→ Si(Li) detectors

DEAR, PRL2005
DAFNE ($e^+ e^-$ collider)
Gas target
→ CCD detectors

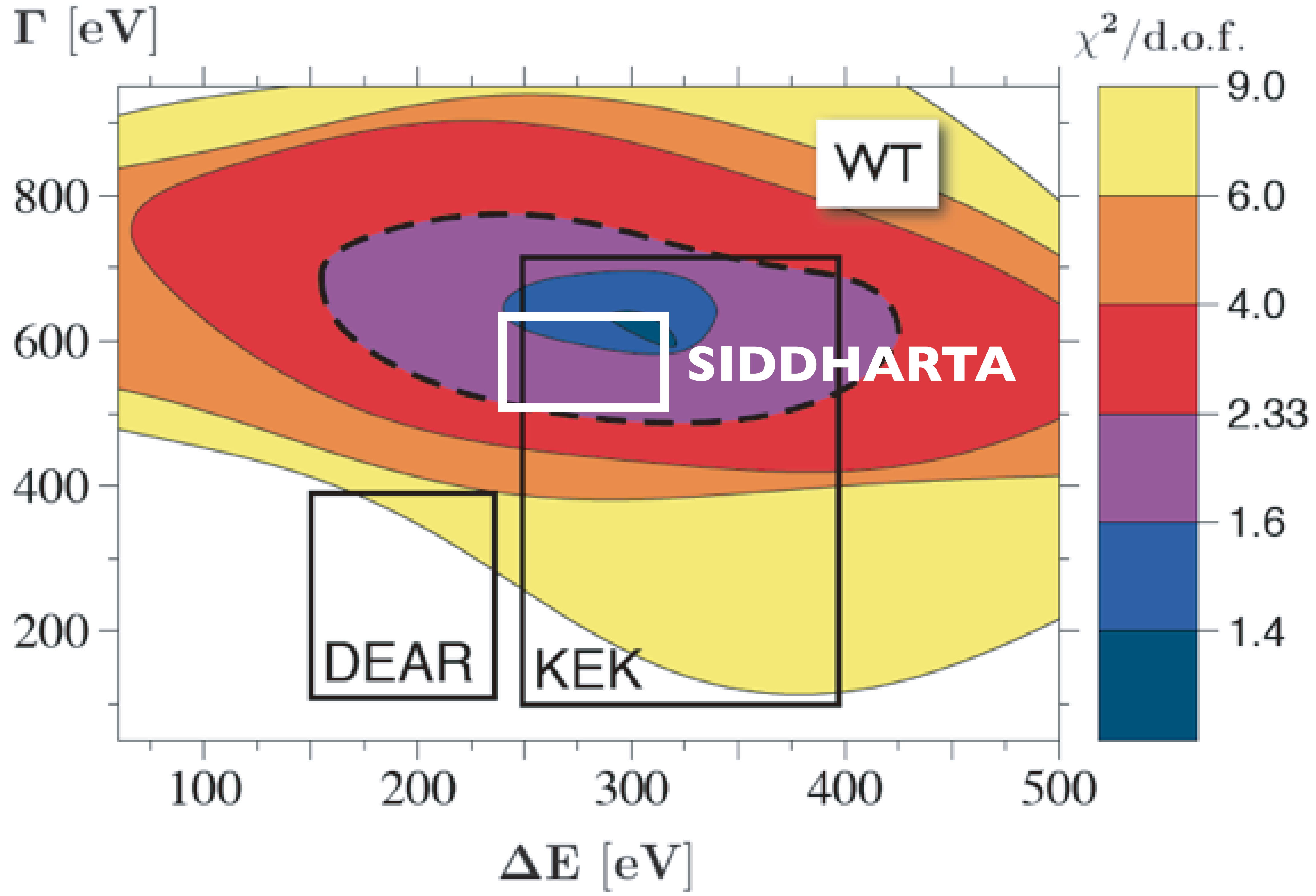
SIDDHARTA, PLB 2011
DAFNE ($e^+ e^-$ collider)
Gas target
→ SDD detectors



ε_{1S}= −283 ± 36(stat) ± 6(syst) eV

Γ_{1S}= 541 ± 89(stat) ± 22(syst) eV

Physics Letters B704 (2011) 113



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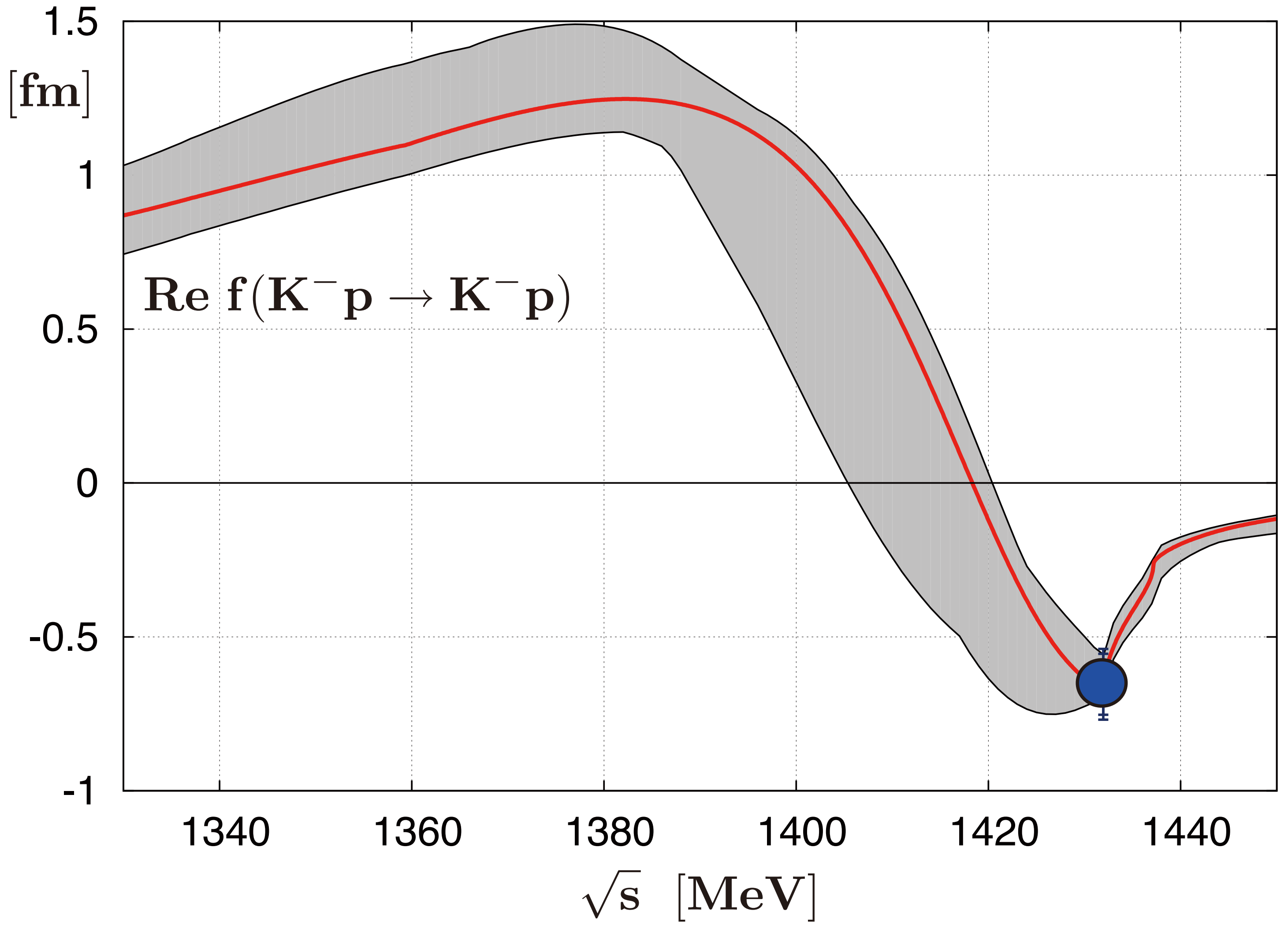
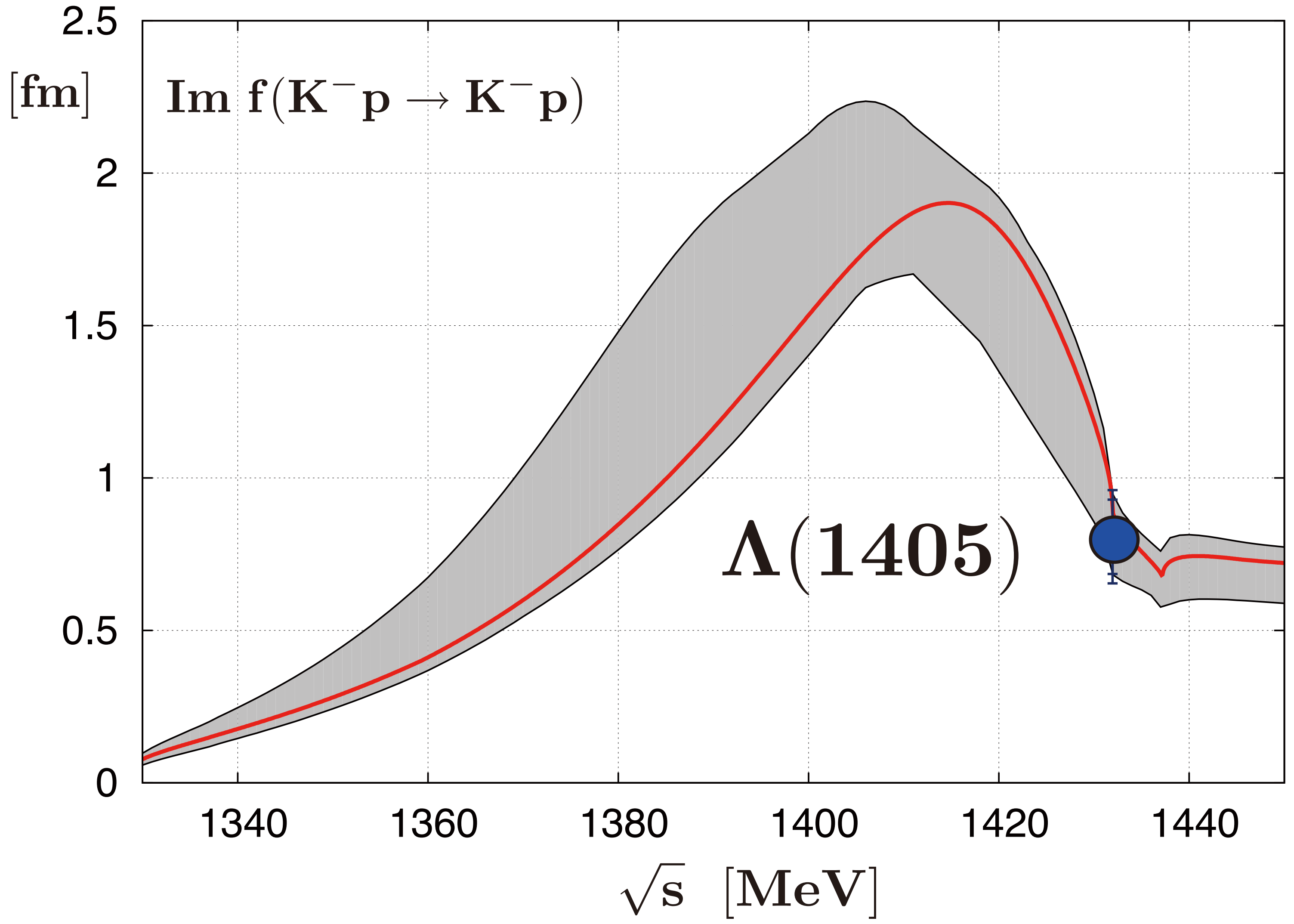
Physics Letters B704 (2011) 113





$$\mathrm{Re}\, a(K^-p) = -0.65 \pm 0.10 \ \ \mathrm{fm}$$
$$\mathrm{Im}\, a(K^-p) = 0.81 \pm 0.15 \ \ \mathrm{fm}$$

Chiral SU(3)
Ikeda, Hyodo, Weise
NPA881 (2012) 98
PLB 706 (2011) 63

NEXT: accurate constraints from K^-d threshold measurements

complete information for both isospin I=0 and I=1 $\bar{K}N$ channels

	Kaonic hydrogen	Kaonic deuterium
Yield (Kα) estimates	3%	→0.3% (depending on 2p state width)
Energy (Kα) e.m.	6.5 keV	7.8 keV
Shift (1s) eV	-283±36(stat)±6(syst)	-800 ? (estimate)
Width (1s) eV	541±89(stat)±22(syst)	800 ? (estimate)

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J-PARC?
DAΦNE?

Ξ⁻ atoms (J-PARC / FAIR)

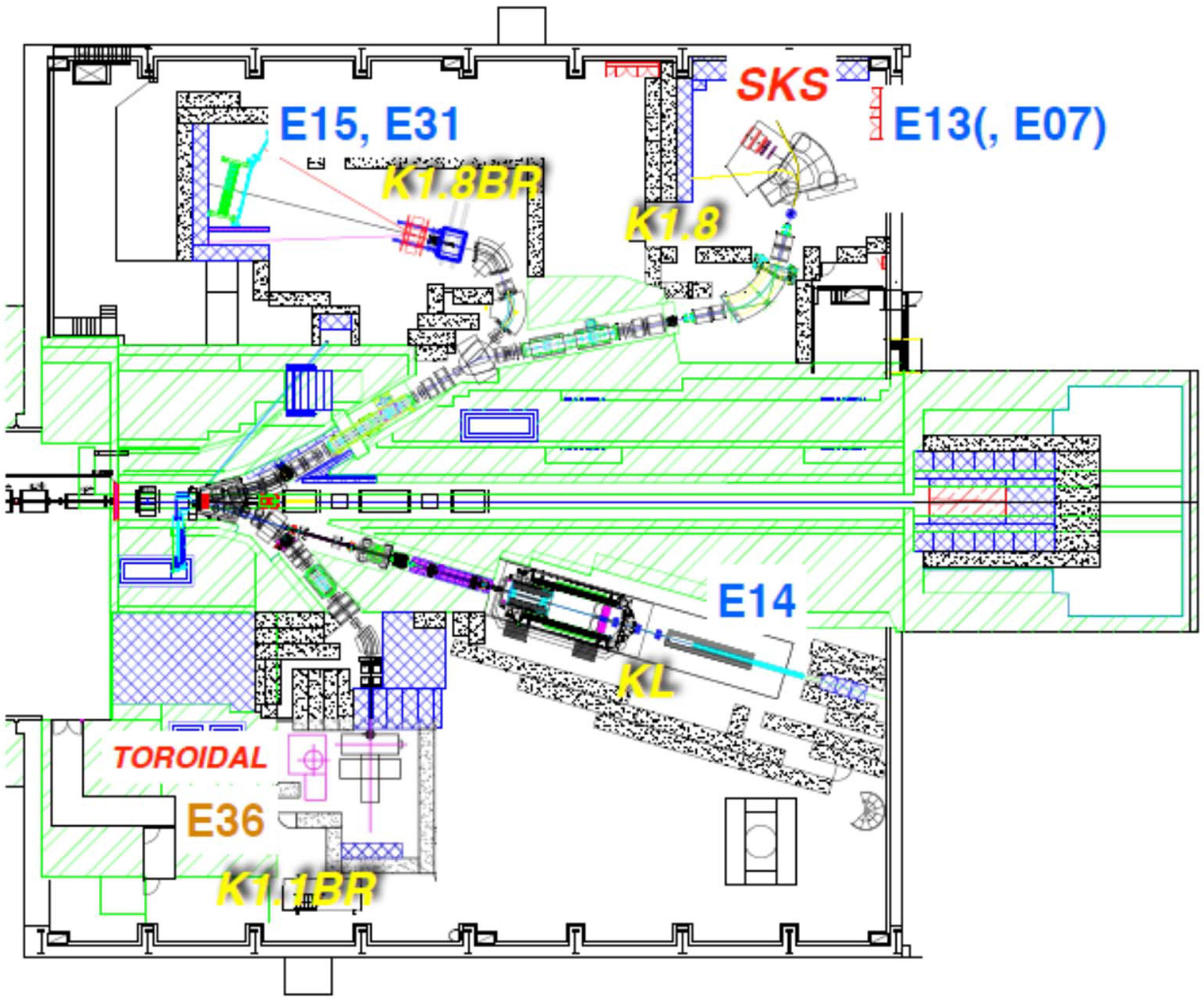
Ryu Hayano, *Int. Conf. on Science and Technology for FAIR in Europe, Worms, Oct 14, 2014*

5

Hypernuclei & J-PARC program

$S = -1$

J-PARC 2014-2015



K1.8 + SKS

- γ-ray spectroscopy (E13)

K1.8BR

- $^3He(K^-,n)$ K^-pp (E15)
- $d(K^-,n)\Lambda(1405)$ (E31)

KL

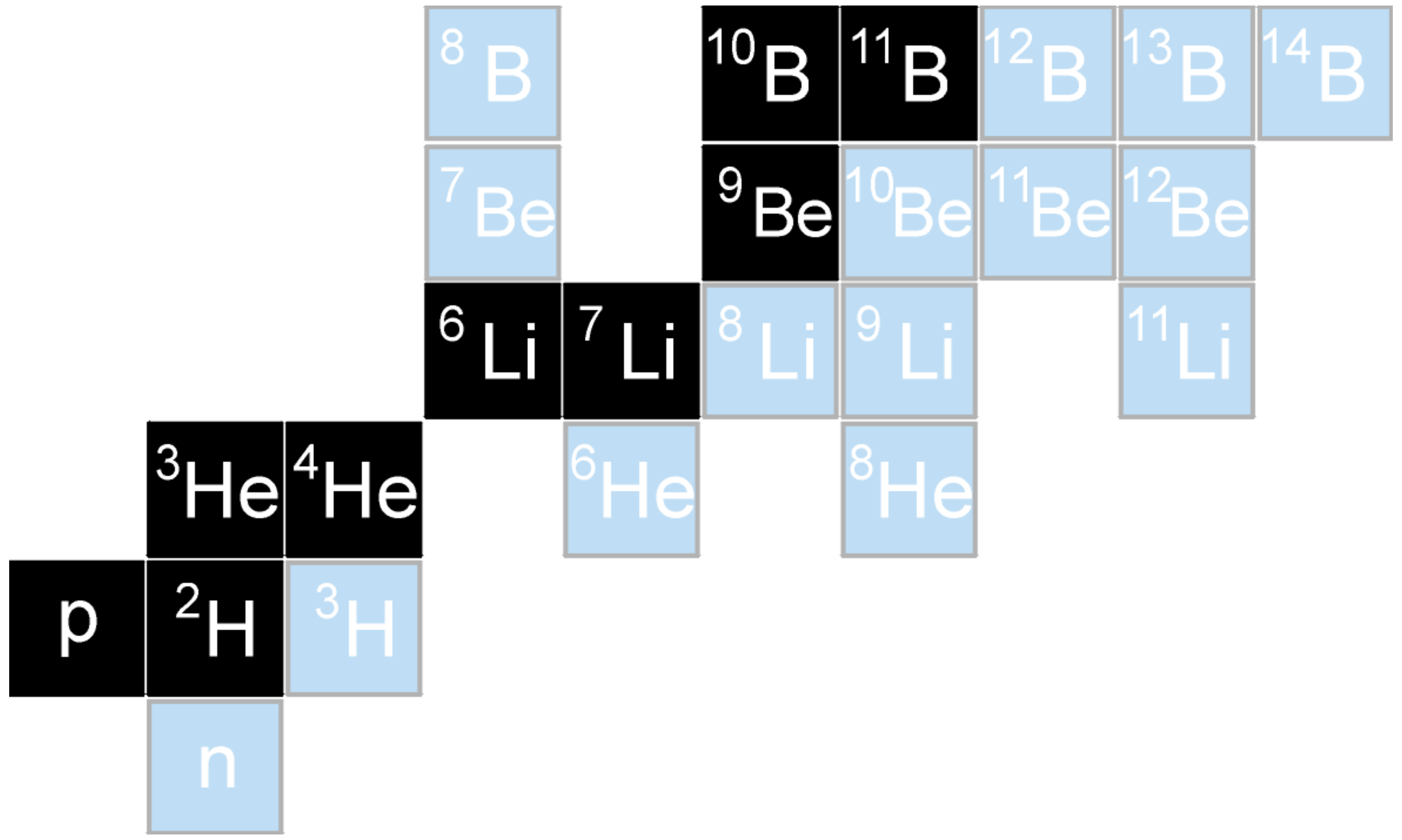
- KOTO (E14)

K1.1BR + Toroidal

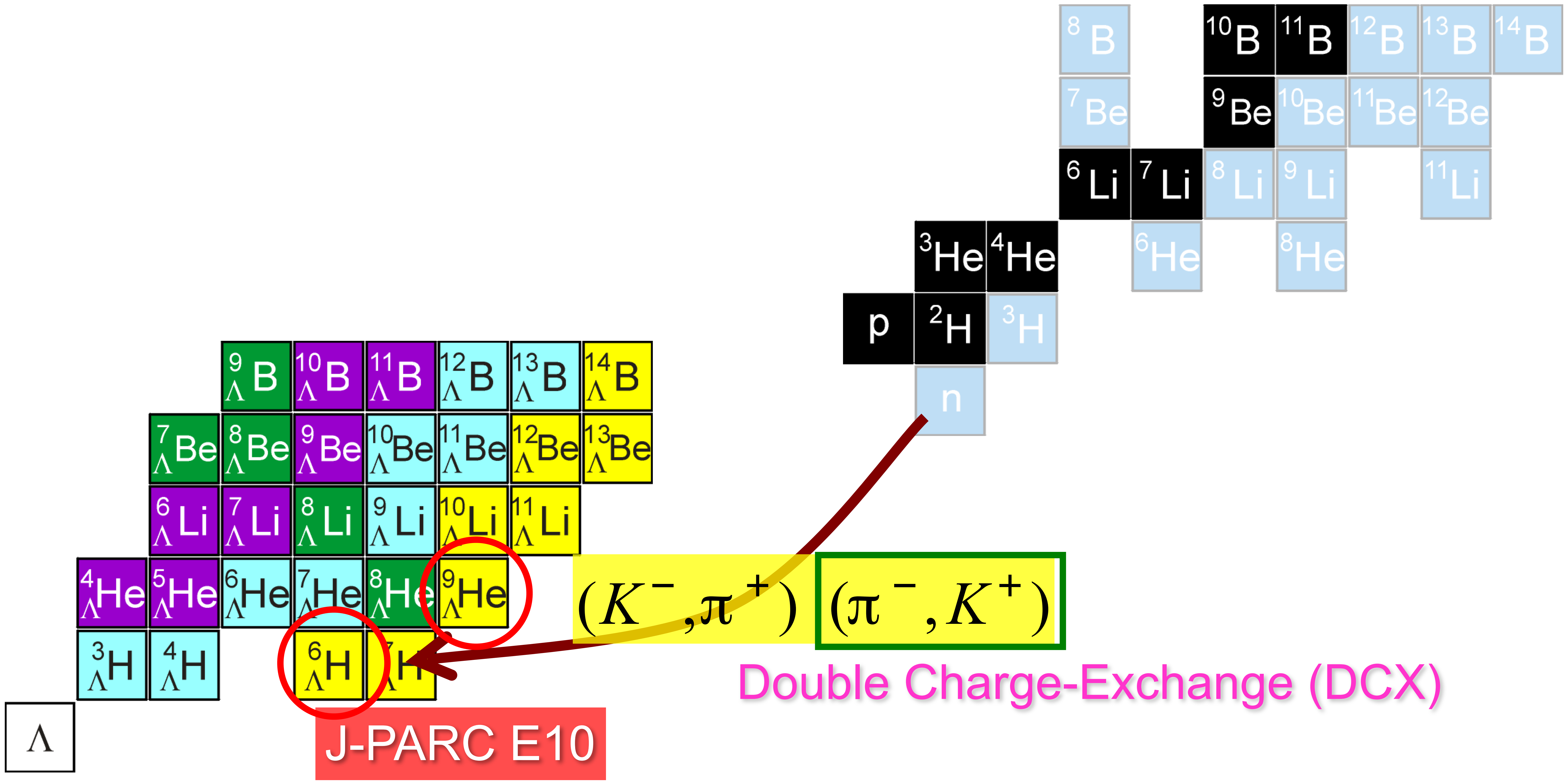
- Lepton Universality (E36)

source, 18th J-PARC PAC (May 2014) T. Takahashi

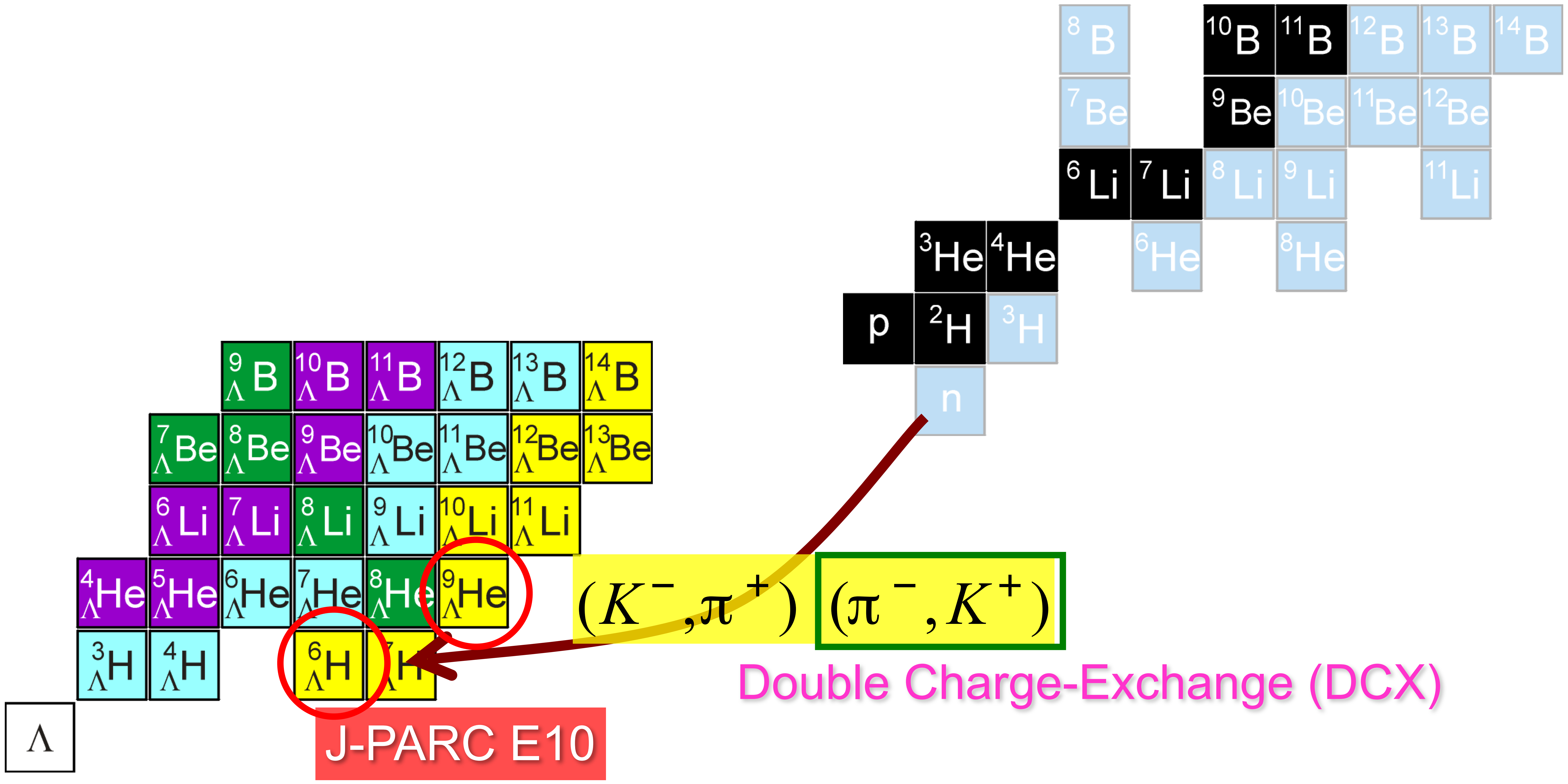
E10: Neutron rich hypernuclei via (π^-,K^+) reaction

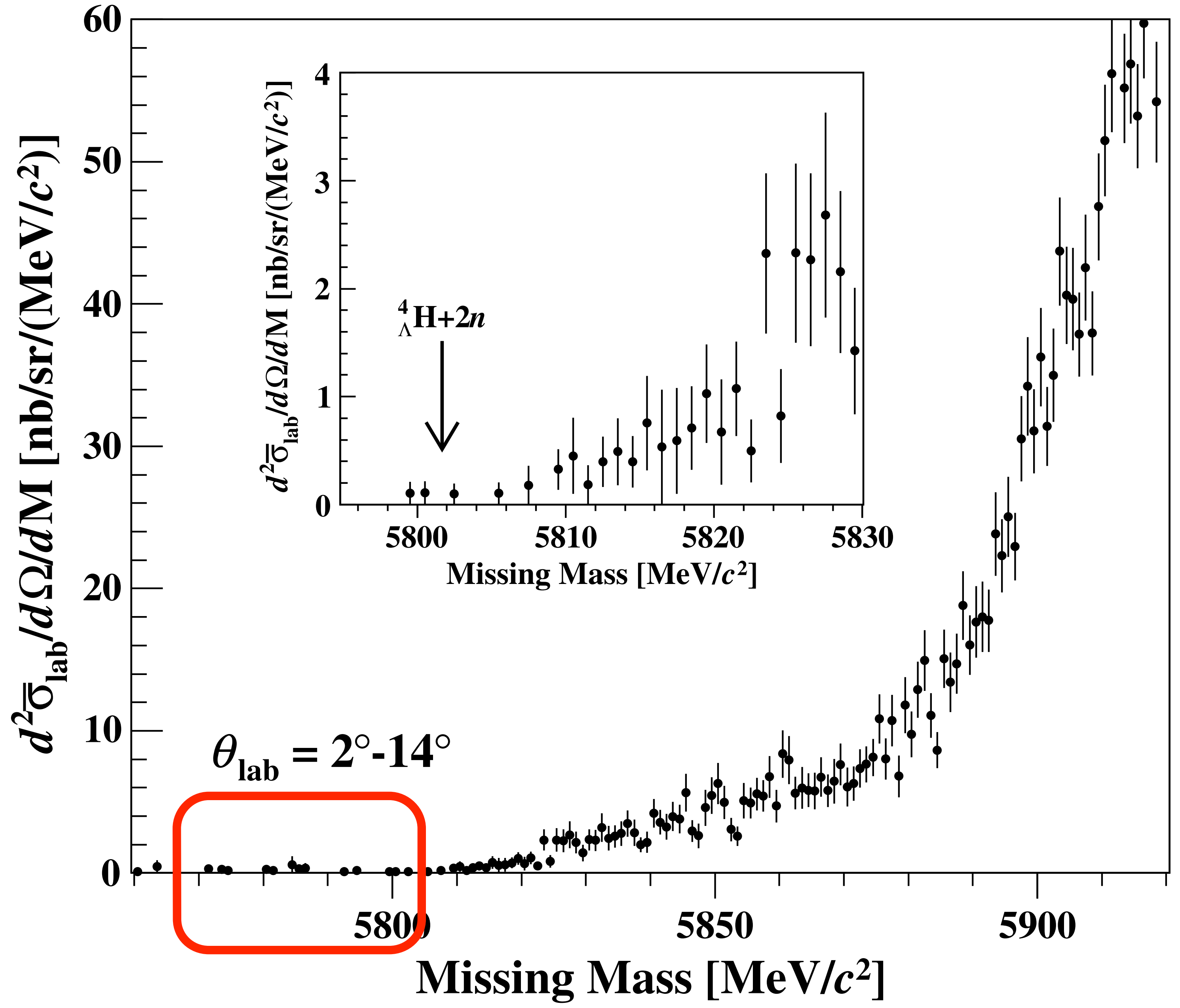


E10: Neutron rich hypernuclei via (π^-,K^+) reaction



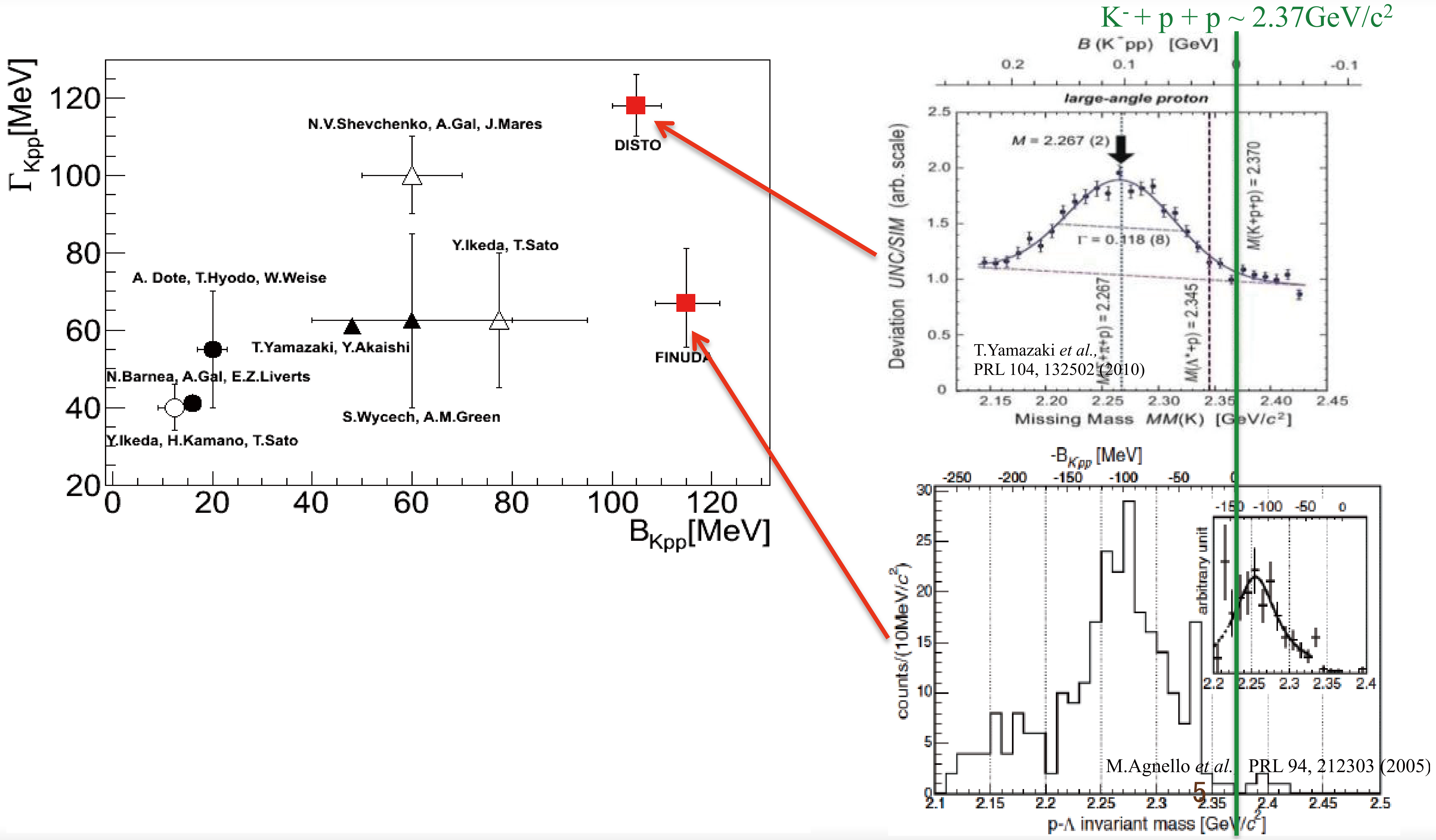
E10: Neutron rich hypernuclei via (π^-,K$^+$) reaction



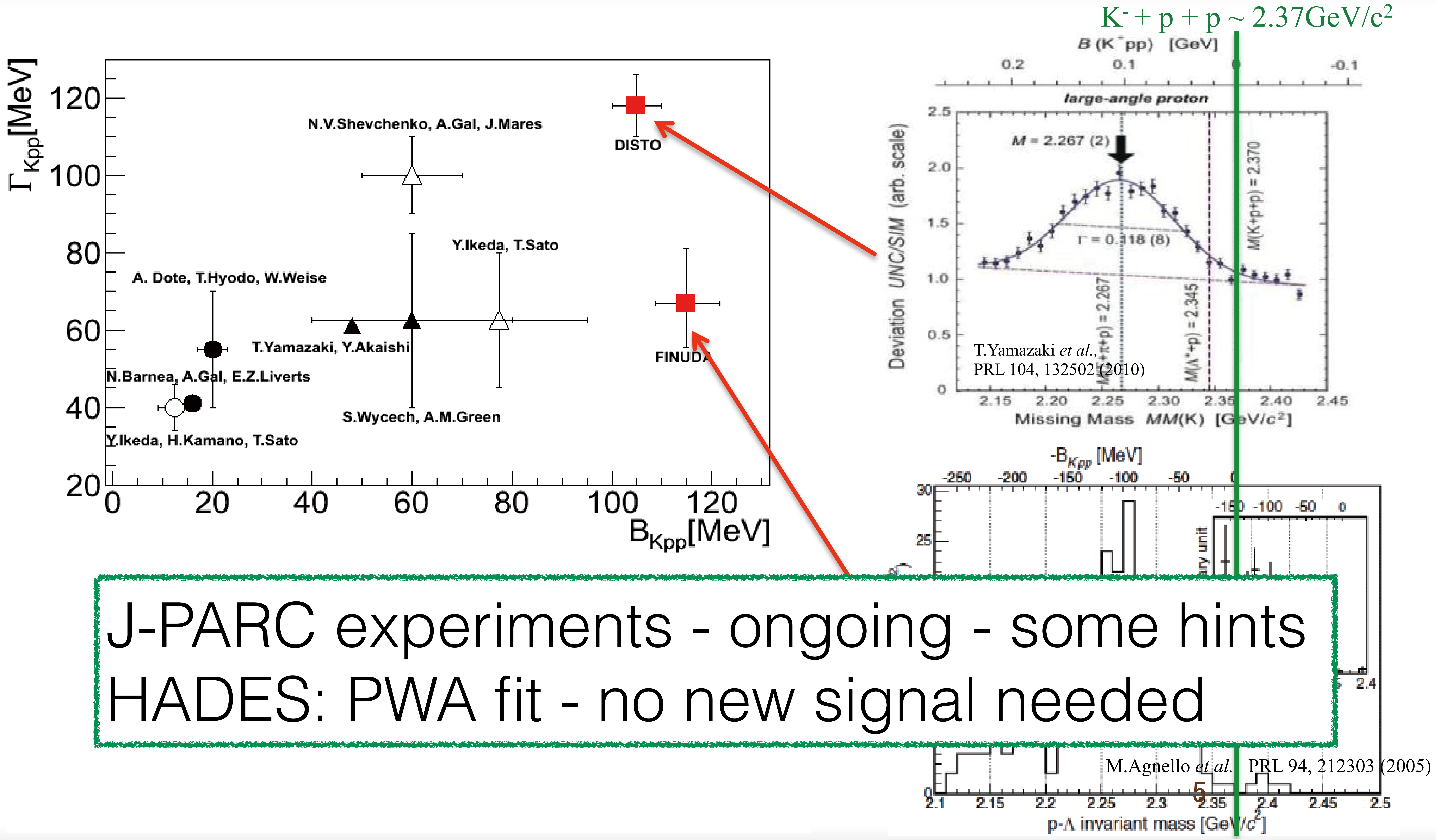


Result (negative)
PLB 729 (2014) 39

so-called "K⁻pp"



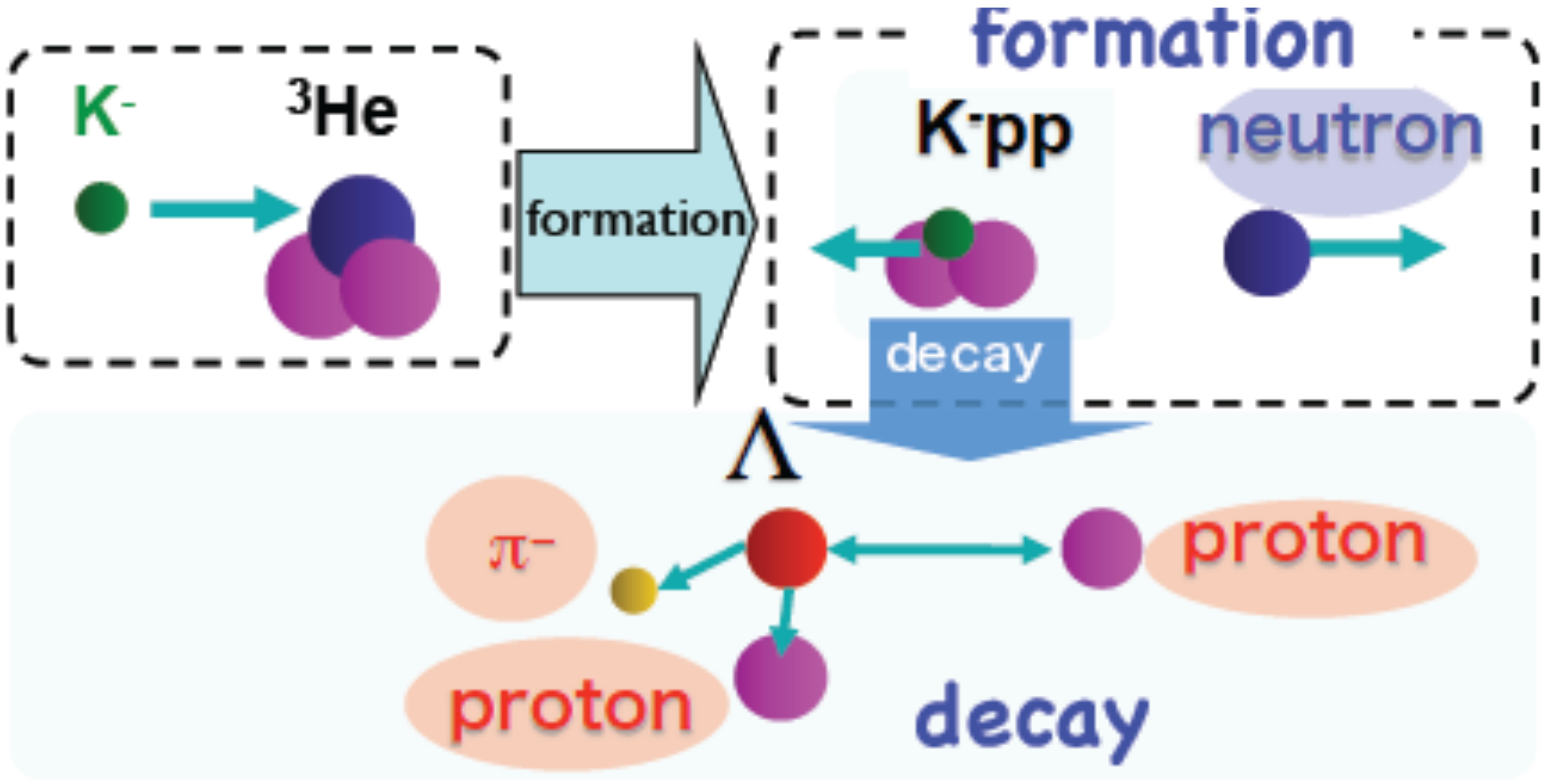
so-called “K⁻pp”



J-PARC experiments - ongoing - some hints
HADES: PWA fit - no new signal needed

E15: search for “K⁻pp”

from Iwasaki



$K^- + {}^3He$ -> “ K^-pp” + n

at 1 GeV/c
by both
missing & invariant mass

formation decay

detect everything!

Formation vs Decay

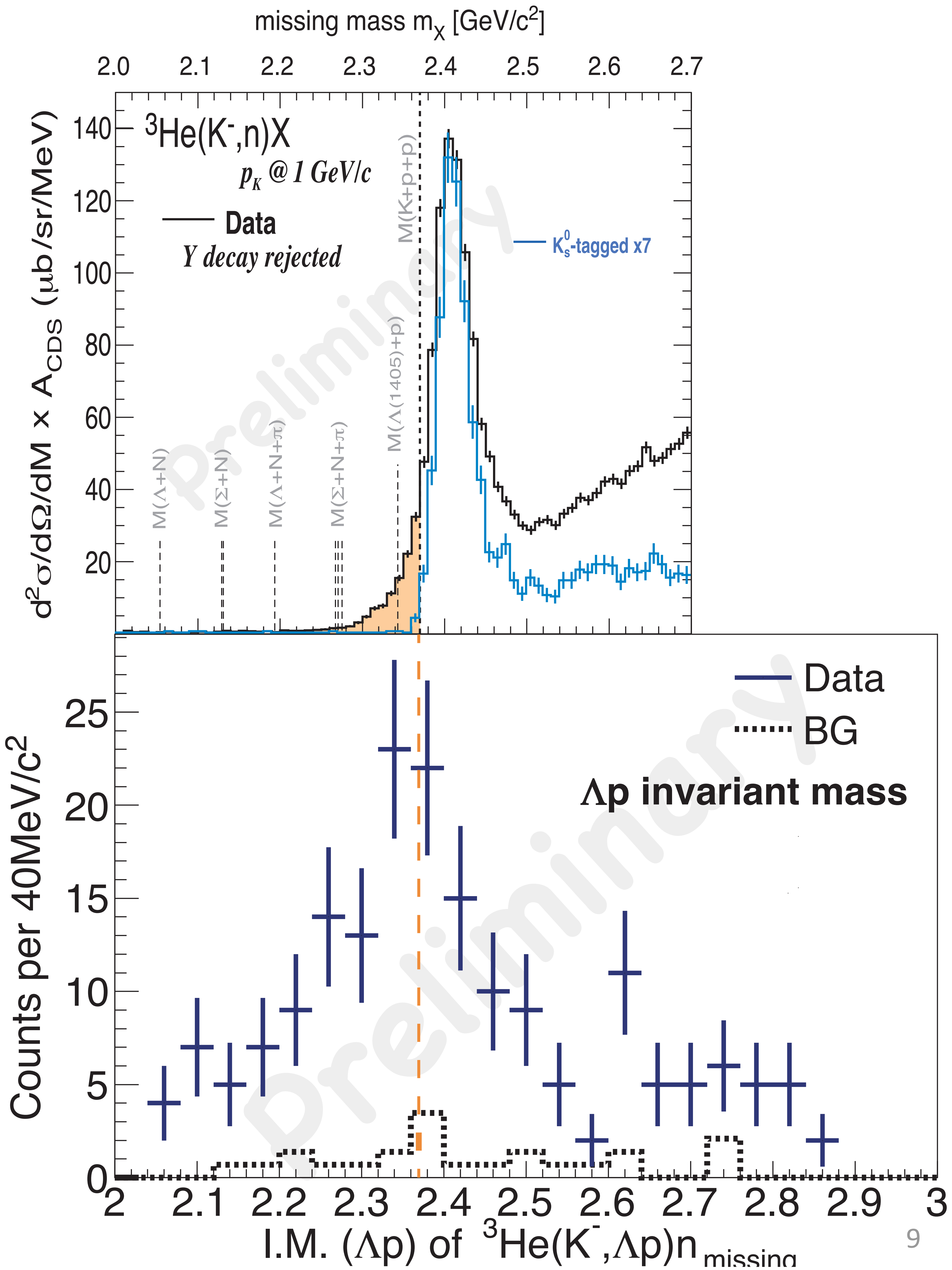
from Iwasaki

Formation channel

semi-inclusive

$K^- + {}^3He \rightarrow n + X\ (\theta_n=0)$

- excess below threshold
- contribution from $\Lambda(1405)n + p_S$ (2NA) may exist



Decay channel

exclusive

$K^- + {}^3He \rightarrow \Lambda + p + n_{mis.}$

- excess cannot be $\Lambda(1405)n + p_S$ (2NA), because of Λpn F.S.

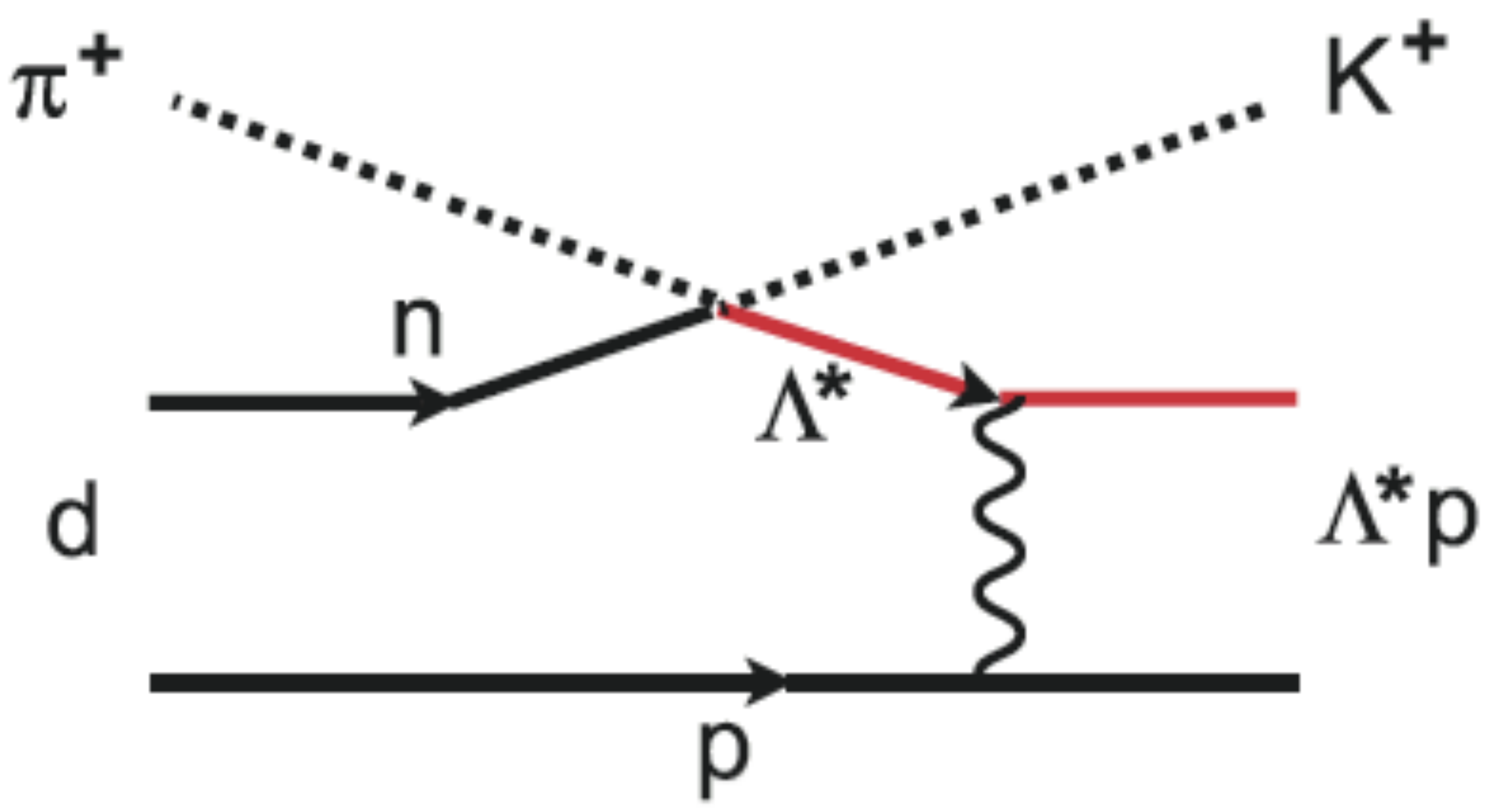
E27 d(π^+,K^+)X

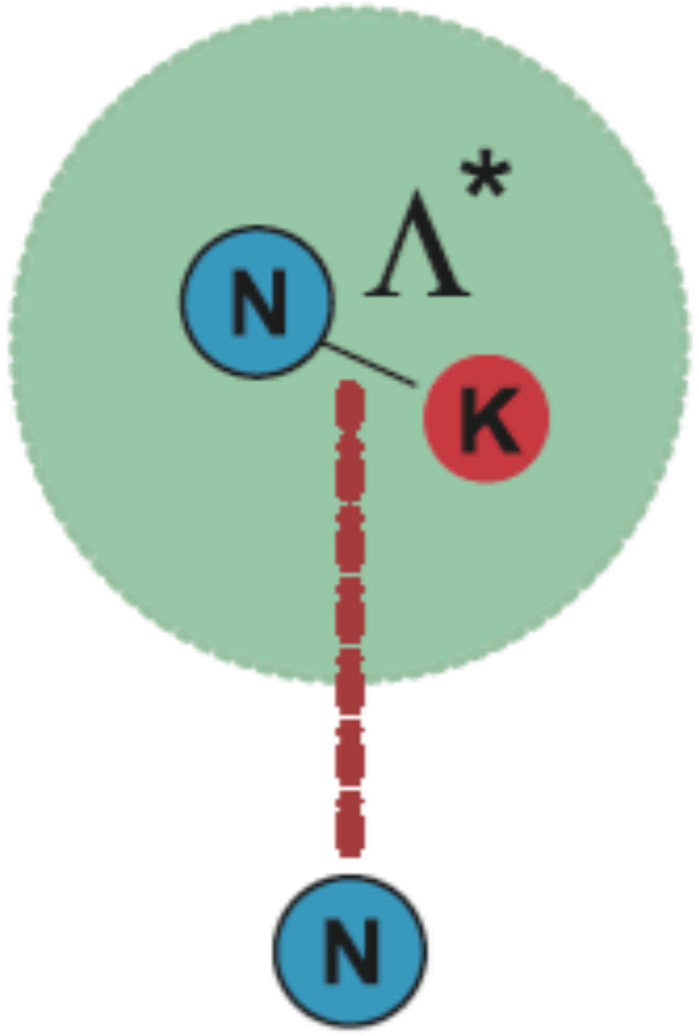
from Ichikawa, E27

π^+ + "n" --> "Λ^*" + K^+

"Λ^*" + "p" --> bound K^-pp ***minor***

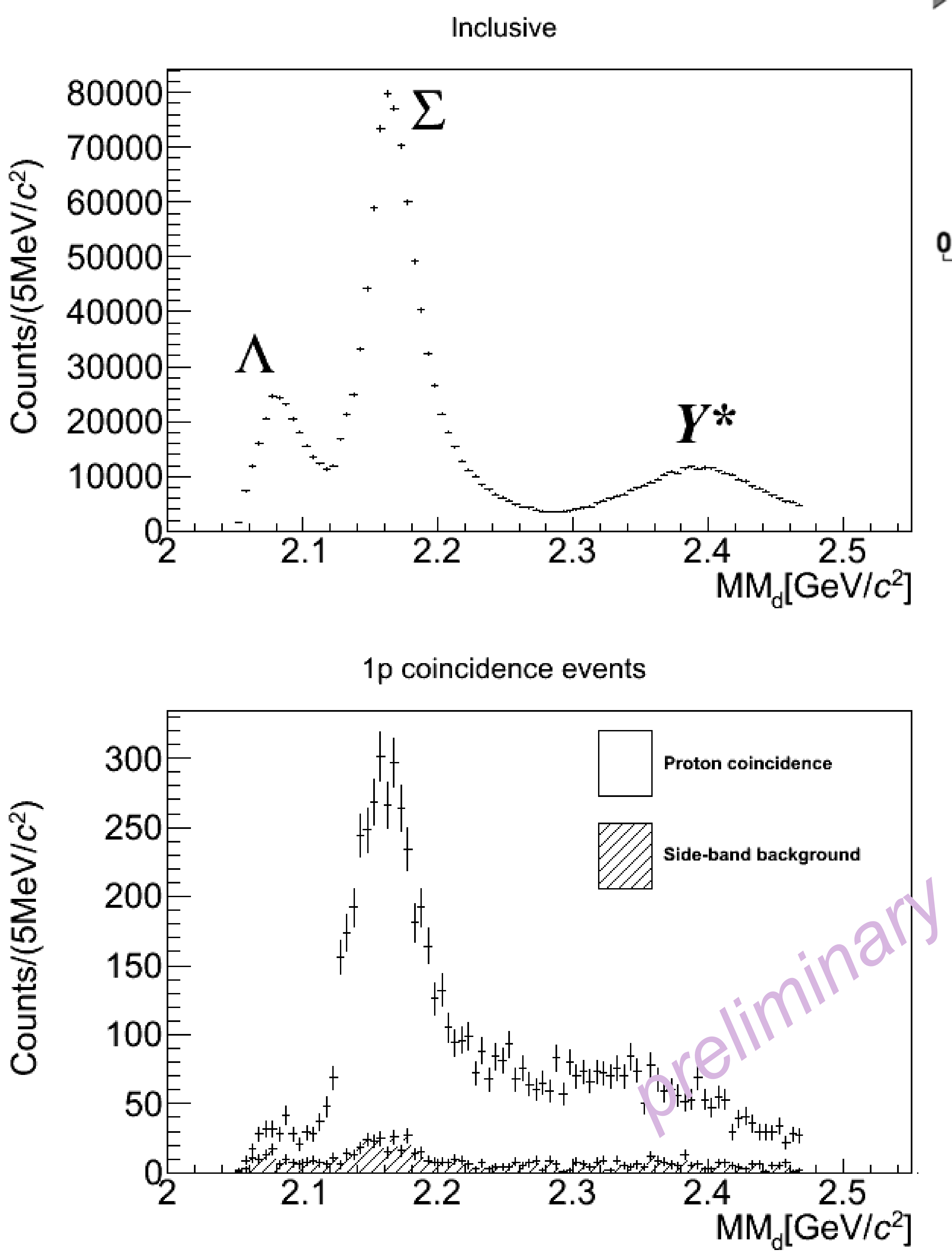
--> quasi-free Λ^* ***dominant***

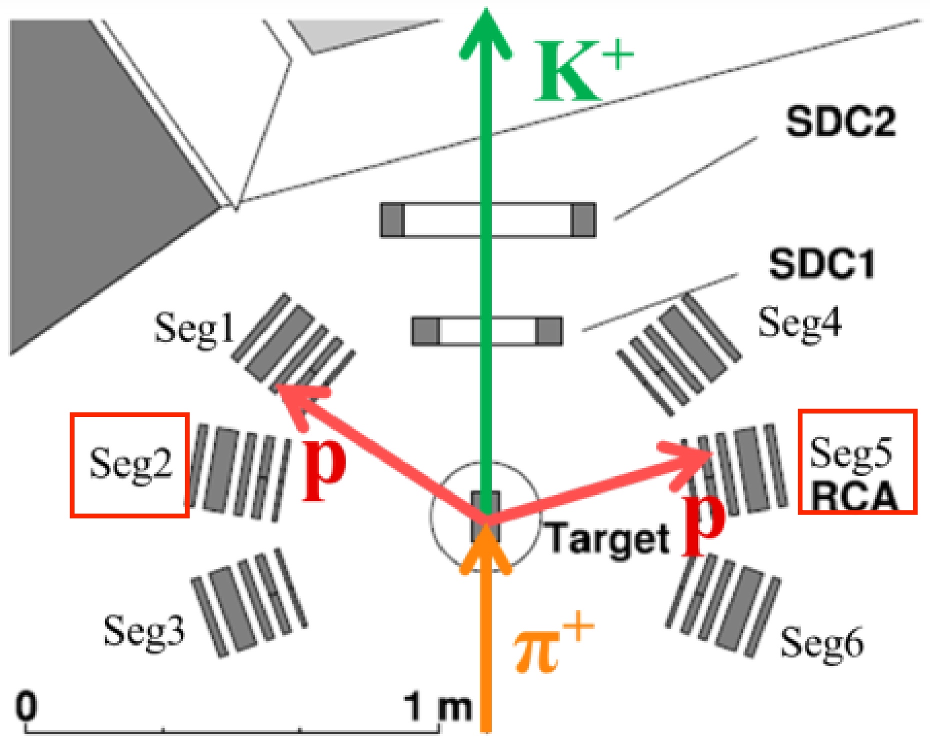




E27 preliminary

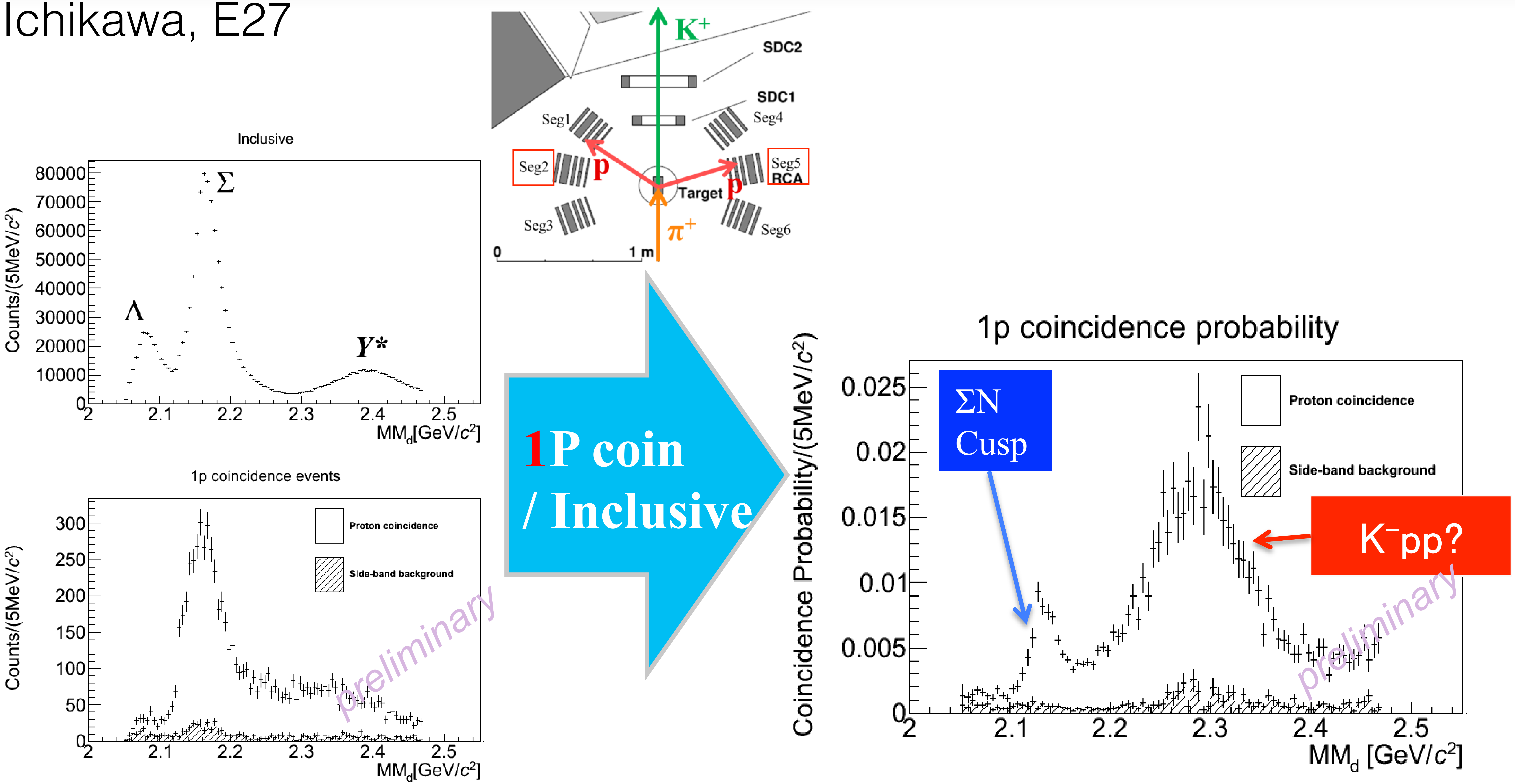
from Ichikawa, E27





E27 preliminary

from Ichikawa, E27



E13: Hypernuclear γ-ray

${}^{4}_{\Lambda}He$, ${}^{19}_{\Lambda}F$, ${}^{7}_{\Lambda}Li$,...

E13: Hypernuclear γ-ray

${}^{4}_{\Lambda}$He, ${}^{19}_{\Lambda}$F, ${}^{7}_{\Lambda}$Li,...

- ${}^{4}_{\Lambda}$He: Charge symmetry breaking in ΛN interaction?

  compare the mirror: ${}^{4}_{\Lambda}$He and ${}^{4}_{\Lambda}$H

E13: Hypernuclear γ-ray

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- $^{4}_{\Lambda}$He: Charge symmetry breaking in ΛN interaction?
  compare the mirror: $^{4}_{\Lambda}$He and $^{4}_{\Lambda}$H
- $^{19}_{\Lambda}$F: First γ-ray measurement on **sd-shell** hypernuclei
  How effective interaction changes compared to **p-shell**?

E13: Hypernuclear γ-ray

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  compare the mirror: $^{4}_{\Lambda}$He and $^{4}_{\Lambda}$H

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- $^{7}_{\Lambda}$Li: **Magnetic moment** of Λ in hypernuclei from B(M1)

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- $^{4}_{\Lambda}$He: Charge symmetry breaking in ΛN interaction?
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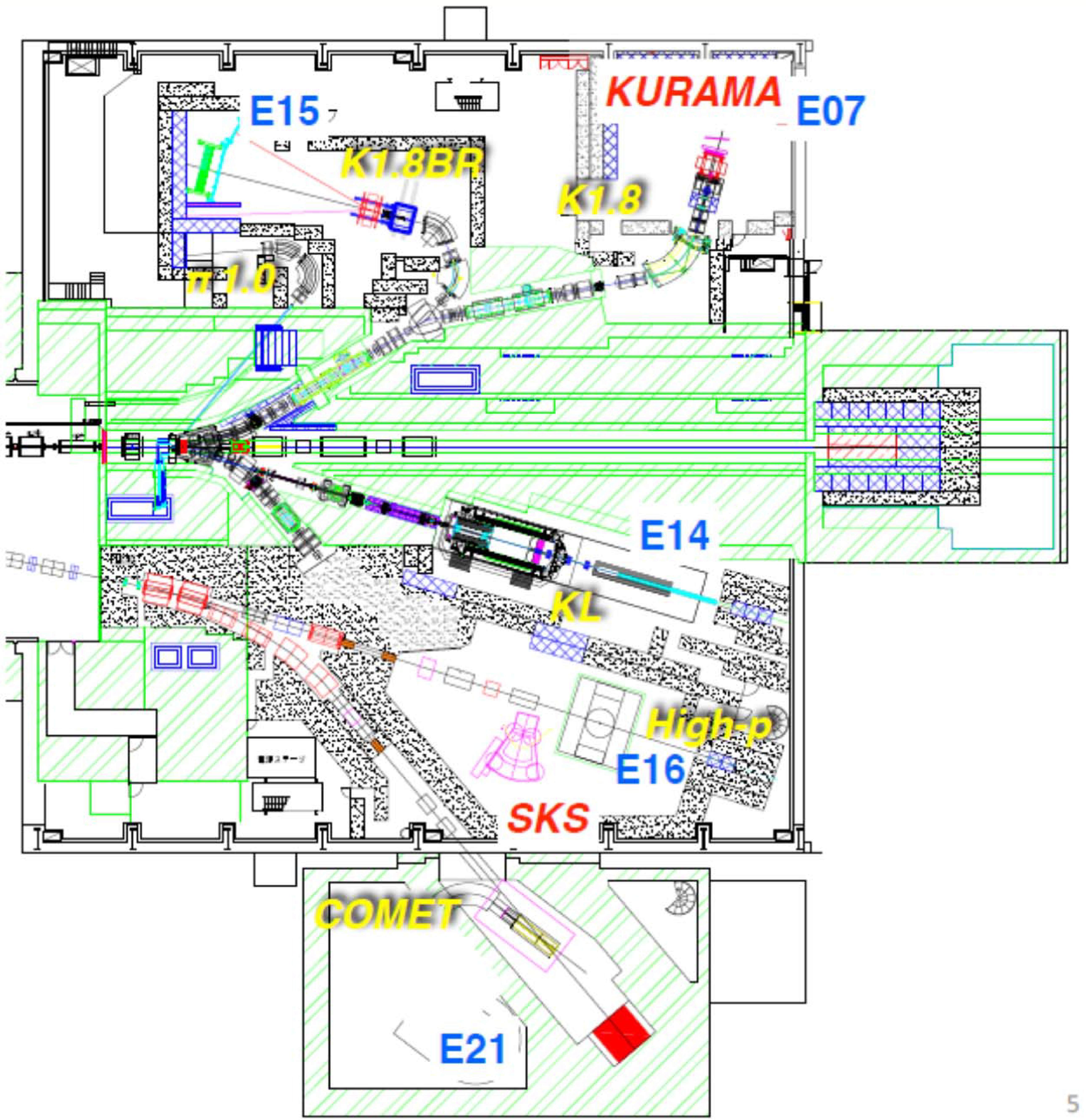
- $^{19}_{\Lambda}$F: First γ-ray measurement on **sd-shell** hypernuclei
  How effective interaction changes compared to **p-shell**?
- $^{7}_{\Lambda}$Li: **Magnetic moment** of Λ in hypernuclei from B(M1)

$$B(M1) = (2J_{up} + 1)^{-1} |\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$

$$= \frac{3}{8\pi} \frac{2J_{low} + 1}{2J_c + 1} (g_\Lambda - g_c)^2 \quad [\mu_N^2]$$

$S=-2$



J-PARC 2016-?

K1.8

- Emulsion Exp. (E07)
- X-ray from Ξ-atom (E03)
- …

K1.8BR

- ^{3}He(K^-,n) K^-pp (E15)
- d(K^-,n)Λ(1405) (E31)

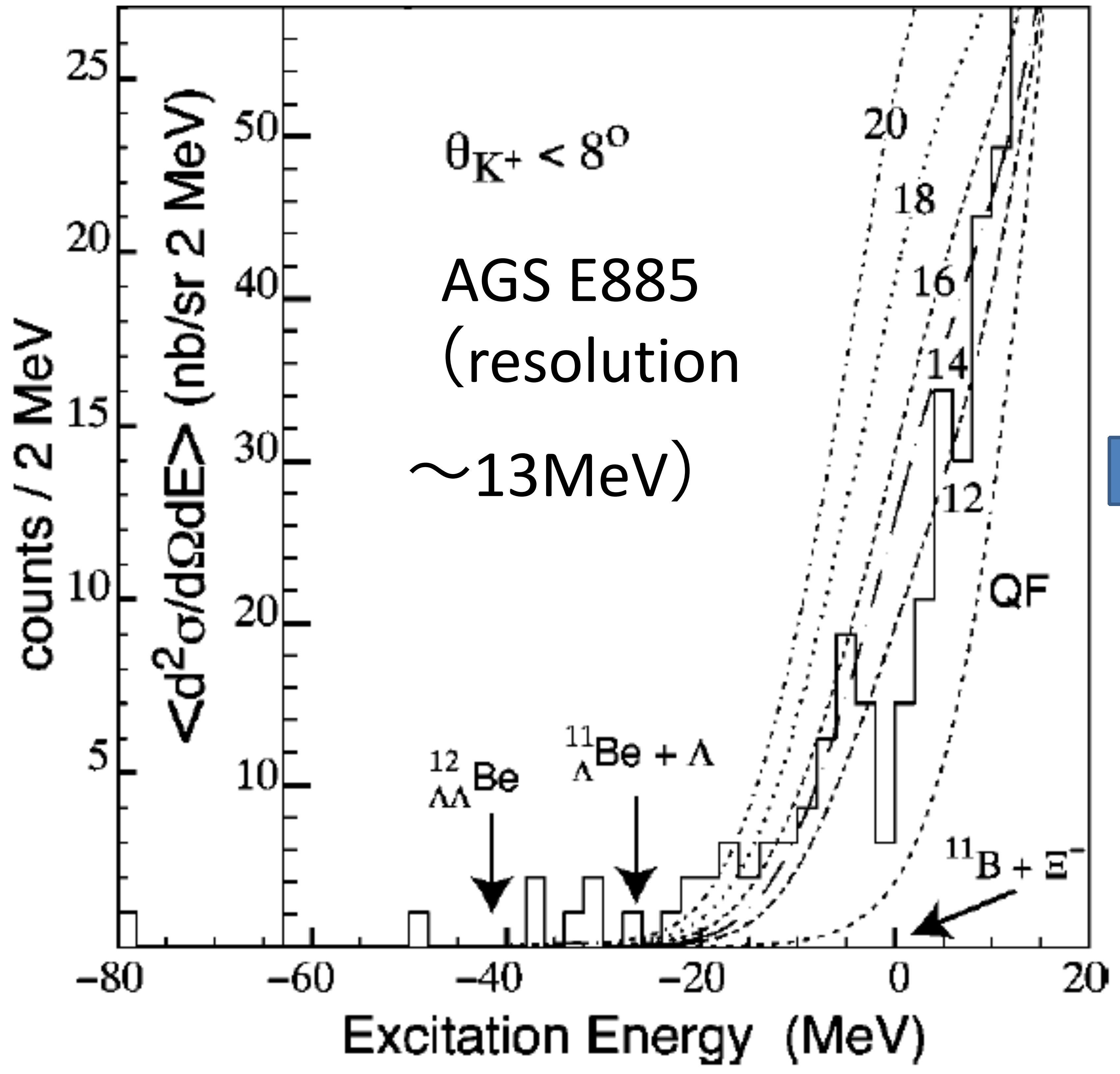
KOTO@KL

E16@High-p (ϕ in nuclei)

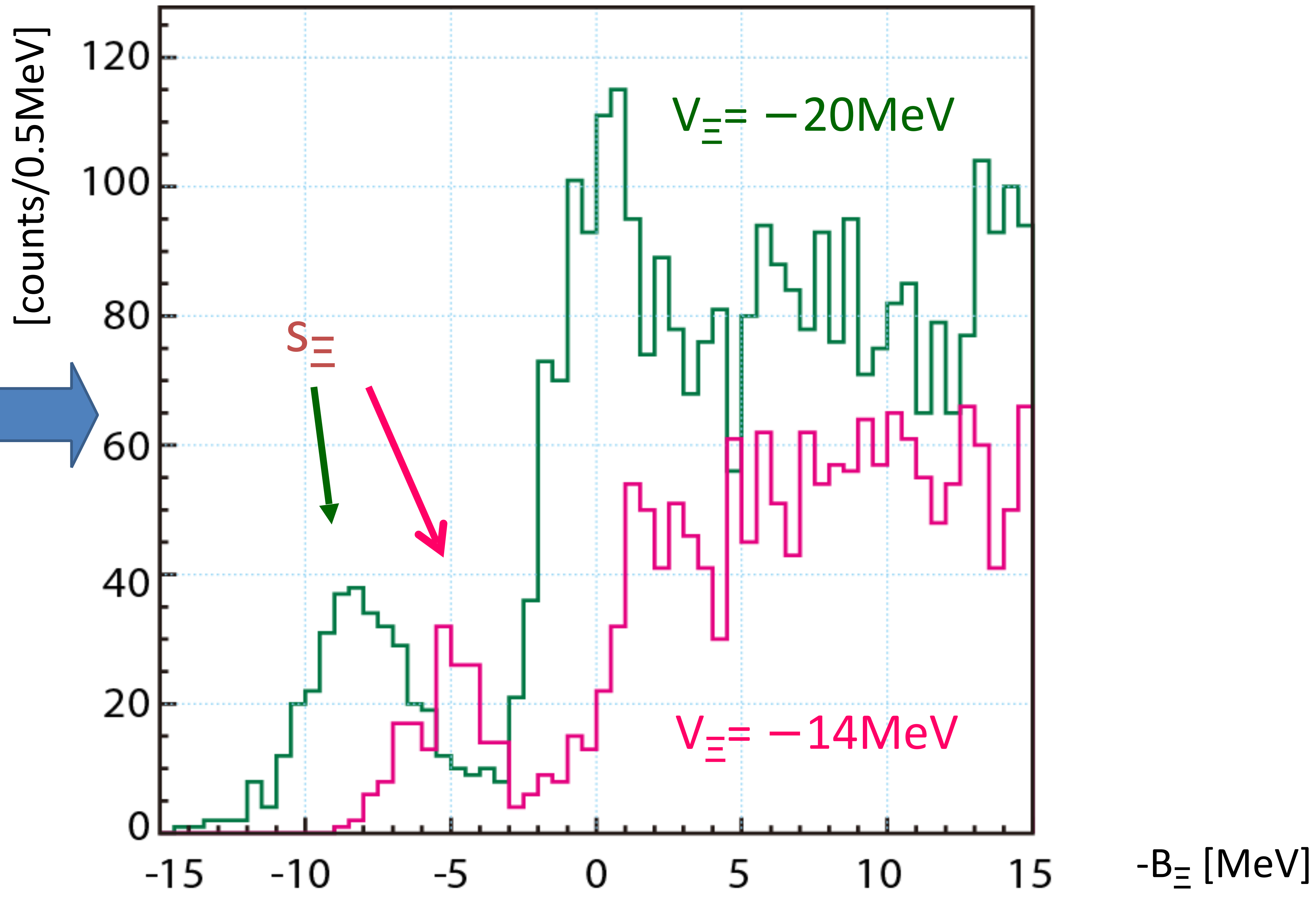
E21@COMET

source, 18th J-PARC PAC (May 2014) T. Takahashi

E05: Missing mass spectroscopy of $^{12}C(K^-,K^+)$

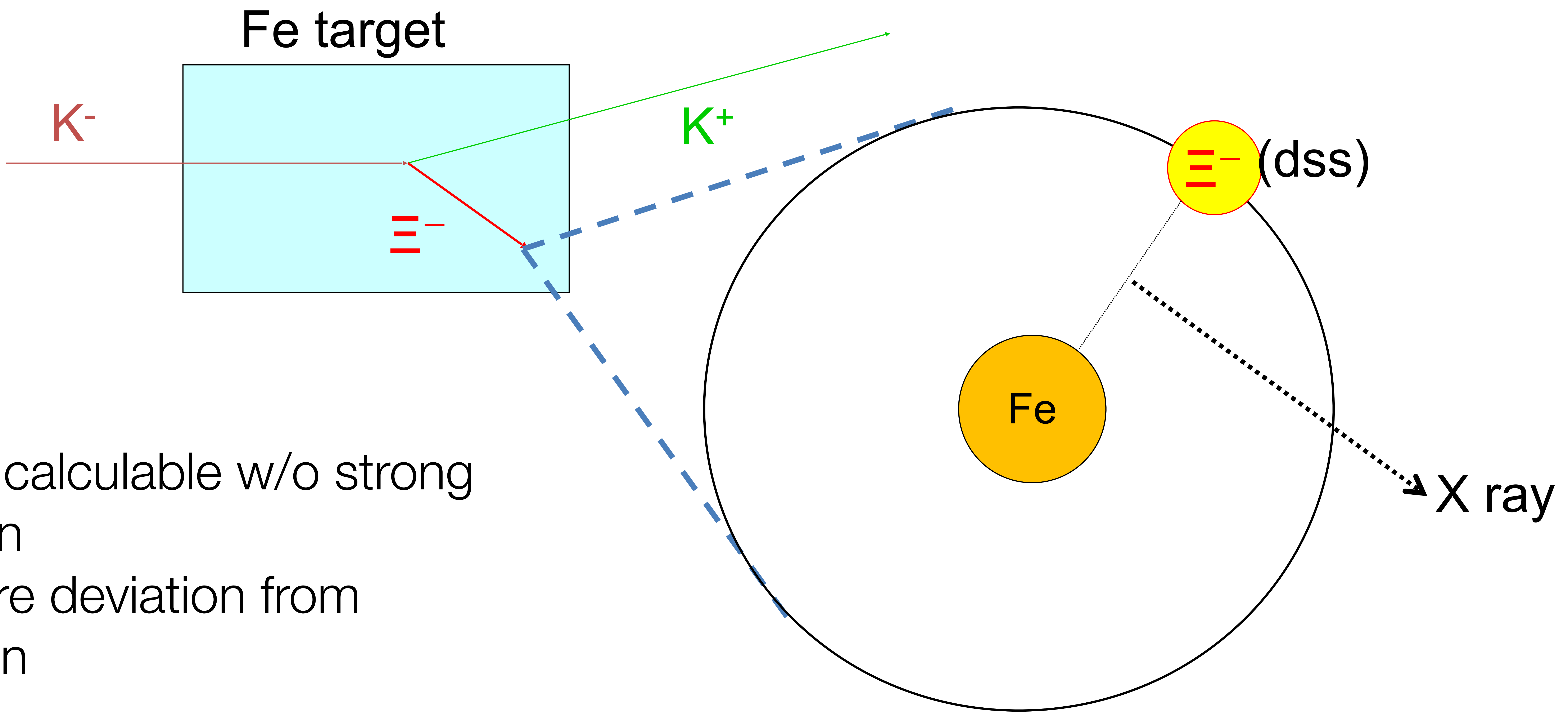


expectation for E05 phase 1
(resolution < 3 MeV)



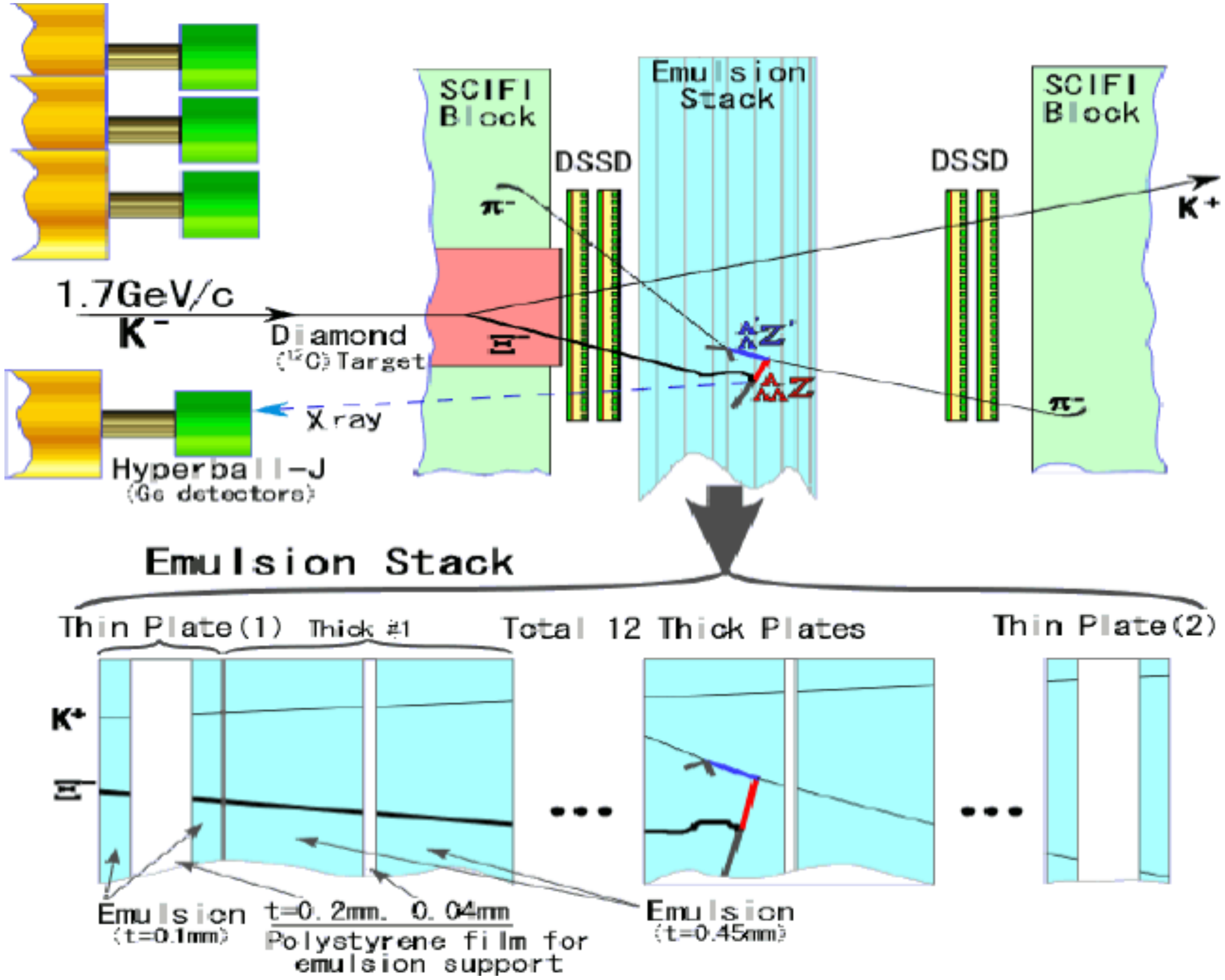
E03: Ξ-atomic X ray

Ξ^- produced by $Fe(K^-,K^+)$ → stopped Ξ^- → X-ray emission



Precisely calculable w/o strong interaction
→Measure deviation from calculation

E07: Hybrid emulsion ΛΛ



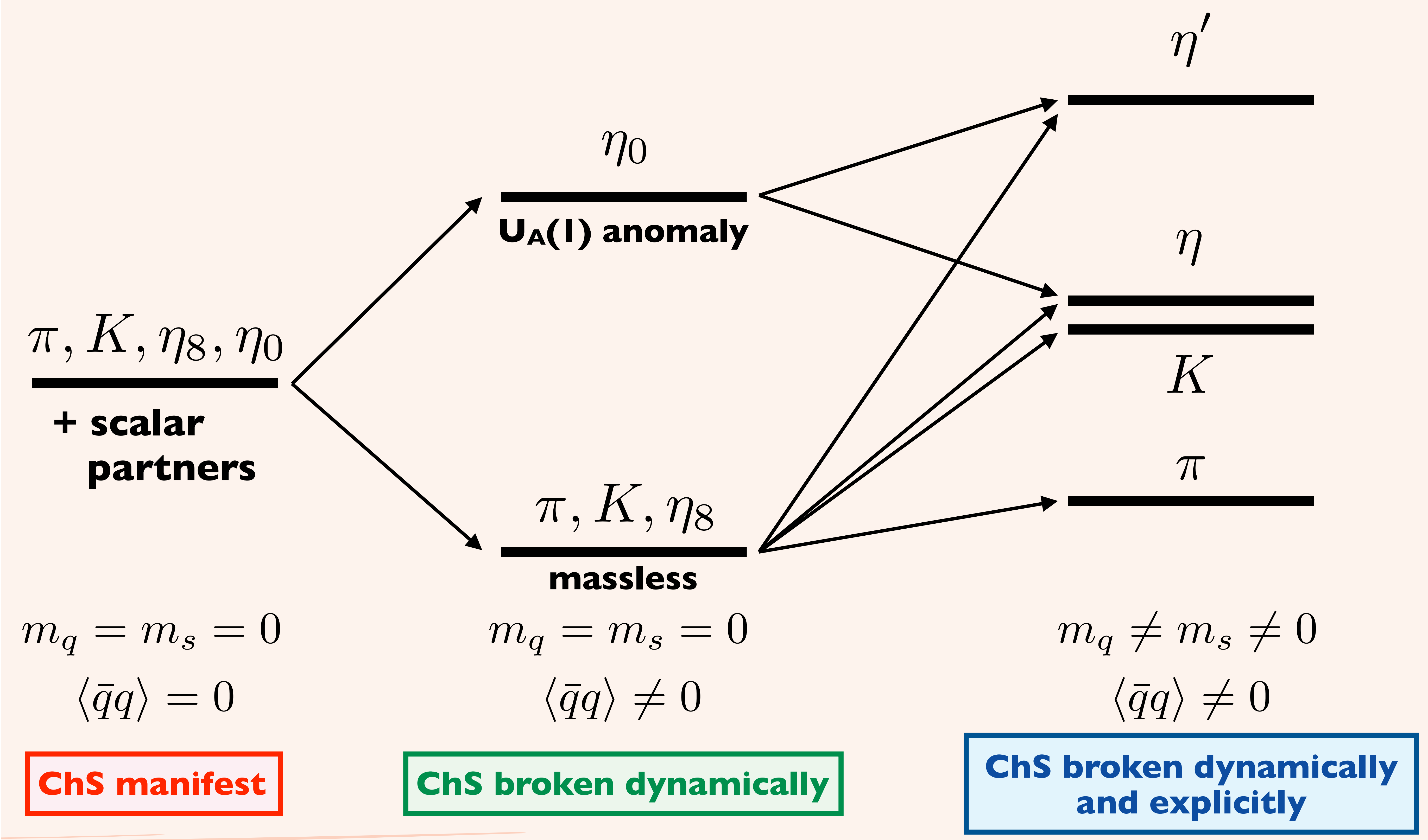
Goal:

- 10000 stopped Ξ^- in emulsion
- 100 or more ΛΛ HN events

6

Hidden strangeness at FAIR

in-medium η' (at FAIR)



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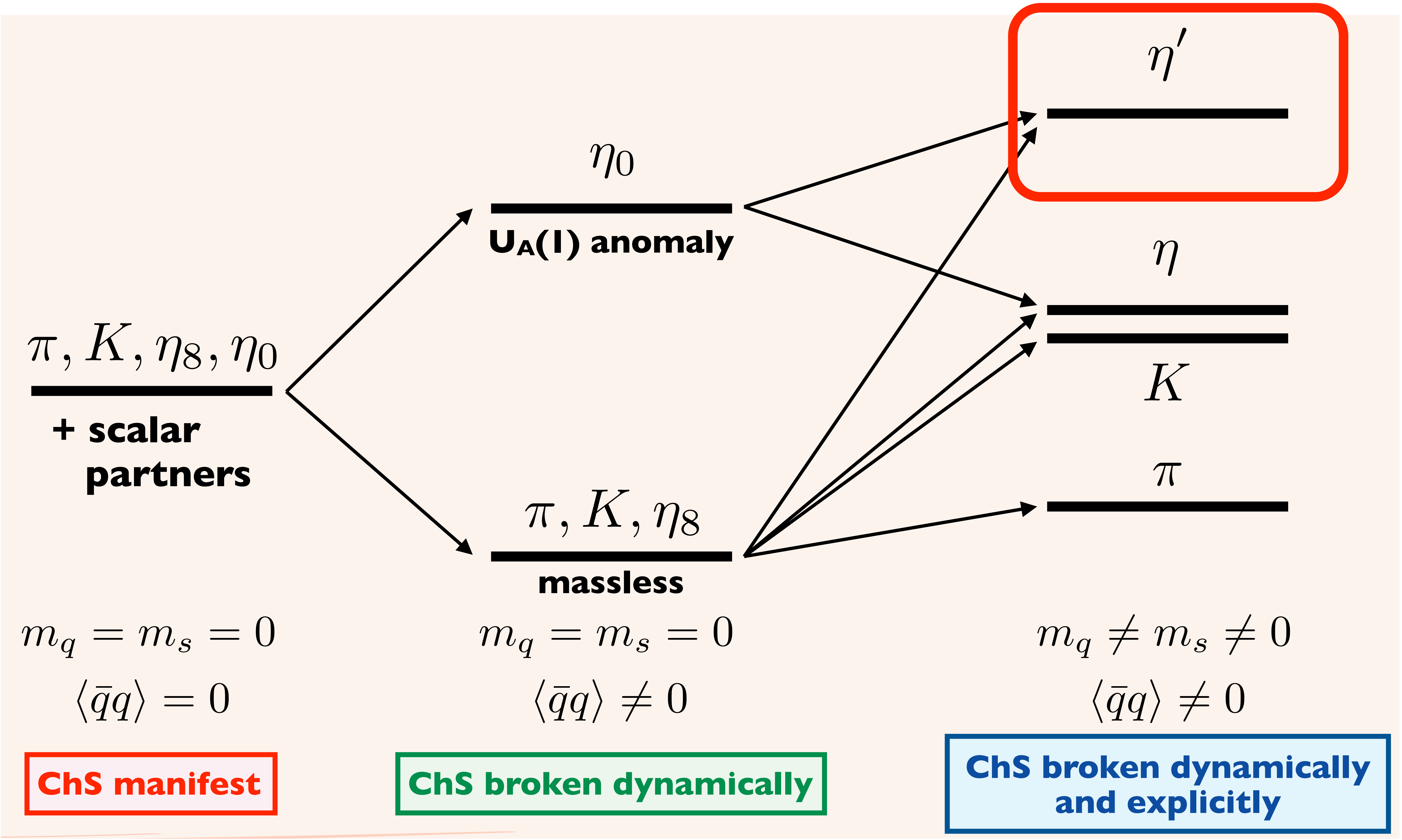

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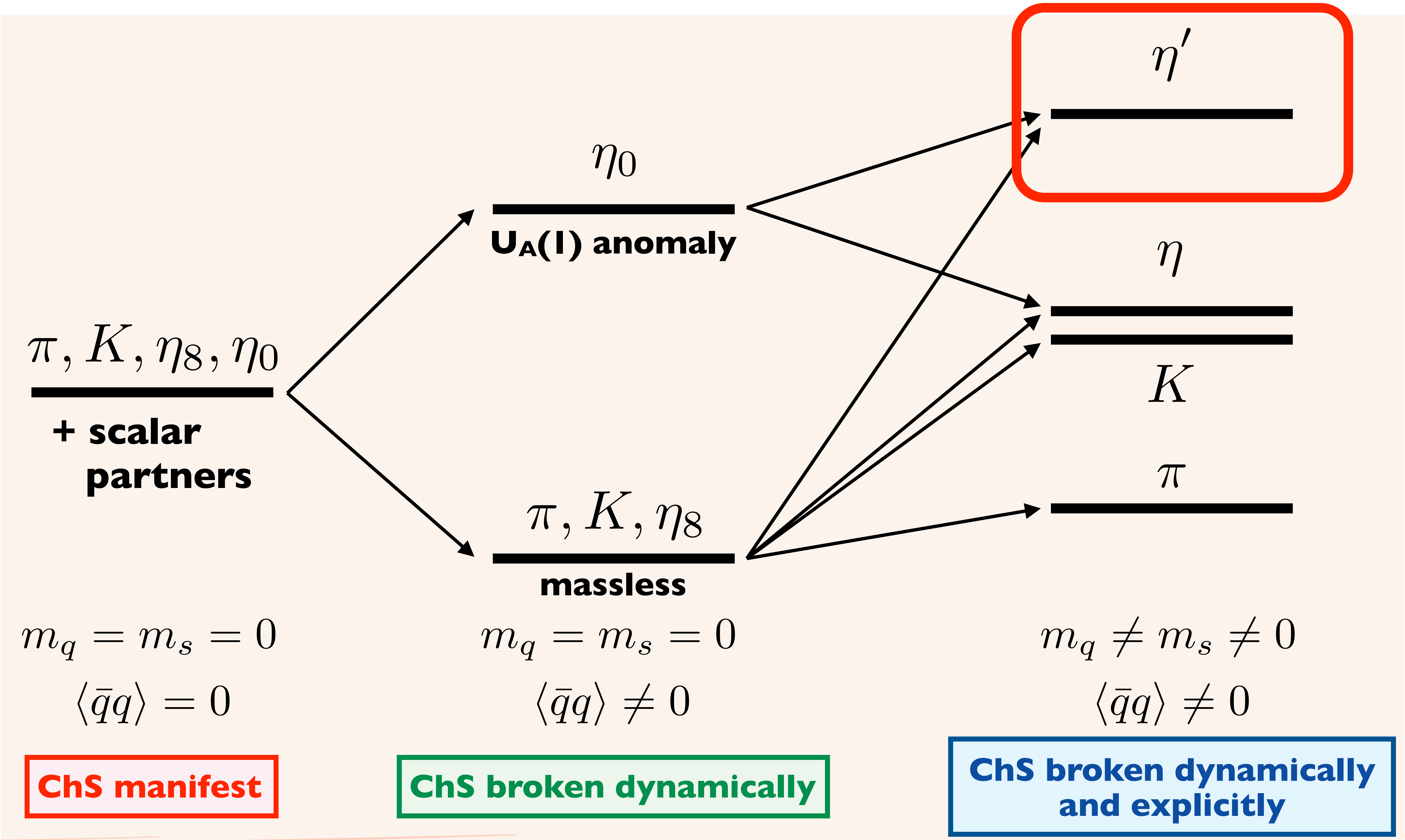
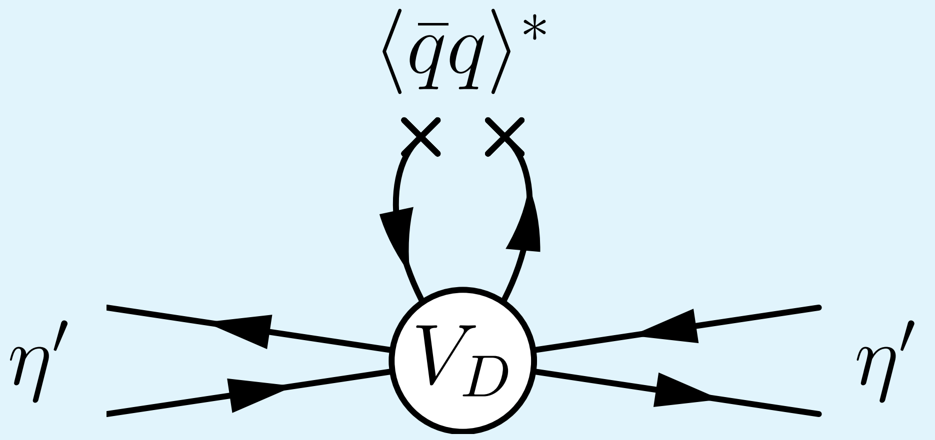
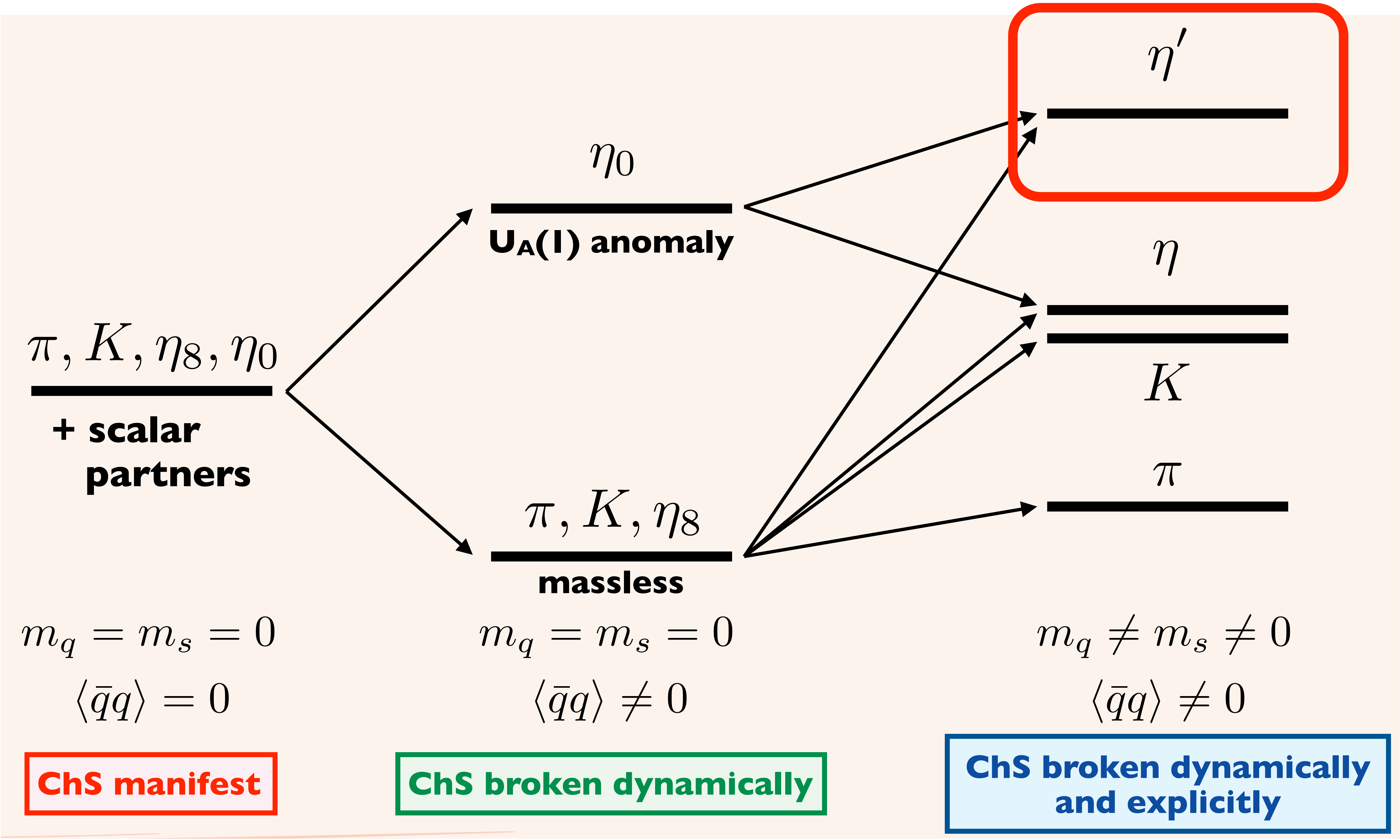


Jido, Nagahiro, Hirenzaki, PRC85 (12) 032201

$\mathrm{U_A(1)}$ anomaly contributes η' mass through ChSB



in-medium η' (at FAIR)



Jido, Nagahiro, Hirenzaki, PRC85 (12) 032201

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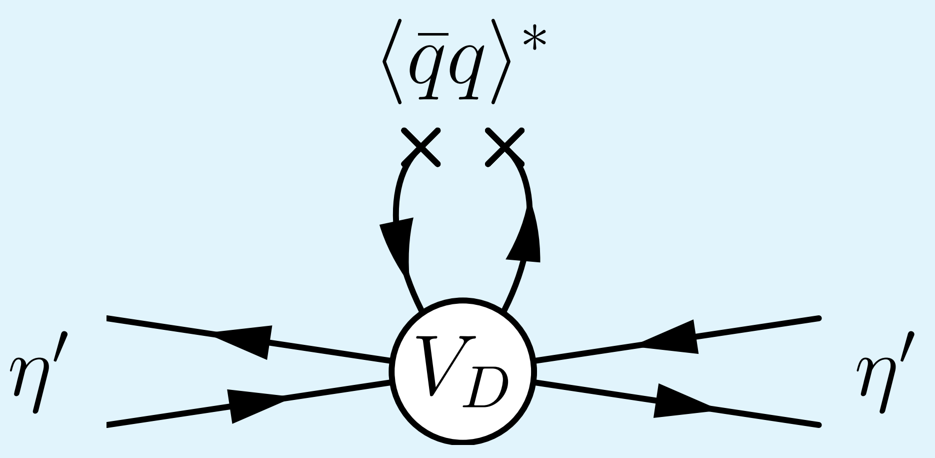
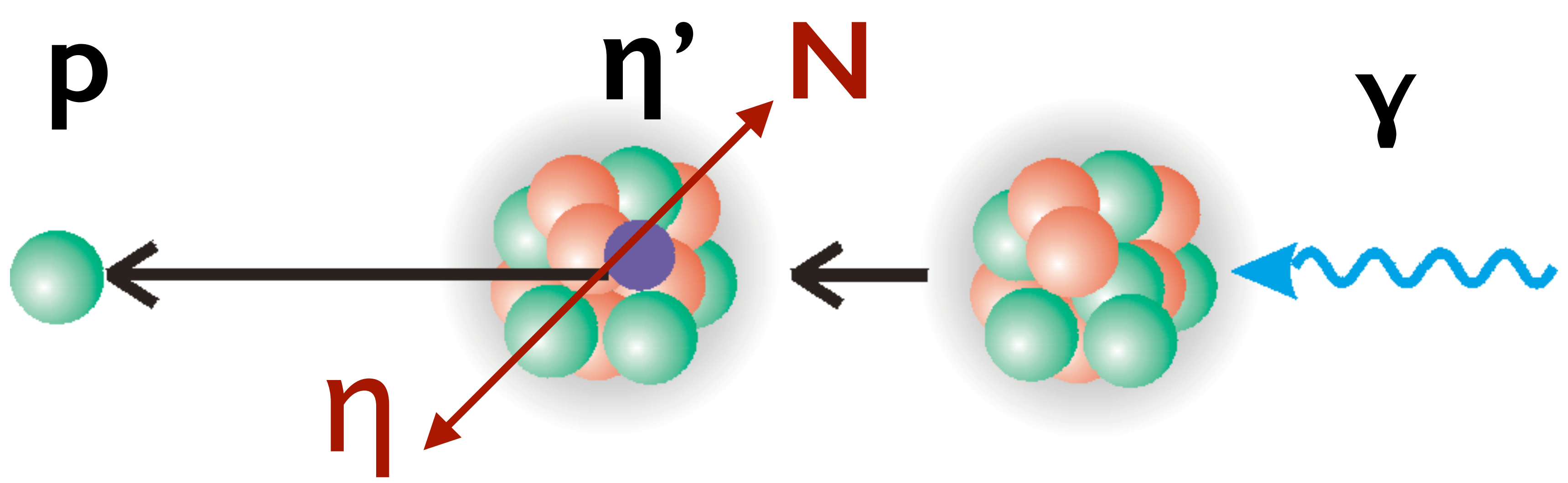


$\Delta m_{\eta'} \sim 150$ MeV @ $\rho = \rho_0$

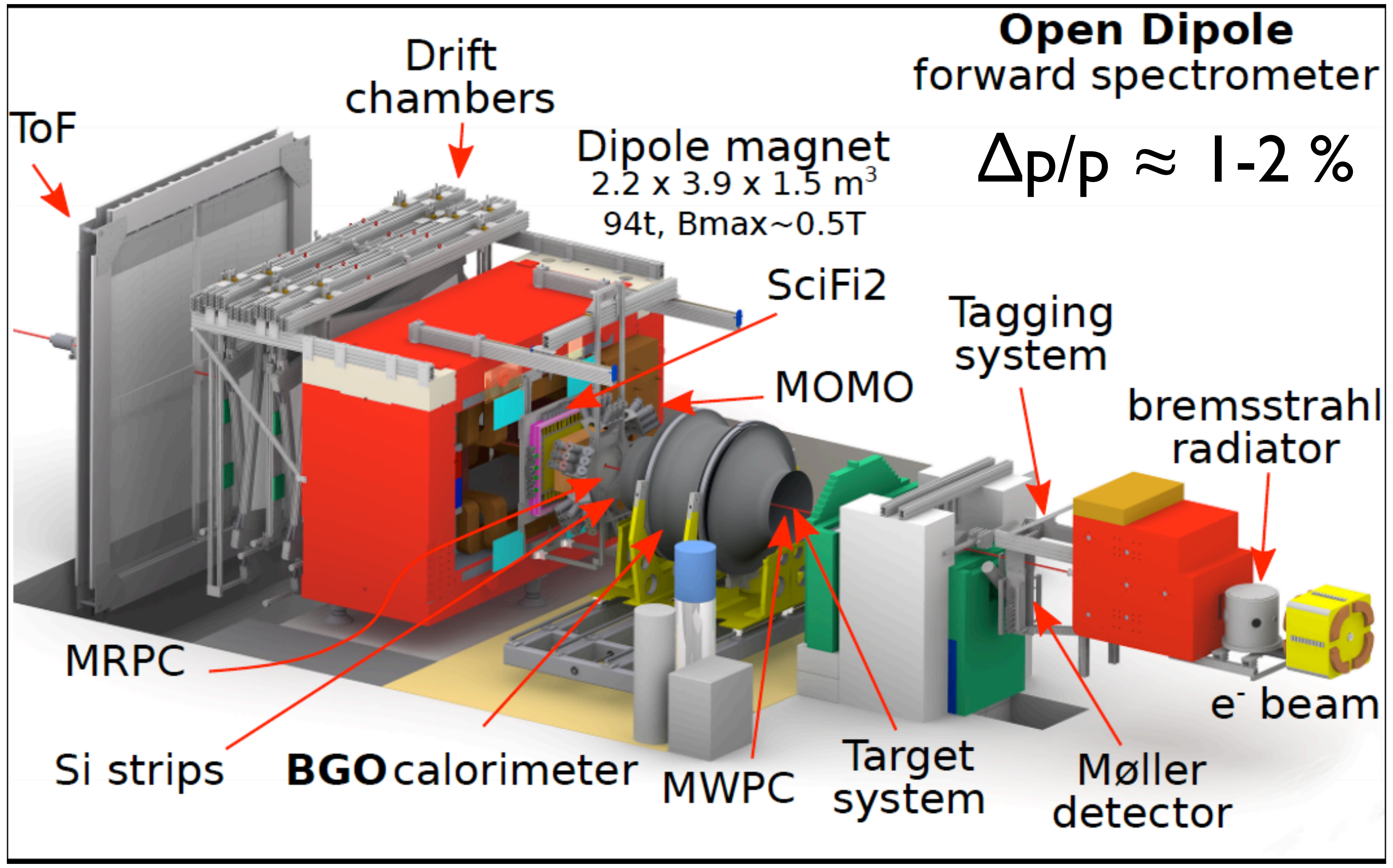
from Metag

BGO-OD@ELSA

$^{12}C(\gamma,p)\ \eta'X$ @ 2.8 GeV



formation and decay of η'-mesic state

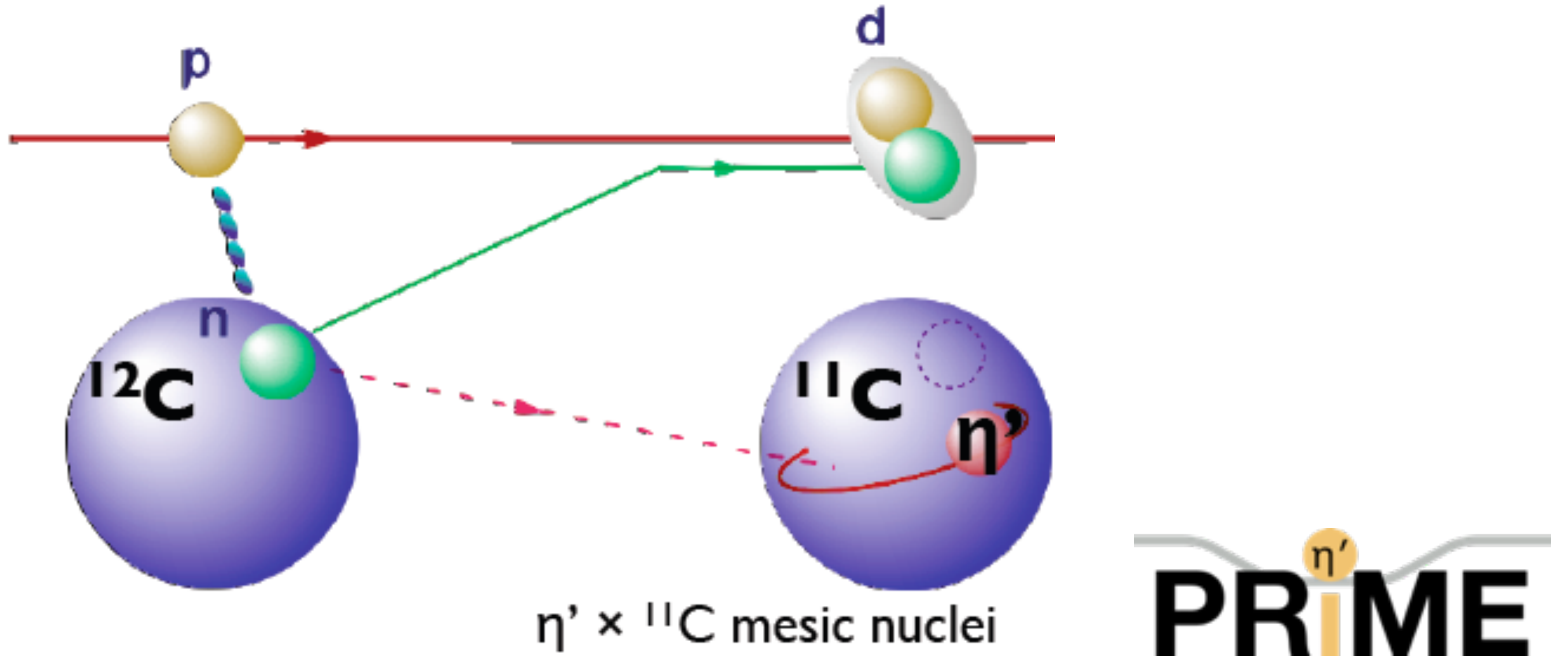


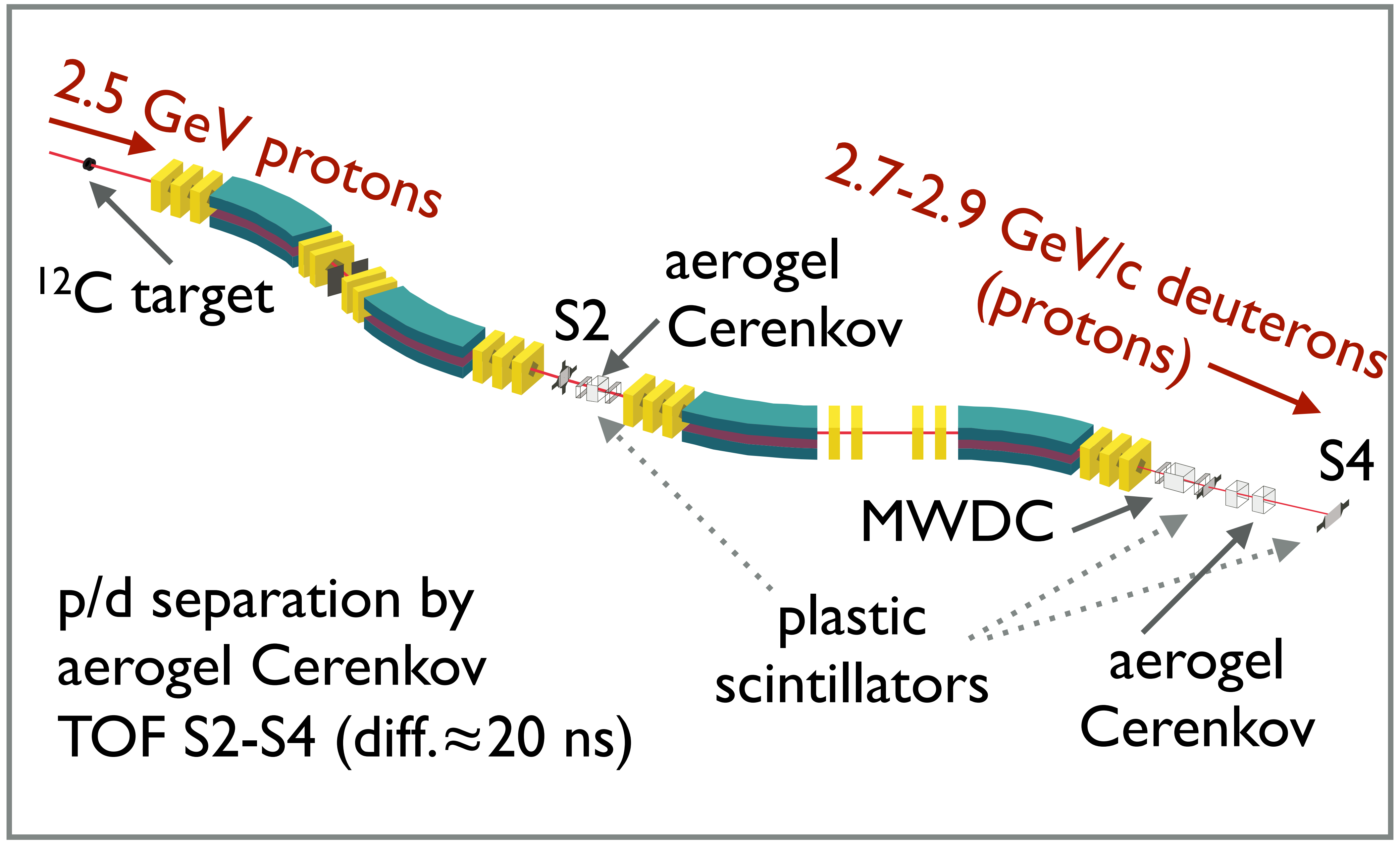
BGO-OD ideally suited for exclusive measurement

FRS@GSI

$^{12}C(p,d)\ \eta'X$ @ 2.5 GeV

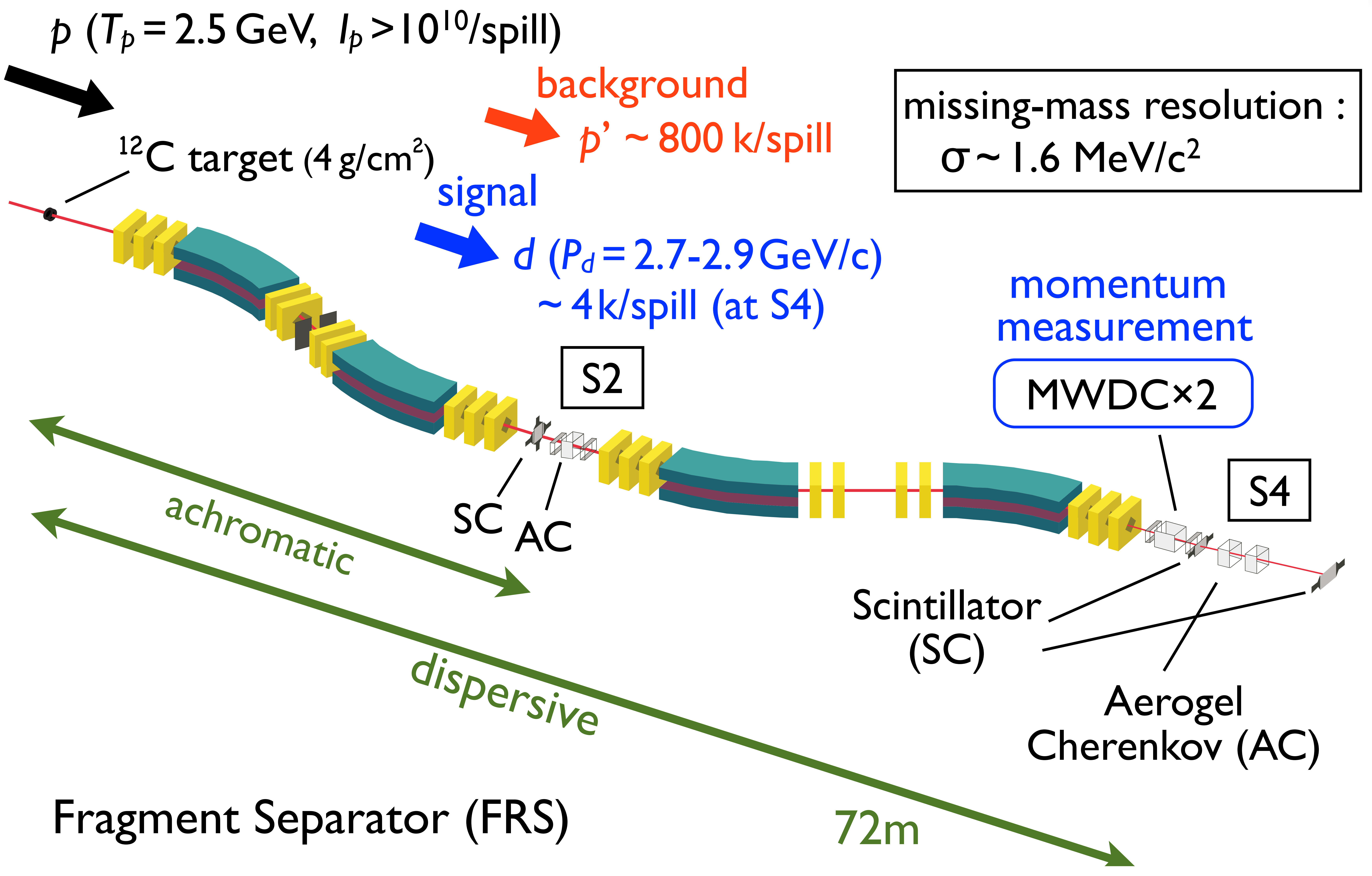
K. Itahashi *et al.*, Prog. Theo. Phys. 128(2012) 601





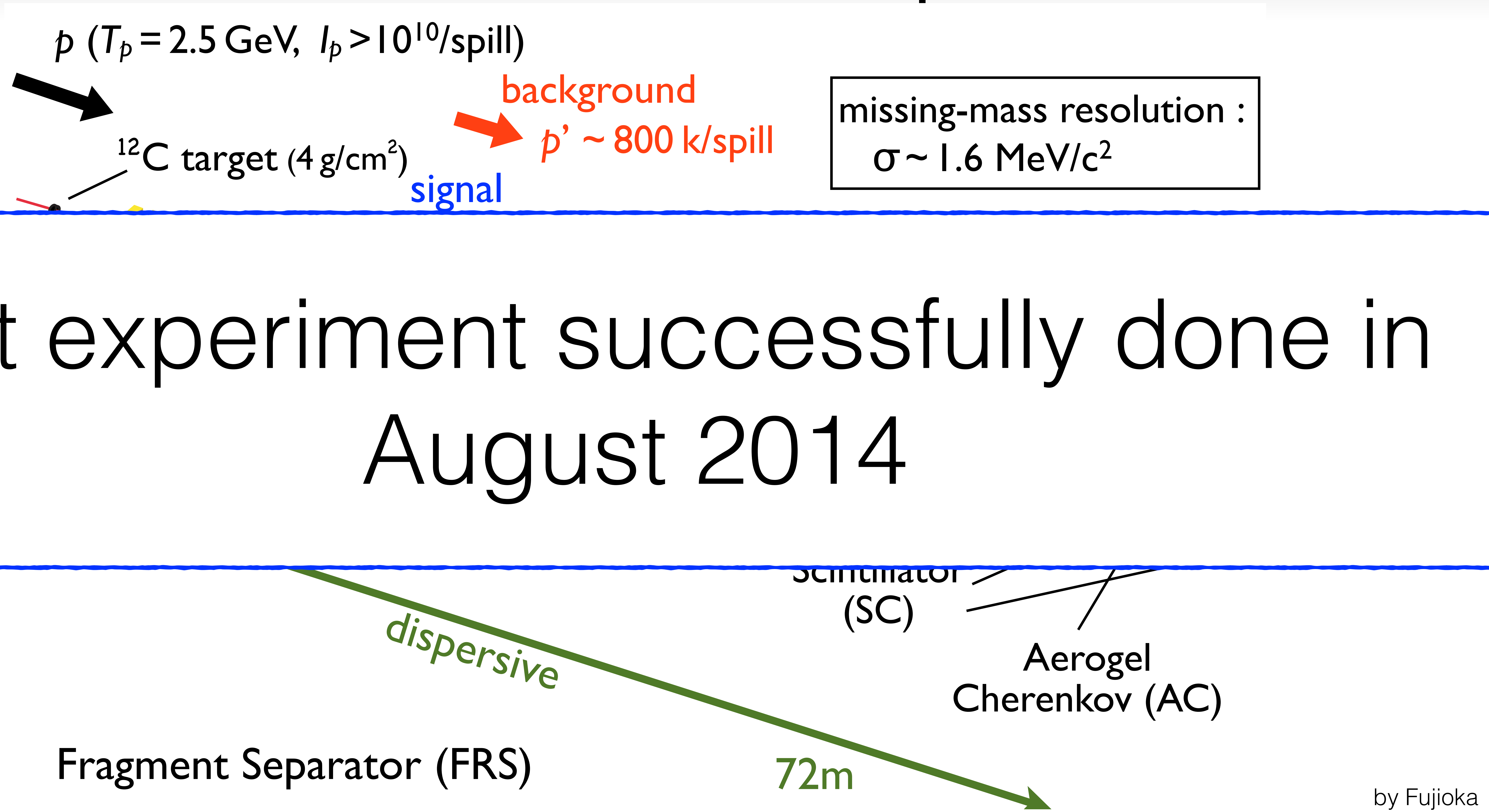
missing mass spectrometry: $\Delta m = 1.6\ \mathrm{MeV}/c^2$

η'-nucleus: an attempt at GSI



by Fujioka

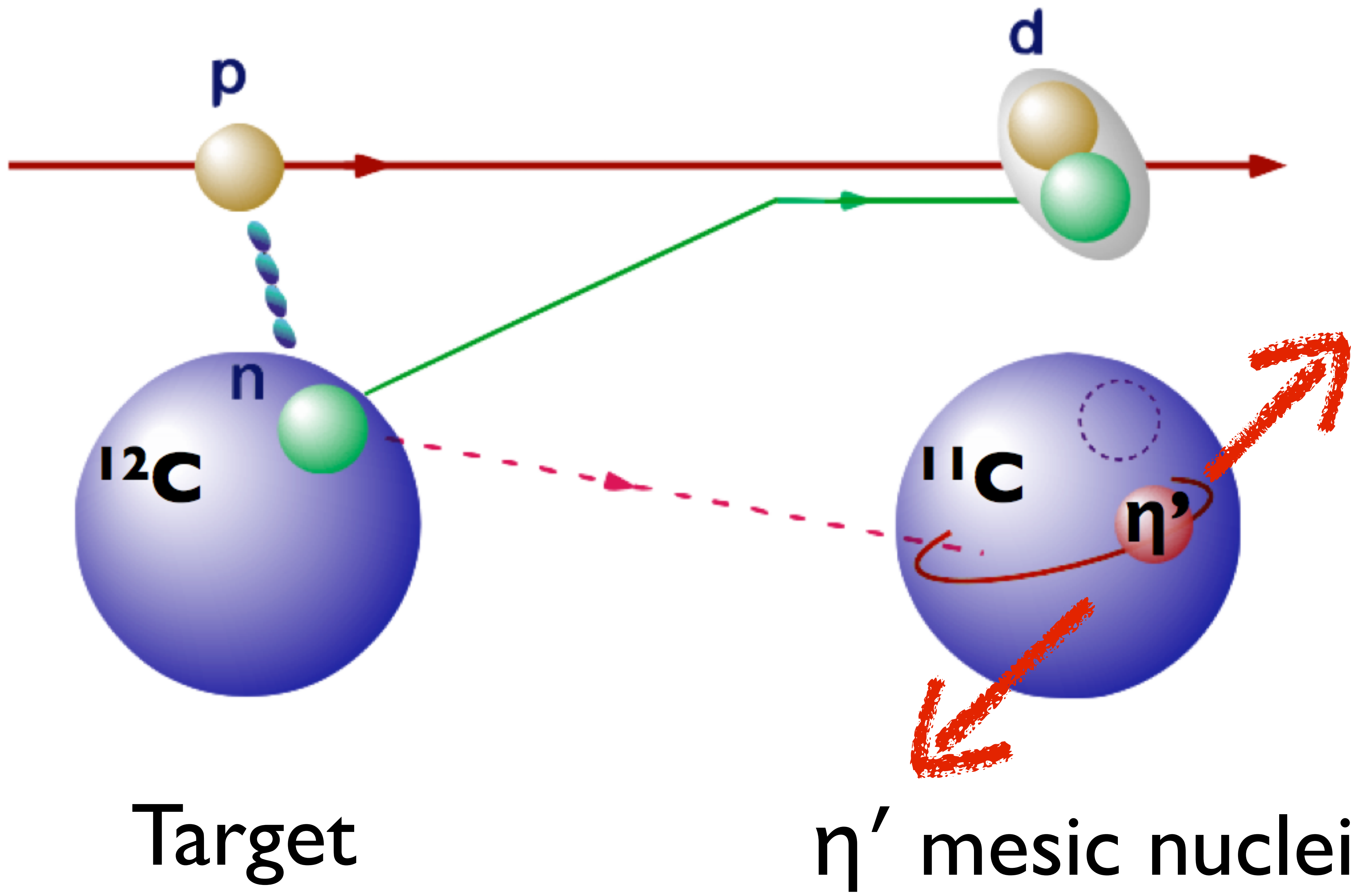
η’-nucleus: an attempt at GSI



pilot experiment successfully done in August 2014

future of η’ at Super-FRS @ FAIR

2nd Step : <u>Semi-exclusive measurement</u> of (*p*,*dp*) with Super-FRS at FAIR



missing-mass measurement w/ S-FRS

decay of η’ mesic nuclei :

- η′N → ηN or πN
- η′NN → NN

Tagging proton in coincidence with deuteron

→ **S/N ratio can be improved**

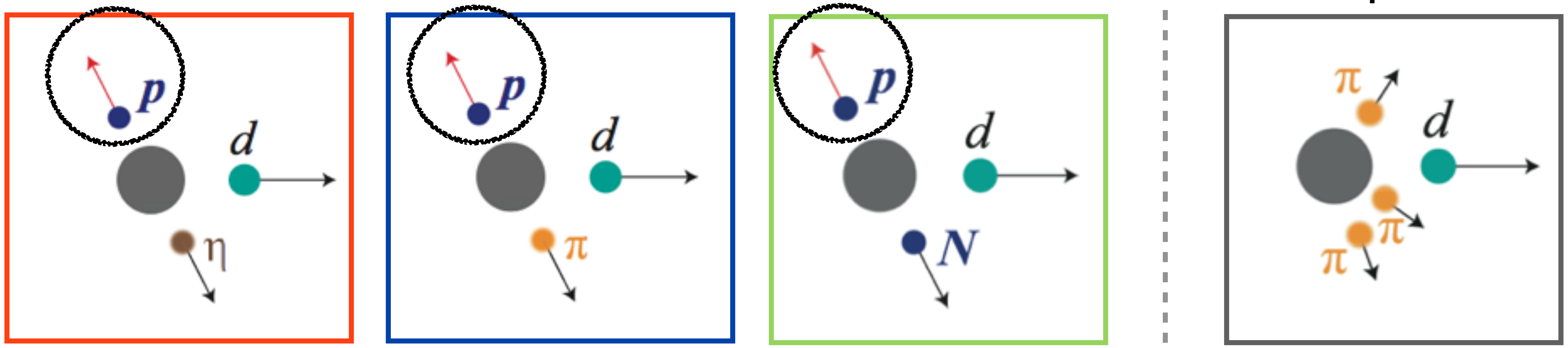
by Fujioka

signal

η′ mesic nuclei

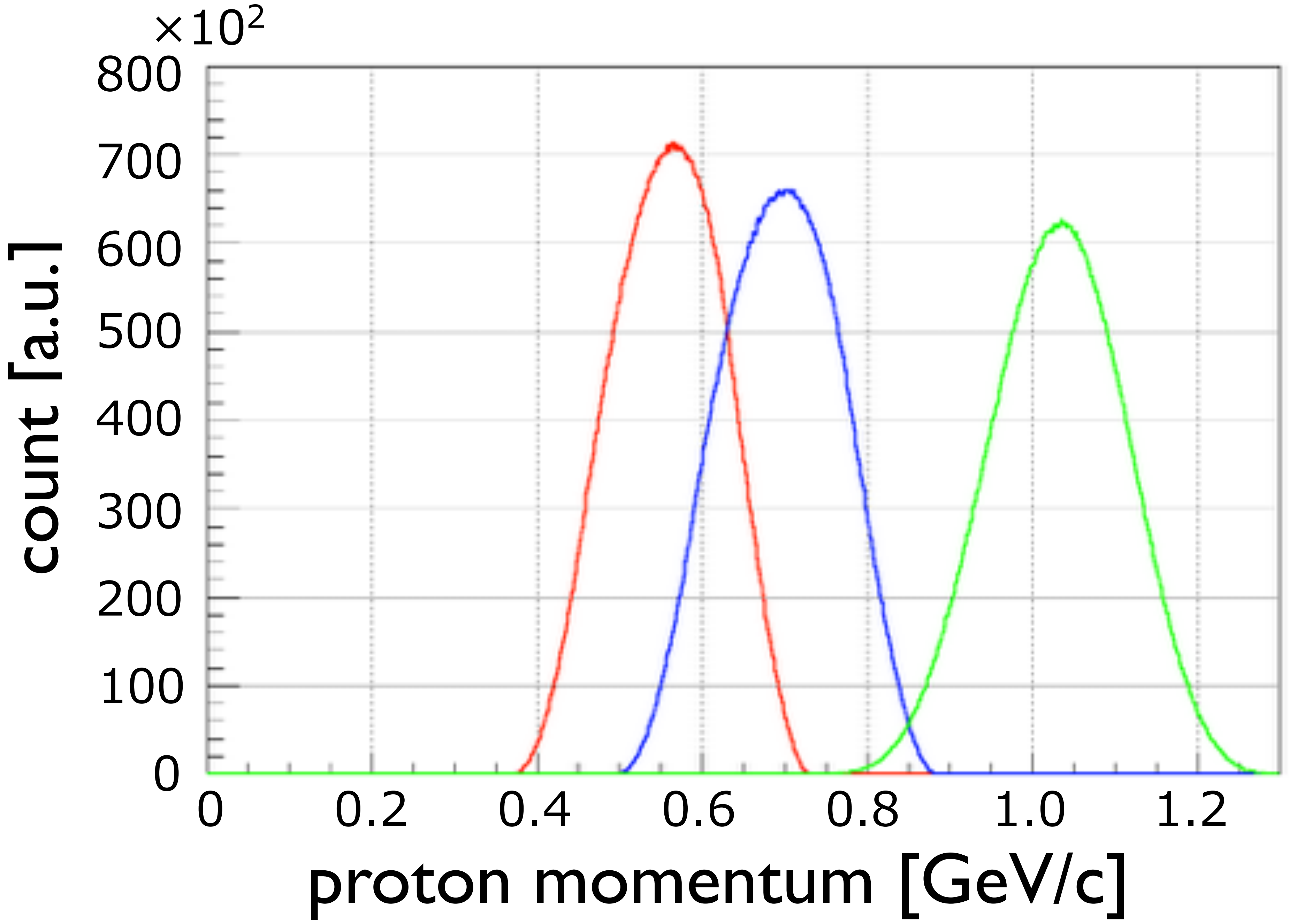
background

multi-π production

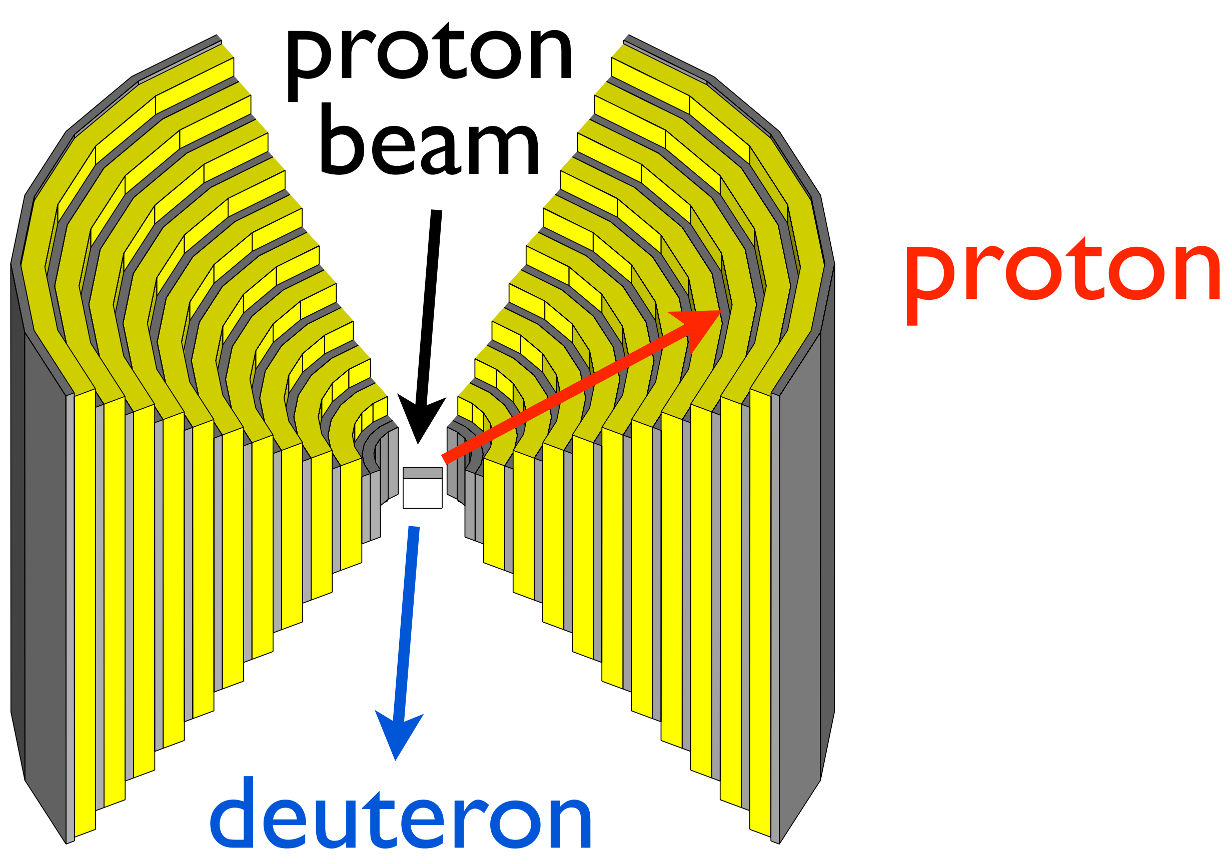


1 nucleon absorption

2 nucleon absorption



sampling calorimeter
(conceptual design)



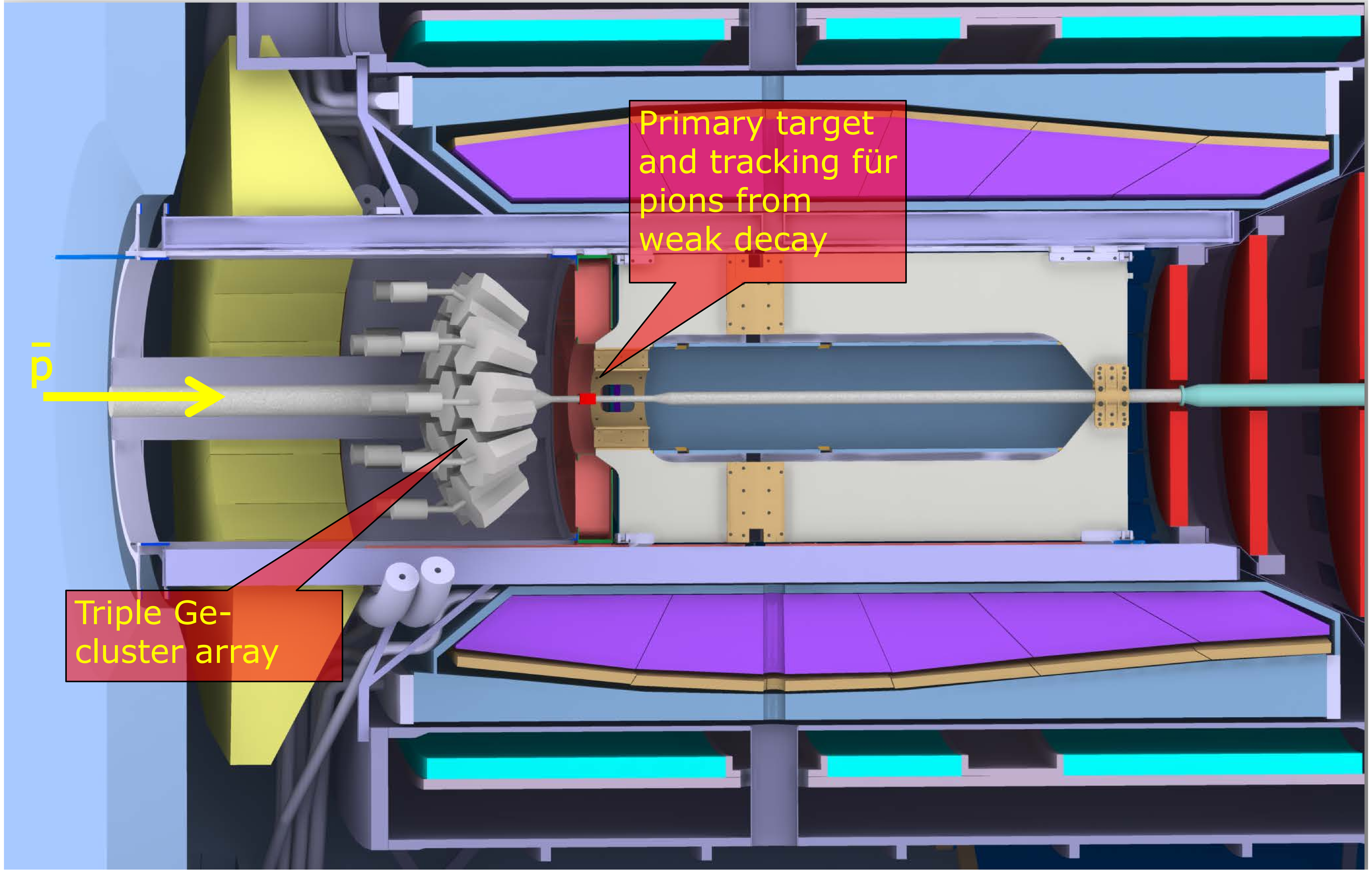
by Fujioka

7

Open strangeness at FAIR

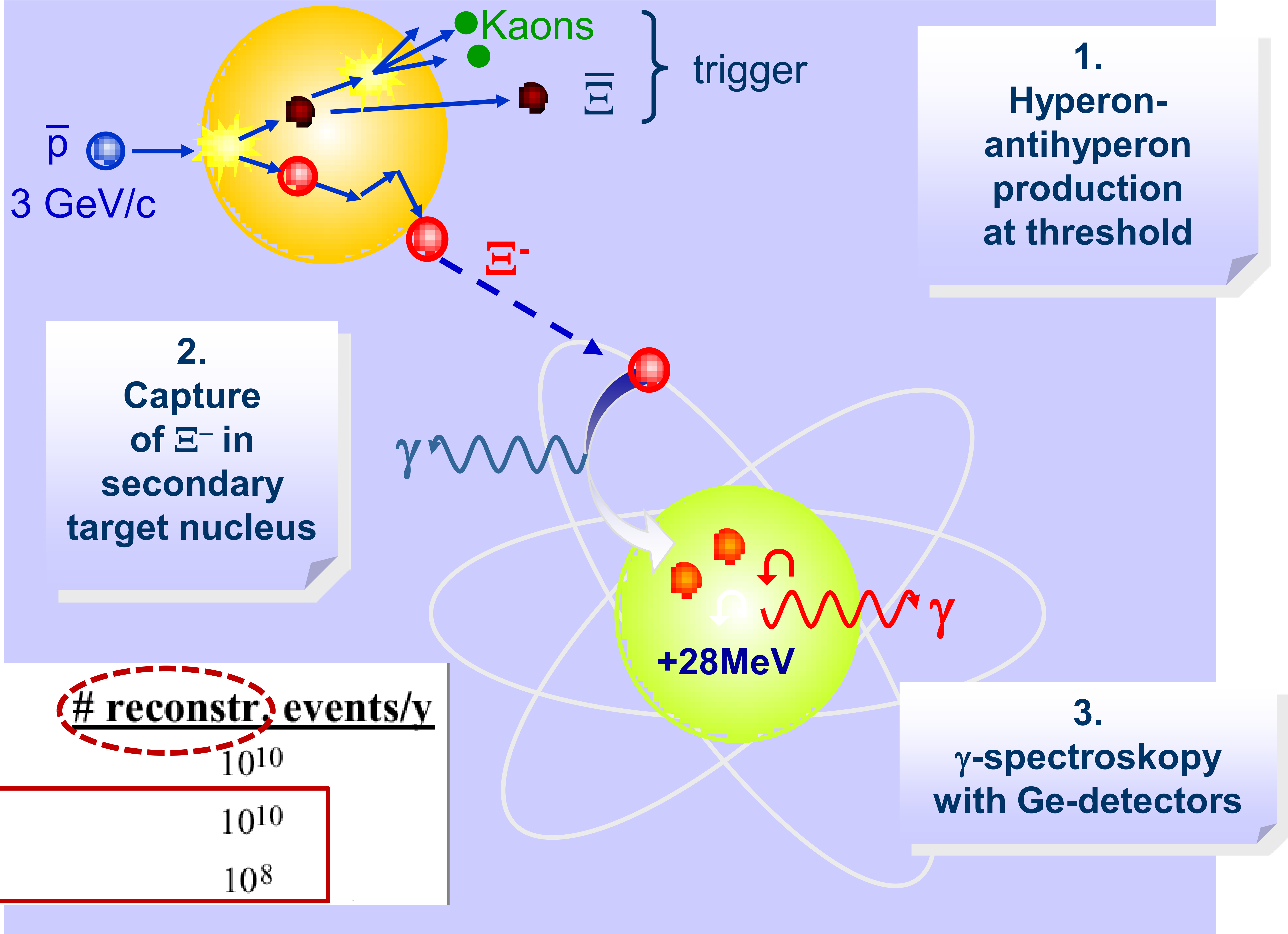
ΛΛ-Hypernuclei at PANDA

from Pochodzalla



ΛΛ-Hypernuclei at PANDA

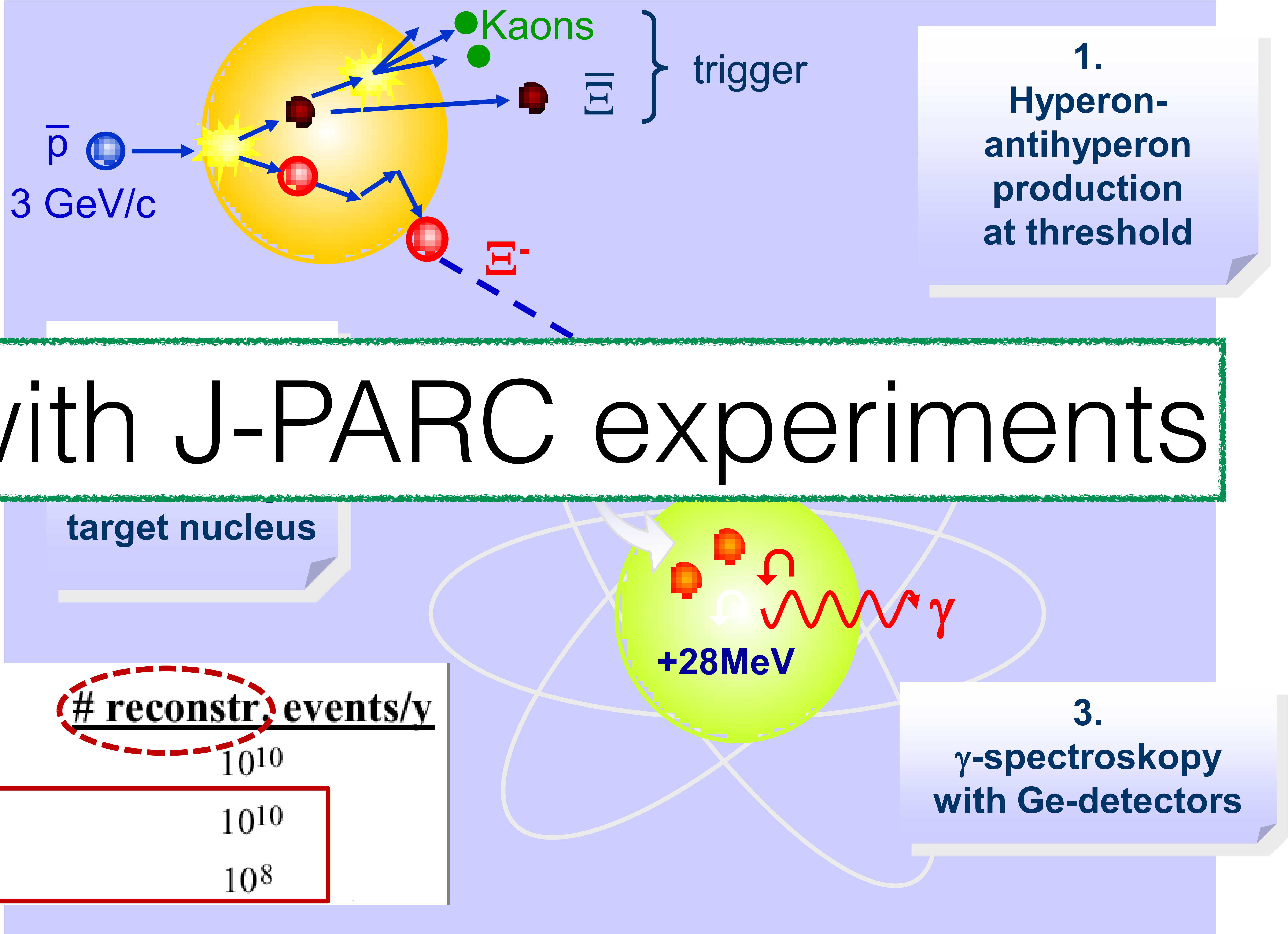
from Pochodzalla



Final State	cross section	# reconstr. events/y
Meson resonance + anything	100μb	10^{10}
$\Lambda\bar{\Lambda}$	50μb	10^{10}
$\Xi\bar{\Xi}$	2μb	10^{8}

ΛΛ-Hypernuclei at PANDA

from Pochodzalla

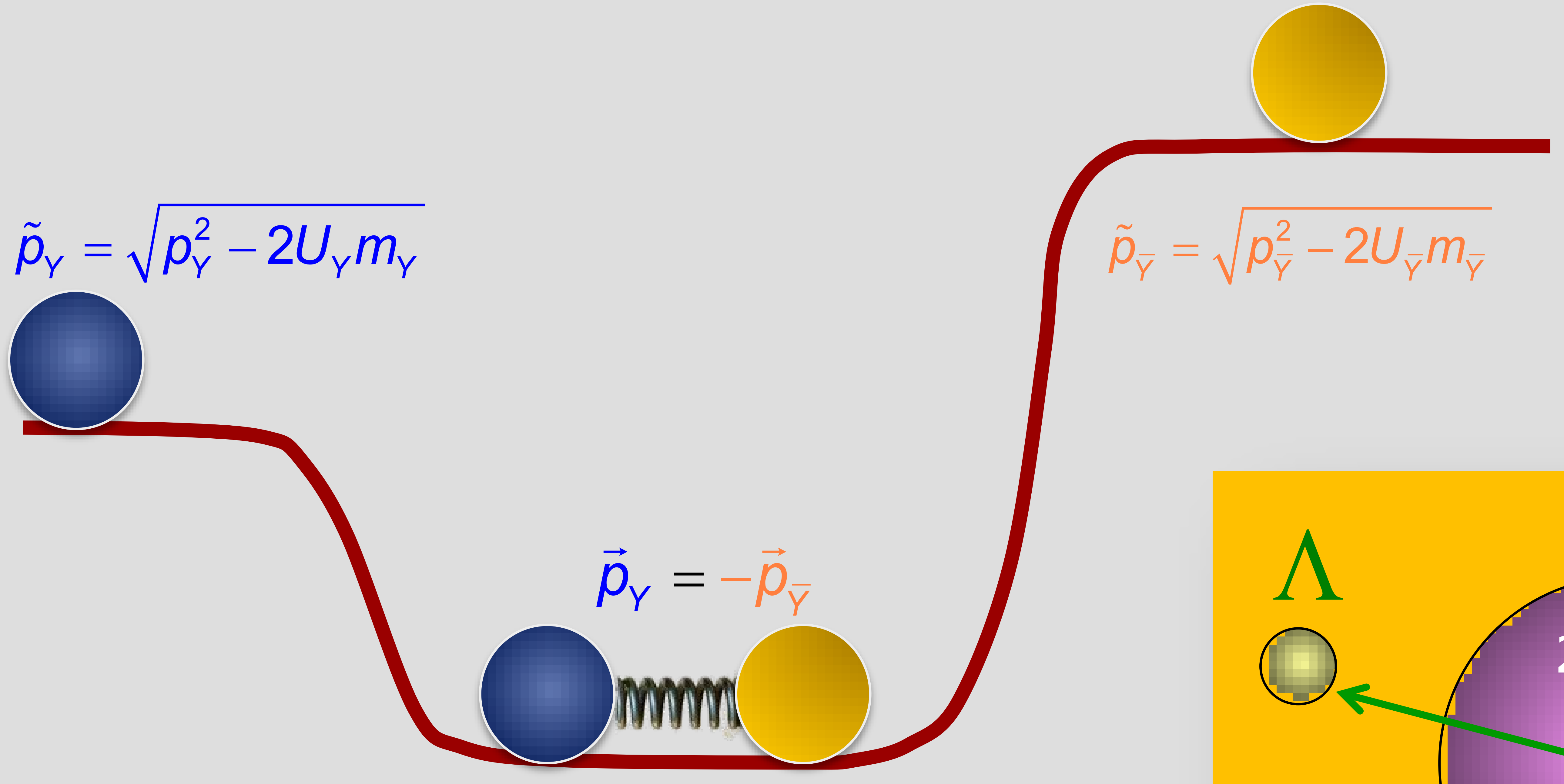


Competition with J-PARC experiments

Final State	cross section	# reconstr. events/y
Meson resonance + anything	100μb	10^{10}
$\Lambda\bar{\Lambda}$	50μb	10^{10}
$\Xi\bar{\Xi}$	2μb	10^{8}

Nuclei with antihyperons: unique at PANDA

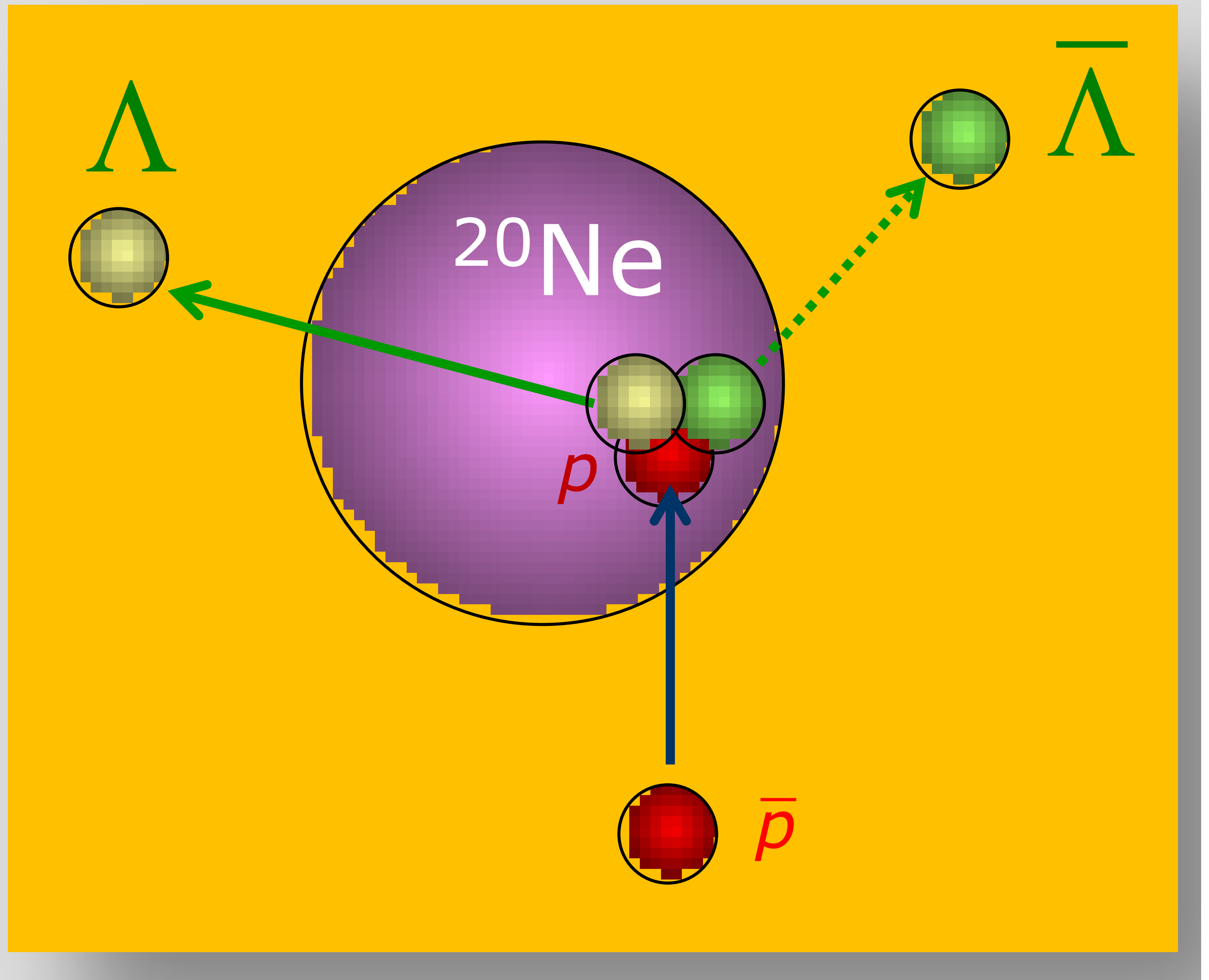
from Pochodzalla



- ⇒ *transverse* momentum close to threshold of *coincident* $Y\bar{Y}$ pairs

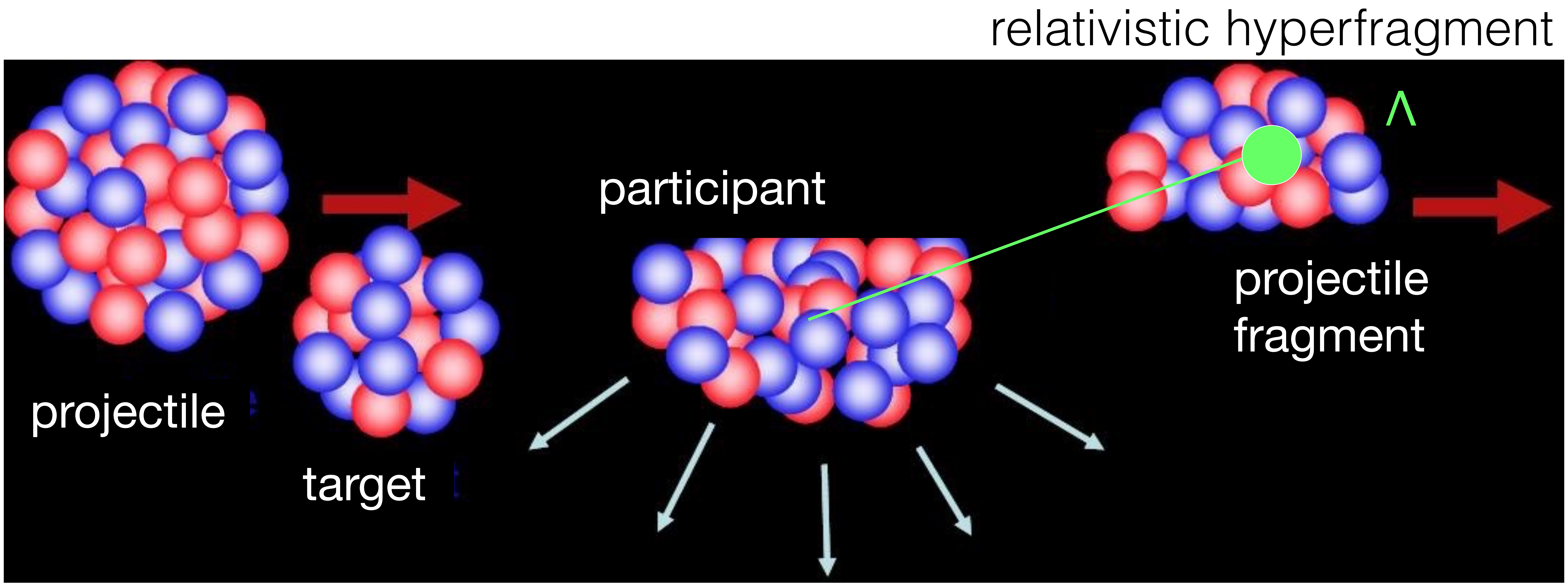
$$\alpha_\perp = \left\langle \frac{p_\perp(\Lambda) - p_\perp(\bar{\Lambda})}{p_\perp(\Lambda) + p_\perp(\bar{\Lambda})} \right\rangle$$

J.P., PLB **669** (2008) 306

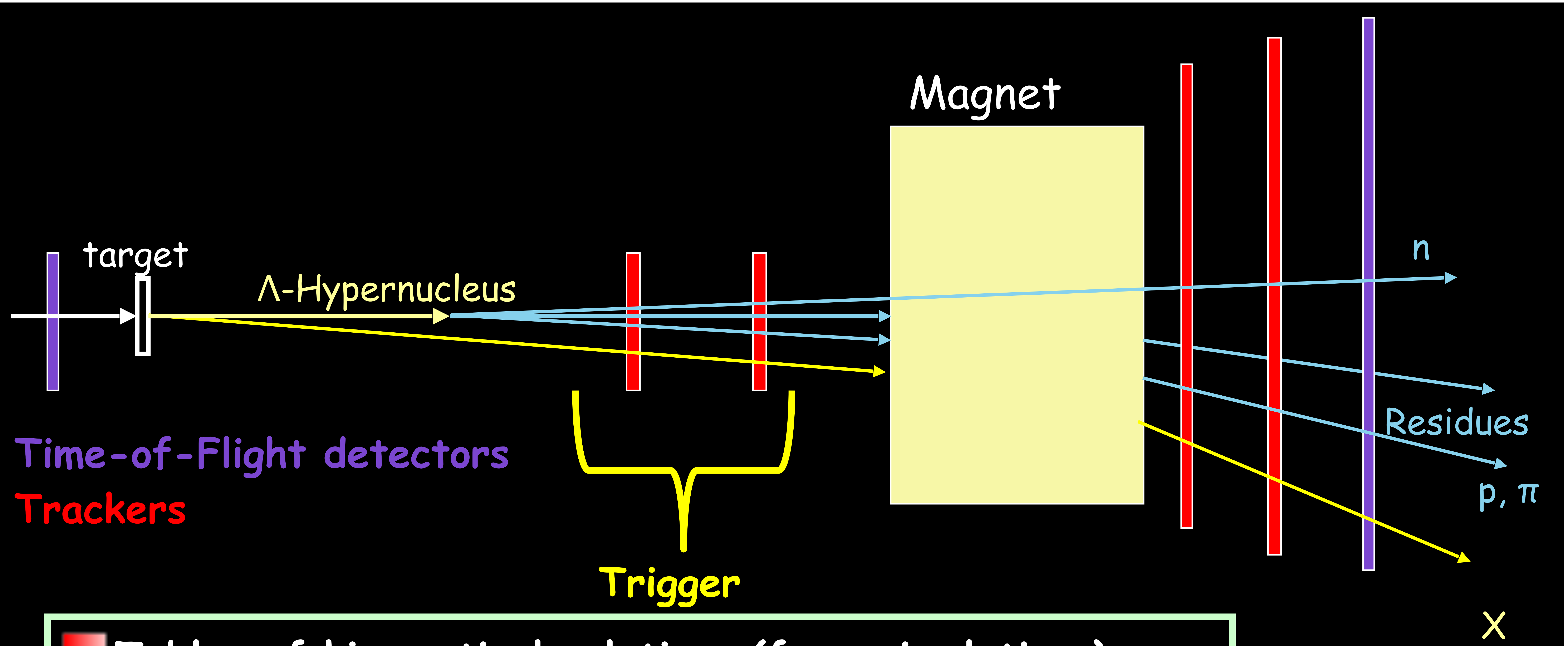


Promising future of HypHI

HypHI


relativistic hyperfragment
Λ
participant
projectile
fragment
projectile
target

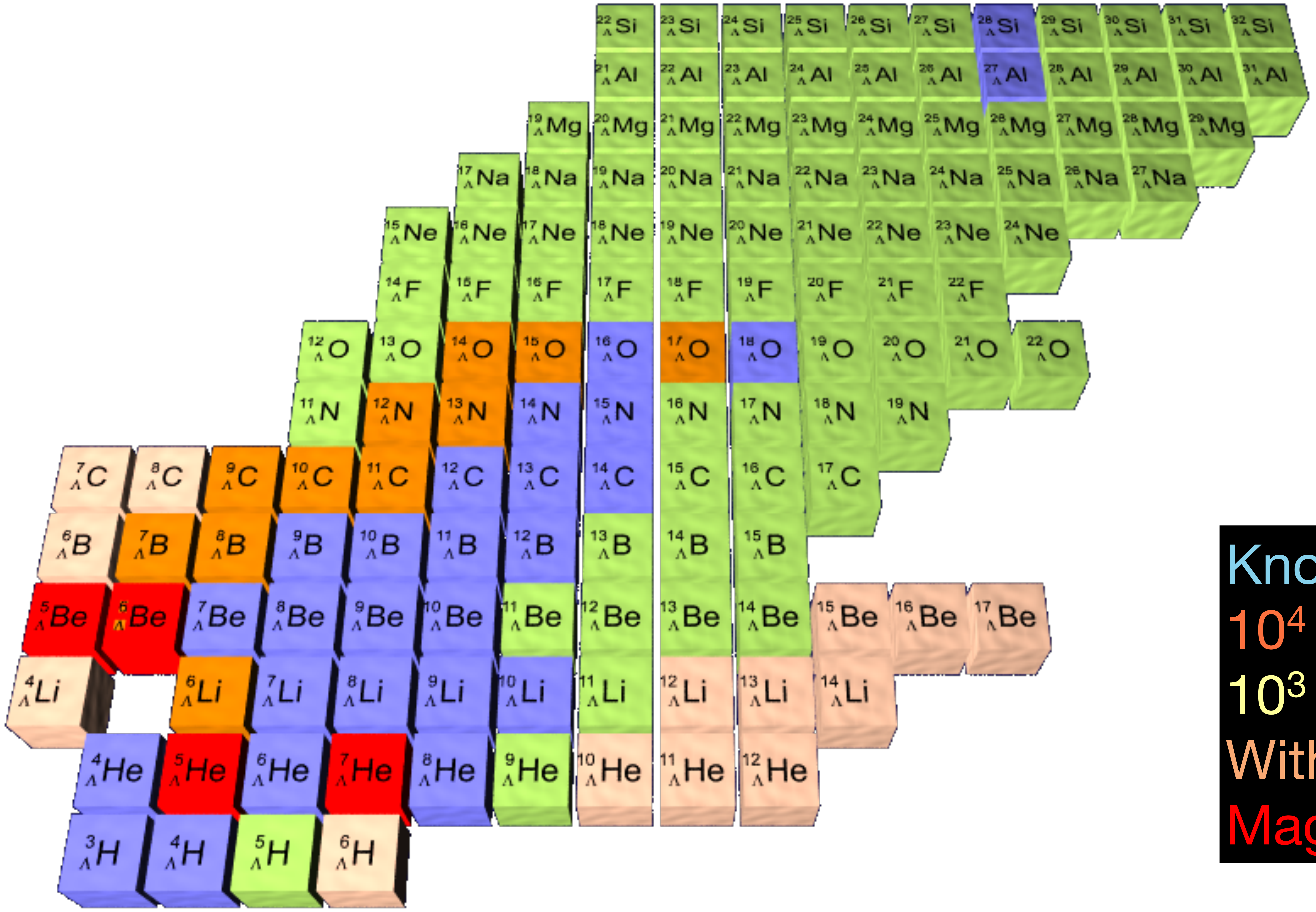
HypHI



- Tables of kinematical relations (from simulations)
- Programmed in fast online hardware (FPGA)

→ Displaced vertex trigger

Possible reach (but nontrivial reconstruction)

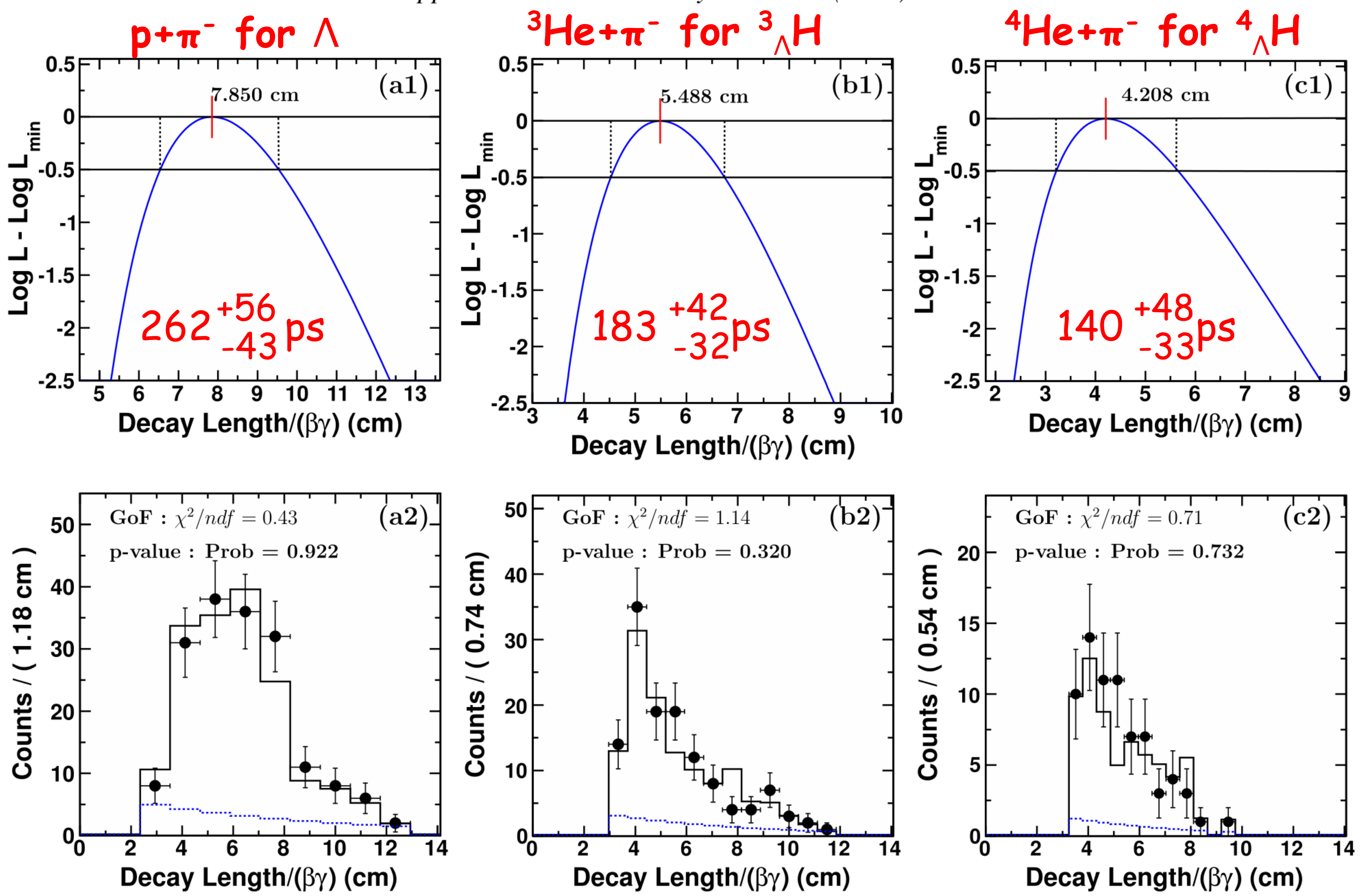


Known hypernuclei
10^4 /week
10^3 /week
With hypernuclear separator
Magnetic moments

some puzzles posed by HypHI

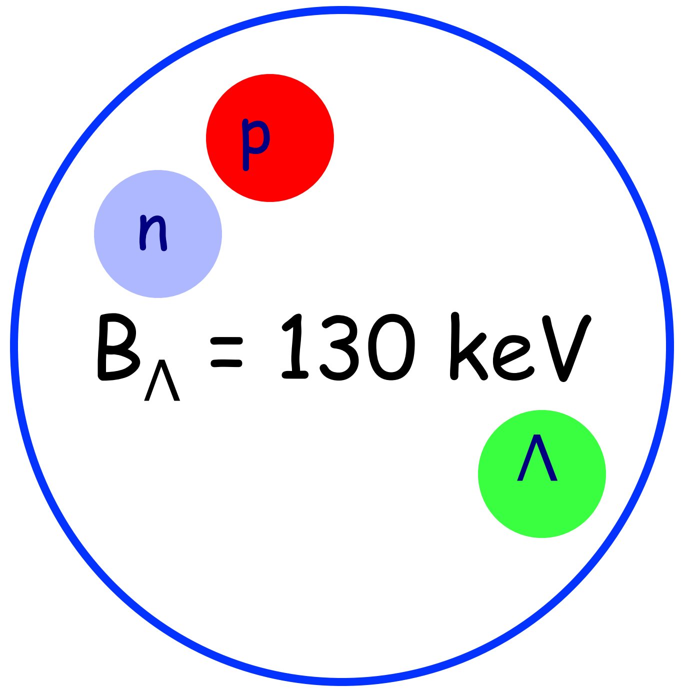
Why $^{3}_{\Lambda}H$ lifetime so short?

C. Rappold et al. / Nuclear Physics A 913 (2013) 170–184 181

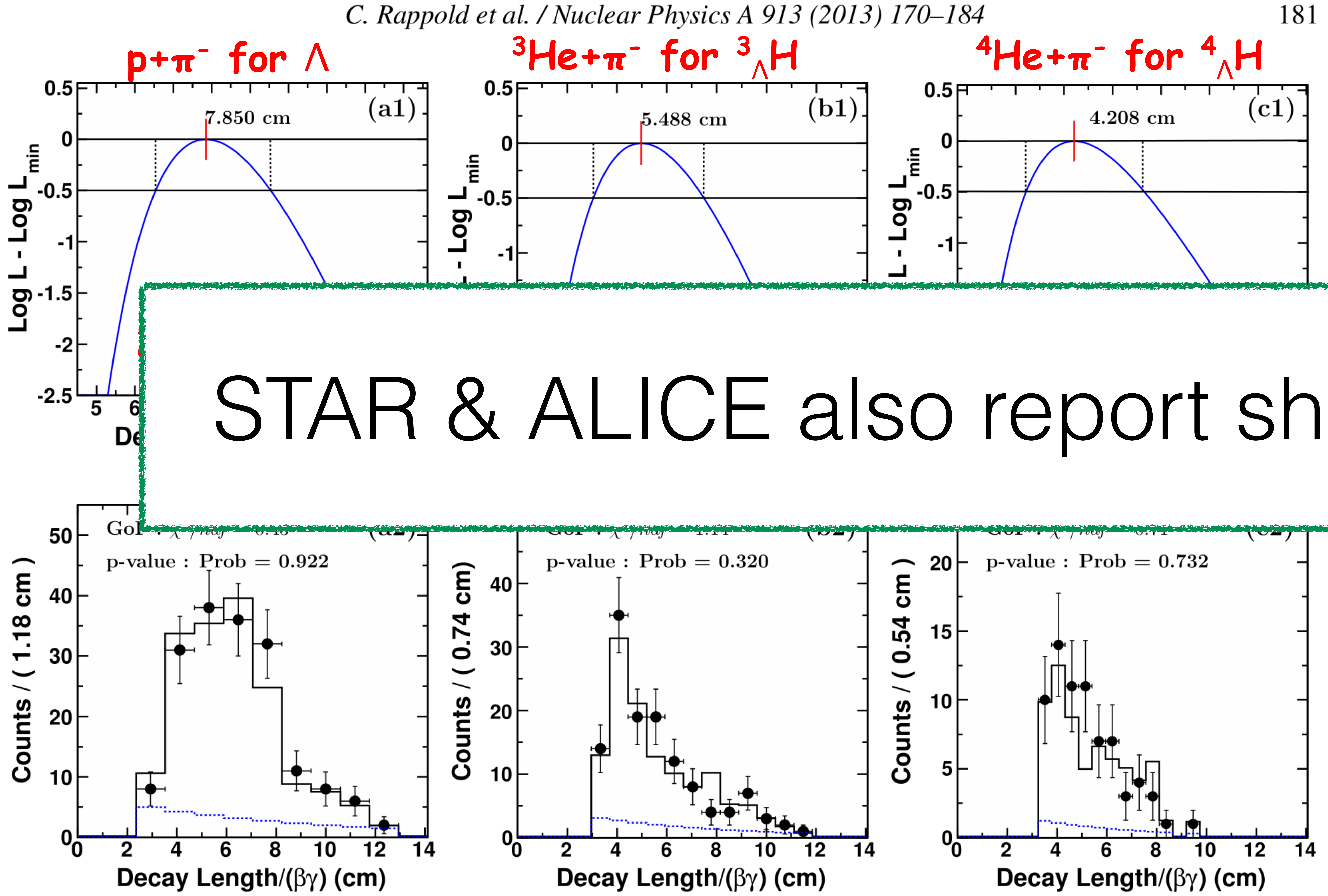


Theoretically,

$\tau(^{3}_{\Lambda}H) \sim \tau(\Lambda)$



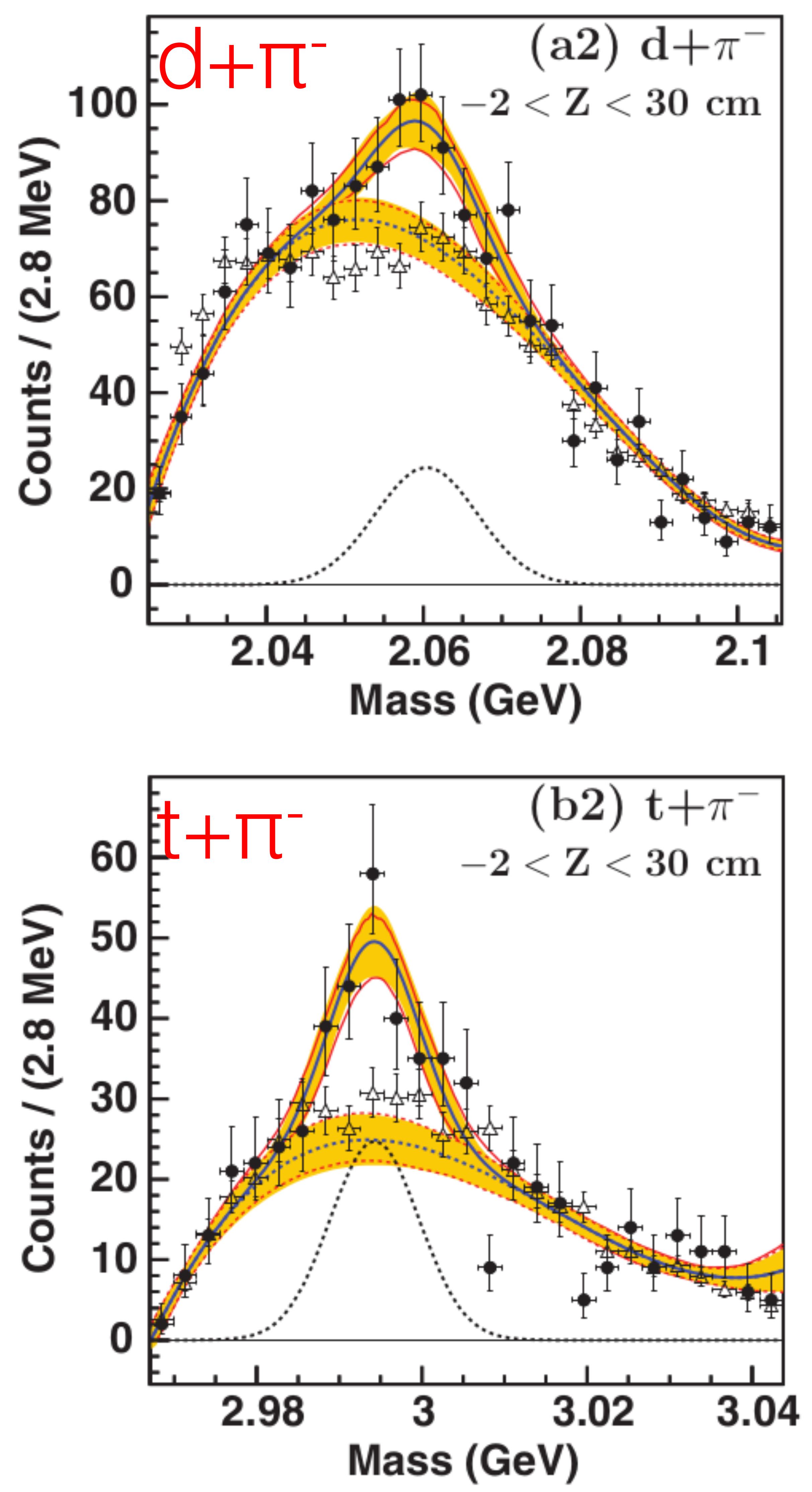
Why $^{3}_{\Lambda}H$ lifetime so short?



Theoretically,
$\tau(^{3}_{\Lambda}H) \sim \tau(\Lambda)$

STAR & ALICE also report short lifetimes

${}^{3}_{\Lambda}n$ (nnΛ) ??



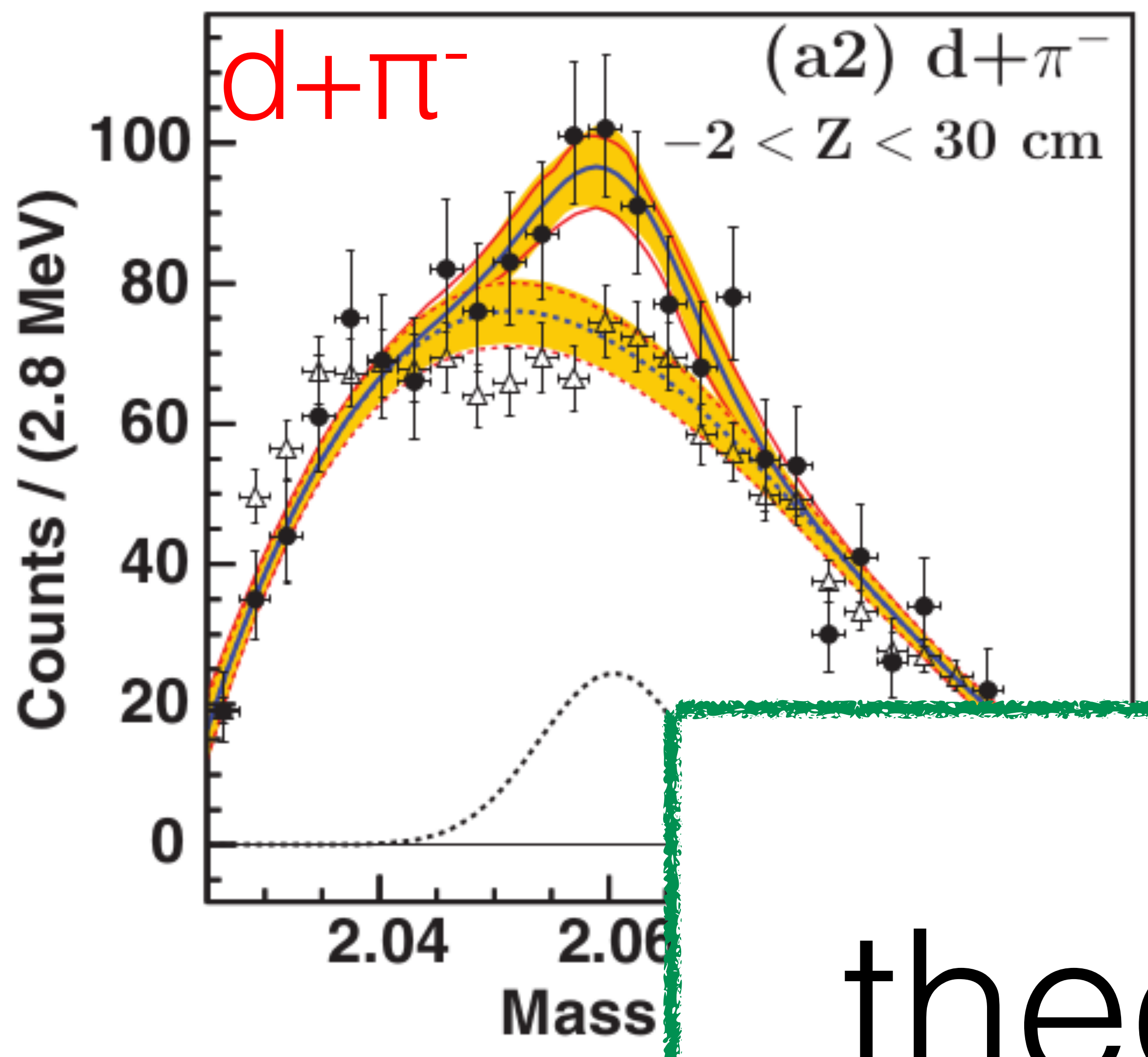
RAPID COMMUNICATIONS

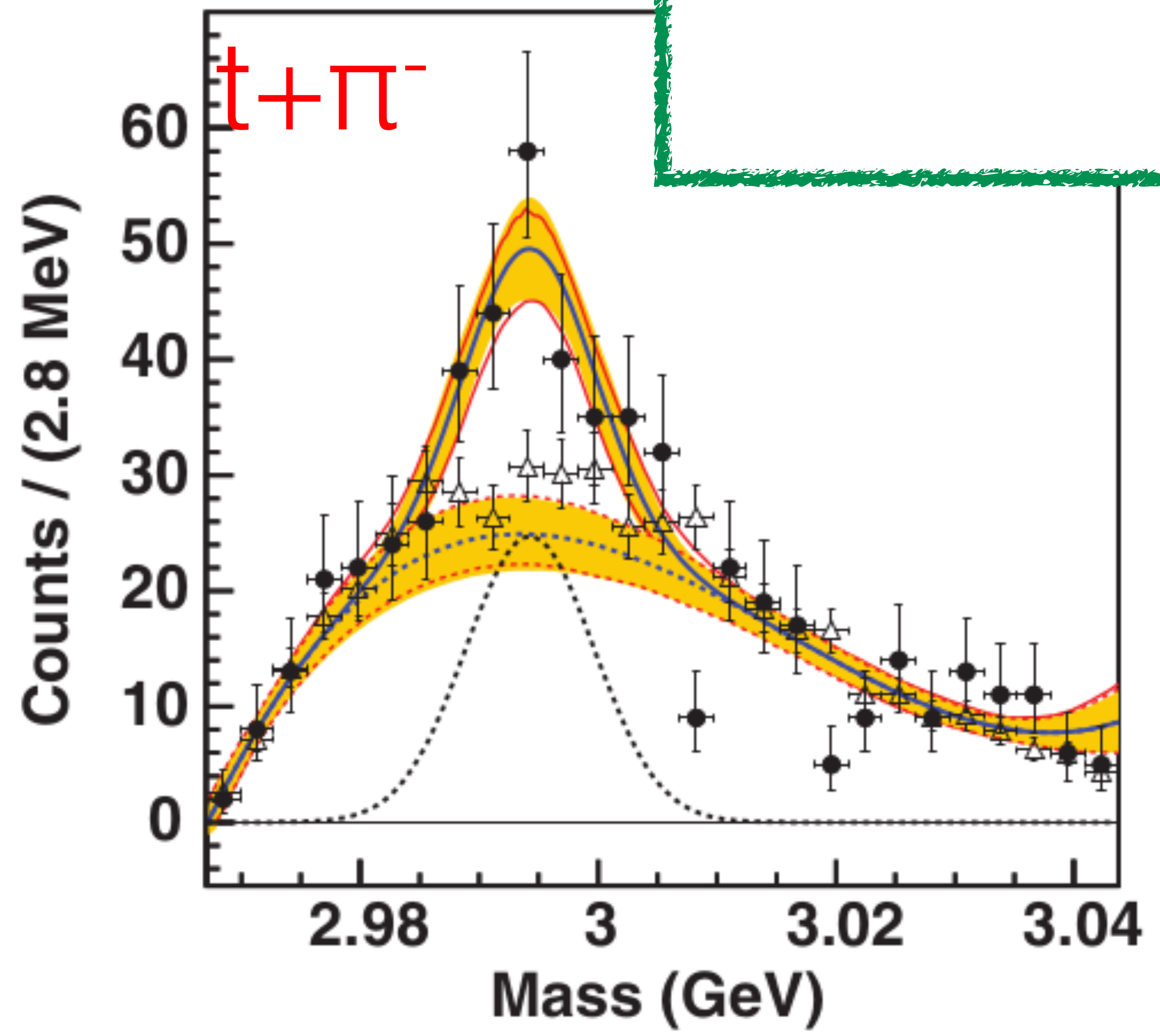
PHYSICAL REVIEW C **88**, 041001(R) (2013)

Search for evidence of ${}^{3}_{\Lambda}n$ by observing $d + \pi^-$ and $t + \pi^-$ final states in the reaction of ^{6}Li + ^{12}C at 2*A* GeV

C. Rappold,[1,2,*] E. Kim,[1,3] T. R. Saito,[1,4,5,†] O. Bertini,[1,4] S. Bianchin,[1] V. Bozkurt,[1,6] M. Kavatsyuk,[7] Y. Ma,[1,4] F. Maas,[1,4,5] S. Minami,[1] D. Nakajima,[1,8] B. Özel-Tashenov,[1] K. Yoshida,[1,5,9] P. Achenbach,[4] S. Ajimura,[10] T. Aumann,[1,11] C. Ayerbe Gayoso,[4] H. C. Bhang,[3] C. Caesar,[1,11] S. Erturk,[6] T. Fukuda,[12] B. Göküzüm,[1,6] E. Guliev,[7] J. Hoffmann,[1] G. Ickert,[1] Z. S. Ketenci,[6] D. Khaneft,[1,4] M. Kim,[3] S. Kim,[3] K. Koch,[1] N. Kurz,[1] A. Le Fèvre,[1,13] Y. Mizoi,[12] L. Nungesser,[4] W. Ott,[1] J. Pochodzalla,[4] A. Sakaguchi,[9] C. J. Schmidt,[1] M. Sekimoto,[14] H. Simon,[1] T. Takahashi,[14] G. J. Tambave,[7] H. Tamura,[15] W. Trautmann,[1] S. Voltz,[1] and C. J. Yoon[3]
(HypHI Collaboration)

$^{3}_{\Lambda}n$ (nnΛ) ??





RAPID COMMUNICATIONS

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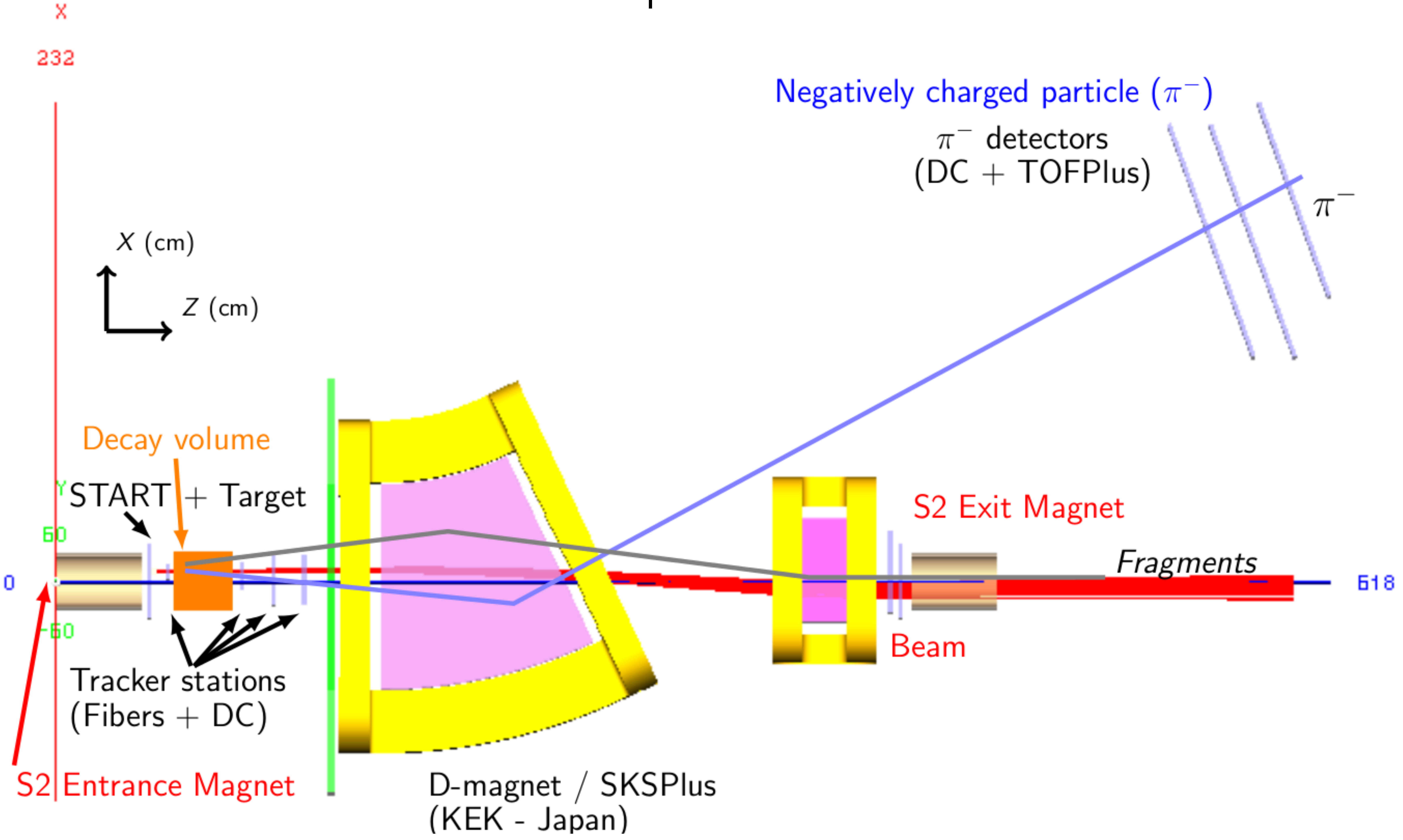
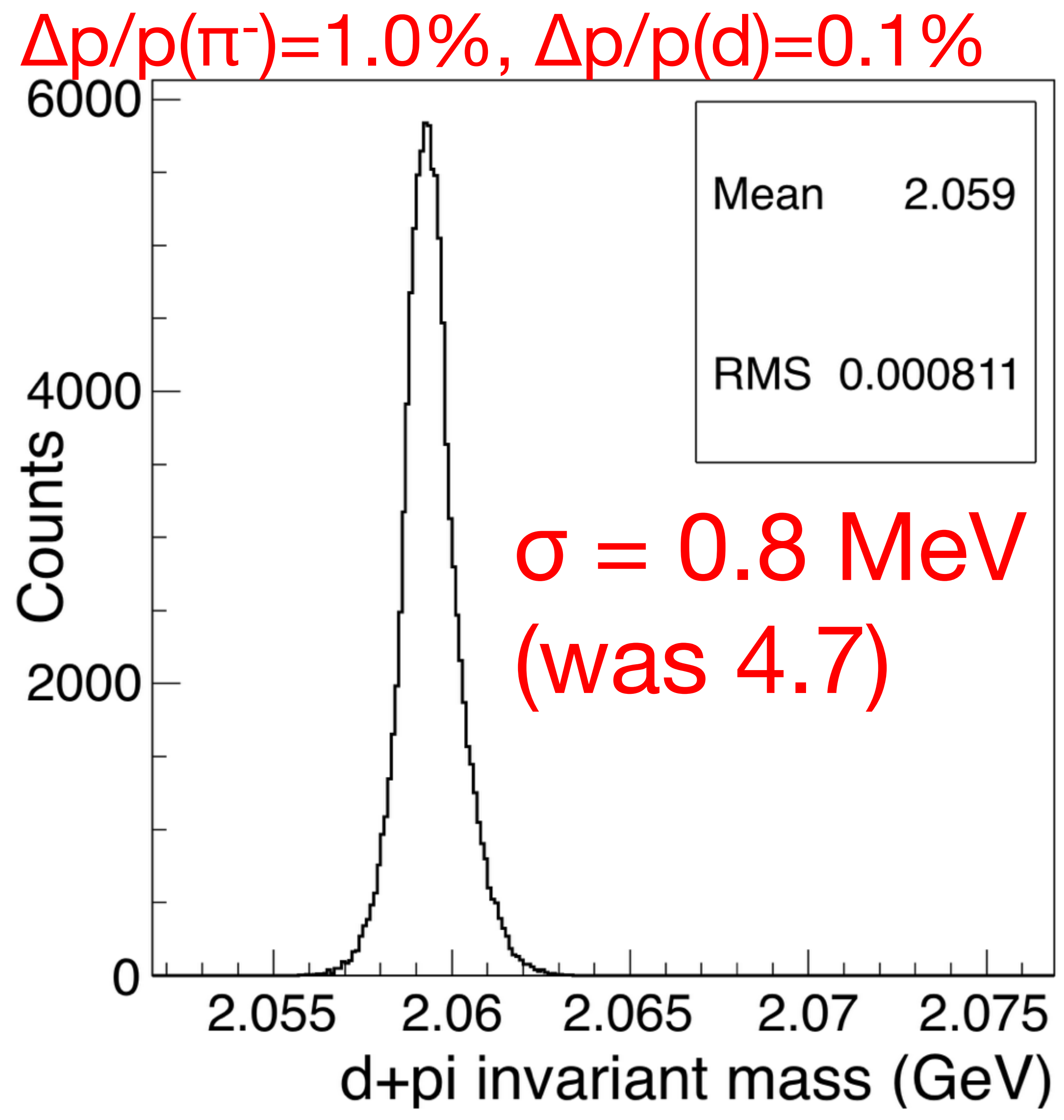
[1,4] F. Maas,[1,4,5]
nann,[1,11]
ann,[1] G. Ickert,[1]
sser,[4] W. Ott,[1]
H. Tamura,[15]

theorists say $^{3}_{\Lambda}n$ is unlikely to exist this must be re-checked

HypHI at FRS is being planned

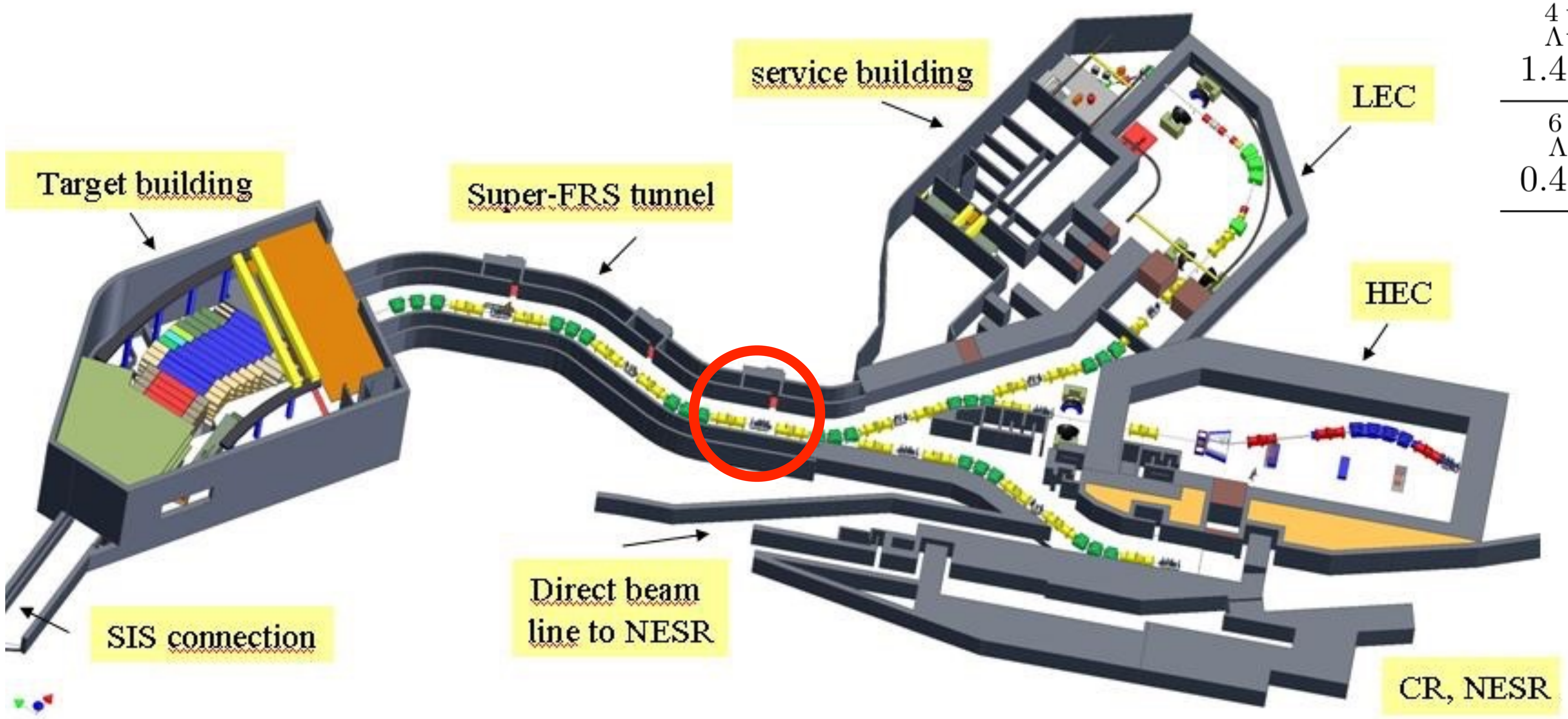
improve invariant mass resolution



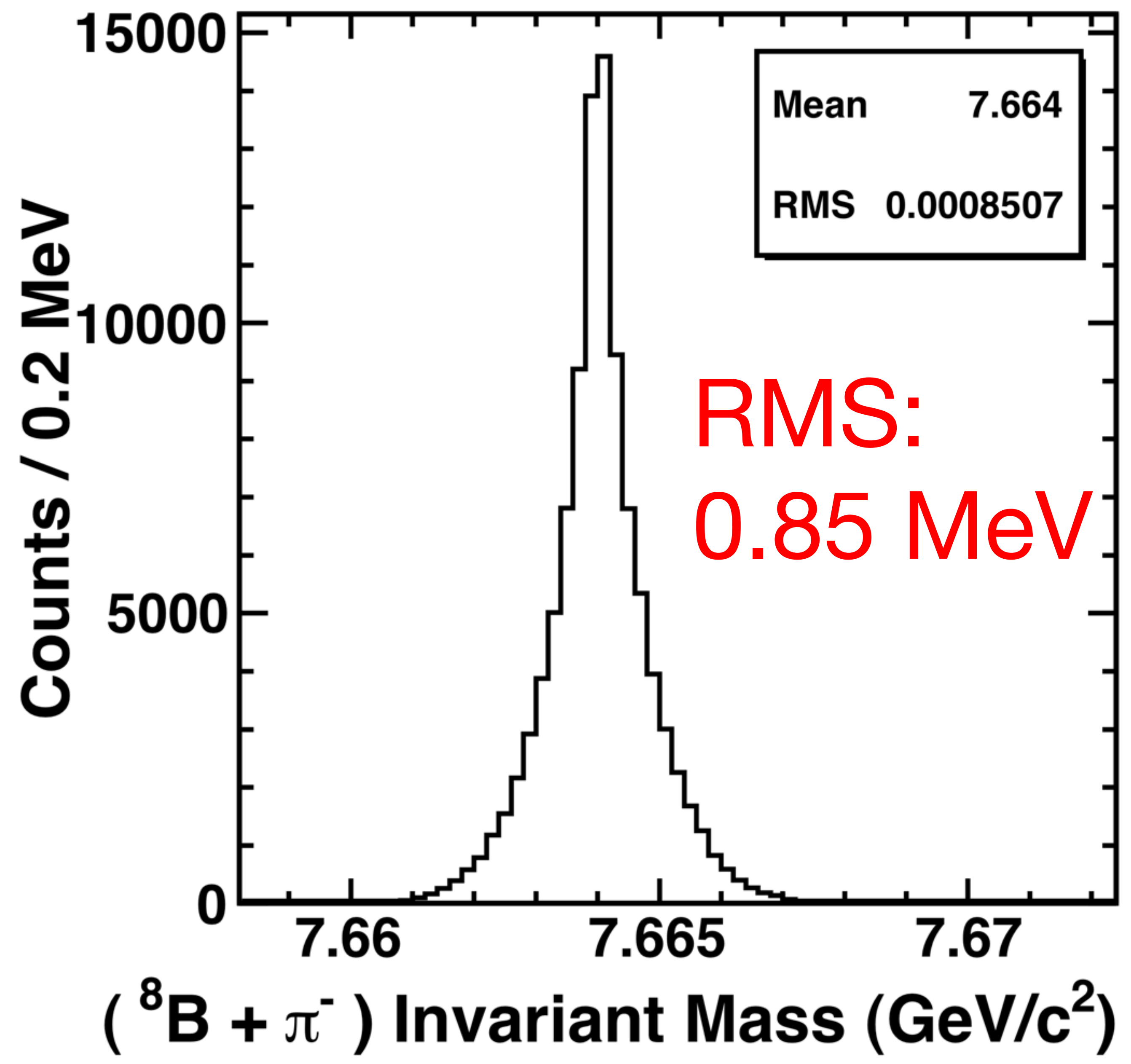


and also

HypHI at Super-FRS is being considered

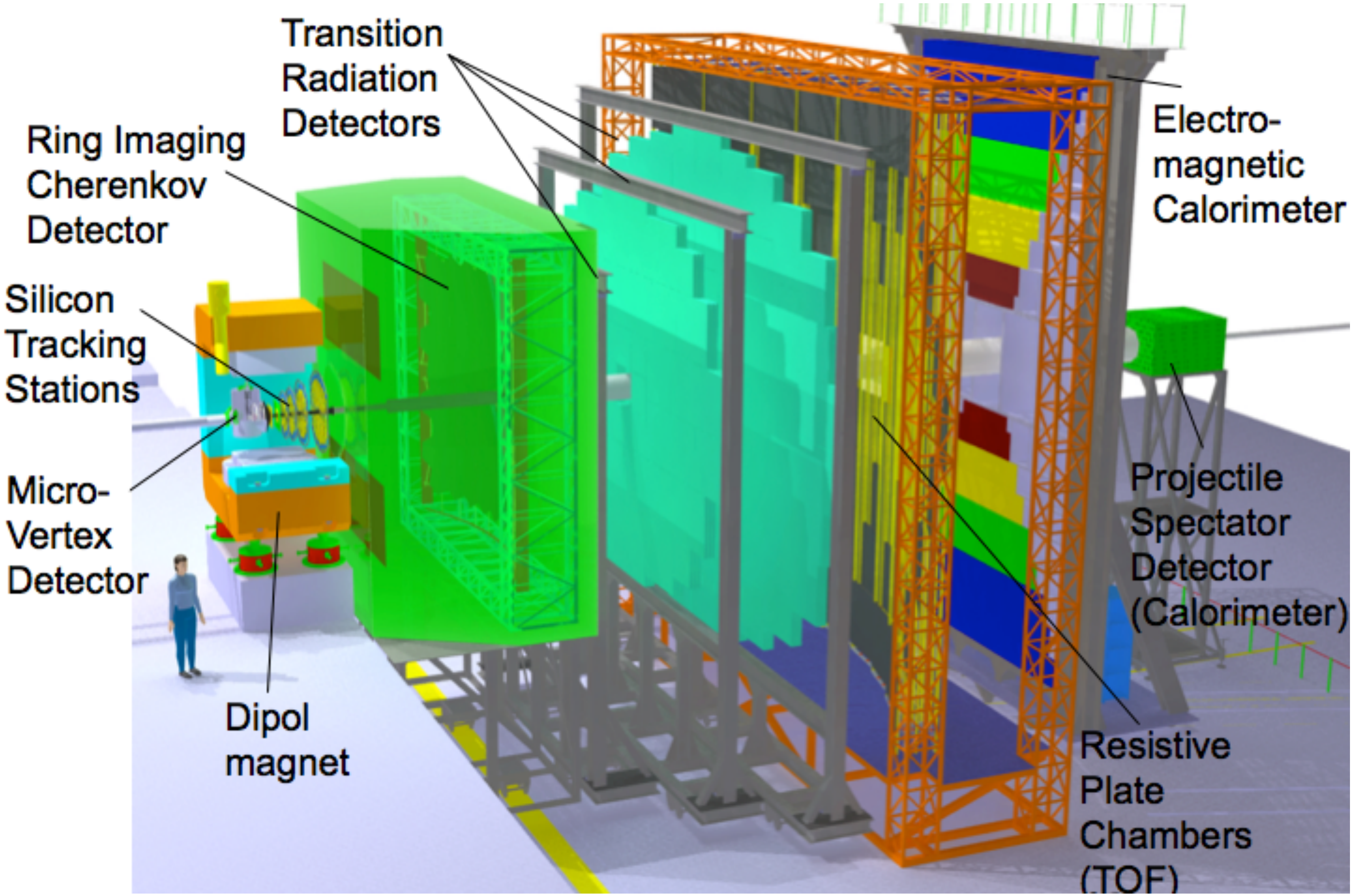


$^{3}_{\Lambda}$H	$^{4}_{\Lambda}$H	$^{3}_{\Lambda}$He	$^{4}_{\Lambda}$He	$^{5}_{\Lambda}$He	$^{6}_{\Lambda}$He
2 μb	1.2 μb	1.2 μb	3.4 μb	2.6 μb	1.4 μb
$^{4}_{\Lambda}$Li	$^{5}_{\Lambda}$Li	$^{5}_{\Lambda}$Be	$^{6}_{\Lambda}$Be	$^{7}_{\Lambda}$Be	$^{8}_{\Lambda}$Be
1.4 μb	1.2 μb	0.4 μb	1.6 μb	0.6 μb	0.8 μb
$^{6}_{\Lambda}$B	$^{7}_{\Lambda}$B	$^{8}_{\Lambda}$B	$^{8}_{\Lambda}$C		
0.4 μb	0.2 μb	0.6 μb	0.2 μb		

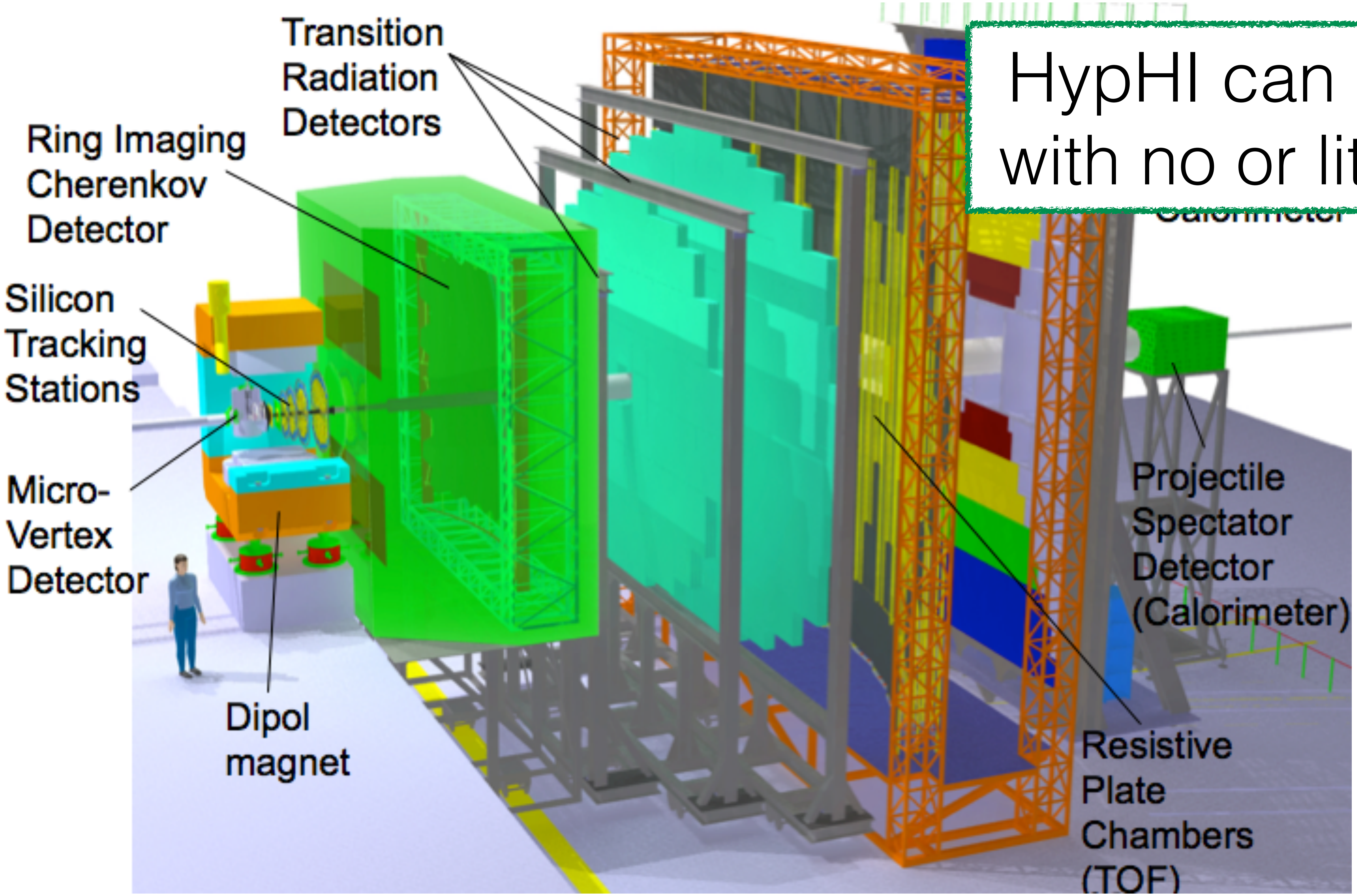


but I think (and Take Saito agrees)
it makes sense to consider …

HypHI @ CBM


Transition
Radiation
Detectors
Ring Imaging
Cherenkov
Detector
Silicon
Tracking
Stations
Micro-
Vertex
Detector
Dipol
magnet
Electro-
magnetic
Calorimeter
Projectile
Spectator
Detector
(Calorimeter)
Resistive
Plate
Chambers
(TOF)

HypHI @ CBM



HypHI can be done @ CBM with no or little modifications

HypHI @ CBM

- Unique - new species, relativistic,
  (no competition with the J-PARC experiments)

HypHI @ CBM

- Unique - new species, relativistic,
  (no competition with the J-PARC experiments)

- Use light relativistic ions (easier reconstruction)

HypHI @ CBM

- Unique - new species, <u>relativistic</u>,
  (no competition with the J-PARC experiments)

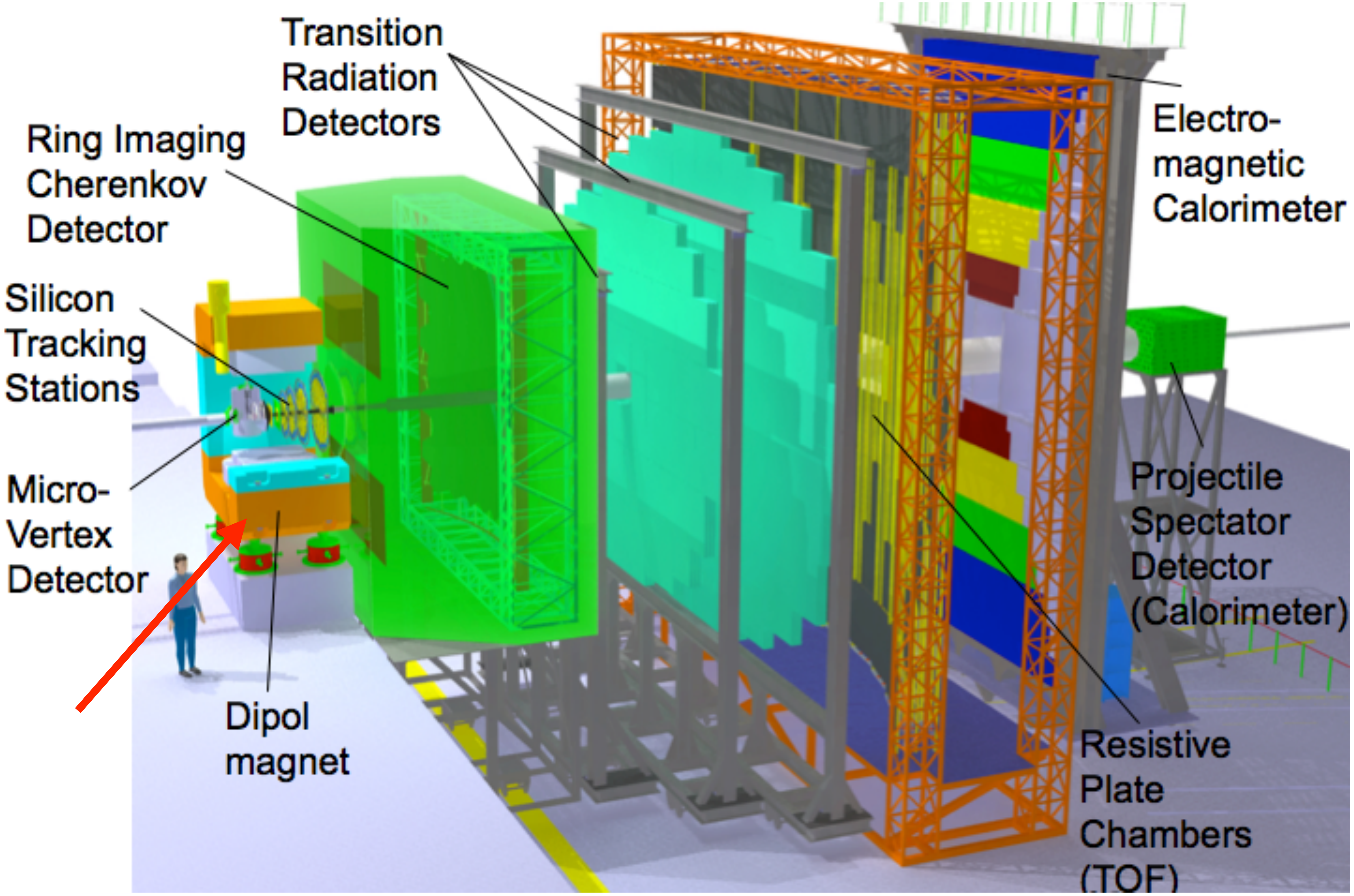
- Use light relativistic ions (easier reconstruction)

- Measure polarization (Λ weak decay asymmetry wrt reaction plane)

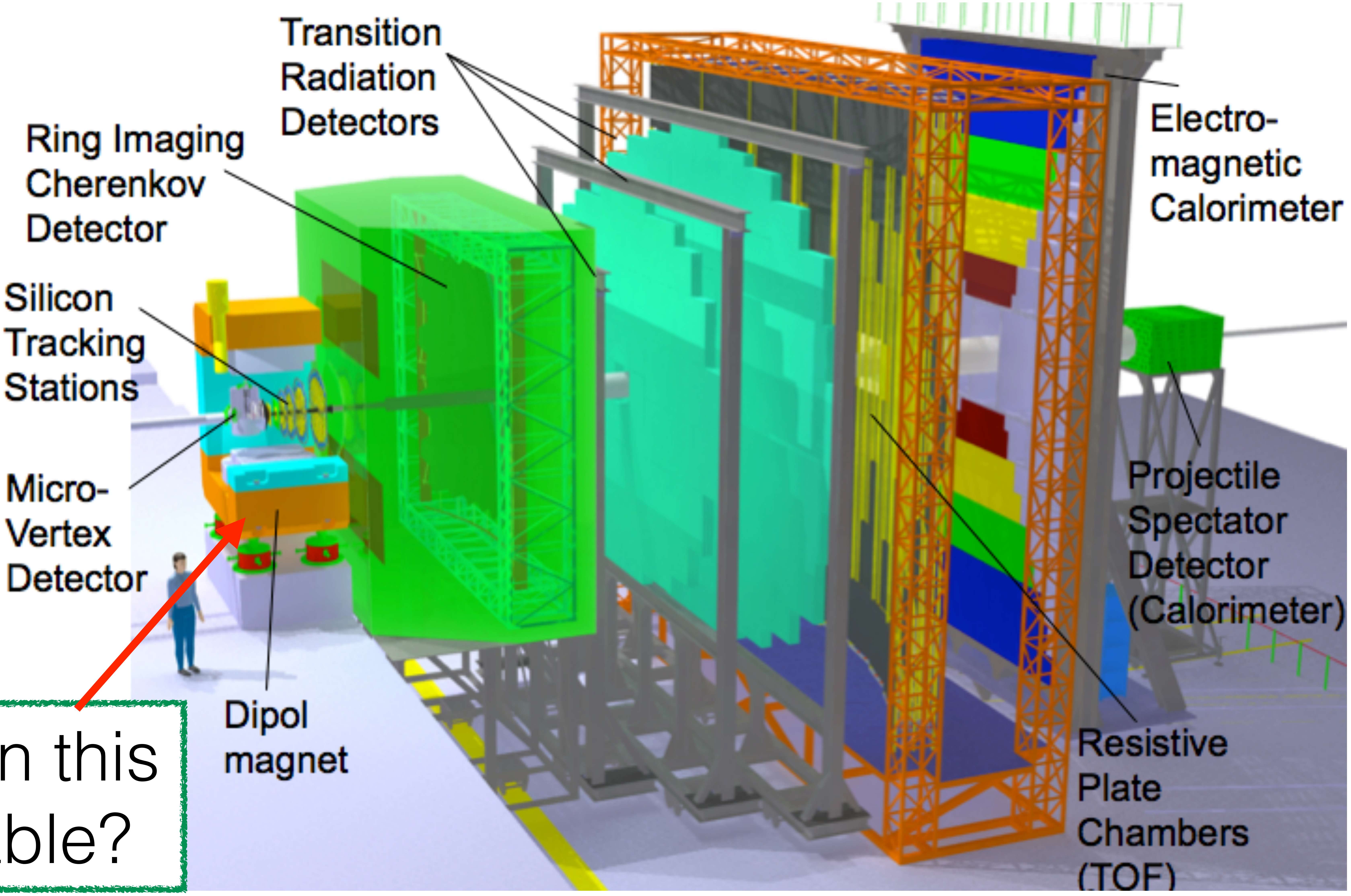
HypHI @ CBM

- Unique - new species, relativistic,
  (no competition with the J-PARC experiments)
- Use light relativistic ions (easier reconstruction)
- Measure polarization (Λ weak decay asymmetry wrt reaction plane)
- Direct measurement of hypernuclear **magnetic moment(s)** (spin precession in the CBM's target dipole)

HypHI @ CBM

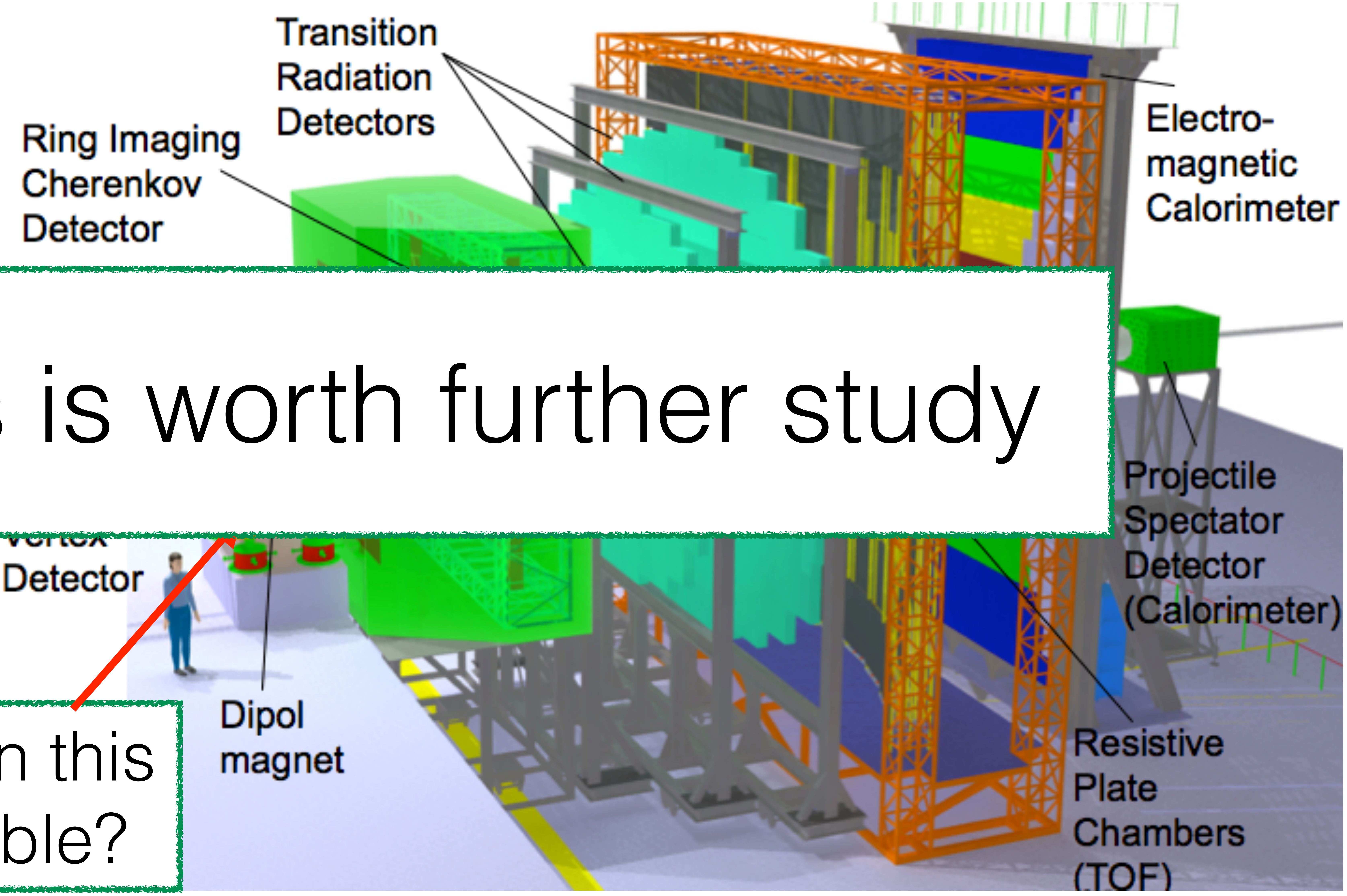

Transition
Radiation
Detectors
Ring Imaging
Cherenkov
Detector
Silicon
Tracking
Stations
Micro-
Vertex
Detector
Dipol
magnet
Electro-
magnetic
Calorimeter
Projectile
Spectator
Detector
(Calorimeter)
Resistive
Plate
Chambers
(TOF)

HypHI @ CBM



spin precession in this magnet observable?

HypHI @ CBM



This is worth further study

spin precession in this magnet observable?

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- Atomic x-ray experiments are also important
- Anti-hyperon experiments @ PANDA are unique
- HypHI @ CBM (μ_Λ in particular) worth pursuing