Brainstorming on opportunities

at the FRS/S-FRS with WASA/S-WASA

Kenta Itahashi
RIKEN Nishina Center

Brainstorming on opportunities of hadron physics at the FRS/S-FRS with WASA/S-WASA

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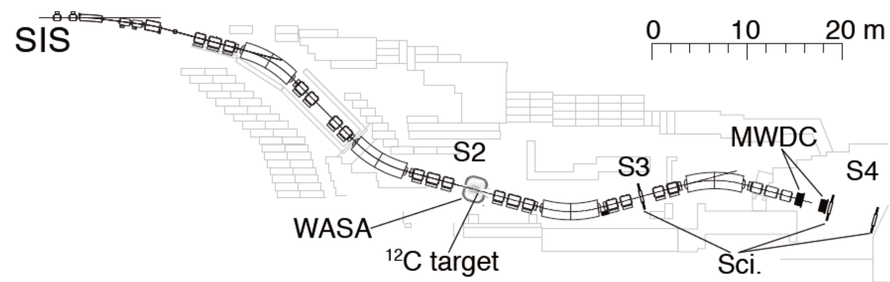
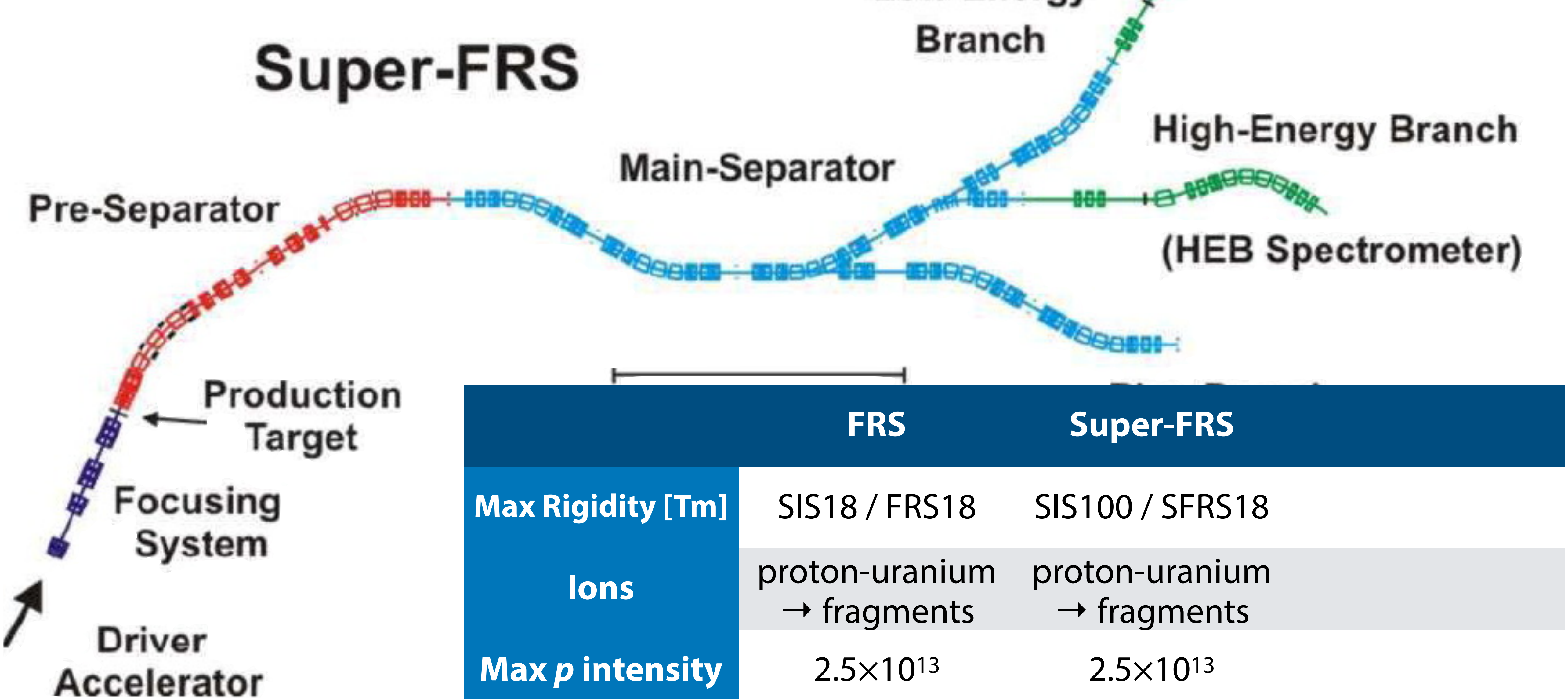
Facilities side by side

FRS



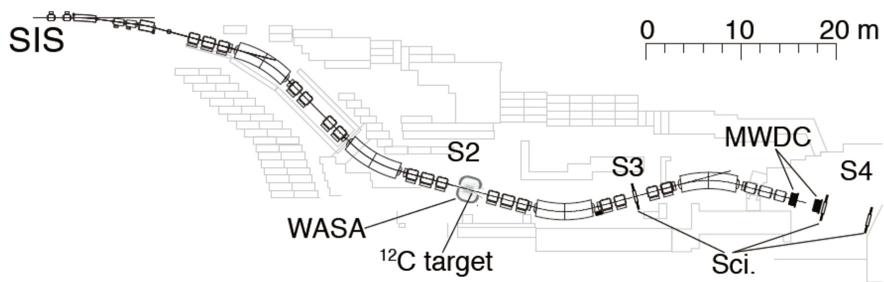


	FRS	Super-FRS
Max Rigidity [Tm]	SIS18 / FRS18	SIS100 / SFRS18
Ions	proton-uranium → fragments	proton-uranium → fragments
Max *p* intensity	2.5×10^{13}	2.5×10^{13}
E×B	-	-
Distance	35-70 m	120-170 m
2nd beams	Fragment etc.	Fragment, pi, pbar

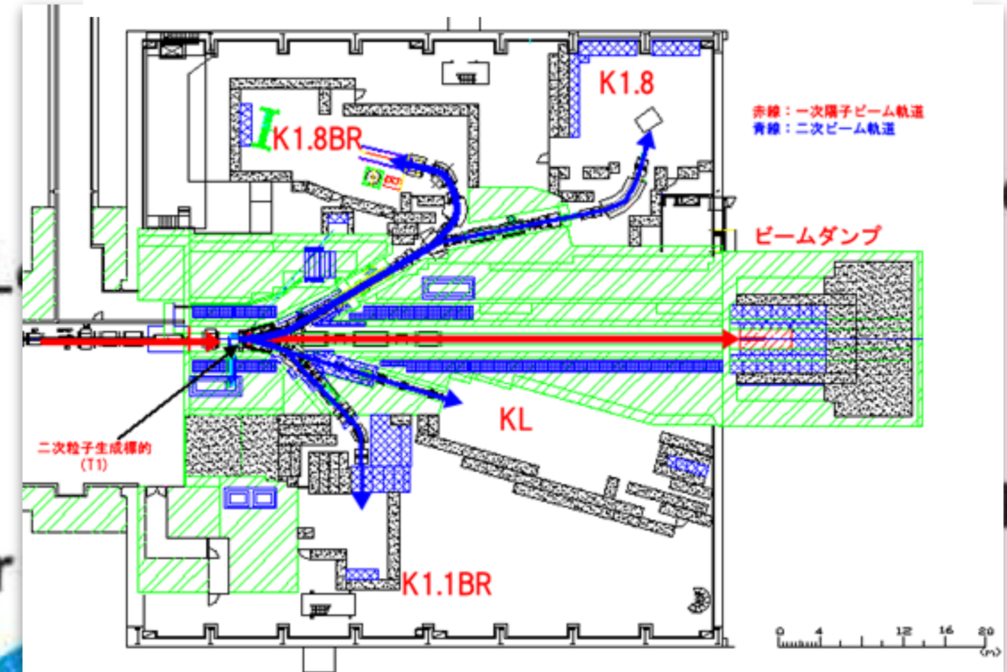
~same scale

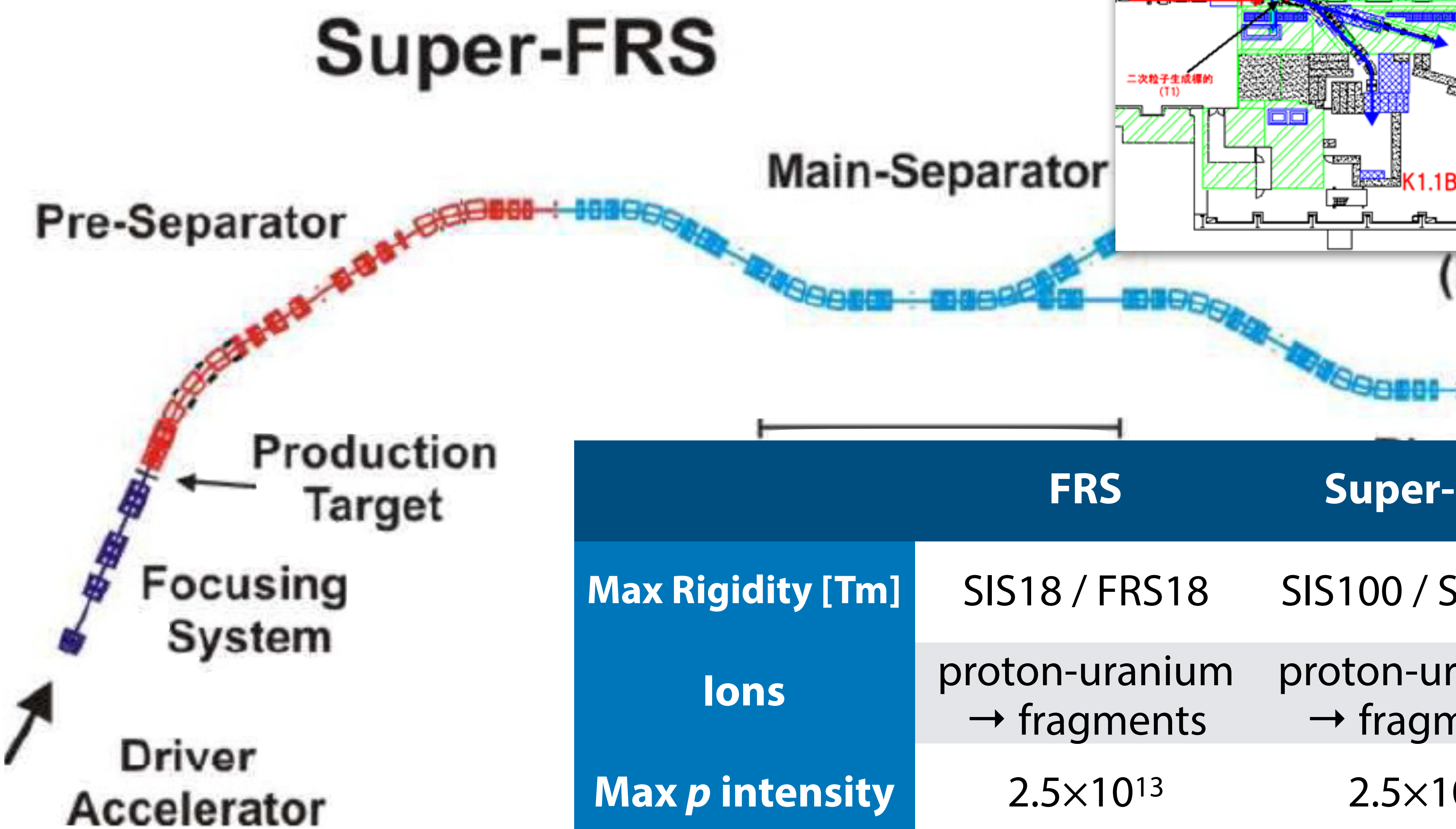
Facilities side

FRS



J-PARC HD hall





	FRS	Super-FRS	J-PARC K1.8
Max Rigidity [Tm]	SIS18 / FRS18	SIS100 / SFRS18	MR100 / K1.8=6
Ions	proton-uranium → fragments	proton-uranium → fragments	proton → π K pbar
Max *p* intensity	2.5×10^{13}	2.5×10^{13}	2.7×10^{14}
E×B	-	-	✓
Distance	35-70 m	120-170 m	~60m
2nd beams	Fragment etc.	Fragment, pi, pbar	pi, pbar, K

~same scale

Super-FRS hadron beam intensities

Advantages

Pion / pbar beams available
Spectroscopy
Dispersion matching
(mu beams?)

Disadvantages

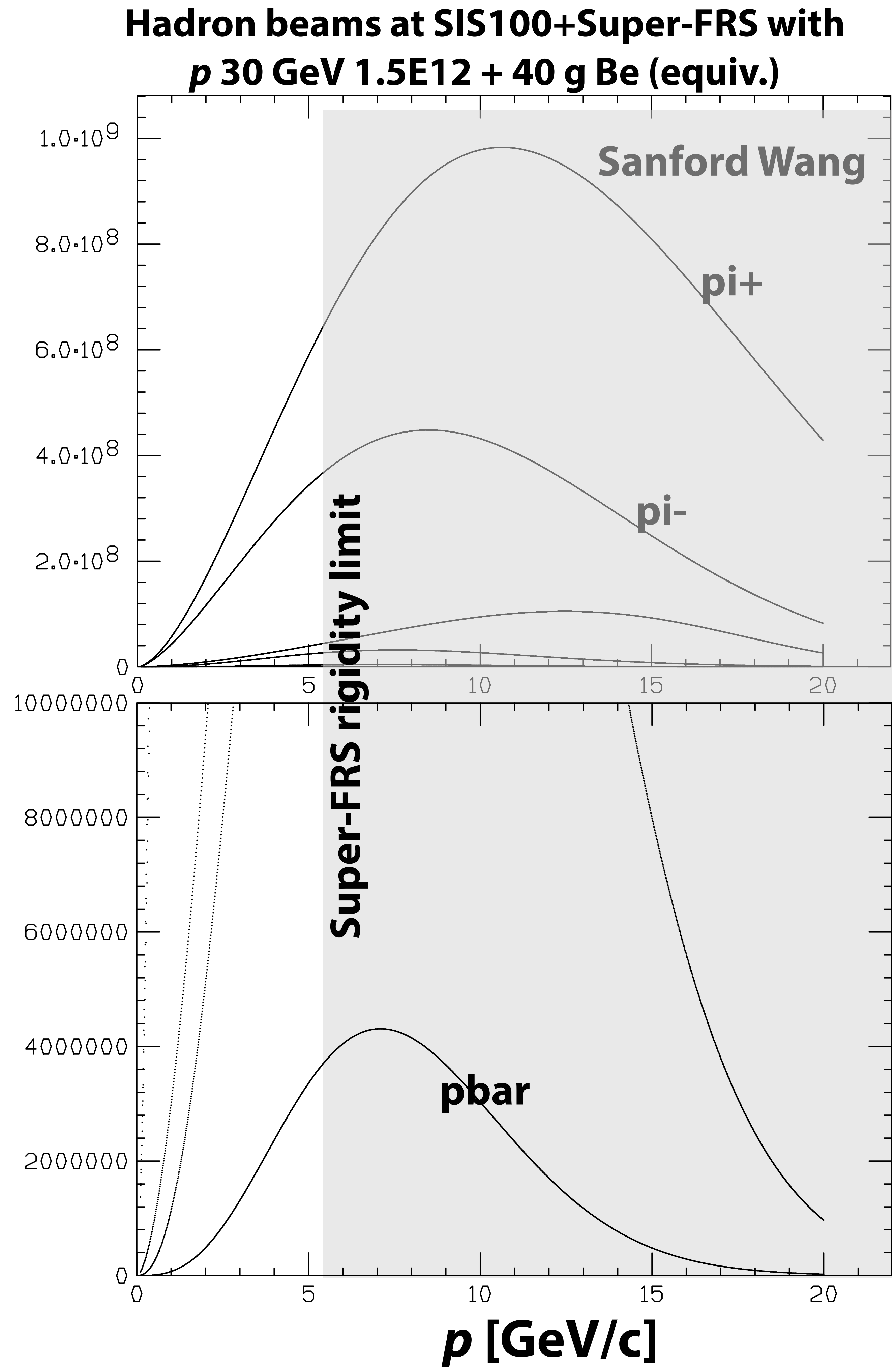
No E×B → need of special optics

Too long beamline → No K beam

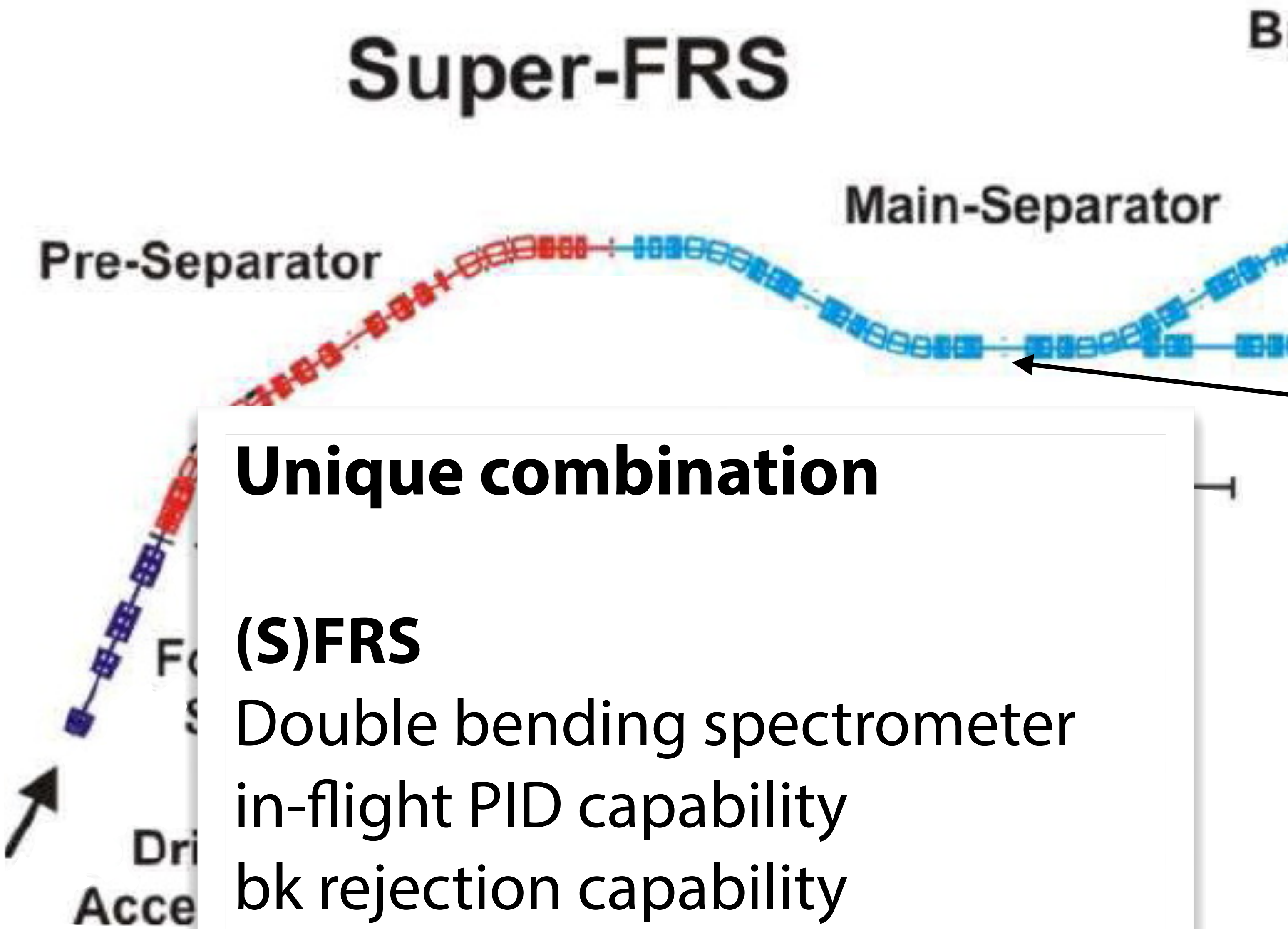
Long spectrometer → No K meas.
FMF2 area is too small…

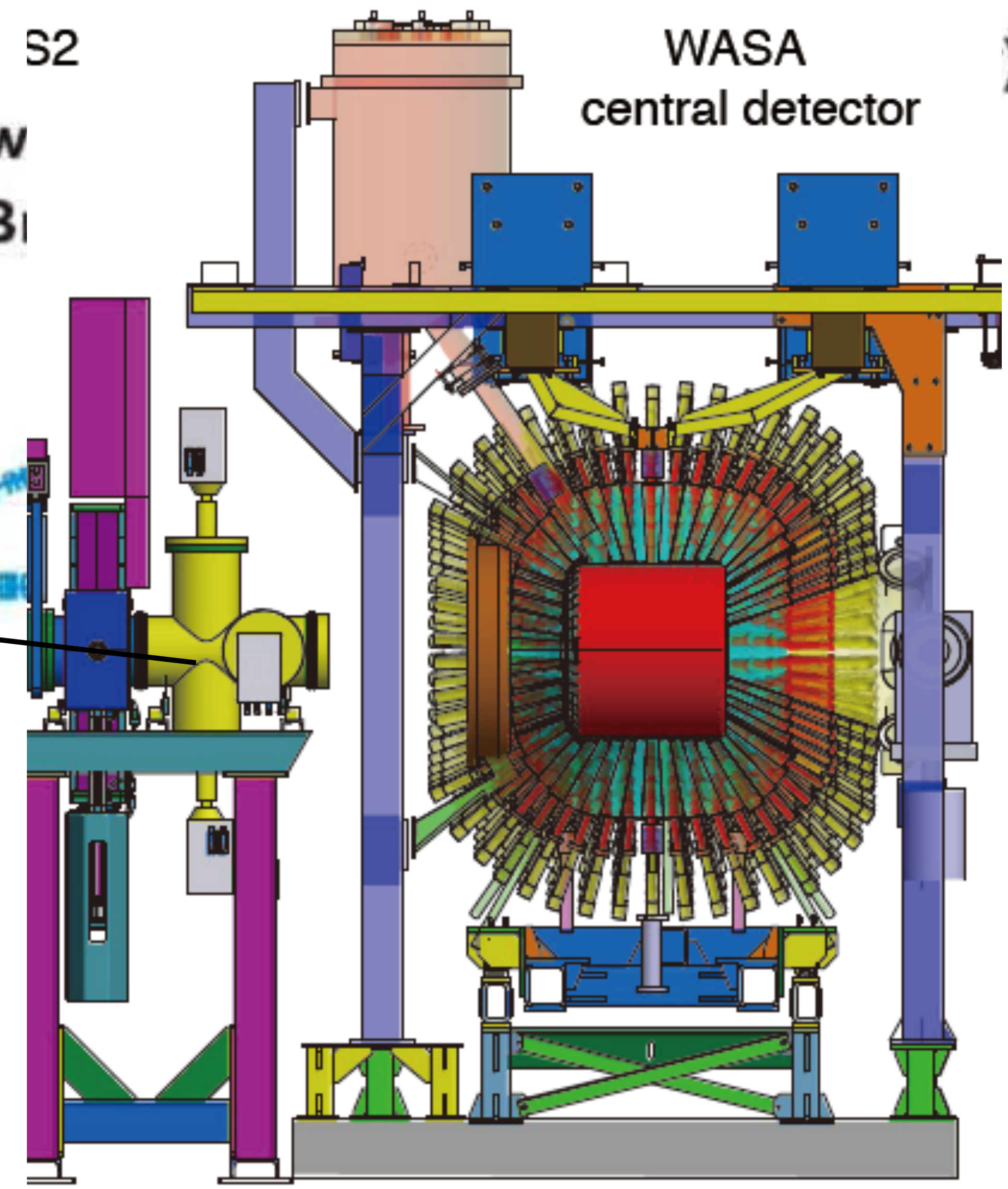
Other facilities

J-PARC K1.8(BR) for pion / K / pbar beams
J-PARC HIHR for DM pion / pbar beams
R^3B for pbar with forward detectors



FRS+Large Ω charged particle detector is unique but





Unique combination

(S)FRS
Double bending spectrometer
in-flight PID capability
bk rejection capability
WASA
Large Ω acceptance
charged PID + p →Rare event tag

WASA is too big…

to fit into service tunnel to FMF2

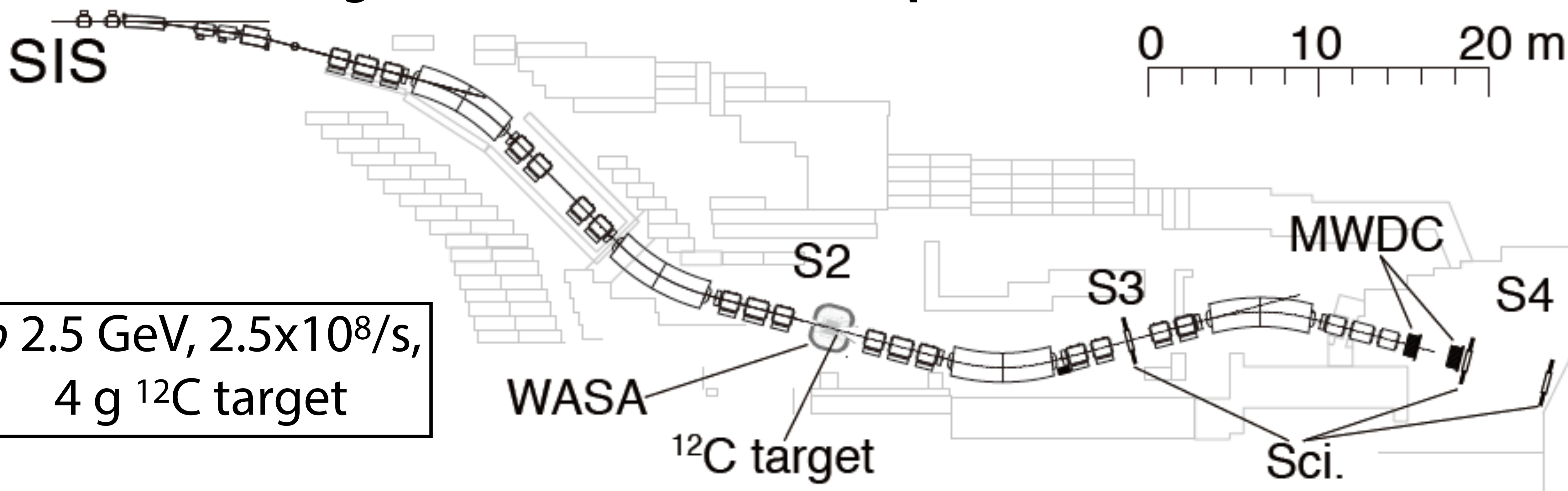
Physics interests may include

1. η' or η mesic nuclei
2. Double kaonic nuclei search
3. Hadron production studies

Feasibility is not yet considered

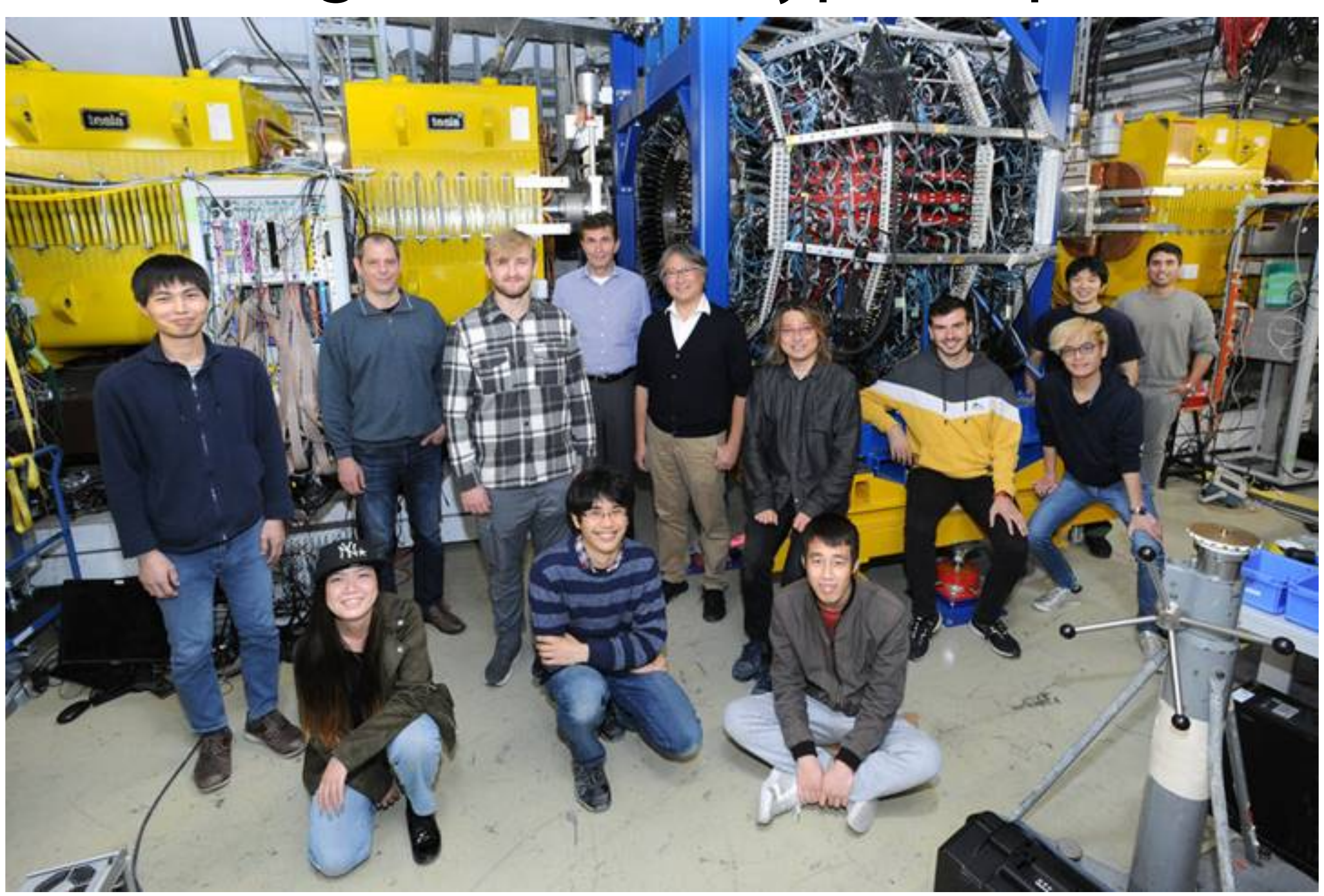
η′-mesic nuclei spectroscopy in ^{12}C(p,d)

Missing mass measurement of η′-mesic nuclei in FRS



p 2.5 GeV, 2.5x10^8/s,
4 g ^{12}C target

Together with HypHI exp.

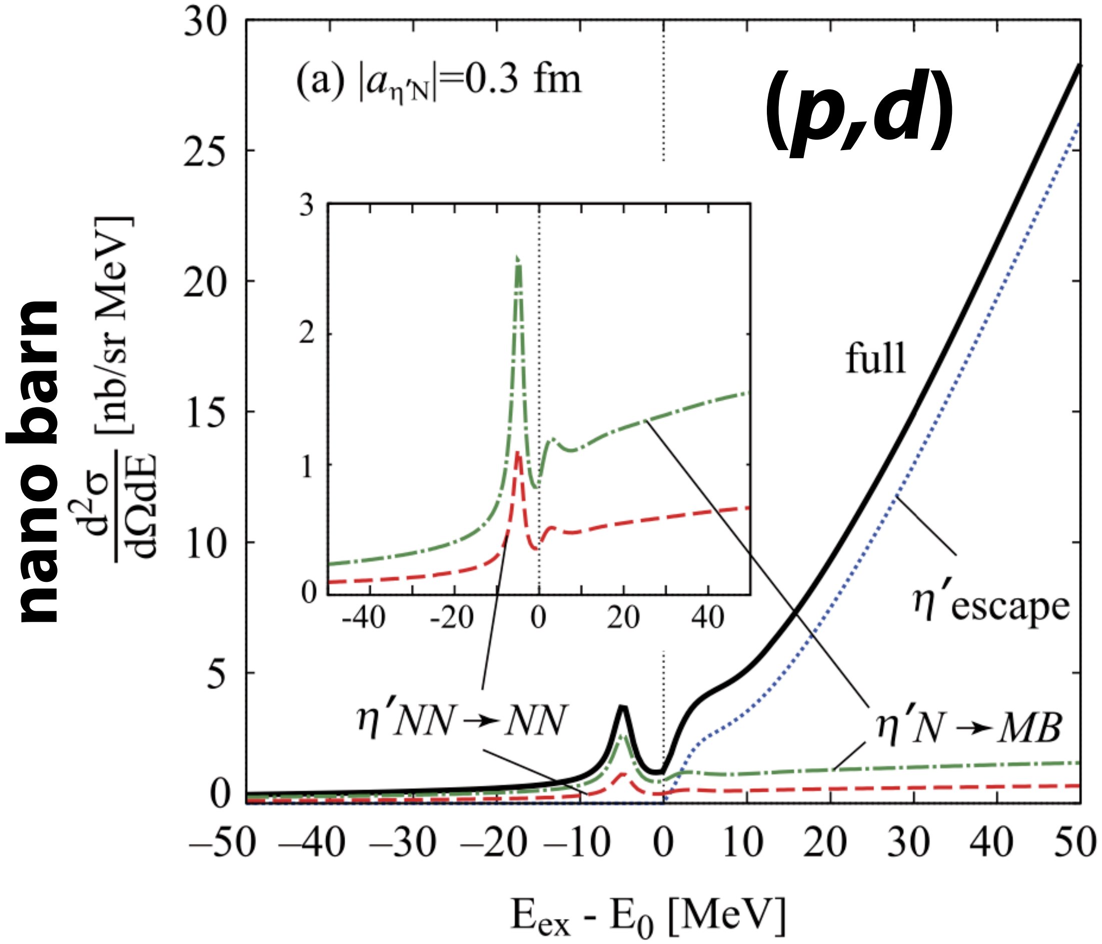


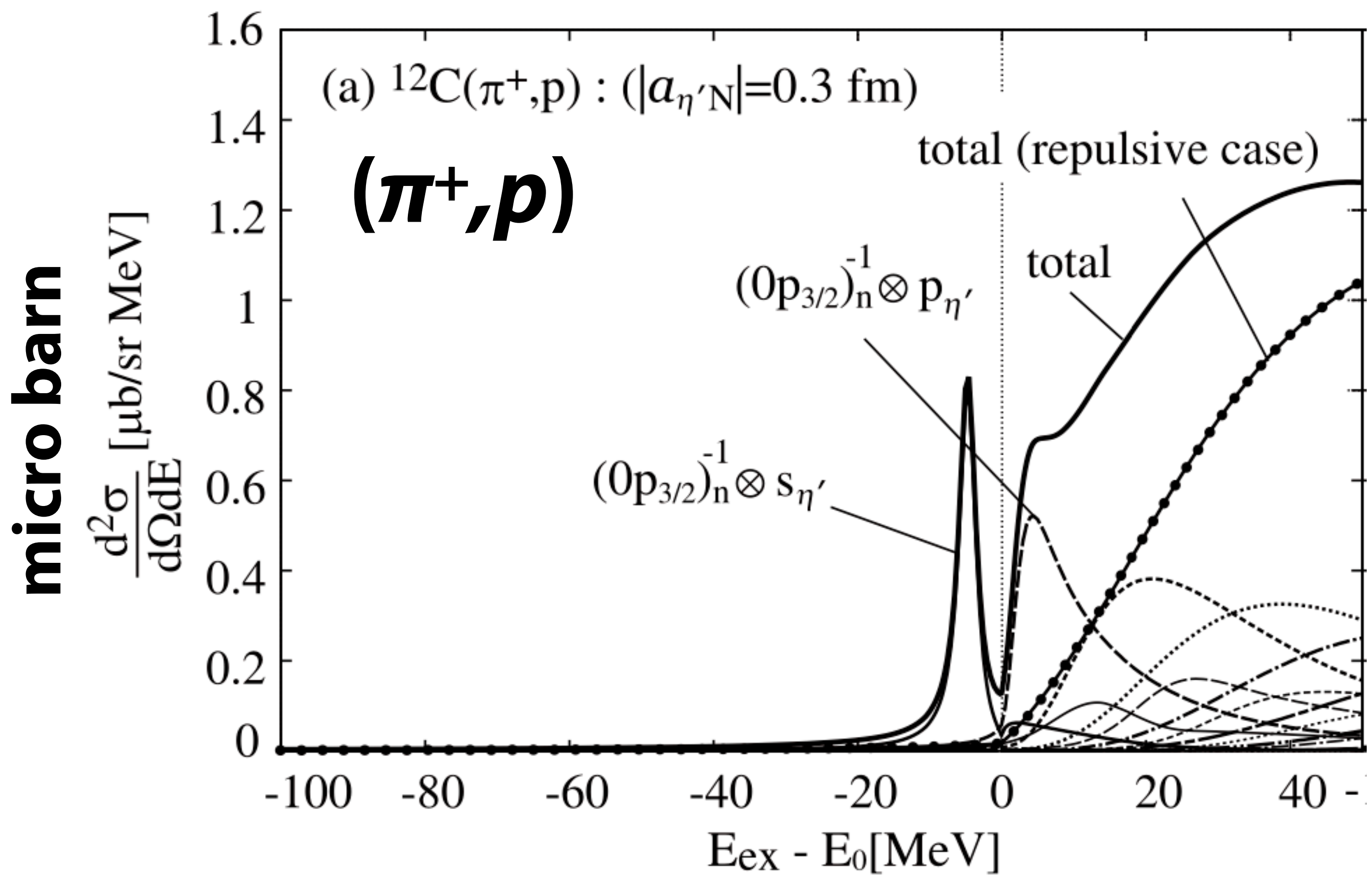
FRS S2-S2: forward spectrometer with ~ 2.5 MeV energy resolution

WASA: η′NN→NN tagging

Pion induced η′-mesic nuclei spectroscopy

η′-mesic nuclei





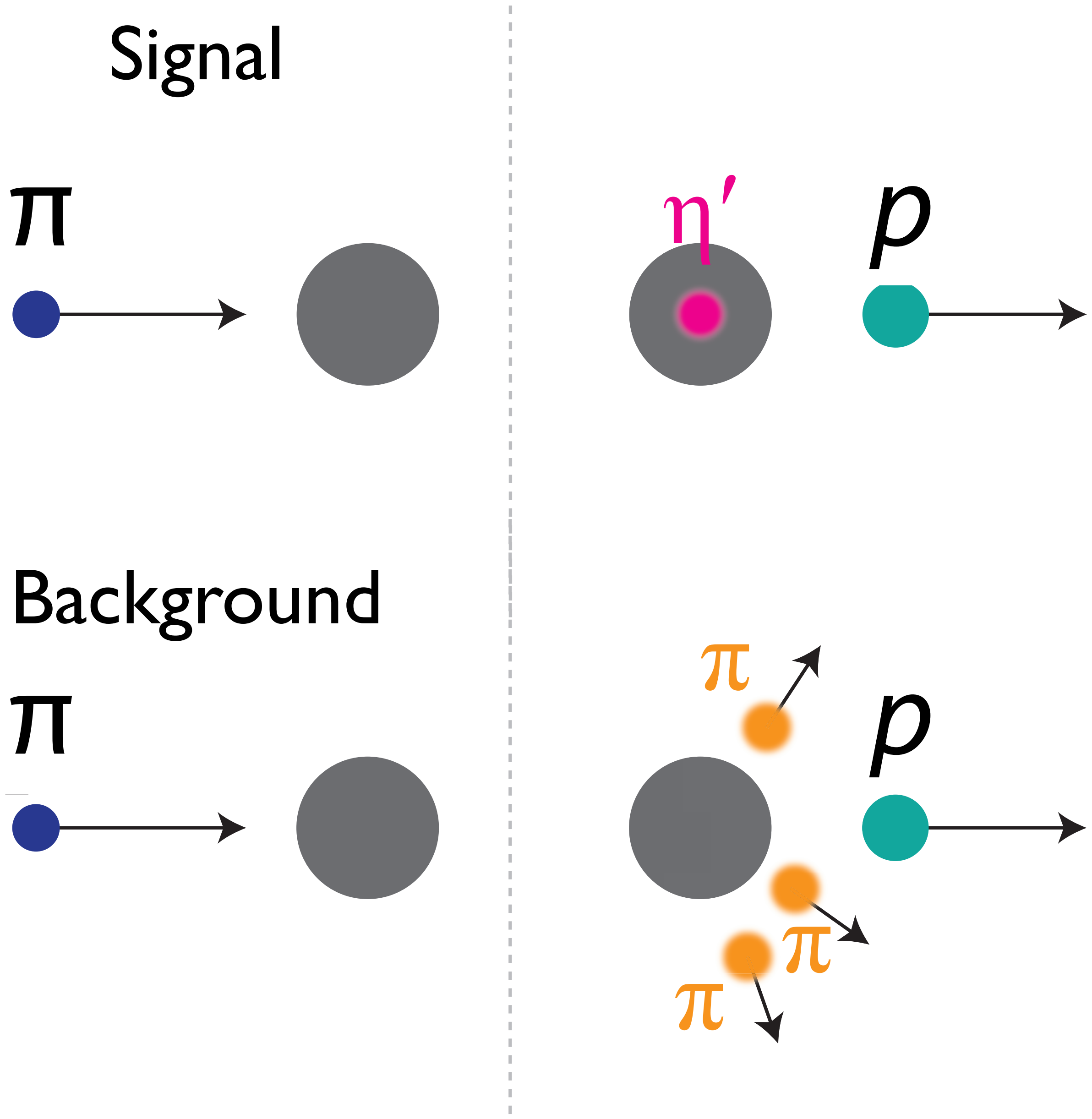
(*π*⁺,*p*) has much larger cross section

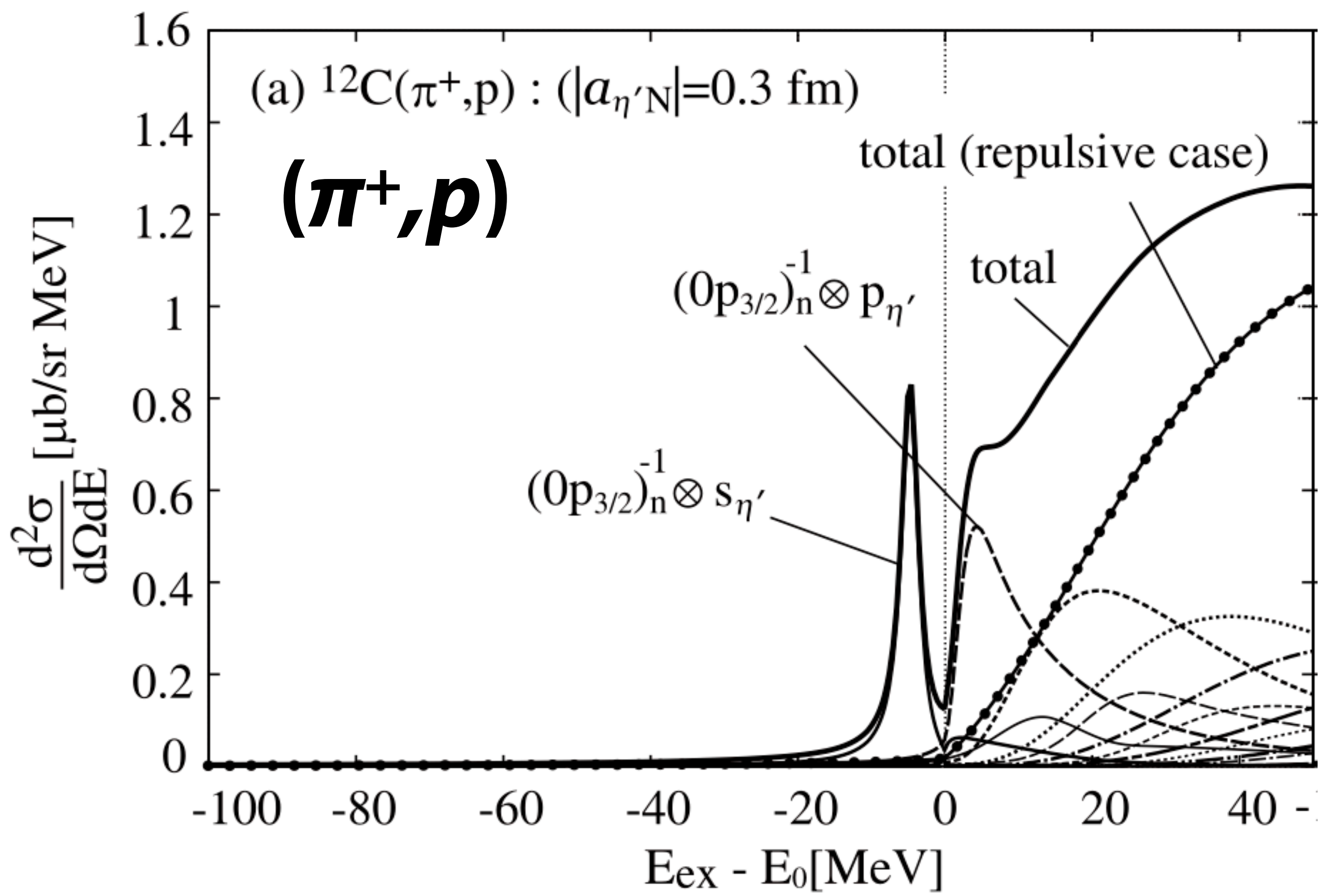
→ Missing mass measurement for spectroscopy in SFRS

First step	(π,p)	DM inclusive measurement	Simple setup
Second step	(π,p) w. decay tagging	semi-exclusive	Large Ω tracker

Nagahiro, NPA914, 360 (2013)
Nagahiro et al., PRC80, 025205 (2009)

Step1: Missing-mass of (*π*,*p*) inclusive measurement





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Nagahiro, NPA914, 360 (2013)
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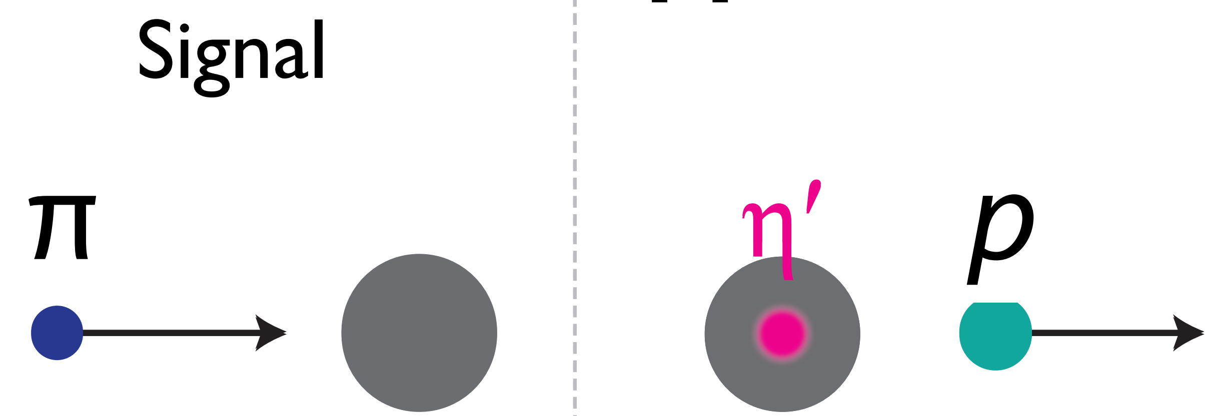
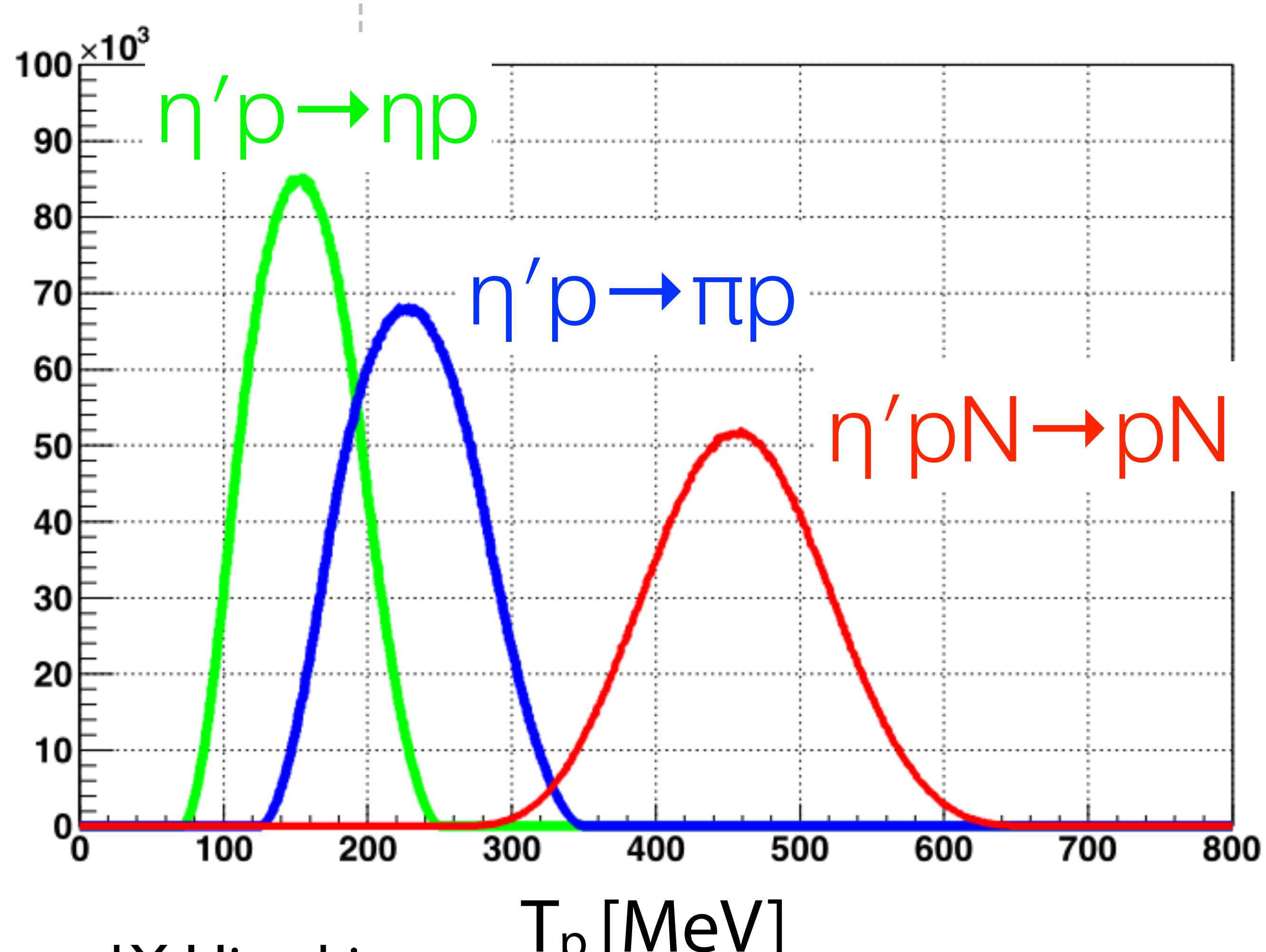
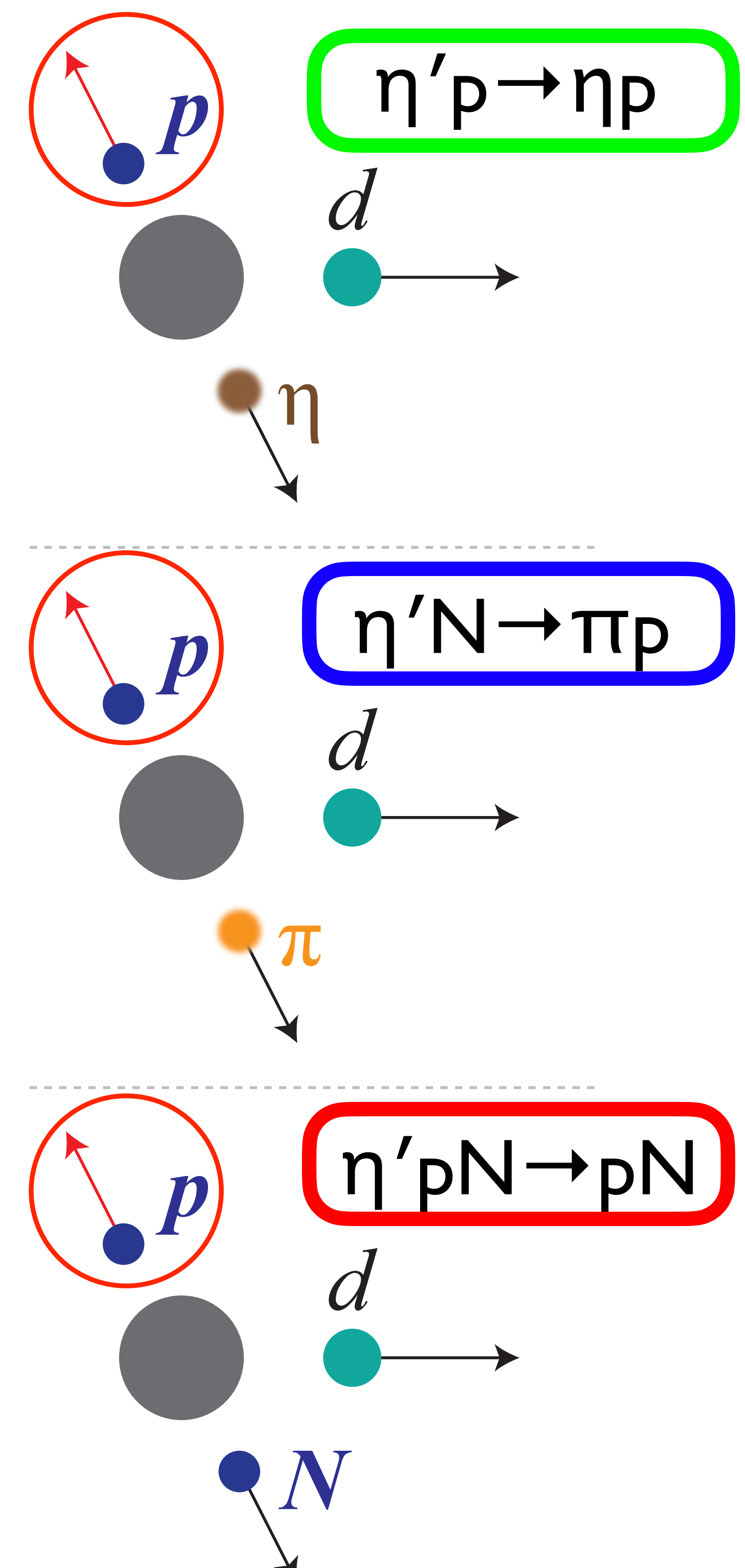
Step 2: Semi-exclusive measurement of $^{12}C(\pi,pp)$ reaction





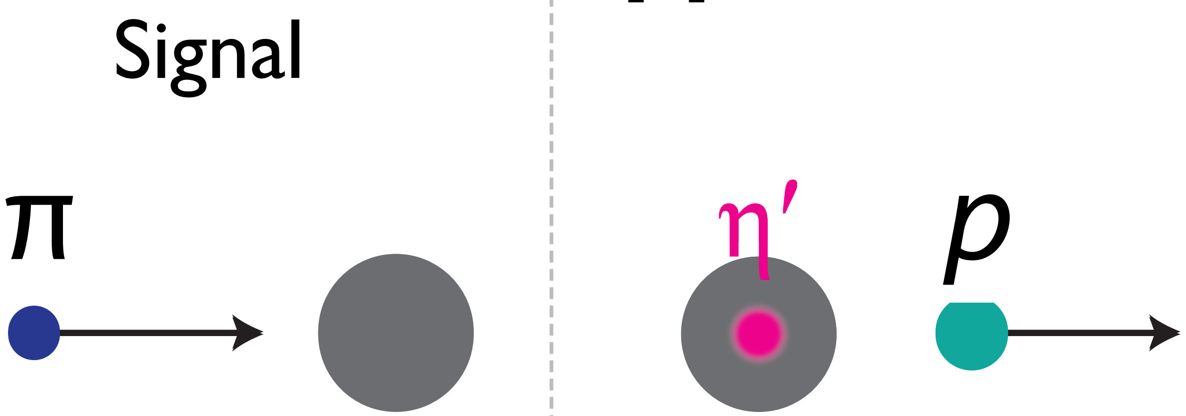
Y.K. Tanaka and Y. Higashi

3 major decay modes of η′-mesic nuclei

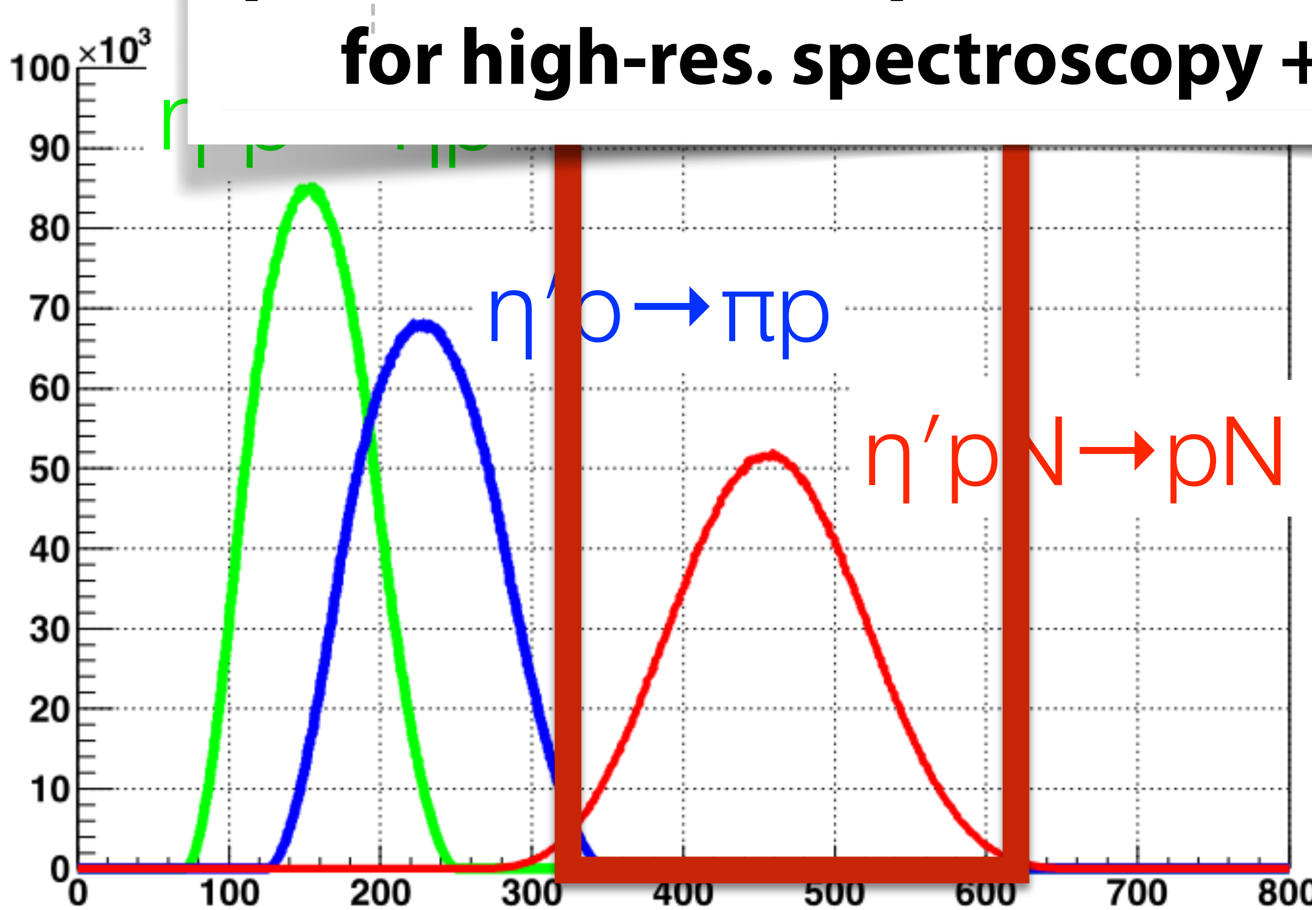


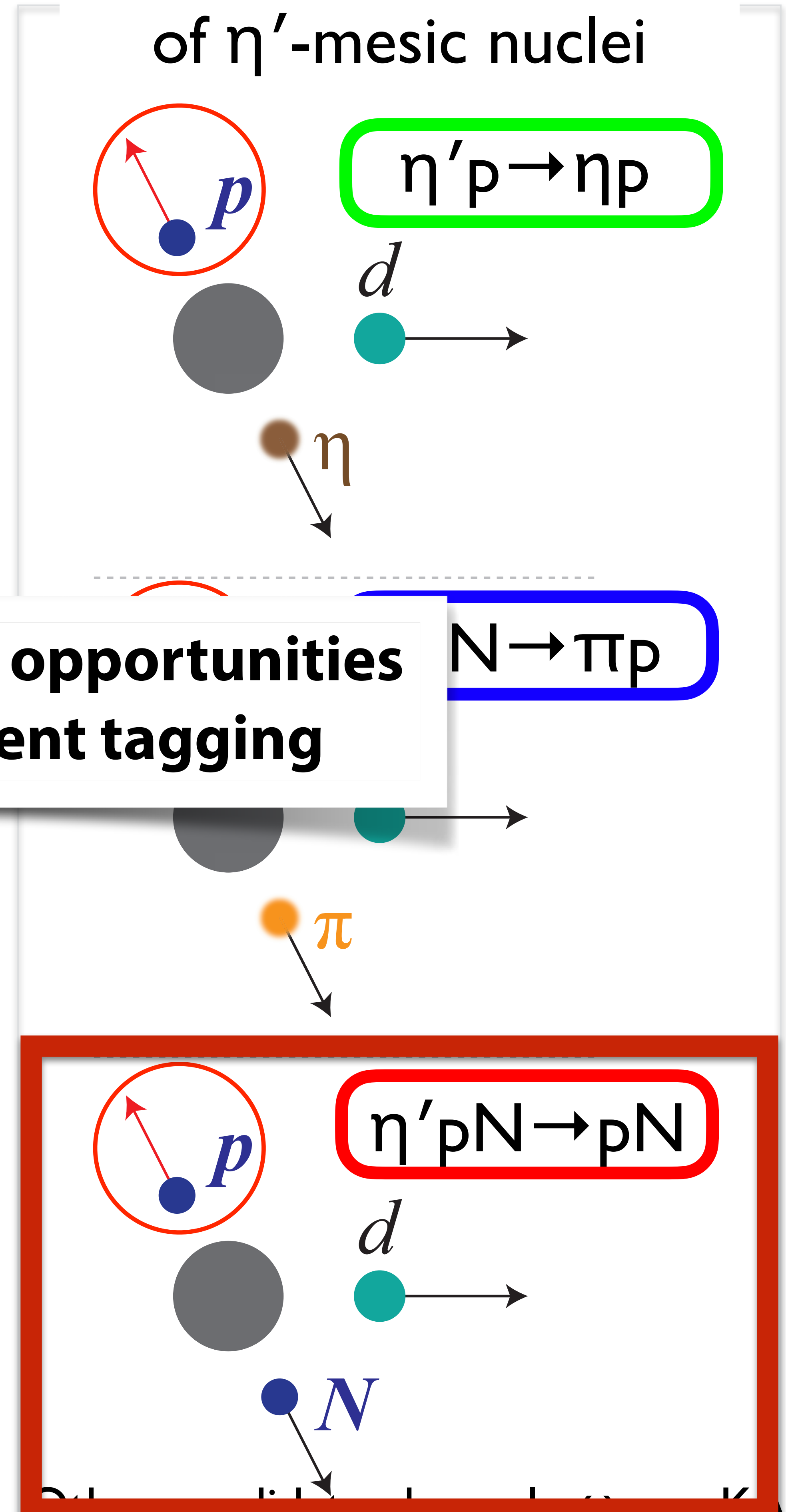
Other candidate channels: ωp or KΛ

Step 2: Semi-exclusive measurement of $^{12}C(\pi,pp)$ reaction



pWASA+SFRS will provide unique opportunities for high-res. spectroscopy + event tagging

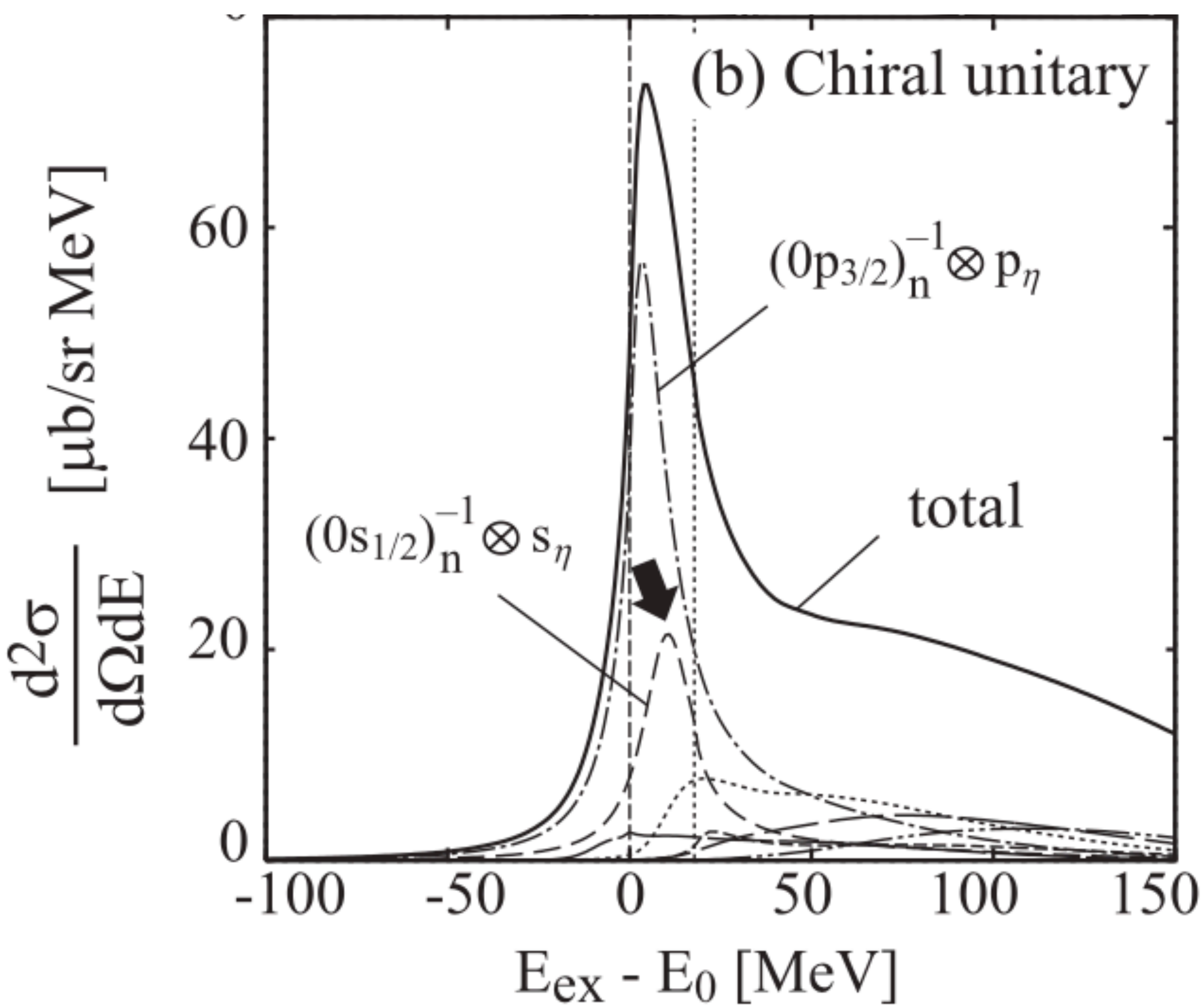




Pion induced η-mesic nuclei spectroscopy

η-mesic nuclei

in (π^+,*p*) or (*d*,^{3}He)



η in nuclei couples to J^π=1/2$^-$

N*(1535) → Nπ

back-to-back Nπ tagging suppress BG

Letter of Intent for J-PARC

Spectroscopy of η mesic nuclei by (π^-, n) reaction at recoilless kinematics

KI et al. (2007)

If we can place a forward neutron counter,
(π-,*n*) can also be a candidate

Nagahiro, NPA914, 360 (2013)
Nagahiro et al., PRC80, 025205 (2009)

Physics interests may include

1. η′ or η mesic nuclei
2. **Double kaonic nuclei search**
3. Hadron production studies

Feasibility is not yet considered

Double Kaonic Nuclear Cluster

Antikaons in Nuclei by Antiproton Annihilation

$$\bar{p} + 3He \rightarrow ppK^{-} + K^{0}$$

Production of ppK⁻ cluster by the annihilation of the n in ^{3}He and creation ...

Missing mass spectrosco...

Invariant mass of ppK⁻ →...

Exclusive formation and ... a 4π-detector allowing K^0...

P. Kienle ECT* Antiproton Workshop 03.07.2006

First idea by late Prof. Em. P. Kienle

Double Antikaon Production in Nuclei by Antiproton Annihilation

- The process: $\bar{p} + p \rightarrow K^{+} + K^{+} + K^{-} + K^{-} - 0.098\ \mathrm{GeV}$
- The cross section: $\dfrac{\sigma(\bar{p}\,p \rightarrow K^{+}K^{-}\pi^{+}\pi^{-})}{\sigma(\bar{p}\,p \rightarrow 2\pi^{+}2\pi^{-})} \sim 0.1$

  $\sigma(\bar{p}\,p \rightarrow 2K^{+}\,2K^{-}) \sim 10\ \mu b$
- The kinematics $\sqrt{M^{2} + \vec{p}_{0}^{\,2}} = 2m_{K}$ $\quad p_{0,lab} \simeq 652\ \mathrm{MeV/c}$
- Double kaon production in nuclei:

$$\bar{p}\ {}^{4}He \rightarrow K^{+}K^{+} + [K^{-}K^{-}pnn]$$

$$\bar{p}\ {}^{6}Li \rightarrow K^{+}K^{+} + [K^{-}K^{-}pp3n]$$

→ With the binding energy exceeding ~ 225 MeV, double kaonic nuclei can be produced even by stopped antiprotons.

P. Kienle ECT* Antiproton Workshop 03.07.2006

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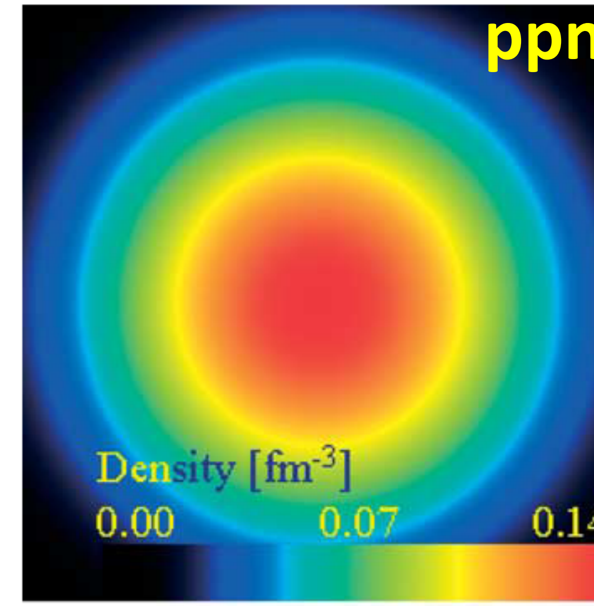
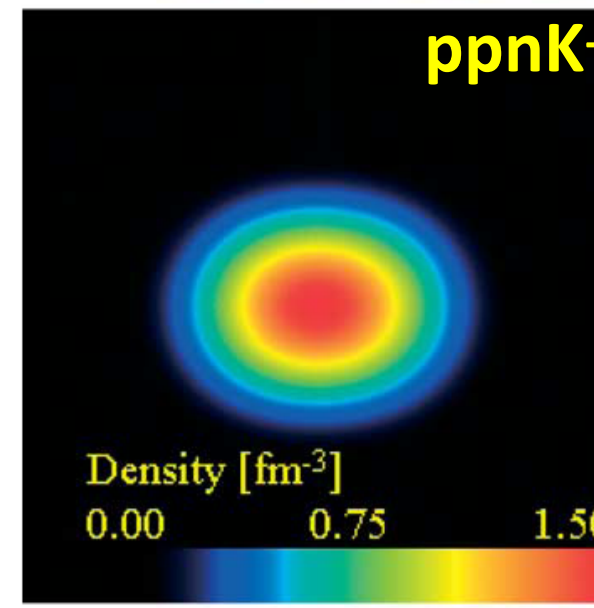
P.Kienle, ECT* 2006

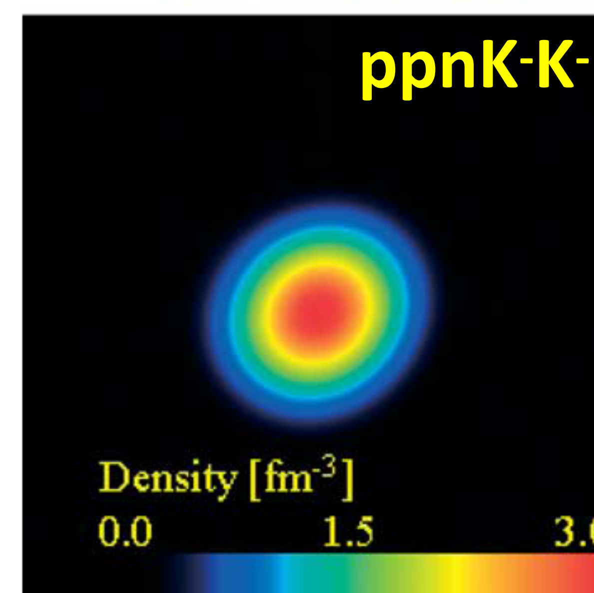
Double Kaonic Nuclear Cluster

AMD calculations show very large binding energies for double K clusters partly due to the very concentrated densities

$\bar{K}$ cluster	Mc^2 [MeV]	E_K [MeV]	Γ_K [MeV]	$\rho(0)$ [fm^{-3}]	R_{rms} [fm]	k_p [fm^{-1}]	k_K [fm^{-1}]
pK^-	1407	27	40	0.59	0.45	1.37	1.37
ppK^-	2322	48	61	0.52	0.99	1.49	1.18
$pppK^-$	3211	97	13	1.56	0.81		
$ppnK^-$	3192	118	21	1.50	0.72		
$ppppK^-$	4171	75	162	1.68	0.95		
$pppnK^-$	4135	113	26	1.29	0.97		
$ppnnK^-$	4135	114	34		1.12		
ppK^-K^-	2747	117	35				
$ppnK^-K^-$	3582	221	37	2.97	0.69		
$pppnK^-K^-$	4511	230	61	2.33	0.73		







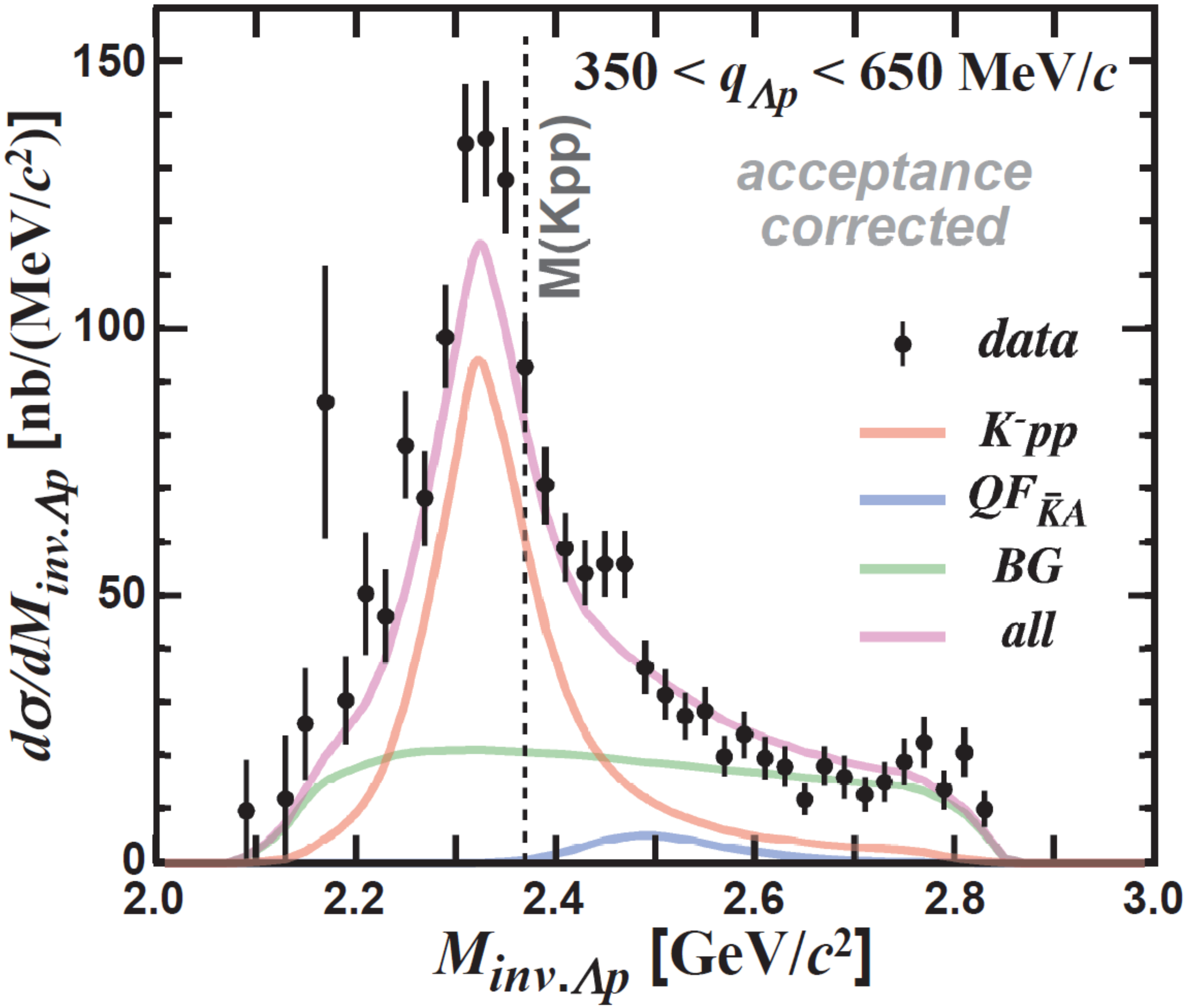
PL,B587,167 (2004)

J-PARC E15 Discovered K⁻pp Bound-State

$$f_{\{Kpp\}}(M,q) = \frac{A_{Kpp}\,(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2}\, e^{-\left(\frac{q}{Q_{Kpp}}\right)^2},$$

B = 47 ± 3 $^{+3}_{-6}$ MeV

Γ=115 ±7 $^{+10}_{-9}$ MeV



Yamaga et al., PhysRevC.102.044002 (2020)

K^-K^-pp search by stopped pbar at J-PARC

Experimental Principle

- We search for S=-2 dibaryon with $p^{bar}+{}^3He$ annihilation at rest (3N absorption):

$$\bar{p} + {}^3He \rightarrow K^+ + K^0 + X, \quad X \rightarrow \Lambda\Lambda$$

final state: $K^+ + K^0 + \Lambda + \Lambda$ ($K^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$, $\Lambda \rightarrow p\pi^-$)

  – if K^-K^-pp state exists with <u>deep bound energy</u>:

$$\bar{p} + {}^3He \rightarrow K^+ + K^0 + \boldsymbol{K^-K^-pp} + B.E. - 109MeV$$

  – if H-dibaryon (resonance) exists:

$$\bar{p} + {}^3He \rightarrow K^+ + K^0 + \boldsymbol{H}$$

We can investigate S=-2 dibaryon with inclusive *or* exclusive measurement

Sakuma, LoI for J-PARC (2009)

Not easy…because

- **Absorption at rest has not enough energy to populate shallow bound states.**
- **In-flight events can contaminate easily.**
- **Number of stopped pbar is limited.**

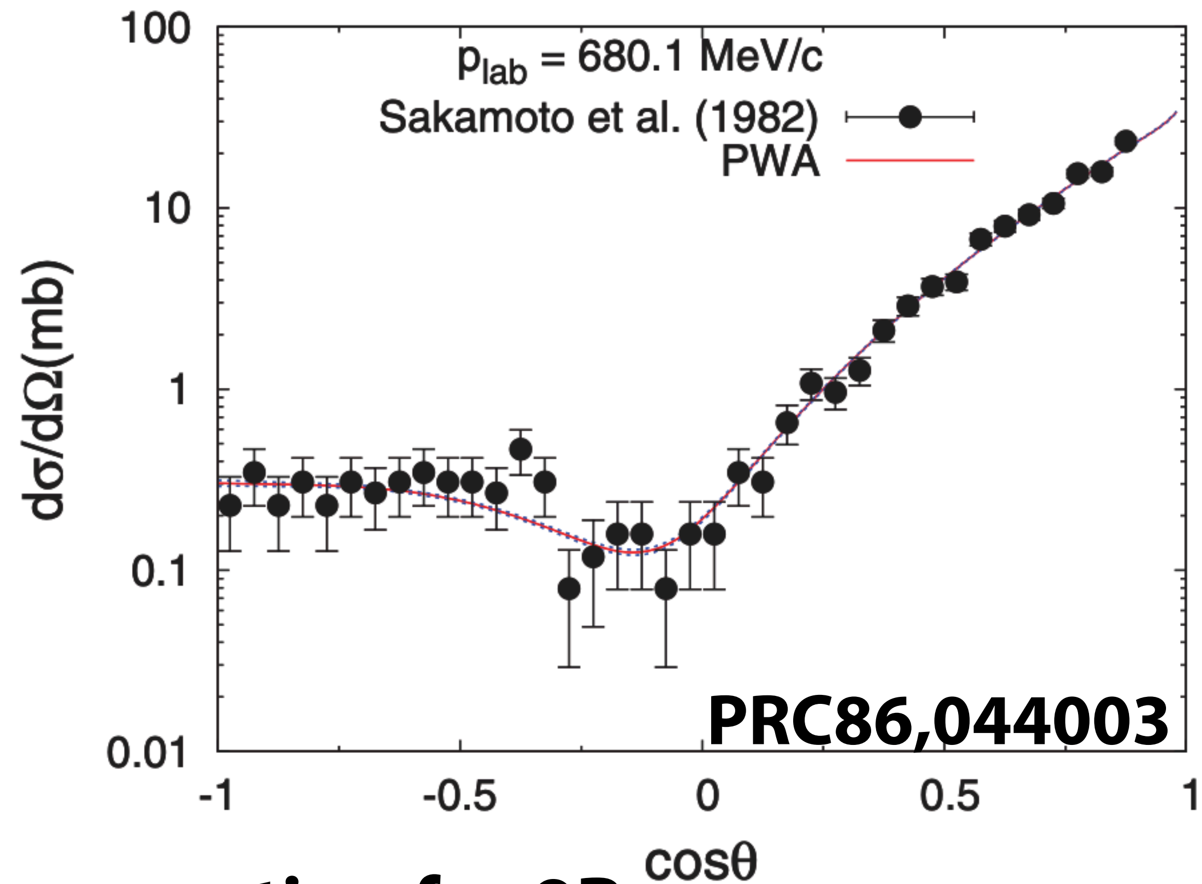
^{9}Be(pbar,p) reaction for DKNC search at Super-FRS

H(pbar,p) at 180 degree
0.3mb/sr -> 40 counts/s
(pbar 1.0E6 beam, 1 mol target

$$\bar{p} + {}^9\mathrm{Be} \to p + \bar{p}^* + {}^8\mathrm{Li}$$

$$\bar{p}^* + {}^8\mathrm{Li} \to K^+K^+ + K^-K^- + {}^7\mathrm{He}$$

$$\bar{p}^* + {}^8\mathrm{Li} \to K^+K^0 + K^-K^- + {}^7\mathrm{Li}$$



If we assume similar cross section for 9Be,
we have 40 pbar/s with q~0 in the nucleus
which may form double K nuclear clusters
(or Λ, ΛΛ or Ξ hypernuclei…)

For KKpp, I came to think of reaction
pbar + 4He -> forward n + pbar + 3He
pbar + 3He -> K+K0 + (K-K-pp)
with different angles for finite *q*
if we have a forward neutron counter

Comments

- **We still need theoretical calculations for cross sections.**
- **Identifying K+K- leads to φ in nucleus**
- **Experiment may be feasible with ~4pi detector at FMF2 such as smaller WASA**

Hadron Production Studies

- Pion/pbar induced hadron production cross section measurement (together with hadron rescattering within the target volume)
- hadron-nucleon final state interaction → low energy scattering length

example:

π+H → $\eta/\omega/\eta'$ + p

π+D → $\eta/\omega/\eta'$ + n + p

π+D → K^+ + Λ + n

pbar + H → …

Other hadrons can also be studied, which may include exotic hadrons if the cross section and energy are sufficient…

May need dev. of neutral detectors

Summary

- Super-FRS may open possibilities of using "exotic" beams such as pion or pbar.
- (Super-)FRS + (p)WASA may provide unique opportunities of high-resolution inflight spectrometer + large acceptance detector
- We may need develop dedicated beam optics to overcome lack of E×B
- Dispersion matching may be advantages for high-resolution spectroscopy

In our sight are:

- Studies of hadron production including FSI or rescattering
- Studies of hadron(s) in nuclei can be performed with SFRS+ pWASA
- d*(2380) in nuclei, dibaryon resonance with nuclear target by $d + A \rightarrow {}^3He\,\pi\pi A'$
- σ-meson [f0(500)] on H or D targets by (π^+,p) or by $(d,{}^3He)$ with full kinematical reconstruction.

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