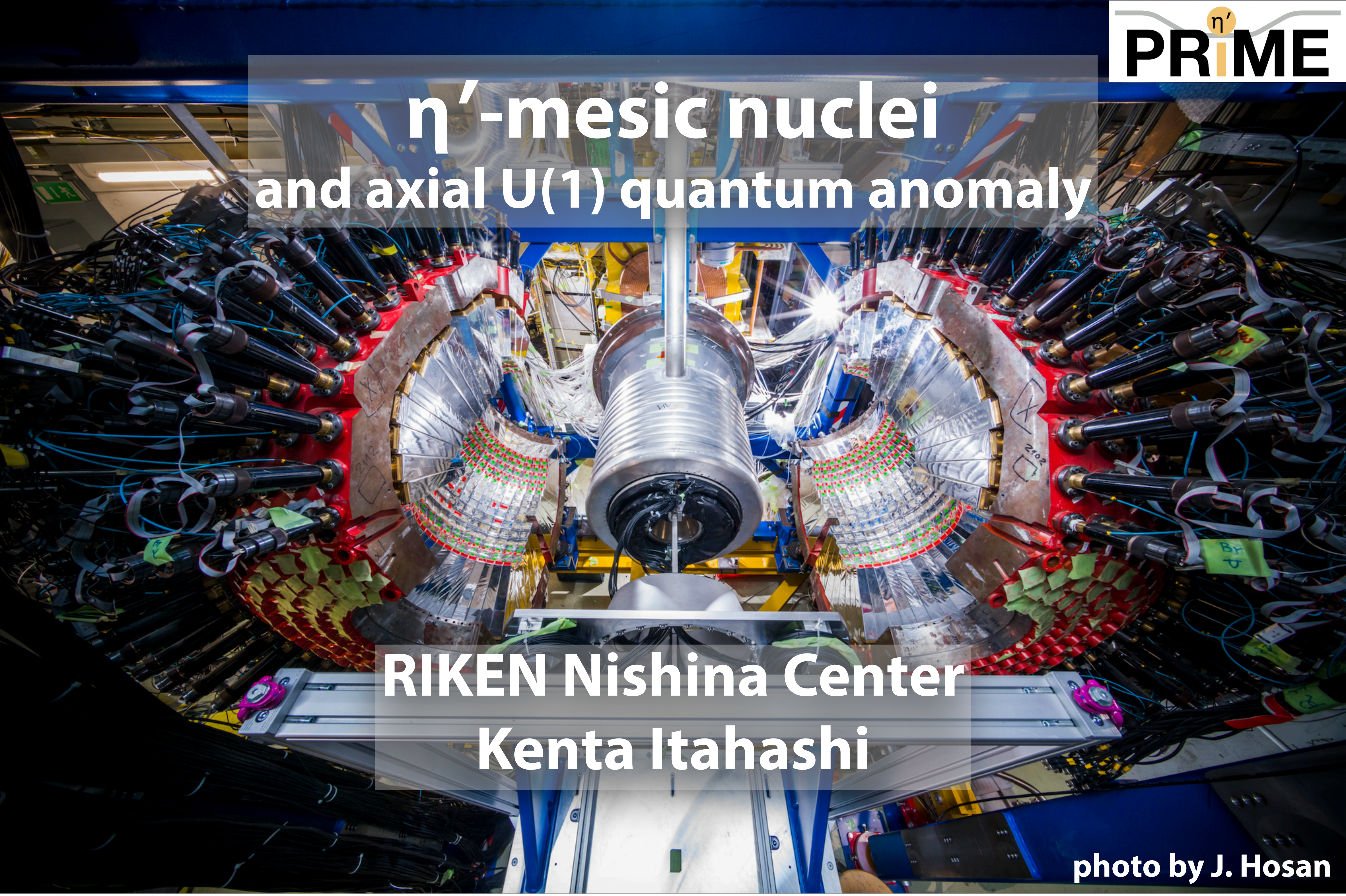
η′ PRiME

η′-mesic nuclei
and axial U(1) quantum anomaly



RIKEN Nishina Center
Kenta Itahashi

photo by J. Hosan

Super-FRS EC

FAIR Phase 0 Research Program

GSI

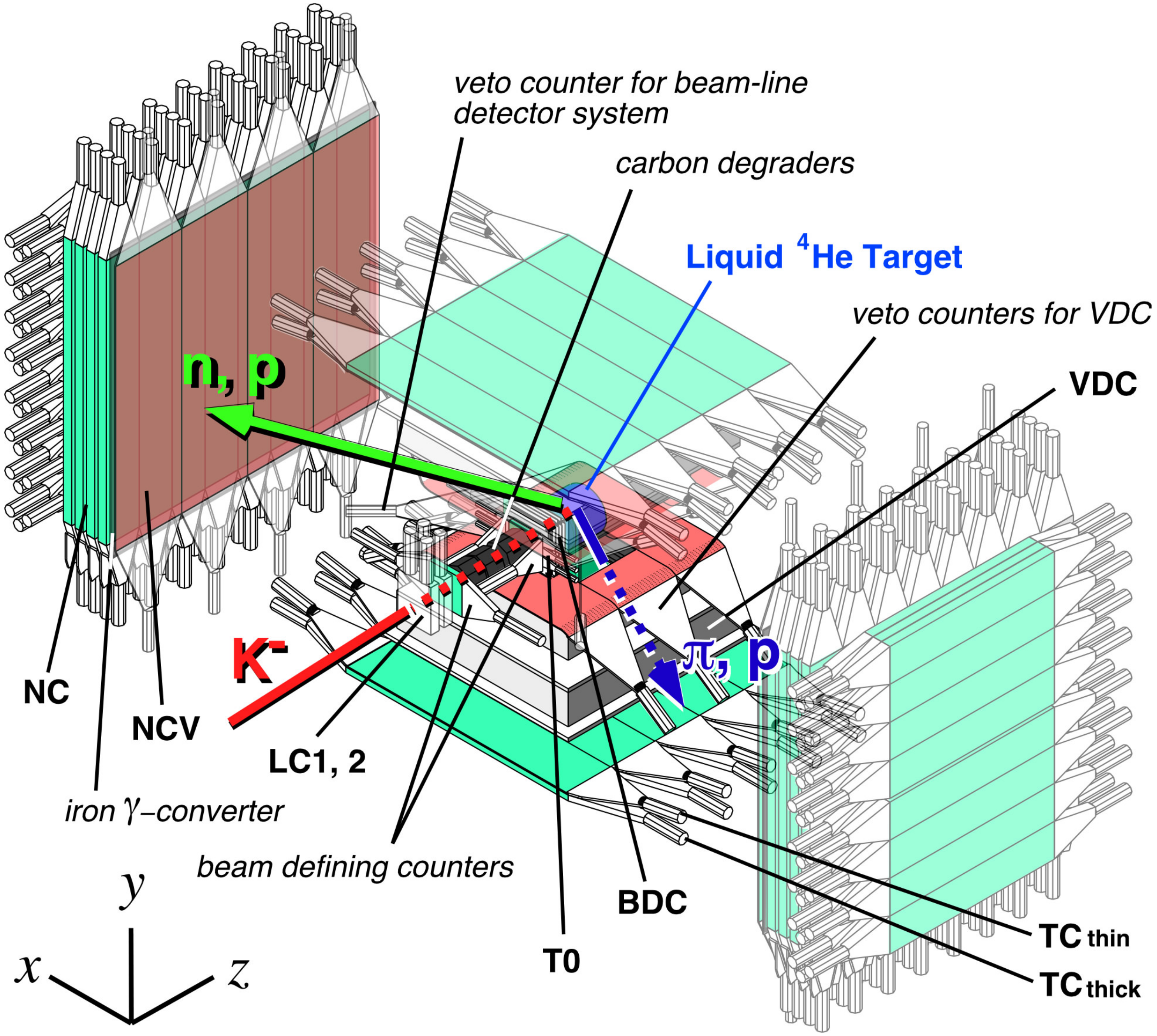
RIKEN

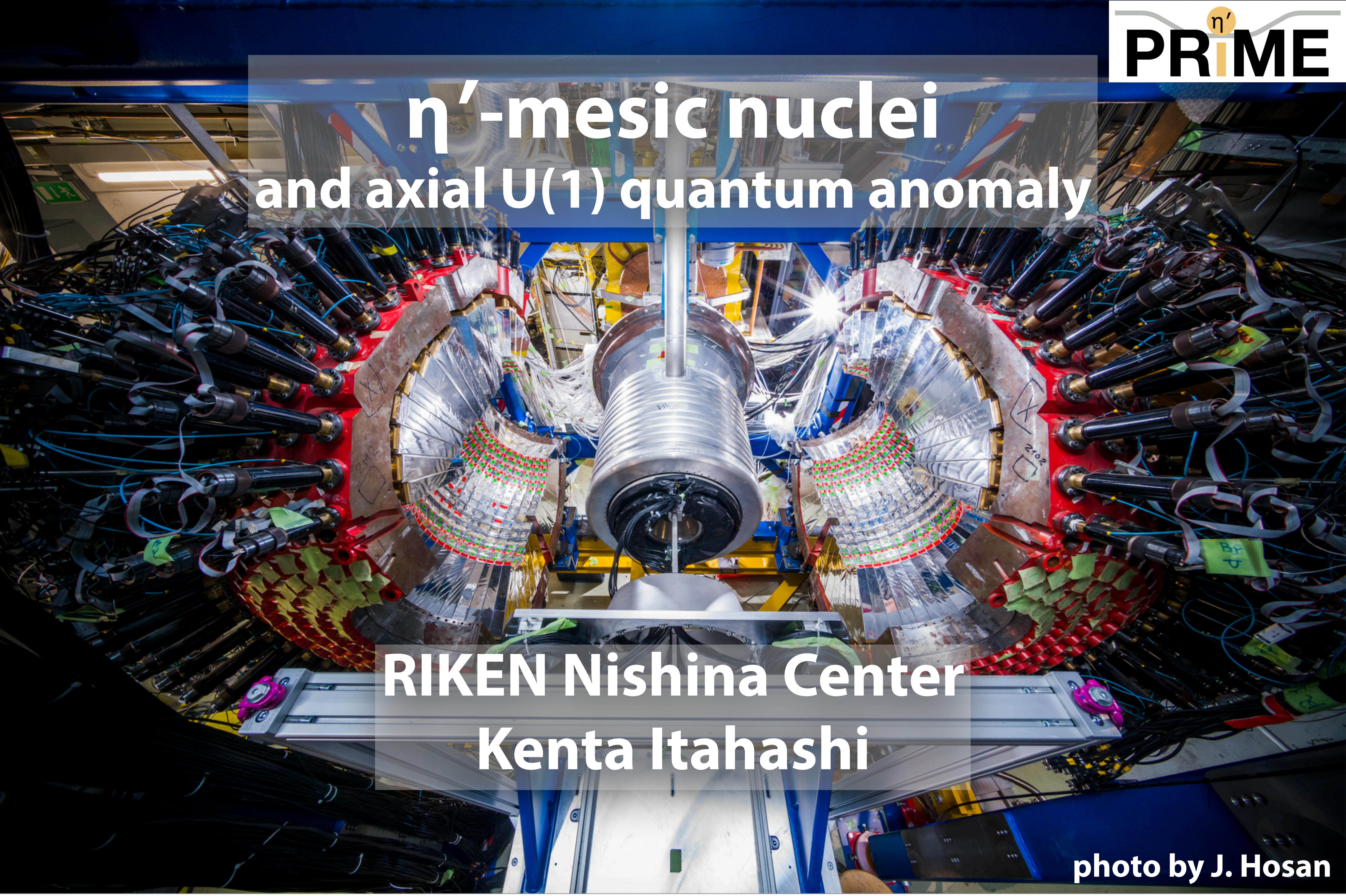
NiSHiNA CENTER

1999 年 東工大岩崎研助手...

KEK-PS E471 実験

第一期 Knucl 探査実験





η′-mesic nuclei and axial U(1) quantum anomaly

RIKEN Nishina Center
Kenta Itahashi

photo by J. Hosan

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日本物理学会創立70周年記念企画

物理学70の不思議？？？

16. 原子核の形
19. 格子QCD
5. 素粒子の世代
13. 陽子＝クォーク3つ？
11. ヒッグス粒子
37. 素粒子と物性
36. 量子コンピュータ
38. モンテカルロ計算
53. フェルミ液体論
14. テトラクォーク
18. 原子核の地図
6. ニュートリノ
45. 光誘起相転移
41. トポロジカル秩序
17. 超重原子核
10. クォークの閉じこめ
39. マヨラナ粒子
30. 乱流
4. クォーク・グルーオン・プラズマ
26. 磁場の起源
49. 物質設計
44. メタマテリアル
8. 暗黒エネルギー
34. 量子力学の検証
55. 隠れた秩序
15. ストレンジ原子核
12. 反物質
7. 暗黒物質
1. 宇
3. イン
21. 中性子星
2. 4次元時空
33. 冷却原子
29. 核融合
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9. 宇宙の物質生成
27. 太陽コ
24. 相対論的ジェット
22. 超大質量ブラックホール
5
25. 宇宙線
35. 量
23. ブラックホールと情報
70. 物理学はどこへ
62. 経済物

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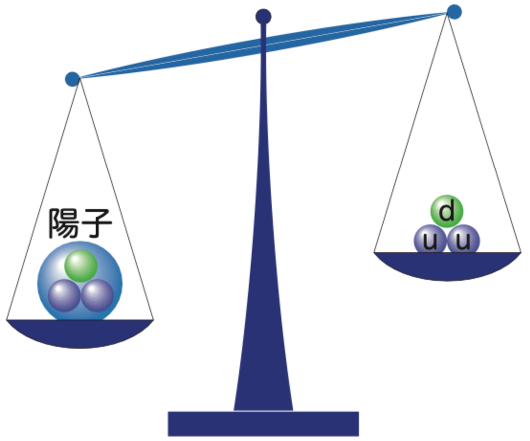
陽子はクォーク３つからできている？

「陽子はアップクォーク（u）2個とダウンクォーク（d）1個で構成される」と教科書にはある．陽子や中性子が約1/3の質量（約300 MeV/c^2）をもつクォークから構成されるとする構成子クォーク模型は，中間子を含む多くの粒子，ハドロンの成り立ちを「上手に」説明する．クォーク模型は一部を除く広範囲のハドロンの質量や量子数をよく再現する．

一方，高エネルギー電子散乱実験から決まる「裸の」u，dクォークの質量は，たかだか5 MeV/c^2である．このu，dクォークの質量は，ヒッグス機構によって与えられる質量に相当するが，uudを合計しても陽子質量の1%程度にしかならない．このことは，陽子が単純にuudの3つのクォークから構成されるとする説明とは矛盾する．

同じく，陽子のスピンは1/2だが，これに対するクォークからの寄与はたかだか30%ほどにすぎないことが知られている．最近の研究により，陽子のスピンはクォークだけでなく，クォークを結びつける糊であるグルーオン，そしてそれらの軌道角運動量の寄与などを，包括的に考慮しなくてはならないことがわかってきている．陽子を含むハドロンは，クォークやグルーオンを自由度とする極めて強く相互作用する複雑な多体束縛系として，量子色力学に基づいた解明が待たれている．

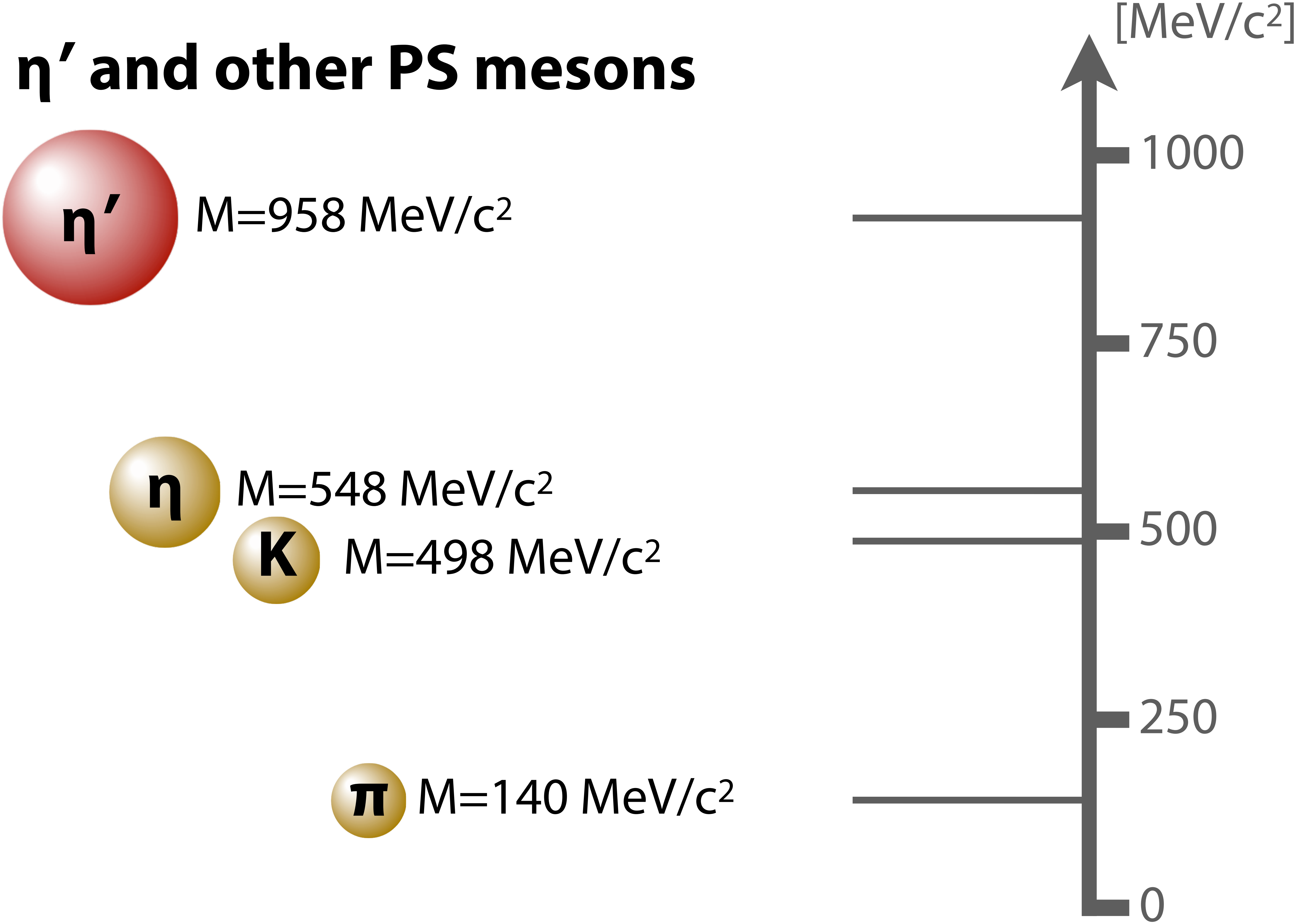


南部陽一郎らは陽子質量の残り99%の起源を，クォークではなく真空の構造に求めた．真空は空っぽの箱ではなく，強い相互作用によりクォーク・反クォーク対が凝縮し満ち溢れた状態であり，ハドロンの質量は動的に生み出されていると考えられている．

このようにハドロンの成り立ちを探ることで，多彩な現象を生み出す量子色力学の世界を垣間見ることができる．そしてそれは，クォーク・反クォーク対が自発的に凝縮した真空の構造を探ることにもつながるのである．

会誌編集委員会

η′ and other PS mesons



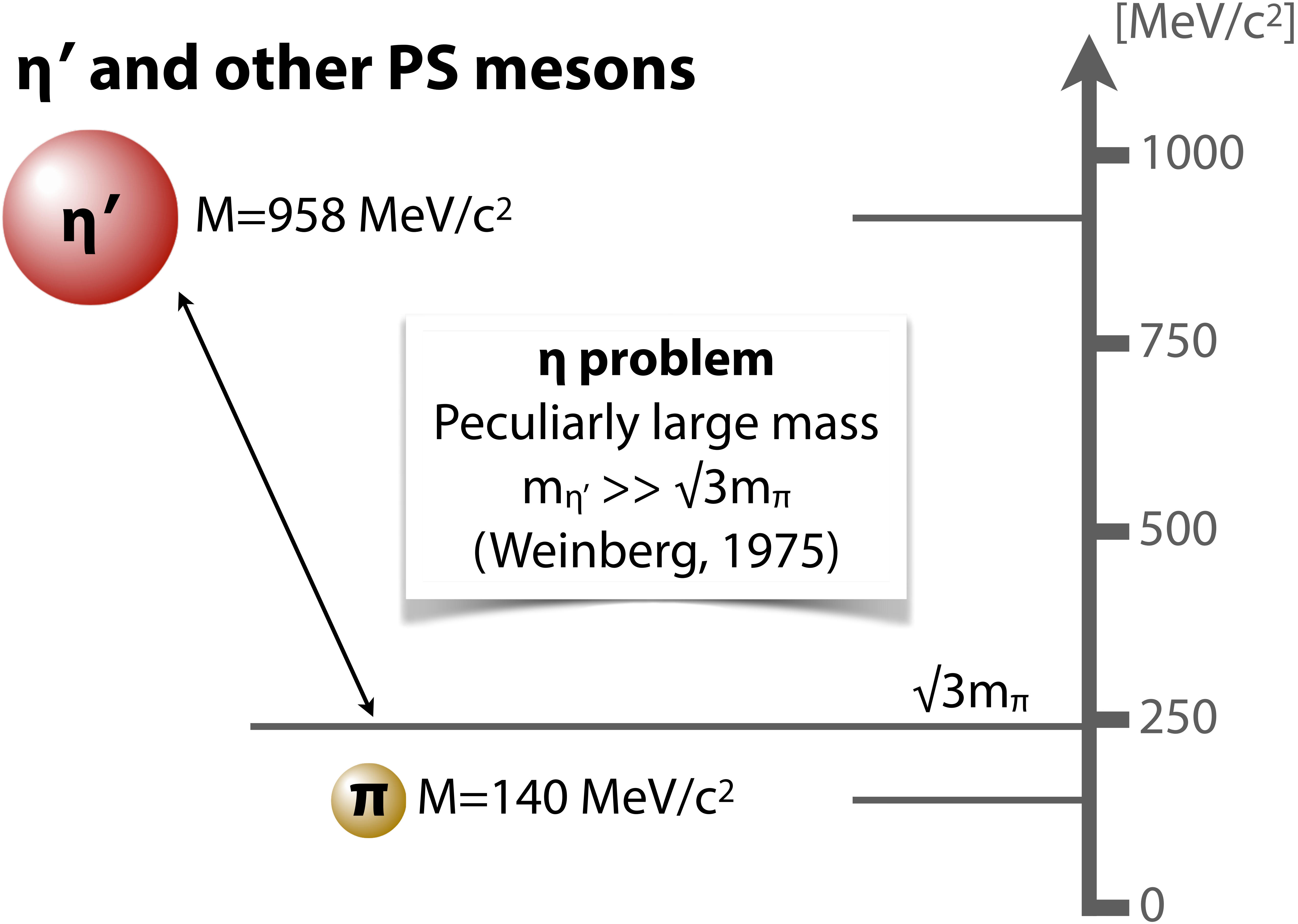
M=958 MeV/c^2

M=548 MeV/c^2

M=498 MeV/c^2

M=140 MeV/c^2

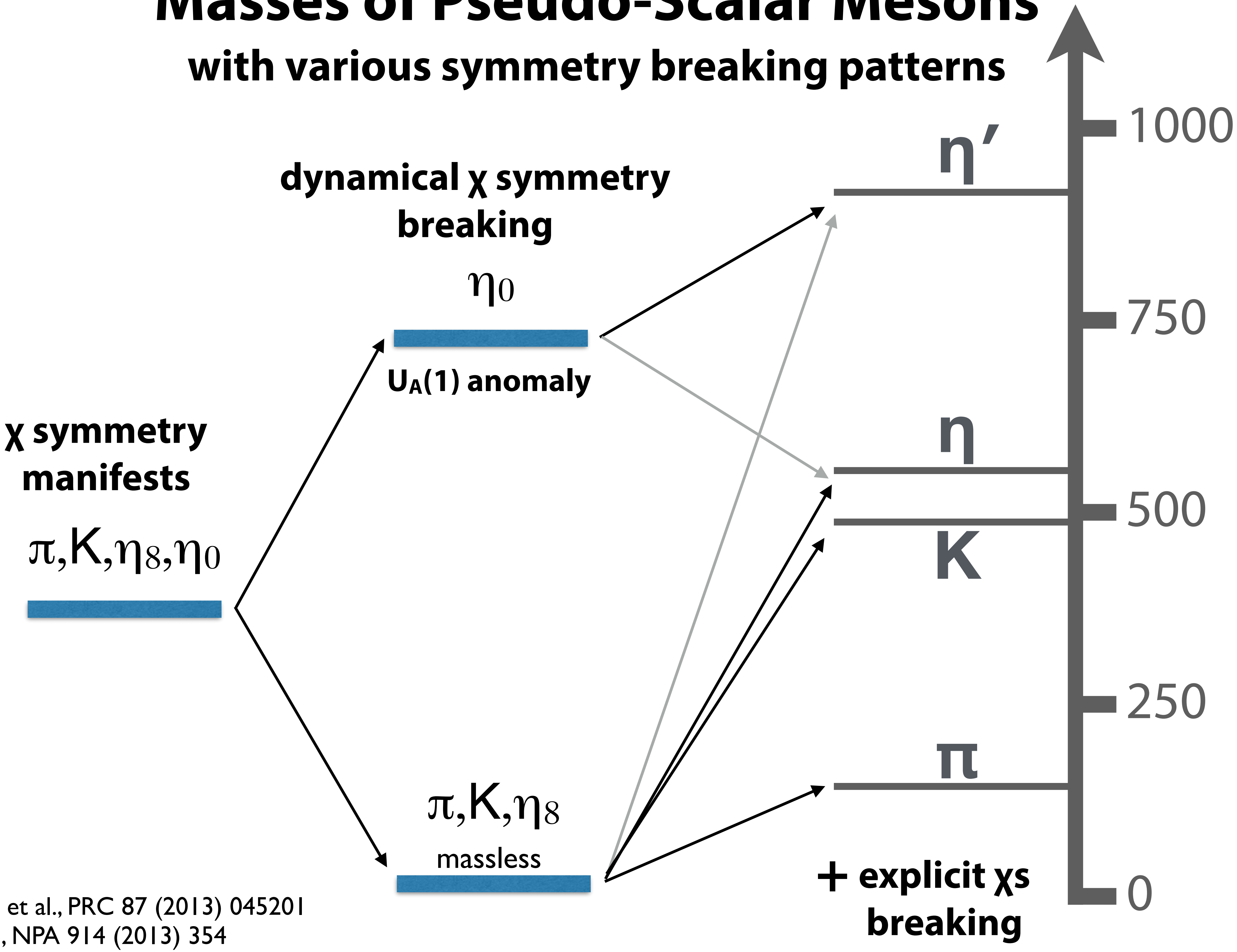
η' and other PS mesons



η problem
Peculiarly large mass
$m_{\eta'} >> \sqrt{3}m_\pi$
(Weinberg, 1975)

Masses of Pseudo-Scalar Mesons

with various symmetry breaking patterns



χ symmetry manifests

π, K, η_8, η_0

dynamical χ symmetry breaking

η_0

U$_A$(1) anomaly

π, K, η_8

massless

+ explicit χs breaking

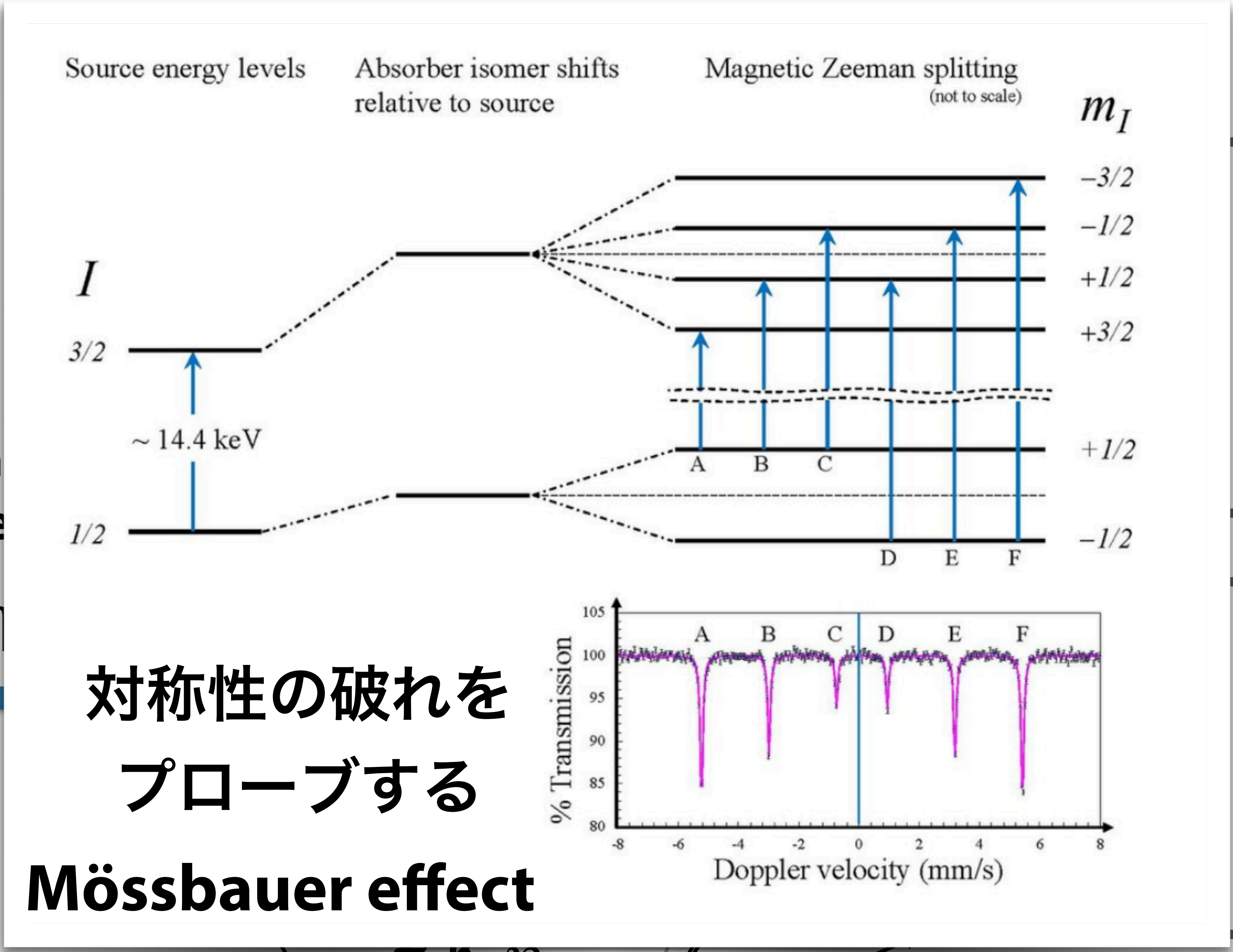
Nagahiro et al., PRC 87 (2013) 045201
Jido et al., NPA 914 (2013) 354

Masses of Pseudo-Scalar Mesons

with various symmetry breaking patterns

χ symm
manife

π,K,η



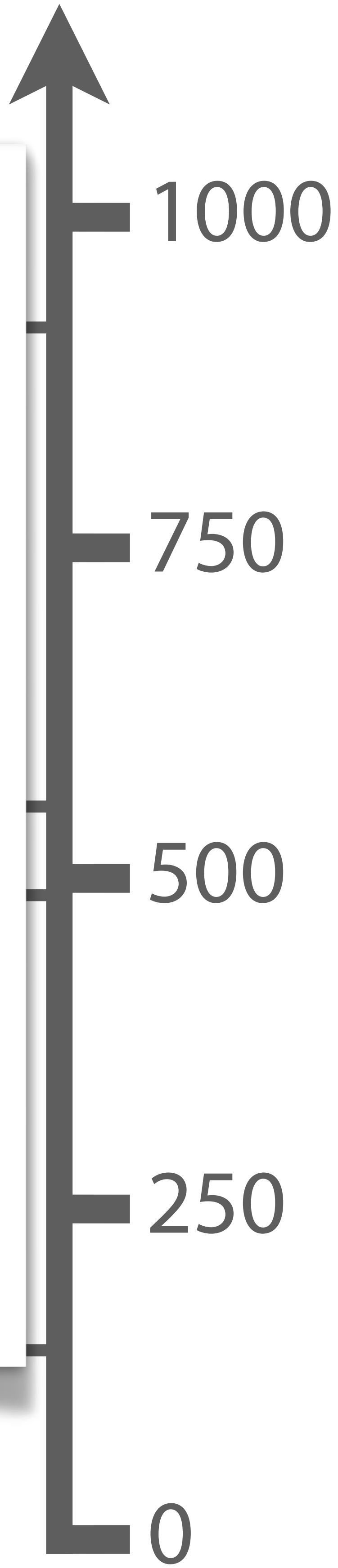
対称性の破れを
プローブする

Mössbauer effect

π,K,η8

massless

+ explicit χs breaking

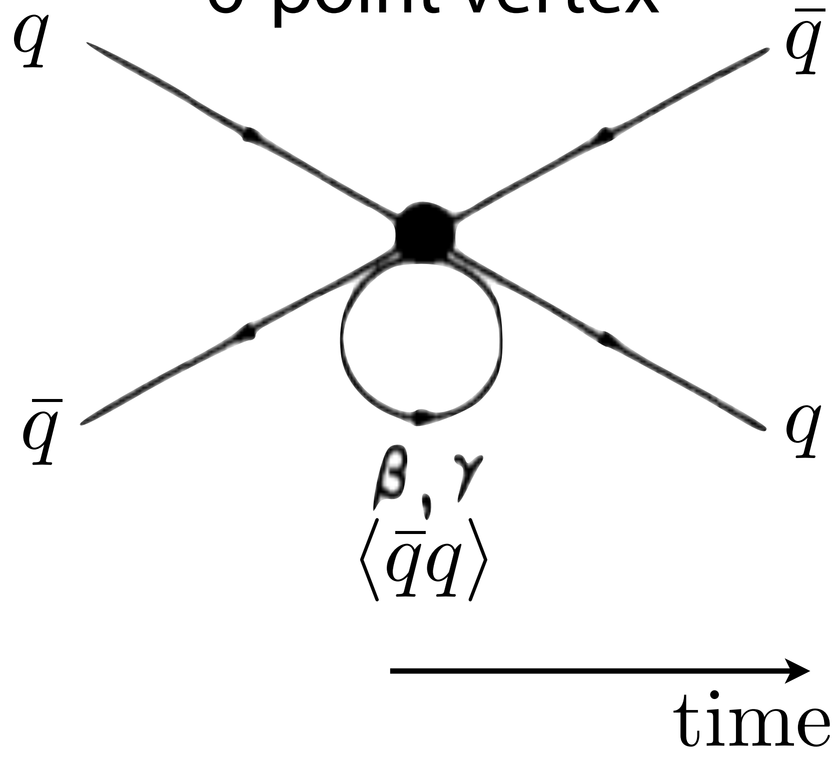


Nagahiro et al., PRC 87 (2013) 045201
Jido et al., NPA 914 (2013) 354

Large η' mass = $U_A(1)$ × chiral condensate

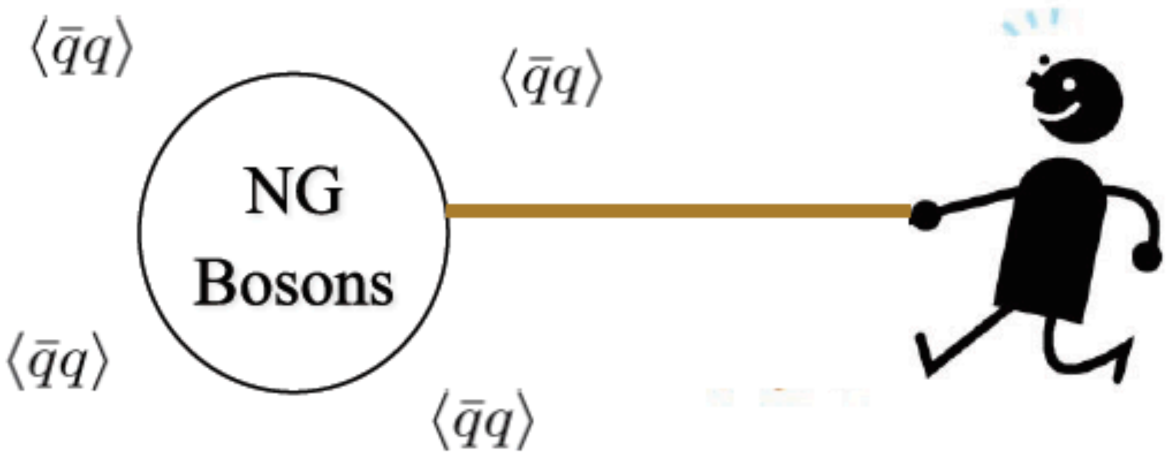
$U_A(1)$ symmetry breaking term of effective Lagrangian

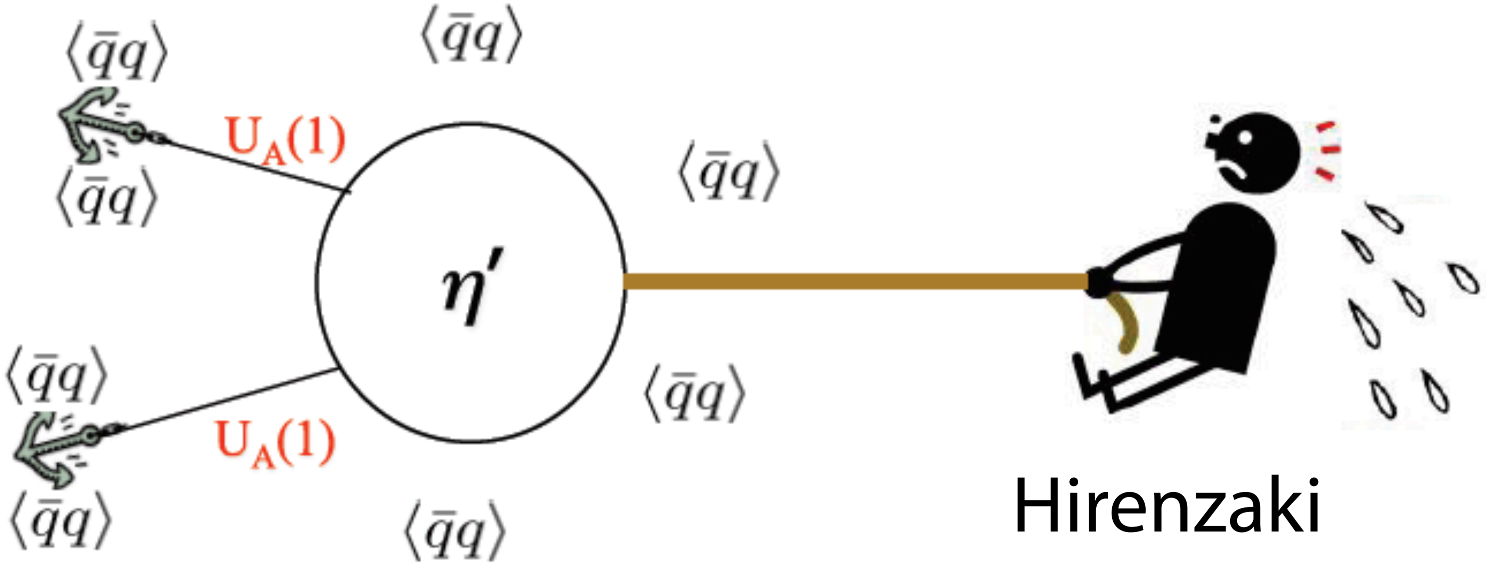
6-point vertex



Kobayashi-Maskawa-'t Hooft interaction

Kobayashi, Maskawa, PTP44(70)1422
't Hooft, PRD14(76)3432.
T. Kunihiro, Phys. Lett. B219(89)363.
Klimt, Lutz, Vogl, Weise, NPA516(90)429.

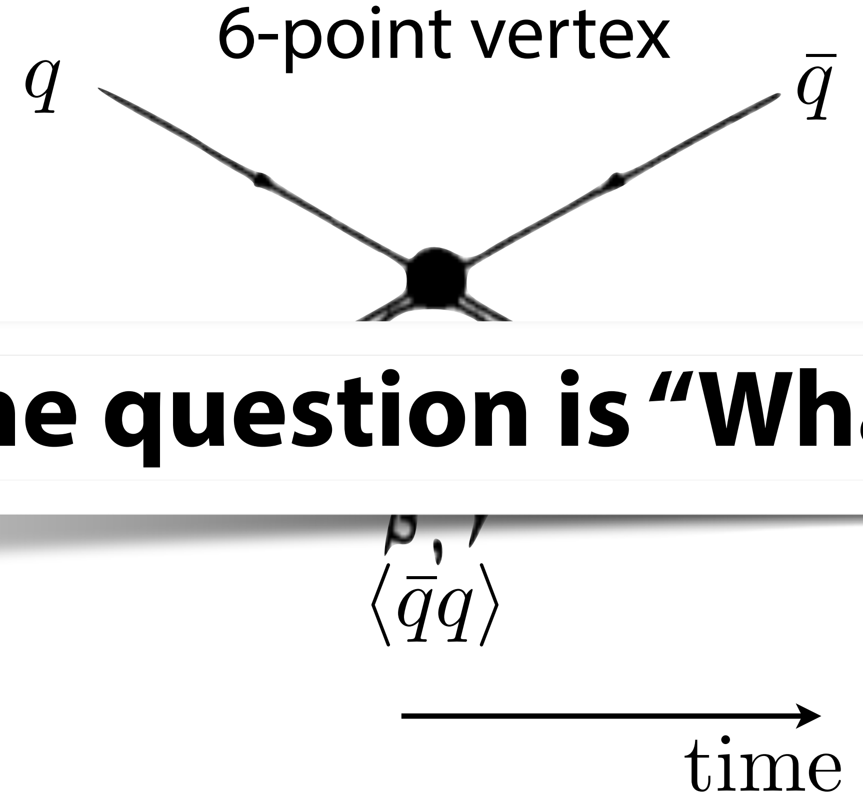




Hirenzaki

Large η′ mass = $U_A(1)$ × chiral condensate

$U_A(1)$ symmetry breaking term of effective Lagrangian



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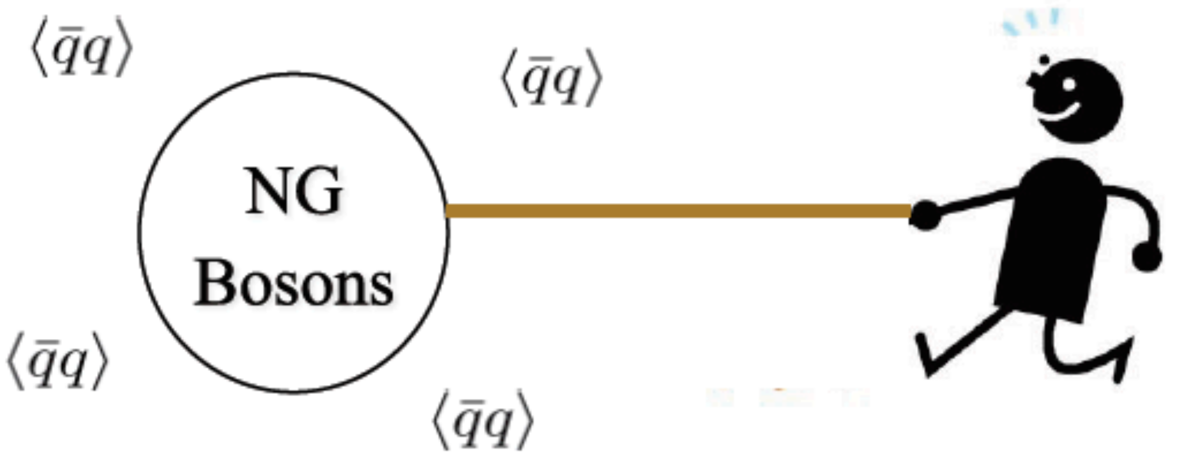
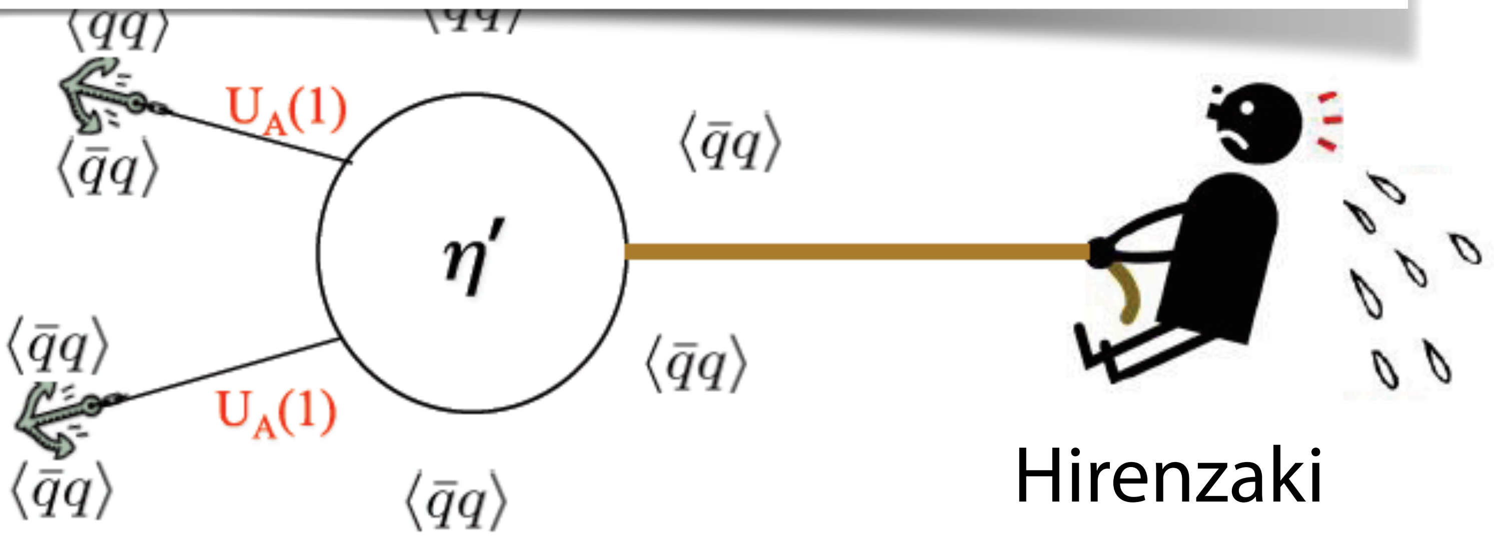
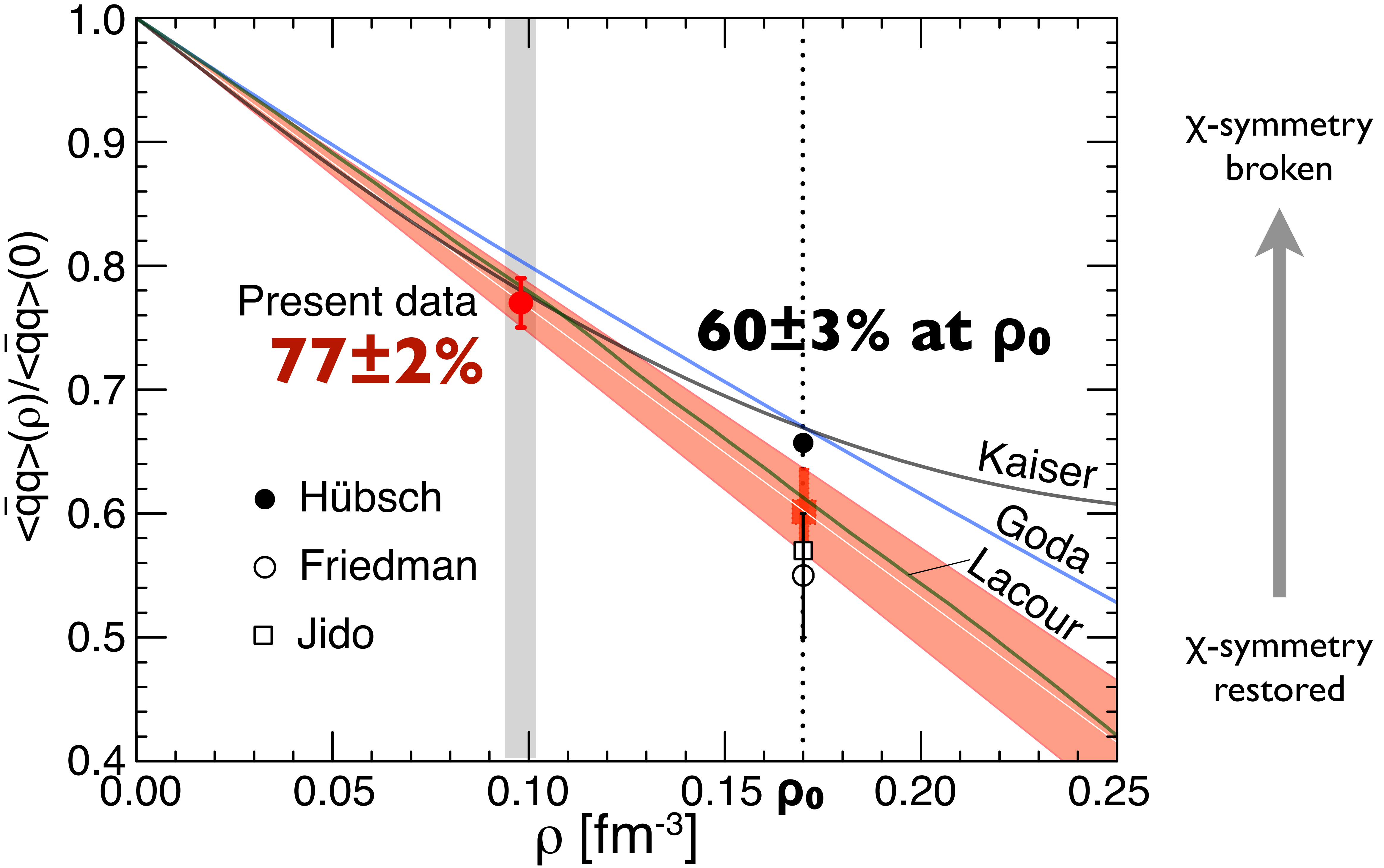




Hirenzaki

The question is "What happens if <qq> is smaller?"

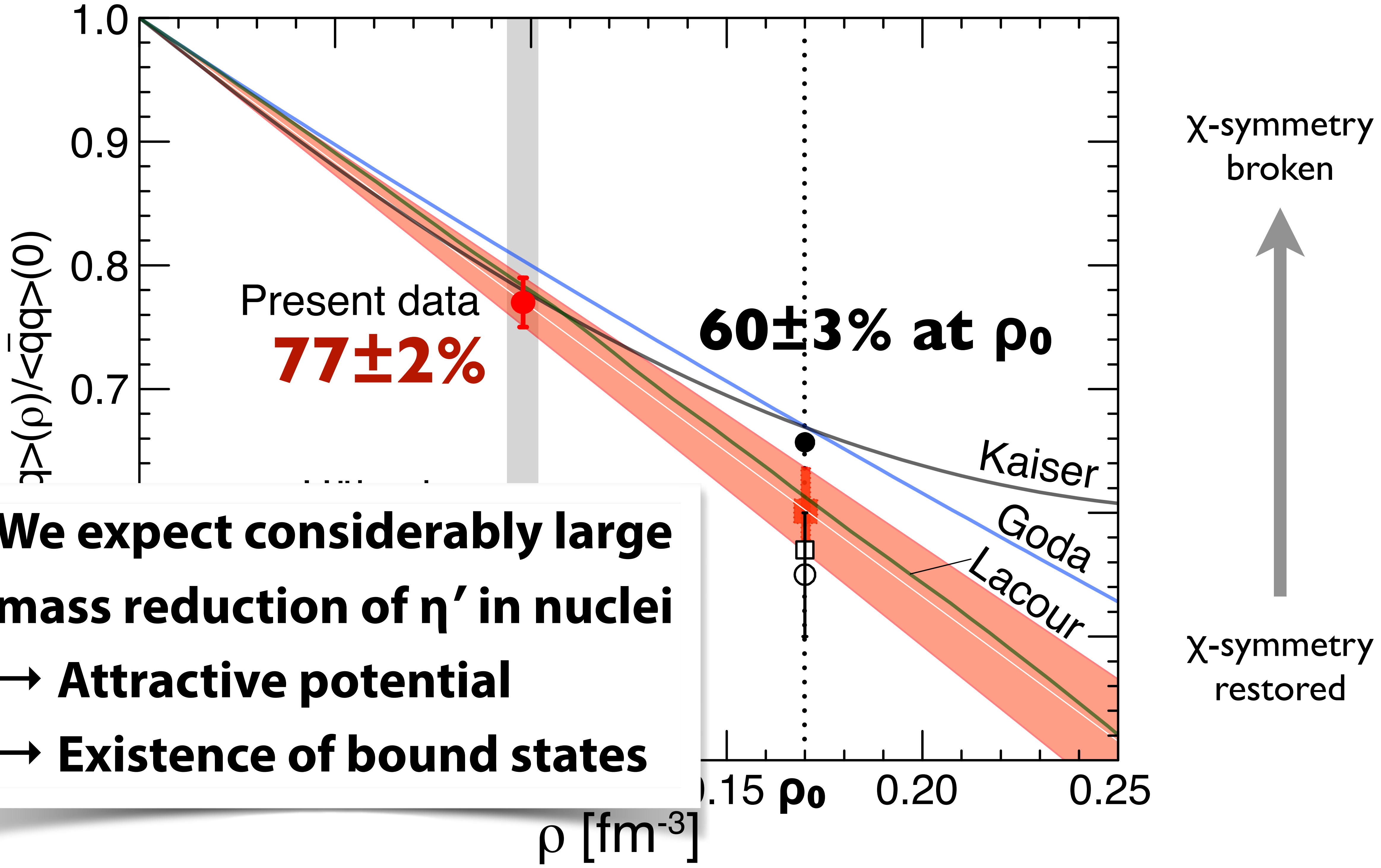
Chiral condensate decreases in nuclear matter
~pionic atom spectroscopy~



T. Nishi, KI et al., Nature Physics **19**, 788 (2023)

Article DOI: 10.1038/s41567-023-02001-x

Chiral condensate decreases in nuclear matter ~pionic atom spectroscopy~



We expect considerably large mass reduction of η′ in nuclei

→ Attractive potential

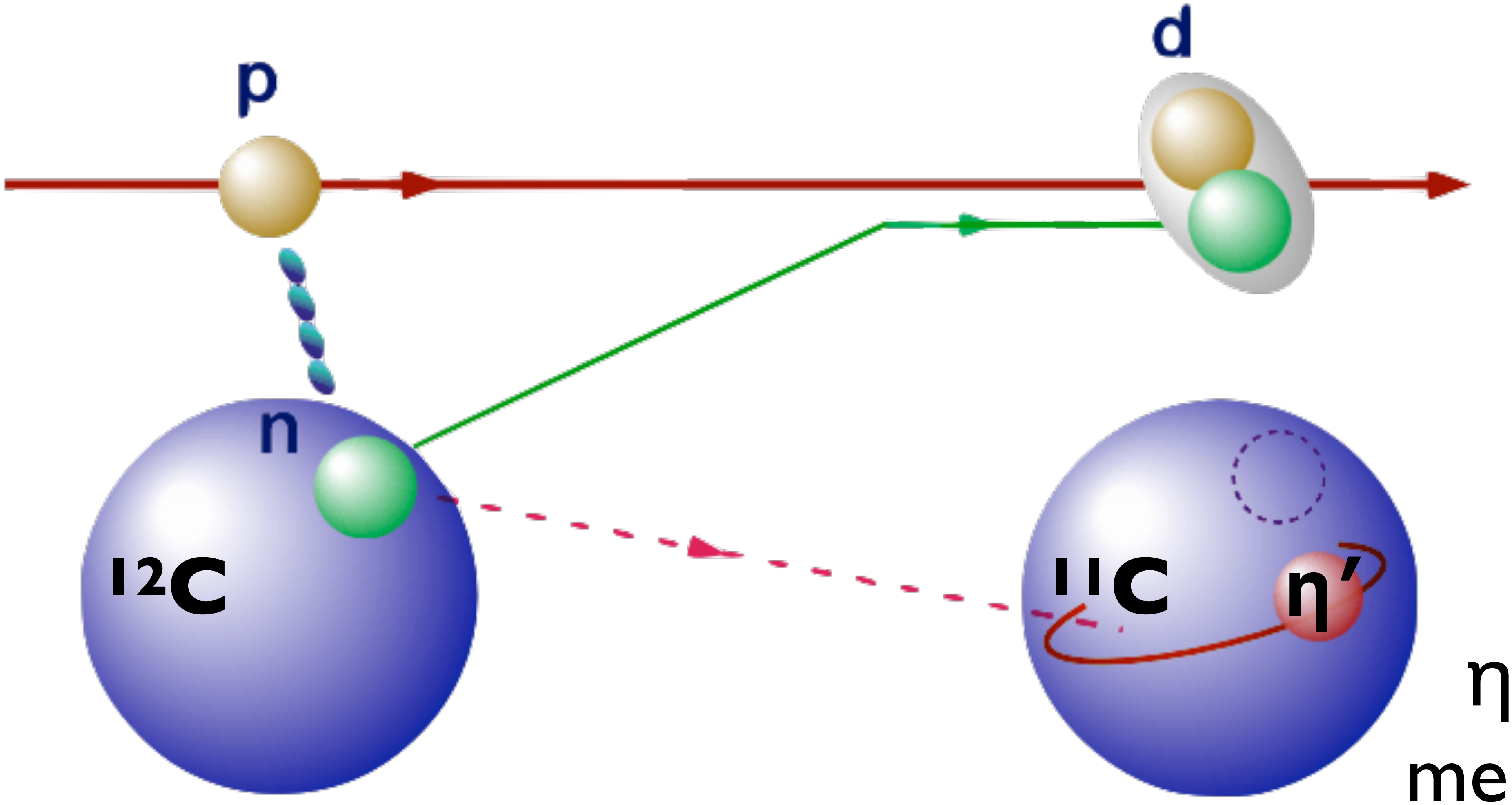
→ Existence of bound states

T. Nishi, KI et al., Nature Physics **19**, 788 (2023)

Article DOI: 10.1038/s41567-023-02001-x

η′ Mesic Nuclei in (*p*,*d*) Reaction

η′ transfer reaction + missing mass measurement



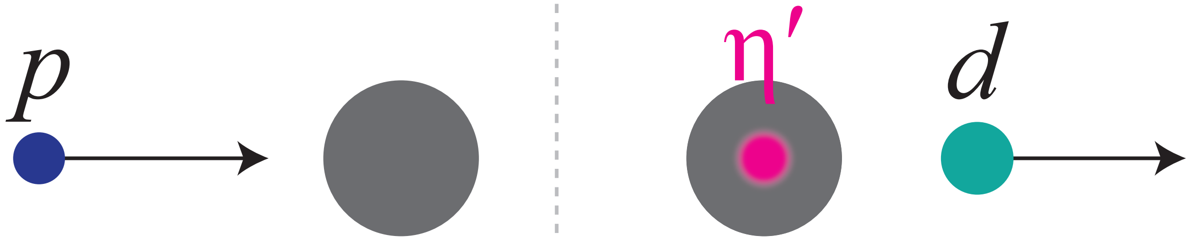
η′ × ^{11}C
mesic nuclei

$T_p = 2.50$ GeV → q ~ 400 MeV/c

KI, Fujioka et al., PTP 128 (12) 601.

Theoretical Prediction

Signal

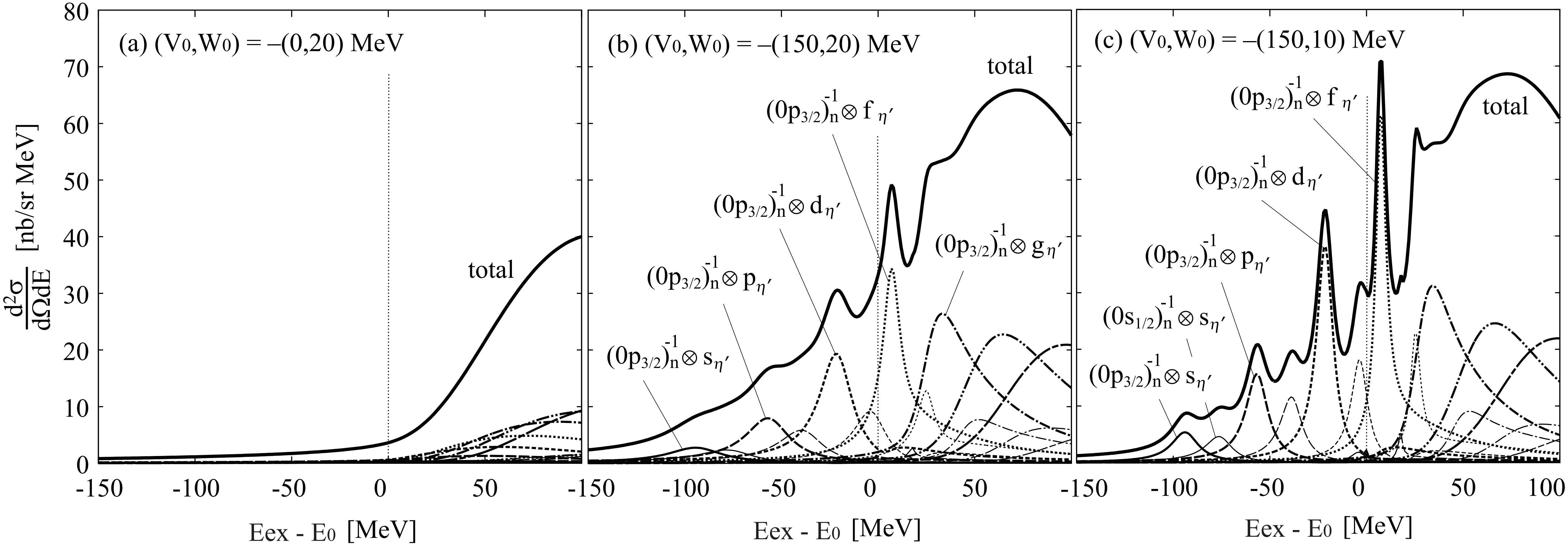


η′-nucleus potential:

$$V_{\eta'}(r) = (V_0 + iW_0)\,\frac{\rho(r)}{\rho_0}$$

ρ: nucleon density
V_0: Real potential depth
W_0: Imaginary potential depth

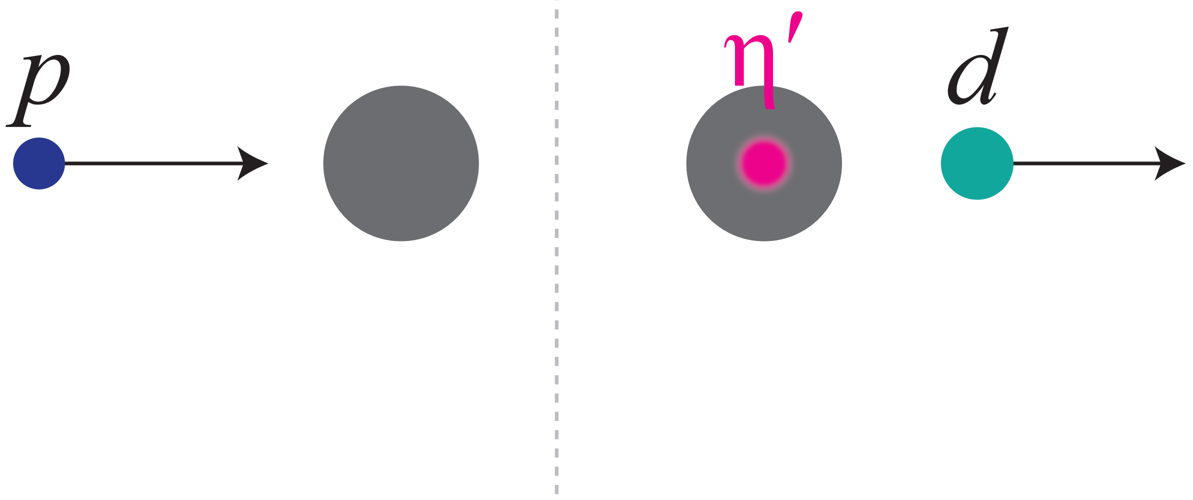
^{12}C(*p*,*d*) at T_p = 2.50 GeV



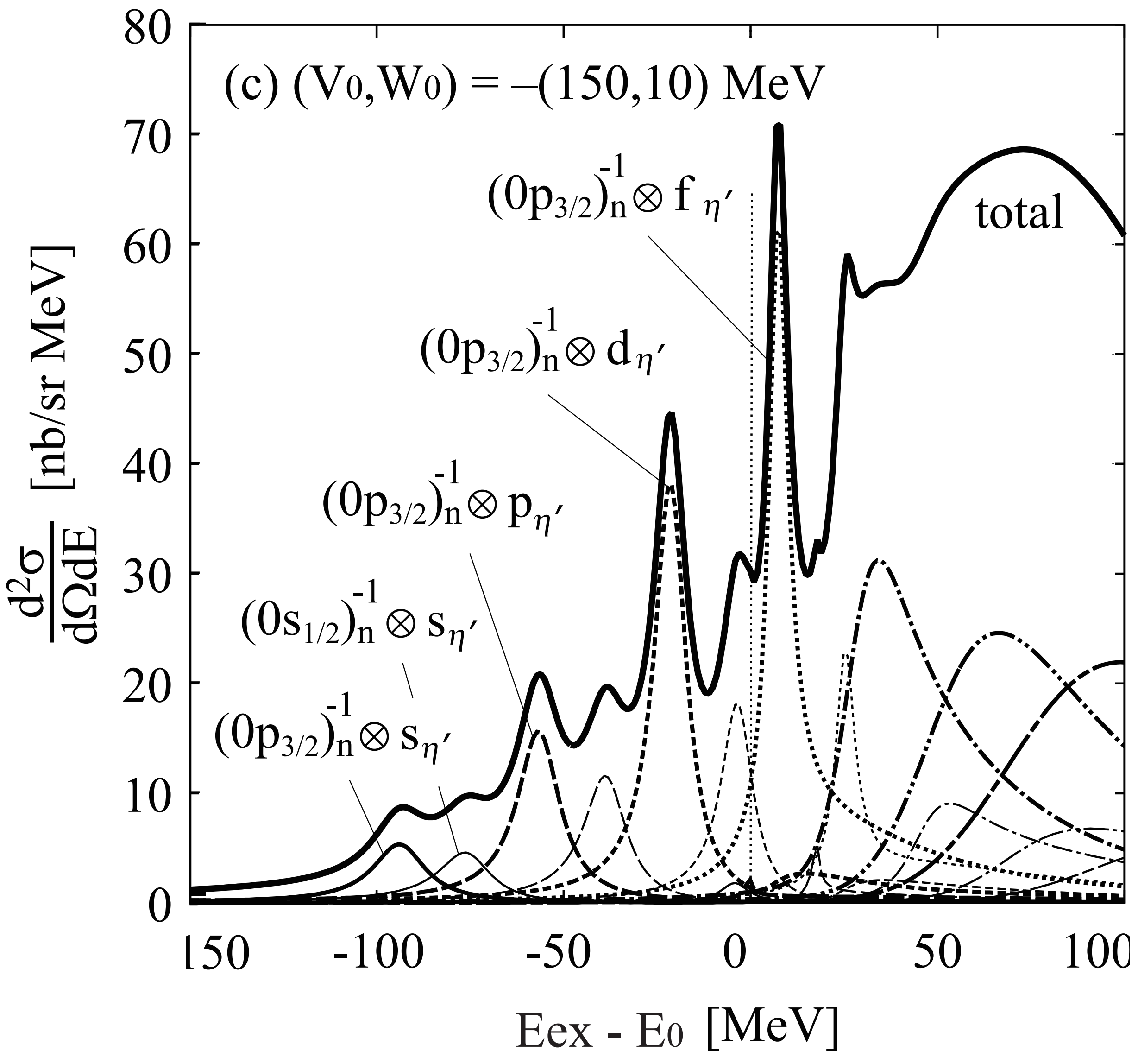
Nagahiro et al., PRC87(13)045201.

Missing-mass of ^{12}C(*p*,*d*) inclusive measurement

Signal



^{12}C(p,d)^{11}C ⊗ η′



Nagahiro et al., PRC87(13)045201.

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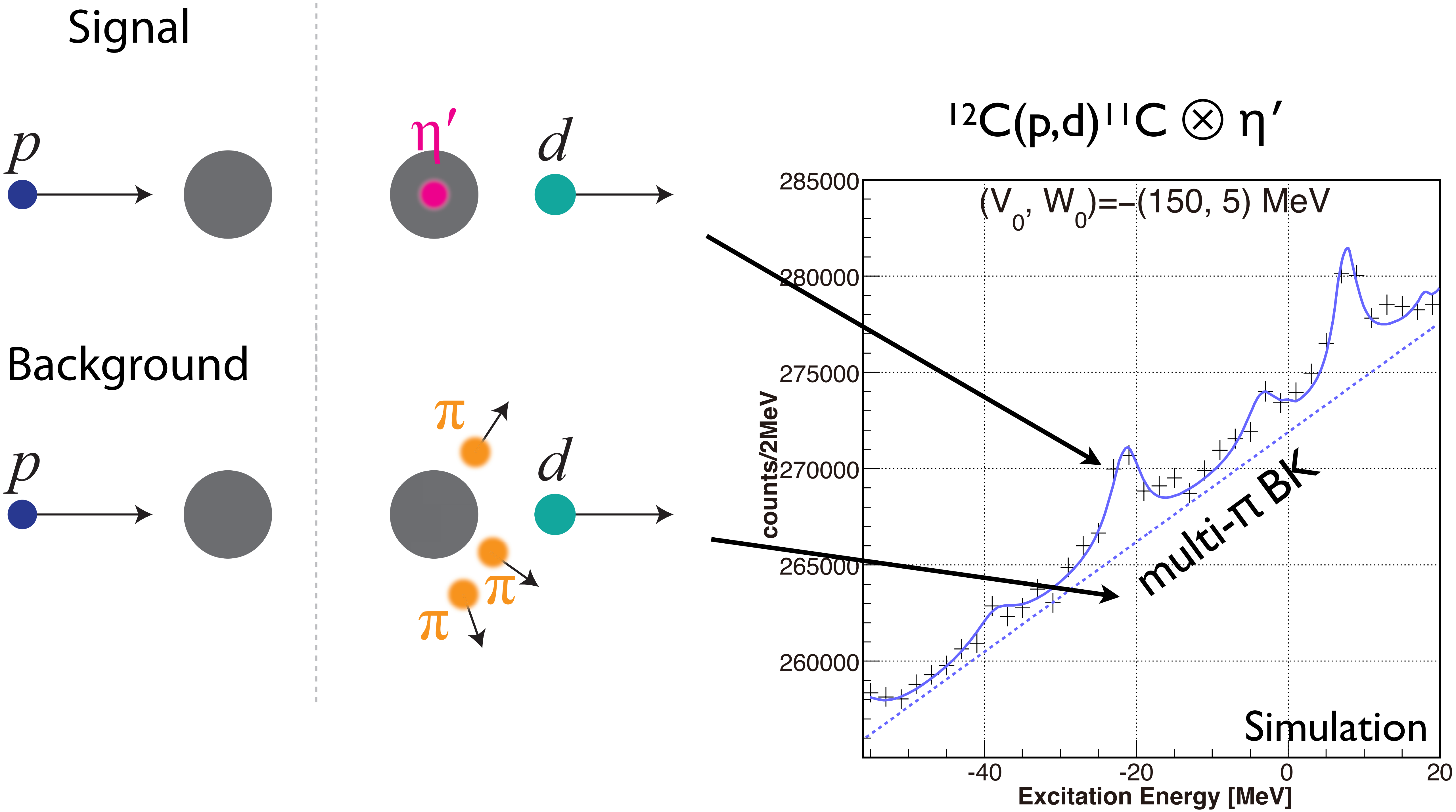
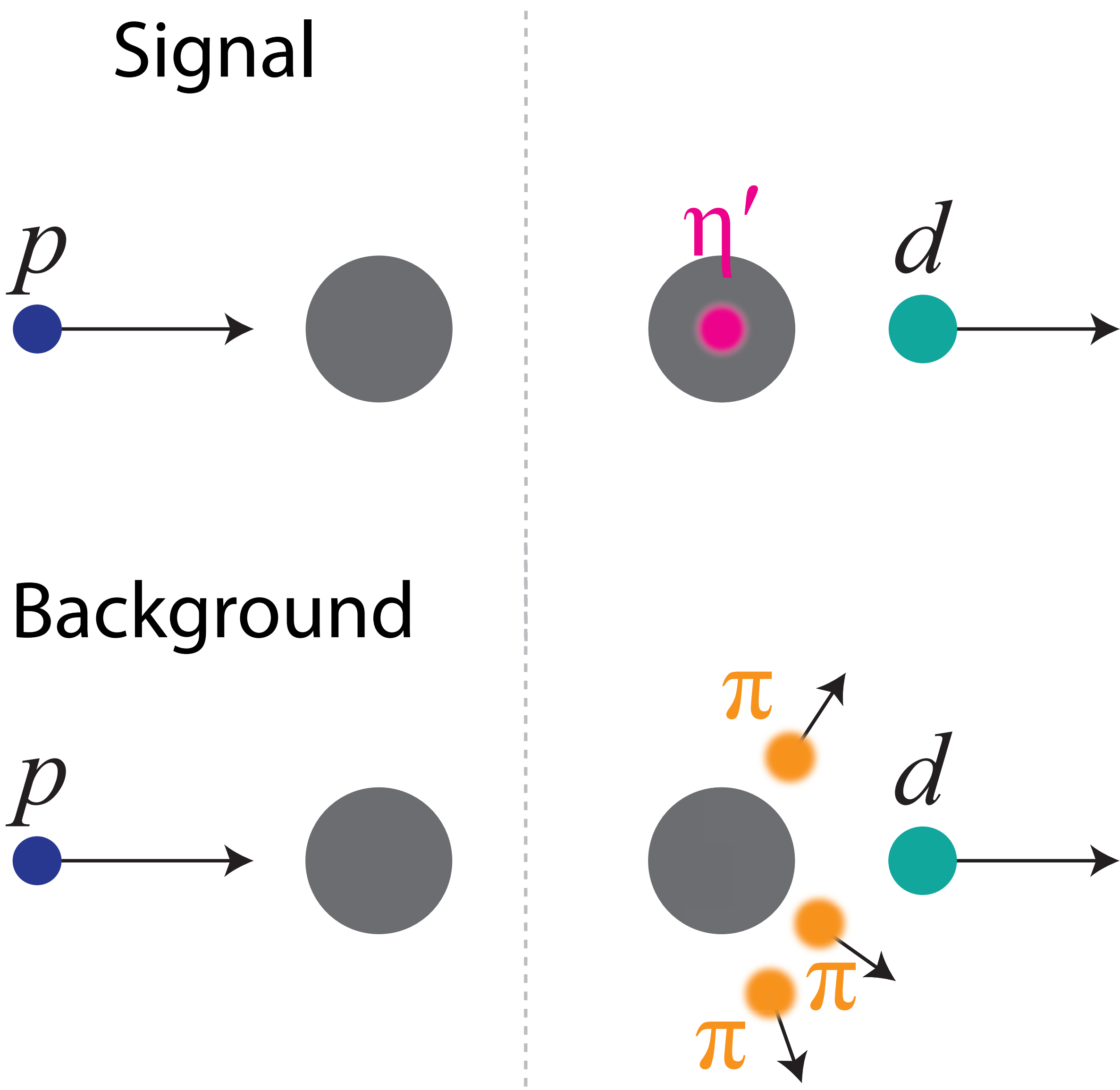
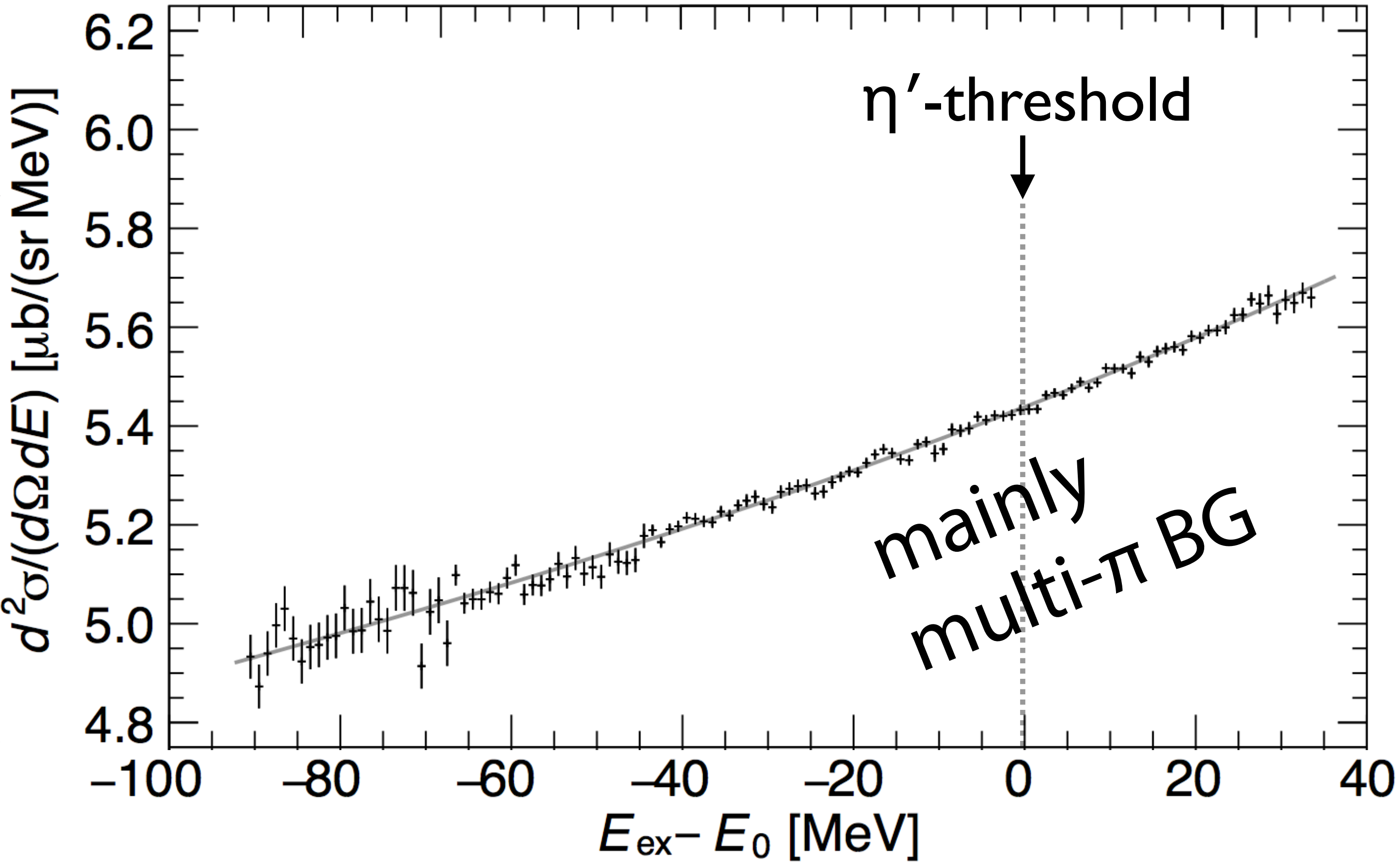


KI, Fujioka et al., PTP 128 (12) 601.

Missing-mass of ^{12}C(*p*,*d*) inclusive measurement



S437:^{12}C(*p*,*d*) in 2014 at FRS/GSI

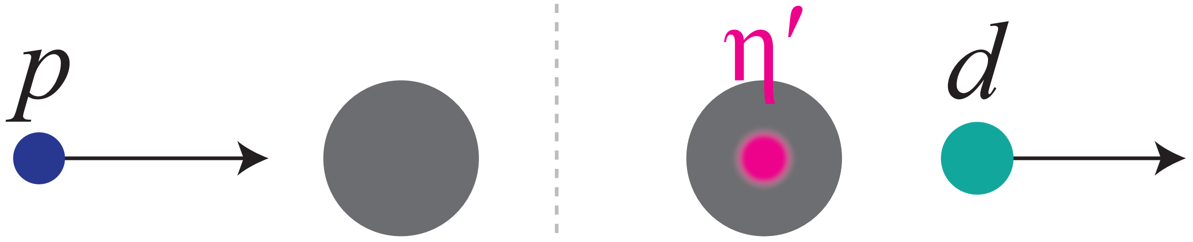


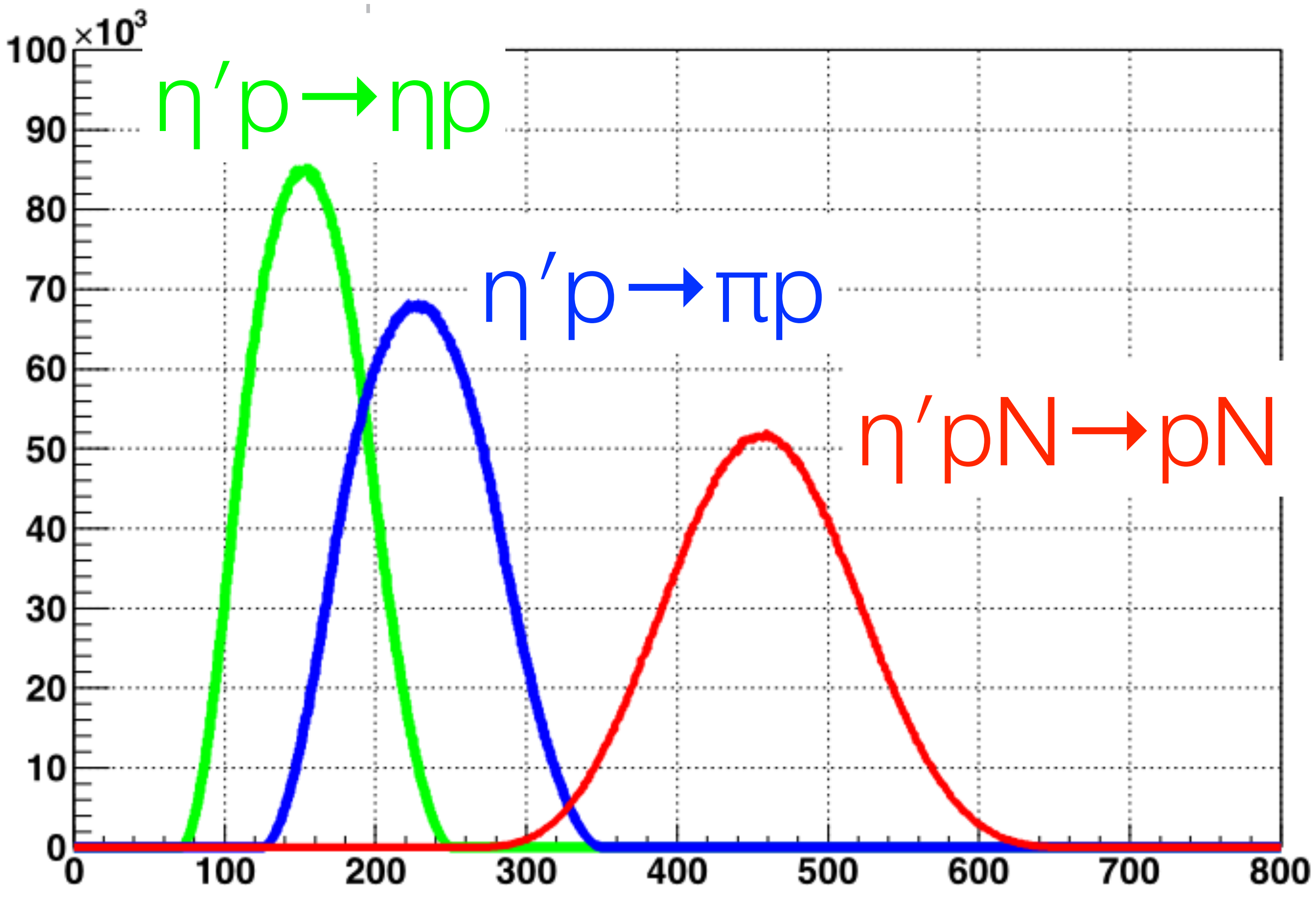
Y.K. Tanaka et al., Phys. Rev. Lett. **117**, 202501(2016)

We achieved extremely high statistical sensitivity demonstrating very good performance of FRS.
But, no peak was observed. Major BG=multi π.
S/BG cross sections must be < 1/100

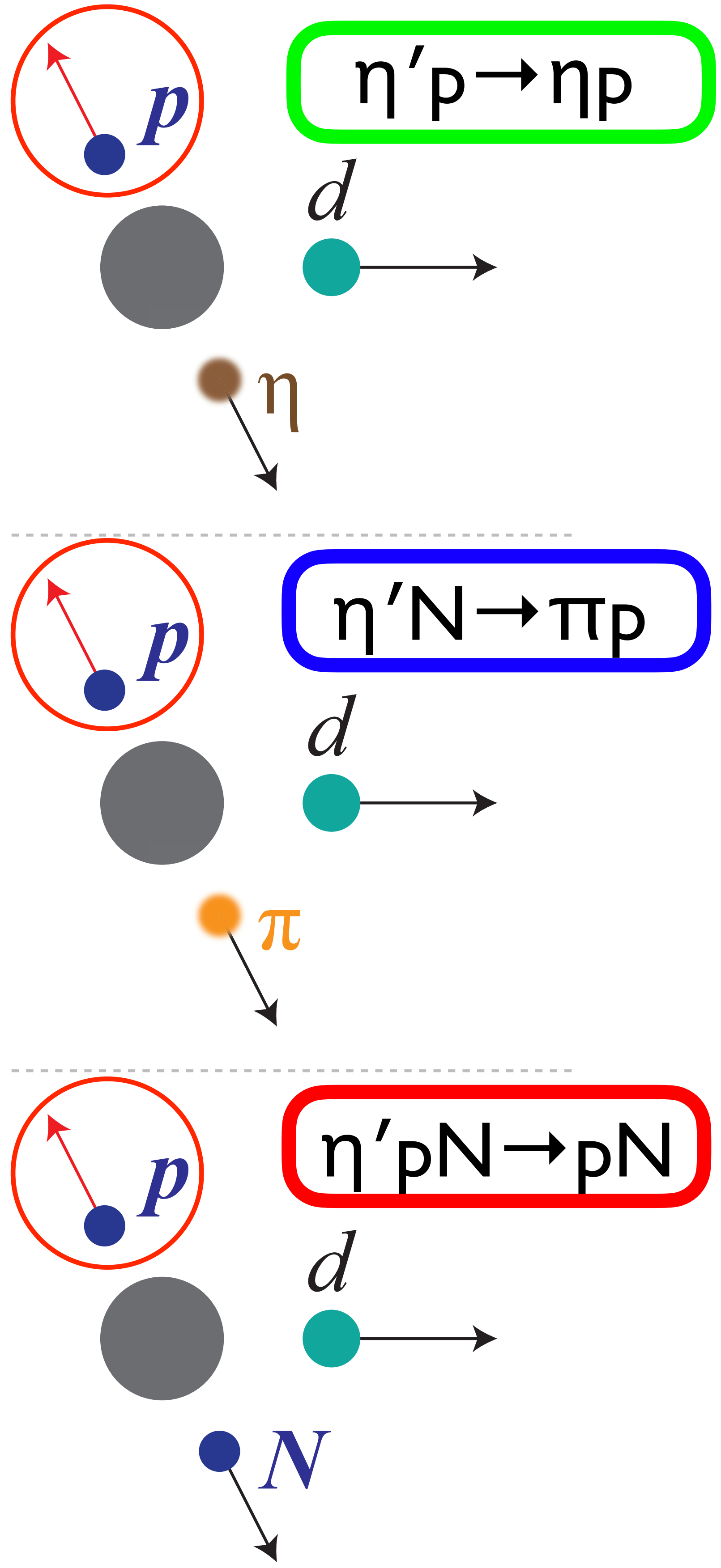
How to select signals

Signal





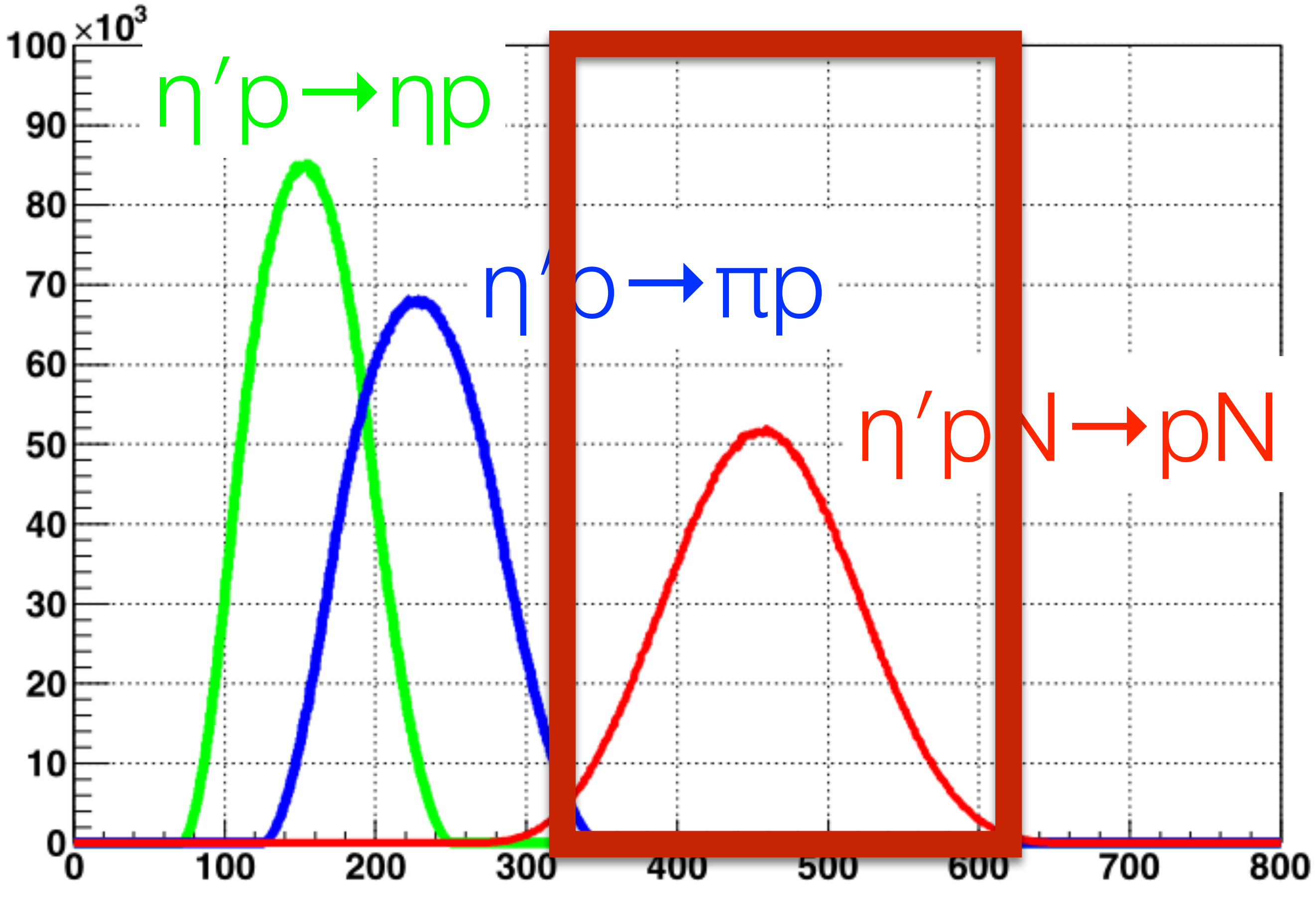
3 major decay modes of η′-mesic nuclei



Y.K. Tanaka and Y. Higashi

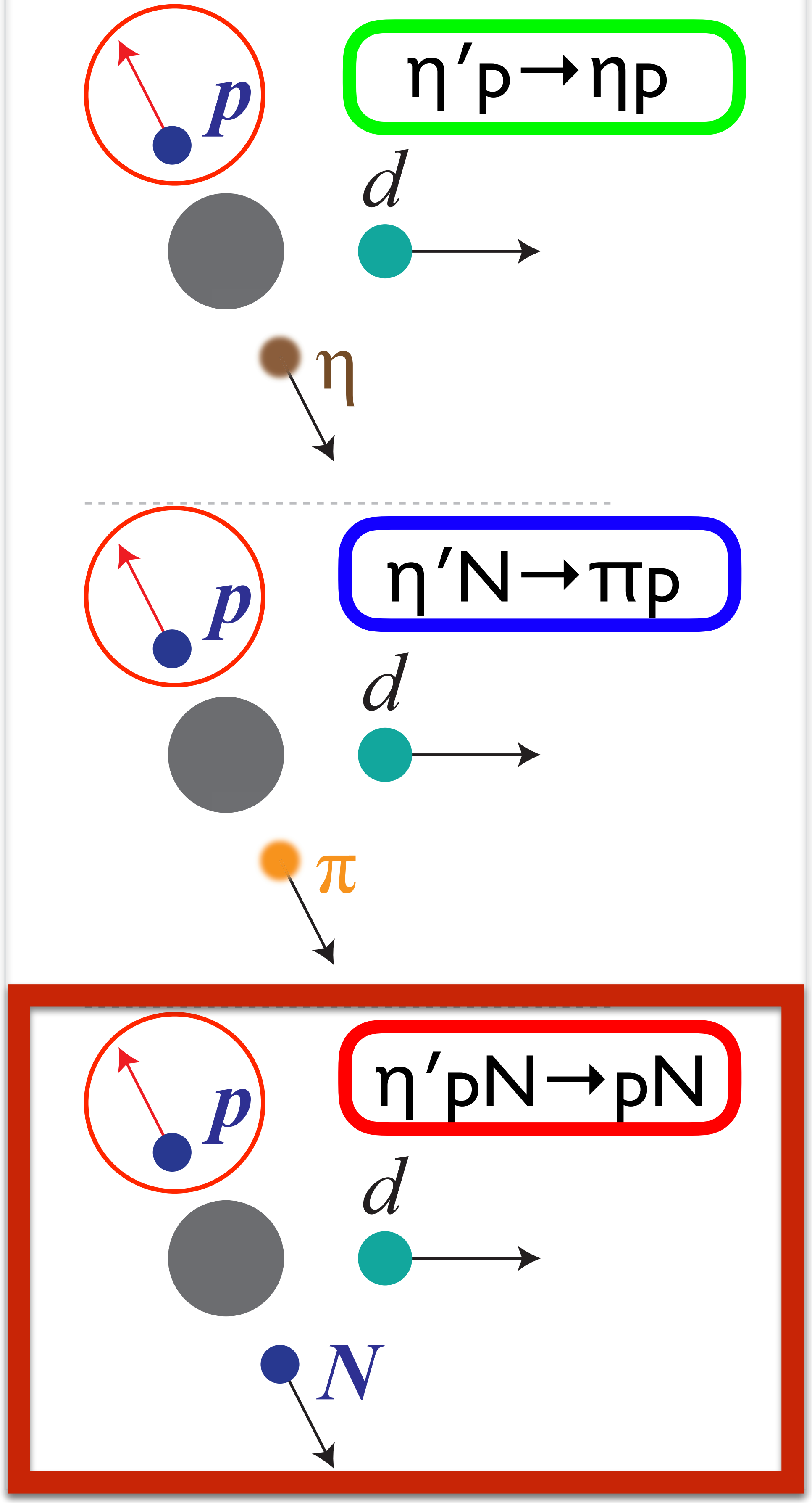
How to select signals

Detect *p* (800-1200 MeV/*c*) emitted in the decay of η′-nuclei for **semi-exclusive** measurement. f ~ 100 improvement in S/BG



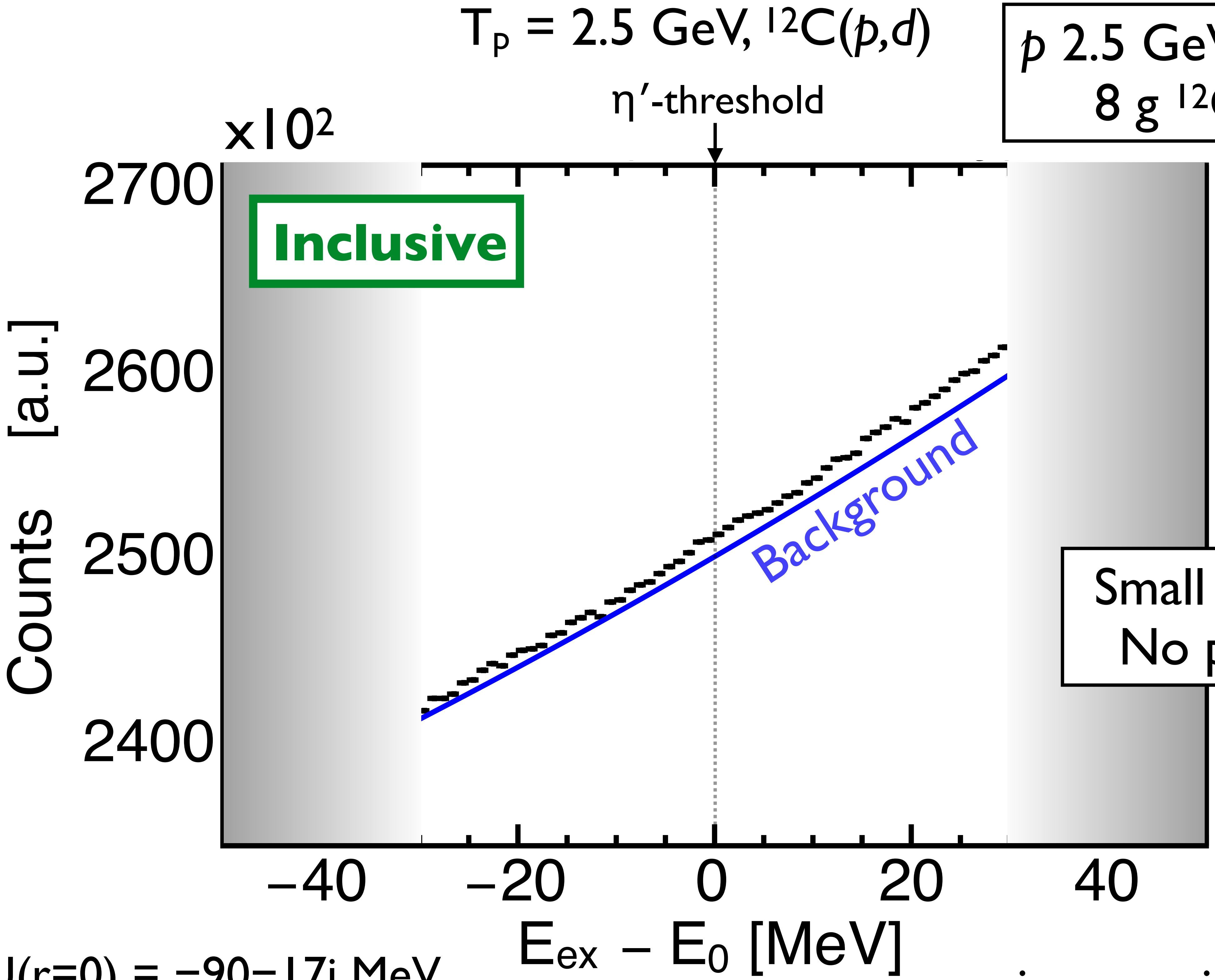
Y.K. Tanaka and Y. Higashi

3 major decay modes of η′-mesic nuclei



Expected spectrum in 4 days of DAQ at FRS

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



U(r=0) = −90−17i MeV

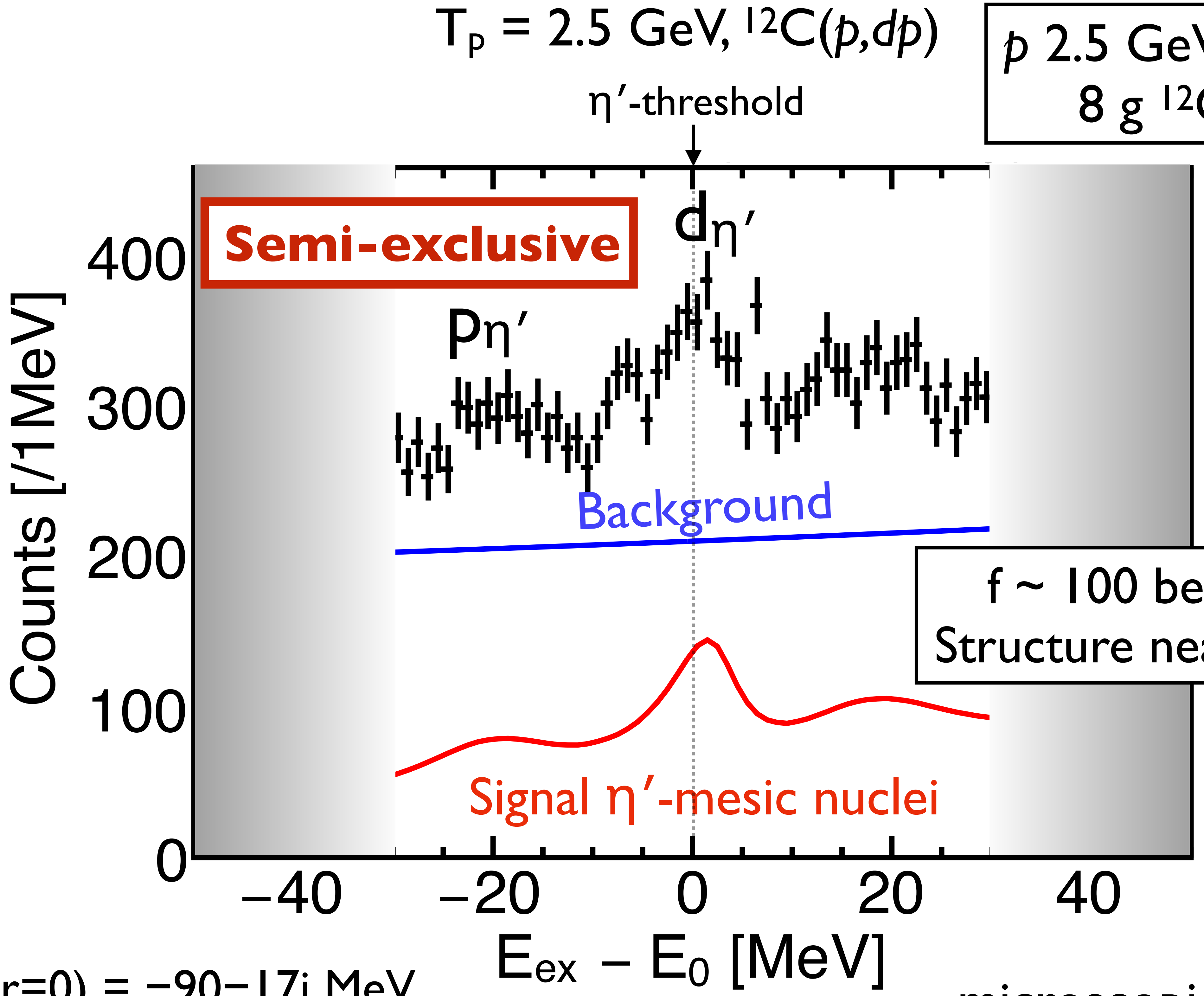
microscopic transport
simulation

NiSHiNA CENTER

S490-η′

Expected spectrum in 4 days of DAQ at FRS

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

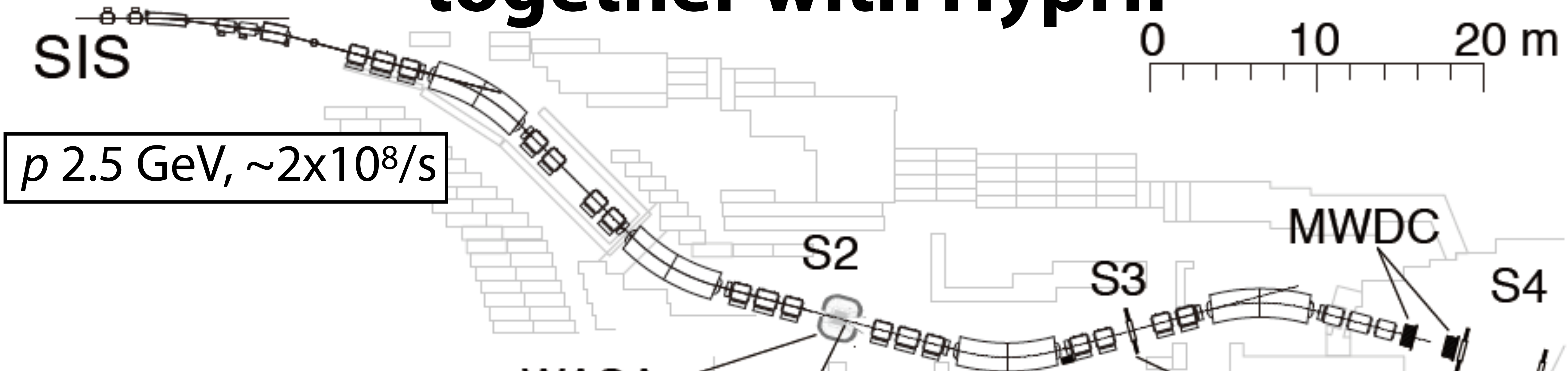


f ~ 100 better S/BG
Structure near threshold

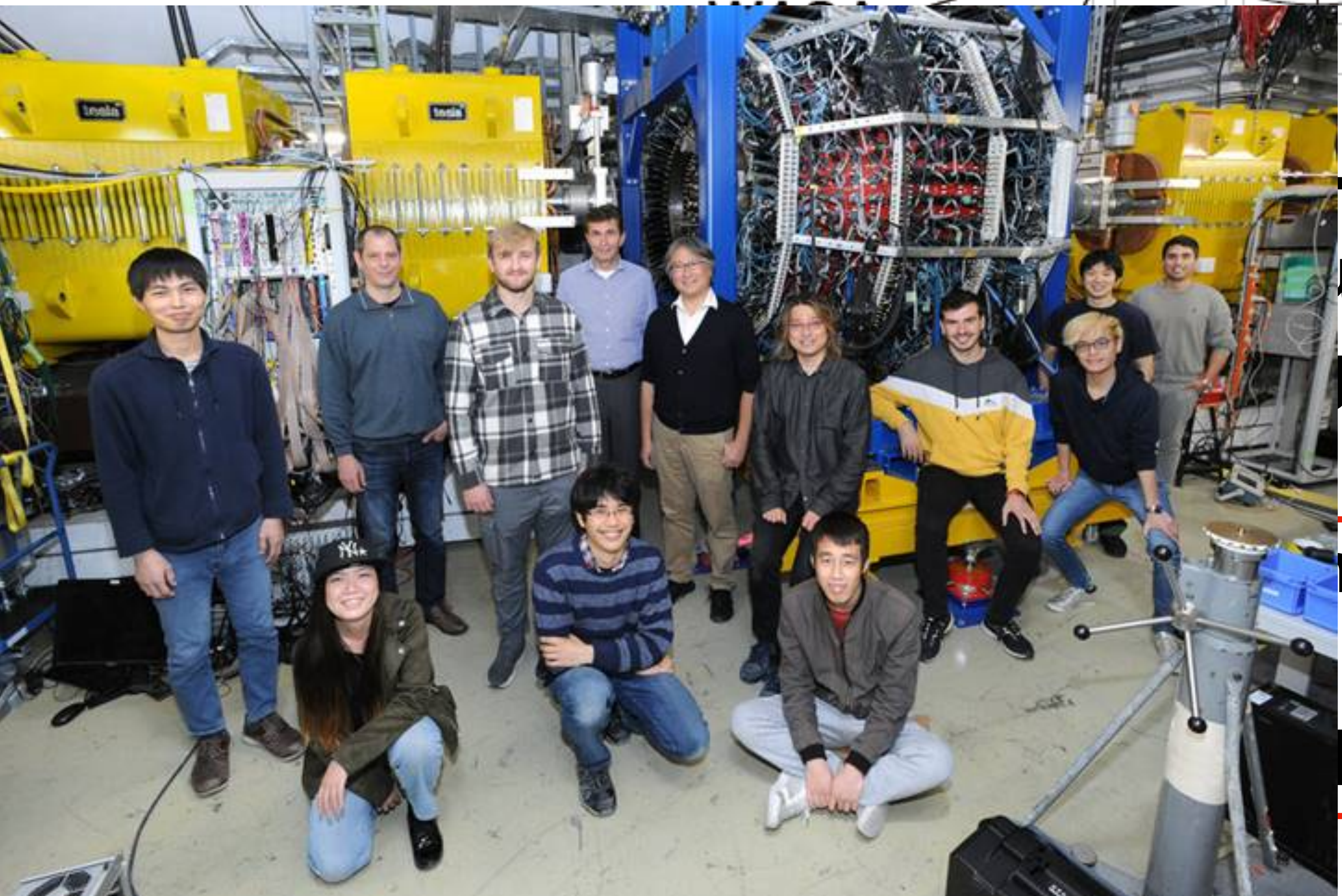
U(r=0) = −90−17i MeV

microscopic transport
simulation

Experimental setup : ^{12}C(*p*,*dp*) in Feb. 2022 together with HypHI



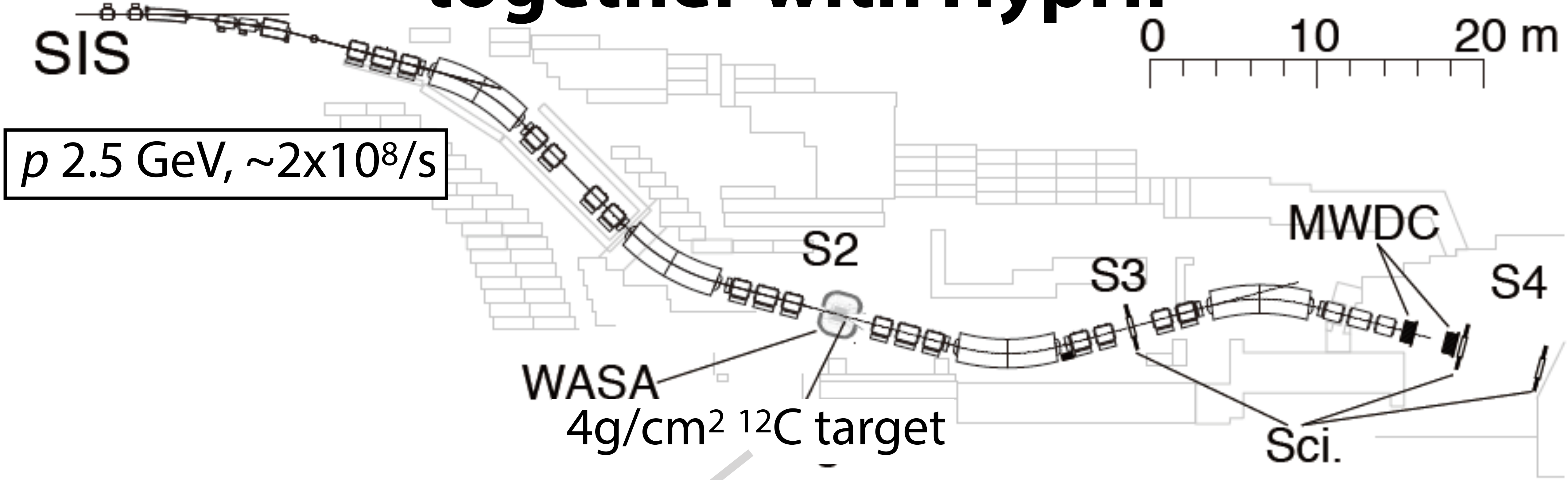
p 2.5 GeV, ~2x10^{8}/s



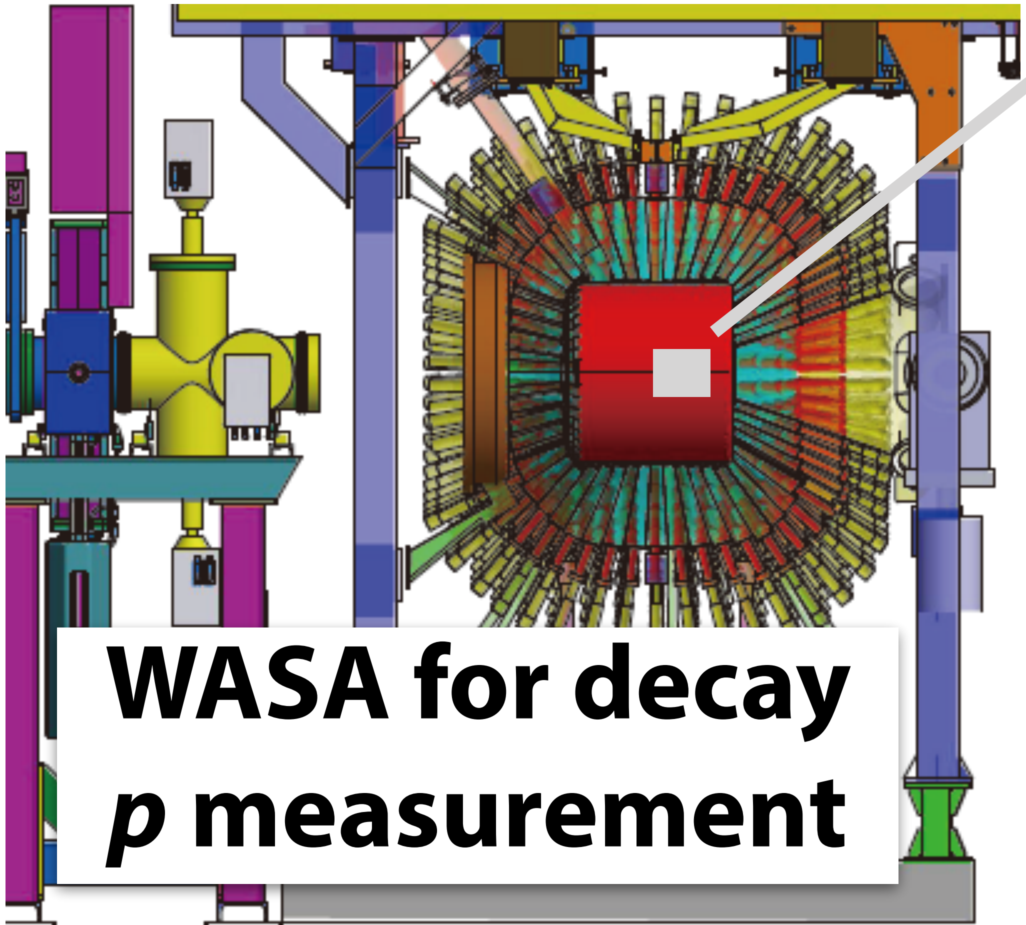
um analysis of (*p*,*d*)
Mass Spectroscopy

nation of forward
spectrometer and
lid angle detector

Experimental setup : ^{12}C(*p*,*dp*) in Feb. 2022 together with HypHI



Momentum analysis of (*p*,*d*) for Missing Mass Spectroscopy



WASA for decay *p* measurement

Combination of forward high-res. spectrometer and large solid angle detector

Inclusive Spectrum at S4

comparable to S437

Acceptance uncorrected

Preliminary

~1.1×10^7 *d* events

Counts [/MeV]

Resolution ~ 2.5 MeV σ

E_{ex}-E_0 [MeV]

Y.K. Tanaka

Inclusive Spectrum at S4

comparable to S437

Acceptance uncorrected

Preliminary

~1.1×10^7 *d* events

Counts [/MeV]

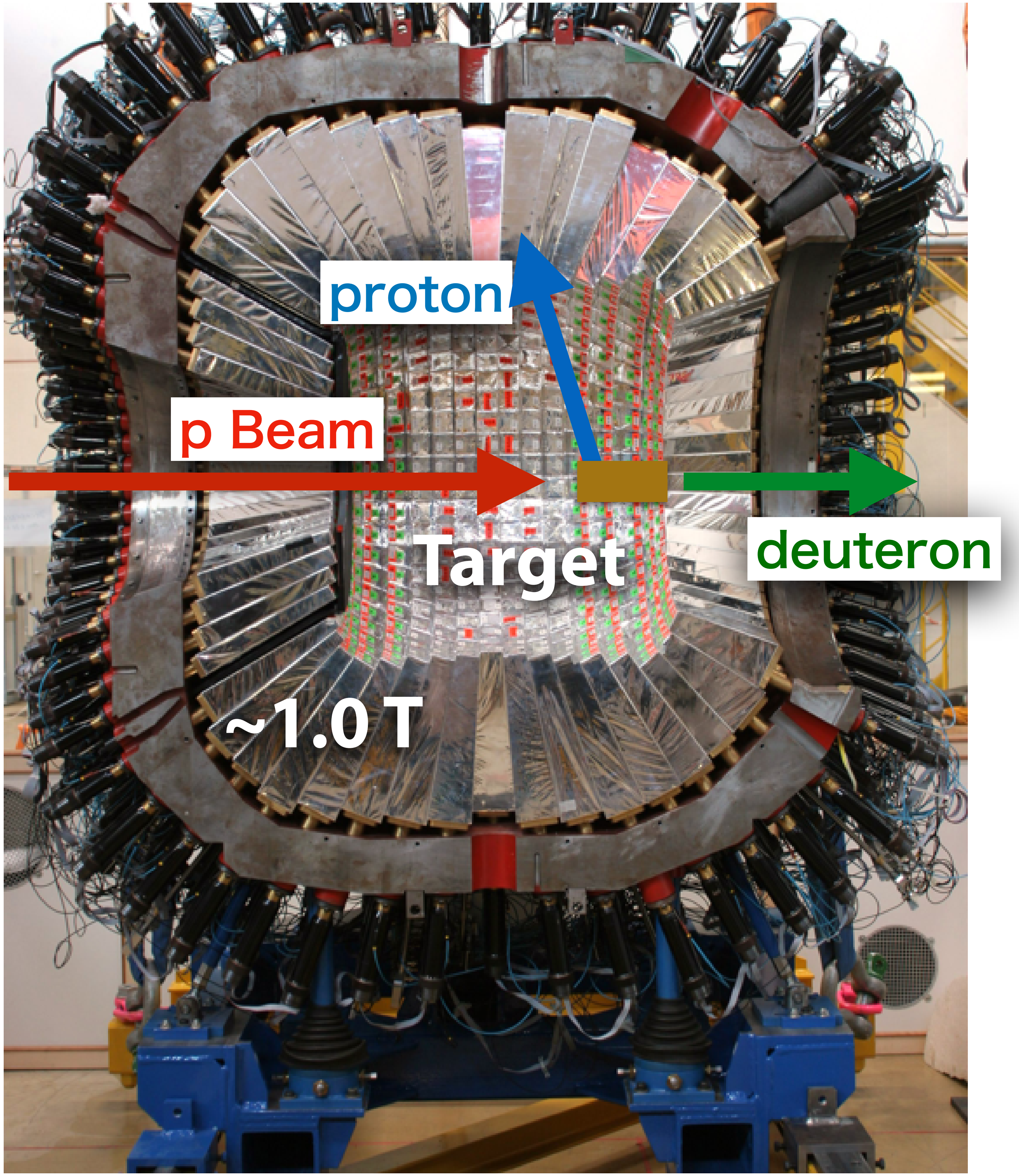
Healthy measurement
Analysis is almost ready

Resolution ~ 2.5 MeV σ

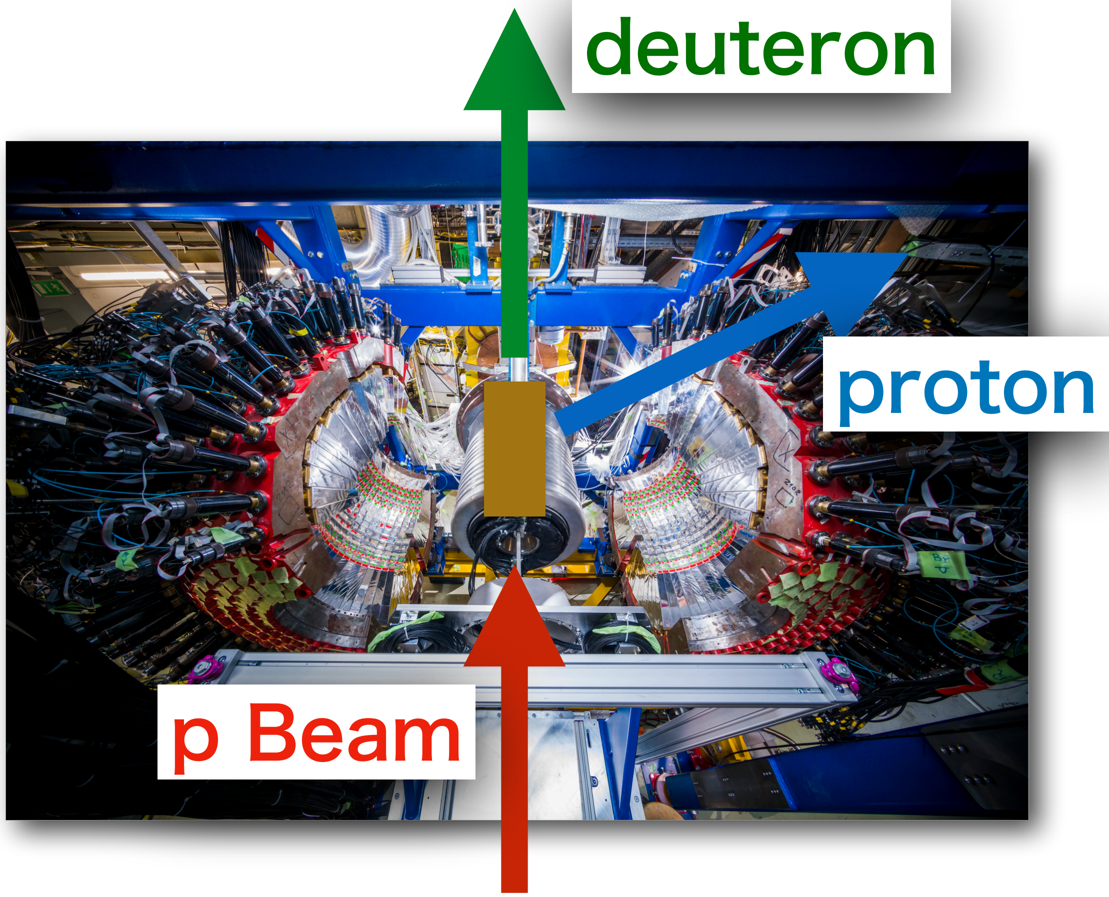
E_{ex}-E_0 [MeV]

Y.K. Tanaka

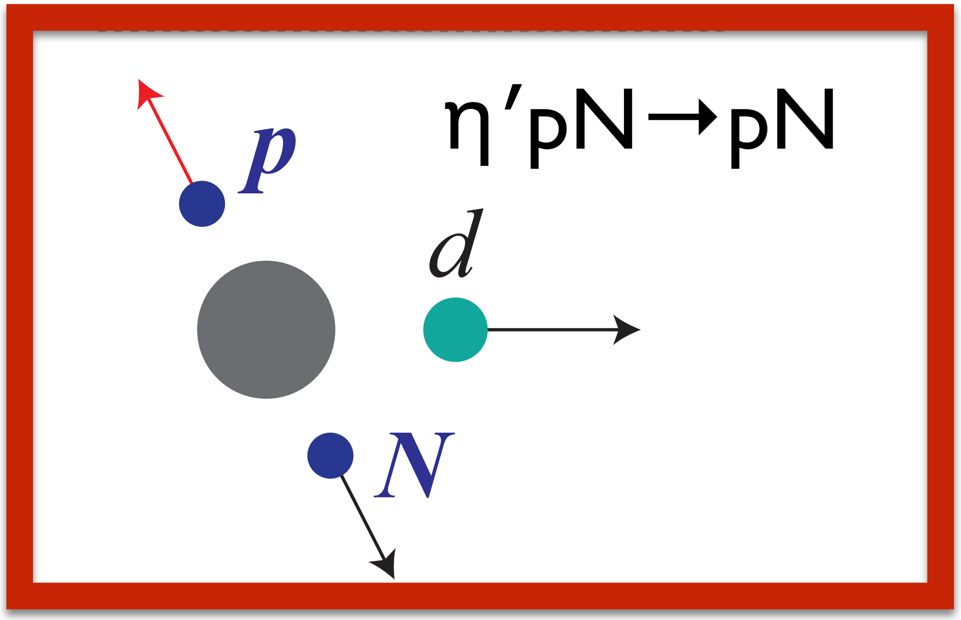
Detectors in WASA



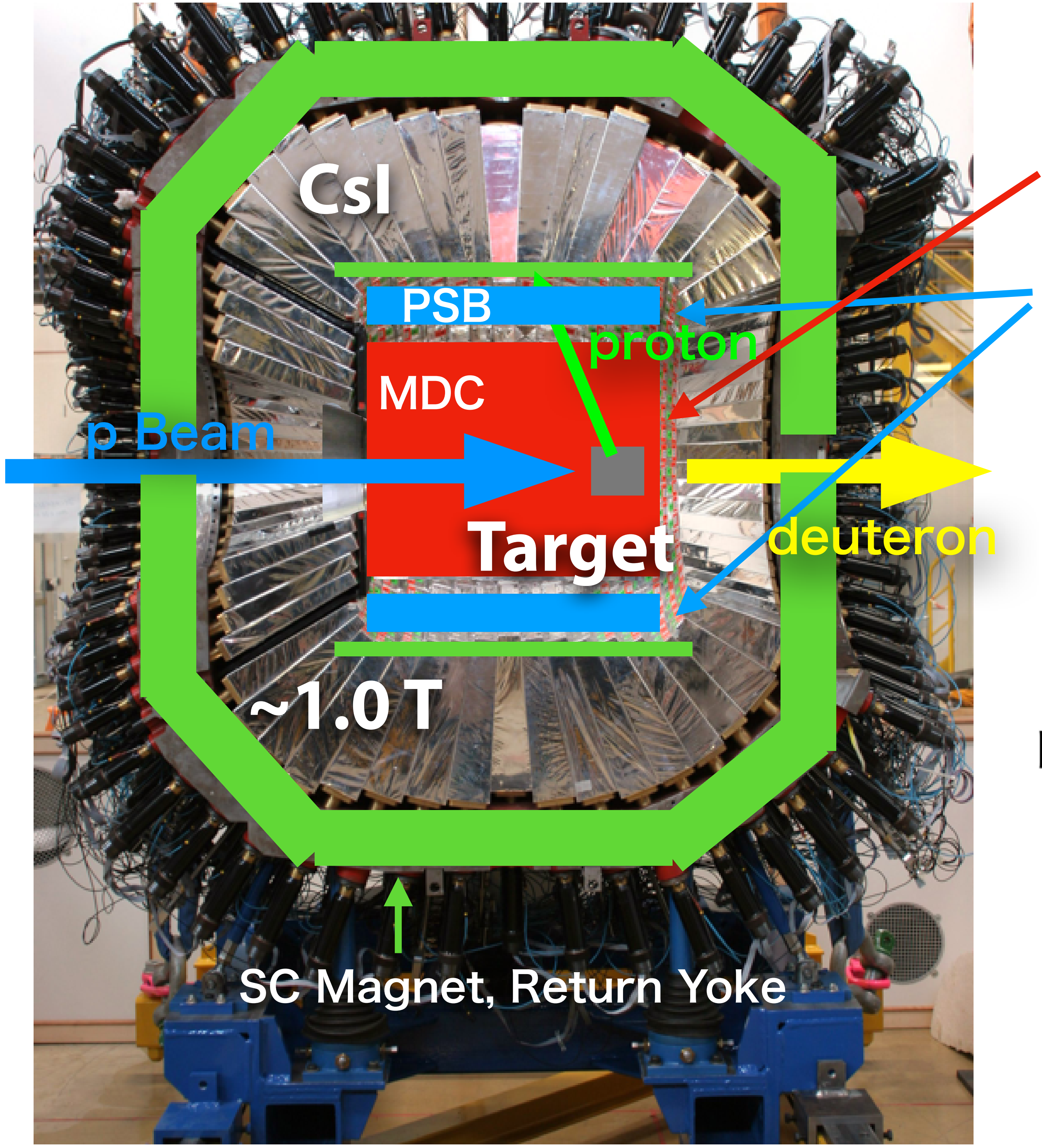
Cooperation with COSY-WASA collaboration



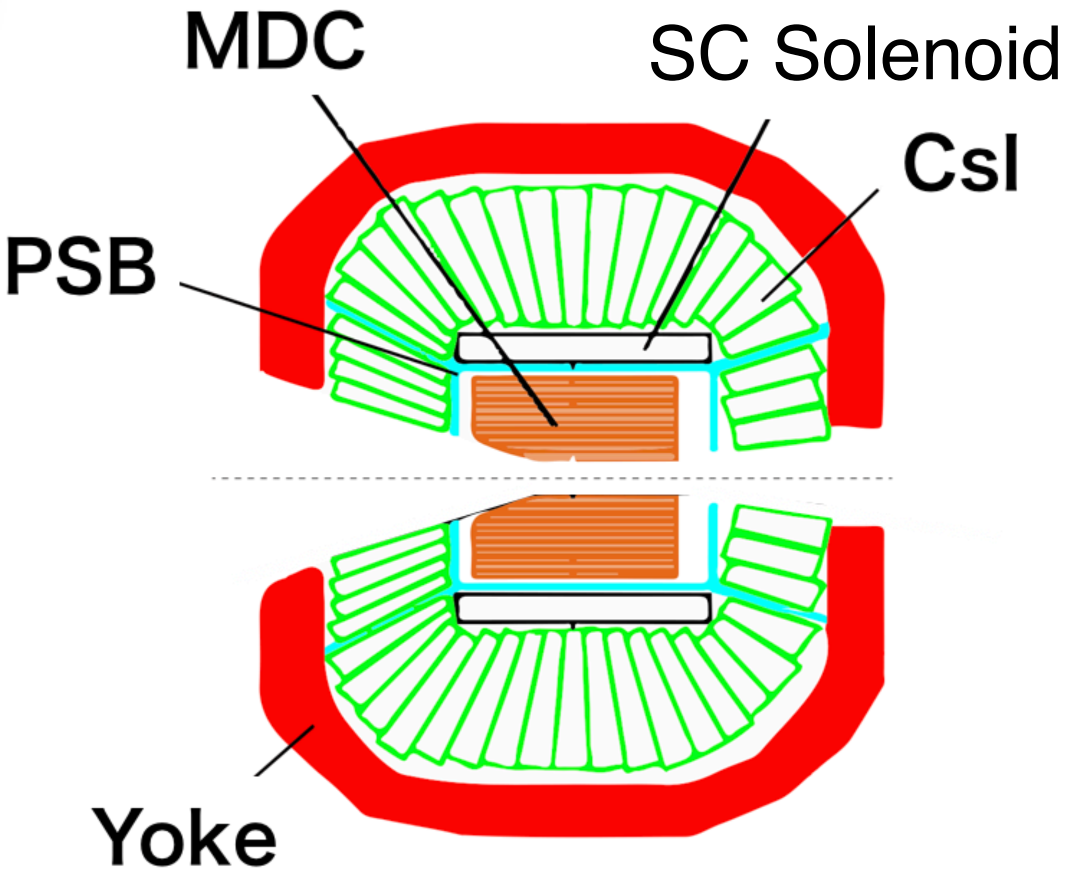
High energy proton tagging in coincidence with forward *d*



Detectors in WASA

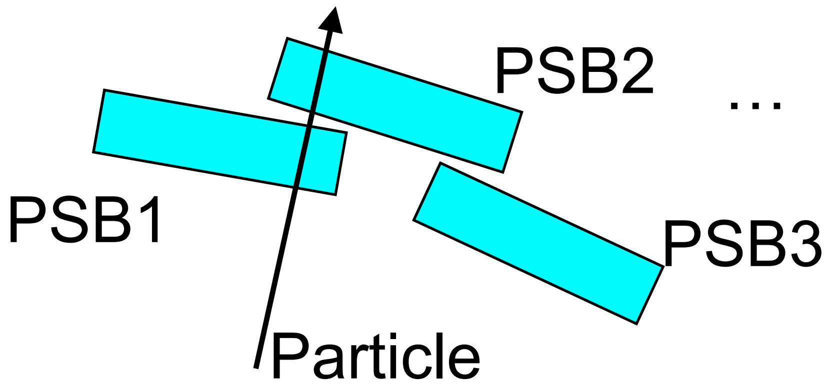


- **MDC (Mini Drift Chamber)**
  Charged particle tracking
- **PSB (Plastic Scintillator Barrel)**
  ΔE + Timing measurement
- **CsI**
  γ detection for calibration

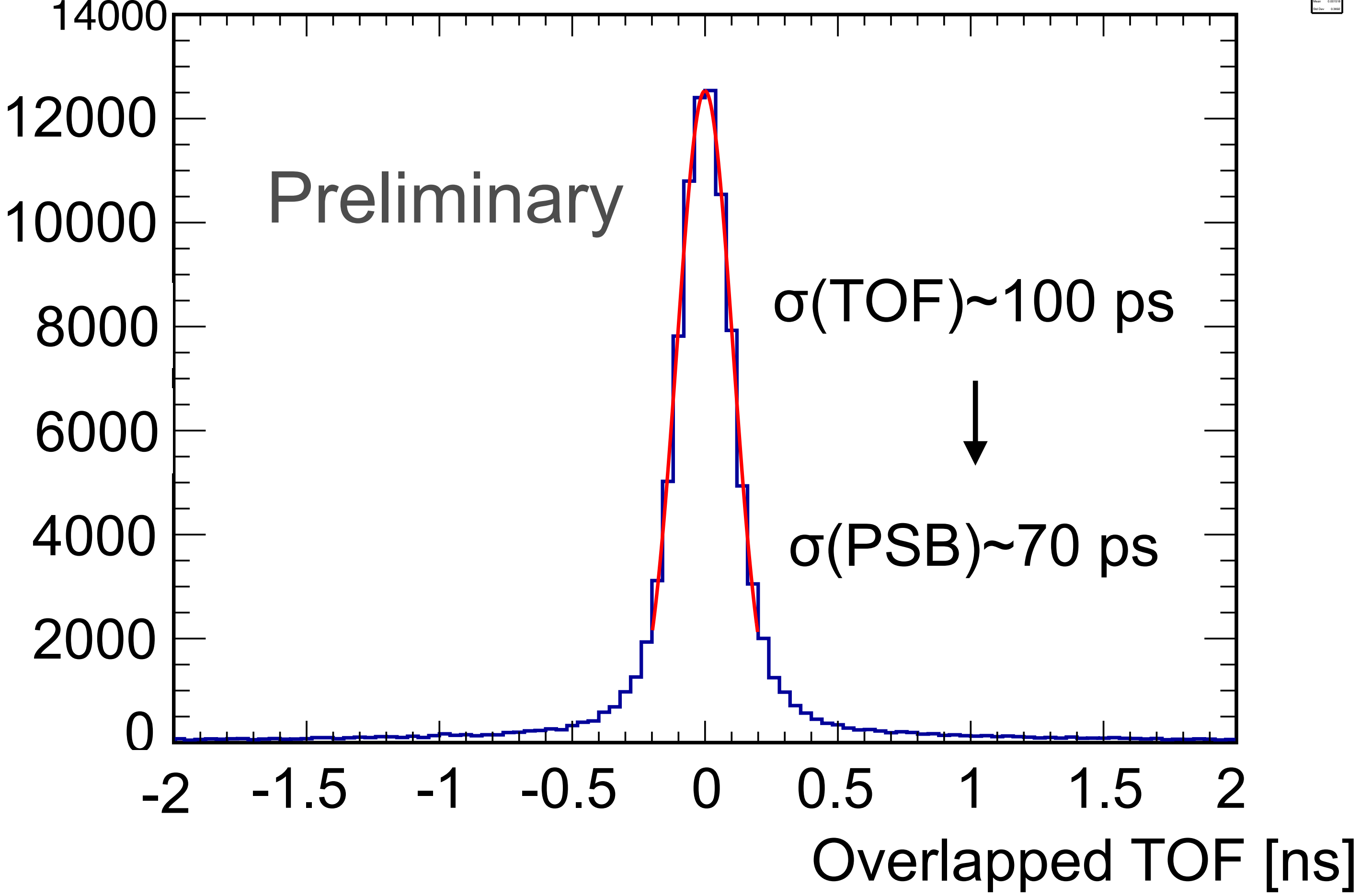


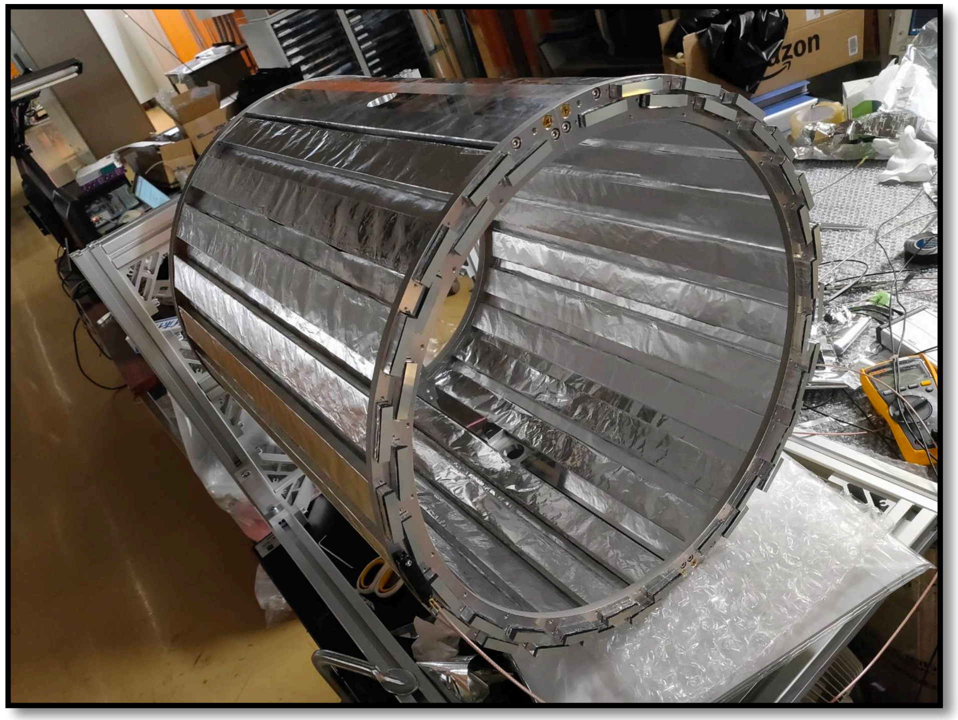
Cooperation with COSY-WASA collaboration

Plastic Scintillator Barell



TOF btw. overlap PSBs





PSB time resolution
~ 70 ps σ
for Z=1 particles

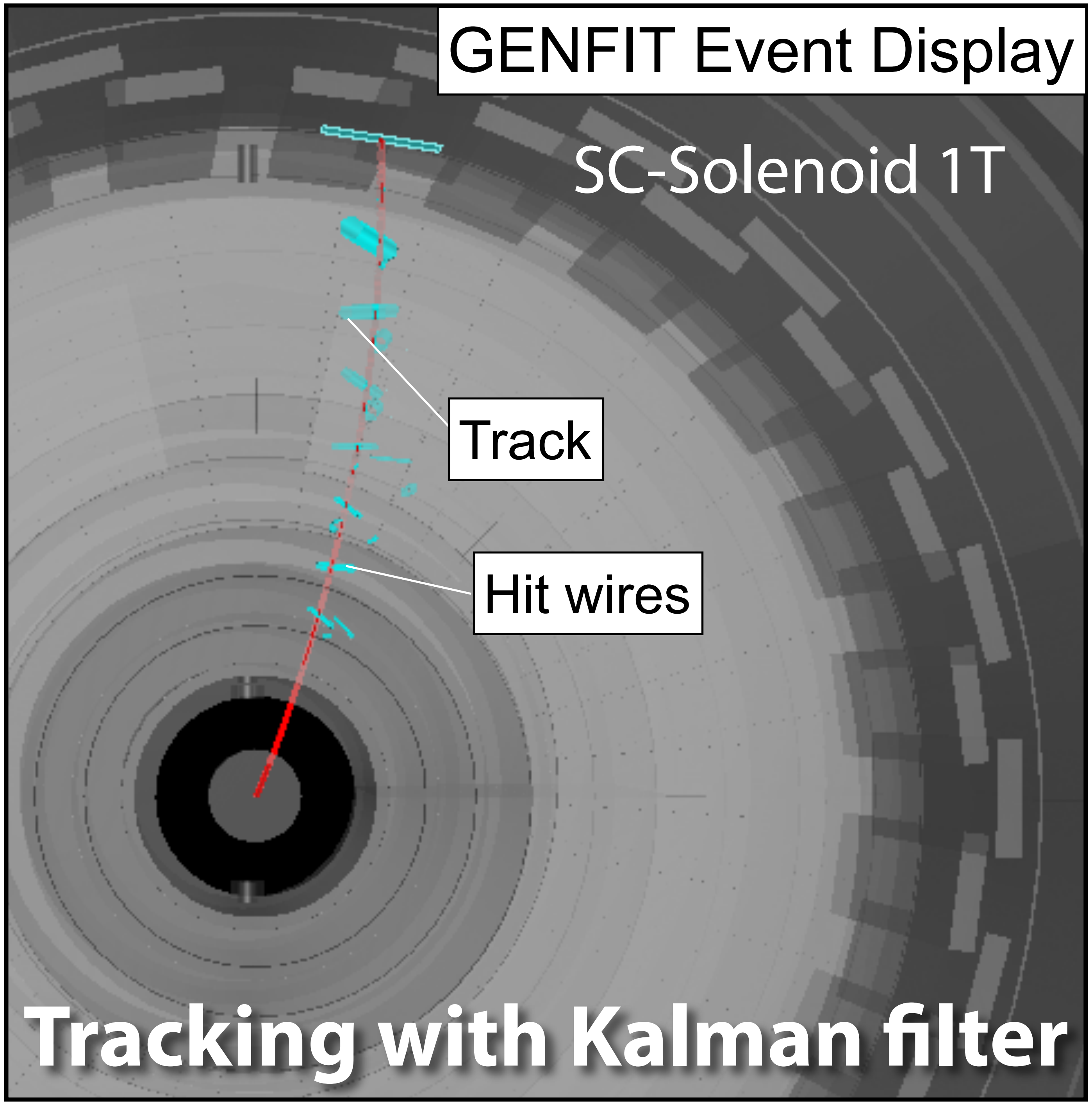
R.Sekiya

Mini Drift Chamber MDC

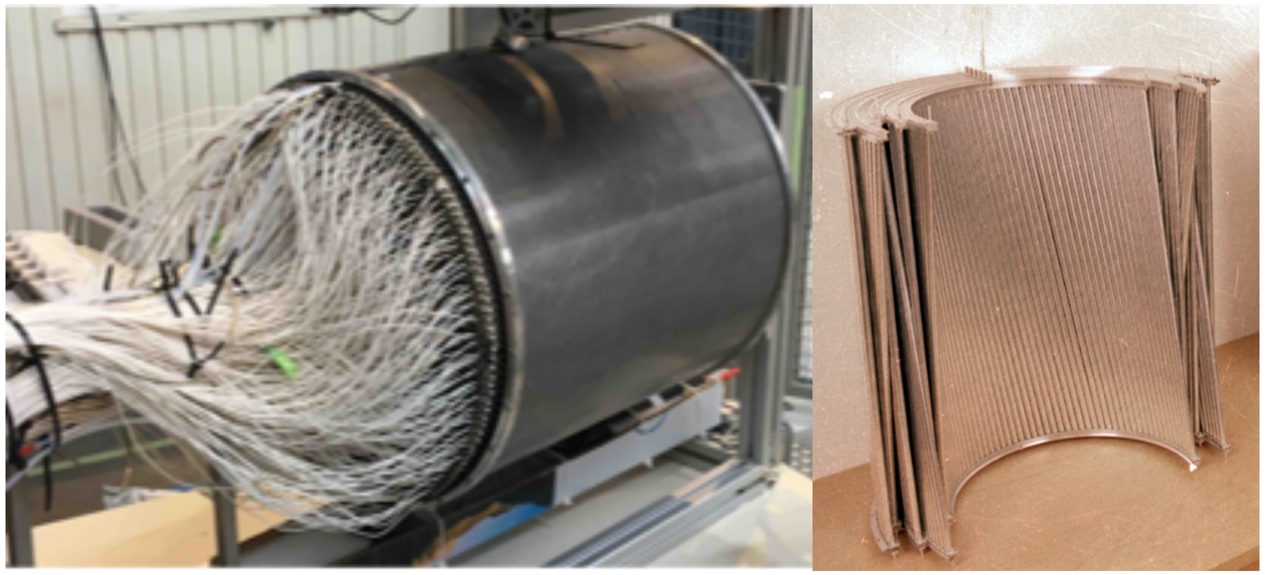
17 layers ~2K straw tube detectors

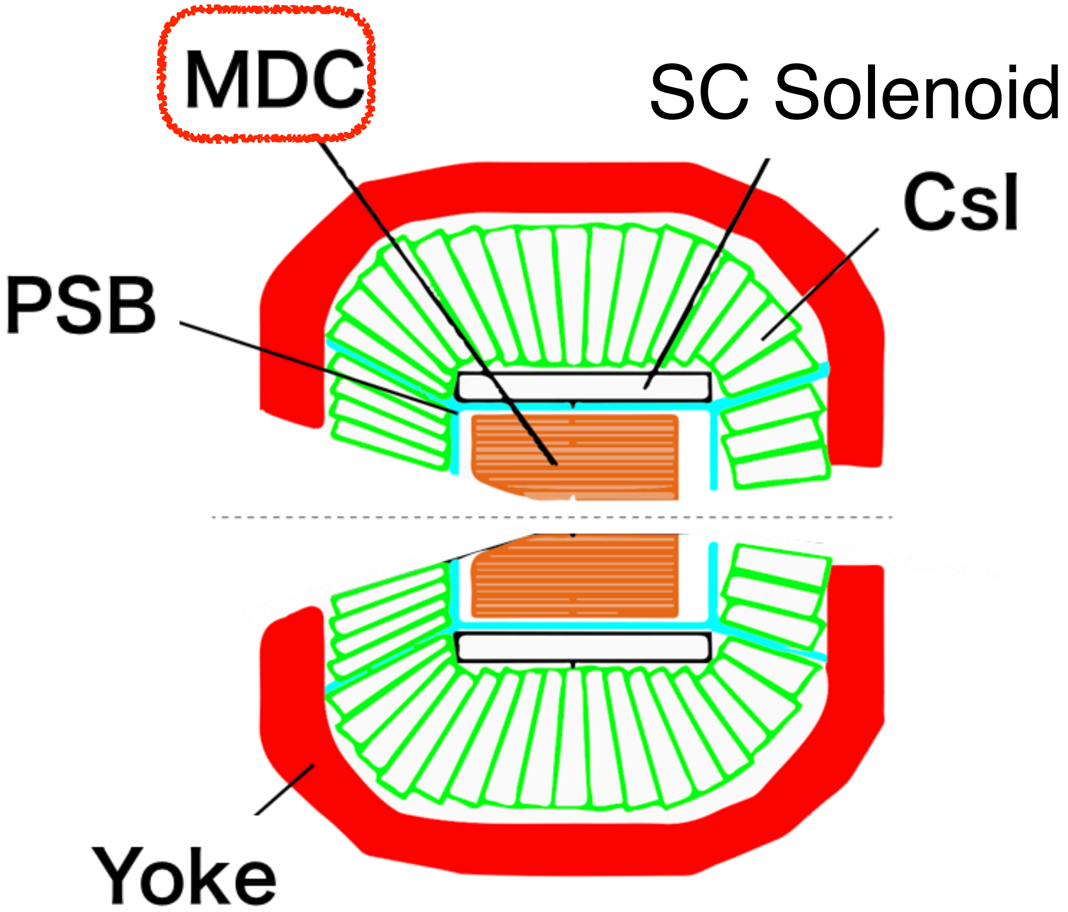
Tracking resolution 250-500 μm

→ $\Delta p/p$ ~ 40-45% at 1 GeV/c



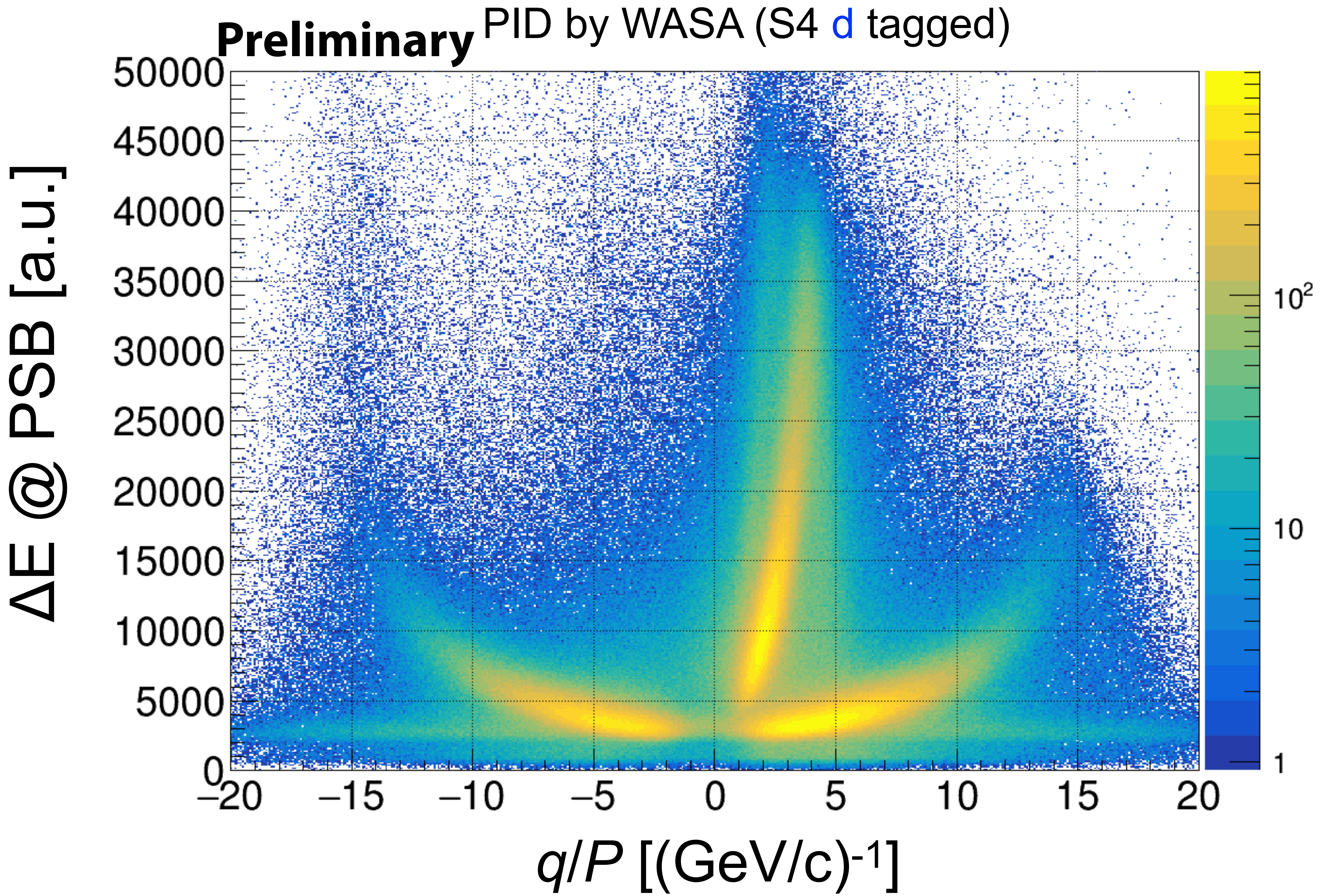
Tracking with Kalman filter





R.Sekiya

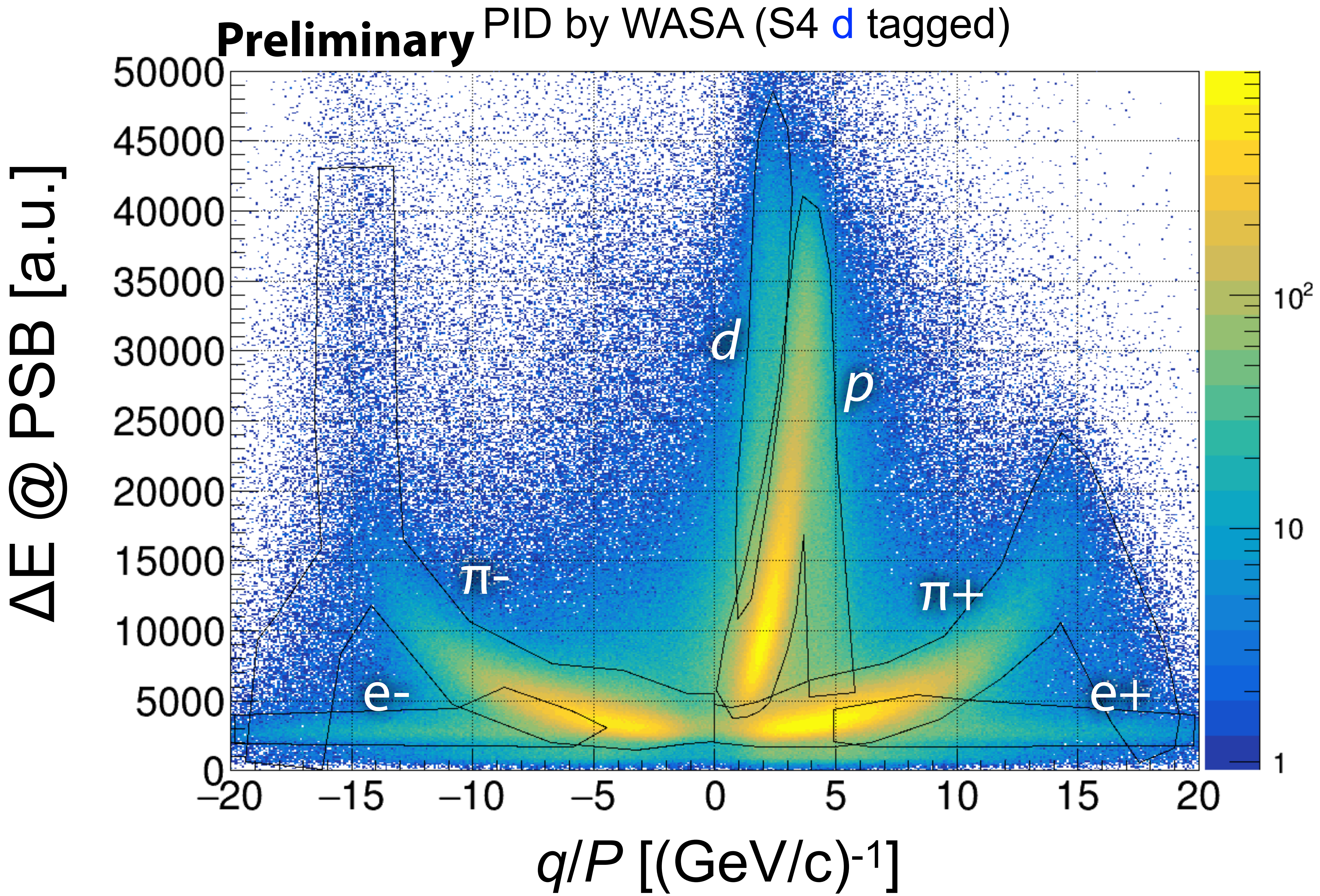
WASA Combined PID with ΔE and *q/p*



R.Sekiya

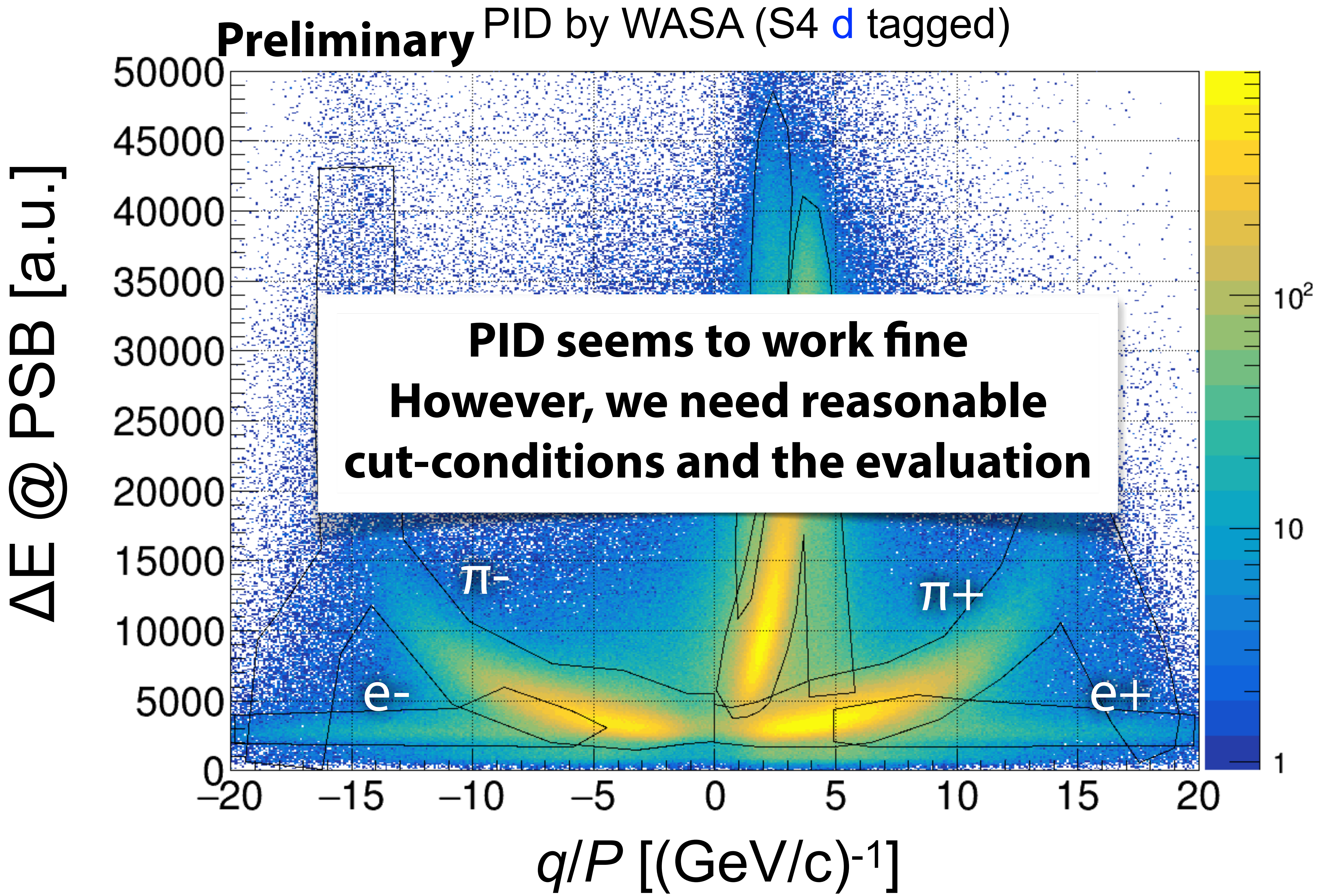
WASA Combined PID with ΔE and *q/p*

Preliminary



R.Sekiya

WASA Combined PID with ΔE and *q/p*



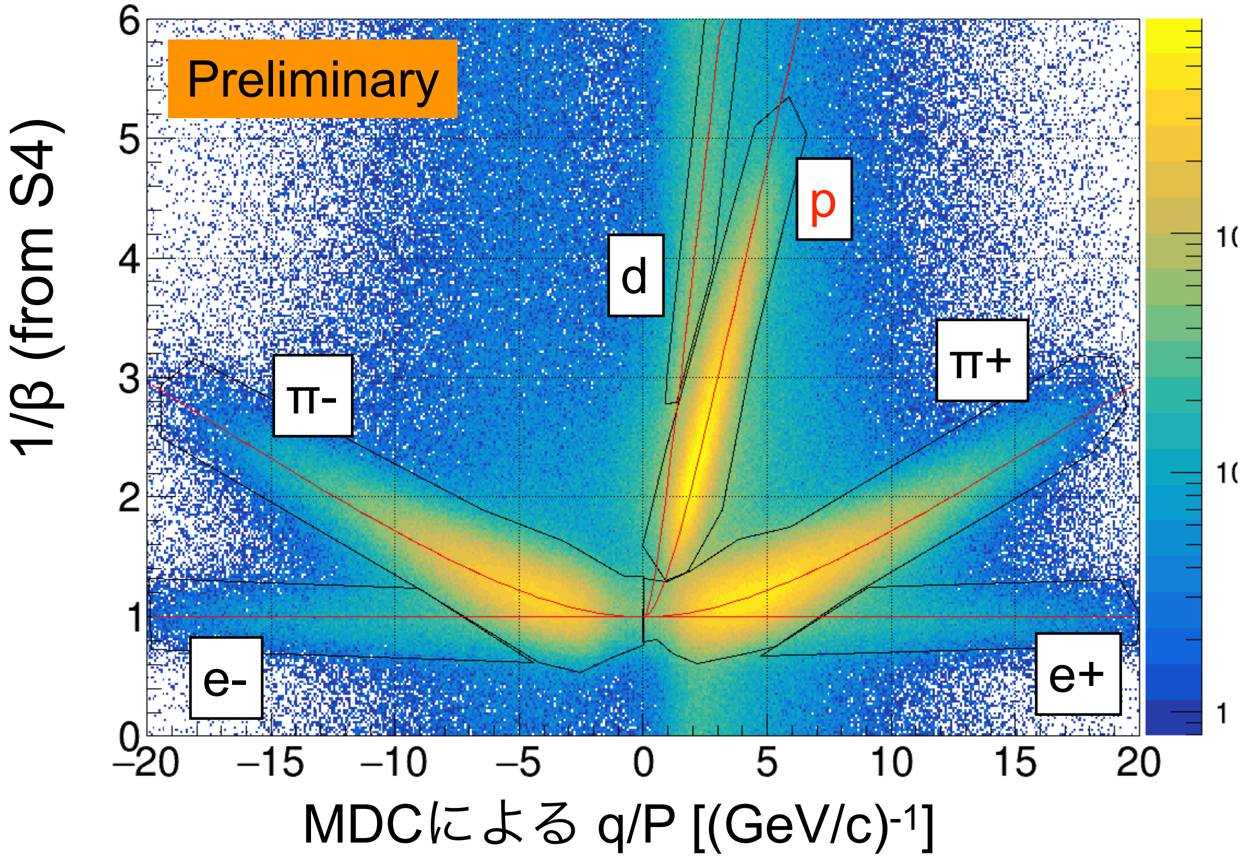
PID seems to work fine
However, we need reasonable cut-conditions and the evaluation

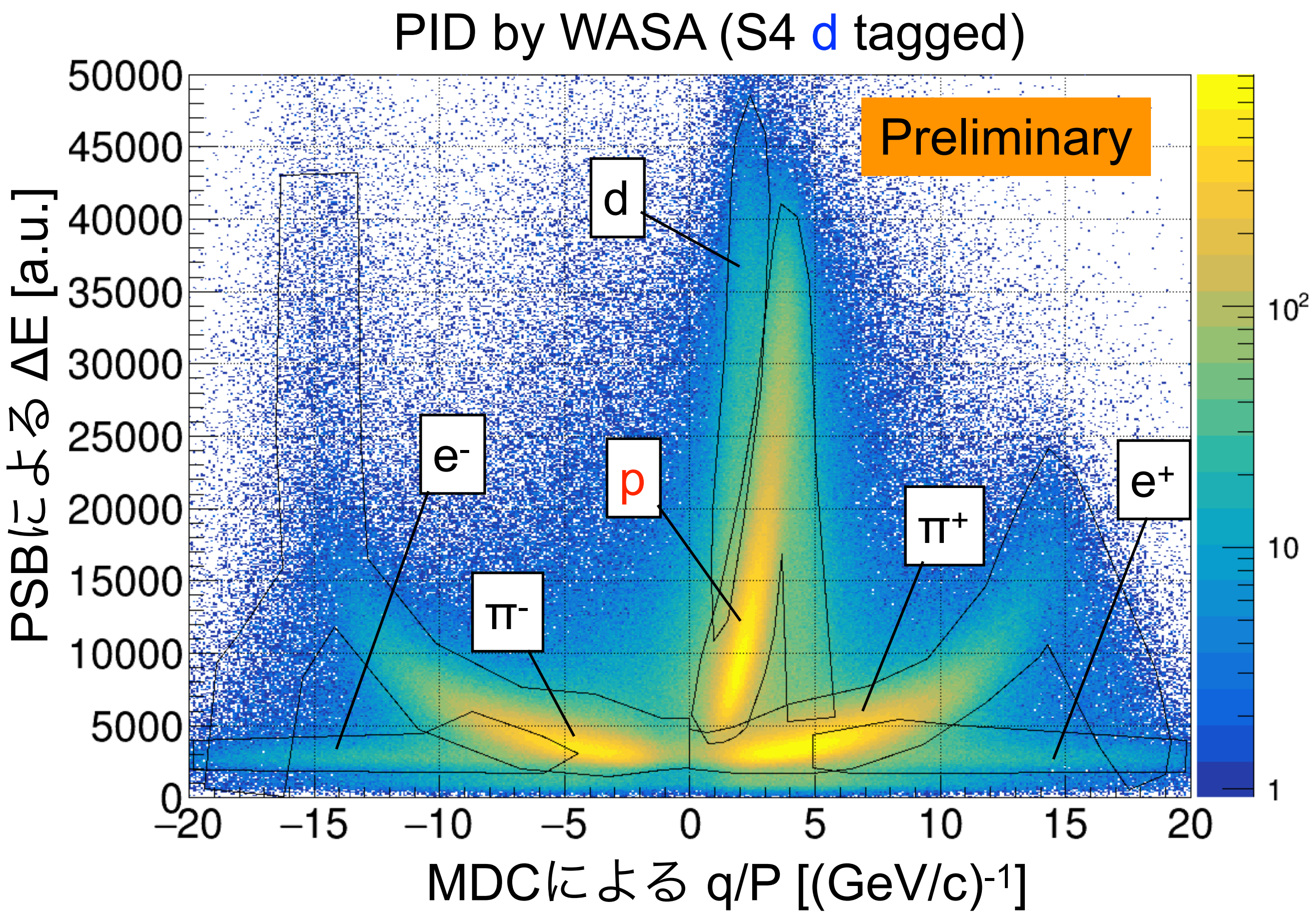
R.Sekiya

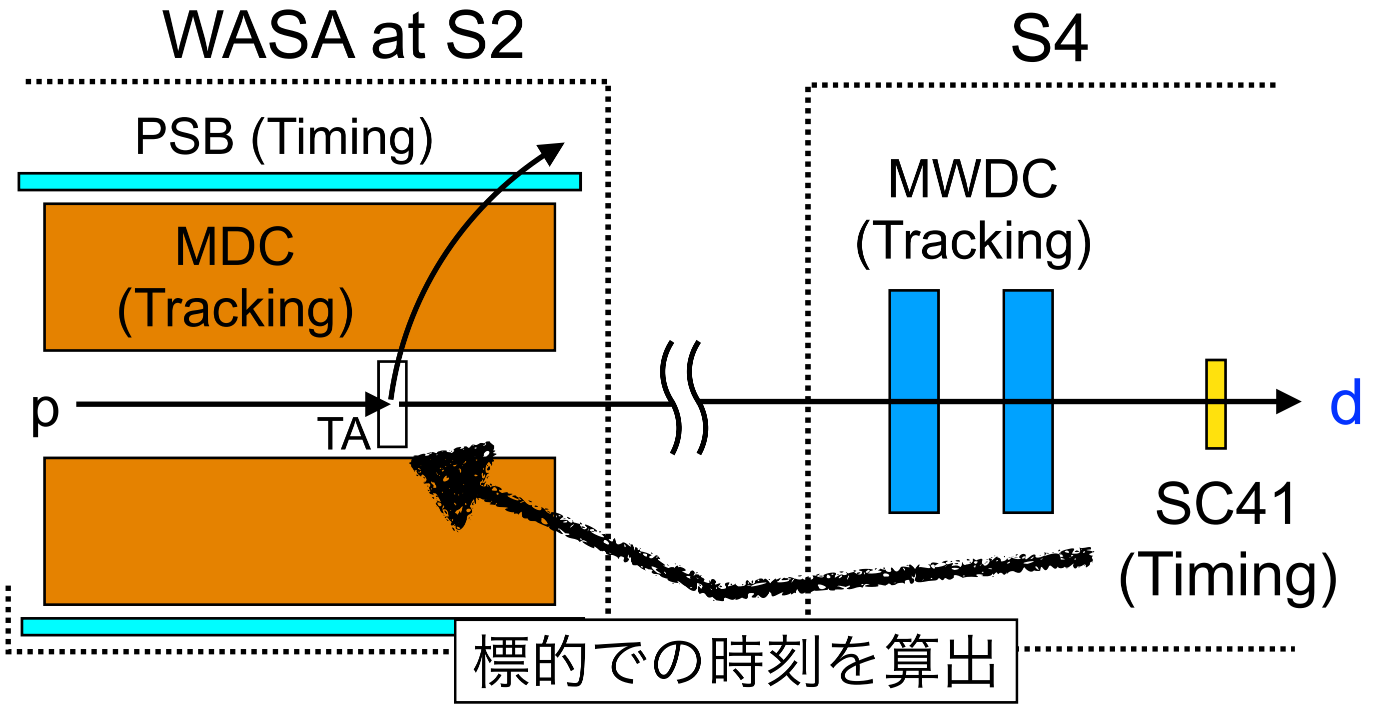
Summary

- η'-mesic nuclei hold a key to understand origin of matter mass and non-trivial structure of QCD vacuum
- We have conducted S437 and S490 experiment to search for eta-prime mesic nuclei and conducted missing-mass spectroscopy of ^{12}C(p,d) reaction
- We combine forward spectrometer FRS and large solid angle detector WASA. By tagging ~1 GeV/*c* proton, we improve S/BG ratio by ~100
- WASA PID works fine with TOF, tracking, and ΔE information. Cut conditions are to be finalized. Semi-exclusive spectra will be ready soon
- We start considerations of next experiments using pion/pbar beams
- For ~1/4 century, I enjoyed working with Iwasaki-san. I truly appreciate the precious days.

WASA-FRS combined PID







標的での時刻を算出

→ βc = TOF(TA-PSB) / L(TA-PSB)

標的起因の p の識別

- P/q (MDC)
- ΔE (PSB)
- β (S4検出器, PSB, MDC)

の情報を駆使してPID