

# Strangeness Physics at J-PARC

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#Institute of Particle and Nuclear Studies, KEK

# Strangeness and Charm Physics at J-PARC

## “What we are discussing to push forward physics at the J-PARC Hadron Experimental Facility”

- From the 3<sup>rd</sup> WS on HEF-ex Project -

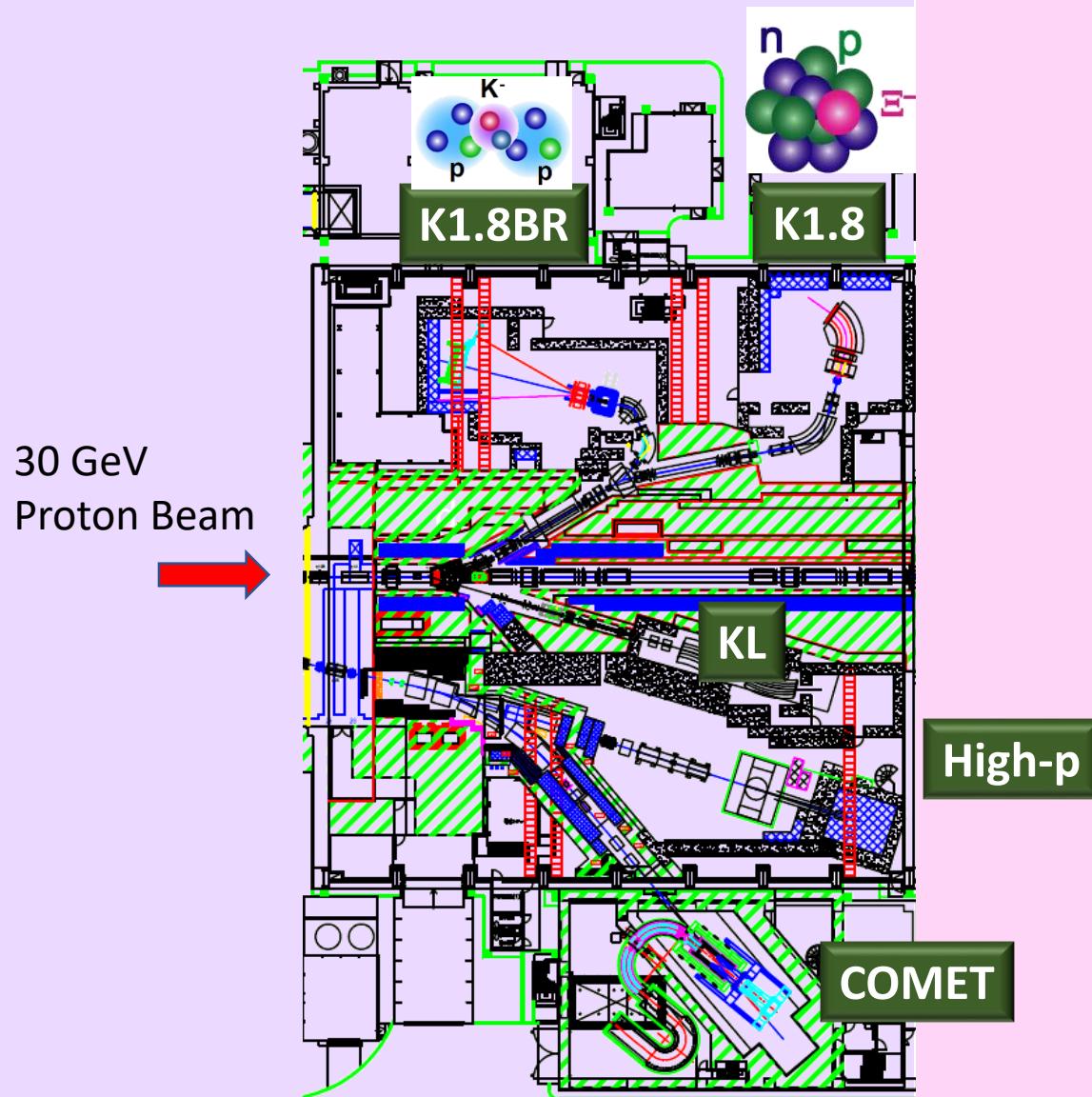
<https://kds.kek.jp/event/44086/>

Hiroyuki NOUMI\*,#

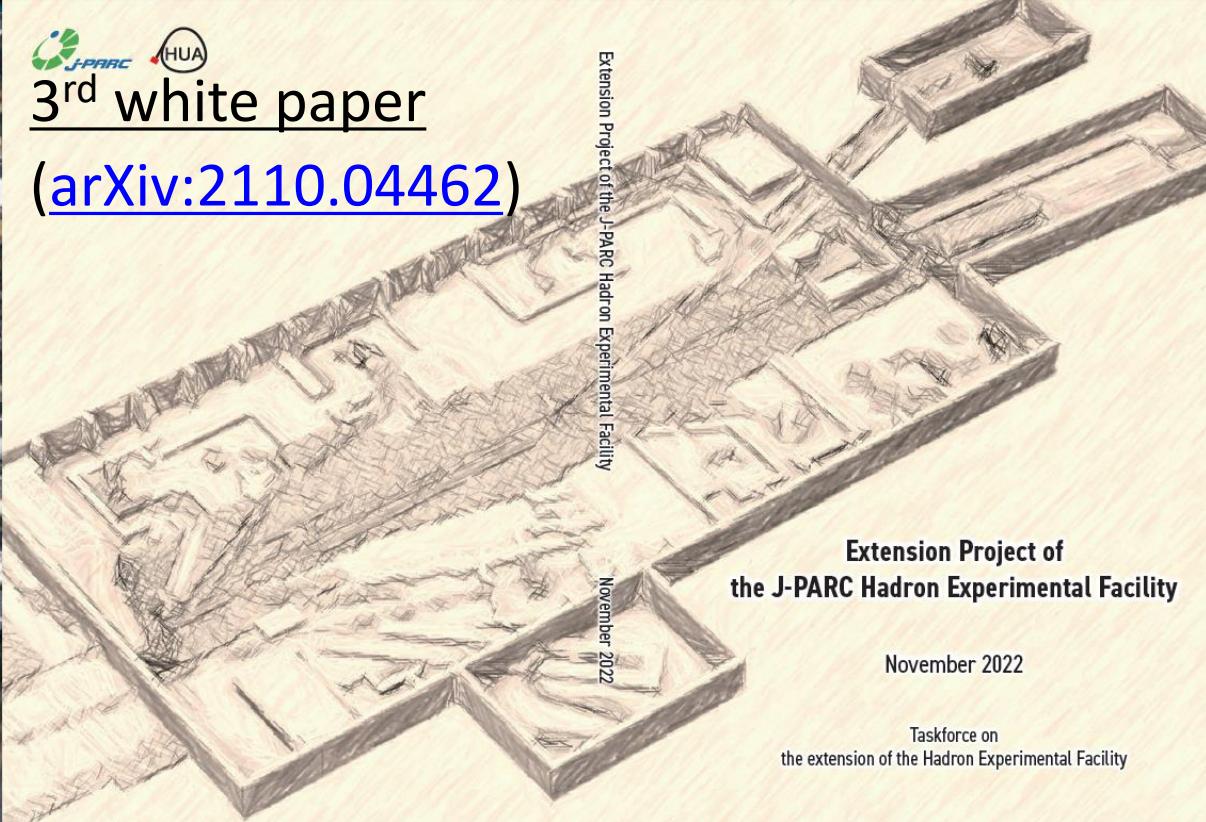
\*Research Center for Nuclear Physics, Osaka University

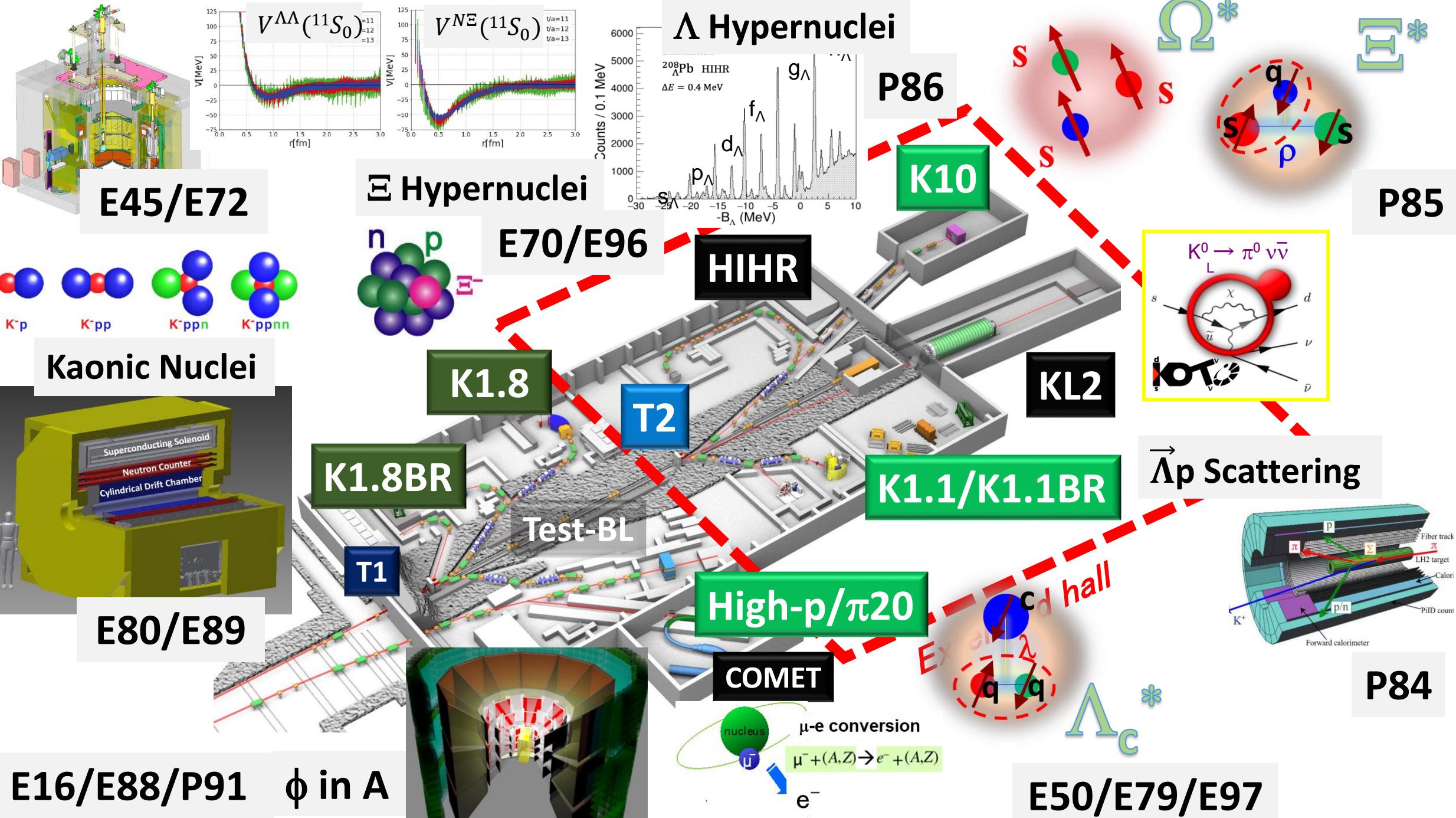
#Institute of Particle and Nuclear Studies, KEK

# Current Hadron Experimental Facility at J-PARC



West





# Origin and Matter Evolution in the Universe

## Matter/Anti-matter Sym. Breaking

- Beyond SM in Flavor Physics

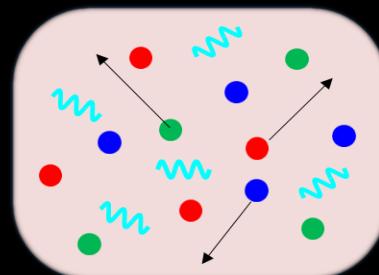
## High Density Matter: NS

- Strangeness Nuclear Physics

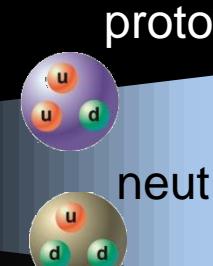
### Formation of Hadrons

- Spectroscopy of Hadrons

Big Bang

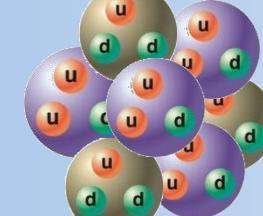


Quark (Gluon)



proton

neutron

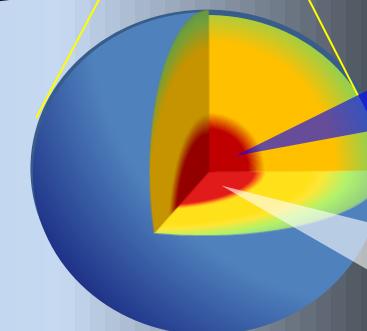


Nucleus

$10^{-15}$  m

$10^{-14}$  m

$2 \times 10^{+8}$  t/cc

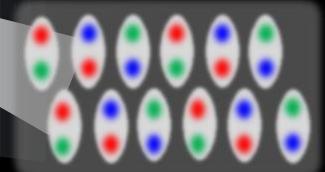


Neutron Star

$10^{+4}$  m



Hyperon Matter?



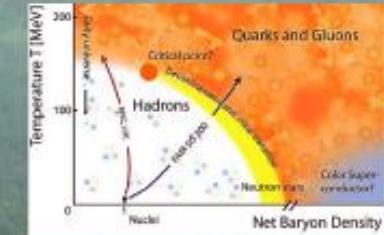
Quark Matter?

$\sim 20 \times 10^{+8}$  t/cc

6

$$\mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s,c,b} \bar{q} ( i \gamma_\mu D^\mu - m_q ) q$$

$$-\frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$



Properties of strongly interacting matter?

Formation of hadronic matter?

Underlying symmetries

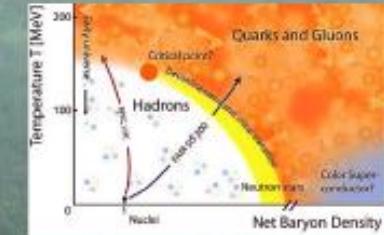
Degrees of freedom: from quarks/gluons to baryons/mesons?

Origin of mass?



$$\mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s,c,b} \bar{q} ( i \gamma_\mu D^\mu - m_q ) q$$

$$- \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$



Properties of strongly interacting matter?

Formation of hadronic matter?

Underlying symmetries

Degrees of freedom: from quarks/gluons to baryons/mesons?

Origin of mass?



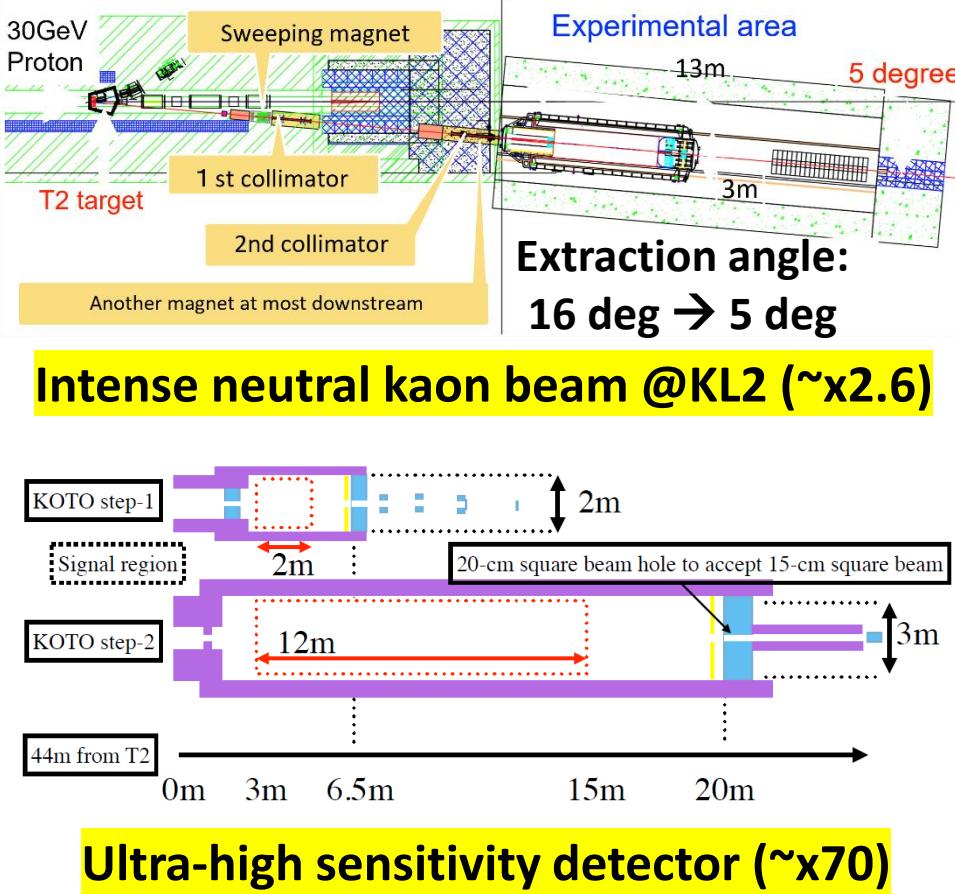
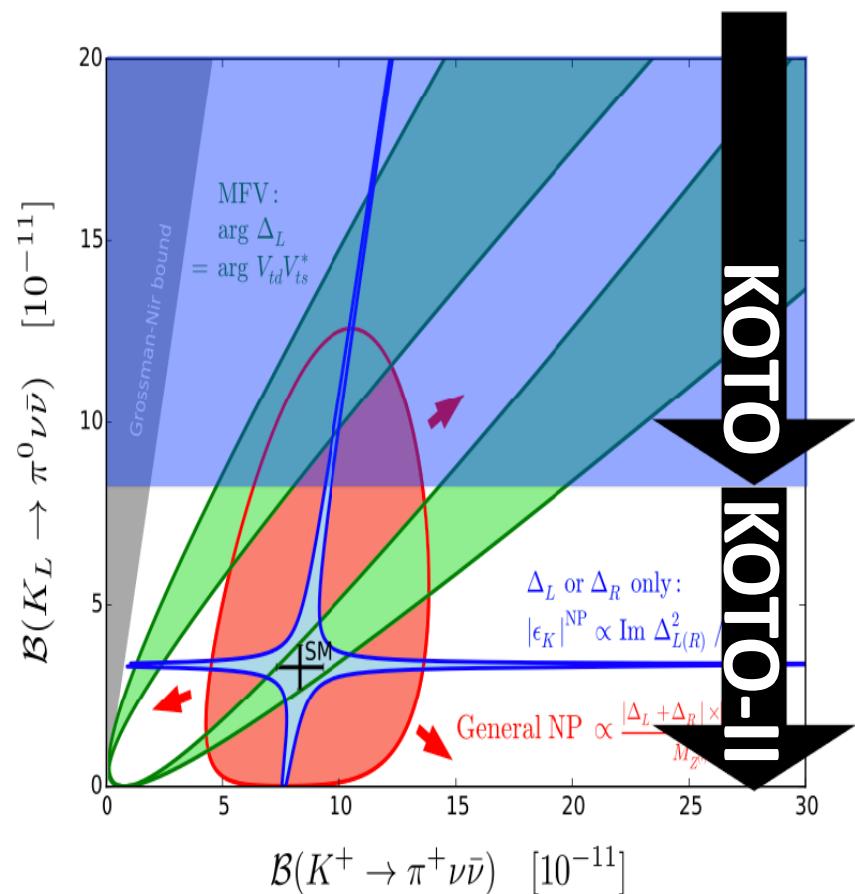
# Flavor Physics: New Physics Search at KOTO Step-2<sup>10</sup>

Is there new physics beyond the Standard Model?

Rare kaon decay:  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

One of the best probes for new physics search

- Directly break CP symmetry
- Suppressed in the SM  $\rightarrow$  Branching ratio  $\sim 3 \times 10^{-11}$
- Small theoretical uncertainties ( $\sim 2\%$ )



New physics search with  
world's highest sensitivity  
more than 100 times

**~40 evts @SM**

- Discover the  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  signal with  $5\sigma$
  - Measure the branching ratio with 30% accuracy
- Indicate new physics, if deviation from the SM  $> 40\%$

# $\mu$ -e conversion @ COMET

- Phase-I

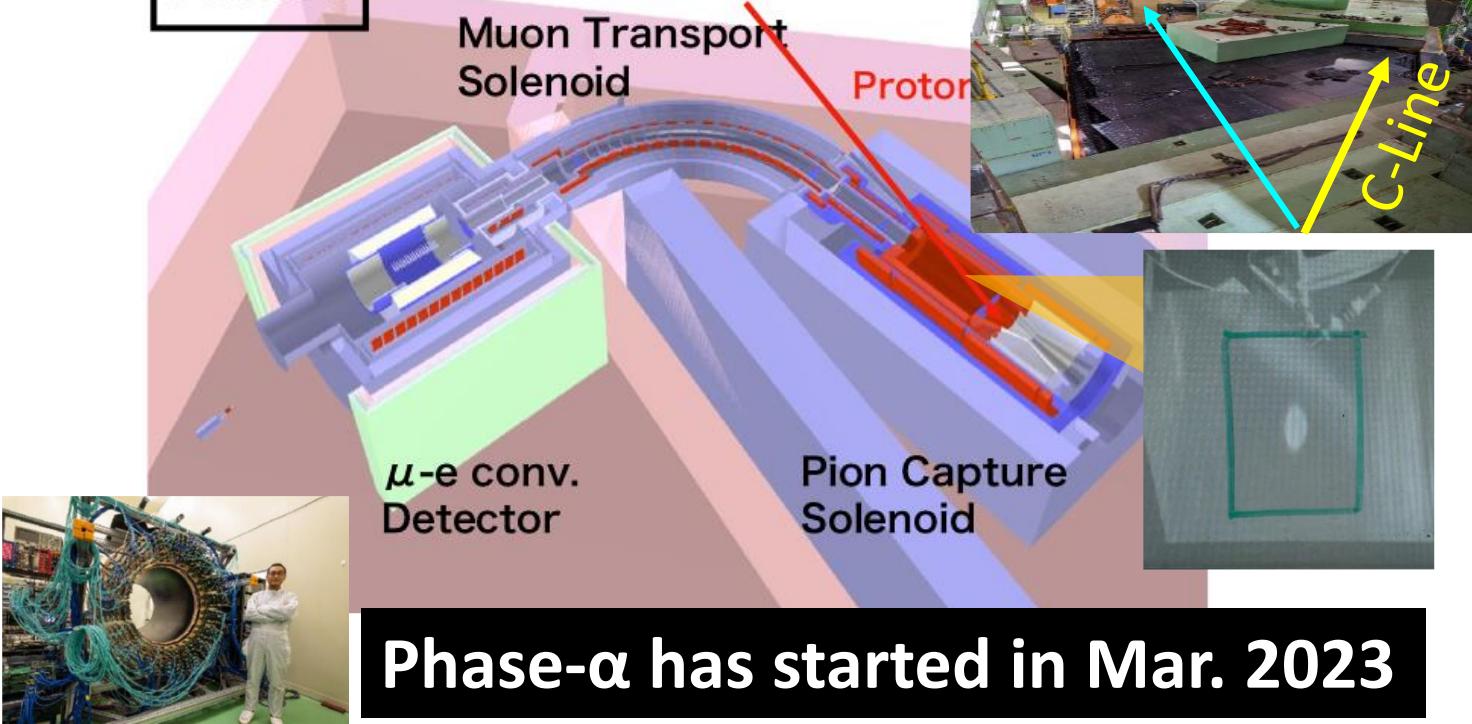
- 3.2 kW bunched SX beam x 150 days
- sensitivity  $<10^{-14}$  (better than x100)
- Ready in FY2023



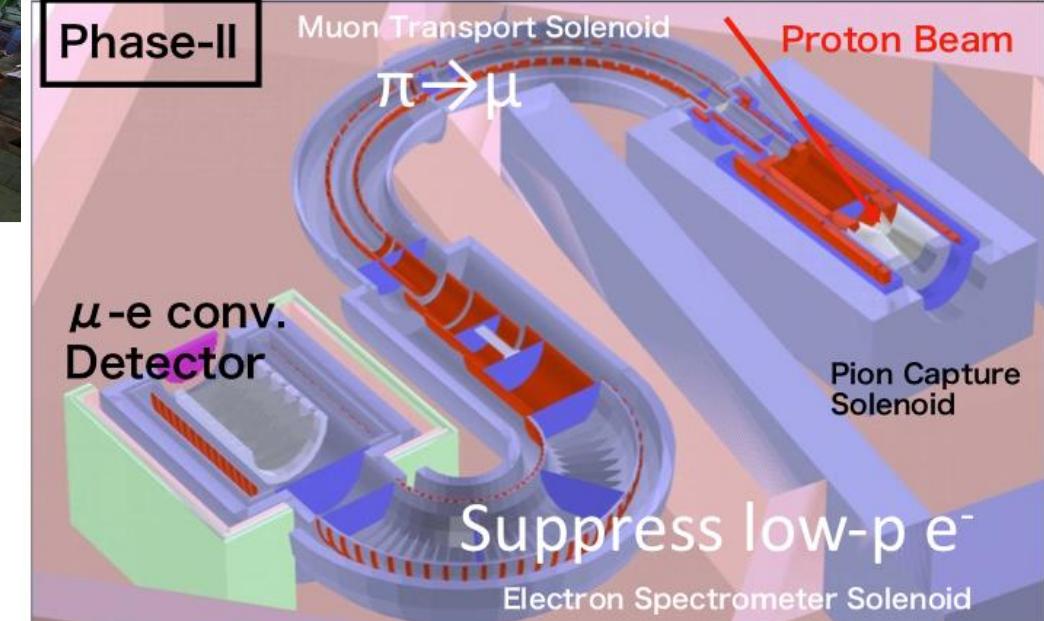
- Phase-II

- 56 kW
- sensitivity  $<10^{-16}$
- around FY2030~

**Phase-I**



**Phase-II**



Phase- $\alpha$  has started in Mar. 2023

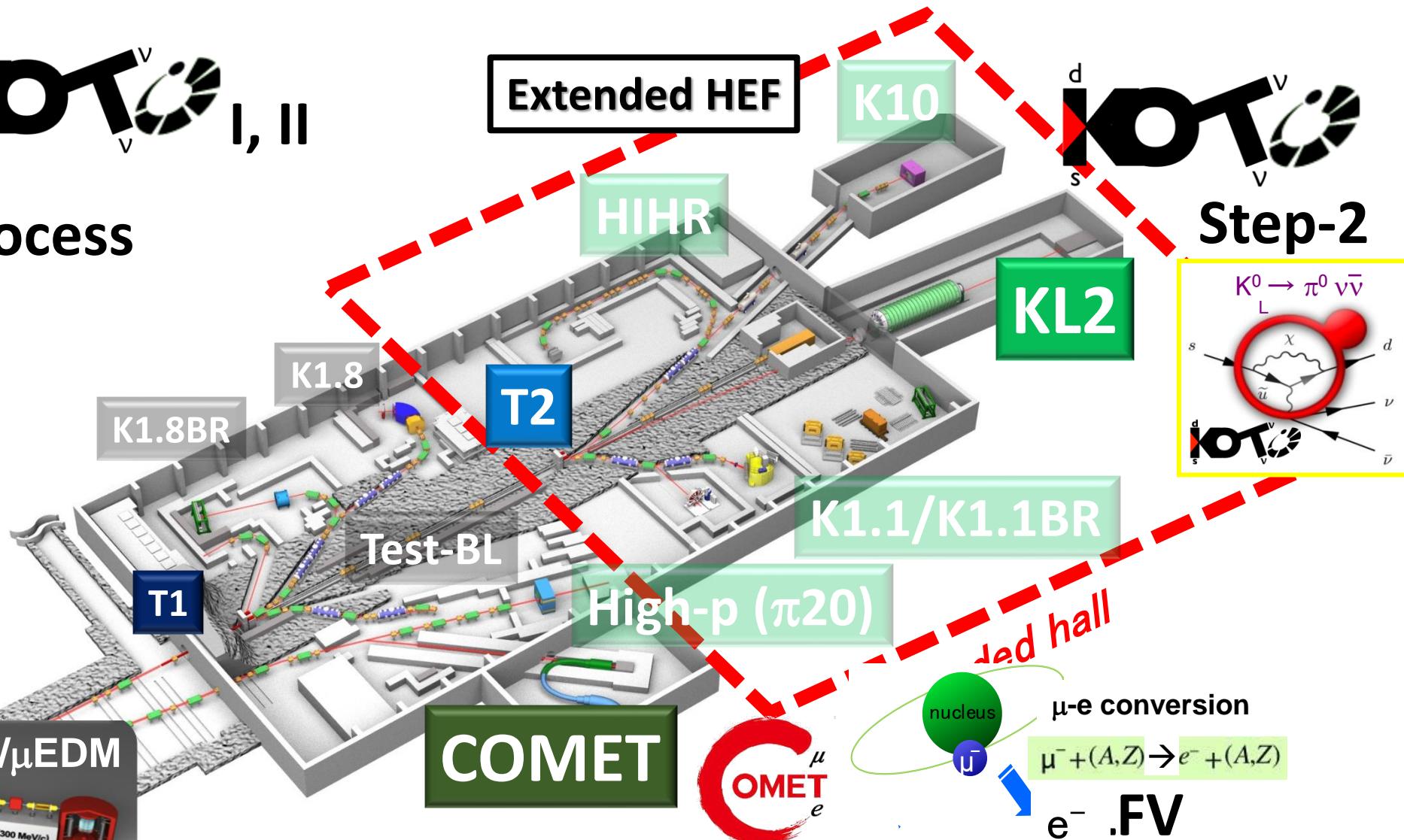
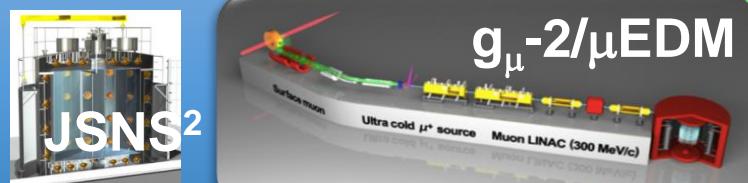
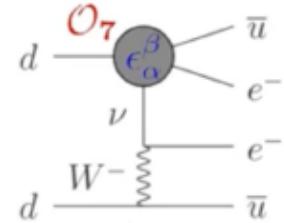
# New physics beyond SM in Rare Process

## In Different Flavors



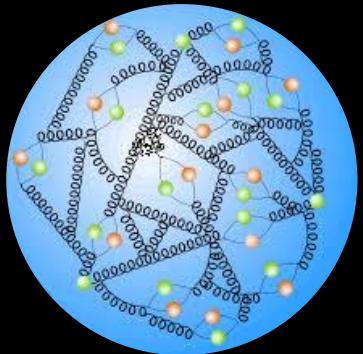
Theoretically Clean, Experimentally Tough

## In Different Process LFV/LNV



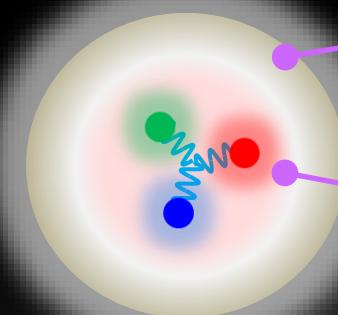
# How does QCD build hadrons?

High  $E$   
perturbative

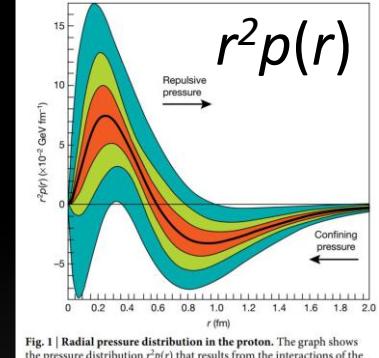


$$\alpha_s = \infty \text{ at } \Lambda_{\text{QCD}}$$

Low  $E$   
non-perturbative

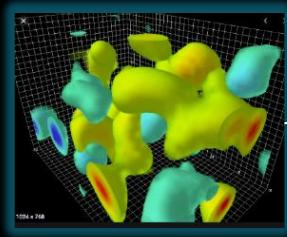


Meson Cloud  
“Constituent” Quark (CQ)

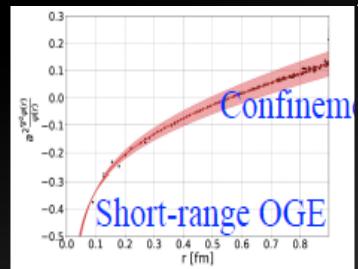
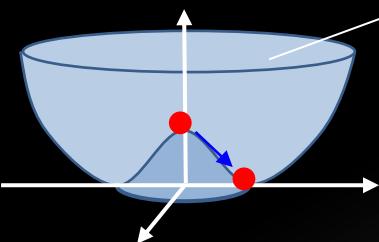


Nature 557  
396 (2018)

Instanton  
(LQCD demo.  
by D. Leinweber)



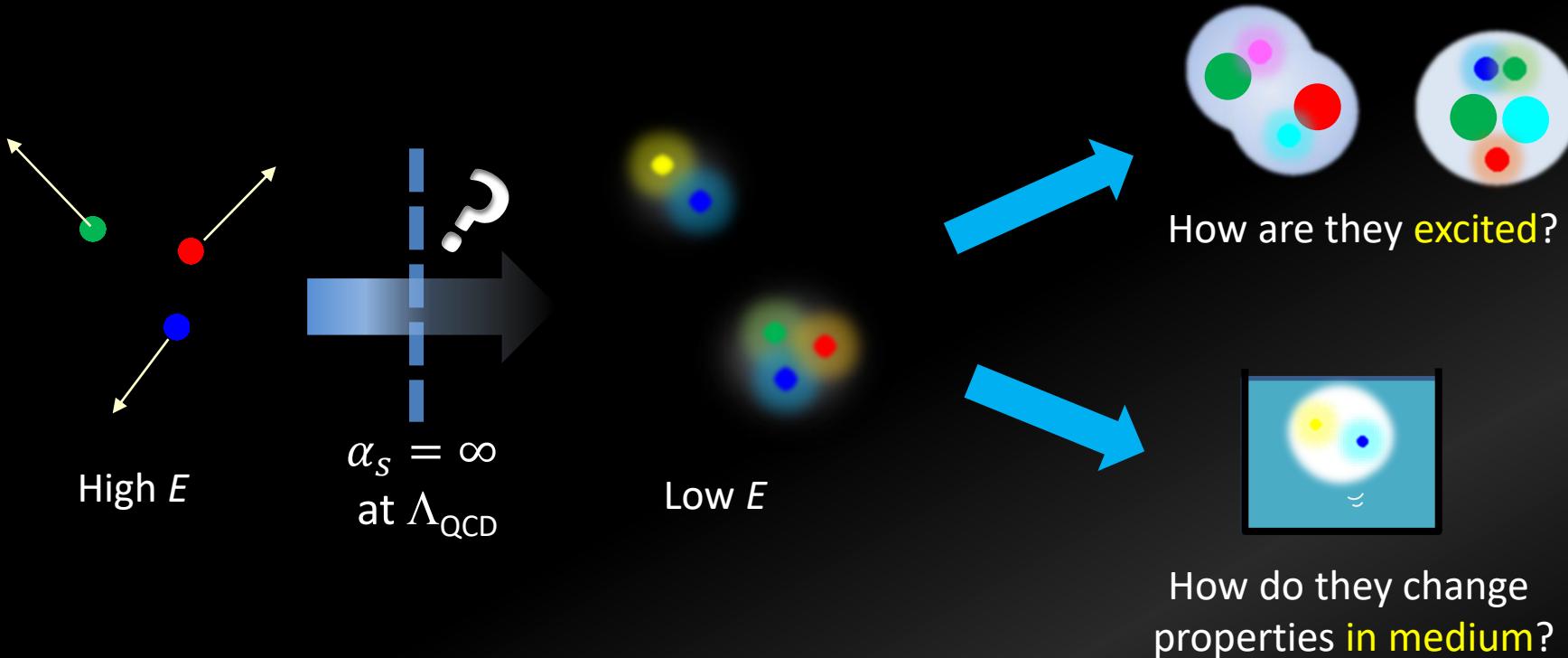
- Non-trivial vacuum
- Spontaneous Breaking of Chiral Symmetry
- Confinement



Eff. DoF dynamically emerge:  
“Massive” CQ  
NG bosons (pion, ...)

*Dynamics of CQ reflects  
the nature of QCD in Low E*

# Spectroscopy of Hadrons

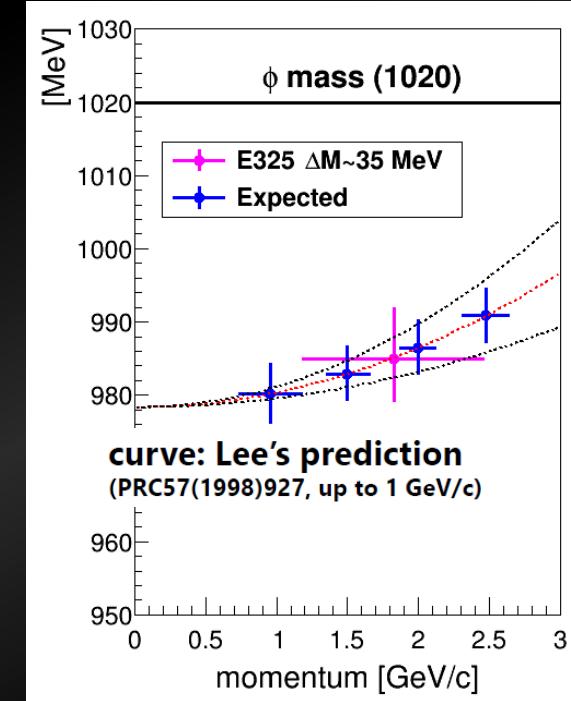
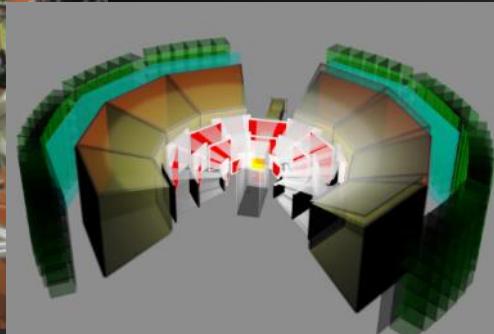
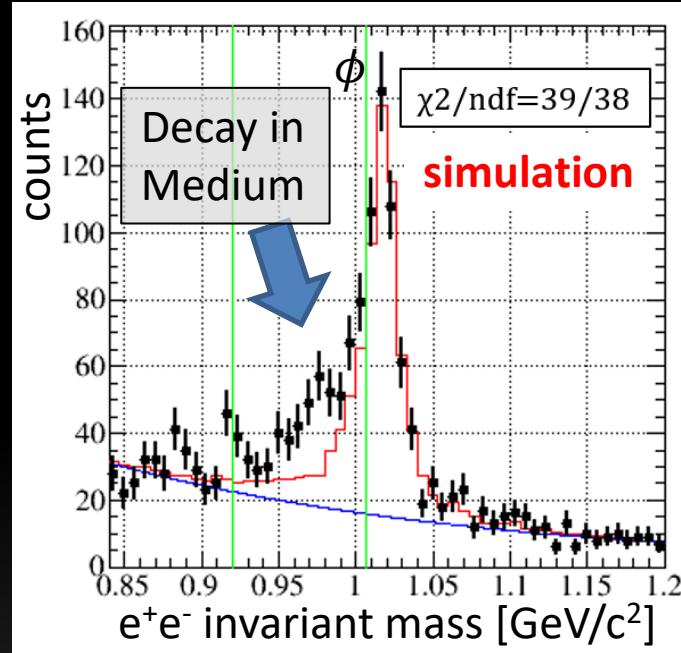
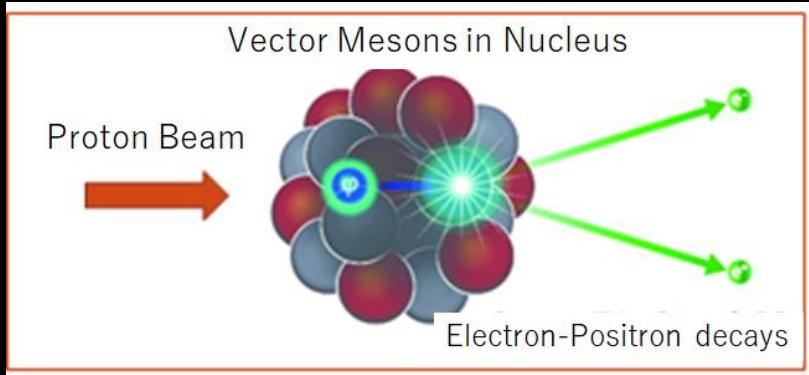


- How does QCD form hadrons?
  - Mechanism of dynamical mass generation
  - Dynamics of effective DoF in Hadrons

# Meson in Nuclear Medium

## Spectral changes of vector mesons in nuclei

- $pA \rightarrow \rho X, \omega X, \phi X \rightarrow e^+ e^- X$  (J-PARC E16)



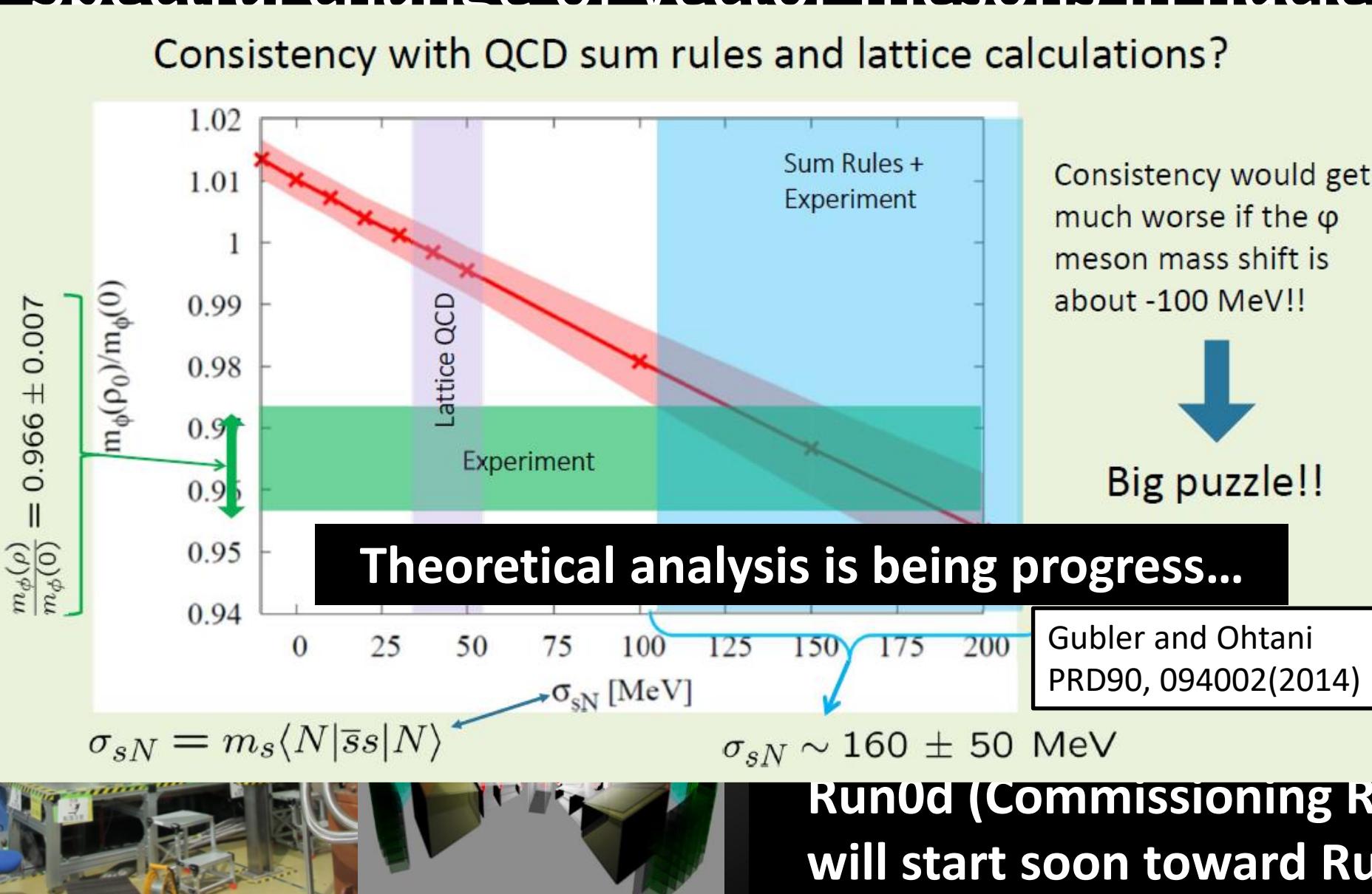
- establish the spectral change of  $\phi$  meson
- $\langle \bar{s}s \rangle_\rho$ , dispersion relation

Run0d (Commissioning Run)  
will start soon toward Run1.

# Meson in Nuclear Medium

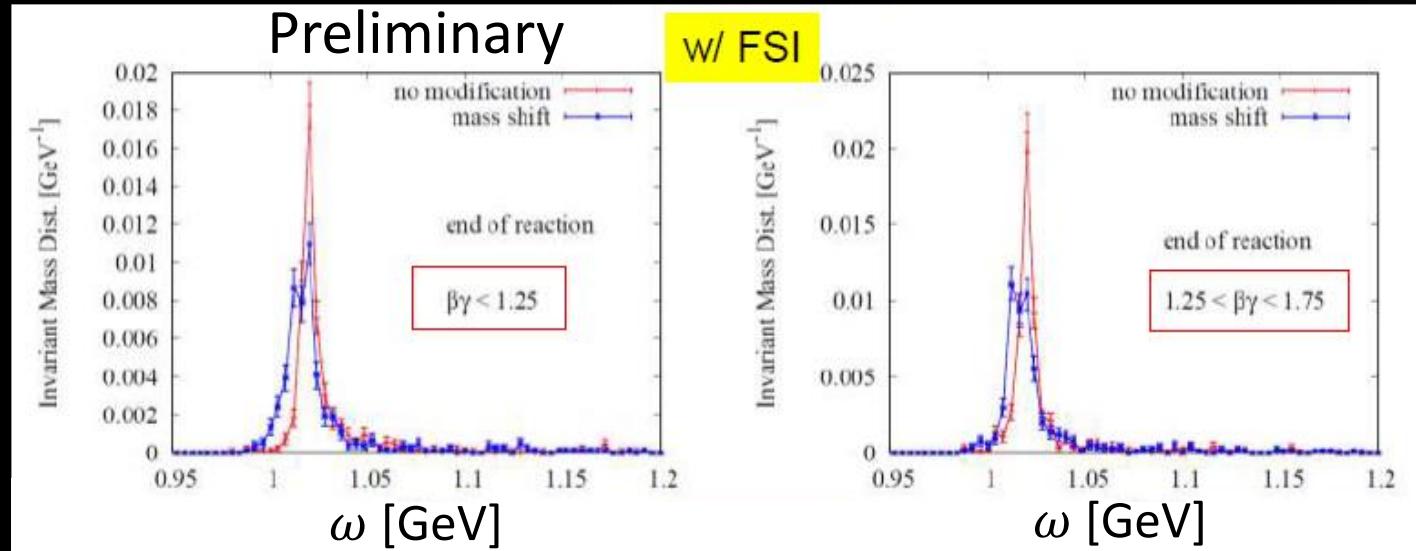
## Spectral change of vector mesons in nuclei

- $pA$

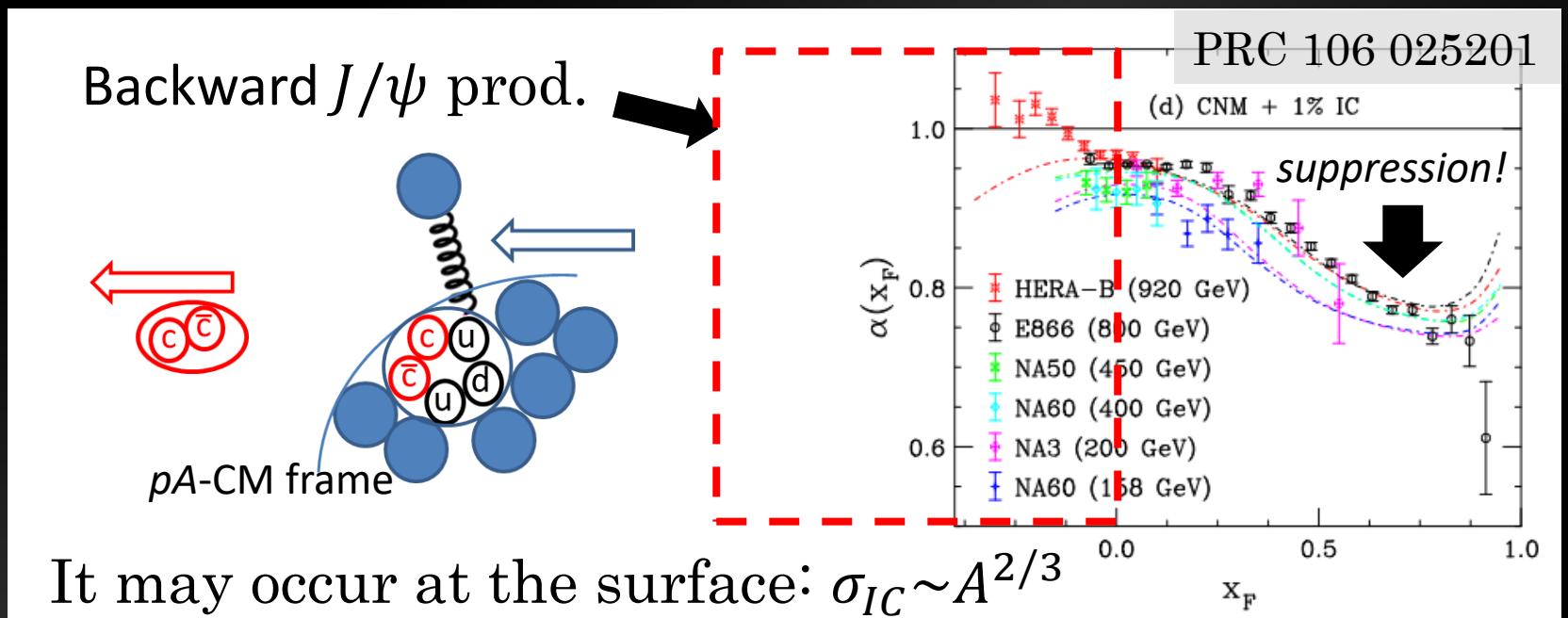


# Meson in Nuclear Medium -- Related Programs

- $pA \rightarrow \phi X$   
 $\rightarrow K^+ K^- X$   
(J-PARC E88)  
– High Statistics



- $pA \rightarrow J/\psi X$   
(J-PARC P91)  
– Intrinsic Charm (IC)  
in a Nucleon  
 $|uud\bar{c}\bar{c}\rangle$

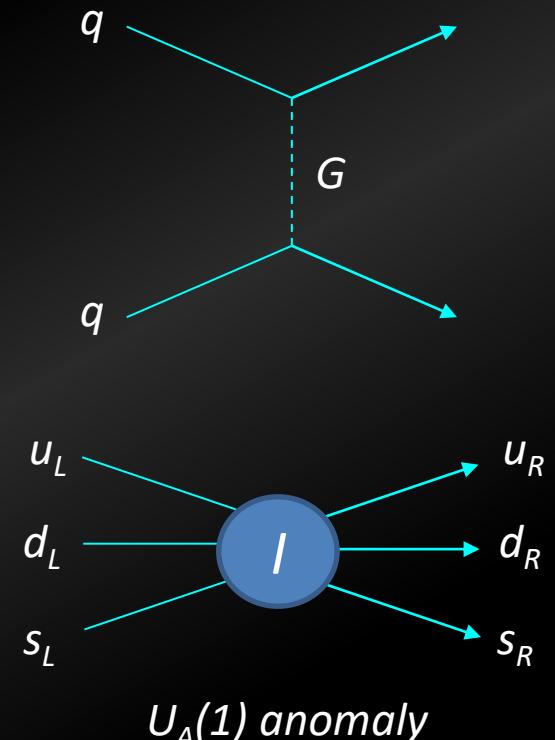
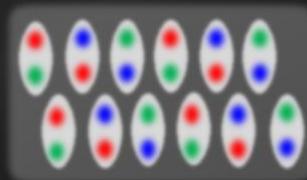


# Spectroscopy of Baryons

## to reveal dynamics of Constituent Quarks

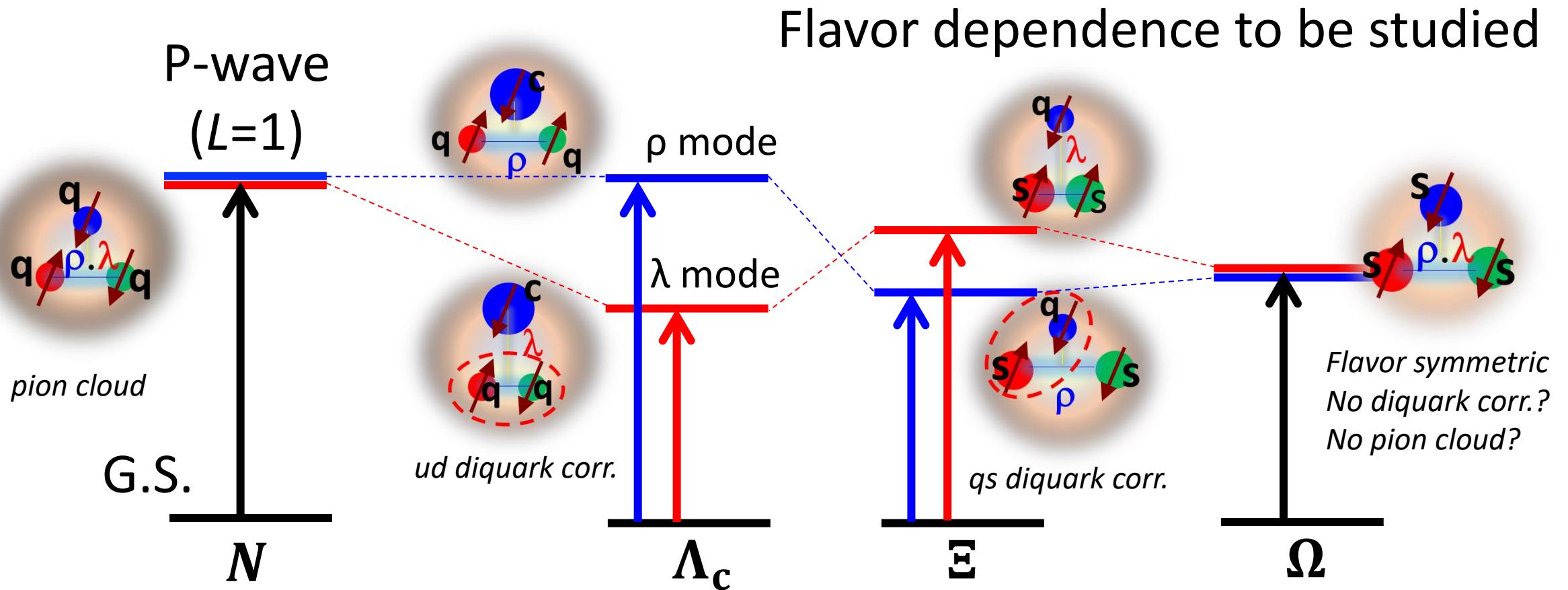
$$H = K + V^{Conf} + \underbrace{V^{Coul} + V^{SS} + V^{LS}}_{\text{"short-range" int.}} + \dots$$

- Diquarks (DQs)
  - Color Magnetic Interaction (*OGE*)
    - Origin of the SS and LS forces is an open question  
*i.e.* Instanton Induced Interaction (*III, KMT int.*)
  - may form “BE condensate” in high-density matter
- Hadronic Molecule
  - Behavior of QCD in a long-range region

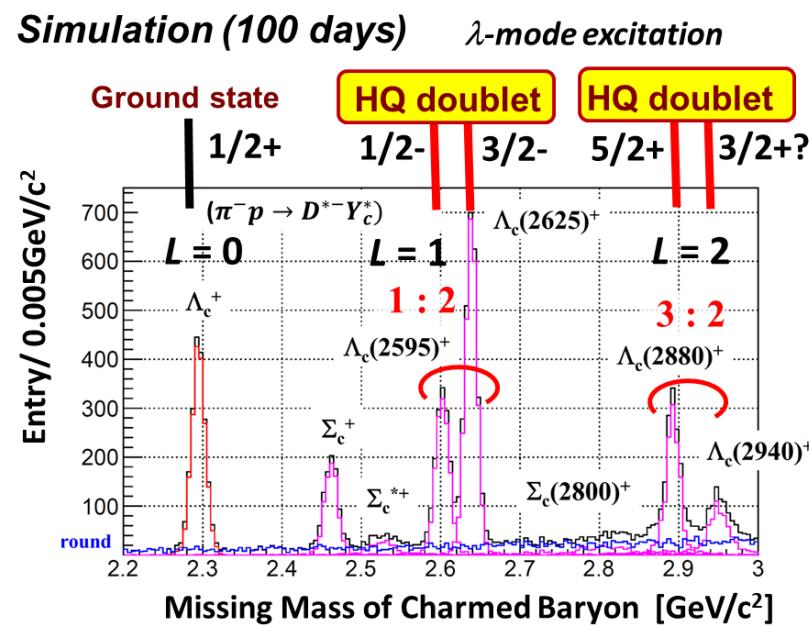
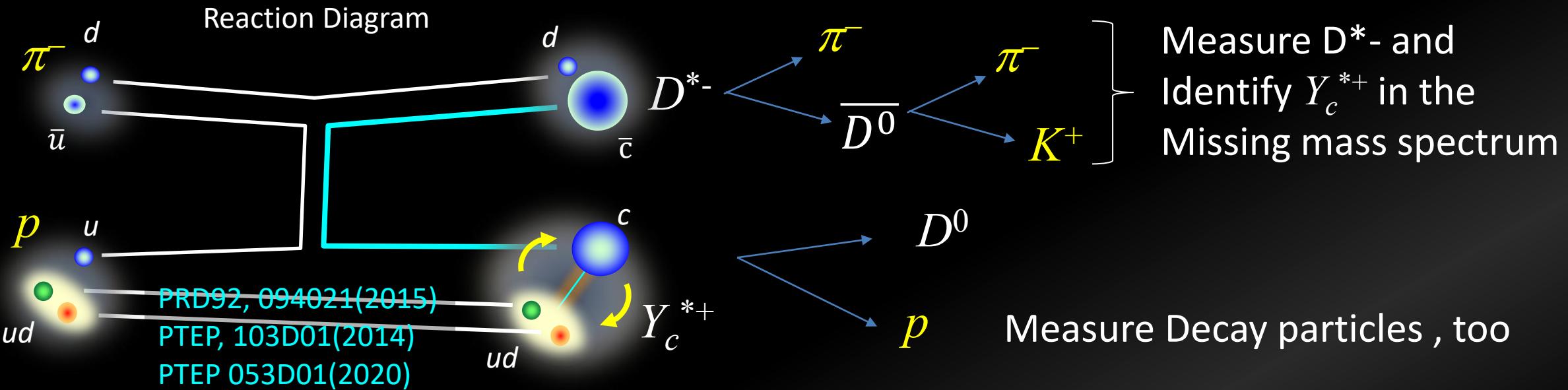


# Spectroscopy of Baryons at p20/K10 Charm and Multi-strange Baryons

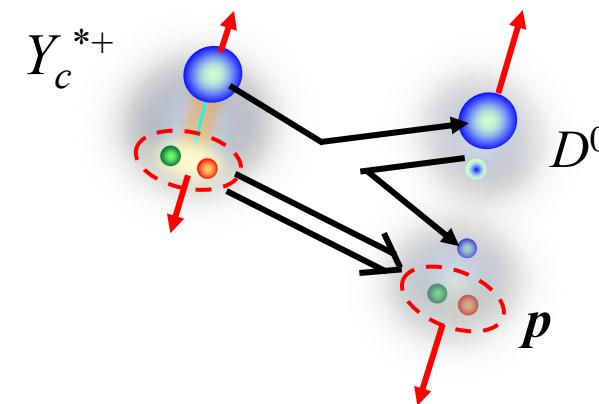
※ Disentangle motions of a quark pair (diquark) by introducing different flavors



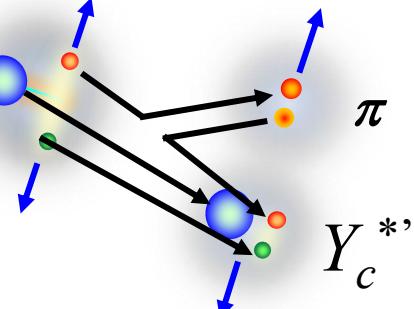
# Production and Decay of Charmed Baryons (E50)



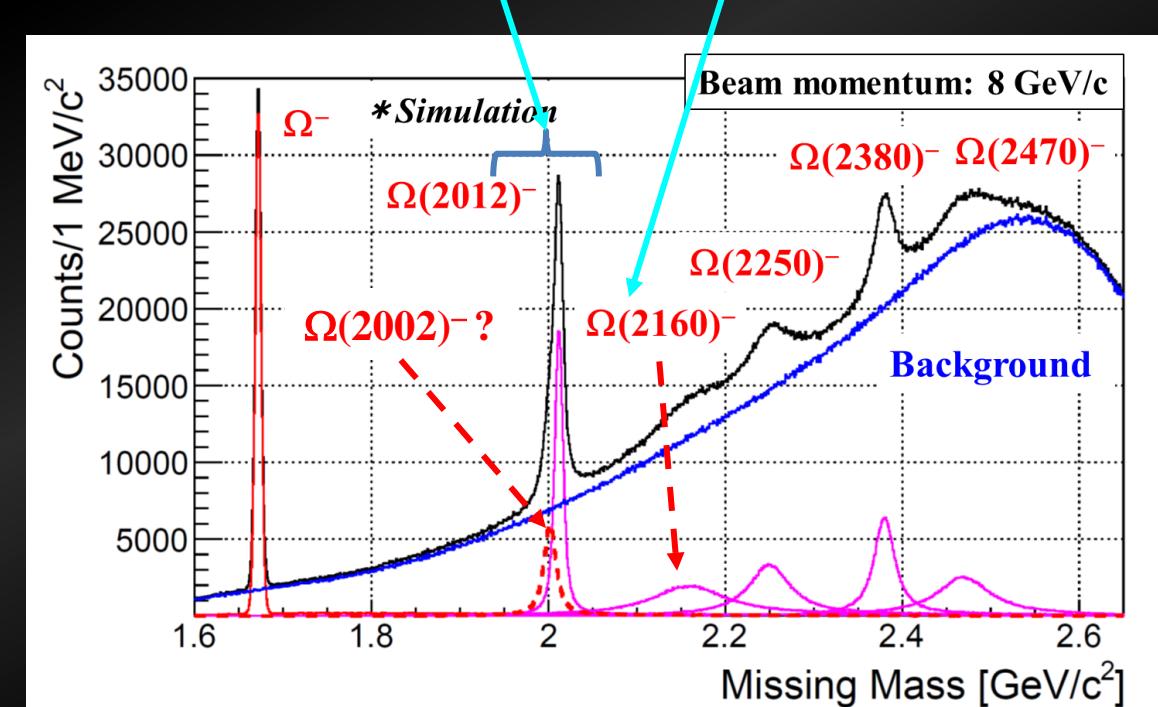
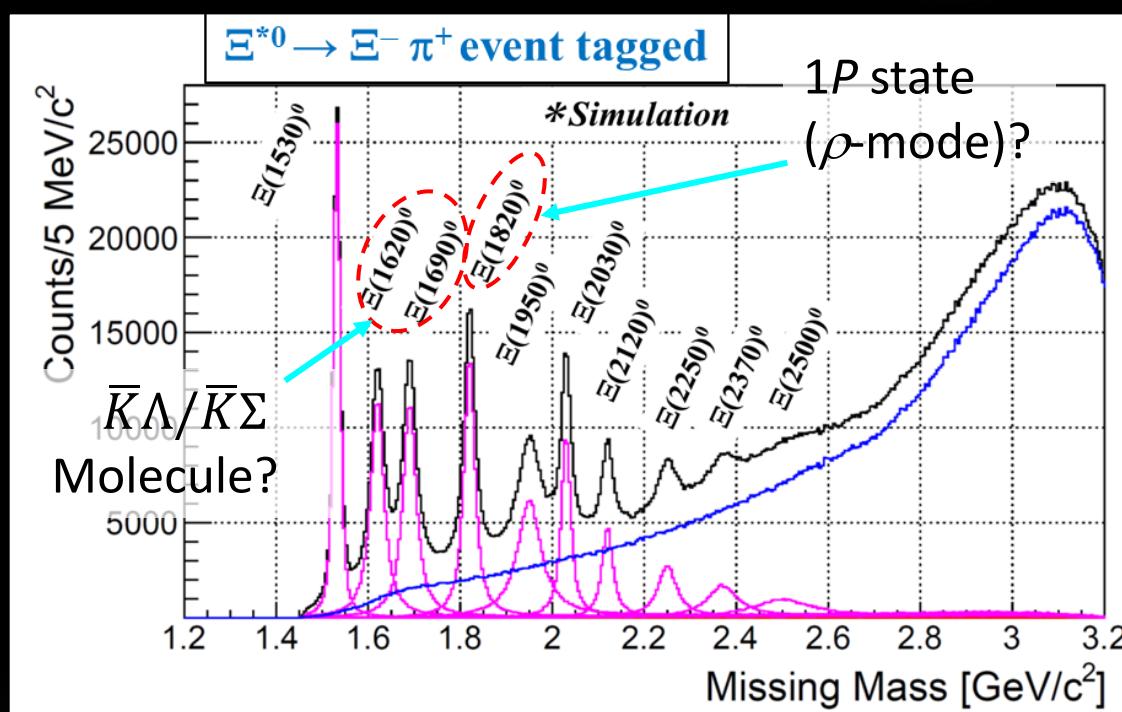
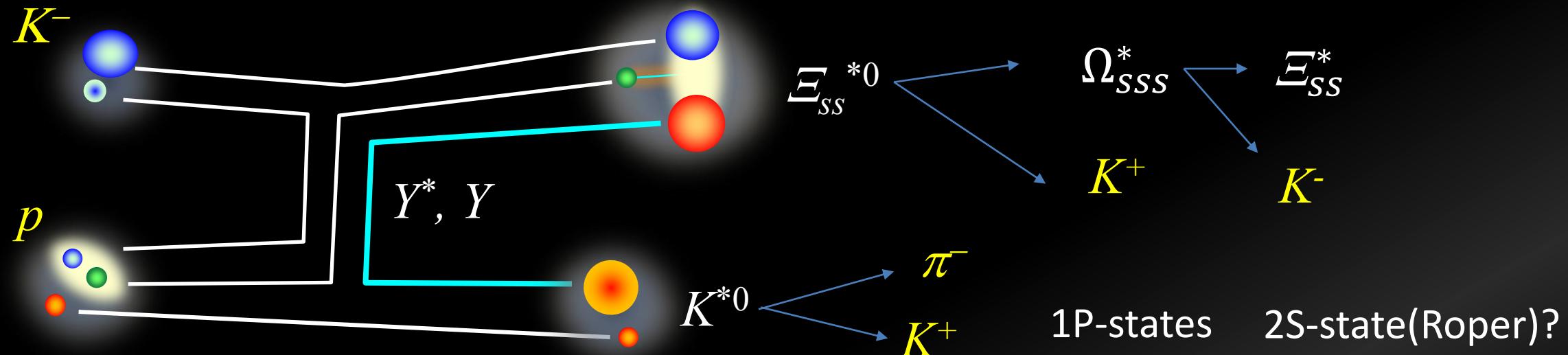
**Decay pattern of  $\lambda$  mode**



**Decay pattern of  $\rho$ -mode**



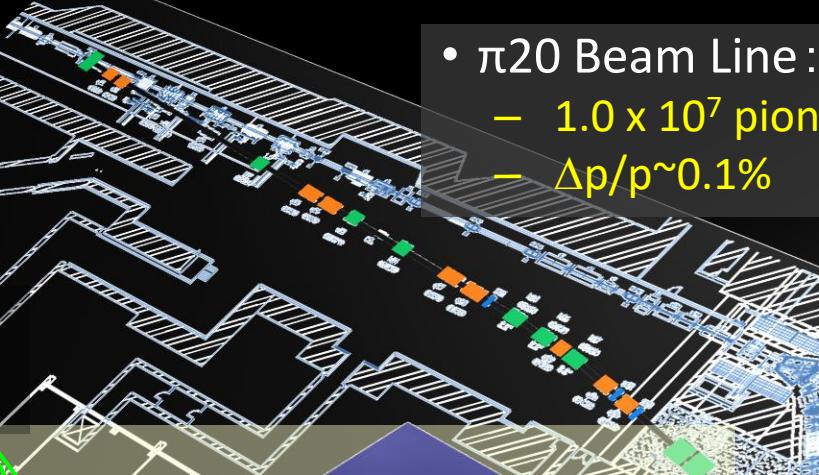
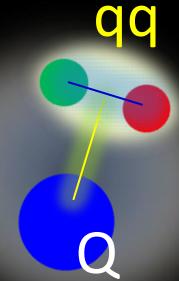
# Production and Decay of Multi-strange Baryons (E97/P85)



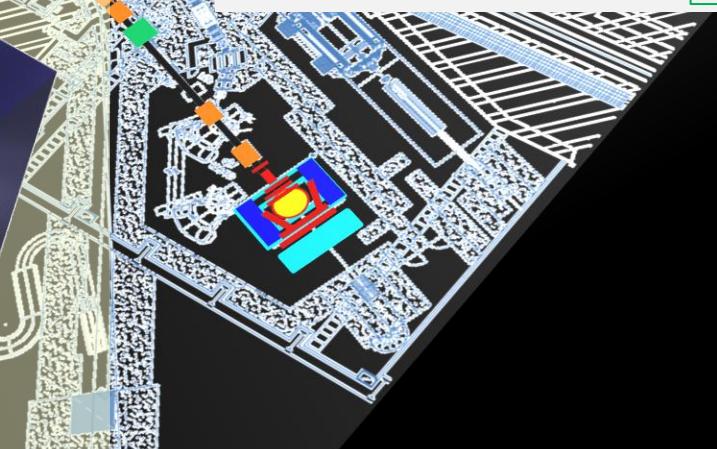
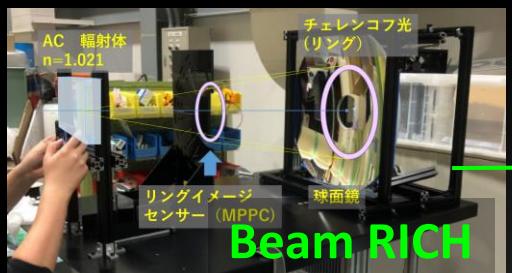
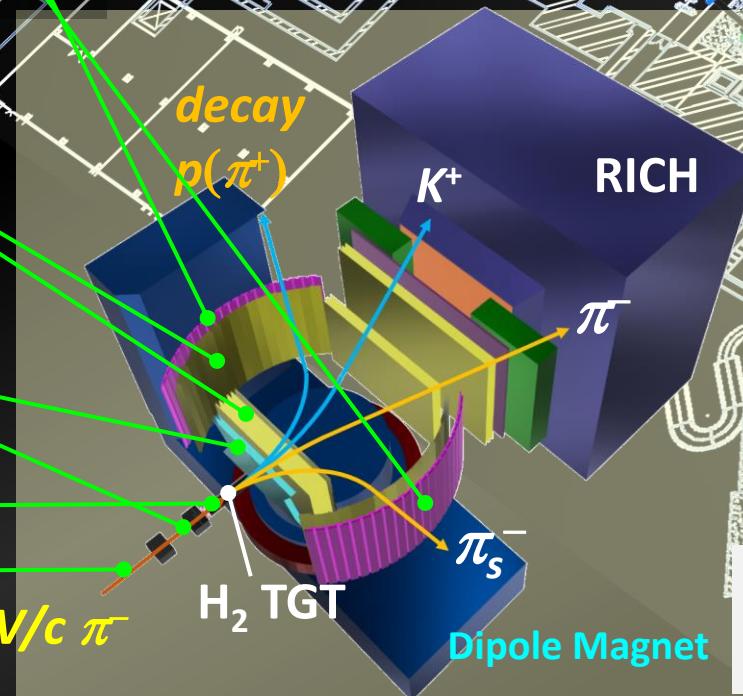
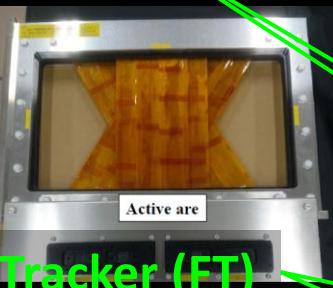
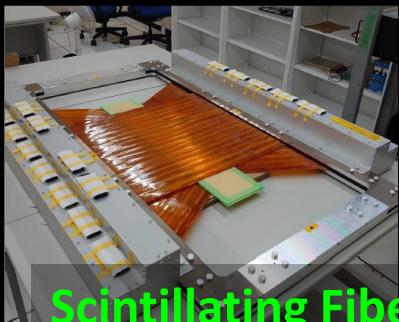
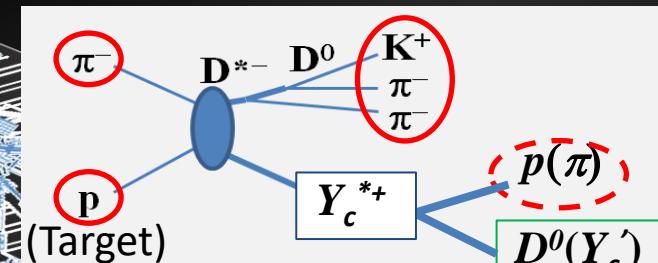
# Charm Baryon Spectroscopy at High-p ( $\pi$ 20)

Diquark [qq]: an effective degree of freedom to describe hadrons

- [qq] would be singled out by Introducing a Heavy Quark
- Characteristic level structure, production rate, and decay branching ratio



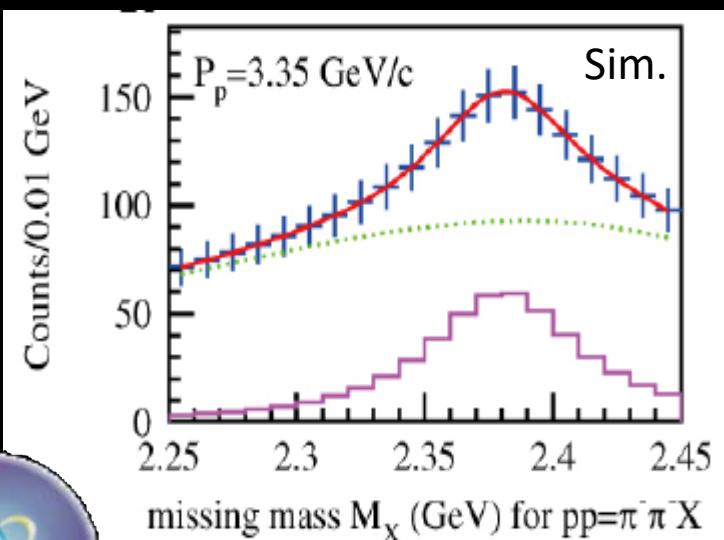
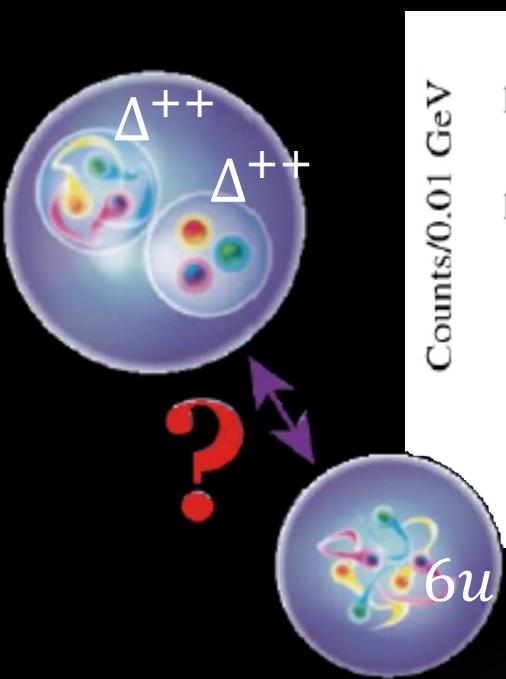
- $\pi$ 20 Beam Line :
  - $1.0 \times 10^7$  pions/sec @ 20GeV/c
  - $\Delta p/p \sim 0.1\%$



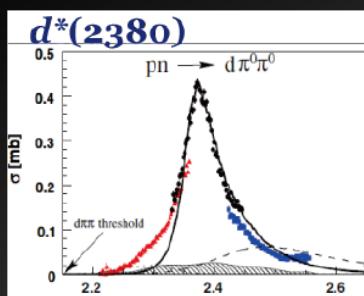
Charm Baryon Spectrometer

# Spectroscopy of Baryons at $\pi^+ p$ $D_{30}$ Dibaryon and $P_c$ -analog $N^*$ state

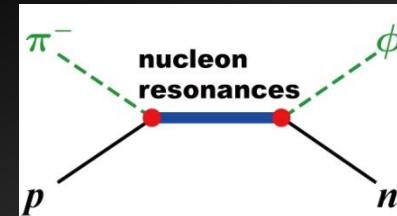
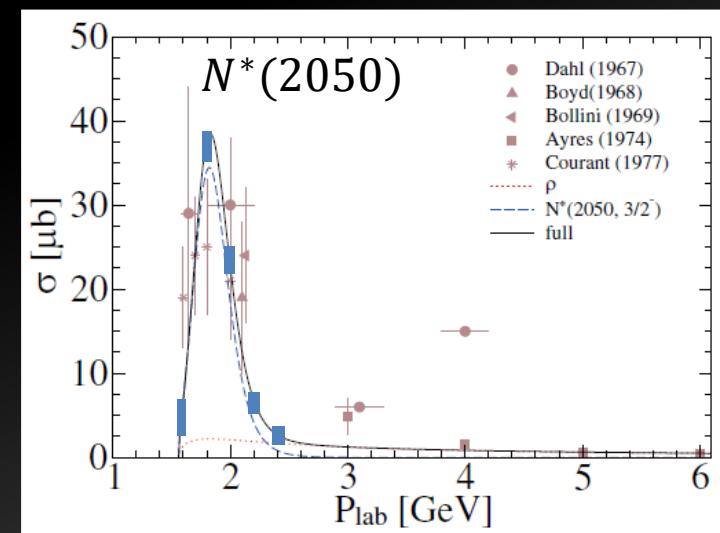
- $pp \rightarrow \pi^- \pi^- D_{30}^{++++}$   
 $\rightarrow \pi^- \pi^- \pi^+ \pi^+ {}^2\text{He}$  (E79)
- $\pi^- p \rightarrow \phi n \rightarrow K^+ K^- n$  (P95)  
-  $N^*(2050)$  coupled to  $\phi n$ ?



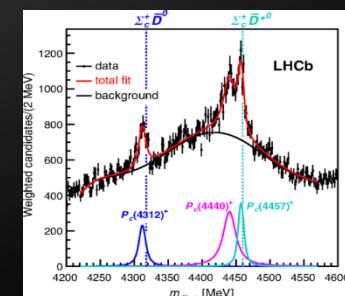
WASA-at-COSY collab.  
PRL 106, 242304(2011)



$D_{03}^+$ ?



Sang-Ho Kim,  
private comm.



$P_C$

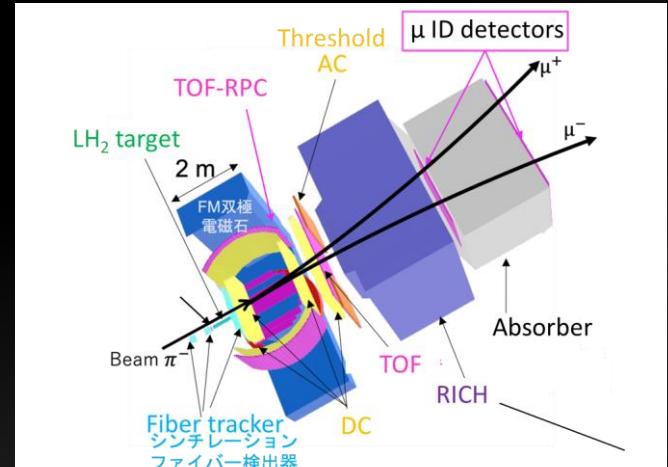
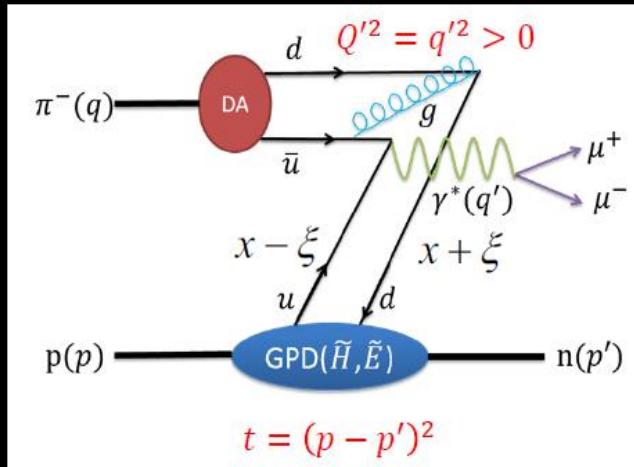
LHCb collab.  
PRL 122, 222001(2019)

# Spectroscopy of Baryons at $\pi 20$

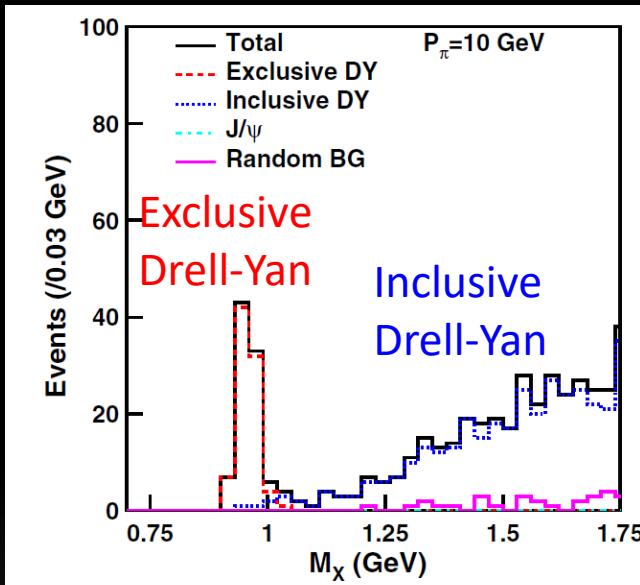
## Baryon Structure in an Exclusive Drell-Yan Process

- $\pi^- p \rightarrow n \mu^+ \mu^-$

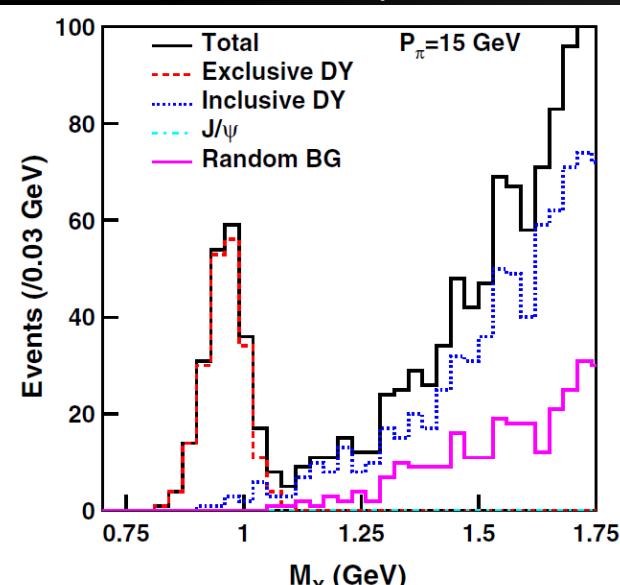
T. Sawada et al.,  
 PRD 93, 114034 (2016)  
 (Lol: KEK/J-PARC- 2019-7)



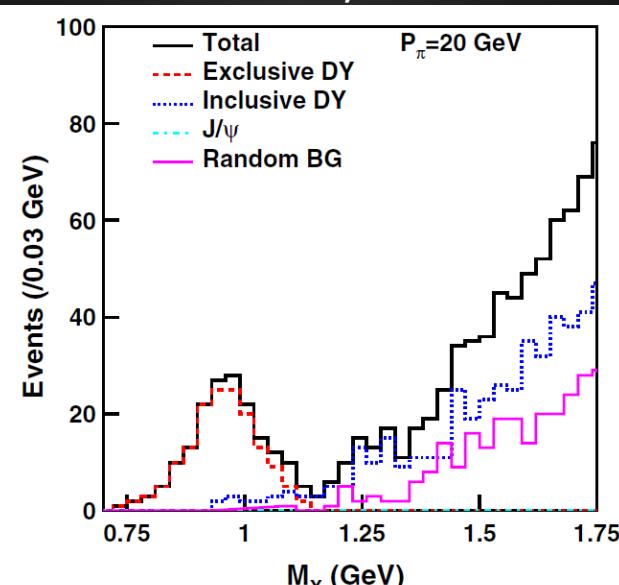
$\pi^-$  beam at 10 GeV/c



15 GeV/c



20 GeV/c



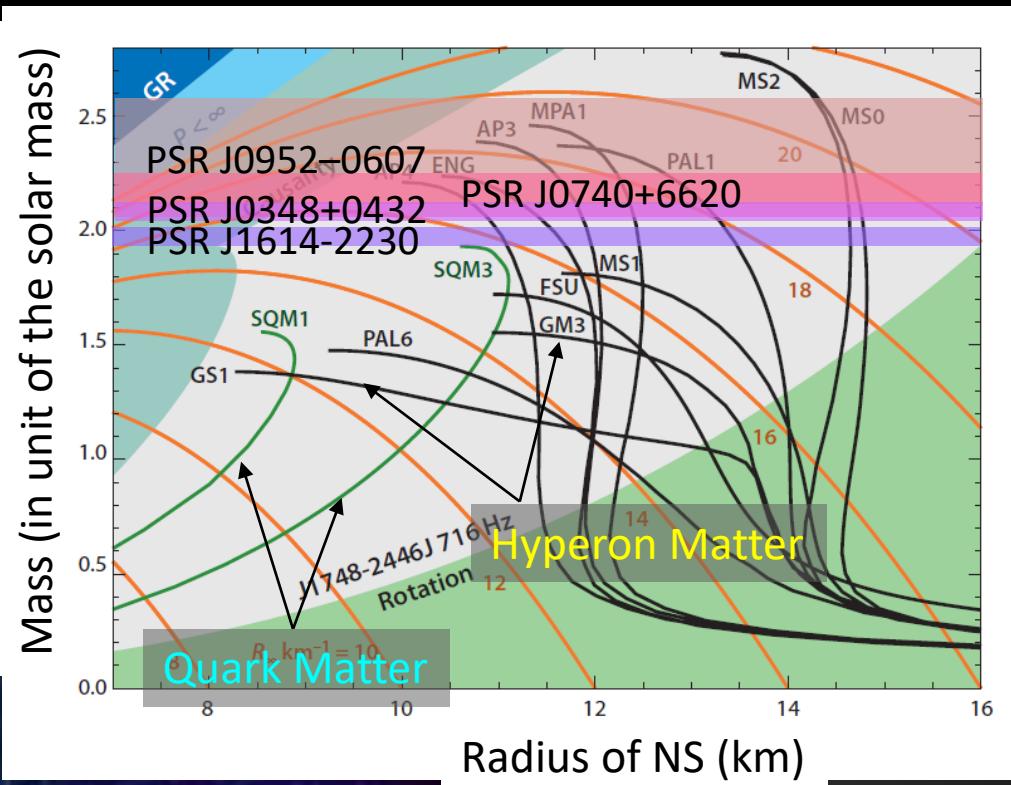
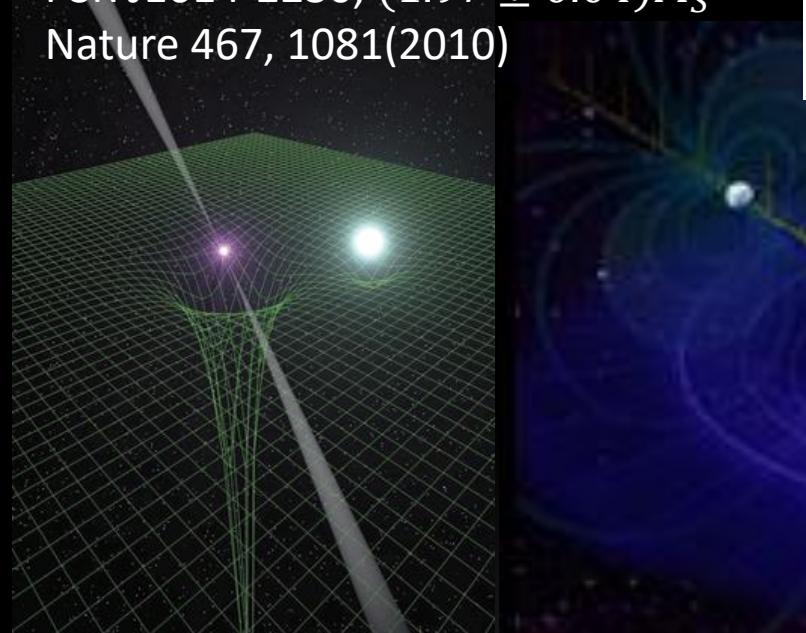
# Stability of Neutron Stars w/ $m \gtrsim 2m_{\odot}$

PSR J0952–0607,  $(2.35 \pm 0.17)M_S$   
 Astr. Jour. Lett. 934, L17(2022)

PSR J0740+6620,  $(2.08 \pm 0.07)M_S$   
 Astr. Jour. Lett. 915, L15(2021)

PSR J0348+0432,  $(2.01 \pm 0.04)M_S$   
 Science 380, 1233232(2013)

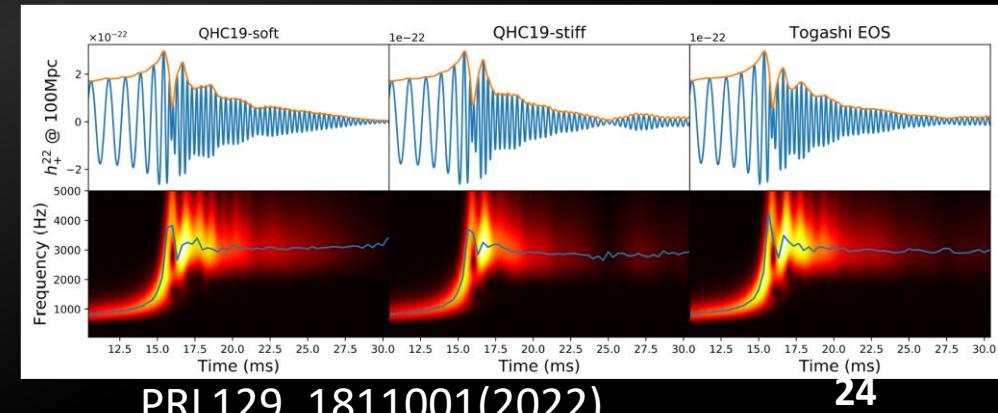
PSR J1614-2230,  $(1.97 \pm 0.04)M_S$   
 Nature 467, 1081(2010)



James M. Lattimer  
 Ann. Rev. Nucl. Part. Sci. 62, 485(2012)



EoS dependence  
 of GW (theory)

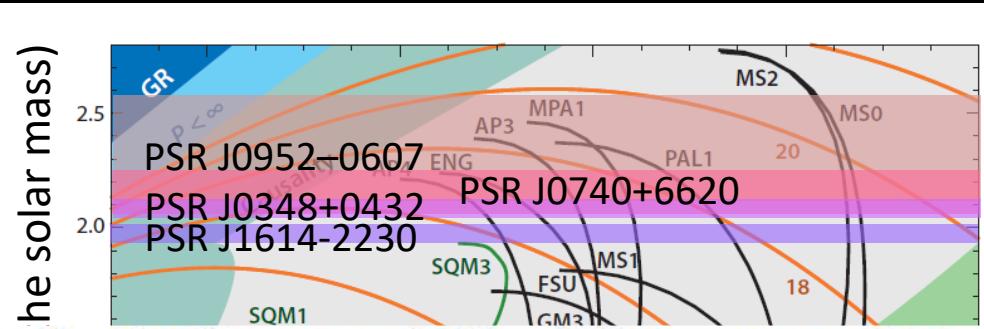


PRL129, 1811001(2022)

# Stability of Neutron Stars w/ $m \gtrsim 2m_{\odot}$

PSR J0952–0607,  $(2.35 \pm 0.17)M_S$   
 Astr. Jour. Lett. 934, L17(2022)

PSR J0740+6620,  $(2.08 \pm 0.07)M_S$   
 Astr. Jour. Lett. 915, L15(2021)

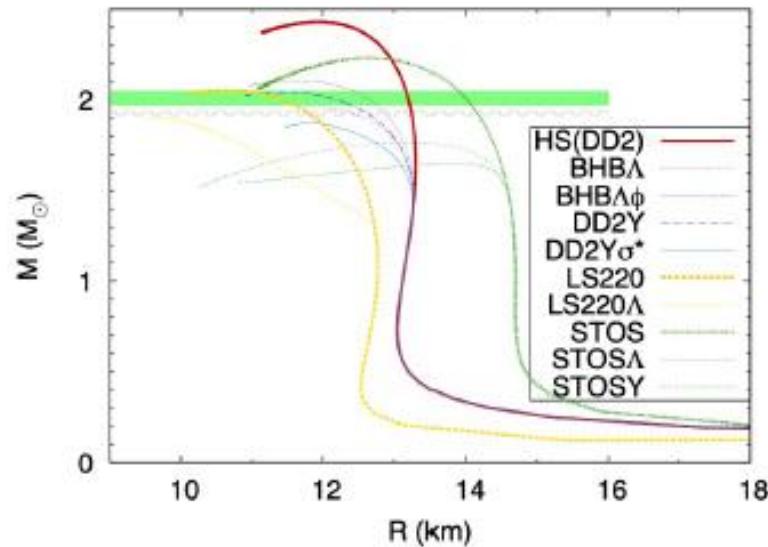


James M. Lattin  
 Ann. Rev. Nucl.



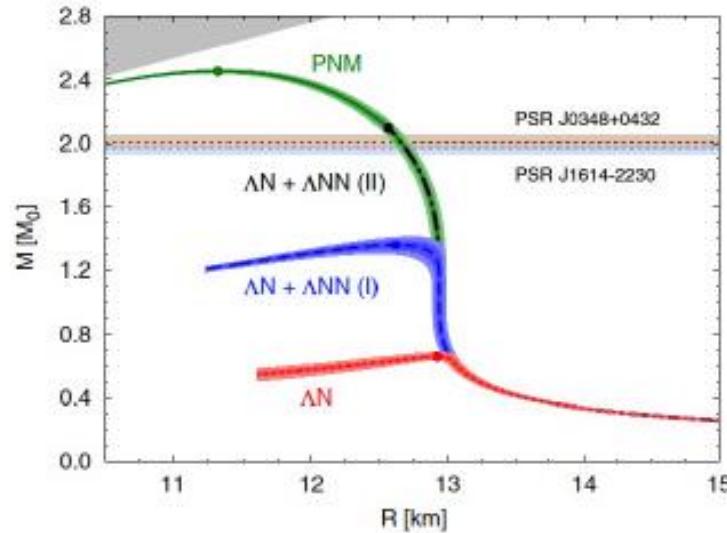
## Possible Solutions of the Hyperon Puzzle Togashi (2<sup>nd</sup> HEFex-WS)

(1) Hyperon-hyperon repulsion  
 (RMF theory)



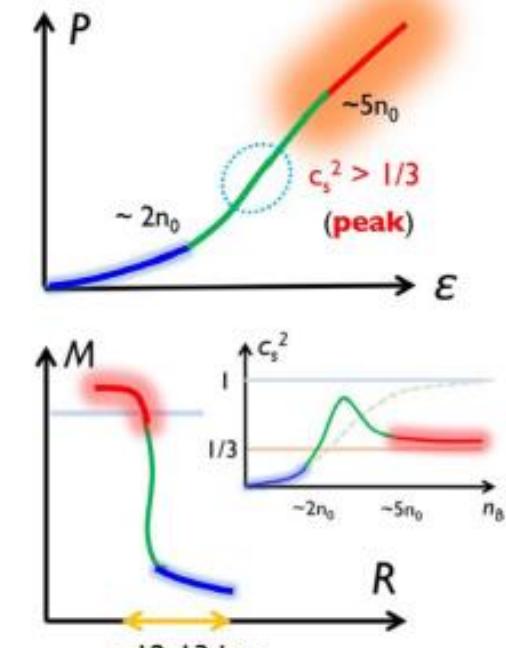
(PRC 96 (2017) 045806)

(2) Hyperonic three-body forces  
 (Microscopic theory)



(PRL 114 (2015) 092301)

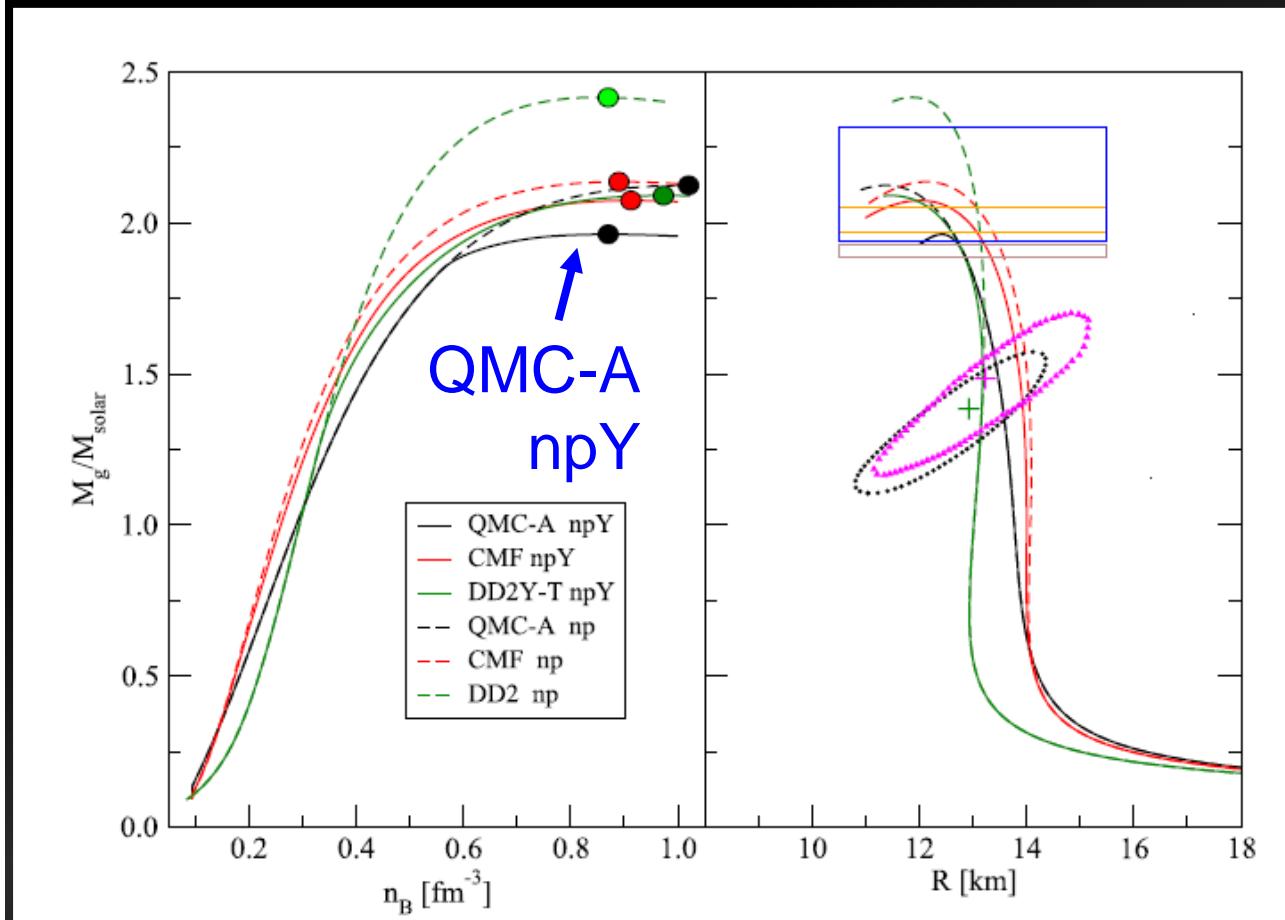
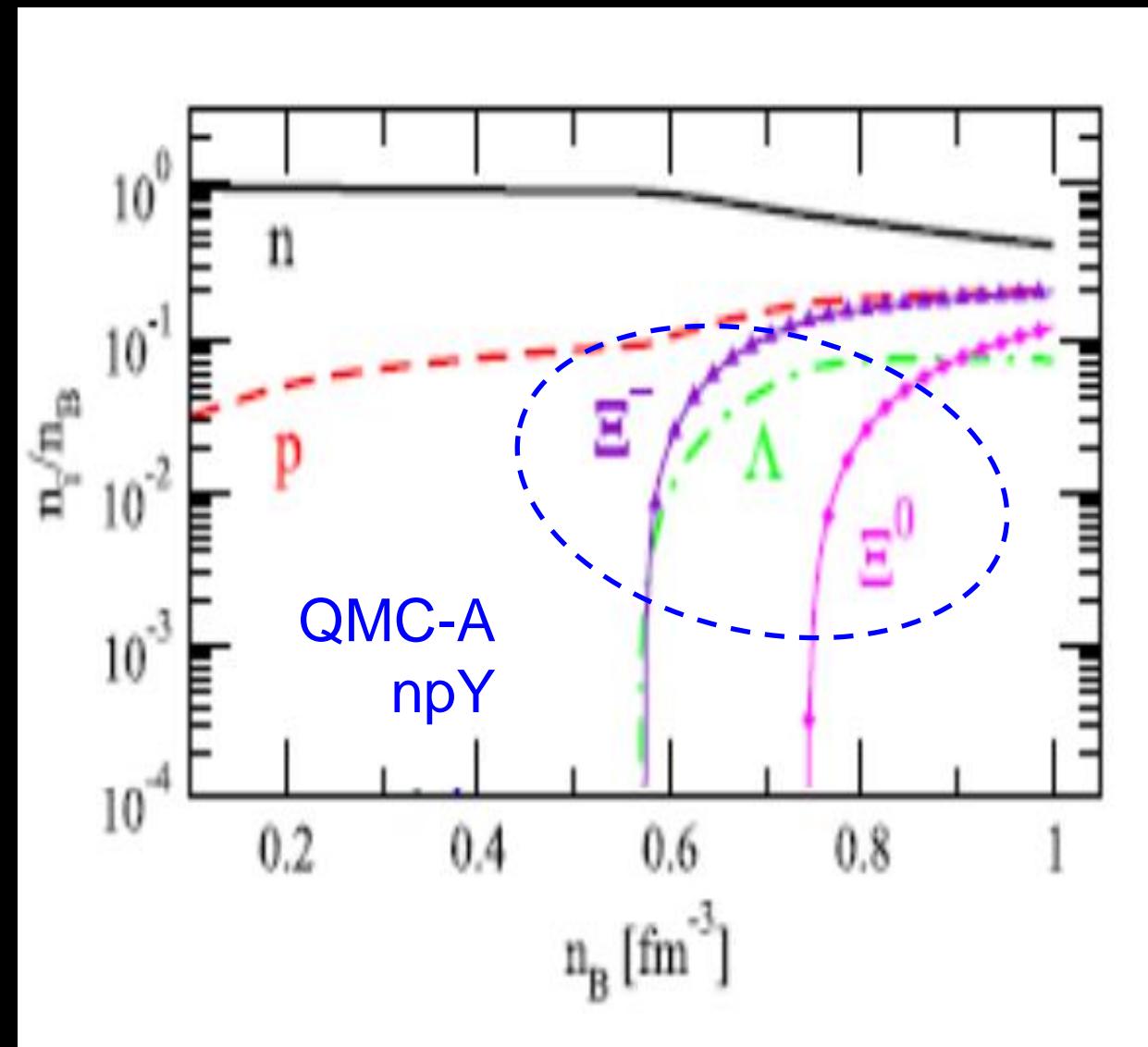
(3) Quark phase transition



(PRD 104 (2021) 063036)

# Composition of Cold NS matter, Mass vs central density and Radius

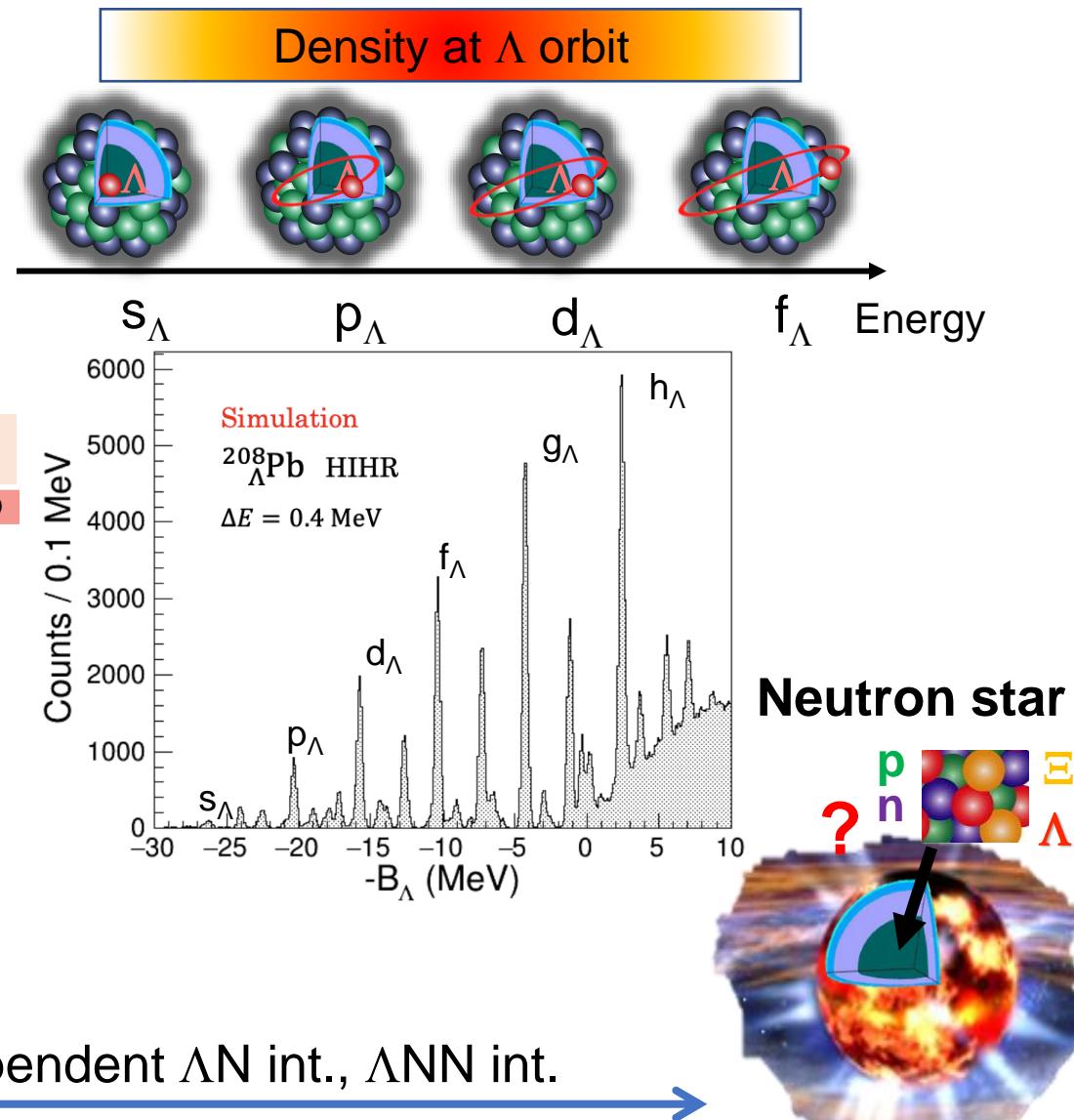
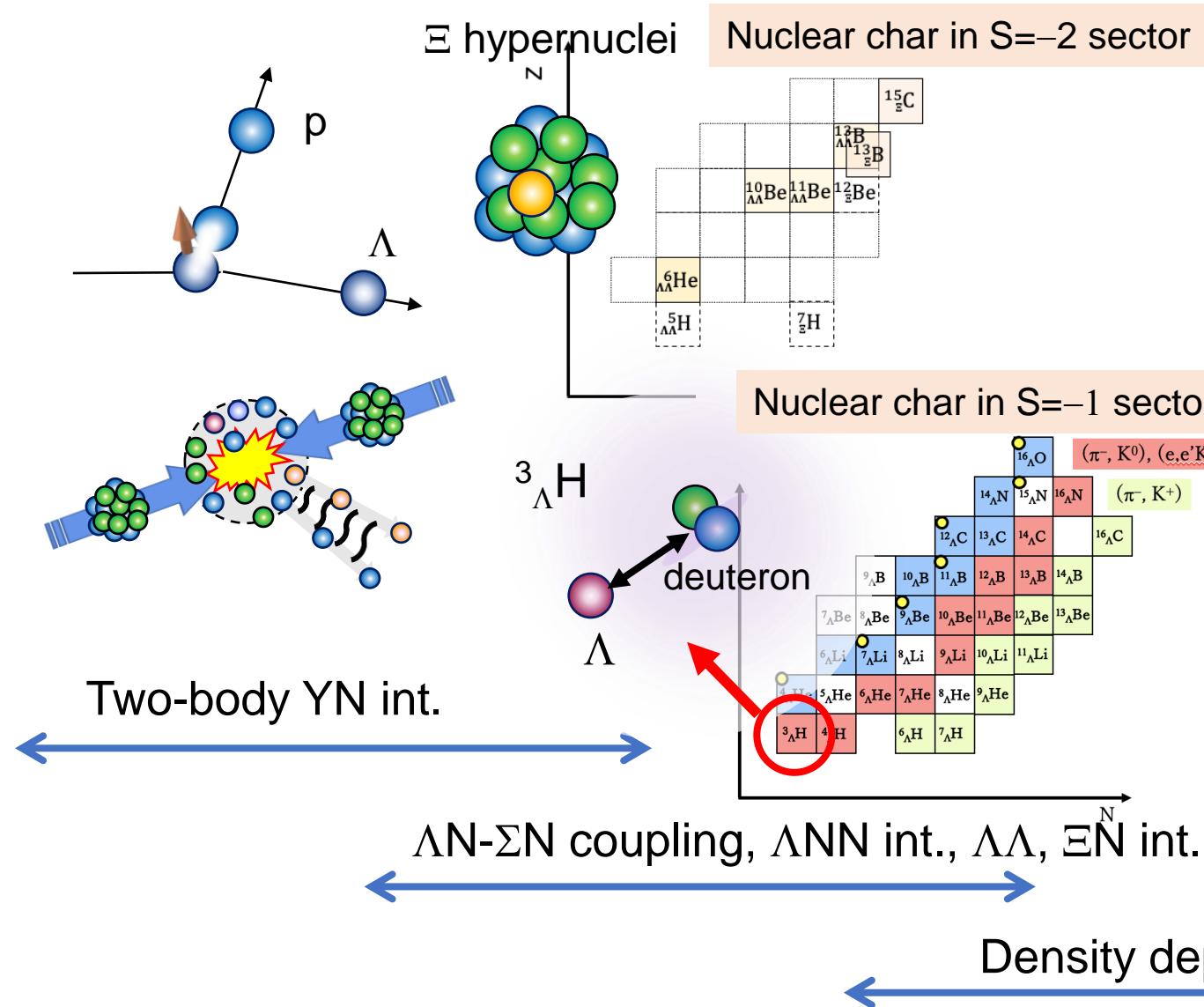
J. R. Stone et al., MNRAS 502, 3476(2021)



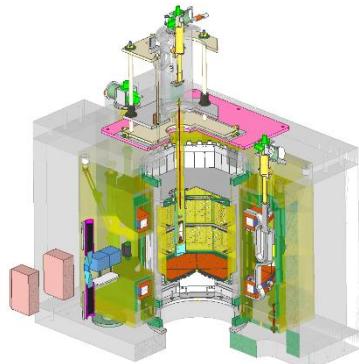
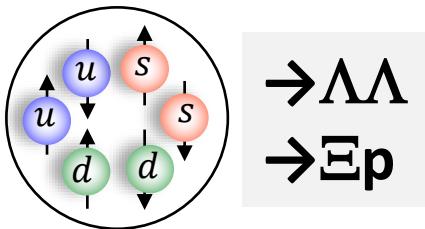
# Hypernuclear physics

Based on Miwa's slide

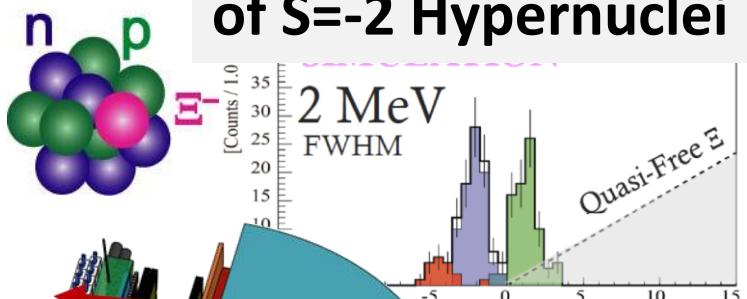
Baryon-Baryon interaction Study of light  $\Lambda$ ,  $\Xi$  hypernuclei Spectroscopy of heavy hypernuclei



## H dibaryon



## Precision Spectroscopy of S=2 Hypernuclei

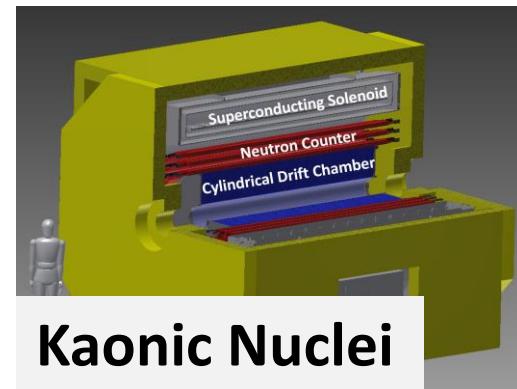
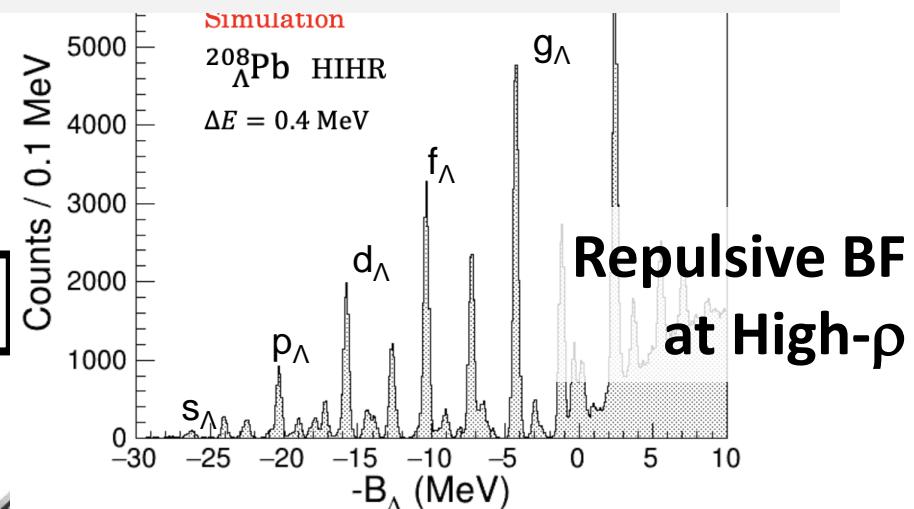


Extended HEF

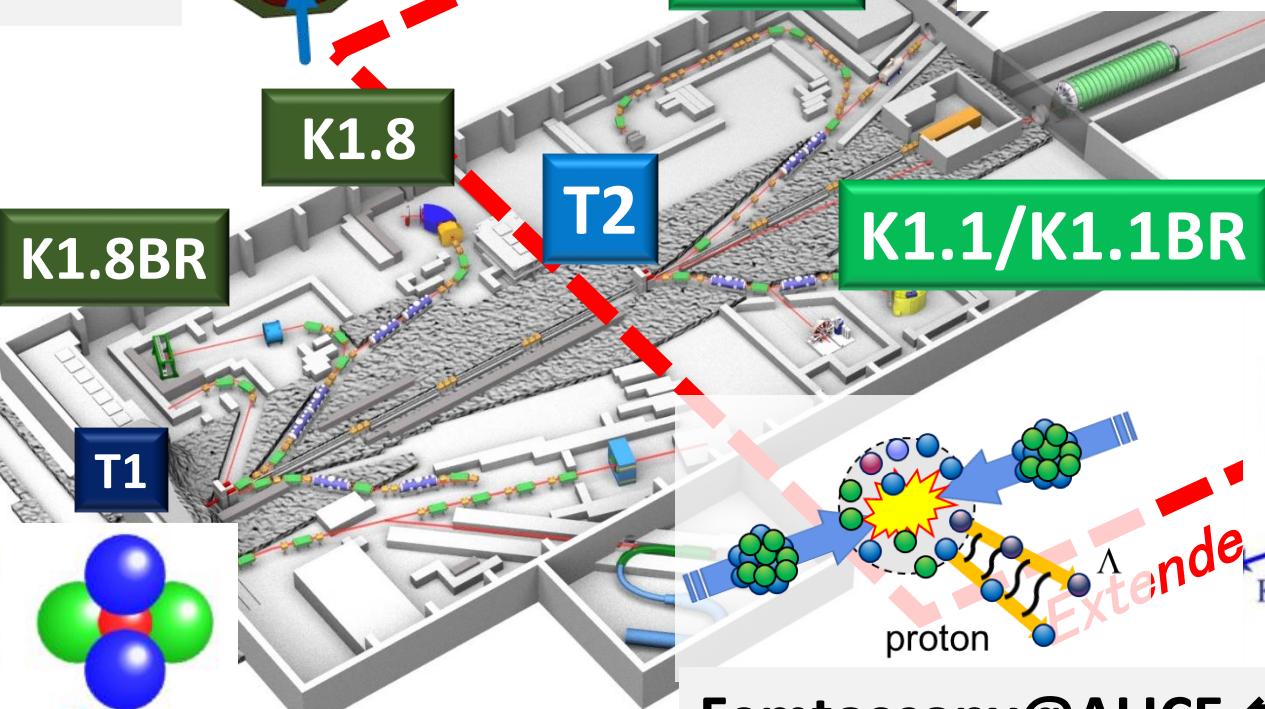
$\Lambda N - \Sigma N$

HIHR

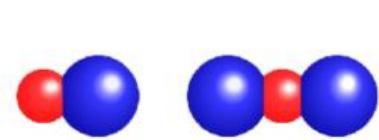
## Superprecision spectroscopy of S=1 Hypernuclei



Kaonic Nuclei

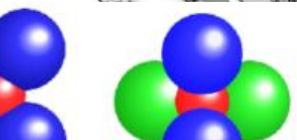


Femtoscopy@ALICE  $\leftrightarrow$  YN scat.@J-PARC



$K^- p$

$K^- pp$



$K^- ppn$

$K^- ppnn$

# World-Wide Network of Subatomic Physics

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