

First measurement of the strange axial coupling constant using neutral-current quasielastic interactions of atmospheric neutrinos at KamLAND



Seisho Abe on behalf of the KamLAND Collaboration

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(Present address: ICRR, University of Tokyo)

NuSTEC CTGWG seminar April 5, 2023

Self-introduction

2023 March: Ph.D. at Tohoku University

- KamLAND experiment (neutrino interaction physics)

Japan Society for the Promotion of Science



2023 April: JSPS fellow (Postdoc) at ICRR, University of Tokyo

- T2K & SK experiments + NEUT
- Hayato-san (NEUT representative, ICRR) is my host researcher



This seminar is based on a paper on arXiv:2211.13911 (see [here](#))

→ Accepted to Physical Review D. Now under publication!

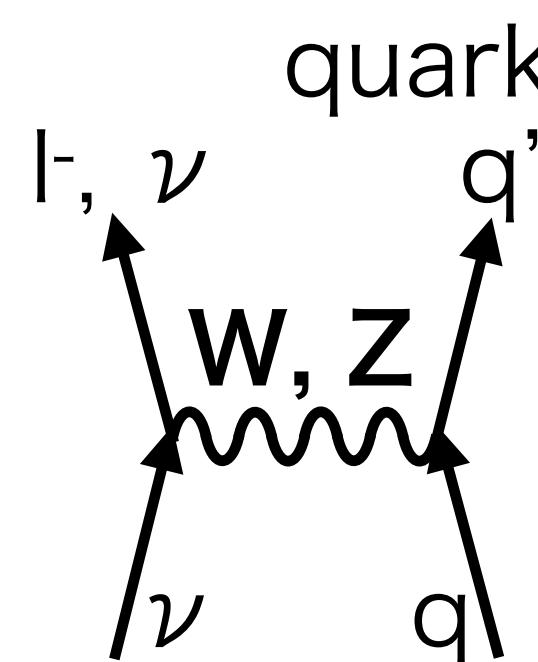
Contents

- ▶ **Physics:**
Neutral-current quasielastic & the strange axial coupling constant
- ▶ **KamLAND experiment:**
Detector, signals...
- ▶ **Analysis:**
Nuclear de-excitation simulation
- ▶ **Results, discussion, and prospects**

Nucleon structure probed by ν interaction

ν -nucleon elastic scattering → Ultimate structure of matter

Elementary process



quark
V-A: Weak

V: Electromagnetic

Quark
current

Left-handed

Both

$$\begin{cases} W: V_{qq'} \gamma^\mu (1 - \gamma^5) \\ Z: I_3 \gamma^\mu (1 - \gamma^5) - 2Q \sin^2 \theta_w \gamma^\mu \end{cases}$$

$V_{qq'}$: CKM matrix, Q : Charge, θ_w : Weinberg angle, I_3 : Weak isospin

Nucleon structure → Form factors

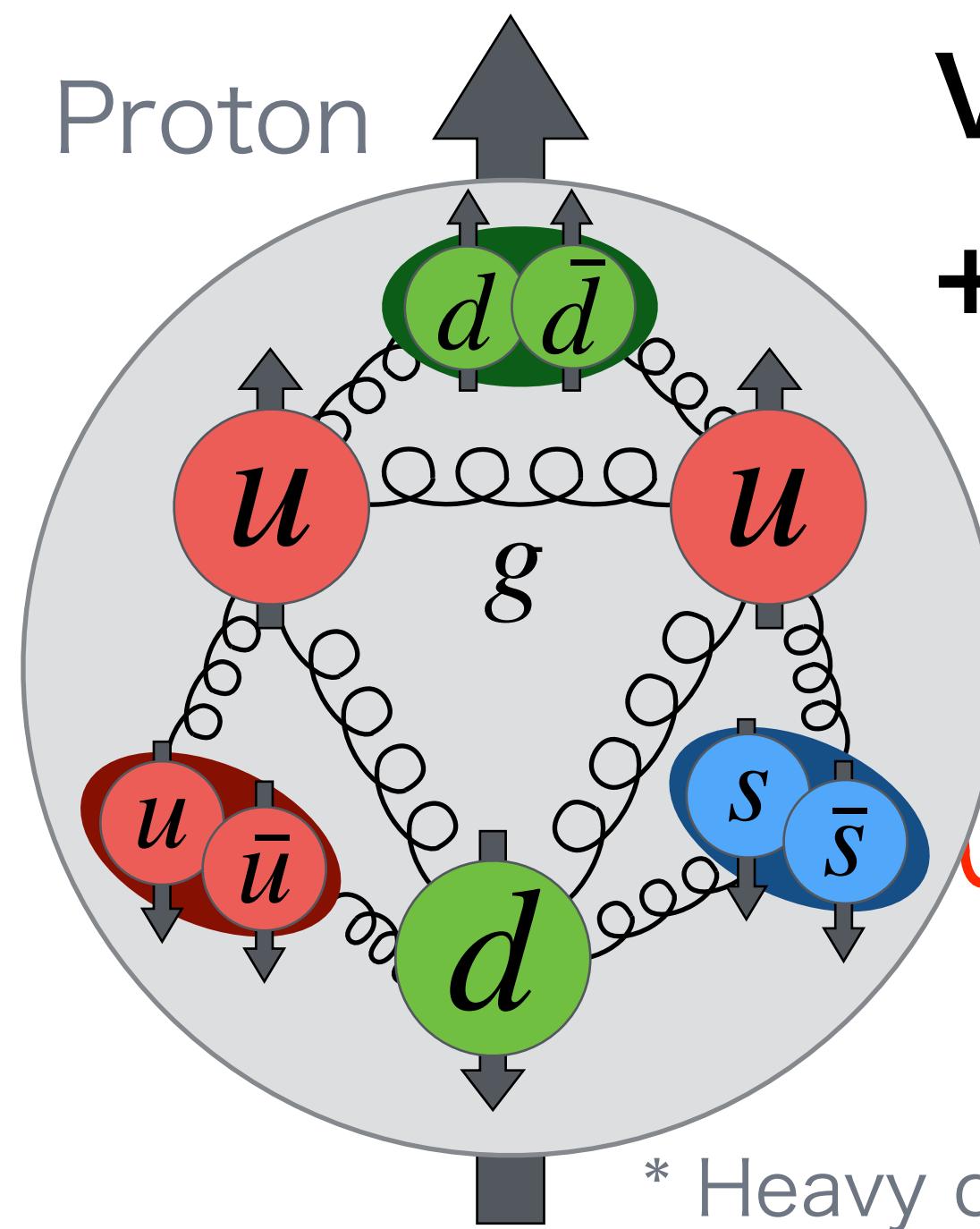
Vector form factor: Electric charge, etc.¹

Well measured by electron scattering exp.

Axial form factor: Spin²

ν int. can measure the spin structure

1. CVC hypothesis 2. Parton model



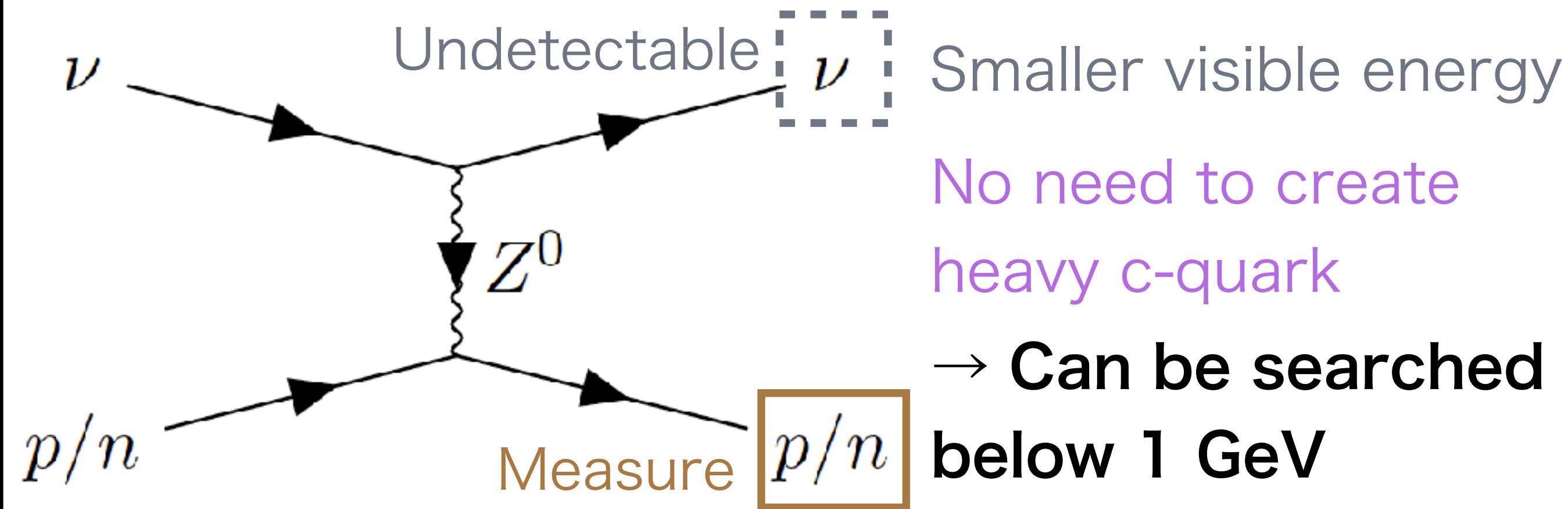
Proton
Valence quarks
+ Sea quarks($q\bar{q}$)*

$s\bar{s}$ is not well
understood

* Heavy quarks (c, t, b) are neglected

Contribution of $s\bar{s}$ to the nucleon spin

✓ Neutral-current quasielastic (NCQE)



Smaller visible energy

No need to create
heavy c-quark

→ Can be searched
below 1 GeV

Axial form factor & strange axial coupling constant

Axial form factor

$$[F_A(Q^2)]_{\text{NC}}^{p/n} = \frac{1}{2} (\pm g_A - g_A^s) \left(1 + \frac{Q^2}{M_A^2} \right)^{-2}$$

ud **s̄s̄**

Q^2 : Four-momentum transfer

Sign: proton(+) neutron(-)

Δq : q -quark contribution to the nucleon spin

Sign: Corresponds to the sign of weak isospin I_3

Axial coupling constant: $g_A = \Delta u - \Delta d$

Determined by the beta-decay (1.2723 ± 0.0023)

Strange axial coupling constant: $g_A^s = \Delta s$

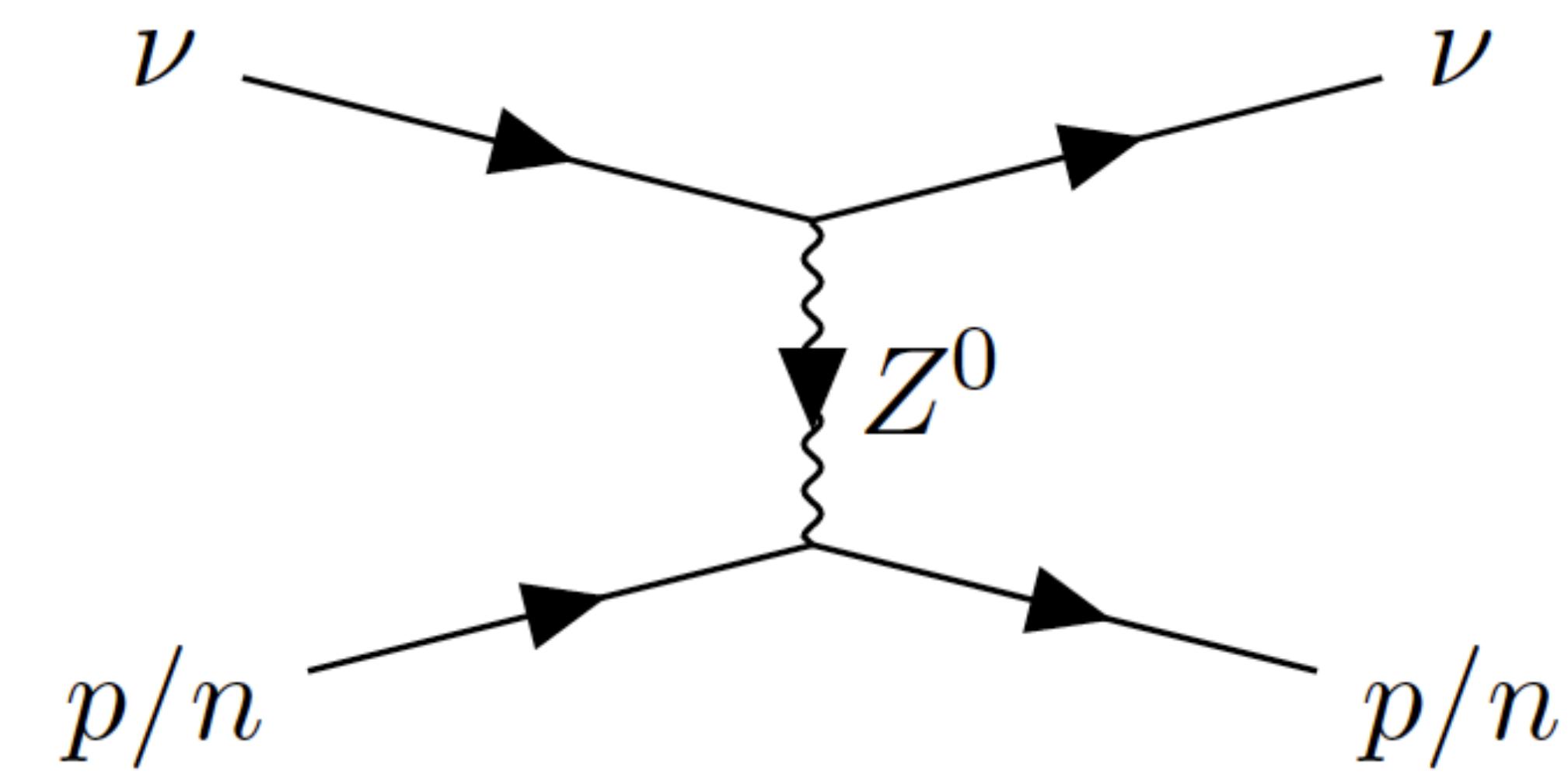
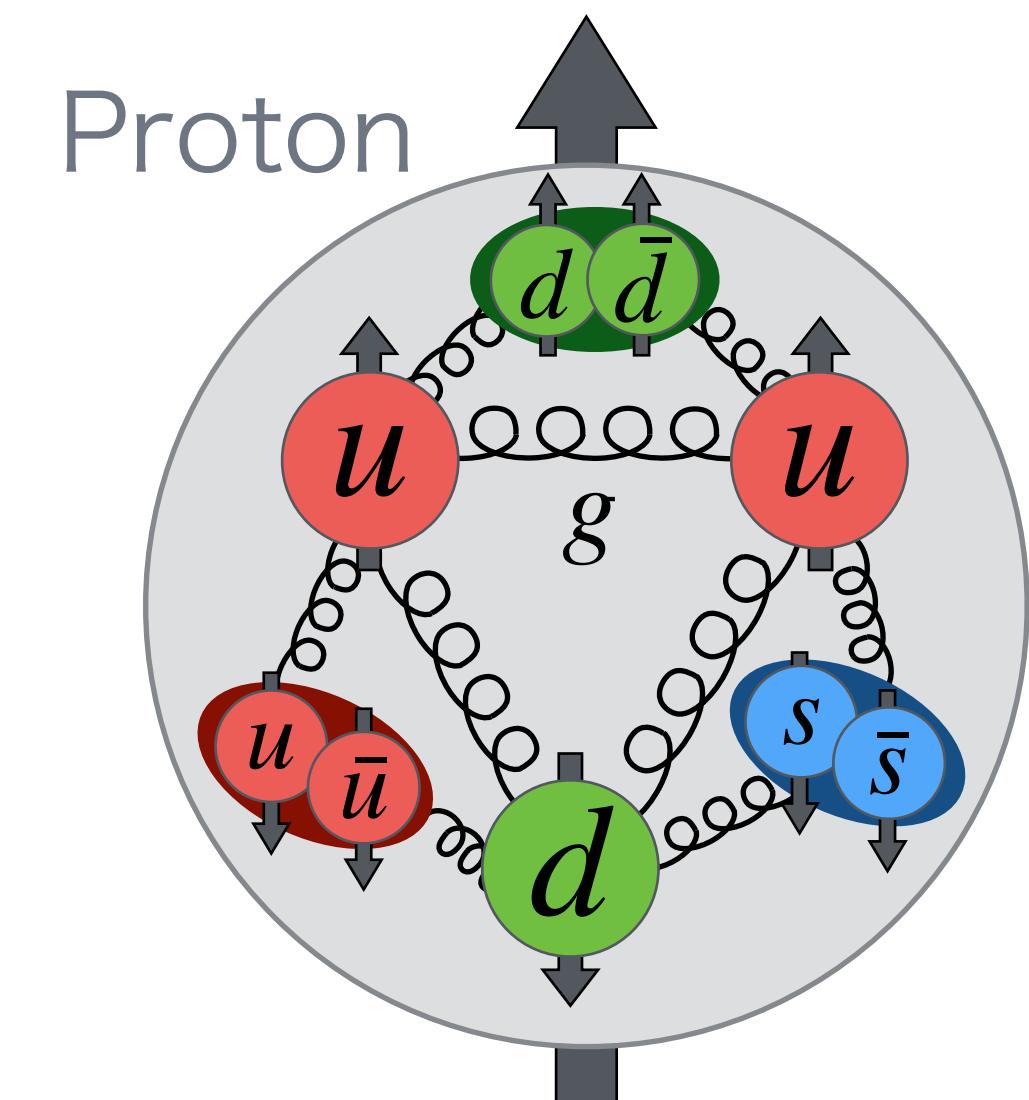
s̄s̄ spin! Target!

Axial mass: $M_A \sim 1 \text{ GeV}$

Discrepancy btw past and recent measurements

Difficult to set reasonable constraints

Divided into **ud and **s̄s̄****



g_A^s & cross section

Axial form factor

$$[F_A(Q^2)]_{\text{NC}}^{p/n} = \frac{1}{2} (\pm g_A - g_A^s) \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

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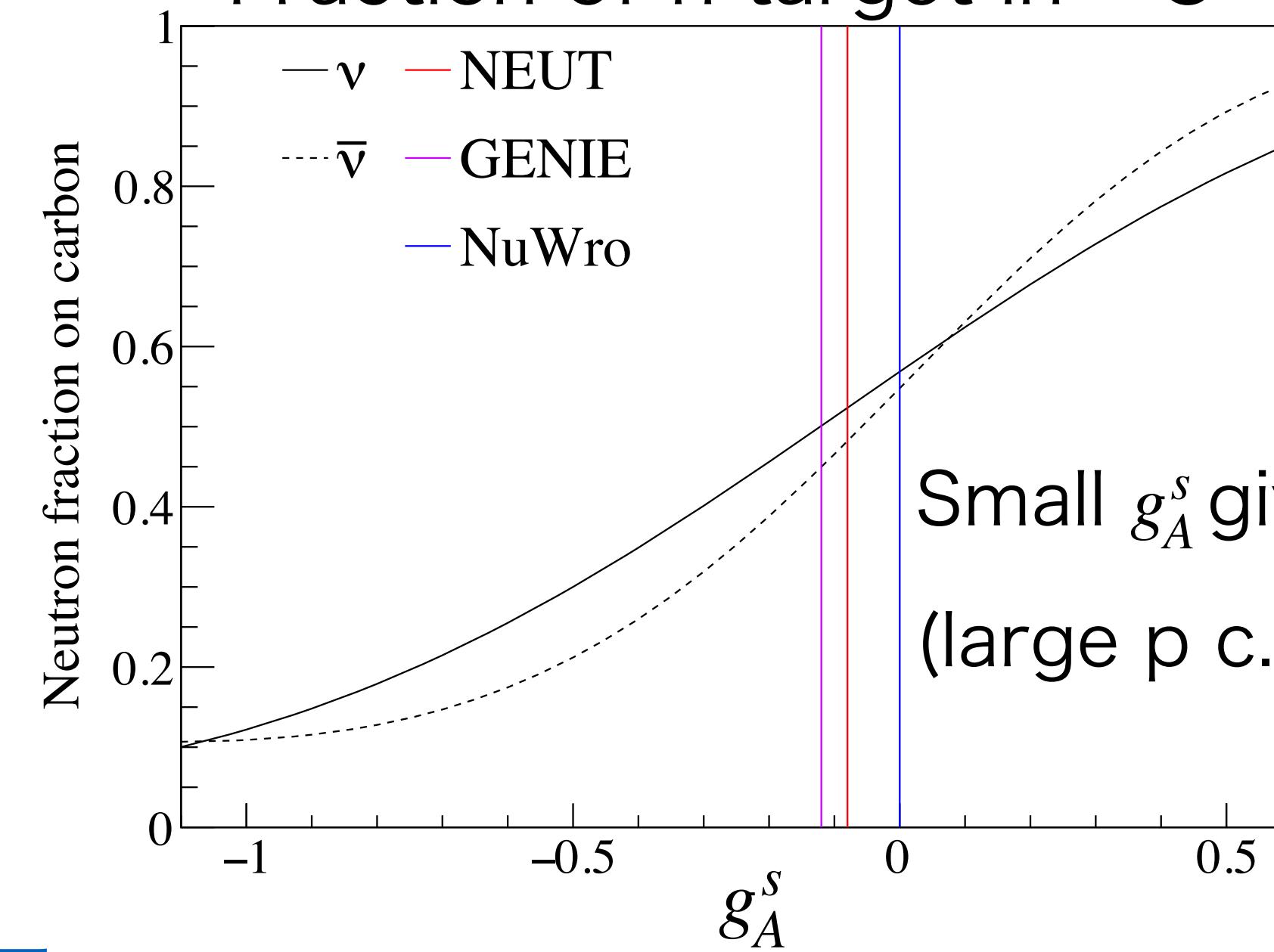
Discrepancy btw past and recent measurements

Difficult to set reasonable constraints

Cross section

- g_A^s : Change c.s. oppositely for p and n
 - Proton: $(+g_A - g_A^s)^2$ vs Neutron: $(-g_A - g_A^s)^2$
- M_A : Change c.s. equally for p and n

Fraction of n target in ^{12}C



Small g_A^s gives small n c.s.
(large p c.s.)

To measure g_A^s ...

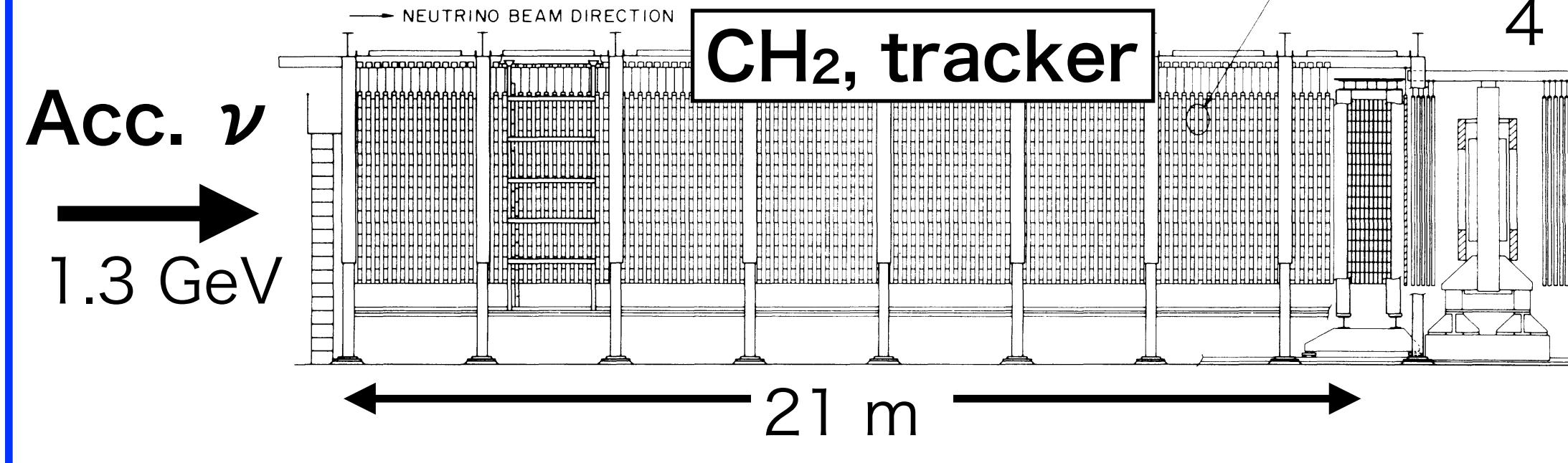
Measure both p and n targets!

p- or n-target only → highly depend on M_A

Features of prior experiments

Use p target → Strong dependence on M_A

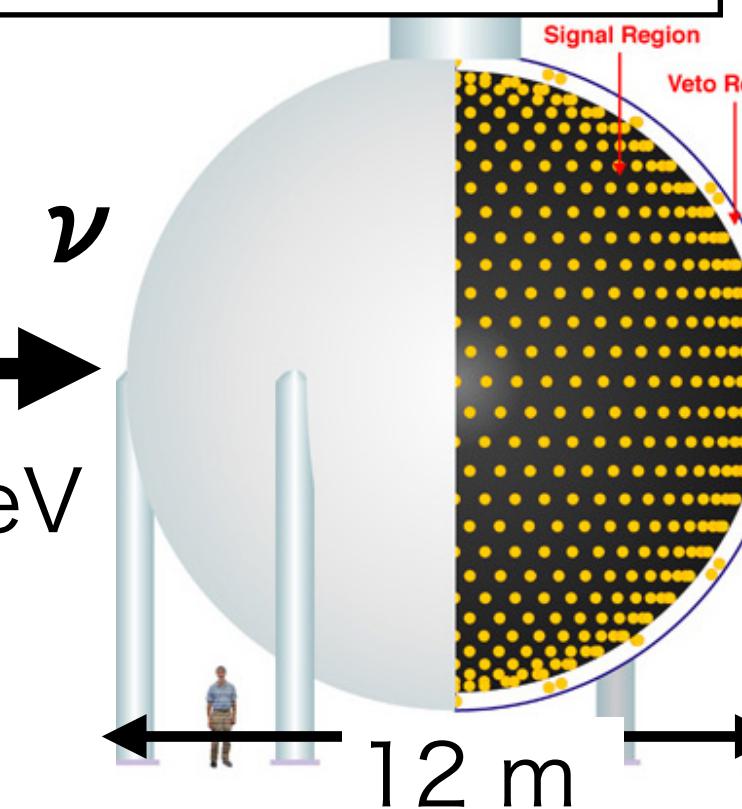
BNL E734 (1987)



MiniBooNE (2013)

CH_2 , Cherenkov + scintillation

Acc. ν
0.8 GeV



Phys. Rev. D 35 785 (1987)

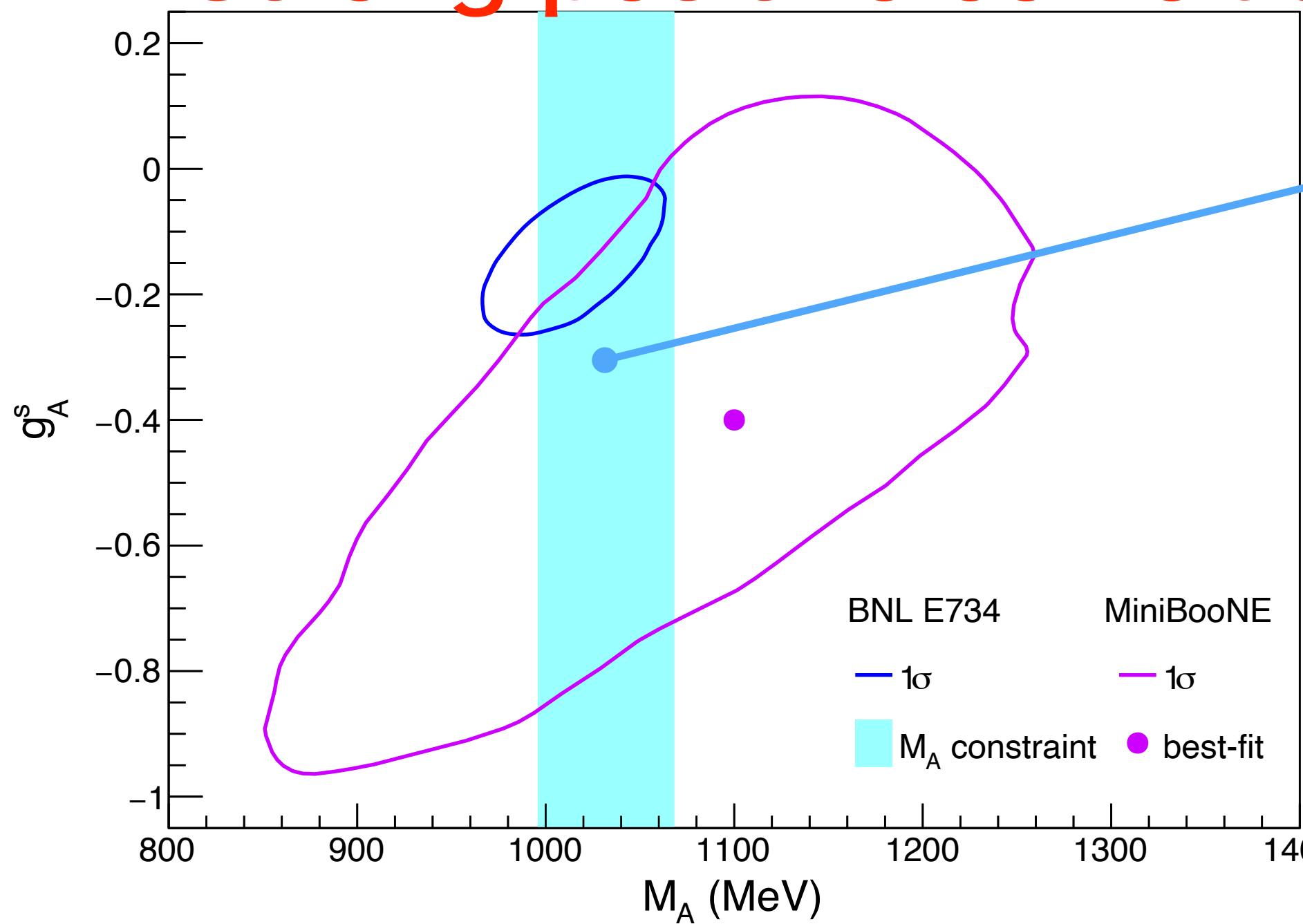
Phys. Rev. C 88 024612 (2013)

Acc. ν & p target

Large stat.

Difficult to measure n target
→ Depends on M_A

Strong positive correlation



Strong constraint on M_A (BNL)

Recent experiments give different values

Difficult to apply similar constraints

MiniBooNE:
 M_A free

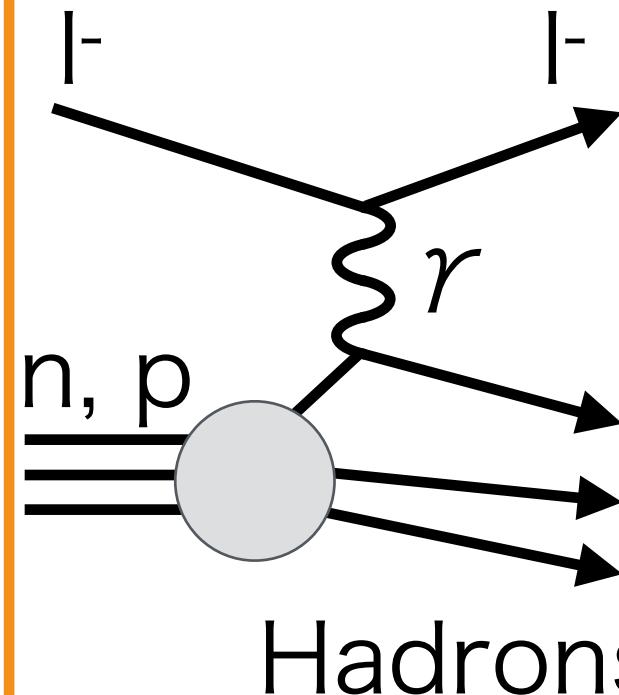
**Requirements for new exp.
Suppress the dependence on M_A**

→ Measure also n target

Measurements of $s\bar{s}$ spin / Aim of this study

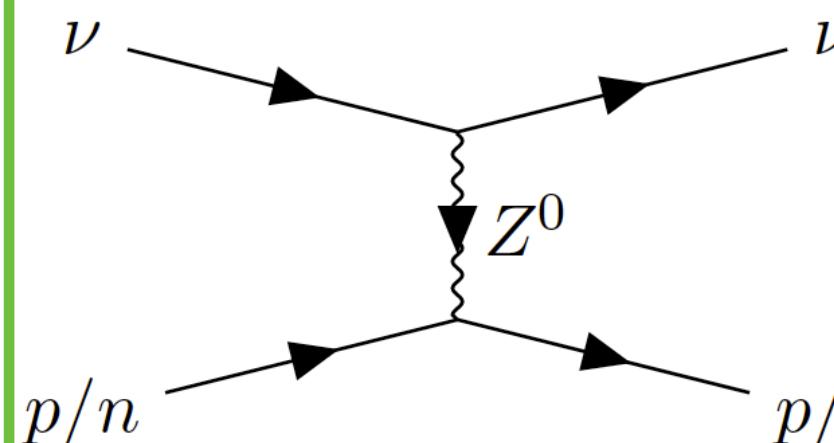
Probing the ultimate structure of matter

Polarized lepton-nucleon DIS



- Smaller error than NCQE
- Assume $SU(3)_{\text{flavor}}$ symmetry**
- (u, d, s): **Not good**
- Breaking \rightarrow Significant impact

NCQE



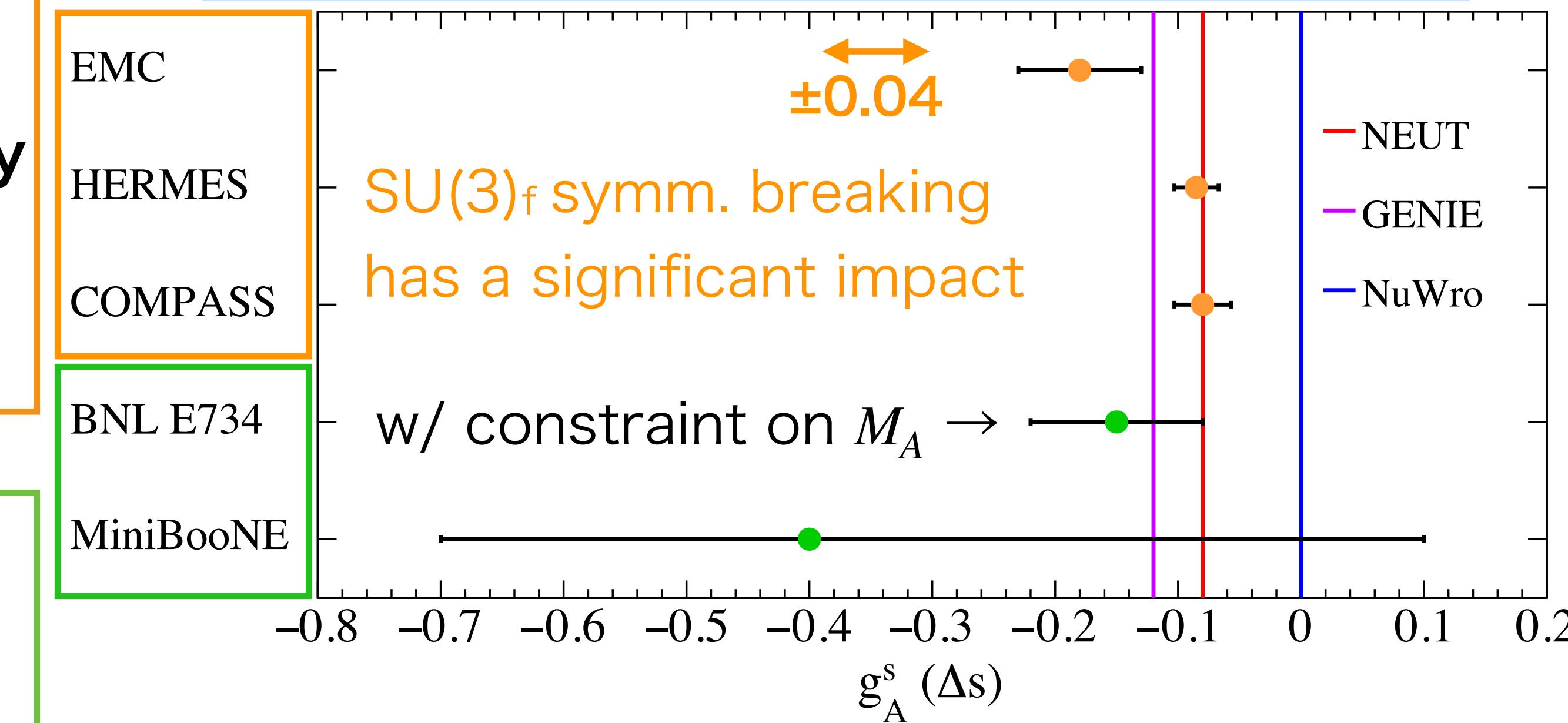
- Independent of $SU(3)_f$**
- If M_A is free, large err.

Issue: Need to determine the value independently on $SU(3)_f$.

→ NCQE ! Needs to suppress M_A -dependence

Negative

Antiparallel to the proton spin

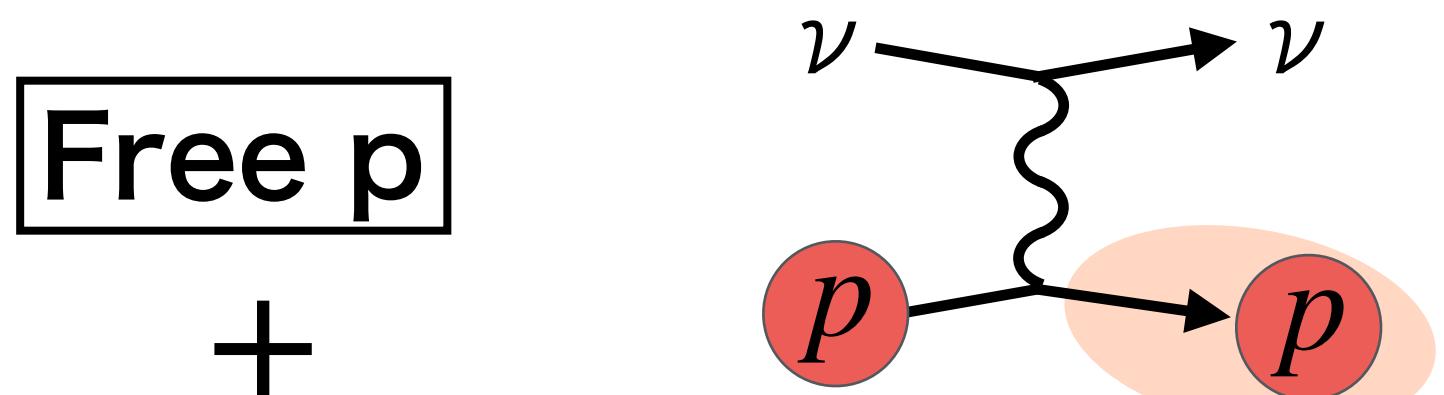


Aim of this study

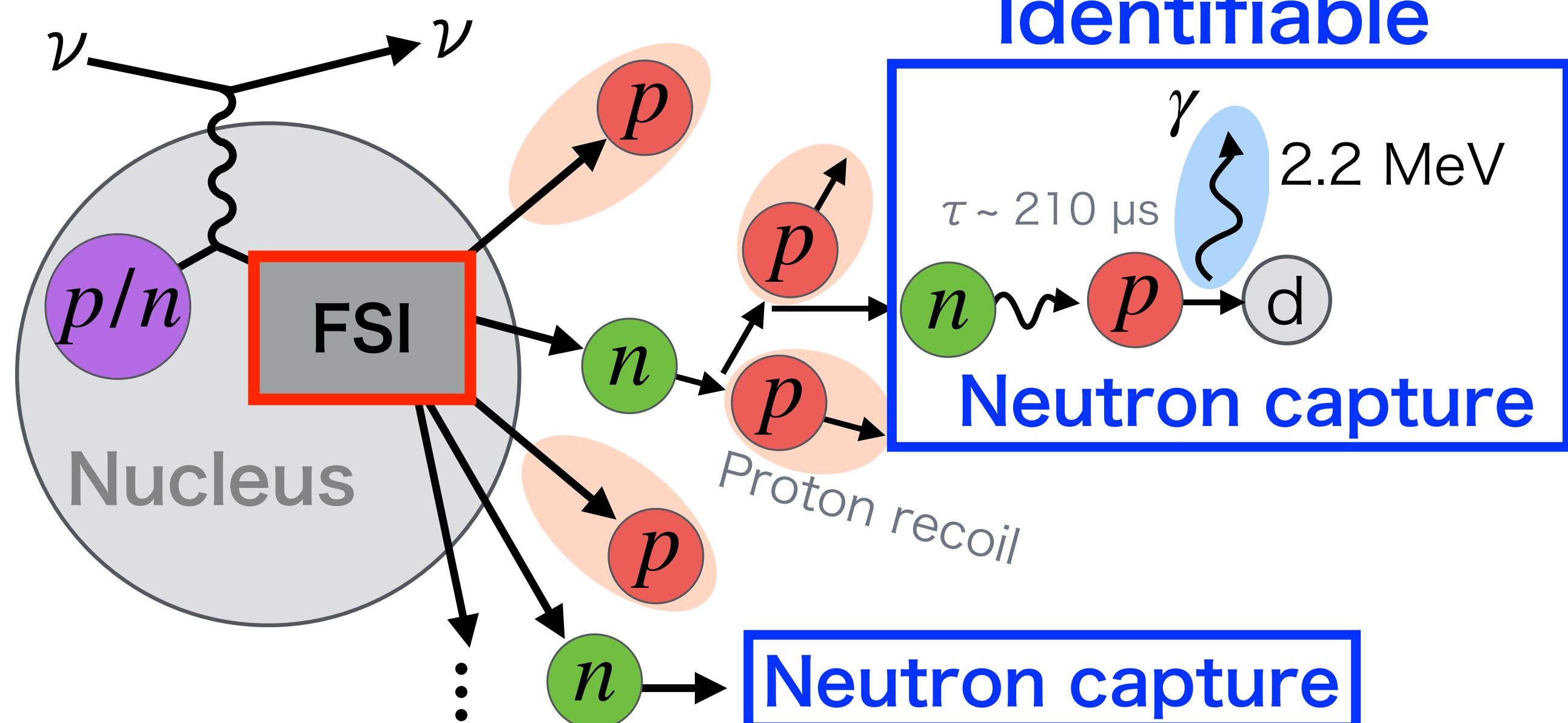
- Independent on $SU(3)_f$ symm.
- Suppression of M_A dependence

Needs to measure both p & n targets

New idea of this study: Neutron multiplicity



Nucleons in nucleus



FSI: Often emits non-target nucleons

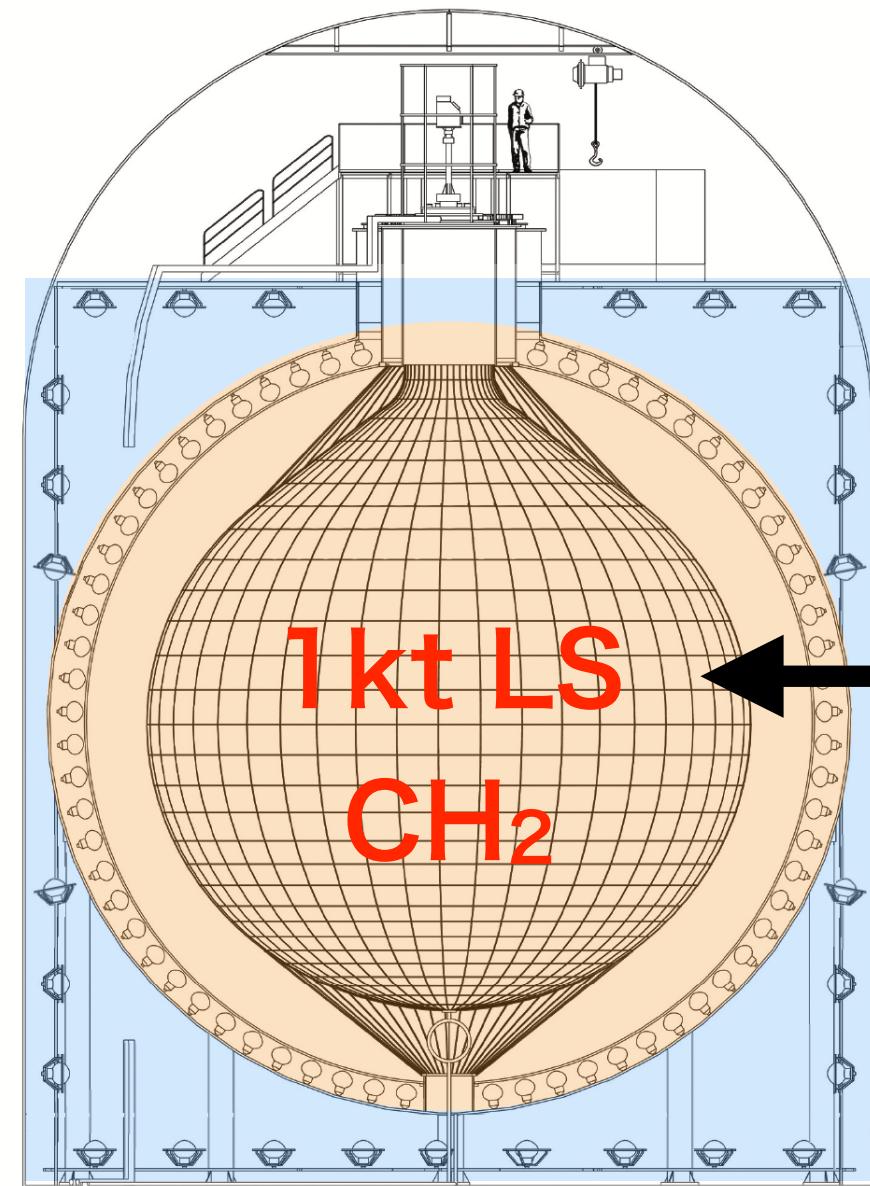
(almost equivalent to p/n)

→ Impossible to distinguish target nucleons for each event

Statistically separate target nucleons using neutron multiplicity distribution

KamLAND(KL)

The largest liquid scintillator (LS) detector



Low-E threshold
+ **high n tag. eff.**

Atmospheric ν
 $\sim 1 \text{ GeV}$

Disadvantage in statistics
→ Covered by methods

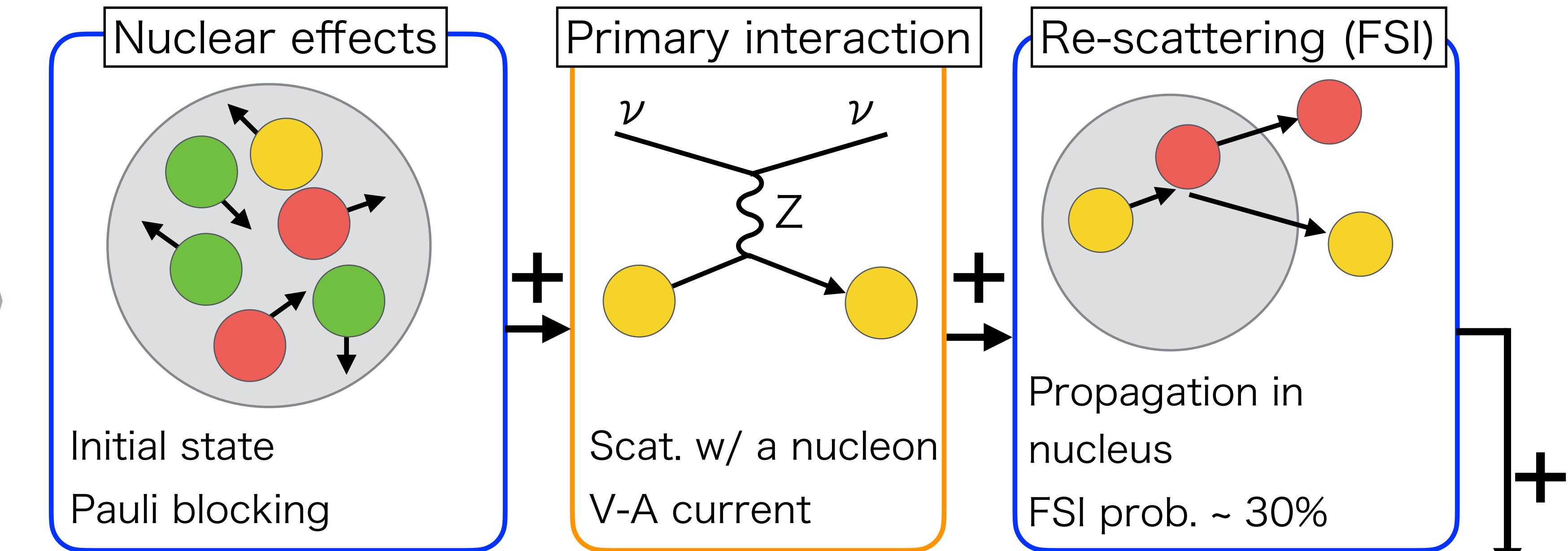
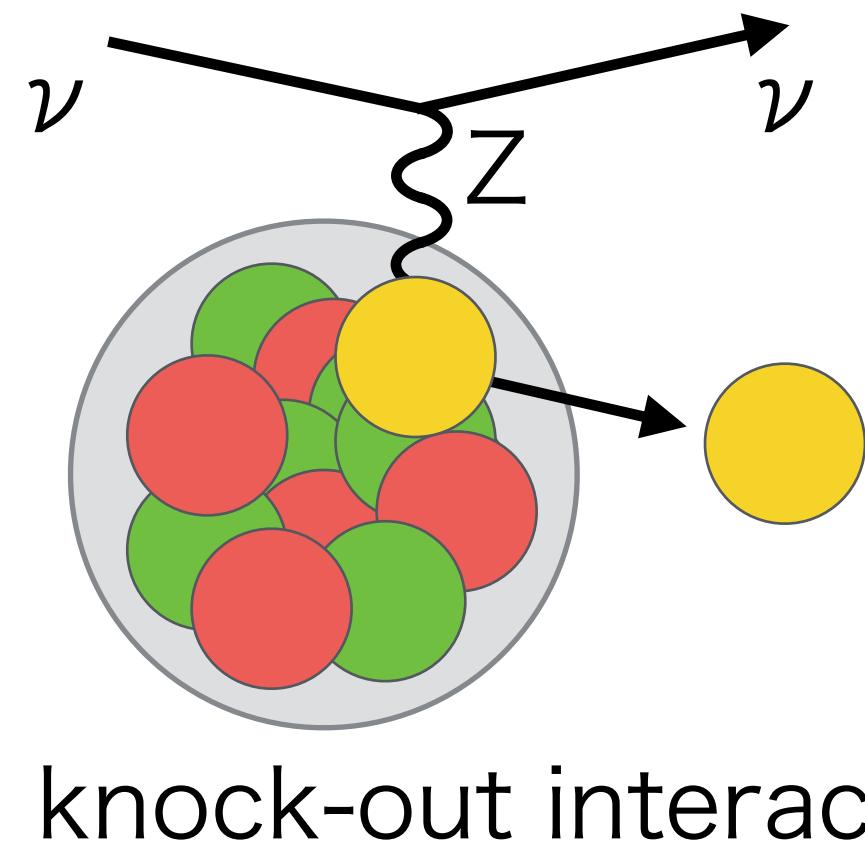
New idea!

First attempt to use new observable!

Precise prediction is a key!

For precise prediction of ν multi.

Description of ν int.
is incomplete...

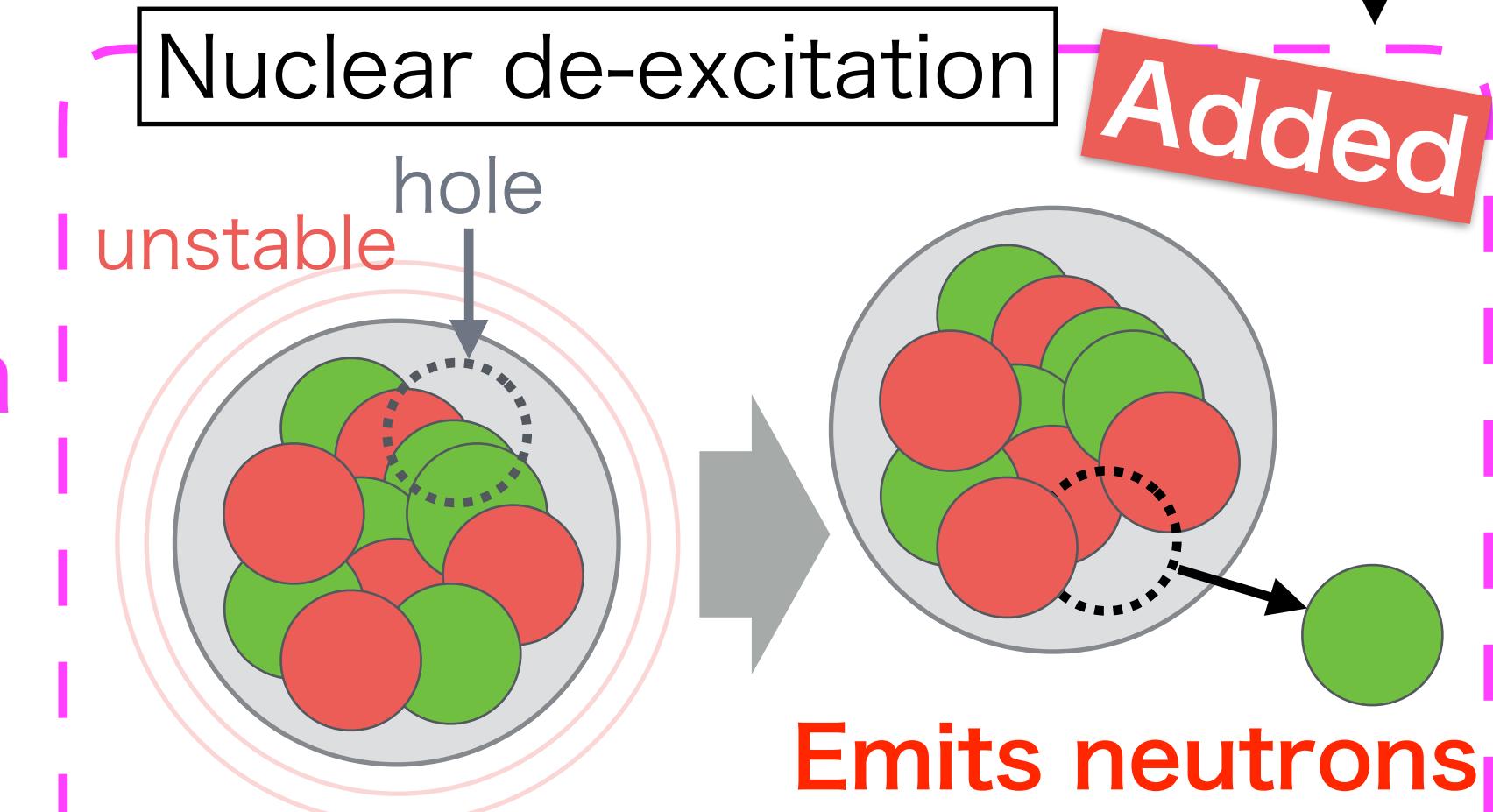


Impulse approx. (IA): primary int. & nuclear effects
weak int. modeled by e scattering

Necessary for precise prediction

Issue: Nuclear de-excitation is not included

- Description finish at where the hole is made.



Develop an original MC, add it into the IA description
→ Not limited to g_A^s , contribute to the entire ν int.

High excitation energy

→ Emit various particles

Overview of this study

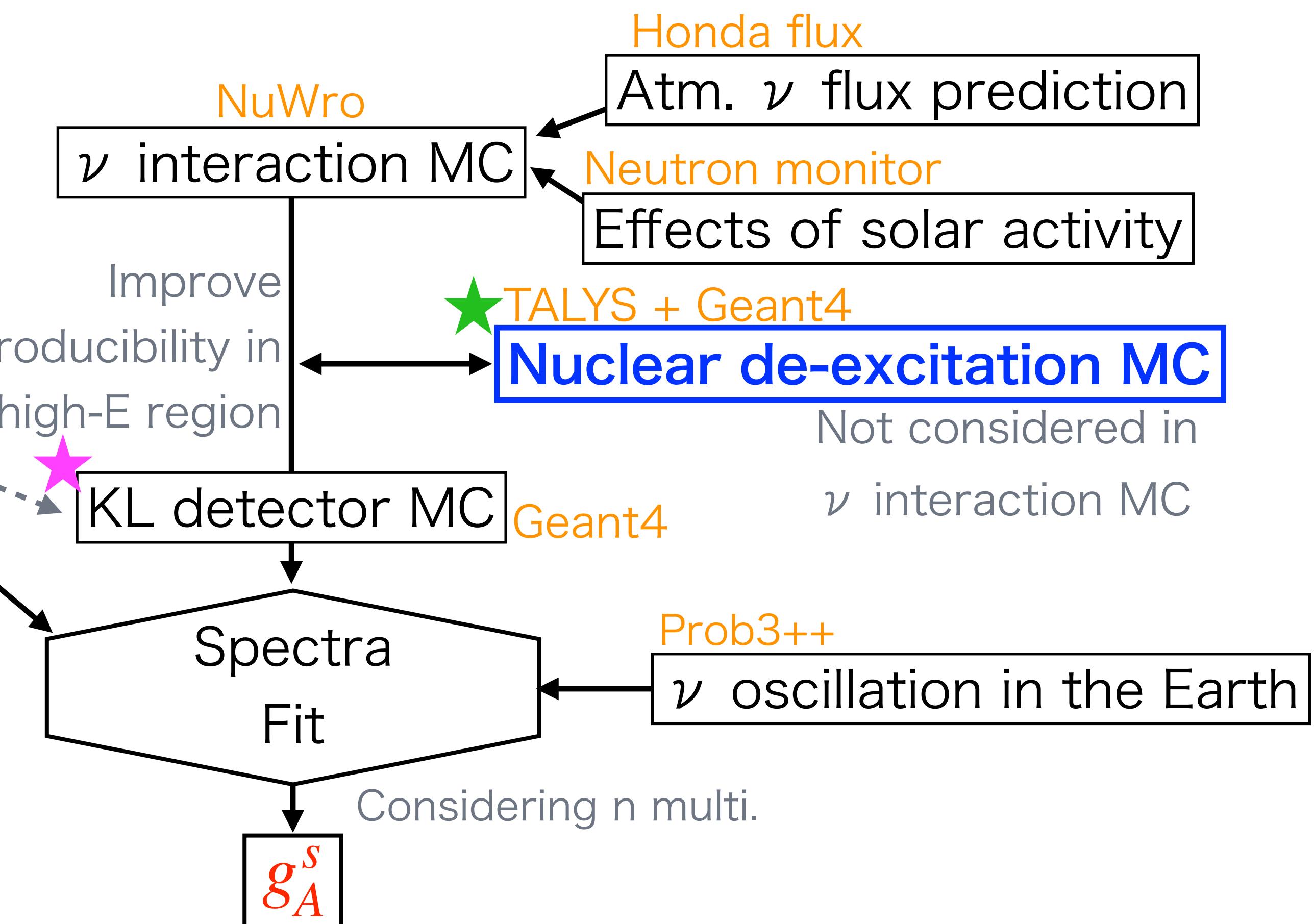
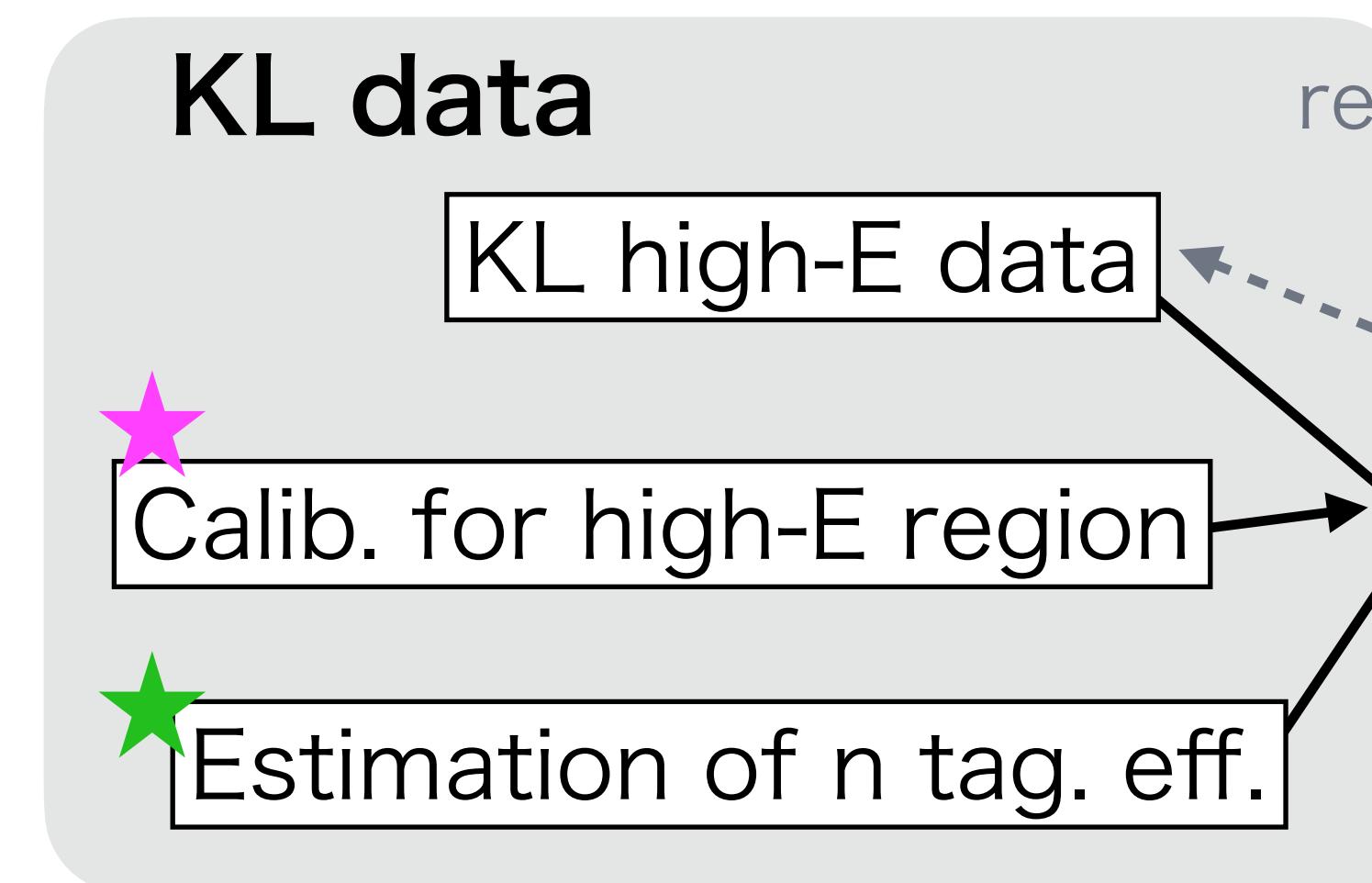
Target

$s\bar{s}$ spin contribution
 Probing nucleon structure → **Measure g_A^s**
 Prediction of n multi. → **Develop de-ex. MC**
 Toward entire ν int. phys.

Main topics of research

- Prediction & measurement of n multi.
- High-E calibration & tuning of KL
 - Good at MeV → Atm. ν is GeV

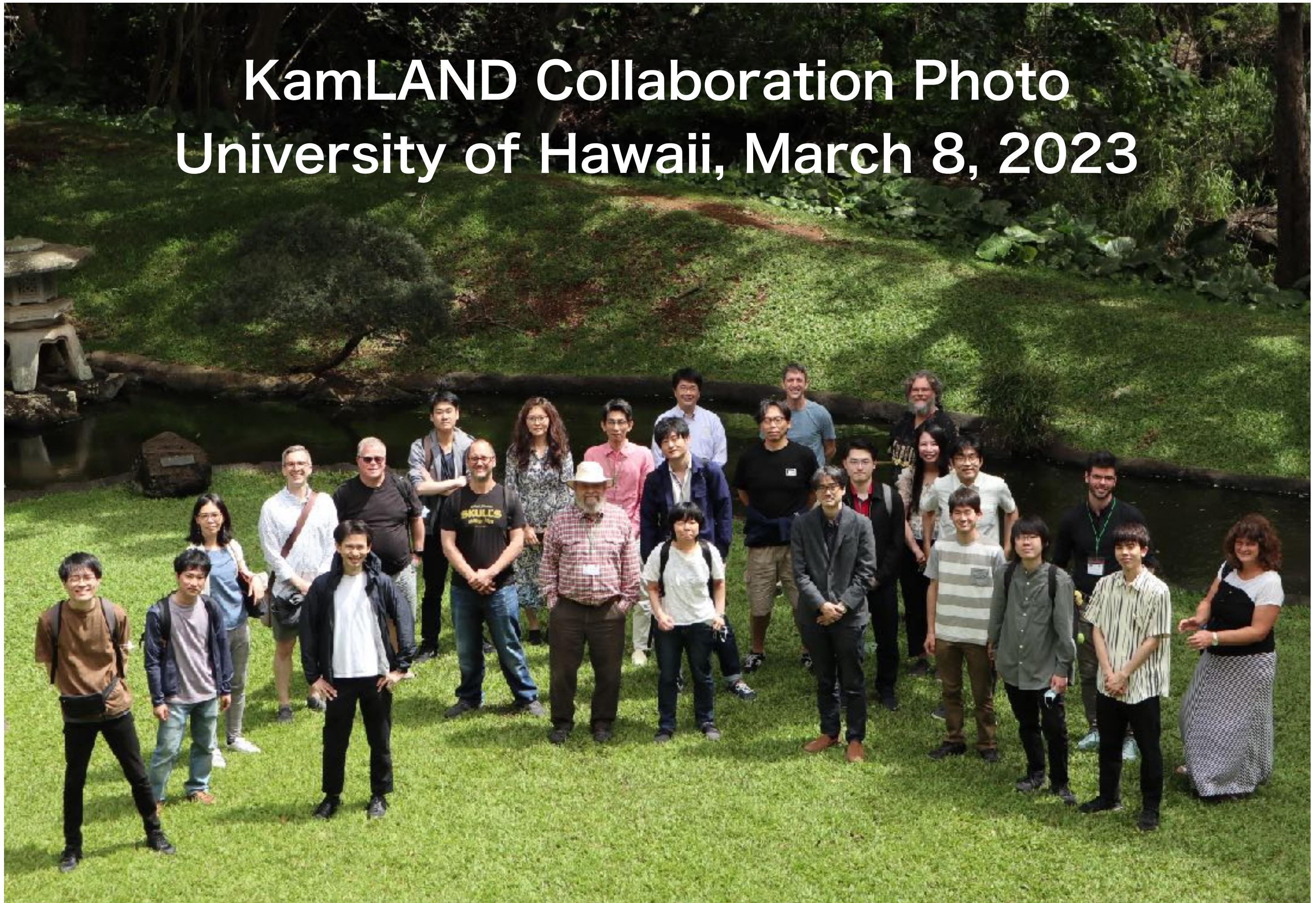
* Various packages and public data are used
 * Topics to be introduced later



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KamLAND(-Zen) Collaboration



KamLAND Collaboration Photo
University of Hawaii, March 8, 2023

> 50 researchers from Japan, USA, and Netherlands

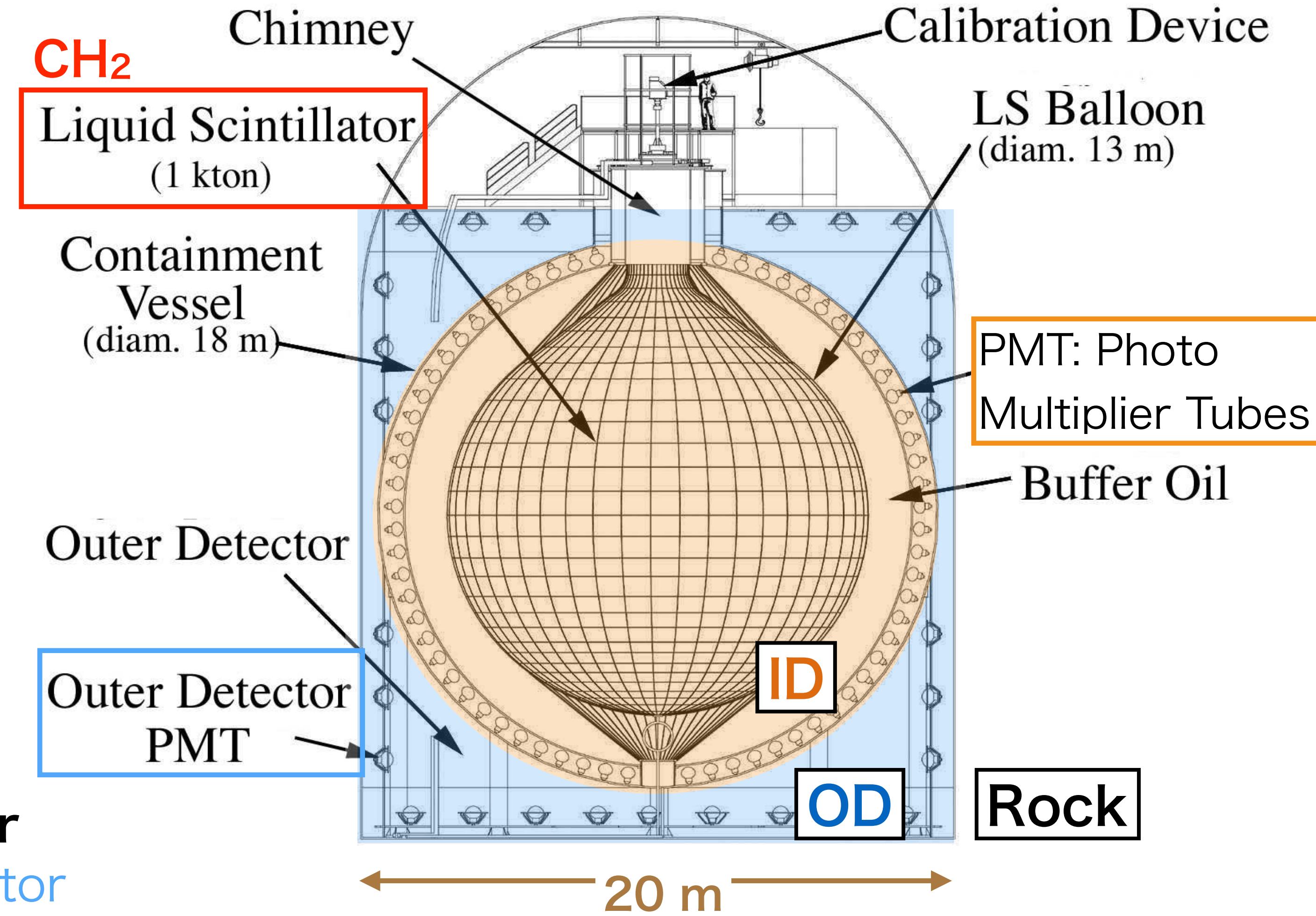
- $0\nu 2\beta$
- Geo, reactor, solar, and astrophysical neutrinos
- Spallation
- Neutrino interaction ← New!



KamLAND (KL) detector



- 1 kton LS: CH_2 ID: Inner Detector
- 3 kton Water Cherenkov veto counter OD: Outer Detector
- Light detection by the PMTs (ID/OD)
- Event reconstruction using time & charge Vertex, energy, etc.



Data set

- Jan. 2003 ~ May 2018: Livetime 10.7 years

Detection of atm. ν

Quite unique NCQE measurements!

Prompt signal

Energy deposition of charged particle → Scintillation

- Various particles can be detected **at low-E threshold**

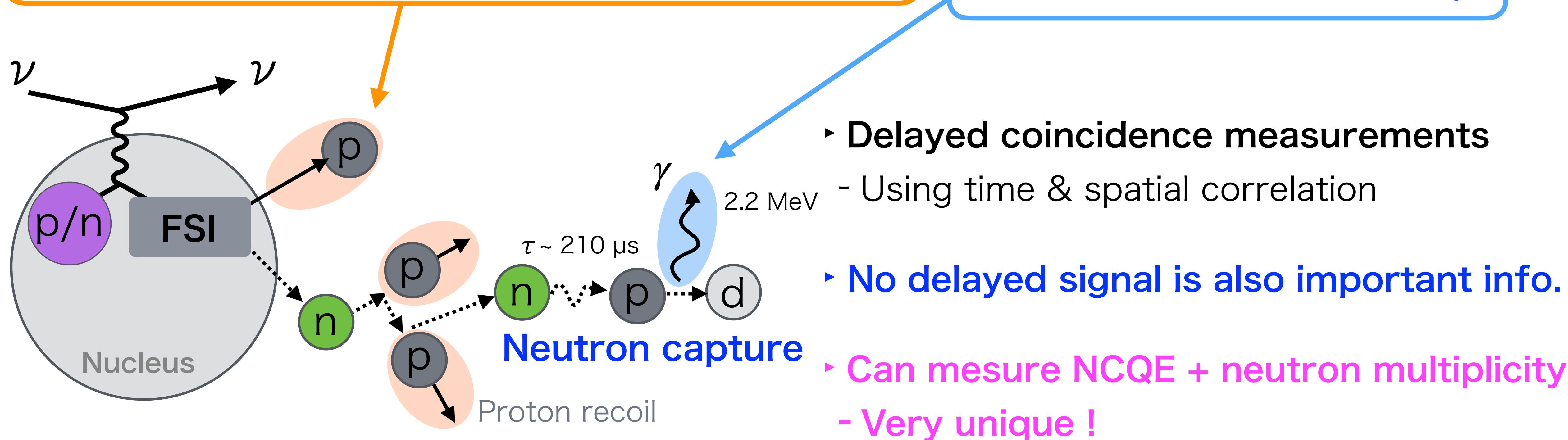
Mainly emitted by NCQE
Charged leptons, pions, protons, and neutrons

Delayed signal

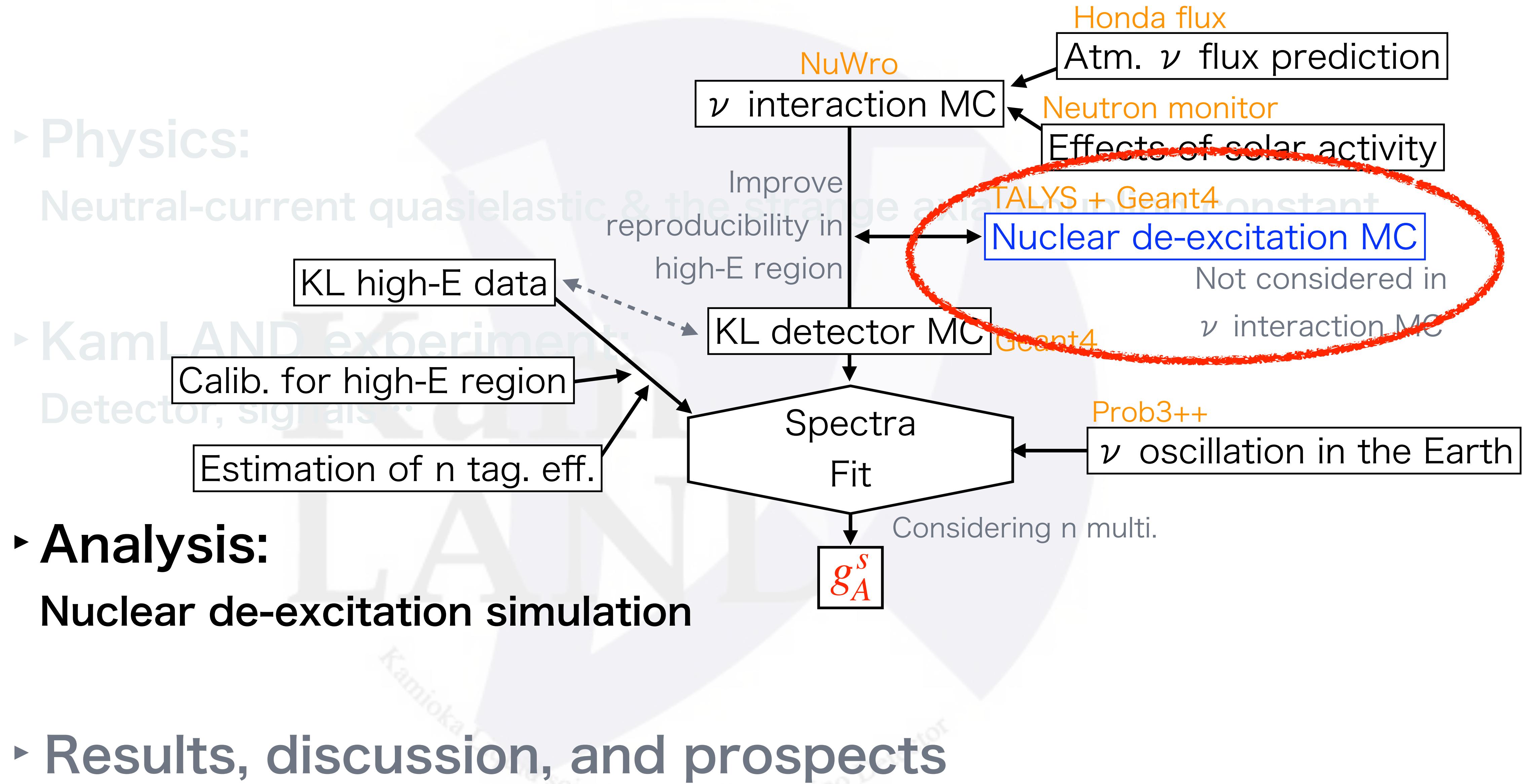
Neutron is captured by a proton

- Emitting 2.2 MeV gamma-ray

Unique signal → Identifiable.
KL achieves > 80% efficiency



Contents



ν interaction MC & nuclear de-excitation

Overview of the de-excitation & importance

Issue in the IA:

Nuclear de-excitation is not considered

Note: KL target is CH_2 . Let me focus on ^{12}C

High excitation E for $s_{1/2}$ -hole

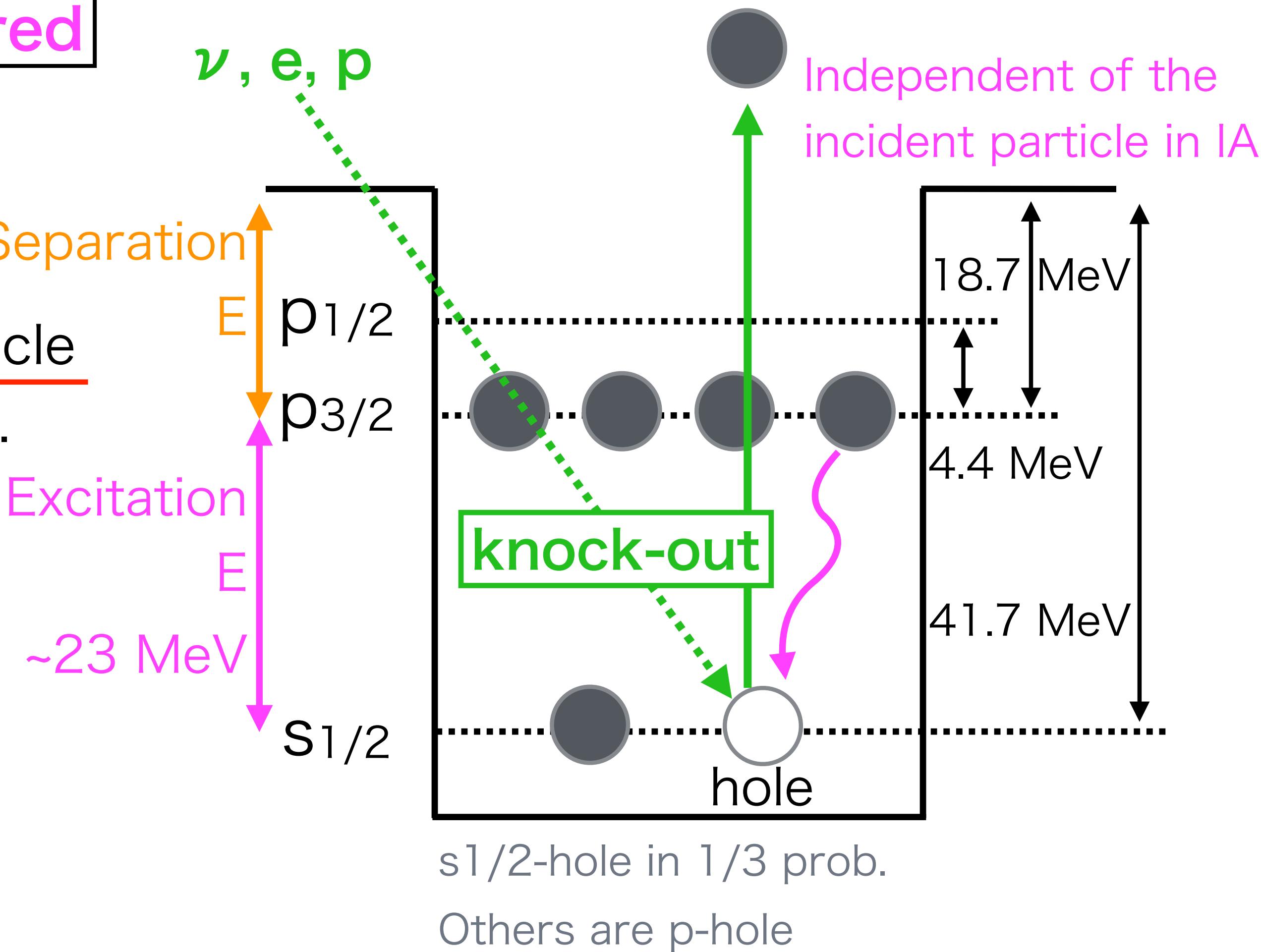
- Higher than the sep. E \rightarrow Emit various particle
neutron, proton, etc.



- Must be considered in any exp. to measure n mutli.
- Develop de-excitation MC. Added to the IA description.

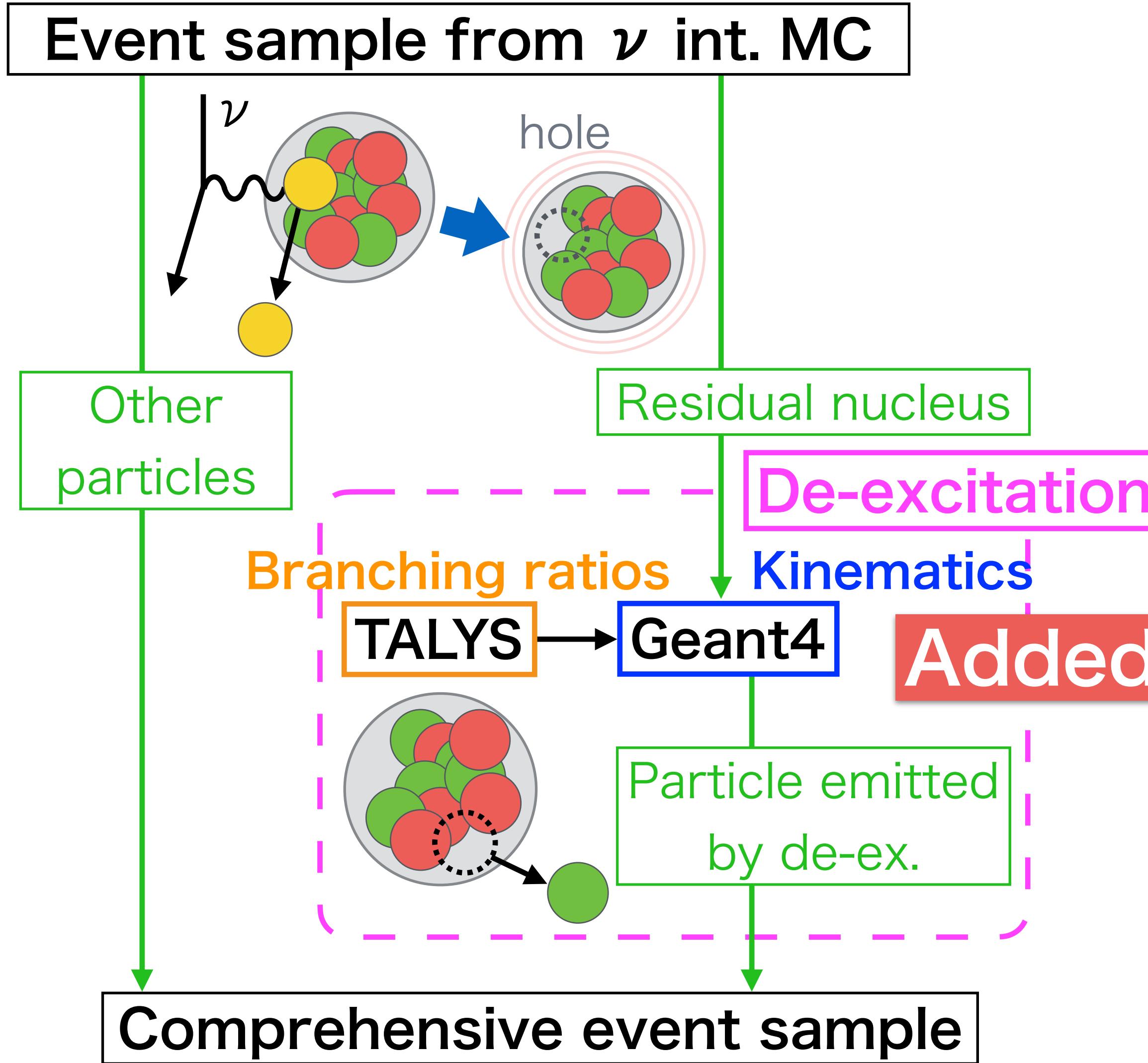
Note) ^{12}C $s_{1/2}$ -hole is discussed

^{12}C neutron $s_{1/2}$ -hole



How to describe the de-excitation process

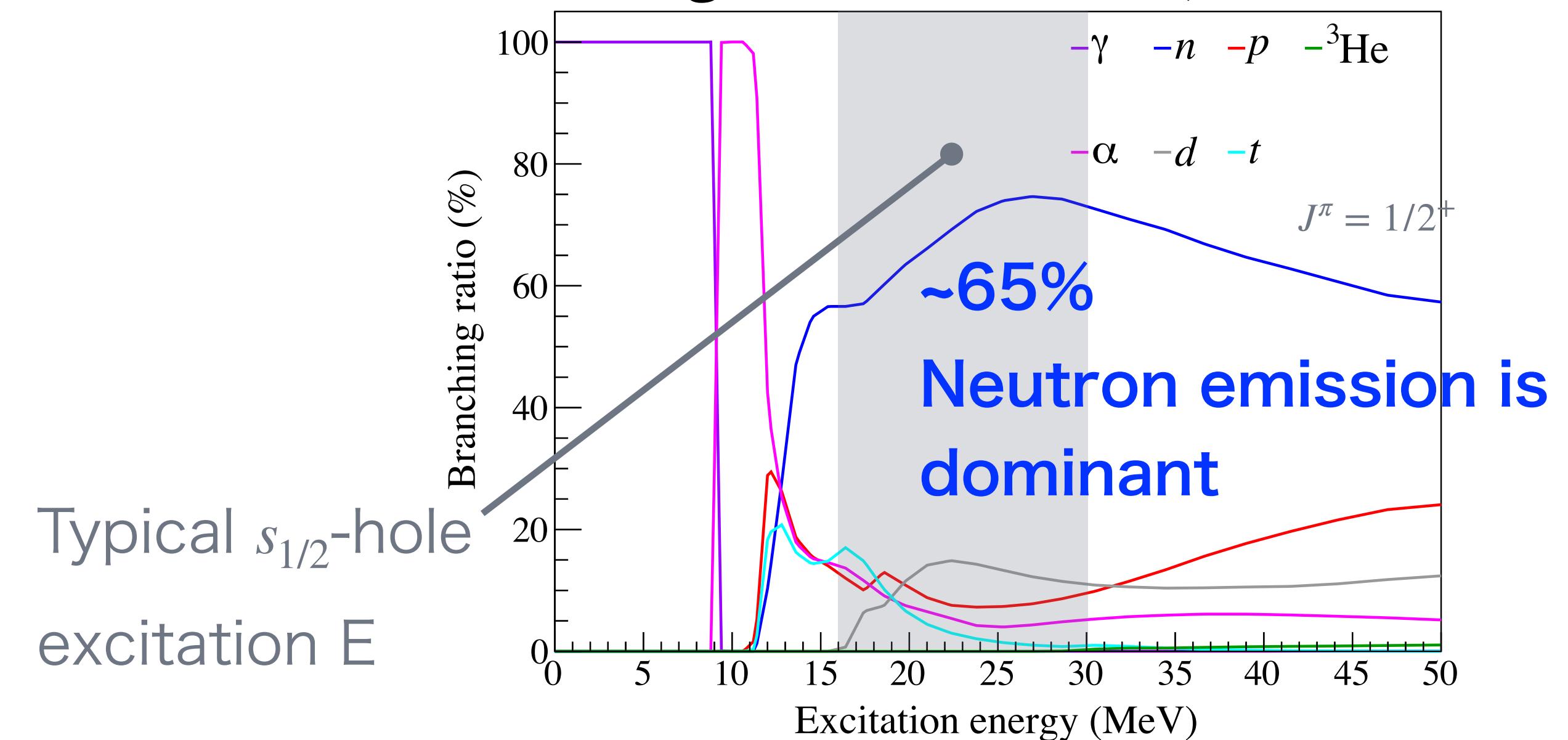
Derived from ν int. MC using two software
Geant4 & TALYS



TALYS: Calculate branching ratios

- Include precise nuclear models

Branching ratio for $^{11}\text{B}^*$ (from TALYS)



Geant4: Calculate kinematics

- Determine particle energy and momentum.
- Smaller energy than knock-out particles

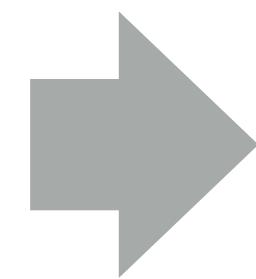
→ Derived smoothly from ν int. MC

Evaluate the validity and accuracy

Compare with exp. data and other predictions

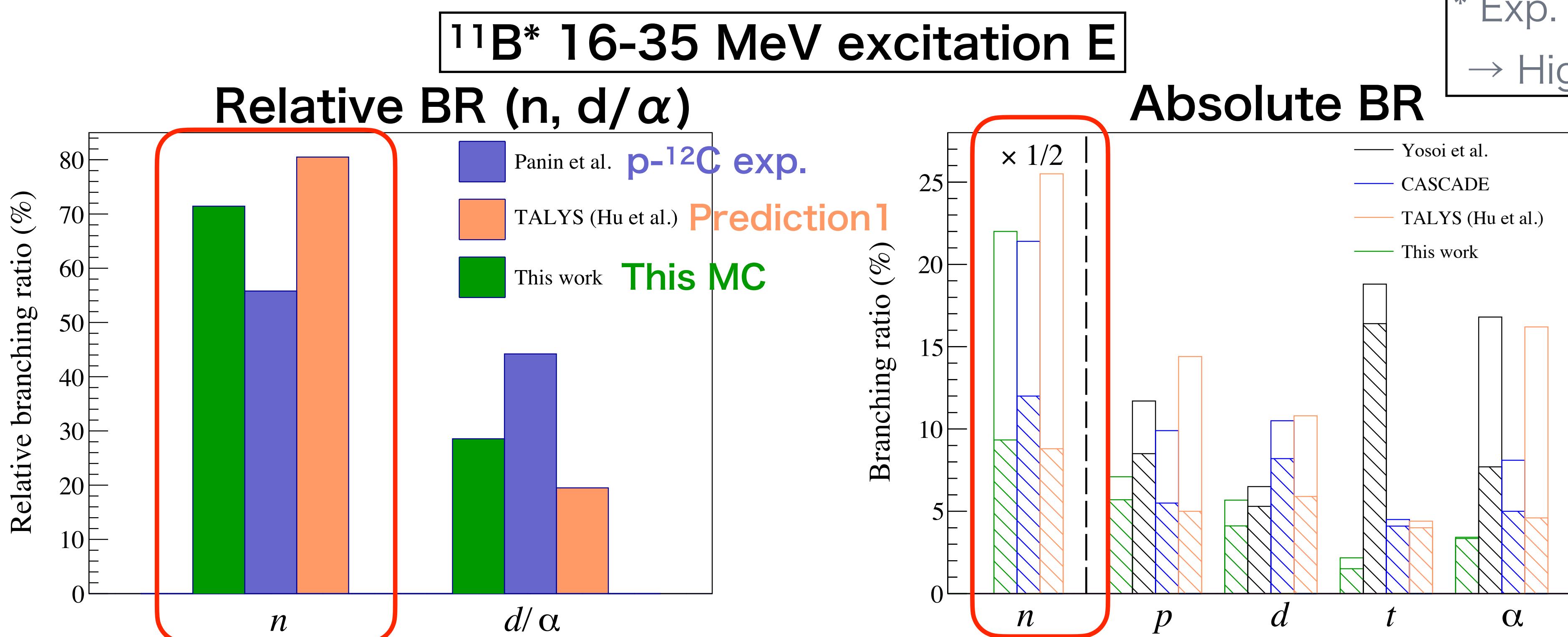
$^{11}\text{B}^*$ s-hole excitation E range

- Neutron BR: Consistent w/ ~20%
Satisfy the requirements of this study
- Some other modes do not agree, but they do not affect neutron emission much.



- Sufficient accuracy
- Differences are considered as systematic errors in the final analysis

* Exp. use ~400MeV beam
→ High enough to assume the IA



Model configuration & Systematic uncertainties

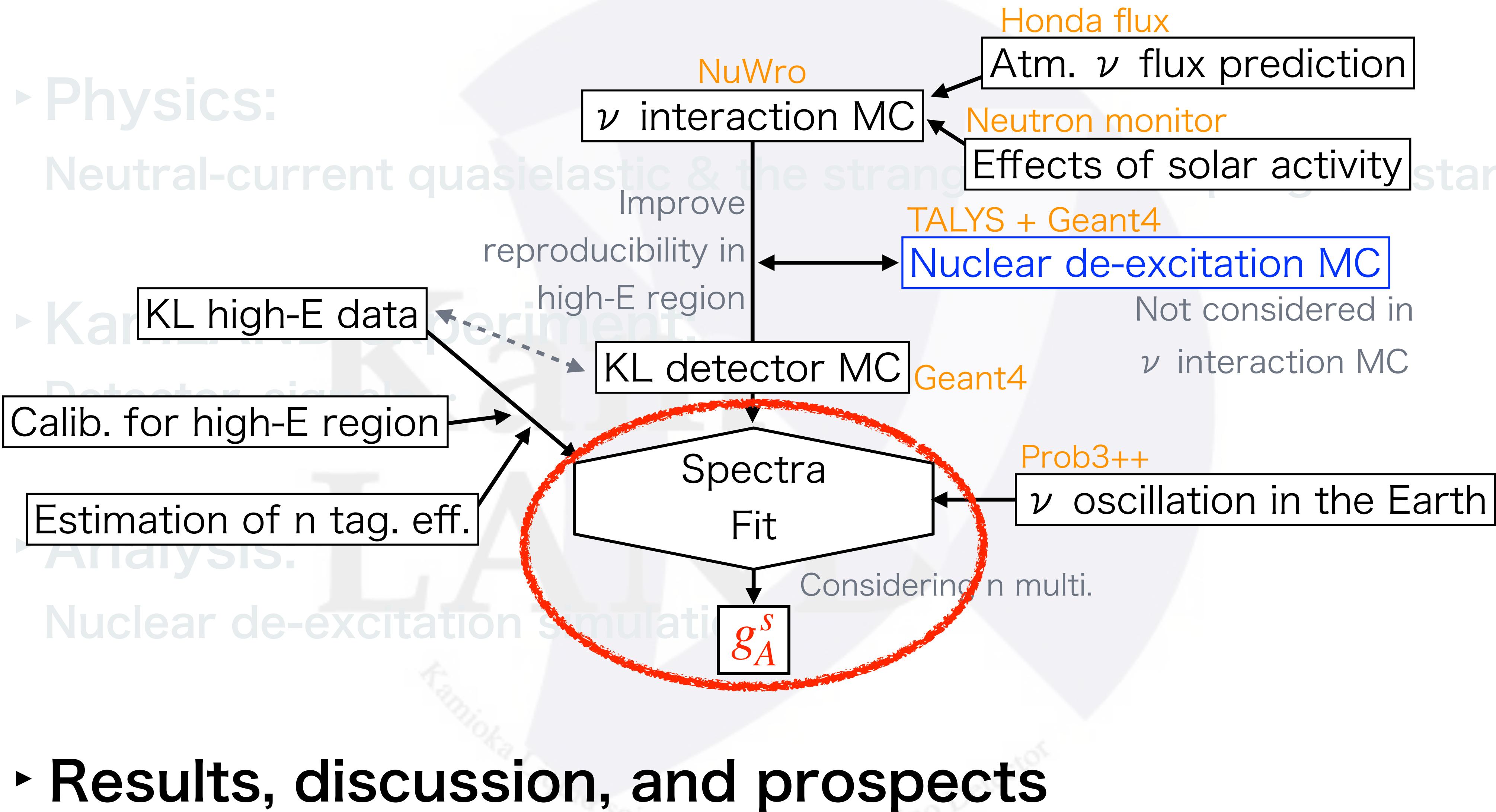
Neutrino MC generator: NuWro version 21.09

The default setting except 2p2h model.

		Model/Param.	Citation and comments
QE	Vector form factors	BBBA05	Nucl. Phys. B, Proc. Suppl 159, 127 (2006) Strange is neglected (assumed to be zero) ¹
2p2h	Cross section	TEM ²	Eur. Phys. J. C 71, 1726 (2011) 20% normalization uncertainty
	np pair fraction for CC³	$0.85^{+0.15}_{-0.20}$	Science 320, 1476 (2008) $\leftarrow e^{-12}C$ Phys. Rev. Lett. 97, 162504 (2006) $\leftarrow p^{-12}C$
RES		Adler-Rarita-Schwinger w/ dipole form	Phys. Rev. D 80, 093001 (2009)
FSI	Nucleon	Custom fit to PDG	Phys. Rev. C 100, 015505
	Pion	Salcedo et al.	Nucl. Phys. A484 (1988), p. 557 Large uncertainty ($\pm 50\%$ in FSI probability)

1. Discussion from polarized electron elastic-scattering experiments.
 - Phys. Rev. C 78, 015207 (2008)
2. Transverse Enhancement Model
3. For NC, it is $(2/p_{CC} - 1)^{-1}$ assuming the same fraction of nn and pp pairs.

Contents



How g_A^s affects the KL data

g_A^s : Change c.s. oppositely for p and n

- Proton : $\propto (+g_A - g_A^s)^2 = (g_A)^2 + (g_A^s)^2 - 2g_A g_A^s$
 - Neutron: $\propto (-g_A - g_A^s)^2 = (g_A)^2 + (g_A^s)^2 + 2g_A g_A^s$
- Pos. Neg.

Negative g_A^s : Large increase in zero n mutli.

(= no neutron)

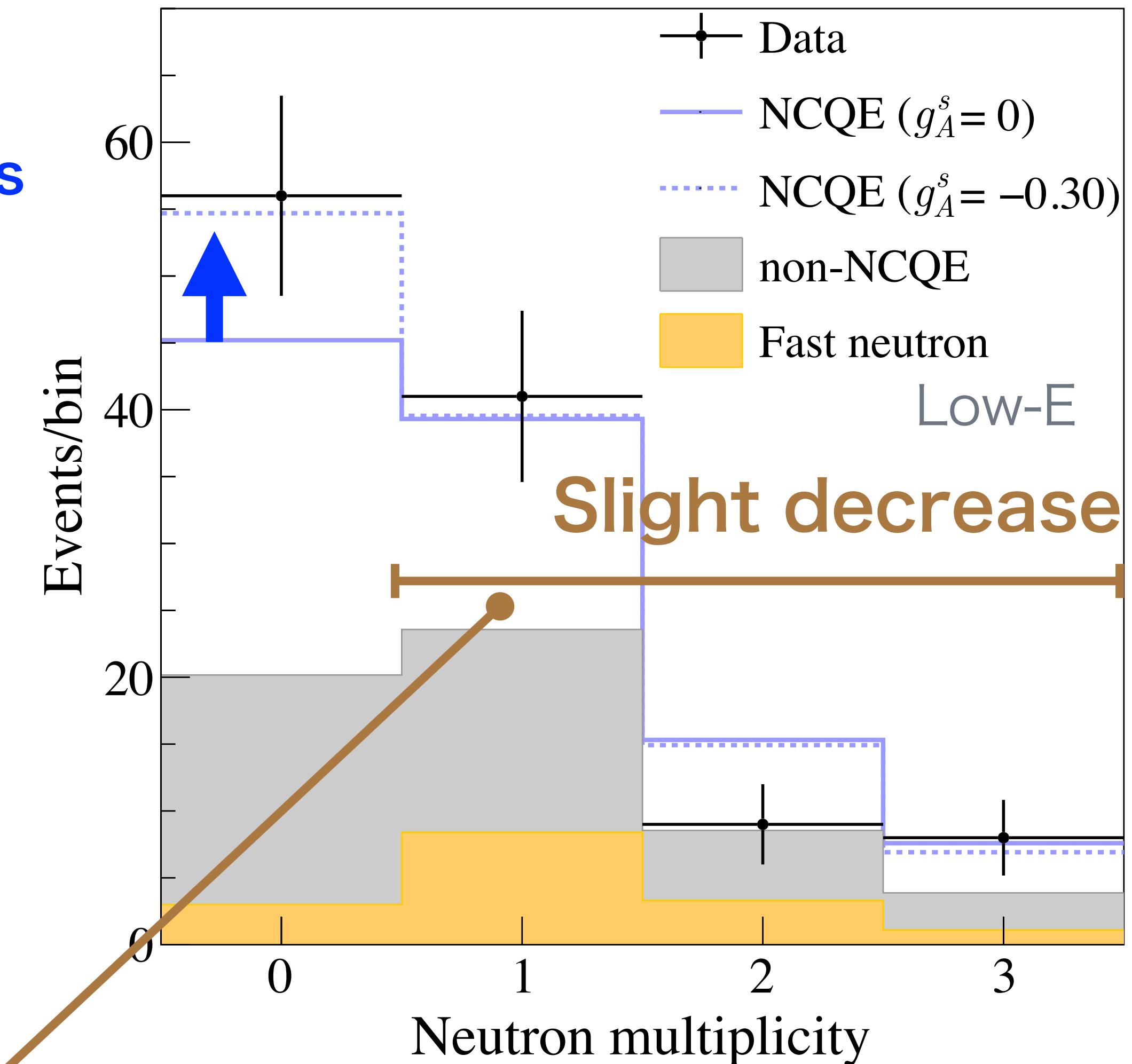
Increase p-target & decrease n-target

$| \text{Increase p-target} | > | \text{Decrease n-target} |$

CH₂

- ¹²C: Increase of p-target has more impact
- H₂: No nuclear effect → zero n multi.

¹²C dominant: Decrease of n-target
is cancelled by the larger increase
of p-target

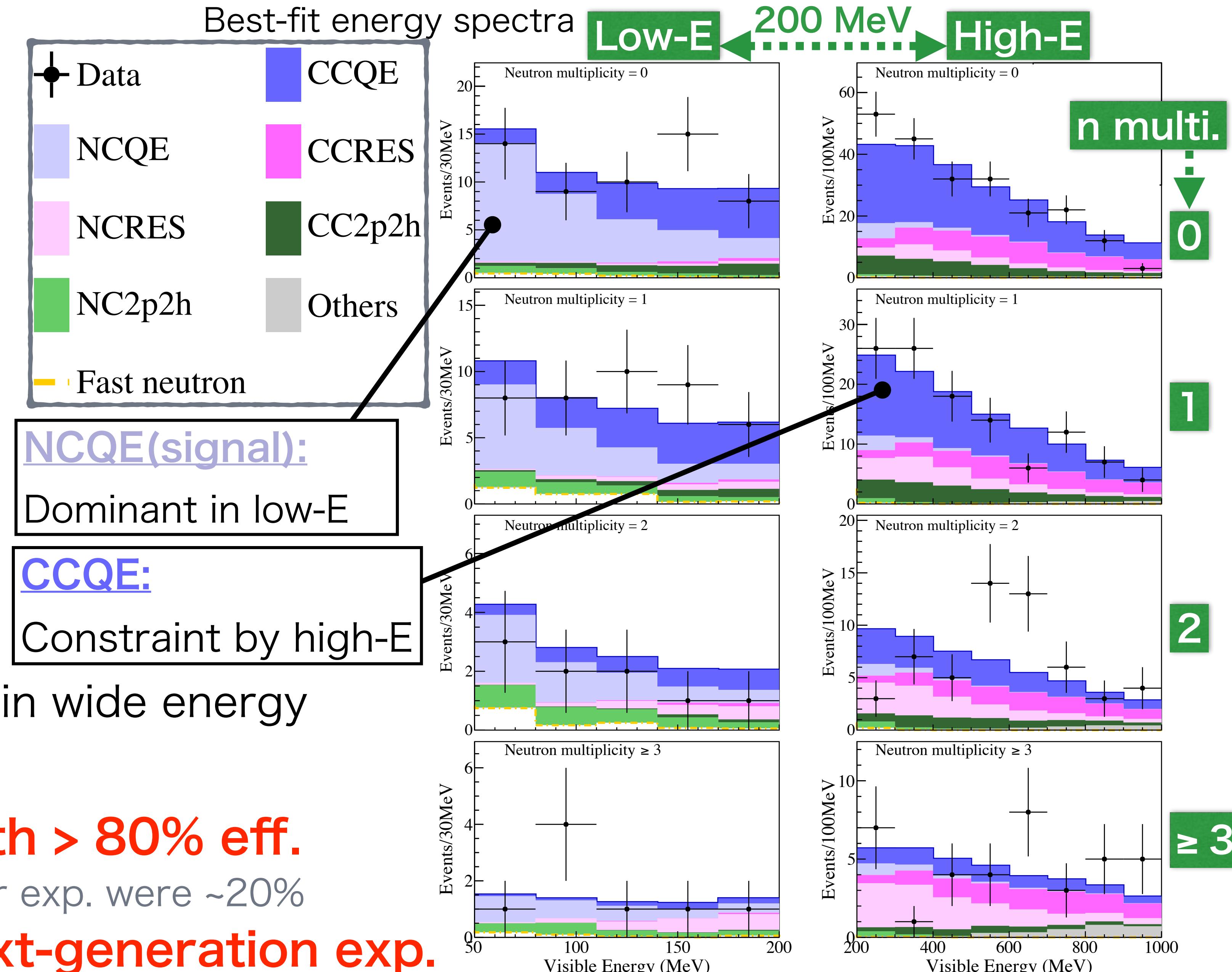


Distorts the shape of n mutli. distribution.
Cannot be explained by norm. (M_A)

Spectra fit considering n multi.

Poisson chi-square

- n multi. : 4 bins ($0, 1, 2, \geq 3$)
 → Sensitive to g_A^s
- Various systematic uncertainty



Results

KL's first measurement of g_A^s

This work

$$M_A = 0.86^{+0.31}_{-0.20} \text{ GeV}$$

$$g_A^s = -0.14^{+0.25}_{-0.26}$$

Ref.: MiniBooNE

$$M_A = 1.10^{+0.13}_{-0.15} \text{ GeV}$$

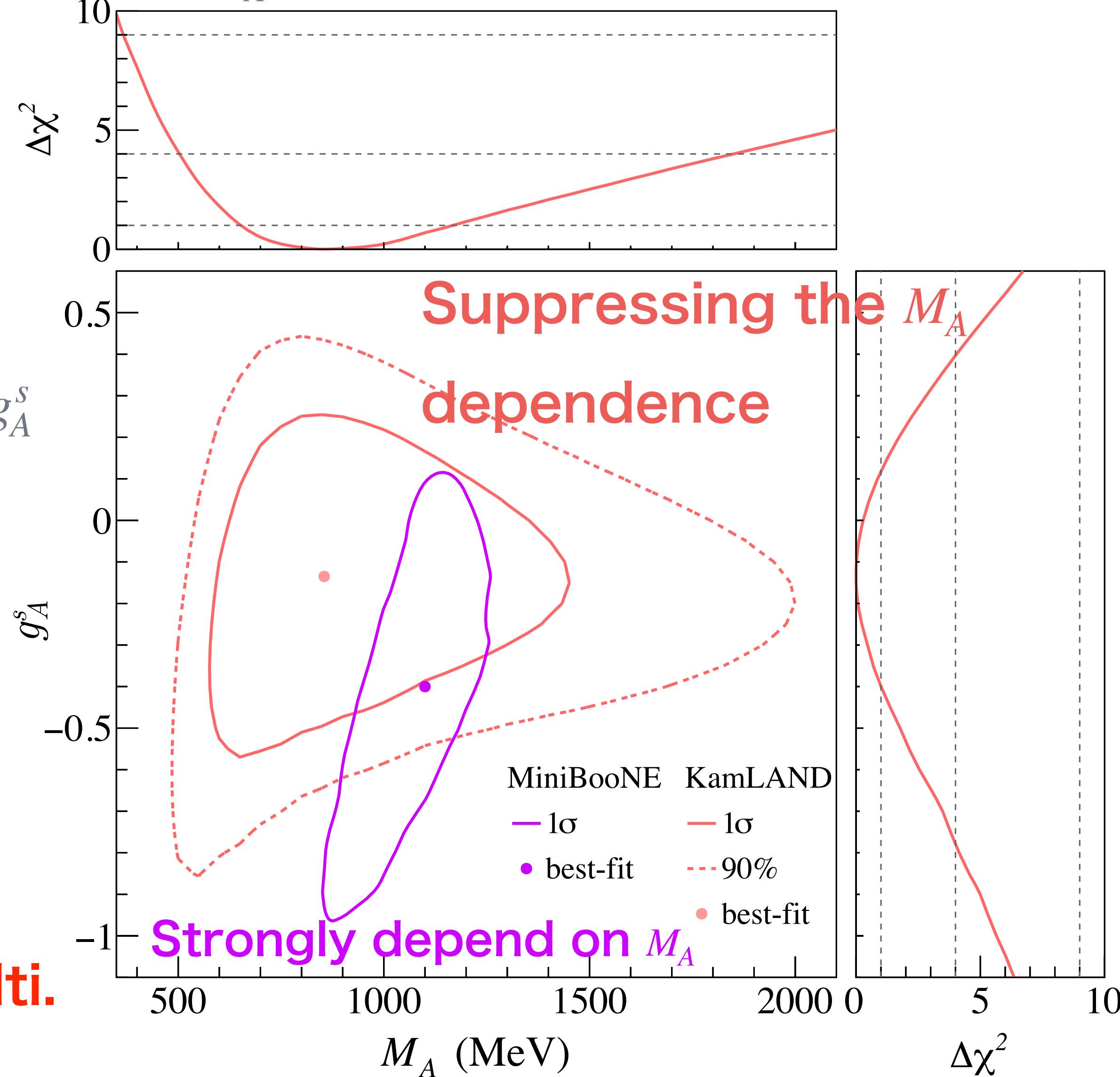
$$g_A^s = -0.4^{+0.5}_{-0.3}$$

Consistent

KL gives smaller err. on g_A^s

- Successfully suppressed dependence on M_A
 - Achieved by using n multi.
 - Essential now because of difficulty to set reasonable constraints on M_A
- World's first g_A^s measurement using n multi.
- New observable & techniques

M_A is treated as a free parameter



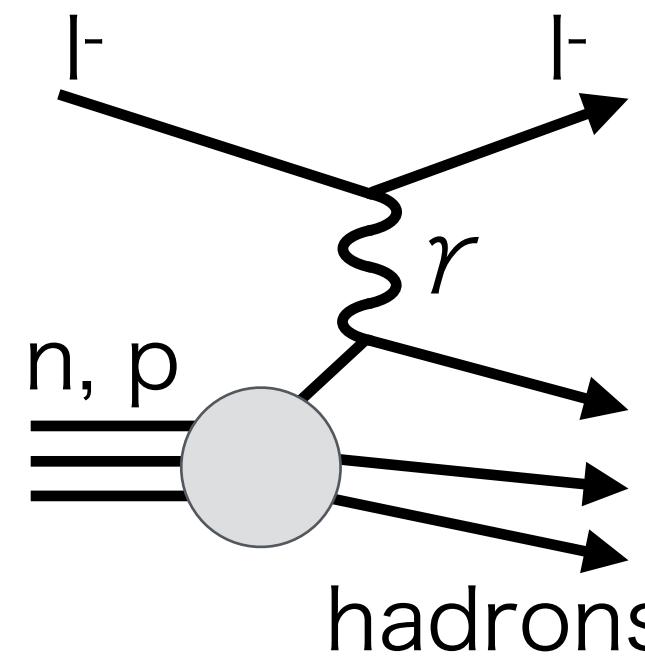
Summary of $s\bar{s}$ spin measurements

Probing the ultimate structure of matter

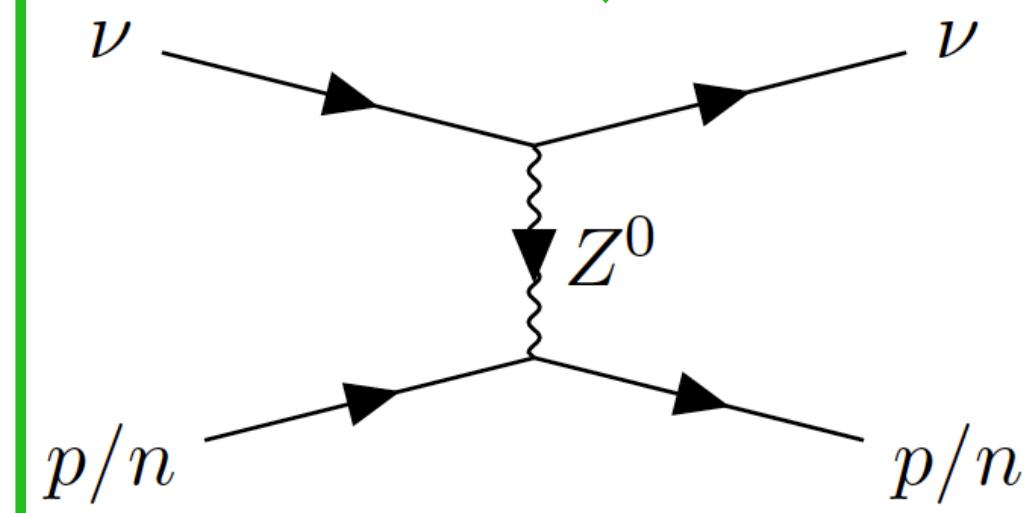
Negative

= Antiparallel to the proton spin

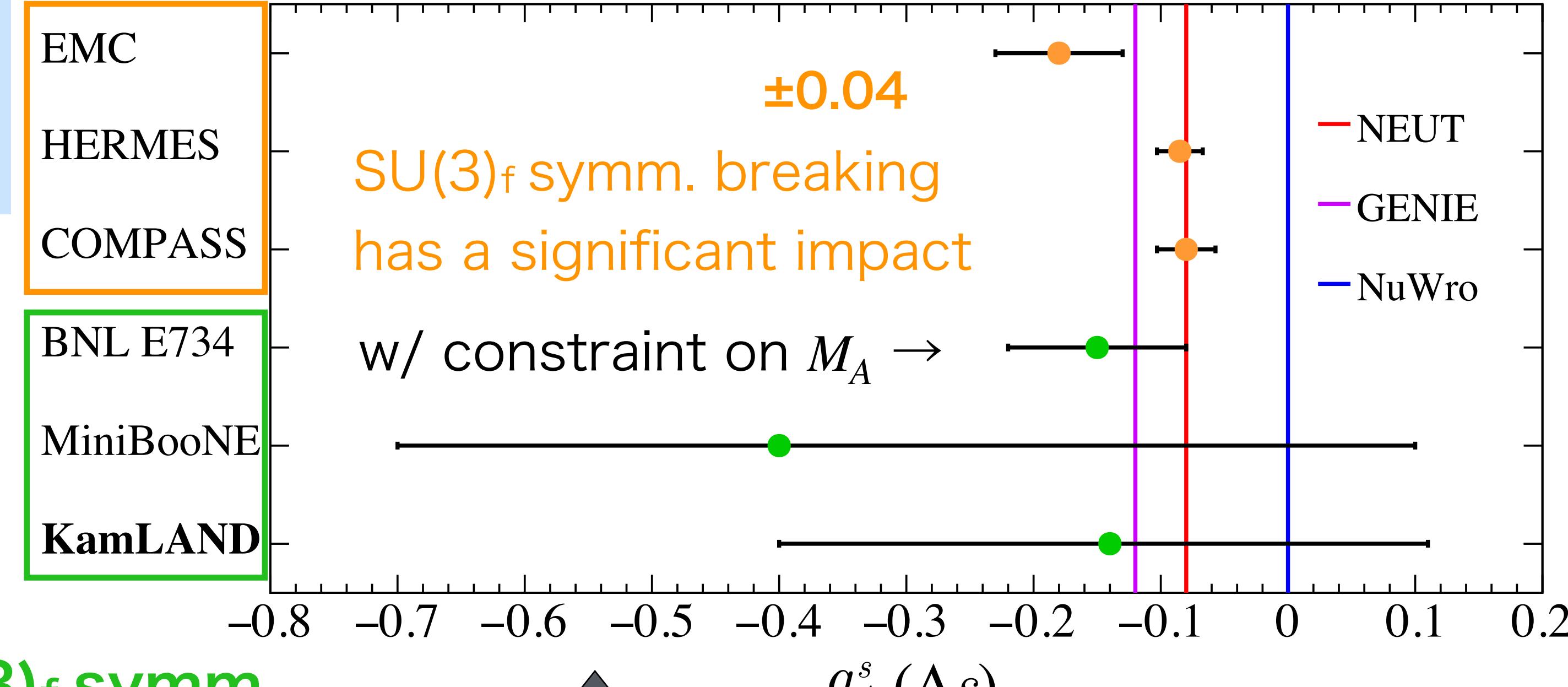
Polarized lepton-nucleon DIS



NCQE

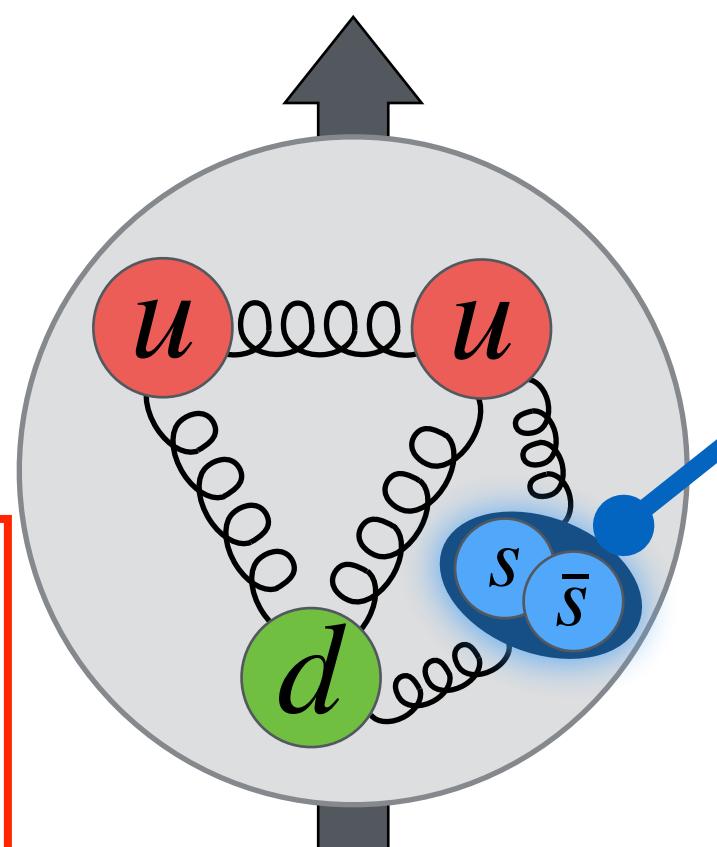


Independent of $SU(3)_f$ symm.
Difficult to constrain M_A



Significance of this study

- ▶ Independent of $SU(3)_f$ symm.
- ▶ Most accurate measurement w/ M_A free
- ▶ World's first g_A^s measurement using n multi.



Aim to be determined independently on $SU(3)_f$

Further increase in sensitivity is required

Future: Improve sensitivity & wide contribution

- Combined analysis w/ J-PARC ν
- Improve n tag eff.

- Use another electronics

- Improve FSI and de-ex. models

- Using e scattering data

g_A^S Determine the value

Probing the ultimate structure of matter

+ Precise prediction of NCQE c.s.

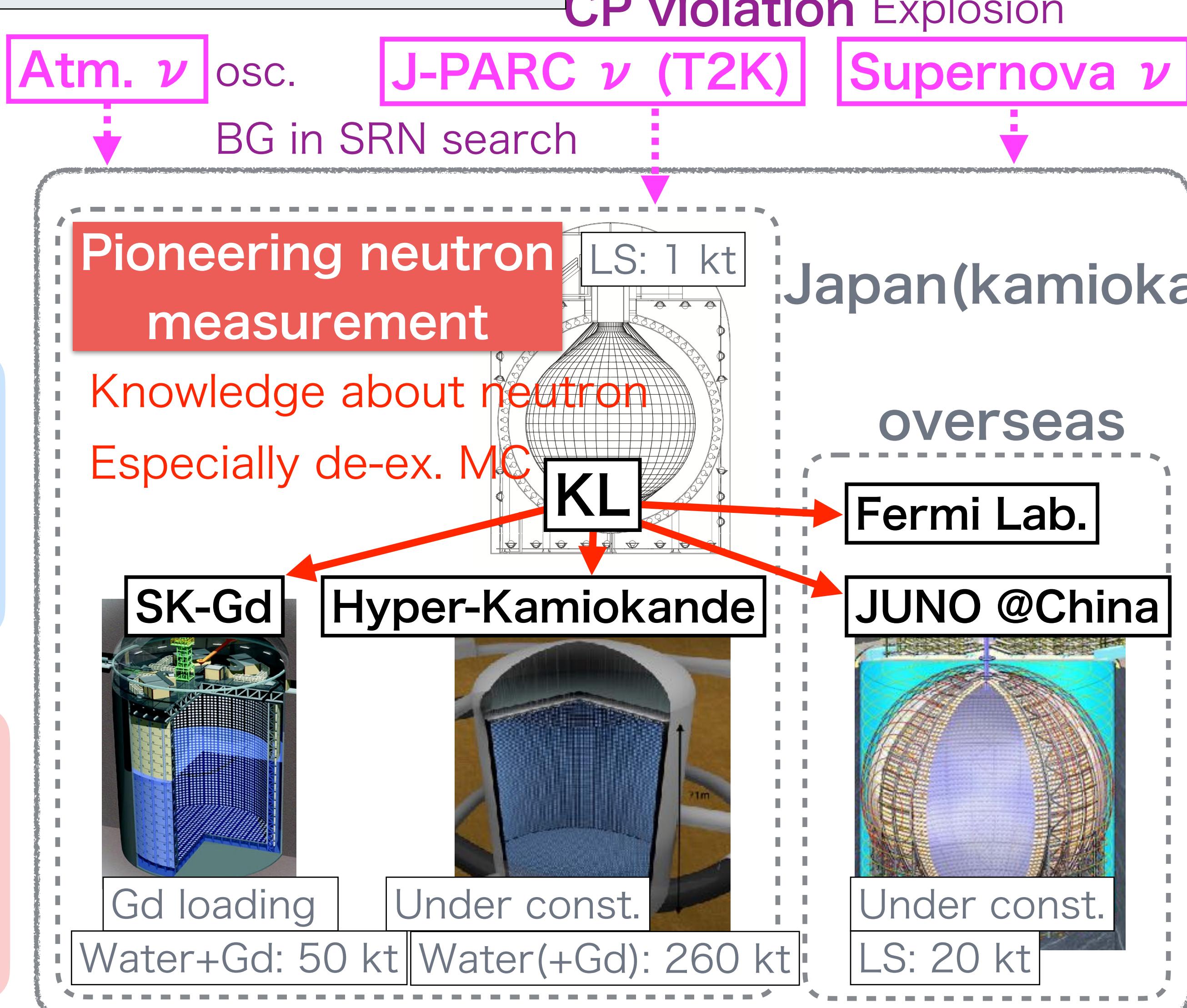
→ Toward the discovery of SRN

ν interaction Neutron!

Great knowledge of neutrons to next-generation detectors (especially de-ex. MC)

→ Contribute to various ν phys. studies!

Next-generation detectors:
Neutron-detectable!



Summary

Target

Probing nucleon structure → Measure g_A^s

s \bar{s} spin contribution

Prediction of n multi. → Develop de-excitation MC

Add to the IA description

Using neutron multiplicity with NCQE → Suppress dependence on M_A

New idea! First attempt to use new observable!

- Measure atm. ν and associated neutron multiplicity using KamLAND
- MC and data are consistent in wide energy region & n multi.

Conclusion

$g_A^s = -0.14^{+0.25}_{-0.26}$: Most accurate measurement w/ M_A free
 + World's first g_A^s measurement using n multi.

Prospects

- Various efforts for not only g_A^s measurements

but also for accurate prediction of ν int. Neutron multiplicity!