Search for proton decay via $p \rightarrow e^+\eta$ and $p \rightarrow \mu^+\eta$ in Super-Kamiokande

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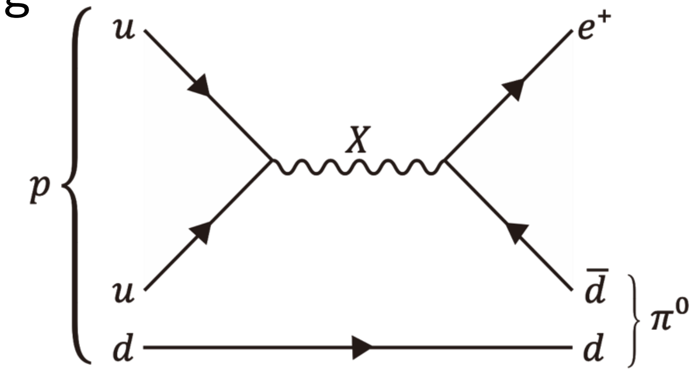
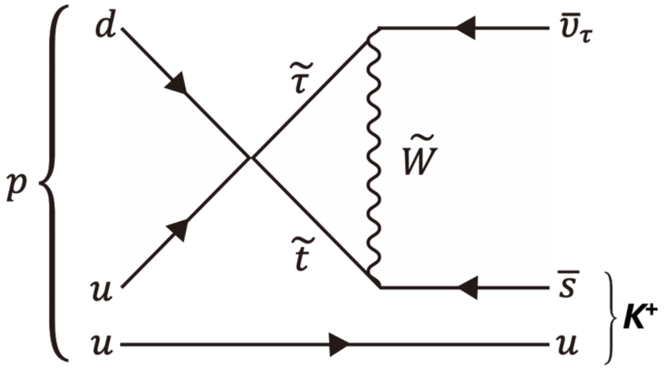
Proton Decay — Key to Probe GUTs

- Grand Unified Theories [1]: Unification of Electromagnetic, weak and strong.
  - ✓ Extension of SM by incorporating SU(3)×SU(2)×U(1) into larger symmetry groups
  - ✓ GUTs scale: ~10^{16} GeV
  - ✓ Baryon number violation allowed

- Proton decay search is the direct probe for GUTs.
  - ✓ Various decay channels depending on models [2]
    - Non-SUSY GUTs: $\boldsymbol{p \rightarrow e^{+}\pi^{0}}$
    - SUSY GUTs: $\boldsymbol{p \rightarrow \bar{\nu} K^{+}}$





[1] P. Nath and P. Fileviez Perez, Phys. Rep. 441, 191 (2007).
[2] N. Sakai and T. Yanagida, Nucl. Phys. B 197, 533 (1982).
J. Hisano, H. Murayama, and T. Yanagida, Nucl. Phys. B 402, 46 (1993).

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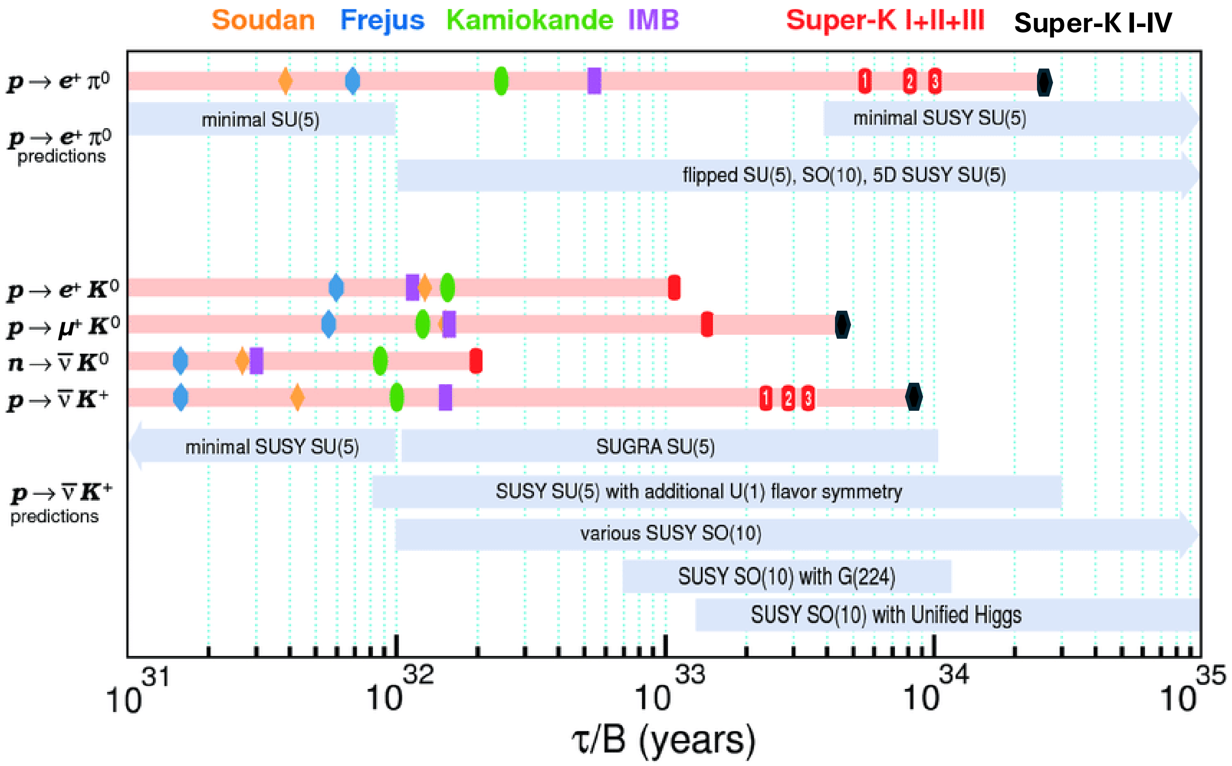
    - ○ Non-SUSY GUTs: $p \to e^+\pi^0$
    - ○ SUSY GUTs: $p \to \bar{\nu}K^+$
  - ✓ **Extremely long lifetimes**



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Various Decay Channels of Protons

- Other possible modes including heavy non-strange mesons. Some models [3] suggest decay rates comparable to $p \to e^+\pi^0$
  - ✓ $p \to l^+\eta$, $p \to l^+\rho$, $p \to l^+\omega$ ($l^+ = e^+, \mu^+$)
  - ✓ Latest search via these modes at Super-Kamiokande [4]

- **To tackle extremely rare searches**:
  - Large number of proton targets
  - High detection efficiency and Low BG
  - Comprehensive search via various decay channels in addition to "the golden channels"
- **$p \to e^+\eta$, $p \to \mu^+\eta$ searches at Super-Kamiokande**

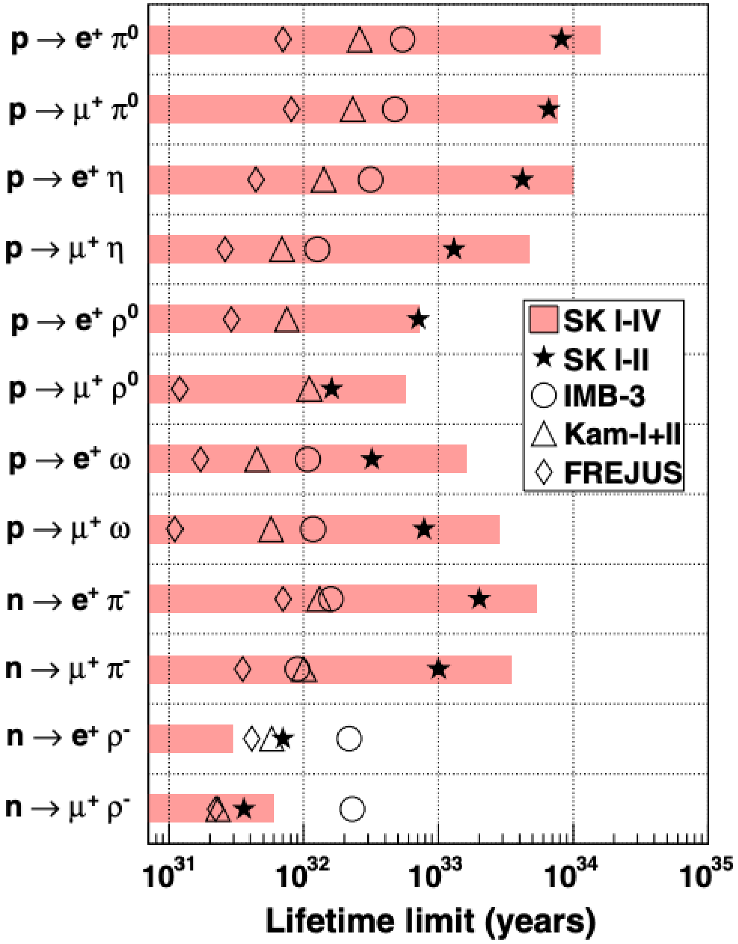


Fig. taken from [4]

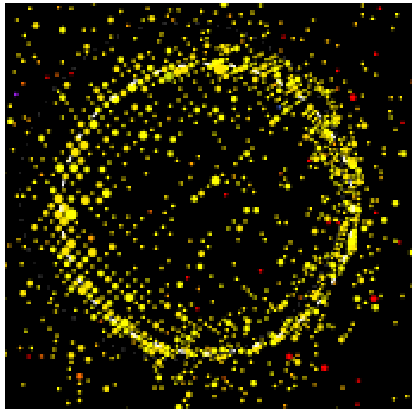
[3] M. Machacek, Nucl. Phys. B 159, 37 (1979)
M. B. Gavela, A. Le Yaouanc, L. Oliver, O. P`ene, and J. C. Raynal, Phys. Lett. B 98, 51 (1981).
J. F. Donoghue, Phys. Lett. B 92, 99 (1980).
[4] K. Abe et al. (The Super-Kamiokande Collaboration), Phys. Rev. D 96, 1 (2017).

Super-Kamiokande Detector

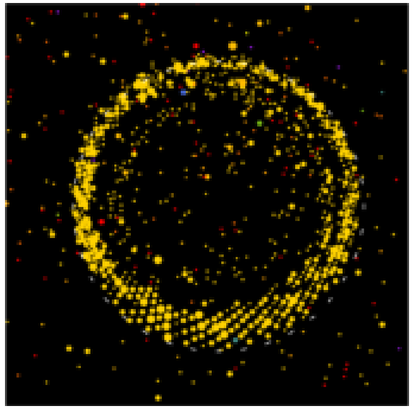
Nucleon **D**ecay **E**xperiment

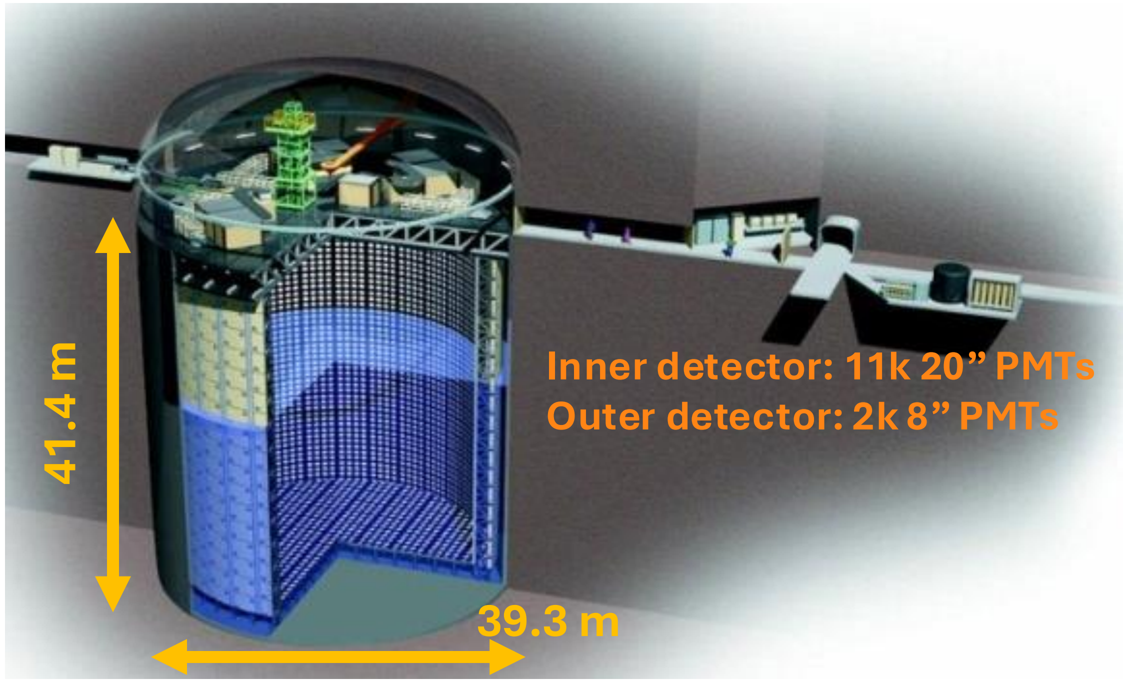
- 50 kton (22.5 kton fiducial) Water Cherenkov detector located at Kamioka mine, Japan.
  ~1000 m underground to reduce cosmic ray BGs.
- Particle Identification:
  - *e*-like: fuzzy rings (EM shower).
  - *μ*-like: rings with sharp edges.

e-like ($e\pm,\gamma$)



μ-like ($\mu^{\pm}$)



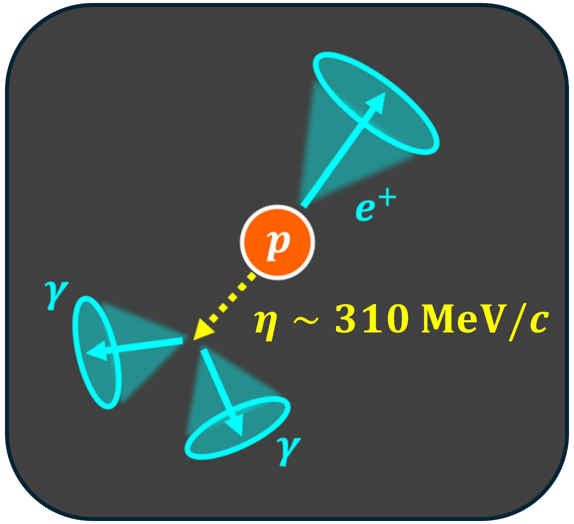


✓ 20+ years data from 1996 (Gd loaded from 2020)
✓ Advantage of free proton
✓ Neutron tagging available from SK-IV period (2008-)

Why eta?

- This Study: ***$p \to e^+\eta$, $p \to \mu^+\eta$ ($\eta \to 2\gamma$, $\eta \to 3\pi^0$)* search**
  - Similar to golden $p \to e^+\pi^0$: 3 *e*-like rings
  - High efficiency: all decay products are detectable
  - Back-to-back emission: monochromatic momentum of η (~310 MeV/*c*)

→ **Reconstruct proton mass and momentum.**



Why eta?

- This Study: ***p→e⁺η, p→μ⁺η (η→2γ, η→3π⁰)* search**
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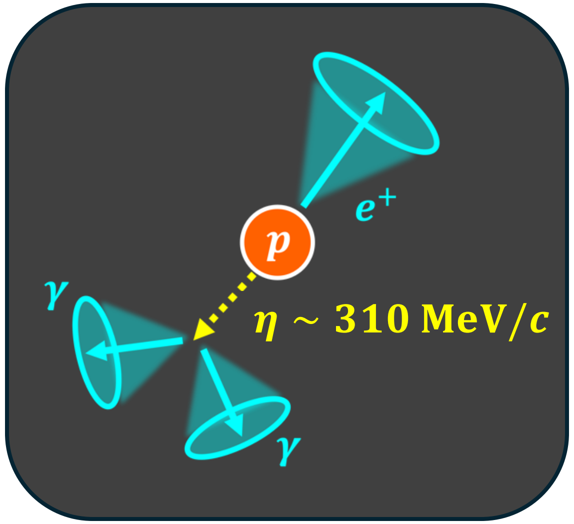


- Previous study [4]: $p \to e^+\eta$ *and* $p \to \mu^+\eta$ search with 0.316 Mton×years exposure
  - Dominant systematic uncertainty from nuclear effect modelling.

- This Study:
  - **Update eta-nuclear interaction** cross section
  - **Additional data of ~18%** Total of 0.373 Mton×yrs.

Modes	Meson nuclear effect	Hadron propagation in water	N-N correlated decay	Fermi momentum	Detector performances	Total
$p \to e^+\eta$ (2γ, upper)	26	...	8	9	2	29
$p \to e^+\eta$ (2γ, lower)	9	...	3	13	2	16
$p \to e^+\eta$ ($3\pi^0$)	12	...	4	15	4	20
$p \to \mu^+\eta$ (2γ, upper)	27	...	9	10	3	30
$p \to \mu^+\eta$ (2γ, lower)	11	...	3	12	3	17
$p \to \mu^+\eta$ ($3\pi^0$)	17	...	6	2	5	19

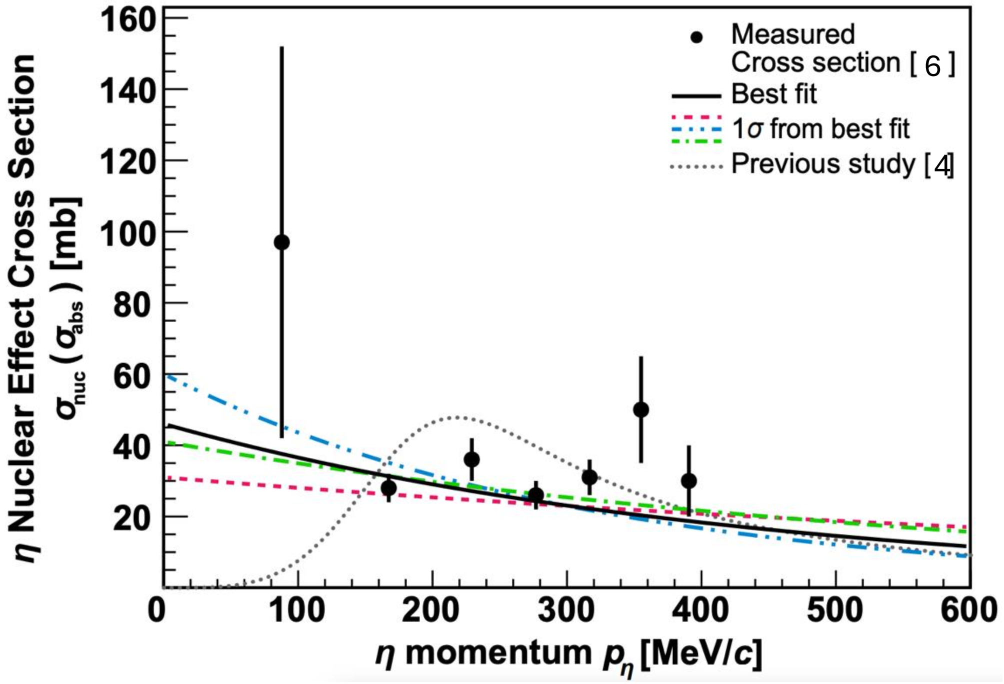
[4] K. Abe et al. (The Super-Kamiokande Collaboration), Phys. Rev. D 96, 1 (2017).

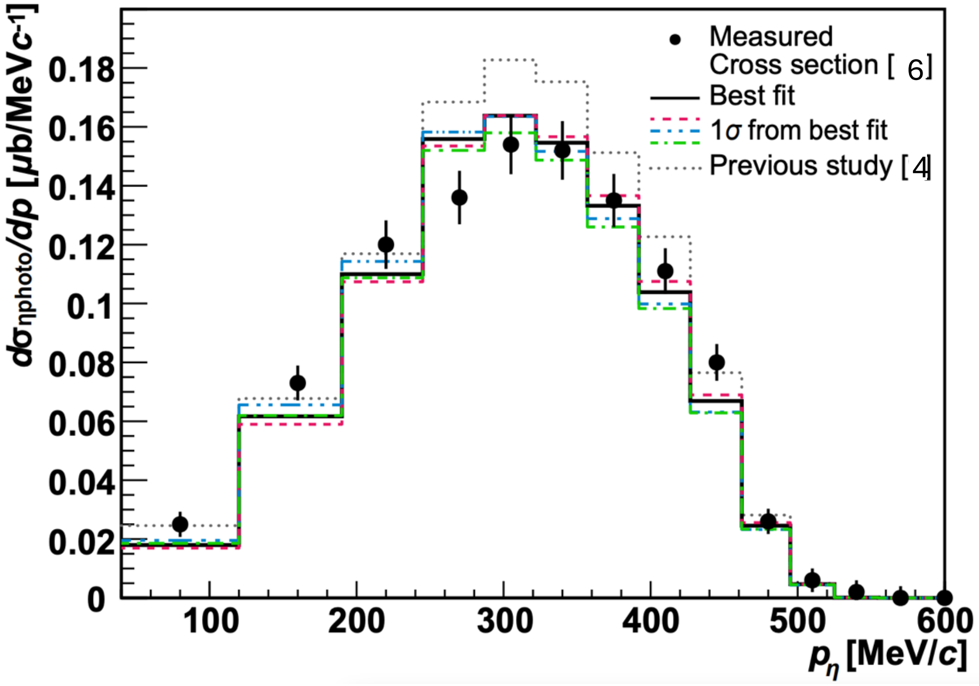
Improved σ_{nuc} Estimation and Uncertainty

- Assume σ_{nuc} as a function of η momentum lab. frame: $\sigma_{nuc} = a \times \exp(-b \times p_\eta)$
- σ_{nuc} and uncertainty estimated by least χ^2 method to fit functional forms to measured $d\sigma_{\eta photo}/dp$ and σ_{abs}
- **Improvements both in signal efficiency (~10%) and a reduction in this previously dominantly sys. uncertainty by ~65%**

*Additional 6% systematic errors on data points not shown in figures.

[6] M. R¨obig-Landau, et al., Phys. Lett. B 373, 45 (1996).





Event Simulations

- **Signal: Proton decay MC**
  - 2 free protons: two body decay, distinct signal
  - 8 bound protons in O nuclei:
    - Subject to Fermi motion, nuclear binding energy, and correlated momentum effects
    - Nuclear effects (deexcited nuclear γ, absorption, scattering)

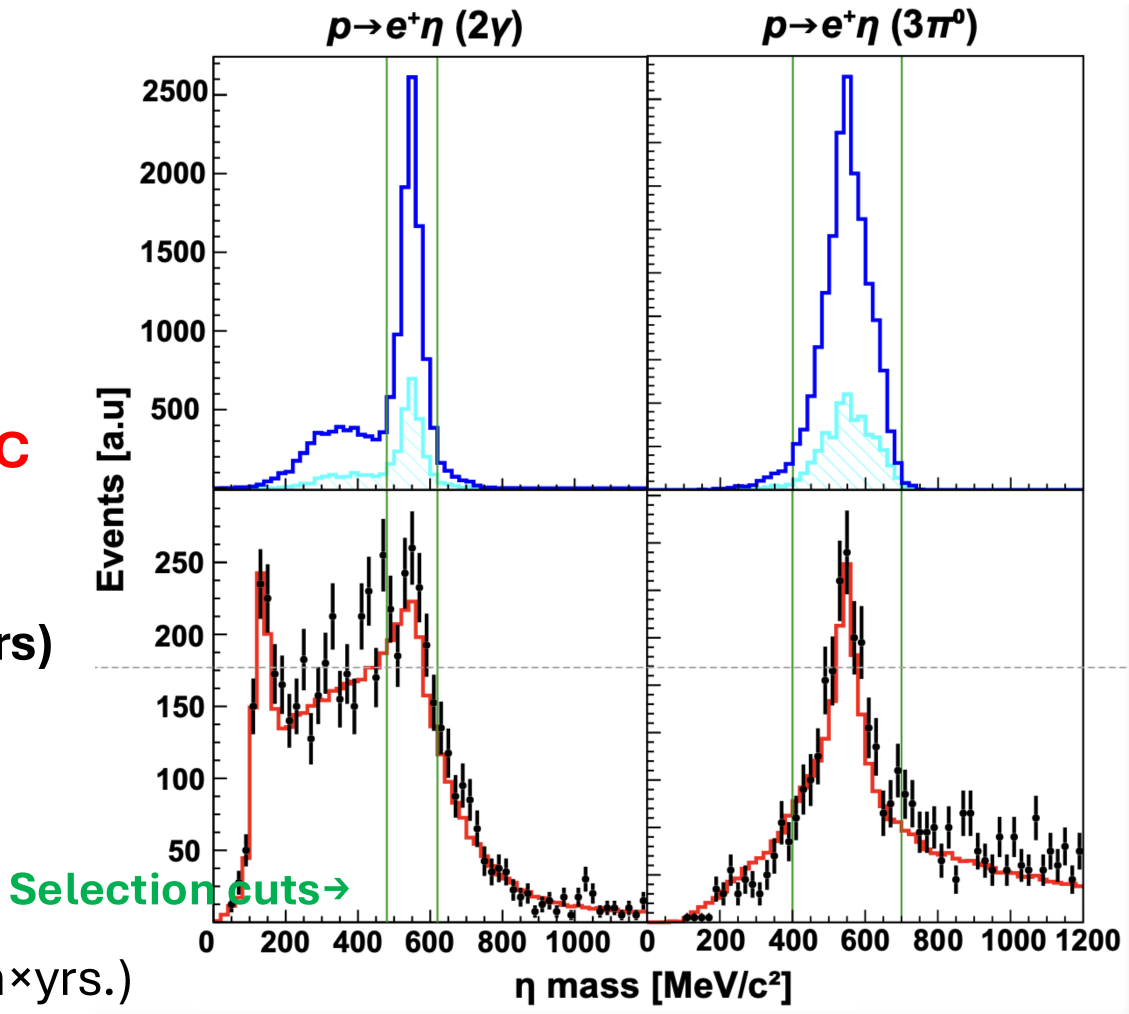
- **Background: Atmospheric ν MC**
  - Flux taken from Honda calculation [7]
  - Meson production (ex. π, η) from atmospheric neutrino interactions in water simulated by NEUT by the Rein-Sehgal Model [8].

[7] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Phys. Rev. D 75, 1 (2007).
M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, Phys. Rev. D 83, 1 (2011).
[8] D. Rein and L. M. Sehgal, Ann. Phys. (N. Y.) 133, 79 (1981).

Event Selections

- 2 proton decay channels: ***p→e⁺η, p→μ⁺η***
- 2 eta decay channels: ***η→2γ, η→3π⁰***
- Event selection cuts on:
  - Number of rings
  - PID
  - Number of Michel e
  - η mass
  - Proton momentum
  - Proton mass

Proton decay MC (bound/free)
Atmospheric ν MC (2000 years)
Data (0.373 Mton*years)

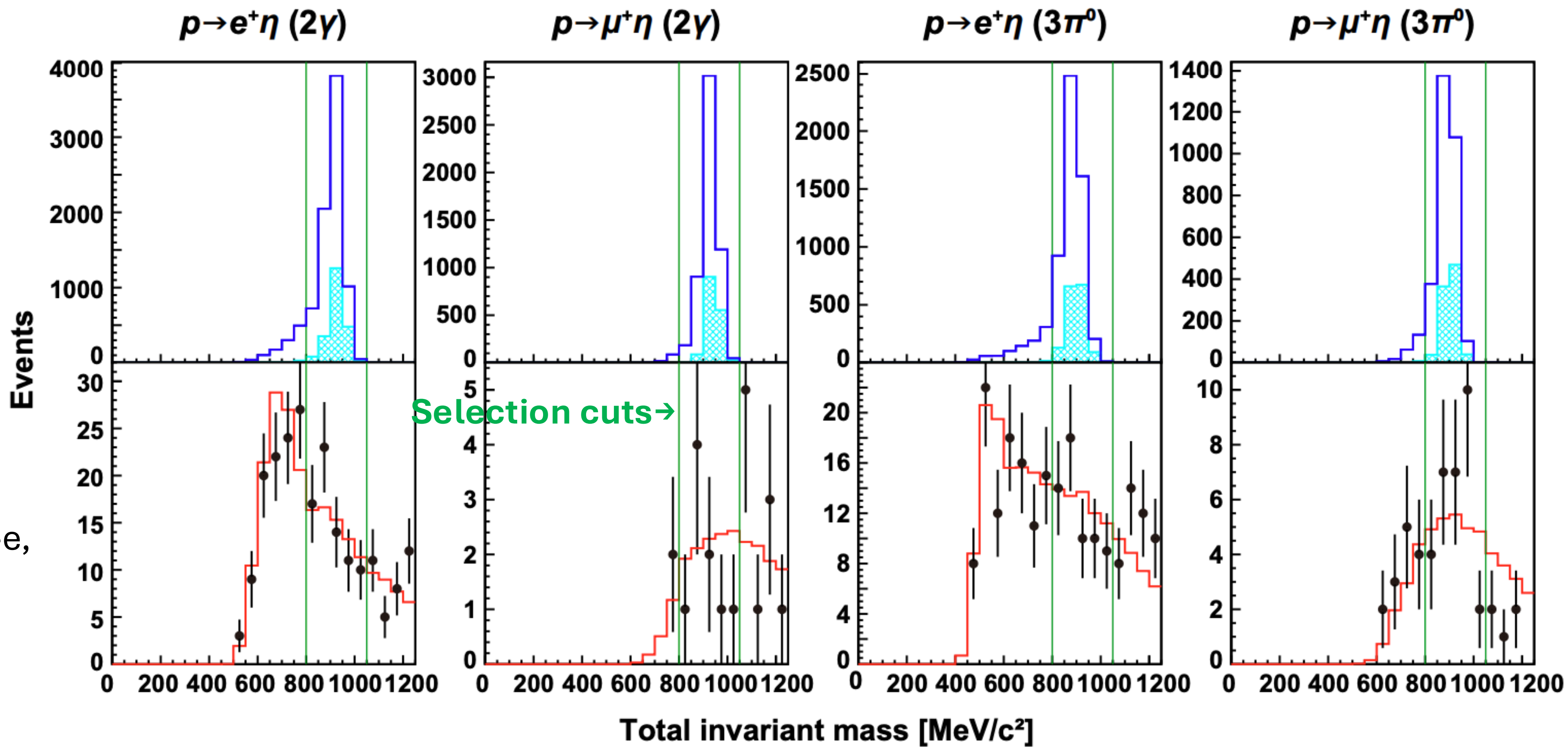


- **Two signal bins defined for p→l⁺η (η→2γ) depending on p momentum**
- P_{proton} < 100 MeV/c expects BG rate of <<0.1 (0.373 Mton×yrs.)

Data Agreement Check: Proton Mass

Proton decay MC (bound)
Proton decay MC (free)
Atmospheric ν MC (2000 years)
Data (0.373 Mton*years)

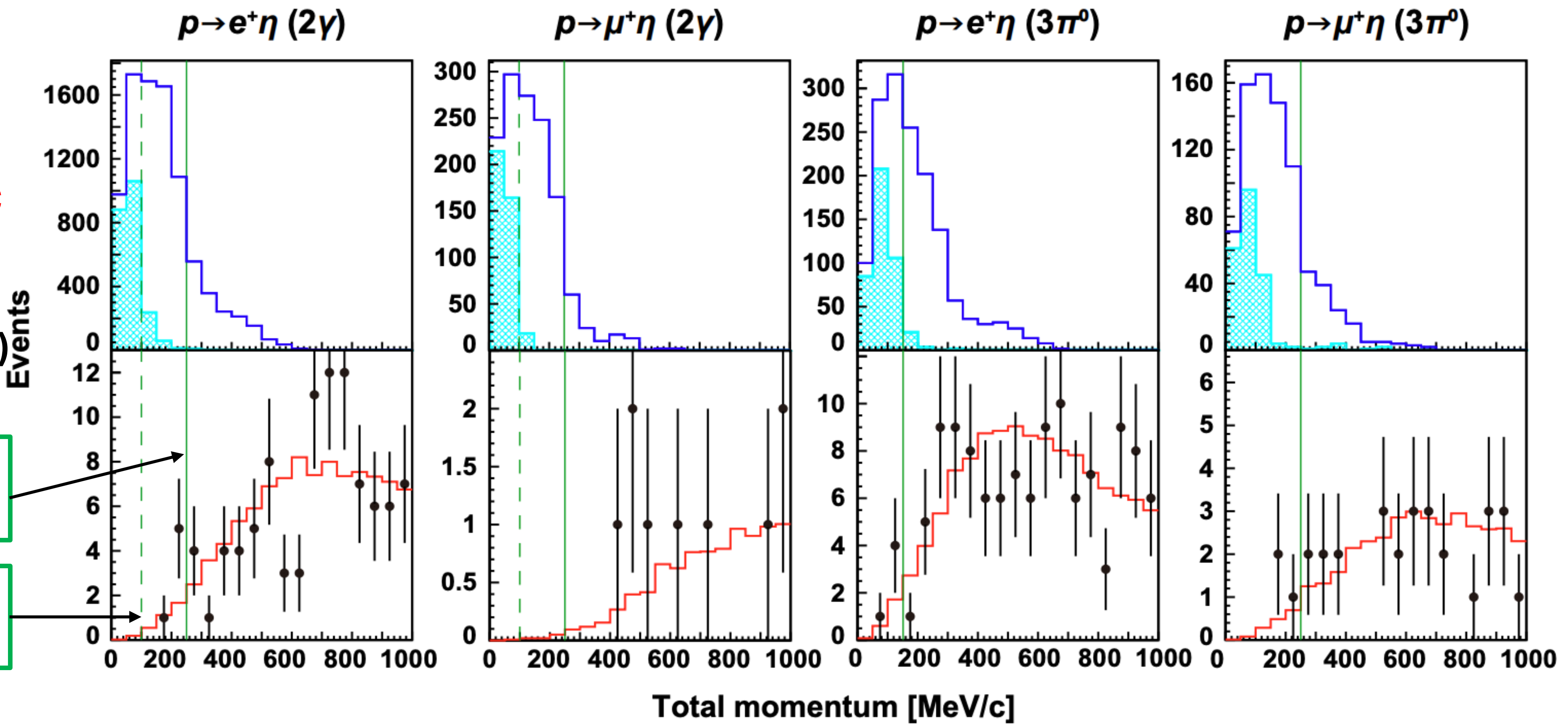
Cuts on #ring, #Michel-e, PID, η mass, #neutron are applied.
Signal Box Blinded.



Data Agreement Check: Proton Momentum

Proton decay MC (bound)
Proton decay MC (free)
Atmospheric ν MC (2000 years)
Data (0.373 Mton*years)

Selection cut (upper box)
Selection cut (lower box)



Backgrounds and Systematics

Breakdown of BG events

Interaction	$p \to e^+ \eta$	$p \to \mu^+ \eta$
CCQE	6%	1%
CC1π	19%	14%
CC multi-π	25%	36%
CC/NC1η	6%	11%
CC others	7%	8%
NC	37%	20%

Mode	Signal Efficiency	Background Rate [events]	Systematic Uncertainty on Signal Efficiency	Systematic Uncertainty on Background Rate
$p \to e^+ \eta$				
($\eta \to 2\gamma$, upper)	12.6%	0.21 ± 0.05	14.7%	31.6%
($\eta \to 2\gamma$, lower)	8.1%	<0.01	15.5%	31.6%
($\eta \to 3\pi^0$)	8.3%	0.20 ± 0.05	17.9%	28.9%
$p \to \mu^+ \eta$				
($\eta \to 2\gamma$, upper)	9.0%	0.11 ± 0.02	15.6%	39.9%
($\eta \to 2\gamma$, lower)	6.6%	0.12 ± 0.02	16.8%	39.9%
($\eta \to 3\pi^0$)	8.6%	0.84 ± 0.08	13.8%	23.0%

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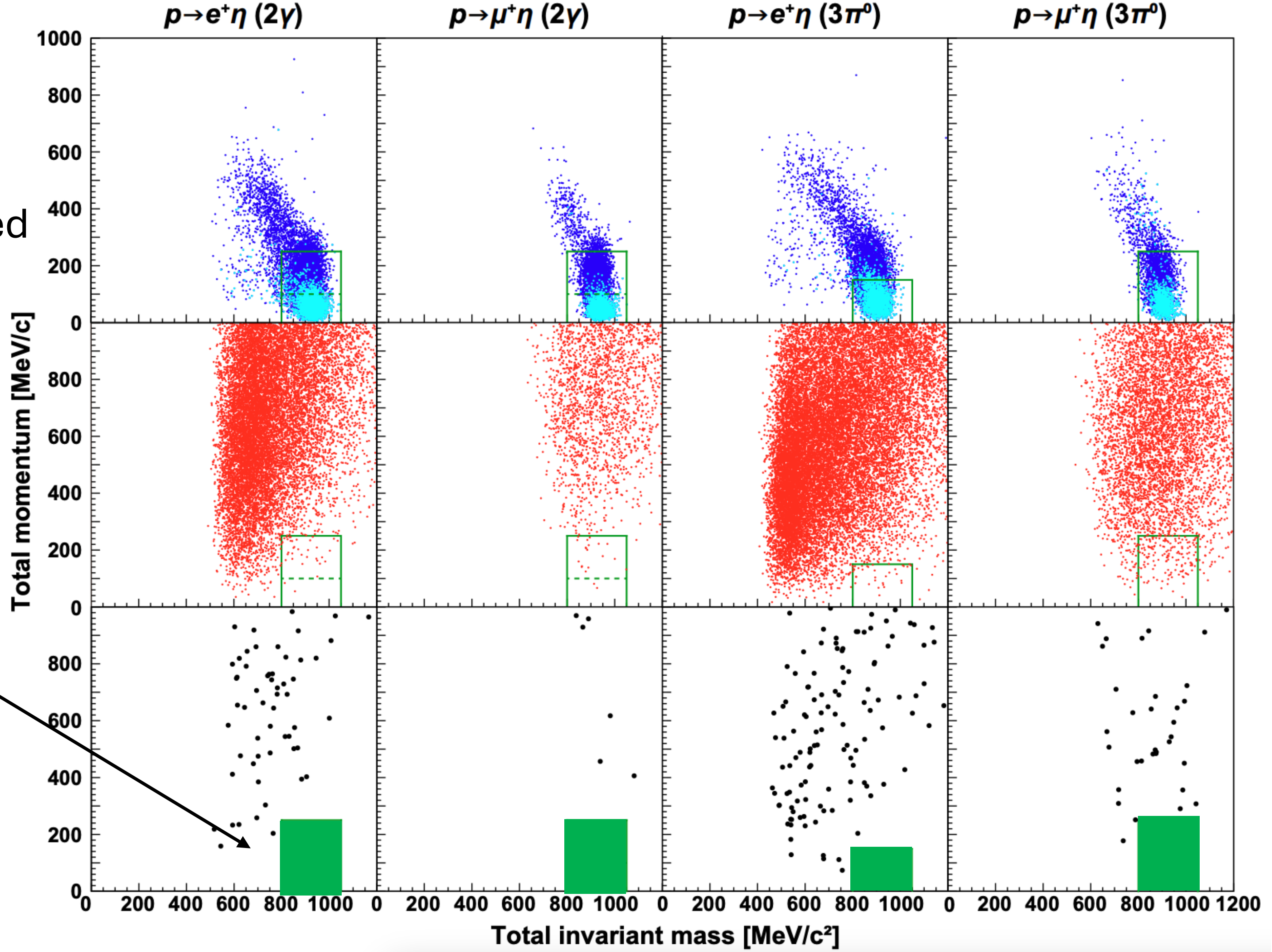
Increase by ~10% from previous study [4]

decrease by ~50% from previous study [4]

[4] K. Abe et al. (The Super-Kamiokande Collaboration), Phys. Rev. D 96, 1 (2017).

Results

- Cuts except final selection
  on proton mass/momentum applied



Proton decay MC (Bound)

Proton decay MC (Free)

Atmospheric ν MC (2000 years)

Data (0.373 Mton*years)

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- Cuts except final selection
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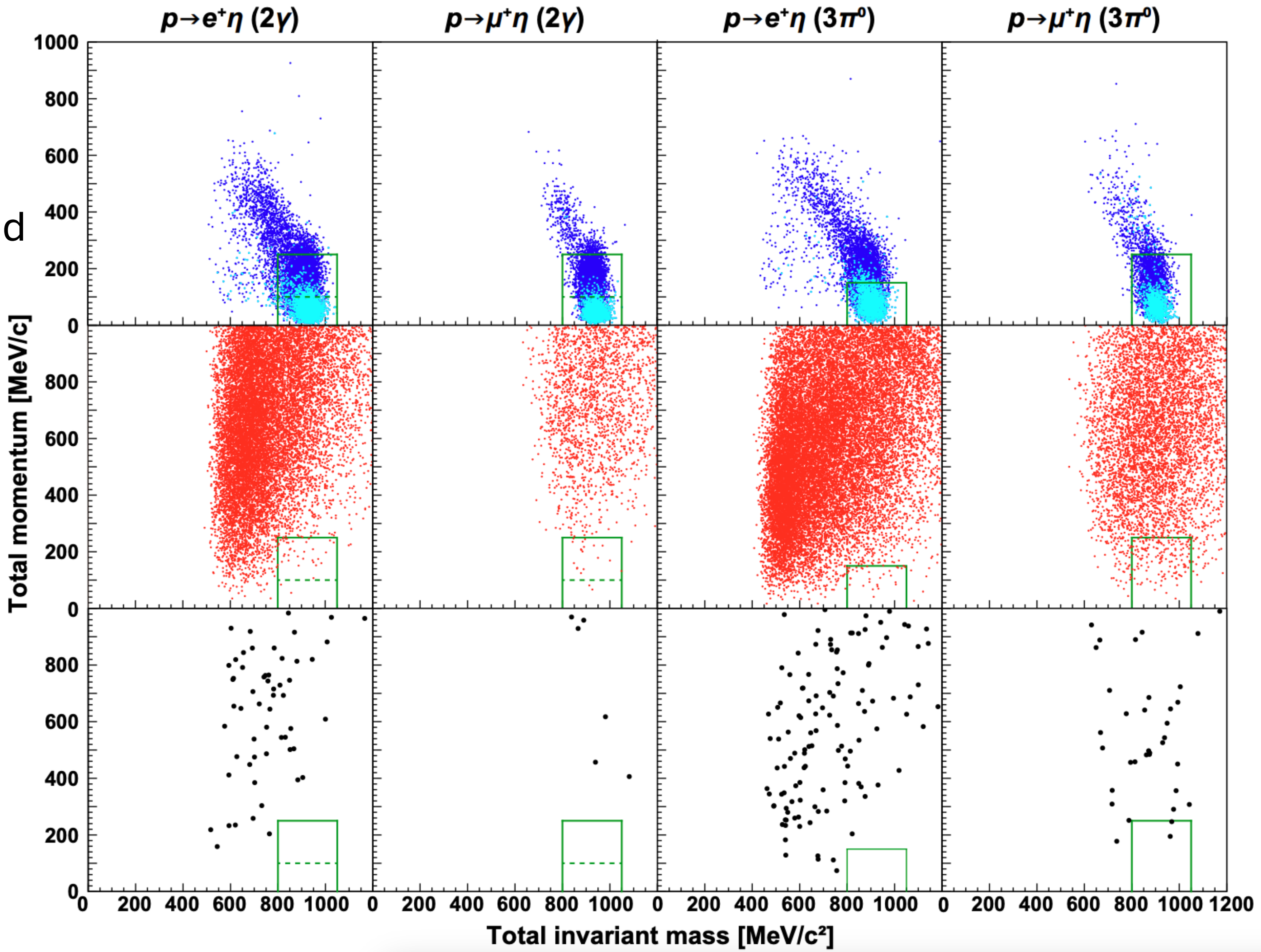
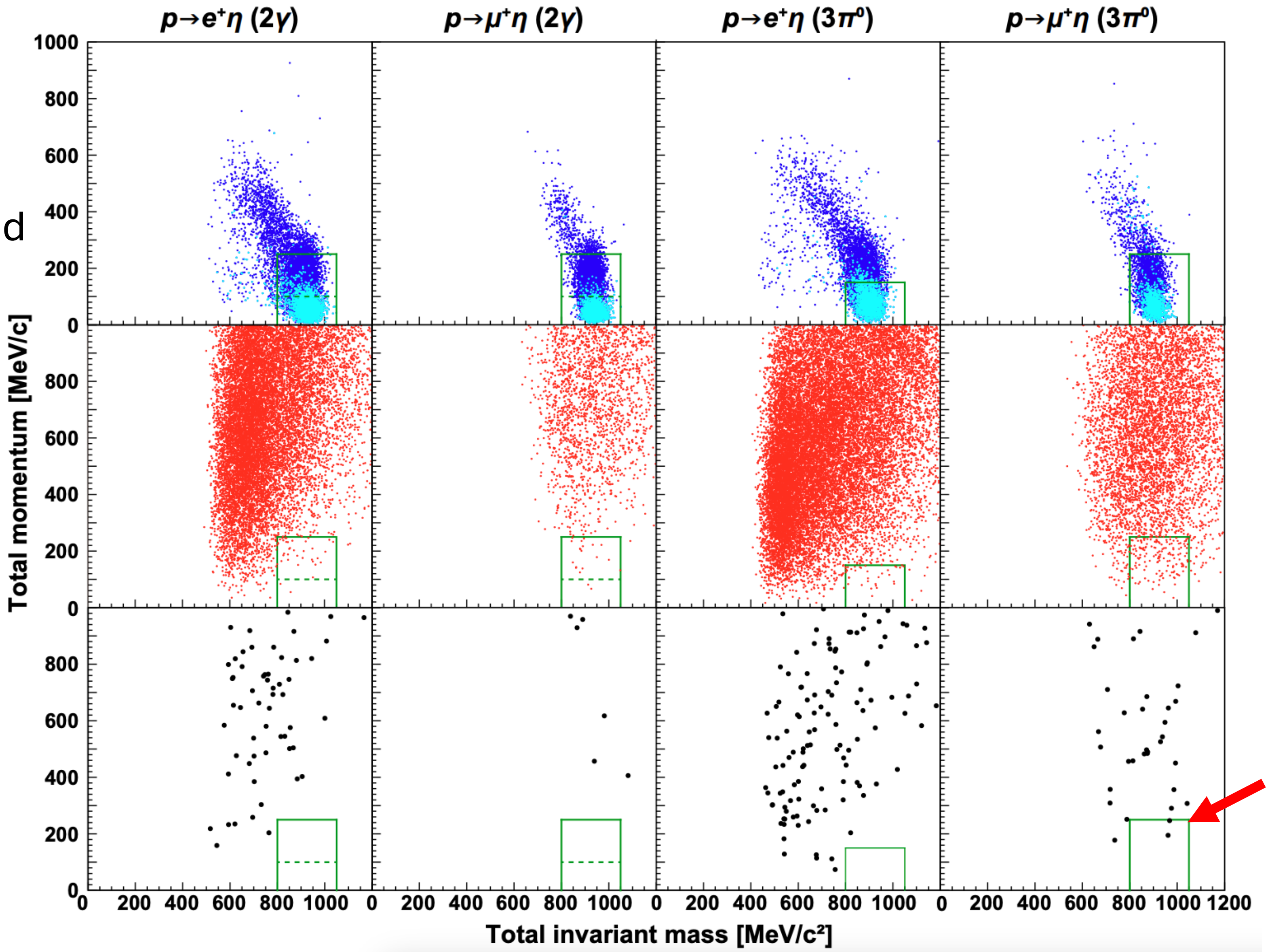


Proton decay MC (Bound)
Proton decay MC (Free)
Atmospheric ν MC (2000 years)
Data (0.373 Mton*years)

Results

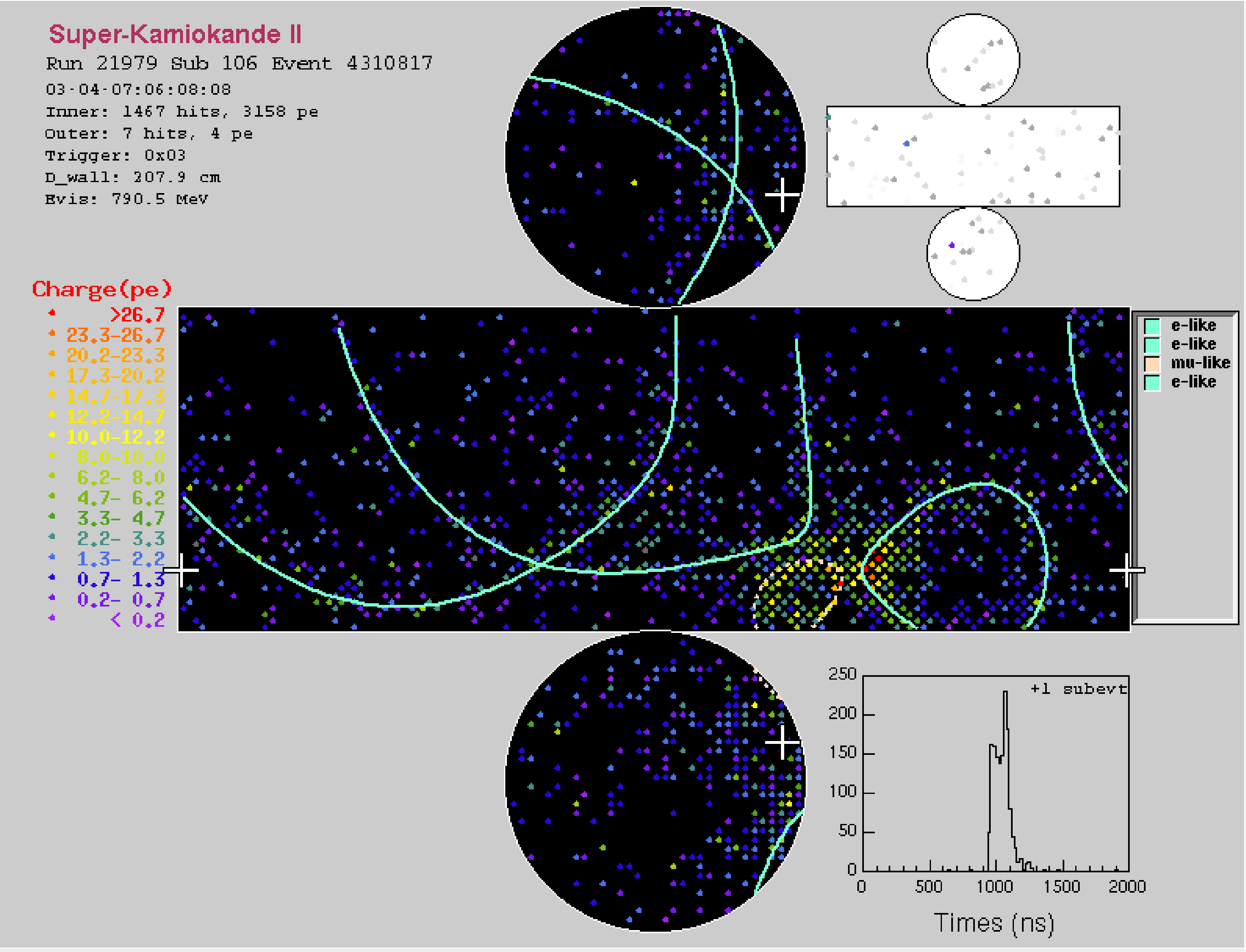
- Cuts except final selection on proton mass/momentum applied
- **Two events remain in the final signal region of *$p \to \mu^+ \eta$ ($3\pi^0$)***



Proton decay MC (Bound)
Proton decay MC (Free)
Atmospheric ν MC (2000 years)
Data (0.373 Mton*years)

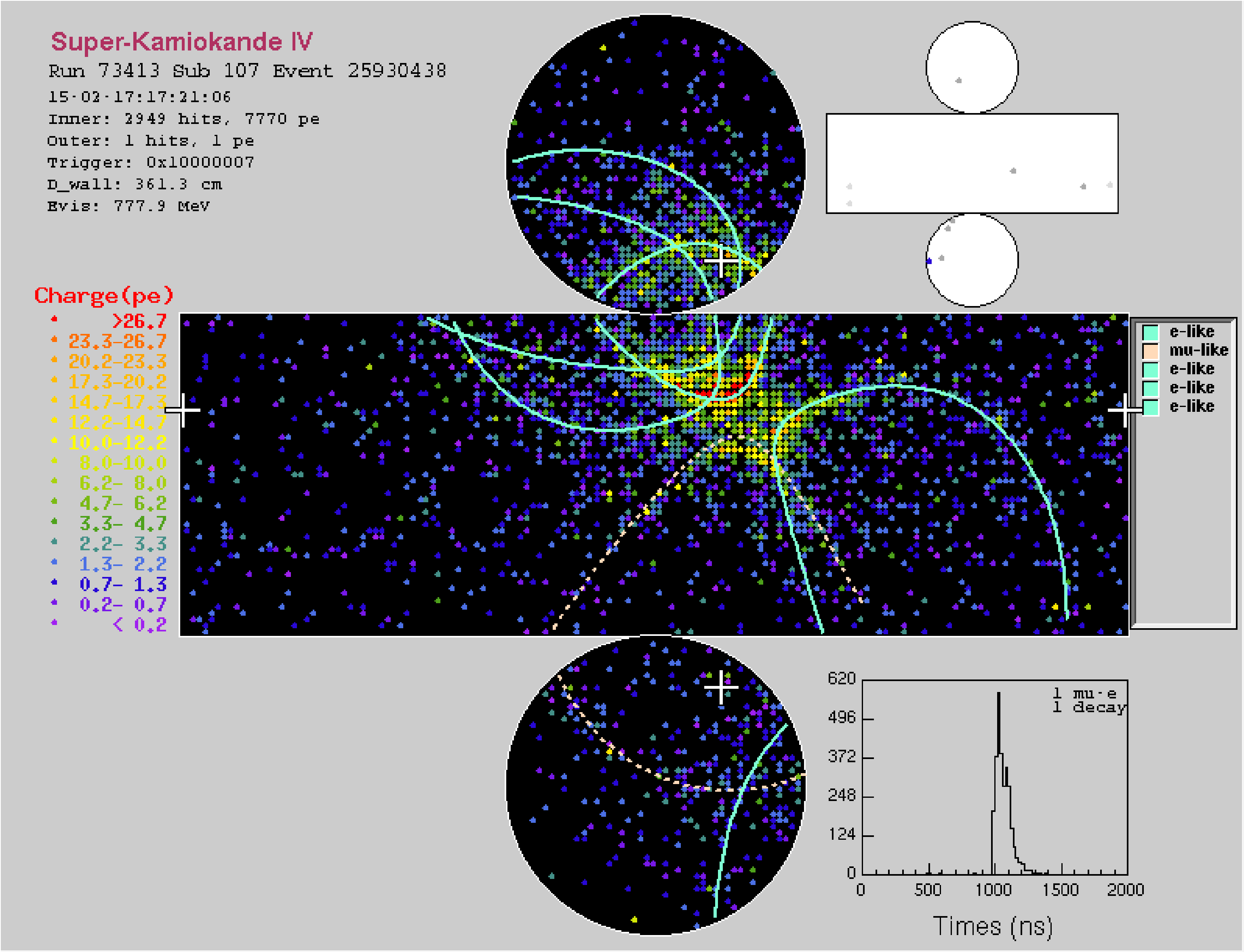
Candidate 1

- 3 e-like ring
- 1 μ-like rings
- p_{proton}: 246.9 MeV/c
- m_{proton}: 968.2 MeV/c^2
- The same event selected in previous analysis



Candidate 2

- 4 e-like ring
- 1 μ-like rings
- p_{proton}: 194.9 MeV/c
- m_{proton}: 961.8 MeV/c^2
- The same event selected in previous analysis



Setting the Most Stringent Limit

Modes	Background [events]	Candidate [events]	Probability [%]	Lifetime limit at 90% CL
p→e⁺η	0.42 ± 0.13	0	65.7	
p→μ⁺η	0.93 ± 0.25	2	23.9	

Setting the Most Stringent Limit

- **Number of candidates consistent with background prediction. No indication of proton decay.**

Modes	Background [events]	Candidate [events]	Probability [%]	Lifetime limit at 90% CL
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Setting the Most Stringent Limit

- **Number of candidates consistent with background prediction. No indication of proton decay.**
- Searches for proton decay via $p \to e^+\eta$ and $p \to \mu^+\eta$ with
  - **Updated nuclear effect**:
    - Improvement of signal efficiency by 10%
    - Reduction of dominantly systematic uncertainty by a factor of 3
  - **Additional 55.7 kton·years of SK-IV data** (~18% increase)

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    - Improvement of signal efficiency by 10%
    - Reduction of dominantly systematic uncertainty by a factor of 3
  - **Additional 55.7 kton·years of SK-IV data** (~18% increase)
- **Lower lifetime limits on both decay channels have increased by a factor of 1.5 relative to the previous analysis, which are the most stringent to date.**

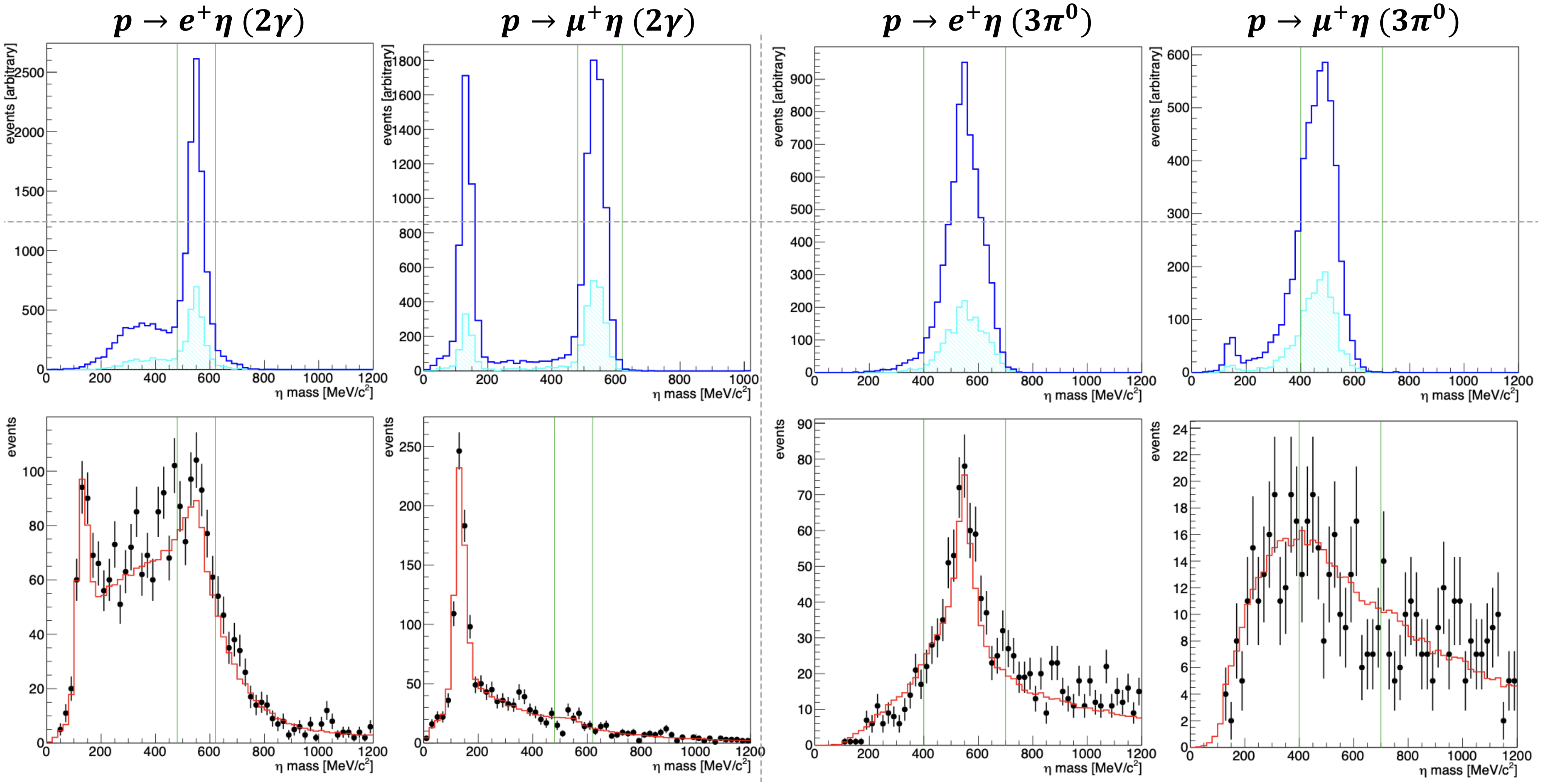
Modes	Background [events]	Candidate [events]	Probability [%]	Lifetime limit at 90% CL
$p \to e^+\eta$	0.42 ± 0.13	0	65.7	**1.4×10^{34} years**
$p \to \mu^+\eta$	0.93 ± 0.25	2	23.9	**7.3×10^{33} years**

Paper available at arXiv:2409.19633

Backup Slides

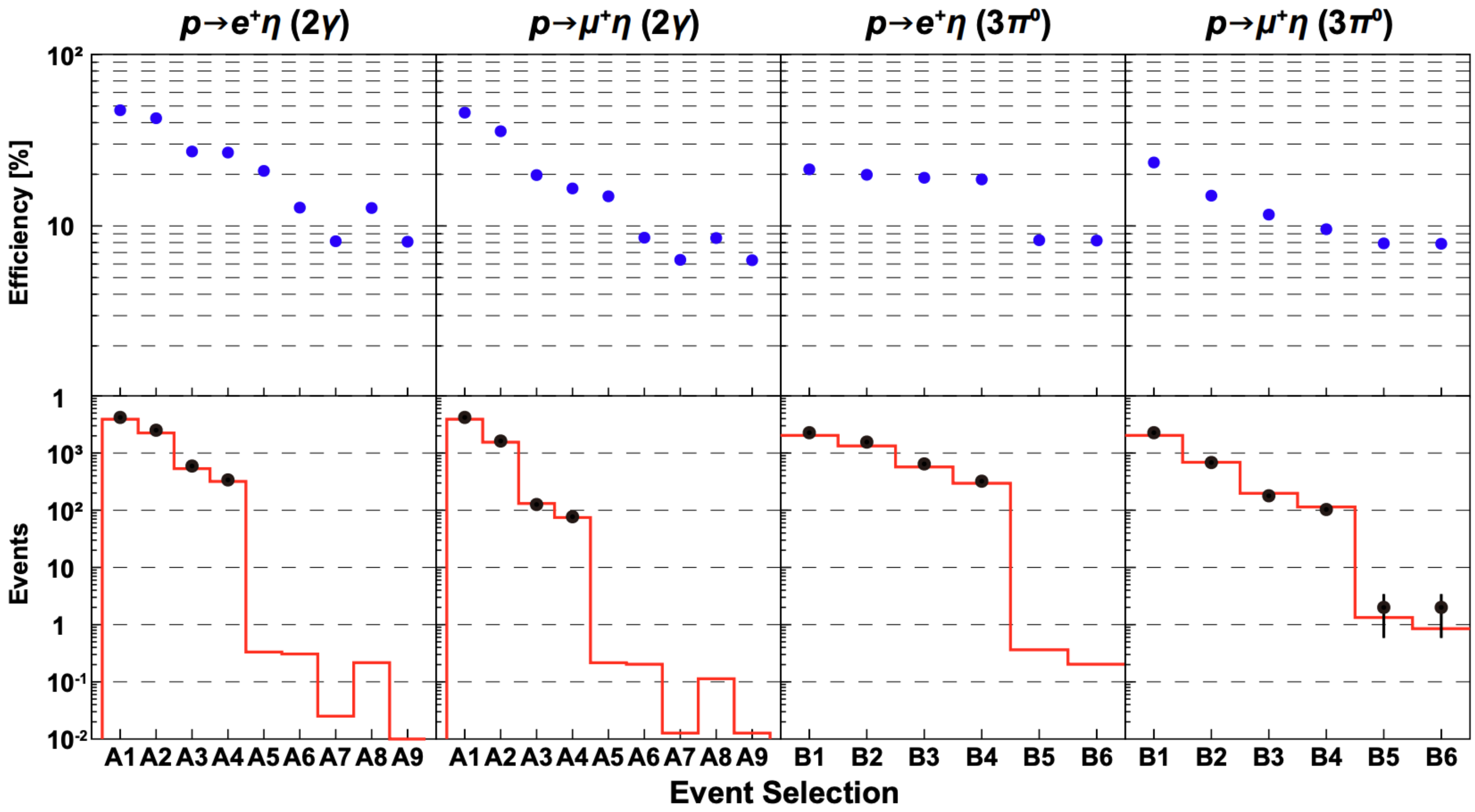
FV, nring and PID cut applied.
Normalized by oscillation weight and livetime.

Proton decay MC (Free protons)
SKI-IV combined Atm. ν MC
Combined SKI~IV data (NEUT5.4.0 may19 ver)



Selection Effectively Identifying Signals

- Nring agreement
- Dint forget to hide the last bin
- Which corresponds to what



Event Selections

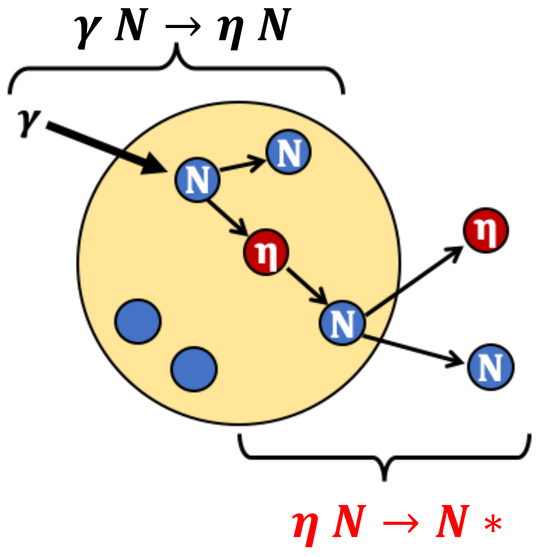
- 2 proton decay channels: **$p \to e^+\eta$, $p \to \mu^+\eta$**, 2 eta decay channels: **$\eta \to 2\gamma$, $\eta \to 3\pi^0$**

	selection		$\eta \to 2\gamma$
A1	Number of Rings		3
A2	PID	**$p \to e^+\eta$**	all e-like
		$p \to \mu^+\eta$	1 μ-like, 2 e-like
A3	η mass		$480 \leq m_\eta \leq 620$
A4	Michel e	**$p \to e^+\eta$**	0
		$p \to \mu^+\eta$	1
A5	p mass		$800 \leq m_p \leq 1050$
	p momentum		$p_p \leq 250$
A6	p momentum		$100 < p_p \leq 250$
A7	Tagged neutron		0
A8	p momentum		$p_p \leq 100$
A9	Tagged neutron		0

	selection		$\eta \to 3\pi0$
B1	Number of Rings		4 or 5
B2	PID	**$p \to e^+\eta$**	all e-like
		$p \to \mu^+\eta$	1 μ-like, the others e-like
B3	η mass		$400 \leq m_\eta \leq 700$
B4	Michel e	**$p \to e^+\eta$**	0
		$p \to \mu^+\eta$	1
B5	p mass		$800 \leq m_p \leq 1050$
	p momentum	**$p \to e^+\eta$**	$p_p \leq 150$
		$p \to \mu^+\eta$	$p_p \leq 250$
B6	Tagged neutron		0

Two-box momentum separation. (upper/lower box)

Eta Affected by Nucleons



- η nuclear effect: impact on the number of observable η
- Intranuclear interaction simulated by NEUT [5]
  - $d\sigma_{\eta photo}/dp$:
    Measured η photo production data of from Mainz experiment [6]
  - σ_{nuc}:
    - **<u>Previous study</u>** Berit-Wigner Formula
    - **<u>This study</u>**

η photoproduction at a nucleon
$\gamma\, p \to \eta\, p, \gamma\, n \to \eta\, n$

η propagation in C nucleus(NEUT)
$\eta\, N \to N*$

η escaped from the nucleon is observable

- Measured $d\sigma_{\eta photo}/dp$ compared with NEUT estimation, which includes the calculated σ_{nuc}
- Source error on σ_{nuc} decided:
  <u>Previous study</u> Conservatively by ranging σ_{nuc} -50% - +100%
  <u>This study</u>

[5] Y. Hayato, Acta Phys. Pol. B 40, 2477 (2009).
[6] M. R¨obig-Landau, et al., Phys. Lett. B 373, 45 (1996).

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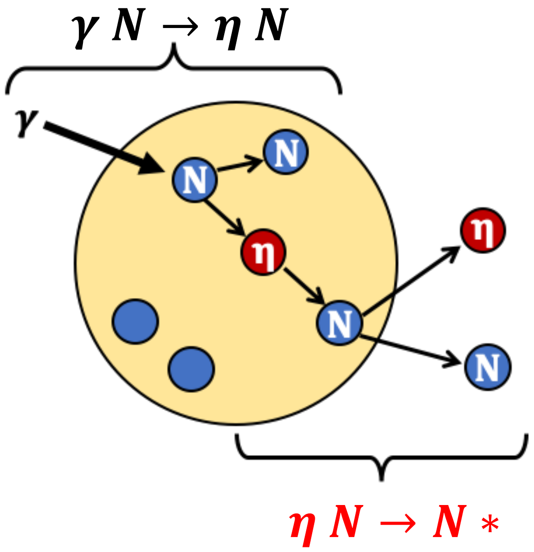
  - $d\sigma_{\eta photo}/dp$:
    Measured η photo production data of from Mainz experiment [6]
  - σ_{nuc}:
    - **<u>Previous study</u>** Berit-Wigner Formula
    - **<u>This study</u>** Measured absorption cross section [6]
      Assume $\sigma_{abs} \sim \sigma_{nuc.}$
      Independently deduced from $d\sigma_{\eta photo}/dp$
- Measured $d\sigma_{\eta photo}/dp$ compared with NEUT estimation, which includes the calculated σ_{nuc}
- Source error on σ_{nuc} decided:
  <u>Previous study</u> Conservatively by ranging σ_{nuc} -50% - +100%
  <u>This study</u> By least χ^2 method to fit formulised σ_{nuc} to data.



η photoproduction at a nucleon
$\gamma p \to \eta p, \gamma n \to \eta n$

↓

η propagation in C nucleus(NEUT)
$\eta N \to N*$

↓

η escaped from the nucleon is observable
<u>Compare with MAINZ experiment data</u>

[5] Y. Hayato, Acta Phys. Pol. B 40, 2477 (2009).
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Analysis Review: Estimation of

Previous analysis[1]: σ_{nuc} estimated by Breit-Wigner formula with uncertainty of -50%+100%.
→ Dominant error on signal efficiency of ~30%.

Estimate σ_{nuc} that can reproduce the measured $d\sigma_{\eta\ photo}/dp$, $\sigma_{\eta N}^{abs}$ in MAINZ experiment[2].

- ✓ $d\sigma_{\eta\ photo}/dp$: Simulated by NEUT.
- ✓ $\sigma_{\eta N}^{abs}$: Considered as $\sigma_{nuc} \sim \sigma_{\eta N}^{abs}$.

→ Evaluate the best σ_{nuc} and its uncertainty by least χ^2 method fitting.
→ **Adopted:** $\boldsymbol{\sigma_{nuc} = 46 * exp(-0.0023 * p_\eta)}$

[2] M. Robig-Landau et al., Phys.Lett. B 373 45 (1996).