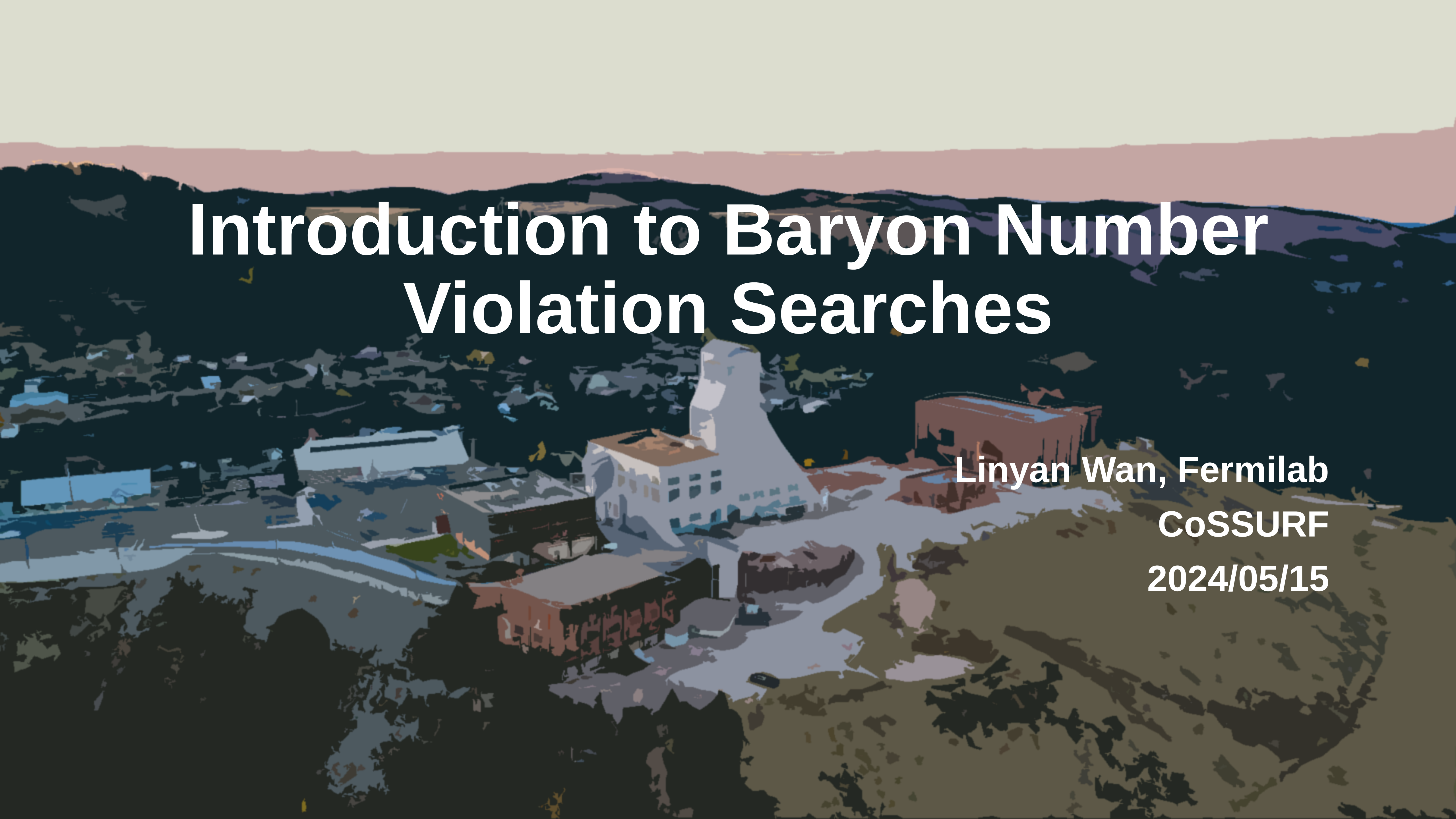


Introduction to Baryon Number Violation Searches

Linyan Wan, Fermilab

CoSSURF

2024/05/15

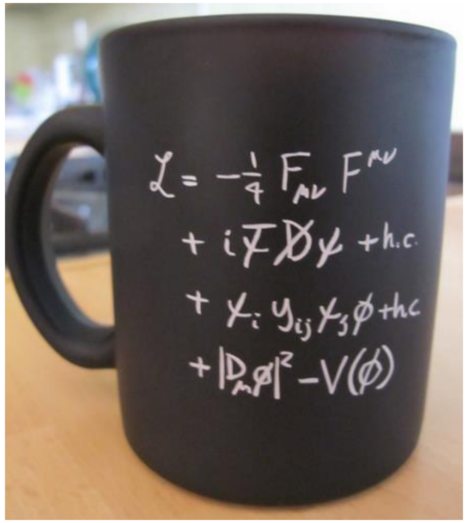
Baryon Number Violation?

- *B* conservation is not guaranteed by any fundamental symmetry.
- In Standard Model, *B* conservation is accidental.
- Predicted in Grand Unification Theories.
- *B* violation is an essential ingredient for baryogenesis.

Baryon Number Violation?

If you ask nicely, I
can allow $\Delta B \neq 0$.

- *B* conservation is not guaranteed by any fundamental symmetry.
- In Standard Model, *B* conservation is accidental.
- Predicted in Grand Unification Theories.
- *B* violation is an essential ingredient for baryogenesis.



The Standard Model

Baryon Number Violation?

- *B* conservation is not guaranteed by any fundamental symmetry.
- In Standard Model, *B* conservation is accidental.
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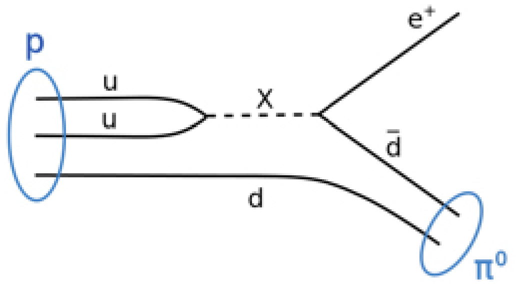
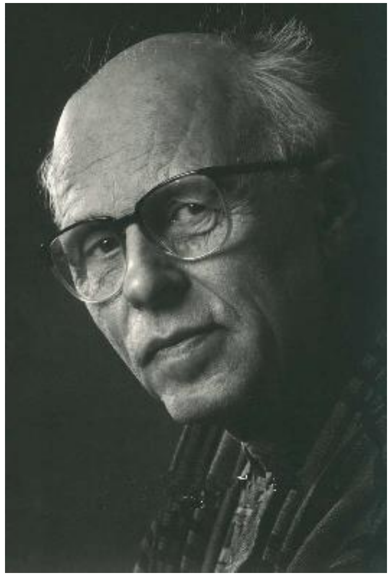


Baryon Number Violation?

- *B* conservation is not guaranteed by any fundamental symmetry.
- In Standard Model, *B* conservation is accidental.
- Predicted in Grand Unification Theories.
- *B* violation is an essential ingredient for baryogenesis.

Together with CP violation and thermal non-equilibrium.



Andrei Sakharov

Baryon Number Violation? Not Yet…

$Z \to pe$

$\tau \to \bar{p}\gamma$

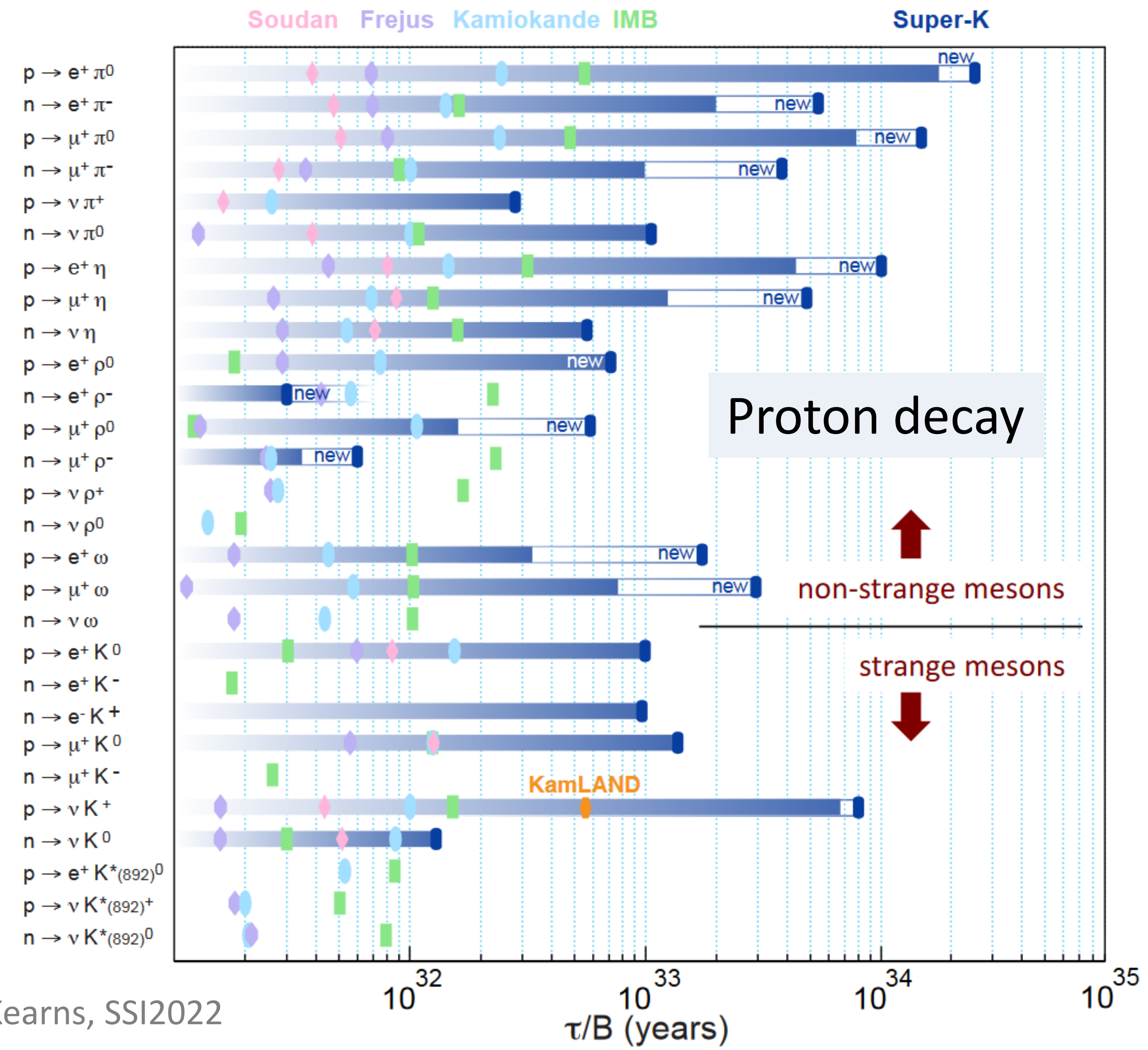
Meson→Baryon

Baryon→Meson

$n \to \bar{n}$

…

No observation in any of these channels.



Ed Kearns, SSI2022

Baryon Number Violation? Not Yet…

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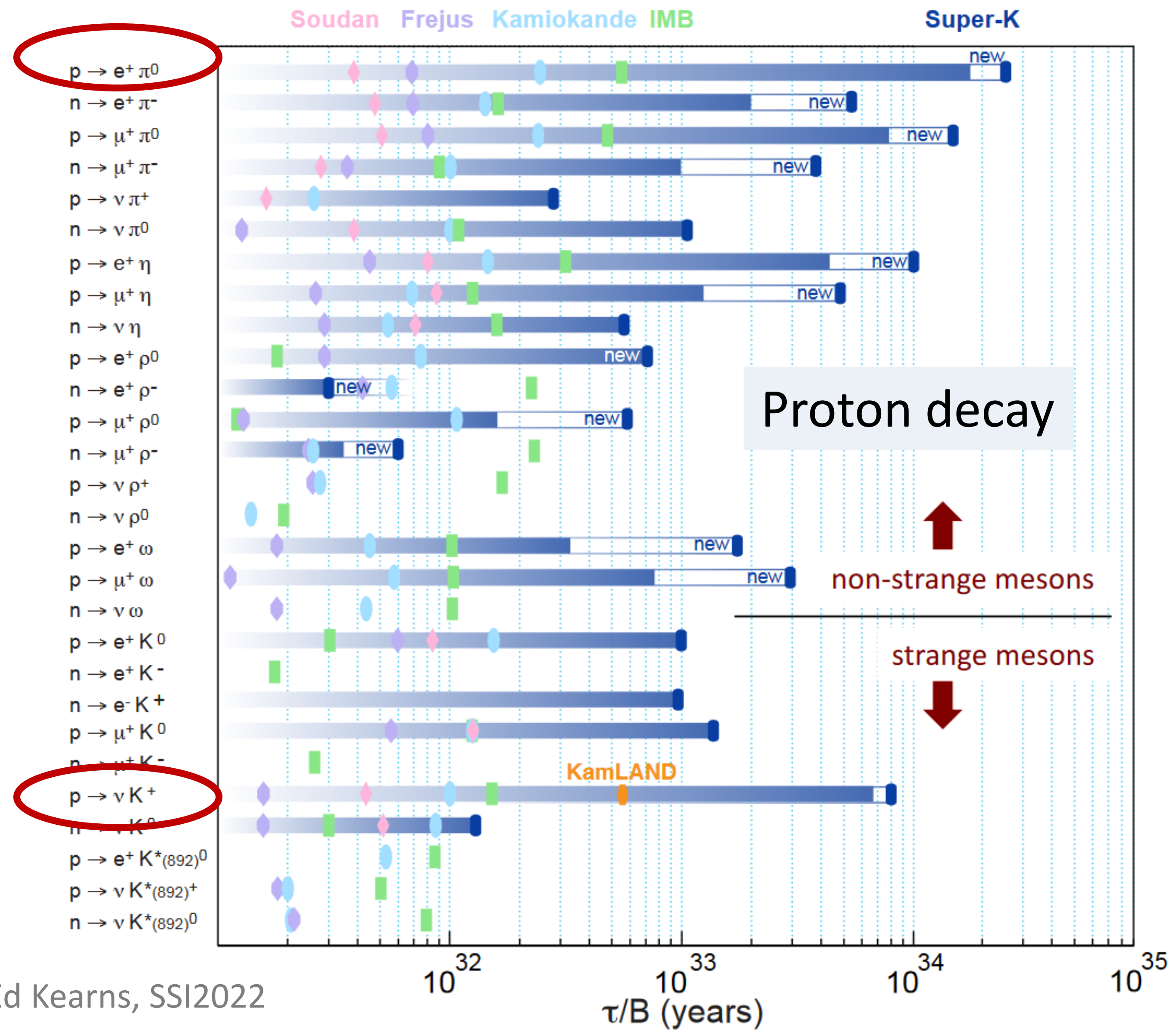
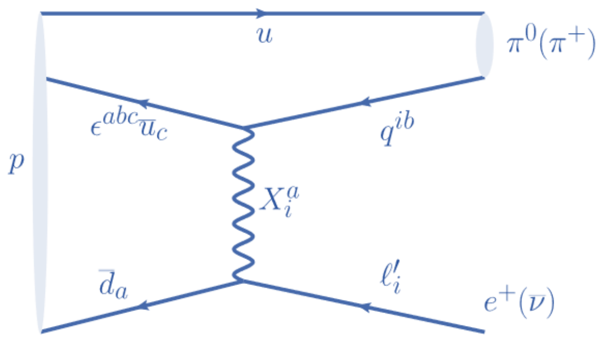


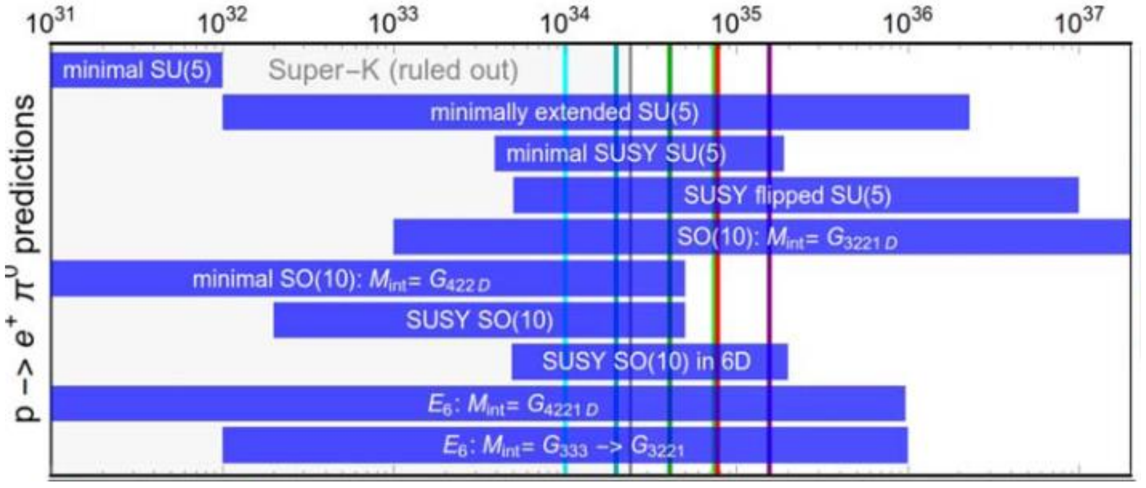
Ed Kearns, SSI2022

Benchmark Mode: $p \rightarrow e^+\pi^0$

2024 J. Phys. G: Nucl. Part. Phys. 51 033001



Lifetime limits [years]

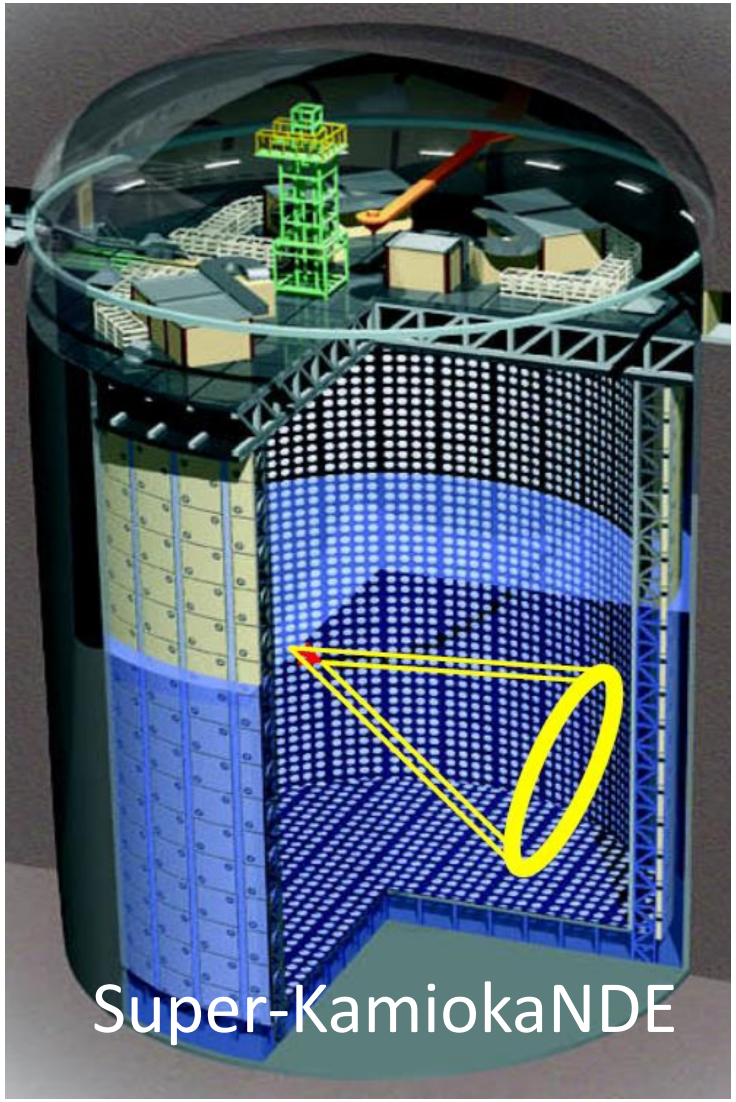


Search Requirements

- Large statistics:
  - Large detector
  - Long exposure
- High efficiency:
  - Sensitive in subGeV energy range
- Minimum background

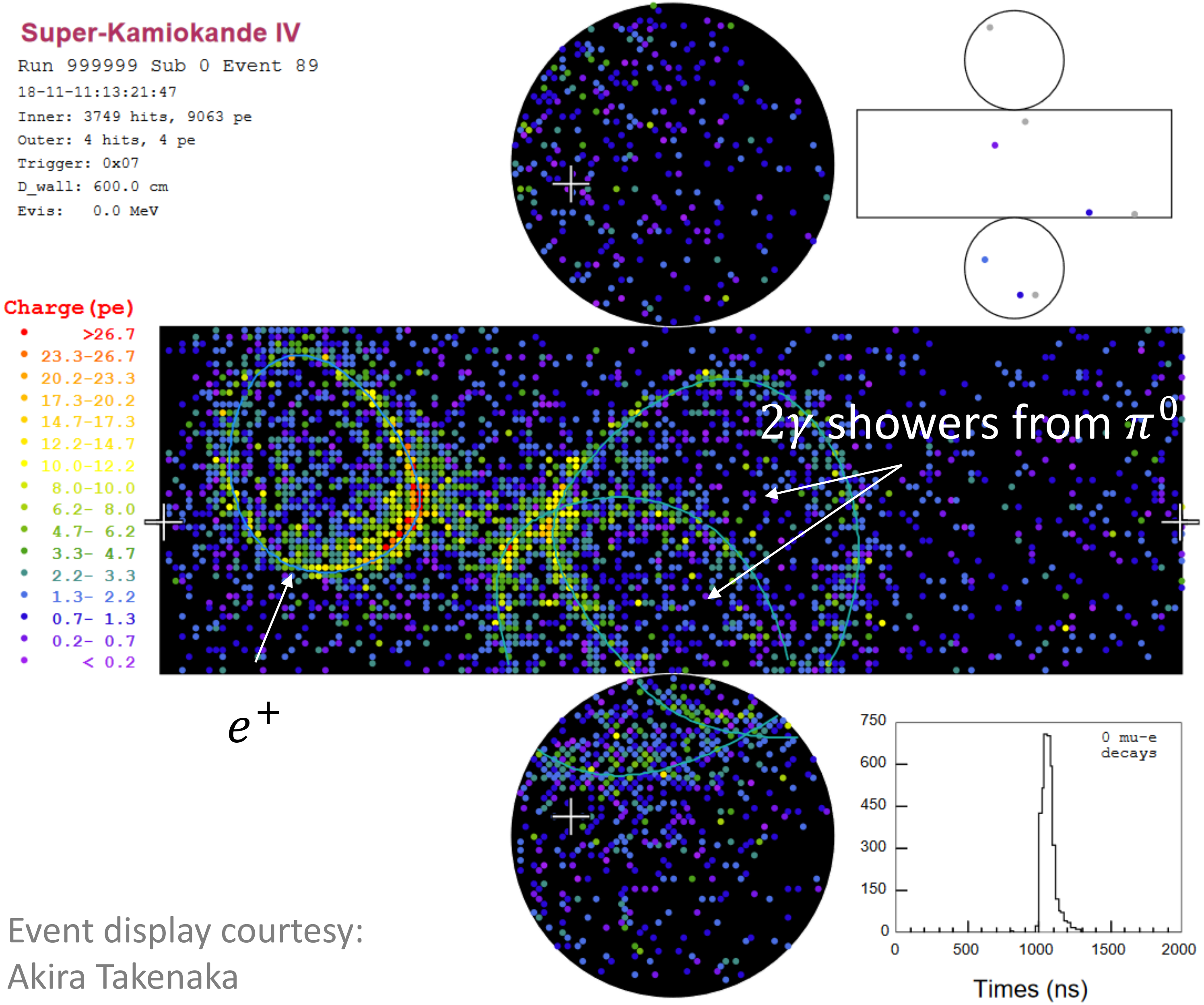
A Neutrino Experiment for BNV Search

- Large statistics:
  - 20 kton water
  - Data taking 1996-now
- High efficiency:
  - If above water Cherenkov threshold
- Minimum background
  - 1 km overburden + outer detector to reject cosmic rays
  - Only background: atmospheric neutrinos



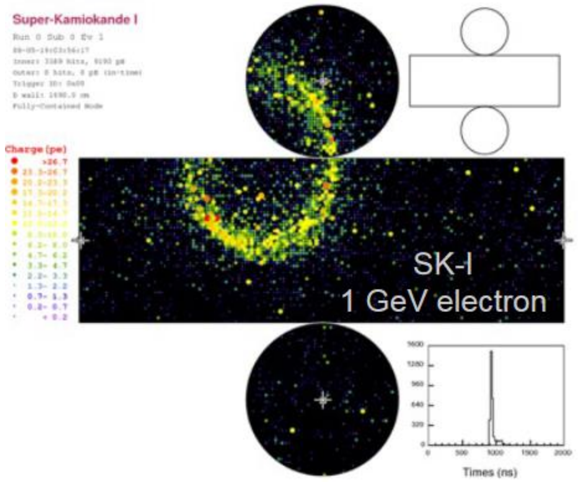
$p \rightarrow e^{+}\pi^{0}$

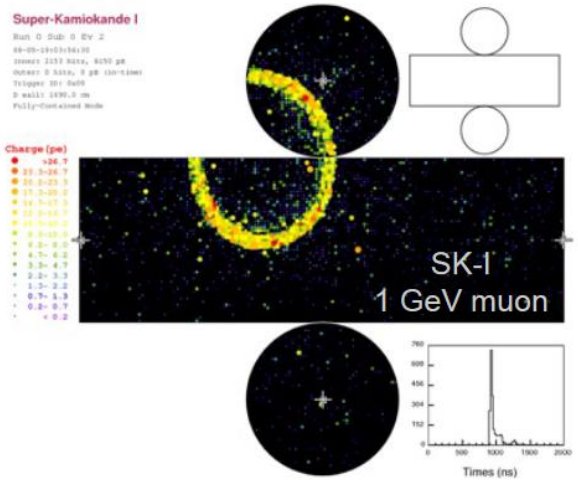
A simulated $p \rightarrow e^{+}\pi^{0}$ event at SK



Event display courtesy:
Akira Takenaka

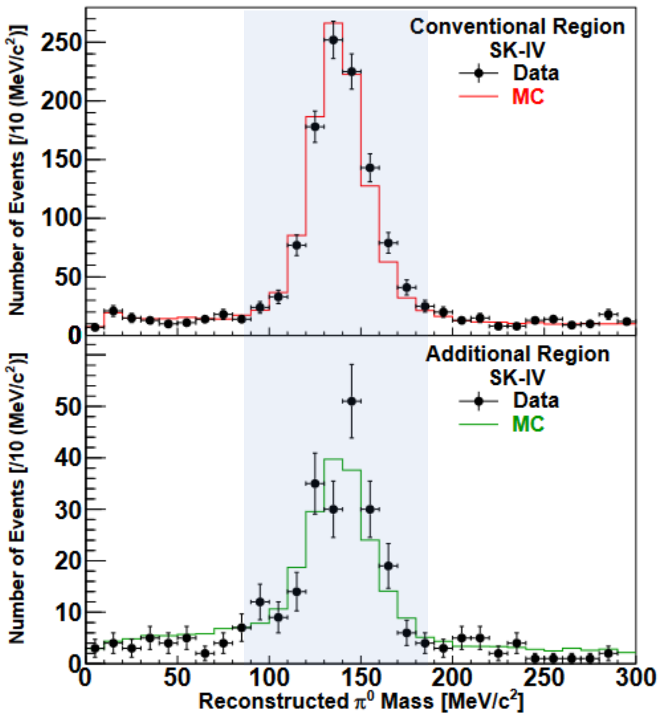
$p \rightarrow e^+\pi^0$





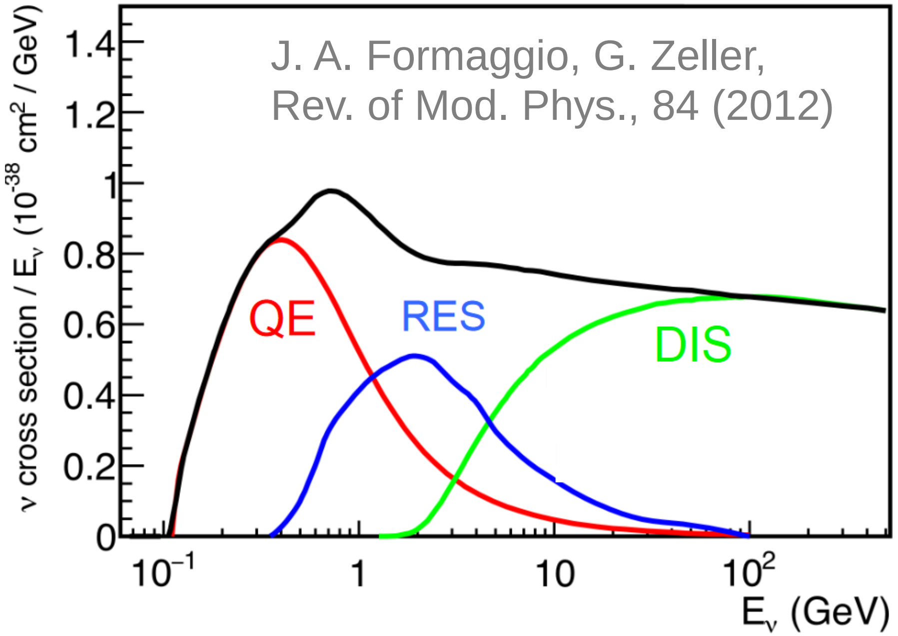
- 2-3 reconstructed Cherenkov rings.
- All rings are electron-like.
- No Michel electrons.
- For events with 3 rings, $85 < m_{\pi^0} < 185$ MeV.

Efficiency ~70%



Phys. Rev. D 102, 112011 (2020)

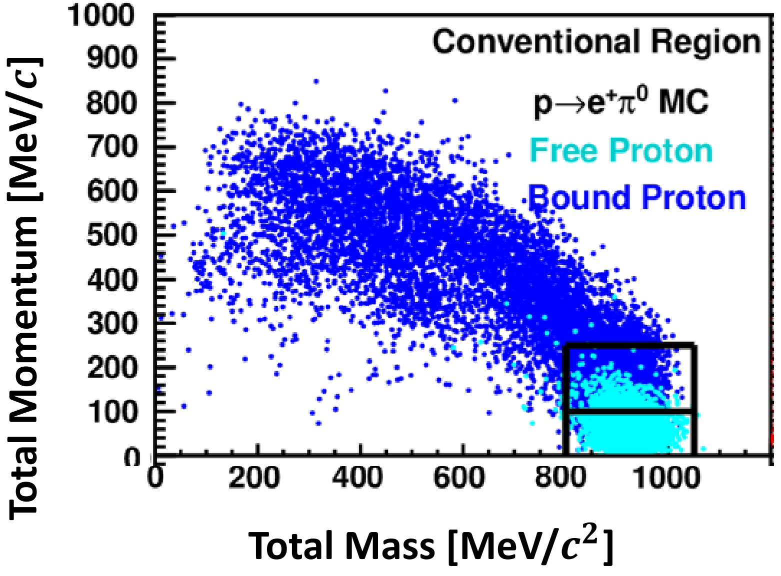
Neutrino Interaction at GeV



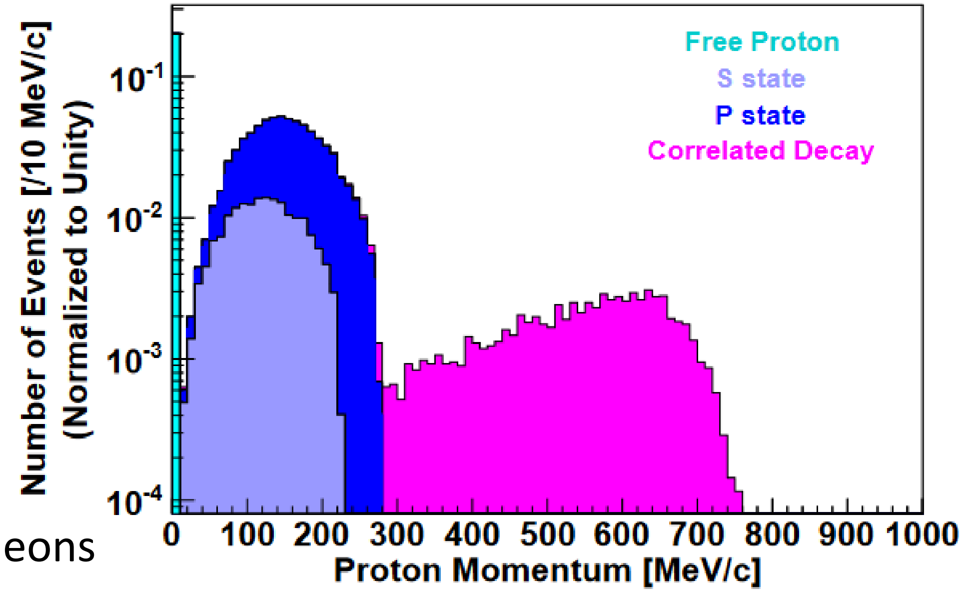
- Main interactions:
  - (Quasi-)Elastic scattering
  - Resonant Meson Production
    - $\bar{\nu}_e + p \rightarrow e^+ + n + \pi^0$
  - Deep inelastic scattering

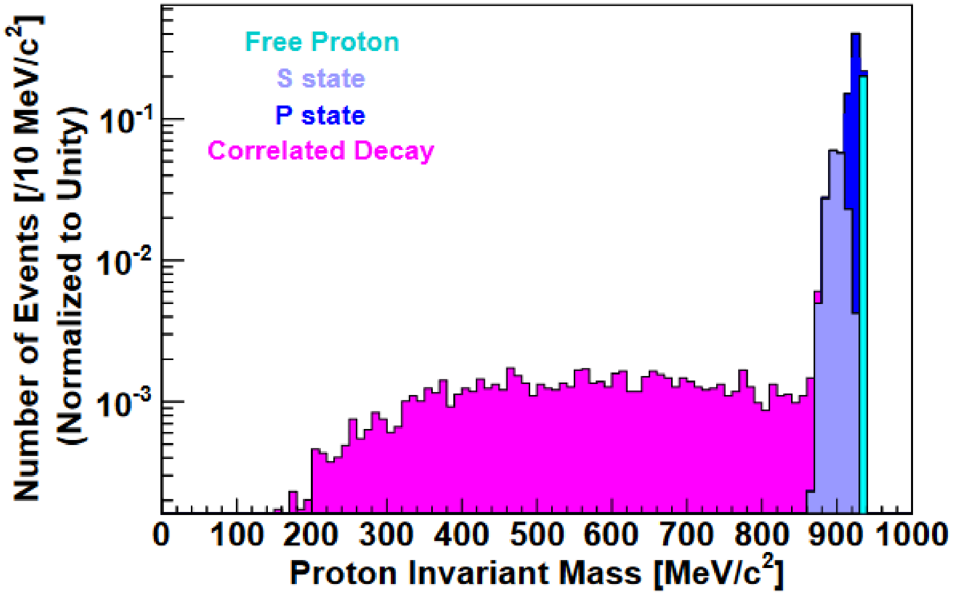
$p \to e^+\pi^0$

Phys. Rev. D 102, 112011 (2020)



Smearing from bound nucleons & final state interaction

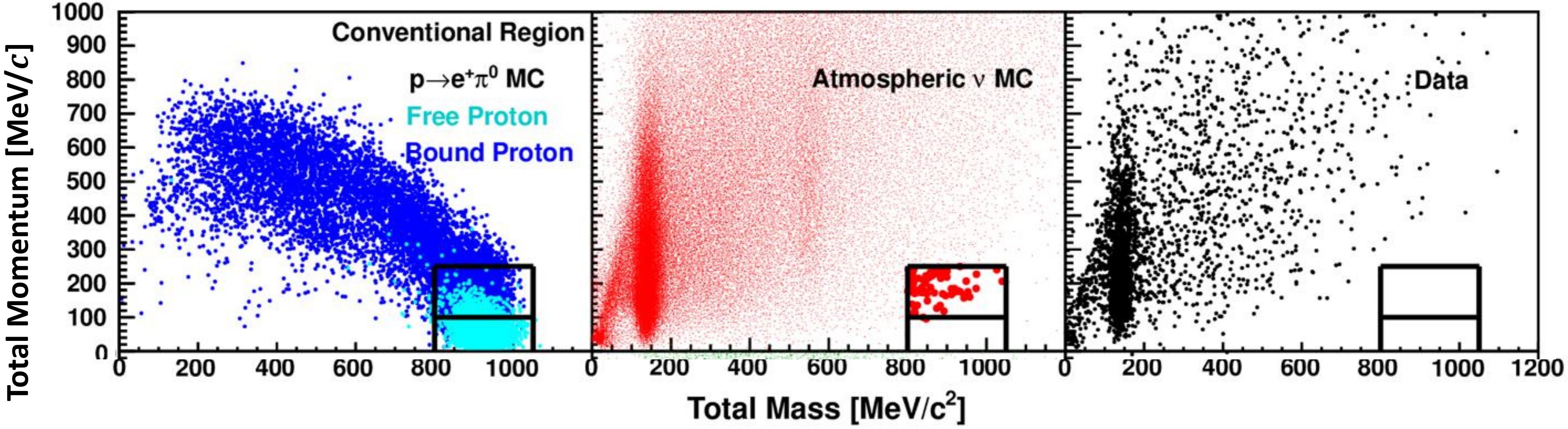




Efficiency ~40%

$p \rightarrow e^{+}\pi^{0}$

Phys. Rev. D 102, 112011 (2020)



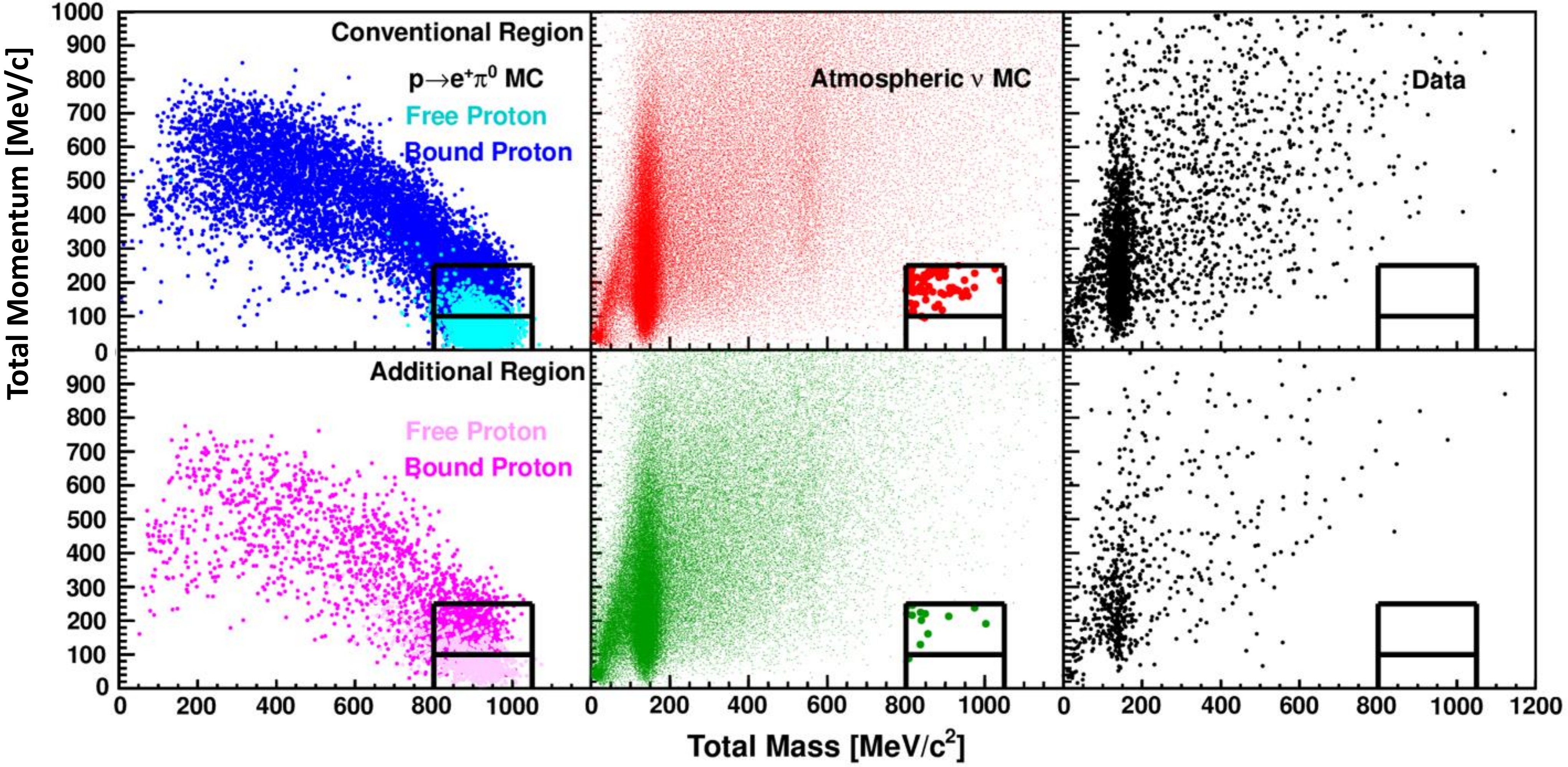
Efficiency ~40%

$p \rightarrow e^{+}\pi^{0}$

: 2.4×10^{34} years @90% CL

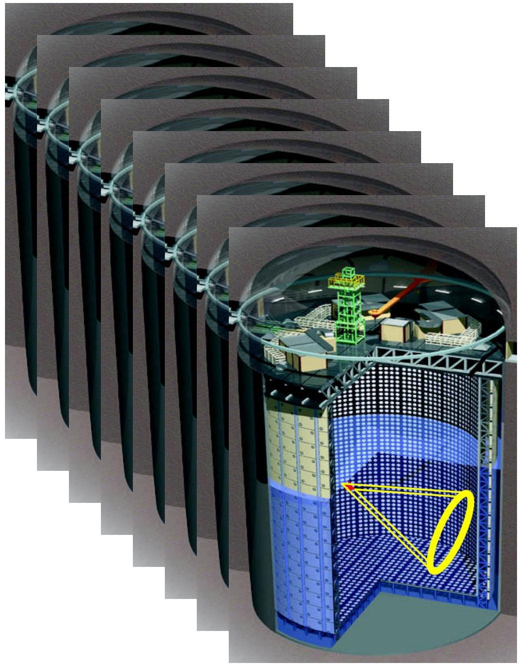
450 kton · year

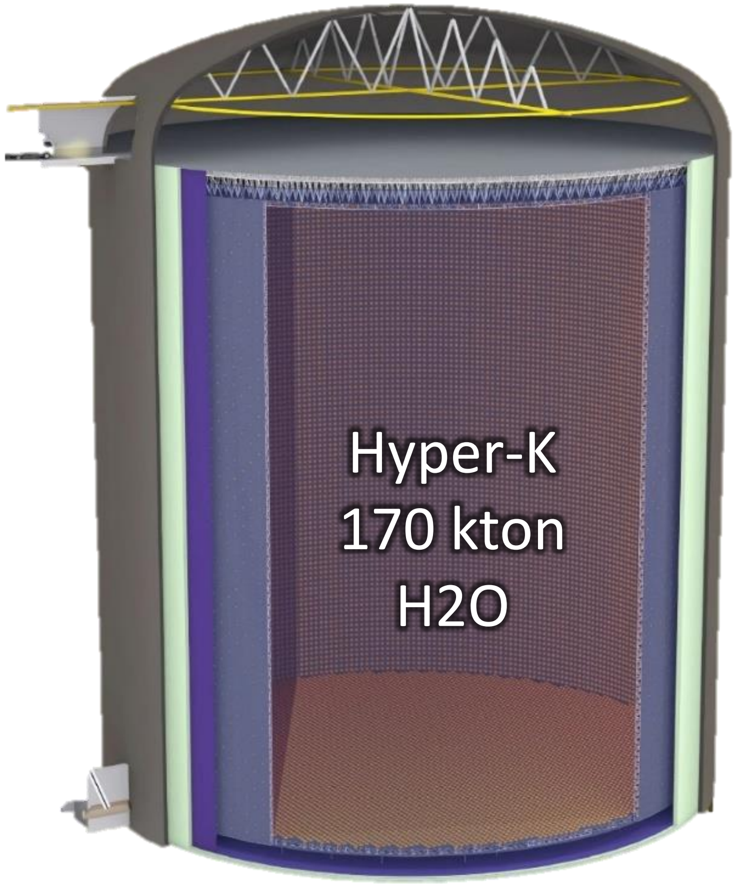
Phys. Rev. D 102, 112011 (2020)



Future Detectors: Hyper-Kamiokande

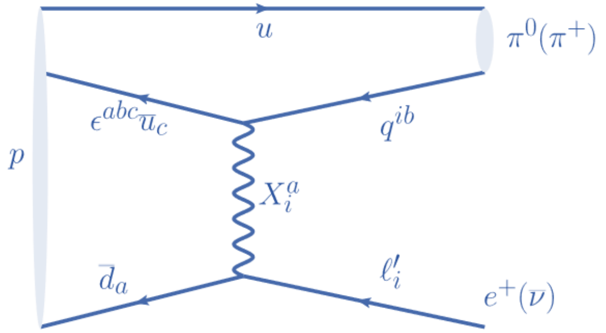
- Large volume
  - 8 x Super-Kamiokande
- Same detection technique, improved photon detector

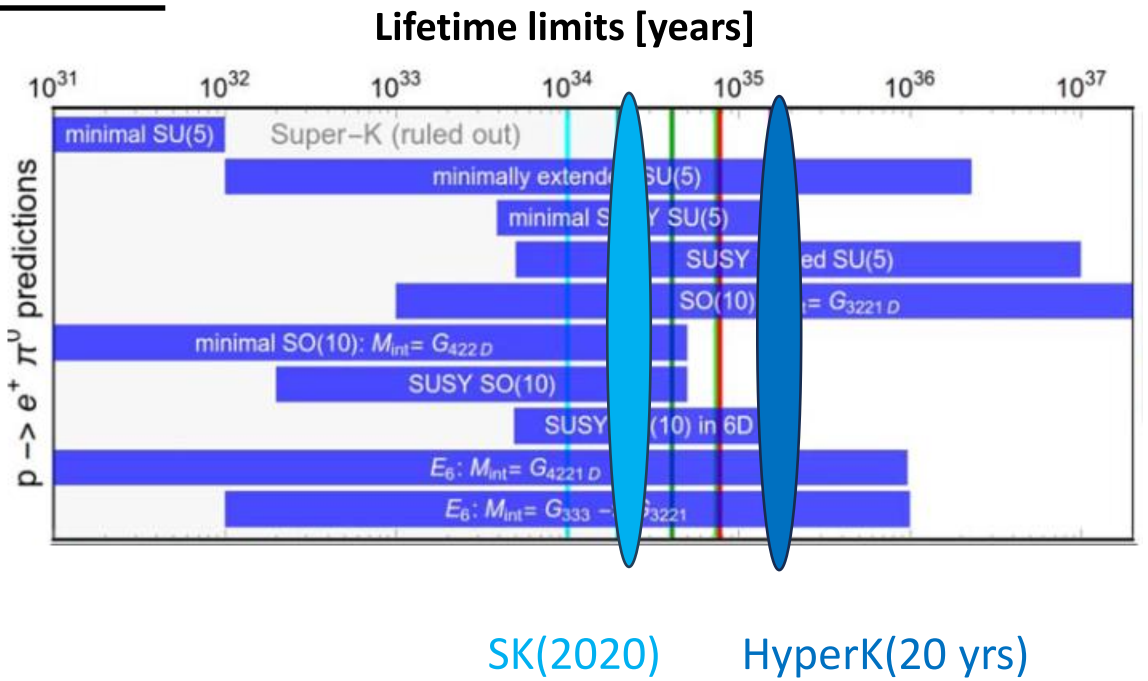




Benchmark Mode: $p \rightarrow e^+\pi^0$

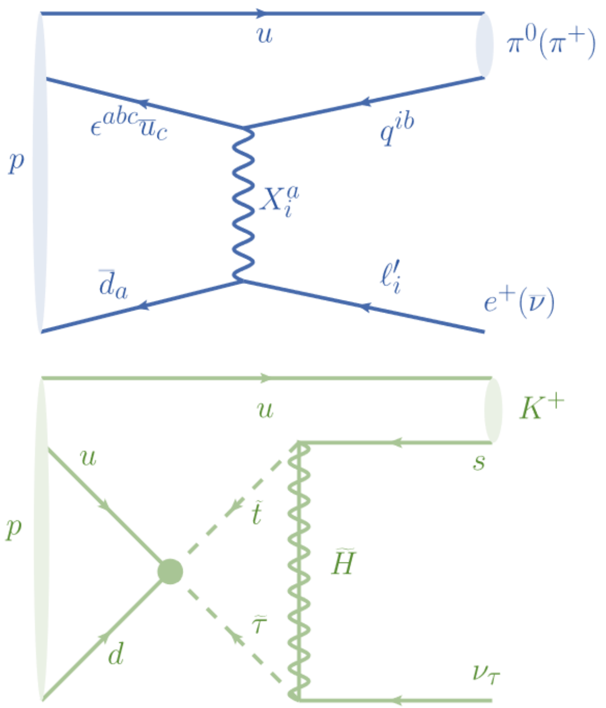
2024 J. Phys. G: Nucl. Part. Phys. 51 033001



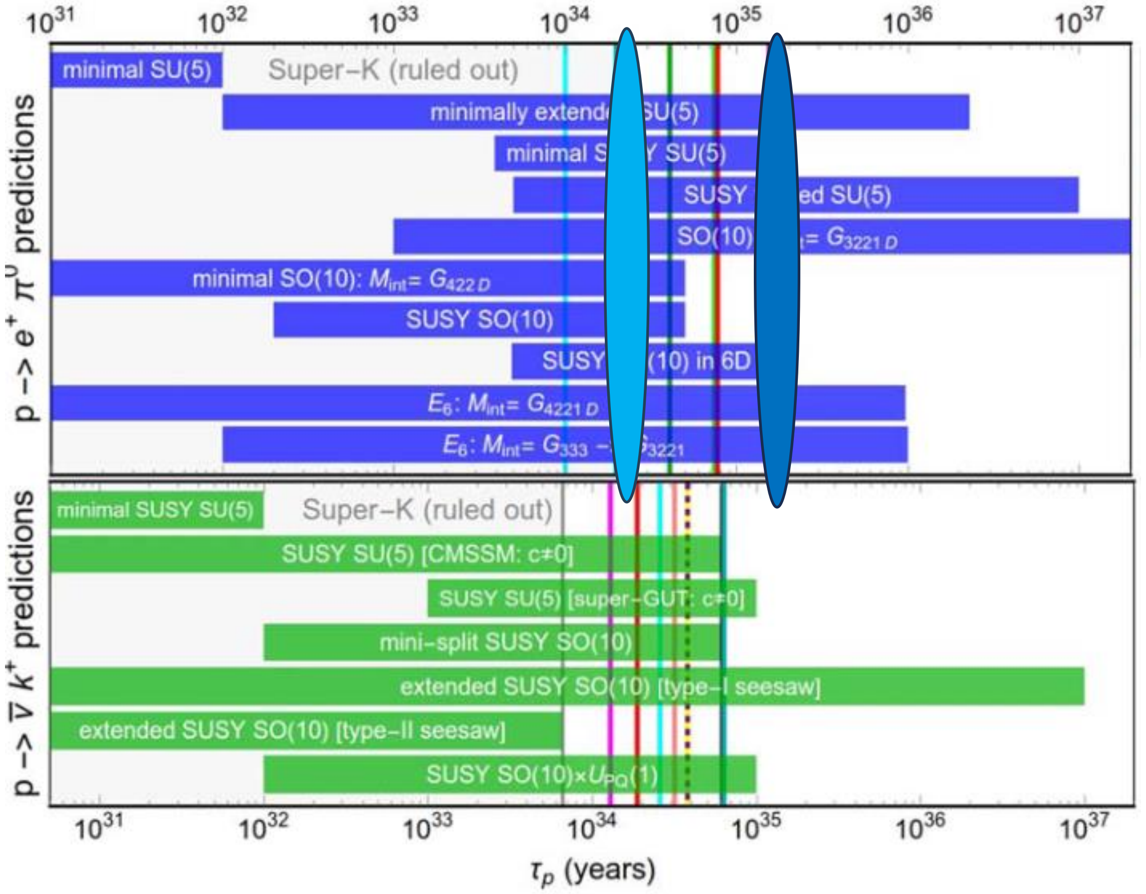


Benchmark Mode: $p \rightarrow \nu K^+$

2024 J. Phys. G: Nucl. Part. Phys. 51 033001



Lifetime limits [years]



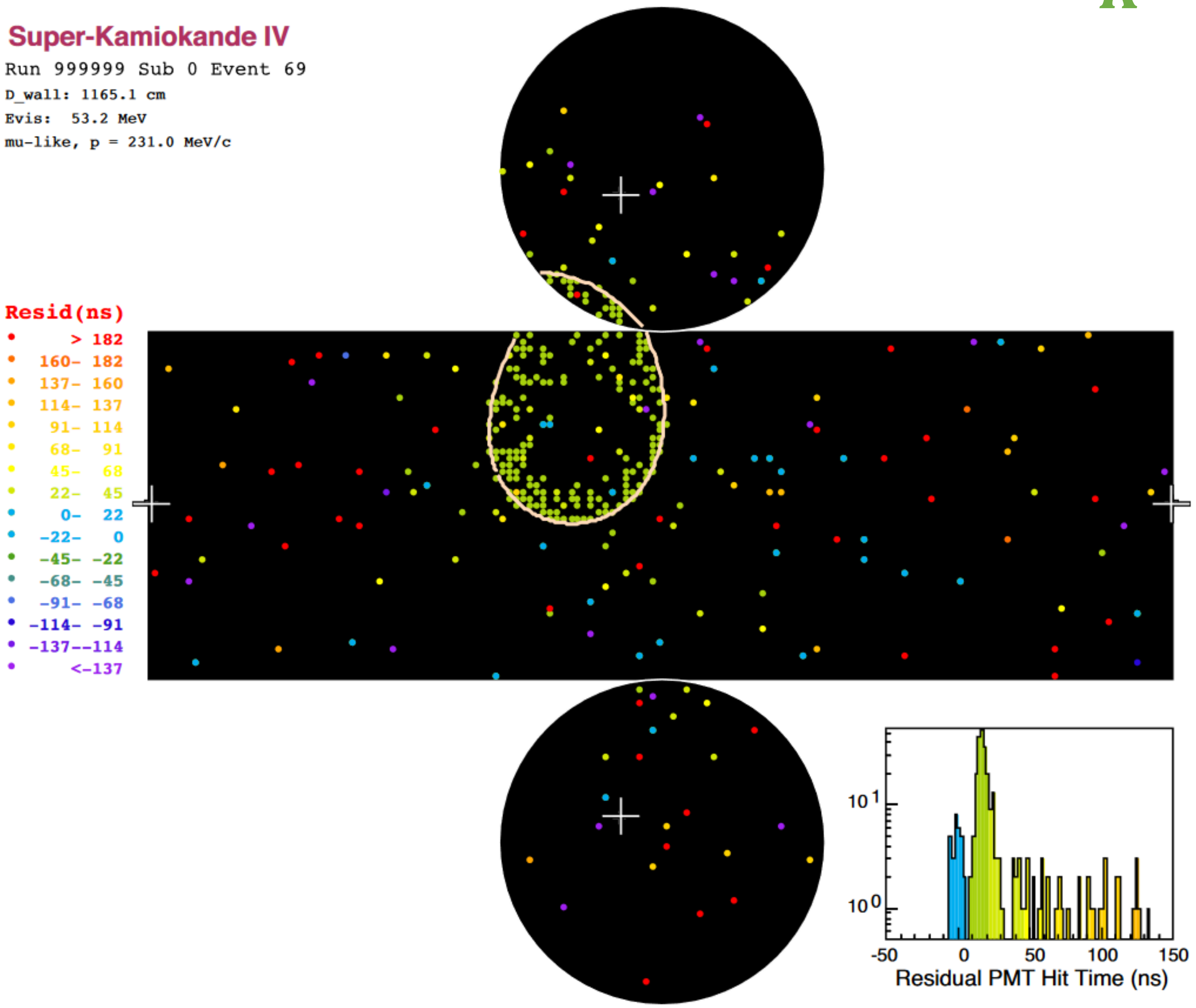
$p \to \nu K^+$ at SK

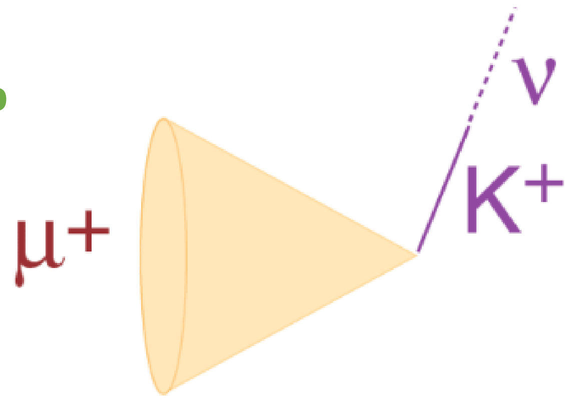
Challenges: ν is invisible, and the K^+ is below water Cherenkov threshold

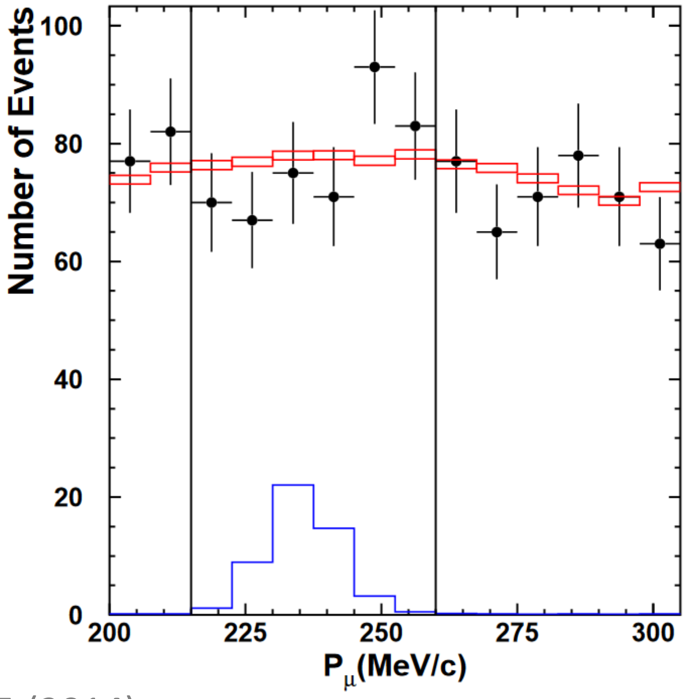
Decay channel	Branching ratio
$K^+ \to \mu^+\nu$	65%
$K^+ \to \pi^+\pi^0$	21%
…	…

$p \to \nu K^+$ at SK

$K^+ \to \mu^+\nu$, BR=65%



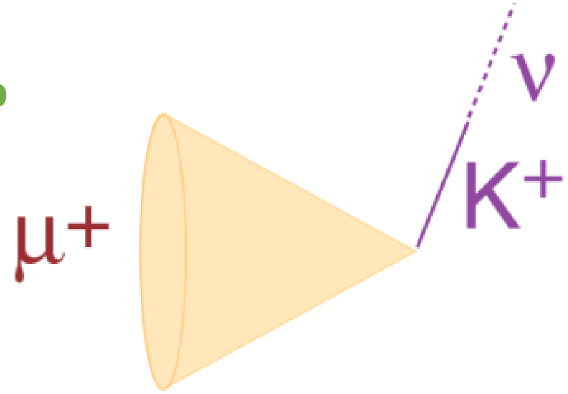




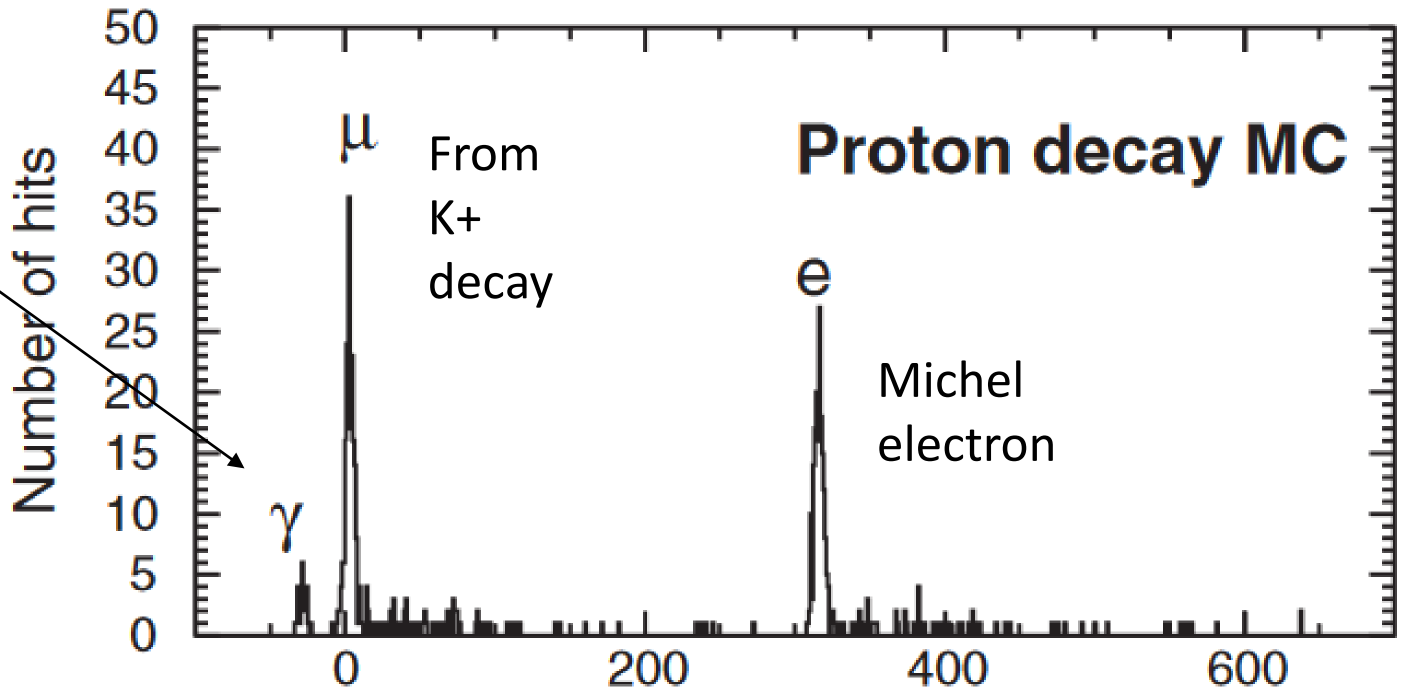
Phys. Rev. D 90, 072005 (2014)

$p \rightarrow \nu K^+$ at SK

$K^+ \rightarrow \mu^+\nu$, BR=65%



From N15 decay

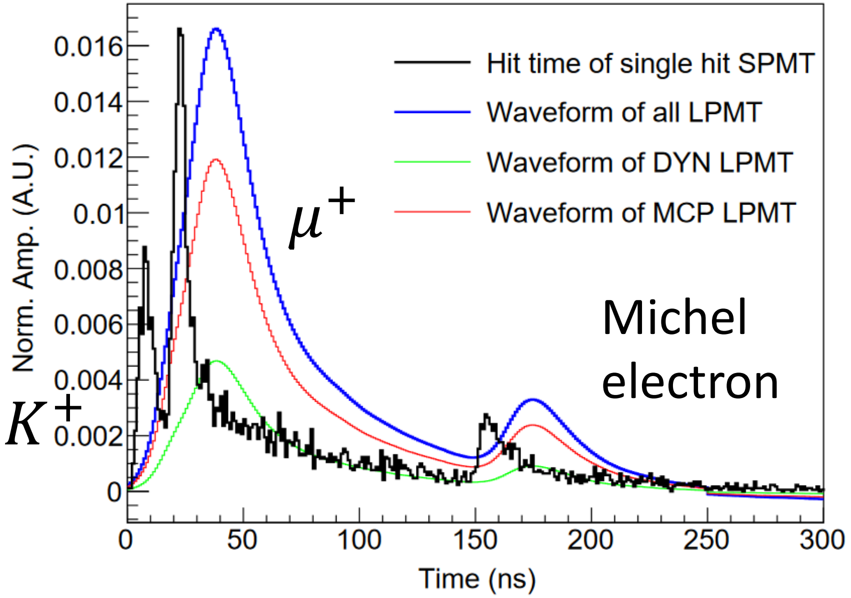


~10% efficiency

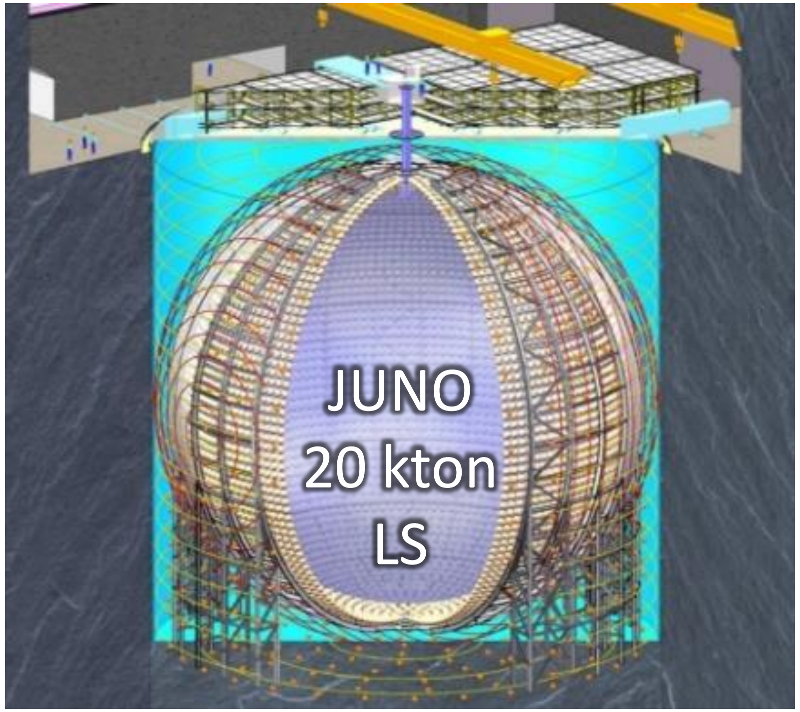
Phys. Rev. D 90, 072005 (2014)

Future Detectors: JUNO

- Large statistics:
  - 20 kton liquid scintillator
- High efficiency:
  - MeV thresholds

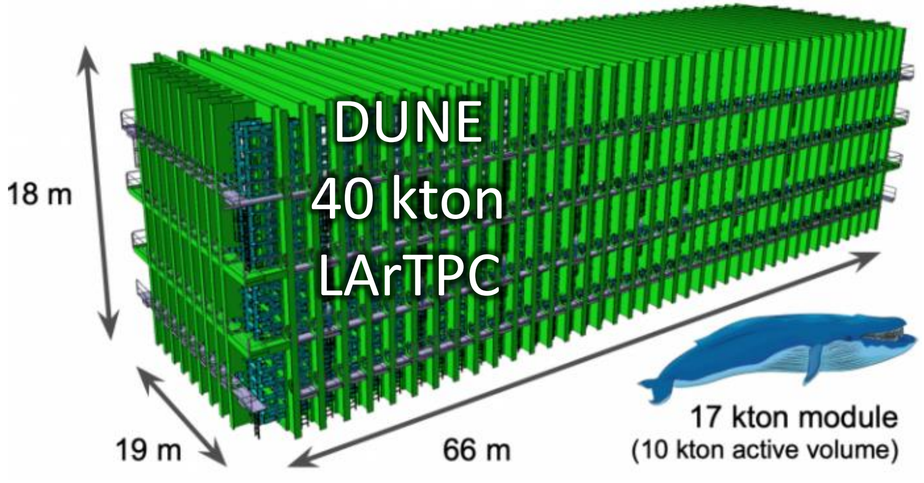


~40% efficiency

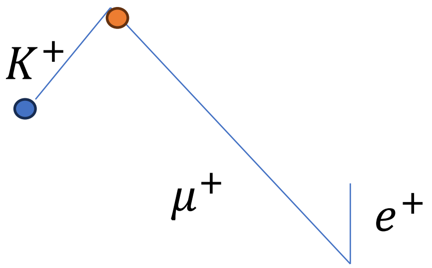


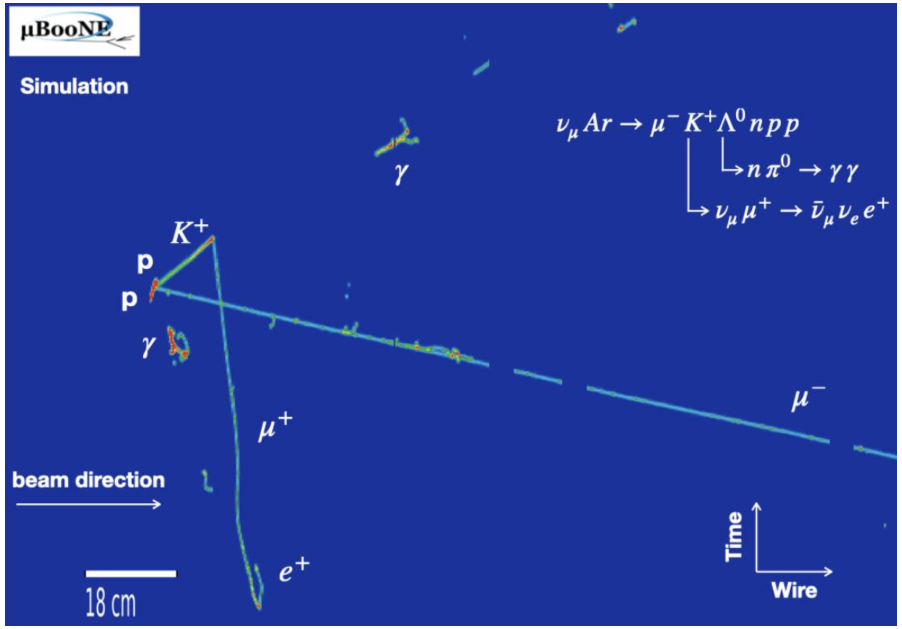
Chinese Phys. C **47** 113002 (2023)

Future Detectors: DUNE



- Large statistics:
  - 40 kton liquid argon
- High efficiency:
  - Topologically visible kaons in LArTPCs
  - Potential enhancement from de-excitation light

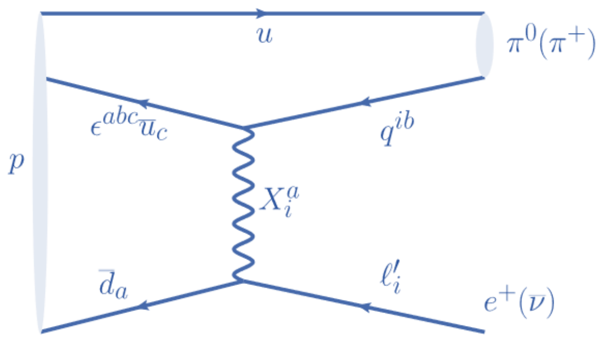


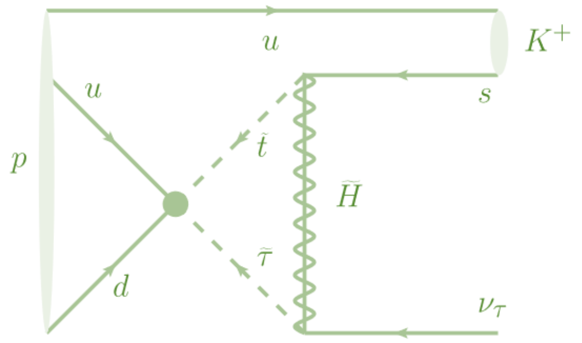


MicroBooNE Public Note - 1071

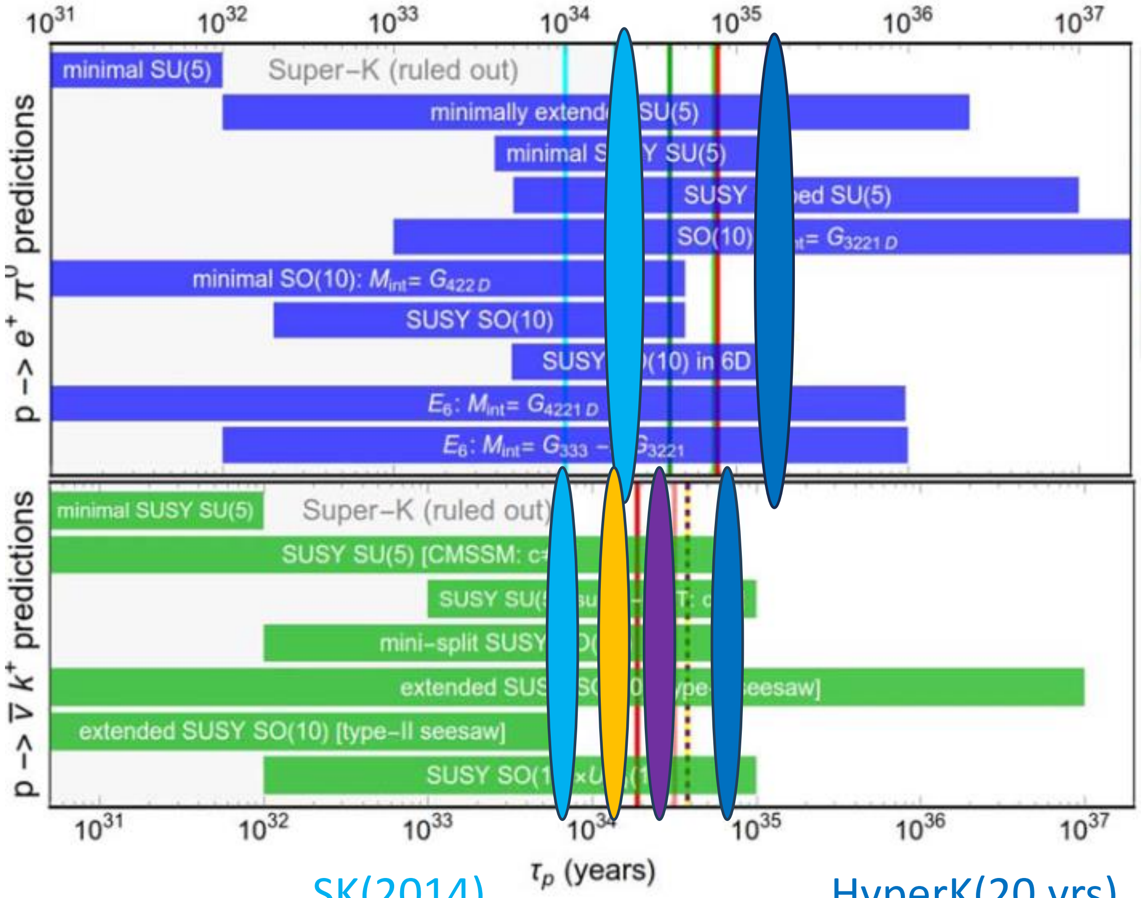
Benchmark Mode: $p \rightarrow \nu K^{+}$

2024 J. Phys. G: Nucl. Part. Phys. 51 033001





Lifetime limits [years]



SK(2014)

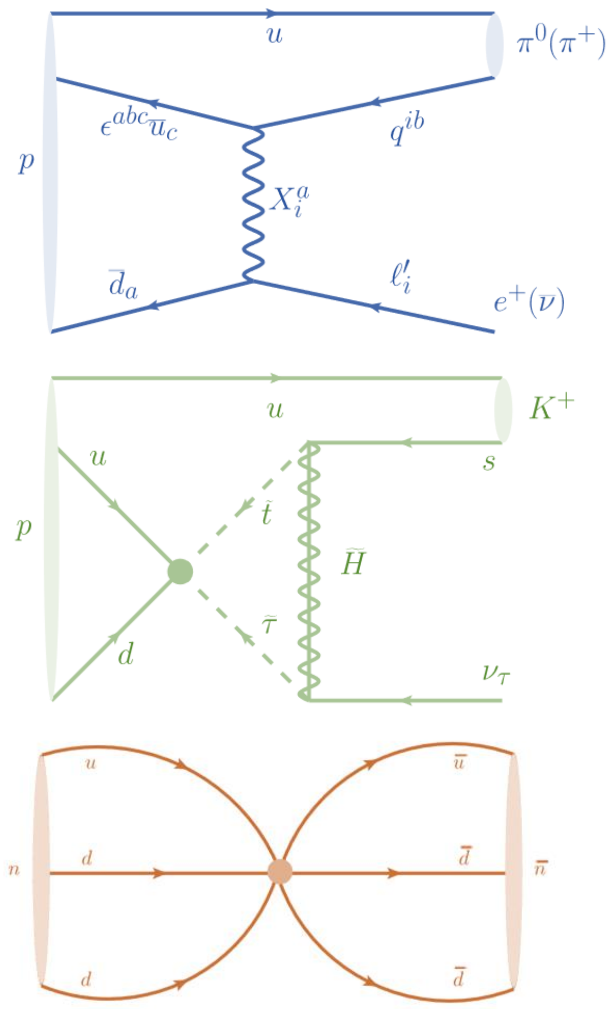
HyperK(20 yrs)

JUNO(20 yrs)

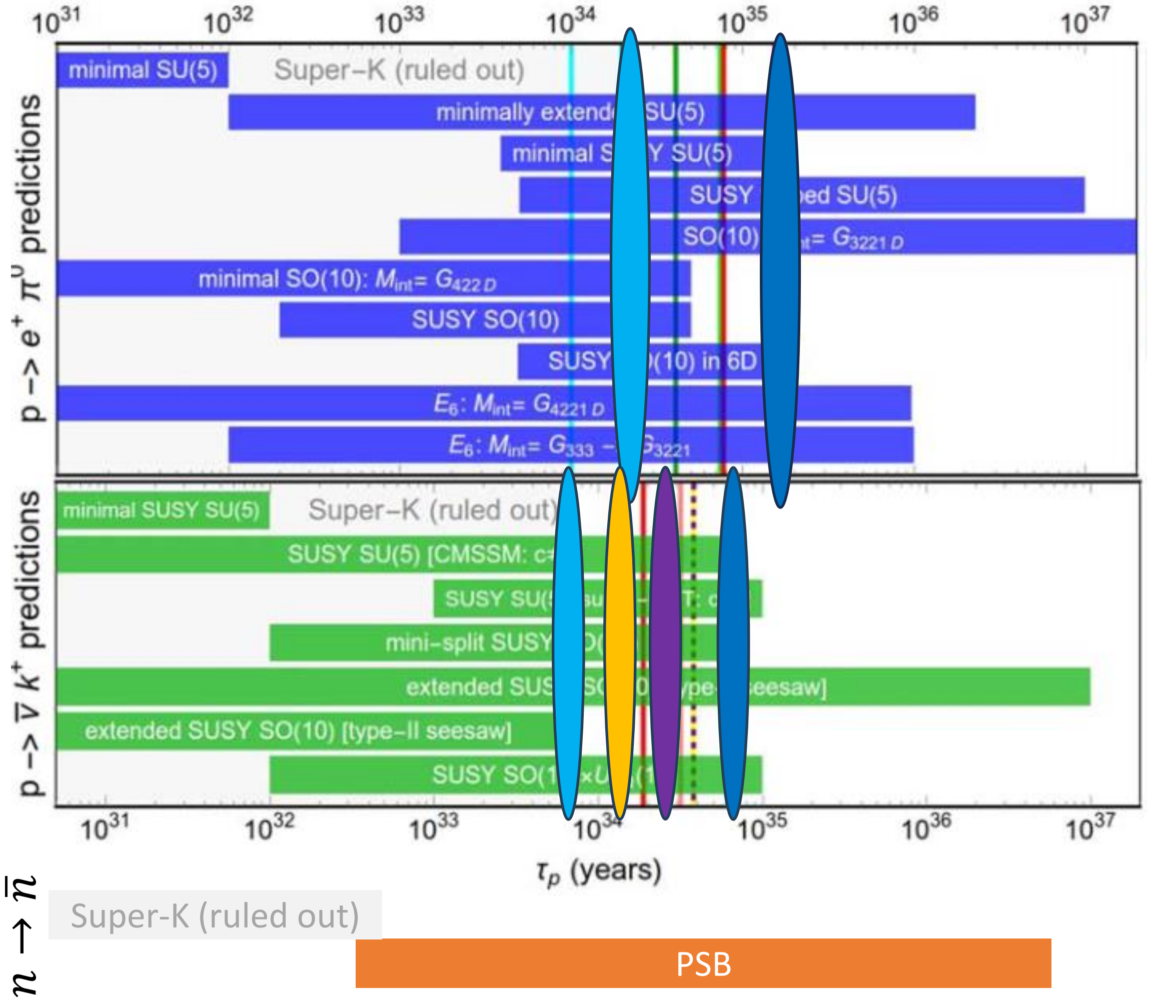
DUNE(20 yrs)

Benchmark Mode: $n \to \bar{n}$

2024 J. Phys. G: Nucl. Part. Phys. 51 033001



Lifetime limits [years]

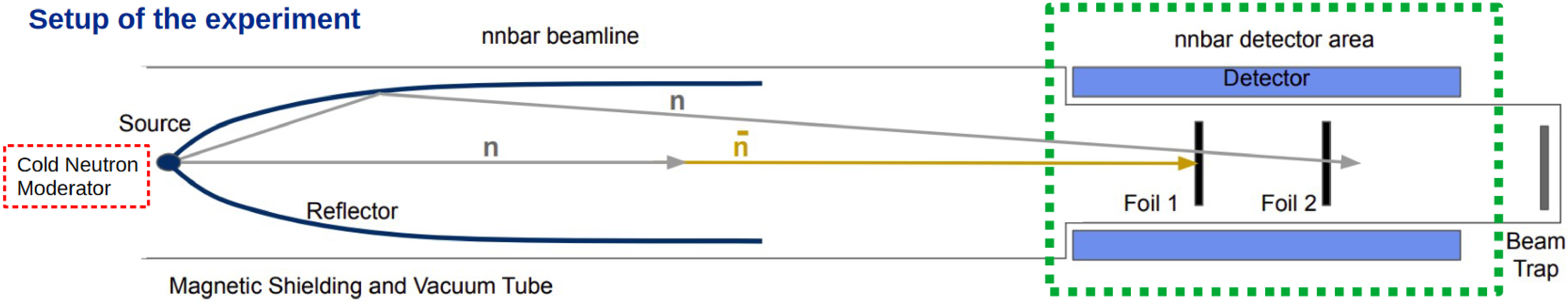


K.S. Babu, et al, PRD 87 115019 (2013)

Free Neutron Oscillation: ESS

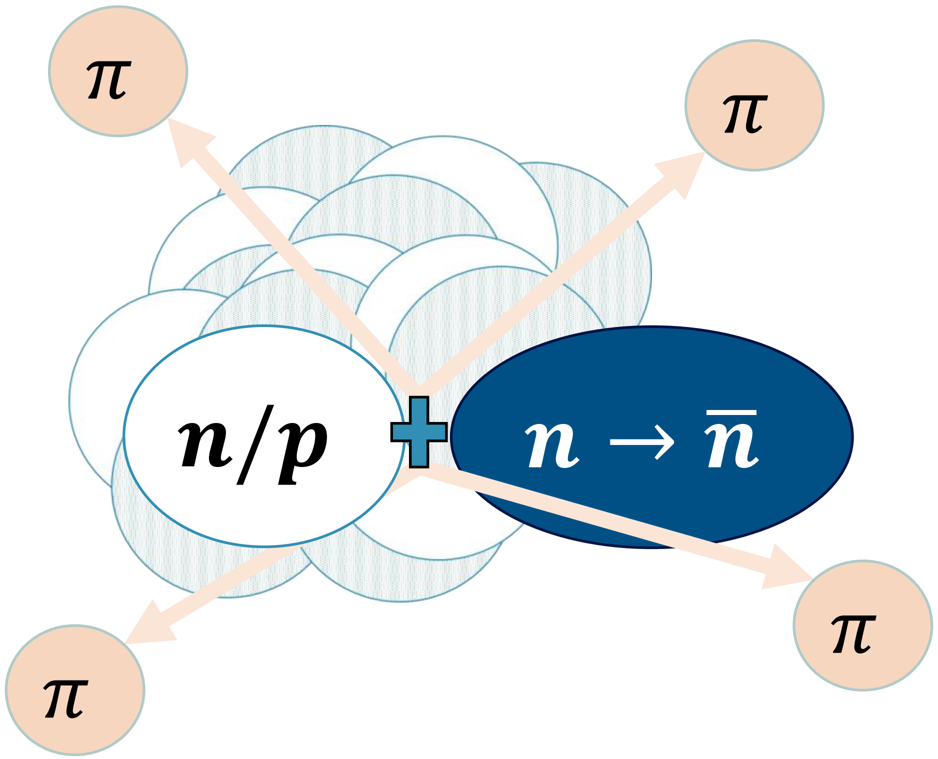
- Proposed Two Stage Experiment at the European Spallation Source
- Phase 1 - HIBEAM: Search for $n \to n'$
- Phase 2 - NNBAR: Search for $n \to \bar{n}$
  - 1000 times better sensitivity than the latest free neutron search at ILL

Z.Phys.C 63 (1994) 409-416



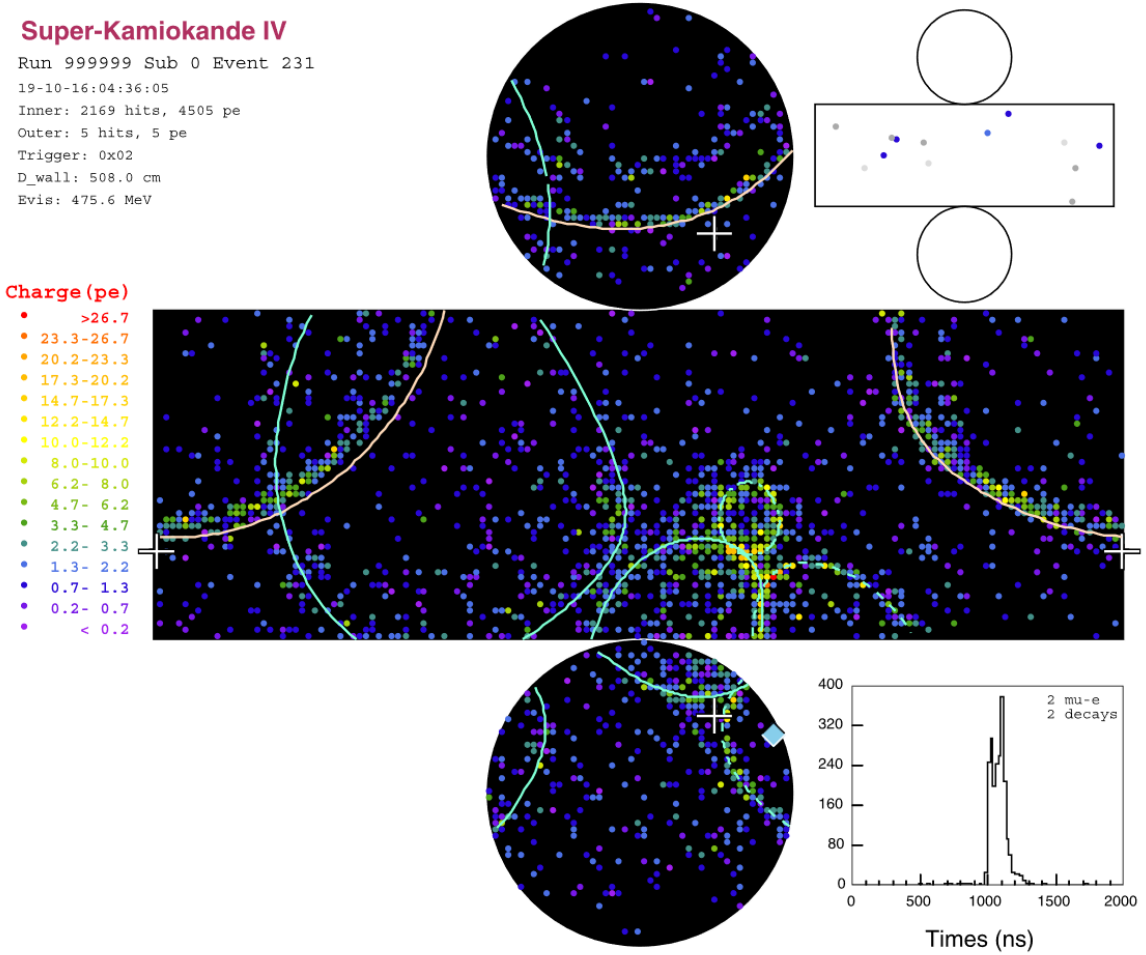
Sze Chun Yiu, CoSSURF 2022

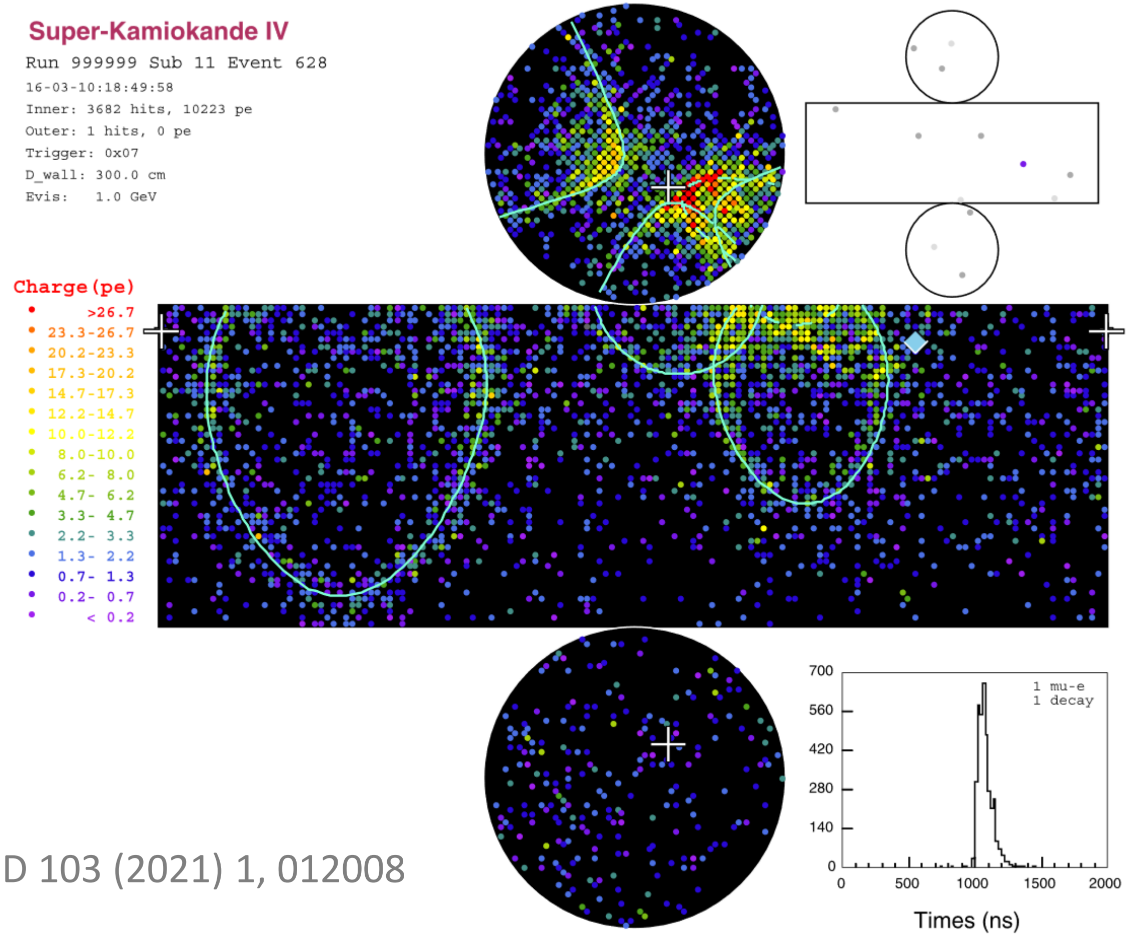
Bound Neutron Oscillation



- Suppressed by nuclear potential
- Multiple meson production from the annihilation after $n \to \bar{n}$ oscillation, mostly pions.

Neutron Oscillation at SK



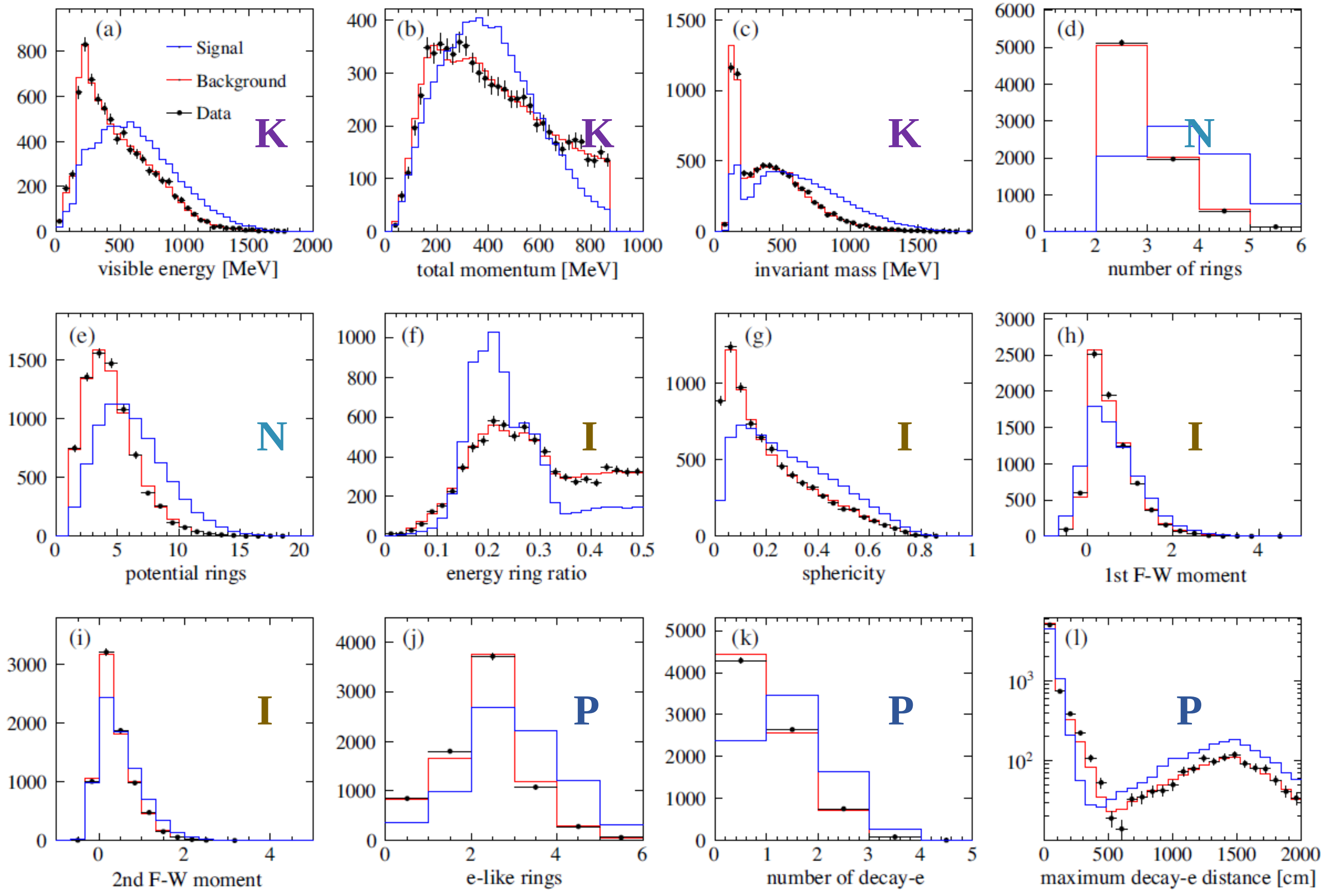


Phys.Rev.D 103 (2021) 1, 012008

A simulated $\bar{n}p$ annihilation producing 6 pions.
5 rings were reconstructed.

A simulated atmospheric neutrino event.
Neutral current deep inelastic scattering.

Quantified Features



Phys.Rev.D 103 (2021) 1, 012008

Signals have more rings and are more isotropic.
Backgrounds have a wider range of kinetics, and fewer rings.

These features are quantified as variables concerning:

- **Kinematics**
- **Number of rings**
- **Isotropy**
- **PID**

Quantified Features

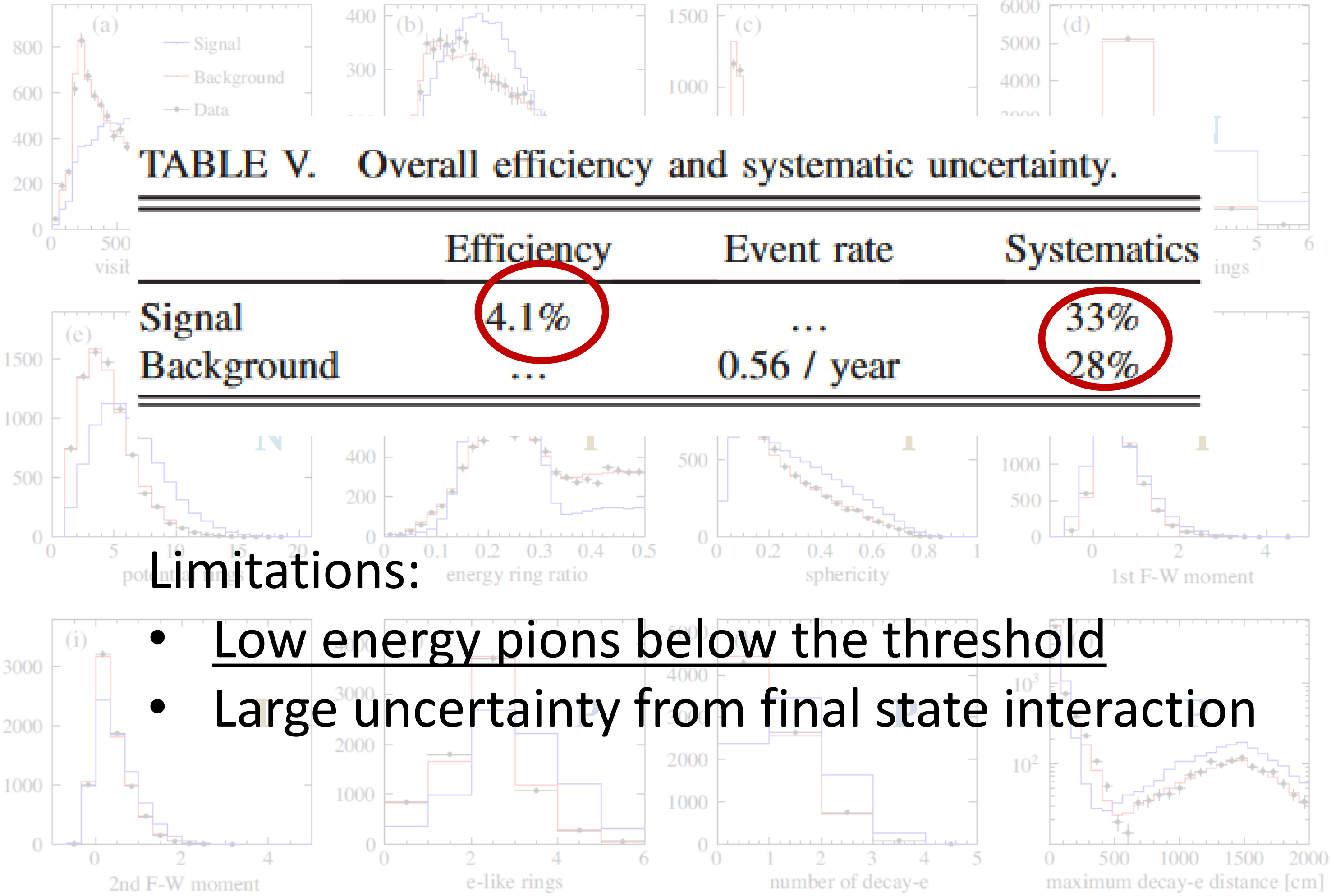


TABLE V. Overall efficiency and systematic uncertainty.

	Efficiency	Event rate	Systematics
Signal	4.1%	…	33%
Background	…	0.56 / year	28%

Limitations:

- Low energy pions below the threshold
- Large uncertainty from final state interaction

Phys.Rev.D 103 (2021) 1, 012008

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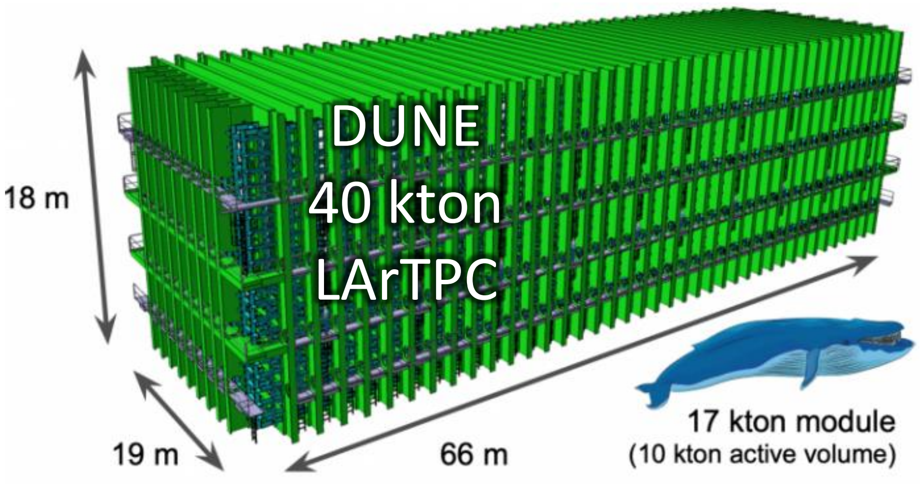
These features are quantified as variables concerning:

- Kinematics
- Number of rings
- Isotropy
- PID

Future Detectors: DUNE

- Large statistics:
  - 40 kton liquid argon
- High efficiency:
  - Low threshold for pions
- Challenge:
  - Smeared kinematics from Fermi motion & final state interaction



Summary

- Baryon Number Violation searches are highly motivated.
- There are active searches in many modes, especially the benchmark modes $p \to e^+\pi^0$, $p \to \nu K^+$, and $n \to \bar{n}$.
  No observation yet.
- Future searches with next-generation large neutrino detectors are promising.