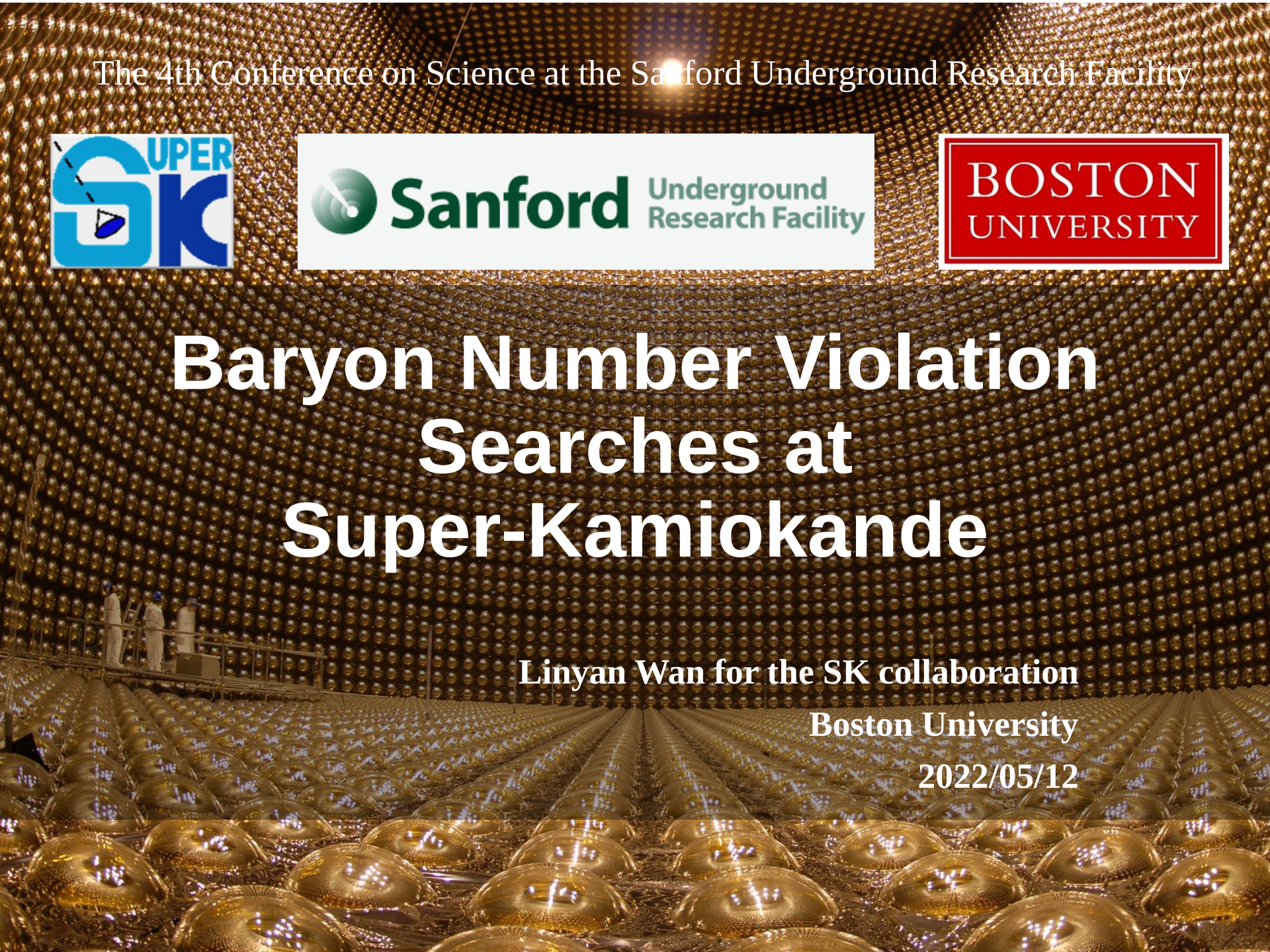


The 4th Conference on Science at the Sanford Underground Research Facility

Baryon Number Violation Searches at Super-Kamiokande

Linyan Wan for the SK collaboration

Boston University

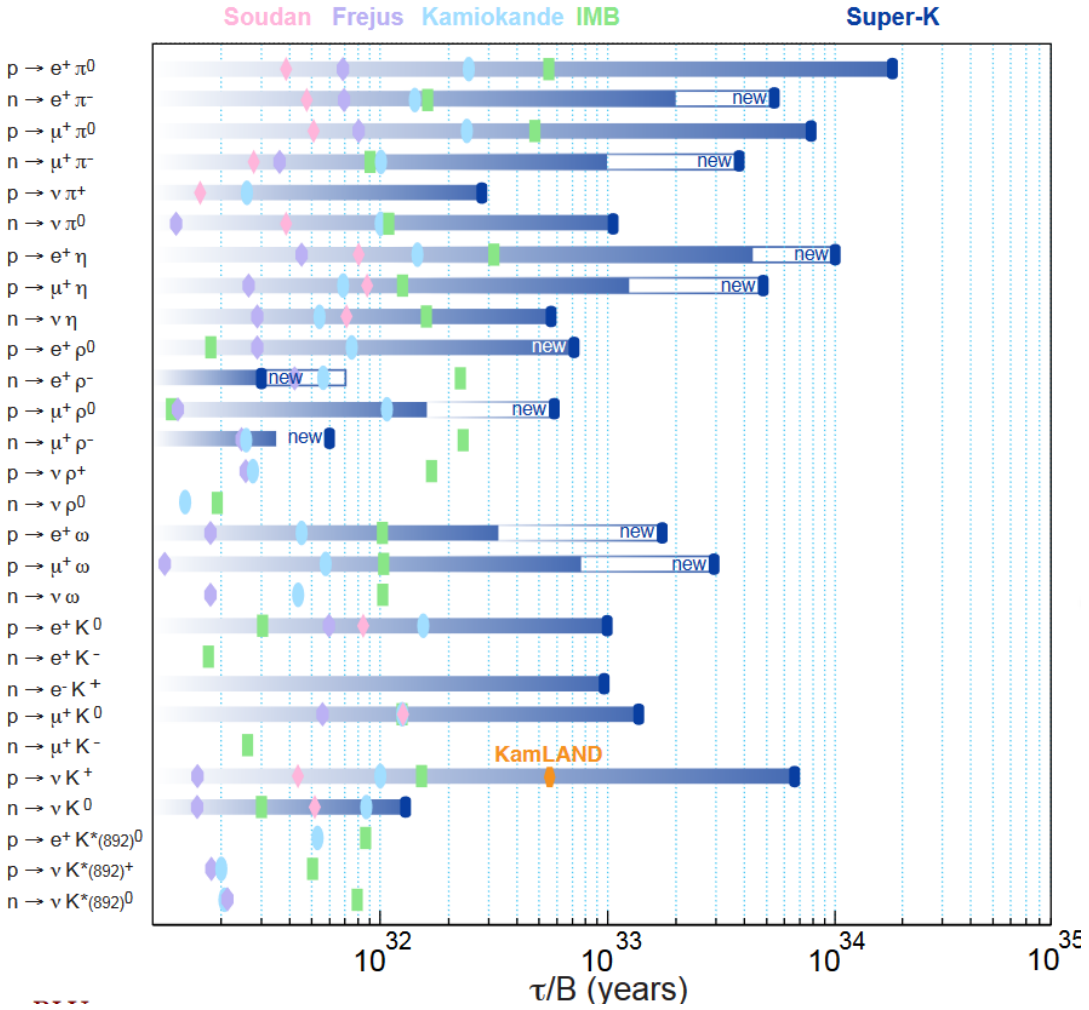
2022/05/12

Proton Decay Search

- Grand Unification Theory
- 10^{15}~10^{16} GeV scale, unreachable by accelerators
- Can be testified by observations of proton decay

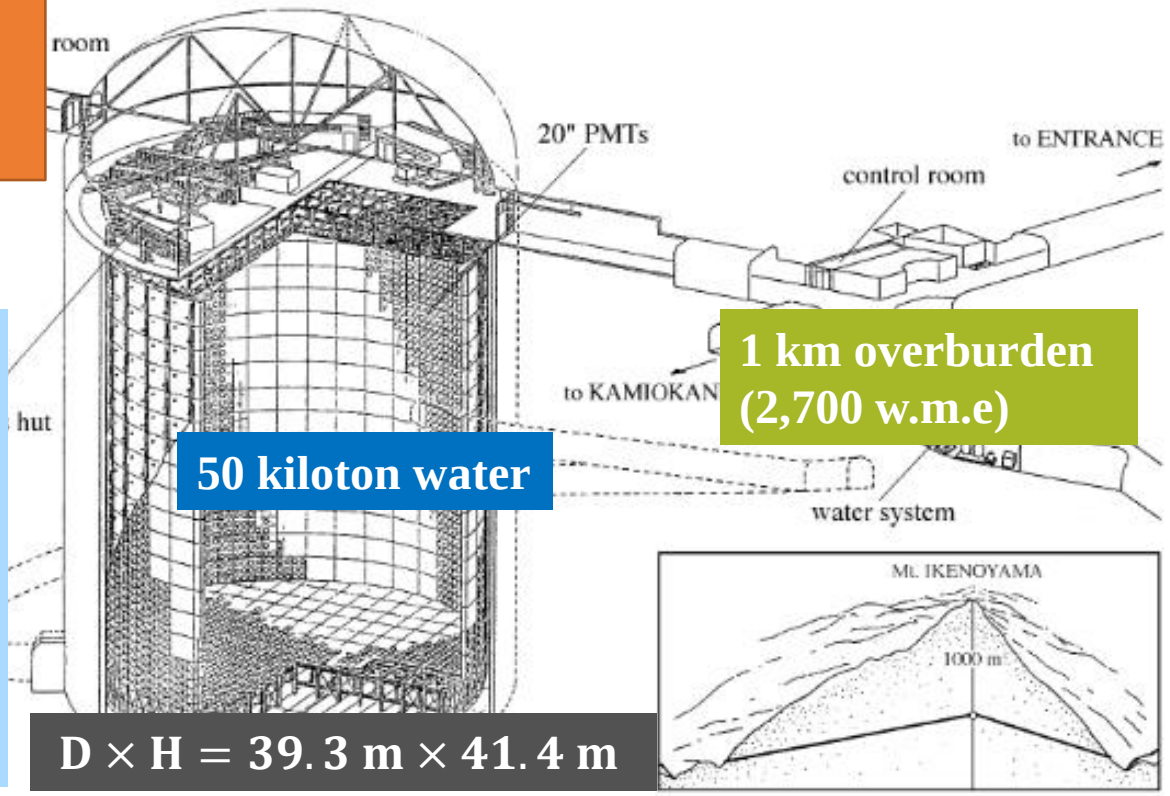
No observation!

Upper limit→



Super-Kamiokande Detector

Large water Cherenkov detector: 1996 ~ so far



50 kiloton water

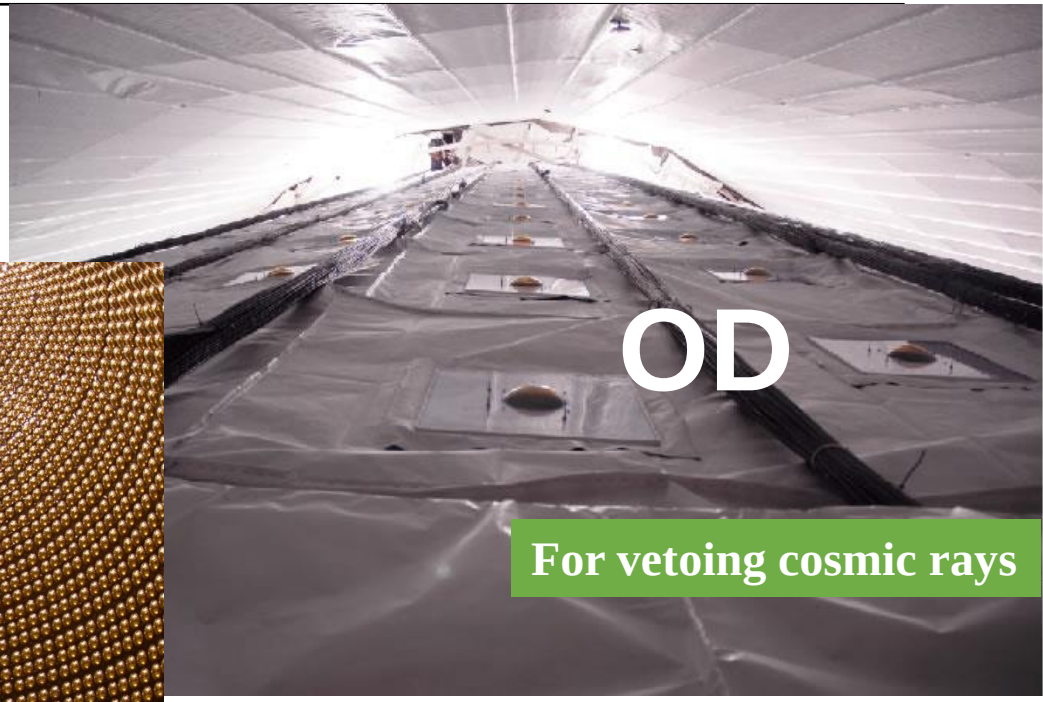
1 km overburden (2,700 w.m.e)

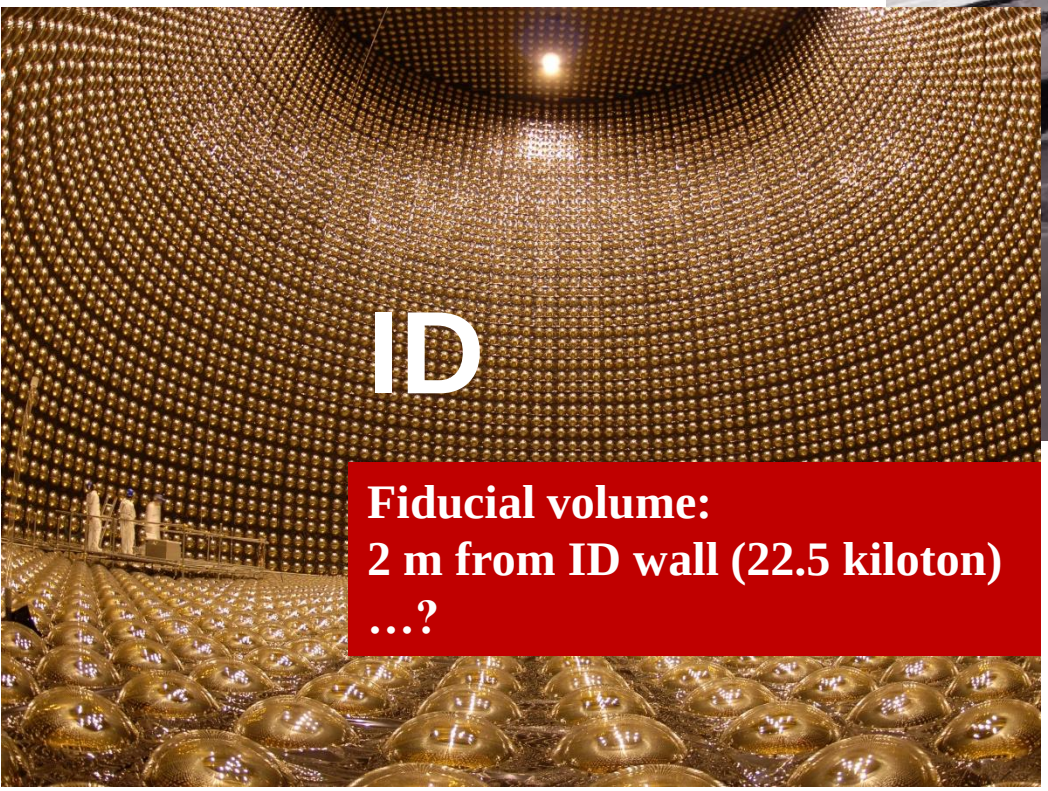
D × H = 39.3 m × 41.4 m

Nucl. Instr. & Meth, A 737C (2014)

SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

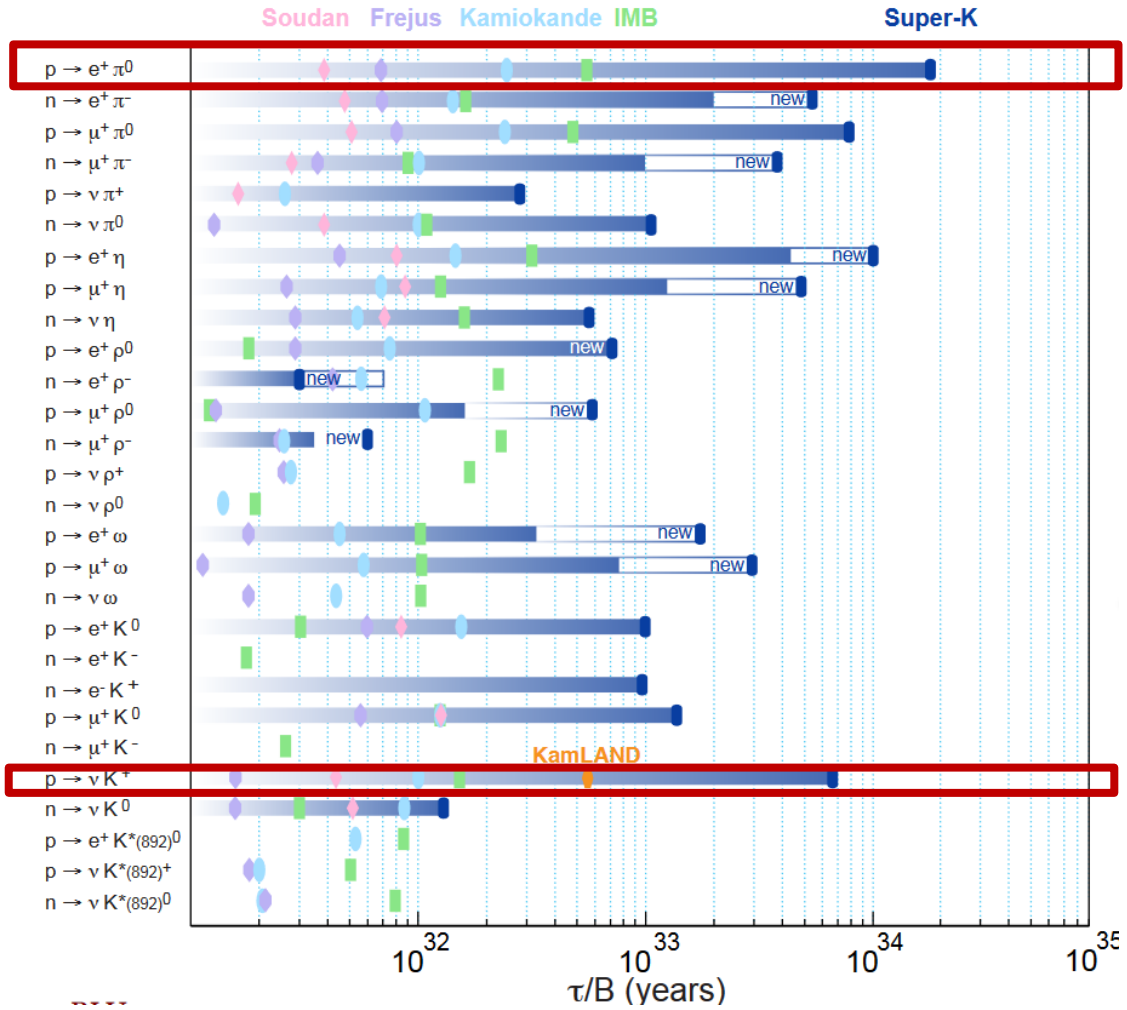
Inner Detector / Outer Detector





Proton Decay Search

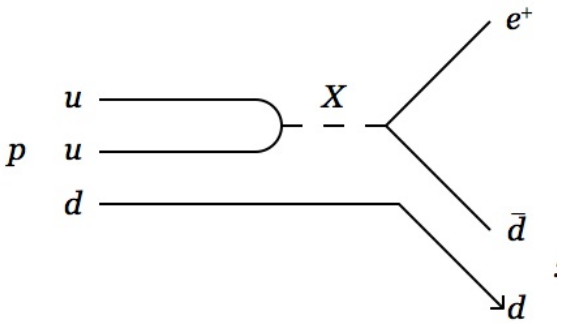
- Benchmark modes
  - $p \to e^+\pi^0$
  - $p \to \nu K^+$

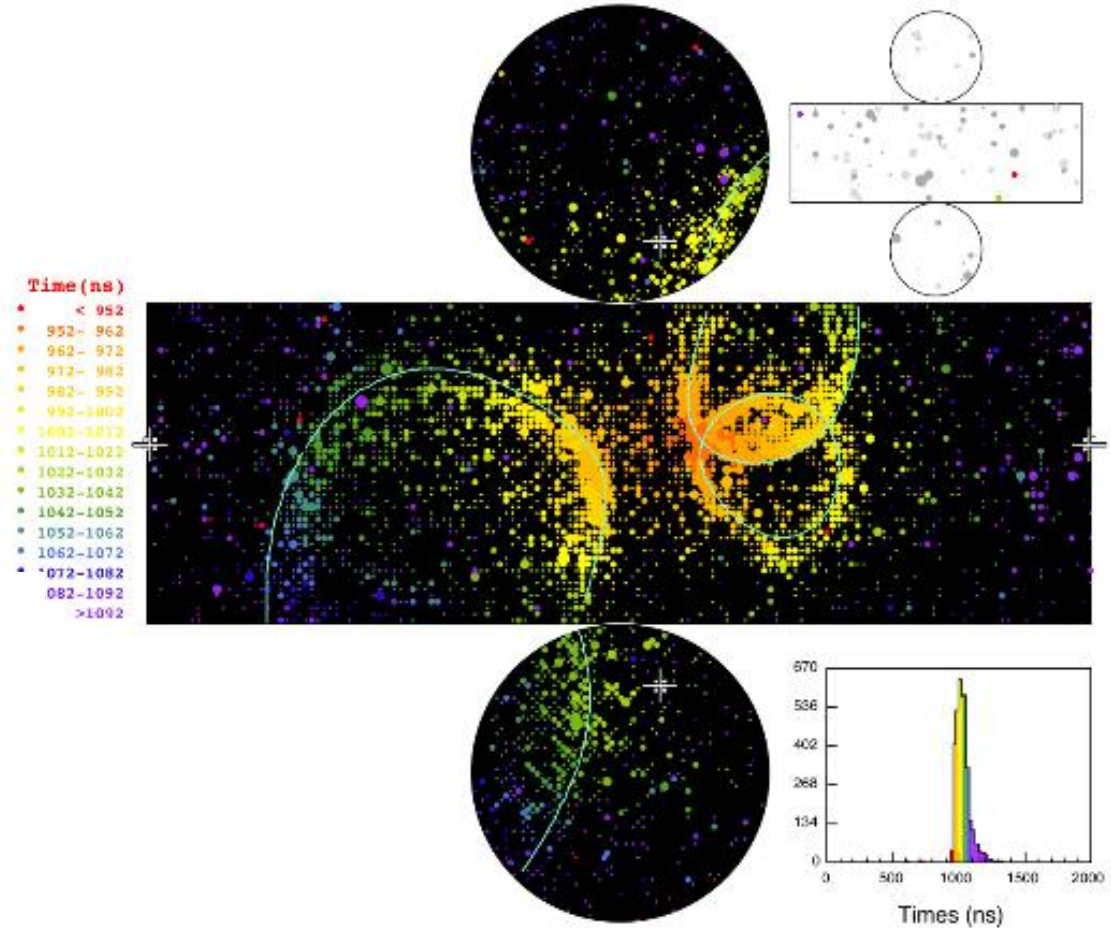


$p \rightarrow e^{+}\pi^{0}$ Search

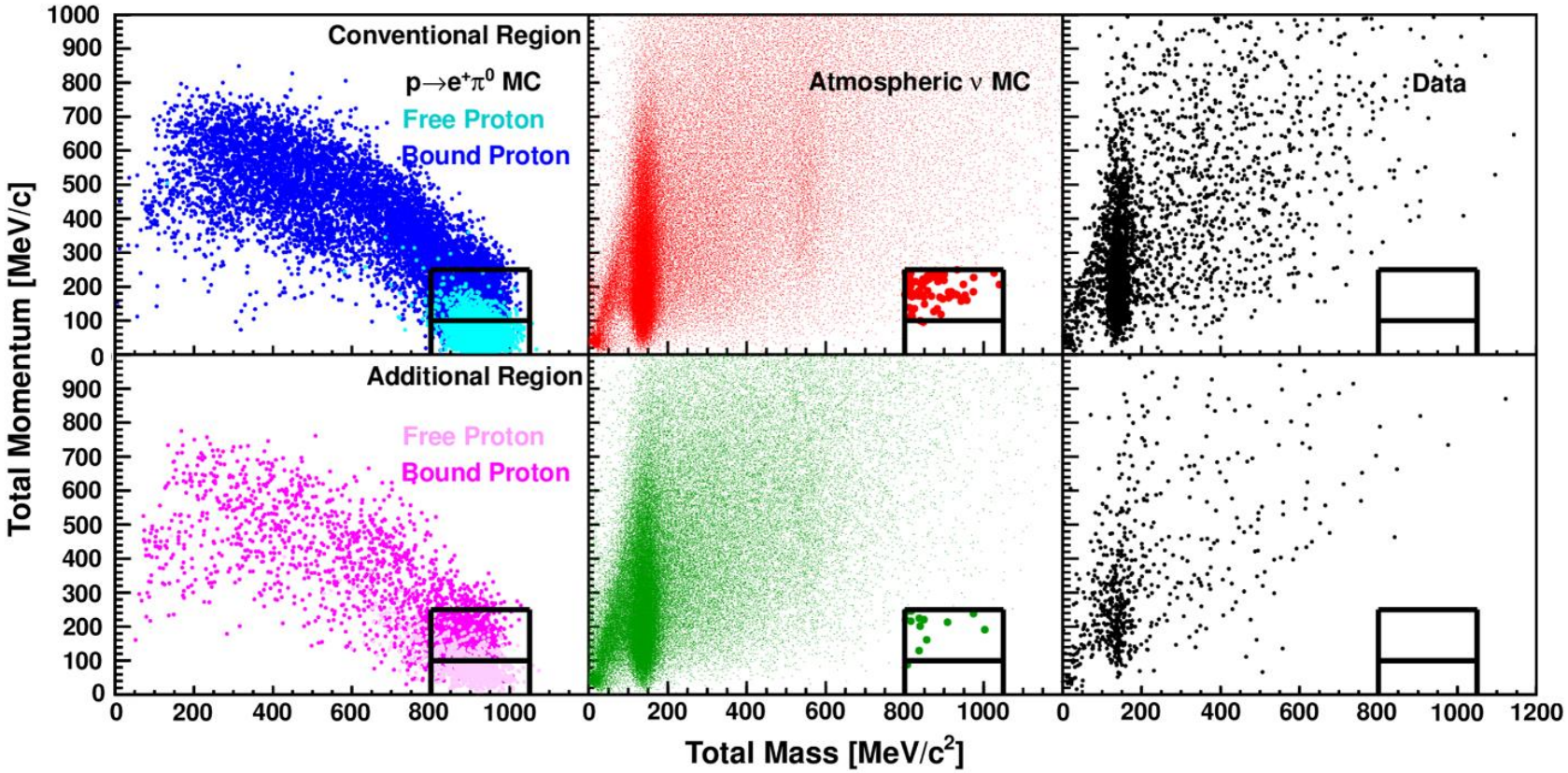
Benchmark mode 1

Signal:
e^{+} and 2γ from π^{0}





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



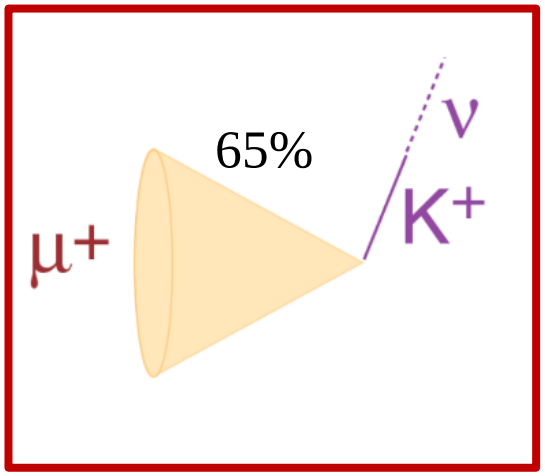
$e^+\pi^0$: 2.4×10^{34} years @90% CL

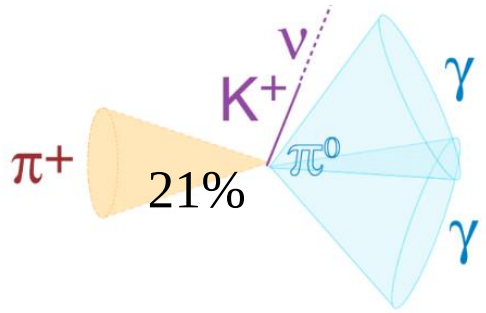
Live-time: 450 kton · year

Phys. Rev. D 102, 112011 (2020)

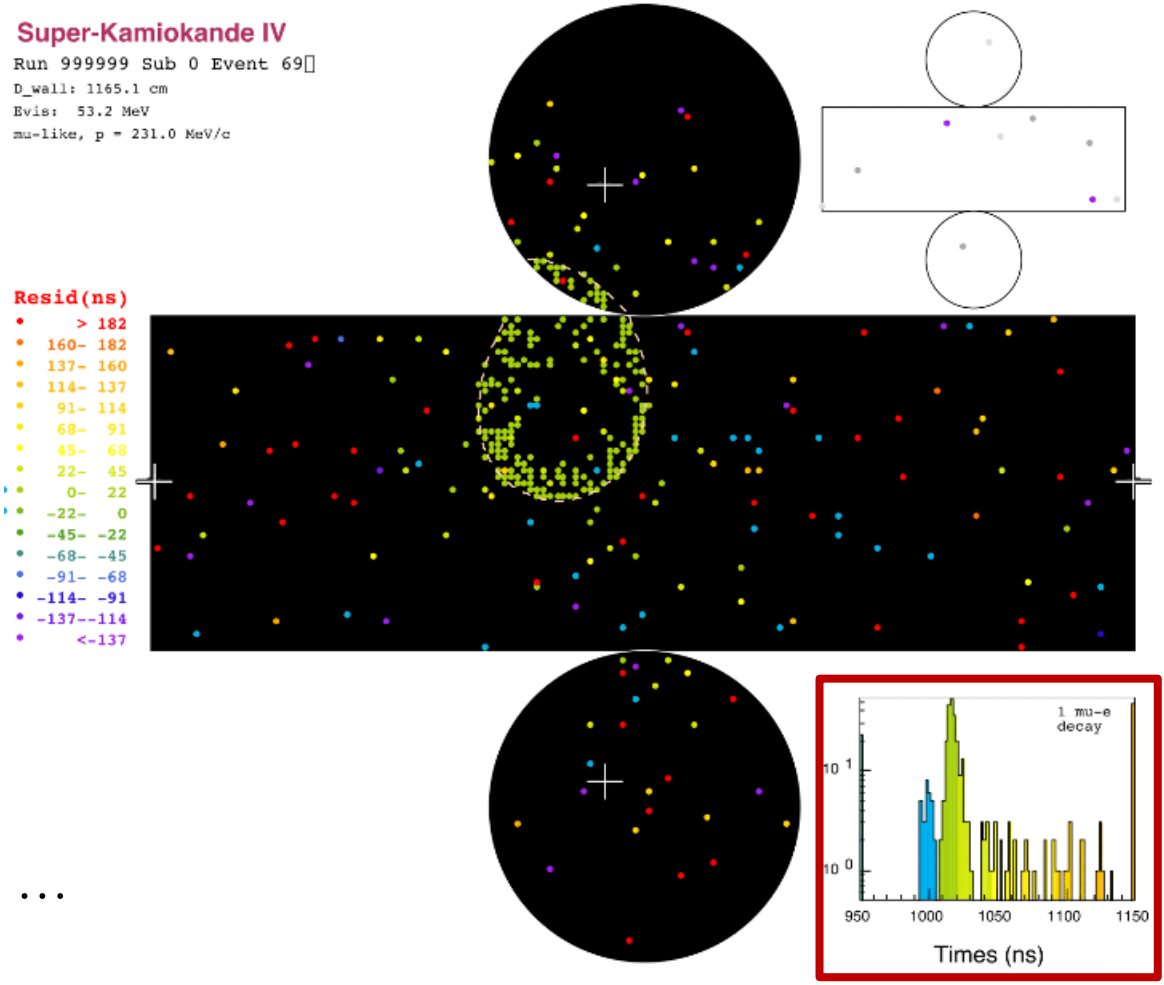
$p \to \bar{\nu} K^+$ Search

Benchmark mode 2



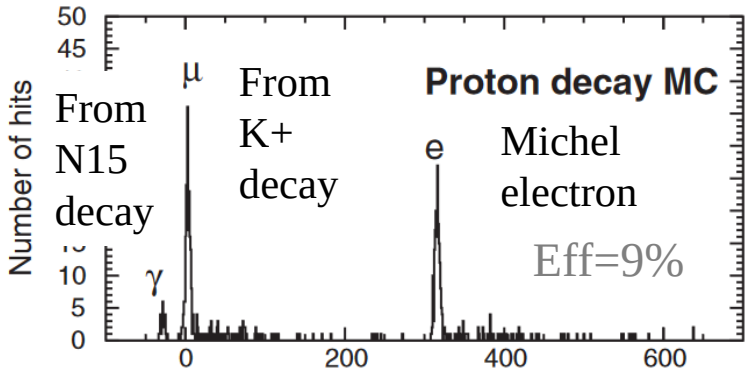


…



$p \to \bar{\nu} K^+$ Search

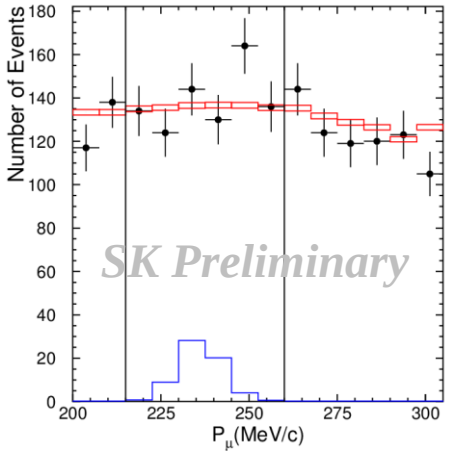
1.1 Prompt gamma tagging



1.2 Monogenic muon from 2-body decay

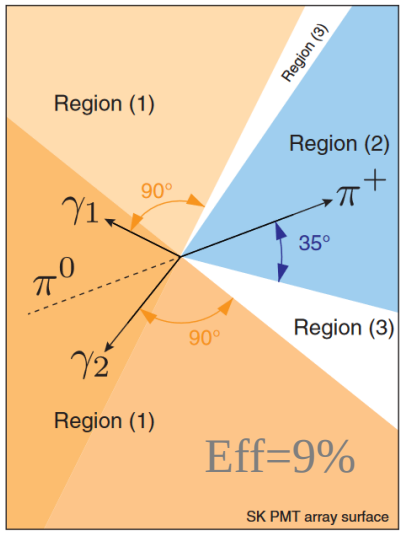
$K^+ \to \mu^+ \nu$

BR=65%



2. $K^+ \to \pi^+ \pi^0$

BR=21%



π^0

Mass ~135 MeV

Momentum ~200 MeV

π^+

Low Cherenkov light yield opposite to π^0 direction

Decay to a muon which then decays to produce an electron ring

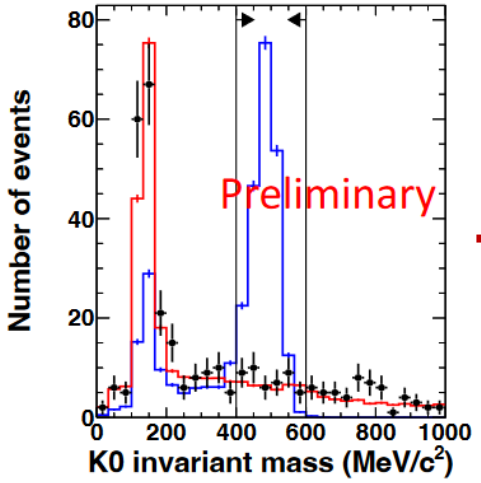
Exposure: 349 kton · year

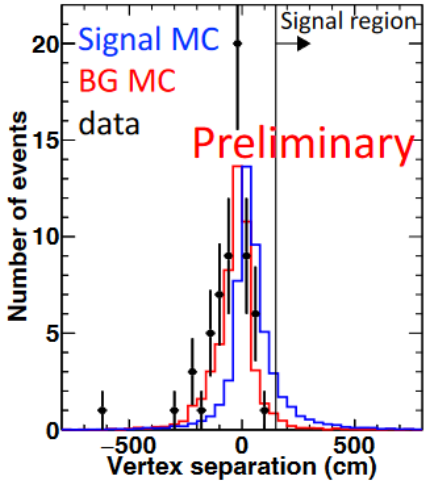
νK^+: 8.0×10^{33} years @90% CL

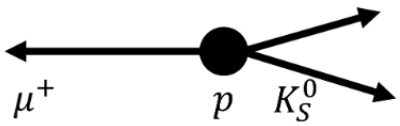
$p \to \mu^+ K^0$ Search

With higher branching ratio than $e^+\pi^0$ for some SUSY SO(10) models:

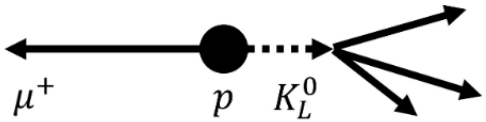
3.6×10^{33} years
@90% CL







$$K_S^0 \to \pi^- + \pi^+ \text{ (BR: 70\%)}$$
$$K_S^0 \to \pi^0 + \pi^0 \text{ (BR: 30\%)}$$



$$K_L^0 \to \pi^\pm + l^\mp + \nu_l \text{ (BR: 67\%)}$$
$$K_L^0 \to \pi^0 + \pi^0 + \pi^0 \text{ (BR: 20\%)}$$
$$K_L^0 \to \pi^+ + \pi^- + \pi^0 \text{ (BR: 13\%)}$$

Topology + Kinematics

Exposure: 370 kton · year

$p \rightarrow$ 3-lepton

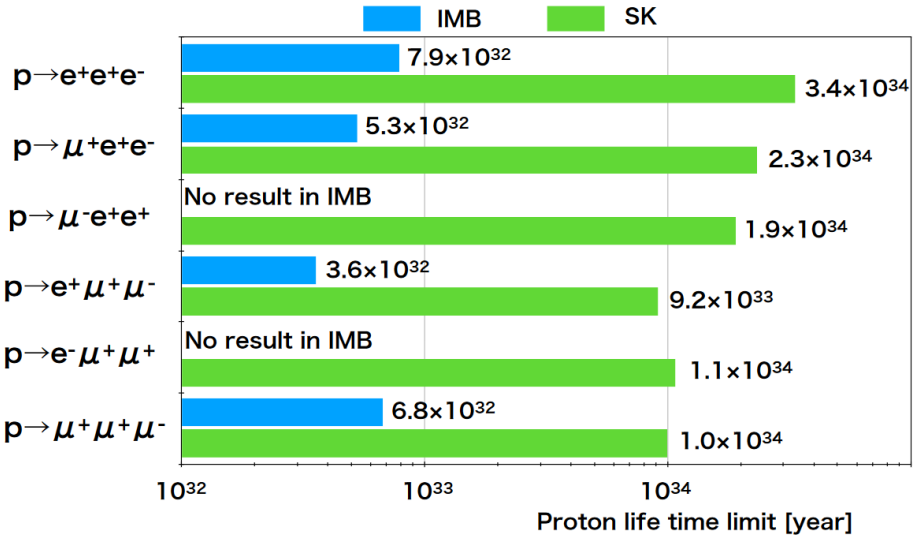
Predicted in a higher dimension ($d = 10$) model with $\Delta B = \Delta L$:

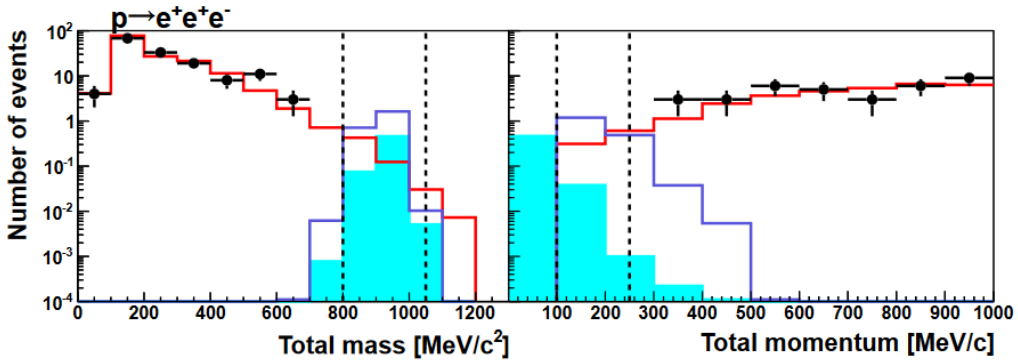
Data

Free proton MC

Bound proton MC

Background MC





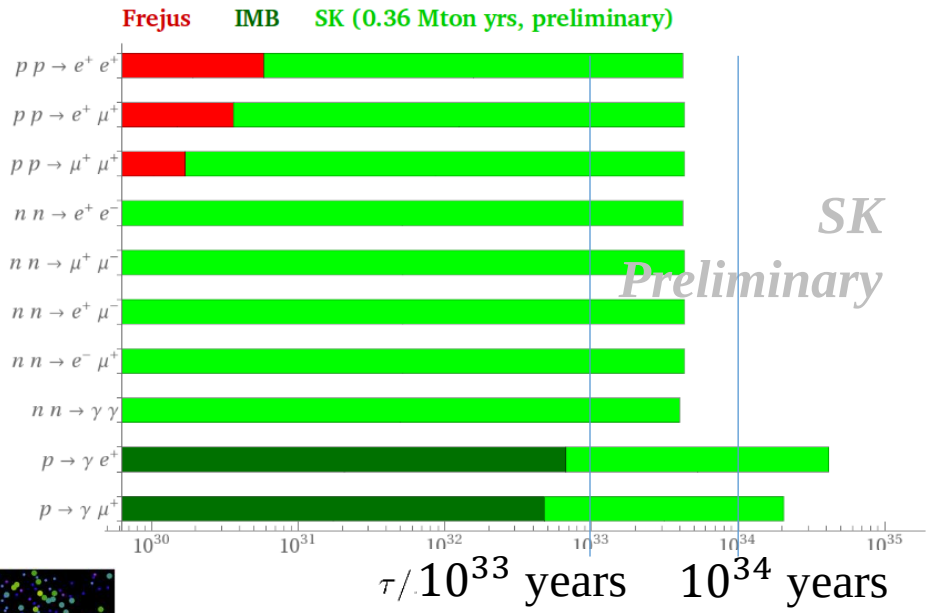
90% CL

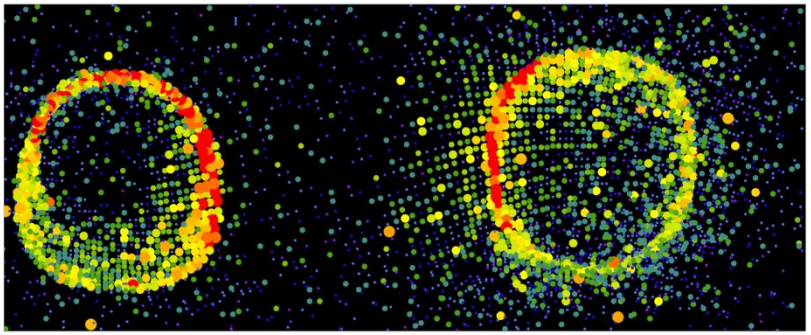
Exposure: 370 kton · year

PHYSICAL REVIEW D 101, 052011 (2020)

Di-Nucleon → 2-lepton

- Signature: 2 back-to-back lepton signals
- Cuts on reconstructed total mass, momentum, and PID





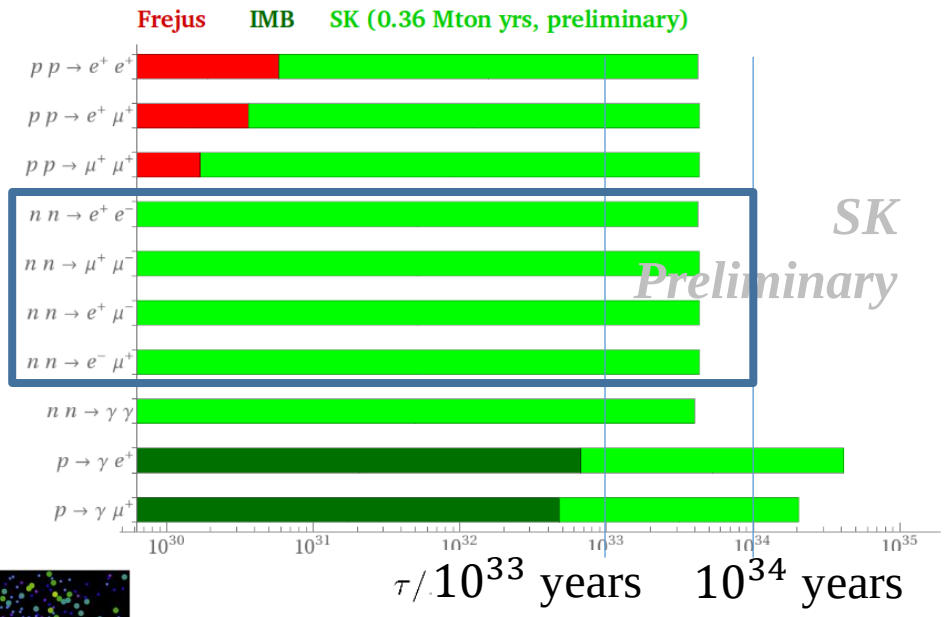
Event display of a MC event

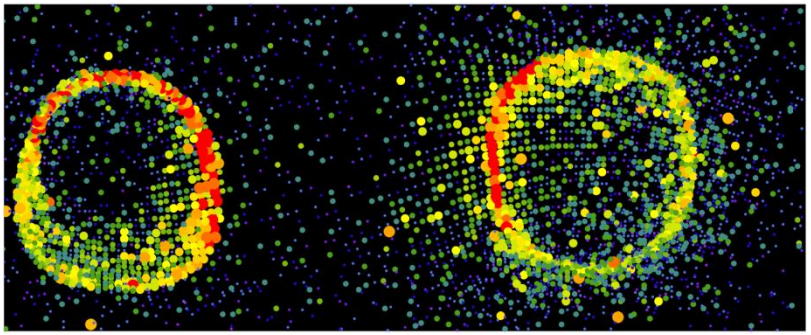
$pp \to e^+\mu^+$

arXiv:1811.12430

Di-Nucleon → 2-lepton

- Signature: 2 back-to-back lepton signals
- Cuts on reconstructed total mass, momentum, and PID
- **4 modes violate $(B - L)$**





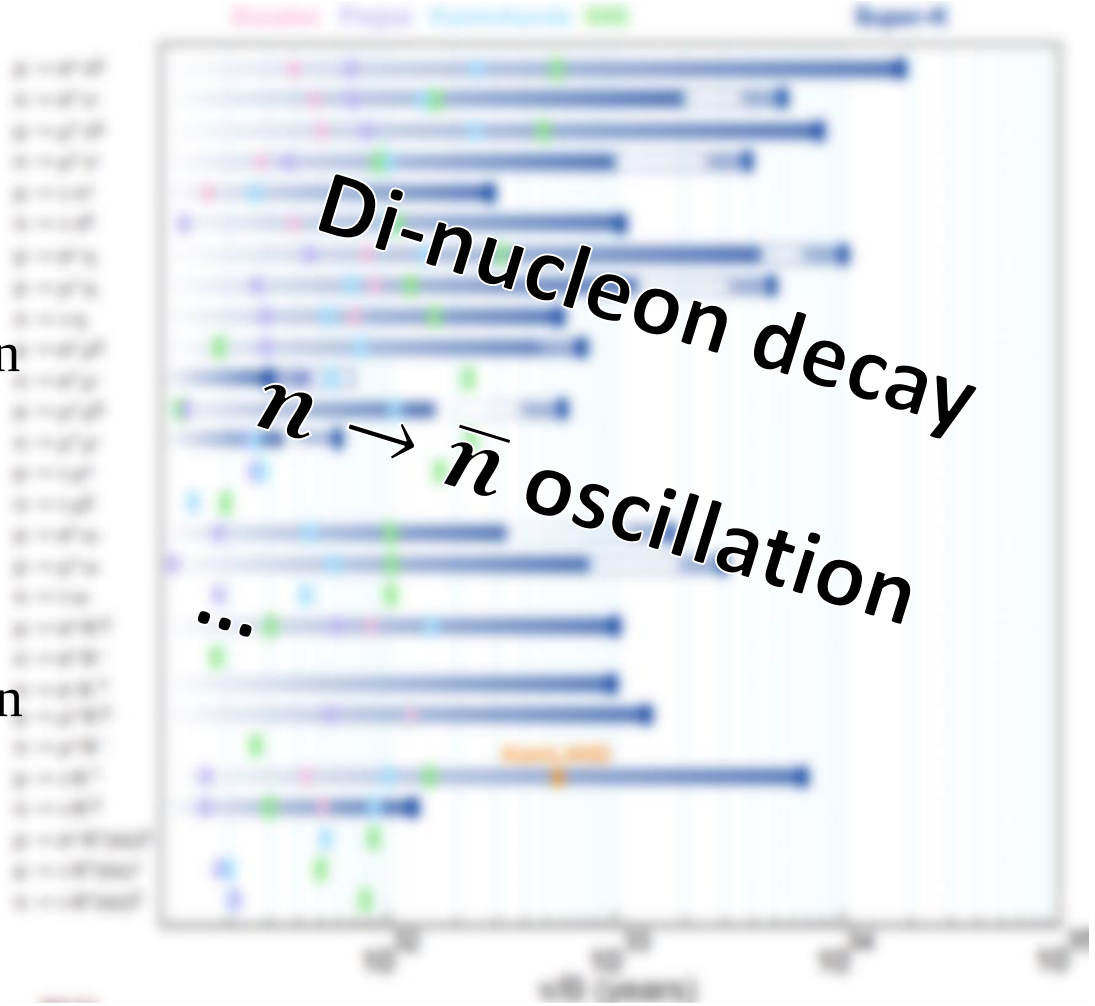
Event display of a MC event

$pp \to e^+\mu^+$

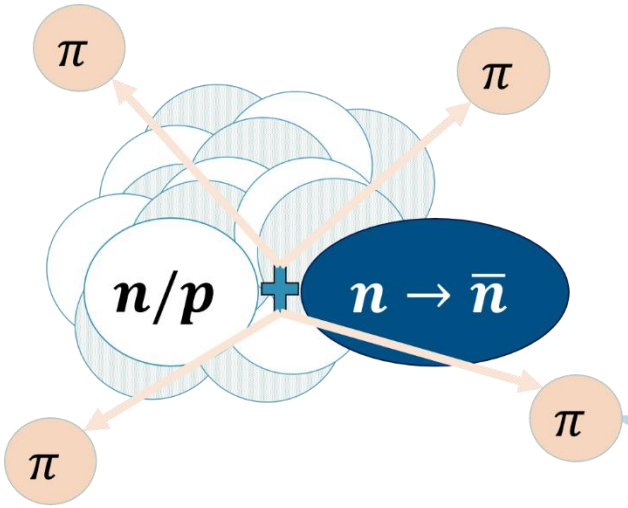
arXiv:1811.12430

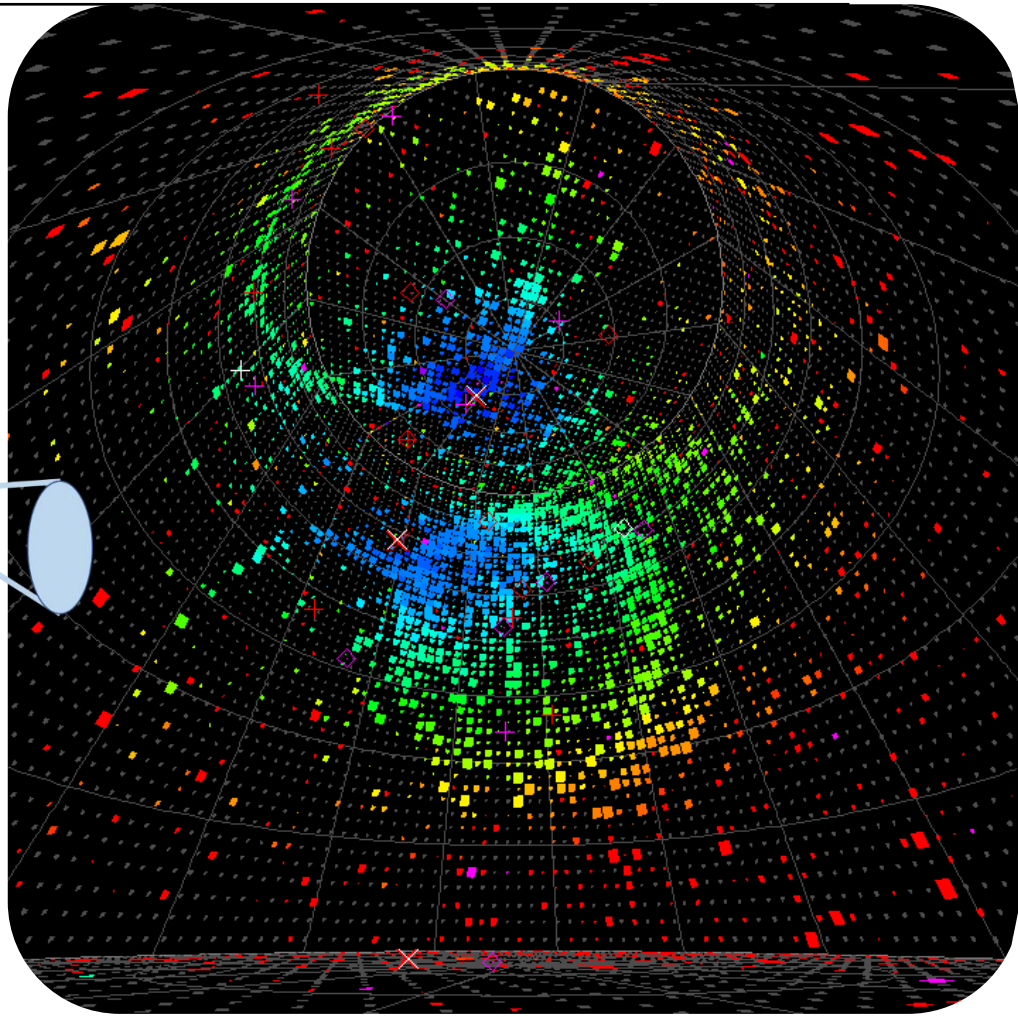
Baryon Number Violation

- Baryon Asymmetry
  - Expect baryon number violation: $\Delta B \neq 0$
- Sphaleron washes out baryon asymmetry from processes conserving $(B - L)$
- $\Delta(B - L) \neq 0$ processes are candidates for post-sphaleron baryogenesis



$n \rightarrow \bar{n}$ Oscillation

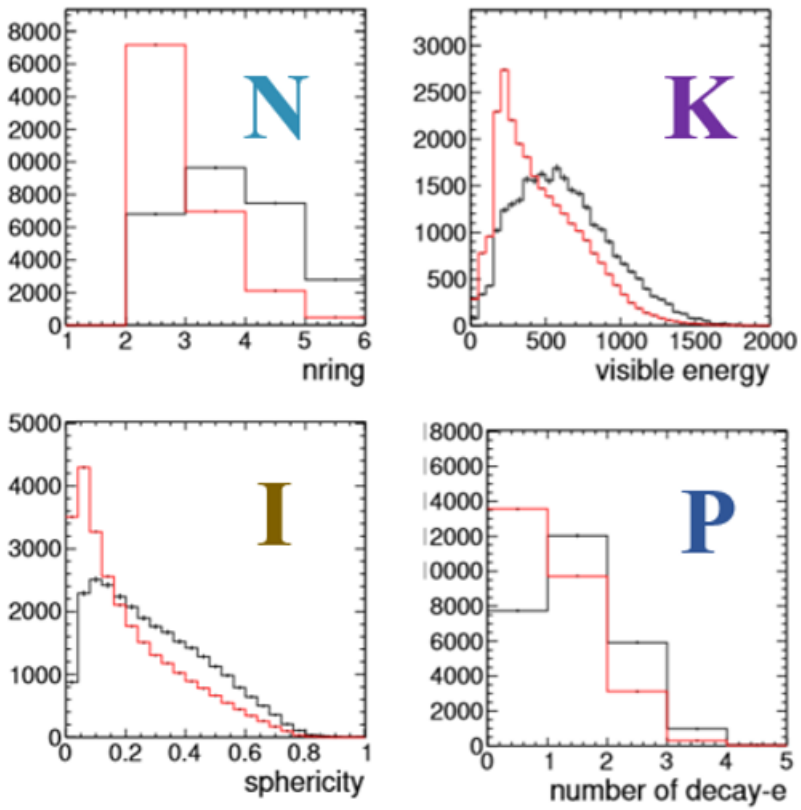




$$\Delta B = 2, \Delta L = 0$$

Search for $n \rightarrow \bar{n}$

Signal v.s. Background



Multi-variate analysis (MVA) with inputs quantifying:

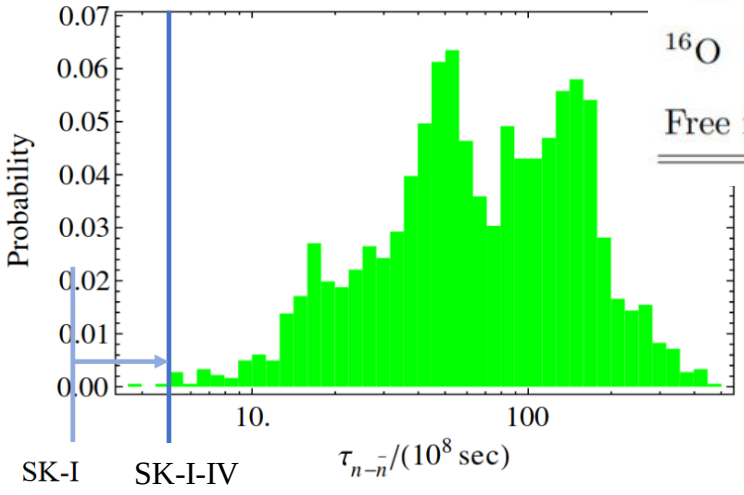
- **Number of rings** (2)
- **Kinematics** (3)
- **Isotropy** (4)
- **PID** (3)

Phys. Rev. D 103, 012008 (2021)

$n \to \bar{n}$ Oscillation

$\tau_{n\to\bar{n}}$ scaled by $\sqrt{1/R}$		$T_{n\bar{n}}(10^{32}$ years)	R $(10^{23}/\mathrm{s})$	$\tau_{n\to\bar{n}}(10^{8}$ s)
^{16}O	SK-I-IV (this study)	3.6	0.517	4.7
^{16}O	SK-I [8] (2015)	1.9	0.517	3.4
^{16}O	Kamiokande [11] (1986)	0.4	0.517	1.6
^{2}H	SNO [9] (2017)	0.1	0.25	1.4
^{56}Fe	Soudan II [10] (2002)	0.7	1.4	1.3
^{56}Fe	Frejus [38] (1990)	0.7	1.4	1.2
^{16}O	IMB [12] (1984)	0.2	0.517	1.2
Free neutron	Grenoble [7] (1994)	-	-	0.9

Reaching the range of theoretical prediction



Phys. Rev. D 103, 012008 (2021)

Green from PSB model

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

Future Improvements

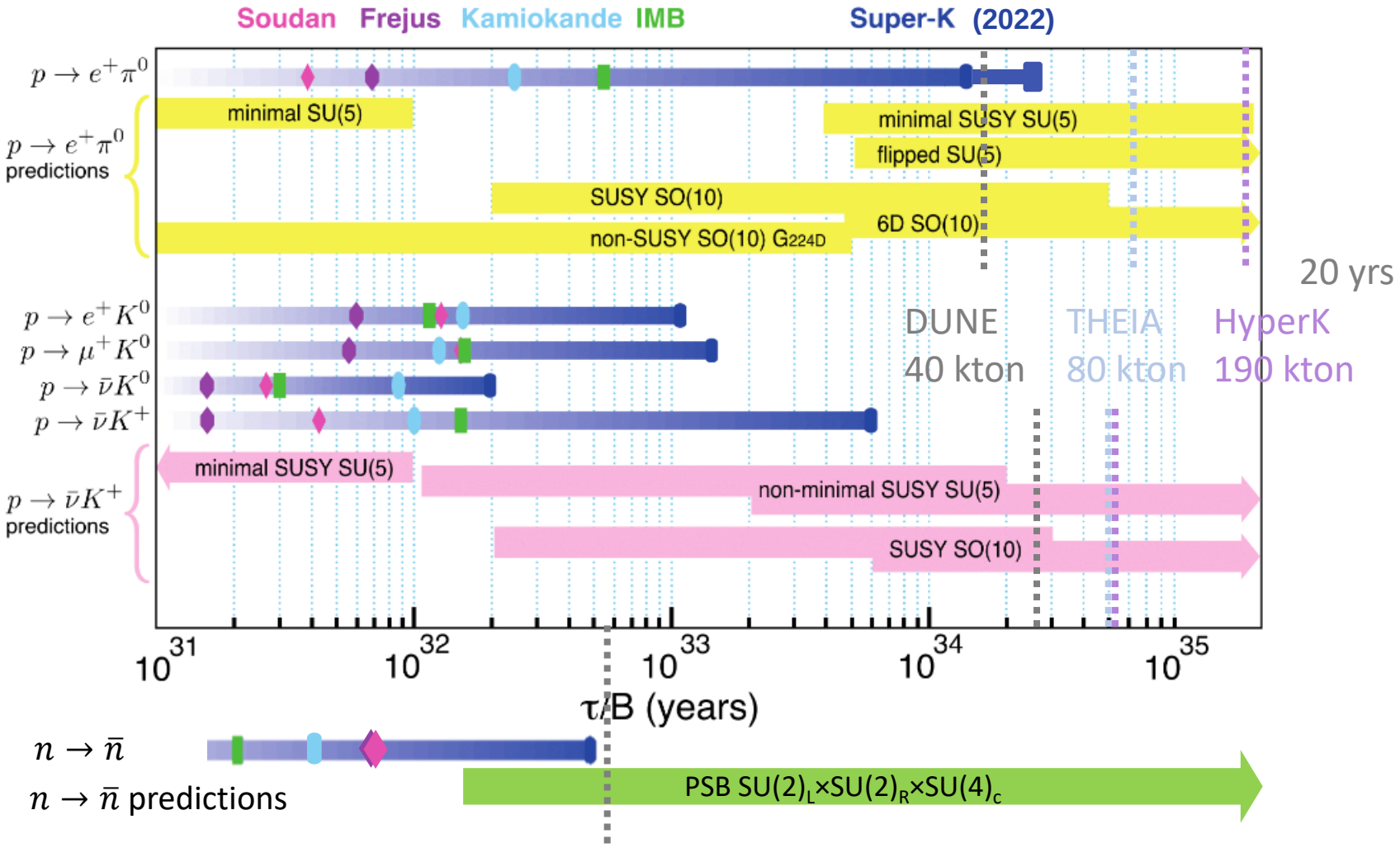
Keys to baryon number violation searches:

Exposure!

Next generation experiments:

HyperK, THEIA, DUNE,…

BNV Searches + Future

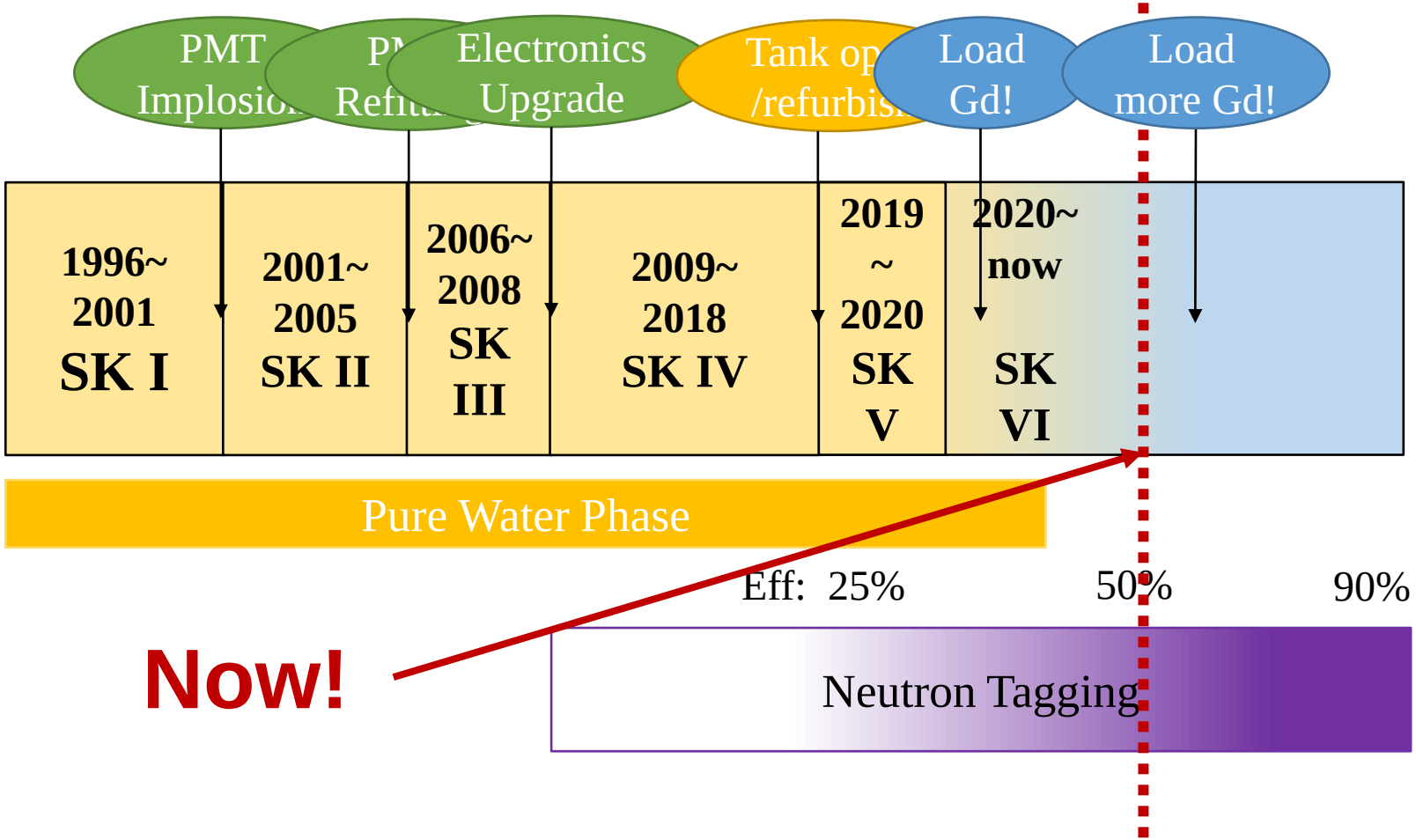


Future Improvements

Keys to baryon number violation searches:

- Exposure
  - Next generation: HyperK, THEIA, DUNE,…
  - SK data taking continues…

SK Goes On…


PMT Implosion
Refitting
Electronics Upgrade
Tank op /refurbish
Load Gd!
Load more Gd!
1996~ 2001 SK I
2001~ 2005 SK II
2006~ 2008 SK III
2009~ 2018 SK IV
2019 ~ 2020 SK V
2020~ now SK VI
Pure Water Phase
Eff: 25%
50%
90%
Now!
Neutron Tagging

Future Improvements

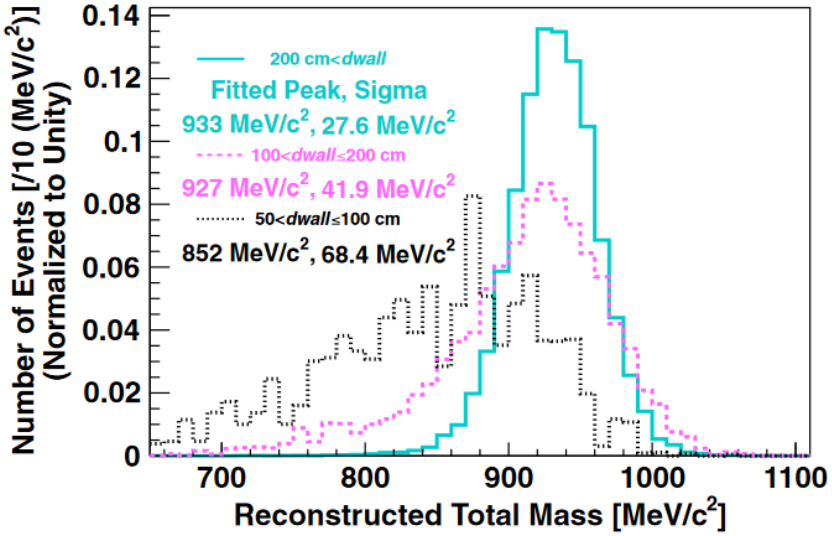
Keys to baryon number violation searches:

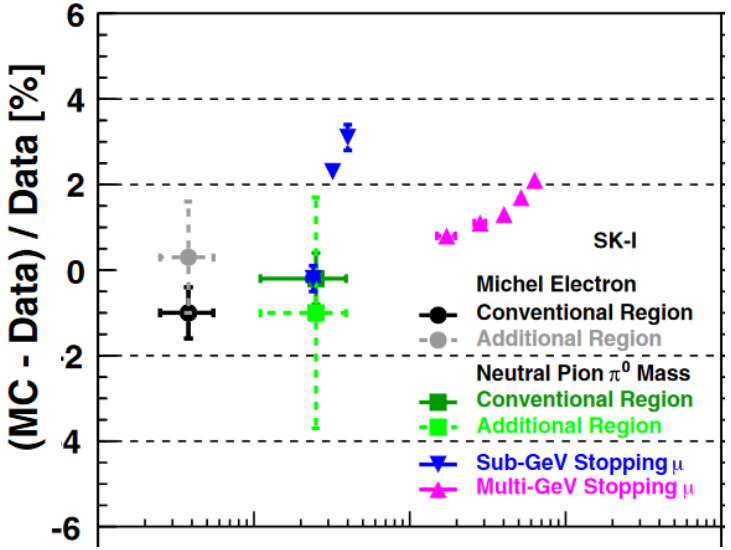
- Exposure
  - Next generation: HyperK, THEIA, DUNE,…
  - SK data taking continues…
- Efficiency
  - Current efficiency < 10% in modes involving K and $n \to \bar{n}$ oscillation, space for improvement
  - Calling for higher efficiency reconstruction and enhanced background rejection

Expanding Fiducial Volume

Typical proton decay search cuts:

- fully contained
- **fiducial volume**
- kinematics
- PID





22.5 kiloton → 27.2 kiloton
20% increase

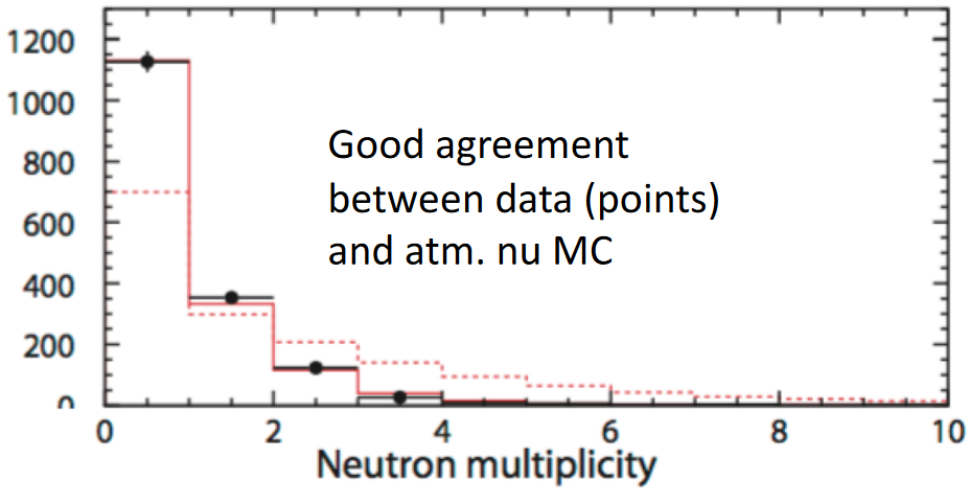
Phys. Rev. D 102, 112011 (2020)

SK-Gd & Future PID tools

Typical proton decay search cuts:

- fully contained
- fiducial volume
- **kinematics**
- **PID**

Proton reconstruction
Multi-ring PID
…



- Background rejection for atmospheric neutrino events w/ neutrons

Summary

- **More modes searched and updated at SK**
- **No observation yet and strong constraints**

New results yet to come!

- New data with high efficiency neutron tagging
- New reconstruction tool
- Expanded fiducial volume

Supported by Office of Science U.S. DEPARTMENT OF ENERGY

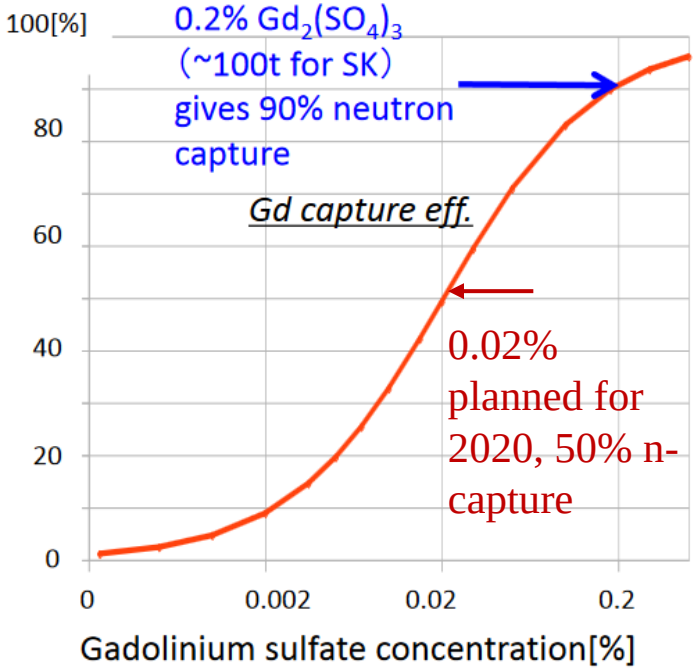
SK-Gd Project

Large cross section for thermal neutron → higher neutron capture efficiency (25% → 90%)

Shorter lifetime → Further discrimination between bkg and correlated $e^+ + \gamma's$ signal.

Refurbishment finished in 2018

Expected Gd loading: **2020**



- Neutron Capture
  $n + Gd \rightarrow Gd + \gamma's$

□ **Gd Capture** $\tau \approx 30\ \mu s$ $E_\gamma \approx 8.0$ **MeV**