Baryon Number Violation Searches in Neutrino Experiments

Jennifer Raaf
Fermi National Accelerator Laboratory
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Why search for baryon number violation?

- **Testing fundamental symmetries is our job!**
  - Conservation of baryon number is observed in Nature, but no compelling reason for it
  - Matter-antimatter asymmetry requires baryon number violation (BNV)
- **There are well-motivated theories, such as Grand Unified Theories (GUTs) that suggest proton decay may exist and be observable**
  - Make specific predictions for decay modes, lifetimes, branching ratios
  - Unify strong, weak, and EM forces into a single underlying force at high energies
    - Standard Model's SU(3) x SU(2) x U(1) is embedded within a larger gauge group
    - Fundamental forces are low energy manifestations of a unified force
  - Can neatly explain many of the puzzling things observed in Nature that are not currently explained by the Standard Model
    - Quantization of electric charge
    - Quantum numbers of quarks and leptons
    - ...

First Grand Unified Theory: SU(5)

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

It makes just one easily testable prediction, $\sin^2\theta_w = \frac{3}{8}$. It also predicts that the proton decays—but with an unknown and adjustable rate.

Had some nice consequences

(charge quantization, unified coupling,...)

but clearly did not get everything right

(value of weak mixing angle, also predicted massless neutrinos and magnetic monopoles)

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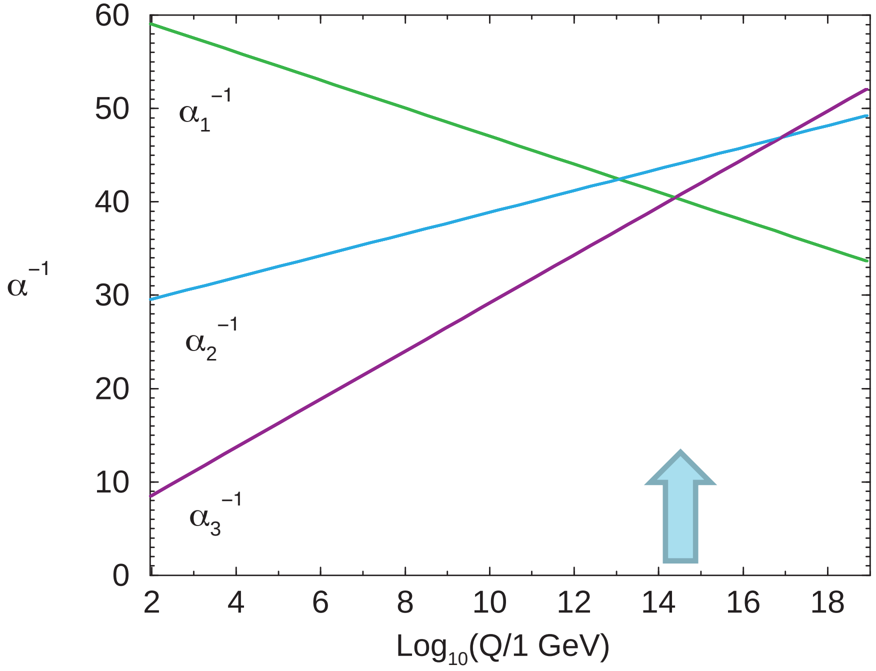
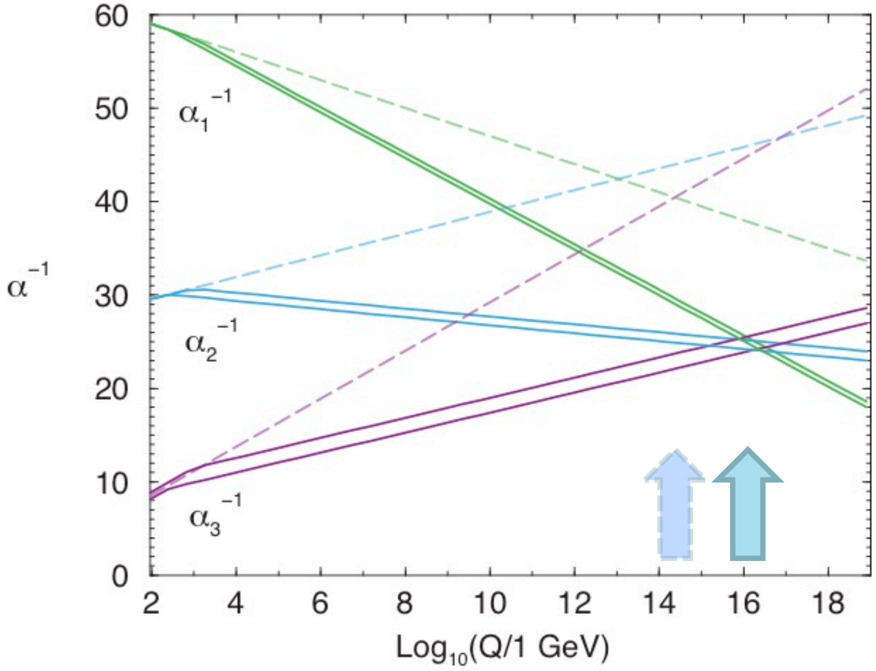
Circumstantial Evidence for Grand Unification

Strong, Weak, EM coupling constants in SM



SUSY GUTs push unification scale higher



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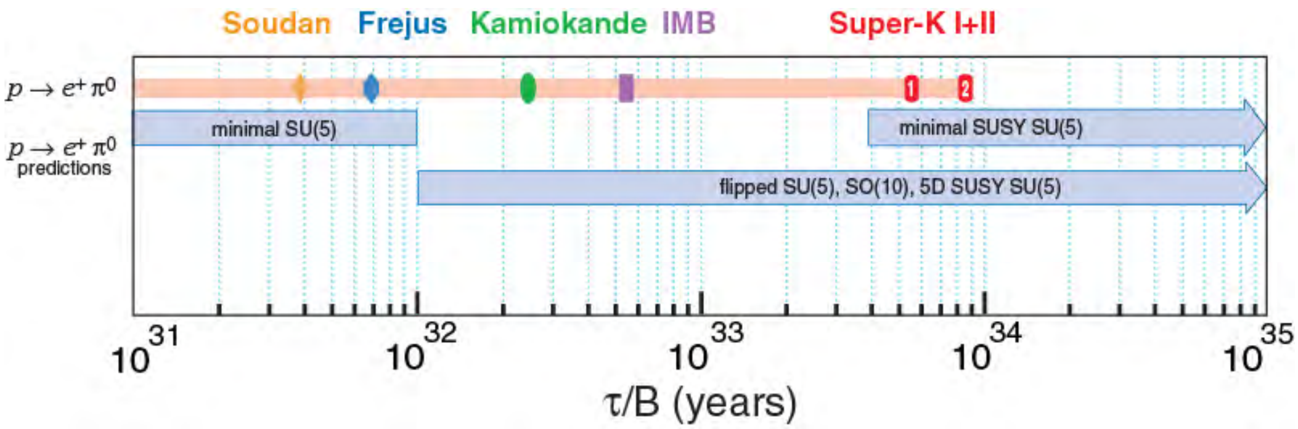
A Neutrino Experimentalist's View of Theory

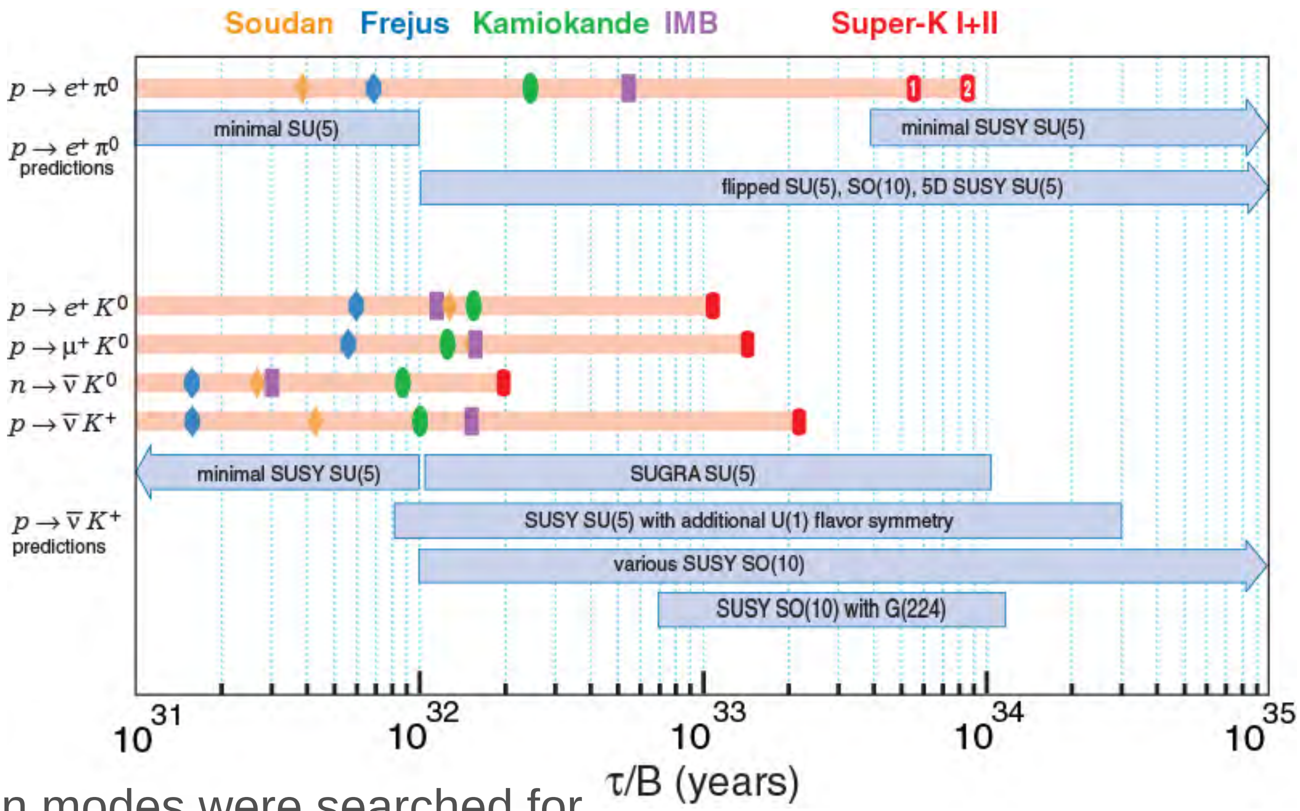
- **Various types of models exist**
  - Supersymmetric & non-SUSY, different gauge groups (SU(5), SO(10), ...)
- **Lifetime predictions within those models are not precise**
  - several orders of magnitude uncertainty
- **Typically two proton decay modes are used as "benchmarks" for models:**
  - $p \longrightarrow e^{+}\pi^{0}$ (mediated by a new heavy gauge boson)
  - $p \longrightarrow \bar{\nu}K^{+}$ (supersymmetric dimension-5 operators)
- **BUT, many other modes are also allowed, and since we don't know which model (if any) is correct, it is important to search for as many modes as possible**
  - Beyond $e^{+}\pi^{0}$ and $\bar{\nu}K^{+}$
    - Conserve B-L (p $\longrightarrow$ antilepton + meson)
    - Conserve B+L ($p \longrightarrow \mu^{-} \pi^{+} K^{+}$ and many others)
    - $\Delta B = 2$ (neutron $\longleftrightarrow$ anti-neutron oscillation, dinucleon decay)
    - 3-body decays ($p \longrightarrow e^{+}\nu\nu$)
    - Invisible decays ($n \longrightarrow \nu\nu\nu$)
    - ...
- **Even if no signal is seen, limits constrain the theories**

Experimental Limits Constrain Theoretical Models



- Minimal SU(5) was ruled out long ago by Kamiokande and IMB measurements, but minimal SUSY SU(5) still viable...

Experimental Limits Constrain Theoretical Models



- ...until kaon modes were searched for

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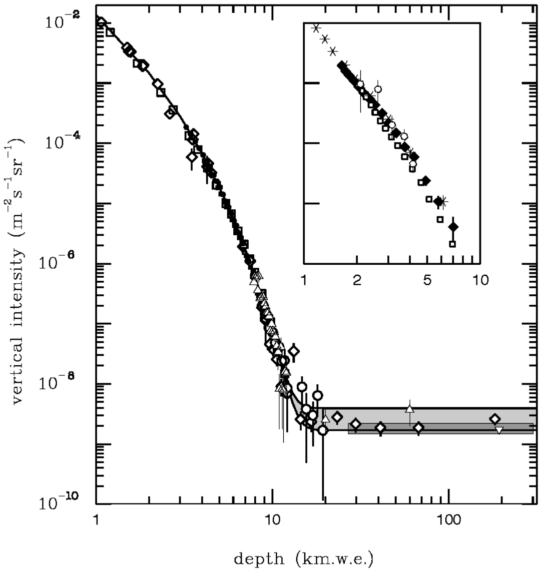
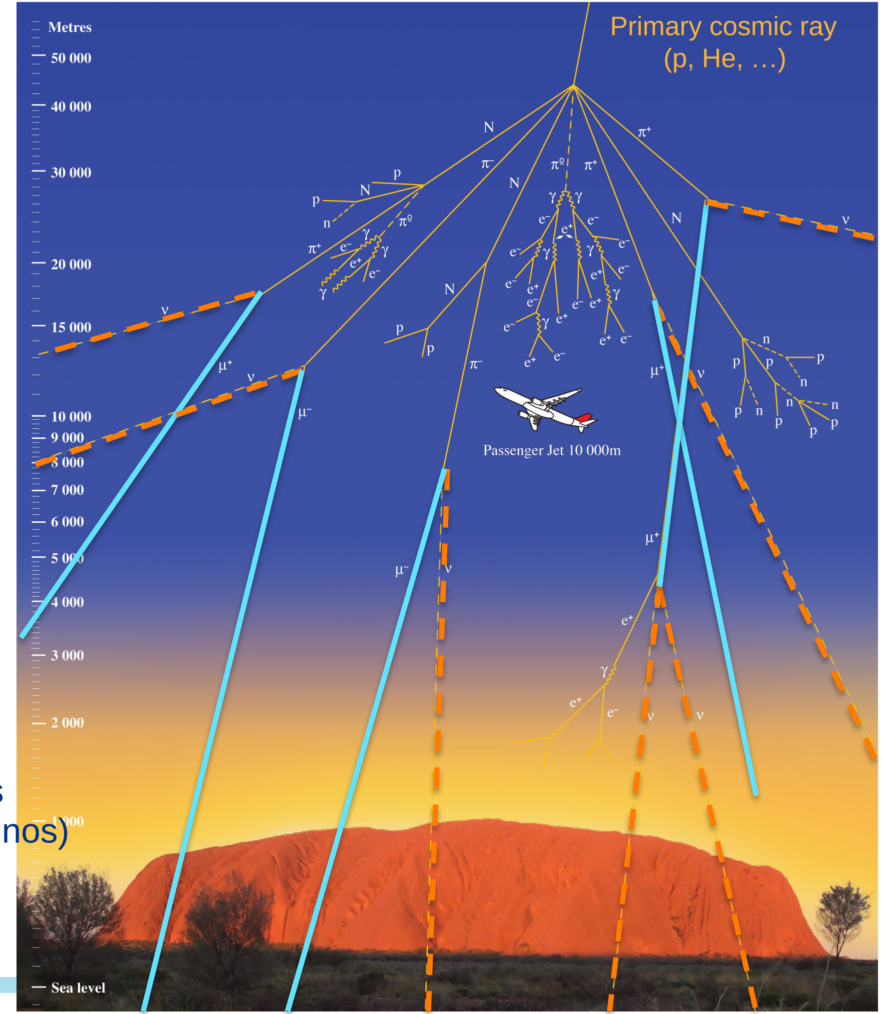
GUTs and Neutrino Experiments

- Neutrino experiments are an ideal place to search for proton decay & other BNV
  - Underground to attenuate cosmic rays
  - Very big, to collect large statistics (neutrino interaction cross sections ~10^{-38} cm^{-2})



Neutrino-induced muons (from atmospheric neutrinos)

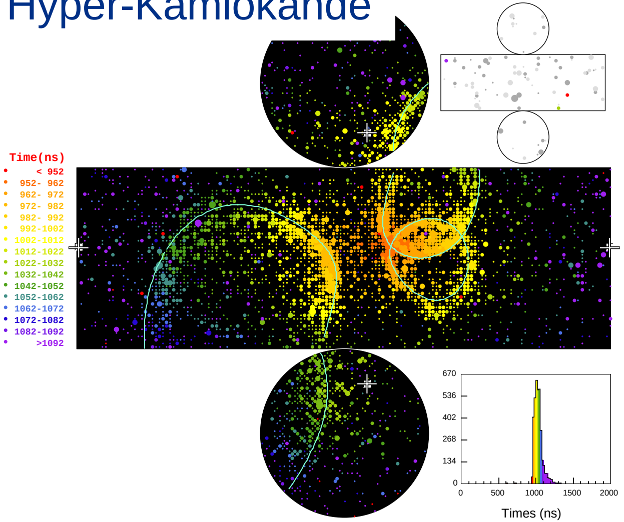


Neutrino Experiments for Nucleon Decay Searches

Water Cherenkov

Super-Kamiokande

Hyper-Kamiokande



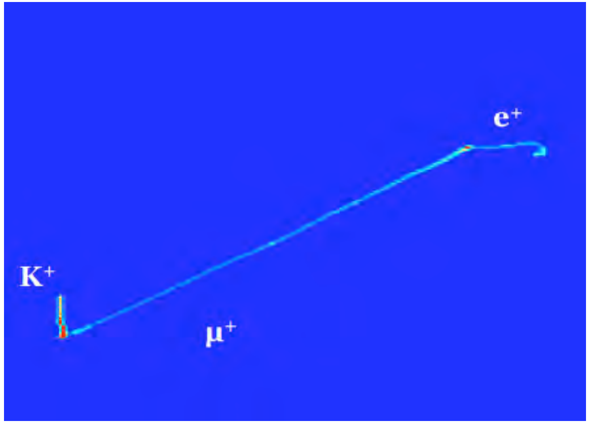
Most massive – superior for $e^+\pi^0$

Broad search capabilities

Kaons below Cherenkov threshold

Liquid Argon Time Projection Chamber

DUNE



Fine-grained detail

Visible kaon track

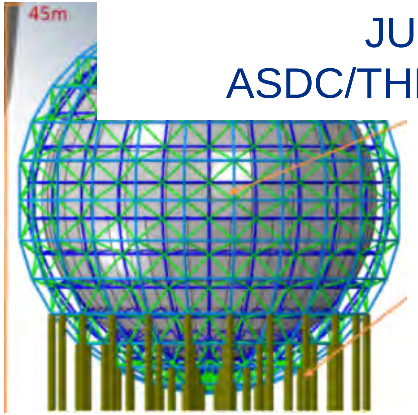
Heavy nucleus, no free protons

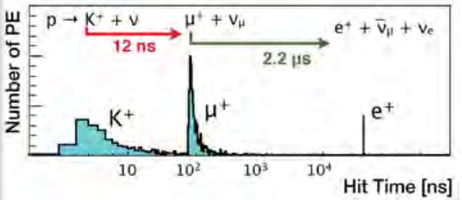
Liquid Scintillator

KamLAND

JUNO

ASDC/THEIA



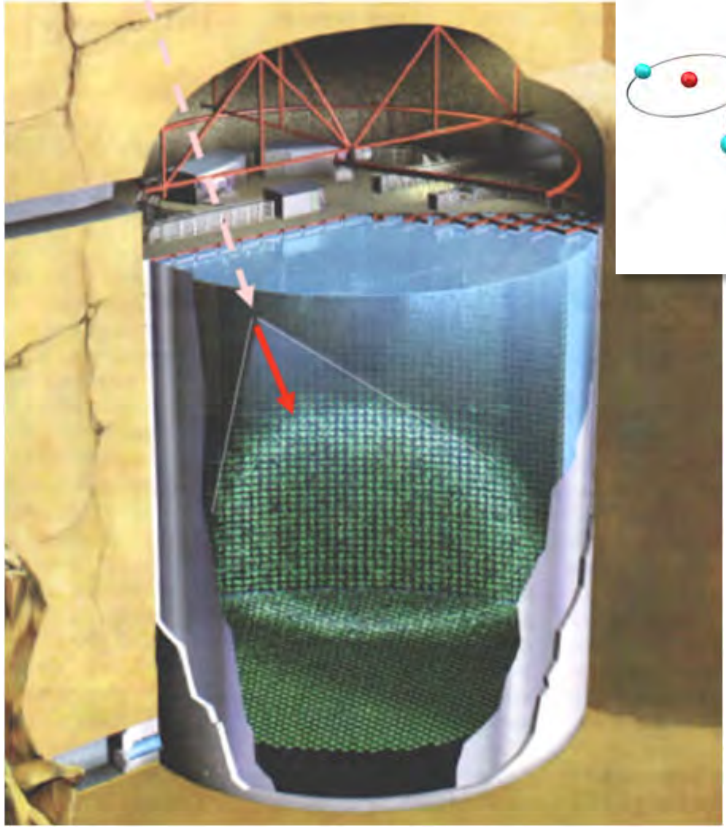


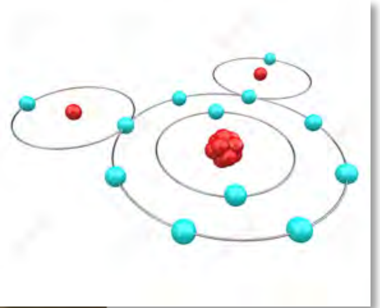
Clean timing signature

Specialize in charged kaon

(also invisible modes)

Super-Kamiokande





50,000 tons of ultra-pure H_2O
(16 bound nucleons (8*p*, 8*n*) + 2 free *p*)

- 22,500 ton fiducial volume
- 7.5×10^{33} *p* + 6×10^{33} *n* to observe

Location: Kamioka zinc mine

Cosmic ray shielding: 2700 meters water equivalent (1000 m rock overburden)

Detection technique

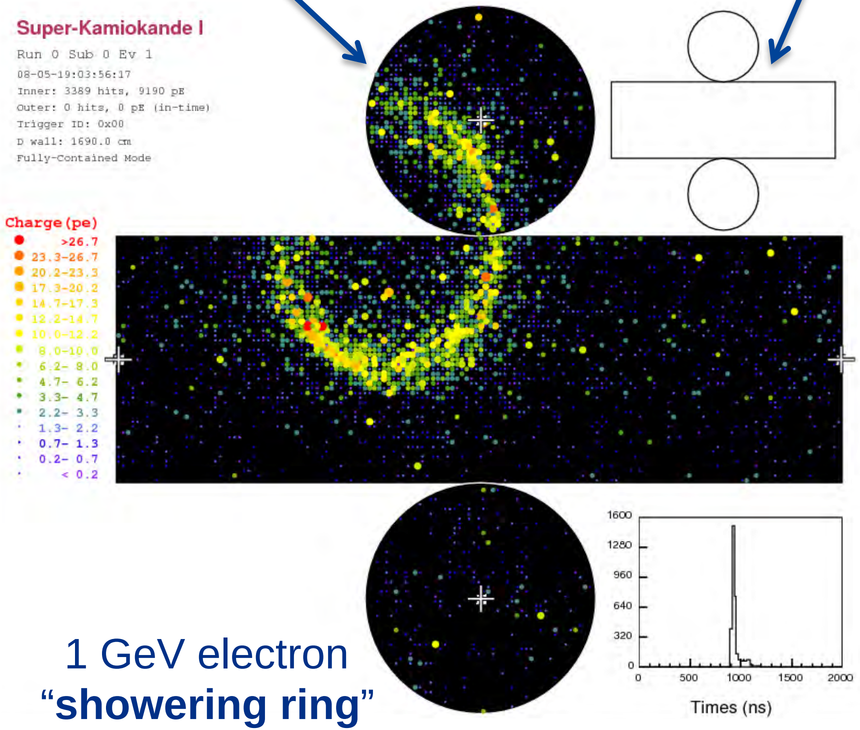
- Cherenkov rings
- ~11,000 50-cm PMTs

Particle ID in Super-K

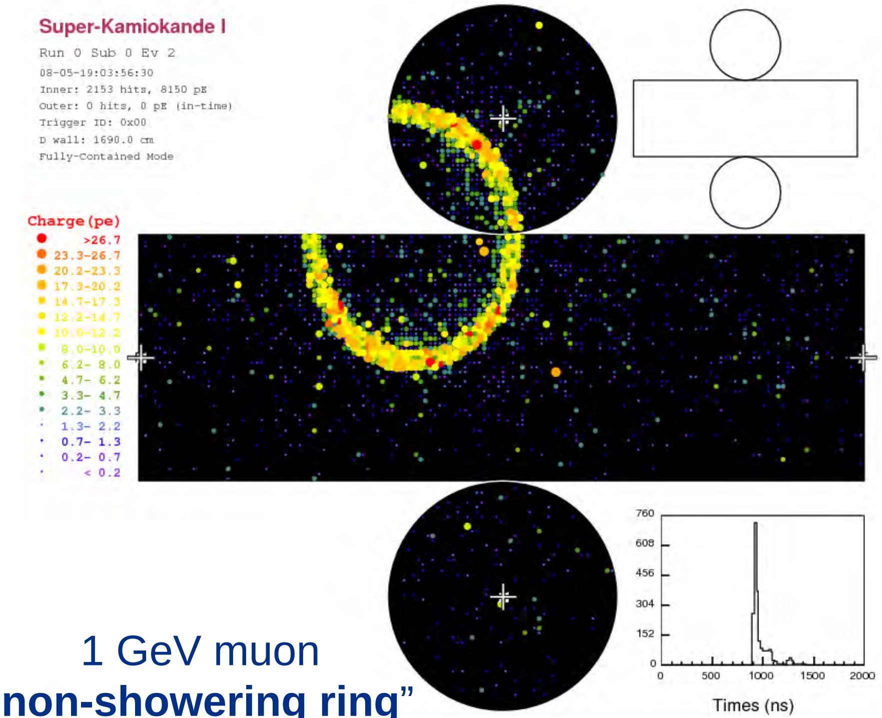
“Unrolled” view: like cutting open a can and laying it out flat

Inner detector

Outer detector

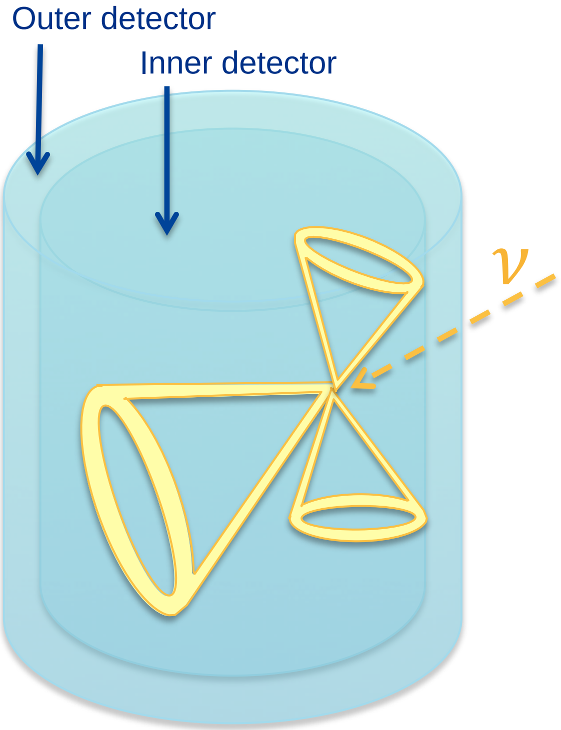


1 GeV electron
“showering ring”



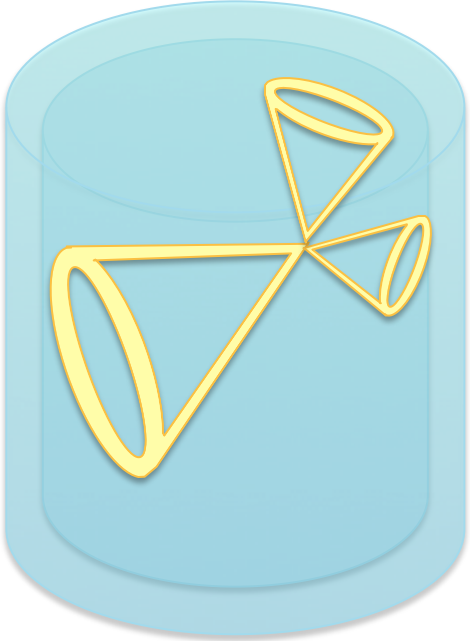
1 GeV muon
“non-showering ring”

Neutrinos vs. Proton Decay in Super-K



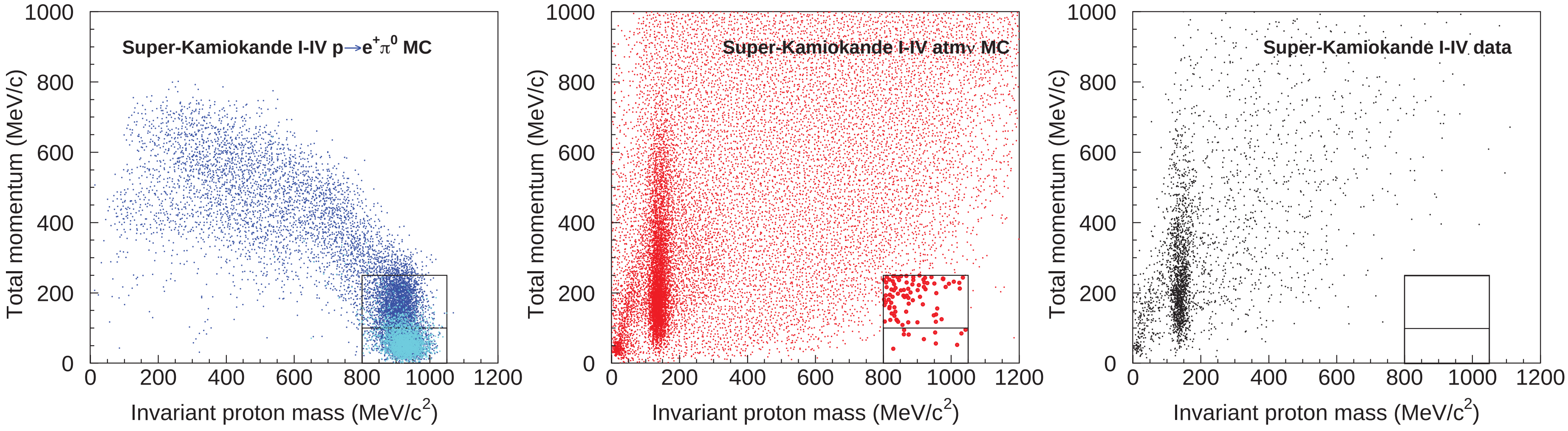
Neutrino interaction

Neutrino interaction	Proton decay	Similar?
Invisible neutrino enters and interacts with proton or neutron of H_2O. Exiting particles make Cherenkov rings.	Proton or bound neutron of H_2O decays. Exiting particles make Cherenkov rings.	YES
Atmospheric neutrino energy range: from ~10's of MeVs to many TeVs	~1 GeV (mass of decaying proton or neutron)	Sometimes
Wide range of net momenta	Net momentum of outgoing particles should be near 0 (up to p_{Fermi} inside nucleus & correl.)	Sometimes


Proton Decay

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

Phys. Rev. D 95 012004 (2017)



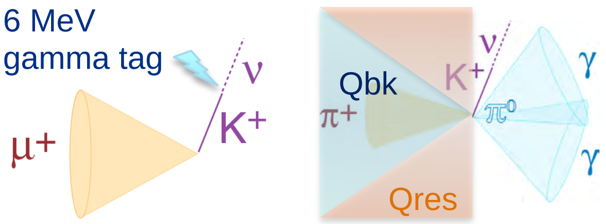
- Fully contained
- Fiducial volume
- 2 or 3 rings
- All rings are EM showers
- π^0 mass 85-185 MeV/c^2

- No μ-decay electrons
- Mass range 800-1050 MeV/c^2
- **Net momentum < 250 MeV/*c***
- ***SK-IV only: veto event if n-capture***

Super-K Data
(306 kton-years)

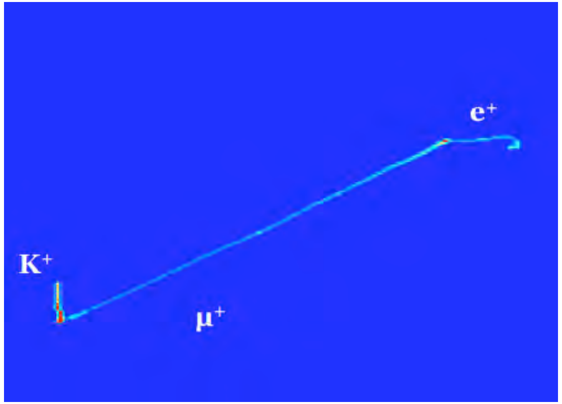
$p \longrightarrow \bar{\nu}\, K^+$

This is a search for kaon decay at rest ($K \longrightarrow \mu\nu$ and $K \longrightarrow \pi^+\pi^0$)



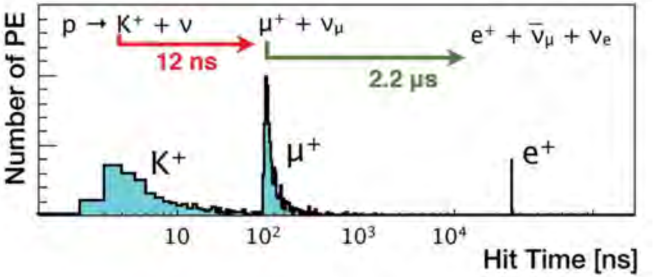
In Cherenkov detectors:

- Look for de-excitation gamma in time with non-showering (muon) ring to identify events with leptonic decay mode of kaon (kaon ring is below Cherenkov threshold)
- Also perform search for hadronic decay mode of kaon, looking for π^+ ring in backward direction of 2 showering rings from π^0 decay



In LArTPC detectors:

- No detection threshold problem
- Use dE/dx to identify stopping kaon & decay products



In scintillator detectors:

- Fast and precise timing capability allows detection of signals from each of the subsequent particles in the decay chain
- Both the prompt and delayed signals have well-defined energy spectra; powerful background rejection

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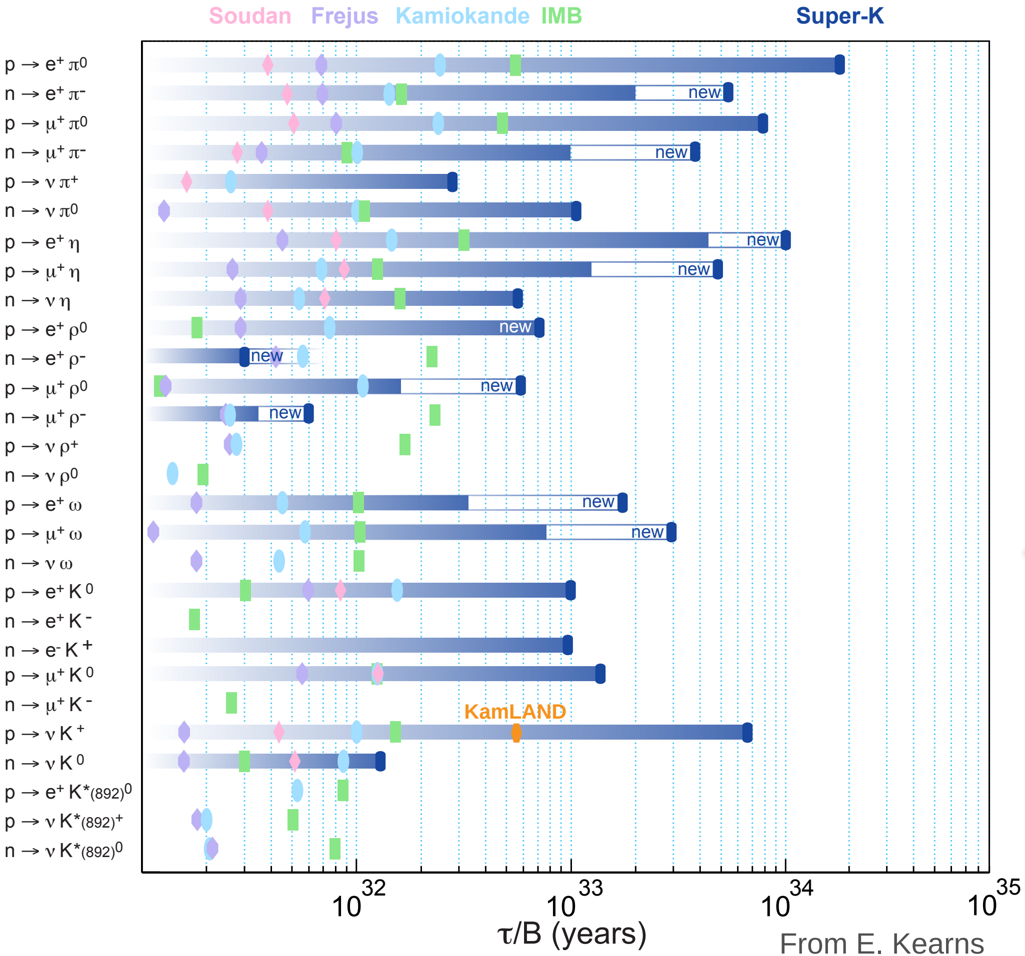


From E. Kearns

antilepton
plus
meson

Conserves (B-L)

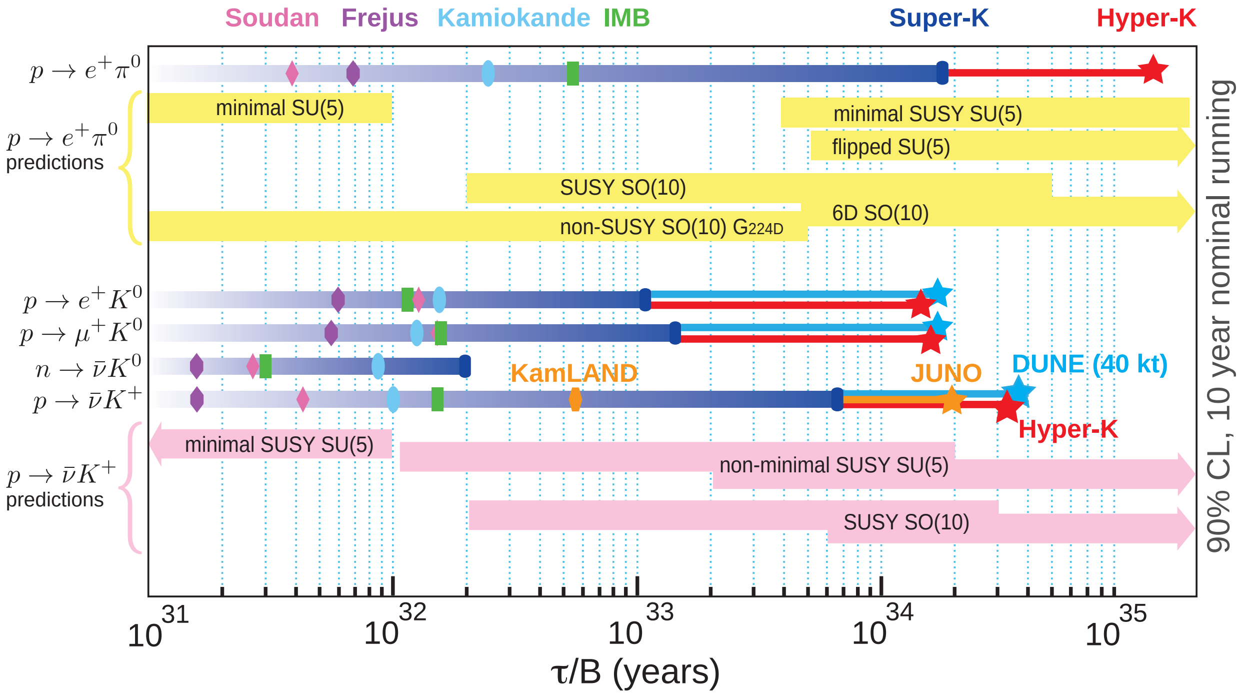
non-strange mesons

strange mesons

Conclusions and the Decades Ahead

- Testing Baryon Number Violation is an essential and high-priority objective of particle physics
- Searches for BNV via nucleon & dinucleon decay and n-n̄ oscillations have been negative so far, but have severely constrained theoretical models
- Ongoing searches are still useful: the larger experiments coming online in the next decade have high potential to observe BNV or further limit theories.

From E. Kearns



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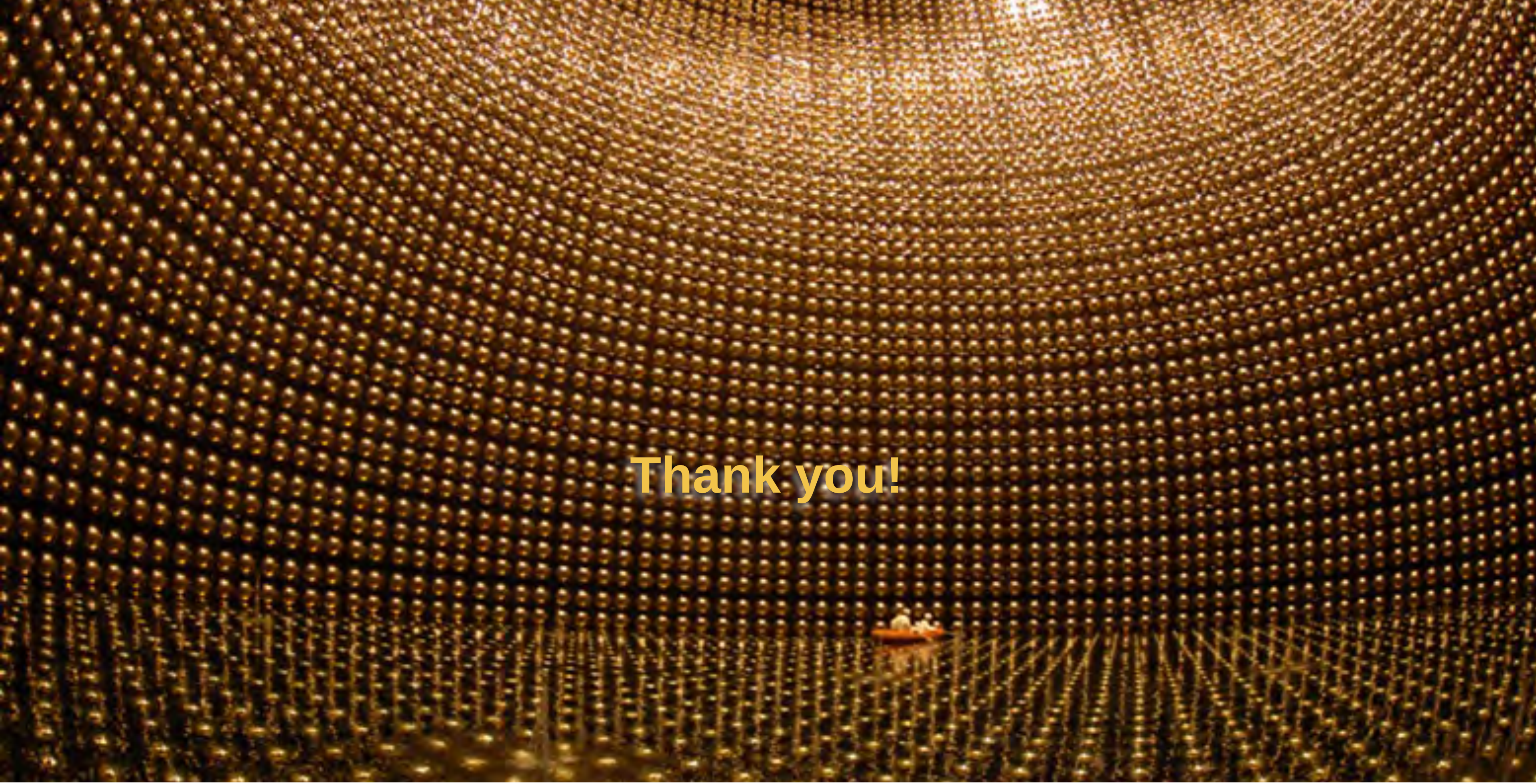
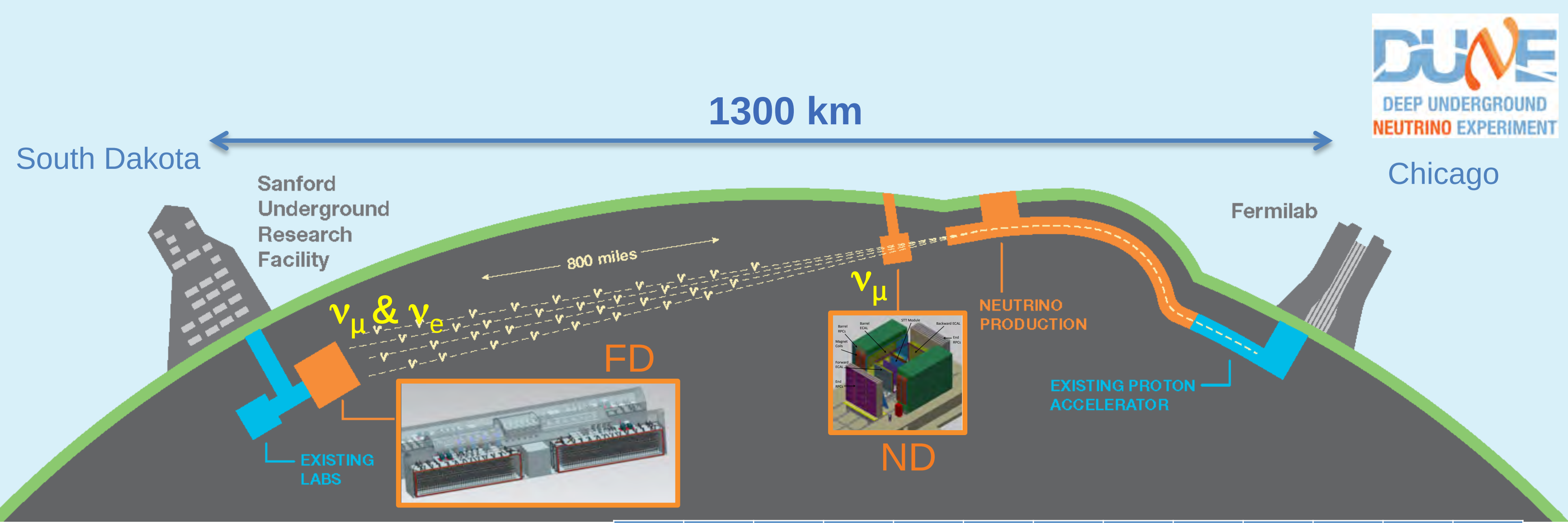


Thank you!

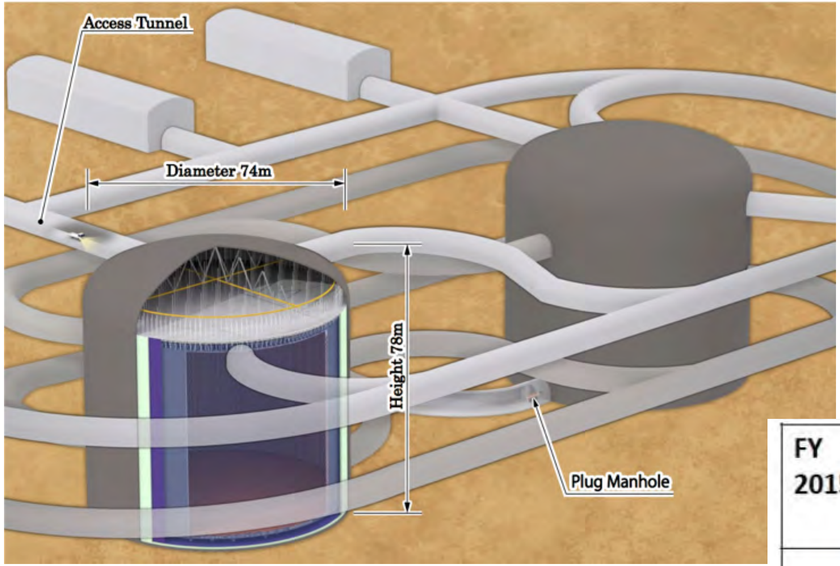
Even bigger detectors in the future: DUNE



Liquid argon time projection chamber
Single and dual phase
4 modules, each one 17-ktons
40 kton fiducial mass

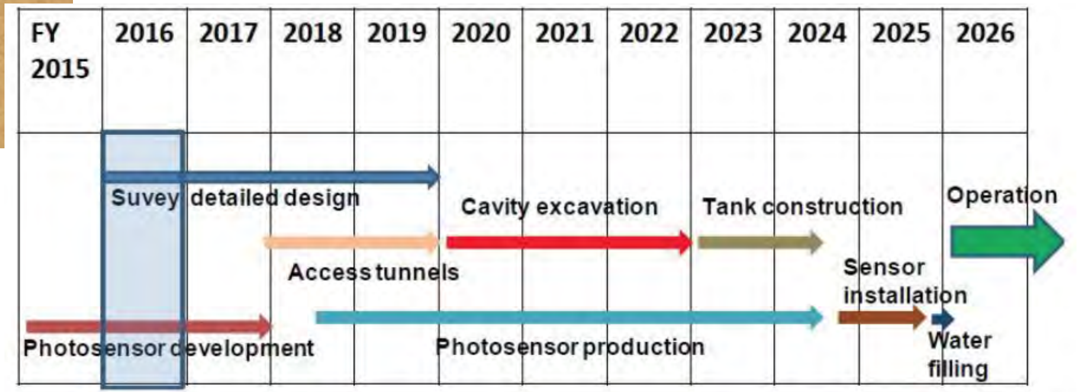
2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
ProtoDUNEs												
	Cavern excavation											
				Cryostat Construction								
						Far Detector Installation						
								Far Detector commissioning				

Even bigger detectors in the future: Hyper-Kamiokande



Two tanks, each tank:

- 260 kton total, 188 kton fiducial mass
- 40000 50-cm high QE PMTs
- 74 m diameter x 60 m high
- 1800 m.w.e. overburden



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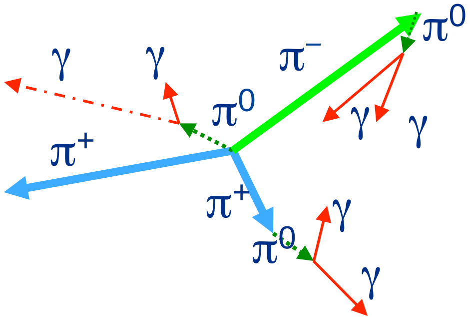
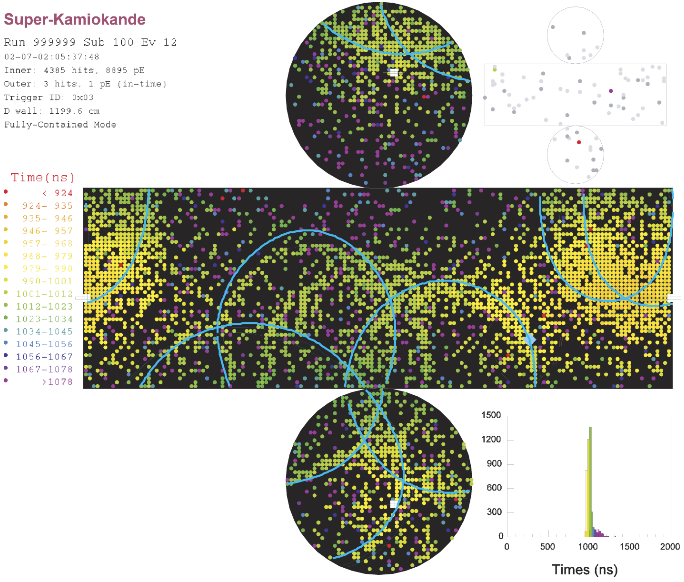
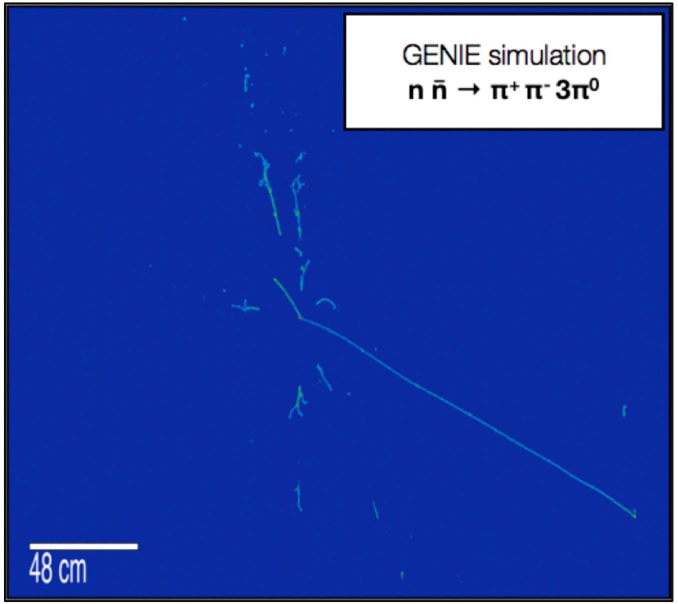
Neutron-Antineutron (n-nbar) Oscillation in Nuclei







- Search for products of anti-neutron annihilation in the nucleus (many pions)
- Isotropic pion distribution with ~2 GeV total energy

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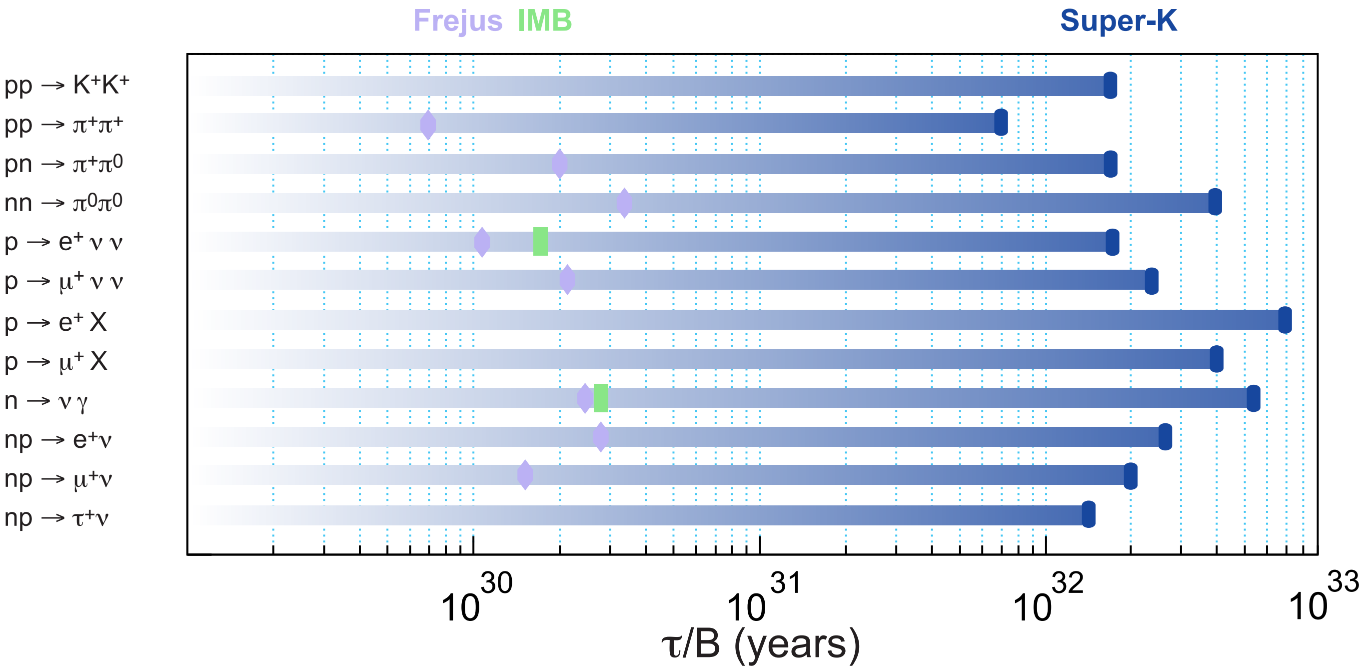
Recent exotic searches

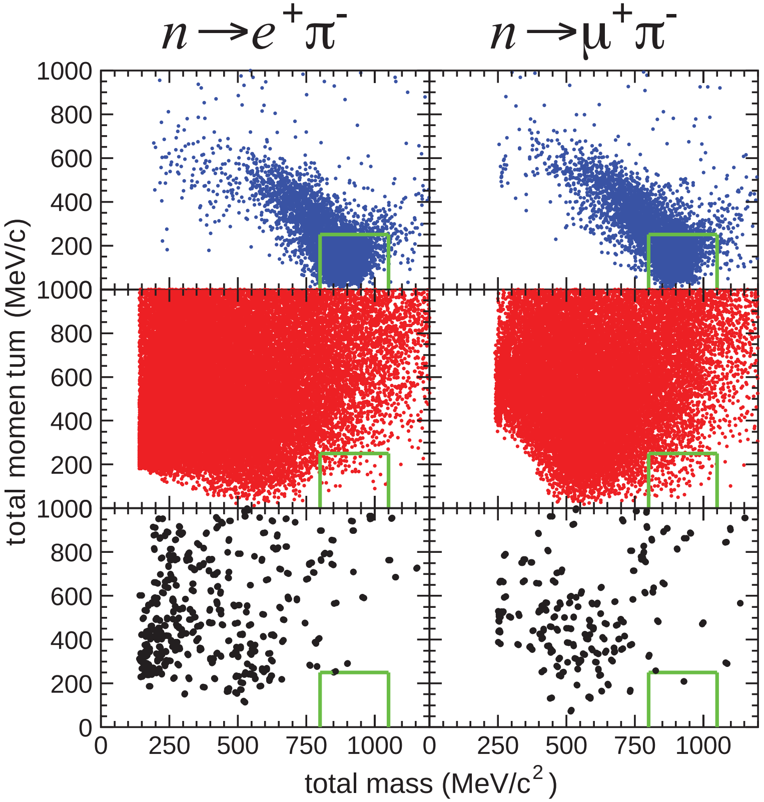
- Generally more than an order of magnitude improvement & some searches have never been performed before now



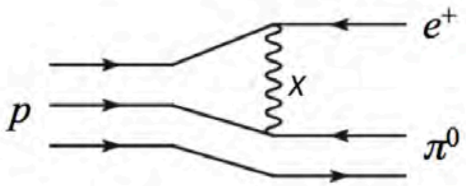
Antilepton plus other mesons

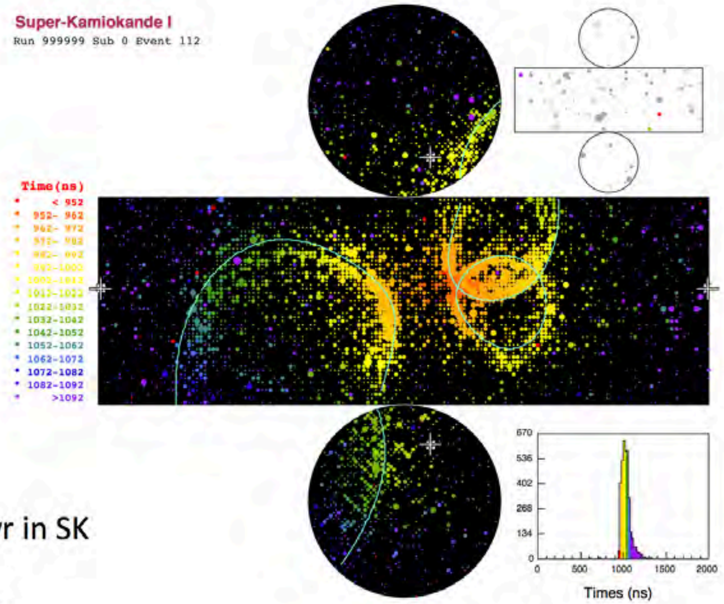
Phys. Rev. D 96 012003 (2017)

Modes	Background (events)	Candidate (events)	Probability (%)	Lifetime Limit ($\times 10^{33}$ years) at 90% CL
$p \to e^+\eta$	0.78±0.30	0	-	10.
$p \to \mu^+\eta$	0.85±0.23	2	20.9	4.7
$p \to e^+\rho^0$	0.64±0.17	2	13.5	0.72
$p \to \mu^+\rho^0$	1.30±0.33	1	72.7	0.57
$p \to e^+\omega$	1.35±0.43	1	74.1	1.6
$p \to \mu^+\omega$	1.09±0.52	0	-	2.8
$n \to e^+\pi^-$	0.41±0.13	0	-	5.3
$n \to \mu^+\pi^-$	0.77±0.20	1	53.7	3.5
$n \to e^+\rho^-$	0.87±0.26	4	1.2	0.03
$n \to \mu^+\rho^-$	0.96±0.28	1	61.7	0.06
total	8.6	12	15.7	-



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





Simple signature: back-to-back reconstruction of EM showers.

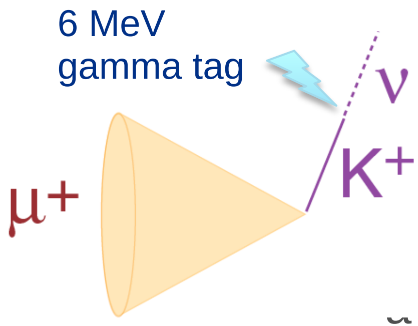
Efficiency ~45% dominated by nuclear absorption of π^0

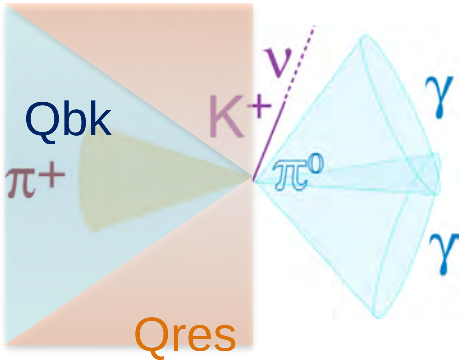
Low background ~0.2 events/100 ktyr in SK

Relatively insensitive to PMT density.

P → nu K+

Kaon is below Cherenkov threshold. This is a search for kaon decay at rest.





γ-tag plus $\pi^+\pi^0$	SK1	(20% coverage) SK2	SK3	(new electronics) SK4 → w. n-cap
Efficiency	15.7 %	13.0 %	15.6 %	~~18.9 %~~ → 17.5 %
Background rate (ev/100 kty)	0.28	0.63	0.38	~~0.4~~ → 0.19

No candidates, 306 kton yr (SK 1+2+3+4 w. n-cap):

$$\frac{\tau}{B} > 6.61 \times 10^{33}\ \mathrm{y}$$

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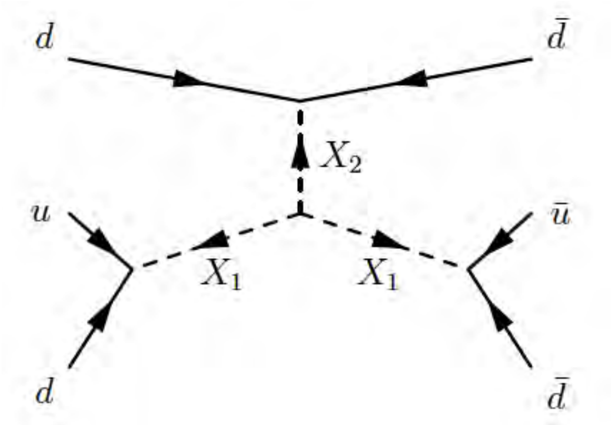
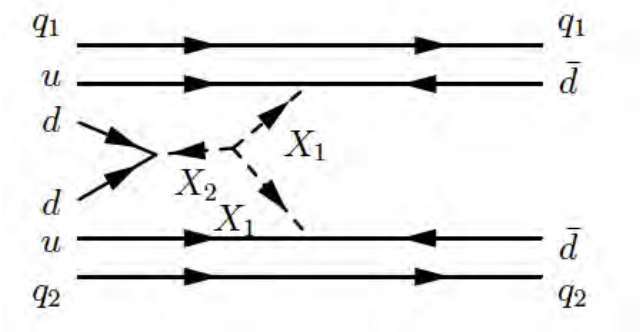
ΔB = 2

nnbar oscillation
(free neutron or inside nucleus)



violates B-L, needed for BAU

dinucleon decay



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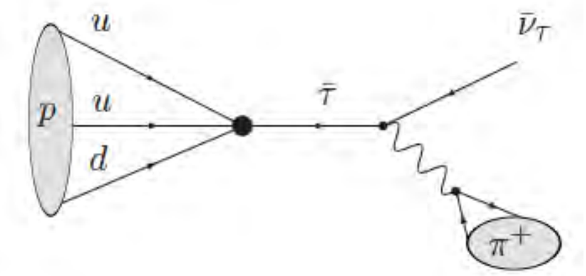
Baryon number violating processes studied at accelerators

Category	Example	Branching fraction	Experiment
Z decays	$Z \longrightarrow p\ e$	$< 1.8 \times 10^{-6}$	OPAL
tau decays	$\tau \longrightarrow$ pbar γ	$< 10^{-5} – 10^{-7}$	LHCb, CLEO, Belle
Heavy meson decay	$B^0 \longrightarrow \Lambda^0\ e^+$	$< 10^{-5} – 10^{-8}$	CLEO, BaBar
Heavy baryon decay	$\Lambda^0 \longrightarrow \pi^-\ e^+$	$< 10^{-5} – 10^{-7}$	CLAS
Top quark	tbar $\longrightarrow$ b u e^-	$< 10^{-3}$	CMS

But arguably (Marciano, 1995) some of these processes may be better constrained by nucleon decay.

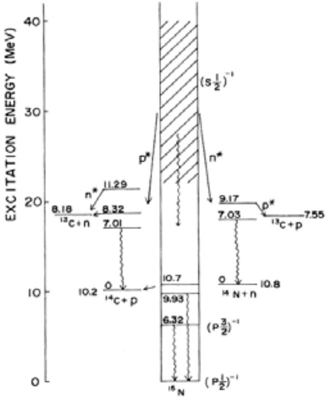
nucleon decay is the most constraining

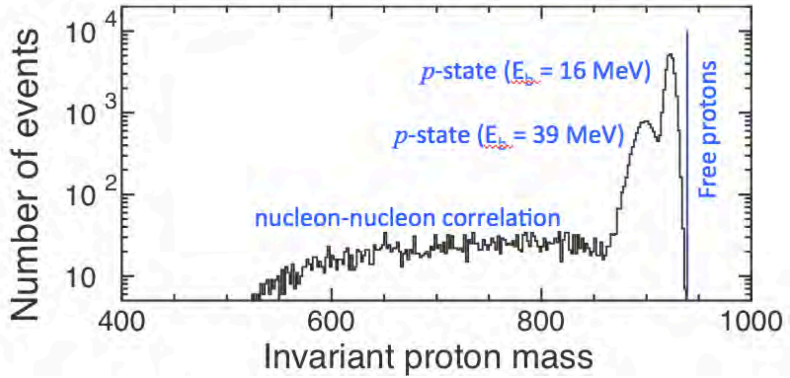


Hou, Nagashima, Soddu hep-ph/0509006

Nuclear Physics of Proton Decay

- Effective mass in ^{16}O
- Correlation with other nucleons
- Fermi motion – by shell
- Initial position (Woods-Saxon)
- Nuclear de-excitation γ
- pion-nuclear interactions
  - Elastic Scattering
  - Charge Exchange
  - Absorption





Hole	Residual	States	(k)	E_γ	E_p	E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5	0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0	~ 20	0.02
	7.03	2^+	^{14}N	7.03	0	~ 13	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	1.6	~ 11	0.01
	g.s.	0^+	^{14}C	0	~ 21	0	0.02
	7.01	2^+	^{14}C	7.01	~ 14	0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~ 11	~ 2	0.03
$(j)_p^{-1}$	others		many states	≤ 3–4			0.16

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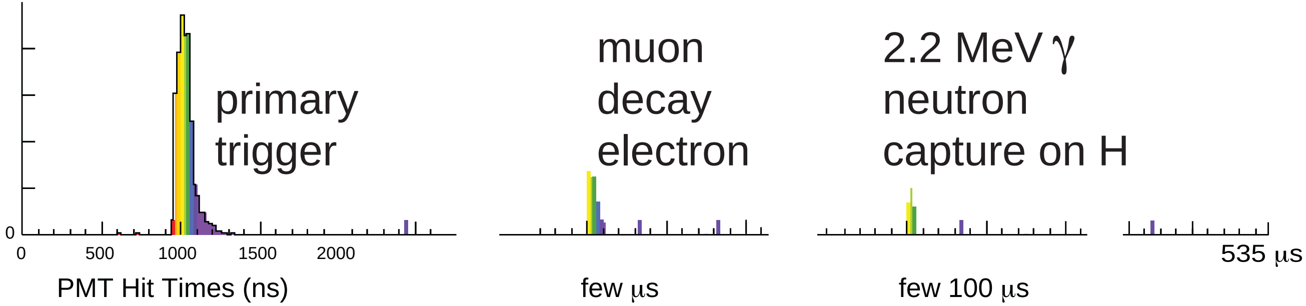
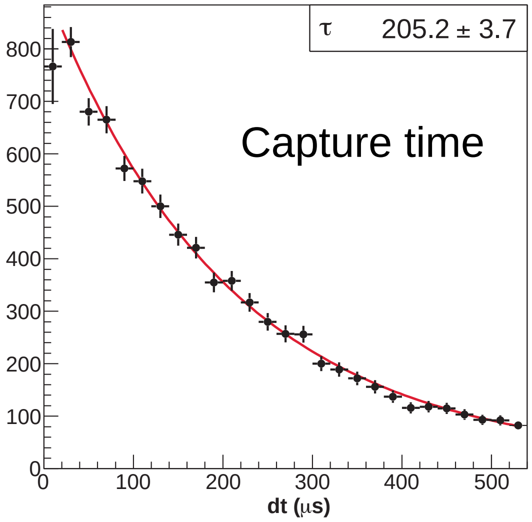
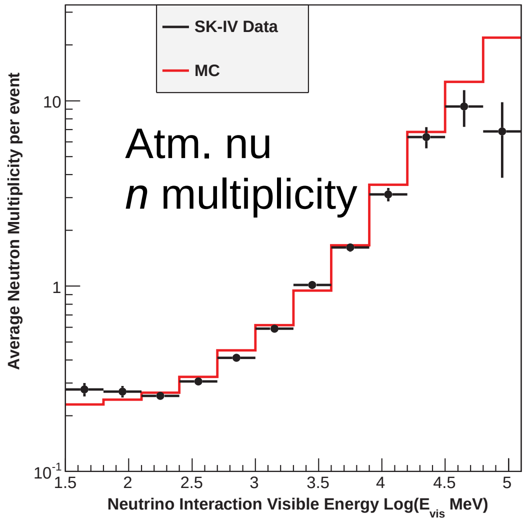
Neutron capture on hydrogen



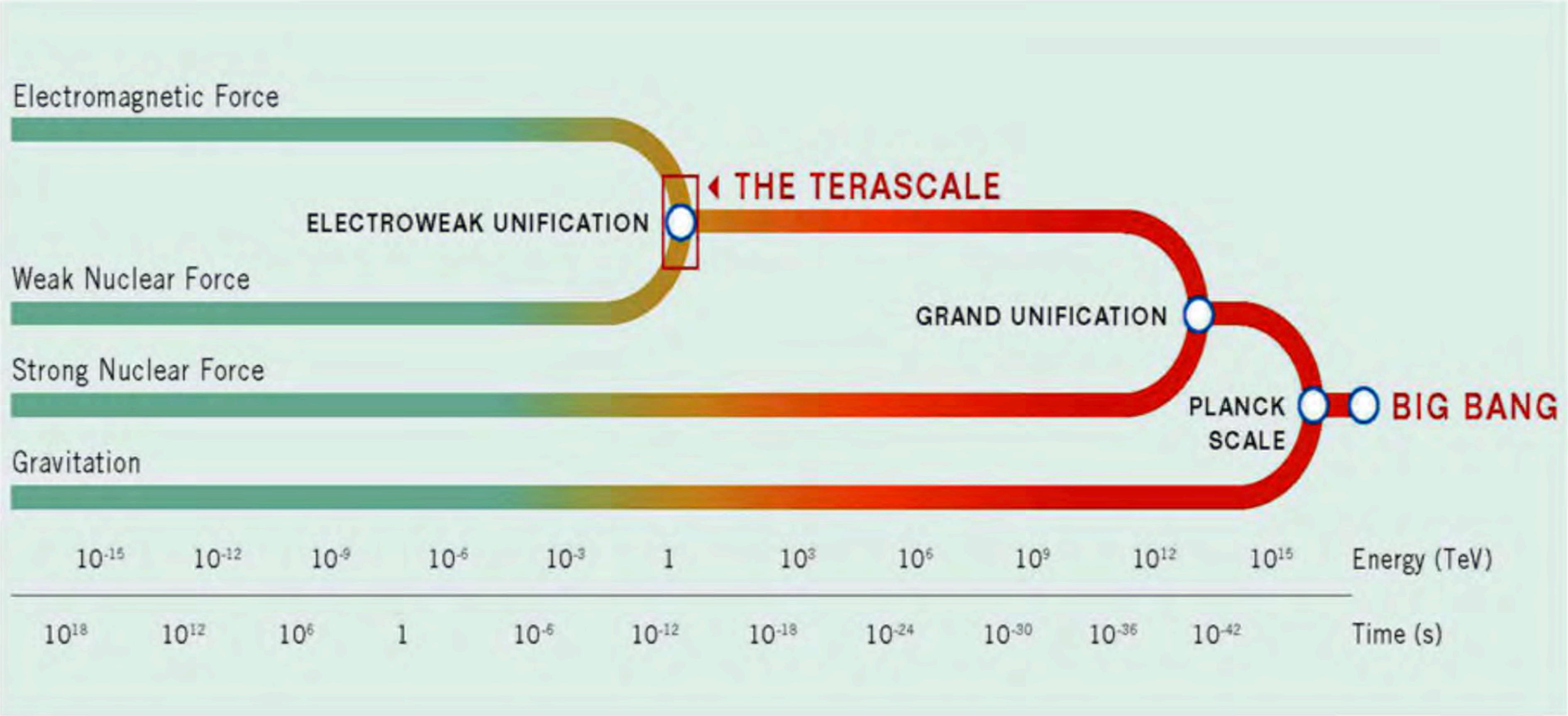




Atmospheric neutrino background is frequently accompanied by neutron production

Detection efficiency = 20.5%
Can increase to ~90% with capture on Gd

SK-Gd construction
in 2018 or 2019



Electromagnetic Force
ELECTROWEAK UNIFICATION
THE TERASCALE
Weak Nuclear Force
GRAND UNIFICATION
Strong Nuclear Force
PLANCK SCALE
BIG BANG
Gravitation
10-15 10-12 10-9 10-6 10-3 1 103 106 109 1012 1015 Energy (TeV)
1018 1012 106 1 10-6 10-12 10-18 10-24 10-30 10-36 10-42 Time (s)