Recent Nucleon Decay Searches at the Super-Kamiokande Experiment

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Moriond EW 2016 @ La Thuile, Italy

Motivation

- Baryon number (B) global accidental symmetry of Standard Model (SM)

  $\rightarrow$ lightest baryon (proton) stable

- Sakharov's conditions for baryogenesis require $\not{B}$ [Sakharov (1967)]
- Many arguments + reductionism suggest a more unifying theory underlying the SM
- Grand Unification (GUT) unites SM gauge groups $G \supset SU(3)_C \otimes SU(2)_W \otimes U(1)_Y$

  $\rightarrow$ coupling unification, charge quantization, etc.

  $\rightarrow$ leptons + quarks in same GUT representation $\rightarrow$ nucleon decay (explicit $\not{B}$)

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- Proton decay is a signature prediction of GUTs and a unique test of $\mathcal{O}(10^{14-16})$ GeV scales
- Lifetime predictions $\mathcal{O}(10^{30+})$ years **... how to observe?**

  $\longrightarrow$ look long at 1 proton or look at very many protons

accelerator can't reach

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- **Large water Cherenkov detectors** $\longrightarrow$ lots of protons and "cheap"
- **State of the art experiment** $\longrightarrow$ **Super-Kamiokande**

The Super-Kamiokande Experiment

- Super-Kamiokande:

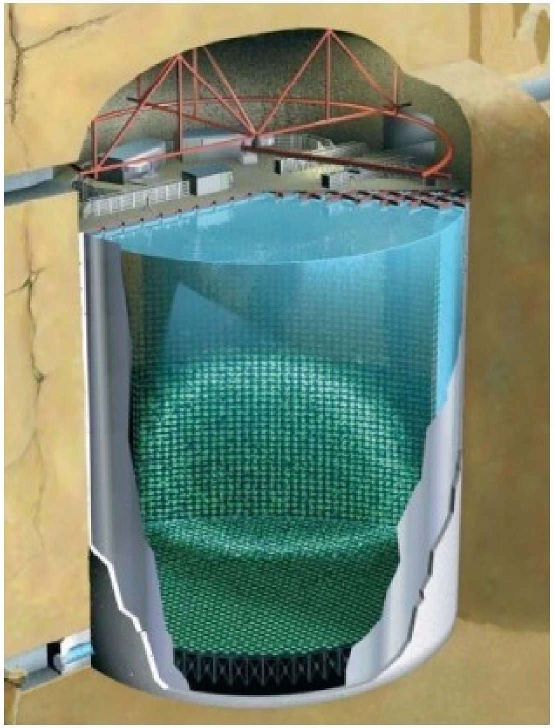
→ 22.5 kTon fiducial volume

→ Inner (11k PMTs, 40% coverage) and outer (2k PMTs) detectors

→ **4 run periods:**
SK-I (1996 - 2001)
SK-II (2003 - 2005): accident, ½ PMT coverage
SK-III (2006 - 2008): restore PMT coverage
SK-IV (2008 - now): upgraded electronics

(Hida, Gifu Prefecture, Japan)

Super-Kamiokande



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- Amazing multipurpose physics detector (range: MeV - TeV)

  → neutrino oscillations, Lorentz invariance, sterile neutrinos

  → nucleon decay (PDK) → ***this talk***

  → solar neutrinos, day/night effect, supernovae relic neutrinos

  → indirect dark matter searches

  → more exotic searches (monopoles, etc.)

2015 Nobel Prize
(neutrino oscillations)

(Hida, Gifu Prefecture, Japan)

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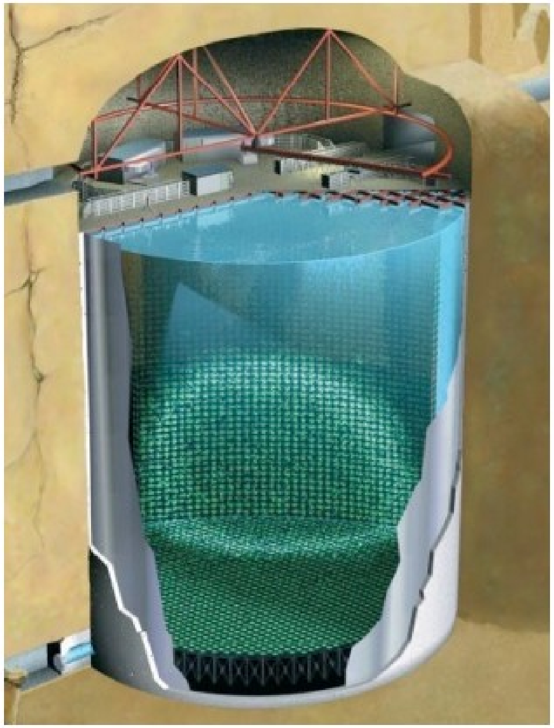

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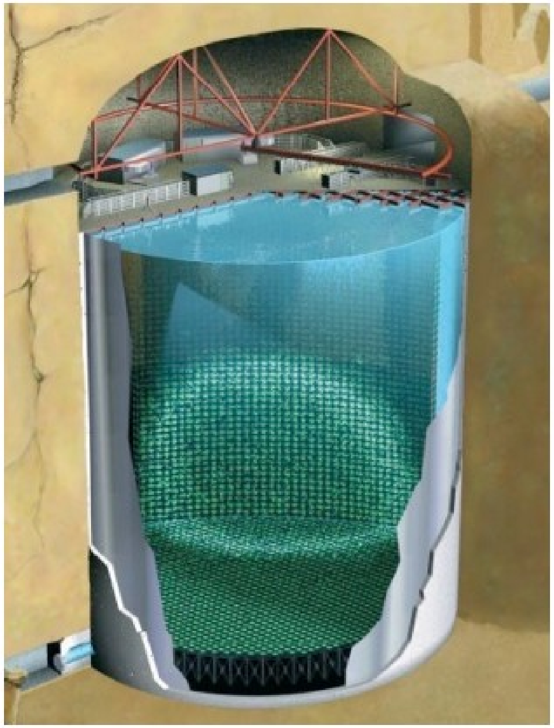
- Future of Super-K:

  SK-GD (201?): add gadolinium (Approved) **[Beacom, Vagins (2004)]**

(Hida, Gifu Prefecture, Japan)

Super-Kamiokande



"Golden channel": $p \rightarrow \pi^0 e^+$

$\pi^0 \rightarrow 2\gamma$

$p_\pi = p_e$ = 459 MeV

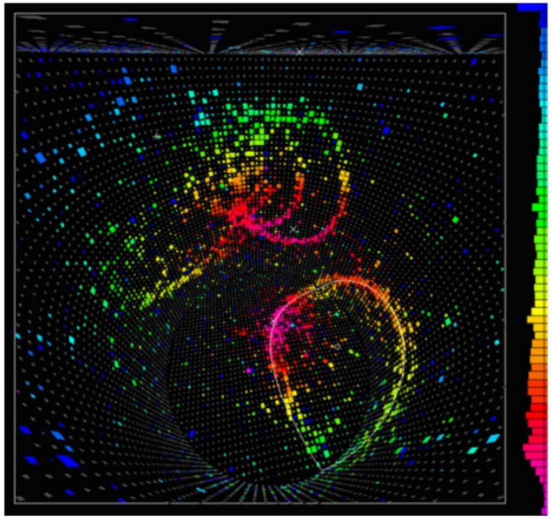
$p_{\gamma/\pi R}$ = 68 MeV

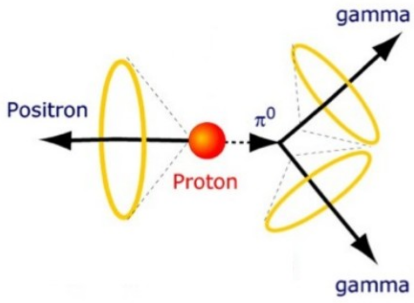
"Silver channel": $p \rightarrow K^+ \nu$

p_K = 340 MeV

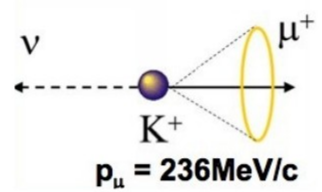
Kaons don't shine !

(1) Signal: Nucleon Decay



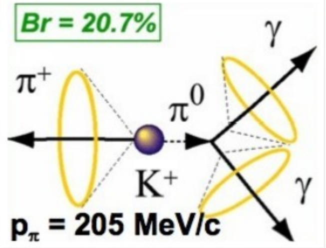


$K^+ \rightarrow \mu^+ + \bar{\nu}$ *Br = 63.5%*



- single cone

$K^+ \rightarrow \pi^+ + \pi^0$ *Br = 20.7%*



- 2 EM cones
- little opposite-side activity

About one order of magnitude less sensitive than $p \rightarrow \pi^0 e^+$

from Malinsky, Brussels (13)

Detecting Nucleon Decay at Super-K

"Golden channel": $p \rightarrow \pi^0 e^+$
$\pi^0 \rightarrow 2\gamma$

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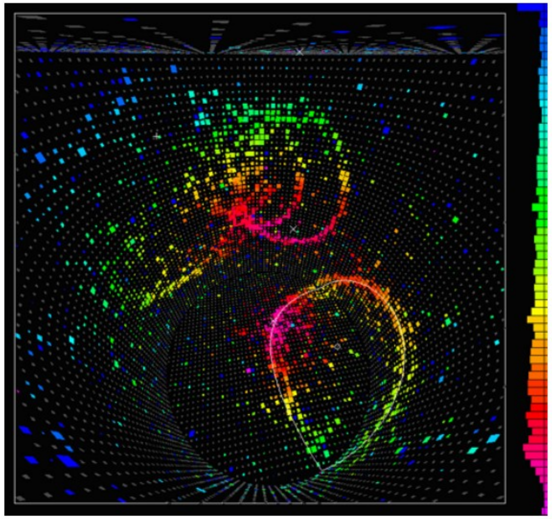

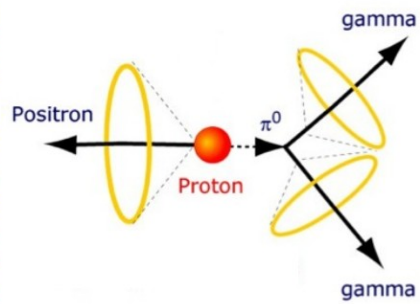

"Silver channel": $p \rightarrow K^+ \nu$ p_K = 340 MeV   Kaons don't shine !

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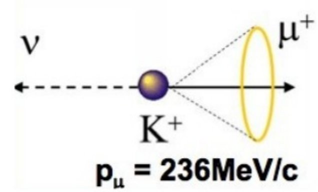

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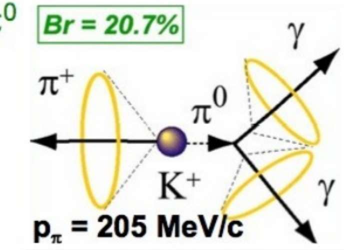

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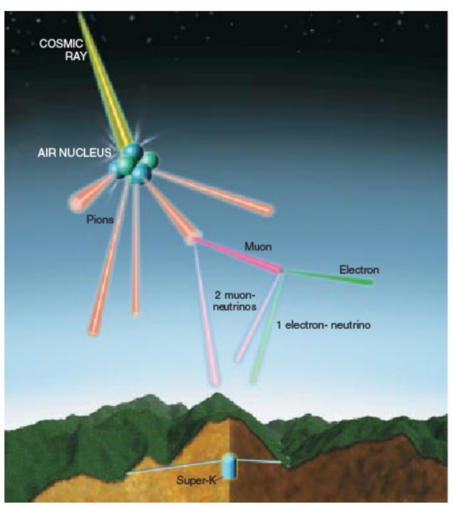
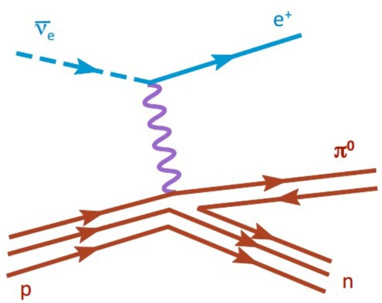
(2) Background: Atmospheric Neutrinos





from Ed Kearns, NEPPRS (09)

Detecting Nucleon Decay at Super-K

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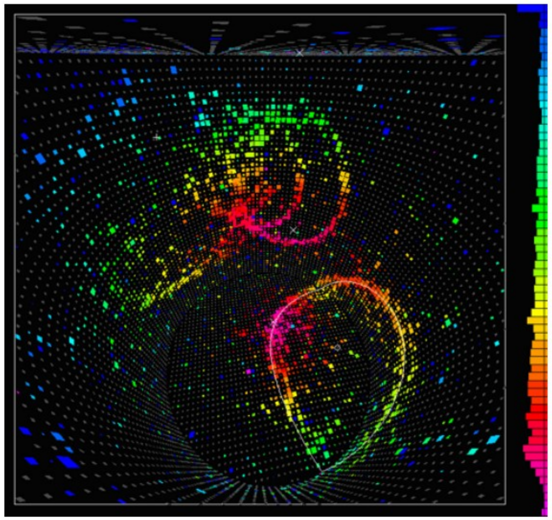

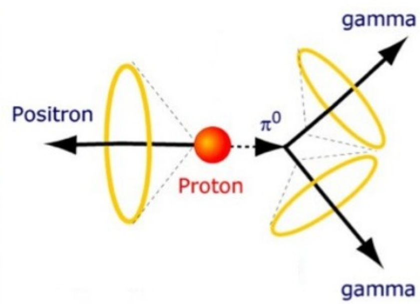

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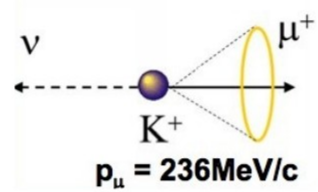

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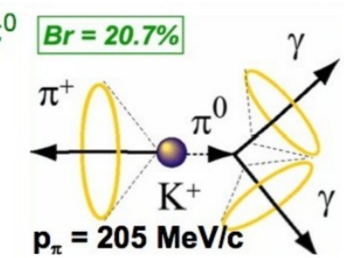

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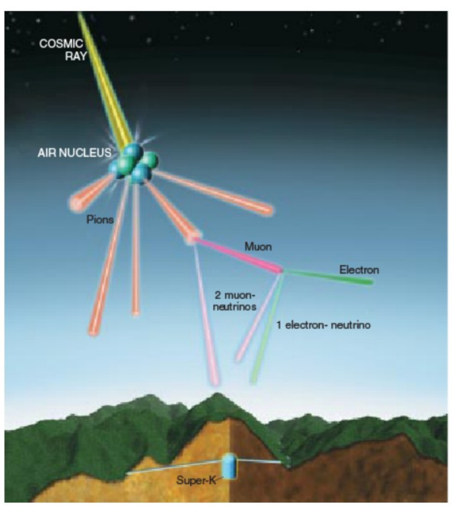
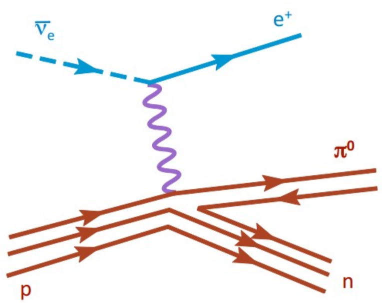




(3) Set Limit

$$\frac{\tau}{B} = \frac{\lambda\varepsilon}{n-b}$$

n = number of observed events
b = expected number of background events
λ = exposure = $N_{proton} \cdot \Delta t$
ε = efficiency

$$\frac{\tau}{B} = \frac{\lambda\varepsilon}{S_{90}}$$

$$S_{90} = \frac{\int_0^{S_{90}} P_{poiss.}(n, x+b)dx}{\int_0^{\infty} P_{poiss.}(n, x+b)dx}$$

use Bayes' method to treat systematics

$$P(\Gamma \mid n) = \iiint \frac{e^{-\Gamma\lambda\varepsilon+b}(\Gamma\lambda\varepsilon+b)^n}{n!} P(\Gamma)\, P(\lambda)\, P(\varepsilon)\, P(b)\, d\Gamma\, d\lambda\, d\varepsilon\, db$$

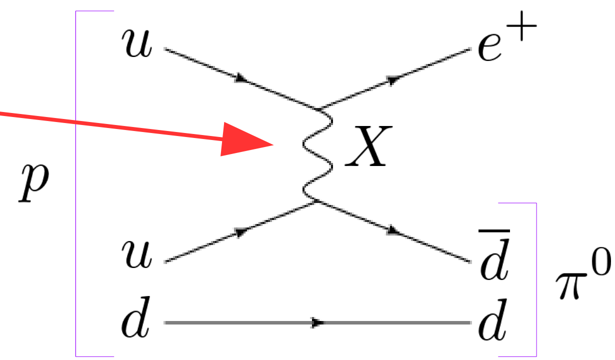
from Ed Kearns, NEPPRS (09)

Benchmark GUT mode: $\mathrm{p} \to \mathrm{e}^+ \pi^0$

- Motivation: dominant decay channel in most GUTs **[Georgi, Glashow (1974)]**
  - → typical predictions $\tau \sim 10^{29-36}$ yrs
  - → ruled out minimal $SU(5)$ **[IMB-3, Kamiokande, Super-K]**

sample $SU(5)$ diagram

GUT gauge boson



lifetime:

$$\tau = \frac{1}{\Gamma} \approx \left[\frac{M_X^2}{\alpha^2}\right]^2 m_p^5$$

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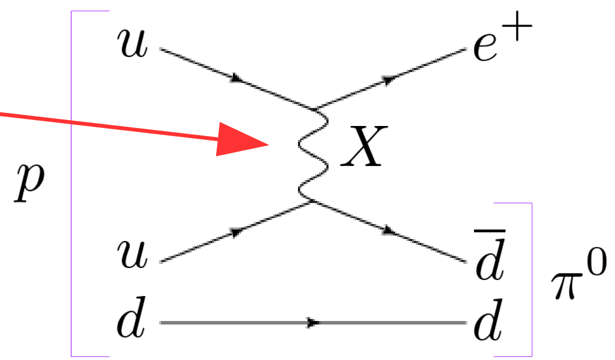

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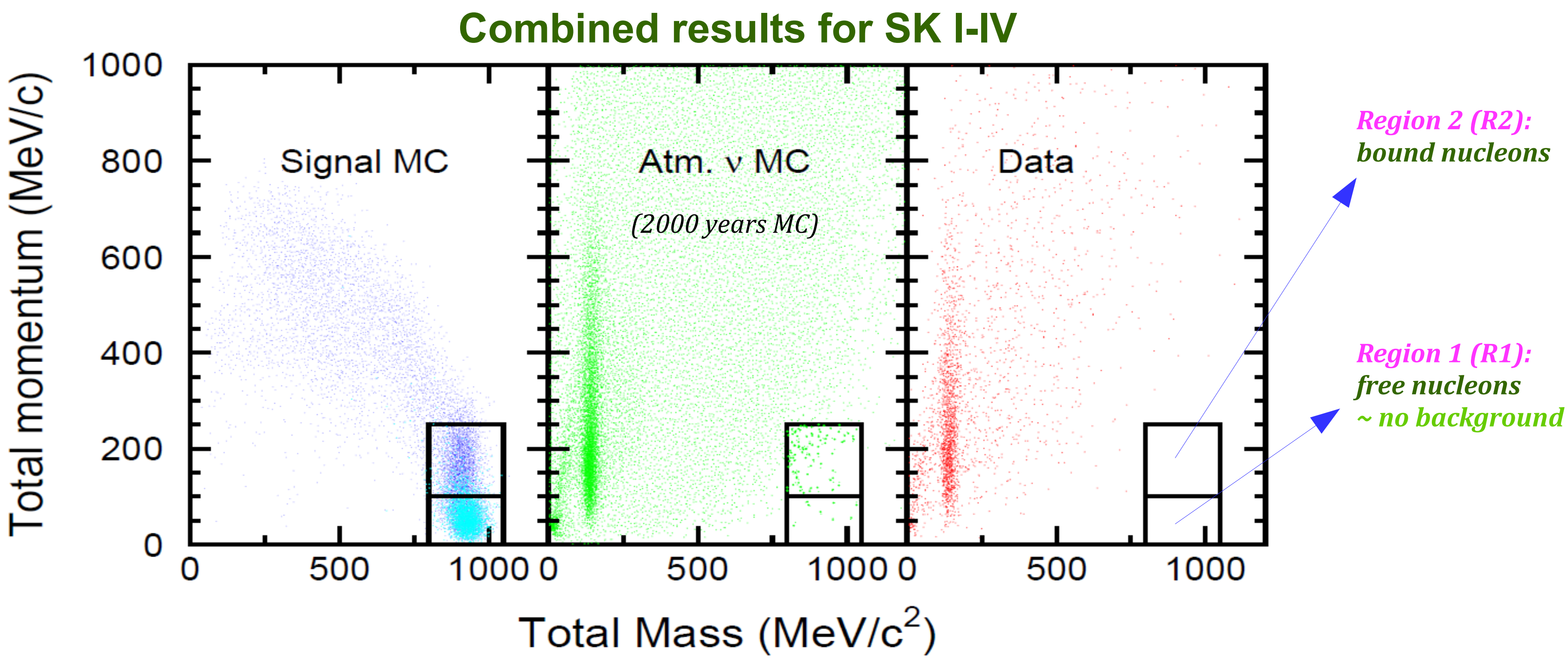
- Search strategy: $e^+, \pi^0 (\to \gamma + \gamma)$ are visible

  → reconstruct invariant mass and momentum of proton

- **Results**:

[Super-K, *preliminary*]



exposure: 306 kt*years

SK I-IV	R1	R2
Av. Eff. (%)	18.8	19.9
BKG	0.07	0.54
Data	0	0

\- *w/ neutron tag in SK4*

- **No significant excess** → lifetime limit (90% C.L.)

$$\tau_{p\rightarrow e^+\pi^0} > 1.7 \times 10^{34} \text{ yrs.}$$

Benchmark GUT mode: $\mathbf{p \rightarrow \mu^{+}\pi^{0}}$

- **Motivation:** can be as dominant as $p \rightarrow e^{+}\pi^{0}$ (e.g. flipped $SU(5)$) **[Ellis, Nanopoulos, Walker (2002)]**
- **Search strategy:** $\mu^{+}(\rightarrow e^{+}\nu\nu), \pi^{0}(\rightarrow \gamma + \gamma)$ all visible, reconstruct nucleon

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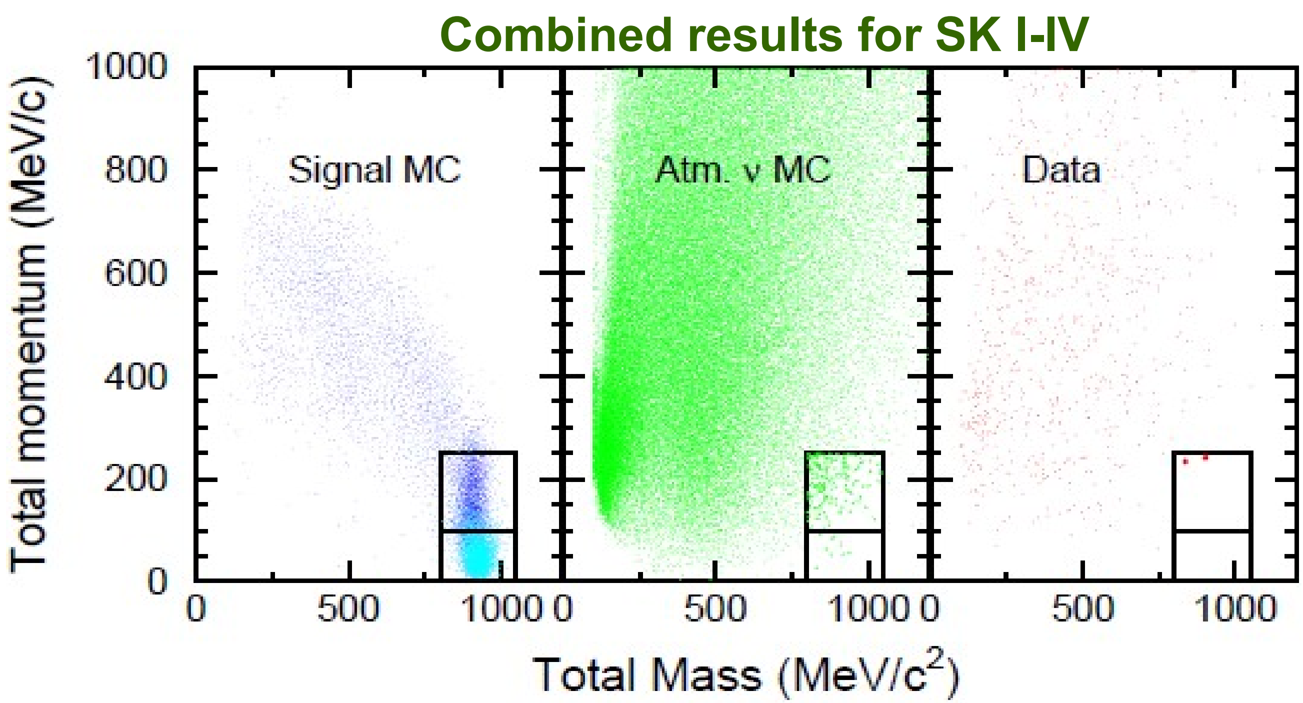


[Super-K, *preliminary*]

exposure: 306 kt*years

SK I-IV	R1	R2
Av. Eff (%)	17.9	16.7
BKG	0.05	0.82
Data	0	2

- w/ neutron tag in SK4
- SK4 better decay-e detection

(details in Appendix)

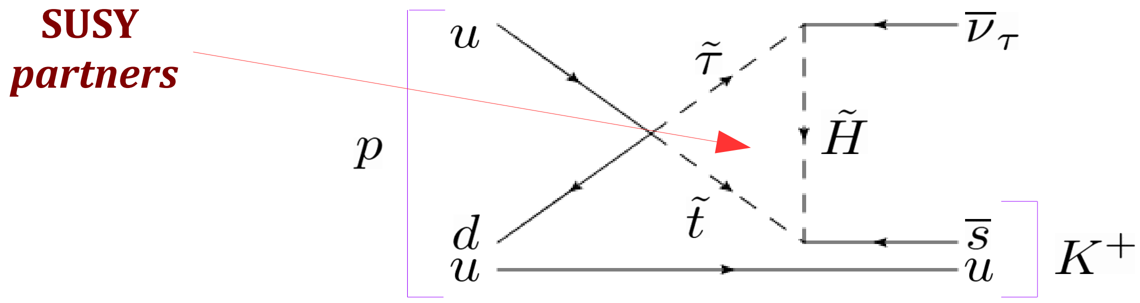
- 2 events pass selection, consistent with background (Poisson prob. 23%, "eye scan")
- No significant excess → lifetime limit (90% C.L.)

$$\tau_{p\rightarrow\mu^+\pi^0} > 7.8 \times 10^{33} \text{ yrs.}$$

Benchmark SUSY GUT mode: $p \to \nu K^+$

- Motivation: dominant decay in most SUSY GUTs [Weinberg (1982); Sakai, Yanagida (1982)]
  - → typical predictions $\tau \sim 10^{29-36}$ yrs
  - → ruled out minimal (TeV-)SUSY $SU(5)$ [Kobayashi+ (SK), PRD (2005)]

sample SUSY $SU(5)$ diagram



lifetime:

$$\tau = \frac{1}{\Gamma} \approx \left[\frac{M_{\tilde{s}}^2}{\alpha^2}\right]^2 m_p^5$$

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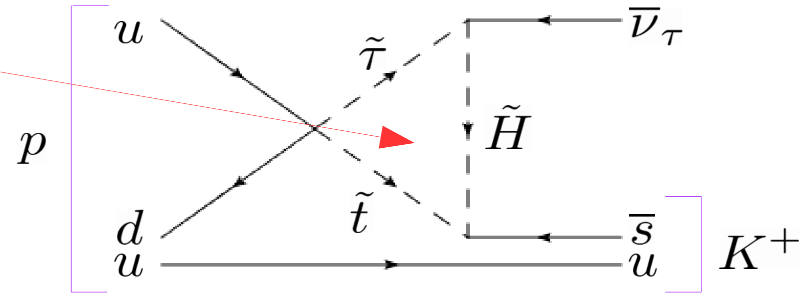
SUSY partners



lifetime:

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- Search strategy: $\nu, K^+(\to \mu^+\nu, \pi^0\pi^+)$ [64%] [21%] both invisible (K+ below threshold)
  - → can't reconstruct proton, can do ...

Search (A) $(K^+ \to \mu^+\nu)$ spectral fit to μ^+ momentum

Search (B) $(K^+ \to \mu^+\nu)$ tag γ from nuclear de-excitation

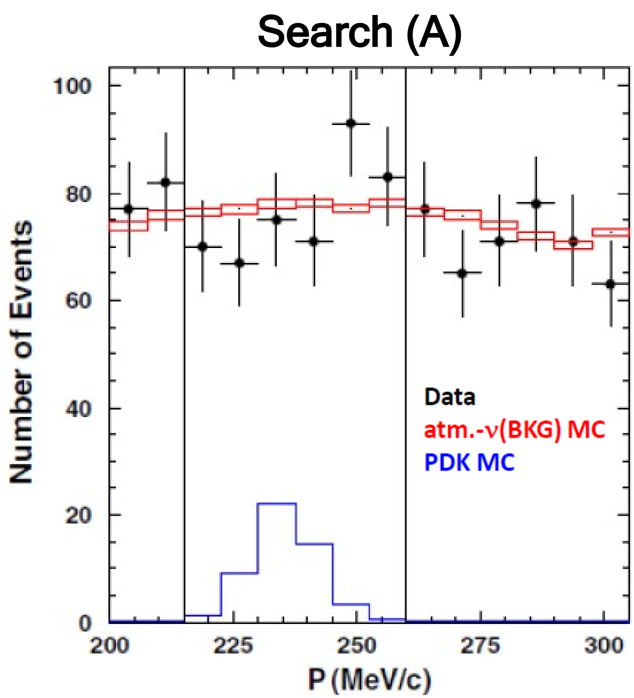
Search (C) $(K^+ \to \pi^0\pi^+)$ reconstruct pion from $\pi^0 \to \gamma\gamma$

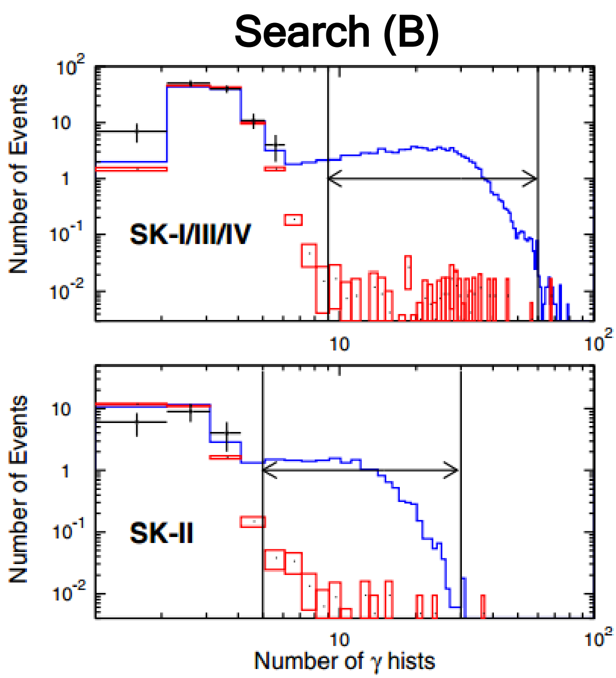
Benchmark SUSY GUT mode: $p \to \nu K^{+}$

Search (A) = spec. fit μ^{+}
Search (B) = prompt γ
Search (C) = pions

- Results:

Sample combined results for SK I-IV





[Abe+ (SK), PRD (2014)]

exposure: 260 kt*years

SK I-IV	Search A	Search B	Search C
Av. Eff (%)	33.7	7.9	8.2
BKG	579.4	0.39	0.56
Data	566	0	0

- w/ neutron tag in SK4
- SK4 better decay-e detection

* Search (C) in Appendix

- No significant excess → lifetime limit (90% C.L.)

$$\tau_{p \to \nu K^{+}} > 6.6 \times 10^{33} \text{ yrs.}$$

$\mathbf{n - \overline{n}}$

- Motivation: $\Delta B = 2$ process

→ parametrizes breaking scale of $U(1)_{B-L}$, can embed into GUT

→ natural connection w/ Majorana neutrinos (see-saw) + baryogenesis

[Babu, Mohapatra (2001); Mohapatra (2009); Kuzmin (1970)]

$$\sim 10^{32}\ \text{yrs.} \quad \tau_{n-\overline{n}} = R \cdot \tau_{n-\overline{n}}^{vac.\,2} \quad (\tau_{n-\overline{n}}^{vac.} \sim 10^{8}\ \text{s.})$$

nuclear suppression $\sim 10^{23}$

→ test of intermediate scale physics

$$\mathcal{O}_{n-\overline{n}} \sim \frac{1}{M^5}(udd)(udd) \quad + \quad \tau_{n-\overline{n}}^{vac.} \sim 10^{8}\ \text{s.} \quad \rightarrow \quad M \sim 100\ \text{TeV}$$

current limit

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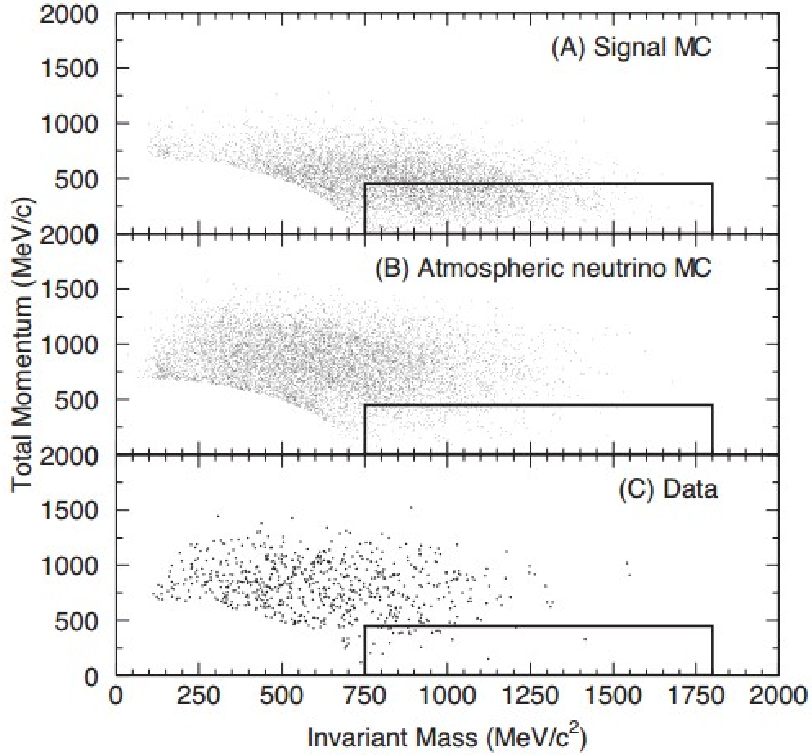
(*current limit*: $\tau^{vac.}_{n-\overline{n}} \sim 10^8$ s.)

- **Search strategy:** $\overline{n}$ is captured by nucleons
  - → look for pions from $\overline{n}+p, \overline{n}+n$ →
  - → reconstruct "di-nucleon" invariant mass and momentum

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

- **Results**:

Results for SK I



* Largest systematic uncertainty due to pion nuclear effects (scattering, etc.)

[Abe+ (SK), PRD (2015)]

exposure: 91.5 kt*years

	SK I
Eff (%)	12.1
BKG	24.1
Data	24

- **No significant excess** → lifetime limit (90% C.L.)

$$\tau_{n-\bar{n}} > 1.9 \times 10^{32}\ \text{yrs.}$$

→ being redone for SK1-4 w/ boosted decision tree (BDT)

→ same BDT technique as in recent SK dinucleon searches, with limits $\mathcal{O}(10^{32}\ \text{yrs.})$

$$pp \to \pi^+\pi^+, np \to \pi^0\pi^+, nn \to \pi^0\pi^0$$

[Gustafson+ (SK), PRD (2015)]

More Exotic Searches

- **Motivation:** large theory uncertainty requires broad search strategy

→ understand well 1-ring atm.-ν background

→ do wide search of channels w/ 1-ring signature:

never searched before!

$$p \to e^+\nu\nu, \quad p \to \mu^+\nu\nu, \quad p \to e^+X, \quad p \to \mu^+X$$

$$np \to e^+\nu, \quad np \to \mu^+\nu, \quad np \to \tau^+\nu, \quad n \to \gamma\nu$$

→ trilepton decays arise in Pati-Salam models, in some $\tau_{p\to e(\mu)\nu\nu} \sim 10^{32\pm1}\mathrm{yrs.}$ [Pati, Salam (1973)]

→ dinucleon decays arise in extended Higgs models [Arnold, Fornal, Wise (2013)]

→ because $m_\tau > 1$ GeV, τ only occurs in dinucleon channels [Bryman (2014)]

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$$p \to e^+\nu\nu, \quad p \to \mu^+\nu\nu, \quad p \to e^+X, \quad p \to \mu^+X$$
$$np \to e^+\nu, \quad np \to \mu^+\nu, \quad np \to \tau^+\nu, \quad n \to \gamma\nu$$

  → trilepton decays arise in Pati-Salam models, in some $\tau_{p\to e(\mu)\nu\nu} \sim 10^{32\pm1}$yrs. [Pati, Salam (1973)]

  → dinucleon decays arise in extended Higgs models [Arnold, Fornal, Wise (2013)]

  → because $m_\tau > 1$ GeV, τ only occurs in dinucleon channels [Bryman (2014)]

- **Search strategy:** only e^+, μ^+ are visible

  → can't reconstruct nucleon(s)

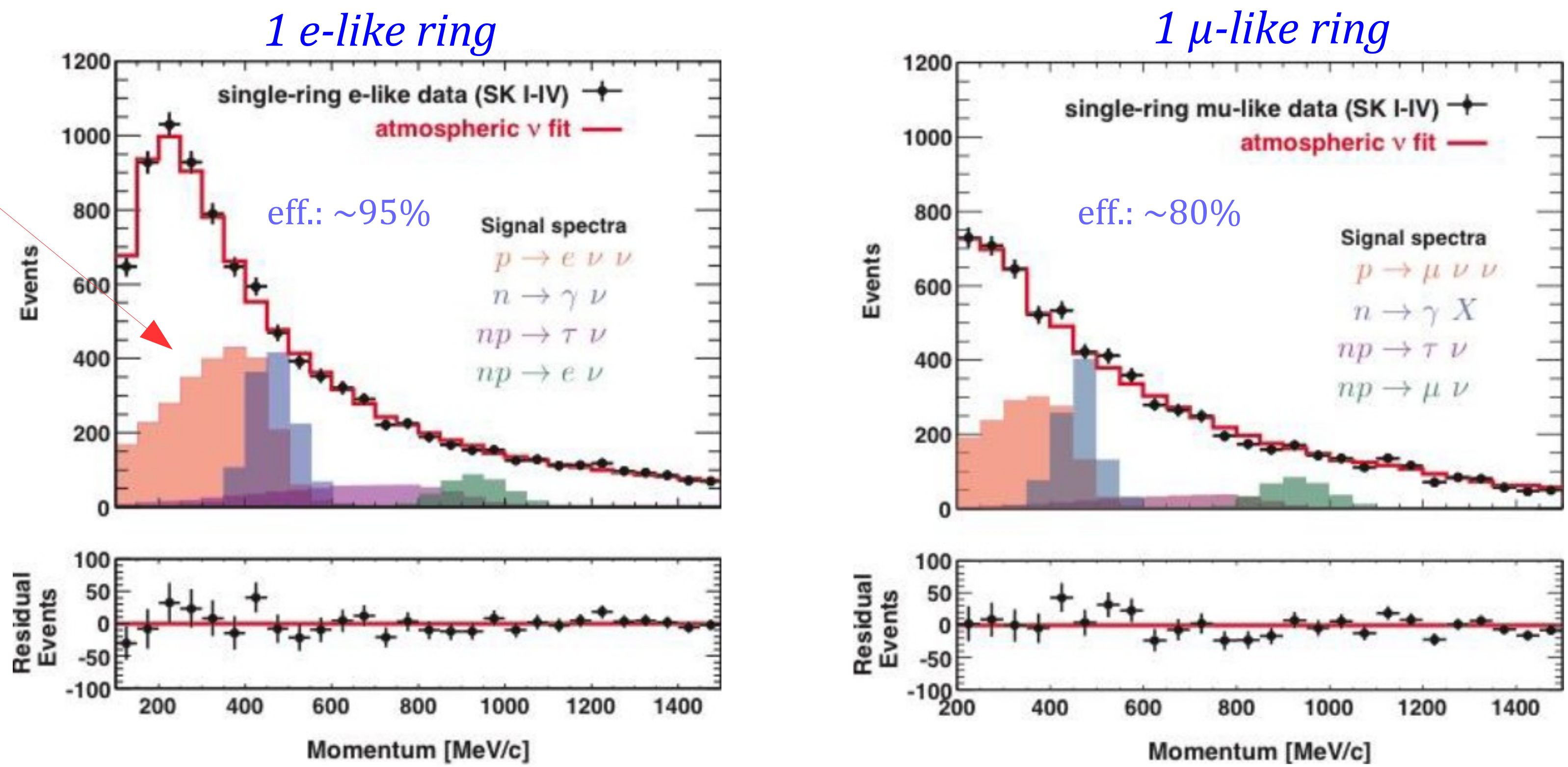
  → do spectral fit for 1-ring momenta

[Takhistov+ (SK), PRL (2014)]
[Takhistov+ (SK), PRL (2015)]

- Results:

Combined results for SK I- IV

Signal @ 90 C.L. (x 5)



exposure: 273.4 kt*years

- No significant excess → lifetime limit (90% C.L.)

→ limit improved > 2 orders

→ constrain Pati-Salam models

$$\tau_{spec.\ modes} > \text{few} \times 10^{32}\ \text{yrs.}$$

Summary of Super-K Results

from S. Mine, TAUP (2015)

Decay mode	$\lvert\Delta(B-L)\rvert$	Lifetime lower limit at 90% CL (years)	Paper (previous result)
$p \to e^+\pi^0$	0	(*) 1.67×10^{34}	(PRD 85, 112001 (2012))
$p \to \nu K^+$	$0(\bar{\nu})$, $2(\nu)$	6.61×10^{33}	(PRD 90, 072005 (2014))
$p \to \mu^+\pi^0$	0	(*) 7.78×10^{33}	(PRD 85, 112001 (2012))
$p \to e^+/\mu^+(\eta,\rho,\omega)$	0	$(0.04\text{-}4.2) \times 10^{33}$	PRD 85, 112001 (2012)
$p \to \mu^+K^0$	0	1.6×10^{33}	PRD 86, 012006 (2012)
$n \to \bar{\nu}\pi^0$, $p \to \bar{\nu}\pi^+$	0	1.1×10^{33}, 3.9×10^{32}	PRL 113, 121802 (2014)
$p \to e^+/\mu^+\nu\nu$	$0(\bar{\nu}\nu)$, $2(\nu\nu,\bar{\nu}\bar{\nu})$	$1.7/2.2 \times 10^{32}$	PRL 113, 101801 (2014)
$p \to e^+/\mu^+X$	?	$7.9/4.1 \times 10^{32}$	arXiv:1508.05530, accepted by PRL
$n \to \nu\gamma$	$0(\bar{\nu})$, $2(\nu)$	5.5×10^{32}	arXiv:1508.05530, accepted by PRL
$pp \to K^+K^+$	2	1.7×10^{32}	PRL 112, 131803 (2014)
$pp \to \pi^+\pi^+$, $pn \to \pi^+\pi^0$, $nn \to \pi^0\pi^0$	2	7.22×10^{31}, $1{,}70 \times 10^{32}$, 4.04×10^{32}	PRD 91, 072009 (2015)
$np \to (e^+,\mu^+,\tau^+)\nu$	$0(\bar{\nu})$, $2(\nu)$	$(0.22\text{-}5.5) \times 10^{32}$	arXiv:1508.05530, accepted by PRL
$n\text{-}\bar{n}$ oscillation	2	1.9×10^{32}	PRD 91, 072006 (2015)

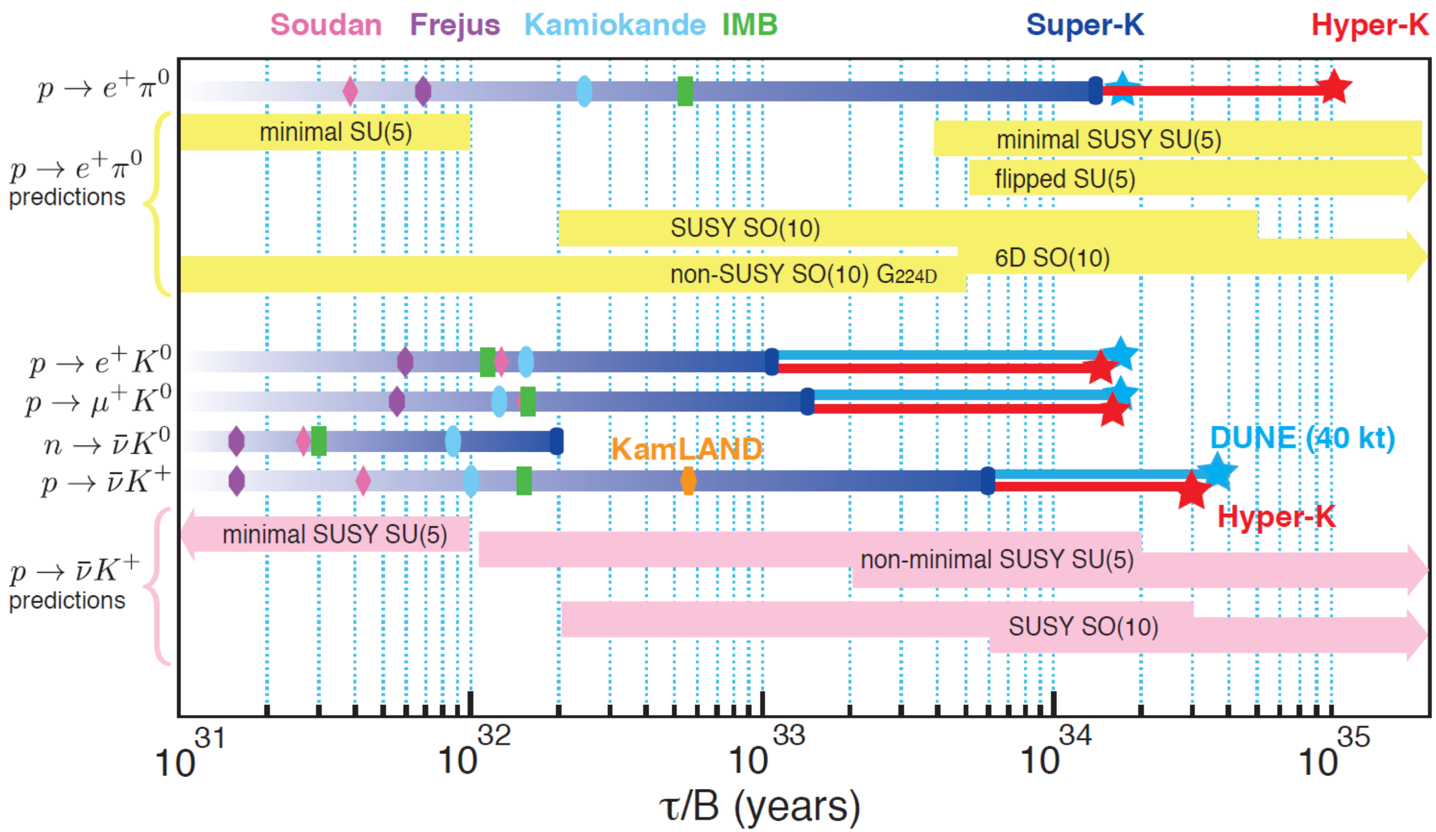
$$\tau > 10^{32} \text{ years!}$$

Future

- **Future**: Hyper-K (+ DUNE/LBNF)
- Hyper-K ≈ SK x 20, improved technology
- Large uncertainty in predictions, however …

  → approaching interesting regime of $\tau \sim 10^{35}$ yrs.

  → will greatly benefit from large volume of Hyper-K



from Ed Kearns

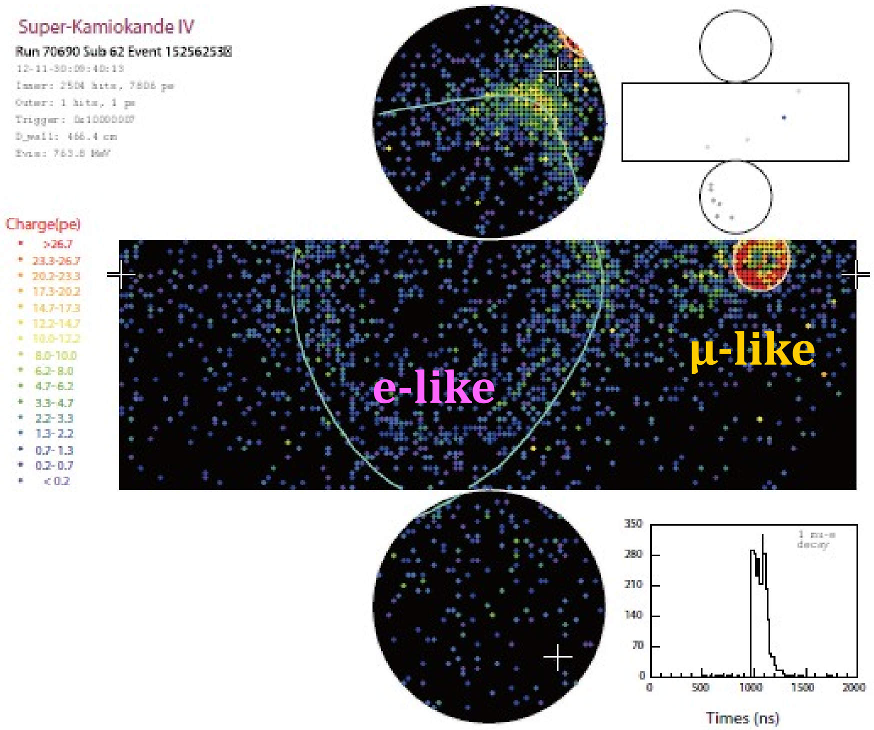
Conclusions

- Baryon number violation appears in many contexts
- Connection between nucleon decay and other physics highlights it as a unique experimental window to high energies
- Uncertainty in theory predictions requires a broad search program and Super-K is the best detector for this
  $\rightarrow$ new future analyses (e.g. $n \rightarrow \nu\nu\nu, pp \rightarrow e^{+}e^{+}$...)
- Approaching interesting limit range of $\tau \sim 10^{35}$ yrs.
  $\rightarrow$ exciting times ahead (Hyper-K + DUNE)

Appendix

Appendix: 2 events passing selection in $p \rightarrow \mu^+\pi^0$

Event 1



$(M_p, P_{\text{tot}}) = (902.5, 248.0)$ MeV

Wall $= 466.0$ cm

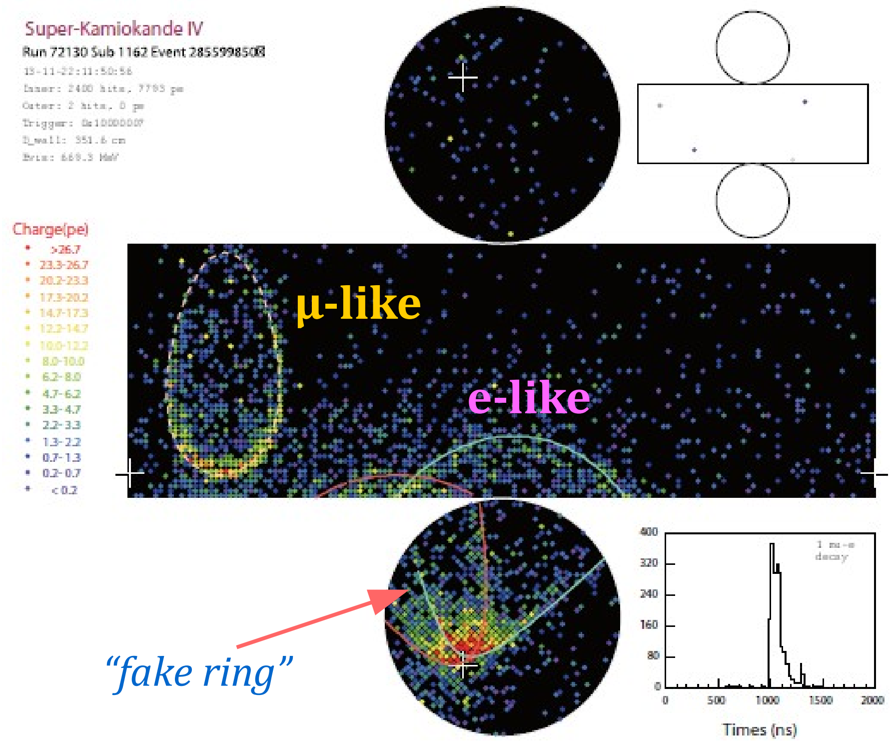
$\#$ rings $= 2$

$P_e = 374.9$ MeV/c

$P_\mu = 551.1$ MeV/c

$\theta_{e-\mu} = 157.9$

Event 2



$(M_p, P_{\text{tot}}) = (832.4, 237.9)$ MeV

Wall $= 351.6$ cm

$\#$ rings $= 2$

$P_e = 460.5$ MeV/c

$P_\mu = 391.3$ MeV/c

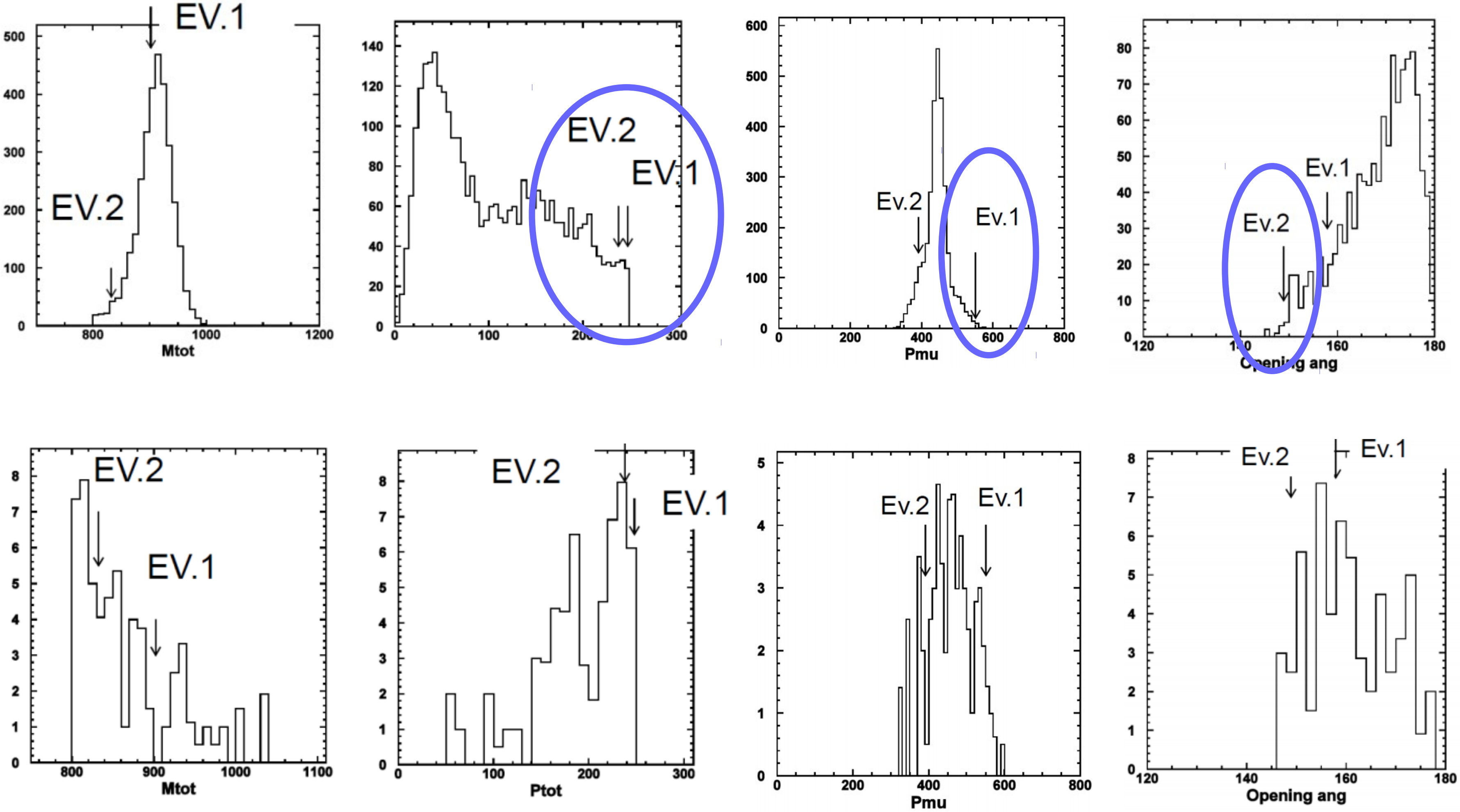
$\theta_{e-\mu} = 148.9$

Appendix: 2 events passing selection in $\mathrm{p} \rightarrow \mu^+\pi^0$

$\mathbf{M_{tot}}$ $\mathbf{P_{tot}}$ $\mathbf{P_{\mu}}$ $\theta_{\mathbf{e}-\mu}$

Signal MC

BKG MC



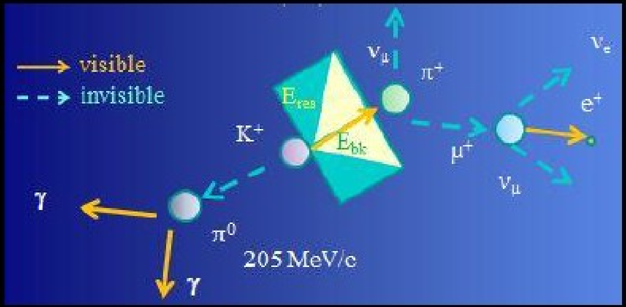
plots from M. Miura

from S. Mine, Moriond (2015)

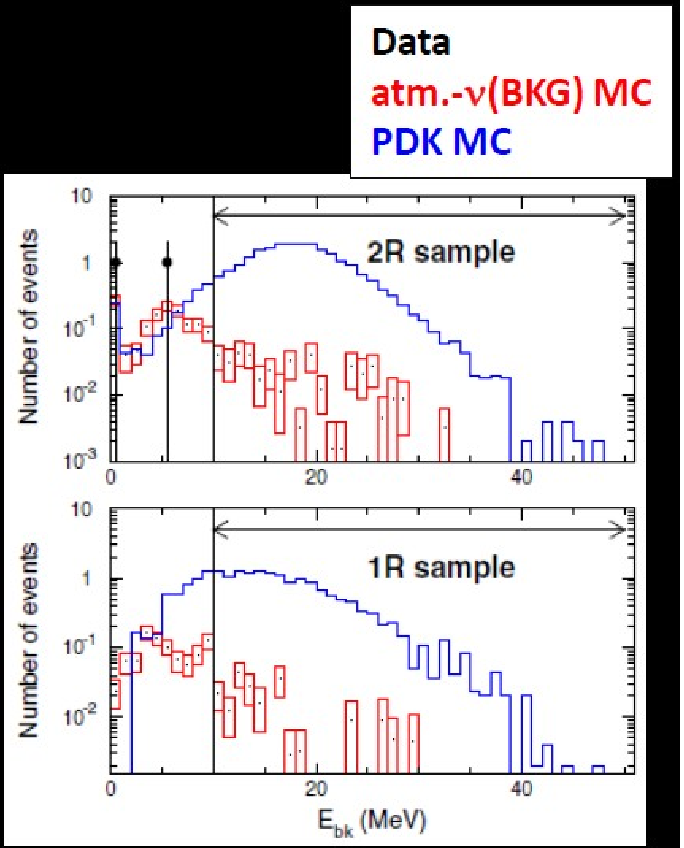
$\pi^+\pi^0$ method:

$(p \to \nu K^+, K^+ \to \pi^+\pi^0)$

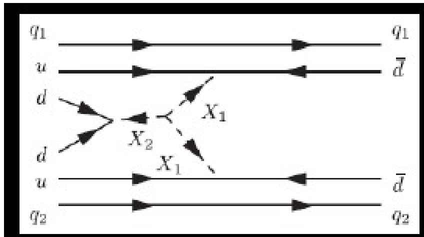
(M.Miura)



- event selections:
  - 1 or 2 e-like rings with Michel-e
  - $85<M_{\pi 0}<185 MeV/c^2$, $175<P_{\pi 0}<250 MeV/c$
  - charge profile likelihood for π^+
  - $10<E_{bk}<50 MeV$ (E_{bk}: visible energy for π^+)
- major improvements in event rec.:
  - single-ring π^0 fitter (new)
  - π^+ charge profile
- in SK-I:
  - expected #BKG: 0.6→0.18
  - signal ε: 6.0%→7.8%
- no data candidate



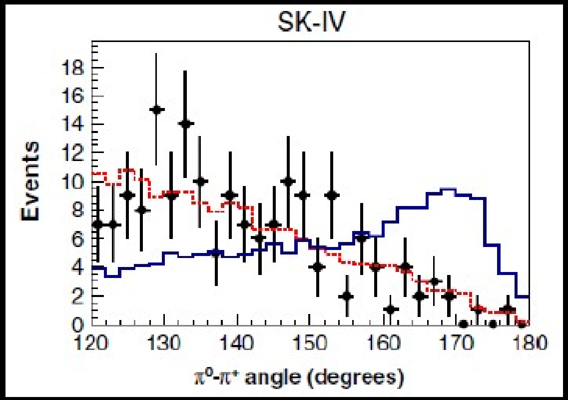
from S. Mine, TAUP (2015)

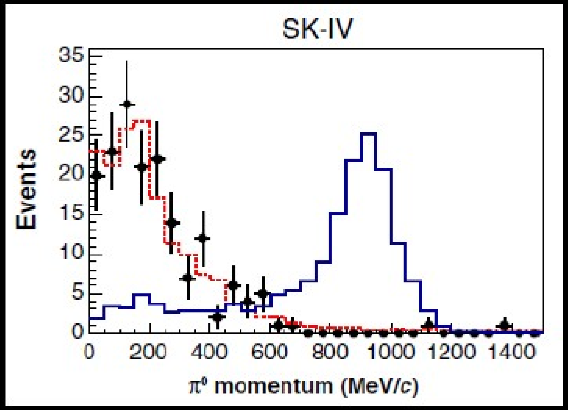


Dinucleon decay $\Delta B = |\Delta(B-L)| = 2$

(plots for $pn \to \pi^+ \pi^0$ in SK-IV as example)

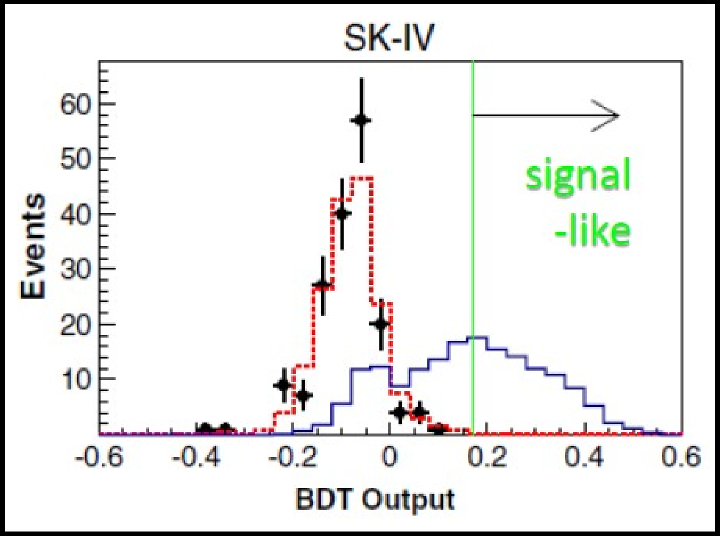
Input variables





DNDK MC
Atm.-ν MC
Data

Boosted Decision Tree Output

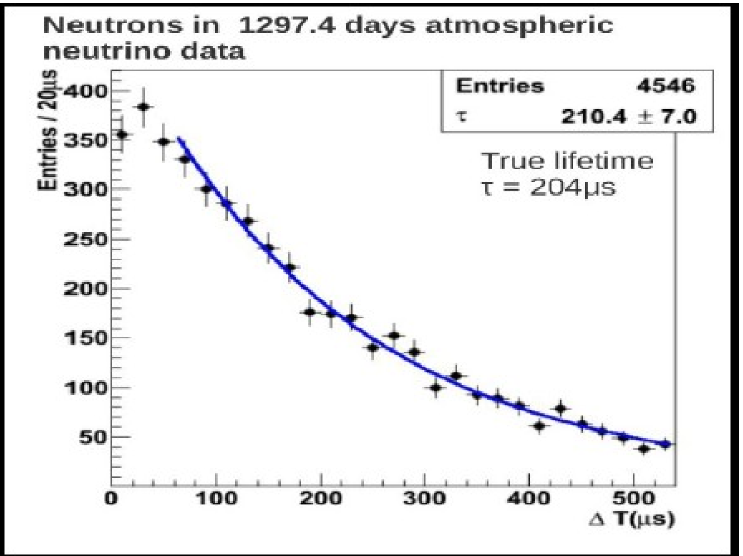


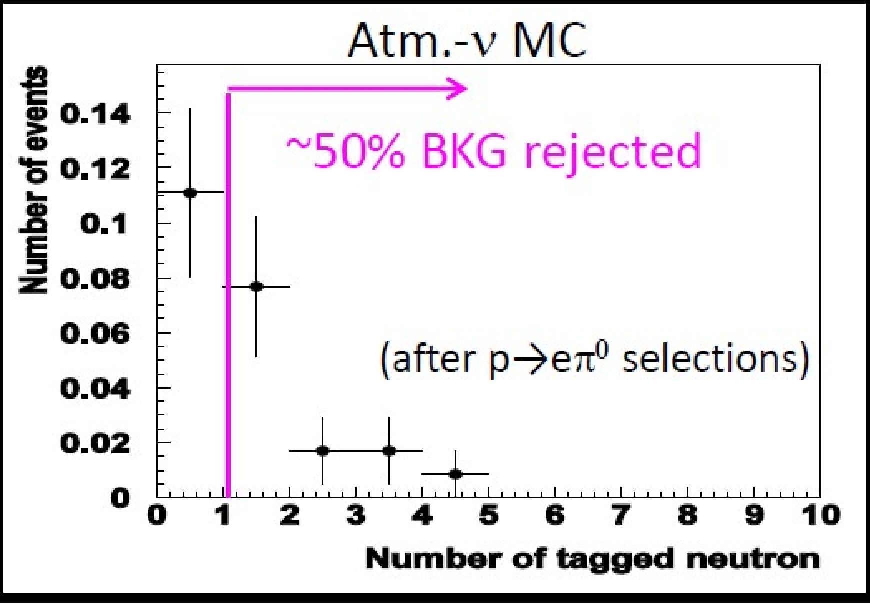
Mode	Frejus limit (^{56}Fe)	This analysis (^{16}O)
$pp \to \pi^+\pi^+$	7.0×10^{29} yrs	7.22×10^{31} yrs
$pn \to \pi^+\pi^0$	2.0×10^{30} yrs	1.70×10^{32} yrs
$nn \to \pi^0\pi^0$	3.4×10^{30} yrs	4.04×10^{32} yrs

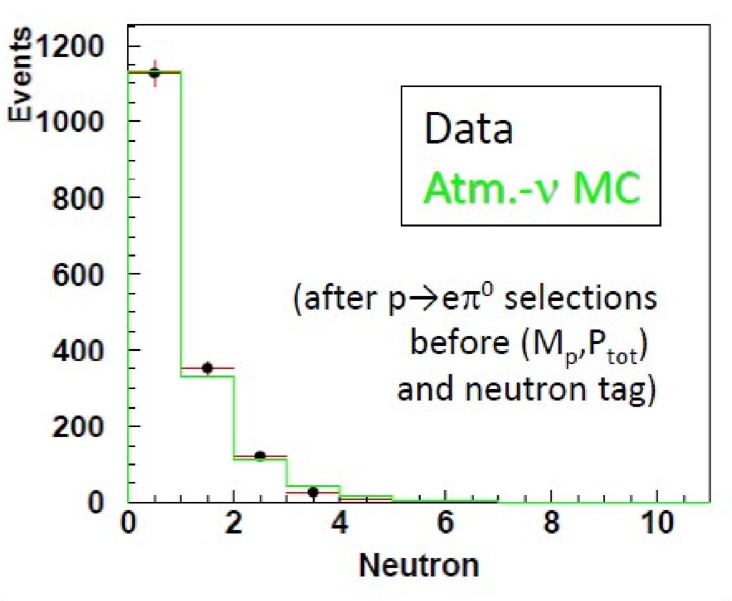
Appendix: Neutron Tagging in SK-IV

from S. Mine, TAUP (2015)

- Atm.-ν BKG frequently accompanied by neutron production
- $n + p \rightarrow d + \gamma(2.2\text{MeV})$
- Hit cluster search for γ enabled by QBEE with deadtime-less DAQ + software trigger
  - detection efficiency: 20.5%

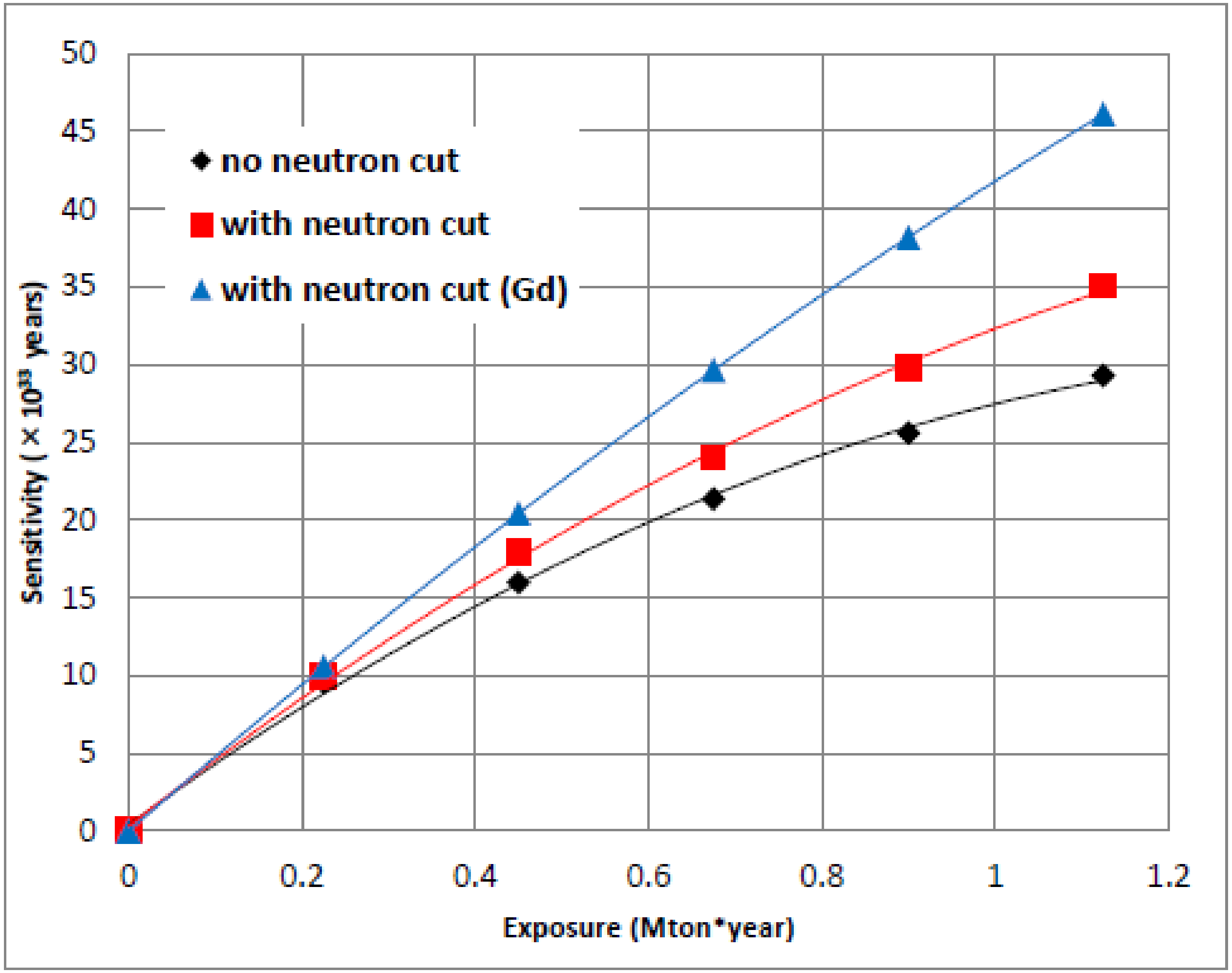






Appendix: Proton Decay w/ Gadolinium

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

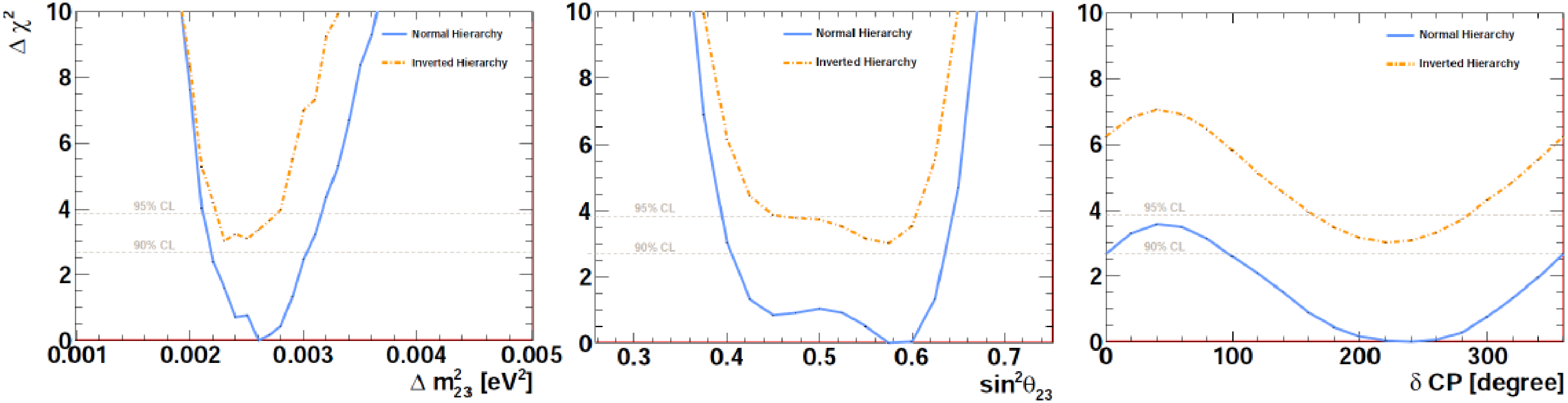


Appendix: Atmospheric Oscillation Results (SK)

from R. Wendell, ICRC (2015)

θ_{13} Fixed Analysis (NH+IH) SK Only

Preliminary



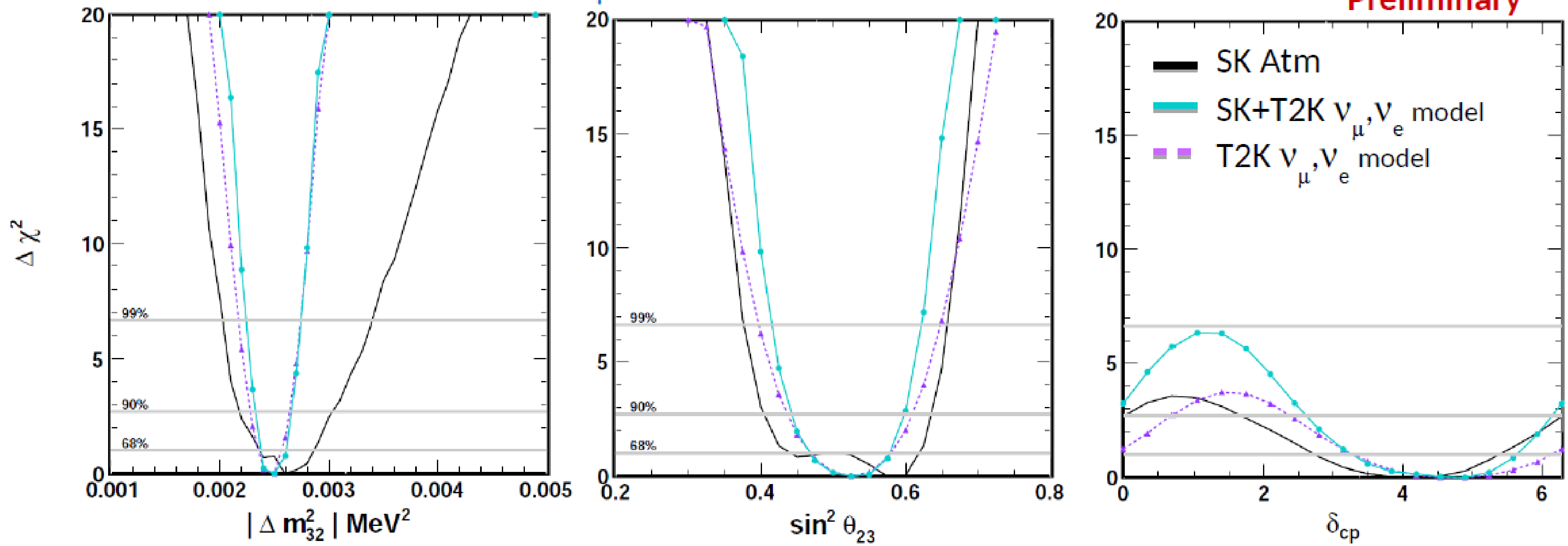
Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} $(\times 10^{-3})$
SK (NH)	582.4	0.0238	4.19	0.575	2.6
SK (IH)	585.4	0.0238	3.84	0.575	2.3

- Offset in these curves shows the difference in the hierarchies
- **Normal** hierarchy favored at: $\chi^2_{NH} - \chi^2_{IH} = -3.0$, not significant

from R. Wendell, ICRC (2015)

Theta13 **Fixed** SK + T2K ν_μ, ν_e Model, Normal Hierarchy

Preliminary



Fit (585 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($\times10^{-3}$)
SK + T2K (NH)	651.5	0.0238	4.89	0.525	2.5
SK + T2K (IH)	654.7	0.0238	4.19	0.550	2.4

- $\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (-3.0 SK only)
- CP Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

Appendix: Sterile Neutrinos

from R. Wendell, ICRC (2015)

Sterile Neutrino Oscillations in Atmospheric Neutrinos

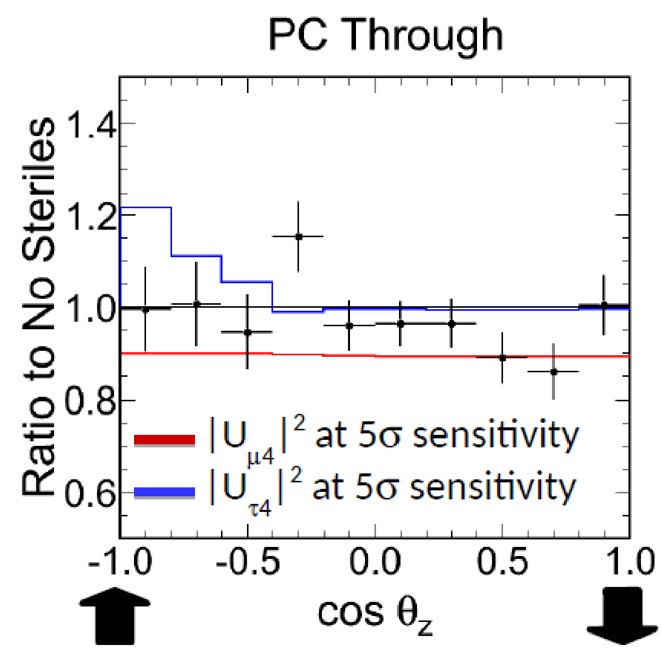
- Sterile Neutrino searches at SK are independent of the sterile Δm^2 and the number sterile neutrinos
  - 3+1 and 3+N models have the same signatures in atmospheric neutrinos
  - For $\Delta m_s^2 \sim 1\ eV^2$ oscillations appear fast:

    $< \sin^2 \Delta m^2 L/E > \sim 0.5$

MNS — Sterile

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

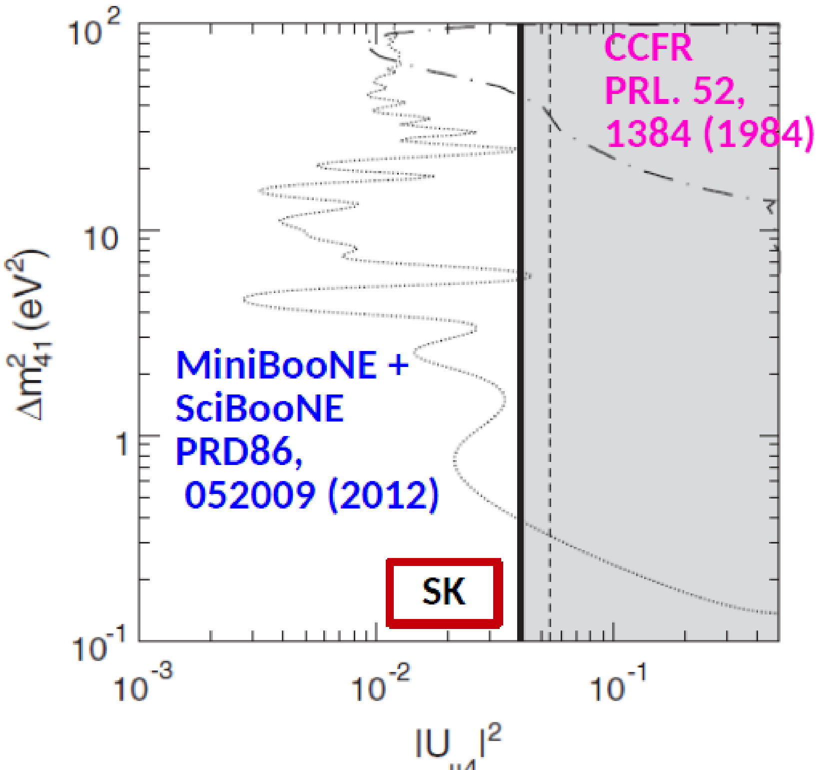
- $| U_{\mu 4} |^2$
  - Induces a decrease in event rate of μ-like data of all energies and zenith angles
- $| U_{\tau 4} |^2$
  - Shape distortion of angular distribution of higher energy μ-like data

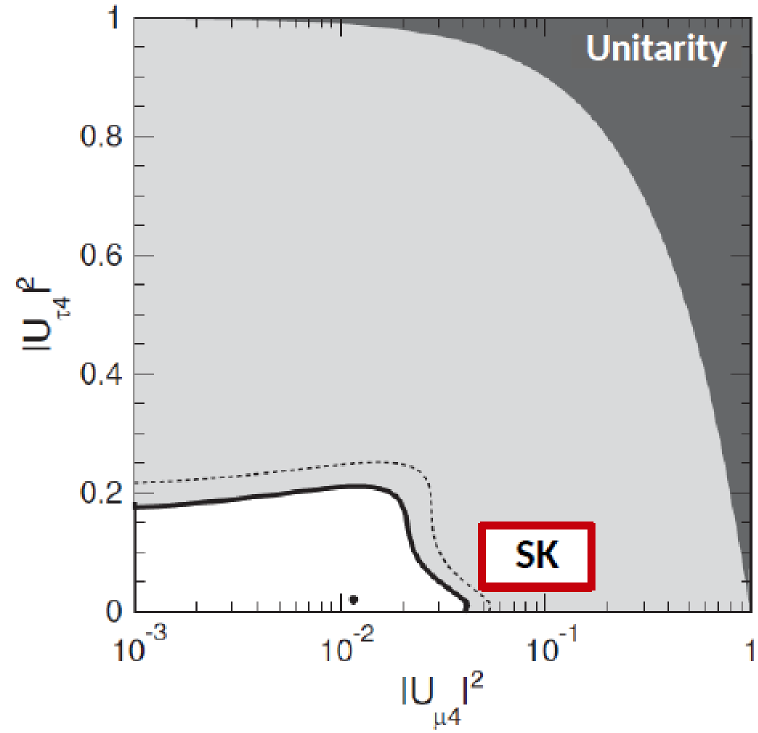


from R. Wendell, ICRC (2015)

Sterile Oscillations Results

PRD.91.052019 (2015)





- Turning off sterile matter effects while preserving standard three-flavor oscillations provides a pure measurement of $|U_{\mu 4}|^2$
- Using sterile matter effects, but decoupling ν_e oscillations provides a joint measurement of $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$, with a slightly biased estimate of the former
- Using SK-I+II+III+IV data (4438 days)
  $|U_{\mu 4}|^2 < 0.041$ at 90% C.L. $|U_{\tau 4}|^2 < 0.18$ at 90% C.L.

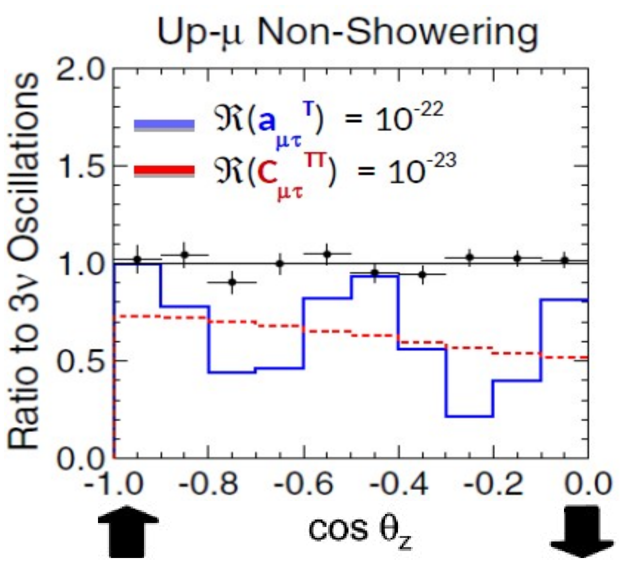
Appendix: Testing Lorentz Invariance

from S. Mine, Moriond (2015)

$$H = UMU^\dagger + V_e + H_{LV}$$

$$H_{LV} = \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - \frac{4E}{3} \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$

Coefficient	Unit	d	CPT	Oscillation effect
Isotropic				
$a^T_{\alpha\beta}$	GeV	3	Odd	$\propto L$
$c^{TT}_{\alpha\beta}$	...	4	Even	$\propto LE$

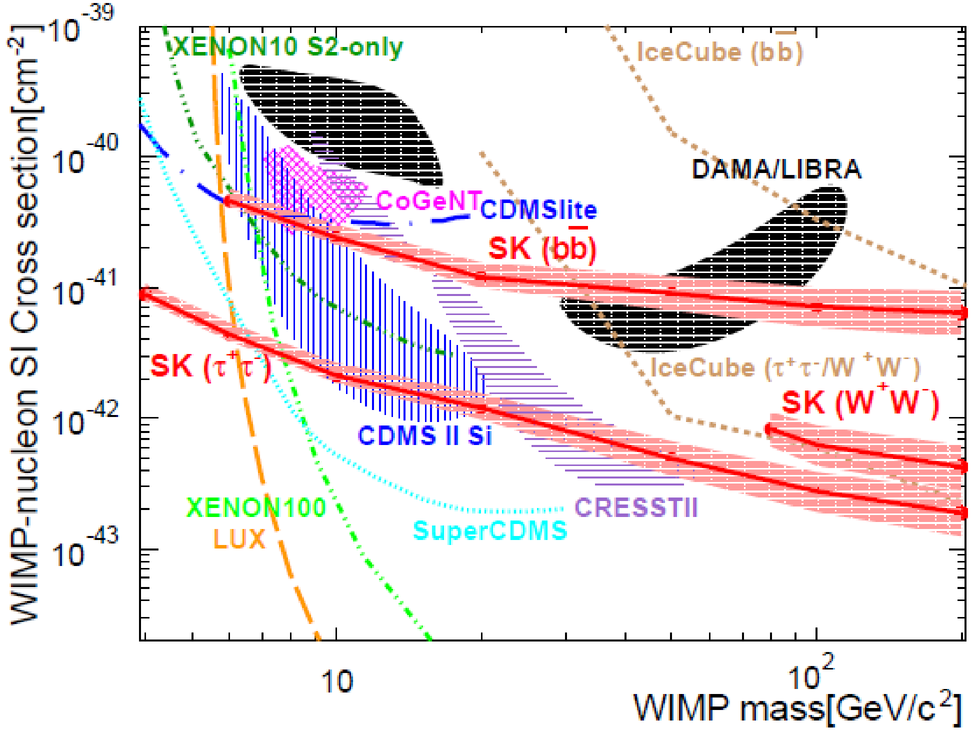


LV Parameter		95% Upper Limit	Best Fit	No LV $\Delta\chi^2$	Previous Limit
$e\mu$	Re (a^T)	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [51]
	Im (a^T)	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	Re (c^{TT})	1.1×10^{-26}	1.0×10^{-28}	0.0	9.6×10^{-20} [51]
	Im (c^{TT})	1.1×10^{-26}	1.0×10^{-28}		
$e\tau$	Re (a^T)	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV [52]
	Im (a^T)	2.8×10^{-23} GeV	1.0×10^{-28} GeV		
	Re (c^{TT})	1.2×10^{-24}	1.0×10^{-28}	0.3	1.3×10^{-17} [52]
	Im (c^{TT})	1.4×10^{-24}	4.6×10^{-25}		
$\mu\tau$	Re (a^T)	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	–
	Im (a^T)	5.1×10^{-24} GeV	1.0×10^{-28} GeV		
	Re (c^{TT})	5.8×10^{-27}	1.0×10^{-28}	0.1	–
	Im (c^{TT})	5.6×10^{-27}	1.0×10^{-27}		

- no evidence of Lorentz violation observed (4,438days ~ 274kt·year)
- set limits for the first time in neutrino μτ sector of SME
- improved existing limits by up to 7 orders of magnitude

[Choi+ (SK), PRL (2015)]

Spin Independent



Spin Dependent