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- on behalf of the Super-Kamiokande Collaboration

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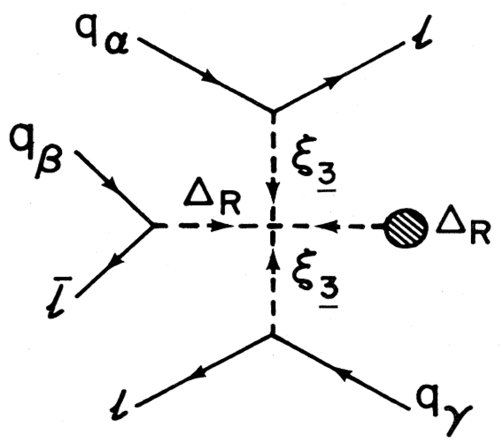
Searches for purely leptonic 3-body proton decay channels $p \to e\nu\nu$ and $p \to \mu\nu\nu$ as well as novel 2-body modes $p \to eX$, $p \to \mu X$ and $n \to \nu\gamma$ at Super-Kamiokande

Abstract

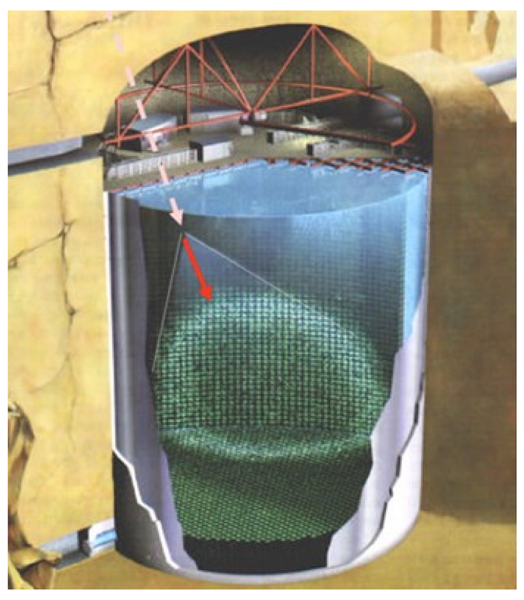
- Unification of couplings and matter hint at a **GUT underlying the SM** [1][2]
- With energies of order ~10^{16} GeV, Grand Unification is **unreachable at accelerators**
- Baryon number violationg **nucleon decay is a definitive prediction and a unique test** of GUT models that can be explored in a non-accelerator setting
- **Simplest unification** based on minimal SU(5) is **ruled out** by nucleon decay limits [3][4][5], with minimal SUSY extensions strongly limited [6]
- Consider other scenarios as well as higher symmetry groups
- Of interest is **SO(10) → SU(4) x SU(2) x SU(2) → SM** chain via Pati-Salam [7] model
- With L-R symmetry, Pati-Salam can lead to interesting decay modes such as |Δ(B-L)|=2 violating decays **p → eνν** and **p → μνν** *(also |Δ(B-L)| conserving modes)*
- Historically, **p → eνν** has been proposed to explain "neutrino anomaly" [8]
- **This analysis will provide results for the first 3-body nucleon decay search of SK via decay modes of p → eνν and p → μνν which may dominate over the typical modes, in some models** [9]

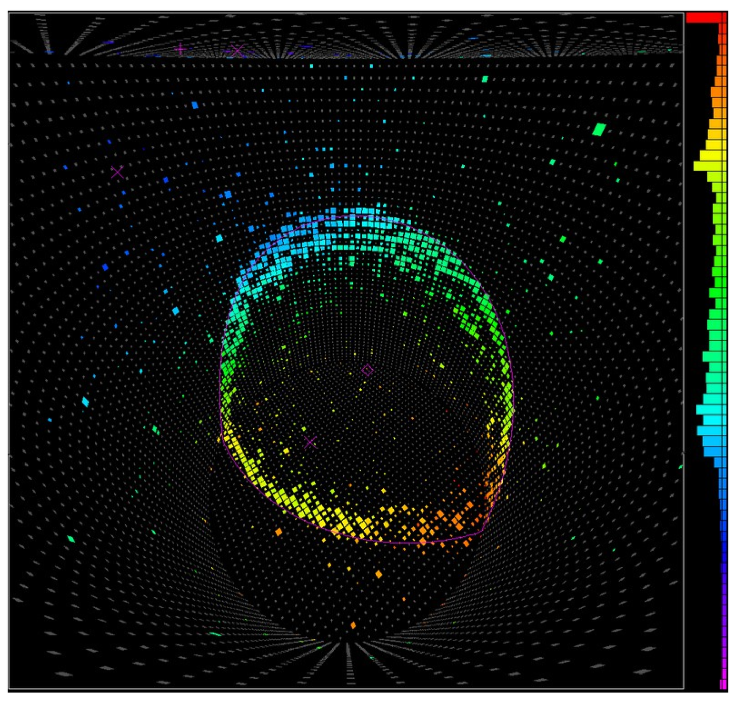
Diagram of
3q → 2l + l̄
from Pati-Salam [9]



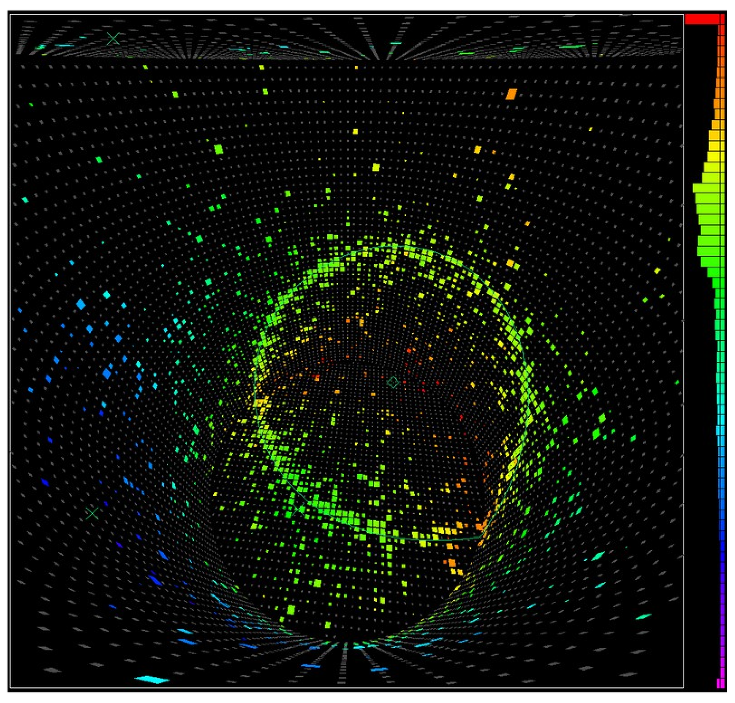
The Super-Kamiokande Detector

- Super Kamiokande is a 50 kiloton water Cherenkov detector located at Kamioka Mozumi Mine, Japan [10]
  - with inner fiducial volume of 22.5 kilotons
- Built in 1996 to search for nucleon decay, study solar and atmospheric neutrinos and keep supernovae watch
- In 1998, announced first evidence of neutrino oscillations [11], implying a non-zero neutrino mass





Event display: ***μ-like event***
energy of 603 MeV and 162 ns time width – recorded on 1998-04-04 08:35:22



Event display: ***e-like event***
energy of 492 MeV and 130 ns time width – recorded on 1998-04-04 21:26:08

Analysis Technique

- For processes with final state neutrinos, which are not observed at SuperK, **one cannot reconstruct invariant mass** and momentum of the parent particle
- Can analyze respective **e-like** and **μ-like** momenta distributions
- 3-body decay implies momenta has a wide spread spectrum from 0 to ~470 MeV
- Large signal and background overlap
- **Spectrum shape** analyzed by employing χ^2 minimization based on Poisson probability with systematic errors considered via quadratic penalties (pull terms) as in [12]

$$\chi^2 = 2\sum_{i=1}^{\text{nbins}}\left(z_i - N_i^{\text{obs}} + N_i^{\text{obs}}\ln\frac{N_i^{\text{obs}}}{z_i}\right) + \sum_{j=1}^{N_{\text{syserr}}}\left(\frac{\epsilon_j}{\sigma_j}\right)^2 \qquad (1)$$

$$z_i = \alpha\cdot N_i^{\text{back}}\left(1+\sum_{j=1}^{N_{\text{syserr}}} f_i^j\frac{\epsilon_j}{\sigma_j}\right) + \beta\cdot N_i^{\text{sig}}\left(1+\sum_{j=1}^{N_{\text{syserr}}} f_i^j\frac{\epsilon_j}{\sigma_j}\right)$$

- Fit is performed for 2 parameters **α** (ATM norm) and **β** (signal norm)
- With **β** at 90CL can obtain lifetime

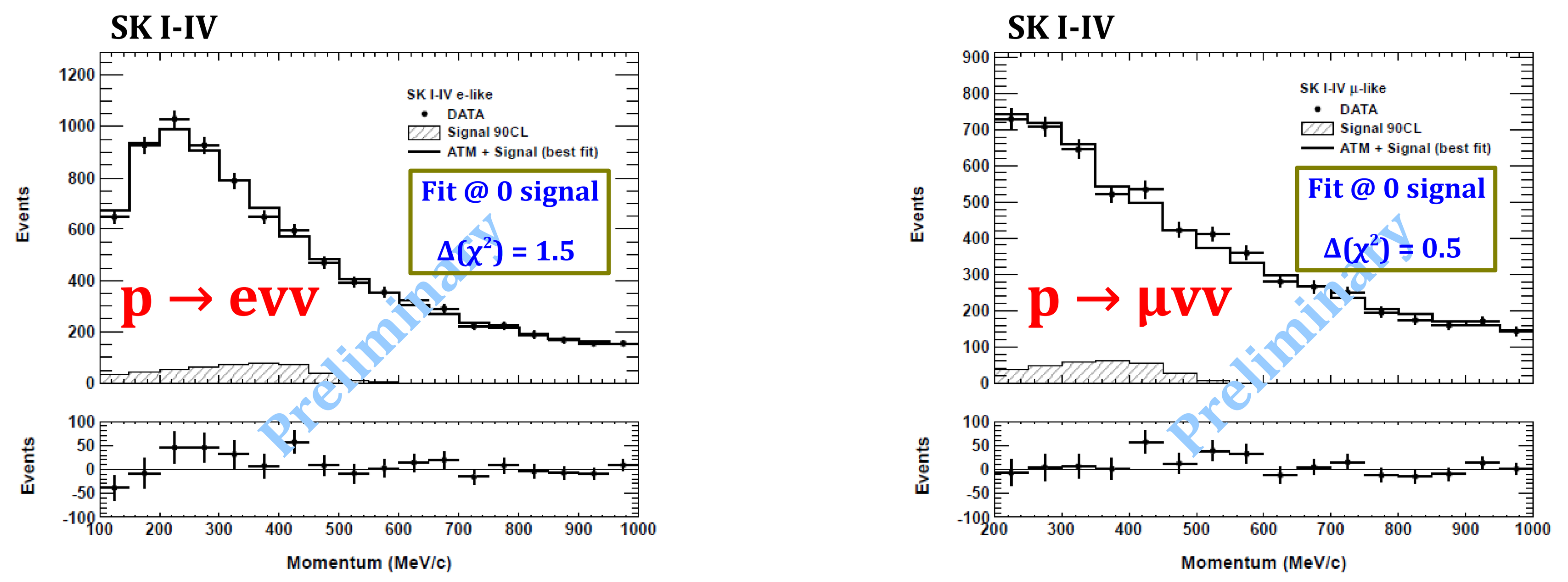
$$\tau_{90\text{CL}}/\mathcal{B} = \frac{\sum_{\text{sk}=\text{SK1}}^{\text{SK4}}\lambda_{\text{sk}}\cdot\epsilon_{\text{sk}}\cdot N^{\text{nucleons}}}{N_{90\text{CL}}} \qquad (2)$$

Analysis Spectrum & Fitting Results

- Flat phase space is used for signal simulation, an approach validified by comparing to charged lepton spectrum approximation [13] based on **μ → eνν̄** formalism
- **Event selection for decay modes:**
  - p → eνν : FCFV sub-GeV 1 ring e-like 0-decay electron events with 100 MeV < p(e) < 1000 MeV
  - p → μνν : FCFV sub-GeV 1 ring μ-like 1-decay electron events with 200 MeV < p(μ) < 1000 MeV

Fit is performed for e-like and μ-like momentum spectra

- Main background contribution originates from charged current CCQE *(~80%)* for both modes, from ν_e and ν_μ, with the other main contribution from pions, CC 1-π *(~15%)*
- 11 dominant systematics selected for both modes, obtained from 154 official SK oscillation analysis [14] systematic errors which affect analysis bins by more than 5%
- **Combined SK1-SK4 results** from the fit, with residuals and 90CL amount of signal

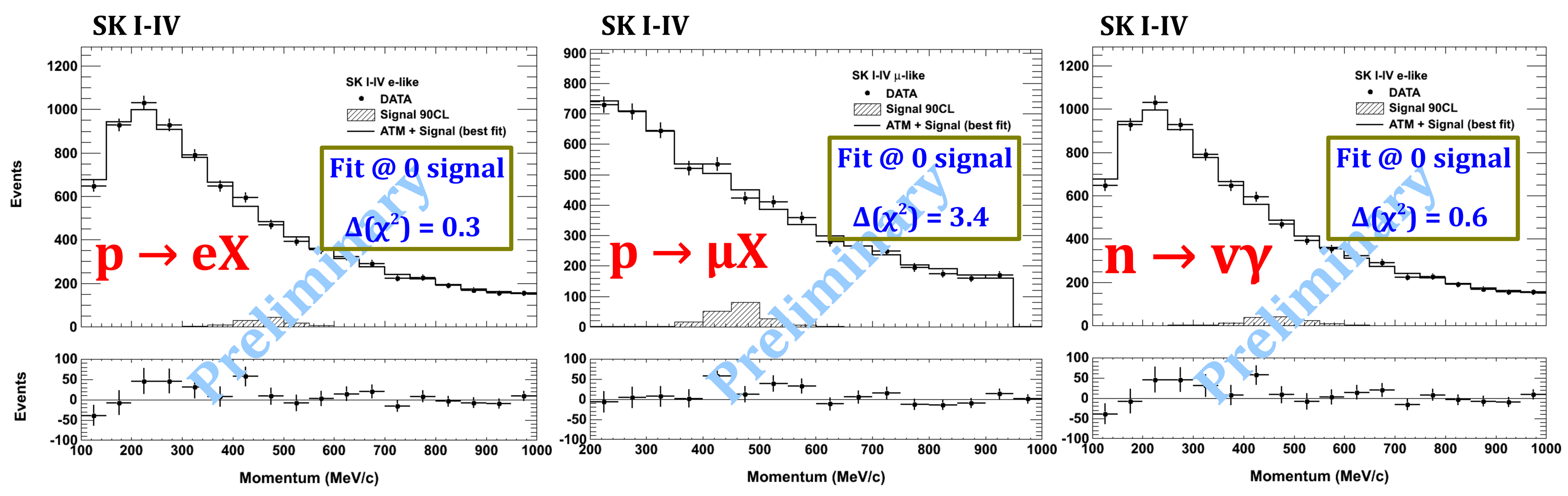


- Average efficiency of ~90% and ~70% for e-like and mu-like signal momenta
- Total SK1-4 exposure of ~273 kton years shows no significant signal excess
- Can set lifetime limits, strongly restricting parameter space of somes models [9]

	p → eνν	p → μνν
This analysis :	1.7 * 10^32 years	2.2 * 10^32 years
PDG 2013 [15]:	1.7 * 10^31 years	2.1 * 10^31 years

Other Novel Searches: $p \to eX$, $p \to \mu X$ and $n \to \nu\gamma$

- Important to study many modes besides most popular ones
- Use spectrum shape analysis technique already established in trilepton analysis
- Consider 2-body searches **p → eX** and **p → μX** where X is invisible, can't be fermion by spin conservation, can generate as neutrino in spin-independent Monte Carlo
- Previous analyses treat these as inclusive modes, assuming a specific model as SU(5) - not the case here, thus no official limits on these searches
- Some models [16] predict **n → νγ**, has similar signal signature to **p → eX**, also analyze
- The error analysis and fit is performed similarly to the trilepton mode scenario above
- The avrg. total efficiency is ~93%, ~84% and 94% for **p → eX, p → μX** and **n → νγ**
- **Combined SK1-SK4 results** from the fit, with residuals and 90CL amount of signal



- Non-observation of significant signal excess over background in these searches, allows us to set lower lifetime limits for analyzed modes

	p → eX	p → μX	n → νγ
This analysis :	7.9 * 10^32 years	4.1 * 10^32 years	5.5 * 10^32 years
PDG 2013 [15]:	–	–	2.8 * 10^31 years

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