Measuring Rare Kaon Decays with KOPIO: Summary of Workshop

2005 RHIC & AGS Users' Meeting
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Michael Sivertz

Observing $K_L \rightarrow \pi^0 \nu\nu$

"Experimentally, the problems are perhaps best represented by the statement that nobody has shown that a measurement of this decay is absolutely impossible"
F.J.Gilman, "CP violation in Rare K Decays", *Blois CP Violations* **1989:481-496**

Poor kinematic signature: 3-body decay.

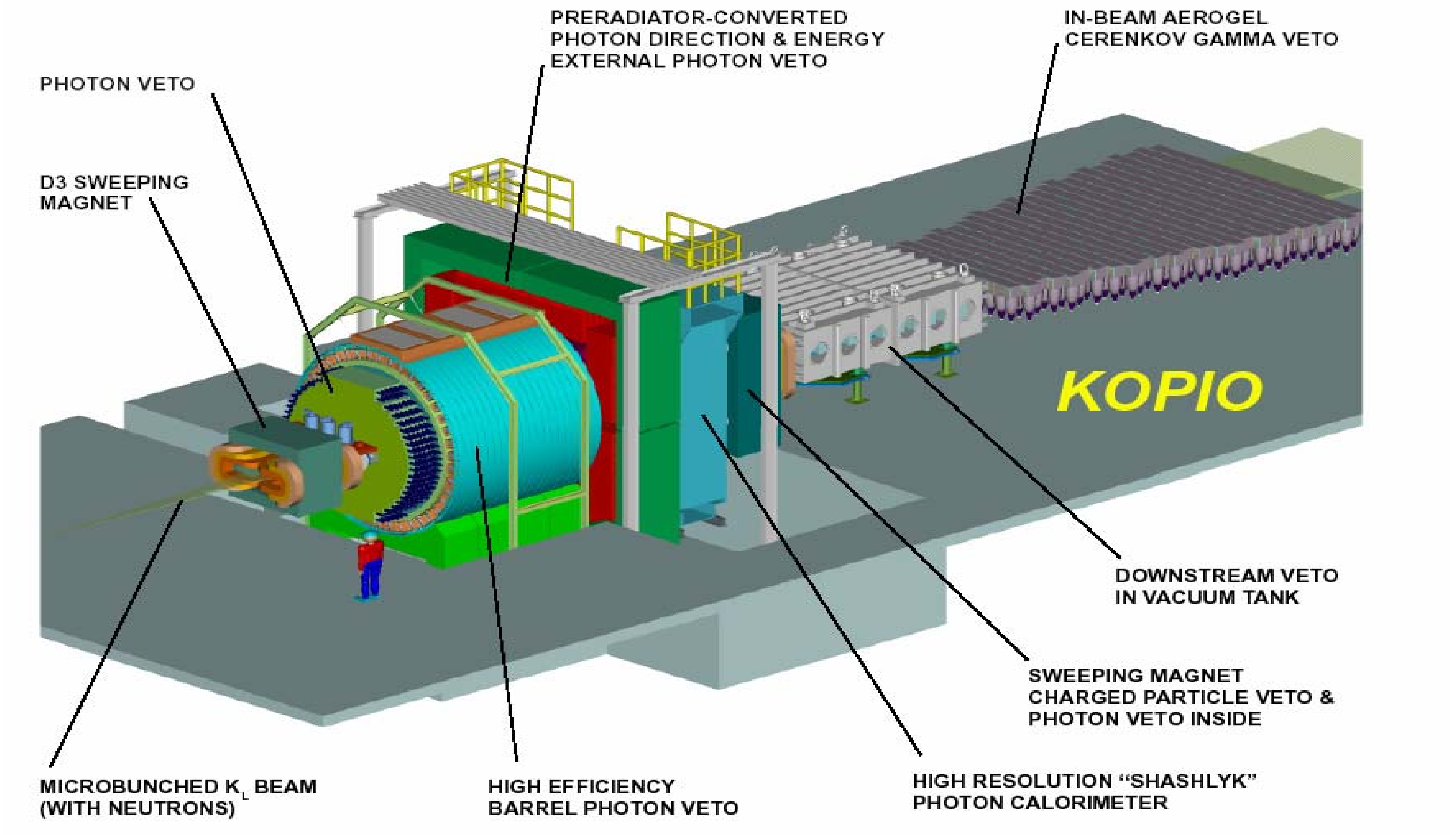
Neutral initial and final states.

Only outgoing $\pi^0 \rightarrow \gamma\gamma$ is observable.

SM prediction $Br(K_L \rightarrow \pi^0 \nu\nu) = 3x10^{-11}$ with a primary background decay $K_L \rightarrow \pi^0 \pi^0$ which needs a suppression of $\sim 10^8$.

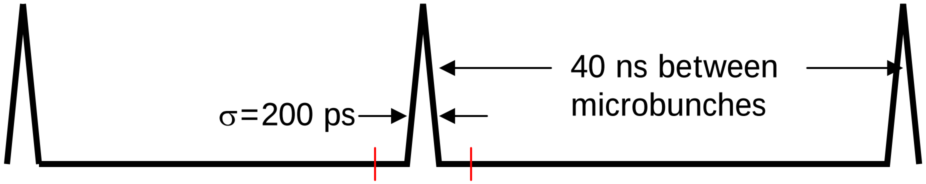
Large window of opportunity for discovering new physics!

KOPIO Detector

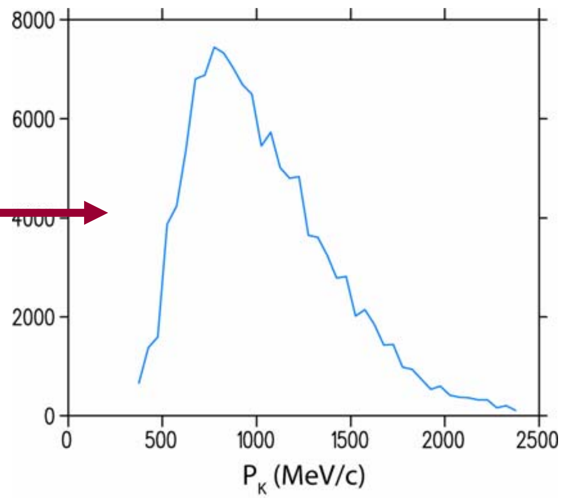


Need AGS to provide

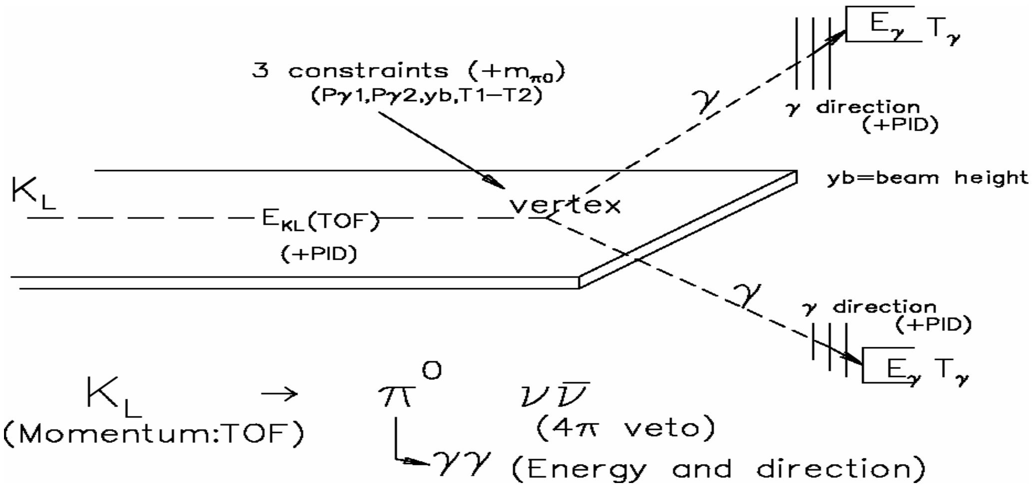
- **Proton Beam**
  - **100TP/spill (upgraded from present 70TP)**
  - **~5s spill, 2.3s interspill**
  - **Microbunching**
    - **Extract debunched beam resonantly between empty buckets**
    - **25MHz frequency**
    - **200ps bunch width**
    - **10^{-3} interbunch extinction**



- **Kaon Beam (Pancake)**
  - **42.5° take-off angle**
  - **Soft momentum spectrum**
    - **0.5-1.5 GeV/c**
  - **3×10^8 K_L/spill**
    - **8% decay in decay region**
  - **10 GHz neutrons**



KOPIO Technique

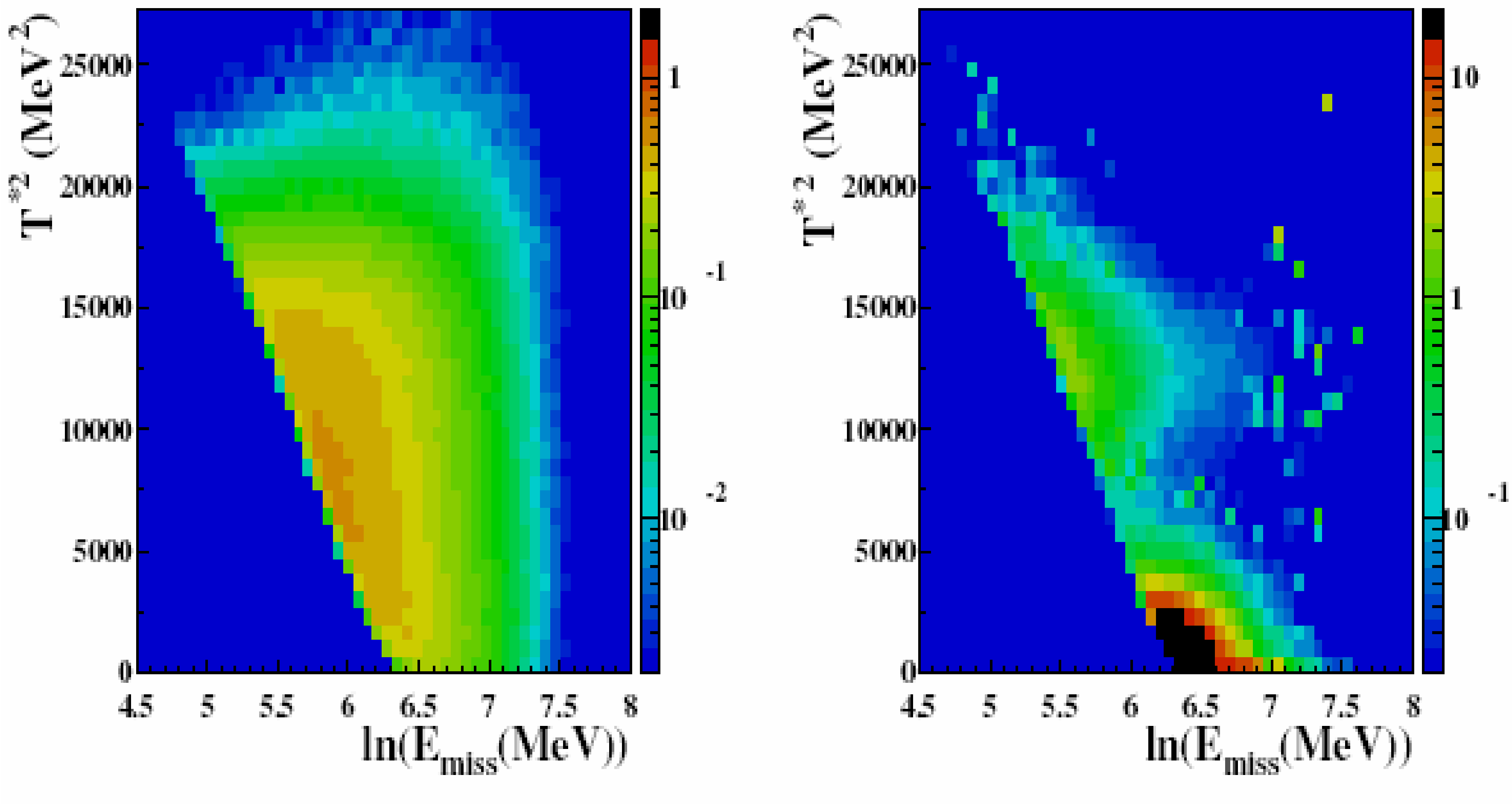


- **Measure everything! (energy, position, angle, time)**
- **Eliminate extra charged particles and extra photons**
  - **KOPIO Veto inefficiencies: $\pi^0 < 10^{-8}$; $\pi^+ < 2x10^{-5}$; $\pi^- < 1.2x10^{-4}$**
- **Suppress backgrounds**
  - **Predict backgrounds *from data*:dual cuts**
  - **Use "blind" analysis techniques**
  - **Test predictions "outside the box"**
- **Weight candidate events with S/N likelihood function**

Kinematic Separation of Signal &Backgrounds

Pion kinetic energy squared (T^{*2}) vs Ln(Missing Energy)

Signal **Backgrounds**



Experiments Seeking $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

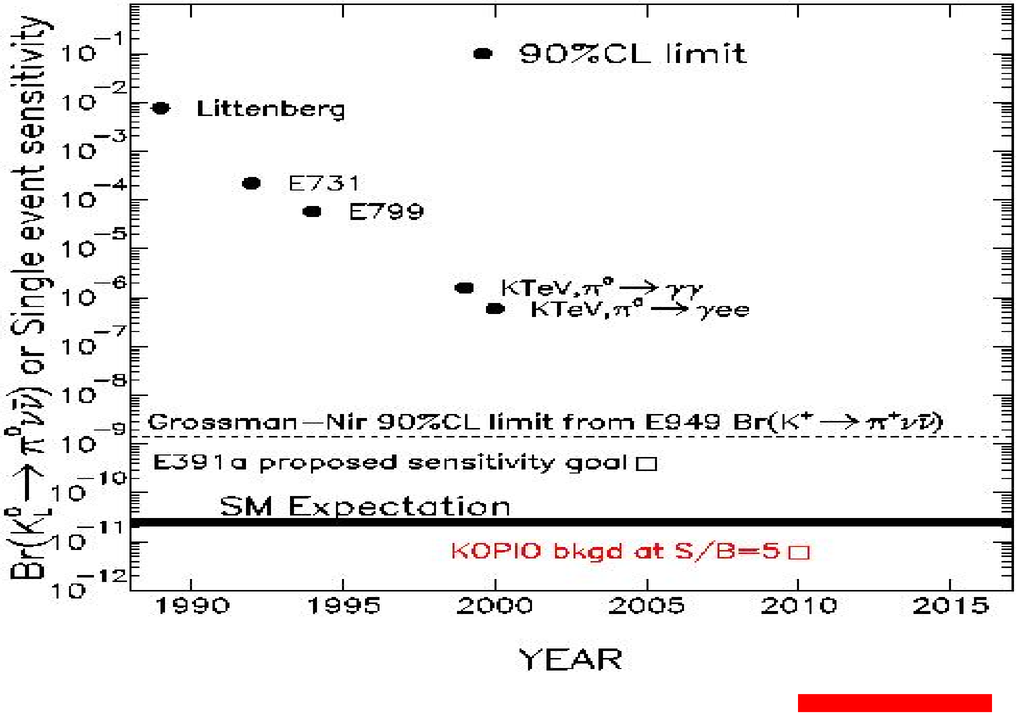
Grossman-Nir Limit $B(K_L \rightarrow \pi^0 \nu \nu) < 1.4 \times 10^{-9}$

(based on $K^+ \rightarrow \pi^+ \nu \nu$ and isospin)

Experimental Searches for $K_L \rightarrow \pi^0 \nu \nu$

- KTeV (FNAL): $B(K_L \rightarrow \pi^0 \nu\nu) < 5.9 \times 10^{-7}$ (90% CL)
- E391a (KEK): Expects sensitivity ~few x 10^{-9}
  - $\Rightarrow$ J-PARC LOI submitted, proposal anticipated
- KOPIO (BNL):
  - proposed single event sensitivity $< 10^{-12}$
  - Discovery (5σ) for $B(K_L \rightarrow \pi^0 \nu\nu) > 5 \times 10^{-11}$ or $< 1.8 \times 10^{-11}$
  - If no new physics, Standard Model gives ~150 events
    - Rule out BRs outside of $(1 \pm 0.24) BR_{SM}$ @ 95% CL
    - Bound non-SM operators (B-system can't access)

Experimental Search for $K_L \rightarrow \pi^0 \nu\nu$



$K_L \to \pi^0 \nu\nu$ Beyond the Standard Model

$K_L \to \pi^0 \nu\nu$ is unique because

- it retains its clean connection to short distance parameters BSM
  - NOT the case for e.g. $B \to J/\psi K_S$ where new physics can be seen but not interpreted.
- it probes the flavor structure of any new physics
- a 10% deviation in B-physics translates into an $\mathcal{O}(1)$ deviation in this decay.
- even if result agrees with B-physics prediction, it gives unique constraint on new physics operators
- a 10% measurement can probe new physics mass scales to > 1000 TeV!

Roles of $K \to \pi\nu\bar{\nu}$ Measurements in Flavor Physics

New flavor physics in the s-d sector may be very different from that in the b sector:

* *If B-physics is consistent with the SM:*

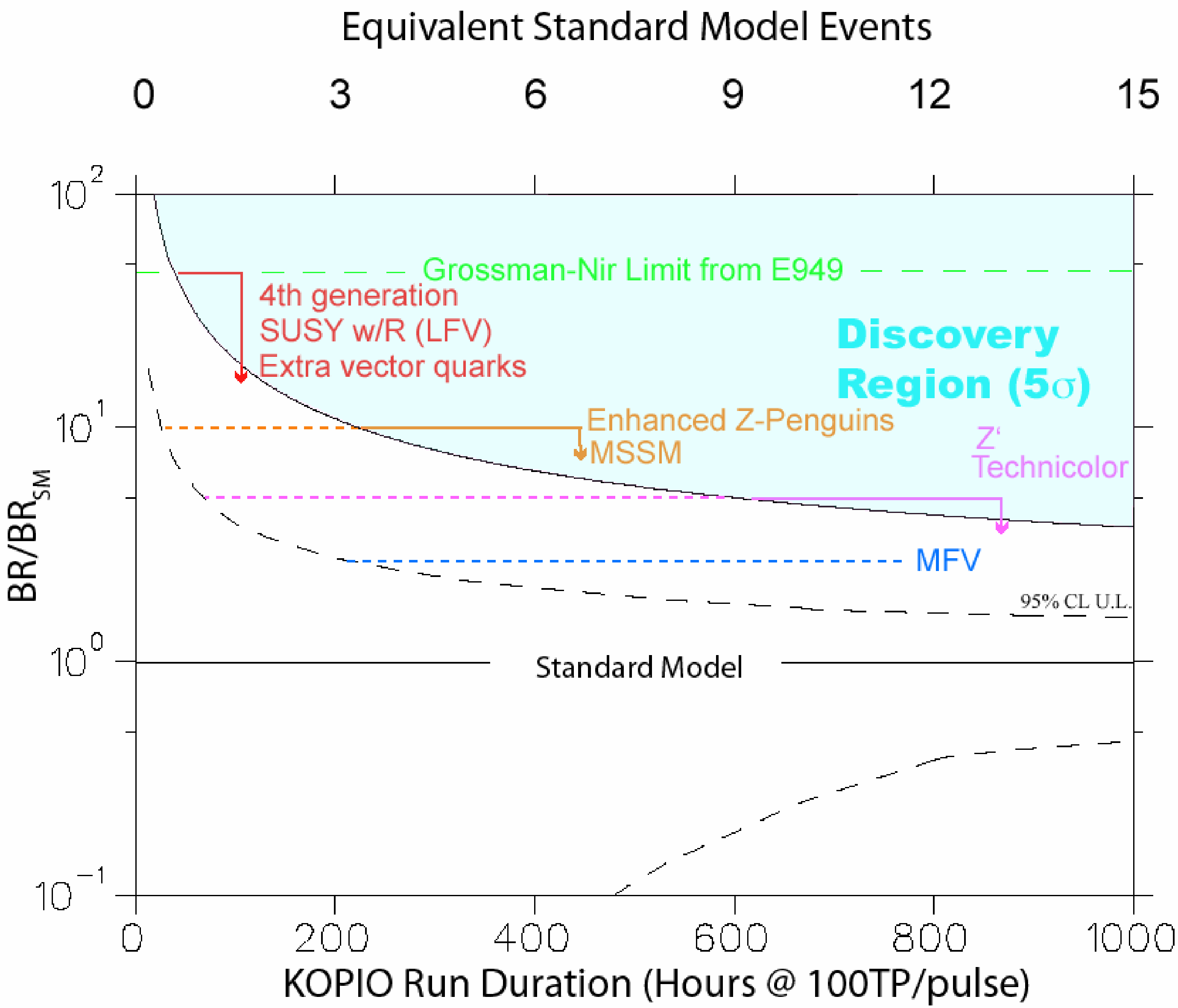
New physics could be revealed $K \to \pi\nu\bar{\nu}$.

* *If deviations from the SM are indicated :*

$K \to \pi\nu\bar{\nu}$ would add crucial additional information; the complexity of the flavor sector beyond the SM is foreseen in many models.

Results from $K \to \pi\nu\bar{\nu}$ will be needed to interpret non-SM physics discoveries at BABAR, BELLE, CDF/D0, and the LHC.

New Physics Potential - Early



Additional Measurements

Search for Neutral long-lived (invisible) particles: X

- e.g. sGoldstino $K_L \rightarrow \pi^o X_S$, $K_L \rightarrow \pi^o \pi^o X_P$
- Limits <5.9x10-11 (E949) <9x10-6 ISTRA

$K_L \rightarrow \pi^o \gamma\gamma$ (10^{-7} KTEV) $K_L \rightarrow \pi^o \pi^o \gamma$ (5.6×10^{-6} NA31)

– χPT predictions inconsistent (10^{-8} or 7×10^{-11})

Radiative Decays: $K_L \rightarrow \gamma\gamma$, $K_L \rightarrow \gamma\gamma^*$ $K_L \rightarrow \gamma^*\gamma^*$ $K_L \rightarrow \gamma\gamma\gamma$

- Improve on $\gamma\gamma$, γe^+e^-, $\gamma\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$, $e^+e^-e^+e^-$, $\gamma\gamma\gamma$

$\pi^o - \pi^o$ scattering length from $K_L \rightarrow \pi^o\pi^o\pi^o$ decays

K_L beta decay: Predictions for $K_L \rightarrow K e \nu$ are $\sim 10^{-8}$.

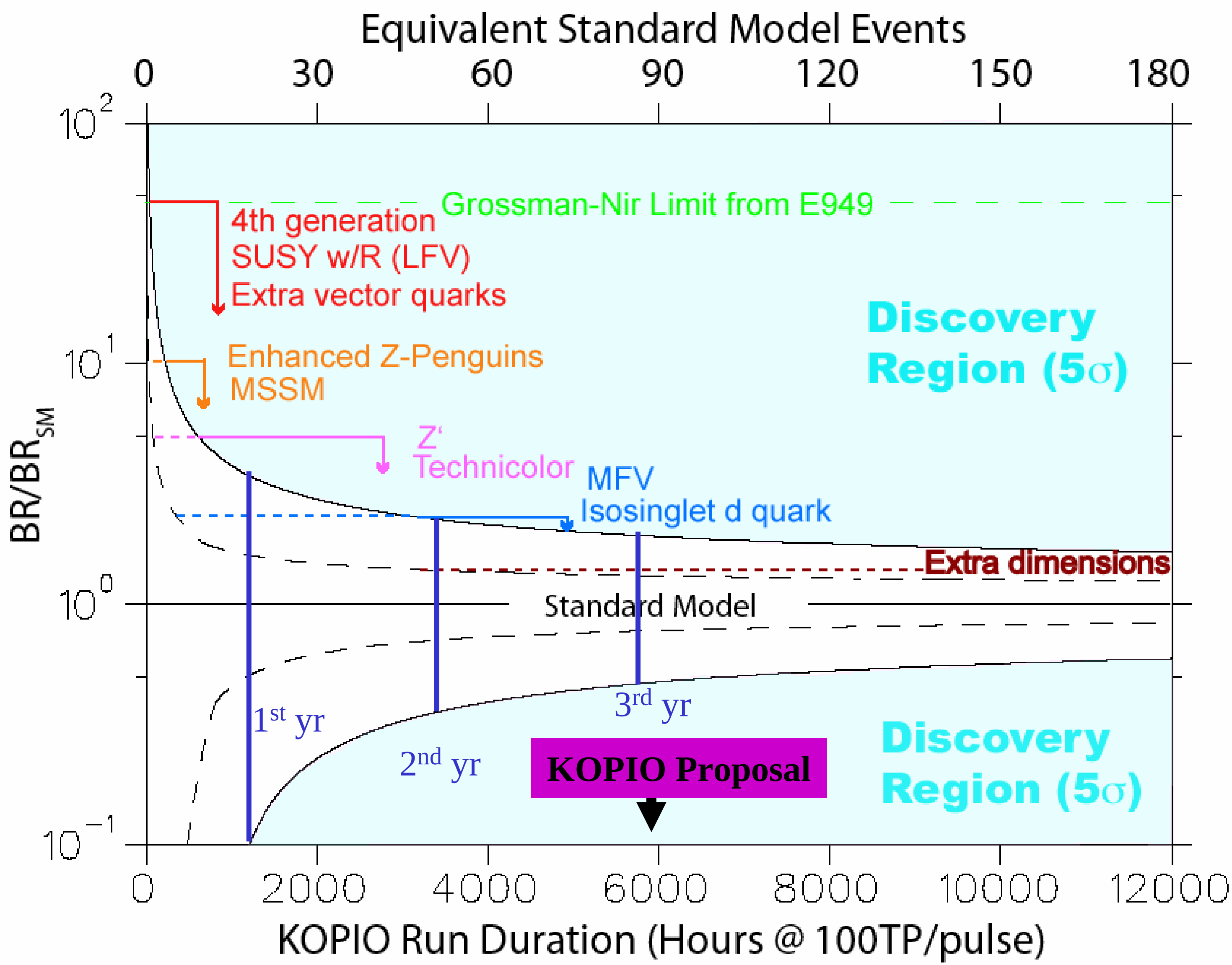
- Proportional to Δm^5 where Δm is the K_L-K^+ mass difference.

Tagged π^o decays: $\pi^o \rightarrow e^+ e^-$ $(6.2 \pm 0.5) \times 10^{-8}$

$\pi^o \rightarrow \nu \ \nu$ $< 1.7 \times 10^{-6}$

K_L Lifetime: Measured to 1% currently.

Discovering/Constraining New Physics



K_L modes simulated for bkgnd studies

Largest back-grounds

Name	Final state	Branching fraction	$\mathcal{B}/\mathcal{B}(K_L^0 \to \pi^0 \nu\bar{\nu})$
Kpnn	$\pi^0\nu\bar{\nu}$	0.3000×10^{-10}	1.000
Kp2	$\pi^0\pi^0$	0.9320×10^{-3}	0.31×10^8
Kcp2	$\pi^+\pi^-$	0.2090×10^{-2}	0.70×10^8
Kgg	$\gamma\gamma$	0.5900×10^{-3}	0.20×10^8
Kp3	$\pi^0\pi^0\pi^0$	0.2105	0.70×10^{10}
Kcp3	$\pi^+\pi^-\pi^0$	0.1259	0.42×10^{10}
Ke3	$\pi^\pm e^\mp \nu$	0.3881	0.13×10^{11}
Km3	$\pi^\pm \mu^\mp \nu$	0.2719	0.91×10^{10}
Ke3g	$\pi^\pm e^\mp \nu\gamma$	0.3530×10^{-2}	0.12×10^9
Km3g	$\pi^\pm \mu^\mp \nu\gamma$	0.5700×10^{-3}	0.19×10^8
Kpgg	$\pi^0\gamma\gamma$	0.1410×10^{-5}	0.47×10^5
Ke4	$\pi^0\pi^\pm e^\mp \nu$	0.5180×10^{-4}	0.17×10^7
Km4	$\pi^0\pi^\pm \mu^\mp \nu$	0.1400×10^{-4}	0.47×10^6
Ke2g	$e^+e^-\gamma$	0.1000×10^{-4}	0.33×10^6
Km2g	$\mu^+\mu^-\gamma$	0.3590×10^{-6}	0.12×10^5

Other Backgrounds

- K^+ contamination of beam: <0.001 of signal rate
- $K_L \to K^+ e^- \nu$, $K^- e^+ \nu$: ~ 0.001 of signal rate
- $nN \to \pi^0 N$: negligible production from residual gas in decay volume if pressure<10^{-6} Torr. Requirements on reconstructed $Z_V(K_L)$ suppress rate from US wall to <0.01 of signal rate
- $\bar{n}$: far smaller than neutron background
- Hyperons: <10^{-5} of signal rate
- Fake photons < 0.05 of signal rate assuming ~$10^{-3} \times 10^{-3}$ suppression from (vetoing) × (γ/n discrimination)
- Two K_L giving single candidate: negligible due to vetoes
- $(K_L \to \pi^\pm X) \times (\pi^\pm \to \pi^0 e^\pm \nu)$: ~0.01 of signal rate
- $K_S \to \pi^0 \pi^0$: ~4 × 10^{-4} of $K_L \to \pi^0 \pi^0$ background rate

KOPIO Operations Plan

- **2010 Test Run – partial detector**
- **2011 Engineering Run – full detector**
  - **“Discovery phase”**
  - **Sensitivity goal: $\sim 10^{-10}$**
- **2012-16 Data Accumulation**
  - **$\sim 3 \times 10^{20}$ protons delivered in 5700 hours**

Summary & Outlook

Excellent discovery potential for non-SM physics

- Unique connection with underlying parameters
- Extremely rapid progress in first part of KOPIO run
- 5σ discovery if BR $0.6 < BR_{SM}$ or $> 1.7\ BR_{SM}$

If find Br ~ Br_{SM}

- Likelihood analysis using ~150 evts
- Precision on BR: ±14%; Im λ_t: ±7%
- Rule out non-SM effects outside $(1 \pm 0.24) \times BR_{SM}$
    - Unique constraint on some BSM operators