$K \to \pi \nu \bar{\nu}$ Decays: Rare Opportunities

Douglas Bryman

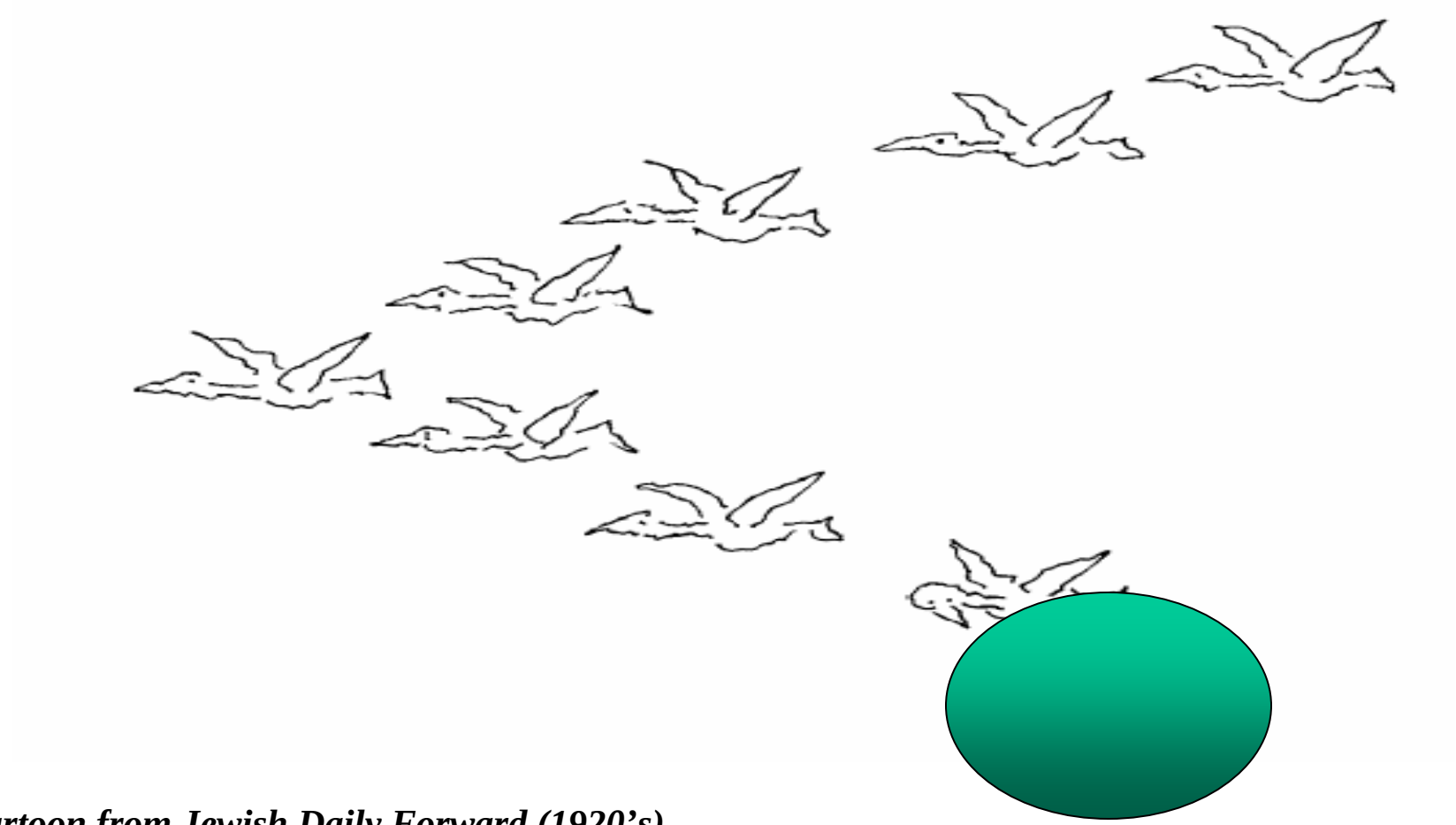
University of British Columbia



Standard Model
Not likely the whole story

- ***Cosmological issues***: inflation, dark matter, dark energy, matter anti-matter asymmetry
- ***Theoretical issues***: gravity, neutrino mass, flavor problem, hierarchy problem,…

Seeking Answers with Rare K Decays



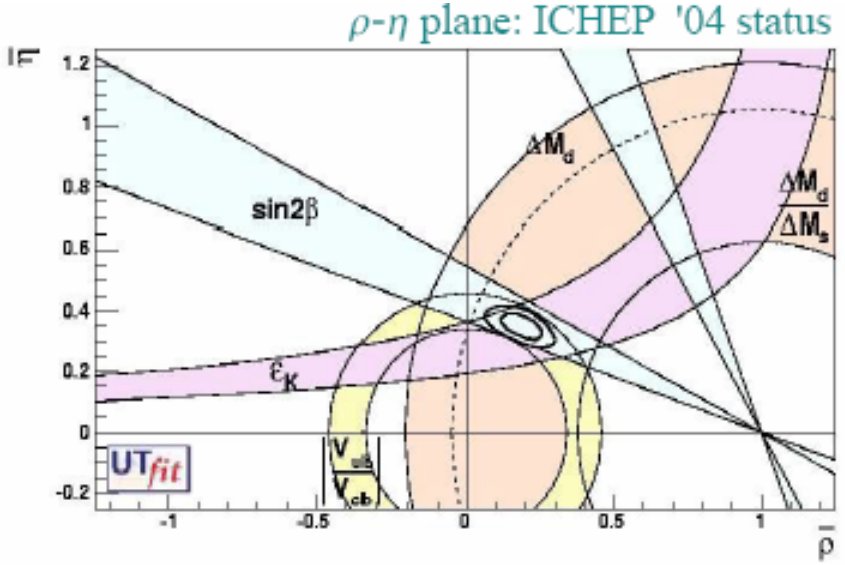
Cartoon from Jewish Daily Forward (1920's)

SM works well at the Electroweak Scale

$$L_{SM} = L_{Gauge} + L_{Higgs}(\phi_i, A_i, \psi_i, Y, v)$$

Flavor degeneracy broken by Yukawa couplings
CKM quark mixing matrix:

$$V_{CKM} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

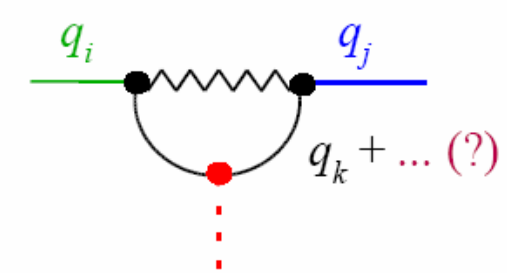


Rare Decays play key roles for SM parameters.

***Even more important*:**
Probing the flavor structure of 'new physics'.

Special Case : $K_L^0 \to \pi^0 \nu\bar{\nu}$

$q_i \to q_j + \nu\bar{\nu}$



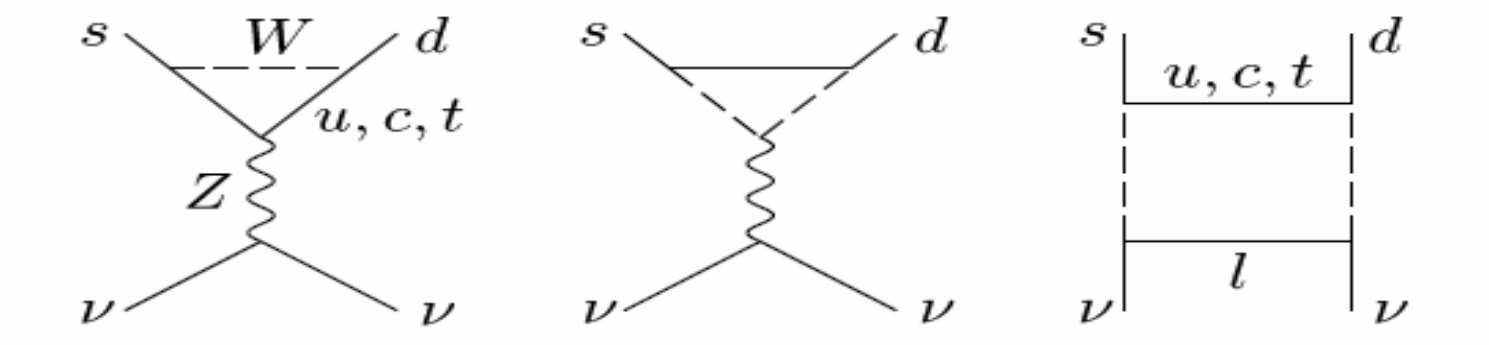
SM

- **No tree level contributions**
- **Suppression by CKM hierarchy**
- **Dominated by short distance physics**
- **Precise determination of CKM parameters**
- **Dominated by direct CP violation in amplitude**
  (K-K mixing effects negligible)

BSM

- ***Still dominated by short distance physics!***
- ***Still dominated by direct CP violation in amplitude.***
- ***Unique access to new CP-violating phases***

$K_L^0 \to \pi^0 \nu\bar{\nu}$ in the SM



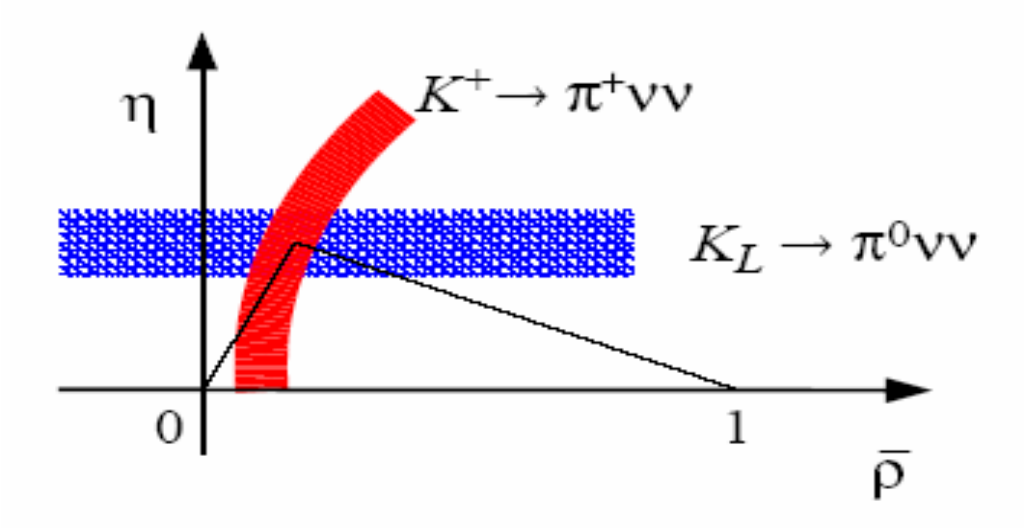
Standard Model (*Buras*): $\mathrm{Im}\,\lambda_t = \mathrm{Im} V_{ts}^* V_{td} = \eta A^2 \lambda^5$

$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) = 1.8\,x10^{-10} \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

$$\sim 4.1\,x10^{-10}\, A^4 \eta^2 = 3.0 \pm 0.6\,x10^{-11}$$

$$B(K^+ \to \pi^+ \nu\bar{\nu}) \sim 1.0\,x10^{-10}\, A^4 \left[\eta^2 + (\rho_0 - \rho)^2 \right] = 7.8 \pm 1.2\,x10^{-11}$$

Golden Relation: $\sin(2\beta)_{\psi K_S} = \sin(2\beta)_{K\to\pi\nu\bar{\nu}}$



New Physics- *Model Independent Description*

(Buras, Isidori, et al.)

L_{SM} ~ Renormalizable part of an effective F. T. :

$$L_{EFT} = L_{SM} + \Sigma \frac{\lambda}{\Lambda^2}$$

Main Issues:

- Size of cutoff scale Λ [TeV]
- Symmetries governing new heavy degrees of freedom

Rare K Decays can probe the flavor structure of the new physics at very high mass scales.

Encoding new physics as

$$H_{EFF}(m_W^2) = \frac{G_F^2 m_W^2}{2\pi^2} X\left(\frac{m_t^2}{m_W^2}\right) \mathrm{Im}\,\lambda_t\, Q_{sd}^{\nu\nu} + \ldots + \left[\frac{\lambda_{SD}}{\Lambda^2}\right]$$

where $\lambda_t = V_{ts}^* V_{td}$, and

$$Q_{sd}^{\nu\nu} = \bar{s}\gamma^\mu(1-\gamma_5)d\,\gamma_\mu(1-\gamma_5)\nu$$

For measurement precision $P = \dfrac{\sigma_B}{B_{SM}(K_L^0 \to \pi^0 \nu\bar{\nu})}$:

$$\frac{\Lambda}{\sqrt{\mathrm{Im}\,\lambda_{sd}}} > \frac{405}{\sqrt{P}}\ \mathrm{TeV}\ \ (90\%\mathrm{C.L.})$$

$$\xrightarrow{P=0.1} 1280\,\mathrm{TeV}!$$

Most pessimistic new physics scenario:

"Minimal Flavor Violation"

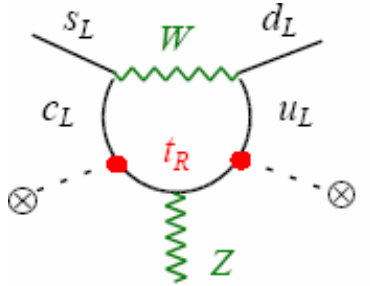
(Examples: Low energy SUSY, univ. extra dimensions,....) $\Lambda \sim$ TeV

Breaking of flavor symmetry occurs at very high scales
- mediated at low energies by terms proportional to SM Yukawa couplings.

Only small deviations likely (at LHC or in rare decays)

But new CP-violating phases are naturally present.

$K_L^0 \to \pi^0 \nu\bar{\nu}$ still sensitive O(50%) whereas previously clean SM observables (e.g. asymmetries in non-leptonic B decays) are no longer clean or not generally sensitive to new physics in decay amplitudes.

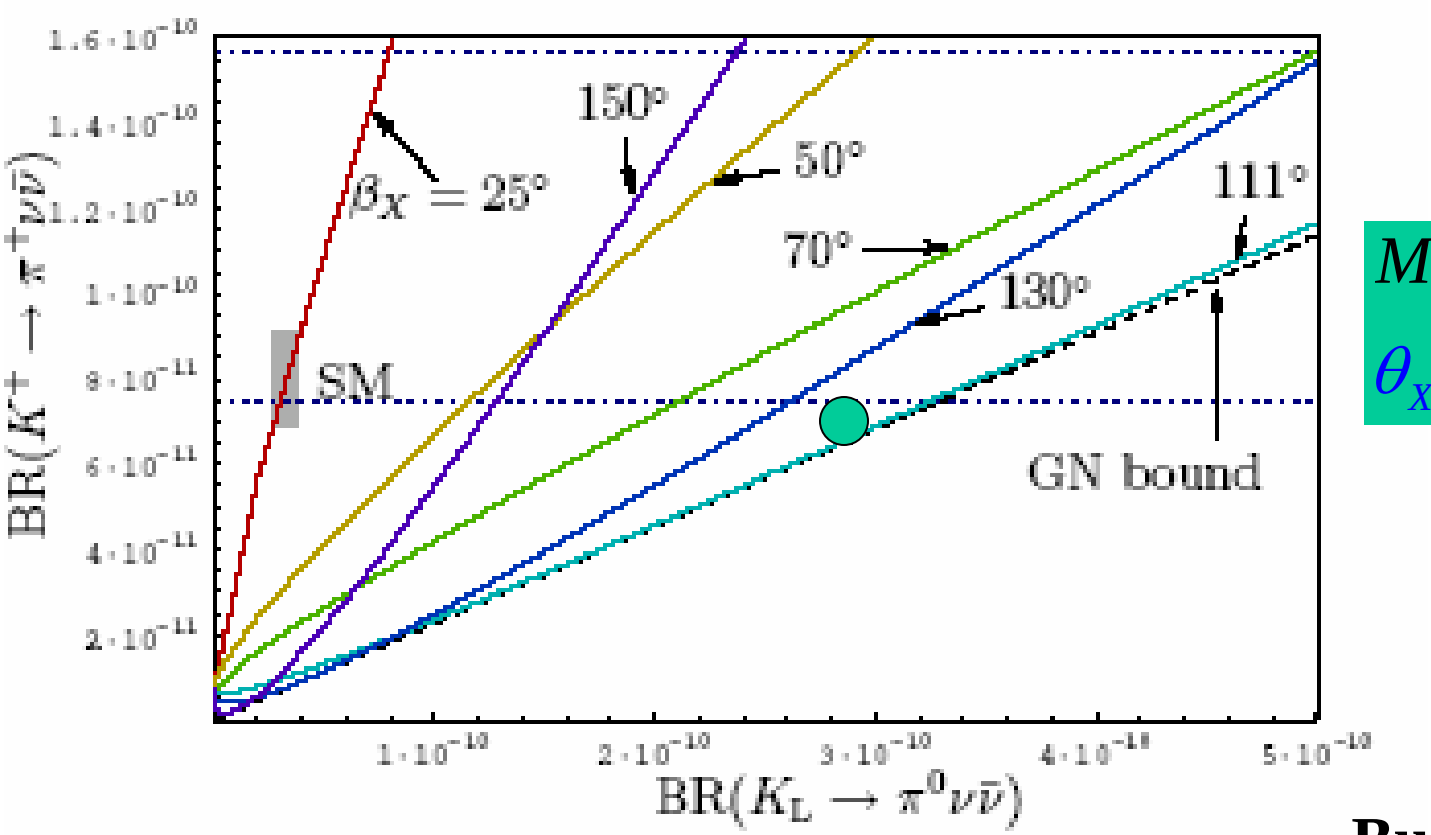


10% measurement of $K_L^0 \to \pi^0 \nu\bar{\nu}$ probes EW-Yukawa structure at the 5% level -- only a high luminosity linear collider could do better. [G. Isidori]

New CP-violating Phase θ_X : $\beta_X = \beta - \theta_X$

$$\frac{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})}{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{SM}} = \left|\frac{X}{X_{SM}}\right|^2 \left[\frac{\sin(\beta - \theta_X)}{\sin(\beta)}\right]^2, \qquad X = |X| e^{i\theta_X}$$

$B(K^+ \to \pi^+ \nu\bar{\nu})$ vs. $B(K_L^0 \to \pi^0 \nu\bar{\nu})$

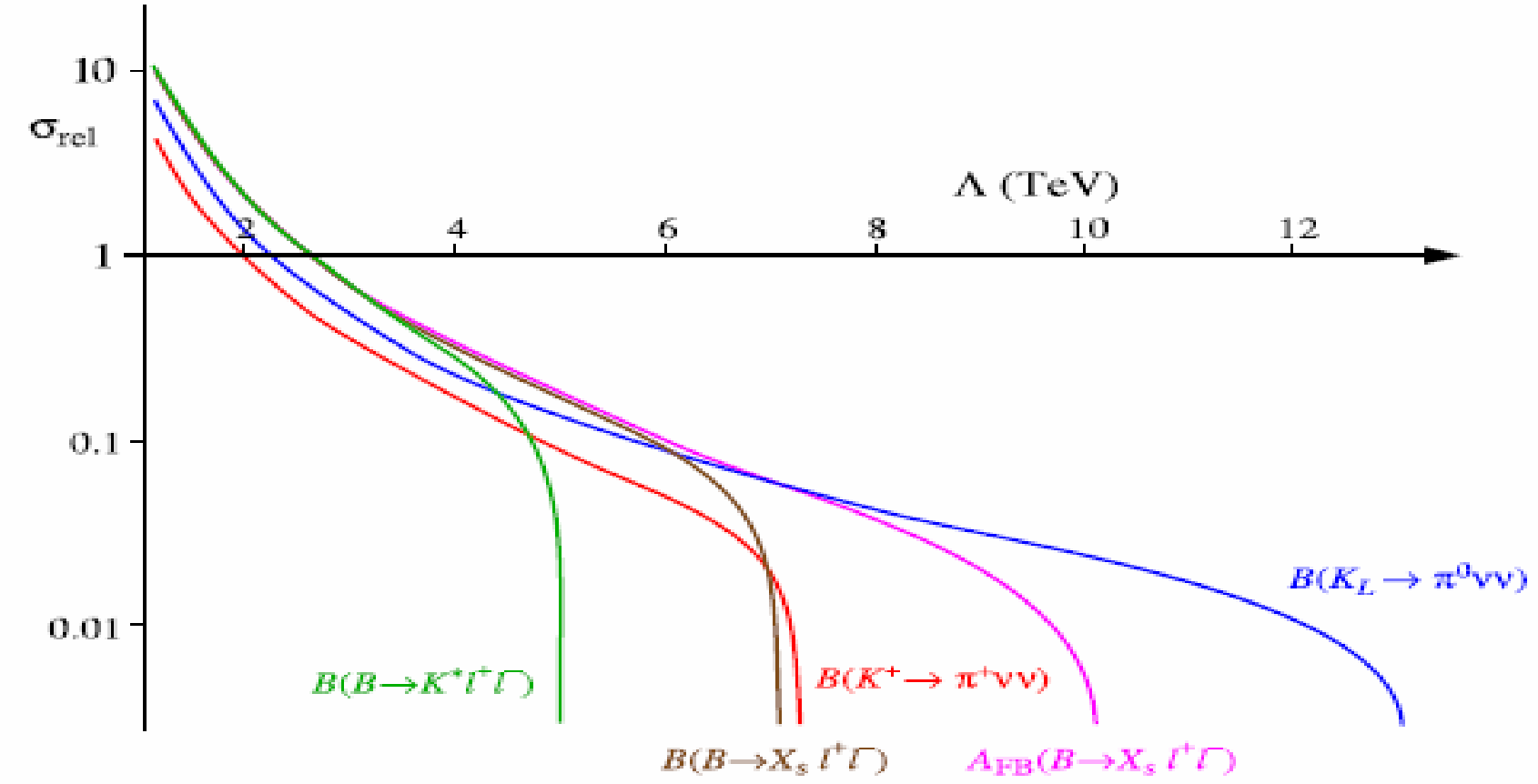


MFV example

$\theta_X = -90^o$

Buras et al. 2004

Comparative Sensitivity to New Physics in MFV Scenario



D'Ambrosio et al. 2002

New Physics: 1-10 TeV Scale

Example: MSSM with generic flavor couplings

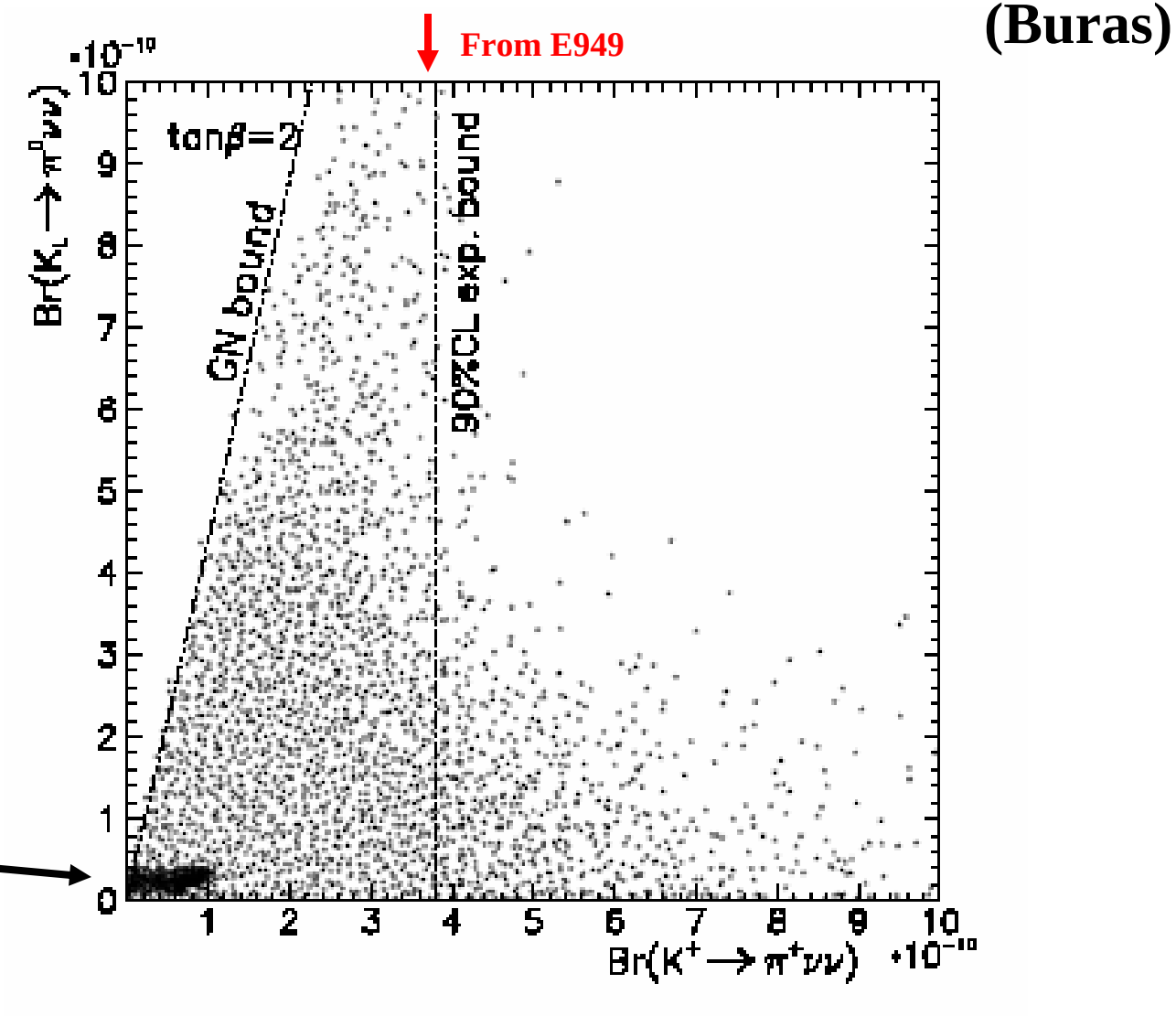
Buras et al. Hep-ph/0408142

- **Challenged by precise SM results in B physics**
- ***But, large portion of the parameter space unexplored***
- ***New sources of CP violation possible***
- **Discovery at LHC?: masses, dominant couplings**
- ***Rare decays*: New Effects of CP violation, flavor mixing**

Scan of MSSM Models

$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) \; vs. \; B(K^+ \to \pi^+ \nu\bar{\nu})$$

(Buras)



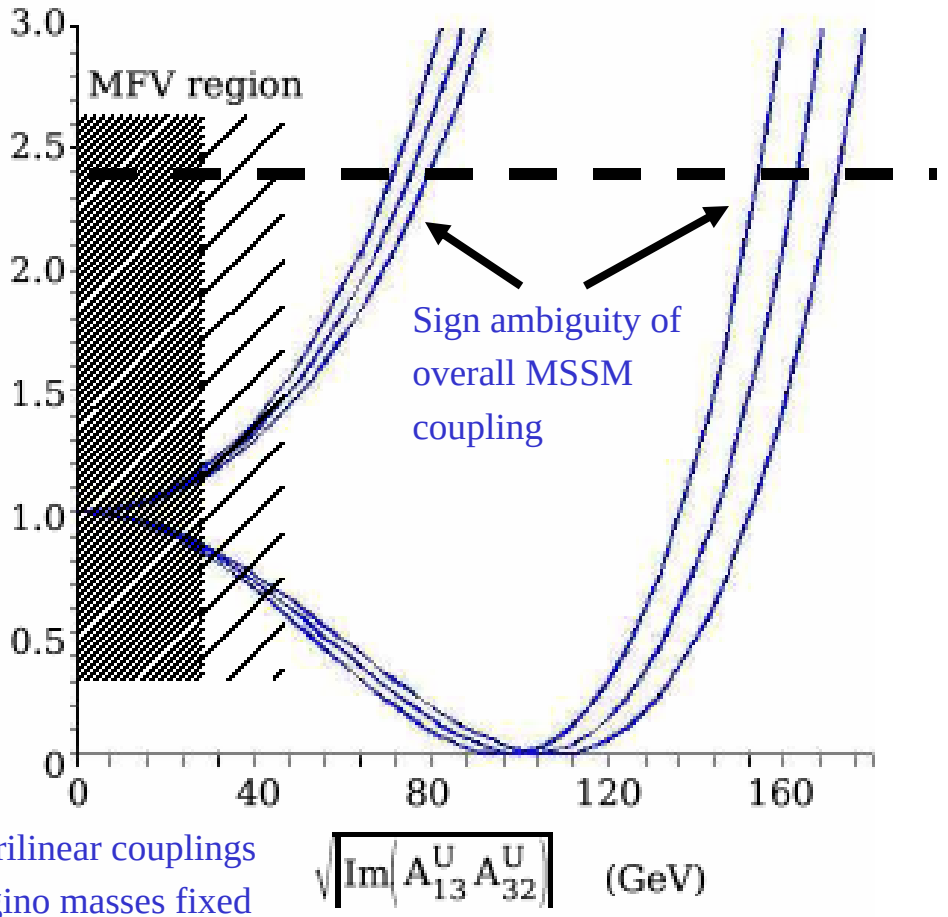
MSSM Example -- Isidori et al. (to be pub.)

squark and chargino masses ($\pm 5\%$)

$\tilde{m}_L = 500\,GeV \quad \tilde{m}_R = 300\,GeV$

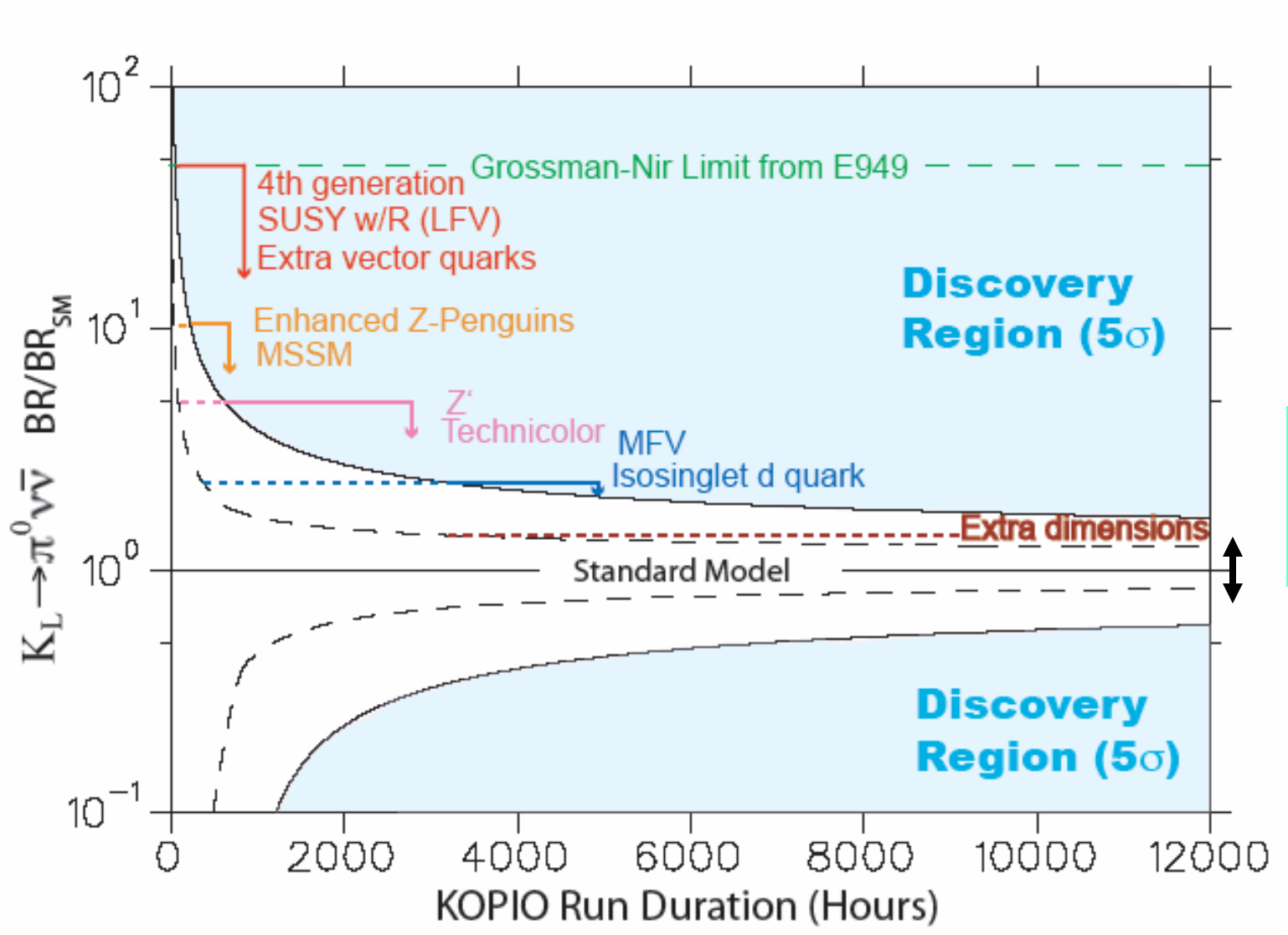
$\tilde{m}_{\chi^\pm} = 200\,GeV$

$$\frac{B(K_L^0 \to \pi^0 \nu\bar{\nu})}{B_{SM}}$$



Soft breaking trilinear couplings
squark & chargino masses fixed

Constraining New Physics with $K_L^0 \to \pi^0 \nu\bar{\nu}$



±10%
Measurement of
$B_{SM}(K_L^0 \to \pi^0 \nu\bar{\nu})$

Theory - Summary

- $K_L^0 \to \pi^0 \nu\bar{\nu}$ (and $K^+ \to \pi^+ \nu\bar{\nu}$) – highly suppressed in SM and most of its extensions → opportunity for new physics.
- Most precisely calculated FCNC processes involving quarks in SM and in its extensions.
- Unique, clean access to the CP-violating and flavor breaking structure of new physics -- access to short distance effects.
- Even if SM holds at high precision, access to very high mass scales - complementary to highest energy colliders.

Overview of Rare Kaon Decay Experiments

State of the art: single event sensitivity, 10^{-12}

Exotic Searches	$K_L^0 \longrightarrow \mu\, e$ *LFV* $K^+ \longrightarrow \pi^+\, f$ *"Axions".*	**<4.7 10^{-12}**
SM Parameters and BSM Physics	$K_L^0 \longrightarrow \mu^+\, \mu^-$ $\lvert V_{td}\rvert$ $K^+ \longrightarrow \pi^+\, \nu\bar{\nu}$ $\lvert V_{td}\rvert$ $K_L^0 \longrightarrow \pi^0\, e^+\, e^-$ *CP* violation $K_L^0 \longrightarrow \pi^0\, \nu\bar{\nu}$ *CP* violation	**10^{-8}: 6200 events** **10^{-10}: 3events**
Low Energy QCD *Chiral Perturbation Theory*	$K_L^0 \to e^+e^-$ $K_L^0 \to \gamma\, l^+\, l^-$ $l = e, \mu$ $K^+ \to \pi^+\, l^+\, l^-$ *...Radiative decays*	**10^{-11}: 4 events**

Experiments Seeking $K^+ \to \pi^+ \nu\bar{\nu}$

- BNL E949

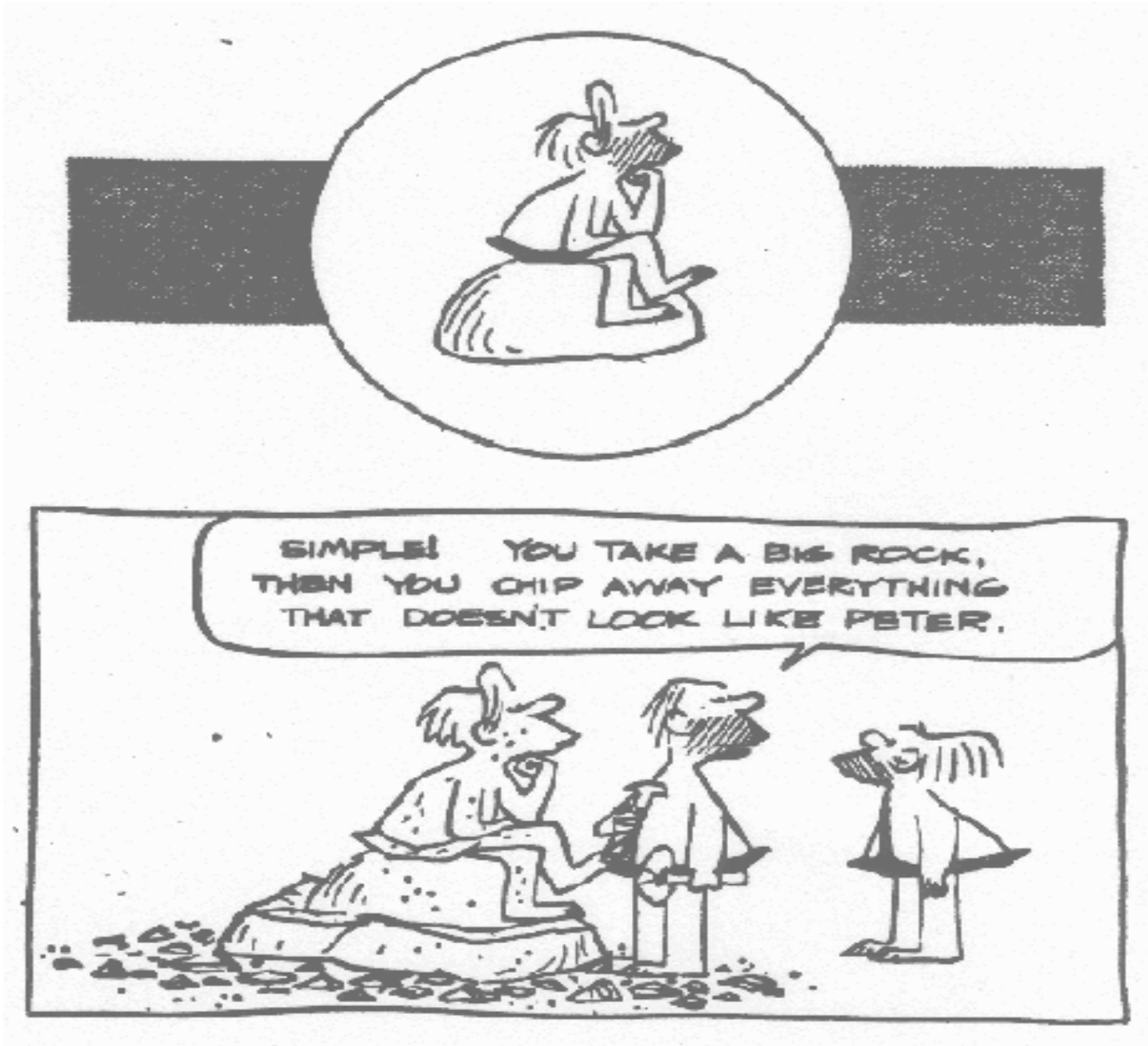
$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.47 \pm^{1.30}_{0.89} \; x\, 10^{-10}$$

- *LOIs*: New Techniques

The Secrets of Rare Decay Experiments



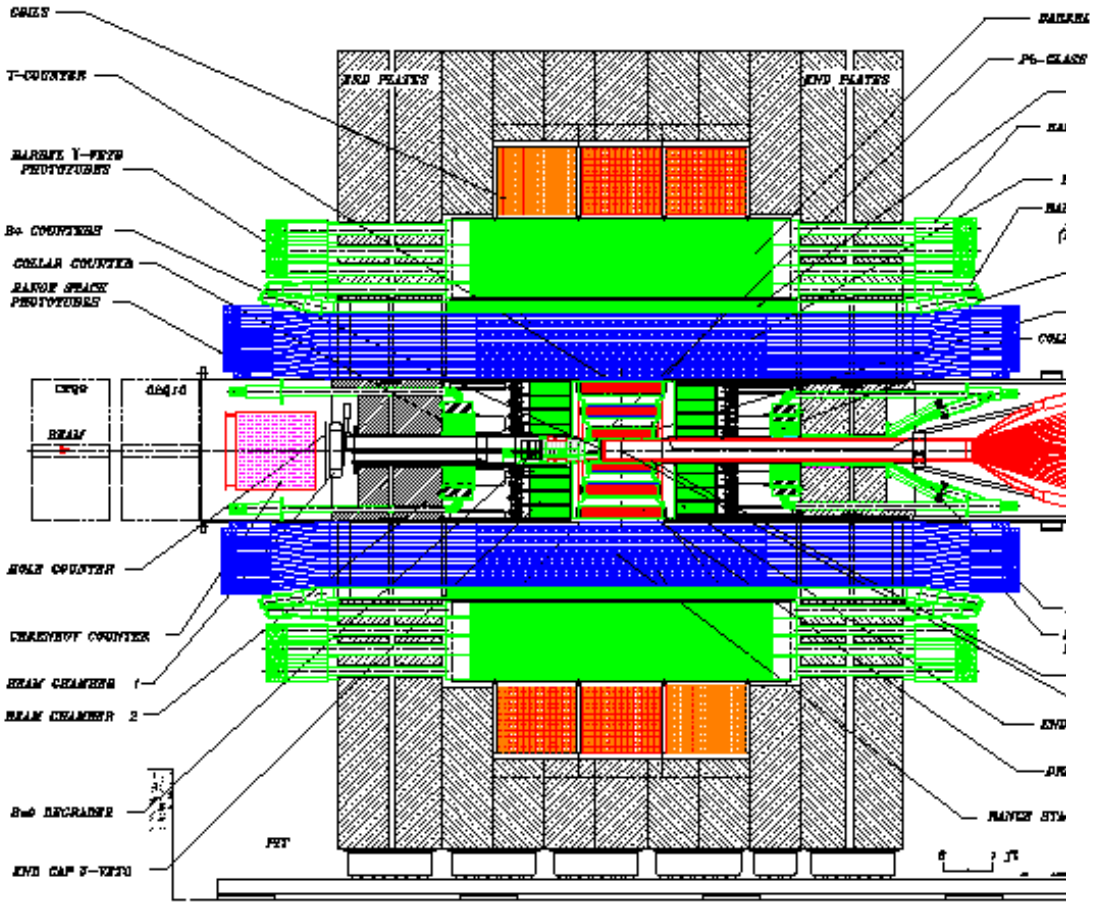
“BC”

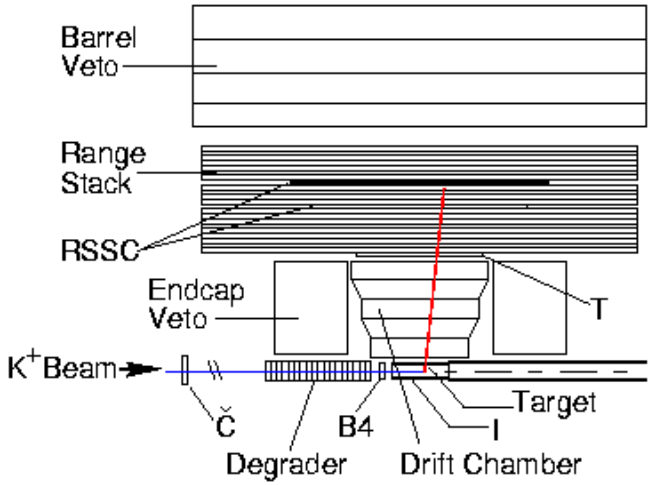

SIMPLE! YOU TAKE A BIG ROCK, THEN YOU CHIP AWAY EVERYTHING THAT DOESN'T LOOK LIKE PETER.

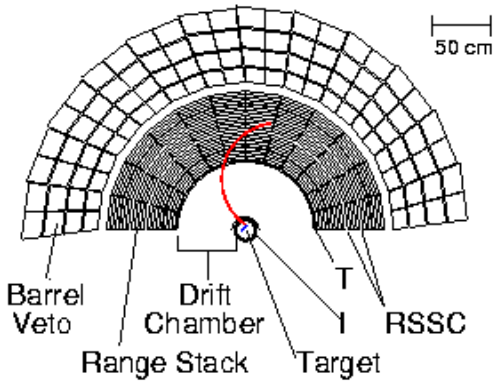
“BC”

BNL E949

Measurement of $K^+ \to \pi^+ \nu\bar{\nu}$



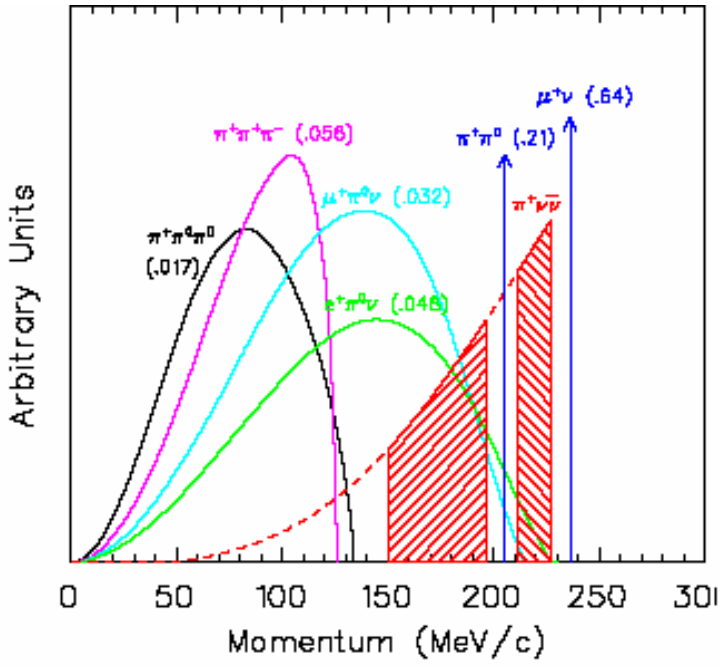




Special Features of Measuring

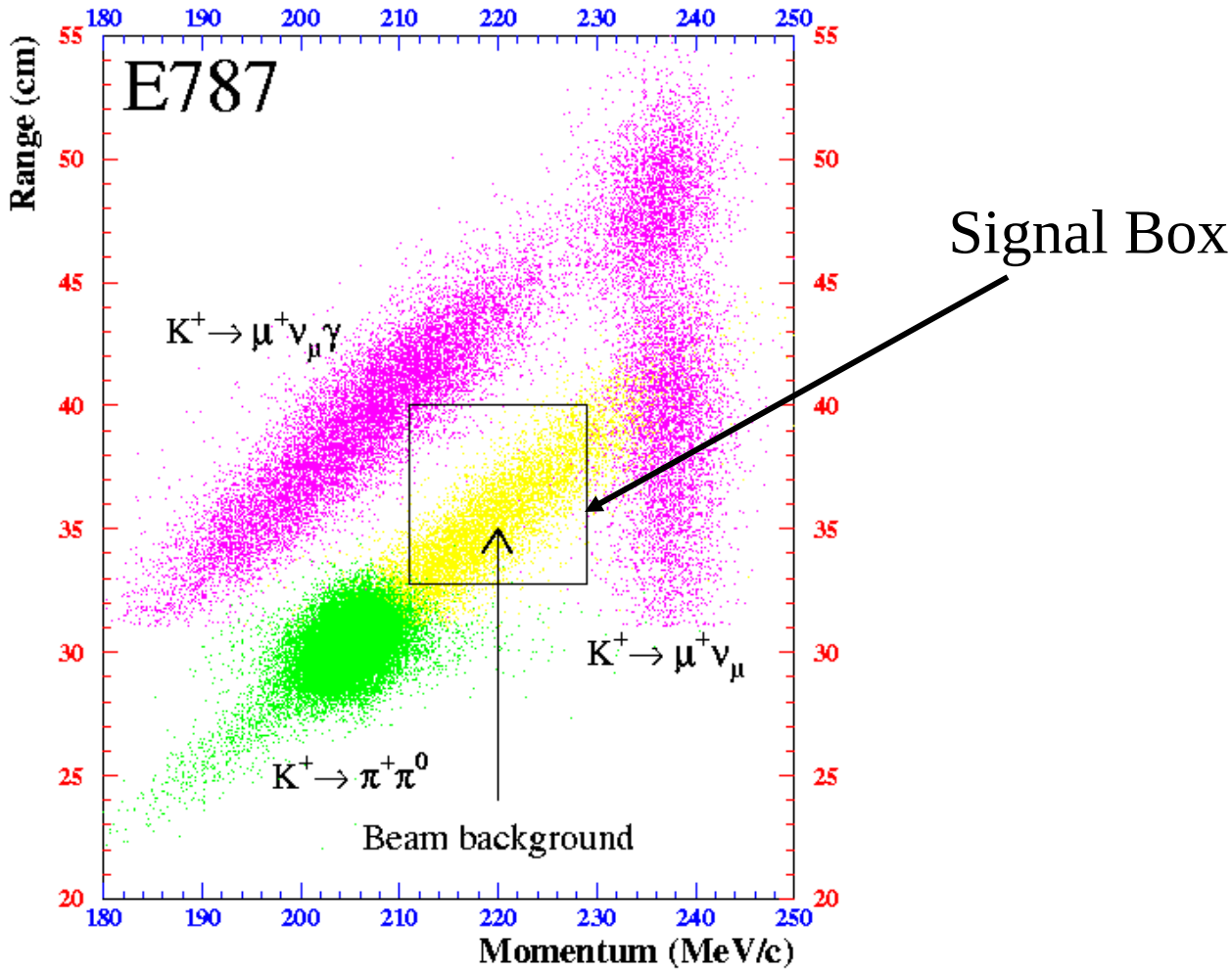
$$K^+ \to \pi^+ \nu\bar{\nu}$$

Background processes exceed signal by $>10^{10}$



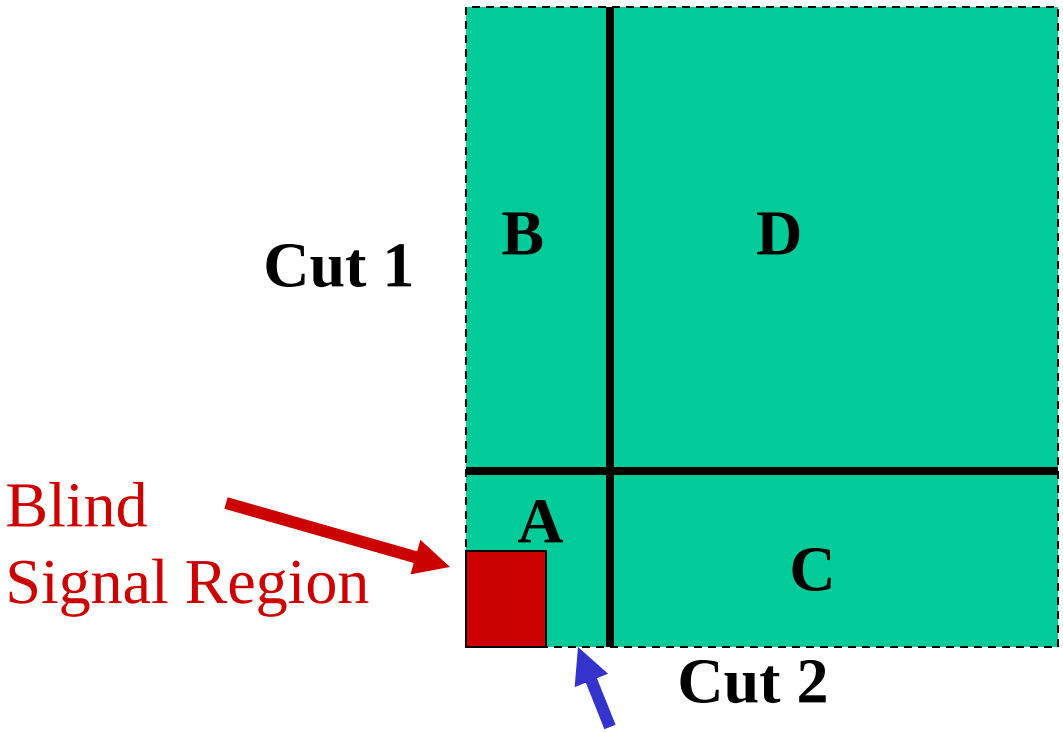
- Determine everything possible about the K^+ and π^+
  - * π^+/μ^+ particle ID better than 10^6 (π^+-μ^+-e^+)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency $< 10^{-6}$
- Suppress backgrounds well below the expected signal (S/N~10)
  - * Predict backgrounds *from data*: dual independent cuts
  - * Use "Blind analysis" techniques
  - * Test predictions with "outside-the-box" measurements
- Evaluate candidate events with S/N function

Background Processes: Range vs. Momentum



Estimating Backgrounds
Dual-Cut BLIND Analysis Method

Cut 1 *vs* Cut 2



If Cuts 1 and 2 are uncorrelated:
A/B=C/D
Background in A:
A=B C/D

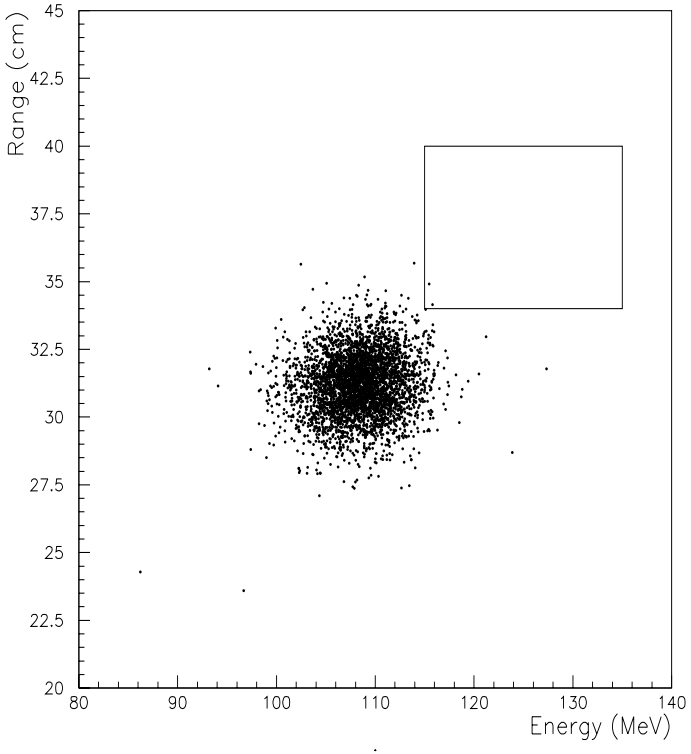
Blind Near Signal Region: Test Predictions

$K^+ \to \pi^+\pi^0$ Background Suppression

Dual cuts: γ Veto and Kinematics (P,R,E...)

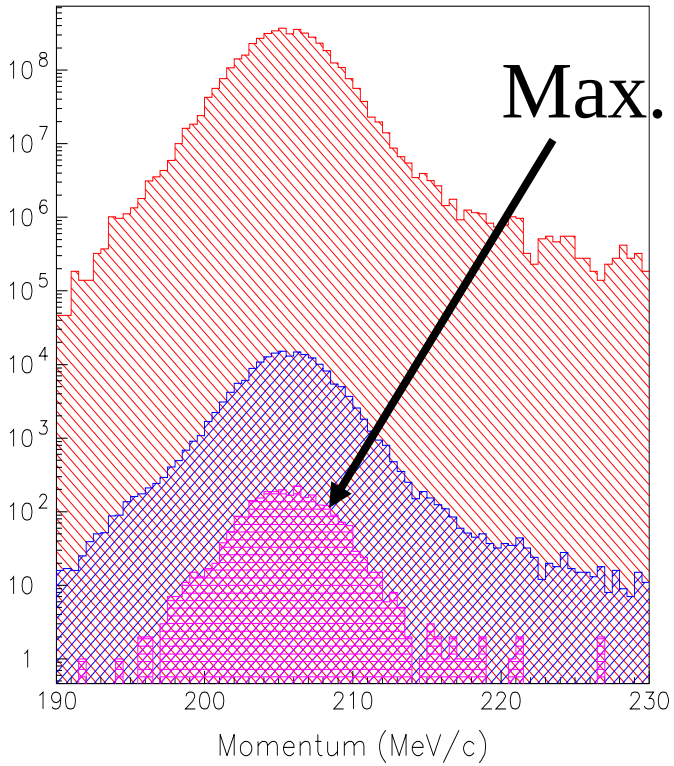
γ Veto Reversed

Range vs. Energy



γ Veto Applied

Momentum



Max. γ veto

Check for correlations

Background Suppression:
E949 Improved Photon Detection Efficiency

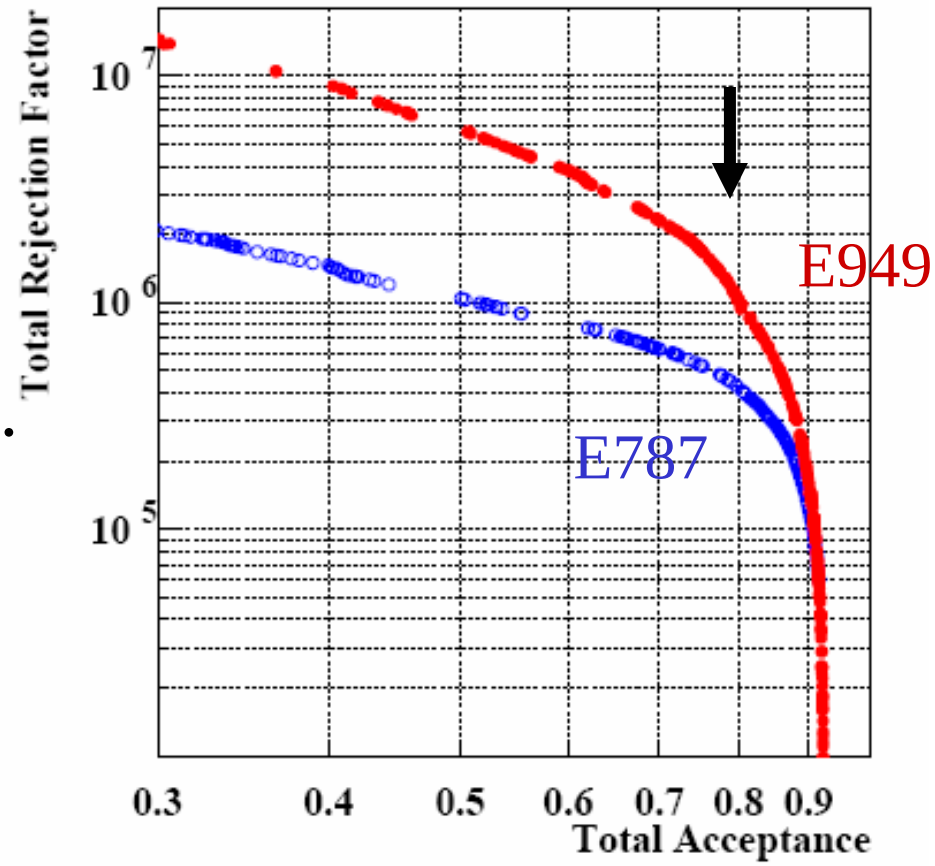
π^0 Rejection: $>10^6$

Twice the rejection

of π^0 backgrounds

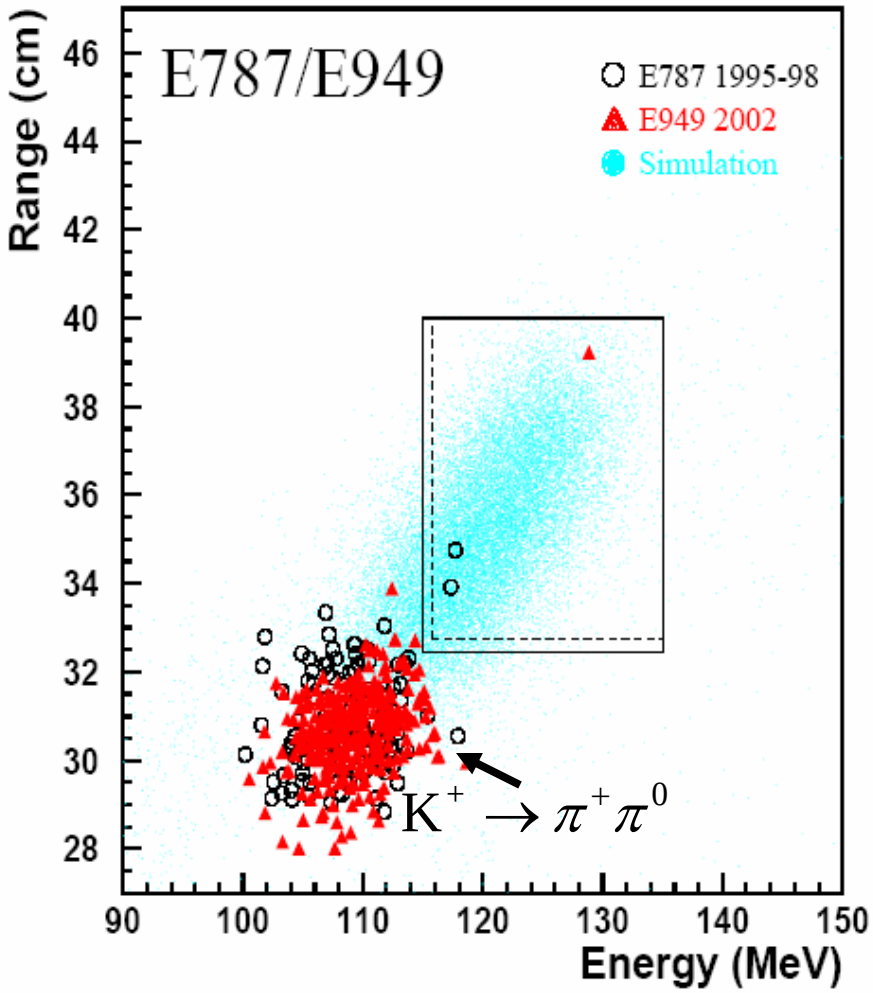
at comparable acceptance.

Rejection vs. Acceptance



Combined E787/E949 Branching Ratio

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.47 \pm^{1.30}_{0.89} \; x\, 10^{-10}$$



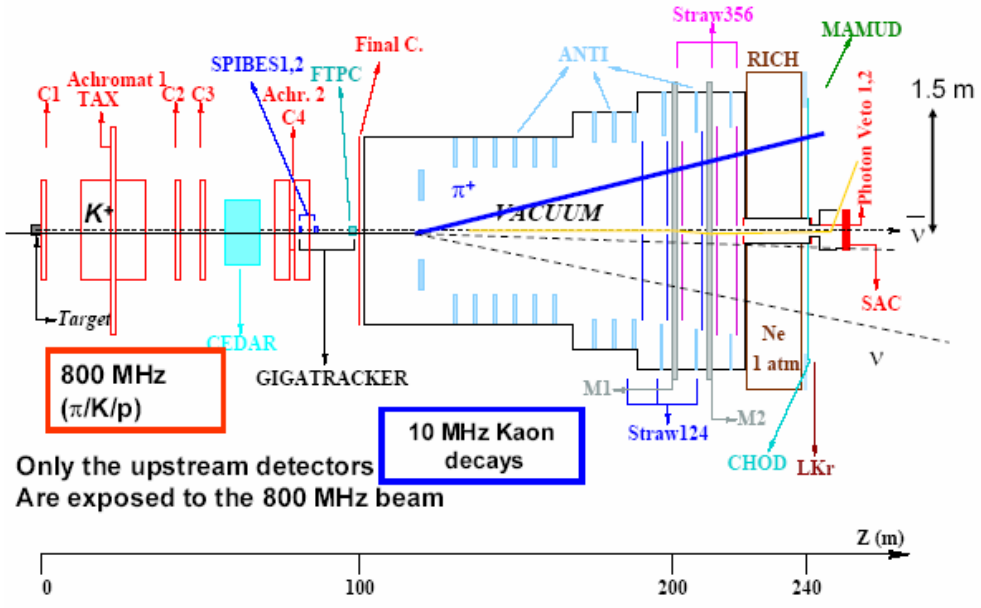
3 events

	E787		E949
N_K	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	1995A	1998C	2002A
S/b	50	7	0.9
W	0.98	0.88	0.48
Background Prob.	0.006	0.02	0.07

New Approaches to $K^+ \to \pi^+ \nu\bar{\nu}$:

High Energy Decay-in-Flight. ***Tschirhart and Cooper (2005) FNAL***
Unseparated Beam ***NA48-3 Group (2005)* CERN**

(Latest) NA48/3 Detector Layout



Acceptance

K^+ momentum: (75.0 ± 0.8) GeV/c

	Region I $0. < m^2_{miss} < 0.01\ (GeV/c^2)^2$	**Region II** $0.026 < m^2_{miss} < 0.068\ (GeV/c^2)^2$
P = [15- 35] GeV/c (RICH)	2.8×10^{-2}	14.8×10^{-2}
P = [10 - 40] GeV/c	3.9×10^{-2}	21.7×10^{-2}

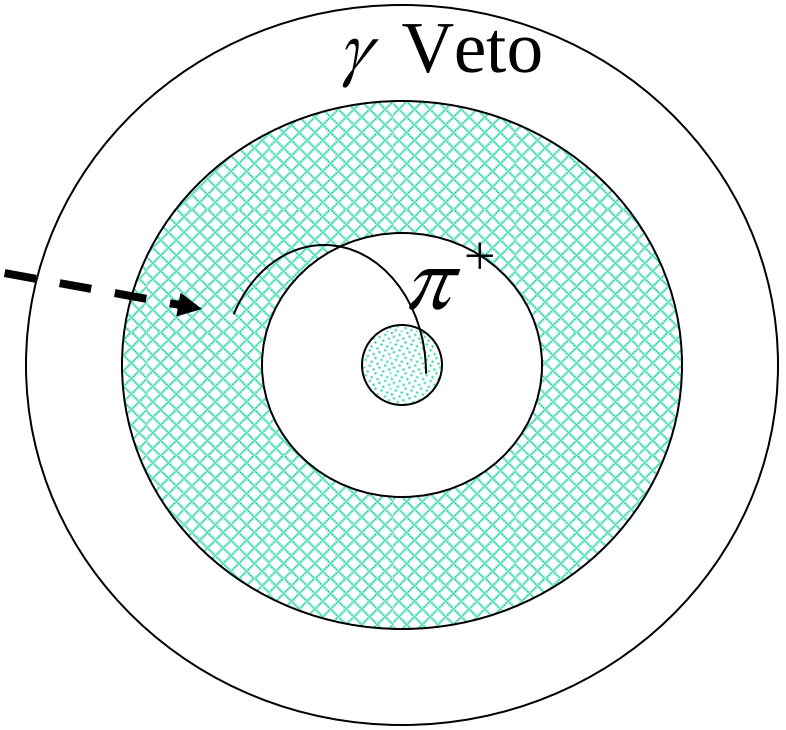
4×10^{12} decays/year
@ BR = 10^{-10} → **I+II (RICH) 70 events/year**

New Approaches to $K^+ \to \pi^+ \nu\bar{\nu}$:

High Field Version of E787/E949

Compact High Rate Detector

- Sci-Fi target and range stack
  for high rate $\pi \to \mu \to e$
- Improved momentum measurement
  suppresses $K^+ \to \pi^+\pi^0, \to \mu^+\nu$
- Improved crystal photon veto detectors

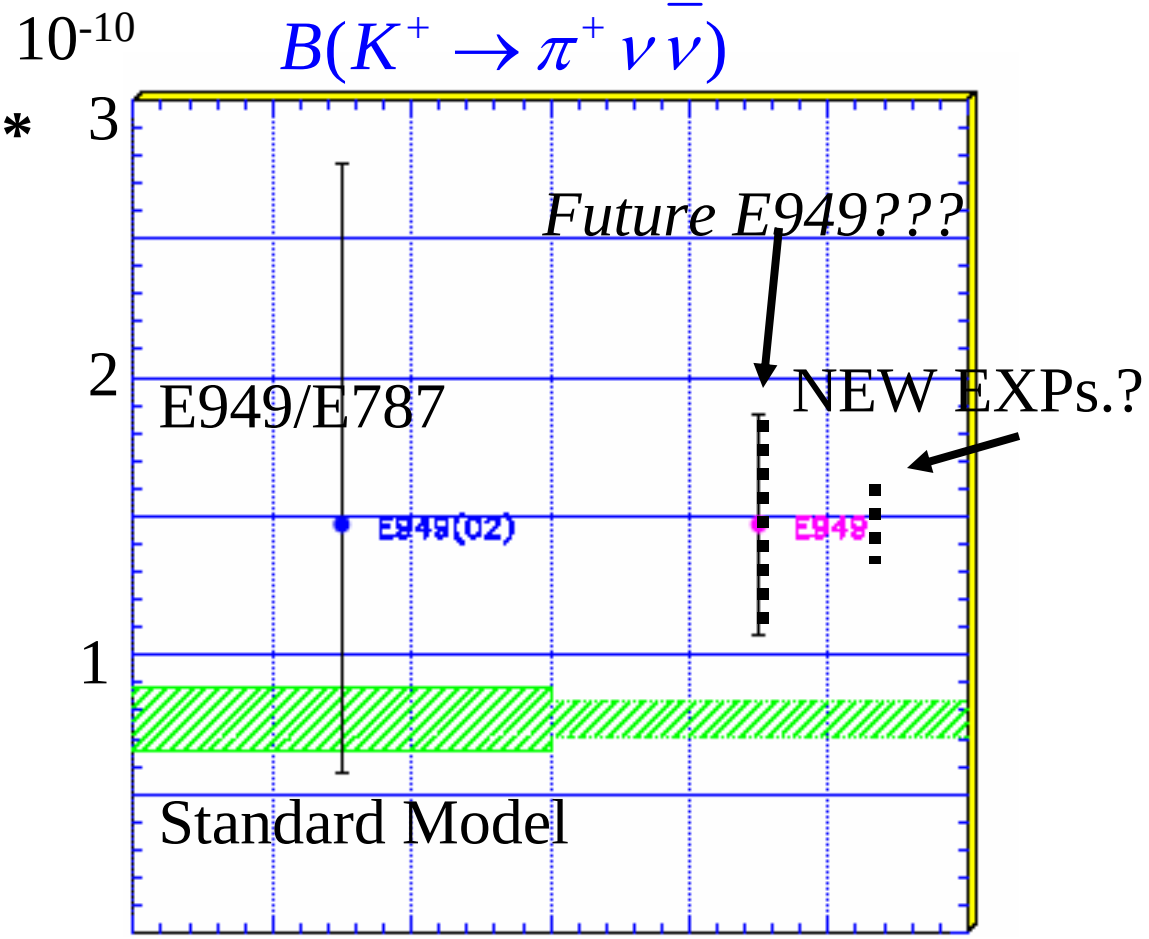


3T field

Possible **J-PARC experiment.**
50-100 events at S/N=5

$K^+ \to \pi^+ \nu\bar{\nu}$ Measurement Prospects

- **E949 Lower Phase Space***
- Complete 949(?)
- New LOIs



*E949 Results Soon:

$\pi^0 \to \nu\bar{\nu}$

$K^+ \to \pi^+\gamma\gamma$

$K^+ \to \pi^+\pi^0\gamma$

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

Limit based on $K^+ \to \pi^+ \nu\bar{\nu}$ via isospin : $< 1.4\,x10^{-9}$ • [*Grossman, Nir*]

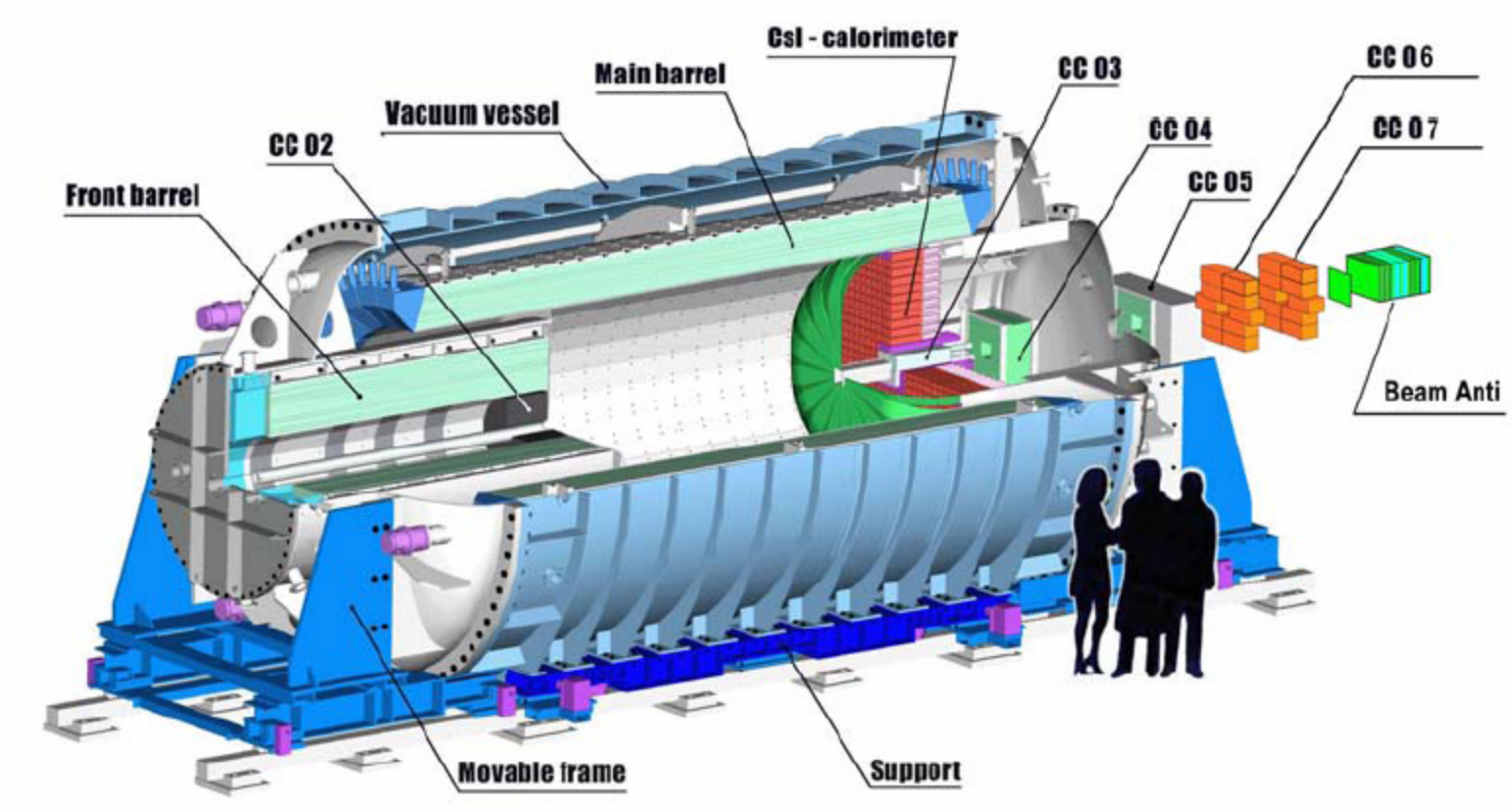
- KTEV (FNAL) result: $B(K_L^0 \to \pi^0 \nu\bar{\nu}) < 5.9\,x10^{-7}$ $(90\%CL)$
- KEK E391a: 10^{-10} – 10^{-9} ??
- KOPIO (BNL): Single event Sensitivity $<10^{-12}$

Discovery (5σ) for $B(\text{"}K_L^0 \to \pi^0 \nu\bar{\nu}\text{"}) > 4.5x10^{-11}$

or 300 "SM" events

LOI at JPARC

KEK PS E391a



Features: * Pencil Beam
* High acceptance
* High P_T selection

* Pilot Project for JHF
* Test reliance on extreme photon veto efficiency

$K_L^0 \to \pi^0 \nu\bar{\nu}$ Measurement

Background suppression factor needed: 10^{10}

Primary Backgrounds

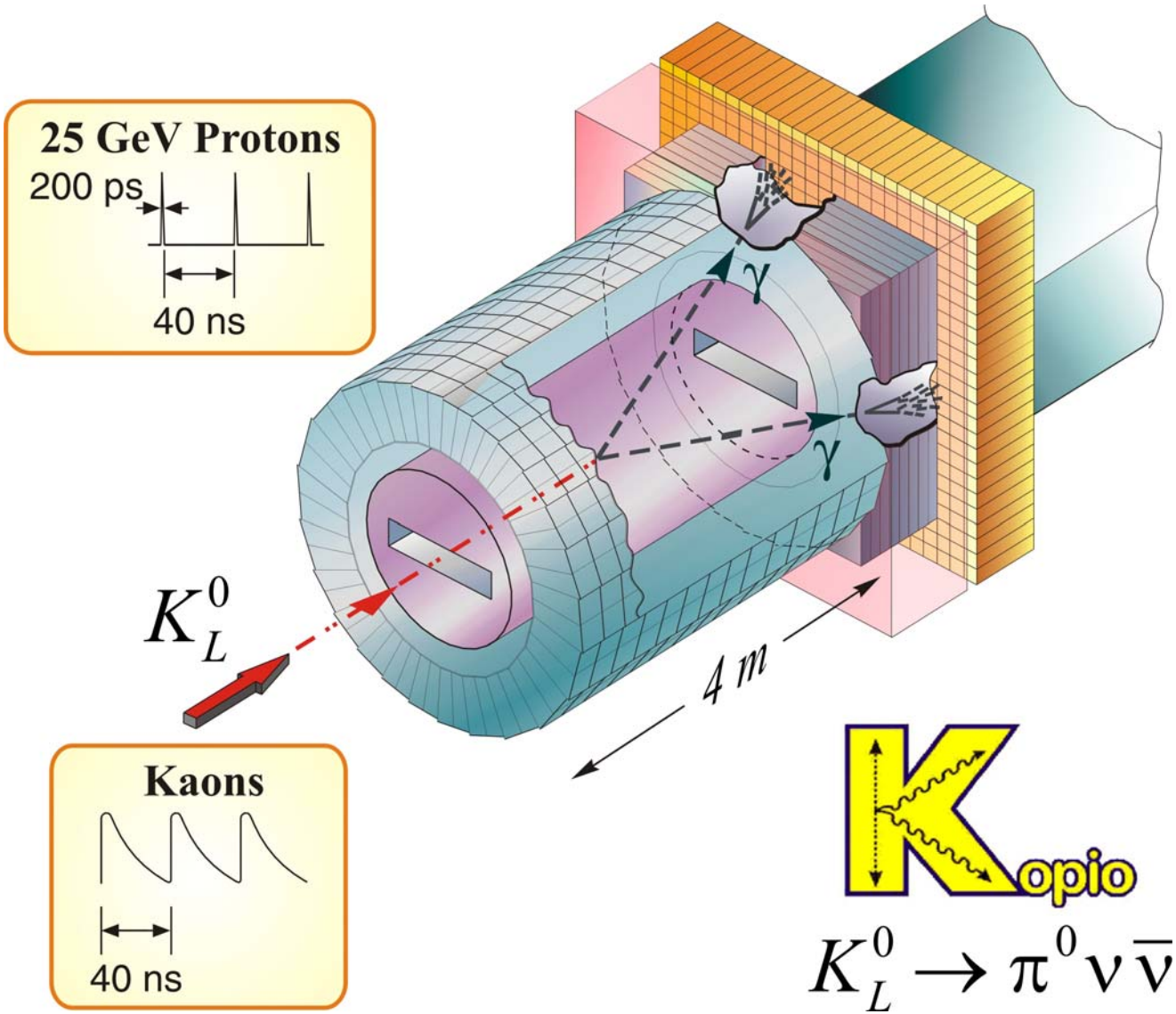
Mode	Branching Ratio
$K_L^0 \to \pi^0\pi^0$	0.93×10^{-3}
$K_L^0 \to \pi^- e^+ \nu \gamma$	0.36×10^{-2}
$K_L^0 \to \pi^+\pi^-\pi^0$	0.1255
$K_L^0 \to \pi^0\pi^0\pi^0$	0.2105

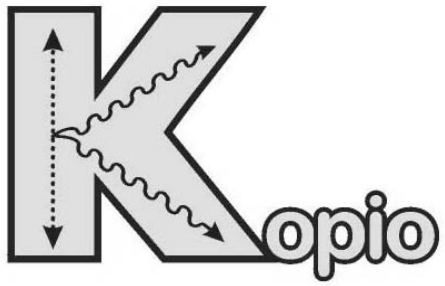
Others

The Challenge

- $B(K_L \to \pi^0 \nu\bar{\nu}) \sim 3\times10^{-11}$;
  need huge flux of K's -> high rates
- Weak Kinematic signature (2 particles missing)
- Backgrounds with π^0 up to 10^{10} times larger
- Veto inefficiency on extra particles must be $\leq 10^{-4}$
- Neutrons dominate the beam
  - make π^0 off residual gas – require high vacuum
  - halo must be very small
  - hermeticity requires photon veto in the beam
- Need convincing measurement of background

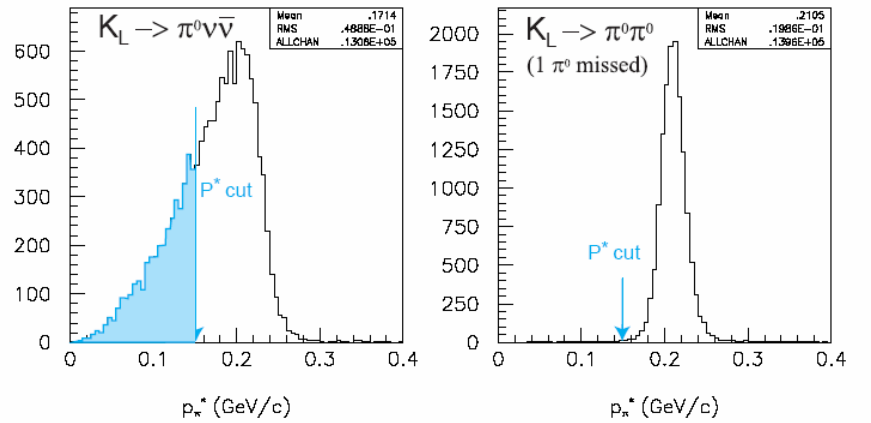
KOPIO Concepts





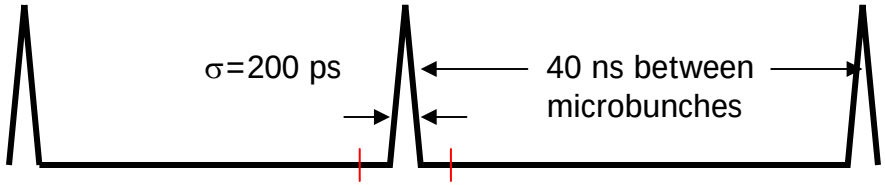
Concepts

Kaon Center of Mass Measurements



- Maximize micro-bunched beam from the AGS
- Measure everything! (Energy, Position, Angle, Time)
- Eliminate extra charged particles or ***photons***
  - * KOPIO: π^0 inefficiency < 10^{-8}
- 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

Nominal AGS Beam Parameters



Proton Beam:

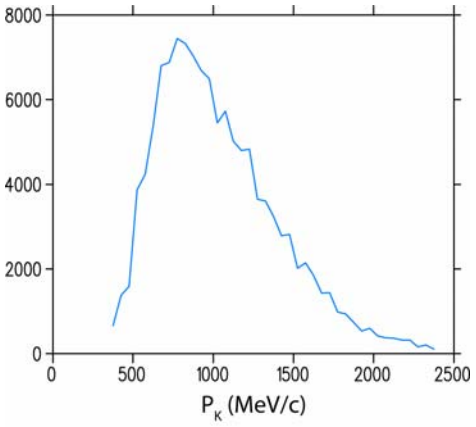
100 Tp/spill (Upgraded from present 70 Tp)

~5.5 s spill, 2.3 s interspill period

25 MHz micro-buching frequency

Bunch width 200ps

Interbunch extinction 10^{-3}



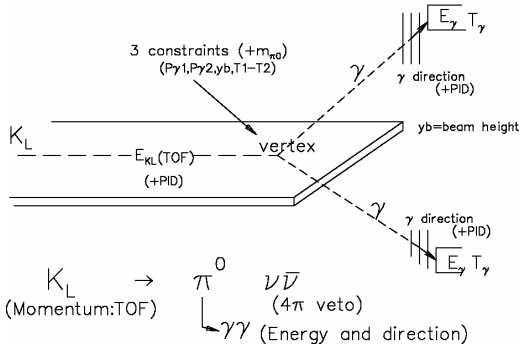
Kaon Beam:

42.5 degree take-off angle

Soft momentum spectrum [0.5,1.5 GeV]

$3x10^8$ K_L / spill, 8 % decay

10 GHz neutrons





KOPIO Collaboration

6 countries 19 institutions 80 scientists 10 Grad students

Arizona State University J.R. Comfort, *J. Figgins*

Brookhaven National Laboratory D. Beavis**,** I-H. Chiang, A. Etkin, J.W. Glenn, A. Hanson, D. Jaffe, D. Lazarus, K. Li, L. Littenberg, G. Redlinger, C. Scarlett, M. Sivertz, R. Strand

University of Cinncinnati K. Kinoshita

IHEP, Protvino G.Britvich, V. Burtovoy, S.Chernichenko, L, Landsberg, A. Lednev, V. Obraztsov, R.Rogalev, V.Semenov, M. Shapkin, I.Shein, A.Soldatov, N.Tyurin, V.Vassil'chenko, D. Vavilov, A.Yanovich

INR, Moscow A. Ivashkin, *D.Ishuk*, M. Khabibullin, A. Khotjanzev, Y. Kudenko, A. Levchenko, O. Mineev, N. Yershov and *A.Vasiljev*.

INFN-University of Perugia G. Anzivino, P. Cenci, *E. Imbergamo*, A. Nappi, M. Valdata

KEK M. Kobayashi

Kyoto University of Education R. Takashima

Kyoto University *K. Misouchi, H. Morii*, T. Nomura, N. Sasao, *T. Sumida*

Virginia Polytechnic Institute & State University M. Blecher, *N. Graham*, A. Hatzikoutelis

University of New Mexico B. Bassalleck, N. Bruner, D.E. Fields, J. Lowe, T.L. Thomas

University of Montreal J.-P. Martin

Stony Brook University N. Cartiglia, *I. Christidi*, M. Marx, P. Rumerio, D. Schamberger

TRIUMF P. Amaudruz, M. Barnes, E. Blackmore, J. Doornbos, P. Gumplinger, R. Henderson, N. Khan, A. Mitra, T. Numao, R. Poutissou, F. Retiere, A. Sher, G. Wait

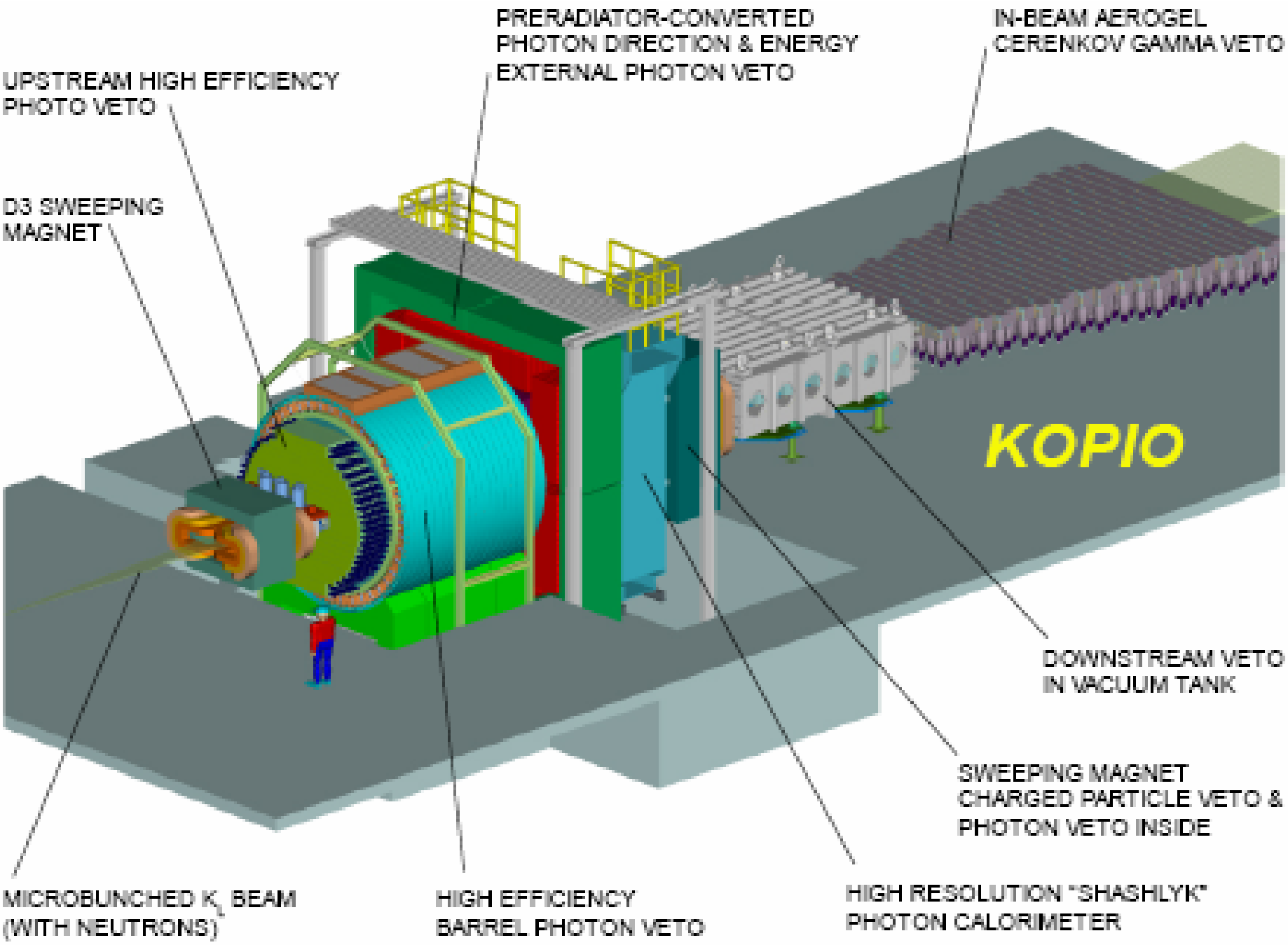
University of British Columbia D. Bryman, M. Hasinoff, *J. Ives*

Tsinghua University S. Chen

University of Virginia E. Frlez, D. Pocanic

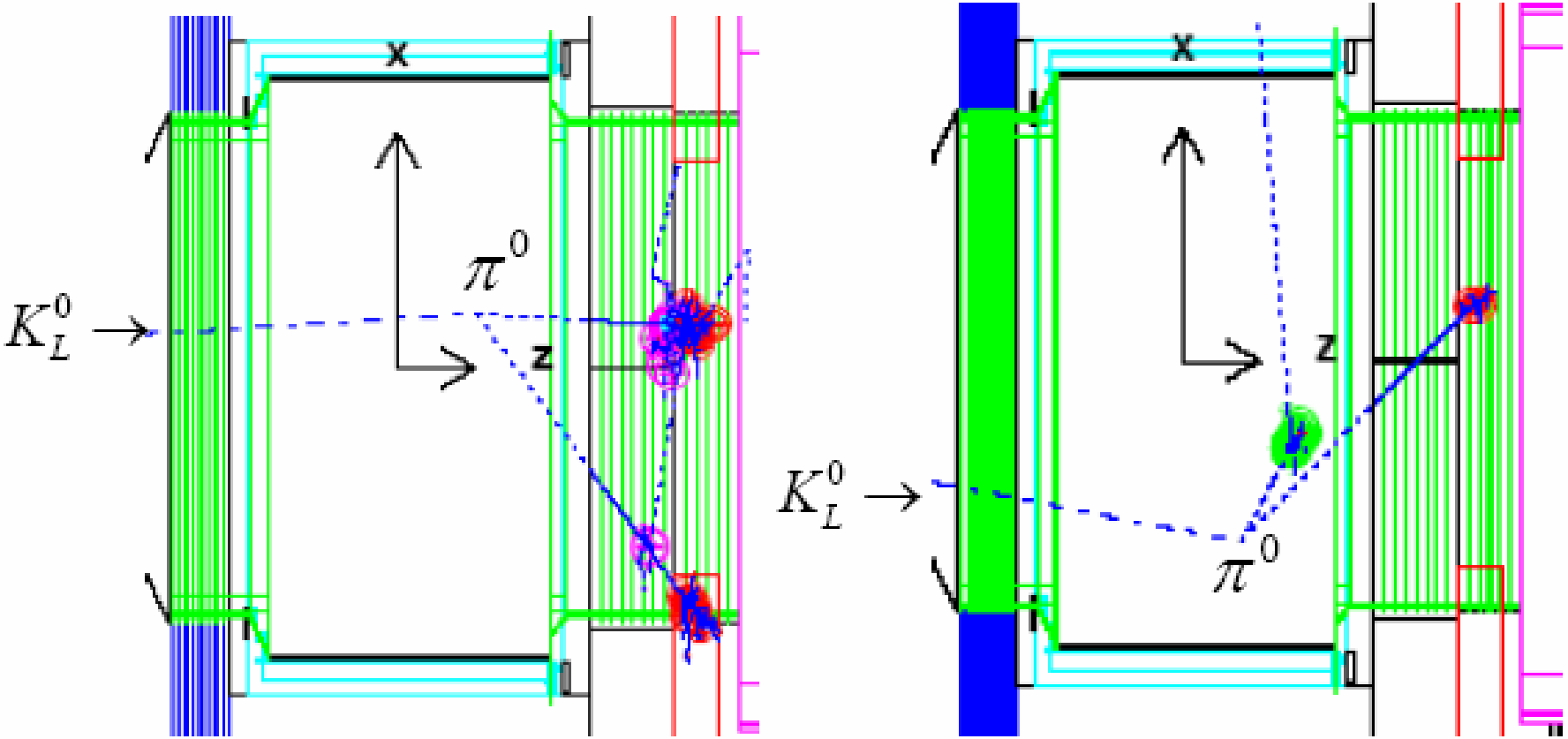
University of Zurich P. Robmann, P. Trüol, A. van der Schaaf, *S. Scheu*

Yale University G. Atoyan, S.K. Dhawan, V. Issakov, H. Kaspar, A. Poblaguev, M.E. Zeller


PRERADIATOR-CONVERTED
PHOTON DIRECTION & ENERGY
EXTERNAL PHOTON VETO
IN-BEAM AEROGEL
CERENKOV GAMMA VETO
UPSTREAM HIGH EFFICIENCY
PHOTO VETO
D3 SWEEPING
MAGNET
KOPIO
DOWNSTREAM VETO
IN VACUUM TANK
SWEEPING MAGNET
CHARGED PARTICLE VETO &
PHOTON VETO INSIDE
MICROBUNCHED K_L BEAM
(WITH NEUTRONS)
HIGH EFFICIENCY
BARREL PHOTON VETO
HIGH RESOLUTION "SHASHLYK"
PHOTON CALORIMETER

Primary detection mode:
2 photons covert in preradiator

Secondary mode:
1 photon in preradiator, 1 in BV



Reconstruct first $\gamma \rightarrow e^+e^-$ in "Preradiator"

Point to K decay vertex in vacuum.

KOPIO Signal and Background Estimates

The key features of the KOPIO approach have been established by measurements supported by simulations

- Micro-bunching and neutral beam design
- Photon pointing, energy resolution
- Vetoing – charged particles and photons

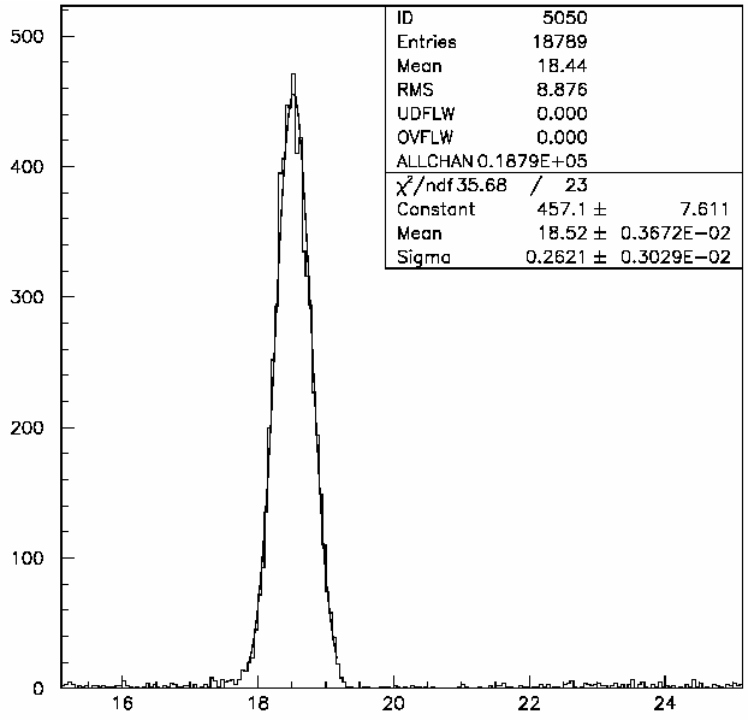
	Expected Performance
μ Bunch Width (Extinction)	200 ps (10^{-3})
θ_γ Resolution (250 MeV)	25 mr
E_γ Resolution	$2.7\% / \sqrt{E_\gamma(GeV)}$
t_γ Resolution	$90ps / \sqrt{E_\gamma(GeV)}$
Photon Veto Inefficiency	E949 or better
Charged Particle Inefficiency	$10^{-5}(\pi^+), 10^{-4}(\pi^-)$

AGS Microbunching Beam test

Microbunch width

Studied the RF extraction mechanism proposed for KOPIO & measured a microbunch rms width of 244 ps -- KOPIO requires <300 ps rms

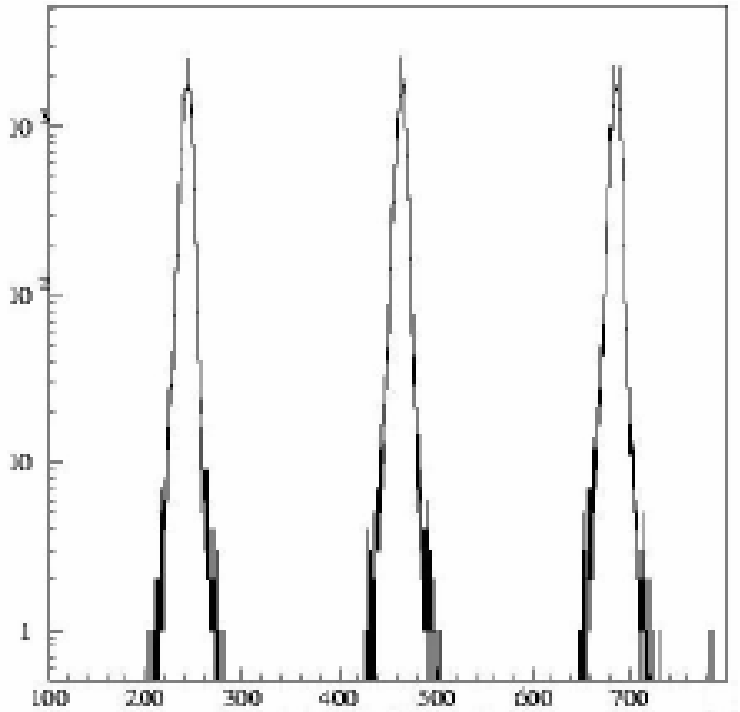
93 MHz



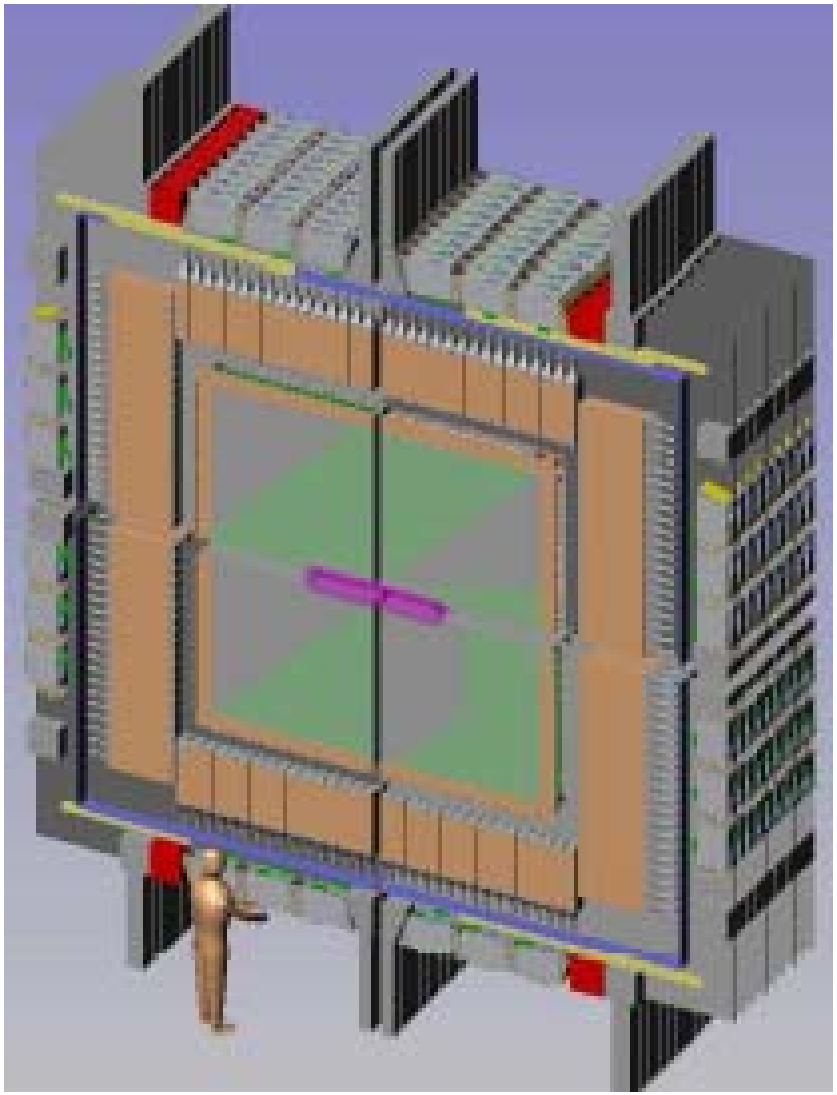
Interbunch extinction

Measured the inter-bunch extinction ratio (flux between bunches/within bunch). KOPIO requires ~ 10^{-3}.

4.5 MHz

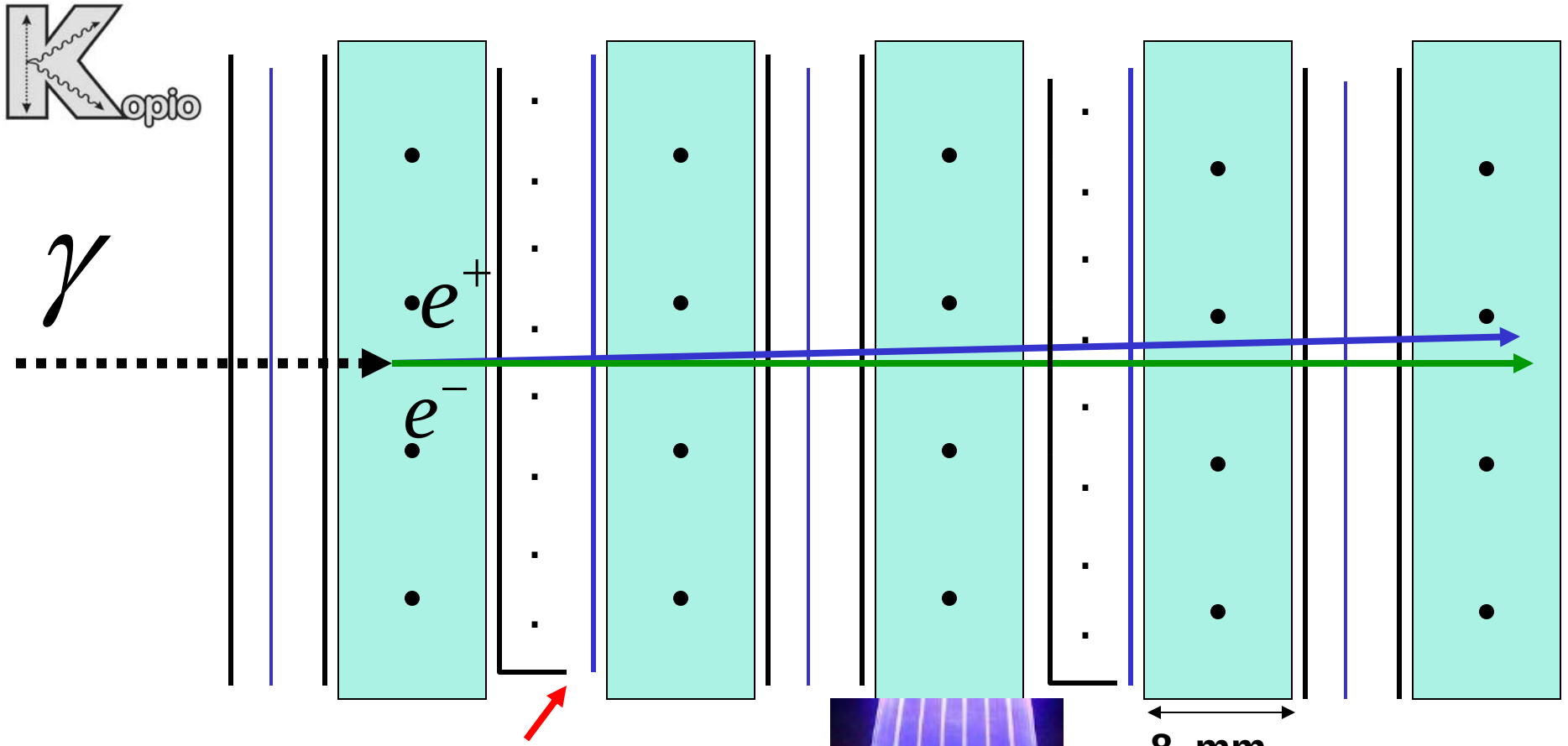


Preradiator



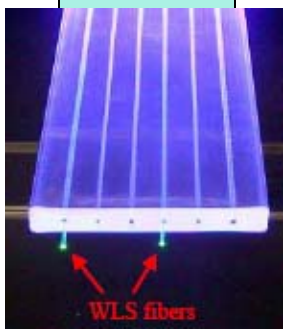
64 Layers (4% X_0/layer, 2.7 X_0)
256 Chambers
288 Scintillator Plates (1200 $m^{2)}$
150,000 Channels Readout

Preradiator Angle Measurement of $\gamma \to e^+e^-$





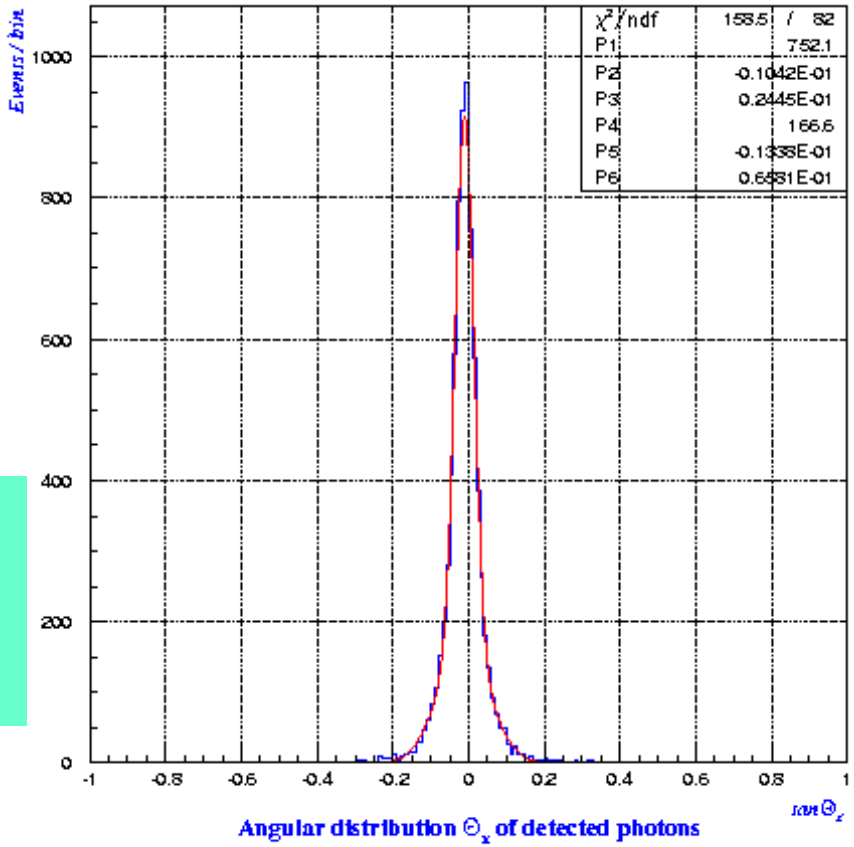
Cathode strip drift chambers



Extruded Scintillator & WLS fibers

KOPIO Prototype Measurements – BNL LEGS Tagged Photon Beams

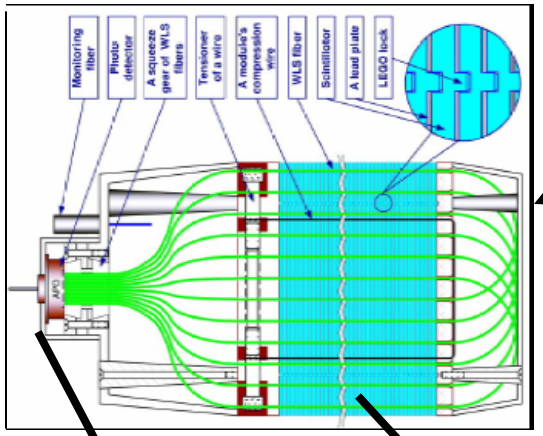
Preradiator Angular resolution:
25 mr at 250 MeV/c

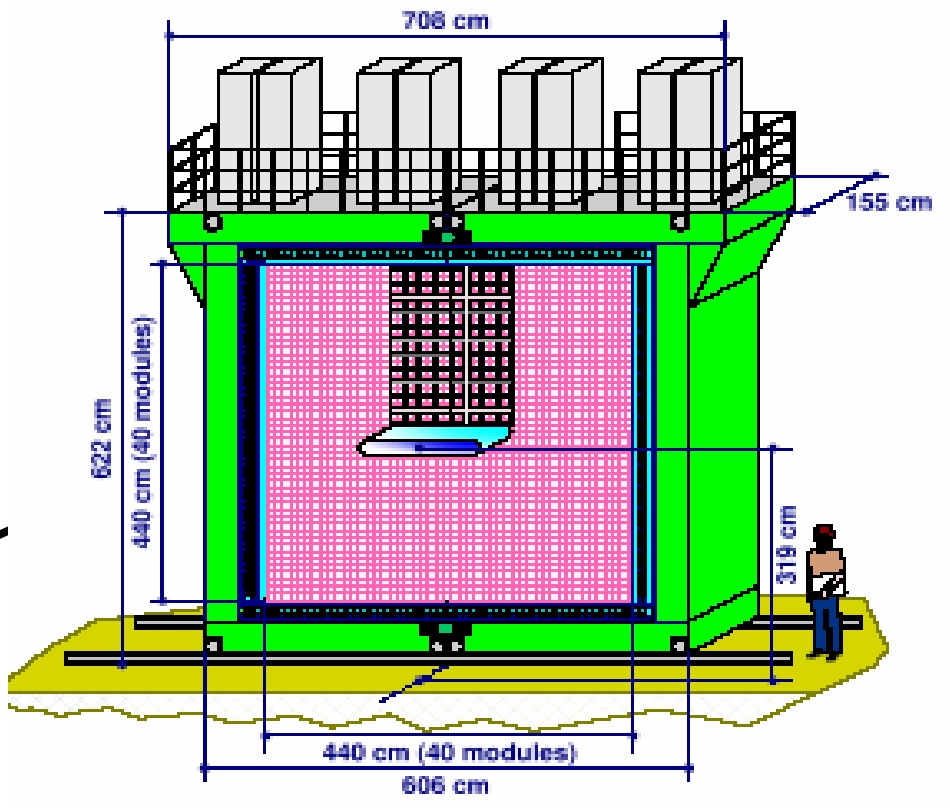


Simulations agree with measurements.

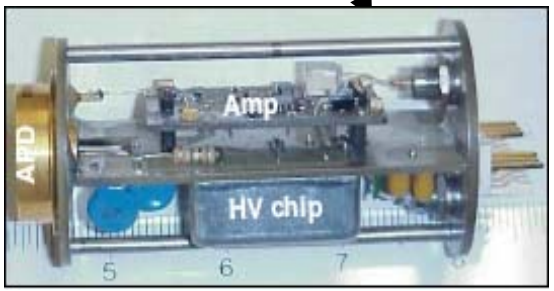
Shashlyk Calorimeter

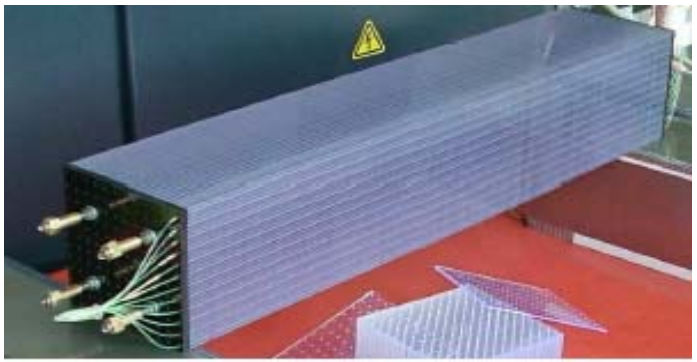
Shashlyk modules prototyped and tested in beams.
Mechanical design in progress



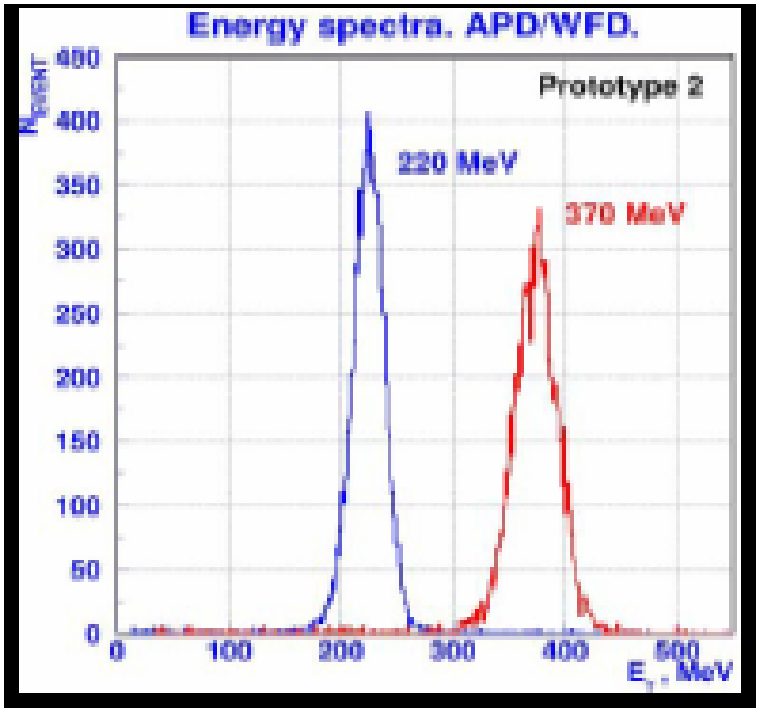


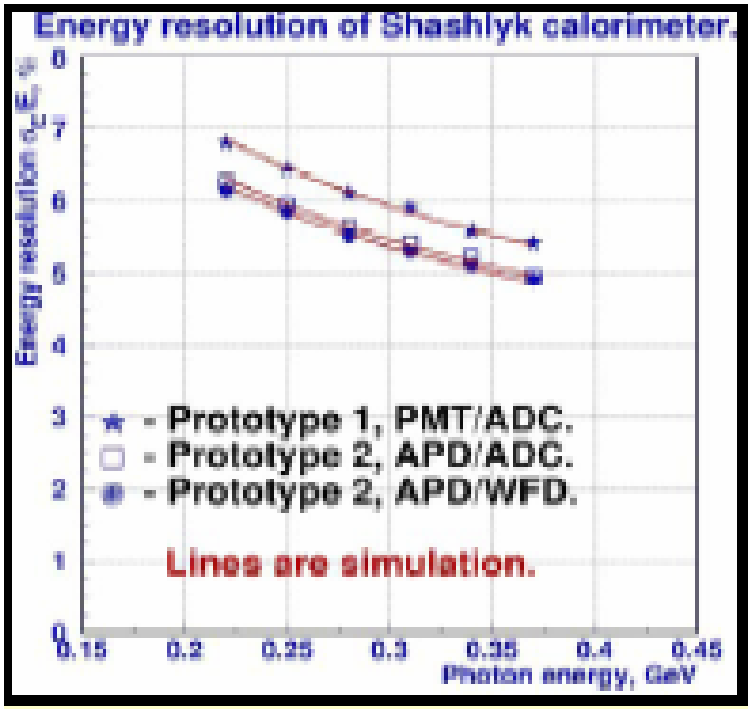
APD





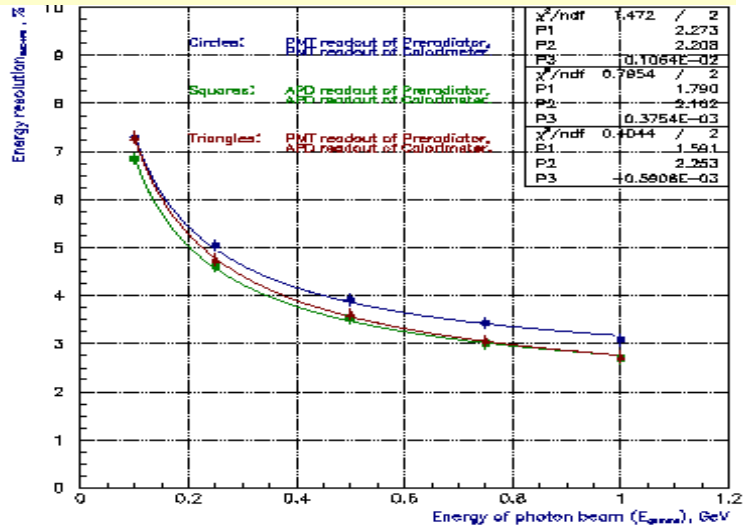
Shashlyk Beam Measurements





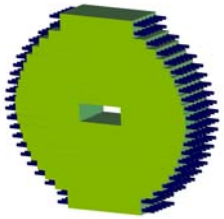
Simulation: Combined Energy Resolution

$$\sigma = \frac{2.7\%}{\sqrt{E(GeV)}}$$

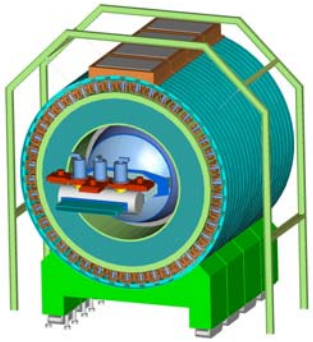


Every detector is a photon veto!

US Wall



Barrel veto



Fine-sampling lead/scintillator-based shower counters of shashlyk & bar geometry. All thick enough so punch-through not an issue. All with sufficient efficiency

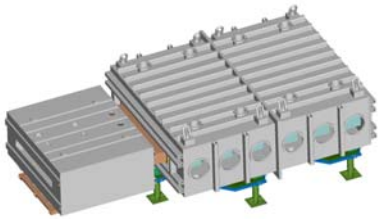
Preradiator

Prerad outer veto

Calorimeter

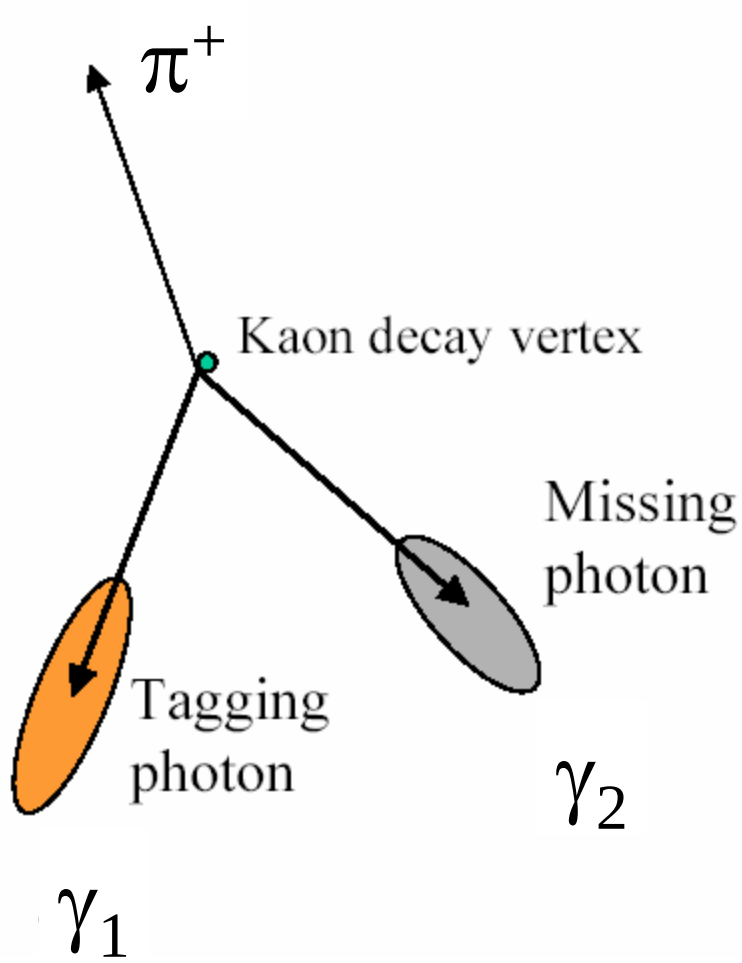
γ vetoes in D4 sweeping magnet

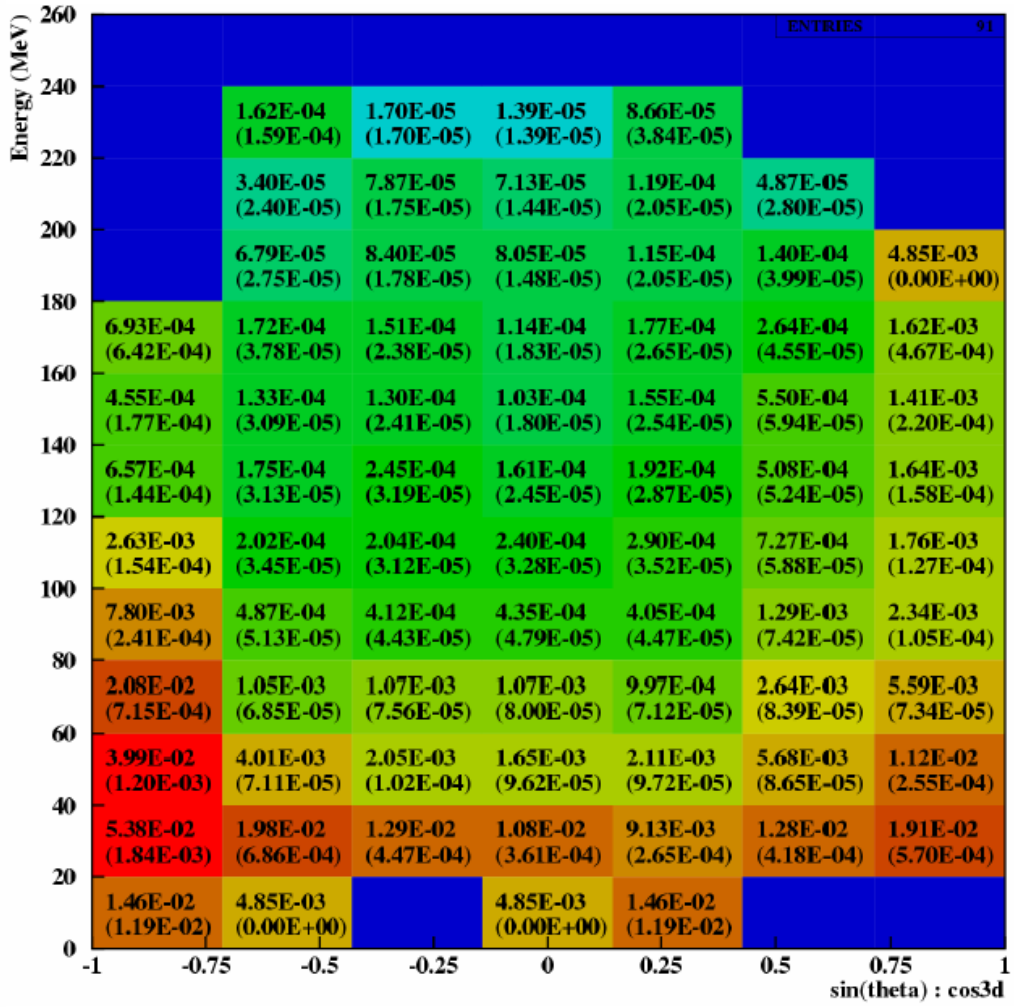
γ vetoes in DS vacuum pipe



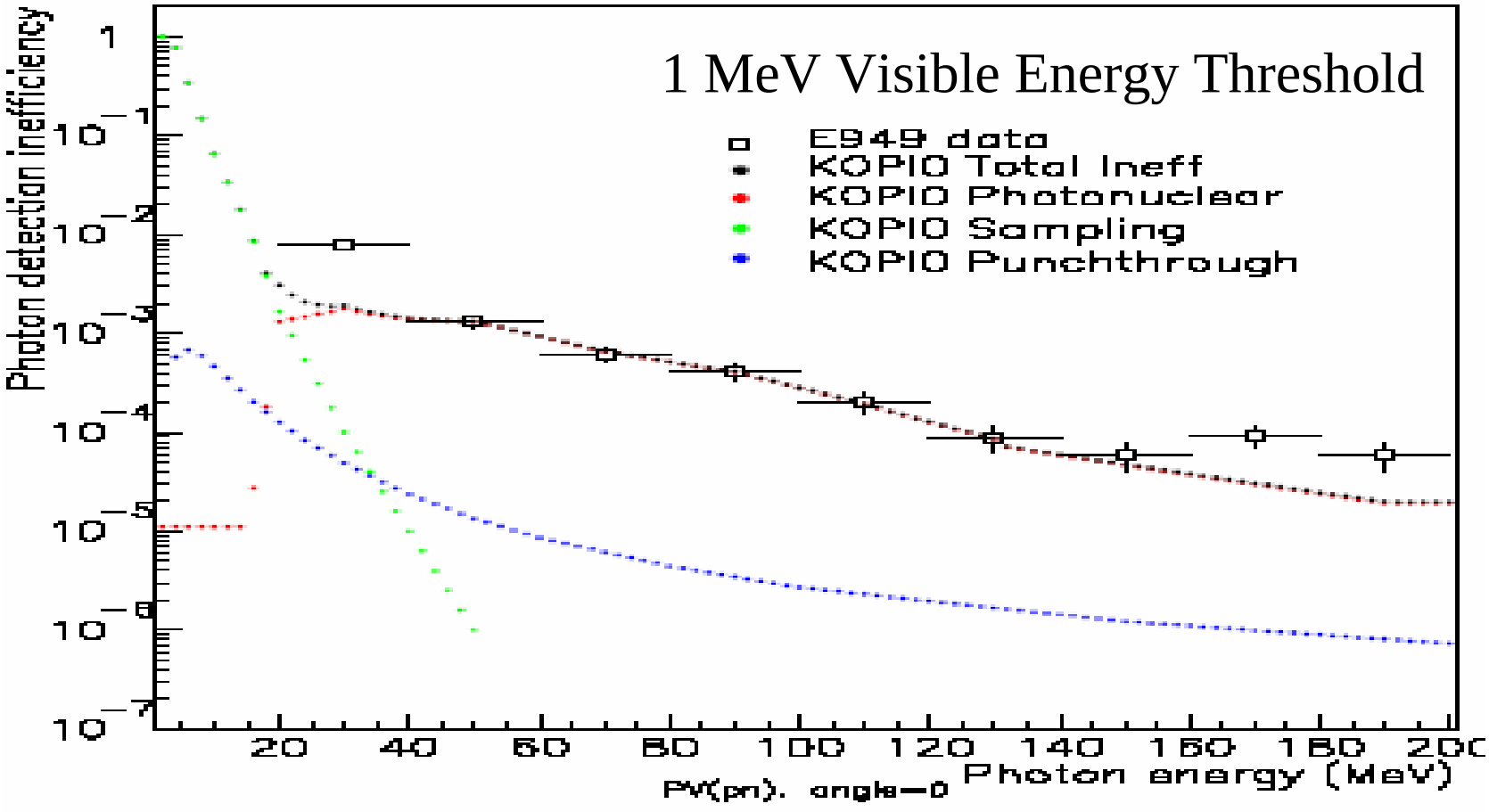
E949 Single Photon Inefficiency Measurement

Kπ2 Decay



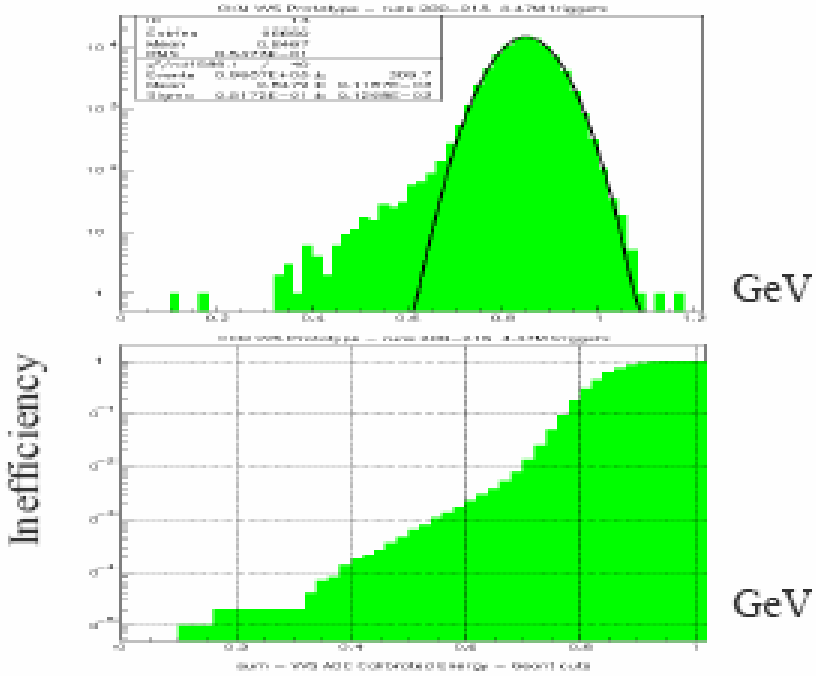


KOPIO PV Estimates and Simulations based on improved E949 Measurements supplemented by FLUKA calculations



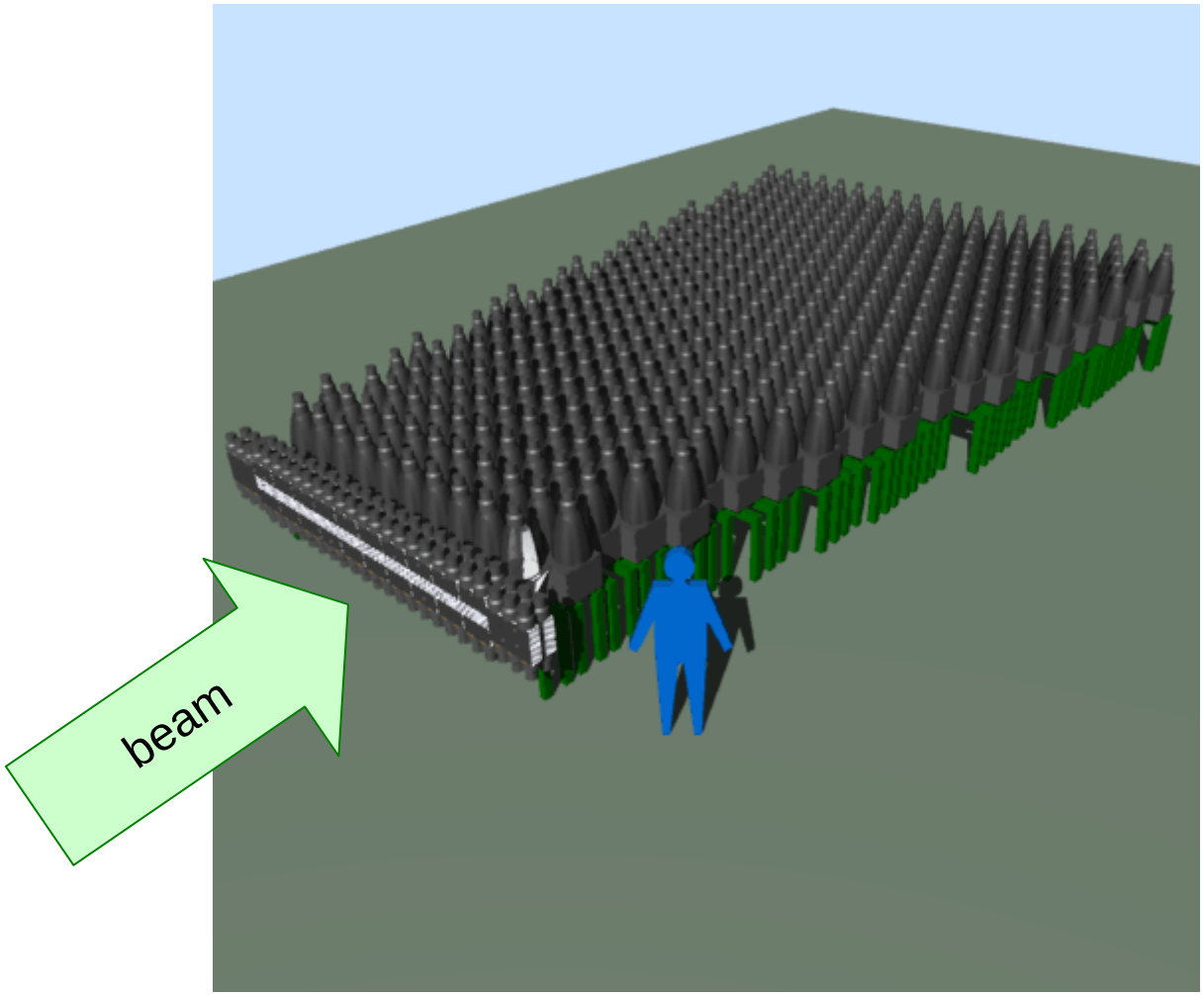
Photon Veto Inefficiency and Technology

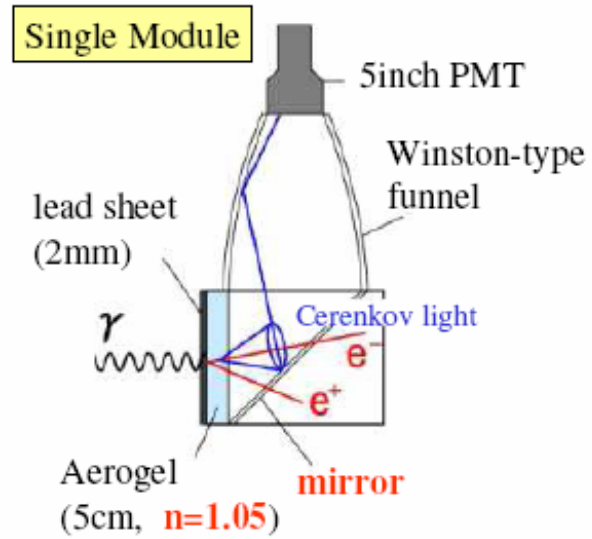
- 0.3% VVS Prototype built
- Tested at JLAB in an e^- beam
- Achieved $<1\times10^{-5}$ (3×10^{-6}) veto inefficiency at 1 GeV (required 3×10^{-5})





Catcher





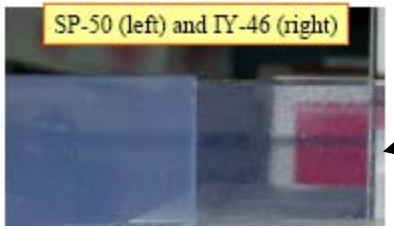
Aerogel Counter

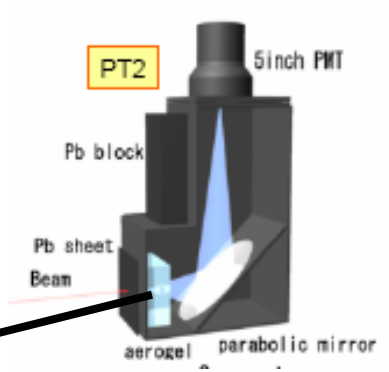
420 modules of
Pb-Aerogel counter

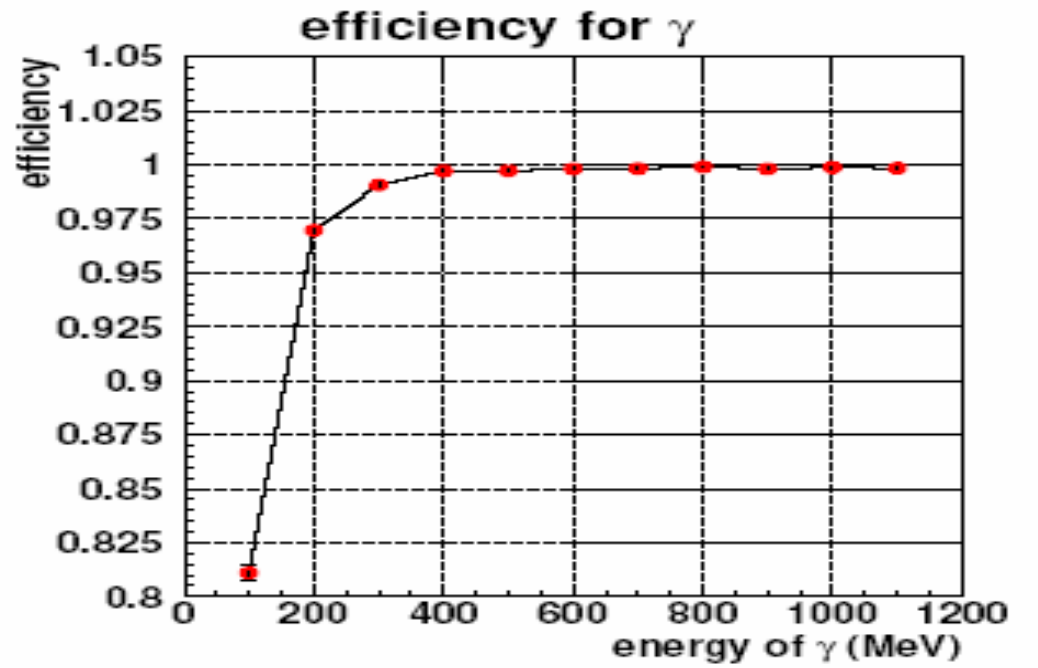
Catcher R&D

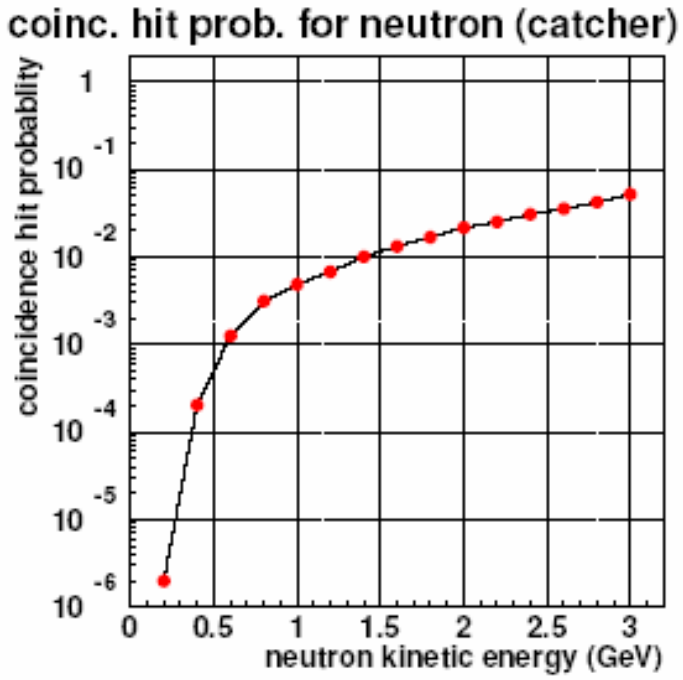
Modules prototyped and tested in beams.

New Aerogel tiles







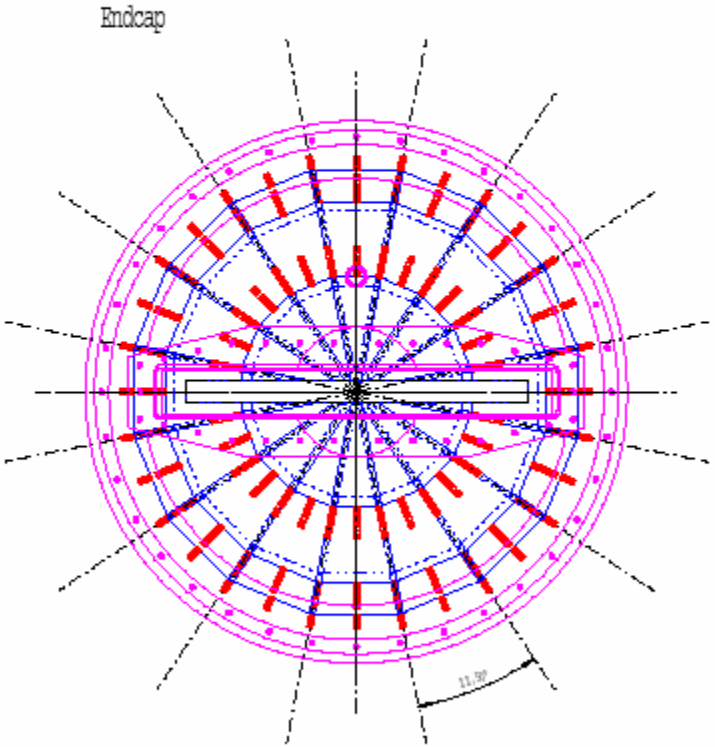


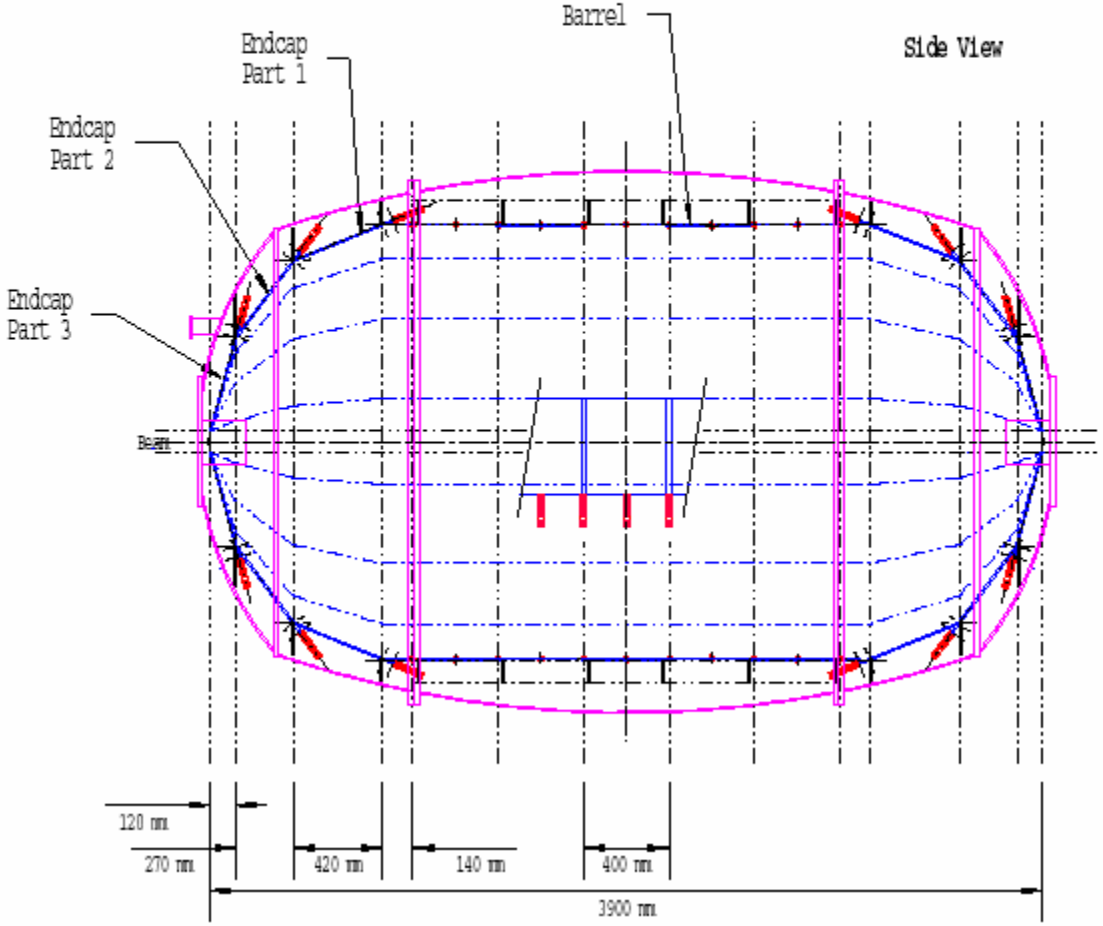
Charged Particle Veto in vacuum

CPV Barrel Detector

Total Area of Scintillator: ~34m²

Total Number of Elements: 180
Total Number of Photomultipliers: 364





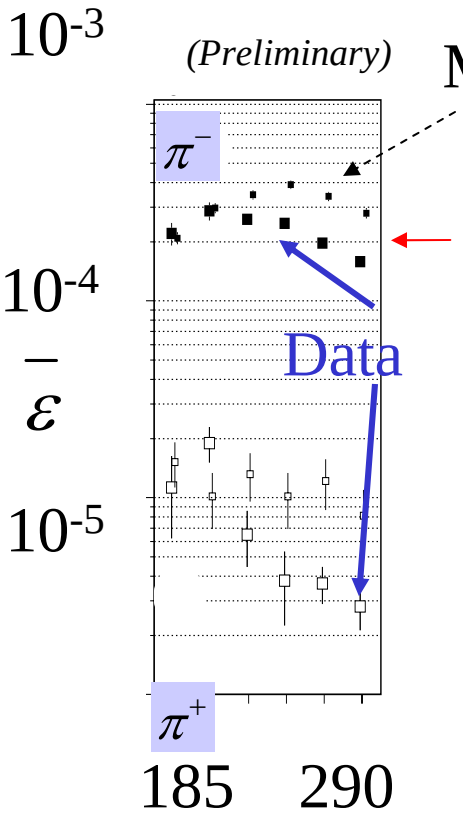
Charged Particle Vetoing

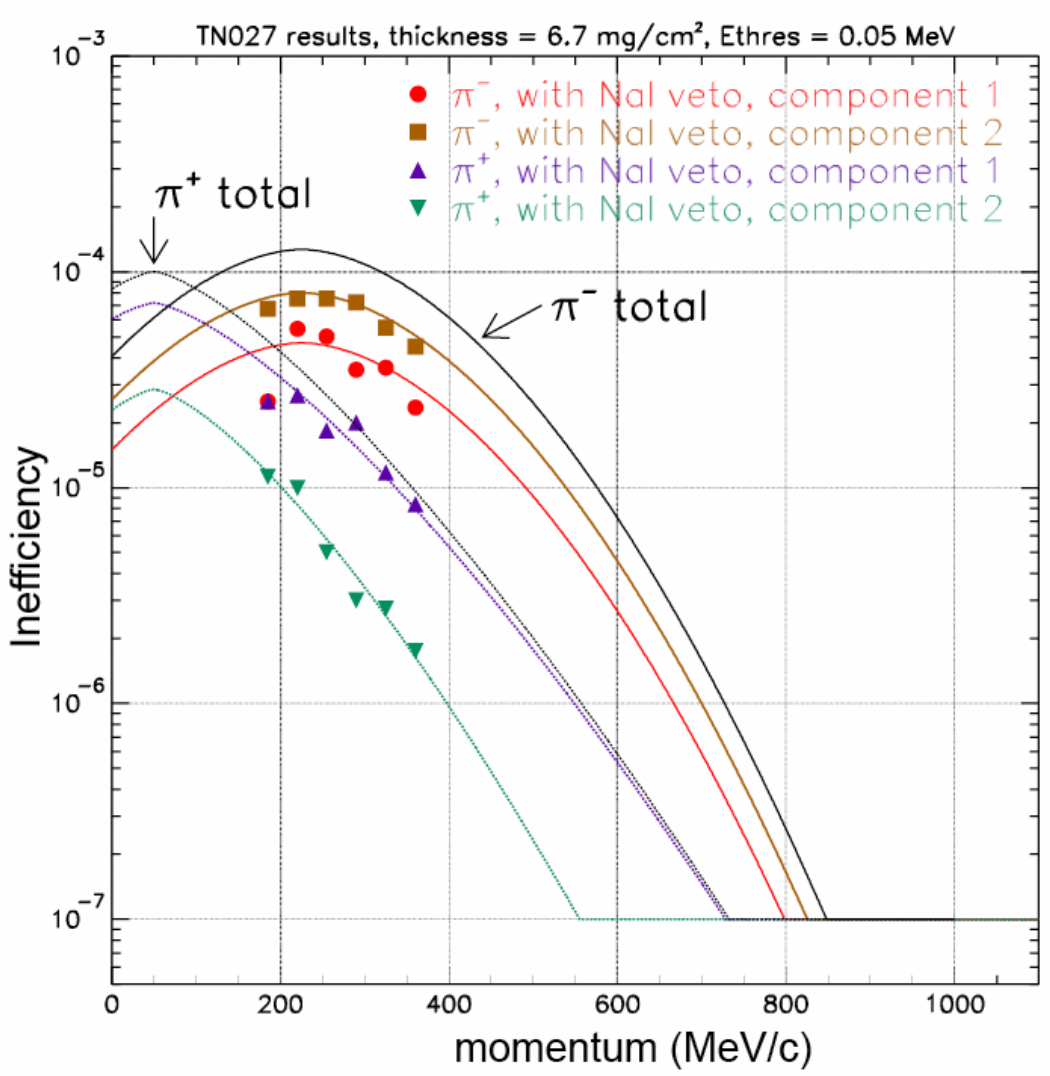
Example Background: $\mathbf{K}_L^0 \to \pi^- e^+ \nu \gamma$

Plastic Scintillator –

backed up by γ vetoes!

PSI Measurement





K_L modes simulated for background Studies

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}

Largest back-grounds

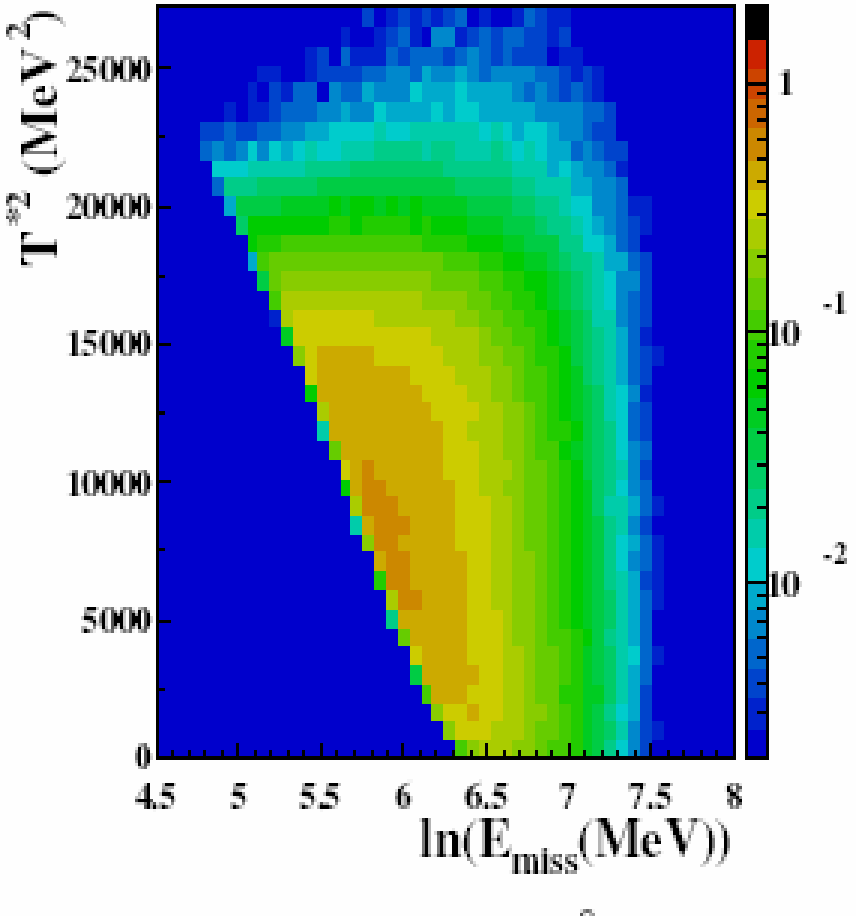
Other Backgrounds

- K^+ contamination of beam: <0.001 of signal rate
- $K_L \rightarrow K^+ e^- \nu$, $K^- e^+ \nu$: ~ 0.001 of signal rate
- $nN \rightarrow \pi^0 N$: 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
- Anti-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 vetos
- $(K_L \rightarrow \pi^{\pm} X) \times (\pi^{\pm} \rightarrow \pi^0 e^{\pm} \nu)$: ~0.01 of signal rate
- $K_S \rightarrow \pi^0 \pi^0$: ~$4 \times 10^{-4}$ of $K_L \rightarrow \pi^0 \pi^0$ background rate

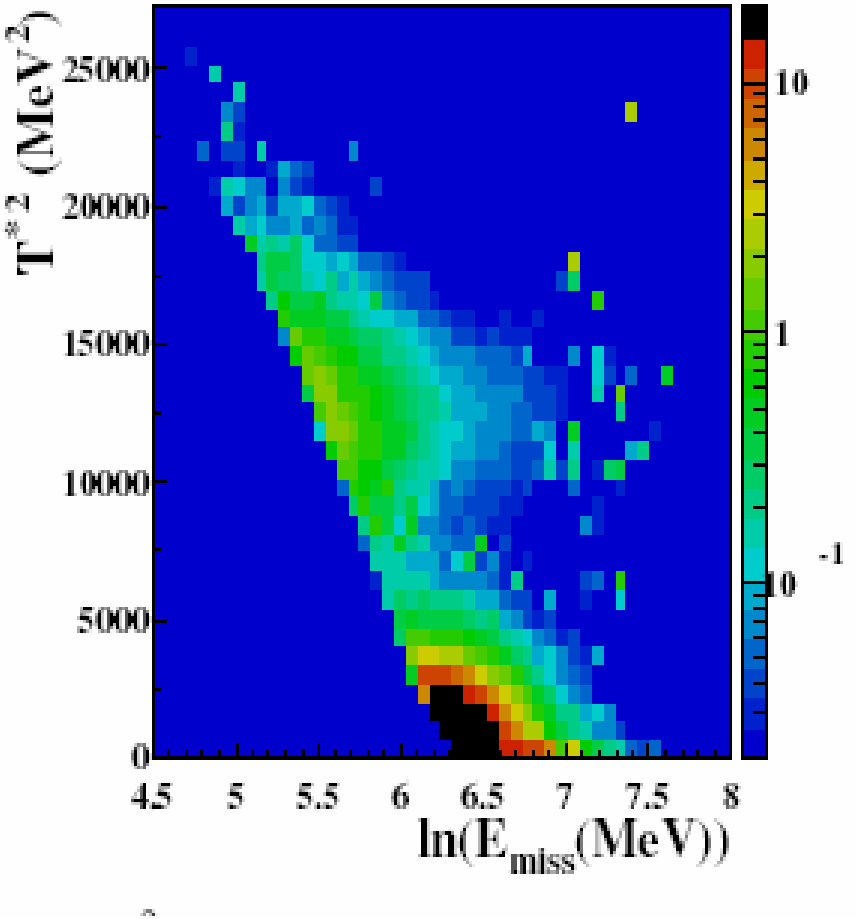
Kinematic Separation of Signal and Backgrounds

Pion Kinetic Energy Squared (T_π^{*2}) vs. Ln (Missing Energy)

Signal



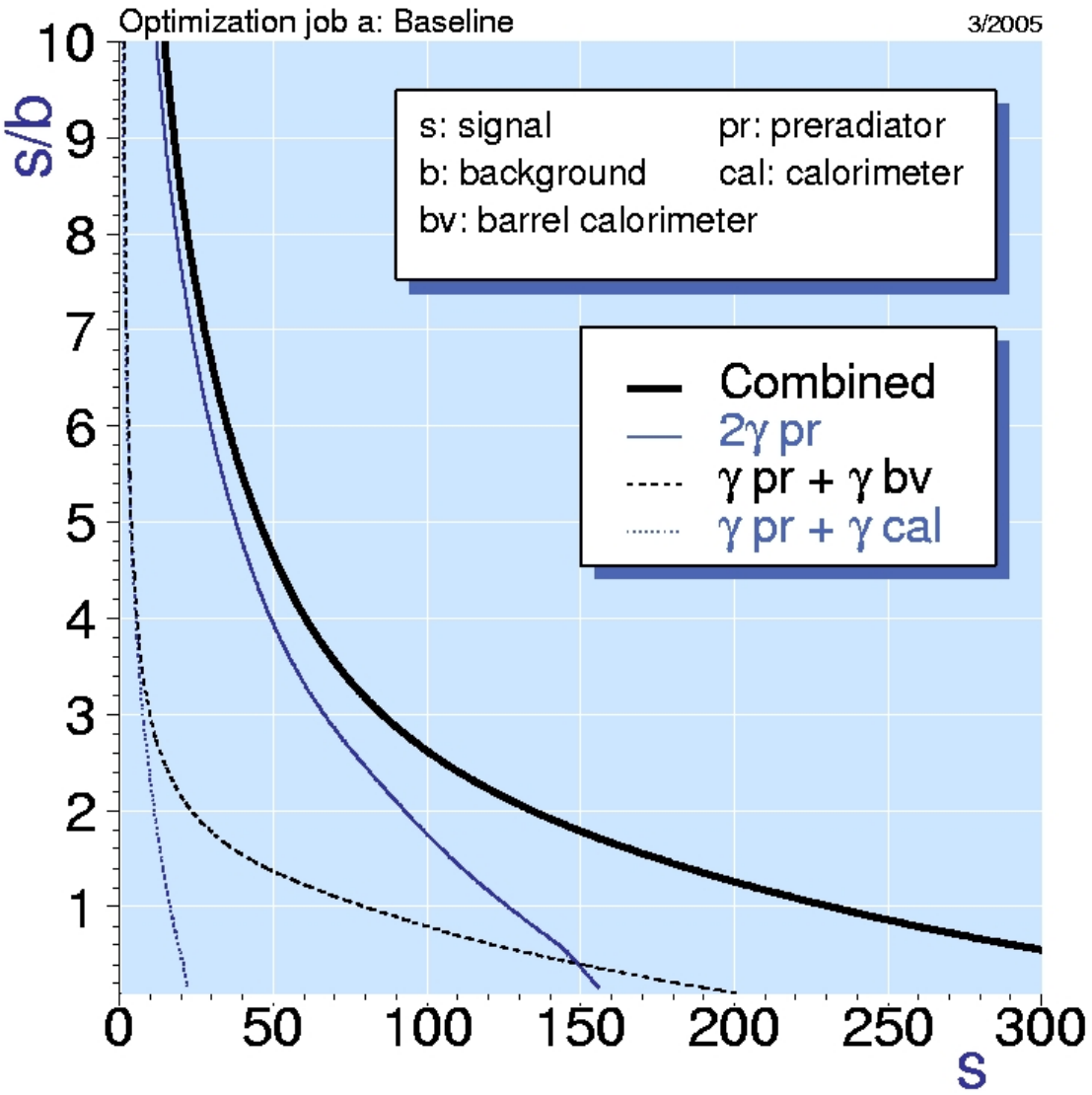
Backgrounds



Normalization Factors and Uncertainties

- Losses
  - Rate dependent trigger effects
  - Signal “self-vetoing”
  - Accidental vetoing
  - Multiple decays/microbunch
- Additional Uncertainties
  - Flux
- Possible Gains
  - Improved photon efficiency

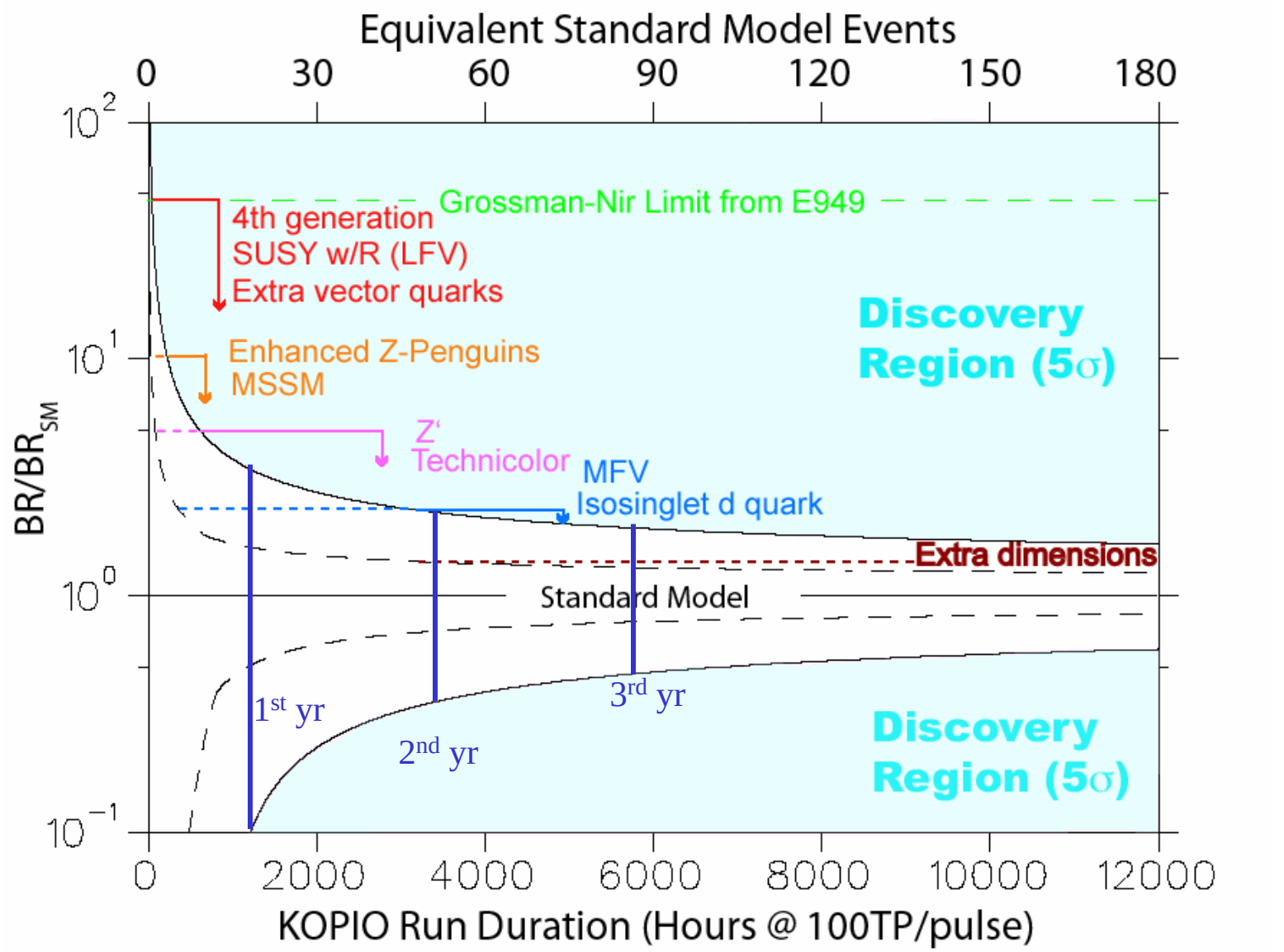
Optimized S/B vs. Signal (SM Events)



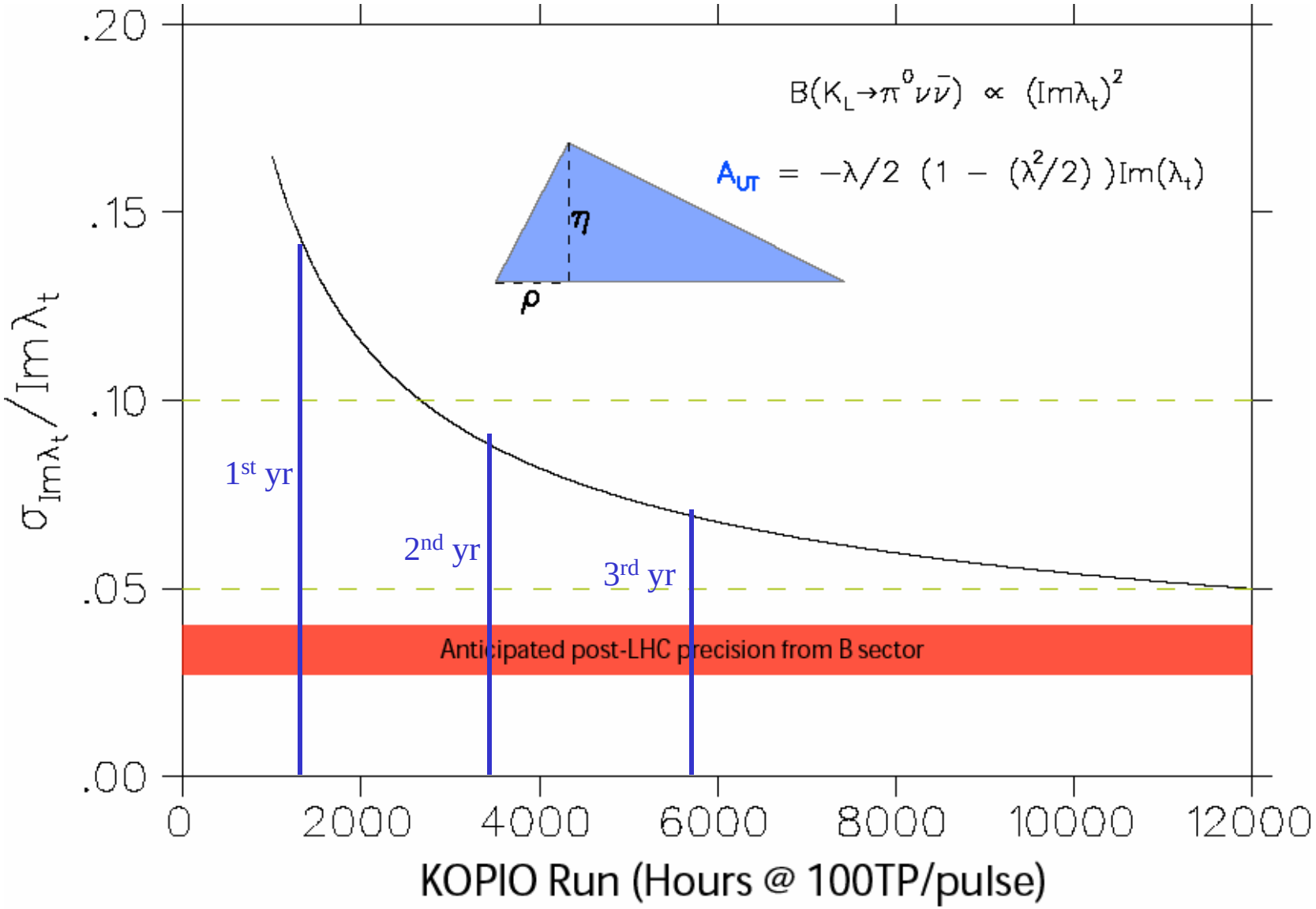
Standard Model Results for $B(K_L^0 \to \pi^0 \nu\nu)$

Events

Discovering/Constraining New Physics



KOPIO: SM Precision



Branching Ratio Measurement Precision Estimates

- Precision at $B(K_L^0 \to \pi^0 \nu \bar{\nu}) = 3.0 x 10^{-11}$

Using probability likelihood method employing all observed events (approximately 300):

$\pm 9\%$

- (Statistical) Precision on $\mathrm{Im}\,\lambda_t$: $\pm 5\%$

KOPIO Operations Plan

- 2010 Test Run – partial detector
- 2011 Engineering Run

  "Discovery phase": Sensitivity goal:~10^{-10}
- 2012-16 Data Acquisition

Summary and Outlook

$$K_L^0 \to \pi^0 \nu\bar{\nu} \quad \text{and} \quad K^+ \to \pi^+ \nu\bar{\nu}$$

- Extraordinary discovery potential for non-SM physics:

Unique connection with underlying short distance parameters.

- K^+ : E949 (3 events), Future: LOI's - new techniques
- K_L^0: KOPIO: 5σ discovery if Br $< 0.6\,\mathrm{Br}_{\mathrm{SM}}^{K_L^0 \to \pi^0 \nu\bar{\nu}}$, $> 1.7\,\mathrm{Br}_{\mathrm{SM}}^{K_L^0 \to \pi^0 \nu\bar{\nu}}$

Clean access to the CP-violating phases of new physics.

In the absence of new physics, precision on Im λ_t: <5%;

Access to very high mass scales!



