Rare Opportunities:
Seeking New Physics with Rare Decays of Light Particles

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"Rare Opportunities" Outline

Lecture I

- Introduction and Overview
- Motivation from theory for modern studies of rare μ, π, and K decays; access to new physics at high mass scales.
- Experiments and experimental techniques for high precision and high sensitivity measurements of rare and ultra-rare processes:

Muons: $\mu \to e\gamma$, Nuclear $\mu \to$ e conversion

Pions: $\pi^+ \to e^+\nu / \pi^+ \to \mu^+\nu$ Branching ratio

Lecture II

Kaons: $K^+ \to e^+\nu / K^+ \to \mu^+\nu$

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

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

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,…

***LHC*: Direct exploration of the TeV energy scale.**
***Flavor Physics* (e.g. Rare Decays):**
Explore the symmetry properties of new degrees of freedom at high mass scales "1-1000 TeV".

The Flavor Puzzle

Quarks

u	c	t
d	**s**	b

Leptons

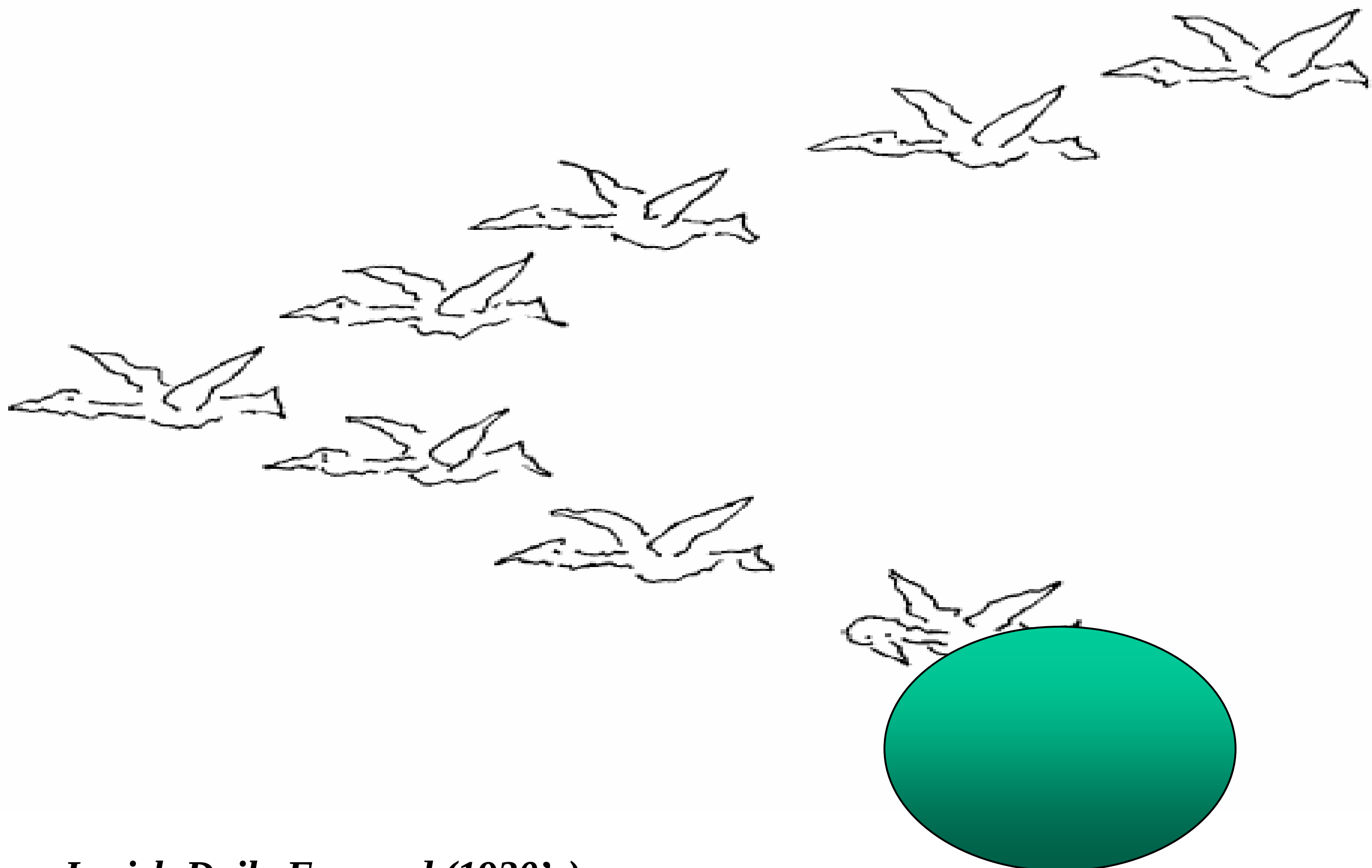
e	μ	τ
ν_e	ν_μ	ν_τ

- Weak states $\nLeftrightarrow$ mass states
- Quark, lepton flavors not conserved
- Three flavors $\Rightarrow$ **CP violation**, BAU,…

Unexplained observations (no theory of flavor):

- Huge mass differences between and within the generations
- Universality of interactions
- Symmetry between lepton and quark sectors

Seeking Answers with Rare Decays



Cartoon from Jewish Daily Forward (1920's)

Overview of Light Particle Rare Decay Experiments

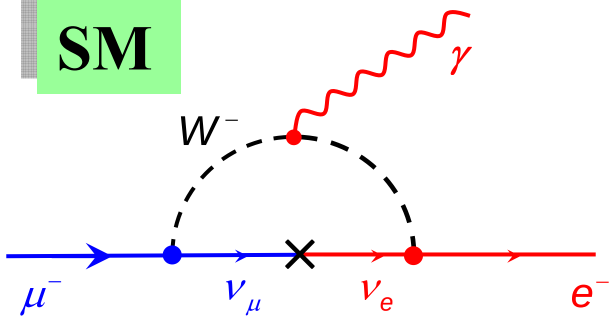
State of the art: single event sensitivity, 10^{-12}

Exotic Searches *New physics if seen; SM effects are negligible.*	$K_L^0 \to \mu\, e$	Lepton Flavor Violation	<4.7 10^{-12}
	$\mu \to e\gamma$	*LFV*	<1.2 10^{-11}
	$\mu^- N \to e^- N$	*LFV*	<7.8 10^{-13}
	$K^+ \to \pi^+ f$	"*Axions*"	
SM Parameters and BSM Physics *New physics if deviations from* ***well-calculated*** *SM predictions occur.*	$\dfrac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$	Lepton Universality	**10^{-4}: 4x10^5 events**
	$\pi^+ \to \pi^0 e\nu$	$\lvert V_{ud} \rvert$	
	$K_L^0 \to \mu^+ \mu^-$	$\lvert V_{td} \rvert$	**10^{-8}: 6200 events**
	$K^+ \to \pi^+ \nu \bar{\nu}$	$\lvert V_{td} \rvert$	**10^{-10}: 3events**
	$K_L^0 \to \pi^0 \nu \bar{\nu}$	*CP* violation	
Low Energy QCD Chiral Perturbation Theory	Radiative decays $K_L^0 \to ee$		**10^{-11}: 4 events**

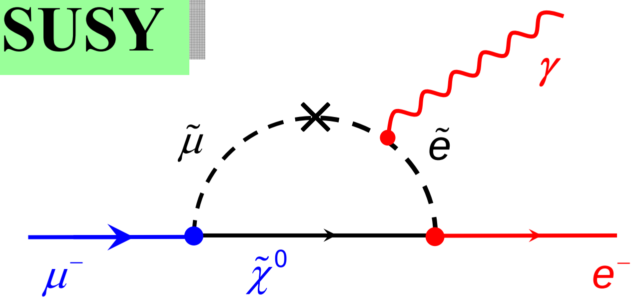
Flavor Violation in the Charged Lepton Sector

$$\mu \to e\gamma$$

SM



SUSY



$$\mathrm{BR}(\mu^- \to e^-\gamma)\big|_{\mathrm{SM}} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-60}$$

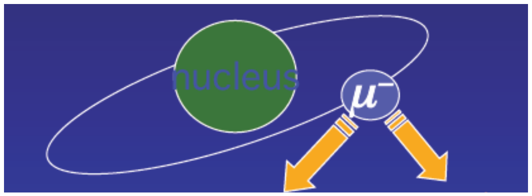
$$\mathrm{BR}(\mu^- \to e^-\gamma)\big|_{\mathrm{SUSY}} \approx 10^{-5}\, \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\bar{m}^2_{\tilde{\ell}}} \left(\frac{100\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^4 \tan^2\beta \approx 10^{-12}$$

$\{\tan\beta \sim$ ratio of <H> for 2 Higgs doublets$\}$

- Observation means new physics.
- Some SUSY models predict BR($\mu \to e\gamma$) near the experimental limit.

S. Ritt PSI

$\mu \rightarrow e$ Conversion



Muon Capture
$\mu^-(N,Z) \rightarrow \nu_\mu(N,Z-1)$

Decay in orbit
$\mu \rightarrow e\nu\bar{\nu}$

Or?

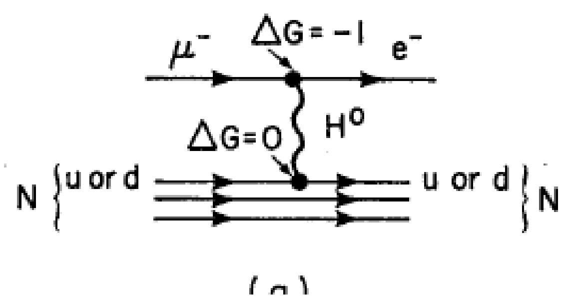
$\mu^- \rightarrow e^-$ *Conversion*

$\mu^-(N,Z) \rightarrow e^-(N,Z)$

Momentum $P_e = m_\mu - b.e. \sim 100 MeV/c$

Coherent, Neutrinoless

Sensitive to a wide variety of models at high mass scales: Non-diagonal Z-μe, H-μe couplings, horizontal gauge bosons, heavy neutrino mixing, …



$$\frac{\Gamma(\mu^-(N,Z) \rightarrow e^-(N,Z))}{\Gamma(\mu^-(N,Z) \rightarrow \nu(N,Z-1))} \sim \frac{1}{(M_H)^4}$$

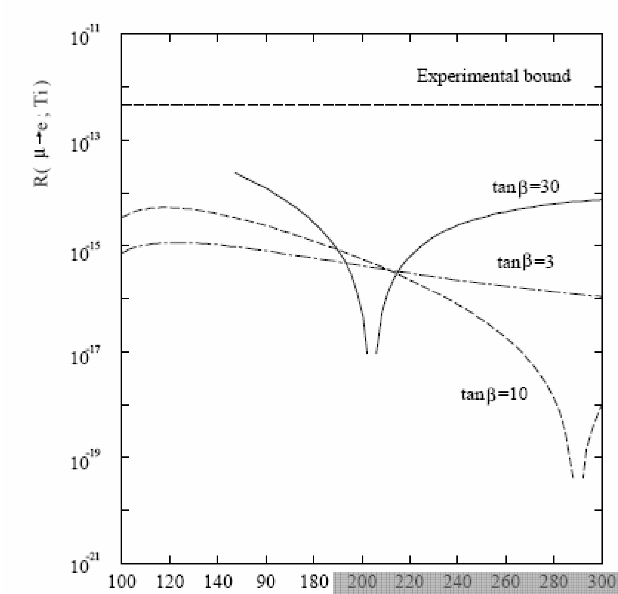
Current limits $\rightarrow M_H > 340\, TeV$

Updated from Cahn and Harari (1980).

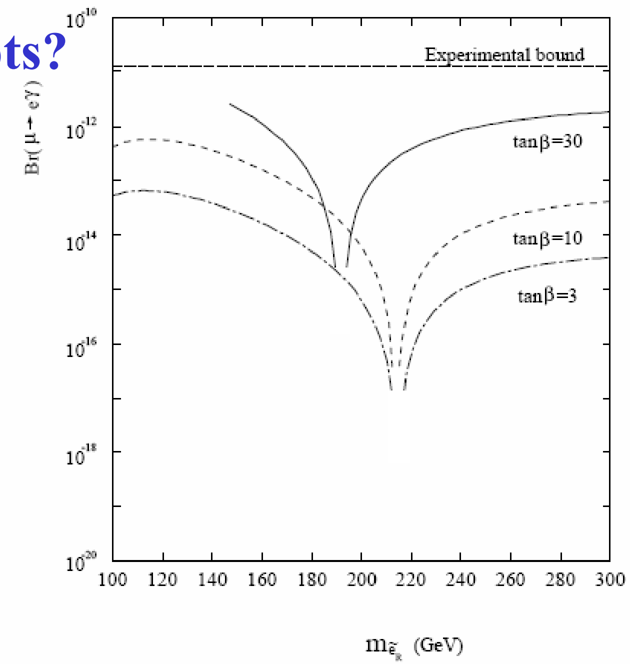
Branching Ratios for $\mu \rightarrow e$ Conversion and $\mu \rightarrow e\gamma$ in a Minimal Supersymmetric Model (MSSM)

$R(\mu^- Ti \rightarrow e^- Ti)$

$R(\mu \rightarrow e\gamma)$



Future expts?



Slepton Mass (GeV)

Process	Current Limit	SUSY-GUT level
μ N → e N	10^{-13}	10^{-16}
μ → e γ	10^{-11}	10^{-14}
τ → μ γ	10^{-6}	10^{-9}

{tan β ~ ratio of <H> for 2 Higgs doublets}

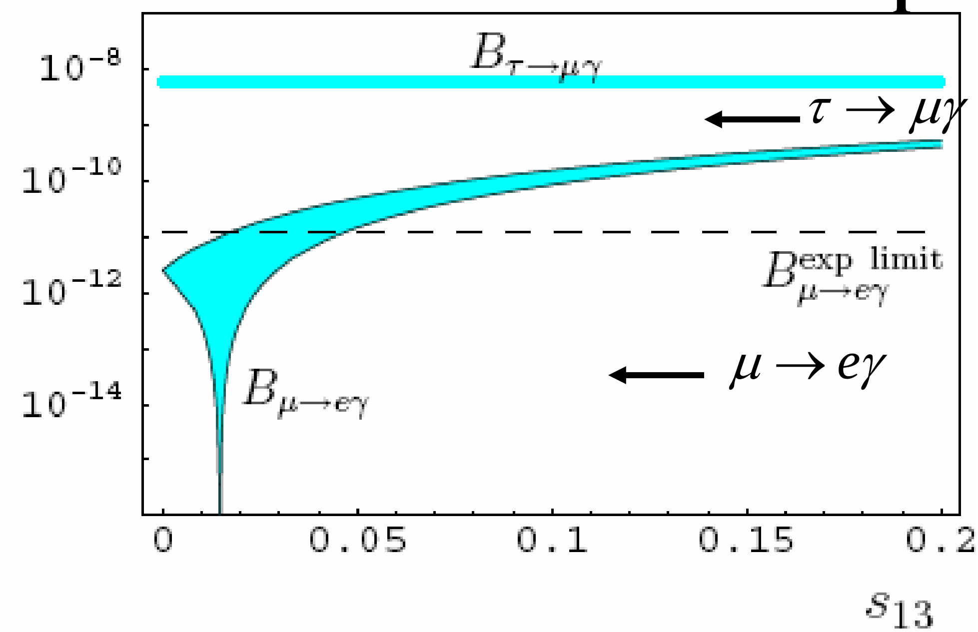
J. Hisano et al., Phys. Lett. B391, 341 (1997).

V. Cirigliano, B. Grinstein, G. Isidori and M. B. Wise (2005); Isidori FPCP (2006).

$\mu \to e\gamma\,/\,\mu - e$ Conversion vs. $\tau \to \mu\gamma$?

Example new physics theory**: Lepton number violation, flavor violation decoupled; Heavy rt-handed neutrinos. LFV in the charged sector related to neutrino mixing matrix.**

Future expts?



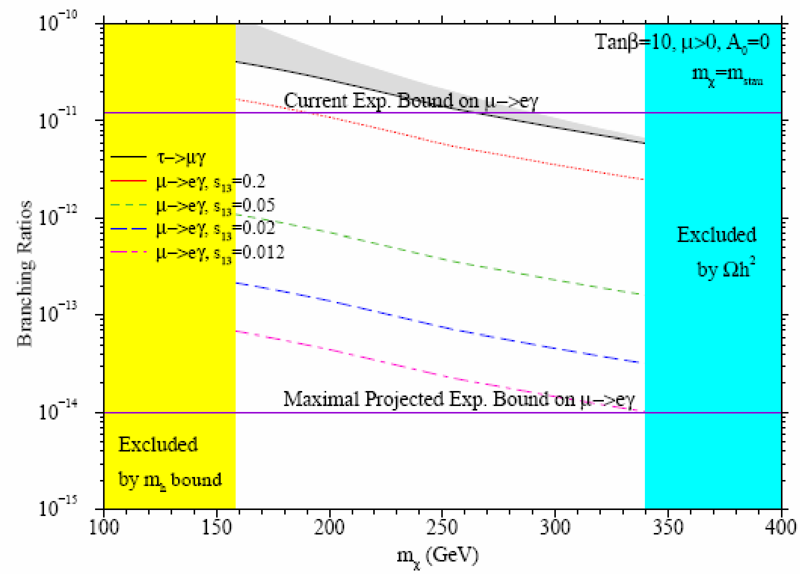
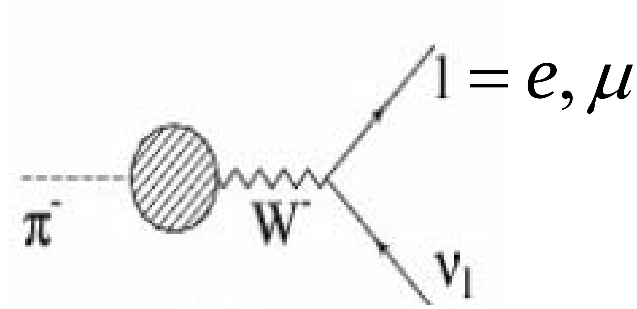


Figure 4: Isolevel curves for $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$ in the MSSM (for $\tan\beta = 10$, $\mu > 0$ and $A_0 = 0$) compared with the present and future experimental resolution on $\mathcal{B}(\mu \to e\gamma)$ [35].

Limits on $\mu \to e\gamma$ & $\mu - e$ Conversion rule out observable $\tau \to \mu\gamma$ in many theories.

$\pi^+ \to e^+ \nu$

Important Element of the SM Story*

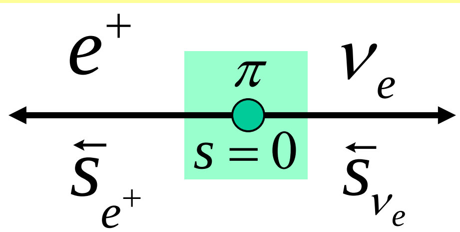


SM $V - A$ Hamiltonian: $(\pi / K) \to l\nu_l$

$$H = \left(\frac{g^2 V_{ud}}{8m_W^2}\right) \bar{l}\gamma_\lambda (1-\gamma_5)\bar{\nu}_l \; \bar{u}\gamma^\lambda (1-\gamma_5) d$$

$$= \left(\frac{g^2 V_{ud}}{8m_W^2}\right) \bar{l}\gamma_\lambda (1-\gamma_5)\bar{\nu}_l \; \bar{u}\gamma^\lambda \gamma_5 d$$

Helicity suppression



Decay Rate: $\pi(K) \to l\nu_l$

$$\Gamma(\pi \to l\nu_l) = \left(\frac{g^2 V_{ud}}{8m_W^2}\right)^2 \frac{m_\pi}{4\pi} f_\pi^2 m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2$$

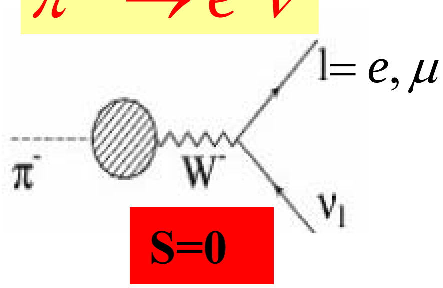
f_π defined via: $\langle 0 | \bar{d}\gamma_\lambda \gamma_5 u | \pi^+(p)\rangle = i f_\pi p_\lambda$

$e-\mu-\tau$ Lepton Universality

Standard Model: e,μ,τ have identical electroweak gauge interactions.

Differ only in mass and coupling to Higgs boson.

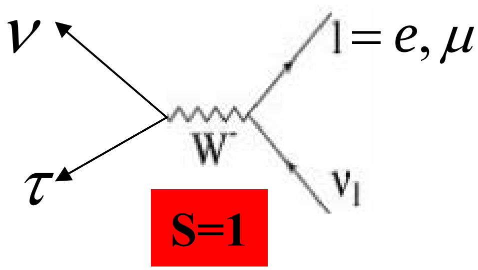
$\pi^+ \to e^+\nu$



$$R^0_{e/\mu} \equiv \frac{\Gamma(\pi^+ \to e^+\nu)}{\Gamma(\pi^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2} \frac{\left(1-\frac{m_e^2}{m_\pi^2}\right)}{\left(1-\frac{m_\mu^2}{m_\pi^2}\right)} = 1.284x10^{-4}$$

Independent of f_π, V_{ud}.

$\tau^+ \to l^+\nu\bar{\nu}$



$$R^\tau_{e/\mu} = (1-\frac{8m_\mu^2}{m_\tau^2}...) = 1.0282$$

Unless... new physics does not respect universality.

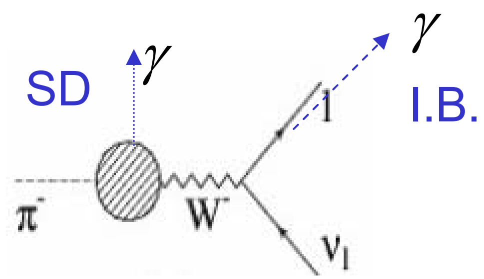
Universality Tests

Mode	g_e/g_μ
$\pi \to e\nu / \pi \to \mu\nu$	0.9985 ± 0.0016
$K \to e\nu / K \to \mu\nu$	1.012 ± 0.010
$\tau \to e\nu\nu / \tau \to \mu\nu\nu$	0.9999 ± 0.0021
$\nu e / \nu\mu$ scattering	1.10 ± 0.05
W decays	0.999 ± 0.011

Kinoshita (1959), **Marciano and Sirlin** (1976, 1995), Finkemeir (1995)

$\pi^+ \rightarrow e^+\nu$

Radiative Corrections; Inner Bremsstrahlung; and Structure-Dependent Radiation:



$$\Gamma(\pi \to l\bar{\nu}_l(\gamma)) = \frac{G_\mu^2 |V_{ud}|^2}{8\pi} f_\pi^2 m_\pi m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2 \left[1 + \frac{2\alpha}{\pi}\ln\left(\frac{m_Z}{m_\rho}\right)\right]_\gamma$$

$$\times \left[1 - \frac{\alpha}{\pi}\left\{\frac{3}{2}\ln\left(\frac{m_\rho}{m_\pi}\right) + C_1 + C_2\frac{m_l^2}{m_\rho^2}\ln\frac{m_\rho^2}{m_l^2} + C_3\frac{m_l^2}{m_\rho^2} + \cdots\right\}\right]\left[1 + \frac{\alpha}{\pi}F(x)\right]$$

-4% for l=e

$$\left[+\pi \ \text{ Structure-dependent } \pi^+ \to e^+\nu\gamma \text{ terms}\right]$$

where $G_\mu = 1.16637(1)\times 10^{-5}\, GeV^{-2},\ V_{ud} = 0.9738$

But, most factors cancel in the ratio

$$R^{th}_{e/\mu} = \frac{\Gamma\left(\pi \to e\nu + \pi \to e\nu\gamma\right)}{\Gamma\left(\pi \to \mu\nu + \pi \to \mu\nu\gamma\right)}$$

$$R^{th}_{e/\mu} = R^{0}_{e/\mu}\left\{1 + \frac{\alpha}{\pi}\left[F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + C_2\frac{m_\mu^2}{m_\rho^2}\ln\frac{m_\rho^2}{m_\mu^2} + C_3\frac{m_\mu^2}{m_\rho^2}\right]\left(+SD_\pi\right)\right.$$

$8x10^{-8}$

F : kinematic factors

C_2=3.1 (Terent'ev)

C_3 : Small but
Model dependent
Marciano : 0 ± 10

Pure Structure Dependent (SD) $\pi \to e\nu\gamma$ corrections are not helicity suppressed but are small and known for π decay:

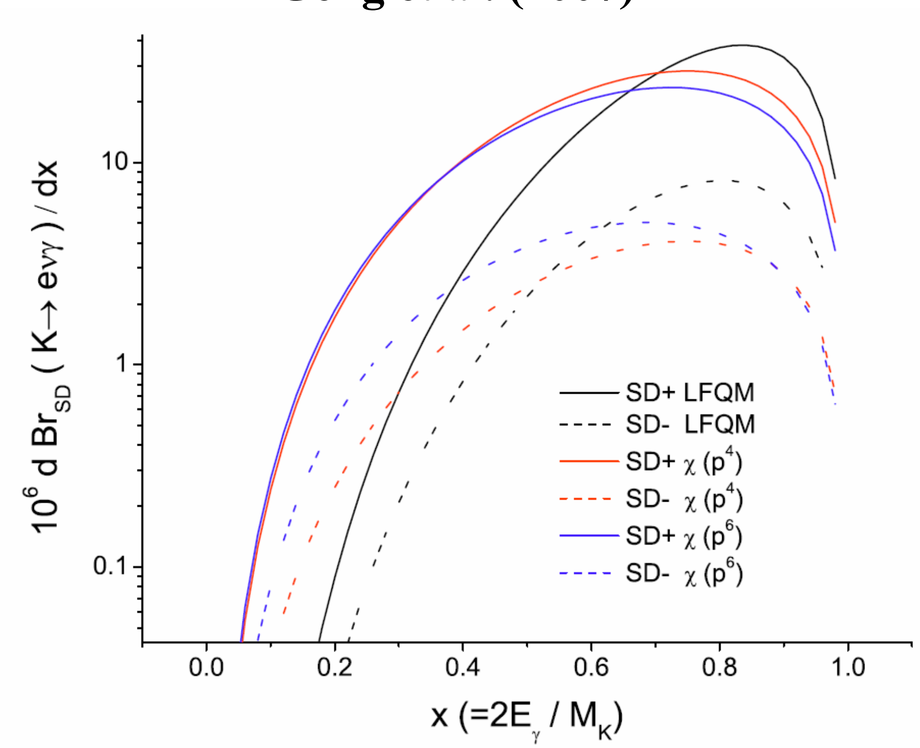
Structure Dependent Radiation in $K \to e\ \nu\gamma$ Decay

SD radiation: Not Helicity Suppressed; Large effect for $K \to e\,\nu$

$$\Gamma(K \to e\,\nu\gamma_{SD}) \sim \Gamma(K \to e\,\nu + K \to e\,\nu\gamma_{IB})$$

Calculated in Chiral Perturbation Theory CHPT $O(p^4)$ (Bijnens, Ecker, Gasser,1992) and CHPT $O(p^6)$ and Light Front Quark Model(Geng et al. 2007, 1998*)

Geng et al. (2007)



Form Factors

$SD^+ : V + A$

$SD^- : V - A$

Interference

Rates	SD^+ (x10^{-5})	SD^- (x10^{-6})
CHPT $O(p^4)$	1.5	1.9
CHPT $O(p^6)$	1.4	1.1
LFQM	1.6	2.9
Experiment	1.52 ± 0.23	< 1600

*Phys. Rev. D 57, 5697 - 5702 (1998)

$\pi^+ \to e^+ \nu$

$$R^{th}_{e/\mu} = \left(1.2353 \pm 0.0004\right) x10^{-4}$$

(Marciano 2005) $\rightarrow \pm 0.0001?$

The most accurately calculated decay process involving hadrons (*and "could be better" W. M.*).

$K^+ \to e^+ \nu$

$$R^{th}_{K \to e/\mu} = \left(2.472 \pm 0.001^*\right) x10^{-5}$$

Finkemeier (1995)

Helicity suppression 5x $\pi^+ \to e^+ \nu$

*Optimistic?

Structure dependent radiation not included.

Experiments

$\pi \to e\nu$

$R_{e/\mu}^{\exp \pi}$ $(\pm 0.4\%)$

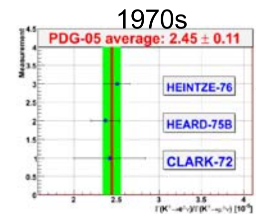
$1.2265(34)(44)x10^{-4}$ TRIUMF (1992)

$1.2346(35)(36)x10^{-4}$ PSI (1993)

$$R_{e/\mu}^{th} - R_{e/\mu}^{\exp} = 43(37)x10^{-8}$$

$K \to e\nu / K \to \mu\nu$

$R_{e/\mu}^{\exp K}$ $(\pm 2\%)$



$2.45(11)x10^{-5}$

$2.416(43)(24)x10^{-5}$ CERN(2006)

$$R_{e/\mu}^{th} - R_{e/\mu}^{\exp} = 56(46)x10^{-8}$$

Two new $\pi \to e\nu$ experiments.

Goals: $\pm(5)x10^{-8}$ (0.05%)

KLOE: Stay tuned next week $(\pm 1-2\%?)$

New $K \to e\nu$ experiment.

Goal: $\pm(10)x10^{-8}$ (0.3%).

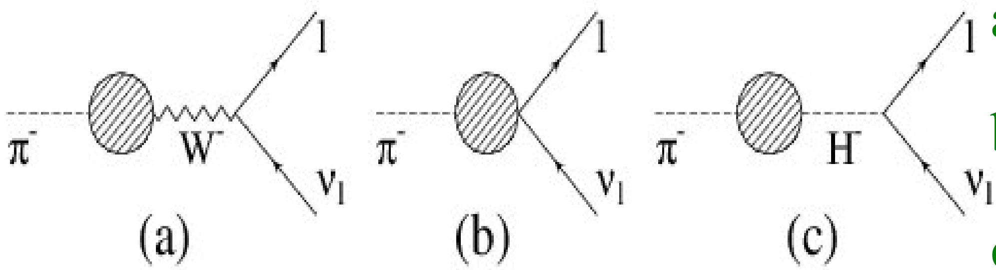
$\pi^+ \rightarrow e^+\nu$

Beyond the Standard Model

High Sensitivity to New **Pseudoscalar** Interactions which are not helicity suppressed.

PS contribution comes as interference with the axial-vector (dominant) interaction.

Effect is proportional to $1/\Lambda^2$ where Λ is the mass of the hypothetical particle.



a) – SM

b) – New four fermion interaction

c) – Charged Higgs

$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m^2_\pi}{m_e(m_d + m_u)} \sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3$$

0.05 % Measurement $\rightarrow$ Λ_{eP} >1000 TeV

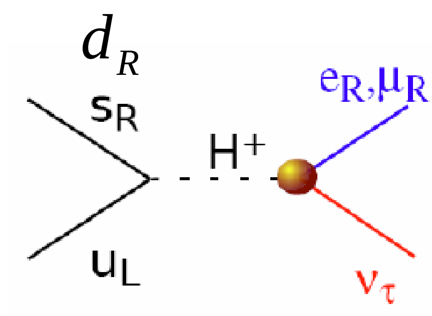
Charged Higgs mass $m_{H^\pm}$ ~200 TeV probed.

Marciano

Charged Higgs and Lepton Flavor Violation

Masiero, Paradisi, Petronzio, hep-ph/0511289 PRD74,(2006)

The unobserved neutrino involved in $\pi^+/K^+ \to e^+\nu$ decay may be ν_e, ν_μ, or ν_τ.



Low Energy SUSY (with R parity*); Large $\tan\beta$.

$$R_{e/\mu}^{NP} = R_{e/\mu}^{SM}\left(1+\Delta r_{NP}^{e/\mu}\right)$$

Current (Future) Experiments:

$\left|\Delta r_\pi^{e/\mu}\right| < 0.004\ (0.0003)$ $\left|\Delta r_K^{e/\mu}\right| < 0.06\ (0.005)$

i) FCNC $M \to l\nu_l;\ \ \Delta r_{NP}^{e/\mu} < 10^{-6}$

*R Parity (MSSM): $R=(-1)^{3B+L+2S}$

ii) Lepton Flavor Violation $\mathrm{M} \to l_i \nu_k; i(= e, \mu), \neq k(= \tau)$.

$$\Delta r^{e/\mu}_{SUSY} = \left(\frac{m_P}{m_H}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 \Delta_P^{(31)} \tan^6 \beta \qquad P = \pi, K$$

$$\leq O_K(0.01), \quad O_\pi(0.0003);$$

For $\Delta_P^{31} \sim 5 10^{-4}, \tan\beta \sim 40$

Effects (optimistically!) in range of planned experiments.

For the parameters above R($\tau \to \mu\gamma$)~10^{-10};

(Present experiment (Babar/Belle) R($\tau \to \mu / e\, \gamma$)<10^{-7}.)

Larger effects in B $\to$ lν, beyond reach of current experiments.

Campbell and Marbury (2003), Marciano

Scalar Interactions: $\pi \to e\nu$ vs. Super-allowed β Decay

$$\left\{\begin{array}{l} CKM \text{ Unitarity: } |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992(10) \\ R_{e/\mu} = \dfrac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))} = 1.231(4)x10^{-4}\ (now \to < 0.1\%) \end{array}\right\} 0.1\% \text{ Precision}$$

Constraining new Physics?

Direct Constraints

$$SM: \frac{G_\mu}{\sqrt{2}} \sim \frac{\pi}{2\Lambda_{SM}^2};\ \Lambda_{SM} \sim 440 GeV$$

$R_{e/\mu}$: $\Lambda_A \sim 20 TeV$, $\Lambda_P \sim 1000 TeV$ (!)

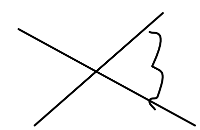
Unitarity: $\Lambda_V \sim 20 TeV$, $\Lambda_S \sim 12\ TeV$

Induced Current Constraints

$R_{e/\mu}$: $\Lambda_V \sim 2 TeV$, $\Lambda_S \sim 60 TeV$ (!)

Unitarity: $\Lambda_A \sim 2 TeV$

Loops



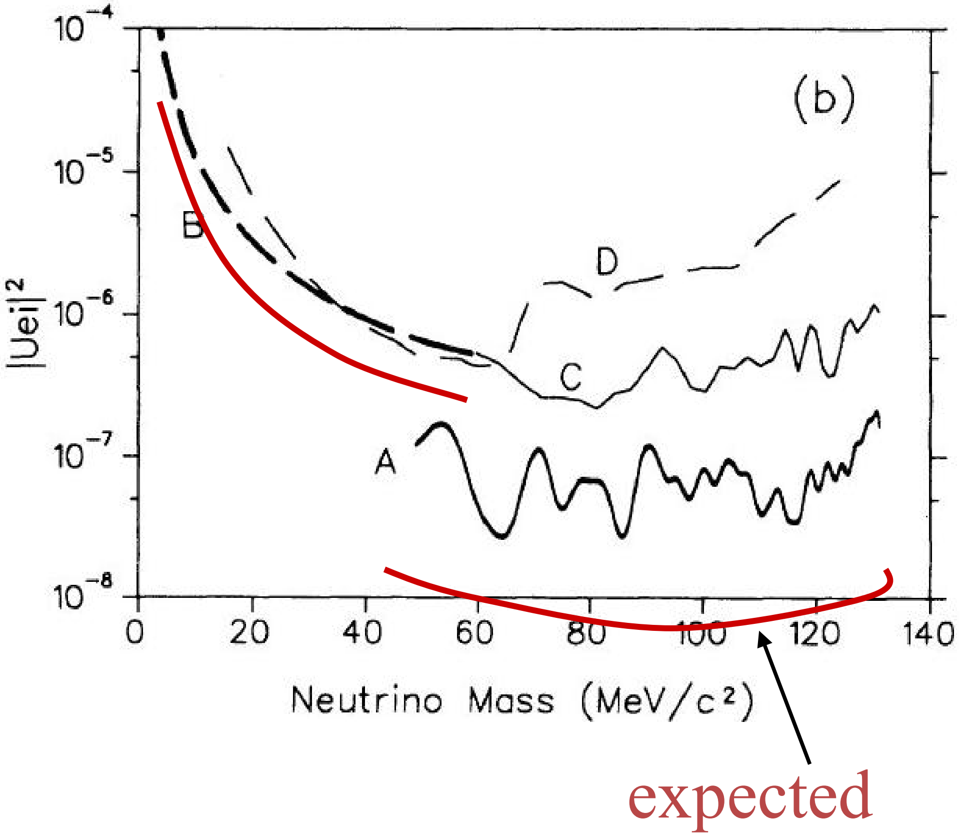
e.g. A induces V

P induces S

$\pi / K^+ \rightarrow e^+ \nu$

Other New Physics Possibilities:

Heavy ν



SM extensions:

-Leptoquarks

-Excited gauge bosons

-Compositeness

-*R-parity violating SUSY*

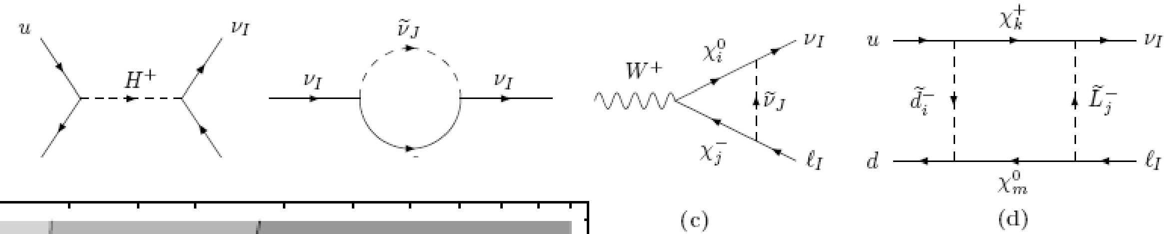
-Extra dimensions

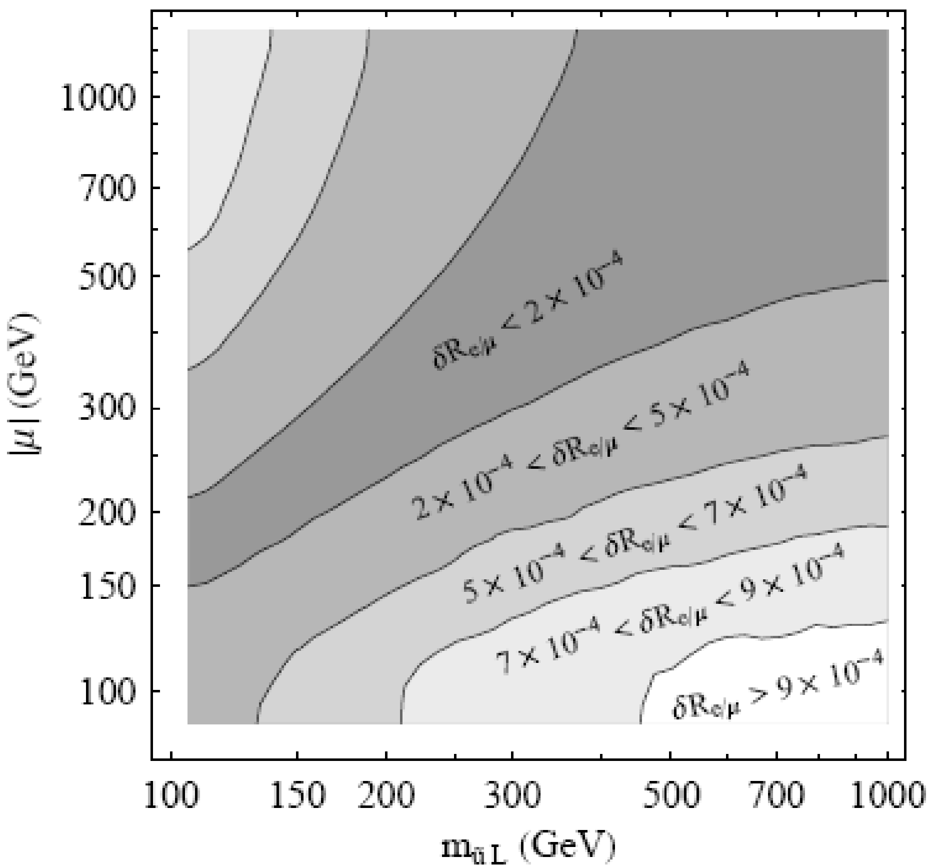
-ν Mass from QCD cond.
(Davoudias,Everett (2006))

- LFV (Isidori, Paradisi (2006)**)**

$\pi^+ \to e^+\nu$ Sensitive to R-Parity Violating MSSM

Ramsey-Musolf, Su, Tulin, arXiv:0705.0028 (2007)





μ vs. $m_{\tilde{u}_L}$

μ: Higgsino mass parameter

$m_{\tilde{u}_L}$: Mass of $\tilde{u}_L$

R Parity (MSSM): $R=(-1)^{3B+L+2S}$

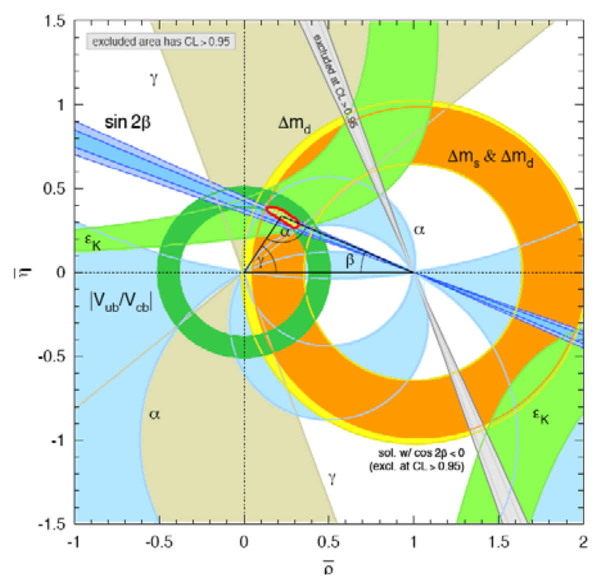
Quark Mixing: SM works well at the Electroweak Scale

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

Flavor degeneracy broken by Yukawa couplings
CKM quark mixing matrix:

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

Wolfenstein parameterization

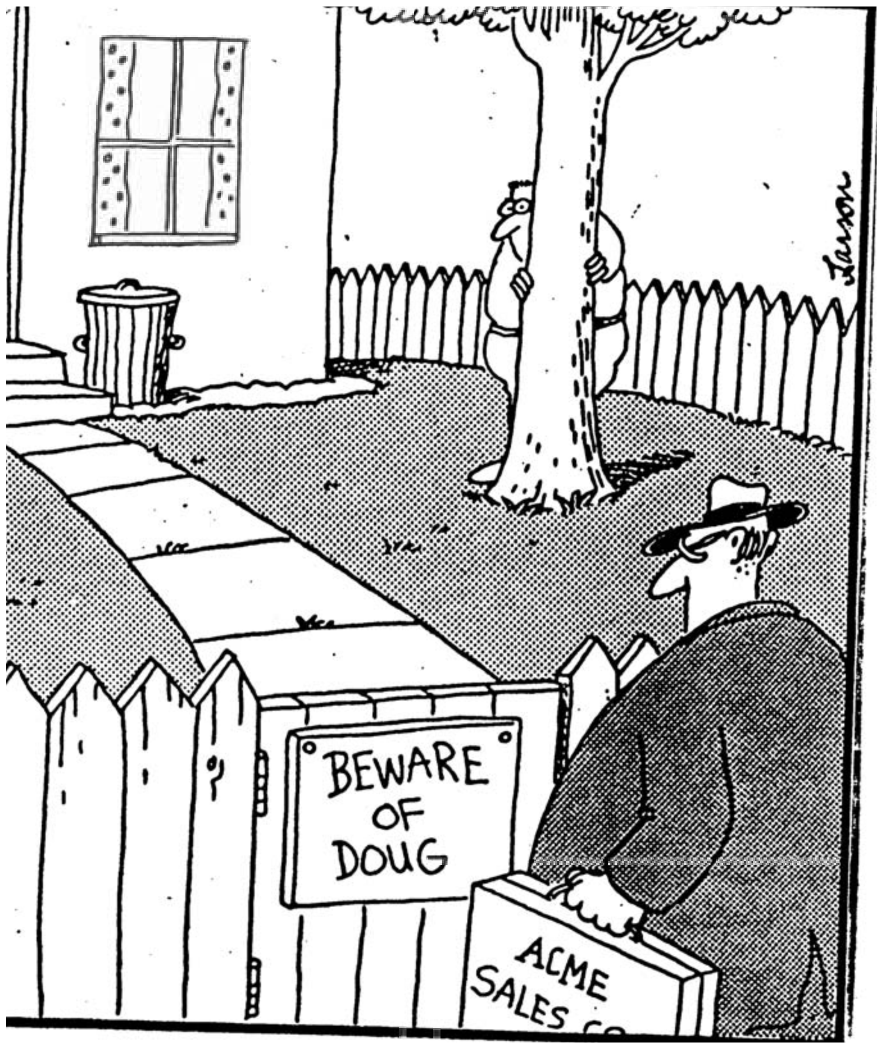


Review of Particle Prop. 2006

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

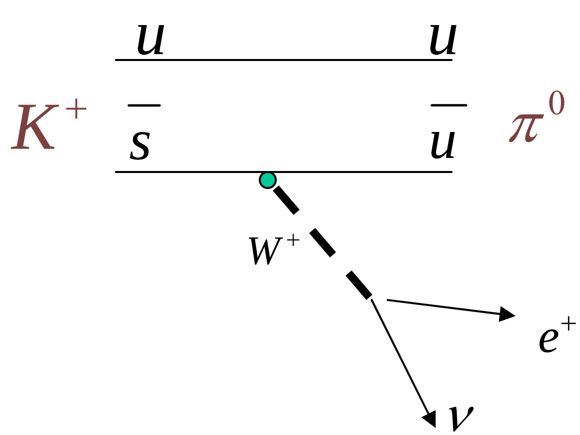
FCNC!

The case of the dog that didn't bark.

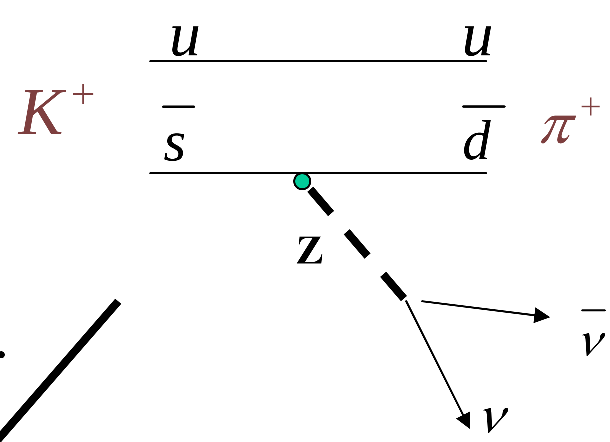


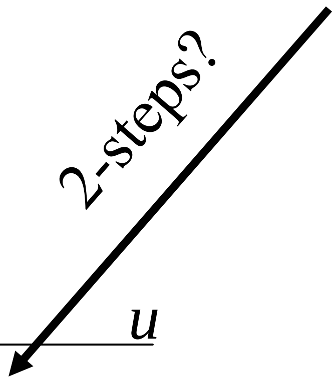
Kaon Milestones: *The G.I.M. Mechanism and Flavor-Changing Neutral Currents:*

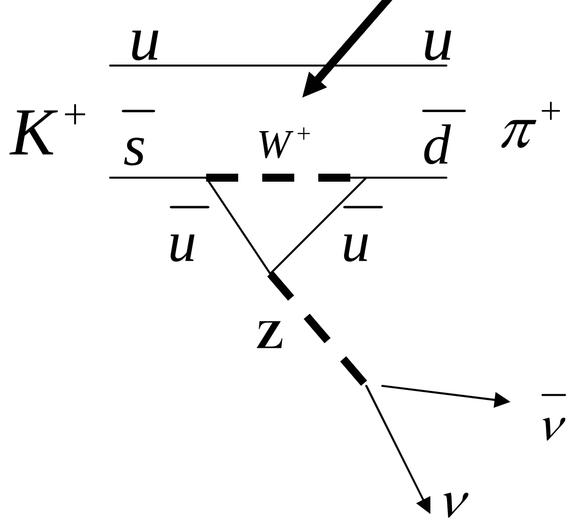
OBSERVED: $K^+ \rightarrow \pi^0 e^+ \nu$



ABSENT: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

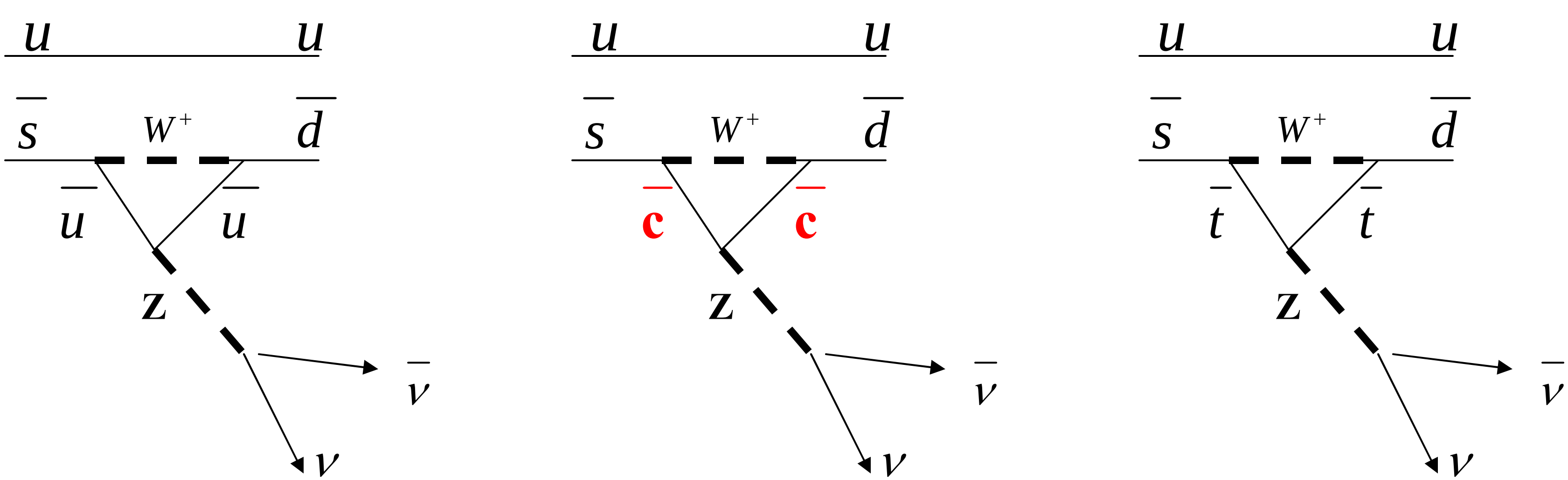






So, why wasn't it observed?

Glashow, **I**opolis, **M**iani "invented" the c quark to solve the problem:



$$V_{us}^{*}V_{ud} + V_{cs}^{*}V_{cd} + V_{ts}^{*}V_{td} = 0$$

Perfect cancellation only if

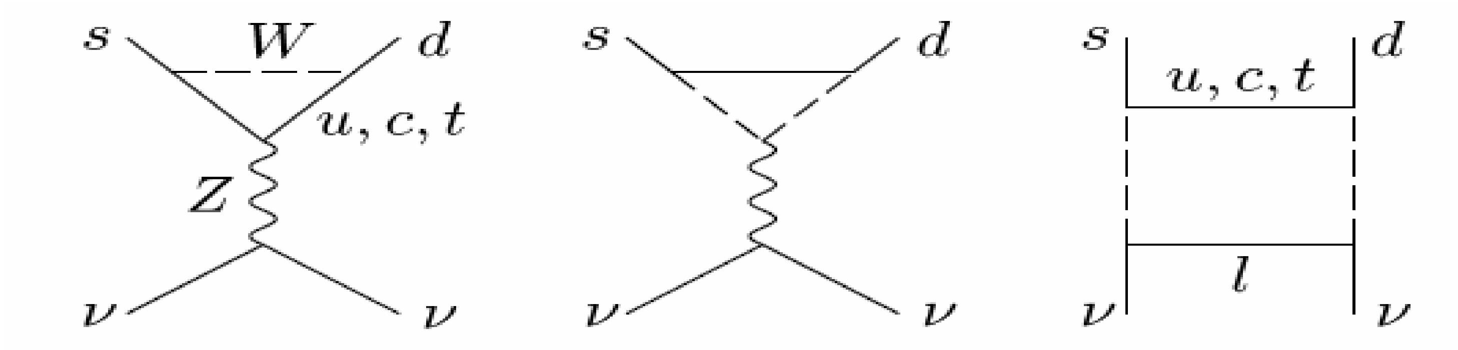
$m_u = m_c = m_t$

(0.0005, 1.5, 170 GeV)

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

should exist!

$K \rightarrow \pi \nu \bar{\nu}$ in the SM



"Jarlscog CP-violation parameter":

$\text{Im}\ \lambda_t = \text{Im}V_{ts}^{*}V_{td} = \eta A^2 \lambda^5$

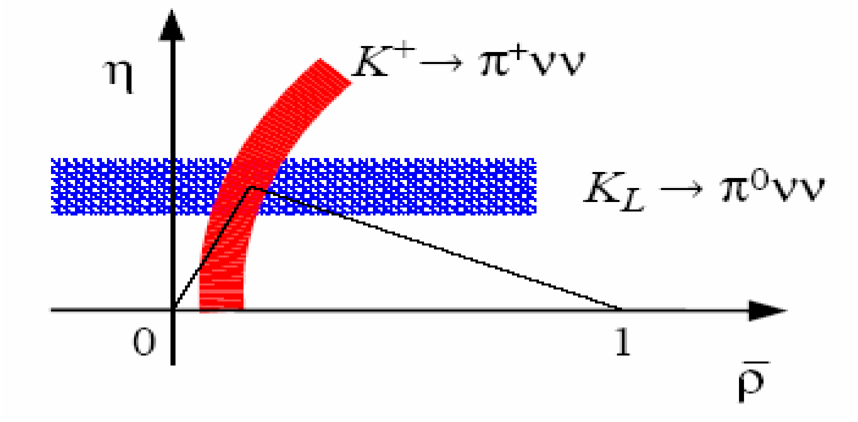
Precise SM Calculations (*Buras, et al.*):

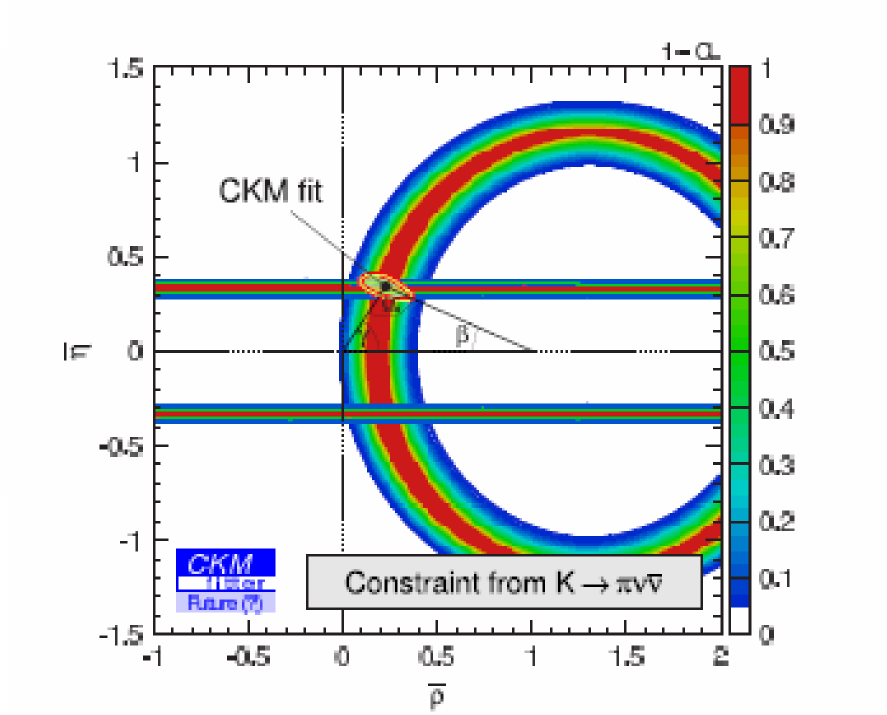
$$B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = 1.8\,x10^{-10} \left(\frac{\text{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 = 3.0 \pm 0.6\,x10^{-11}$$

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

K^+ uncertainty: m_C

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





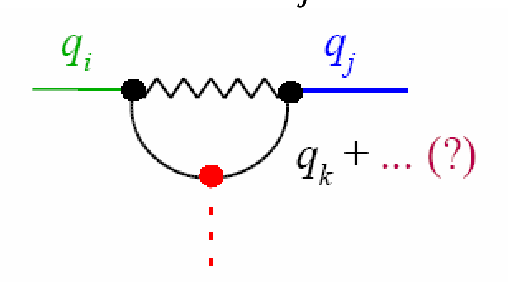
Constraints from 10% Measurements of $K \to \pi\nu\bar{\nu}$
(J.Charles et al., hep-ph/0406184, Eur. Phys. J. C41, 1 (2005), http://ckmfitter.in2p3.fr/ .

Rare Decays play key roles for SM parameters e.g. V_{us}.

***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

- **Dominated by direct CP violation in amplitude**
- **(K-K mixing effects negligible)**
- **Dominated by short distance physics**
- **No tree level contributions**
- **Suppressed by CKM hierarchy**
- ***Yield precise determination of CKM CPV phase***

BSM

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

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: Cutoff scale Λ [TeV], Symmetries

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

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

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

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

Most pessimistic new physics scenario:

"Minimal Flavor Violation"

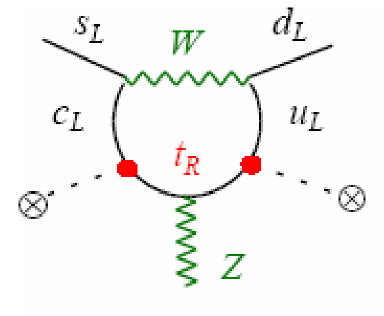
(Examples: Low energy SUSY, univ. extra dimensions,....) $\Lambda \sim$ TeV

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.

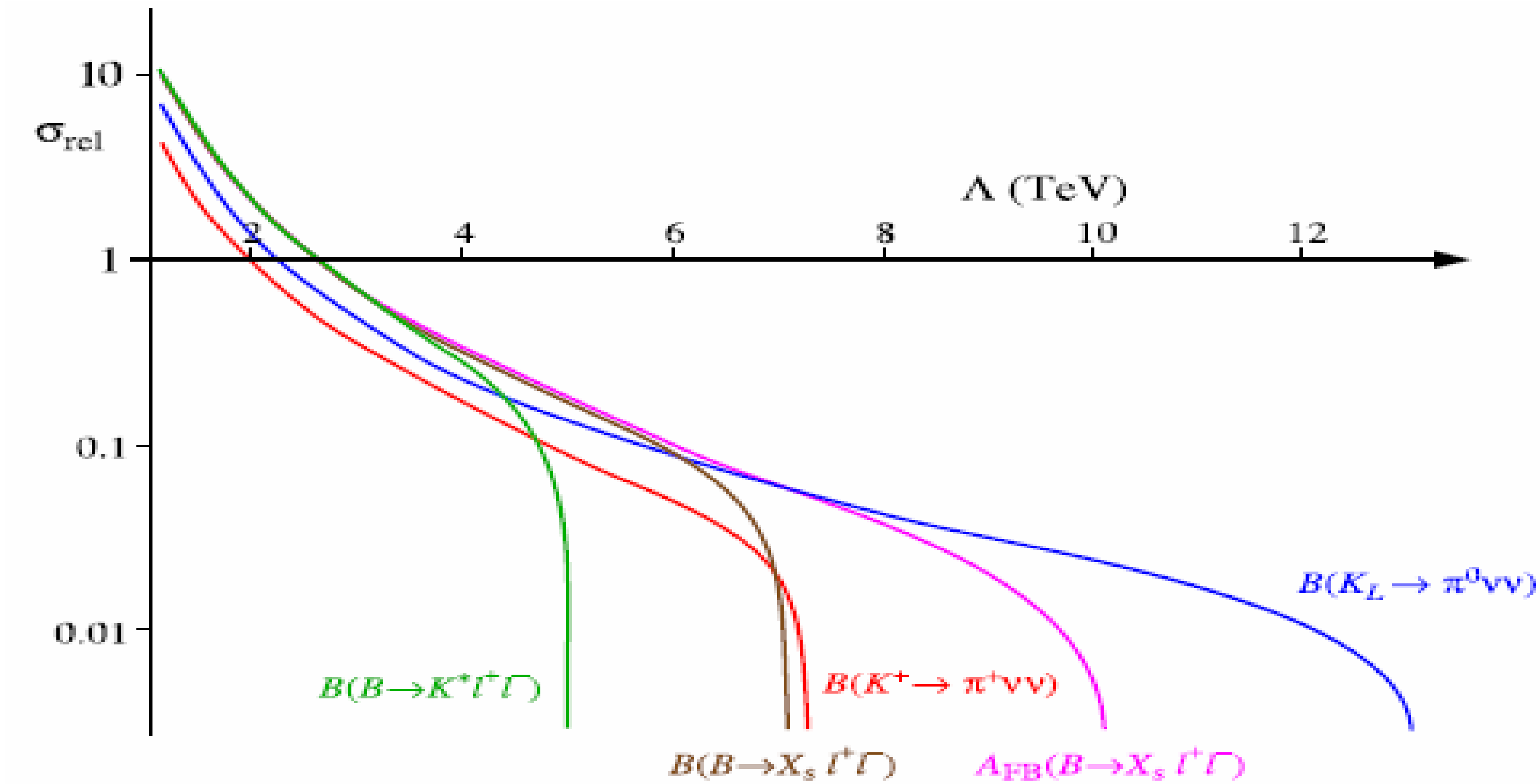


10% measurement of $K_L^0 \to \pi^0 \nu \bar{\nu}$ probes EW-Yukawa structure at the 5% level -- only a high luminosity linear collider could do better. [G. Isidori]

Comparative Sensitivity to New Physics in the 'Minimal Flavor Violation' Scenario

Precision

$\Lambda \sim \text{TeV}$



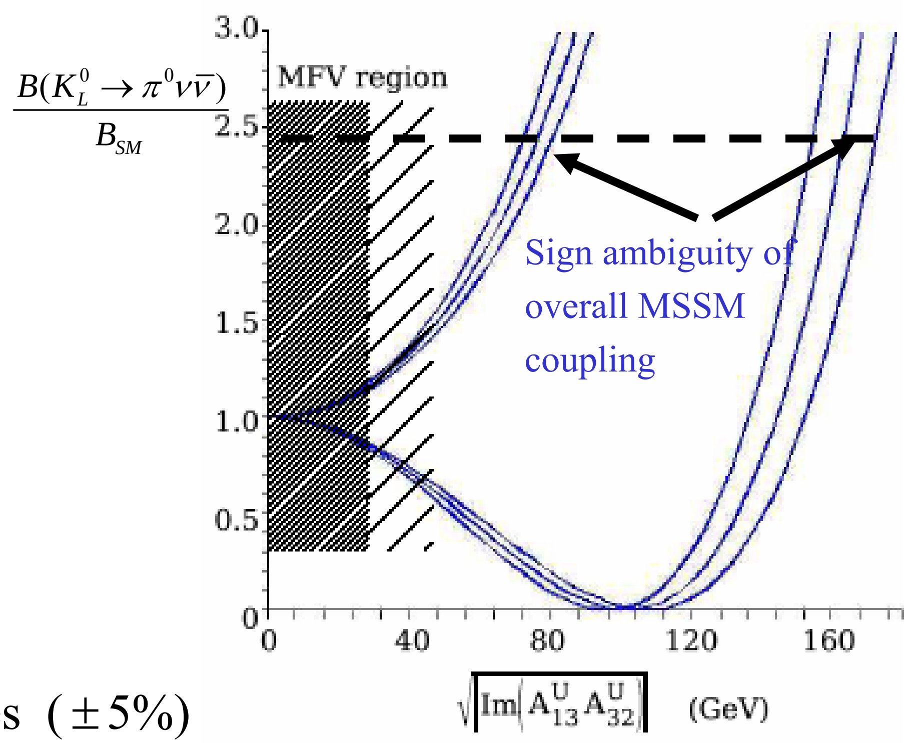
D'Ambrosio et al. 2002

Buras et al. Hep-ph/0408142, Isidori et al. (2006)

New Physics: 1-10 TeV Scale

Example: MSSM with generic flavor couplings

- **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**



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

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

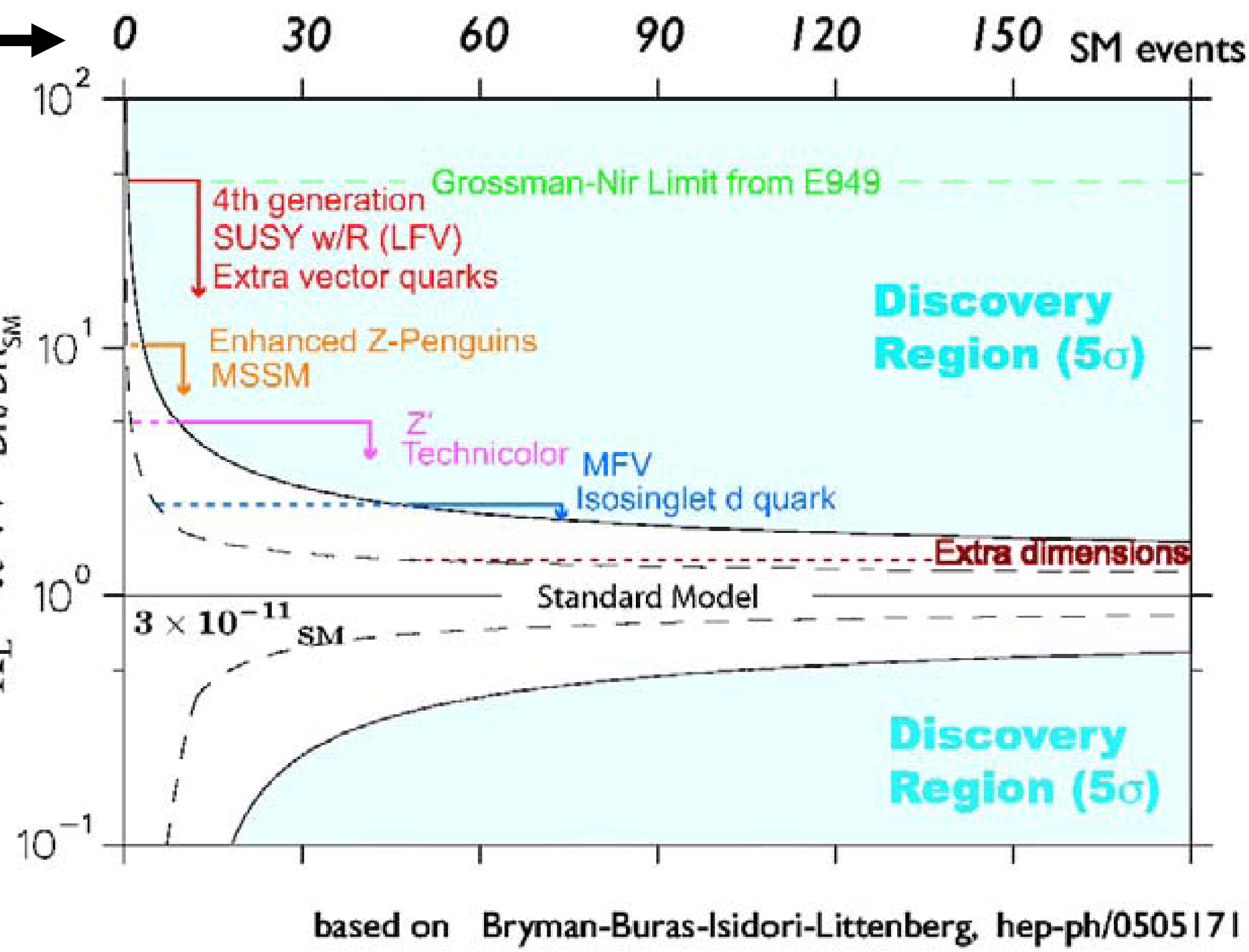
$\tilde{m}_{\chi^\pm} = 200\,GeV$

Soft breaking trilinear couplings squark & chargino masses fixed

$K_L^0 \to \pi^0 \nu \bar{\nu}$ Discovery Potential

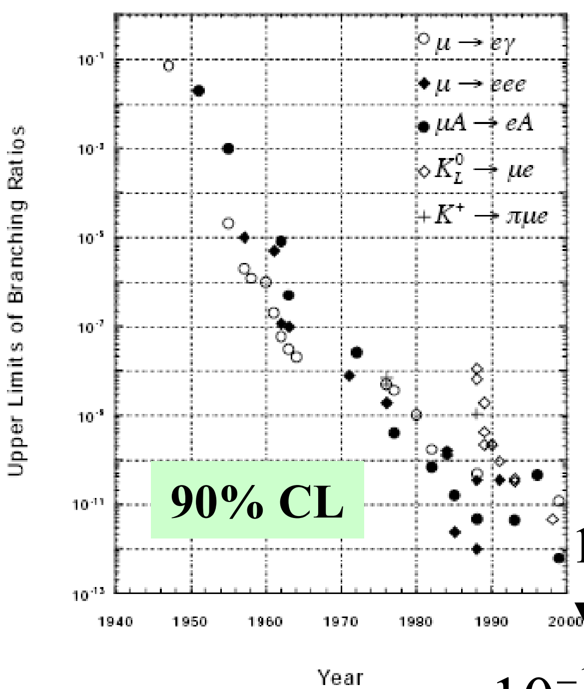
$K_L^0 \to \pi^0 \nu \bar{\nu}\,(BR / BR_{SM})$ vs. Events Observed

Experiment Sensitivity for SM



Experiments

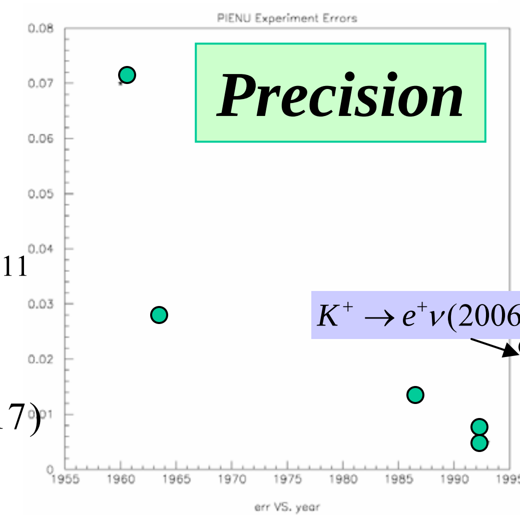
Lepton Flavor Violation



10^{-11}

$10^{-13(17)}$

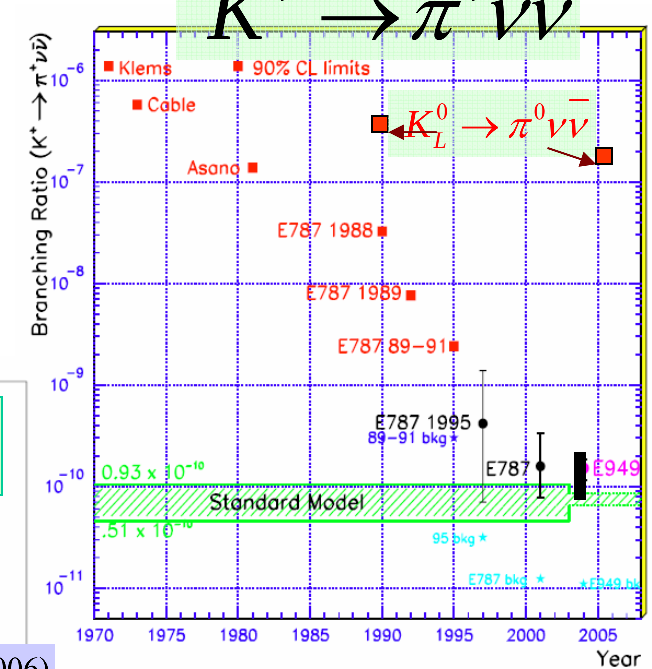
$\pi^+ \to e\nu$



0.4%

0.04%

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

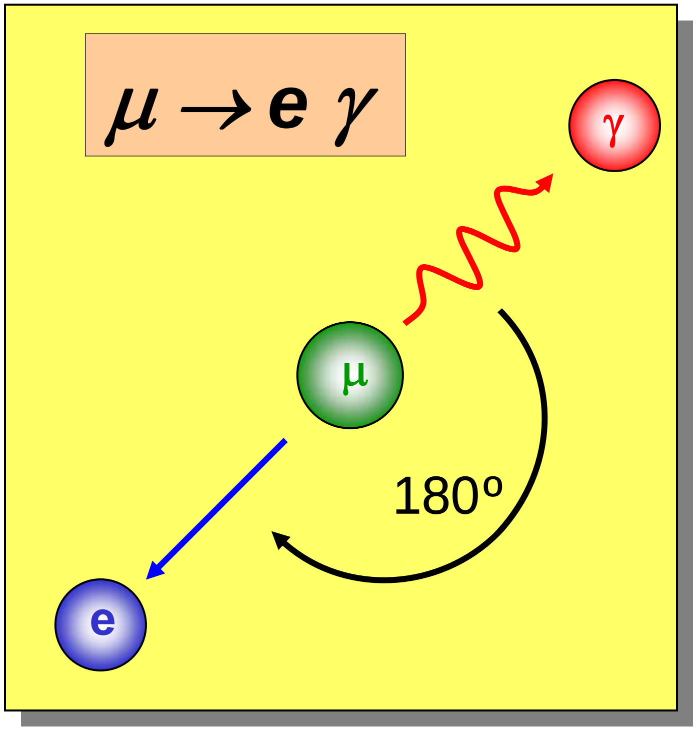


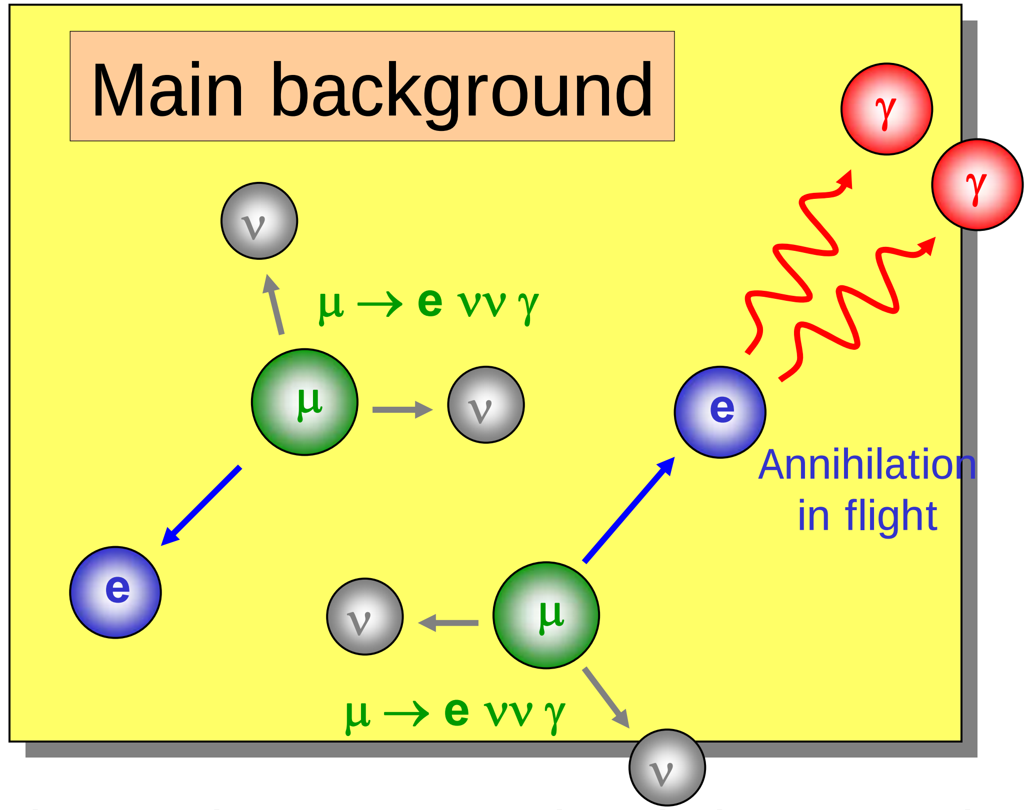
3

100

Decay topology

S. Ritt 2006





$\mu \to e\,\gamma$ signal very clean

- $E_g = E_e = 52.8$ MeV
- $\theta_{\gamma e} = 180^o$
- e and γ in time

Background: Energy, spatial, timing resolutions
Good pile-up rejection

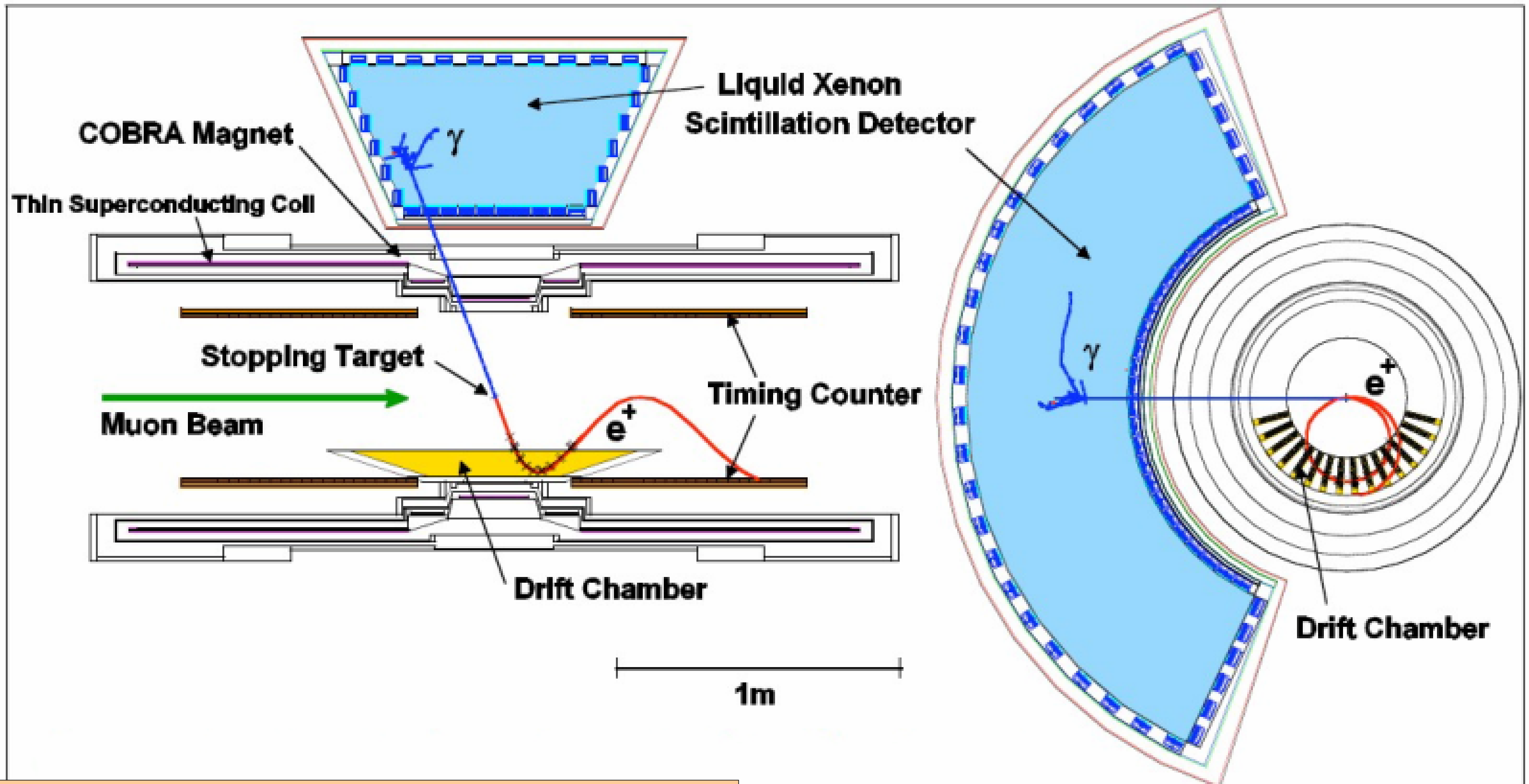
$$\Delta B(\mu \to e\gamma) = \left(\frac{R_\mu}{d}\Delta t\right)\left(\frac{\Delta E_e}{m_\mu/2}\right)\left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2\left(\frac{\Delta\theta}{2}\right)^2 f\left(\theta_\gamma\right)\eta_{IVB}$$

M. Ahmed et al. 2002

$\mu \rightarrow e\ \gamma$

MEG Experiment at PSI

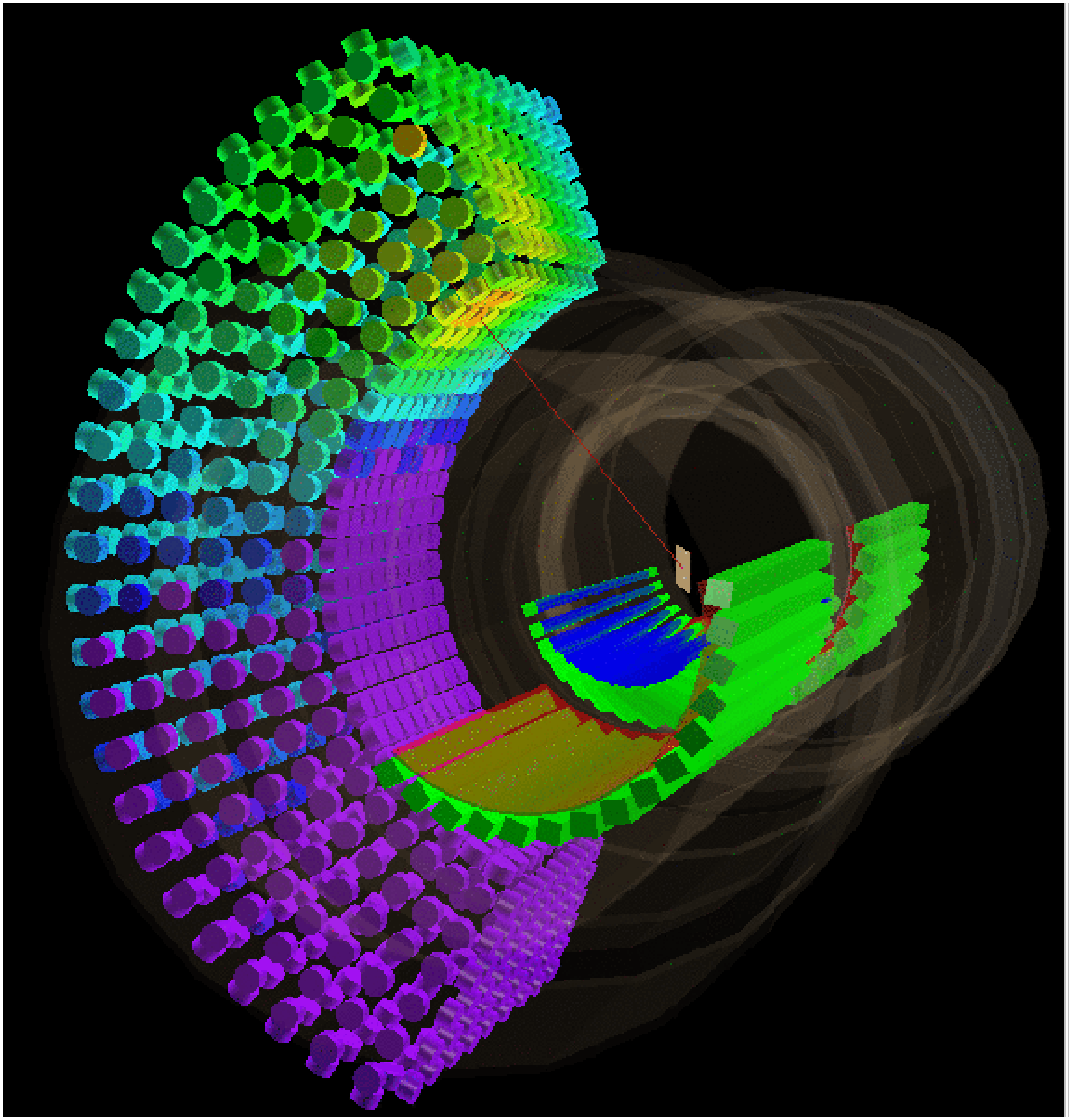
Goal (limit) <1.310^{-13} (0.01 x prev. exp)

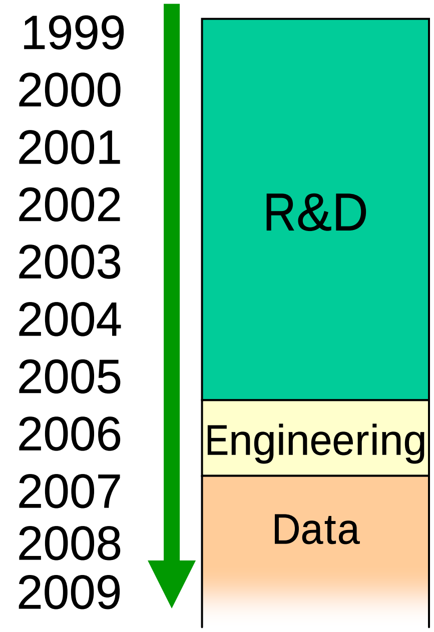


- $10^7 – 10^8$ μ/sec, 100% duty factor
- LXe for efficient γ detection
- Solenoidal magnetic spectrometer

Limitations: Accidental coincidences.

S. Ritt 2006





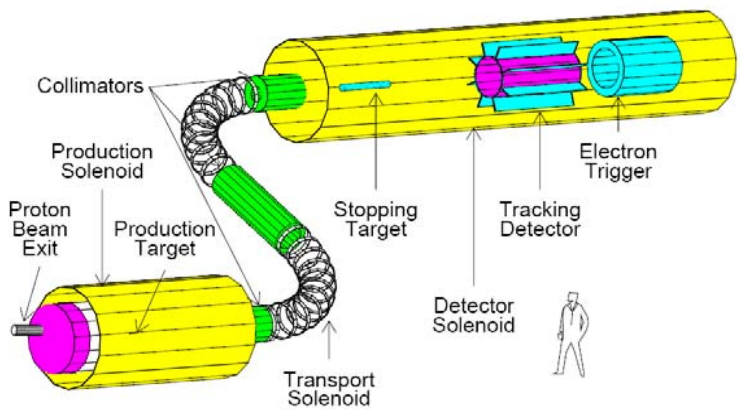
Plans

- Data taking from 2007 on to reach 10^{-13} sensitivity (90% CL)
- Obtain a “significant” result before the LHC era
- Eventual reach 10^{-14} during LHC era

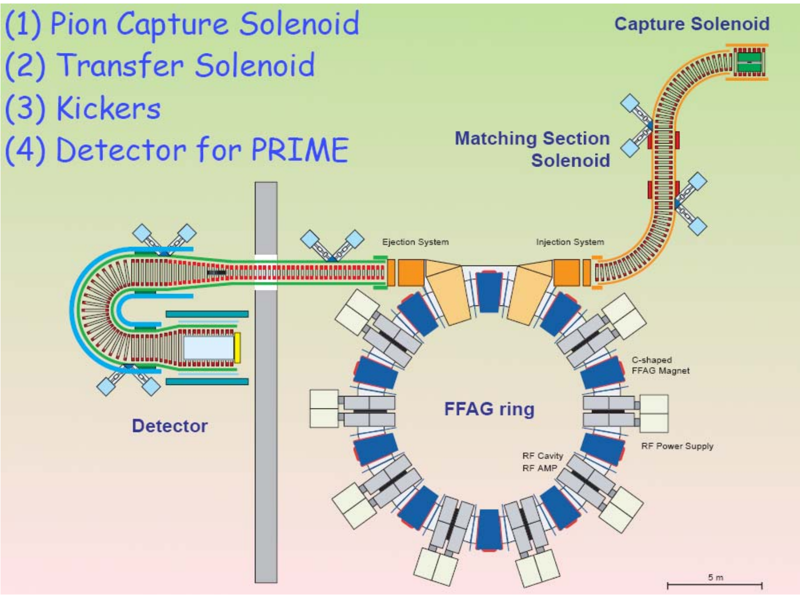
$\mu^- N \rightarrow e^- N$ Concepts: Sensitivity<10^{-17}

Lobashov (1980): Solenoidal Pion Collector; μ Flux x 1000.

MECO proposal



PRISM Concept (JPARC LOI Cooled beam (Kuno)

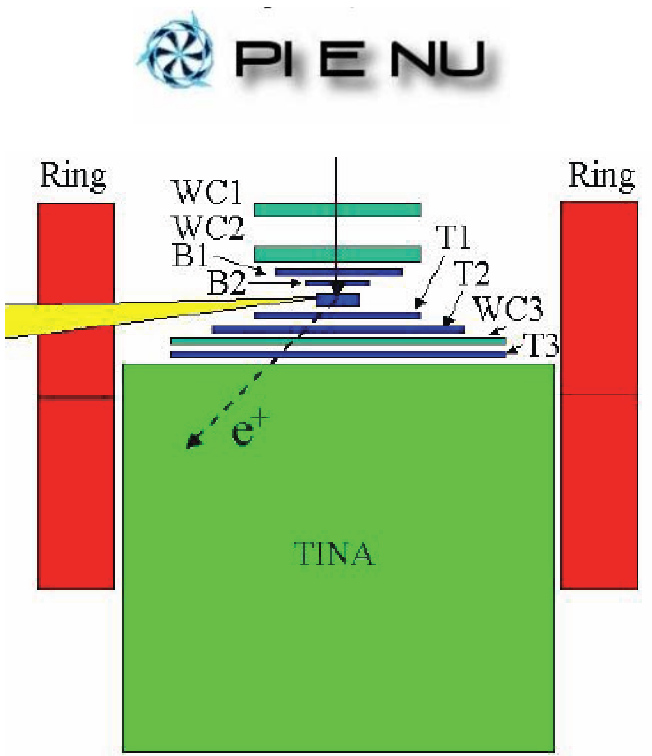


- **Singles experiment – not limited by accidentals**
- **Background (decay-in-orbit) known and calculable.**
- **High resolution detector feasible.**

$New\ \pi^+ \rightarrow e^+\nu$ Experiments

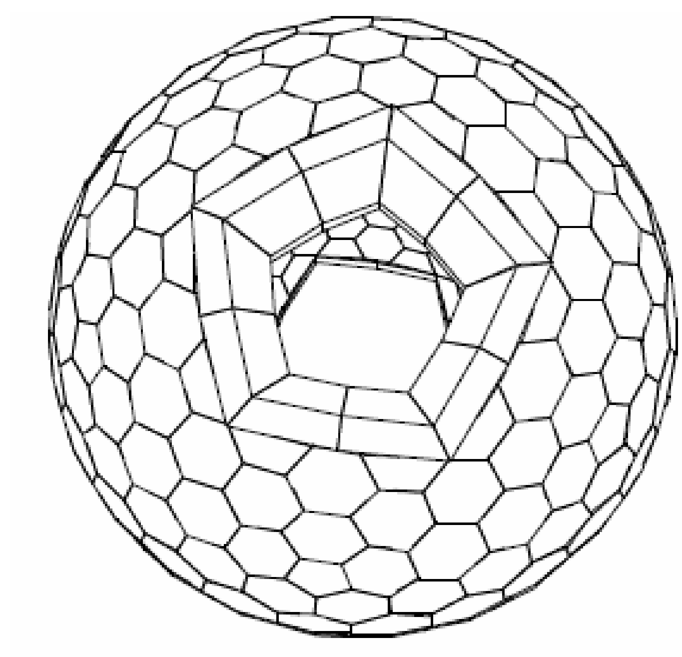
Precision Goals for $R_{e/\mu}^{\exp\pi} : < 0.1\%$

TRIUMF PIENU



ASU, BNL, Osaka, TRIUMF, UBC, VPI

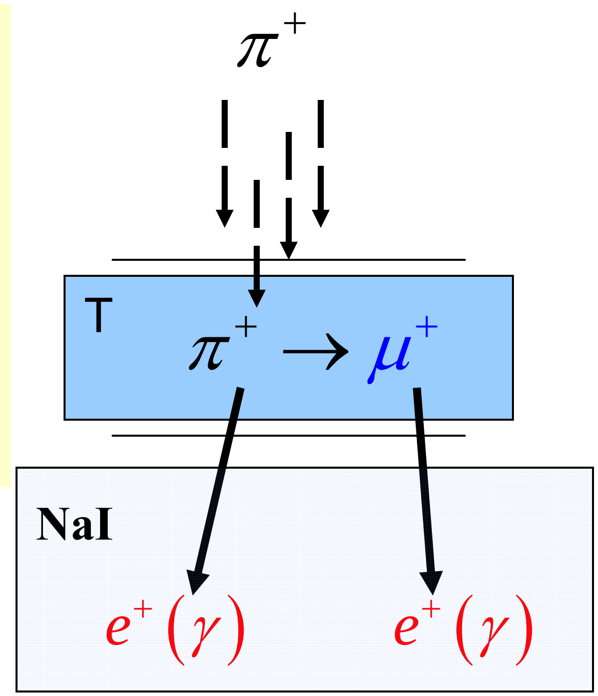
PSI PIBETA Spectrometer

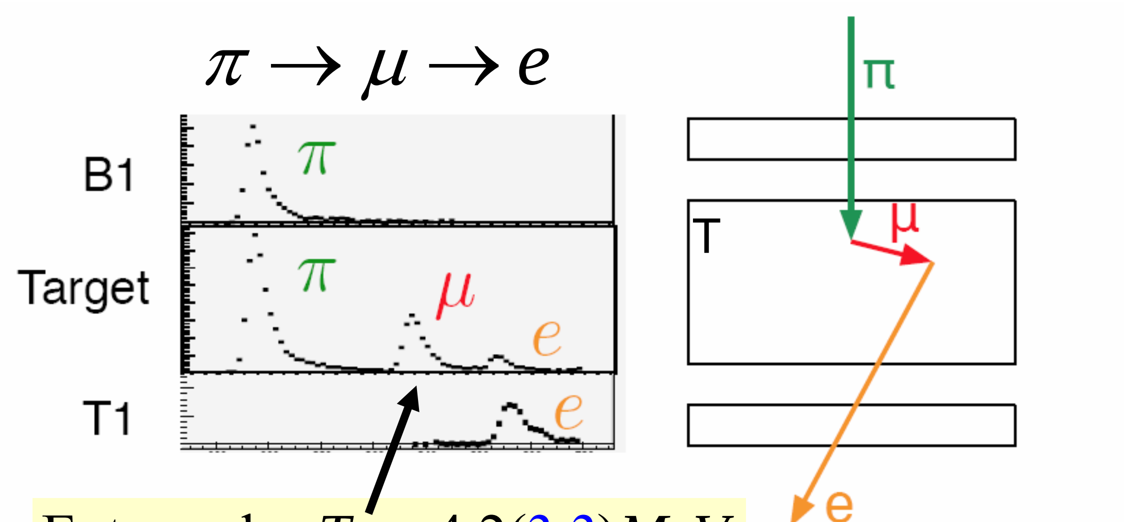


INS (Pol.), IHEP, JINR, PSI, RBI, Virginia, Zurich

Experiment Concepts

Low Momentum π Beam at p=75 MeV/c. πs lose energy and stop in a target of plastic scintillator (T). Scintillation detectors viewed by photo-multiplier tubes and all signals are digitized at 500 MHz.





Extra pulse $T_\mu = 4.2(3.3) MeV$ for $\pi \to \mu \to e$ only.

$\tau_\pi = 26ns, \tau_\mu = 2200ns$

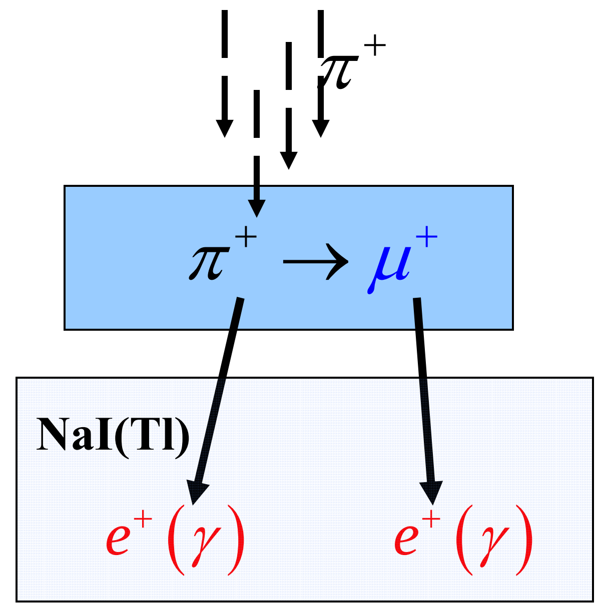
Measure positron energies in a NaI(Tl) crystal spectrometer (no magnetic field!):

$$\left[\pi^+ \to e^+ \nu\right] \qquad P_e = 70 MeV/c$$

$$\left[\pi^+ \to \mu^+ \nu\right] \quad P_\mu = 30 MeV/c$$

$$T_\mu = 4.2 MeV, \; R_\mu = 1.4 mm$$

$$\left[\mu \to e^+ \nu \bar{\nu}\right] \quad P_e = 0 - 53 MeV$$



Electrons have fairly uniform interactions over the range P[1-70 MeV]:

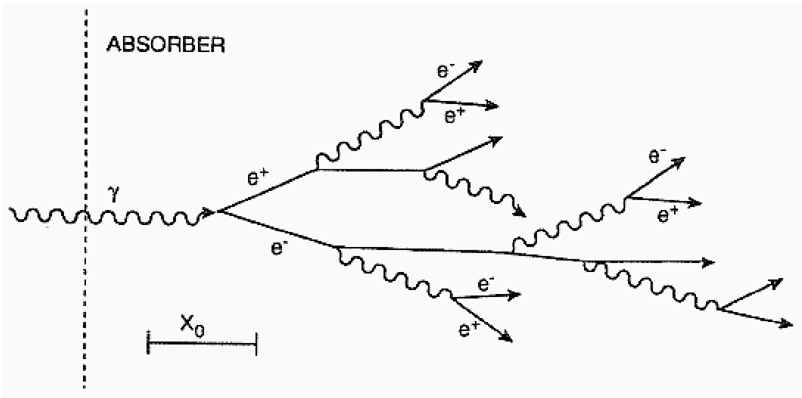
Systematic effects cancel (to 1st order) in the ratio $\dfrac{\Gamma(\pi \to \mathrm{e})}{\Gamma(\pi \to \mu \to \mathrm{e})}$

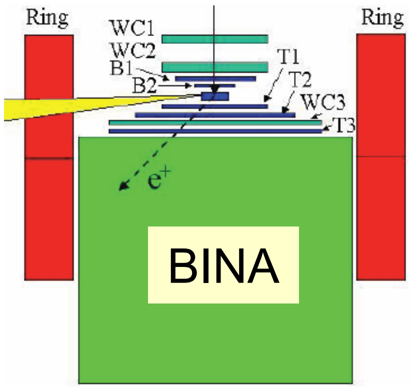
e.g. solid angle, Multiple Coulomb Scattering, $\dfrac{dE}{dx}$, annihilation, bremsstrahlung, timing.

N.B.: When aiming for high precision: must rely on measurements for corrections rather than simulations whenever possible!

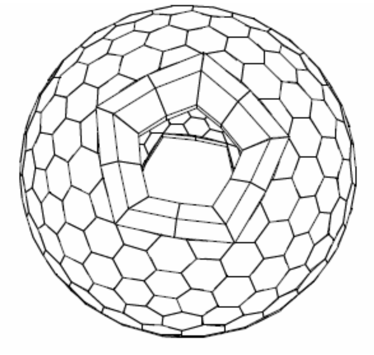
Electromagnetic Calorimeters

Photons and electrons : EM showers

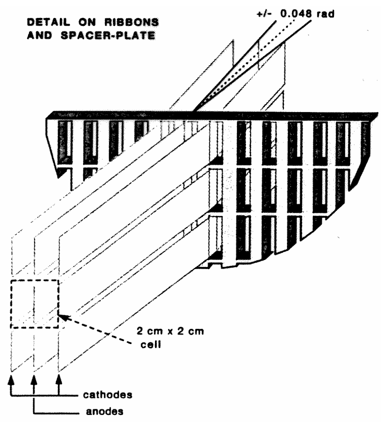




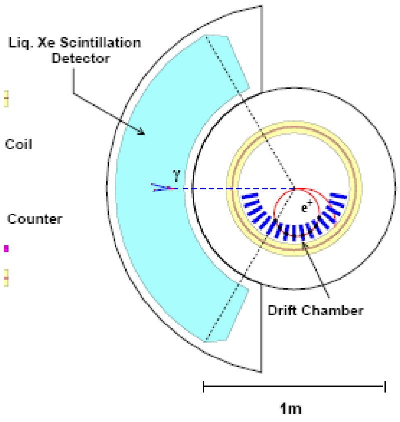
Single Crystal NaI(Tl)



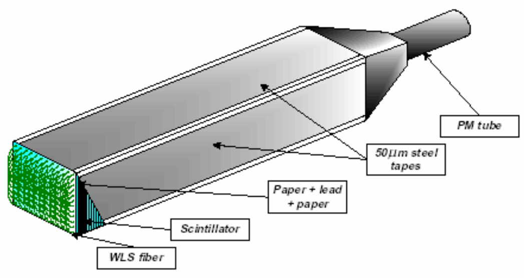
Pure CsI
Crystal Ball



NA48 LKr
Ionization Calorimeter



MEG LXe Scint.



Shashlyk Pb/SciFi
Sampling Calorimeter

KLOE Pb/sci-fi

Properties of Scintillating Crystals

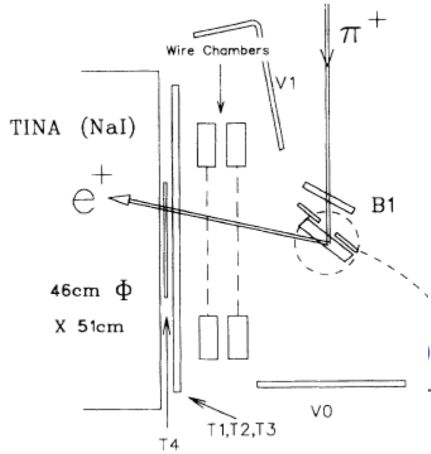
Crystal		CsI(Tl)	CsI	BaF_2	BGO	CeF_3	$PbWO_4$
Density	$g.cm^{-3}$	4.51	4.51	4.89	7.13	6.16	8.28
Rad. length	cm	1.85	1.85	2.06	1.12	1.68	0.89
Moliére radius	cm	3.8	3.8	3.4	2.4	2.6	2.2
Int. length	cm	36.5	36.5	29.9	22.0	25.9	22.4
Decay Time	ns	1000	35 6	630 0.9	300	10-30	<20> **(2,10,38)**
Peak emission	nm	565	420 310	300 220	480	310- 340	425
Rel. Light Yield	%	45	5.6 2.3	21 2.7	9	10	0.7
d(LY)/dT	%/°C	0.3	- 0.6	- 2 ~ 0	- 1.6	0.15	-1.9
Refractive Index		1.80	1.80	1.56	2.20	1.68	2.16

Virdee

Comparing Some EM Calorimeters

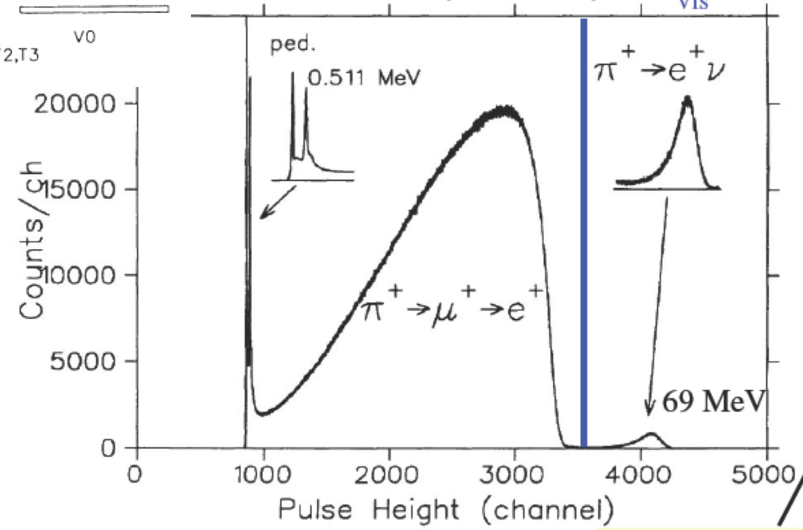
	BNL NaI(Tl)	PSI Pure CsI	NA48 LKr (Ionization)	Shashlyk Pb/Scint./WLS Fiber
Density (g/cc)	**3.67**	**4.53**	**2.41**	**2.75**
Rad. Length (L_0 cm) **No. L_0**	**2.59** **19**	**1.85** **12**	**4.7** **27**	**3.15** **15.9**
Moliere Radius (cm)	**4.5**	**3.8**	**4.7**	**5.49**
Sampling Fraction (%)	**100**	**100**	**100**	**10**
Lt. Decay (ns)	**250**	**10, 36, 1000**		**2.7**
Lt. (rel. NAI, %)	**100**	**0.1(f),0.02(s)**		**3 p.e./MeV**
En. Res. (%) 70 MeV **E in [GeV]**	**2**	**5.4**	$0.5 + 3.5/\sqrt{E}$	$3./\sqrt{E}$
Position Res. (cm)	**---**	**2.5**	**0.9**	**3**
Timing (ns)	**1**	**0.5**	**0.26**	$\frac{0.08}{\sqrt{E}}$
Rad. Damage		**Fair**	**Excellent**	**Good**

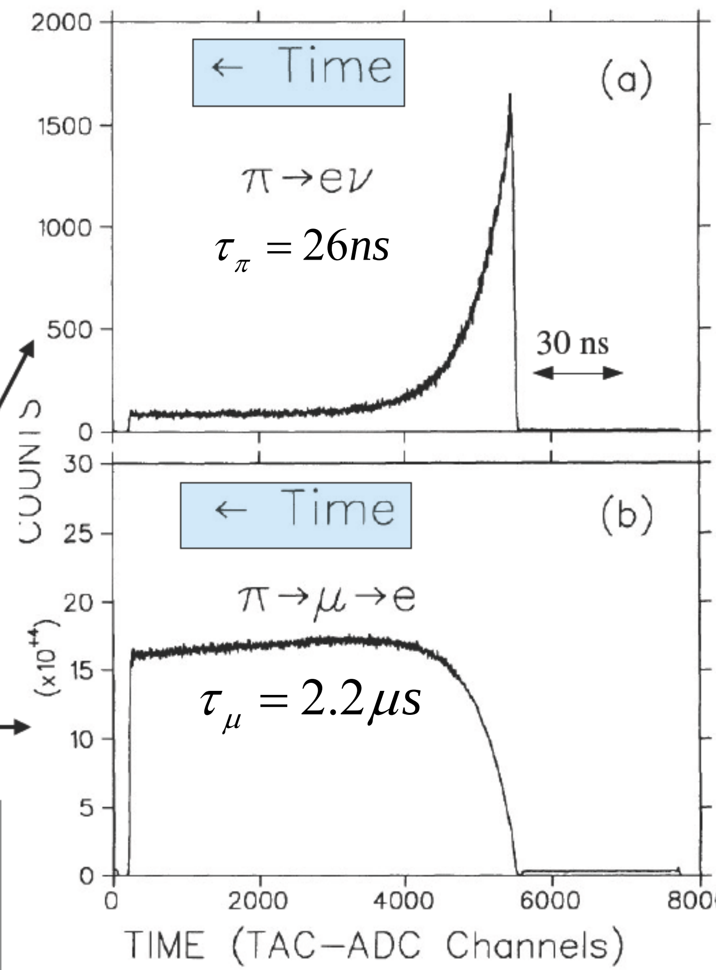
Previous TRIUMF Experiment **Britton et al. (1993)**



Energy and Time spectra

...arate events by Energy: (E_{vis} ~52 MeV)





π–μ–e region

π→eν

Fit both spectra simultaneously and obtain the ratio.

Collaboration

M. Aoki, M. Blecher, D. Bryman, J. Comfort, P. Gumplinger, S. Kettell, T. Krupovnickas, Y. Kuno, L. Kurchaninov, L. Littenberg, W. Marciano, G. Marshall, T. Numao, A. Olin, R. Poutissou, M. Ramsey-Musolf, F. Retiere, A. Sher, V. Selivanov, B. Walker, K. Yamada

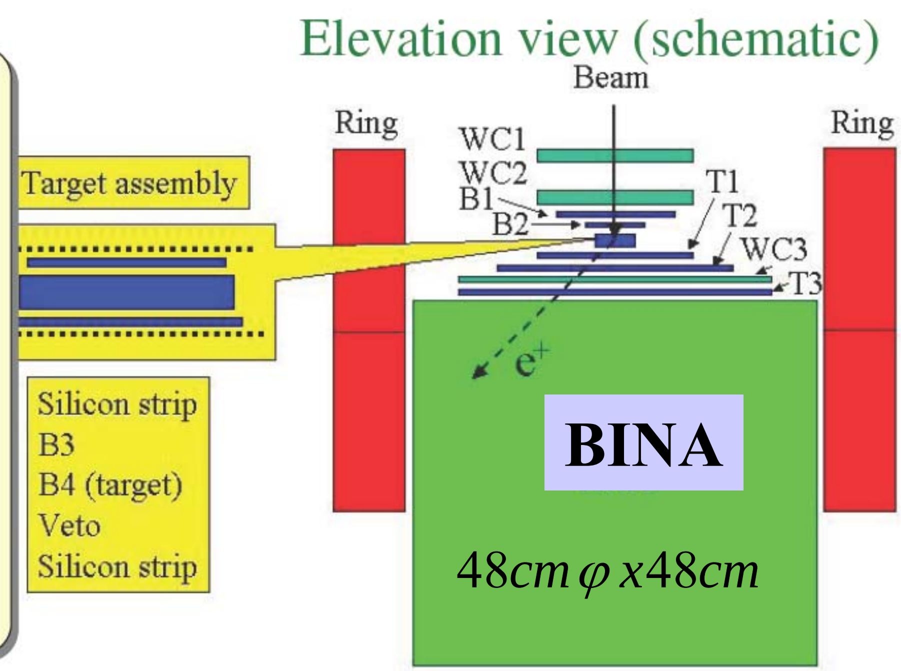
Canada-Japan-Russia-US

Arizona State University, BNL, Caltech, Kurchantov Institute, Osaka University, TRIUMF, University of BC, Virginia Polytechnic Institute and State University

TRIUMF PIENU Experiment

Precision goal: <0.05%

WC1(2,3)	Wire chambers
B1(2)	Beam counter
B3(4), Veto	Target counters
T1(2,3)	Telescope counters
TINA	NaI
	(dE/E= 2% @ 66 MeV)
Ring	CsI crystals



Solid angle: 25% (2.9%)

π^+ rate: ~ 70kHz (100kHz)

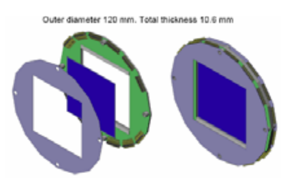
Tina rate: ~ 40kHz (30kHz)

Trigger rate: ~ 1kHz

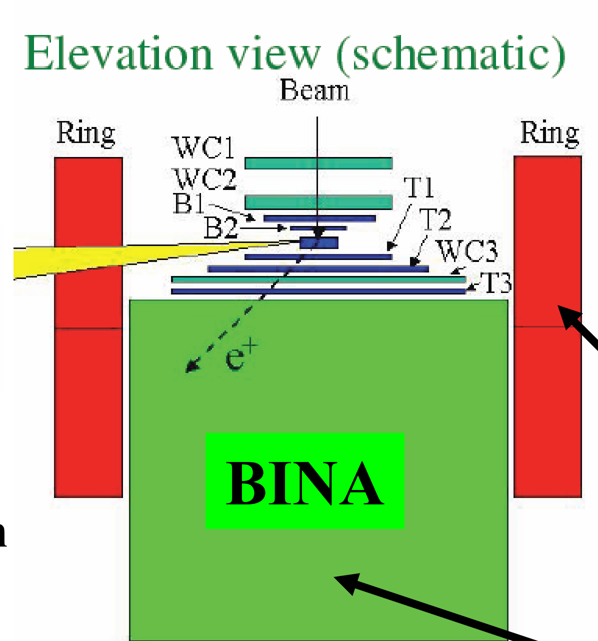
Statistics: $\sim 5\times10^6$ $\pi\rightarrow e\nu$ (× 30 E248)

Equipment

- **Single crystal NaI(Tl) detector (BNL)**
  Energy resolution <2% (RMS) at 70 MeV
- **E949 Pure CsI crystal collar**
- **500 MHz digitizers**
- **Silicon strip and drift chamber tracking**



Si Strips
300 (80) µm pitch



Pure CsI

48 cm dia. x 48 cm ~19 X0

Britton et al. (1993)

Tail correction

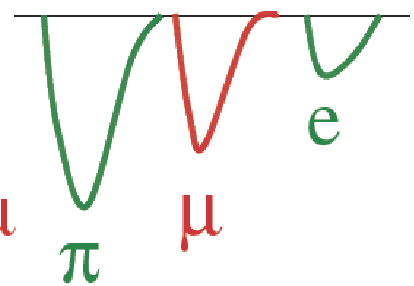
(the main source of systematics)

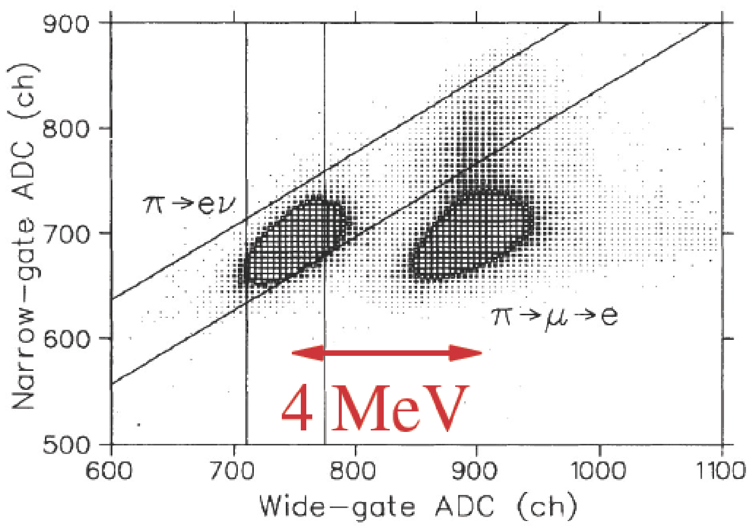
$\pi - e\nu$

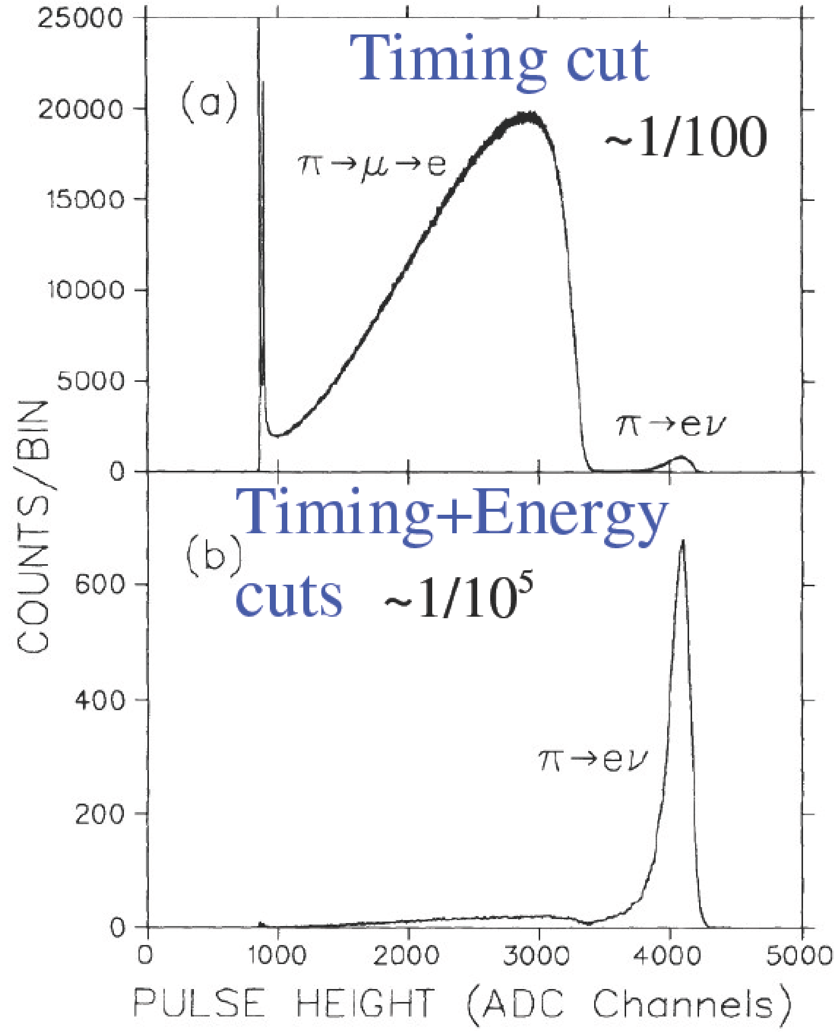
$T\pi + \Delta Ee$

$\pi - \mu - e$

$T\pi + \Delta Ee + E\mu$







Britton et al. 1994

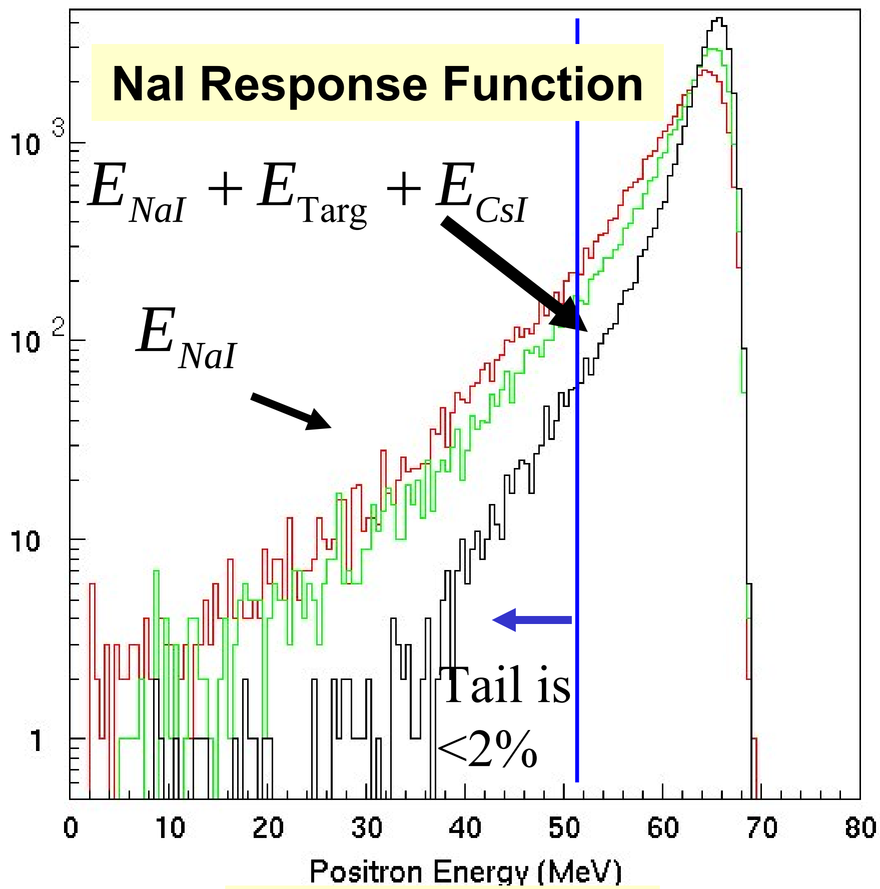
TABLE I. $\pi \to e\nu$ branching ratio summary.

Raw branching ratio R' ($\times 10^{-4}$)	1.1994 ± 0.0034(stat) $\pm$ 0.0023(sys)
Multiplicative corrections	
Tail correction	1.0193 ± 0.0025
Pion stop time t_0	0.9998 ± 0.0008
Time calibration	1.0000 ± 0.0003
Monte Carlo *	1.0027 ± 0.0011
$V1$ veto	1.0009 ± 0.0005
Wire-chamber inefficiency	0.9998 ± 0.0004
π lifetime	1.0000 ± 0.0009
Branching ratio R_{expt} ($\times 10^{-4}$)	1.2265 ± 0.0034(stat) $\pm$ 0.0044(sys)

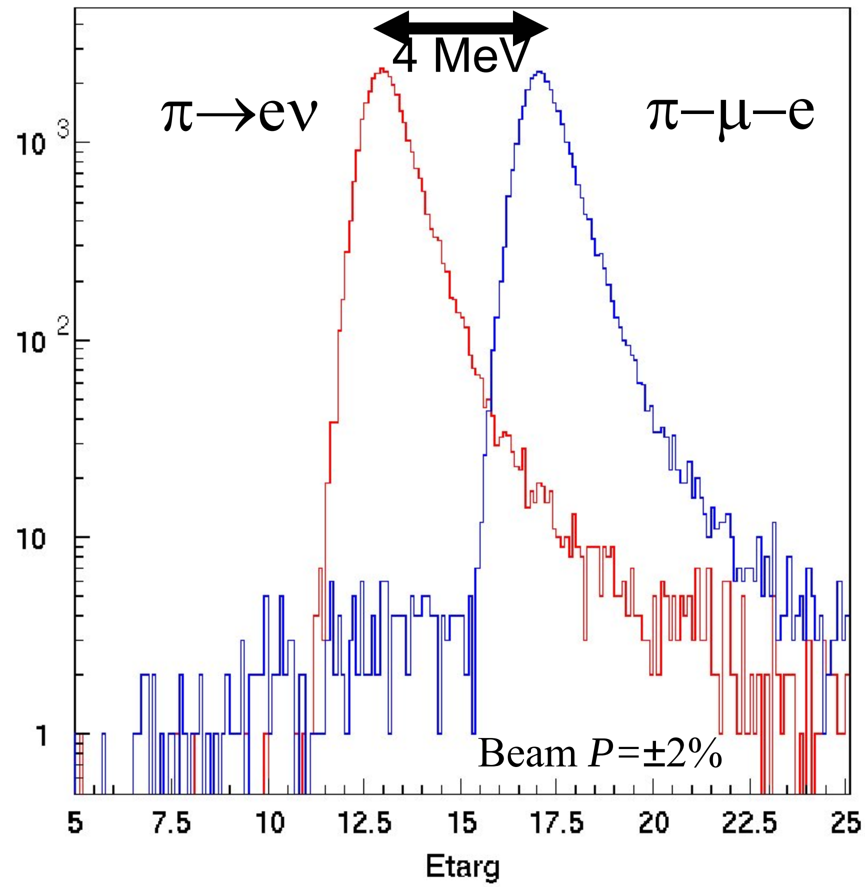
•MC: dE/dx, annihilation in flight, multiple Coulomb scattering, Bhabba and Moller scattering

Resolution and NaI Tail

Simulations for New PIENU Experiment



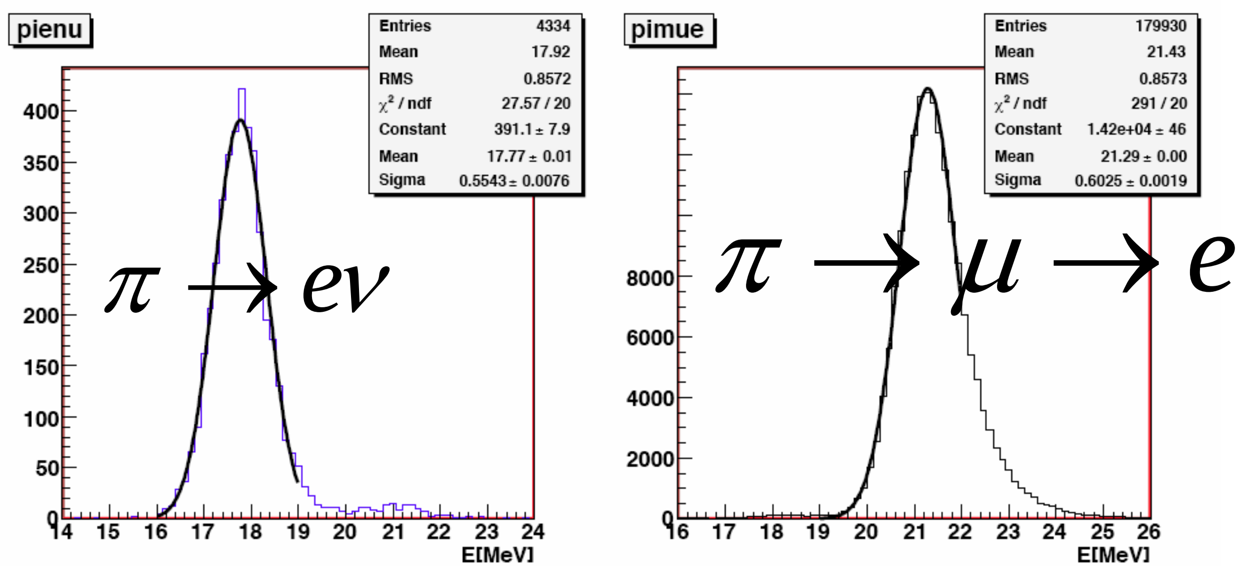
π→eν events



Target energy

Beam Test Data

total energy deposit in the target



Good separation in the target dE/E ~3%

Expected Uncertainties

Largest systematics come from:

Low energy tail ($\pi \rightarrow e\nu$)
0.03%

Britton et al. : 0.25%Uncertainty of the correction - limited by statistics
& contamination by in-flight pion decays

PI E NU Better dE/dx in target (x2)
and smaller statistical uncertainty (x5):

Energy dependent Acceptance difference 0.03%

PI E NU
Larger solid angle x5:

PI E NU

Uncertainties Summary

Sources	**Britton et al. 1993**	PI E NU
Statistical error	0.0028	0.0005
Low energy tail ($\pi \rightarrow e\nu$)	0.0025	0.0003
Acceptance differences	0.0011	0.0003
Pion lifetime	0.0009	0.0002
Others (time calibration, etc.)	0.0011	0.0003
Expected systematic error	0.0031	0.0006

PI E NU

PIENU Experiment Plan

• 2006/7:	Beam Tests
• 2007:	Assembly
• 2008-2009	Data runs
• 2008-10	Analysis/publications

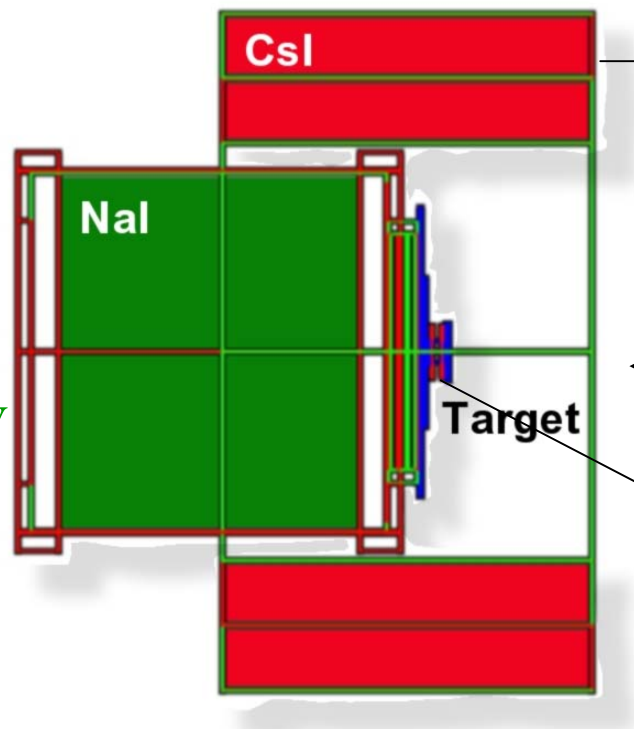
Students, Postdocs: Interested? See me later!

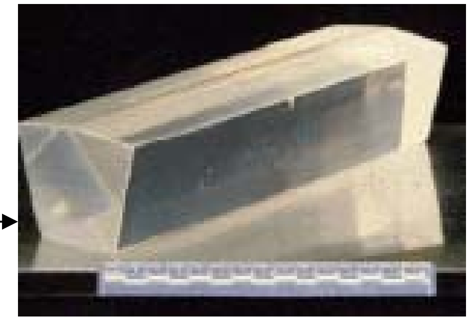
Detector build-up

Brookhaven NaI crystal (BINA)
Radius=24 cm
Length = 48 cm(19 *X0*)

Energy resolution:

~<2% (FWHM) at 70 MeV

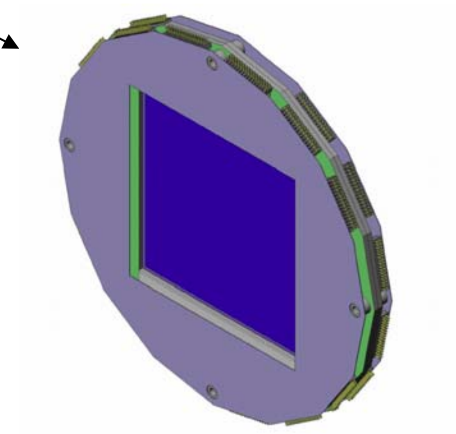




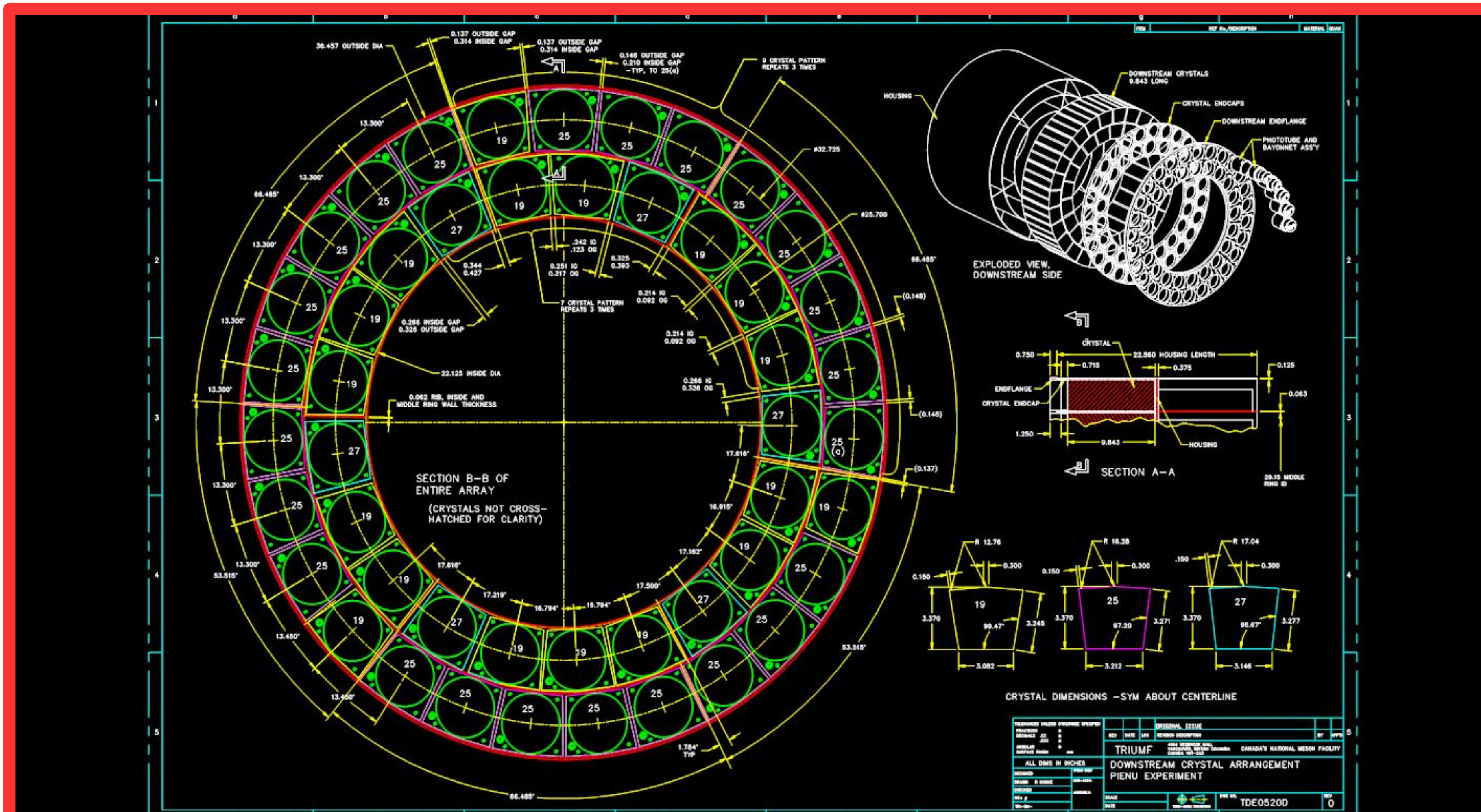
Pure CsI crystals

π **Beam**

Si Strips
300 (80) µm pitch

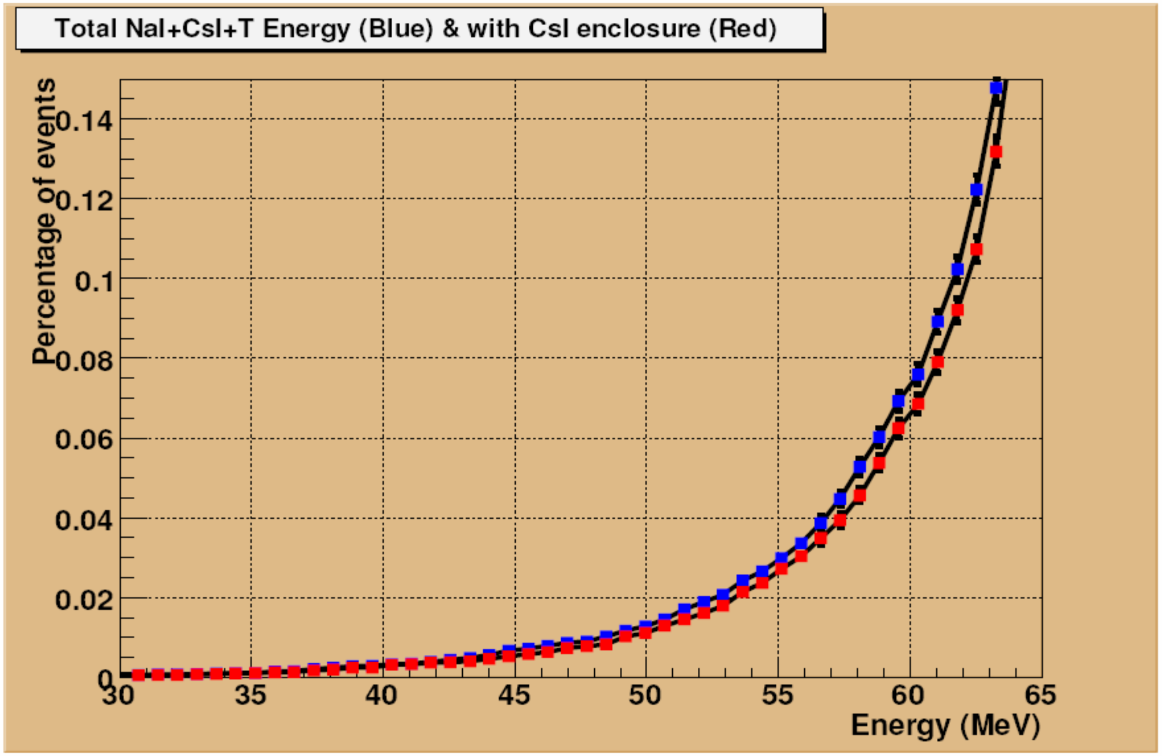


CsI enclosure



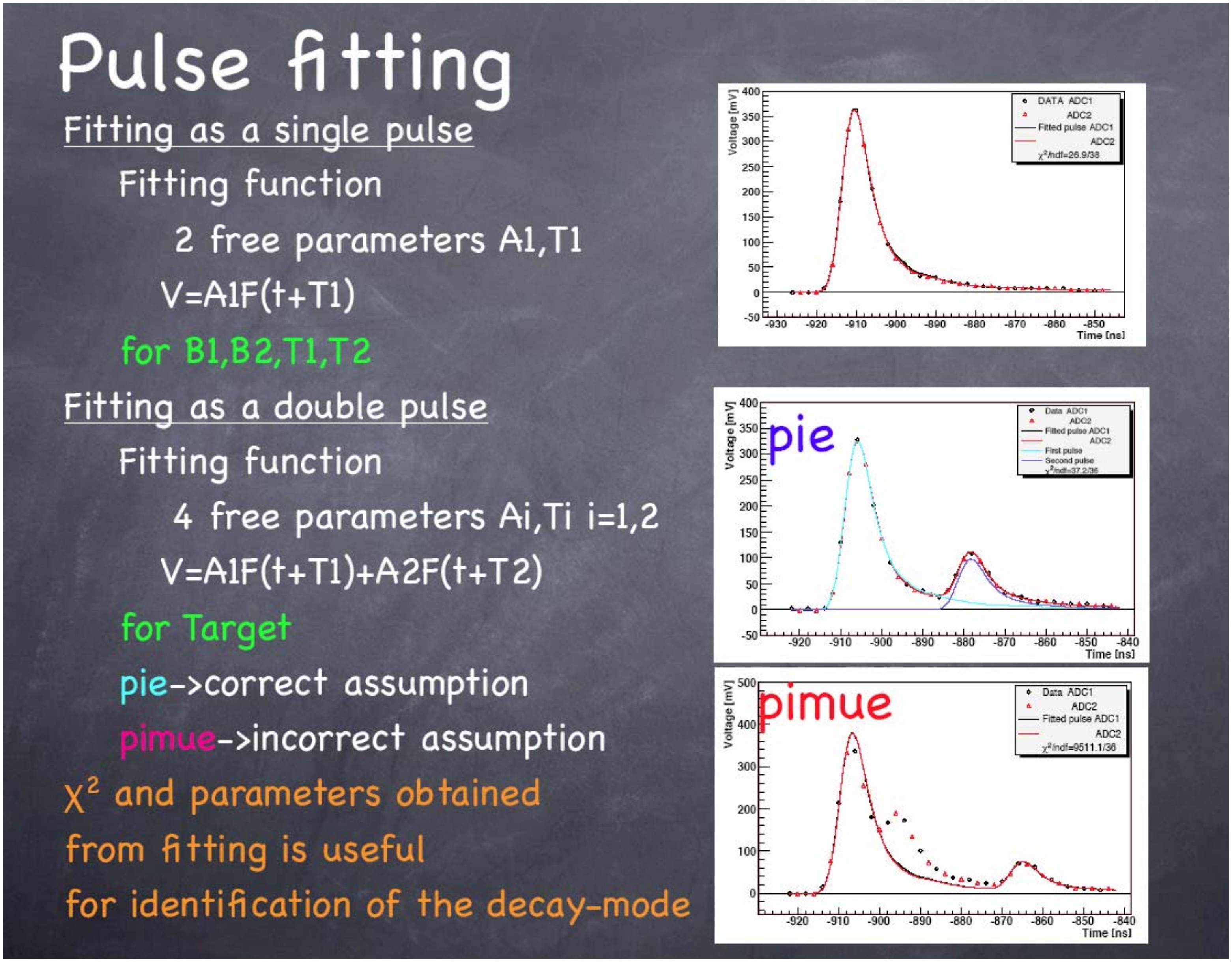
To reach 0.05% precision, everything must be studied/known to 0.01%: GEANT3 & 4 MC Studies Example:

Dead material and Gaps between crystals



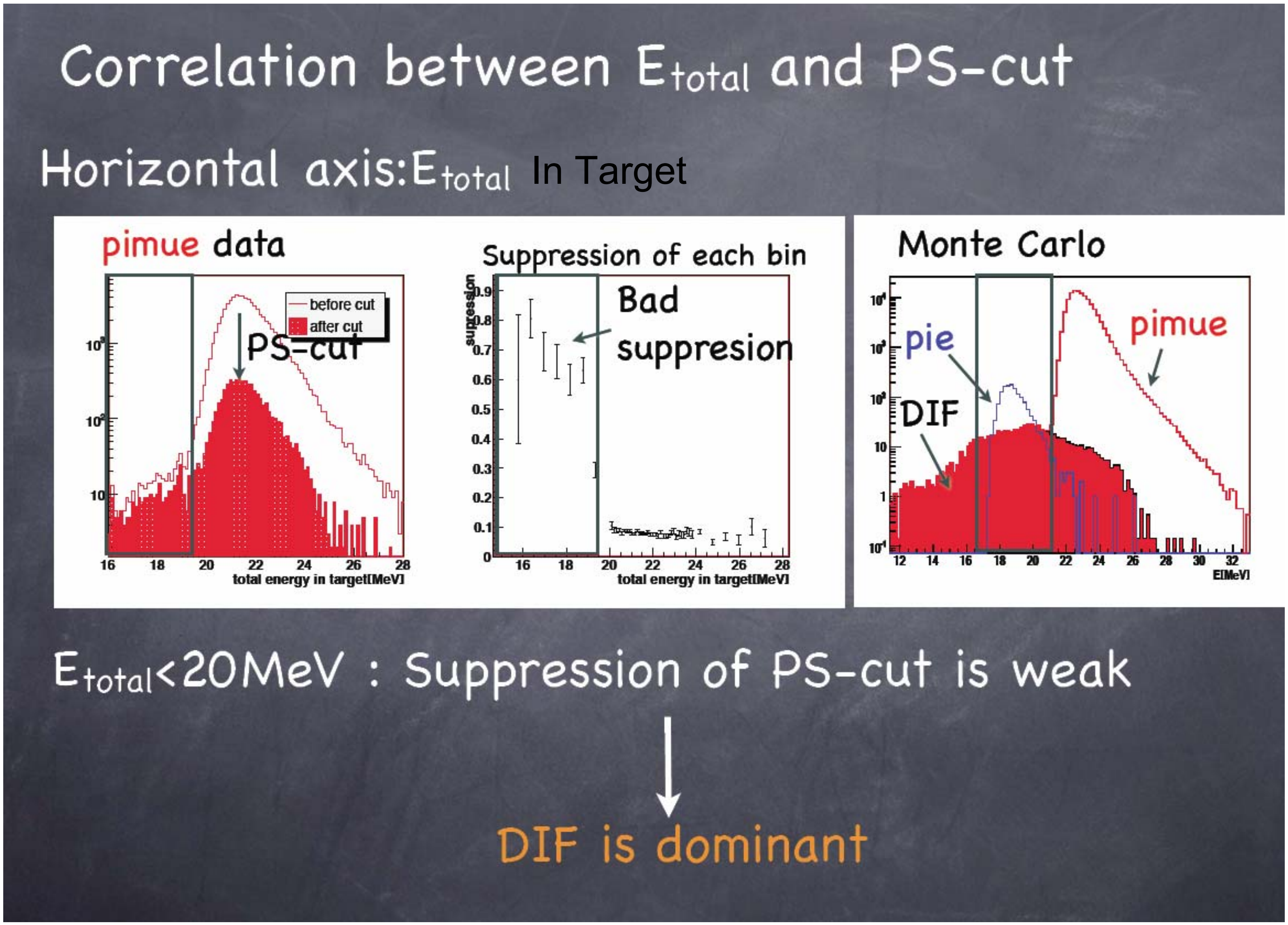
Support material in gaps between crystals: <10% effect, known to <1% precision.

From analysis of the Beam Test data:

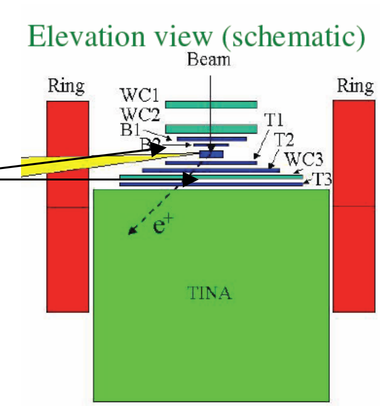


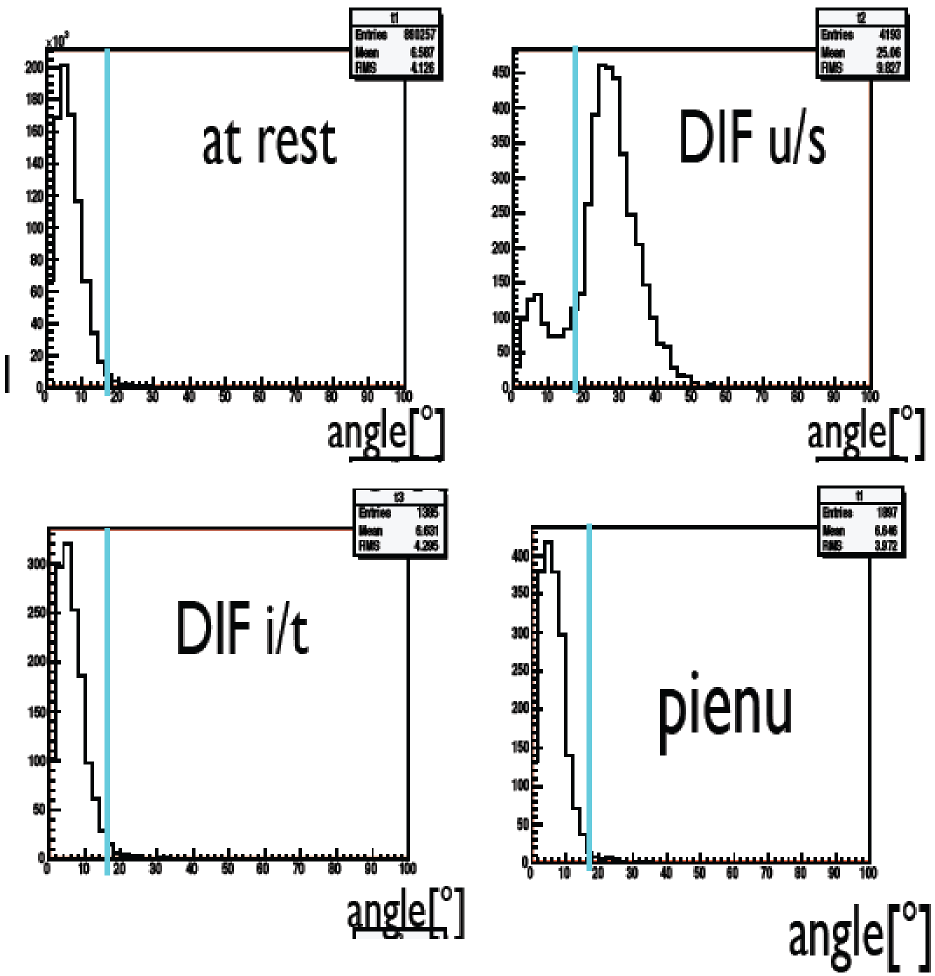
From analysis of the Beam Test data:

Decays in Flight



Si Strip and WC tracking helps veto decays in flight

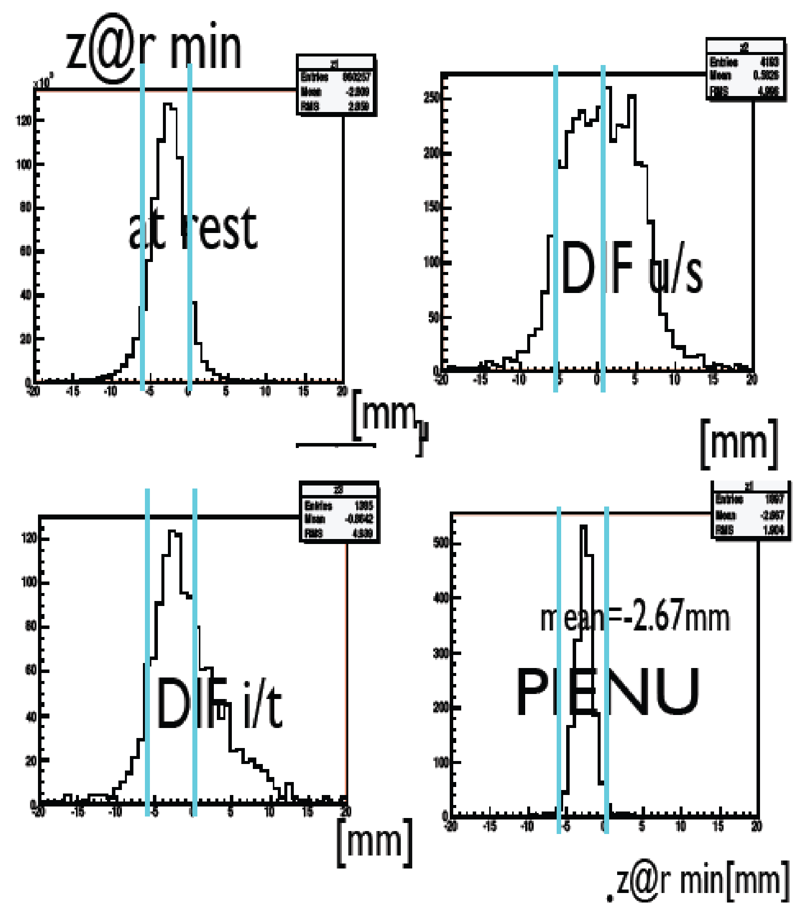




Measuring the angle between the incident beam pion (using WC) and the charged particle entering the target (using Silicon Strip detectors) helps in significantly reducing decays in flight

(factor ~8)

SS and WC tracking helps veto decays in flight



Using SS tracking to determine Z of the vertex helps to suppress decays-in-flight even further.

total factor ~30

$\pi^+ \to e^+\nu$ at PSI

Precision Goal: 0.05%

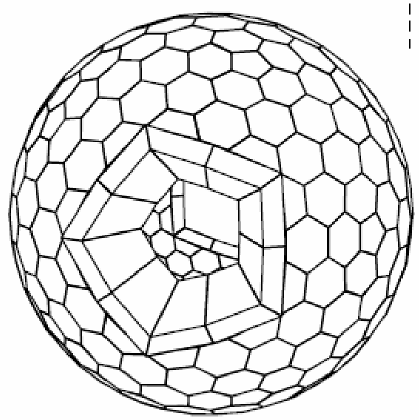
PI Beta Spectrometer: 12 X0 pure CsI

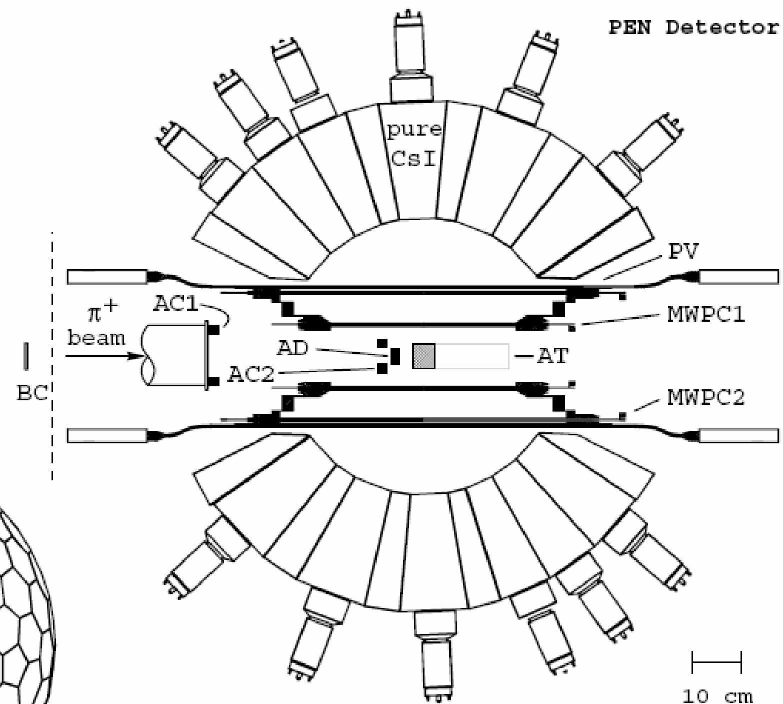
Previously measured

$\pi^+ \to \pi^0 e^+\nu, \pi^+ \to e^+\nu\gamma$

The PEN Experiment:

- stopped π^+ beam
- active target
- 240-det. CsI(pure) calorimeter
- central tracking
- digitized waveforms



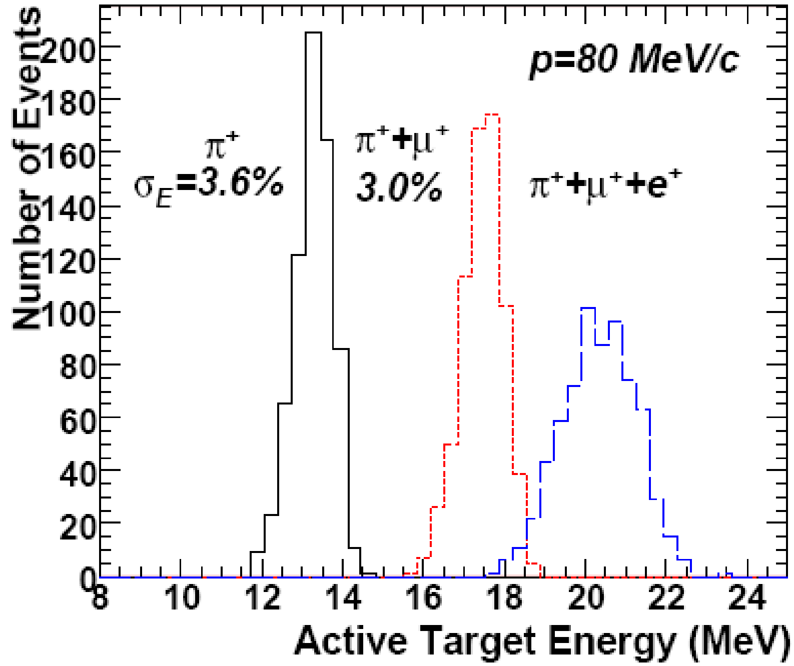


Detector schematic cross section

PEN Active Target detector energy resolution

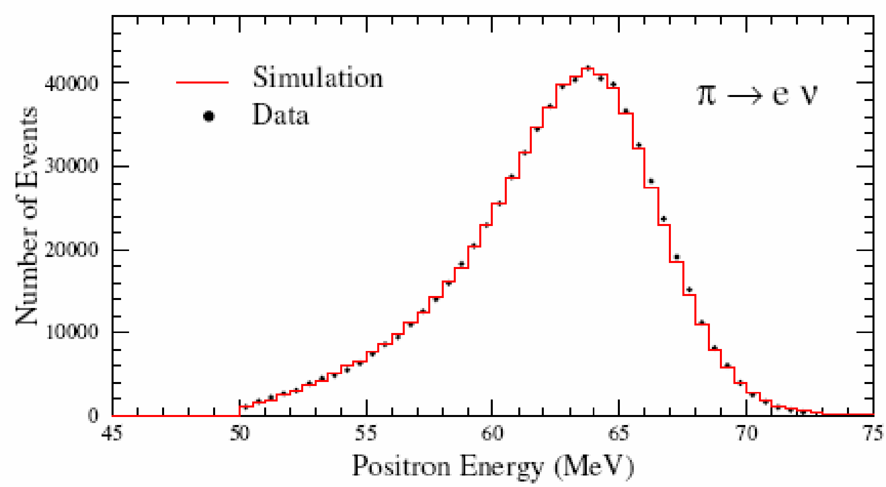
- stopped pion signal
- stopped pion with $\pi \longrightarrow \mu\nu$
- stopped pion with $\pi \longrightarrow \mu \longrightarrow e$

[From 2006 PEN test run]



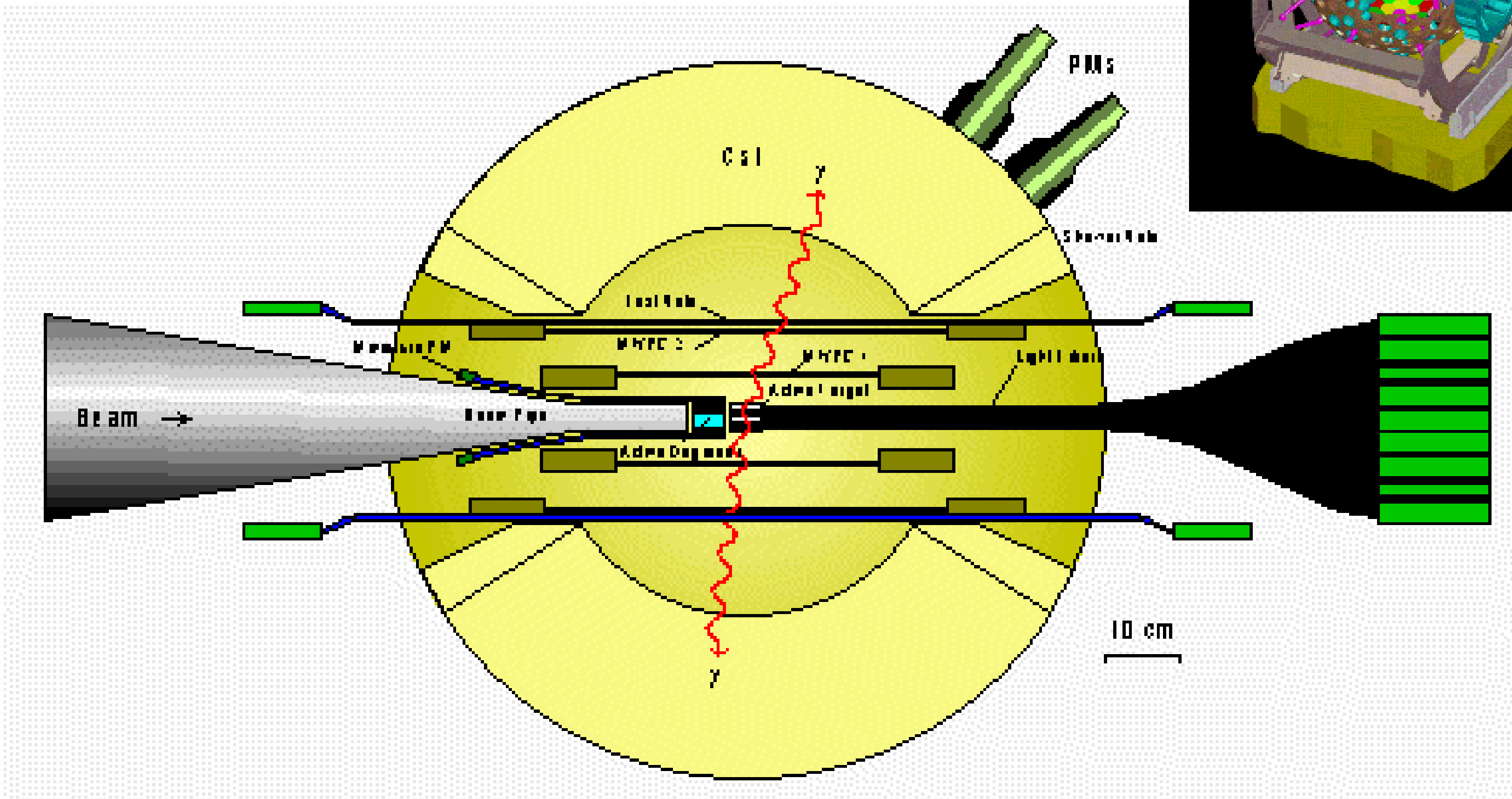
Calorimeter energy resolution for $\pi^+ \longrightarrow e^+\nu$ after subtraction of late decay events.

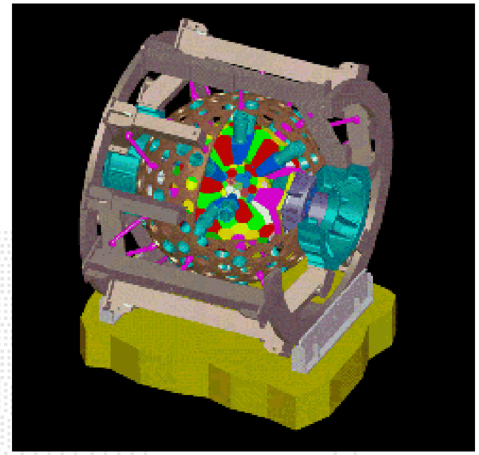
[From 2004 PIBETA run]



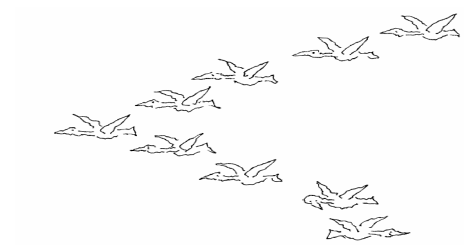
12.8% FWHM at 66 MeV

PSI π-β Target Arrangement





“Rare Opportunities”



Lecture I

- Introduction and Overview
- Motivation from theory for modern studies of rare μ, π, and K decays; access to new physics at high mass scales.
- Experiments and experimental techniques for high precision and high sensitivity measurements of rare and ultra-rare processes:

  Muons: $\mu \rightarrow e\gamma$, Nuclear $\mu \rightarrow e$ conversion

  Pions: $\pi^+ \rightarrow e^+\nu / \pi^+ \rightarrow \mu^+\nu$ Branching ratio

Lecture II

Kaons: $K^+ \rightarrow e^+\nu / K^+ \rightarrow \mu^+\nu$

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

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

Rare Opportunities:
Seeking New Physics with Rare Decays of Light Particles

Douglas Bryman
University of British Columbia

“Rare Opportunities” Outline

Lecture I

- Introduction and Overview
- Motivation from Theory for modern studies rare μ, π, and K decays.
- Experiments: $\mu \to e\gamma$, Nuclear $\mu \to e$ conversion

  $\pi^+ \to e^+\nu / \pi^+ \to \mu^+\nu$ Branching ratio

Lecture II

- Rare K decays:

  $K^+ \to e^+\nu / K^+ \to \mu^+\nu$ Branching ratio

  $K^+ \to \pi^+\nu\bar{\nu}, K_L^0 \to \pi^0\nu\bar{\nu}$

Overview of Light Particle Rare Decay Experiments

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

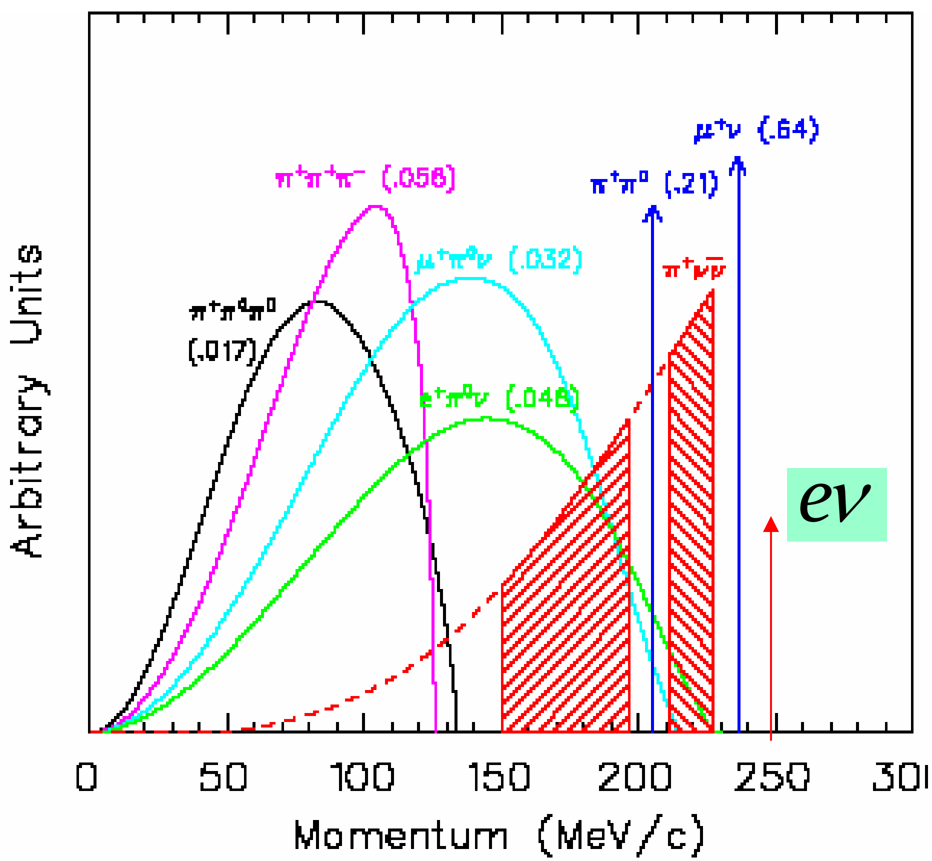
Category	Process	Physics	Sensitivity
Exotic Searches *New physics if seen; SM effects are negligible.*	$K_L^0 \to \mu\, e$	Lepton Flavor Violation	**<4.7 10^{-12}**
	$\mu \to e\gamma$	*LFV*	**<1.2 10^{-11}**
	$\mu^- N \to e^- N$	*LFV*	**<7.8 10^{-13}**
	$K^+ \to \pi^+\ f$	"*Axions*"	
SM Parameters and BSM Physics *New physics if deviations from* ***well-calculated*** *SM predictions occur.*	$\dfrac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$	Lepton Universality	**10^{-4}: 4x10^{5} events**
	$\pi^+ \to \pi^0 e\nu$	$\lvert V_{ud} \rvert$	
	$K_L^0 \to \mu^+\mu^-$	$\lvert V_{td} \rvert$	**10^{-8}: 6200 events**
	$K^+ \to \pi^+ \nu\bar{\nu}$	$\lvert V_{td} \rvert$	**10^{-10}: 3events**
	$K_L^0 \to \pi^0 \nu\bar{\nu}$	*CP* violation	
Low Energy QCD Chiral Perturbation Theory	Radiative decays $K_L^0 \to ee$		**10^{-11}: 4 events**

K^+ Decay Modes $\tau_{K^+} = 12.4ns$

Decay Mode	Branching Ratio
$K^+ \to \mu^+\nu$	63% (called $K_{\mu 2}$)
$K^+ \to \pi^+\pi^0$	21%
$K^+ \to \pi^+\pi^+\pi^-$	6%
$K^+ \to \pi^+\pi^0\pi^0$	2%
$K^+ \to \pi^0\mu^+\nu$	3% (called $K^+_{\mu 3}$)
$K^+ \to \pi^0 e^+\nu$	5% (called K^+_{e3})

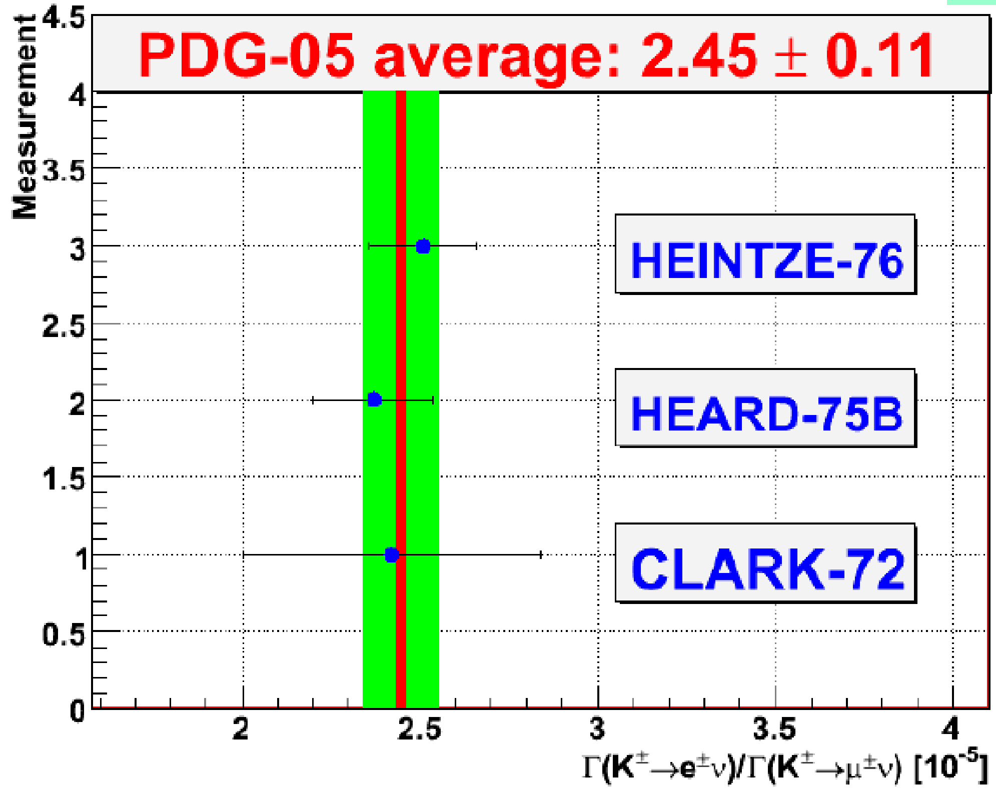
$K^+ \to e^+\nu \qquad 4x10^{-5}(K_{e2})$

$K^+ \to \pi^+\nu\bar{\nu} \qquad 10^{-10}$



Previous $K \rightarrow e\nu$ experiments done at CERN with low energy stopped K^+ beams.

$\pm 4.5\%$



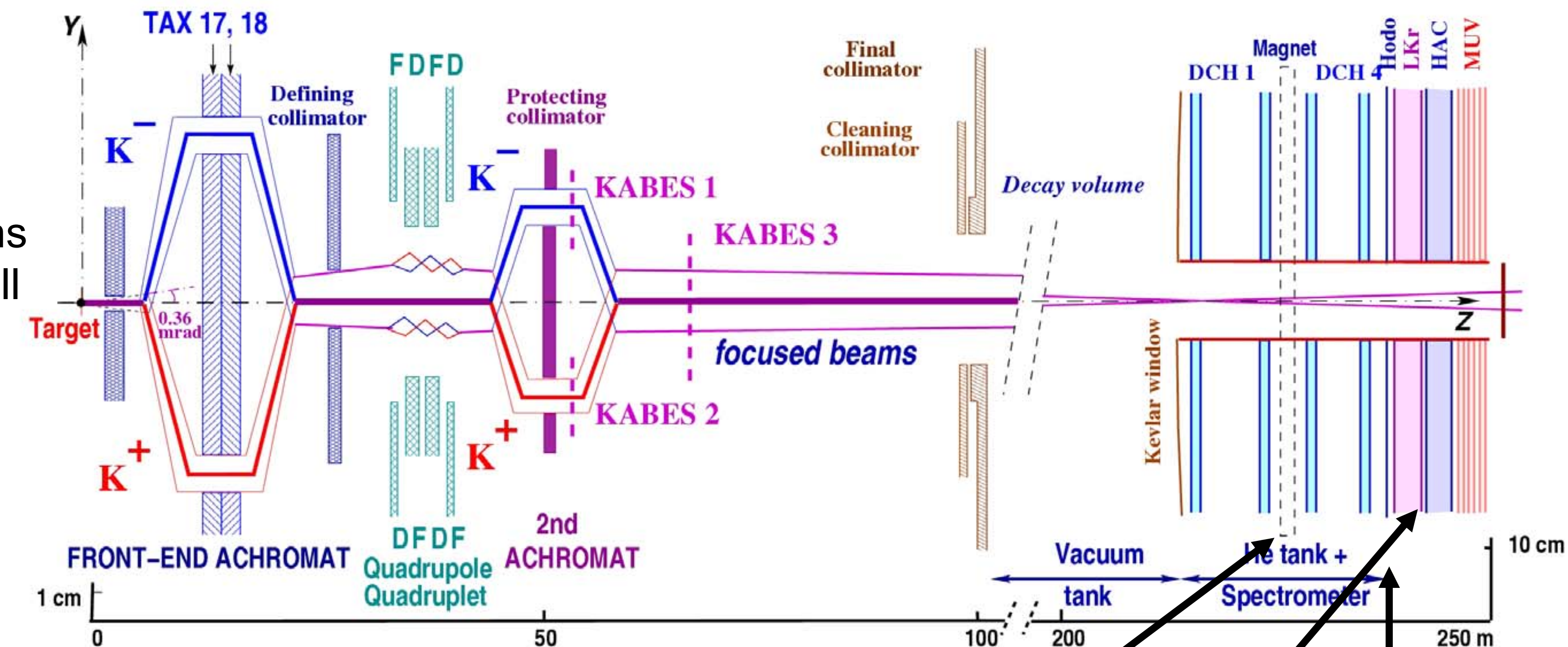
New Measurements of $K \to e\nu / K \to \mu\nu$ at CERN

K^+ and K^- decay-in-flight NA48/2/3 P326

Momentum (60±3) ->75±1 GeV/c

$$K \rightarrow e\nu \;\; \& \;\; K \rightarrow \mu\nu$$

1.5 x 10^{12} protons per spill



e/μ Particle ID from E/p

Momentum Analysis

Trigger Hodoscopes

Energy Measurement
Liquid Krypton Calorimeter

Goal: 150,000 Ke2 events

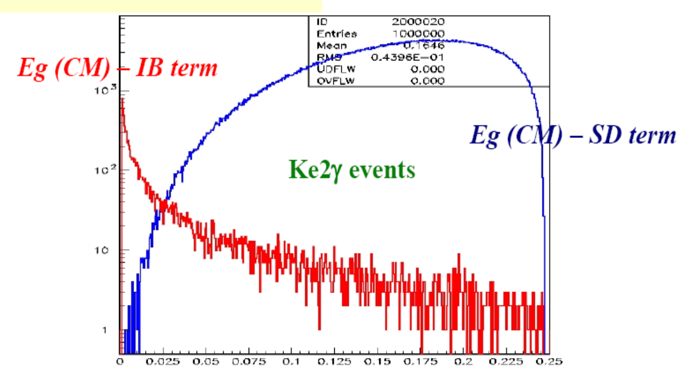
R_K~±0.34%

$K \to e\nu$ & $K \to \mu\nu$ Selection Criteria

- Exactly one track
- Restricted decay vertex for reconstruction
- $K \to e\nu \quad E/P > 0.95$
- $K \to \mu\nu \quad E/P < 0.2$
- "Missing Mass" $M_X \approx 0$ defines $K^{\pm} \to l^{\pm}\nu$

$$|M_X|^2 = (E_K - E_l)^2 - (\mathbf{p}_K - \mathbf{p}_l)^2 < 0.015\,GeV^2$$

- $E_{\gamma}^{LKr} < 2GeV$ (Radiative Decay) - limited by calorimeter response.

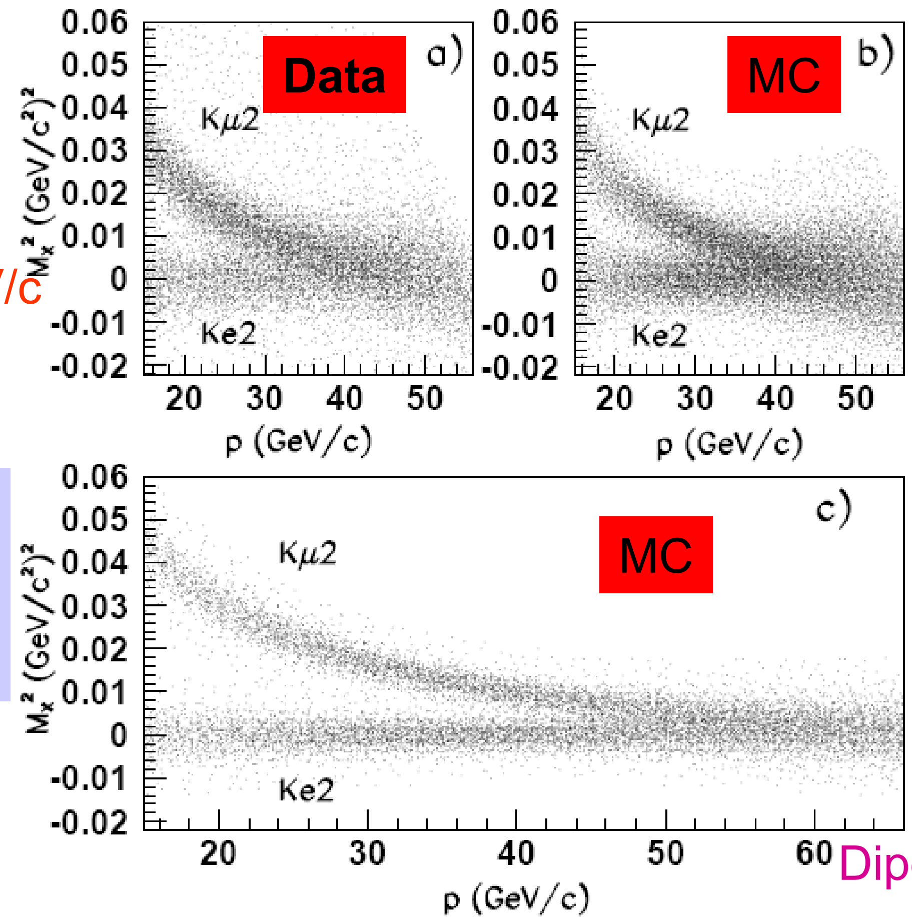


Missing Mass Technique

(μ reconstructed as e)

M_X^2 *vs.Momentum*

NA48 DATA 2004:
K_{e2} candidates
and a $K_{\mu 2}$ sample
P_K = 60 GeV/c
Dipole Pt kick 120 MeV/c



2004 MC :
Equal samples of
K_{e2} and $K_{\mu 2}$

Some μ (5x10^{-6})
misidentified as e
for p>25 GeV

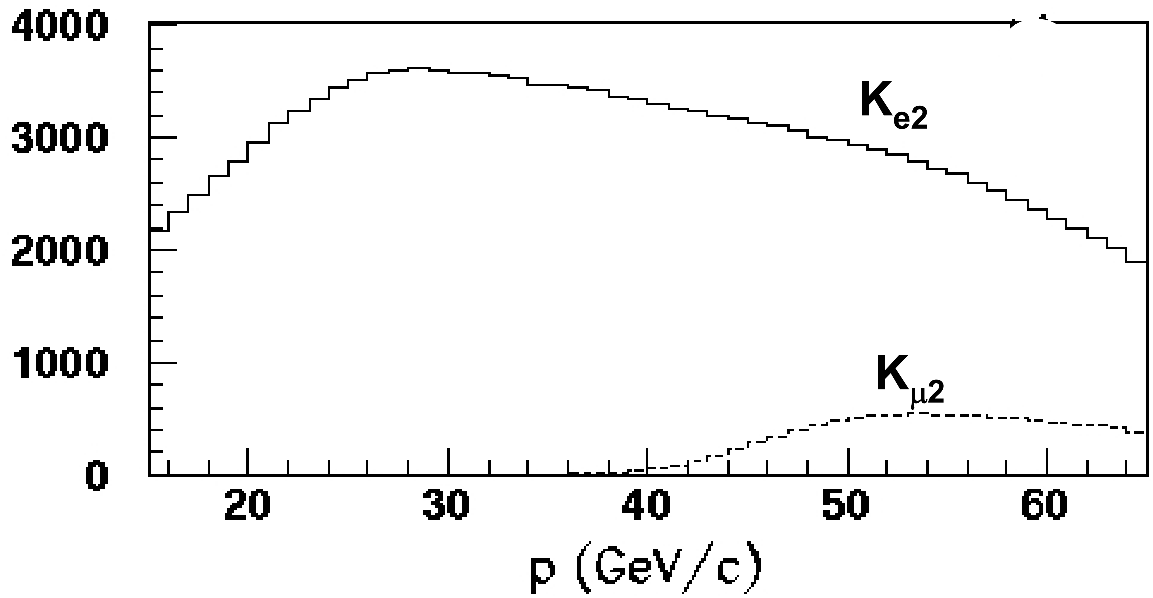
Background:
$K_{\mu 2}$ misidentified
as K_{e2} for P>35 GeV/c.

2007 MC :
Equal samples of
K_{e2} and $K_{\mu 2}$
PK = 75GeV/c
Dipole Pt kick: 263 MeV/c

Expected momentum distribution of electrons from K_{e2} decay and of fake electrons from $K_{\mu2}$ for 150,000 K_{e2} decays

NA48/3 Monte Carlo 2007

Decay vertex interval: 12m < z < 102 m
(z=0 corresponds to collimator downstream end)

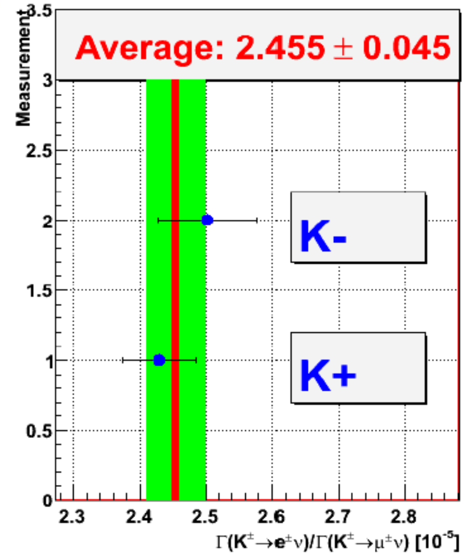


For p **< 35 GeV/c, 64,000 (43%) of events are background free.**

For *p* > 35 GeV, the fraction of muons from $K_{\mu2}$ decay with $0.95 < E / p < 1.05$ will be measured by inserting a small lead plate in a region between the two hodoscope planes to give positive μ ID.

Errors

Sourse	Relative error	
Ke2 sample statistics	1.85%	*
Kmu2 sample statistics	0.05%	
E/p correction for the electrons (E/p>0.95 cut)	0.18%	*
E/p correction for the muons (E/p<0.2 cut)	Negligible	
Trigger efficiency	0.3%	
Acceptance Kmu2	0.03%	
Acceptance Ke2	0.3%	
Radiative corrections	0.12%	
Background subtraction	1.59%	*
Total statistical error	***1.85%***	
Total systematics error	***1.66%***	



$$R_{e/\mu}^{\exp K} = 2.416(43)(24)x10^{-5}$$ CERN(2006)

$$R_{K\to e/\mu}^{th} = \left(2.472 \pm 0.001^{*}\right) x10^{-5}$$

Substantial Improvements (±0.34%) planned for 2007.

The NA48 2007 R_K run

	2004 special run	2007 run
SPS duty cycle (s/s)	4.8/16.8	9.6/39.6
Eff.× no. of days	$\sim 0.9 \times 2.3 = 2.1$	$\sim 0.6 \times 120 = 72$
Eff. no of pulses	$1.08 \cdot 10^4$	$1.6 \cdot 10^5$
Protons per pulse	$2.5 \cdot 10^{11}$	$1.5 \cdot 10^{12}$
K12 beam: p (GeV/c)	± 60	± 75
Acceptance (mr^2)	0.36×0.36	0.18×0.18
$\Delta\Omega$ (sr)	$4 \cdot 10^{-7}$	$1 \cdot 10^{-7}$
$\Delta p/p$ effective (%)	± 3	± 2.5
RMS (%)	~ 3.0	~ 1.8
TRIM3 x' (mr)	0	∓ 0.3
p_T (MeV/c)	0	∓ 22.5
MNP33 x' (mr)	± 2.0	± 3.5
p_T (MeV/c)	± 120	± 263
Triggers/pulse	45,000	96,000
Good K_{e2}/pulse	$\sim$0.37	~ 0.94
Good K_{e2} (total)	4000	150,000

$K \rightarrow \pi\nu\bar{\nu}$ Experiments

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

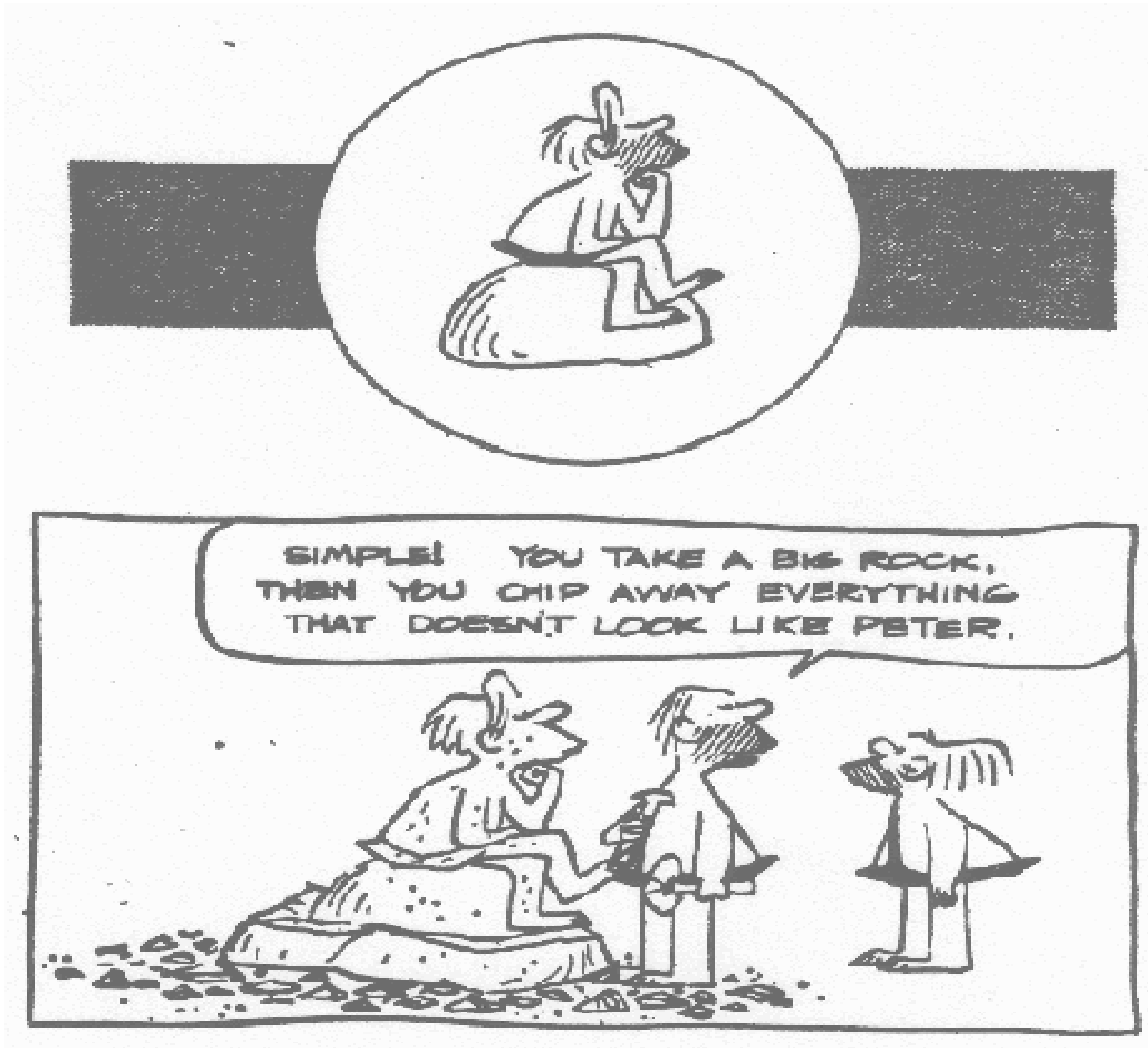
- BNL E949 $B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 1.47 \pm^{1.30}_{0.89} \; x \, 10^{-10}$
- New Proposed Techniques: CERN, JPARC

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

- New Proposed Techniques – KEK/JPARC

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”

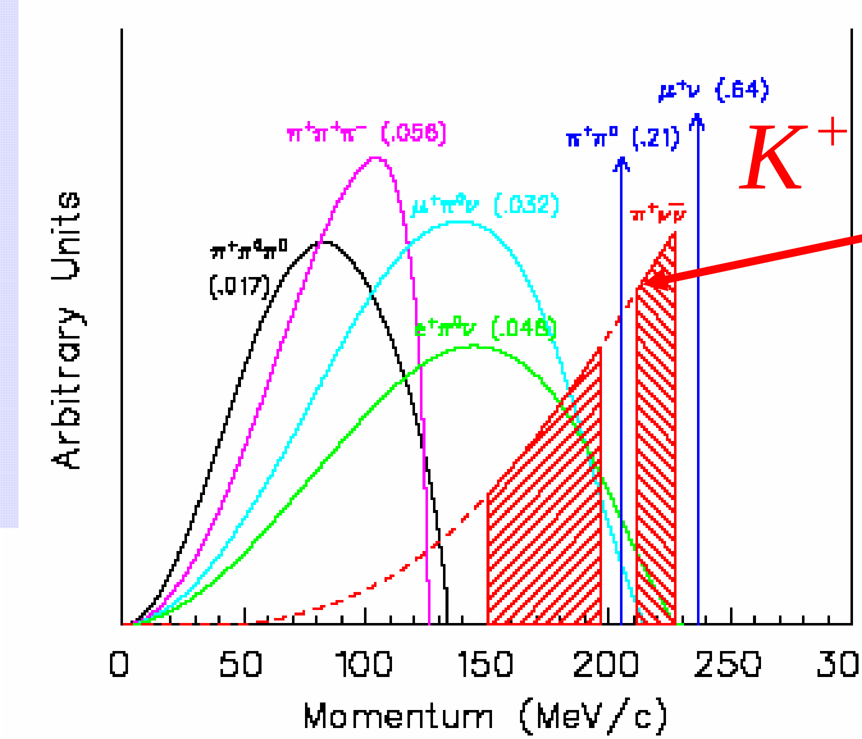
The Six Steps to Measuring $K \rightarrow \pi\nu\bar{\nu}$ Reactions

Step 1: Know the enemy.

K^+ Decay Modes $\tau_{K^+} = 12.4ns$

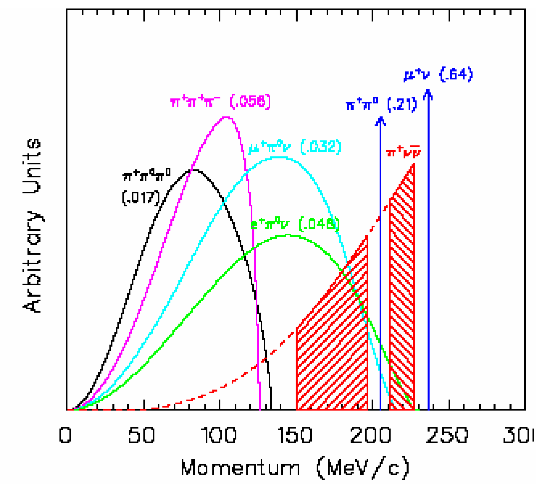
Decay Mode	Branching Ratio	Background Rejection
$K^+ \to \mu^+\nu$	63% (called $K_{\mu 2}$)	μ PID, Two-Body Kinematics
$K^+ \to \pi^+\pi^0$	21%	Photon Veto, Two-Body Kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	Charged Particle Veto, Kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	Photon Veto, Kinematics
$K^+ \to \pi^0\mu^+\nu$	3% (called $K^+_{\mu 3}$)	Photon Veto, μ PID
$K^+ \to \pi^0 e^+\nu$	5% (called K^+_{e3})	Photon veto, E/p

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



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

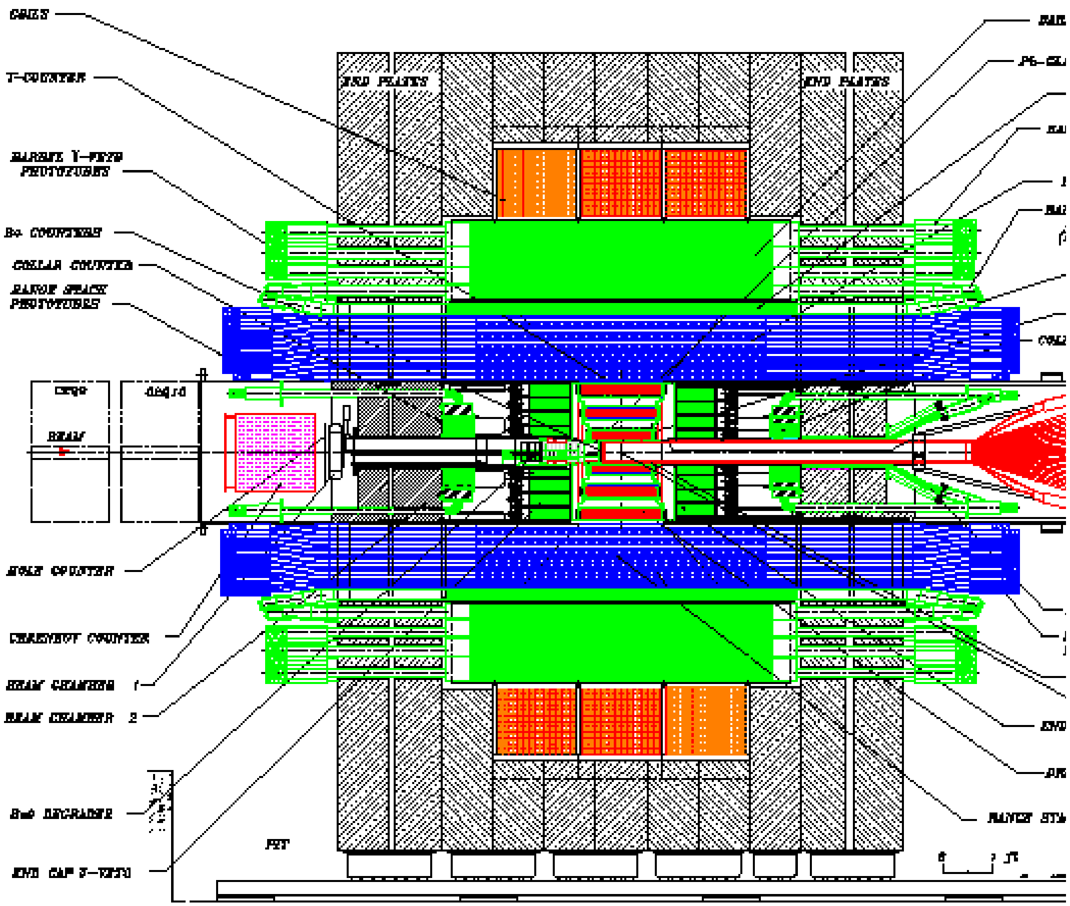
Approaching $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

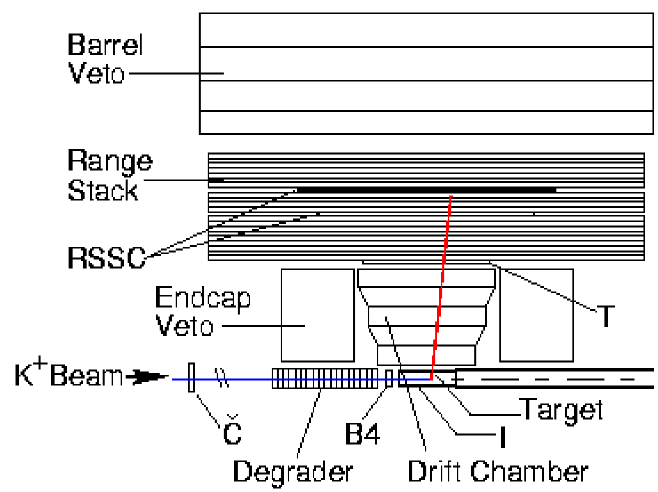


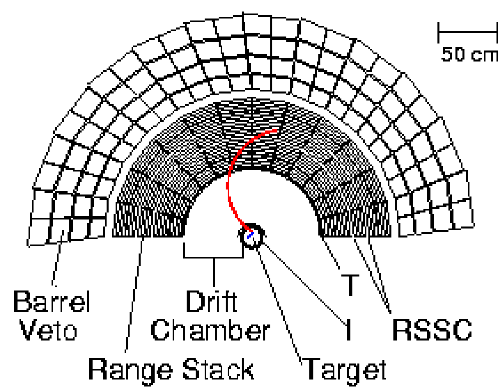
- Determine everything possible about the K^+ and π^+
  - * π^+/μ^+ particle ID better than 10^6 (π^+-μ^+-e^+)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency $< 10^{-6}$
- Suppress backgrounds well below the expected signal (S/N~10)
  - * Predict backgrounds *from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

Step 2: Create a giant filter

BNL E949 Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

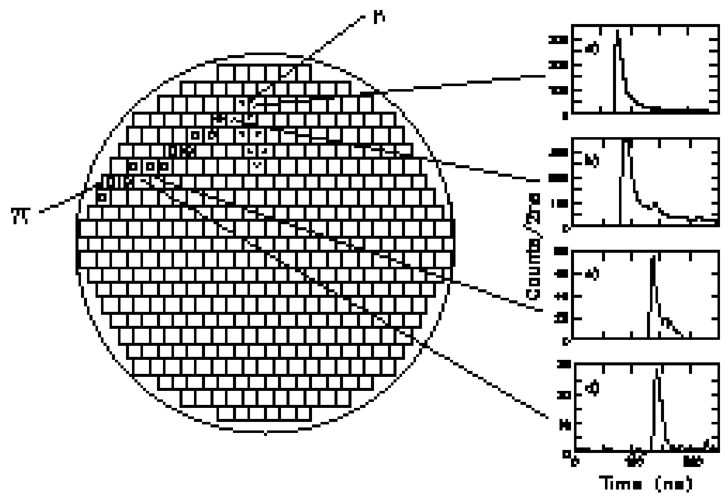






Special Instruments Required: 500 MHz Transient Digitizers

$K \rightarrow \pi$



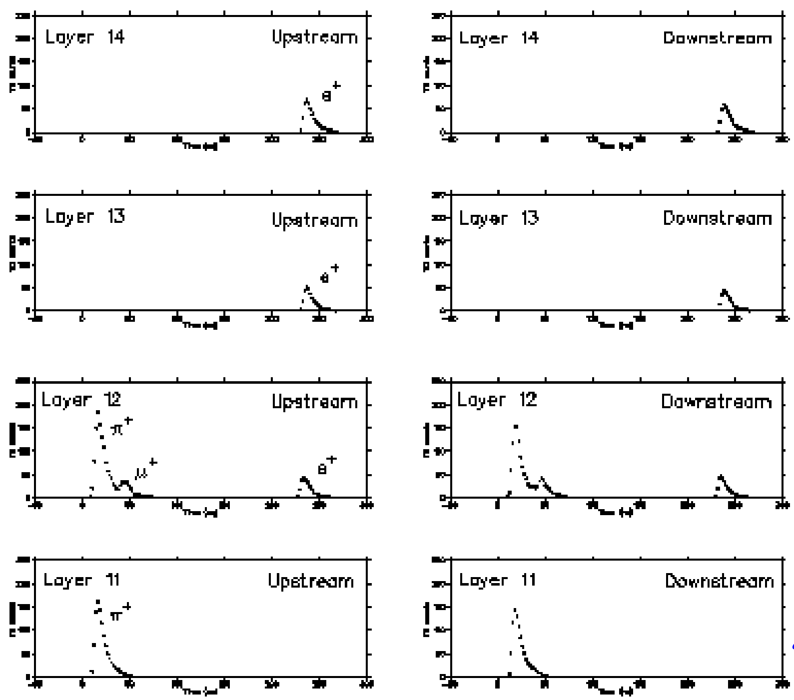
K stop

$K \rightarrow \pi$

π

π

$\pi \rightarrow \mu \rightarrow e$



$e \Uparrow$

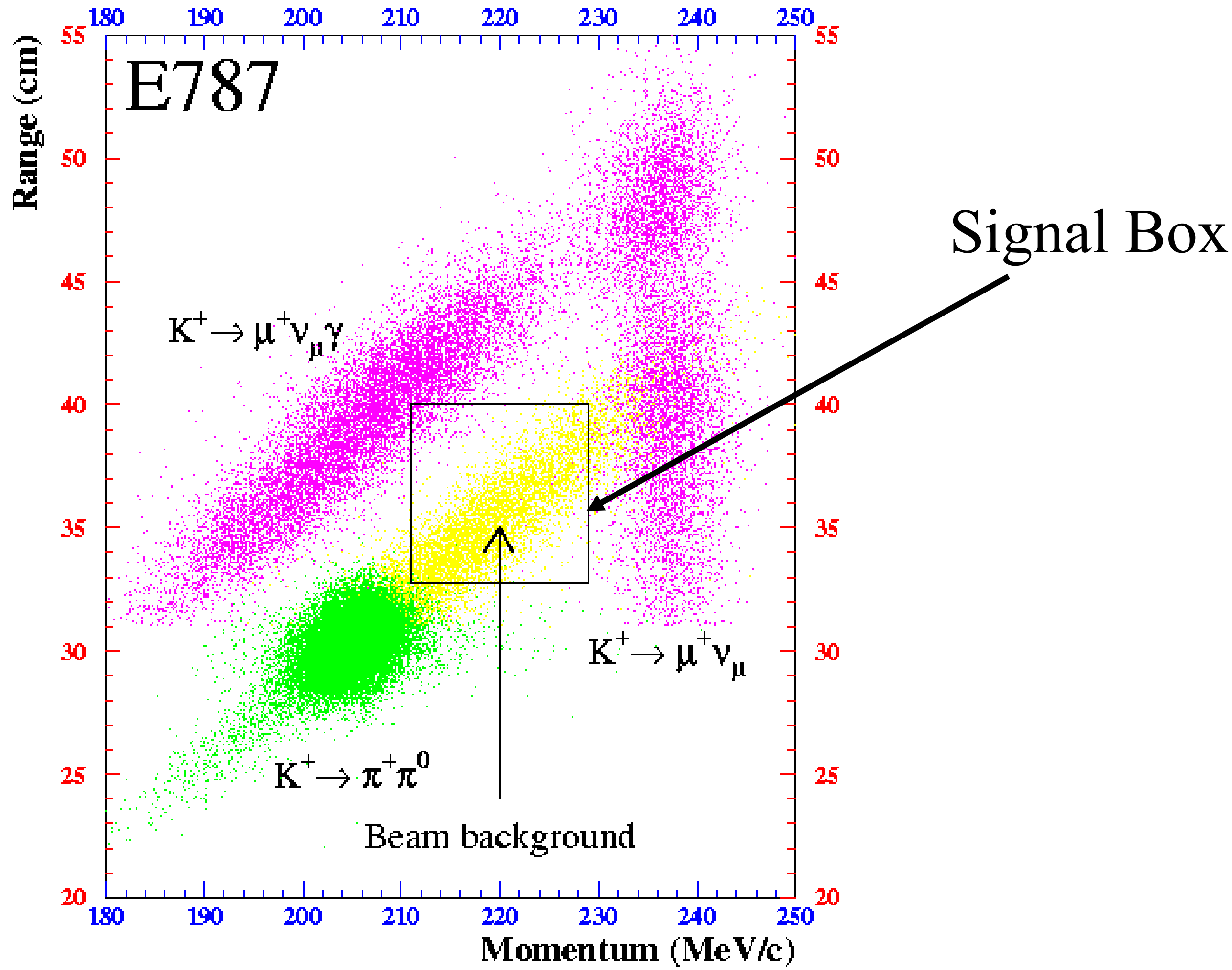
$e \Uparrow$

$\pi \rightarrow \mu \,/\, \mu \rightarrow e$

π enters $\uparrow$

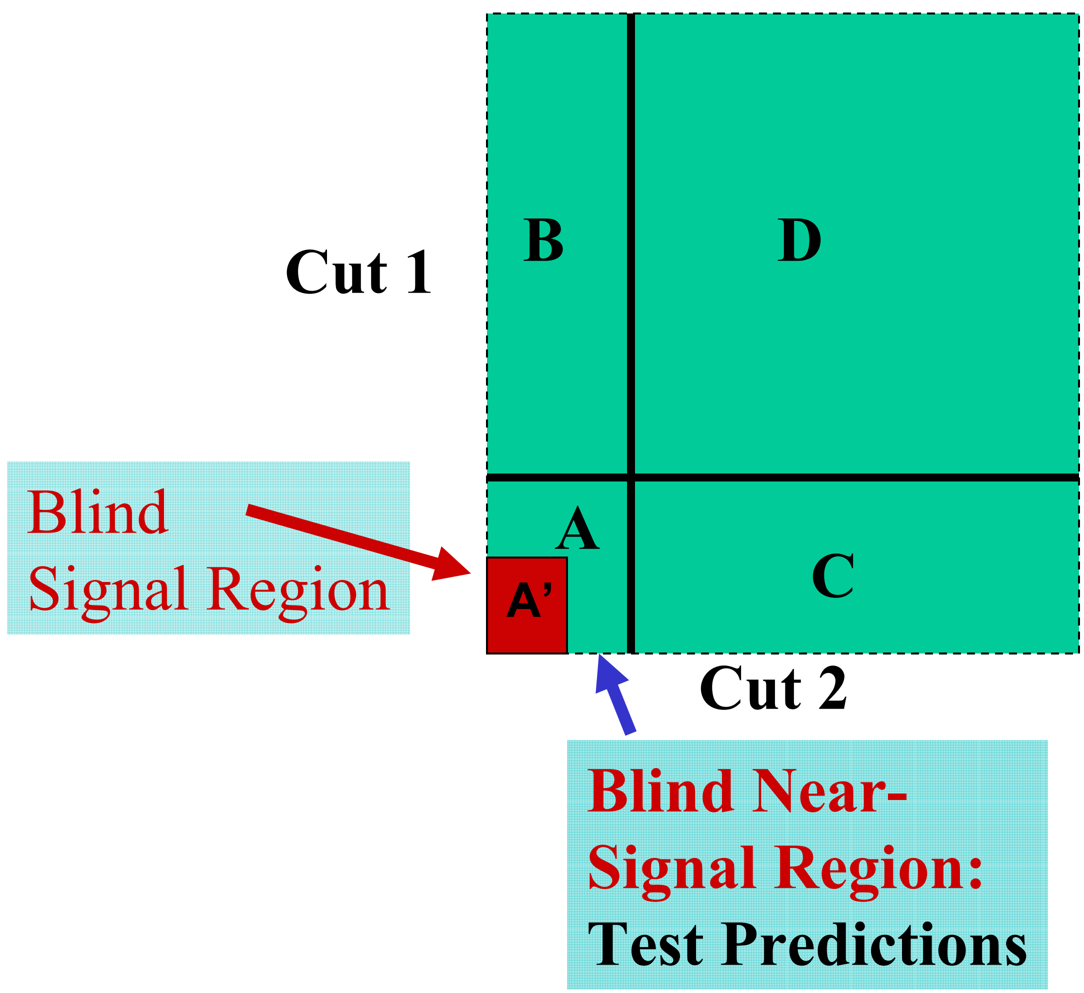
Step 3: Demolish the Backgrounds

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

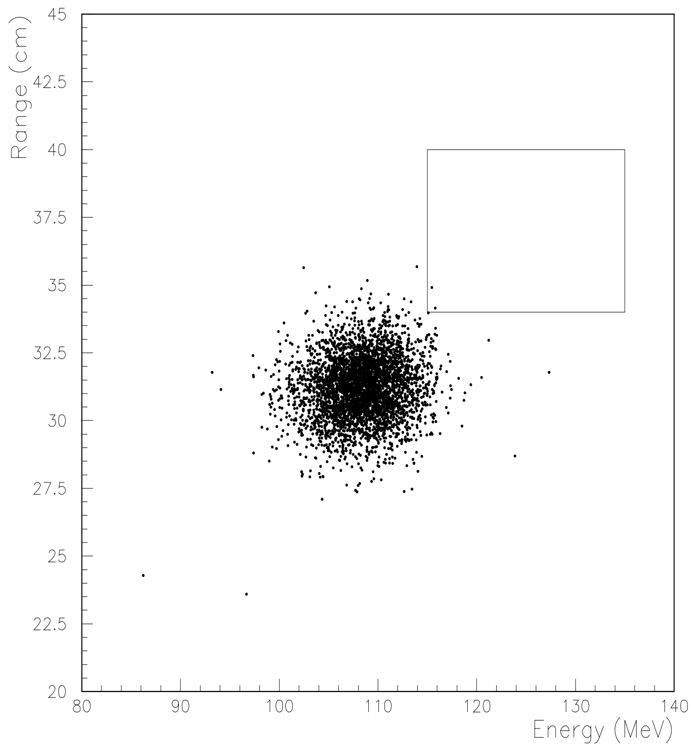
Use a subset (e.g. 1/3) of the data to finalize cuts which are then applied to the remainder of the data. Background estimates are also subject to blind analysis.

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

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

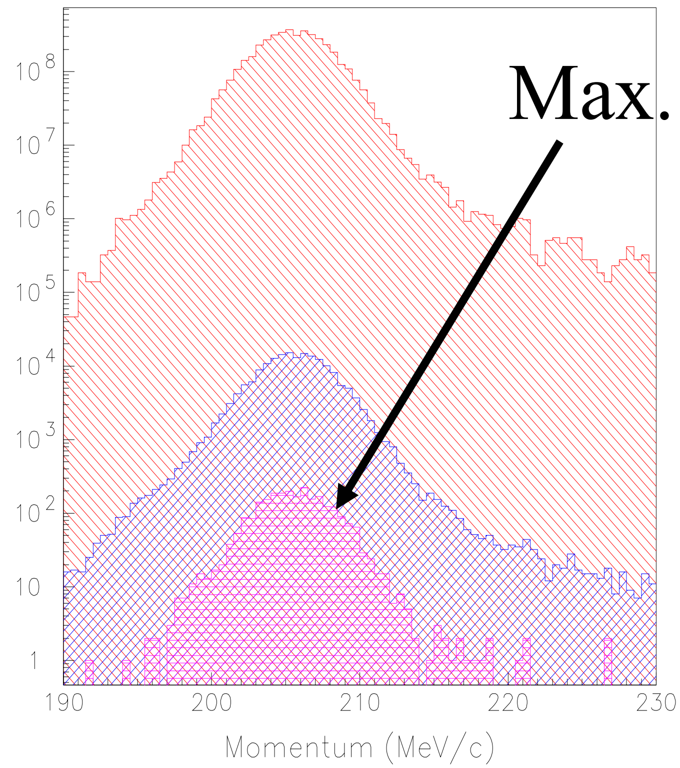
γ Veto Reversed

Range vs. Energy



γ Veto Applied

Momentum



Important step: Check for correlations.

Background Suppression:

E949 Improved Photon (π^0) Detection Efficiency

Photon Detection Efficiency limited by

- Photonuclear interactions ("$\gamma \rightarrow$ n")
- Sampling Fluctuations
- Punch-through

π^0 Rejection: $>10^6$

(for $K^+ \rightarrow \pi^+\pi^0$ background)

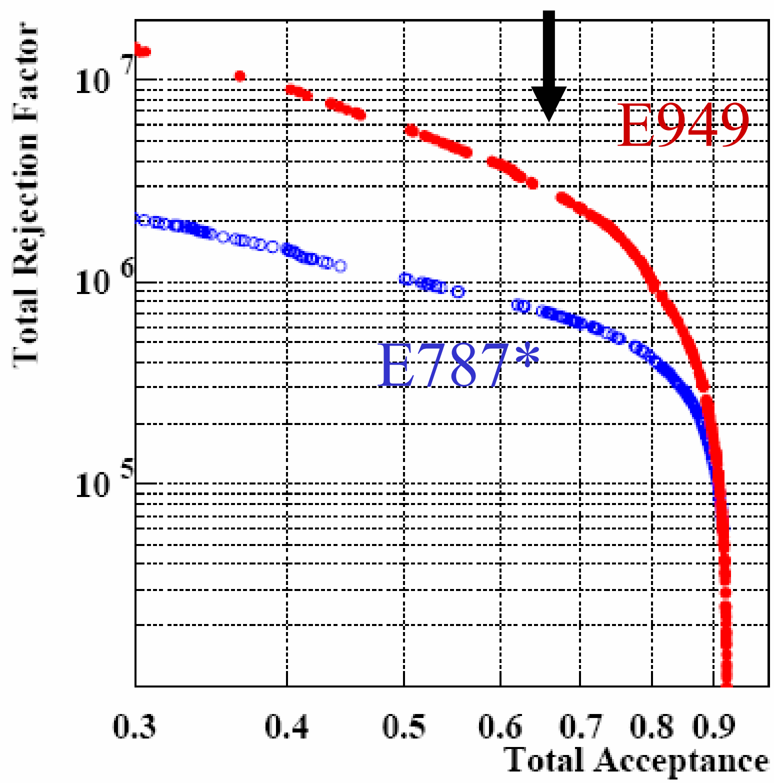
Twice the rejection

of π^0 backgrounds

at comparable acceptance

for $K^+ \rightarrow \pi^+\nu\bar{\nu}$.

Rejection vs. Acceptance

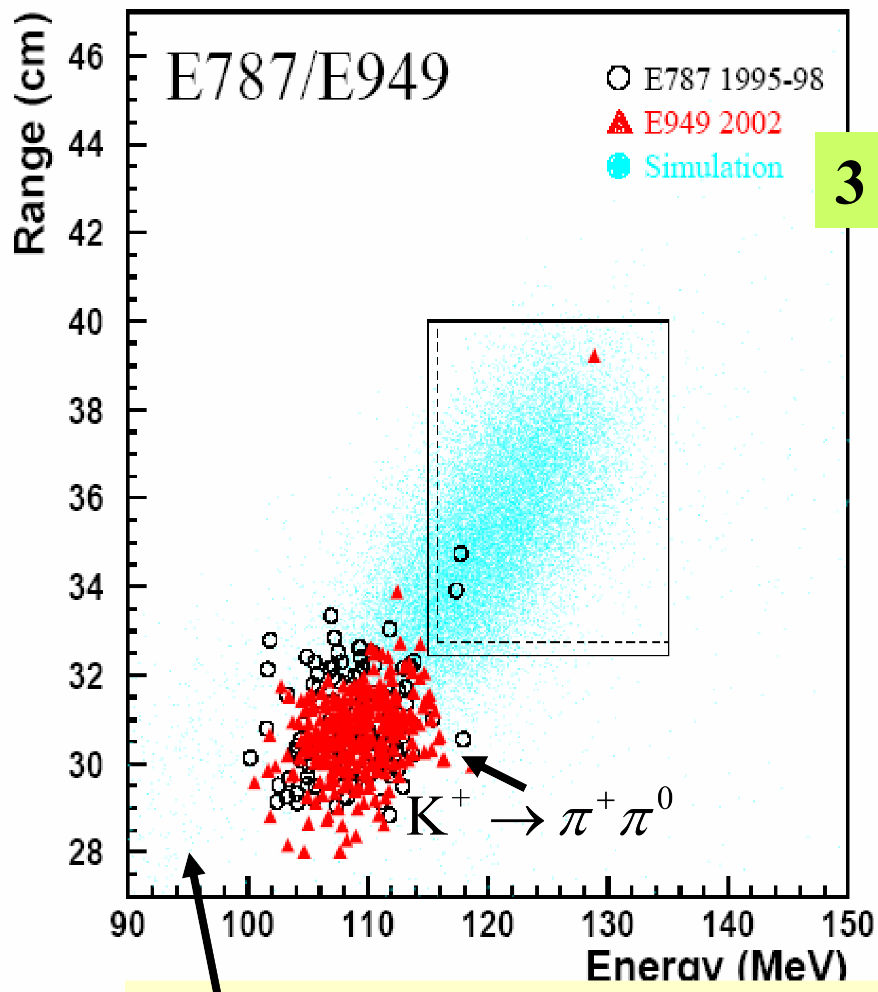


* E787 was a previous version of E949.

Step 4:Open the Box

Combined E787/E949 Branching Ratio

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



$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = 7.8 \pm 1.2\, x 10^{-11}$$

3 events observed– consistent with SM

	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

Low energy phase space data under analysis.

Step 5: Get lots of events!

CERN Proposal P-326 : $K^+ \to \pi^+ \nu\bar{\nu}$

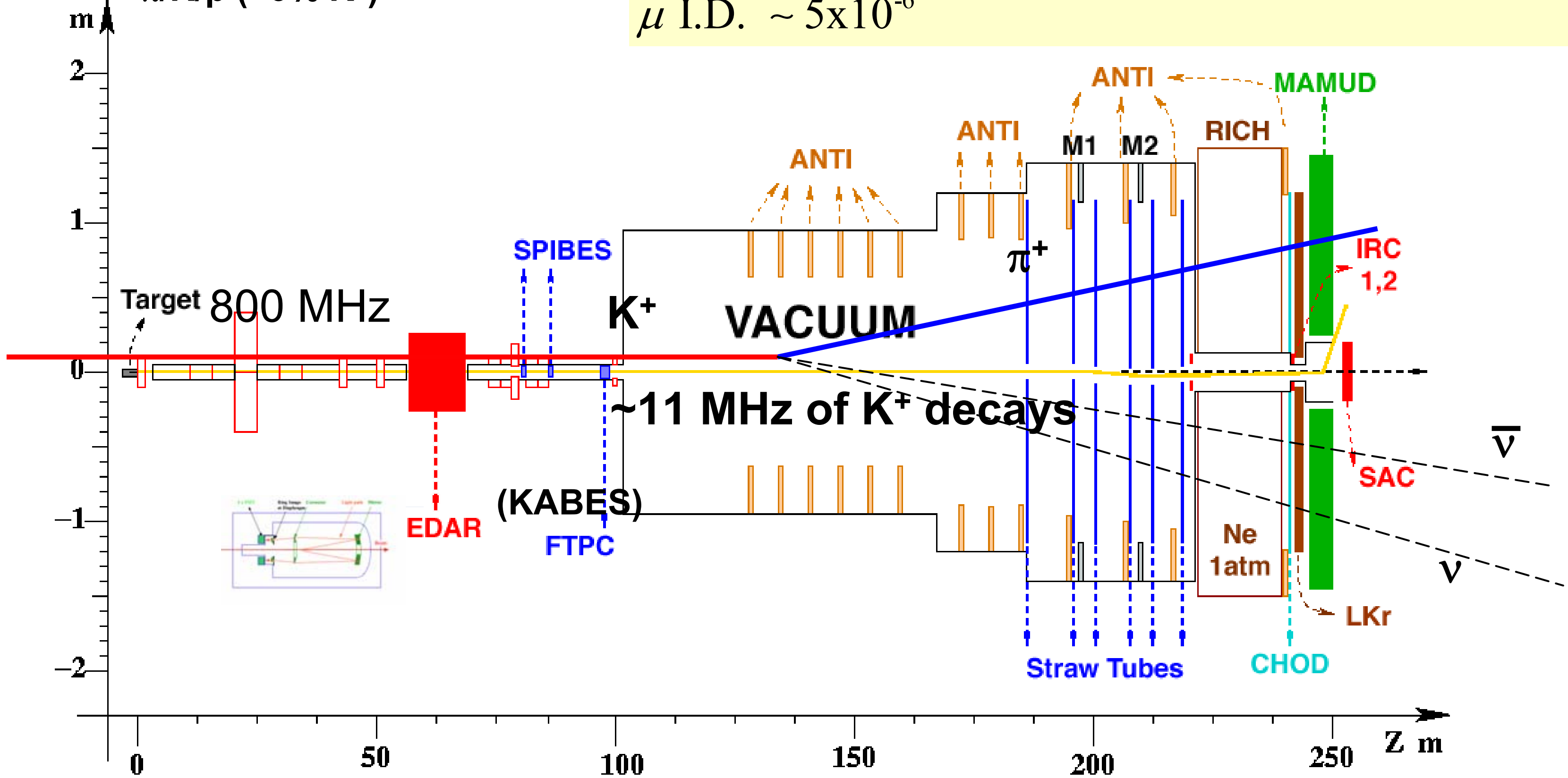
Goal: >80 events for $\mathrm{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 10^{-10}$

SPS primary p: 400 GeV/c
Secondary beam:
- **75 GeV/c , 800 MHz**
- **π/K/p (~6% K$^+$)**

Measure $P_K, P_\pi, \theta_{K\pi}$

Hermetic detector for $\pi^0 \to \gamma\gamma$ Decays $\bar{\varepsilon}_{\pi^0} \sim 10^{-8}$

μ I.D. ~ $5\mathrm{x}10^{-6}$

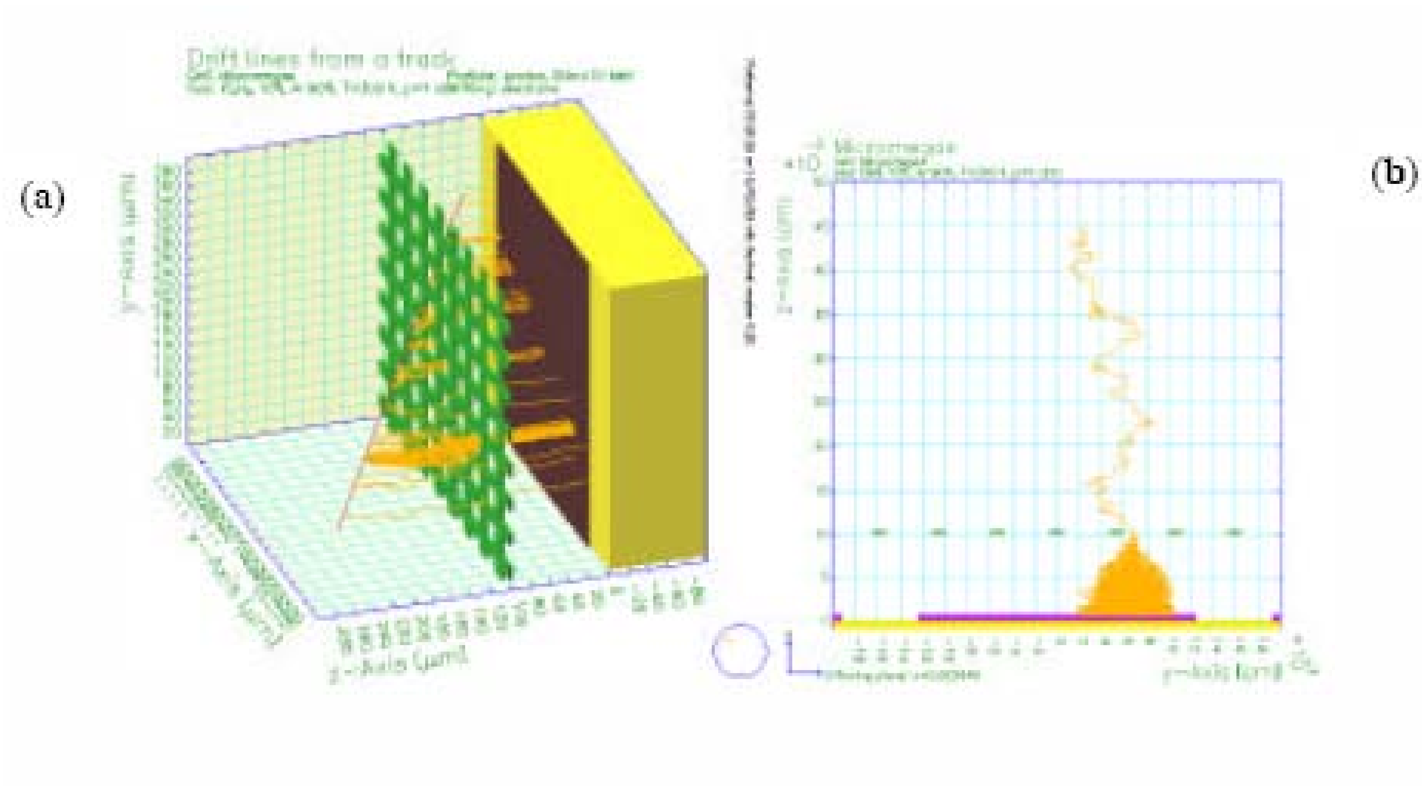


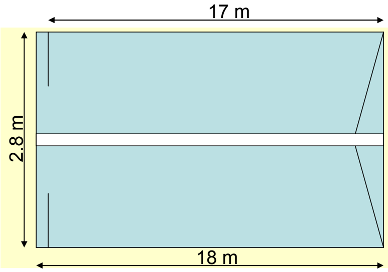
Resolutions: $\dfrac{\Delta P_K}{P_K} \sim 0.3\%, \dfrac{\Delta P_\pi}{P_\pi} \sim 1\%, \ \Delta\theta_{K\pi} \sim 60\mu rad$

P-326 Detector Challenges

Detector/System	
CEDAR	Differential Cerenkov Detector – tag K
Gigatracker (SPIBES, FTPC)	Si micro-pixels, TPC- measure P_K @ 1 GHz
Straws tracker in vacuum	Charged particle detectors
Large Angle Vetoes	Photon Veto detectors (9-50 mrad) : Pb/Sccint.WLS fiber readout
SAC/IRC	Small, intermediate angle P.V. (<1 mrad): shashlyk Pb, scintillating fiber towers./PbWO4
MAMUD	Muon particle i.d. (range); Magnetized Fe/Scint. Hadron calorimeter.
RICH	Ring Imaging Cerenkov Detector – pi/mu i.d.
LKr Consolidation	Calorimeter – P.V. (1-9 mrad)

Gigatracker Micromegas Tracking/TPC

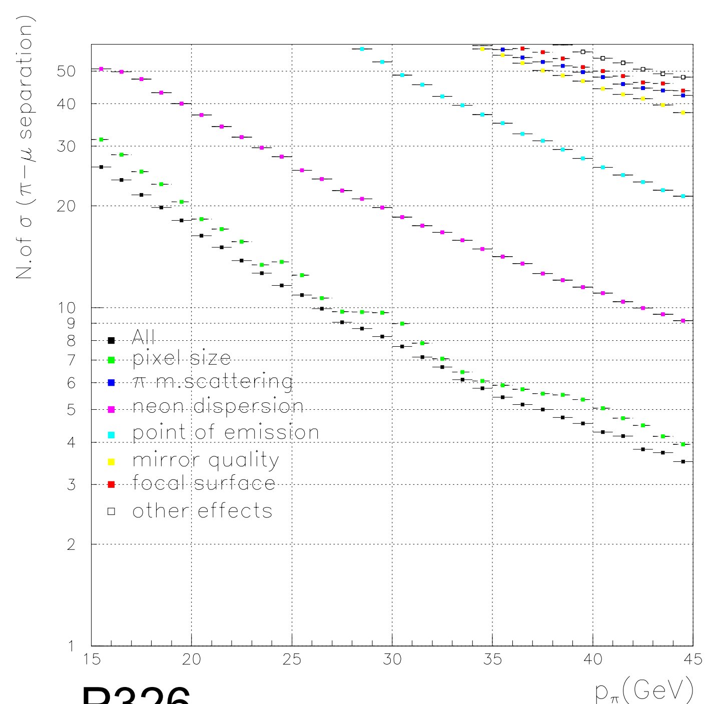




RICH counter

- **RICH Specifications for $K^+ \rightarrow \mu^+ \nu$ rejection:**
  - **Separate π–μ at ≥3 σ from 15 to 35 GeV**
  - **Time resolution: ≤100 ps**
- Radiator: Neon
- 1 atm, $(n-1)=67\times10^{-6}$
- π threshold = 12 GeV
- (15 GeV for full eff.)
- Length: ~18 m (**5.6% X_0**)
- Focal: 17 m 2 mirrors (eff.)
- ~2000 PMTs
- Hamamatsu 7400-U03
- Dispersion: 1.6×10^{-6} (convoluted with PMT response)
- Pixel size: 18 mm
- Single Anode PMTs
- PMTs matrix on the focal plane with compact hex packing

Sigma π–μ separation vs. Momentum

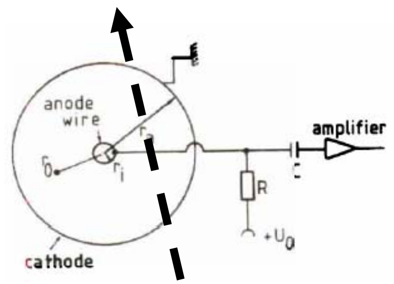


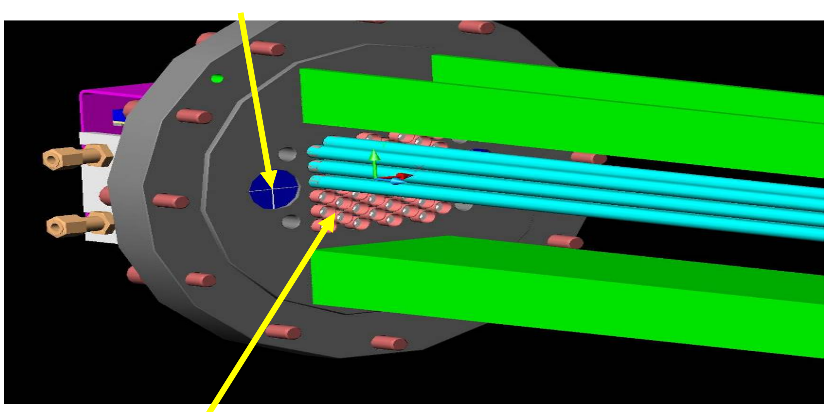
P326

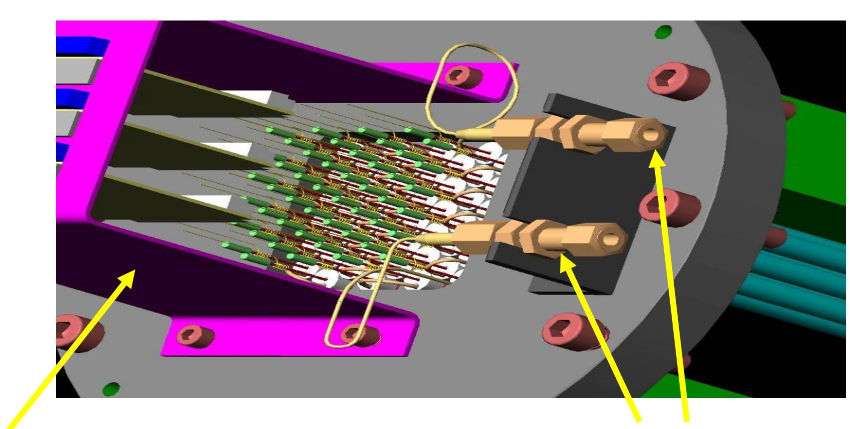
3 sigma at 35 GeV

Straw Tracking in Vacuum

Gas proportional chamber; wires (anode) strung in thin "soda straw" cathodes.





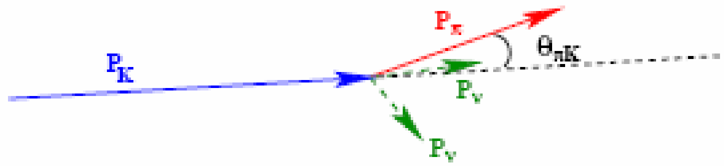


48 holes for straws: 8 layer x 6 straws

R/O electronics box

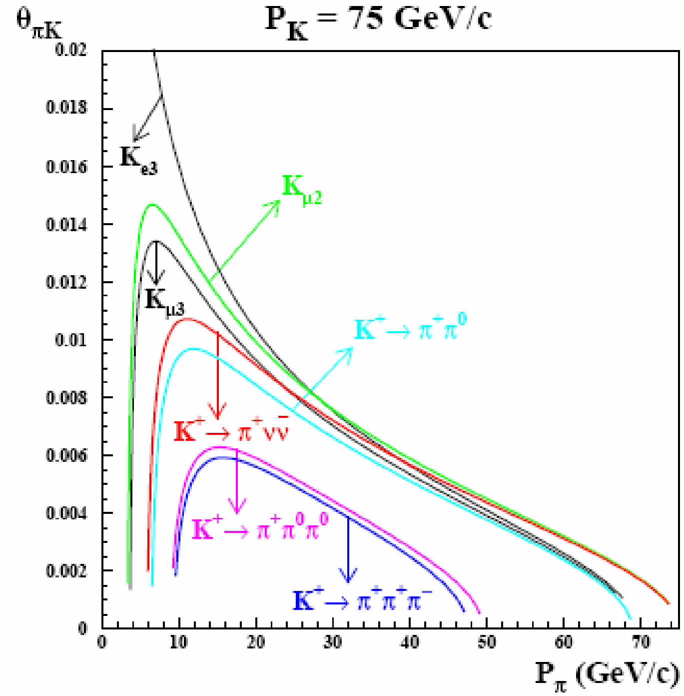
Gas connectors

$K^+ \to \pi^+ \nu \bar{\nu}$ Kinematics and Backgrounds at 75 GeV

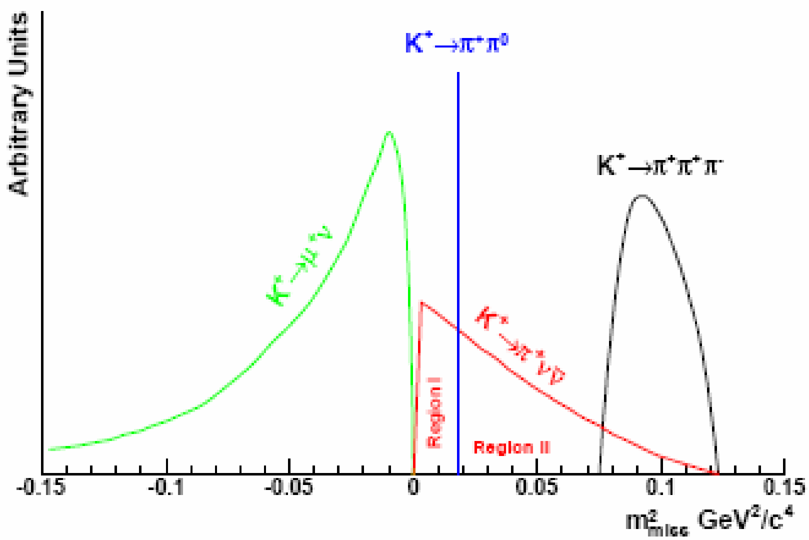


$$m^2_{miss} \simeq m^2_K \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m^2_\pi \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||$$

$\theta_{\pi K}$ vs. P_π



Missing Mass $K^+ \to \pi^+ (M_{miss})$



No Missing Mass Constraints:

	$K^+ \to e^+ \pi^0 \nu$	$K^+ \to \mu^+ \nu \gamma$	$K^+ \to \pi^+ \pi^0 \gamma$
BR	4.87×10^{-2}	5.50×10^{-3}	2.75×10^{-4}
Acceptance	13.4%	15.3%	17.9%
η_μ	–	10^{-5}	–
η_{π^0}	5×10^{-8}	–	5×10^{-8}
η_γ	–	2×10^{-4}	10^{-3}
$\eta_{\pi e}$	10^{-3}	–	–
S/B	30	5	4000

P326 Proposal (2006)

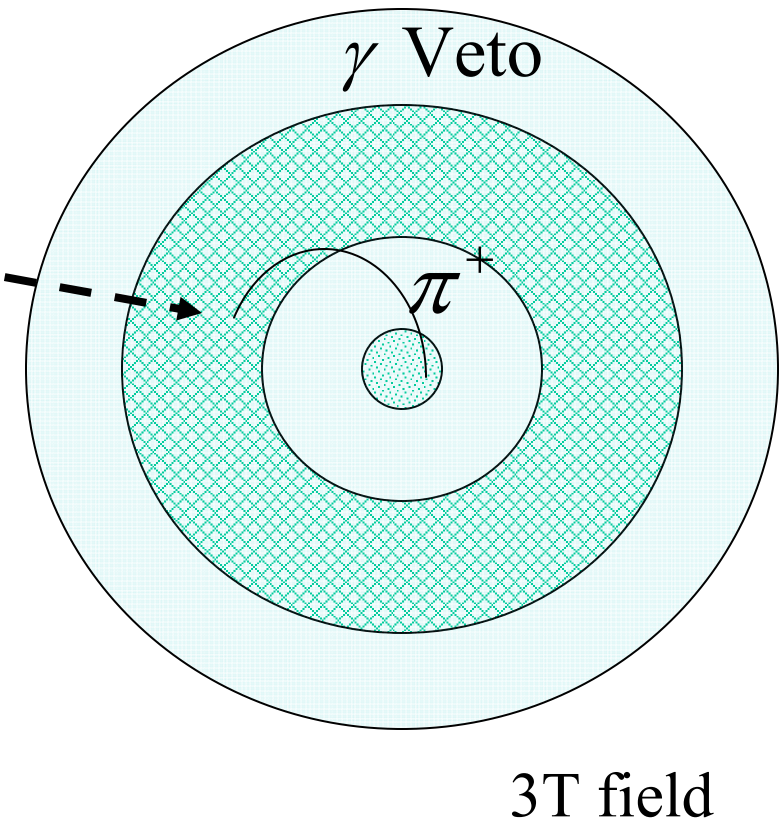
New Approaches to $K^+ \to \pi^+ \nu \bar{\nu}$:

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

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



Step 6: Tackle Something even harder:

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

Theory: $\left(3.0 \pm 0.6\right) x 10^{-11}$

Limit from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ via isospin : $< \underline{1}.4\, x 10^{-9}$ • $[Grossman, Nir]$

- KTEV (FNAL) result: $B(K_L^0 \rightarrow \pi^0 \nu \nu) < 5.9\, x 10^{-7}$ $(90\% CL)$
- KEK E391a: $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 x 10^{-7}$ $(90\% CL)$
- JPARC Proposal:

Phase 1: Single event Sensitivity 10^{-10}

- KOPIO Concept: $< 10^{-12}$

The Challenges

- $B(K_L \rightarrow \pi^0 \nu\nu) \sim 3\times10^{-11}$;
  need huge flux of K's -> high rates
- Weak Kinematic signature (π^0 +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

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

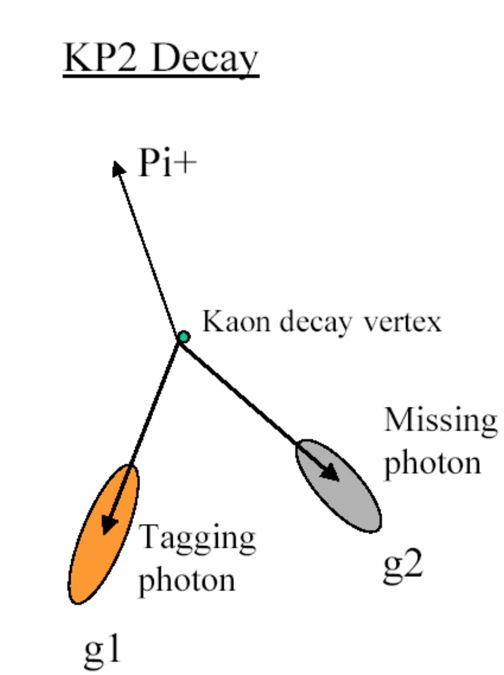
Background suppression factor needed: 10^{10}

Primary Backgrounds

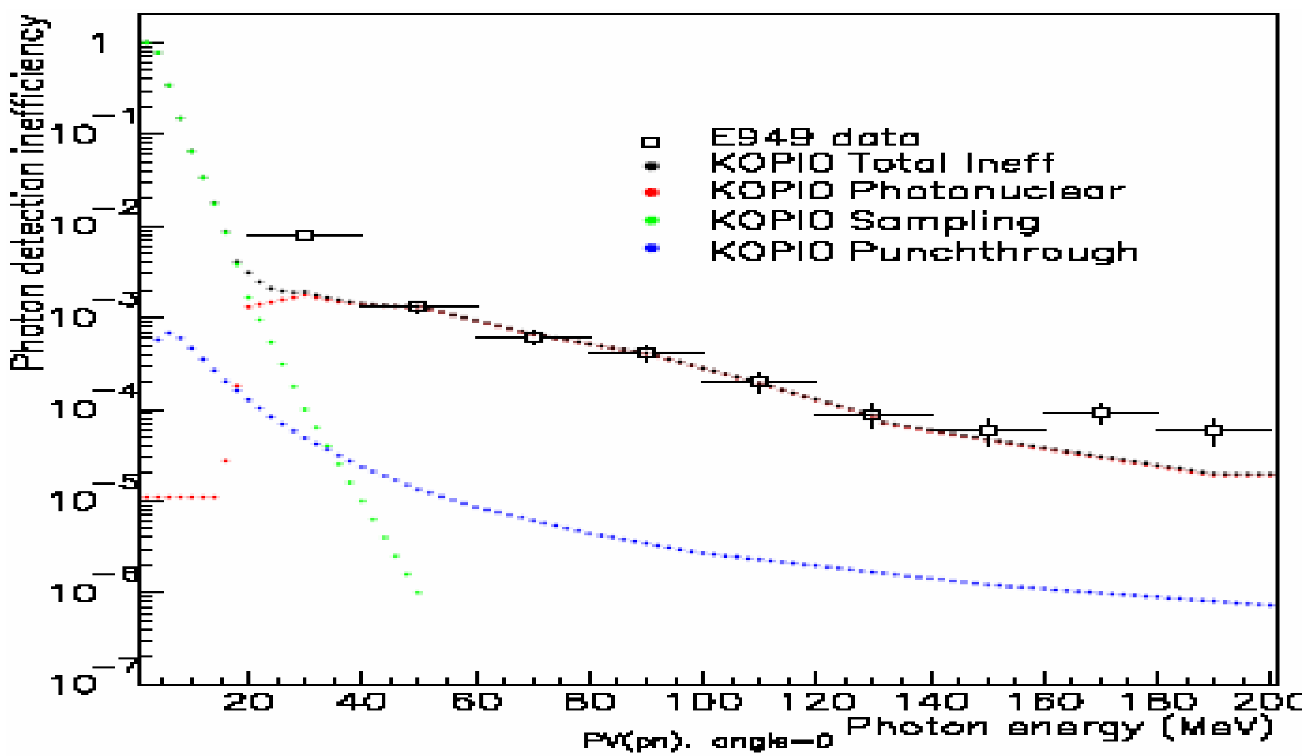
Mode	Branching Ratio
$K_L^0 \rightarrow \pi^0 \pi^0$	$0.93 \; x \; 10^{-3}$
$K_L^0 \rightarrow \pi^- e^+ \nu \gamma$	$0.36 \; x \; 10^{-2}$
$K_L^0 \rightarrow \pi^+ \pi^- \pi^0$	0.1255
$K_L^0 \rightarrow \pi^0 \pi^0 \pi^0$	0.2105
Others	

Photon Veto Efficiency Estimates and Simulations based on improved E949 Measurements supplemented by FLUKA calculations

Photon Detection Efficiency limited by
- Photonuclear interactions ("$\gamma \rightarrow$ n")
- Sampling Fluctuations
- Punch-through



1 MeV Visible Energy Threshold



Photon Veto Inefficiencies Assumed for JPARC $K_L^0 \rightarrow \pi\nu\nu$

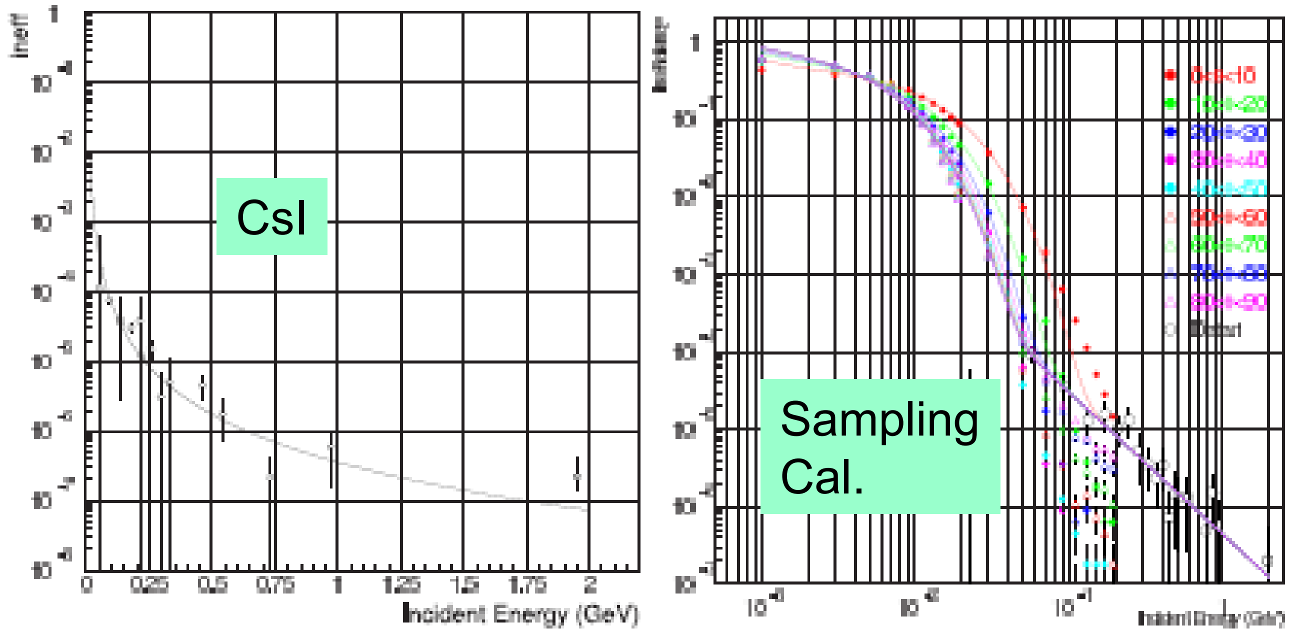
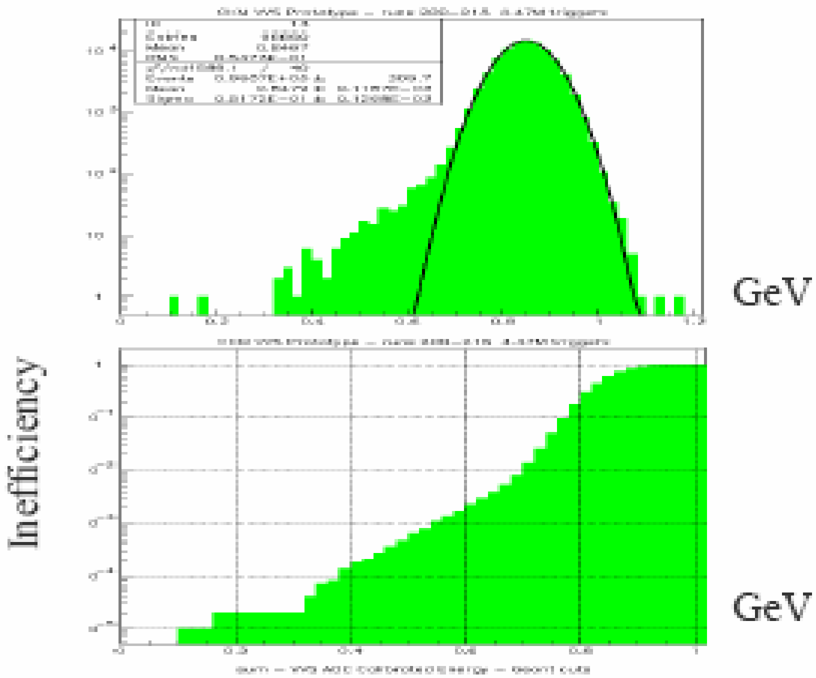


Figure 56: Photon detection inefficiencies for CsI crystals (Left) and a sampling calorimeter (Right) as a function of incident photon energy. The open black circles are experimental data for photonuclear interactions. Monte Carlo results for the inefficiencies due to punch-through and sampling fluctuations are shown in the Right figures as colored points. Different colors indicate different incident angles on the detector. The solid curves are the model inefficiency functions obtained by fitting the data and Monte Carlo results.

Photon Veto Inefficiency and Technology

- 0.3% VVS Prototype built
- Tested at JLAB in an e^- beam
- Achieved <1x10^{-5} (3x10^{-6}) veto inefficiency at 1 GeV (required 3x10^{-5})



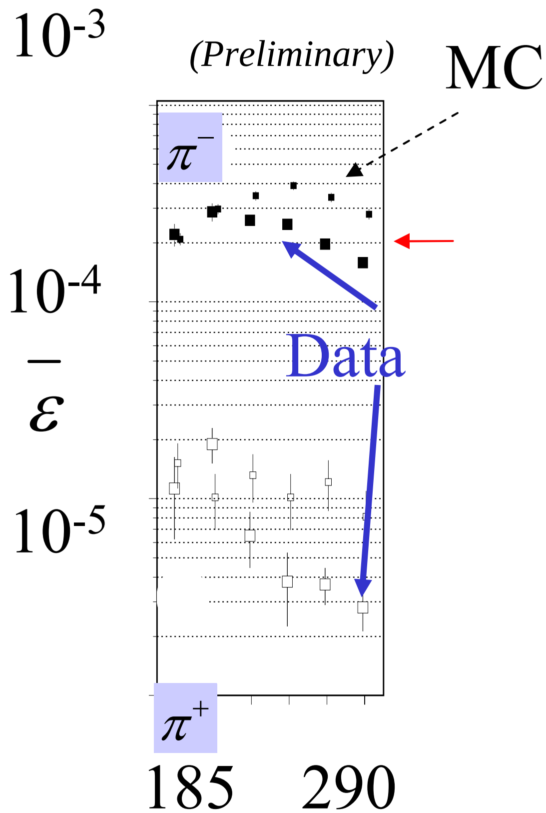
Charged Particle Vetoing

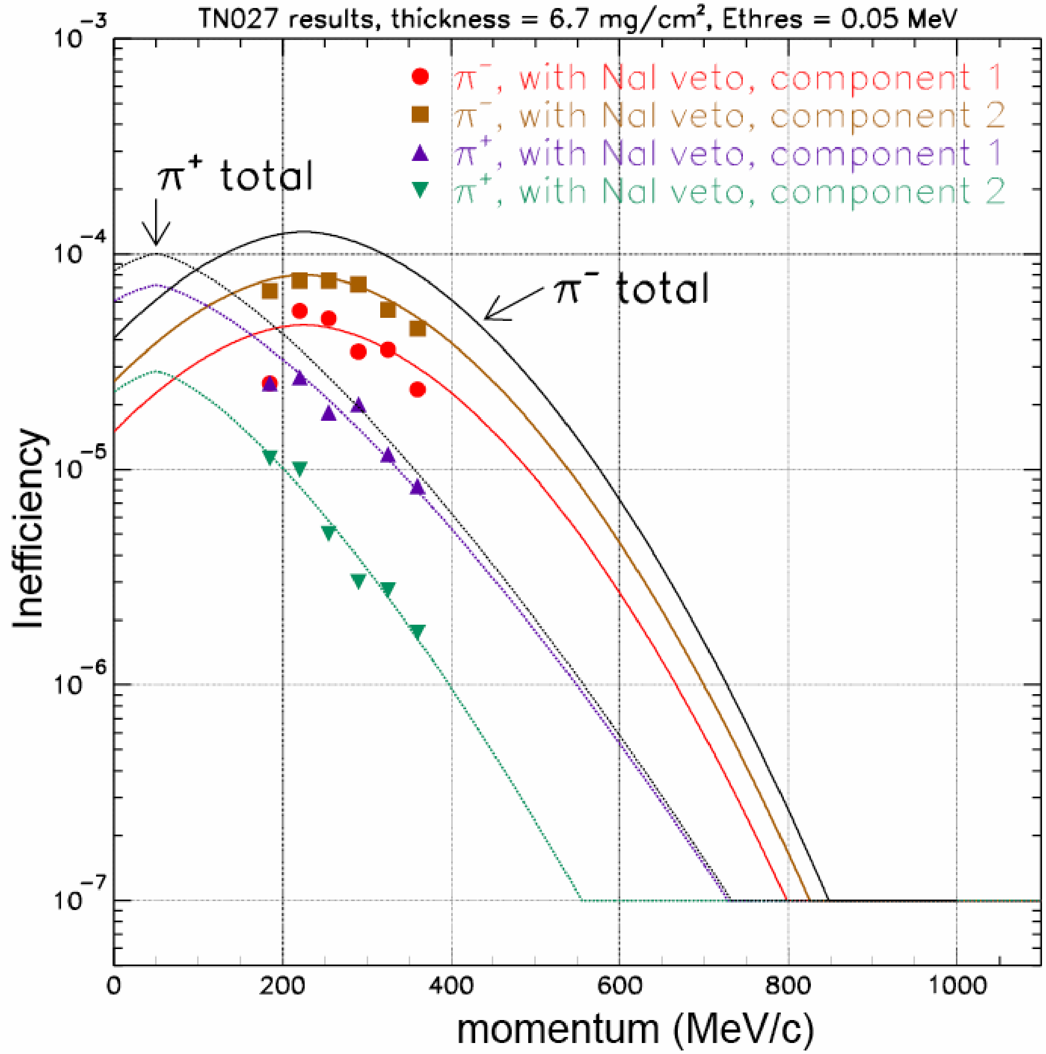
Example Background: $\mathbf{K}_L^0 \rightarrow \pi^- e^+ \nu \gamma$

Plastic Scintillator –

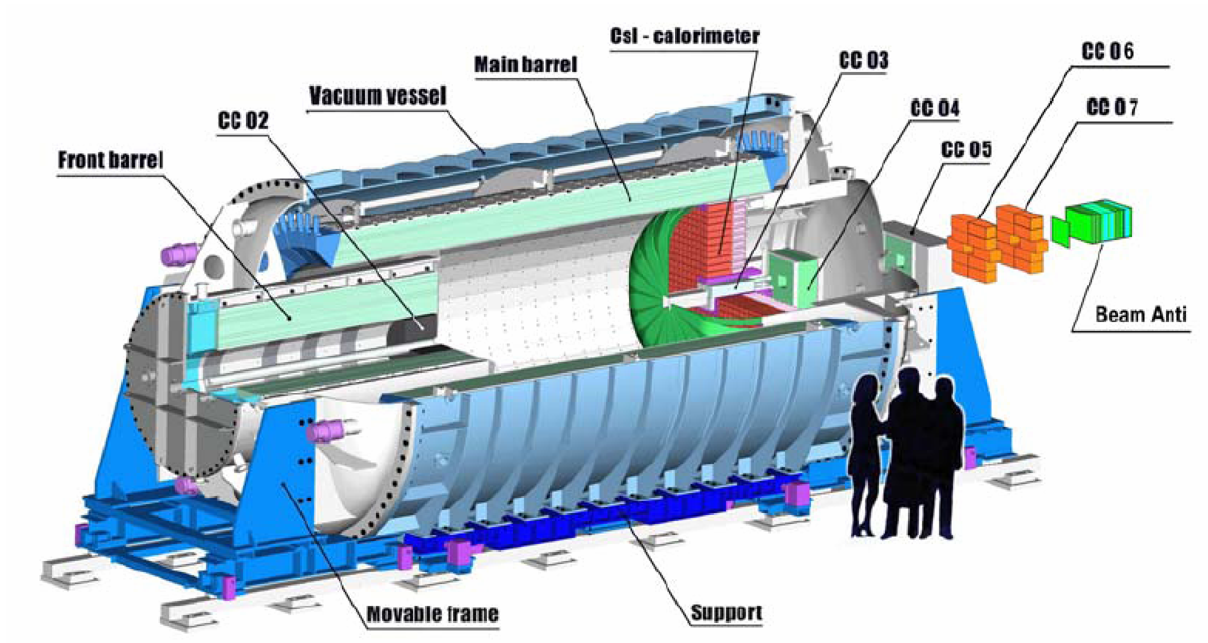
backed up by γ vetoes!

PSI Measurement





KEK PS E391a >>> JPARC with KTEV CsI



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

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

2006 Result: $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 x 10^{-7}$ (90%CL)

KEK PS E391a >>> JPARC

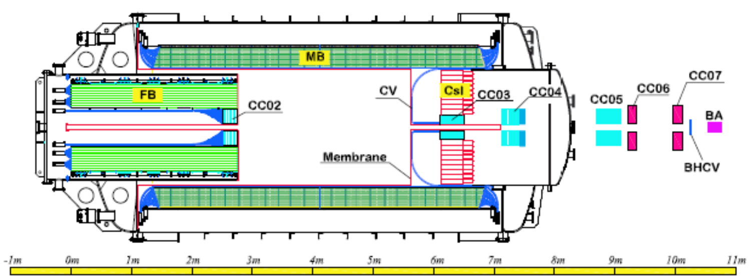


FIG. 1: Cross section of the E391a detector. K_L^0's enter from the left side.

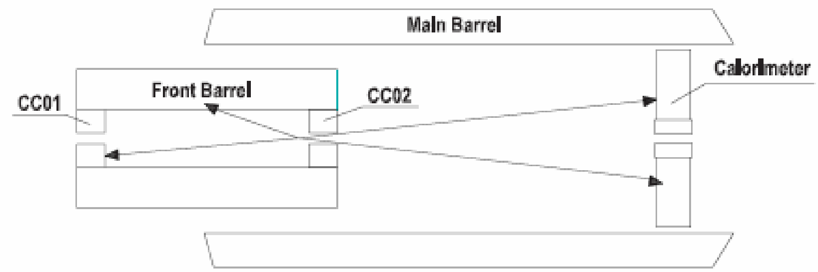


Figure 26: Schematic view of the role of the upstream decay chamber.

$$\text{S.E.S.} = 1/(N_K \times \text{decay probability} \times \text{acceptance}) = 4.0 \times 10^{-12}$$

With a Standard Model prediction of $\mathcal{B}(K_L \to \pi^0 \nu \overline{\nu}) = 2.8 \times 10^{-11}$, we expect to observe 7.0 events in Step 1. If the acceptance loss is 50% as we estimated, the S.E.S. is 8.0×10^{-12} and 3.5 Standard Model events are expected.

Calorimetry and Photon Vetos

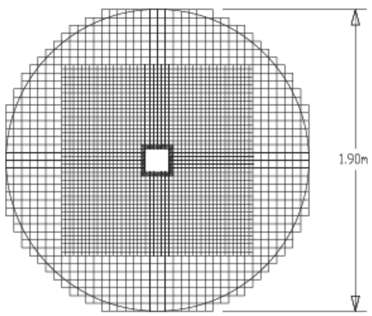


Figure 15: Layout of the Calorimeter for the J-PARC experiment with the KTeV CsI crystals. The $2.5 \times 2.5 \times 50\text{-cm}^3$ crystals are used for the inner region, and $5.0 \times 5.0 \times 50\text{-cm}^3$ crystals are used for the outer region.

KTEV Pure CsI

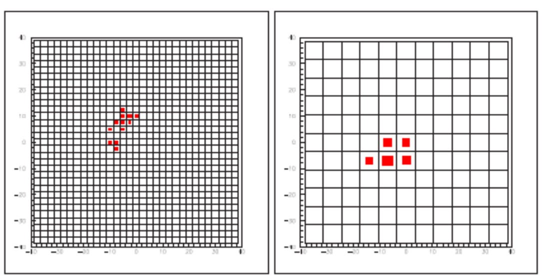


Figure 16: Event display for two photons in the calorimeter close to each other for Step 1 (Left) and E391a (Right).

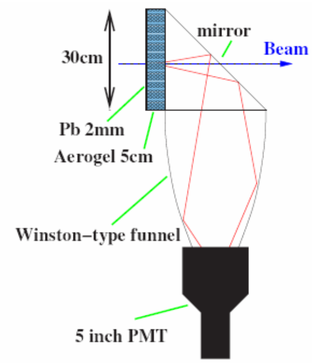


Figure 30: Schematic view of the BHPV module.

Beam Veto
Pb/Aerogel

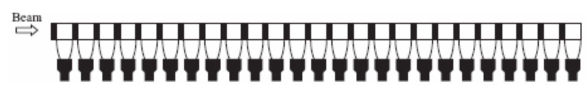


Figure 31: Schematic side view of the BHPV arrangement.

Transverse Momentum P_T *vs.* Vertex Position (Z)

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

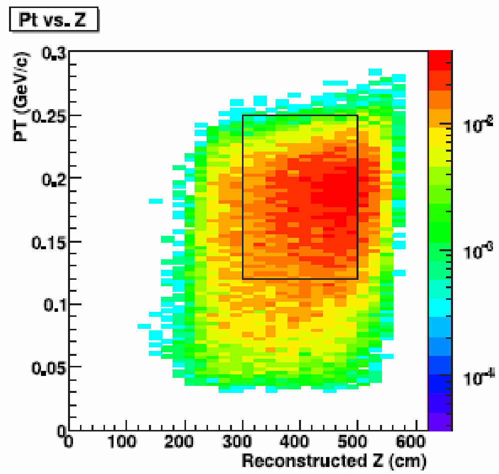


Figure 33: Distribution of P_T vs. the reconstructed z position for the $K_L \to \pi^0 \nu \bar{\nu}$ signal events. The box shows the signal region.

$K_L^0 \rightarrow \pi^0 \pi^0$ "Odd"

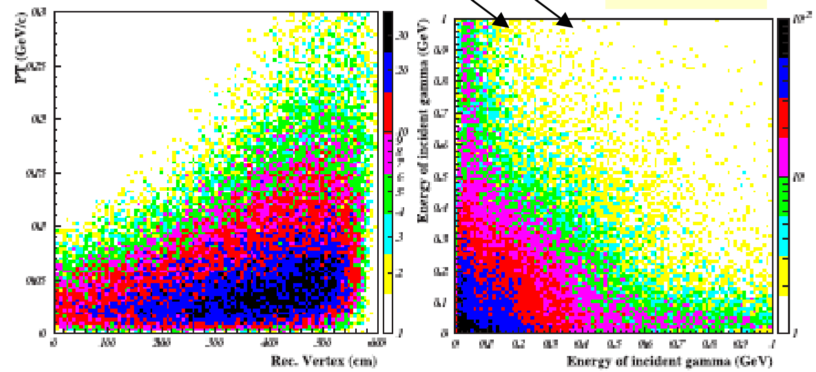


Figure 35: Left: reconstructed vertex and P_T distribution for odd-pairing $K_L \to \pi^0\pi^0$ background. The reconstructed vertex is not correct which make the P_T lower than the signal box. Right: Energy distribution of photons that enter the veto counters. Even though many events have low energies for both of the photons, the events are rejected through the high-P_T selection. As a result, the photons needed to be rejected by the veto counters have distributions similar to those for even pairing.

$K_L^0 \rightarrow \pi^0 \pi^0$ "Even"

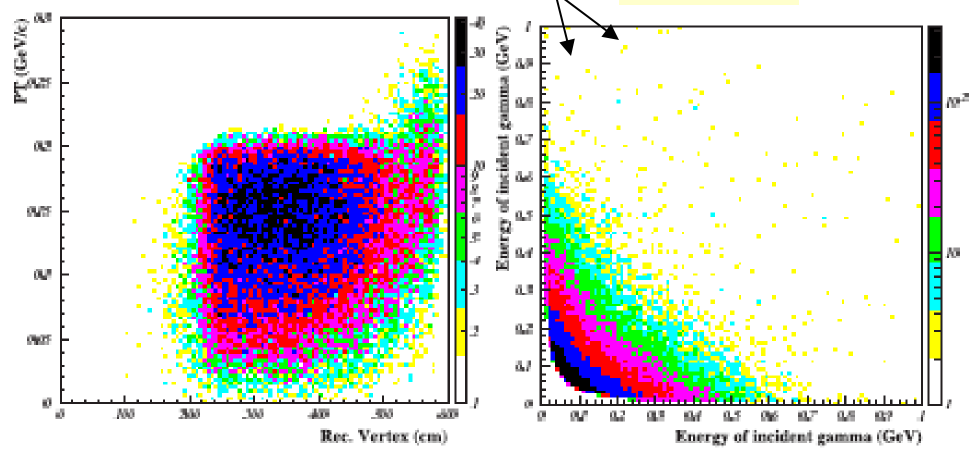


Figure 34: Left: reconstructed vertex and P_T distribution for even pairing $K_L \to \pi^0\pi^0$ background. It has a distribution similar to that of the $K_L \to \pi^0 \nu \bar{\nu}$ decay. Right: Energy distribution of gammas that enter the veto counters. At least one photon has sufficiently high energy to trigger the counter with a high detection efficiency.

KEK PS E391a >>> JPARC with KTEV CsI

Estimates: Signal (SM) 7

Background 5 (dominated by $K_L^0 \rightarrow \pi^0 \pi^0$)

Table 7: The estimated number of background events for Step 1. The single event sensitivity is 4.0×10^{-12}, with which 7.0 standard model events are expected. With a 50% of acceptance loss, both the number of expected signal events and background events would be scaled accordingly.

Background source	#Background events
Other K_L decays	
$K_L \rightarrow \pi^0\pi^0$	3.65
$K_L \rightarrow \pi^+\pi^-\pi^0$	0.93
$K_L \rightarrow \pi^- e^+ \nu$	0.01
$K_L \rightarrow \gamma\gamma$	negligible
$K_L \rightarrow \pi^0\pi^0\pi^0$	negligible
Neutron Interaction	
With Residual gas	0.07
At the CC02	0.26
At the C.V.	negligible
Accidental Coincidence	0.20

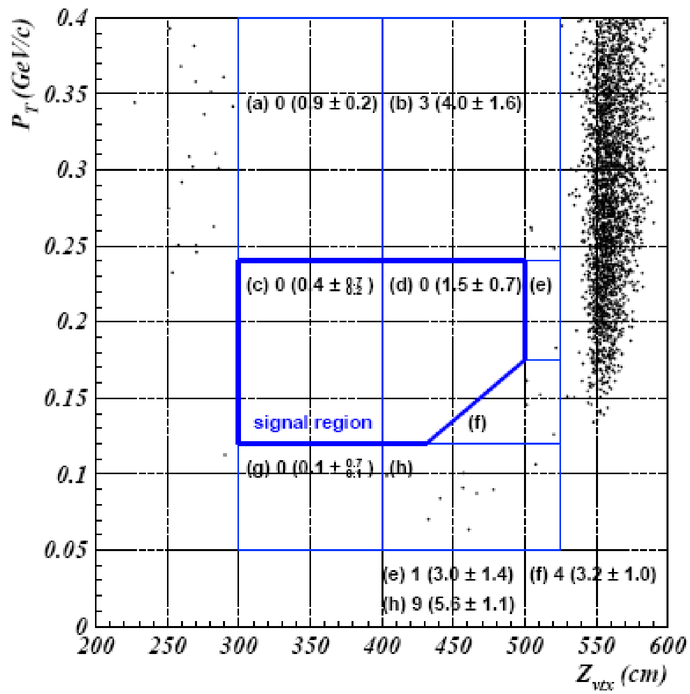


FIG. 3: $Z_{\rm vtx}$ versus P_T with all the event selection cuts. The number of observed (total expected background) events are shown. The expected number of background events was consistent with the observed number of events for all the regions.

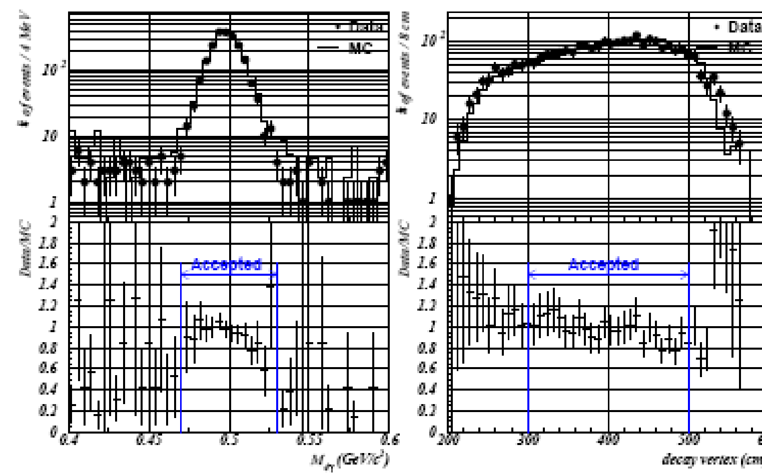


FIG. 4: Distribution of the invariant mass (left) and the decay vertex (right) for the $K_L^0 \to \pi^0\pi^0$ decays. In the top plot, the dots show the data and the histogram shows the MC. The bottom plot shows the ratio of the data to the MC.

Kl0->pi pi nu nubar

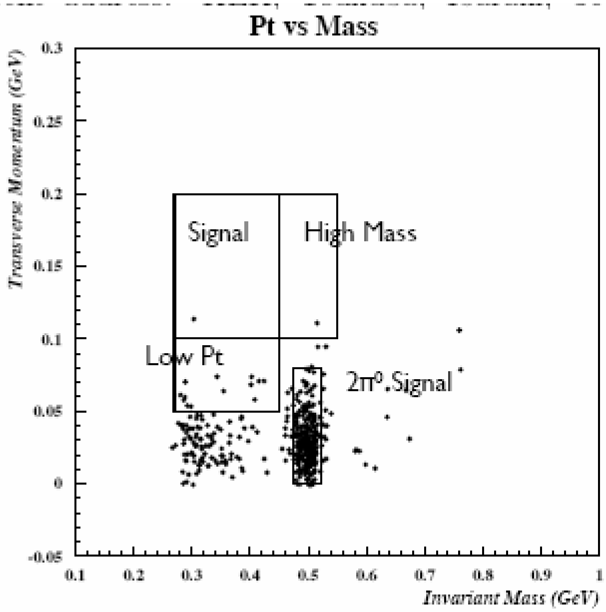
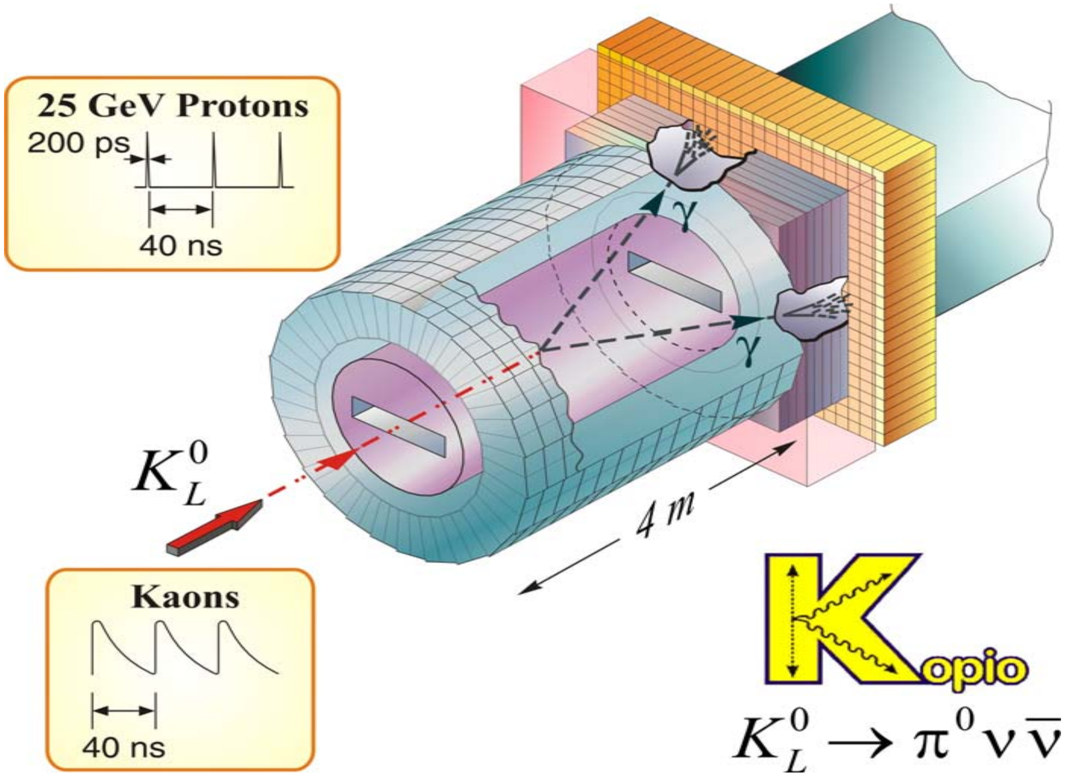


FIG. 4: P_T plotted against mass. The rectangular regions correspond to the regions in Table II.

TABLE II: Prediction of background events in different regions.

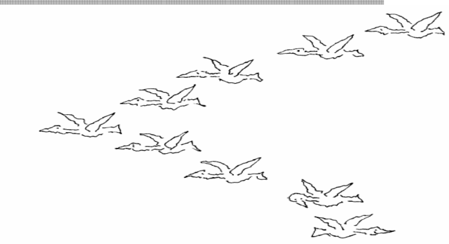
Region	$N_{\bar{A}B}$	$N_{A\bar{B}}$	$N_{\bar{A}\bar{B}}$	Prediction	Data
Low P_T	380	72	115	21.1 ± 3.3	13
High Mass	46	9	4	0.78 ± 0.48	1
Low Z	5	0	0	0	0
High Z	0	0	6	0	0
Signal	84	18	2	0.43 ± 0.32	1

KOPIO Concepts: Goal >100 events



- Use TOF to work in the K_L^0 c.m. system
- Identify main 2-body background $K_L^0 \rightarrow \pi^0\pi^0$
- Reconstruct $\pi^0 \rightarrow \gamma\gamma$ decays with pointing calorimeter
- 4π solid angle photon and charged particle vetos

Summary

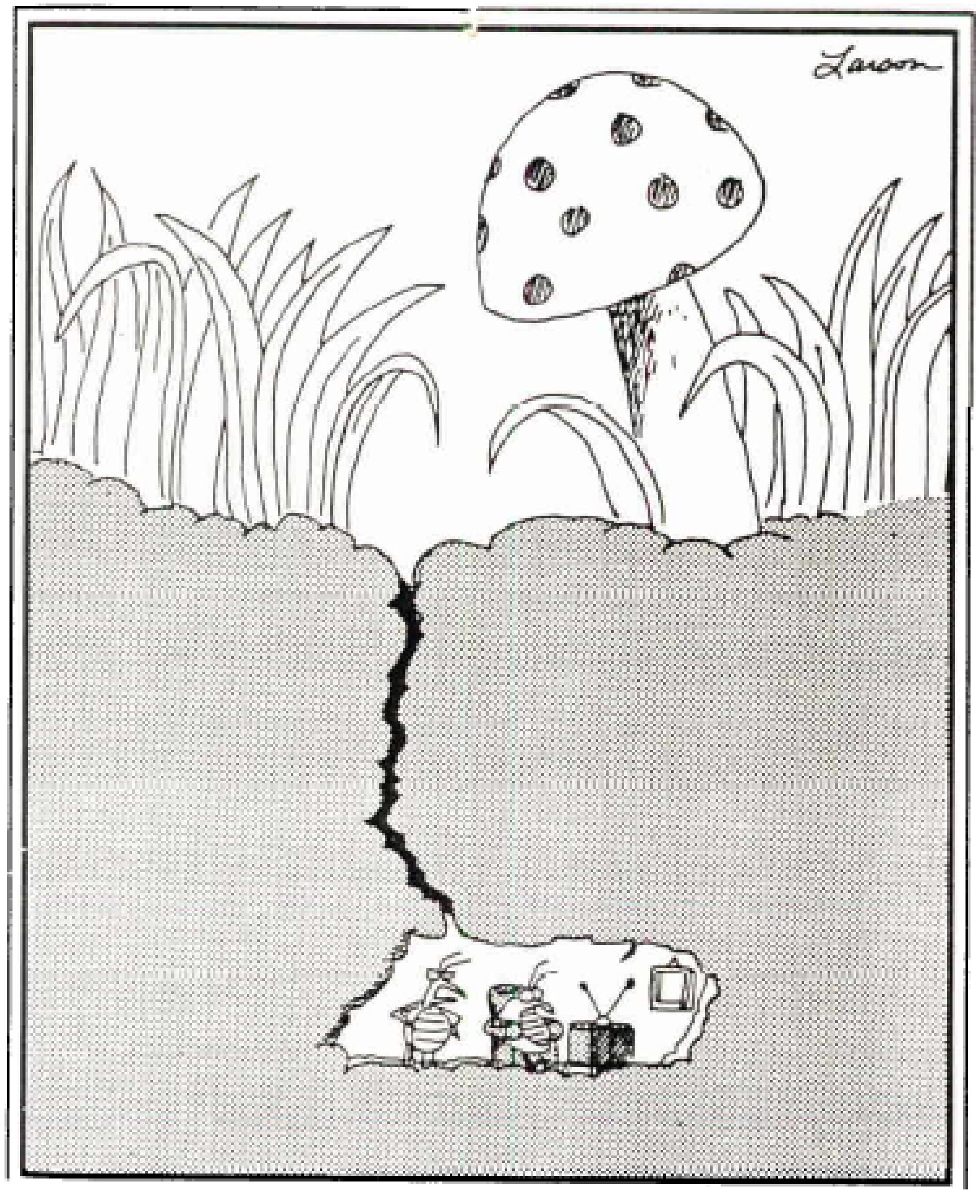


Rare Decays of $\mu, \pi,$ and K offer unique, clean access to the flavor breaking and CP-violating structure of hypthetical new physics -- access to short distance effects and high mass scales are complementary to collider studies at the LHC.

Star Attractions: New Physics Sensitvity

- $\mu \to e$ Conversion and $\mu \to e\gamma$ **PSI-MEG** $\frac{1}{M_H^4}$
- $\frac{\pi / K \to e\nu}{\pi / K \to \mu\nu}$ PI E NU **PSI-PEN** **KLOE NA48/3** $\frac{1}{M_H^2}$
- $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ $\frac{1}{M_H^2}$

JPARC **CERN P-326**



“You call this a niche?”