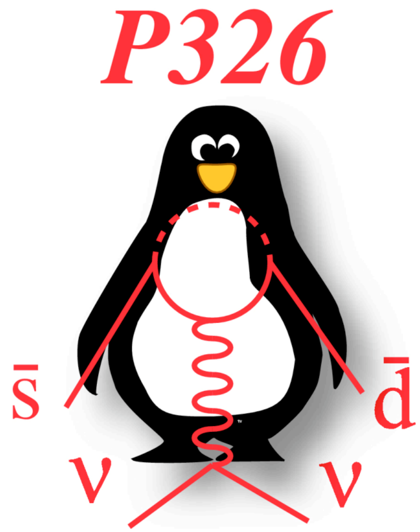
The NA62/P326 experiment at CERN



Cristina Lazzeroni
University of Birmingham

CERN-SPS-2007-035
SPS-M-760

New physics searches

- FCNC are forbidden at the Tree level
  - look for New Physics in the Penguin loops
- Lepton Flavour Violation
  - Not a fundamental symmetry
- Various NP models
  - MFV
  - MSSM
  - ....
- But try to use channels that are
  - Experimentally well measurable
  - Theoretically clean
  - Sensitive to NP
- .... Not many on the market !

CKM Unitarity and Rare Kaon Decays

The unitarity of the CKM matrix can be expressed by triangles in a complex plane: there are six triangles but one is more "triangular":

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

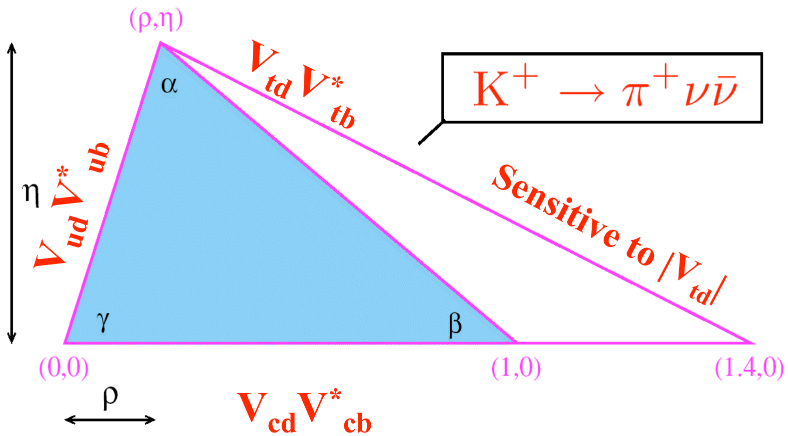
It is customary to employ the Wolfenstein parameterization:

$V_{us} \sim \lambda$ $\quad V_{cb} \sim \lambda^2 A$ $\quad V_{ub} \sim \lambda^3 A(\rho - i\eta)$ $\quad V_{td} \sim \lambda^3 A(1-\rho - i\eta)$

Golden modes

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

$K_L \to \pi^0 e^+ e^-$ $\begin{cases} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to ee\gamma\gamma \end{cases}$



$\lambda_t = V_{td} V^*_{ts}$

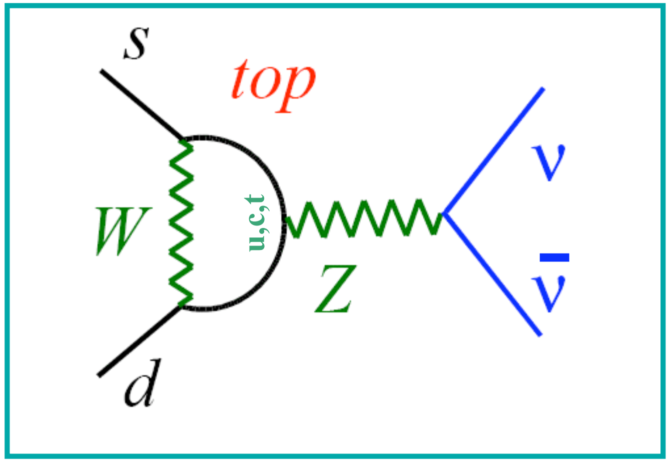
$Im\ \lambda_t = A^2 \lambda^5 \eta$

$Re\ \lambda_t = A^2 \lambda^5 \rho$

$K_L \to \pi^0 \mu^+ \mu^-$ $\begin{cases} K_L \to \gamma\gamma,\ K_L \to e^+ e^- \gamma \\ K_L \to e^+ e^- e^+ e^-,\ e^+ e^- \mu^+ \mu^- \end{cases}$

The 4 Golden Modes of Kaon Physics

	Short-distance contrib (Γ_{sd}/Γ)	Irreducible theory err. on amplitude	Total SM BR
$K^0_L \to \pi^0 \nu \nu$	>99%	1%	3×10^{-11}
$K^+ \to \pi^+ \nu \nu$	88%	3%	8×10^{-11}
$K^0_L \to \pi^0 e^+e^-$	38%	15%	3.5×10^{-11}
$K^0_L \to \pi^0 \mu^+\mu^-$	28%	30%	1.5×10^{-11}



- **Short distance dynamics dominated**
  - **W-top quark loops constitute the dominant contribution**

(+ small charm contribution in the $K^+ \to \pi^+\nu\nu$ decay)

- **Predicted with high precision in SM if short-distance dominated.….**

…but potentially different beyond SM

To compare:

Theoretically 'clean' B →s γ :

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{X}_s\gamma) - \Gamma(B \to X_s\gamma)}{\Gamma(\bar{B} \to \bar{X}_s\gamma) + \Gamma(B \to X_s\gamma)}$$

Theory Predition:

$$A_{CP} = (0.42 \pm 0.03^{+0.15}_{-0.08})\%$$

$$BR(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

$B^+ \to \tau^+ \nu$

Standard Model:

$$B(B^+ \to \tau^+ \upsilon) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left[1 - \frac{m_\tau^2}{m_B^2}\right] \tau_B f_B^2 |V_{ub}|^2$$

SM Prediction $B = (1.6 \pm 0.4) \times 10^{-5}$

$$R_{B \to \tau\upsilon} \equiv \frac{SUSY}{SM} \approx \left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2} m_B^2\right)^2$$

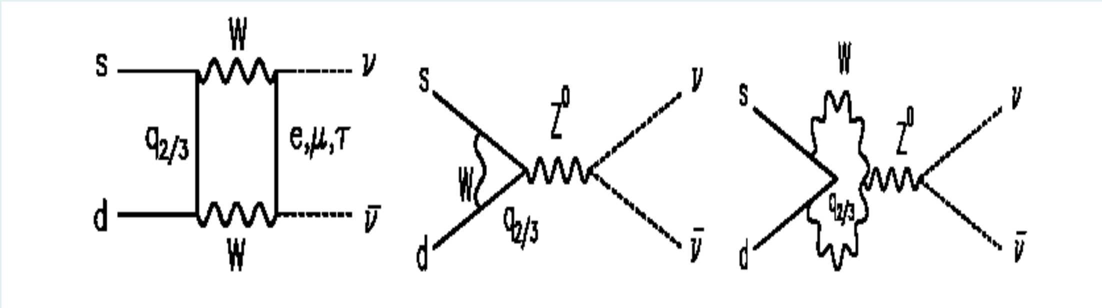
B→s νν (K*νν)

Like K*ll but..

- No photon penguin
- Reduced long-distanced effects.
- Smaller SM BF:
  - $(1.3^{+0.4}_{-0.3}) \times 10^{-5}$

K→πνν : Theory in the Standard Model

- **FCNC loop processes**
- **Short distance dynamics dominated**
- **One semileptonic operator**
- **Hadronic Matrix Element related to measured quantities in semileptonic K decay**



$\lambda = V_{us}$
$\lambda_c = V^*_{cs} V_{cd}$
$\lambda_t = V^*_{ts} V_{td}$

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \cdot \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$B(K^0_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \cdot \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

Top contribution

Charm contribution

was the largest theoretical error now reduced by NNLO calc

$$\kappa_+ = r_{K^+} \cdot \frac{3\alpha^2 Br(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \cdot \lambda^8$$

The Hadronic Matrix Element is measured and isospin rotated

Standard Model Predictions

- $BR(K^+ \to \pi^+ \nu \bar{\nu}) \approx (1.6\times10^{-5}) |V_{cb}|^4[\sigma\eta^2+(\rho_c-\rho)^2] \to (8.0 \pm 1.1)\times10^{-11}$
- $BR(K_L \to \pi^0 \nu \bar{\nu}) \approx (7.6\times10^{-5}) |V_{cb}|^4\eta^2 \to (3.0 \pm 0.6)\times10^{-11}$

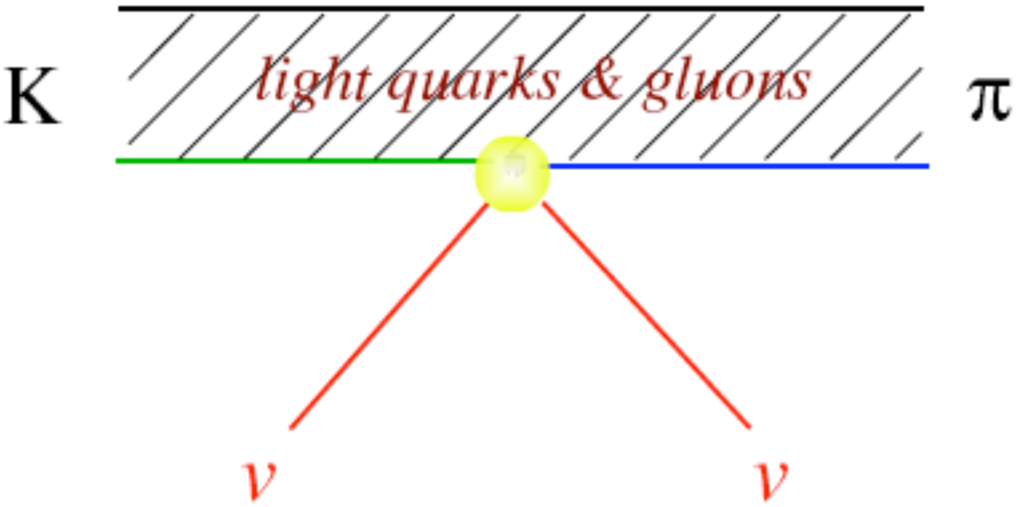
➢ **The uncertainty of the SM prediction is mostly due to uncertainty of the CKM parameters and not to hadronic matrix elements**

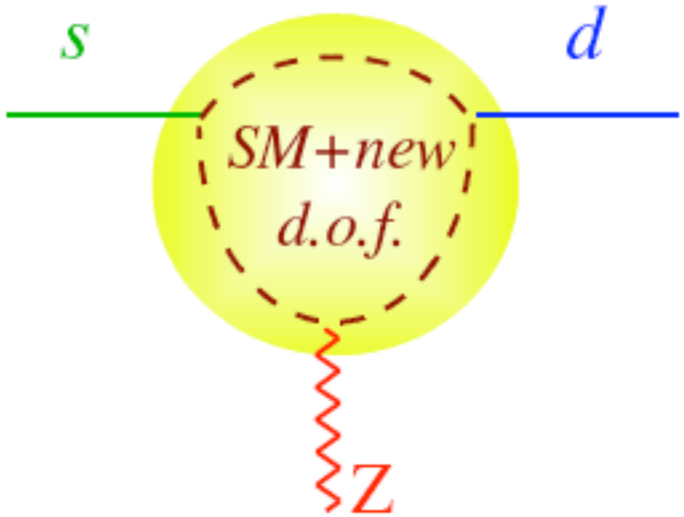
➢ **Combining information from $BR(K^+ \to \pi^+ \nu \bar{\nu})$ and $BR(K^0 \to \pi^0 \nu \bar{\nu})$**

(Buras et al. hep-ph/0508165)

For a 10% uncertainty on P_c one can extract, in principle, a 3.4%⊕exp. determination of sin2β from kaon decays.

It is currently 3.7% from B decays





- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Predicted with high precision within the SM at the short-distance level

Rare sensitivity and cleanness, compared to even B system

88% of total rate, irred. theo. error = 3%

$$A(K \to \pi\nu\nu) = f\left(c_{SM}\frac{y_t^2 V_{ts}^* V_{td}}{16\pi^2 M_W^2} + c_{new}\frac{\Delta_{sd}}{\Lambda^2}\ ;\ \delta_{long}\right)$$

hadronic matrix element from $BR(K^+ \to \pi^0 e^+ \nu)$

energy scale of new d.o.f

Two basic scenarios: *by G.Isidori*

Minimal Flavour Violation

flavour symmetry broken only by the (SM) Yukawa couplings

⬇

- Small deviations (10-20%) from SM
- Stringent correlations among the two $K \to \pi\nu\nu$ modes and a few rare B decays [$B \to K\nu\nu$, $B_{s,d} \to l^+l^-$]

A precise exp. info on one of the two $K \to \pi\nu\nu$ modes is a key ingredient to verify or disproof the MFV hypothesis

New sources of Flavour Symmetry breaking around the TeV scale

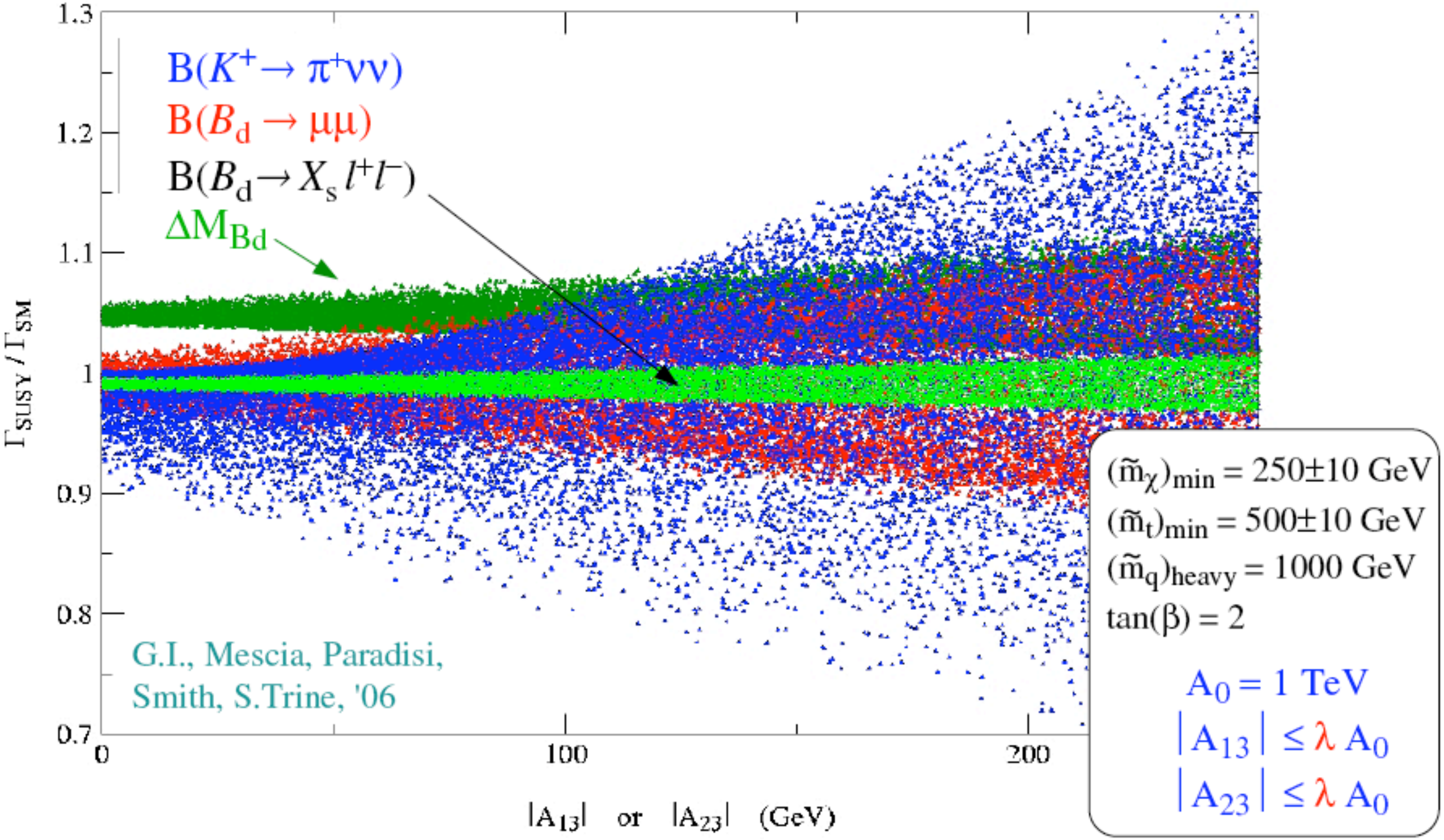
⬇

- Potentially large effects, especially in the three CPV K_L decays (no λ^5 suppression)
- Correlations with observables in B physics not obvious

In presence of sizable non-MFV couplings mandatory to explore also the $K_L \to \pi\, ll$ modes

- Non-standard effects induced by chargino-squarks amplitudes largely dominant in $K \to \pi\nu\nu$ with respect to similar effects in B physics
- The A terms are still largely unconstrained

squark-sector trilinear terms

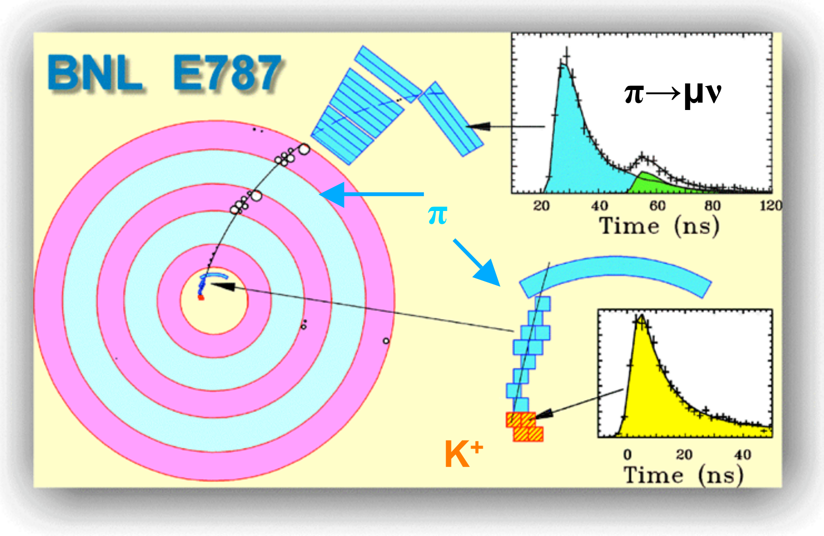


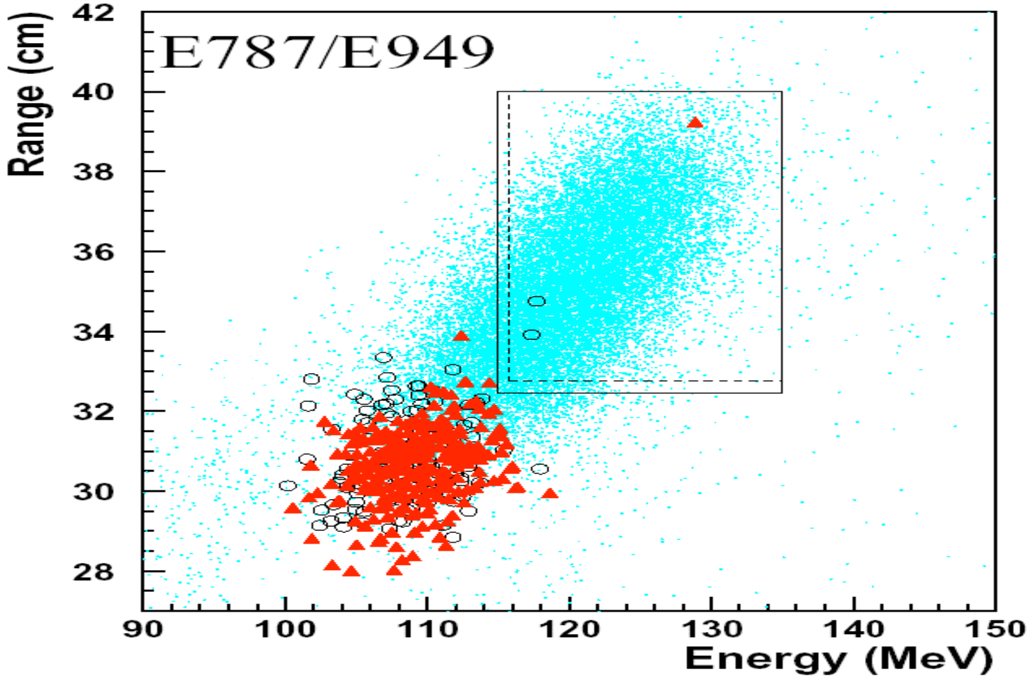
BNL E787/949: $K^+ \rightarrow \pi^+ \nu\nu$

$1.8 \cdot 10^{12}$ Stopped K^+

($211 < P_\pi < 229$ MeV/c)

~ 0.1 % signal acceptance





$$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$$

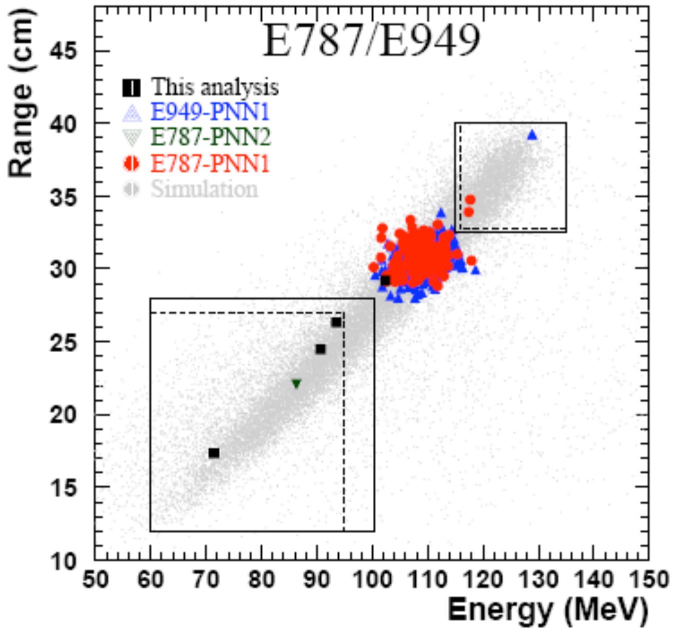
hep-ex/0403036 PRL93 (2004)

- 3 Events
- Compatible with SM within errors

New measurement of the $K^+ \rightarrow \pi^+ \nu\nu$ branching ratio (BNL E949)

Three events for the decay $K^+ \to \pi^+\nu\bar{\nu}$ have been observed in the pion momentum region below the $K^+ \to \pi^+\pi^0$ peak, $140 < P_\pi < 199$ MeV/c, with an estimated background of $0.93 \pm 0.17(\text{stat.})^{+0.32}_{-0.24}(\text{syst.})$ events. Combining this observation with previously reported results yields a branching ratio of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ consistent with the standard model prediction.

2



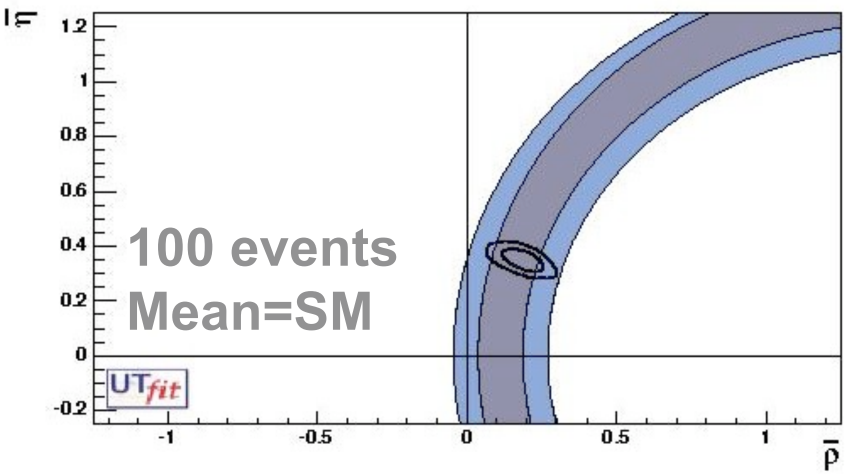
Process	Background events
$K_{\pi 2}$ TG	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$
Muon	0.011 ± 0.011
Beam	0.001 ± 0.001
Total	$0.927 \pm 0.168^{+0.320}_{-0.237}$

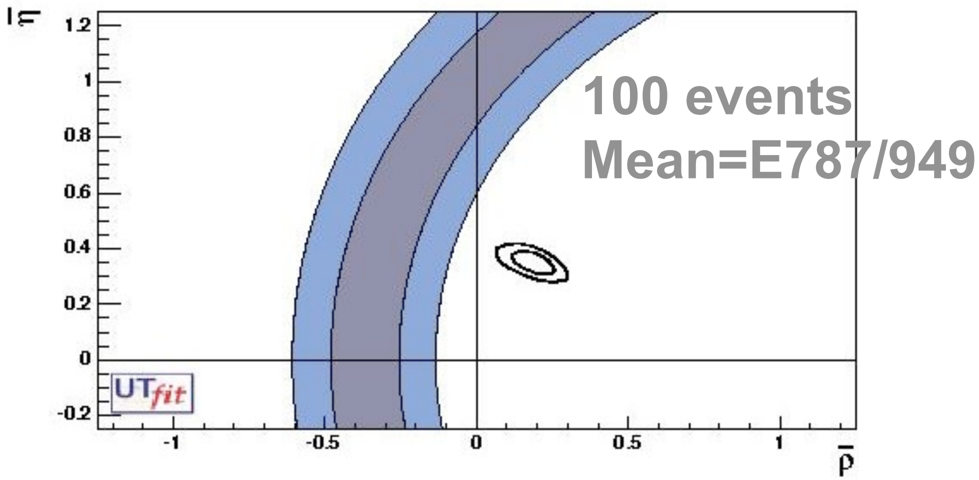
TABLE I: Summary of the estimated number of events in the signal region from each background component. Each component is described in the text.

$$BR(K^+ \rightarrow \pi^+ \nu\nu) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$$

SM expectation = (8.0±1.1) x 10^{-11} dominated by CKM uncertainty

E787/E949: $BR(K^+ \rightarrow \pi^+ \nu\nu) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$





E391a: $K^0_L \rightarrow \pi^0 \nu\nu$

E391a @ KEK 12 GeV proton synchrotron (Tsukuba, Japan)

Best Limit from direct search

RUN II (2005)

- **Pencil beam, p_K peaked around 2 GeV/c**
- **Total K^0_L decays: 5.1×10^9**
- **Acceptance: 0.67 %**
- **Background in signal box: 0.41±0.11 events**
- **S.E.S. = $(2.9 \pm 0.3) \times 10^{-8}$**

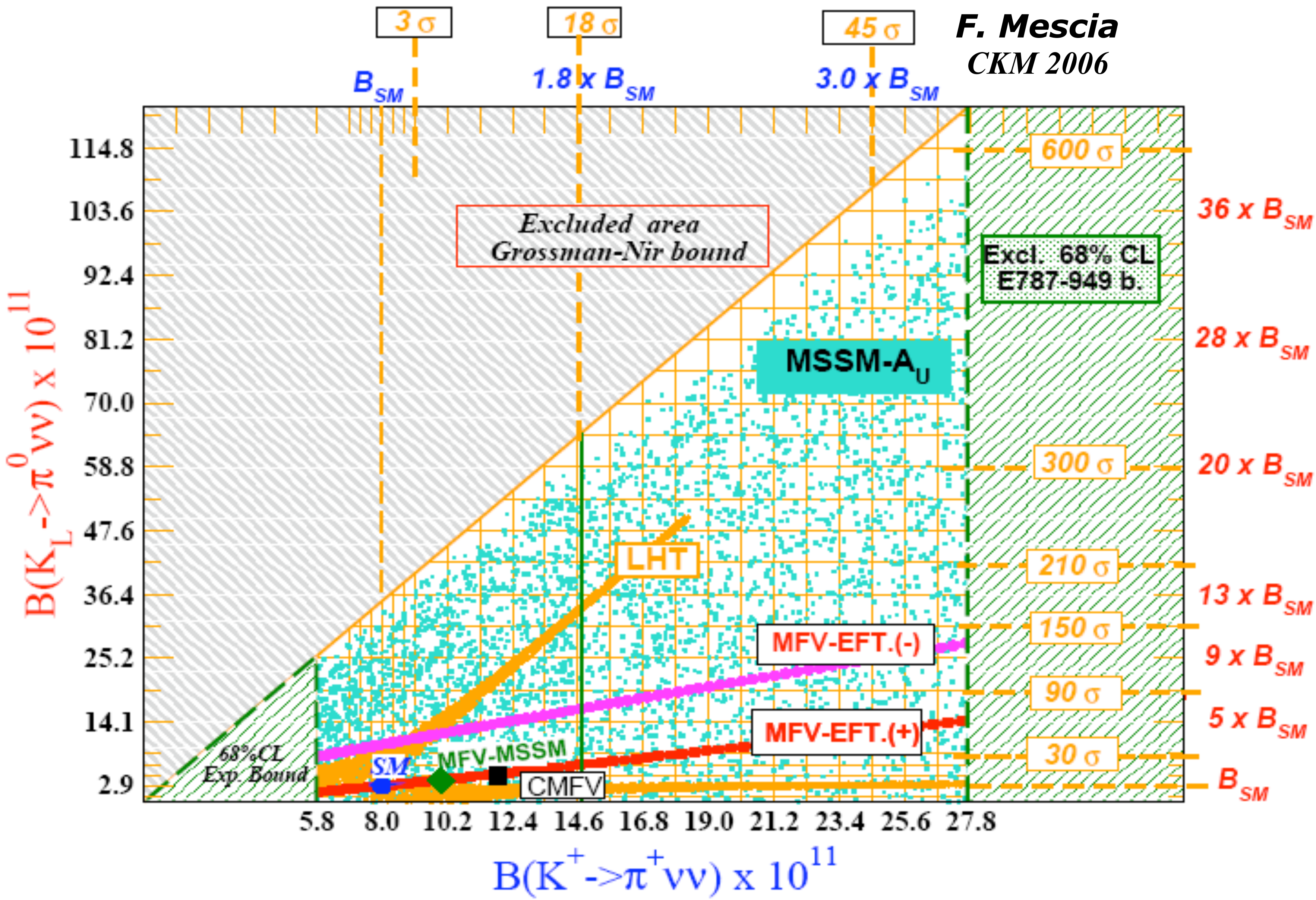
$$BR(K^0 \rightarrow \pi^0 \nu\bar{\nu}) < 6.7 \times 10^{-8} \ (90\%CL)$$

arXiv:0712.4164v1 (27 Dec 2007)

For the future:

J-PARC Proposal (April-May 2006) → expect 3.5 S.M. events with 50% acceptance

New Physics Reach of the K → π νν decays



Experimental situation

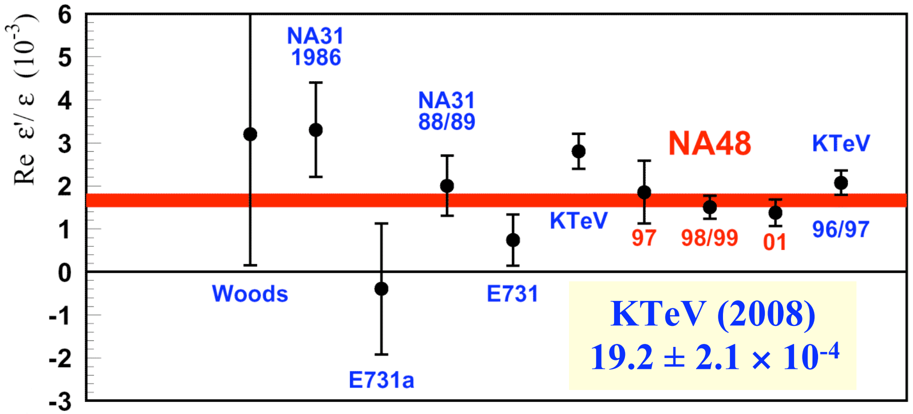
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
  - 7 events found by E787/E949
  - Measurement in agreement with SM within errors
  - Future experiments should aim at O(100) events
  - FNAL proposal (K^+ decays at rest) cancelled
  - Proposal for K^+ decays in flight : CERN P-326/NA62
  - LOI at J-PARC to study decays at rest
- $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$
  - Several opportunities
  - First result E391a (SES~$3 \cdot 10^{-8}$)
  - Current Upper limit is 3 orders of magnitude above MS prediction
  - Proposal at J-PARC (expected 3.5 events MS)
  - Proposal at U-70 , IHEP, Protvino (expected 1.1-2.4 events MS)
  - KOPIO terminated
- $K^0_L \rightarrow \pi^0 e^+ e^- (\mu^+ \mu^-)$
  - Precise knowledge of short-distance contributions
  - Measurement of K_S decays allows more precise SM prediction
  - Limited by background
  - Need increase ~100 in K flux

NA48@CERN

NA48: ε'/ε	1997
ε'/ε	1998
ε'/ε	1999
K_L no spectrometer / NA48/1 K_S	2000
ε'/ε lower inst. intensity	2001
NA48/1: K_S	2002
NA48/2: $K^{\pm}$	2003
NA48/2: $K^{\pm}$	2004

Direct CP-Violation established

$$\mathrm{Re}\ \varepsilon'/\varepsilon = 14.7 \pm 2.2 \times 10^{-4}$$



+ K_L Rare Decays

First observation of
$K^0_S \rightarrow \pi^0 e^+e^-$ and $K^0_S \rightarrow \pi^0 \mu^+\mu^-$

- Search for Direct CP-Violation in charged kaon decays
- ππ scattering: PLB 633 (2006) $(a_0-a_2)m_+ = 0.268 \pm 0.017$

NA62@CERN : $K^{\pm} \rightarrow \pi^{\pm} \nu \nu$

Collaboration

Bern, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Mainz, Merced, Moscow, Napoli, Perugia, Pisa, Protvino, Roma I, Roma II, Saclay, San Luis Potosi, Stanford, Sofia, Torino, Triumf

Birmingham expressed interest,
SoI submitted to PPAN in July

Istalled in same location as NA48

➡ **precision of 10% (100 events)**

- **September 2005:** P326 proposal to SPSC at CERN
- **December 2005:** R&D approved by Research Board at CERN

- **October-November 2006:** Test beam at CERN (LKr and Cedar)

- **February 2007: approval of NA62 (**run in June-October) to measure

  $$R_K = \Gamma(K^+ \rightarrow e^+\nu) / \Gamma(K^+ \rightarrow \mu^+\nu)$$

- **June 2007:** NA62 appears in CERN Medium Term Plan 2007-2011 (CERN Council)
- **Autumn 2007:** Test beams at CERN and LNF (Straw tubes, Veto, RICH)
- **December 2007:** Proposal Addendum sent to SPSC

- **September-November 2008:** Test beam at CERN - shorten by LHC accident
- Summer 2008: Approved by italian funding agents on condition of CERN approval
- November **2008:** Recommended for approval by SPSC

- **2009 – 2011:** Technical design and completion of detectors
- 2011 - 2012 : Commissioning
- **2012-2014:** Data taking

NA62 : principle of experiment

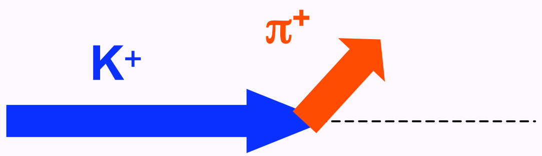
$\mathcal{O}(100)$ events $K^+ \to \pi^+ \nu\bar{\nu}$ in 2 years

~ 10% background

BR(SM) = 8×10^{-11}
~ 10^{12} K^+ decays
Acceptance= 10%

- K decays in flight
- Intense beam of protons from SPS
- High energy K (P_K = 75 GeV/c)
- Cherenkov K ID: CEDAR

Kinematic rejection



$m^2_{miss} = (P_K - P_\pi)^2$

Signature:
- Incoming **high** momentum K^+
- Outgoing **low** momentum π^+

- Kaon: beam tracking
- Pion: spectrometer
- Excellent timing for K-π association

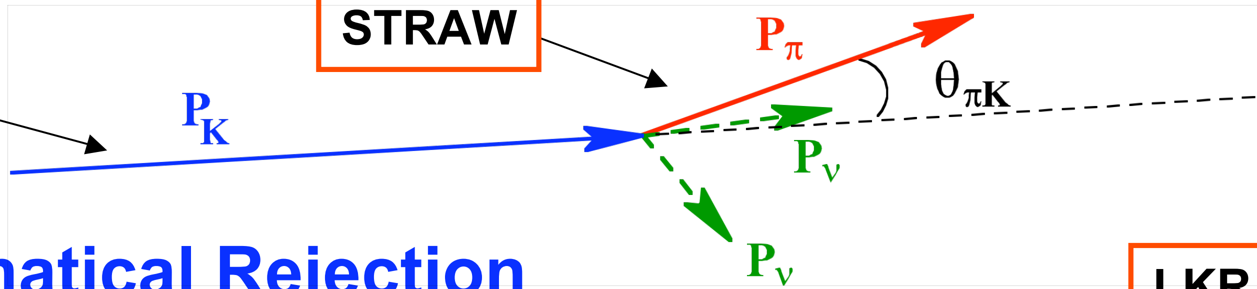
Veto and PID

- γ / μ : calorimeter
- Charge Veto : spectrometer
- π / μ separation : RICH

Principle of the Experiment

Gigatracker, CEDAR

STRAW

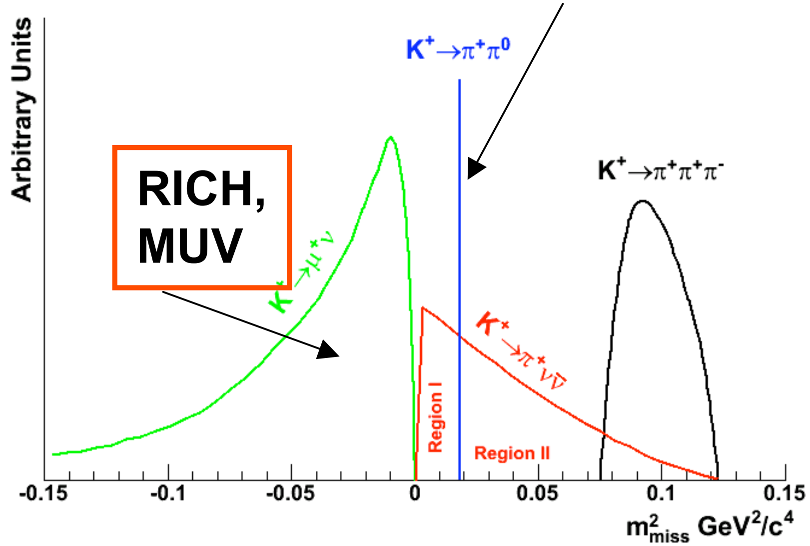


1) Kinematical Rejection

LKR,LAV,…

$$m_{miss}^2 \approx m_K^2\left(1-\frac{|P_\pi|}{|P_K|}\right)+m_\pi^2\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta_{\pi K}^2$$

RICH, MUV



2) Photon vetoes to reject $K^+ \to \pi^+\pi^0$:

P(K^+) = 75 GeV/c

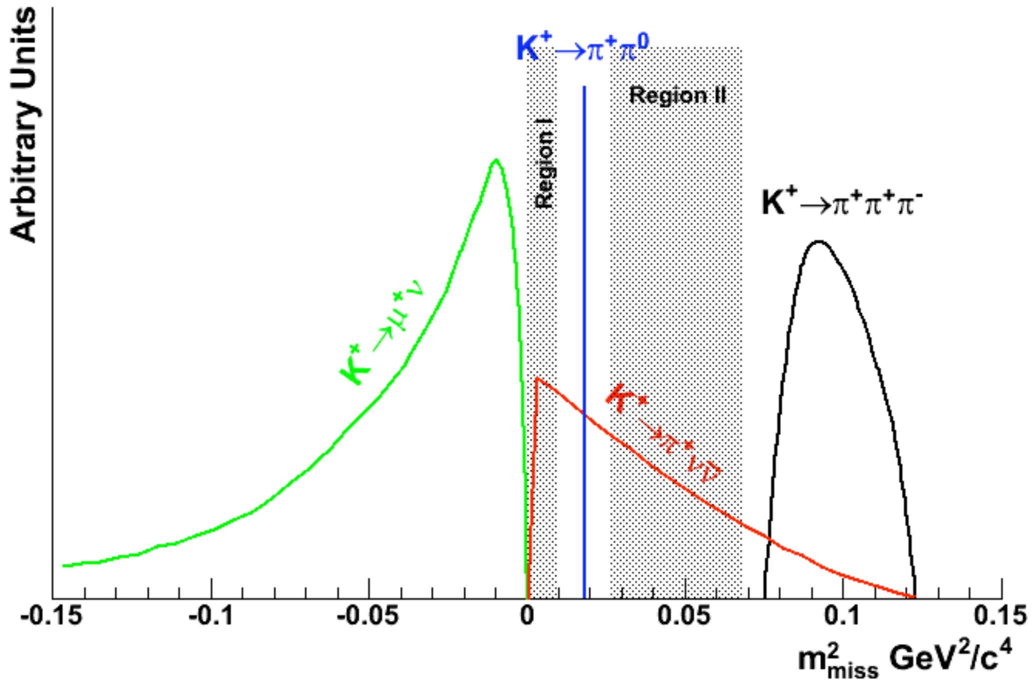
Requiring P(π^+) < 35 GeV/c

P(π^0) > 40 GeV/c ➡ It can be hardly missed in the calorimeters

3) PID for $K^+ \to \mu^+\nu$ rejection

Background with kinematic threshold

Decay	BR
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	0.634
$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)	0.209
$K^+ \to \pi^+\pi^+\pi^-$ $K^+ \to \pi^+\pi^0\pi^0$	0.073



92% K^+ decays

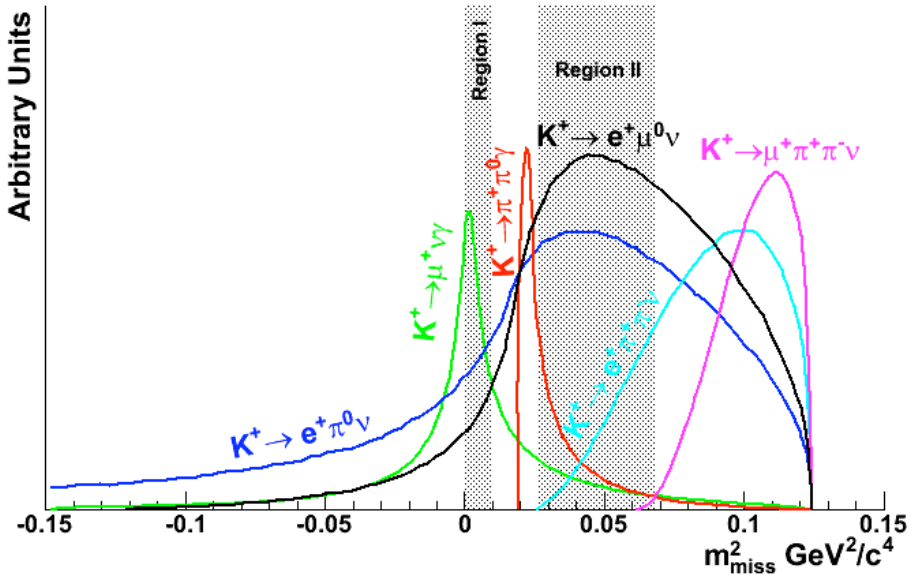
- **Definition of signal region**
- **$K^+ \to \pi^+\pi^0$: division between Region I and Region II**

Region I: $0 < m^2_{miss} < 0.01$ GeV^2/c^4

Region II: $0.026 < m^2_{miss} < 0.068$ GeV^2/c^4

Background with no kinematic threshold

Decay	BR
$K^+ \to \pi^0 e^+ \nu$ (K_{e3})	0.049
$K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$)	0.033
$K^+ \to \mu^+ \nu \gamma$ ($K_{\mu 2\gamma}$)	6.2×10^{-3}
$K^+ \to \pi^+ \pi^0 \gamma$	1.5×10^{-3} (2.75×10^{-4} PDG)
$K^+ \to \pi^+ \pi^- e^+ \nu$ (K_{e4})	4.1×10^{-5}
$K^+ \to \pi^+ \pi^- \mu^+ \nu$ ($K_{\mu 4}$)	1.4×10^{-5}



8% K^+ decays

- Across signal region
- Rejection using Veto and Particle ID

- **Background from detector:** accidental interactions due to material on the beam line

Kinematic rejection

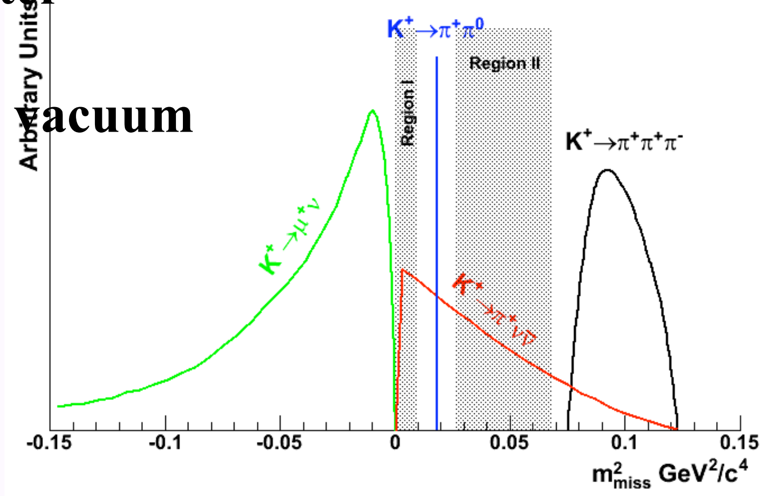
Signal region:

- Signal acceptance ≥ 10%
- Minimize background due to non-gaussian tails

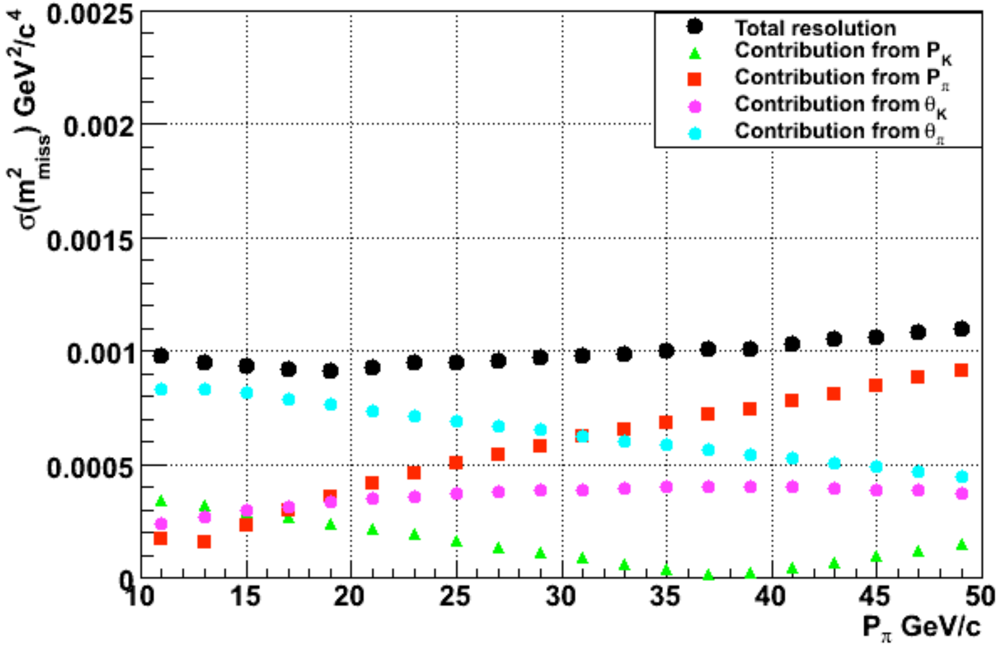
➔ $\sigma(m^2_{miss}) \sim 10^{-3}$ GeV^2/c^4

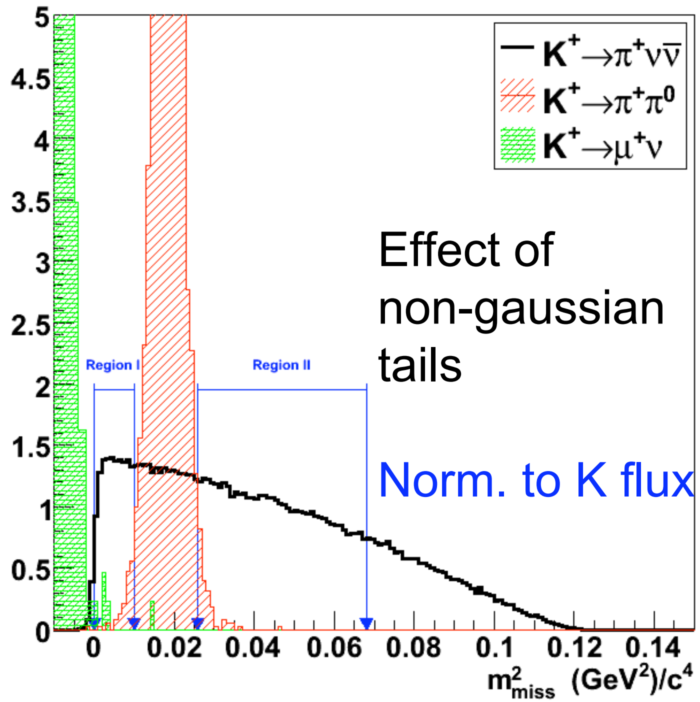
$\sigma(P_K) < 0.5\%$ e $\sigma(\theta_K) < 25$ μm → K spectrometer

minimize multiple scattering → chambers in vacuum



Missing Mass Resolution





Non-gaussian tails can be induced, for instance, by the wrong association between the incoming kaon and the pion

→ 200 ps time resolution is required

Signal Acceptance

Generation:

$K^+ \to \pi^+ \nu\nu$ generated with form factors

- 10% effect on acceptance

Analysis:

Not yet optimized for $S/\sqrt{B}$

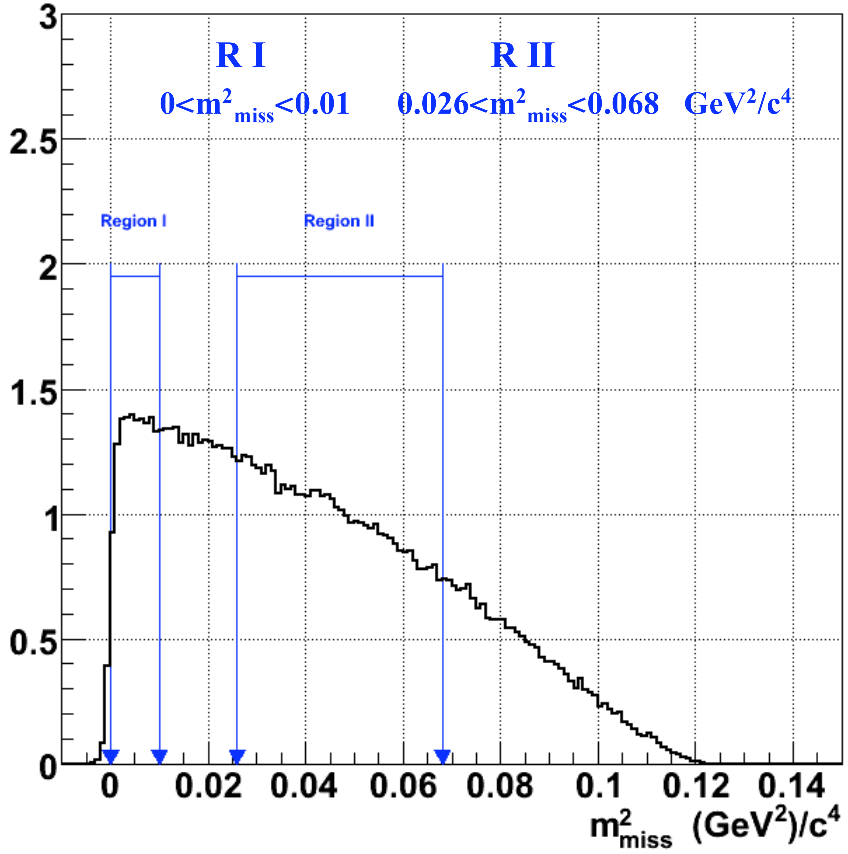
→ conservative estimate of background

Remind:

$K_{\pi 2}$ $m^2_{miss} = 0.0182$ $K_{\mu 2}$ $m^2_{miss} < 0$ $[GeV^2/c^4]$

- Region I e II
- Momentum Range: $15 < P_\pi < 35$ GeV/c
  - Cherenkov threshold in RICH
  - Large $E_{e.m.}$ to reject $K_{\pi 2}$
  - μ/π separation ($K_{\mu 2}$ at high P)

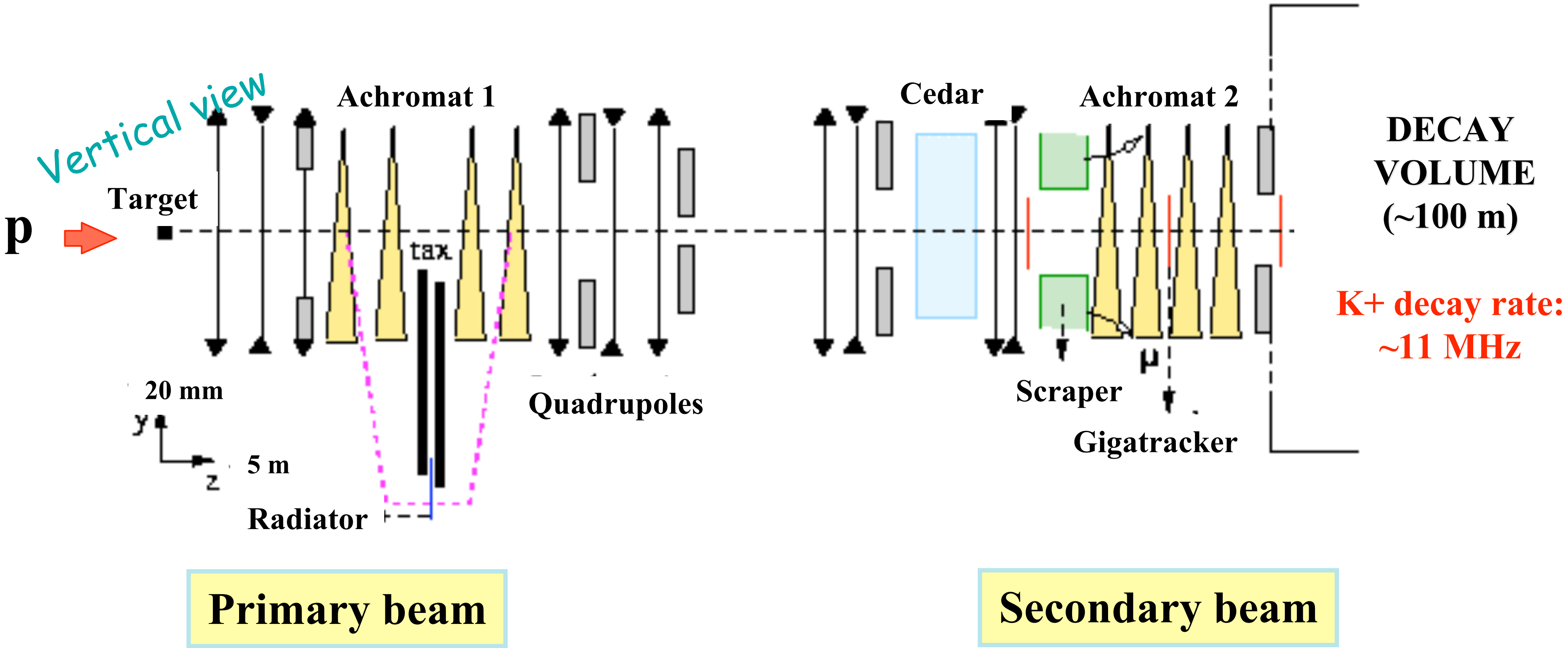
  but ridution of 50% in acceptance



Acceptance (fiducial volume 60 m):

- Region I: 3.5%
- Region II: 10.9%
- Total: 14.4%

Beam line



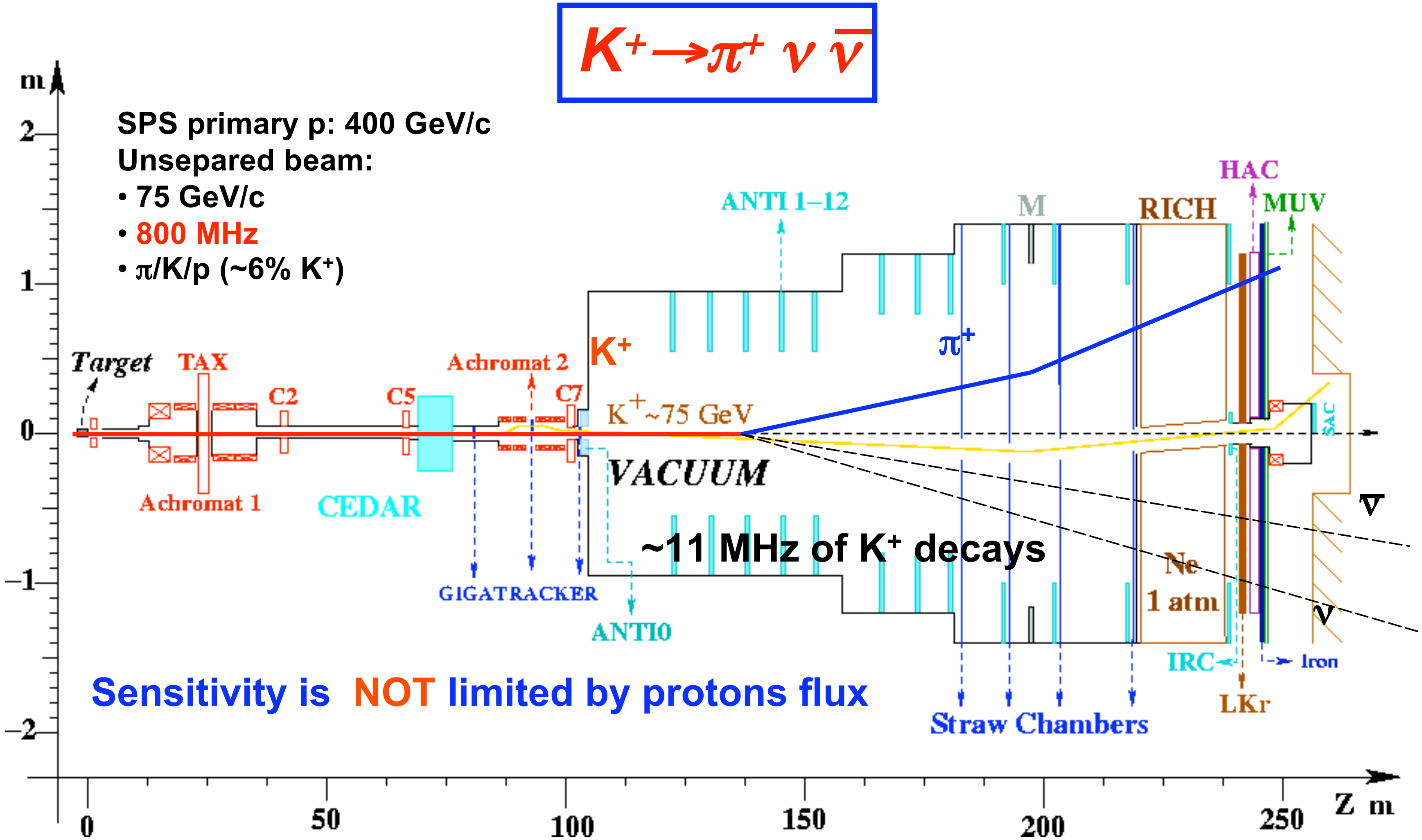
- P proton = 400 GeV/c
- Proton/pulse 3.3×10^{12} (×3.3 NA48/2)
- Duty cycle 4.8/16.8 s

- P Kaon = 75 GeV/c ($\Delta P/P \sim 1.2\%$)
- Fraction of K^+~6.0% (p 23% π^+70% μ^+ 1% e^+<0.1%)
- Negligible amount of e^+ (1X_0 W radiator)
- Beam acceptance = ×25 NA48/2
- Integrated average rate = 760 MHz
- K^+ decays / year = 4.8×10^{12}

Detector requirements

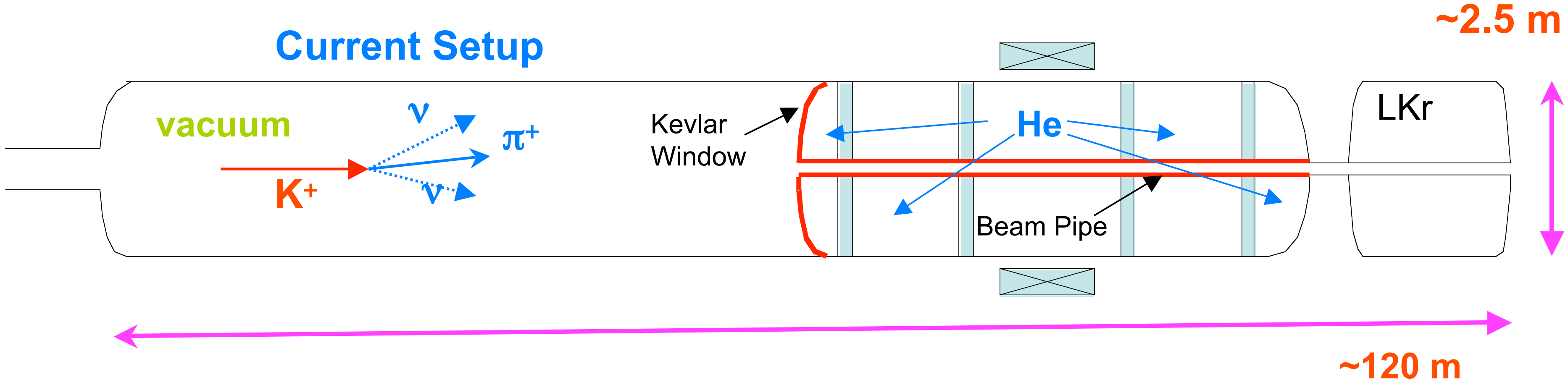
- **Rejection of 2-body backgrounds ($\pi^+\pi^0$, $K_{\mu 2}$)**
  - **Maximum kinematic rejection → beam characteristics, beam spectrometer, downstream spectrometer, CEDAR**
- **Rejection of $\pi^+\pi^0$**
  - **Hermeticity → ANTI, SAC, maximum π momentum**
- **Rejection of $K_{\mu 2(\gamma)}$**
  - **particle ID → RICH (minimum π momentum), Muon Detector**
- **Rejection of 3-body charged background (K_{e4}):**
  - **Charged particle hermeticity → downstream spectrometer**
- **Rejection of non-physical background:**
  - **<1 event/year → vacuum, beam spectrometer, ANTI, CEDAR**

NA62 Proposed Detector Layout



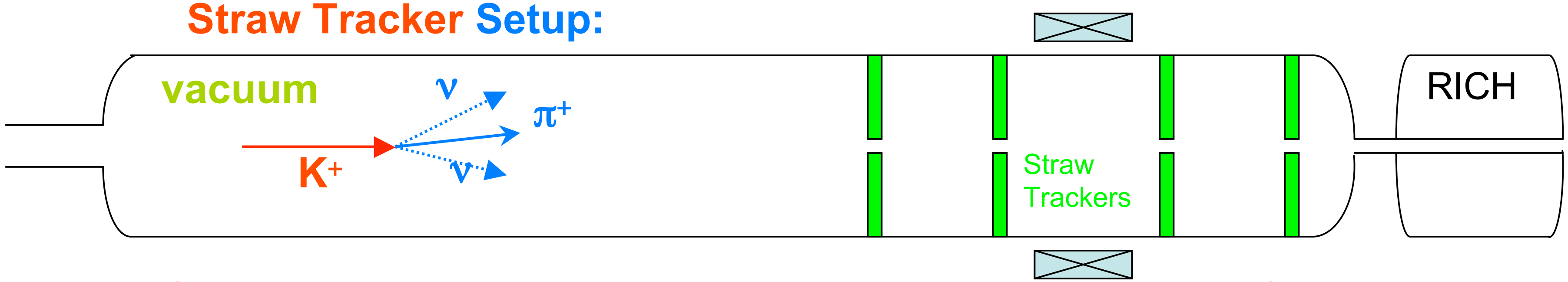
NA62 Straw Tracker

Current Setup



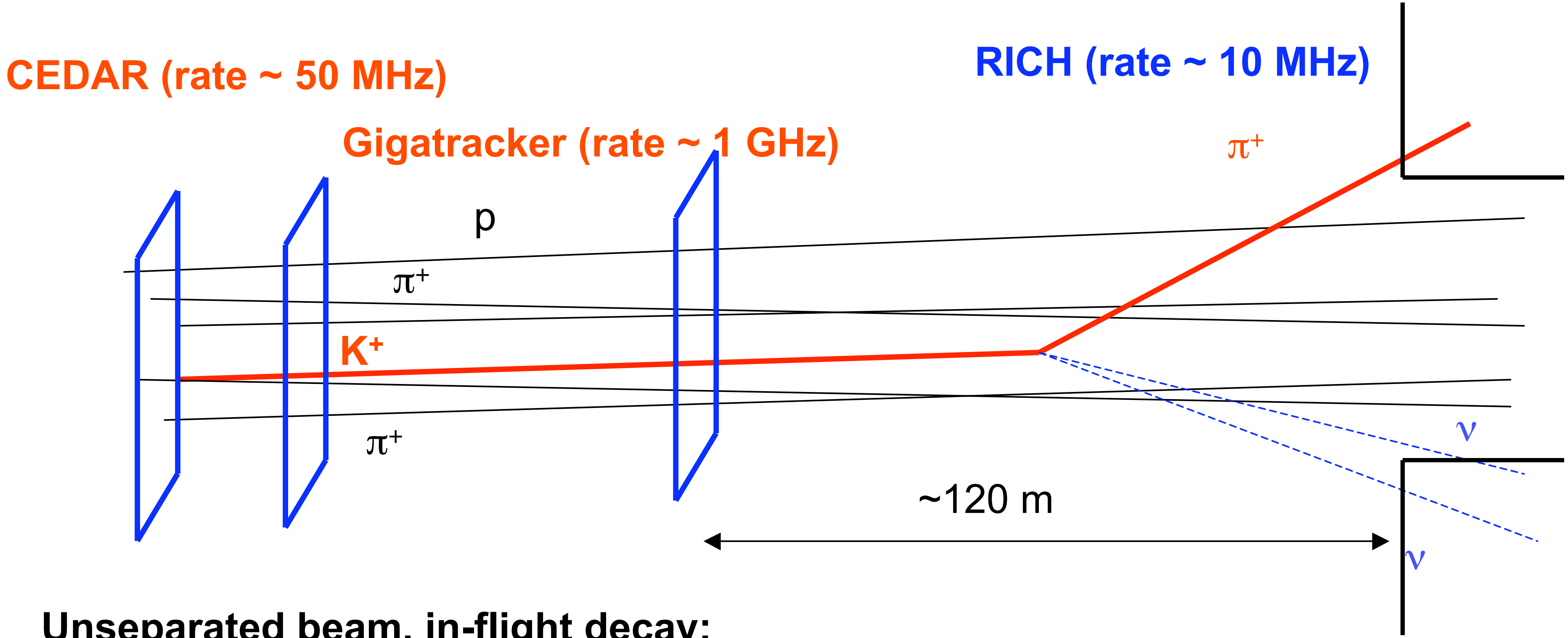
Straw Trackers operated in vacuum would enable us to:
- **Remove the multiple scattering due to the Kevlar Window**
- **Remove the acceptance limitations due to the beam-pipe**
- **Remove the helium between the chambers**

Straw Tracker Setup:



- **The Straw Tracker is essential to study ultra-rare-decays in flight**

PreciseTiming



Unseparated beam, in-flight decay:

How do you associate the parent kaon to the daughter pion in a **~1 GHz beam** ?

K^+ : Gigatracker, CEDAR with very good time resolution **(~ 100 ps)**
π^+ : **RICH** (Neon, 1 atm) read out by Photomultipliers

Example of background rejection

$K^+ \rightarrow \mu^+ \nu$ ($K_{\mu 2}$)

Largest BR: 63.4%

Need ~10^{-12} rejection factor

- Kinematics: 10^{-5}
- Muon Veto: 10^{-5} ⟹ MUD
- Particle ID: 5×10^{-3} ⟹ RICH

$K^+ \rightarrow \pi^+ \pi^0$ ($K_{\pi 2}$)

2nd Largest BR: 20.9%

Need ~10^{-12} rejection factor

- Kinematics: 5×10^{-3}
- Photon Veto: 10^{-5} per photon

⟹ **Large angle:**
13 ANTIs (10 < acceptance < 50 mrad)

⟹ **Medium angle:**
NA48 LKr (1 < acceptance < 10 mrad)

⟹ **Small angle:**
IRC SAC (acceptance < 1 mrad)

Assuming the above performance and an acceptance of 10%, a S/B > 10 is obtained if

$(\Delta m_{miss})^2 \sim 10^{-3}$ GeV^2/c^4

Resolution requirements:

P_π ➞ < 1 %

P_K ➞ < 0.5%

$\theta_{K\pi}$ ➞ 50-60 μrad

Physical background

Decay	Events/year
Sig *(acc=14.4%, flux = 4.8·10^{12} evt/year)*	55
$K^+ \to \pi^+\pi^0$	4.3%
$K^+ \to \mu^+\nu$	2.2%
$K^+ \to e^+\pi^+\pi^-\nu$	≤3%
Other 3-body decays	≤1.5%
$K^+ \to \pi^+\pi^0\gamma$	~2%
$K^+ \to \mu^+\nu\gamma$	~ 0.7%
$K^+ \to e^+(\mu^+)\ \pi^0\nu$, others	neglig
Total	≤13.5%

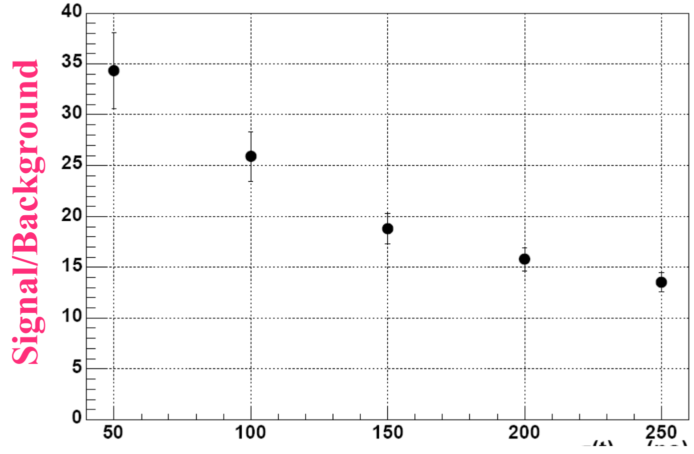
The tracking system

The Gigatracker (*i.e.* the beam spectrometer)

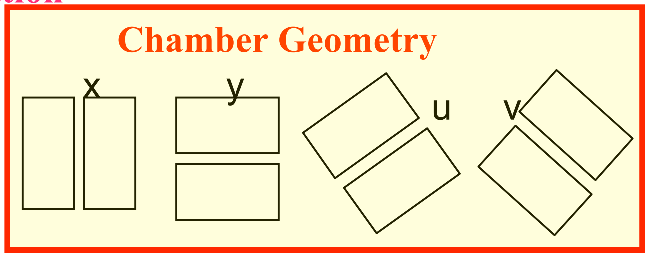
- **3 Si pixel stations across the 2nd achromat**: (60×27 mm^2)

- Rate 760 MHz (charged particles) → **~ 80 MHz / cm^2**
- $300{\times}300$ μm^2 pixels → (**$\sigma(P_K)/P_K$ ~ 0.2%**, **σ(dX,Y/dZ) ~ 12 μrad**)
- 200 Si μm sensor + 100 Si μm chip → **Low X/X_0**
- 54000 channels

Excellent time resolution needed for K^+/π^+ association → **σ(t)~200 ps / station**



Time resolution (ps)

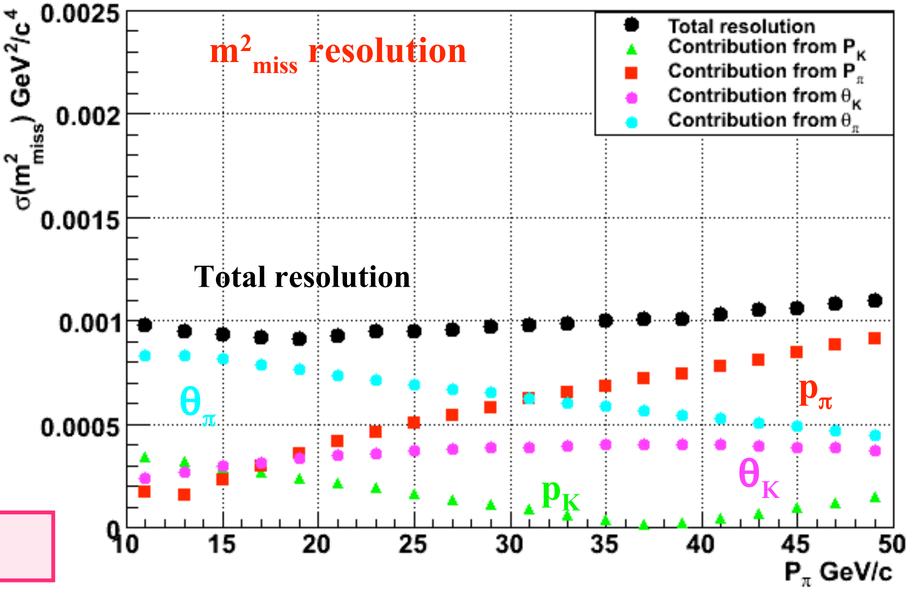


The Magnetic Spectrometer (*i.e.* the downstream tracker)

- **4 chambers with 4 double layers of straw tubes each** (∅ 9.6 mm)
- **1 magnet (P_{kick} = 260 MeV/c), 8000 wires in total**

- Rate: ~ 45 KHz per tube (max 0.8 MHz beam halo)
- Low X/X_0 → **0.1% X_0 per view in vacuum**
- Good hit space resolution → **130 μm per view**
- Veto for charged particles → **5cm radius beam hole**

displaced in the bending plane according to beam path



$\sigma(P_k)/P_k$ = 0.3% ⊕ 0.007%P , σ (dX,Y/dZ) = 45 ÷ 15 μrad

m^2_{miss} resolution ~$1.1{\times}10^{-3}$ GeV^2/c^4

✓ **Full length Prototype tested in actual vacuum tank**

The particle ID system

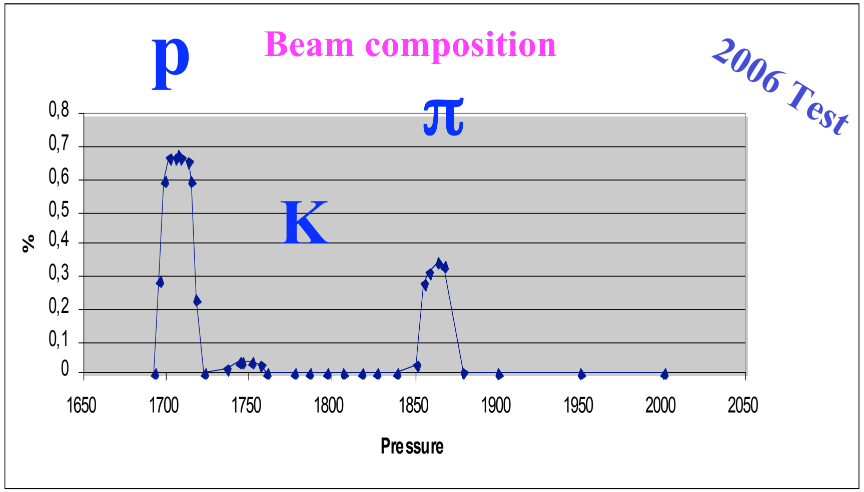
The CEDAR (*i.e.* the kaon ID)

- **CEDAR: existing Cherenkov counter at CERN**

- Adapted to NA62 need: → • **H_2 instead of Nitrogen** • **New photo detector and electronics**

- Vary gas pressure and diaphragm aperture to select Kaons

- 500 readout channels



The RICH (*i.e.* the pion ID)

- **18 m long tube (∅ 2.8 m), 17 m focal lentgh mirrors**

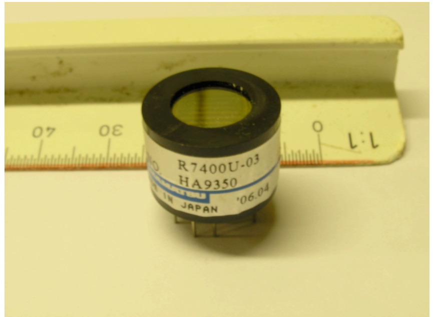
- Ne @ 1 atm (**π thr = 13 GeV/c**)

- **>3σ π/μ** separation up to 35 GeV/c

- High granularity → **(2100 PMTs)**

- Small pixel size → **(18 mm PMT)**

- Disentangle pileup in Gigatracker → **σ(t)~100 ps**



✓ **PMTs tested in 2006**

✓ **Full length Prototype Tests in 2007-2008**

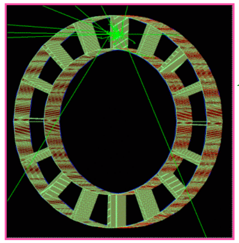
The Veto system

Photon vetoes

<u>Options tested:</u>
Lead-scintillator tiles (CKM)
Lead-scintillator fibers (KLOE-like)
OPAL Lead-Glass (barrel)

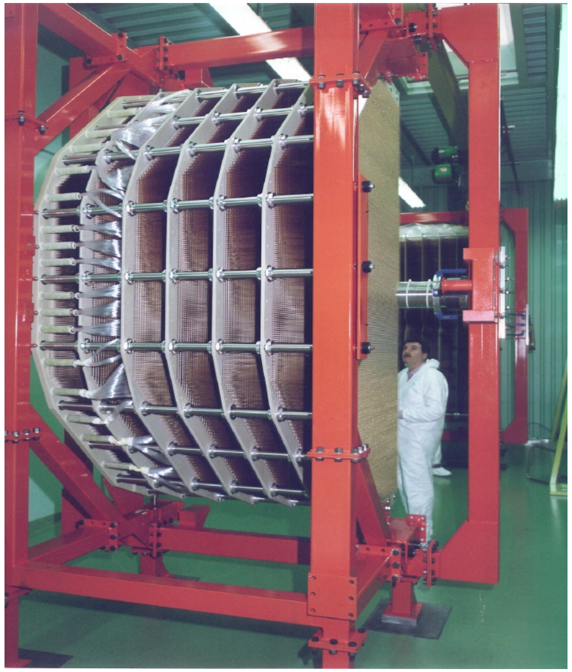
All satisfying requirements, OPAL Lead Glass is the most cost-effective solution

- **Large angle (10-50 mrad): 12+1 ANTIS**
  - Rings calorimeters (in vacuum)
  - Rate: ~4.5 MHz (μ) + ~0.5 MHz (γ) (OR 12)
  - 10^{-3} inefficiency for $0.05 < E_\gamma < 1$ GeV
  - 10^{-4} inefficiency for $E_\gamma > 1$ GeV
  - 2500 channels



ANTI ring

The NA48 LKr calorimeter



- **Medium angle (1-10 mrad): NA48 LKr Calorimeter**
  - Rate: ~8.7 MHz (μ) + ~4 MHz (γ) + ~4 MHz (π) → New Readout
  - 10^{-4} inefficiency for $1 < E_\gamma < 5$ GeV
  - 10^{-5} inefficiency for $E_\gamma > 1$ GeV → Few 10^{-7} inefficiency for $E_\gamma > 10$ GeV tested on NA48/2 data ($K^+ \to \pi^+ \pi^0$)
  - 13000 cells, no zero suppression
- **Small angle (< 1 mrad): Shashlik technology**
  - Rate: ~0.5 MHz (μ)
  - 10^{-5} inefficiency for high energy (>10GeV) photons

Muon veto MUD

- **Sampling calorimeter + Magnet for beam deflection**
  - Rate: ~7 MHz (μ) + ~3 MHz (π)
  - 10^{-5} inefficiency for μ detection

→
- Sensitivity to the MIP
- em/hadronic cluster separation
- 5Tm B field in a 30×20 cm^2 beam hole: deviate the beam out from the SAC

Preliminary SoI

Statement of Interest (first step) submitted by me to 22nd July PPAN-STFC meeting :
"Search for New Physics beyond the Standard Model with the NA62 experiment at CERN" and the CEDAR

Feedback:
PPAN agreed that there was good and exciting science likely to emerge from the project and the proposal built upon the strong science role that the applicant has established.
However PPAN was concerned by the lack of a developed science consortium for what was a significant package of research. For the project to be viable, PPAN believed that a stronger research community in the UK would need to be identified.

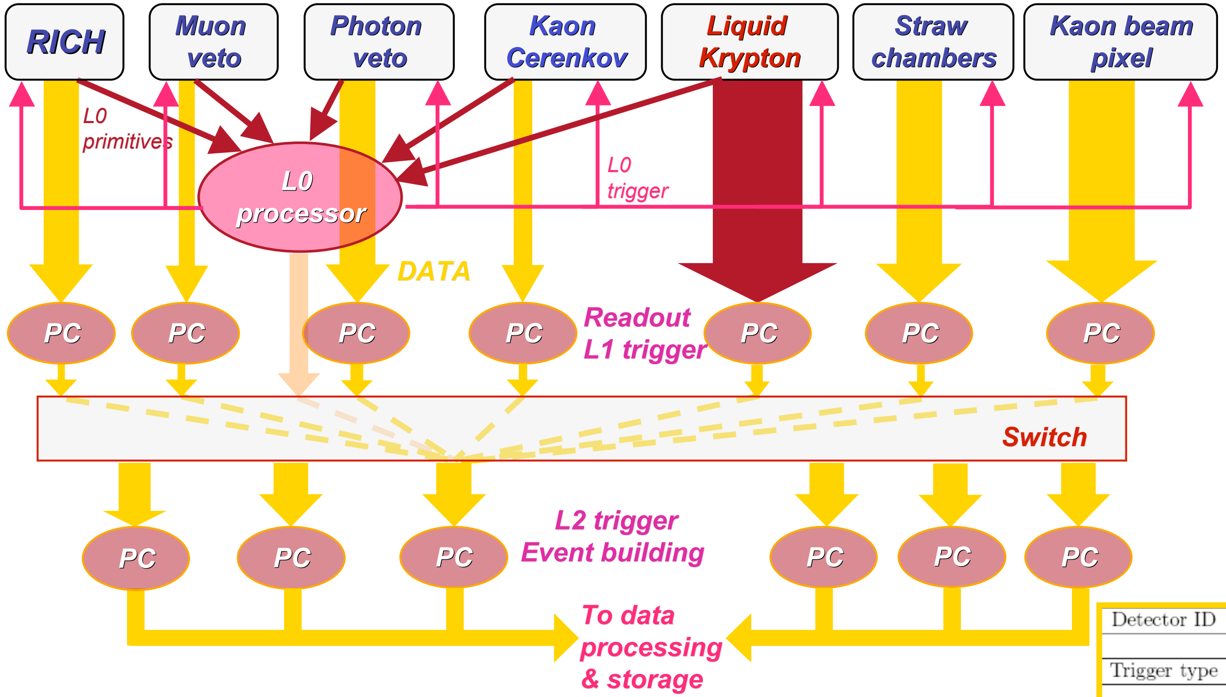
Possible UK contributions

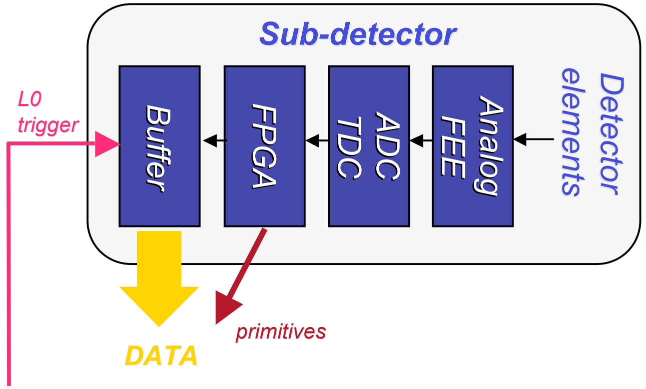
CEDAR: Identify kaons in the beam line

- light collection system
- photo-detectors
- front-end electronics
- trigger and daq

Simulation of the Experiment
Data process
Distributed Computing

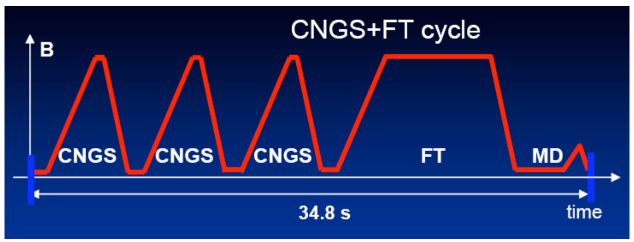
NA62 TDAQ scheme





Now under development, based on the **TELL1** board (LHCb)

Detector ID	Event number		
Data block byte count			
Trigger type	Reserved	Reserved	Timestamp (high)
Timestamp (low)			
Detector event data			
Reserved (trailer)			



16.8 s/34.8 s CNGS+fixed target

0 s/22.8 s LHC+CNGS

0 s/21.6 s LHC filling

~ 30% of spill-time/total time, not synchronous events

(no bunch crossing!)

NA62 data volume

***10 MHz** event rate → ~300 kHz at the L0 + control + calibration*

*Maximum **1 MHz** at the **output of L0** trigger*

L1 + L2** in software, reduction by a factor **~50

- ***20 kHz** event rate*
- ***~ 1 GB/s** (**without** Krypton zero-suppression, but **with** data compression) **~ 500 kB/event***
- ***300 MB/s** average over the spill*
- *~ 40 TB/day → 3 PB/year*

Only a fraction to be logged to tape:

- *Need **L3 trigger** and/or Krypton **zero-suppression***
- *Use pre-scaling & control samples*
- *Need on-line monitoring*
- *Keep the system **highly flexible***

Sub-detector	R-O type	Rate (MHz)	Total channels	Active channels	N. of bits Time	N. of bits Channel
CEDAR	F 1GHz	60	256	(32)	256 × 8/ns	
Gigatracker	TDC	1000	18K × 3	6	20	12
Antis	F 40 MHz	10	2500	(3.3)	2500 × 8/25 ns	
Straws	TDC	20	2K × 6	33	18	14
RICH	TDC	15	2K	40	21	11
IRC	F 40 MHz	40	48	(8)	48 × 10/25 ns	
LKr	F 40 MHz	20	13.2K	(150)	13.2K × 10/25 ns	
N. Hodoscope	TDC	20	32	4	21	5
MAMUD	TDC	15	2080	73	20	12
Mu Hodoscope	TDC	15	512	4	21	9
SAC	F 40 MHz	10	64	(8)	64 × 10/25 ns	

130 GB/s raw at the L0 output

-1 PB/year to log to tape

(at 150 MB/s…)

Of course, need also:

- CPU for processing: ~3000 kSpecInt2k

- Disk buffers: ~ 200 TB

Monte Carlo

- *Several kinds of Monte Carlo already existing:*
    - *It is not **conceivable** to generate 10^{13} kaon decays with full tracking of particles inside a detailed GEANT description of the experiment…*
- *GEANT4 detailed simulations of detectors response*
- *Fast simulation using:*
    - *Physics generators*
    - *Accurate beam and halo parameterizations*
    - *Simulation of setup as passive materials*
    - *Parameterization of detectors response from GEANT4*
    - ***Trigger simulation***
- ***Full reconstruction in C++***
- ***~1 MB/event** with MC info*
- ***10^8 events/year/kSpecInt2k** [generation step faster]; 100 TB/year*

CEDAR : Basic principles

- The CEDAR is used to identify Kaons in the beam using Cerenkov light
- The Kaons are a small fraction of the total flux (in units of 10^6 per spill):

Protons	500	
Kaons	150	→ *6.6% only*
Pions	1600	
Electrons	1	
Muons	20	

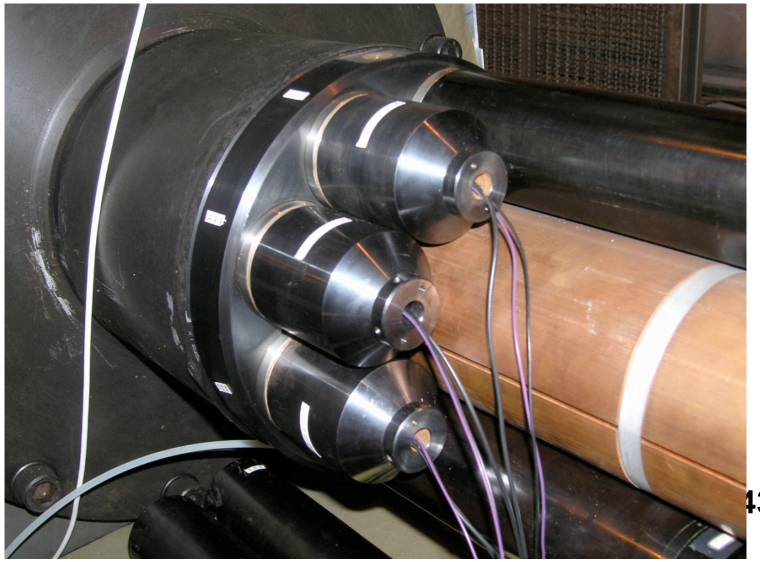
- The CEDAR is blind to all particles except Kaons (i.e. the wanted type)
  - A diaphragm blocks the light from other particles
- Nevertheless the rate is very high: 1.5 10^8 / 3 sec = 50 MHz
- Two types of CEDAR exist (as AB standard):

North type	100-300 GeV/c, filled with He at ~10 bar, θ ~25 mrad
West type	up to 150 GeV/c filled with N2 at < 1.7 bar, θ ~31 mrad

- CEDAR requires a parallel beam for adequate performance

CEDAR: R&D program

- CEDAR W-type filled with N tested at CERN in November 2006, using a 100 GeV hadron beam with 10^5 - 10^7 ppp
- Test in 2006 mainly devoted to study time capability
- Proof that CEDAR works !



Why Hydrogen ?

- Absolute necessity to minimize material on beam line
- 4x lower pressure allows thinner windows
- Optics requires chromatic corrections depending on gas and quartz n(λ)

Resolution is ok
Proposal to modify existing CEDAR to be filled with H_2

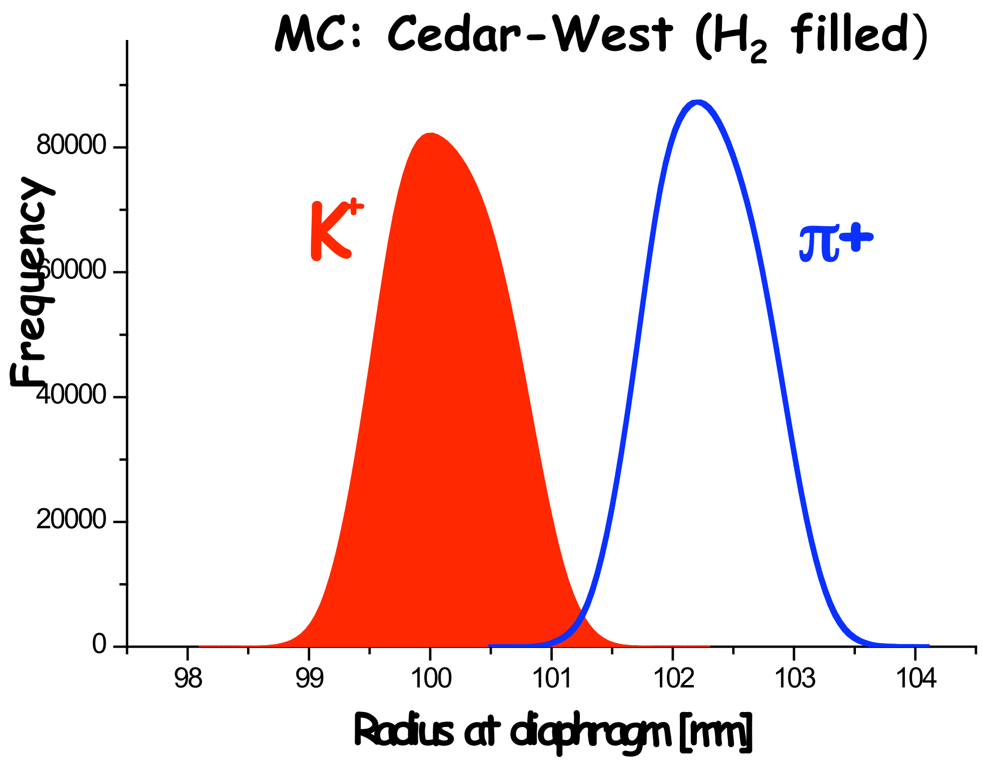


Photo-detector for the CEDAR

Current optics condenses the Cherenkov light from the diaphragm into 8 rectangular light spots ~10x30 mm^2 each

Kaon rate = 50 MHz and ~100 photons per Kaon

→photon rate = 100 ph x 50 MHz / (300 mm^2 x 8)
~ 2 MHz / mm^2 (rate of singles from accidentals, after-pulses, dark noise not included)

Solution to be investigated: SiPM

Key points for the new detector:

- Single photon counting application
- Stand very high photon rate / unit area (occupancy in time and space)
- Reduced active area (beam activity)
  (minimum ~150 mm^2 / spot due to optics phase space)
- UV/Blue light sensitivity with the highest efficiency (PDE)
- Excellent timing resolution on single photon (100 ps)
- Exposition to the halo of intense hadron beam (radiation damage)

Other physics opportunities

- **P-326 Kaon Flux ~100 times NA48/2 Kaon Flux**

- **Other physics opportunities can be addressed:**
  - **Lepton – flavor violation:**
    - ✓ $K_{e2}/K_{\mu 2}$, $K^+ \to \pi^+ \mu^+ e^-$, $K^+ \to \pi^- \mu^+ e^+$
  - **Tests of CPT**
    - ✓ $K^+ \to \pi^+ \pi^- e^+ \nu$ (Ke4)
  - **Search for new low mass particles:**
    - ✓ $K^+ \to \mu^+ N$ *(light RH neutrinos)*
    - ✓ $K^+ \to \pi^+ \pi^0 P$ *(pseudoscalar sGoldstino)*
  - **Hadron spectroscopy**
  - …

$R_K = \Gamma(K^+ \rightarrow e^+\nu(\gamma))/\Gamma(K^+ \rightarrow \mu^+\nu(\gamma))$

$$R_M = \frac{\Gamma(M \to e\nu(\gamma))}{\Gamma(M \to \mu\nu(\gamma))} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{1-\left(\frac{m_e}{m_M}\right)^2}{1-\left(\frac{m_\mu}{m_M}\right)^2}\right)^2 \times \left(1+\delta R_M\right)$$

The latest SM theoretical predictions:

$R_\pi = (1.2352 \pm 0.0001) \times 10^{-4}$

$R_K = (2.477 \pm 0.001) \times 10^{-5}$

Experimental Situation before NA62

$\pi \longrightarrow e\nu$

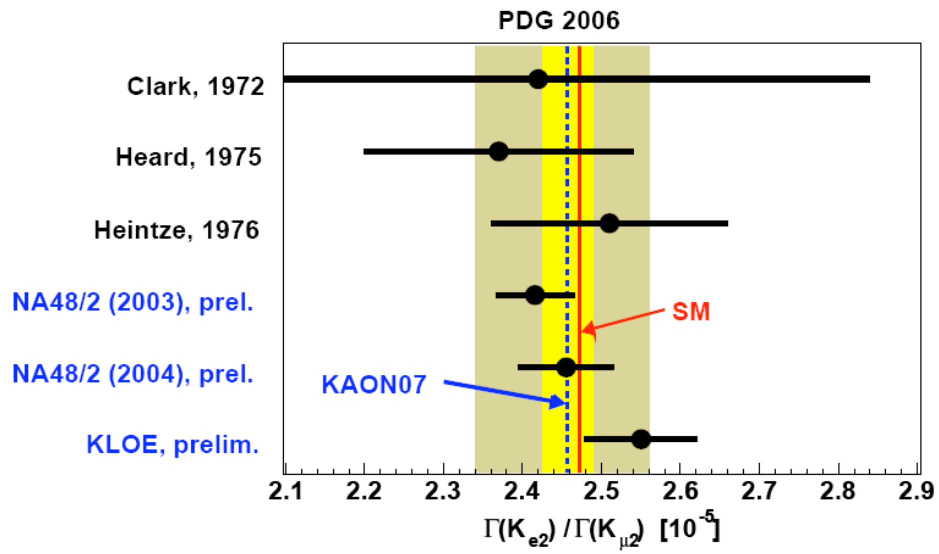
$R^{\exp\pi}_{e/\mu}$ (±0.4%)

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

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

New experiments planned at TRIUMF and PSI to reach <0.1% on R_π

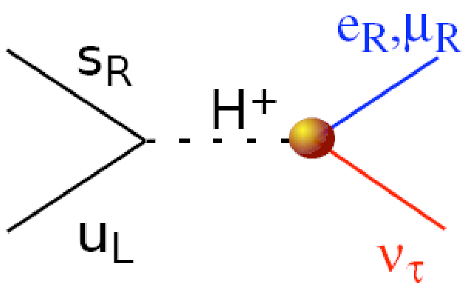
$$R_K = 2.457 \pm 0.032 \times 10^{-5}$$



R_K and SUSY

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

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)} \;, \quad i = e, \mu, \tau$$



$$eH^\pm\nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \quad t_\beta = 40 \quad M_{H^\pm} = 500 \mathrm{GeV}$$

$$\Downarrow$$

$$\Delta r_{K\,SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right) \left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

Charged-Higgs mediated SUSY LVF contributions:
$R_K^{SUSY} = R_K^{SM} \cdot (1 + \Delta R_{SUSY})$, $|\Delta R_{SUSY}| \sim$ up to few %.

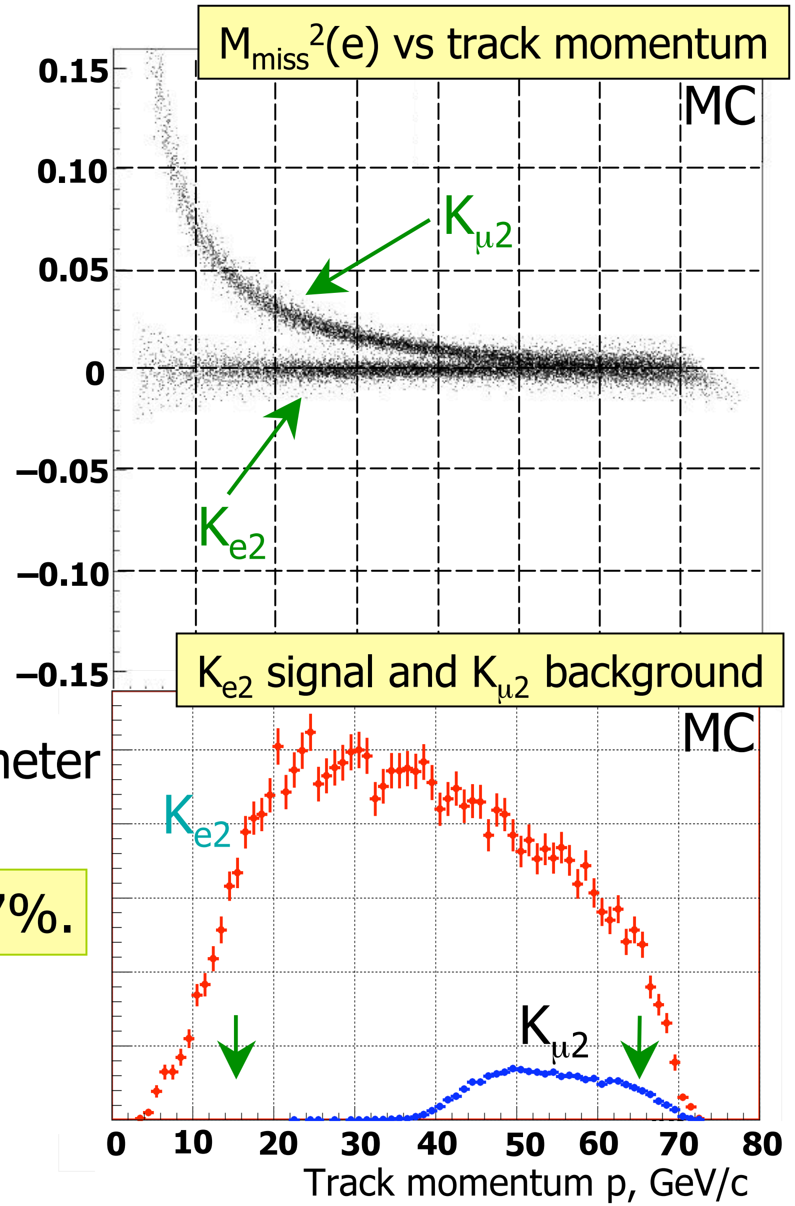
NA62 aims to test the SM prediction with a precision better than 0.5%

Experimental Technique

Kinematic ID of the K_{l2} candidates:

$M_{miss}^2(l)=(P_K-P_l)^2$

Good kinematical separation for **p<40GeV/c**
e/μ PID required for **p>40GeV/c**



Tools

- **P_K:** narrow band beams: **$\Delta P_K/P_K$~2%**
- **$P_{e,\mu}$:** maximum P_t kick: **263MeV/c**
  δp/p = 0.47%+0.020%p [p in GeV/c].
- **E/p:** Energy in LKR / Momentum in Spectrometer

Expected $K_{\mu 2}$ background in analysis region: 7%.

Analysis strategy

Express analysis:
~40% of the 2007 K^+ sample

$K_{e2}/K_{\mu2}$ candidates collected <u>simultaneously</u>:

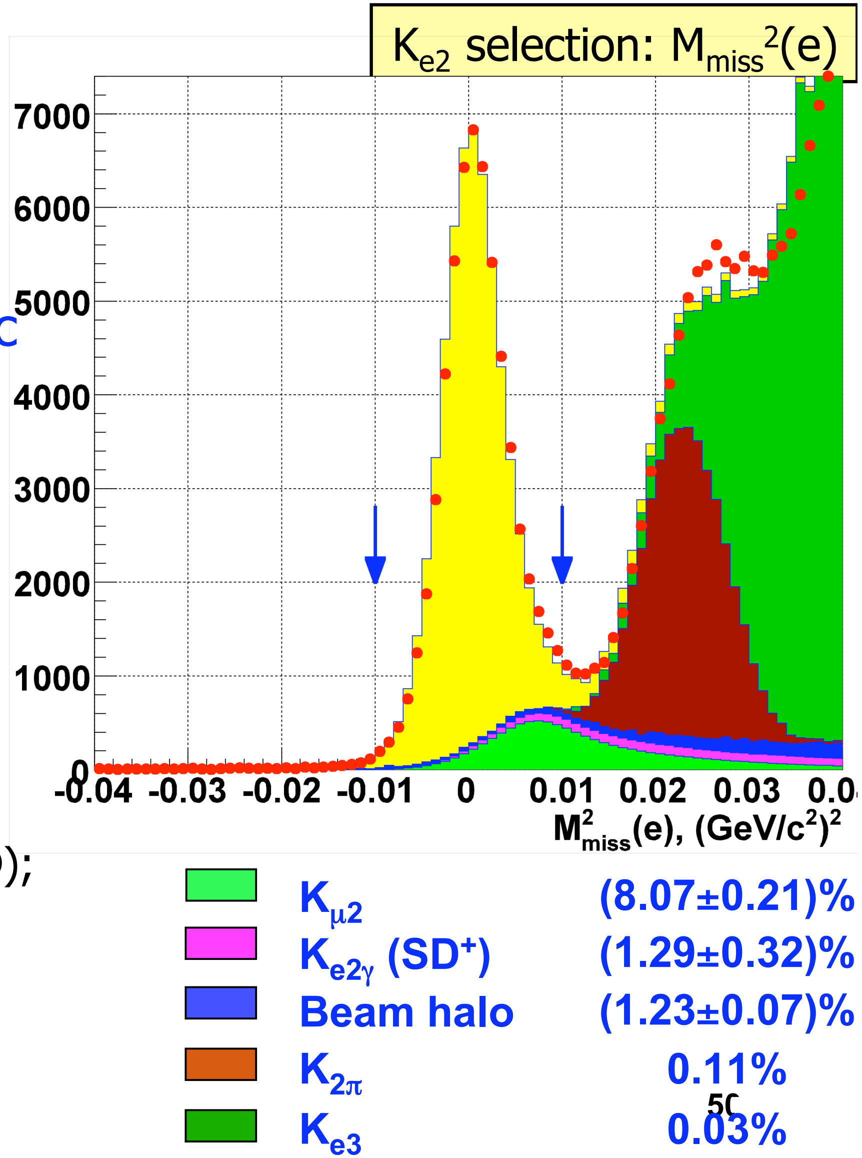
- result independent of kaon flux;
- cancellation of certain systematic effects (parts of reconstruction/trigger eff., etc.)

The MC simulation is used only for geometric acceptance

Measurement in <u>track momentum bins</u>:

$$R_K = \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \frac{A(K_{\mu2}) \times f_\mu \times \varepsilon(K_{\mu2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})}$$

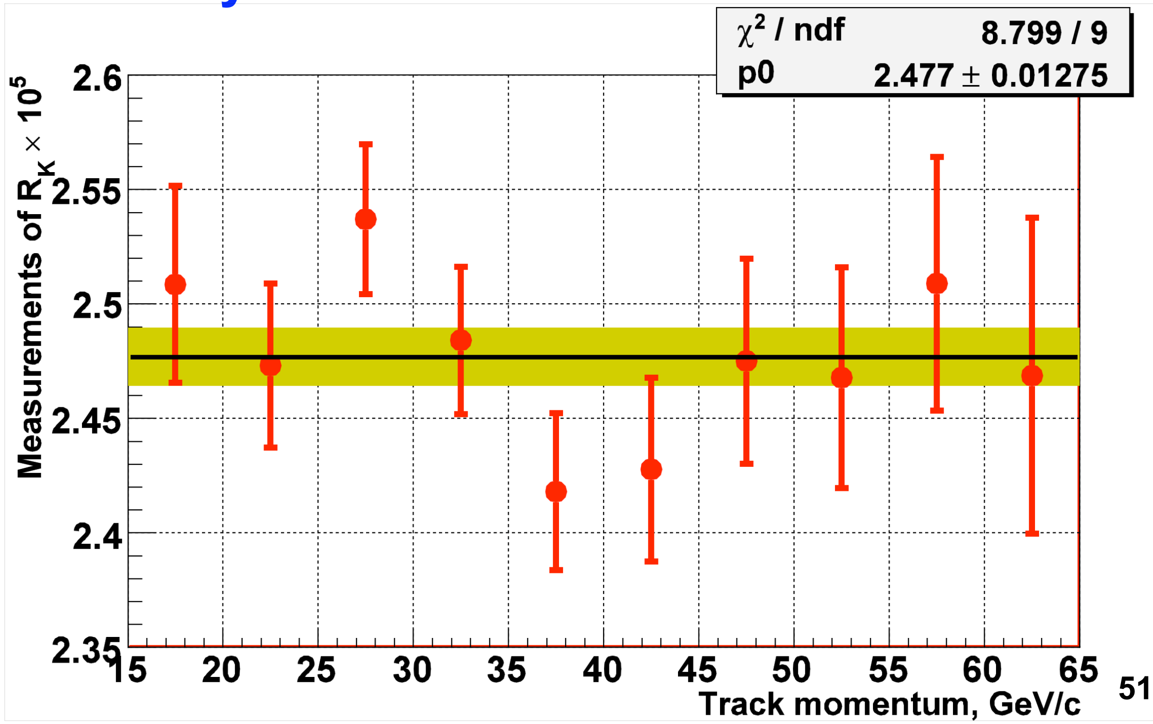
- **$A(K_{e2})$, $A(K_{\mu2})$:** MC geometric acceptances (no ID);
- **f_e, f_μ:** measured particle ID efficiencies;
- **$\varepsilon(K_{e2})/\varepsilon(K_{\mu2})$:** E_{LKr} trigger condition efficiency.



Measurement of R_K

- 300 TB of raw data collected in 2007
- The 2007 K_{e2} data sample allows us to achieve a statistical precision of $\delta R_K/R_K$=0.3%
- Preliminary studies of systematic uncertainties demonstrate the feasibility of a total precision better than $\delta R_K/R_K$=0.5%.
- 2008 data taking aims at systematic checks

Presented at SPSC on 4/11/2008



New opportunities in Kaon Physics

Thursday 27 November 2008
from **13:00** to **17:00**
Europe/London
at **University of Birmingham (*G33 - Aston Webb Building*)**
chaired by: ***Cristina Lazzeroni***
support: cristina.lazzeroni@cern.ch

Description: Institute of Physics half-day meeting.

This meeting will review recent results in Kaon Physics, exploring the use of kaon decays in precision tests of the Standard Model and in searches for new physics. All presentations will be given in a form accessible to students and to researchers from other areas of high-energy physics.

For further information, contact the organiser: cristina.lazzeroni@cern.ch

Thursday 27 November 2008 |

Thursday 27 November 2008

top

13:00	Welcome (10')	Cristina Lazzeroni (*High Energy Physics Group, University of Birmingham*)
13:10	Review of Kl3 results in UKQCD (20')	Jonathan Flynn (*Southampton U*)
13:30	Review of Kl3 results and Vus in Flavianet (20')	Matthew Moulson (*Laboratori Nazionali di Frascati (LNF) - Istituto Nazionale Fisi*)
13:50	Lepton Flavour Violation in Kaon decays (20')	Paride Parisi (*University of Munich*)
14:10	Search for LFV in kaon decays from KLOE and NA48/NA62 (20')	Evgueni Goudzovski (*University of Birmingham*)
14:30	Rare Kaon decays in SM and beyond (I) (30')	Martin Gorbhan (*University of Munich*)
15:00	Rare Kaon decays in SM and beyond (II) (30')	Christopher Smith (*Karlsruhe*)
15:30	The NA62 experiment at CERN (30')	Augusto Ceccucci (*CERN*)
16:00	K+ to pi+ nu nubar measurement from E949 (20')	Ilectra Chrisitidi (*Aristotle University of Thessaloniki*)
16:20	Discussion (30')	

NA62: Conclusions

Exciting physics, precise test of SM and meaningful search for new physics in kaon rare decay $K^+ \rightarrow \pi^+ \nu \nu$

PPAN: we agree that good and exciting physics will come from this project

- Project is well defined, timescale suitable to complement LHC
Now it is the time to join !

- Several aspects where UK can take leadership, looking for collaborators

Spares

TRIGGER

- A possible scheme……

Level	L0 "hardware"	L1-L2 "software"
Input	~10 MHz	1 MHz
Output	1 MHz	$\mathcal{O}$(KHz)
Implementation	Dedicated hardware	TDAQ farm
Actions	RICH minimum multiplicity, Muon veto, LKr (γ) veto, CEDAR	**L1 = single sub-detectors** **L2 = whole event**

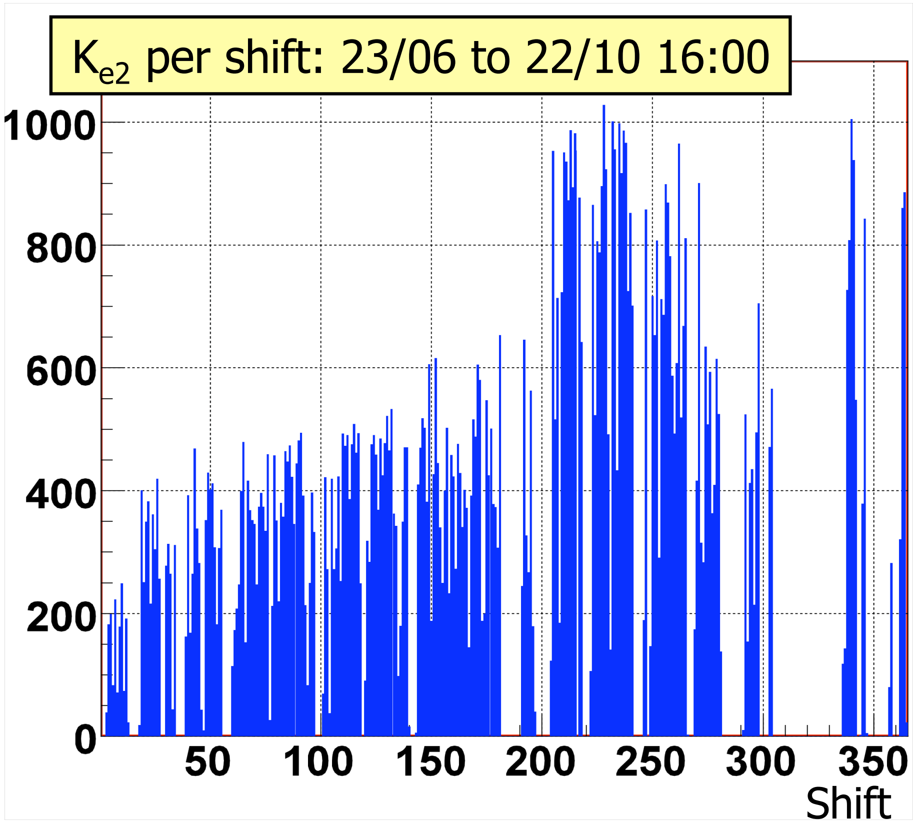
- 1track × μ! × γ! → 1 MHz L1 trigger input → PC farm
- Software trigger reduction ~ 40

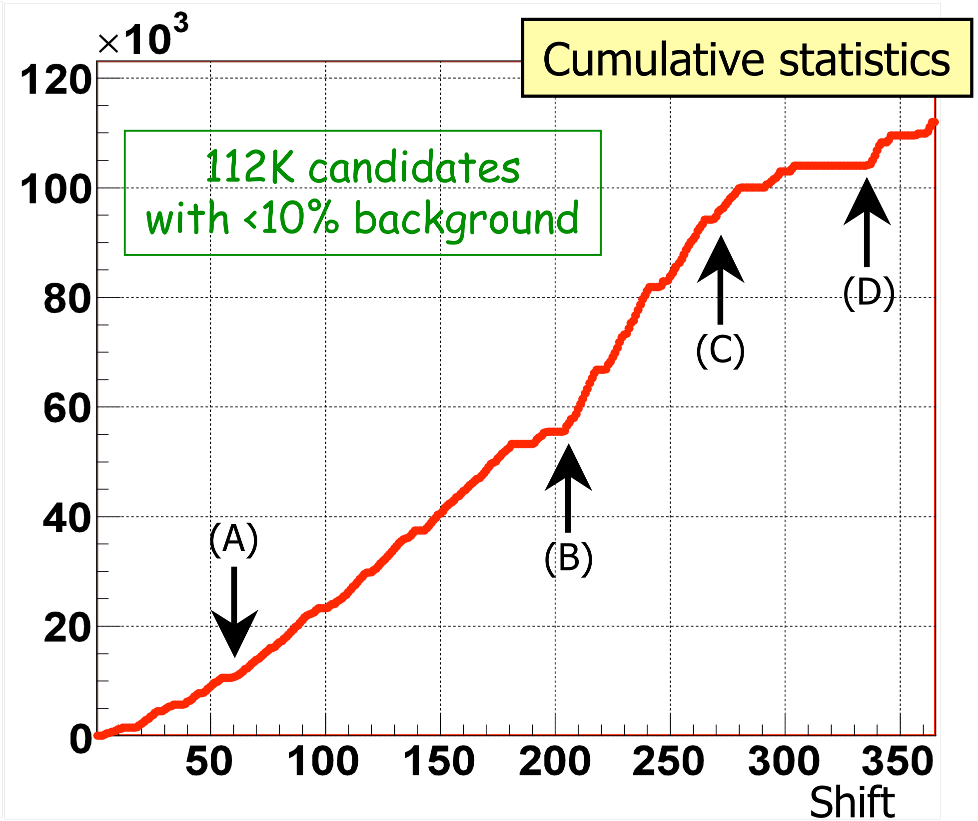
- Main work on possible solutions for the L0 hardware
  - **TELL-1 board (LHCb) based implementation for all non FADC sub detectors**
  - **Design of a new 100 ps TDC daughter-card**
    - **Two prototypes under study**

NA62: detectors

- **CEDAR:** **differential Cherenkov to identify kaons in beam line (50MHz)**
- **GIGATRACKER:** **Beam Tracking (Si micropixel) (800 MHz)**
- **STRAW Chambers:** **Spectrometer made of 4 stations of straw tubes chambers, to detect kaon decay products (~10 MHz)**
- **RICH:** **Ring Image Cherenkov, to detect pion from kaon decay, to distinguish pion/muon and to fast trigger**
- **LAV:** **photon ANTI-counters at large angle (lead glass)**
- **LKR:** **photon Veto in forward region and electromagnetic calorimeter (LKr NA48)**
- **IRC/SAC:** **photon Veto at medium/small angle**
- **MUD, sweeper:** **muon detector (hadron calorimeter NA48, scintillators for fast trigger) with sweeping magnet to deflect non-decayed beam particles**

Data sample recorded in 2007





Main Features:

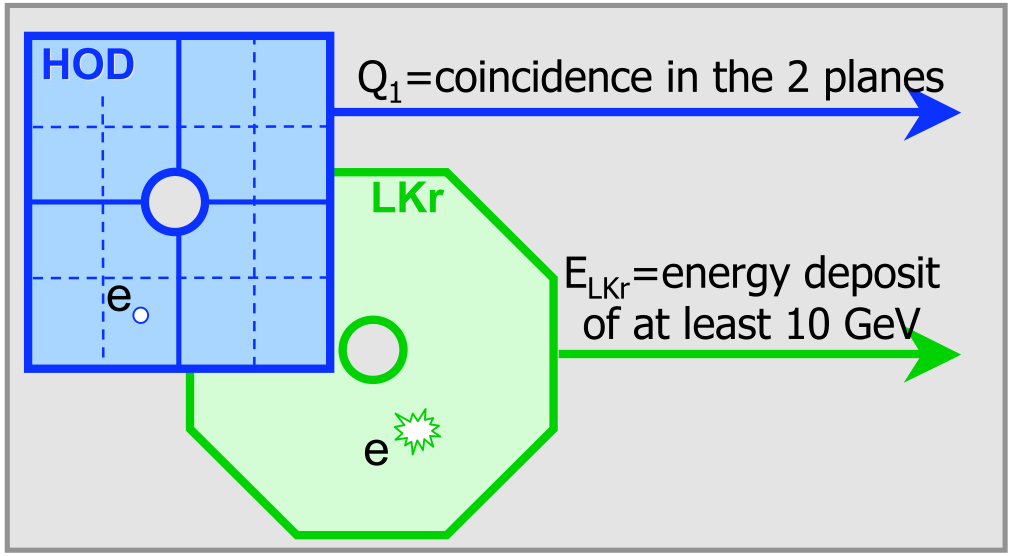
A) **Start running with K^+ beam only;**

B) **Pb wall dismantled & new multiplicity condition in trigger;**

C) **Dedicated K^- period started;**

D) **Resumed K^+ data taking during the straw prototype test.**

Trigger logic



improvements of trigger purity during the run:

1) introduction of drift chamber multiplicity conditions (1TRK);
2) optimization of downscalings;
3) optimization of beam steering;
4) dismantling the Pb wall.

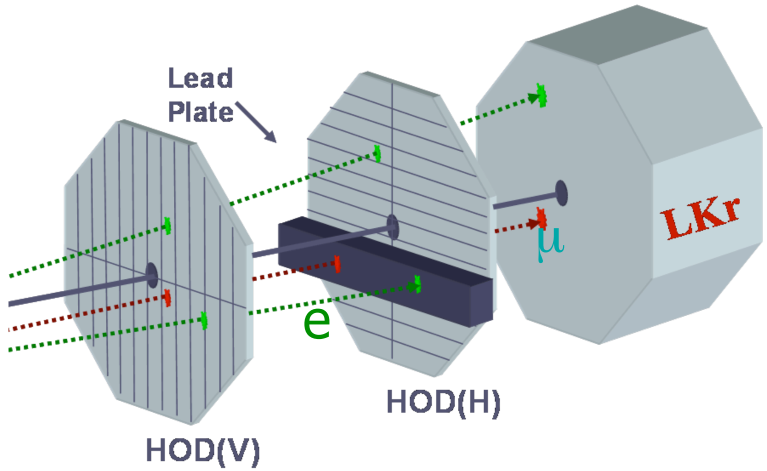
Trigger	Condition		Rates/SPS spill		Purity	
	Start-up	End-of-run	Start-up	End-of-run	Start-up	End-of-run
K_{e2}	$Q_1 \times E_{LKr}$	$Q_1 \times E_{LKr} \times$1TRK	0.23	0.54	0.6×10^{-5}	1.3×10^{-5}
$K_{\mu 2}$	$Q_1/50$	$Q_1 \times$1TRK/150	290	160	1.8%	1.8%

Electron/muon identification

Electron ID is based on LKr energy deposition: $0.95<E/p<1.05$.

A muon is mistaken as electron if its
E/P falls between 0.95 and 1.05:

A measurement of $p(\mu \rightarrow e)$ is necessary:
lead wall inserted between the HOD planes.
Tracks traversing the wall + MIP in HOD(H):
samples of pure muons.



Thickness: Pb(4.5cm)+Fe(2.0cm)
18% of geom. Acceptance
Installed: ~50% of running time

Pure muon samples collected:

1) From $K_{\mu 2}$ decays;
2) Special μ runs

Each sample: ~2,000 muons with $E/p>0.95$ and $35GeV/c<p<65GeV/c$.

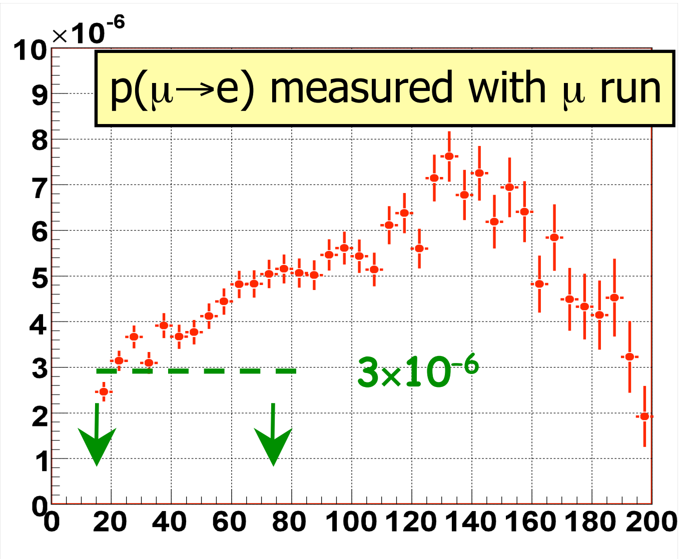
Backgrounds

Main backgrounds in K_{e2} sample [subtracted using special runs]

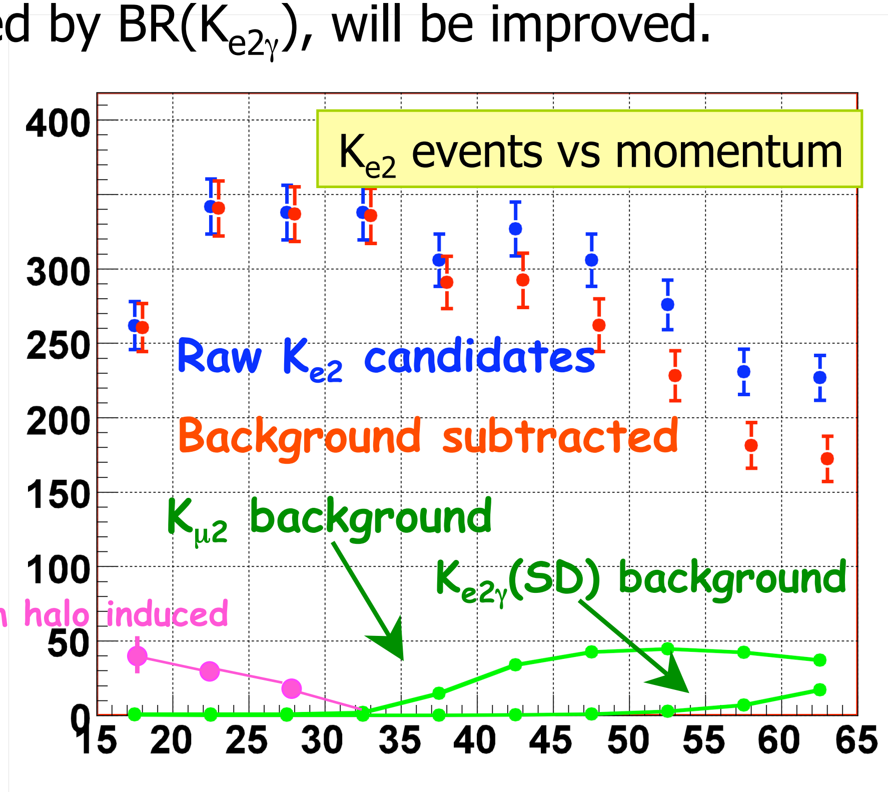
1) $K_{\mu 2}$ decays: estimated **(7.5±0.2)%** by measuring $p(\mu \to e)$.
2) From beam halo: estimated **(1.3±0.1)%** using runs with blocked K^+ beam. Reducible by stricter CDA cuts.

Other backgrounds in K_{e2} sample [more trivial to subtract]

1) $K_{e2\gamma}$(SD): **(0.7±0.1)%**, precision limited by BR($K_{e2\gamma}$), will be improved.
2) K_{e3} , $K^+ \to \pi^+\pi^0$: << 1%



p, GeV/c



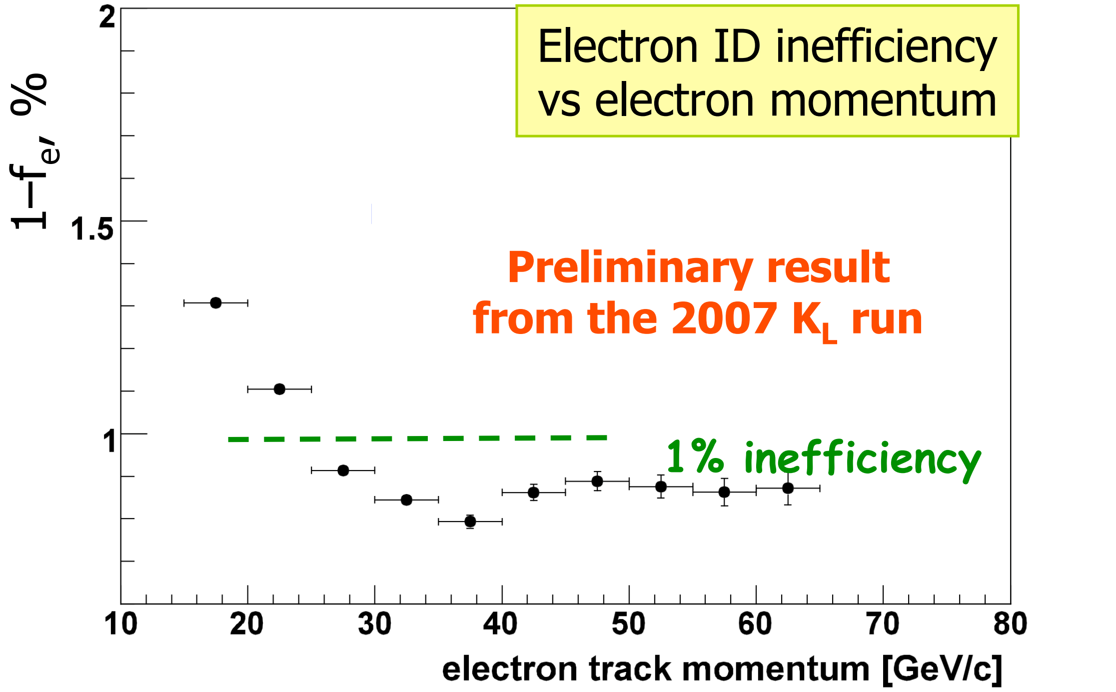
p, GeV/c

Electron Identification

Electron ID efficiency f_e measured from the data:

- clean sample of electrons by kinematic selection of $K^{\pm}\to\pi^0 e^{\pm}\nu$ decays: collected simultaneously with main data taking, but p<50GeV/c.
- 15h special K_L run: kinematic selection of pure $K_L\to\pi^{\pm}e^{\pm}\nu$ decays in the whole analysis track momentum range 15GeV/c<p<65GeV/c.

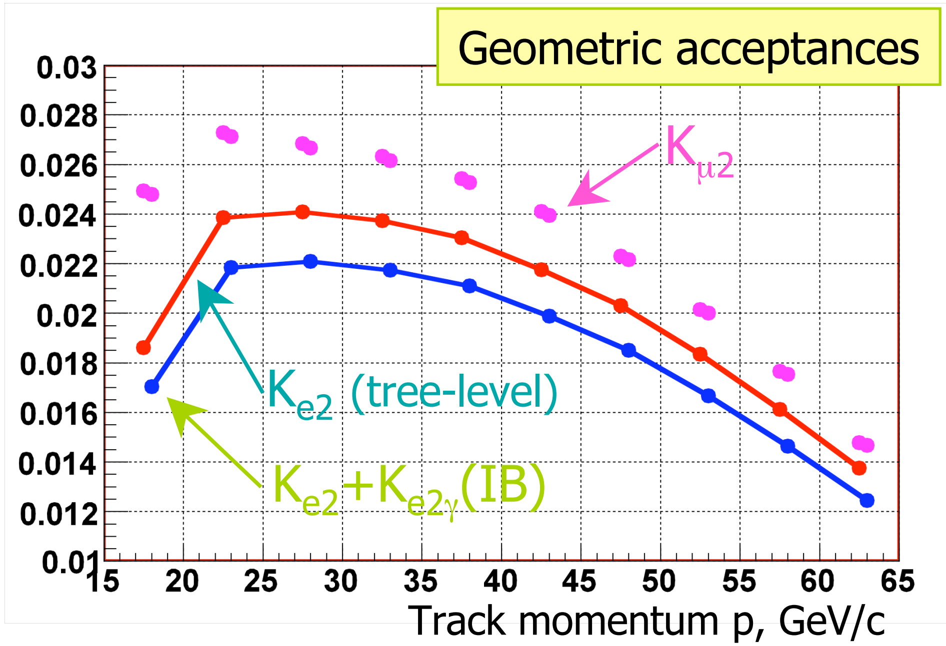
Expected precision of f_e measurement: much better than 0.1%.



Other effects

Acceptance correction:

- p-dependent, $A(K_{\mu2})/A(K_{e2})\sim1.2$;
- K_{e2} radiative corrections strongly affect of the acceptance;
- 2004 conclusion: the correction can be evaluated with a 0.1% precision after appropriate MC tuning.



Trigger efficiency:

- All efficiencies are monitored with control trigger samples;
- Q_1 efficiency mostly cancels in R_K;
- Preliminary measurement: $1-\varepsilon(E_{LKr})\approx1-\varepsilon(K_{e2})/\varepsilon(K_{\mu2})<0.1\%$;

Other known sources of uncertainies (@ 0.1% level):

- Global inefficiency of LKr calorimeter readout.

Spares

Quark Mixing and CP-Violation

Cabibbo-Kobayashi-Maskawa (CKM) matrix:

- Non-diagonal (e.g. $V_{us} \neq 0$)
  → Flavour Violation
- 3 or more quark generations
  → CP-Violation in SM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$N_g=2$ $N_{phase}=0$ $\Rightarrow$ No CP-Violation

$N_g=3$ $N_{phase}=1$ $\Rightarrow$ CP-Violation Possible

e.g., $Im\,\lambda_t = Im\,V_{ts}^* V_{td} \neq 0 \rightarrow CPV$

GIM mechanism
→ No FCNC at tree level
Violation at one loop depending on quark masses and CKM couplings

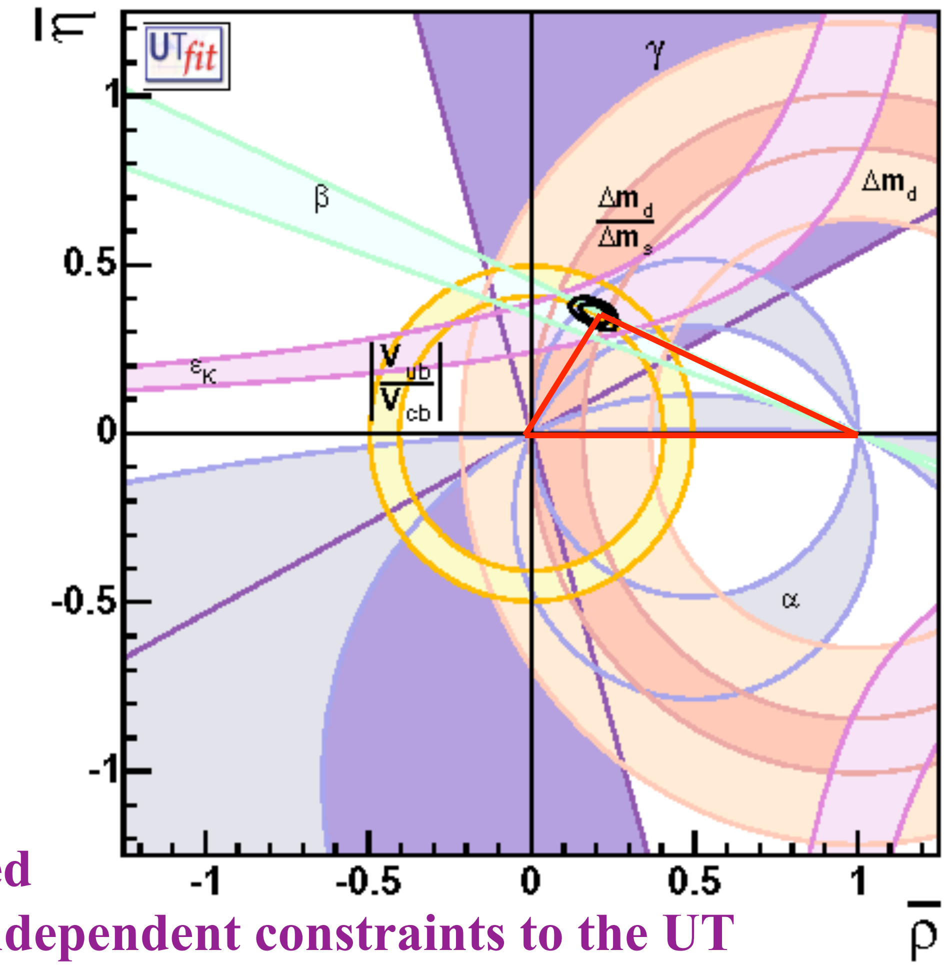
Status of the Unitarity Triangle (S.M.)

Allowed regions for ρ and η in S.M.

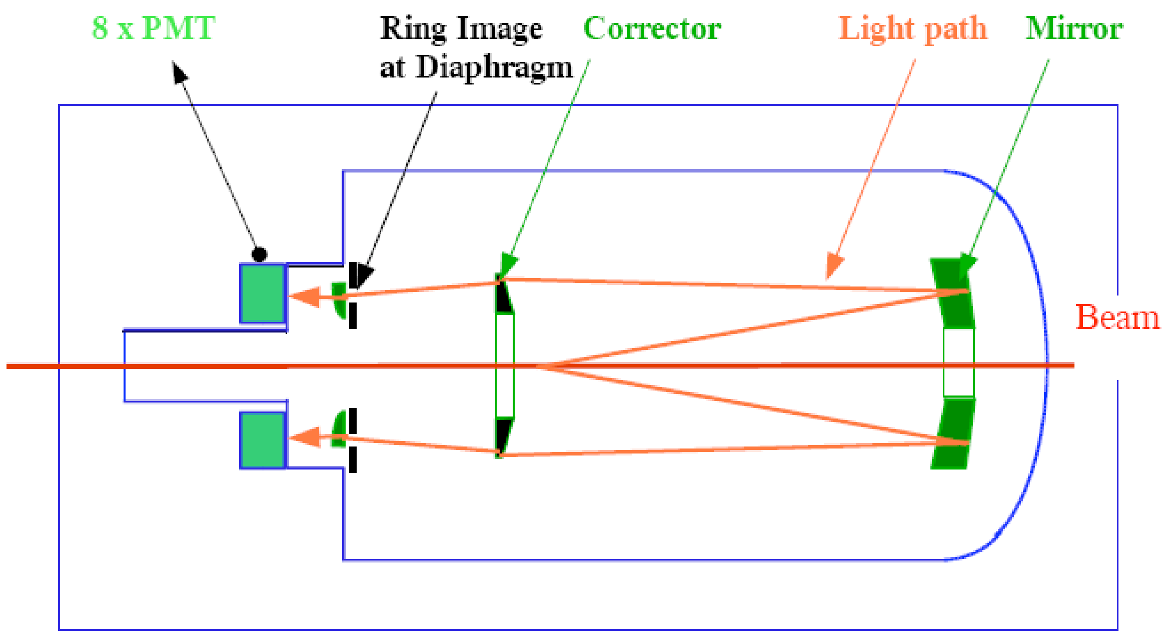
(UTfit Group , *M.Bona et al. hep-ph/0606167*)

• **68% and 95% confidence regions from the constraints given by measurements of $|V_{ub}|/|V_{cb}|$, ε_K, Δm_{Bd}, Δm_{Bs} and α,β,γ**

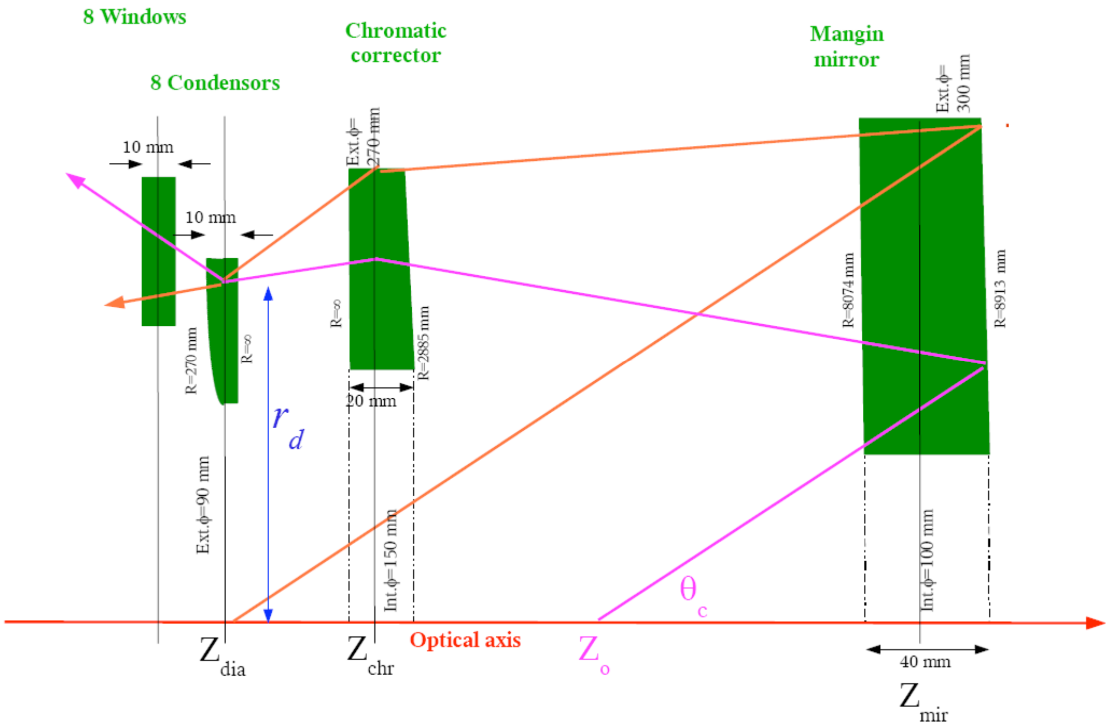
$$\rho = 0.197 \pm 0.031$$
$$\eta = 0.351 \pm 0.020$$



- **Rare kaon decays are loop-dominated**
- **Assuming SM they provide strong independent constraints to the UT**

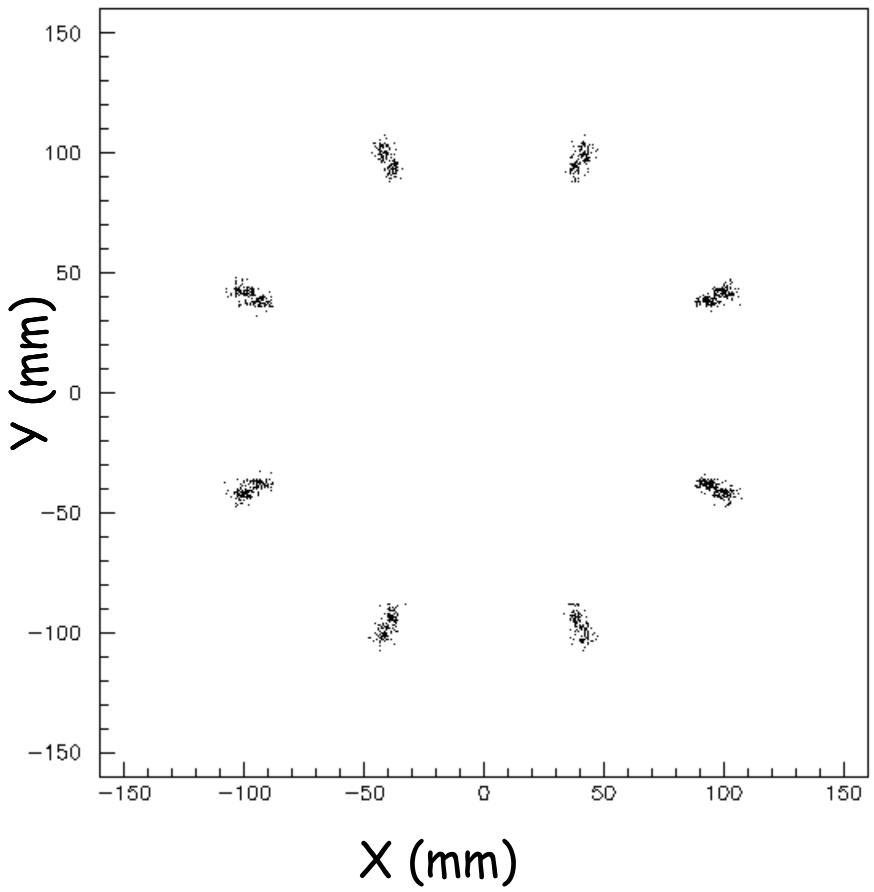

8 x PMT
Ring Image
at Diaphragm
Corrector
Light path
Mirror
Beam

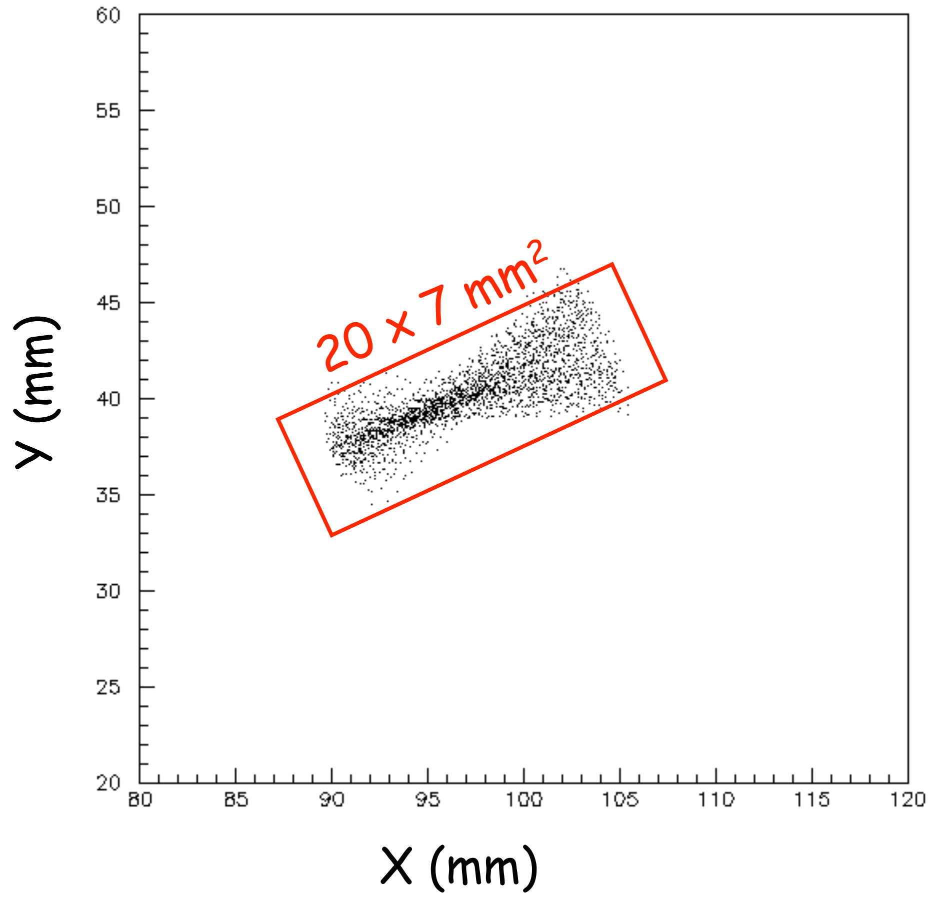

CEDAR


8 Windows
8 Condensors
Chromatic
corrector
Mangin
mirror
10 mm
10 mm
20 mm
40 mm
Ext.ϕ=90 mm
Ext.ϕ=270 mm
Int.ϕ=150 mm
Ext.ϕ=300 mm
Int.ϕ=100 mm
R=270 mm
R=∞
R=∞
R=2885 mm
R=8074 mm
R=8913 mm
r_d
θ_c
Z_{dia}
Z_{chr}
Optical axis
Z_o
Z_{mir}

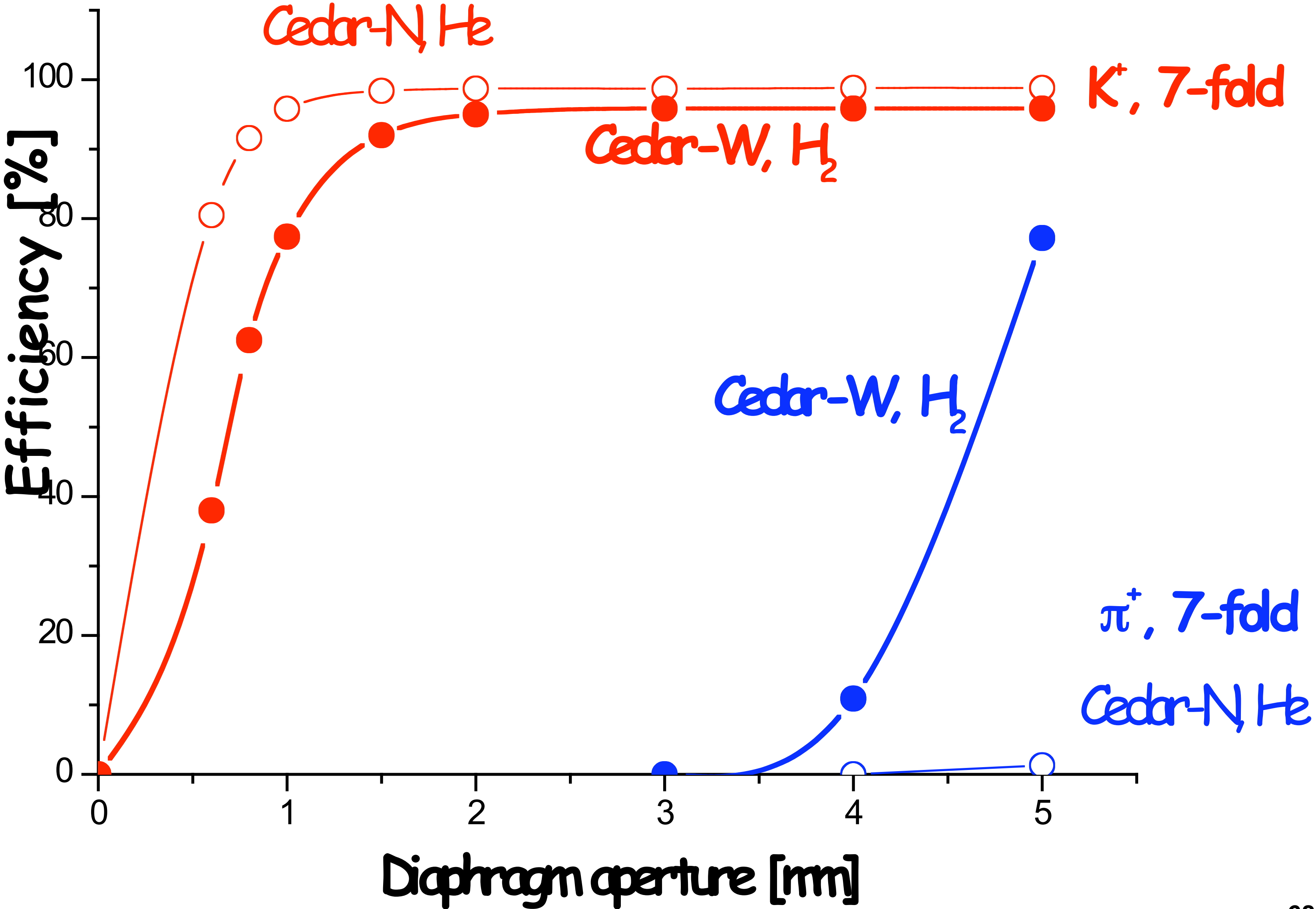
66

Spot at 'old' PMT location, e.g. for PMT #1:





Cedar N(He) versus W(H_2) Comparison



Comparison SiPM vs PMT

for applications of photon counting and timing at high rates

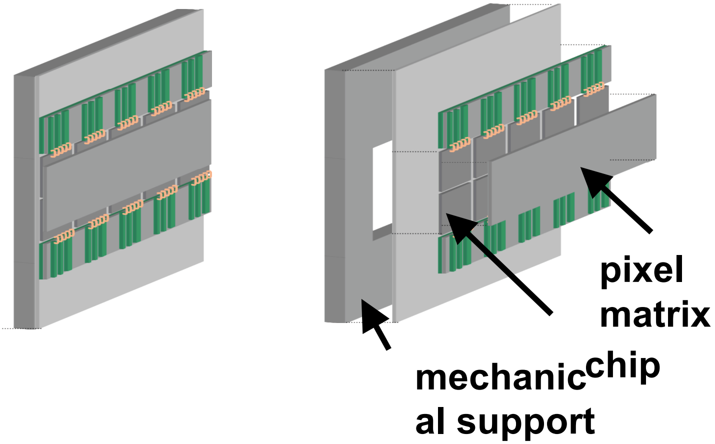
	PMT	SiPM
Reference device (eff. area)	HPK R7600 ($18x18\ mm^2$)	HPK S10362-11-50C ($1x1\ mm^2$)
Gain (G)	$\geq 10^6$	$\geq 10^6$
$\delta V/V$ for $\delta G/G$=1%	3×10^{-4}	6×10^{-4}
δT for $\delta G/G$=1%	5^o C	0.3^o C
Max average anode current	100 μA ($350\ mm^2$)	3 μA ($1\ mm^2$)
Efficiency (on active area)	~25% @ 400nm ~40% (UBA)	~95% @ 400nm
Fill Factor	36%	40% to 80%
Time resolution	~300ps	50ps to 100ps
Dark noise (1 p.e.)	few kHz	0.5 MHz @room T
After-pulse (thr. @ 1 p.e.)	1 % level	10 % level
B-field immunity	No	Yes
Radiation damg.	No (also at single photon level ?)	Yes

cell geometry

Gigatracker: R&D program

Readout chip: **Front-End Blocks in 0.13 μm CMOS**

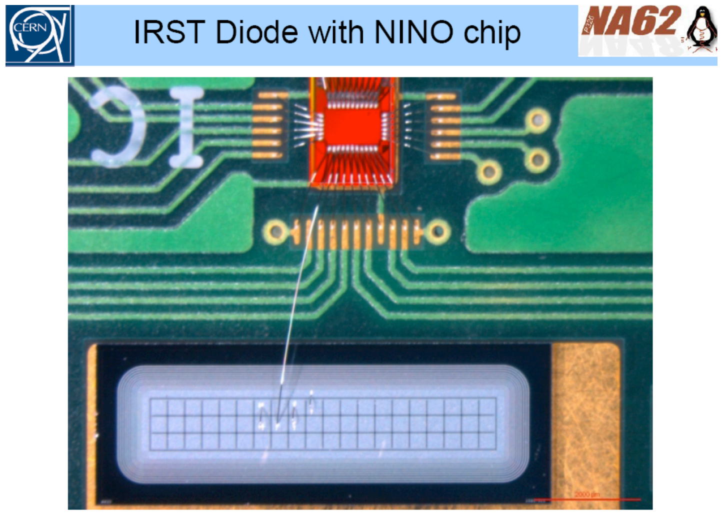
- Submitted in February 07
- Wafers delivery ≈ May 07
- ASICs characterization (t resolution, jitter, time walk)
- Tests card in progress

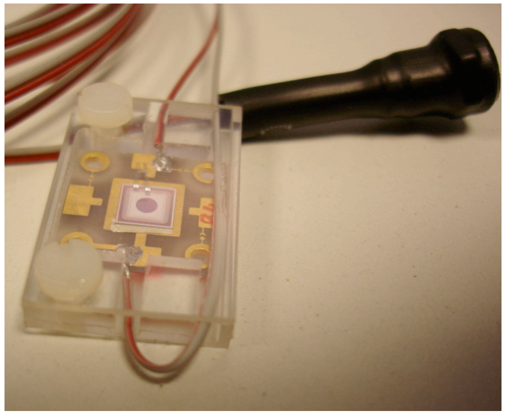


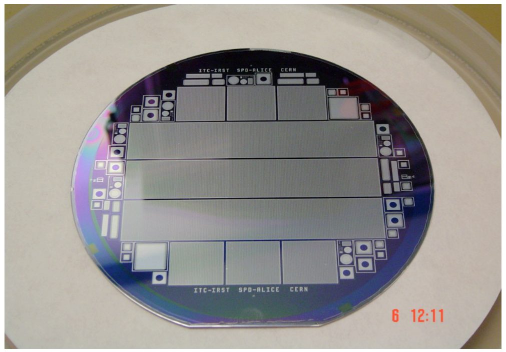
Si diode irradiation tests (started in 2006)

- Prototype wafers (200μm thick) produced by itc-IRST using ALICE pixel layout
- 3 mm × 3 mm and 7 mm × 7 mm test-diodes
- Test diodes irradiated with n and p (Ljubljana, CERN)
- Fluences: 1E12 to 2E14 1MeV n cm^{-2} (range P326)
- Pre and post irradiation measurements (annealing) to study diode characteristics

CFD and NINO front-end blocks



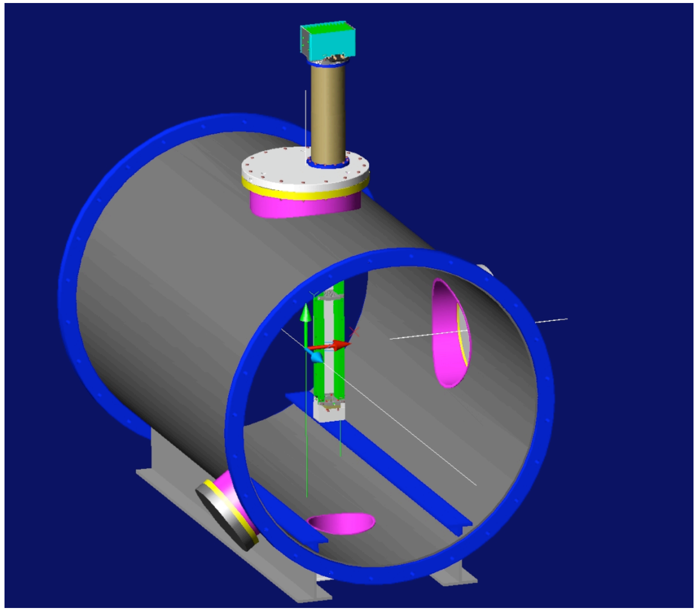


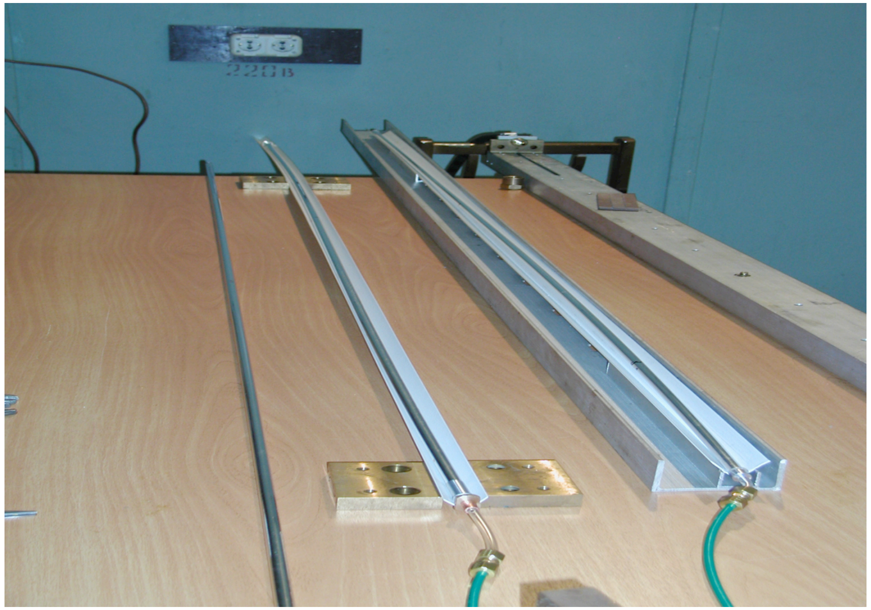


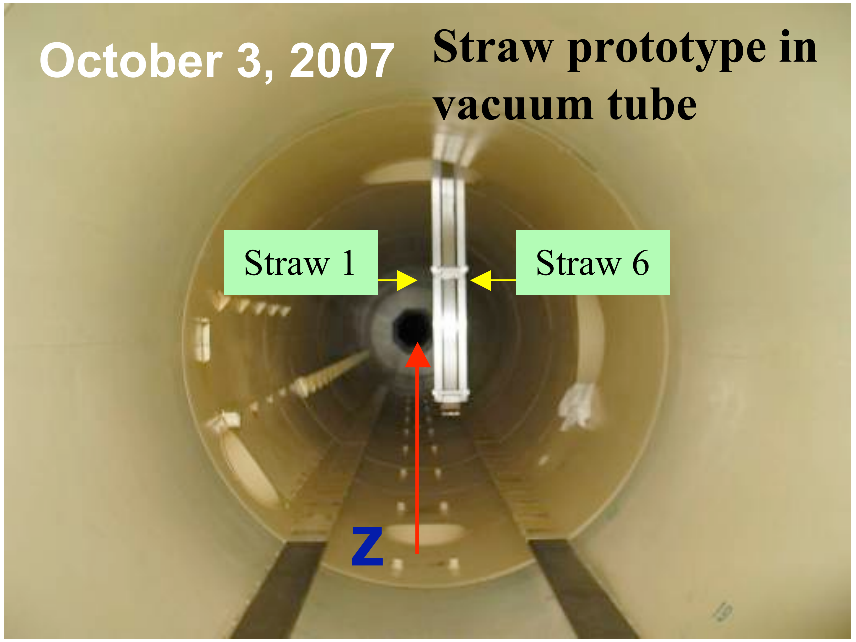
Spectrometer: R&D program

- Chosen technology: tube of mylar (25 μ m, D=1 cm, L=2.1 m)
- 100 straws (need 8000) produced in Dubna
- Tests on gas leakage (CO_2 80% + Isobutane 10% + CF_4 10%)
- Tests on tube expansion in vacuum
- Prototype assembled & cosmic ray tests

October 2007:
Prototype integration in NA48 set-up and test on beam



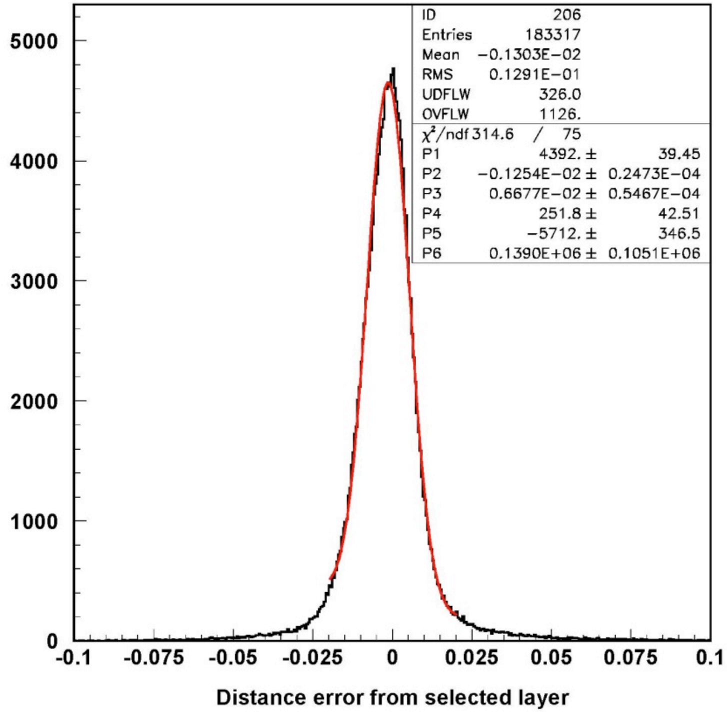




Spectrometer Test 2007: Aluminum straws (preliminary)

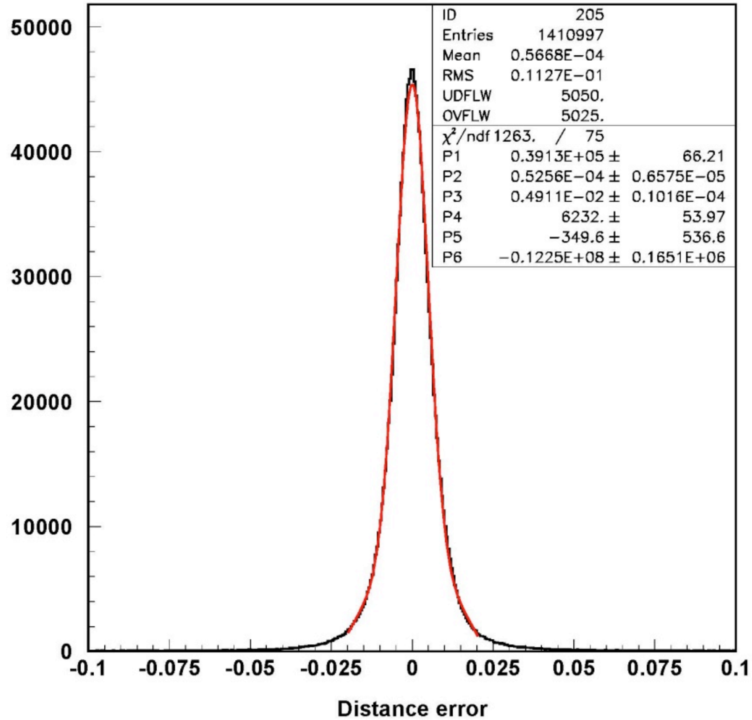
Data were collected with hadron, muon and kaon decays

Resolution



R.M.S.=130 μm
sigma=67 μm

Residuals



R.M.S.=113 μm
sigma=49 μm

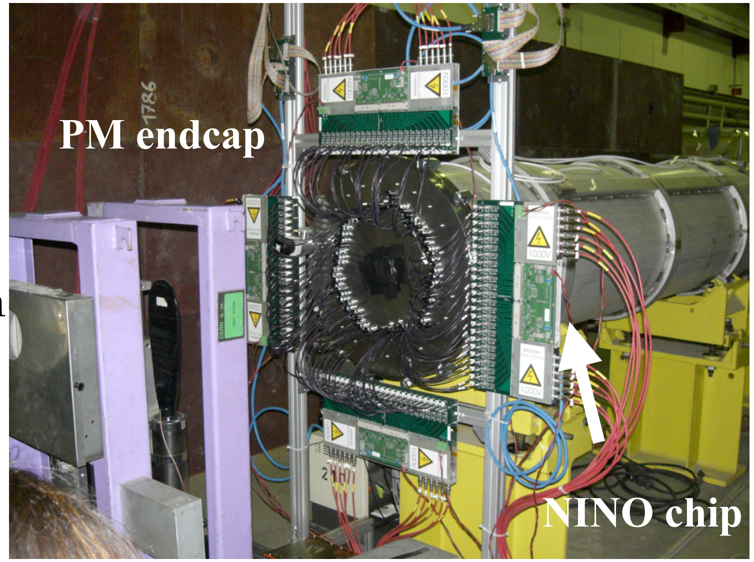
RICH: R&D program

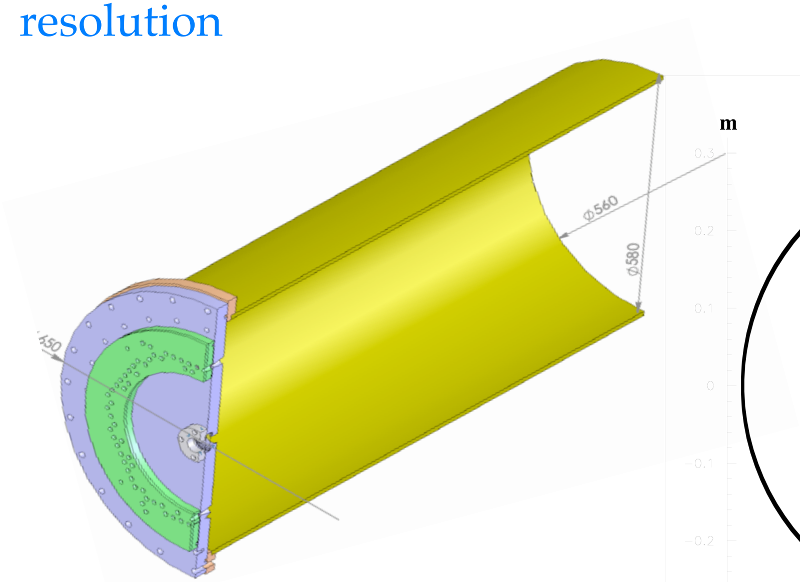
Design, construction and test of a RICH prototype (CERN, Firenze, Perugia)

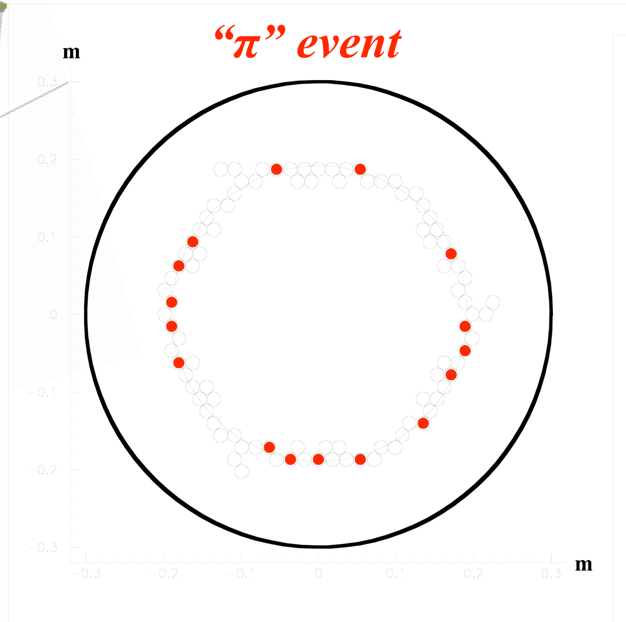
- Full length prototype (17 m, 0.6 m diameter, stainless steel tube at CERN) tested in 2007:

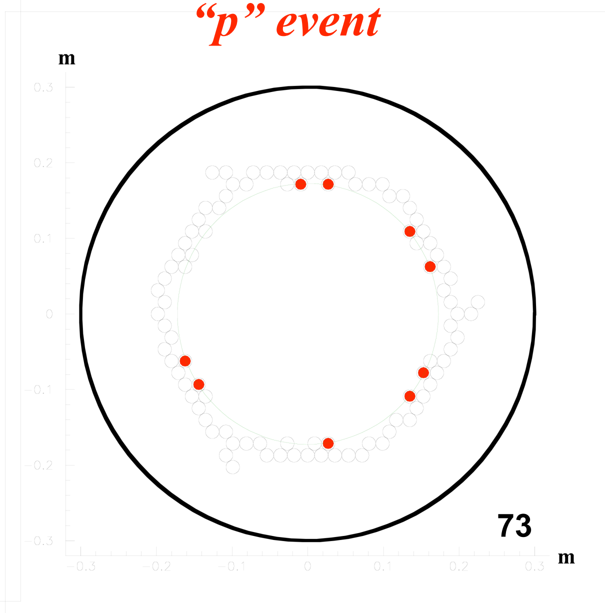
integration in the NA48 set up

- Endcap with 96 Hamamatsu PMs readout through Winston's cones
- PMs tested at SPS (2006) and Firenze/Perugia (with laser) – Hamamatsu R7400-U
- Measured FWHM per single γ per phototube 380ps (150 ps electronics and 110 ps laser included)
- PM size is the main limitation to Cerenkov angle resolution

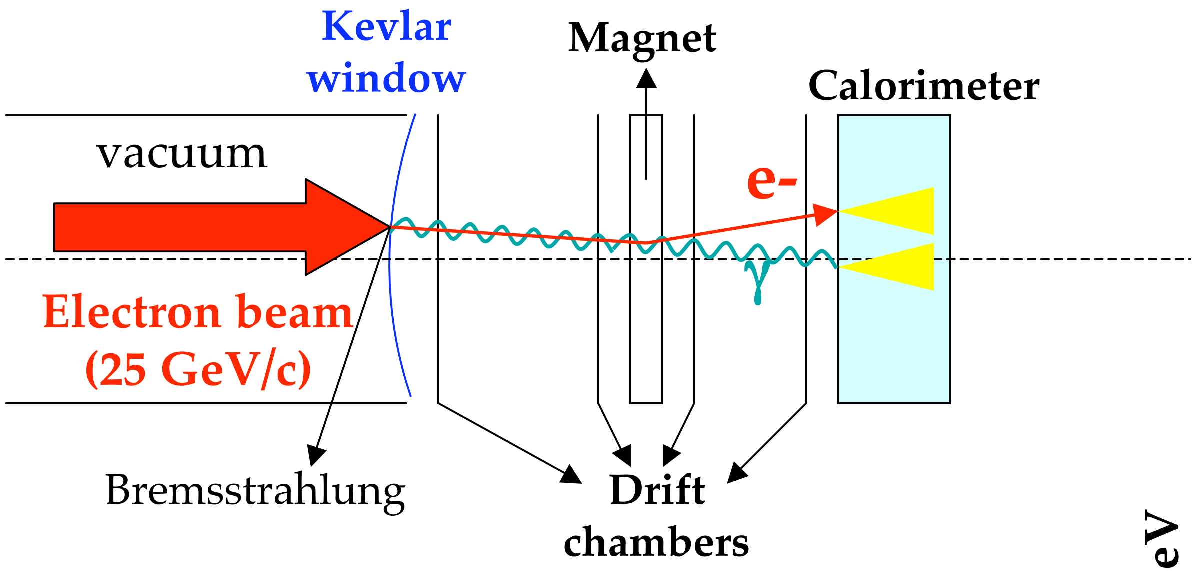




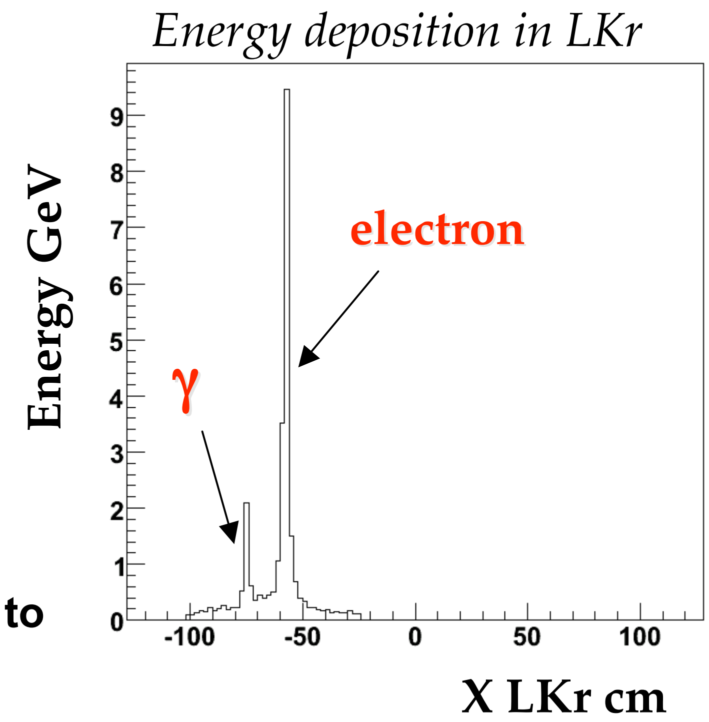




Liquid Kripton Calorimeter



October 2006 test:
Tagged photon beam
Using the existing NA48 setup



- 2×10^{8} electrons collected
- 10^{-5} ineff.sensitivity below 10 GeV

- Consolidation of the readout
- **Custom boards (FPGA based) sending data directly to PC Farm**
- **Test of the new electronics in 2007 NA48 run**

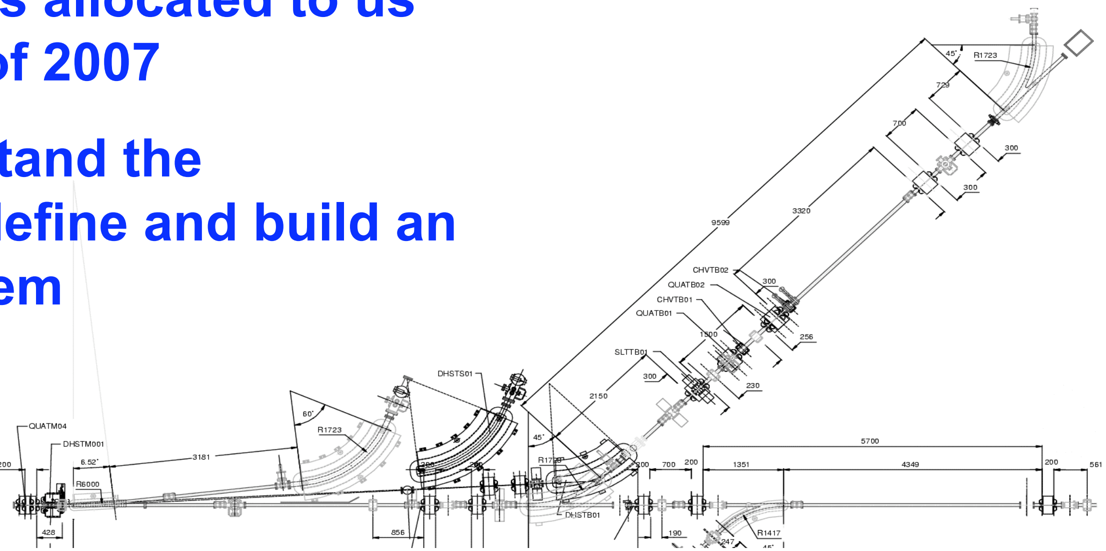
Large Angle Photon Vetoes (LAV) BTF setup

Prototypes tested at the Beam Test Facility in Frascati

The BTF can provide single electrons and positrons at 50Hz rate with an energy 100 MeV< E_e <750 MeV

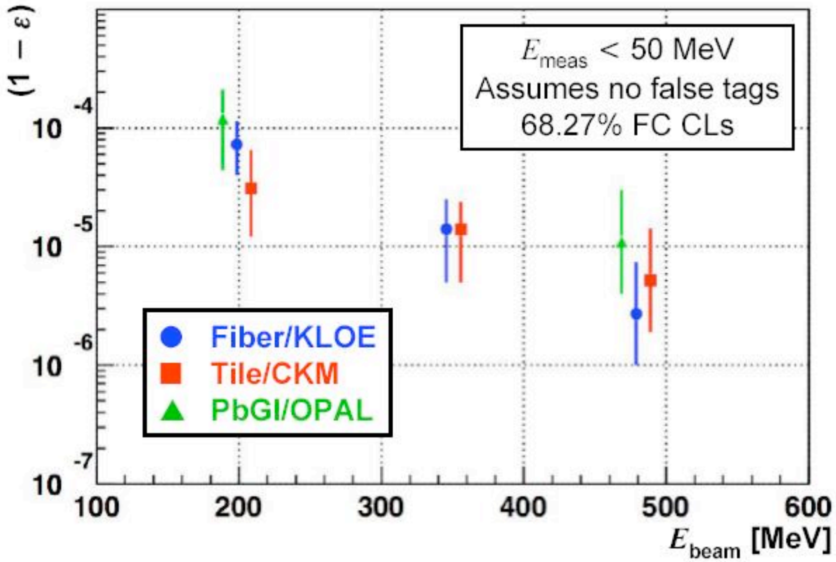
Several beam periods allocated to us during the first half of 2007

Hard work to understand the background and to define and build an efficient trigger system



All LAV options satisfy the requirements

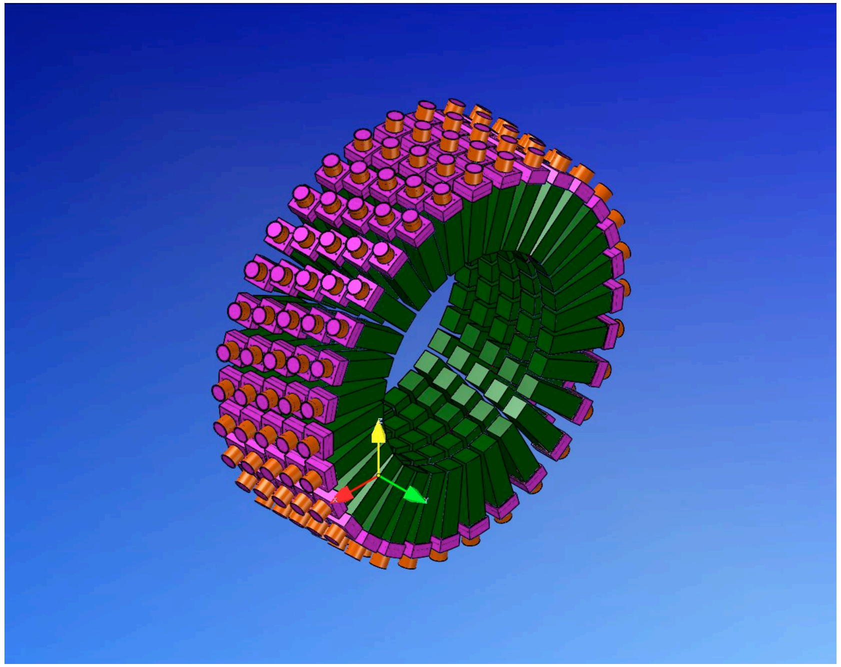
Efficiencies for electron detection similar for all 3 technologies



Tile (CKM) and lead glass (OPAL) results are preliminary

With inefficiency at this level, the LAV contribution to the average inefficiency is $0.2 \cdot 10^{-8}$

Baseline Choice: OPAL Lead-Glass



- **During the 2007 run we have exposed a few Lead-Glass blocks to radiation doses similar to those expected during the experiment lifetime.**
- **No radiation damage was measured**

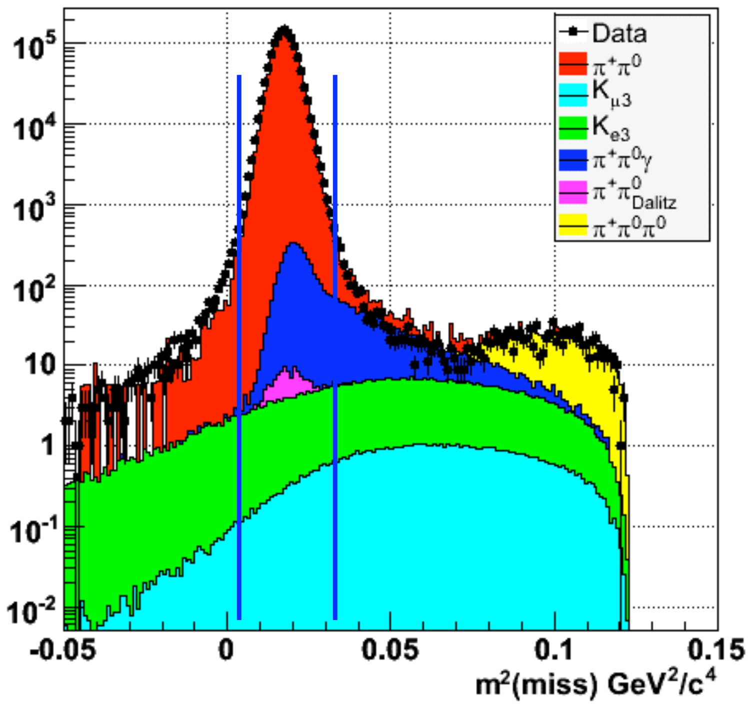
Test of a set of OPAL LG in Naples

LKr inefficiency measured with data

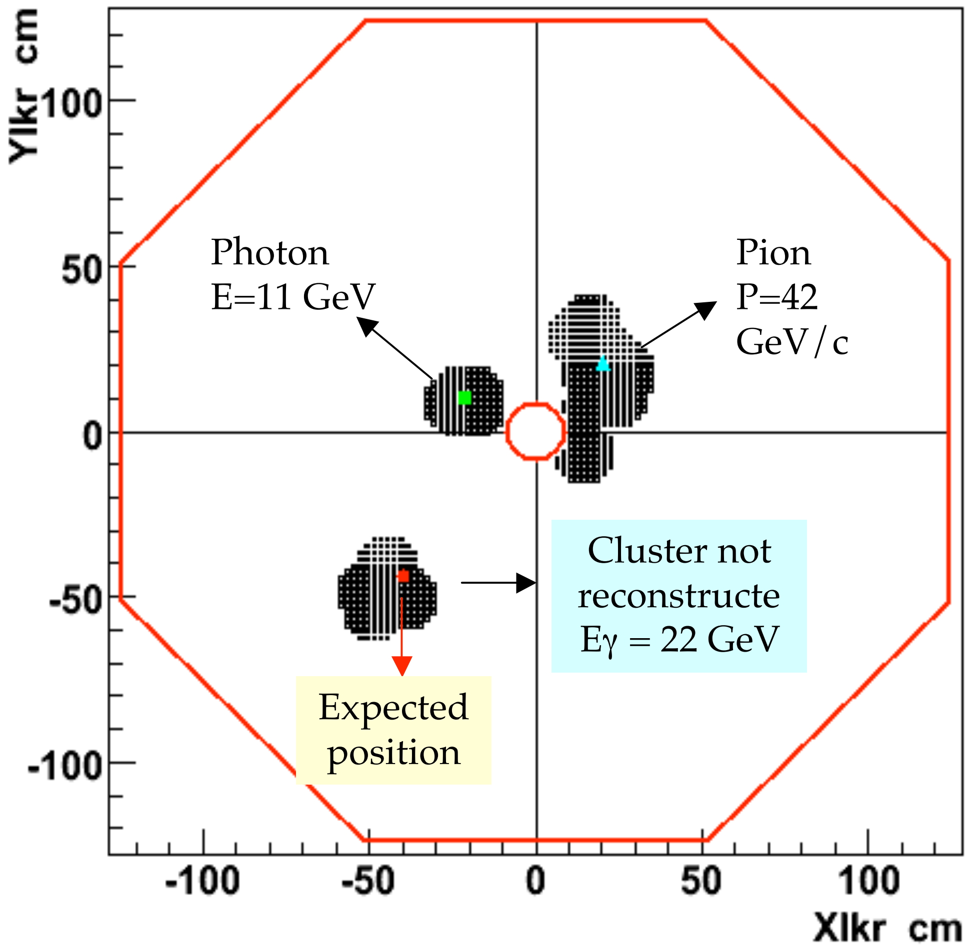
LKr ineff. per γ (E_γ > 10 GeV):

$\eta \sim 7 \times 10^{-6}$ **(preliminary)**

$K^+ \rightarrow \pi^+ \pi^0$ **selected kinematically**



π^+ **track and lower energy** γ **are use to predict the position of the other** γ



Detector Status (I)

Detector	Function	Status	Current Collaboration
CEDAR	▪Event by event K^+ identification (50 MHz)	▪CEDAR Exists ▪To be modified for H_2 ▪Needs New Front end ▪Needs New Read – out	Birmingham interest
GTK	▪Gigatracker for beam tracking ▪Three Stations of Si μpixels 300 x 300 μm ▪~200 ps per station time resolution ▪0.5 % radiation length per station ▪800 MHz beam	▪Sensor qualified after irradiation ▪0.13 μm CMOS front end blocks under test ▪Next step: 8 x 8 pixel array (bump bonded to R/O chip)	CERN Ferrara Torino
LAV	▪12 Ring Calorimeters for photon detection ▪Three different technologies tested ▪Chosen solution: OPAL lead glass	▪Performed prototype beam tests ▪Design of Mechanics under way	Frascati Pisa Roma 1 Naples
STRAW	▪4 Large (6 m^2) straw tracker stations to track ~10 MHz particles from kaon decays	▪Full length prototype beam tested inside actual vacuum tank	CERN Dubna Mainz

Detector Status (II)

Detector	Function	Status	Current Collaboration
RICH	▪Pion muon separation ▪17 m STP Ne radiator: $(n-1)\times 10^6=63$ ▪Spherical mirrors (r.c. 34 m) ▪~2000 Hamamatsu R7400 06 (18 mm ø) ▪Fast timing of the outgoing charged track	▪Full length prototype (96 PMT) tested Oct-Nov '07 ▪Timing demonstrated ▪400 PMT prototype to be tested in 2008	CERN Florence Merced Perugia San Luis Potosi George Mason Stanford
LKR	▪NA48 Liquid Krypton Calorimeter for forward photon. 20 tons of liquid krypton. Available!	▪Validated as veto ▪Cryogenics being consolidated ▪Electronics to be updated/replaced	CERN Pisa Roma II
MUD	▪Muon Detector based on the NA48 Hadron Calorimeter + iron and a fast veto plane for triggering	▪Sample tested this year	Protvino Moscow (INR)
IRC/SAC	▪Intermediate Ring and Small Angle Calorimeter to detect photons at small angle	▪Shashlik prototype (SAC) tested in 2006	Sofia INR

Updated Sensitivity vs. Proposal

Decay Mode	New layout	Proposal
Signal: $K^+ \to \pi^+ \nu\nu$ *[flux = 4.8×10¹² decay/year]*	55 *evt/year*	65 *evt/year*
$K^+ \to \pi^+ \pi^0$ $[\eta_{\pi 0} = 2\times10^{-8}$ (3.5×10^{-8})]	4.3% (7.5%)	4.2%
$K^+ \to \mu^+ \nu$	2.2%	1.9%
$K^+ \to e^+ \pi^+ \pi^- \nu$	≤3%	~3%
Other 3 – track decays	≤1.5%	~1.5%
$K^+ \to \pi^+ \pi^0 \gamma$	~2%	2%
$K^+ \to \mu^+ \nu\gamma$	~0.7%	0.7%
$K^+ \to e^+(\mu^+)\ \pi^0 \nu$, others	negligible	negligible
Expected background	≤13.5% (≤17%)	~13%

- The 15% acceptance reduction is offset by better immunity to Ke4 backgrounds and a more conservative layout of the straw tracker
- 3.5×10^{-8} π^0 ineff. allows for a 10 cm γ blindness around the π^+ in LKR

Conclusions on $K^+ \rightarrow \pi^+ \nu\nu$ Sensitivity

- More detailed simulation available
- Better understanding of the apparatus
- Detailed kinematical reconstruction
- **Slightly improvement in M^2_{miss} resolution**
  - 3 view-planes hit by a particle on average (instead of 4 as assumed in the Proposal)

- Study of the impact of the updated layout on the signal acceptance and 2-body background rejection:
- **Signal acceptance: 14.4%**
  - 17% (Proposal) → 14.4% (single spectrometer)
  - The number of events in the proposal (40/y@10^{-10} BR) assumed 10% overall efficiency
- **Background: ≤17%**
  - 13% (Proposal) → 13.5% because of the new configuration
  - 13.5% → 17% because of a more realistic treatment of photon rejection (assumption of a r=10 cm blind area around the π^+ LKR impact point)

Background rejection

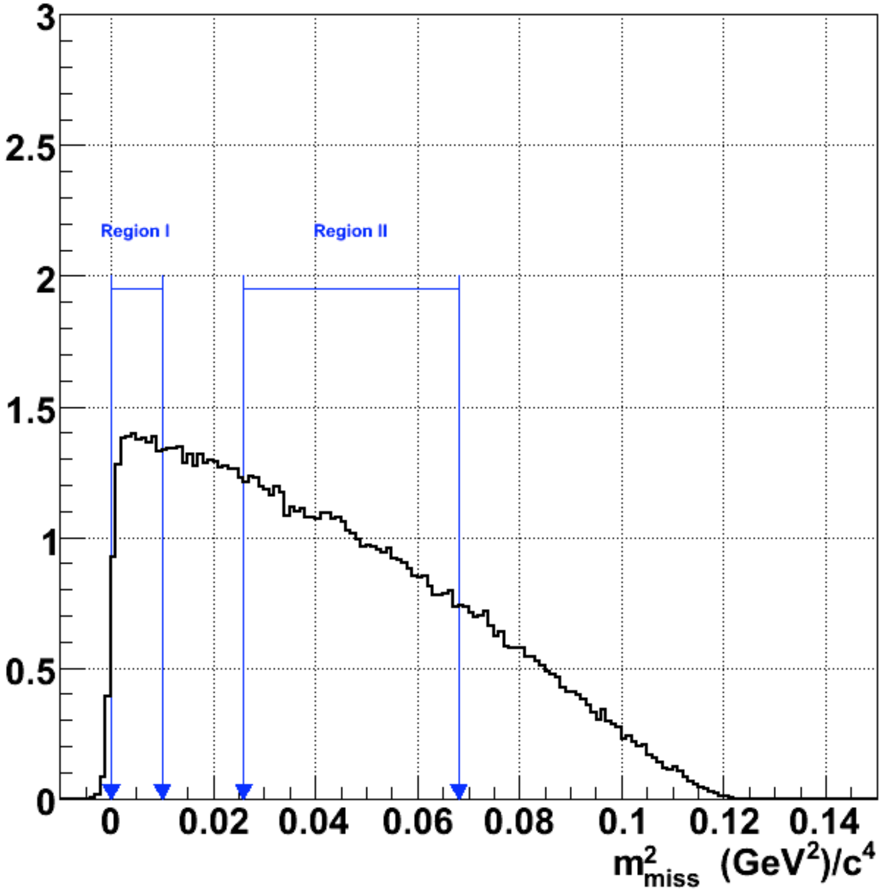
Kinematical rejection inefficiency (backgrounds kinematically-constrained)

- Sources:
  - Non-gaussian tails in M^2_{miss} → **Depends on spectrometer configuration**
    - High angle Multiple Scattering (ex. δ-rays)
    - Hadronic elastic scattering
    - Intrinsic limit since depends on the detector material (cannot be further reduced)
  - Wrong π-K matching → **Depends on σ(t) and σ(θ): similar or better wrt Proposal**
    - Beam rate
    - Beam resolution >> Gigatracker resolution
    - Gigatracker time resolution, CDA resolution
    - Can be controlled varying the beam rate

Photon rejection, μ rejection, particle ID inefficiencies

- Sources:
  - LKr inefficiency at high energy → **Better understanding wrt the Proposal**
  - Geometrical coverage of LAV → **Similar wrt the Proposal**
  - RICH performance → **Similar wrt the Proposal**
  - MUD performance → **Similar wrt the Proposal**

Signal acceptance



- Acceptance = 14.4%
  (3.5% Region 1, 10.9% Region 2)
- Tighter cut: cut on P_π
  (-50% of signal events rejected)
- -15% wrt the Proposal
  - Effect of the acceptance cut at RICH and LKr
  - Higher π dispersion since we use 1 magnet only
  - Long lever arm after the magnet for better hermeticity against decays with >1 charged particle

Signal acceptance

- Generation:
  - $K^+ \to \pi^+ \nu\nu$ decays generated with vector form factors
    - Small effect on the acceptance

- Selection:
  - 1 track reconstructed in gigatracker with good χ^2
  - 1 track reconstructed in straw spectrometer: hits with at least 2 views and good χ^2
  - 1 track in the RICH → particle-ID and timing
  - Downstream track in RICH, LKr, MUD acceptance → particle-ID
  - $5 < Z_{vertex} < 65$ m from the 3rd gigatracker station → definition of the fiducial region
  - CDA<0.8 cm (s(CDA)~0.1 cm) → against mis-reconstruction of the track slope
  - $P_\pi > 15$ GeV/c → π-threshold in RICH 13 GeV/c
  - $P_\pi < 35$ GeV/c → for $\pi^+\pi^0$ rejection purposes and better μ/π separation
  - Region 1: $0 < M^2_{miss} < 0.01$ GeV^2/c^4
  - Region 2: $0.026 < M^2_{miss} < 0.068$ GeV^2/c^4

Background rejection

Rejection of $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}$ and $K^{\pm}\rightarrow\mu^{\pm}\nu$:

- Geometrical acceptance (A_{geo}): 15% lower wrt the Proposal
- Kinematical rejection inefficiency (η_{kin}):
  - Effect of the non gaussian tails: $A_{geo}\times\eta_{kin} = 3\times10^{-5}$ ($K^{+}\rightarrow\pi^{+}\pi^{0}$), 0.31×10^{-5} ($K^{+}\rightarrow\mu^{+}\nu$)
    - η_{kin} re-evaluated with the new layout.
    - No redundancy on P measurement (resolution of P measurement from RICH too high).
  - Effect of wrong K-π matching : $A_{geo}\times\eta_{kin} = 8.5\times10^{-5}$ ($K^{+}\rightarrow\pi^{+}\pi^{0}$), 0.43×10^{-5} ($K^{+}\rightarrow\mu^{+}\nu$)
    - η_{kin} from the proposal
- π^{0} and μ rejection:
  - π^{0} rejection inefficiency:
    Intrinsic veto inefficiency of the LKr: 2×10^{-8} (number used in the Proposal)
    More realistic use of the LKr: 3.5×10^{-8}
  - μ detection inefficiency: 10^{-5} from MUD, $10^{-3}\div10^{-2}$ from RICH (as in the Proposal)

Other backgrounds:

- No other relevant dependence on the new layout expected
- Expected better coverage against decays with >1 charged particle in final state
- Analysis in progress

SPARES

$K^0_L \to \pi^0 e^+e^-$ ($\mu^+\mu^-$) in SM

- **Using the K_S measurements, the K_L BR can be predicted (extracting the short-distance physics contribution)**
- **Interference between short and long distance physics**

Constructive

$$B_{K^0_L \to \pi^0 e^+ e^-} = 3.7^{+1.1}_{-0.9} \times 10^{-11}$$

$$B_{K^0_L \to \pi^0 \mu^+ \mu^-} = 1.5^{+0.3}_{-0.3} \times 10^{-11}$$

now favored by two independent analyses

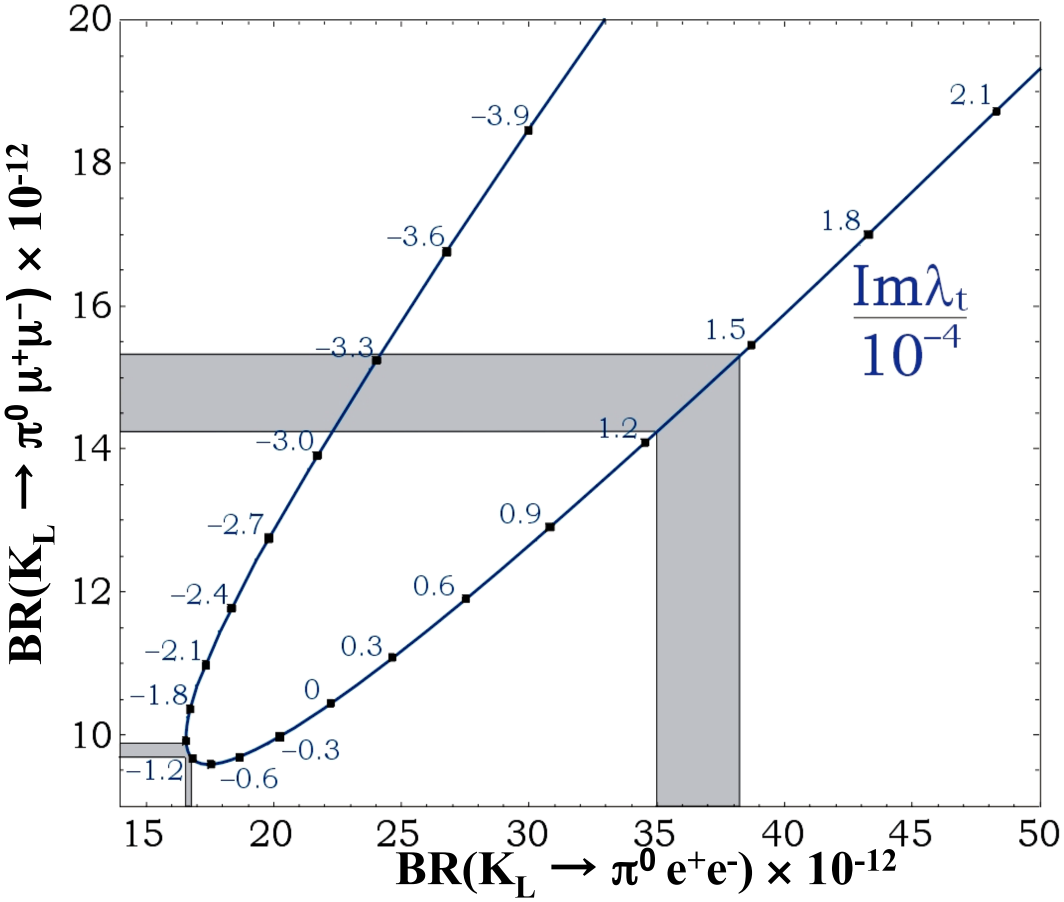
(nucl.phy.B 672,387 - hep-ph/0404136)

Destructive

$$B_{K^0_L \to \pi^0 e^+ e^-} = 1.7^{+0.7}_{-0.6} \times 10^{-11}$$

$$B_{K^0_L \to \pi^0 \mu^+ \mu^-} = 1.0^{+0.2}_{-0.2} \times 10^{-11}$$

$\lambda_t = V_{td}V^*_{ts}$



BR(K_L → π^0 ee) < 2.8 × 10^{-10} @90%CL *KTeV* **PRL93, 021805 (2004)**

BR(K_L → π^0 μμ) < 3.8 × 10^{-10} @90%CL *KTeV* **PRL86, 5425 (2001)**

- **Sensitivity to New Physics : clean probe up to Λ~100 TeV scale**
- **Two possible scenarios:**

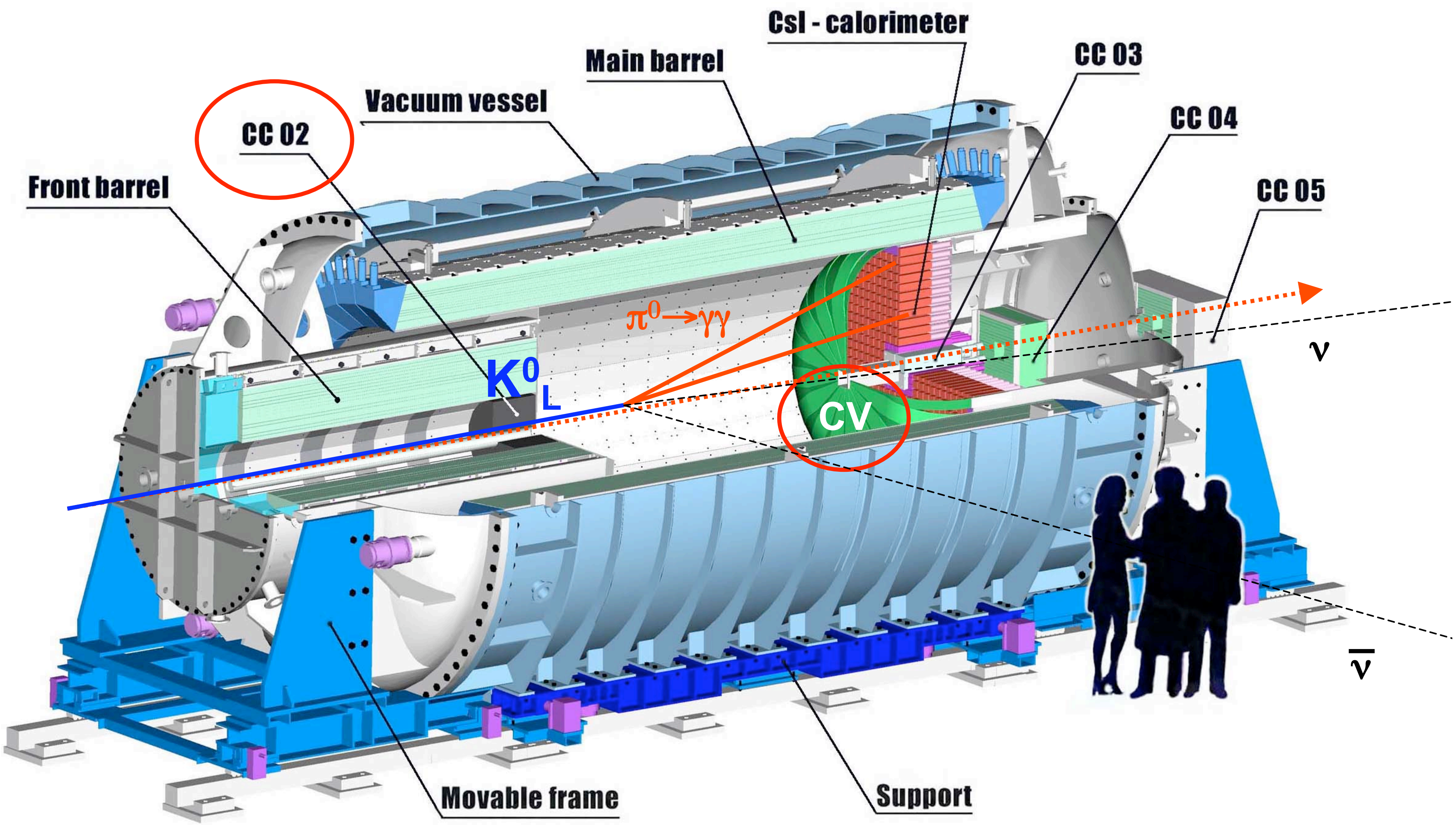
<u>Minimal Flavour Violation (MFV)</u>

- **Flavour and CP violation governed by universal CKM matrix**
  - **No Extra Complex Phases**
- **Same operators as in SM effective Hamiltonian**
- **Different coefficients**
- **Stringent correlation for FCNC predictions with B rare decays**

<u>New sources of Flavour Symmetry Breaking ~ TeV scale</u>

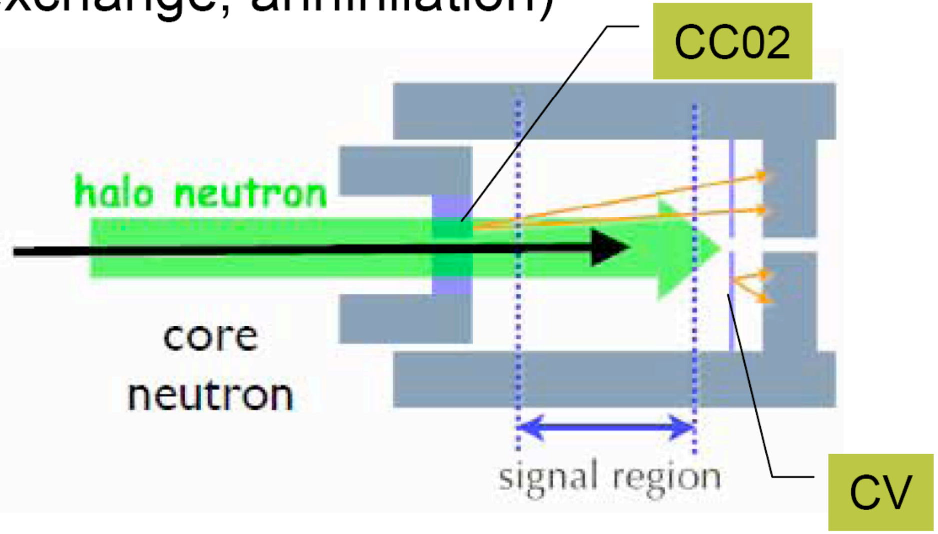
- **Minimal Supersymmetric extension of SM (MSSM)**
- **Extra Phases can lead to large deviations from SM predictions, especially for the CP-Violating modes**

State of the art: KEK E391a



E391a: technique

- Kaon Decay
  - $K_L \rightarrow \pi^0\pi^0$ (2γ missed; due to inefficiency or fusion)
  - $K_L \rightarrow \pi^+\pi^-\pi^0$ (2 charged pion missed)
  - $K_L \rightarrow \pi^- e^+ \nu$ (charge exchange, annihilation)
- Halo neutron
  - Interact with "CC02","CV"
  - Produce π^0, η

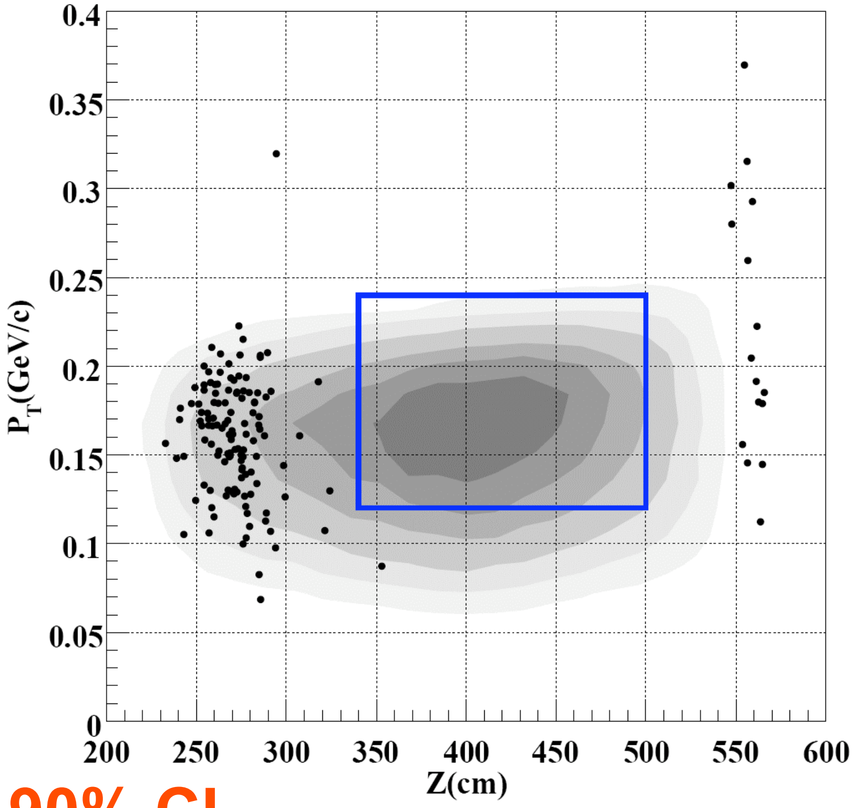


Slide from T. Nomura

E391a: Run II

PRL 100, 201802 (2008) [arXiv:0712.4164]

Background Source	Estimated # BG
$K^0_L \to \pi^0\,\pi^0$	0.11 ± 0.09
CC02	0.16 ± 0.05
CV	0.08 ± 0.04
CV-η	0.06 ± 0.02
Total	**0.41± 0.11**

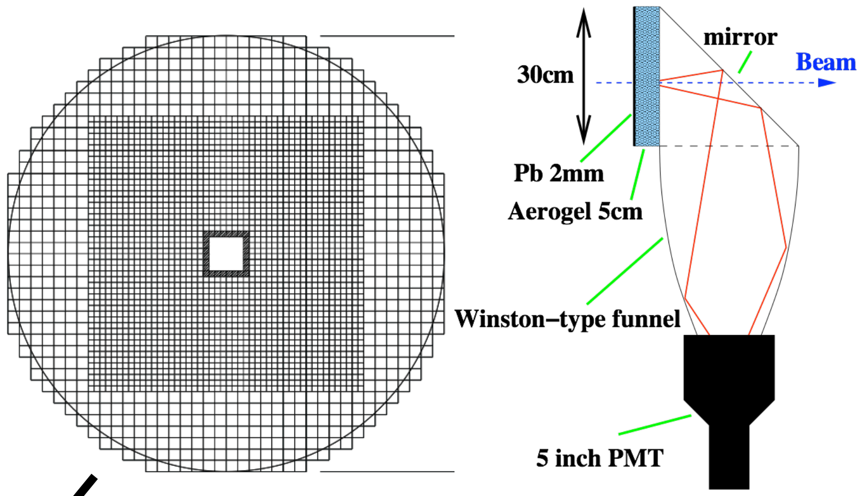


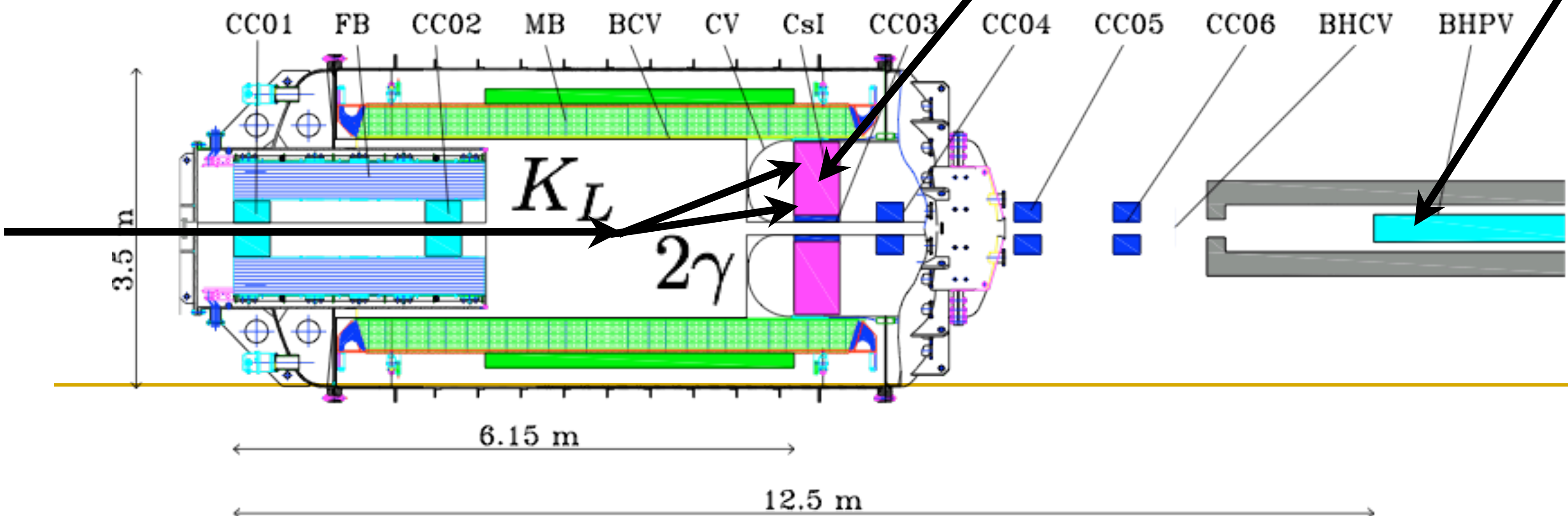
$BR(K^0_L \to \pi^0\,\nu\nu) < 6.7 \times 10^{-8}$ 90% CL

Improvement by about a factor of three w.r.t. previous best limit

Upgrades for E14 (J-Parc Step 1)

- CsI calorimeter with a finer granularity
- New photon veto in the beam
- Waveform digitization for higher rates





E14@J-PARC Stage 1

- 3 snowmass years
- "KL alone" beamline

(KL yield based on GEANT4/QGSP)

		standard cuts	CsI cluster shape cut	acceptance loss (50%)
Signal	$K_L \to \pi^0 \nu \overline{\nu}$	6.0 ± 0.1	5.4 ± 0.1	2.70 ± 0.05
K_L BG	$K_L \to \pi^0 \pi^0$	3.7 ± 0.2	3.3 ± 0.2	1.7 ± 0.1
	$K_L \to \pi^+ \pi^- \pi^0$	0.18 ± 0.08	0.16 ± 0.07	0.08 ± 0.04
	$K_L \to \pi^- e^+ \nu_e$	0.13 ± 0.01	0.03 ± 0.003	0.02 ± 0.001
halo n BG	CV	—	—	0.08
	η	8.1	0.6	0.3

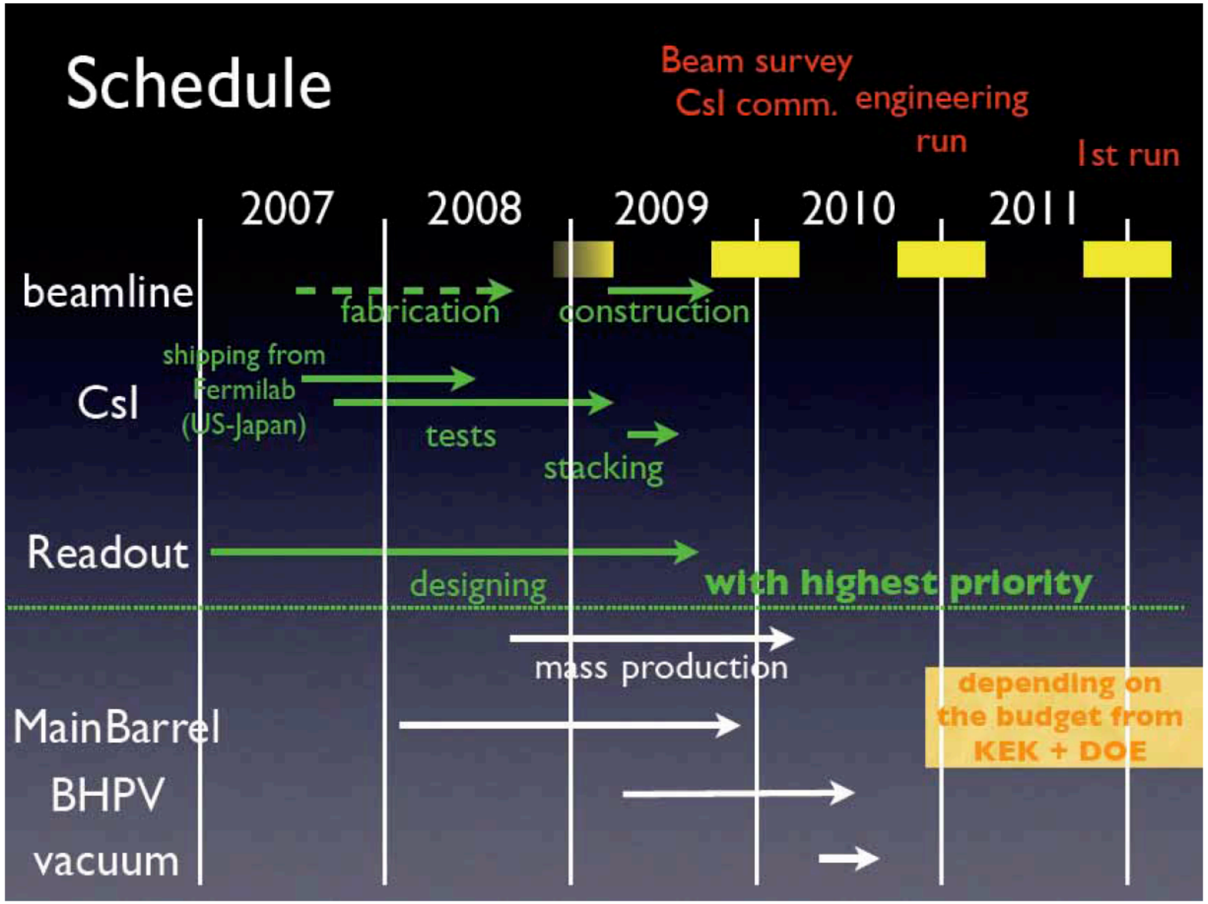
Note:
Detailed simulation of CV/CC02 BG in progress

Slide from T. Nomura

Status of E14

- **Stage I Approved**
- **Recommended for stage II approval by J-PARC PAC**
- **Significant resources already secured**

Schedule from T. Nomura



$K_L \to \pi^0 \nu\nu$ Long Time Prospects