J-PARC実験:
K中間子崩壊による
レプトン・ユニバーサリティの破れの探索

KEK, IPNS
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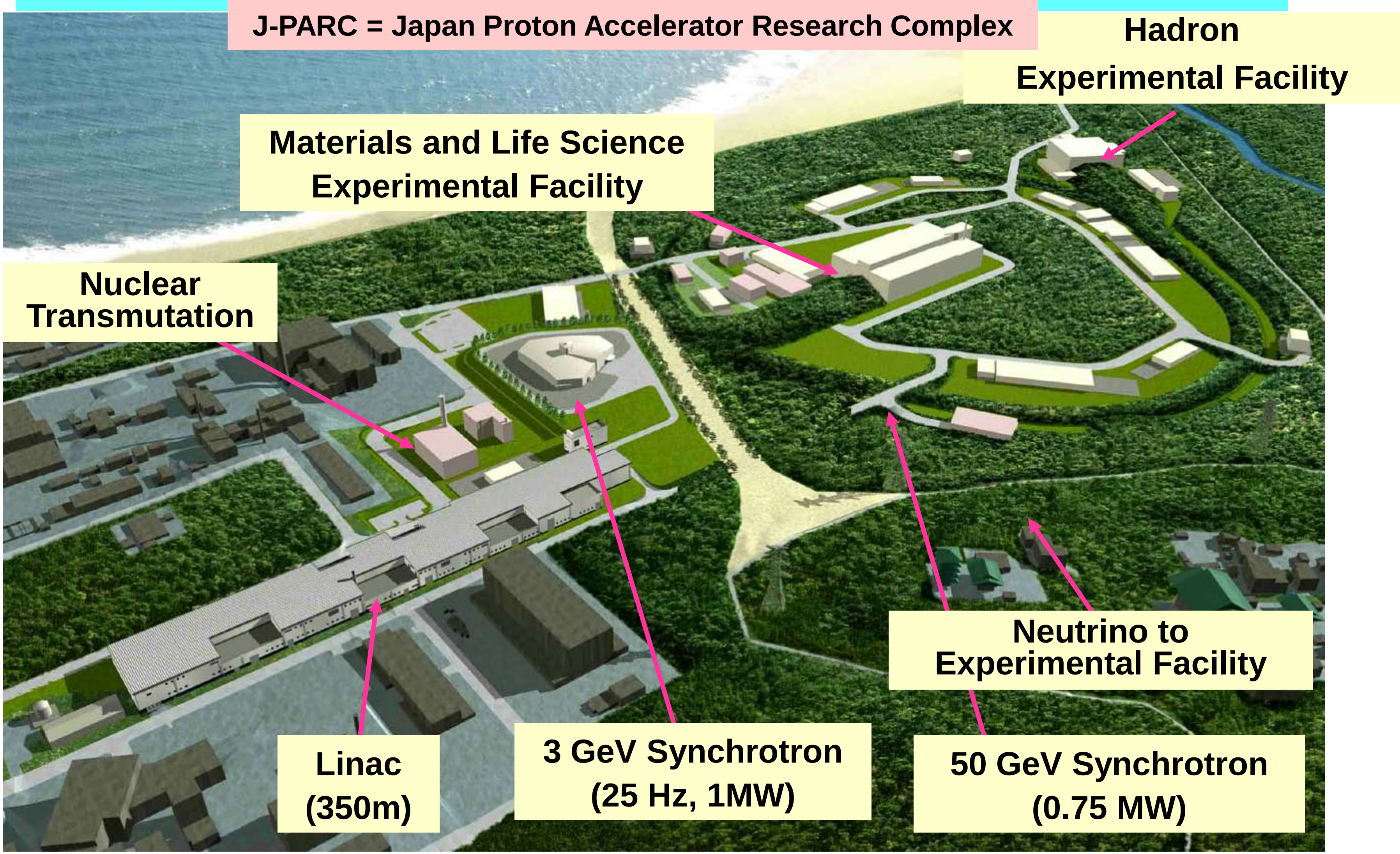
東京大学 ICEPP セミナー

話の内容

1. J-PARC と TREK実験
2. レプトン普遍性(LU)の破れ
3. LUの破れの探索 実験 (P36)
   - これまでのリミットとP36の目標感度
   - TREK測定器
   - 系統誤差の評価
   - 重いニュートリノ探索
4. ビームライン、測定器R&D
5. まとめ

J-PARC と TREK実験

J-PARC Facility

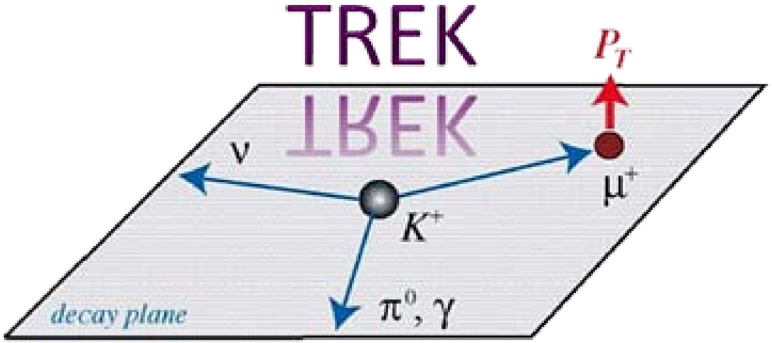


Currently, 190 kW for FX and 6 kW for SX

TREK (J-PARC E06)

Time Reversal Experiment with Kaons:

Search for New Physics beyond the Standard Model by Measurement of T-violating Transverse Muon Polarization (P_T) in $K^+ \rightarrow \mu^+\pi^0\nu$ Decays



$K^+ \rightarrow \mu^+\pi^0\nu$

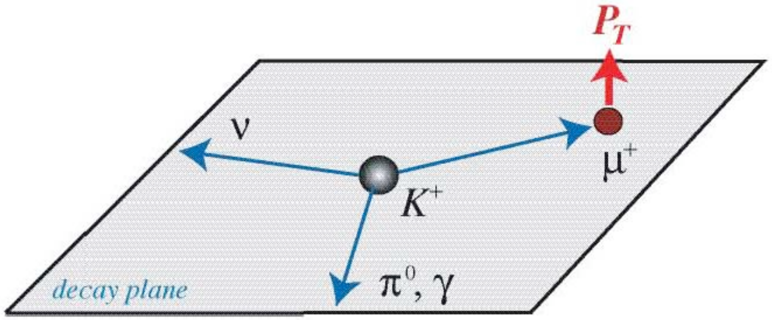
Official website:

http://trek.kek.jp

Transverse μ^+ polarization (P_T) in $K_{\mu 3}$

$K^+ \to \pi^0 \mu^+ \nu$ decay

$$P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|(p_{\pi^0,\gamma} \times p_{\mu^+})|}$$



- P_T is T-odd, and spurious effects from final state interaction are small: $P_T(\text{FSI}) < 10^{-5}$

  Non-zero P_T is a signature of T violation.

- Standard Model (SM) contribution to P_T: $P_T(\text{SM}) < 10^{-7}$

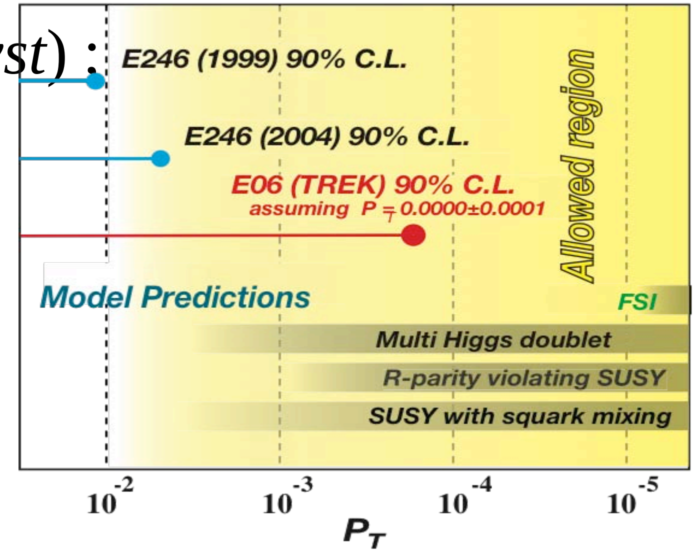
> *P_T in the range $10^{-3} \sim 10^{-4}$ is a sensitive probe of CP violation beyond the SM.*

- There are theoretical models of new physics which allow a sizable P_T without conflicting with other experimental constraints.

Sensitivity of E06

Current limit from E246 :

•P_T = - 0.0017 ± 0.0023(*stat*) ± 0.0011(*syst*) ;
($|P_T| < 0.0050$: 90% *C.L.*)



Sensitivity goal :

$\delta P_T \sim 10^{-4}$

(1.4×10^7 sec)

- J-PARC full beam power of 270 kW is necessary for the E06 TREK experiment : ==> Future experiment
- A possible experiment at 30 kW with the TREK detector sub-system :

Search for Lepton Universality Violation

TREK collaboration

• Canada	U. Saskatchewan
	TRIUMF
	UBC
	U. Montreal
	U. Manitoba
• USA	Hampton U.
	U. South Carolina
	Iowa State U.
• Russia	INR
• Vietnam	National Science U.
• Japan	KEK
	Tohoku U.
	Osaka U.
	TITech

レプトン普遍性(LU)の破れ

Lepton universality

- Standard Model:
  - Three generations for quarks and leptons
  - Leptons: *e*, μ, and τ

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

  - Different masses but same gauge couplings
  - Up to now, it is valid experimentally

Lepton Universality

- Why are the weak couplings of *e*, *μ*, and *τ* nearly equal?
- Even a small difference would signal a profound discovery : → ***Necessity of experimental efforts***

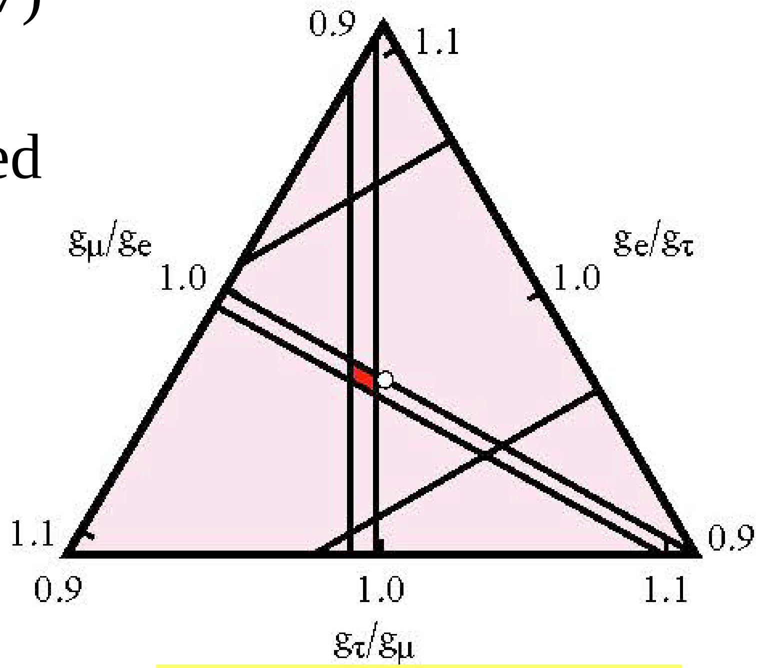
Limits of universality

by J.R.Patterson
1995

$g_\mu/g_e = 1.0012 \pm 0.0015$ (1997)

- μ-e universality has been well established
- Recent development of τ spectroscopy
  - τ_τ, m_τ, $\tau_\tau/\tau_\mu = (m_\tau/m_\mu)^5(g_\tau/g_\mu)^2$
  - τ Michel parameters
  - Couplings to W and Z^0

  g_τ/g_μ = 1.0003 +/- 0.0029 (1997)



Universality Triangle

No evidence yet for universality violation ?

Recent data on LU

- Summary by A. Pich [arXiv:1201.0 537v1 [hep-ph] (2012)

	$\Gamma_{\tau\to\nu_\tau e\bar\nu_e}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{\tau\to\nu_\tau\pi}/\Gamma_{\pi\to\mu\bar\nu_\mu}$	$\Gamma_{\tau\to\nu_\tau K}/\Gamma_{K\to\mu\bar\nu_\mu}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to\mu\bar\nu_\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0007 ± 0.0022	0.992 ± 0.004	0.982 ± 0.008	1.032 ± 0.012
	$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\tau\to\nu_\tau e\bar\nu_e}$	$\Gamma_{\pi\to\mu\bar\nu_\mu}/\Gamma_{\pi\to e\bar\nu_e}$	$\Gamma_{K\to\mu\bar\nu_\mu}/\Gamma_{K\to e\bar\nu_e}$	$\Gamma_{K\to\pi\mu\bar\nu_\mu}/\Gamma_{K\to\pi e\bar\nu_e}$
$\lvert g_\mu/g_e\rvert$	1.0018 ± 0.0014	1.0021 ± 0.0016	0.998 ± 0.002	1.001 ± 0.002
	$\Gamma_{W\to\mu\bar\nu_\mu}/\Gamma_{W\to e\bar\nu_e}$		$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to e\bar\nu_e}$
$\lvert g_\mu/g_e\rvert$	0.991 ± 0.009	$\lvert g_\tau/g_e\rvert$	1.0016 ± 0.0021	1.023 ± 0.011

- LEP-II :

$$R^W_{\tau\ell} = \frac{2\,\mathrm{BR}\,(W\to\tau\,\overline{\nu}_\tau)}{\mathrm{BR}\,(W\to e\,\overline{\nu}_e)+\mathrm{BR}\,(W\to\mu\,\overline{\nu}_\mu)} = 1.055(23)$$

2.4 σ deviation

- BABAR :

Evidence for an excess of $\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau$ decays

[Phys. Rev. D 82, 072005 (2010)]

$$\mathcal{R}(D^{(*)}) = \mathcal{B}(\overline{B}\to D^{(*)}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}\to D^{(*)}\ell^-\overline{\nu}_\ell)$$

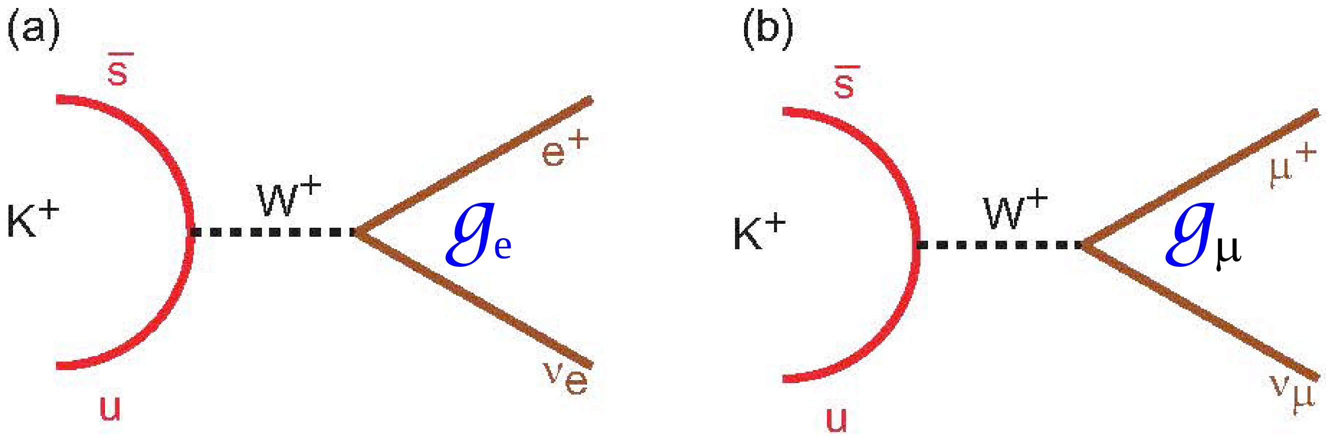
3.5 σ deviation

High precision test of g_μ/g_e is still important

Universality test by K_{l2} decays

Typical test in particle decay at low energy

$K \rightarrow e\nu$ $K \rightarrow \mu\nu$



$$\Gamma(K_{l2}) = g_l^{\,2}\,(G^2/8\pi)\, f_K^{\,2} m_K m_{l2}\, \{1-(m_l^{\,2}/m_K^{\,2}\}^2$$

$$g_e = g_\mu\ ?$$

K_{l2} decays in the SM

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r)$$

helicity suppression

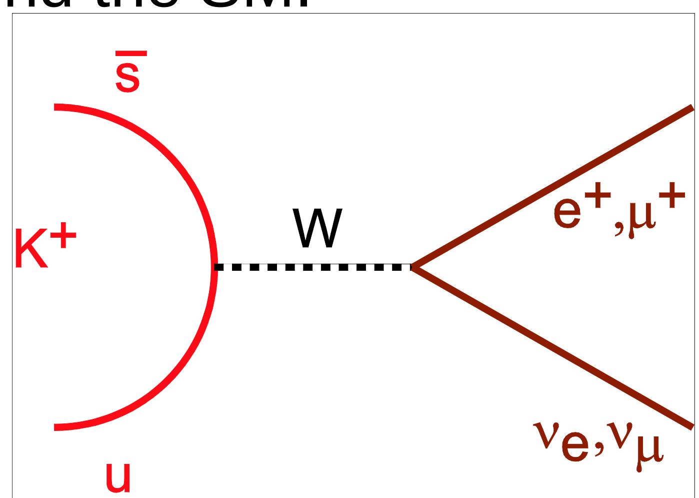
radiative correction (Internal Brems.)

Standard Model:

- By forming ratio of the $\Gamma(K_{e2})$ to the $\Gamma(K_{\mu 2})$, hadronic form factors are cancelled out and the R_K^{SM} is highly precise.
- Strong helicity suppression of the electronic channel enhances sensitivity to effects beyond the SM.

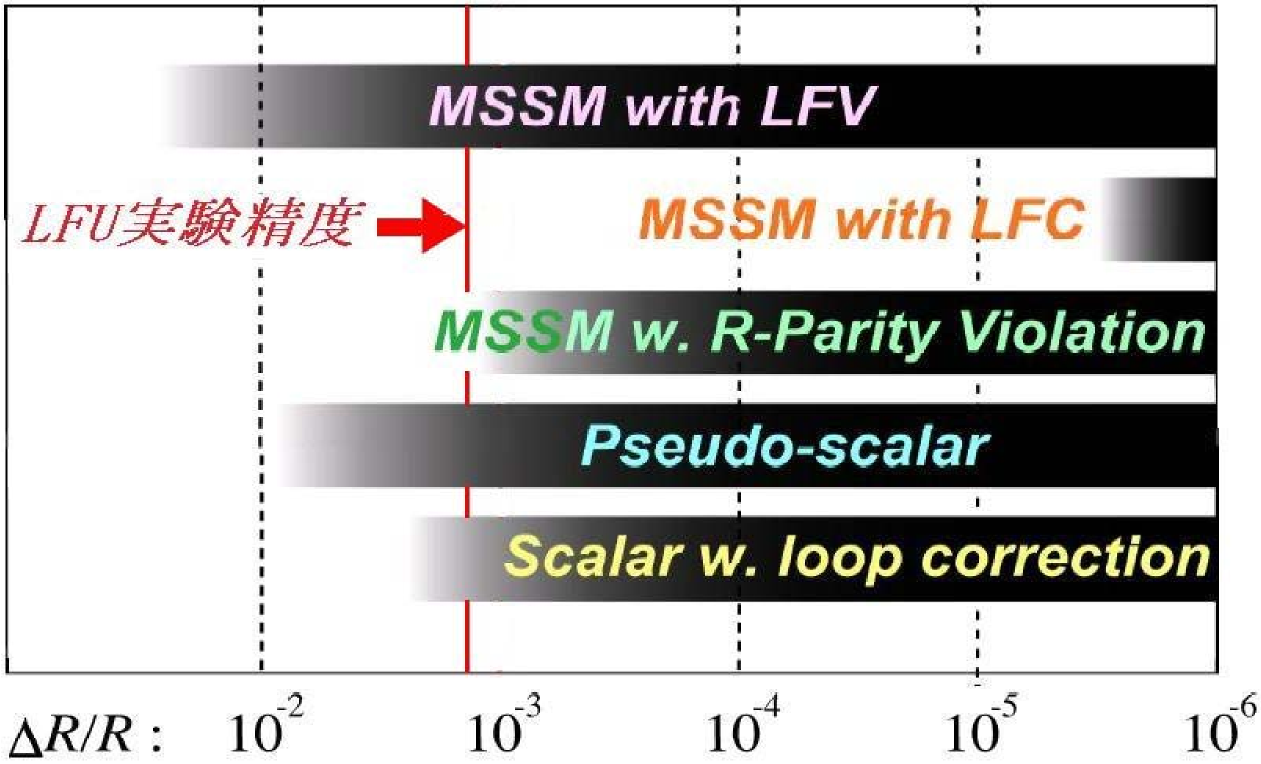
$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Uncertainty is $\Delta R_K/R_K \sim 0.04\%$



K_{l2} decay beyond the SM

$$R = \frac{\Gamma(e^{+}\nu)}{\Gamma(\mu^{+}\nu)} = R_{SM} + \Delta R_{NP}$$



$$g_e / g_\mu = (R / R_{SM})^{1/2}$$

MSSM with LFV

Contribution from MSSM

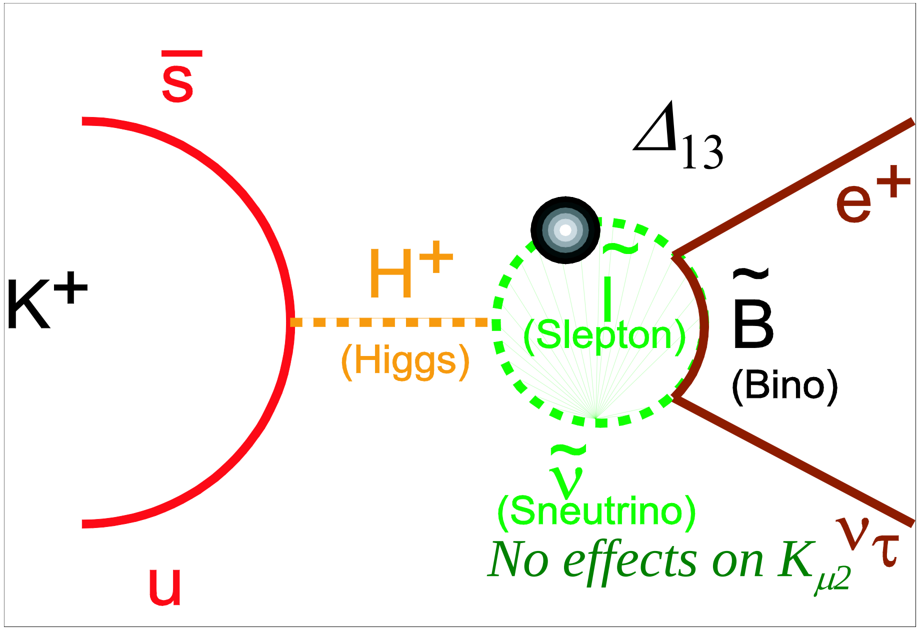
- A charged Higgs-mediated SUSY LFV contribution to K_{e2} can be strongly enhanced by emitting a τ neutrino.

$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{M_{H+}^4}\cdot\frac{m_\tau^2}{m_e^2}\Delta_{13}^2\tan^6\beta\right)$$

Effects in pion decay is suppressed by a factor $(m_\pi/m_K)^4 \sim 6\times10^{-3}$

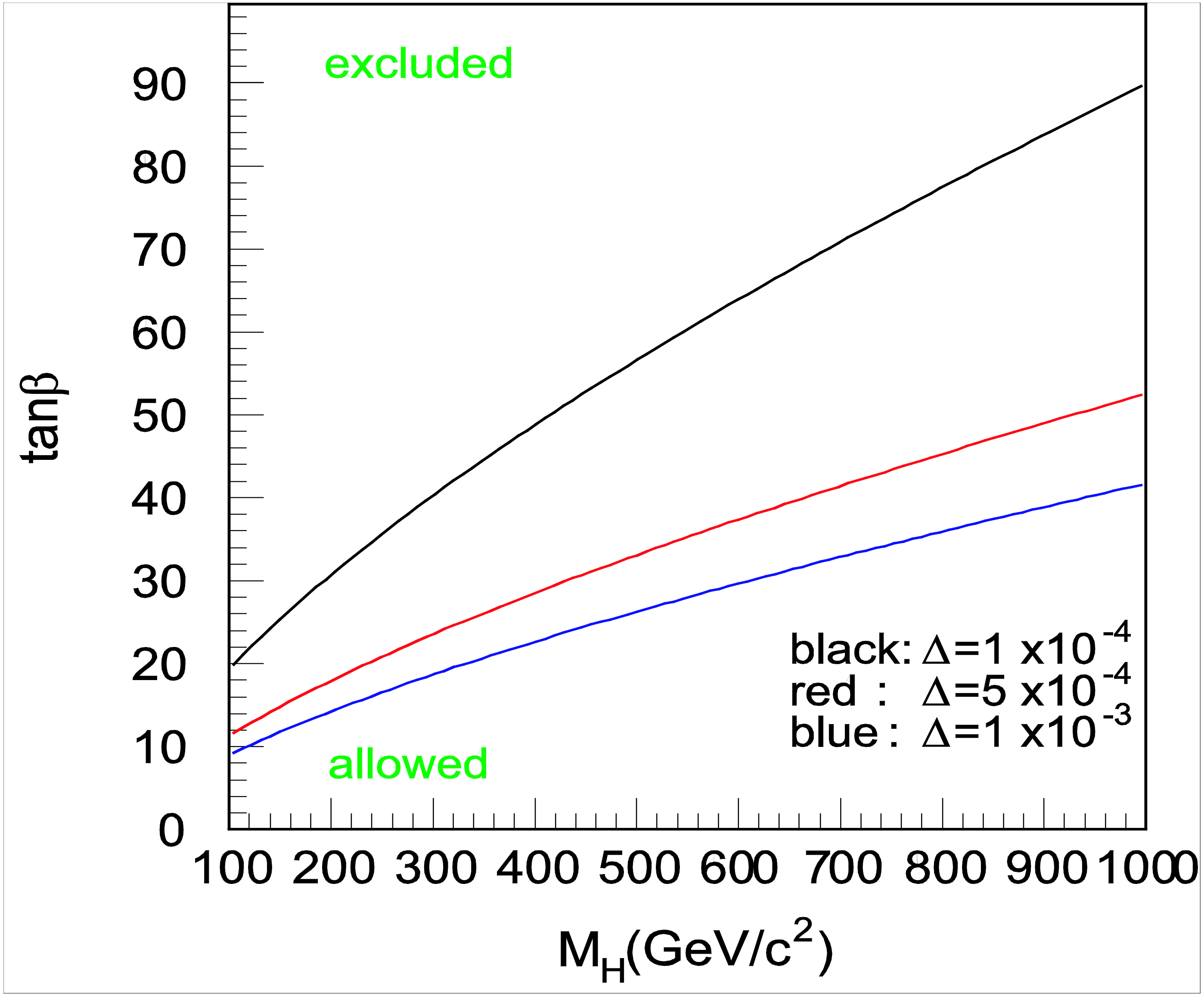
Using
$\Delta_{13}=5\times10^{-4}$, $\tan\beta=40$,
$M_H=500\,\mathrm{GeV}/c^2$

$R_K^{LFV}=R_K^{SM}(1\pm0.013)$



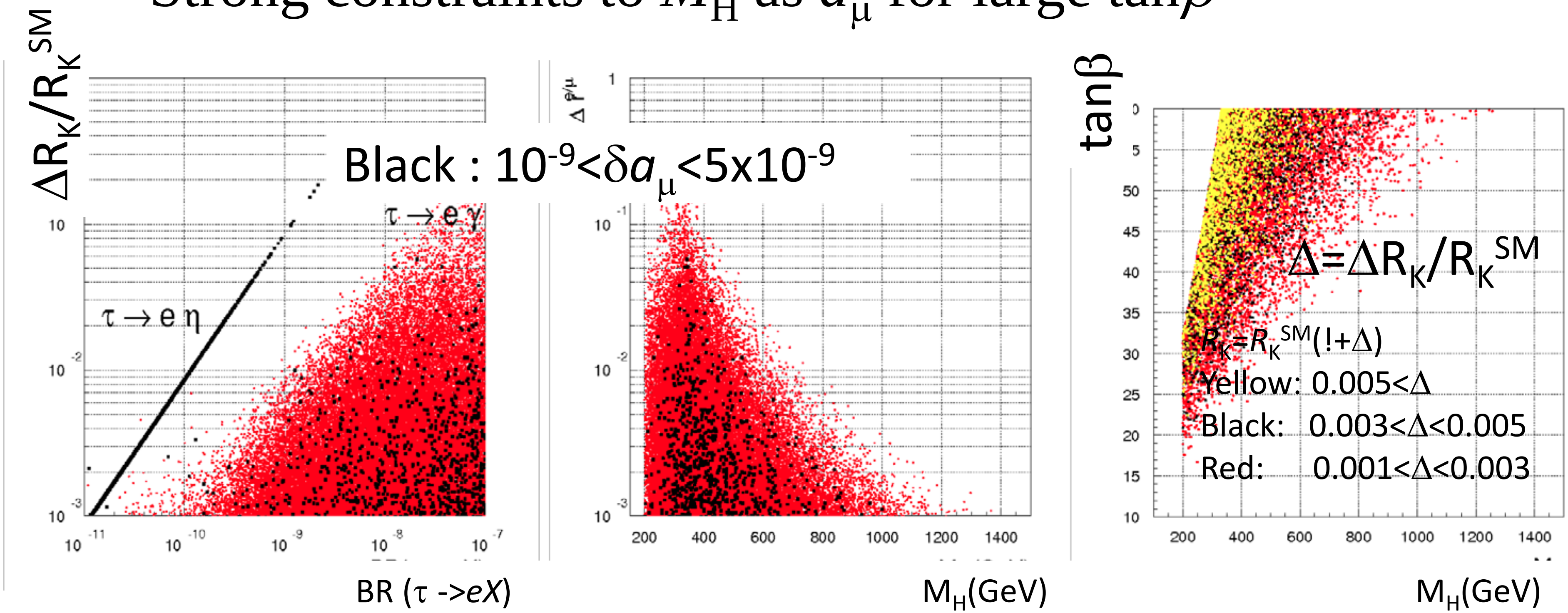
No effects on $K_{\mu2}$

SUSY with LFV



Comparison with LFV in τ decay

- LFV effect may be found in ΔR_K
- $\Delta R_K/R_K \approx 1\%$ corresponds to $Br\ (\tau \to eX\ ) \leq 10^{-10}$
  - Strong correlation to $Br\ (\ \tau \to e\eta\ )$
  - Additive to R_K^{SM} (no interference: $R_K > R_K^{SM}$)
- Strong constraints to M_H as a_μ for large tanβ

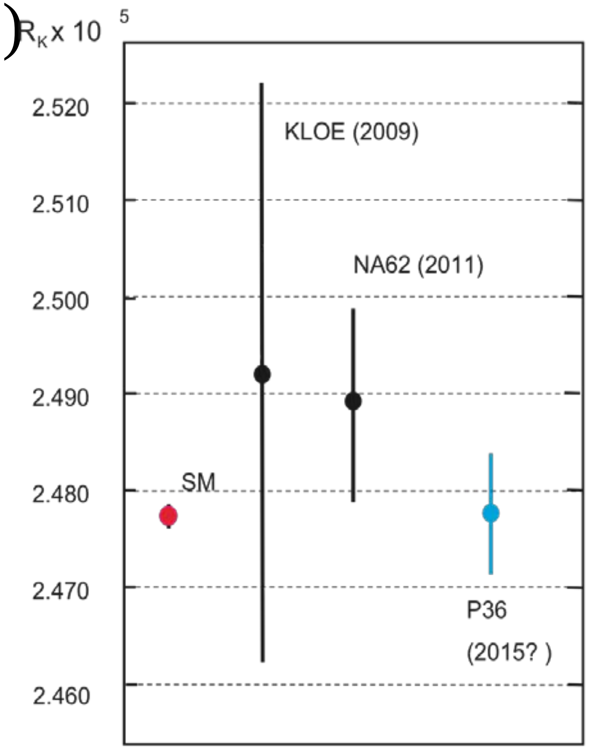


[Masiero, Paradisi and Petronzio; 2008]

Experimental status of R_K

- KLOE @ DAFNE (in-flight decay) (2009)
  - $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
- NA62 @ CERN (in-flight decay) (2011)
  - $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$
- World average (2011)
  - $R_K = (2.488 \pm 0.009) \times 10^{-5}$

    $\sigma(R_K)/R_K = 0.0037$



- P36 aims for:

$\sigma(R_K)/R_K = 0.0020$ (stat) $\pm$ 0.0015 (syst)

Systematics :

- *In-flight-decay experiments : kinematics overlap*
- *P36 stopped K^+ : detector acceptance and target*
- *Thorough systematic error analysis for P36*

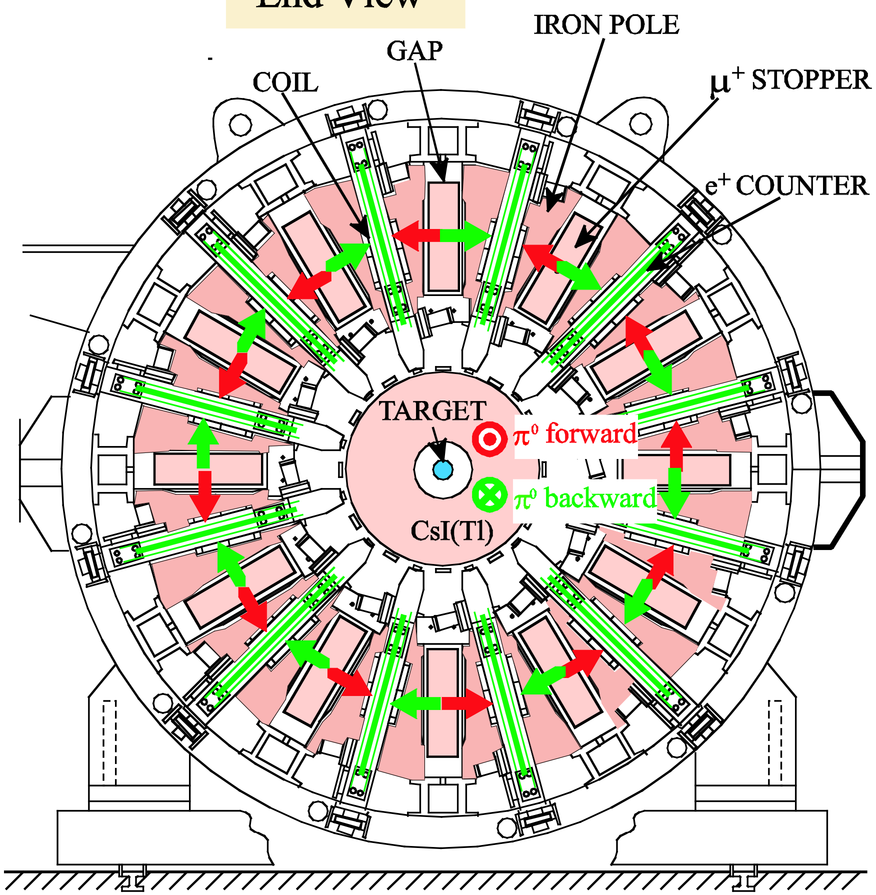
Experiment at J-PARC : P36

- High intensity beam of K^+
  - not the highest intensity of J-PARC (30 kW)
- Stopped beam experiment
  - different systematics from NA62
- Use of TREK detector
  - sub detector system of the TREK experiment

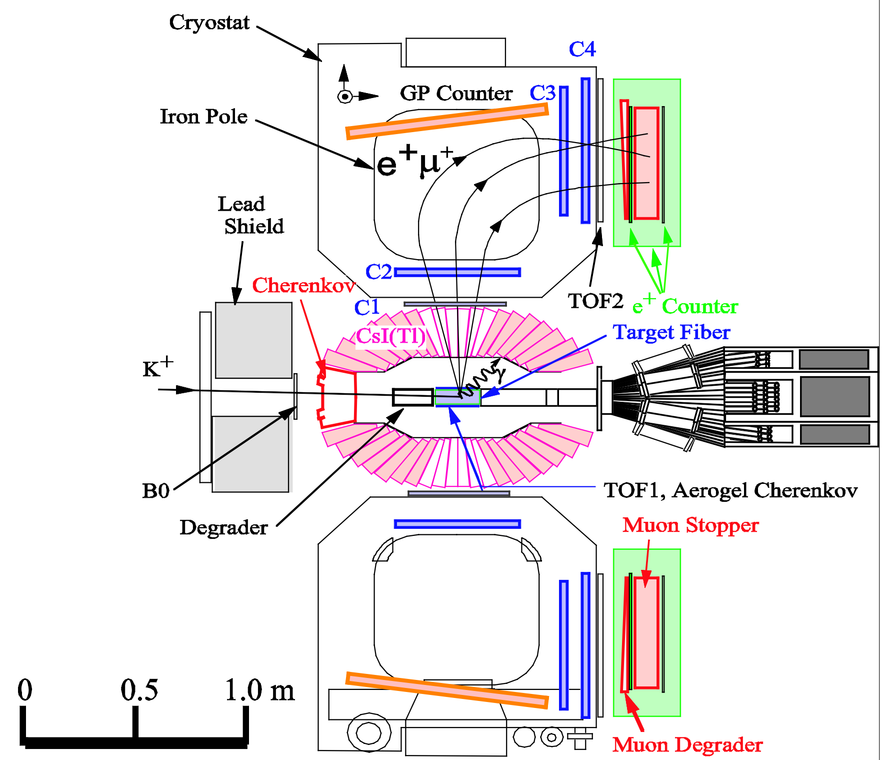
- Proposal was submitted PAC in June 2010
- Decision is made soon in July

Experimental setup

End View



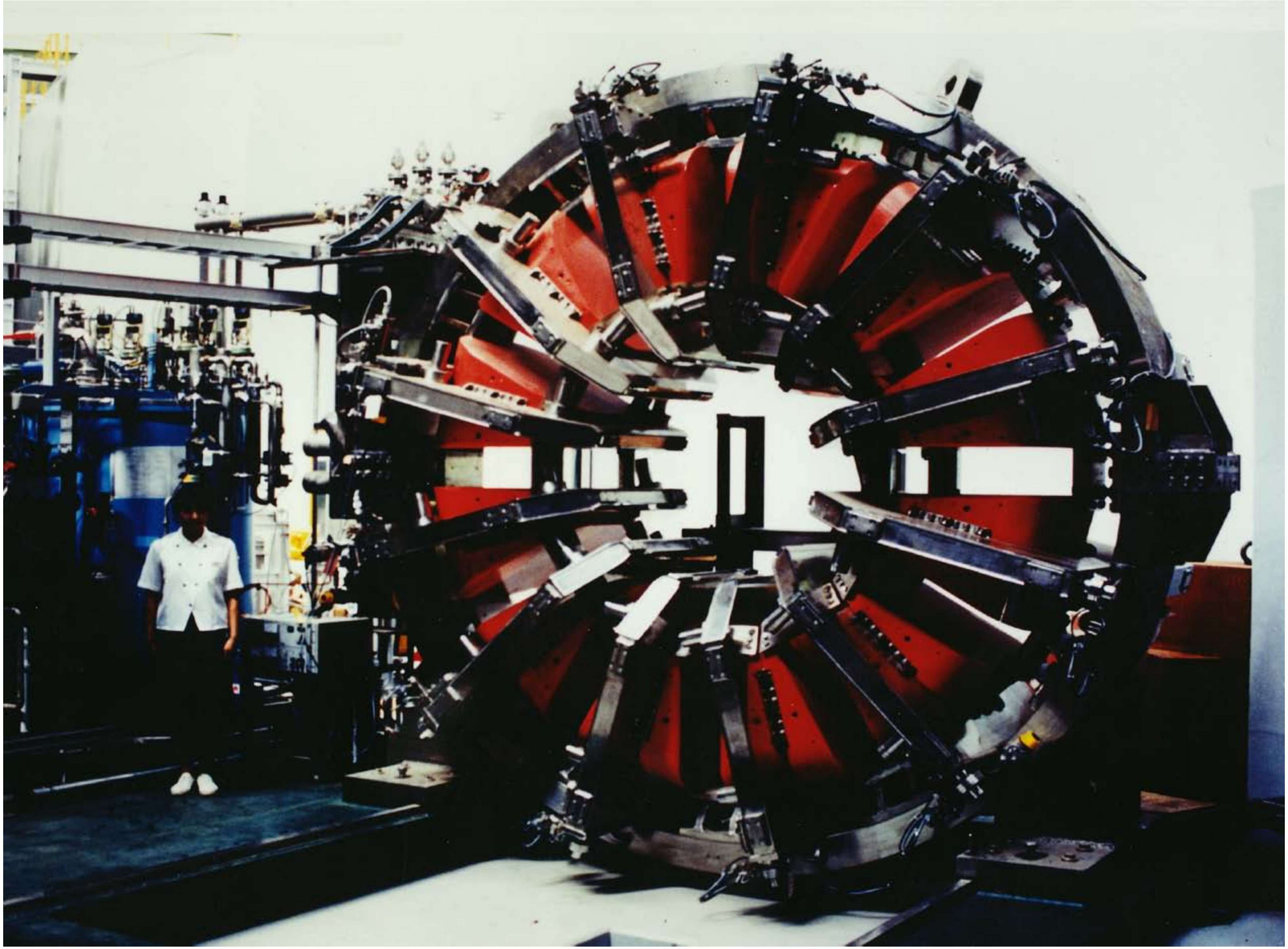
Side View



- Stopped K^+ decay
- momentum measurement
  SC Toroidal spectrometer

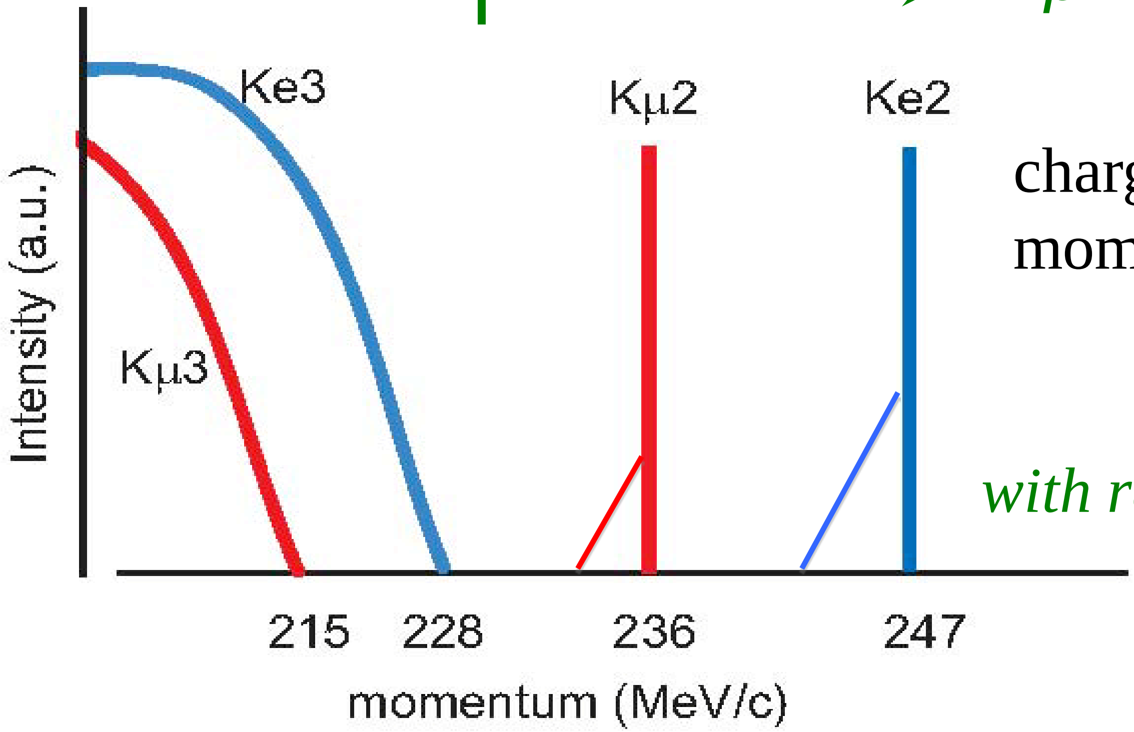
- e^+,μ^+ identification
  TOF and Cherenkov
- γ measurement :CsI(Tl)
- μ^+ polarimeter (for E06)

SC Toroidal magnet



K_{e2} / $K_{\mu 2}$ discrimination

Backgrounds ⟼ p > 228 MeV/c

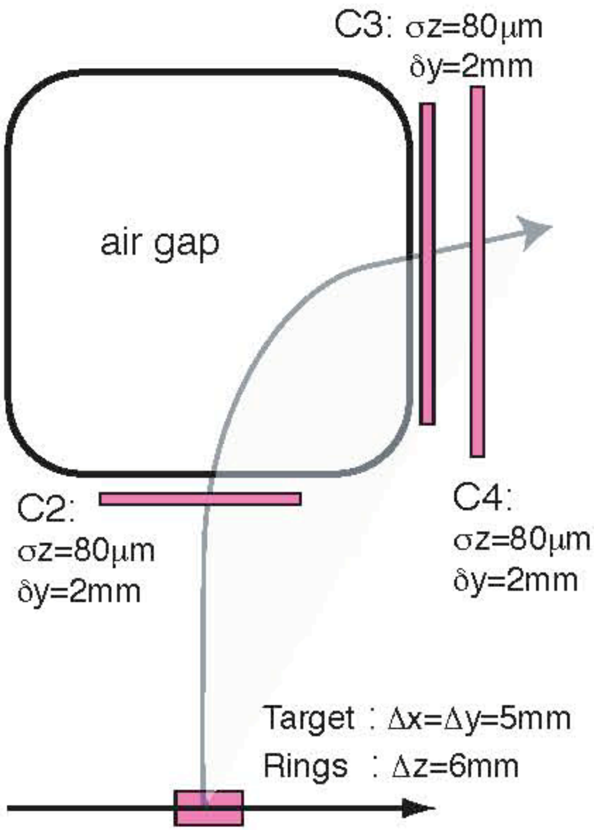


charged particle momentum spectrum

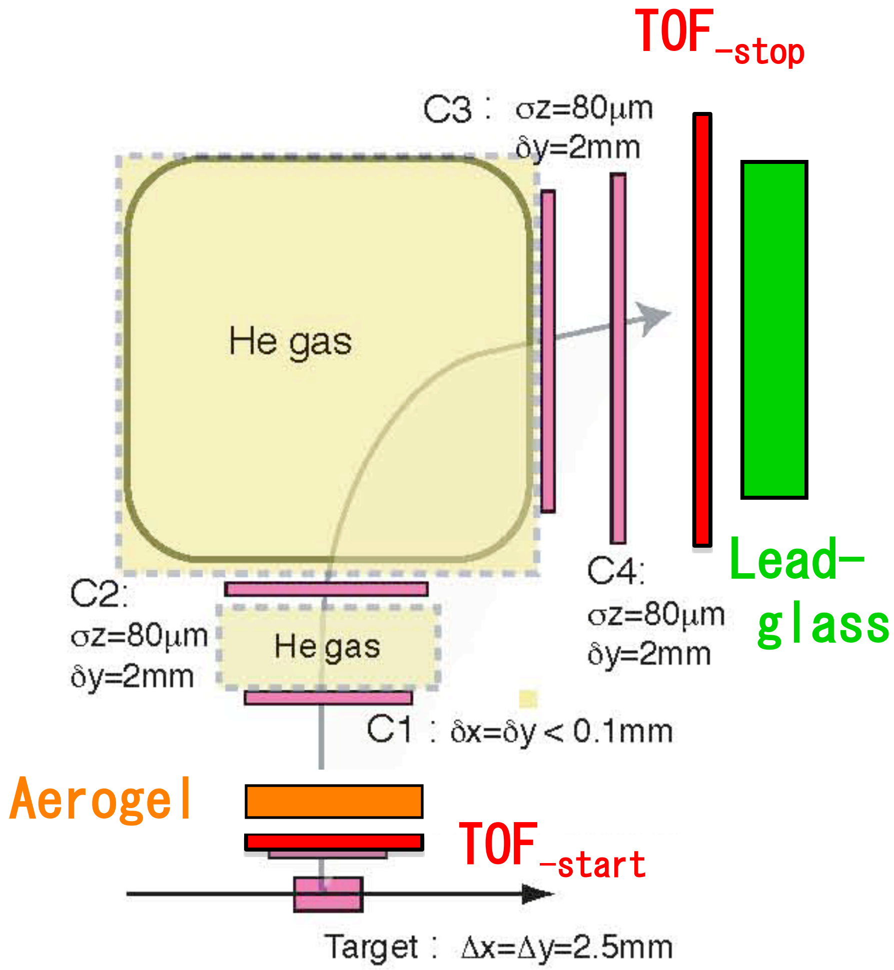
with radiative decay tails

- e/μ separation not only in momentum spectrum but with PID using TOF + Cherenkov counters
- Inclusion of radiative decay (CsI(Tl))
- Rejection of K_{e3} and $K_{\mu 3}$

Tracking and PID



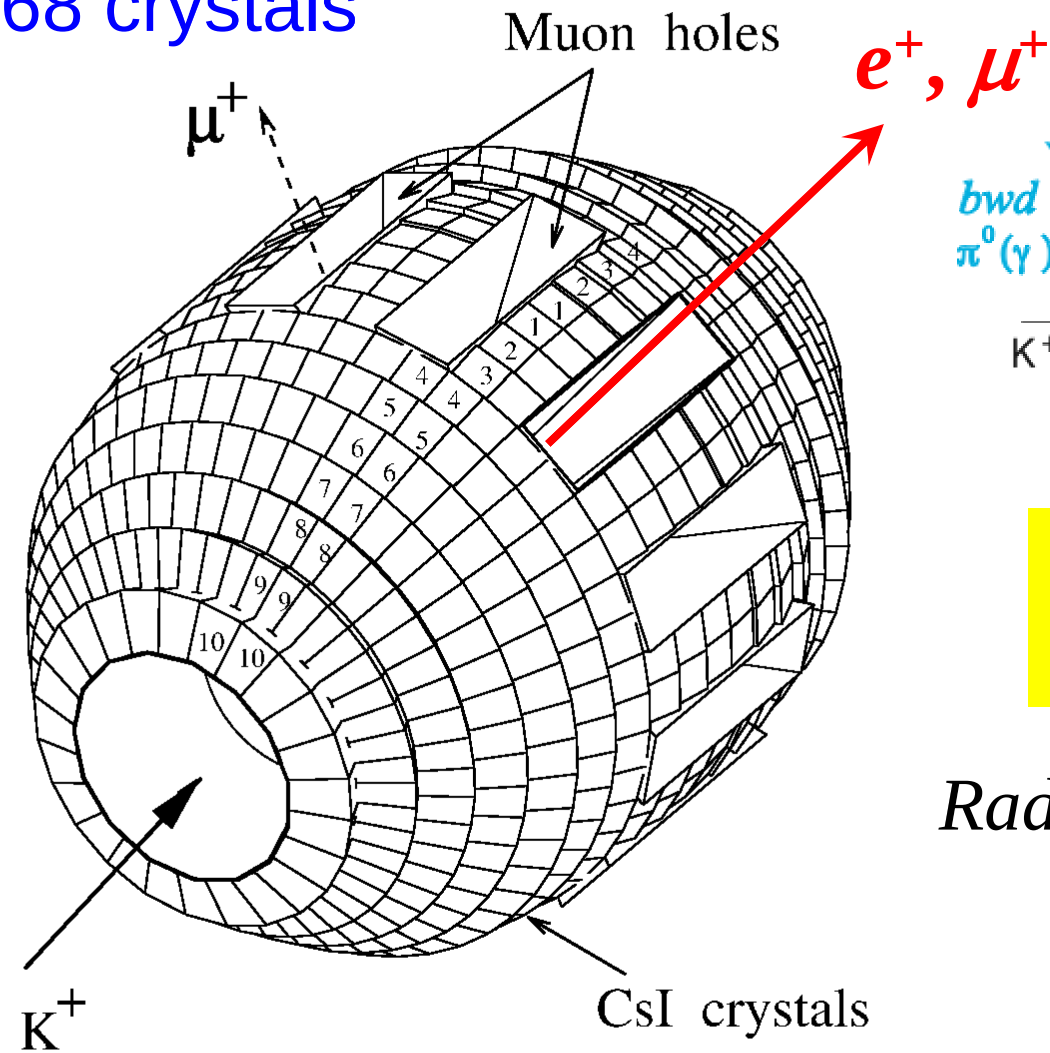
KEK-PS E246

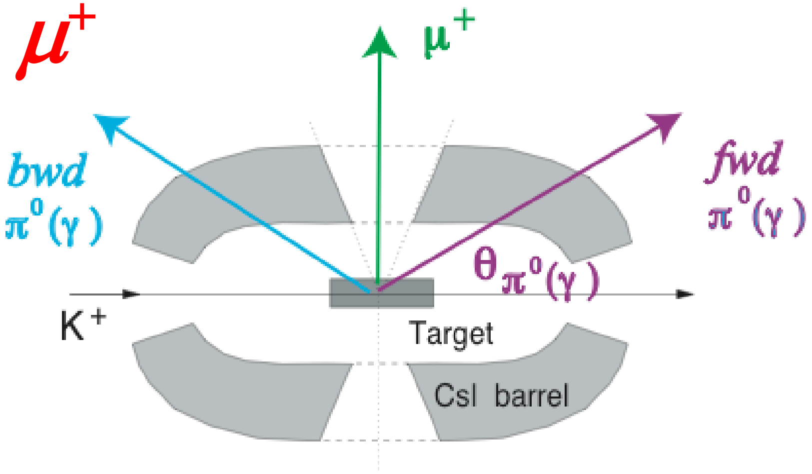


J-PARC P36

CsI(Tl) calorimeter

768 crystals





$E\gamma$: 0 ~ 300 MeV

$\varepsilon = \Omega \sim 3\pi$

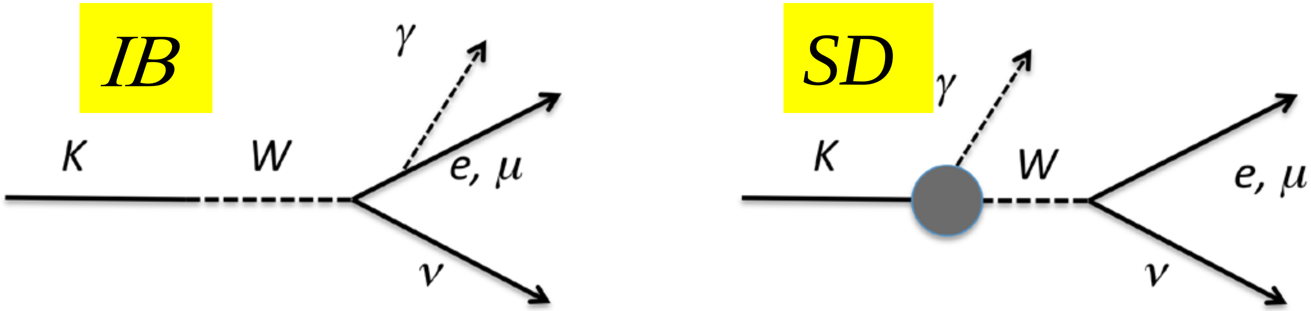
Radiative decays

1) *with one photon, or*

2) *without photon*

Decay modes

Decay mode	Branching ratio	Relative intensity	Momentum(MeV/c)
$K^+ \to e^+\nu$	1.6×10^{-5}	1	247
$K^+ \to \mu^+\nu$	6.3×10^{-1}	40000	236
$K^+ \to e^+\nu\gamma(IB)$		~ 0.1	
$K^+ \to e^+\nu\gamma(SD)$	1.5×10^{-5}	~ 1	
$K^+ \to e^+\nu\pi^0$	4.8×10^{-2}	3000	<228
$K^+ \to \mu^+\nu\gamma$	5.5×10^{-3}	400	
$K^+ \to \mu^+\nu\pi^0$	3.2×10^{-2}	2000	<215



"$K^+ \to e^+ \nu\gamma$ (SD)" is now a disturbing background

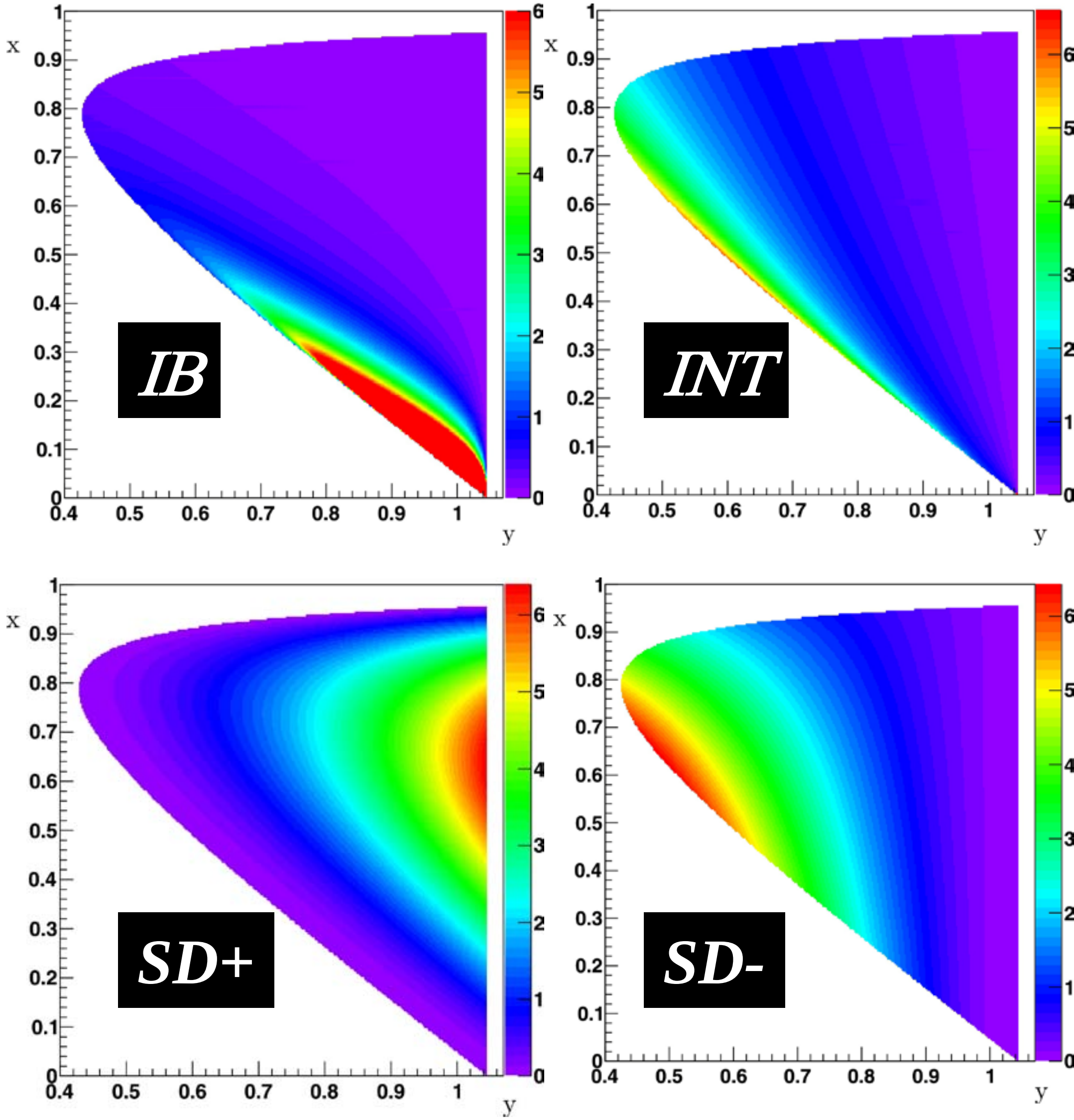
IB and SD

$$x \equiv \frac{2E_\gamma}{M_K} \text{ and } y \equiv \frac{2(E_l+M_l)}{M_K}$$

$$\begin{aligned}
\frac{d\Gamma_{K_{\mu\nu\gamma}}}{dxdy} &= A_{IB} f_{IB}(x,y) \\
&+ A_{SD}[(F_V+F_A)^2 f_{SD^+}(x,y) + (F_V-F_A)^2 f_{SD^-}(x,y)] \\
&- A_{INT}[(F_V+F_A) f_{INT^+}(x,y) + (F_V-F_A) f_{INT^-}(x,y)],
\end{aligned}$$

$$\begin{aligned}
f_{IB}(x,y) &= \left[\frac{1-y+r}{x^2(x+y-1-r)}\right] \\
&\times\left[x^2 + 2(1-x)(1-r) - \frac{2xr(1-r)}{x+y-1-r}\right], \\
f_{SD^+} &= [x+y-1-r][(x+y-1)(1-x)-r], \\
f_{SD^-} &= [1-y+r][(1-x)(1-y)+r], \\
f_{INT^+} &= \left[\frac{1-y+r}{x(x+y-1-r)}\right][(1-x)(1-x-y)+r], \\
f_{INT^-} &= \left[\frac{1-y+r}{x(x+y-1-r)}\right][x^2-(1-x)(1-x-y)-r],
\end{aligned}$$

$$\begin{aligned}
r &= \left[\frac{M_l}{M_K}\right]^2, \\
A_{IB} &= \Gamma(K_{l2})\frac{\alpha}{2\pi}\frac{1}{(1-r)^2}, \\
A_{SD} &= \Gamma(K_{l2})\frac{\alpha}{8\pi}\frac{1}{r(1-r)^2}\left[\frac{M_K}{F_K}\right]^2, \\
A_{INT} &= \Gamma(K_{l2})\frac{\alpha}{2\pi}\frac{1}{(1-r)^2}\frac{M_K}{F_K}.
\end{aligned}$$



CsI(Tl) data

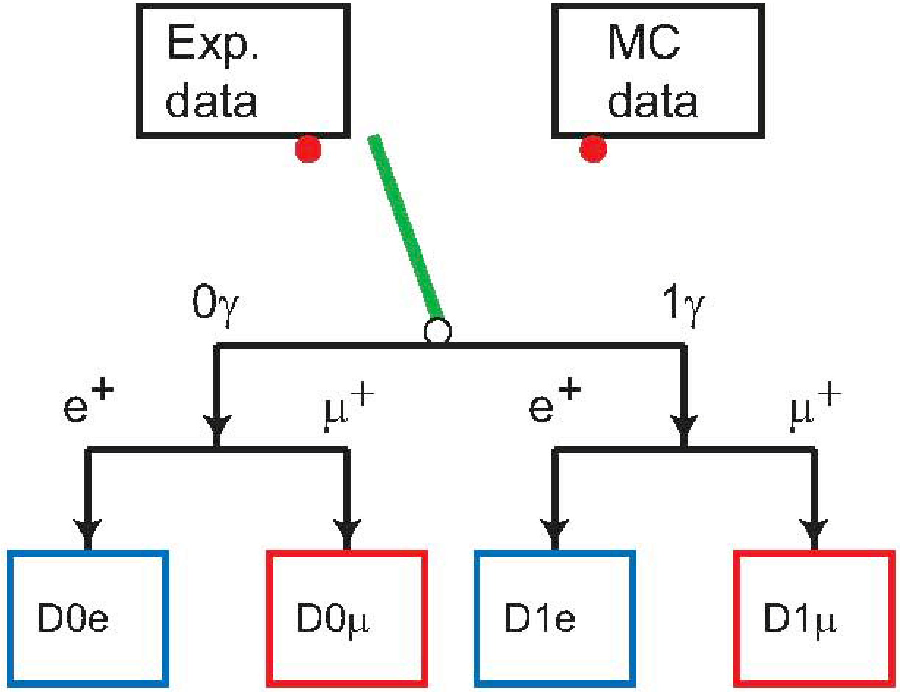
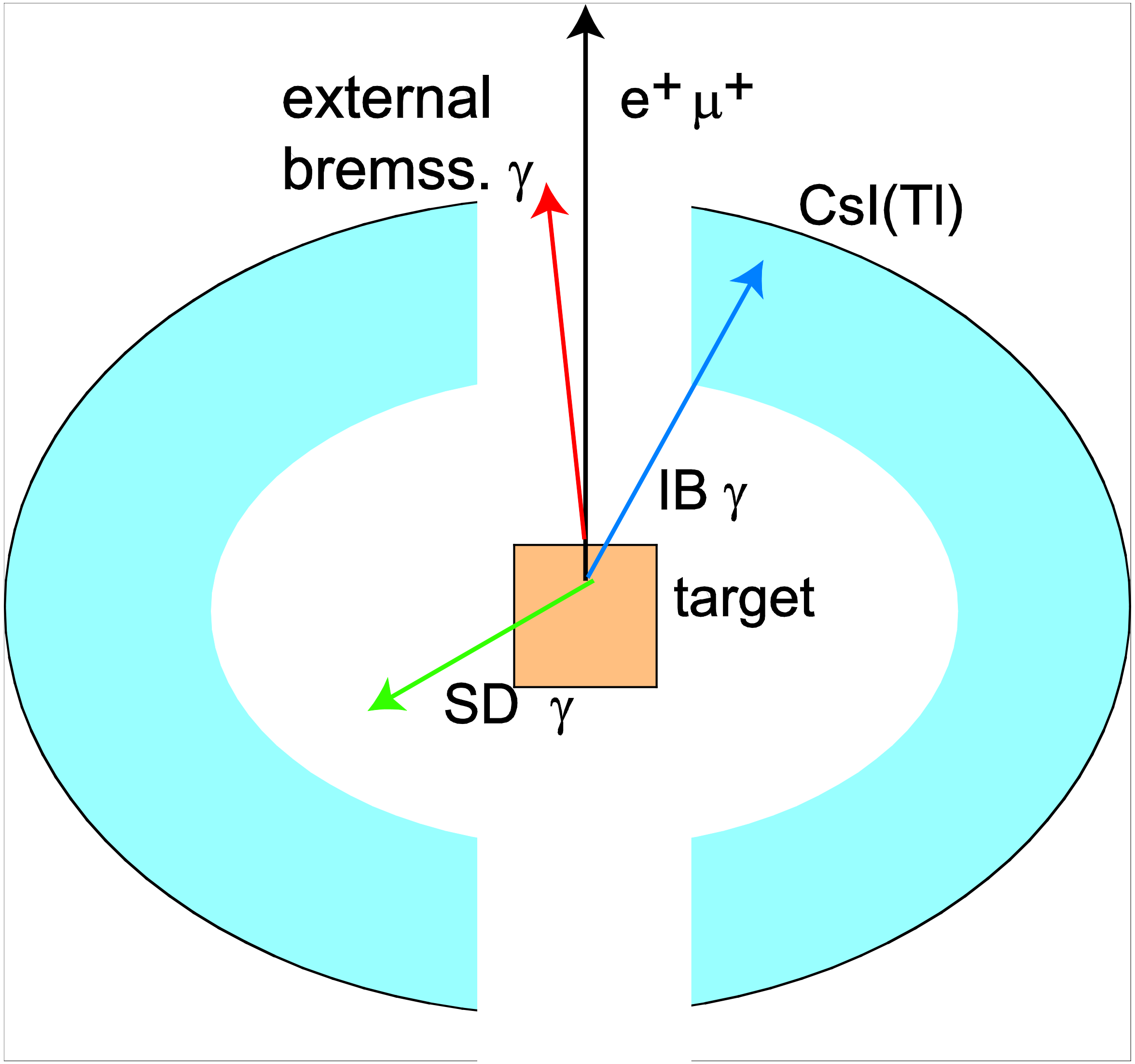


Figure 16: Flow chart for the data handling. The experimental and simulation data are analyzed by the same program codes. The accepted events after applying the analysis are separated into four categories: no photon detection (D0) for e^+ (D0e) and μ^+ (D0μ), and one photon detection (D1) for e^+ (D1e) and μ^+ (D1μ).

Photon detection



	D0	D1
EB	O	×
IB	O	Δ
SD	Δ	O

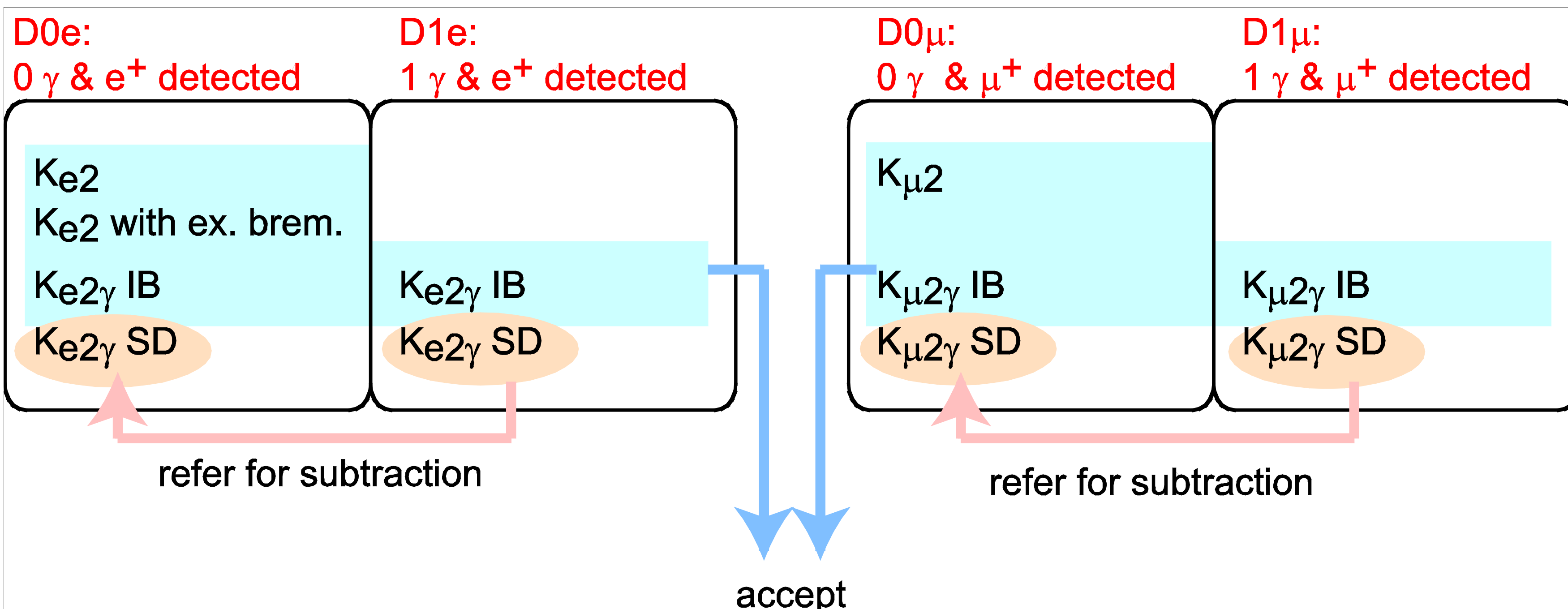
Overview of the analysis

Number of accepted events

$\tilde{N}(K_{e2}) = N(K_{e2}) + N(K_{e2\gamma})$
$\tilde{N}(K_{\mu2}) = N(K_{\mu2}) + N(K_{\mu2\gamma})$

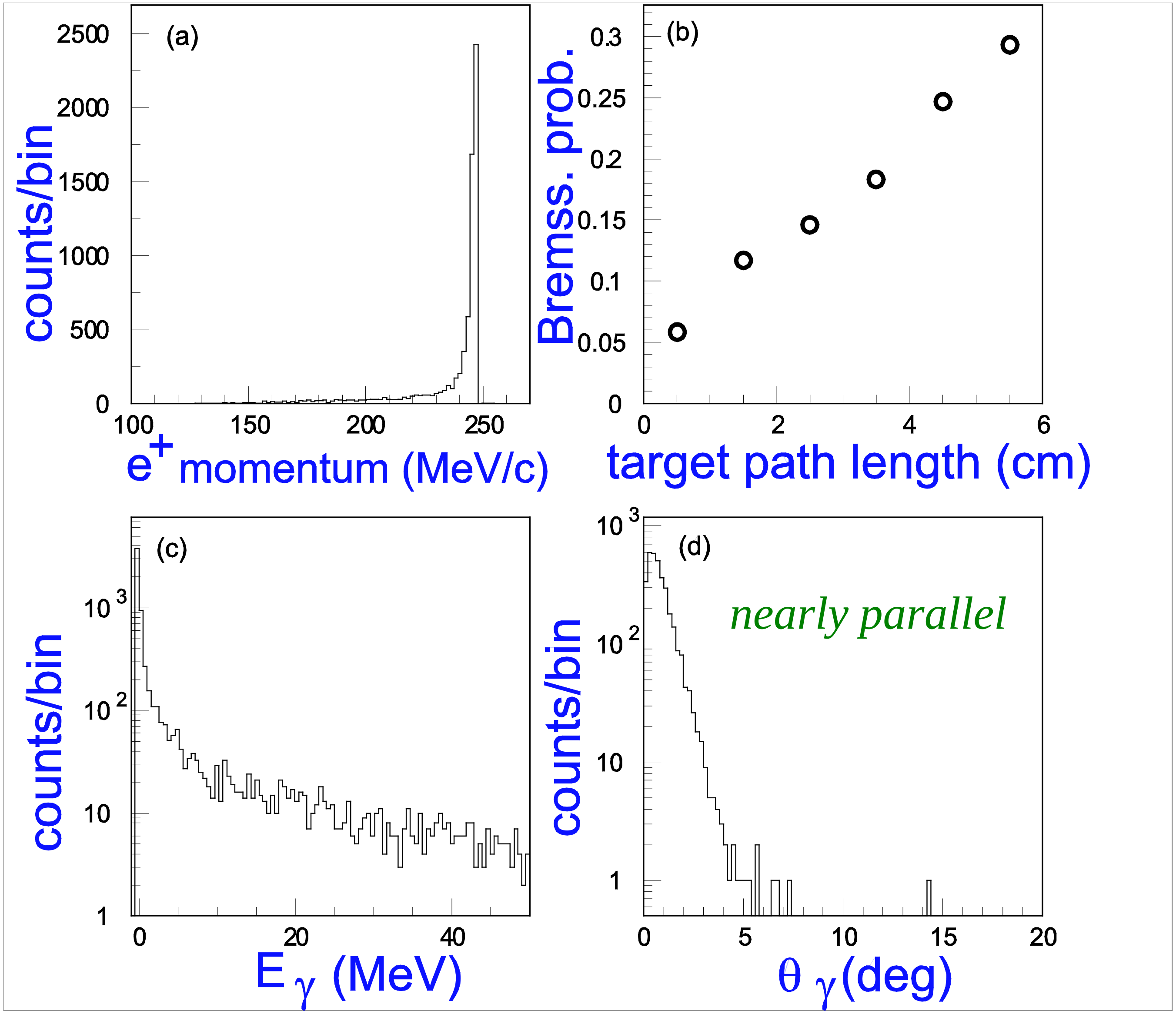
$$N(K_{e2}) = N_K \times \Omega(K_{e2}) \times Br(K_{e2}),$$
$$N(K_{\mu2}) = N_K \times \Omega(K_{\mu2}) \times Br(K_{\mu2}).$$

$$\Gamma(K_{e2})/\Gamma(K_{\mu2}) = \boxed{N(K_{e2})/N(K_{\mu2})} \cdot \boxed{\Omega(K_{\mu2})/\Omega(K_{e2}).}$$
$$= N(K_{e2})/N(K_{\mu2}) \cdot N(K_{\mu2})^{\mathrm{MC}}/N(K_{e2})^{\mathrm{MC}}$$

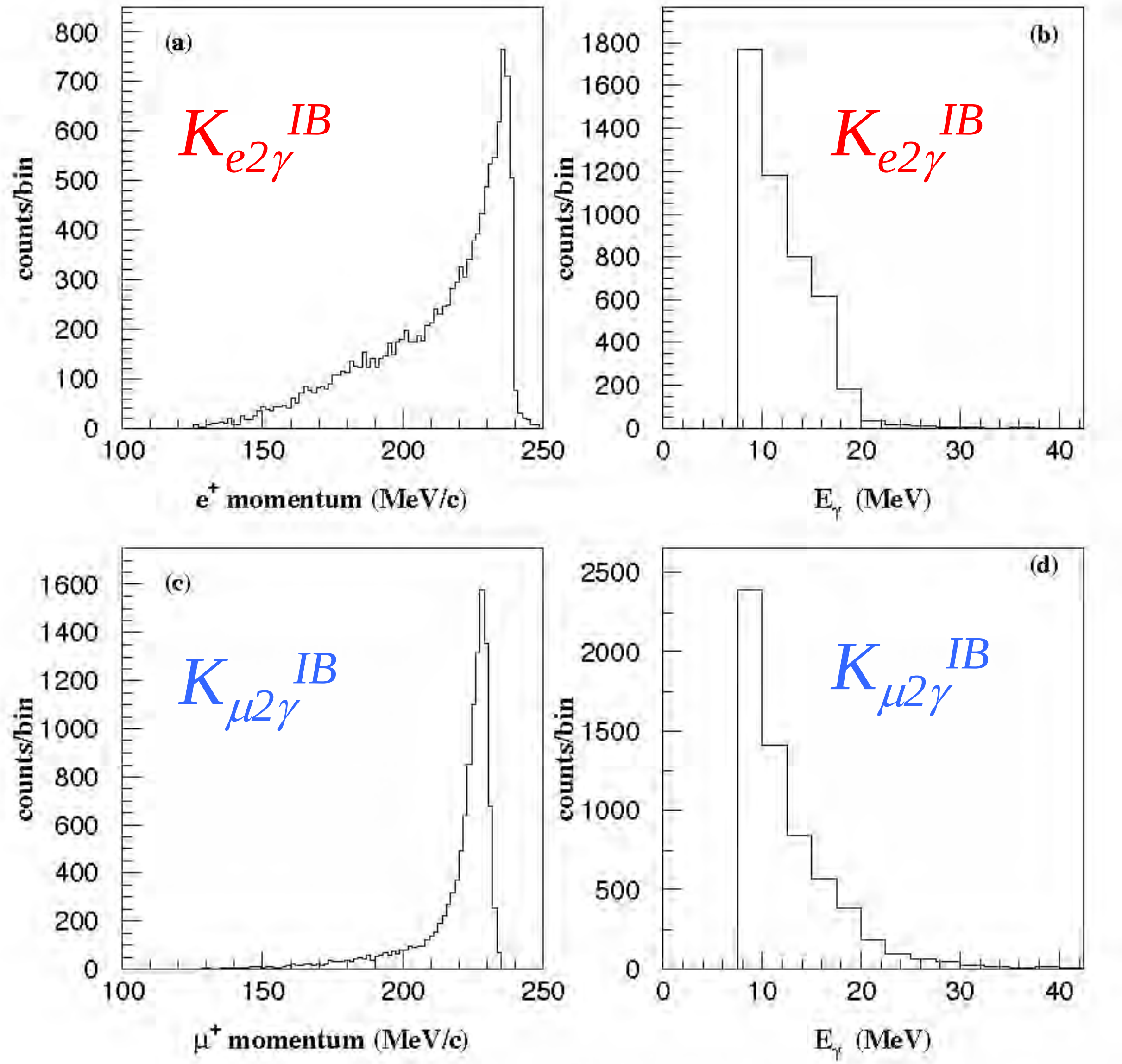


K_{e2} spectra in D0

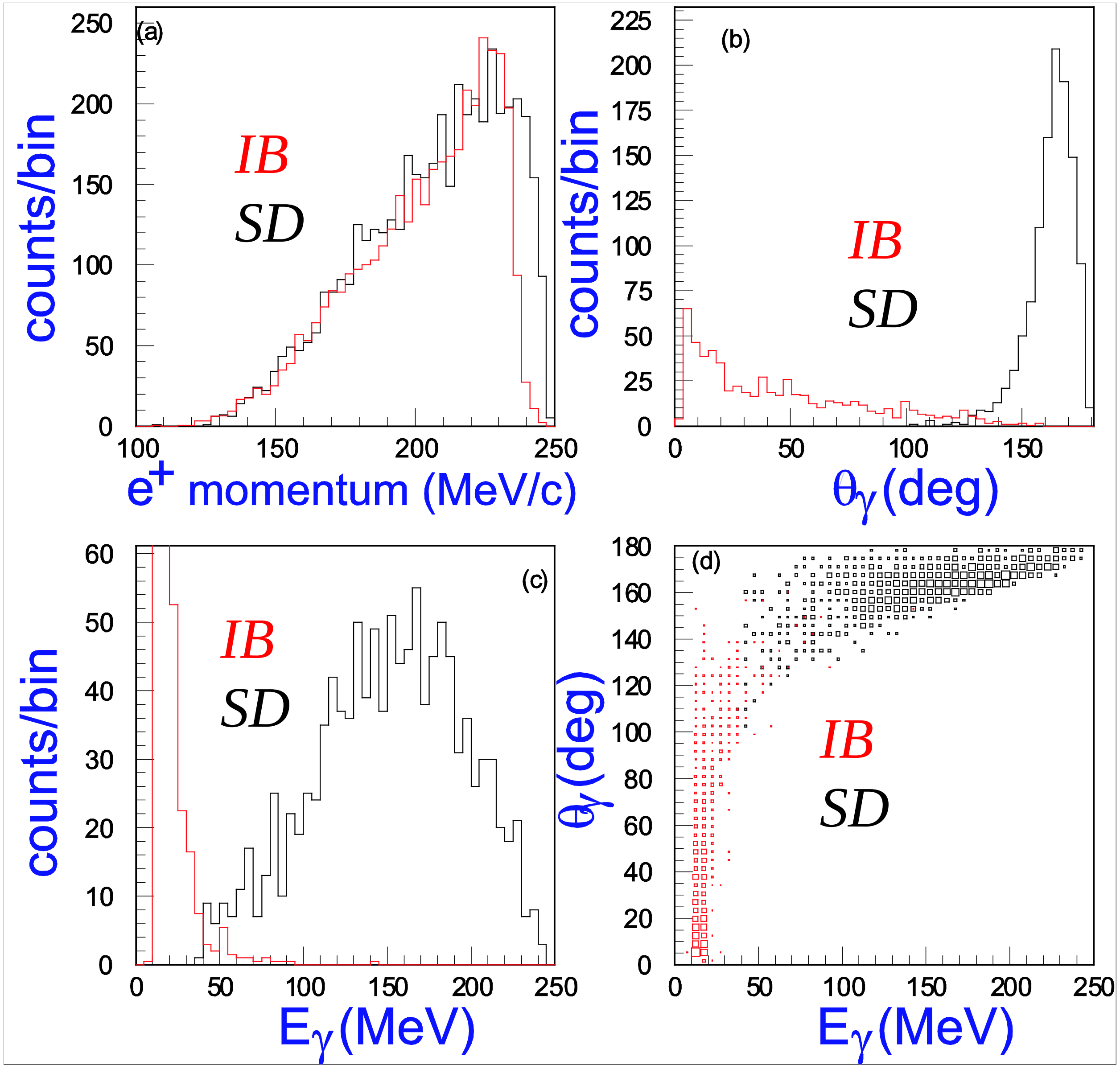
Emission of external bremsstrahlungs photon



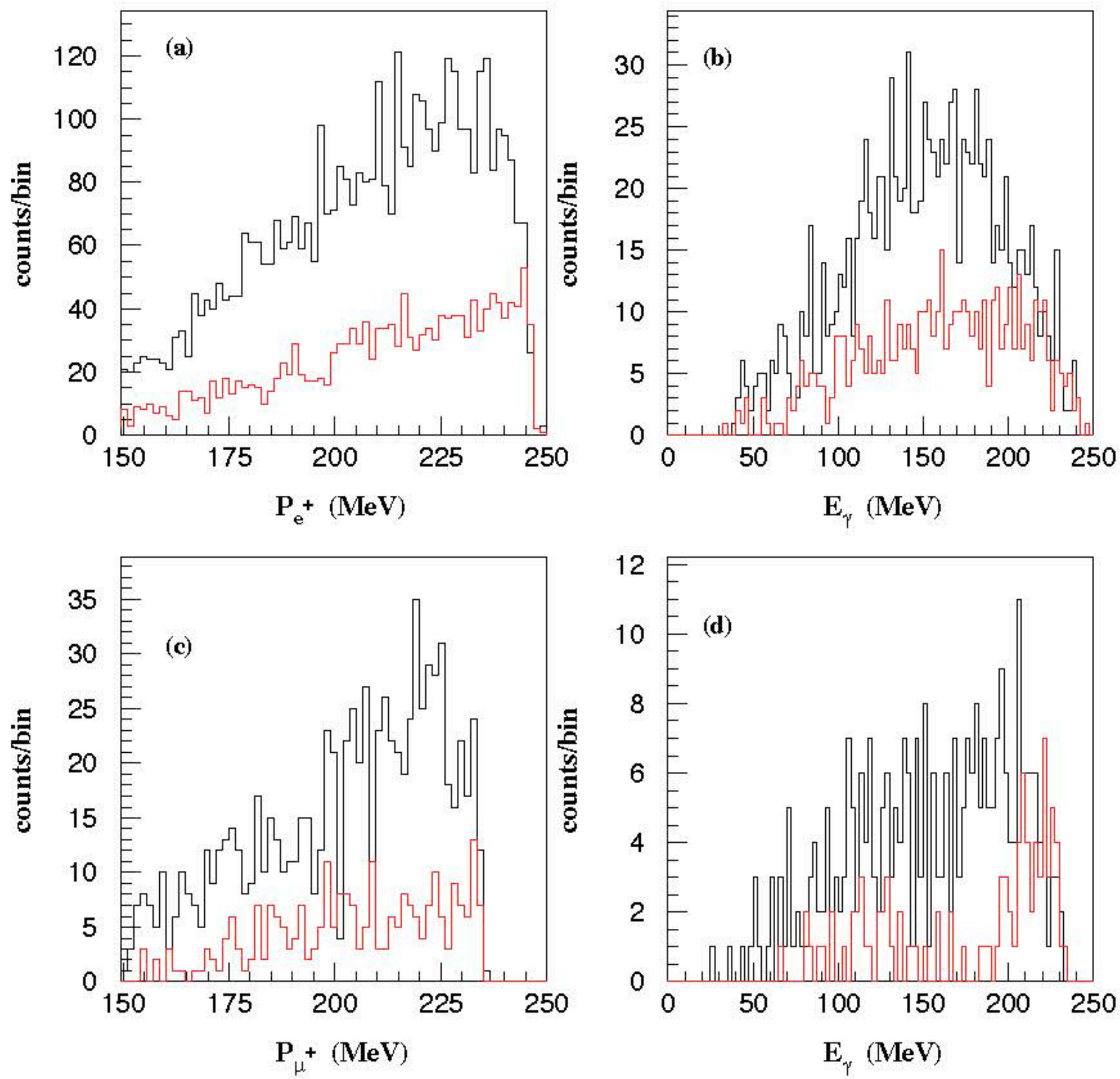
$K_{e2\gamma}{}^{IB}$ and $K_{\mu2\gamma}{}^{IB}$ in D0



$K_{e2\gamma}^{IB}$ (red) and $K_{e2\gamma}^{SD}$ (black) in D1



SD components



← Ke2γ

← Kμ2γ

Red : D0
Black: D1

較正実験と系統誤差

Estimate of $\Omega(K_{e2})/\Omega(K_{\mu 2})$ ratio

□ $\delta R_K/R_K = \delta Q/Q + \cdot\ \cdot\ \cdot\ \cdot$ $[Q=\Omega(K_{e2})/\Omega(K_{\mu 2})]$

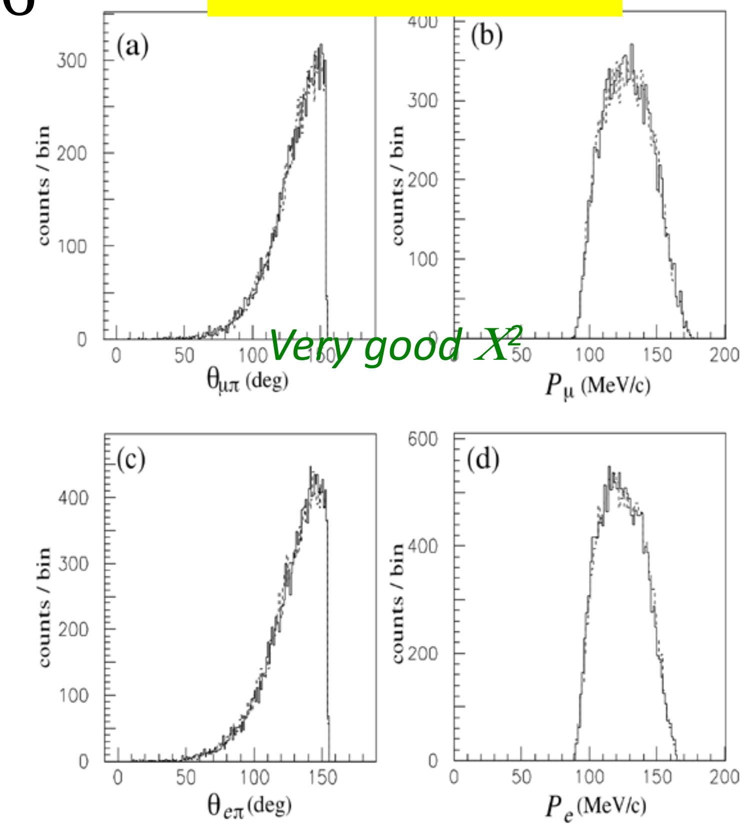
- Most essential source of the systematic error
- Detection of $K_{l2(\gamma)}$
  - (A) Momentum spectrum (spectrometer)
  - (B) PID (Aerogel Cherenkov + TOF + Lead glass counter)
  - (C) γ detection (CsI(Tl) for radiative decays
- (A) is most difficult to estimate. Error comes from:
  - Different momentum of K_{e2} / $K_{\mu 2}$ (247/236 MeV/c)
  - Different interactions in the target material
- Estimate of Q also by using data desirable

Q estimate by a MC simulation

$$Q = \frac{N_{MC}^{accpt}(K_{e2} : B = 1.4\mathrm{T})}{N_{K_{e2}}^{decay}} \Big/ \frac{N_{MC}^{accpt}(K_{\mu 2} : B = 1.4\mathrm{T})}{N_{K_{\mu 2}}^{decay}}$$

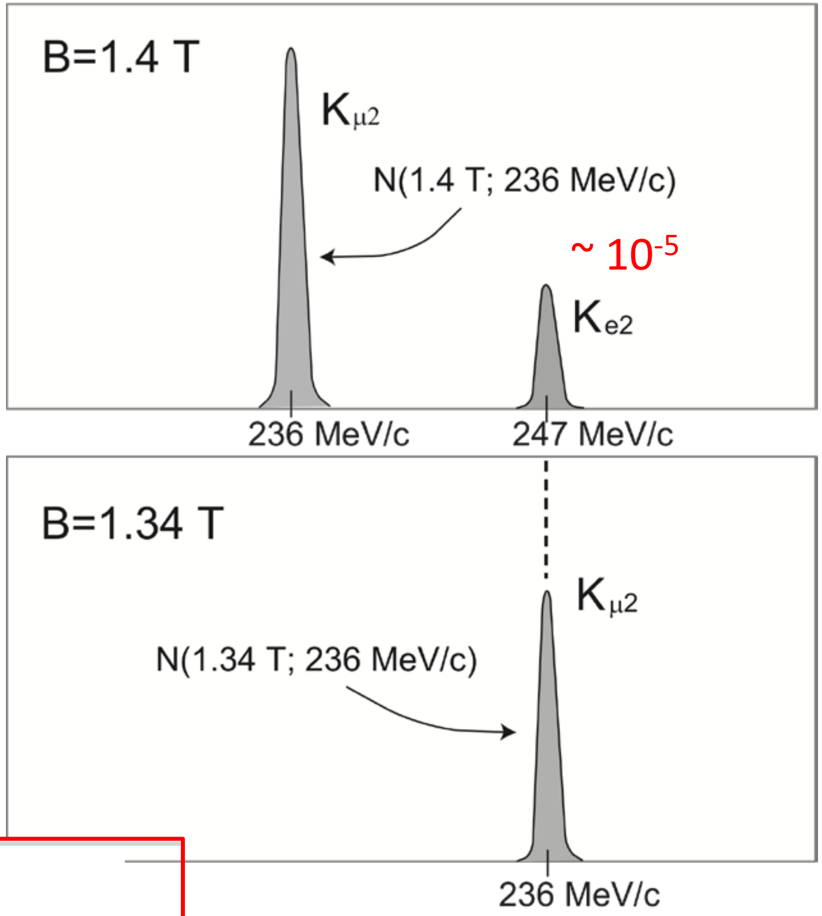
- Use of the MC code used in E246
- Precise geometry input needed
- Physics input: K^+ distribution
- Checked by using data
- 100 times more events in P36 than in E246
- However, the result has to be checked by using data

Fit to E246 data



Use of $K_{\mu 2}$ peak

- Calibration run with reduced field to realize the same trajectory distribution
  - – n : beam normalization between two runs
  - β : magnetic field effect
    - ➢ Precise field calculation, and
    - ➢ Tracking simulation needed



$$Q = \frac{N(K_{\mu 2}; \mathrm{B} = 1.34\ \mathrm{T})}{N(K_{\mu 2}; \mathrm{B} = 1.4\ \mathrm{T})} \times \beta \times n,$$

- Error arises from the uncertainty of corrections, n and β

Use of $K_{\mu 3}$ spectrum

- Use of wide *p* spectrum
- Calibration run with reduced field of 0.9 T

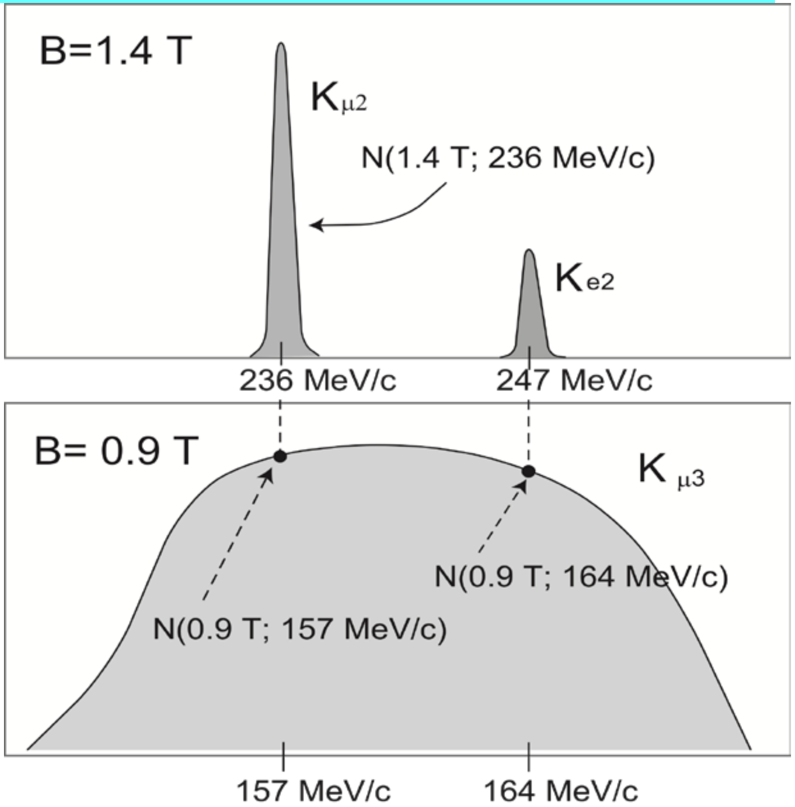
164 MeV/c : 247 MeV/*c* Ke2

157 MeV/c : 236 MeV/*c* $K_{\mu 2}$

α : spectral ratio

β : magnetic field effect

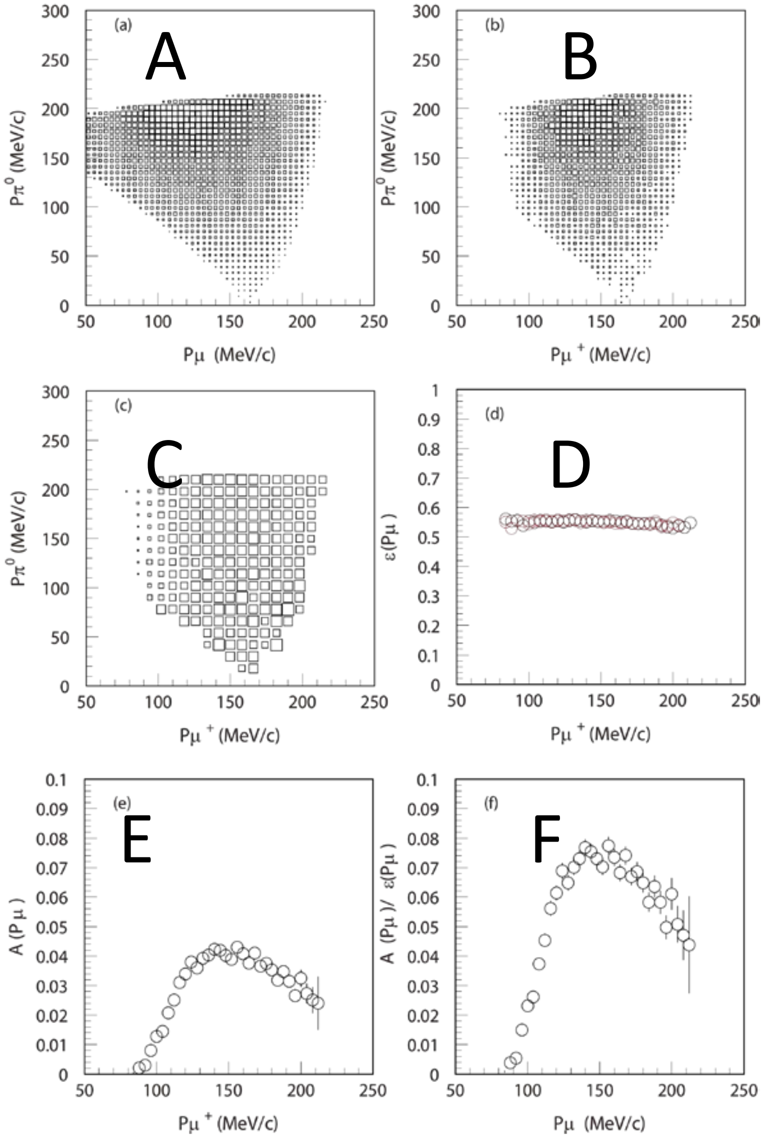
γ : CsI(Tl) efficiency effect



$$Q = \frac{N(K_{\mu 3}; B = 0.9\ \mathrm{T}; 164\ \mathrm{MeV}/c)}{N(K_{\mu 3}; B = 0.9\ \mathrm{T}; 157\ \mathrm{MeV}/c)} \times \alpha \times \beta' \times \gamma.$$

- One calibration run: no necessity of beam normalization
- Most promising method

$K_{\mu3}$ method with E246 data



- Validity check with E246 data at reduced magnetic field of 0.9 T

  A. MC Dalitz plot of $K_{\mu3}$
  B. Experimental Dalitz plot
  C. Acceptance plot : B/A
  D. CsI(Tl) efficiency curve
  E. Projection of C onto p_μ
  F. Spectrometer acceptance curve

$$F = E/D$$

$$Q = F(164\ \text{MeV/c}) \,/\, F(157\ \text{MeV/c})$$

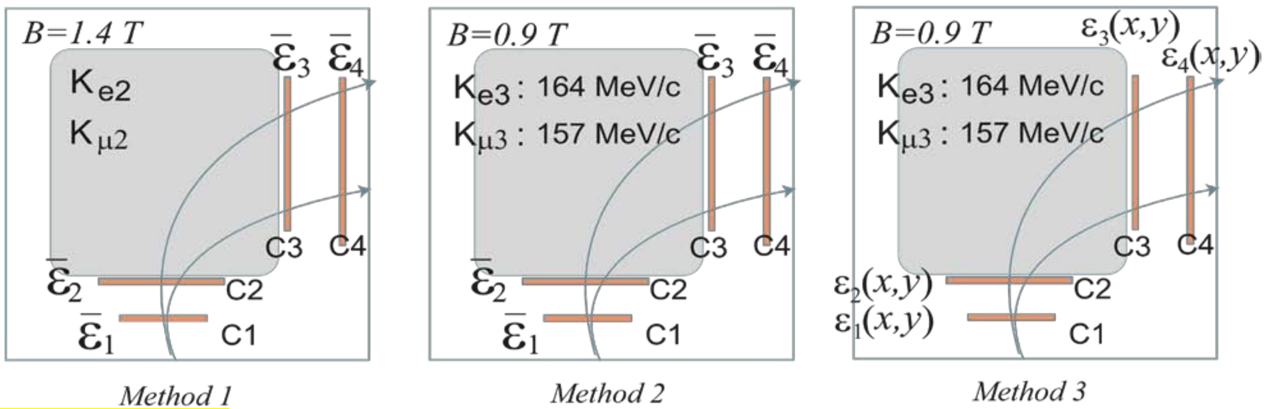
- Main error comes from

1. Ambiguity of the FF in the A and D
2. Energy loss correction in the target

$\delta R_K/R_K = 0.00078$: same for P36

Chamber efficiency

- Efficiency calibration by means of "Sandwich Method"
- Use of real data or calibration run data



Average efficiency

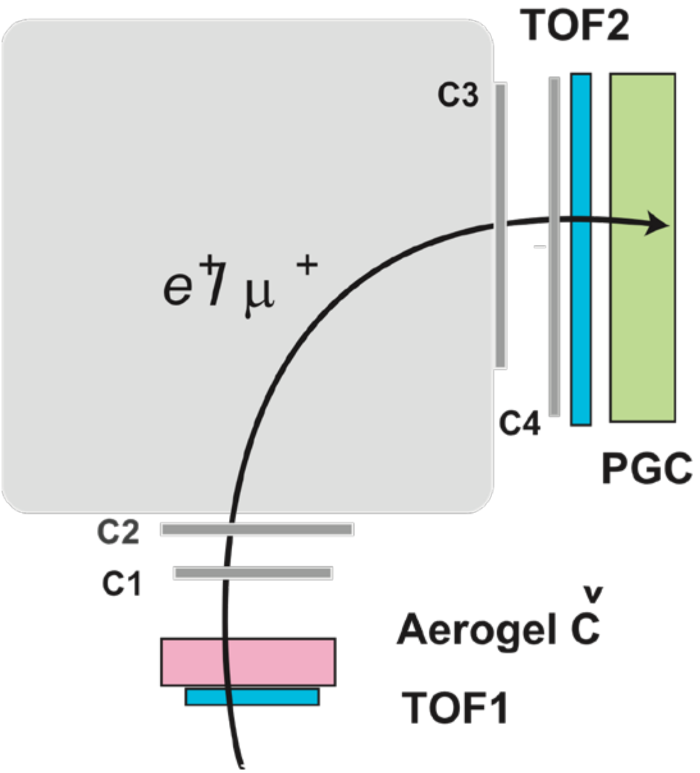
$$\bar{\epsilon}_3 = \frac{N(C1 \otimes C2 \otimes C3 \otimes C4)}{N(C1 \otimes C2 \otimes C4)}$$

Position dependent efficiency

$$\epsilon_3(x3, y3) = \frac{n(C1 \otimes C2 \otimes C3 \otimes C4)}{n(C1 \otimes C2 \otimes C4)}$$

Method	Mode@field	Time	ϵ or $\bar{\epsilon}$	$\Delta R_K / R_K$
1 average $\bar{\epsilon}$	$K_{e2}/K_{\mu2}$ @ 1.4 T	total run	0.98	5.6×10^{-3}
			0.99	4.0×10^{-4}
			0.995	2.8×10^{-4}
2 average $\bar{\epsilon}$	$K_{e3}/K_{\mu3}$ @ 0.9 T	3 days	0.98	8.0×10^{-4}
			0.99	5.7×10^{-4}
			0.995	4.1×10^{-4}
3 $\bar{\epsilon}(x, y)$	$K_{e3}/K_{\mu3}$ @ 0.9 T	5 days	0.995	10×10^{-4}

PID performance



- Particle identification by
  - a) TOF
  - b) Aerogel Cherenkov (AC)
  - c) Lead Glass (PGC)
- Efficiency calibration with the "sandwich method" using real K_{e2} data.

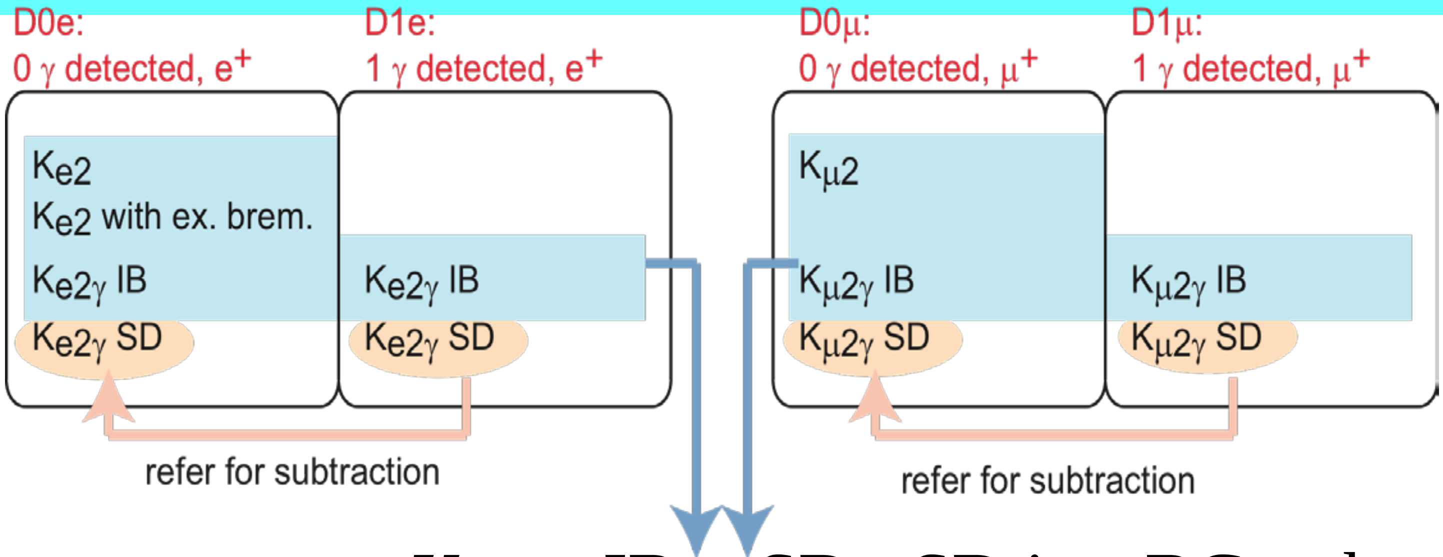
Element for check	Tracking elements	PID
AC	C1, C2, C3, C4	TOF$\otimes$PGC
TOF	C1, C2, C3, C4	AC$\otimes$PGC
PGC	C1, C2, C3, C4	TOF$\otimes$AC

- K_{e2} statistics limits the accuracy of PID efficiency to

$$\delta R_K / R_K = 0.00035$$

- We may also use K_{e3} events at reduced field

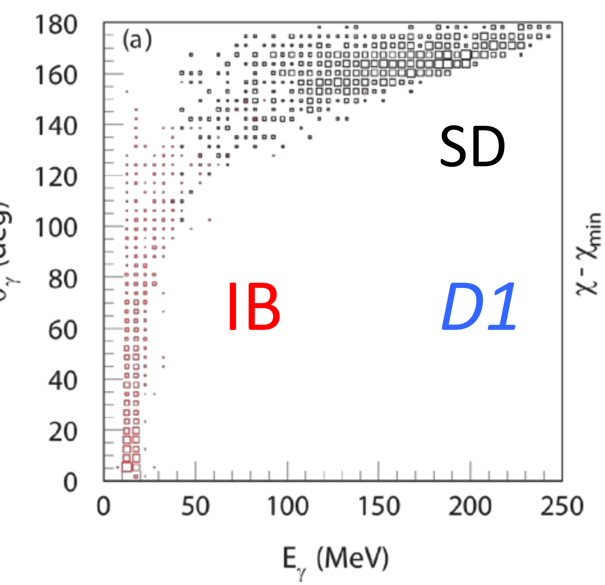
Subtraction of structure dependent $K_{l2\gamma}$



- $K_{e2\gamma}$ = IB + SD : SD is a BG to be subtracted

Relevant mainly to $K_{e2\gamma}$

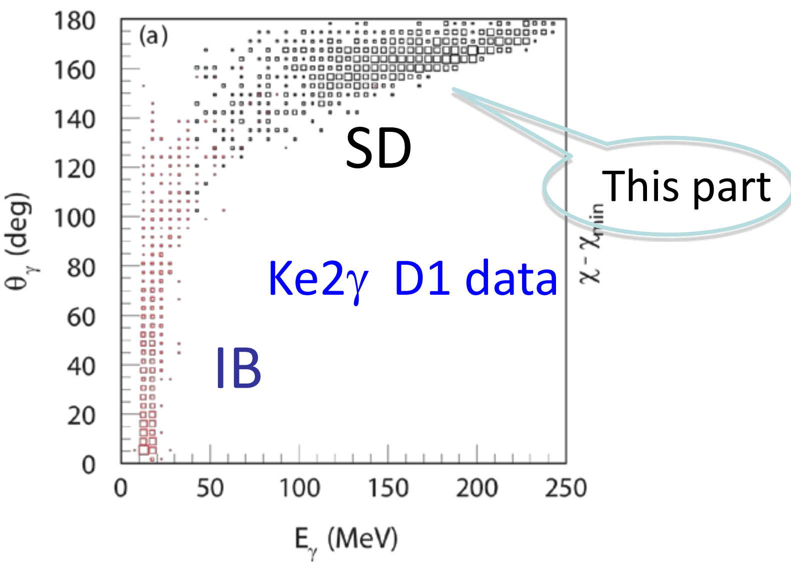
- How to subtract SD
    1. IB and SD : good separation in D1
    2. SD form factor determination in D1
    3. calculation of D0-SD using this FF
    4. determination of D0-IB



$\delta R_K / R_K = 0.00036$

SD subtraction - CsI(Tl) efficiency -

- Photon detection uncertainty arise from:
  - Effective solid angle depending on $\rho(K^+)$
  - Instability of detection threshold E_{th}
  - Clustering efficiency depending on event rate
- Main effect in P36 is the detection efficiency of $K_{e2\gamma}$ (SD dominated), which is used for the D0-SD subtraction. Other effects are relative harmless.

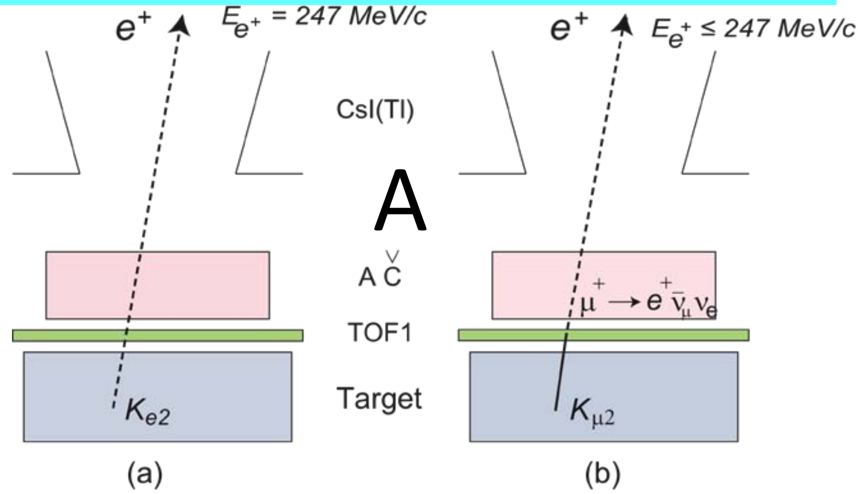


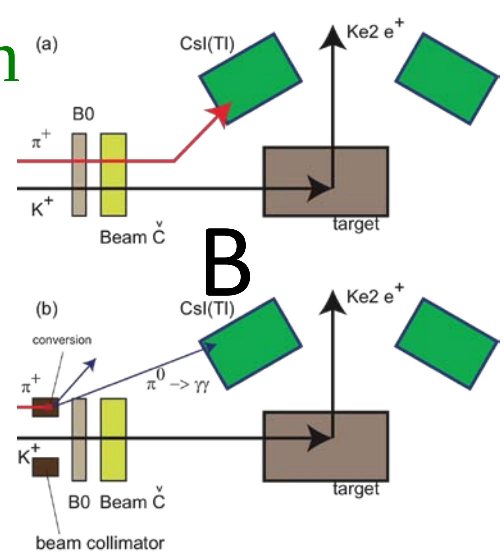
$$\delta R_K / R_K = 0.0007$$

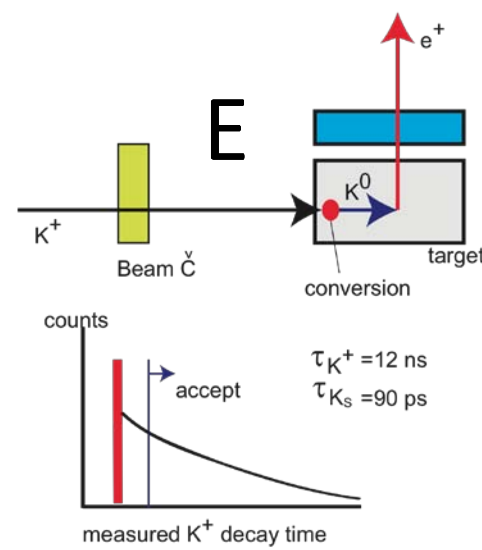
- ➢ Necessity of gain monitoring
- ➢ Event rate stability required

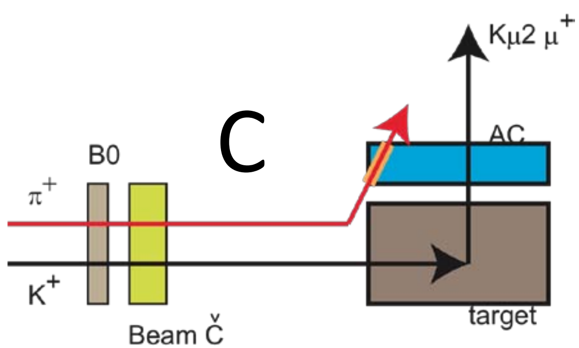
Backgrounds

- Physics backgrounds
  A. In-flight μ^+ decay
  B. Photon conversion
- Beam origin accidentals
  C. Beam hit in CsI(Tl)
  D. Beam hit in AC
  E. K^+ to K^0 conversion
  F. K^+ in-flight decay



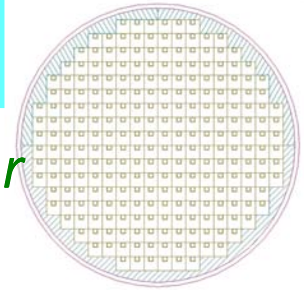






- $\delta R_K/R_K$ in "Summary Table"

Target interaction

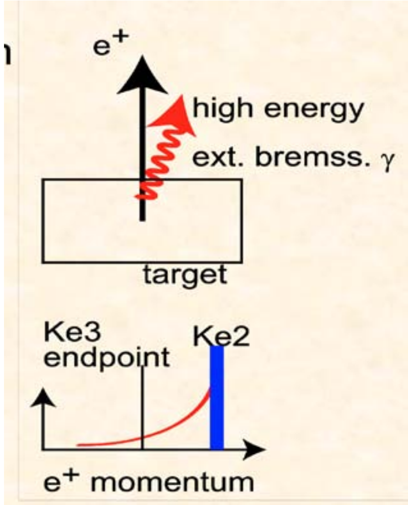


Uncertainty of e^+/μ^+ penetration length produces an error

- Error due to decay vertex resolution

Interaction	Probability uncertainty
Bremsstrahlung for positrons	0.038%
Annihilation for positrons	$\leq$0.010%
Photon conversion for both decays	0.010%
Total	0.041 %

$\delta R_K/R_K$ = 0.00041



- Error due to material thickness uncertainty

Interaction	Relevant to	Correction error	$\Delta R_K/R_K$
Bremsstrahlung (rejected)	$\tilde{K}_{e2}$	0.003	2×10^{-4}
Annihilation in flight	$\tilde{K}_{e2}$	$\ll 10^{-4}$	$\ll 10^{-4}$
Photon conversion	$K_{e2\gamma}$, $K_{\mu 2\gamma}$	3×10^{-3}	$\sim 10^{-5}$
Total			2×10^{-4}

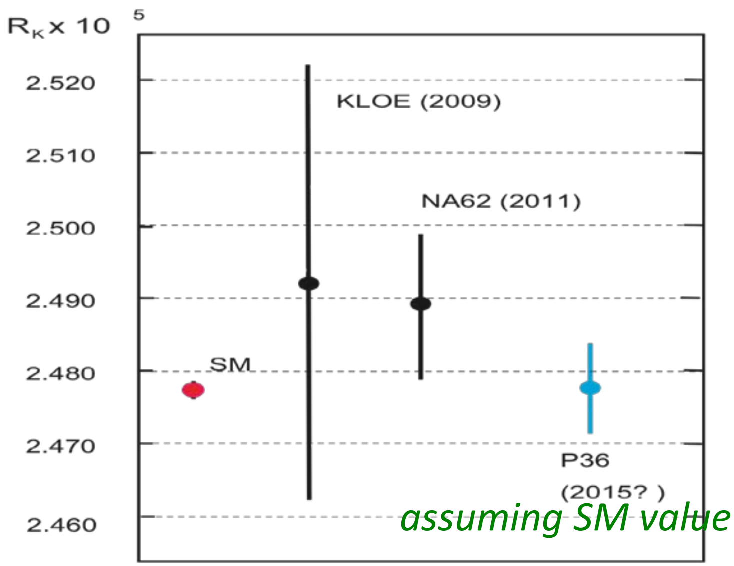
$\delta R_K/R_K$ = 0.00020

Summary of systematic errors

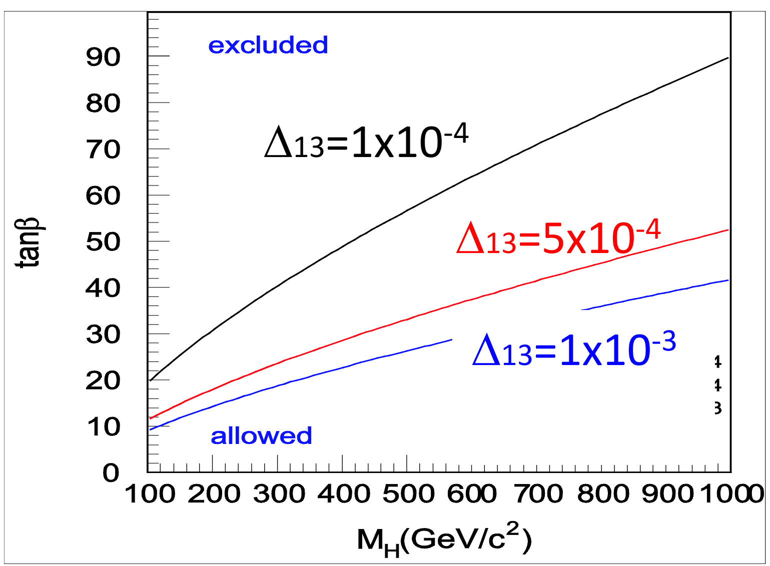
Error source	$\Delta R_K/R_K$	Comment	Addendum 1
(1) **Detector performance**			
Chamber efficiency	0.0004	Method-1	0.00035
PID performance	0.00035	$K_{e2}/K_{\mu 2}$ run	0.00035
CsI(Tl) performance	0.0007	Ambiguity of efficiency	—
Trigger and DAQ	small	to be measured	—
(2) **Background**			
Muon decay in flight	0.00015	Distance to AC	0.00025
Photon conversion	0.0002		0.0002
CsI(Tl) beam hit	0.00018		0.0004
AC beam hit	0.0001		< 0.0001
K^+ conversion	0.00003		< 0.0001
(3) **Analysis**			
Code and cut parameters	small	$\ll 0.001$	—
SD subtraction	0.00036		0.00036
(4) **MC simulation**			< 0.001
Acceptance ratio	0.00078	based on E246	—
Magnetic field	small	< 0.0001	—
Input parameters	small	$\ll 0.0001$	—
Kaon stopping distribution	0.00015		—
Target interactions	0.0004		0.0002
Material thickness	0.0002		—
IB theory	small	$\ll 0.001$	—
Total	0.0015		0.0013

$\delta R_K/R_K$(syst) = 0.0015 while $\delta R_K/R_K$ (stat) = 0.0020

Impact of P36



Constraint on LFV SYSY (90% C.L.)



- A single experiment cannot go beyond its systematic error limit.
- More than two experiments can reduce the systematic limit.
- The combined average with NA62 might be able to indicate a significant deviation from the SM prediction.

重いニュートリノの探索

LUV実験の副産物物理

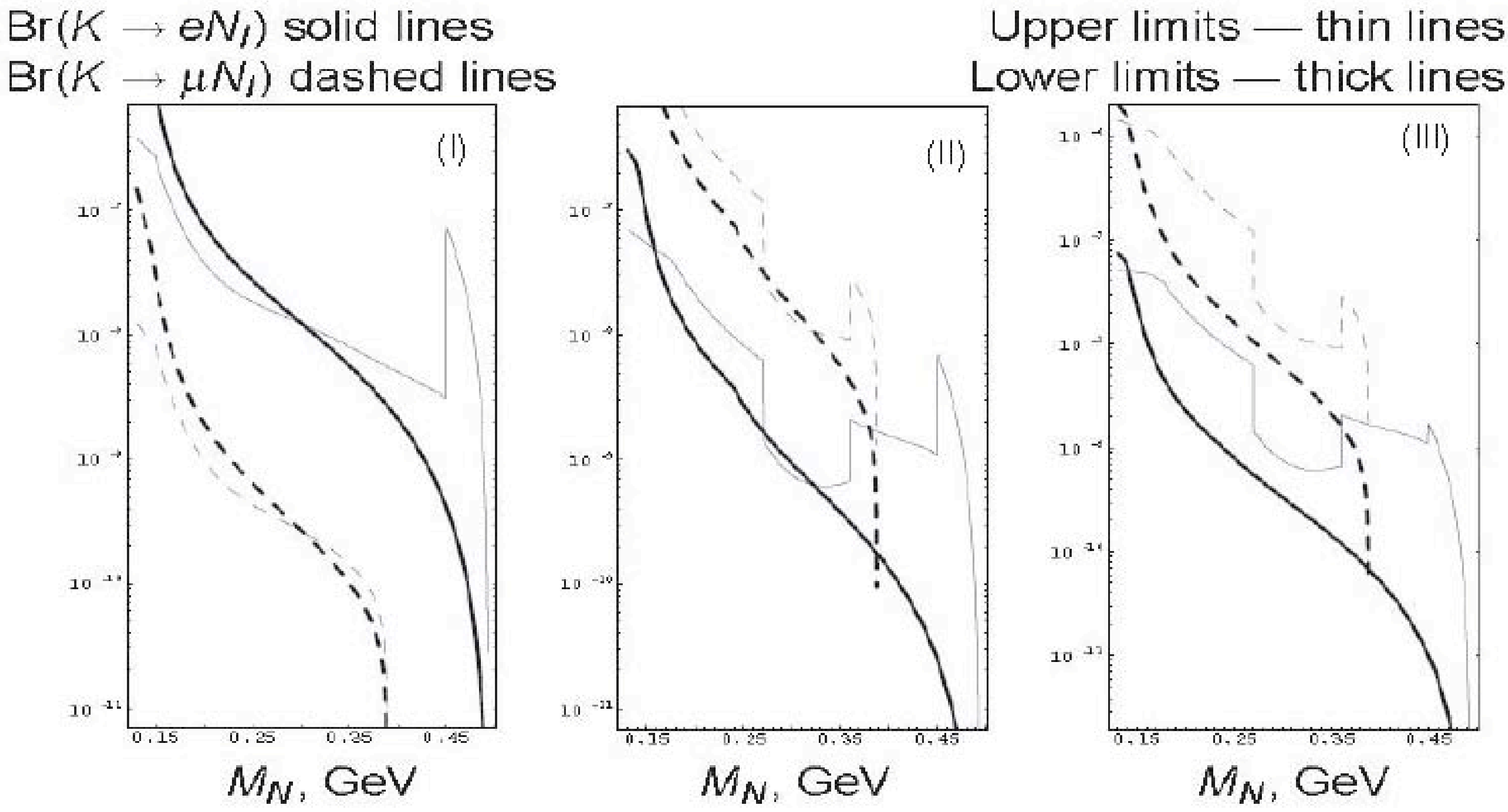
Search for heavy sterile ν (N) in $K^+ \rightarrow \mu^+ N$

- In the framework of renormalizable extension of the SM, the νMSM, 3 light singlet right-handed ν (sterile ν) are introduced.
- The νMSM can simply explain :
  - ν oscillation
  - Light sterile ν play a role of dark matter.
  - Baryon asymmetry can be induced by leptogenisis through ν oscillation.

$$L_N = -1/\sqrt{2} f_\alpha L_\alpha (N_2 + N_3)\Phi - M_2 N_2^c N_2/2 - M_3 N_3^c N_3/2 + h.c.$$

BR in νMSM

Gninenko and Gorbunov, hep-ph/0907.4666v1



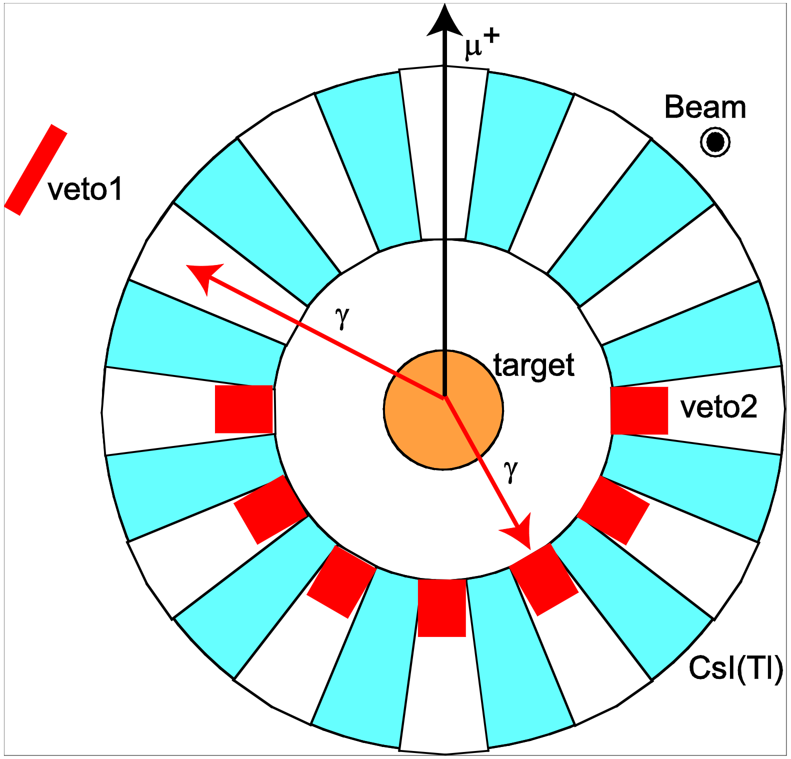
$BR \leq 10^{-6}$ for three "extreme hierarchies" of Yukawa couplings ; $f_e : f_\mu : f_\tau$

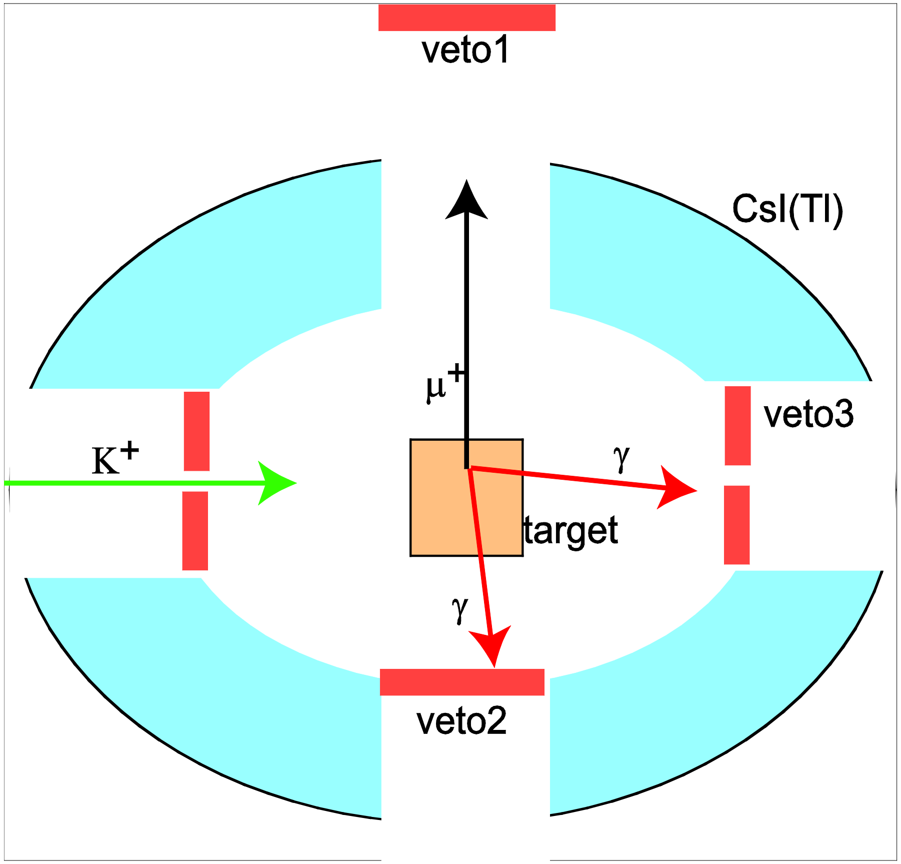
Experimental method

- Two body decay: p (μ^+) is monochromatic.
- μ^+ polarization is large.
  - μ^+ are generated through right-handed current.
  - The E246 polarimeter will be put behind C4.
- Two settings of spectrometer field: 0.65 T, 1.4 T.
  - 1.4 T: only veto1 will be used.
    Data will be taken with the R_K experiment.
  - 0.65 T: $K_{\mu 3}$ with a 2 photon escape is serious background.
    Veto counters will be installed.

Photon veto

In order to suppress the main B.G. of $K_{\mu 3}$ with two γ's escaping





Experimental sensitivity

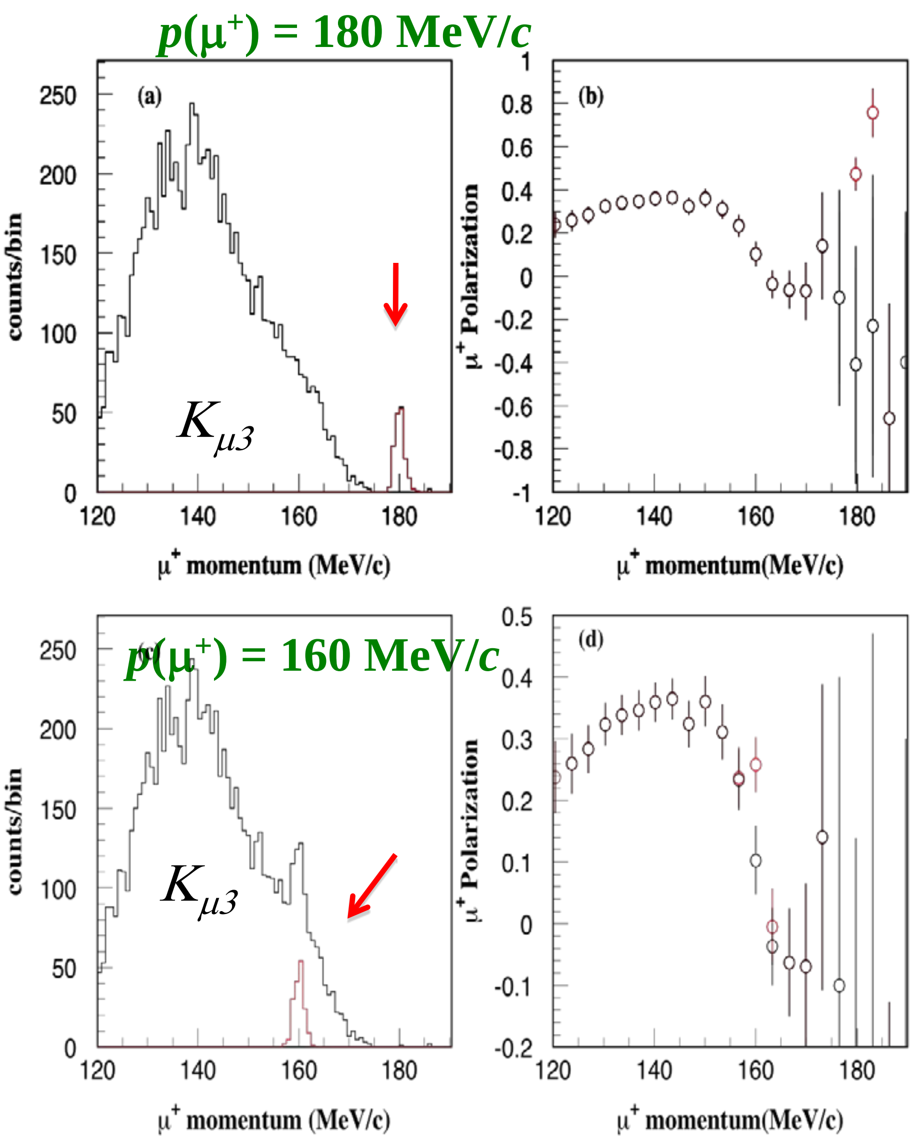
Assumption

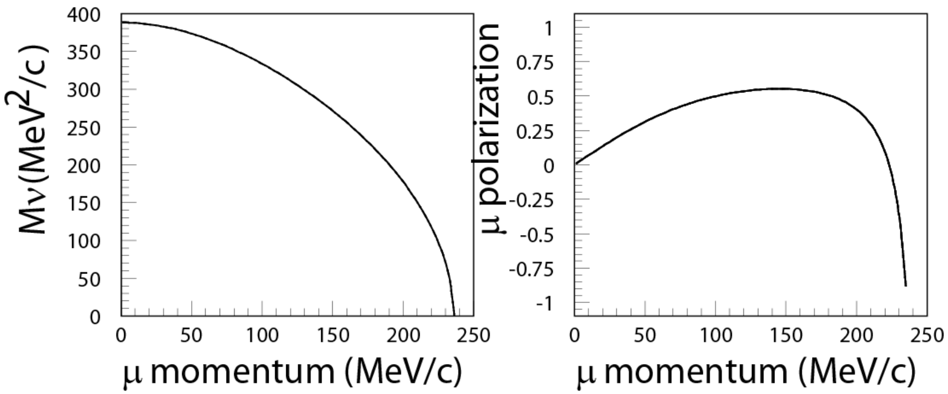
- σ_p = 1MeV/c
- pectrometer field = 0.65 T
- running time: 30 days

Sensitivity

- $BR(K^+ \rightarrow \mu N) \sim 10^{-8}$

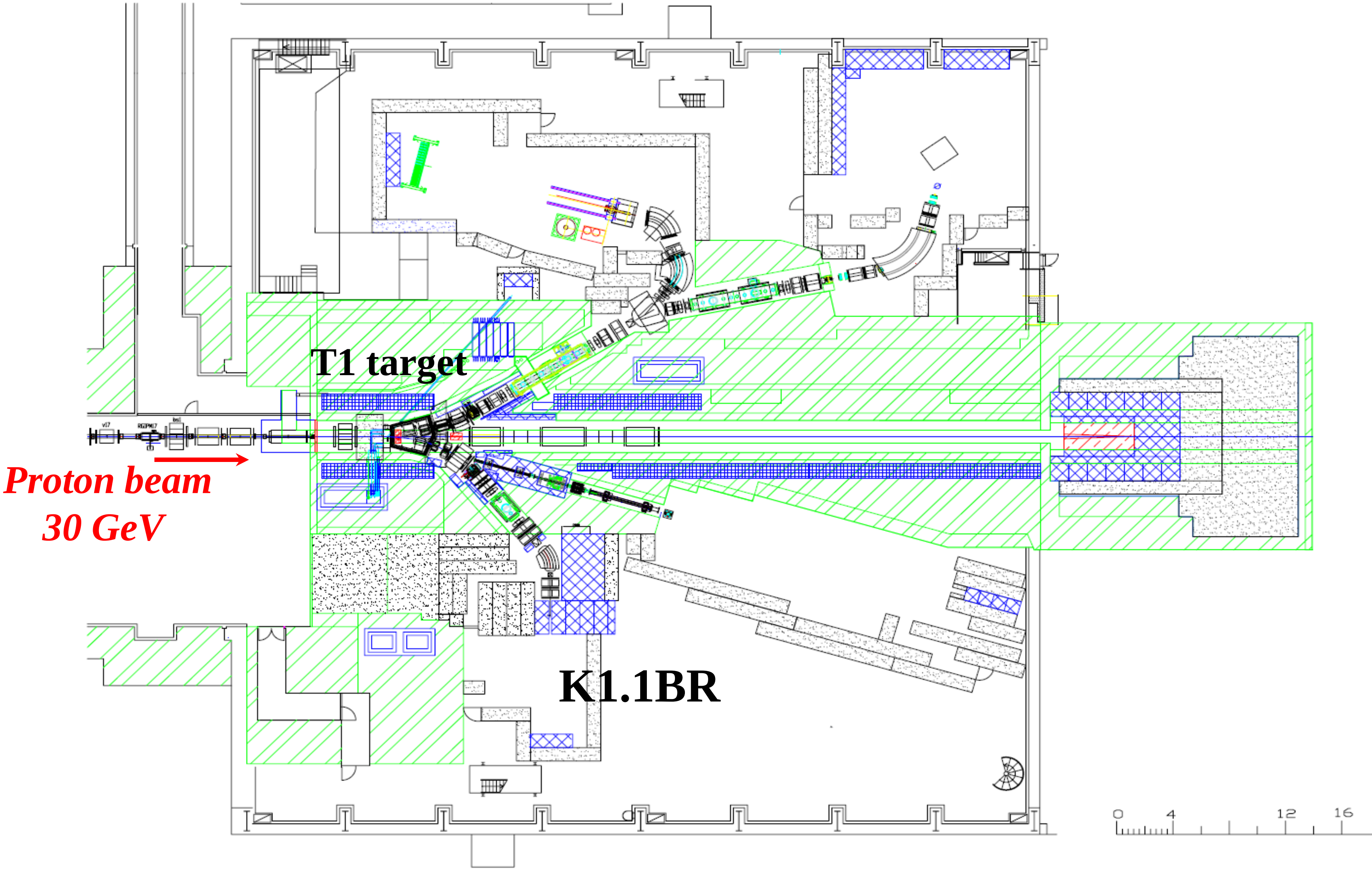
Polarization measurement will be effective !



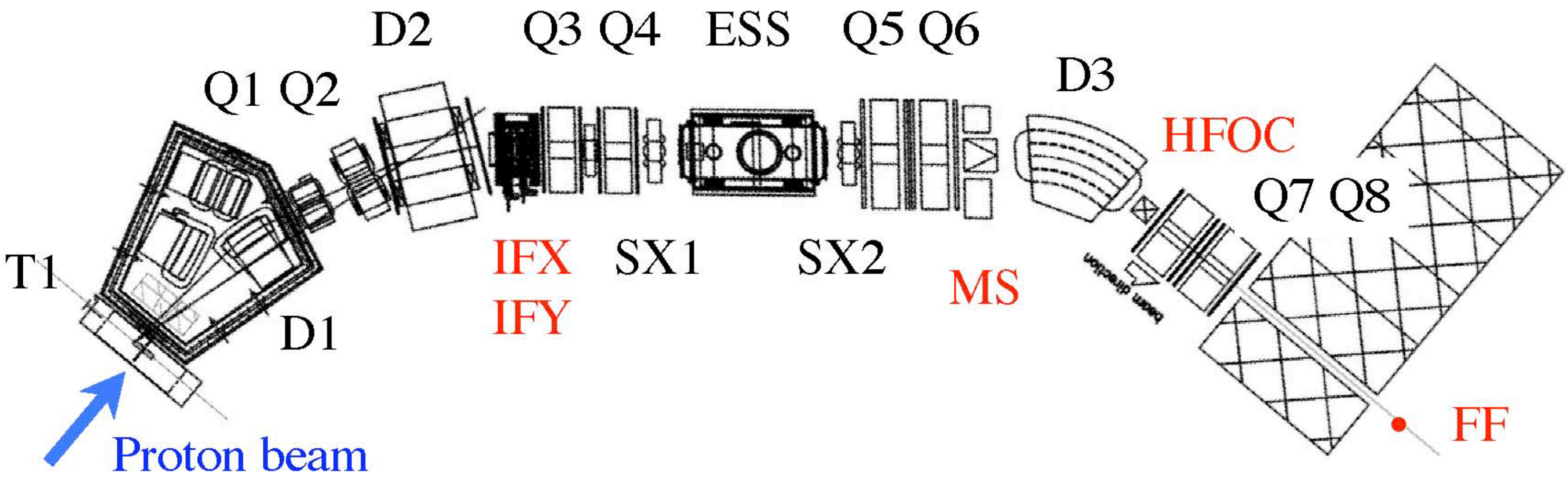


ビームライン

Hadron Experimental Hall



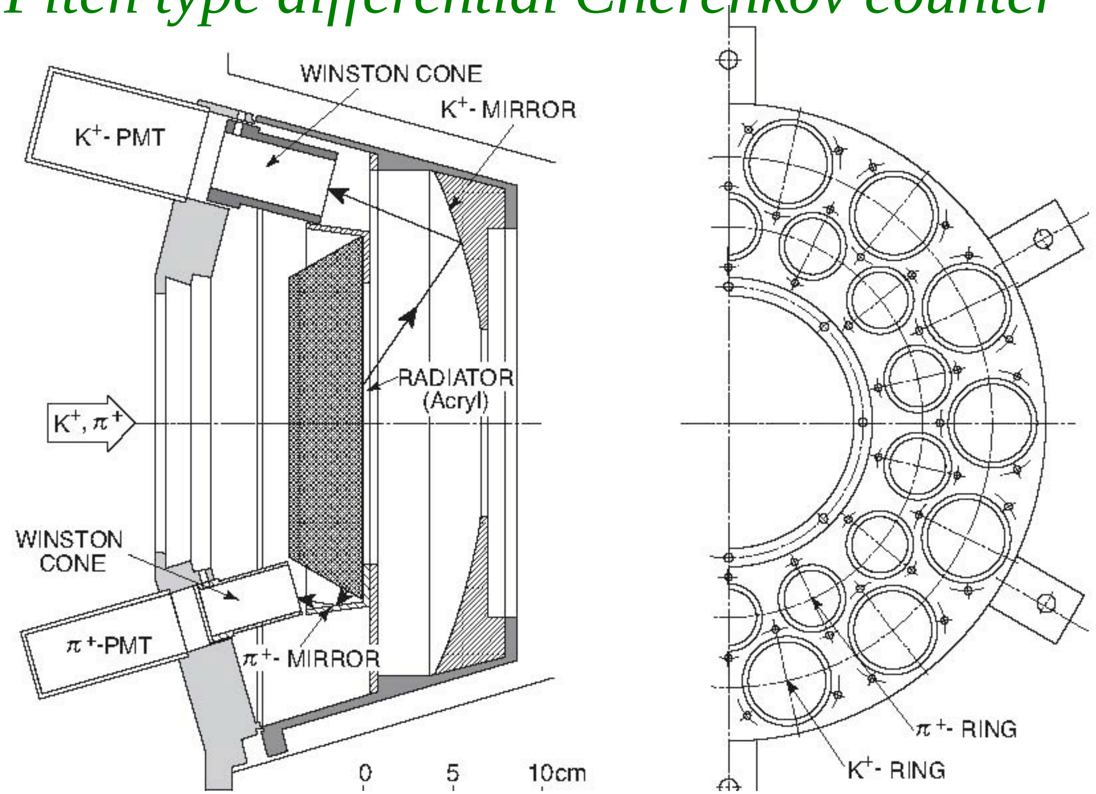
K1.1BR beam line

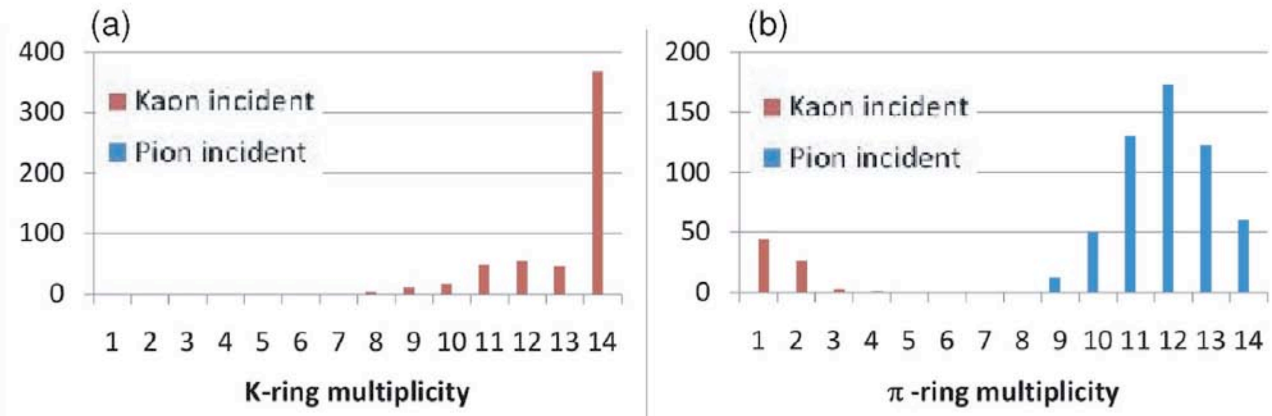


Operation beam momentum p	800 MeV/c
Length of the beam line	20.3 m
K^+ intensity at p	2×10^5/s @30 kW
K^+/π^+ ratio at p	$\sim$2
Beam spot size at final focus	1 cm [H], 1 cm[V] in σ
R_{16}, R_{26}	R_{16} <0.1 cm/%, R_{26}=17.6 mr/%
Acceptance	4.5 msr% ($\delta p/p$)
Momentum bite	±3%

Beam Cherenkov counter

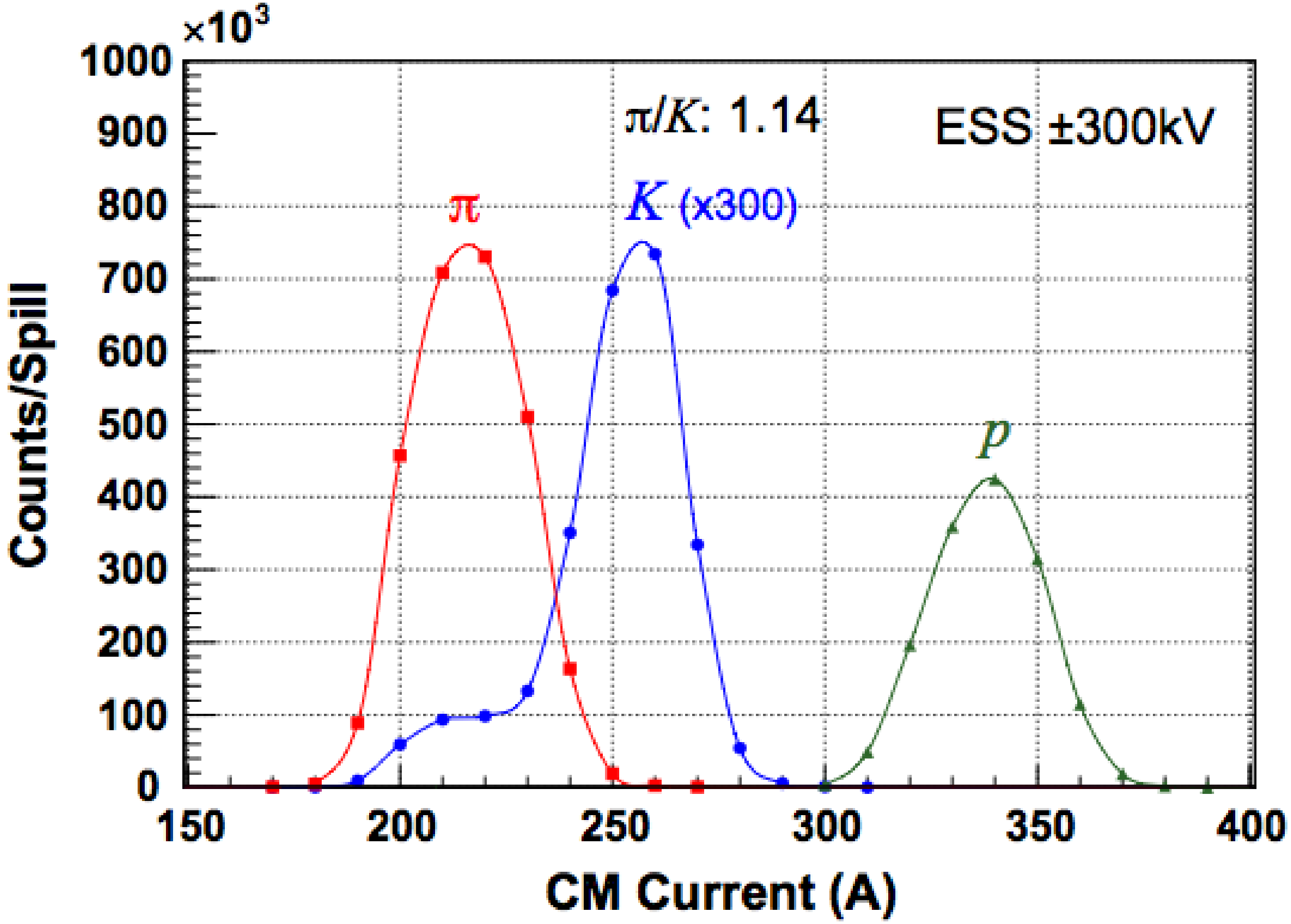
Fitch type differential Cherenkov counter



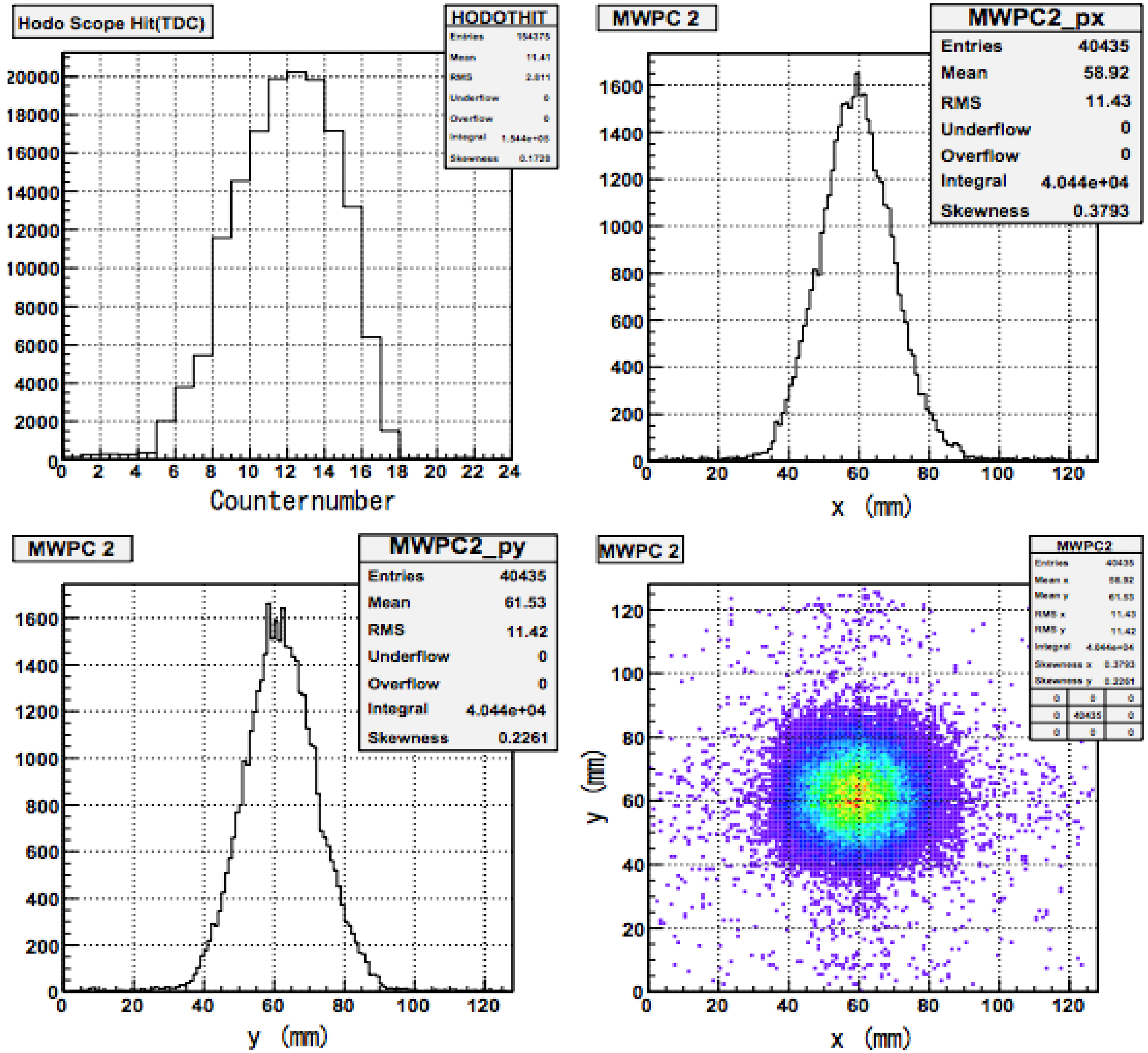


Kaon separation curve

Beam tuning in November 2010

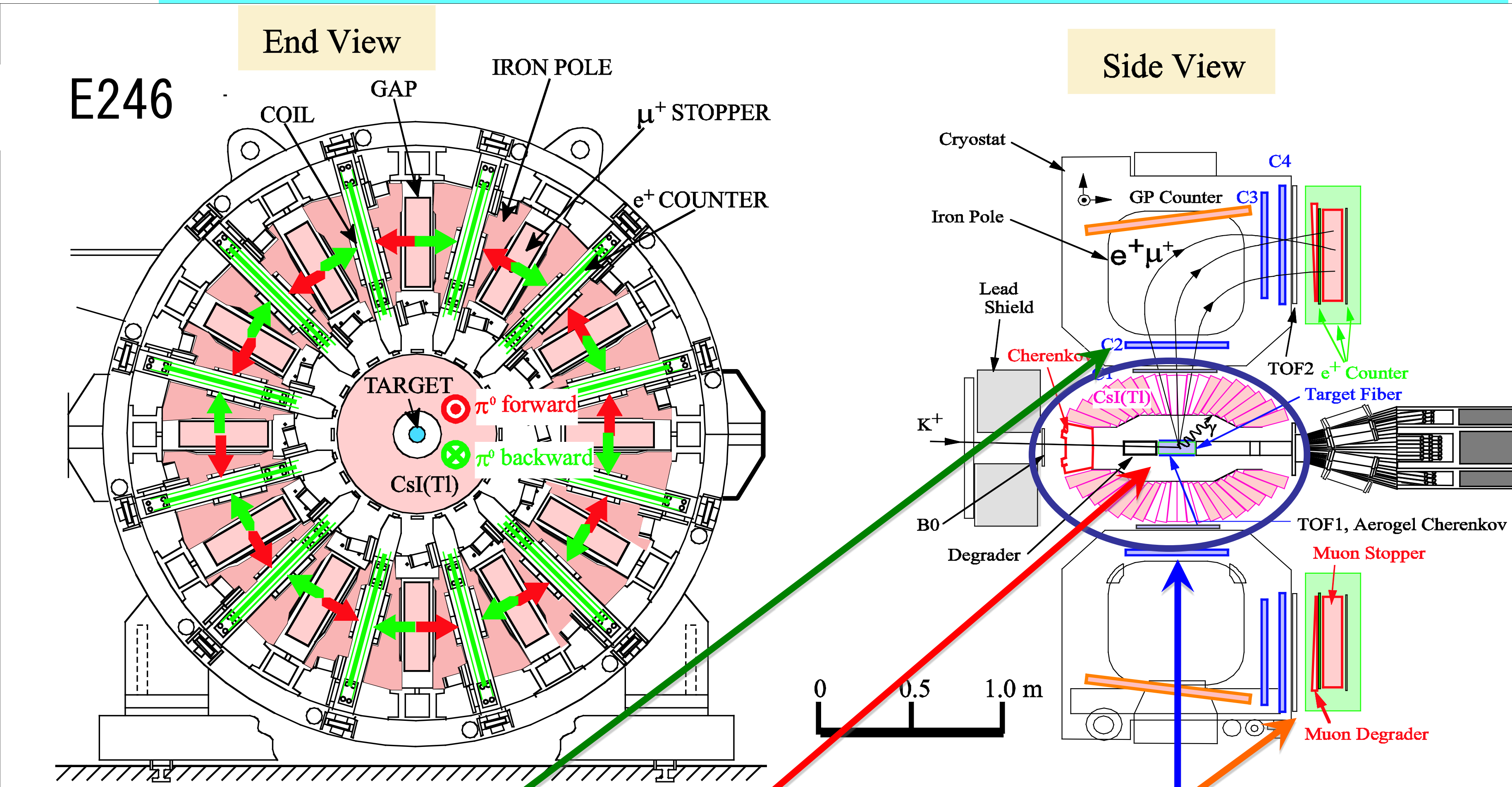


Kaon beam spot at FF



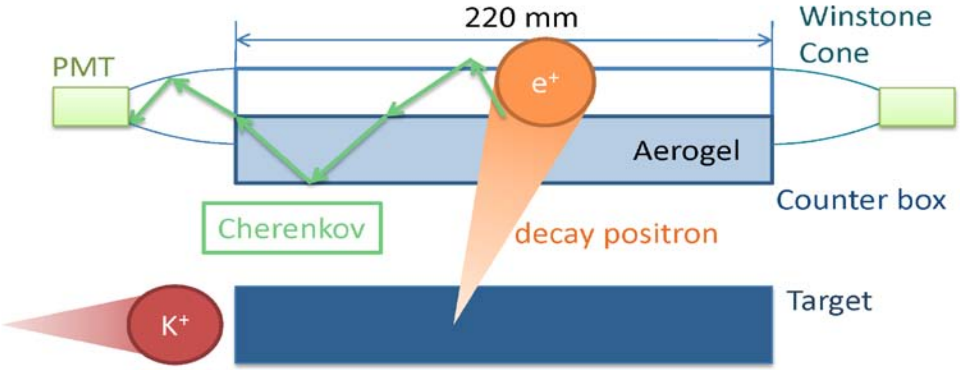
Detector R&D

Detector upgrade

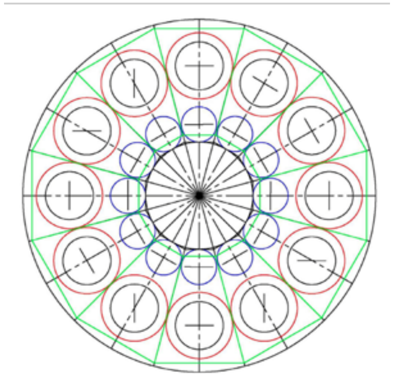


- C1 GEM
- Aerogel Cerenkov
- TOF
- CsI(Tl) readout

Aerogel Cherenkov counter

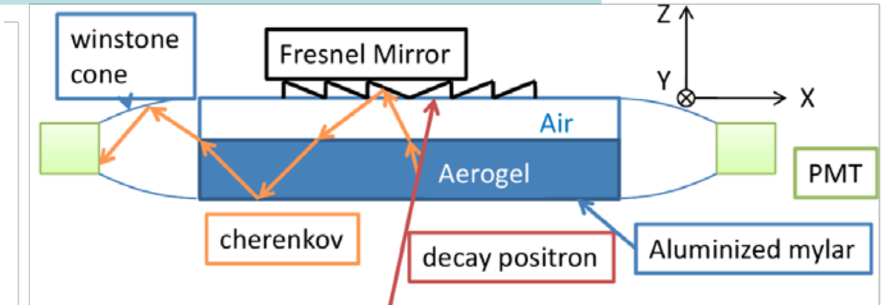


$n = 1.05$



- **1st Prototype counter**

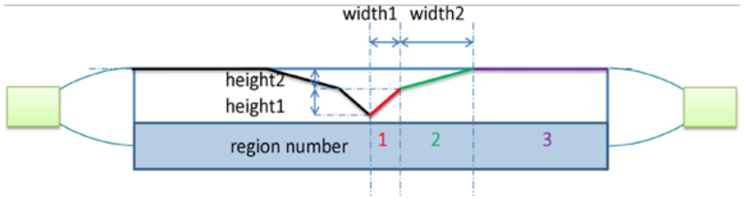
Sawtooth mirror



ε~99% but non-uniformity

- **2nd Prototype counter**

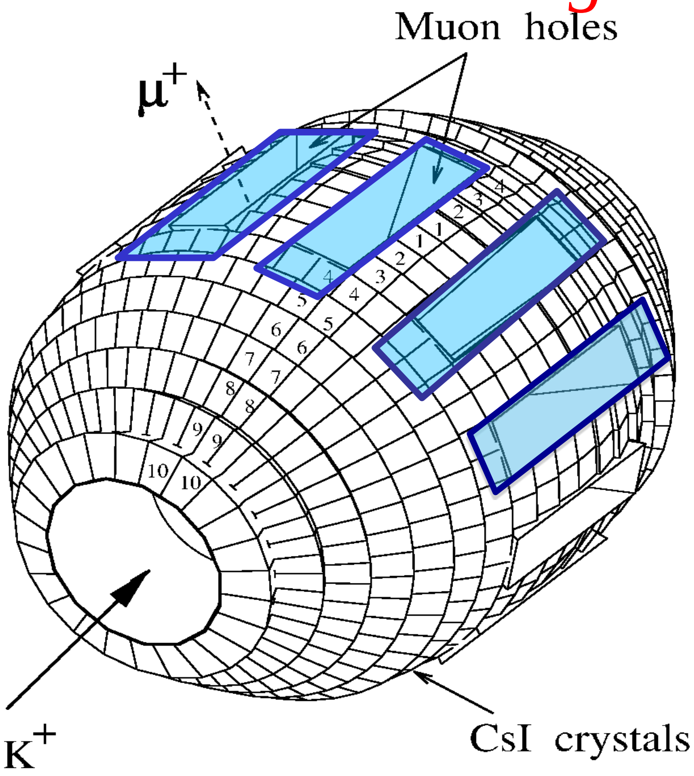
Polygonal mirror



Beam test in June

C1: Planar GEMs for P36

- *For higher tracking performance*

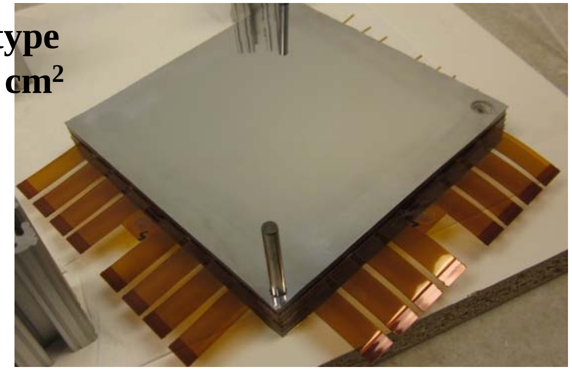


12 C1 triple-GEMs to cover muon holes of CsI(Tl)

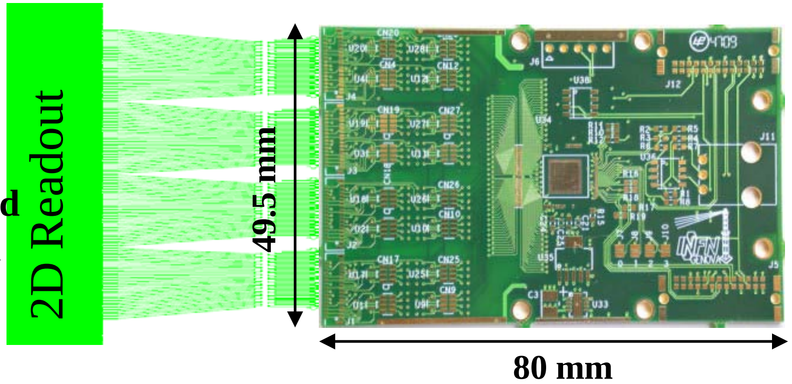
Stereo readout in shadow of CsI crystals based on APV25-S1 (128 channels per chip)

Active length (z)	**480 mm**
Active width (y)	**200 mm**
Spatial resolution	**<100 μm**
Readout strips: pitch	**400 μm**
No. of channels (z)	**1200 (<10x128)**
No. of channels (y)	**500 (<4x128)**
Total no. of channels	**1700**
APV chip per chamber	**14**
Total cost ($$)	**350,000**

Prototype 10x10 cm²



APV based frontend readout

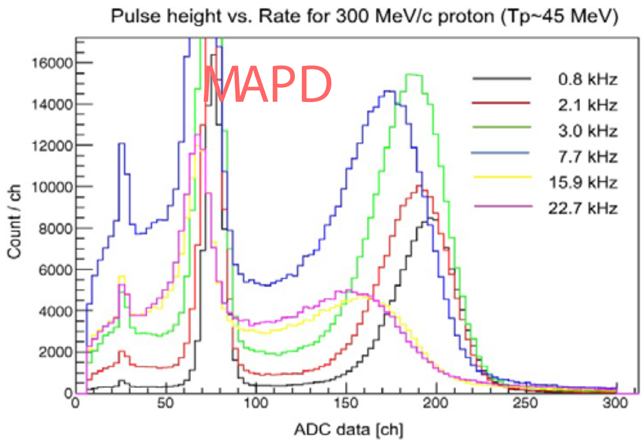


- **Beam tests at FNAL**

CsI(Tl) Readout

• *For higher rate performance*

- Possible 3 candidate schemes:
  - – PIN-diode readout (same as in E246)
    - Best *K/π* ratio is required (Beam line K1.1BR)
  - – APD readout (developed in 2010)
    - Already established, but rather expensive
  - – MAPD readout (development in progress now)
    - Good *S/N* ratio, and cost effective
    - Rate capability test @ TRIUMF in autumn of 2011



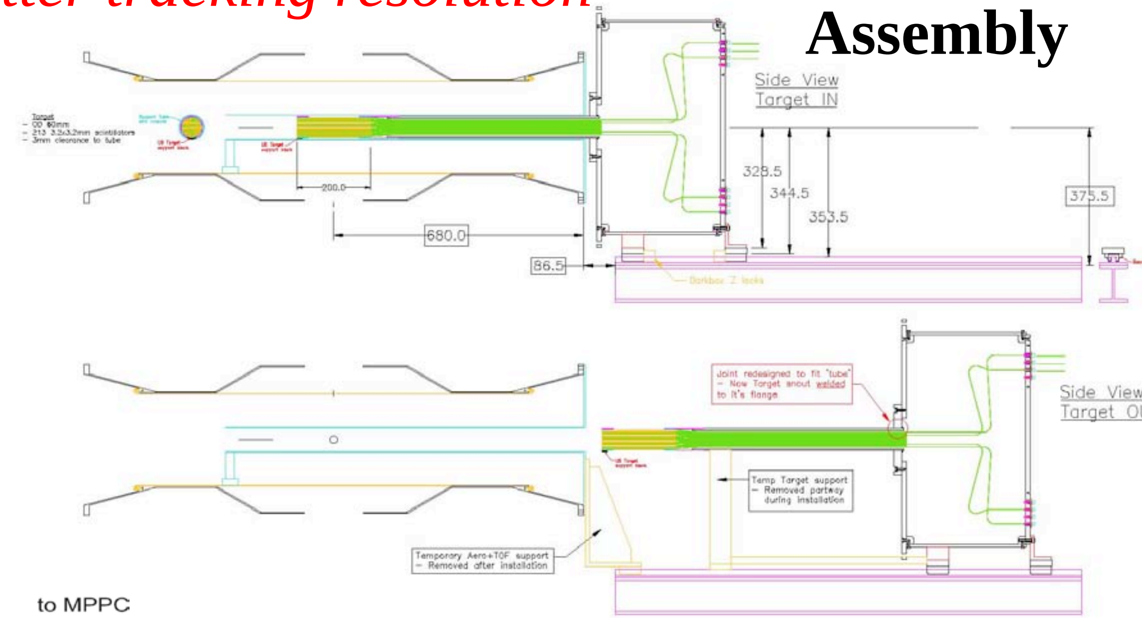
•There is still rate dependence
•Better one is now being developed

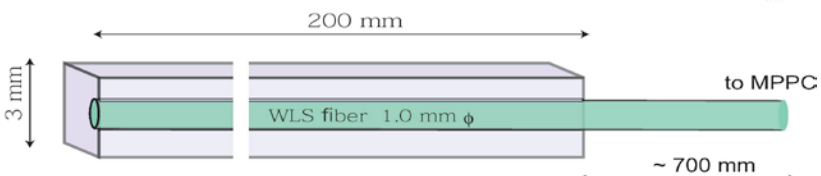
Target for P36

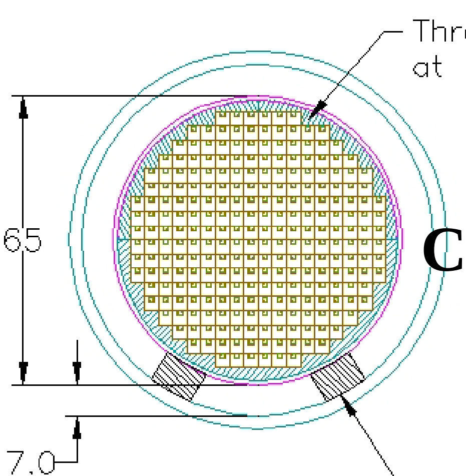
For better tracking resolution

- 256 pieces of
- 3 x 3 x 200 mm^3 SciFi
- WLS fiber of ~1m
- MPPC readout
- EASIROC electronics
- Production in Canada

Assembly



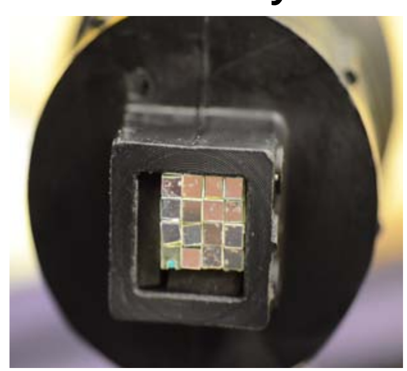


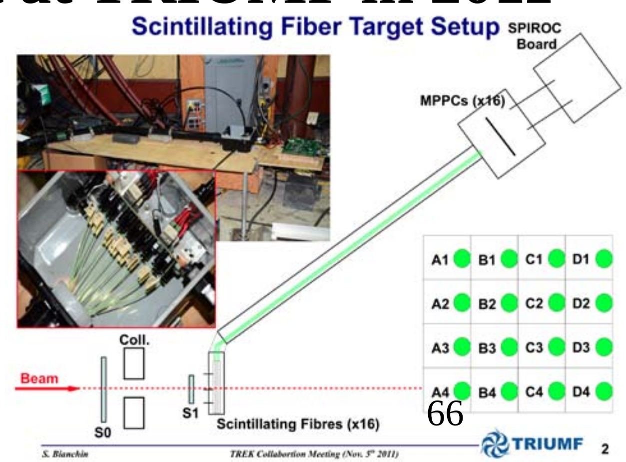


Cross section

Beam test at TRIUMF in 2011

4x4 array





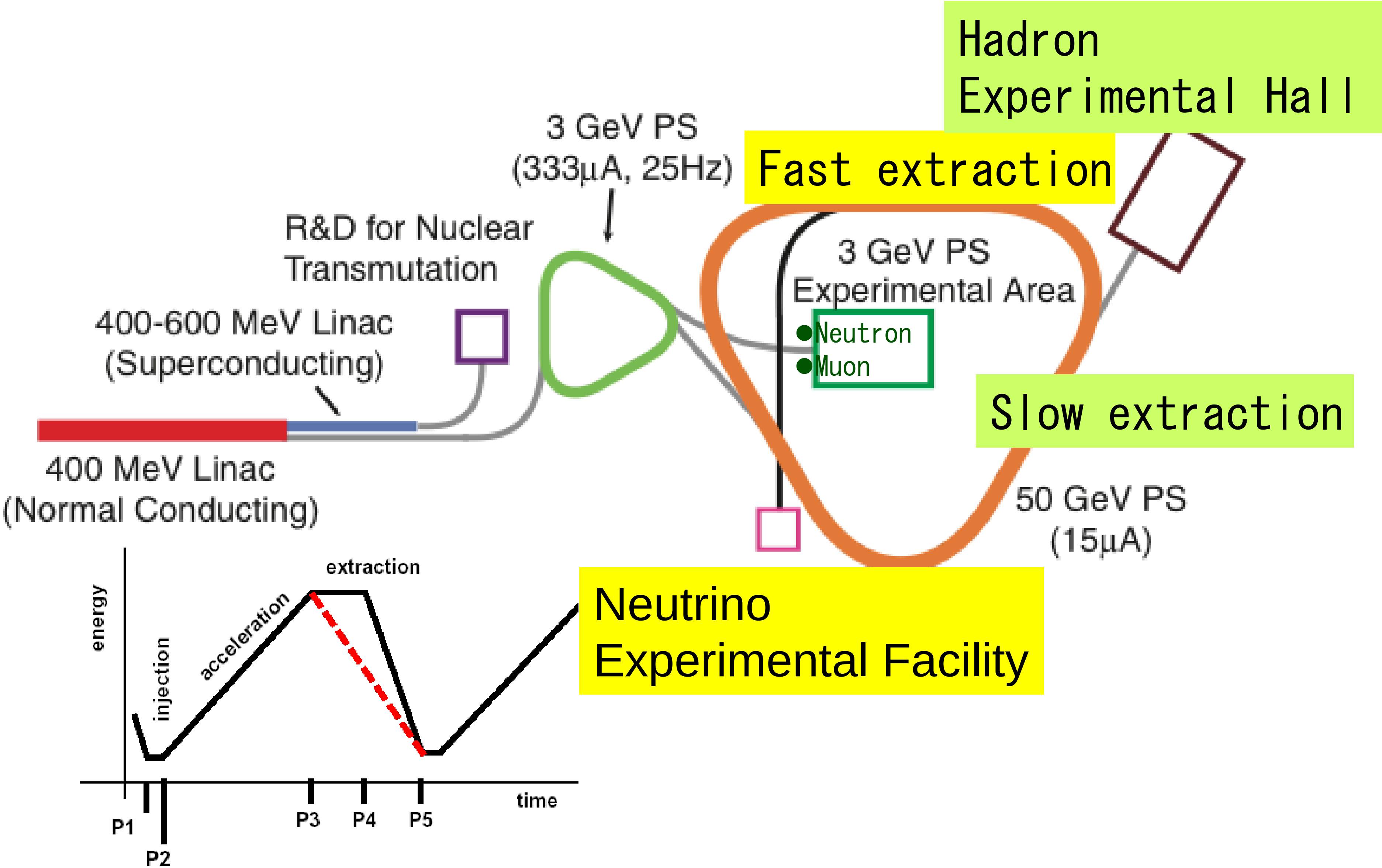
Time schedule

	2012	2013	2014	2015	2016	later
P36	R&D etc.	Detector construction				
		He refrigerator installation				
				Run@K1.1BR		
E06			Polarimeter construction			
				(If K1.1BR available)	Run@K1.1BR	
					(If K1.1BR not available)	Run in extended Hadron Hall ?

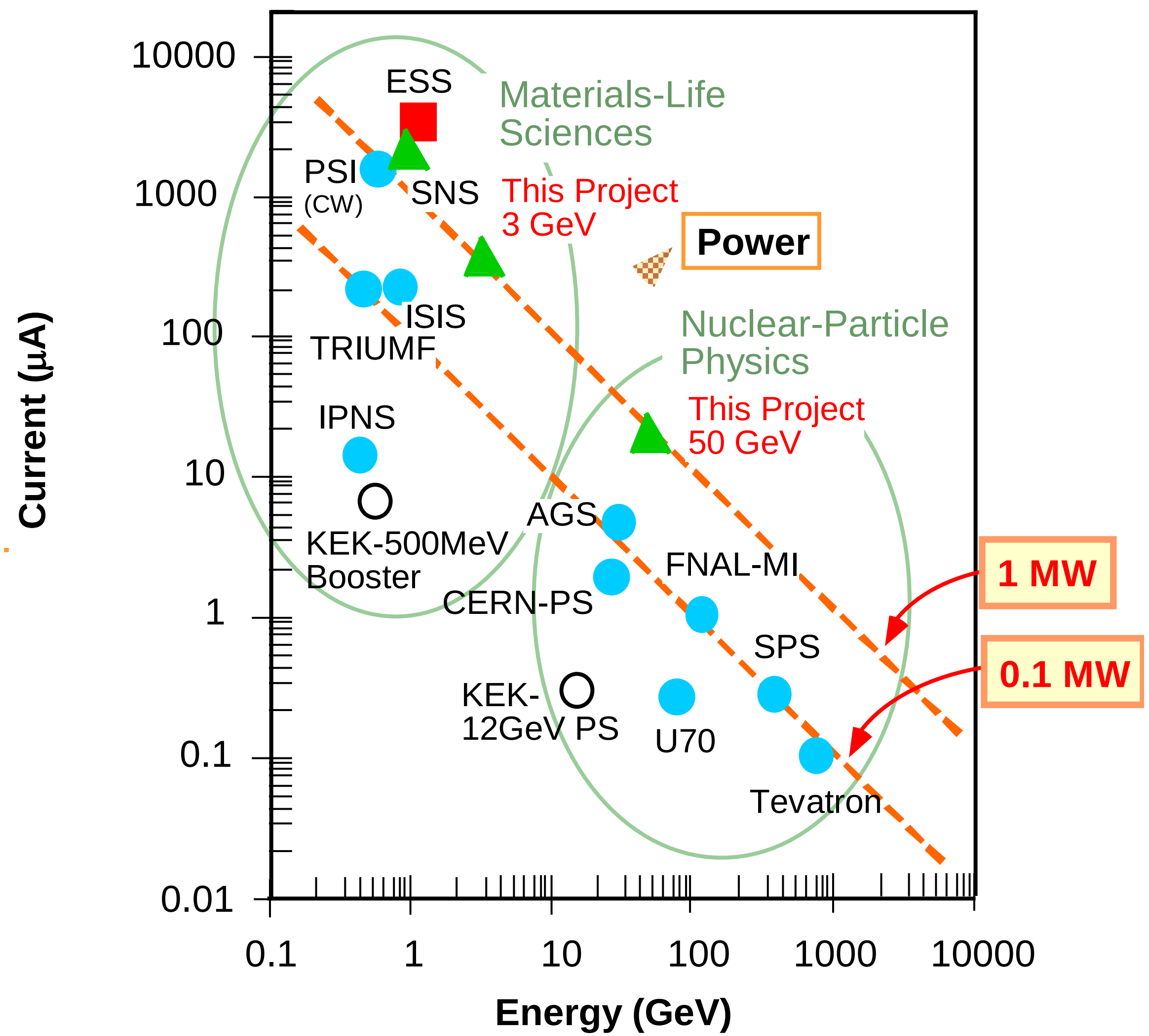
Summary

- Violation of lepton universality is a sensitive probe of LFV SUSY interaction.
- $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ is a good channel to search for LU violation.
- J-PARC P36 experiment aims for the sensitivity of $\delta R_K/R_K = 0.25\%$.
- We aim to run P36 in 2015. The detector is now being prepared.
- Participation of young people are very welcome.

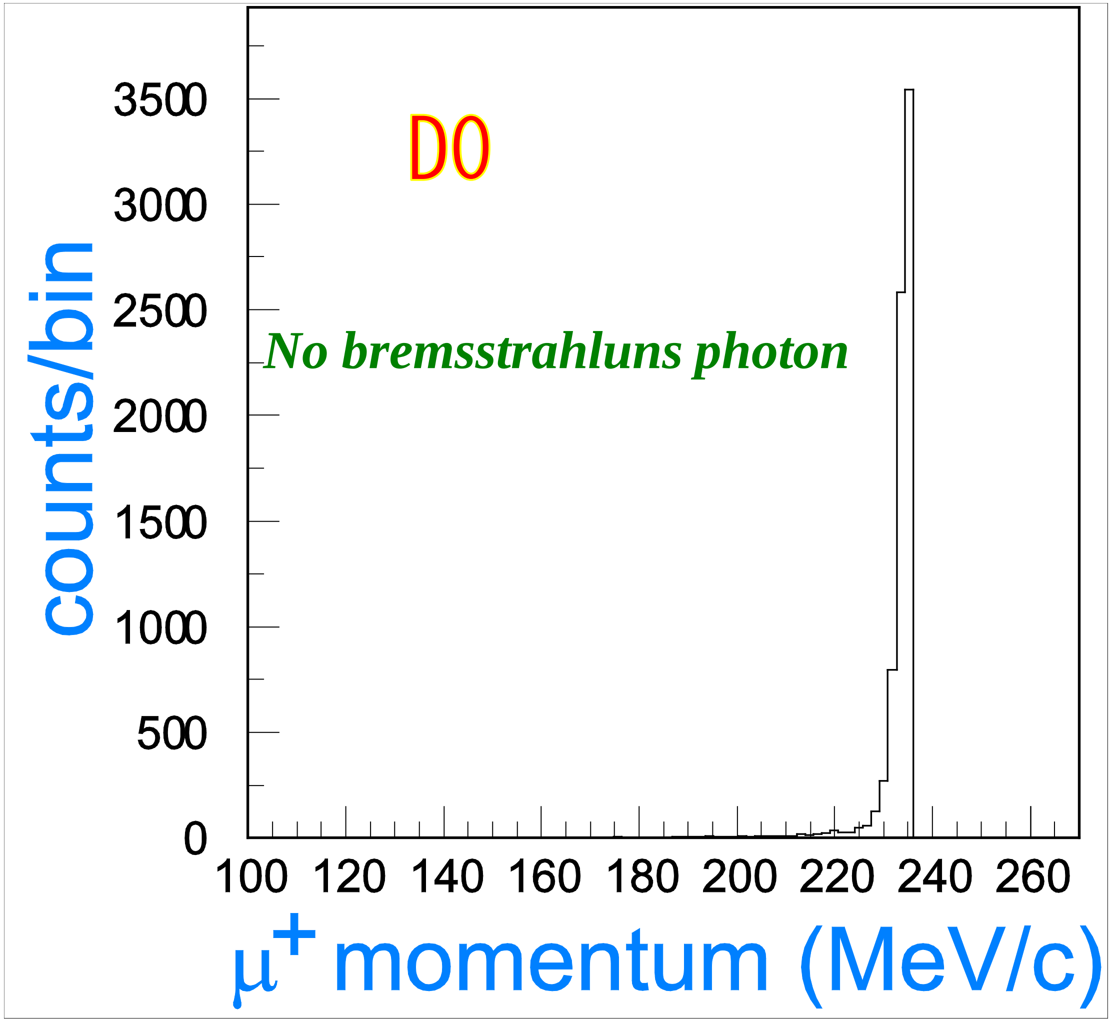
J-PARC accelerator complex



Proton accelerators in the world



$K_{\mu 2}$ momentum spectrum



Aerogel Cherenkov counter

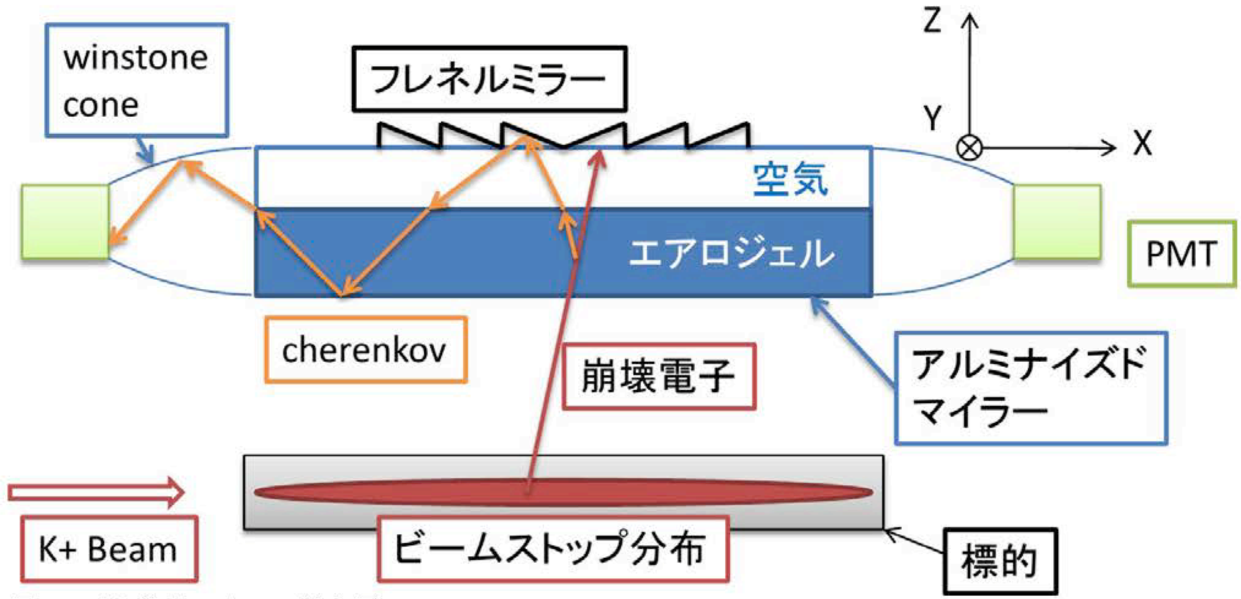
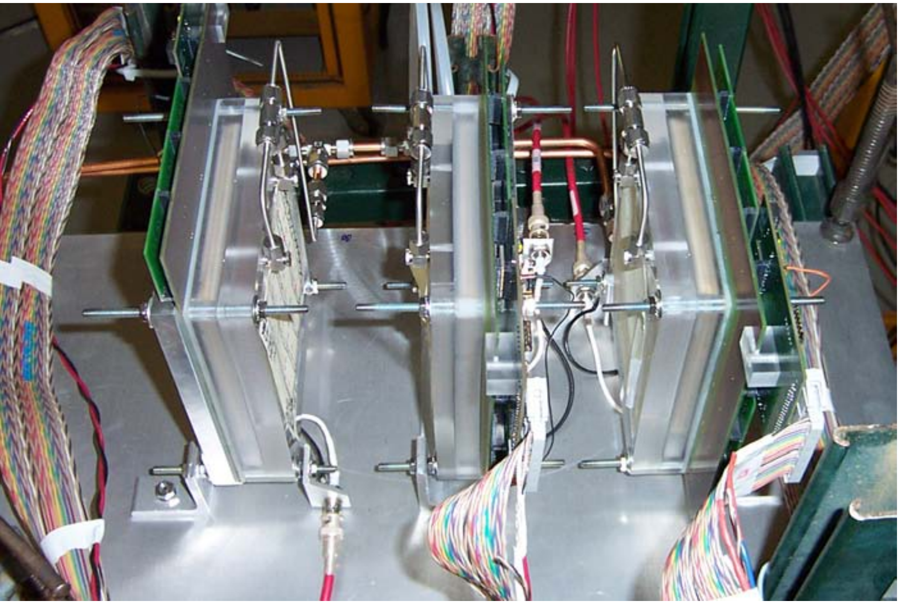


図 1：AC カウンターの概念図

図 2：AC カウンター実験の電子入射の組み合わせ

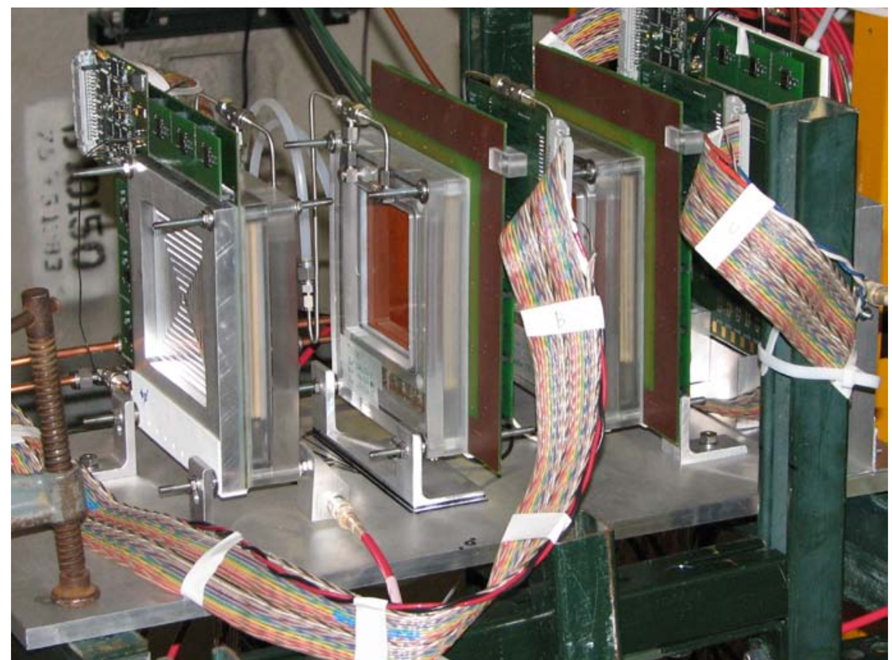
GEM test at FNAL



Telescope of 3 Triple GEM prototypes (10 x 10 cm^2) using TechEtch foils
Middle detector rotatable $\pm 30^o$

F. Simon et al., IEEE2007, arXiv:0711.3751

- 120 GeV proton beam from Main Injector
- unseparated secondary beam at 32 GeV, 16 GeV, 8 GeV and 4 GeV

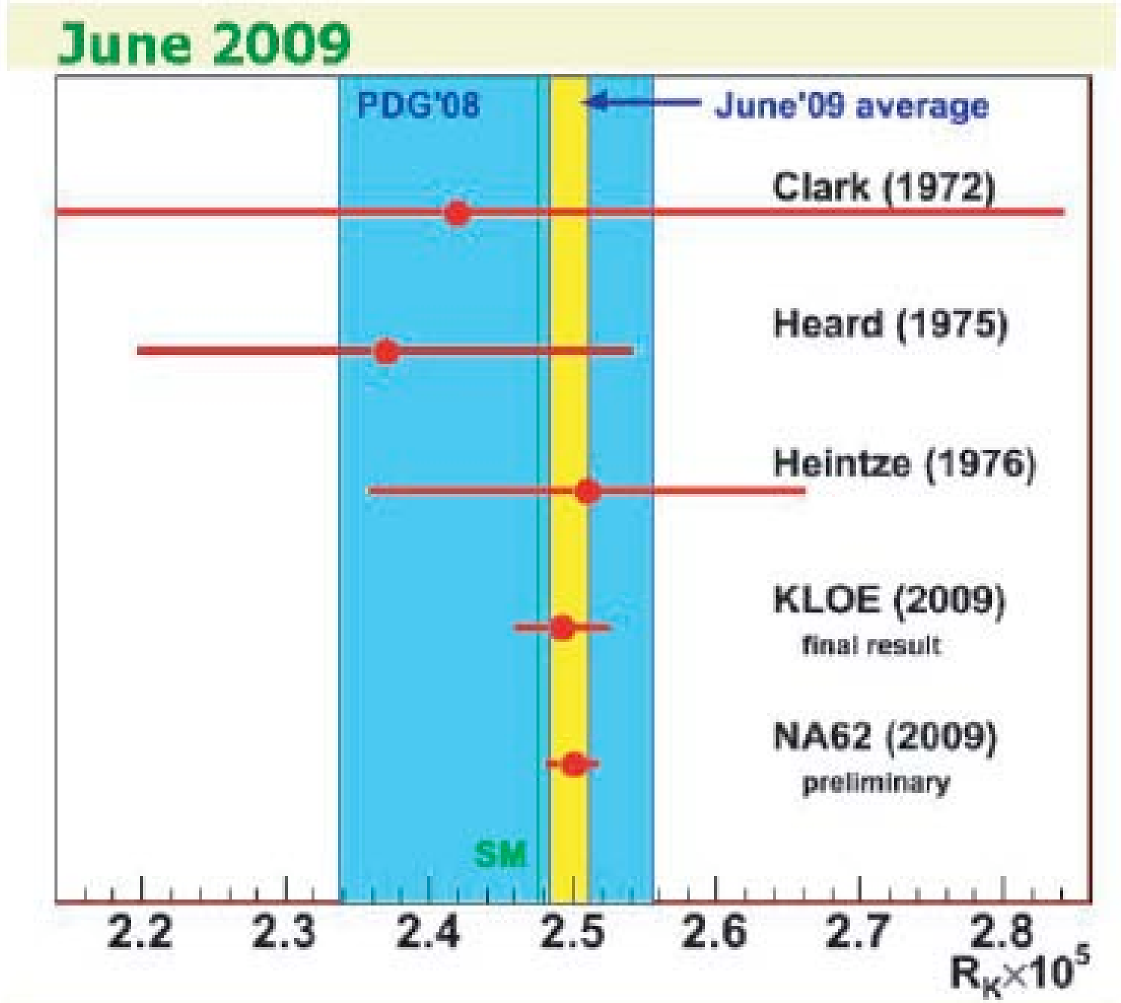


Experimental status summary

Measurement	Kaon Beam	PID	R_K ($\times 10^{-5}$)	$\Delta R_K/R_K$
PDG08 [1]			2.45±0.11	5%
KLOE [13]	In-flight ($\phi \to K^\pm$)	E/p and TOF	2.493±0.025±0.019	1.3%
NA62 [14]	In-flight (p($K^\pm$) = 74 GeV/c)	E/p	2.500±0.016	0.4%
TREK	Stopped K^+	TOF and $\hat{C}$		0.2%
SM [38]			2.472±0.001	0.04%

Measurement	Pion Beam	PID	R_π($\times 10^{-4}$)	$\Delta R_\pi/R_\pi$
PDG08 [1]			1.230±0.004	0.3%
PIBETA [39]	stopped π^+	E/p	1.2346±0.0035±0.0036	0.4%
Britton et al. [40]	stopped π^+	$\pi \to \mu \to e$	1.2265±0.0034±0.0044	0.4%
PEN [30]	stopped π^+	E/p		$< 0.05\%$
PIENU [31]	stopped π^+	$\pi \to \mu \to e$		$< 0.1\%$
SM [1]			1.2353±0.0004	0.03%

Status of $K_{e2}/K_{\mu 2}$



Is the 1.9 σ deviation a significant effect?

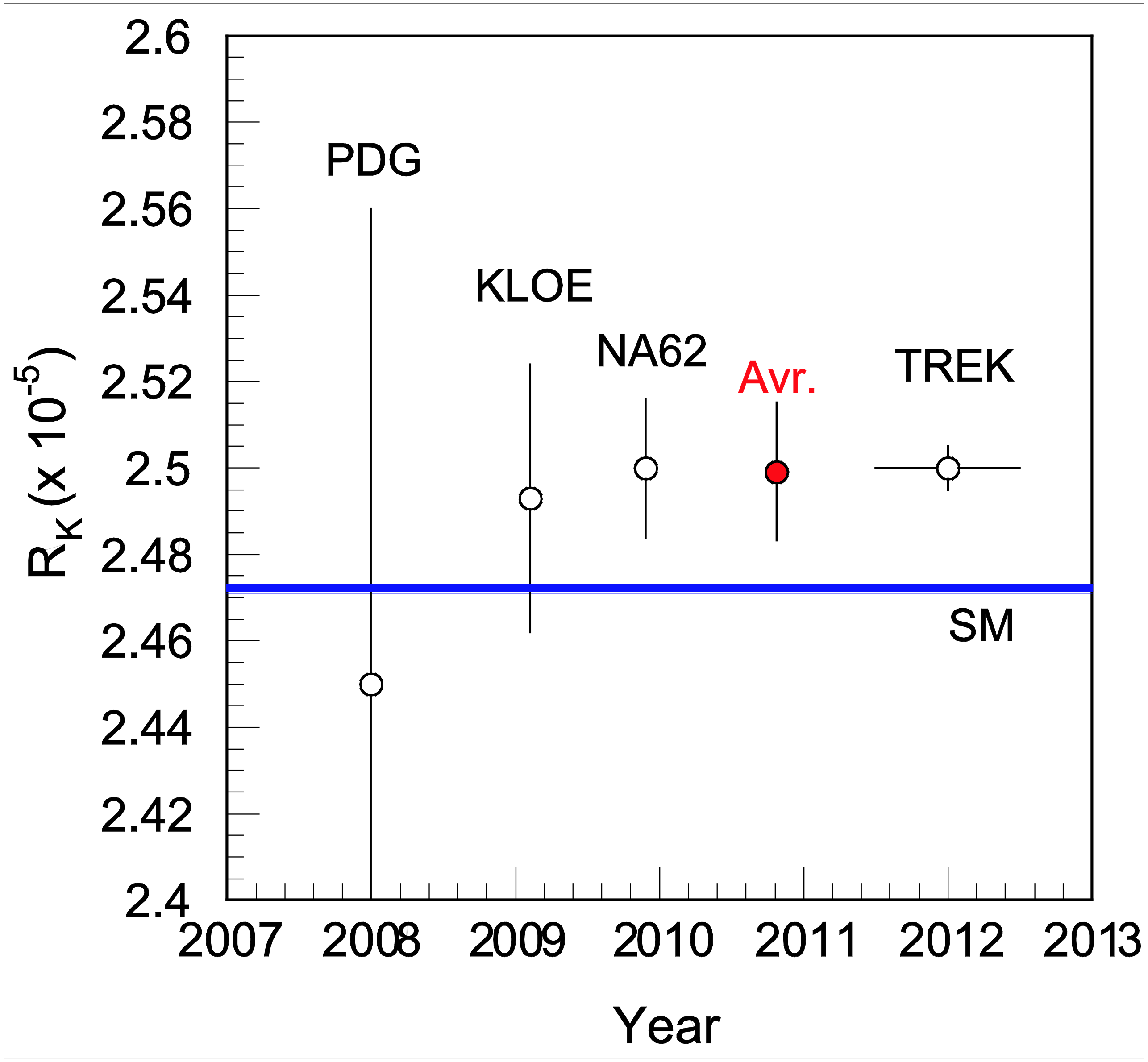
Statistical error

50 days @ 30 kW

	statistics
1. Beam:1500kW・day (= 30 kW・50 days)	1×10^{12}
2. Kaon stopping eff. : 0.25	3×10^{11}
3. Branching ratio of K_{e2}: 1.55×10^{-5}	4×10^{6}
4. Detector acc. : 0.07	3×10^{5}

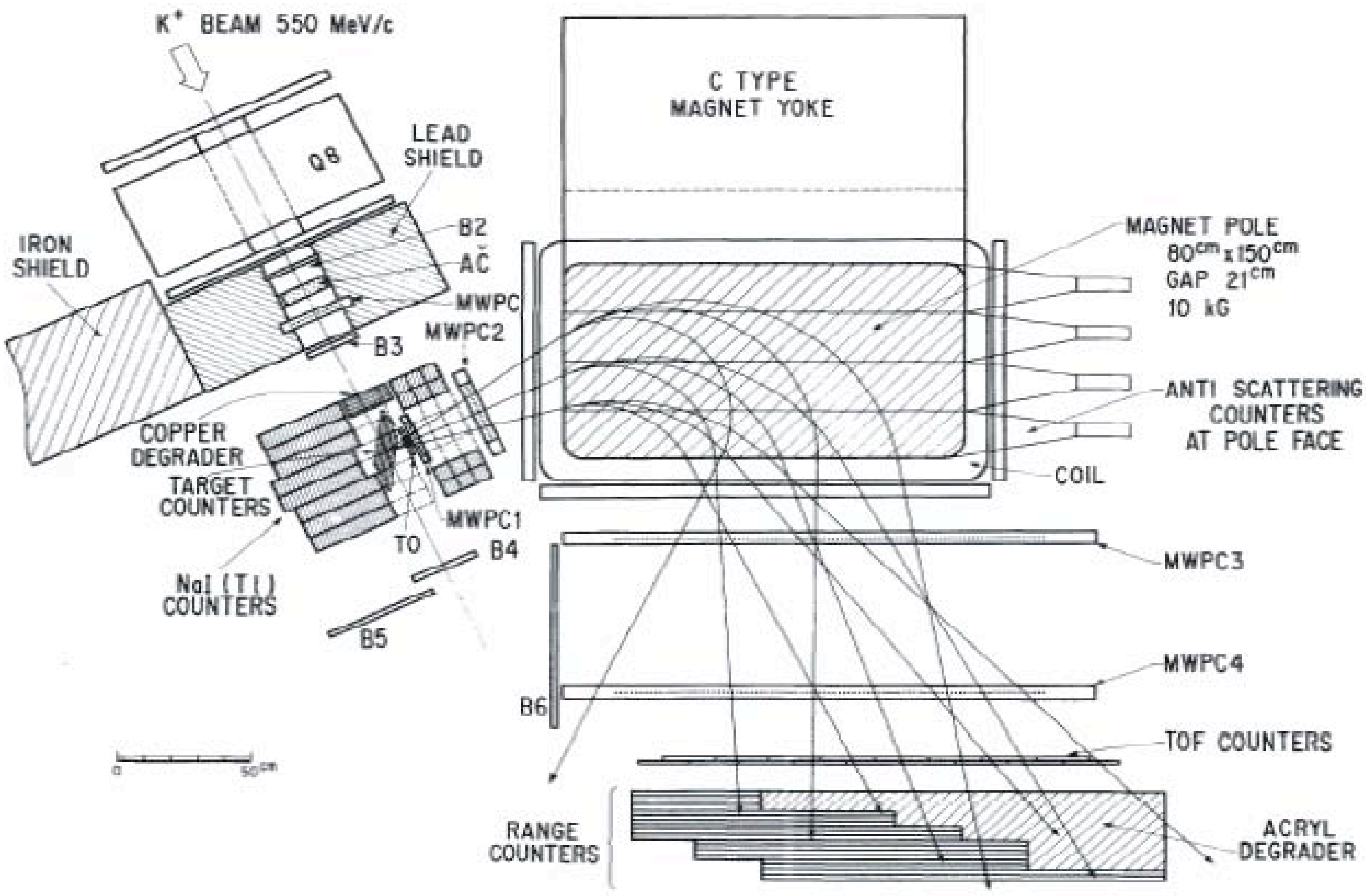
Statistical error $\Delta R_K/R_K = 0.2\%$

Expectation



KEK-PS E99 experiment

Hayano et al. 1982



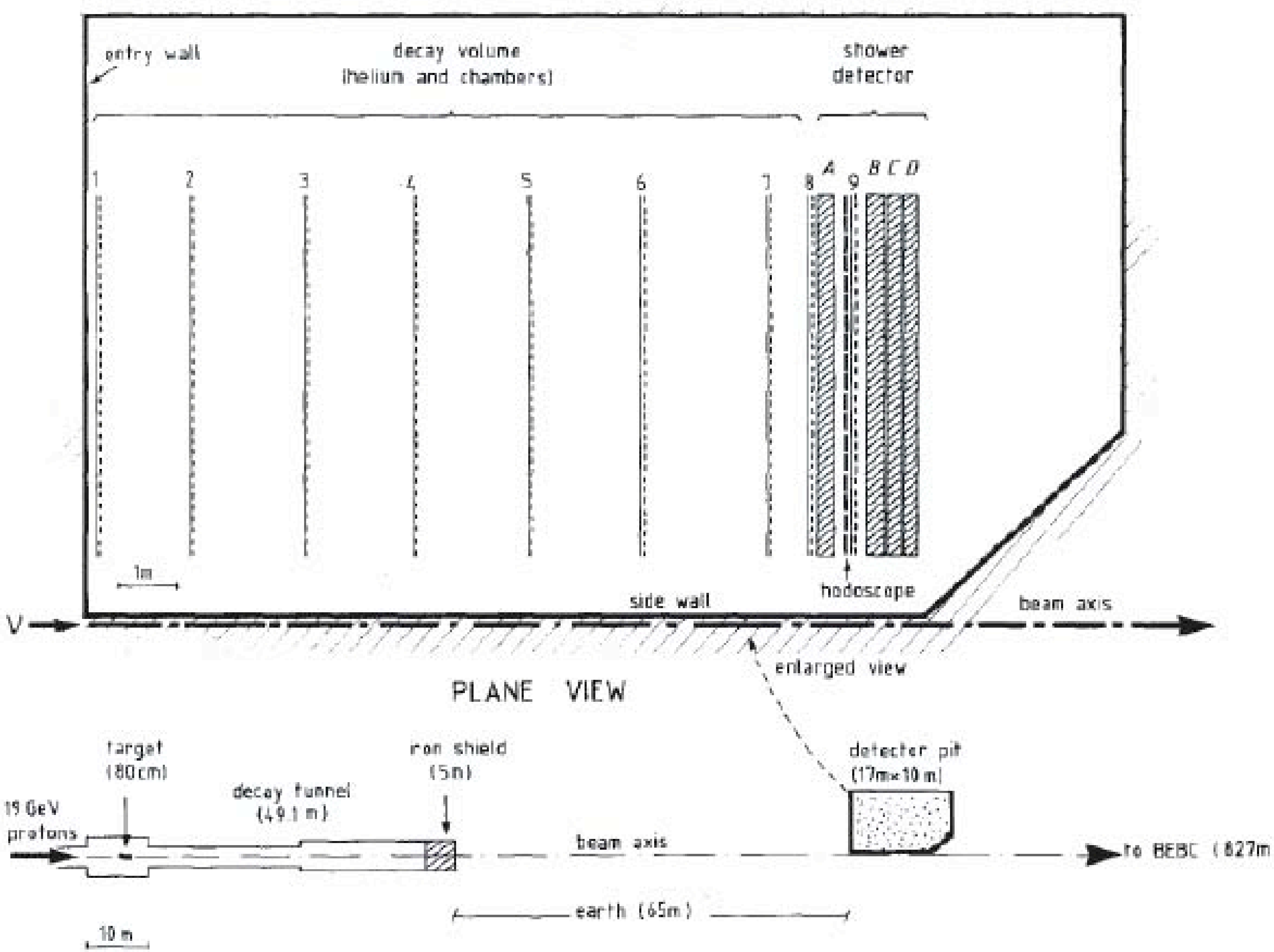
Comparison with E99

Items	KEK-PS E99	This proposal
$\Omega(\mu^+)$	0.8%	7%
$\Omega(\pi^0)$	92%	>99.9%
spectrometer	dipole, 4 trackers	toroidal, 4-5 trackers
calorimeter	$11.5X_0$ NaI(Tl)	$13.5X_0$ CsI(Tl)
μ^+ polarimeter	not used	used
sensitivity	10^{-6}	10^{-8}

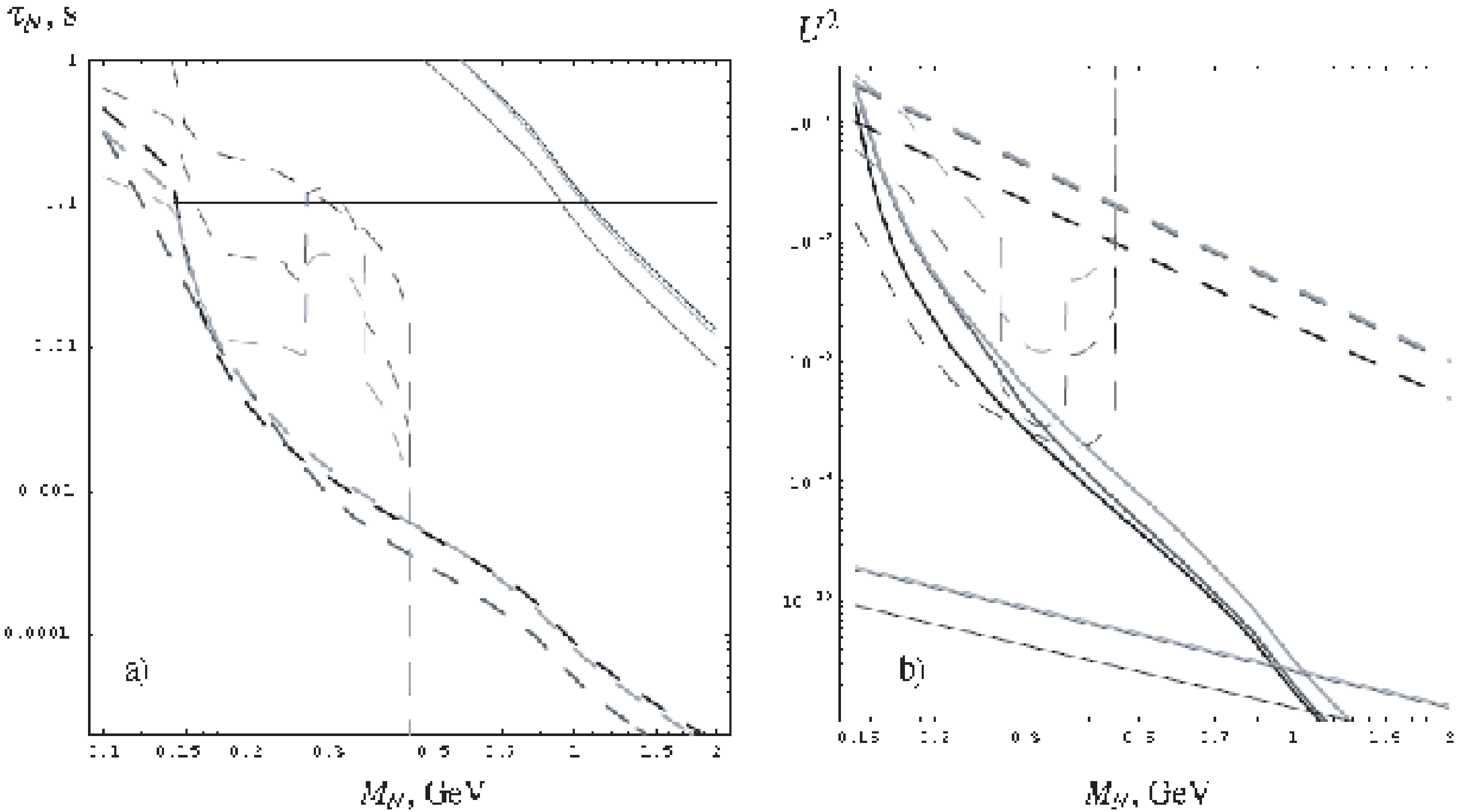
$|U\mu i|^2$ $< 10^{-5}$ for $\mu_{\nu i} = 100$ MeV/c^2

$< 10^{-6}$ for $\mu_{\nu i} = 200 \sim 300$ MeV/c^2

CERN PS191 experiment



Result of PS191



Lepton universality

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

- Standard Model:
  - Three generations for quarks and leptons
  - Leptons: *e*, μ, and τ
    - Different masses but same gauge couplings
    - Up to now, it is valid experimentally

Lepton Universality

- Even a small difference would signal a profound discovery : → ***Necessity of experimental efforts***

Related (or remaining) questions:

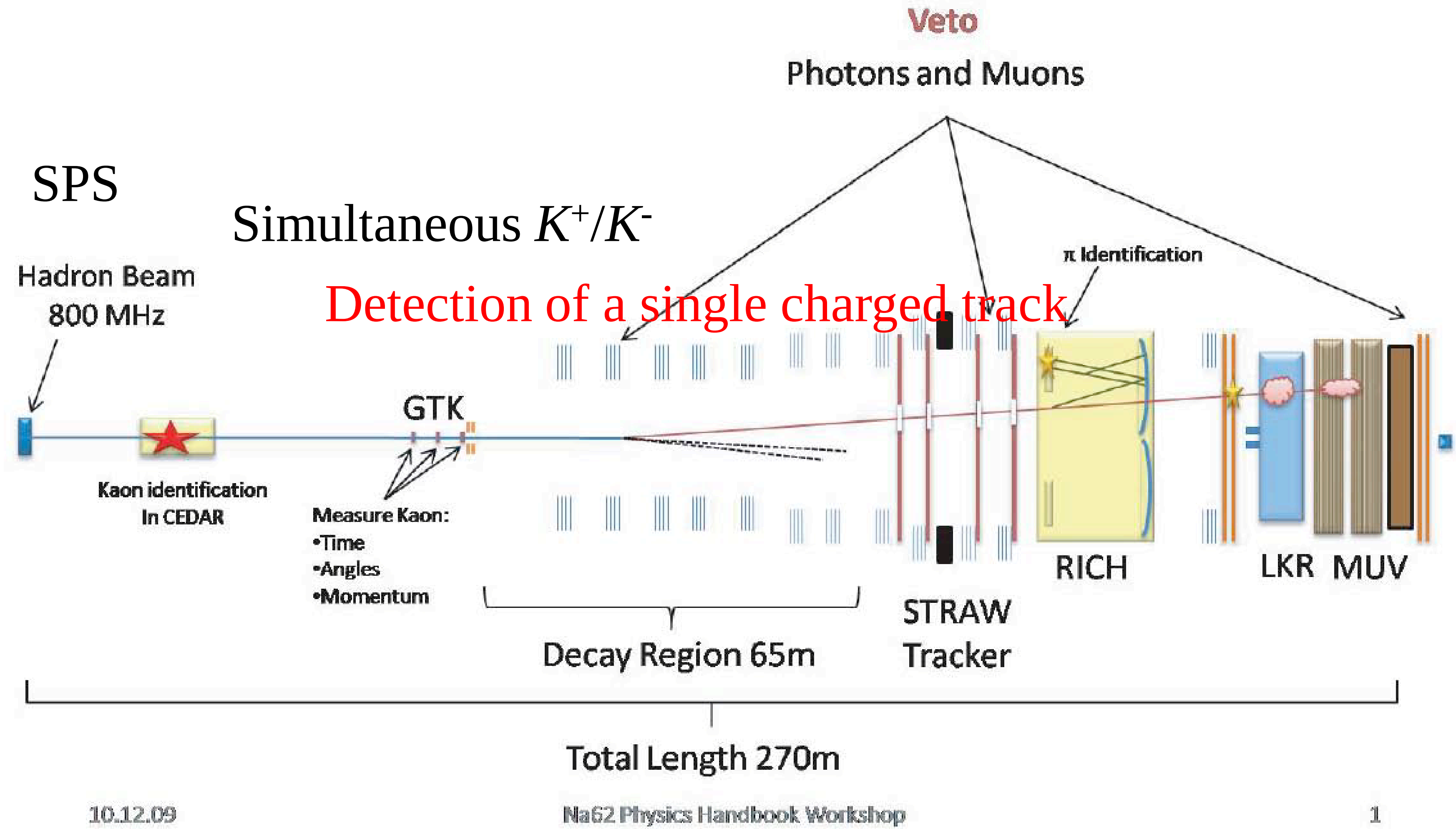
1. Why are there three generations?
2. Why are the weak couplings of *e*, *μ*, and *τ* nearly equal?
3. Why are their masses so different?
4. Why weak bosons couple to leptons in a single generation?

NA62 experiment at CERN

SPS

Simultaneous K^+/K^-

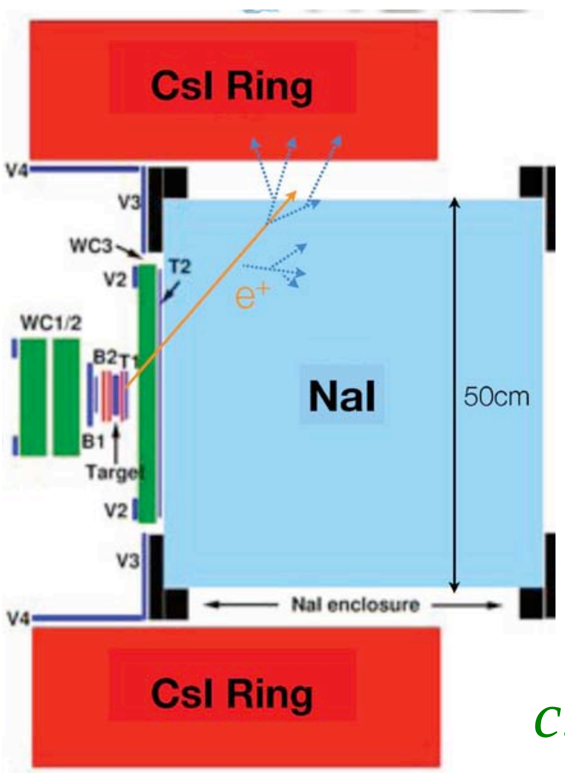
Detection of a single charged track

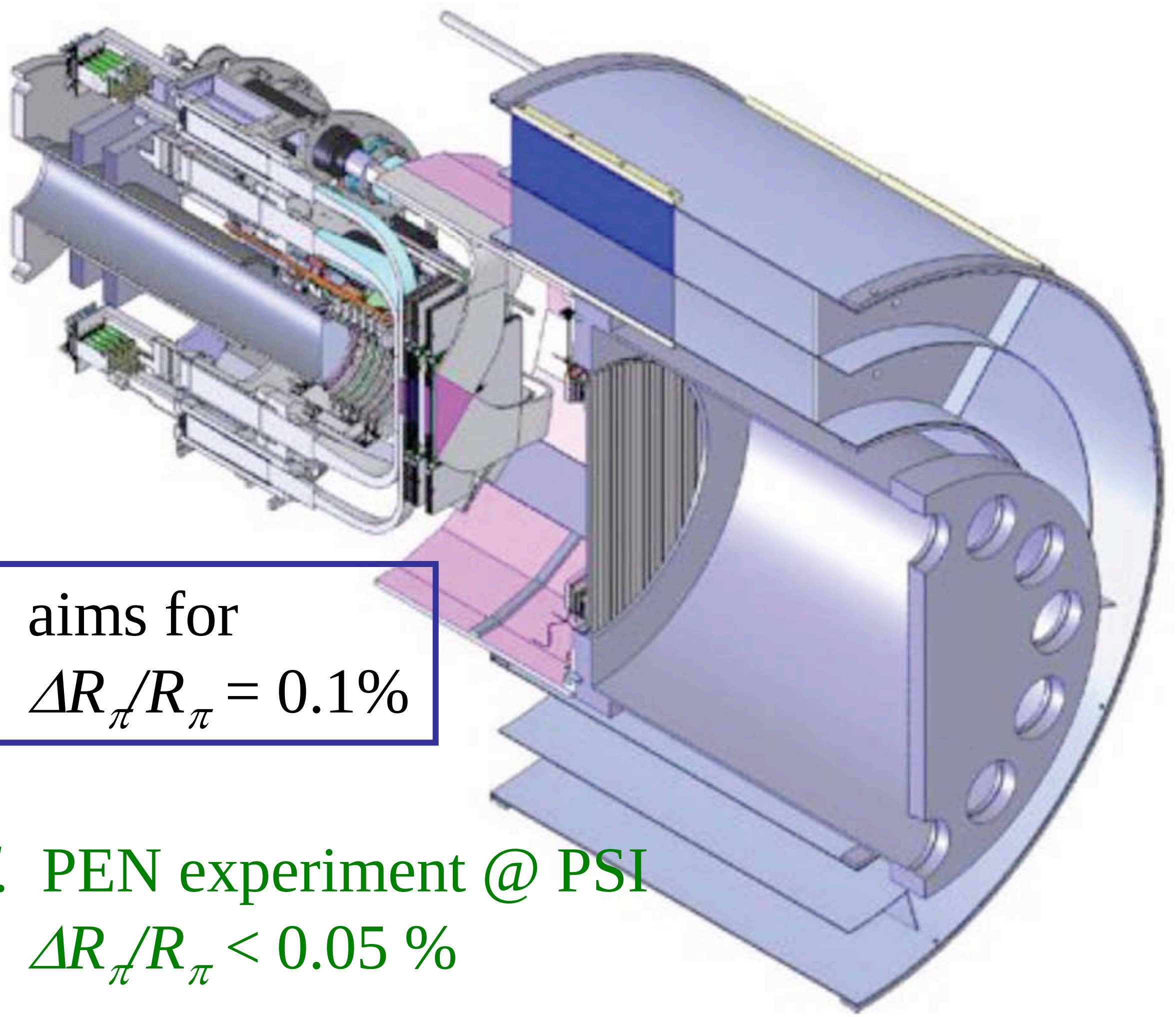


PIENU experiment at TRIUMF

Measurement of $R_\pi = \pi_{e2} / \pi_{\mu 2}$

$$R_\pi^{SM} = (12.352 \pm 0.001) \times 10^{-5}$$



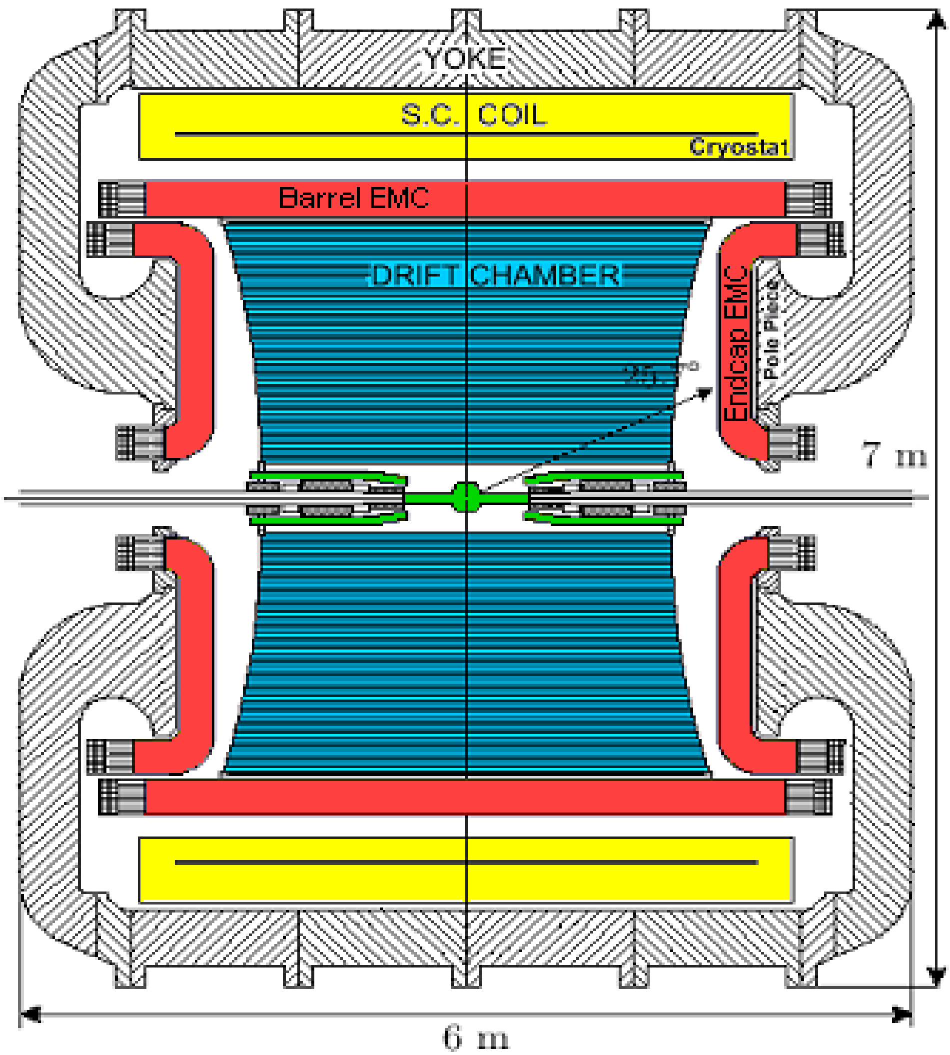


aims for
$\Delta R_\pi / R_\pi = 0.1\%$

c.f. PEN experiment @ PSI
$\Delta R_\pi / R_\pi < 0.05\ \%$

KLOE experiment at DAΦNE

$e^+e^- \to \phi \to K^+K^- : W \sim m_\phi = 1.02$ GeV



K^+K^-

- $\beta = 0.245$
- $p^* = 127$ MeV/c
- $\lambda_\pm = 95$ cm

KLOE detector

- DC (4 m^ϕ x 3.3m^L)
- EMC (Pb/SciFi)
- SCM (0.52 T)

$K^\pm_{e2(\gamma)} : K^\pm_{\mu 2(\gamma)}$ measurement

$R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$

$K_{e3}/K_{\mu3}$

$$\Gamma(K_{\mu3})/\Gamma(K_{e3}) = (g_\mu/g_e)^2 \text{ x } R_{pre}$$
$$R_{pre} = 0.6457 - 0.1531\lambda_+ + 1.5646\,\lambda_0$$
$$f_0(q^2) = f_+(q2) + [q^2/(m_K{}^2 - m_\pi{}^2)]\, f_-(q^2)$$
$$\sim f_+(0)\,[1+ \lambda_0(q^2/m_\pi{}^2)]$$

KEK-PS E246

$\Gamma(K_{\mu3})/\Gamma(K_{e3}) = 0.671$ +/- 0.009 [E246]
$\lambda_+ = 0.0278$ +/- 0.0040 [E246]
$\lambda_0 = 0.039$ +/- 0.0040 [Ref.]

- B_0 = 0.65 T and 0.9 T
- $p_{\mu/e}$ measurement
- π^0 detection as 2γ in CsI
- $K_{e3}/K_{\mu3}$ discrim. with TOF

$g_\mu/g_e = 0.971$ +/- 0.019

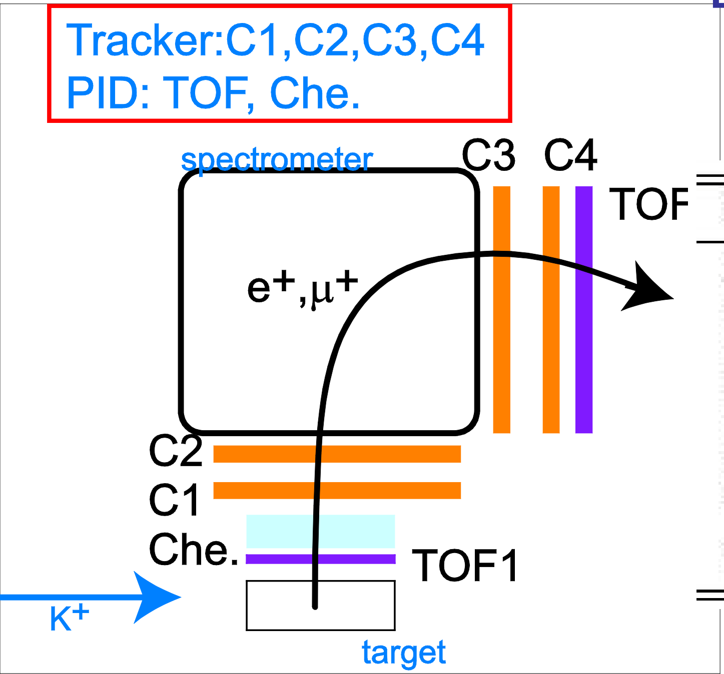
($g_\mu f_+{}^\mu(0)\,/\,g_e f_+{}^e(0) = 0.971$ +/- 0.019)

Consistent with one !

Efficiency determination

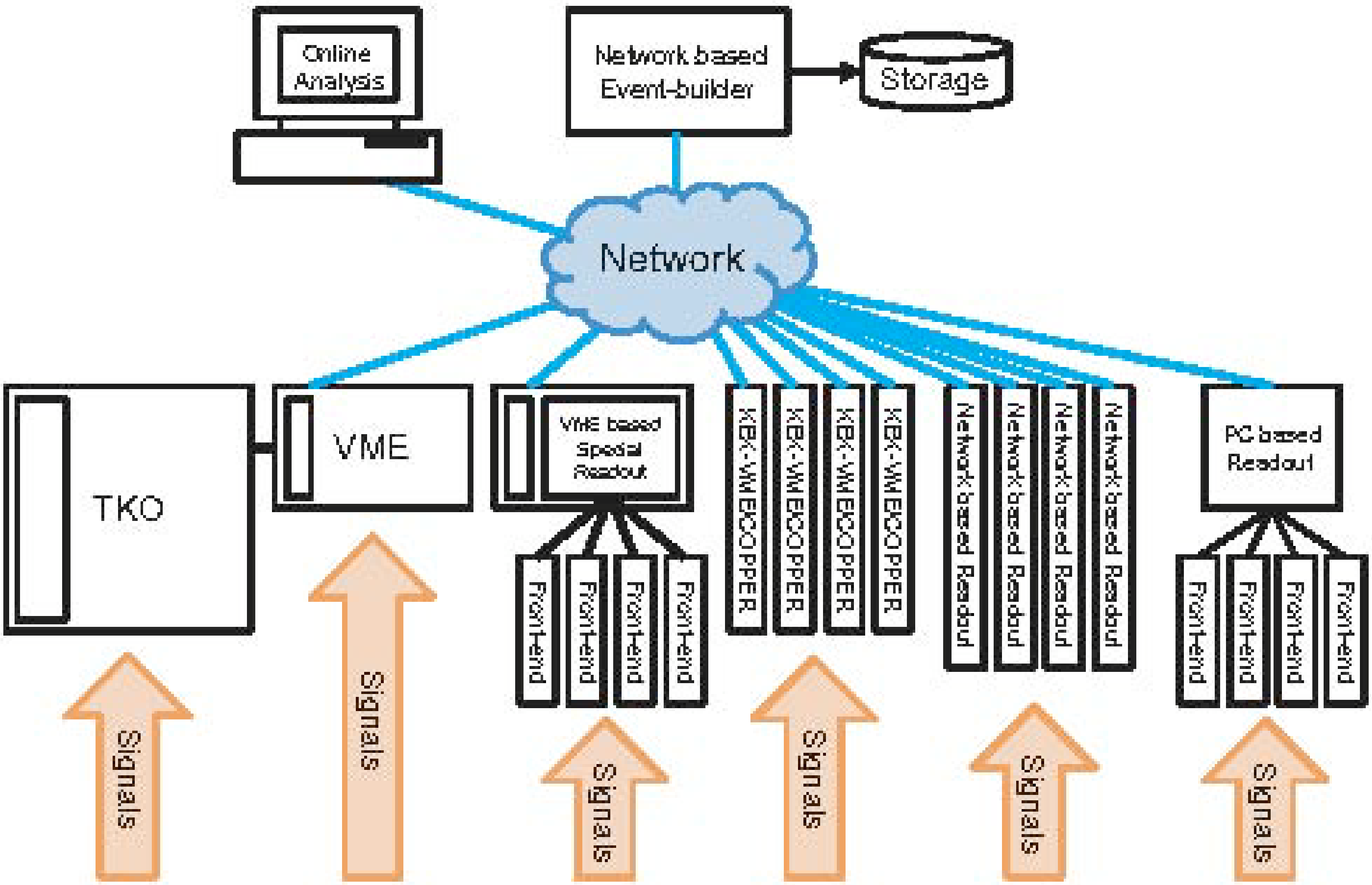
- PID performance and chamber efficiencies will be directly measured by using experimental data.
- We can easily accumulate sufficient K_{e3} and $K_{\mu3}$ events by changing the magnetic field to B=0.65 T.

$$\text{Effi.(Che)} = \frac{N(\text{Tracker} \otimes \text{TOF} \otimes \text{Che.})}{N(\text{Tracker} \otimes \text{TOF})}$$



Element for check	Tracking elements	Trigger
C1	C2, C3, C4	TOF1⊗TOF2
C2	C1, C3, C4	TOF1⊗TOF2
C3	C1, C2, C4	TOF1⊗TOF2
C4	C1, C2, C3	TOF1⊗TOF2
PID by Cherenkov	C1, C2, C3, C4	TOF1⊗TOF2
PID by TOF	C1, C2, C3, C4	TOF1⊗C4

Data taking



Online Analysis
Network based Event-builder
Storage
Network
TKO
VME
VME based Special Readout
KEK-VME COPPER
KEK-VME COPPER
KEK-VME COPPER
KEK-VME COPPER
Network based Readout
Network based Readout
Network based Readout
Network based Readout
PC based Readout
Front-end
Front-end
Front-end
Front-end
Front-end
Front-end
Front-end
Front-end
Signals
Signals
Signals
Signals
Signals
Signals