Int. Workshop on Radiative Corrections from Medium to High Energy Experiments

ECT*, Trento, July 18-22, 2022

Measurement of structure dependent radiative $K^+ \rightarrow e^+\nu\gamma$ decays using stopped positive kaons

Michael Kohl[1,2] <kohlm@jlab.org> *

on behalf of the TREK/E36 Collaboration

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Outline

- **Lepton non-universality?**
- **TREK Program**
  - **E06: Search for Time Reversal Symmetry Violation**
  - **E36: Test of Lepton Universality**
    Search for Light Bosons } Lower intensity
- **TREK Apparatus**
- **Status & First Results**

E36 data taking completed in 2015

http://trek.kek.jp

The TREK E06 and E36 program

- **E06**
  (Time Reversal Experiment with Kaons, TREK)

“ **Measurement of T-violating transverse muon polarization (P_T) in $K^+ \rightarrow \pi^0 \mu^+ \nu$ decays** ”

Proposal to PAC 1 (2006) 100-270 kW

Stage-1 approved since July 2006

Spokespeople: Jun Imazato and M.K.

- **E36** (Test of Lepton Universality, Search for Heavy Neutrinos and Light Bosons)

“ **Measurement of $\Gamma(K^+ \rightarrow e^+\nu) / \Gamma(K^+ \rightarrow \mu^+\nu)$ and search for heavy sterile neutrinos using the TREK detector system** ”

Proposal to PACs 10 (2010), 11,13-18 30-50 kW

Stage-1 approved since August 2012

Stage-2 approved since September 2013

Spokespeople: M.K. and Suguru Shimizu

Timeline of TREK E06 and E36

- 2006: E06 (T-violation) Proposal (PAC1)
- 2009: J-PARC PS and HF start operating
- 2010: E36 (LFU/HNS) Proposal (PAC10)
- 2011: E36 stage-1 recommended (PAC11)
- 2012: E36 stage-1 approved (PAC15)
- 2013: E36 stage-2 recommended (PAC17)
- 2014: E36 stage-2 approved (PAC18)
- Detector preparation November 2014 – April 2015
- First commissioning run April 8 (24) – May 7, 2015
- Second commissioning run June 3 – 26, 2015
- Implemented improvements in summer 2015
- Production run October 14 – November 24, 2015
- Run extended until December 18, 2015
- 2016-2022: Analysis in progress and first results

Limits of lepton universality (LU)

- e, μ, and τ: Different masses, same gauge couplings
- Lepton universality has been rather well established at 10^{-3} – 10^{-2} level
- Summary by A. Pich, arXiv:1201.0537v1 [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

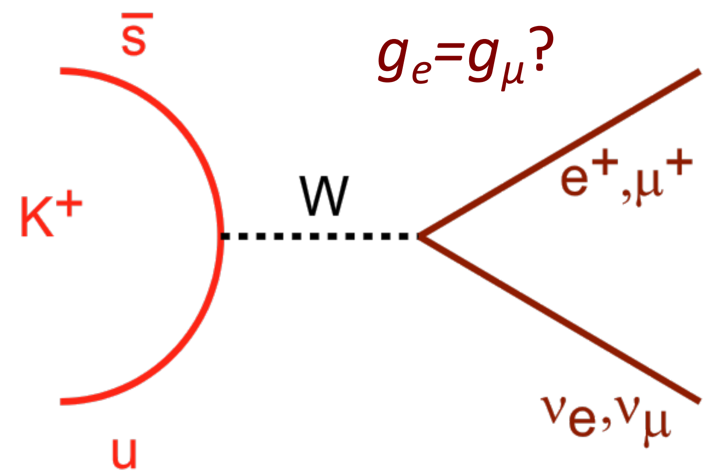
	$\Gamma_{W\to\mu\bar\nu_\mu}/\Gamma_{W\to e\bar\nu_e}$		$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to e\bar\nu_e}$
$\lvert g_\mu/g_e\rvert$	0.991 ± 0.009	$\lvert g_\tau/g_e\rvert$	1.0016 ± 0.0021	1.023 ± 0.011

- Couplings to *W* and *Z*^{0} (LEP-II [PDG 2010])
  $$R^W_{\tau\ell} = \frac{2\,\mathrm{BR}\,(W\to\tau\,\bar\nu_\tau)}{\mathrm{BR}\,(W\to e\,\bar\nu_e)+\mathrm{BR}\,(W\to\mu\,\bar\nu_\mu)} = 1.055(23)$$
  2.4σ dev.
- Belle, Babar, LHCb (HFLAV 2019)
  $$\mathcal{R}(D^{(*)}) = \mathcal{B}(\overline{B}\to D^{(*)}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}\to D^{(*)}\ell^-\overline{\nu}_\ell)$$
  3.6σ dev.
- LHCb (update from March 2021)
  $BR(B^+\to K^+\mu^+\mu^-) / BR(B^+\to K^+e^+e^-) = 0.846^{+0.042}_{-0.039}{}^{+0.013}_{-0.012}$
  3.1σ dev.
- Muon anomalous mag. moment (Apr 2021) $a_\mu = 116\,592\,061(41)\times10^{-11}$
  4.2σ dev.
- Proton charge radius puzzle (since 2010)
  r_e (μH) = 0.84087 ± 0.00039 fm, r_e (CODATA2014) = 0.8751 ± 0.0061 fm
  5.6σ dev.

Lepton universality in Standard Model K_{l2}

Standard Model:

- $$\Gamma(K_{l2}) = g_l^2 \frac{G^2}{8\pi} f_K^2 m_K m_l^2 \left(1 - \frac{m_l^2}{m_K^2}\right)^2$$



- **In the ratio of *Γ(K$_{e2}$)* to *Γ(K$_{\mu2}$)*, hadronic form factors are cancelled**

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

helicity suppression *radiative correction (Internal Brems.)*

- **Strong helicity suppression of the electronic channel enhances sensitivity to effects beyond the SM**

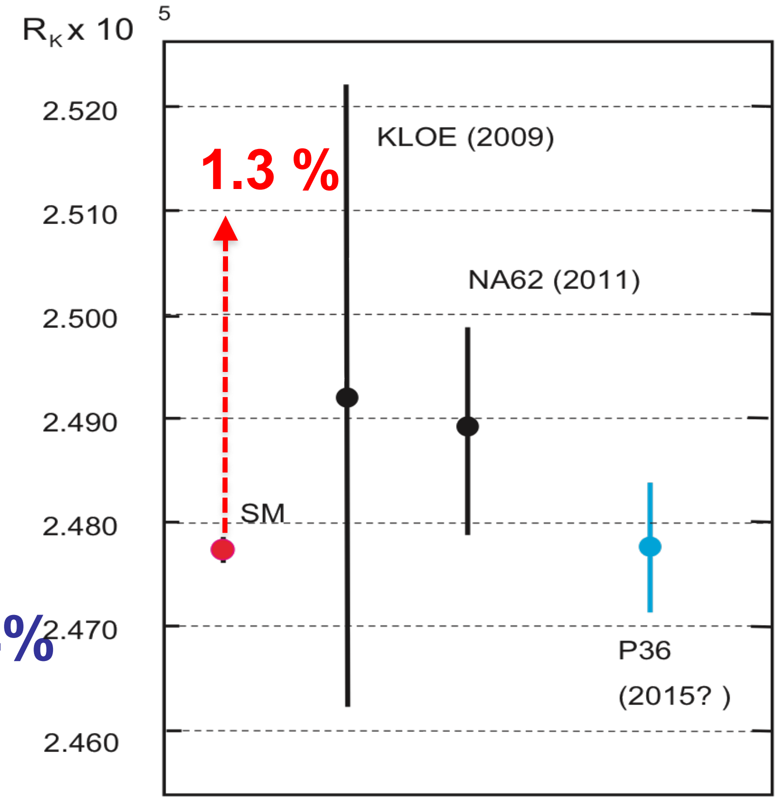
- **Highly precise SM value**

  R_K^{SM}= (2.477±0.001) x 10^{-5} with δ_r = -0.036; (→ $\delta R_K/R_K$=0.04%)

  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)

Experimental status of R_K

- **Highly precise SM value**
  $R_K = (2.477 \pm 0.001) \times 10^{-5}$ (with $\delta_r = -0.036$), $\delta R_K/R_K = 0.04\%$
  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)
- **KLOE @ DAΦNE (in-flight decay)**
  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
  F. Ambrosino et al., Eur. Phys. J. C64, 627 (2009)
- **NA62 @ CERN-SPS (in-flight decay)**
  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$
  C. Lazzeroni et al., PLB719, 105 (2013)
- **World average (2012)**
  $R_K = (2.488 \pm 0.009) \times 10^{-5}$, $\delta R_K/R_K = 0.4\%$

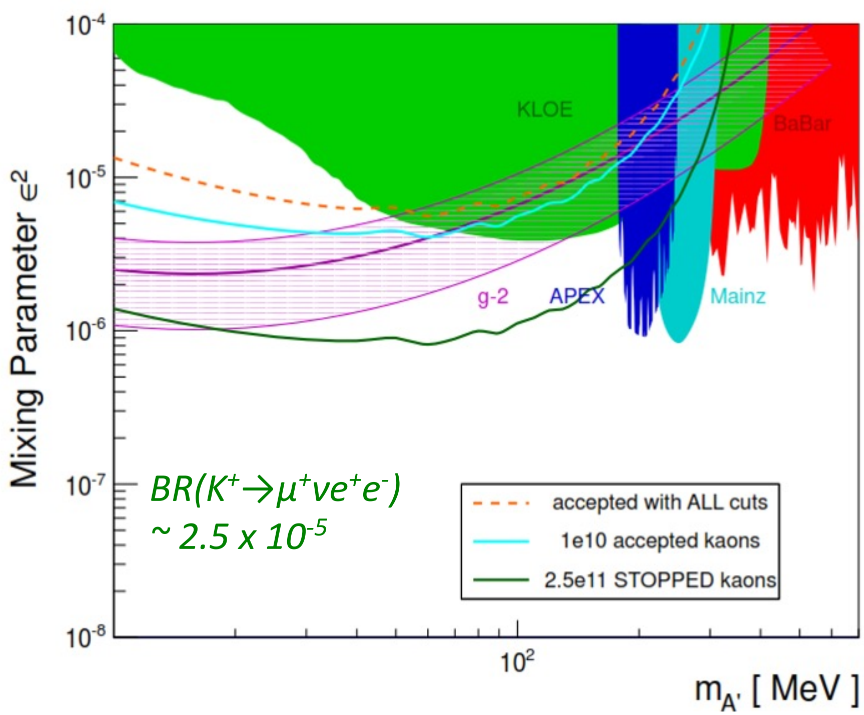


- **Dominant systematics:**
  - **In-flight-decay experiments: kinematics overlap**
  - **E36 stopped K^+: detector acceptance and target**
  - **E36 complementary to in-flight experiments**
- **E36 orig. goal: $\delta R_K/R_K = \pm\, 0.2\%$ (stat) $\pm\, 0.15\%$ (sys) [0.25% tot.]**

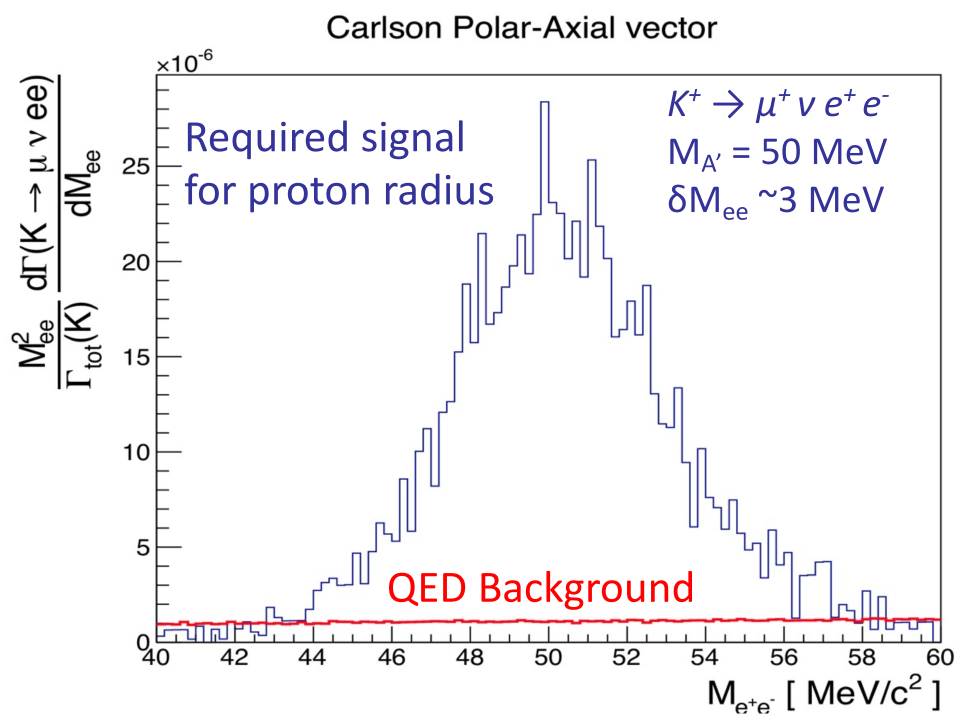
Dark photon / light neutral boson search

- **Dark photons (universal coupling) well motivated by dark matter observations (astronomical, direct, positron excess) and g_μ-2 anomaly**
- **Light neutral bosons (selective coupling) for Be-8 anomaly & R_p puzzle**
- **Search for visible decay mode of $A' \rightarrow e^+e^-$ in K^+ decays**
  Kaons: $K^+ \rightarrow \mu^+ \nu A'$; $K^+ \rightarrow \pi^+ A'$ (also invisible decay);
  Pions: $\pi^0 \rightarrow \gamma A'$, using $K^+ \rightarrow \pi^+\pi^0$ (21.13%) and $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.27%)

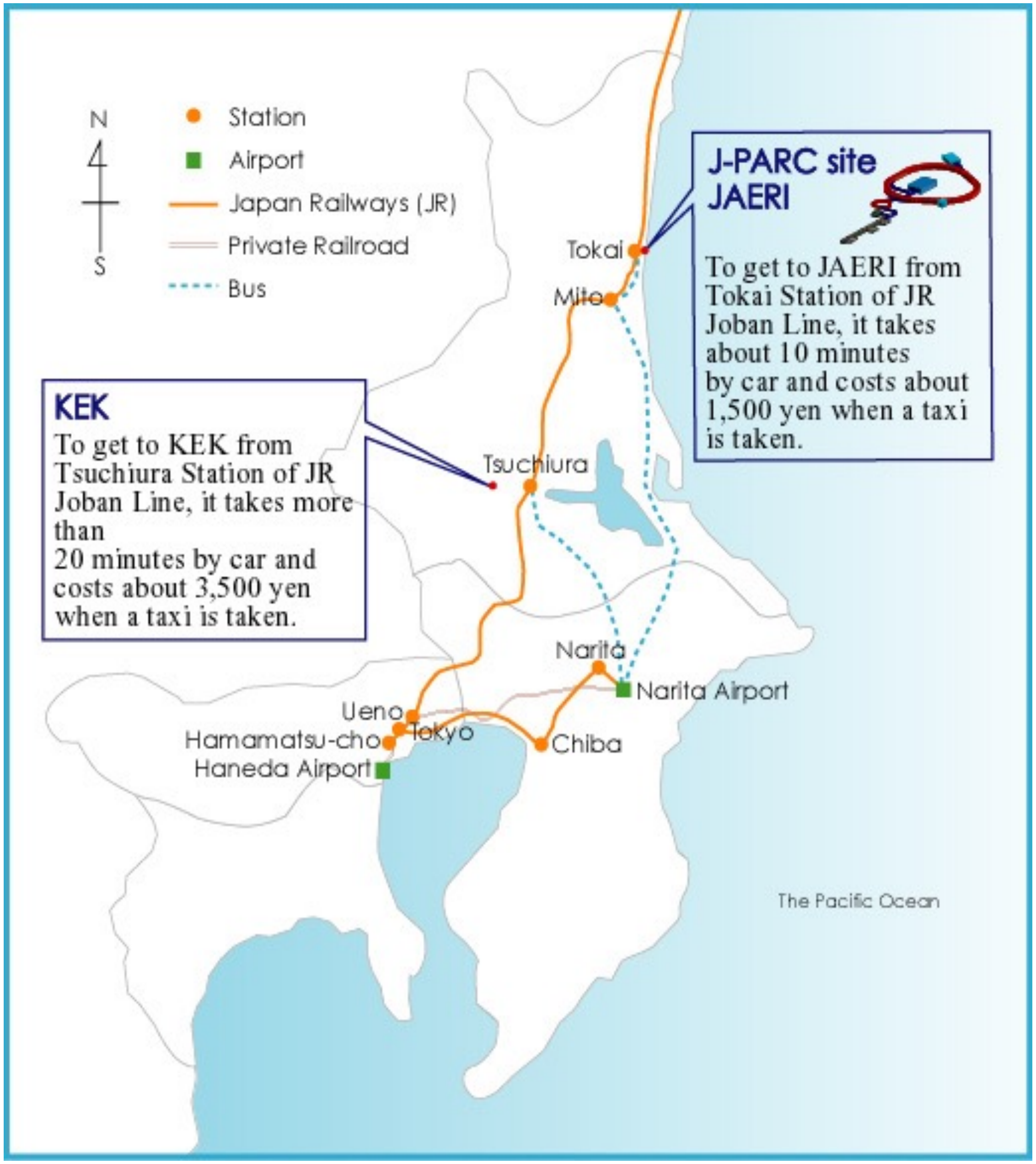
E36: Dark photon exclusion limit

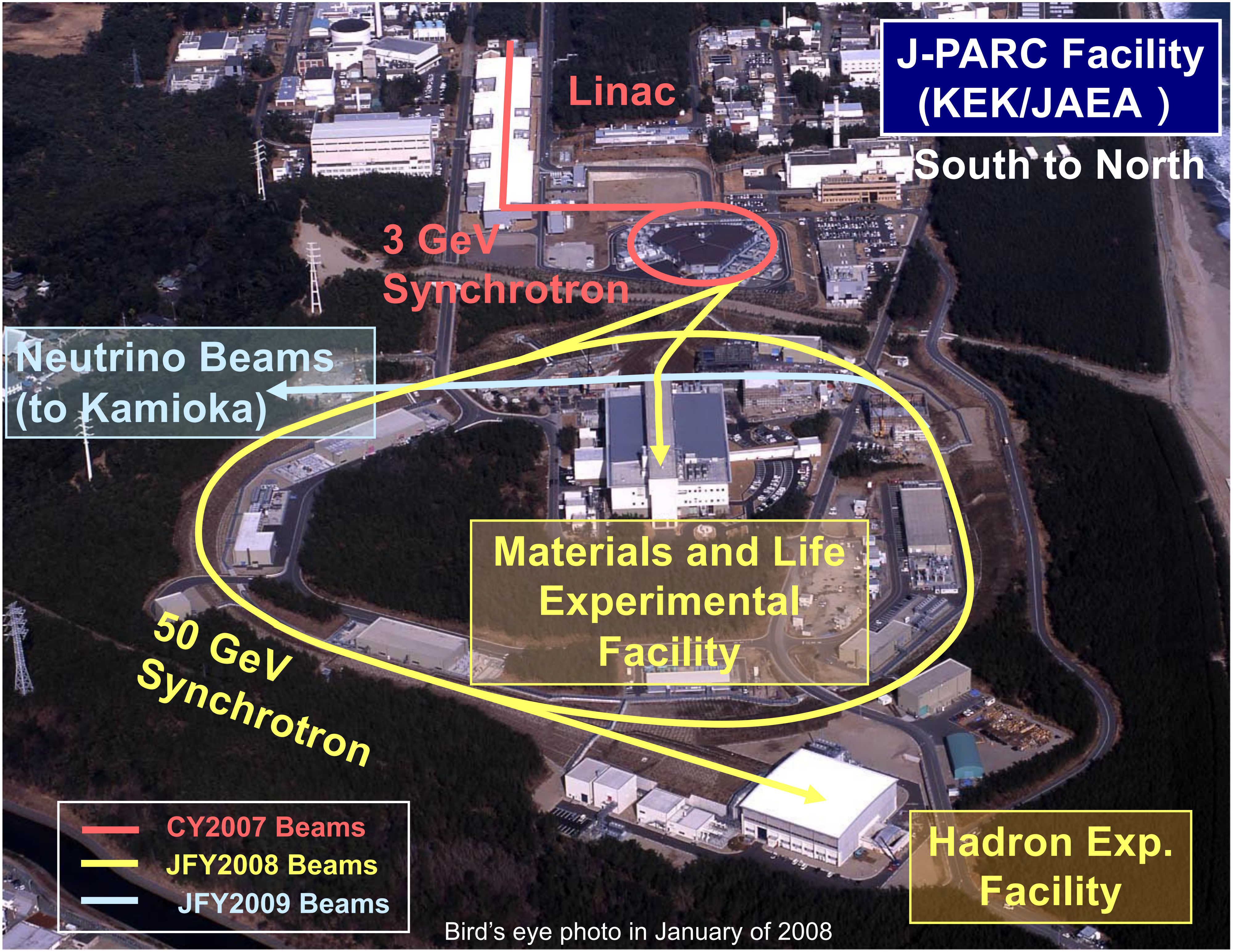


E36: Light boson expected signal



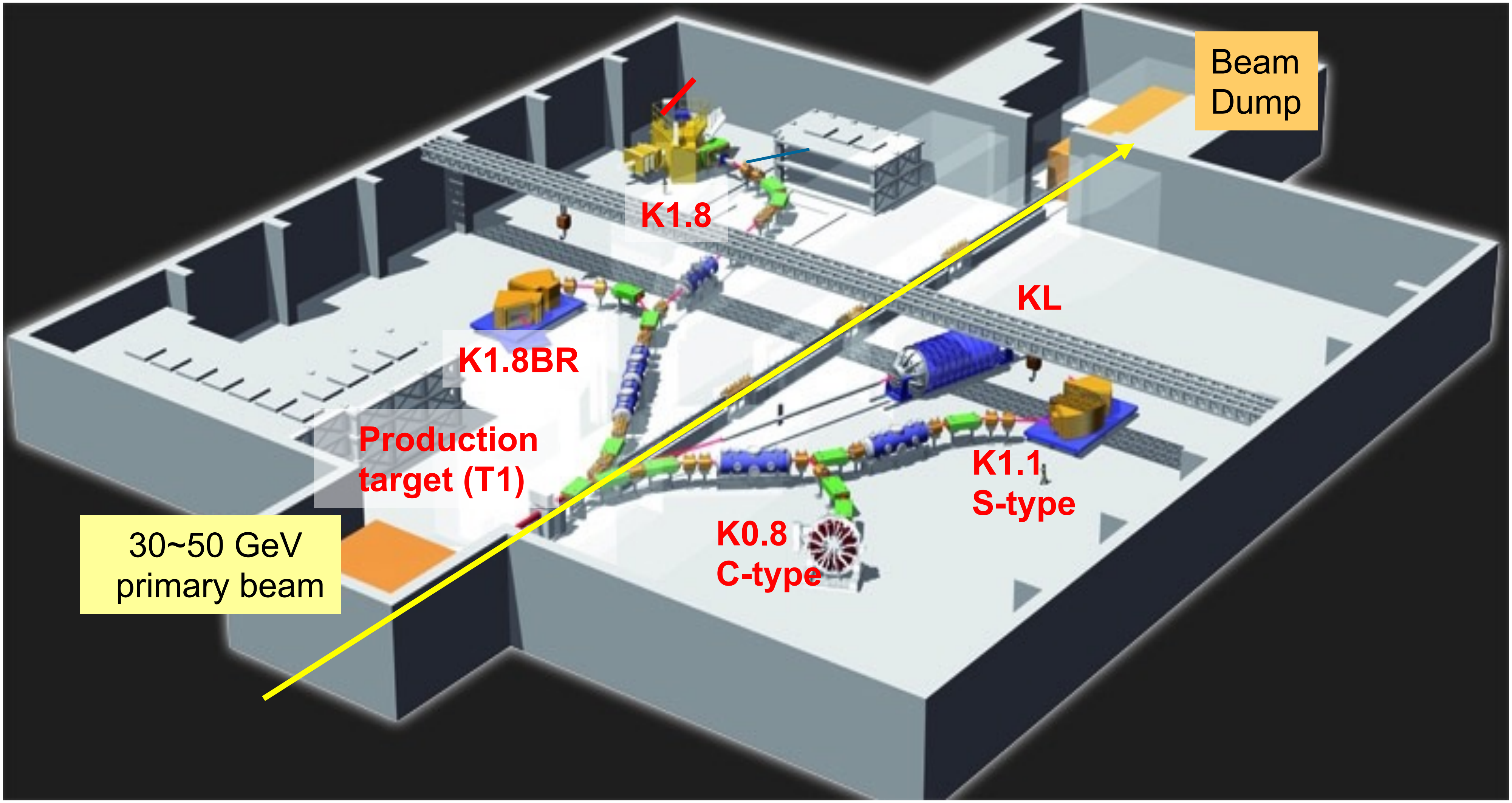
Location of J-PARC





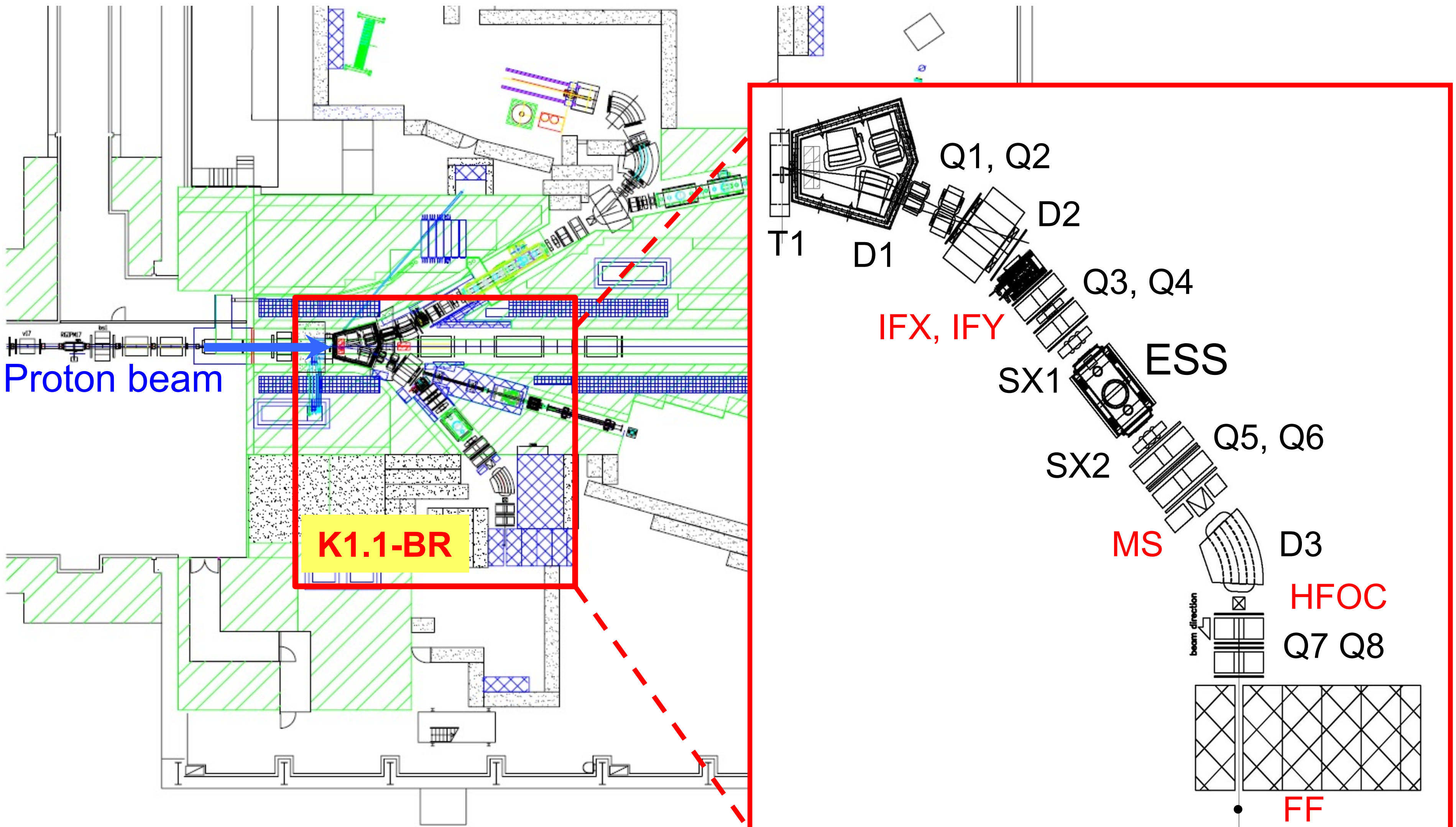
Bird's eye photo in January of 2008

J-PARC Hadron Experimental Hall



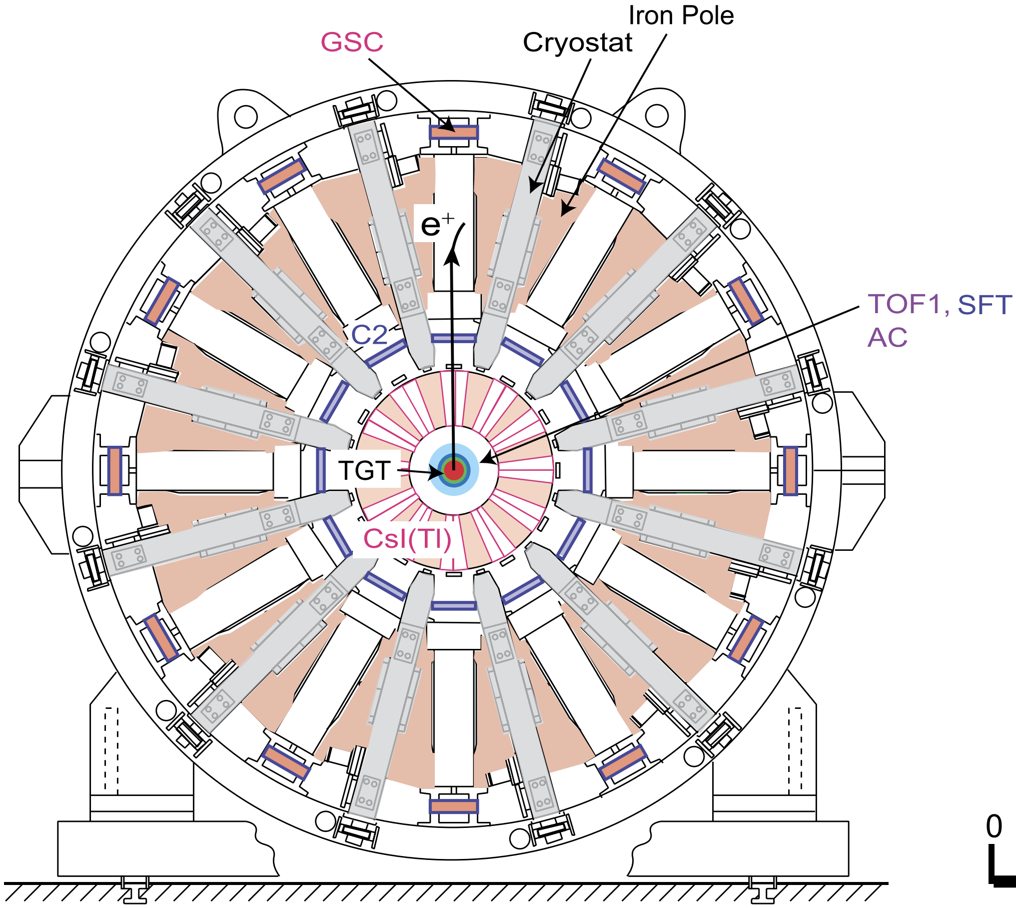
K1.1BR beamline

- K1.1BR constructed in 2009/10, commissioned by TREK Coll. in Oct. 2010
- Re-aligned after 3/11 earthquake, re-commissioned June 2012, paused 2013/14
- Operated April-December 2015; decommissioned in 2016 for COMET+high-p
  π/K ratio ~1.3, av. kaon flux 2.3×10^5 Hz at 40 kW   [1.4×10^6/(2s-spill) at 6s-rep.]

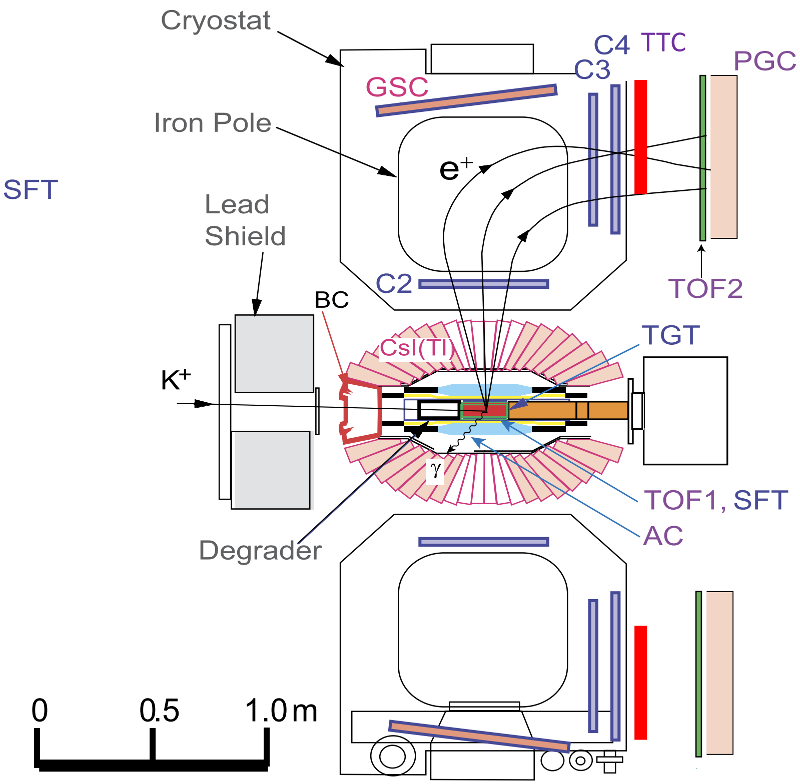


The TREK apparatus for E36

End View



Side View



Modest upgrade of KEK-PS E246

Stopped K^+

- K1.1BR beamline
- Fitch Cherenkov
- K^+ stopping target (TGT)

Tracking (π,μ,e)

- MWPC (C2, C3, C4)
- Spiral Fiber Tracker (SFT)
- TGT, TOF1,2, TTC

PID

- TOF2-TOF1 (TOF)
- Aerogel Ch. (AC)
- Pb glass (PGC)

Gamma

- CsI(Tl)
- Gap scintillators (GSC)

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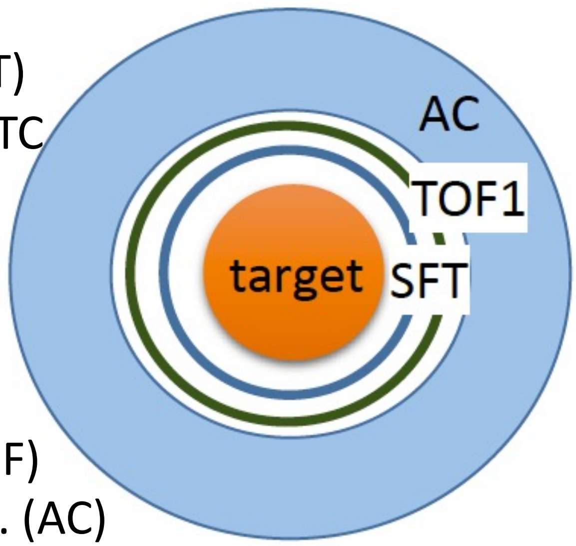
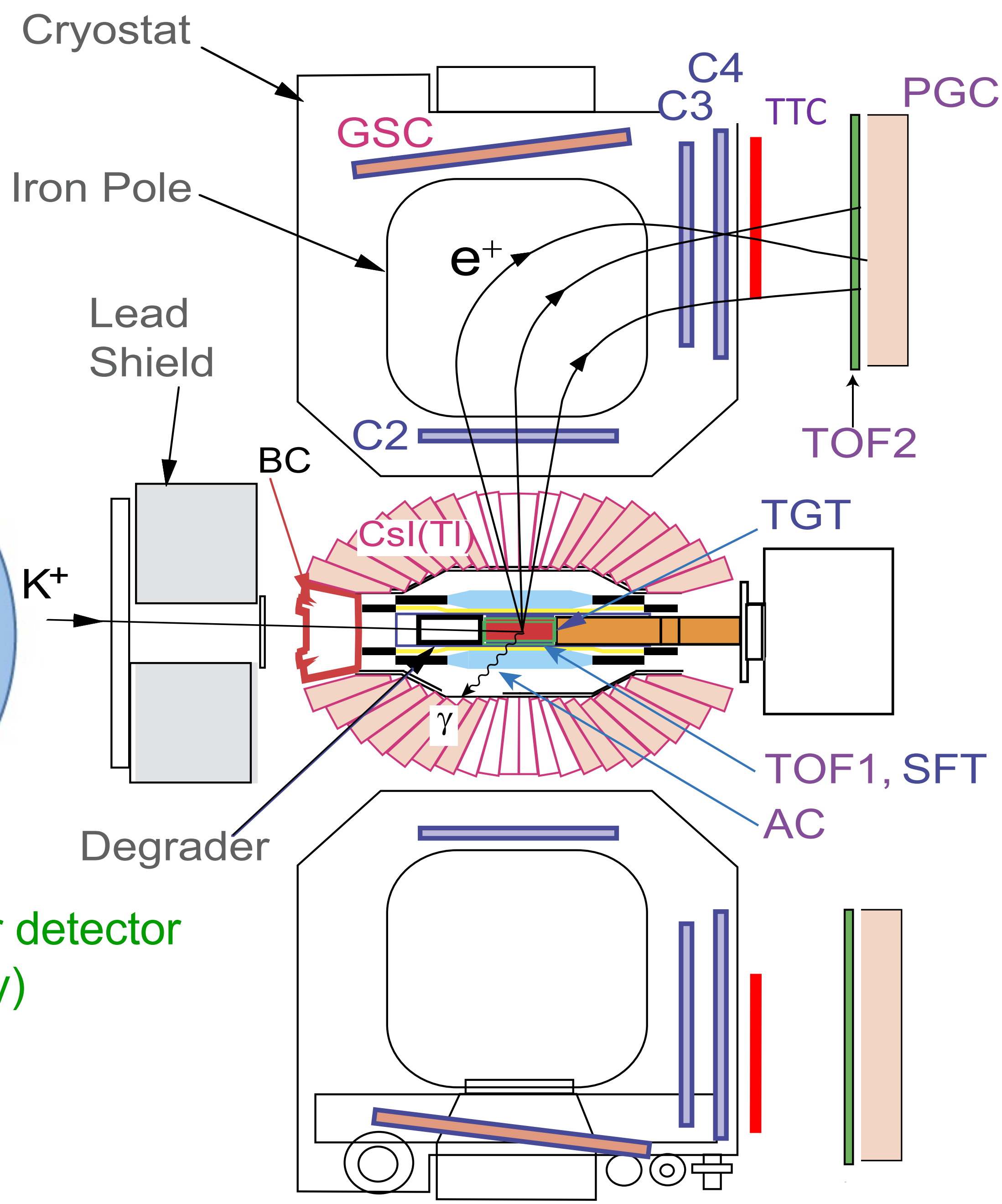
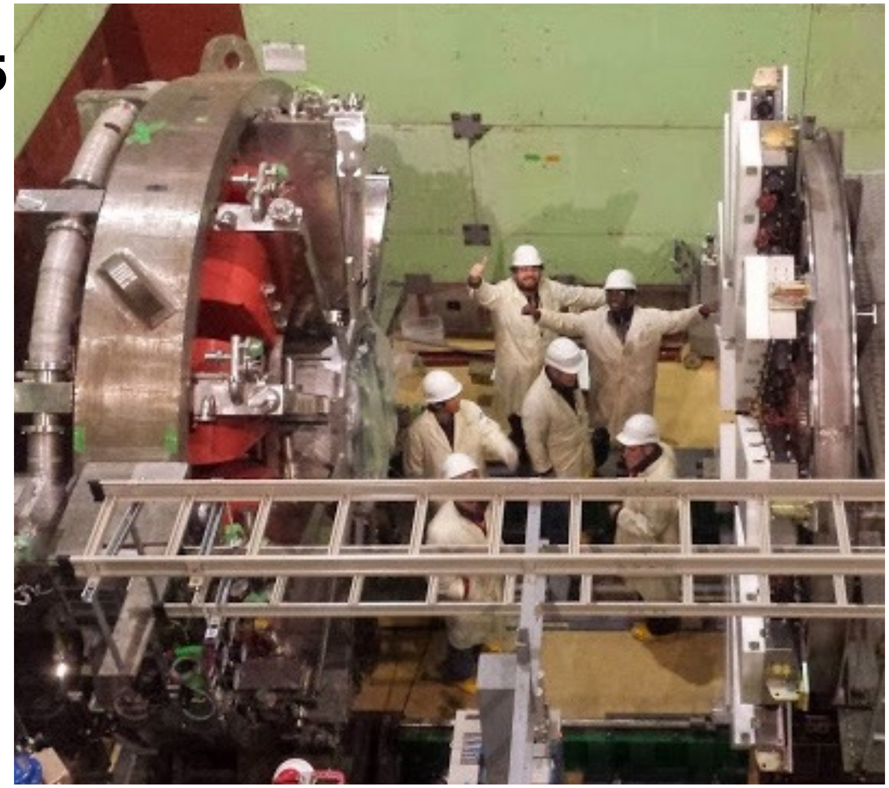


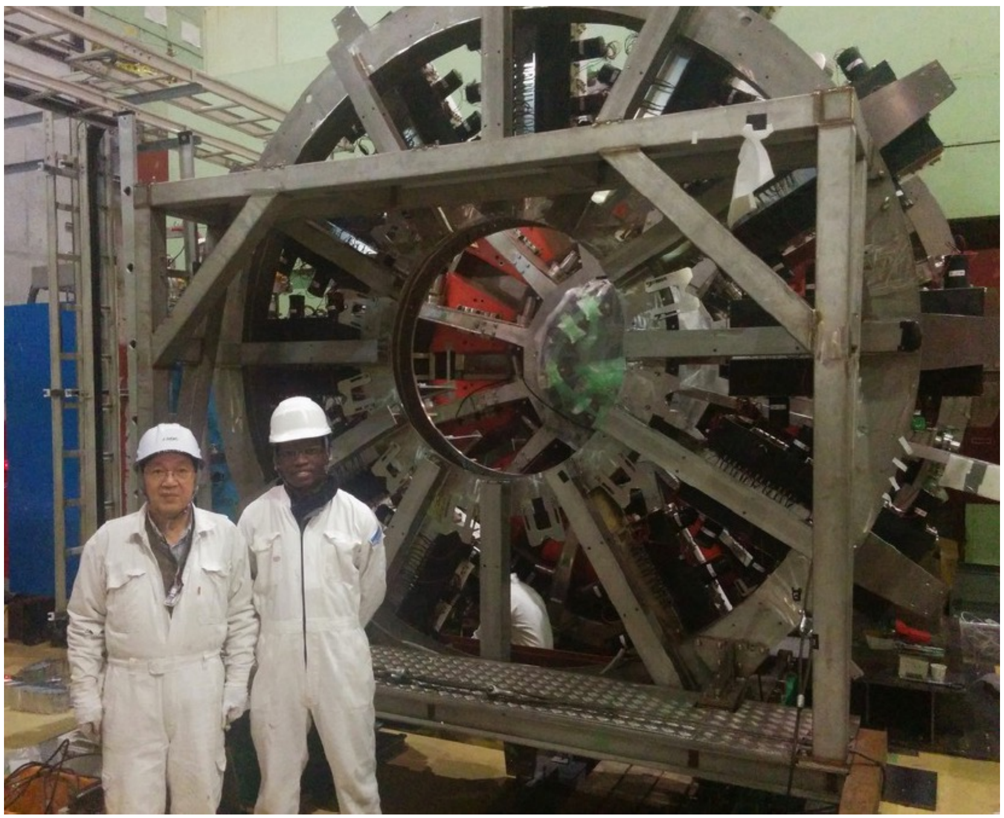
Zoomed inner detector (schematically)



TREK/E36 installation and commissioning

- Completed detector installation April 2015
- Electronics and DAQ set up and tested (area available only mid-January 2015)
- Conditioning of MWPCs





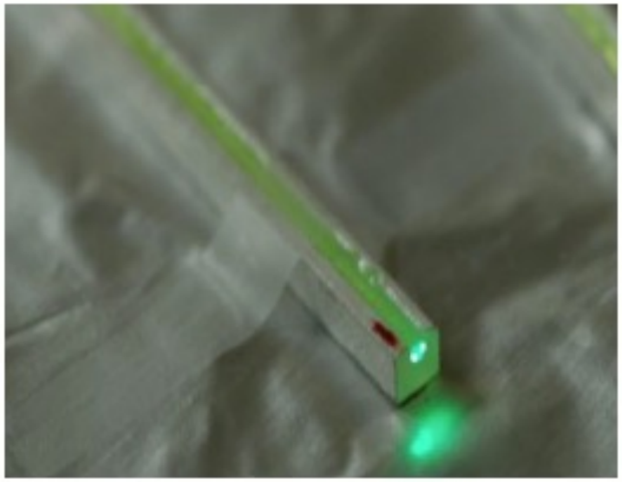
Bishoy Dongwi (Hampton U.)

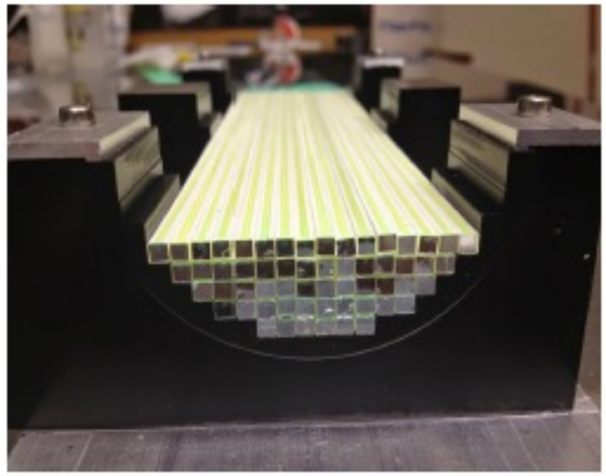
- Commissioning of TGT+TOF1+SFT with cosmic rays
- Check-out of all detectors with beam
- Commissioning of toroidal magnet including cryogenics

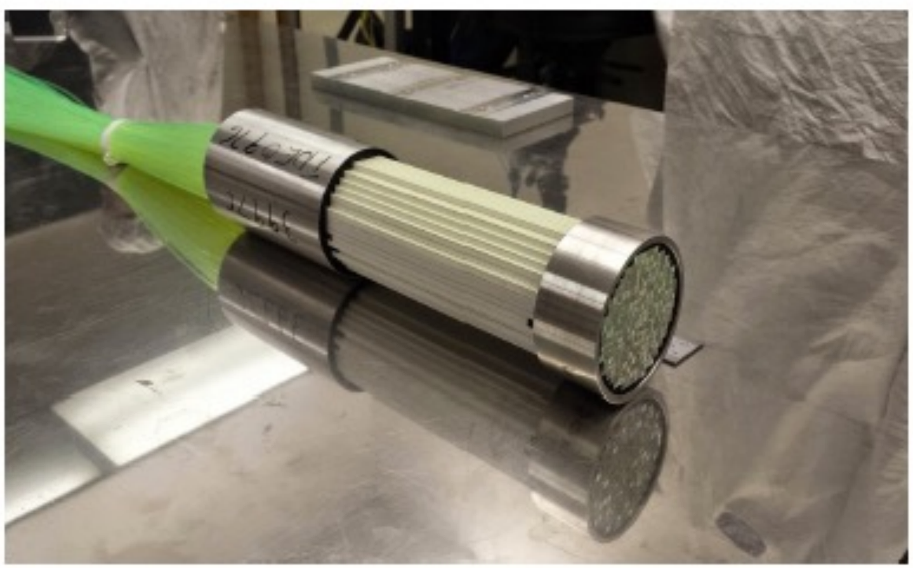
Scintillating-fiber kaon stopping target

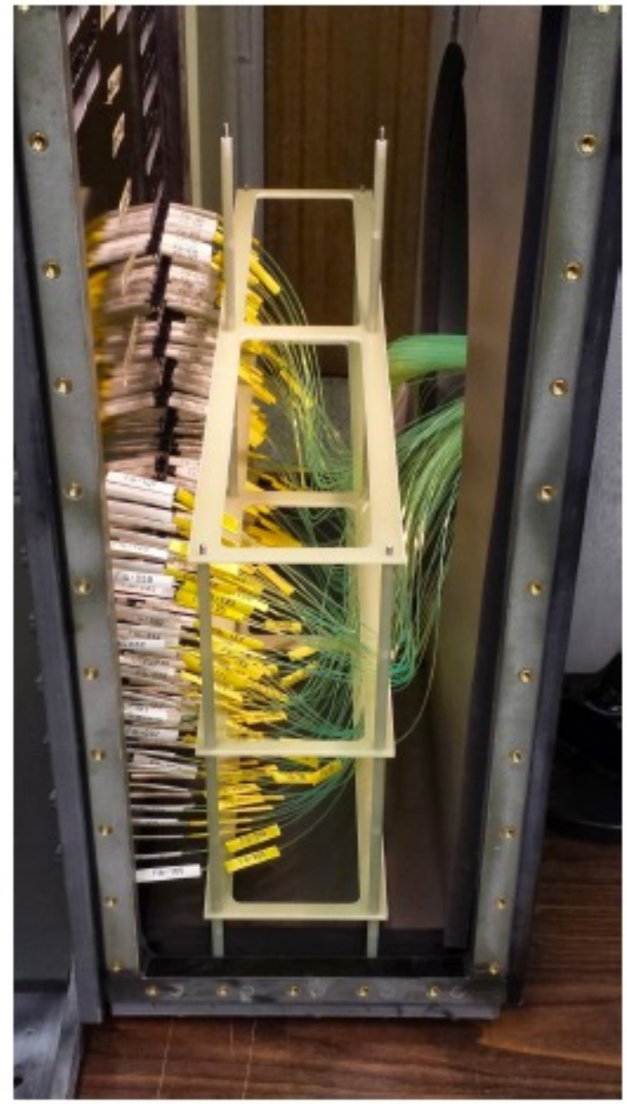
- Built at TRIUMF (delivered to J-PARC in September 2014)
- 256 scintillating fibers (3x3 mm^2), WLS fiber in groove, diameter 6 cm
- MPPC readout with VF-48 FADC

M. Hasinoff, S. Bianchin



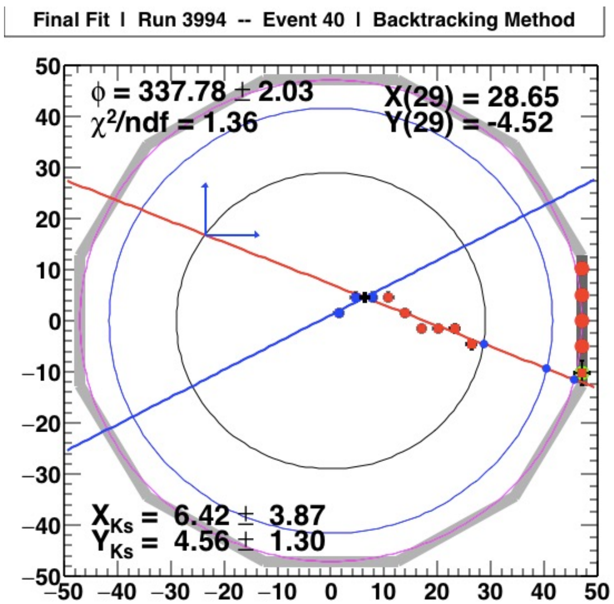


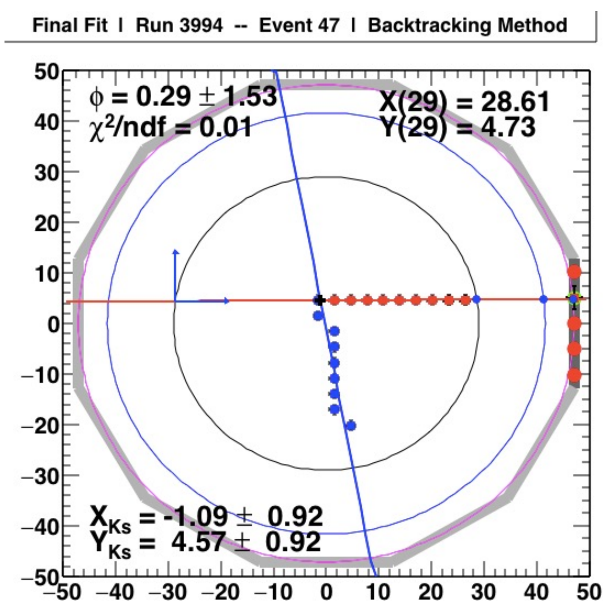




Target performance

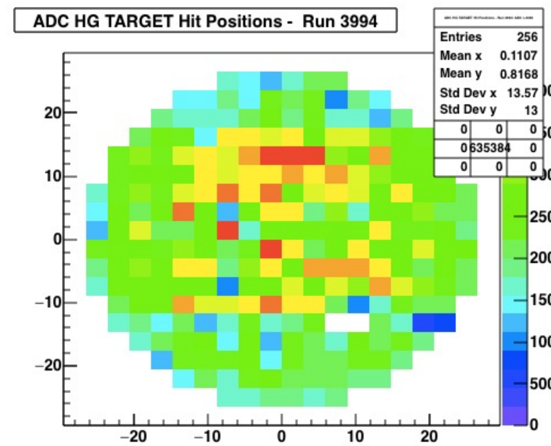
Kaon stop + decay particle



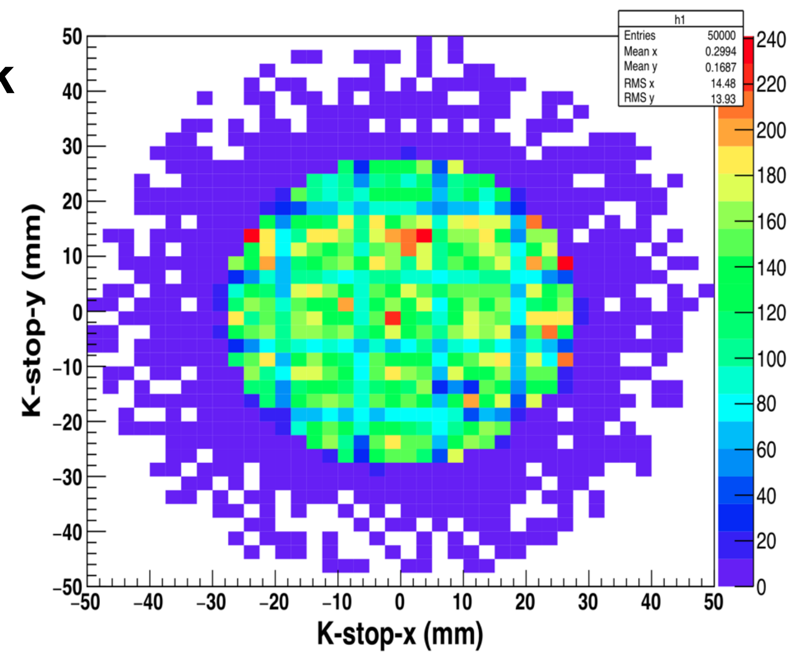


Kaon beam profiles

From fibers w/ highest signals



From track intercepts

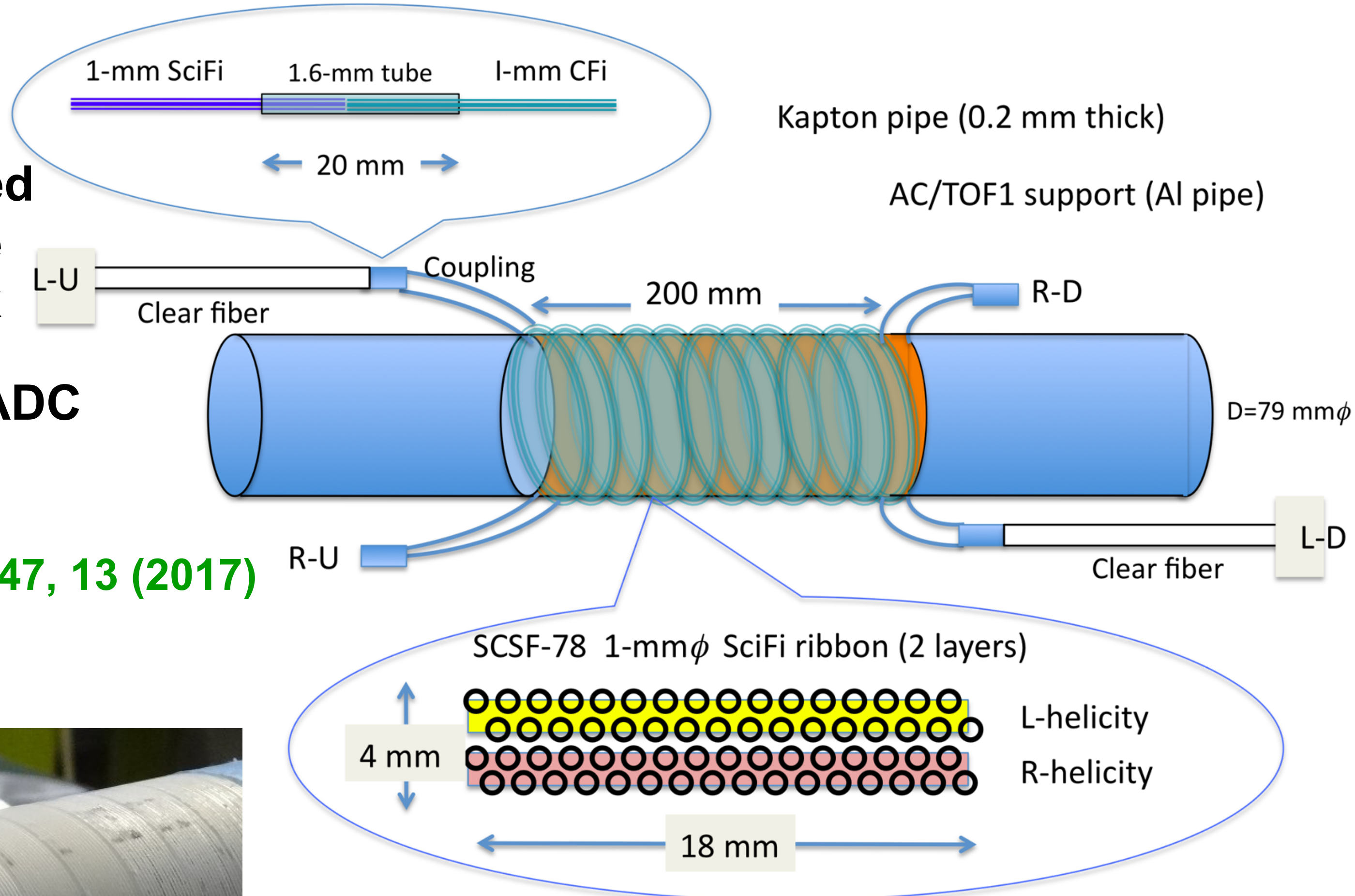


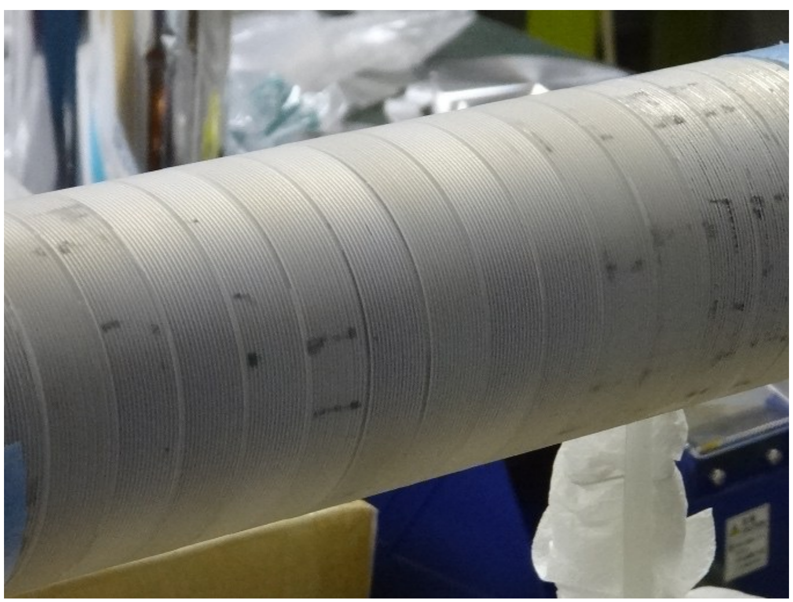
Preliminary

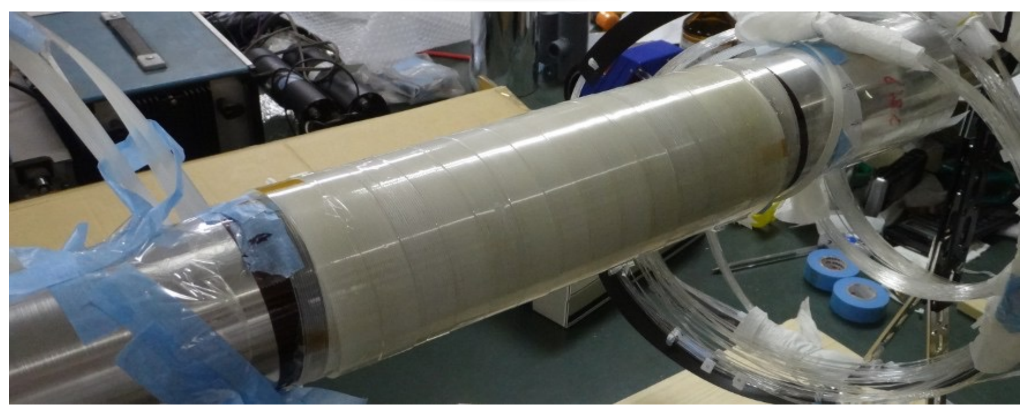
S. Bianchin

Spiral fiber tracker (SFT)

- **Double-layer fibers in 2 helicities wrapped around target bundle for near target vertex**
- **Using same VF-48 FADC as for fiber target**
- **V. Mineev *et al.*, NIM A847, 13 (2017)**

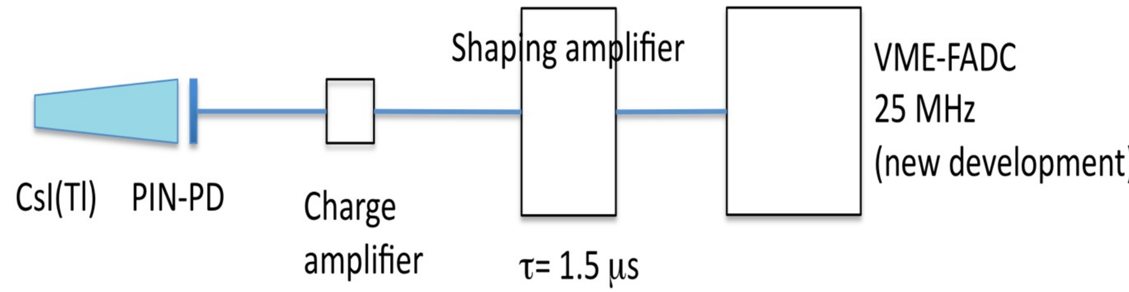




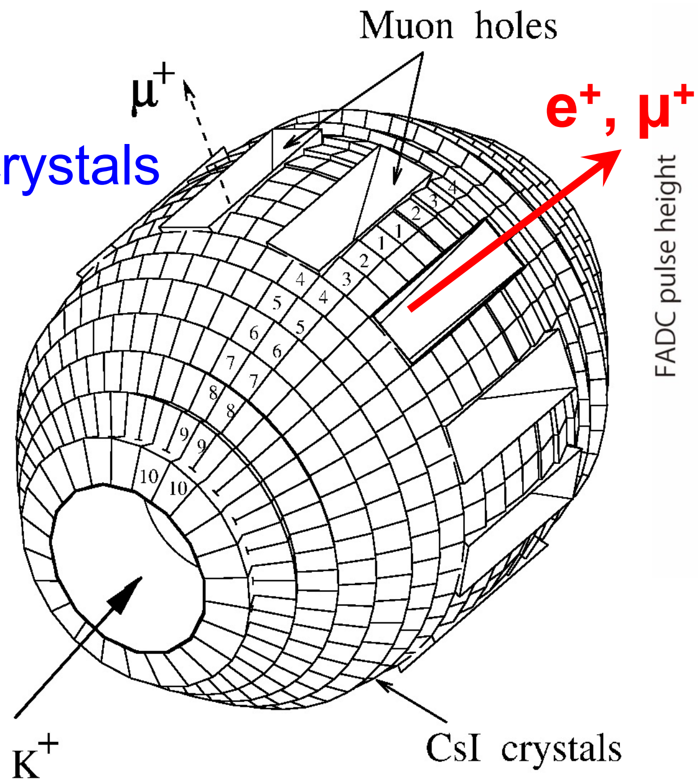


CsI(Tl) calorimeter

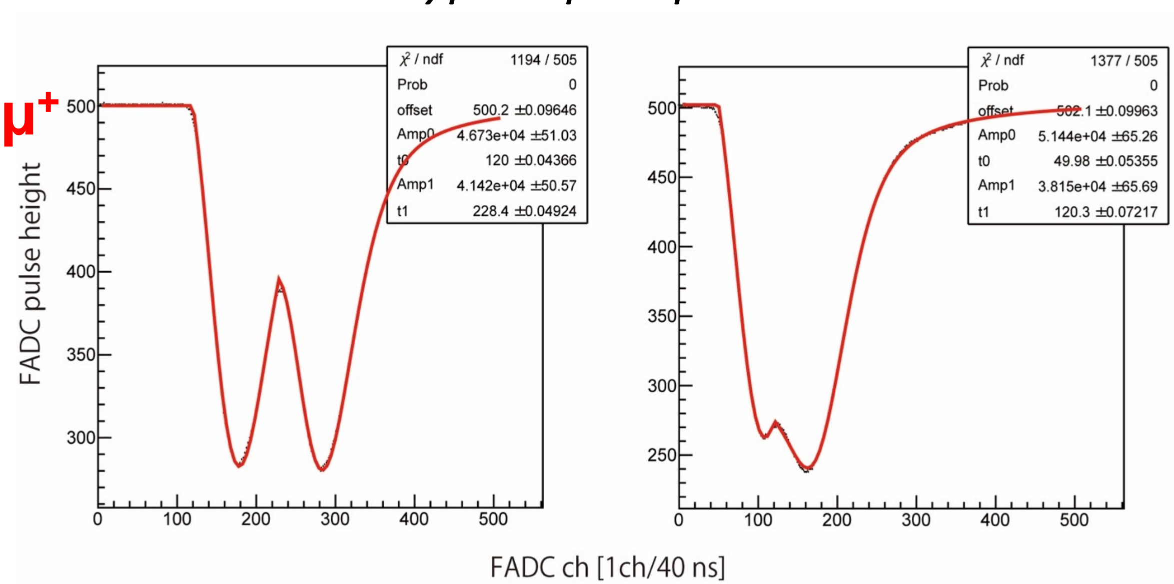
Crystal length	**250 mm**
Number of crystals	**768**
Segmentation	**7.5°**
Coverage	**~75%**
Readout	**PIN diodes**
Maximum rate	**~200 kHz**



768 crystals



Typical pileup events

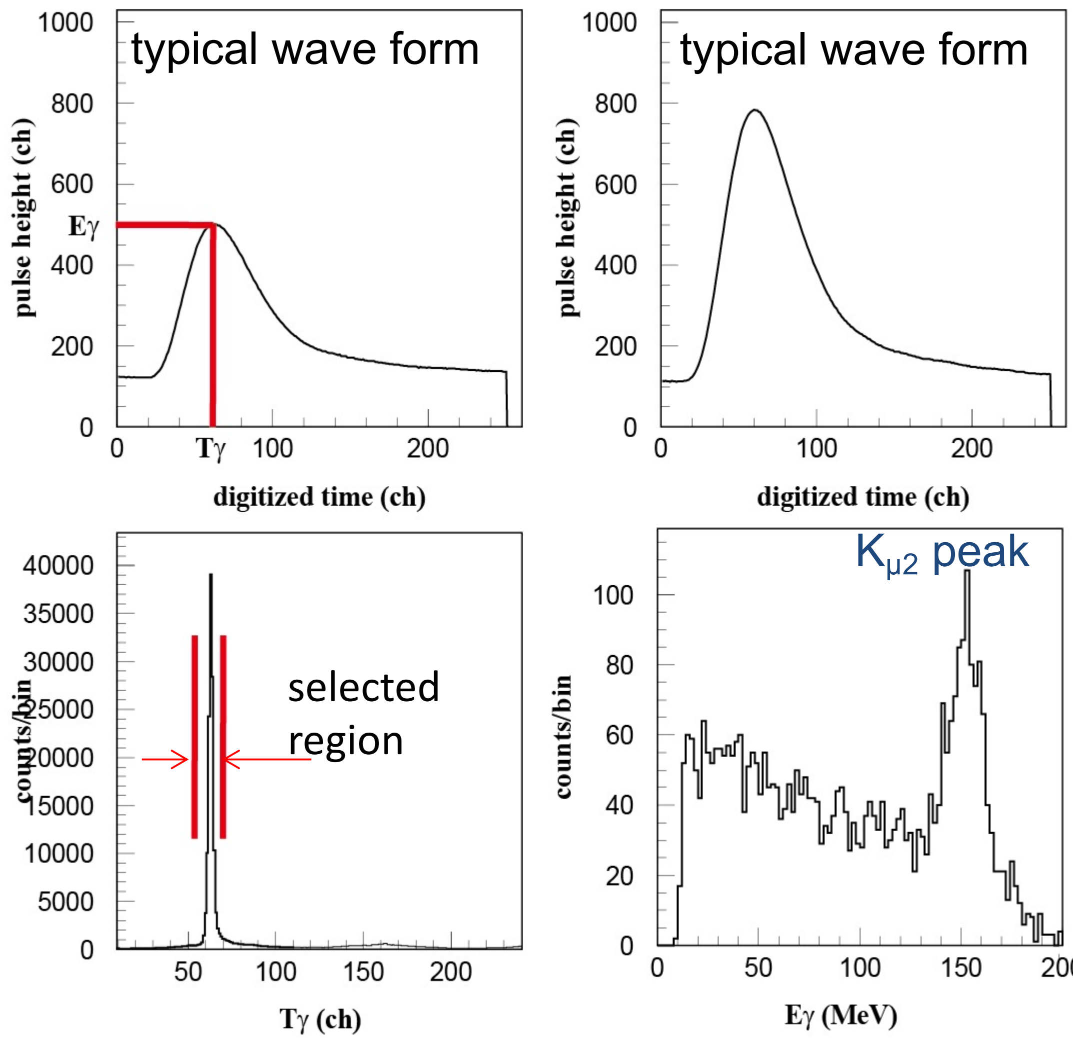


- *possible to separate with FADC*
- *has been implemented successfully*
- ***H. Ito et al., NIM A901, 1 (2018)***

Detection of photons from ***$K^+ \to \mu^+(e^+)\ \nu\ \gamma$ from IB+SD***
Detection of ***e^+, e^- from A' decay***

CsI(Tl) calorimeter calibration

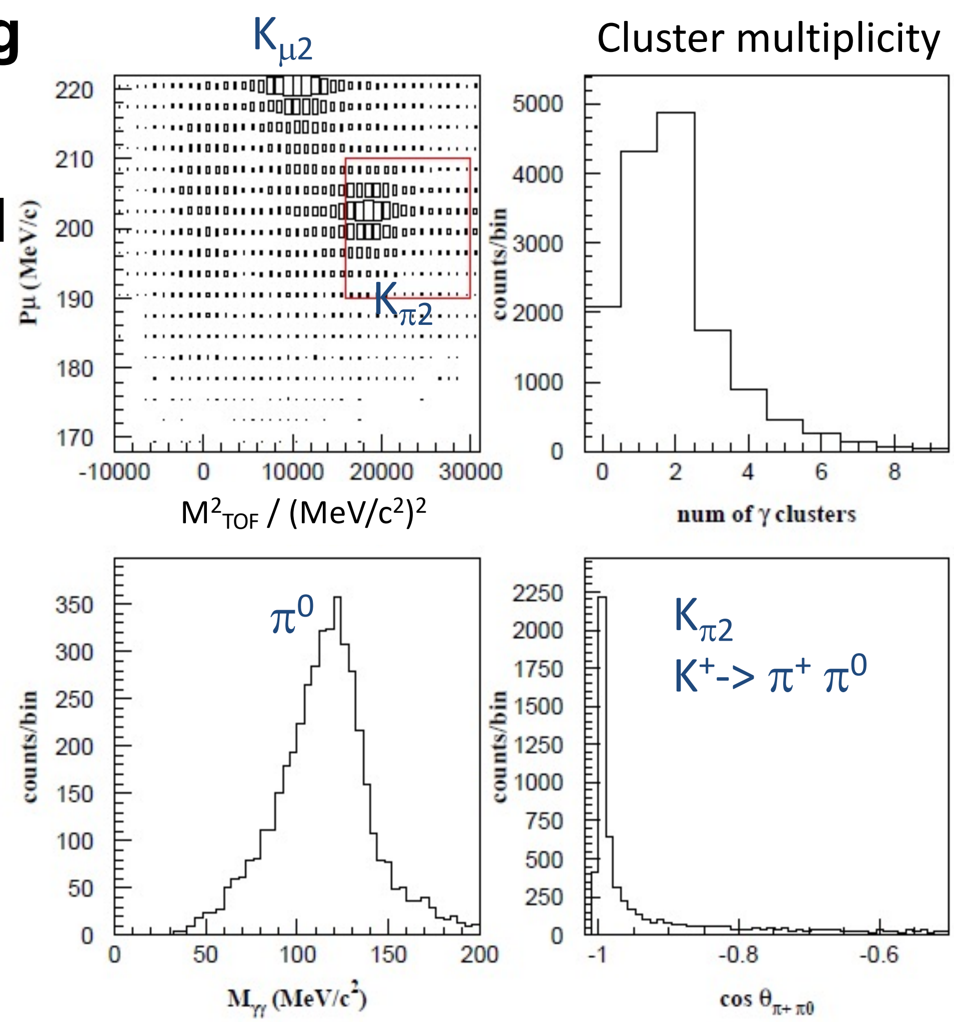
- **Energy and timing obtained by pulse shape data from FADC (VF48)**
- **Events from the K^+ decays were selected**
- **$K_{\mu 2}$ events with single crystal hit used for the energy calibration**
- **Deposited muon energy used for energy calibration of each crystal**



H. Ito et al., NIM A 901, 1 (2018)

Combining spectrometer + calorimeter

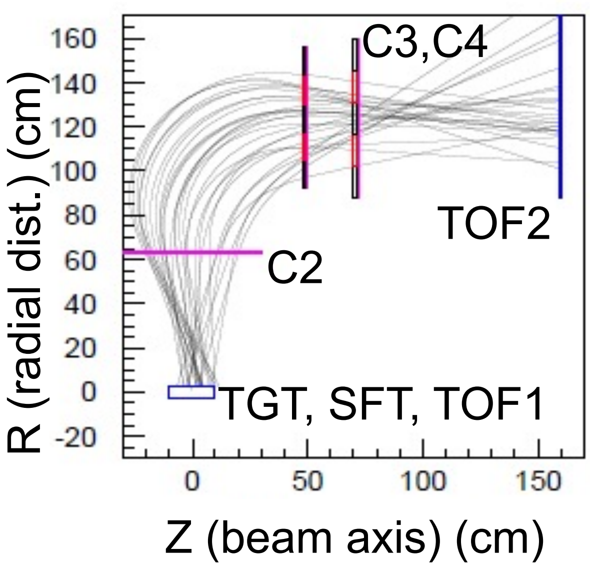
- **$K_{\pi 2}$ events selected by analyzing momentum and TOF (M^2)**
- **π^0 invariant mass reconstructed by selecting two-cluster events**
- **Large π^+ / π^0 opening angle observed to select $K_{\pi 2}$**
- **Confirmed that the total E36 system works correctly and is consistent with E246**

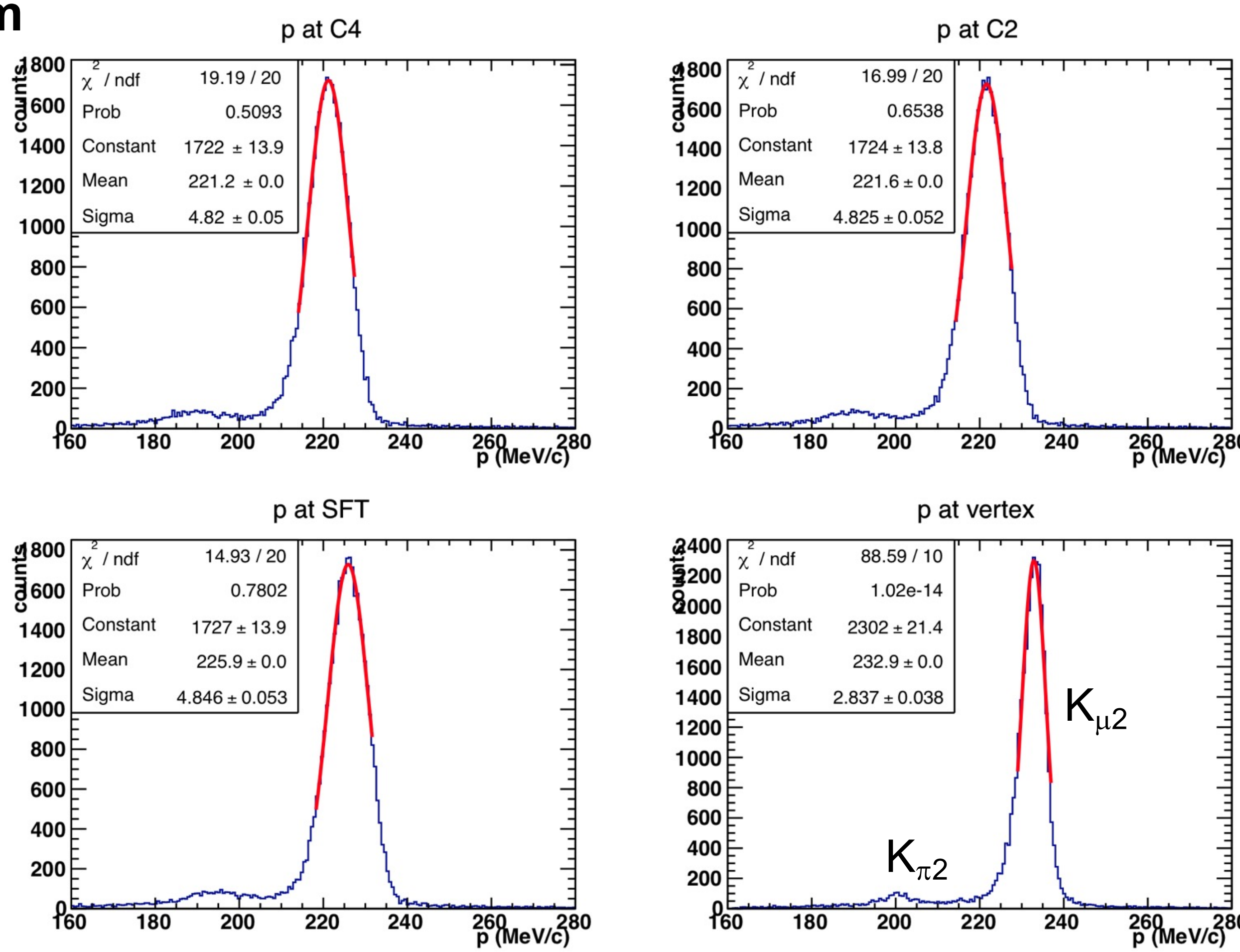


H. Ito et al., PLB 826, 136913 (2022)

Momentum determination

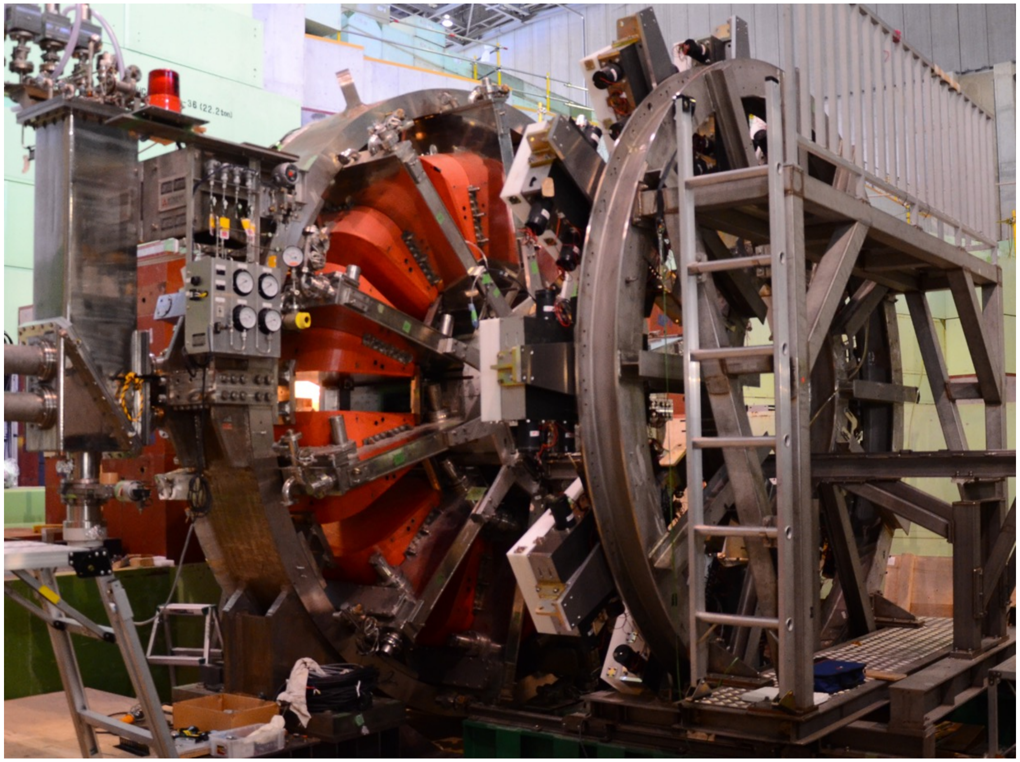
- **Charged particle momentum from tracking with C2, C3, C4 based on Kalman Filter technique (Tongtong Cao, Thir Gautam)**
- **Momentum evaluated at C4, C2, SFT, and vertex, corrected for energy loss, shifted from expected value by O(1%) (mag. field and vertex uncertainty)**
- **Monochromatic peaks from $K_{\mu 2}$ and $K_{\pi 2}$ observed**
- **Momentum resol. ~1.2%, improve to ~1% with target and SFT in KF for more accurate vertex**

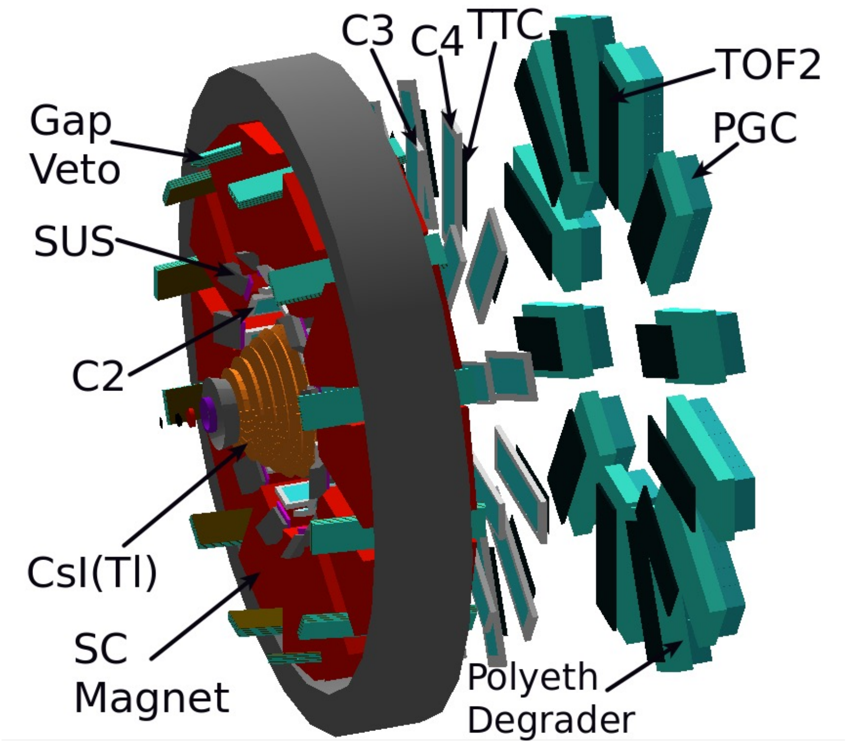


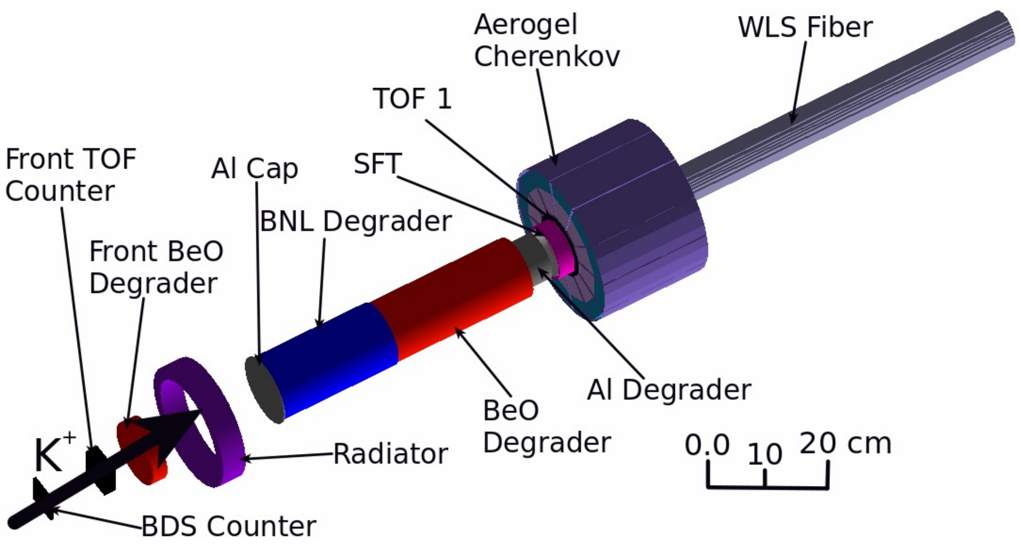


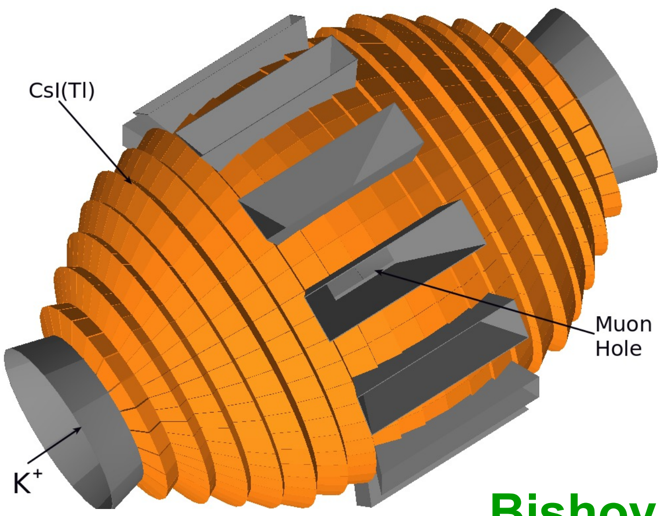
Preliminary

Geant4 description of TREK/E36









CsI(Tl)

Bishoy Dongwi

Geant4 description of TREK/E36

K^+ Channels

Label	Branch	Ratio
0	$K^+ \to e^+\nu$	1.582×10^{-5}
1	$K^+ \to \mu^+\nu$	6.355×10^{-1}
2	$K^+ \to e^+\pi^0\nu$	5.07×10^{-2}
3	$K^+ \to \mu^+\pi^0\nu$	3.352×10^{-2}
4	$K^+ \to e^+\pi^0\pi^0\nu$	2.55×10^{-5}
5	$K^+ \to \pi^+\pi^-e^+\nu$	4.247×10^{-5}
6	$K^+ \to \pi^+\pi^-\mu^+\nu$	1.4×10^{-5}
7	$K^+ \to \pi^+\pi^0$	2.067×10^{-1}
8	$K^+ \to \pi^+\pi^0\pi^0$	1.760×10^{-2}
9	$K^+ \to \pi^+\pi^+\pi^-$	5.583×10^{-2}
10	$K^+ \to \mu^+\nu\gamma$	6.2×10^{-3}
11	$K^+ \to e^+\nu\gamma$	9.4×10^{-6}
12	$K^+ \to \mu^+\pi^0\nu\gamma$	1.25×10^{-5}
13	$K^+ \to \pi^+\pi^+\pi^-\gamma$	1.04×10^{-4}
14	$K^+ \to \mu^+\nu A'$	$\epsilon^2 \times ratio\ of\ channel\ 16$
15	$K^+ \to \pi^+ A'$	$\epsilon^2 \times ratio\ of\ channel\ 17$
16	$K^+ \to \mu^+e^+e^-\nu$	2.5×10^{-5}
17	$K^+ \to \pi^+e^+e^-$	3×10^{-7}

π^0 Channels

Label	Branch	Ratio
0	$\pi^0 \to \gamma\gamma$	9.8823×10^{-1}
1	$\pi^0 \to e^+e^-\gamma$	1.174×10^{-2}
2	$\pi^0 \to \gamma A'$	$\epsilon^2 \times ratio\ of\ channel\ 2$

ROOT based generator

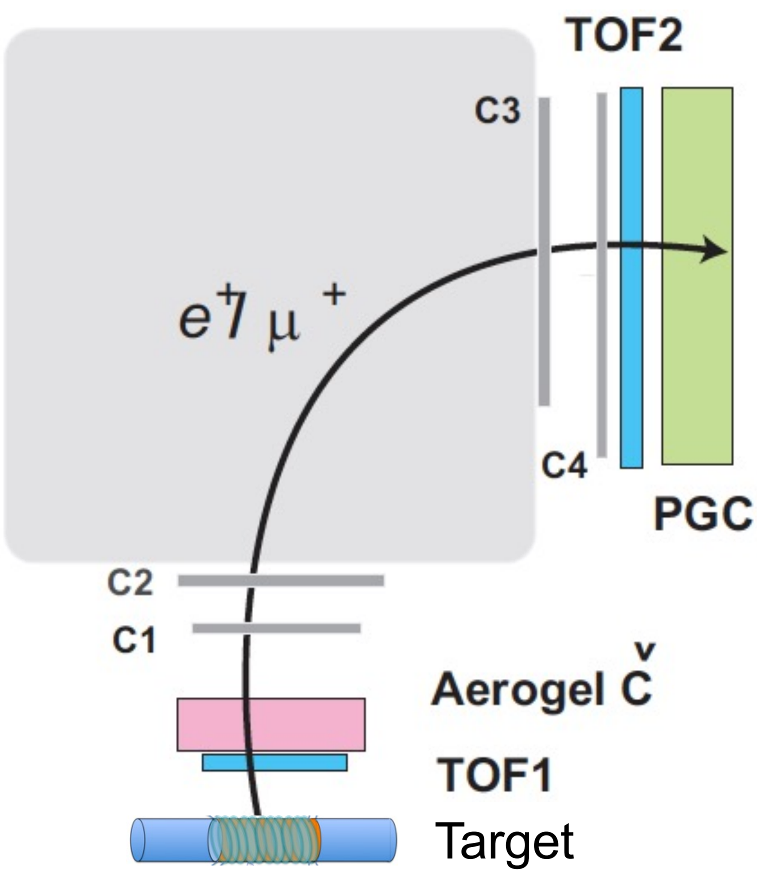
- Interactive: utilizes *Messenger Classes*
- Allows for selection of decay modes and branching ratios

Bishoy Dongwi
Tongtong Cao

μ^+/e^+ identification (designed)

PID with:

- TOF
- Aerogel Č
- Lead glass

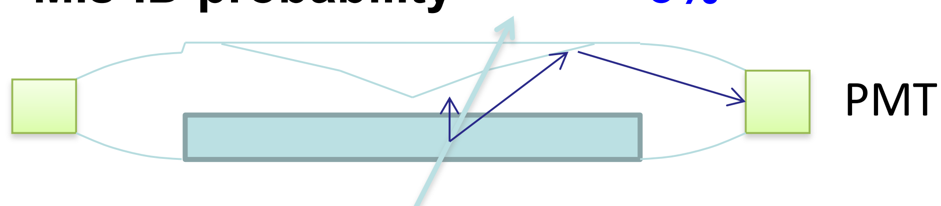


TOF

Flight length	250 cm
Time resolution	<100 ps
Mis-ID probability	7x 10^{-4}

Aerogel Č counter

Radiator thickness	4.0 cm
Refraction index	1.08
e^+ efficiency	>98%
Mis-ID probability	3%



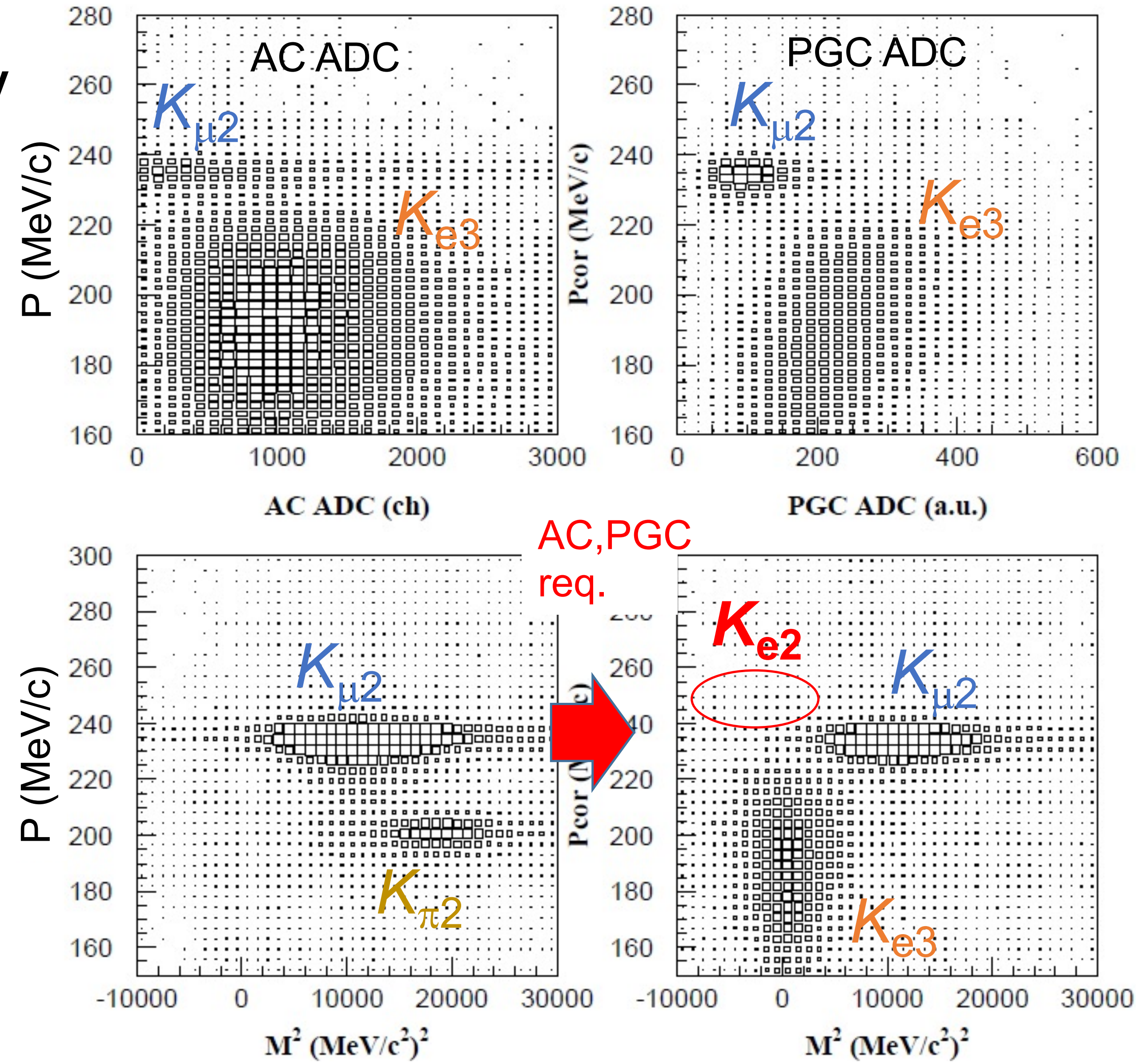
Lead glass (PGC)

Material	SF6W
Refraction index	1.05
e^+ efficiency	98%
Mis-ID probability	4%

$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

Particle identification by AC, PGC, and TOF

- **Positrons are selected by AC, PGC and TOF**
- **PID performance optimized by combining three PID systems**
- **Suppression of muon mis-identification below O(10^{-8}) level**

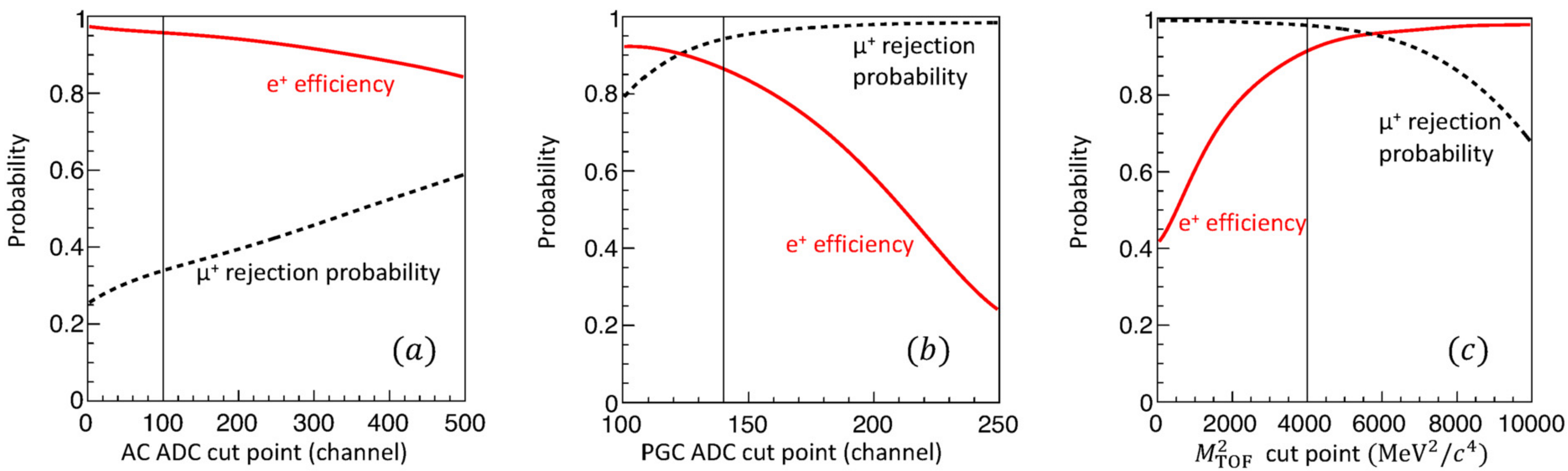


Preliminary

μ⁺/e⁺ identification (typical performance)

- Redundant PID to maximize e^+ efficiency and minimize μ^+ mis-ID
- PID with:

Aerogel (AC) Leadglass (PGC) Time of flight (TOF)



— e^+ efficiency ---- μ^+ rejection

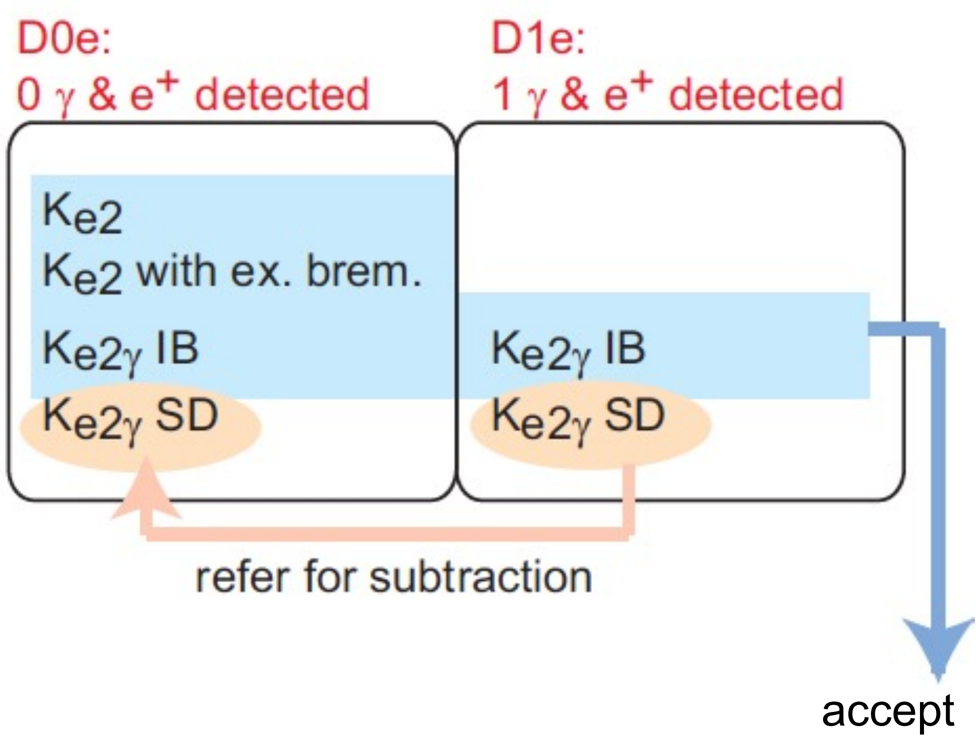
H. Ito et al.,
PLB 826, 136913 (2022)

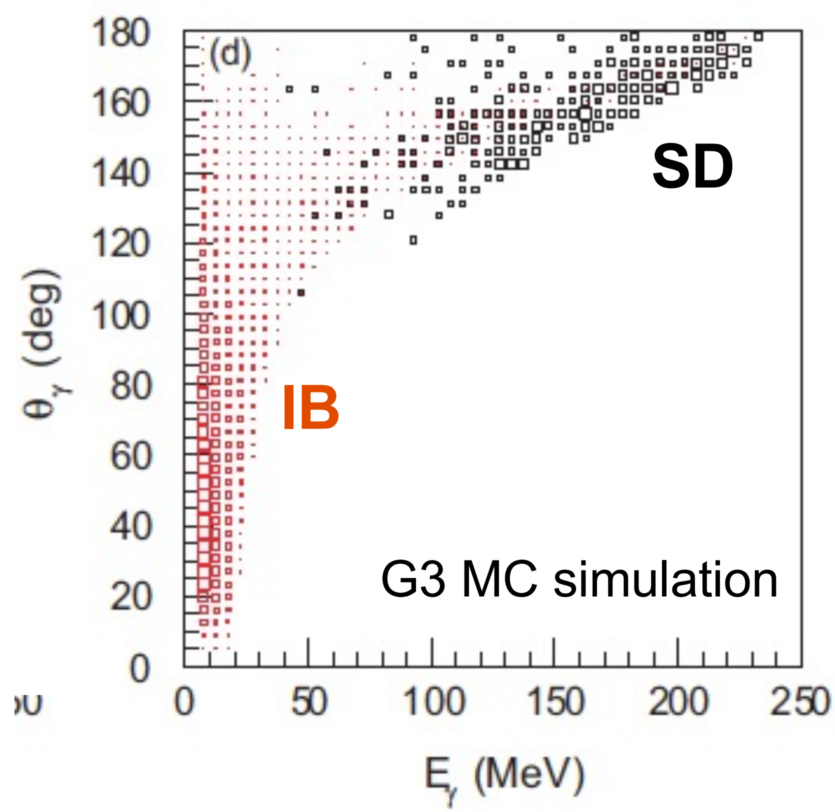
PID performance limitation requires subtraction of residual muon background

Extraction of $K_{e2\gamma}$(SD) and $K_{e2(\gamma)}$

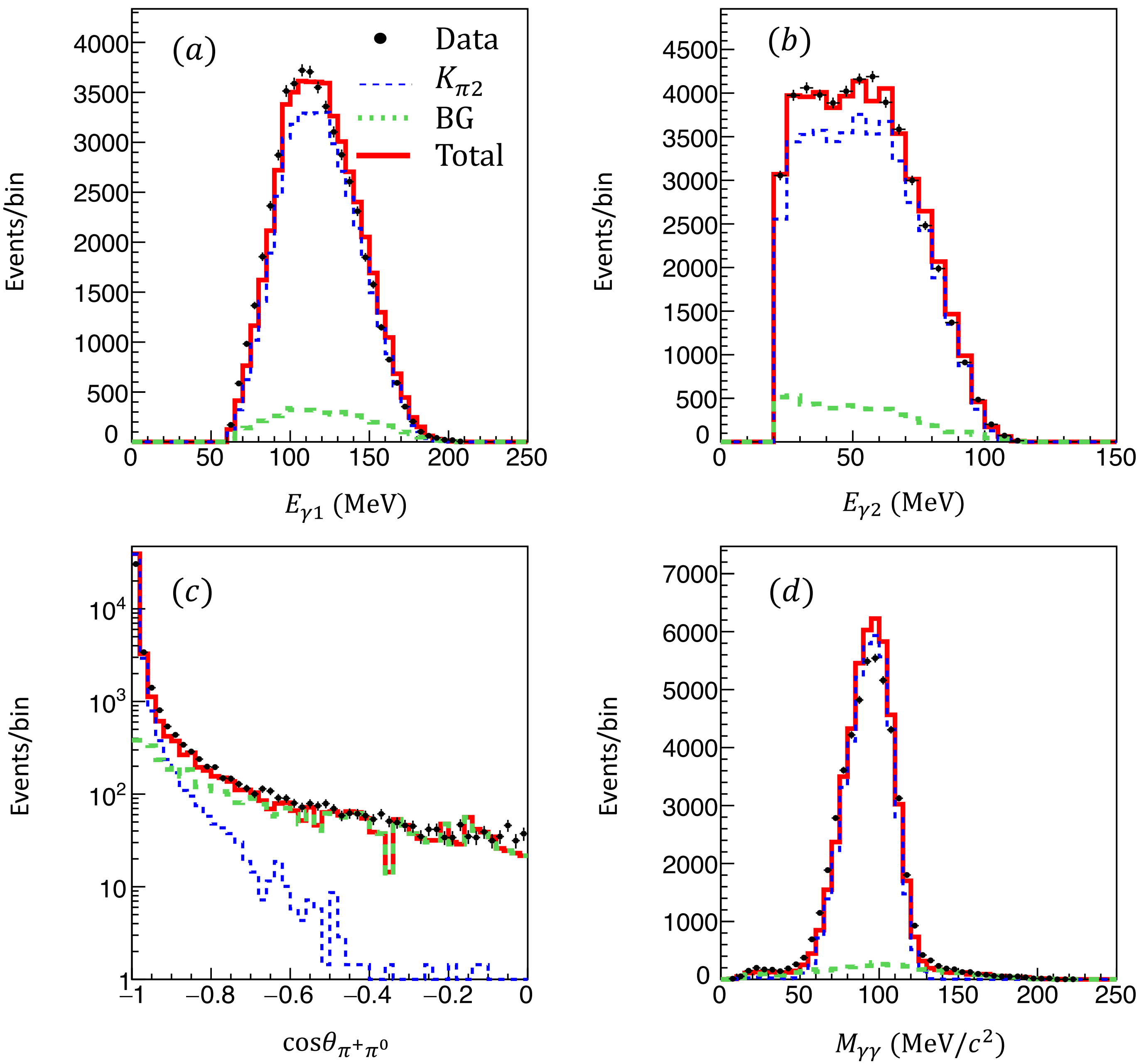
- **Subtraction of structure dependent $K_{e2\gamma}$ (SD) required**
- **Internal bremsstrahlung (IB) to be included in K_{e2}: "$K_{e2(\gamma)}$"**
- **E36 and KLOE can measure the SD events**
- **$K_{e2\gamma}$ (SD) is important input for NA62 analysis ($\delta R_K/R_K$=0.4%)**

K. Horie, S. Shimizu





CsI(Tl) calibration and accidental bg.



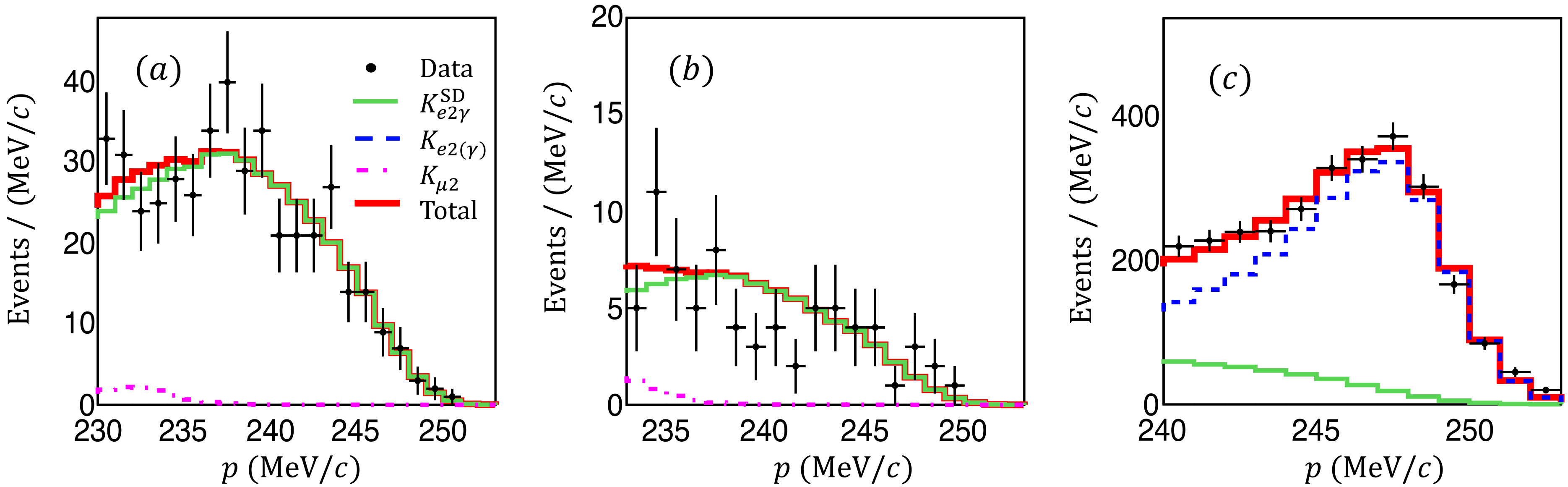
- **$K_{\pi2}$ ($K^+ \rightarrow \pi^+\pi^0$) recon. 2-cluster events**
- **Accidental bg: $K_{\mu2}$ + 1-cluster (~19%) exp. acc. spect.**
- **Mixing exp. acc. with simulated 1-cluster $K_{\pi2}$ for acc. background in 2-cluster evts.**

Extraction of $K_{e2\gamma}$(SD) and $K_{e2(\gamma)}$

- Positron momentum spectrum
- PID applied with AC, PGC, TOF
- Decomposition of $K_{e2(\gamma)}$, $K_{e2\gamma}^{SD}$, $K_{\mu 2}$, K_{e3} *yields*
- Internal bremsstrahlung (IB) effect included in $K_{e2(\gamma)}$

H. Ito et al., PLB 826, 136913 (2022)

C. Gatti, EPJC 45, 417 (2006)



CsI: 1-cluster — CsI: 2-cluster — CsI: any cluster

E36 (CsI) result for $K_{e2\gamma}$ (SD):

$BR(K_{e2\gamma}^{SD})/BR(K_{e2(\gamma)}) = 1.12 \pm 0.07$ stat. ± 0.04 sys.

Systematics

Table 2
Summary of the systematic uncertainties for the $Br(K_{e2\gamma}^{\mathrm{SD}^+})/Br(K_{e2(\gamma)})$ ratio determination.

Source	Systematic uncertainty
Hole size of CsI(Tl) calorimeter	0.017
CsI(Tl) misalignment	< 0.001
Imperfect reproducibility of photon angular distribution	< 0.001
Accidental backgrounds in CsI(Tl)	0.004
Photon energy threshold of CsI(Tl)	0.007
Photon energy calibration of CsI(Tl)	< 0.001
Photon timing window	0.009
CsI(Tl) detection efficiency	0.012
AC detection(PID) efficiency	0.007
PGC detection(PID) efficiency	0.007
TOF detection(PID) efficiency	0.019
$K_{\mu 2}$ background subtraction	0.015
$K_{e2\gamma}^{\mathrm{SD}^+}$ form factor	0.011
K^+ stopping distribution	0.003
Material thickness in the central parts	< 0.001
Positron momentum resolution	0.002
Magnetic field	0.002
In-flight kaon decay	0.002
Total	0.036

Comparison of $K_{e2\gamma}$(SD) w/ KLOE & Theory

E36: BR($K_{e2\gamma}^{SD}$)/BR($K_{e2(\gamma)}$) = 1.12 ± 0.07 stat. ± 0.04 sys.

H. Ito *et al.*, PLB 826, 136913 (2022)

Comparison with KLOE: convert E36 ratio, reduce phase space

$$\frac{Br(K_{e2\gamma}^{\mathrm{SD}^+})}{Br(K_{\mu 2})} = \frac{Br(K_{e2\gamma}^{\mathrm{SD}^+})}{Br(K_{e2(\gamma)})} \times \frac{Br(K_{e2(\gamma)})}{Br(K_{\mu 2})} = \frac{Br(K_{e2\gamma}^{\mathrm{SD}^+})}{Br(K_{e2(\gamma)})} \times R_K^{\mathrm{SM}}$$

$$R_\gamma = \frac{Br(K_{e2\gamma}^{\mathrm{SD}^+},\ p > 200\ \mathrm{MeV}/c,\ E_\gamma > 10\ \mathrm{MeV})}{Br(K_{\mu 2})}$$

E36: $R_\gamma = (1.85 \pm 0.11_{\mathrm{stat}} \pm 0.07_{\mathrm{syst}}) \times 10^{-5}$

KLOE: $R_\gamma = (1.483 \pm 0.066_{\mathrm{stat}} \pm 0.013_{\mathrm{syst}}) \times 10^{-5}$

F. Ambrosino *et al.*, Eur. Phys. J. C64, 627 (2009)

Lattice-QCD: $R_\gamma = (1.74 \pm 0.21) \times 10^{-5}$

R. Frezzotti, *et al.*, Phys. Rev. D 103, 053005 (2021)

ChPT:

$R_\gamma = 1.477 \times 10^{-5}$

J. Bijnens, G. Ecker, J. Gasser, Nucl. Phys. B 396, 81 (1993)

E36: Agree with Lattice (~1σ), disagree with ChPT (~3σ)

New extraction of $K_{e2\gamma(\gamma)}$(SD) [preliminary]

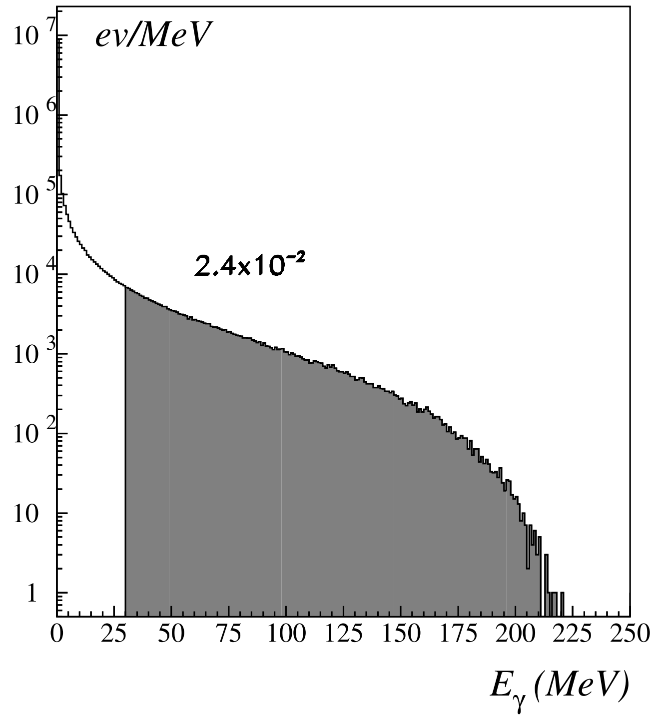
- Caveat: IB correction was only applied to $K_{e2(\gamma)}$, not to $K_{e2\gamma}$ (SD) Narrow e^+ momentum interval requires accounting for acceptance loss due to hard photon IB tail
- Similarly, acceptance of $K_{e2\gamma(\gamma)}$ (SD) affected by hard photon radiation, too
- Implementation: Following prescription by Gatti, using radiative MC generators for both $K_{e2(\gamma)}$ and $K_{e2\gamma(\gamma)}$ (SD)
  C. Gatti, Eur. Phys. J. C 45, 417 (2006)

- E36: Additional E36 data from Gap Scintillation Counters (GSC)
  → New, preliminary E36 result for CsI(Tl) + GSC:

Previously: $BR(K_{e2\gamma})/BR(K_{e2(\gamma)})$ = 1.12 ± 0.07 stat. ± 0.04 sys.
H. Ito *et al.*, PLB 826, 136913 (2022)

$BR(K^{SD}_{e2\gamma(\gamma)})/BR(K_{e2(\gamma)})$ = 1.25 ± 0.14 stat. ± 0.08 sys. – GSC
$BR(K^{SD}_{e2\gamma(\gamma)})/BR(K_{e2(\gamma)})$ = 1.19 ± 0.07 stat. ± 0.04 sys. – CsI(Tl) [+6%]
Error-weighted mean: 1.20 ± 0.07 (prel.) → $R_\gamma = (1.97 \pm 0.12) \times 10^{-5}$
Agree with Lattice (~1σ), disagree with ChPT (~4σ)
A. Kobayashi *et al.*, to be published

MC prescription by Gatti



C. Gatti, Eur. Phys. J. C 45, 417 (2006)

Example spectrum

Fig. 1. Energy spectrum for $K^0 \to \pi e \nu \gamma$ MC decays. 2.4% of the events have $E_\gamma > 30\,\mathrm{MeV}$

- **Analytic expressions for IB**

$$b = -\frac{1}{8\pi^2}\sum_{m,n}\eta_m\eta_n e_m e_n \beta_{mn}^{-1}\ln\frac{1+\beta_{mn}}{1-\beta_{mn}}$$

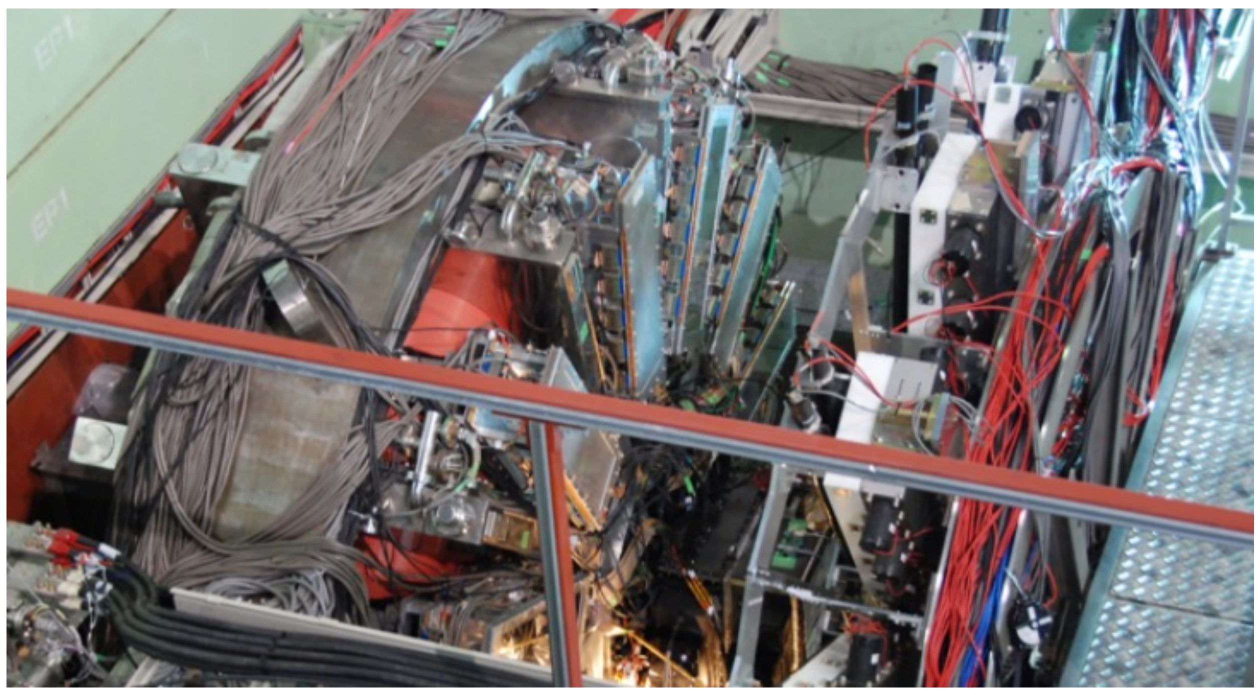
$$\frac{\mathrm{d}\Gamma_{\mathrm{incl}}}{\mathrm{d}E_\gamma} = \Gamma_0 b\frac{E_\gamma^{b-1}}{M^b} = \frac{\mathrm{d}\Gamma_{\mathrm{Brem}}}{\mathrm{d}E_\gamma}\left(\frac{E_\gamma}{M}\right)^b$$

$$\frac{\mathrm{d}\Gamma_{\mathrm{Brem}}}{\mathrm{d}E_\gamma} = \Gamma_0\frac{b}{E_\gamma}$$

- **Works also for differential decay widths**
- **Simple implementation in MC generators**

Summary

- **Lepton universality is challenged (BaBar, Belle, LHCb)**
- **TREK/E36: Measurement of $K_{e2(\gamma)}/K_{\mu 2(\gamma)}$ ratio – test of lepton universality; Measurement of structure-dependent BR($K^{SD}_{e2\gamma}$)**
- **Search for dark photons / light neutral bosons**
- **Production running has been completed (Oct. 14 – Dec. 18, 2015)**
- **Analysis underway (calibration, simulation, systematic error studies); first results on $K_{e2\gamma}$; expect further results soon (R_K; light bosons)**
- **TREK/E06 (T-violation) in the future (Hadron Hall Extension)**



TREK (E36/E06) collaboration

~30 collaborators

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