The stopped K^+ decay experiment TREK/E36 at J-PARC

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New Physics beyond the Standard Model

New Physics beyond the Standard Model

In the world of weak interactions do electrons, muons and tauons behave the same way?

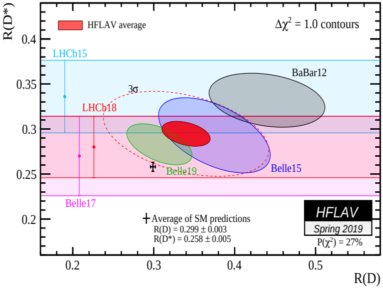
Lepton universality violation?

$\mu - \tau$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B\to D^{*}\tau\nu)}{\mathcal{B}(B\to D^{*}\mu\nu)}$$

$\mu - e$

$$R_K[q^2_{min}, q^2_{max}] = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B\to K\mu^+\mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B\to Ke^+e^-)}{dq^2}}$$



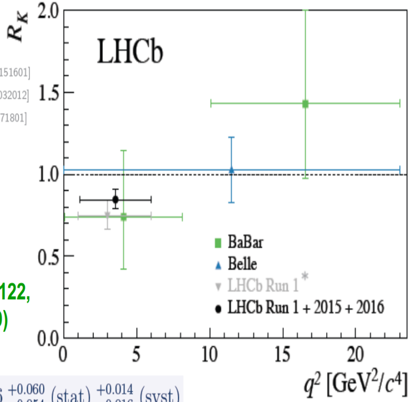
HFLAV average of combined R(D) and R(D^*) is 3.0σ from the SM prediction

LHCb (Phys. Rev. Lett. 113)

[LHCb, PRL 113 (2014) 151601]

[BaBar, PRD 86 (2012) 032012]

[Belle, PRL 103 (2009) 171801]



R. Aaji, PRL 122, 191801 (2019)

$$R_K = 0.846\ ^{+0.060}_{-0.054}\ (\text{stat})\ ^{+0.014}_{-0.016}\ (\text{syst})$$

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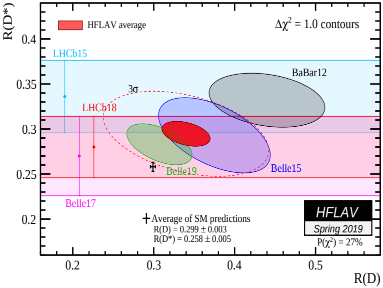

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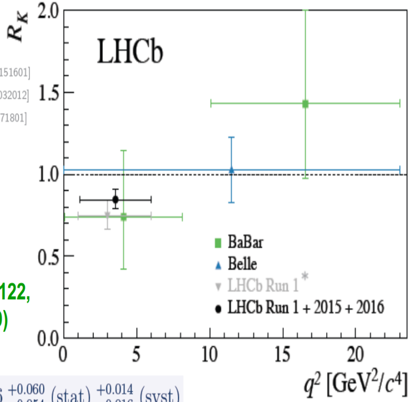

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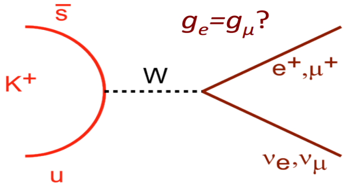
Lepton non-universality is the flagship for physics beyond the Standard Model

Lepton universality in K^+ decays

2-body decay of K^+

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



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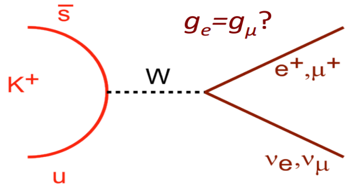


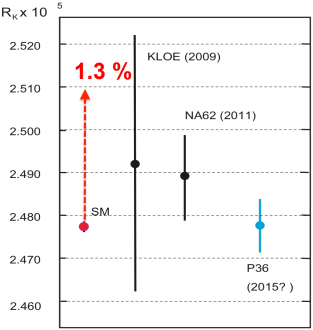
Decay width ratio of electronic (K_{e2}) and muonic ($K_{\mu 2}$) decay modes

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

- Hadronic form factors cancel
- Strong helicity suppression of electronic channel enhances sensitivity to effects beyond SM
- SM prediction is highly precise: $\boxed{R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}}$

Other measurements of lepton universality

- **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)**
  $R_K = (2.488 \pm 0.009) \times 10^{-5}$, $\delta R_K/R_K = 0.4\%$
- **Systematics:**
  - In-flight-decay experiments: kinematics overlap
  - E36 stopped K^+: detector acceptance and target
  - E36 complementary to in-flight experiments

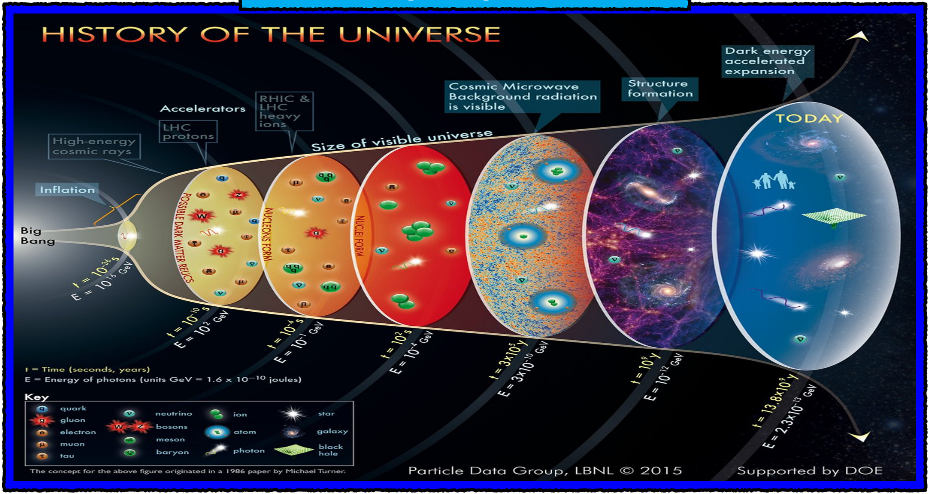


- **E36 goal:** $\delta R_K/R_K = \pm 0.2\%$ (stat) $\pm 0.15\%$ (syst) [0.25% total]

The TREK/E36 Experiment at J-PARC: an overview

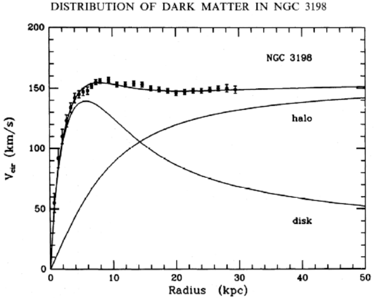
Big bang and nucleosynthesis to present

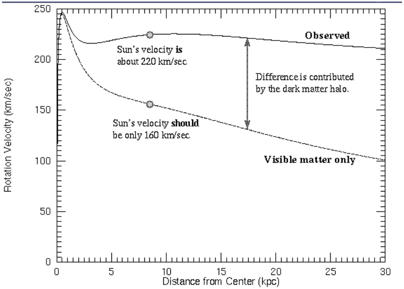
From the Big Bang to the present



Rotation curves of galaxies

Vera Rubin

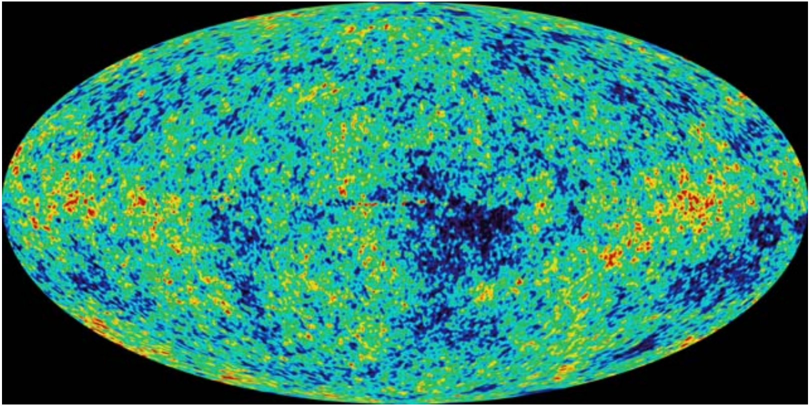




- Studied rotation curves of galaxies
- Found that they are FLAT!

Katherine Freese (Public lecture)

Cosmic Microwave Background (CMB)



(Jeff Filippini, UC Berkeley Cosmology Group (August 2005))

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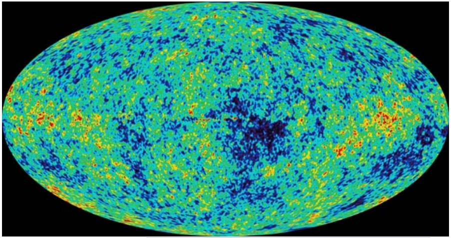

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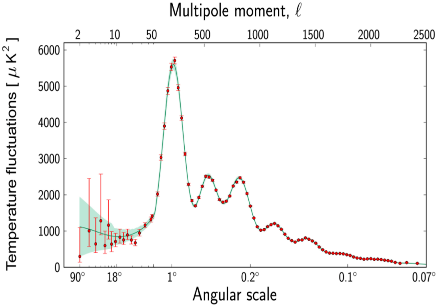
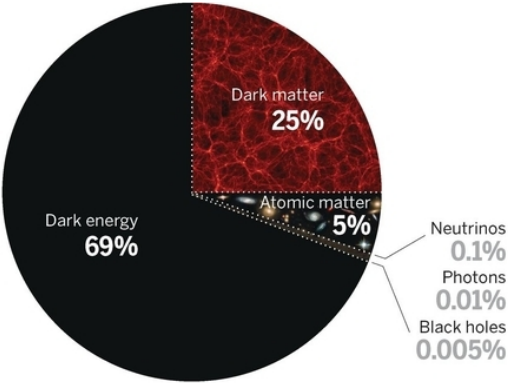


CMB and power spectrum:

- Left over heat of the Big Bang
- Almost uniform background of radio waves that fill the universe
- Due to redshifting as the universe expands
- Power spectrum of CMB measures the amount of fluctuation in the CMB temperature spectrum at different angular scales
- Oscillations in the hot gas of the early universe, resonant frequencies and amplitudes

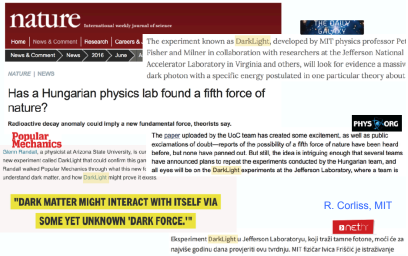
Energy of the universe

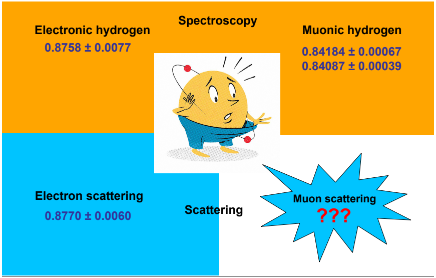


2014 P5 report

"It is imperative to search for dark matter along every feasible avenue," and the breadth of "well-motivated ideas for what dark matter could be, [which] include weakly interacting massive particles (WIMPs), gravitinos, axions, sterile neutrinos, asymmetric dark matter, and hidden sector dark matter"

Anomalies





- Proton radius puzzle, $(g-2)_\mu$
- Strong CP problem
- Positron excess and ^{8}Be anomaly

Dark matter quagmire

[G. Bertone and T. Tait, ARXIV:1701.01840]

Neutral boson search in stopped K^+ decays

K^+ decays ~ 10^{10}

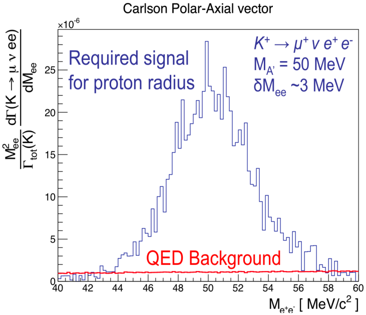
Signal 1: $K^+ \to \pi^+ A'$, $A' \to e^+e^-$

Background: BR($K^+ \to \pi^+ e^+ e^-$) ~ 2.9×10^{-7} ~ 2,900 ev.

Signal 2: $K^+ \to \mu^+ \nu A'$, $A' \to e^+e^-$

Background: BR($K^+ \to \mu^+ \nu\ e^+ e^-$) ~ 2.5×10^{-5} ~ 250,000 ev.

Add. background from $K^+ \to \mu^+ \nu \pi^0 \to \mu^+ \nu\ e^+ e^- (\gamma)$

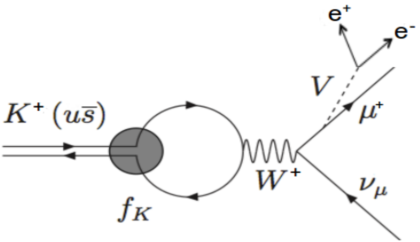


π^0 decays — 1) 3×10^8 — 2) 2×10^9

π^0 production: $K^+ \to \mu^+ \nu \pi^0$ (3.3%) — $K^+ \to \pi^+\pi^0$ (21.1%)

Signal 3: $\pi^0 \to \gamma A'$, $A' \to e^+e^-$

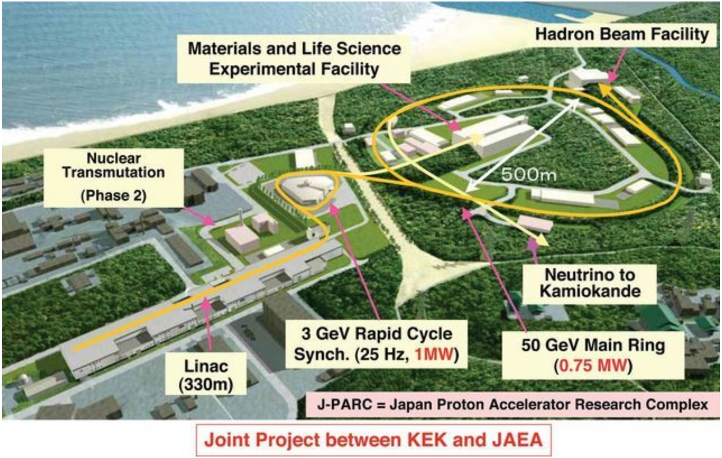
Background: BR($\pi^0 \to \gamma\ e^+ e^-$) ~ 1.2% ~ 0.3 (2.3) $\times 10^7$ ev.



PRD 89, 0350003(2014)

Onto the Land Of The Rising Sun we go!

Bird's eye view of J-PARC



Timeline of TREK/E36

TREK: Time Reversal Experiment with Kaons

December 2014

- Installed detector components

February - June 2015

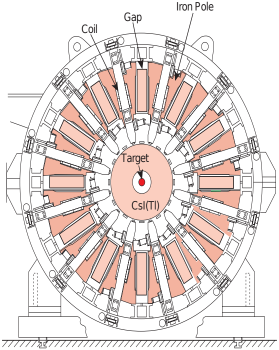
- Completed installation of C3 & C4
- Cabling
- Detector maintenance

September - December 2015

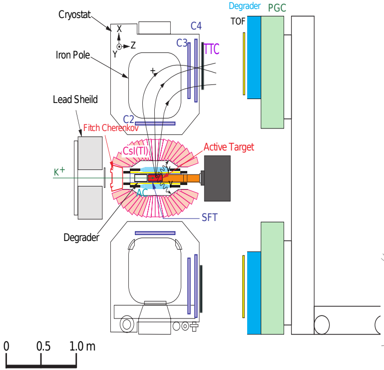
- Physics run
- Data taking

E36 detector geometry

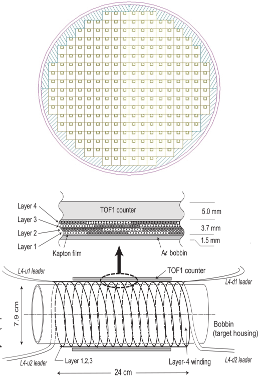
End view



Side view

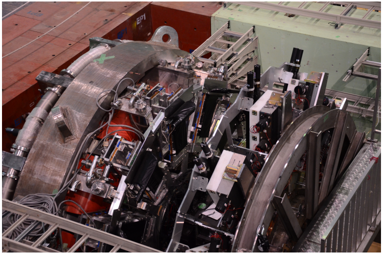


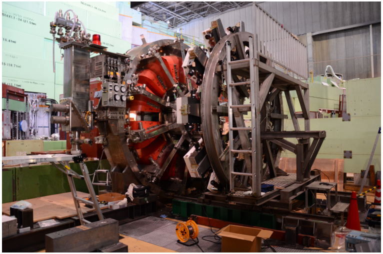
Target & SFT



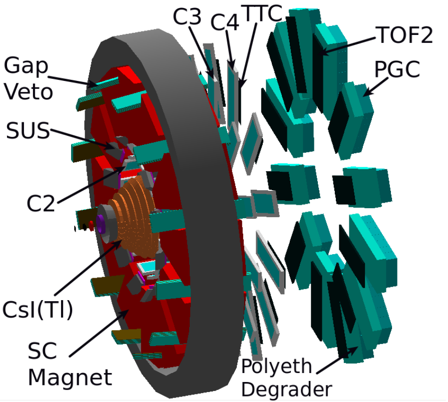
Stopped K^+ method	Momentum measurement	Particle ID	Gamma ray
K1.1BR beamline	MWPC (C2, C3, C4)	TOF	CsI(TI)
K^+ stopping target	Spiral fiber tracker (SFT)	AC	
	Thin trigger counter (TTC)	PGC	

Geant4 generated geometry



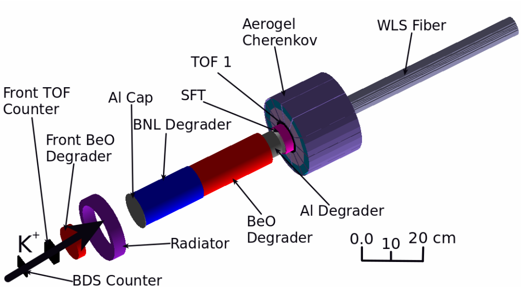


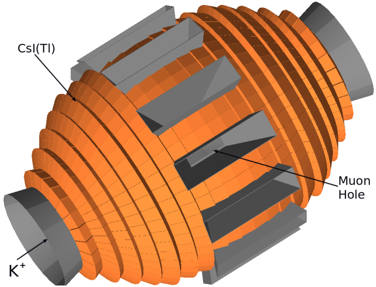
- Detector Assembly



- e36g4MC detector geometry

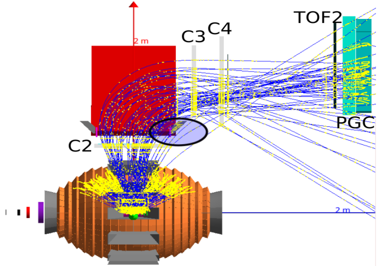
Geant4 cont.: Central Detector

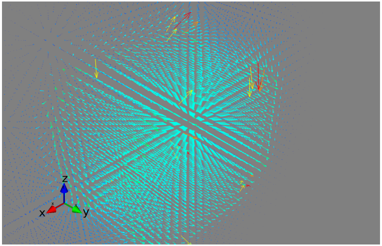




- Central Detector

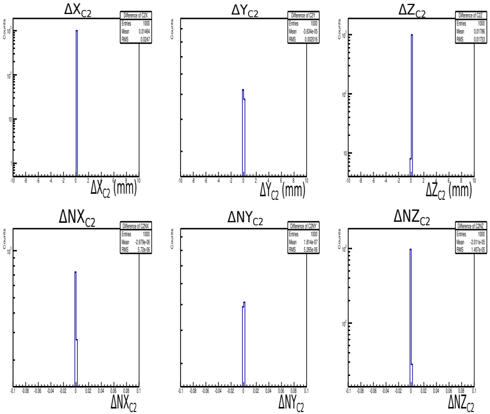
Tracking package and the e36g4MC comparison



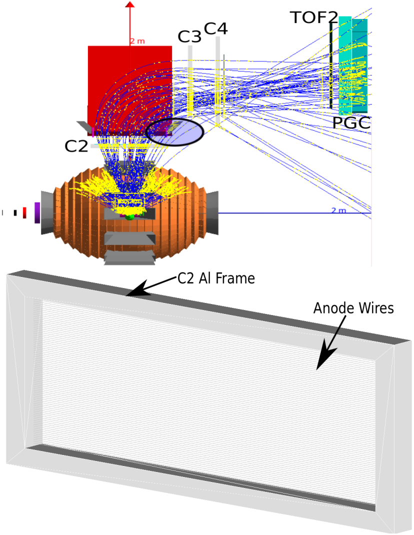


TOSCA generated field (P. Monaghan)

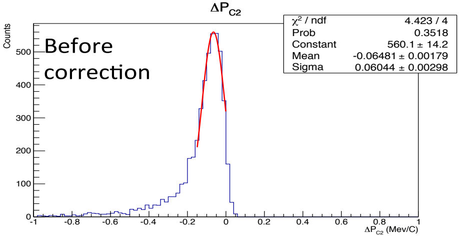
- Consistency check: propagation and magnetic field evaluation
- Simulated data: tracks propagated and reconstructed with Kalman Filter (KF)
- Established that KF tracking/propagation fully consistent with G4

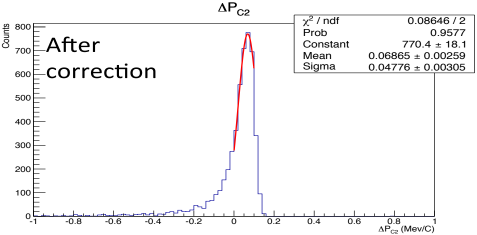


Tracking package and the e36g4MC comparison



- Energy loss/material budget comparison
- Anode plane $\longrightarrow$ anode wires





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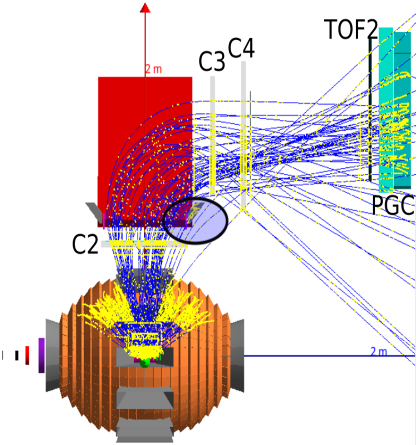
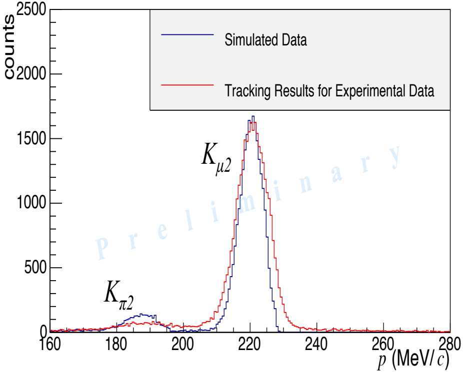
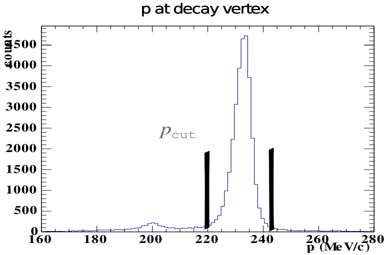
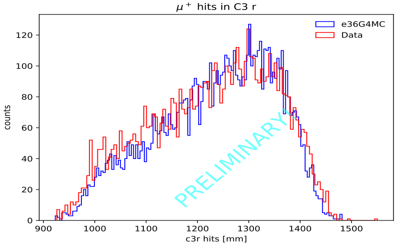


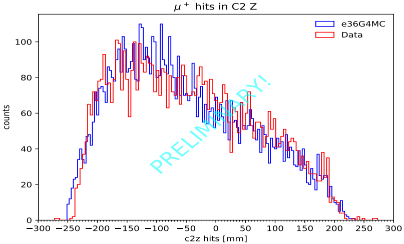
- Energy loss/material budget comparison
- Momentum distribution of $K_{\mu 2}$ and $K_{\pi 2}$ at C4
- No detector resolution in the simulation

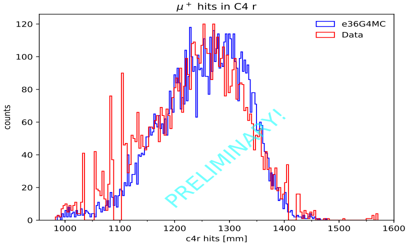


$K^+ \to \mu^+\nu_\mu \; (P_{\mu^+} = 236 \text{ MeV/c})$



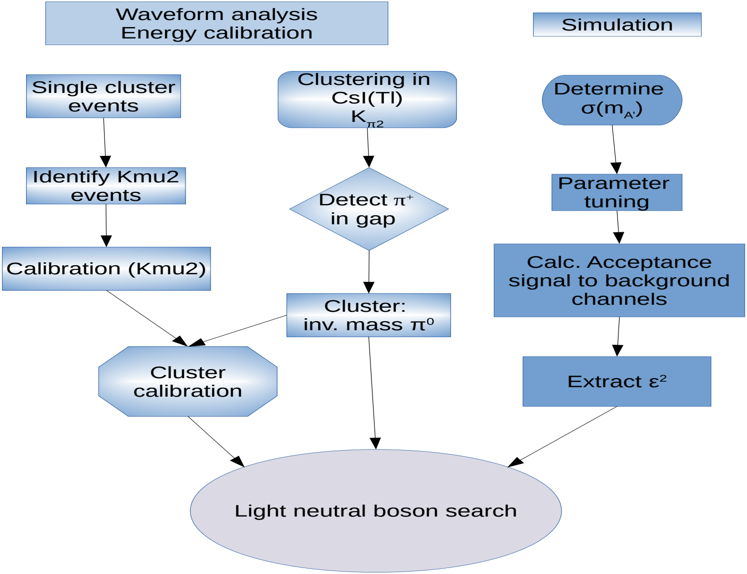






- Trigger on Target $\otimes$ TOF1 $\otimes$ TTC $\otimes$ TOF2
- $z = 2.5$cm and $x = y = 0.0$cm $\sigma_z = 8.75$cm, $\sigma_{x,y} = 0.15$cm
- Updates in progress

Search for light neutral bosons



Generator channels

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}

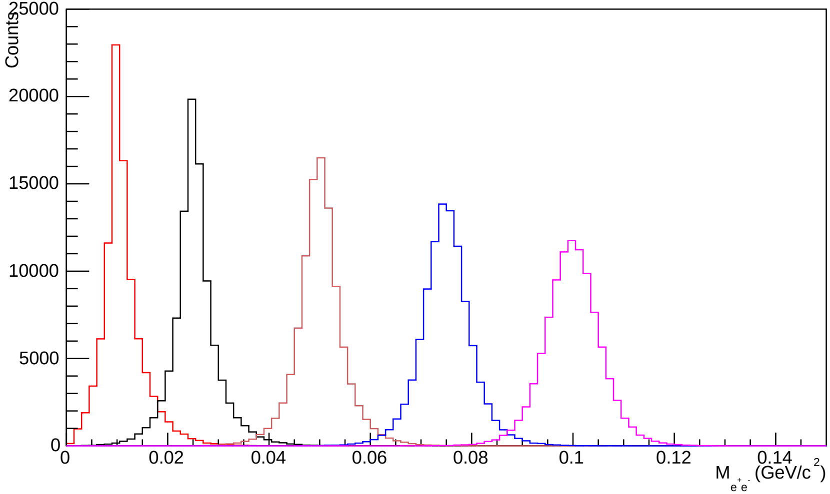
π^0 Channels

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

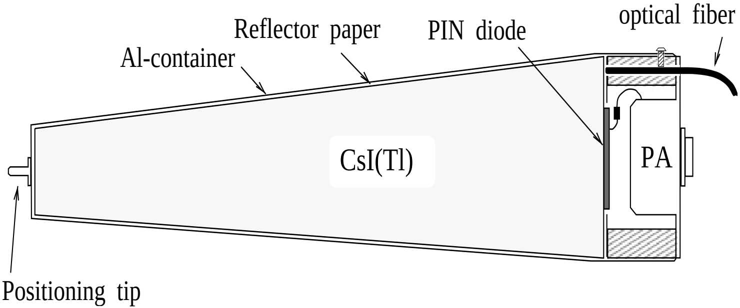
- Interactive: utilizes Messenger Classes
- Allows for selection of decay modes and branching ratios

Generator in action: Cut range for $\delta(m_{A'})$



- σ is determined by Gaussian fit of $m_{e^+e^-}$
- Relationship between σ and $m_{A'}$

CsI(Tl) analysis



- PIN photodiodes: readout the scintillation light of the CsI(Tl) crystals
- PIN diodes and pre-amplifier was assembled in an Al container
- Output signal from pre-amplifier was fed into shaping amplifier with 1 μs shaping time
- VF48 flash ADCs used to record shaping amplifier outputs

J. A. Macdonald (Nucl. Instrum. Meth., A506 2003)

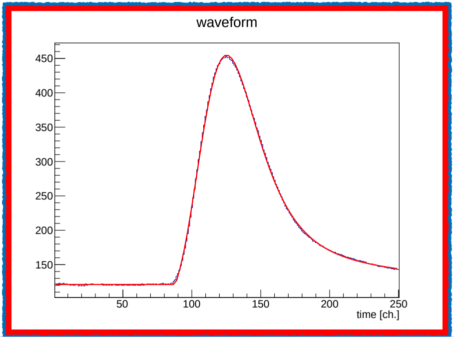
CsI(Tl) waveform analysis

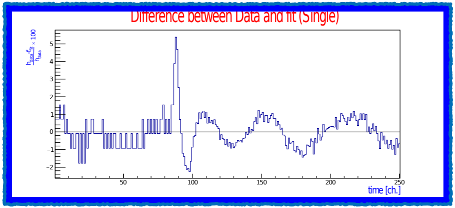
- μ rising factor

$$F(t) = \frac{A}{1 - e^{-(t-\tau_0)/\lambda}} \cdot \mathrm{Freq}\left[\frac{t-\tau_0-d}{\mu}\right] \cdot \left(\frac{t-\tau_0}{\tau_1} e^{\left[1-\frac{t-\tau_0}{\tau_1}\right]} + \epsilon \frac{t-\tau_0}{\tau_2} e^{\left[1-\frac{t-\tau_0}{\tau_2}\right]}\right)$$

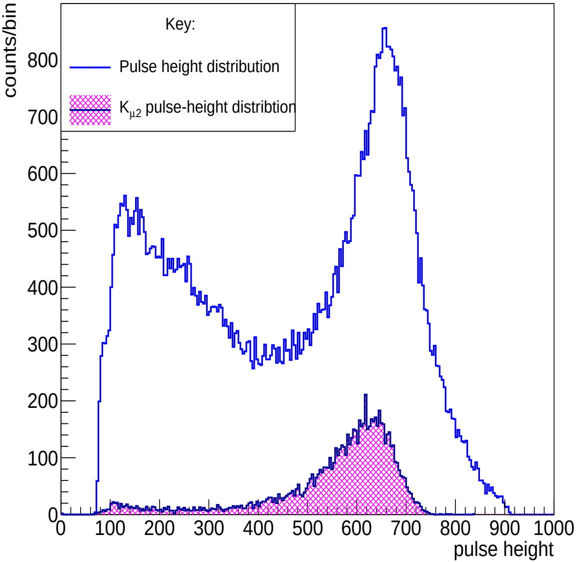
- λ is slow shape constant
- τ_0 is rise time
- τ_1 decay constant
- τ_2 local decay constant

H. Ito (Nucl. Instrum. Meth., A901 2018)





Pulse fitting in action: Pulse height distribution

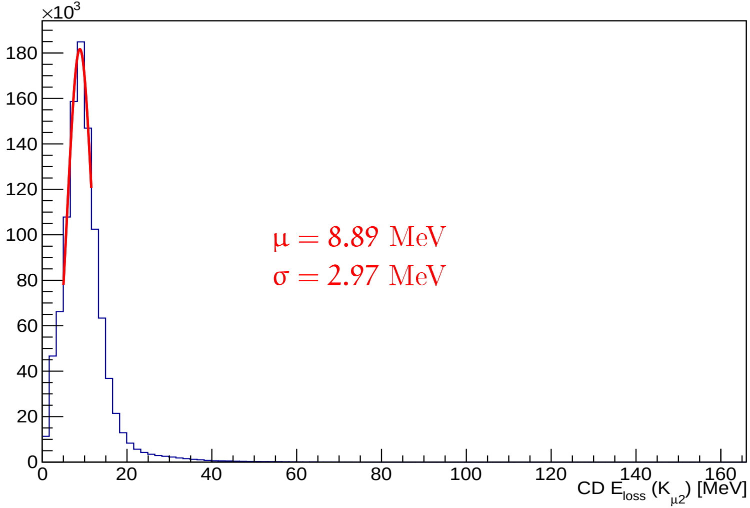


$K_{\mu 2}$ selection criteria

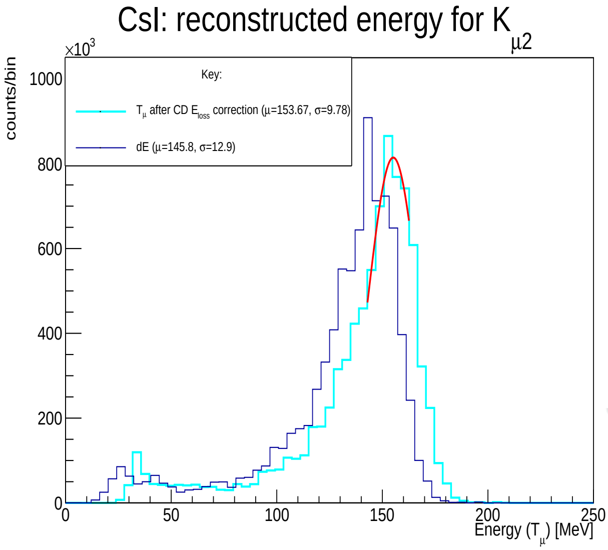
- Require single crystal per event
- First pulse time coincides with the K^+ decay
- Require a second peak

Pulse fitting in action: energy calibration from $K_{\mu 2}$

Energy loss from Central Detector (CD E_{loss})

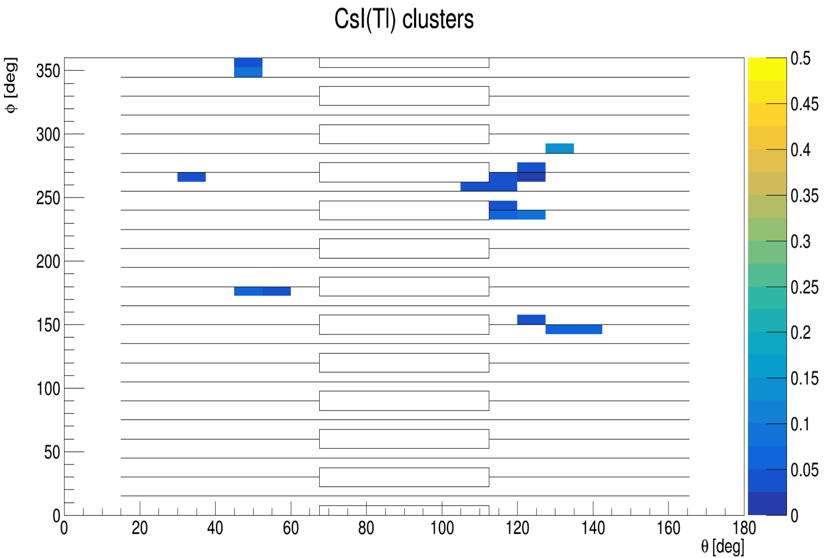


Pulse fitting in action: energy calibration from $K_{\mu 2}$

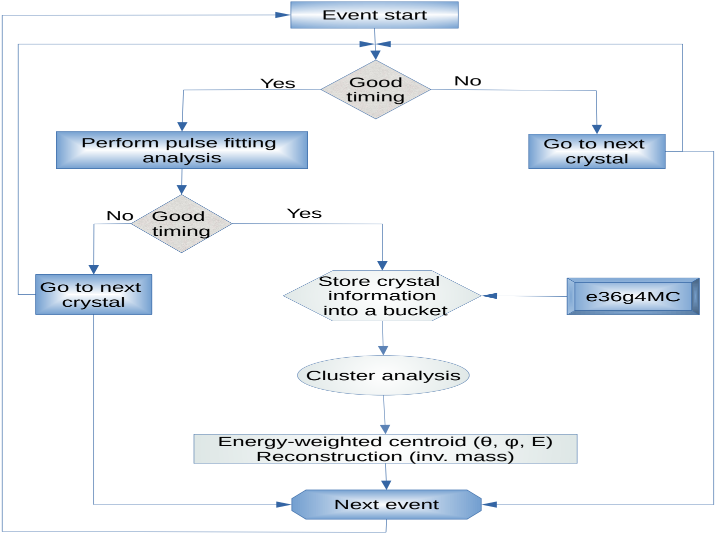


- $C_i = \frac{dE_{CsI}}{(A-P)_i}$, $i = 1, ..., 768$
- A is the waveform amplitude and P is the baseline
- $T_\mu = dE_{CsI} + CDE_{loss}$
- Correction for energy loss from CD system

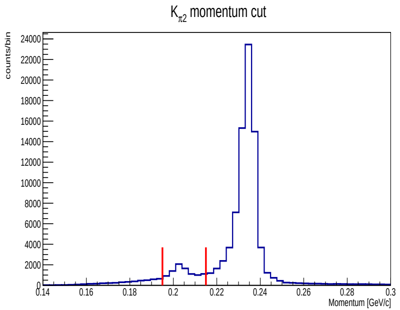
Cooker framework event viewer

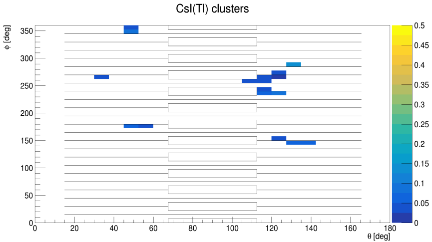


CsI cluster analysis



CsI cluster analysis cont...



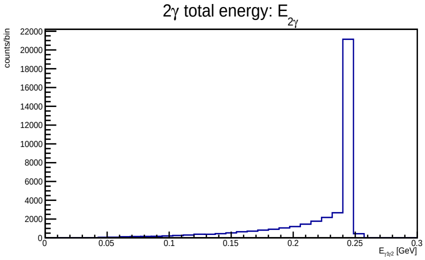


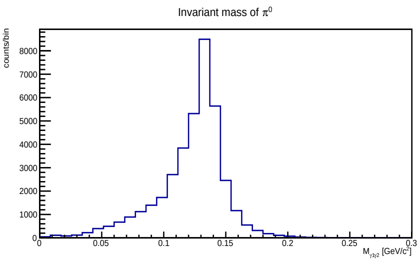
Cluster criterion: $K^+ \rightarrow \pi^+\pi^0$

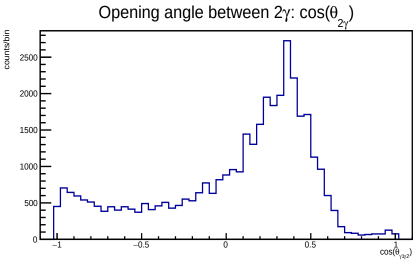
- High hardware trigger due to high rate
- Several clustering patterns need to be considered
- $N_{crys} \geq 2$ and $N_{crys} = 1$ (single crystal clusters)
- Currently single crystal clusters are considered as well
- Analysis is performed for $\pi^0 \rightarrow \gamma\gamma$, while allowing for a maximum of 3 cluster
- In case of 3 clusters, sum over combinations in search for which clusters have

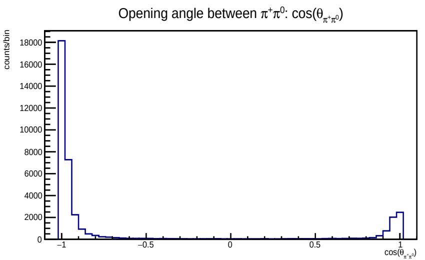
$$.90 \leq M_{inv}(\pi^0) \leq .140 \text{ GeV}/c^2$$

e36g4MC CsI $K_{\pi 2}$ cluster analysis

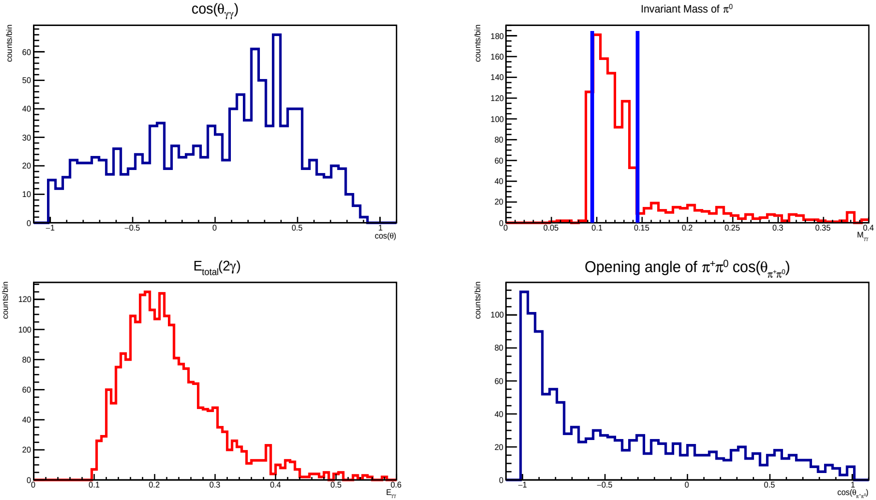








CsI $K_{\pi 2}$ cluster analysis



- $E_{total}(2\gamma)$: total energy of 2γ clusters
- $\cos(\theta_{\gamma\gamma})$: opening angle of 2γ clusters

Summary

Summary and future work

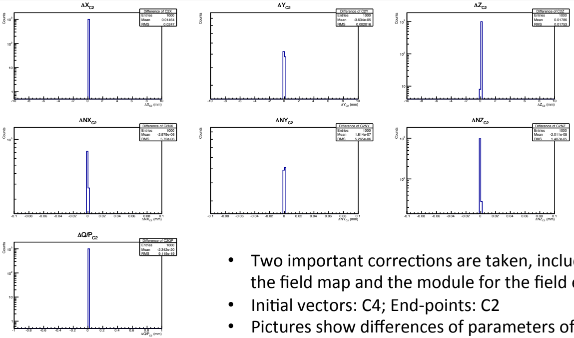
- Universe is littered with anomalies that must be explained (exciting times!)
- TREK/E36 has been built, completed data-taking, decommissioned and analysis is currently underway
- e36g4MC has been developed from scratch
- K^+ decay generator has been implemented into the e36g4MC
- Extraction of exclusion limits for light boson search
- Energy calibration for CsI(Tl) using both $K_{\mu 2}$ and $K_{\pi 2}$
- CsI cluster finder developed within Cooker analysis framework
- Event viewer implemented


ありがとうございました
(Thank You)

Backup

Tracking: propagation with G4 and reconstruction with Kalman Filter

Use geantinos as the primary particle
Propagate through magnetic field and compare the results



Geantinos propagate in the field without any physics.

- Two important corrections are taken, including the setup of the field map and the module for the field evaluation.
- Initial vectors: C4; End-points: C2
- Pictures show differences of parameters of state vectors at C2 extracted from two packages
  - ✓ Magnetic field map is consistent with each other
  - ✓ Evaluation of magnetic field is consistent with each other

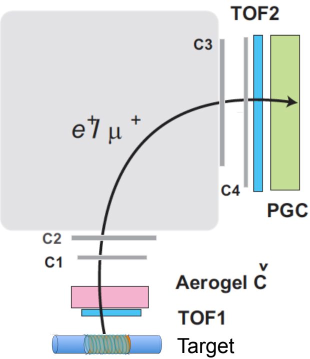
Runge-Kutta methods are consistent

T. Cao

μ/e miss-identification

PID with:

- TOF
- Aerogel Č
- Lead glass

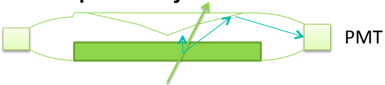


TOF

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%

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

M. Kohl (ICHEP 2016)