Searching for Heavy Photons Using TREK

Peter Monaghan
(& Michael Kohl)
Hampton University

Nuclear Physics Group Meeting, HU, 4th March 2014

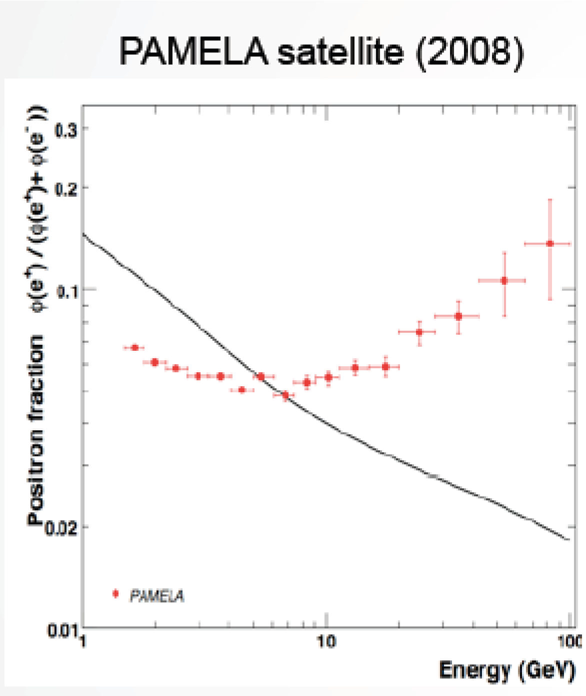
Search for light U(1) gauge boson A'

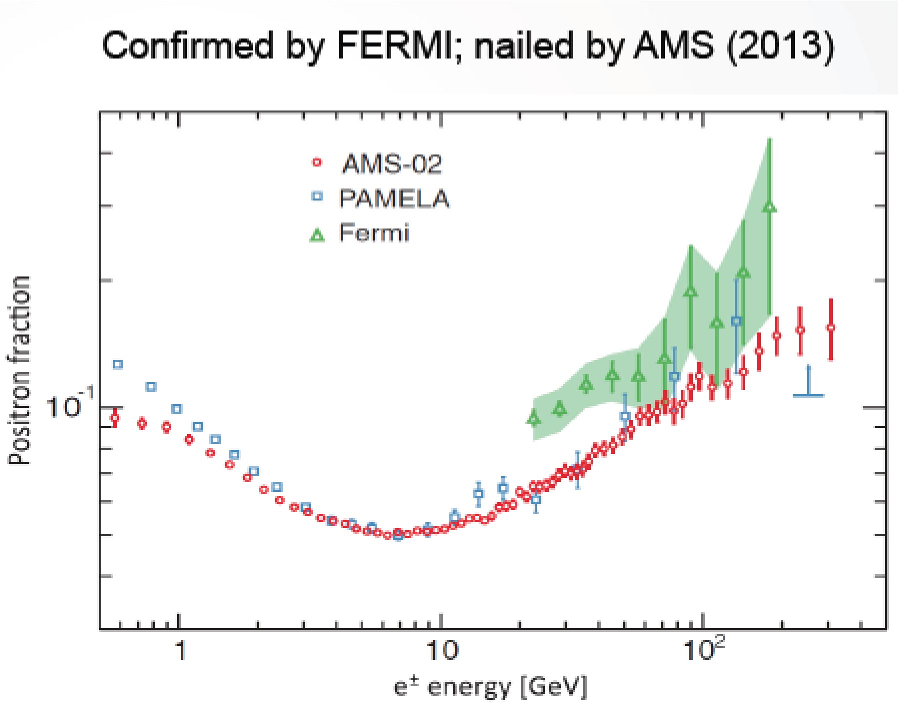
- 23% of the universe are Dark Matter
→ Rotation of galaxies; gravitational lensing; DAMA/LIBRA; WMAP
→ >100 GeV WIMPs favored
- U(1) hidden sector extension of the Standard Model:
Dark Matter interacting with SM via U(1) gauge boson (Fayet 2004)
- Astrophysical motivation for Dark Matter annihilation: positron excess PAMELA, FERMI, AMS-02

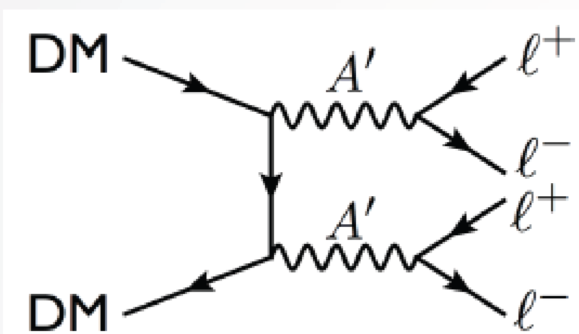
- Muon anomalous magnetic moment $g_\mu - 2$
→ Kinetic mixing model (Holdom 1986, Pospelov 2009)

- Beyond kinetic mixing: Proton radius puzzle R_p
- Lepton-flavor non-universal interaction (preferred coupling to muons)
→ Coupling to right-handed muons (Batell, McKeen, Pospelov) due to constraints from neutrino scattering
→ Fine-tuned non-universal couplings (Carlson, Rislow)

Positron excess from DM annihilation?





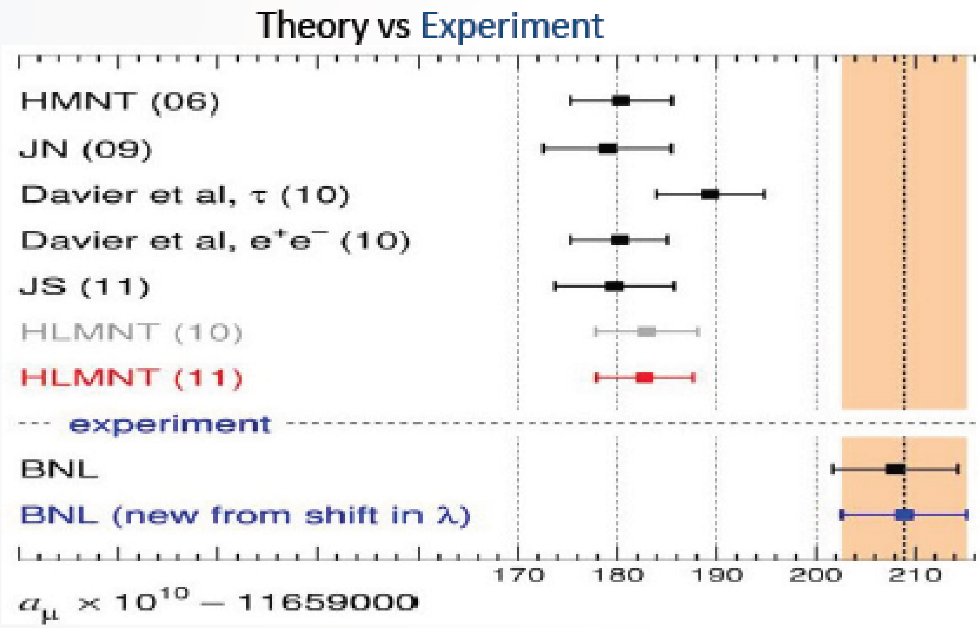


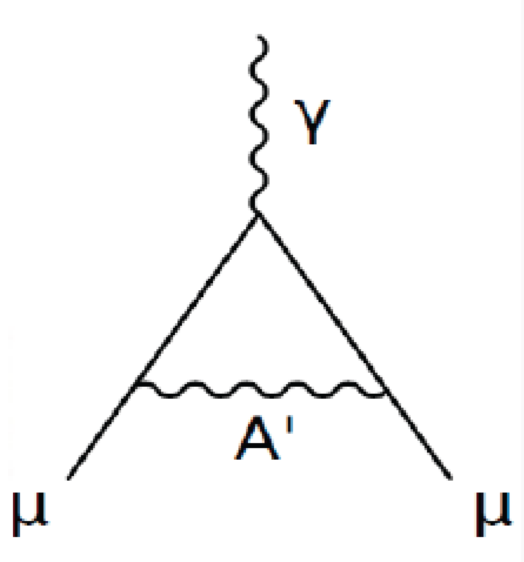
Arkani-Hamed

- **Arkani-Hamed, Finkbeiner, Slatyer, Weiner** and **Pospelov & Ritz** proposed DM annihilation to hidden sector photons (A's) in the mass range 20-1000 MeV/c^2 as the source of HE cosmic e+e-.

Muon anomalous magnetic moment

Muon g-2 experiment disagrees with theory at the 3 sigma level.
A heavy photon with $m \sim$ 10-100 MeV and $\varepsilon \sim 10^{-2} - 10^{-3}$ could solve the problem!

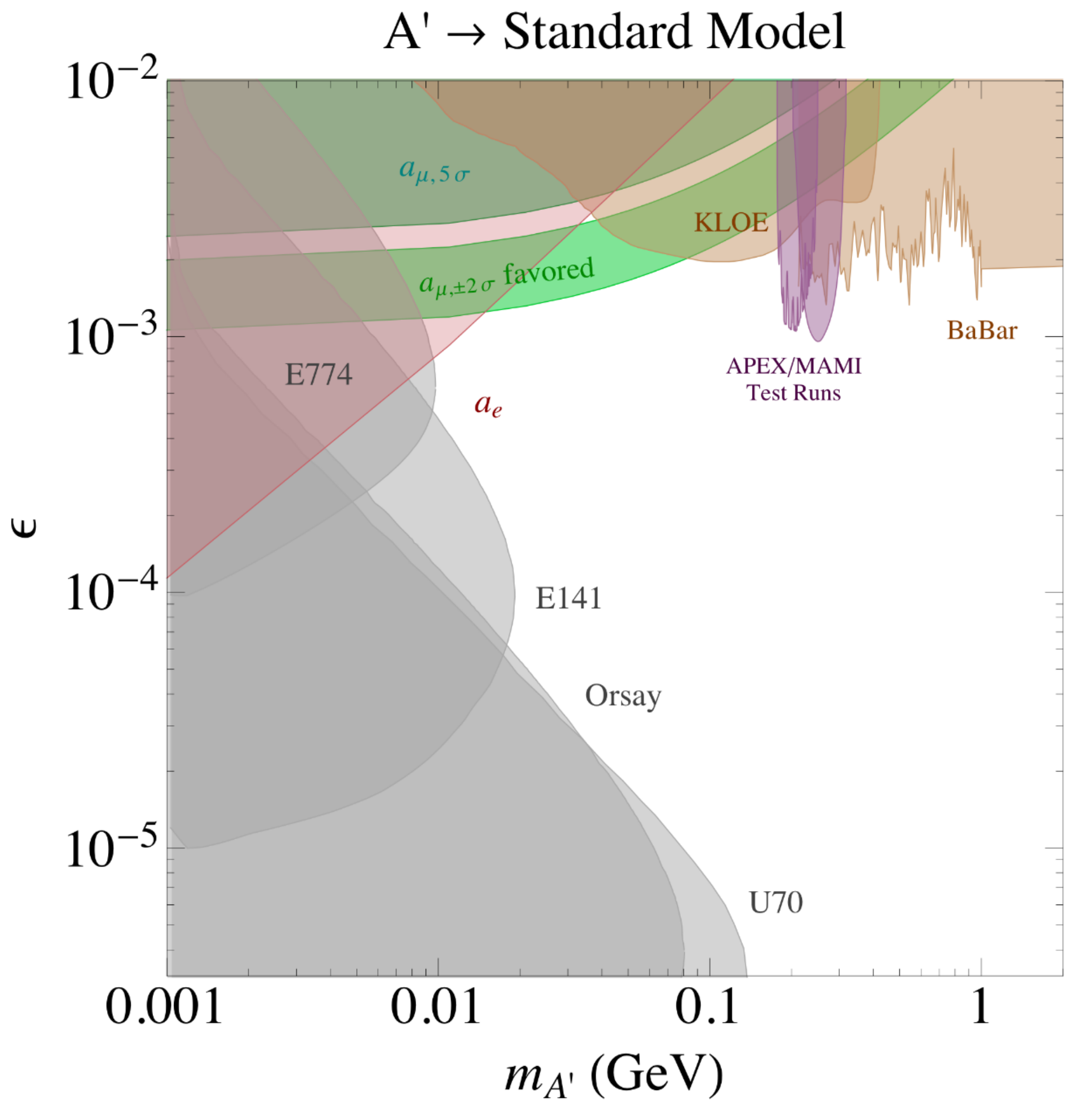




Anomaly ‘usually’ explained by SUSY with large tanβ

Search for light U(1) gauge boson A'

- Light mediator of dark force coupled to SM via kinetic mixing; motivated by astrophysics, $g_\mu - 2$, (and proton radius puzzle R_p)



R. Essig

Possible kaon decay channels in E36

K^+ decays ~ 10^{10}

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

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

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

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

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

π^0 decays ~ 3×10^8 – 2×10^9

π^0 production: $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.27%); $K^+ \rightarrow \pi^+\pi^0$ (21.13%)

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

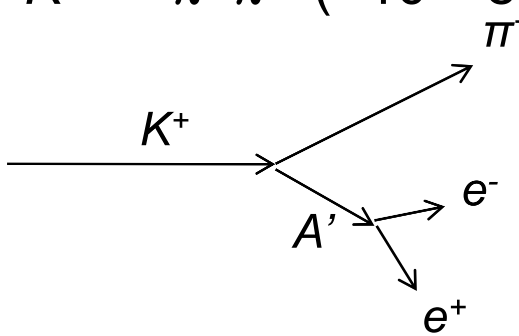
Background: BR($\pi^0 \rightarrow \gamma\ e^+ e^-$) ~ 1.2% ~ (0.3–2.3)x$10^7$ ev.

P. Adlarson et al., 1304.0671 [hep-ex] (WASA/COSY): “World’s largest sample” 5x10^5

Search for light U(1) gauge boson A'

- Light mediator of dark force coupled to SM via kinetic mixing; motivated by astrophysics, $g_\mu - 2$, (and proton radius puzzle R_p)
- Possibly enhanced coupling to muons, not probed by electroproduction
- Measure all charged decay particles and search for peak in the e^+e^- invariant mass spectrum in the range 0-380 MeV

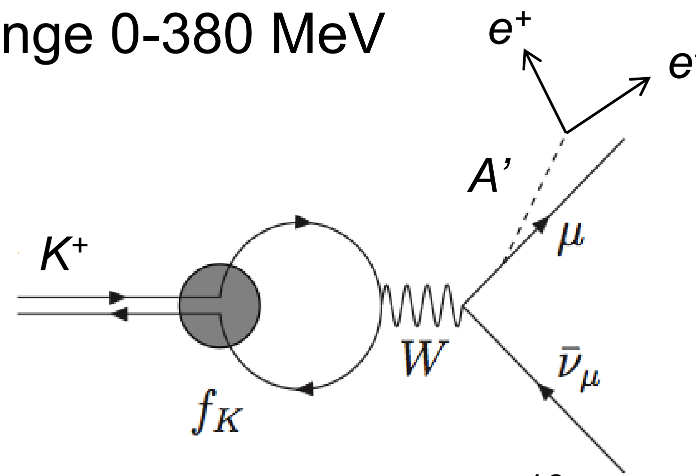
$K_{\pi 2}$: $K^+ \rightarrow \pi^+ \pi^0$ (~10^{10} events)



$K^+ \rightarrow \pi^+ e^+ e^-$ $(\Delta S = 1)$

Signal: BR($K+ \rightarrow \pi^+ A'$) ~10^{-8}
$A' \rightarrow e^+e^-$ (~100 events)

Background:
BR($K^+ \rightarrow \pi^+ e^+ e^-$) ~ 2.9 x 10^{-7}



$K_{\mu 2}$: $K^+ \rightarrow \mu^+ \nu$ (~10^{10} events)

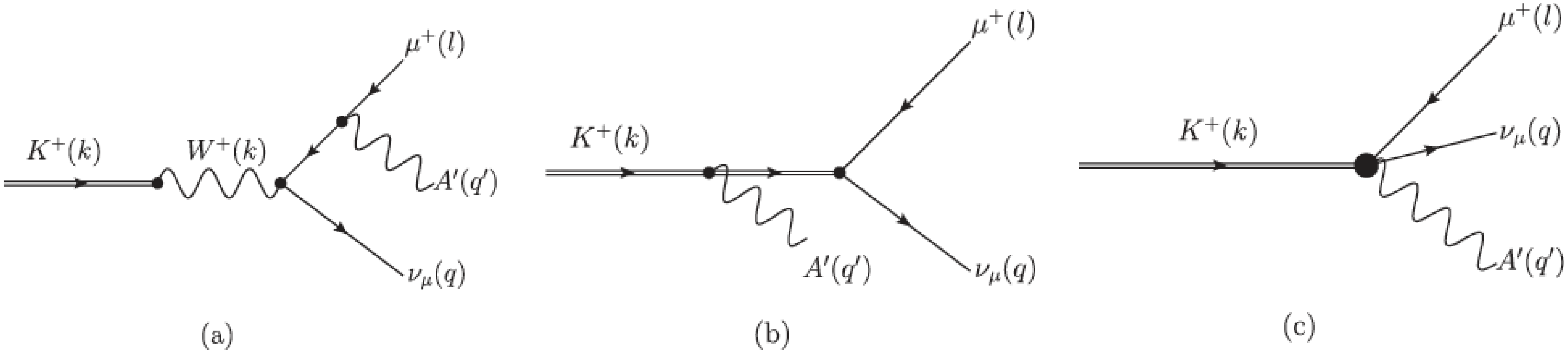
$K_{\mu 2\gamma}$: $K^+ \rightarrow \mu^+ \nu \gamma$ (~10^7 events)

Signal: BR($K^+ \rightarrow \mu^+ \nu A'$) ~$10^{-8}$
$A' \rightarrow e^+e^-$ (~100 events)

Background:
BR($K^+ \rightarrow \mu^+ \nu\ e^+ e^-$) ~ 2.5 x 10^{-5}

The rare kaon decay $K^+ \to \mu^+ \nu A \to \mu^+ \nu\, e^+ e^-$

T. Beranek



- Approximate γ' signal as in case of Fixed Target Searches
- Reach estimate possible by

$$\varepsilon^2 = \frac{2}{\sqrt{BR\left(K^+_{\mu^+\nu_\mu l^+ l^-}\right)(m_{\gamma'}) \times N_{K^+}}} \frac{2N\alpha}{3\pi} \frac{\delta m}{m_{\gamma'}}$$

Radiative kaon decay $K^+ \to \mu^+ \nu e^+ e^-$

C. Carlson; T. Beranek

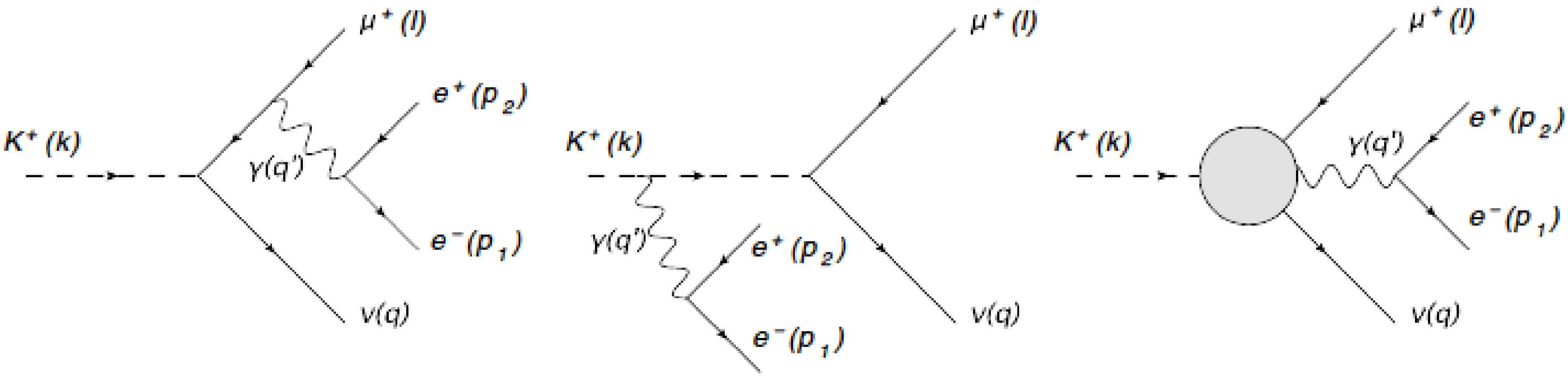
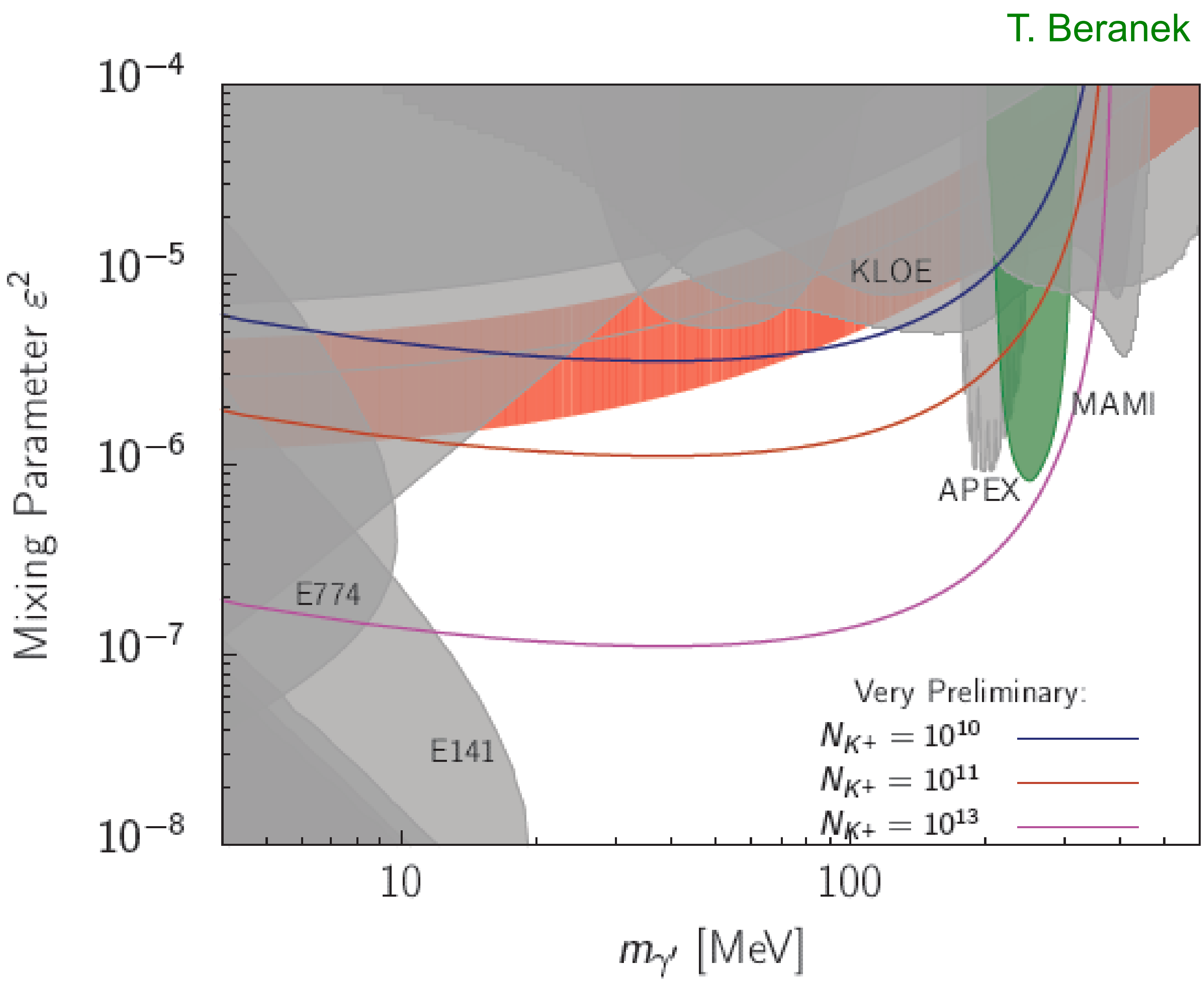


FIG. 1: QED contribution to $K^+ \to \mu^+ + \nu_\mu + e^+ + e^-$.

- Background: SM process with time-like (virtual) photon exchange
  - Calculable in QED, $BR(K^+ \to \mu^+ \nu \; e^+ e^-) = 2.49 \times 10^{-5}$
    J. Bjnens et al., Nucl. Phys. B396, 81 (1993), hep-ph/9209261
  - Measured for $m_{ee} > 145$ MeV/c^2
    A. Poblaguev et al., Phys. Rev. Lett. 89, 061803 (2002), hep-ex/0204006

Exclusion limit – visible decay mode

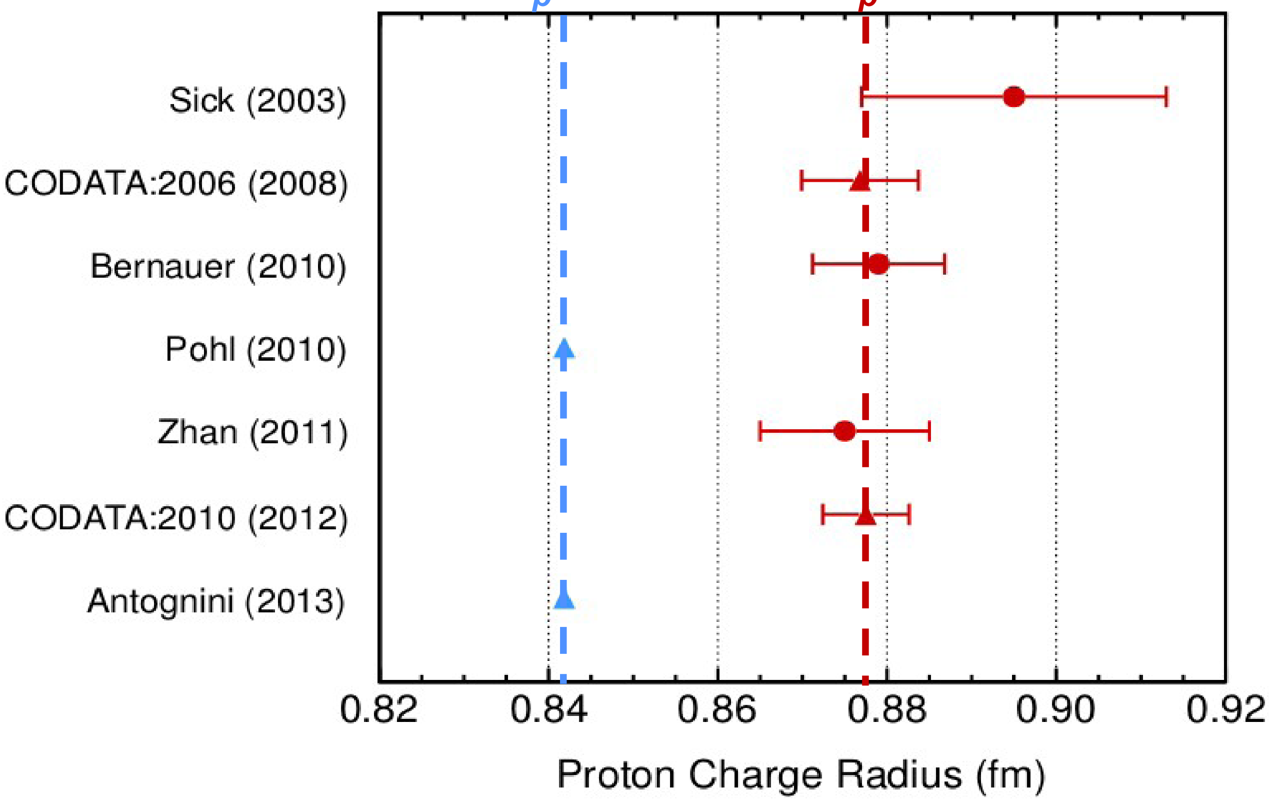


The proton radius puzzle

- >7σ discrepancy between **muonic** and **electronic** measurements
- High-profile articles in Nature, NYTimes, etc.
- Puzzle unresolved, possibly New Physics

Muonic **R_p = 0.84 fm**

Electronic **R_p = 0.88 fm**



▲ Spectroscopy

● Scattering

R_P = 0.84184(67) fm

R_P = 0.875(10) fm

R_P = 0.8758(77) fm

R_P = 0.84087(39) fm

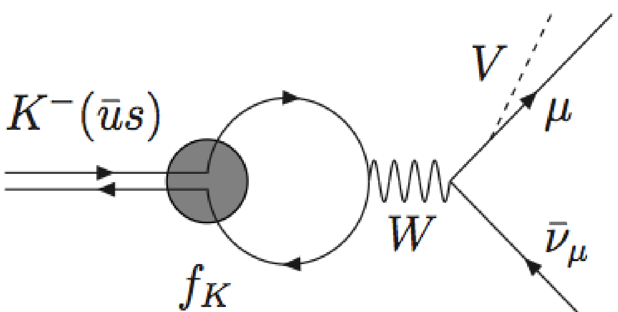
Lepton universality and the proton radius

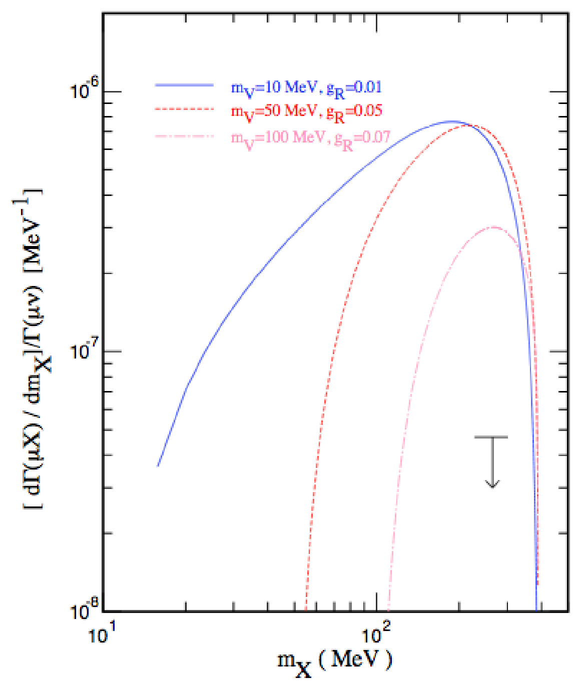
Batell, McKeen, Pospelov, PRL107, 011803 (2011), arXiv 1103.0721:
can solve proton radius puzzle

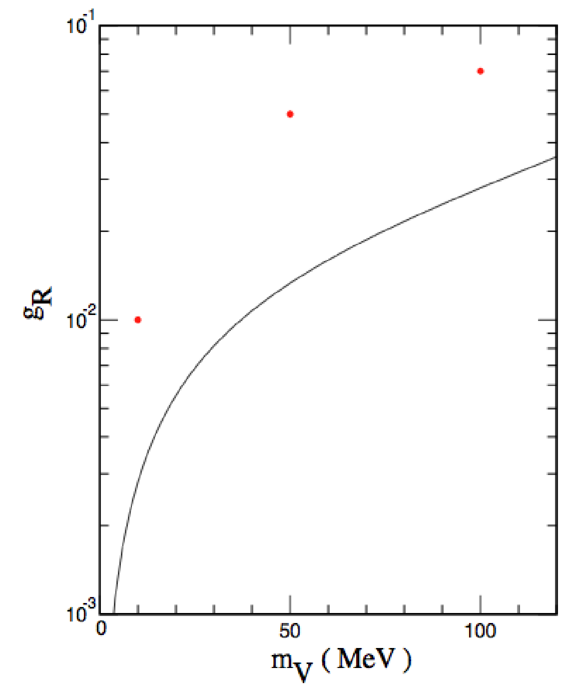
- new e/μ differentiating force consistent with g_μ-2
- <100 MeV gauge boson V or dark photon
- resulting in large PV μp scattering (coupling to right-handed muons)

Barger, Chiang, Keung, Marfatia (arXiv:1109.6652):

- constrained by K → μν decay ***(but only if V decays invisibly!)***

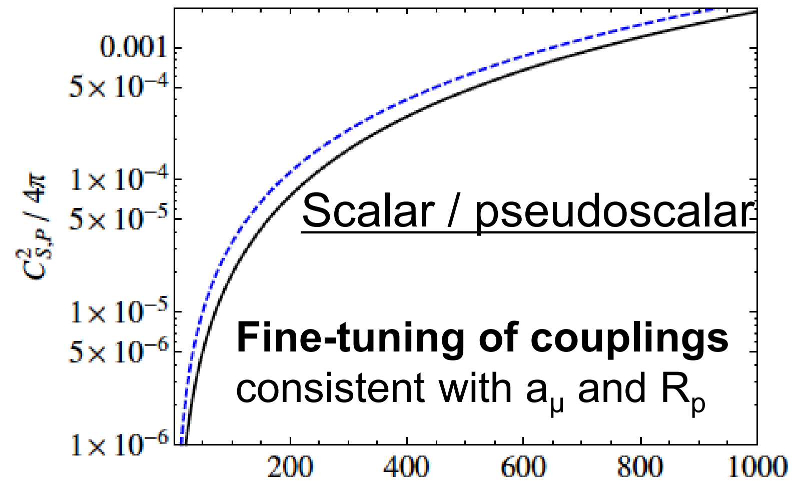


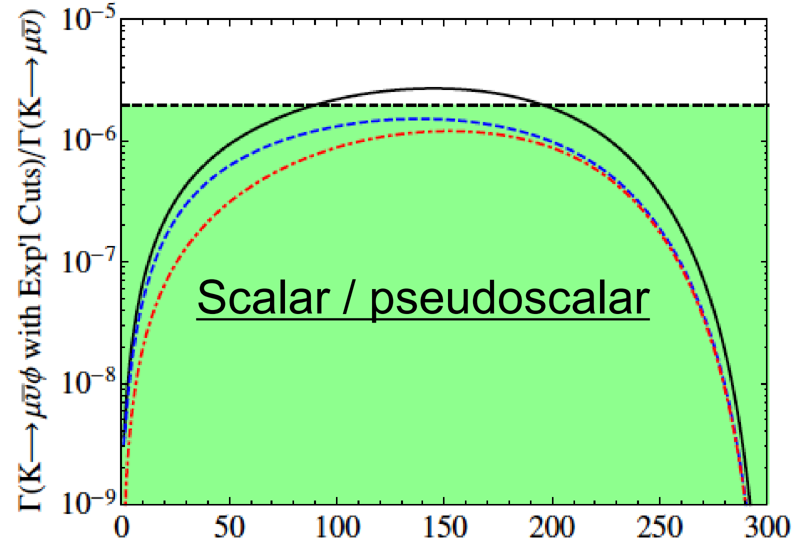


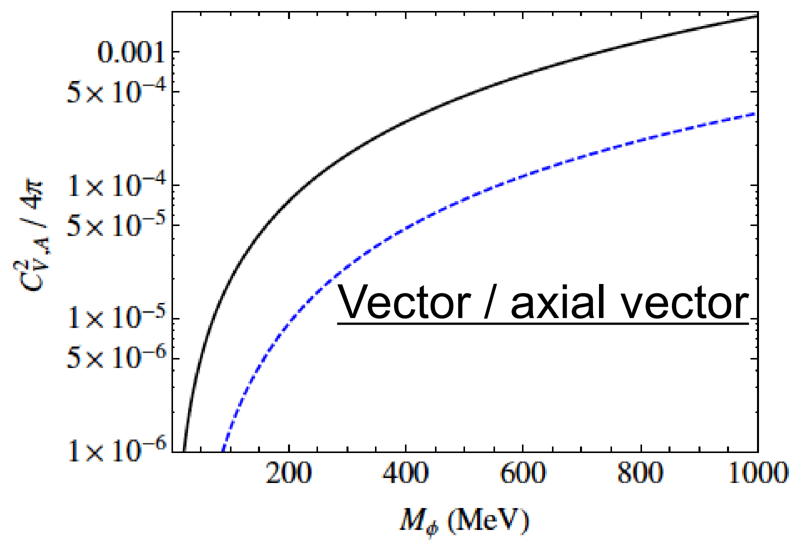


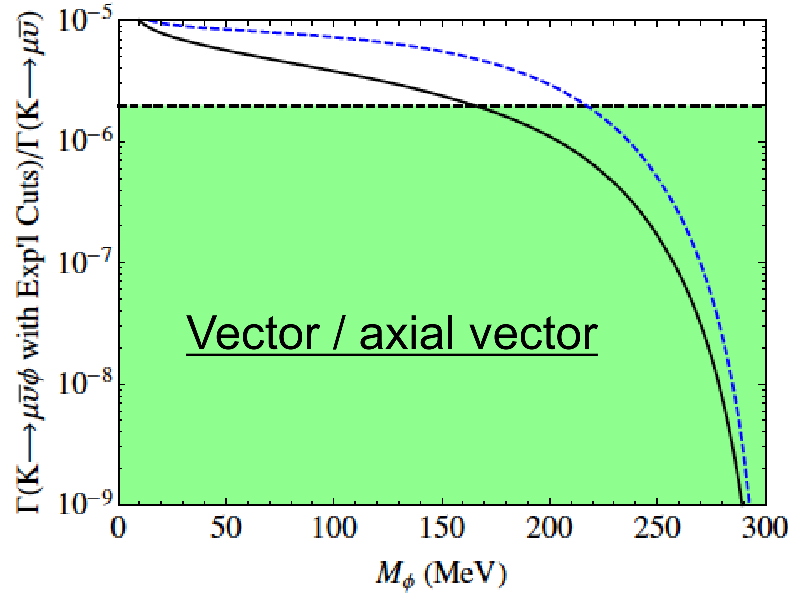
U(1) boson, g_μ-2, and the proton radius

C. Carlson and B. Rislow, 1206.3587v2 [hep-ph]







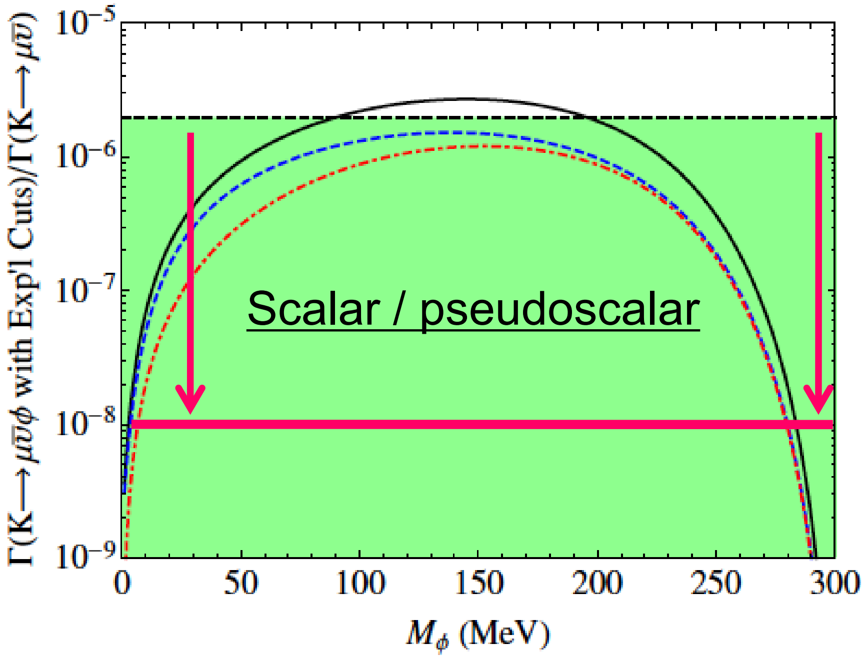


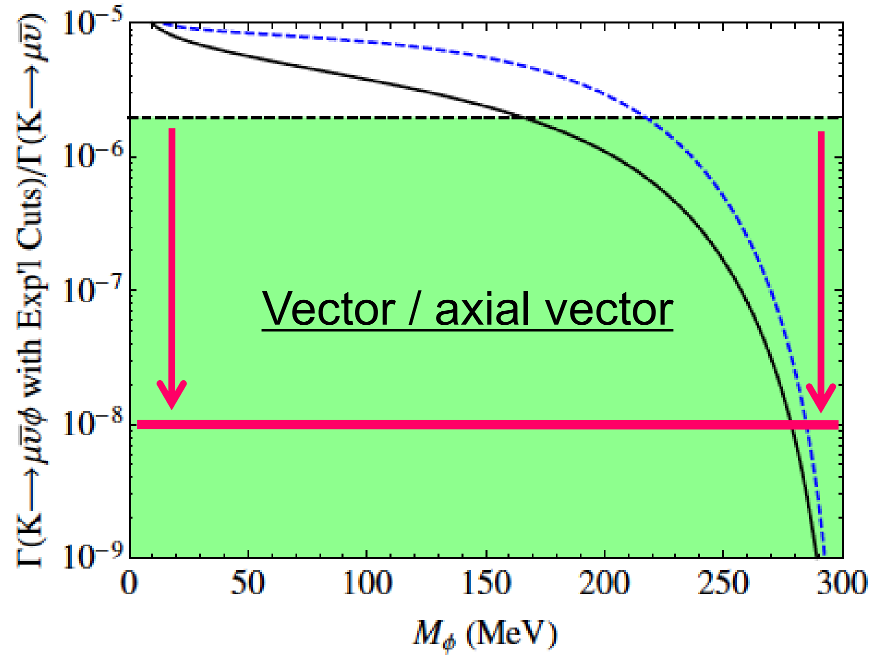
Experimental limit (invisible decay) from stopped kaon experiment at Bevatron

C. Pang, R. Hildebrand, G. Cable, and R. Stiening, Phys. Rev. D8, 1989 (1973)

Proton radius and New Physics

C. Carlson and B. Rislow, Phys. Rev. D **86**, 035013 (2012); [arXiv1206.3587v2]





New Physics involving light U(1) bosons can explain proton radius puzzle
Fine tuning, preferred coupling to muon (not electron) – lepton non-universality
Emission of Φ as radiative correction to K → μν decay

Experimental limit taken from stopped kaon experiment at Bevatron in 1970's:
C. Pang, R. Hildebrand, G. Cable, and R. Stiening, Phys. Rev. D8, 1989 (1973)

E36 can probe entire allowed range: BR($K^+ \to \mu^+ \nu A'$) ~10^{-8}

Search for a new particle in $K^+ \to \mu^+ \nu e^+ e^-$

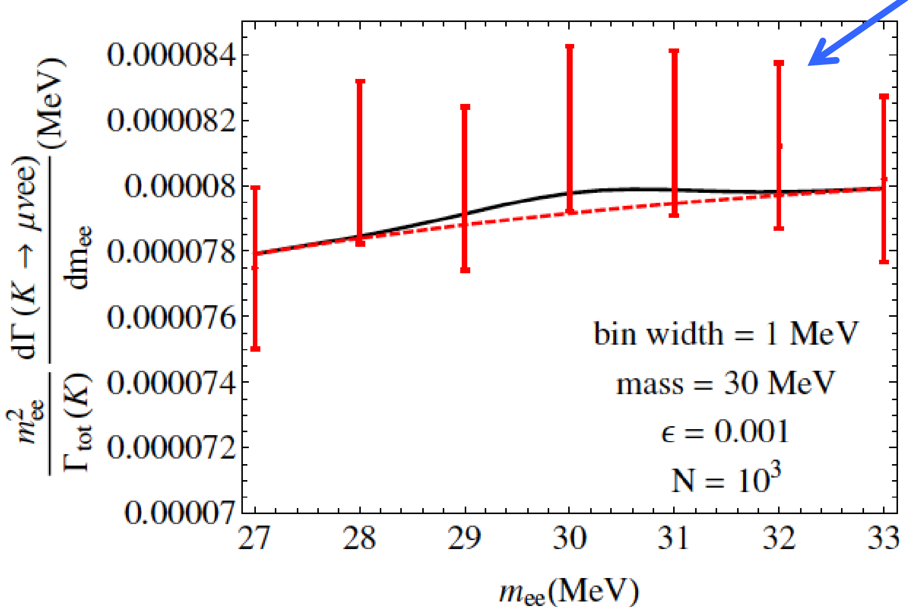
QED background: $K^+ \to \mu^+ \nu e^+ e^-$

- $\Gamma(K^+ \to \mu^+ \nu ee) \sim 2.5 \times 10^{-5}$
- *Expect 10^{10} stopped K^+ in E36*
- *250k QED evts or ~1000 / MeV*

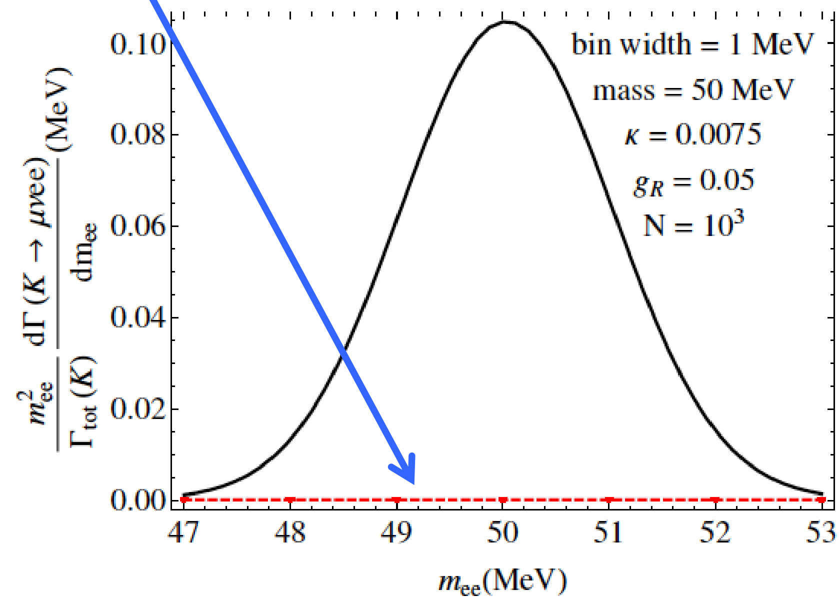
Signal: $K^+ \to \mu^+ \nu A', A' \to e^+ e^-$

C. Carlson, B. Rislow, hep-ph/1310.2786

same background!



Dark photon model
(universal coupling)



Batell model
(universality-violating,
right-handed muons)

B. Batell, D. McKeen, and M. Pospelov, PRL107, 011803 (2011), 1103.0721

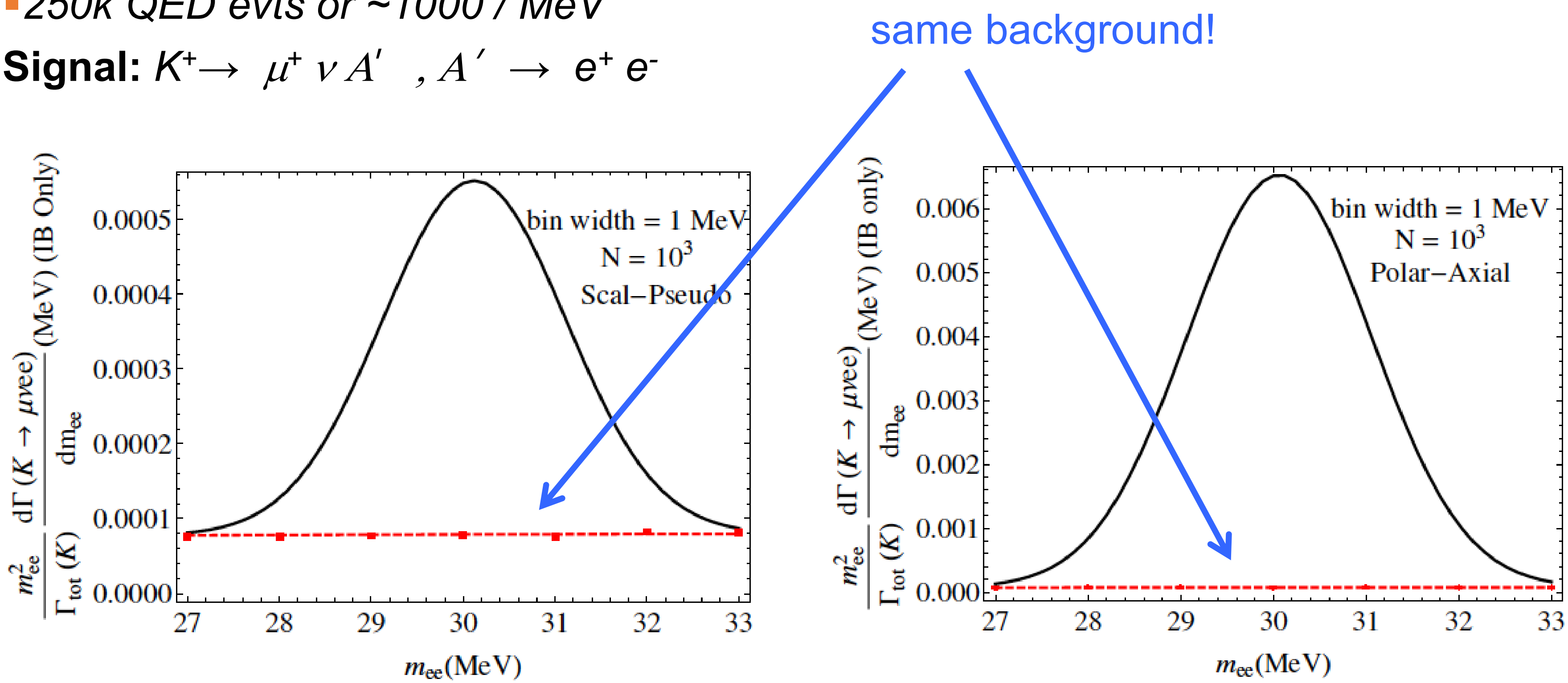
Search for a new particle in $K^+ \to \mu^+ \nu e^+ e^-$

QED background: $K^+ \to \mu^+ \nu e^+ e^-$

- $\Gamma(K^+ \to \mu^+ \nu ee) \sim 2.5 \times 10^{-5}$
- *Expect 10^{10} stopped K^+ in E36*
- *250k QED evts or ~1000 / MeV*

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

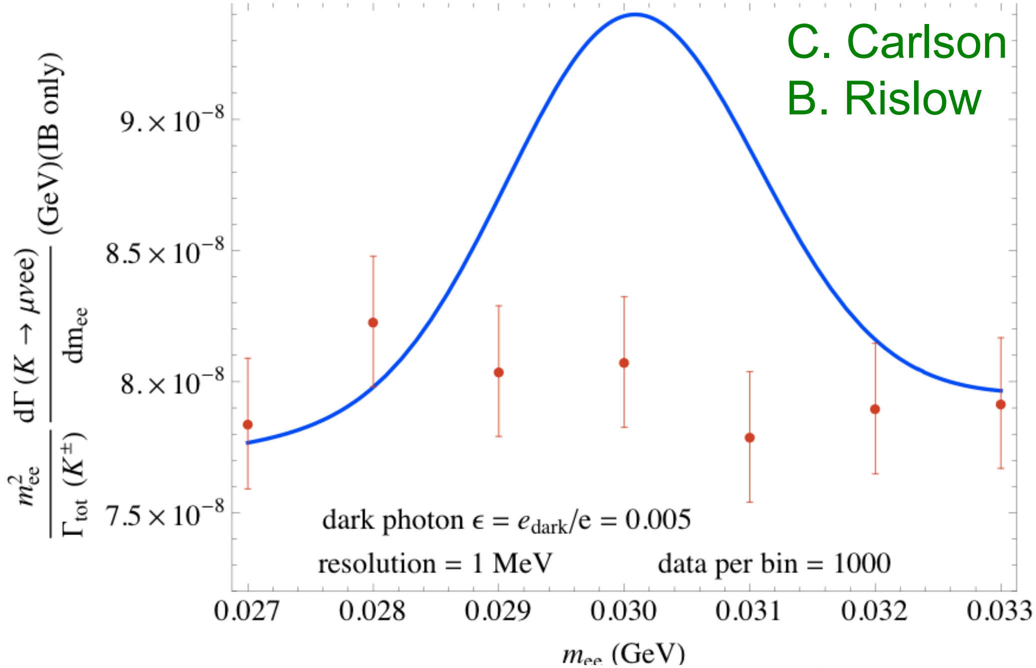
C. Carlson, B. Rislow, hep-ph/1310.2786



Carlson&Rislow model
(universality-violating, fine tuned)

HUGE signals predicted, E36 very stringent test

Search for a new particle in $K^+ \to \mu^+ \nu e^+ e^-$



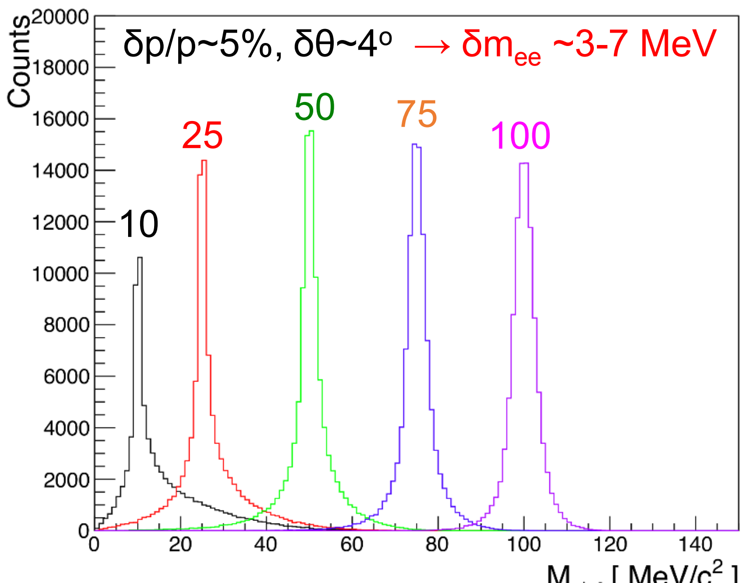
QED background: $K^+ \to \mu^+ \nu e^+ e^-$

- $\Gamma(K^+ \to \mu^+ \nu ee) \sim 2.5 \times 10^{-5}$
- *Expect 10^{10} stopped K^+ in E36*
- *250k QED evts or ~1000 / MeV*

Signal: $K^+ \to \mu^+ \nu A'$
$A' \to e^+ e^-$ (30 MeV)

Assumed:

- *Eff. coupling $\varepsilon^2 \sim 2.5 \times 10^{-5}$*
- *m_{ee} resolution 1 MeV*
- *Number of kaons: 10^{10} K^+*



Investigated for E36:

- Detect μ^+ in toroid, e^+e^- in CsI(Tl)
- Achievable resolution for m_{ee}
- Fluctuation of QED background

→ Exclusion limits for ε^2 versus m_{ee}

Determination of Mixing Parameter, ε^2

- Provided by T. Beranek – context of dark photon model.
- Based on cross section ratio derived in eqn. 19 of Bjorken *et al.*, Phys. Rev. **D80**, 075018 (2009)
- Requires signal > 2*(background fluctuation)

$$\varepsilon^2 = \frac{2}{\sqrt{BR\left(K^+_{\mu^+\nu_\mu l^+ l^-}\right)(m_{\gamma'}) \times N_{K^+}}} \frac{2N\alpha}{3\pi} \frac{\delta m}{m_{\gamma'}}$$

$BR\left(K^+_{\mu^+\nu_\mu l^+ l^-}\right)(m_{\gamma'}) \times N_{K^+}$ = total number of events in mass bin at $m_{\gamma'}$ with width δm

δm ← mass cut

$m_{\gamma'}$ ← Chosen heavy photon mass

Estimating ε² from Simulations

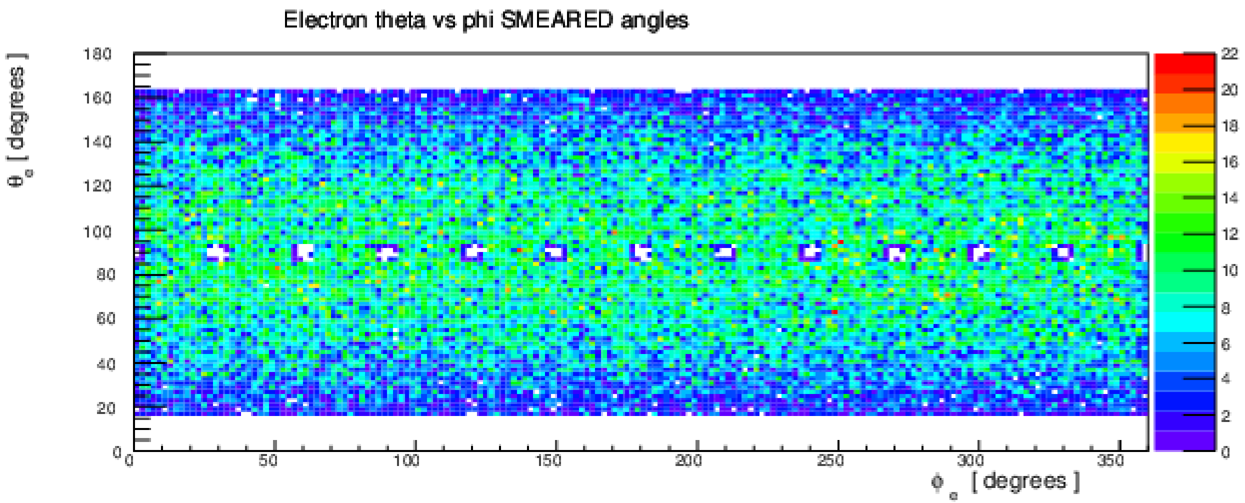
Two sets of simulations ⟹ signal and background events

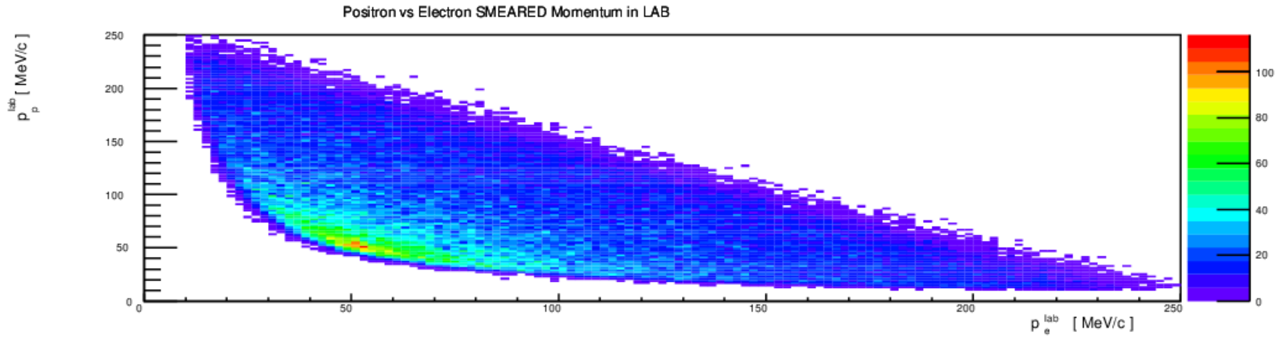
Background : $K \rightarrow \mu^+\nu_\mu e^+e^-$

Signal : $K \rightarrow \mu^+\nu_\mu A'$ $\quad A' \rightarrow e^+e^-$

- Signal simulation throws invariant mass of $\mu^+\nu_\mu$ system, for a chosen A' mass
- Throw angles of A' in lab
- Allow it to decay to e^+e^- pair in its own rest frame; throw angles
- Boost e^+e^- vectors back to lab frame and reconstruct mass
- Smear momenta and angles of e^+e^- pair in lab; reconstruct mass
- Apply threshold cut at 5 MeV and acceptance cuts for CsI calorimeter

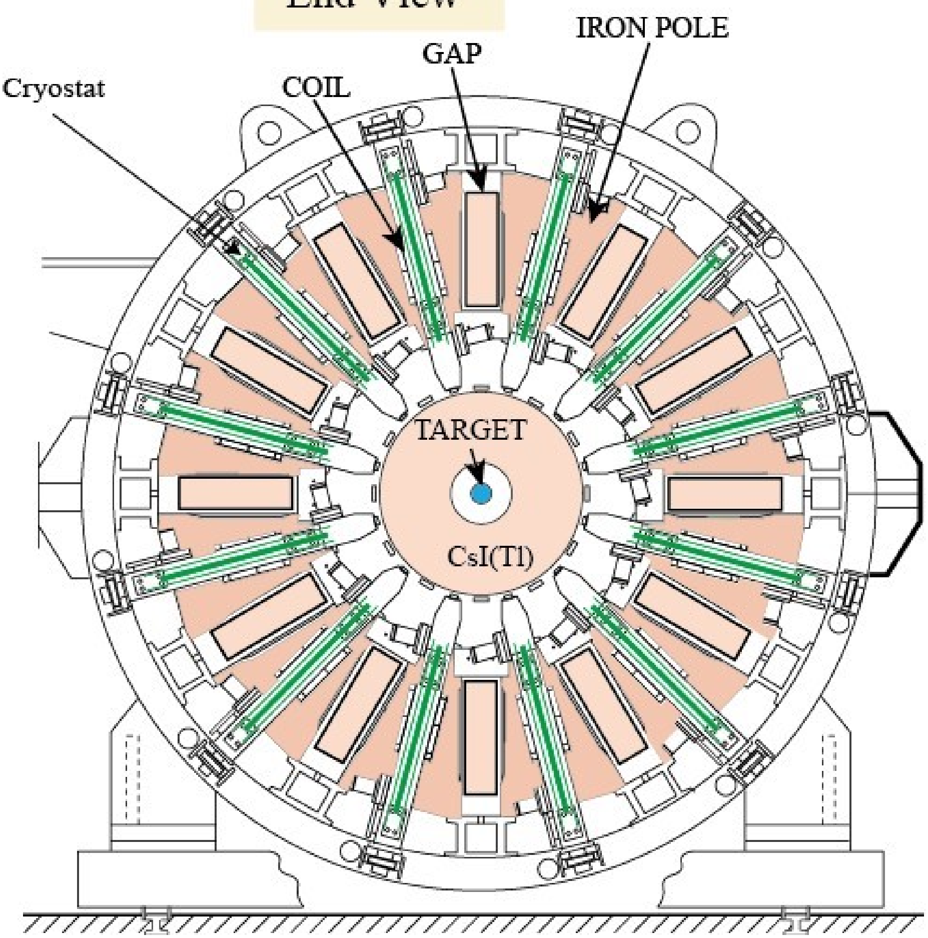
Smear e^+ & e^- Angles & Momenta

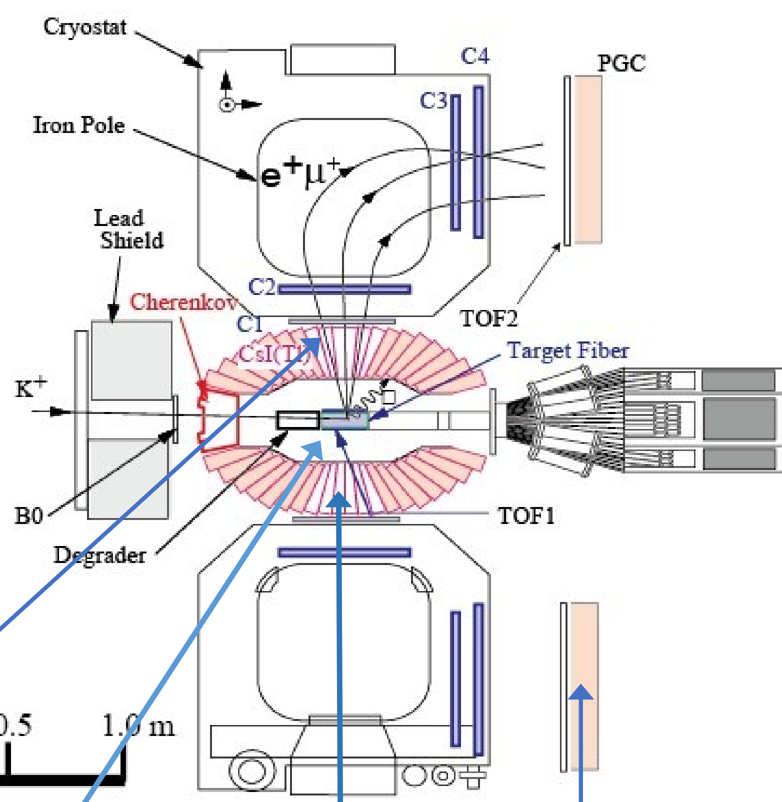




- Smear angles and momenta with gaussian
- Apply acceptance cuts to angles

TREK Detector System

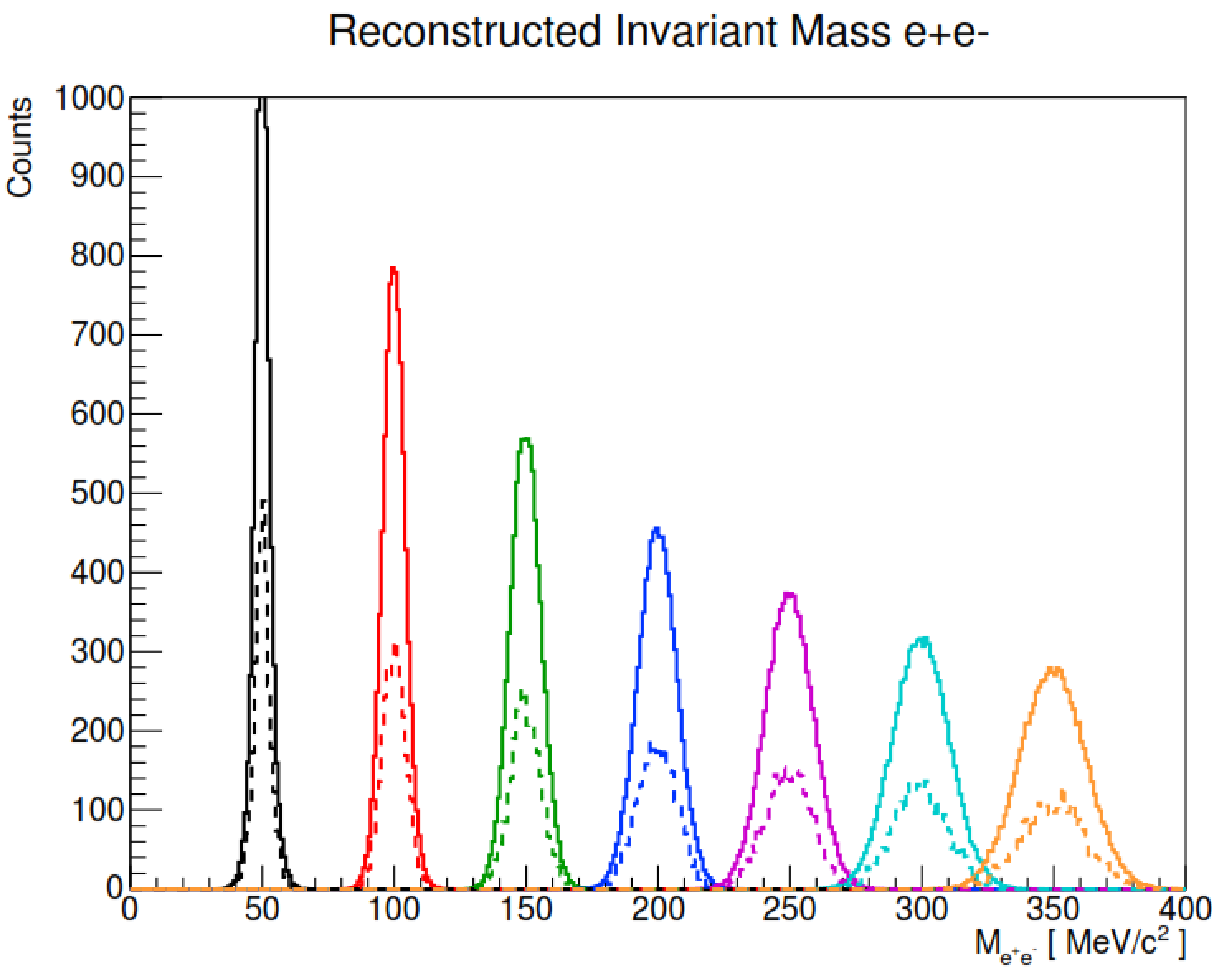




- C1 GEM
- Aerogel Cherenkov

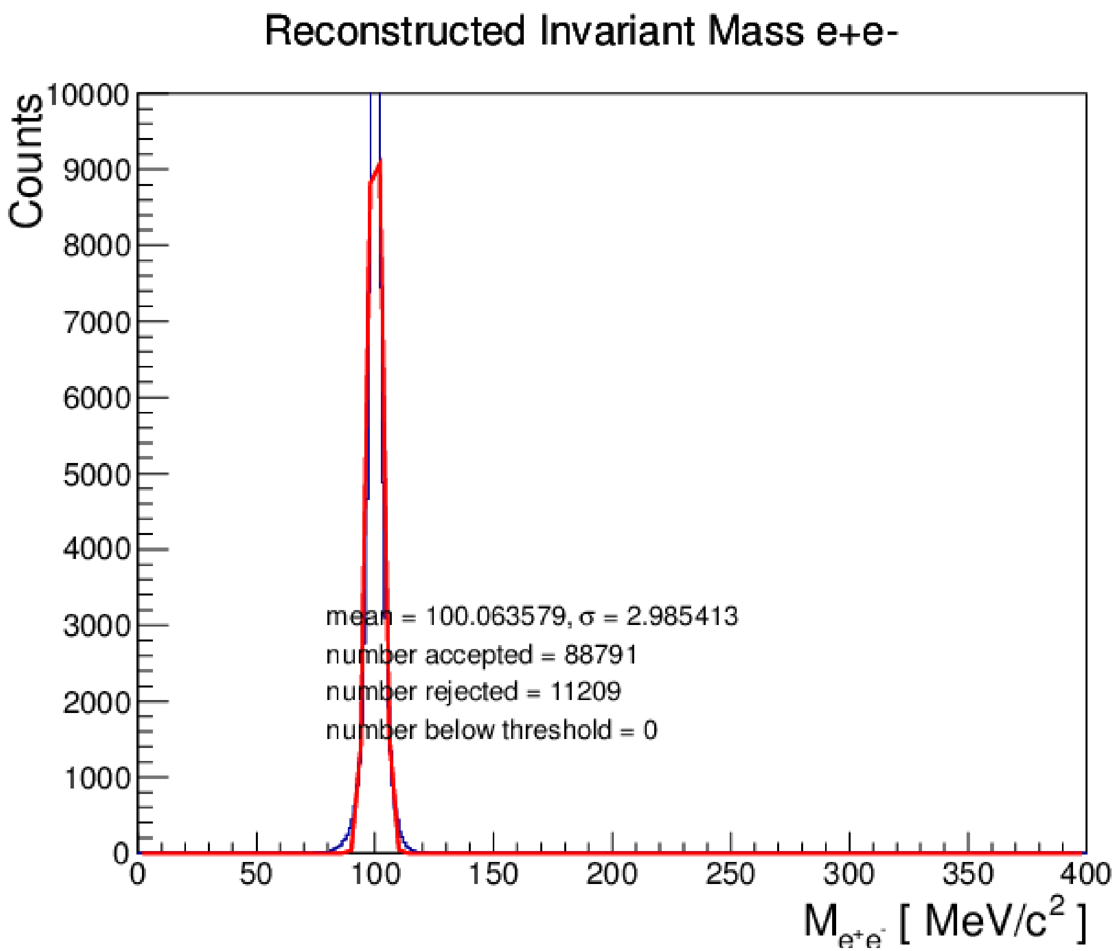
- TOF, Leadglass
- CsI calorimeter

Reconstructed Invariant Mass



- Solid line is before acceptance cut
- Dashed line is after CsI acceptance cut applied.
- Use sigma for mass cut with $\delta m = 2*\sigma$

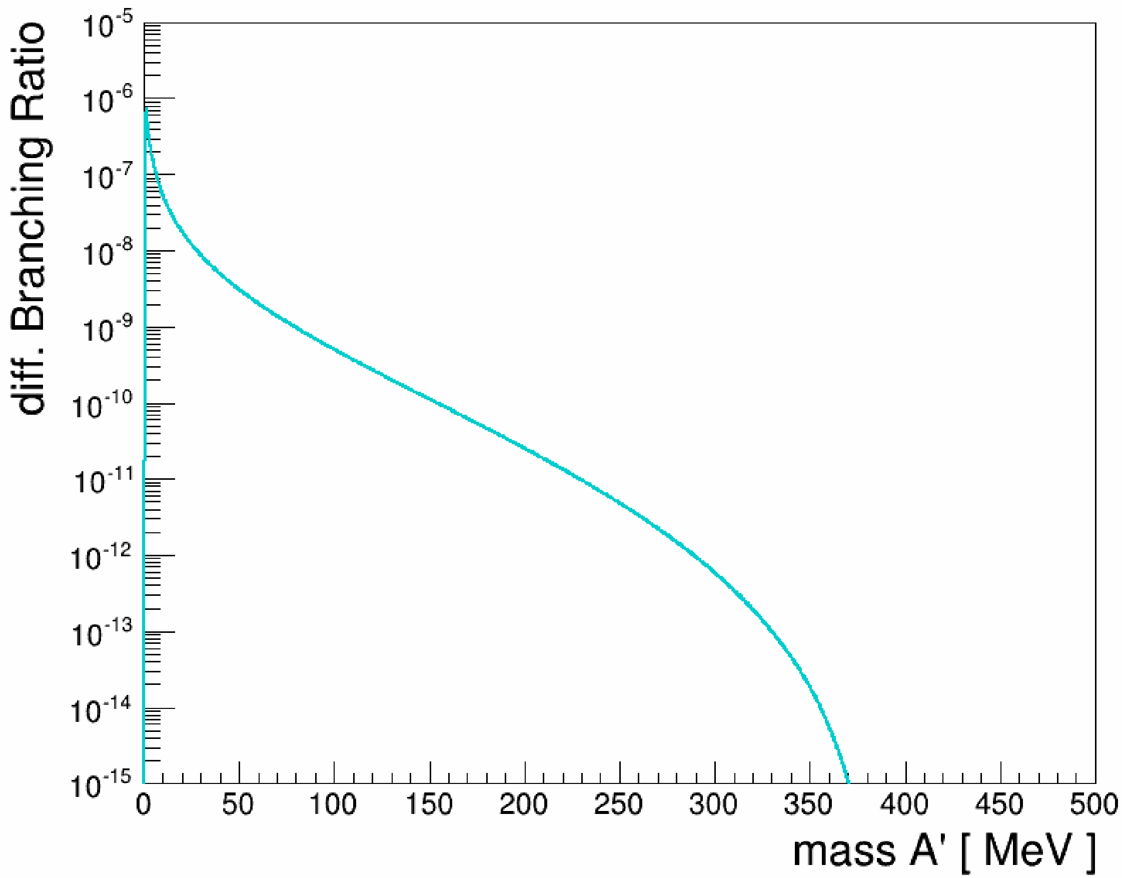
Signal Width to Determine δm



- Example for 10 MeV
- Fit a Gaussian and find the sigma value
- Use sigma for mass cut with δm = 2*σ

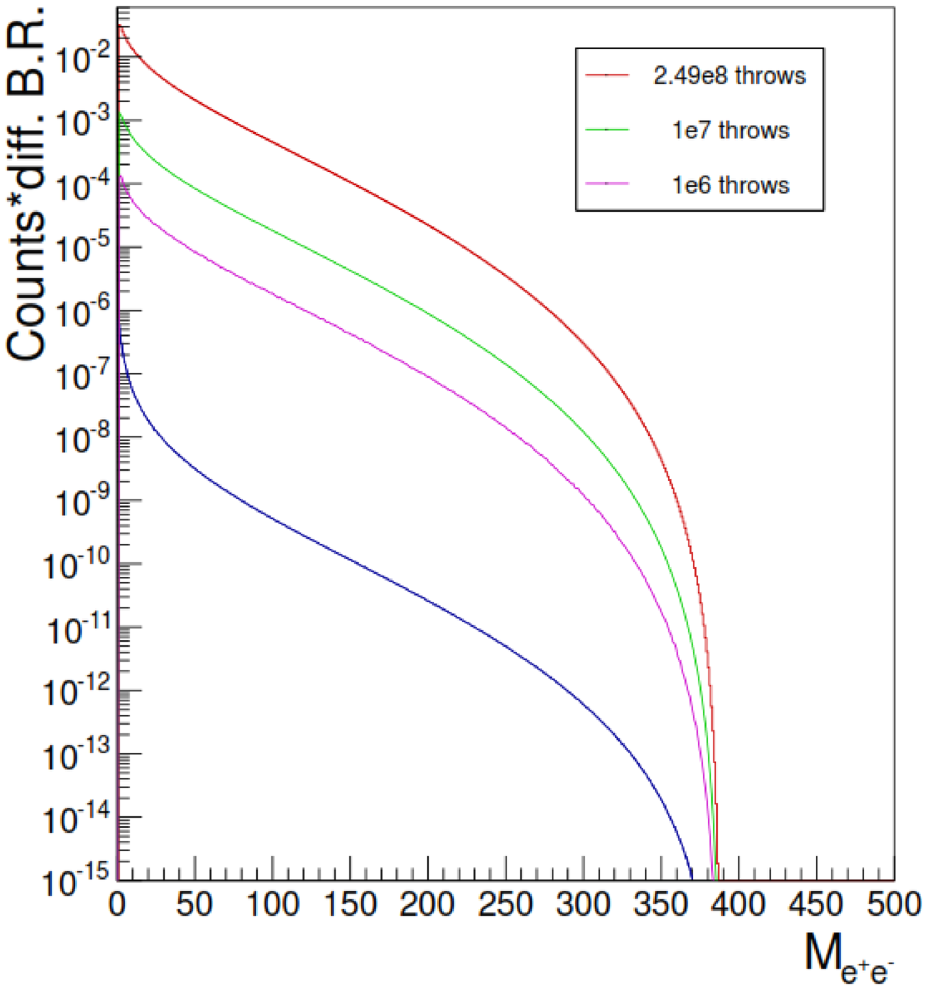
Background Differential Branching Ratio

$$K \rightarrow \mu^+ \nu_\mu e^+ e^-$$



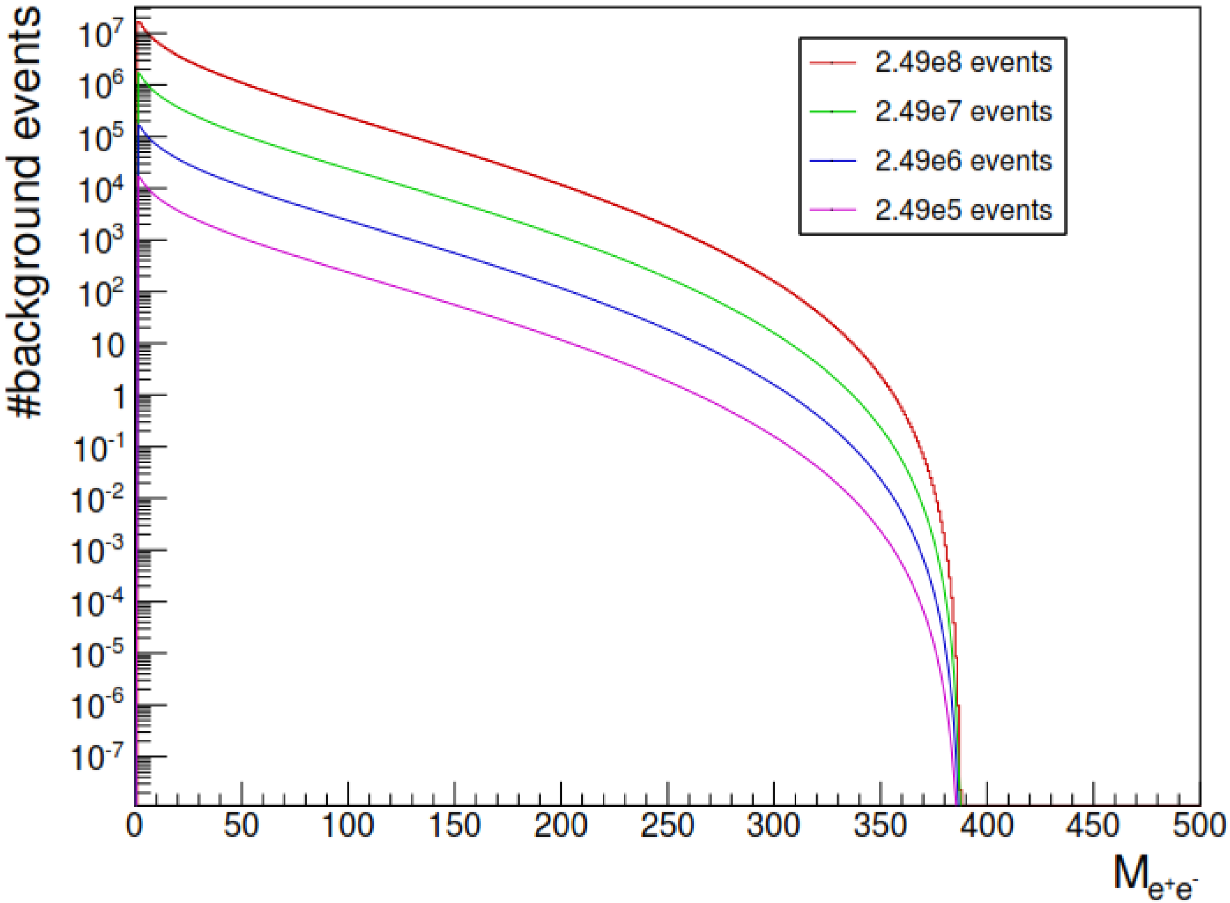
- Provided by T. Beranek
- Total integral = 2.36e-5
- Weight every throw with value of BR at the mass of the event thrown.
- Renormalise the weighted curve to transform into counts arising from a given number of initial stopped kaons.

Weighted Throws in Simulation



- Weight each throw by diff. BR
- The higher the number of throws the smoother the curve and less statistical fluctuations.
- Next can convert this into a distribution of background events.

Background Event Simulation

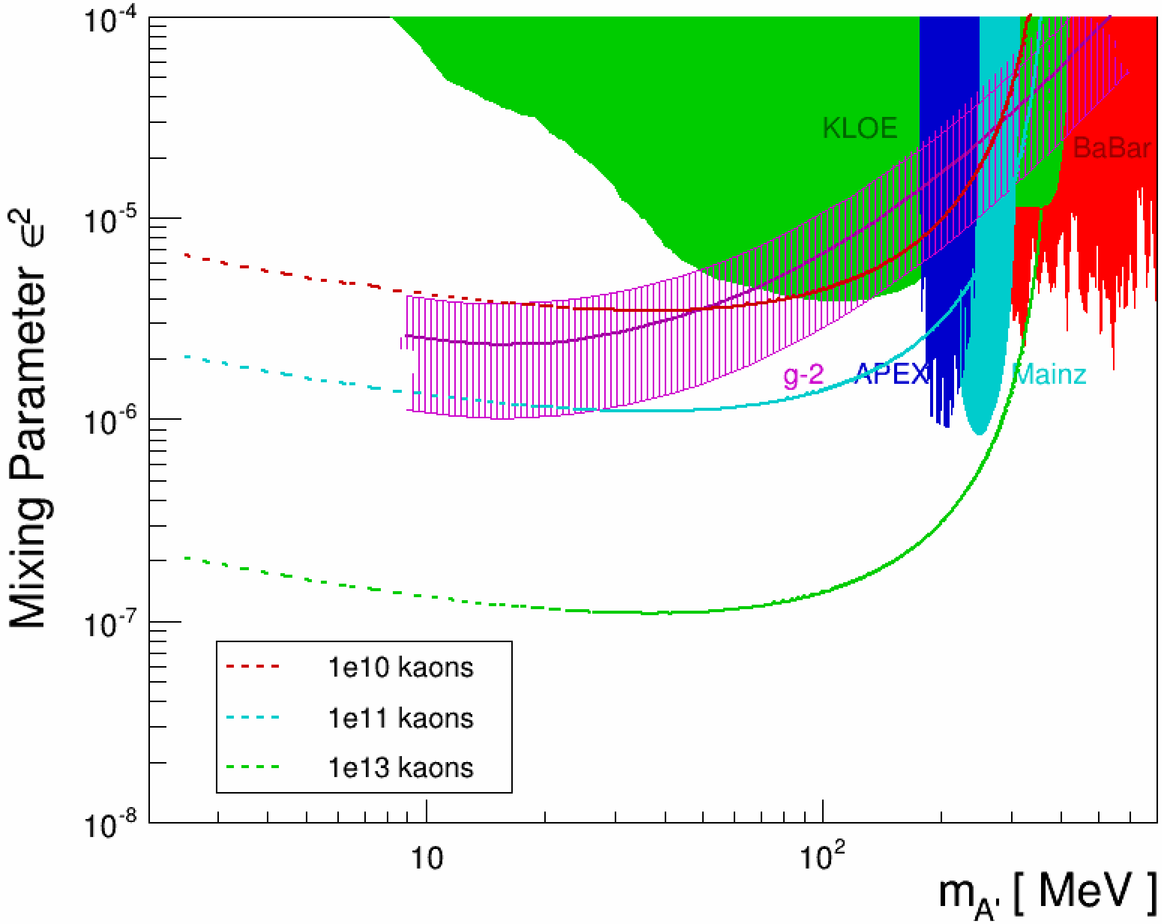


- Renormalise to account for Bijnens B.R. = 2.49e-5
- Total integral should be the number of expected events given by,

  N_{kaons} x Total B.R.
- Use distributions to evaluate ε^2

Total branching ratio = 2.49×10^{-5}
from Bijnens et al., Nucl. Phys. B396 (1993) 81-118

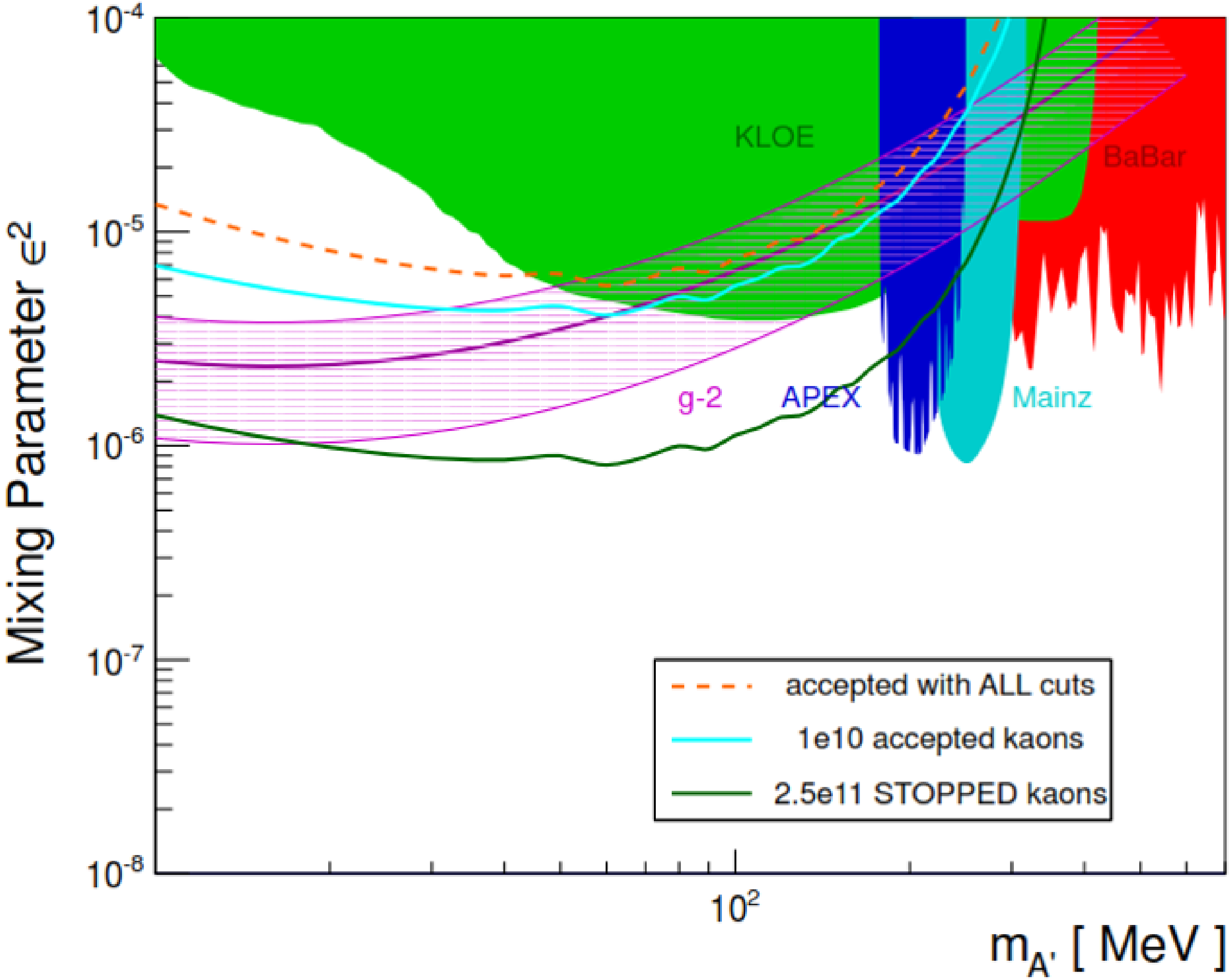
Ideal Theoretical ε^2



$$\varepsilon^2 = \frac{2}{\sqrt{BR\left(K^+_{\mu^+\nu_\mu l^+ l^-}\right)(m_{\gamma'}) \times N_{K^+}}} \frac{2\,N\,\alpha}{3\pi} \frac{\delta m}{m_{\gamma'}}$$

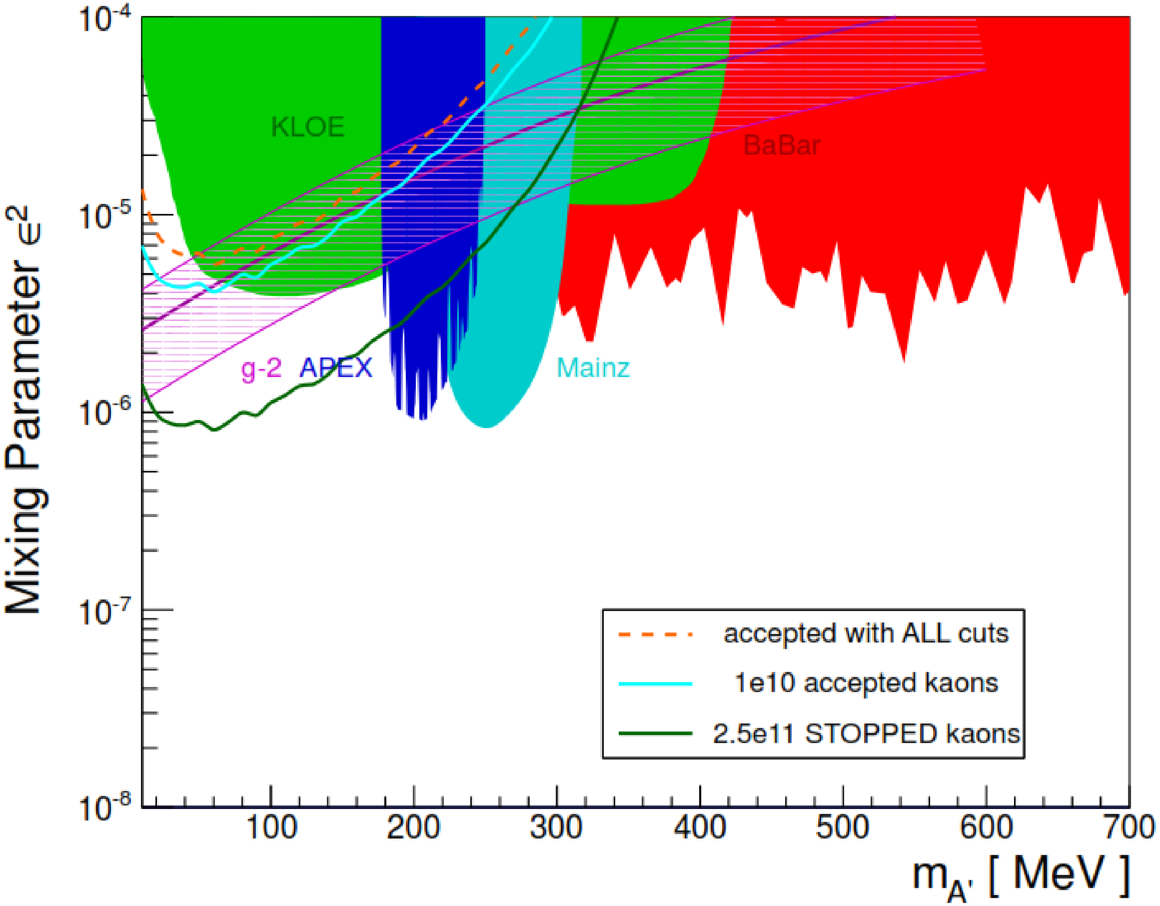
- Ideal curves from T. Beranek
- Chose $\delta m = 1$ MeV
- Assumes perfect 4π acceptance

Simulated ε^2



- δm cut varies
- depends on width found in signal simulations
- Use $\delta m = 2^*\sigma$
- $\sigma \sim 2.5 - 11$ MeV
- Rescaled to take account of the acceptance
- Apply detector acceptance cuts

Linear Scale ε^2 Comparison



- With standard E36 specification, ε^2 probes *g-2* band
- more stopped kaons → ε^2 curve probes lower

TREK/E36:

Kaons delivered:	1.0×10^{12}
&& stopped:	2.5×10^{11}
&& μ^+ accepted:	1.8×10^{10}
&& e^+e^- accepted:	1.0×10^{10}

Summary

- Many experiments searching for heavy photons
  → electron scattering, kaon decay,
- Using rare kaon decay channel, can probe parameter space for dark photon model – universal coupling.
- TREK E36 specifications lend to an exclusion curve in the g-2 region
- Simulations presented are a first step
- Other background decay channels to be investigated
- If other models (e.g. right-handed muon) are correct, then exclusion region for those signals should be straightforward to measure.