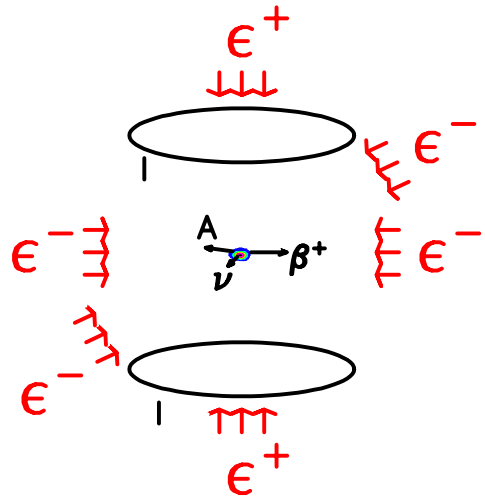
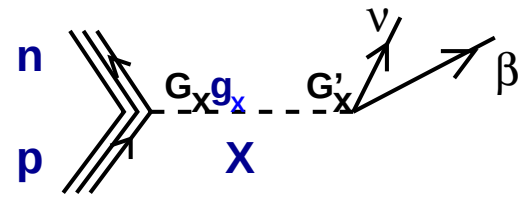
TRIUMF Neutral Atom Trap 2016+

Angular correlations of products for polarized and unpolarized β decays are sensitive to separate terms of:

$$H_{\rm int} = \sum_X (\bar{\psi}_p O_X \psi_n)(C_X \bar{\psi}_e O_X \psi_\nu + C'_X \bar{\psi}_e O_X \gamma_5 \psi_\nu)$$

'X': Lorentz vector, axial vector, scalar, tensor





- **Spin-polarized experiments in progress Goal 0.001 accuracy $\to$ sensitivity to $M_X/G_X \sim M_W/\sqrt{0.001} \sim 2$ TeV**

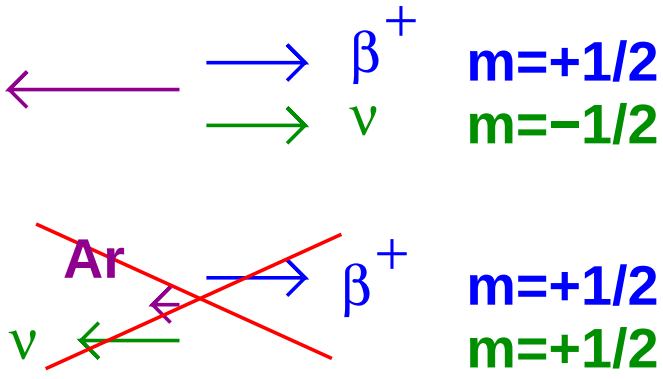
- **^{38m}K β-ν upgrade is sensitive to 'scalar' only and is complementary to other experimental constraints**

  - **Time reversal violation in radiative β decay** is not produced this way; is sensitive e.g. to MeV-scale QCD-like hidden sector models; TRV asymmetry 0.1 is allowed
  - **The E_ν spectrum of ^{92}Rb and reactor ν anomalies**

Lepton helicity → angular distribution

For ^{38m}K, $0^+ \to 0^+$ decay:

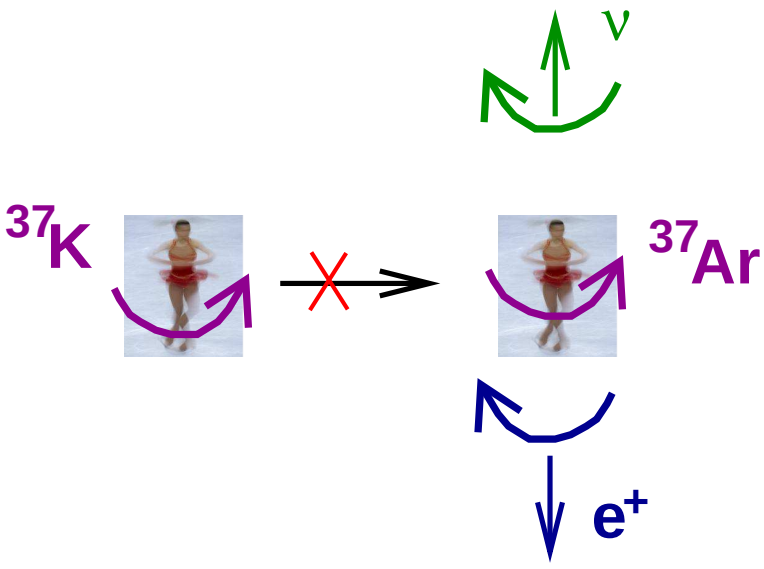
leptons have opposite helicity for W (vector) boson exchange



$$W[\theta_{\beta\nu}] = 1 + b\frac{m}{E} + a\frac{v_\beta}{c}\cos\theta_{\beta\nu}$$

$\Rightarrow$ **a** $= +1$, **b** $= 0$ $\quad a = -1$ for scalar

- **independent of isospin mixing and nuclear structure**
- **Radiative corrections 2×10^{-3}, recoil order term is 3×10^{-4}**



← This decay pattern needs non-S.M. chirality

TRIumf Neutral Atom Trap collaboration

TEXAS A&M UNIVERSITY

**S. Behling
**B. Fenker
D. Melconian

TRIUMF

*A. Gorelov
J.A. Behr
M.R. Pearson
K.P. Jackson

UNIVERSITY OF MANITOBA

**M. Anholm
G. Gwinner

TEL AVIV UNIVERSITY

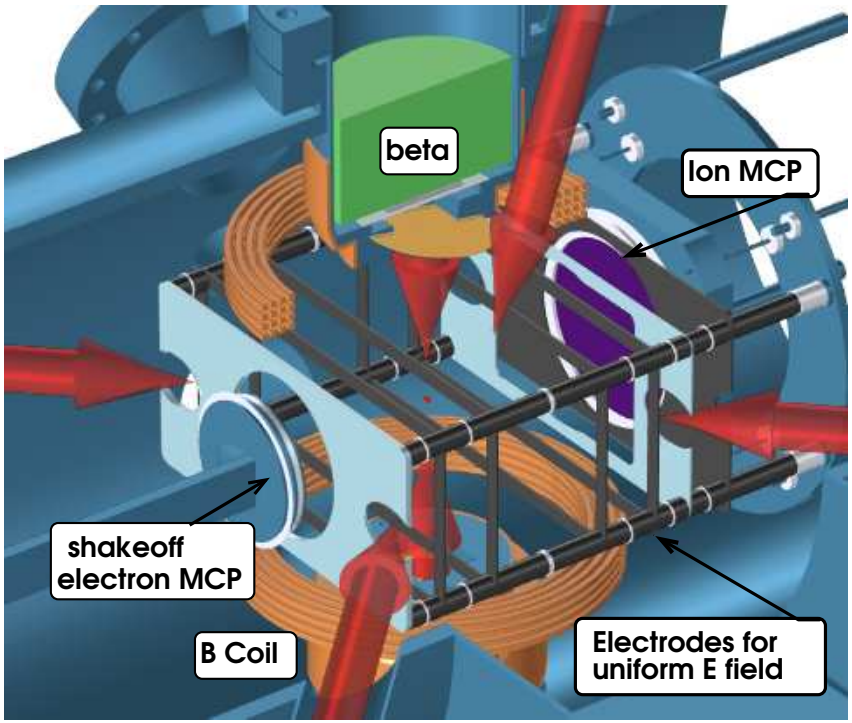
D. Ashery

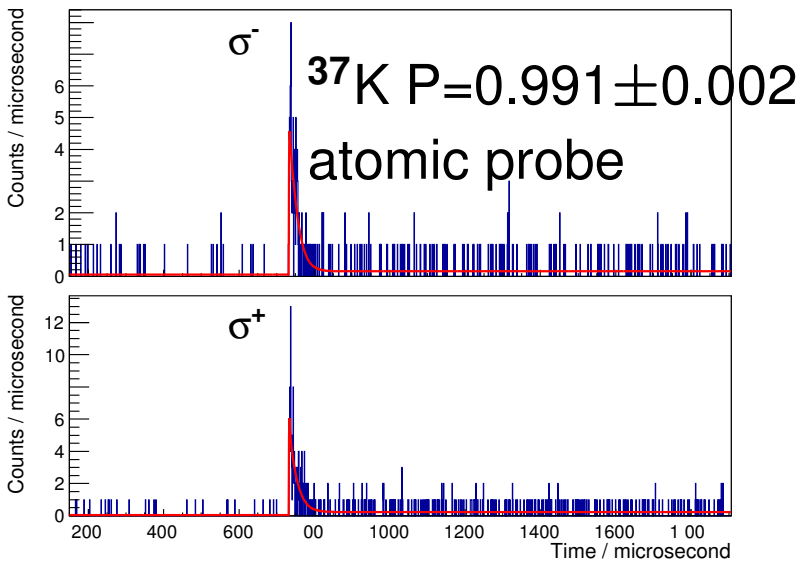
Undergrad
1 at a time

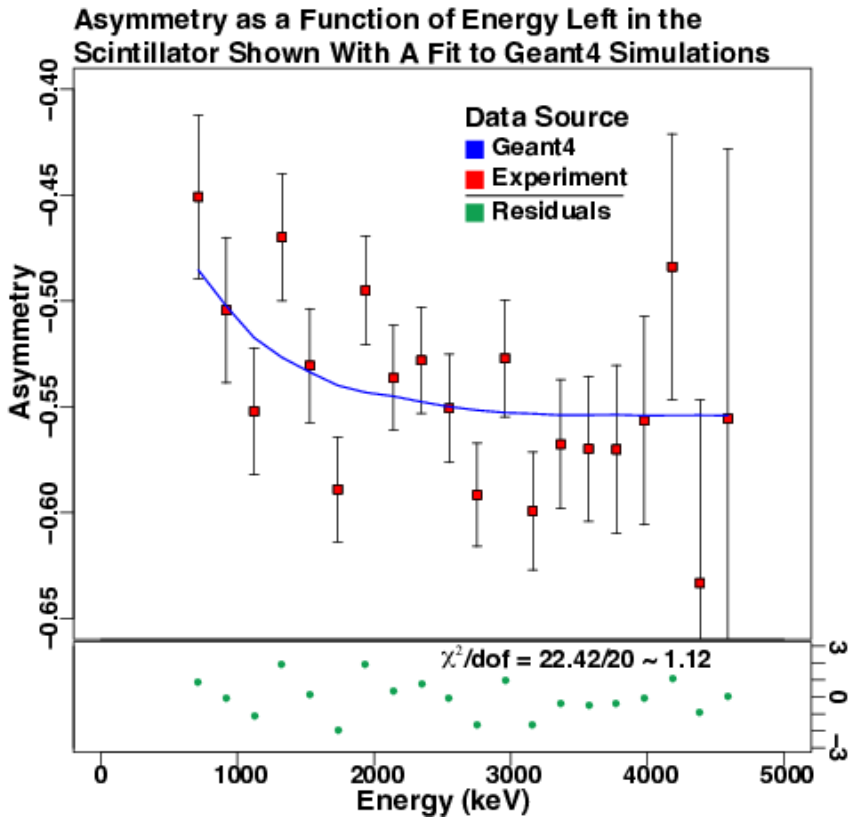
** Grad student * PDF

Supported by NSERC, NRC through TRIUMF, WestGrid, Israel Science Foundation, State of Texas

TRIUMF $^{37}\vec{K}$ A_β, A_{recoil}: scalar, tensor, V+A

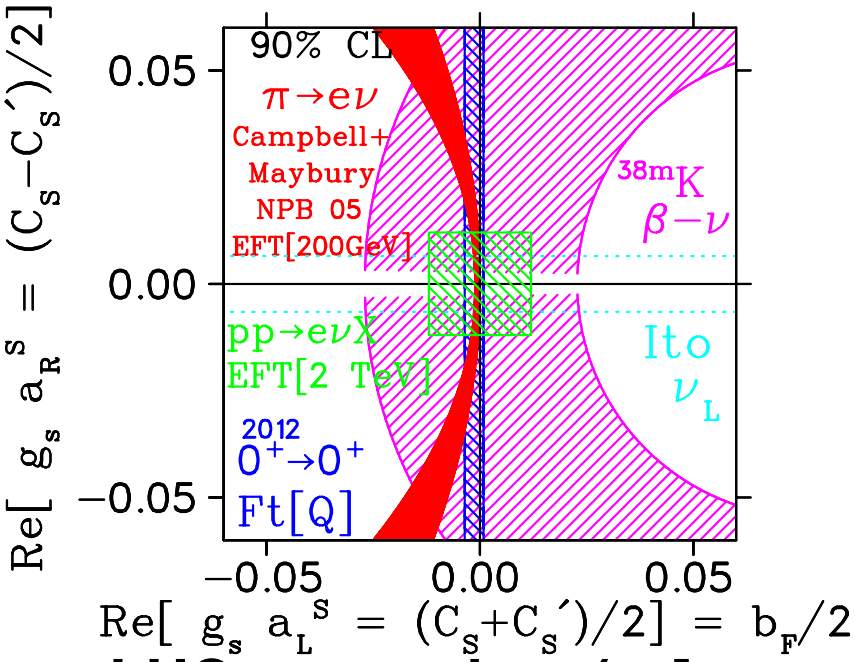


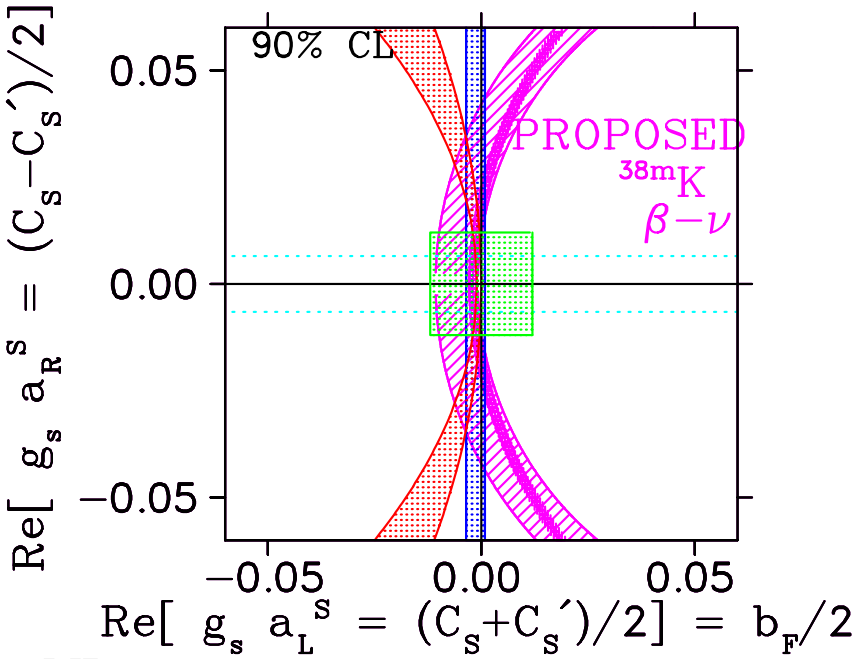




A_β = -0.5635(63)(71)
S. Behling, Ph.D. thesis, TAMU, 2012 data
2014 data: $\sigma_{A\beta} \sim 0.002$ (stat) and β-recoil coincidences

Direct and indirect sensitivity to scalars





- **LHC constraints (σ [p p $\to$ e ν X] Cirigliano, González-Alonso, Graessler JHEP02(2013)046 limits scalars coupling to wrong-handed ν**
- **$\pi \to e\nu$ (Campbell Murray NPB 04) has improved 2x**
- **Possible contribution to m_ν from $C_S - C_s'$ should be understood**

TRV in radiative β decay

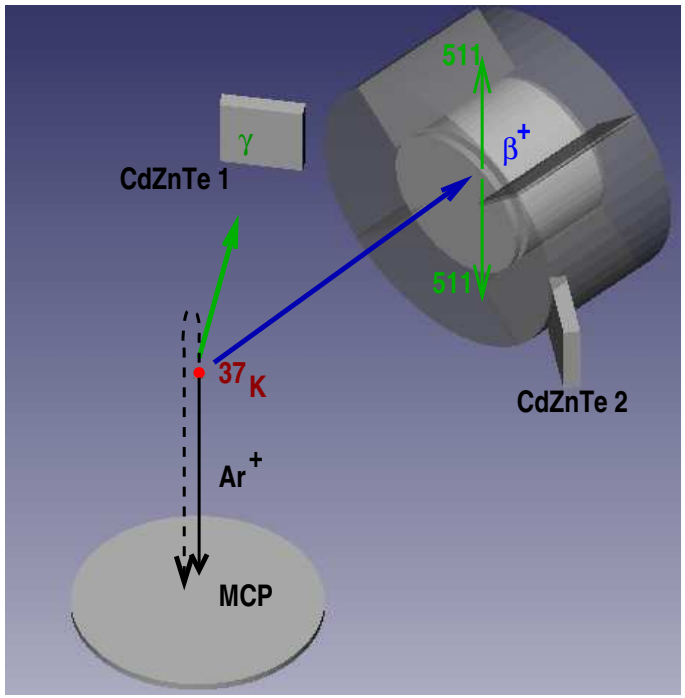
Inspired by a S.M. term emergent from QCD (Harvey Hill Hill PRL 99 261601):

Gardner, He PRD 87 116012 (2013)

$$-\frac{4c_5}{M^2}\frac{eG_F V_{ud}}{\sqrt{2}}\epsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu,L}F_{\nu\rho}$$

$$\to Im(c_5 g_V)\frac{E_e}{p_e k}(\vec{p_e}\times\vec{k_\gamma})\cdot\vec{p_\nu}$$

e.g., QCD-like hidden sector with scale $\sim$ MeV, few constraints

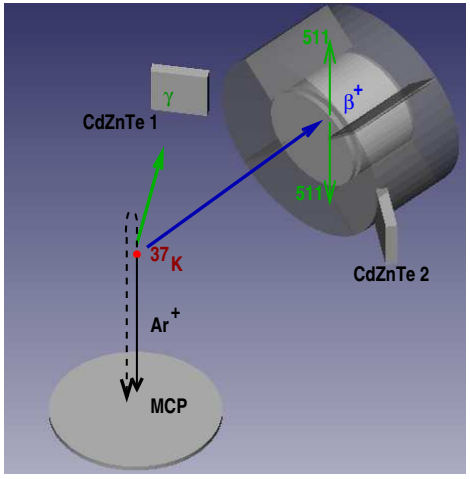


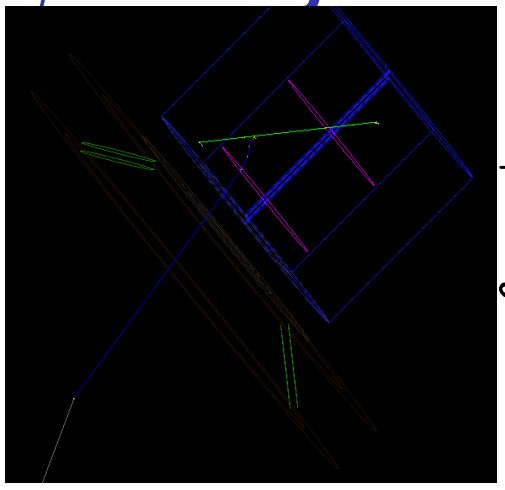
- ^{37}K $A\sqrt{B.R.} \sim$ 200x neutron
- final state false TRV $\approx$ 0.001
- the new ‘c5’ term needs Fermi or Fermi+GT transition
- ^{38m}K 40,000 atoms $\to$ TRV A_γ to 0.01 per 10 days

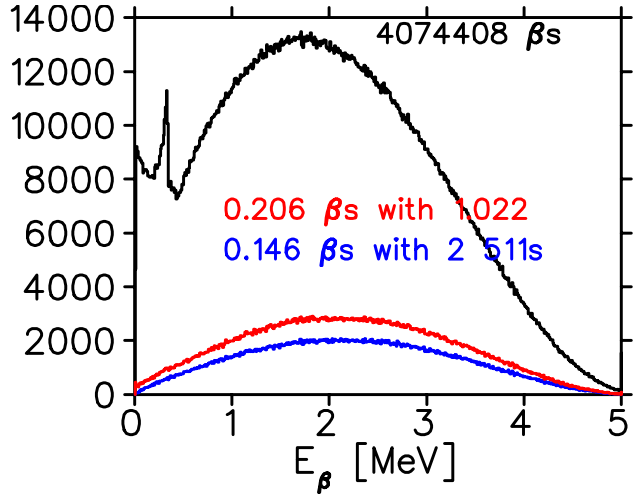
Relatively unexplored compared to other TRV exps like EDMs. (radiative K decay TRV at INR Moscow 2007; 4-body final states at LHCb and BABAR).

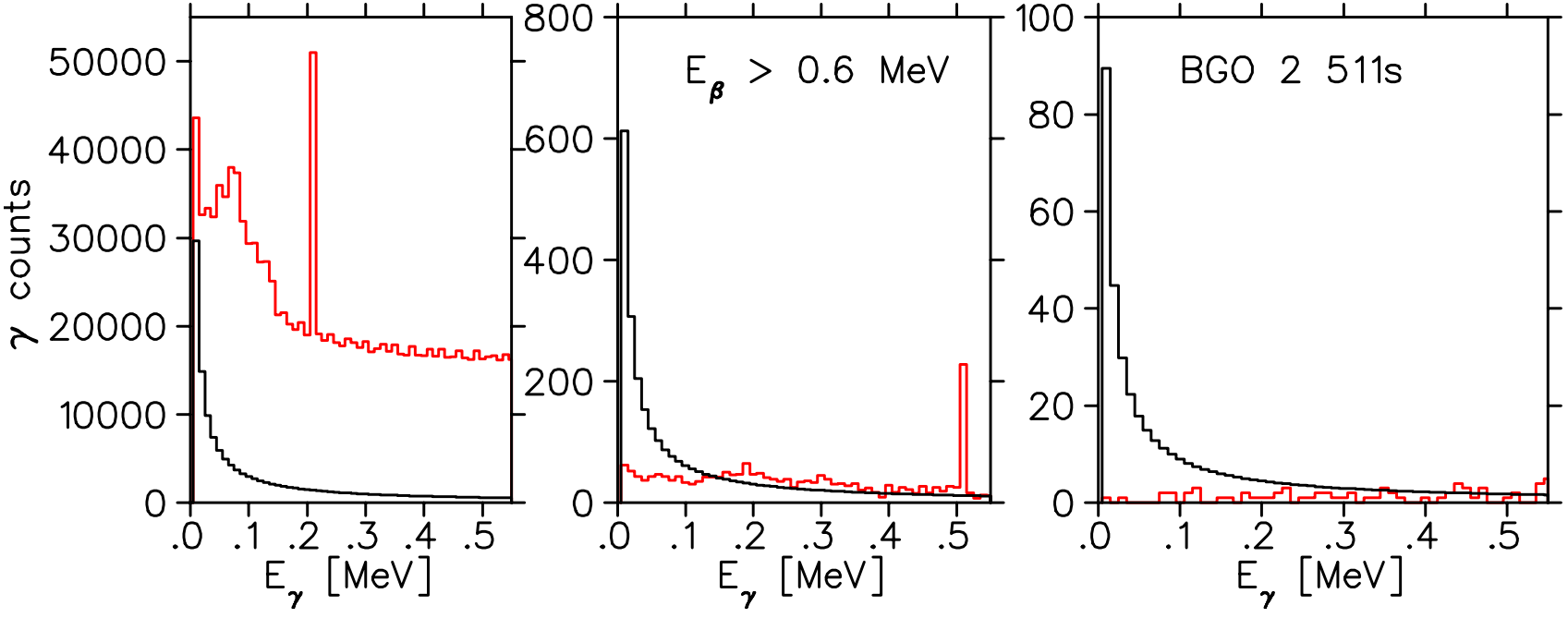
TRV Asym $\sim$ 0.1 is allowed by other experiments

TRINAT radiative β decay GEANT4









TRV in radiative β decay and EDMs

Dekens, Voss 1502.04629: dim 6 operators at TeV scale

$$\mathcal{L}_6^{\text{eff}} = -\frac{8ic_w}{gv^2} V_{ud}\,\text{Re}\,C_{\varphi\tilde{W}B}(\Lambda)\,\varepsilon^{\mu\nu\alpha\beta}(\bar{u}_L\gamma_\mu d_L)(\bar{e}_L\gamma_\nu\nu_L)F_{\alpha\beta}$$

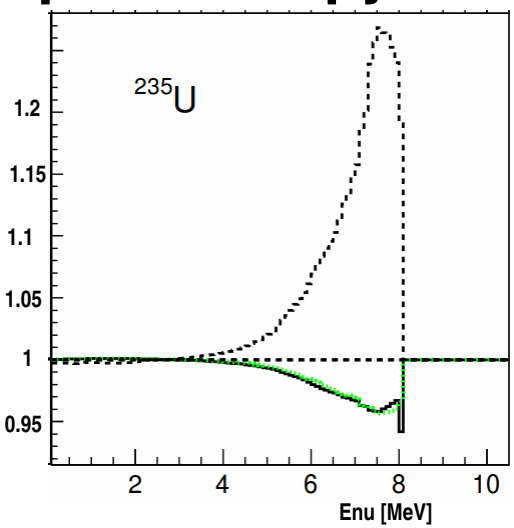
$\to 10^{-10}$ asymmetries if constants ~ 1.
Also generates EDMs $\to$ constants ~ 0.01
So TeV-scale general dim 6 ops **can** make TRV $\gamma\nu\beta$ **and** EDMs, but don't make measureable nuclear radiative β decay; result $\sim \boldsymbol{p^2_{\text{lepton}}/\text{scale}^2}$.

The toy nonperturbative QCD-like MeV-scale example of Gardner and He is tuned to maximize contribution to neutron β decay and avoid other experiments. E.g. direct searches by colliders bury the possible effective mesons in jets.
Do EDMs constrain the Gardner term anyway? Can a nonperturbative estimate be made?

^{92}Rb and the new reactor ν anomaly

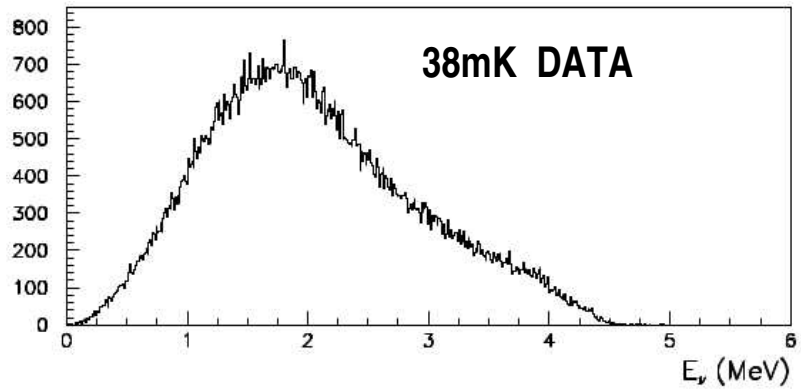
The reactor ν flux is 92% $\pm$ 4% of what is expected, to which JB says 'well done'. But there's another reactor anomaly:

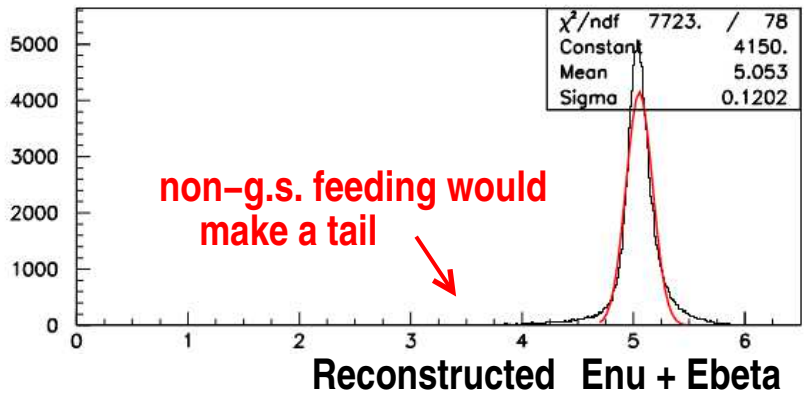
^{92}Rb NNDC 2012: $0^- \to 0^+$ g.s. 95%
Jyväskylä 1504.05812v3.pdf total absorption spectroscopy 87.5$\pm$2.5% $\to$



a 4.5% change at interesting E_ν, from one isotope.

We could measure the Eν spectrum

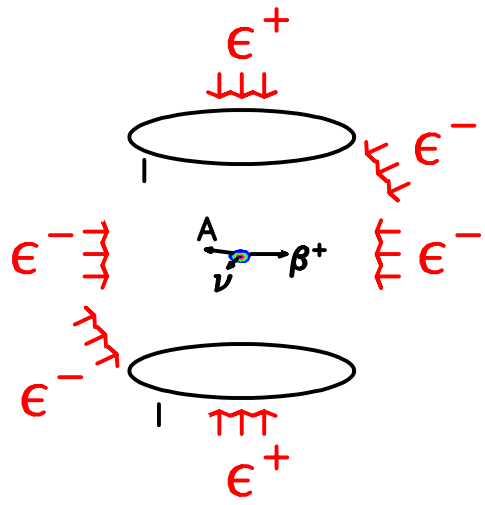




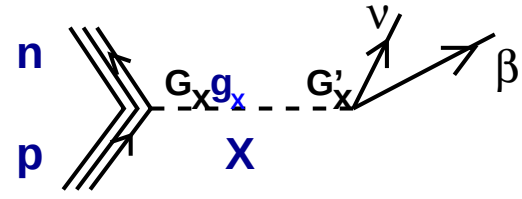
with few % sensitivity to decays to higher-lying states

TRIUMF Neutral Atom Trap 2016+

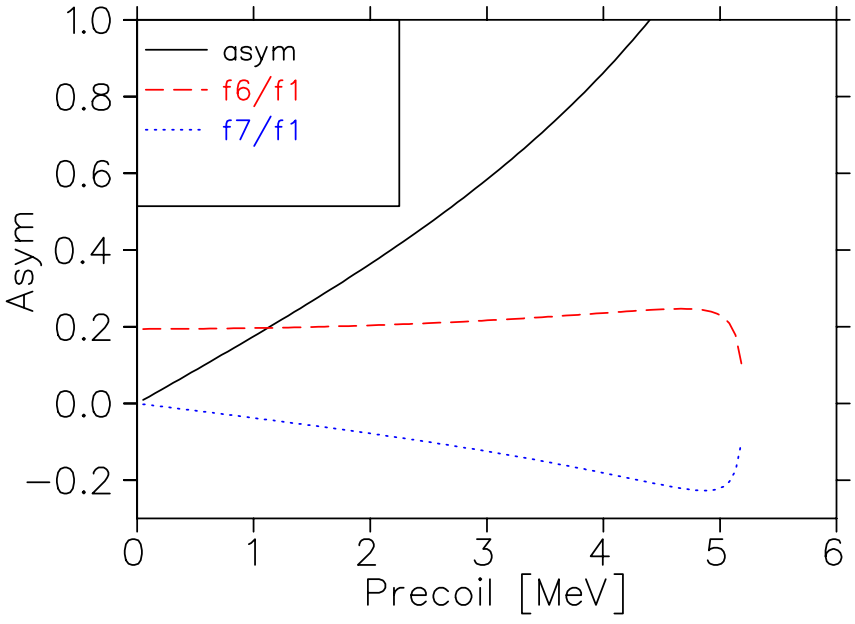
- **Spin-polarized experiments in progress A_β of ^{37}K 1st result to 1.5% (better fractional error than any but the neutron); blinded data being analyzed $\sim$ 0.002 accuracy. Goal 0.001 accuracy in A_β, $A_{\rm recoil} \to$ sensitivity to $M_x/G_x \sim M_W/\sqrt{0.001} \sim 2$ TeV**



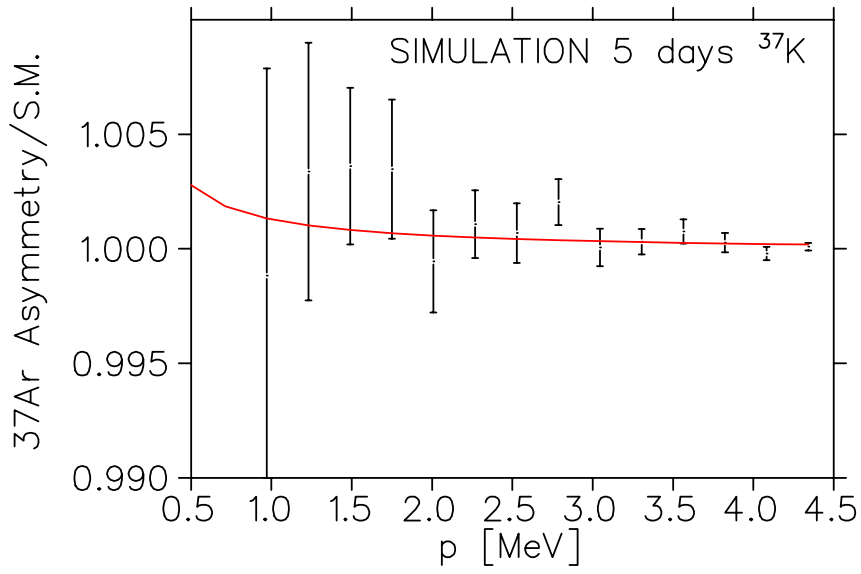
- **^{38m}K β-ν upgrade goal is 5x better, complementary to other scalar measurements**
  - **Time reversal violation in radiative β decay** TRV asymmetry 0.1 is allowed, sensitive to MeV-scale QCD-like hidden sector models
  - **^{92}Rb ν spectroscopy could help with the reactor ν shape anomaly**



^{37}K decay recoil asymmetry



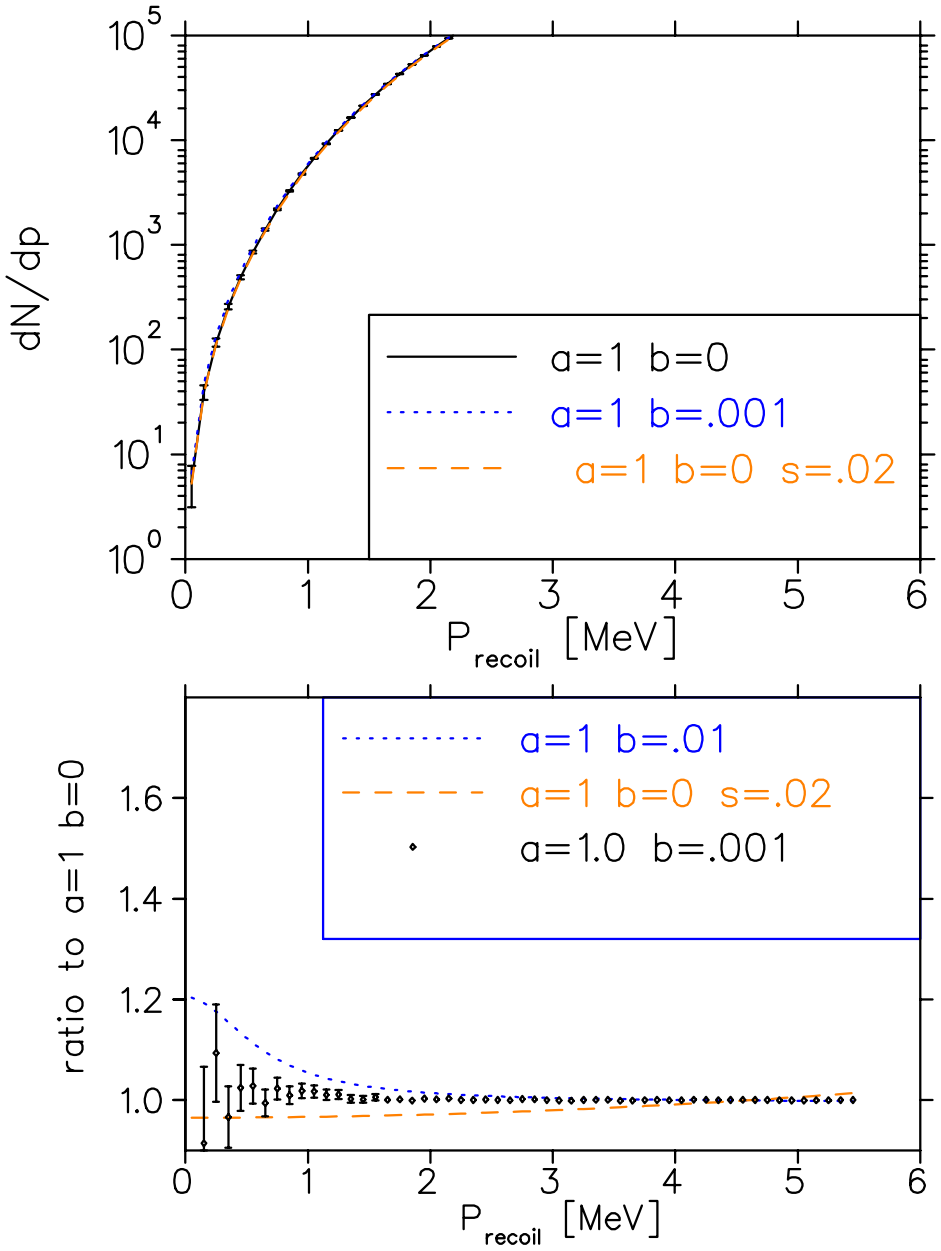
recoil singles asymmetry



Simulation for 5 days
10,000 atoms trapped

Would extract $C_t + C_t'$= 0.0018+-0.0008, possible from SUSY [Profumo PRD 75 075017] with uncertainty smaller than world average in nuclear β decay

^{38m}K decay precoil spectrum



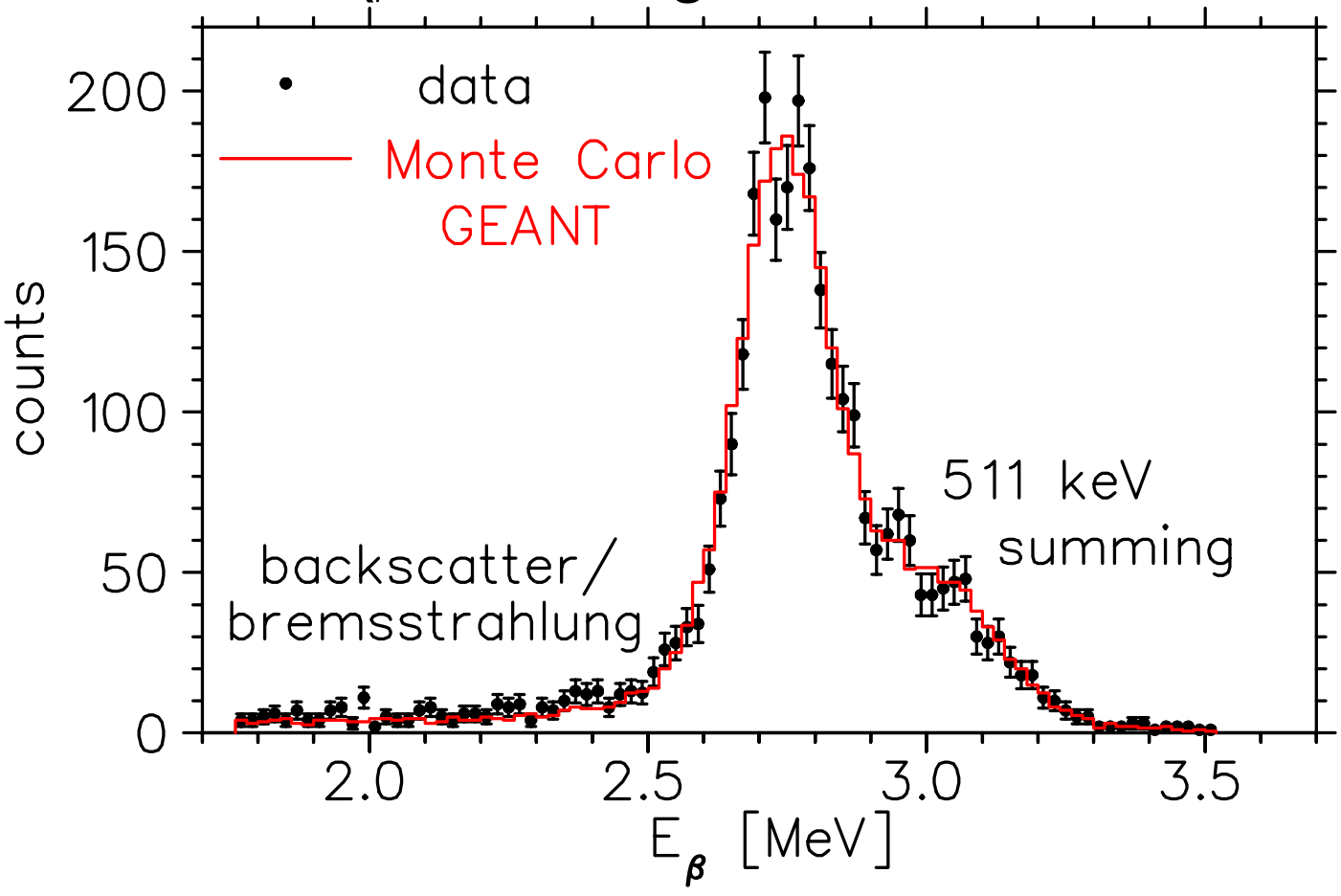
Simulation

Alternate high-statistics method for $a_{\beta\nu}$

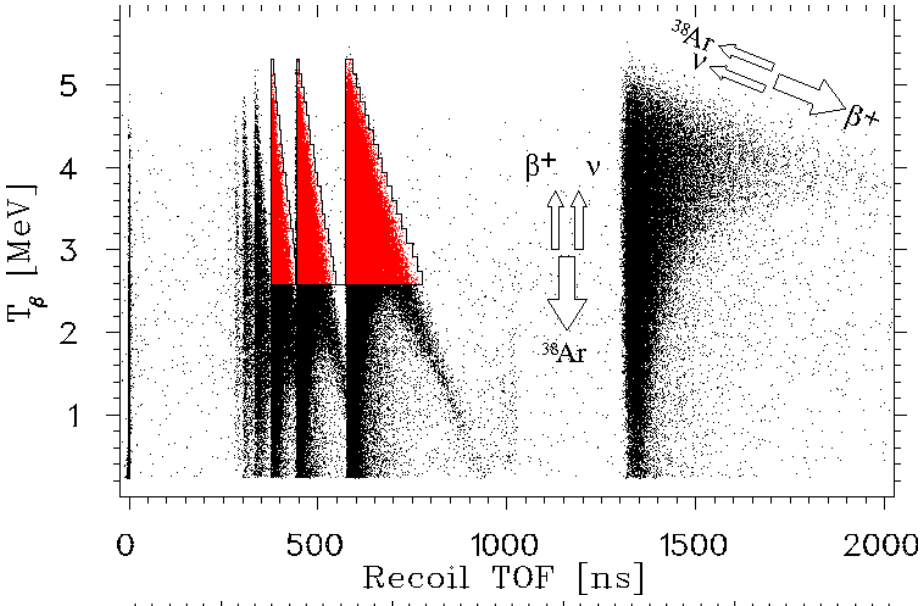
Must be done at same time as full kinematic coincidence method, to characterize detectors and test for backgrounds

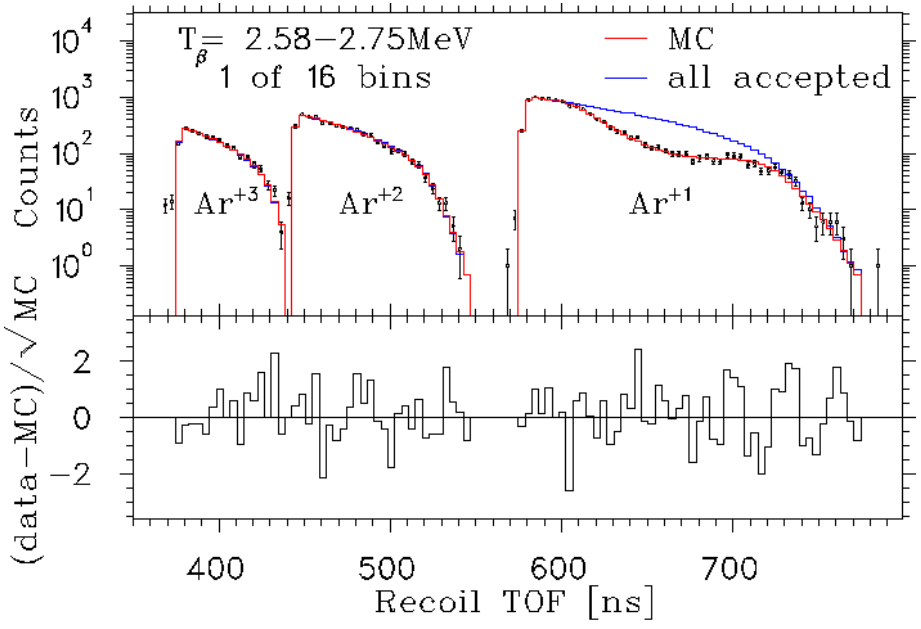
In-situ calibrations

E_β detector response for "monoenergetic" β's from kinematics of other observables (β-recoil angle and recoil momentum)

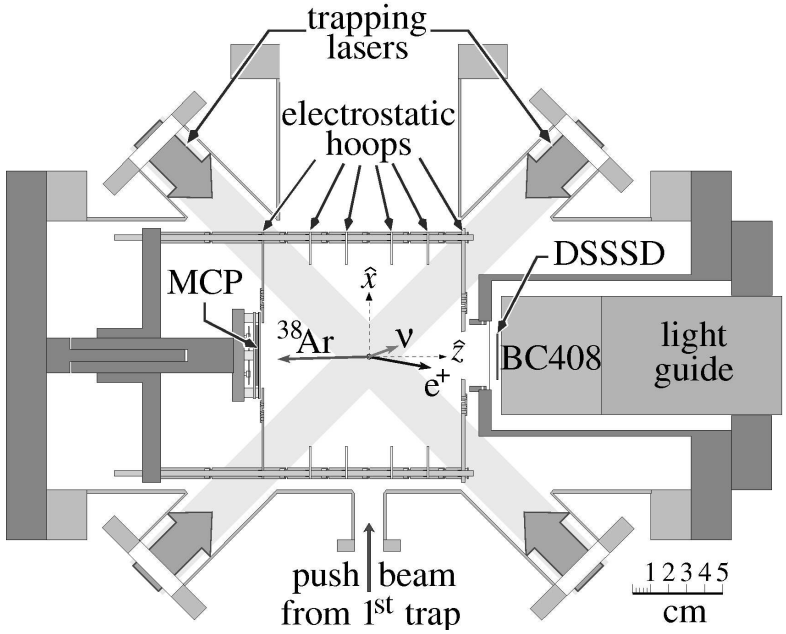


^{38m}K β-ν correlation





β-recoil coincidences



Gorelov PRL 2005

$$a = 0.9981 \pm 0.0030 \pm^{0.0032}_{0.0037}$$

- **New geometry goal is to collect all recoils**
- **To go to lower E_β, reconstruct it**

^{38m}K β-recoil error budget

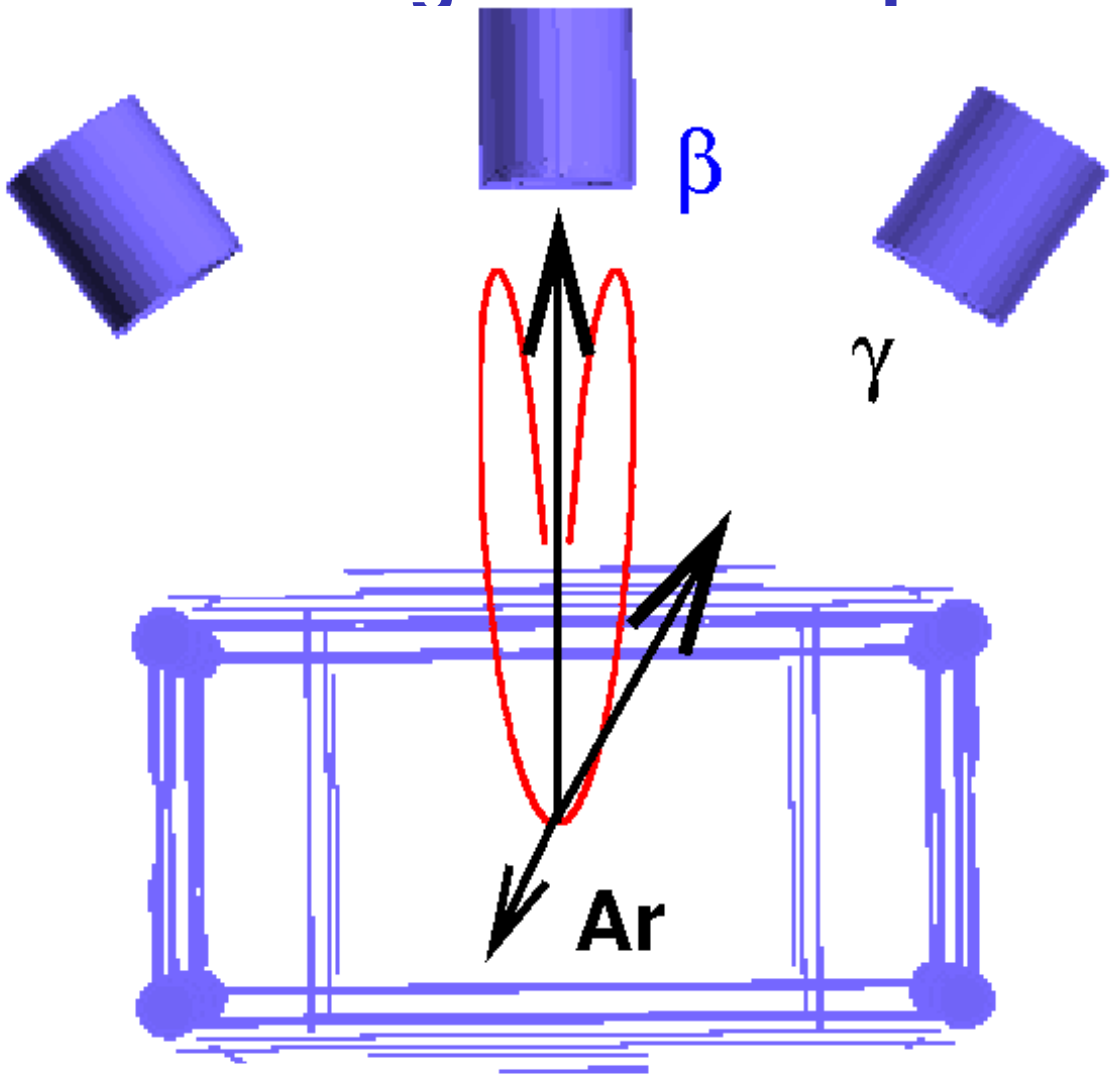
Error	PRL	Future
$\vec{E}$ field/trap width :	0.17%	0.04%
E field nonuniformity	0.14%	0.03%
β^+ backscattering bkgd	None	None
$E_{\beta+}$ Detector Response:		
Lineshape tail/total	0.06%	0.03%
511 keV Compton sum	0.09%	0.04%
Calibration, nonlinearity	0.17%	0.08%
MCP Eff[E_{Ar+}]	0.07%	0.03%
MCP Eff[θ]/XY position	0.08%	0.04%
e^- shakeoff [E_{recoil}]	0.18%	0.08%
Sum systematics	0.37%	0.14%
Total error	0.48%	0.19%

Planned Improvements:

- **Larger MCP and $\vec{E}$ field**
- **larger ISAC yields $1/\sqrt{5}$ statistical error**
- **E_β calibration from interwoven background-free ^{37}K**

- **Most systematic errors determined by statistics-limited data evaluation.**

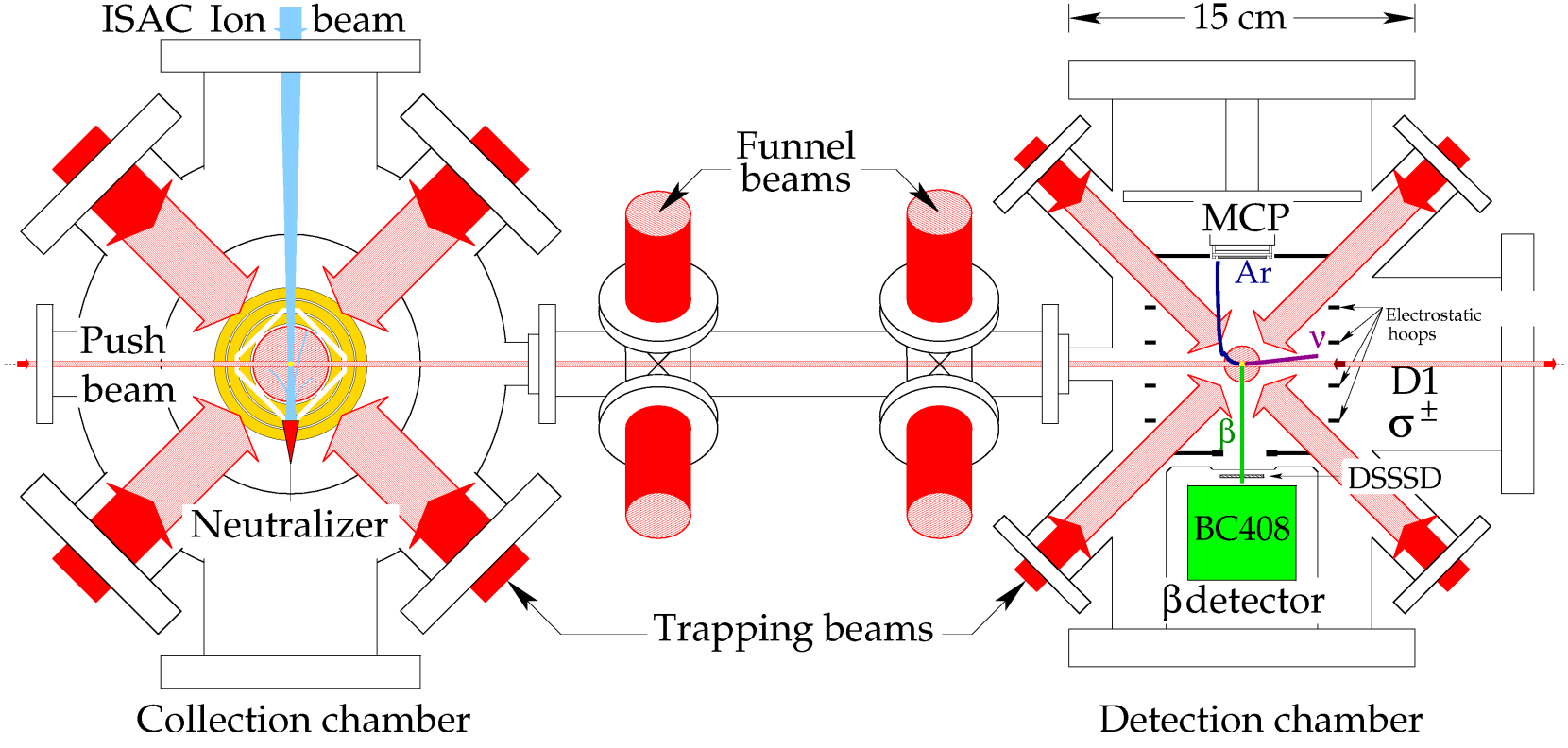
Bremsstrahlung is forward-peaked



You don't have to cover all solid angle with detectors to see the photons

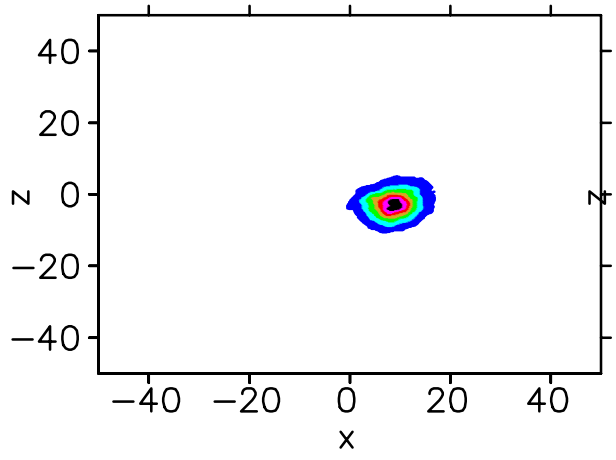
TRIUMF's β decay Neutral Atom Trap

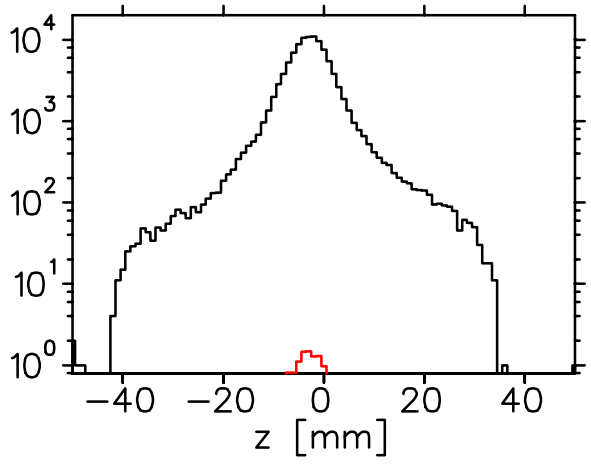
- **Isotope/Isomer selective**
- **Evade 1000x untrapped atom background by $\rightarrow$ 2nd MOT**
- **75% transfer (must avoid backgrounds!); 10^{-3} capture**
- **0.7 mm cloud for β-Ar^+ $\rightarrow$ ν momentum $\rightarrow$ β-ν correlation**
- **99% polarized, known atomically (in progress)**

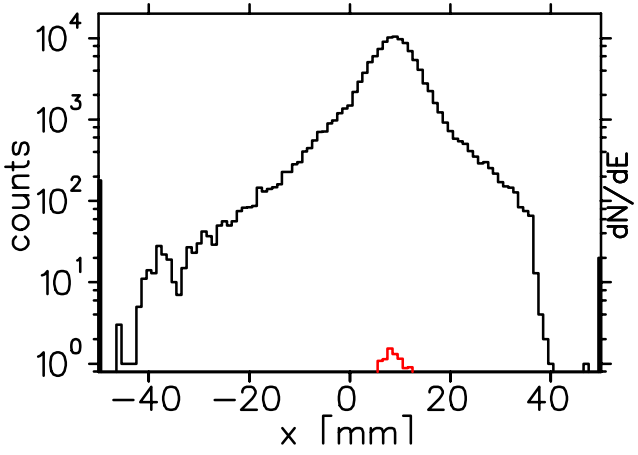


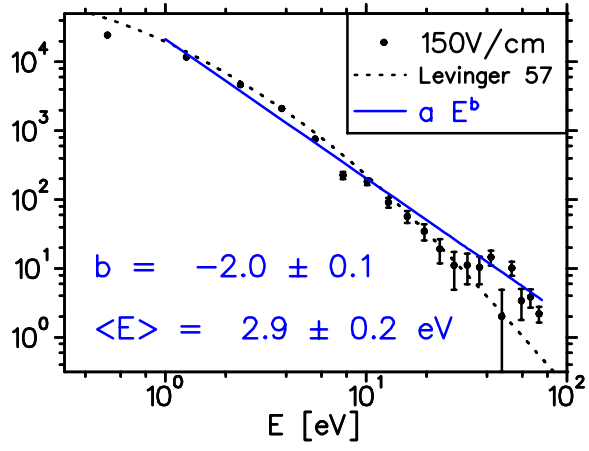
^{37}K shakeoff e^- energy

- $|\vec{E}|$=150 V/cm (B_z= 2G), $E_{shokeoff} \rightarrow$ radius distribution
- $\sim$1% above 25 eV threshold for double DNA strand breaks
- average energy makes $< 10^{-5}$ contribution to Ft value





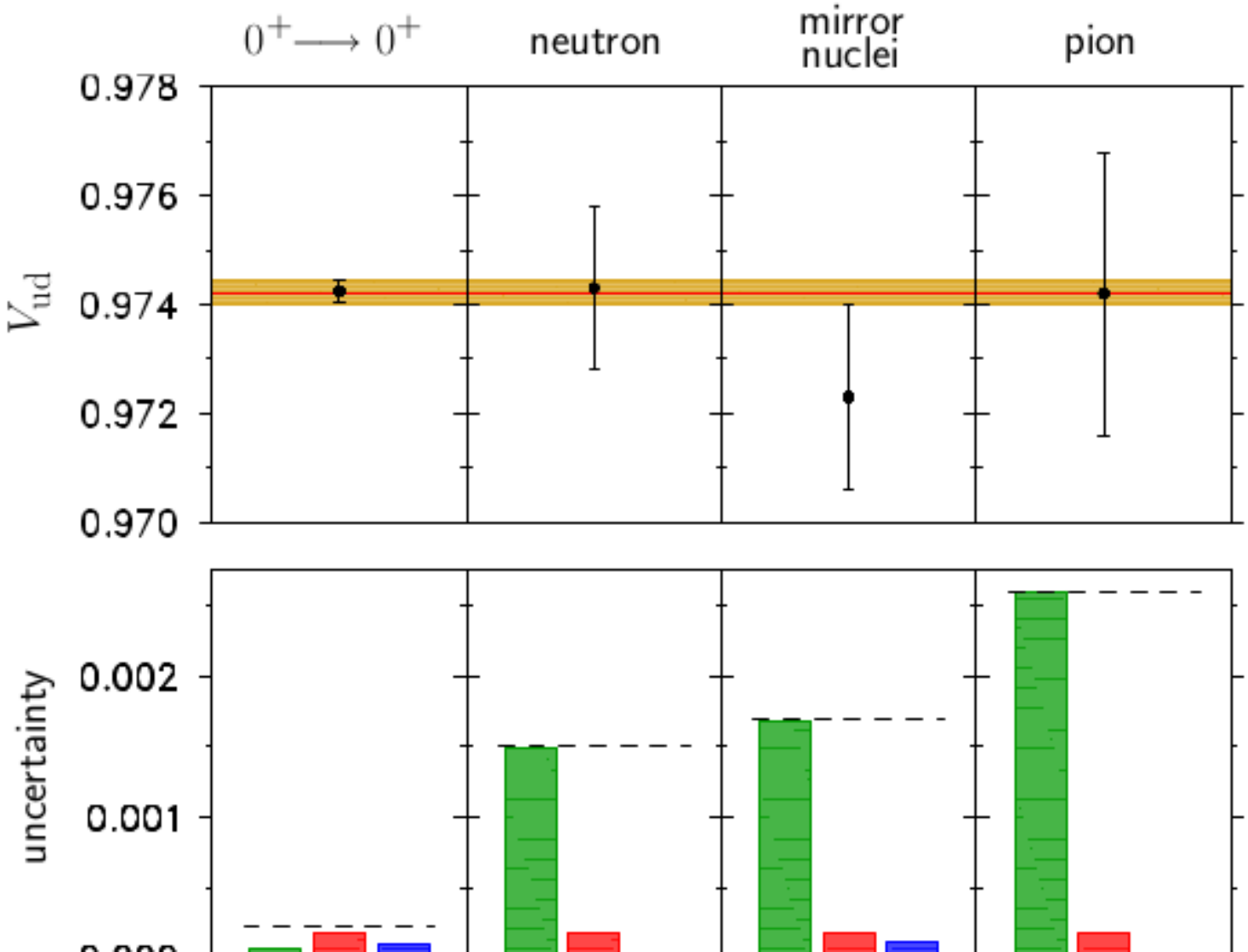




TRIUMF

Mirrors and Vud [Fenker, SSP2015]

Measure V_{ud} with mirror nuclei



^{37}K and Vud [Fenker, SSP2015]

- Atomic structure allows for laser-trapping *AND* optical pumping
- Isobaric analogue decay simplifies nuclear structure corrections
- Strong branch to ground state is a very clean decay
- $I^\pi = \frac{3}{2}^+ \to \frac{3}{2}^+$ is a mixed Fermi-Gamow Teller decay

$\Delta t_{1/2} = 0.08\%$
(Shidling *et al.* 2014)
$\Delta BR = 0.14\%$
$\Delta Q_{EC} = 0.003\%$

$\Delta \mathcal{F}t = 0.18\%$
$\Delta \rho = 0.4\%$

$A_\beta(0) = -0.5706(7)$
$\to \Delta A_\beta = 0.12\%$