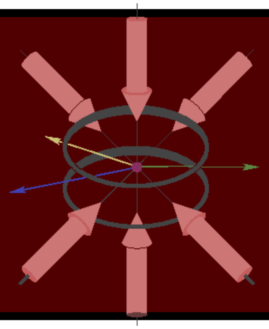
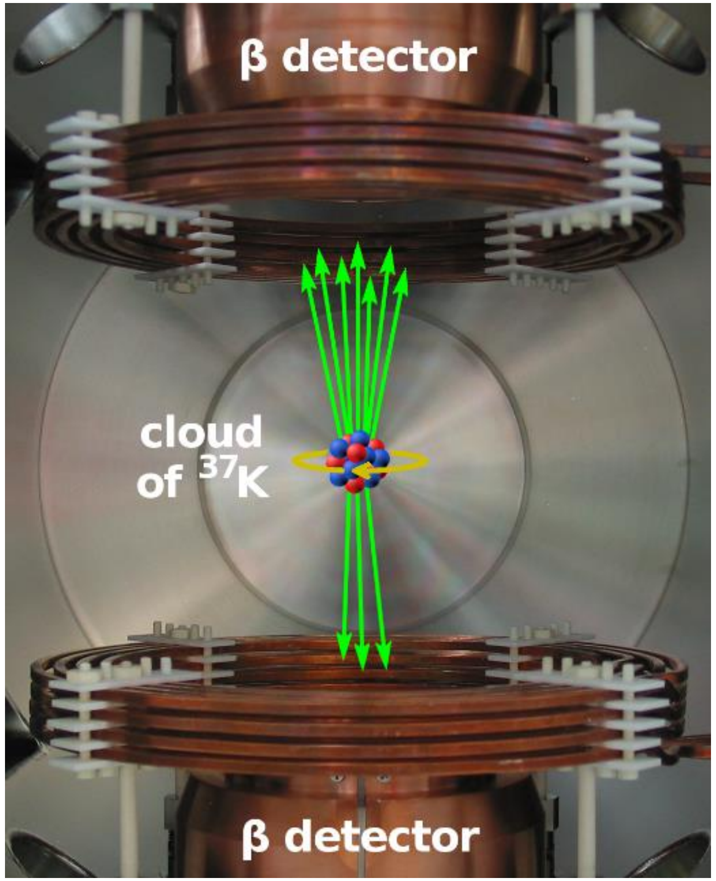
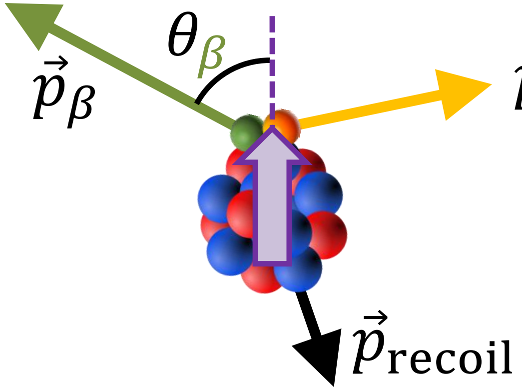
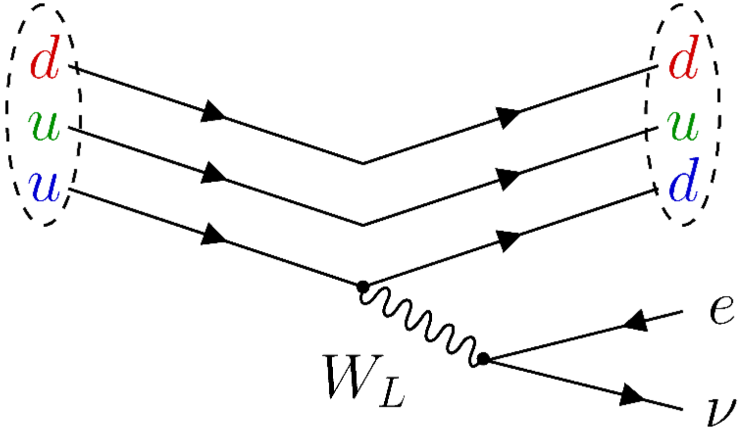
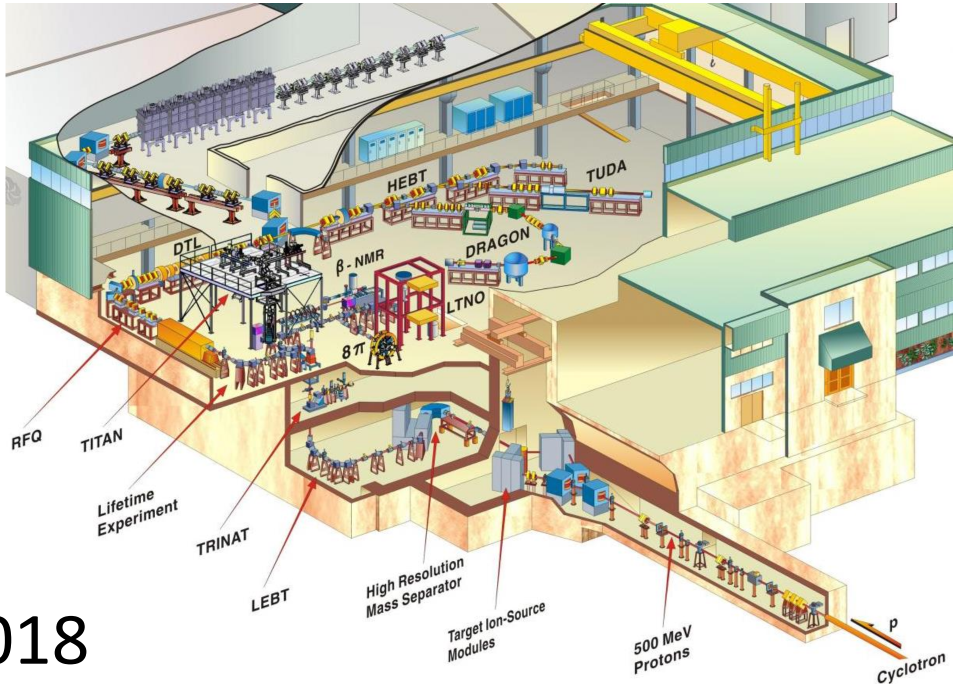
In Situ Characterization of β scattering at TRINAT

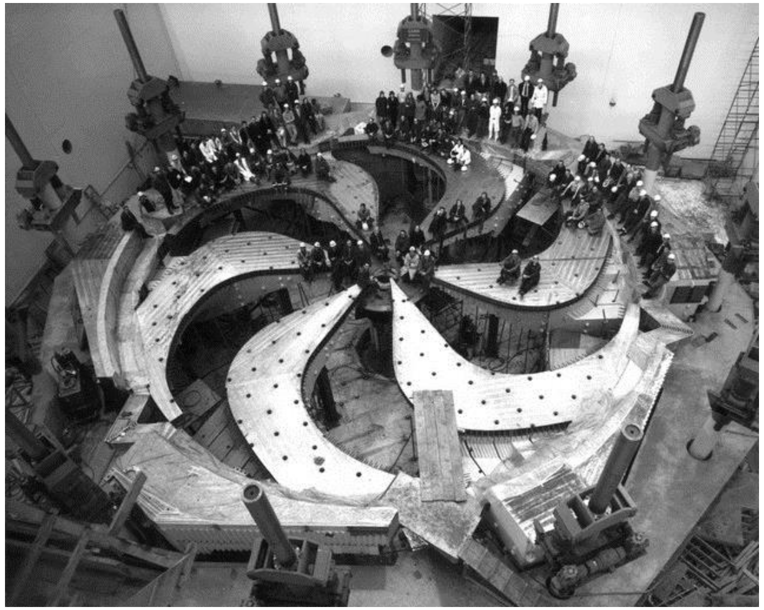












Dan Melconian – DNP, 2018

β decay to search for new physics

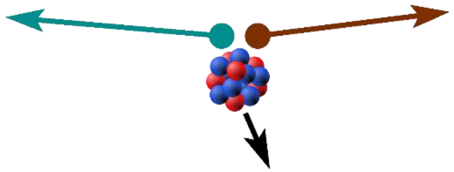
Start with (part of) the often-quoted **angular distribution** of the decay:

(Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

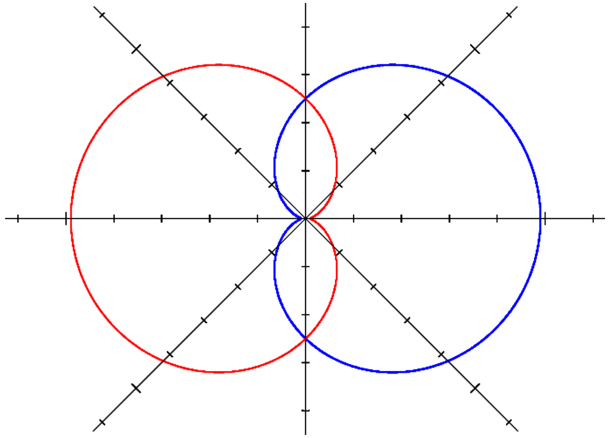
basic decay rate | β-ν correlation | Fierz interference

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_\nu} = \frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_\beta E_\beta (A_0 - E_\beta)^2 \, \xi \left[1 + a_{\beta\nu}\left(\frac{v_\beta}{c}\right)\cos\theta_{\beta\nu} + b\frac{m_e}{E_\beta} + \ldots\right]$$

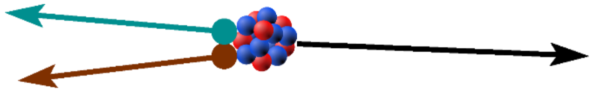
scalar



$$a_{\beta\nu}^{\text{scalar}} = \frac{-|C_S|^2 - |C_S'|^2}{|C_S|^2 + |C_S'|^2}$$



vector



$$a_{\beta\nu}^{\text{vector}} = \frac{|C_V|^2 + |C_V'|^2}{|C_V|^2 + |C_V'|^2}$$

$$a_{\beta\nu} = \frac{|C_V|^2 + |C_V'|^2 \; - \; |C_S|^2 - |C_S'|^2}{|C_V|^2 + |C_V'|^2 \; + \; |C_S|^2 + |C_S'|^2} = 1?$$

$$b = \frac{-2\Re e(C_S^* C_V + C_S'^* C_V')}{|C_V|^2 + |C_V'|^2 \; + \; |C_S|^2 + |C_S'|^2} = 0?$$

β decay to search for new physics

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(Jackson, Treiman and W[...] Phys Rev **106** and Nucl Phys **4**, 1957)

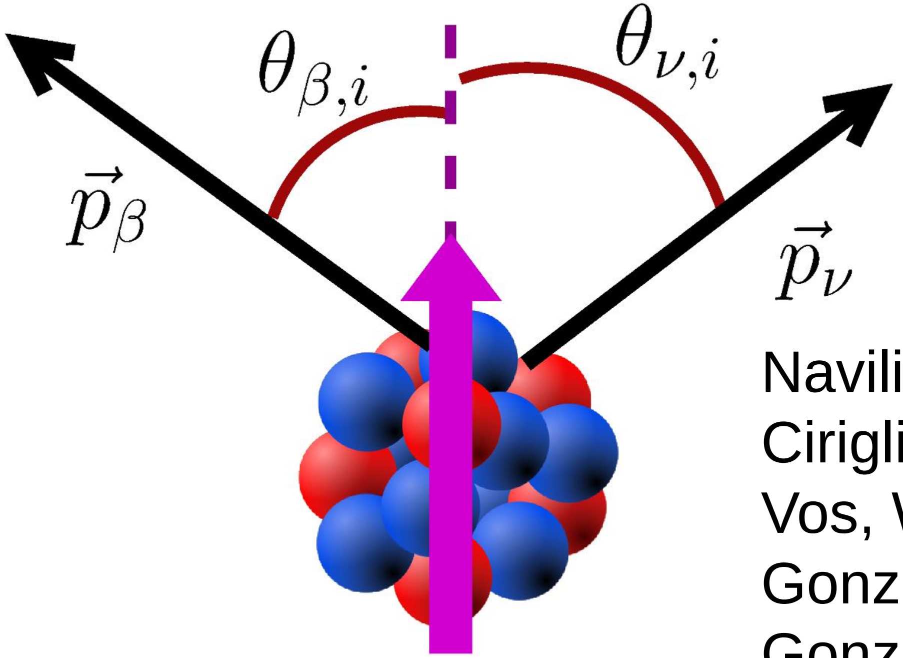
basic deca[y] ... β-ν correlation ... Fierz interference

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_\nu} = \frac{G_F^2|V_{\mathrm{ud}}|^2}{(2\pi)^5} p_\beta E_\beta \ldots \frac{m_e}{\ldots} \ldots \cdots\Big\} + \cdots\Big]$$

β asymmet[ry]

β-decay parameters depend on the form of the weak interaction

$\Longrightarrow$ sensitive to new physics $\Longleftarrow$



Naviliat-Čunčić and González-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, González-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić, PRC **94**, 035503 (2016)
González-Alonso, Naviliat-Čunčić and Severijns, arXiv:1803.08732

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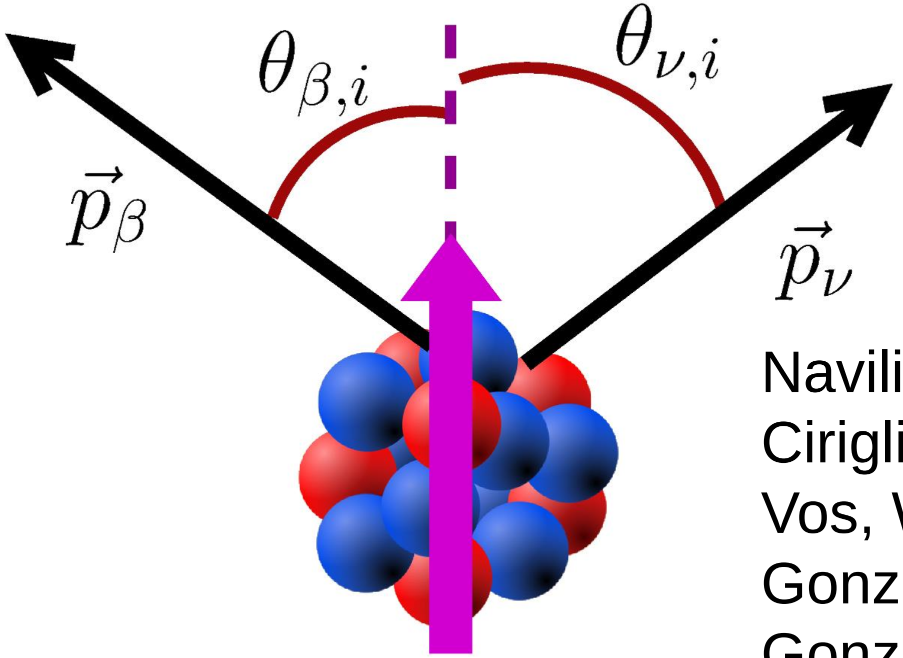

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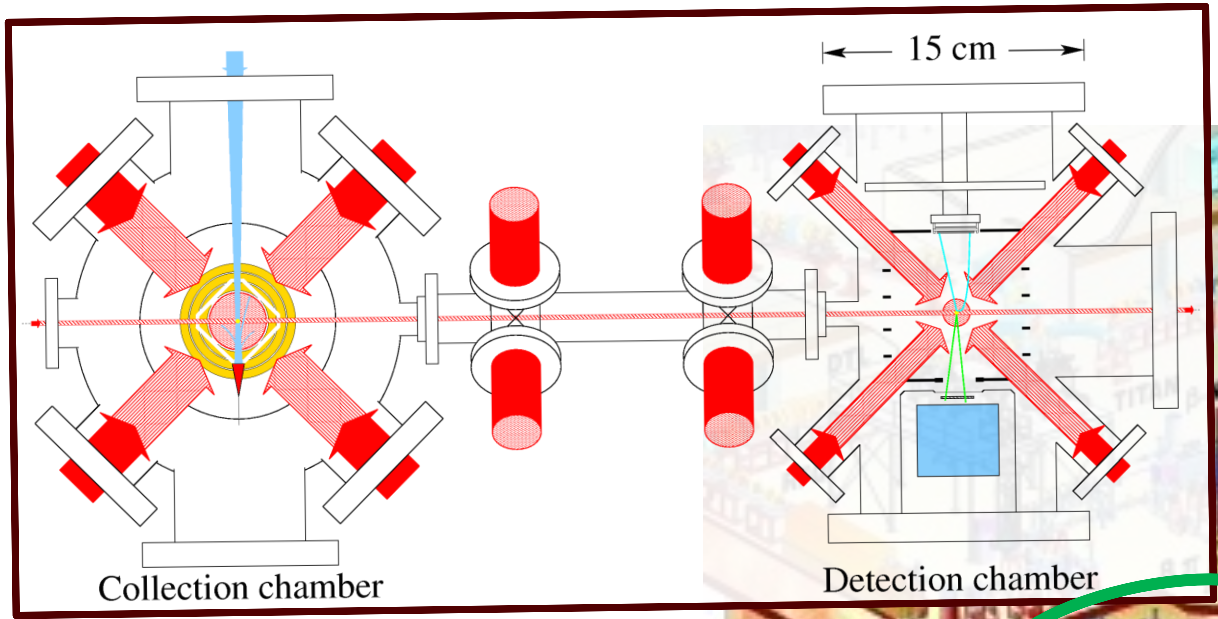
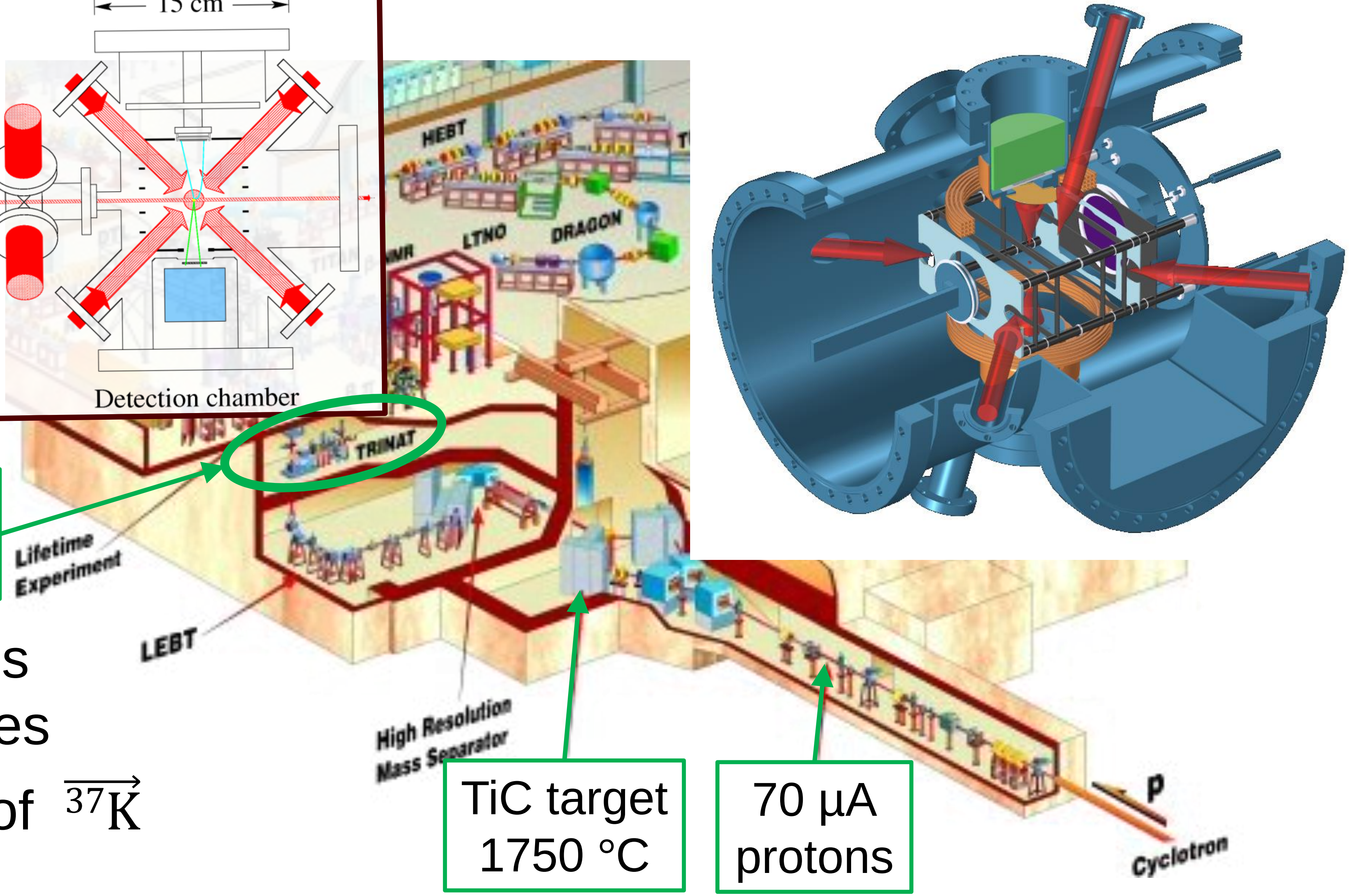
The TRIUMF Neutral Atom Trap



up to 8×10^7 ^{37}K/s
5000×10^7 ^{80,92}Rb/s



TiC target
1750 °C

70 µA
protons

- Angular correlations of K and Rb isotopes
- Recent result: A_β of $\overrightarrow{^{37}\mathrm{K}}$

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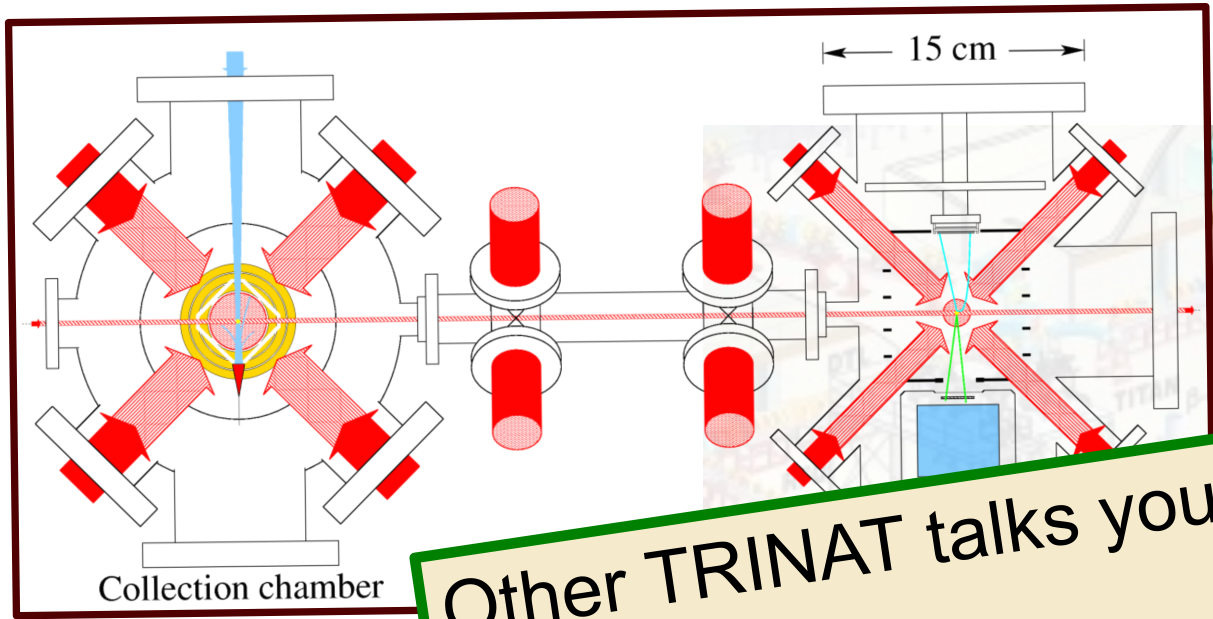
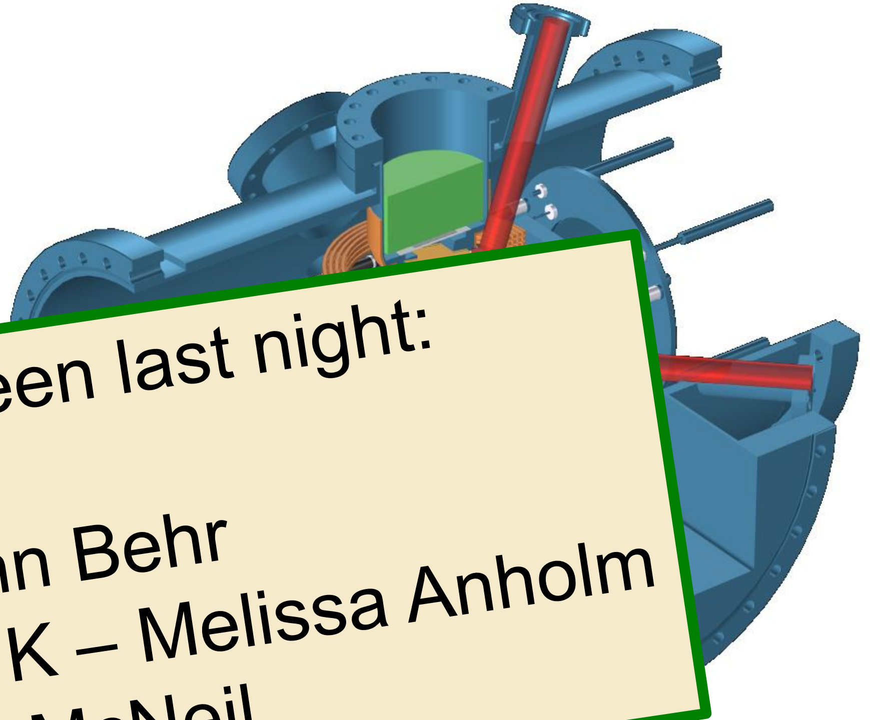


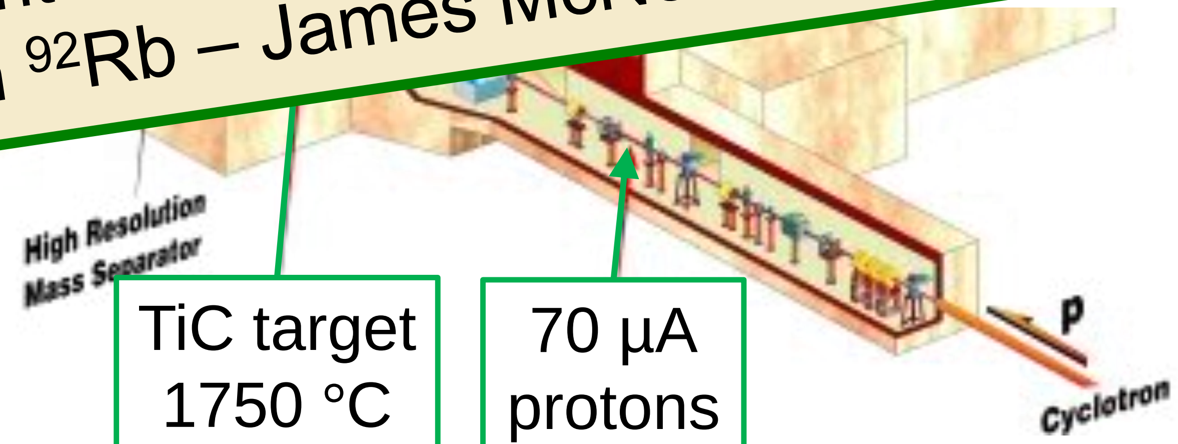
up to 8×10^7 3…
5000×10^7 8…

- Angular corr… of K and Rb isotopes
- Recent result: A_β of $\overrightarrow{^{37}\mathrm{K}}$

Other TRINAT talks you may have seen last night:

Time-reversal violation in ^{38m}K – John Behr
Towards measurement of Fierz in ^{37}K – Melissa Anholm
$\bar{\nu}$ energy spectrum in ^{92}Rb – James McNeil





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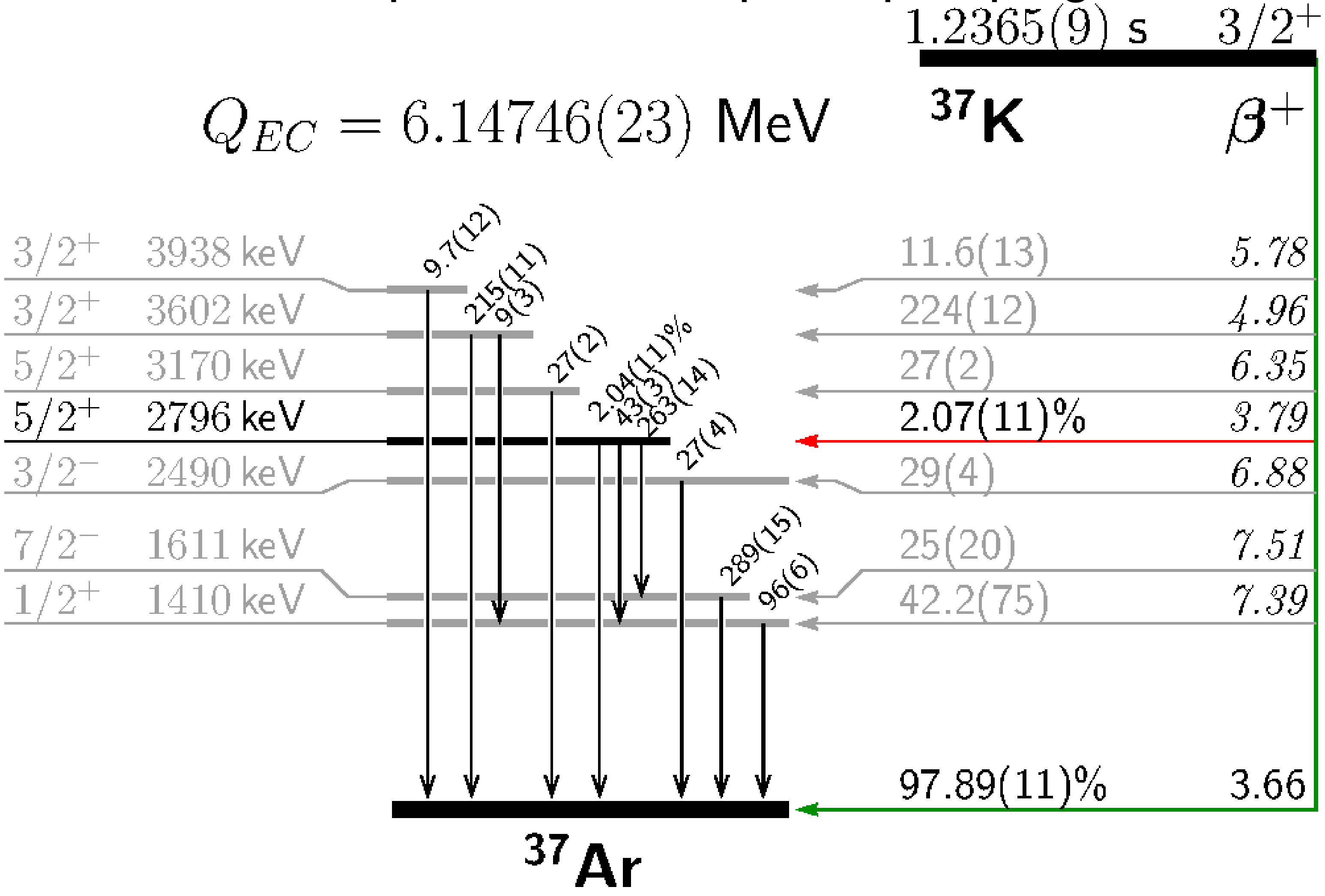
Isobaric analogue decay of ^{37}K

- Beautiful nucleus to test the standard model:
  - Alkali atom ⇒ "easy" to trap with a MOT and polarize with optical pumping
  - Isobaric analogue decay
    - ⇒ theoretically clean; recoil-order corrections under control
  - Lifetime, *Q*-value and branches (*i.e.* the $\mathcal{F}t$ value) well known
  - Strong branch to the ground state
  - Easy to polarize via optical pumping



The Ft is measured well enough (for now)

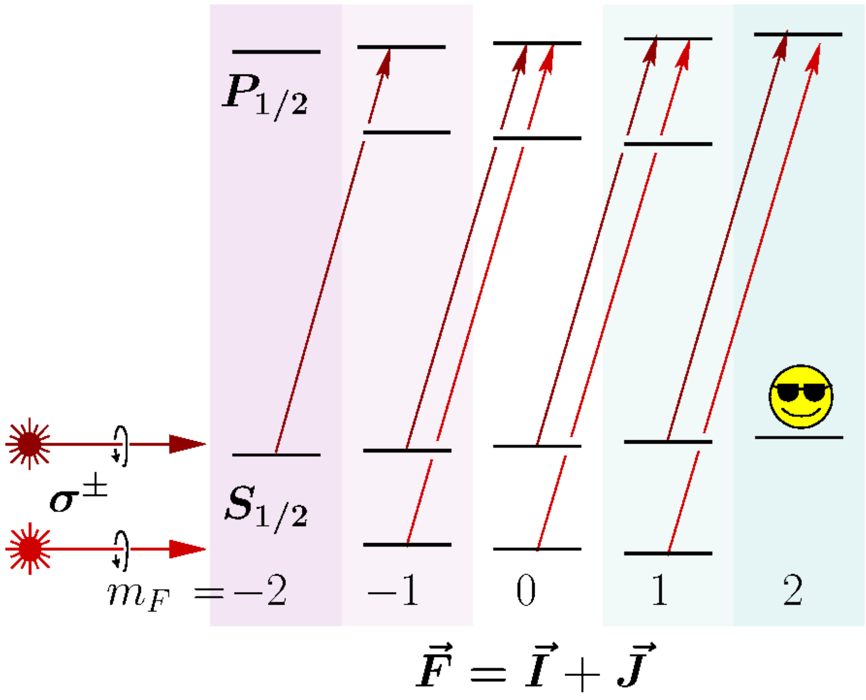
$$dW = dW_0 \left[1 + a\frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu} + b\frac{\Gamma m_e}{E_\beta} + \frac{\langle \vec{I} \rangle}{I} \cdot \left(A_\beta \frac{\vec{p}_\beta}{E_\beta} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\beta \times \vec{p}_\nu}{E_\beta E_\nu} \right) + \begin{matrix}\text{alignment}\\ \text{term}\end{matrix} \right]$$

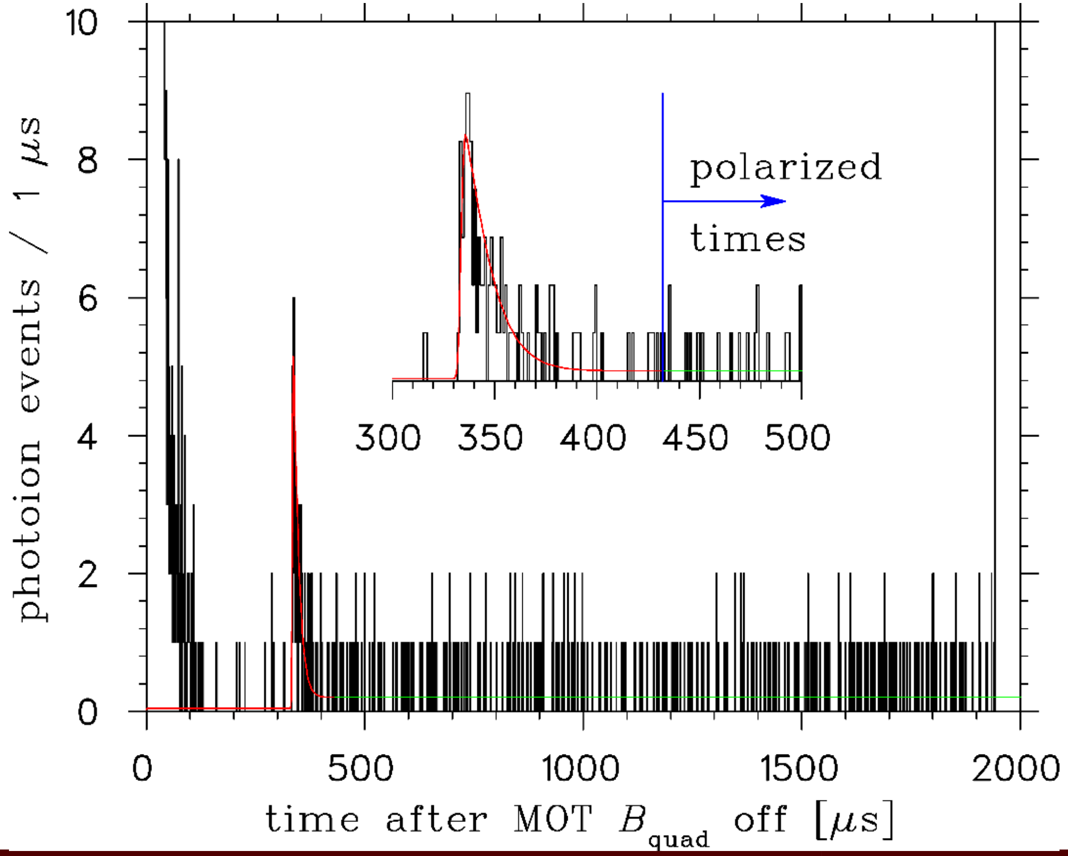
Correlation	SM expectation
$\beta - \nu$ correlation	$a_{\beta\nu} = 0.6648(18)$
Fierz interference	$b = 0$ (sensitive to scalars & tensors)
β asymmetry	$A_\beta = -0.5706(7)$
ν asymmetry	$B_\nu = -0.7702(18)$
Time-violating correlation	$D = 0$ (sensitive to imaginary couplings)

Currently analyzing data for improving the branching ratio (which currently limits these predictions)

Optical pumping is fast and *efficient*!

- No time to go into details, but basically
  - Measure the rate of photons (⇔ fluorescence) as a function of time
  - Model sublevel populations using the optical Bloch equations
  - Determine the average nuclear polarization: $\langle |P_{\mathrm{nucl}}| \rangle = 0.9913(9)$





B.Fenker *et al*, New J. Phys. **18**, 073028 (2016)

The β asymmetry measurement

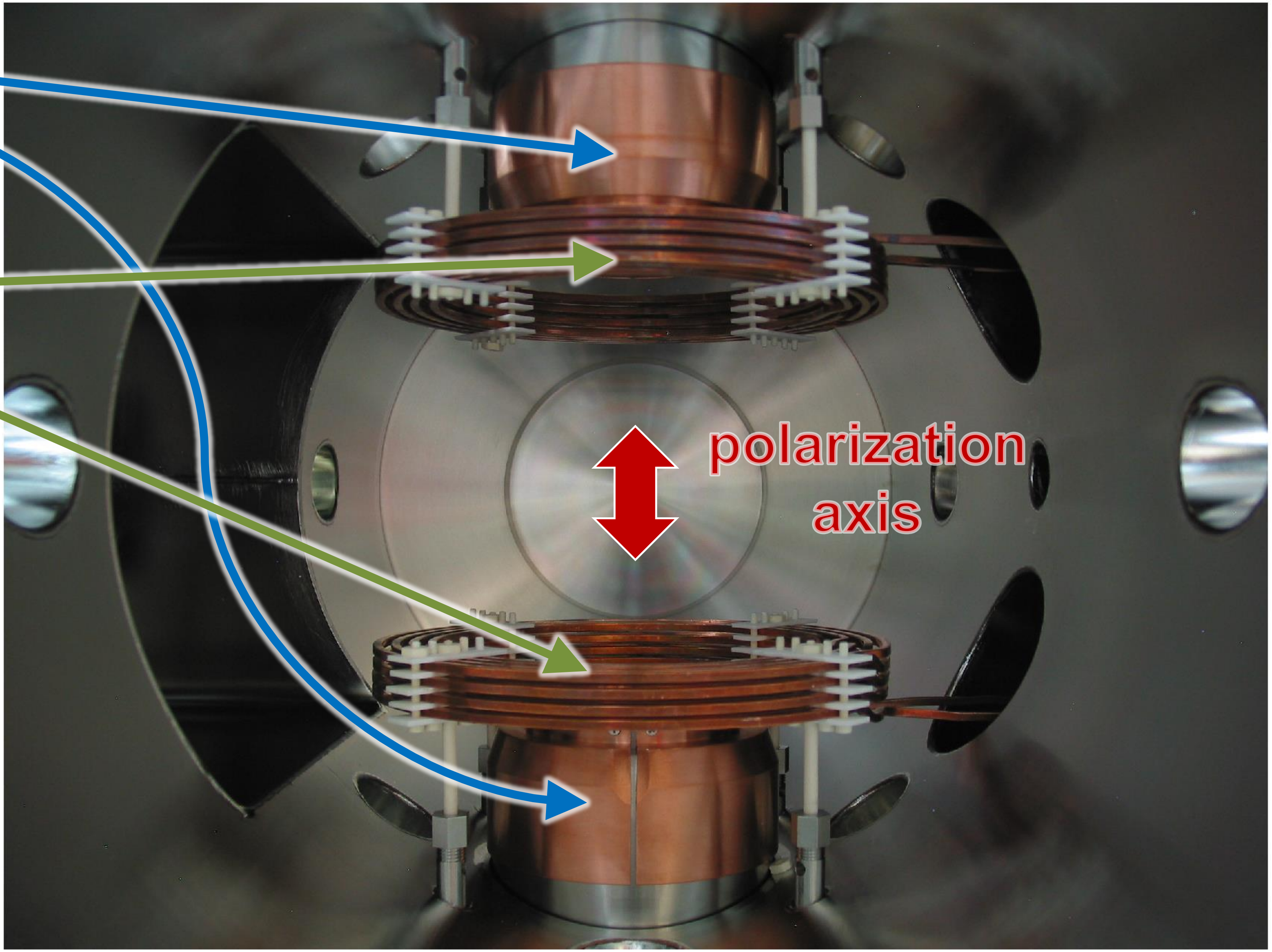
E_β **detectors**:
Plastic scintillator

ΔE_β **detectors**:
Double-sided Si-strip

Use **all** information via the super-ratio:

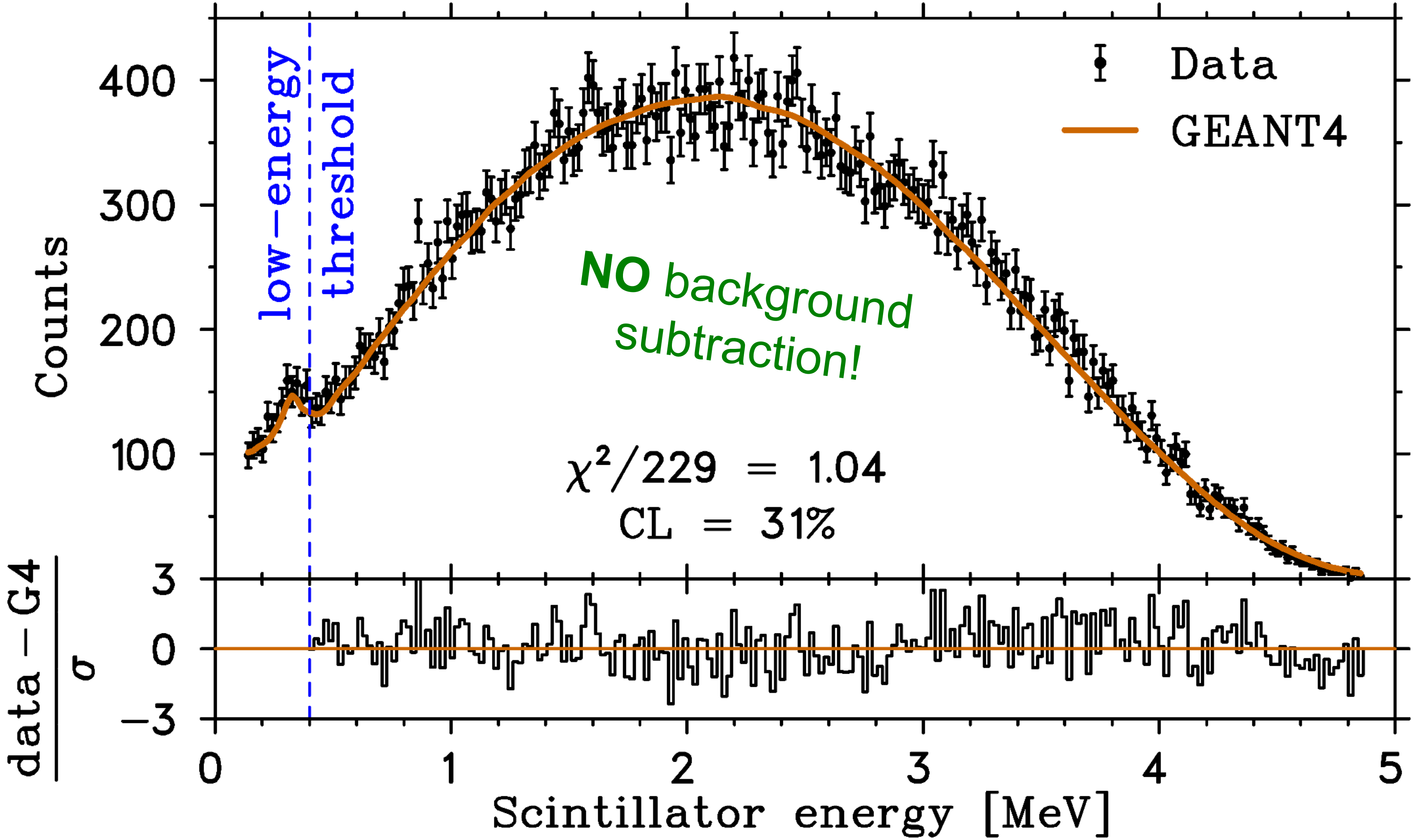
$$A_{\text{obs}}(E_e) = \frac{1-S(E_e)}{1+S(E_e)}$$

with $S(E_e) = \sqrt{\frac{r_1^{\uparrow}(E_e)\, r_2^{\downarrow}(E_e)}{r_1^{\downarrow}(E_e)\, r_2^{\uparrow}(E_e)}}$



^{37}K β asymmetry measurement

- Energy spectrum – ***great agreement*** with GEANT4 simulations:



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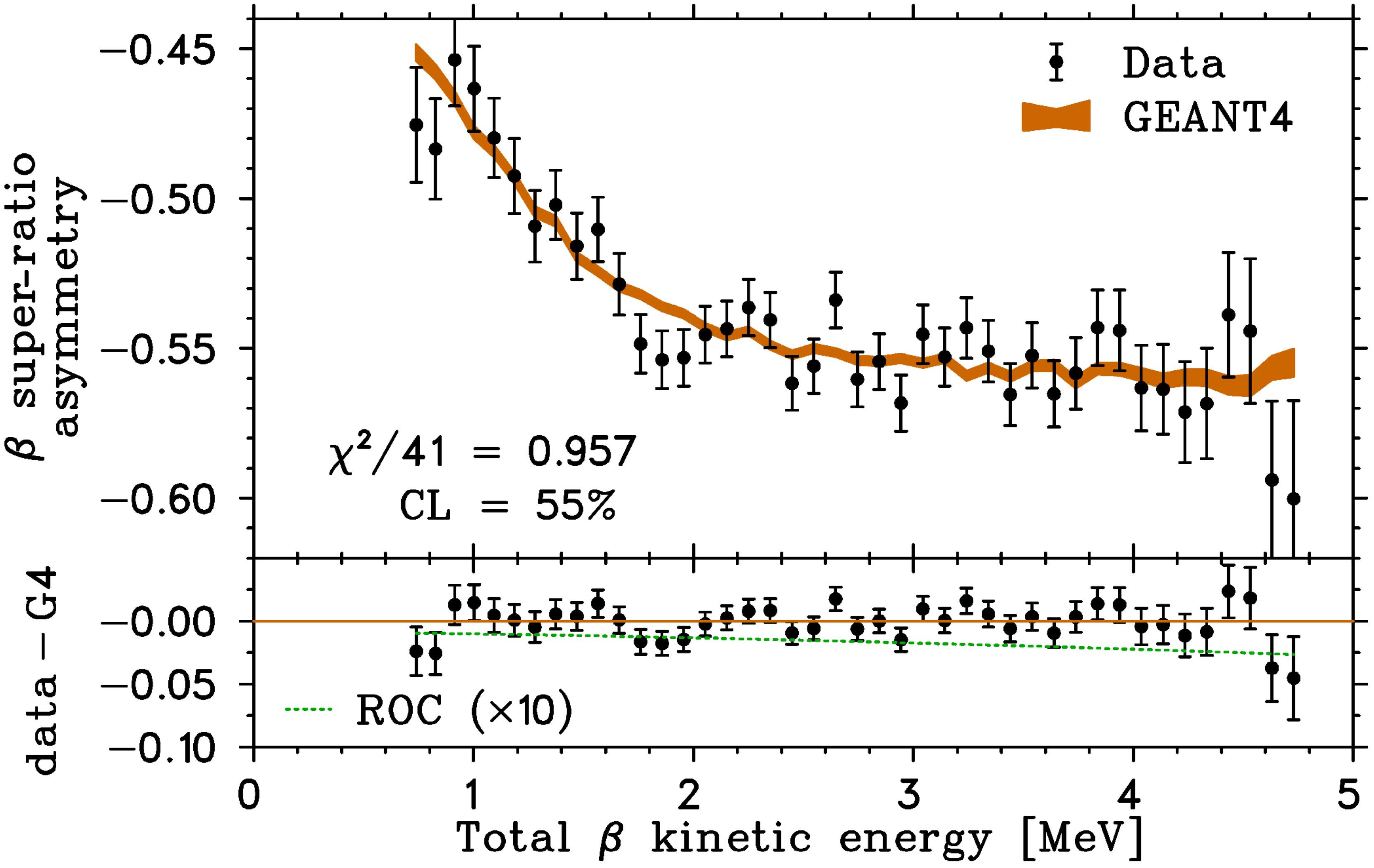
- Asymmetry as a function of β energy after unblinding



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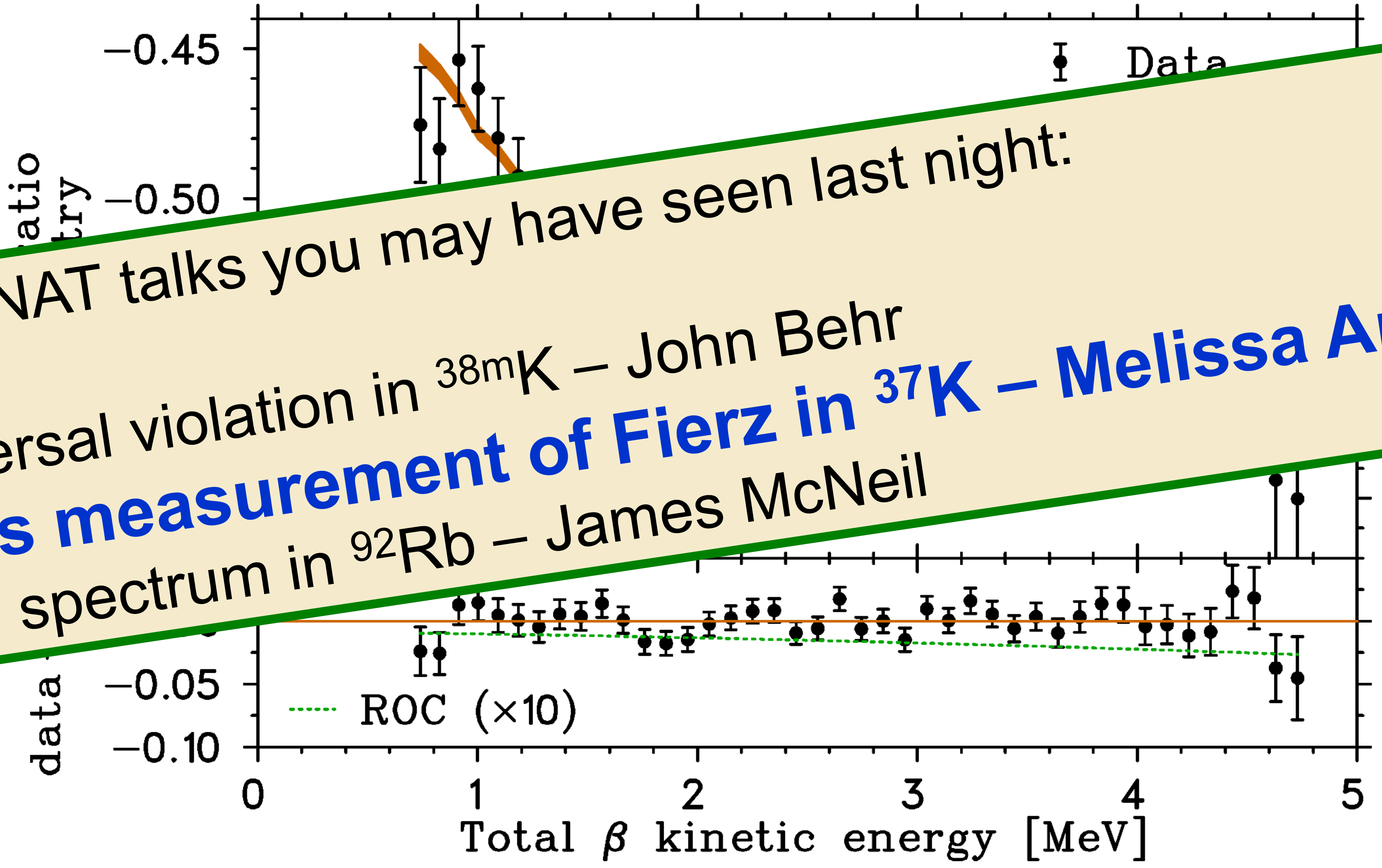

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(Dominant) Error budget and A_β result

Source	Correction	Uncertainty, ΔA_β
Systematics		
Background	1.0014	8×10^{-4}
β scattering	1.0230	7×10^{-4}
Trap position		4×10^{-4}
Trap movement		5×10^{-4}
ΔE position cut		4×10^{-4}
Shake-off e^- TOF region		3×10^{-4}
TOTAL SYSTEMATICS		13×10^{-4}
STATISTICS		13×10^{-4}
POLARIZATION		5×10^{-4}
TOTAL UNCERTAINTY		19×10^{-4}

$A_\beta^{\mathbf{meas}} = -0.5707(19)$ *cf* $A_\beta^{\mathrm{SM}} = -0.5706(7)$ (includes recoil-order corrections, $\Delta A_\beta \approx -0.0028\frac{E_\beta}{E_0}$)

B.Fenker *et al*, PRL **120**, 062502 (2018)

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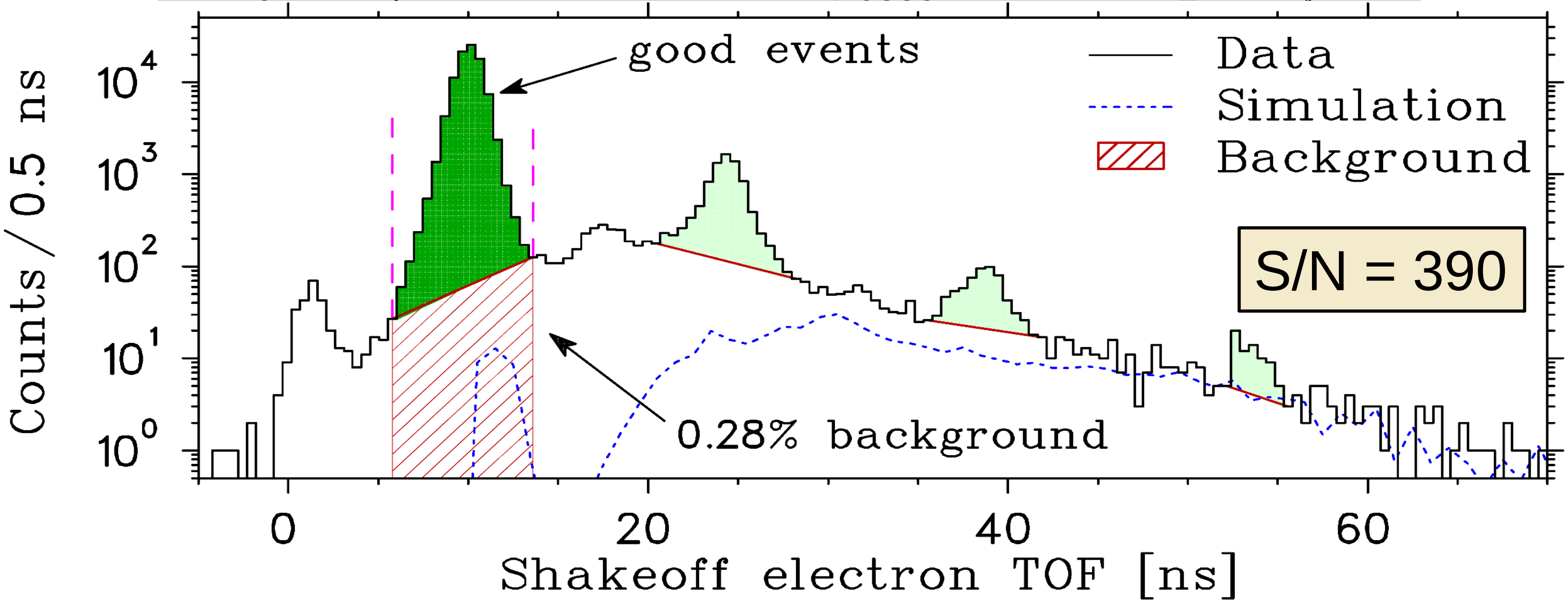

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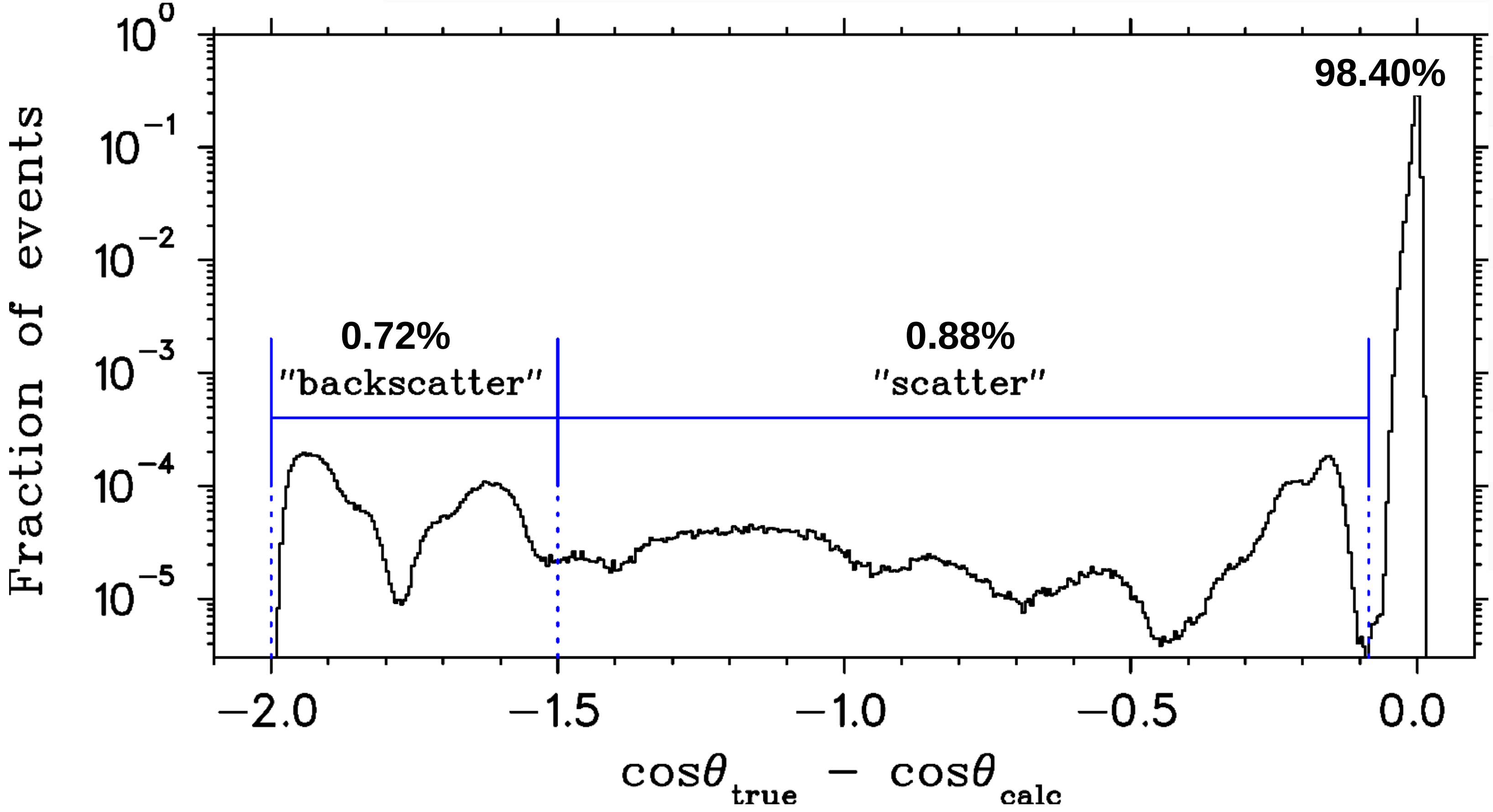

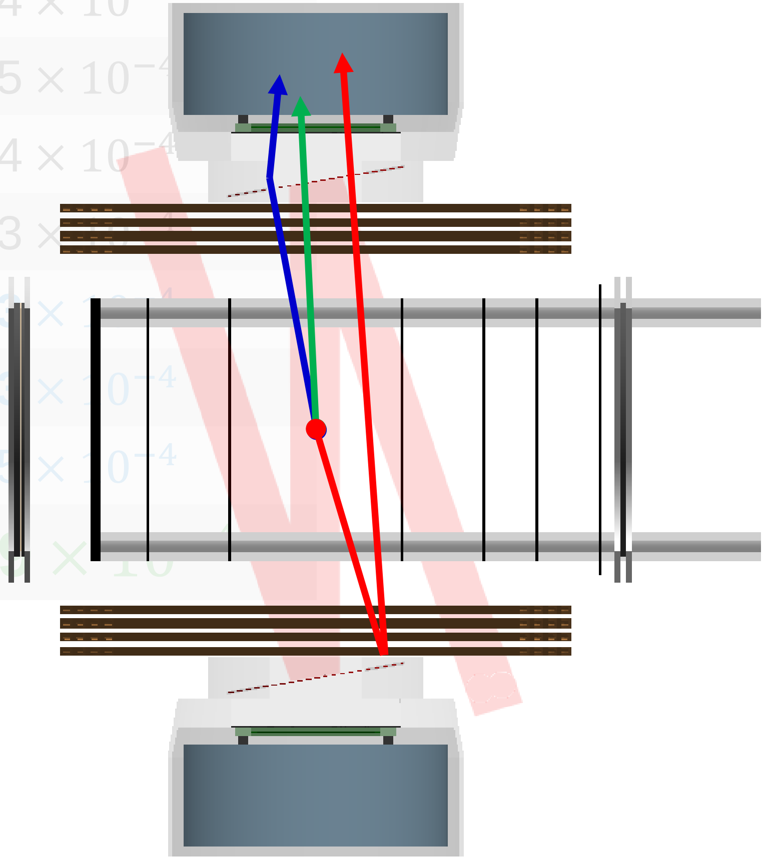

(Dominant) Error budget and A_β result

How well can we trust GEANT4 to simulated β scattering?

	Correction	Uncertainty, ΔA_β
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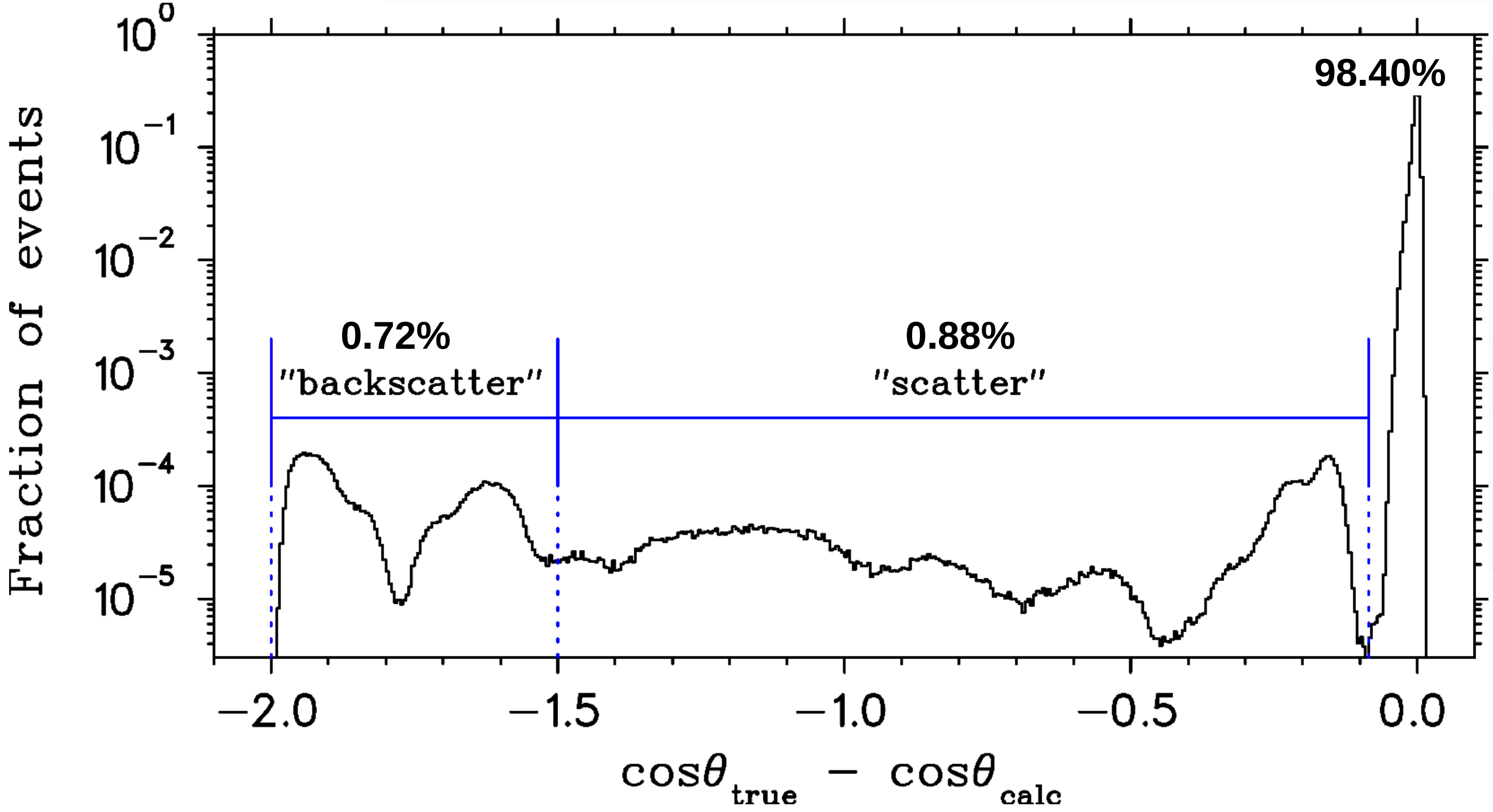
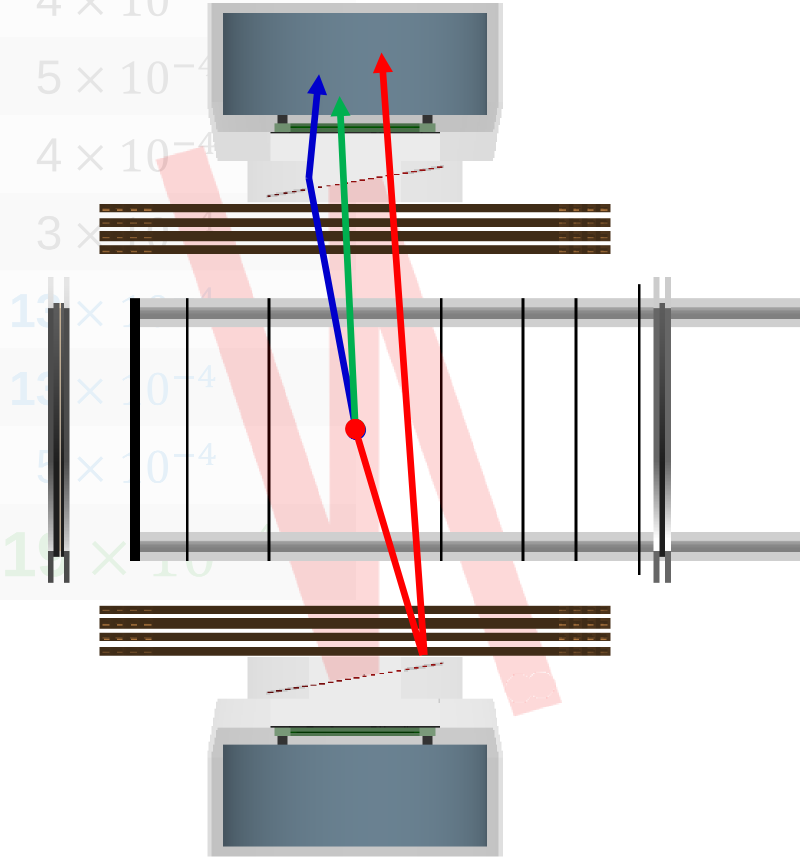
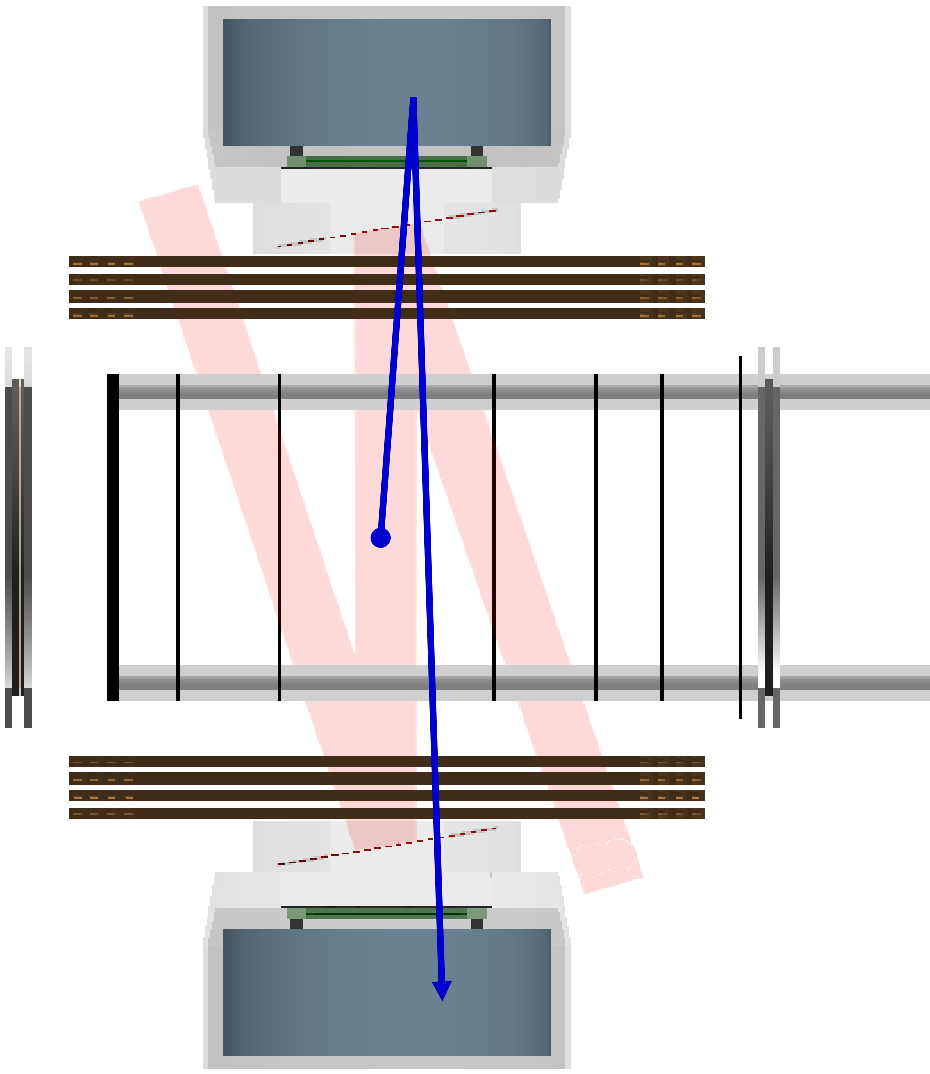




Measurement of β scattering

- Our geometry allows us to measure backscattering of βs and compare to GEANT4 simulations
- Obvious, very clean check: both telescopes register a β event
- Due to small solid angle to go from one to the other ($\sim 0.25\%$), not enough statistics with current data set ($\sim 10^{-4}$ of non-scattered)



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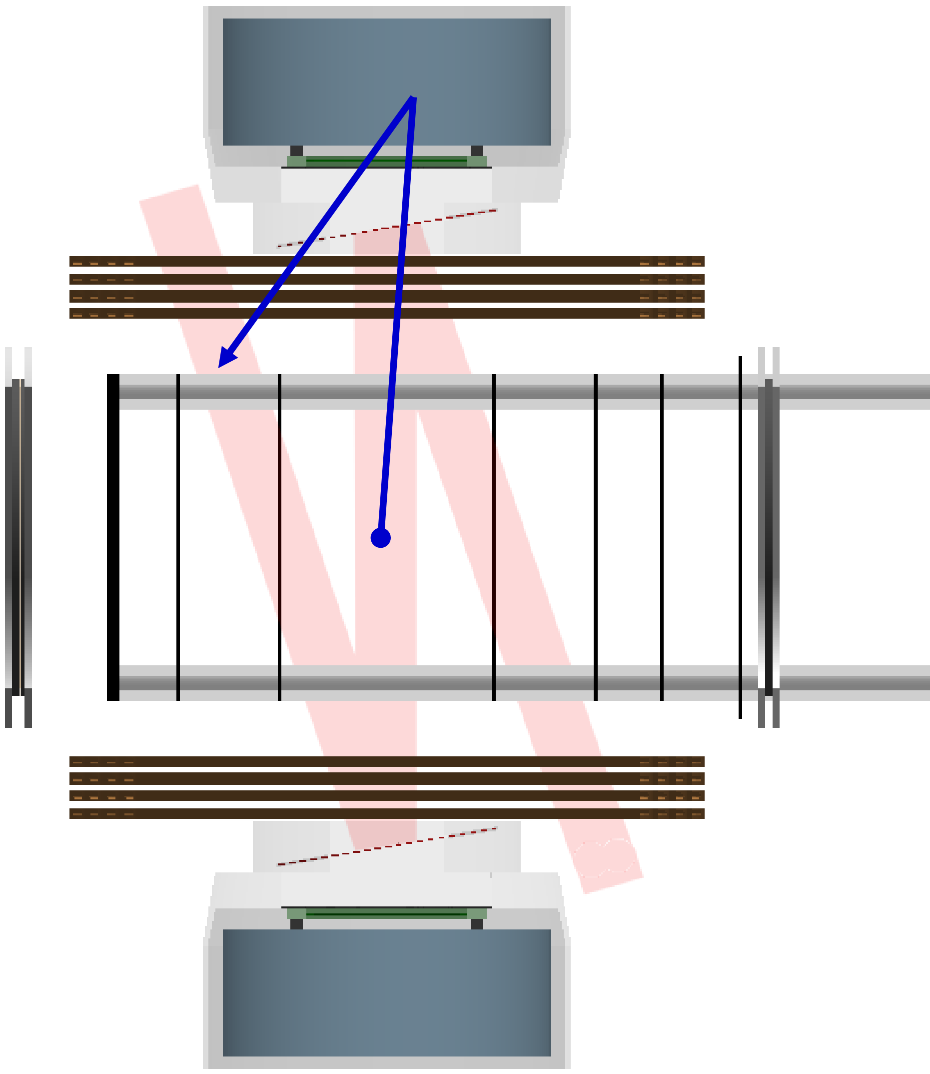
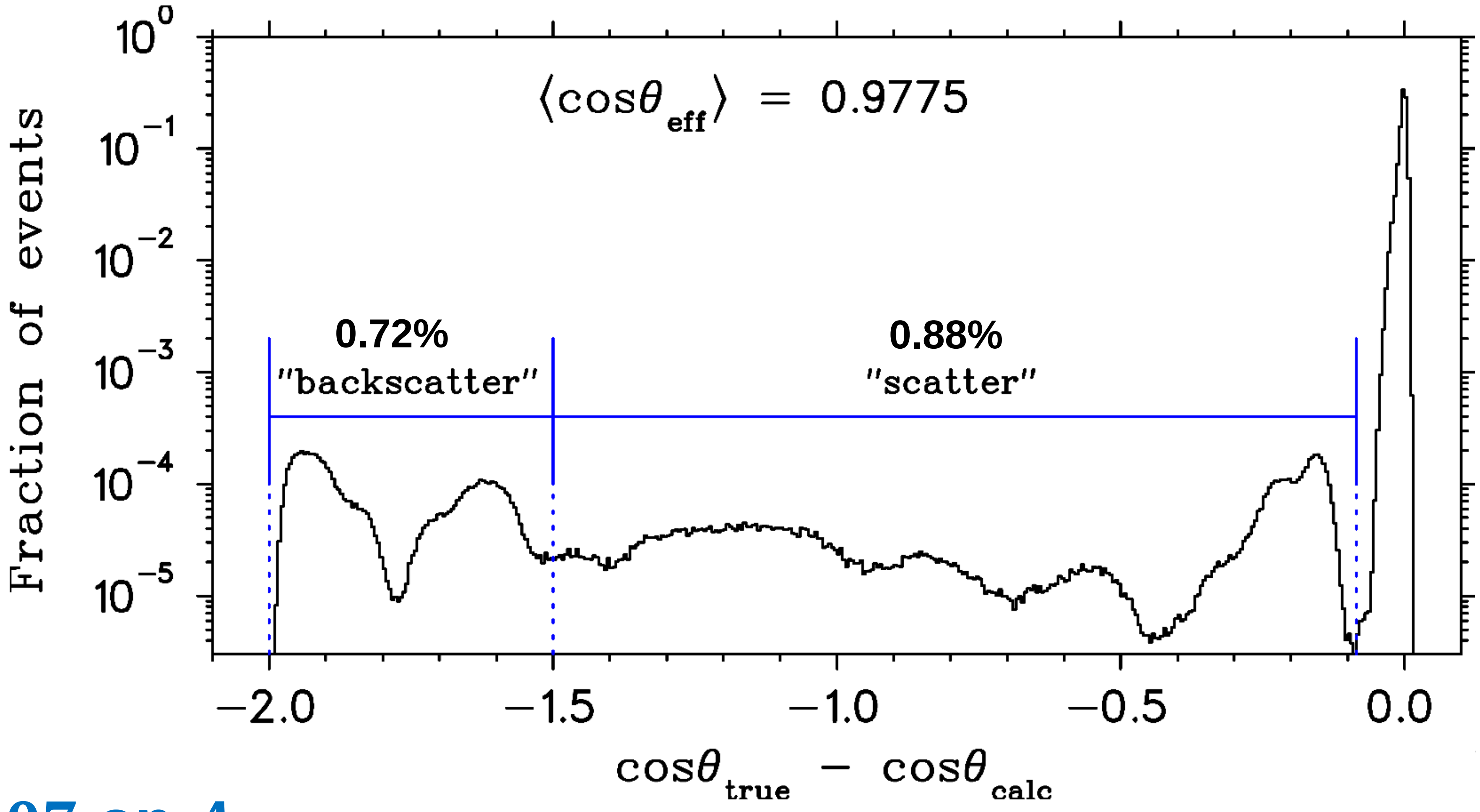
- Due to small solid angle to go from one to the other $(\sim 0.25\%)$, not enough statistics with current data set $(\sim 10^{-4}$ of non-scattered)
- Much more common: backscattered out of the scintillator
- Signature: two separate pixels in the double-sided Si-strip detector with energy deposited in the scintillator



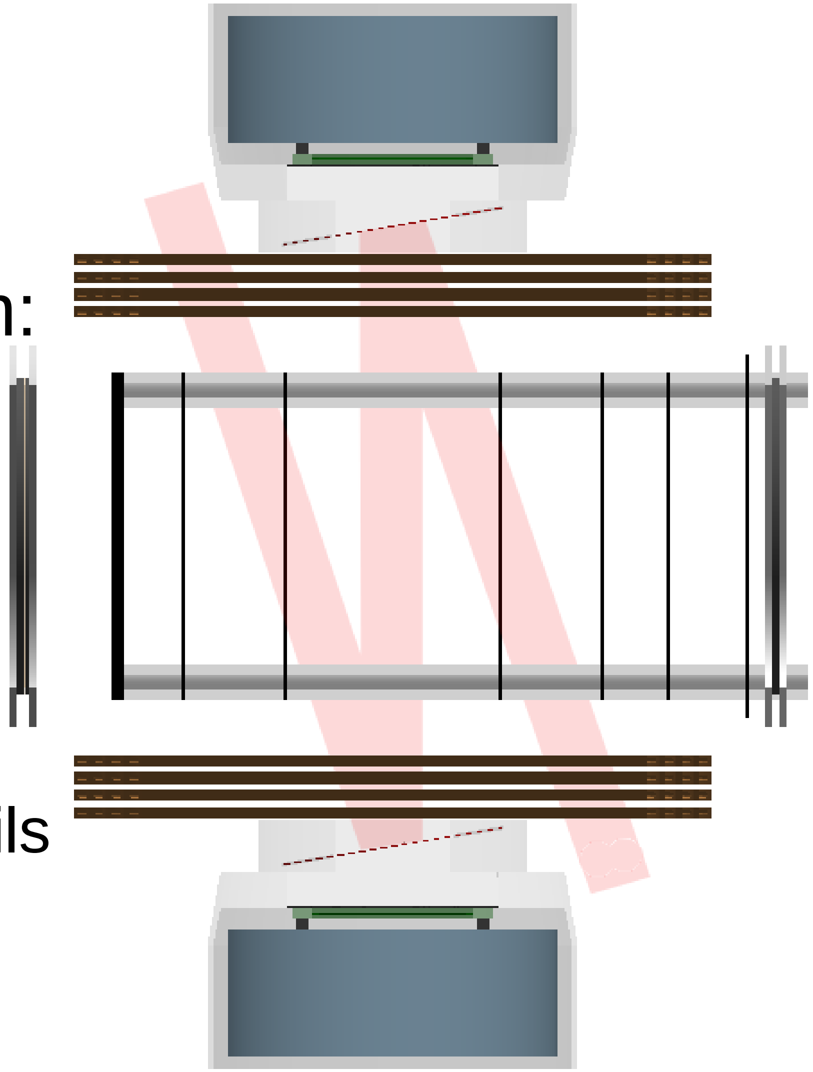
How does GEANT4 do?

- With non-standard options: **Surprisingly well**!!
- Take 2σ limit on observed deviation, or 5.1%, for "backscattered" events
- Assign 10% uncert to "scattered" events
- All together, a ± 0.0012 uncert on $\langle \cos\theta_{\text{eff}} \rangle$ and $\pm \mathbf{0.0007}$ **on** A_β



Looking forward: reducing β scattering systematic

- Goal: better benchmark our MC simulations
- ^{80,92}Rb production **>500x** higher than ^{37}K; recent run has many more β^- decays
  - Much more precise scintillator backscatter benchmark
- Further tests with minimal disruption of our system:
  - Rb data in hand which should have enough decays to see two-telescope backscatters (under analysis)
  - Replace upper telescope with other active detectors (thick Si, CsI, BGO, …)
  - Compare with/without inactive scattering volumes (W, Ta, stainless, …), normalizing to shake-off e^-/recoils



If you have ideas, let's talk!
(I'll buy the mai tais!)

Final thoughts and mahola!

- Path forward to reduce dominant systematics of A_β measurement (higher $\vec{E}$ field, much thinner mirrors, …); **0.1% precision is within reach!**
- Stay tuned for energy dependent physics (Fierz, 2nd-class currents)

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