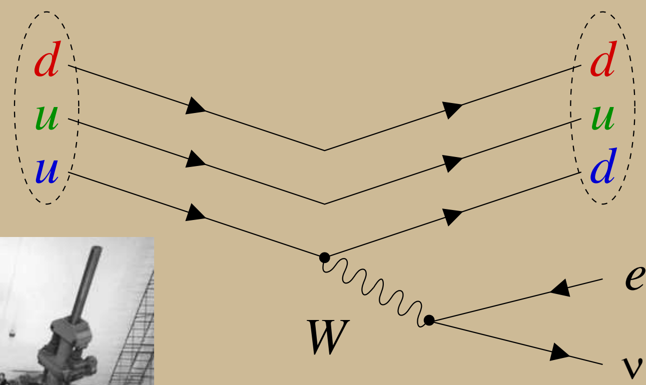
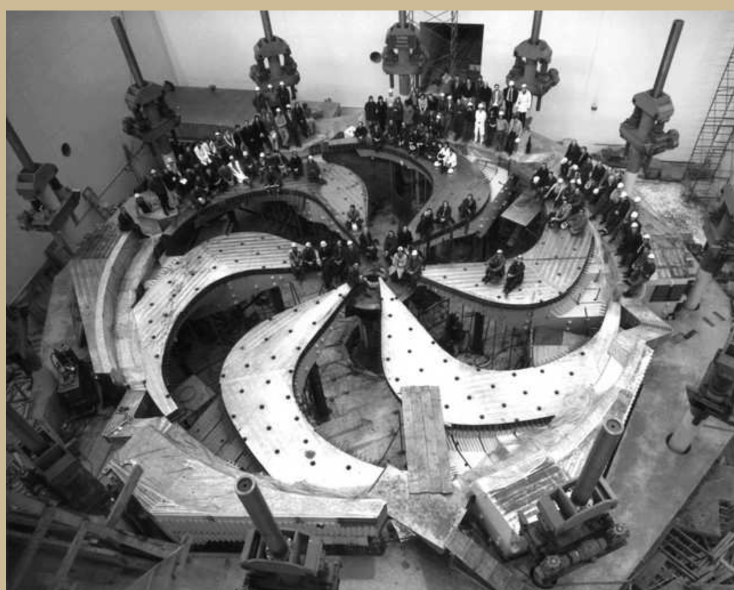
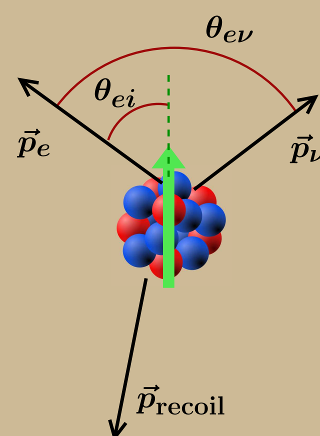
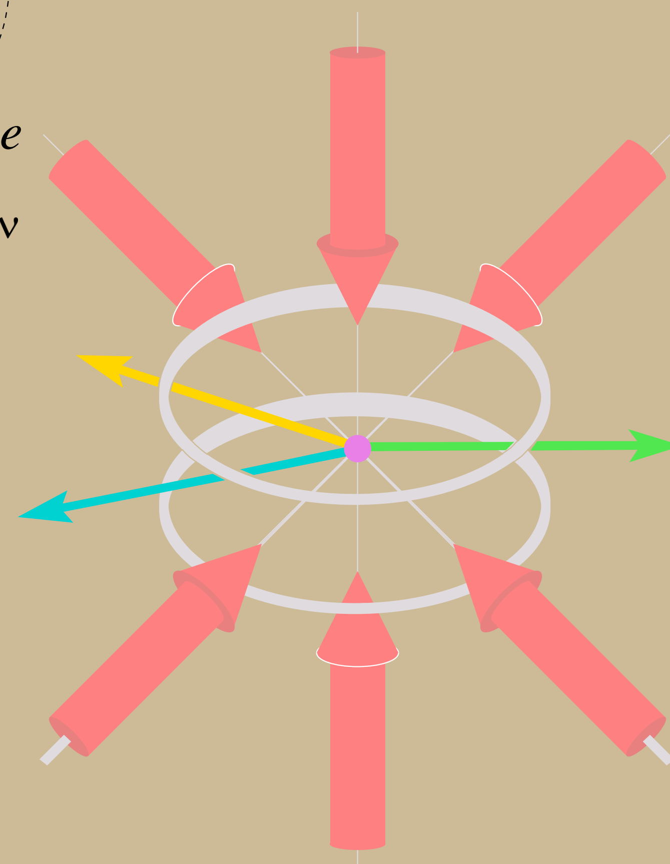
Nuclear β Decay: Using the Atomic Nucleus to Probe Symmetries of the Weak Interaction









Dan Melconian

March 24, 2018

Overview

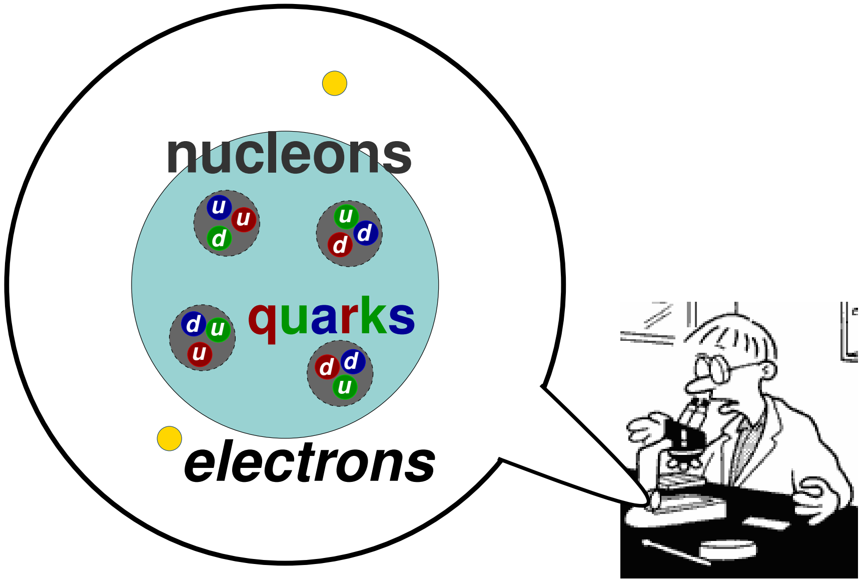
Introduction

- Fundamental symmetries
- What is our **current understanding**?
- How do we test what lies **beyond**?

The TRIUMF Neutral Atom Trap

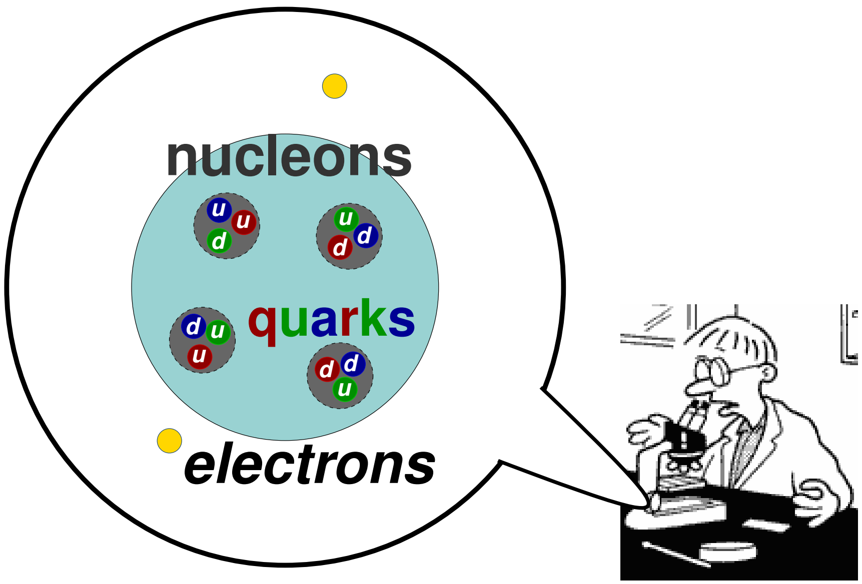
- Angular correlations of **polarized ^{37}K**
- **Recent results**
- Looking **forward**

Scope of fundamental physics



the atom

From the very smallest scales . . .



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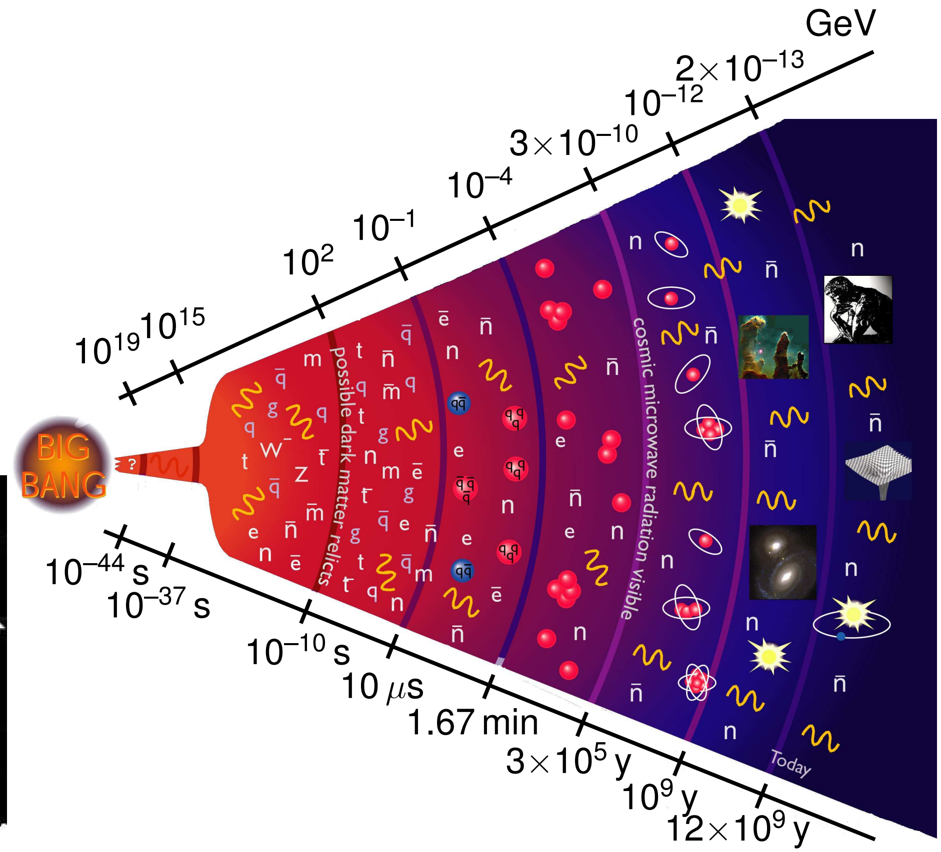

. . . to the very **largest**

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and there are other symmetries too:

time	$\Leftrightarrow$	energy
space	$\Leftrightarrow$	momentum
rotations	$\Leftrightarrow$	angular momentum
	$\vdots$	

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	1st	2nd	3rd	Q	mediator	force
leptons	$\begin{pmatrix}\nu_e\\ e\end{pmatrix}$	$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}$	$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$	0 -1	g	strong
					$W^\pm$ Z°	weak
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✔ It **predicted** the existence of the $W^{\pm}$, $Z_{\circ}$, g, c and t

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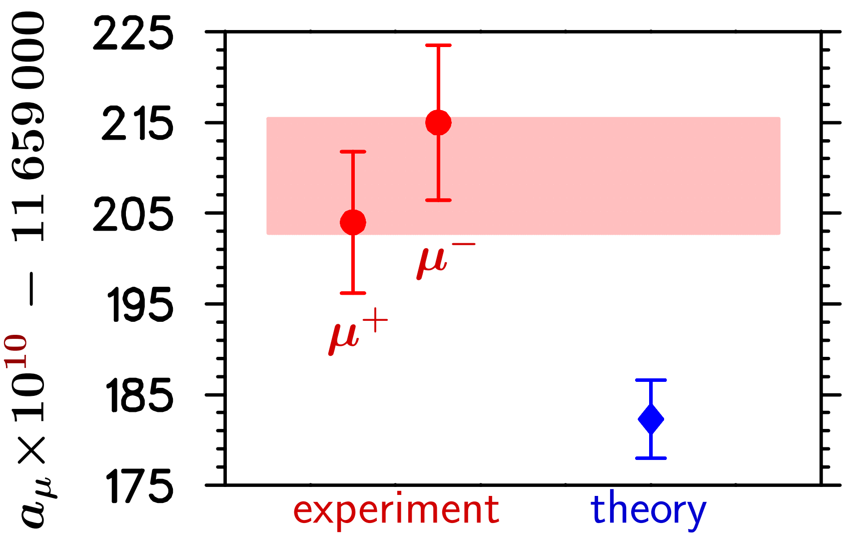

$$a_\mu \equiv \frac{1}{2}(g-2)$$

a tantalizing 3.5σ discrepancy...

(see 2017 PDG)

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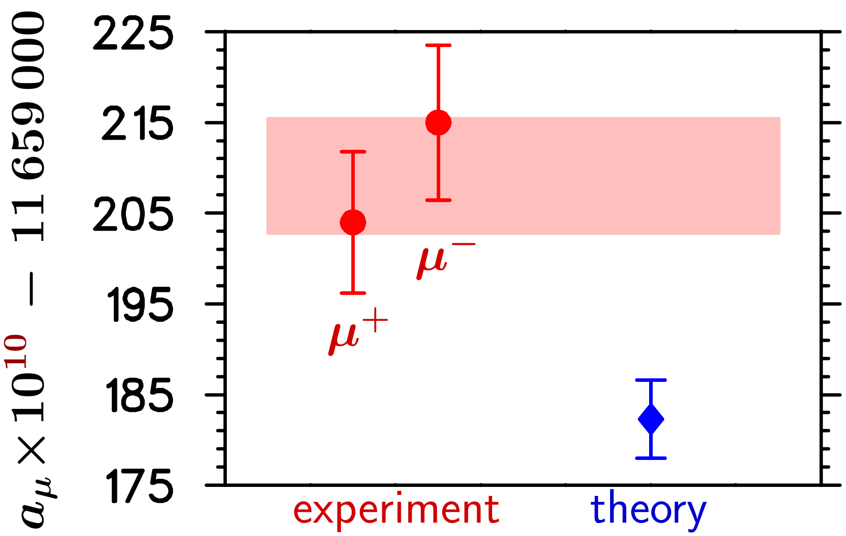

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Wow ...this is

the most precisely tested theory ever conceived!

But there are still questions . . .

- **parameters values**: Does our "ultimate" theory *really* need **25** arbitrary constants? Do they **change** with time?
- **dark matter**: SM physics makes up **less than 5%** of the energy-matter of the universe!
- **baryon asymmetry**: Why more **matter** than **anti-matter**?
- **strong *CP***: Do **axions** exist? **Fine-tuning**?
- **neutrinos**: **Dirac** or **Majorana**? Mass **hierarchy**?
- **fermion generations**: Why **three** families?
- **weak mixing**: Is the CKM matrix **unitary**?
- **parity violation**: Is parity **maximally** violated in the weak interaction? No **right-handed** currents?
- **gravity**: Of course, we can't forget about a **quantum** description of **gravity**!

How we ***all*** test the SM

- **colliders**: CERN, SLAC, FNAL, BNL, KEK, DESY . . .
- **nuclear physics**: traps, exotic beams, neutron, EDMs, $0\nu\beta\beta$, . . .
- **neutrinos**: sterile νs, oscillations, coherent scattering, . . .
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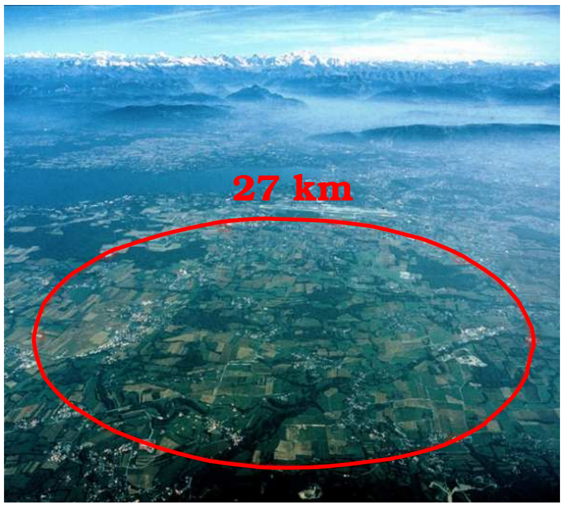
often they are **interdisciplinary**

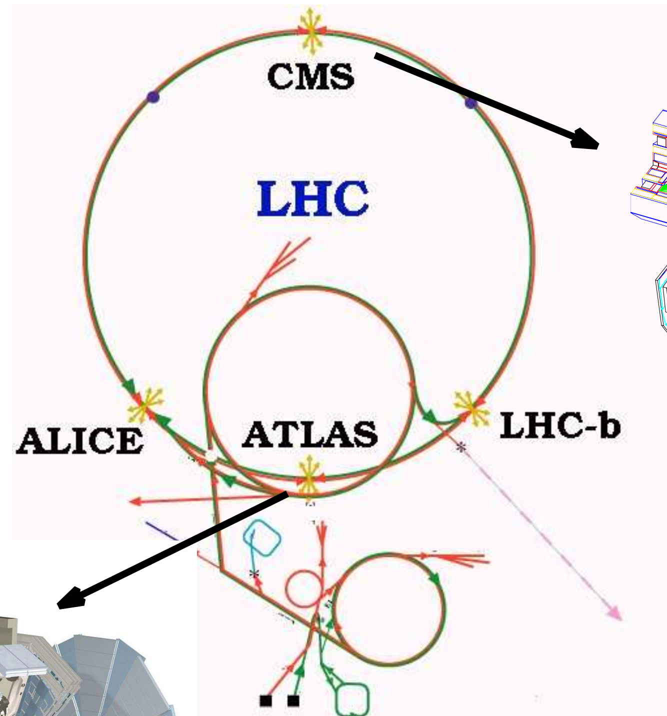
(which makes it extra *fun*!)

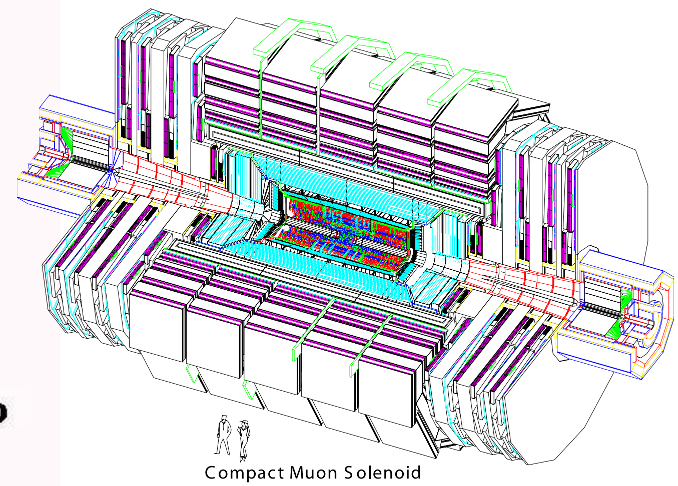
How does high-energy physics test the SM?

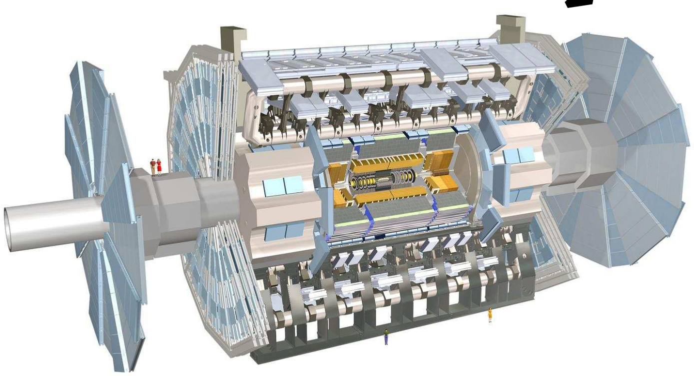
Colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, ...

direct search of particles









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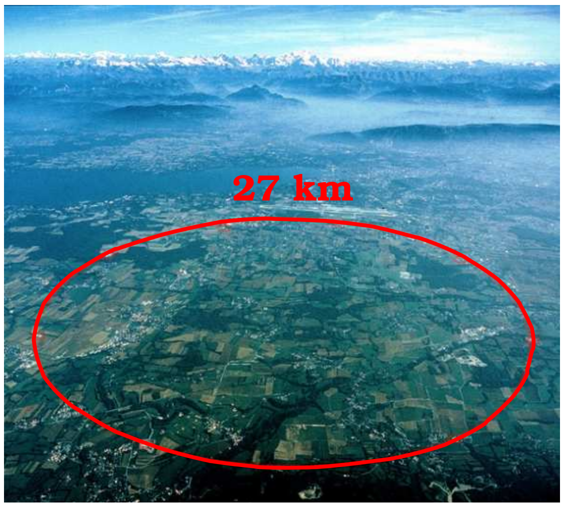

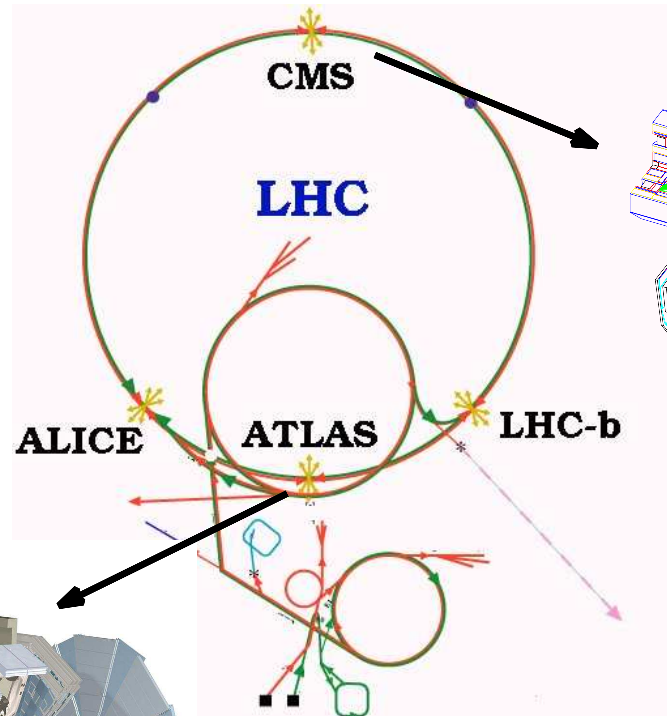

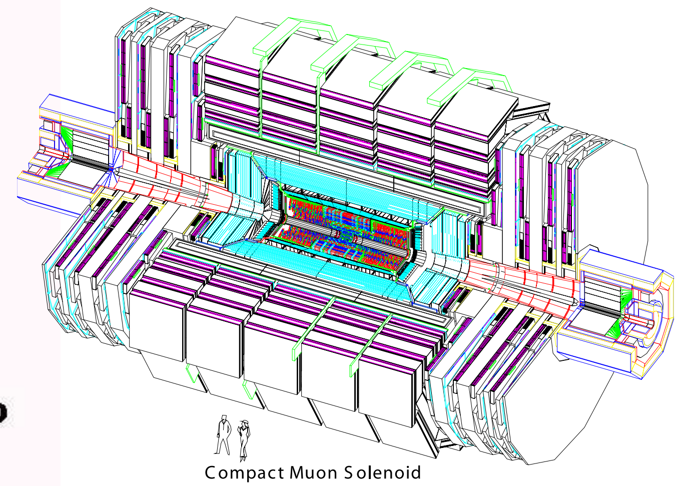

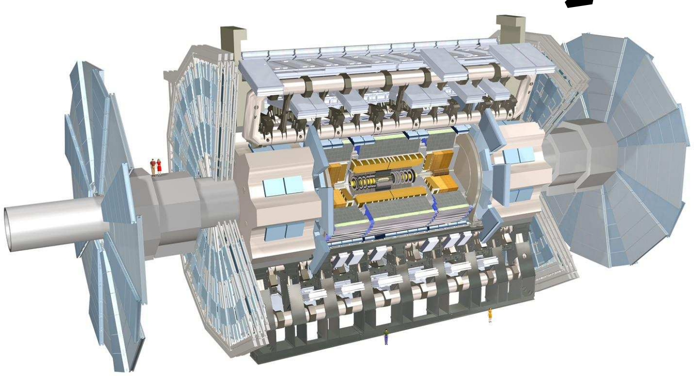

- large multi-national collabs
- *billion* $ price-tags

How does nuclear physics test the SM?

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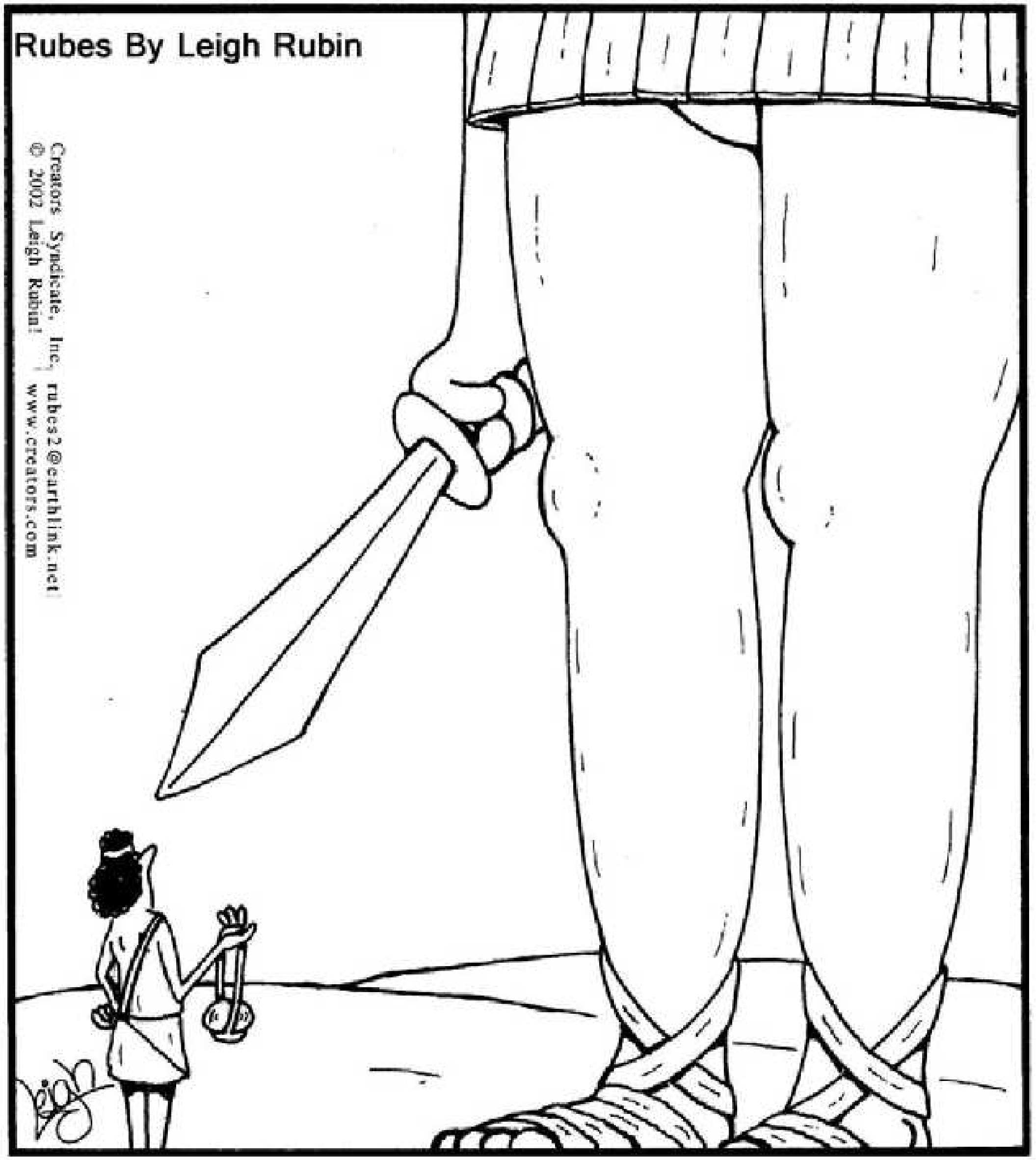
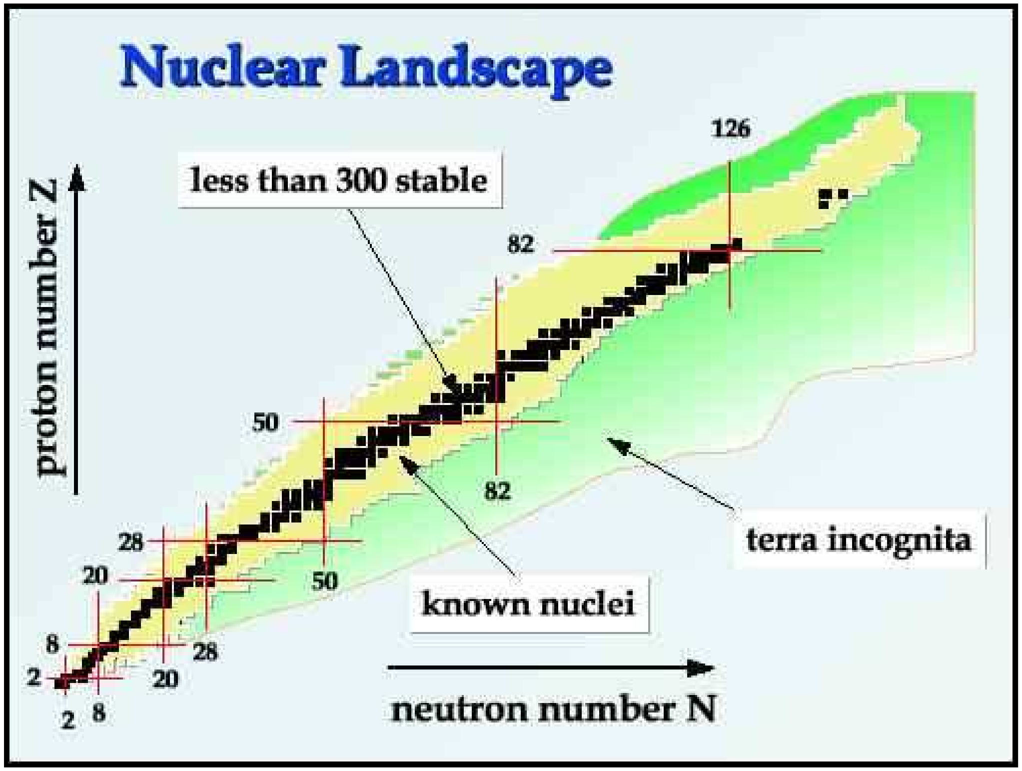


Overcoming temptation, David opted against the obvious, unsportsmanlike cheap shot.

How does nuclear physics test the SM?

Nuclear physics: radioactive ion beam facilities

indirect search via precision measurements



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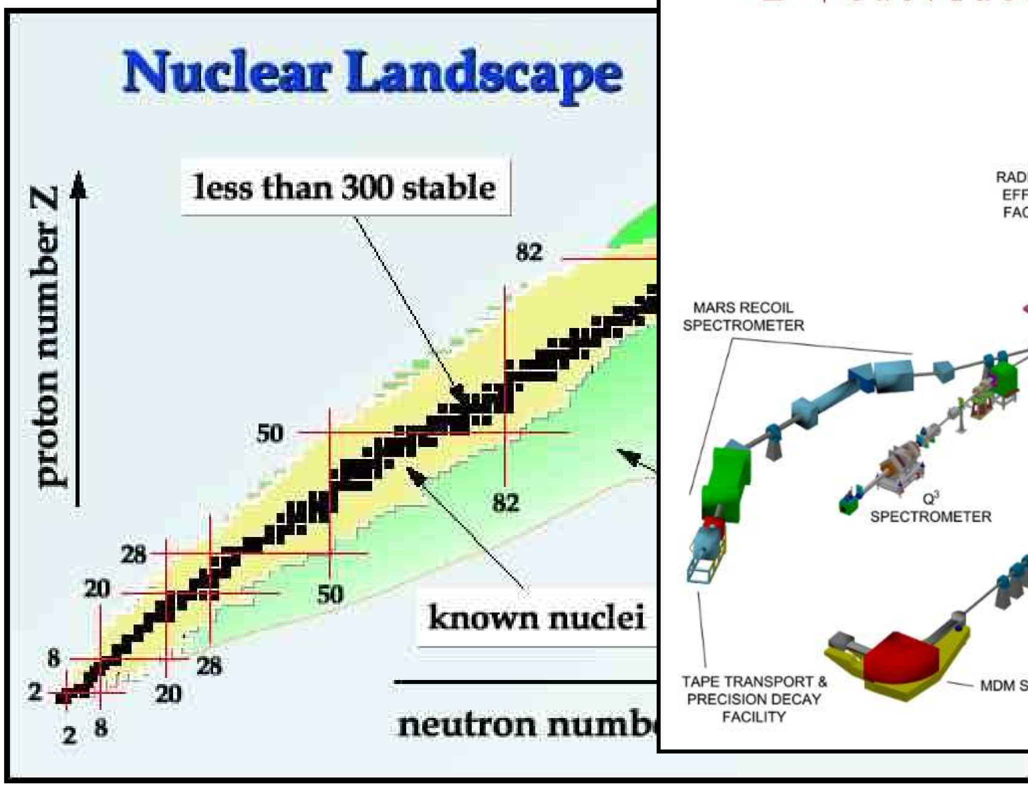

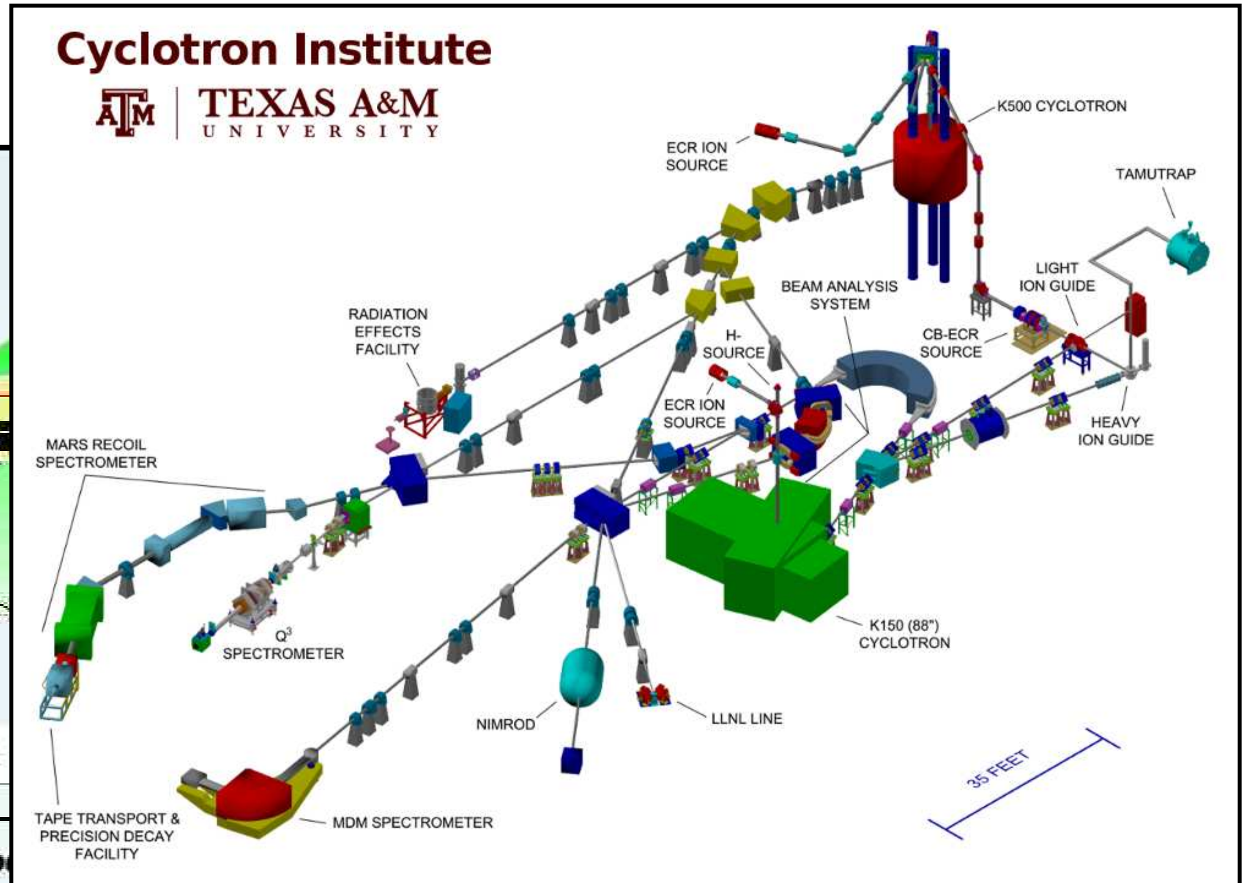

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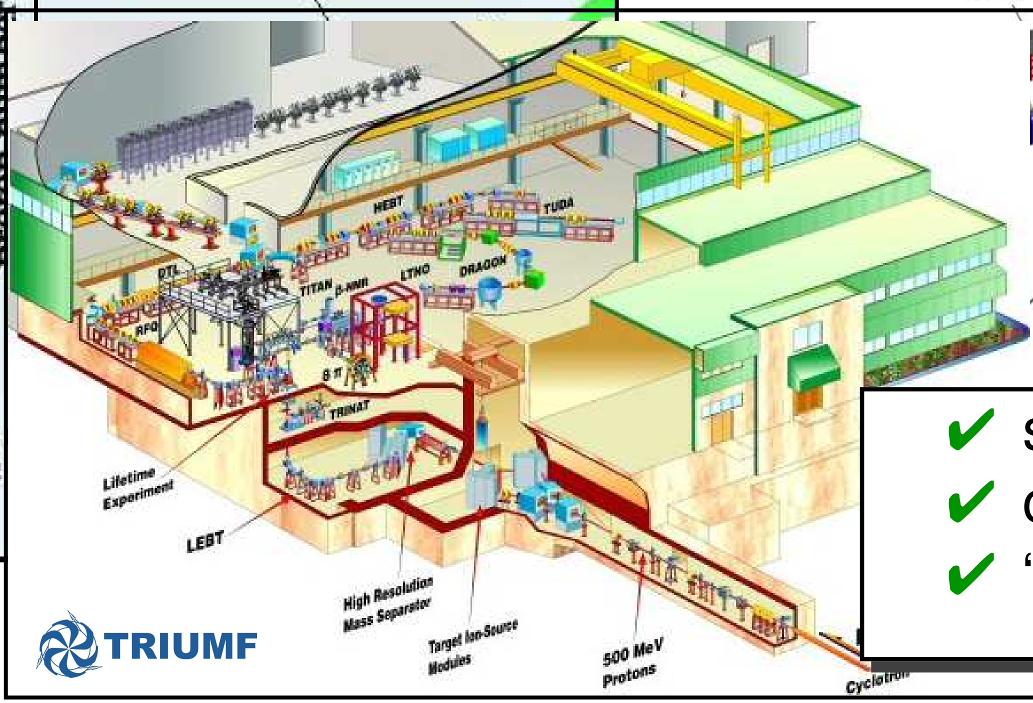

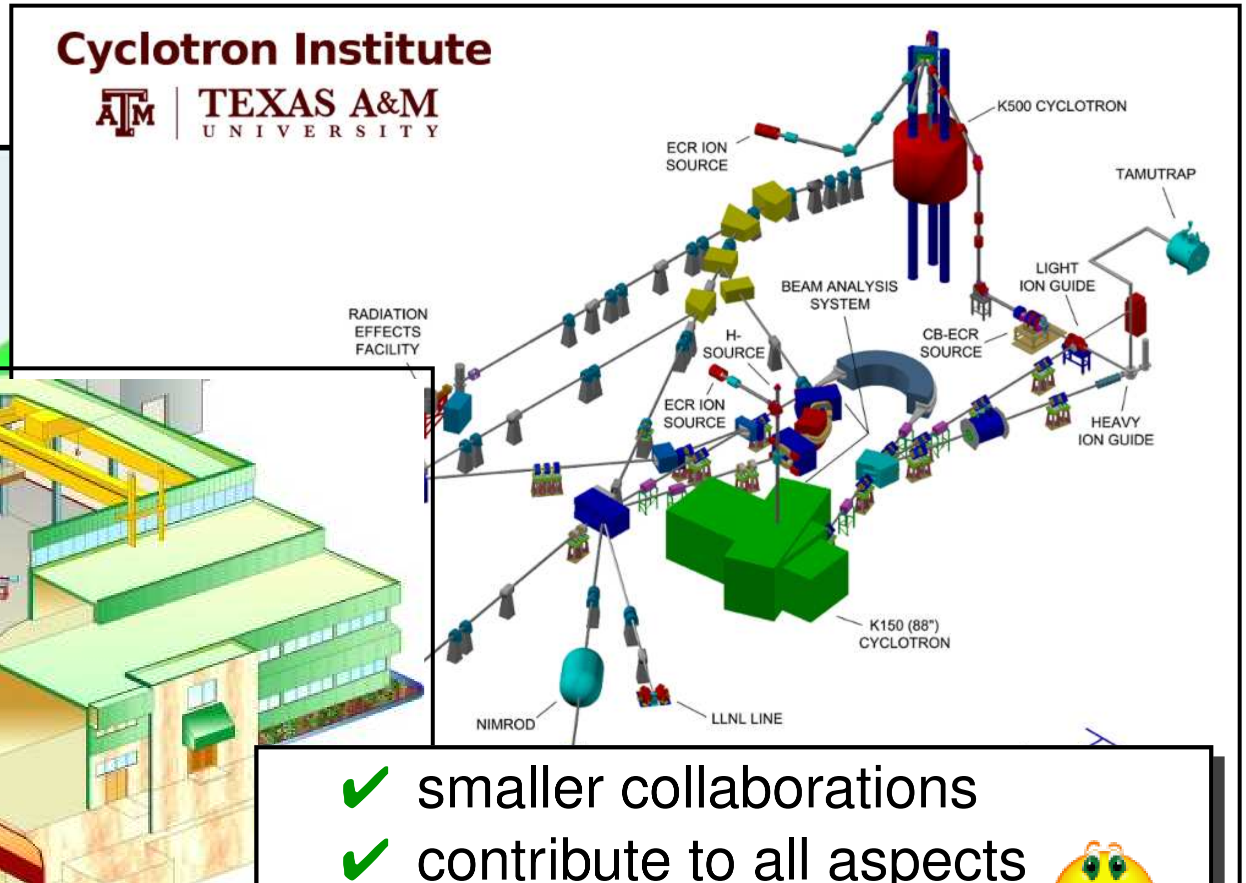

- ✔ smaller collaborations
- ✔ contribute to all aspects
- ✔ “table-top” physics

A primer in β decay

- Initially quite a mystery:
  - why does the "β" particle has a continuous energy spectrum? is angular momentum not conserved?
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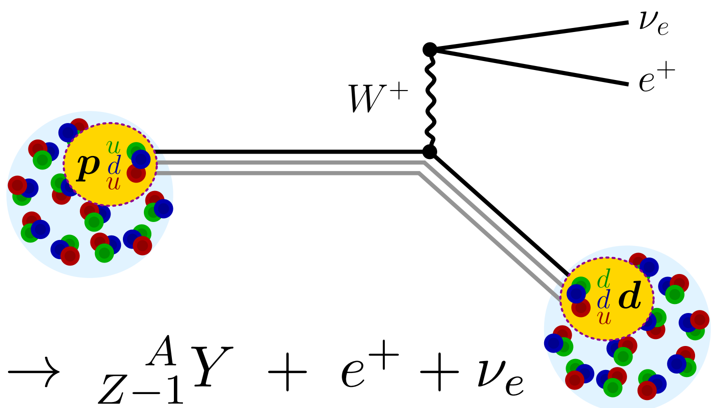

$$^{A}_{Z}X \rightarrow {}_{Z-1}^{\;\;A}Y + e^+ + \nu_e$$

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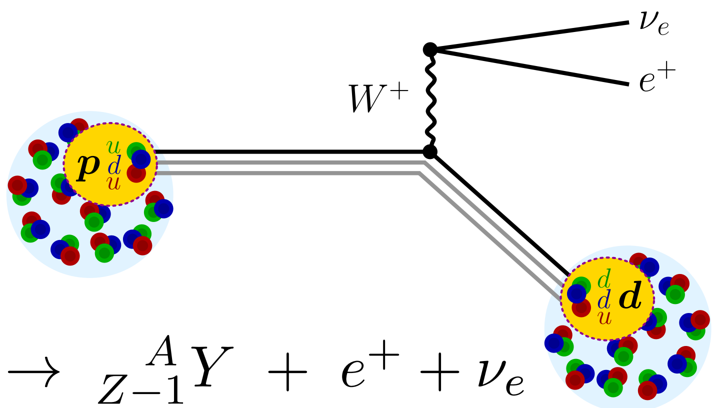

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu_e $$

- But is it ***completely*** left-handed. . . ?

Extensions to the SM predict right-handed currents

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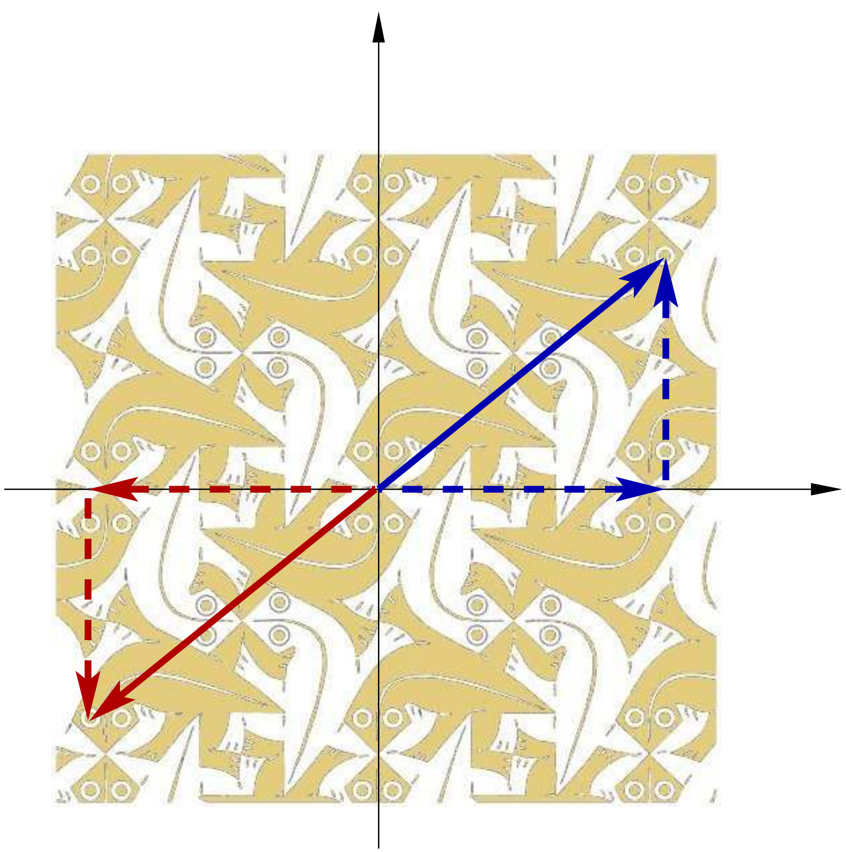
$\vec{A}$ = M.C. Escher reptiles

$\hat{P}\vec{A} = +\vec{A}$



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Simplest extensions: "*manifest left-right symmetric*" models

$\rightsquigarrow$ only 2 new parameters: W_2 mass and a mixing angle, ζ:

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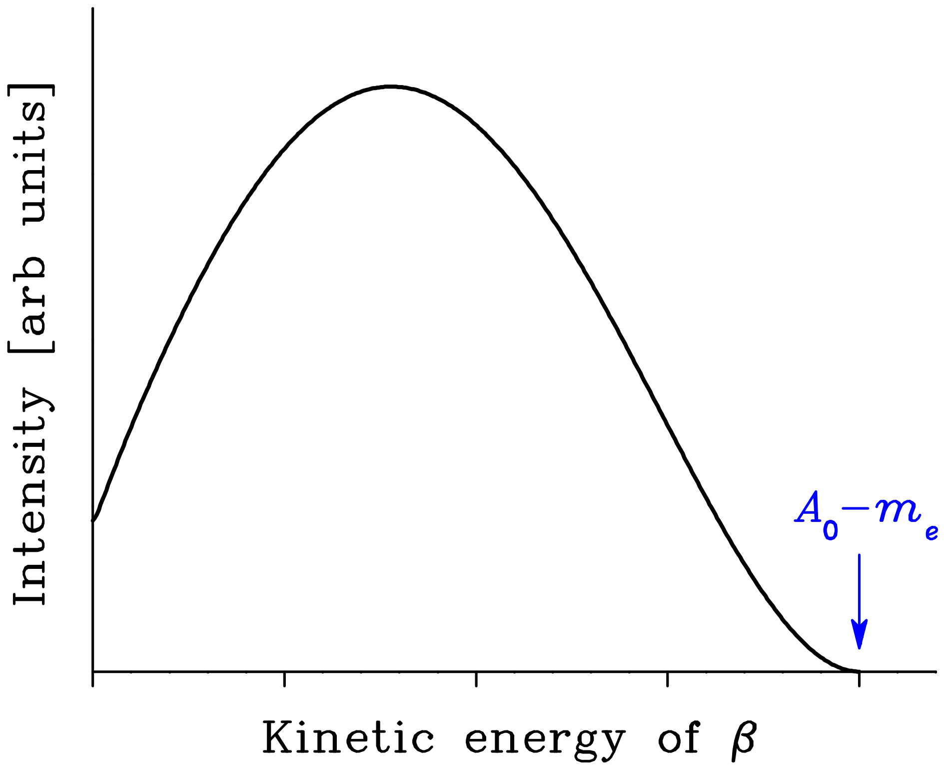
The existence of RHCs would affect the values of β decay parameters

How do I test the SM?

- Begin by looking at the rate for β decay

$$\frac{dW}{dE_e} = \overbrace{\frac{G_F^2 |\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2}^{\text{basic decay rate}}$$



How do I test the SM?

- Expand to the often-quoted **angular distribution** of the decay:
  (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{\boldsymbol{a_{\beta\nu}} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{\boldsymbol{b} \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} \right)$$

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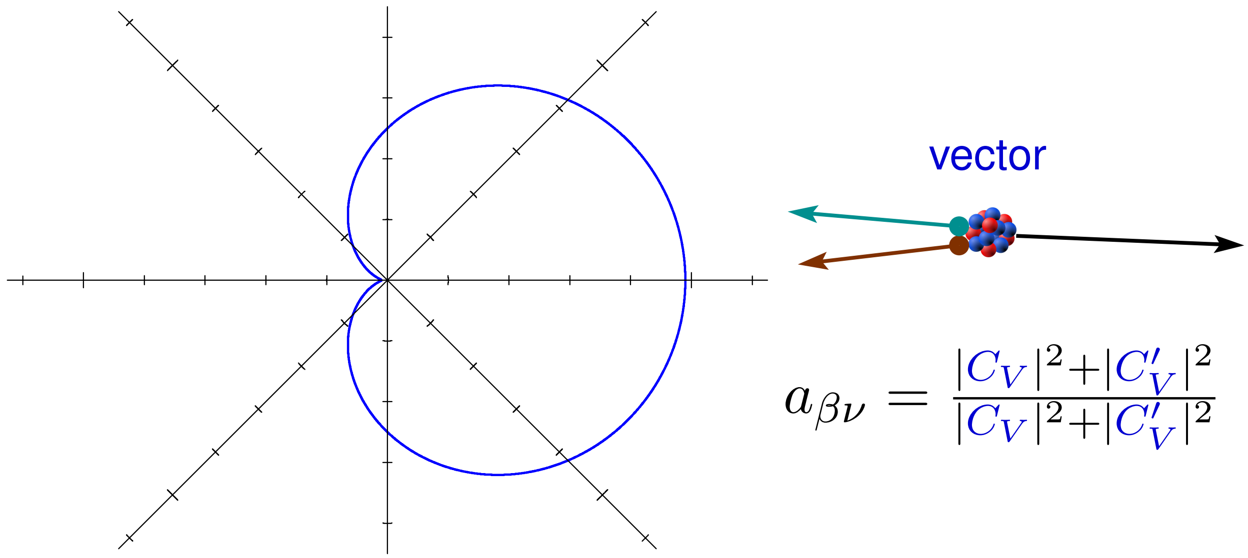

$$a_{\beta\nu} = \frac{|C_V|^2 + |C_V'|^2}{|C_V|^2 + |C_V'|^2}$$

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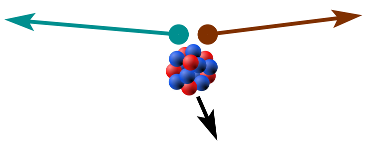
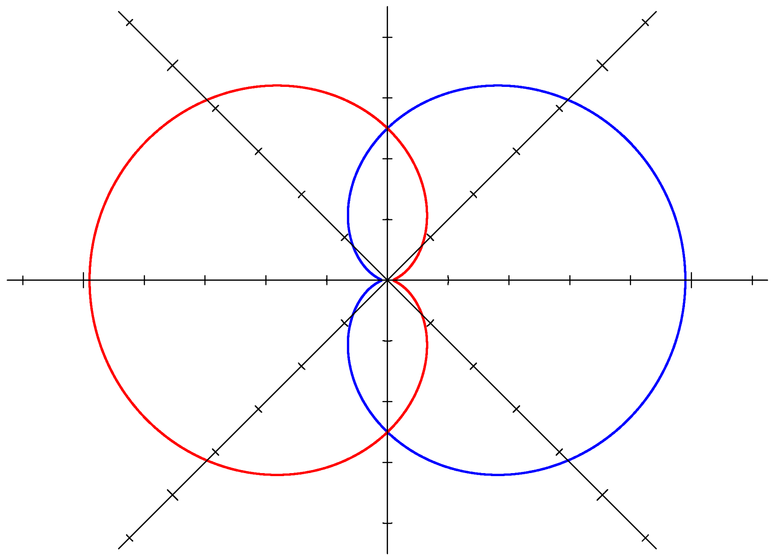
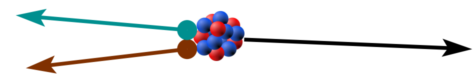
scalar



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



vector



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How do I test the SM?

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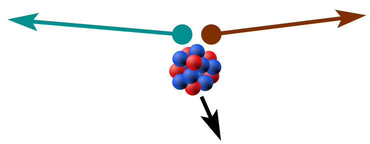

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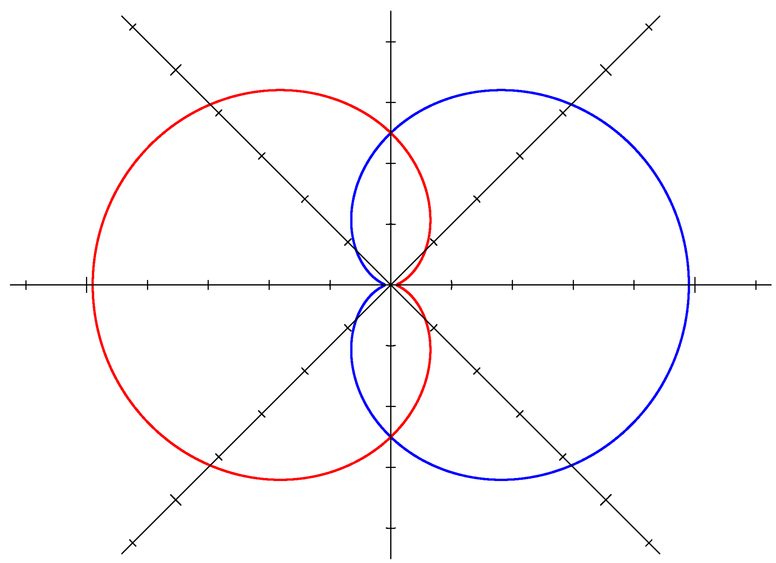

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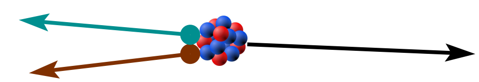

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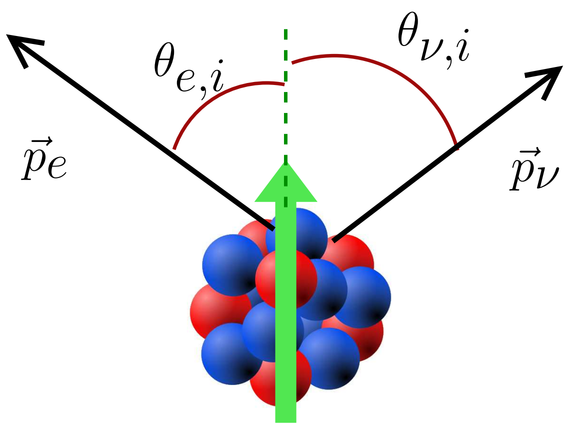

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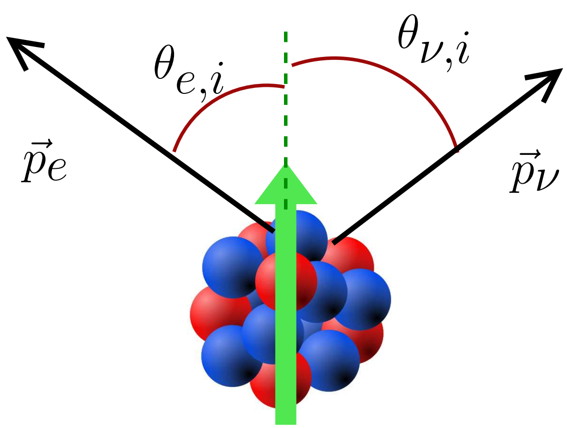

E.g. $A_\beta = \frac{-2\rho}{1+\rho^2}\left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)}\right]$

where $x \approx (M_L/M_R)^2 - \zeta$

and $y \approx (M_L/M_R)^2 + \zeta$

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basic decay rate — $\beta-\nu$ correlation — rm

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 \ldots$$

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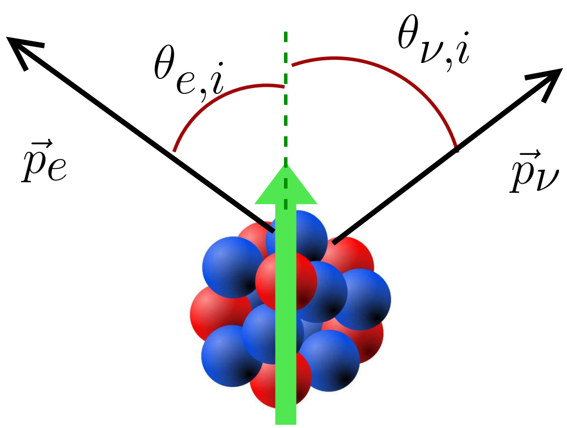
β asym — ν asym — T-violating

> β-decay parameters depend on the currents mediating the weak interaction
> $\Rightarrow$ sensitive to **new physics** $\Leftarrow$



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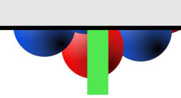
$\vec{p}_e$

Goal must be $\lesssim \mathbf{0.1\%}$ to complement LHC

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)



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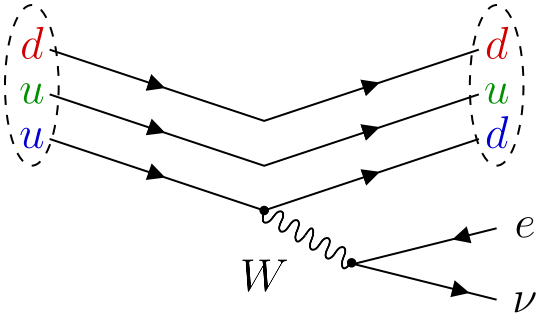
How to acheive our goal?



- Perform a β decay experiment on **short-lived** isotopes

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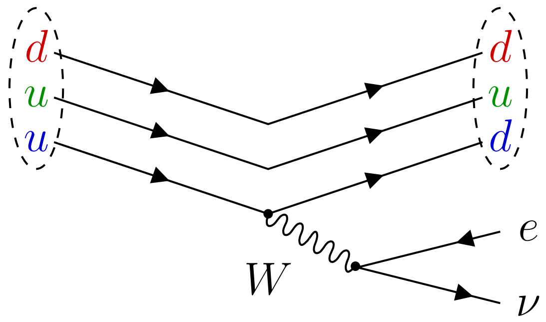

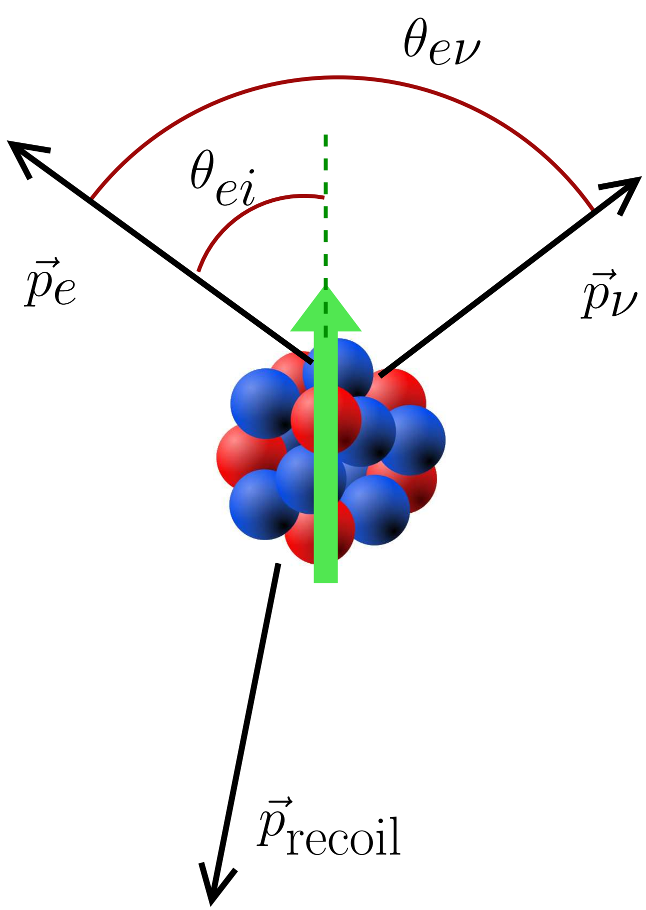

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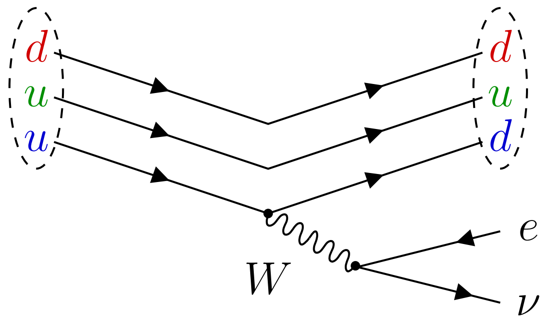

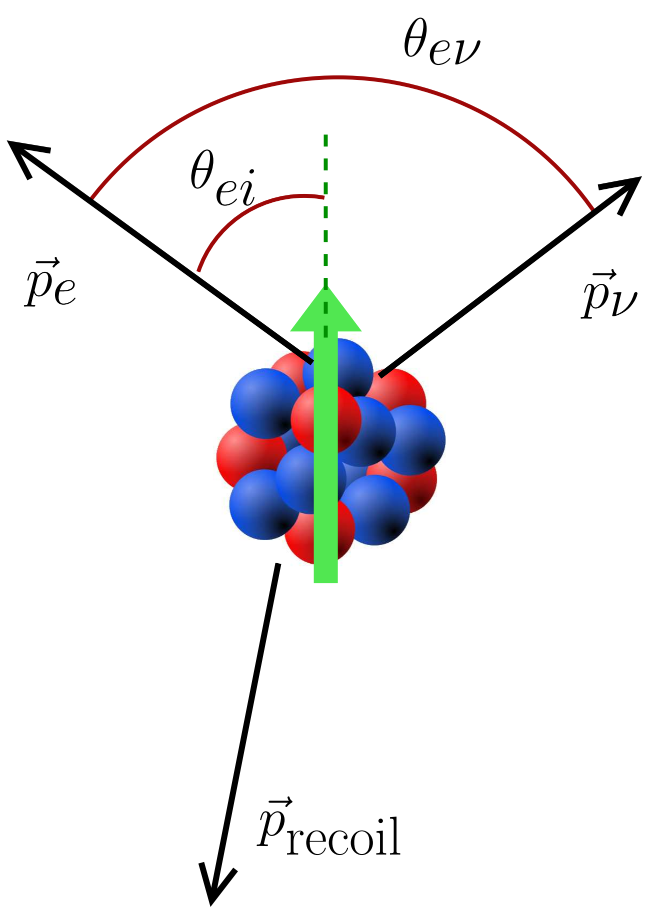

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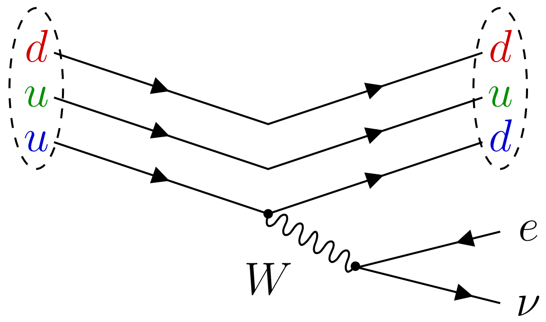
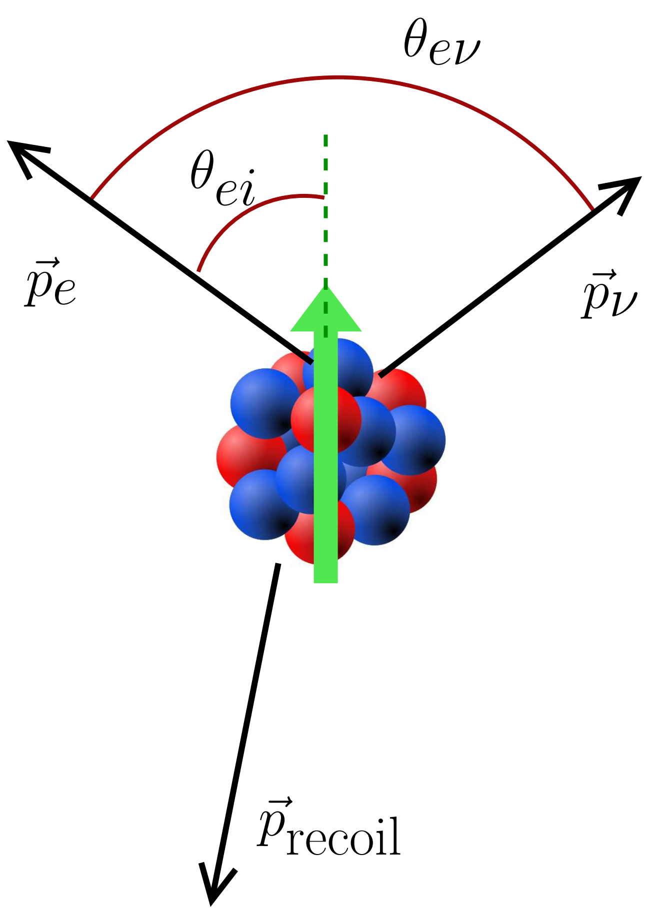
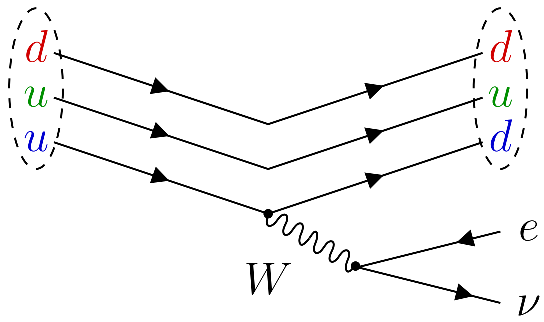




- Perform a β decay experiment on **short-lived** isotopes
- Make a **precision measurement** of the angular correlation parameters
- **Compare** the SM predictions to observations
- Look for **deviations** as an indication of **new physics**

How to acheive our goal?



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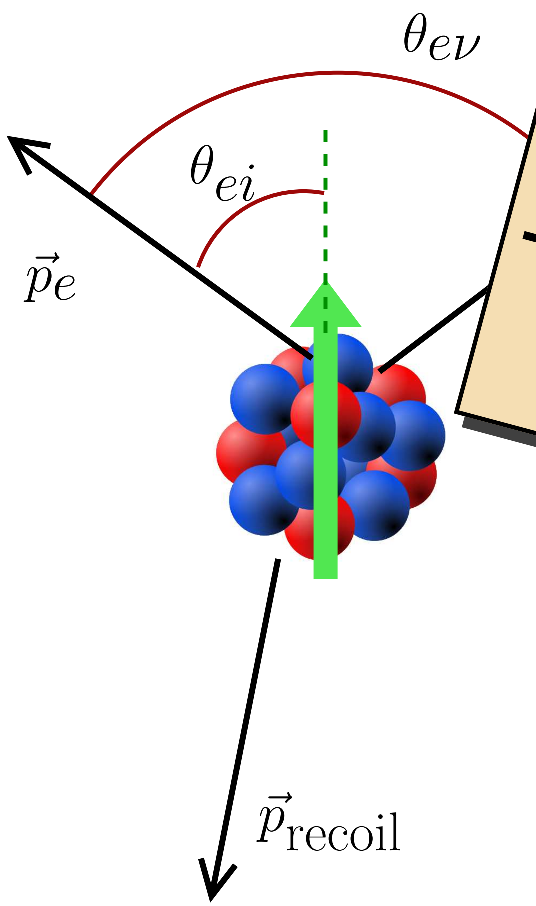


Perform a nuclear measurement – often using atomic techniques – to test high-energy theories

C.S. Wu's experiment – Parity violation

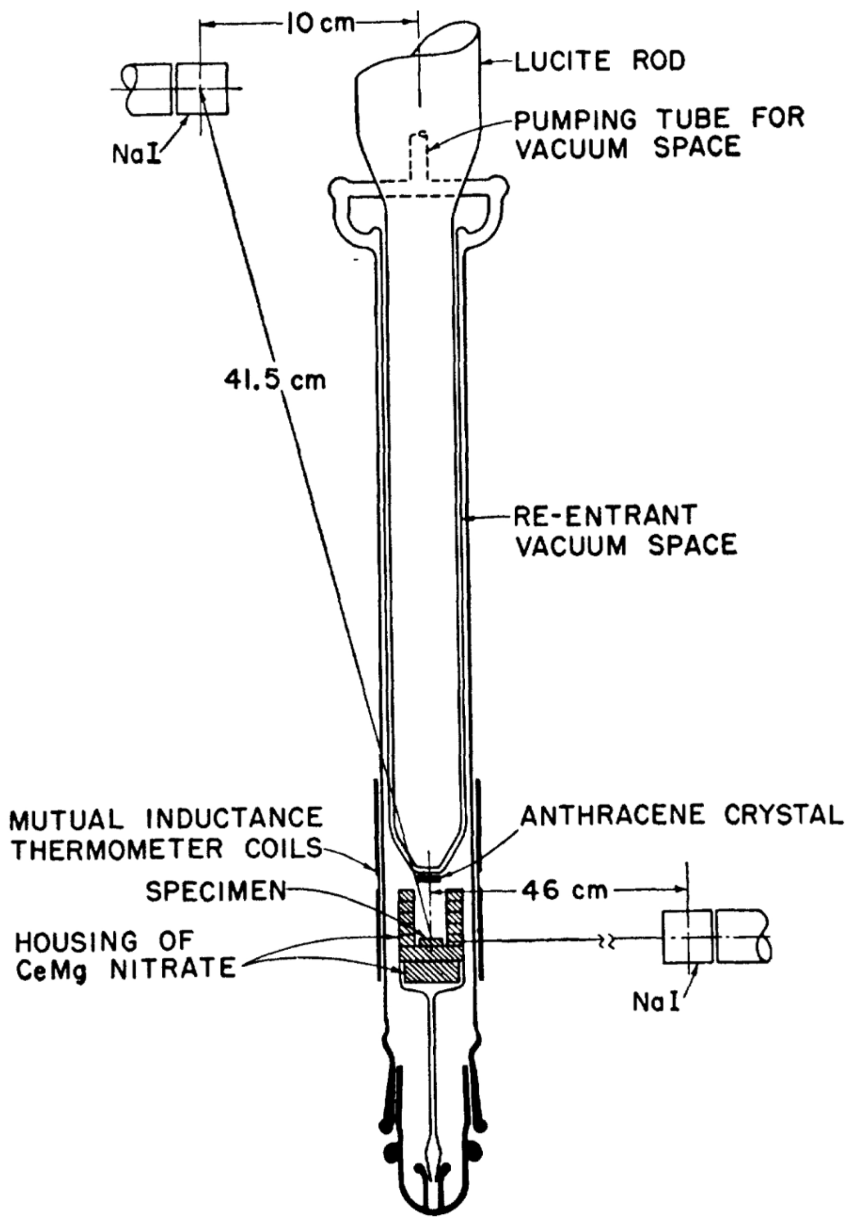
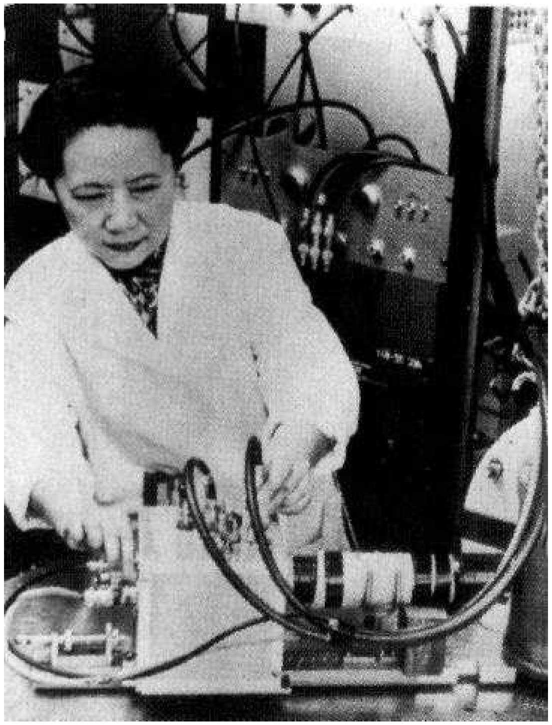
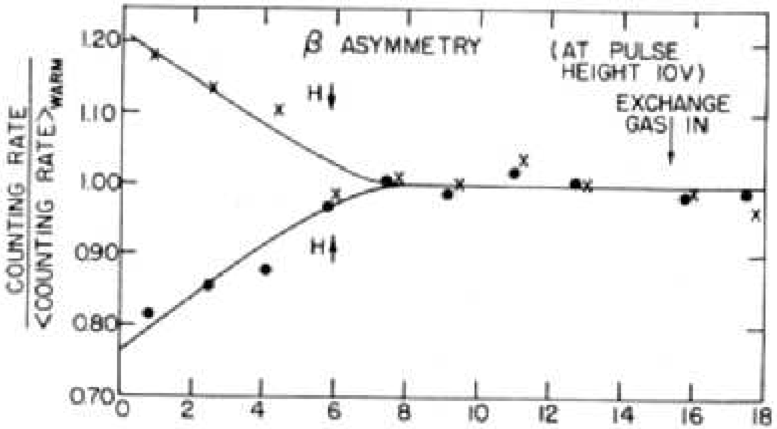


FIG. 1. Schematic drawing of the lower part of the cryostat.





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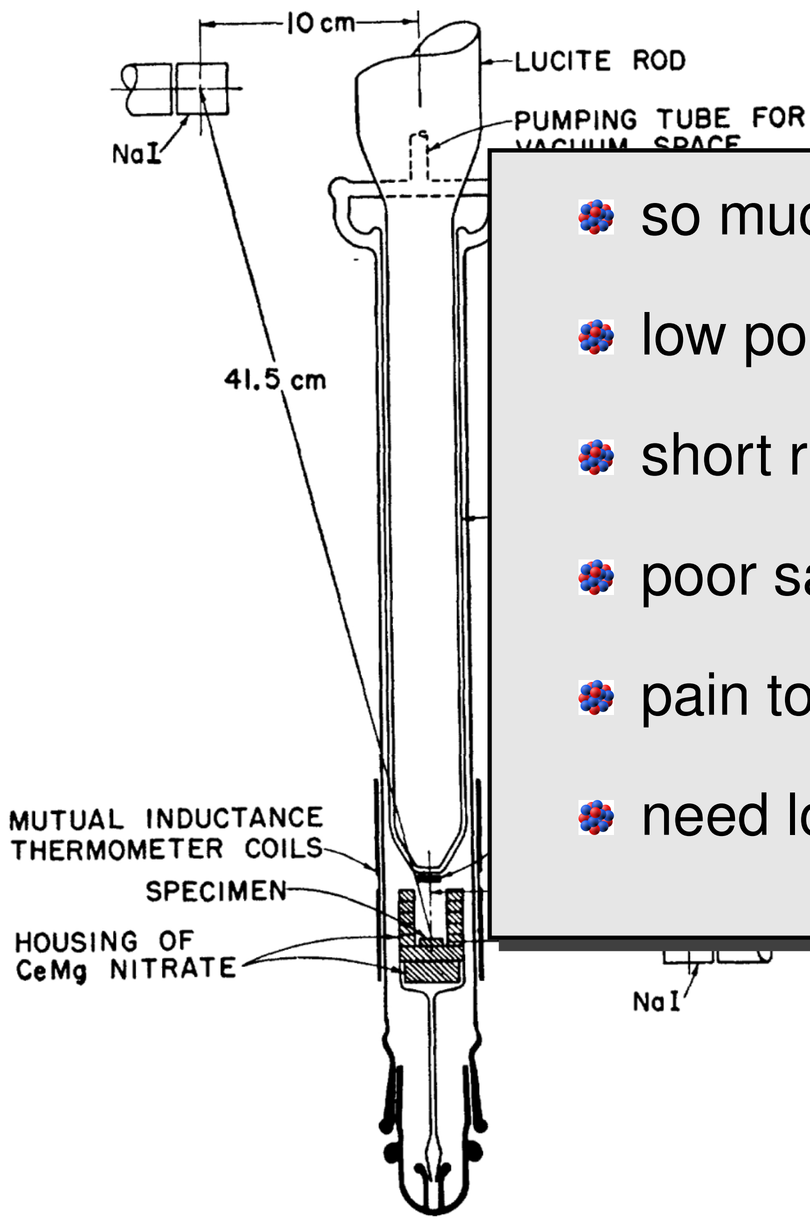

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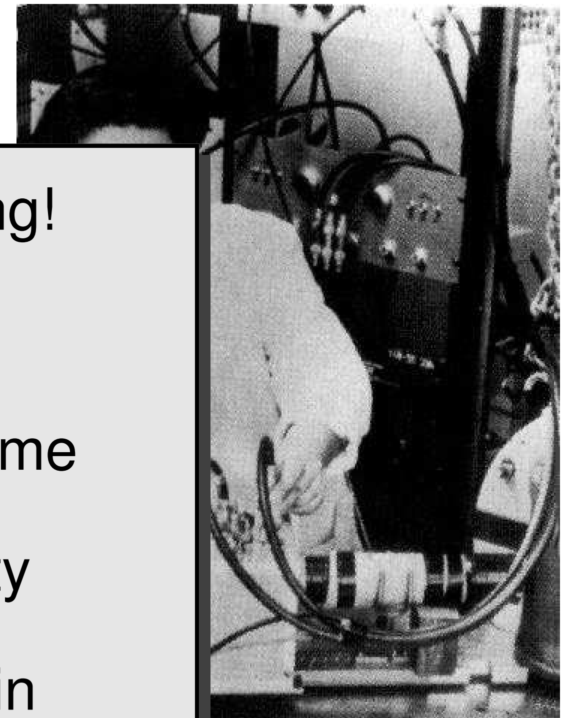
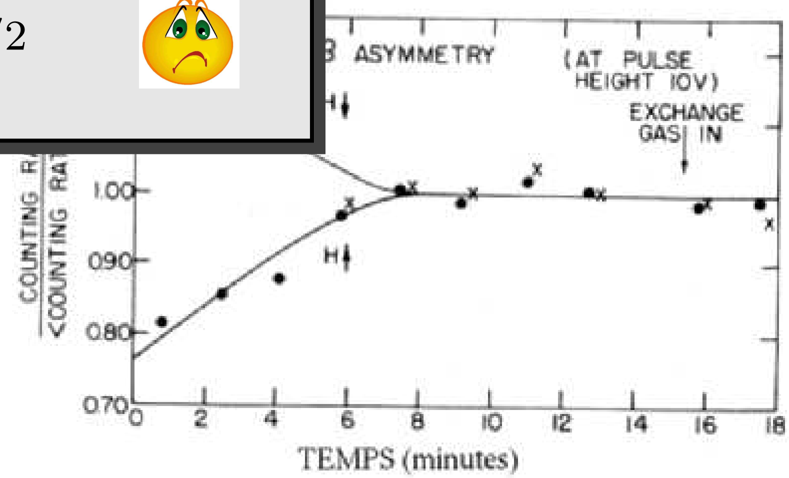


- so much scattering!
- low polarization
- short relaxation time
- poor sample purity
- pain to flip the spin
- need long $t_{1/2}$



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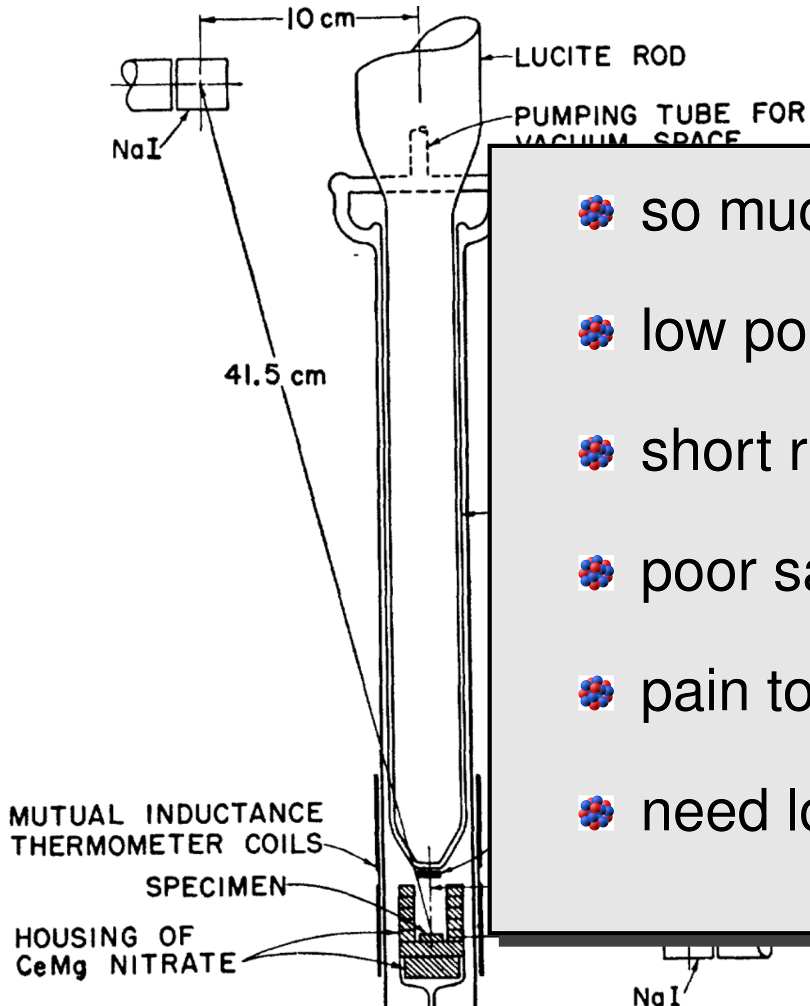

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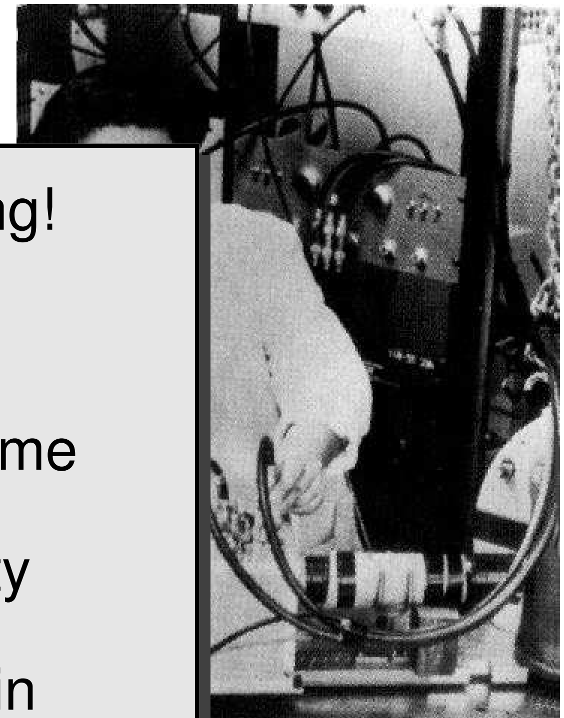

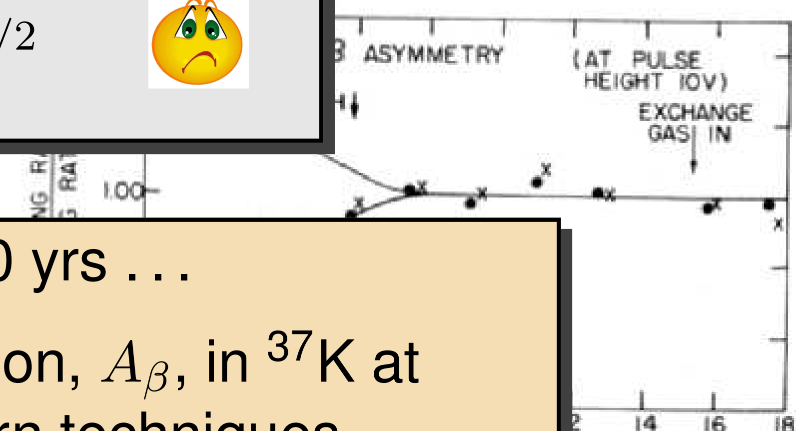

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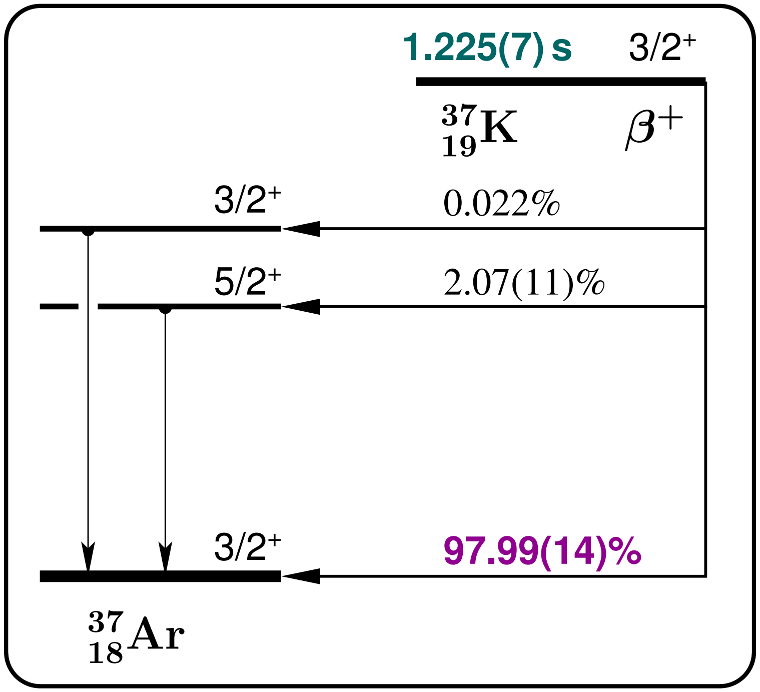
Fast-forward 70 yrs . . .

Measure same correlation, A_β, in ^{37}K at TRIUMF using modern techniques

Almost as simple as $0^+ \rightarrow 0^+$:



- **isobaric analogue** decay
- **strong** branch to g.s.

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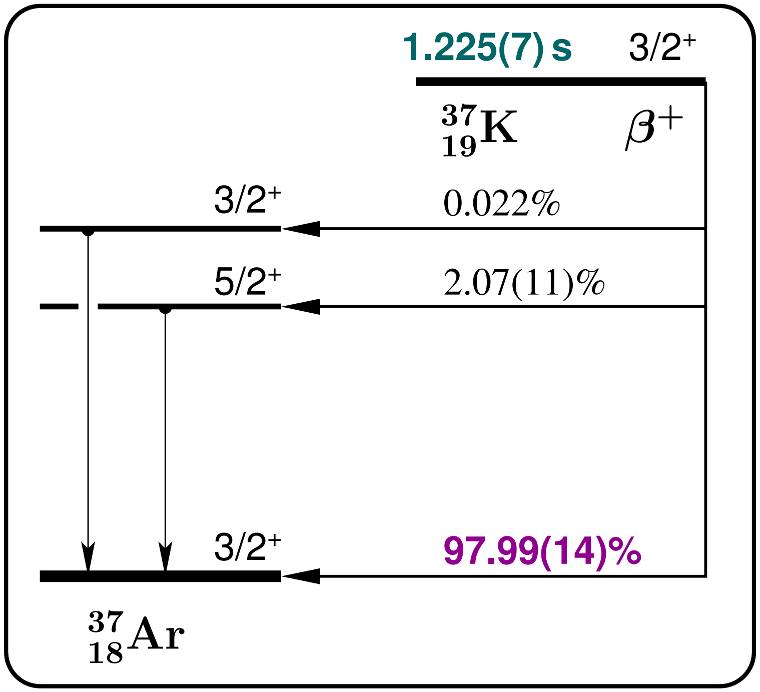

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- **mixed** Fermi/Gamow-Teller

$\Rightarrow$ need $\rho \equiv G_A M_{GT} / G_V M_F$ to get SM prediction for correlation parameters

Get ρ from the comparative half-life:

$$\rho^2 = \frac{2\mathcal{F}t^{0^+\to 0^+}}{\mathcal{F}t} - 1$$

The β^+-decay of ^{37}K

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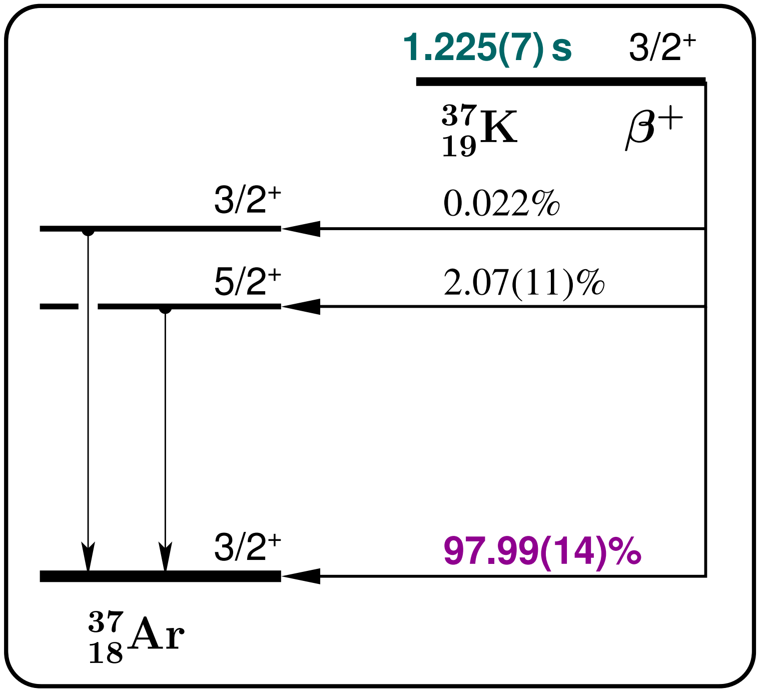

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Q_{EC}: ±0.003%

BR: ±0.14%

$t_{1/2}$: ±0.08%

$\Bigg\}\ \mathcal{F}t = 4605(8) \Rightarrow$

$$\rho = 0.5768(21)$$

$\Rightarrow A_\beta^{SM} = -0.5719(7)$, predicted to <0.1% ✓

Thank you, AMO physicists!!

Atomic methods have opened up a new vista in precision work and provide the ability to push β decay measurements to $\lesssim 0.1\%$

- laser-cooling and trapping (magneto-optical traps)
- sub-level state manipulation (optical pumping)
- characterization/diagnostics (photoionization)

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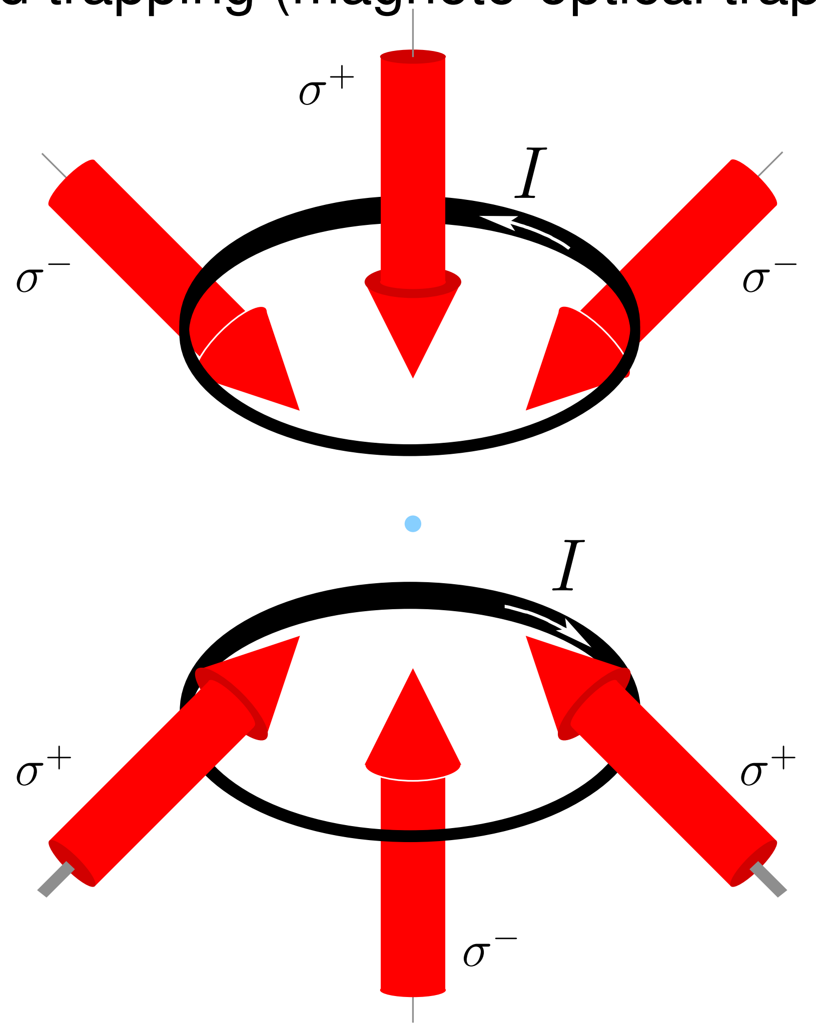

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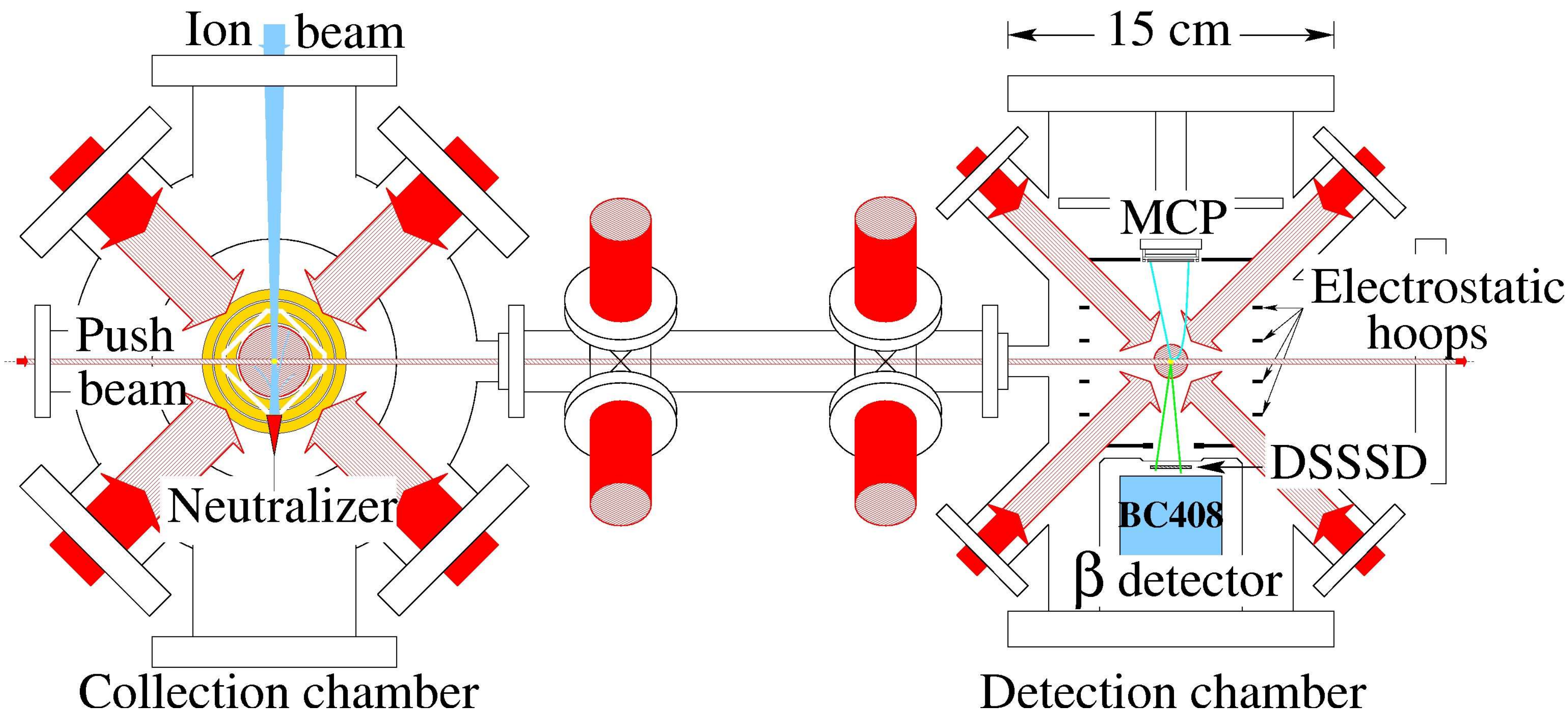

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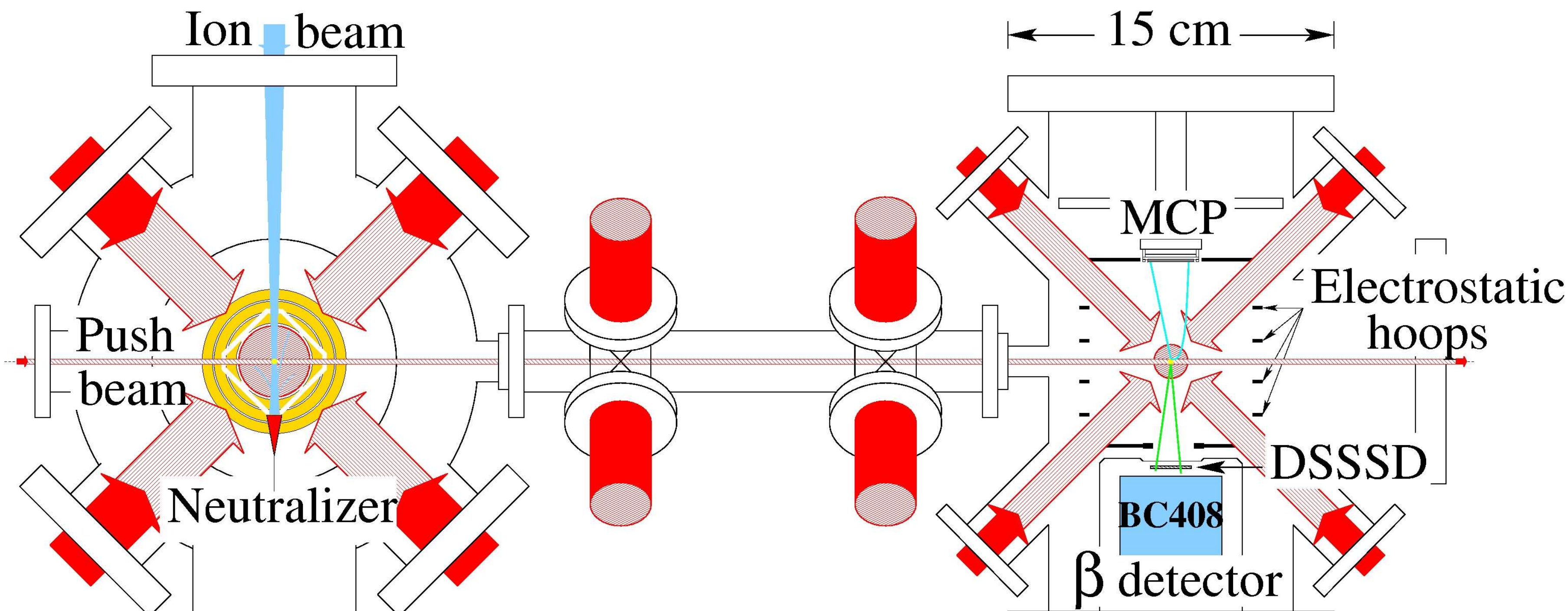

Traps provide a **backing-free**, very **cold** ($\lesssim 1$ mK), **localized** ($\sim 1\ \mathrm{mm}^3$) source of **isomerically-selective**, **short-lived** radioactive atoms

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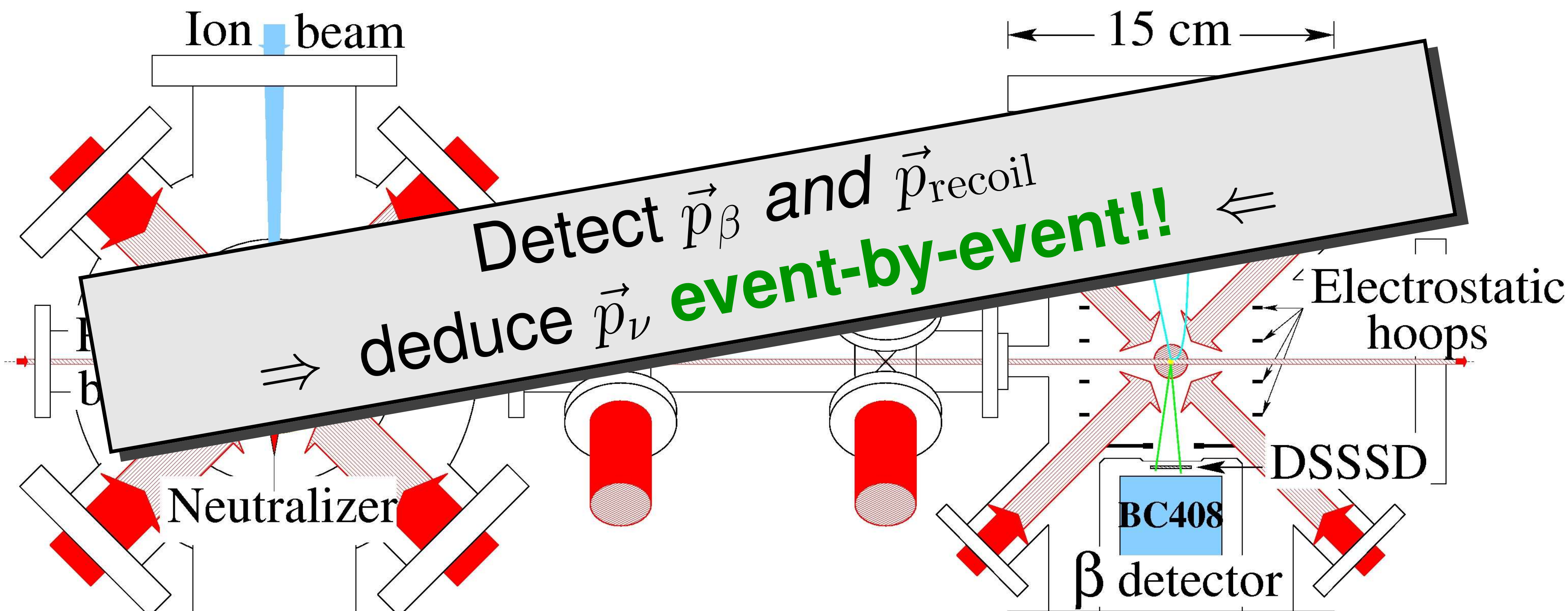

Detect $\vec{p}_\beta$ and $\vec{p}_{\rm recoil}$ $\Leftarrow$

$\Rightarrow$ deduce $\vec{p}_\nu$ **event-by-event!!**

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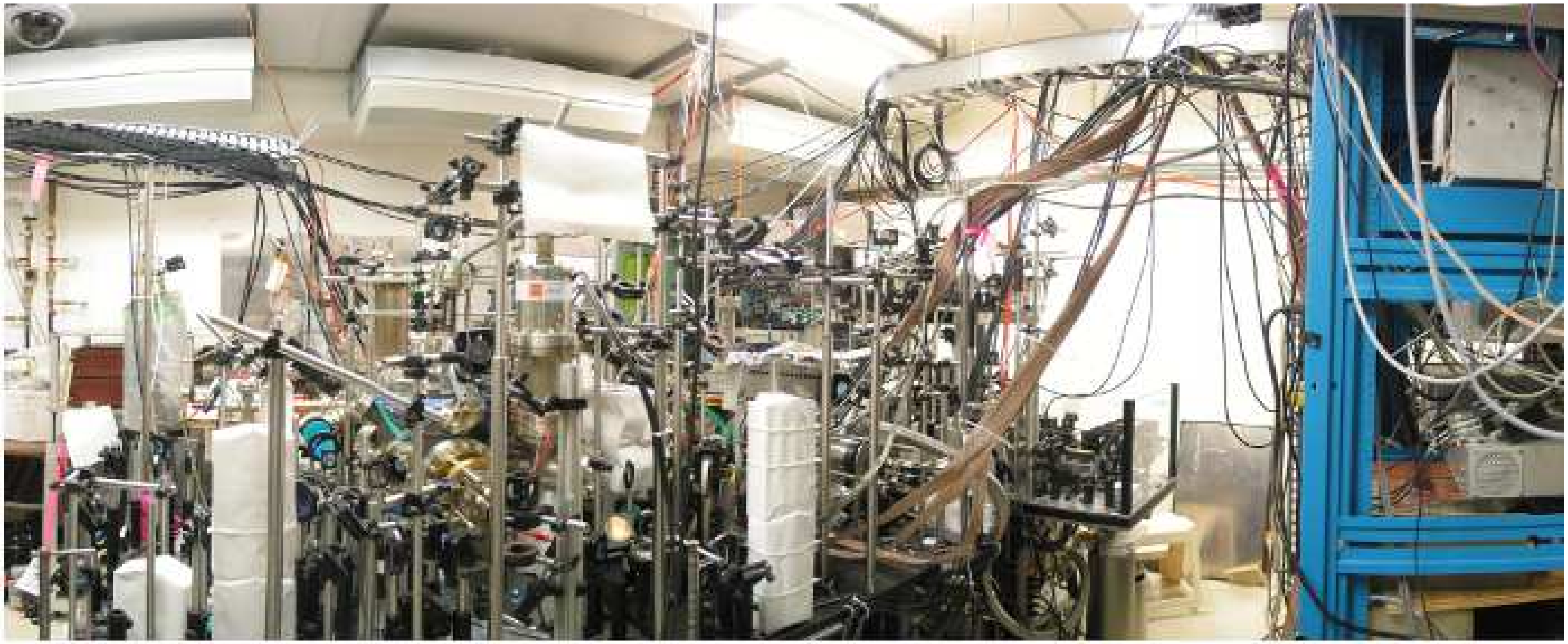
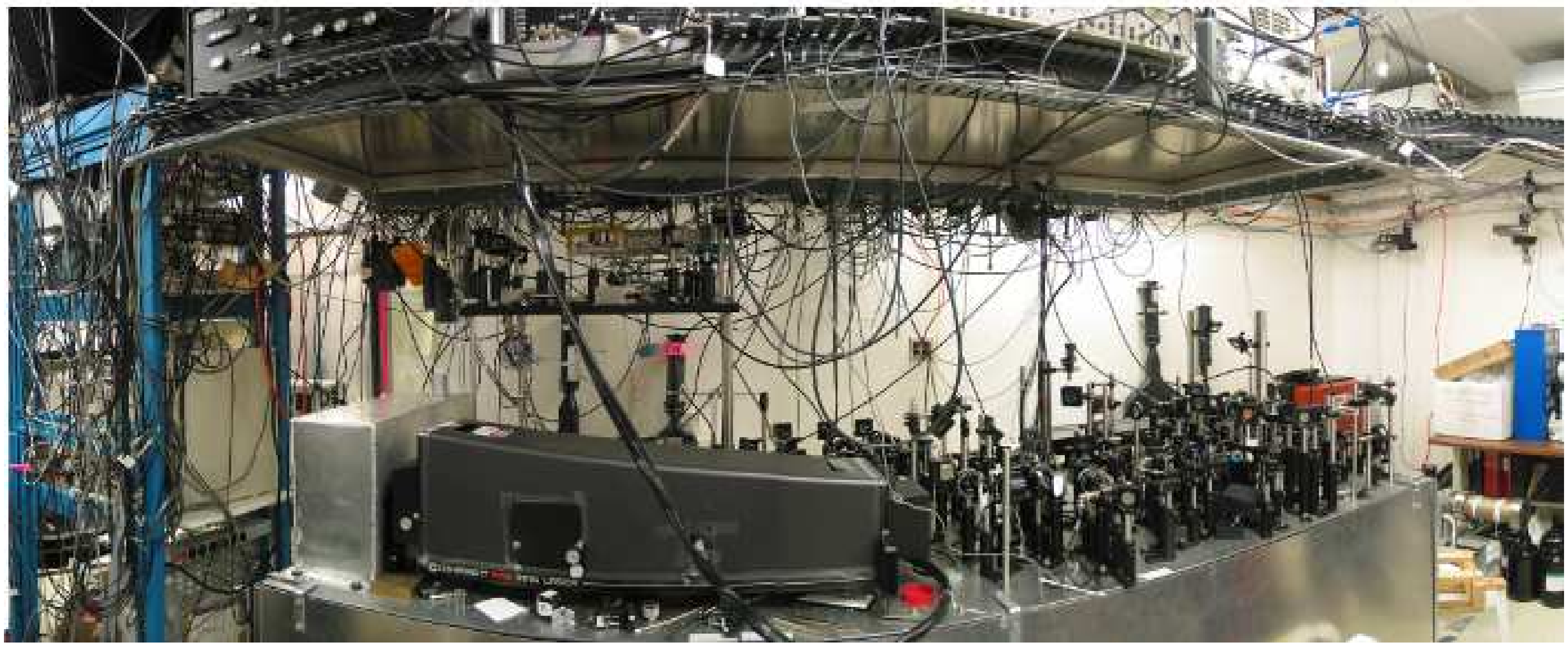
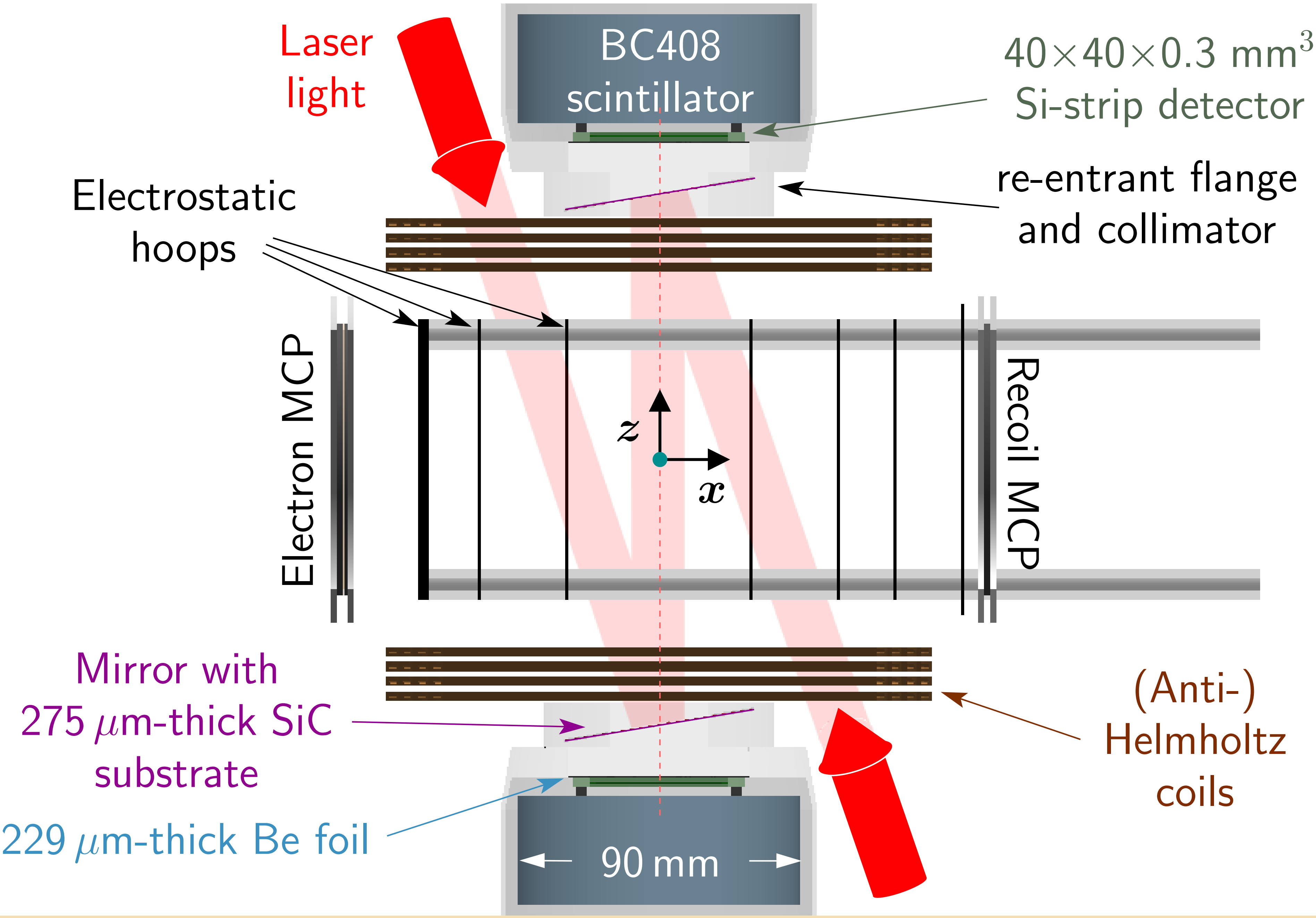
The TRINAT lab

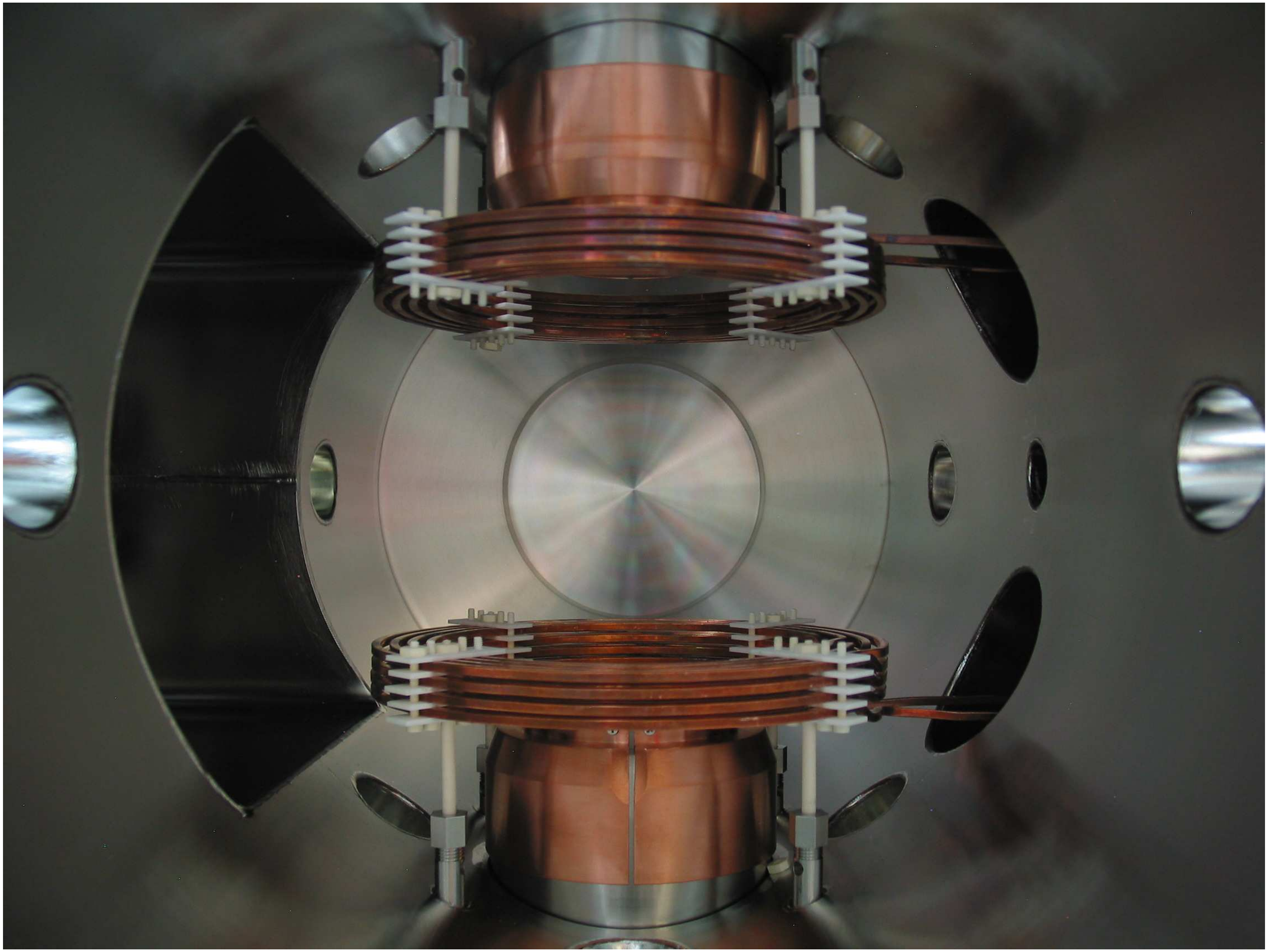




The measurement chamber



Outline of polarized experiment



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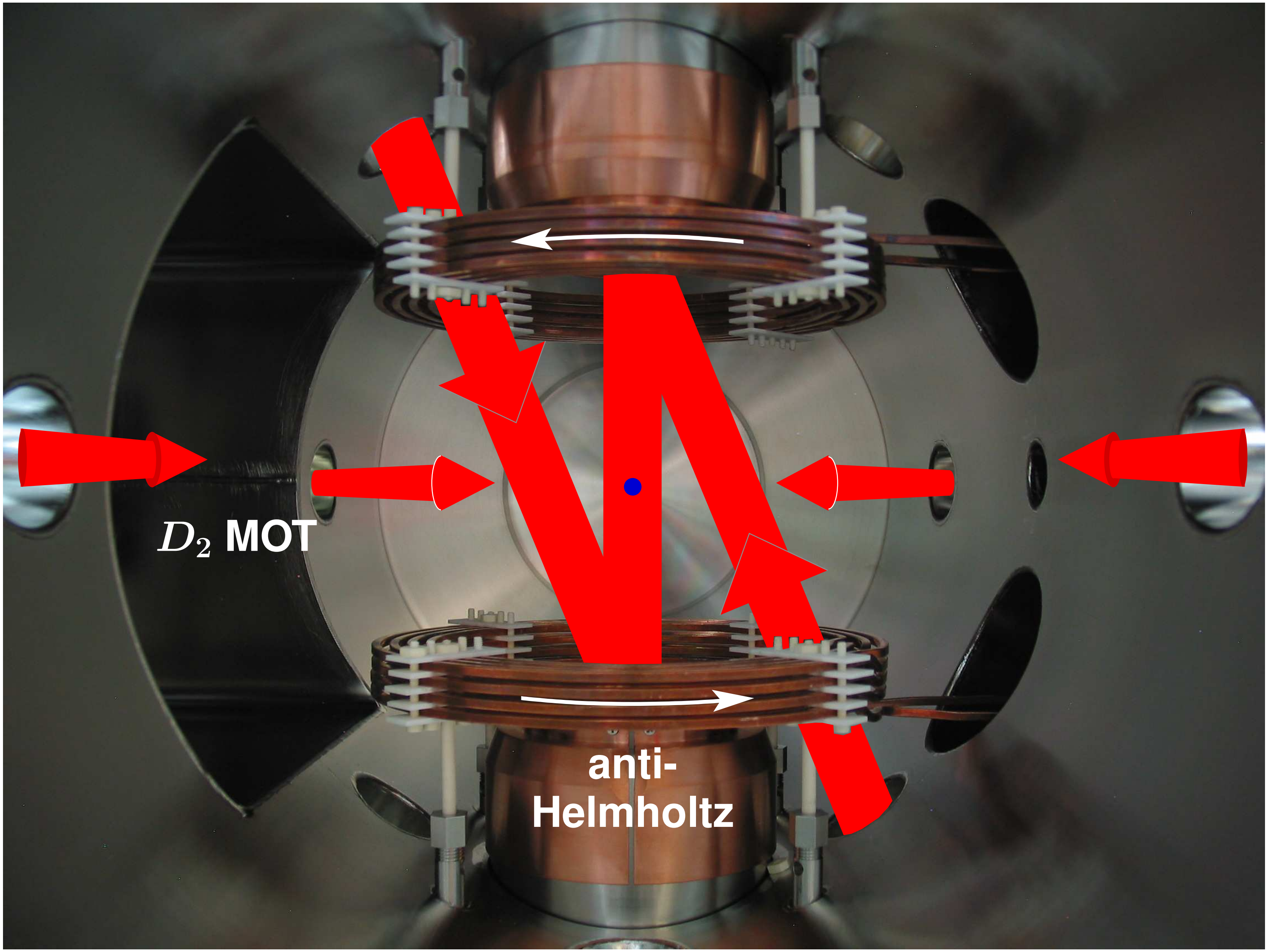

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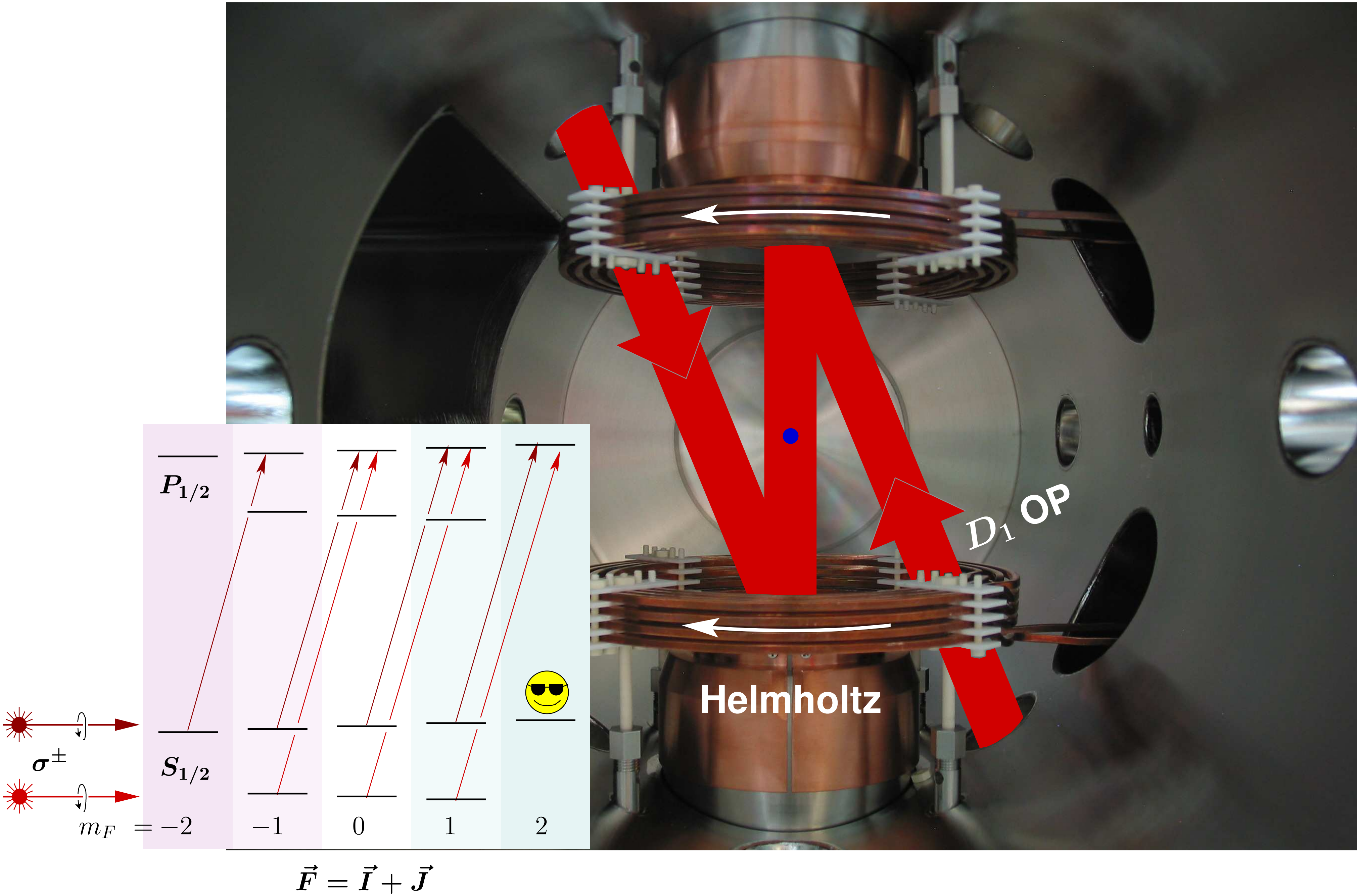

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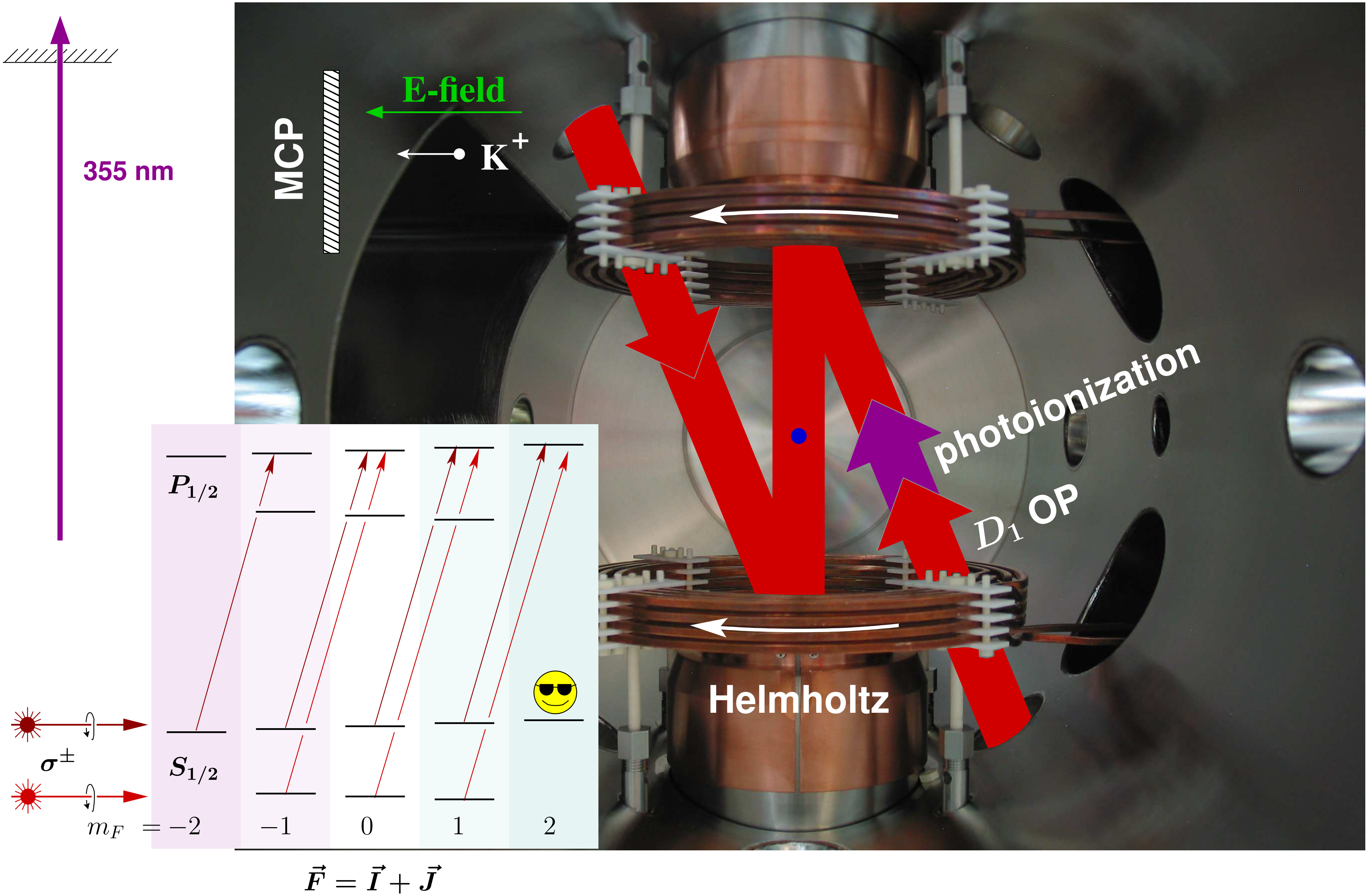
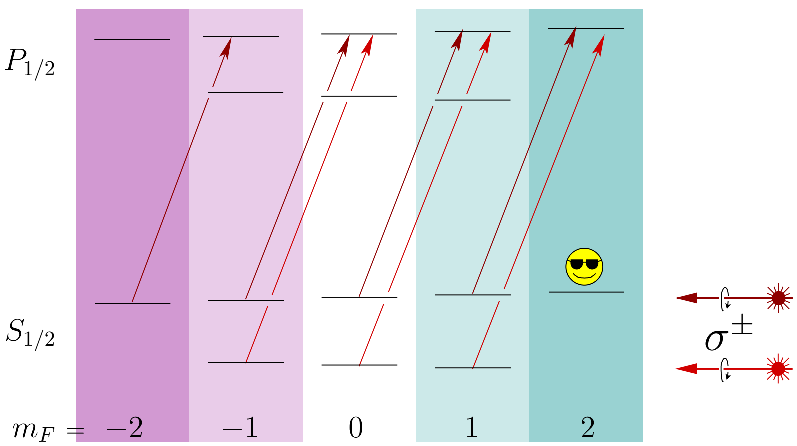
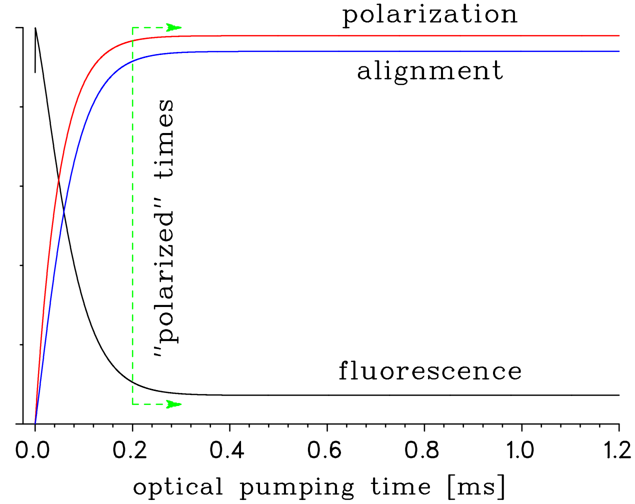


Deduce P based on a model of the excited state populations





Atomic measurement of P

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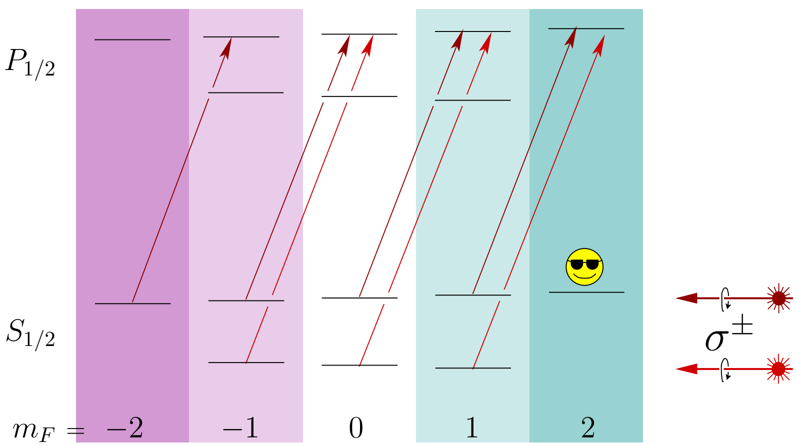

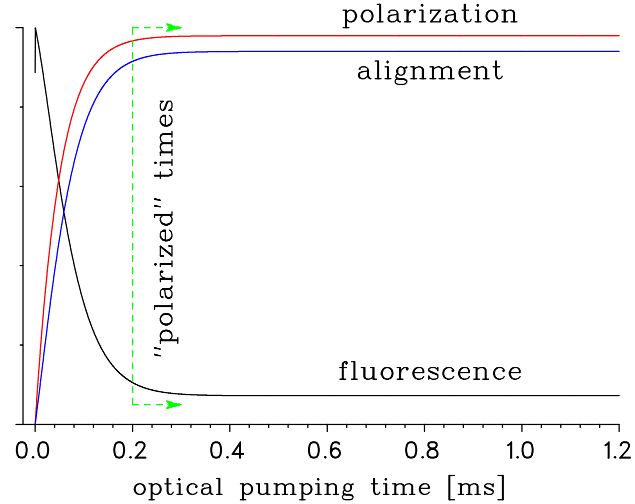

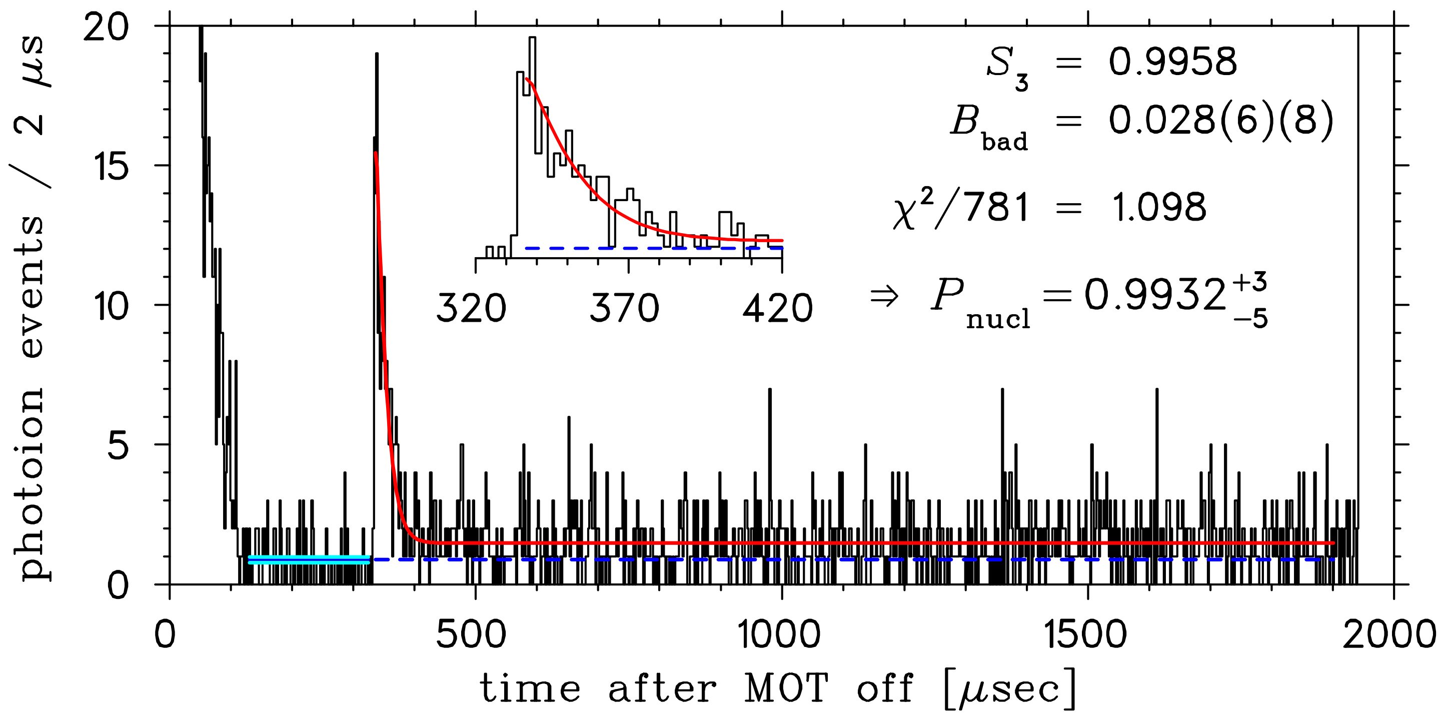

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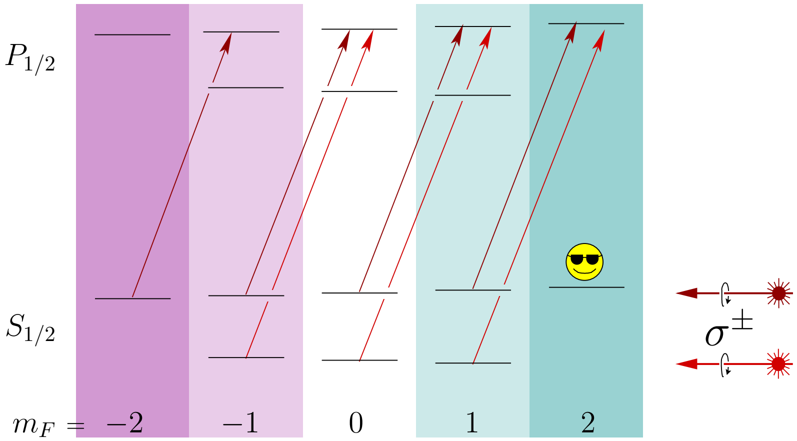
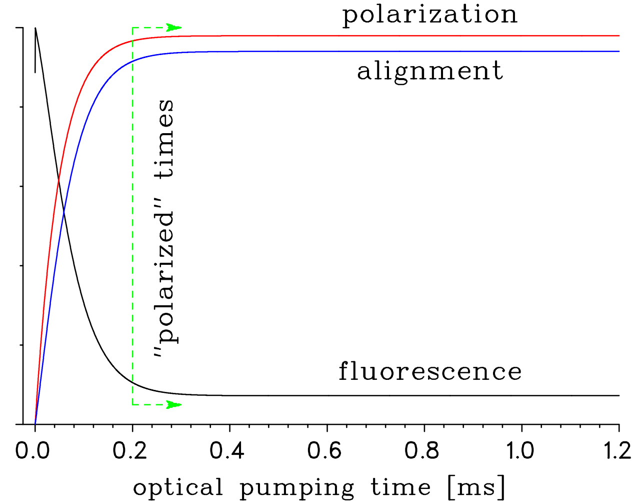
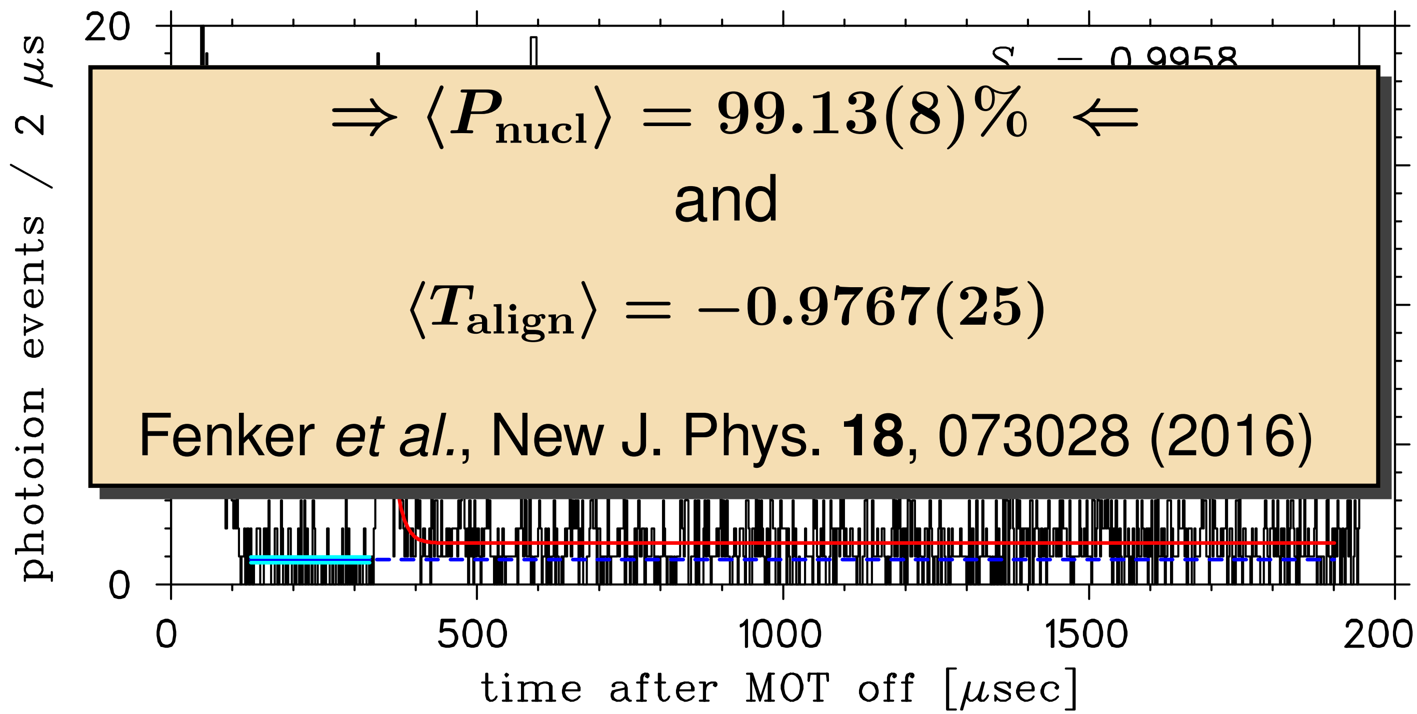






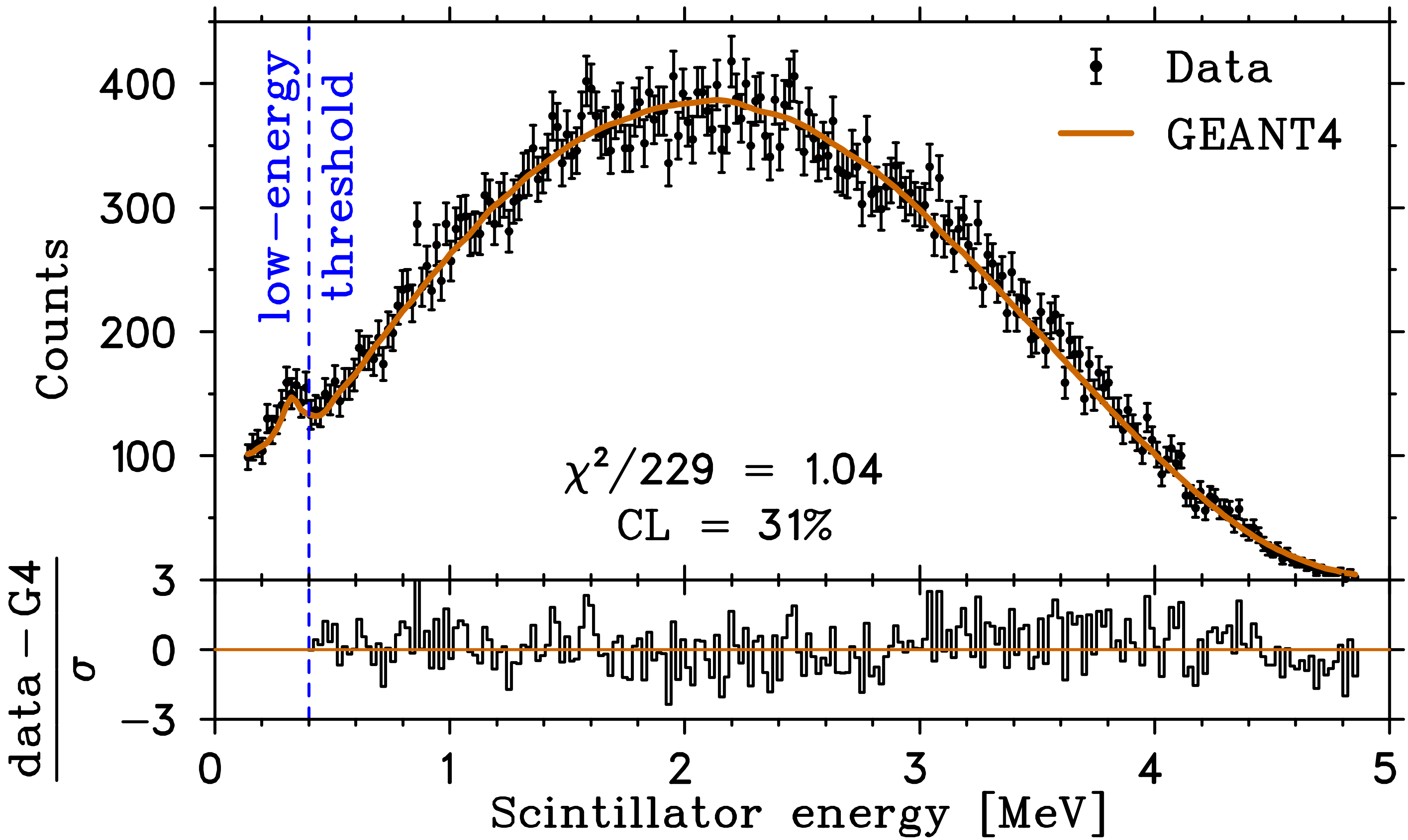
$$\Rightarrow \langle \boldsymbol{P_{\mathrm{nucl}}} \rangle = \mathbf{99.13(8)\%} \Leftarrow$$

and

$$\langle \boldsymbol{T_{\mathrm{align}}} \rangle = \mathbf{-0.9767(25)}$$

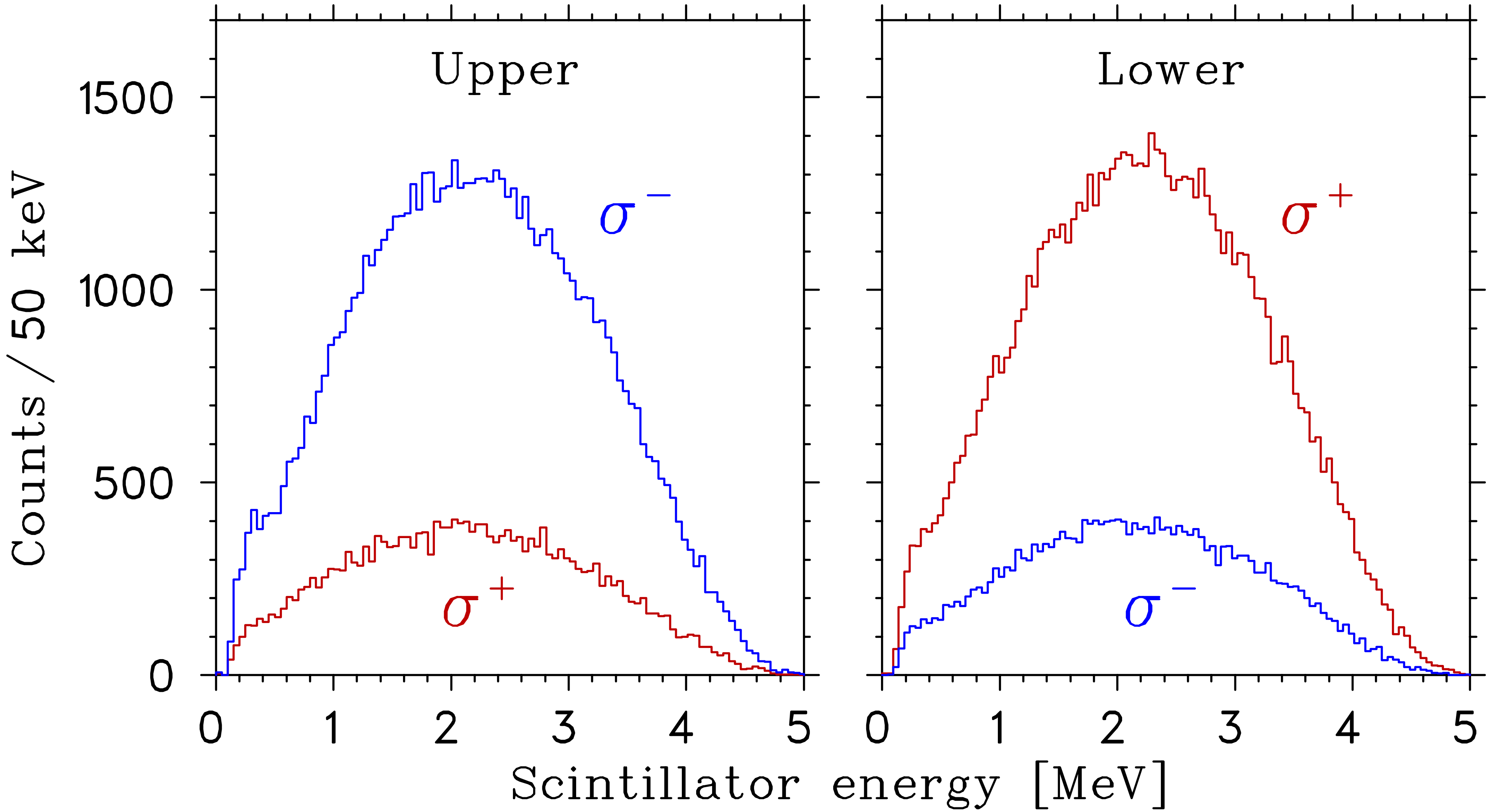
Fenker *et al.*, New J. Phys. **18**, 073028 (2016)

Energy Spectrum Compared to GEANT4



Note: there is **no background subtraction**!

Asymmetry Measurement (briefly)



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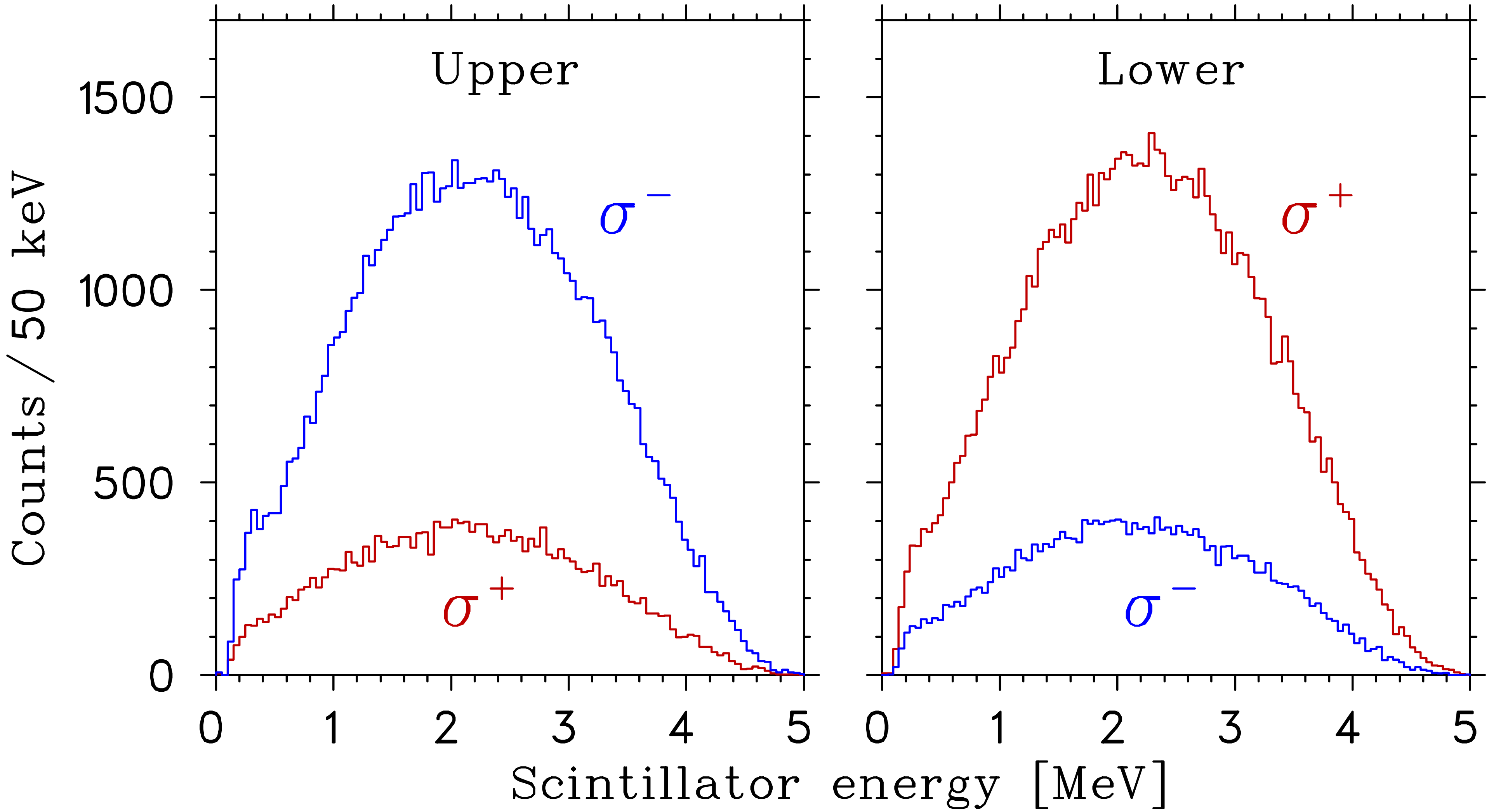

$$A_{\text{obs}}(E_e) = \frac{1 - S(E_e)}{1 + S(E_e)}, \quad \text{where } S(E_e) \equiv \sqrt{\frac{r_1^-(E_e) r_2^+(E_e)}{r_1^+(E_e) r_2^-(E_e)}}$$

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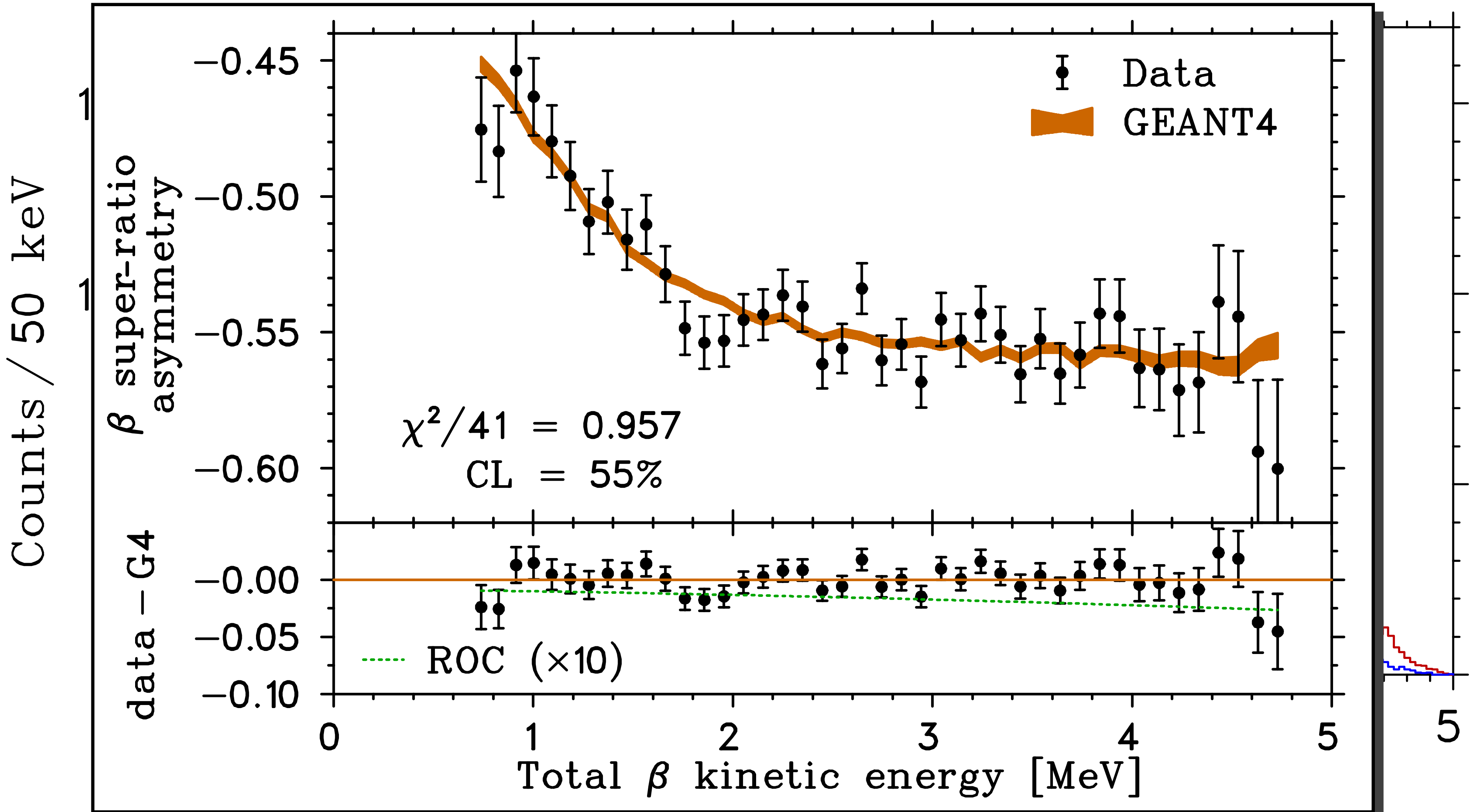

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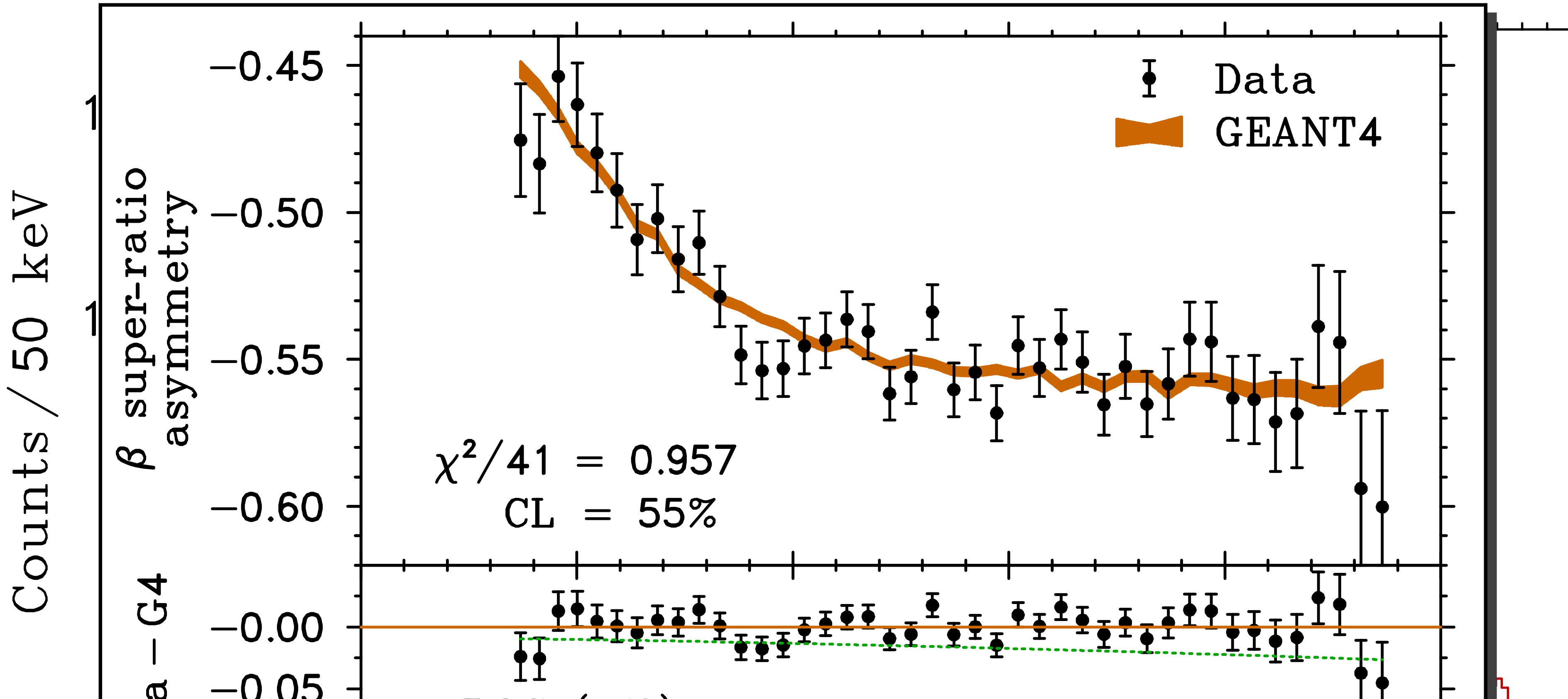


PHYSICAL REVIEW LETTERS **120,** 062502 (2018)

Precision Measurement of the β Asymmetry in Spin-Polarized ^{37}K Decay

B. Fenker,[1,2] A. Gorelov,[3] D. Melconian,[1,2,*] J. A. Behr,[3] M. Anholm,[3,4] D. Ashery,[5]
R. S. Behling,[1,6] I. Cohen,[5] I. Craiciu,[3] G. Gwinner,[4] J. McNeil,[7,3] M. Mehlman,[1,2] K. Olchanski,[3]
P. D. Shidling,[1] S. Smale,[3] and C. L. Warner[3]

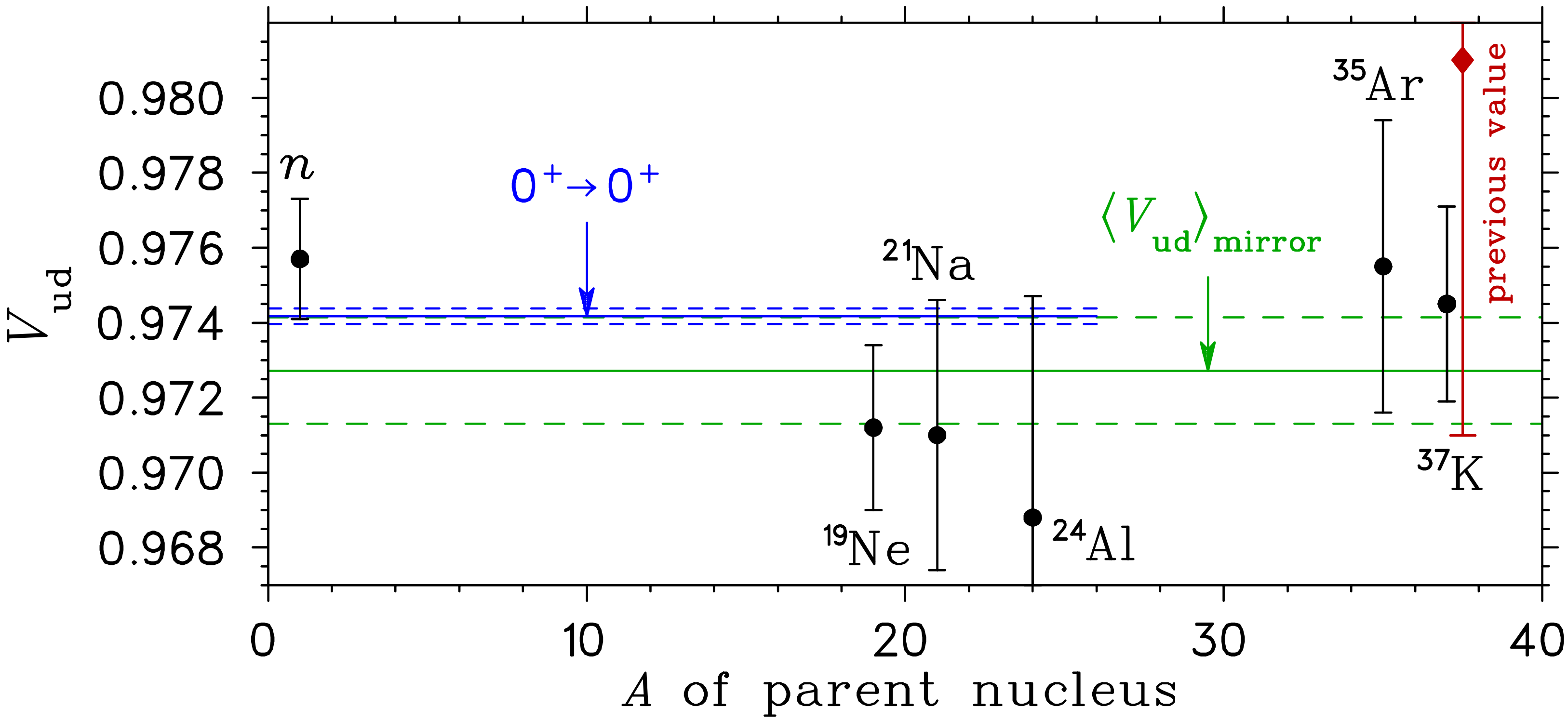
A_β Error Budget

Source		Correction	Uncertainty
Systematics			
Background		1.0014	0.0008
β scattering[a]		1.0230	0.0007
Trap (σ^+ vs σ^-)	position (typ $\lesssim \pm 20\ \mu$m)		0.0004
	sail velocity (typ $\lesssim \pm 30\ \mu$m/ms)		0.0005
	temperature (typ $\lesssim \pm 0.2$ mK)		0.0001
Si-strip	radius[a] ($15.5^{+3.5}_{-5.5}$ mm)		0.0004
	energy agreement ($\pm 3\sigma \rightarrow \pm 5\sigma$)		0.0002
	threshold ($60 \rightarrow 40$ keV)		0.0001
Shakeoff electron TOF region ($\pm 3.8 \rightarrow \pm 4.6$ ns)			0.0003
Thicknesses	SiC mirror[a] ($\pm 6\ \mu$m)		0.0001
	Be window[a] ($\pm 23\ \mu$m)		0.000 09
	Si-strip[a] ($\pm 5\ \mu$m)		0.000 01
Scintillator only vs $E + \Delta E$[a]			0.0001
Scintillator threshold ($400 \rightarrow 1000$ keV)			0.000 03
Scintillator calibration (± 0.4 ch/keV)			0.000 01
Total systematics			0.0013
Statistics			0.0013
Polarization		1.0088	0.0005
Total		1.0338	0.0019

[a]Denotes sources that are related to β^+ scattering.

Impact of A_β Measurement

- In terms of CKM unitarity, our A_β result improved V_{ud} for this nucleus by nearly a factor of five: $|V_{ud}| = 0.981^{+12}_{-10} \rightarrow 0.9745(25)$.



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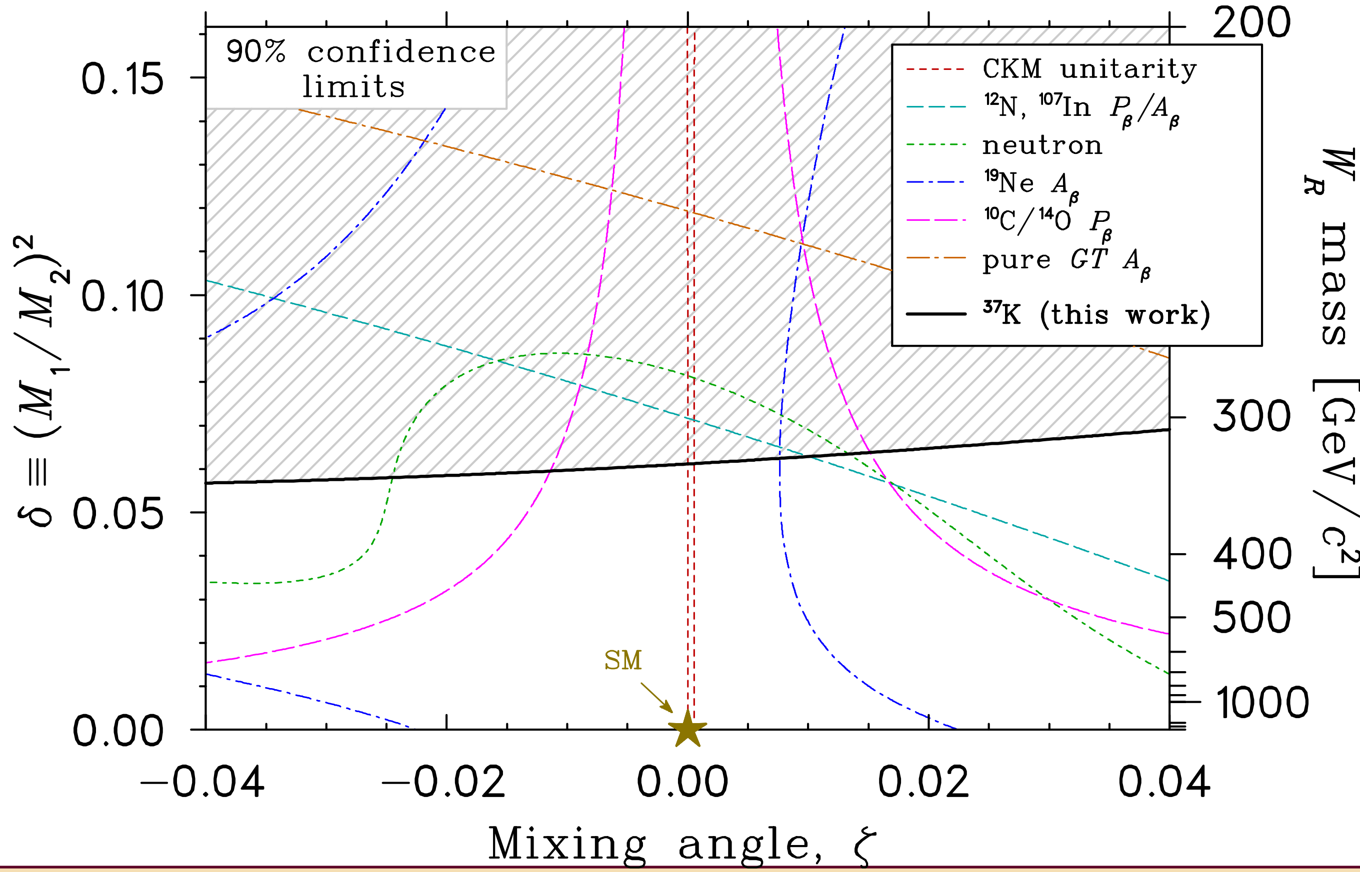

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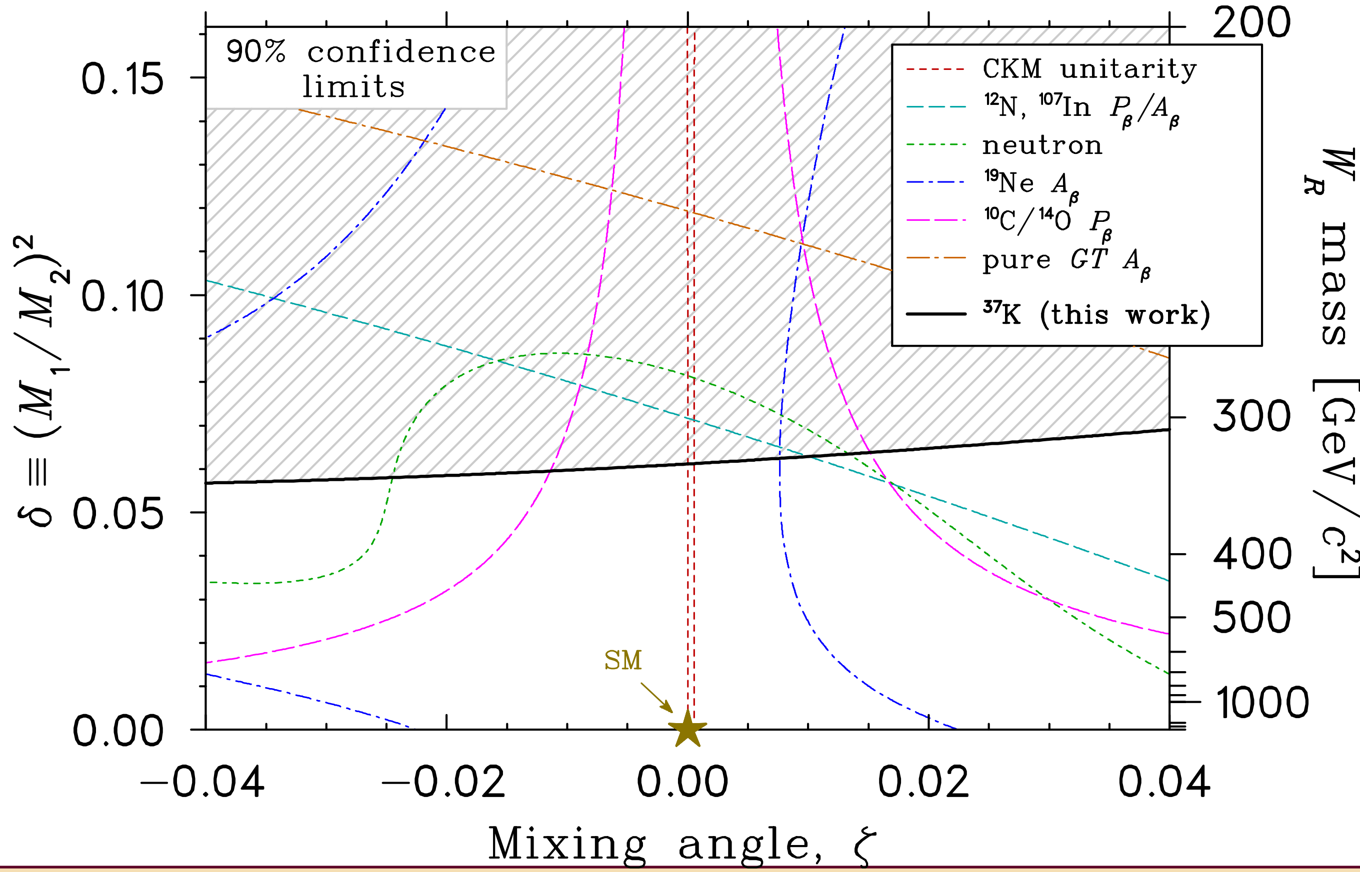
- Analysis of Fierz and second-class currents (E-dependent observables) to be finished soon



Summary

- The SM is fantastic, but **not** our "ultimate" theory. There are many exciting avenues to find more a complete model
- **Nuclear approach:** precision measurement of correlation parameters
- (AC-)MOT + opt. pumping = ***cool*** physics
  - extremely precise, high nuclear polarization: $\langle P \rangle = 99.13(8)\%$
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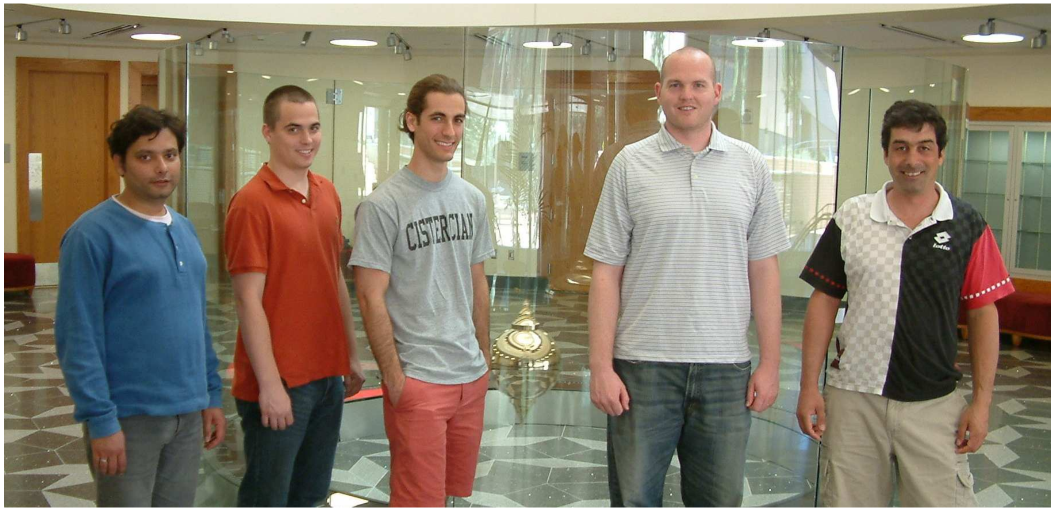
  - on the way to a 0.1% measurement of A_β and other (un)polarized correlations
- If you're interested in this (or other nuclear physics – structure, astro, EoS, RHIC, reactions, . . .) and considering grad school:

BEST GRAD SCHOOLS U.S.News & WORLD REPORT RANKINGS

Nuclear @ TAMU #12 in 2010, #13 in 2014, now tied for **#7** overall and **#5** among **public universities**

The Mad Trappers/Thanks

TAMU: **B. Fenker**, S. Behling,
M. Mehlman, P. Shidling
+ TAMU/REU undergrads
+ ENSICAEN interns



TRINAT:

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And thank you for your attention!

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