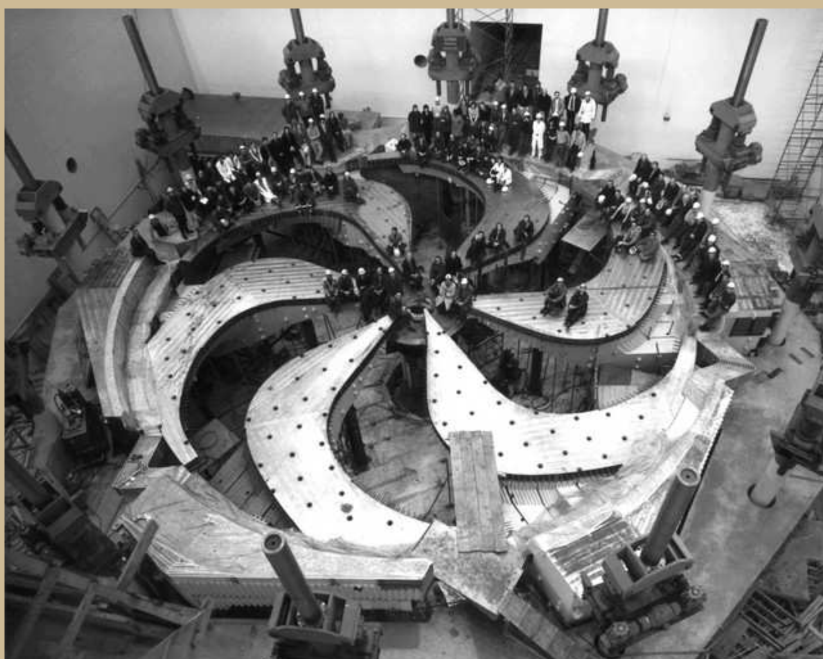
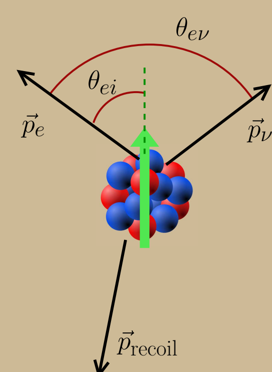
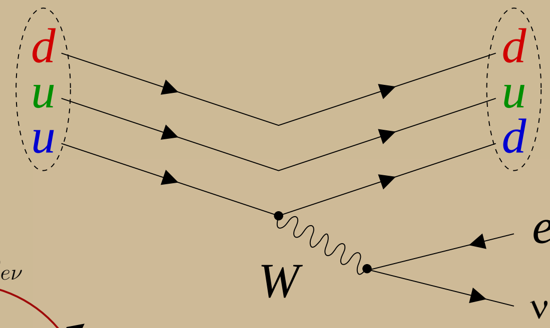
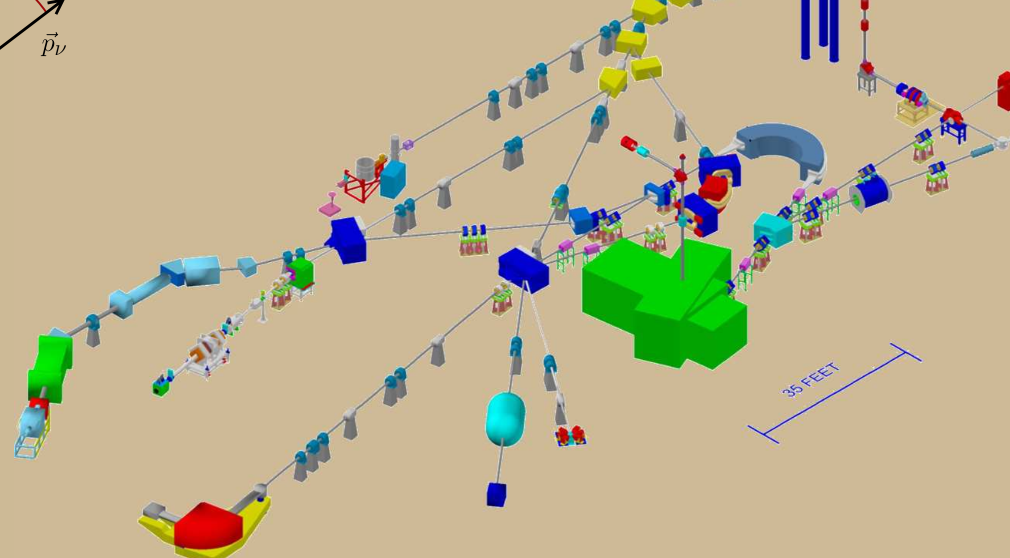
Probing Properties of the Weak Interaction using Trapped Atoms and Ions









Dan Melconian

February 3, 2014

Overview

1. Fundamental symmetries

- what is our **current understanding**?
- how do we test what lies **beyond**?

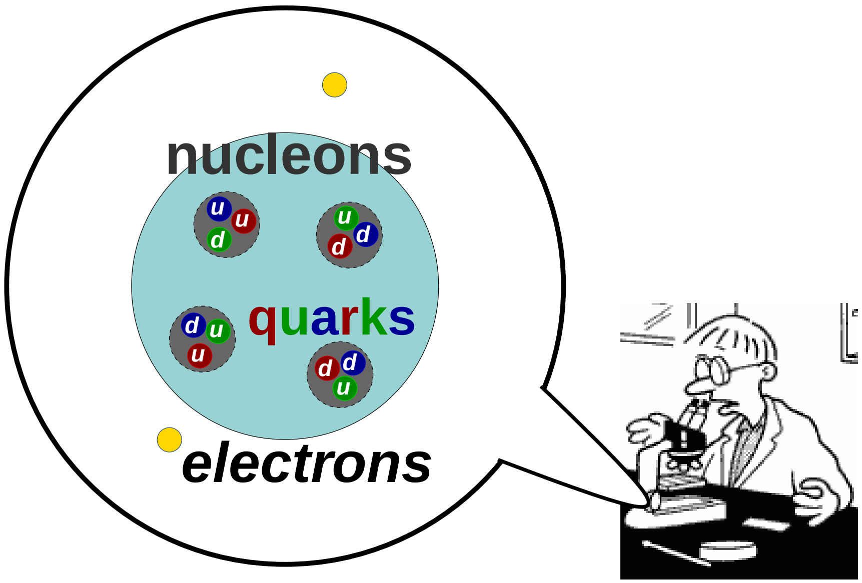
2. TAMU Penning Trap

- **physics** of superallowed β decay
- **ion trapping** of proton-rich nuclei at T-REX

3. TRIUMF Neutral Atom Trap

- angular correlations of **polarized ^{37}K**
- **preliminary results** of a recent run

Scope of fundamental physics



the atom

from the very smallest scales . . .

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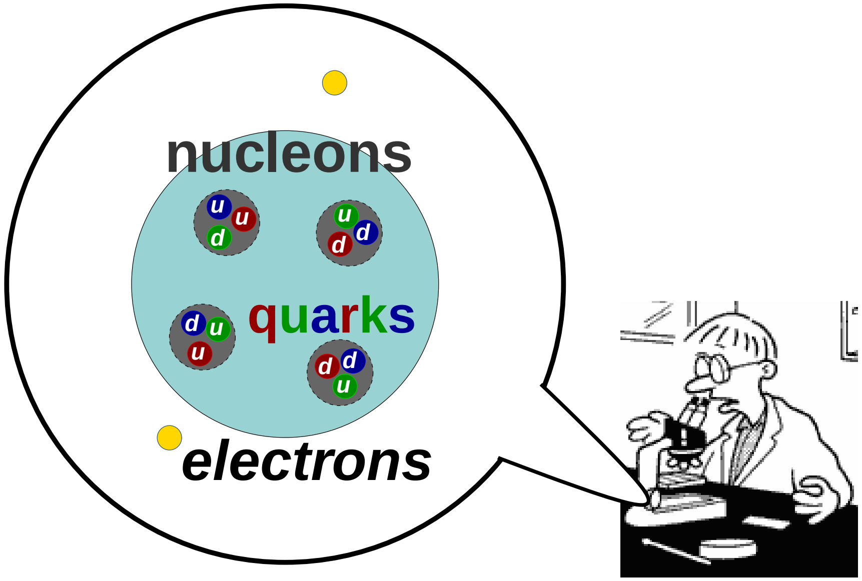

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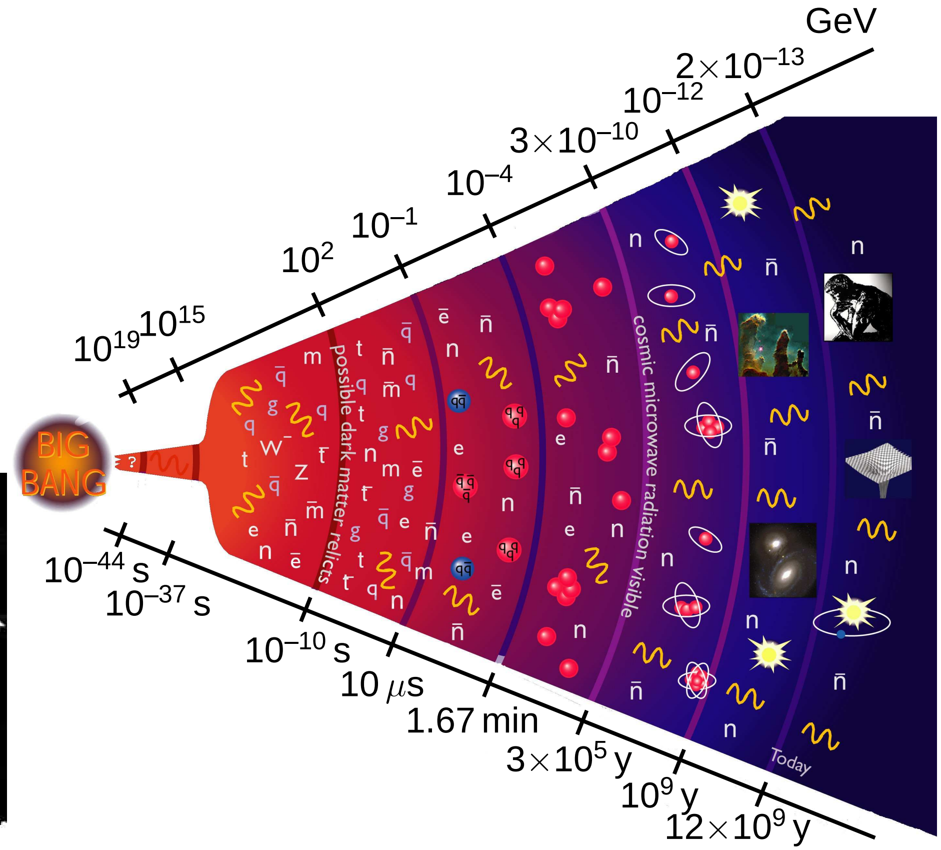

. . . to the very **largest**

The Standard Model

All of the ***known*** elementary particles and their interactions are described within the framework of

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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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- $$\underbrace{SU(3)}_{\text{strong}} \times \overbrace{\underbrace{SU(2)_L}_{\text{weak}} \times \underbrace{U(1)}_{\text{E\&M}}}^{\text{electroweak}} + \underbrace{(\text{classical general rel})}_{\text{gravity}}$$

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- **12 elementary particles**, **4 fundamental forces**

	1st	2nd	3rd	Q	mediator	force
leptons	$\binom{\nu_e}{e}$	$\binom{\nu_\mu}{\mu}$	$\binom{\nu_\tau}{\tau}$	0 -1	g	strong
					$W^\pm$ Z°	weak
quarks	$\binom{u}{d}$	$\binom{c}{s}$	$\binom{t}{b}$	$+2/3$ $-1/3$	γ	EM

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✔ it **predicted** the existence of the $W^{\pm}$, $Z_{\circ}$, g, c and t

$\rightsquigarrow$ and now **the Higgs!**

✔ is a **renormalizable** theory

✔ GSW $\Rightarrow$ **unified** the **weak** force with **electromagnetism**

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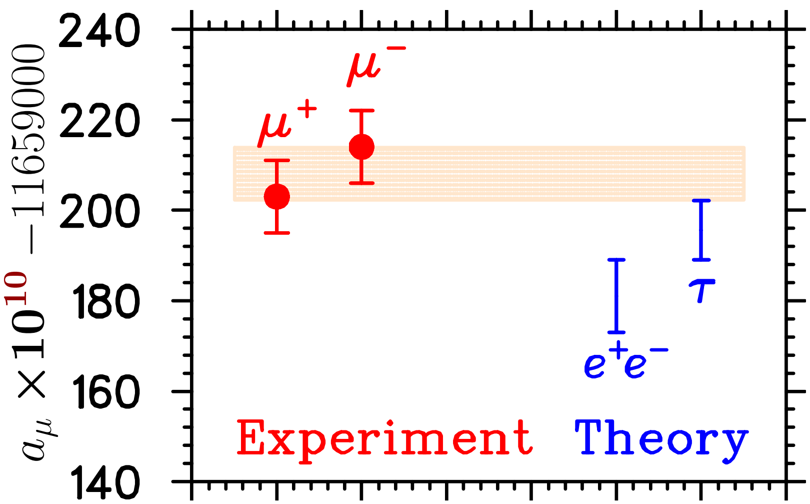

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± 1 **part-per-*million*!!**

(PRL **92** (2004) 161802)

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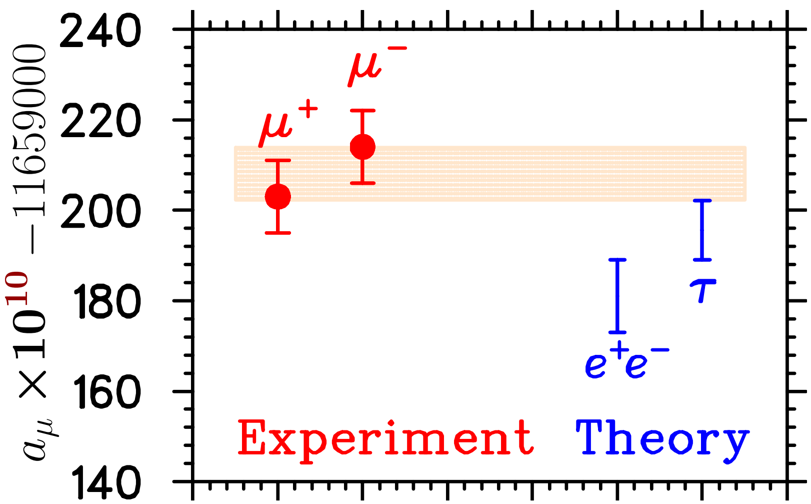

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Wow . . . this is

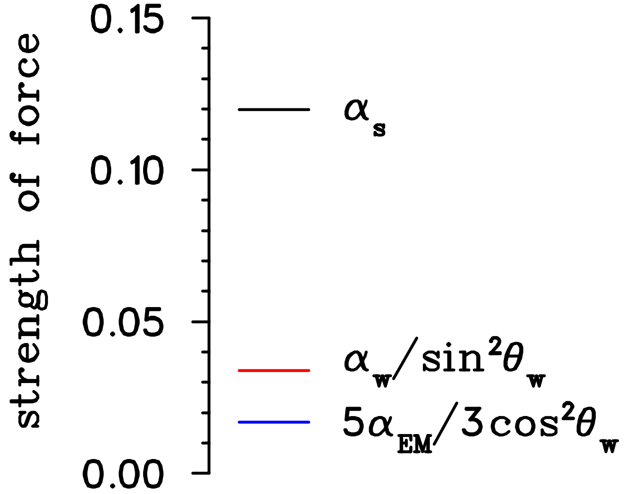
the most precisely tested theory ever conceived!

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 **only 4%** 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 can't forget about a **quantum** description of **gravity**!

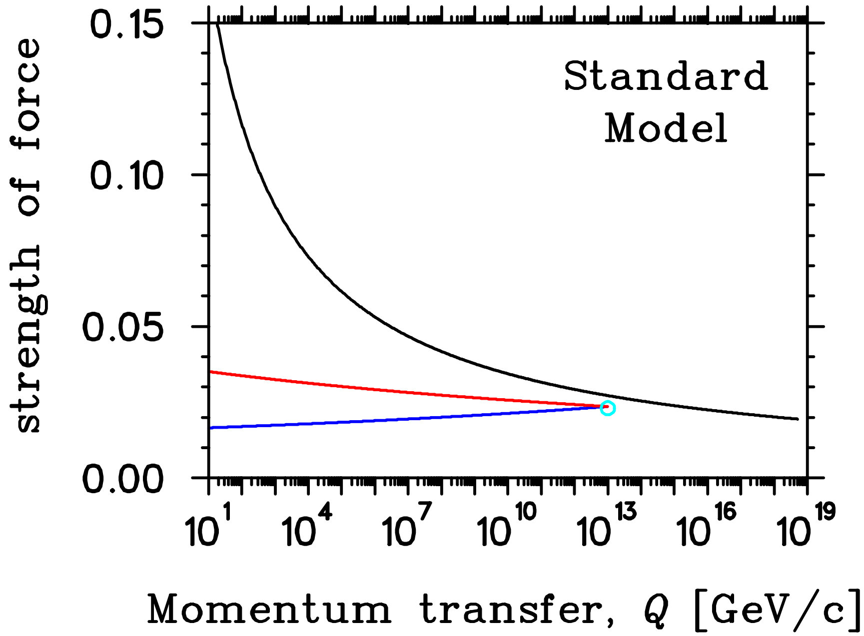
Beyond the Standard Model

At our energy scales, we see four distinct forces . . .



Beyond the Standard Model

But these coupling ‘constants’ **aren’t** really *constant*: $\alpha_i \longrightarrow \alpha_i(Q)$

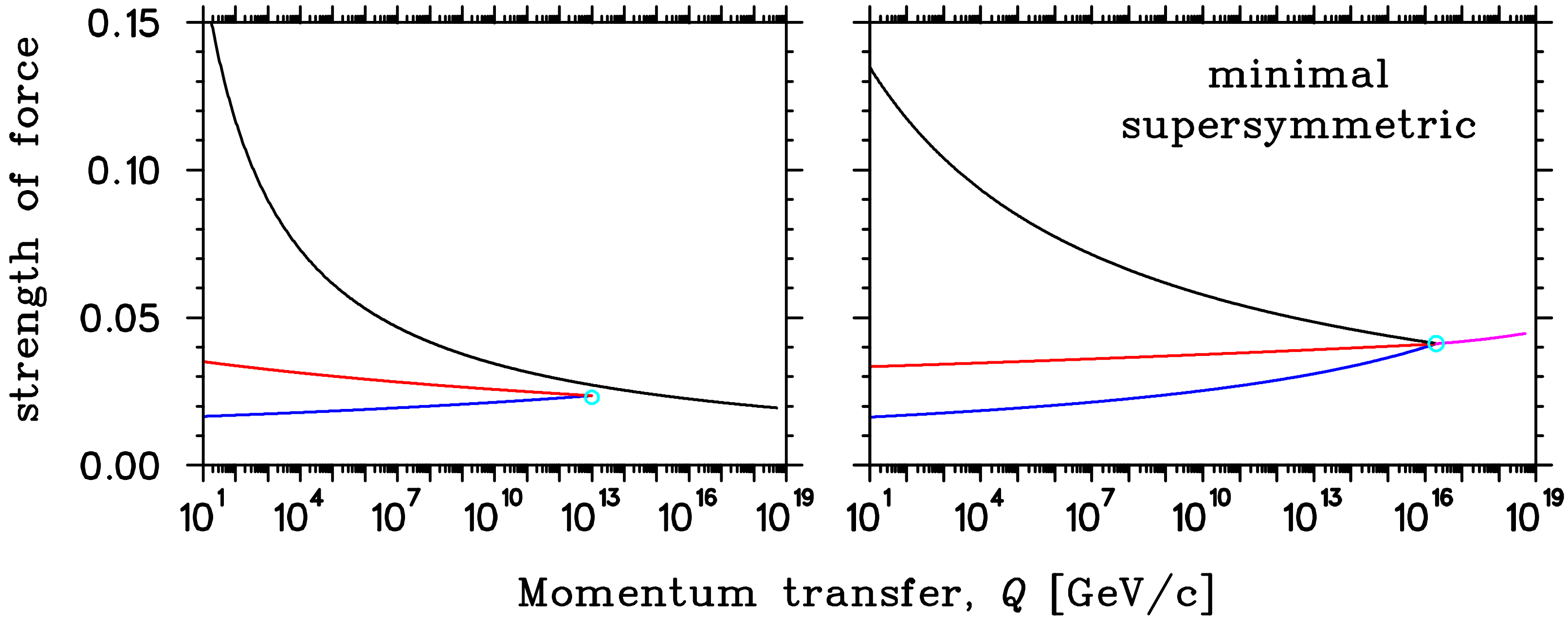


→ electromagnetic and weak strengths equal at $\approx 10^{13}$ GeV

→ strong force gets weaker, but doesn’t unify with EW. . . .

Beyond the Standard Model

But what if there is **new physics** we haven't seen yet?



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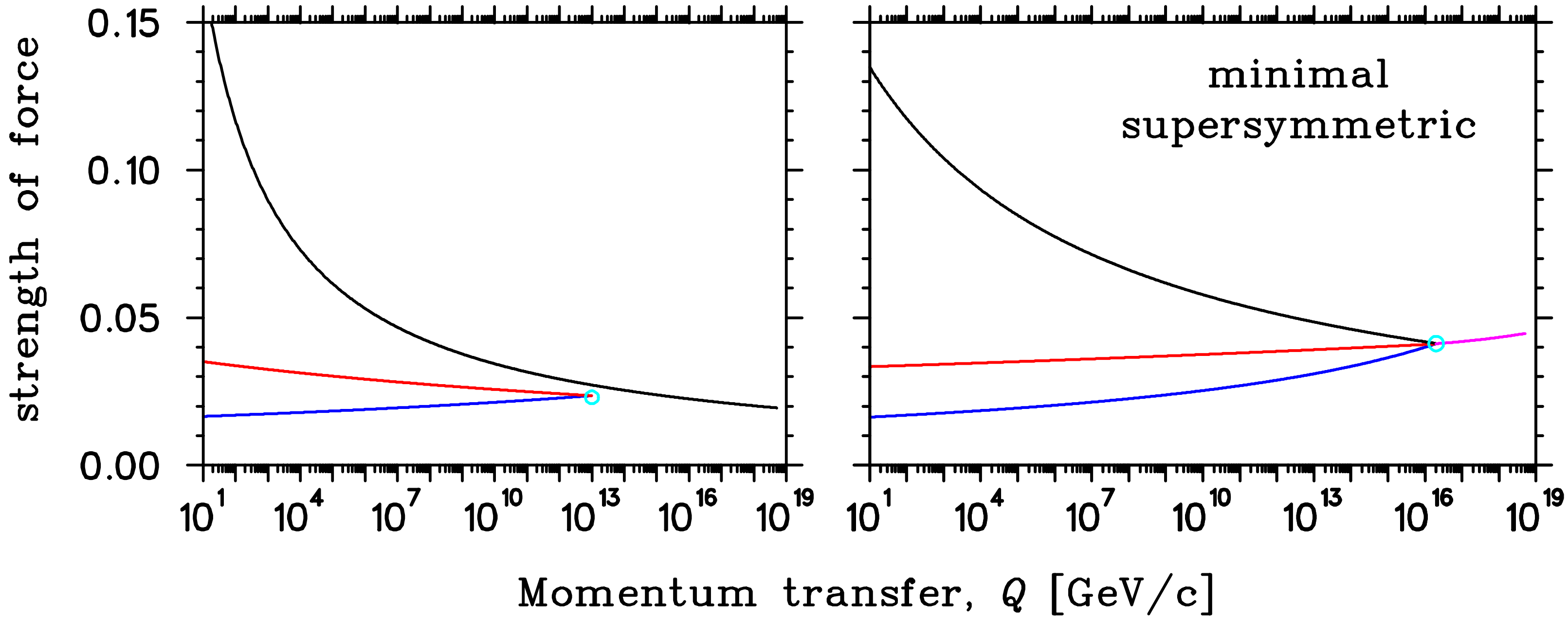

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Are the three theories of **E & M**, **weak** and **strong** interactions all **low-energy limits** of **one unifying** theory?

How do we test the SM?

- **colliders**: CERN, SLAC, FNAL, BNL, KEK, DESY . . .
- **nuclear physics**: traps, exotic beams, neutron, EDMs, $0\nu\beta\beta$, . . .
- **cosmology** & **astrophysics**: SN1987a, Big Bang nucleosynthesis, . . .
- **muon decay**: Michel parameters: ρ, δ, η, and ξ
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- different experiments probe different (new) physics
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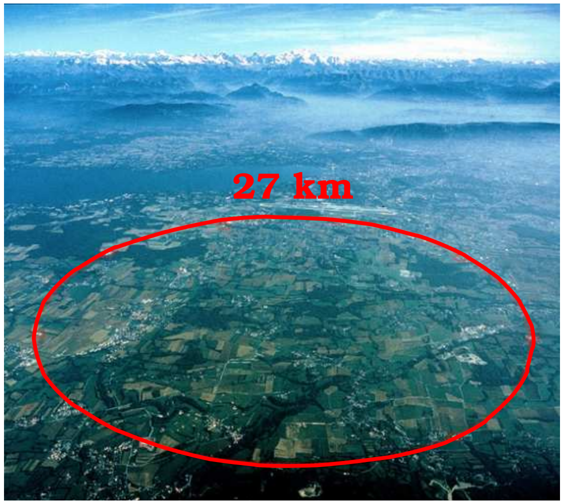
often they are **interdisciplinary**

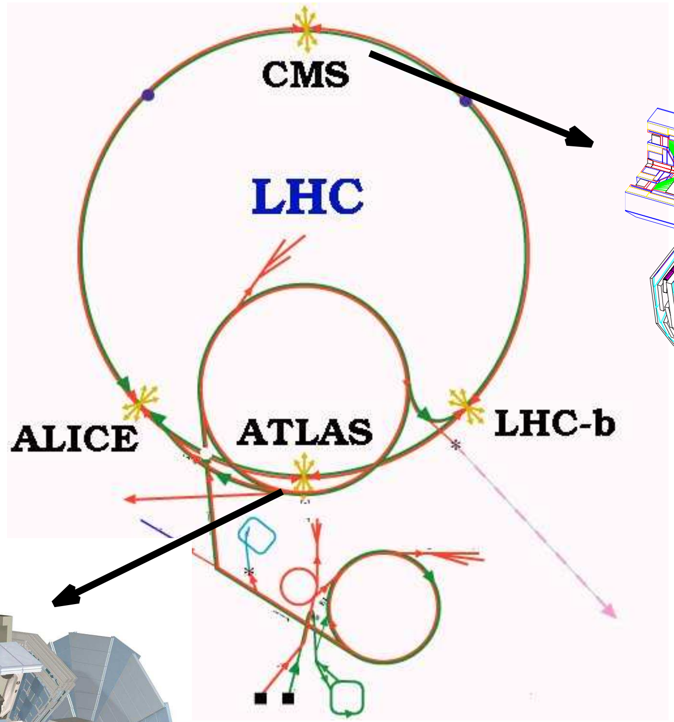
(fun and a great basis for graduate students!)

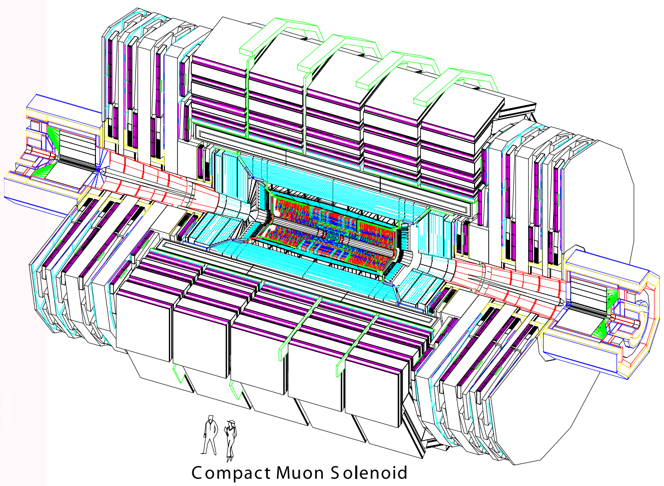
How does high-energy test the SM?

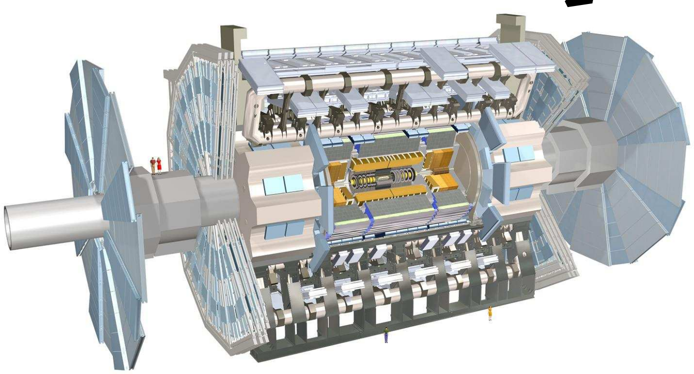
colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, ...

direct search of particles









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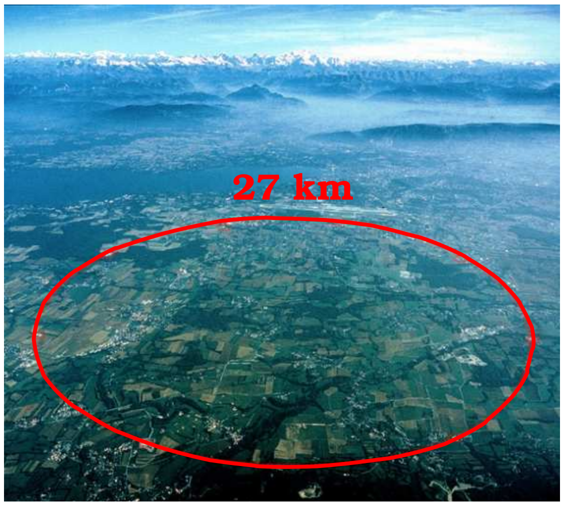
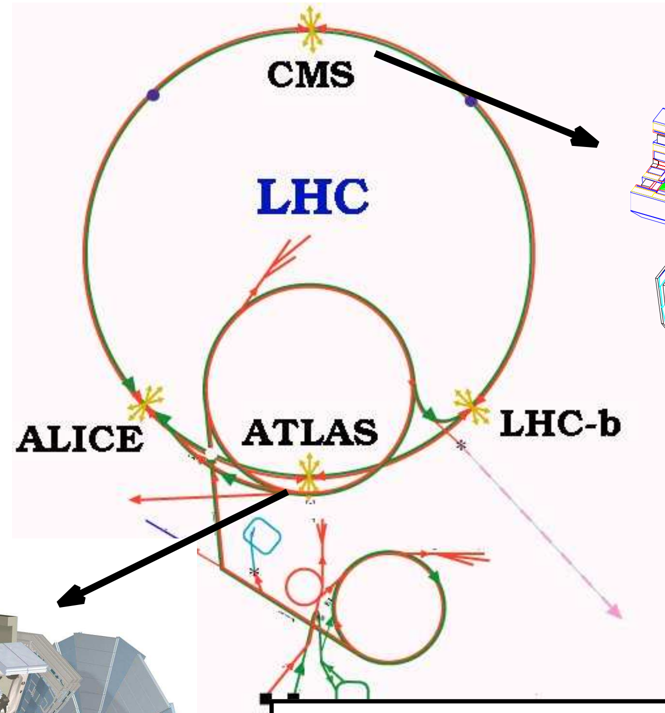
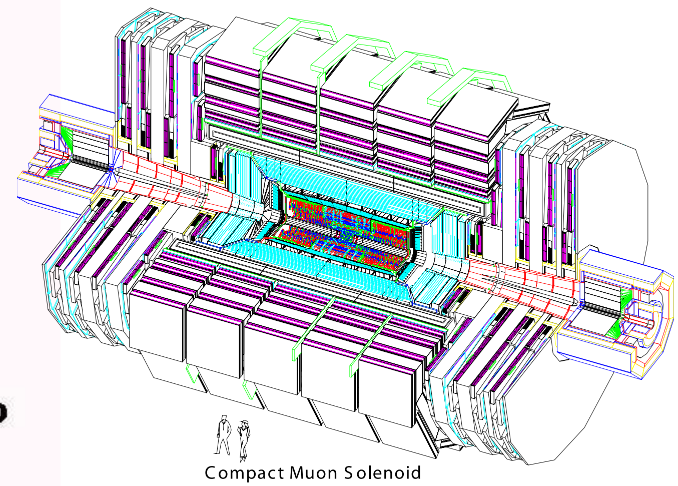
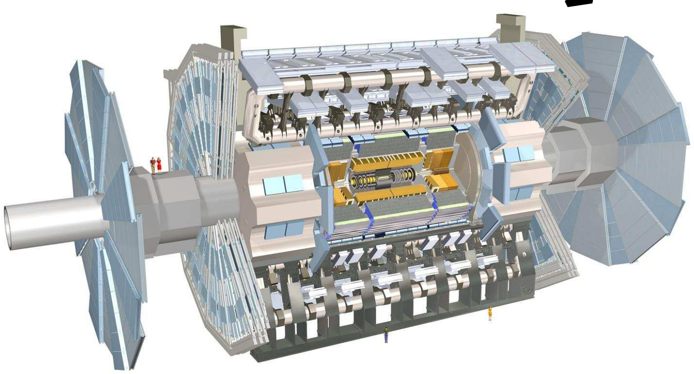








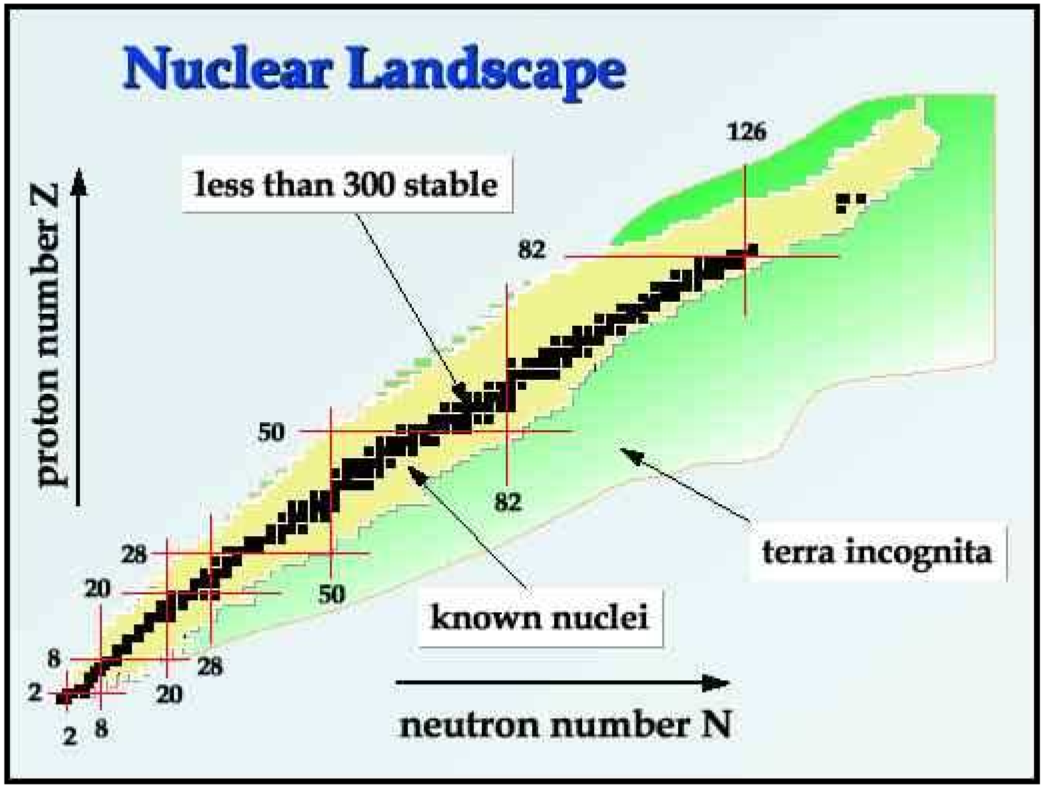
"go **big** or go home"

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

Ways we can test the SM?

nuclear physics: radioactive ion beam facilities

indirect search via precision measurements



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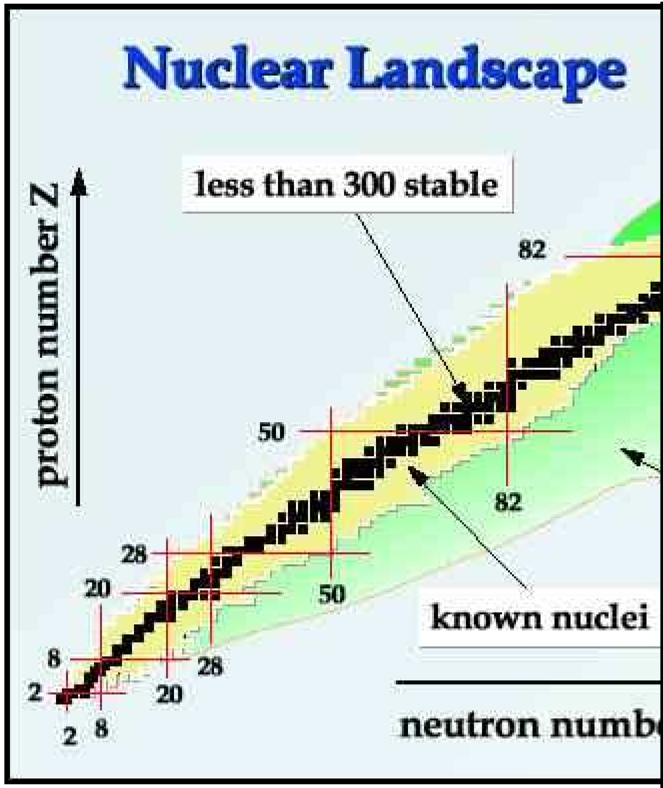

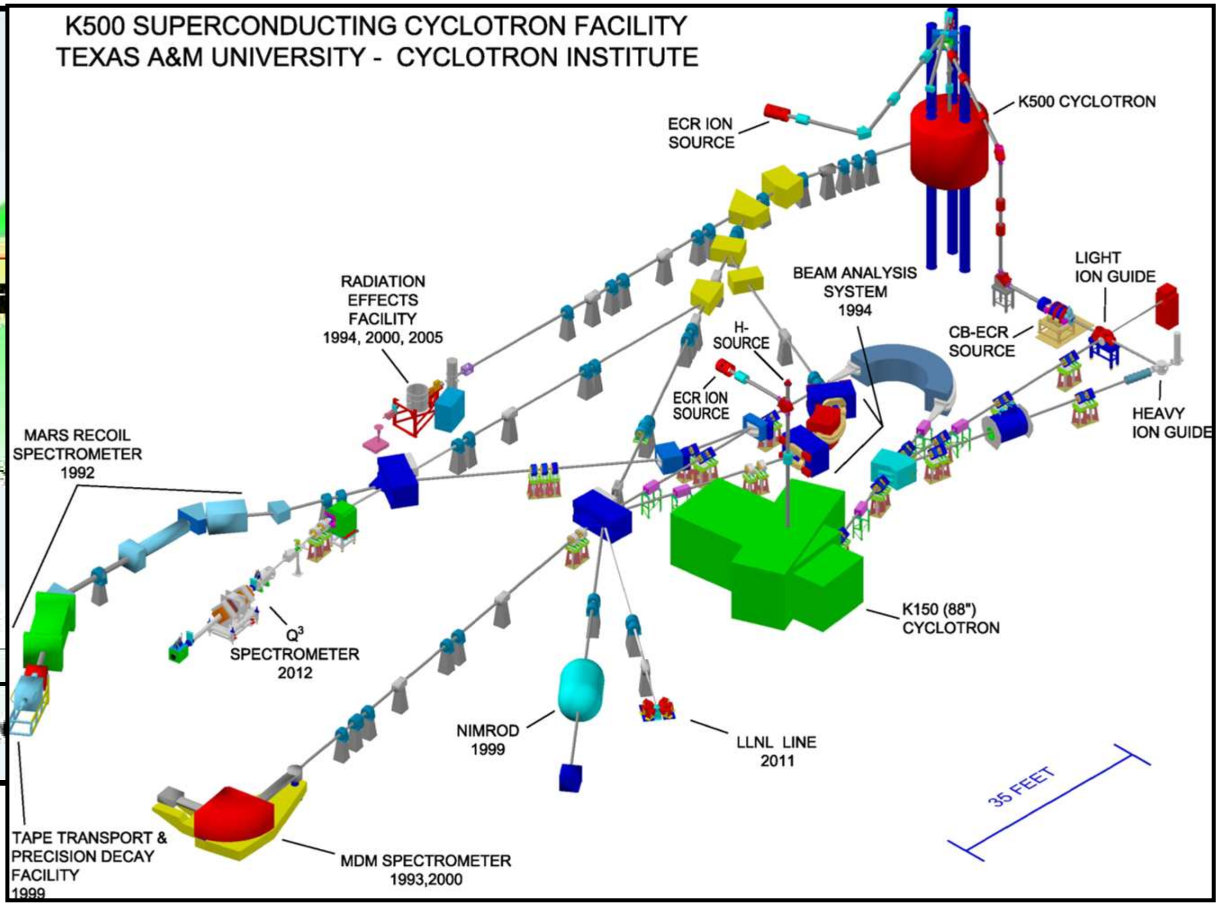

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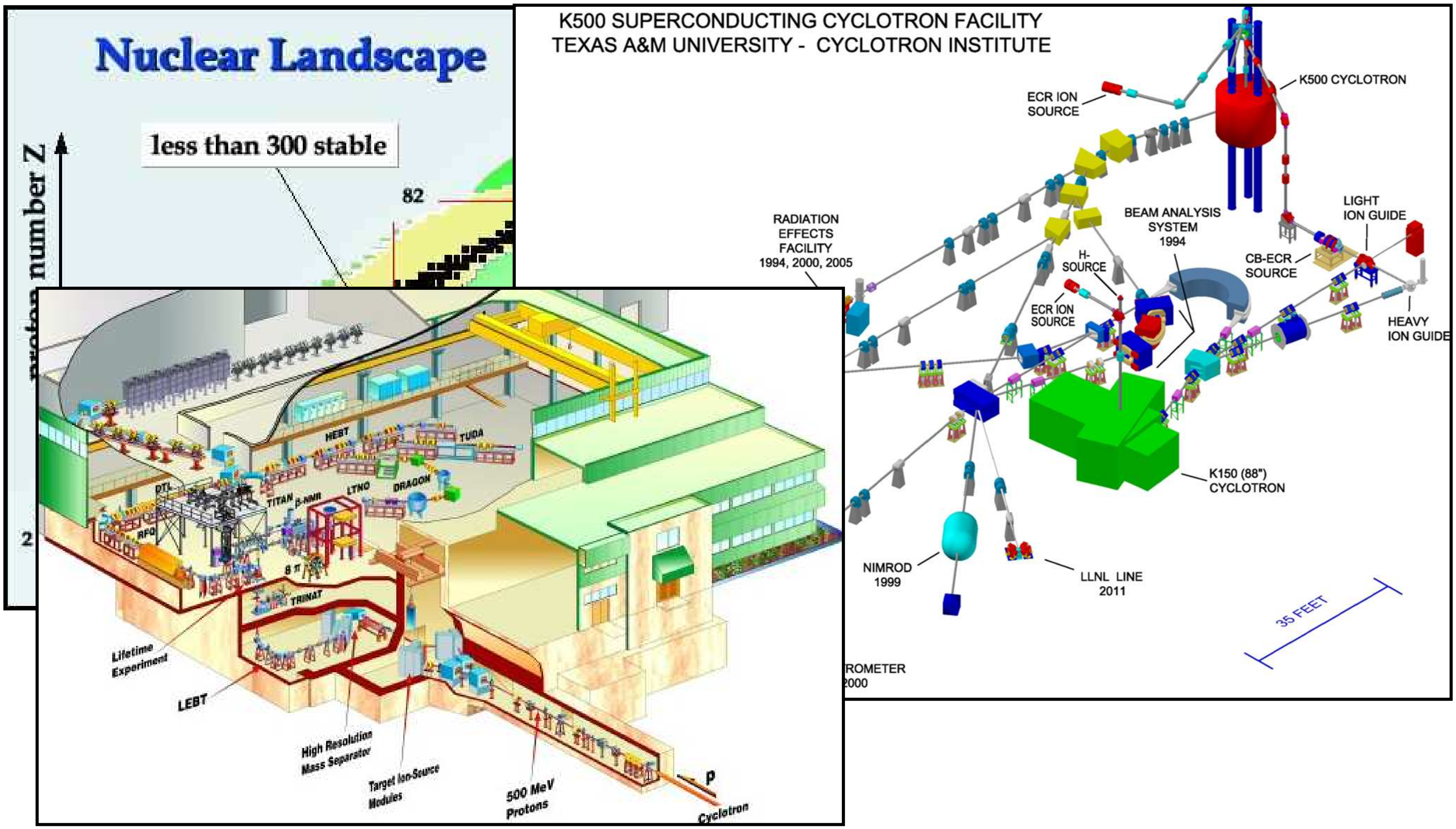

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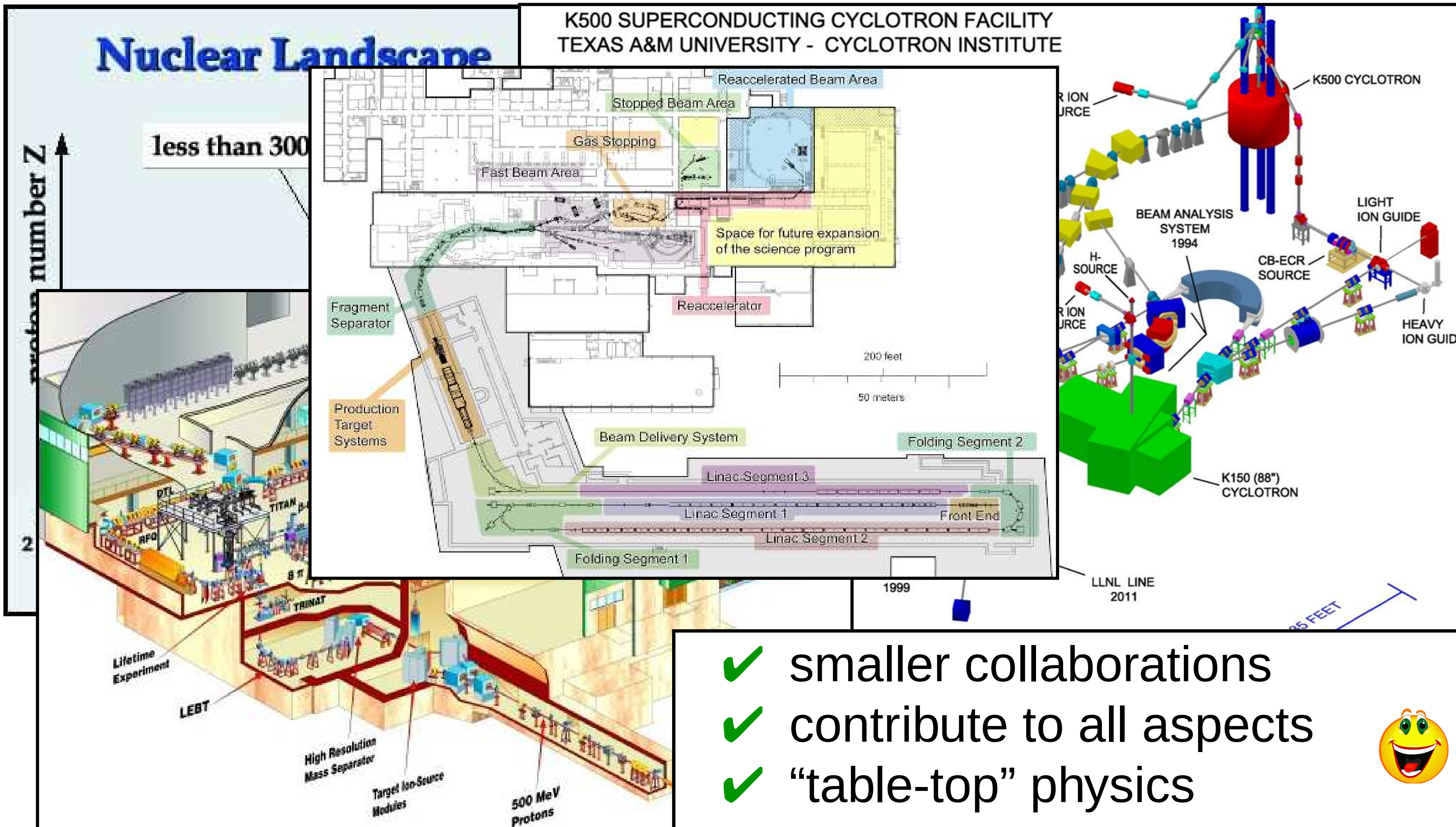
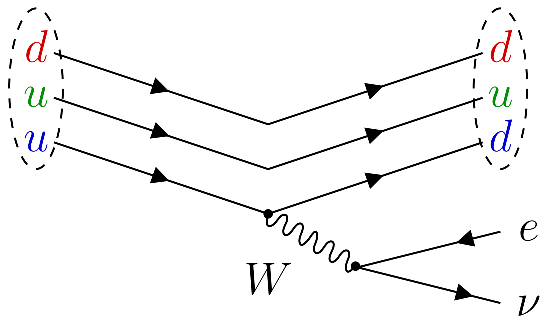
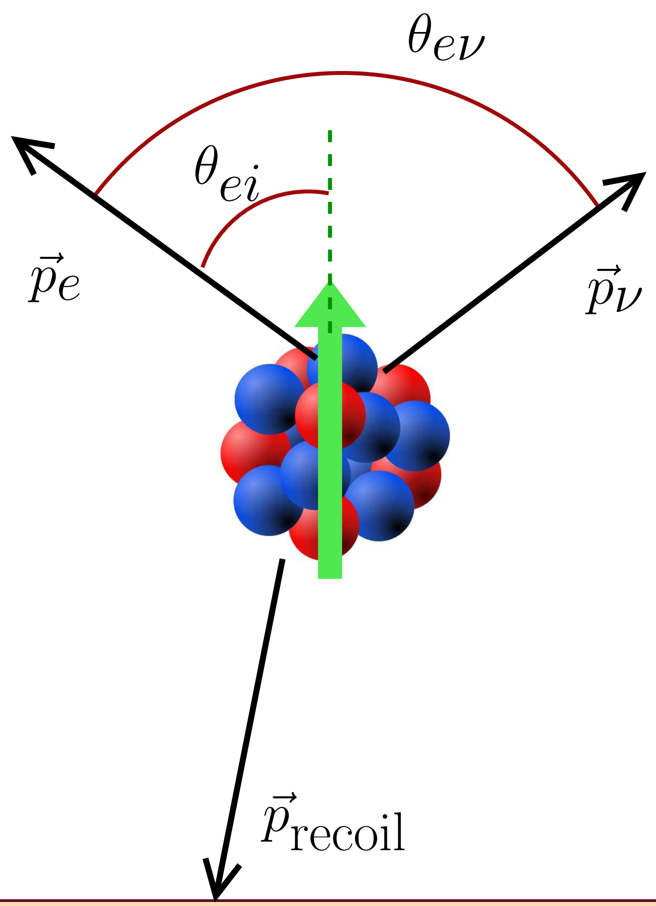


- ✔ smaller collaborations
- ✔ contribute to all aspects
- ✔ “table-top” physics

How do I plan to test the SM?





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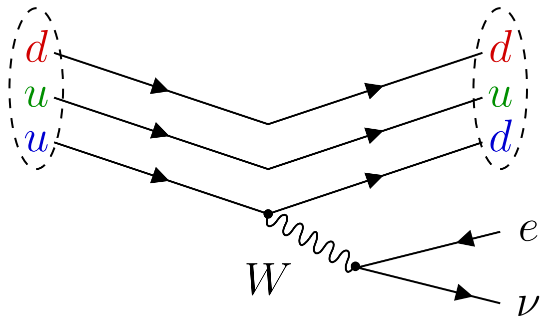

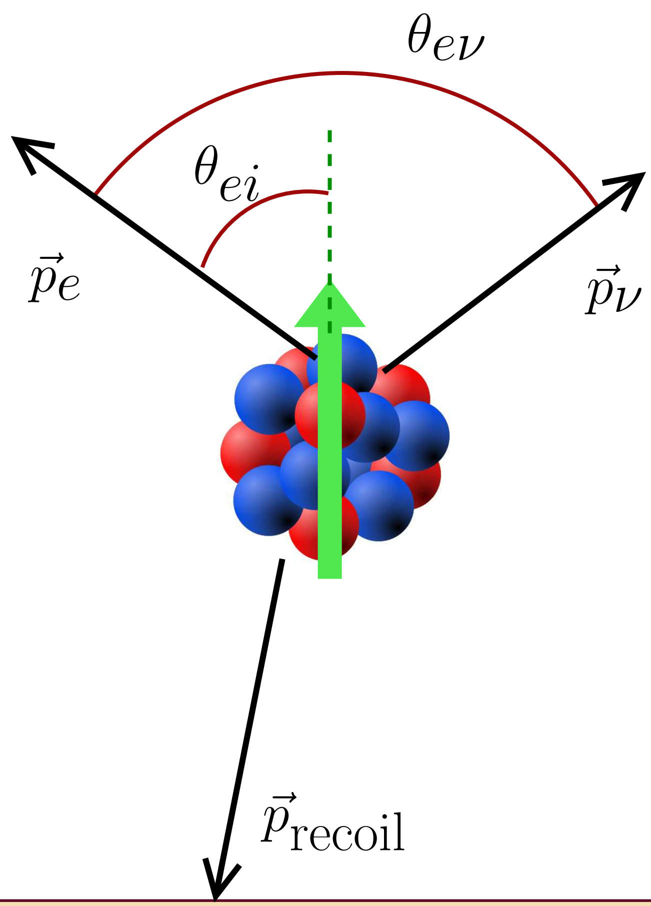

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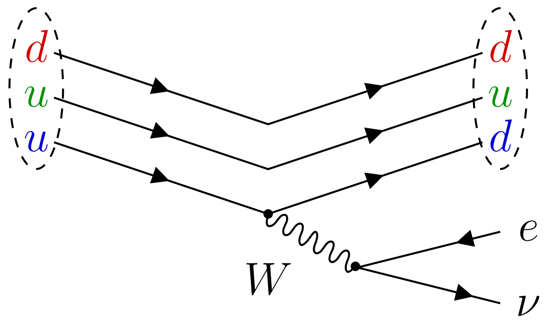

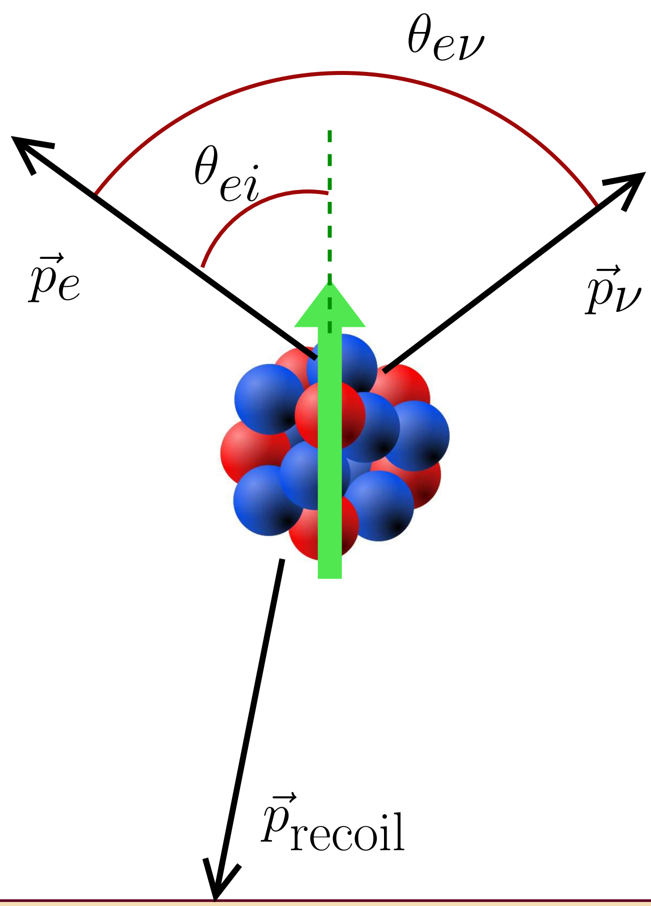

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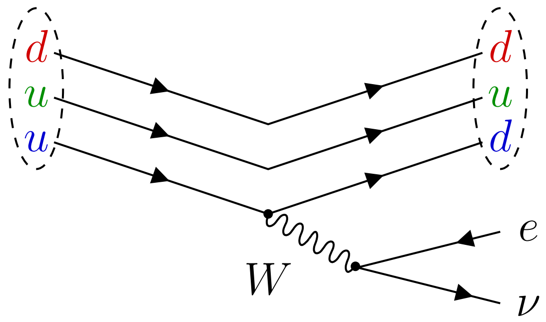

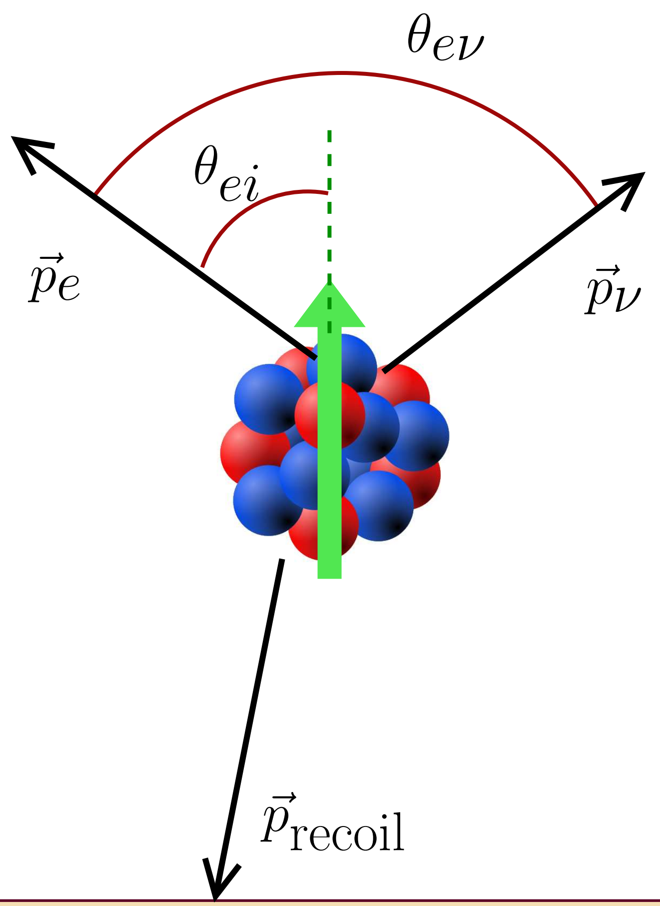

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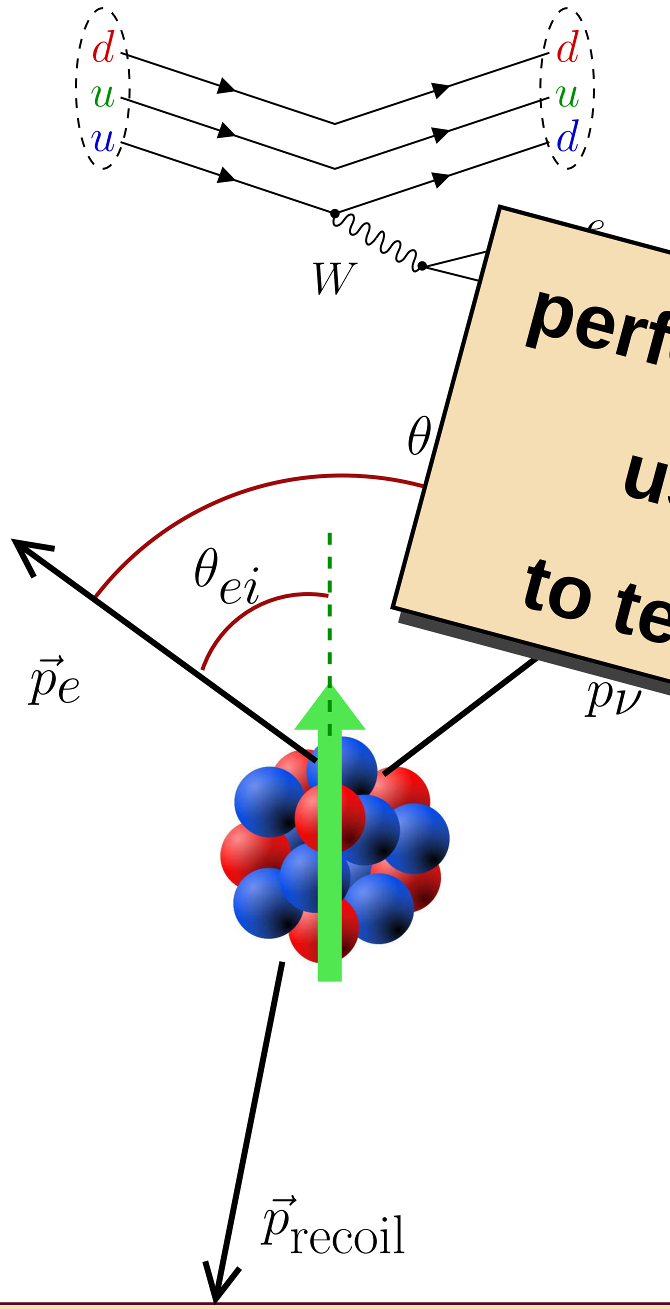

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- precision measurement ... relation param-

- ... ons to observa...

perform a nuclear measurement using atomic techniques to test high-energy theories!

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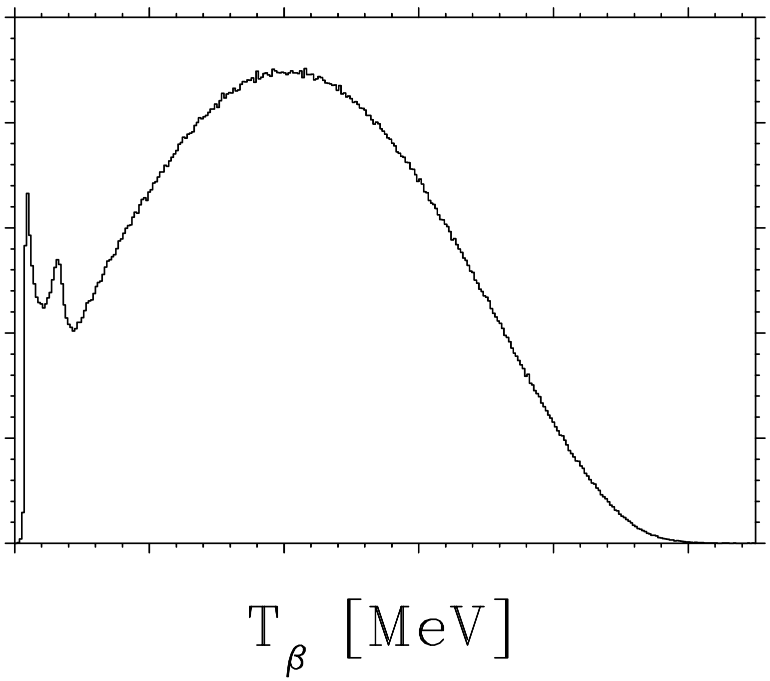
A little more specifically. . .

Test SM via the **angular distribution** of β decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}}$$



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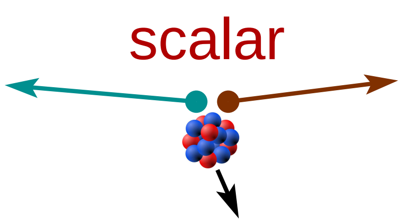

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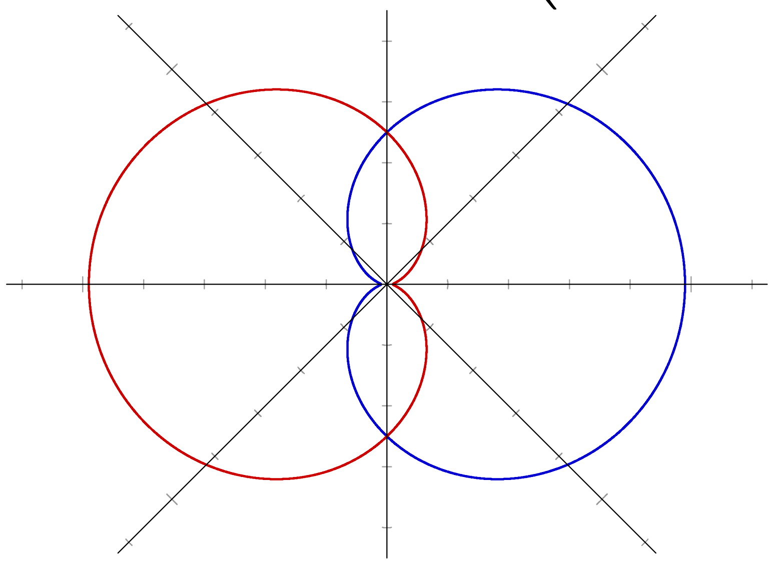

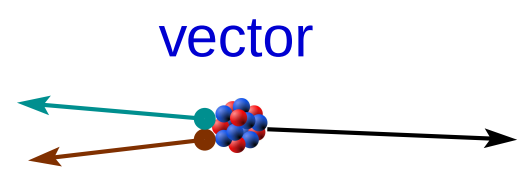

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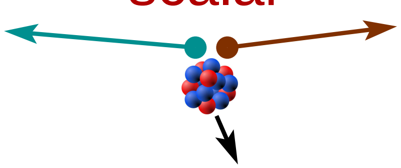
scalar



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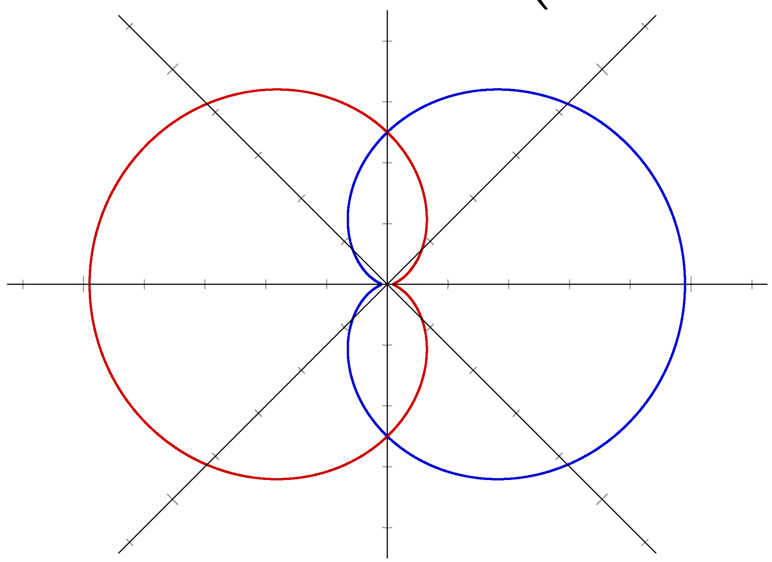
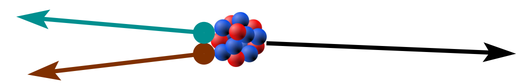


vector



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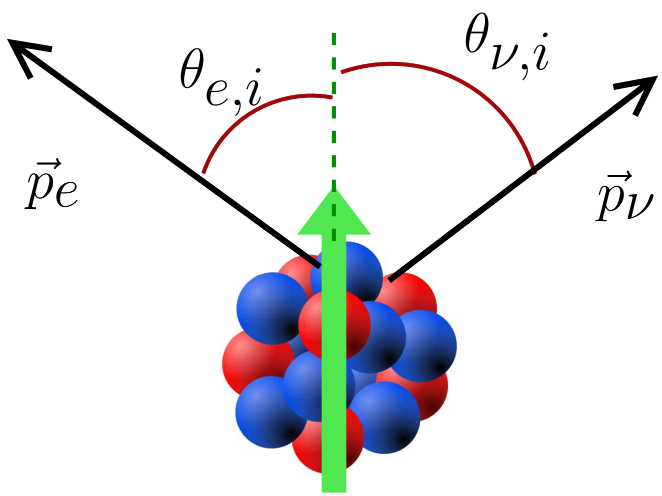
A little more specifically. . .

Test SM via the **angular distribution** of β decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{b \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} + \frac{\langle \vec{I} \rangle}{I} \cdot \left[\underbrace{A_\beta \frac{\vec{p}_e}{E_e}}_{\beta \text{ asym}} + \underbrace{B_\nu \frac{\vec{p}_\nu}{E_\nu}}_{\nu \text{ asym}} + \underbrace{D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}}_{T\text{-violating}} \right] \right)$$



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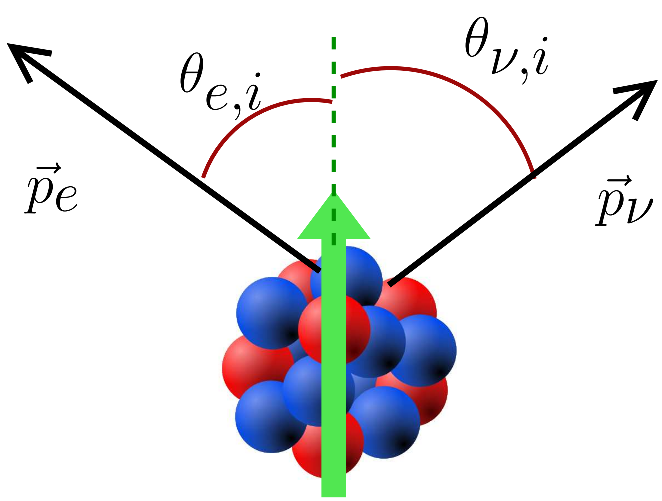

$$A_\beta = \frac{-2\rho}{1+\rho^2} \left[(1 - xy) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right]$$

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

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

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β-decay parameters depend on the currents mediating the weak interaction

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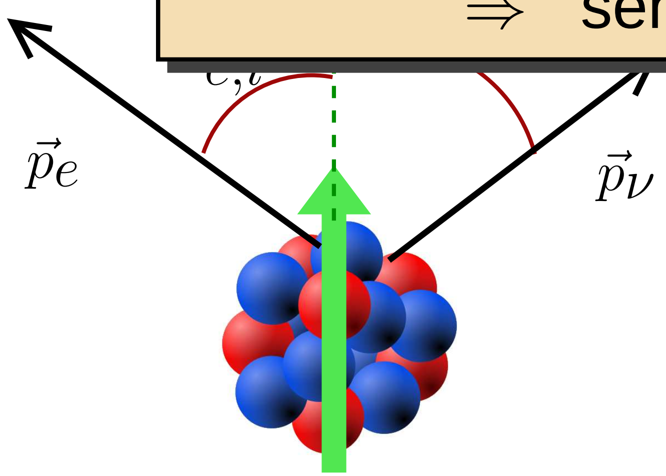

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Goal must be **0.1%** to complement LHC

see Profumo, Ramsey-Musolf and Tulin, PRD **75** (2007)
and Cirigliano, González-Alonso and Graesser, JHEP **1302** (2013)

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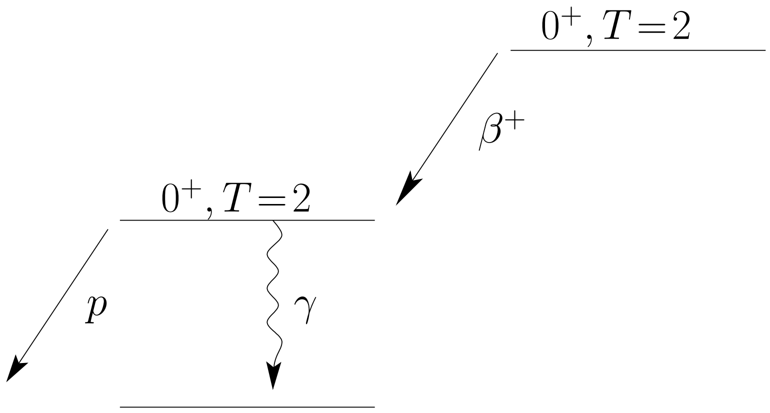

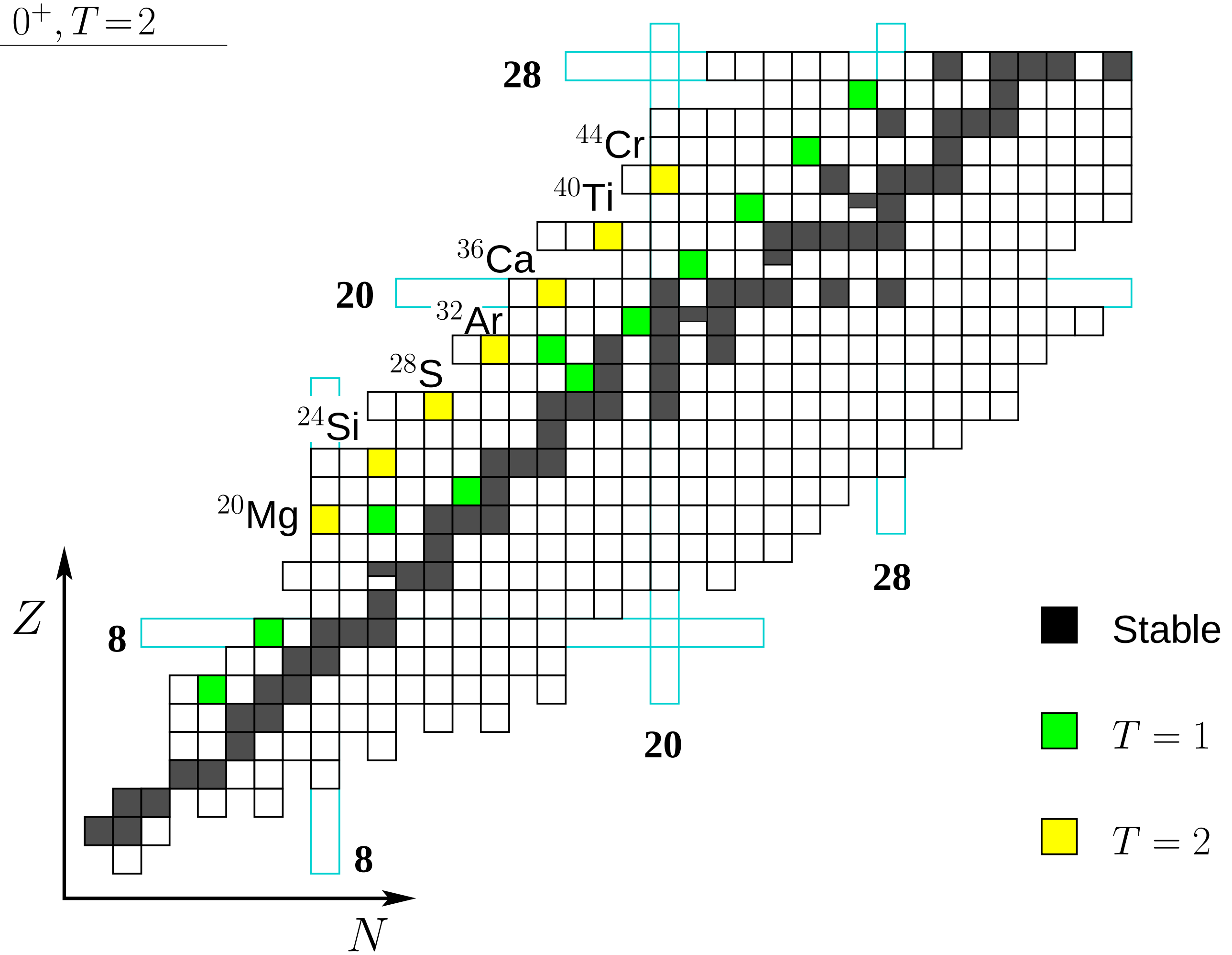

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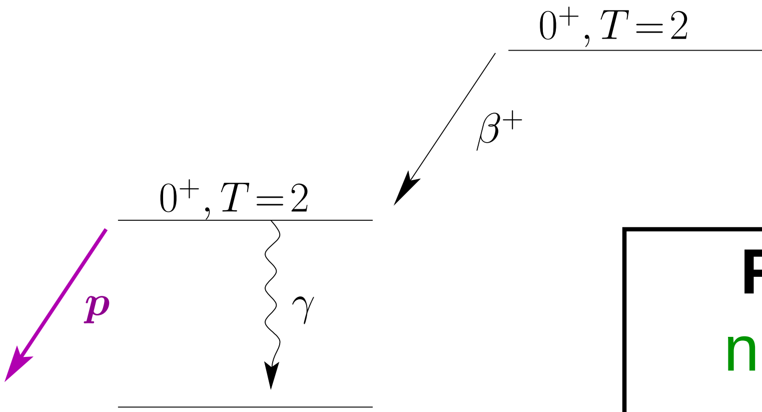
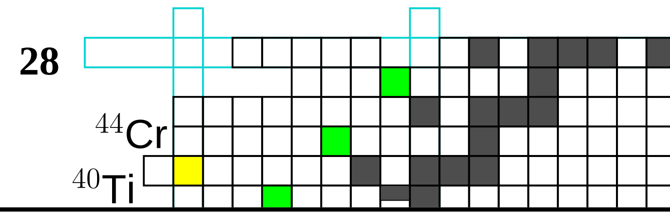
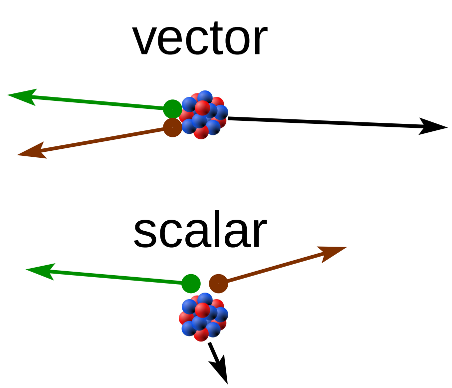
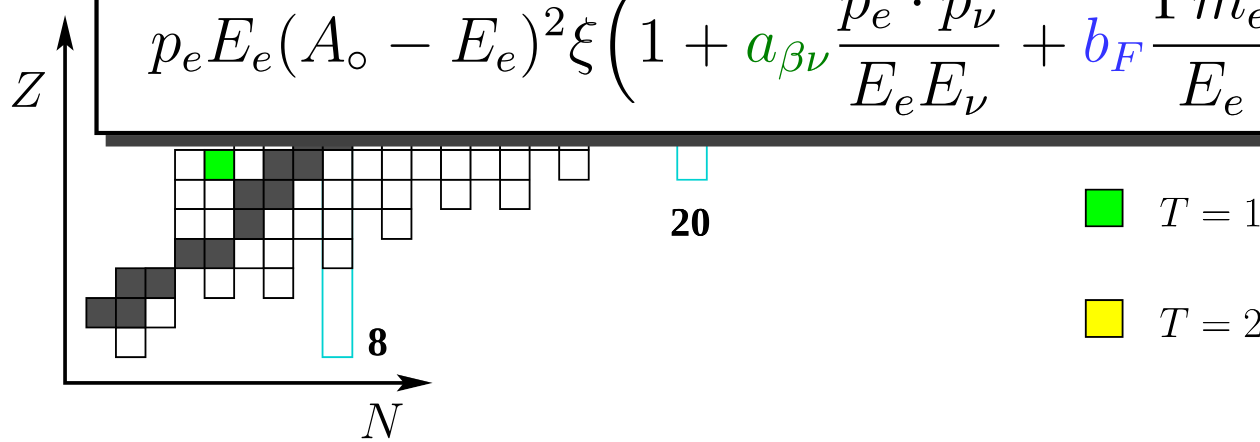




Recall: pure Fermi decay $\Leftrightarrow$ minimal nuclear structure effects; decay rate is simply given by:

$$p_e E_e (A_\circ - E_e)^2 \xi \left(1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e}\right)$$





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$\beta - \nu$ correlation from ^{32}Ar

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of ^{32}Ar

E. G. Adelberger,[1] C. Ortiz,[2] A. García,[2] H. E. Swanson,[1] M. Beck,[1] O. Tengblad,[3] M. J. G. Borge,[3] I. Martel,[4]
H. Bichsel,[1] and the ISOLDE Collaboration[4]
[1]*Department of Physics, University of Washington, Seattle, Washington 98195-1560*
[2]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[3]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[4]*EP Division, CERN, Geneva, Switzerland CH-1211*
(Received 24 February 1999)

The positron-neutrino correlation in the $0^+ \rightarrow 0^+$ β decay of ^{32}Ar was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the standard model prediction. For vanishing Fierz interference we find $a = 0.9989 \pm 0.0052 \pm 0.0039$, which yields improved constraints on scalar weak interactions.

Doppler shape of delayed proton depends on $\vec{p}_e \cdot \vec{p}_\nu$!

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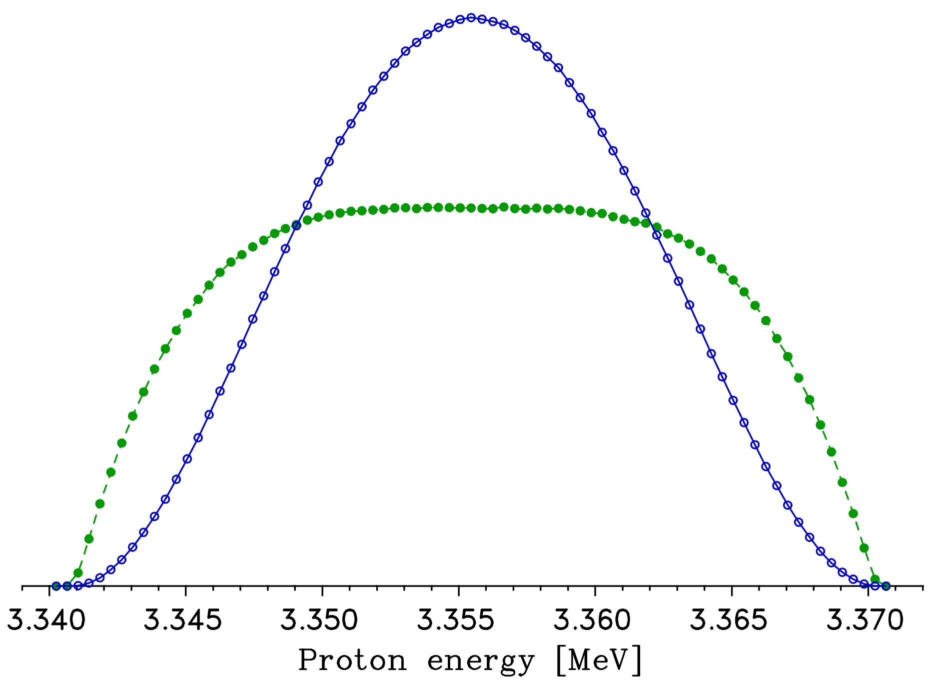

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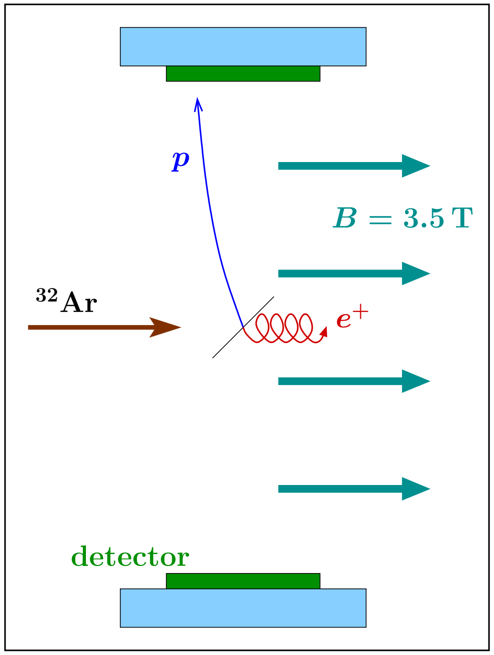

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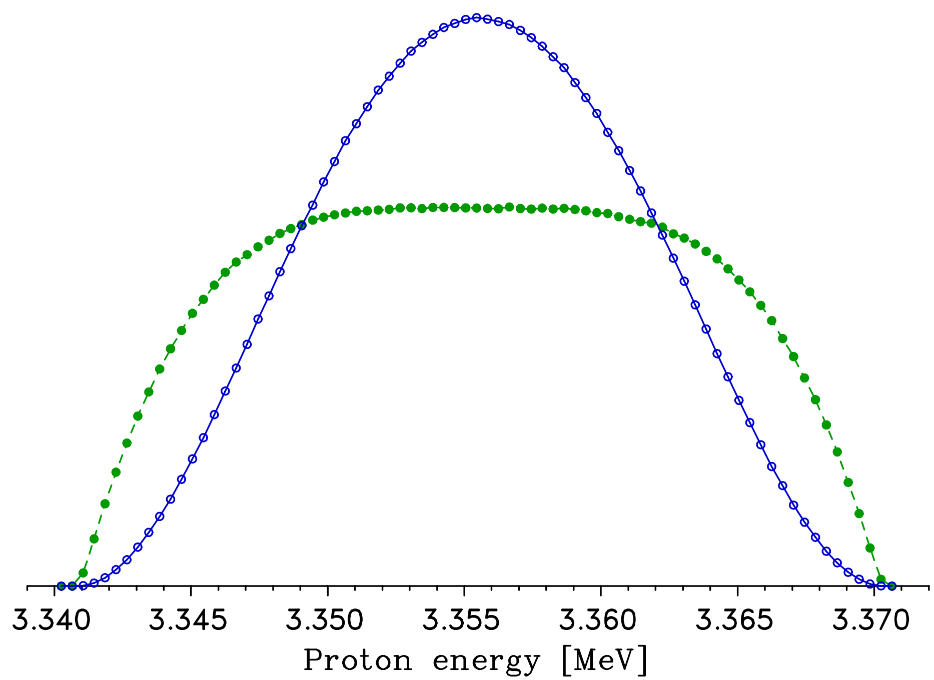

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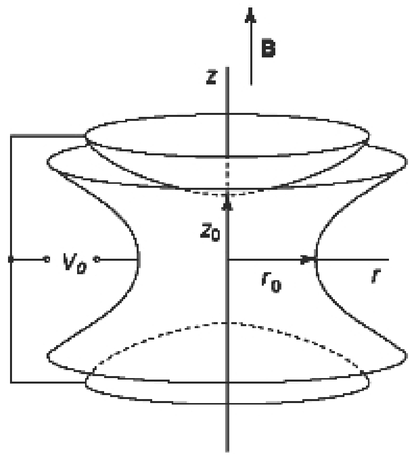

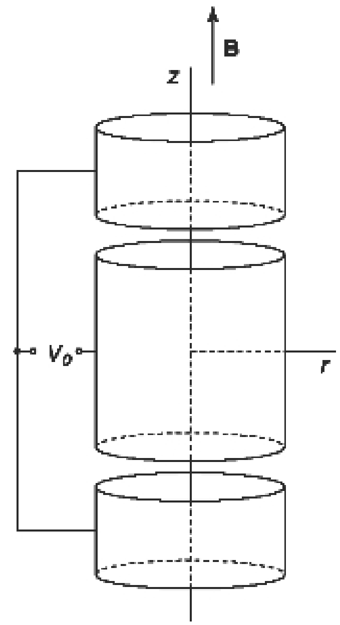

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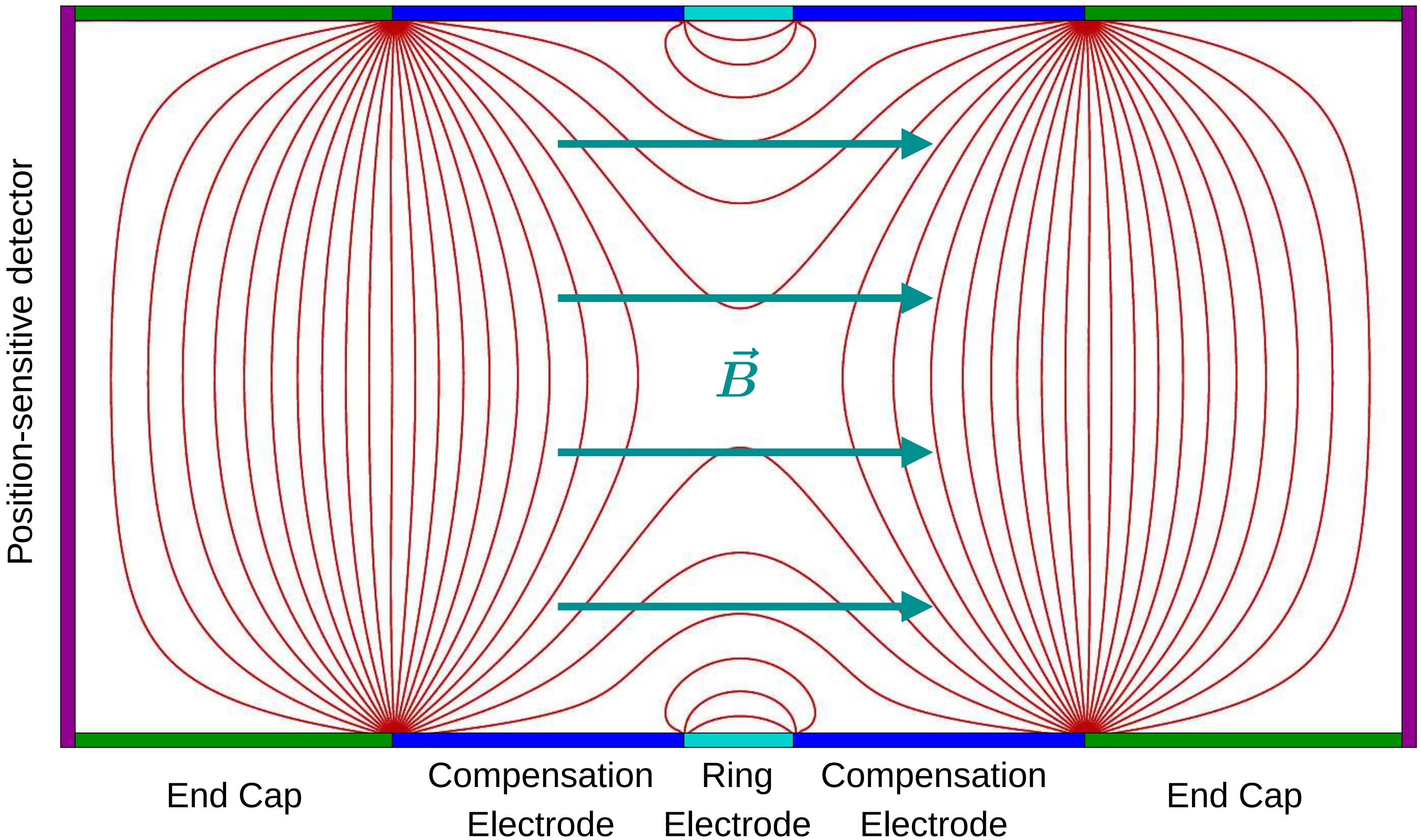

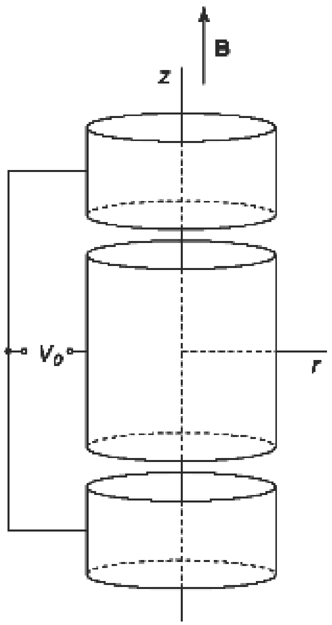

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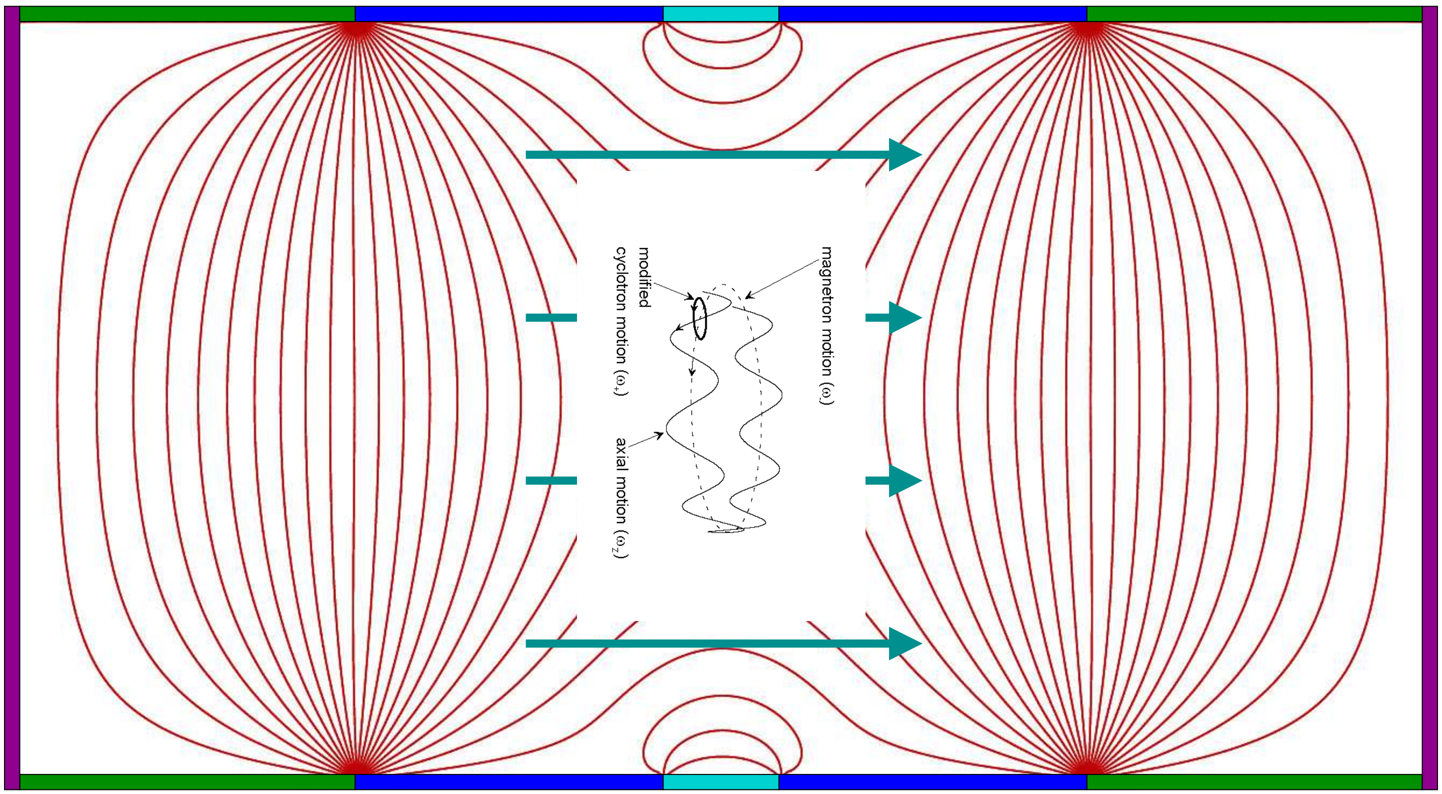
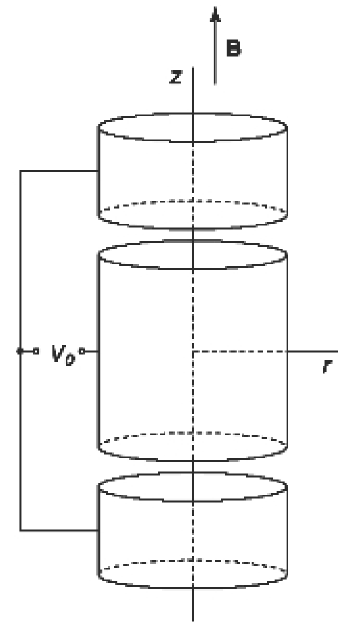
Position-sensitive detector



End Cap | Compensation Electrode | Ring Electrode | Compensation Electrode | End Cap



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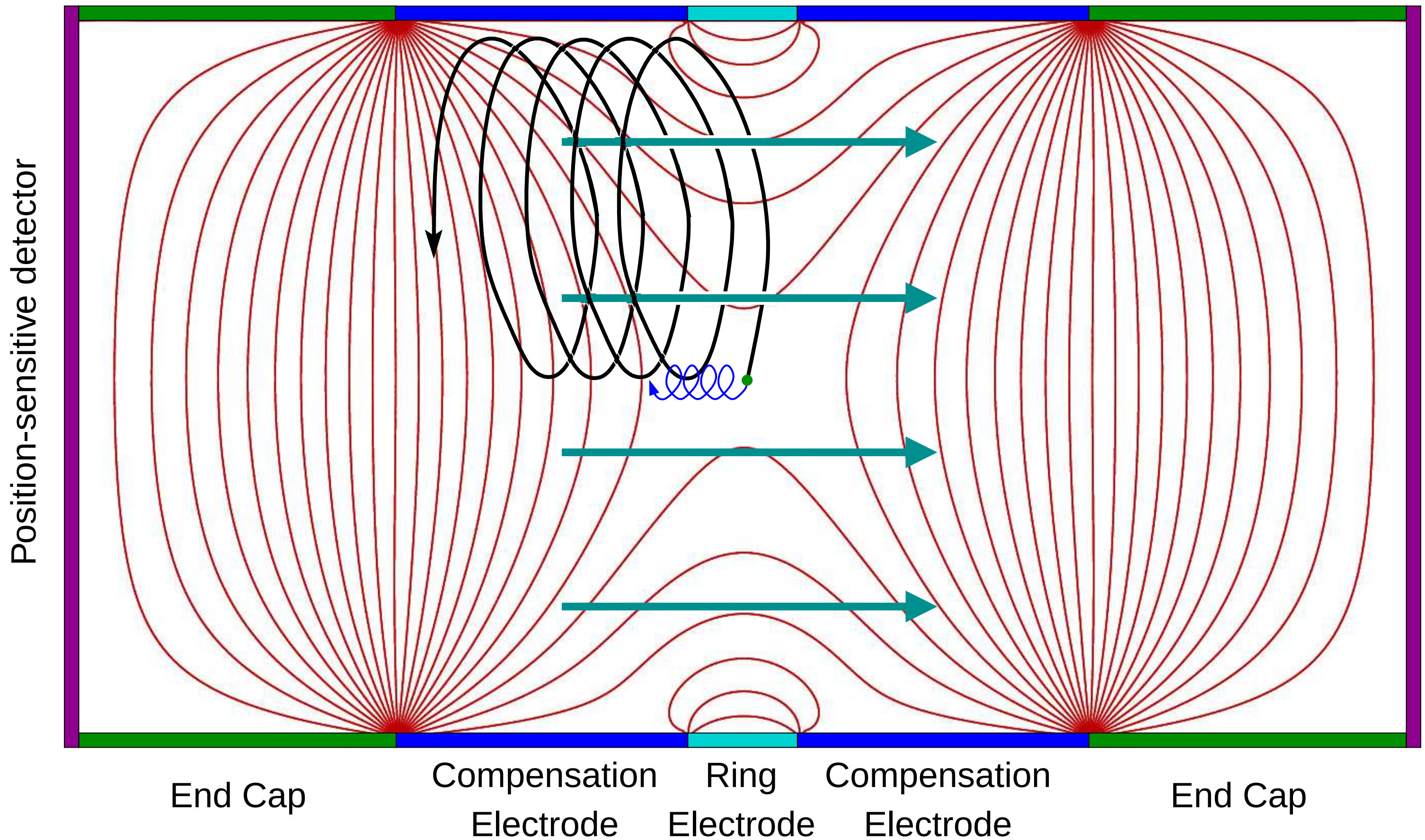

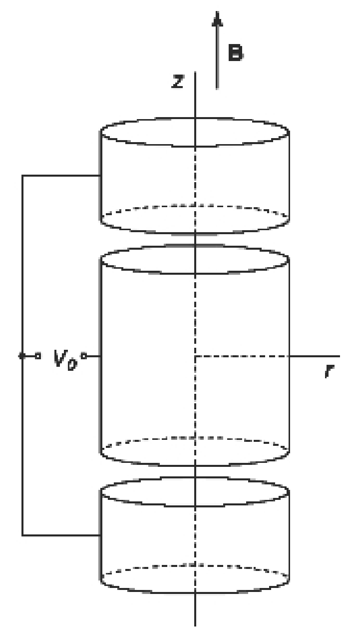

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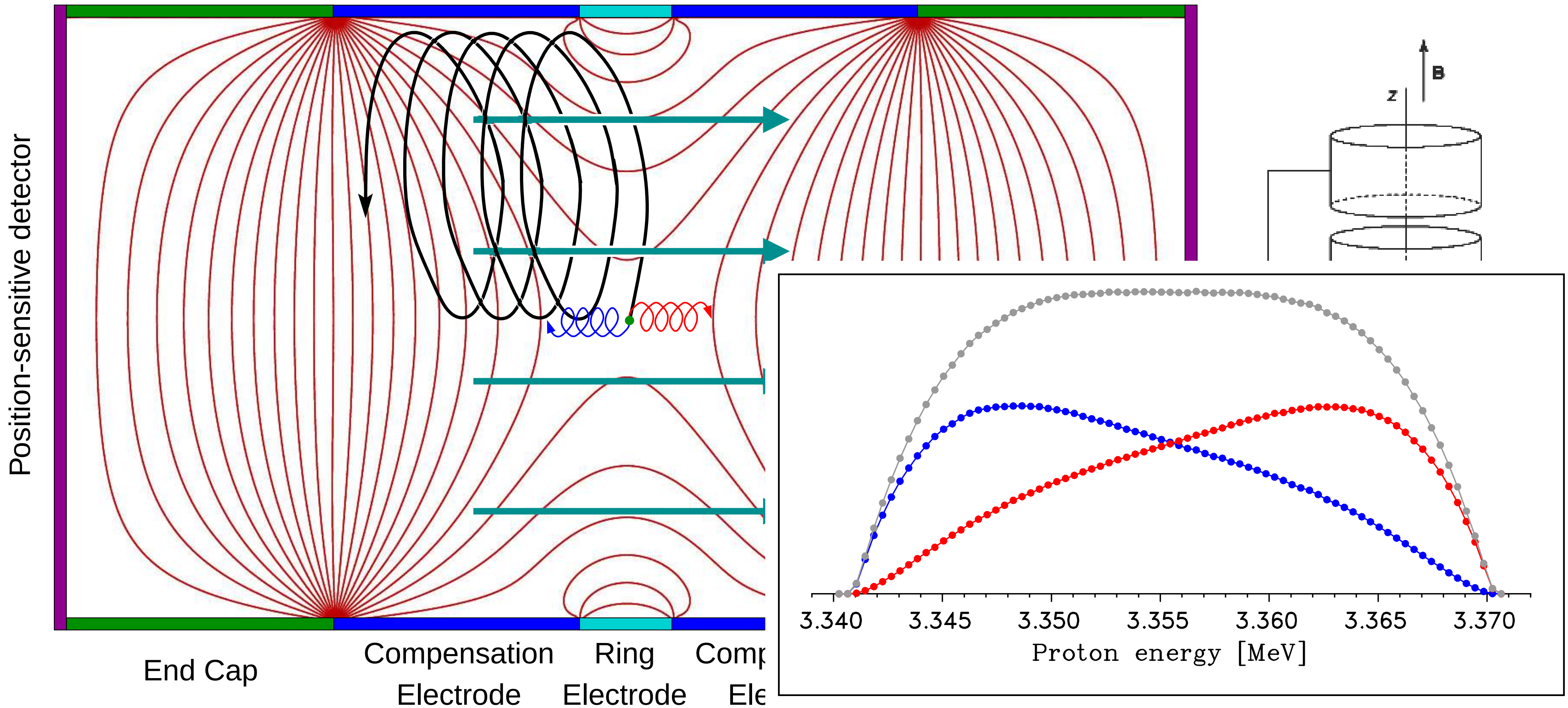
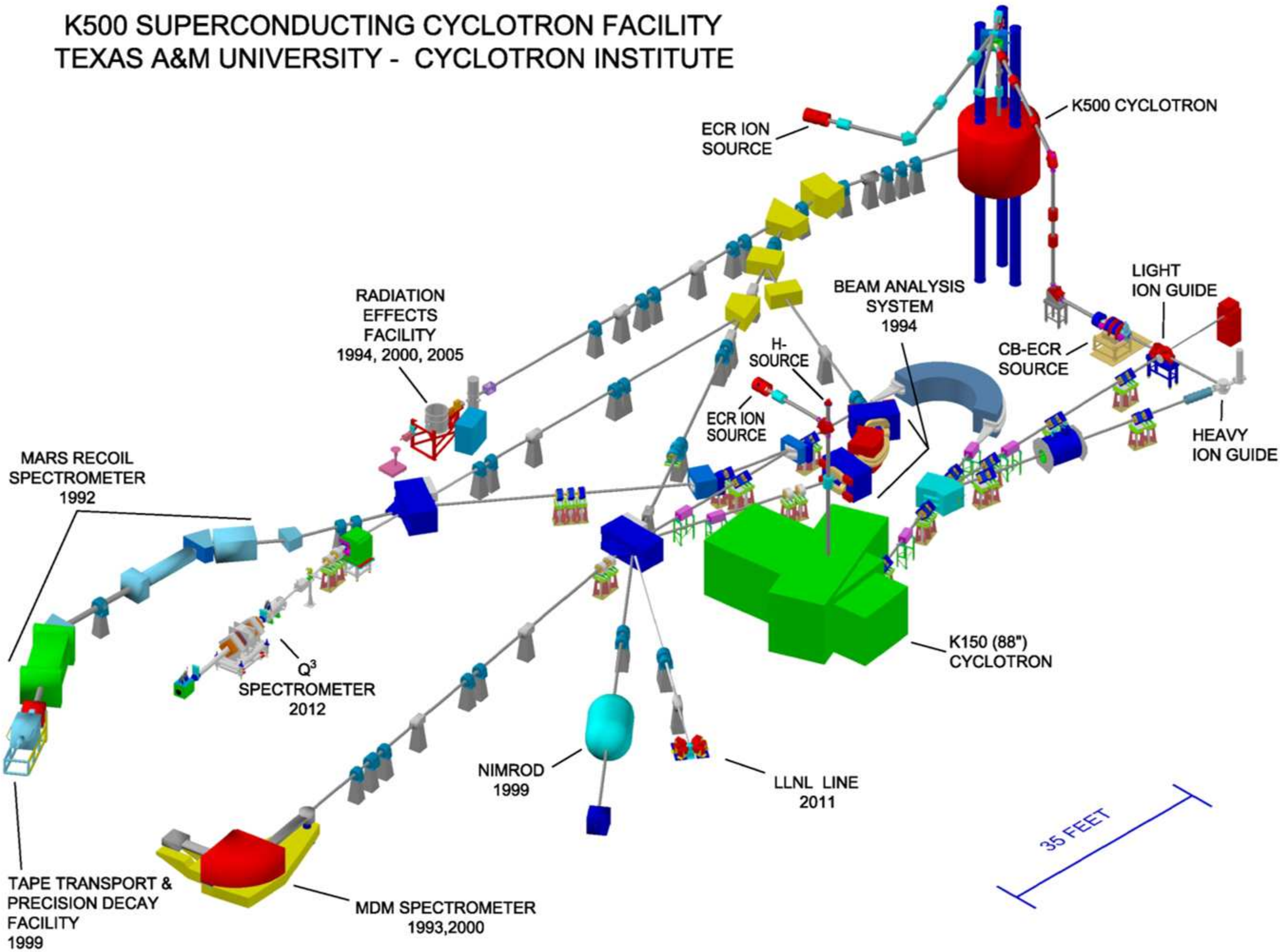


A Penning trap at T-REX CI/TAMU



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- *uniquely* suited for studying β-delayed proton decays:
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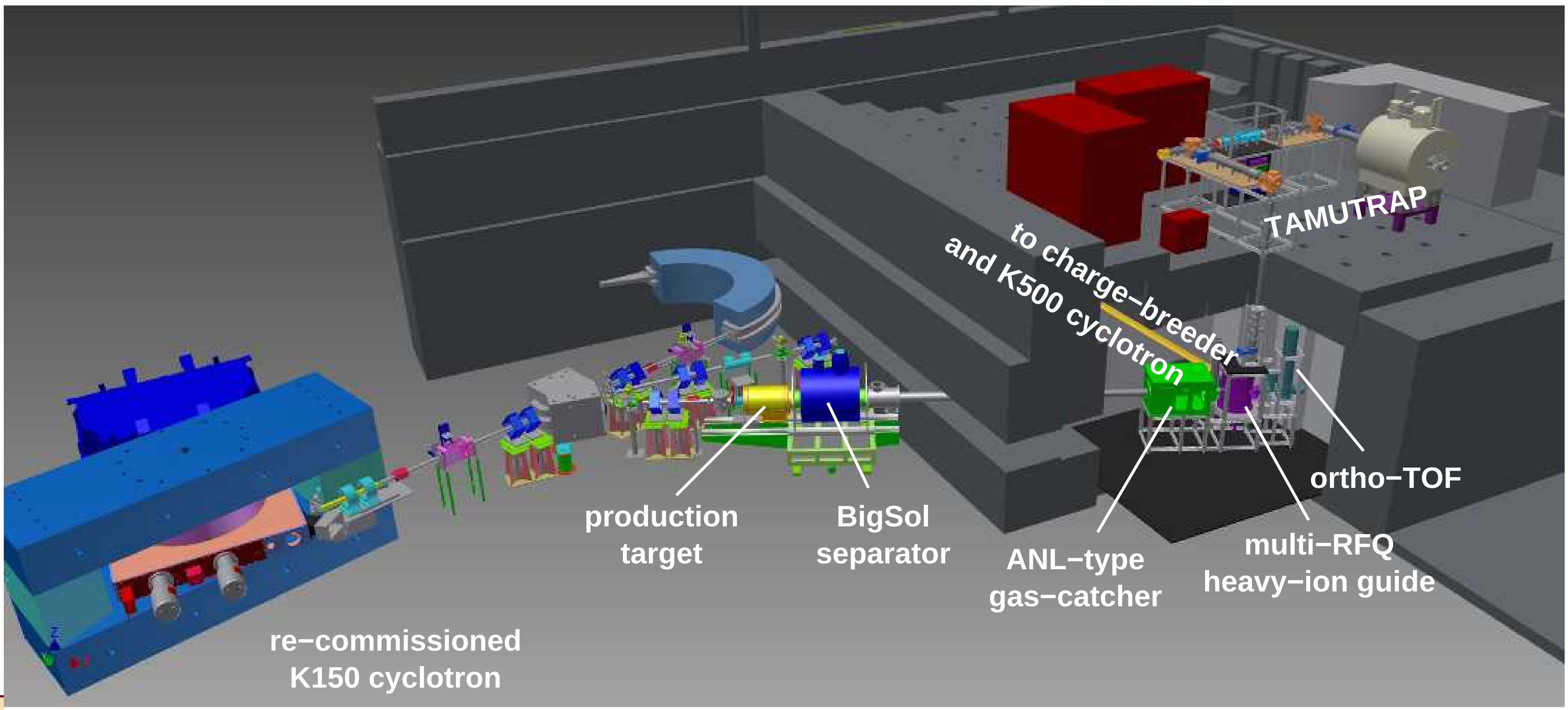
- also amendable to mass measurements, EC studies, laser spectroscopy, ...⟨insert your idea here⟩



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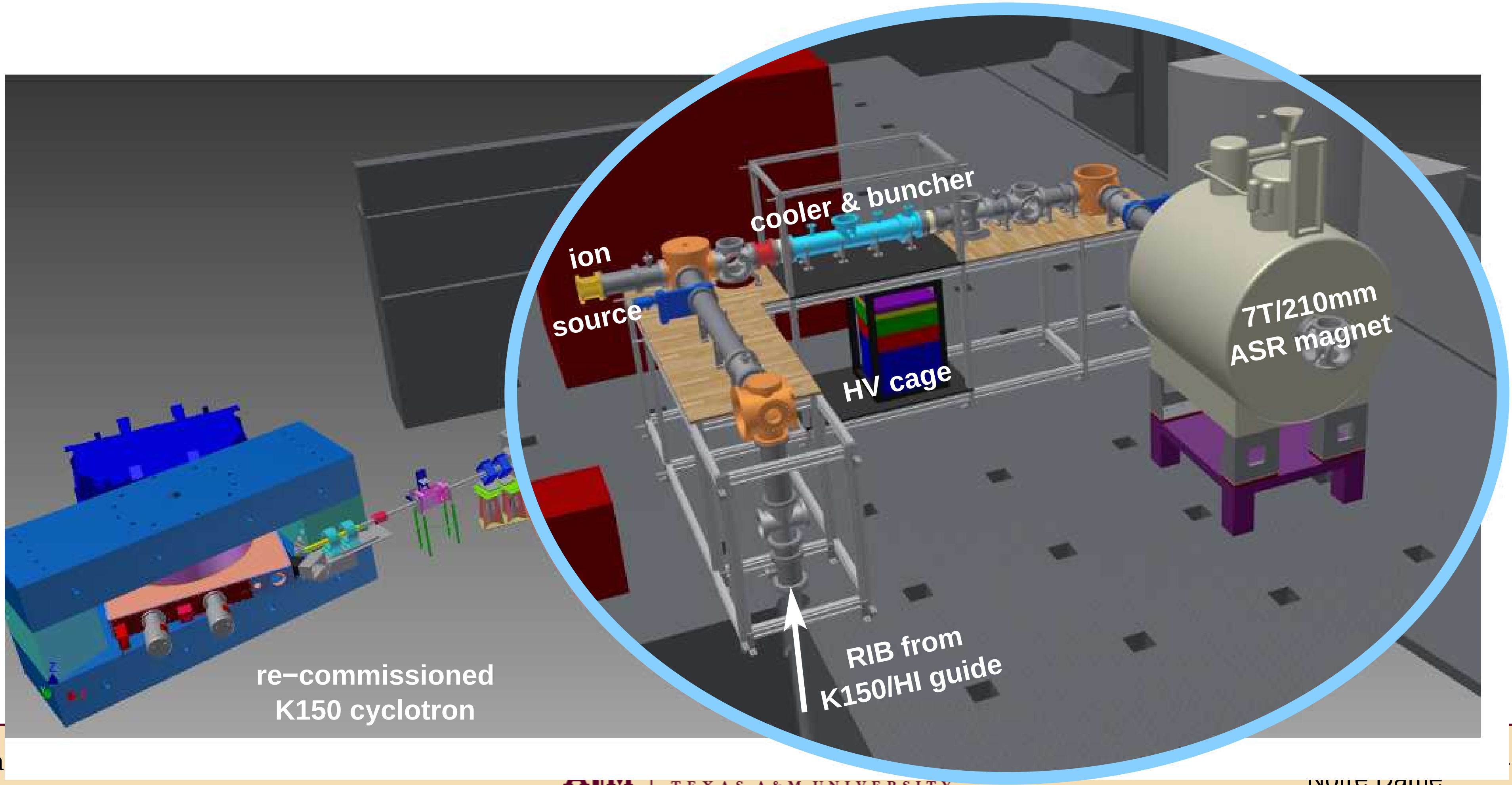

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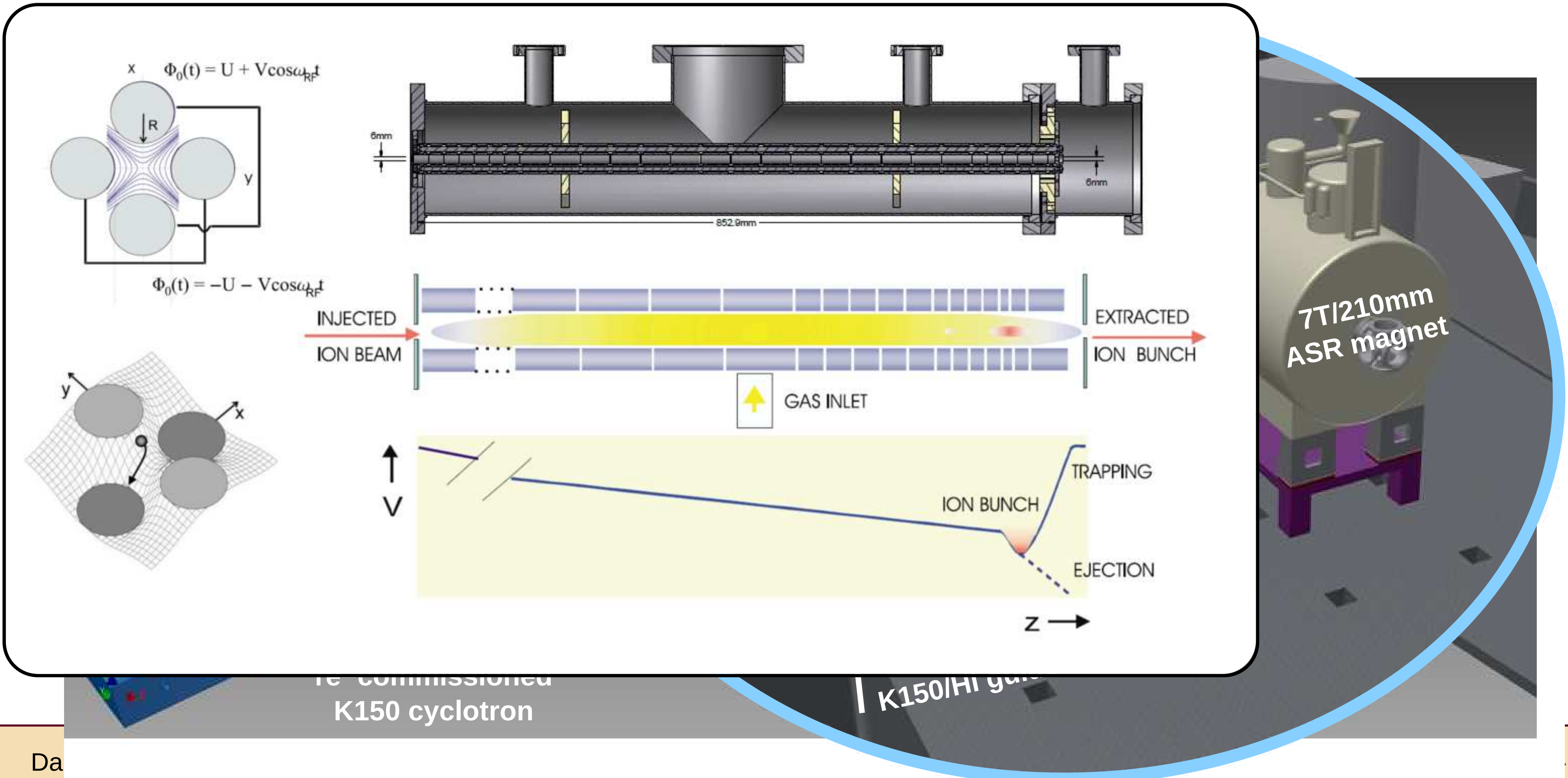

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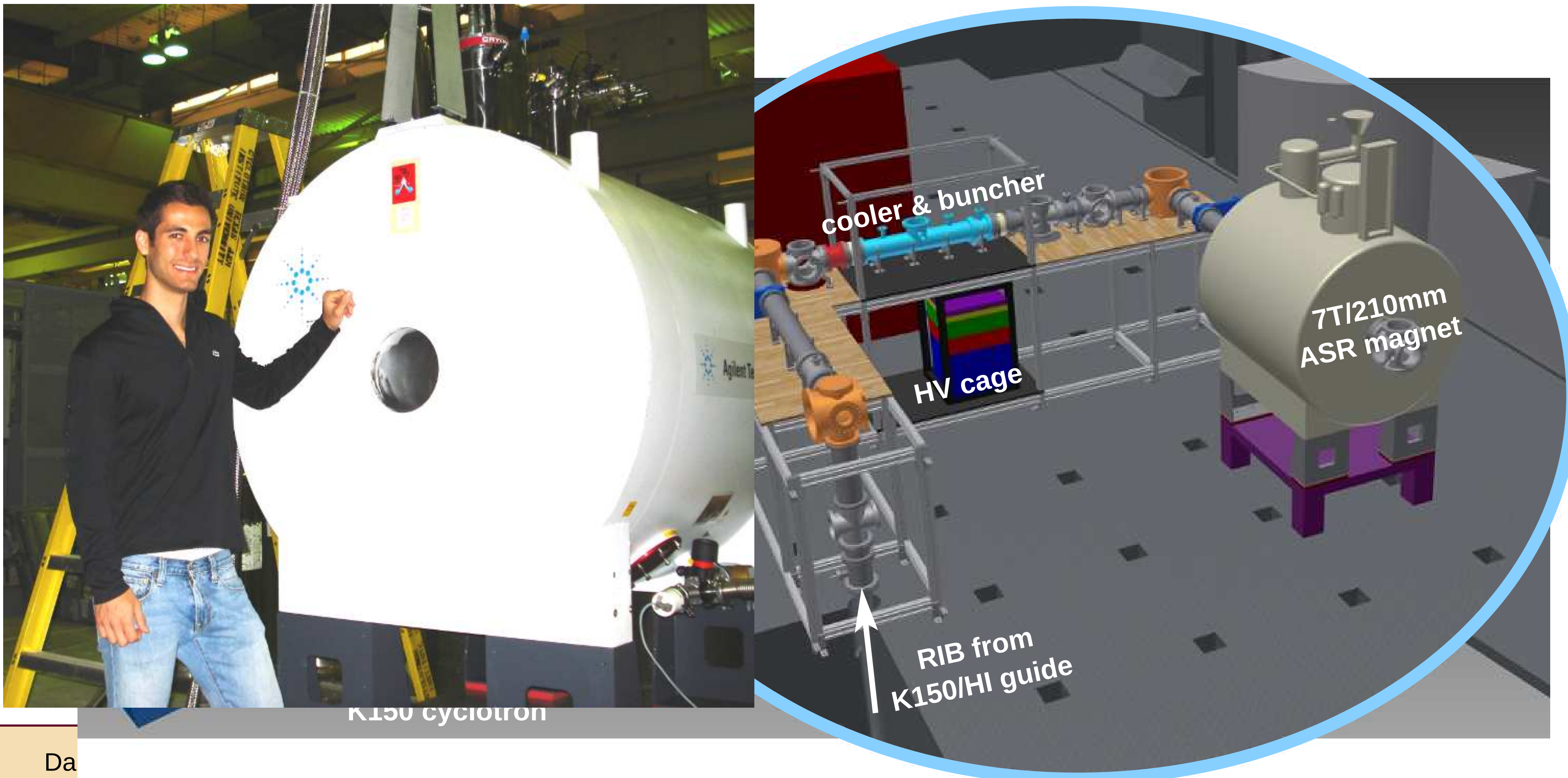

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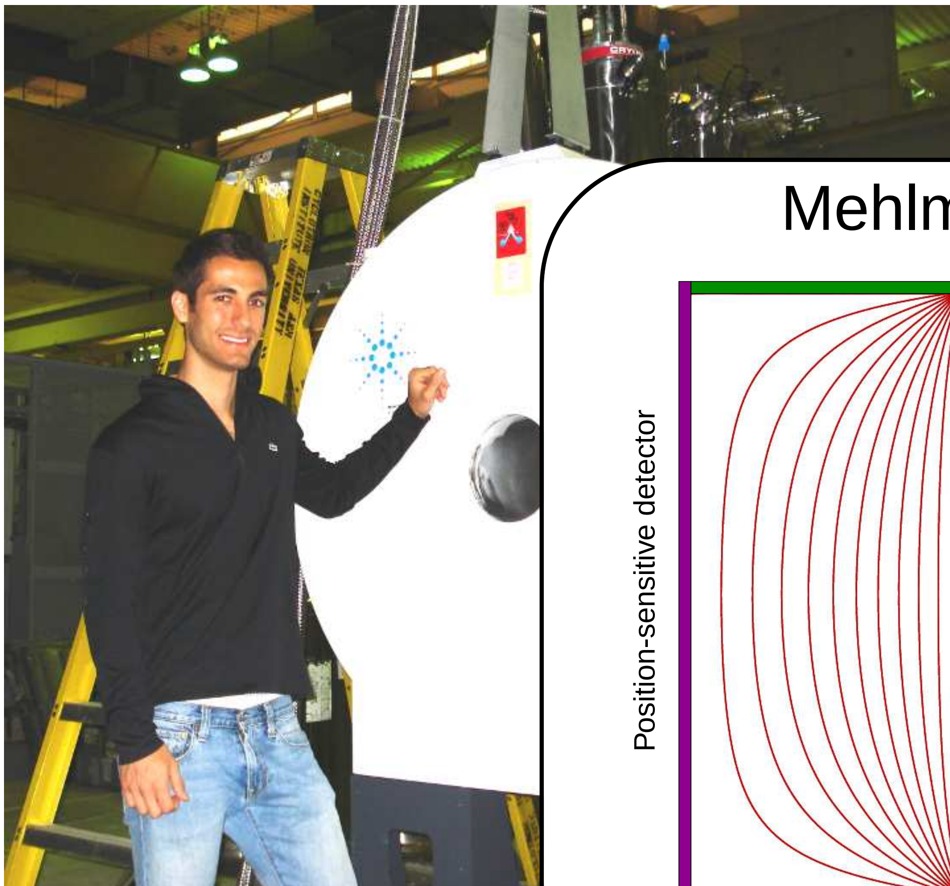
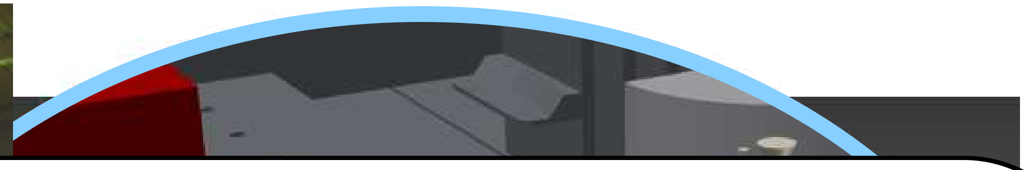
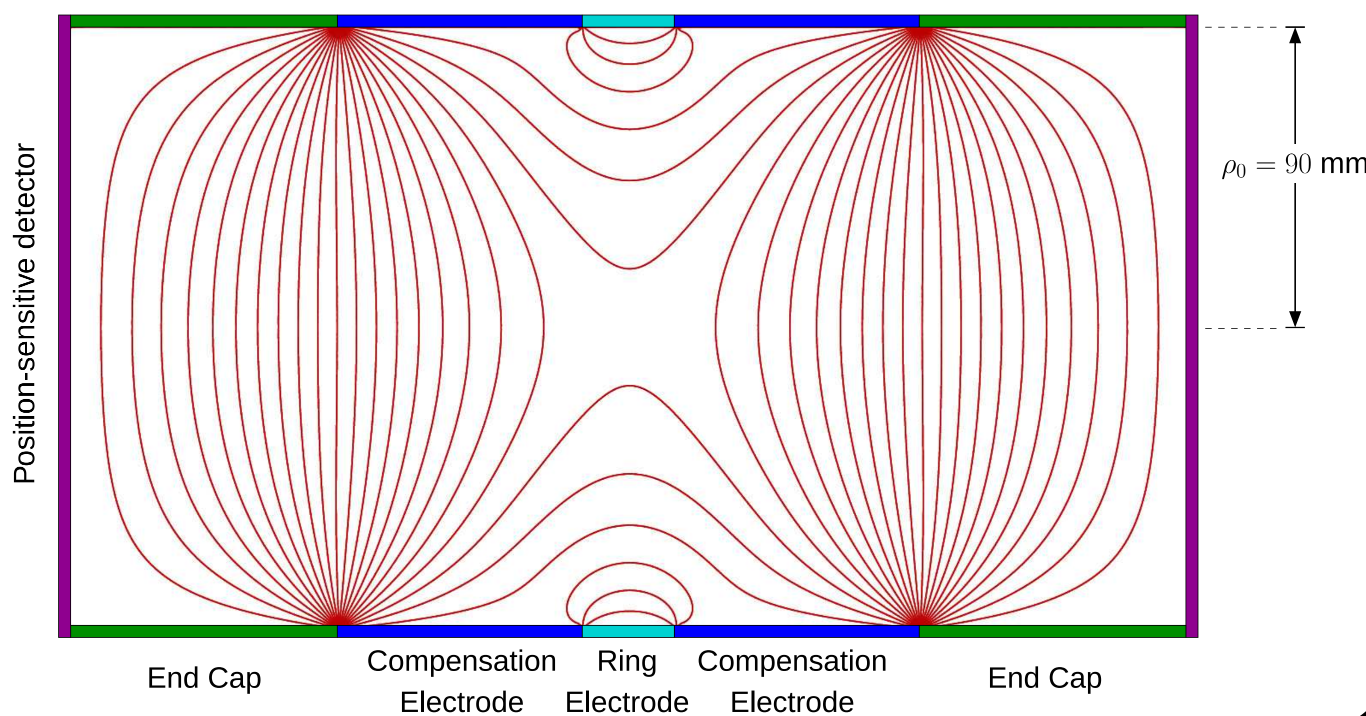




Mehlman *et al.*, NIM **A712**, 9 (2013)



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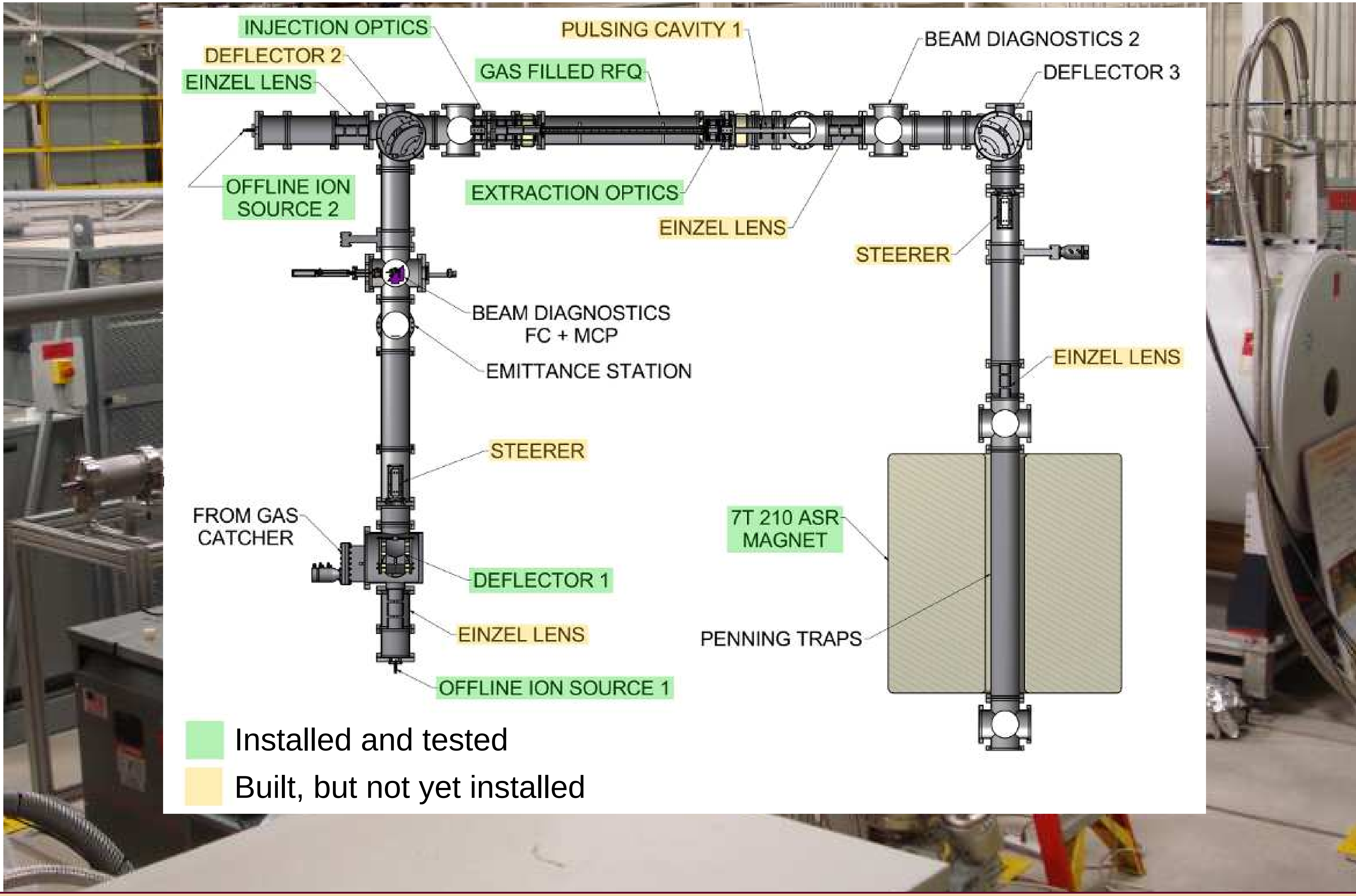

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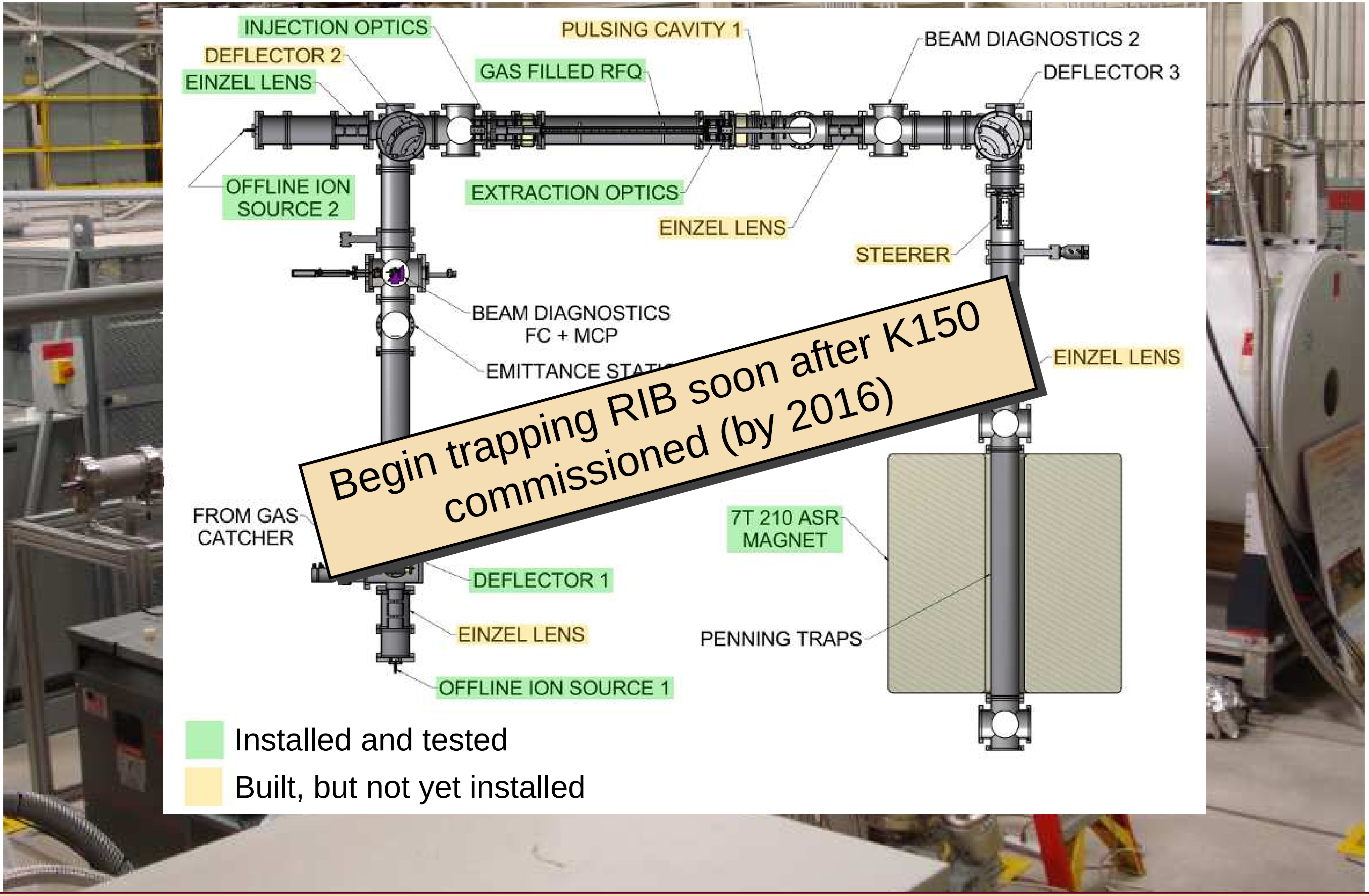

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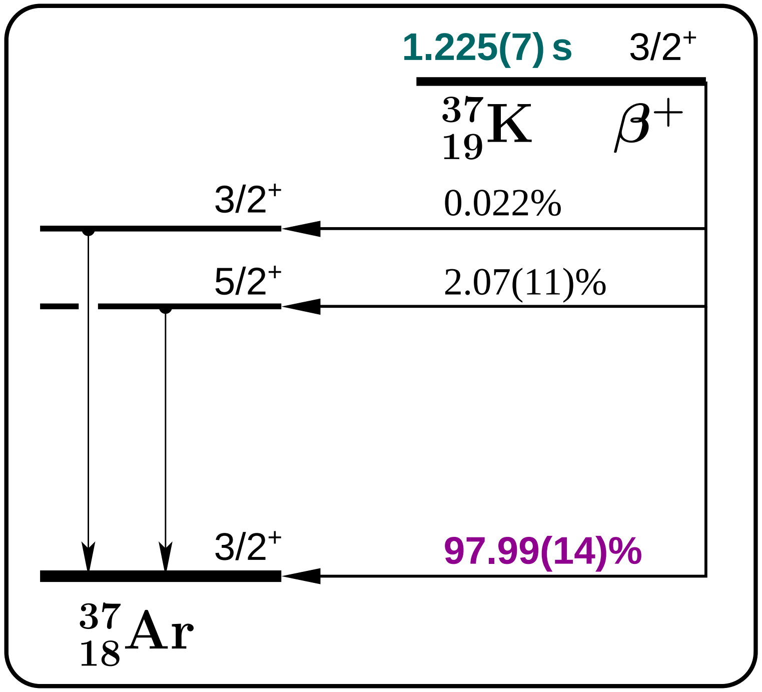

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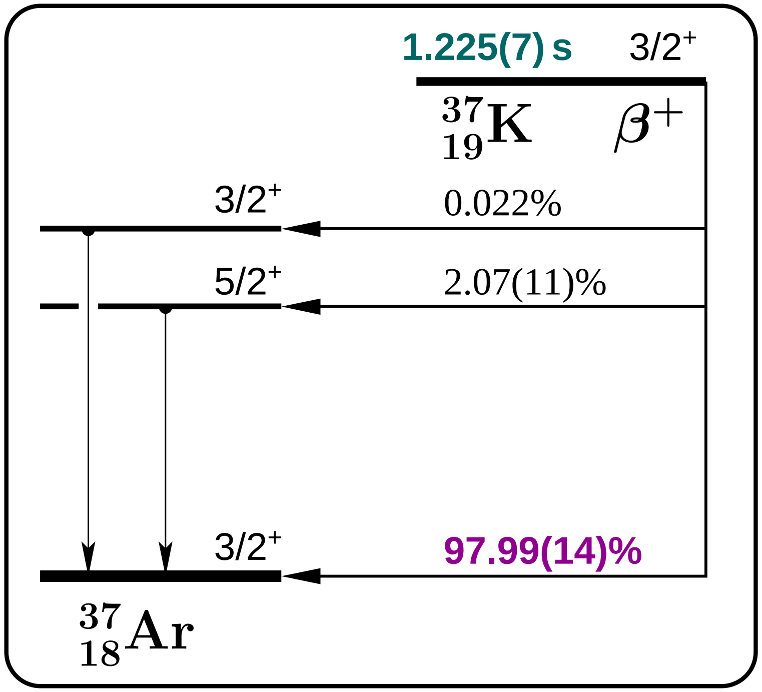

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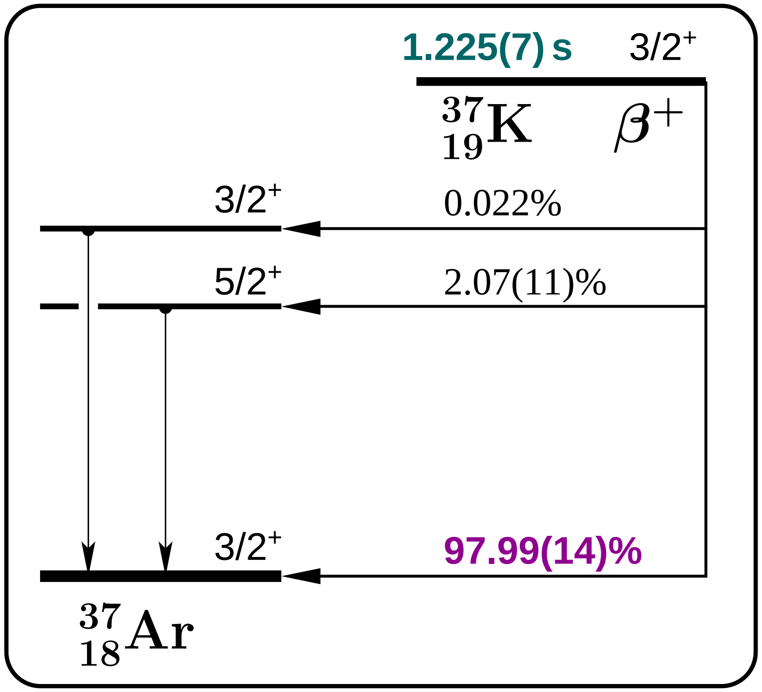

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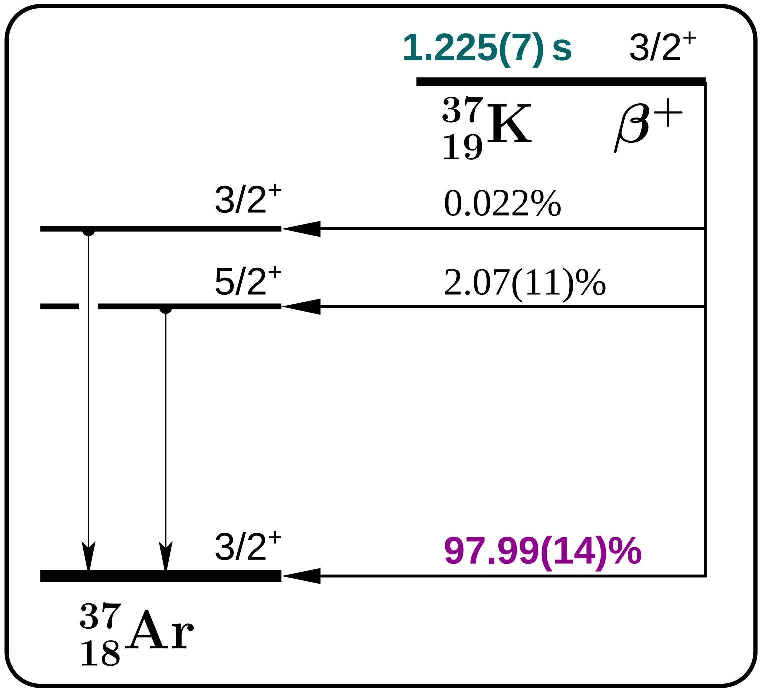

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Q_{EC}: $\pm$0.003%
BR: $\pm$0.14%
$t_{1/2}$: **$\pm$0.57%**

$$\mathcal{F}t = 4562(28) \quad \Rightarrow \quad \rho = 0.5874(\mathbf{71})$$

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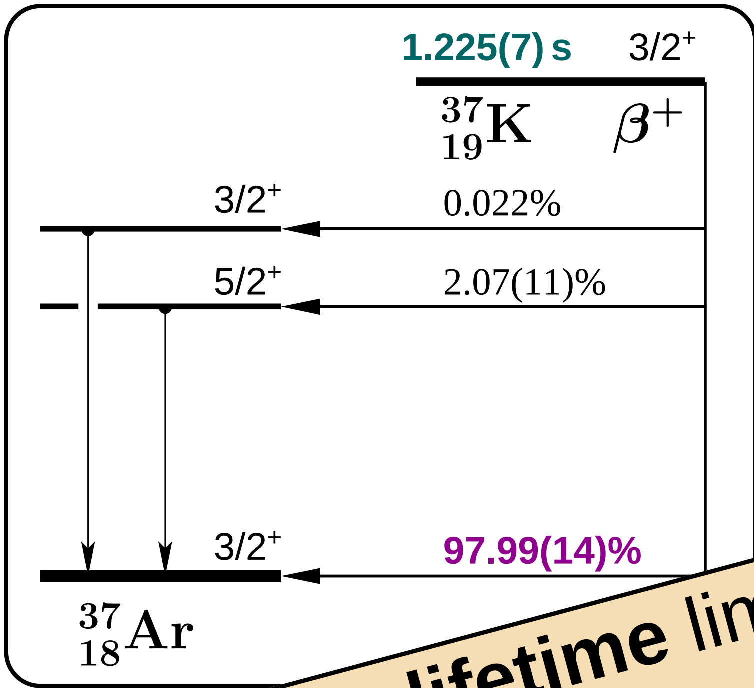

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- **mixed** Fermi/Gamow-Teller

$\Rightarrow$ nee... $M_{GT}/G_V M_F$ ... for correla-

The **lifetime** limits the $\mathcal{F}t$ value
and hence precision of ρ
and hence the SM predictions
of the correlation parameters

get ρ ... $-\,1$ ... $\mathcal{F}t$

Q_{EC}:

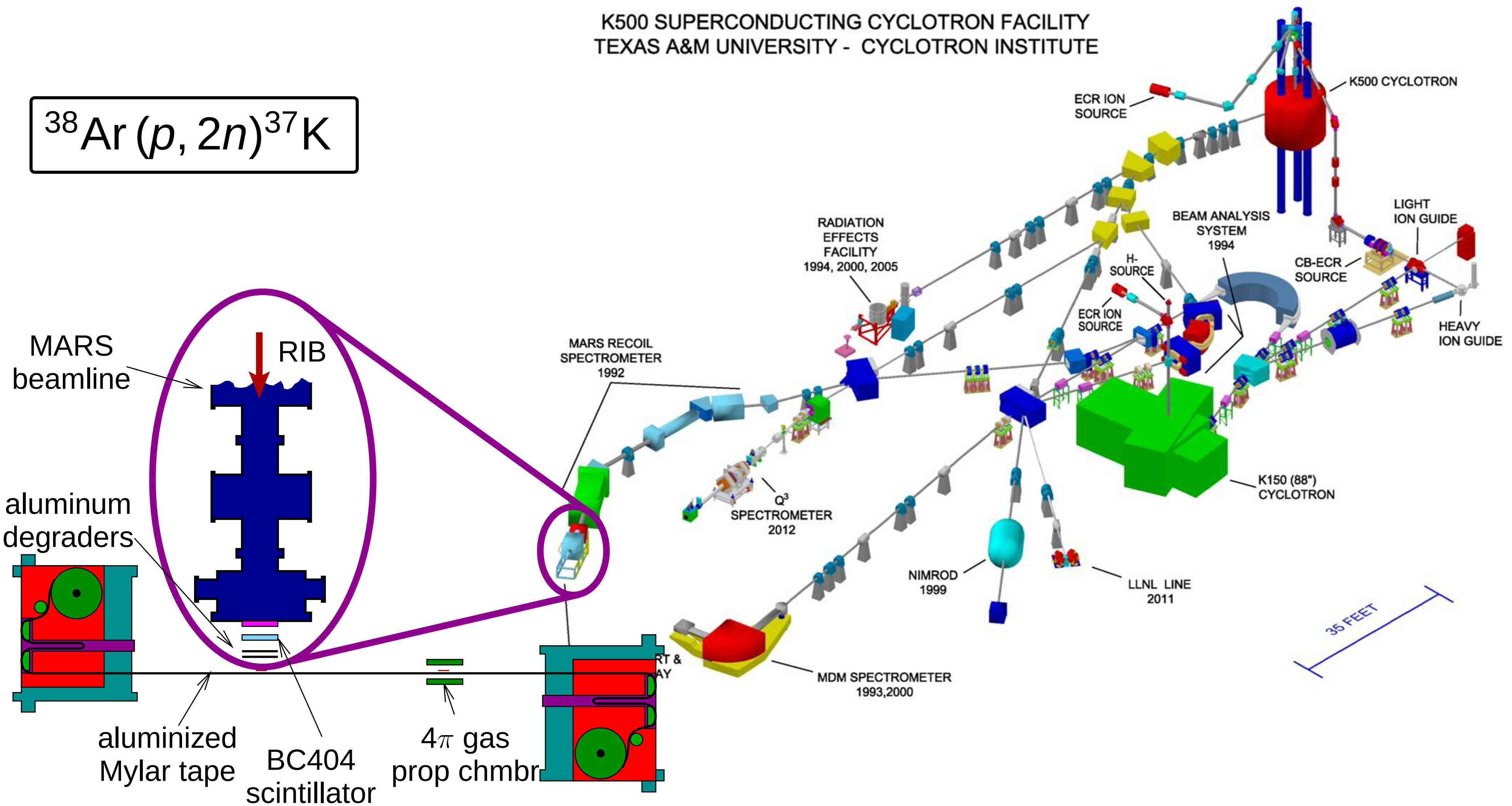
BR: ...%

$t_{1/2}$: $\pm$**0.57%**

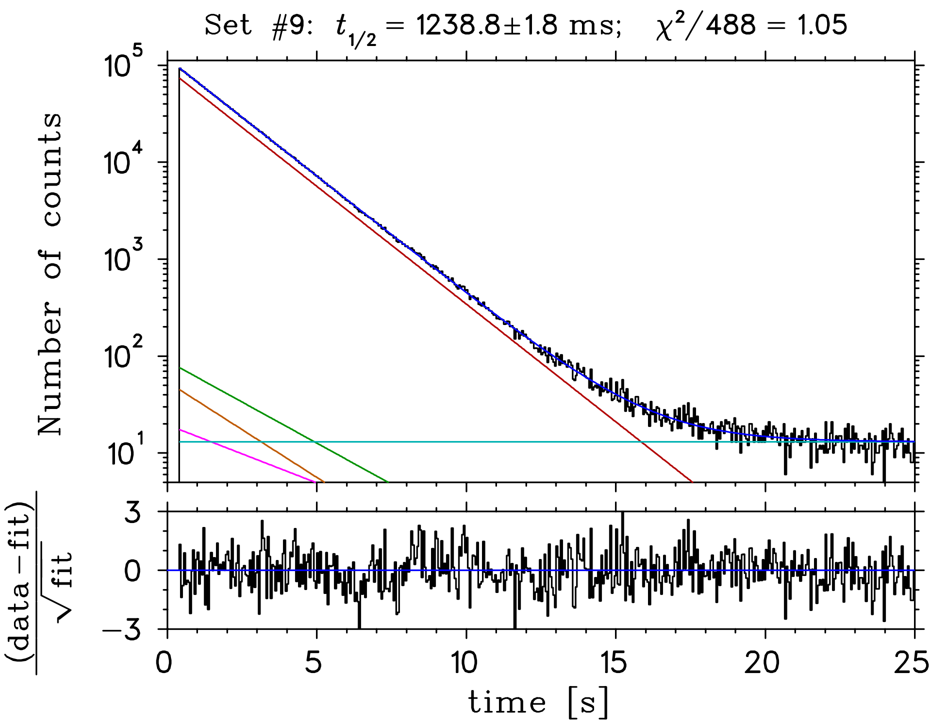
$\mathcal{F}t = 4562(28) \Rightarrow \rho = 0.5874(\mathbf{71})$

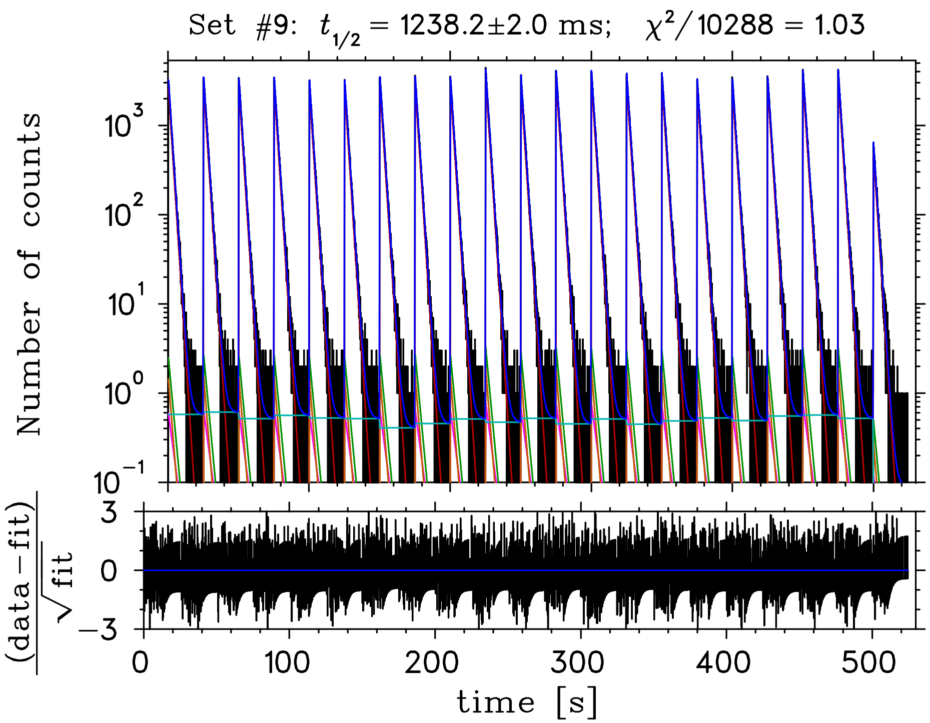
Measuring the lifetime at the CI

$^{38}\mathrm{Ar}\,(p, 2n)^{37}\mathrm{K}$



Improving the lifetime





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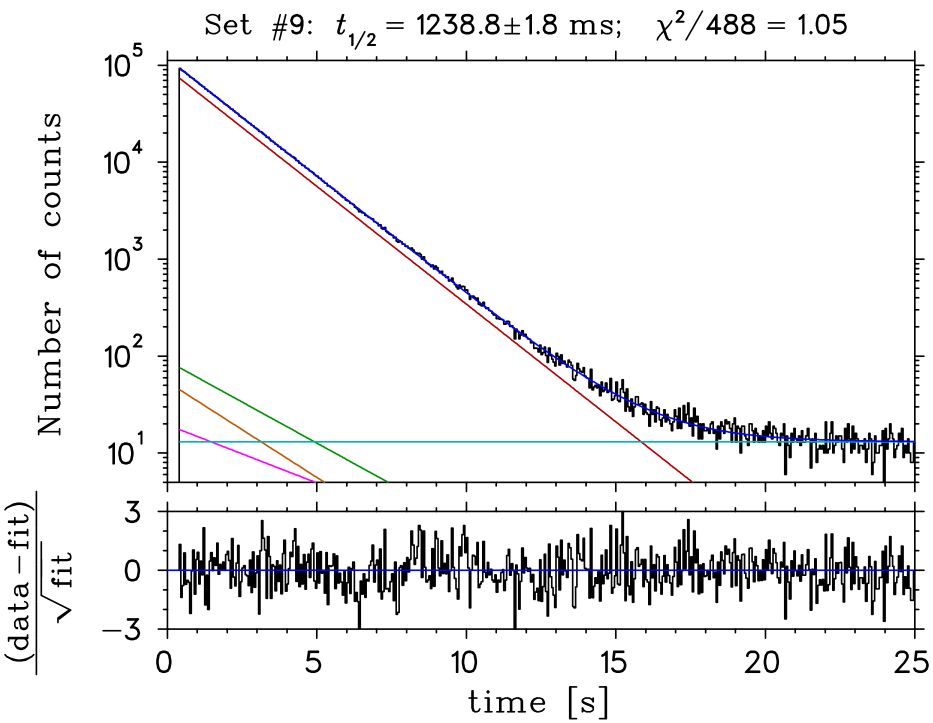
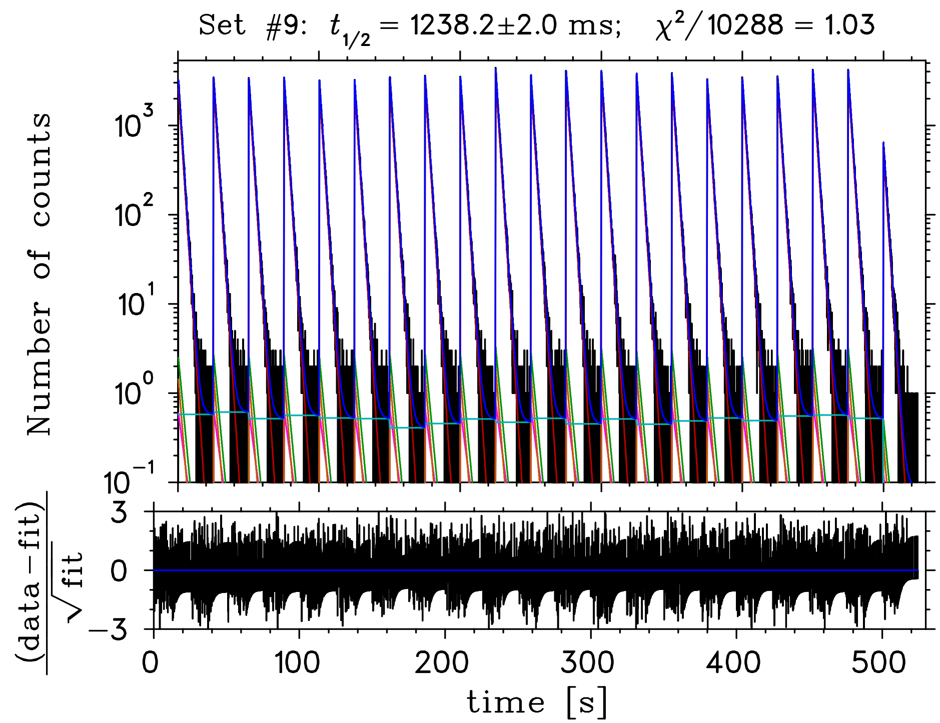




nearly a $10\times$ improvement: $t_{1/2} = 1236.51 \pm 0.47 \pm 0.83$ ms

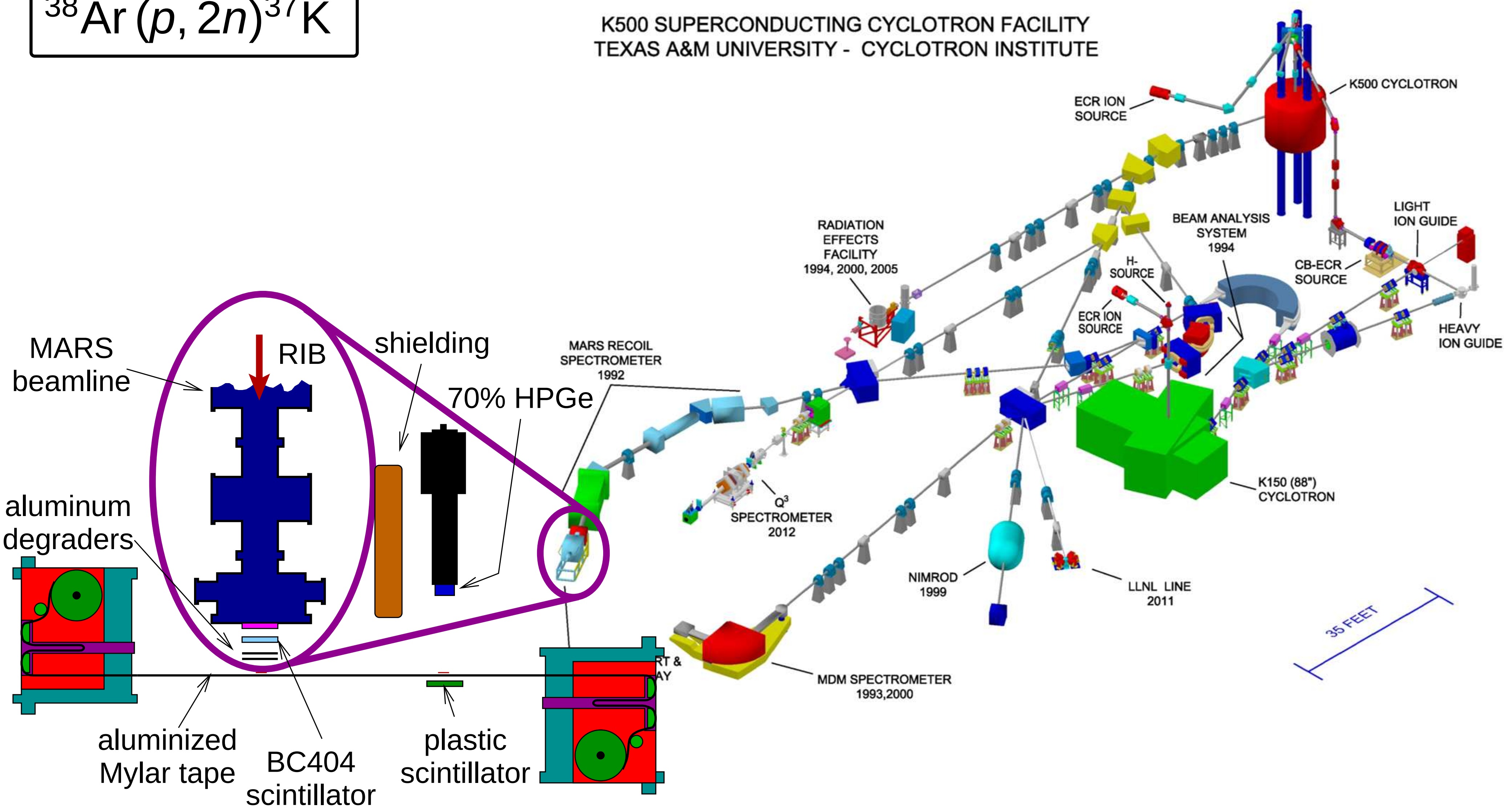
$$\Rightarrow \quad \Delta\mathcal{F}t = 0.62\% \quad \longrightarrow \quad 0.18\%$$

and $\quad \Delta\rho = 1.2\% \quad \longrightarrow \quad \mathbf{0.4\%}$

P. Shidling *et al.*, in preparation

Branching ratio — analysis just starting

$^{38}Ar(p, 2n)^{37}K$

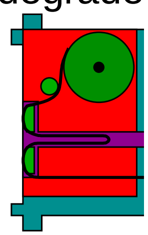


Branching ratio — analysis just starting

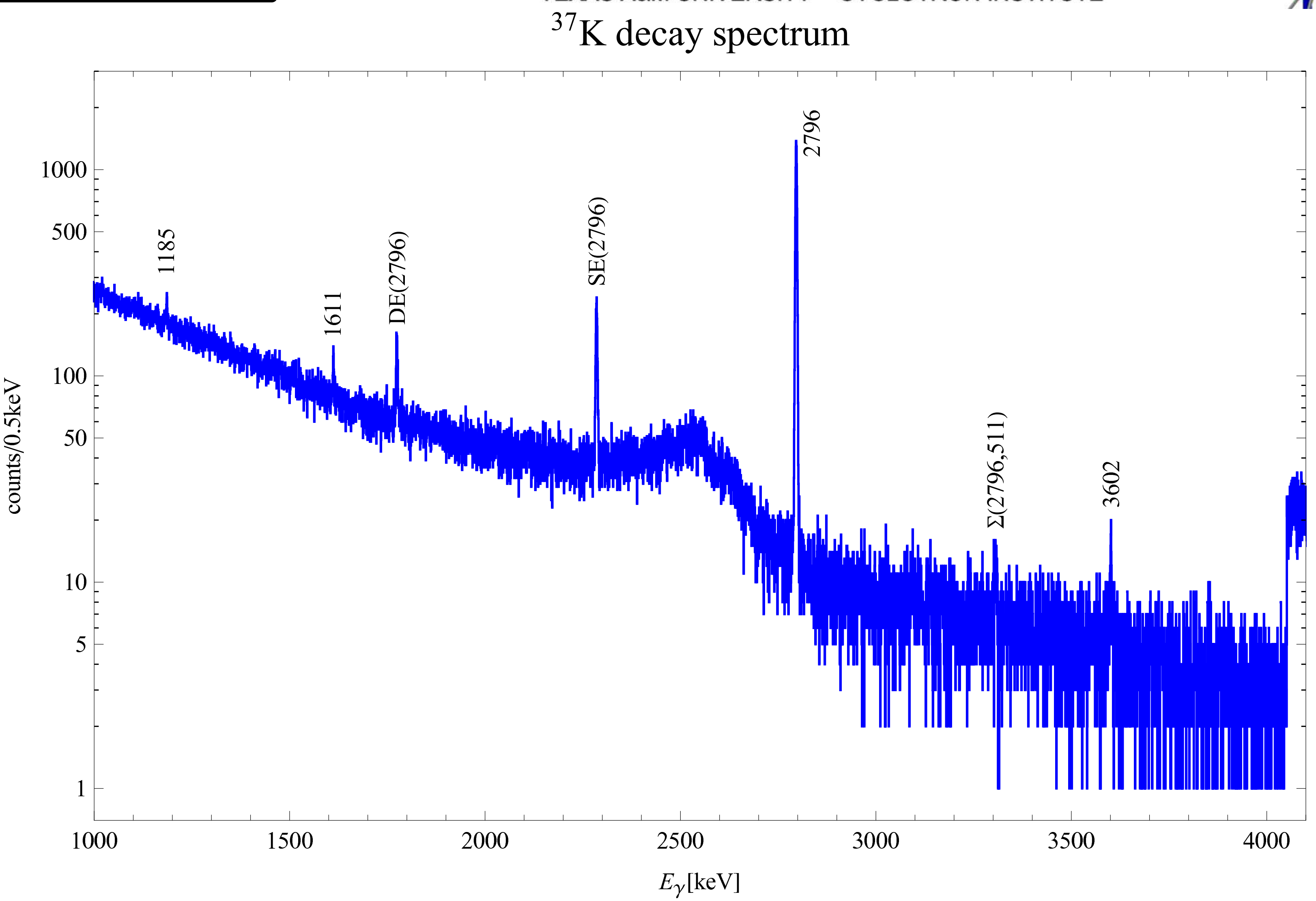
$^{38}Ar\,(p, 2n)^{37}K$

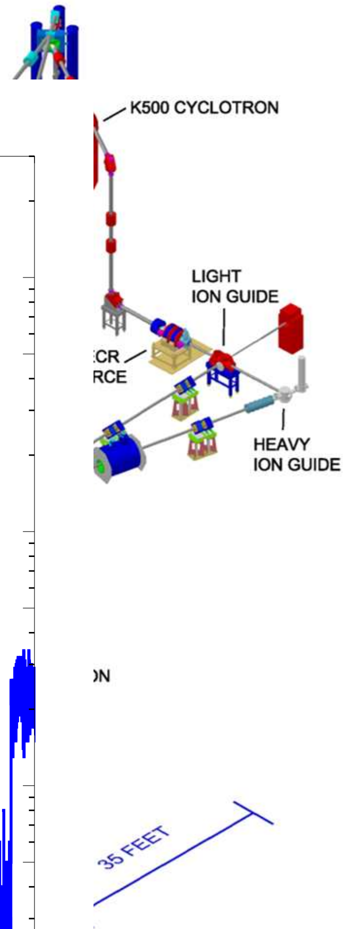
MARS
beamlir

aluminu
degrade



K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE





Angular distribution of a $\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$ decay

$$dW \sim 1 + a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\Gamma\frac{m}{E_e} + \frac{\vec{I}}{I}\cdot\left[A_\beta\frac{\vec{p}_e}{E_e} + B_\nu\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right]$$

Correlation	SM prediction
$\beta-\nu$ correlation:	$a_{\beta\nu} = 0.6580(\mathbf{61})$
Fierz interference parameter:	$b = 0$ (sensitive to scalars and tensors)
β asymmetry:	$A_\beta = -0.5739(\mathbf{21})$
ν asymmetry:	$B_\nu = -0.7791(\mathbf{58})$
Time-violating D coefficient:	$D = 0$ (sensitive to imaginary couplings)

Precision measurements of these correlations to $\lesssim \mathbf{0.1\%}$ complement collider experiments and test the SM

see Profumo, Ramsey-Musolf and Tulin, PRD **75** (2007)
and Cirigliano, González-Alonso and Graesser, JHEP **1302** (2013)

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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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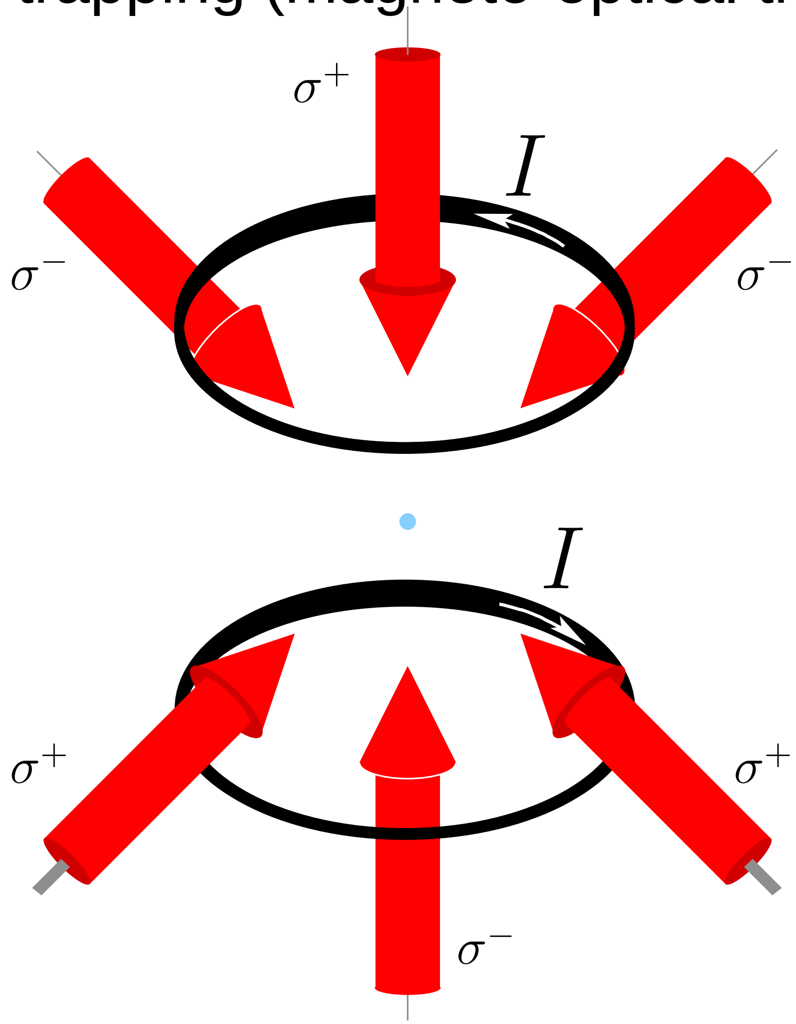

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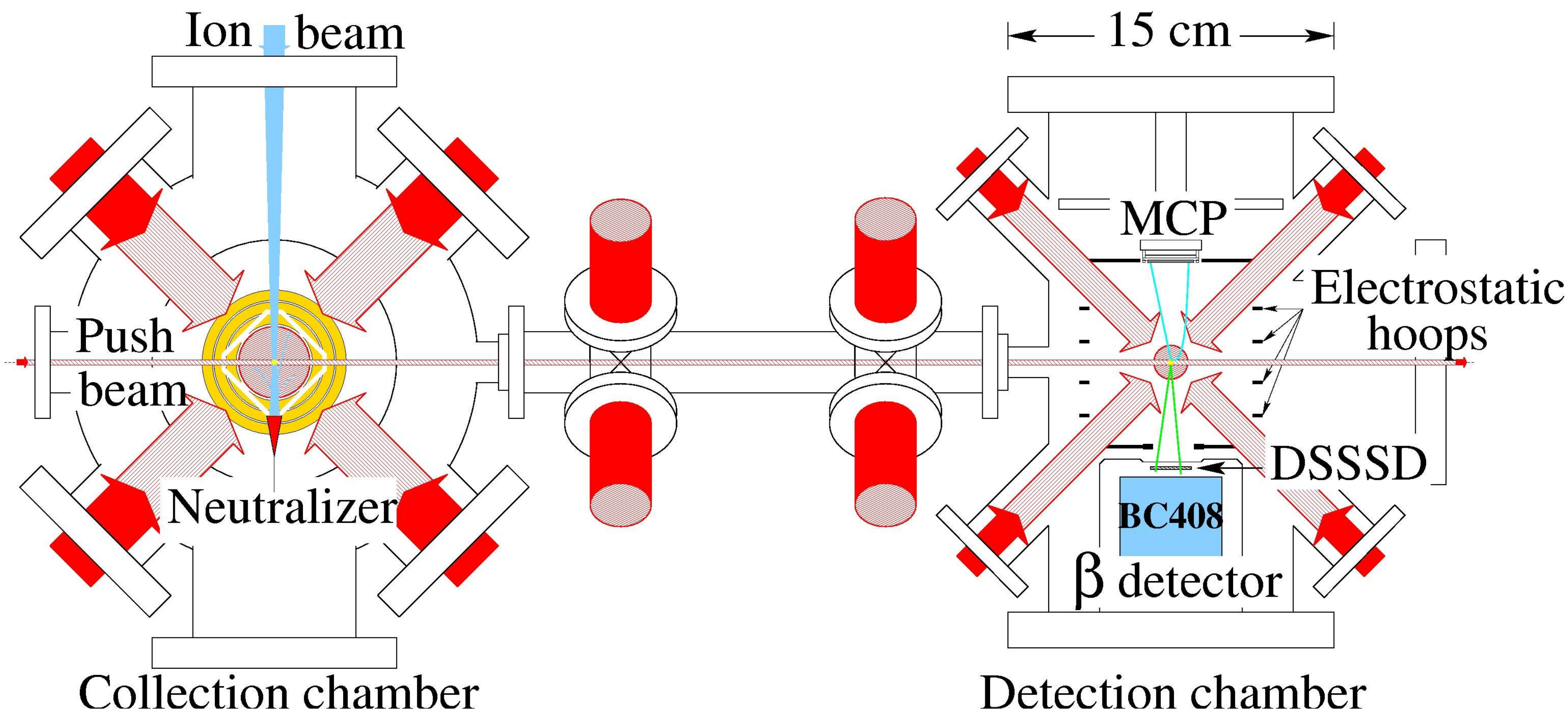

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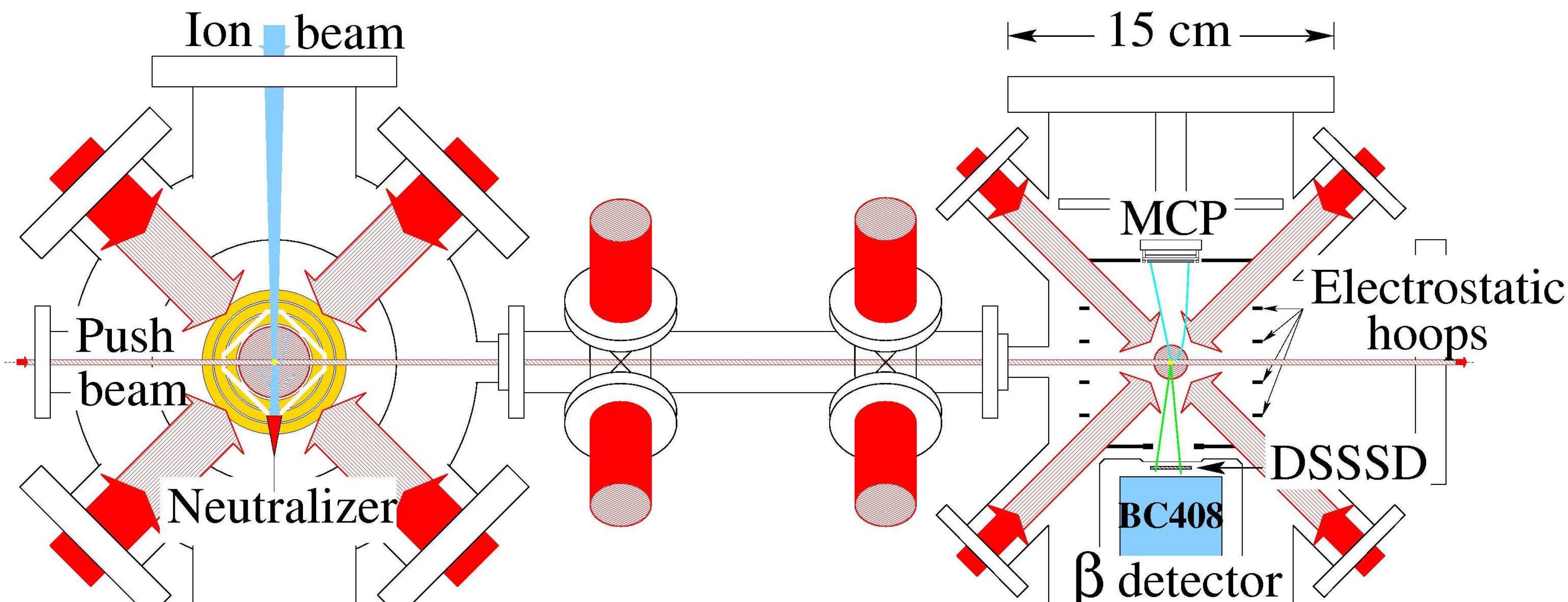

Traps provide a **backing-free**, very **cold** ($\lesssim 1$ mK), **localized** ($\sim 1\ \mathrm{mm}^3$) source of **isomerically-selective**, **short-lived** radioactive atoms

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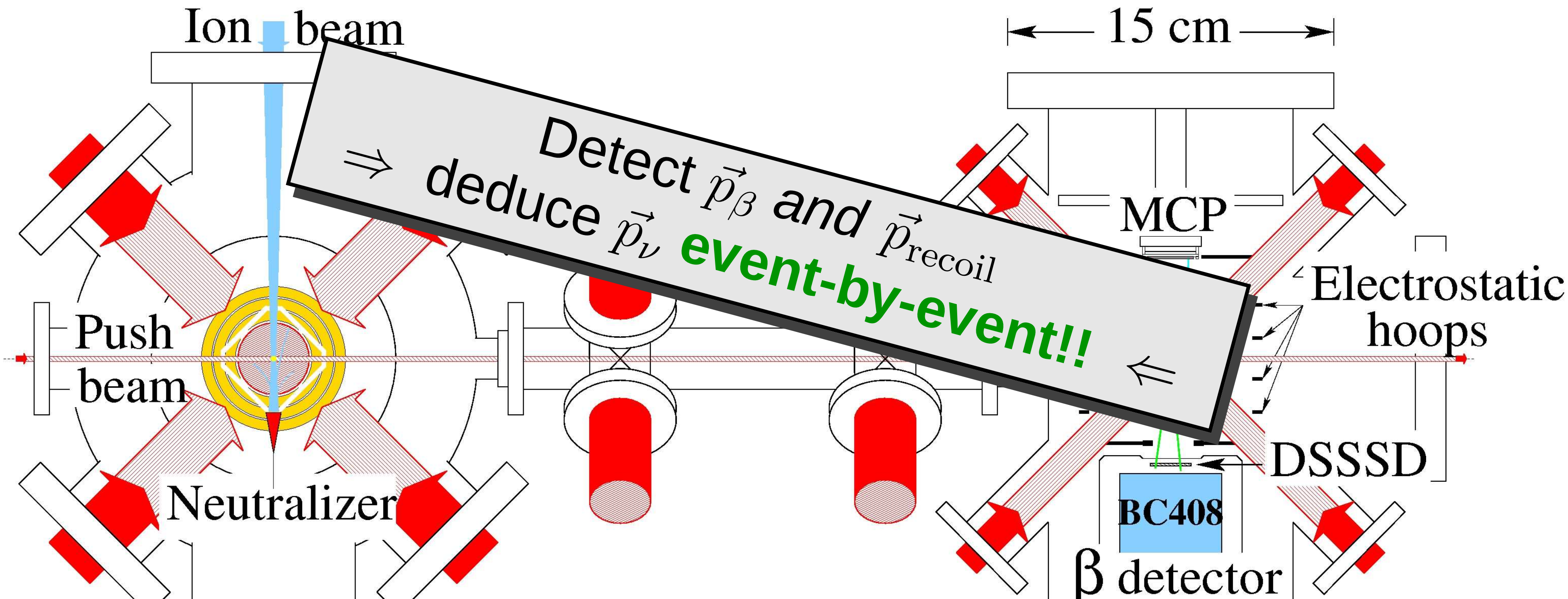

Detect $\vec{p}_\beta$ and $\vec{p}_{recoil}$

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

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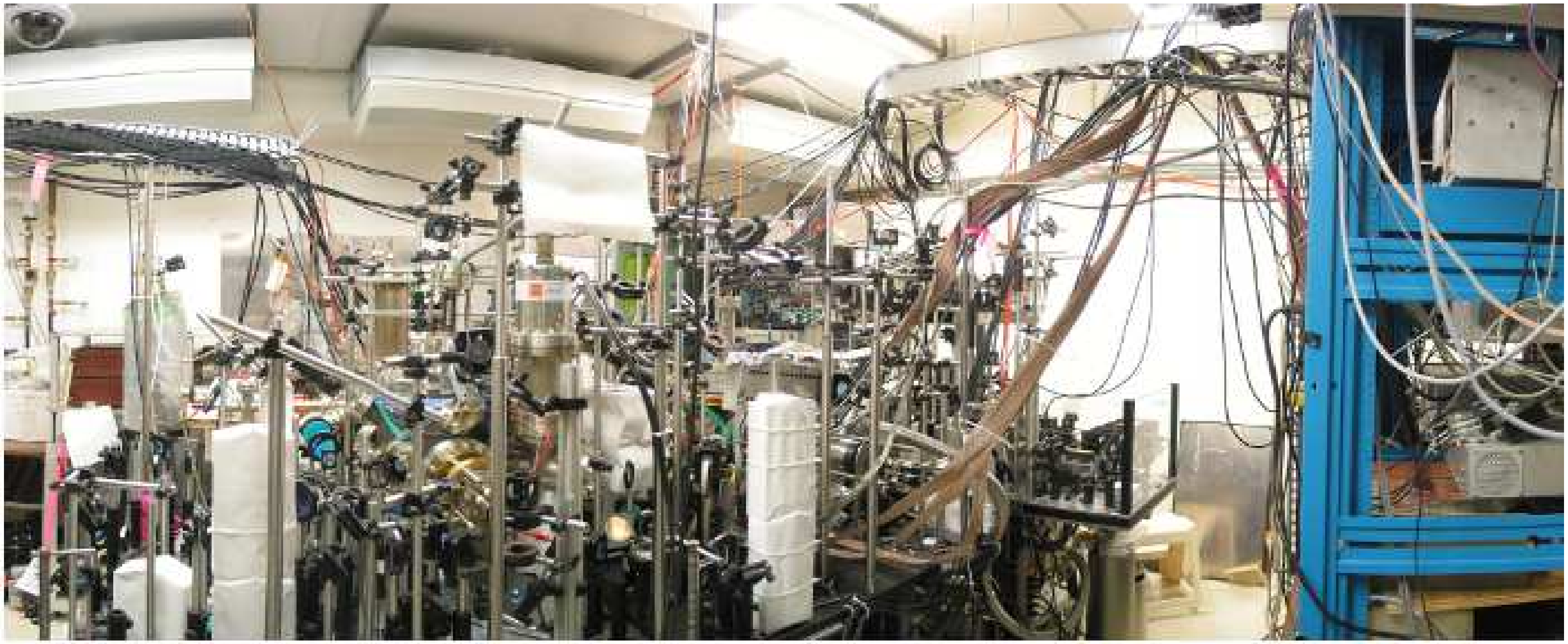
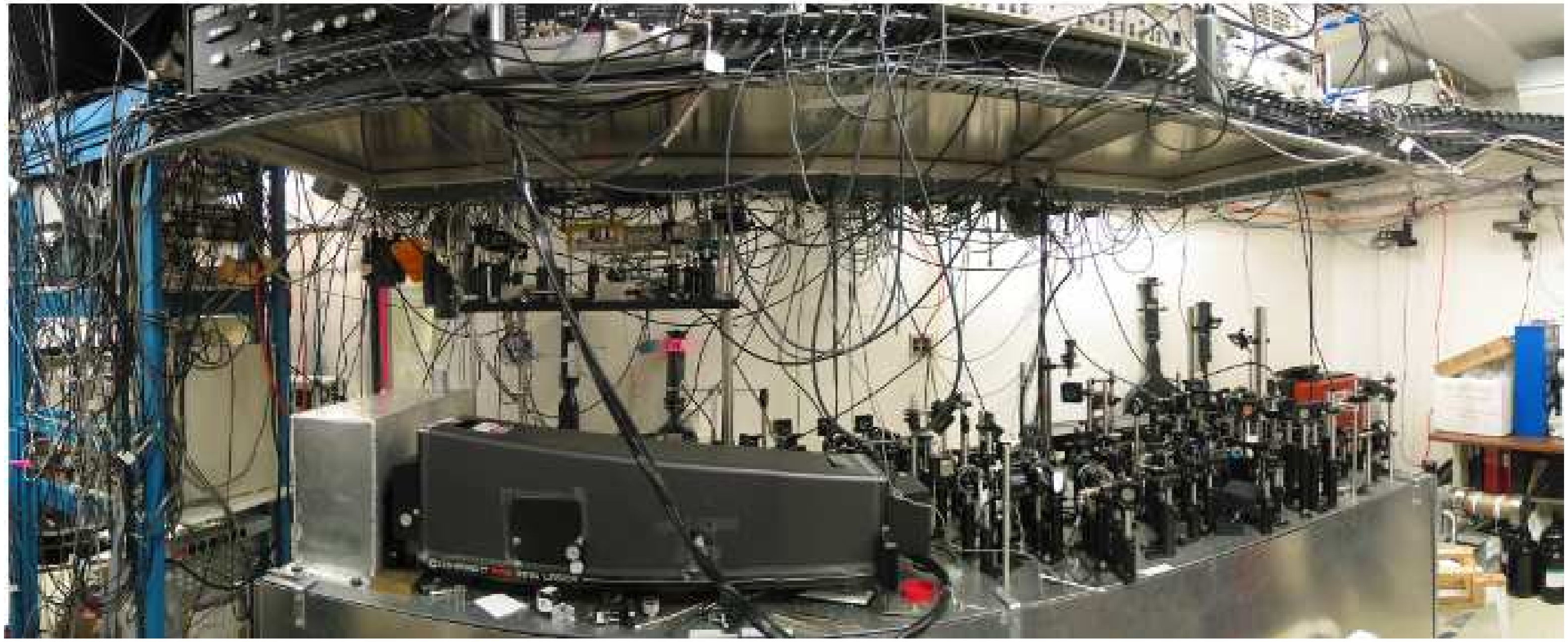
The TRINAT lab





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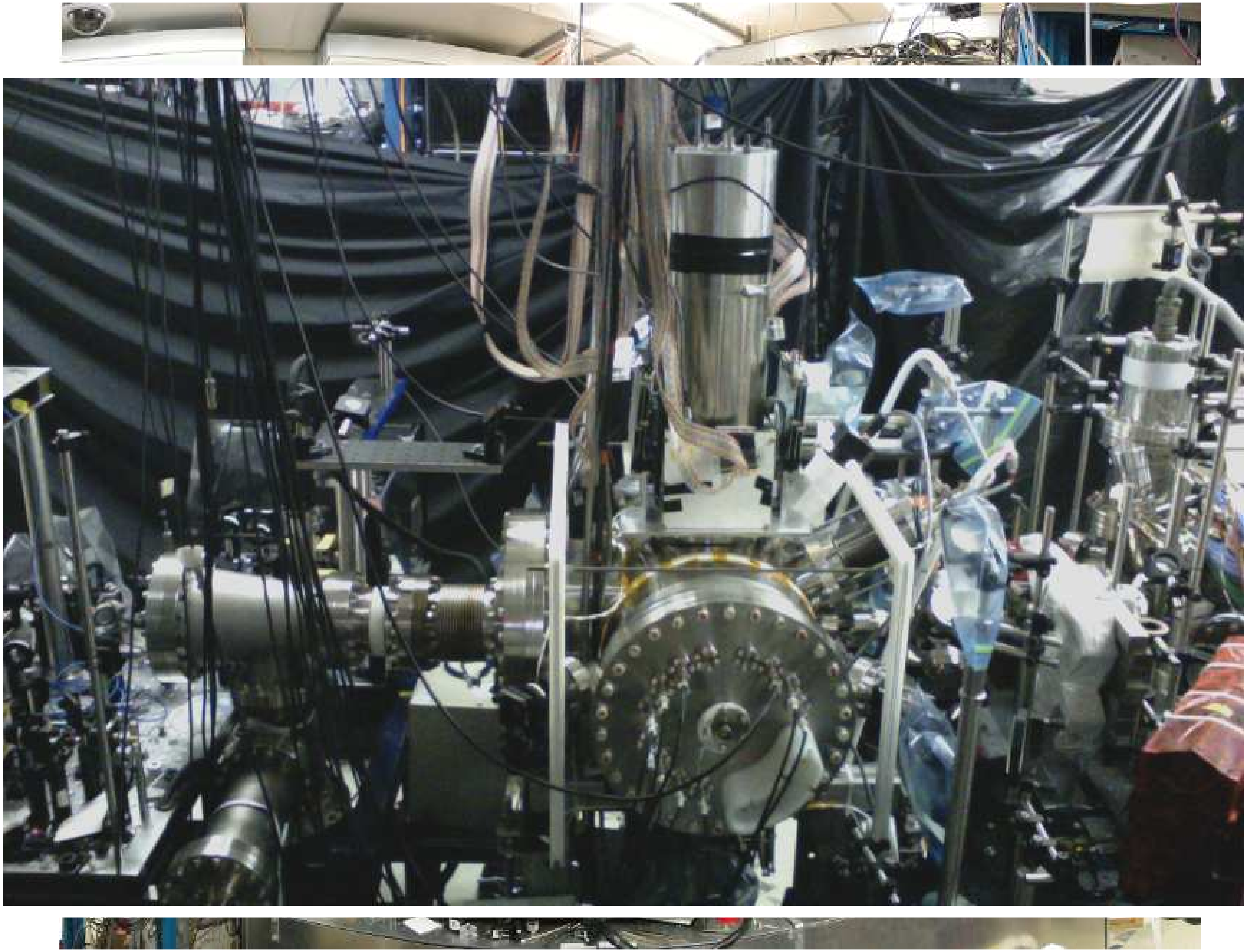
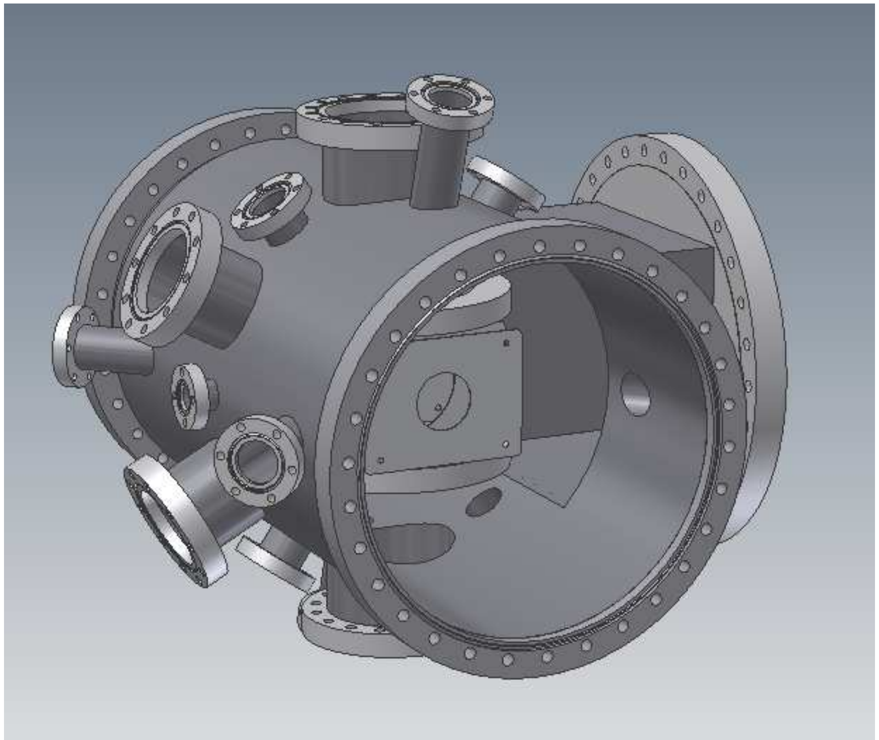
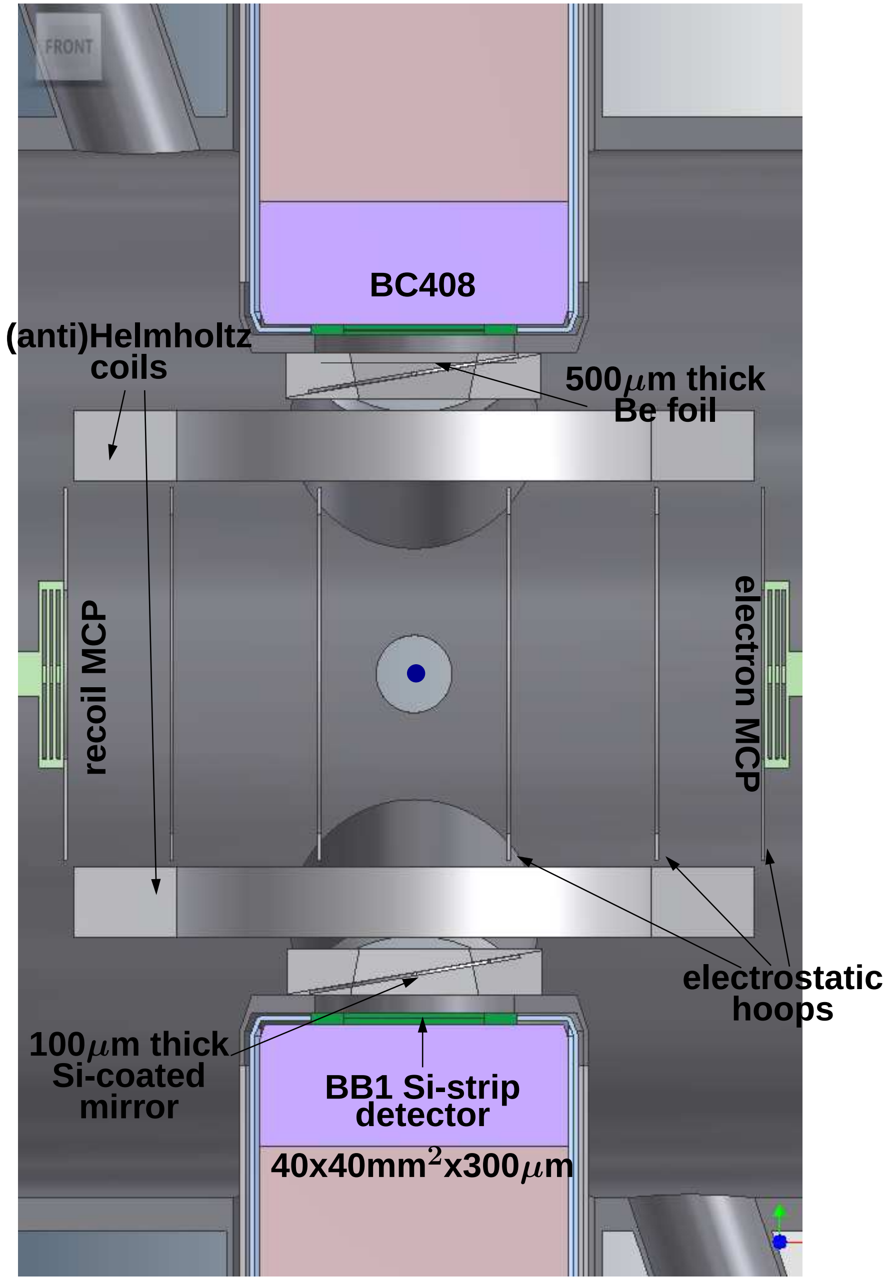


The new chamber

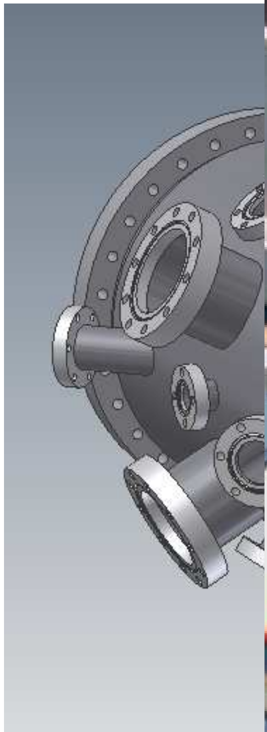


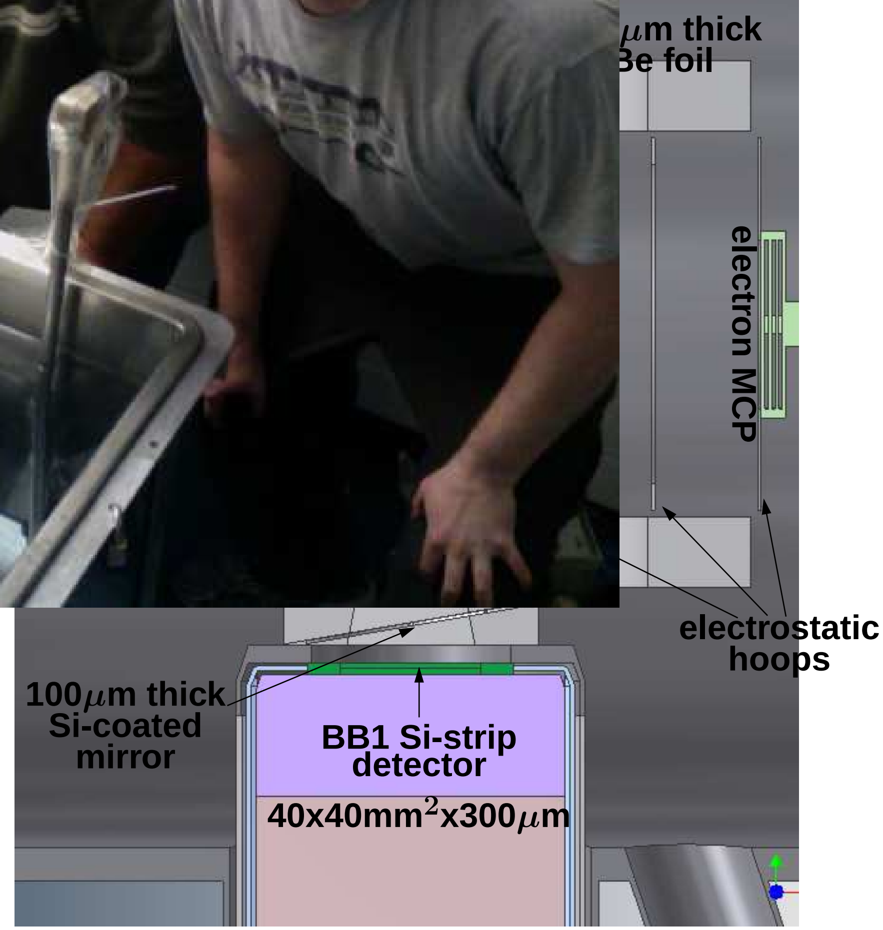


- Shake-off e^- detection
- Better control of OP beams
- $B_{\rm quad} \rightarrow B_{\rm OP}$ quickly: AC-MOT (Harvery & Murray, PRL **101** (2008))
- Increased β/recoil solid angles
- Stronger E-field

⋮

The new chamber





- Shake-o
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- B_{quad}
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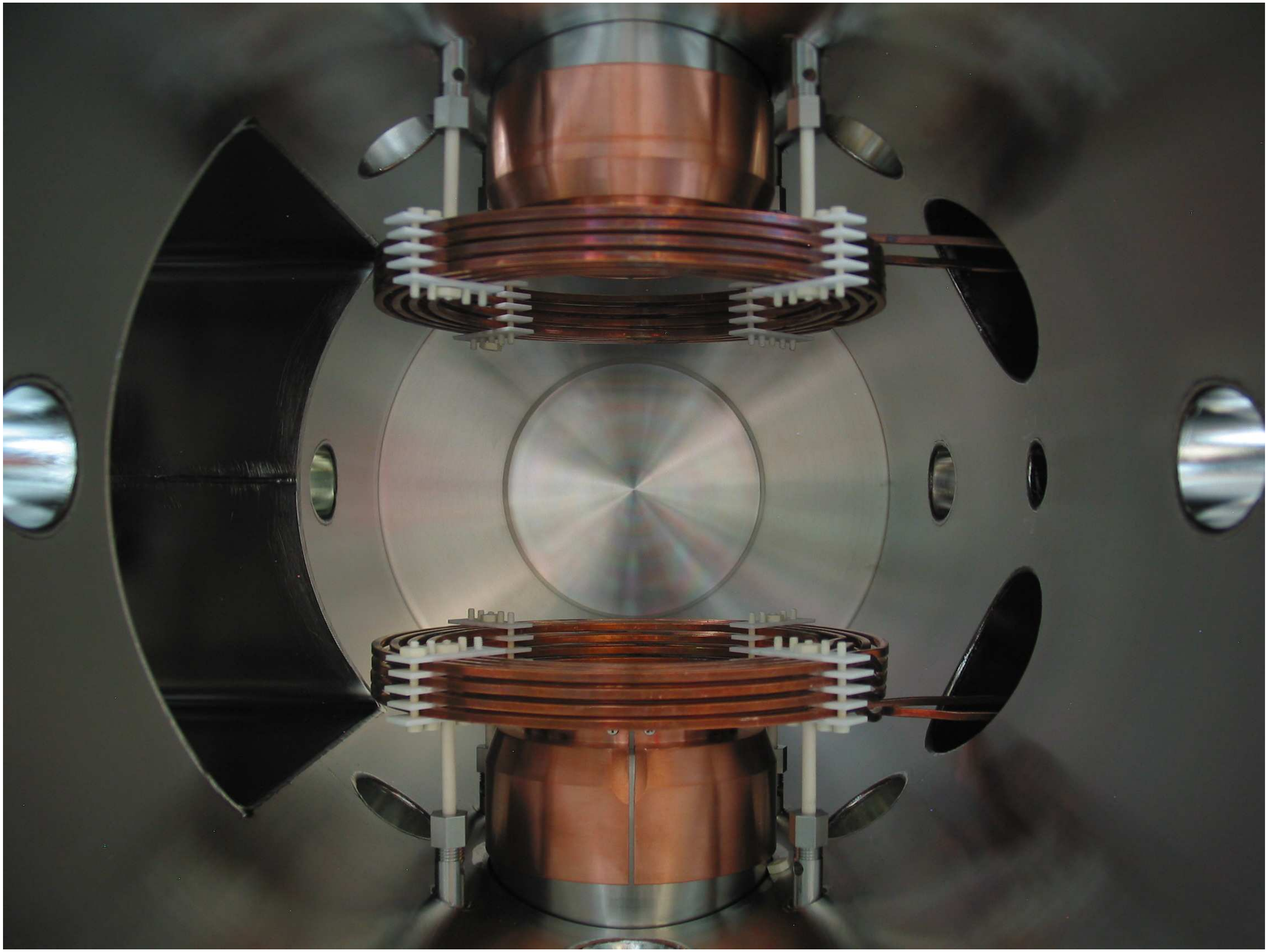
Outline of polarized experiment



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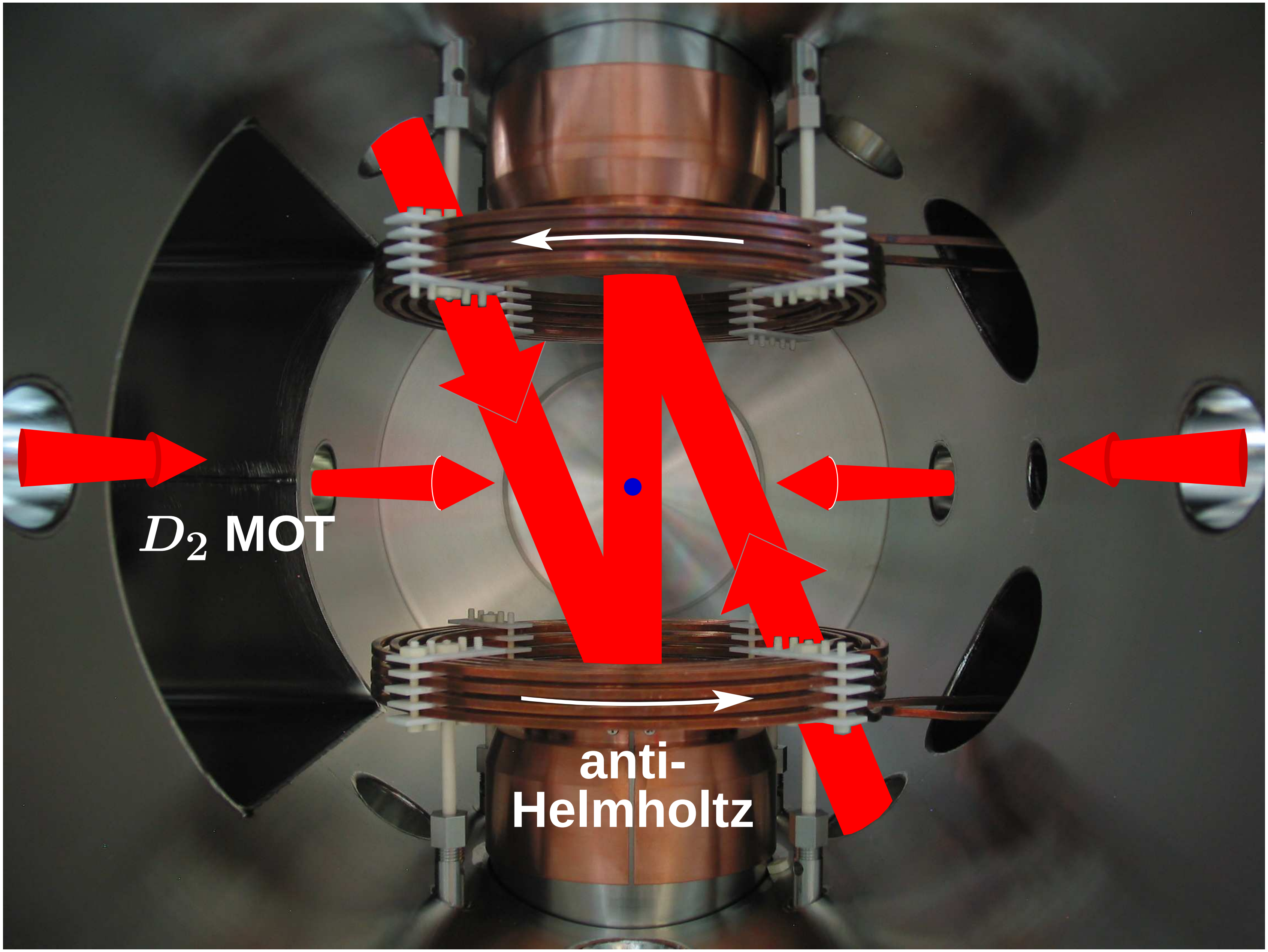

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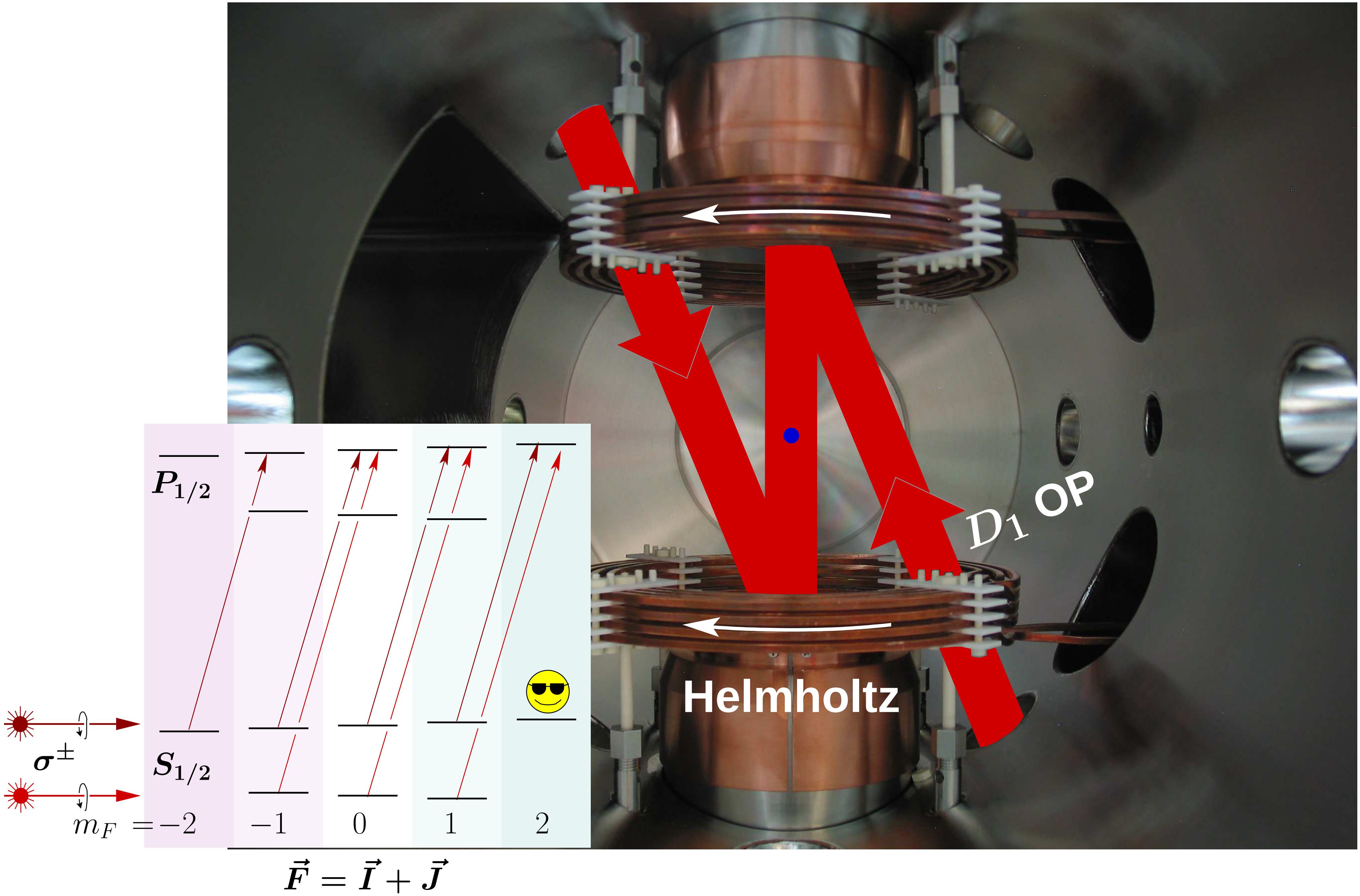

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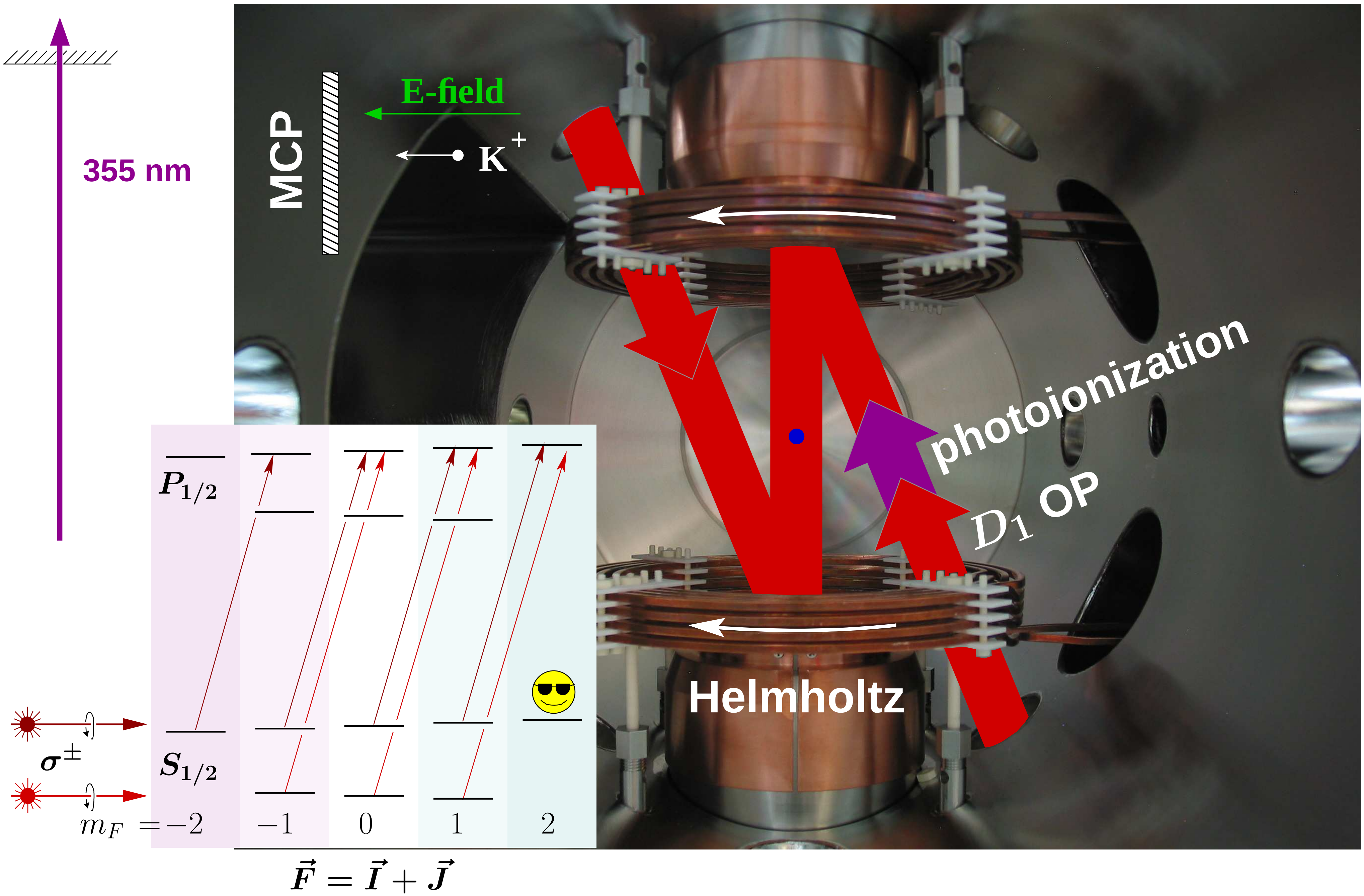
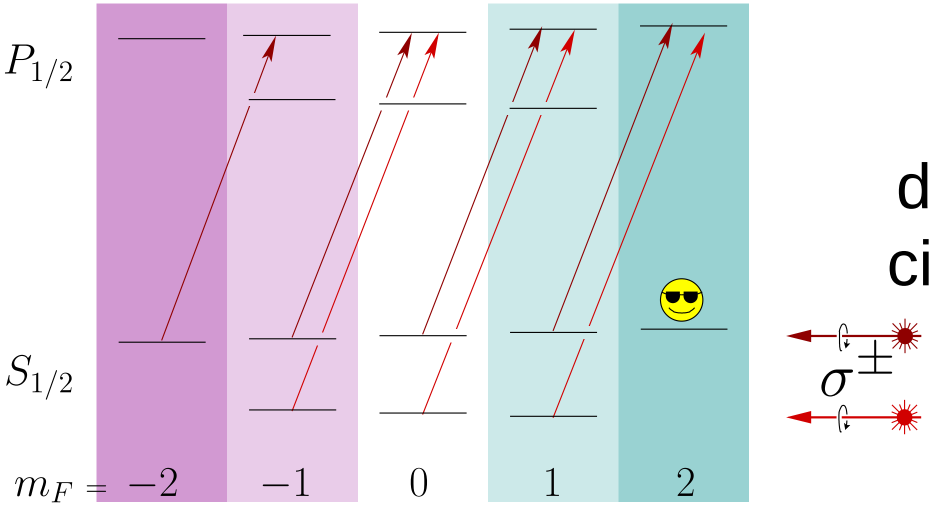
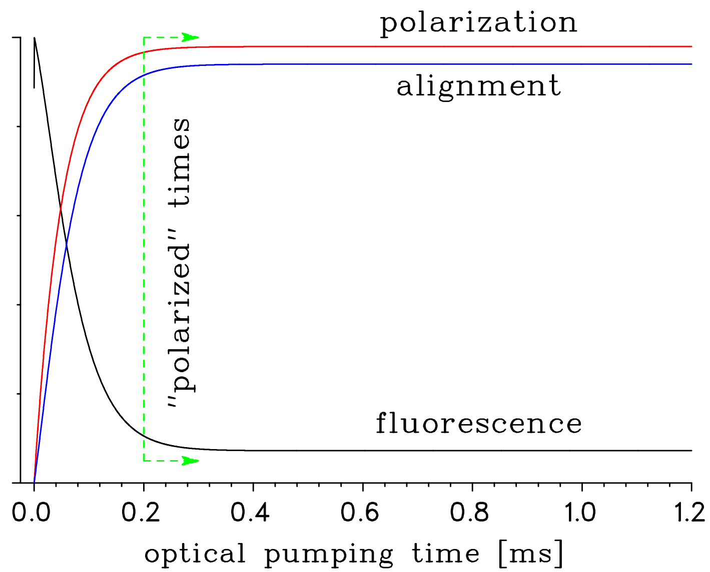


Atomic measurement of P



deduce P based on a model of the excited state populations:



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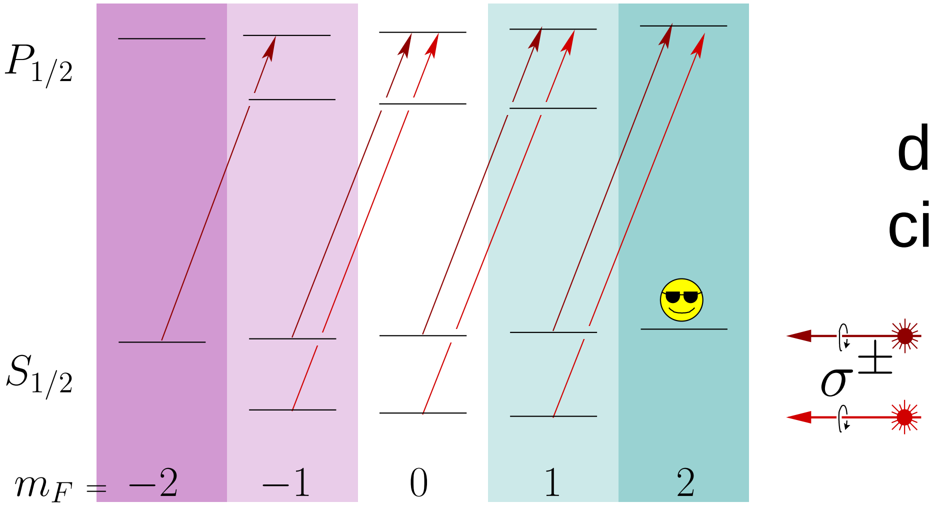

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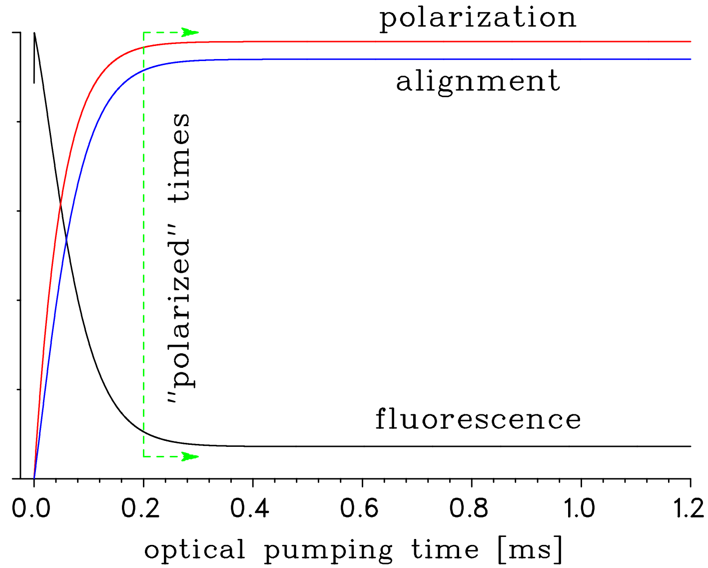
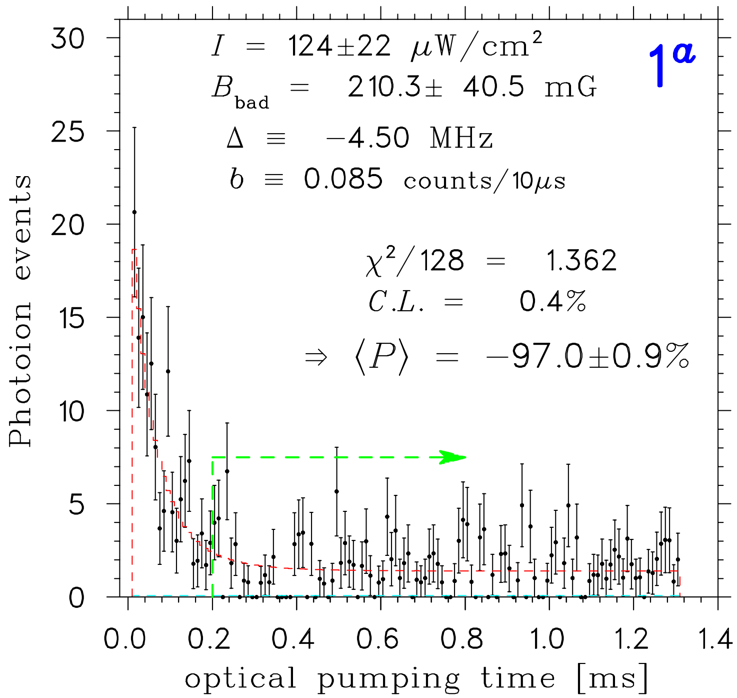
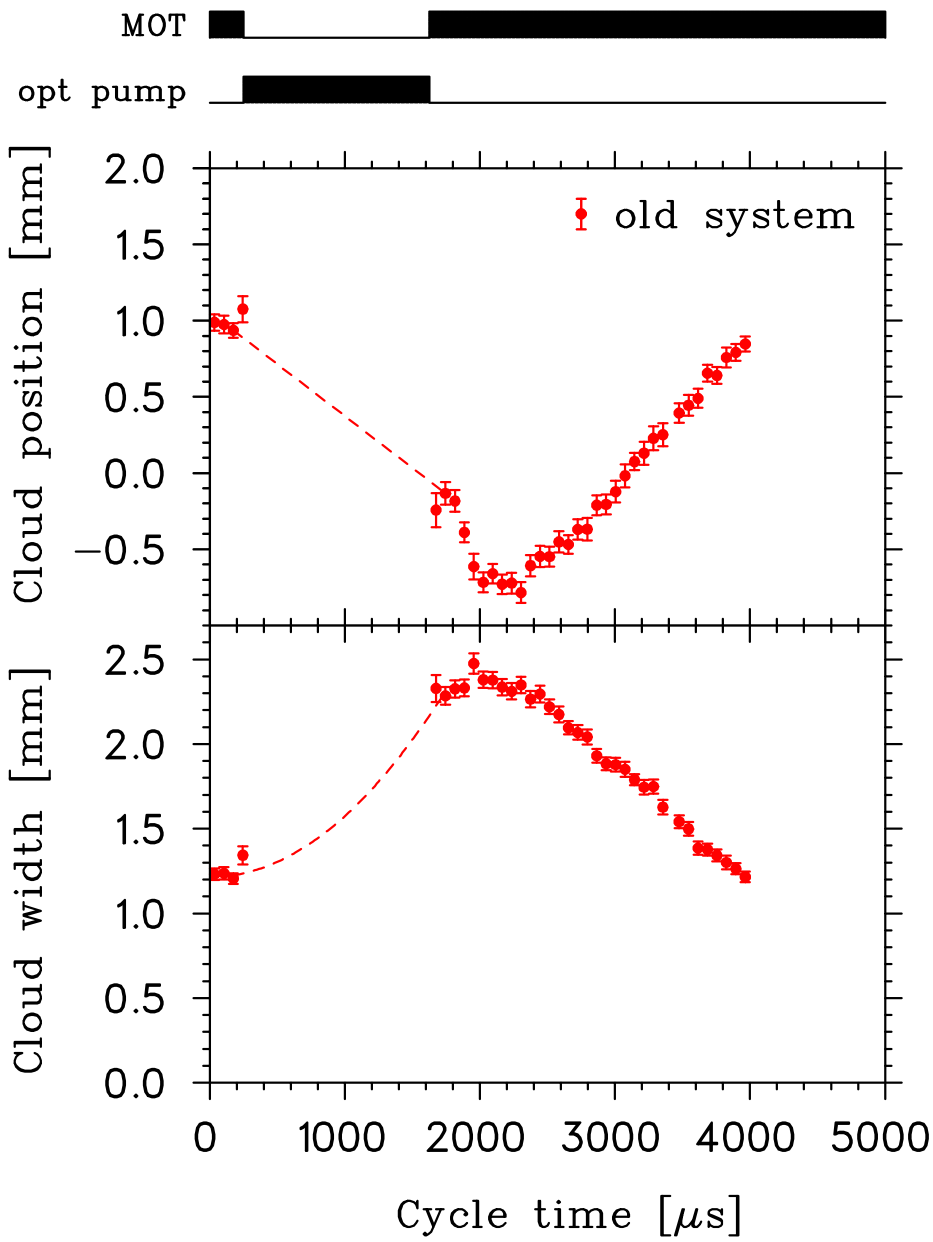




$$\Rightarrow P_{\mathrm{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$$

The cloud is better controlled now!



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  - kludged “Helmholtz” coils
  - eddy currents

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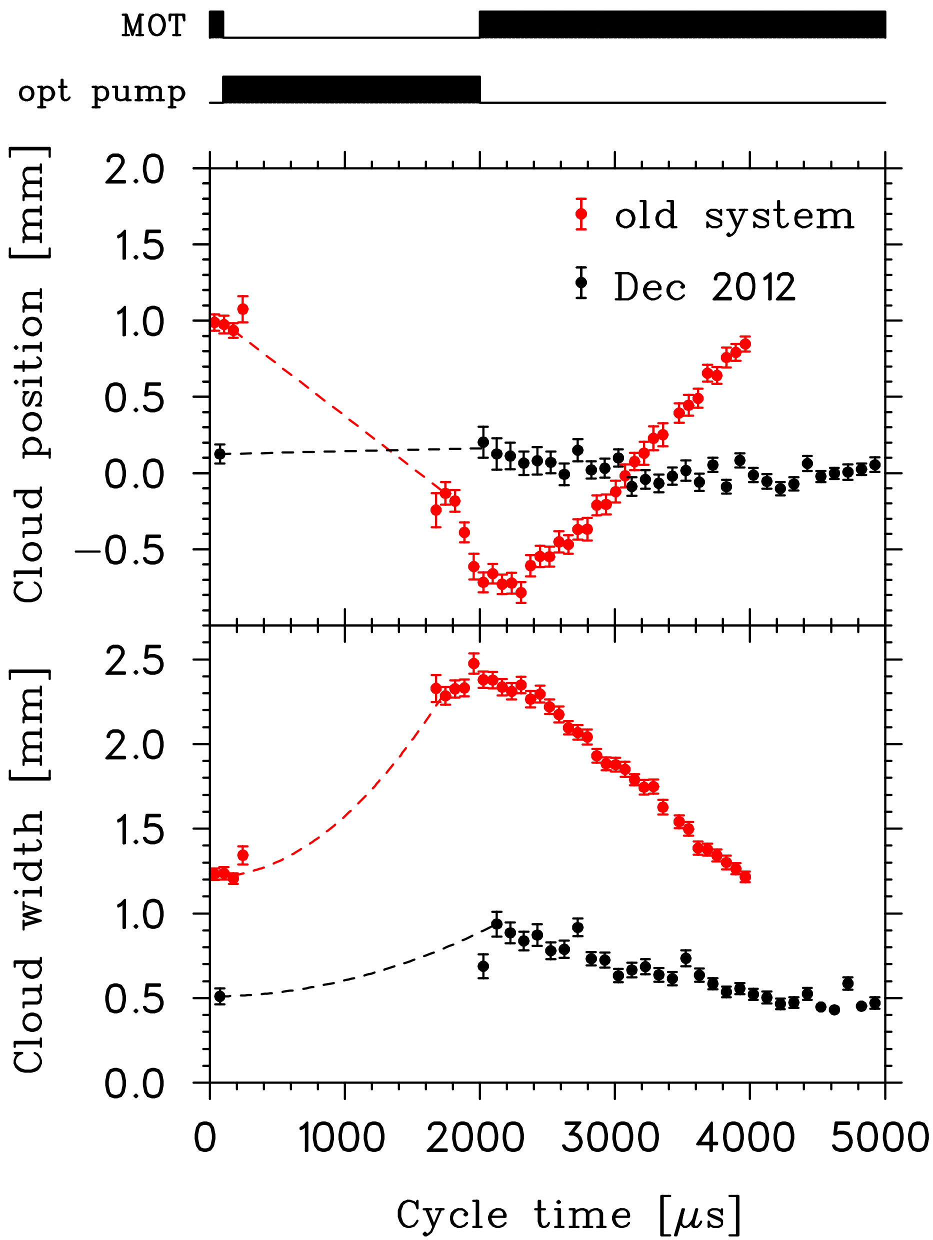
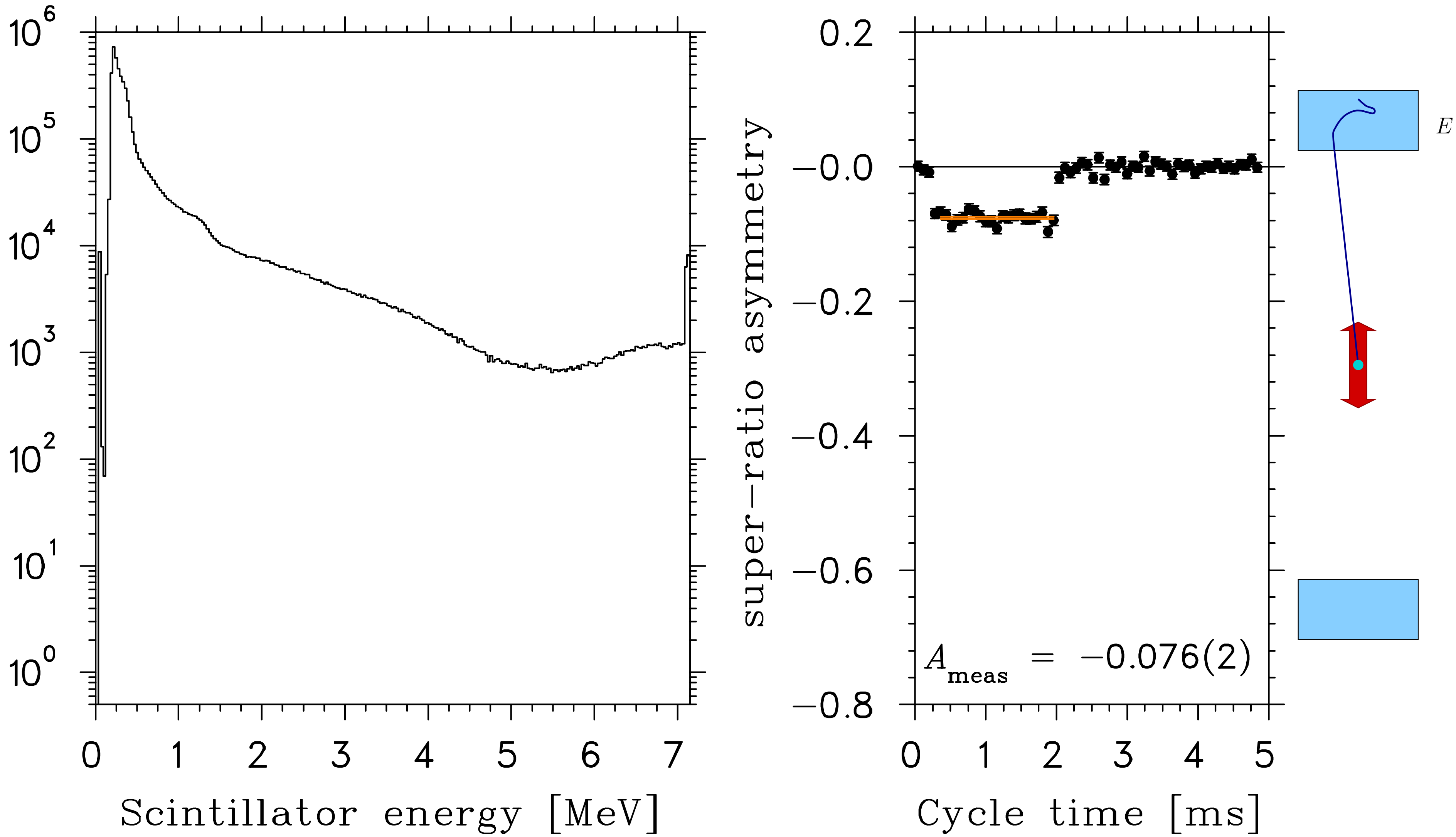


- old system:
  - retroreflected beams
  - kludged "Helmholtz" coils
  - eddy currents
- Dec 2012:
  - beams balanced
  - anti-Helmholtz → Helmholtz well-defined fields
  - ac-MOT ⇒ fast switching and low eddy currents

much more stable!
lower cloud temperature!

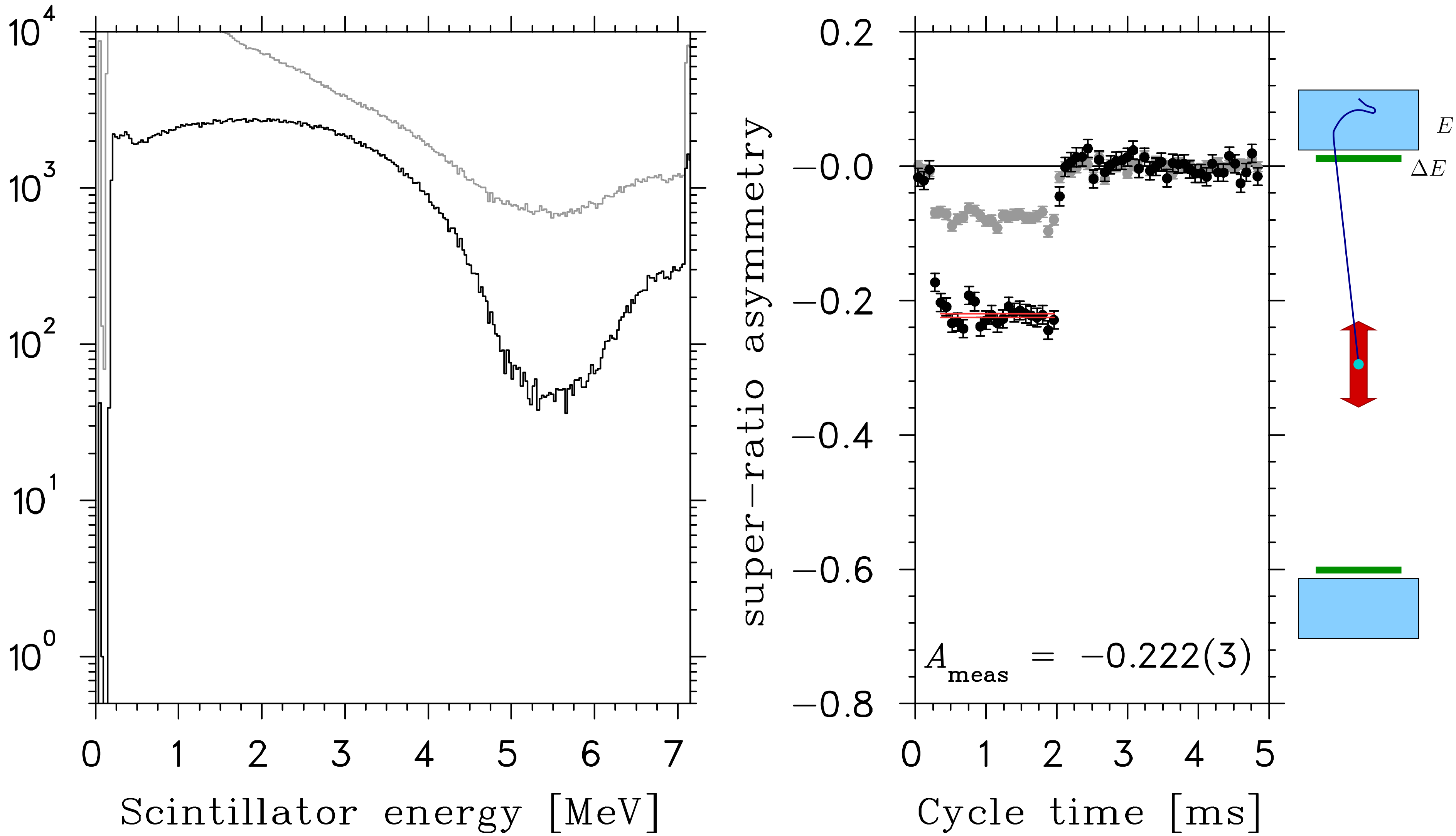
Scintillator spectra — Fall 2012

Just the raw data; a slight lower-energy cut to get rid of 511s



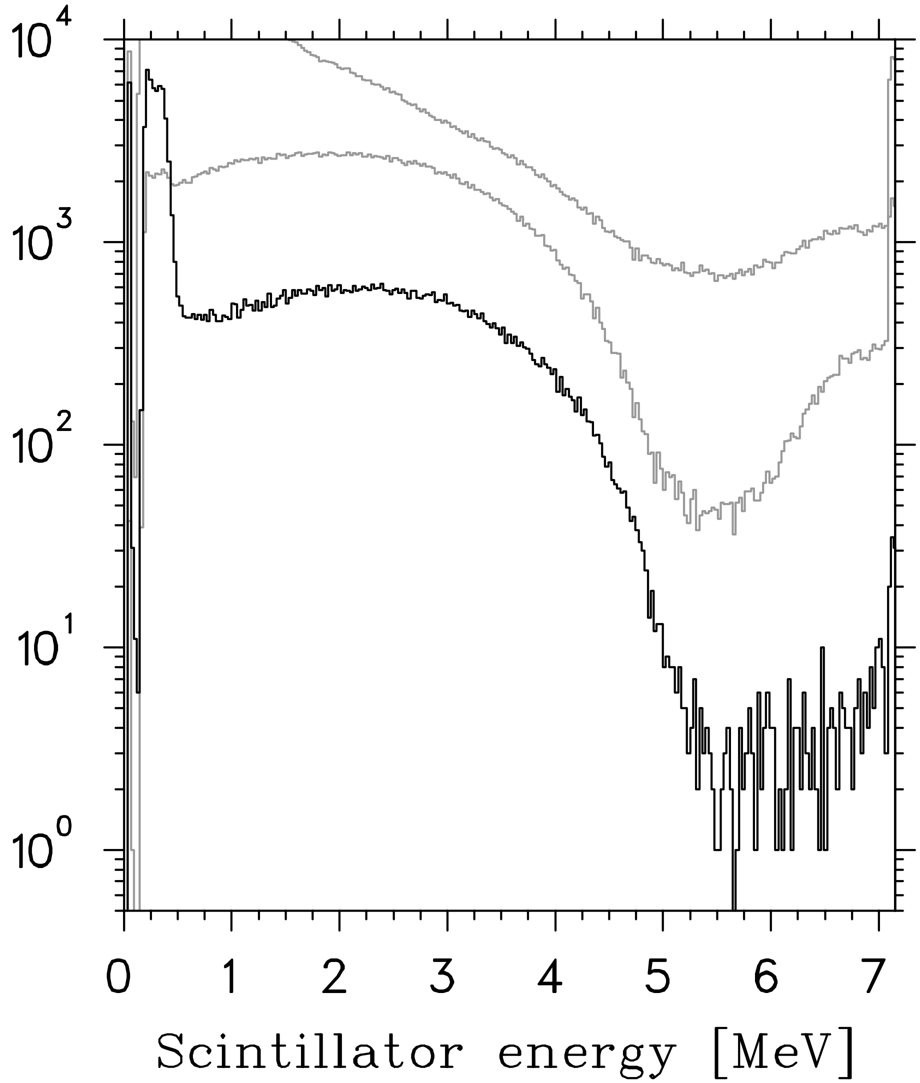
Scintillator spectra — Fall 2012

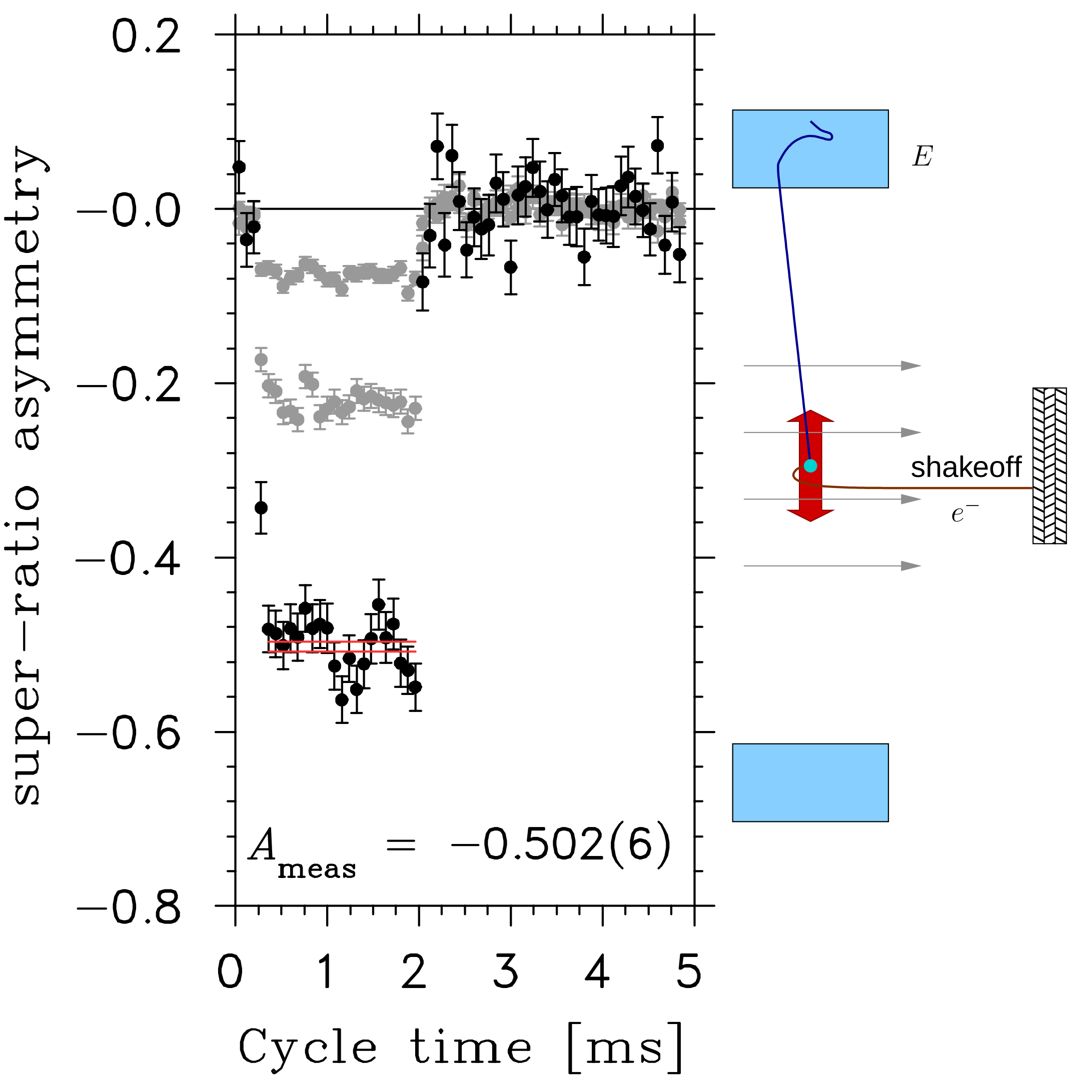
Requiring a ΔE coincidence $\Rightarrow$ remove γs



Scintillator spectra — Fall 2012

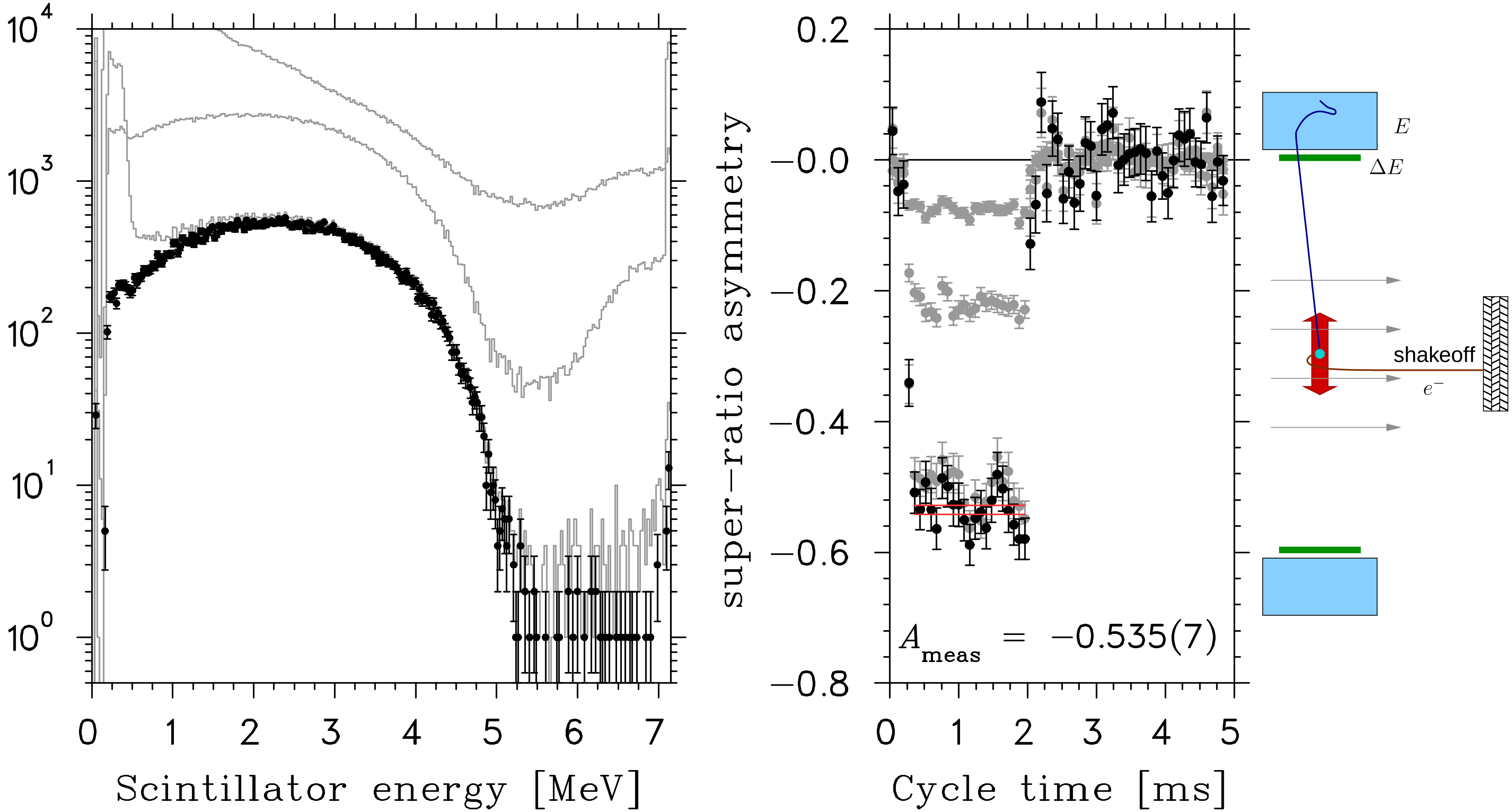
Requiring a shake-off e^- $\Rightarrow$ decay occured from trap!





Scintillator spectra — Fall 2012

Put in all the basic analysis cuts ⇒ clean spectrum!!



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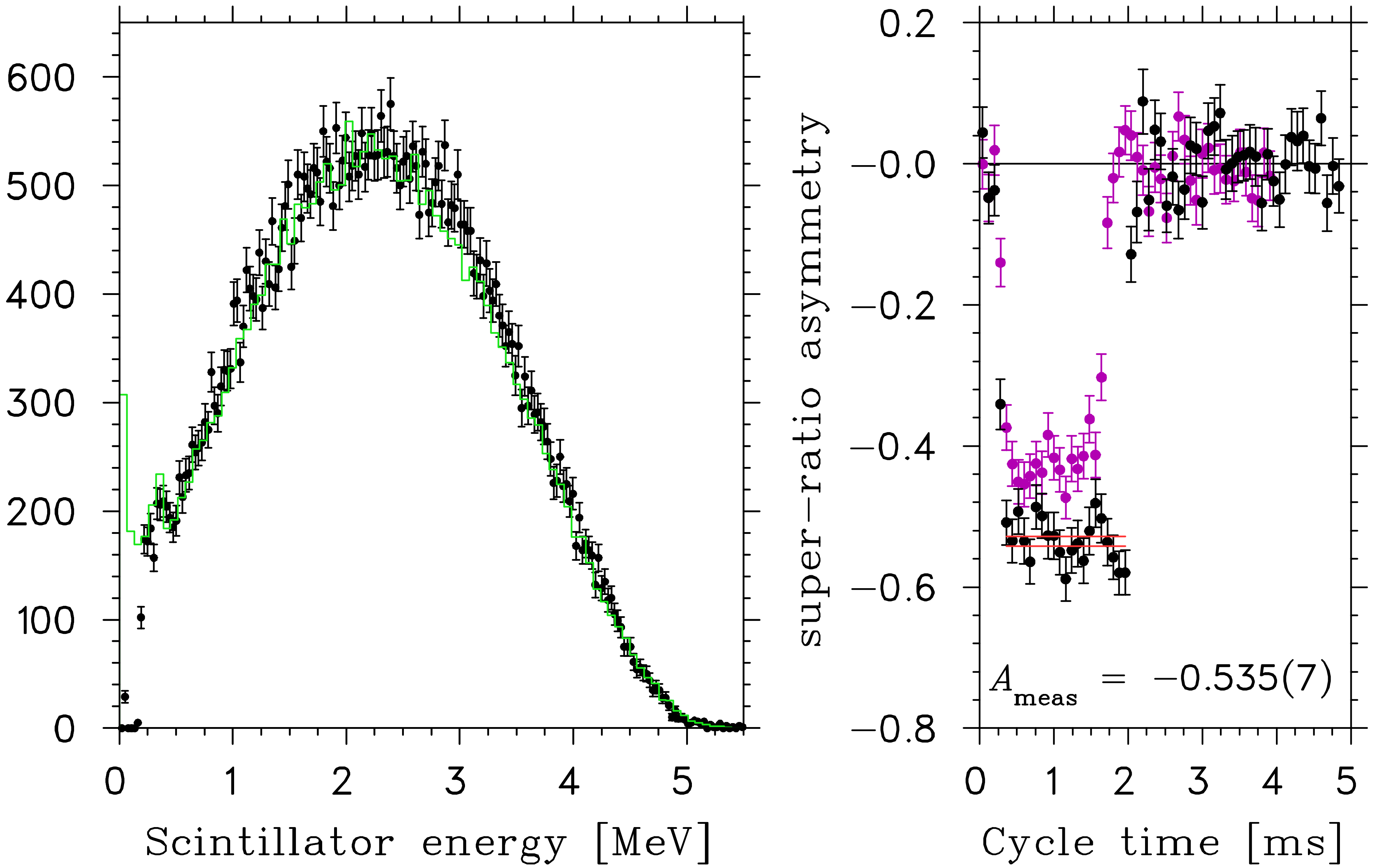

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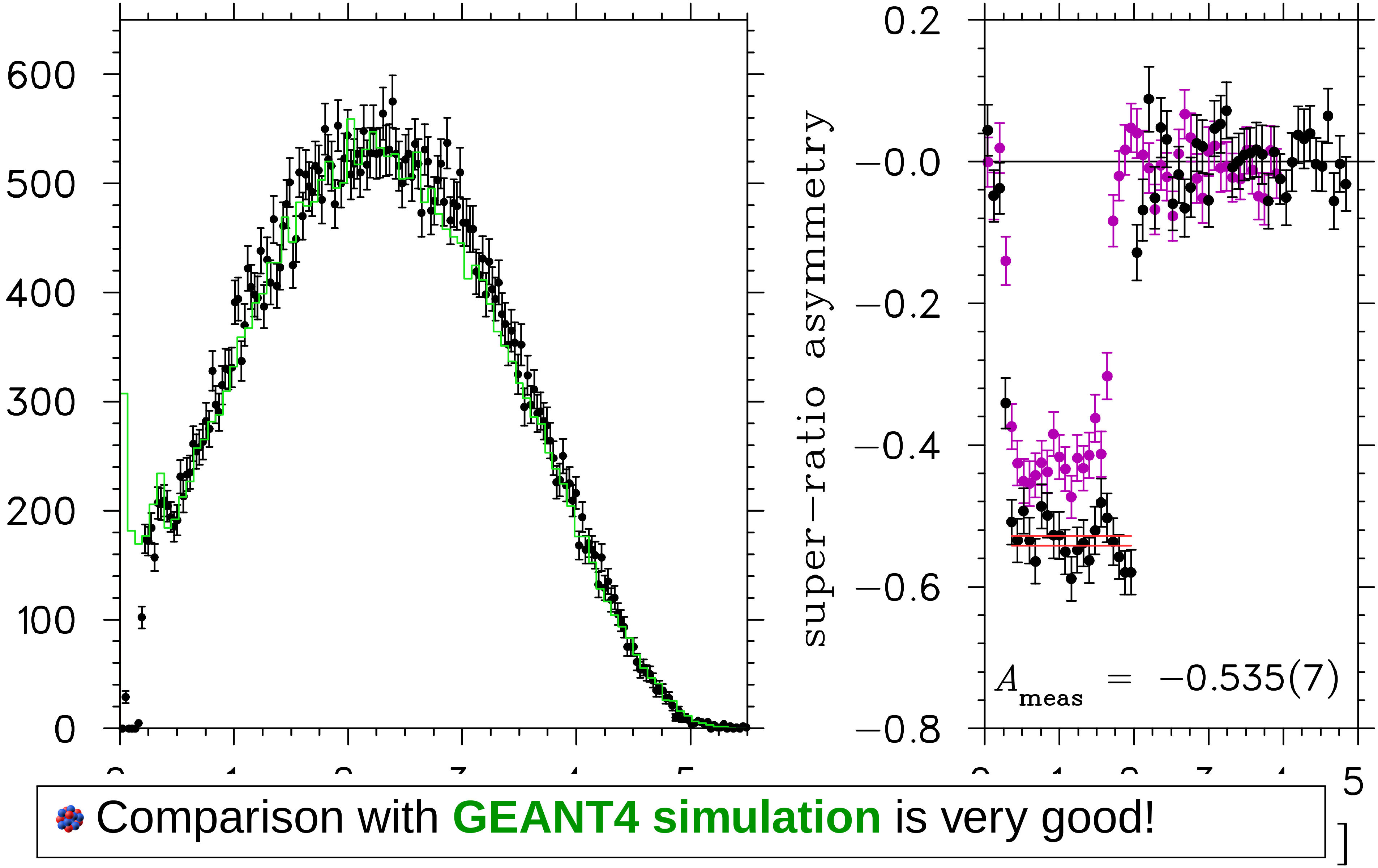

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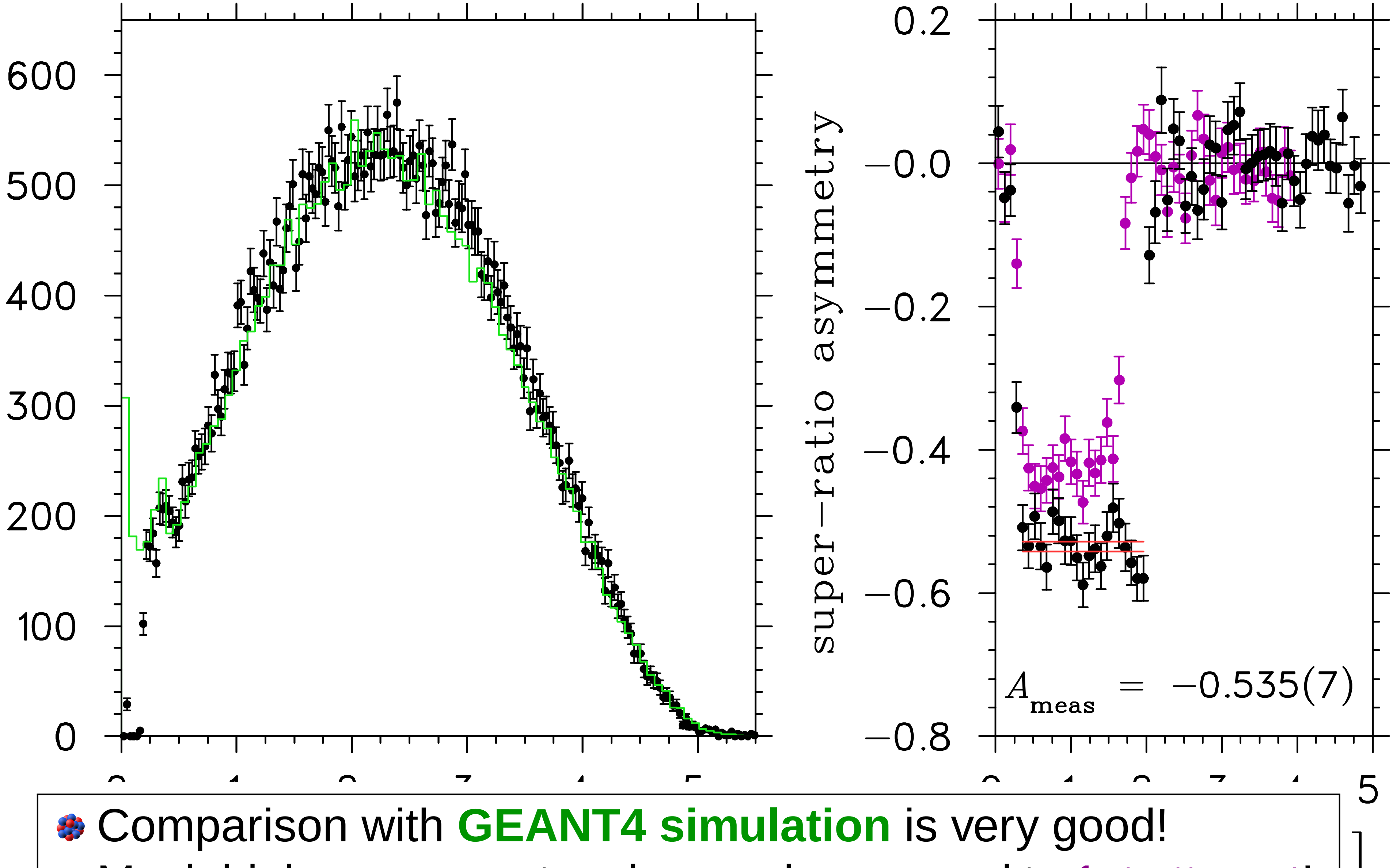

- Comparison with **GEANT4 simulation** is very good!
- Much higher asymmetry observed compared to 1st attempt!

Summary

- SM is fantastic, but **not** our “ultimate” theory
- many exciting avenues to find more a complete model

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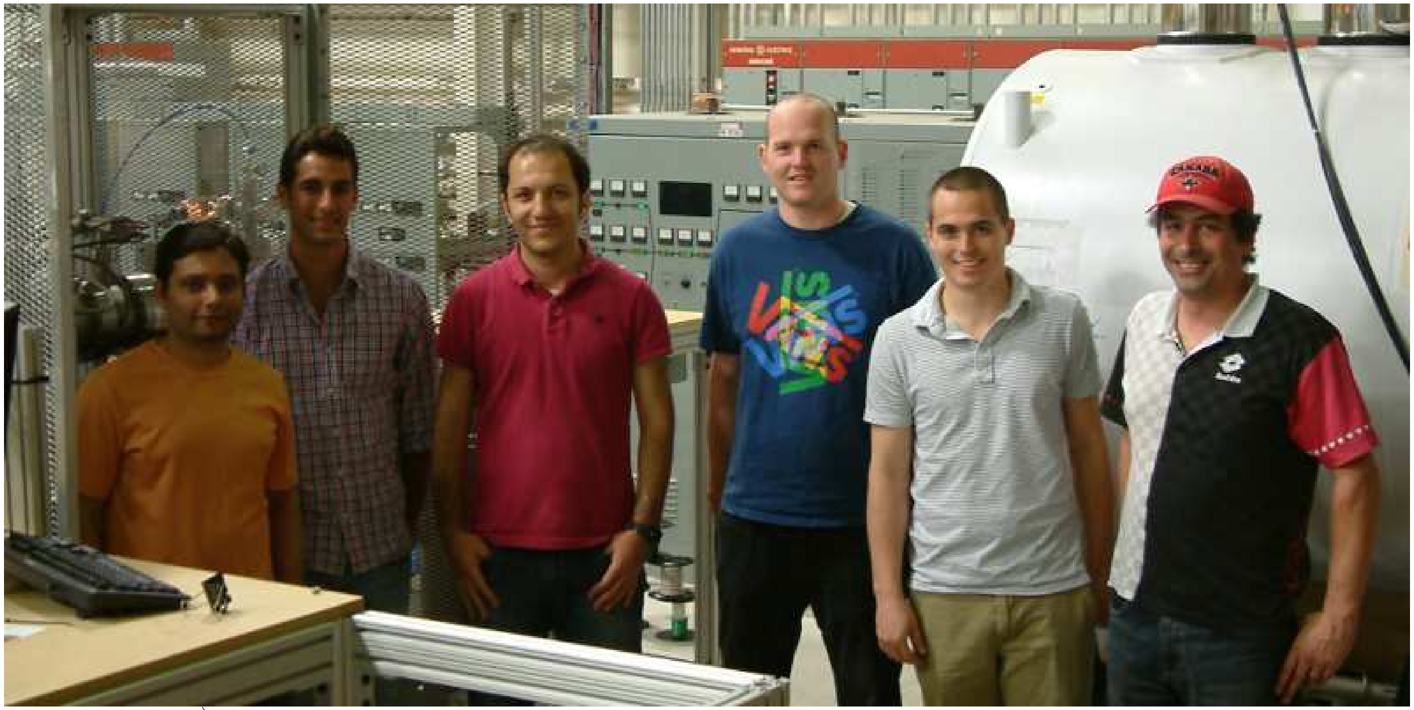
- **nuclear approach:** precision measurement of correlation parameters

- Penning trap + RIB CI = ***cool*** physics
- (AC-)MOT + opt. pumping = ***cool*** physics

The Mad Trappers/Thanks

TAMU: Spencer Behling, Mike Mehlman, Ben Fenker, Praveen Shidling
+ TAMU/REU undergrads



TRINAT: TRIUMF M. Anholm, J.A. Behr, A. Gorelov,
L. Kurchananov, K. Olchanski, K.P. Jackson

D. Ashery G. Gwinner

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TAMU/Cyclotron Institute