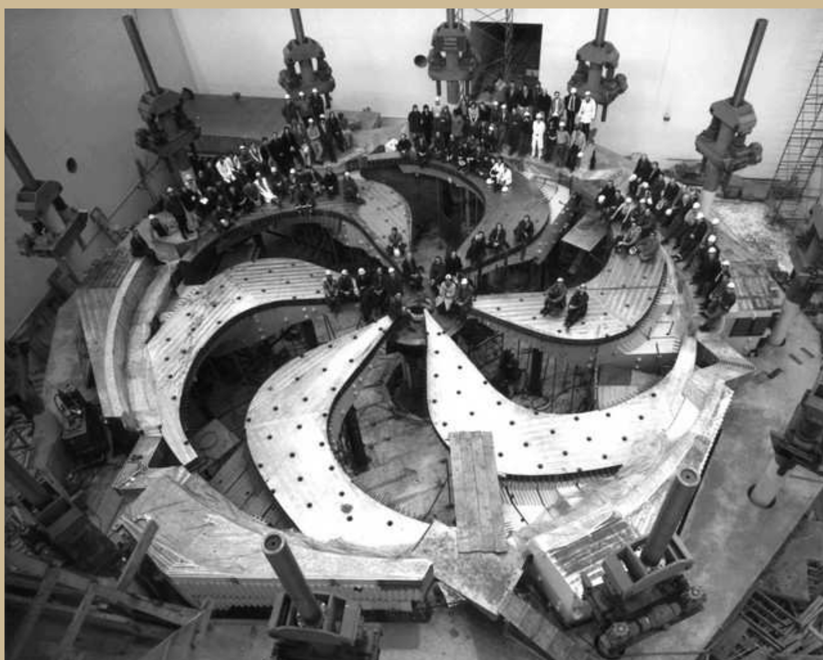
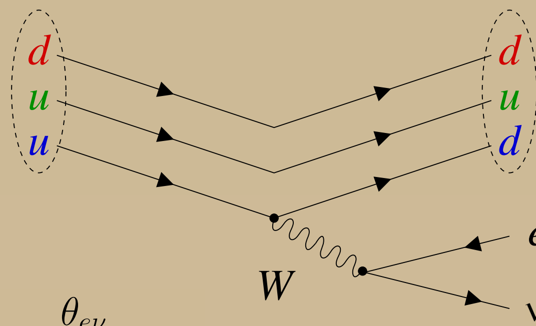
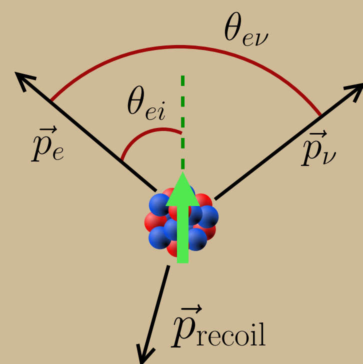
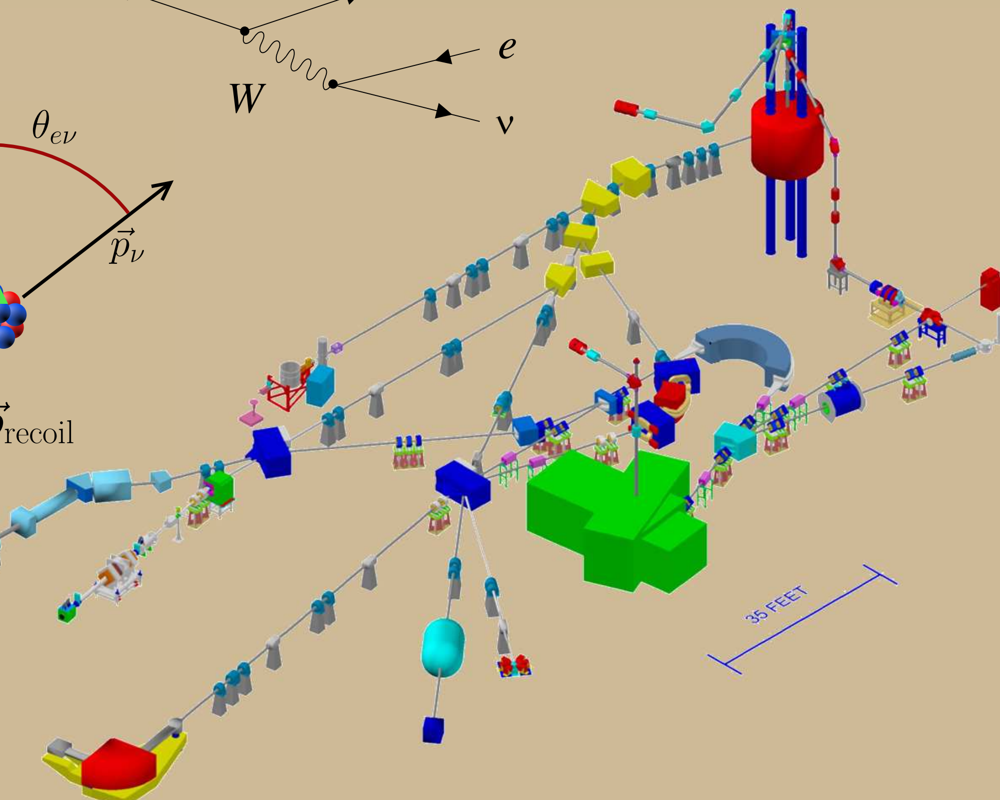
Measurements of Correlations in β-decay using Laser and Ion Traps









Dan Melconian

Aug 29, 2014

Overview

1. Fundamental symmetries

- brief **motivation**
- **game plan** for testing the SM

2. TAMU Penning Trap (being built)

- **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

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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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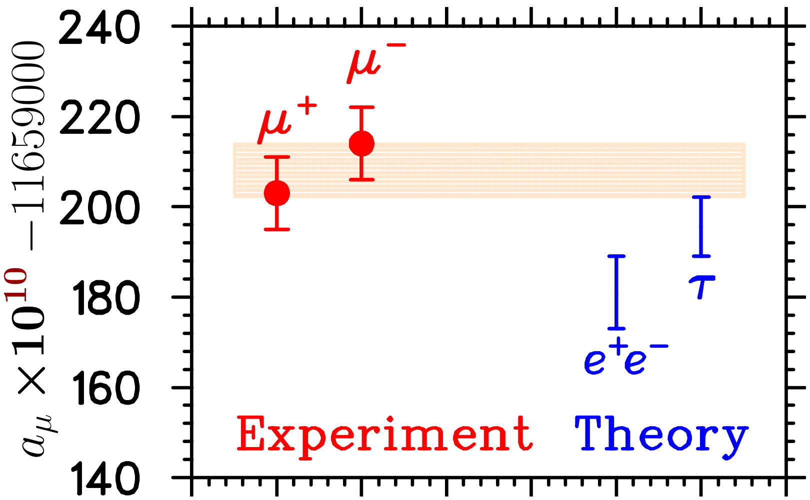

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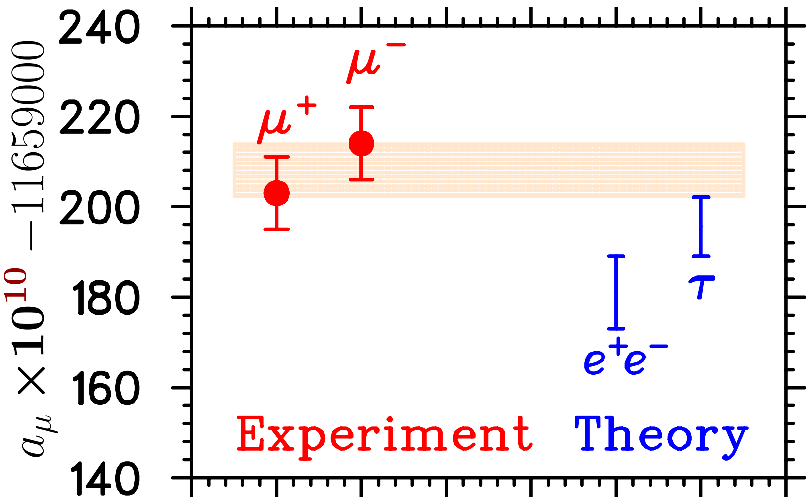

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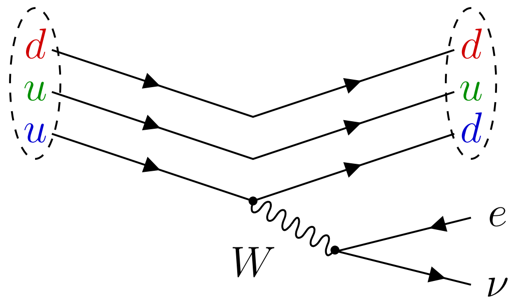
Wow . . . this is

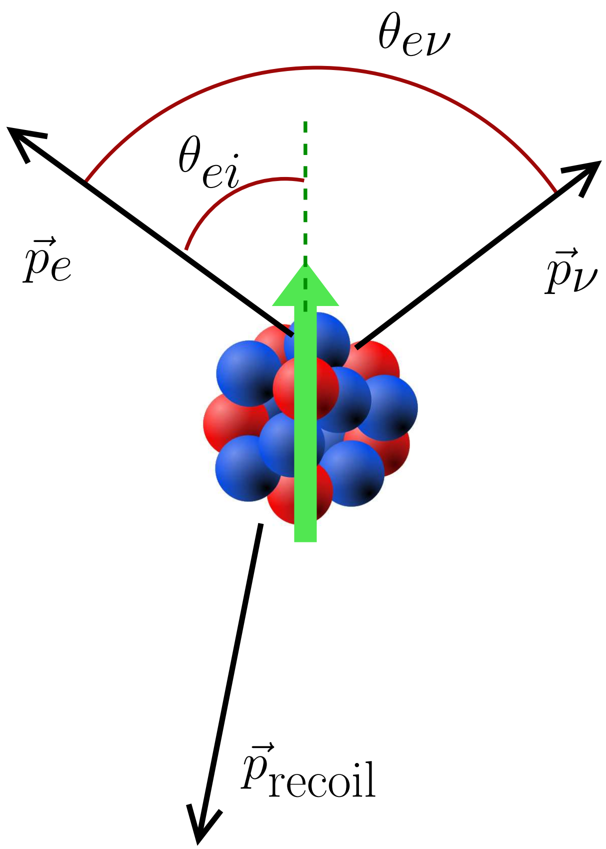
the most precisely tested theory ever conceived!

But we also know there's more to discover

- **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**!

How do I plan to test the SM?





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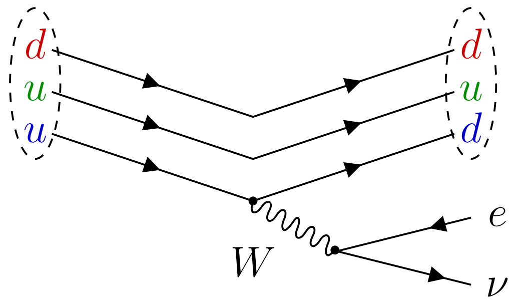

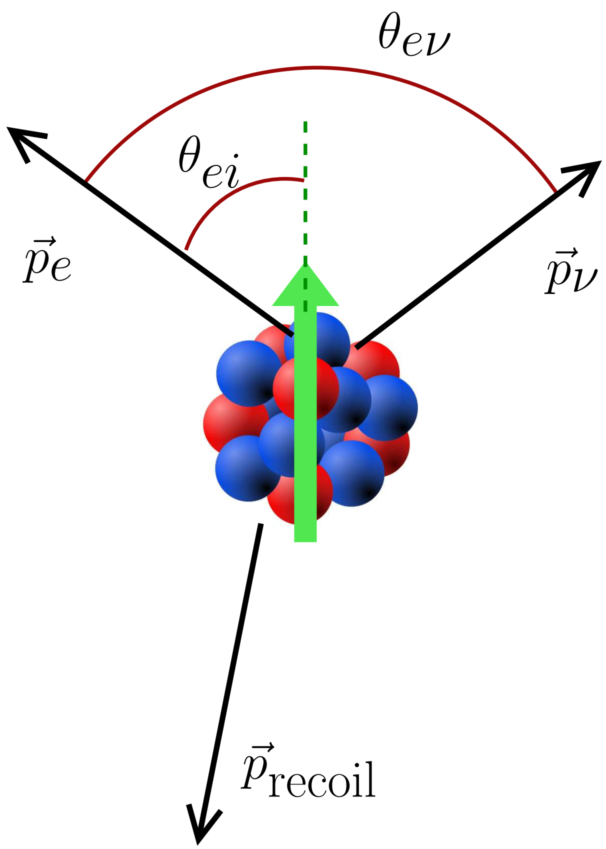

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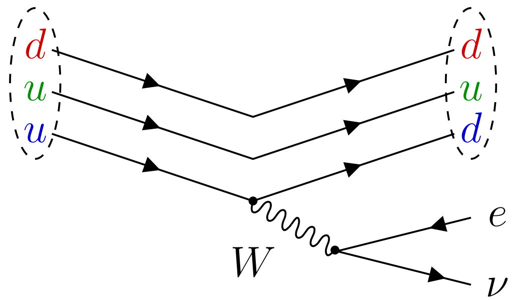

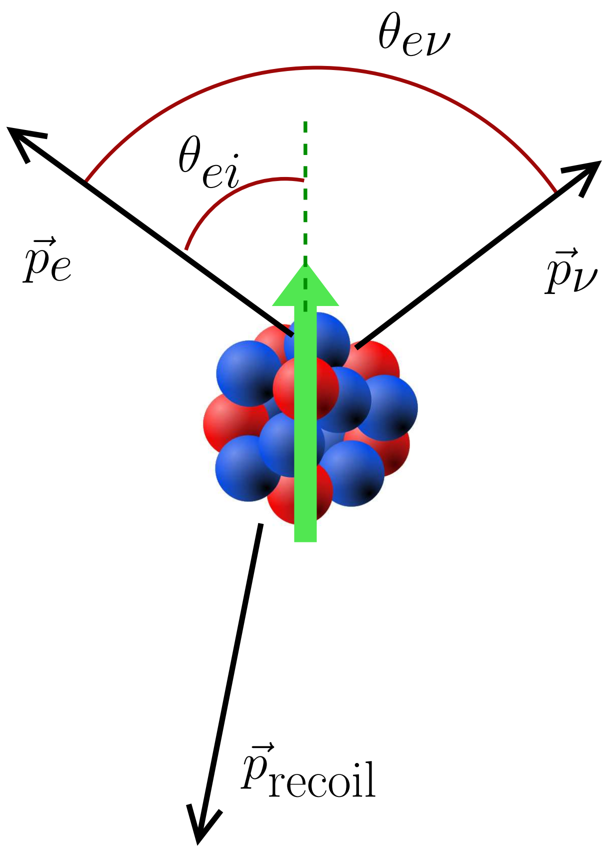

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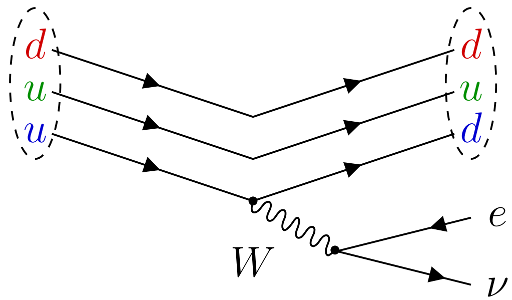
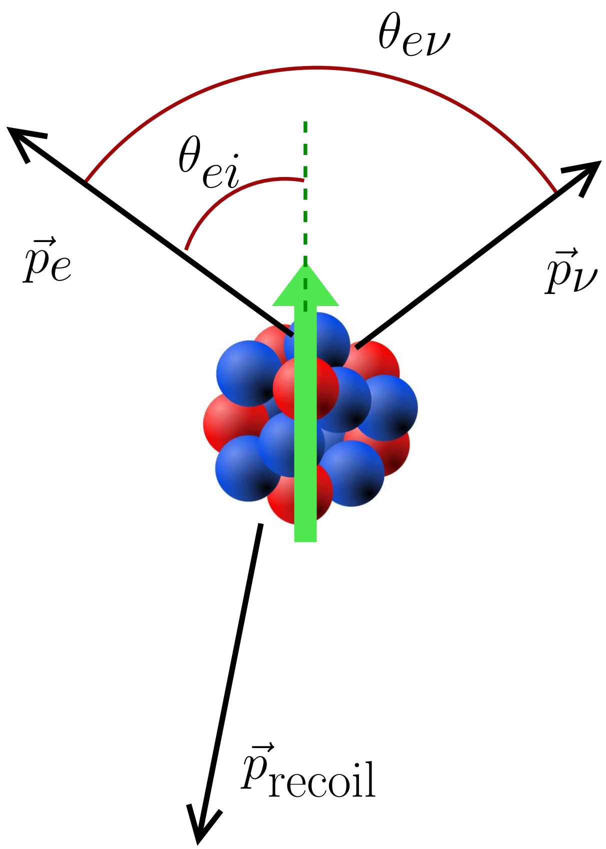


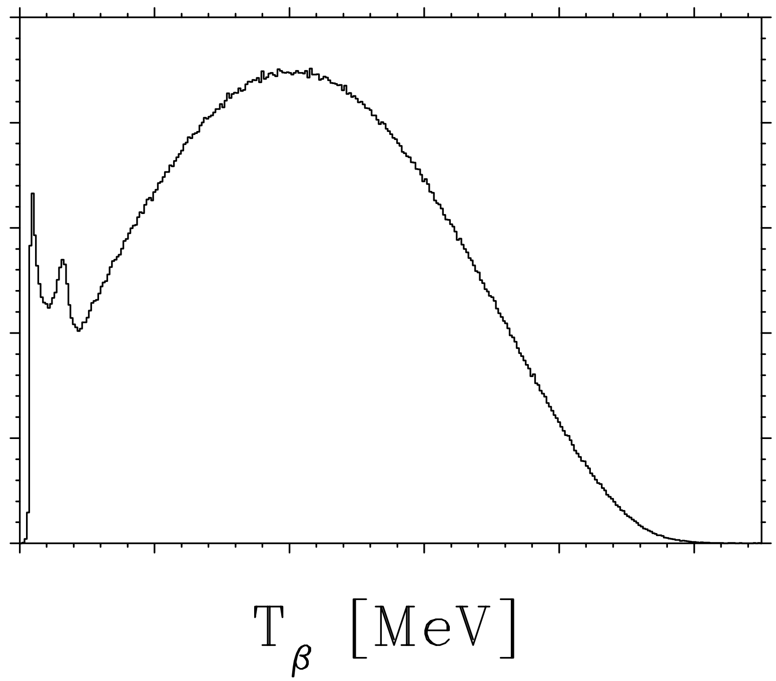


- perform a β decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters
- **compare** the SM predictions to observations
- look for **deviations** as an indication of **new physics**

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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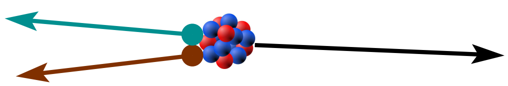

$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2}{|C_V|^2 + |C'_V|^2}$$

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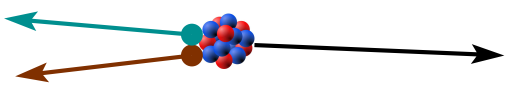

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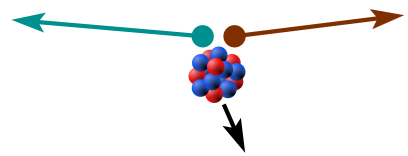

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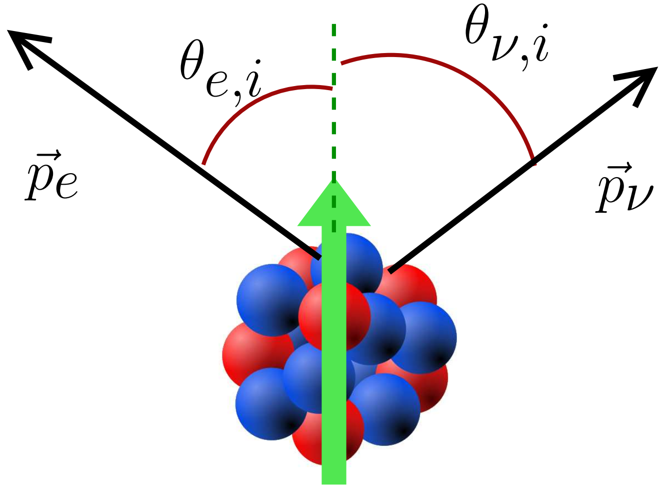

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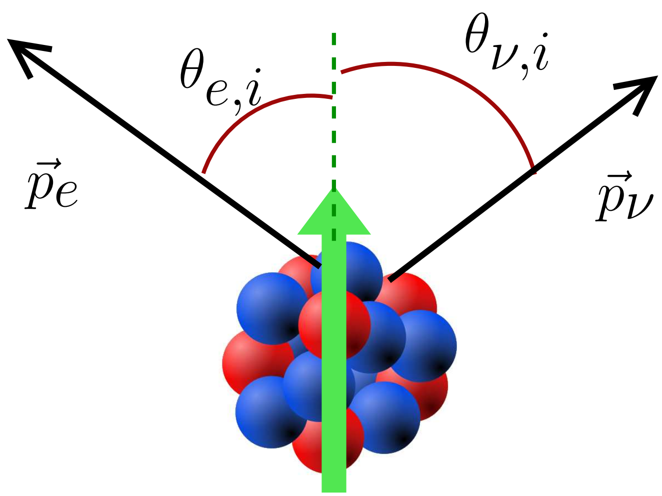

$$A_\beta = \frac{-2\rho}{1+\rho^2} \left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right]$$

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

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

are right-handed current parameters that are zero in the SM

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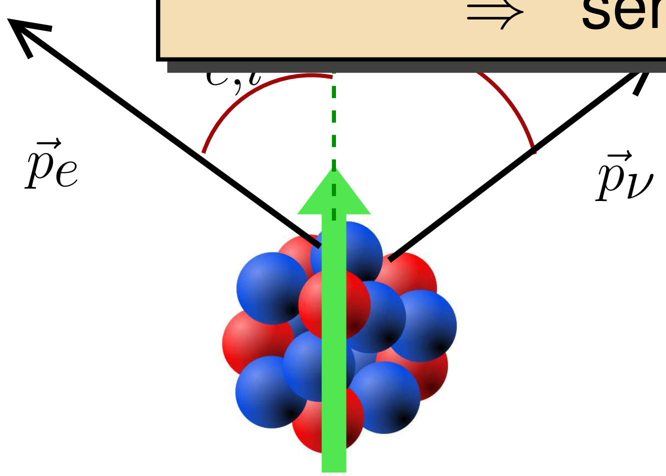
$\Rightarrow$ sensitive to new physics $\Leftarrow$



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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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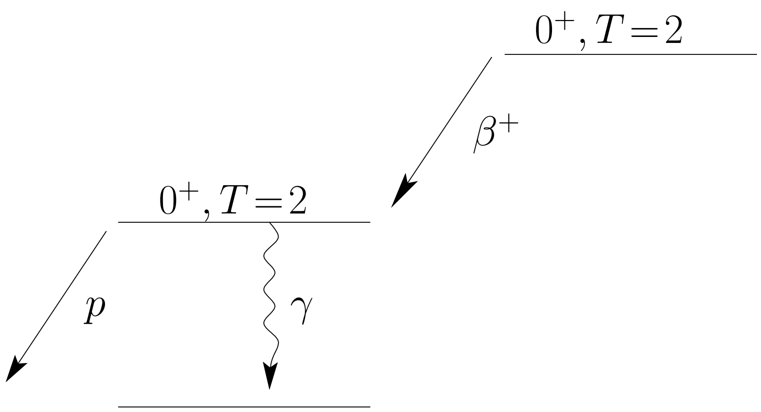

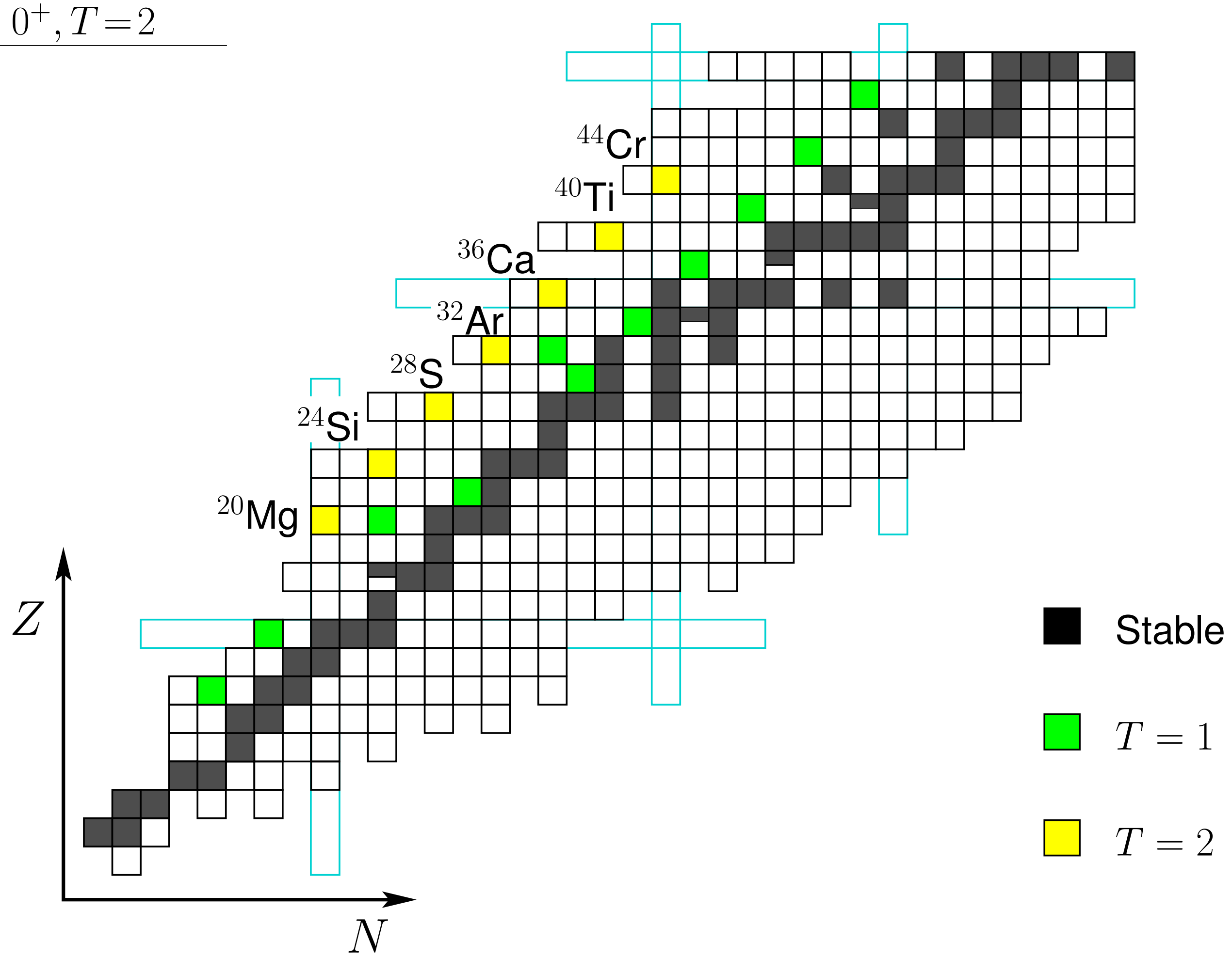

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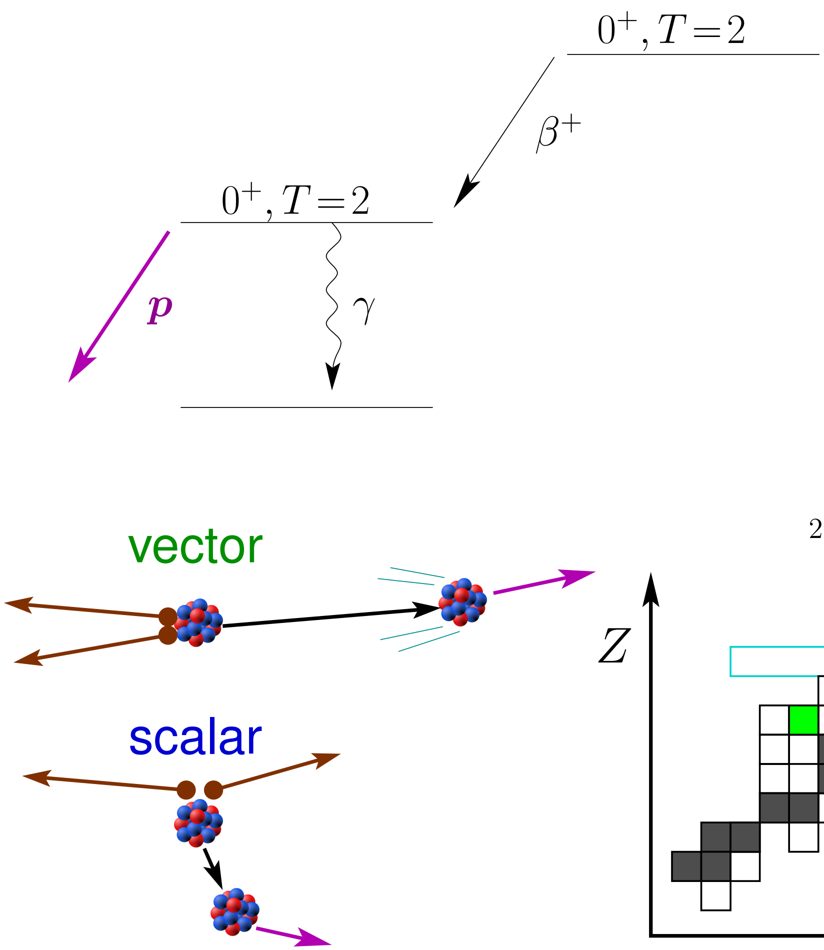

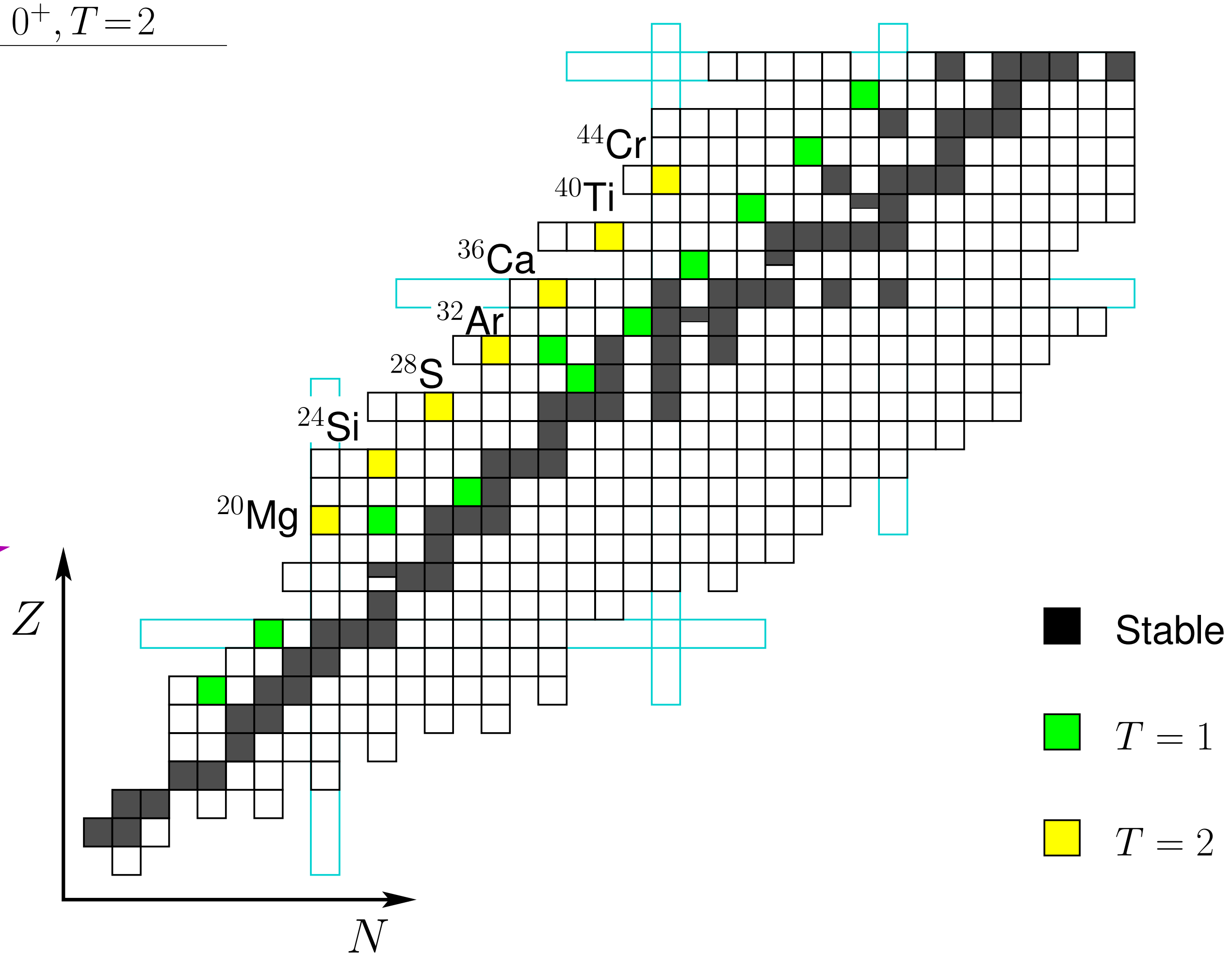

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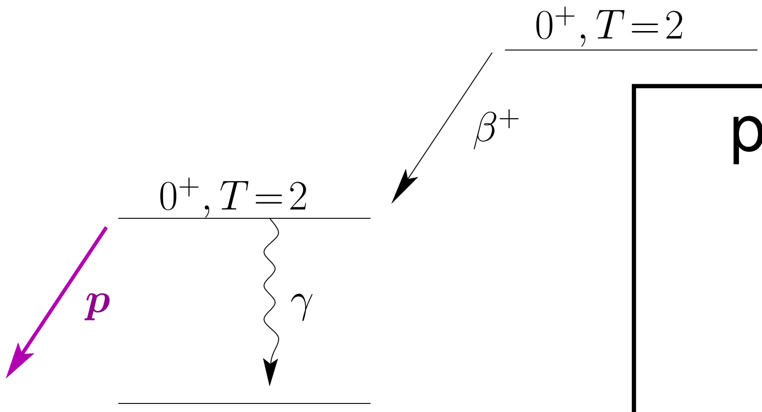

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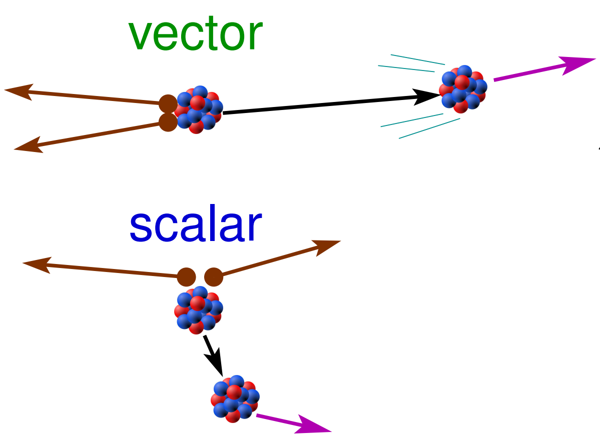

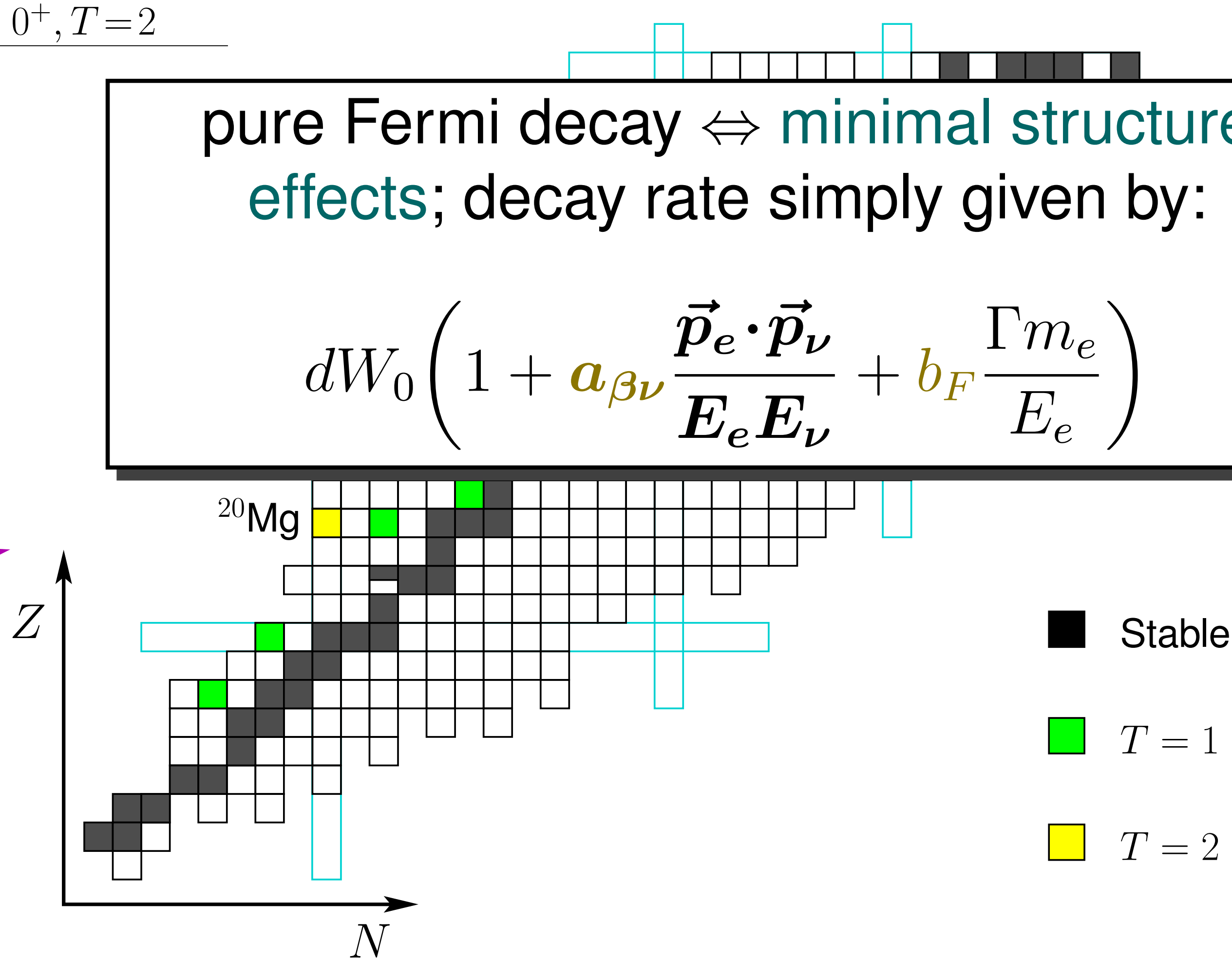

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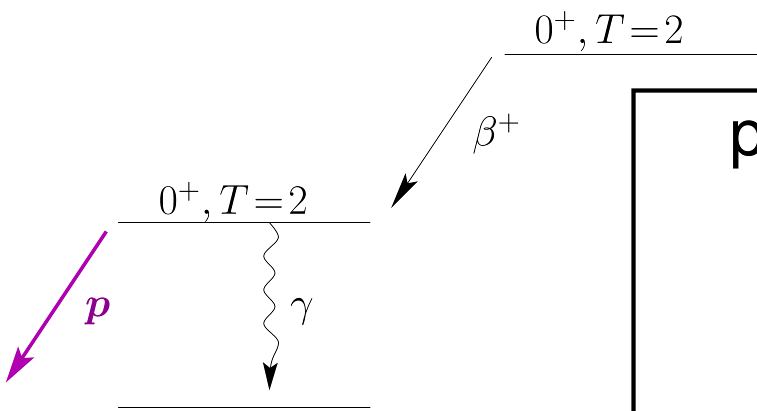

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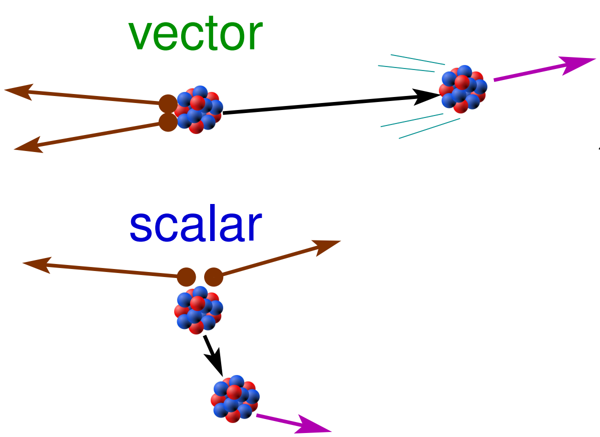

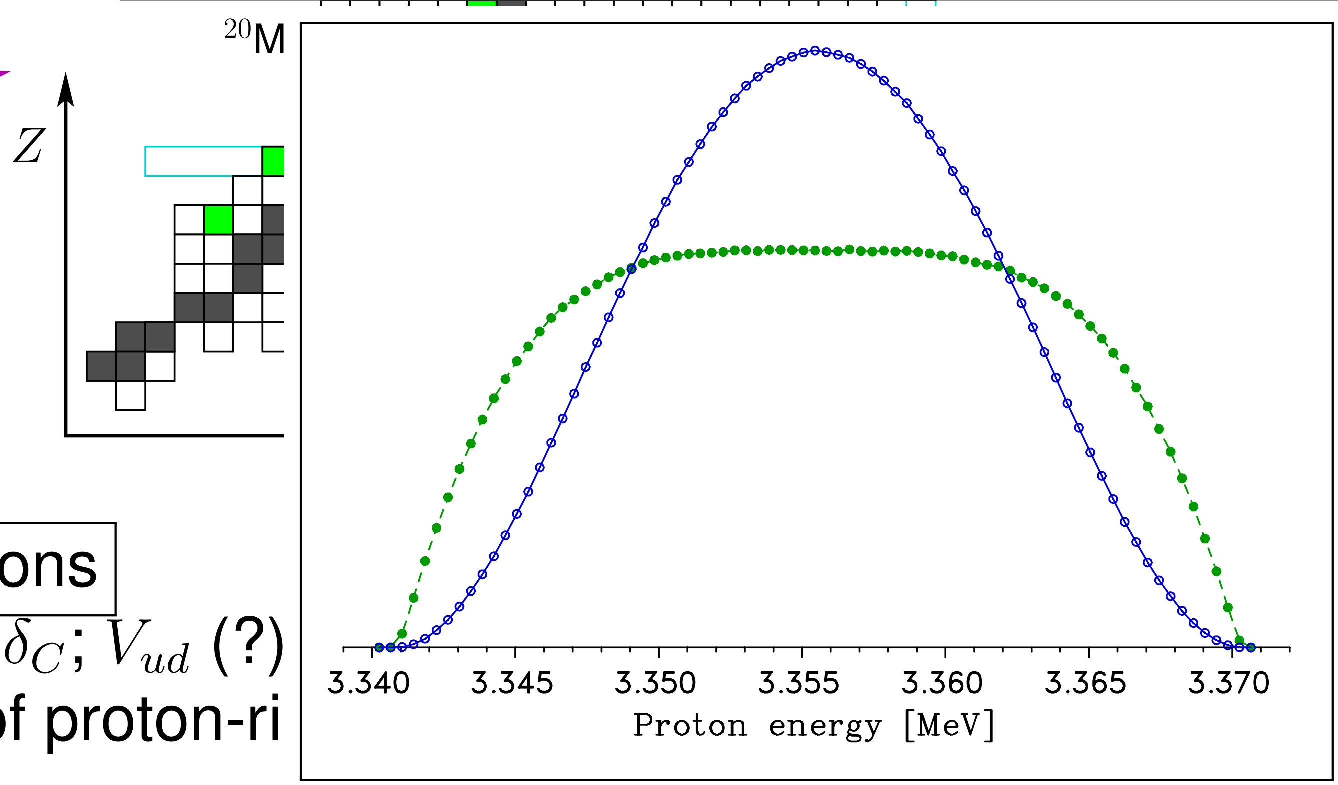

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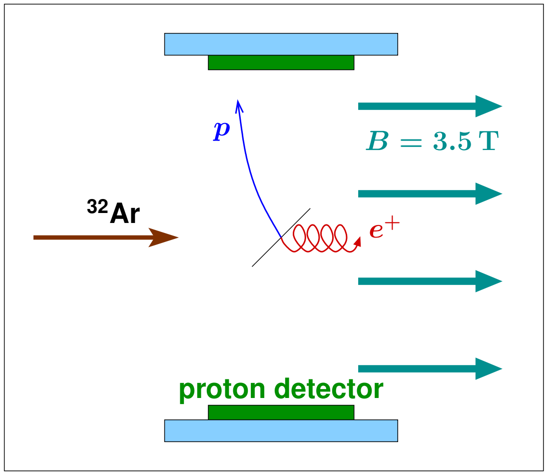

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

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

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[2] *Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[3] *Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
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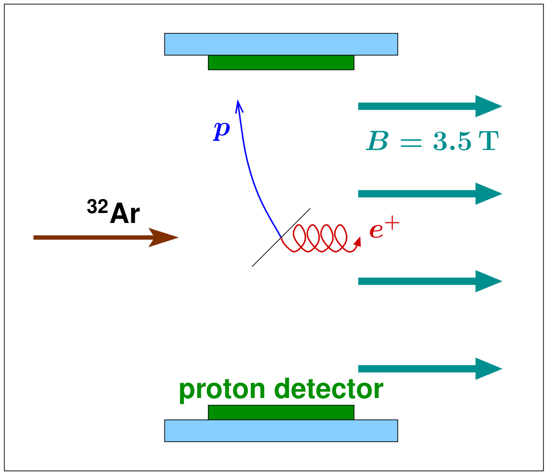
(Received 24 February 1999)

The positron-neutrino correlation in the $0^+ \longrightarrow 0^+$ 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.

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



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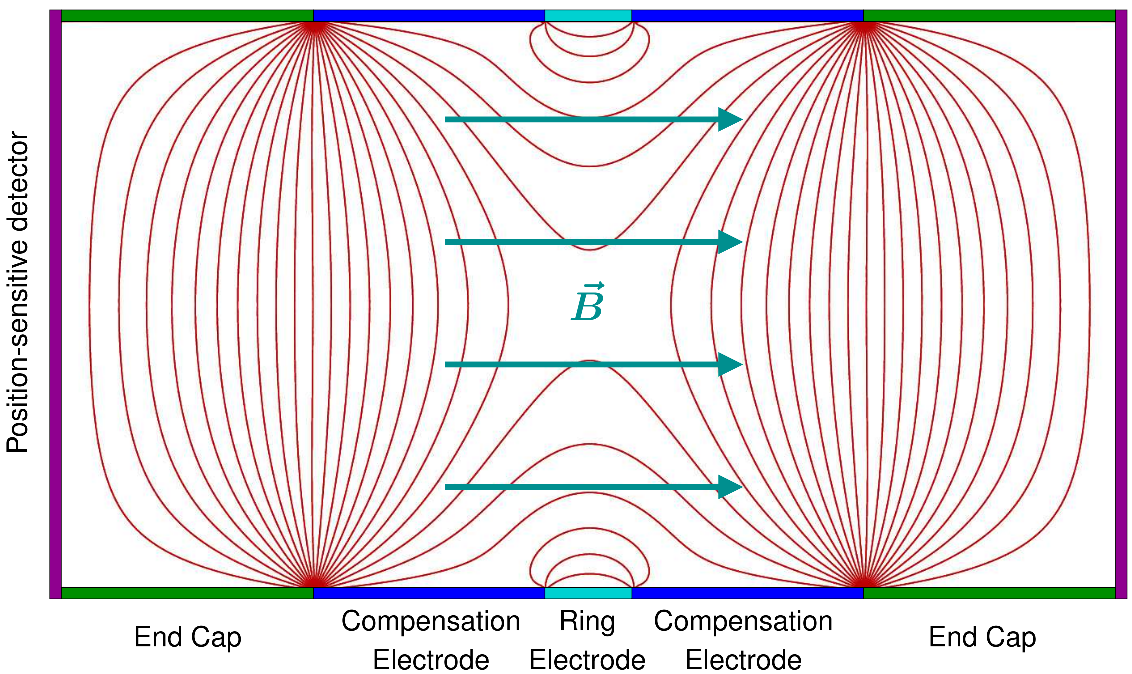
Mehlman *et al.*, NIM **A712**, 9 (2013)



But why throw away useful information?

$\rightsquigarrow$ increase sensitivity and solid angle using a Penning trap to observe $e - p$ coincidences!

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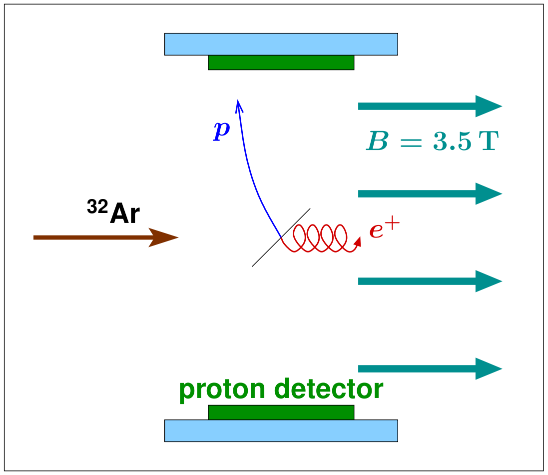
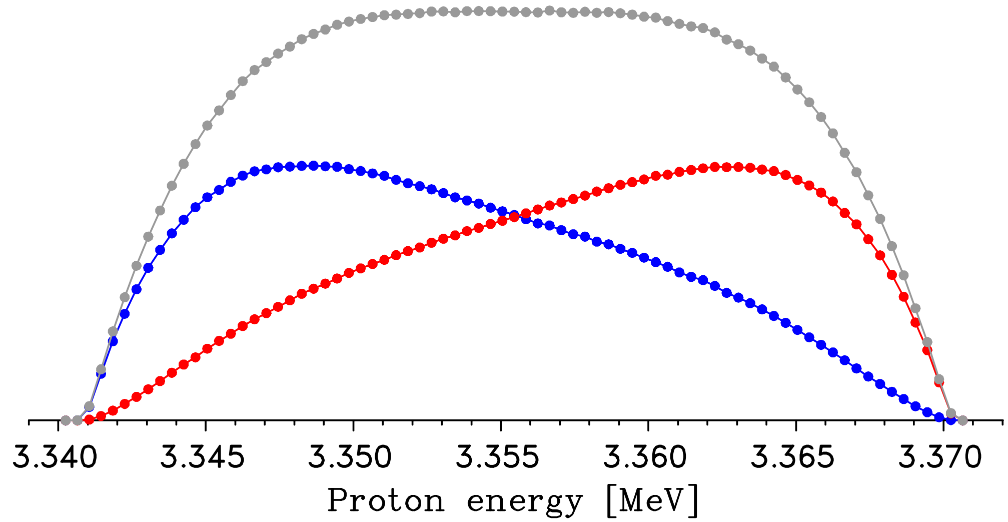
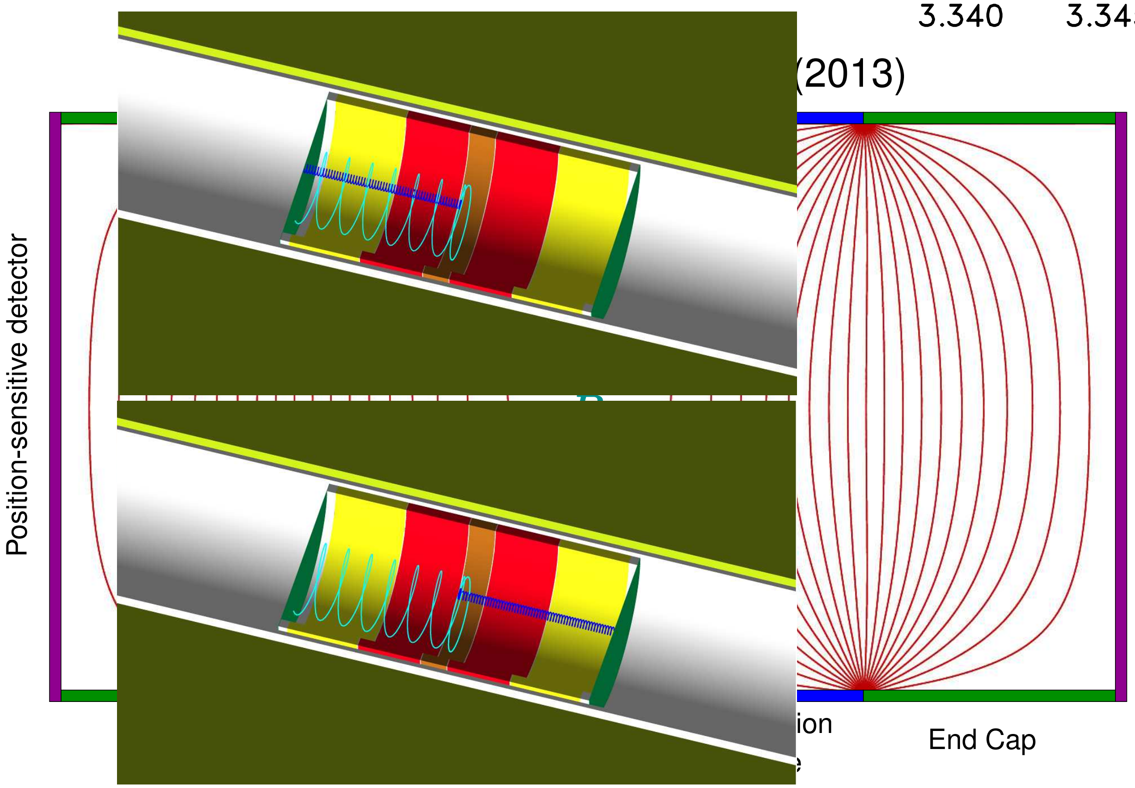


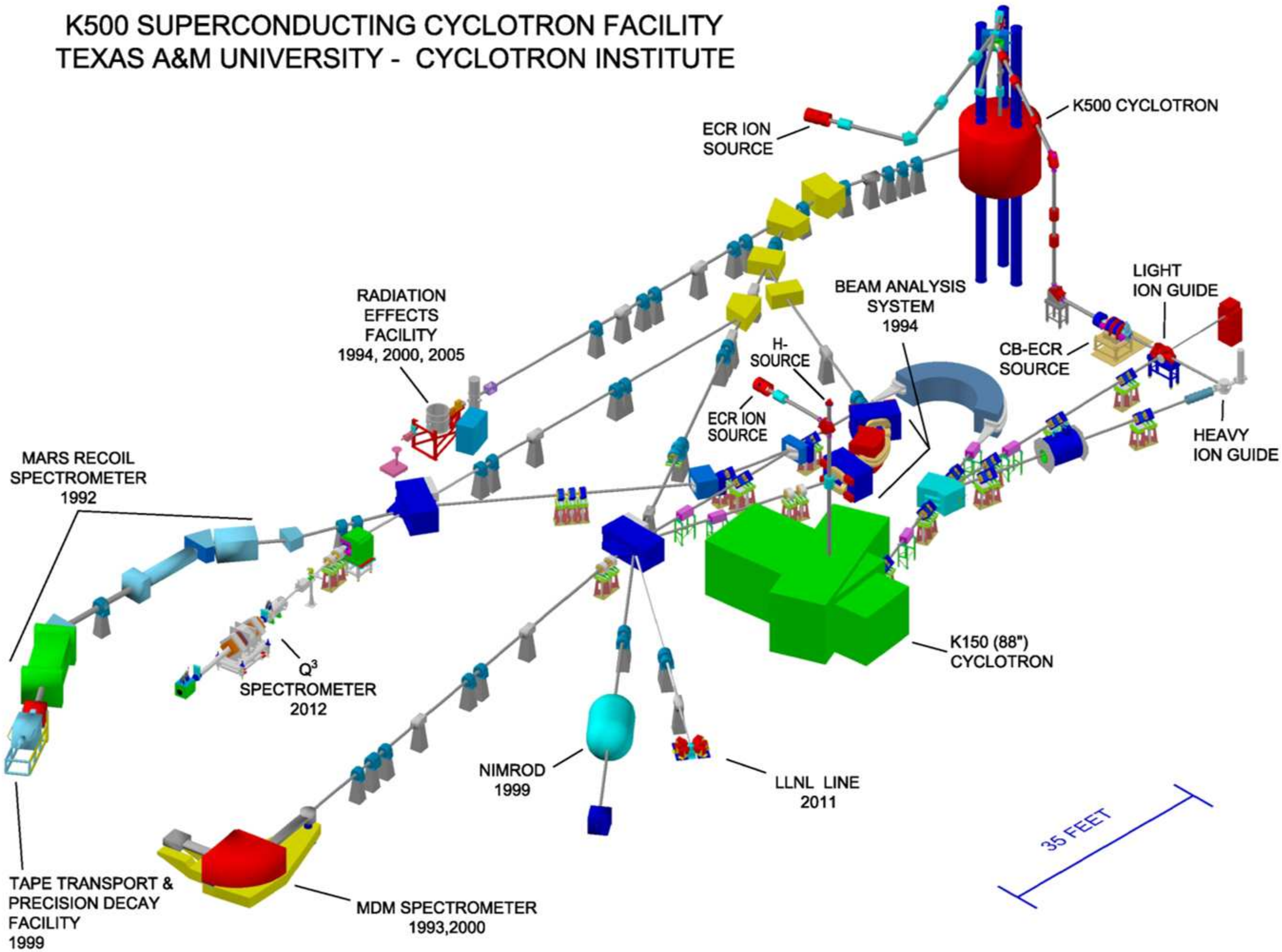




But why throw away useful information?

$\rightsquigarrow$ increase sensitivity and solid angle using a Penning trap to observe $e - p$ coincidences!

A Penning trap at T-REX CI/TAMU



The Texas A&M University Penning Trap

- will be the **world's most open-geometry** ion trap!
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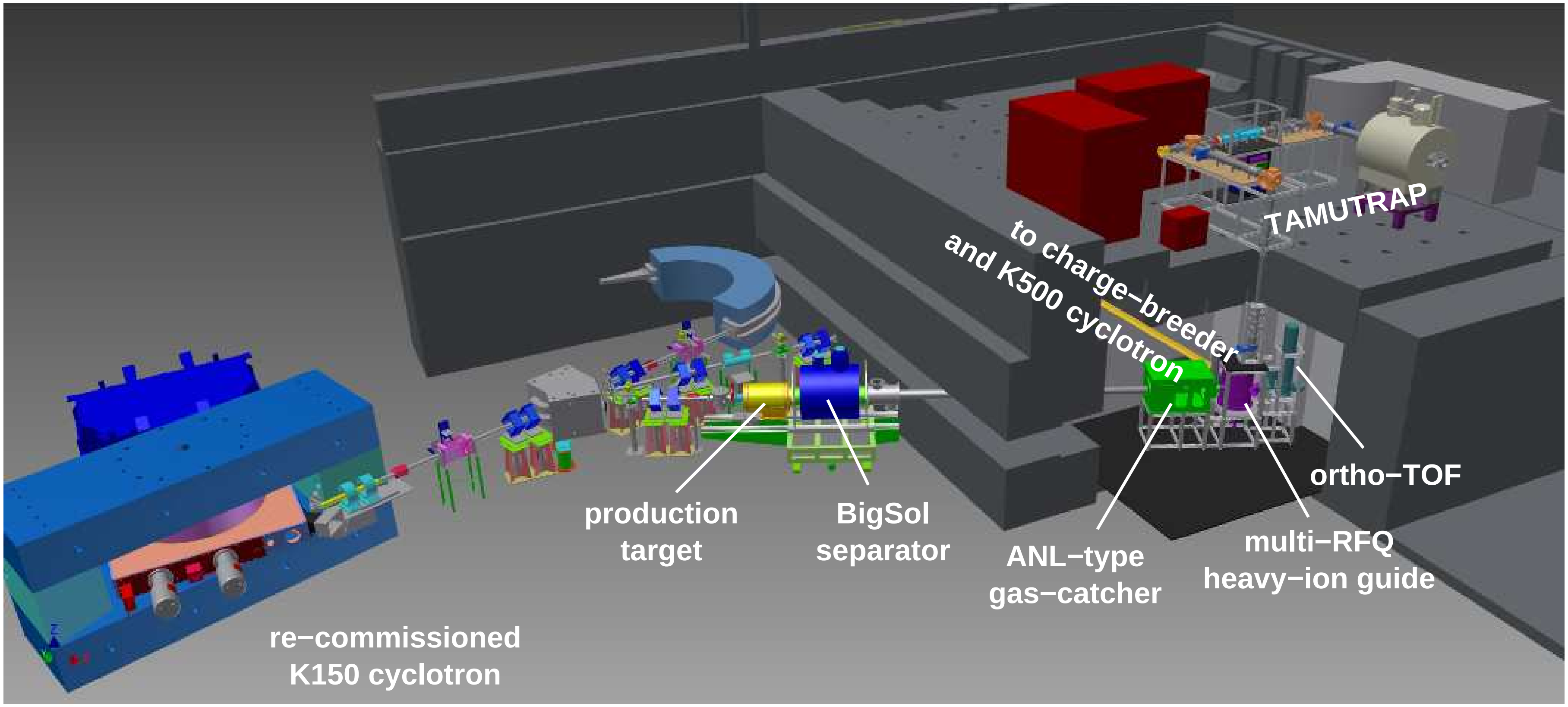

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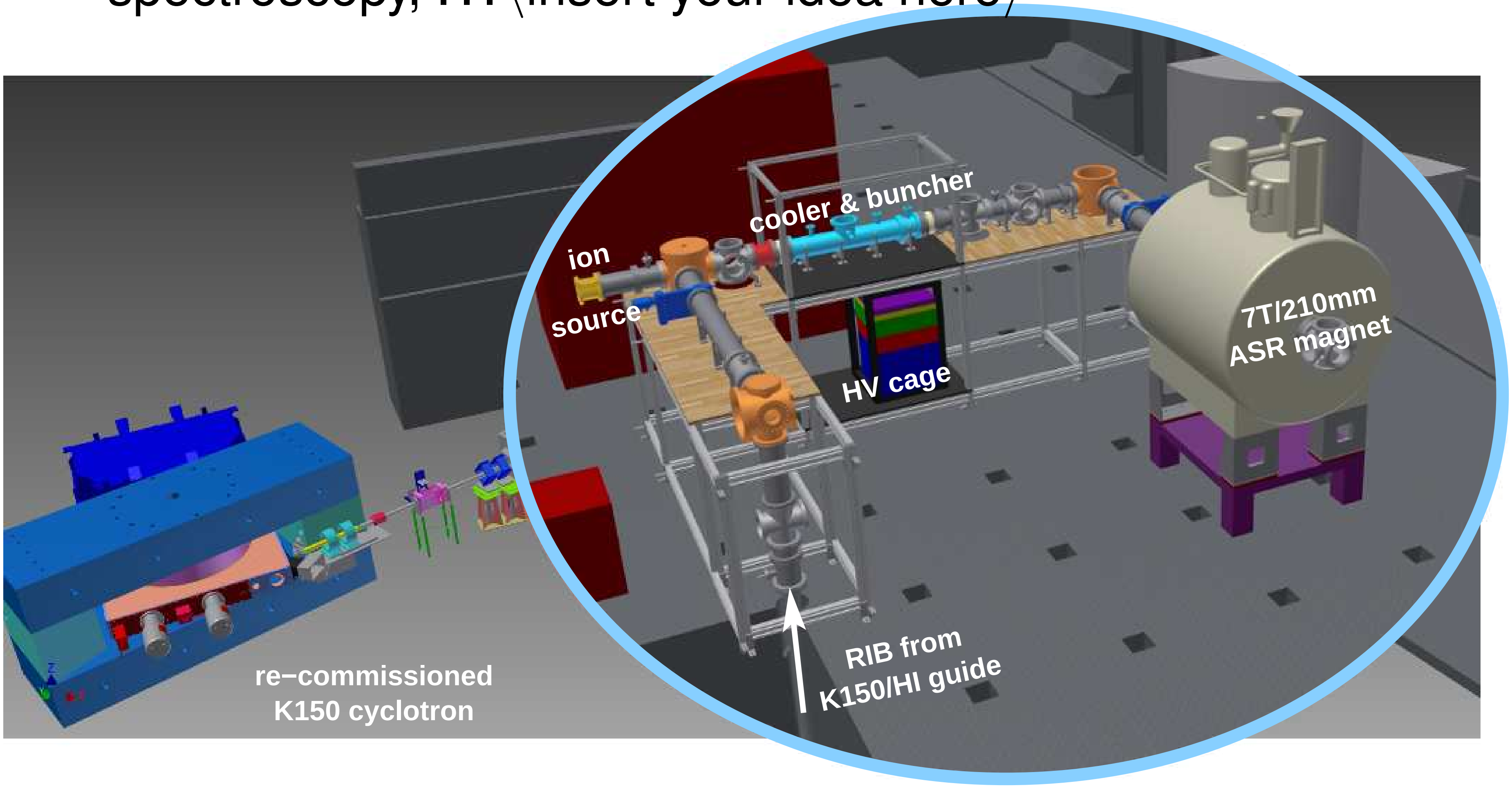

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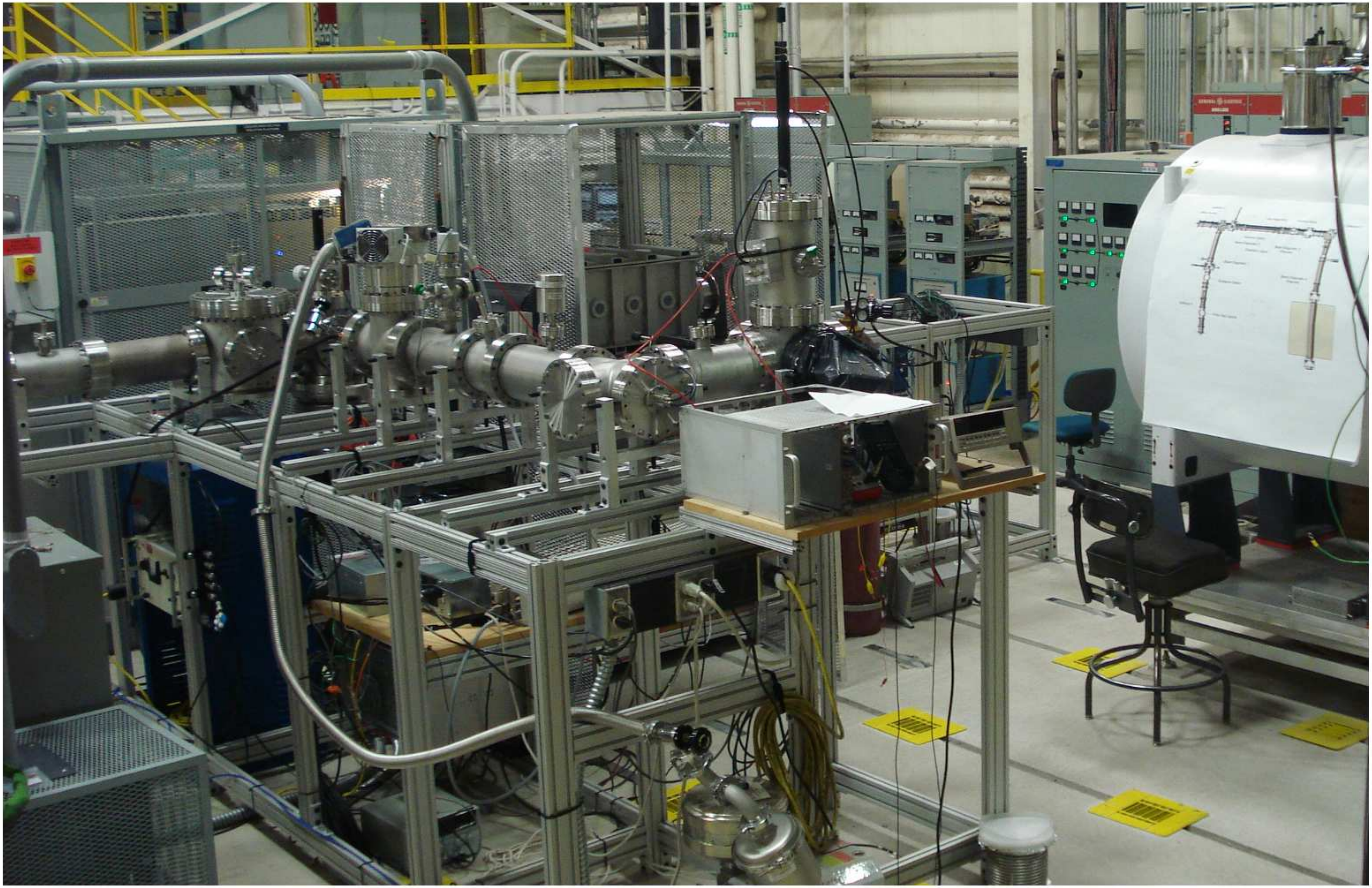

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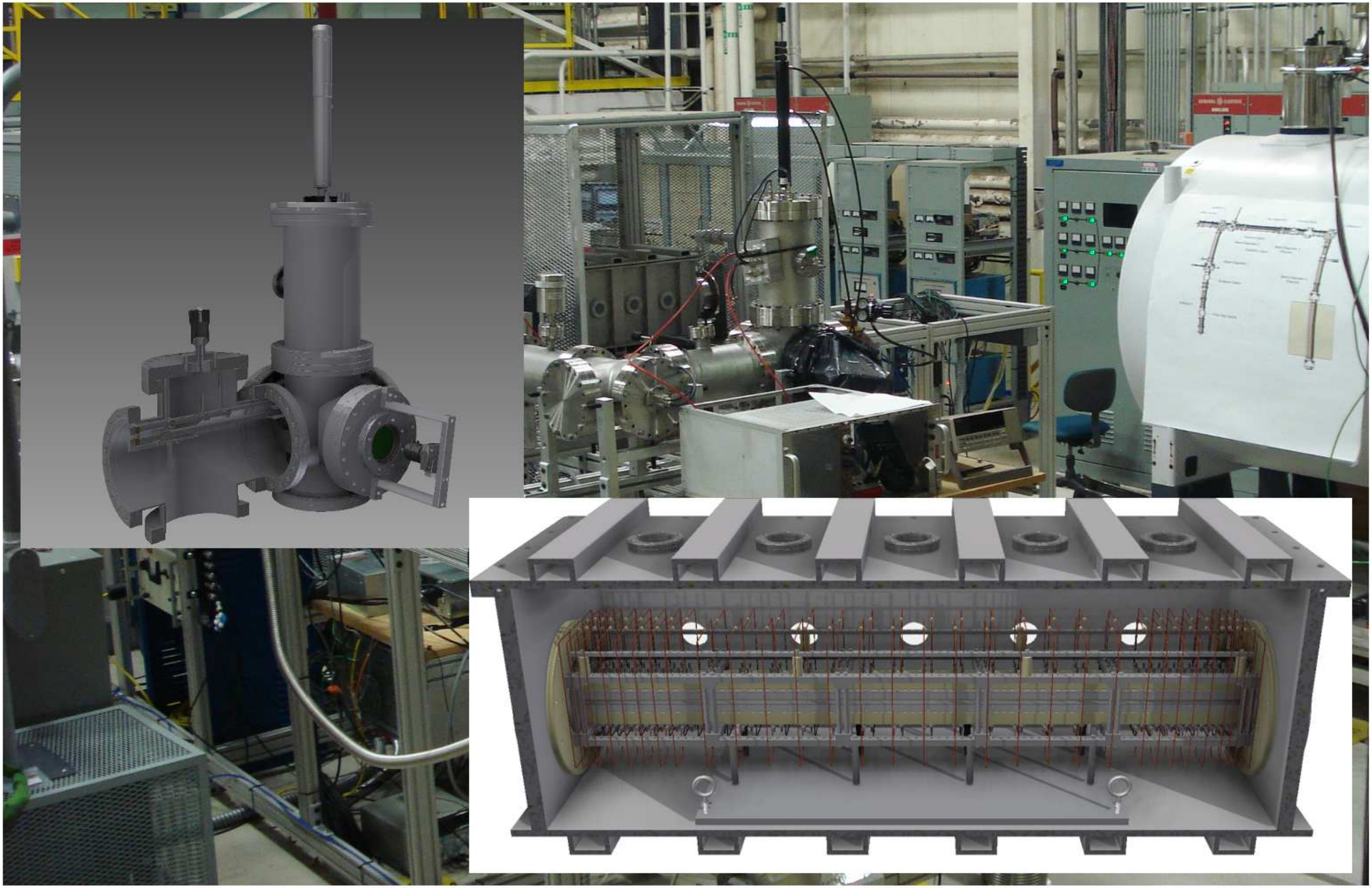

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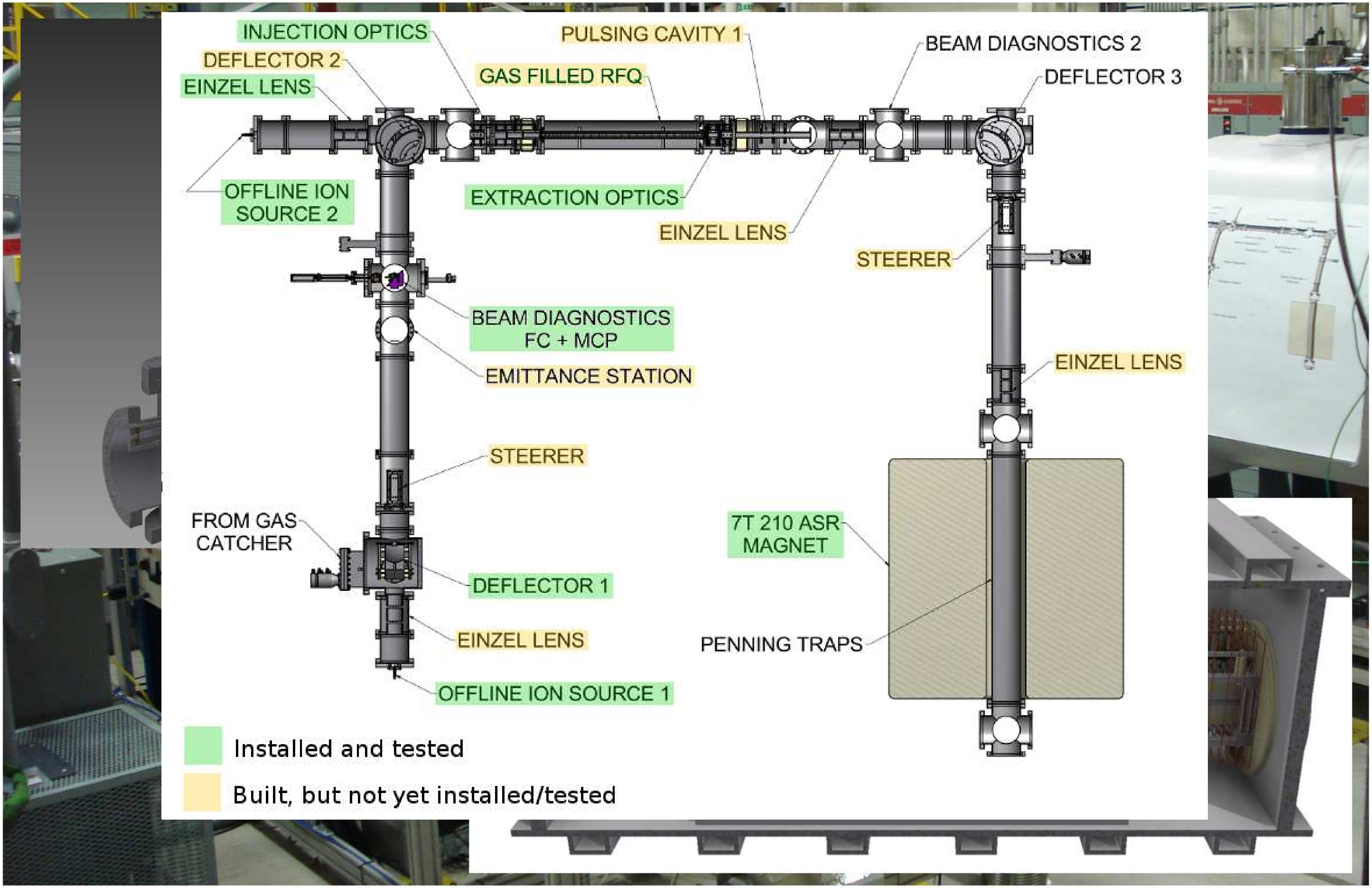

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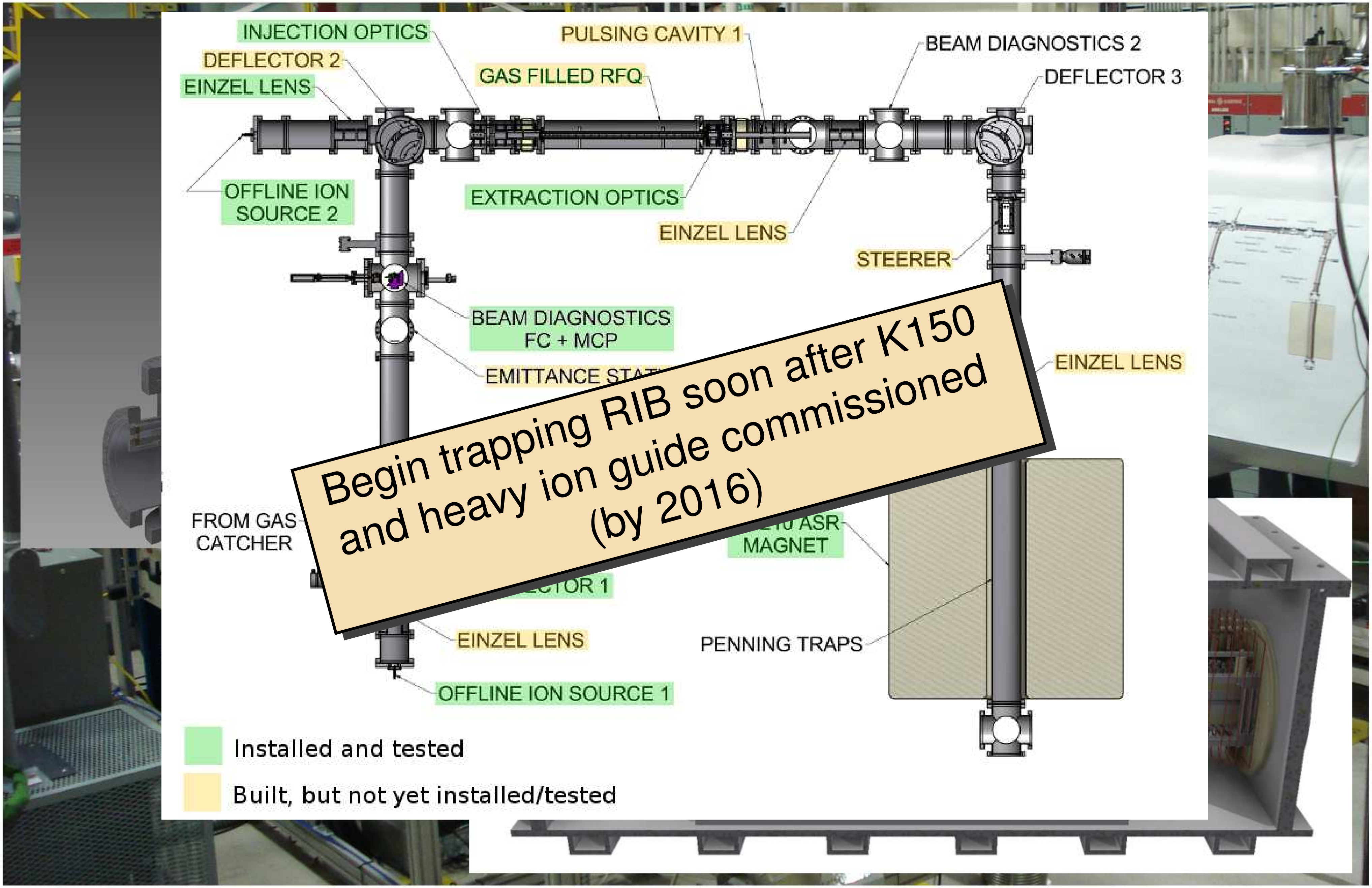


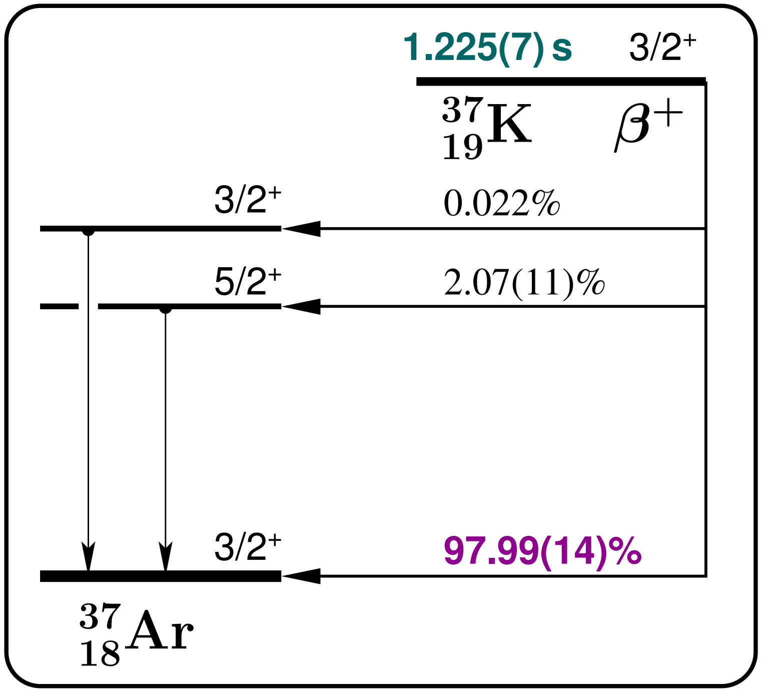
Begin trapping RIB soon after K150 and heavy ion guide commissioned (by 2016)

Overview

1. **Fundamental symmetries**
   - brief **motivation**
   - **game plan** for testing the SM
2. **TAMU Penning Trap (being built)**
   - **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

The β^+-decay of ^{37}K

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



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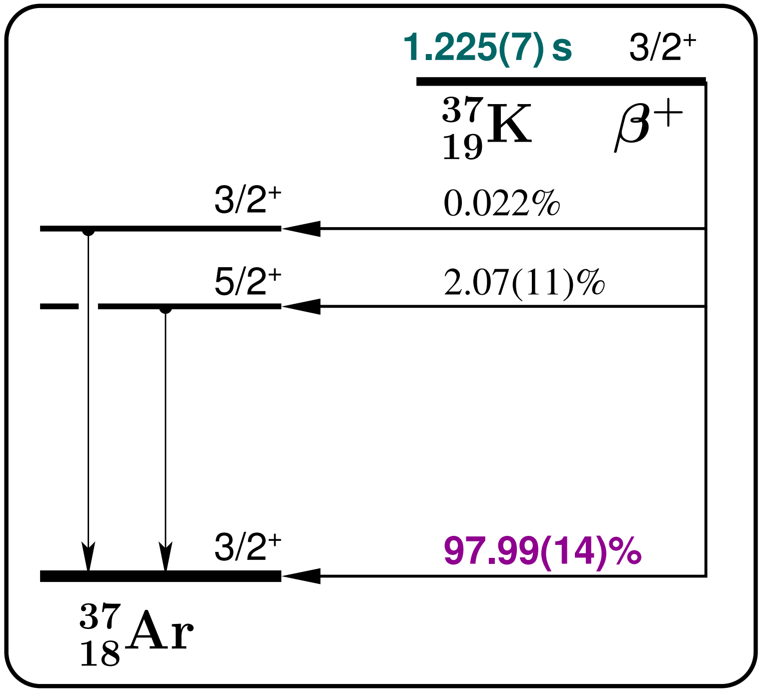

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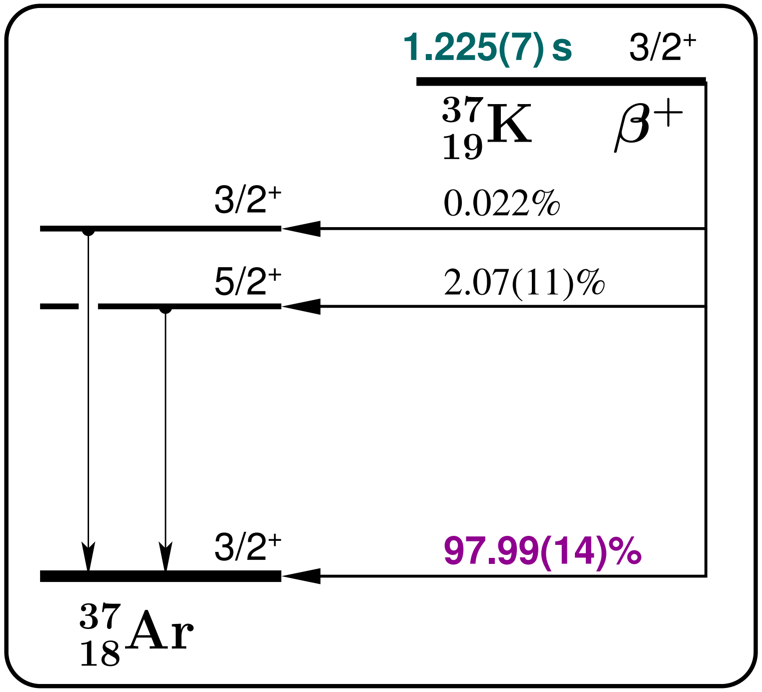

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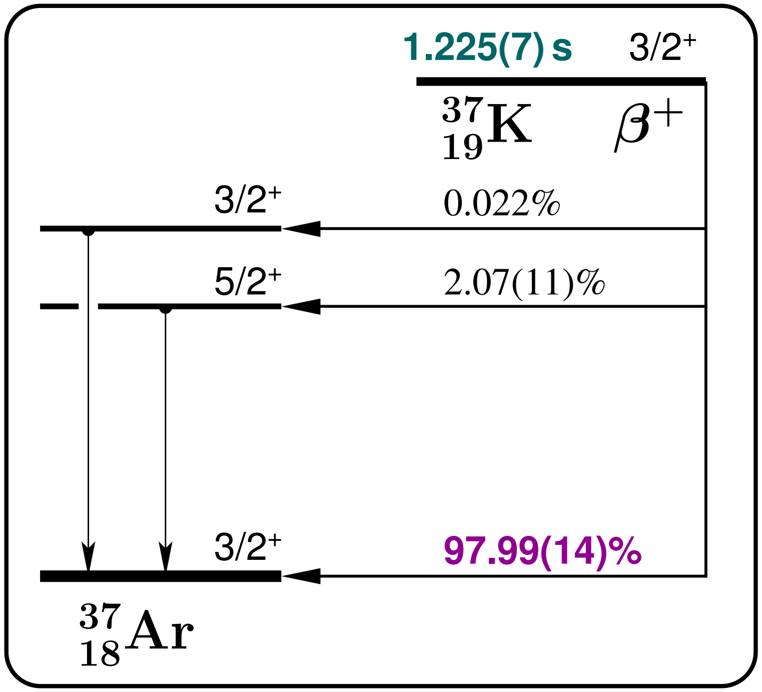

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$$\left.\begin{array}{r l} Q_{EC}\text{:} & \pm 0.003\% \\ BR\text{:} & \pm 0.14\% \\ t_{1/2}\text{:} & \boldsymbol{\pm 0.57\%} \end{array}\right\} \boldsymbol{\mathcal{F}t} = 4562(28) \quad \Rightarrow \quad \boxed{\boldsymbol{\rho} = 0.5874(\mathbf{71})}$$

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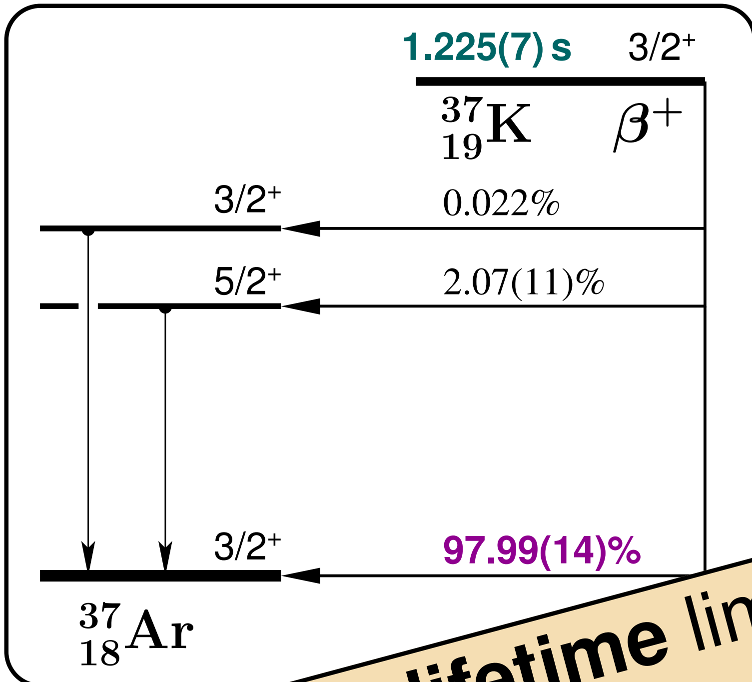

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$\Rightarrow$ nee… $M_{GT}/G_V M_F$ … for correla-

get ρ … $- 1$ … $\mathcal{F}t$

Q_{EC}:

BR: …%

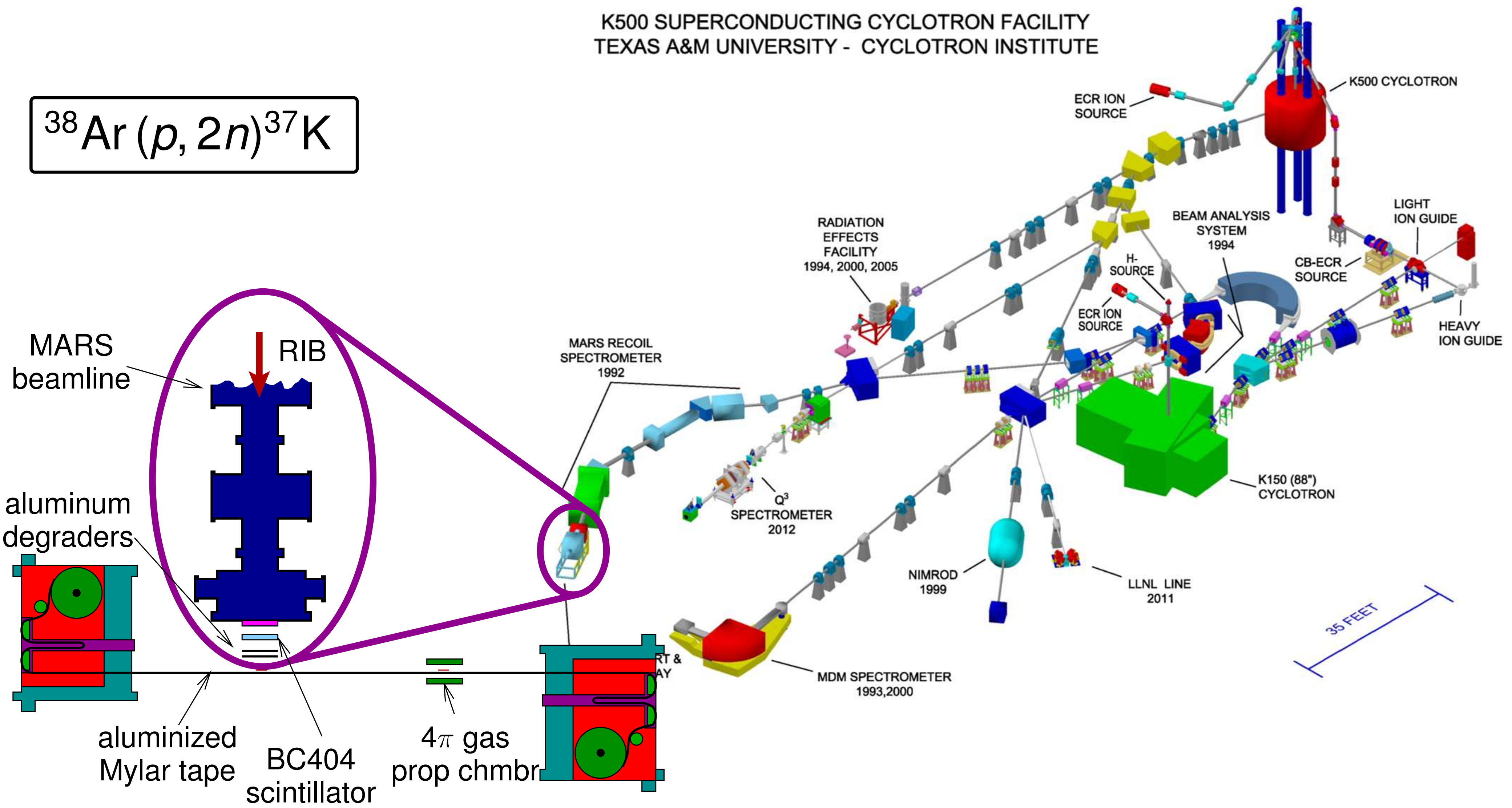
$t_{1/2}$: $\pm$**0.57%**

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

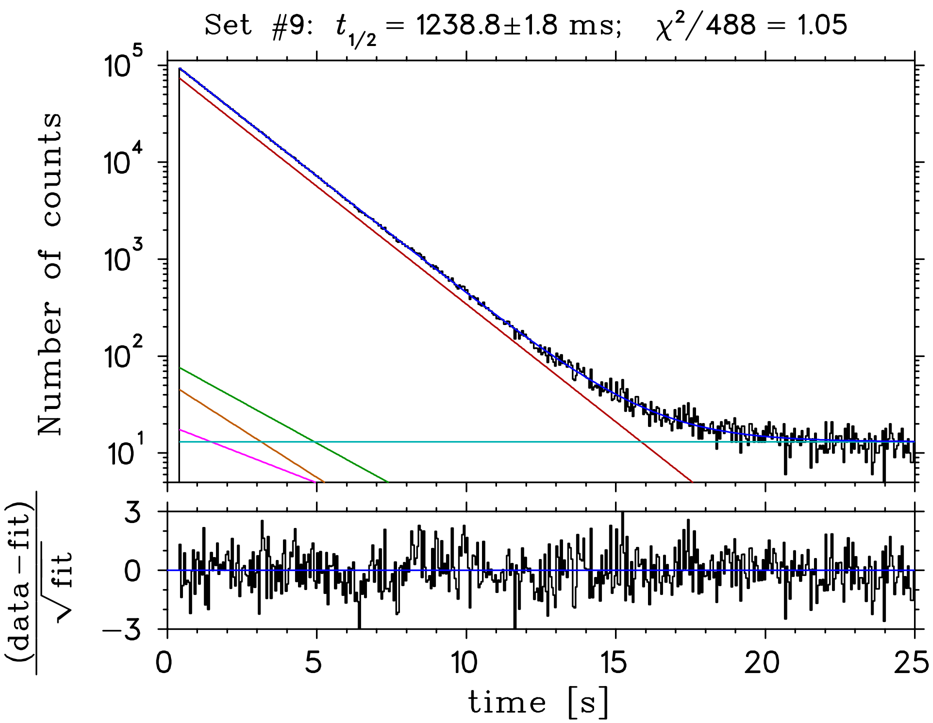
The **lifetime** limits the $\mathcal{F}t$ value
- and hence precision of ρ
- and hence the SM predictions of the **correlation parameters**

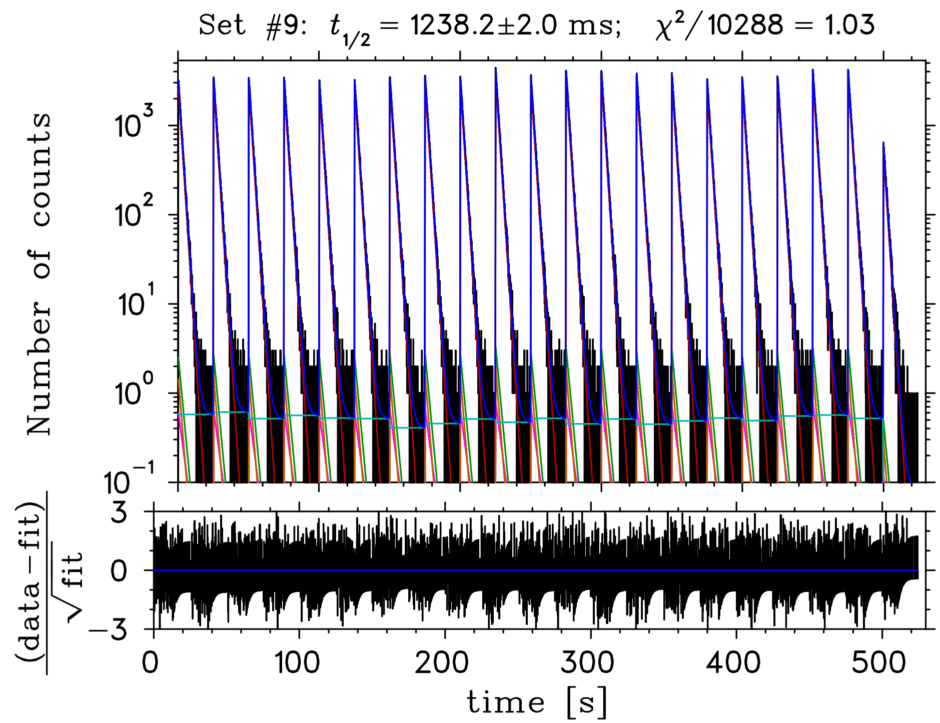
Measuring the lifetime at the CI

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



Improving the lifetime





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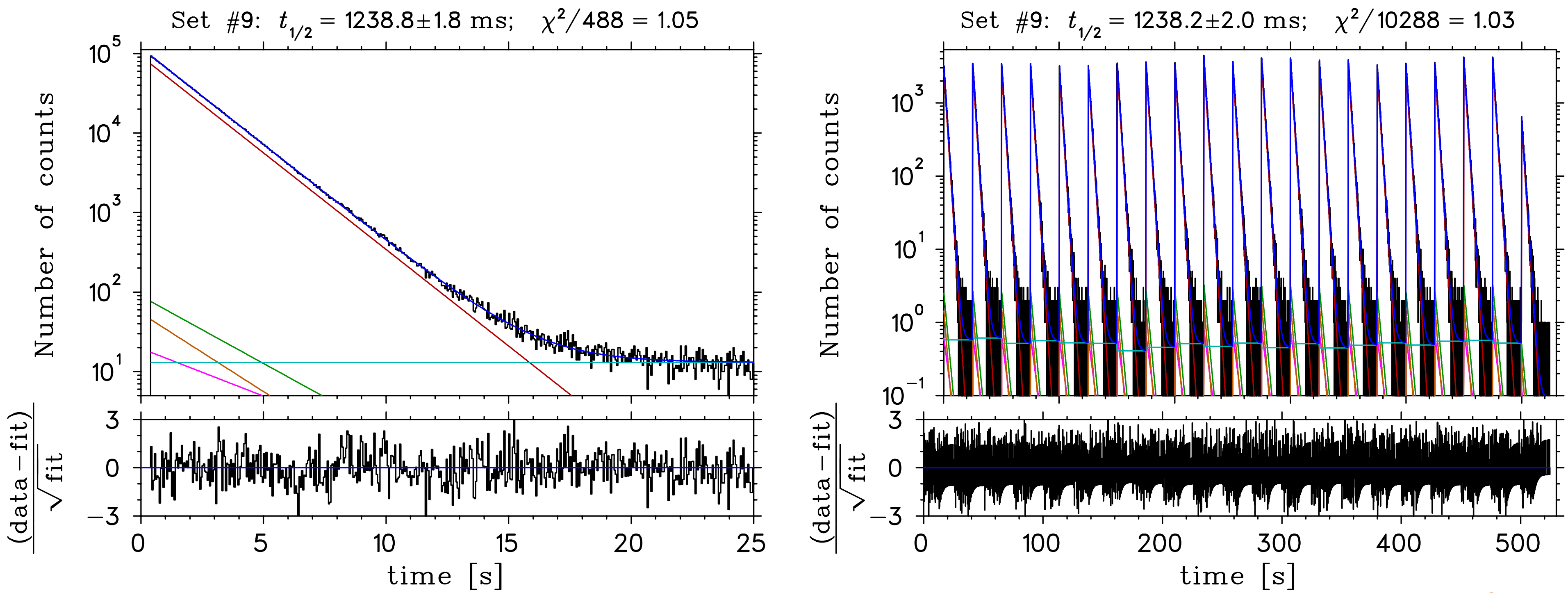

nearly a $10\times$ improvement: $\boxed{t_{1/2} = 1236.51 \pm 0.47 \pm 0.83 \text{ ms}}$

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

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

P. Shidling *et al.*, Phys Rev C (R), in press
arXiv:1407.1742

Branching ratio — analysis just starting

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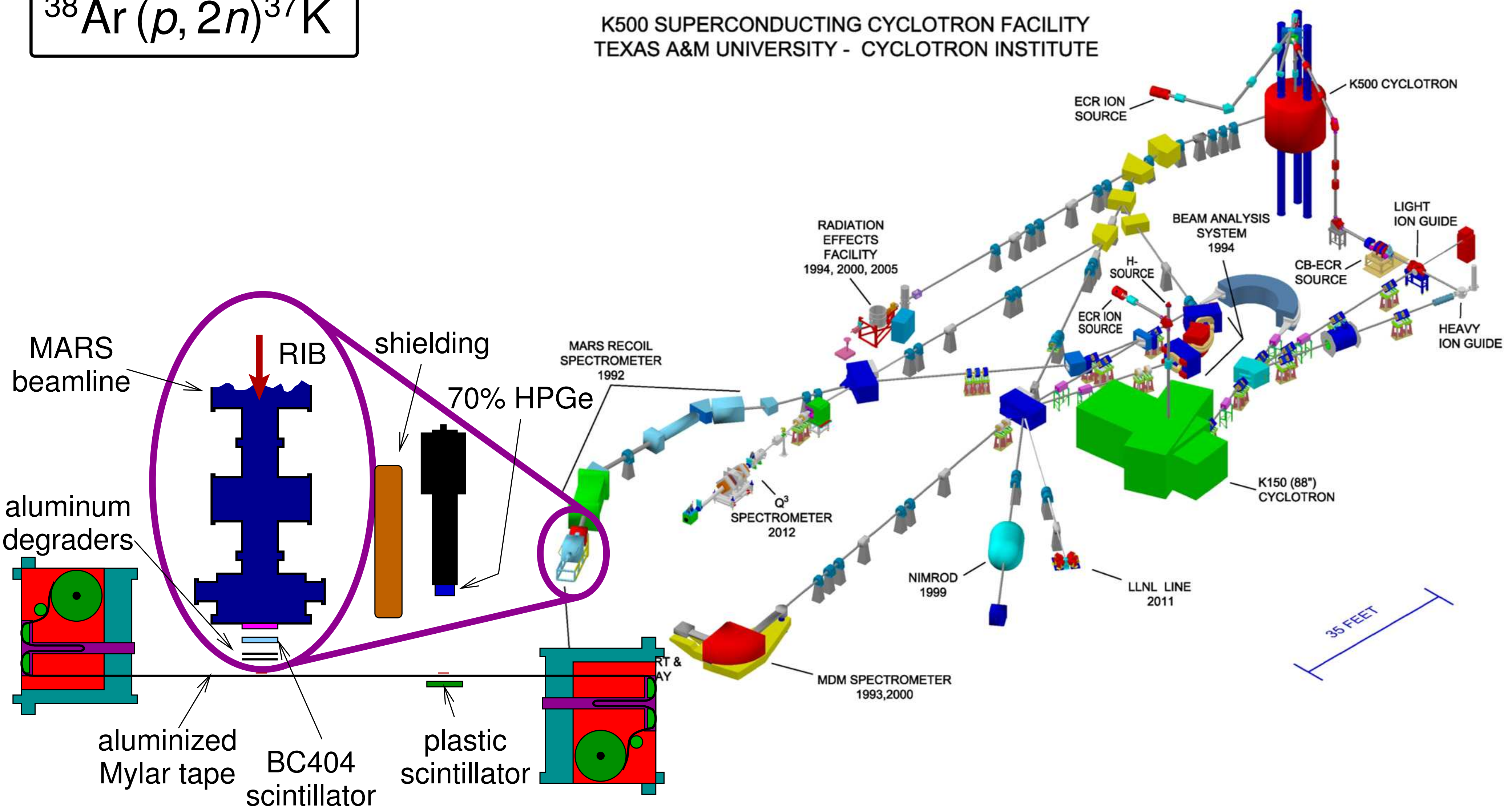

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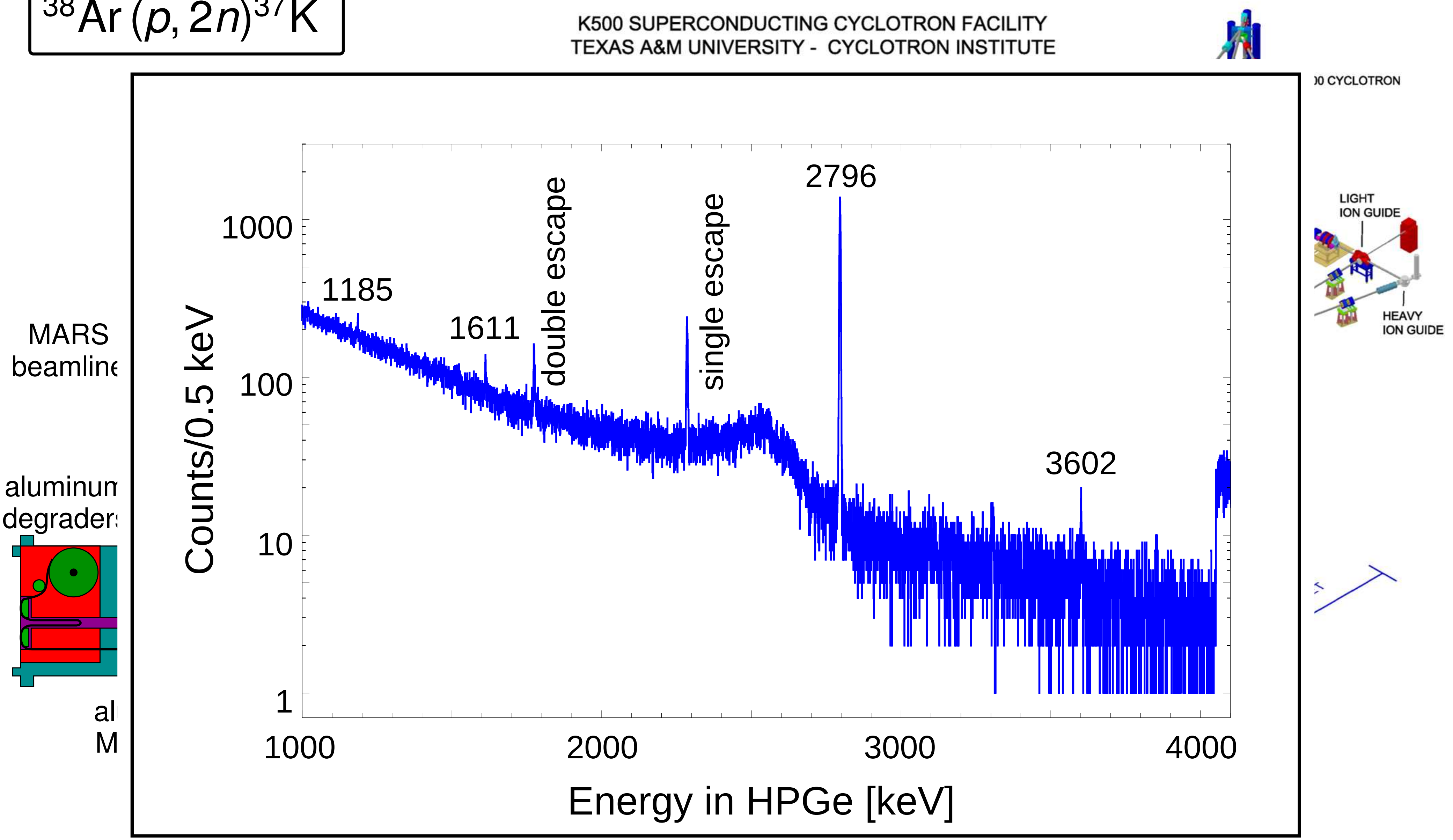
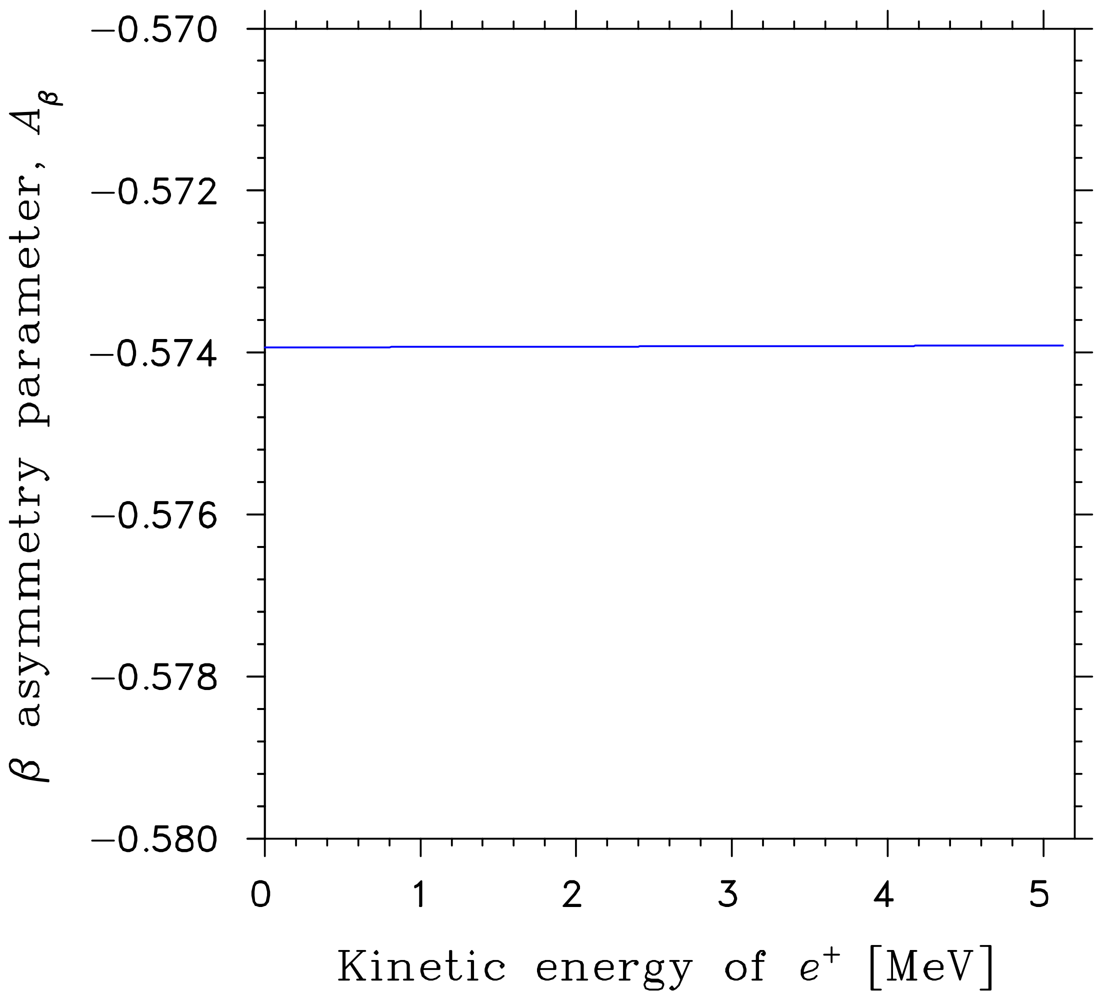


What can we learn, e.g. from A_β?

$$A_\beta = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\tfrac{3}{5}} - \tfrac{\rho}{5}\right) + \ldots$$



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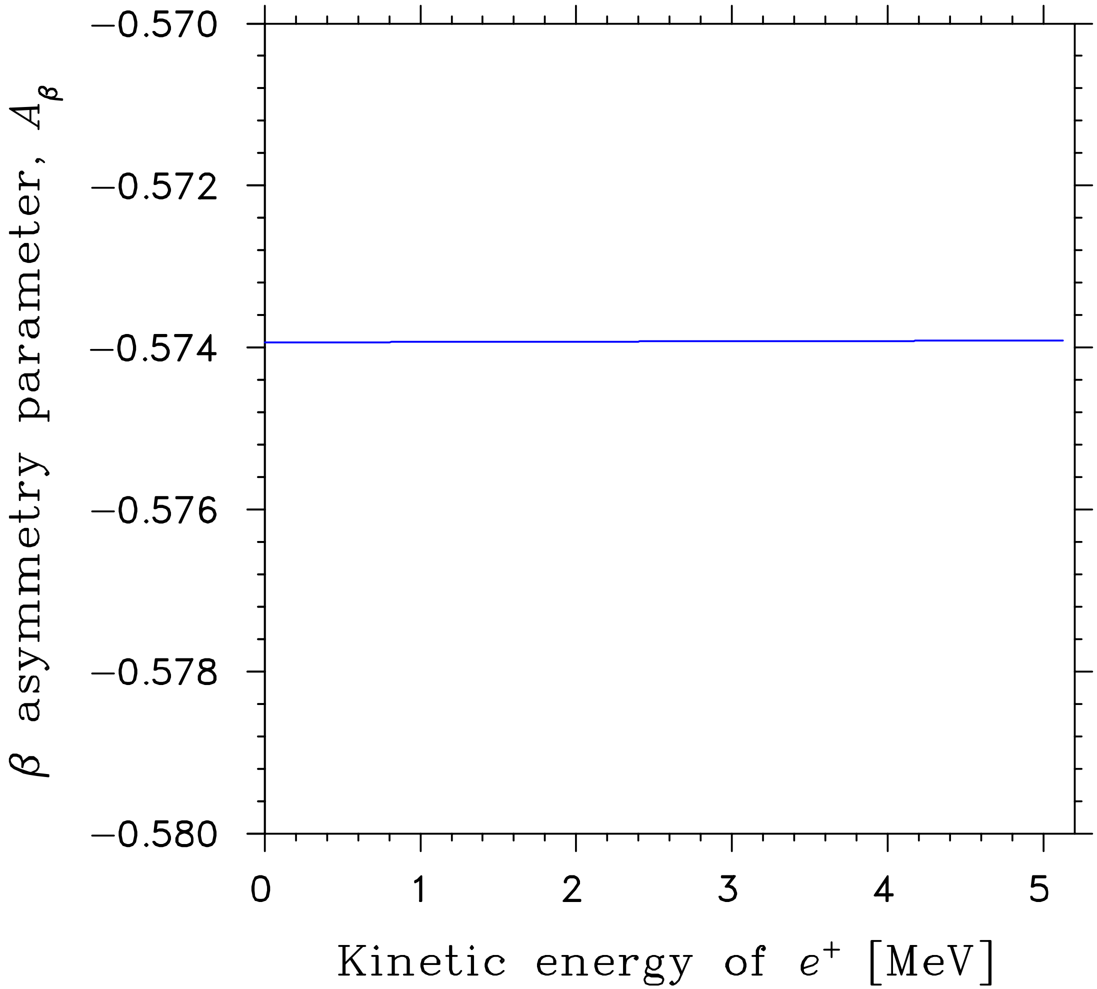

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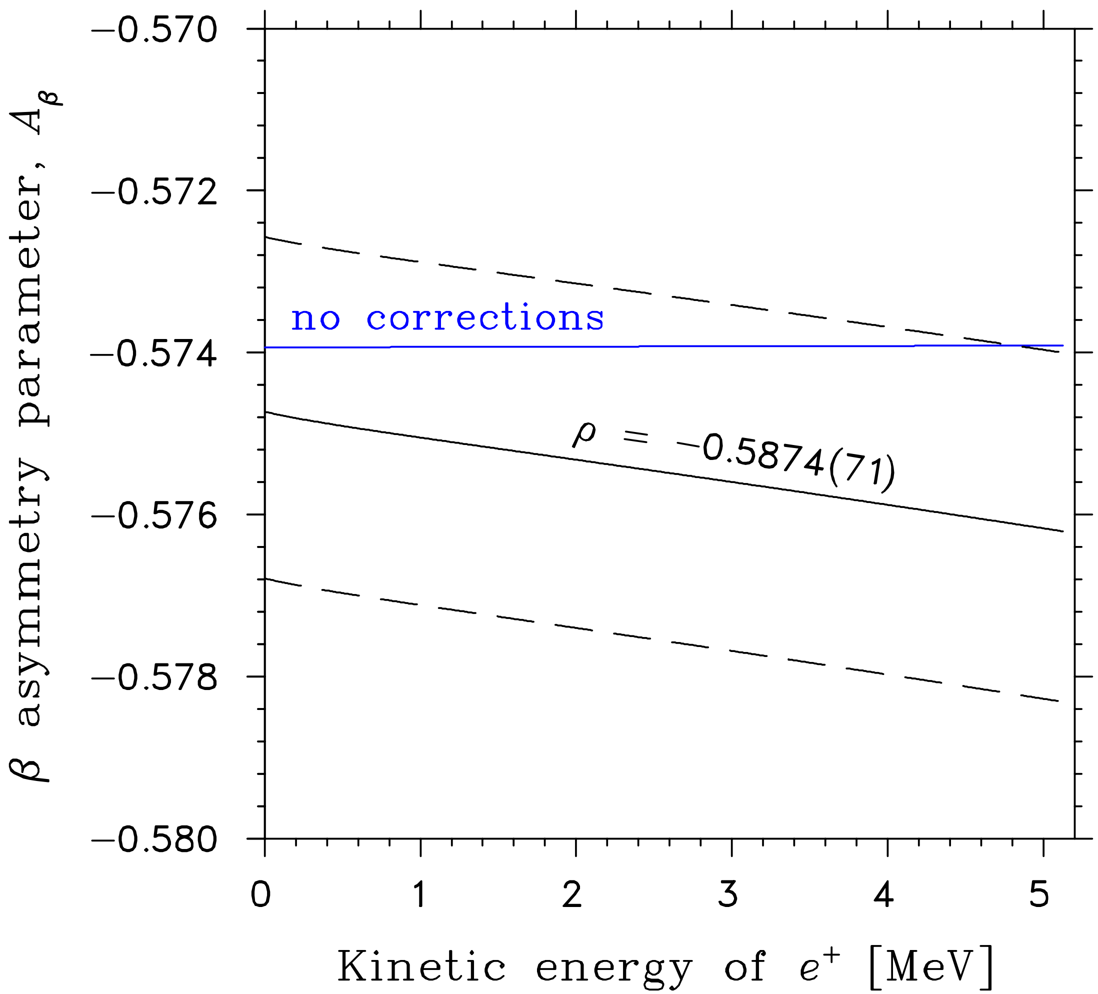

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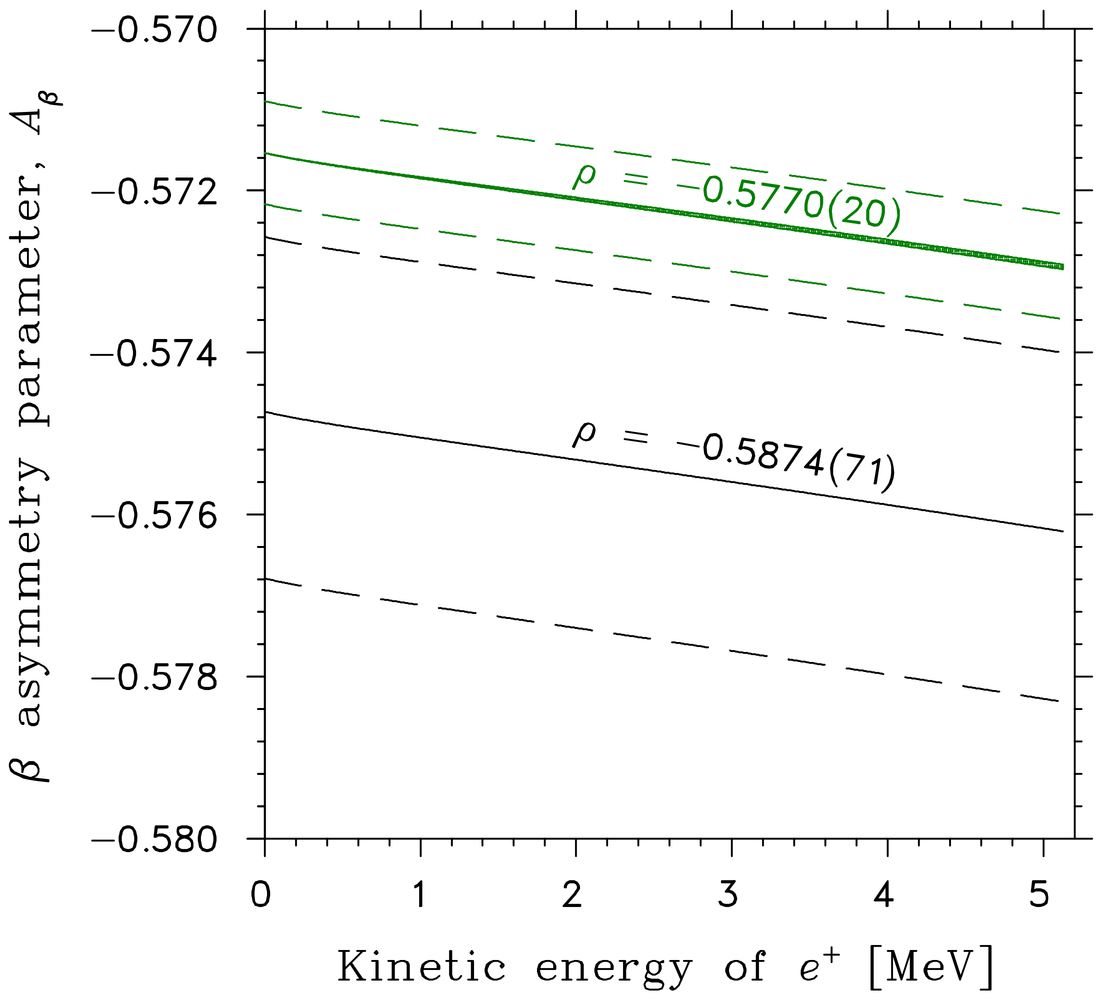

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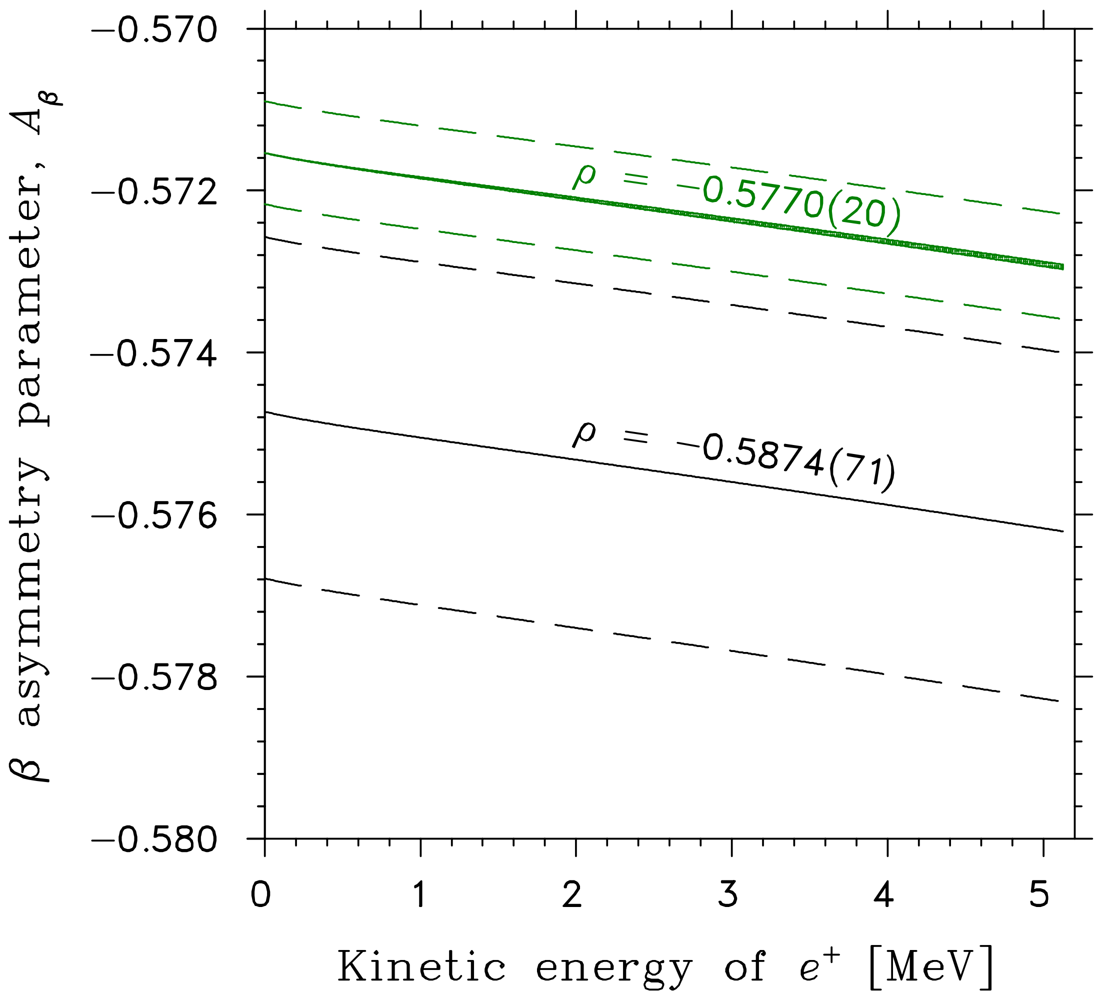

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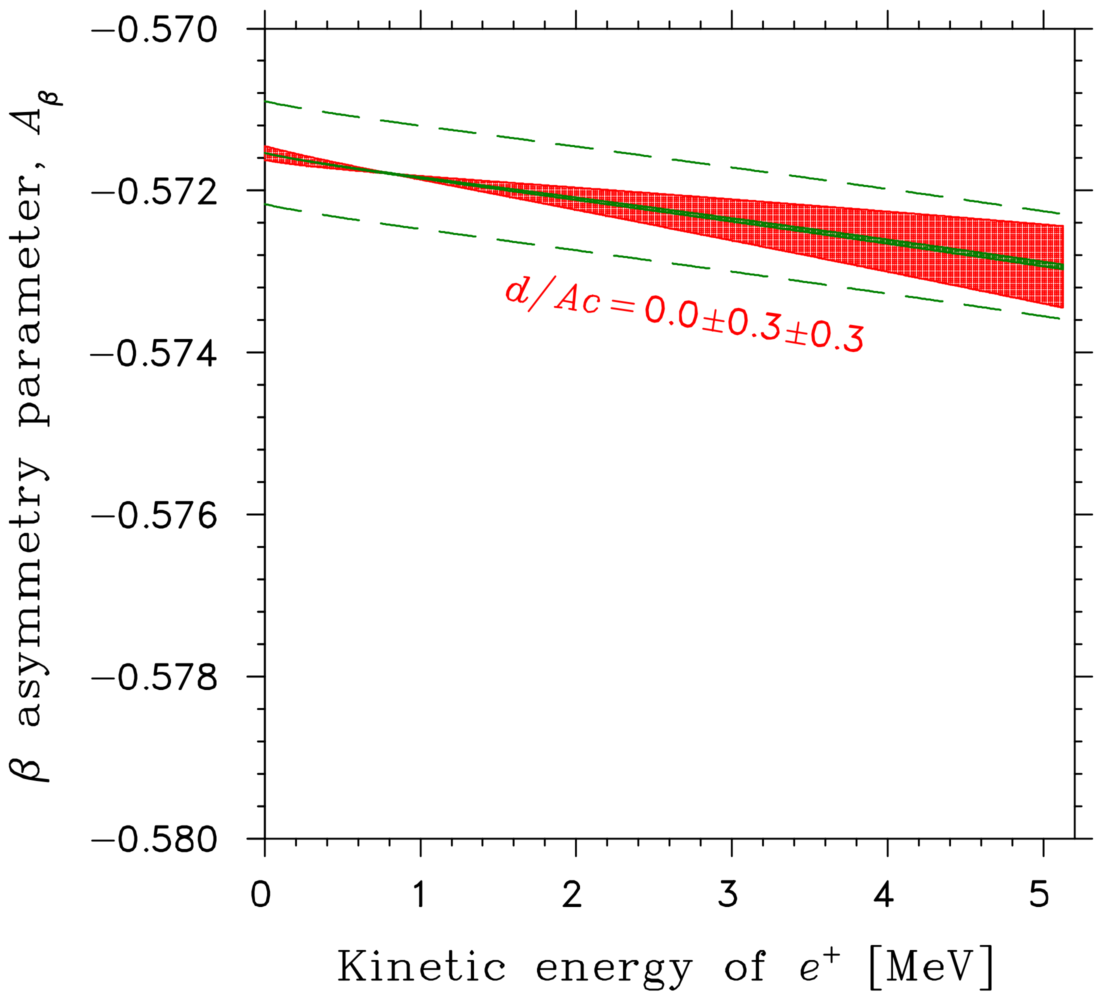

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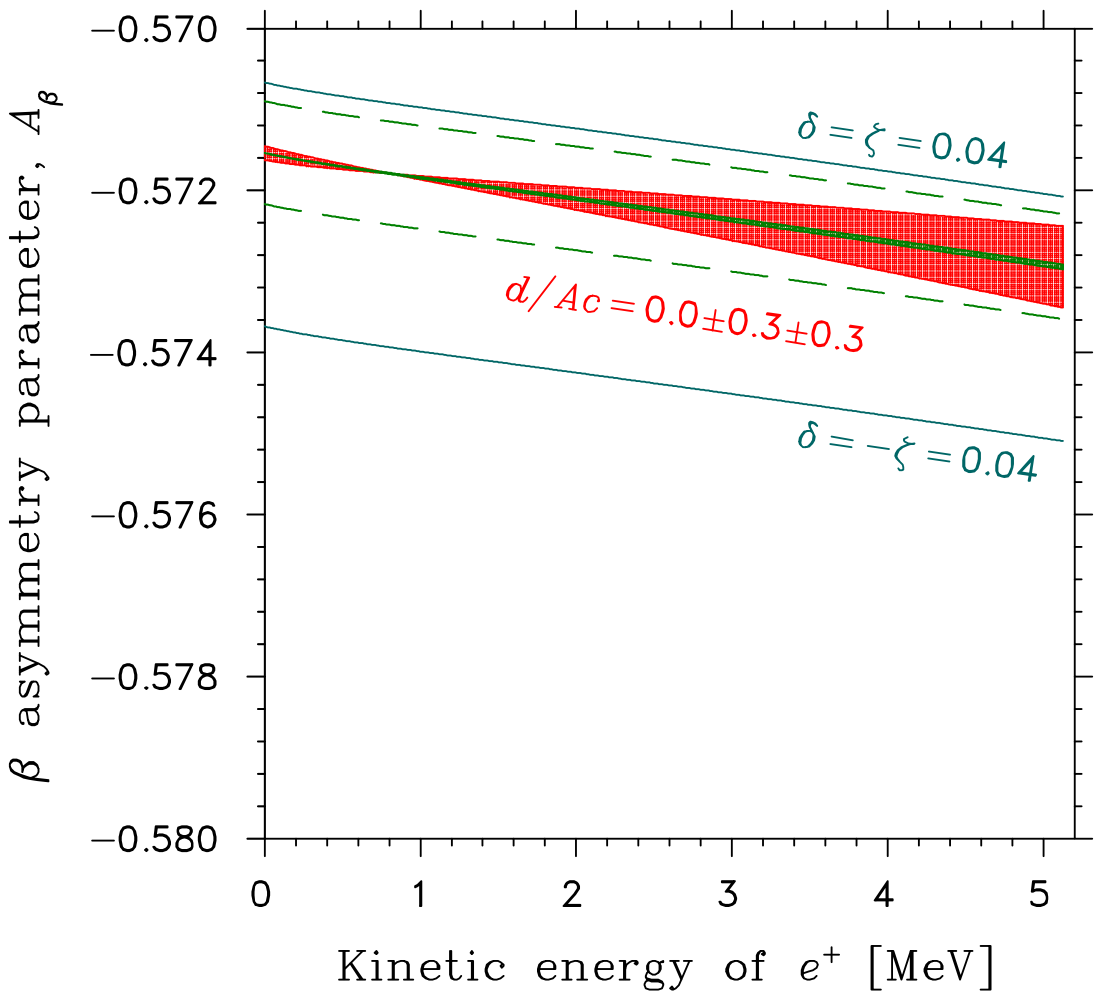

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TRINAT, in a nutshell

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

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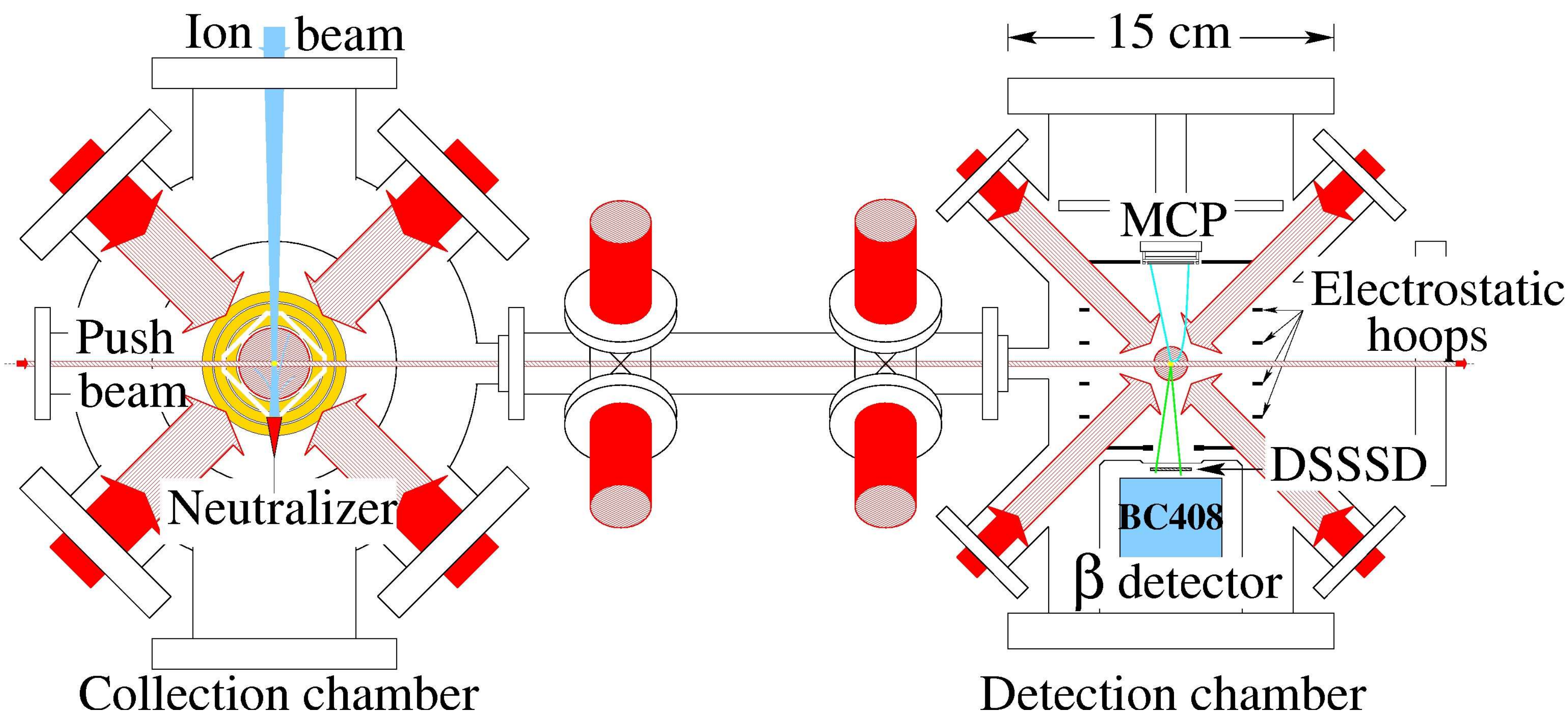

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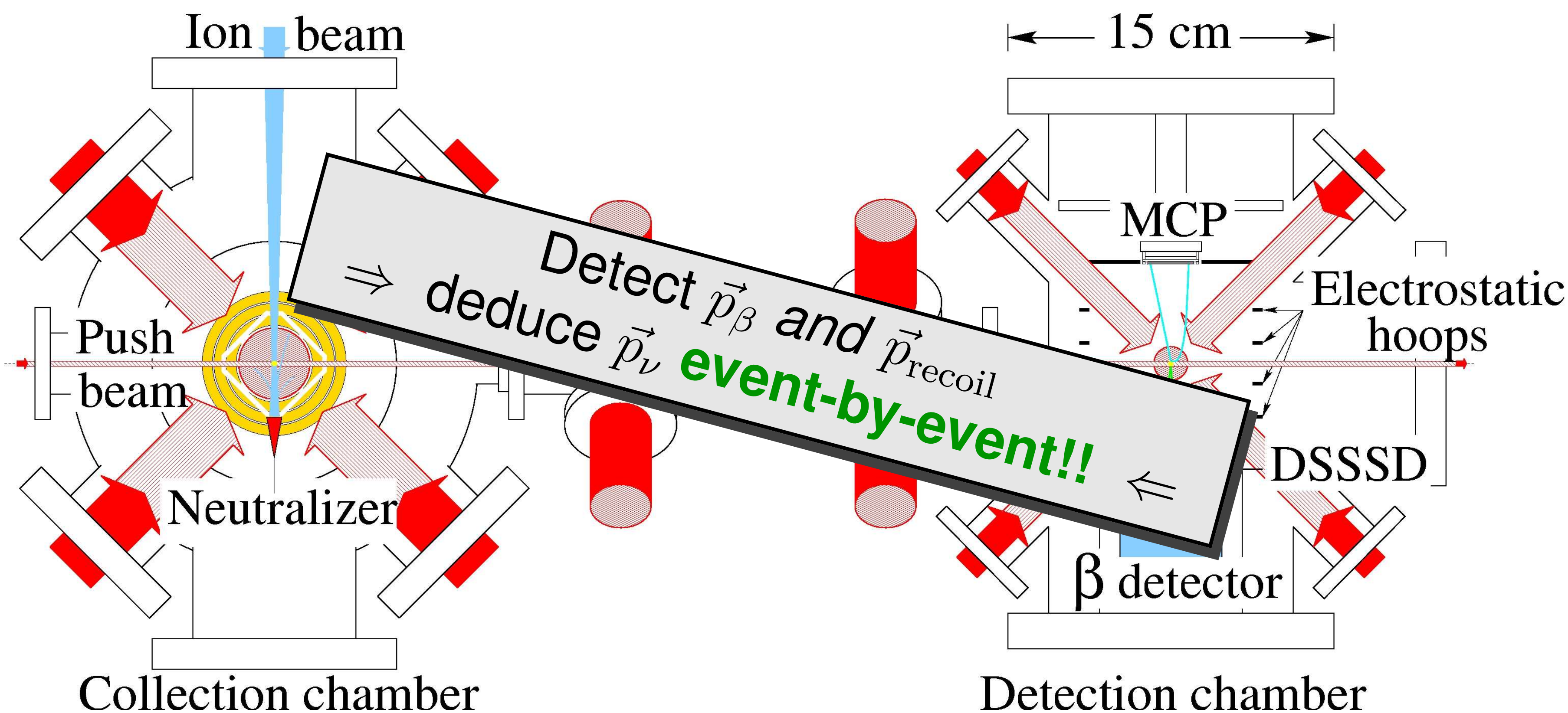

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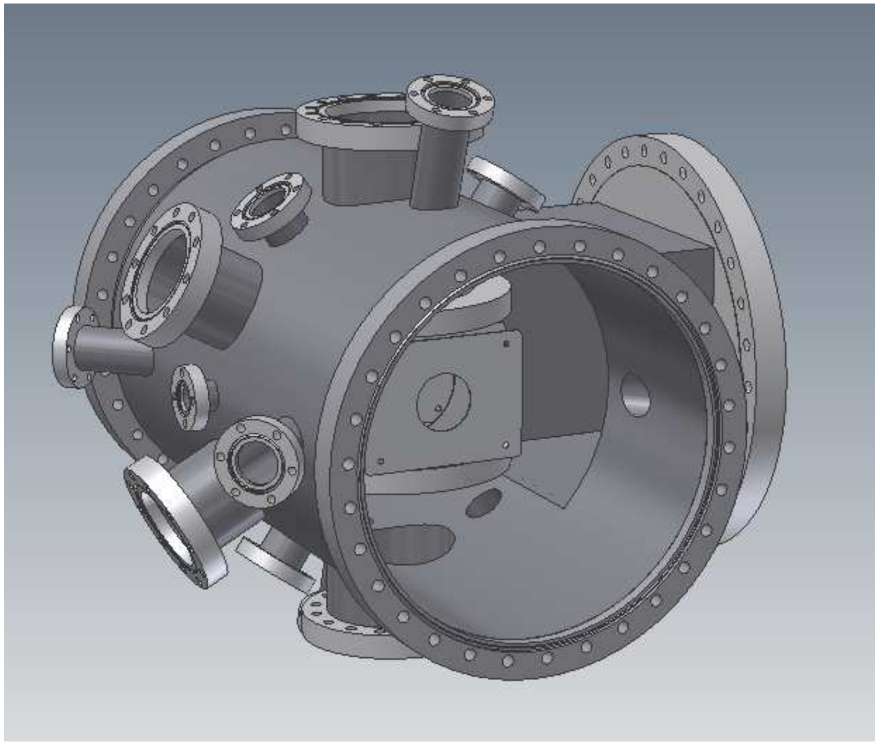
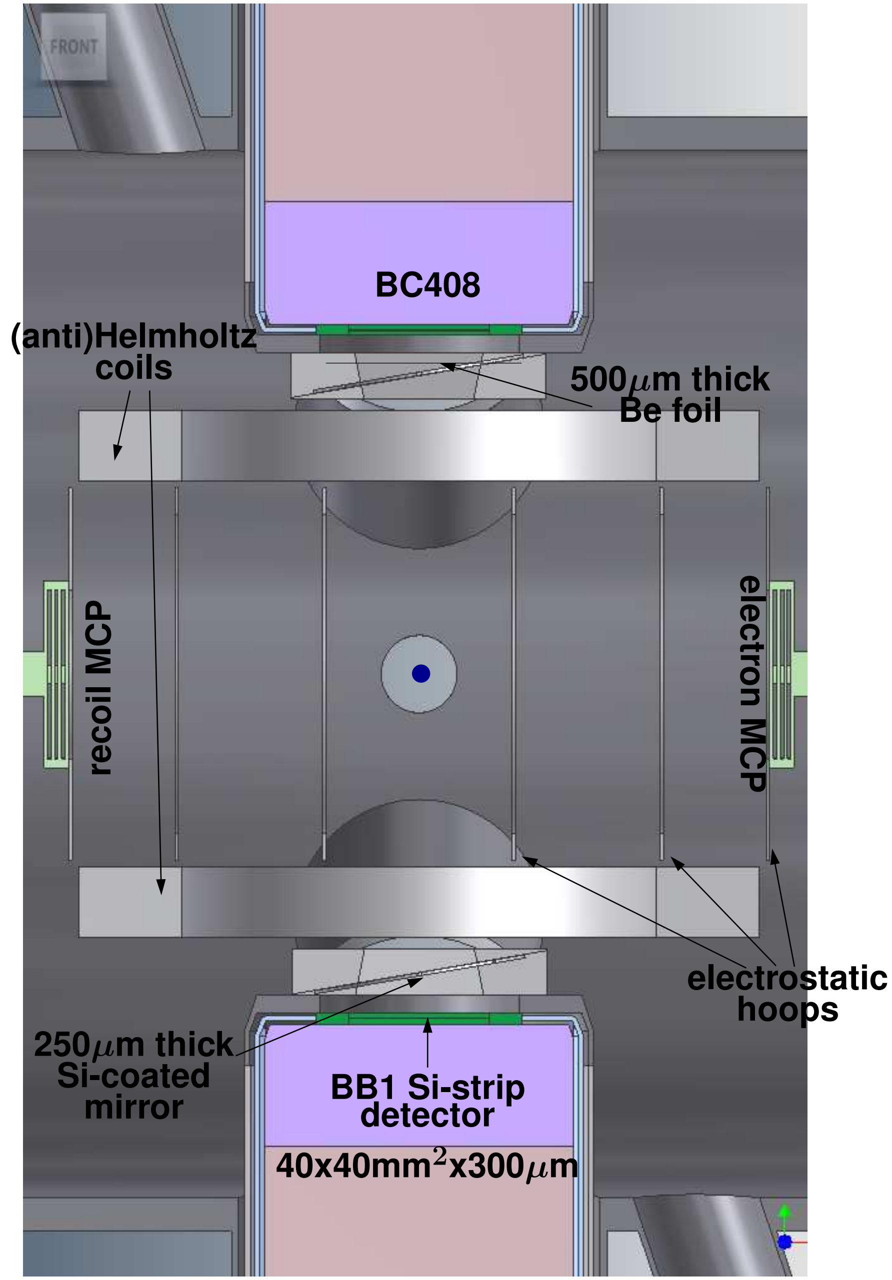
Highlights of the measurement trap



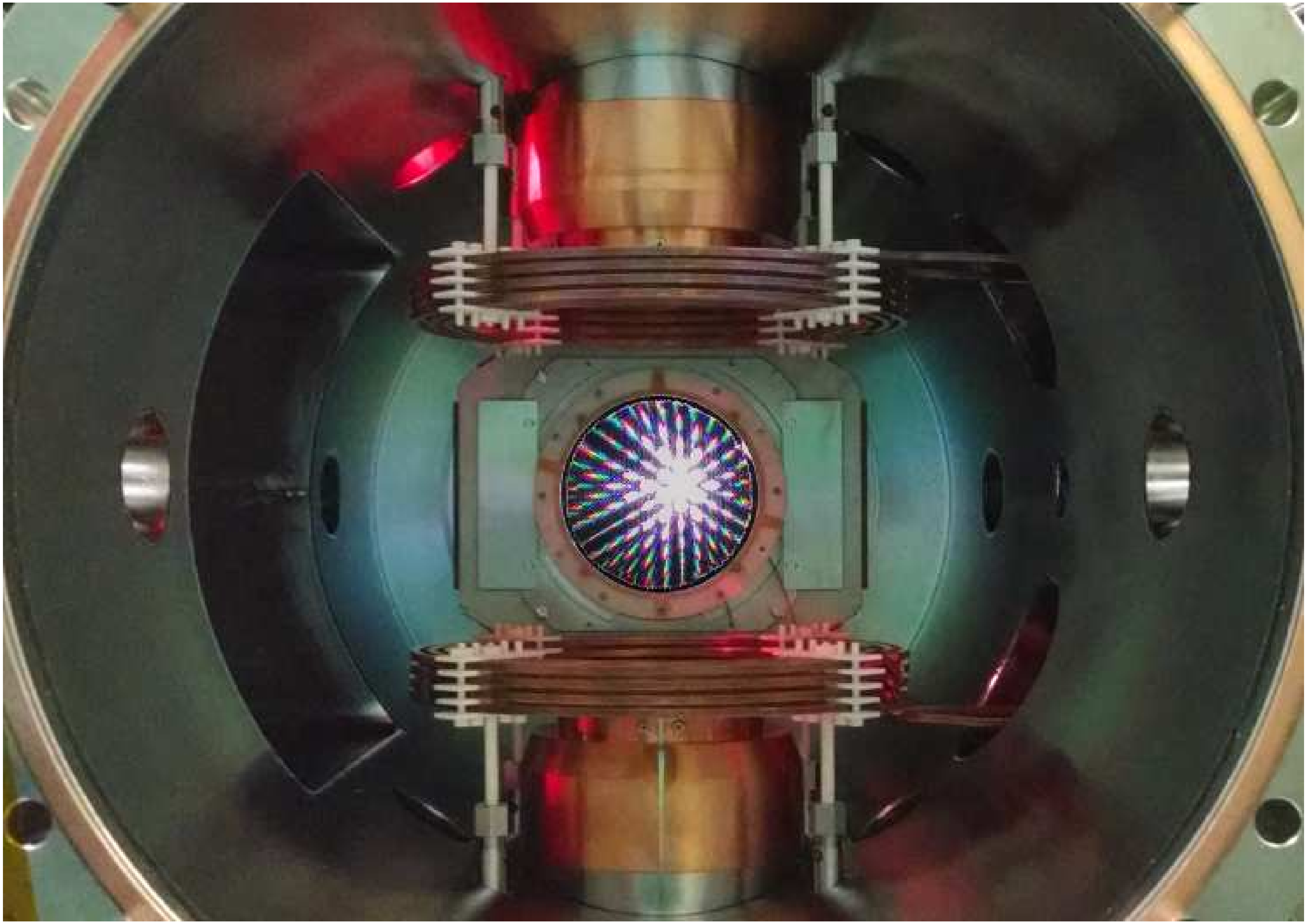
- $B_{\rm quad} \rightarrow B_{\rm OP}$ quickly: AC-MOT (Harvery & Murray, PRL **101** (2008))

- Better control of laser beams
- Shake-off e^- detection
- Increased β/recoil solid angles

$\vdots$



Outline of polarized experiment



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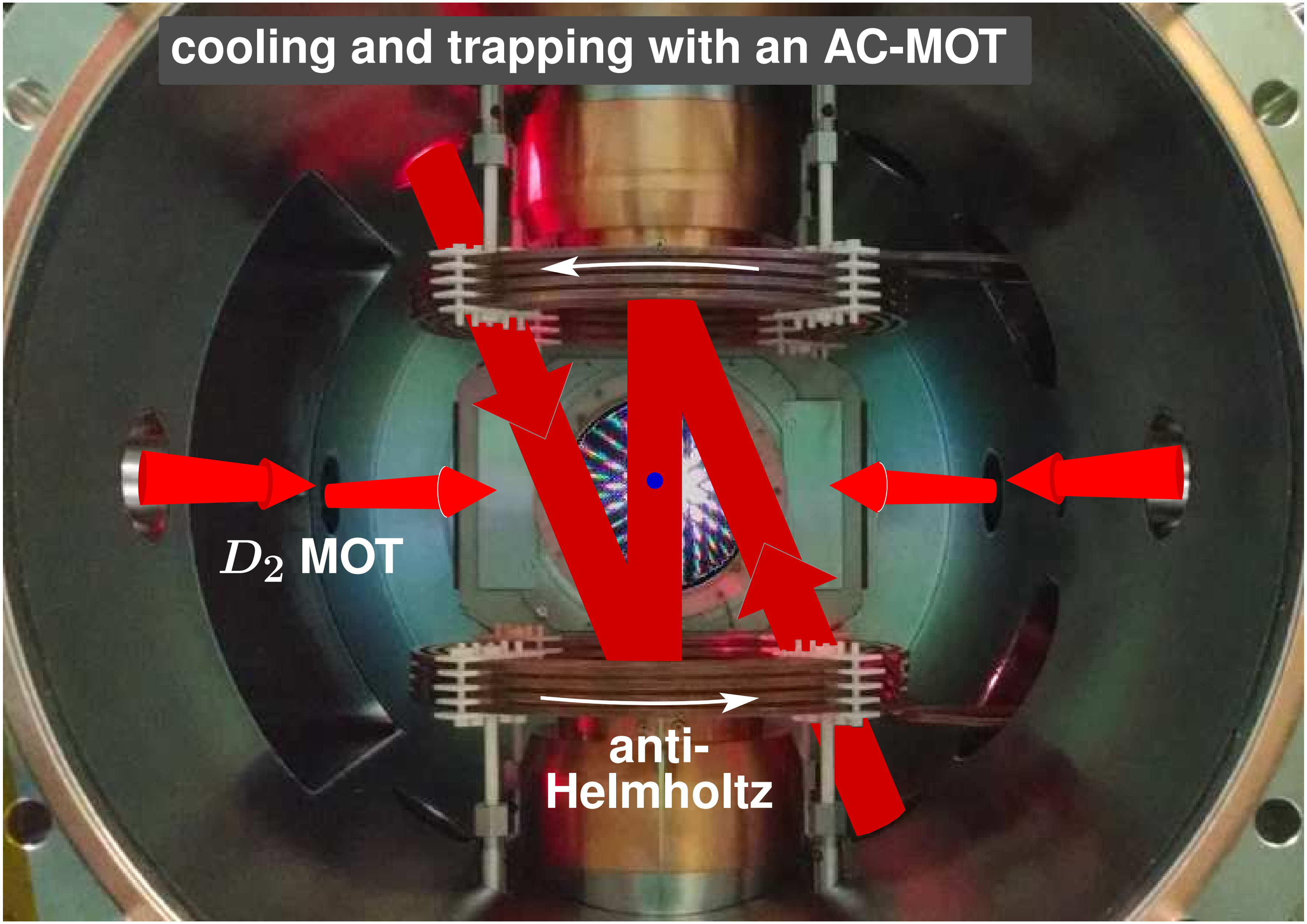

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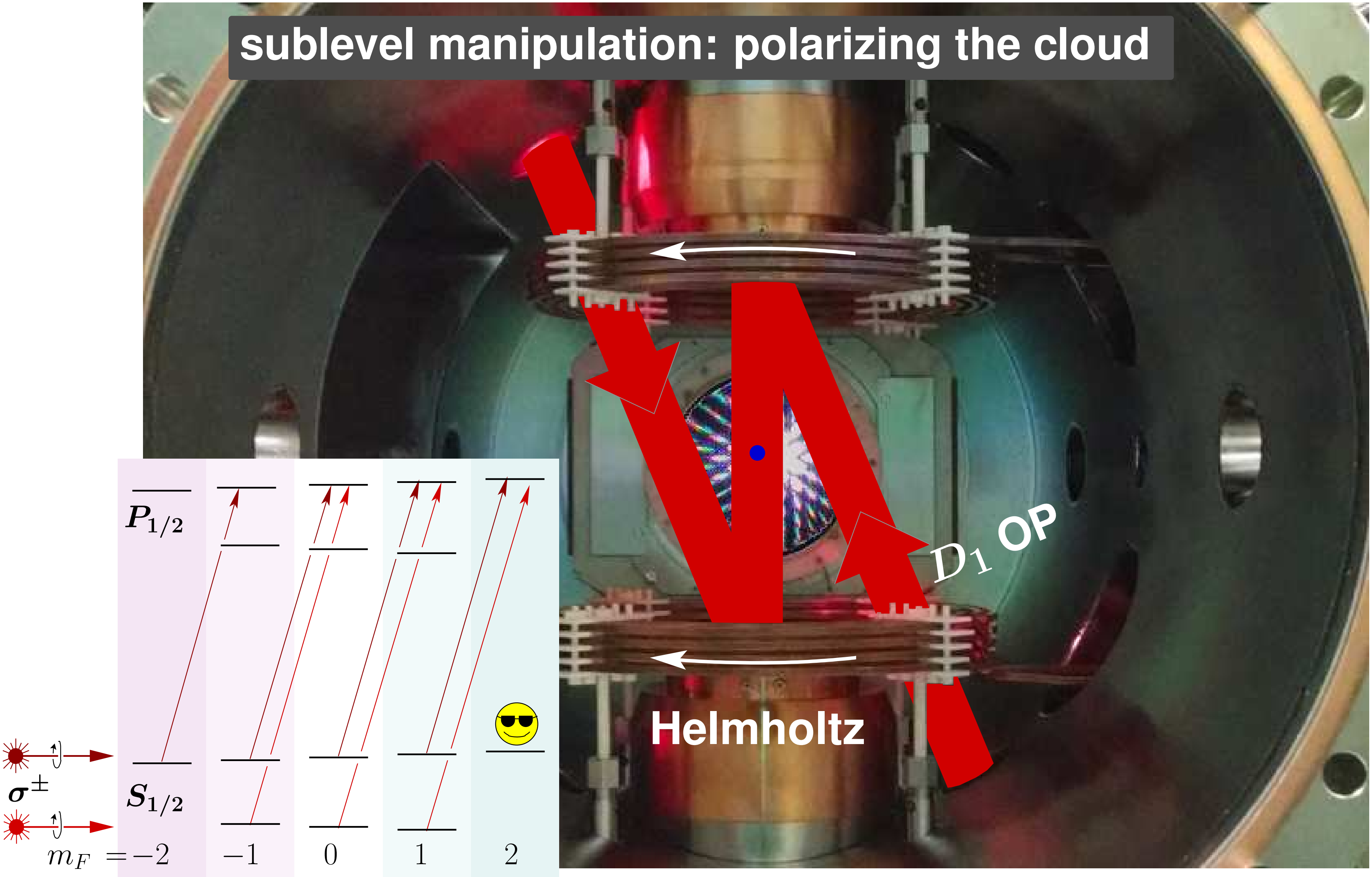

$\vec{F} = \vec{I} + \vec{J}$

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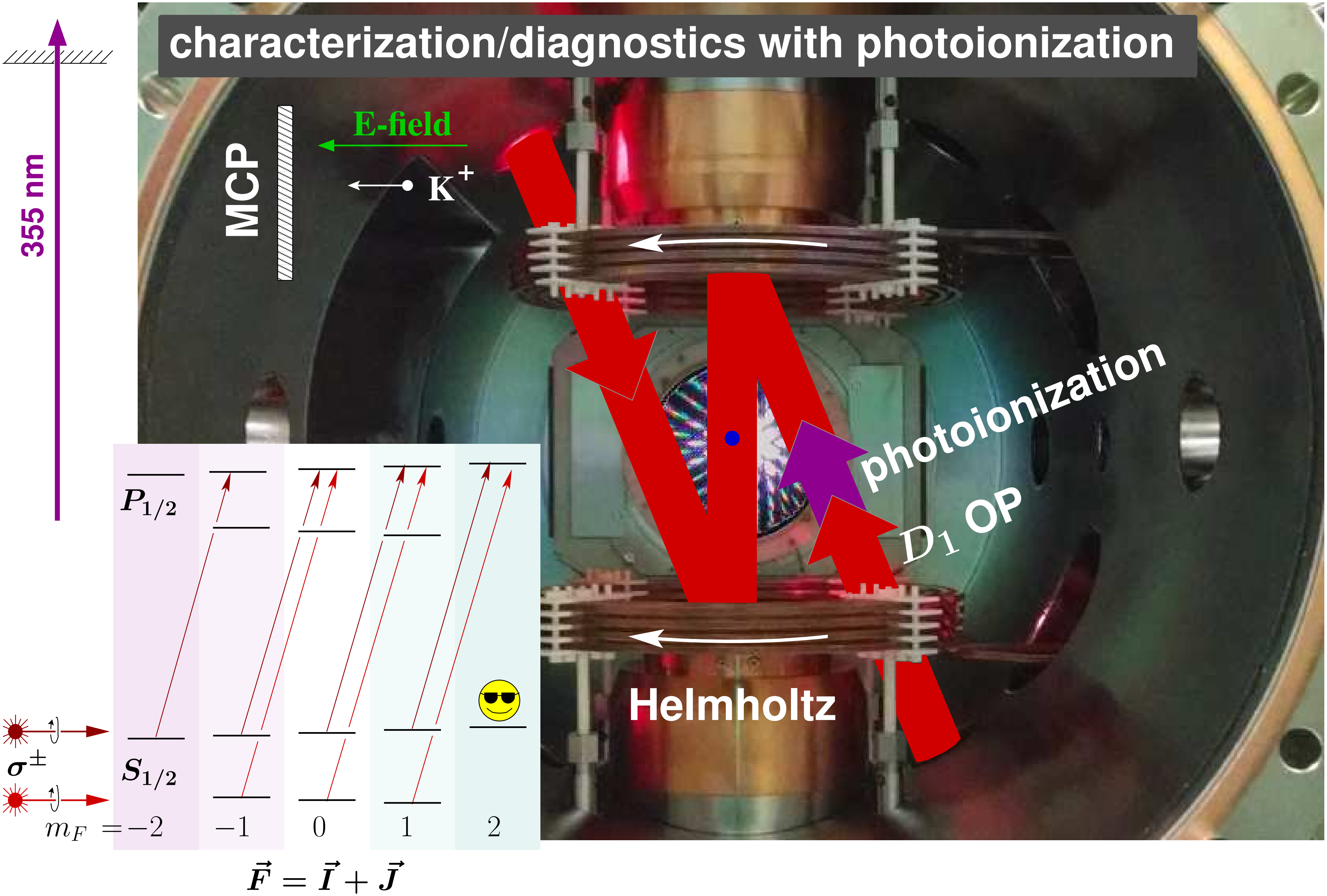
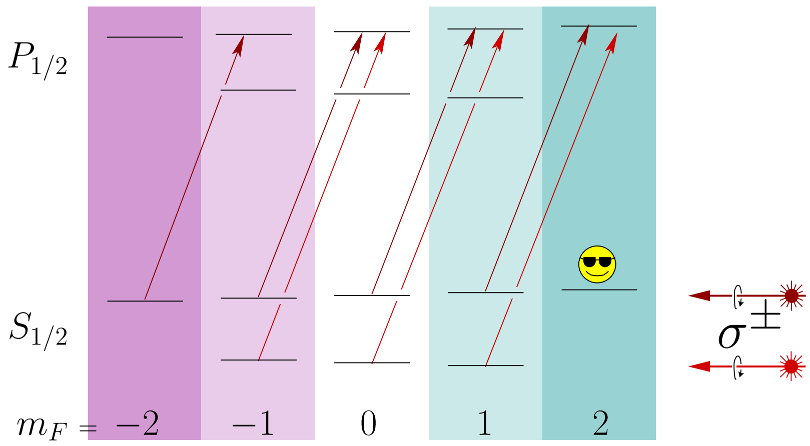
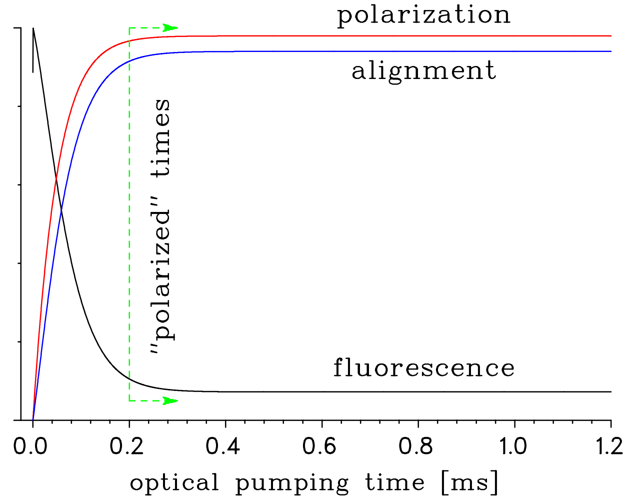


Atomic measurement of P

Deduce P based on model of excited state populations:





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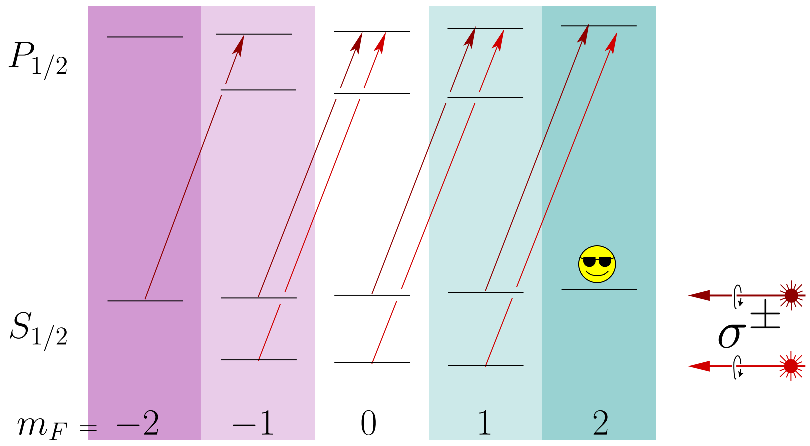
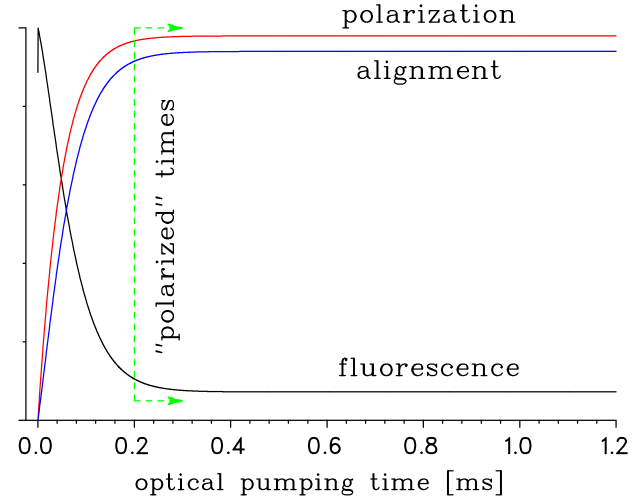
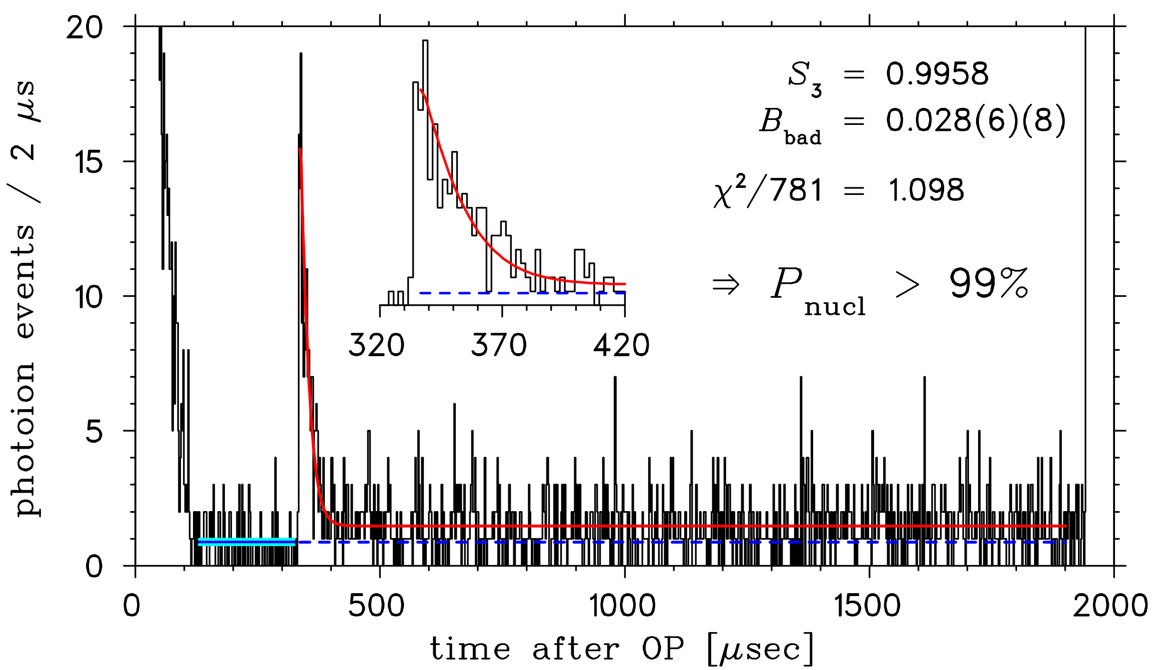
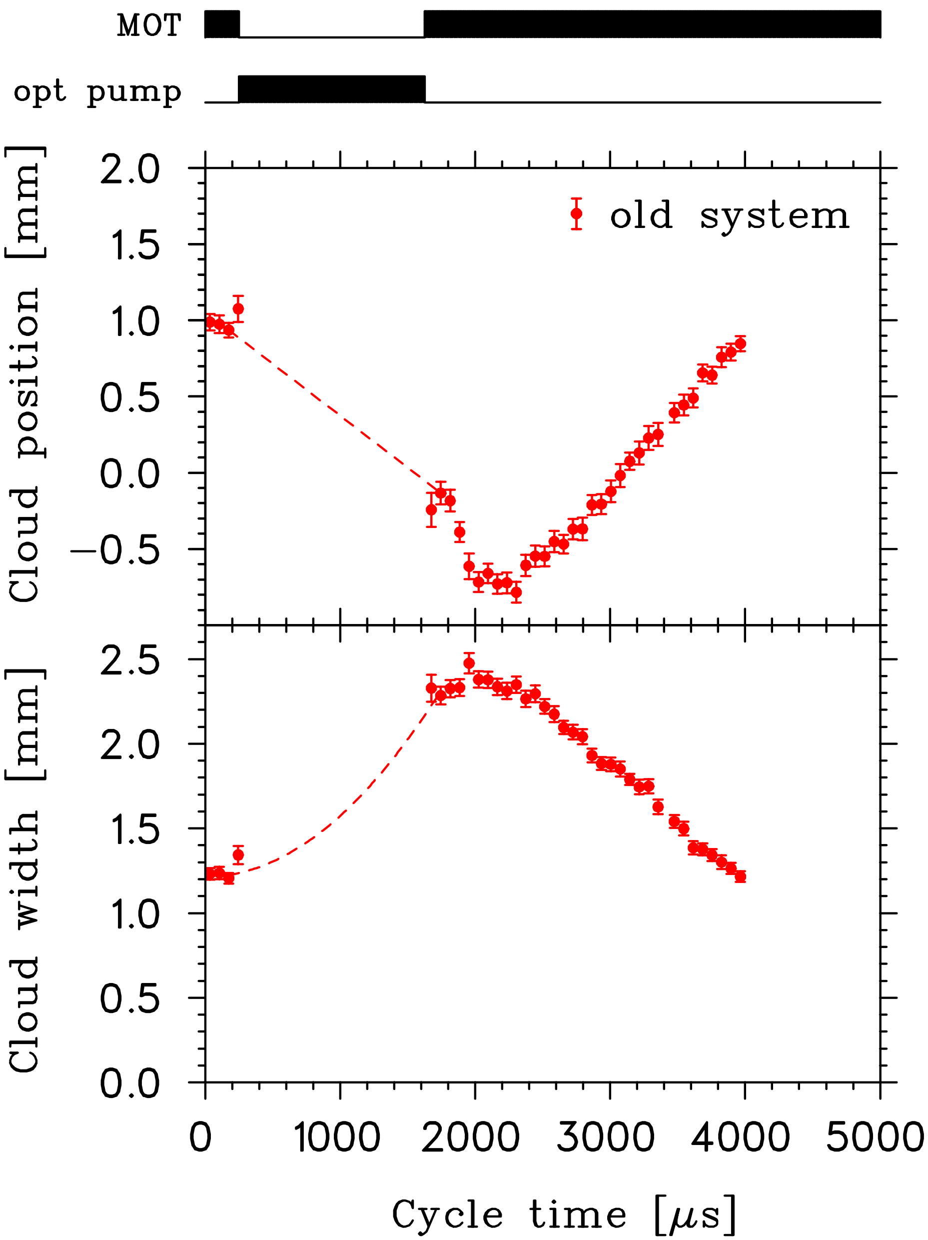






1^{st} improvements for polarized program



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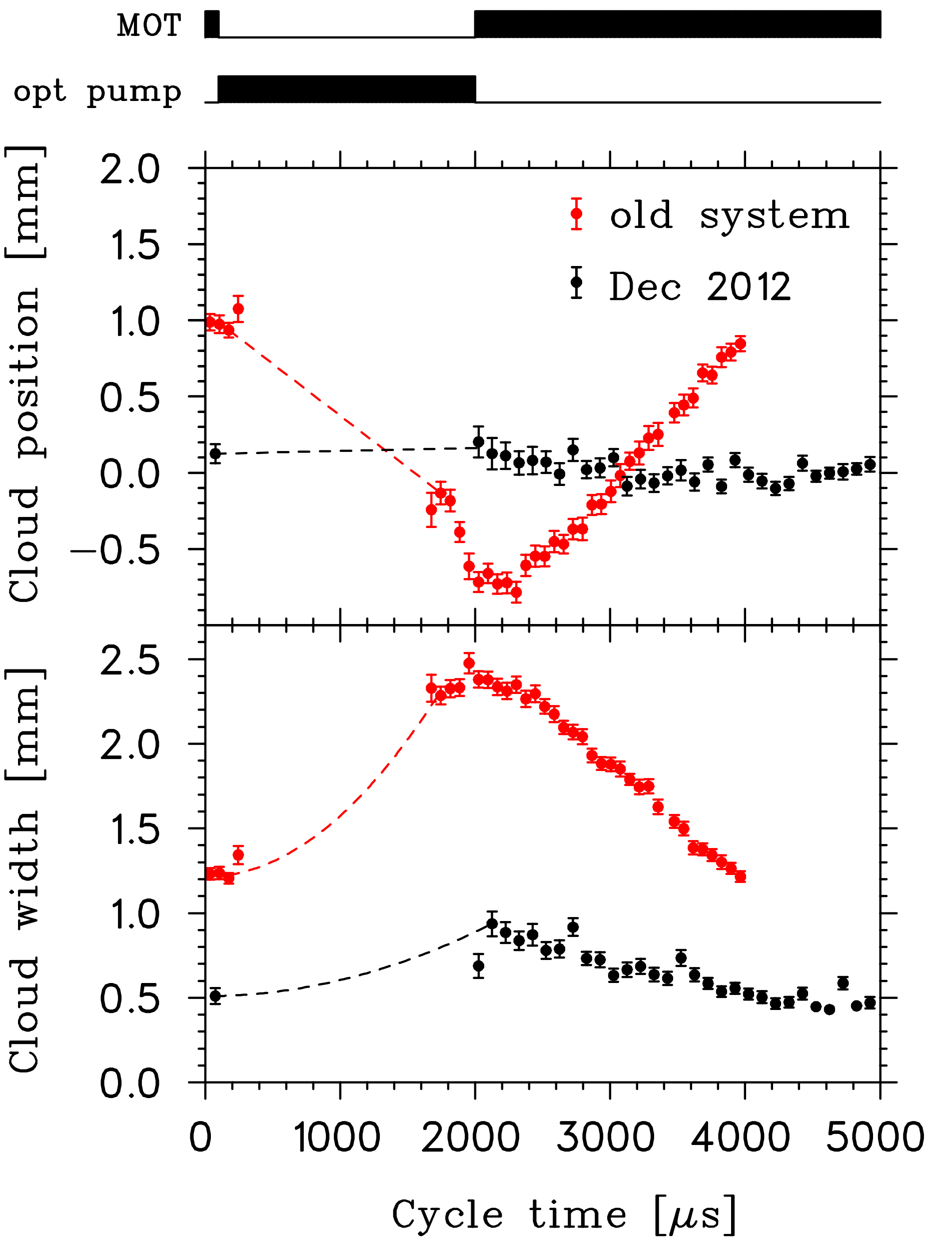

- old system:
  - retroreflected beams
  - "Helmholtz" coils not really Helmholtz
  - eddy currents
- Dec 2012:
  - beams balanced
  - (anti-)Helmholtz very well-defined
  - ac-MOT $\Rightarrow$ fast switching and low eddy currents

much more stable!
lower cloud temperature!

June 2014 run

Debugging the new system: some key improvements in a very recent 2nd run:

June 2014 run

Debugging the new system: some key improvements in a very recent 2nd run:

- ISAC developed a high-power TiC target:
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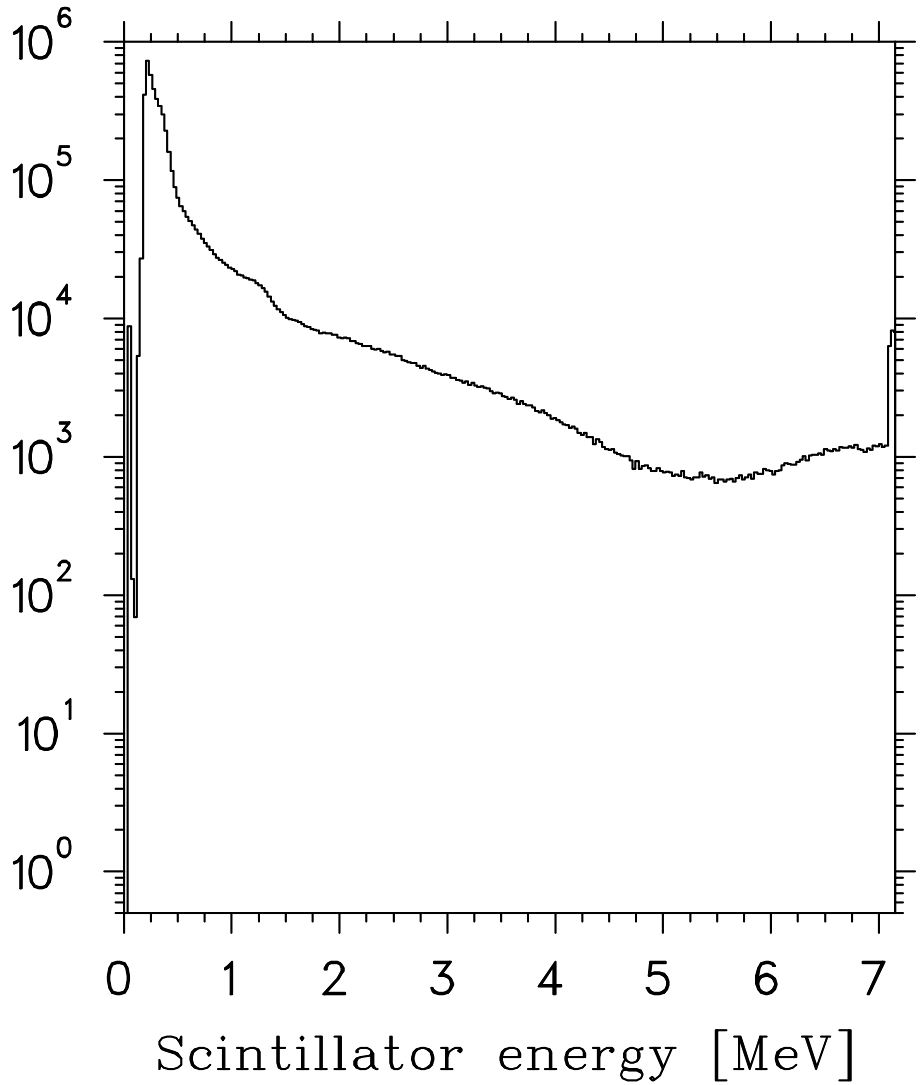
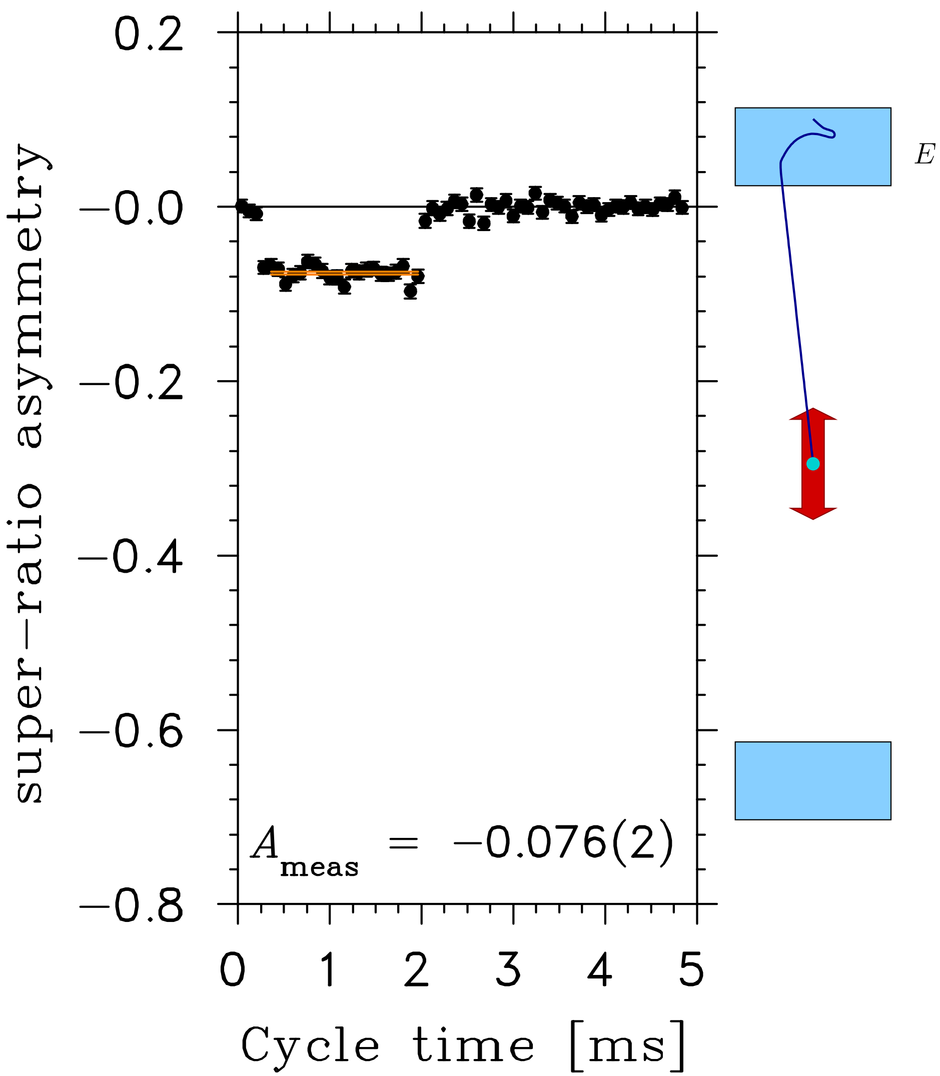
- $\approx 20\times$ more β-decay events!
  - 2×10^6 enough stats for $\leq 0.5\%$ measurement of A_β
  - also $a_{\beta\nu}$ and $\beta-$recoil correlation

Scintillator spectra — Fall 2012

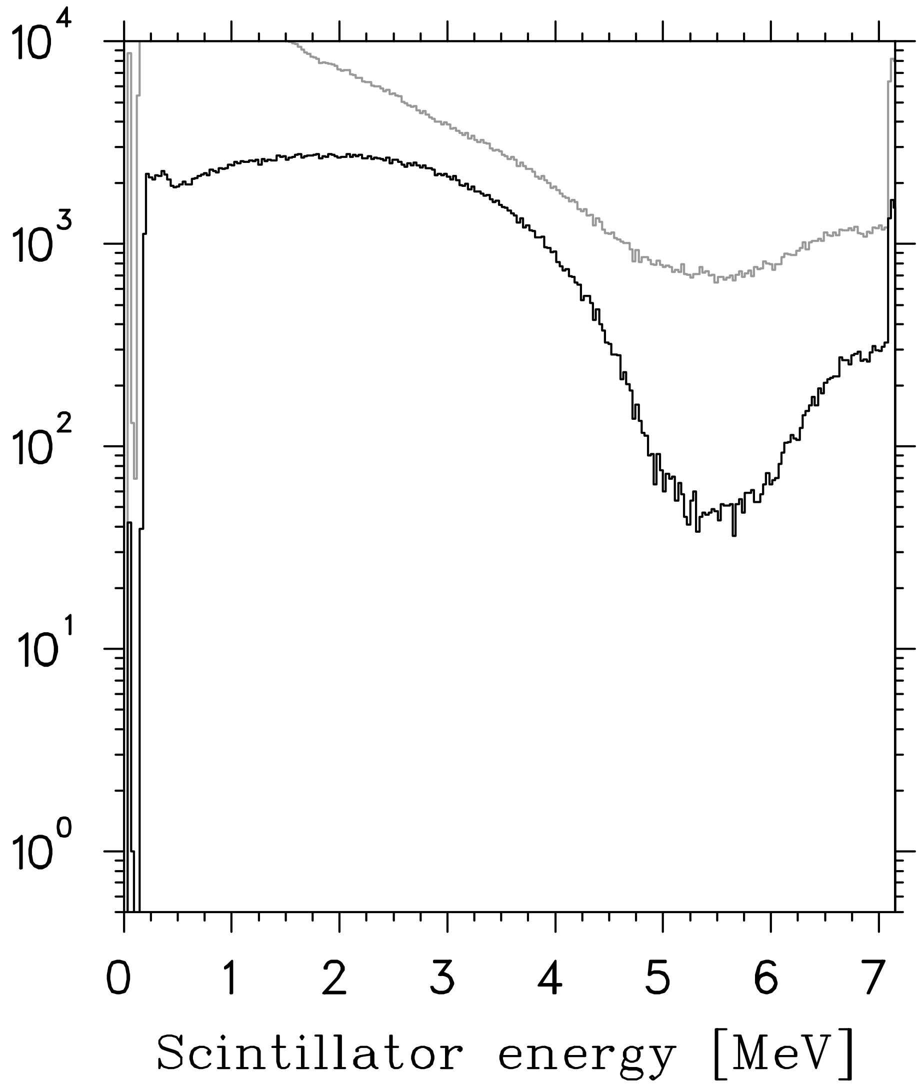
Just the raw data; a slight lower-energy cut to get rid of 511s

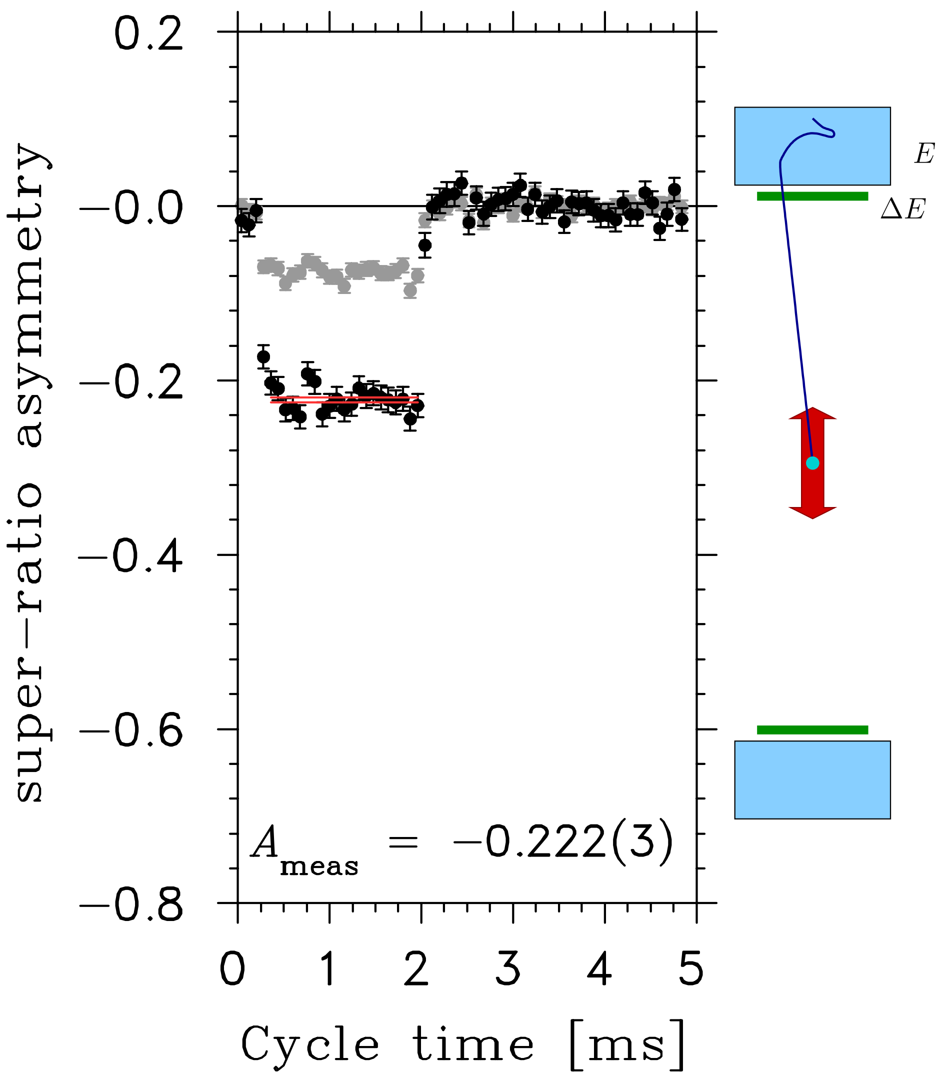




Scintillator spectra — Fall 2012

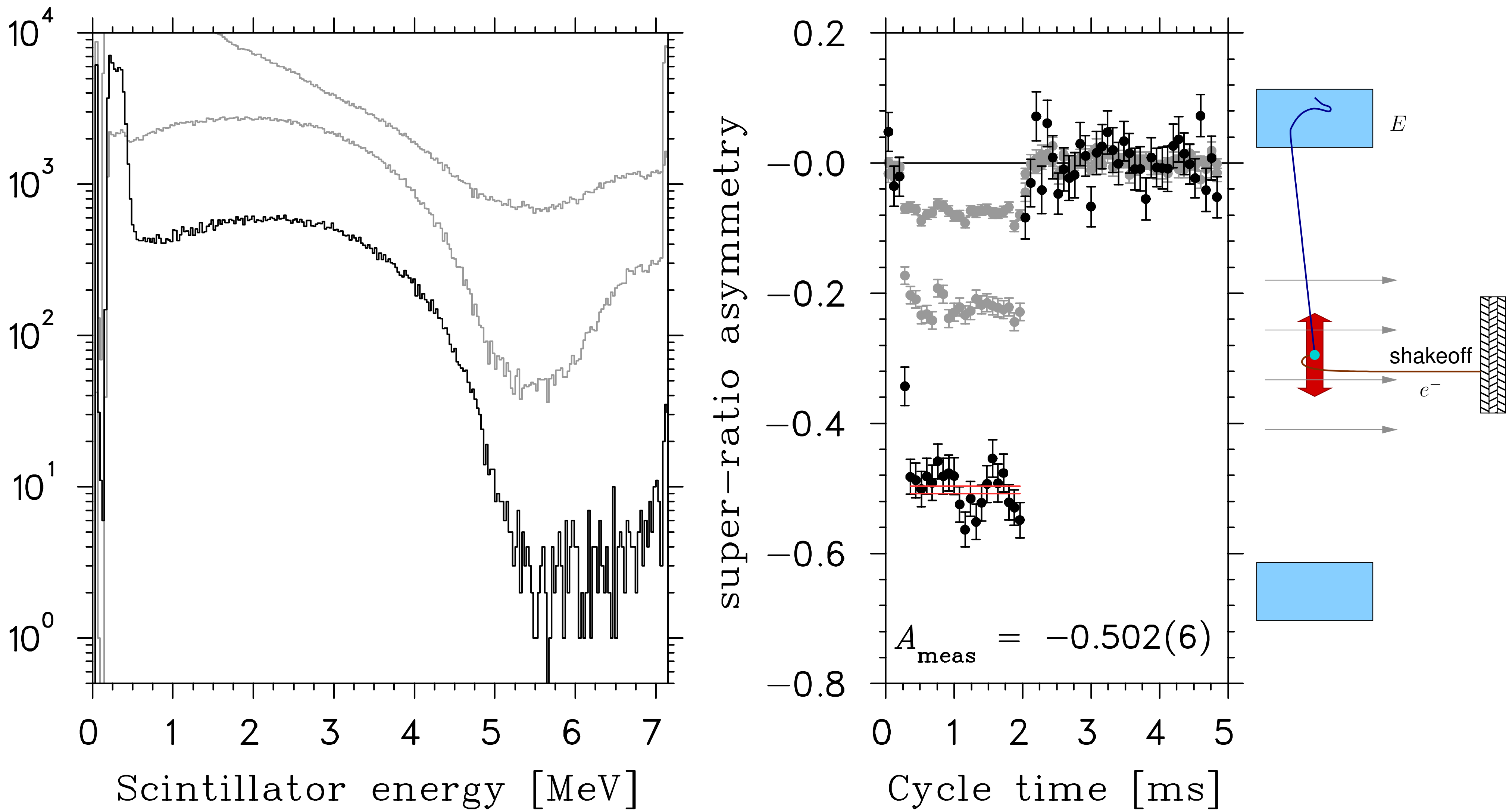
Requiring a ΔE coincidence $\Rightarrow$ remove γs





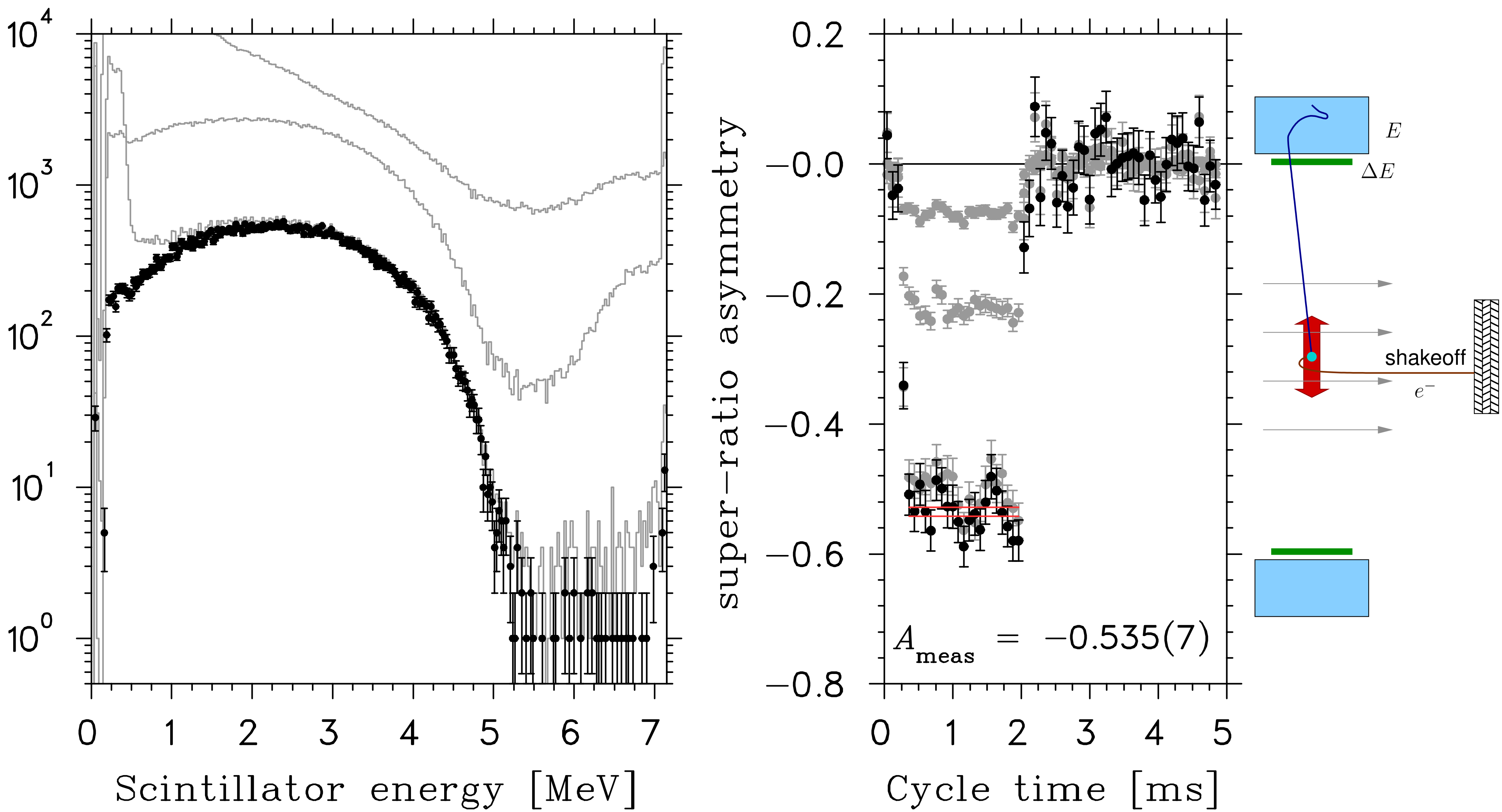
Scintillator spectra — Fall 2012

Requiring a shake-off e^- ⇒ decay occured from trap!

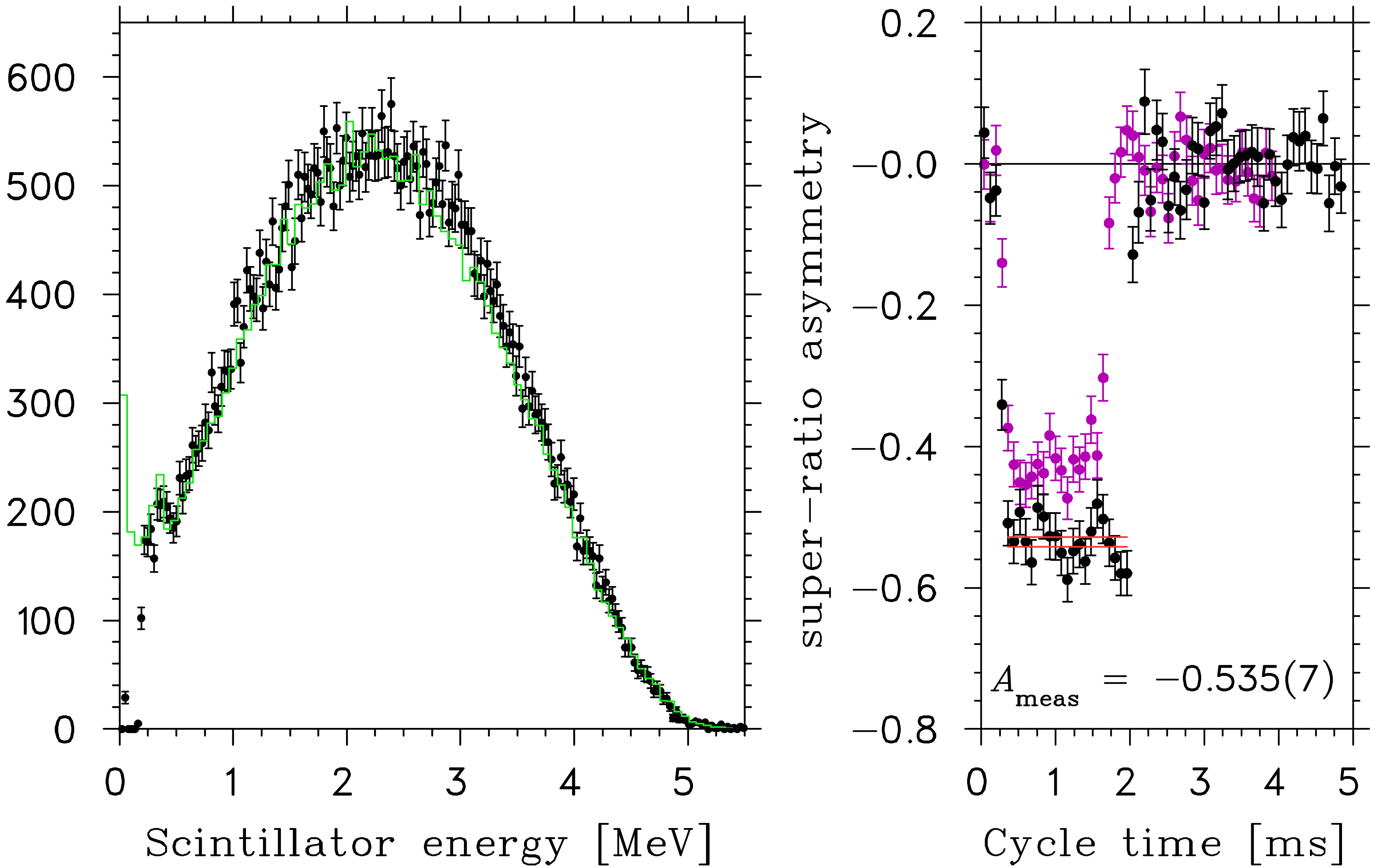


Scintillator spectra — Fall 2012

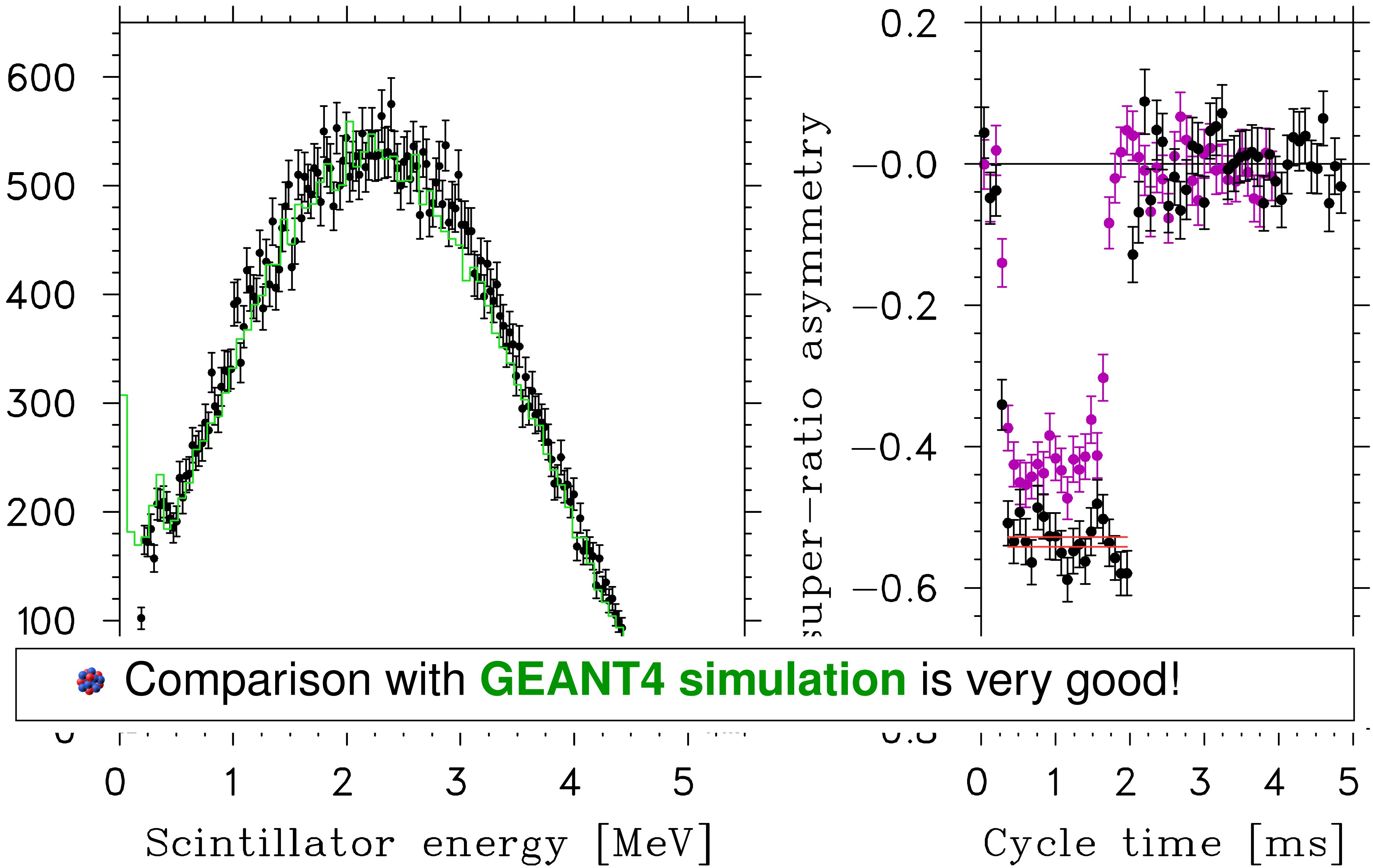
Put in all the basic analysis cuts ⇒ clean spectrum!!



Scintillator spectra — Fall 2012

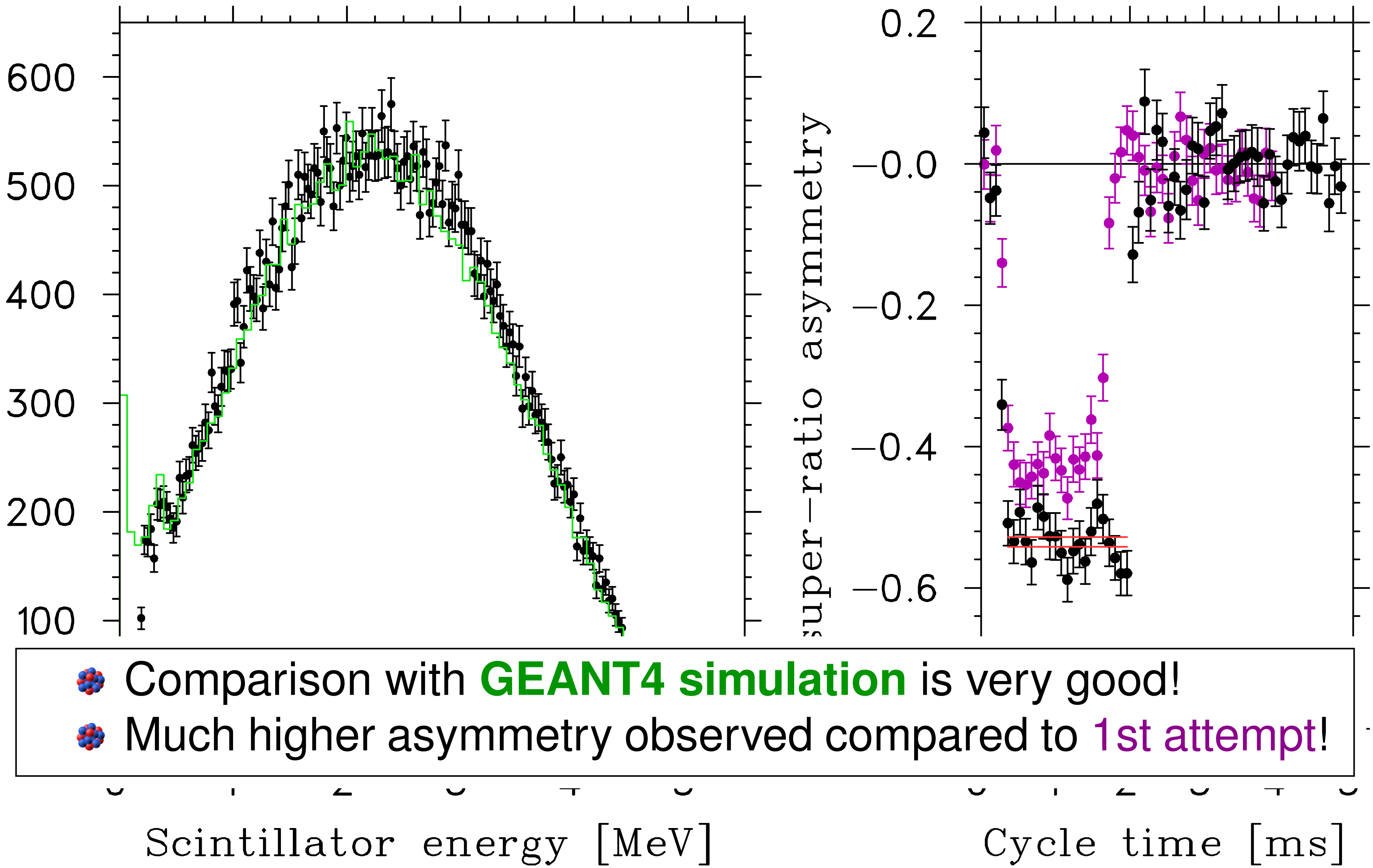


Scintillator spectra — Fall 2012



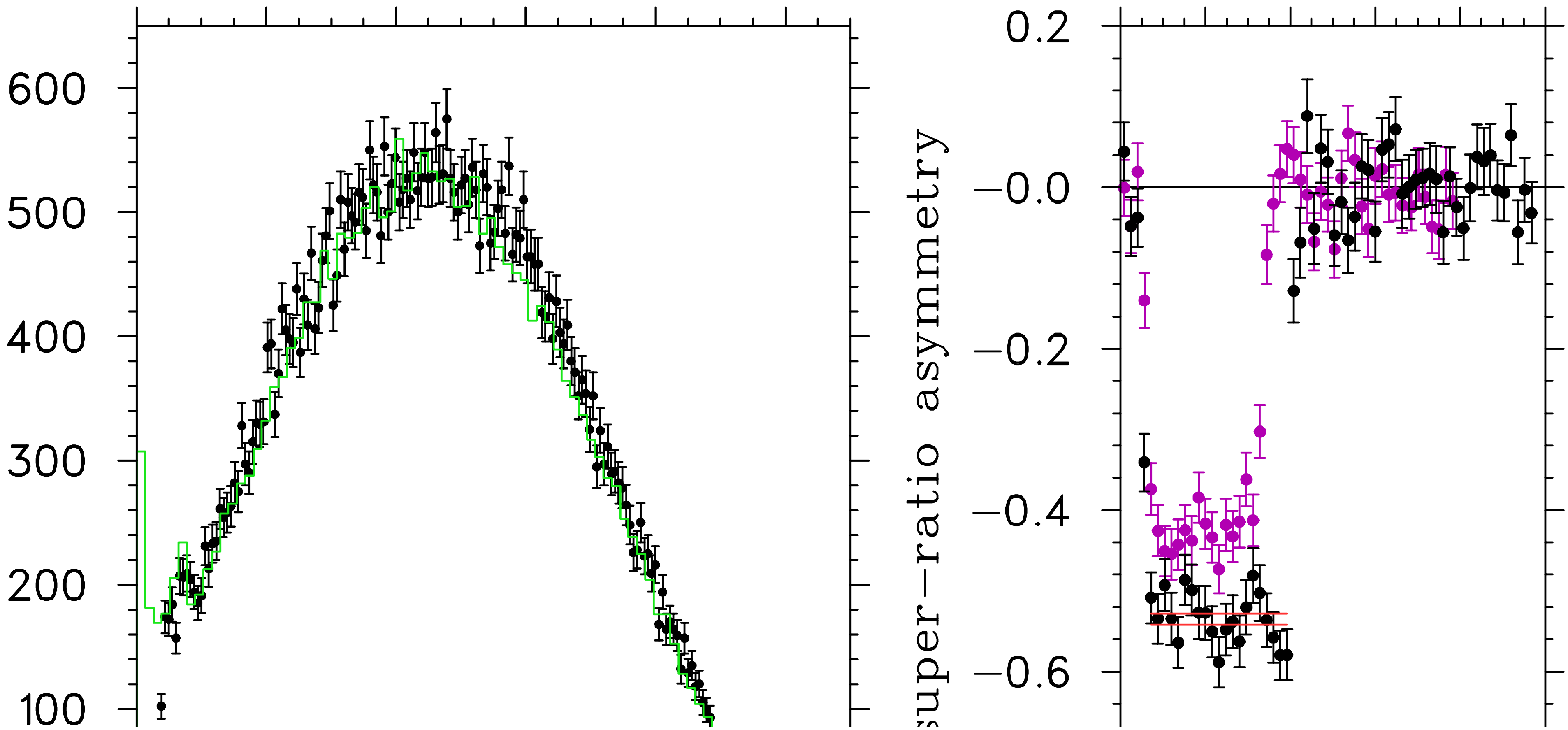
- Comparison with **GEANT4 simulation** is very good!

Scintillator spectra — Fall 2012



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

Scintillator spectra — Fall 2012



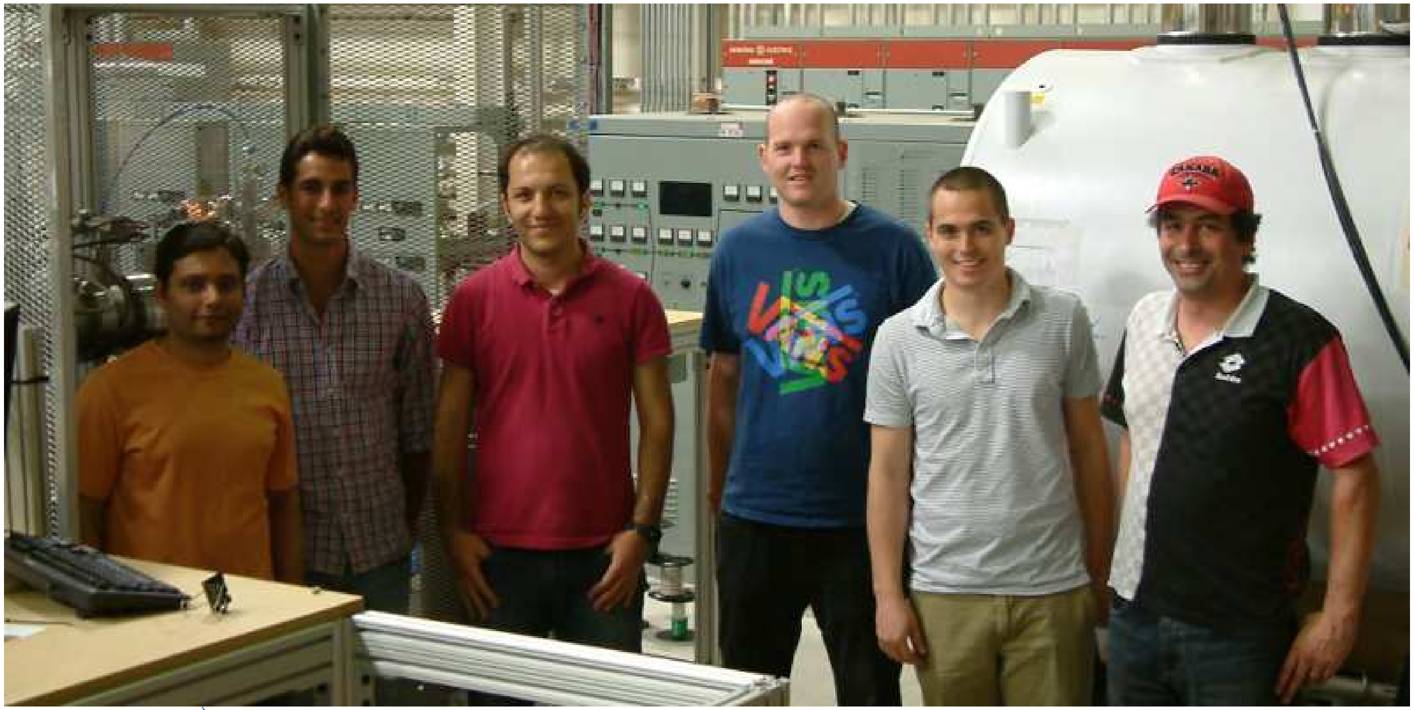
- Comparison with **GEANT4 simulation** is very good!
- Much higher asymmetry observed compared to 1st attempt!
- Stay tuned; student wants to graduate, so results should be forthcoming soon

Summary

- Angular correlations in β decay can be used to probe physics beyond the standard model
  - to be competitive, precision must be 0.1%
- TAMUTRAP: unique facility to study β-delayed proton decays
  - scalar currents through $a_{\beta\nu}$: enhanced sensitivity
  - ft/V_{ud} and other applications
- TRINAT: unique facility to study polarized angular distributions in ^{37}K
  - with $t_{1/2}$ and B.R. measurements at TAMU, ρ well-determined
  - very clean A_β measurement; analyses underway

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

Funding/Support:

DOE DE-FG02-93ER40773, Early Career ER41747

TAMU/Cyclotron Institute

In case you haven't already heard. . .

TENURE-TRACK POSITION

PHYSICS & ASTRONOMY
TEXAS A&M UNIVERSITY

EXPERIMENTAL NUCLEAR PHYSICS
TEXAS A&M UNIVERSITY

The Physics and Astronomy Department at Texas A&M University seeks applications for a tenure-track assistant professor position in experimental nuclear physics under the auspices of the Nuclear Solutions Institute. This institute combines basic and applied nuclear science with nuclear security technology and policy; it already encompasses a broad spectrum of faculty members drawn from across the university. A selected candidate must hold an earned Ph.D. in physics or a related area. The appointment is expected to begin on or before September 1, 2015.

The successful candidate for this position will assume a tenure-track position in the Department of Physics and Astronomy with a joint appointment in the Cyclotron Institute and the Nuclear Solutions Institute. More senior candidates may be considered at the associate professor or professor level. He/she is expected to assume full teaching responsibilities at the graduate and undergraduate levels and is also expected to conduct a vigorous research program based at the Cyclotron Institute and employing the facilities there, which include two cyclotrons – a newly refurbished K150 and a superconducting K500 – together with a wide variety of modern experimental equipment. An upgrade project, nearing completion, will utilize the two accelerators to make radioactive beams available to all target locations.

Each application should include:

- a cover letter specifying that the application is for the nuclear physics position,
- a *curriculum vita*,
- a list of publications,

In case you haven't already heard. . .

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PHYSICS & ASTRONOMY
TEXAS A&M UNIVERSITY

EXPERIMENTAL NUCLEAR PHYSICS
TEXAS A&M UNIVERSITY

The Physics and Astronomy Department at Texas A&M University seeks applications for a tenure-
track ass … he Nuclear
Solutions … ar security
technolog … rom across
the unive … area. The
appointm …

The succ … artment of
Physics a … Solutions
Institute … el. He/she
is expect … and is also
expected … employing
the facili … conducting
K500 – t … ct, nearing
completi … locations.

Each app …

- a co …
- a *curriculum vita*,
- a list of publications,

- Open search: no specific subfield
- Just need to have (big part of) your program based locally at the CI
- Application review will begin early October

Let me know if you're interested!

dmelconian@comp.tamu.edu