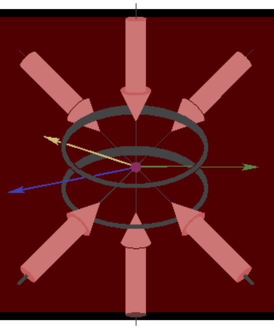
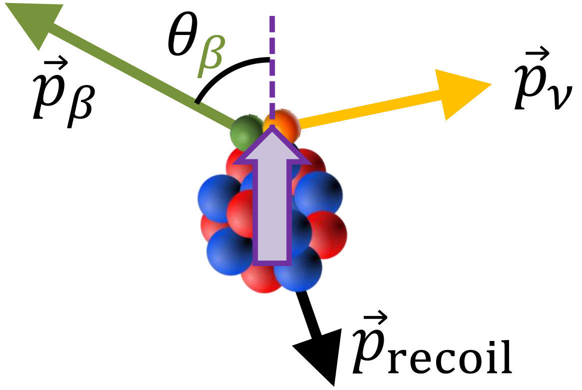
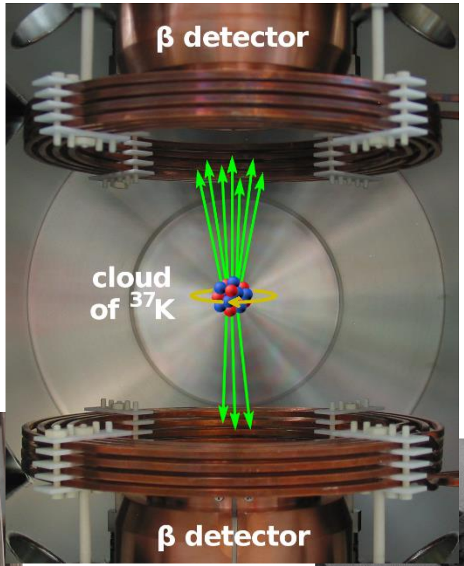
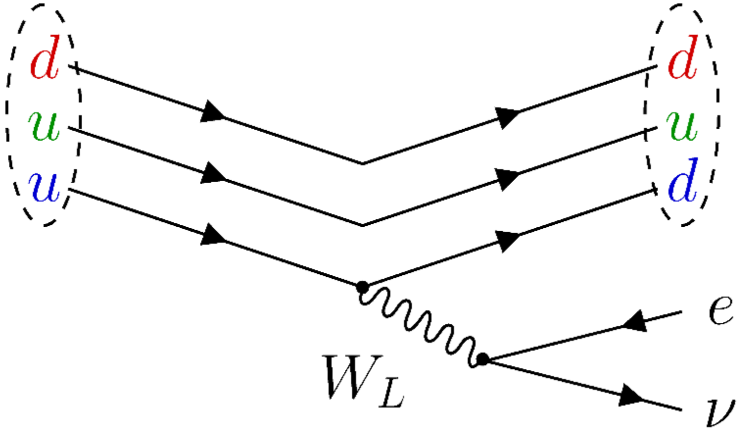
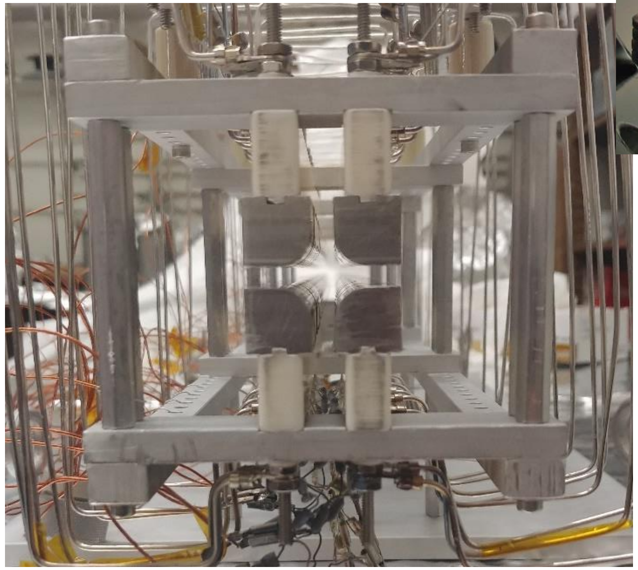
Fundamentally cool physics with trapped atoms and ions

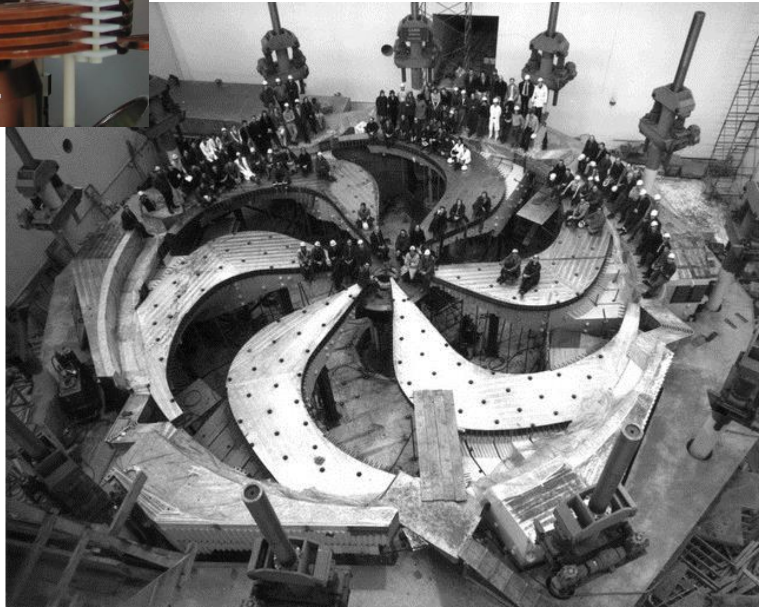


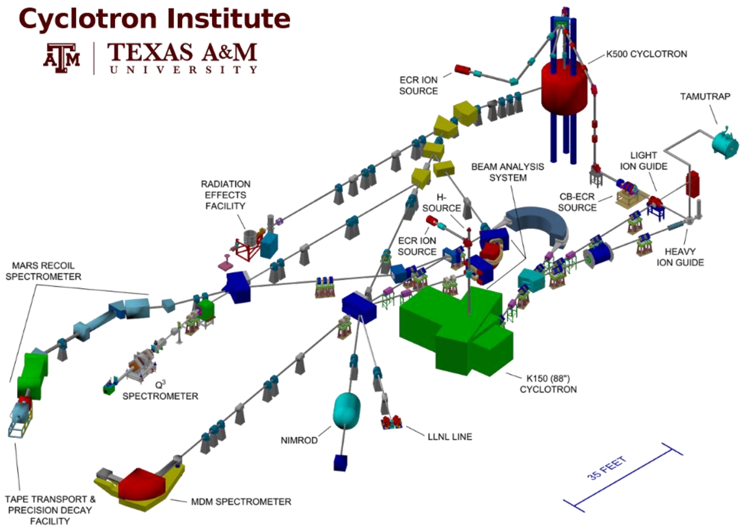












Dan Melconian – TAMU, 2018

Outline

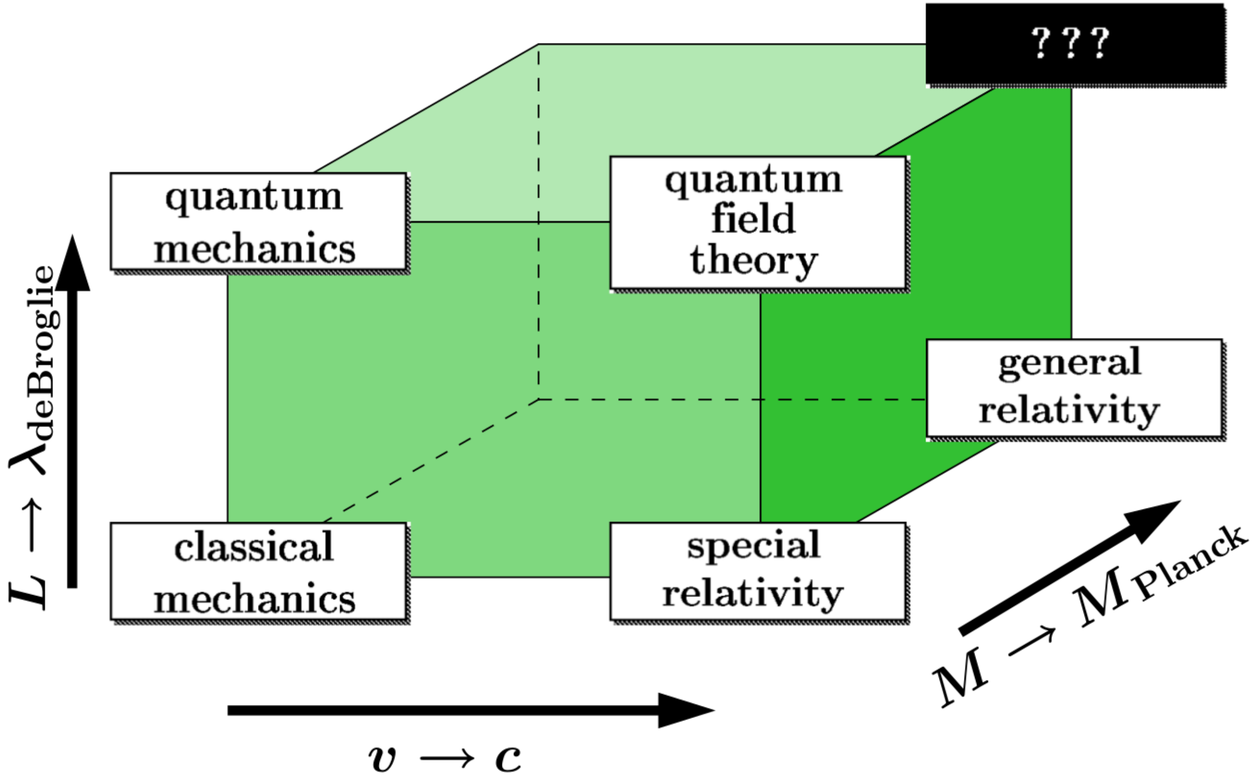
- Introduction
  - Testing the standard model via the precision frontier
  - Angular correlations of β decay
- TAMUTRAP
  - Trapping ions at the Cyclotron Institute
  - Commissioning with mass measurement of ^{23}Na
- ^{37}K at TRIUMF
  - The TRINAT facility
  - Polarizing the cloud
  - Recent measurement of A_β
- Future work

The standard model

- Pioneering experiments in β decay, and many other systems, lead to what we now know as the fundamental particles and forces of nature

THE STANDARD MODEL

- Quantum mechanics + special relativity $\Rightarrow$ quantum field theory



The standard model

- Pioneering experiments in β decay, and many other systems, lead to what we now know as the fundamental particles and forces of nature

THE STANDARD MODEL

- Quantum mechanics + special relativity ⇒ quantum field theory
- Electroweak + strong

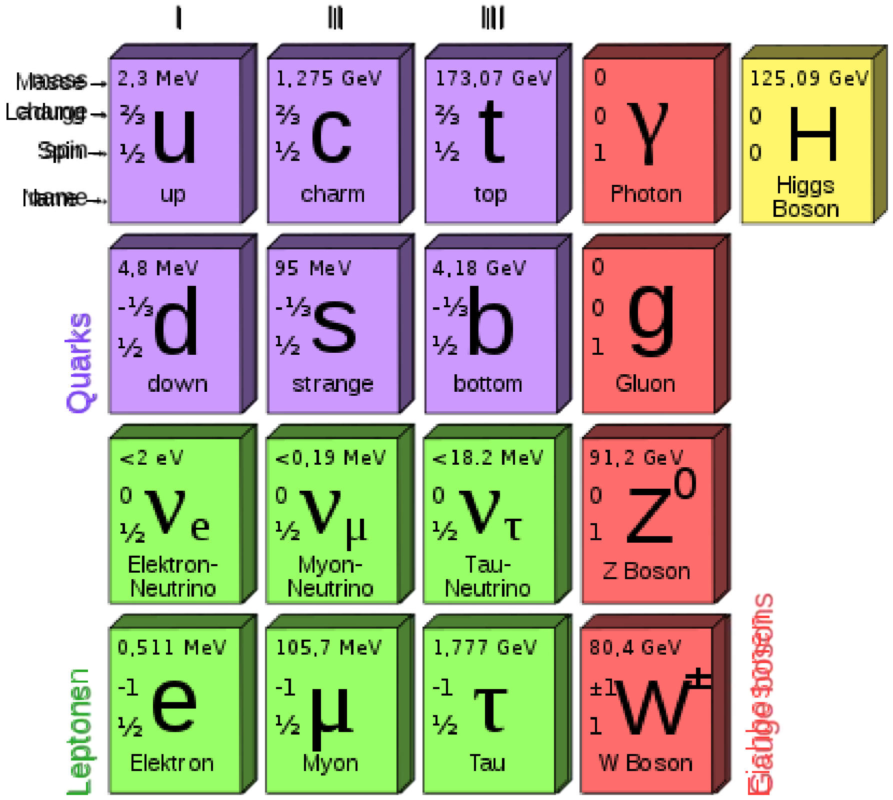
$$\underbrace{SU(3)}_{\text{strong}} \times \overbrace{\underbrace{SU(2)_L}_{\text{weak}} \times \underbrace{U(1)}_{\text{E\&M}}}^{\text{electroweak}} \;+\; \underbrace{(\text{classical general rel})}_{\text{gravity}}$$

The standard model

- Pioneering experiments in β decay, and many other systems, lead to what we now know as the fundamental particles and forces of nature

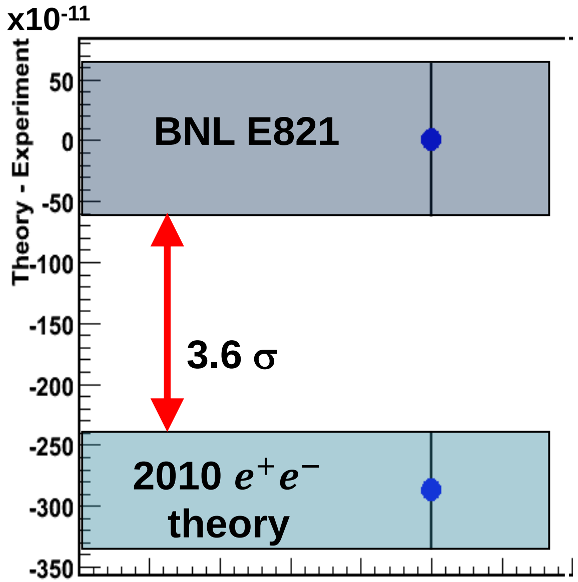
THE STANDARD MODEL

- Quantum mechanics + special relativity ⇒ quantum field theory
- Electroweak + strong
- 12 elementary particles and
  4 fundamental forces…and 1 Higgs!



Does the standard model work?

- Short answer: Yes. *Stubbornly* well!
  - ✓ It predicted the existence of the $W^{\pm}$, Z_0, g, c, t and H
  - ✓ It is a renormalizable theory
  - ✓ GSW → unifited weak force with electromagnetism
  - ✓ QCD explains quark confinement
- Experimentally tested in many different systems



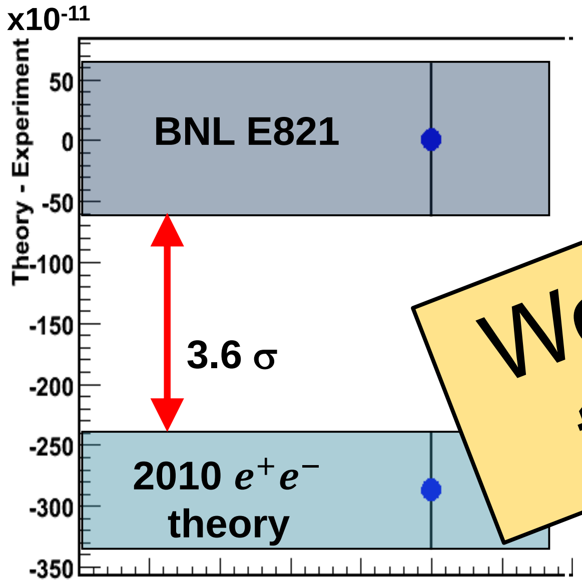
$$\boldsymbol{a_\mu \equiv \frac{1}{2}(g-2)}$$

Theory uncertainty: 0.42 ppm
Experimental uncertainty: 0.54 ppm

$$\Delta a_\mu(\text{expt} - \text{theory}) = (287 \pm 80) \times \mathbf{10^{-11}} \quad (3.6\sigma)$$

Does the standard model work?

- Short answer: Yes. *Stubbornly* well!
  - ✓ It predicted the existence of the $W^{\pm}$, Z_0, g, c, t and H
  - ✓ It is a renormalizable theory
  - ✓ GSW → unifited weak force with electromagnetism
  - ✓ QCD explains quark confinement
- Experimentally tested in many different systems



2)

...ainty: 0.42 ppm

...mental uncertainty: 0.54 ppm

Wow! This is the most precisely tested theory ever conceived!

$$\Delta a_\mu(\text{expt} - \text{theory}) = (287 \pm 80) \times \mathbf{10^{-11}} \quad (3.6\sigma)$$

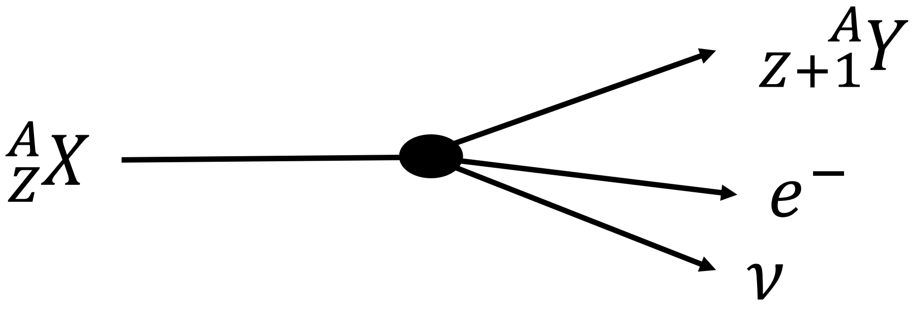
But the standard model *can't* be the final answer

- **Dark matter**: SM physics makes up less than 5% of the universe
- **Baryon asymmetry**: Why more matter than anti-matter?
- **Neutrinos**: Dirac or Majorana? Mass hierarchy?
- **Parameter values**: does our "ultimate" theory *really* need ~25 arbitrary constants? Do they change with time?
- **Fermion generations**: Why three families?
- **Weak mixing**: Is the CKM matrix unitary?
- **Parity violation**: Is nature really left-handed?
- **SM cobbled together**: Strong unified with electroweak?
- **Gravity**: Quantum description??

Point is: we know there *must* be physics beyond the SM

A primer on β decay

- Soon after the neutrino was hypothesized by Pauli, Fermi came up with his theory of β decay:
  - A contact (4-point) interaction
  - New force is weak; Fermi's Golden Rule
  - β energy largely determined by phase space
  - Purely vector (inspired by E&M)



$$\Rightarrow \frac{dW}{dE} = \frac{G_F}{\sqrt{2}}\, p_\beta E_\beta \left(E_\beta - A_0\right)^2$$

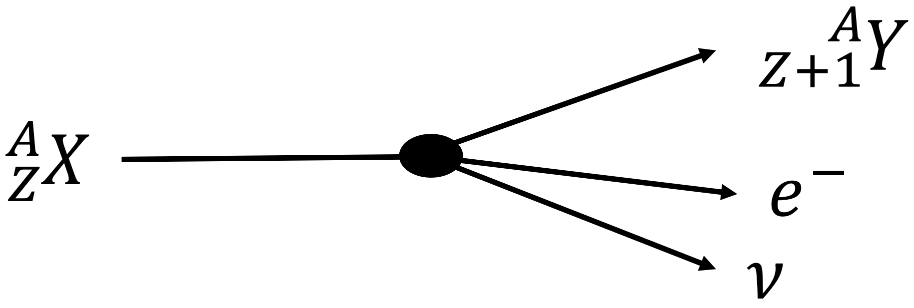
Strength of interaction

Density of final states of the electron/positron

Density of final states available to the neutrino, with $A_0 = M - M' = E_e + E_\nu$ and $m_\nu = 0$

A primer on β decay

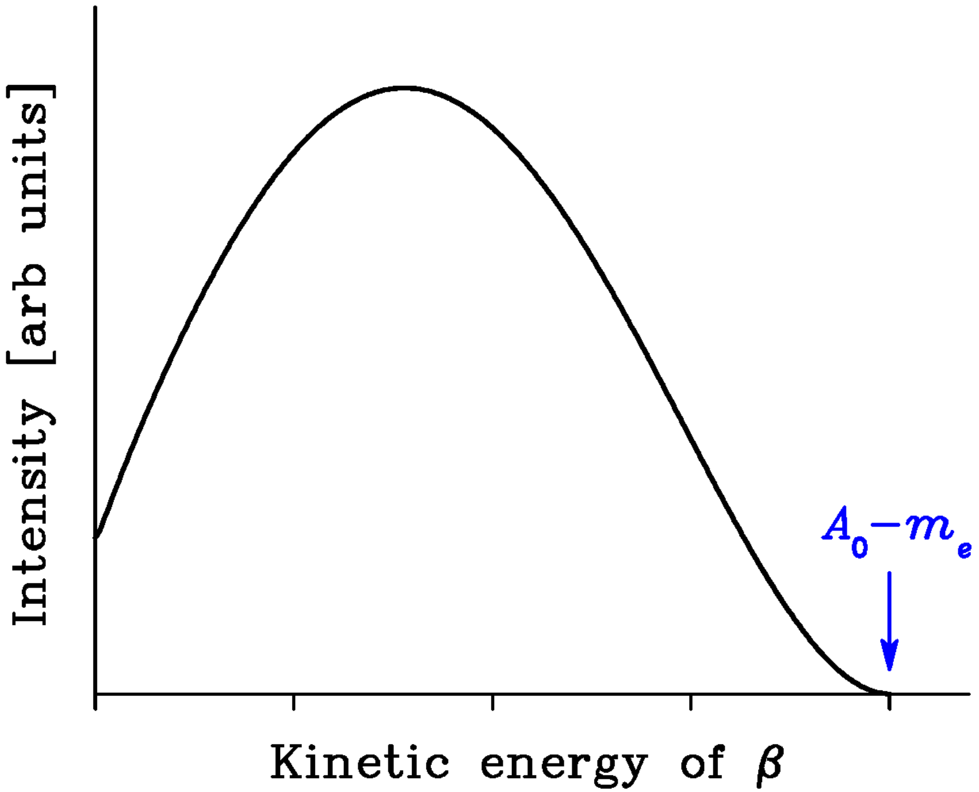
- Soon after the neutrino was hypothesized by Pauli, Fermi came up with his theory of β decay:
  - A contact (4-point) interaction
  - New force is weak; Fermi's Golden Rule
  - β energy largely determined by phase space
  - Purely vector (inspired by E&M)



$$\Rightarrow \frac{dW}{dE} = \frac{G_F}{\sqrt{2}} p_\beta E_\beta (E - A_0)^2$$

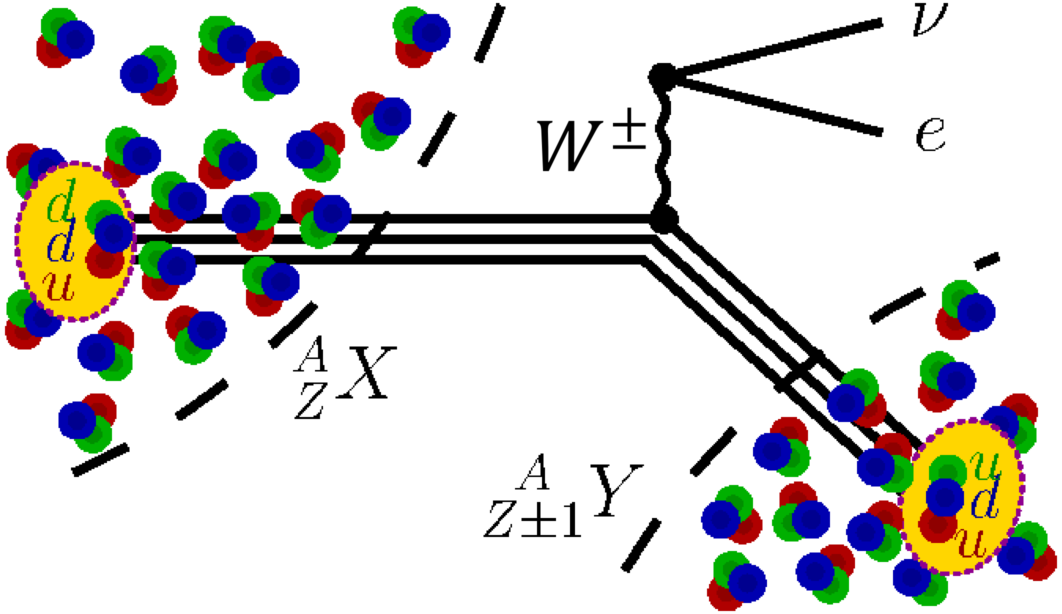
Strength of interaction

Density of final states of the leptons



A primer on β decay

- Soon after the neutrino was hypothesized by Pauli, Fermi came up with his theory of β decay
- This is, of course, not correct; but to a good approximation it works very well



- In the SM, we understand it now as
  - Mediated by the massive charged $W^{\pm}$ bosons coupling to quarks
  - Extremely short-ranged: $\approx 10^{-18}$ m, or 0.1% the diameter of the proton
  - "Real" coupling is g_W; effective one is G_F: $\frac{g_W^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}$

    Note: E&M coupling $\alpha_{\mathrm{E\&M}} \approx \frac{1}{137}$ versus "weak" coupling $\alpha_{\mathrm{weak}} = \frac{g_W^2}{4\pi} \approx \frac{1}{30}$!
  - Based on experiments, form is $(V - A)$, even though initially looked like (S, T)

β decay and the standard model

- SM Hamiltonian is

vector: $\hat{P}|\vec{V}\rangle = -|\vec{V}\rangle$

$$H_\beta = \left(\overline{\psi}_n\gamma_\mu\psi_p\right)\left(C_V\overline{\psi}_e\gamma^\mu\psi_\nu + C_V'\overline{\psi}_e\gamma^\mu\gamma_5\psi_\nu\right)$$
$$- \left(\overline{\psi}_n\gamma_\mu\gamma_5\psi_p\right)\left(C_A\overline{\psi}_e\gamma^\mu\gamma_5\psi_\nu + C_A'\overline{\psi}_e\gamma^\mu\psi_\nu\right)$$

axial vector: $\hat{P}|\vec{A}\rangle = +|\vec{A}\rangle$

where $C_V = C_V' = 1$

and $C_A = C_A' \approx 1.26$ is a renormalization since not purely leptonic

- Transformation under parity?
  - What we observe is the square of an amplitude: $\left|M_{fi}\right|^2 \sim (V-A)(V-A)$
  - Apply a parity operator:

$$\hat{P}\left\{\left|M_{fi}\right|^2\right\} = \hat{P}\{VV + AA - 2VA\} = (-V)(-V) + (+A)(+A) - 2(-V)(+A)$$
$$= \quad VV + AA + 2VA$$

  - Parity is maximally violated; only left-handed fermions couple to the W

β decay and the standard model

- SM Hamiltonian is

v

$$H_\beta = \quad (\bar{\psi}_n \gamma_\mu \psi_p$$
$$- (\bar{\psi}_n \gamma_\mu \gamma_5 \psi$$

a

where $\quad C_V = C_V' = 1$

and $\quad C_A = C_A' \approx 1.26$ is a rer

- Transformation under parity?
  - What we observe is the square
  - Apply a parity operator:

$$\hat{P}\left\{\left|M_{fi}\right|^2\right\} = \hat{P}\{VV + AA - 2VA\} = (-V)(-V) + (+A)(+A) - 2(-V)(+A)$$
$$= \quad VV + AA + 2VA$$

  - Parity is maximally violated; only left-handed fermions couple to the W

Beyond the standard model

- The most general Hamiltonian that obeys Lorentz invariance is

		parity
$H_\beta = (\overline{\psi}_n\psi_p)(C_S\overline{\psi}_e\psi_\nu + C_S'\overline{\psi}_e\gamma_5\psi_\nu)$	Scalar	$+$
$+ (\overline{\psi}_n\gamma_5\psi_p)(C_P\overline{\psi}_e\gamma_5\psi_\nu + C_P'\overline{\psi}_e\psi_\nu)$	Pseudoscalar	$-$
$+ (\overline{\psi}_n\gamma_\mu\psi_p)\ (C_V\overline{\psi}_e\gamma^\mu\psi_\nu + C_V'\overline{\psi}_e\gamma^\mu\gamma_5\psi_\nu)$	Vector	$-$
$- (\overline{\psi}_n\gamma_\mu\gamma_5\psi_p)(C_A\overline{\psi}_e\gamma^\mu\gamma_5\psi_\nu + C_A'\overline{\psi}_e\gamma^\mu\psi_\nu)$	Axial vector	$+$
$+ \frac{1}{2}(\overline{\psi}_n\sigma_{\lambda\mu}\psi_p)(C_T\overline{\psi}_e\sigma^{\lambda\mu}\psi_\nu + C_T'\overline{\psi}_e\sigma^{\lambda\mu}\gamma_5\psi_\nu)$	Tensor	N/A

- The coupling constants, C_i, C_i', may be complex and are not predicted by the SM
- No reason why $C_V = C_V'$ and $C_A = C_A'$ are the only non-zero ones…

  $\Rightarrow$ 19 free parameters to be determined by experiment
  (10 complex couplings minus one overall phase)

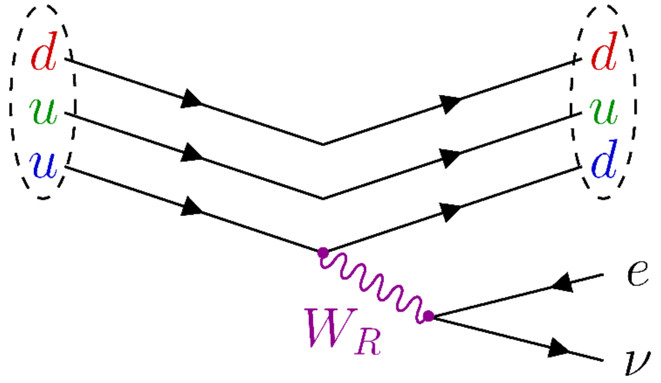
Beyond the standard model

- The most general Hamiltonian that obeys Lorentz invariance is

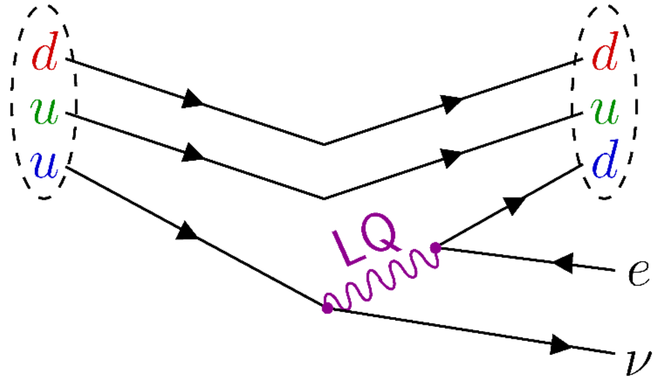
$$\begin{aligned} H_\beta = \; & (\overline{\psi}_n \psi_p)(C_S \overline{\psi}_e \psi_\nu + C_S' \overline{\psi}_e \gamma_5 \psi_\nu) \\ & + (\overline{\psi}_n \gamma_5 \psi_p)(C_P \overline{\psi}_e \gamma_5 \psi_\nu + C_P' \overline{\psi}_e \psi_\nu) \\ & + (\overline{\psi}_n \gamma_\mu \psi_p)\;(C_V \overline{\psi}_e \gamma^\mu \psi_\nu + C_V' \overline{\psi}_e \gamma^\mu \gamma_5 \psi_\nu) \\ & - (\overline{\psi}_n \gamma_\mu \gamma_5 \psi_p)(C_A \overline{\psi}_e \gamma^\mu \gamma_5 \psi_\nu + C_A' \overline{\psi}_e \gamma^\mu \psi_\nu) \\ & + \frac{1}{2}(\overline{\psi}_n \sigma_{\lambda\mu} \psi_p)(C_T \overline{\psi}_e \sigma^{\lambda\mu} \psi_\nu + C_T' \overline{\psi}_e \sigma^{\lambda\mu} \gamma_5 \psi_\nu) \end{aligned}$$

	parity
Scalar	$+$
Pseudoscalar	$-$
Vector	$-$
Axial vector	$+$
Tensor	N/A

Right-handed bosons, or scalar/tensor leptoquarks, or…



$C_i \neq C_i'$



$C_S, C_T \neq 0$

- Profumo, Ramsey-Musolf, Tulin, Phys. Rev. D **75**, 075017 (2007)
- Vos, Wilschut, Timmermans, Rev. Mod. Phys. **87**, 1483 (2015)
- Bhattacharya *et al.*, Phys. Rev. D **94**, 054508 (2016)

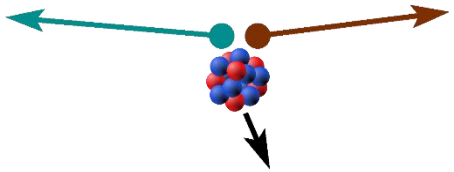
β decay to search for new physics

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

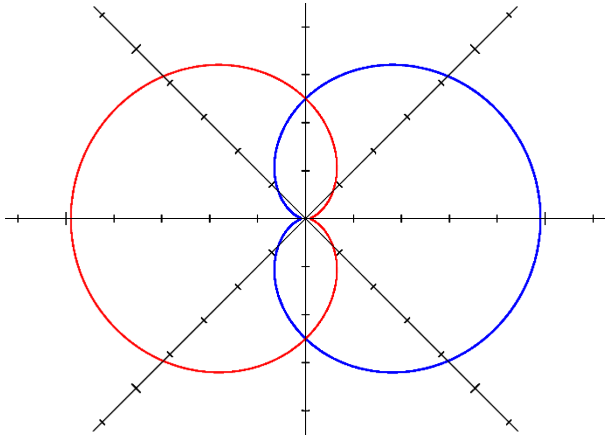
(Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e\,d\Omega_e\,d\Omega_\nu} = \overbrace{\frac{G_F^2|V_{\mathrm{ud}}|^2}{(2\pi)^5}\, p_\beta E_\beta \left(A_0 - E_\beta\right)^2}^{\text{basic decay rate}}\ \xi \left[1 + \overbrace{a_{\beta\nu}\left(\frac{v_\beta}{c}\right)\cos\theta_{\beta\nu}}^{\beta\text{-}\nu\text{ correlation}} + \overbrace{b\,\frac{m_e}{E_\beta}}^{\text{Fierz interference}} + \dots\right]$$

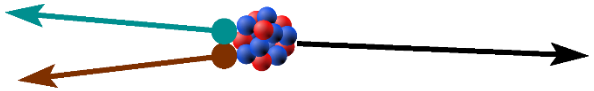
scalar



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



vector



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

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

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

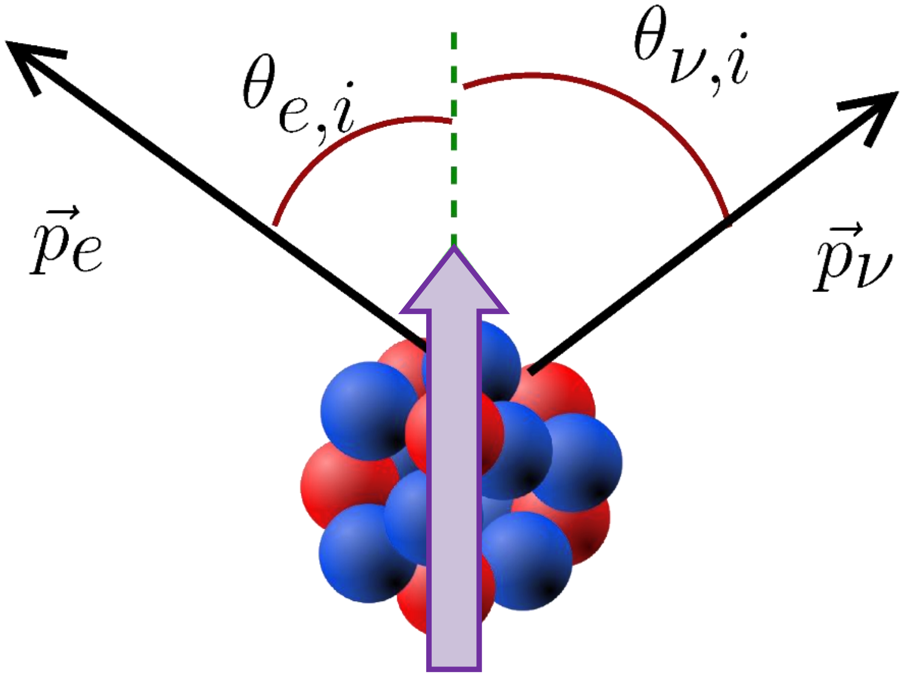
β decay to search for new physics

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

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

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_\nu} = \underbrace{\frac{G_F^2|V_{\rm ud}|^2}{(2\pi)^5} p_\beta E_\beta (A_0 - E_\beta)^2}_{\text{basic decay rate}} \xi \Big[1 + \underbrace{a_{\beta\nu}\left(\frac{v_\beta}{c}\right)\cos\theta_{\beta\nu}}_{\beta\text{-}\nu\text{ correlation}} + \underbrace{b\frac{m_e}{E_\beta}}_{\text{Fierz interference}} +$$

$$P\left\{ \underbrace{A_\beta\left(\frac{v_\beta}{c}\right)\cos\theta_{\beta,i}}_{\beta\text{ asymmetry}} + \underbrace{B_\nu\cos\theta_{\nu,i}}_{\nu\text{ asymmetry}} + \cdots \right\} + \cdots \Big]$$



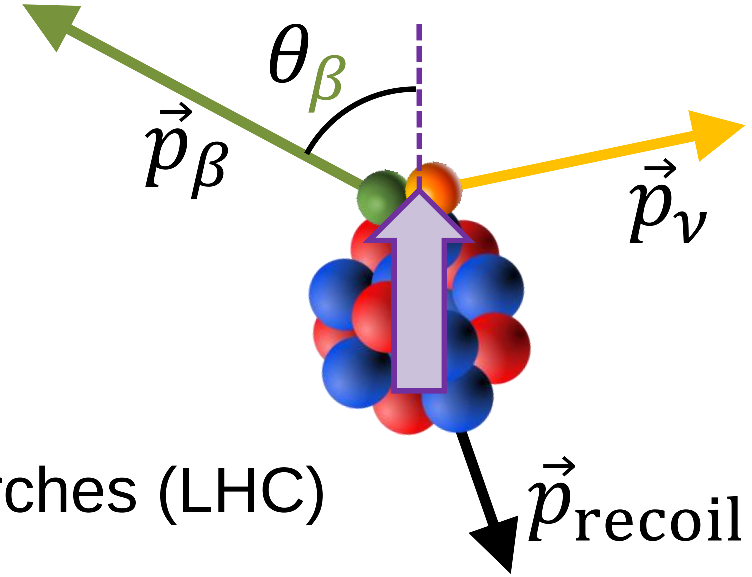
β-decay parameters depend on the form of the weak interaction

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

The precision frontier

- Goal:
  - To complement high-energy experiments by pushing the precision frontier
  - Angular correlations in β decay: values sensitive to new physics

- Global gameplan:
  - Measure the β-decay parameters
  - Compare to SM predictions
  - Look for deviations $\Leftrightarrow$ new physics
  - Precision of $\leq \mathbf{0.1\%}$ needed to complement other searches (LHC)



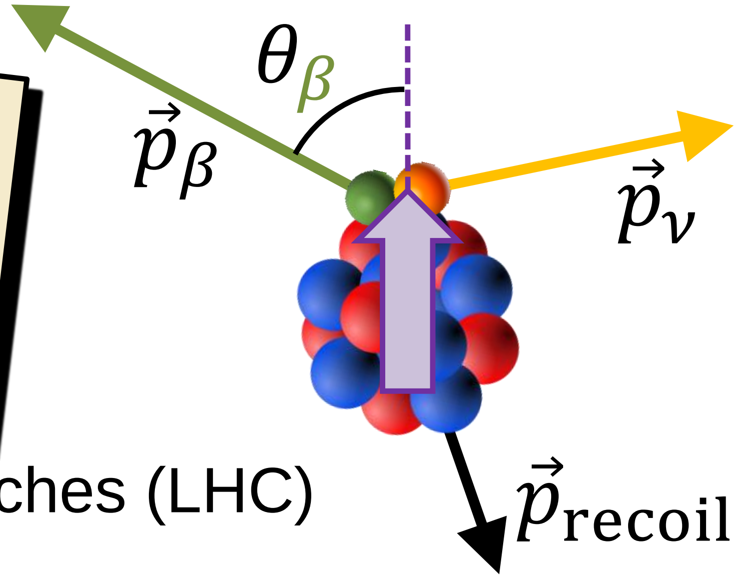
Naviliat-Cuncic and Gonzalez-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, Gonzalez-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić, PRC **94**, 035503 (2016)
González-Alonso, Naviliat-Čunčić and Severijns, arXiv:1803.08732

The precision frontier

- Goal:
  - To complement high-energy experiments by pushing the precision frontier
  - Angular correlations in β decay: values sensitive to new physics

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

- G
  - Compare to SM p
  - Look for deviations $\Leftrightarrow$ new physics
  - Precision of $\leq \mathbf{0.1\%}$ needed to complement other searches (LHC)

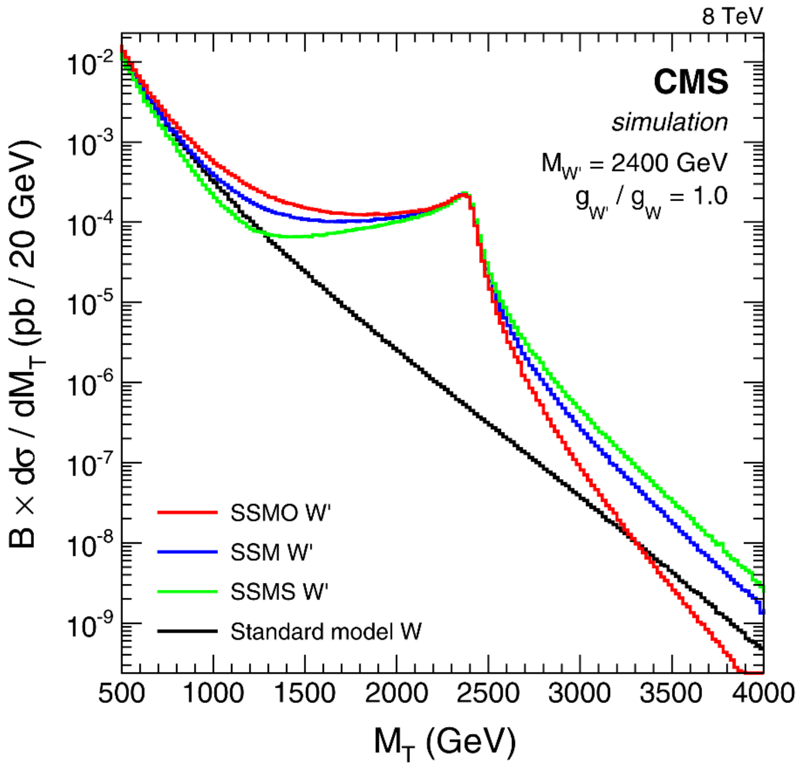


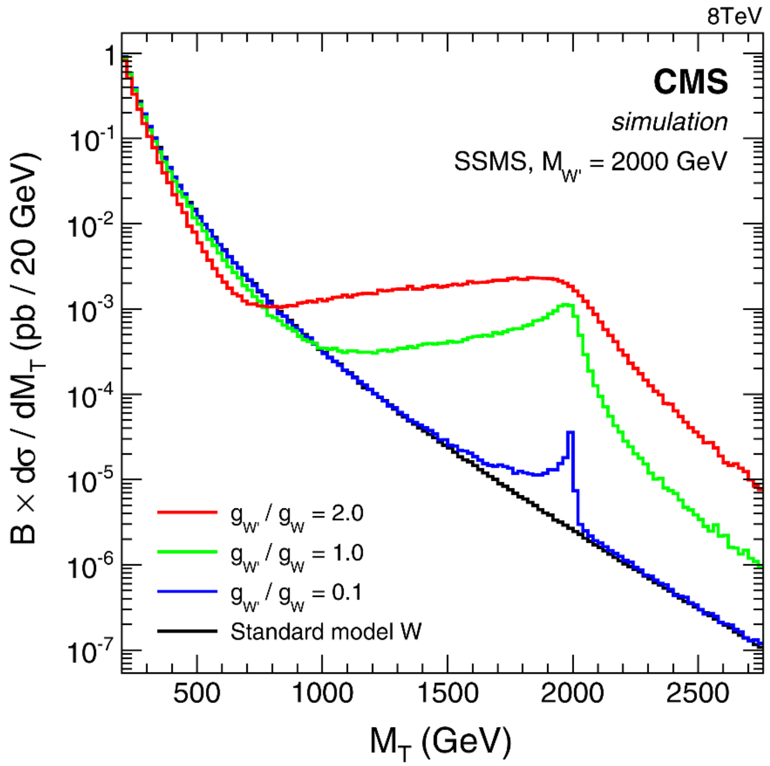
Naviliat-Cuncic and Gonzalez-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, Gonzalez-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić, PRC **94**, 035503 (2016)
González-Alonso, Naviliat-Čunčić and Severijns, arXiv:1803.08732

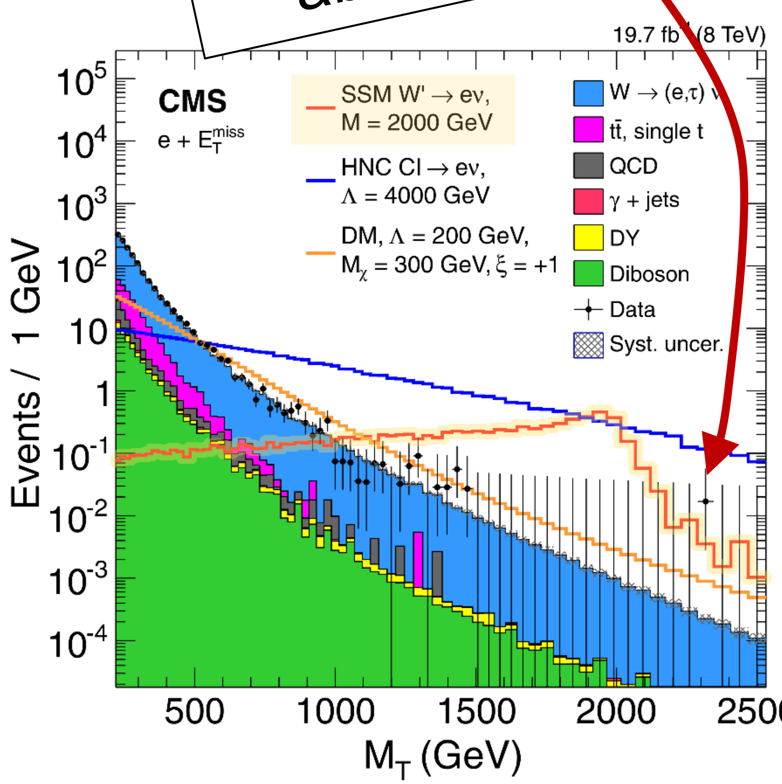
The energy frontier

- CMS collaboration, Phys. Rev. D **91**, 092005 (2015)
  - Look for direct production ⇒ excess of events in the missing transverse energy
  - $\sigma(pp \to e + \mathrm{MET} + X)$ channel with $\int L = 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$
  - No excess observed ⇝ place limits
    (see Gonzalez-Alonzo, arXiv:1803.08732 for EFT interpretation)

Only see one event above 1.5 TeV

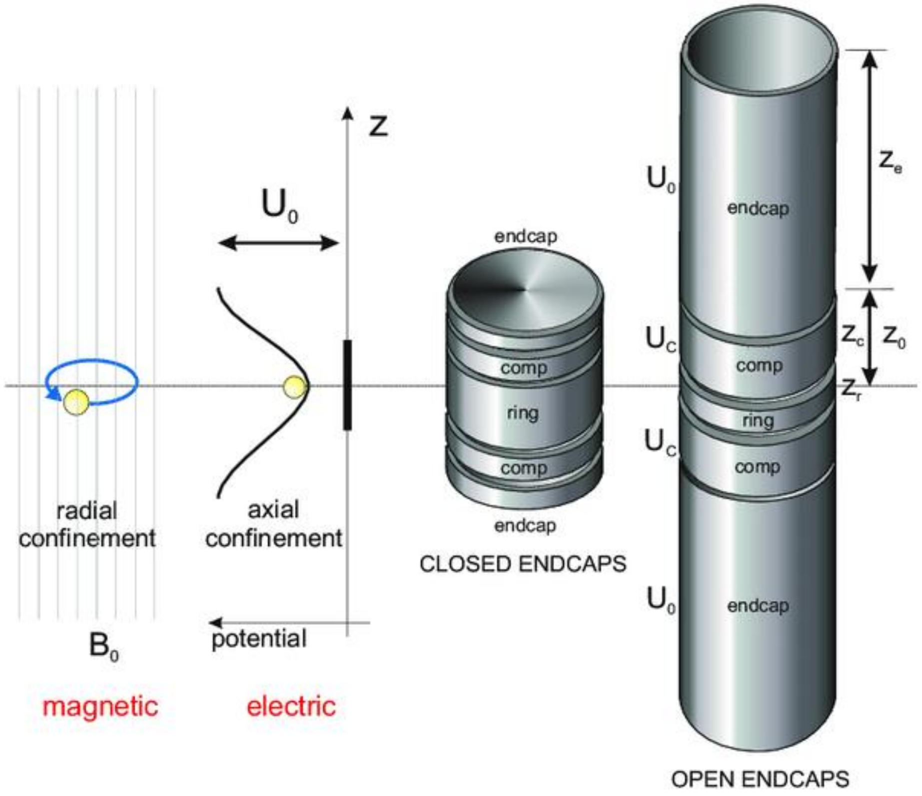






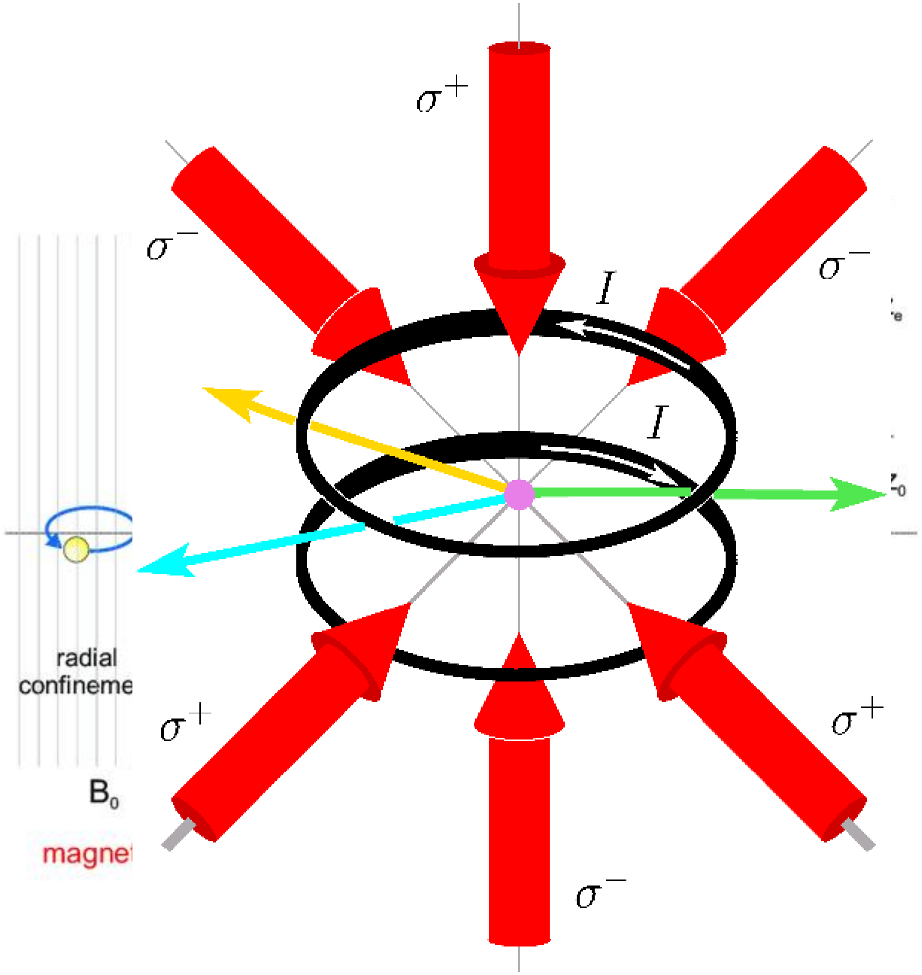
0.1% is a tall order…how to reach that precision?

- Ion traps
  - Well-known for mass measurements (ISOLTRAP, JYFLTRAP, LEBIT, TITAN,…)
  - Beta-Decay Paul Trap @ ANL
    - β-ν correlation of ^{8}Li to 1%; poised to reach 0.1% precision
  - No other correlation experiments completed yet, but a number are planned:
    - TAMUTRAP @ Texas A&M (^{32}Ar; ^{20}Mg, ^{24}Si, ^{28}S, ^{36}Ca, ^{40}Ti)
    - LPCTrap @ GANIL (^{6}He)
    - EIBT @ Weizmann Institute → SARAF (^{6}He to start)
    - NSLTrap @ Notre Dame (^{11}C, ^{13}N, ^{15}O, ^{17}F)



0.1% is a tall order…how to reach that precision?

- Ion traps
  - Well-known for mass measurements (ISOLTRAP, JYFLTRAP, LEBIT, TITAN,…)
  - Beta-Decay Paul Trap @ ANL
    - β-ν correlation of ^{8}Li to 1%; poised to reach 0.1% precision
  - No other correlation experiments completed yet, but a number are planned:
    - TAMUTRAP @ Texas A&M (^{32}Ar; ^{20}Mg, ^{24}Si, ^{28}S, ^{36}Ca, ^{40}Ti)
    - LPCTrap @ GANIL (^{6}He)
    - EIBT @ Weizmann Institute → SARAF (^{6}He to start)
    - NSLTrap @ Notre Dame (^{11}C, ^{13}N, ^{15}O, ^{17}F)
- Magneto-optical traps
  - Atoms are cold and confined to a small volume
  - Isomerically selective; low backgrounds
  - Very shallow trap, minimal volumes to scatter off



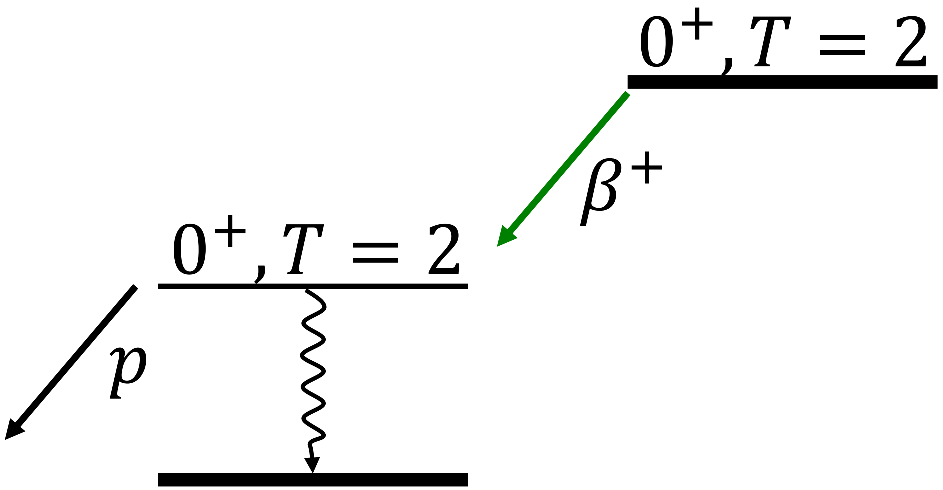
Outline

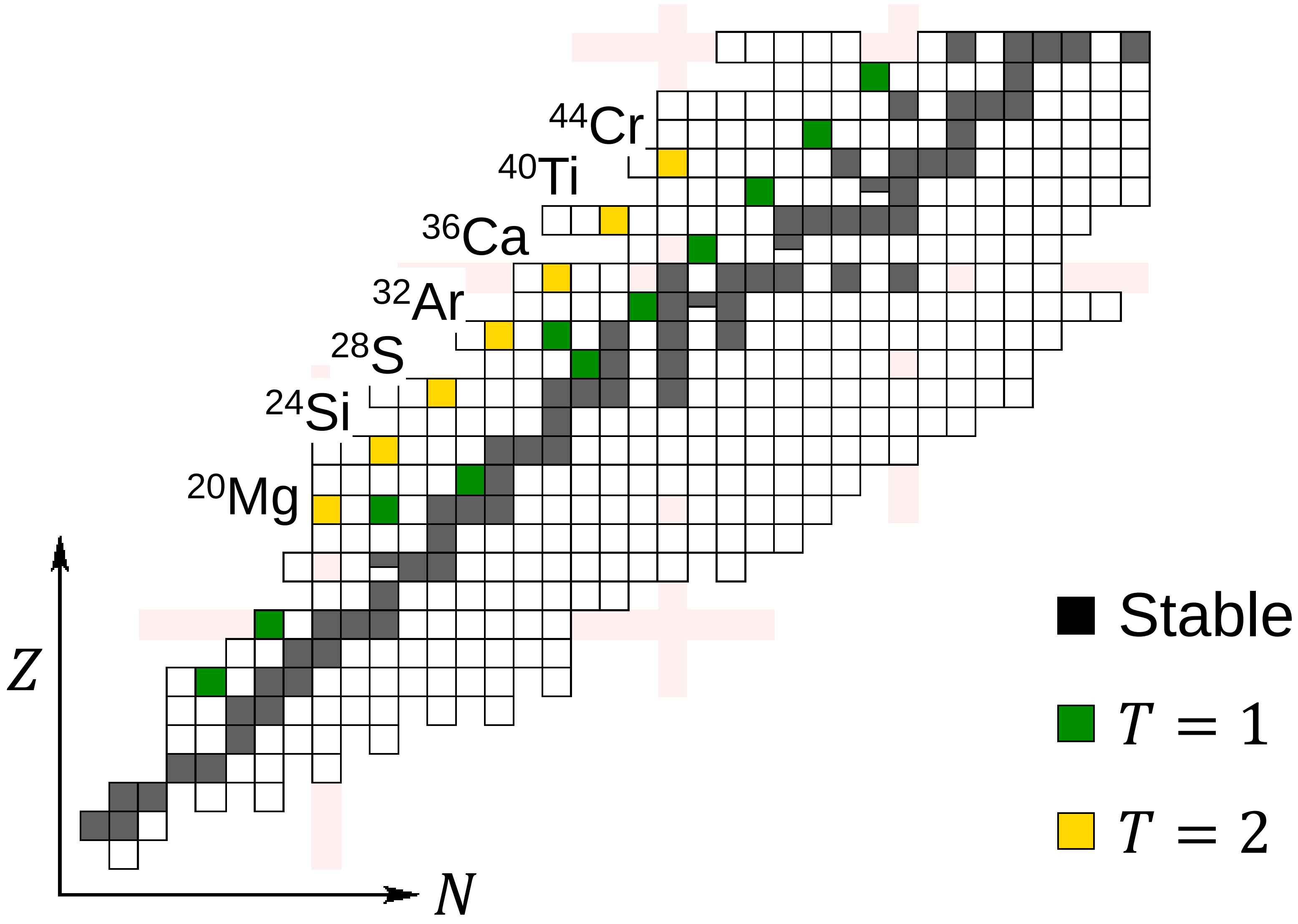
- Introduction
  - Testing the standard model via the precision frontier
  - Angular correlations of β decay
- TAMUTRAP
  - Trapping ions at the Cyclotron Institute
  - Commissioning with mass measurement of ^{23}Na
- ^{37}K at TRIUMF
  - The TRINAT facility
  - Polarizing the cloud
  - Recent measurement of A_β
- Future work

$T = 2$ Superallowed Decays

$$dW \sim 1 + a_{\beta\nu}\left(\frac{v_\beta}{c}\right)\cos\theta_{\beta\nu}$$

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

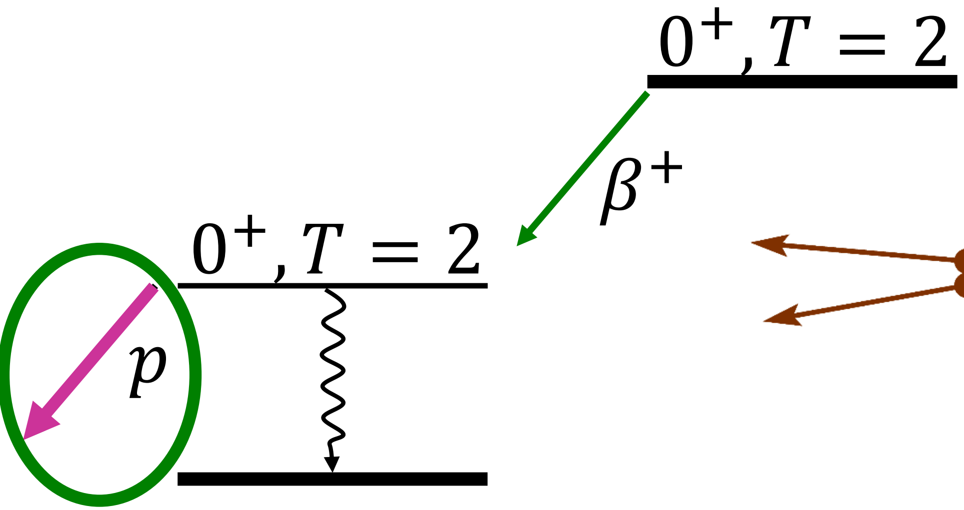


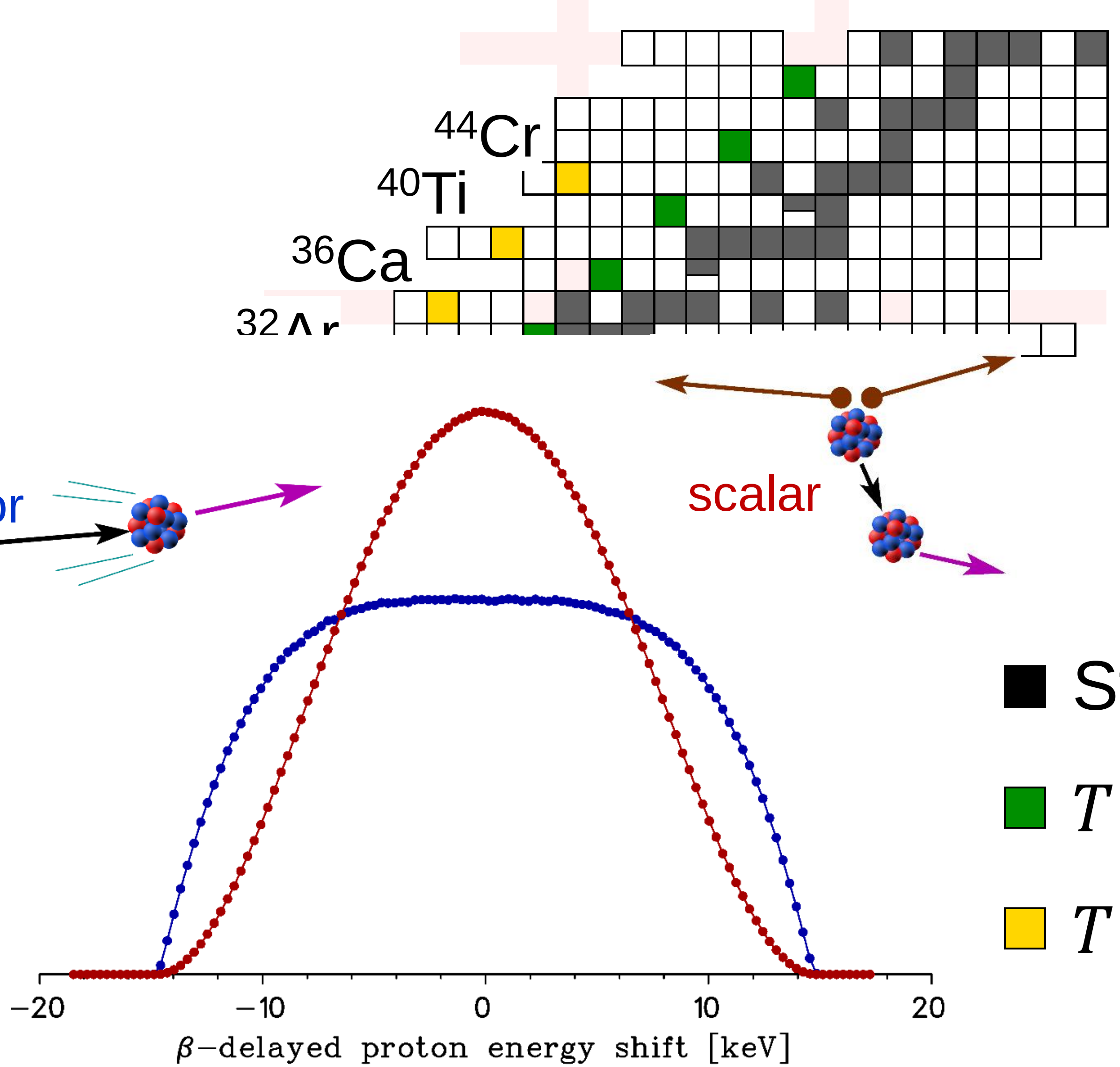


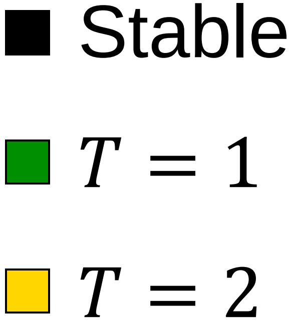
$T = 2$ Superallowed Decays

$$dW \sim 1 + a_{\beta\nu}\left(\frac{v_\beta}{c}\right)\cos\theta_{\beta\nu}$$

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



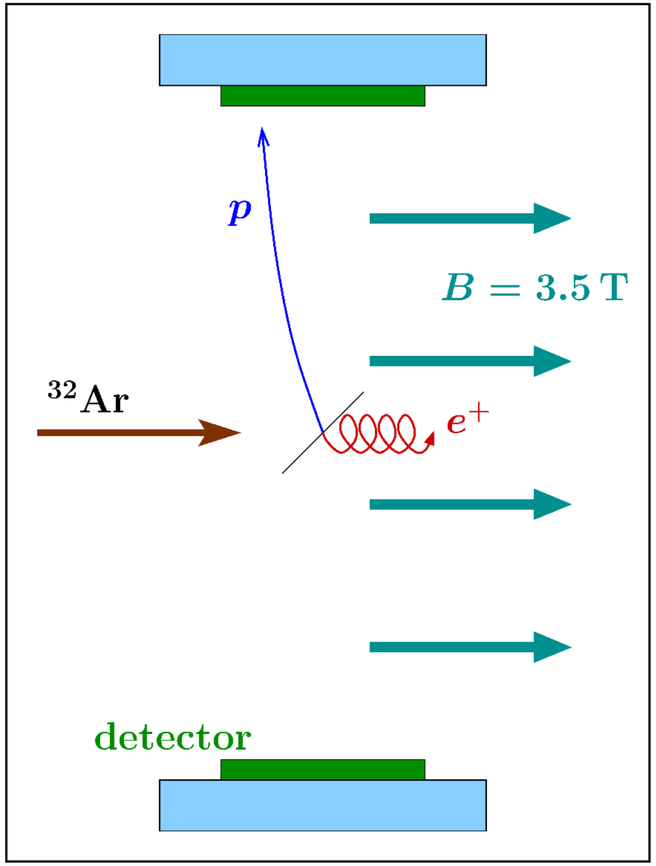




Doppler shape of delayed proton depends on $\cos\theta_{\beta,\nu}$!

$a_{\beta\nu}$ of $T = 2$ superallowed decays

- Demonstrated once in ^{32}Ar: $\Delta a_{\beta\nu} = 0.65\%$
- Increased sensitivity if the β is observed in coincidence
- Aim for $\leq 0.1\%$ precision utilizing Penning traps



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*

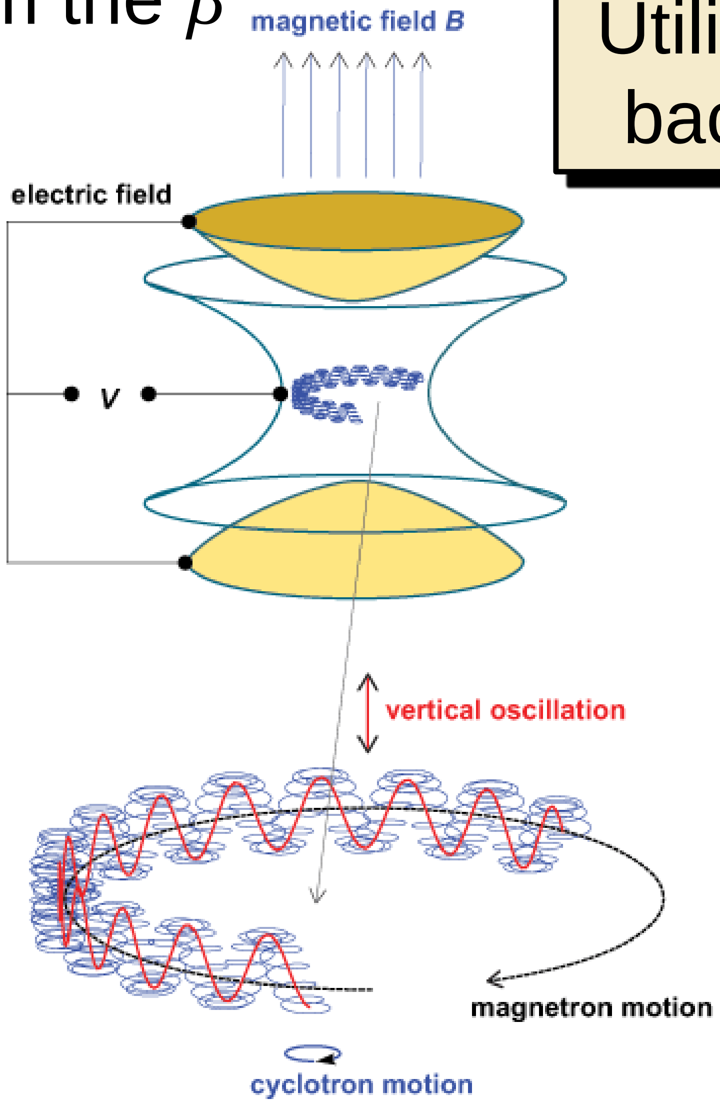
(Received 24 February 1999)

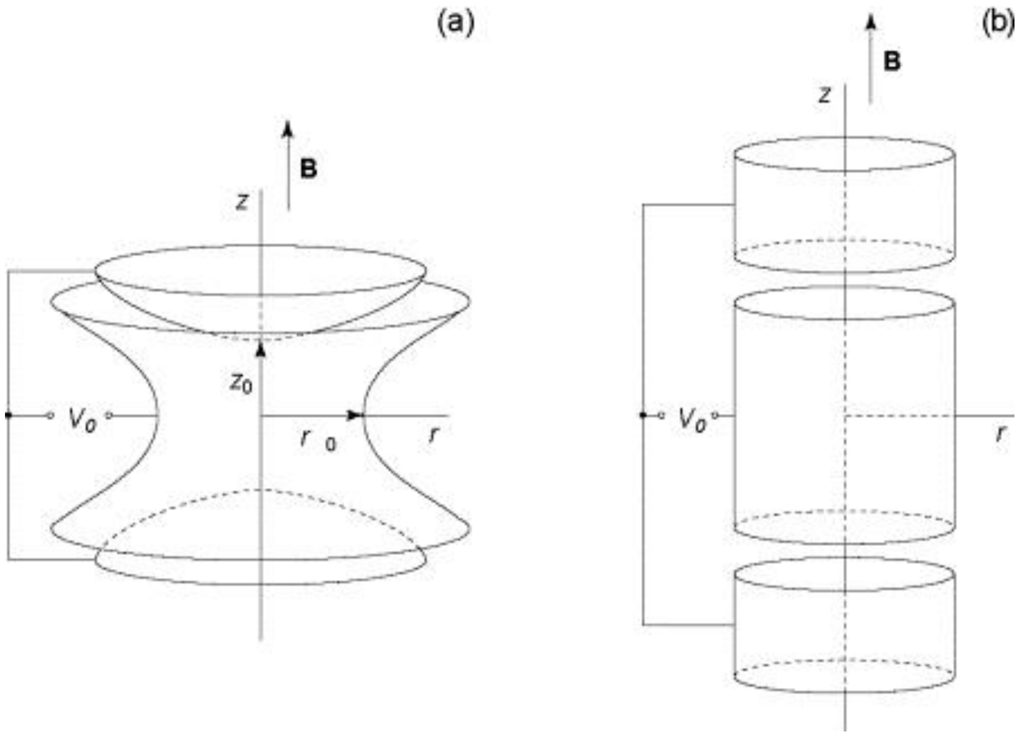
The positron-neutrino correlation in the $0^+ \rightarrow 0^+$ β decay of ^{32}Ar was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the standard model prediction. For vanishing Fierz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

But why throw away useful information?

- We can gain sensitivity and reduce backgrounds by using information from the β

Utilize the technology of Penning traps to provide a backing-free source of localized radioactive ions!!

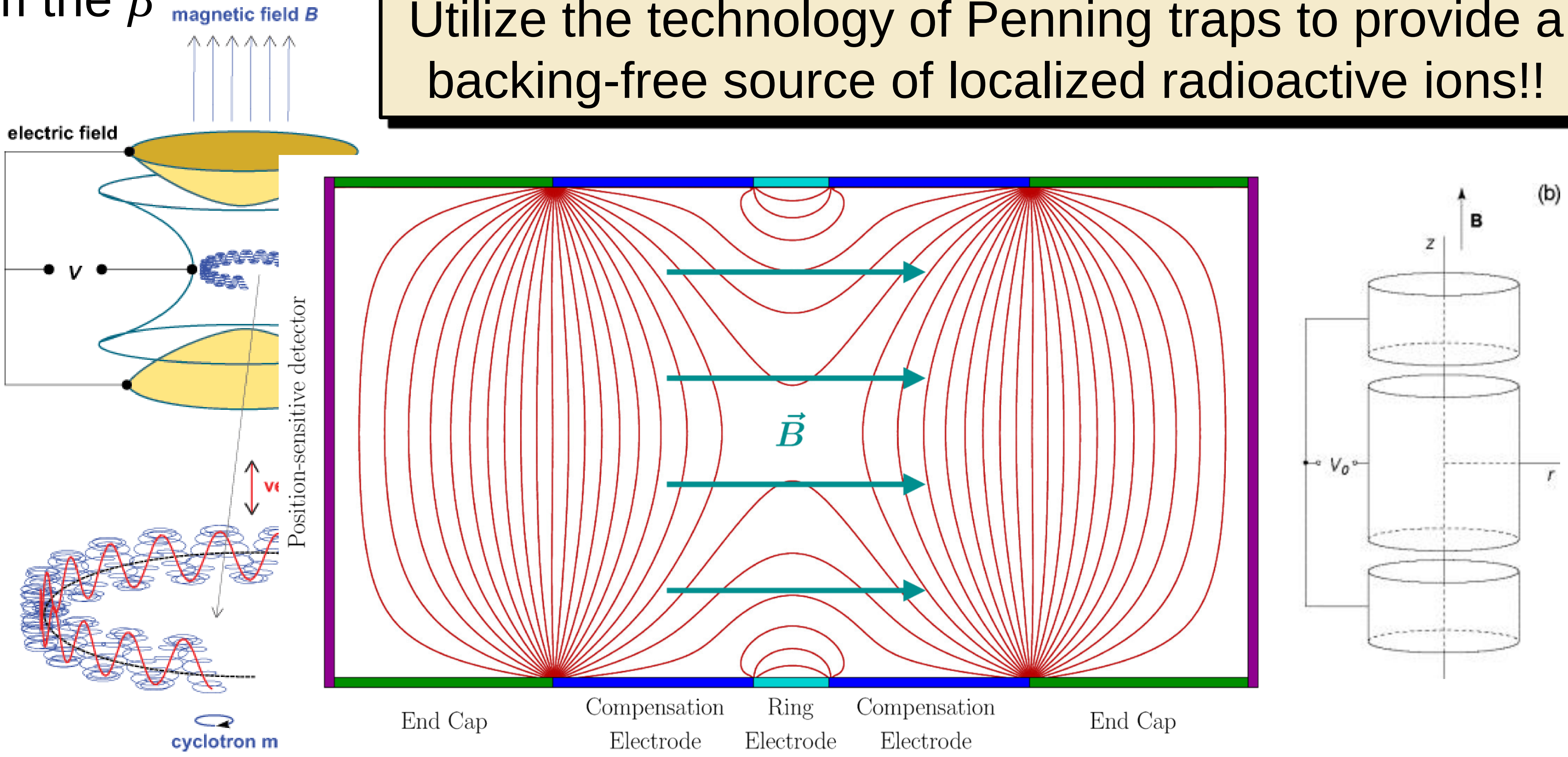




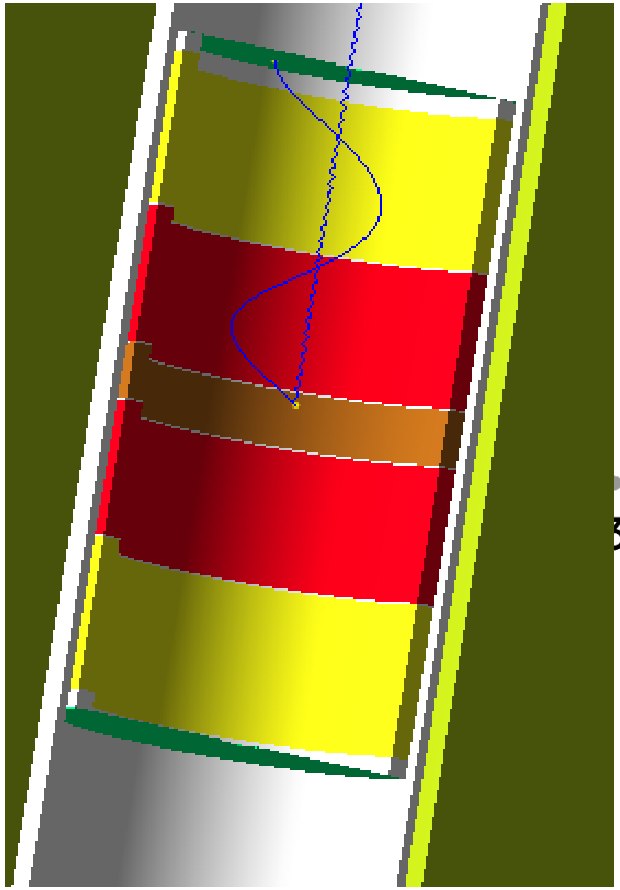
But why throw away useful information?

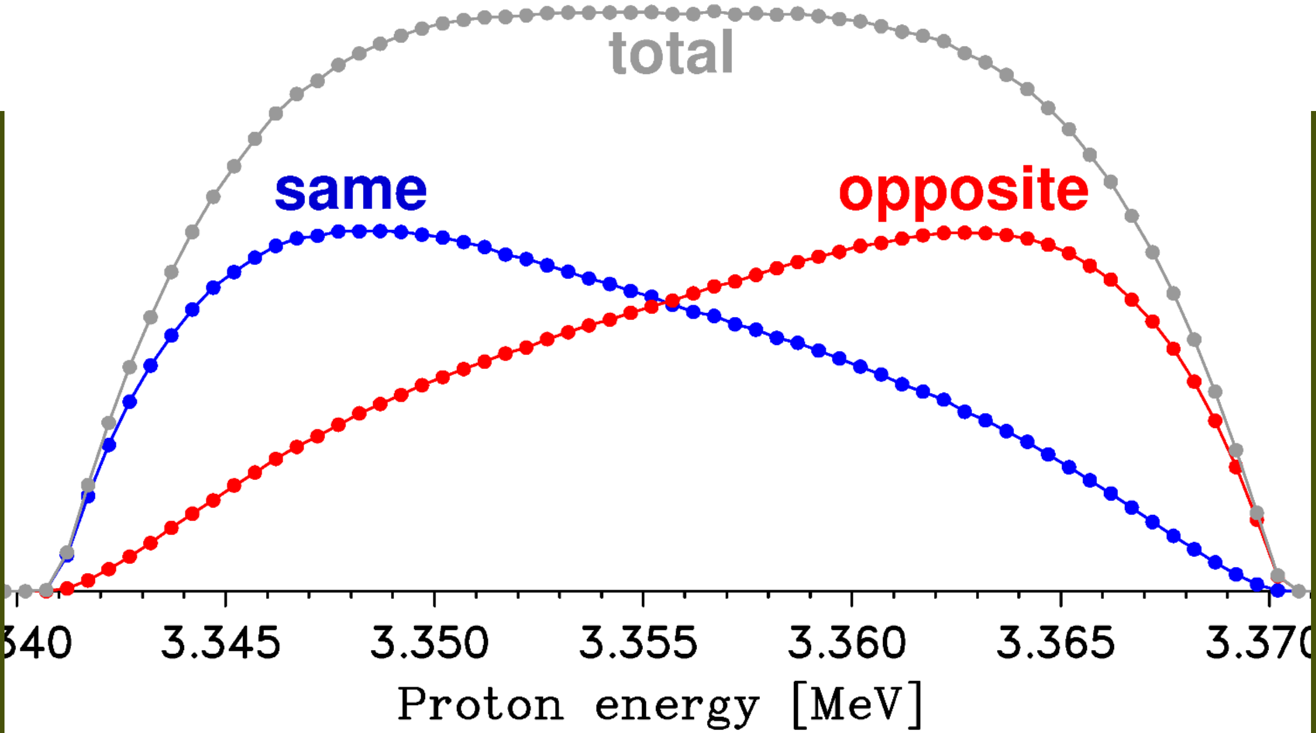
- We can gain sensitivity and reduce backgrounds by using information from the β

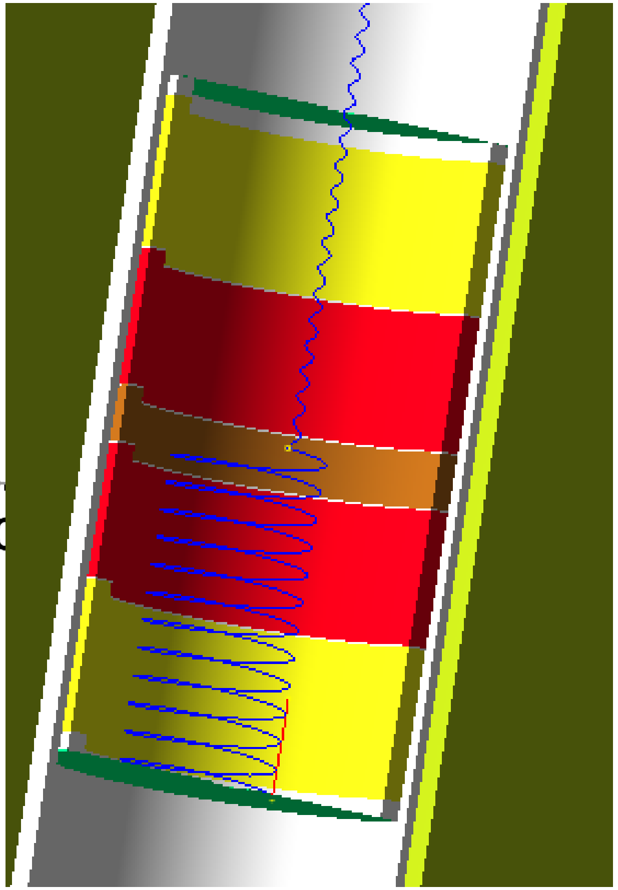
Utilize the technology of Penning traps to provide a backing-free source of localized radioactive ions!!

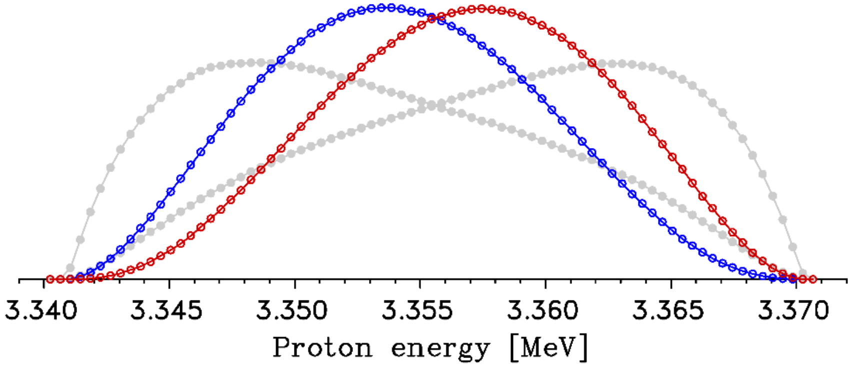


Measure means instead of 2nd moments







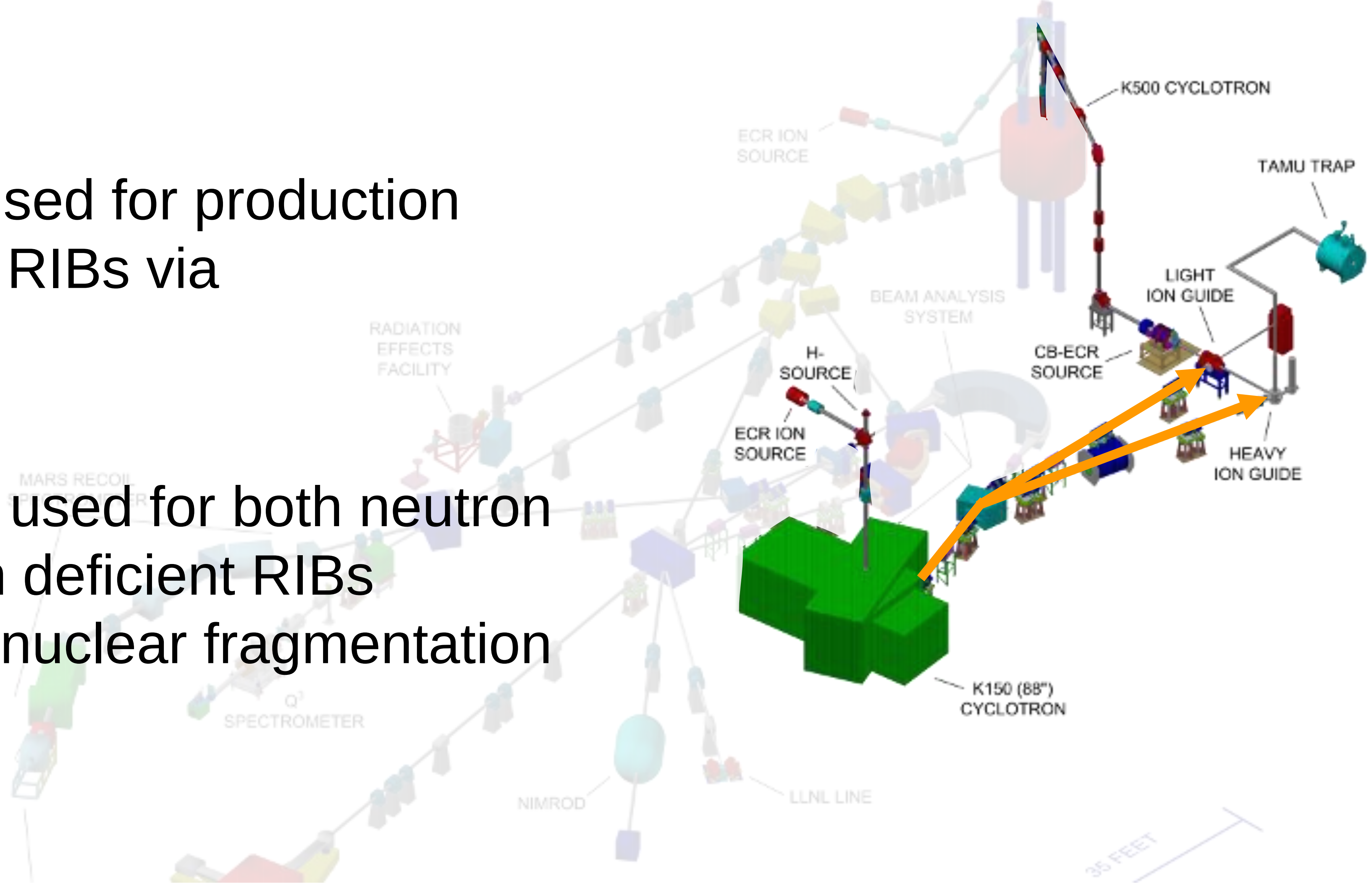


The T-REX Upgrade Project

- Re-commission the K150 for high intensity beams and/or to re-accelerate RIBs in the K500

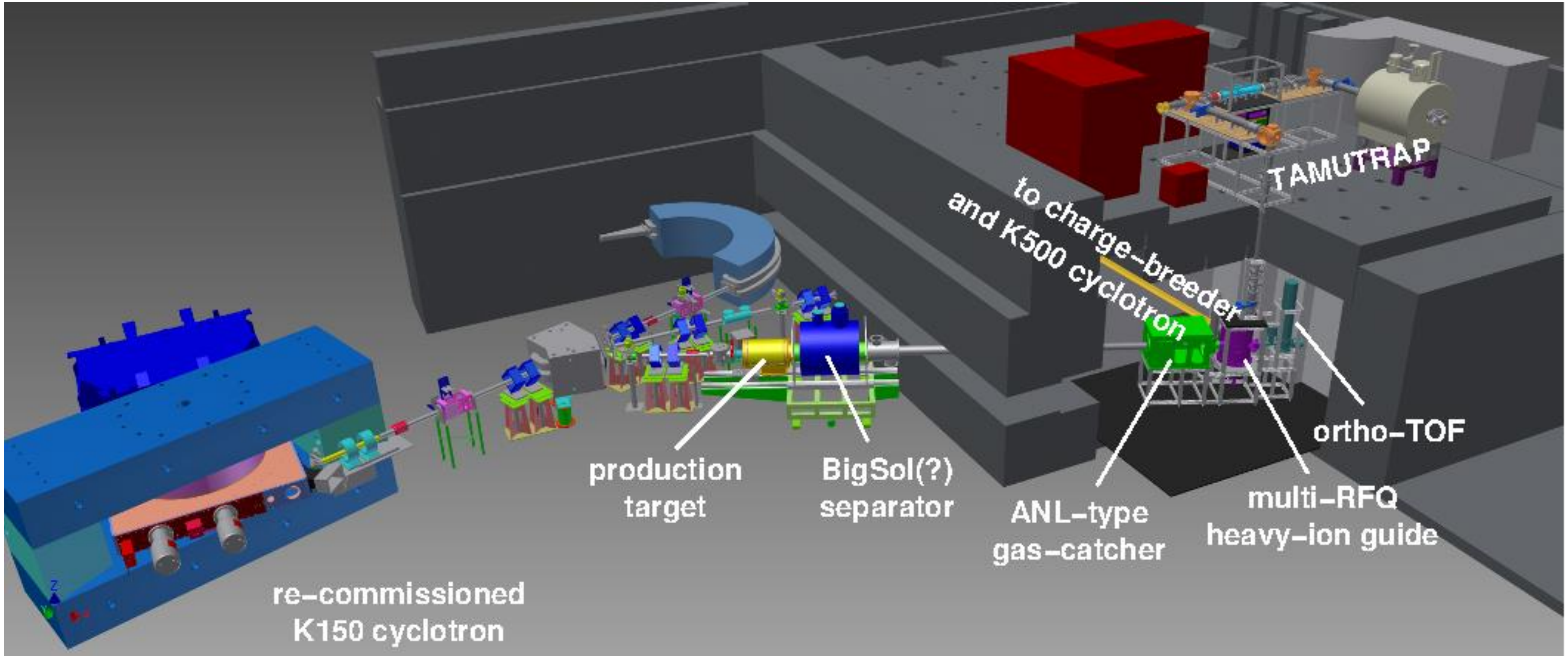
- Light Ion Guide – used for production of neutron deficient RIBs via $A(p,xn)B$ reactions

- Heavy Ion Guide – used for both neutron deficient and proton deficient RIBs (deep inelastic and nuclear fragmentation reactions)



The original plan

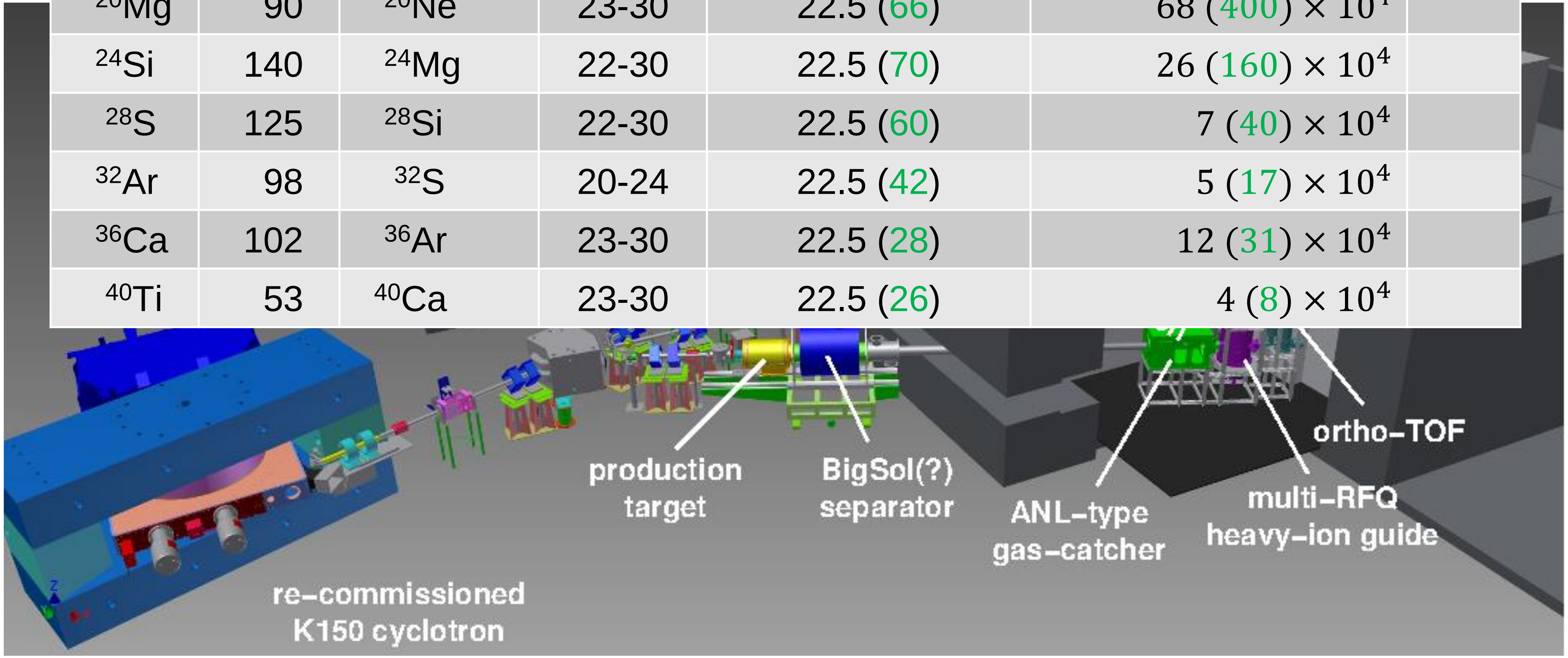
- Use the heavy ion guide to produce the proton-rich nuclei



The original plan

- Use the heavy ion guide to produce the proton-rich nuclei
  - ^{3}He target, 10% overall efficiency, assuming K150 specs from White Paper

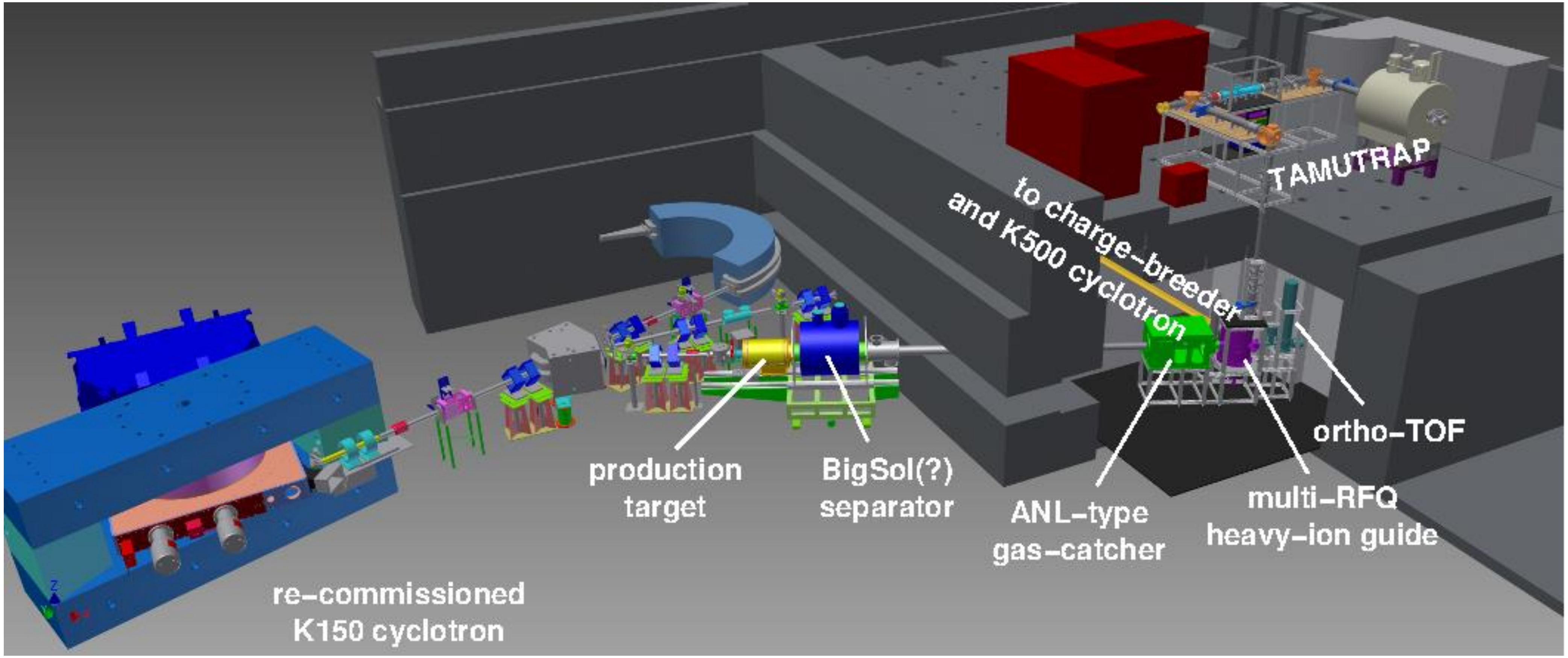
RIB	$t_{1/2}$ [ms]	Projectile	Energy [MeV/u]	Target thickness [mg/cm^2]	Expected rate @ target chamber [pps]
^{20}Mg	90	^{20}Ne	23-30	22.5 (66)	$68\ (400) \times 10^4$
^{24}Si	140	^{24}Mg	22-30	22.5 (70)	$26\ (160) \times 10^4$
^{28}S	125	^{28}Si	22-30	22.5 (60)	$7\ (40) \times 10^4$
^{32}Ar	98	^{32}S	20-24	22.5 (42)	$5\ (17) \times 10^4$
^{36}Ca	102	^{36}Ar	23-30	22.5 (28)	$12\ (31) \times 10^4$
^{40}Ti	53	^{40}Ca	23-30	22.5 (26)	$4\ (8) \times 10^4$



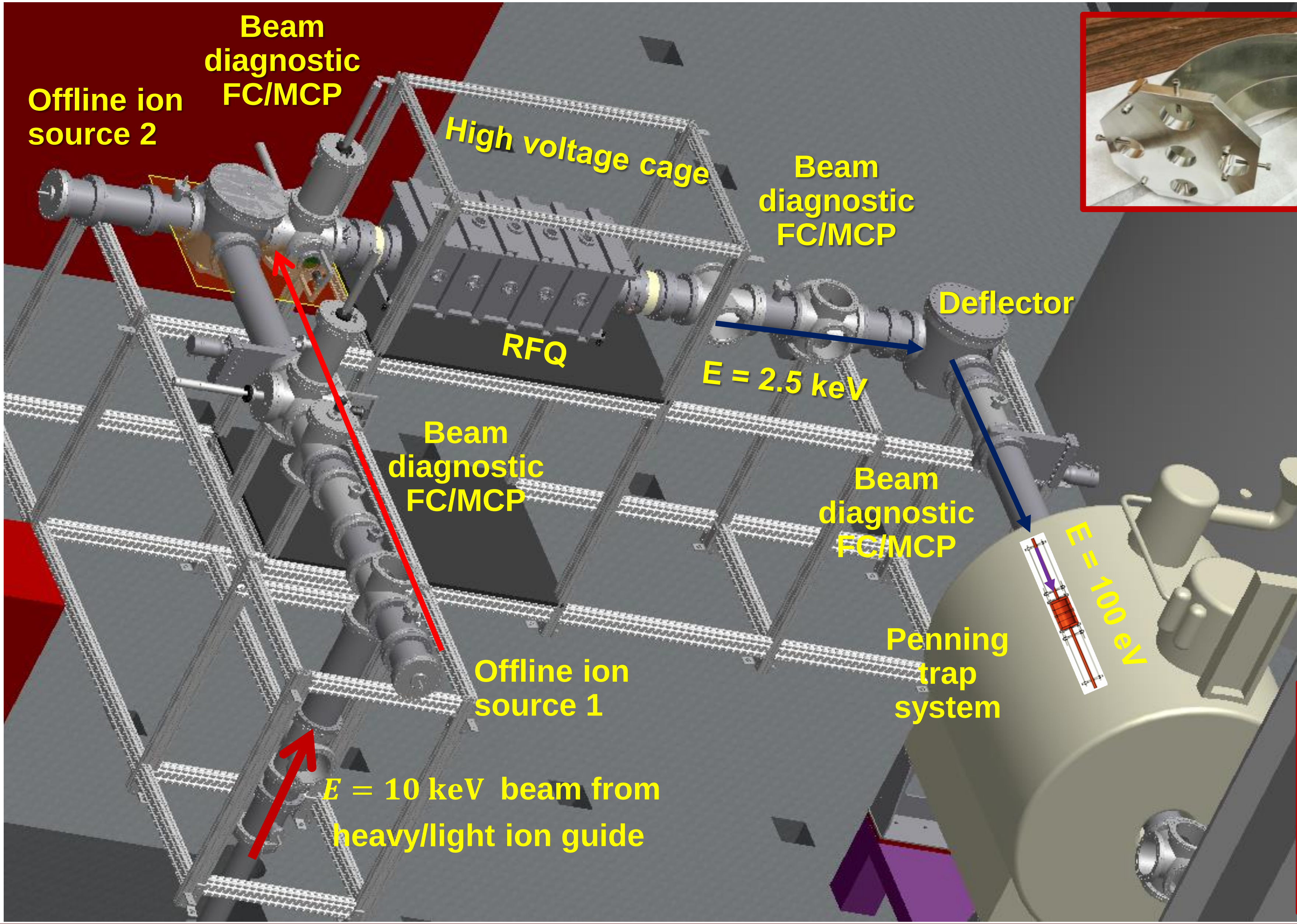
Issues with original plan

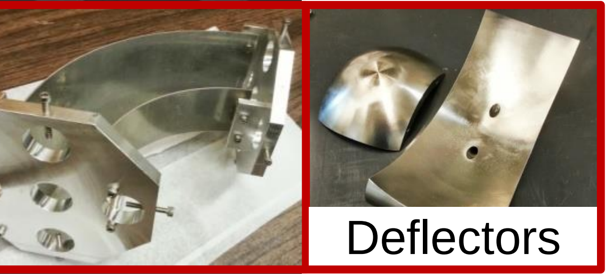
- Ion source not performing to specs
- K150 not able to go to full energy
- No separator, no one working on it

"*You can expect one ion every 9 or 10 seconds*"

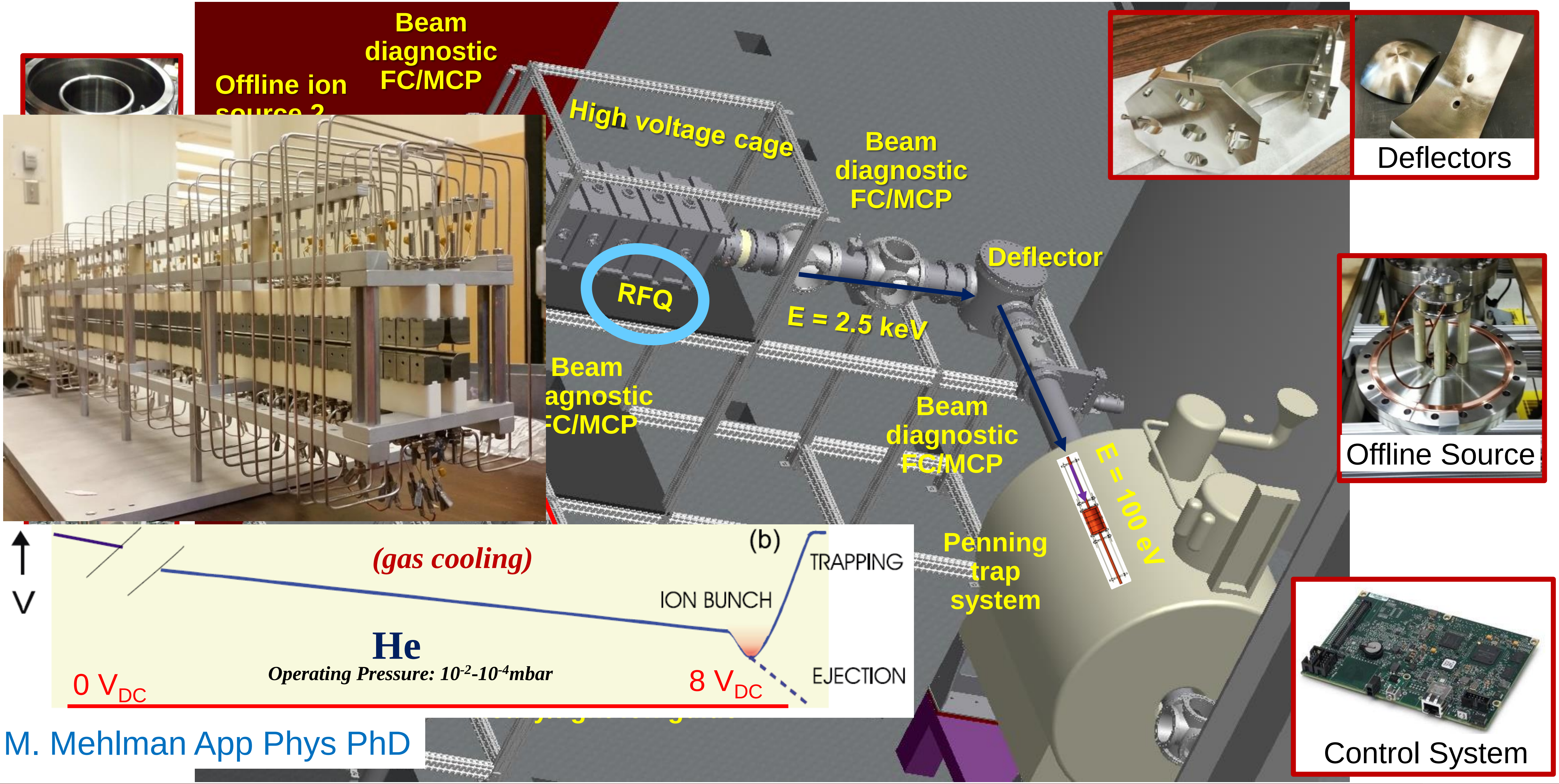


In the meantime, we haven't been picking our noses…





In the meantime, we haven't been picking our noses…

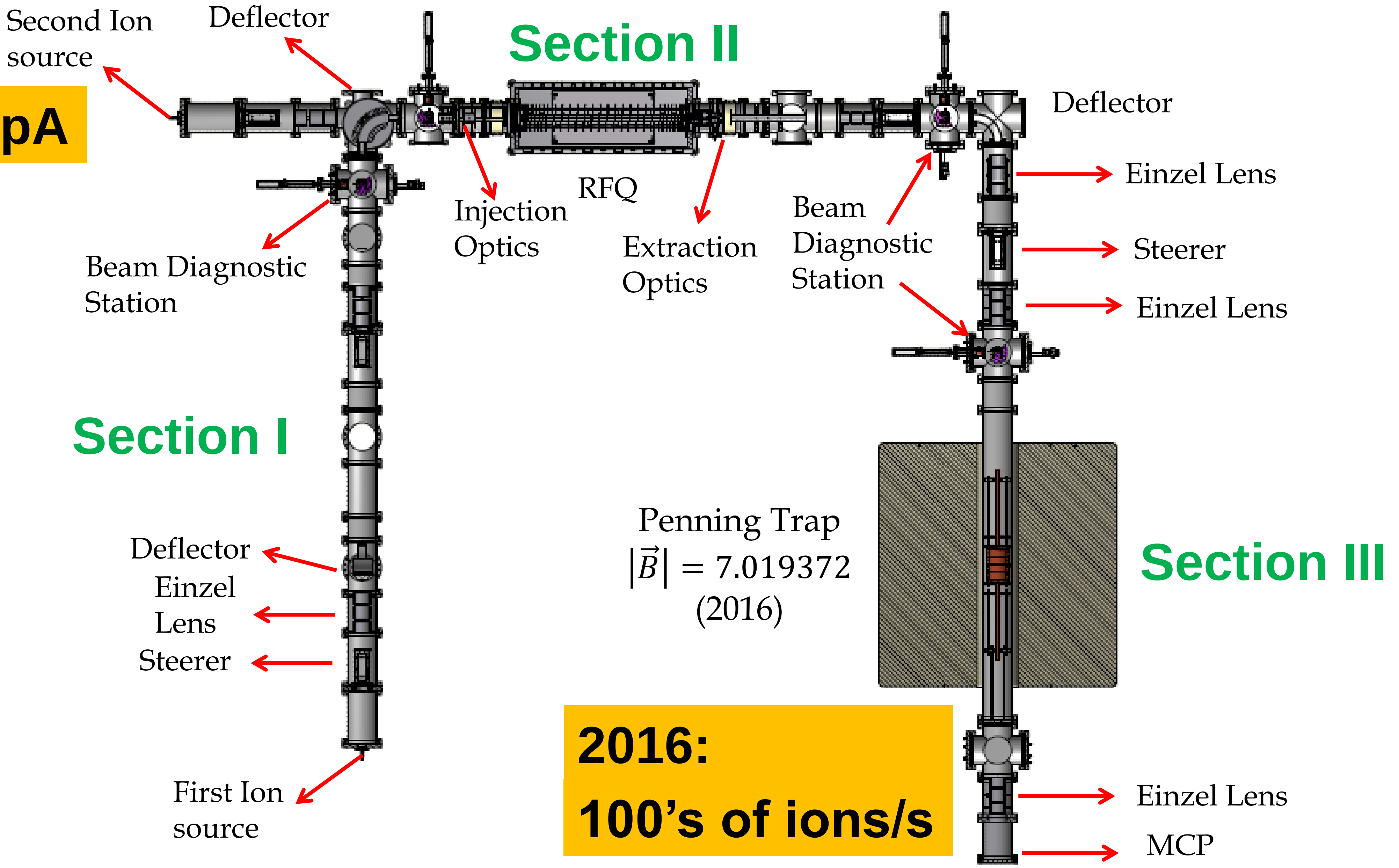


Deflectors
Offline Source
Control System

M. Mehlman App Phys PhD

Optimizing the TAMUTRAP beamlines

2016: 120 pA



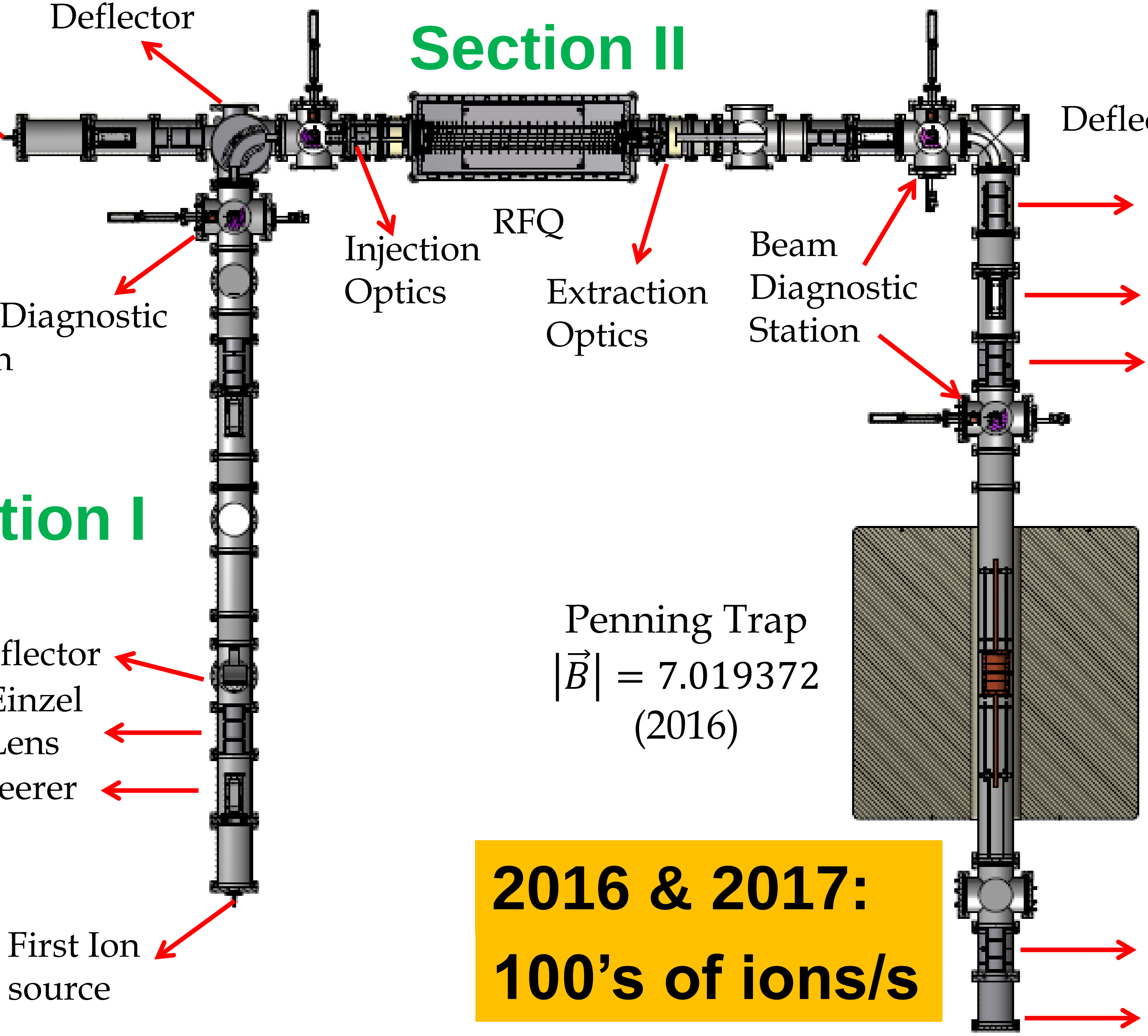
2016:

100's of ions/s

Optimizing the TAMUTRAP beamlines

2016: 120 pA

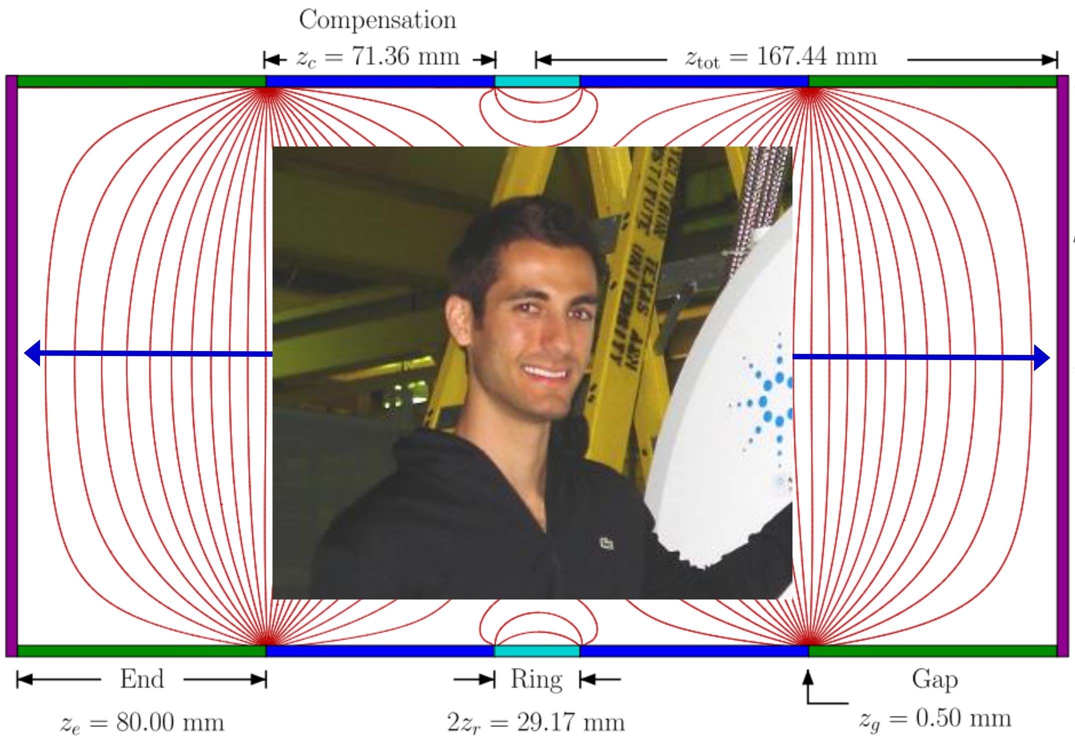
2017: <1 pA



2016 & 2017: 100’s of ions/s

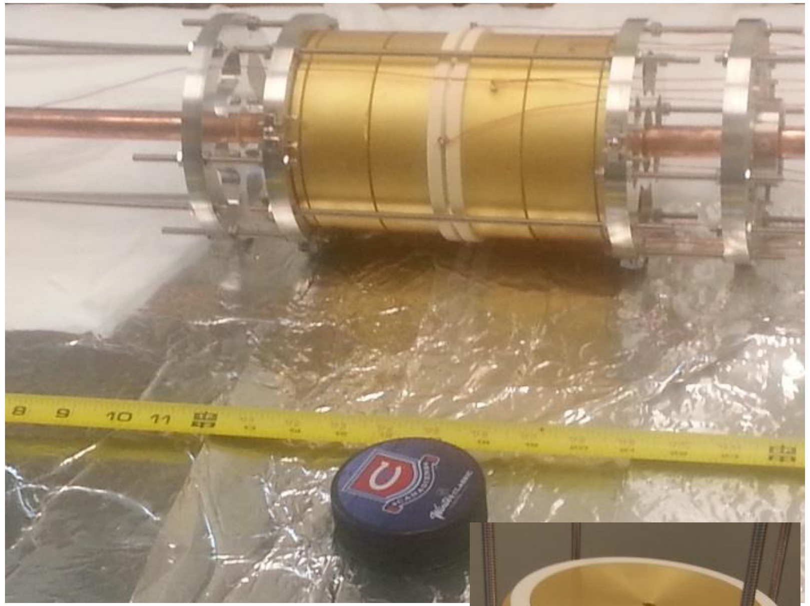
Prototype Penning trap commissioned (2016)

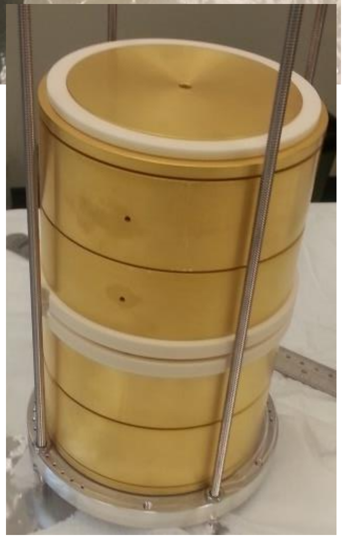
- Most cylindrical Penning traps have a length-to-radius ratio of $l/r = 11.75$
- To confine the protons from $T = 2$ decays, need $r = 90\text{ mm}$
  - Needed a new design to make it fit in the 7T magnet



M. Mehlman *et al*., NIMA **712** (2013) 9

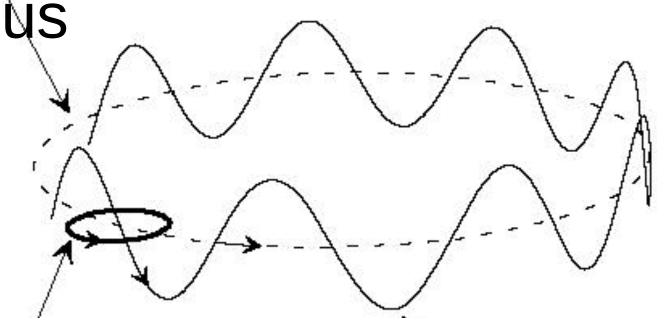
$l/r = 3.72$

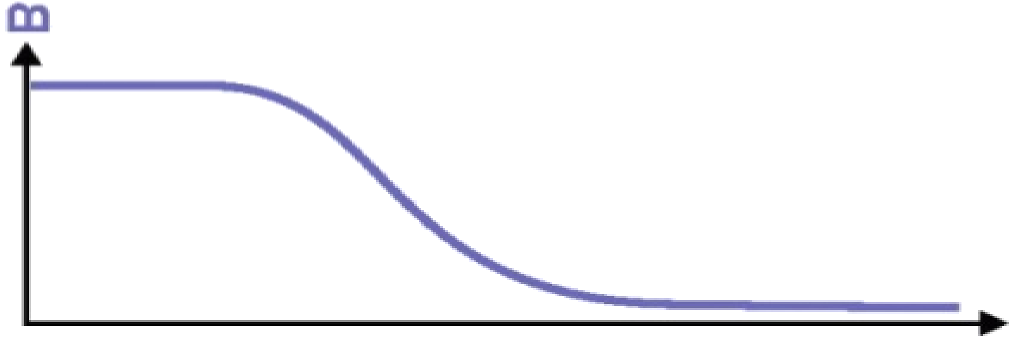




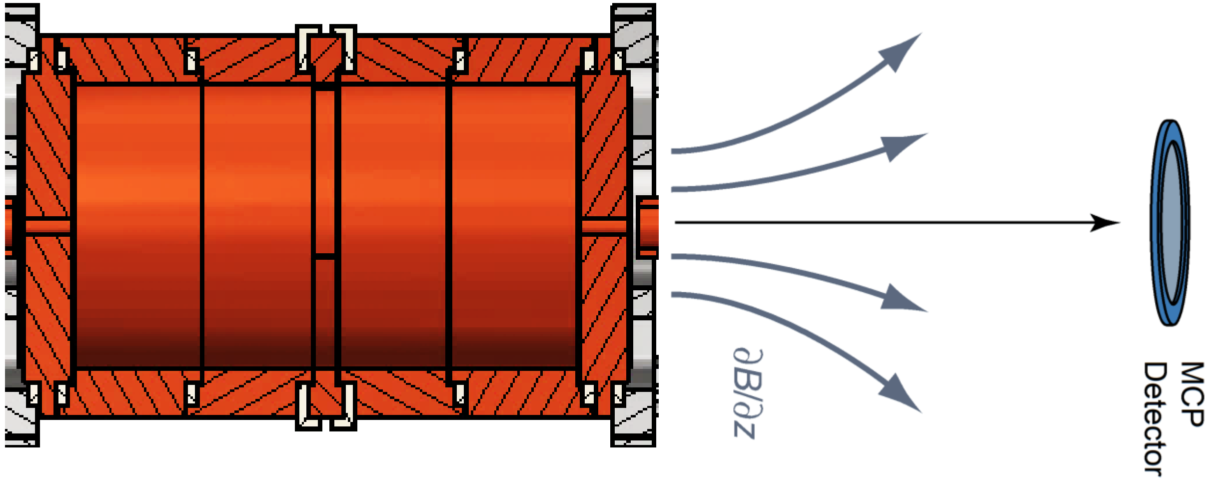
As we wait for RIB, learn to measure masses

- Time-of-flight cyclotron resonance technique
  - Dipole radial excitation at f_- $\Rightarrow$ increase magnetron radius
  - Quadrupole excitation near f_c $\Rightarrow$ increase radial energy
  - Eject along field $\Rightarrow$ radial energy converted to axial





$$f_- + f_+ = f_c \text{ where } f_c = \frac{1}{2}\cdot\frac{q}{m}\cdot B$$



When rf frequency is in resonance, ions will end up with more axial energy and hence a shorter TOF

Mass measurement of ^{23}Na

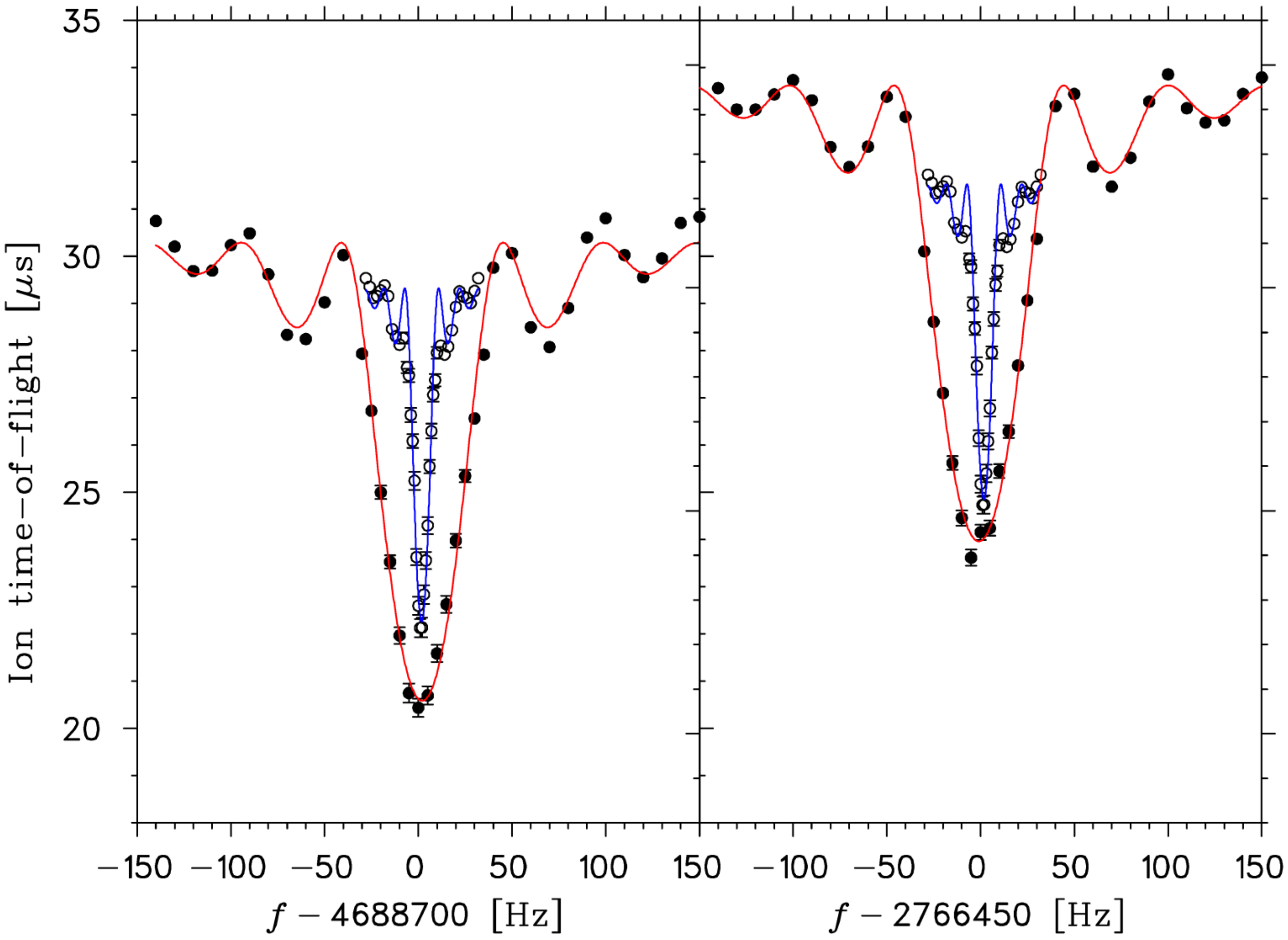
- Find resonant frequencies for ^{23}Na and reference ^{39}K
- Use AME value for ^{39}K, and calculate $M(^{23}\mathrm{Na})$
- 20 ms excitation (solid points, red curve)

  $\Rightarrow M_{\mathrm{diff}} = \text{calc} - \mathrm{AME}$
  $= 2.8 \pm 2.5\ \mathrm{keV}$

  a 0.13 ppm measurement
- 100 ms (open points, blue)

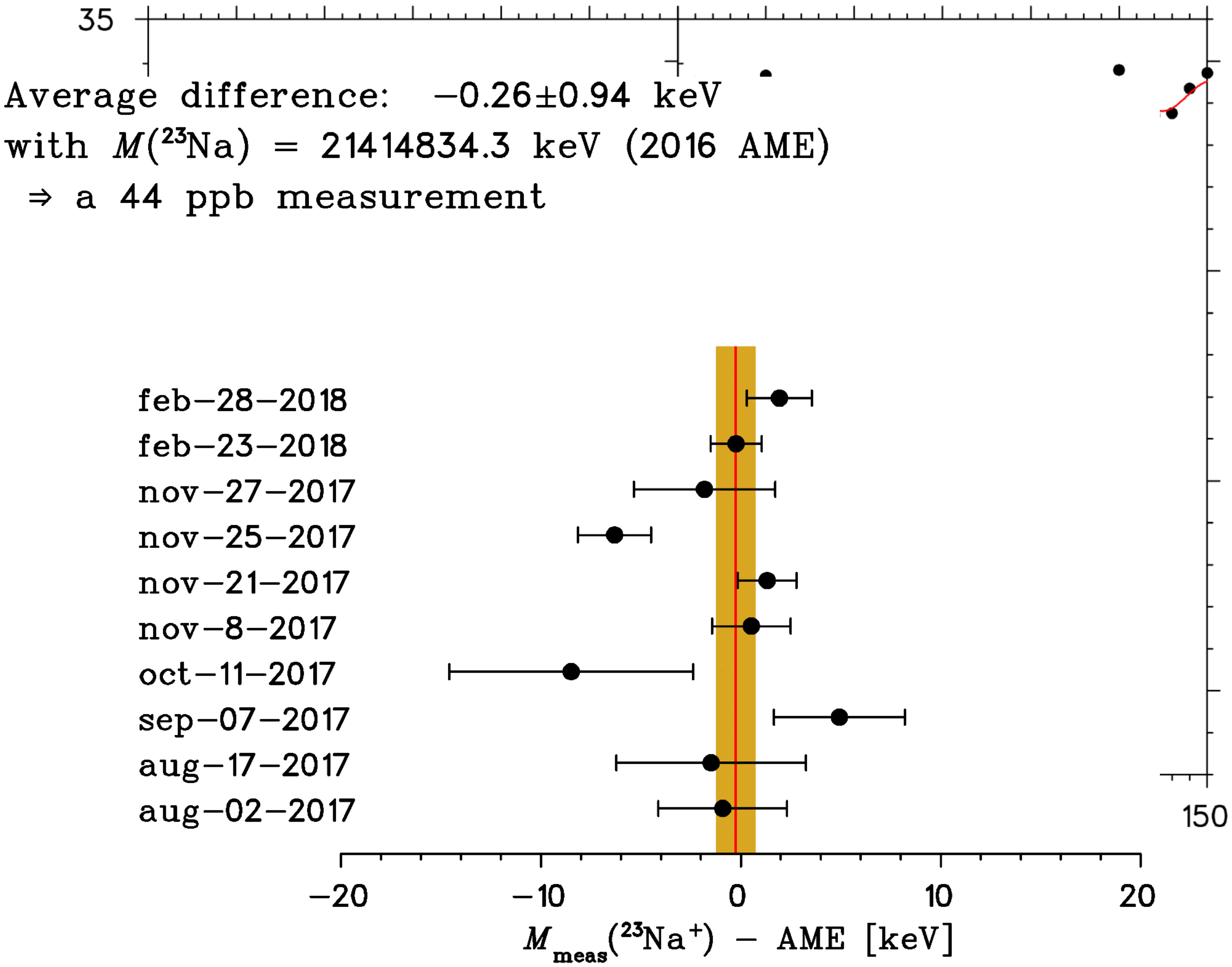
  $\Rightarrow M_{\mathrm{diff}} = -0.3 \pm 1.3\ \mathrm{keV}$

  a 0.06 ppm measurement



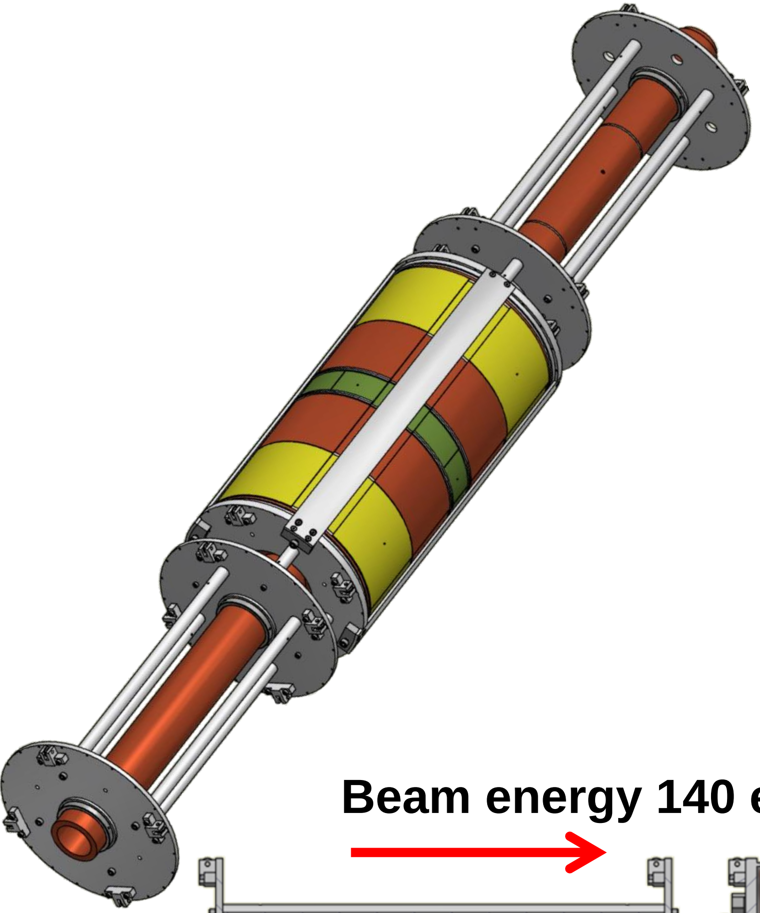
Mass measurement of ^{23}Na

- Find resonant frequencies for ^{23}Na and reference ^{39}K
- Use AME value for ^{39}K, and calculate $M(^{23}\mathrm{Na})$
- 20 ms excitation (solid points, red curve)
  $\Rightarrow M_{\mathrm{diff}} = \text{calc}-\mathrm{AME}$
  $= 2.8 \pm 2.5\ \mathrm{keV}$
  a 0.13 ppm measurement
- 100 ms (open points, blue)
  $\Rightarrow M_{\mathrm{diff}} = -0.3 \pm 1.3\ \mathrm{keV}$
  a 0.06 ppm measurement

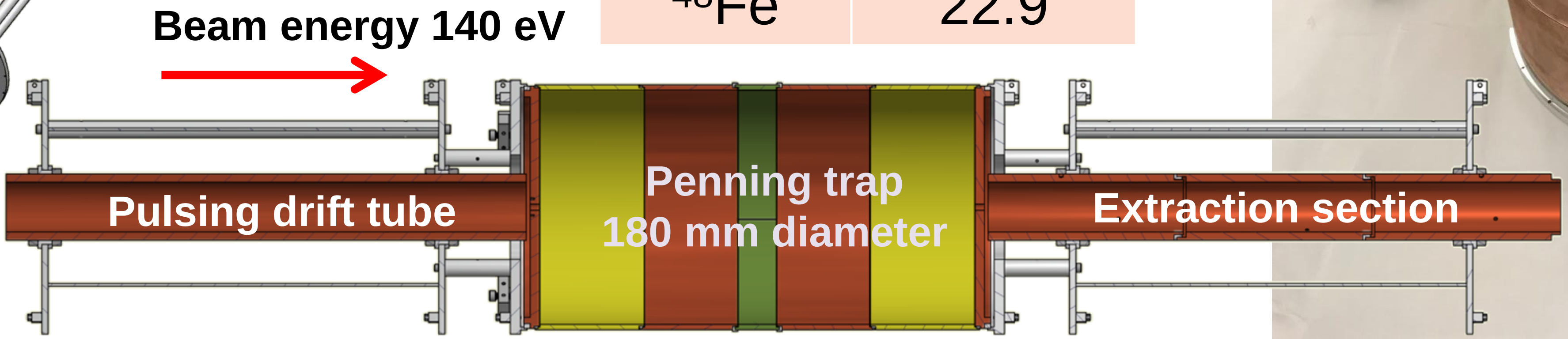


About to install the full-sized Penning trap!

- 180 mm in diameter



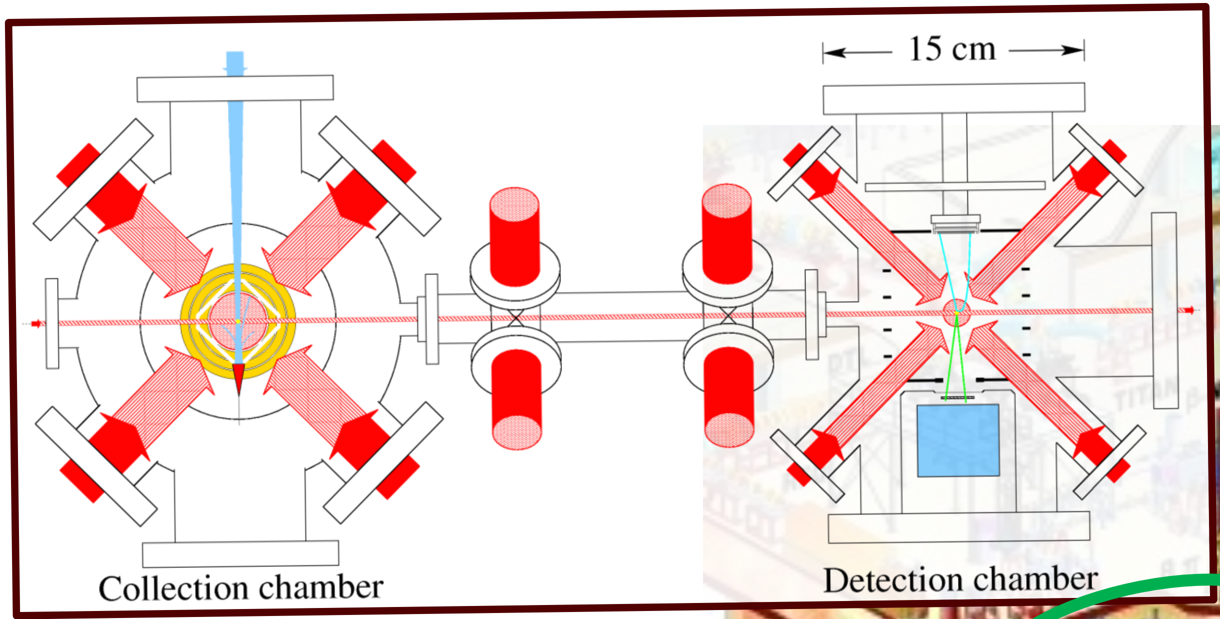
Nuclide	Larmour radius (mm)
^{20}Mg	42.7
^{24}Si	40.8
^{28}S	39.7
^{32}Ar	37.8
^{36}Ca	33.0
^{40}Ti	39.9
^{48}Fe	22.9

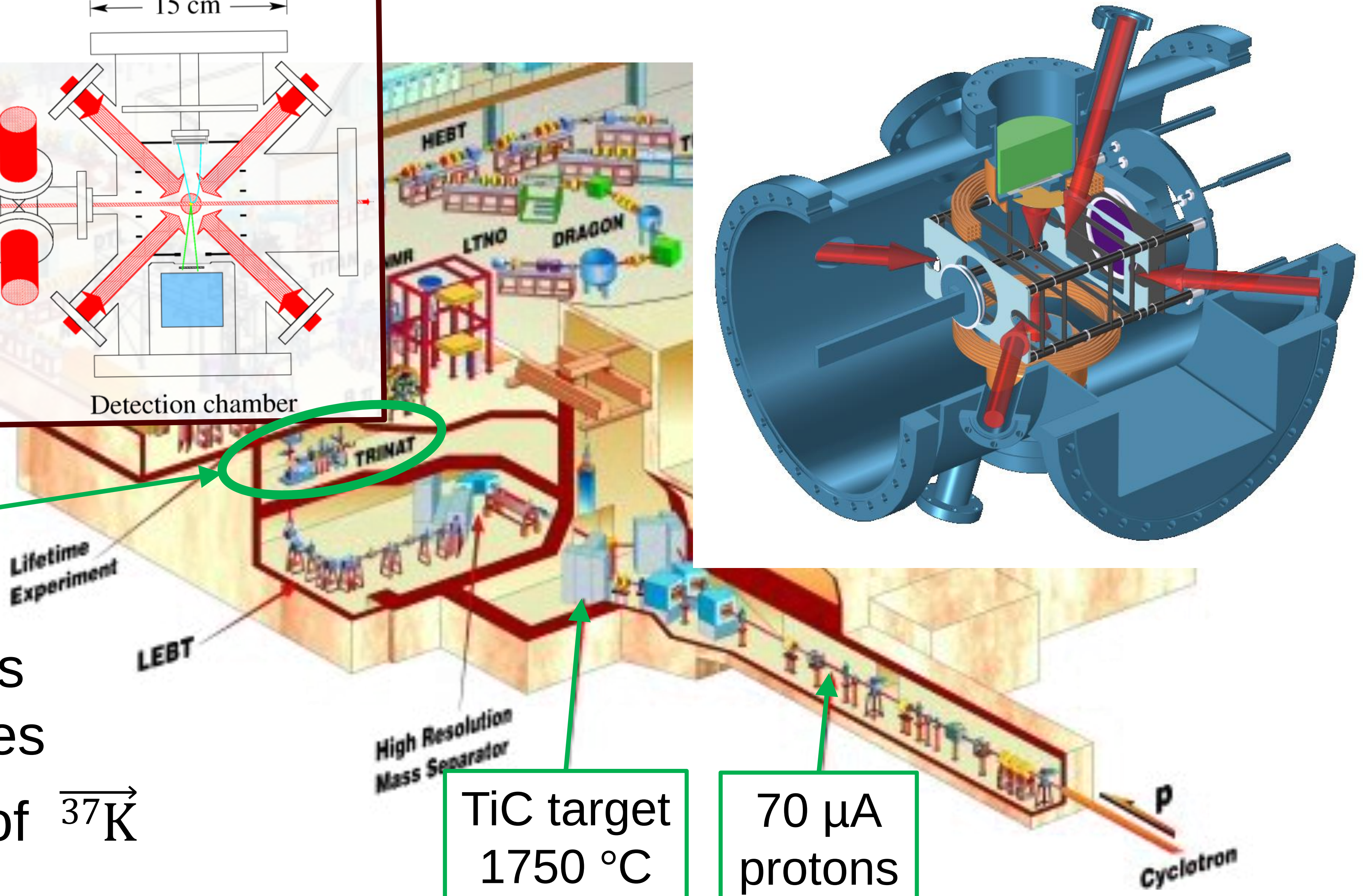


Outline

- Introduction
  - Testing the standard model via the precision frontier
  - Angular correlations of β decay
- TAMUTRAP
  - Trapping ions at the Cyclotron Institute
  - Commissioning with mass measurement of ^{23}Na
- ^{37}K at TRIUMF
  - The TRINAT facility
  - Polarizing the cloud
  - Recent measurement of A_β
- Future work

The TRIUMF Neutral Atom Trap





up to 8×10^7 ^{37}K/s

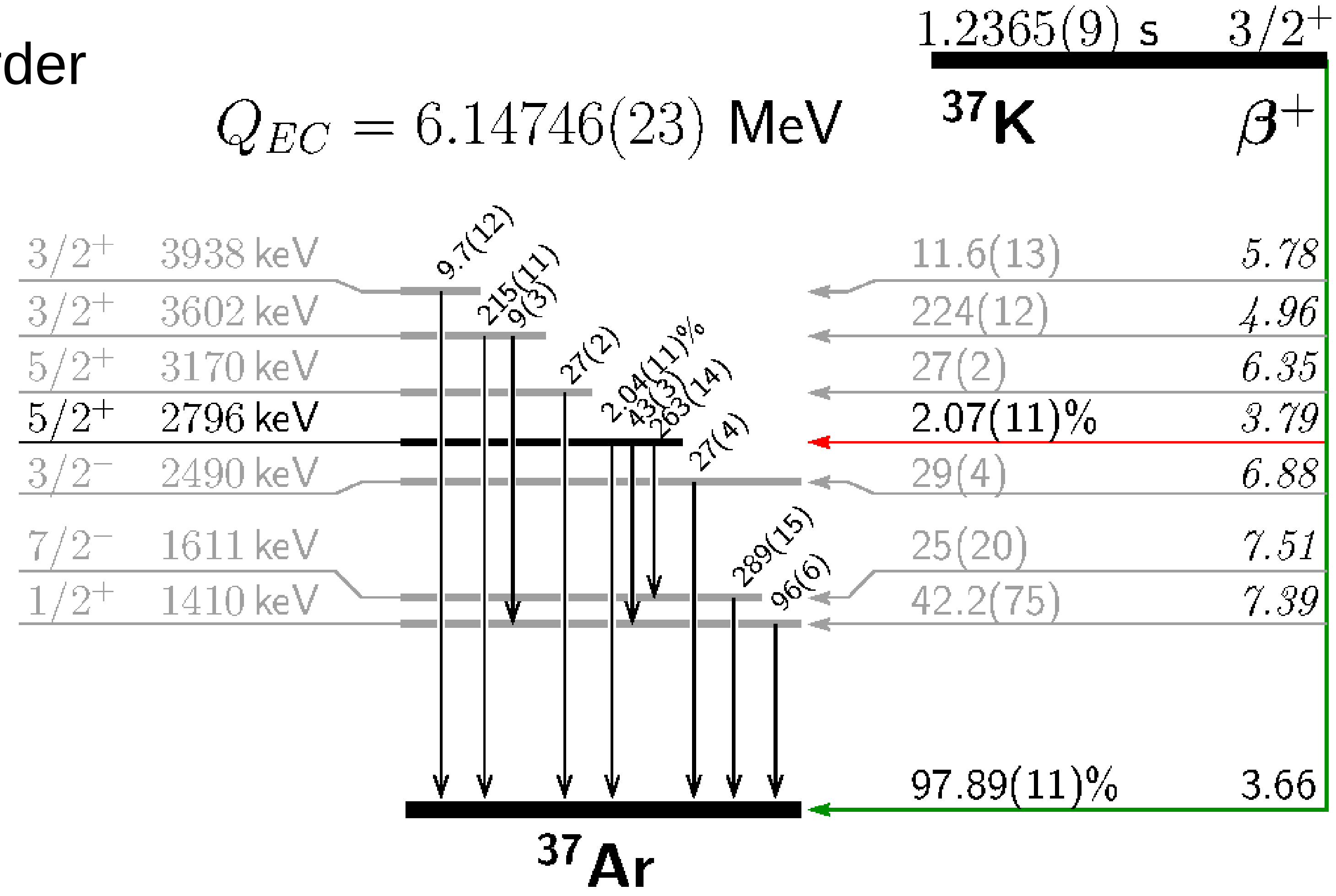
TiC target
1750 °C

70 μA
protons

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

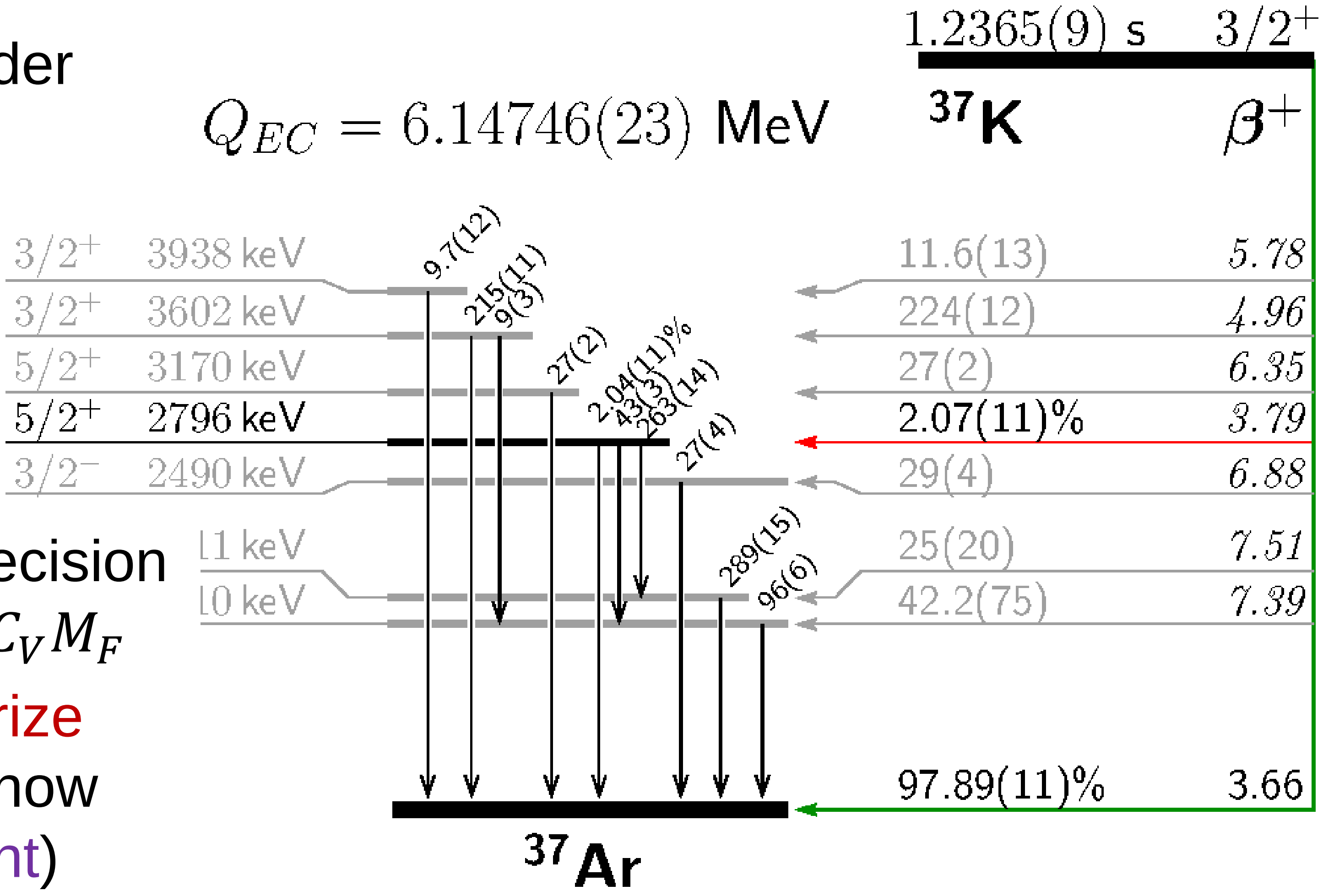
Isobaric analogue decay of ^{37}K

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



Isobaric analogue decay of ^{37}K

- Beautiful nucleus to test the standard model:
  - Alkali atom ⇒ "easy" to trap with a MOT and polarize with optical pumping
  - Isobaric analogue decay
    ⇒ theoretically clean; recoil-order corrections under control
  - Lifetime, Q-value and branches (*i.e.* the $\mathcal{F}t$ value) well known
  - Strong branch to the g.s.
- But there are challenges…
  - Can't calculate $C_A M_{GT}$ to high precision ⇒ need to measure $\rho \equiv C_A M_{GT} / C_V M_F$
  - Nuclear spin 3/2 ⇒ need to polarize the atoms, and especially know how polarized they are (also alignment)



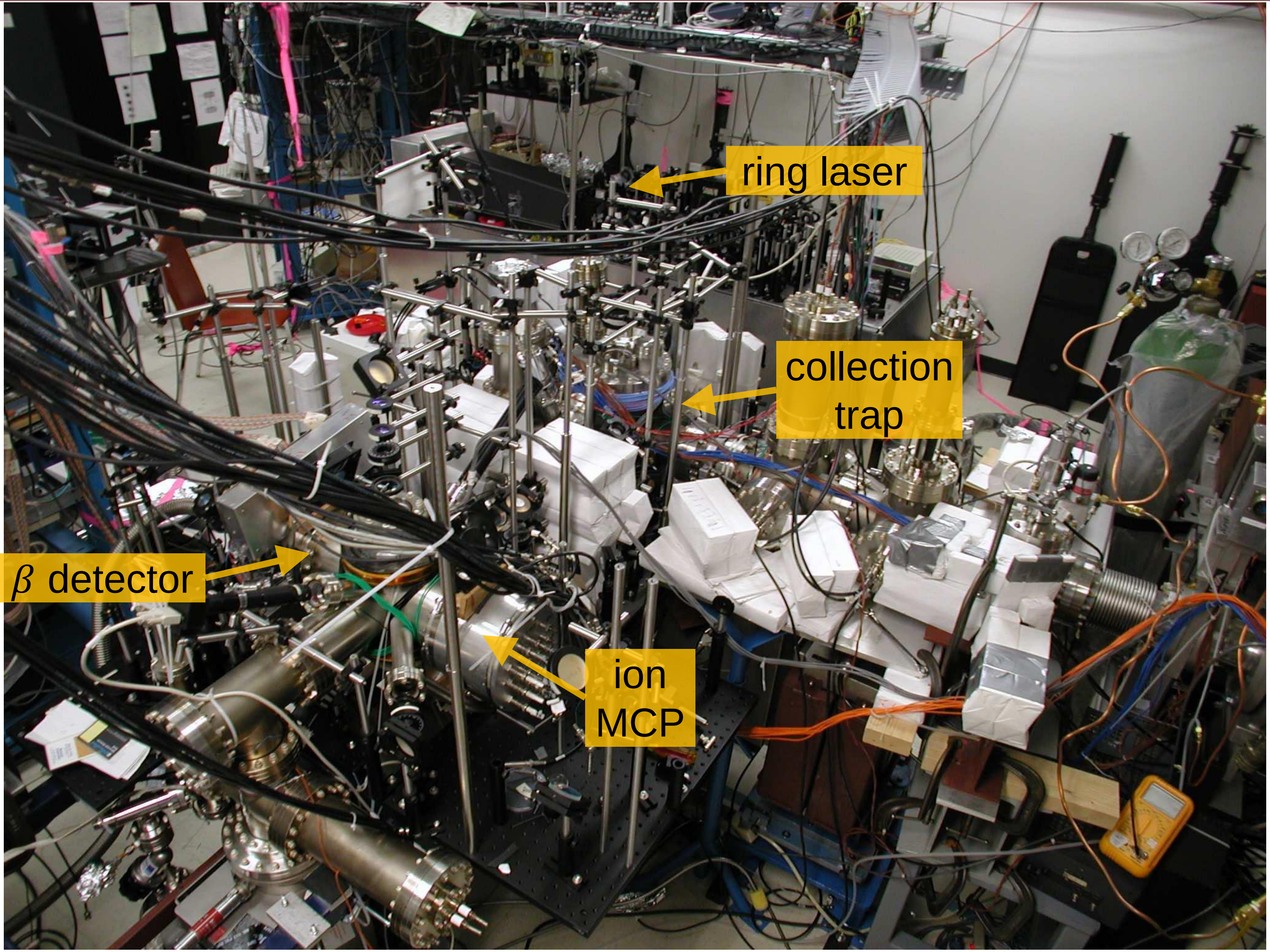
The Ft is measured well enough (for now)

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

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

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

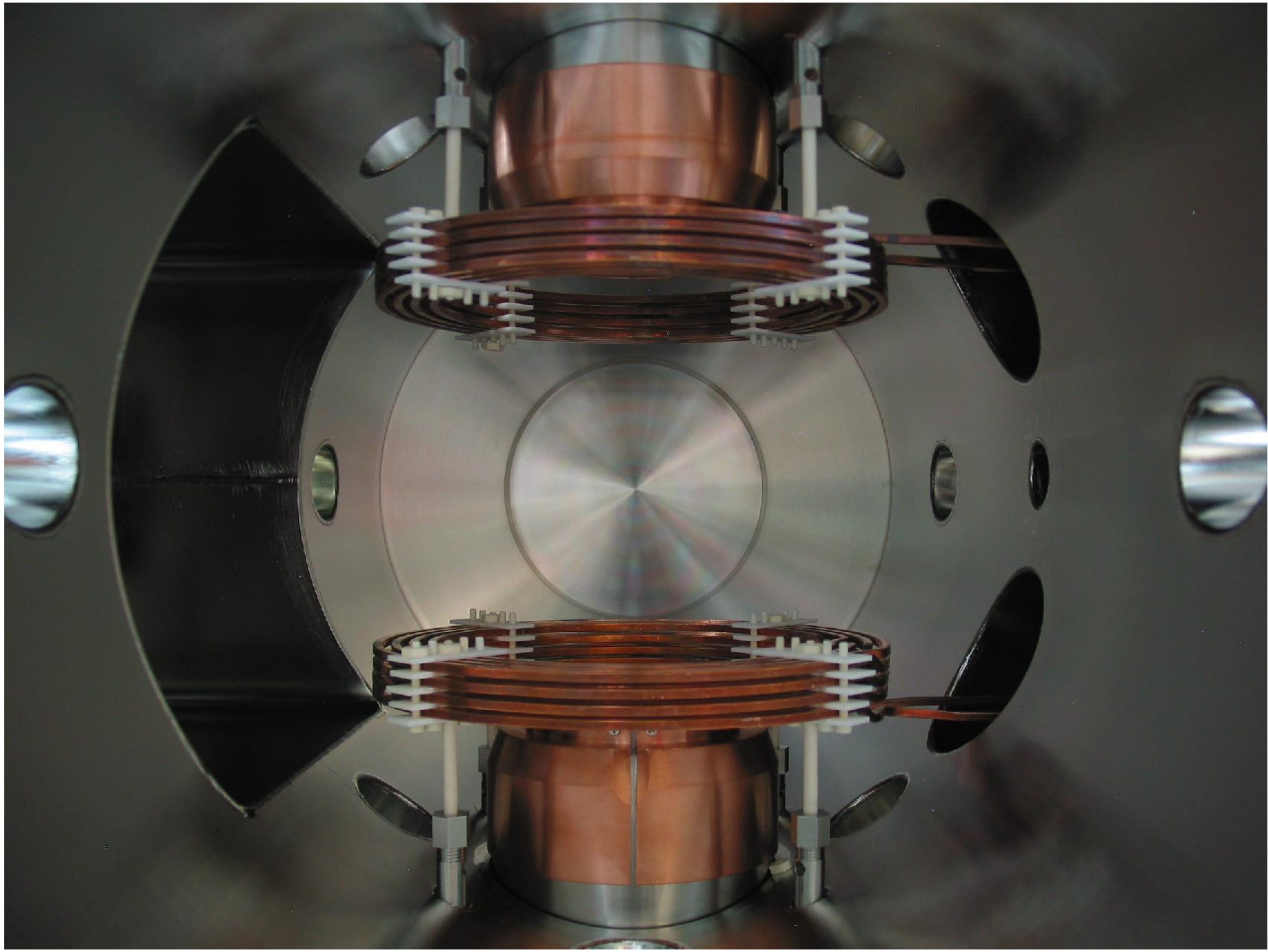
The TRINAT lab (an older picture)



RIB from ISAC

Outline of β asym & polarization measurements

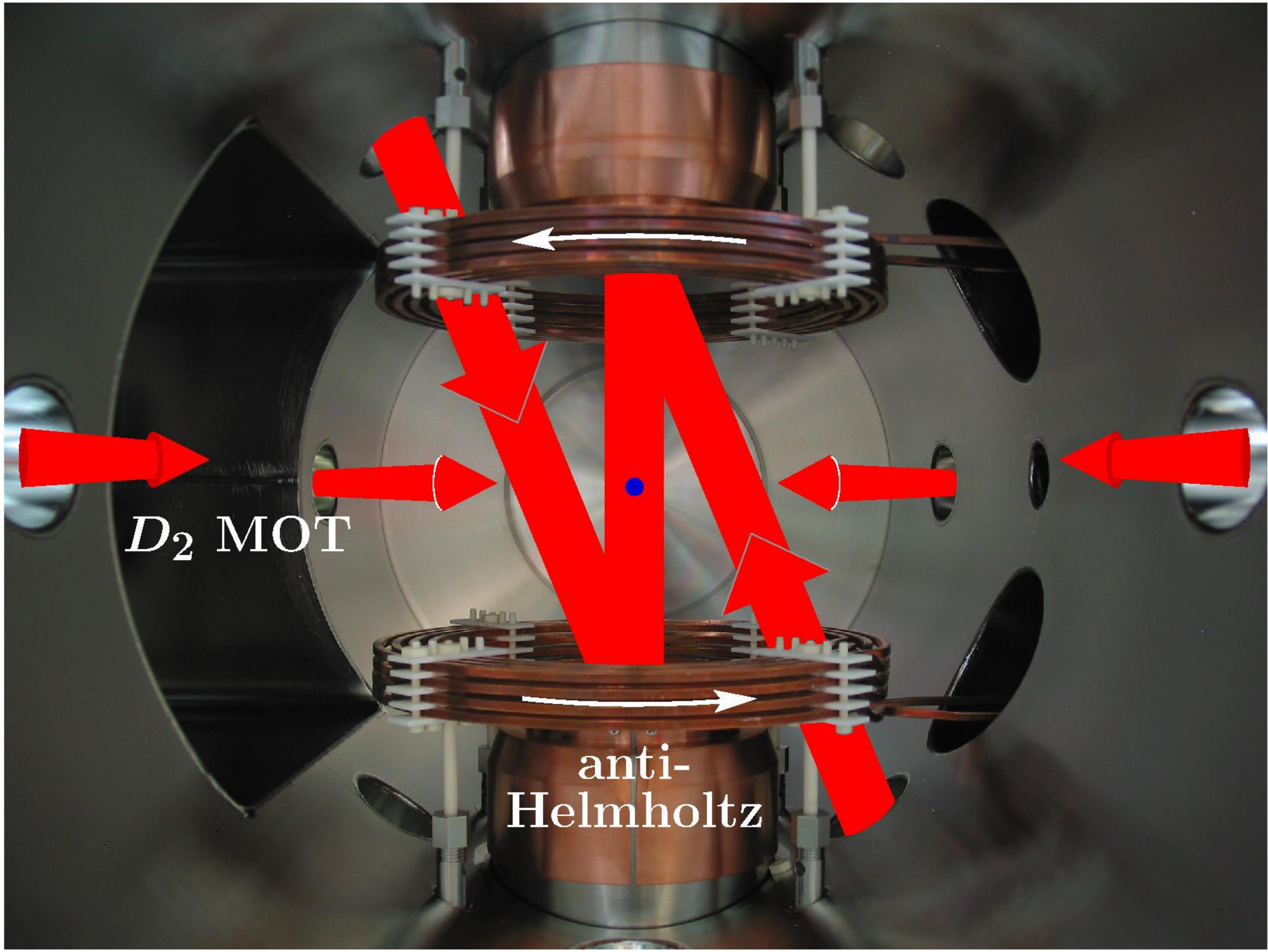
- Not shown:
  - Recoil MCP detector into page
  - Shake-off e^- MCP out of page
  - Hoops for electric field to collect recoil and shake-off e^-
  - The β telescopes within the re-entrant flanges (top *and* bottom)



Outline of β asym & polarization measurements

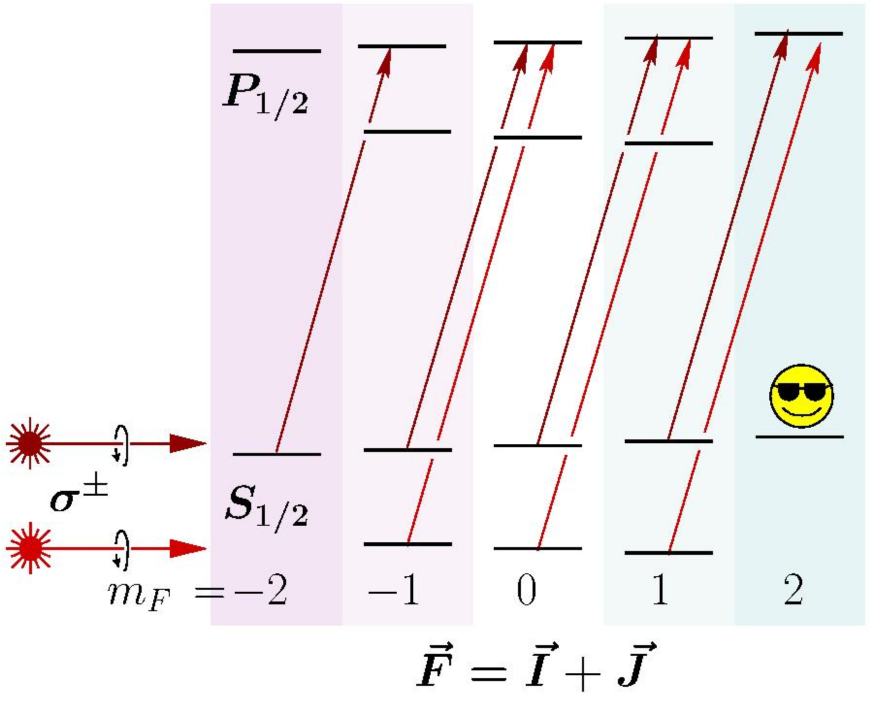
- MOTs provide a source that is:
  - Cold ($\sim 1\ \mathrm{mK}$)
  - Localized ($\sim 1\ \mathrm{mm}^3$)
  - In an open, backing-free geometry

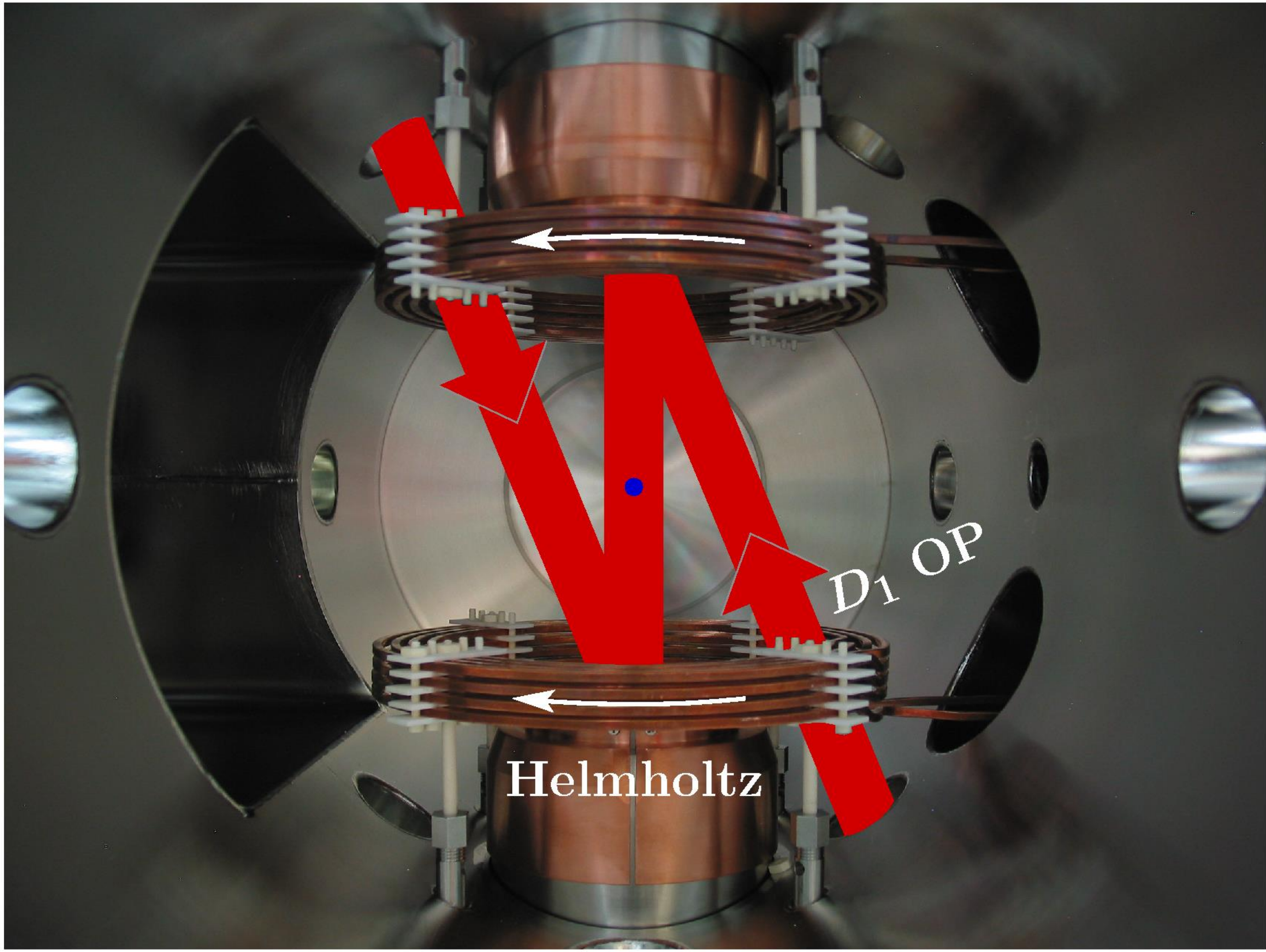
- Allows us to detect $\vec{p}_\beta$ and $\vec{p}_{\mathrm{rec}}$ $\Rightarrow$ deduce $\vec{p}_\nu$ *event-by-event*



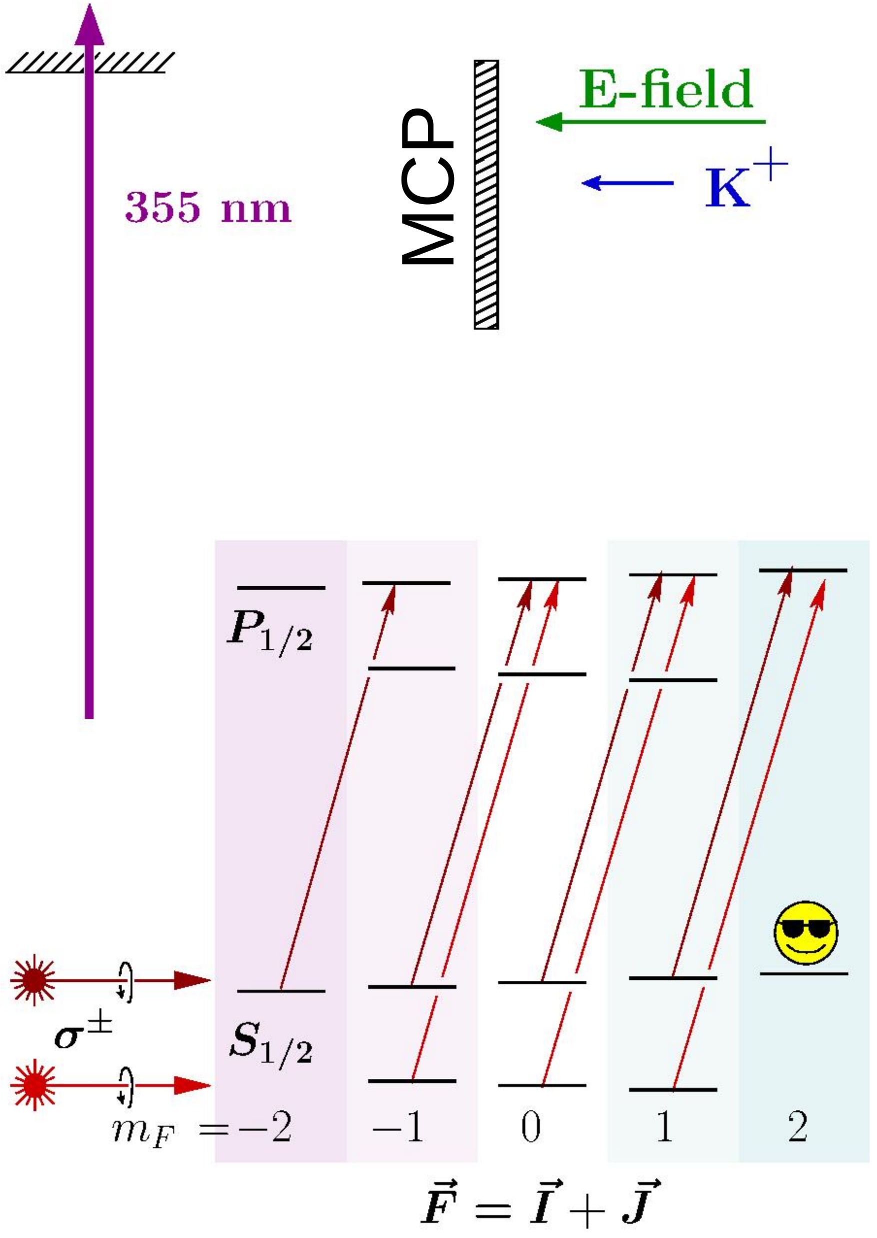
Outline of β asym & polarization measurements

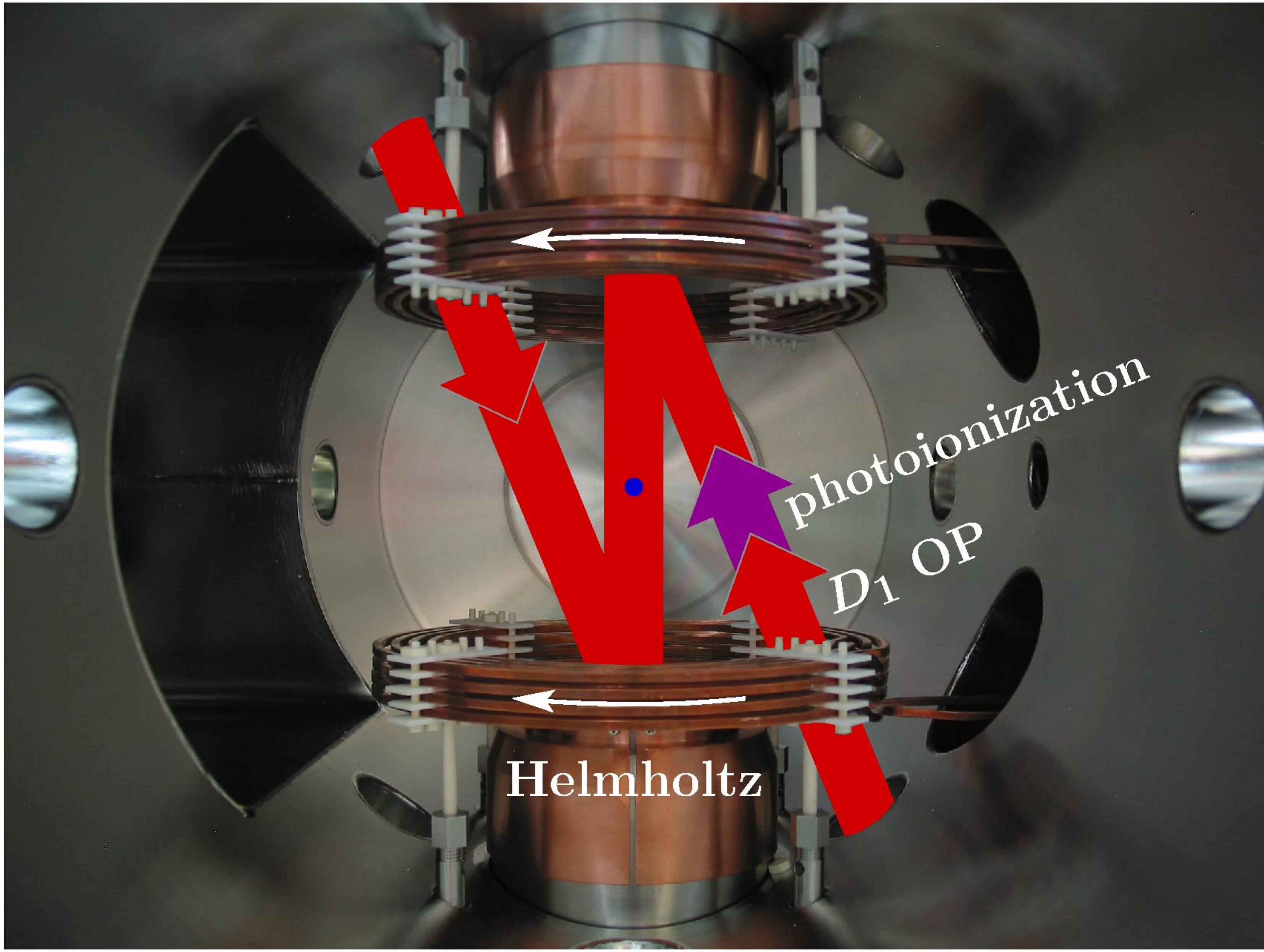
- Optical pumping:
  - Polarized light transfers ang momentum to atom
  - Nuclear and atomic spins are coupled
  - Polarize as (cold) atoms expand





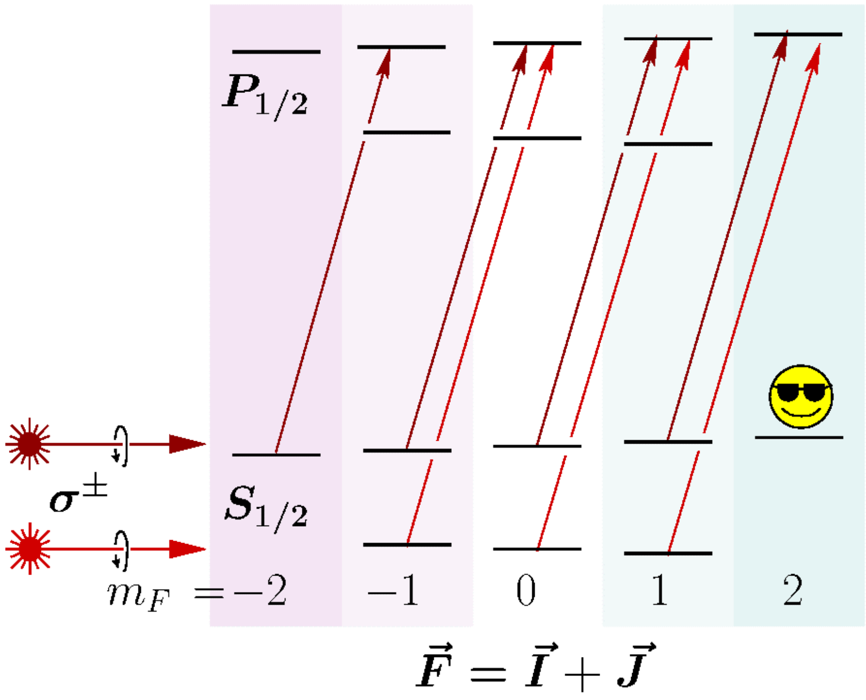
Outline of β asym & polarization measurements

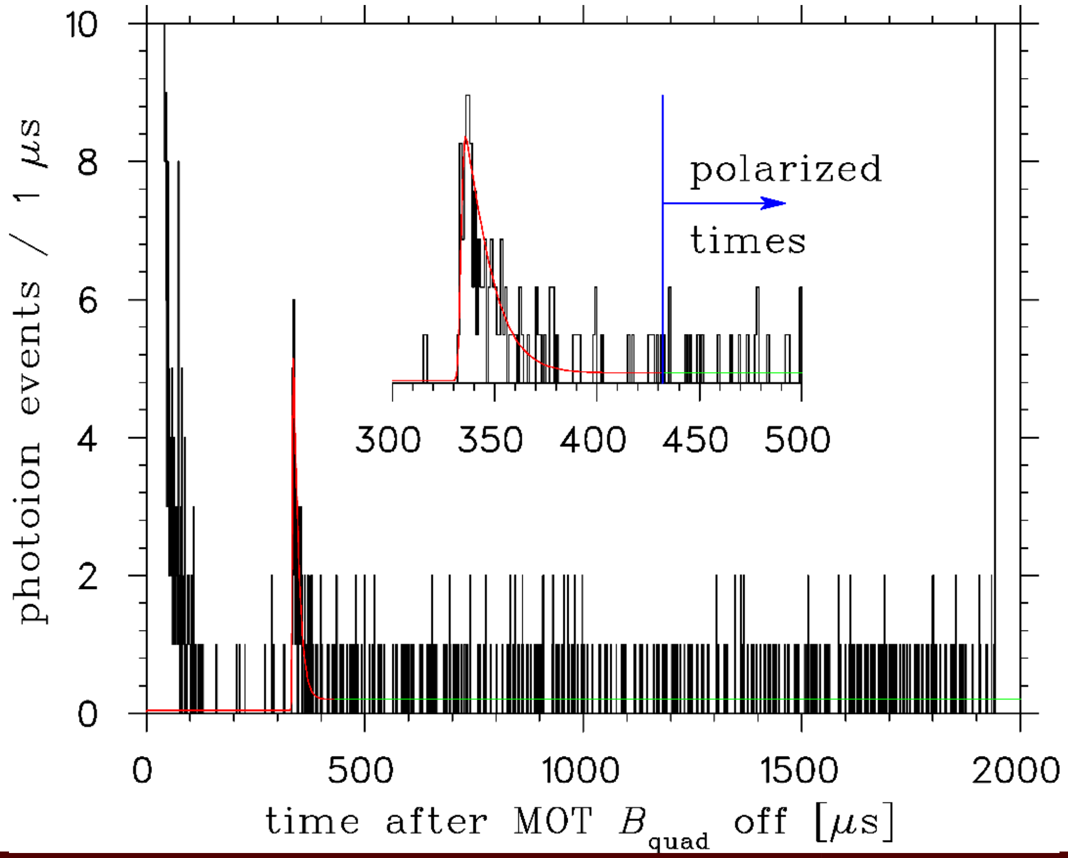




Optical pumping is fast and *efficient*!

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





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

The β asymmetry measurement

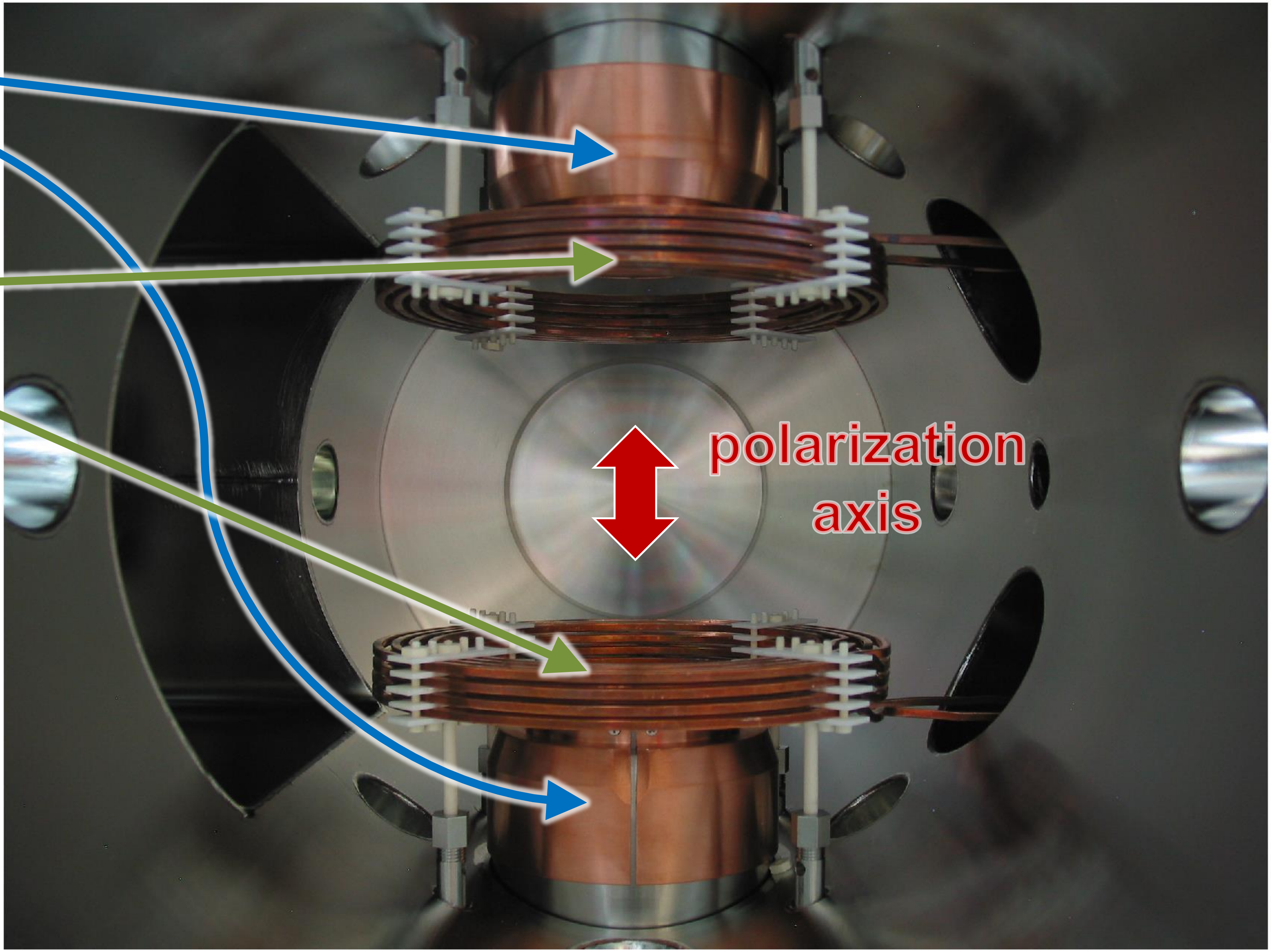
E_β **detectors**:
Plastic scintillator

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

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

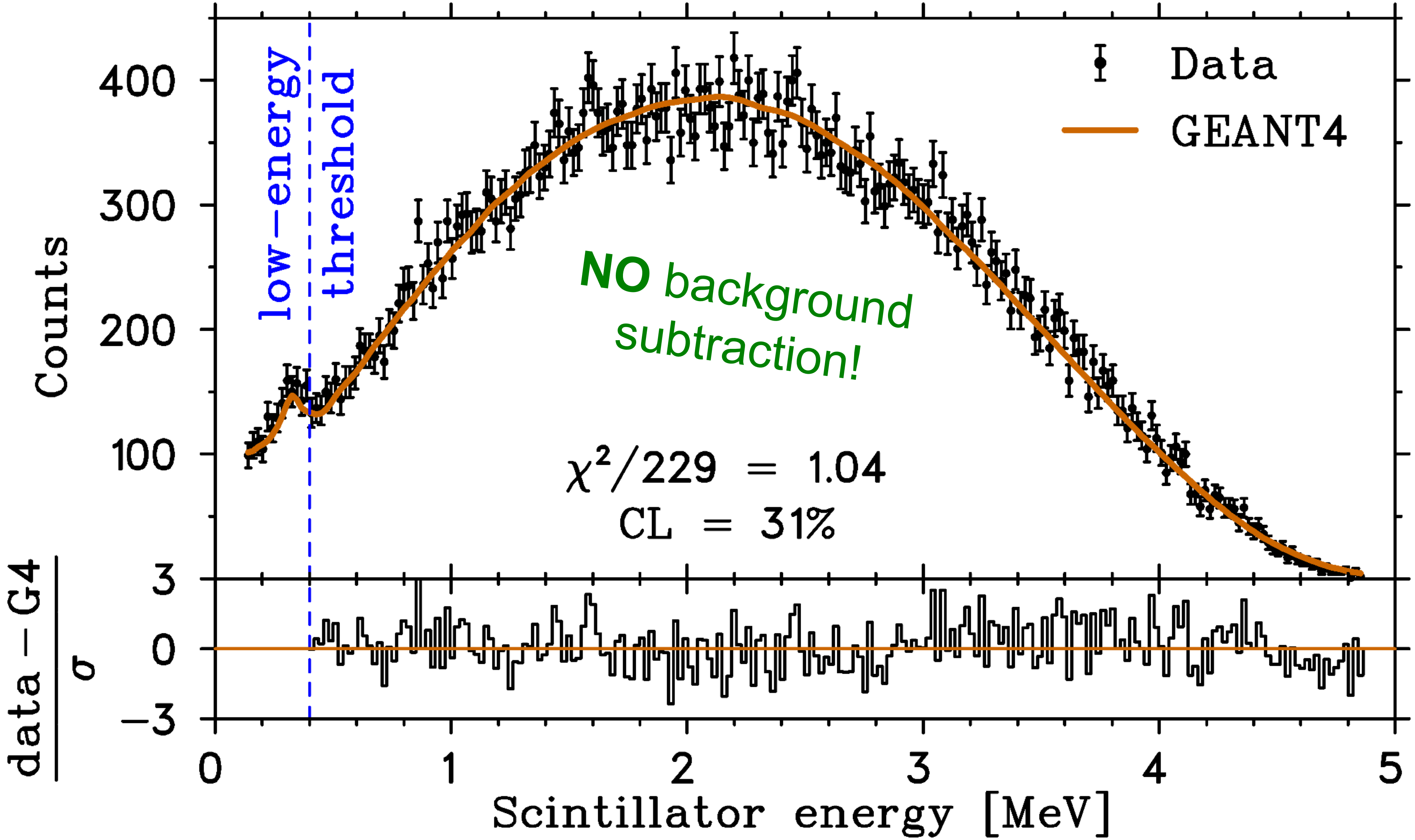
$$A_{\text{obs}}(E_e) = \frac{1-S(E_e)}{1+S(E_e)}$$

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



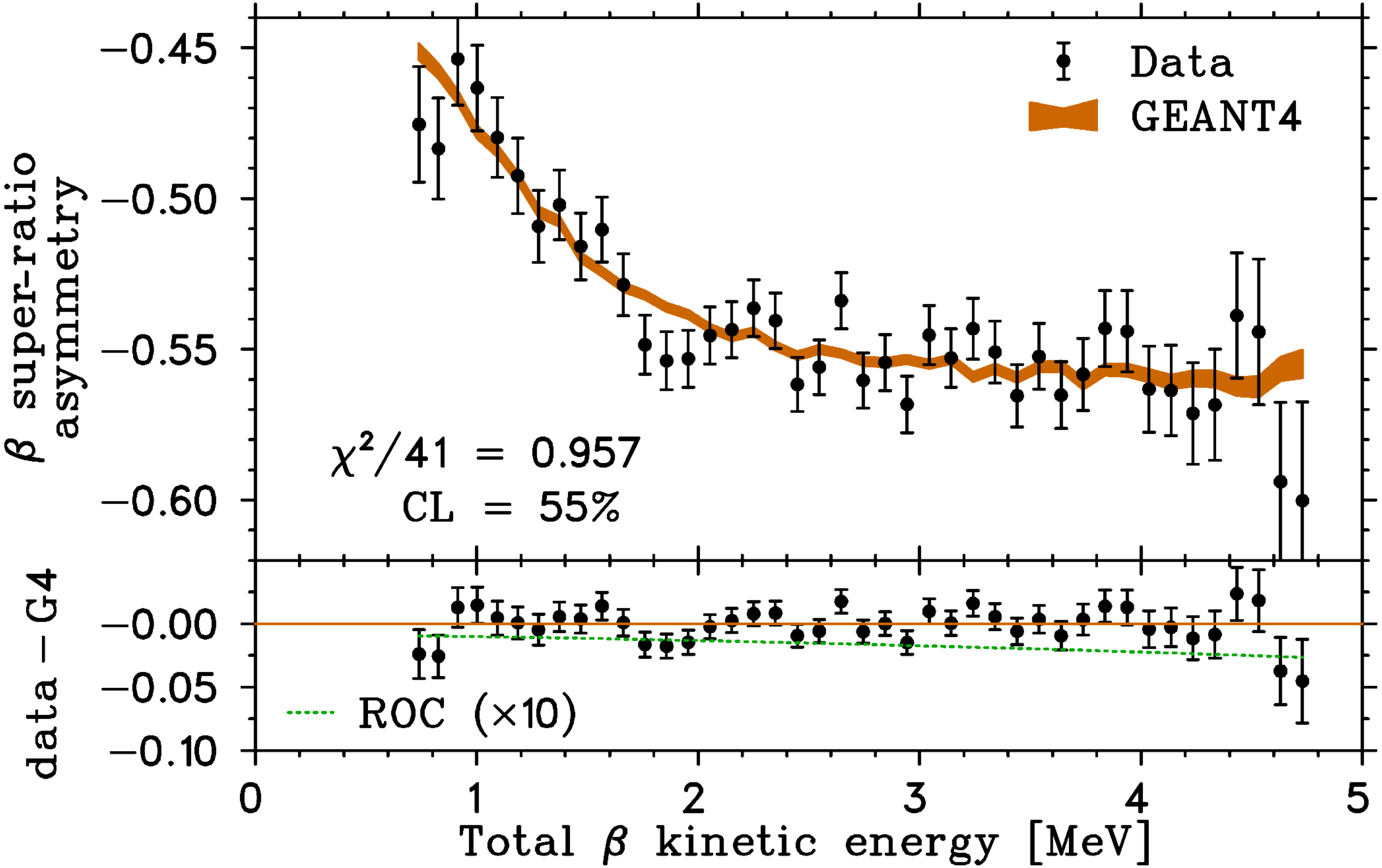
^{37}K β asymmetry measurement

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



^{37}K β asymmetry measurement

- Asymmetry as a function of β energy after unblinding (again, **no** background subtraction!):



(Dominant) Error budget and A_β result

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

(Dominant) Error budget and A_β result

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]

[1]*Cyclotron Institute, Texas A&M University, 3366 TAMU, College Station, Texas 77843-3366, USA*
[2]*Department of Physics and Astronomy, Texas A&M University, 4242 TAMU, College Station, Texas 77843-4242, USA*

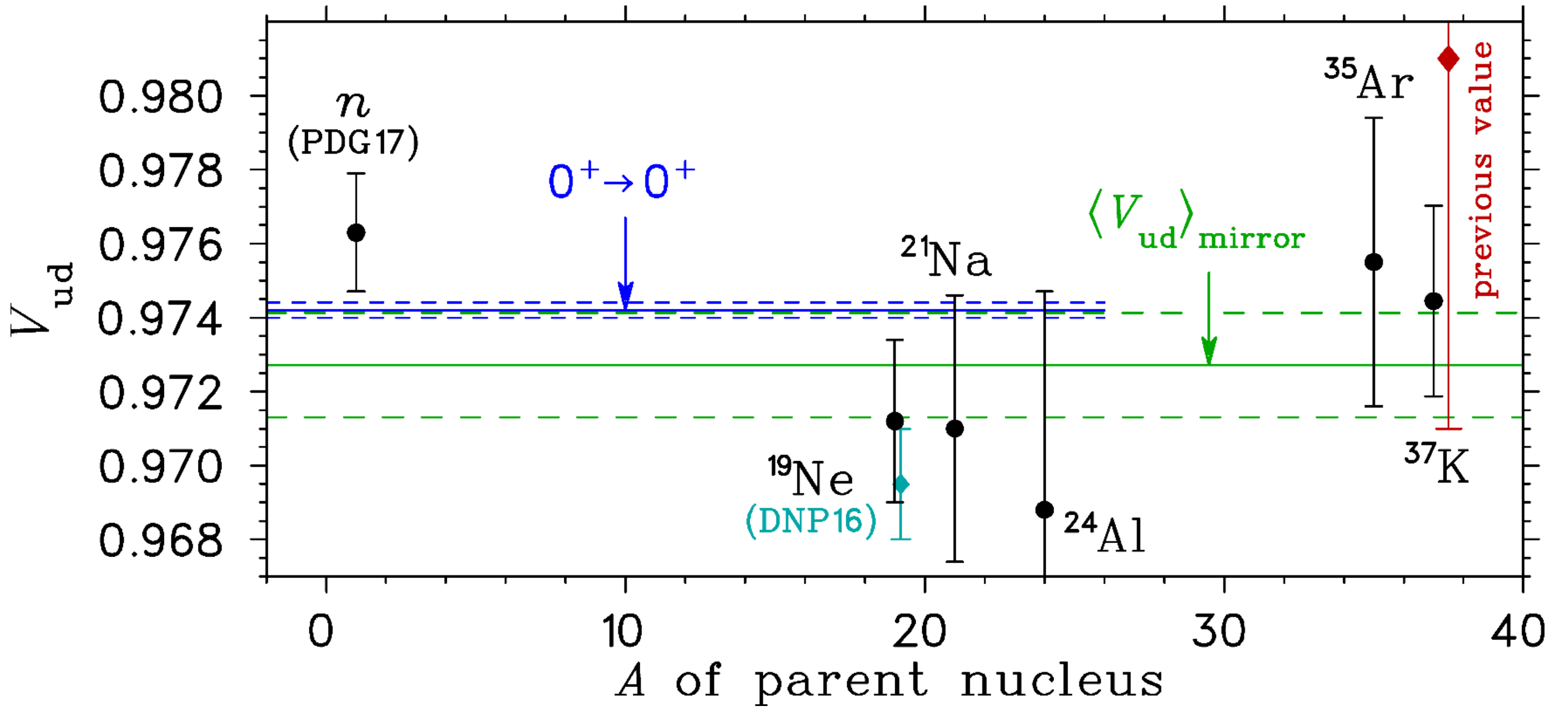
TOTAL SYSTEMATICS	13×10^{-4}
STATISTICS	13×10^{-4}
POLARIZATION	5×10^{-4}
TOTAL UNCERTAINTY	19×10^{-4}

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

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

Interpretation and future prospects

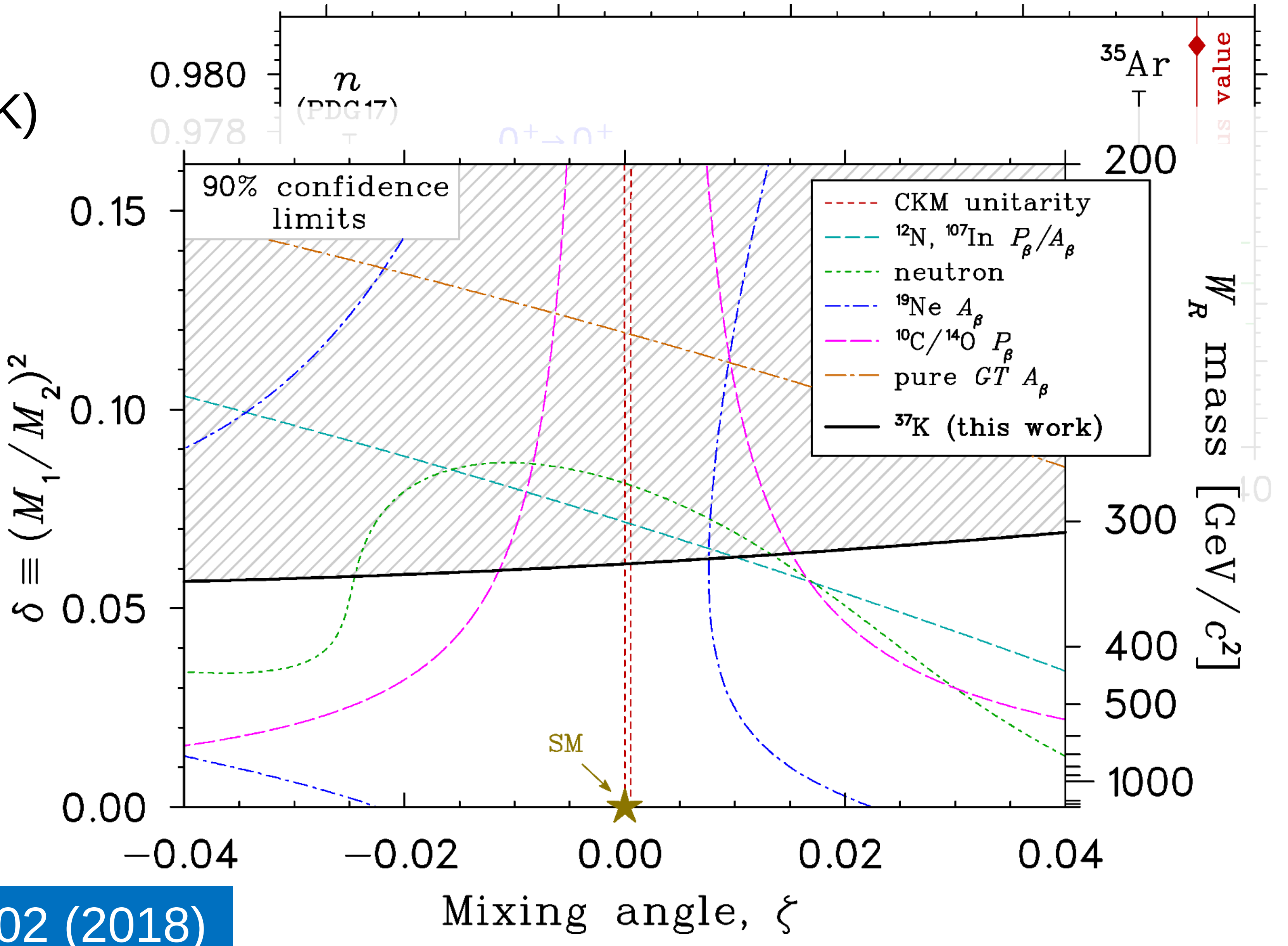
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays



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

Interpretation and future prospects

- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays
- Also other physics to probe:
  - Right-handed currents
  - 2nd class currents
  - Scalar & tensor currents



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

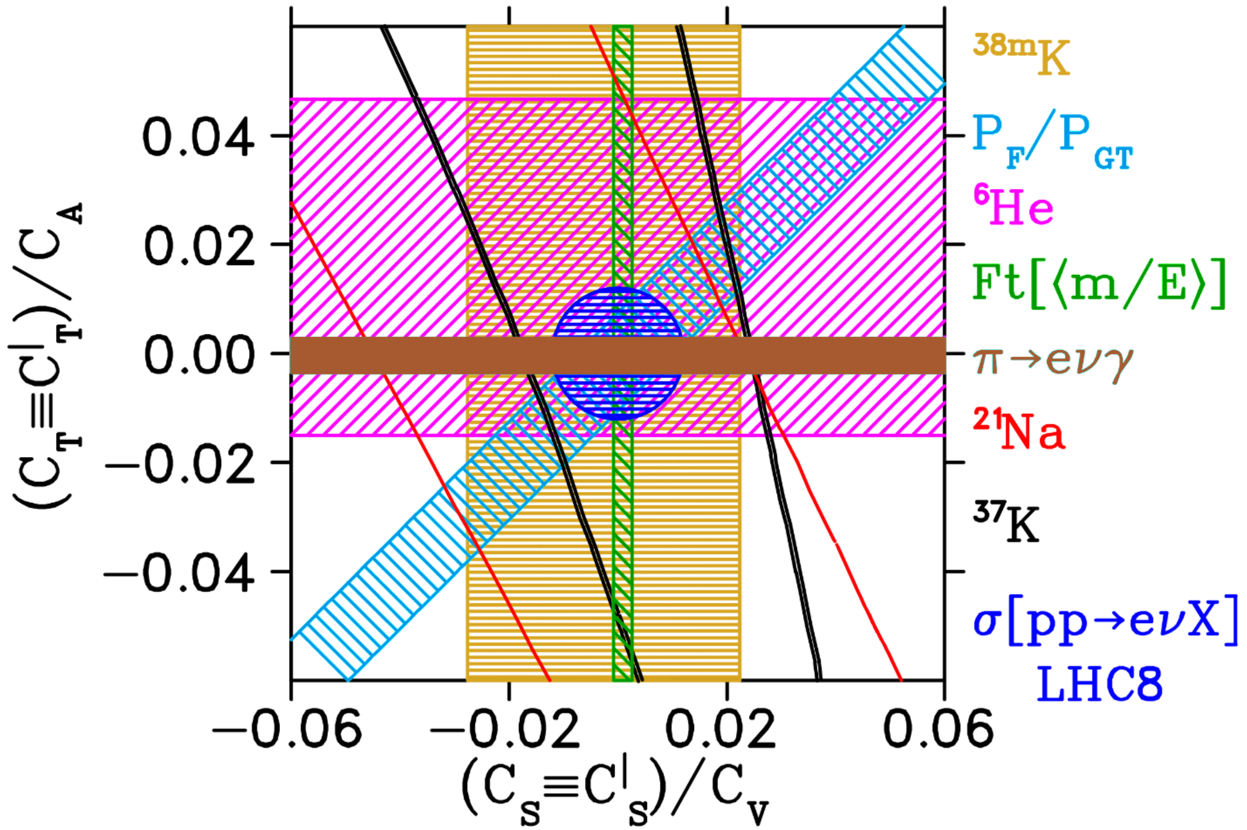
Future TAMUTRAP plans

- After gold-coating, we're ready to install the world's largest Penning trap
  - Test/debug with more mass measurements
  - Finalize designs of proton/β detectors

- None of this matters as long as we can't get radioactive ions delivered to TAMUTRAP…
  - Designing a gas cell to use the light ion guide
  - Work with the accelerator group to improve K150 performance
  - Thinking about a mass separator for the heavy ion guide
  - By early next year, trap fission products from ^{252}Cf (?)

Future TRINAT plans

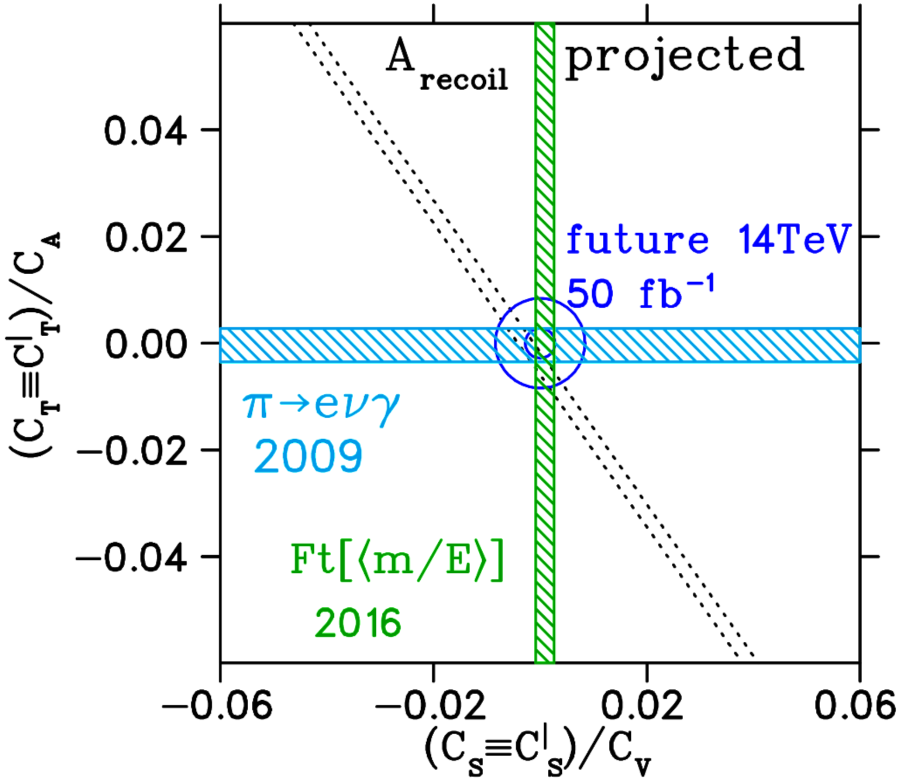
- Complete analysis as a function of $E_\beta \Rightarrow$ Fierz, 2nd class currents
- Improve A_β measurement by $3-5\times$ with next run at TRIUMF



PRELIMINARY

Future TRINAT plans

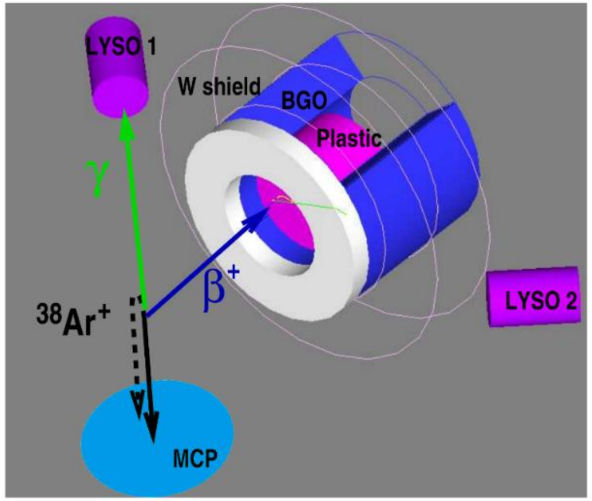
- Complete analysis as a function of $E_\beta \Rightarrow$ Fierz, 2nd class currents
- Improve A_β measurement by $3-5\times$ with next run at TRIUMF
- Measure $A_{\text{recoil}} \propto A_\beta + B_\nu$
  - Technique demonstrated in ^{80}Rb [Pitcairn *et al*., PRC **79**, 015501 (2009)]
  - High statistics measurement!

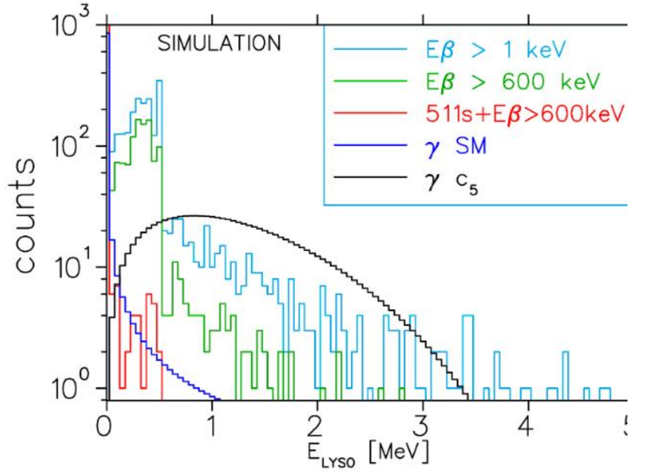


(assumes the LHC sees a 2σ signal)

Future TRINAT plans

- Complete analysis as a function of $E_\beta \Rightarrow$ Fierz, 2nd class currents
- Improve A_β measurement by $3-5\times$ with next run at TRIUMF
- Measure $A_{\text{recoil}} \propto A_\beta + B_\nu$
  - Technique demonstrated in ^{80}Rb [Pitcairn *et al*., PRC **79**, 015501 (2009)]
  - High statistics measurement!
- Measure triple-vector $(\vec{p}_e \times \vec{k}_\gamma)\cdot\vec{p}_\nu$ (T-violating) correlation in ^{38m}K
  - Motivated by Gardner and He, PRD **87**, 116012 (2013)





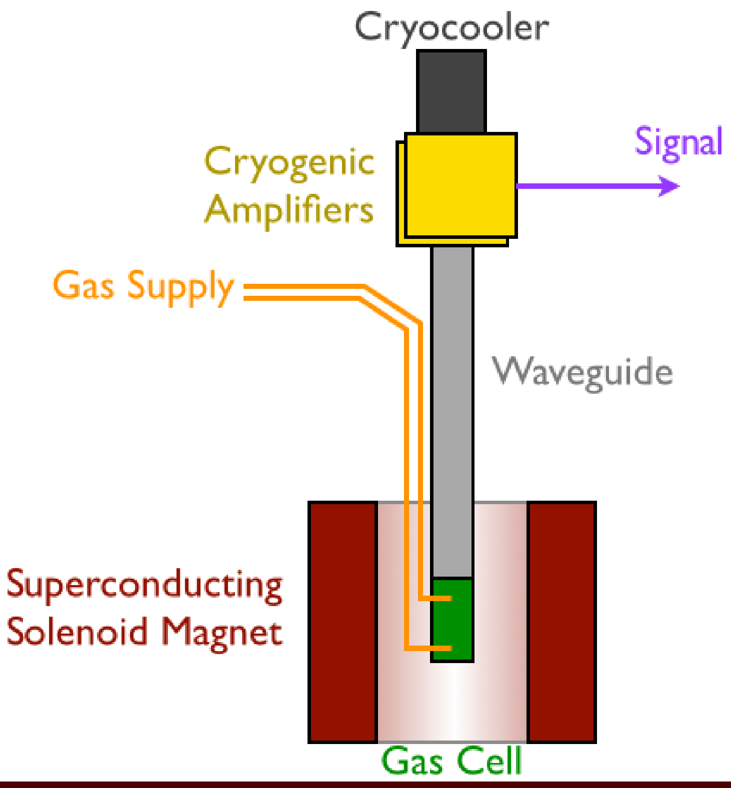
- Effect 250x larger than for the neutron
- Fake final state effect small: 8×10^{-4}
- unique measurement in 1st generation
- $\sigma\sim0.02$ in 1 week

Like Strigari said…

- "And now for something completely different"

^{6}He at UW – CRES technique

- New idea: use the Cyclotron Radiation Emission Spectroscopy (CRES) technique
  - Project 8 collaboration gets $\frac{FWHM}{E} \approx 10^{-3}$ resolution for conversion electrons of 18 – 32 keV

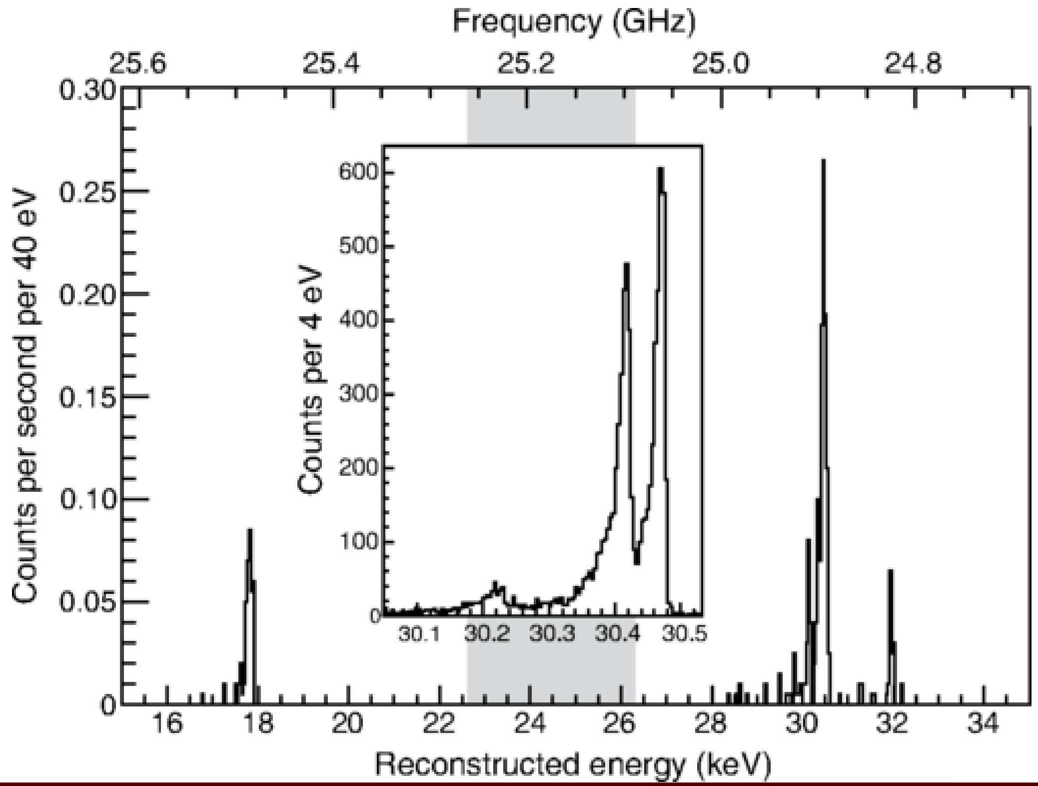


Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

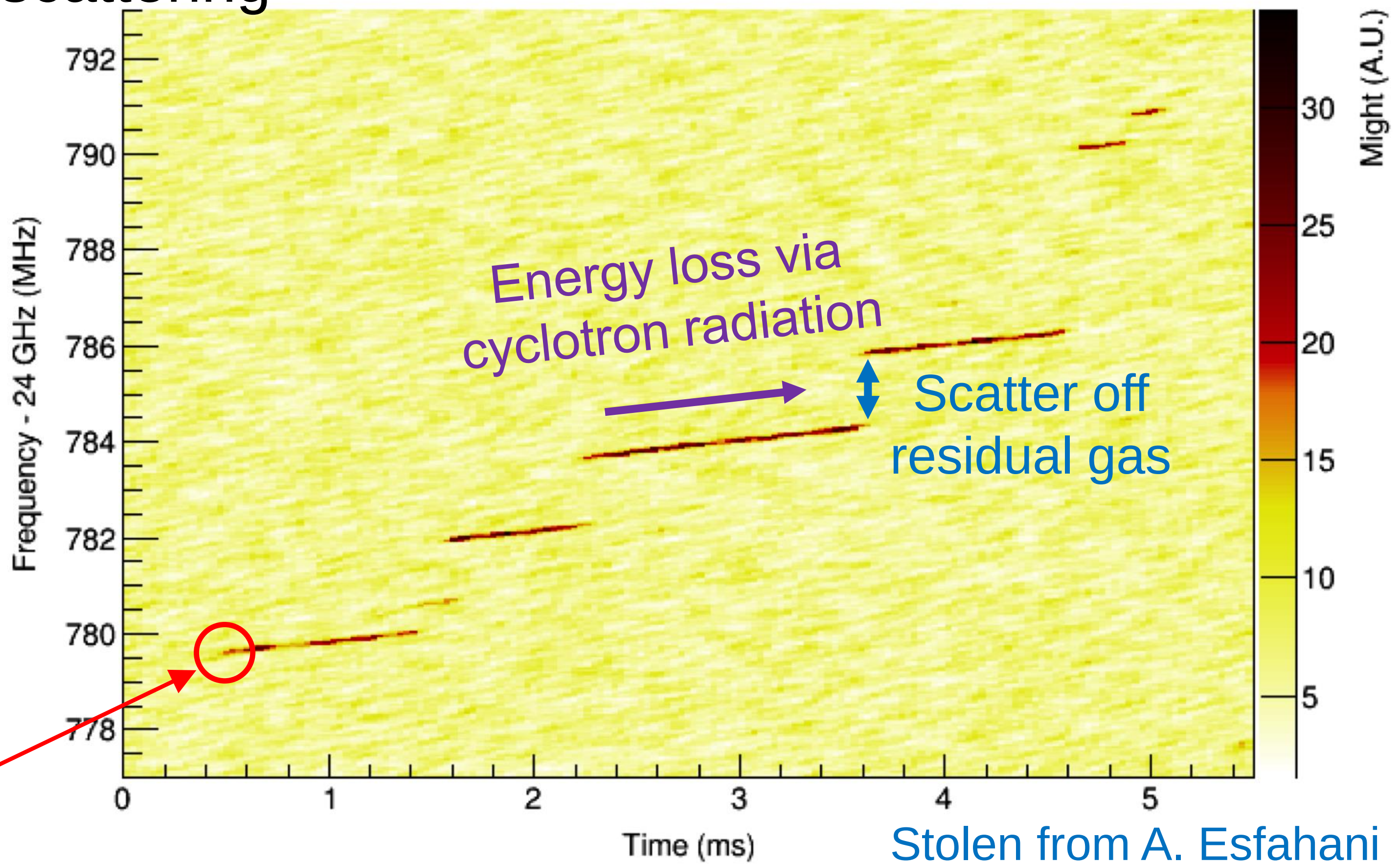
D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Sternberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender,[1] and N. L. Woods[4]

(Project 8 Collaboration)



^{6}He at UW – CRES technique

- Why CRES for ^{6}He?
  - Measures β energy at creation, before complicated energy-loss mechanisms
  - High resolution allows debugging of systematic uncertainties
  - No background from photon or e scattering
  - ^{6}He in gaseous form works well with the technique
  - ^{6}He ion trap allows sensitivity higher than any other proposed
  - Counts needed not a big demand on running time



$$2\pi f = \frac{qB}{m + E_{\text{kin}}}$$

Initial frequency → E

Stolen from A. Esfahani

Emerging ^{6}He little-*b* collaboration

W. Byron[1], M. Fertl[1] , A. Garcia[1], B. Graner[1], G. Garvey[1], M. Guigue[4], K.S. Khaw[1], A. Leredde[2], D. Melconian[3], P. Mueller[2], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[5], H.E. Swanson[1], B.A. Vandeevender[4], F. Wietfeldt[6], A. Young[5]

[1]*University of Washington,* [2]*Argonne National Lab,* [3]*Texas A&M,* [4]*North Carolina State University,* [5]*Pacific Northwest National Laboratory,* [6]*Tulane University*

- Phase I: proof of principle (next 3 yrs)
  - 2 GHz bandwidth
  - Show detection of cyclotron radiation from ^{6}He
  - Study power distribution

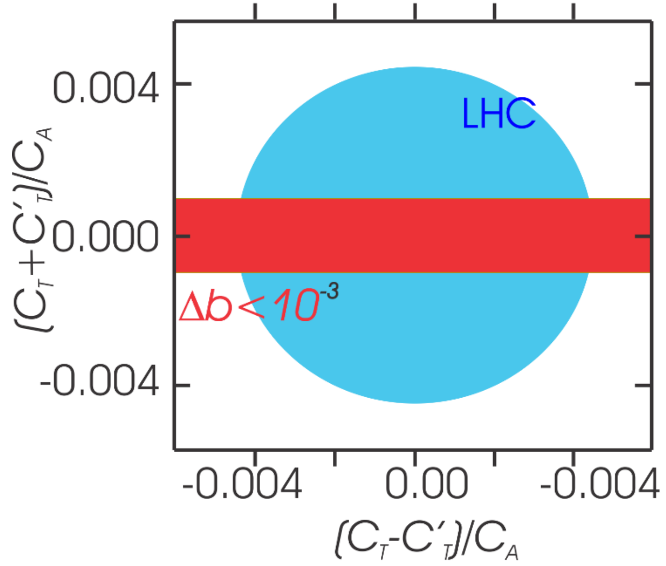
Emerging ^{6}He little-*b* collaboration

W. Byron[1], M. Fertl[1] , A. Garcia[1], B. Graner[1], G. Garvey[1], M. Guigue[4], K.S. Khaw[1], A. Leredde[2], D. Melconian[3], P. Mueller[2], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[5], H.E. Swanson[1], B.A. Vandeevender[4], F. Wietfeldt[6], A. Young[5]

[1]University of Washington, [2]Argonne National Lab, [3]Texas A&M, [4]North Carolina State University, [5]Pacific Northwest National Laboratory, [6]Tulane University

- Phase I: proof of principle (next 3 yrs)
  - 2 GHz bandwidth
  - Show detection of cyclotron radiation from ^{6}He
  - Study power distribution
- Phase II: first measurement ($b < 10^{-3}$)
  - 6 GHz bandwidth
  - ^{6}He and ^{19}Ne measurements

Effect	Δb No trap	Δb Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}



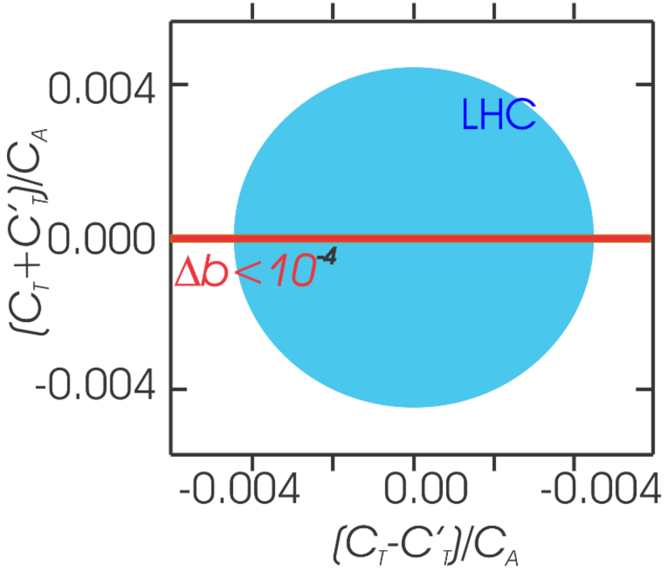
Emerging ^{6}He little-*b* collaboration

W. Byron[1], M. Fertl[1] , A. Garcia[1], B. Graner[1], G. Garvey[1], M. Guigue[4], K.S. Khaw[1], A. Leredde[2], D. Melconian[3], P. Mueller[2], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[5], H.E. Swanson[1], B.A. Vandeevender[4], F. Wietfeldt[6], A. Young[5]

[1]University of Washington, [2]Argonne National Lab, [3]Texas A&M, [4]North Carolina State University, [5]Pacific Northwest National Laboratory, [6]Tulane University

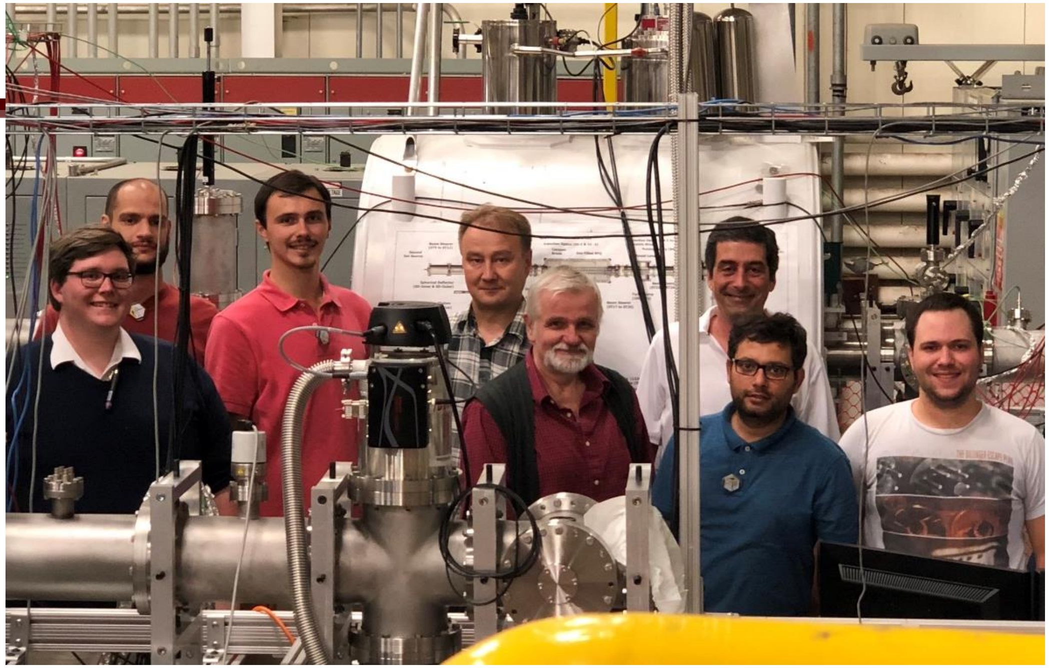
- Phase I: proof of principle (next 3 yrs)
  - 2 GHz bandwidth
  - Show detection of cyclotron radiation from ^{6}He
  - Study power distribution
- Phase II: first measurement ($b < 10^{-3}$)
  - 6 GHz bandwidth
  - ^{6}He and ^{19}Ne measurements
- Phase III: ultimate measurement ($b < 10^{-4}$)
  - Ion trap for no limitation from geometric effect

Effect	Δb No trap	Δb Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}



Many thanks to go around!

TEXAS A&M UNIVERSITY



B. Fenker – Programmer analyst at Tessella
S. Behling – Post-doc at PNNL
M. Mehlman – Scientist at Exponent (→ Google)

V. Kolhinen
P.D. Shidling

D. McClain
M. Nasser
A. Ozmetin
B. Schroeder

TRIUMF

J.A. Behr
I. Craiciu
A. Gorelov
S. Smale
C.L. Warner

University of Manitoba

M. Anholm
G. Gwinner

Tel Aviv University

D. Ashery
I. Cohen

University of British Columbia

J. M^{c}Neil

Support provided by:

- The DOE and State of Texas
- NSERC, NRC through TRIUMF
- Israel Science Foundation