A Measurement of the ^{19}Ne Beta Asymmetry & a Determination of $|V_{ud}|$

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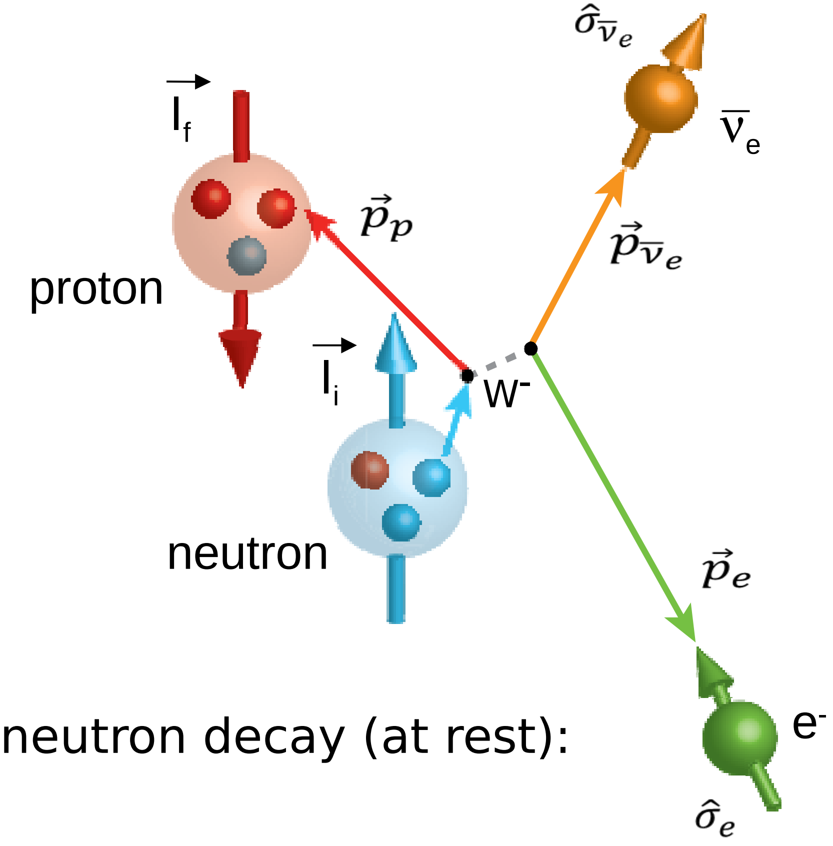
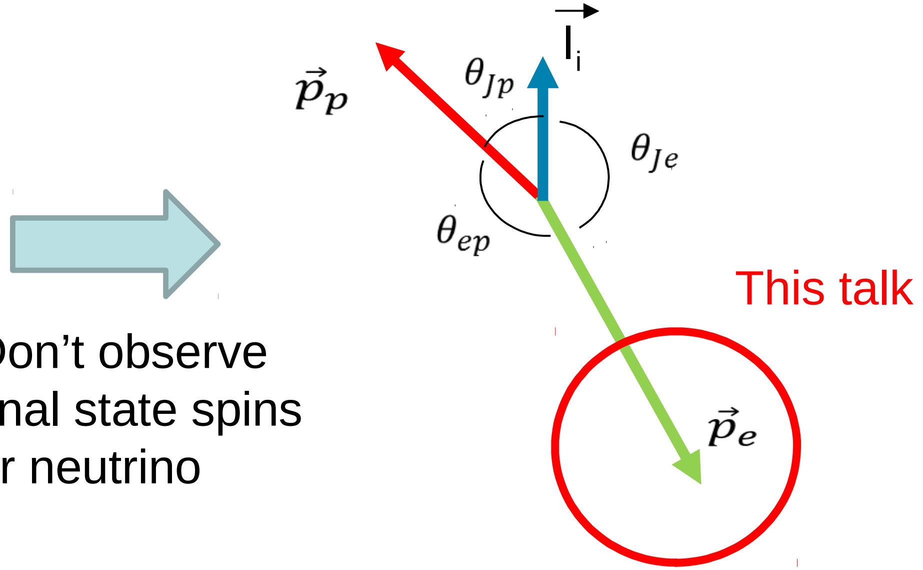
Beta Decay Observables



neutron decay (at rest):

Don’t observe final state spins or neutrino



Many accessible observables

$\{\vec{I}_i, \vec{I}_f, \vec{p}_p, E_p, \hat{\sigma}_e, \vec{p}_e, E_e\}$

Decay rate

Energy spectrum: p, e

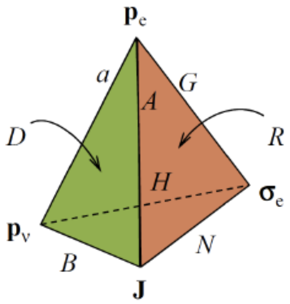
Directional distribution (**angular correlations**)

Use momentum consv: $\vec{p}_{\overline{\nu}_e} = -\vec{p}_p - \vec{p}_e$

Beta Decay Parameters

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

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



On-going or planned efforts to measure:

(1) **Decay rates and β-spectra (**$\boldsymbol{G_F V_{ud}, \xi, b}$)

(2) **Unpolarized angular correlations (**$\boldsymbol{a_{\beta\nu}, b}$**)**

(3) **Polarized angular correlations (**$\boldsymbol{A_\beta, B_\nu, b, b_\nu}$**)**

(4) New program to measure **circular polarization asymmetry**

Mirrors are isobaric analog mixed decays → two measurements needed to determine both V and A Couplings:
Decay Rate + Angular Correlation

Angular Correlations in Nuclei – Polarized Systems

Rather limited set of measurements on polarized nuclei at present-->

Species	Decay	Method	Corr.	Corr. unc	Group	
^{19}Ne	F/GT	Atomic Beam	A_β	~2%	Princeton	Complete In 1995
^{37}K	F/GT	Optical Trap	A_β	~0.1%	TRINAT-TAMU	ongoing
^{21}Na, ^{37}K	F/GT	Atomic Beam	σ-A_β	~0.1%	NSCL	ongoing

any others?

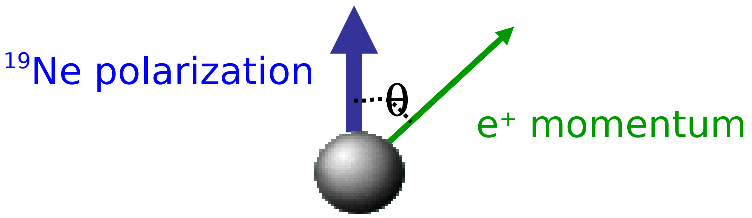
^{19}Ne (Princeton): in situ polarimetry precision at 1.5%
^{37}K (TRINAT-TAMU): in situ polarimetry precision at ~0.1%
Spin-asymmetry (NSCL): running soon, very strong constraints on RHC

} Motivated to determine mixing ratio...

Many more measurements (on mirrors as well as other systems) planned for unpolarized nuclei..

More experiments coming (see later in talk)!

The β-asymmetry



$$R = R_o(1 + (v/c)\, P\, A(E) \cos\theta)$$

β-asymmetry = A(E) in angular distribution of β

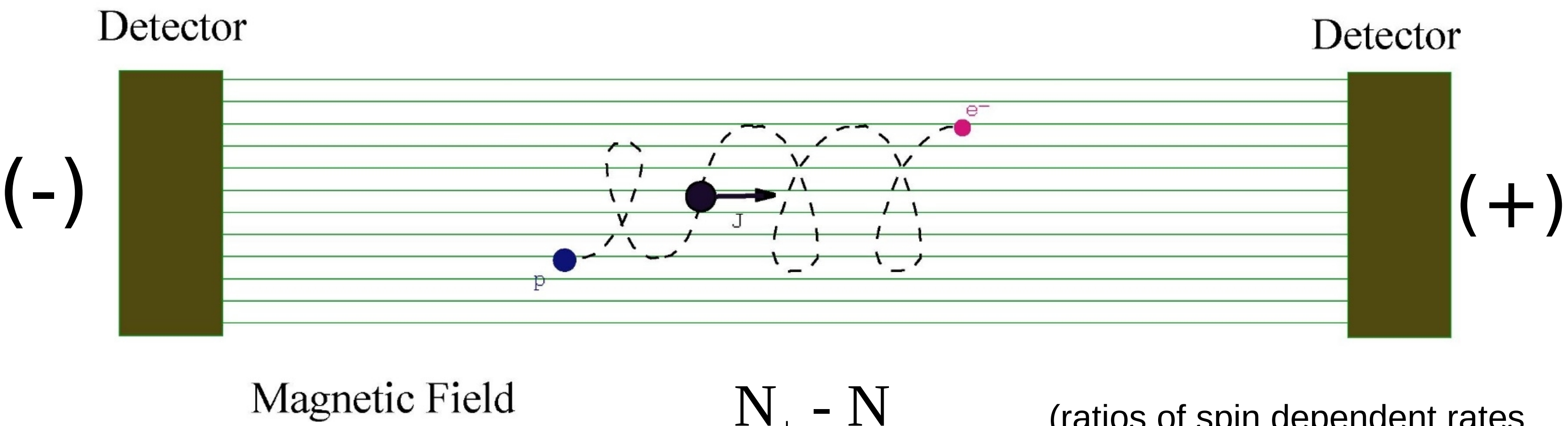
$$A_\beta(0) = \frac{\rho^2 - 2\rho\sqrt{J(J+1)}}{(1+\rho^2)(J+1)}$$

$$\rho \equiv \frac{C_A M_{GT}}{C_V M_F}$$

Ignoring recoil order terms – just a function of ρ!

Measurement Challenges

β directional distribution: $1 + P\frac{v}{c}A(E)\cos\theta$
(polarized neutrons)



$$A(E) \propto \frac{N_+ - N_-}{N_+ + N_-}$$

(ratios of spin dependent rates are used to cancel efficiencies)

Must determine: → **Systematic effects:**

- Beta rates → Backgrounds
- Beta spectra → Calibration/Linearity
- <cosθ> → Scattering (esp. backscattering)
- Polarization → Absolute polarization required!

Spin ratios provide robust 1st order strategy for experiment – “super-ratio” eliminates detector efficiencies and rate variations

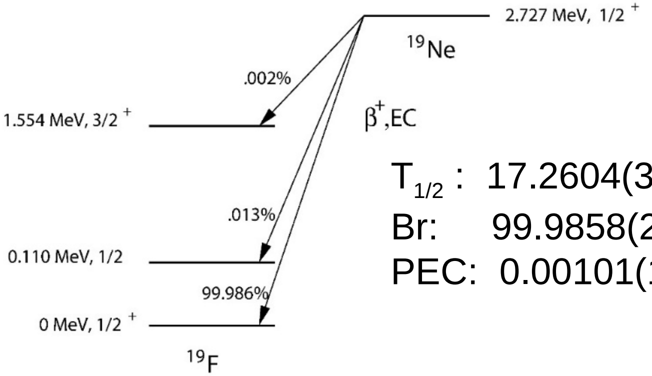
A_β in ^{19}Ne$(1/2^+) \longrightarrow$ ^{19}F$(1/2^+)$ Positron Decay

Calaprice group, thesis of Gordon Jones (1995); G. L. Jones, A. Ackerson, M. S. Anderson, F. P. Calaprice, F. Loeser, A. Razaghi, A. R. Young

Hero who finished analysis: **D. C. Combs**

$$A_\beta = -0.0391(14)$$

(current)



$T_{1/2}$: 17.2604(34)
Br: 99.9858(20)
PEC: 0.00101(1)

$T_{1/2}$ to ground state: 17.2818(94)

K.E. max = 2.216 keV

- Accidental cancellation makes A_β very sensitive to ρ: $\delta A/A \sim 13 d\rho/\rho$

Relaxes demands on systematic error budget!
(δA translates into much smaller $\delta\rho$)

- Critical work sorting out nuclear corrections for mirrors done in 2008 & 2009:

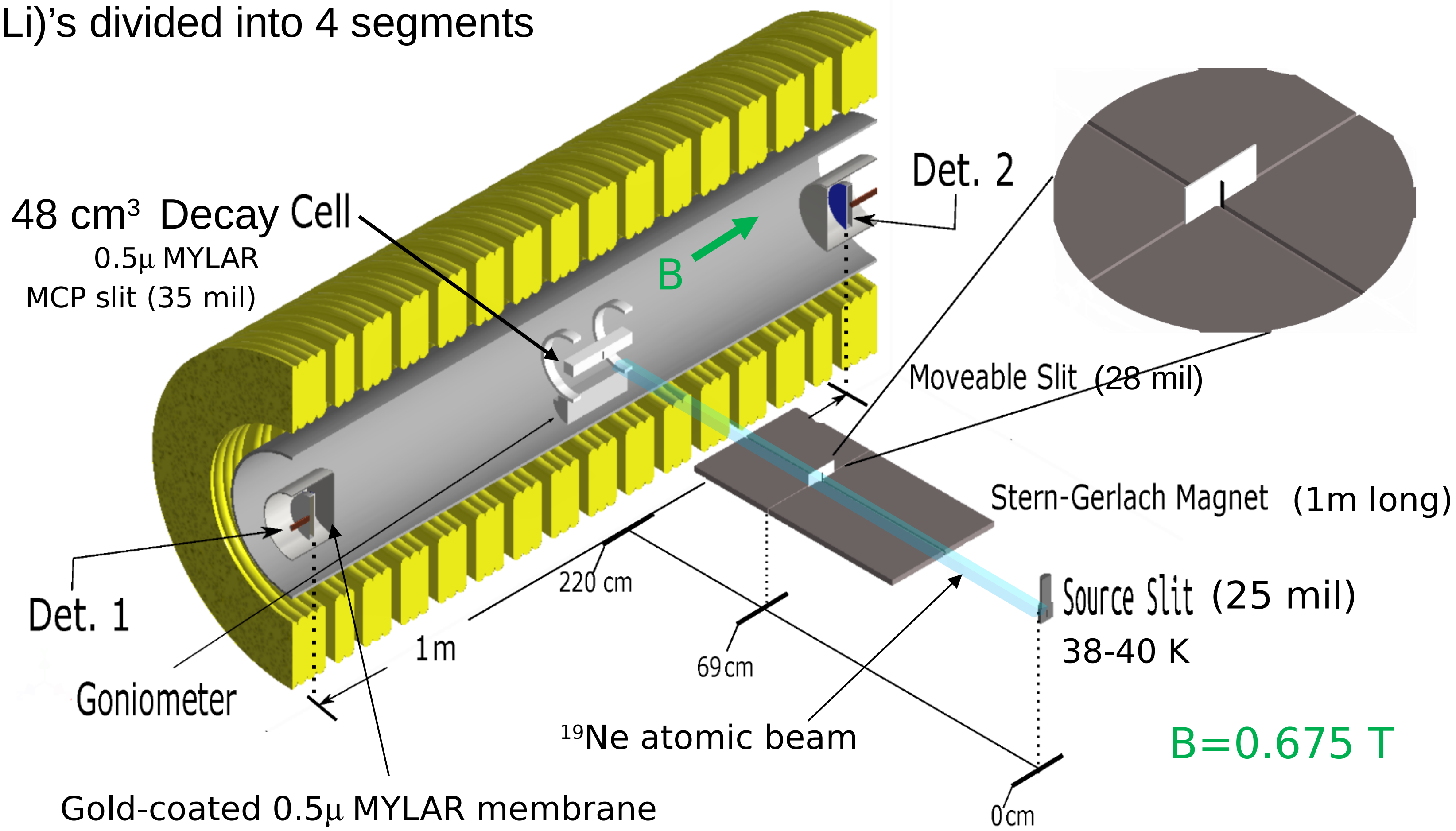
Severijns et al., PRC **78**, 055501 (2008)
Naviliat and Severijns, PRL **102**, 142302 (2009)

$M_F = 1$
$f_A/f_V = 1.0143(29)$
$(1+\Delta_R) = 1.02361(38)$
$(1+\delta_R) = 1.01533(12)$
$(1+\delta_{NS}) = .9948(4)$

Princeton/Berkeley Polarized Atomic Beam Apparatus

(State of the Art until well after 2000)

Detectors: 3 mm thick, 7.46 cm diam.
Si(Li)'s divided into 4 segments

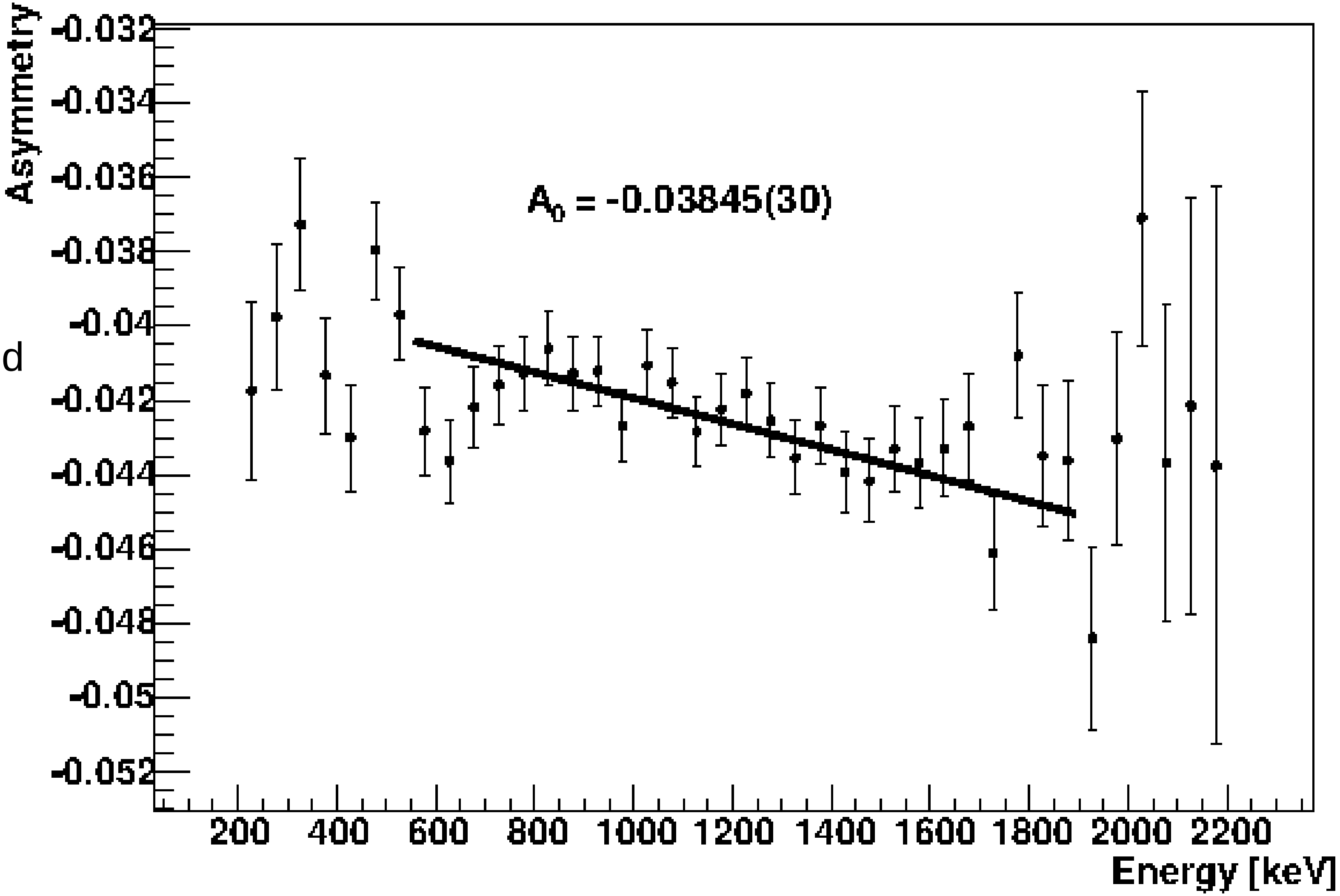


B=0.675 T

~2000 – 3000 polarized decays/sec in cell

Asymmetry

MC-corrected
asymmetry



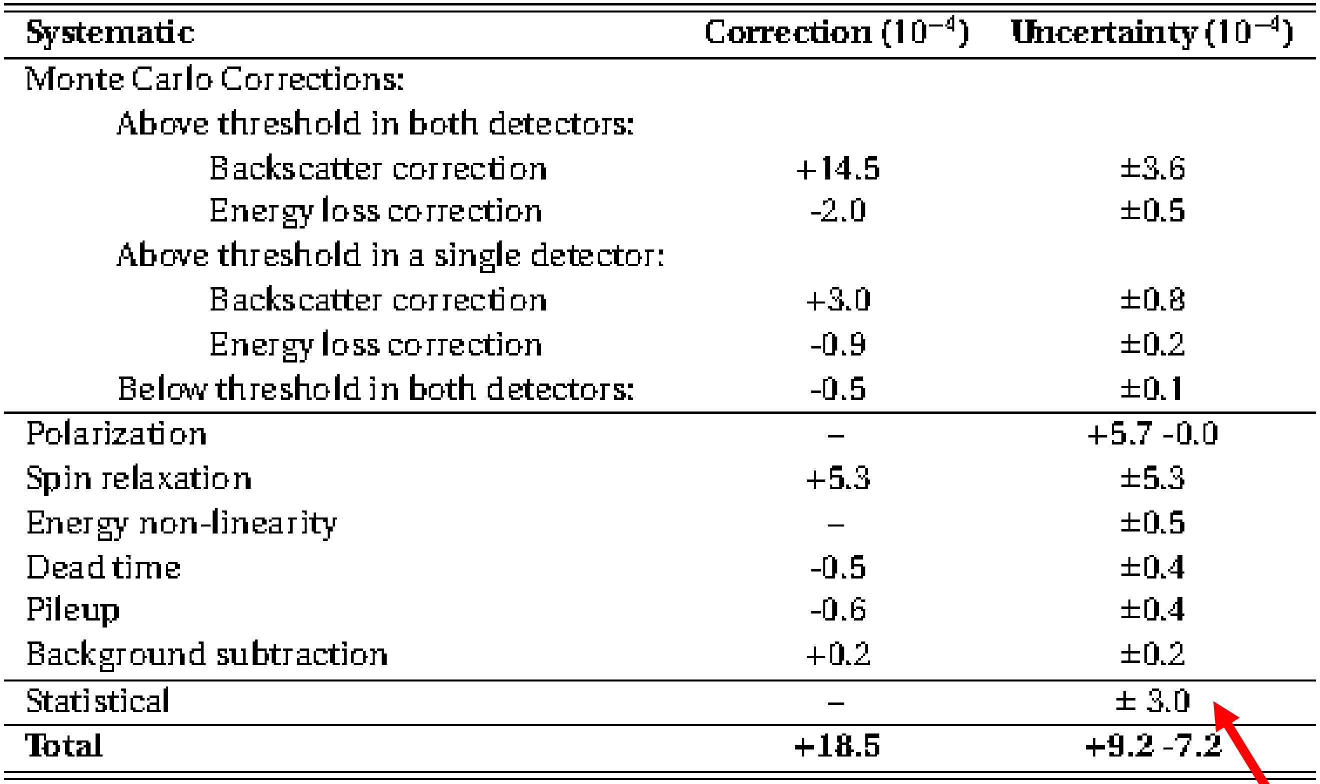
$$A_o = -0.03845\,{}^{+0.00087}_{-0.00065} \pm 0.00030_{stat}$$

ρ=-1.6015(29)

P=+1.6015(29) for convention of Severijns et al

Data taken in 1994; D. C. Combs Analysis 2017

Error Budget ^{19}Ne



Systematic	Correction (10^{-4})	Uncertainty (10^{-4})
Monte Carlo Corrections:		
Above threshold in both detectors:		
Backscatter correction	+14.5	±3.6
Energy loss correction	-2.0	±0.5
Above threshold in a single detector:		
Backscatter correction	+3.0	±0.8
Energy loss correction	-0.9	±0.2
Below threshold in both detectors:	-0.5	±0.1
Polarization	–	+5.7 -0.0
Spin relaxation	+5.3	±5.3
Energy non-linearity	–	±0.5
Dead time	-0.5	±0.4
Pileup	-0.6	±0.4
Background subtraction	+0.2	±0.2
Statistical	–	± 3.0
Total	**+18.5**	**+9.2 -7.2**

Not limited by statistics

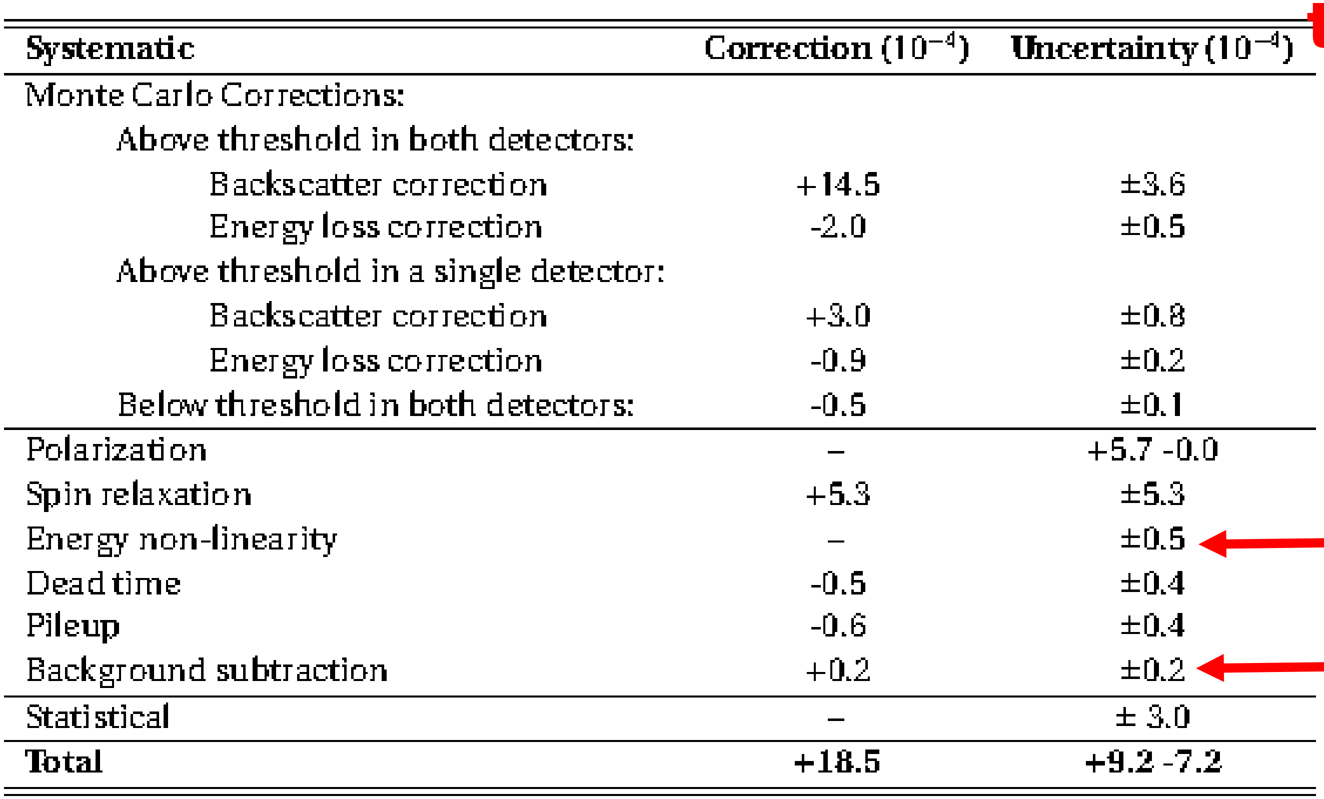
δA/A = 2.47%

(previous value, 3.9%)

Data taken in 1994; D. C. Combs Analysis 2017

Error Budget ^{19}Ne

Systematic errors: the usual suspects…



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Scattering corrections (2)

Polarization (1)

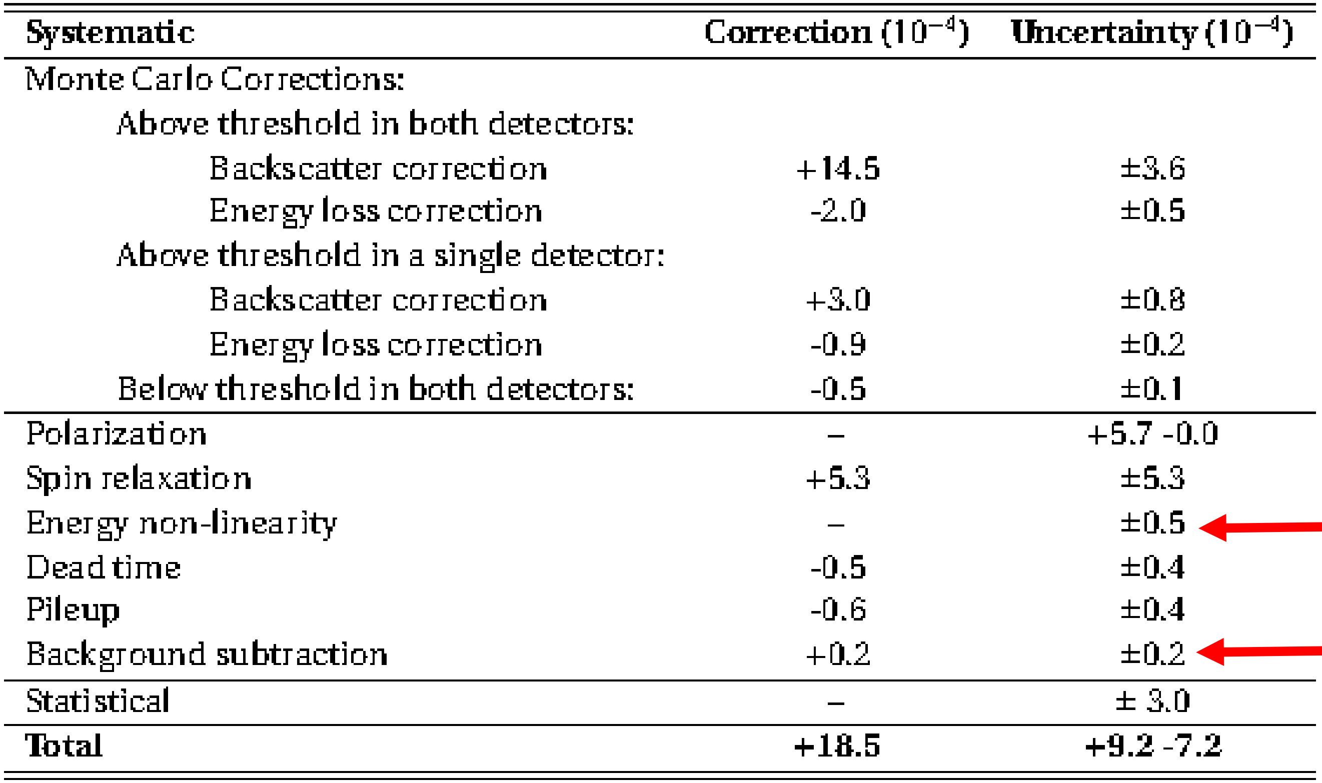
Calibration/linearity

Background Subtraction

$\delta A/A = 2.47\%$

Data taken in 1994; D. C. Combs Analysis 2017

Error Budget ^{19}Ne



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Scattering corrections (2)

Polarization (1)

Calibration/linearity

Note: A_o not sensitive

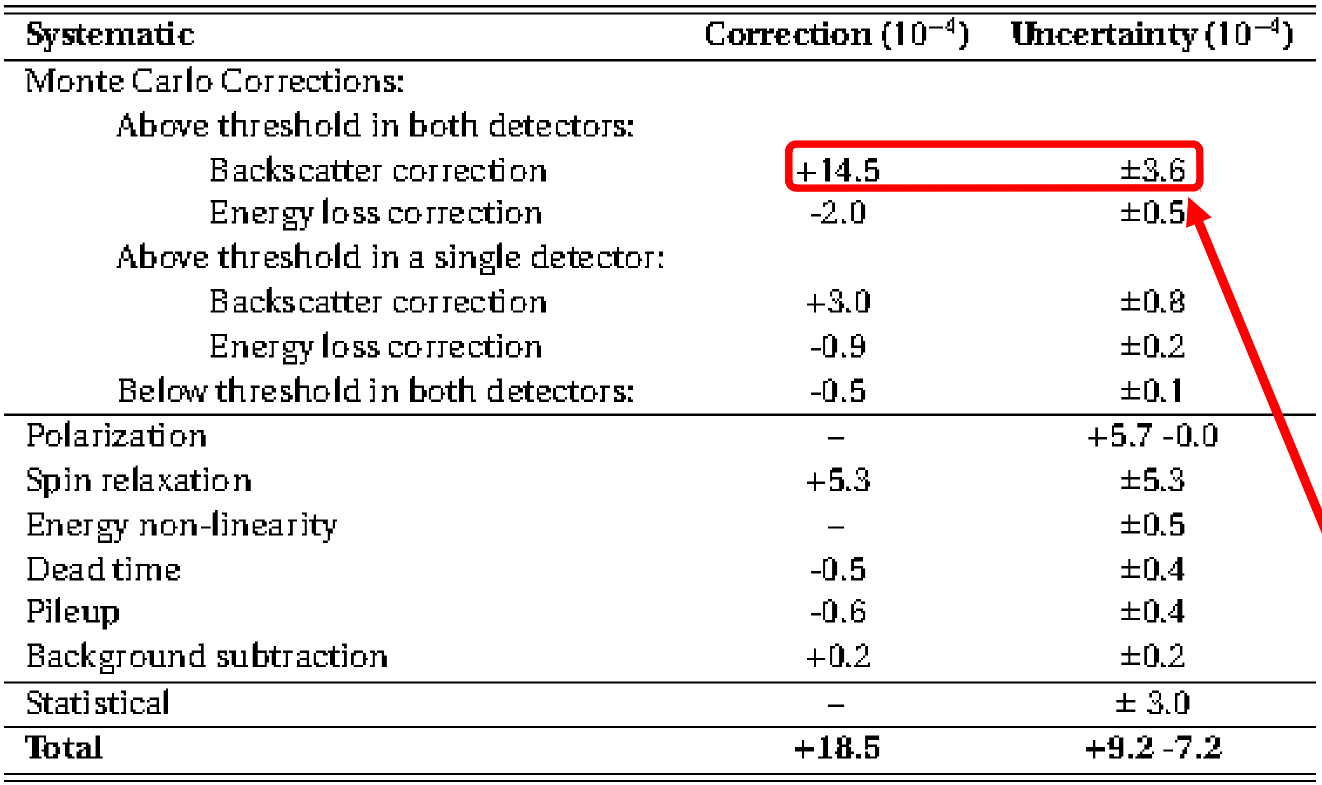
Background Subtraction

Note: signal to background ~ 111
not a challenge here...

$\delta A/A = 2.47\%$

Data taken in 1994; D. C. Combs Analysis 2017

Error Budget ^{19}Ne



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Scattering corrections (2)

(relatively large using Si dets)

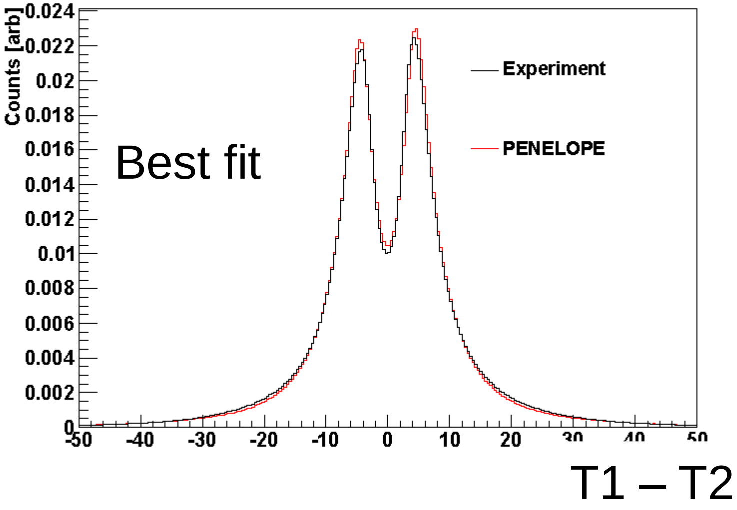
Polarization (1)

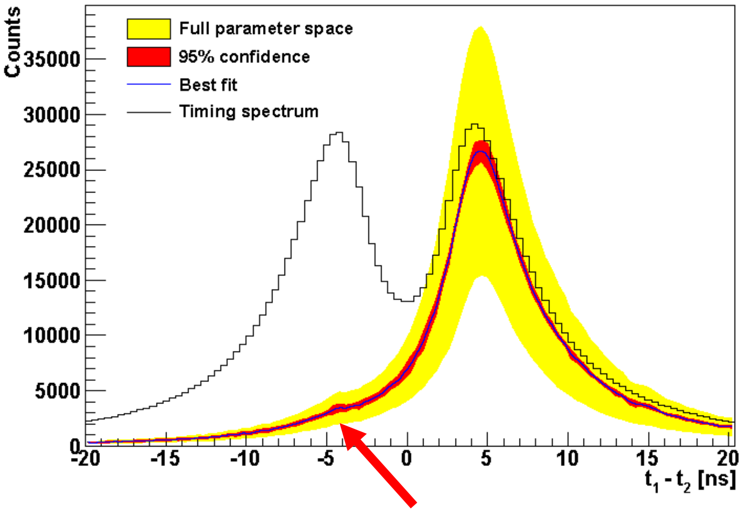
$\delta A/A = 2.47\%$

Dustin Combs thesis: re-analysis of scattering corrections,including backscattering reconstruction

Scattering Correction

Strategy: use timing to reconstruct backscatters which hit one detector (e.g. D1) and then scatter into the second (D2) – use T1-T2 to determine initial direction of beta!





Full PENELOPE model of both beta-asymmetry timing spectrum and timing calibration measurements, together with detector model including charge transport of quasiparticles in Si

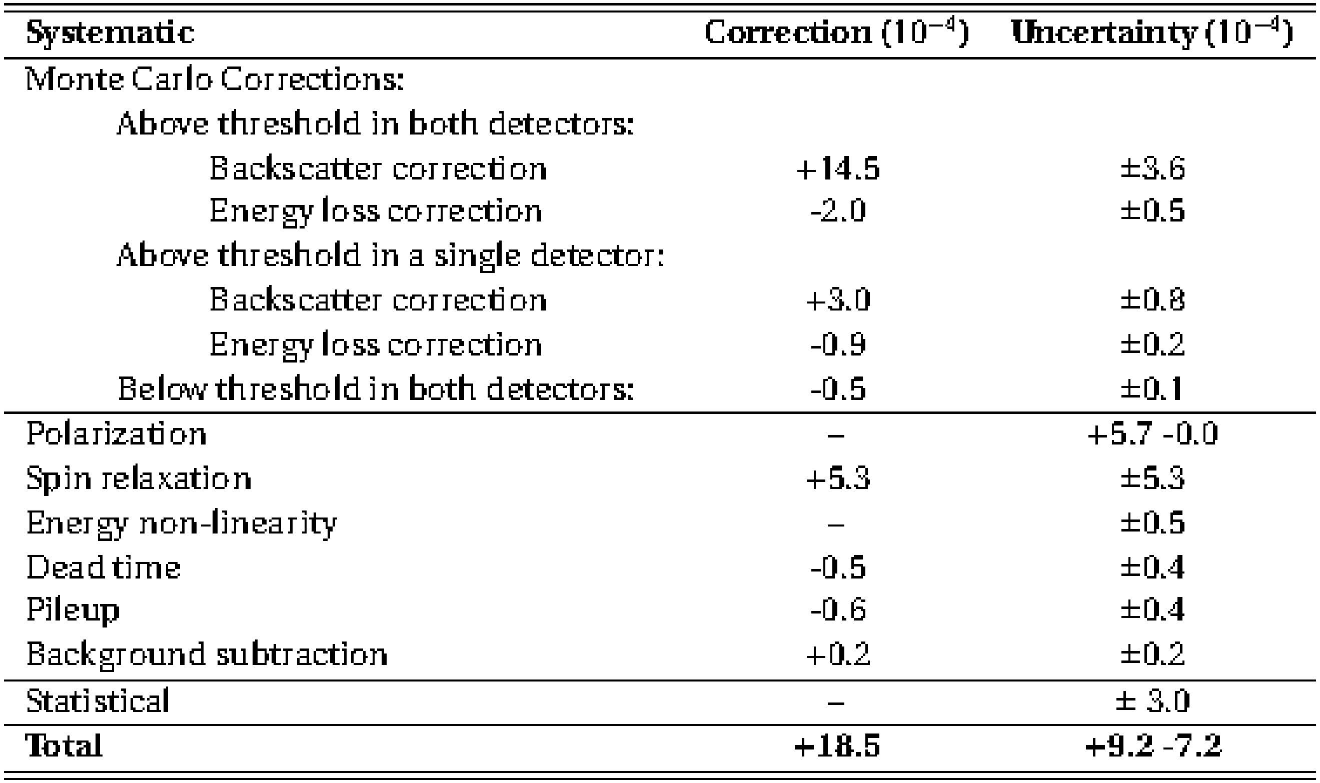
Overlap region results in Errors in assignment of dir!

$\Delta A_\beta / A_\beta = 3.8(0.9)\%$

PENELOPE v2002 – vetted with direct tests and in the UCNA experiment
Backscattering most challenging – 25% uncertainty assigned to MC results

Data taken in 1994; D. C. Combs Analysis 2017

Error Budget ^{19}Ne



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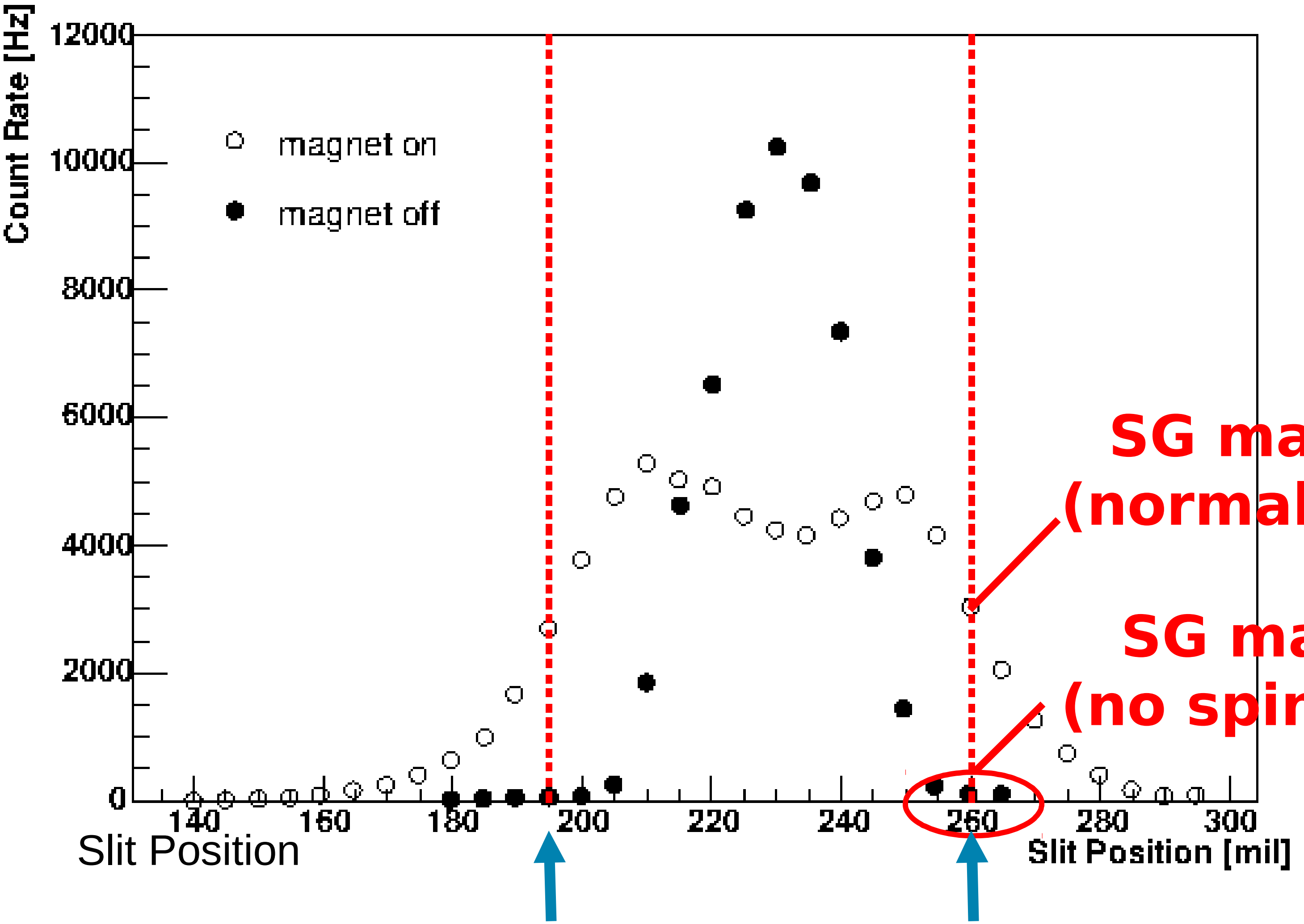
Scattering corrections (2)

Polarization (1)

$\delta A/A = 2.47\%$

Gordon Jones did an excellent job of optimizing the performance of the polarizer, a device in use for almost 40 years – expected polarization was > 99%

Polarization (old school)



SG magnet on (normal running)

SG magnet off (no spin selection)

Slit Position

δP < 1.5%

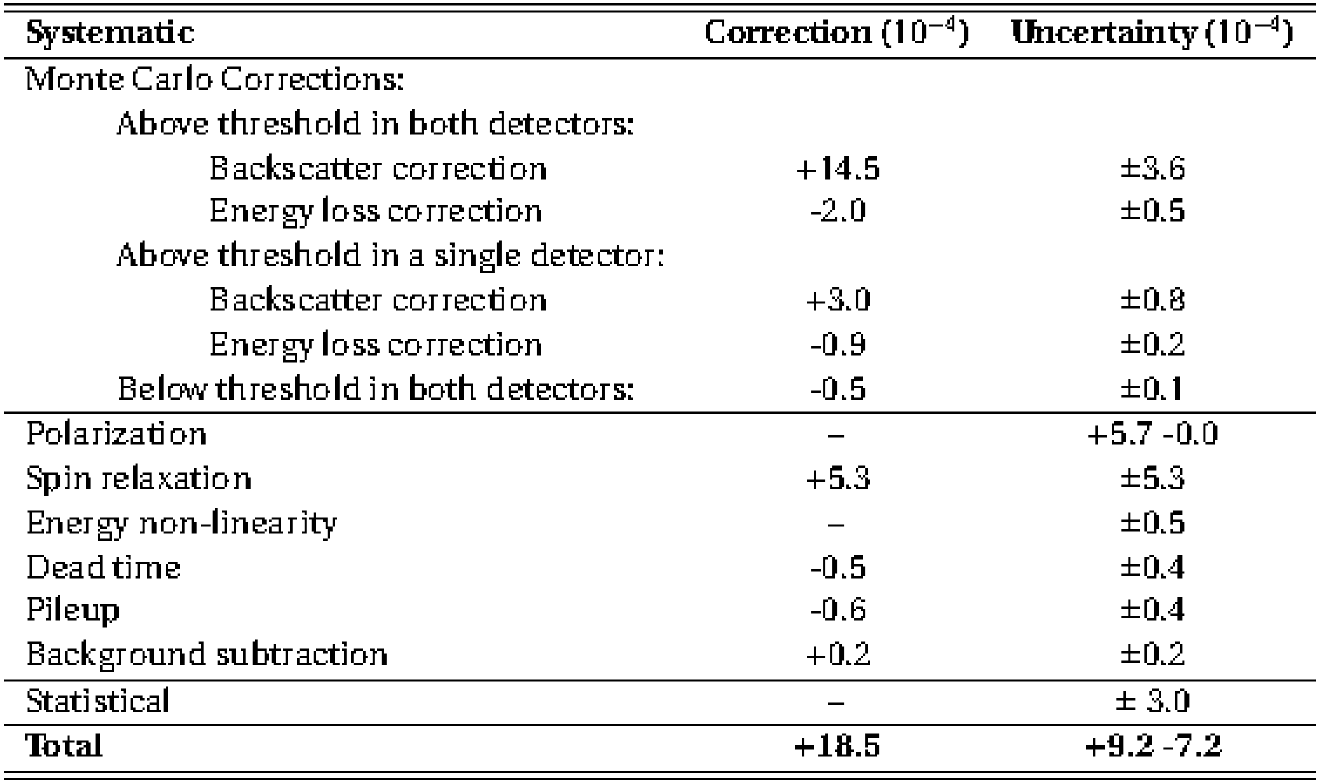
Run Settings

Determine maximum unpolarized background

Set conservative lower limit on polarization by assuming background completely depolarized

Data taken in 1994; D. C. Combs Analysis 2017

Error Budget ^{19}Ne



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Scattering corrections (2)

Polarization (1)

δA/A = 2.47%

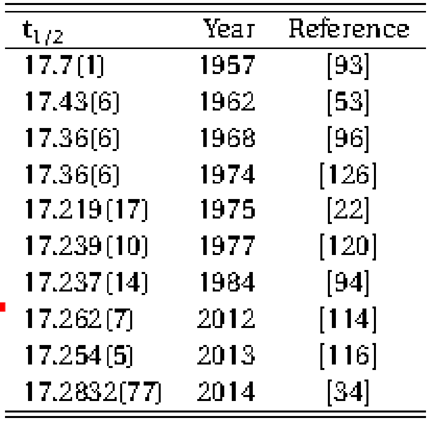
Extracting V_{ud}

Determined by beta asymmetry

$$f_V t(1+\delta_R')(1+\delta_{NS}^V-\delta_C^V) = \frac{K}{G_F^2 V_{ud}^2}\,\frac{1}{|M_F^0|^2 C_V^2 (1+\Delta_R^V)(1+\frac{f_A}{f_V}\rho^2)},$$

Determined by half-life, endpoint energy, etc...

Lifetime



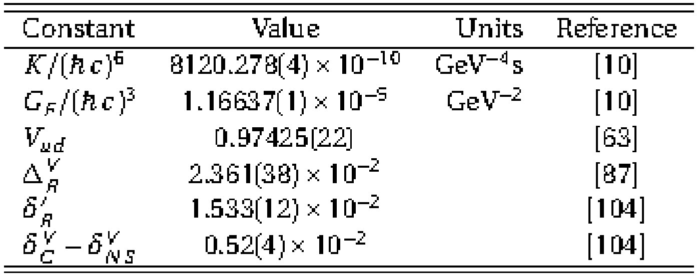
$t_{1/2}$	Year	Reference
17.7(1)	1957	[93]
17.43(6)	1962	[53]
17.36(6)	1968	[96]
17.36(6)	1974	[126]
17.219(17)	1975	[22]
17.239(10)	1977	[120]
17.237(14)	1984	[94]
17.262(7)	2012	[114]
17.254(5)	2013	[116]
17.2832(77)	2014	[34]

4 recent lifetime measurments, including TUNL group, with Average $t_{1/2}$ = 17.2574(32)

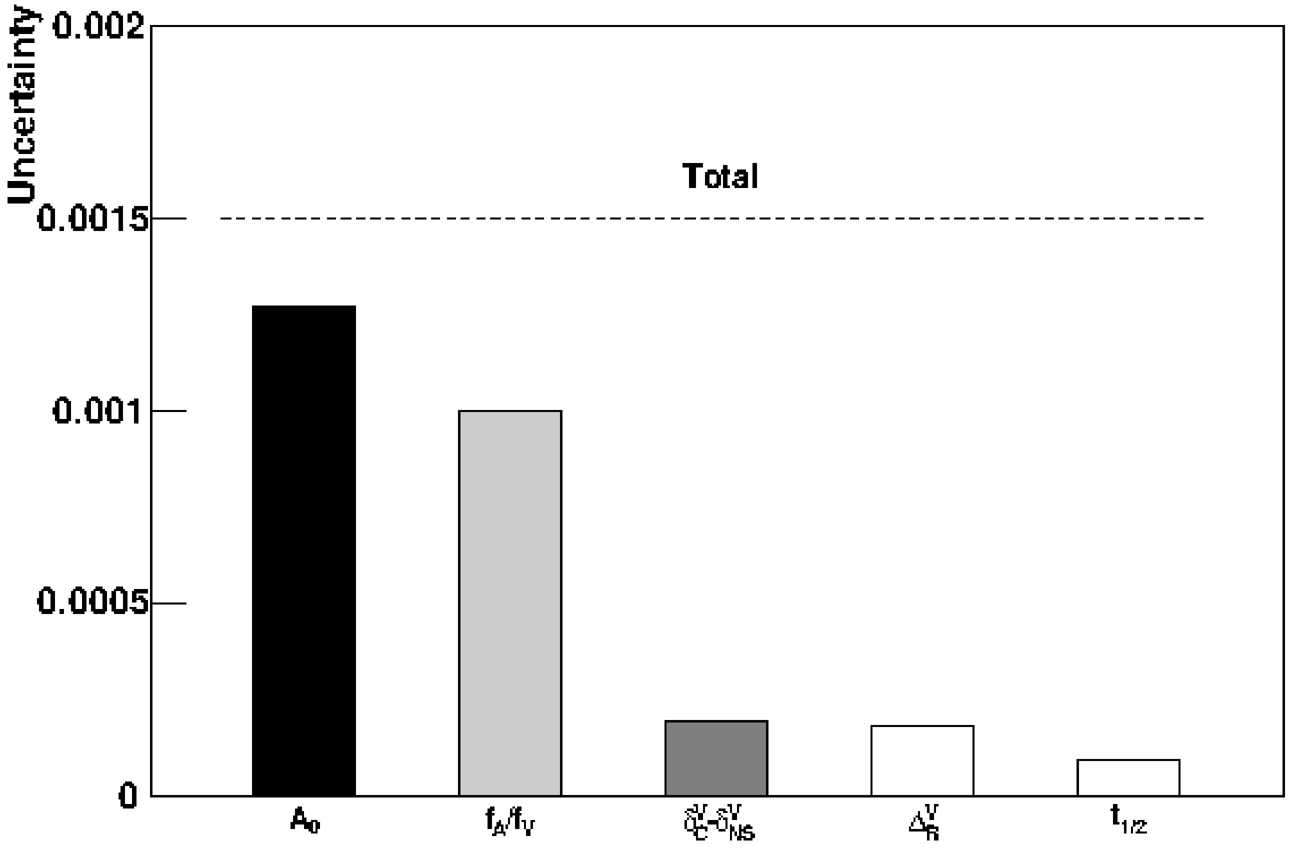
+ 17.2569(21) 2017

δ'_R, δ_{NS}, δ_C, Δ_V, f_A/f_V derived from theory!

Inputs



Constant	Value	Units	Reference
$K/(\hbar c)^6$	$8120.278(4)\times10^{-10}$	$\mathrm{GeV}^{-4}\mathrm{s}$	[10]
$G_F/(\hbar c)^3$	$1.16637(1)\times10^{-5}$	GeV^{-2}	[10]
V_{ud}	0.97425(22)		[63]
Δ_R^V	$2.361(38)\times10^{-2}$		[87]
δ_R'	$1.533(12)\times10^{-2}$		[104]
$\delta_C^V-\delta_{NS}^V$	$0.52(4)\times10^{-2}$		[104]


Uncertainty
0.002
0.0015
0.001
0.0005
0
Total
A_0
f_A/f_V
$\delta_C^V-\delta_{NS}^V$
Δ_R^V
$t_{1/2}$

$V_{ud} = 0.9698(16)$

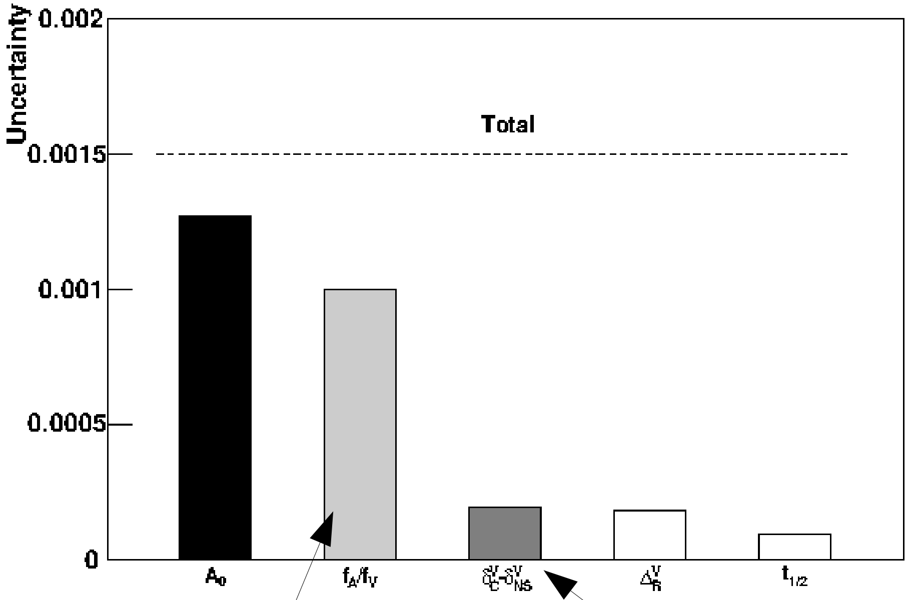
Status of ^{19}Ne

- Overall uncertainty $dA_\beta/A_\beta = 2.47\%$
- Leading uncertainty from polarization (1.5% from beam polarization, 1.1% from depolarization), next is scattering (0.9%)
- Lifetime uncertainty ~0.02%
- Results in $\delta V_{ud}/V_{ud} = 0.16\%$ for ^{19}Ne alone (superior to the PDG 2018 neutron value)
- Uncertainty from A now comparable to theory uncertainties (f_A/f_V)!

Theory Needs

$$f_V t(1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C) = \frac{K}{G_F^2 V_{ud}^2}\frac{1}{|M_F^0|^2 C_V^2(1+\Delta^V_R)(1+\frac{f_A}{f_V}\rho^2)},$$

One other quantity that depends weakly on a shell-model calculation is the ratio f_A/f_V (column 4 in Table VIII). Here a modest shell-model calculation is sufficient. We can also use these shell-model calculations to determine the relative sign of the Fermi and Gamow-Teller matrix elements, which can then be taken as the sign of ρ in Eq. (22). Finally, the resulting Ft mirror values and corresponding values for ρ (using $Ft^{0+\rightarrow 0+}$ = (3071.4 ± 0.8) s [25], and assigning an error of 20% to the calculated deviations of f_A/f_V from unity) are recorded in Table IX.



Modest improvement movtivated

Need order of magnitude improvement!

$$\frac{\partial |V_{ud}|^2}{\partial r} \approx -\rho^2$$

$$r = \frac{f_A}{f_V}$$

ρ^2 a factor of 4 or more greater than other mirrors except neutron (where f_A/f_V correction is order 10^{-5})

Next Generation Angular Correlations

How has the field moved forward to improve?

- Ion trap measurements of the beta-neutrino correlations, $a_{\beta\nu}$
- Laser trap measurements of A_{β}, $a_{\beta\nu}$

How to improve precision:

- Produce highly localized, “massless” source (no cell)

  Ion and optical traps ideal
- Reduce/eliminate scattering effects from grids, apertures, detectors

  Use position sensitive reconstruction, low mass, low Z components
- Eliminate backgrounds

  Two-stage trapping, pure samples, coincidence signals, event reconstruction

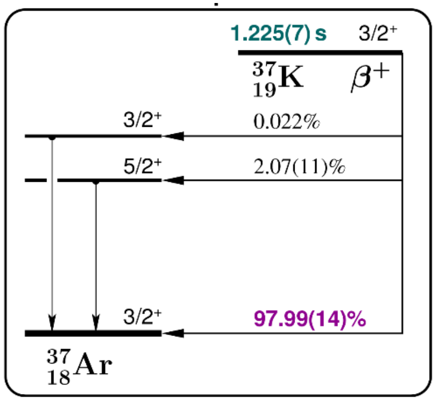
Common elements of current expts

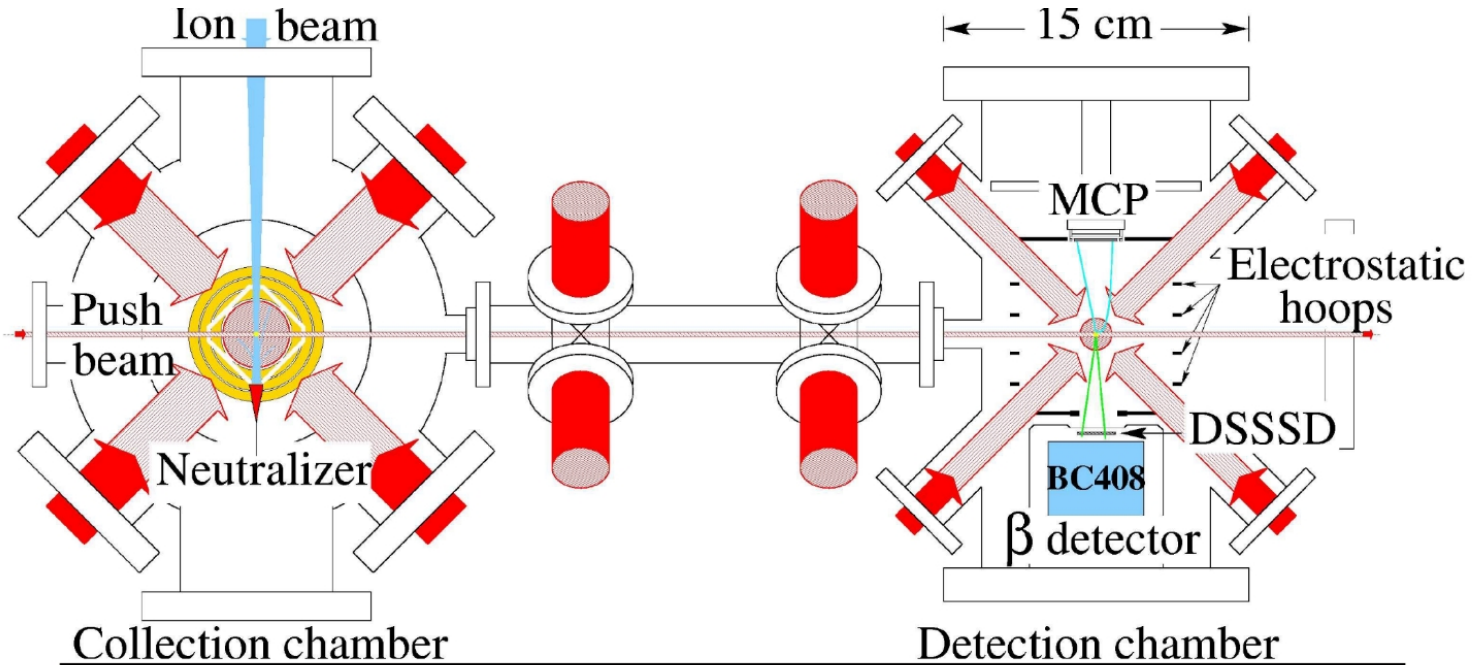
When are we projected to be ready for an significant jump in the precision of these measurements?

Now!

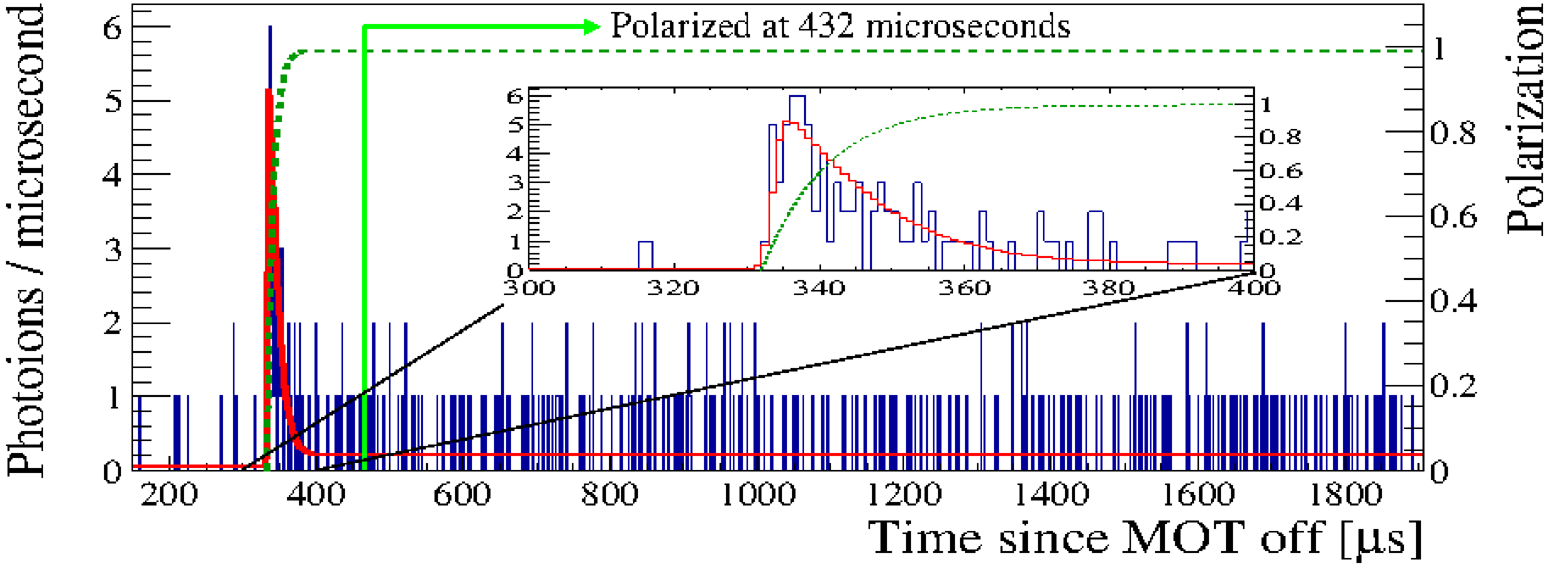
Example:

Laser-trapped species include Alkali metals (^{37}K) and meta-stable noble gas atoms (^{19}Ne)



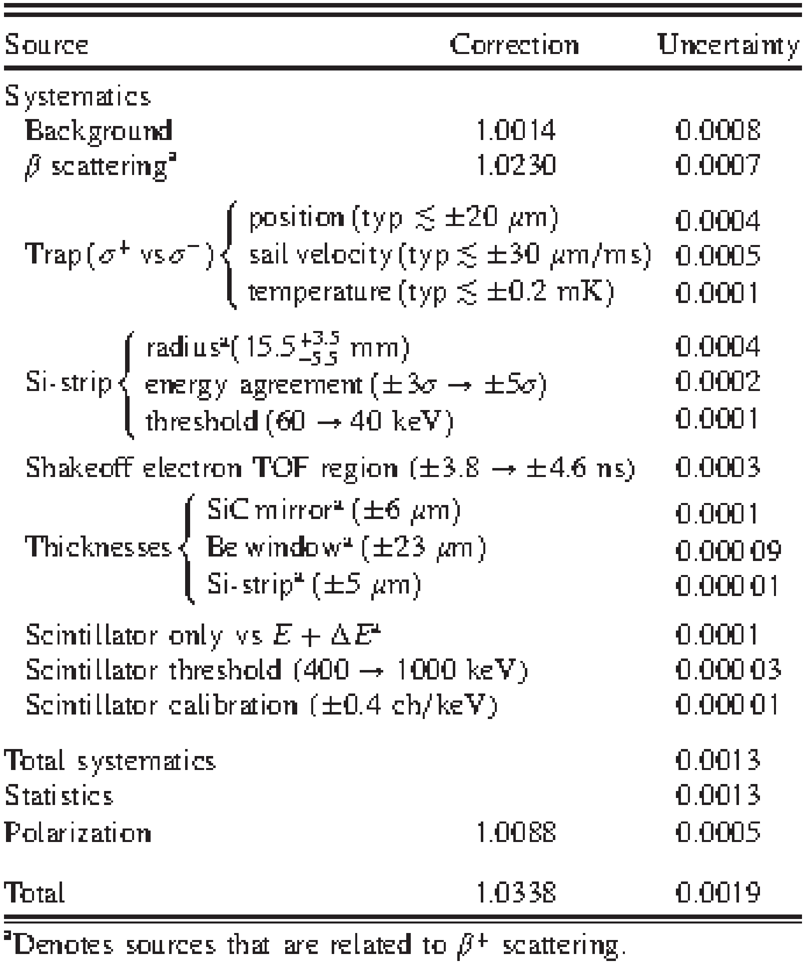


Over order of magnitude improvement relative to Princeton Measurement



In situ polarimetry to 0.05% (!)

Over order of magnitude improvement relative to Princeton Measurement



Source	Correction	Uncertainty
Systematics		
Background	1.0014	0.0008
β scattering[a]	1.0230	0.0007
Trap (σ^+ vs σ^-): position (typ $\lesssim \pm 20$ μm)		0.0004
sail velocity (typ $\lesssim \pm 30$ μm/ms)		0.0005
temperature (typ $\lesssim \pm 0.2$ mK)		0.0001
Si-strip: radius[a] ($15.5^{+3.5}_{-5.5}$ mm)		0.0004
energy agreement ($\pm 3\sigma \rightarrow \pm 5\sigma$)		0.0002
threshold (60 → 40 keV)		0.0001
Shakeoff electron TOF region (±3.8 → ±4.6 ns)		0.0003
Thicknesses: SiC mirror[a] (±6 μm)		0.0001
Be window[a] (±23 μm)		0.00009
Si-strip[a] (±5 μm)		0.00001
Scintillator only vs $E + \Delta E$[a]		0.0001
Scintillator threshold (400 → 1000 keV)		0.00003
Scintillator calibration (±0.4 ch/keV)		0.00001
Total systematics		0.0013
Statistics		0.0013
Polarization	1.0088	0.0005
Total	1.0338	0.0019

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

Leading systematic corrections come from scattering and backgrounds

Total precision improved by an **order of magnitude**

Technology exists to push ^{19}Ne to precision levels competitive with superallowed decays!

Implications

- Incredible progress made on scattering corrections and polarimetry open the door to sub-.1% measurements on ^{19}Ne (being pursued by Ron's group at HUJI), ^{37}K and ^{21}Na! This will certainly impact the global beta decay landscape…

- Theory input is also needed. In the short run, the precision of f_A/f_V must be specified over an order of magnitude more precisely for ^{19}Ne. In the longer run, a deeper understanding of the nuclear structure corrections are needed to convincingly establish precision levels at the 0.02% level and below!

Would high precision beta spectra help constrain NS models?