A direct measurement of the muon neutrino mass by pion decay in flight

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Potential Fermilab Muon Campus & Storage Ring Experiments

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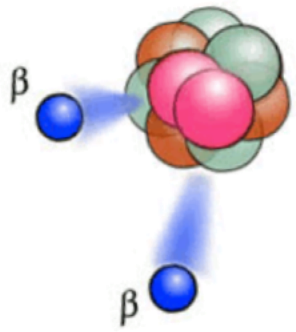
BNL NuMass Experiment
Approved 20 years ago as BNL Experiment E952

“The Committee was impressed by the quality of the P952 proposal. The improvement of the limit on the muon neutrino mass by a factor of 20 over the current limit will be a major advance. The experiment makes ingenious use of BNL's investment in the g-2 storage ring by using it as a spectrometer and so is uniquely matched to BNL's capabilities. The collaboration, consisting of many members of the g-2 group, along with some new members, has the expertise to successfully mount this challenging experiment The PAC feels that this is a *must do* experiment and that the laboratory should approve P952 and move forward as expeditiously as possible. “

Access to the neutrino mass

Neutrinoless double beta decay: ^{76}Ge, ^{130}Te, ^{136}Xe

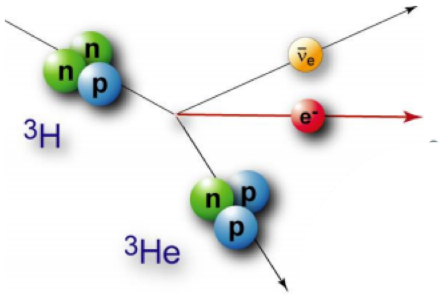


Model-dependent
Majorana neutrino

Kinematics of weak decay

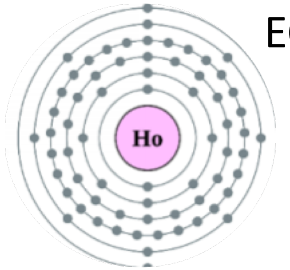
Model-independent
Conservation of E, p

tritium beta decay: Project 8, KATRIN



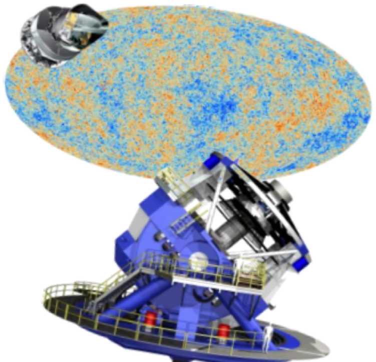
Electron capture on ^{163}Ho:

ECHo, Holmes



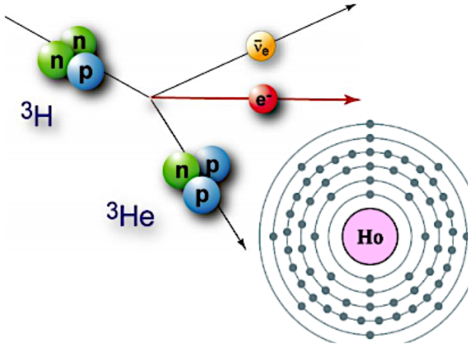
Cosmology: Large scale structure via CMB, GRS, lensing

Model-dependent
ΛCDM



Current Mass Limits for SM neutrinos

$m(\nu_e)$



tritium beta decay

< 2 eV (95% CL) Mainz and Troisk

< 0.8 eV (90% CL) KATRIN 2021 ➔ **0.2 eV** (90% CL)

Project 8 (CRES technique) ➔ **< 2 eV** ➔ **< 0.04 eV ?**

Electron capture on ^{163}Ho: ECHo, Holmes ➔ **< 1.5 eV** (90% CL)

< 23 eV TOF spread from SN1987A

< 0.1 eV Double β-decay for Majorana ν's ➔ **< 0.01 eV** in 5-10 years.

$m(\nu_\mu)$ **< 190 keV** $\pi \rightarrow \mu\nu$ (stopping π's)

$m(\nu_\tau)$ **< 18.2 MeV (90% CL)** Inv. Mass of $\tau \rightarrow \nu$ + hadrons (e^+e^- Colliders)

$\Sigma m(\nu_i)$ **< 0.2 eV** ΛCDM Cosmology

Current Limits on Sterile Neutrinos

D.A. Bryman and R. Shrock, Phys Rev D 100, 073011 (2019)

$$\nu_\ell = \Sigma_{i=1}^{3+k} U_{\ell i} \nu_i$$

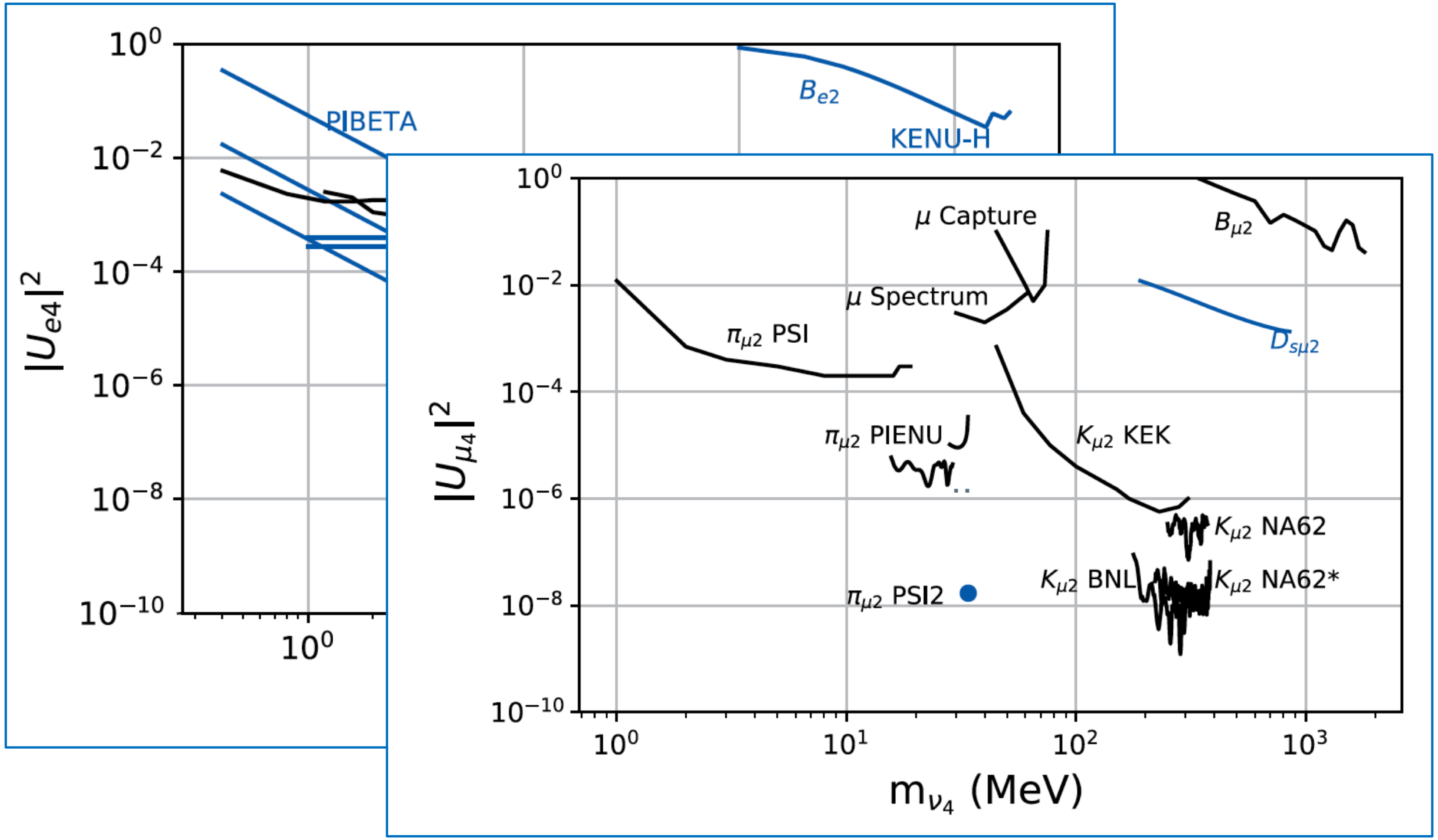
$$\ell = e, \mu, \tau, \chi_1, \chi_2 \ldots \chi_k$$

heavy υ

Kinematic factor

$$R_{ei} = \frac{\Gamma(\pi \to e\nu_i)}{\Gamma(\pi \to e\nu_l)} = |U_{ei}|^2 \rho_{ei}$$

conventional υ

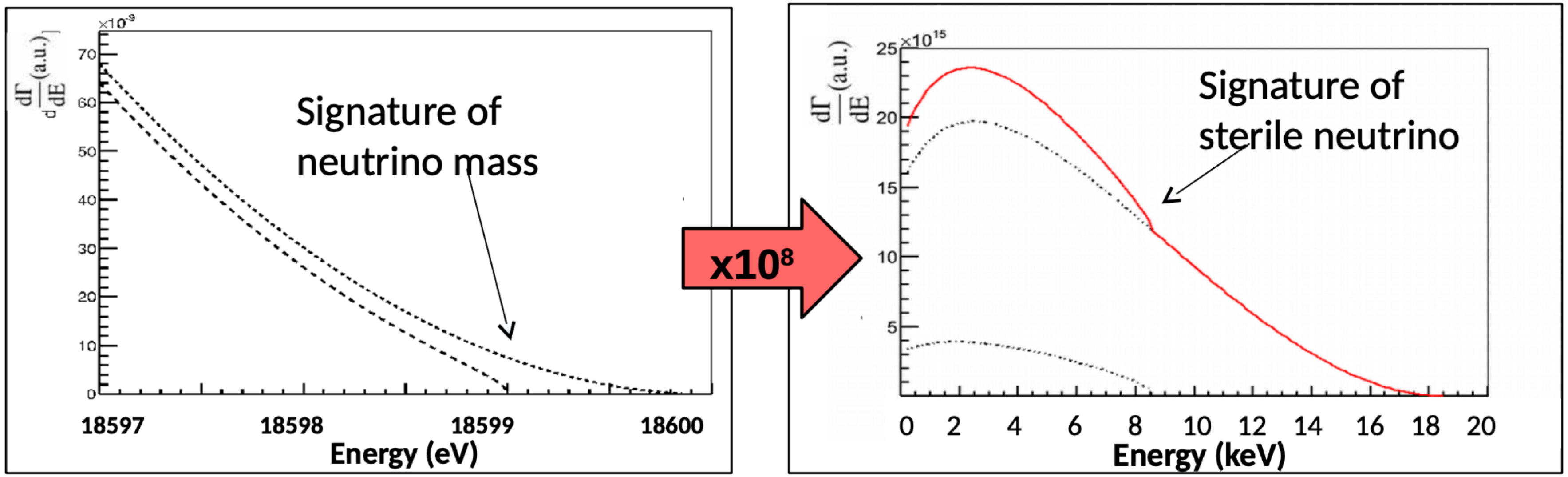


Nuclear beta decay: Search for kinks in Kurie plots, decay rate anomalies

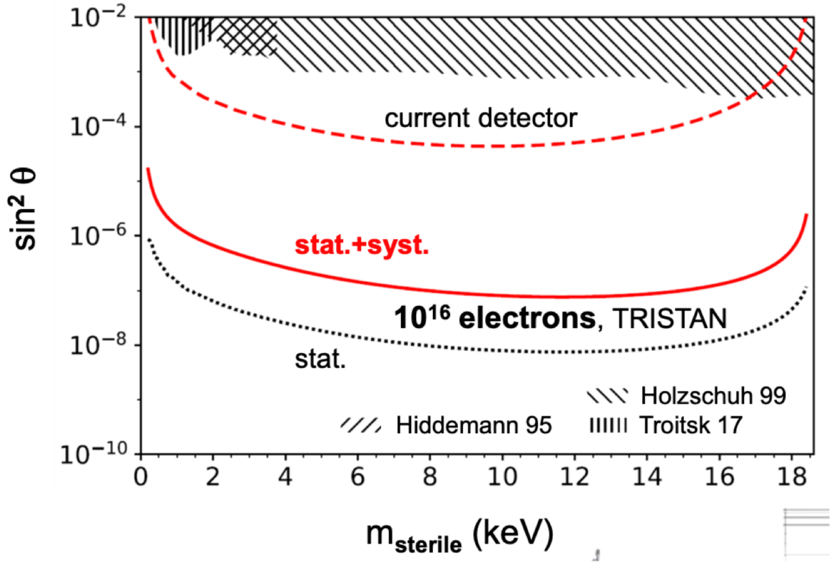
Two-body leptonic decays: peak searches and decay rate analysis

New Limits on Sterile Neutrinos expected from TRISTAN (@KATRIN)

TRitium
Investigation on
STerile (**A**)
Neutrinos



$$\frac{dN}{dE} = \cos^2\theta_s \cdot \frac{dN}{dE}(m_{active}) + \sin^2\theta_s \cdot \frac{dN}{dE}(m_{sterile})$$



DIRECT MEASUREMENTS OF M(ν_μ)

Pure 2-body decay $\pi \to \mu\ \nu$

- No model-dependent nuclear/atomic environment
- Pions live a reasonably long time

Two types of Experiments

Pion Decay at Rest

Parent π momentum is well-known
Limited by the uncertainty in the pion mass

$$p_\mu^2 + m_\mu^2 = \frac{\left[m_\pi^2 + m_\mu^2 - m_\nu^2\right]^2}{4m_\pi^2}$$

Pion Decay in Flight

Need to measure p_π-p_μ
Momentum Resolution limited by
multiple scattering in detectors

$$m_\nu^2 = \left[\sqrt{p_\mu^2 + m_\mu^2} - \sqrt{p_\pi^2 + m_\pi^2}\right]^2 - p_\nu^2$$

DIRECT MEASUREMENTS OF $M(\nu_\mu)$

Pion Decay at Rest

Series of experiments at PSI with final best limit given by $m(\nu_\mu) < 190\ \mathrm{keV/c^2}$ (90% CL)

Solution B after adjusting for the newer charged pion mass measurements via X-ray spectroscopy of exotic atoms

1996: Assamagan et al. Phys Rev D53 p.6065
Solution A: $m^2(\nu_\mu) = -0.143 \pm 0.024$ (MeV/c²)²
Solution B: $m^2(\nu_\mu) = -0.016 \pm 0.023$ (MeV/c²)²

Pion Decay in flight

Best limit given by $m(\nu_\mu) < 500$ keV/c²

1982: Anderhub et al. Phys Lett B114 p.76
$m^2(\nu_\mu) = -0.14 \pm 0.20$ (MeV/c²)²

Limit expected from BNL NuMass Experiment limit < 8 keV/c² (< 1 keV/c² @ FNAL?)
Huge parameter space between 1- 500 keV to be explored for admixtures of sterile neutrinos or other decays

The g-2 Storage Ring

g-2 Experiment **Weak-focusing Storage Ring: Muons stored for 800 ms**

Bunched beam
Electrostatic Quadrupoles
Muon Kicker

NuMass Experiment **Spectrometer: $\pi \to \mu\nu$ observed evt-by-evt**

Dribble the beam out
Deliver pions and protons to ring
Pion kicker without transients, no quads

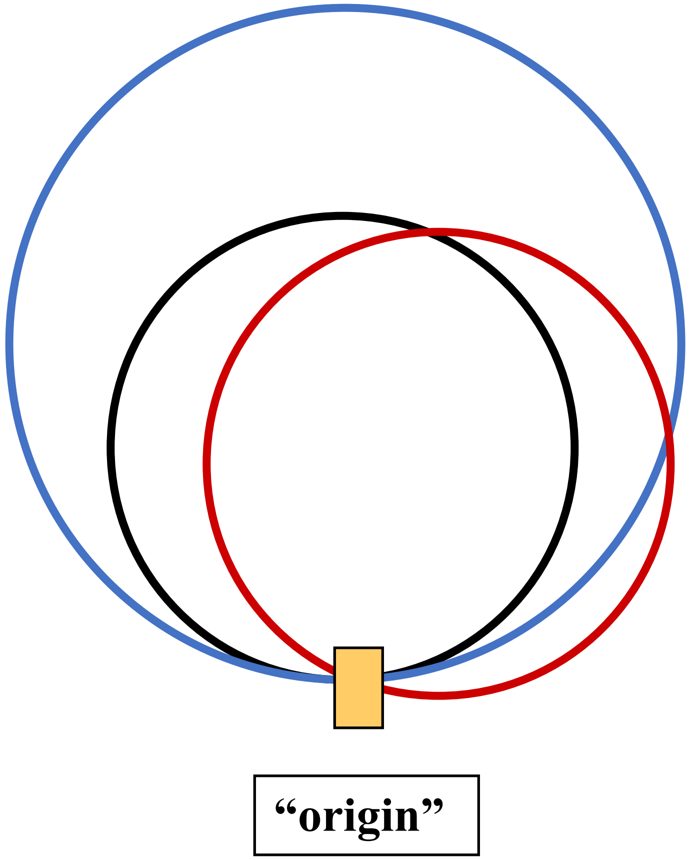
Keep the Same Momentum - 3 GeV

Retain excellent shimming and B-field uniformity
0.1 ppm over 4.5 cm
Trolley runs in vacuum to map field
Fixed probes to track changes
Active shimming and thermal insulation to minimize change

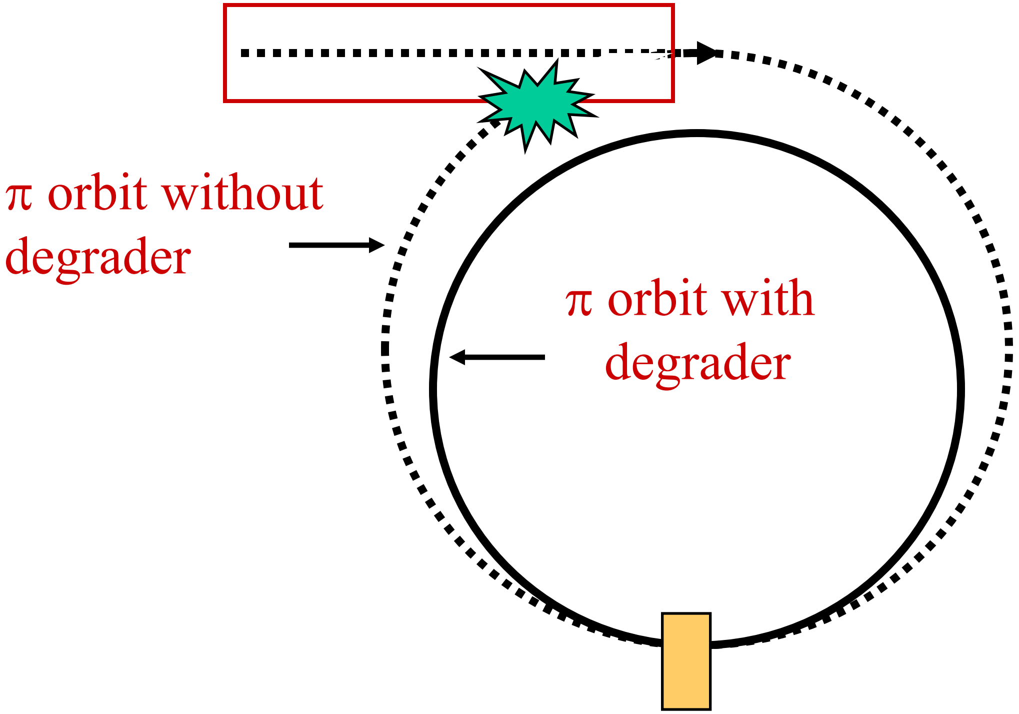
In a perfectly uniform B-field
Any charged particle returns to origin independent of B, p, θ

- Origin can produce a range of angles and momenta
- Uniformity is more important than value of B
- 1st harmonic (and other nonuniformities) are always monitored

  ➔ using residuals of pre-scaled protons and undecayed pions



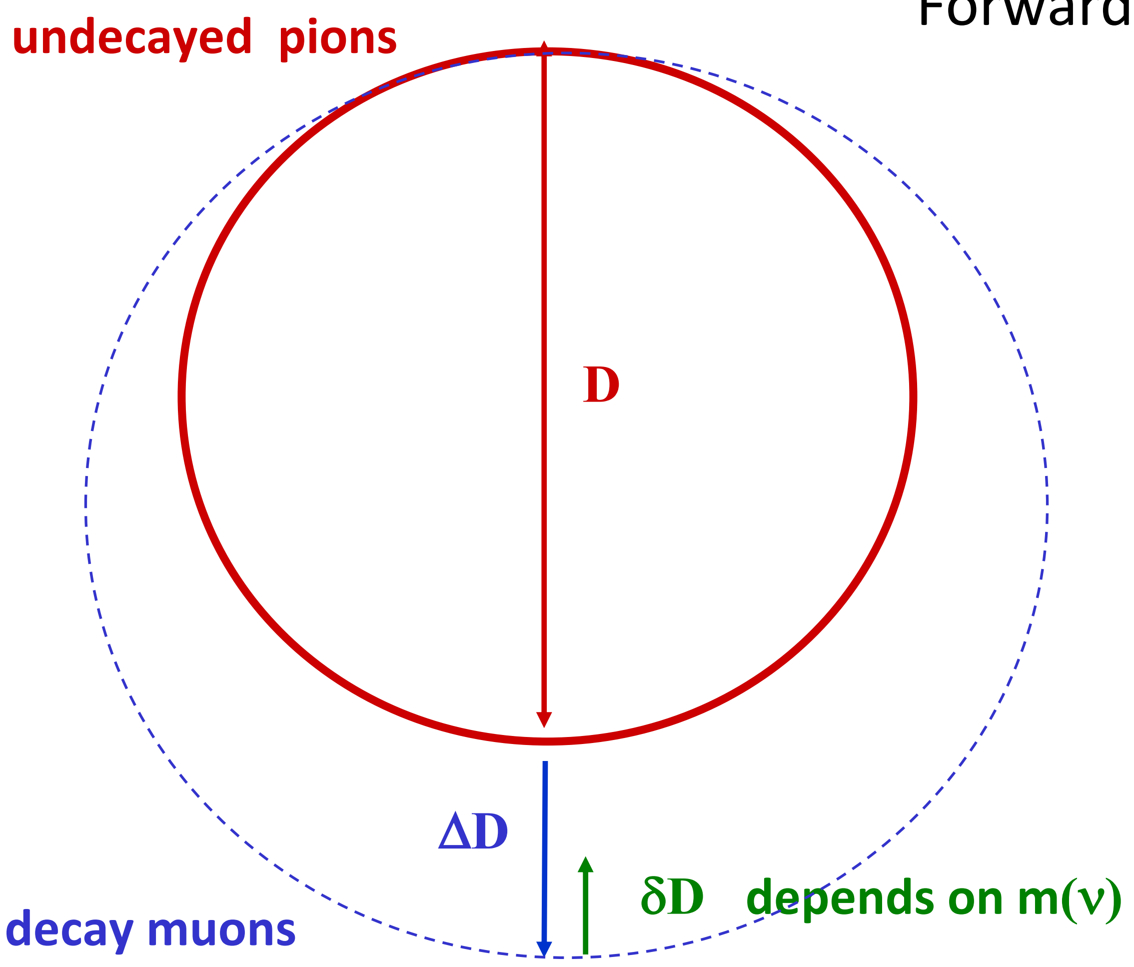
Put pions on orbit using dE/dx Injection with 5.2 cm Beryllium



"Pion Kicker"

$\Delta p = -16.2$ MeV/c
$X/X_o = 14.7$ %
θ (rms) = 1.56 mr

Conceptual Design



Forward-going decay muons orbit a larger diameter by ΔD

q = 29.7 MeV/c

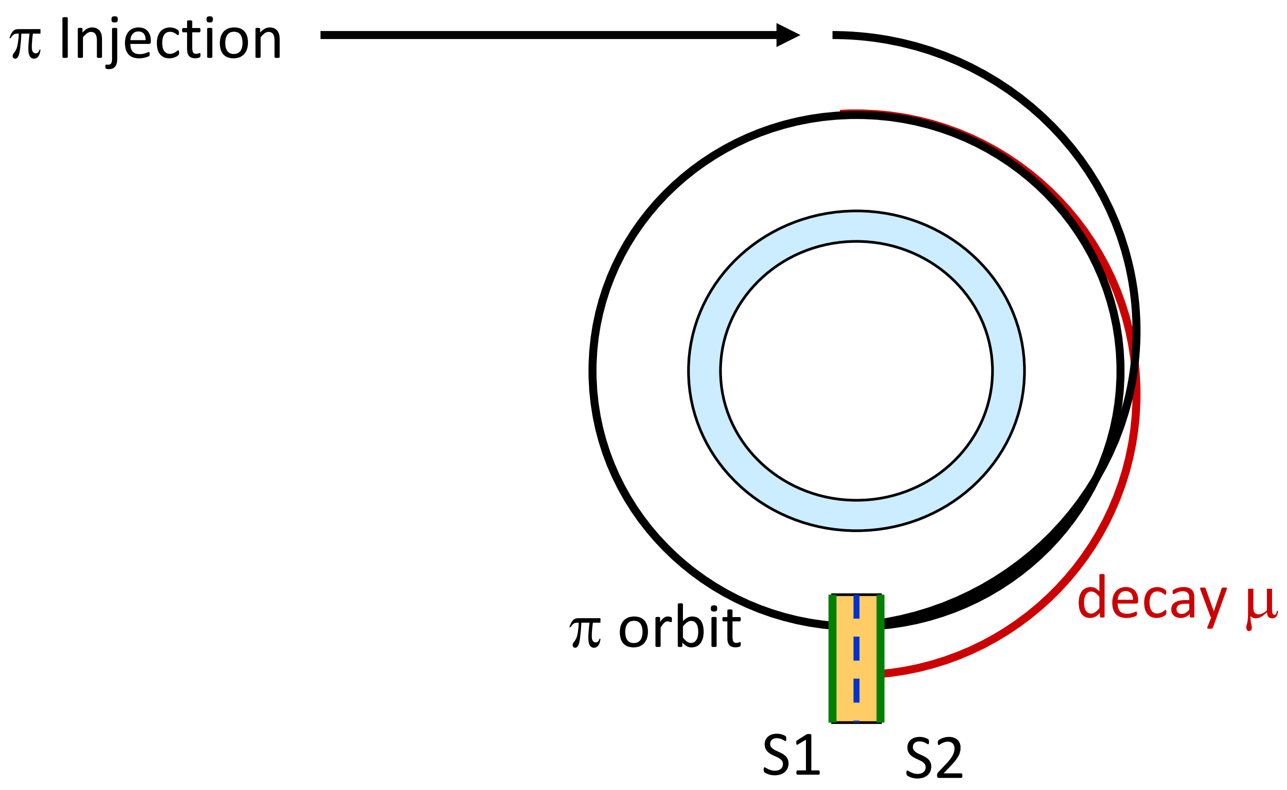
$\nu_\mu \longleftarrow \pi \longrightarrow \mu$

$$\frac{\Delta D}{D} = \frac{p_\mu - p_\pi}{p_\pi} = \frac{0.7\ MeV/c}{3\ GeV/c} = \frac{3.26\ mm}{14\ m}$$

non-zero m_ν shrinks ΔD by δD

$$\frac{\delta D}{D} = \frac{-m_\nu^2}{2qm_\pi}$$ = 0.04 mm for current limit

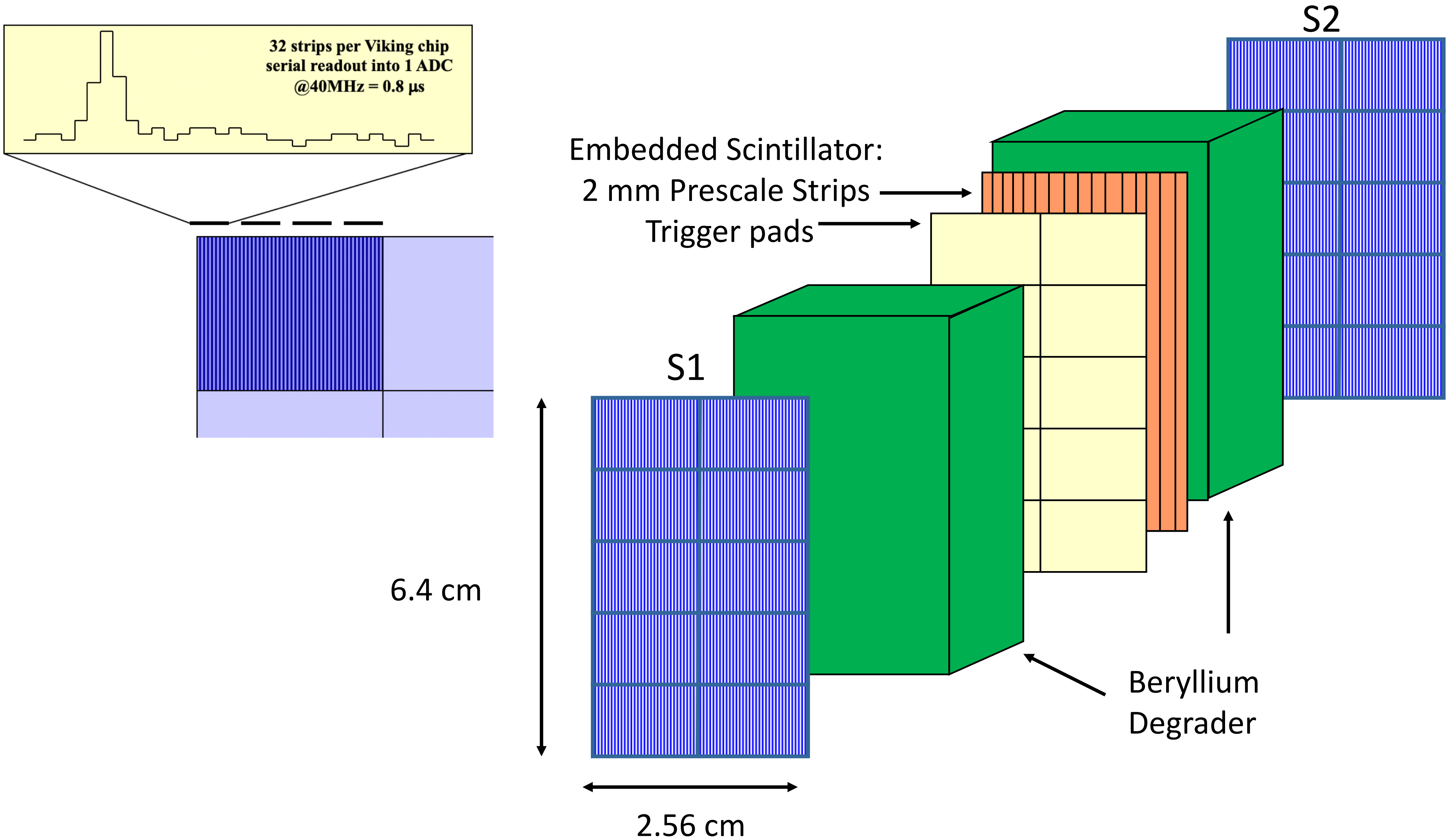
Experimental Method



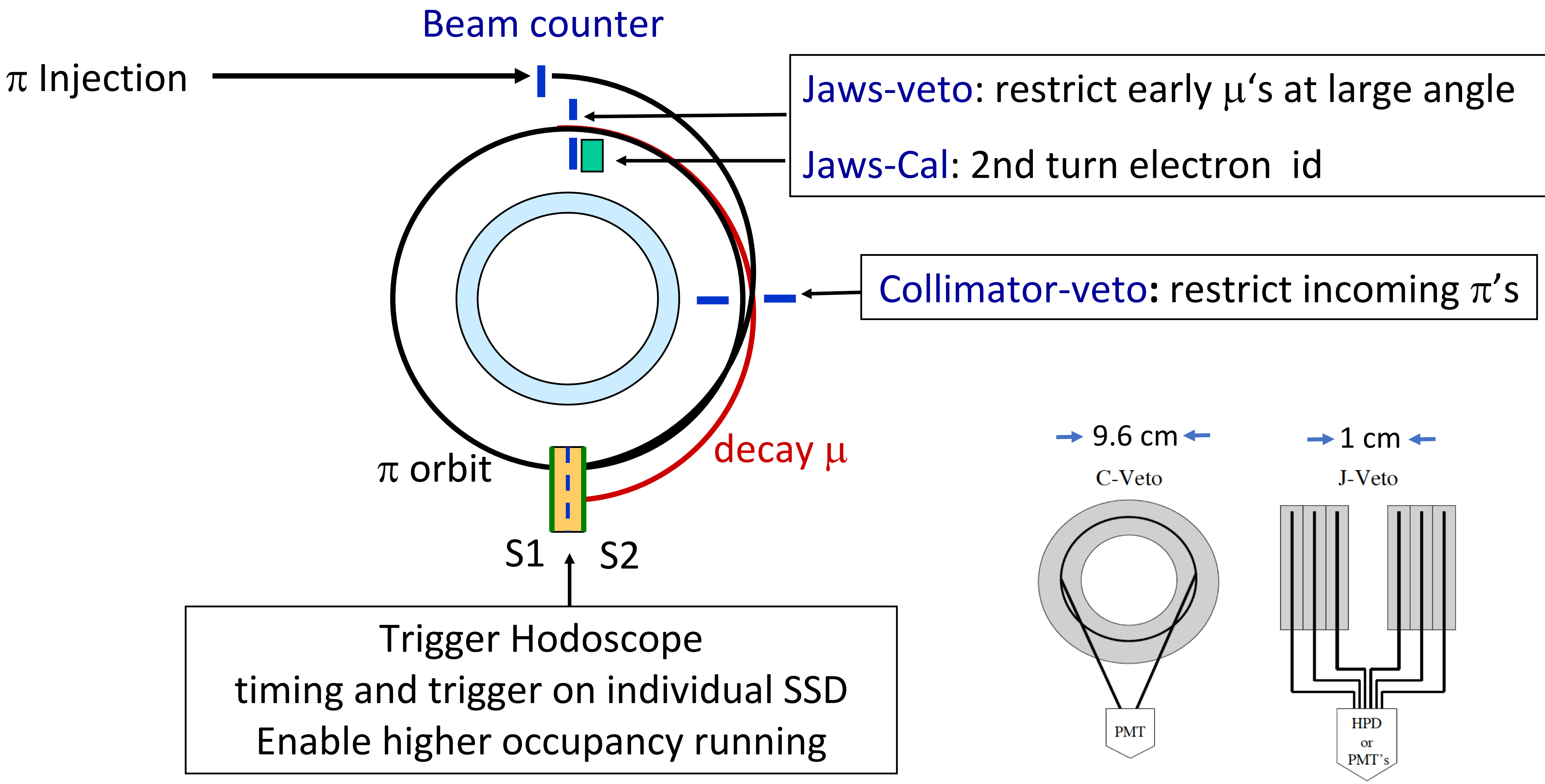
Pion enters S2 (silicon microstrip detector array) and then is kicked onto orbit by Be

Measure the position of the pion leaving S1
Measure the position of the decay muon 150 ns later entering S2

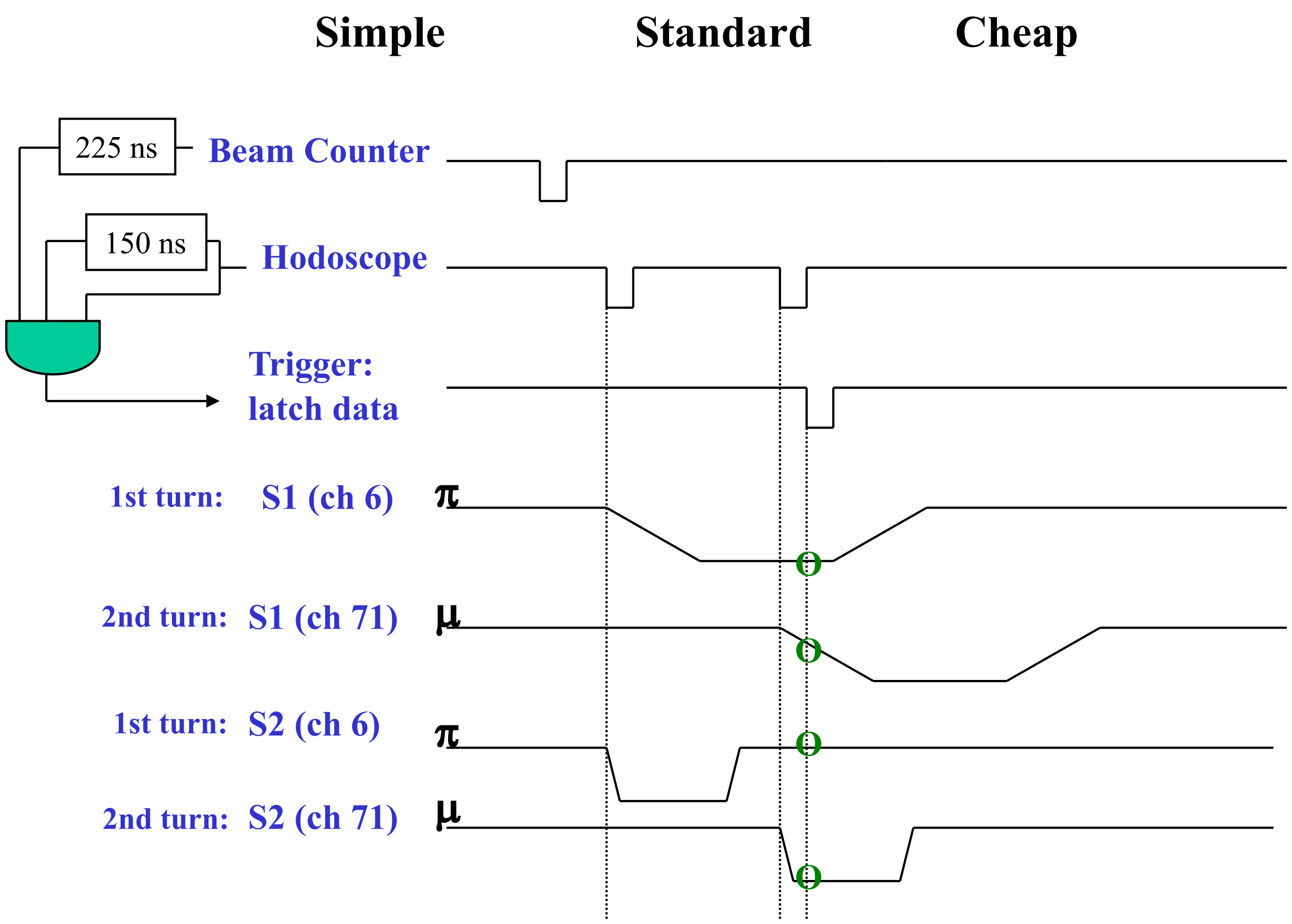
Silicon μstrip Detectors (S1, S2): 1.28 cm long vertical strips at 50 μm pitch



Auxiliary Scintillator Detectors

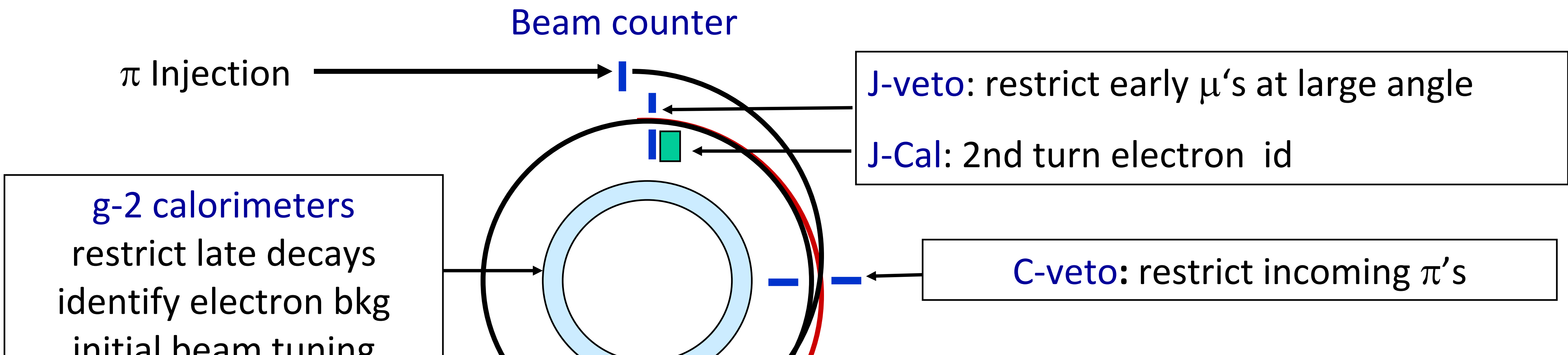


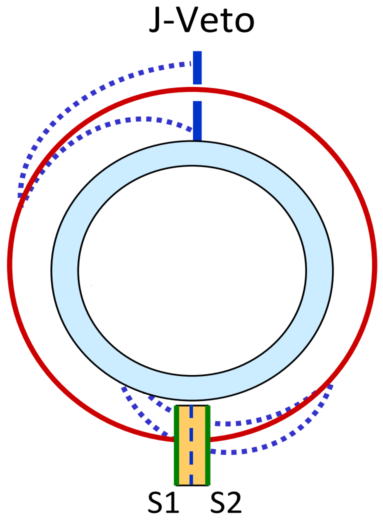
Sample & Hold Readout System



After the first trigger, the long shaping time of S1 ensures that the signal from the first hit of the pion in S1 is still holding charge when the muon in S2 is latched 150 ns later, and the second hit in S1 is not yet at full charge. The short shaping time of S2 means that the earlier hit of the pion in S2 is no longer there when the latch is set, just the new S2 hit. So what gets latched is one hit in S1 of the pion and one hit in S2 of the decay muon.

Use the g-2 calorimeters

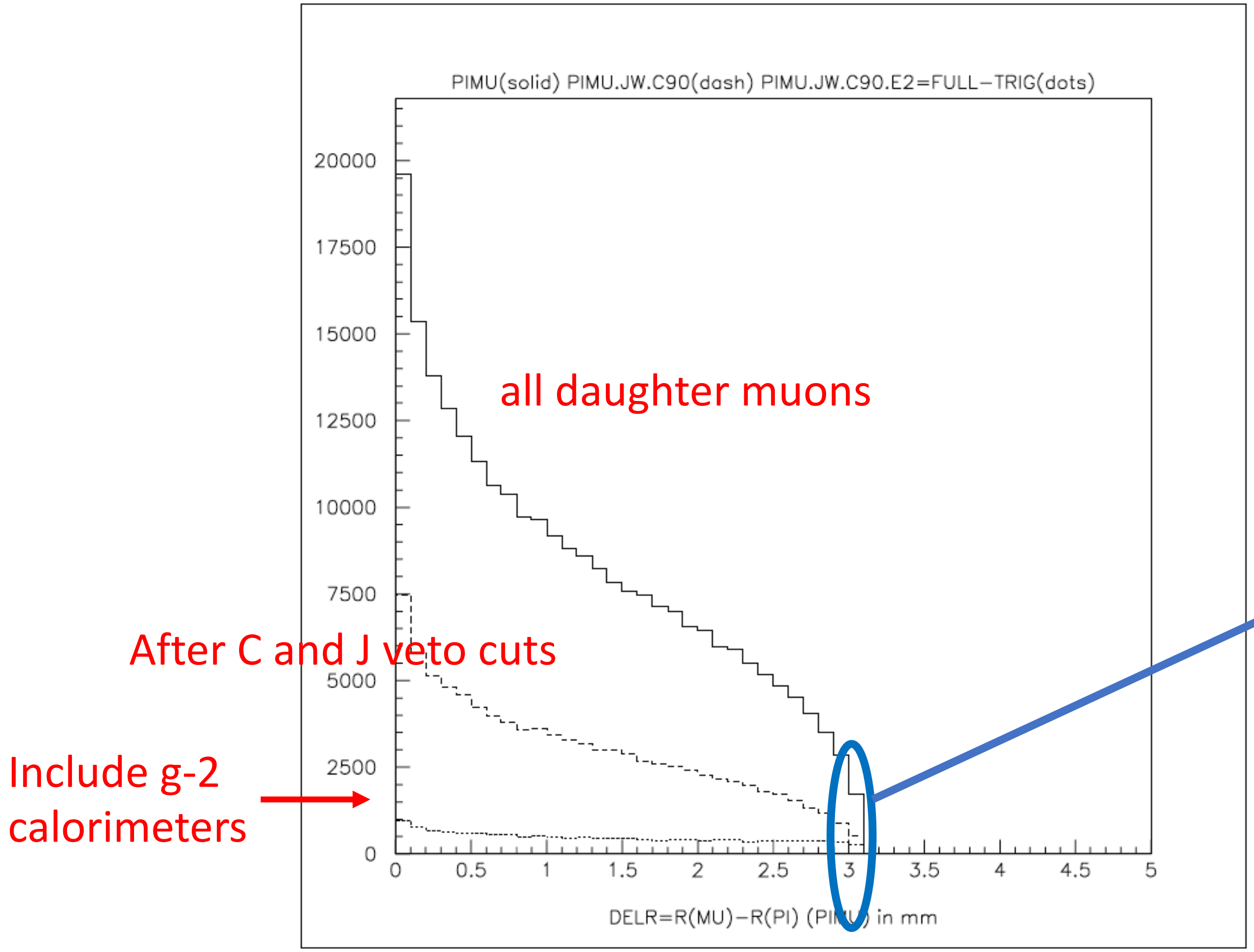


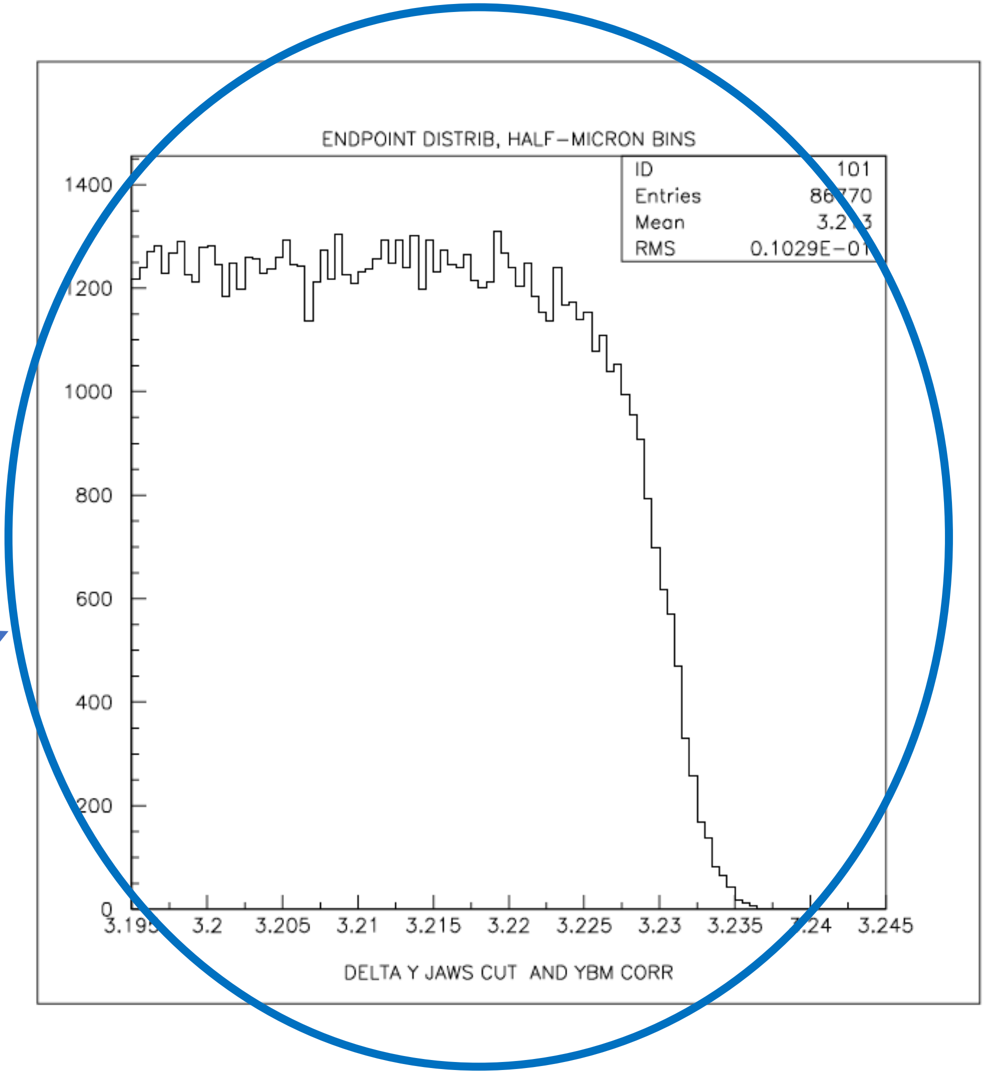


Non-forward-going muons move to the inside of S2
Vetoed offline by the g-2 calorimeters and J veto

Decay muon on S2 referenced to parent pion on S1 on evt-by-evt basis

$R_\mu(S1) - R_\pi(S2)$ Distribution





Sources of Background

- Beam-gas scatters

  vacuum is 10^{-6} torr

- Injected p (27% at BNL)

  7 ns/turn slower

- Injected e (12% at BNL)

  lose 1 MeV/turn from SR (4.7 mm inward)

  identify in J-Veto calorimeter (or position)

- $\mu \Rightarrow e\nu\nu$ ($\gamma\tau = 64\ \mu s$)

  injected μ (1%) and $\pi \Rightarrow \mu\nu$

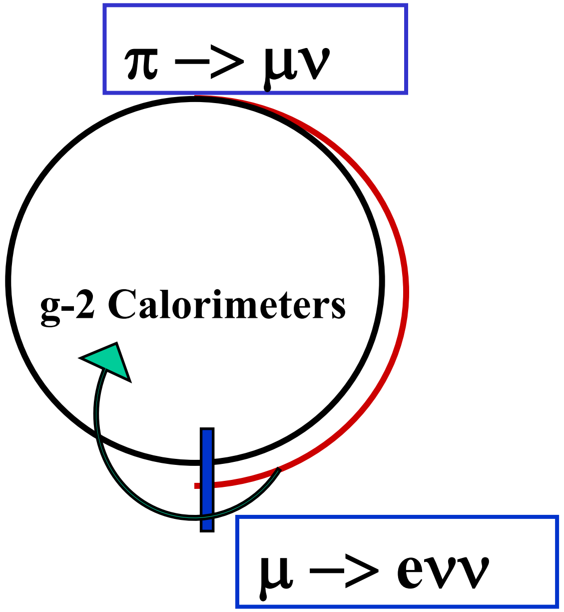
  < 10^{-4} of good $\pi - \mu$ events

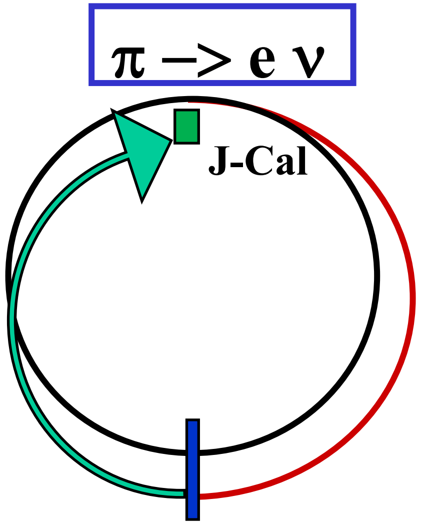
  rejected by g-2 calorimeters

- $\pi \Rightarrow e\nu$ (BR = 1.2×10^{-4})

  low tail out to ~ 5 mm

  calorimeter at inner J-Veto





Monte Carlo beam parameters and acceptance cuts

Δ P = 5.5 MeV	
Δ x = 5.95 mm	Δ y = 22.53 mm
$\Delta\theta_x$ = 3.4 mr	$\Delta\theta_y$ = 2.55 mr
r (C-veto) = 48 mm	
x (J-veto) = $\pm$ 5 mm	

Table 1: Monte Carlo Input Parameters

π through Inflector	1
π hits S1/S2 1st time	.143
π hits S1/S2 2nd time	.0377
μ hits S1/S2 2nd time	.000473
$\pi - \mu$ events	.0001898
$\pi - \mu$ events + J-Veto	.0000794
$\pi - \mu$ events + J-Veto + C-Veto	.0000695
$\pi - \mu$ events + J-Veto + C-Veto + g2-Veto	.0000086
π hits on C-Veto	.0947
π hits on J-Veto	.4348
μ hits on J-Veto	.0117
μ hits beam pipe before J-Veto	.0927
μ hits beam pipe after J-Veto	.0936

Table 2: Monte Carlo Acceptances

BNL configuration and rates

E949 Running Conditions

25 Gev protons

70 TP in a 4.1 s spill / 6.4 s cycle

E952 Parameters

2.8 x 10^6 π^+ into g-2 ring/TP

5.4 x 10^{12} π^+ for an 8 keV result

Running Time

5% of SEB beam ➔ 492 hrs / (crystal extr. eff.)

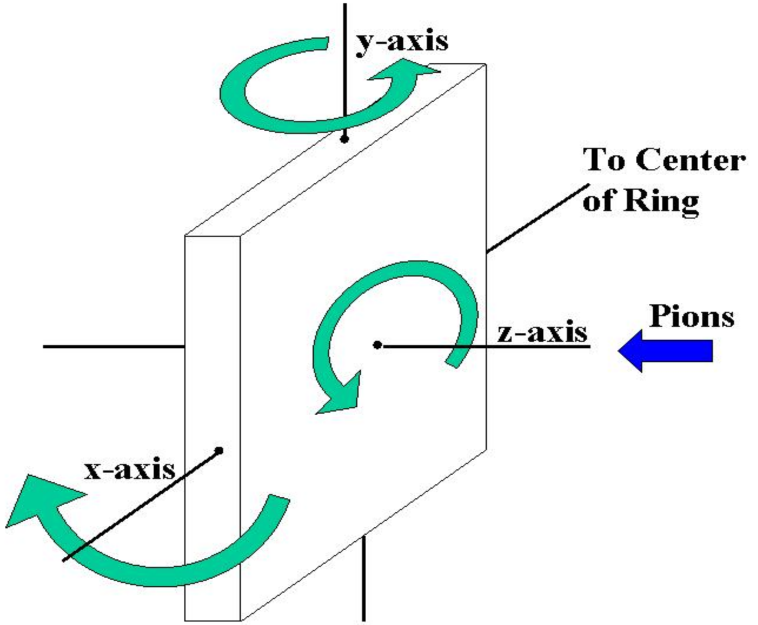
Entering Ring	Detector	Triggers: $\pi-\pi$	Triggers: $\pi-\mu$	Offline: $(\pi-\mu)$ + veto's
8 x 10^6 part/s	1 x 10^6 part/s	1.8 x 10^5 s^{-1}	910 s^{-1}	42 s^{-1}
	400 Hz/strip	55 μs/SSD	11 ms/SSD	
	Prescale in trigger ➔	100 MB/s	0.5 MB/s	

Scintillator Hodoscope

Radial segmentation = 2 mm   Vertical segmentation = 12.8 mm

- 4 ns gate for 3-fold coincidence trigger
  Accidentals at 0.004, flagged by beam counter
- Veto events $\Delta r < 2$mm to enrich $\pi - \mu$ events
  x 50 prescale => 0.5 MB/s or 37 DLT tapes
- Select readout SSD
  0.7% dead time
  1/10 data volume
- 1 ns timing resolution (TDC) + 2mm segmentation
  reject accidentals offline (another factor of .002)

Detector Angular Alignment

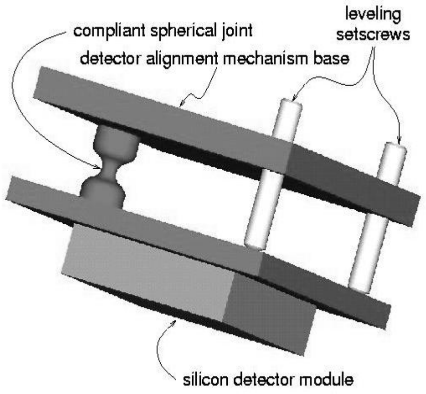


- Not very sensitive to uncertainties in angles around x-axis
- Mis-alignment around z-axis is in principle correctible
  depending on our vertical segmentation
- Mis-alignment around y-axis is worst potential systematic
  reduces effective strip pitch and expands apparent radial profile
  26 mrad angle ➔ > 1 μm expansion in the radial residual over 3 mm
- Pion and Proton runs with remotely adjustable angle
  narrowest distribution will correspond to perpendicularity with beam in y-axis rotation

Precision Alignment and Remote Positioning
Micro-machine Solutions designed by UMN Mechanical Engineering

1. Initial alignment

align to 10 μm the 20 SSD's to each other on the package
measure relative alignment to 0.1 μm in situ
stability of position is crucial, as is relative angles

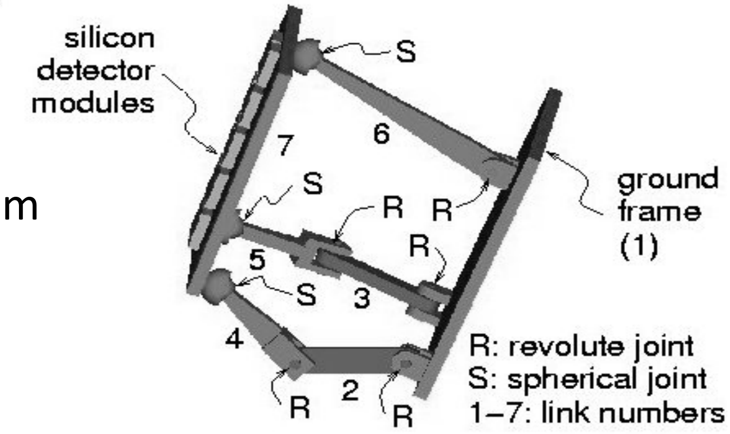


12 mm x 12 mm
5 mm thick

2. In situ rotation of S1:S2 package (y-, z-axes)

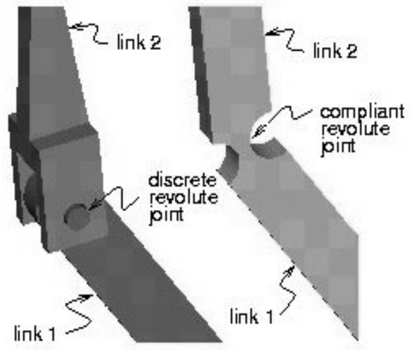
Accuracy of 0.1 mrad over a range of 50 mrad
The mechanism sits outside of the particle detection window
Compliant joints to eliminate joint slop
Position is monitored by detecting the applied force
Also could add mirror + laser port

35mm x 75mm
x 50mm.



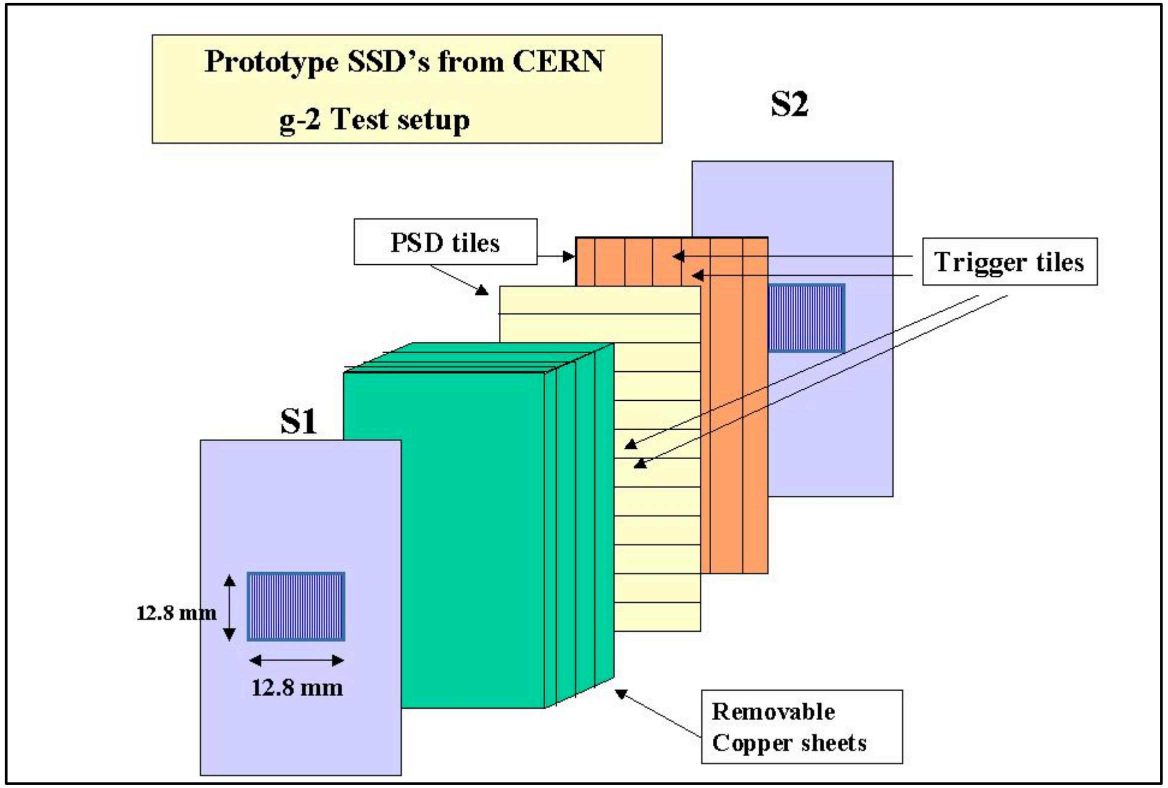
3. In situ J-veto translation (2 cm of horizontal motion)

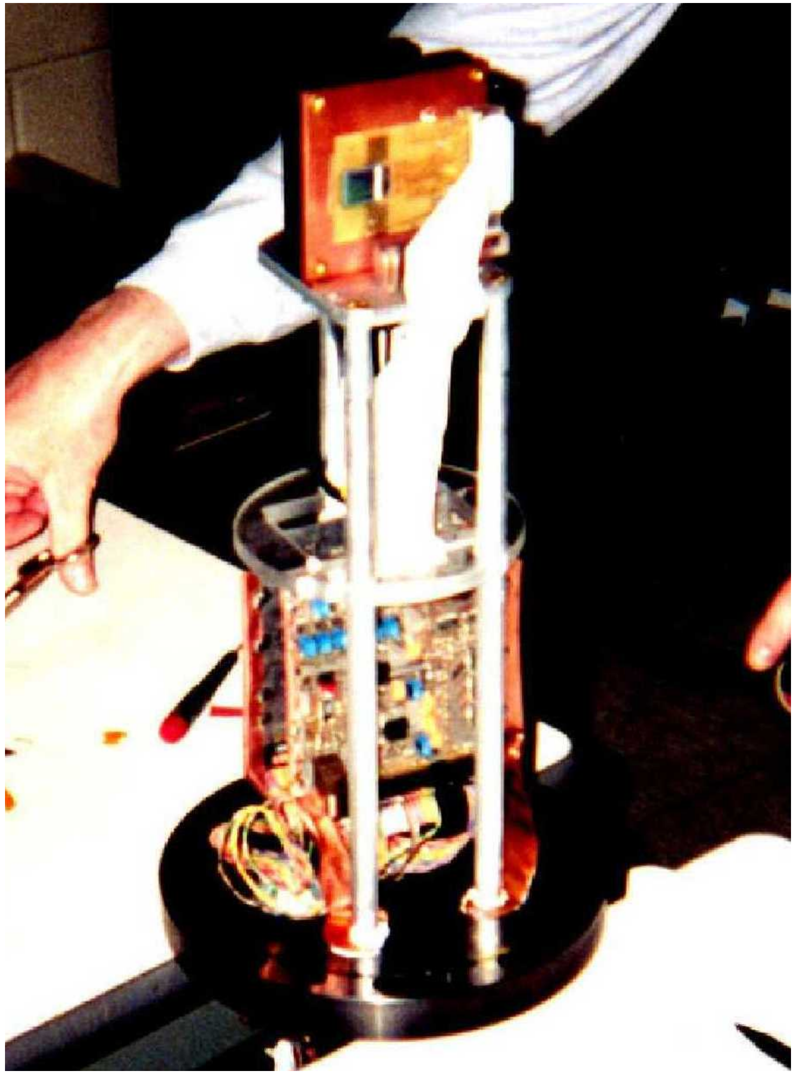
Only Challenge: provide a sliding joint and actuator that are
compatible with the high vacuum environment



BNL test run for NuMass

Learned how to make de-tuned fast extraction, steered pions onto SSD
Prototype SSD sandwich worked in vacuum and B-field
Integrated readout (via WFD) with rest of g-2 DAQ
Discovered 50 ppm 1st harmonic in g-2 ring
Backgrounds were manageable



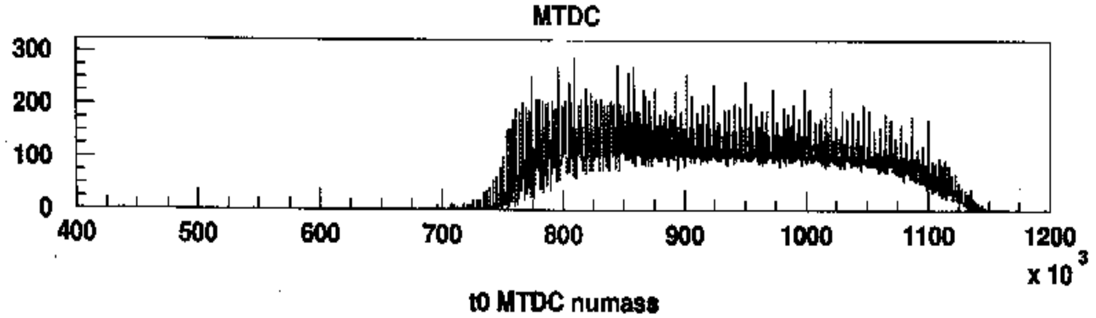


BNL test run for NuMass

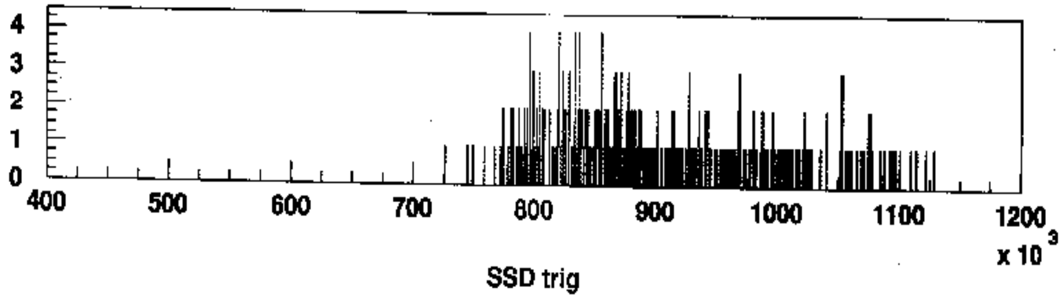
10-50 charged particles every 2.7 μs over
~ 400 μs spill, repeated 12 times every 3.2 seconds

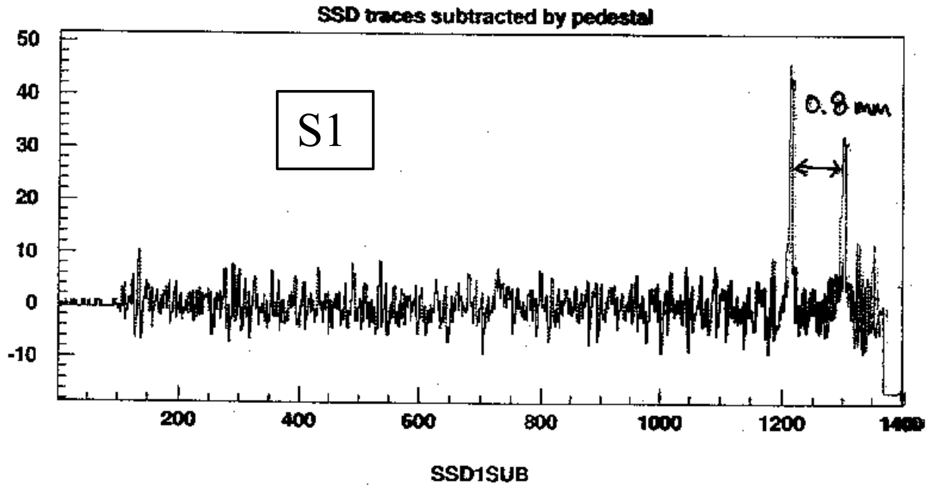
Online event trace read out by a g-2 WFD with 8-bit resolution.
Each trace represents 256 ADC channels at 50 micron pitch.
Channel transitions occur every 5 WFD samples

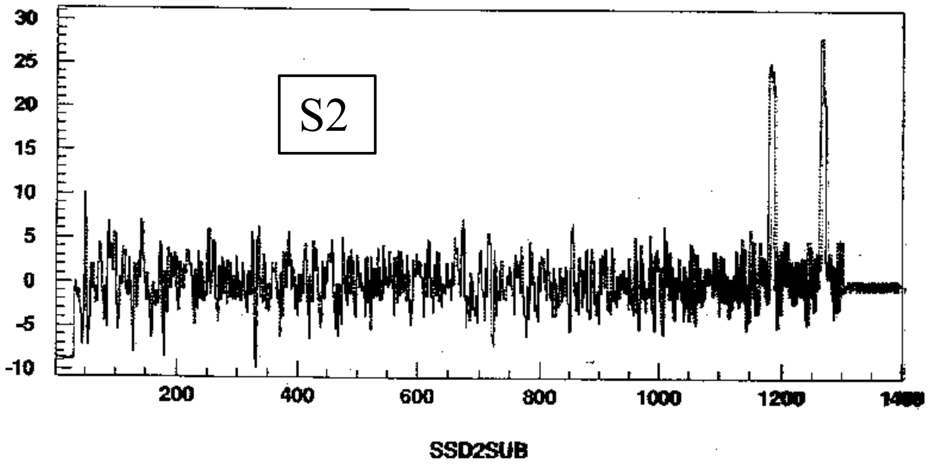
T0 beam monitor



Trigger hodoscope







NuMass at FNAL ?   Questions

Can we get a slow extracted pion beam into the g-2 storage ring?

Pions are also needed for any pion lifetime measurement

But resonant extraction might be too hard.

No delivery ring - we NEED undecayed pions and protons, but not a lot of them.

Put target in M5   (alternate NuMass running with Mu2e by switching targets)
and NOT in M1

Need 3 GeV pions

Improvements in Detector Technology

Highest impact would be to improve the position resolution of the edge

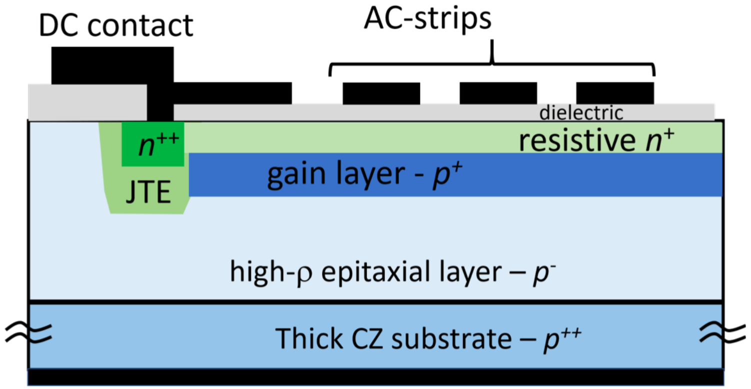
Hard to get better position resolution than the 1.4 μm from charge-sharing in SSD ! Other ideas???

Pixel detectors and monolithic construction could improve alignment and stability

AC LGAD looks promising. Position resolution is similar to SSD, AND it comes with 30 ps timing

- Tightens trigger and TOF ➔ allows for higher intensity running
- Relaxes requirements on the auxiliary scintillator detectors
- Can be made very thin to avoid mult. scat. in the detector

  which can



What FNAL g-2 improved on

- Better azimuthal uniformity in B-Field
- Better beam dynamics plus straw tubes and fiber harps
- Better Calorimeters

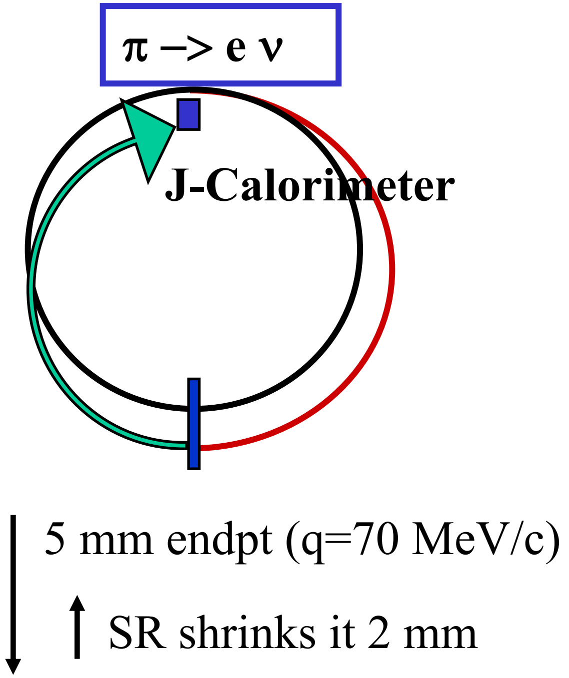
Changes in the Theoretical and Experimental Landscape

20 years ago, we didn't have mass-squared differences anchored to an eV-scale ν_e measurement

Today, this becomes a sterile neutrino search, or even $\pi \to e\,X$

Enhance it with $\pi \to e\,\nu$ and branching ratio measurement

Determine the best technology for the J-calorimeter



The strategy for this type of experiment is

1. Keep it cheap
2. Parasitic running if at all possible
3. Highly leveraged on g-2 previous investments (B-field uniformity, DAQ, calorimeters)

Determine what position resolution is required to be competitive with PiENu, PiENuXe on mixing parameters

Backup Slides

Elements of the Experimental Technique

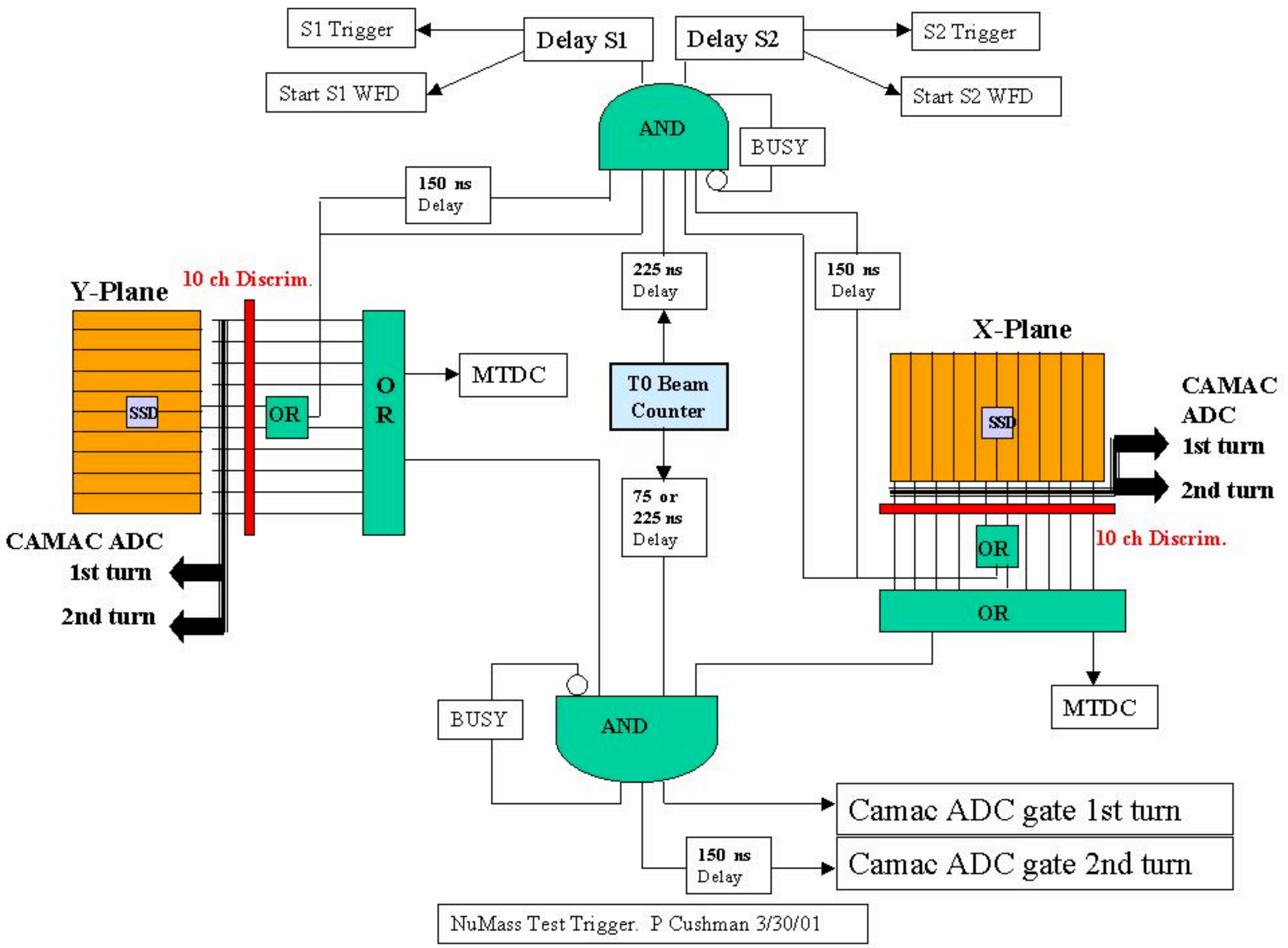
- Translate Δp to Δr in 0.1 ppm uniform B-Field — no multiple scattering
  no need to measure decay angle or location

- Reference each μ to parent π — pion injection with slow extraction

- In situ alignment — Continuous alignment monitoring using prescaled undecayed pions and protons (TOF: 7 ns/turn later than pion)
  Remote angular adjustment of detector and positioning of active vetoes

- Detector Requirements — < 1.4 mm resolution in the horizontal (via silicon)
  Time resolution from scintillators and PMT's
  Tight triple coincidence trigger
  TDC's on all vetoes and the embedded hodoscope

NuMass BNL test trigger configuration



NuMass BNL final trigger configuration