

The NUMASS Experiment: BNL E952

Presented by B.L. Roberts for P. Cushman



A Direct Measurement of the Muon Neutrino Mass From 170 keV => 8 keV and beyond...

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Why do a DIRECT Measurement ?

★ It is a fundamental constant!

Its uncertainty also affects our knowledge of other fundamental constants

e.g. G_{fermi}

$$\frac{\delta G_F}{G_F} = \frac{\delta \tau_\mu}{2\tau_\mu} - \frac{5\delta m_\mu}{2m_\mu} + \frac{4m_\nu^2}{m_\mu^2}$$

0.5 ppm MuLan	0.38 ppm	10 ppm
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★ Direct access to mass rather than Δm^2 , no oscillation hypothesis

★ It closes the intermediate mass (10 – 170 keV) loophole

e.g.

Neutrino Decay: $\nu_\mu \rightarrow \nu_e \nu_e \nu_e$ via Δ_L^0 (minimal LR symmetric model)

is consistent with **Mass Density of Universe, Primordial nucleosynthesis, CMB, Diffuse γ -ray bkgd SN1987a** as long as $m(\nu_\mu) > 35$ keV (from Z-width)

Supernovae: For $m(\nu_X) > 10$ keV, $\Delta t \sim \text{day} \Rightarrow$ pulse is below background.

Results are only valid for Dirac Neutrinos .

Check out all those 17 keV papers for more exotic loopholes

Direct Measurements of Neutrino Mass

Current Limits

$$\begin{aligned} m(\nu_e) &< 4.35 - 15 \text{ eV} \\ &< 23 \text{ eV} \\ &< 0.5 - 9 \text{ eV} \end{aligned}$$

Tritium β -decay endpoint
TOF spread from SN1987A
Double β -decay for Majorana ν 's

$$m(\nu_\mu) < 170 \text{ keV}$$

$\pi \rightarrow \mu\nu$ (stopping π 's)

$$m(\nu_\tau) < 18.2 \text{ MeV}$$

Inv. Mass of $\tau \rightarrow \nu + \text{hadrons}$
(e^+e^- Colliders)

Muon Neutrino Direct Limits from *Pion Decay at Rest*



1979: Daum et al. (Phys Rev D20 p.2692)

Solution A

Solution B

$$m^2(\nu_\mu) = +0.13 \pm 0.14 \quad - \quad (\text{MeV}/c^2)^2$$

$$m(\nu_\mu) < 570 \text{ keV}/c^2$$



1984: Abela et al (Phys Lett B146 p.431)

Solution A

Solution B

$$m^2(\nu_\mu) = -0.163 \pm 0.080 \quad - \quad (\text{MeV}/c^2)^2$$

$$m(\nu_\mu) < 250 \text{ keV}/c^2$$



1996: Assamagan et al. (Phys Rev D53 p.6065)

Solution A

Solution B

$$m^2(\nu_\mu) = -0.143 \pm 0.024 \quad -0.016 \pm 0.023 \quad (\text{MeV}/c^2)^2$$

$$m(\nu_\mu) < 170 \text{ keV}/c^2$$

Muon Neutrino Direct Limits from *Pion Decay in Flight*



1982: Anderhub et al. Phys Lett **B114** p.76

$$m^2(\nu_\mu) = -0.14 \pm 0.20 \text{ (MeV}/c^2)^2$$

$$m(\nu_\mu) < 500 \text{ keV}/c^2$$



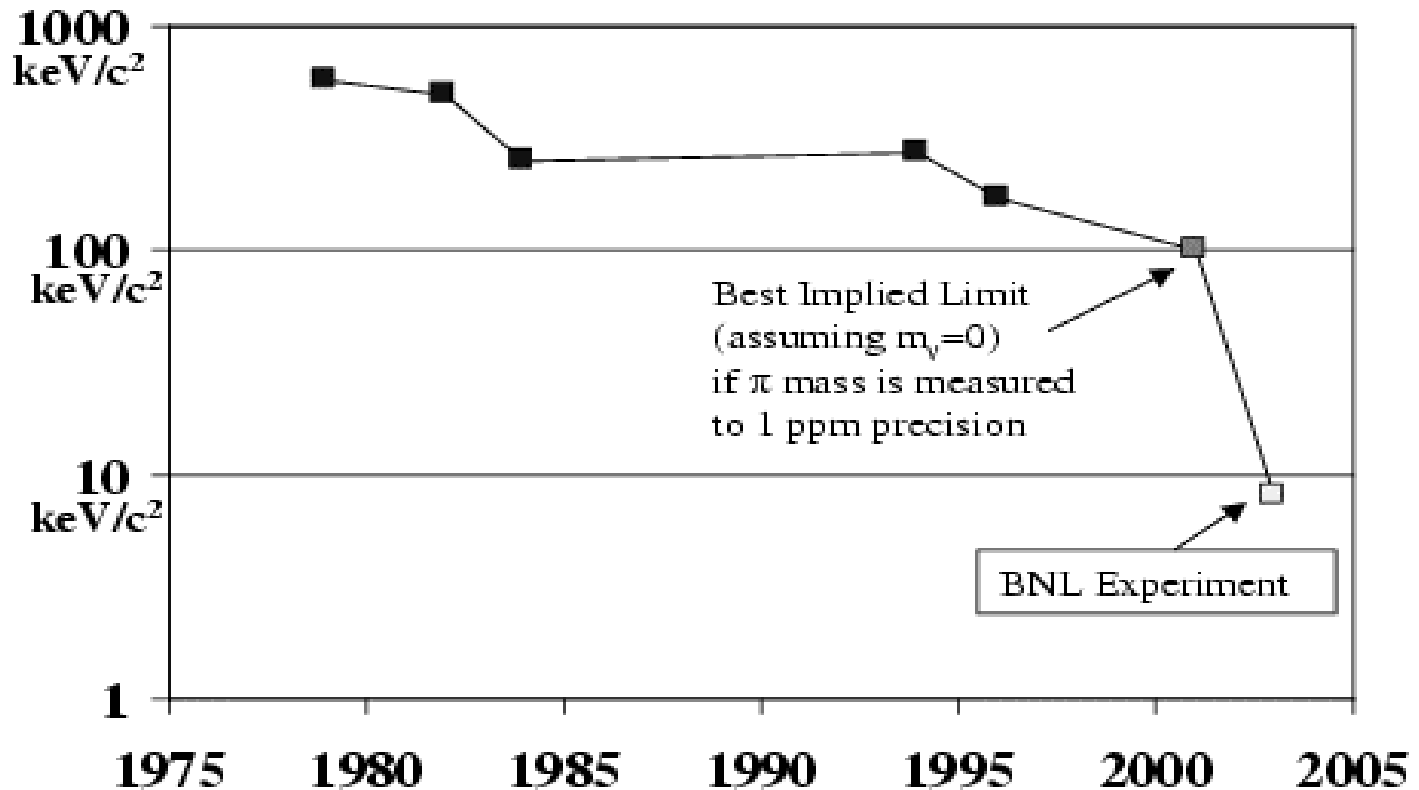
200? Neutrino Mass Experiment

$$m(\nu_\mu) < 8 \text{ keV}/c^2$$

Muon Neutrino Direct Limits

Graphical Form

History of the Muon Neutrino Mass Limit



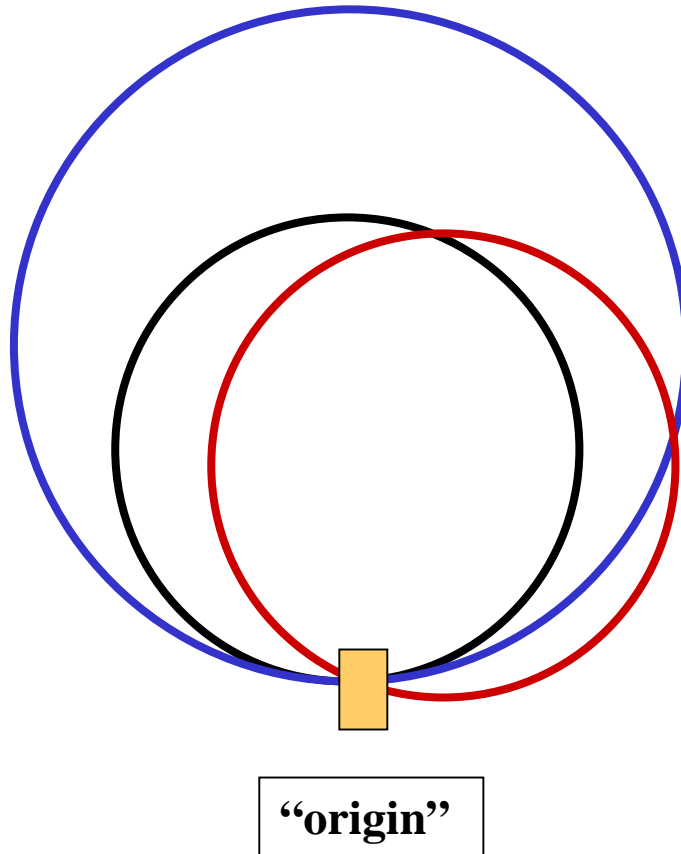
If you believe atmospheric neutrino result: $\nu_\mu \Rightarrow \nu_\tau$ with only $\Delta m^2 \sim .002$

Then this experiment reduces the τ neutrino mass limit by **3 orders of magnitude!**

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 prescaled pions and undecayed protons



G-2 Storage Ring becomes a Precision Spectrometer

G-2 Experiment

Weak-focussing Storage Ring: Muons stored for 800 μ s
Quadrupoles
Muon Kicker

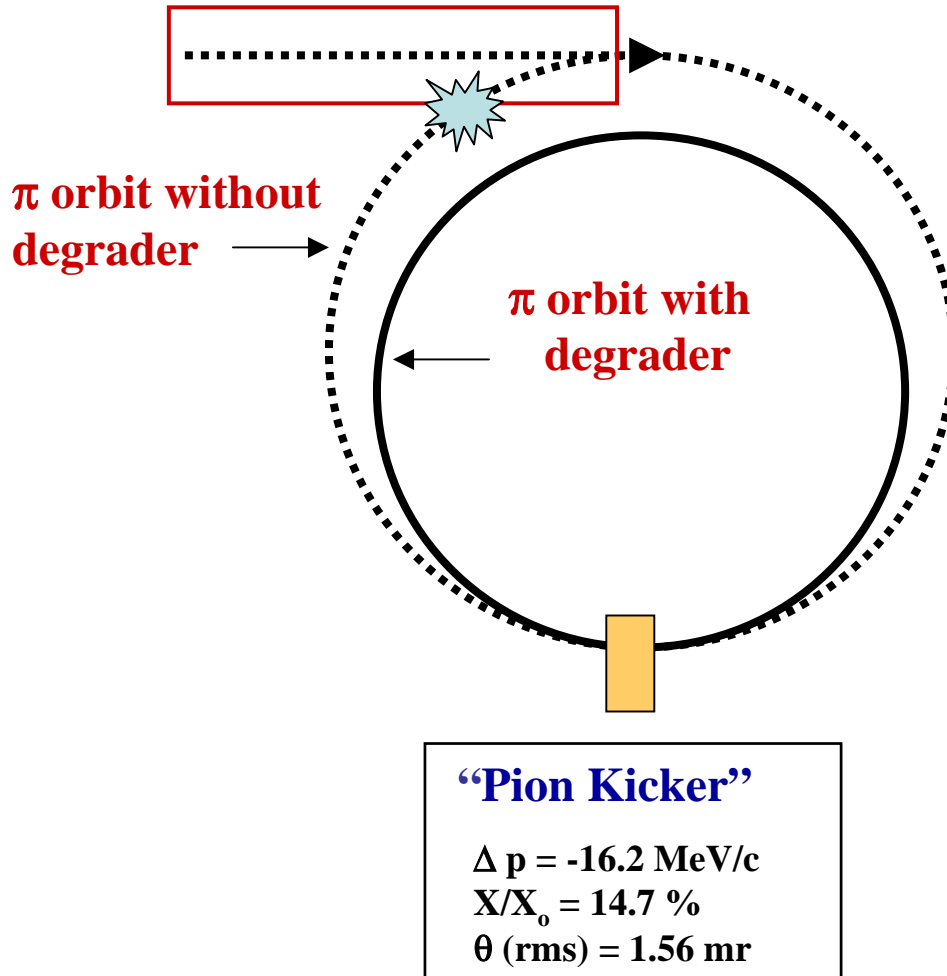
NuMass Experiment

Spectrometer: $\pi \rightarrow \mu\nu$ observed evt-by-evt
No Quads
Pion kicker

Same Momentum - 3 GeV (re-examine at new facility)

retain excellent shimming and B-field uniformity
0.1 ppm over orbital path range
Trolley runs in vacuum to map field
Fixed probes to track changes
Active shimming and thermal insulation to minimize change

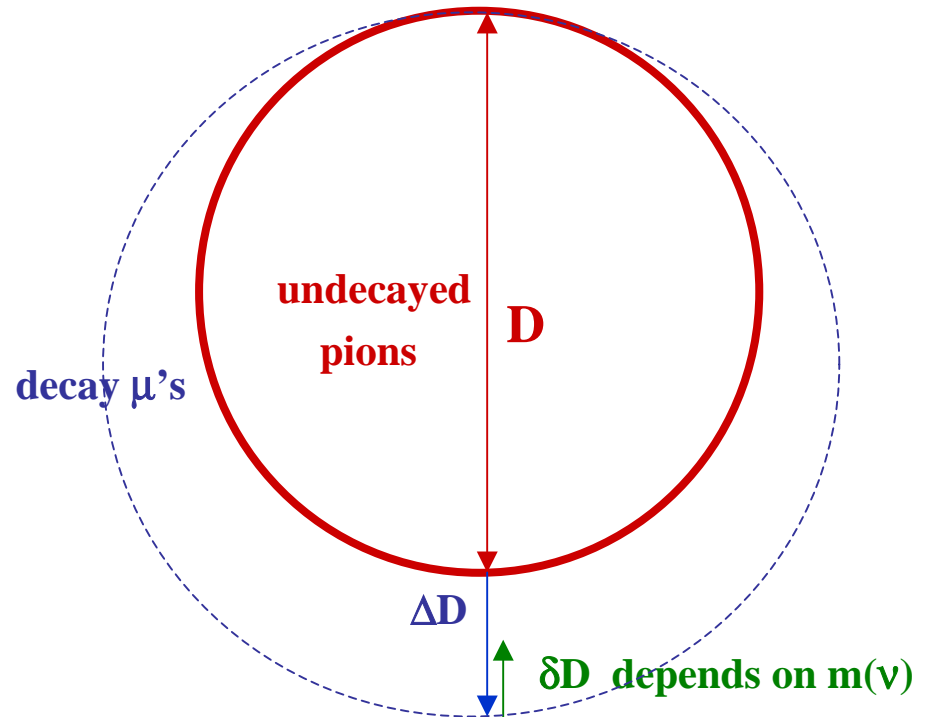
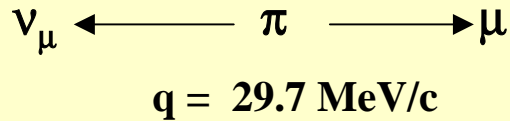
Put pions on orbit using dE/dx Injection 5.2 cm Beryllium



Conceptual Design

Forward-going decay muons
orbit a larger diameter by ΔD

CM



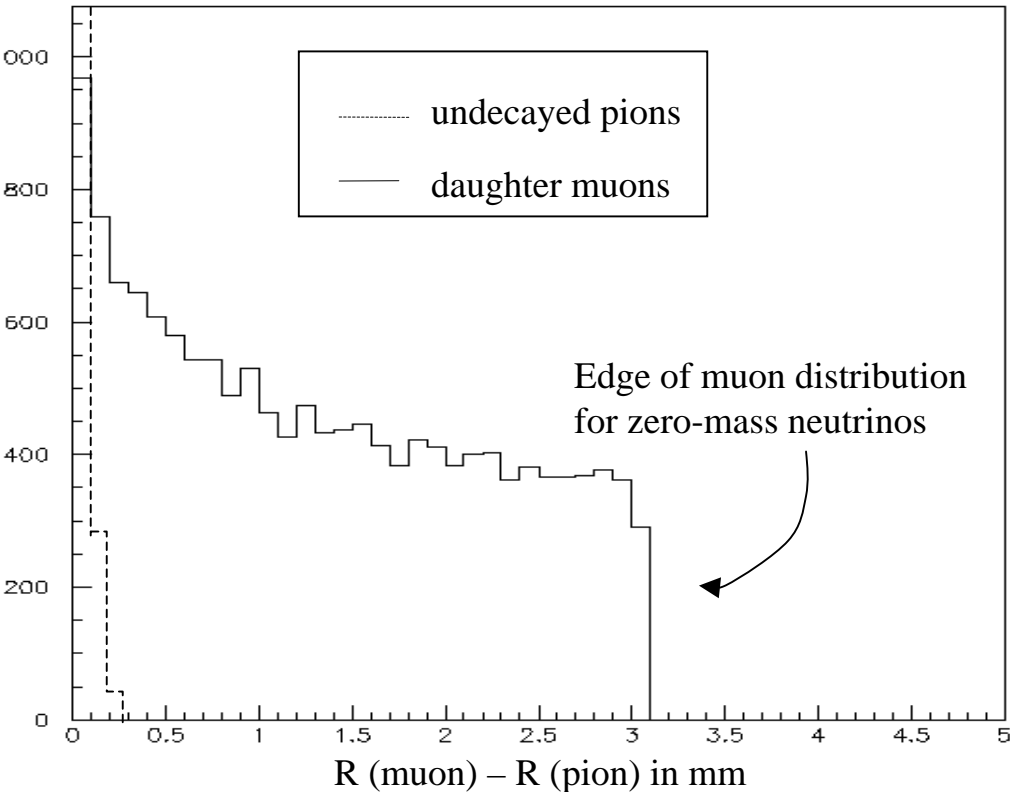
$$\frac{\Delta D}{D} = \frac{p_\mu - p_\pi}{p_\pi} = \frac{0.7 \text{ MeV}/c}{3 \text{ GeV}/c} = \frac{3.26 \text{ mm}}{14 \text{ m}}$$

However, if m_ν is non-zero, then ΔD shrinks by $\frac{\delta D}{D} = \frac{-m_\nu^2}{2 q m_\pi}$

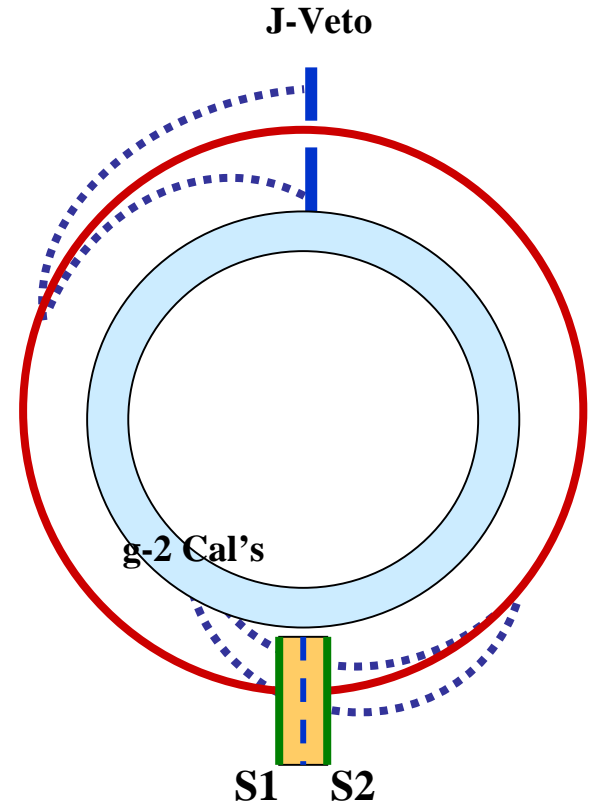
($\delta D = 0.04 \text{ mm}$ for current limit)

Concept Continued

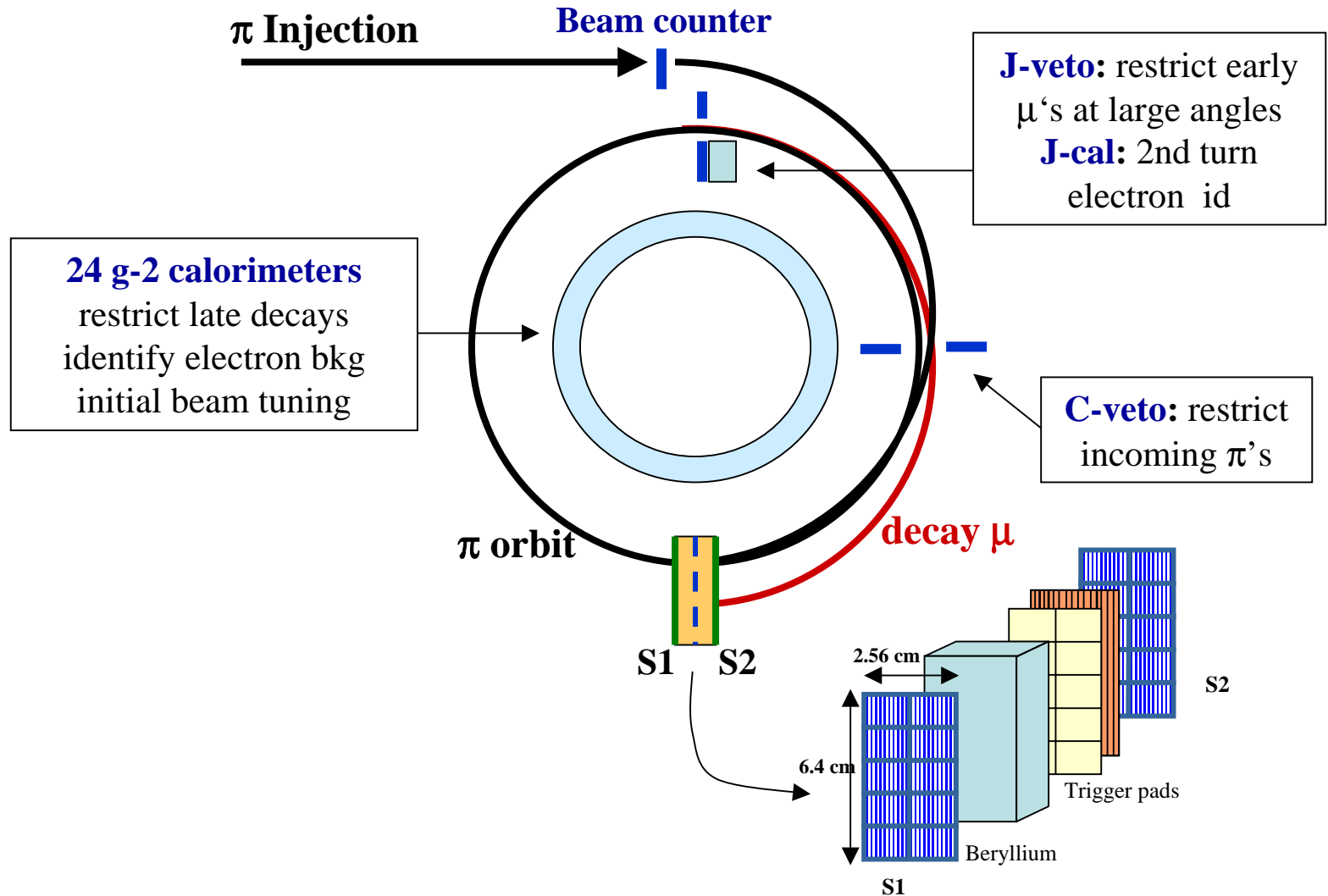
Radial distribution of forward-going muons has sharp outer edge.



Auxiliary detectors veto non-forward going muons



Experimental Method

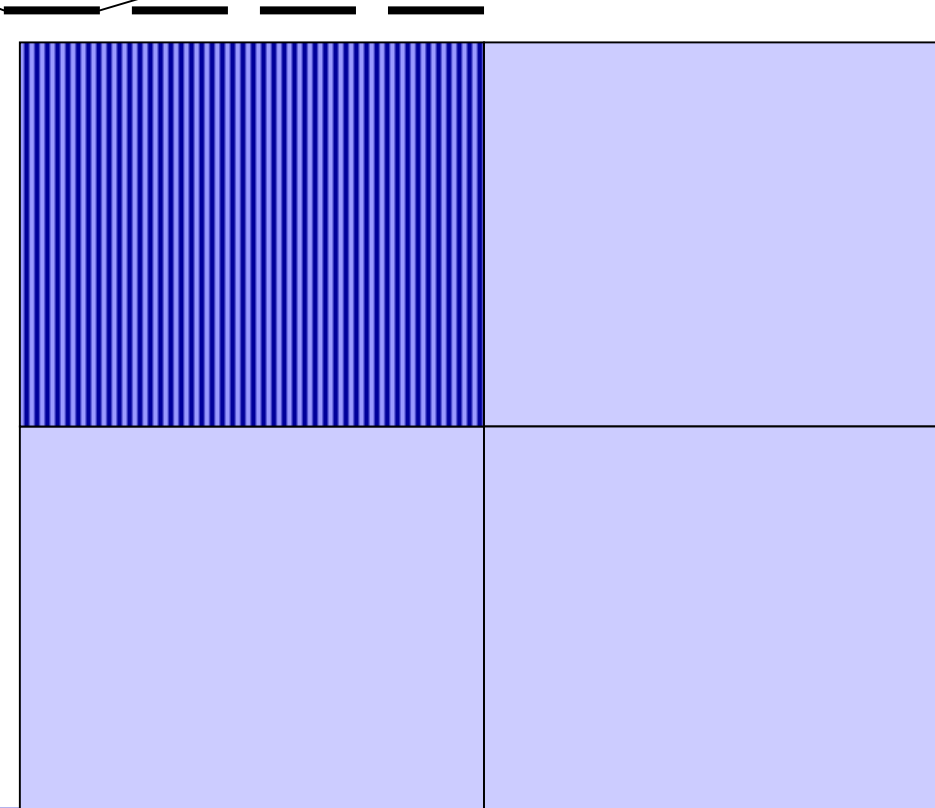
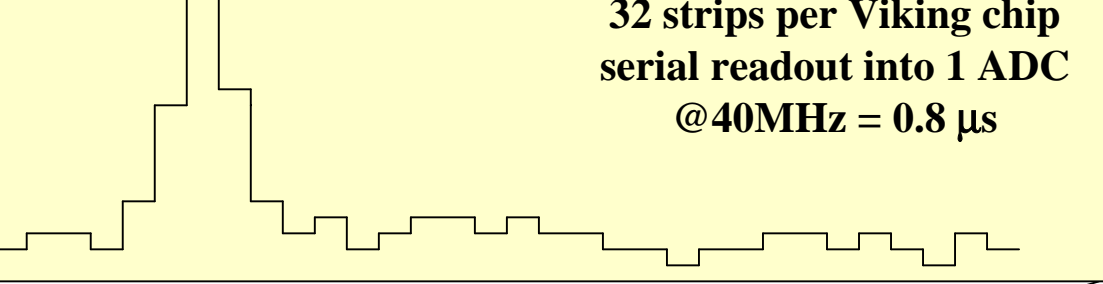


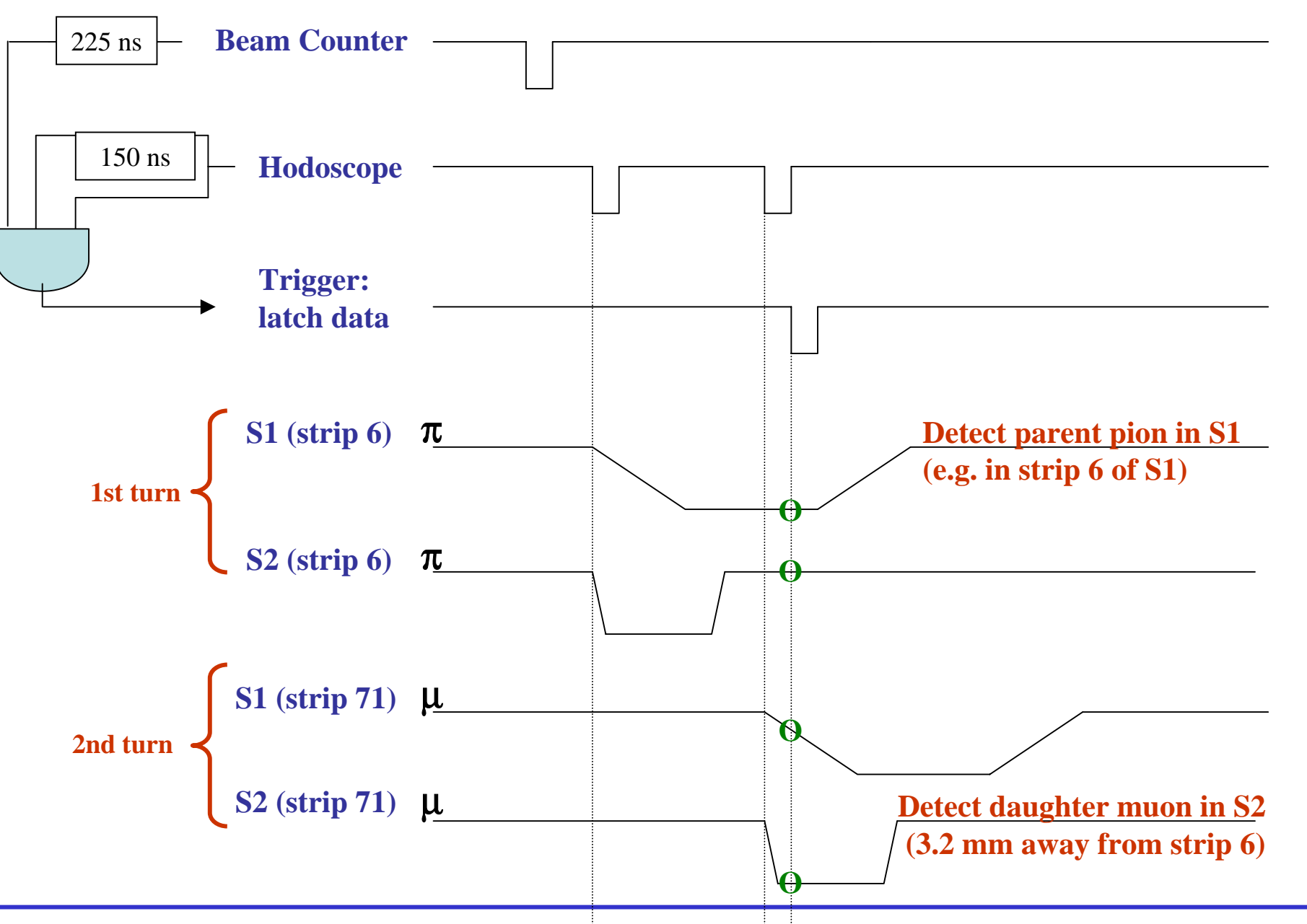
Highlights of the Experimental Technique

- **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**
slow extraction
- **In situ alignment**
protons (7 ns/turn late)
prescaled undecayed pions
remote positioning of active vetoes
remote angular adjustment of detector
- **Position resolution from silicon with upgrade to emulsion**
1.4 μm SSD \Rightarrow 0.5 μm emulsion reel
- **Time resolution from scintillators and PMT's**
tight triple coincidence trigger
TDC's on all vetoes and embedded hodoscope

Readout System

32 strips per Viking chip
serial readout into 1 ADC
@40MHz = 0.8 μ s





Proposed Parasitic Running with AGS Crystal Extraction

E949 Running Conditions

25 GeV protons
70 TP in a 4.1 s spill / 6.4 s cycle

E952 Parameters

$2.8 \times 10^6 \pi^+$ into g-2 ring/TP
 $5.4 \times 10^{12} \pi^+$ for an 8 keV result

Running Time

5% of SEB beam $\Rightarrow \frac{492 \text{ hrs}}{\text{(crystal extr. eff.)}}$

Instantaneous rates (100% extr. eff.)

Triggers

Offline

Entering Ring

Detector

$\pi-\pi$

$\pi-\mu$

$(\pi-\mu)+\text{vetoes}$

$8 \times 10^6 \text{ part/s}$

$1 \times 10^6 \text{ part/s}$

$1.8 \times 10^5 \text{ s}^{-1}$

910 s^{-1}

42 s^{-1}

400 Hz/strip

55 $\mu\text{s}/\text{SSD}$

11 ms/SSD

Prescale in trigger 

100 MB/s

0.5 MB/s

Scintillator Hodoscope

Radial segmentation = 2 mm Vertical segmentation = 12.8 mm

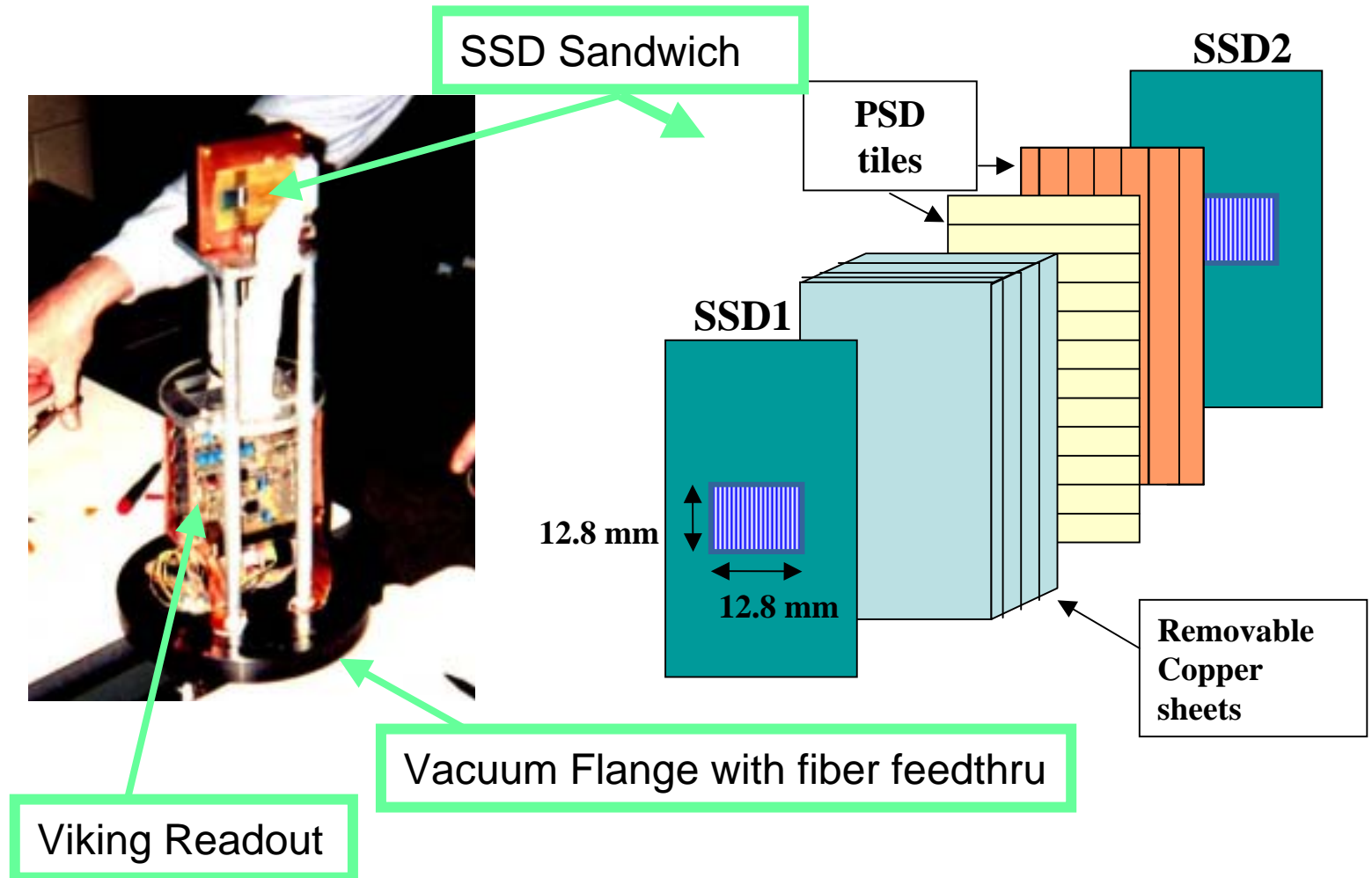
- **4 ns gate for 3-fold coincidence trigger**
Accidentals at 0.004, flagged by beam counter
- **Veto events $\Delta r < 2\text{mm}$ to enrich $\pi\text{-}\mu$ events**
x 50 prescale => 0.5 MB/s or 37 DLT tapes
- **Select readout SSD**
0.7% dead time
1/10 data volume
- **1 ns timing resolution (TDC)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

Sources of Background

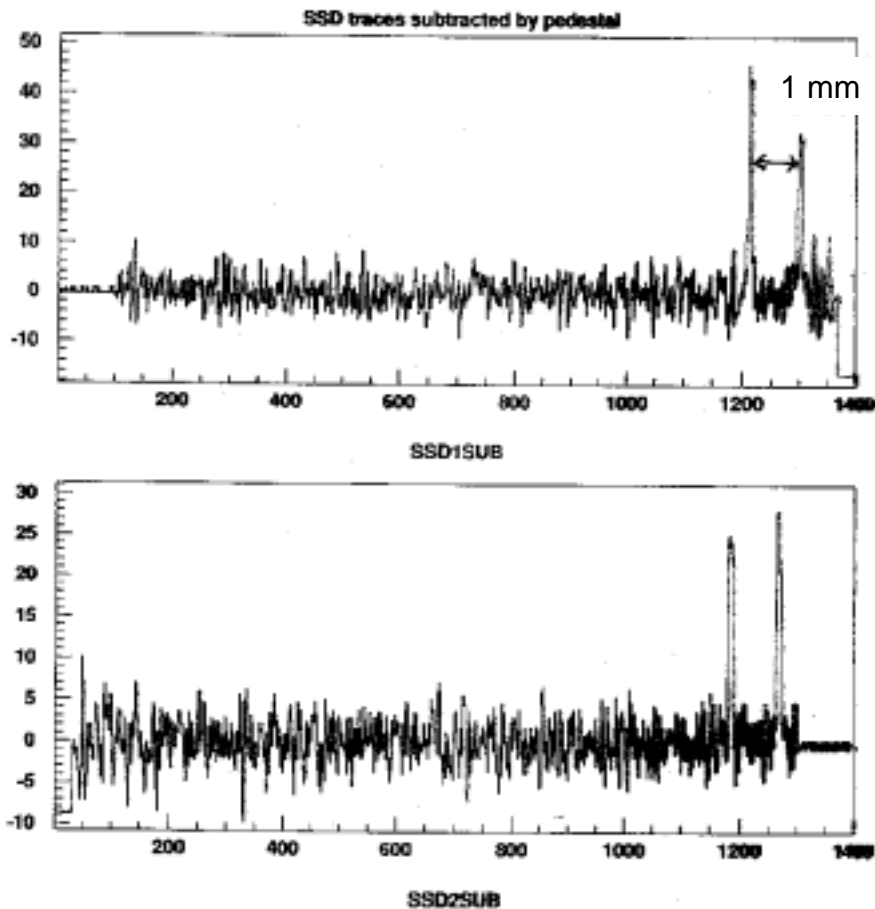
- **Beam-gas scatters**
vacuum is 10^{-6} torr
- **Injected p (27%)**
7 ns/turn slower
- **Injected e (12%)**
*lose 1 MeV/turn from SR (4.7 mm inward)
identify in J-Veto calorimeter (or position)*
- **$\mu \Rightarrow e\nu$ ($\gamma\tau = 64 \mu\text{s}$)**
*injected μ (1%) and $\pi \Rightarrow \mu\nu$
 $< 10^{-4}$ 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*

PROOF OF PRINCIPLE

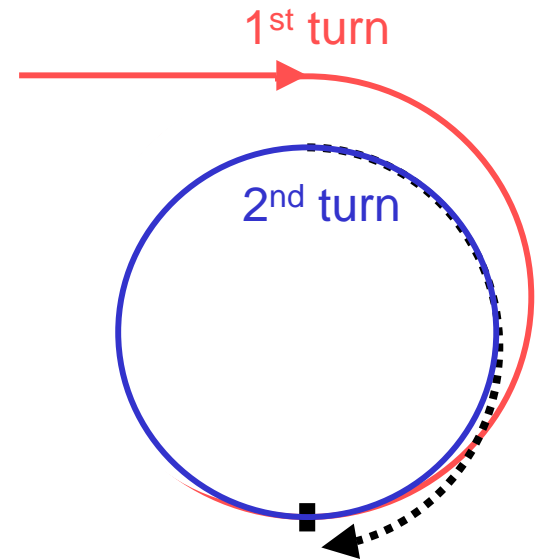
Test of a prototype silicon microstrip detector in the g-2 ring



Test successfully measured 1st and 2nd passage of pion



Online traces from silicon strip detectors triggered by embedded scintillator.



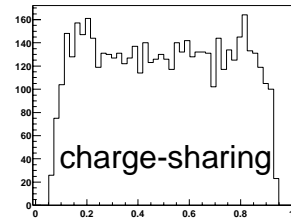
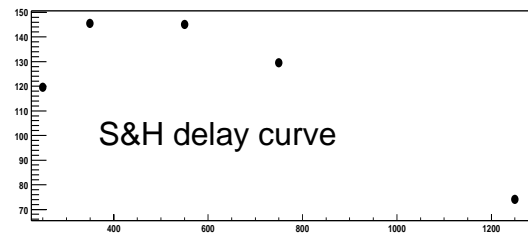
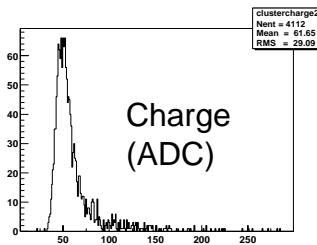
The right side of ring has less average B-field than the left.

1st harmonic ~ 50 ppm

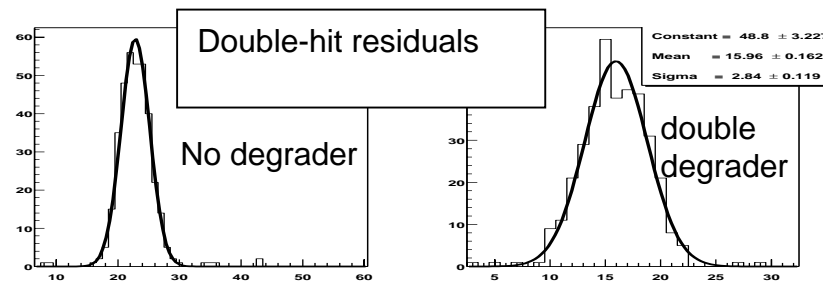
And lots of other important parameters as well

- Establish pion injection and orbit parameters in g-2 ring and steer pions to detector
- Pion kicker (degrader) in vacuum returns pions to origin
measure 1st harmonic of g-2 magnet
- Read out the SSD/serial Viking system through g-2 WFD's
- Run SSD in Vacuum and 1.45 T B-field and establish characteristics

*MIP response,
Charge-sharing,
alignment
position resolution
signal:noise*



- Trigger tile-fiber scintillator hodoscope on MIP's (with vacuum feedthru's)
- Timing and linearity study of SSD hold time
- Multiple scattering in degrader
- Resolution for both single and double hits



Conclusions

... Physics

There are mysteries in the neutrino mass spectrum
which a complementary, direct measurement can help unravel.

Oscillation Exp. only sensitive to Δm^2

ν disappearance \Rightarrow oscillation \Rightarrow mass

No direct access to the 3 flavor (or more?) mass hierarchy

Astrophysics/Cosmology

assumes no sterile ν , standard model interactions, stable ν

Supernovae

only applies to Dirac neutrinos

model-dependent at supernuclear densities

... Experiment

G-2 storage ring: state-of-the-art spectrometer at bargain prices

Beamline can be parasitic with SEB, easily switched to RHIC, FEB

Upgrade path uses the SSD to locate track and emulsion to further refine
position: Can improve limit to below 1 keV