

Window of Opportunity

... Physics ...

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

Oscillation Exp. only sensitive to Δm^2

*\mathbf{n} disappearance \Rightarrow oscillation \Rightarrow mass
2-flavor mixing is much easier to write down*

Astrophysics/Cosmology

no sterile \mathbf{n} , standard model interactions, stable \mathbf{n}

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

An order of magnitude improvement in a **fundamental constant**

**A stricter limit is part of this decade's
focus on neutrino physics**

PRESENT

Atmospheric: $\bar{\nu}_\mu \Rightarrow \bar{\nu}_X$ and $Dm^2 \sim .0012 - .008 \text{ eV}^2$ (SuperK: $\bar{\nu}_\mu \Rightarrow \bar{\nu}_\tau$ slightly favored)

Solar Neutrino: $\nu_e \Rightarrow \nu_X$ and $Dm^2 \sim 10^{-6} \text{ eV}^2$ or is it 10^{-11} eV^2 ? (SNO may help)

LSND $\bar{\nu}_\mu \Rightarrow \bar{\nu}_e$ and $Dm^2 \sim .03-1.0 \text{ eV}^2$

FUTURE

MINOS - Beams early 2004

CERN - Beams early 2005

K2K - 220 evts by 2005 (if Dm^2 large)

MiniBoone in 2003, Boone in ??

The next Supernova - Tools to interpret and limit

Closing Loopholes

Neutrino decay

$n_m \rightarrow n_e \bar{n}_e$ via Δ_L^0 (minimal LR symmetric model) consistent with

{ Mass Density of Universe Primordial nucleosynthesis
Microwave Bkgd Diffuse γ Bkgd SN1987a **}**

as long as $m(\nu_\mu) > 35 \text{ keV}$ (from Z-width)

Supernovae

For $m(n_x) > 10 \text{ keV}$, $Dt \sim \text{day} \Rightarrow$ pulse is below background
if SNO sees no delayed pulse, then take your pick:

No n_x produced? Oscillated to $n_{(\text{sterile})}$? They decayed? n_m is massive?

Check out all those 17 keV papers for more exotic loopholes

It is, after all, a Fundamental Constant !

Its uncertainty affects our knowledge of other fundamental constants

For example:

* Mass of the pion
as measured by decay of stopped p 's

* G_{fermi}
theoretical precision negligible compared to experimental variables
other electroweak variables, such as M_Z , continue to improve

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

0.5 ppm
MuLan 0.38 ppm 10 ppm

Direct Measurements are ...more direct!

Current Limits

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

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)

DIRECT MEASUREMENTS OF $M(n_m)$

Pure 2-body decay $p^- \rightarrow m n$

→ *No model-dependent nuclear/atomic environment*

→ *Pions live a reasonably long time*

Pion Decay at Rest

Parent π momentum is well-known

Limited by the uncertainty in the pion mass

Pion Decay in Flight

Need to measure $p_\pi - p_\mu$

Momentum Resolution limited by mult.scatter in detectors

Pion Decay at Rest

Series of experiments at PSI



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

Solution A

Solution B

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

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



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

Solution A

Solution B

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

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



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

Solution A

Solution B

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

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

Pion Decay in Flight

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

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

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

★ 2002: BNL g-2 Neutrino Mass Experiment?

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

If SuperK definitively proves $n_m \Rightarrow n_t$ ($\Delta m^2 \sim .007$)

Then this experiment reduces the τ neutrino mass limit

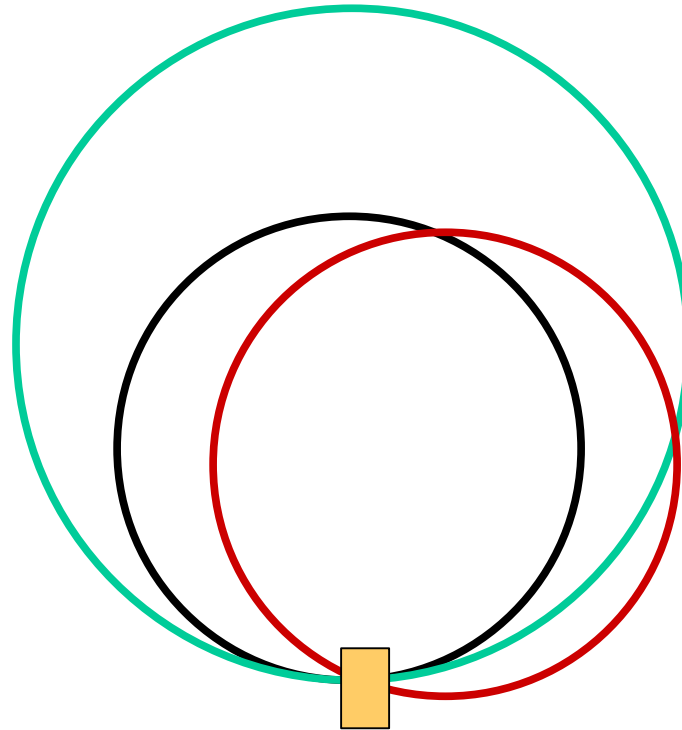
by 3 orders of magnitude!

Highlights of the Experimental Technique

- **Translate D_p to D_r in 0.1 ppm uniform B-Field**
no multiple scattering
no need to measure decay angle or location
- **Reference each m to parent p**
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**
1.4 μm SSD
- **Time resolution from scintillators and PMT's**
tight triple coincidence trigger
TDC's on all vetoes and embedded hodoscope

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

- * 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



“origin”

G-2 Storage Ring

G-2 Experiment

Weak-focussing Storage Ring: Muons stored for 800 ns

Quadrupoles

Muon Kicker

NuMass Experiment

Spectrometer: $p^- \rightarrow \pi^-$ observed evt-by-evt

No Quads

Pion kicker

Same Momentum - 3 GeV

retain excellent shimming and B-field uniformity

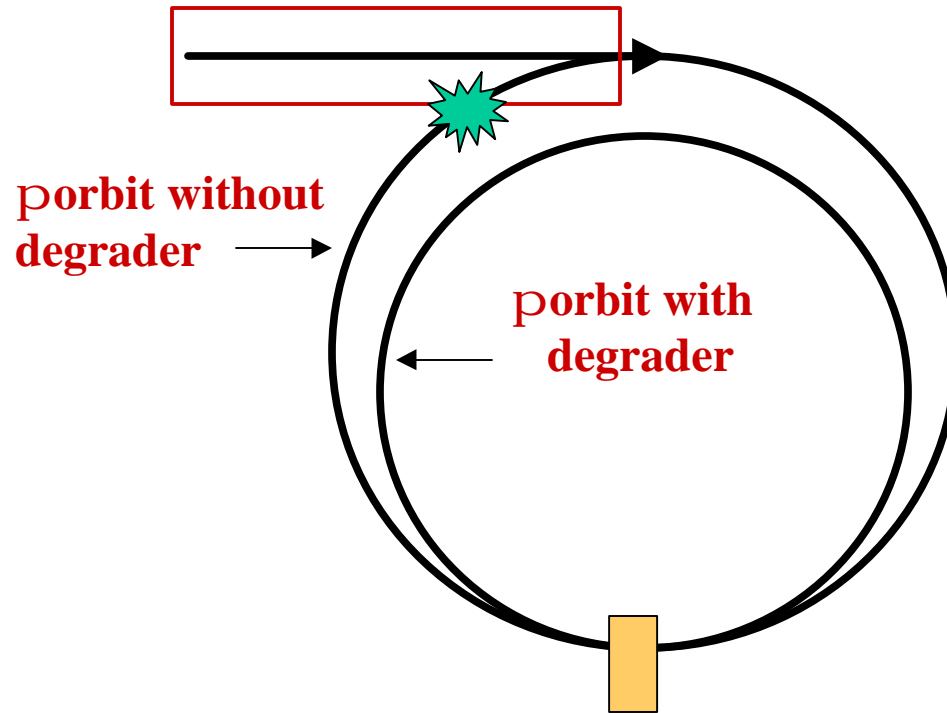
0.1 ppm over 4.5 cm

Trolley runs in vacuum to map field

Fixed probes to track changes

Active shimming and thermal insulation to minimize change

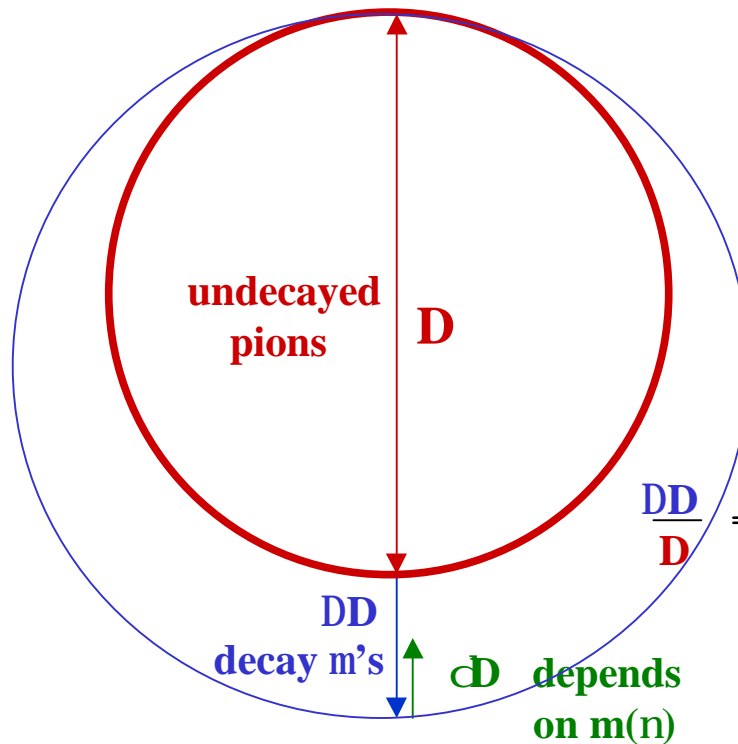
**Put pions on orbit using dE/dx Injection
5.2 cm Beryllium**



“Pion Kicker”

$D p = -16.2 \text{ MeV/c}$
 $X/X_0 = 14.7 \%$
 $q (\text{rms}) = 1.56 \text{ mr}$

Conceptual Design



Forward-going decay muons orbit a larger diameter by DD

CM

$n_m \longleftarrow p \longrightarrow m$

$q = 29.7 \text{ MeV}/c$

$$\frac{DD}{D} = \frac{p_m - p_p}{p_p} = \frac{0.7 \text{ MeV}/c}{3 \text{ GeV}/c} = \frac{3.26 \text{ mm}}{14 \text{ m}}$$

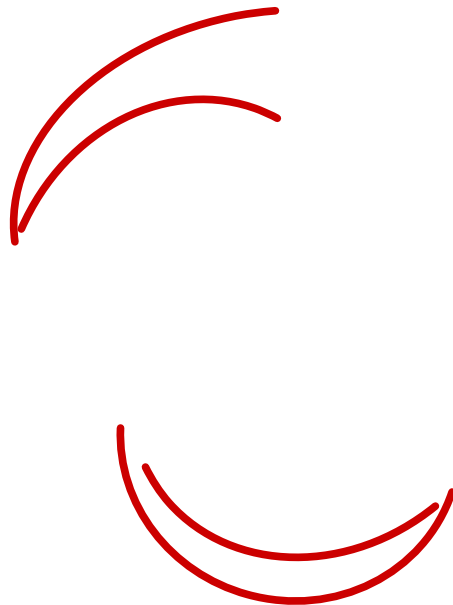
non-zero m_n shrinks DD

$$\frac{cD}{D} = \frac{-m_n^2}{2 q m_p}$$

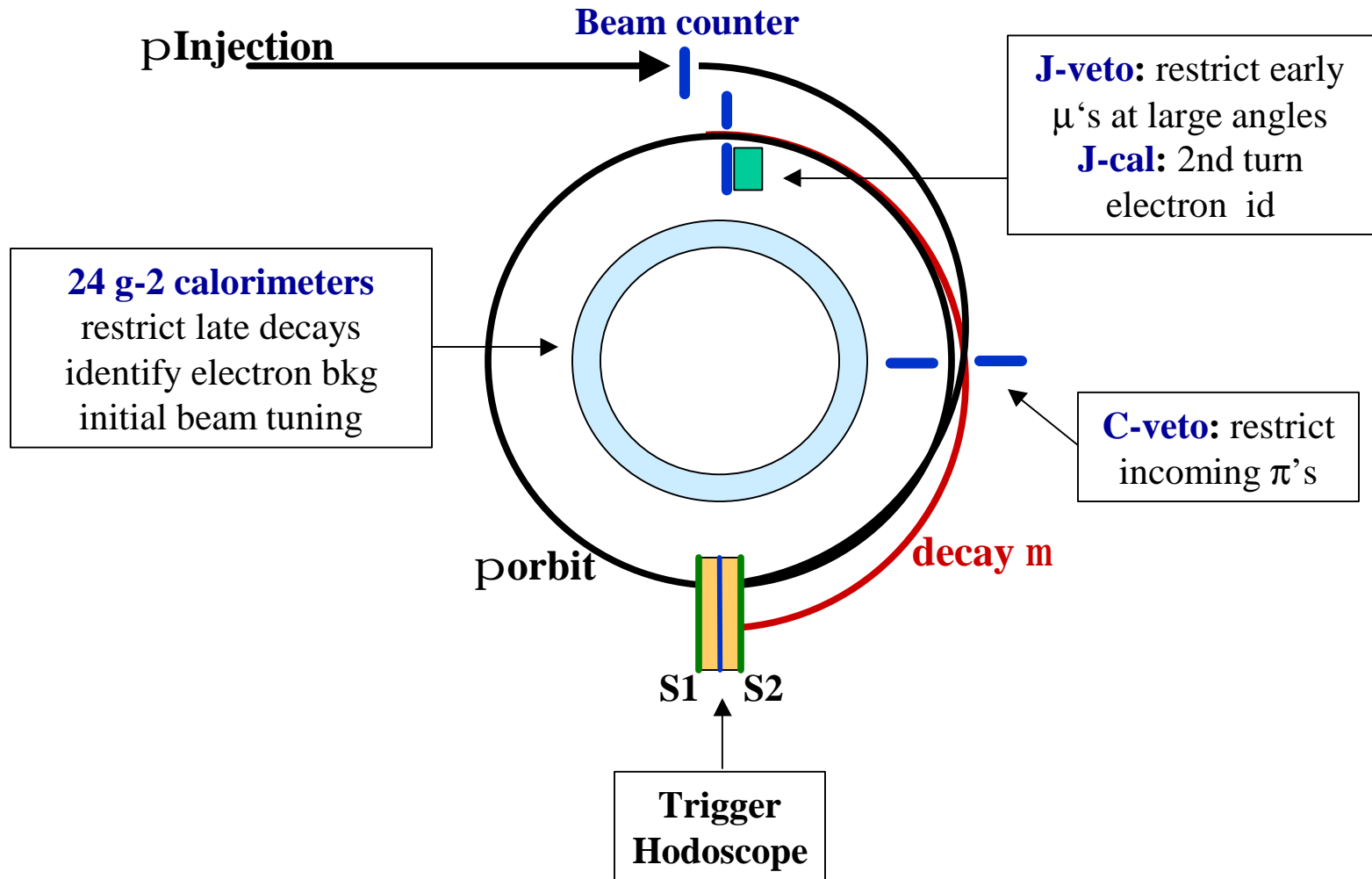
0.04 mm for current limit

Non-forward going muons are
lower momentum

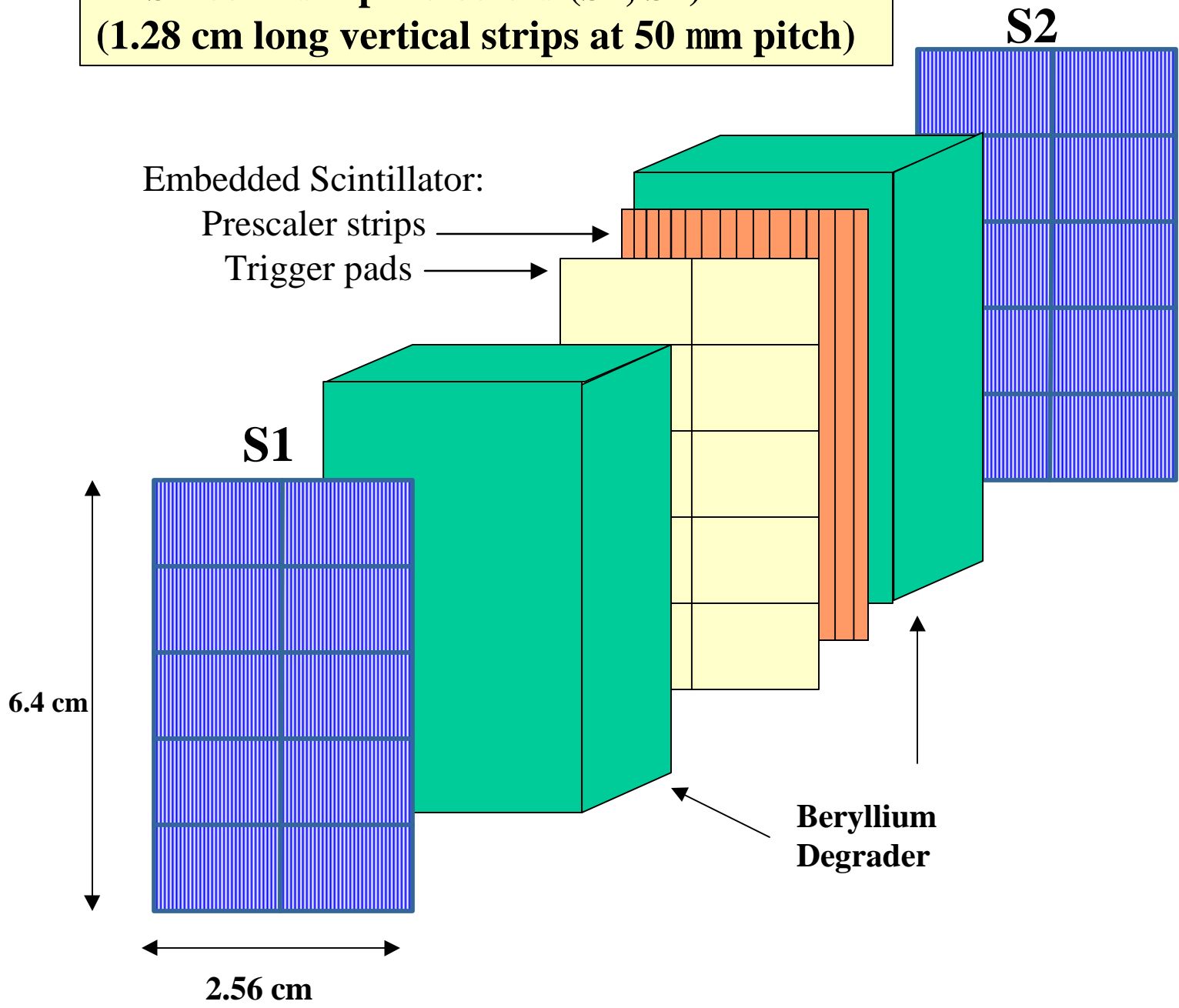
Move to the inside of S2
Lost on the g-2 Cal's and vetoes

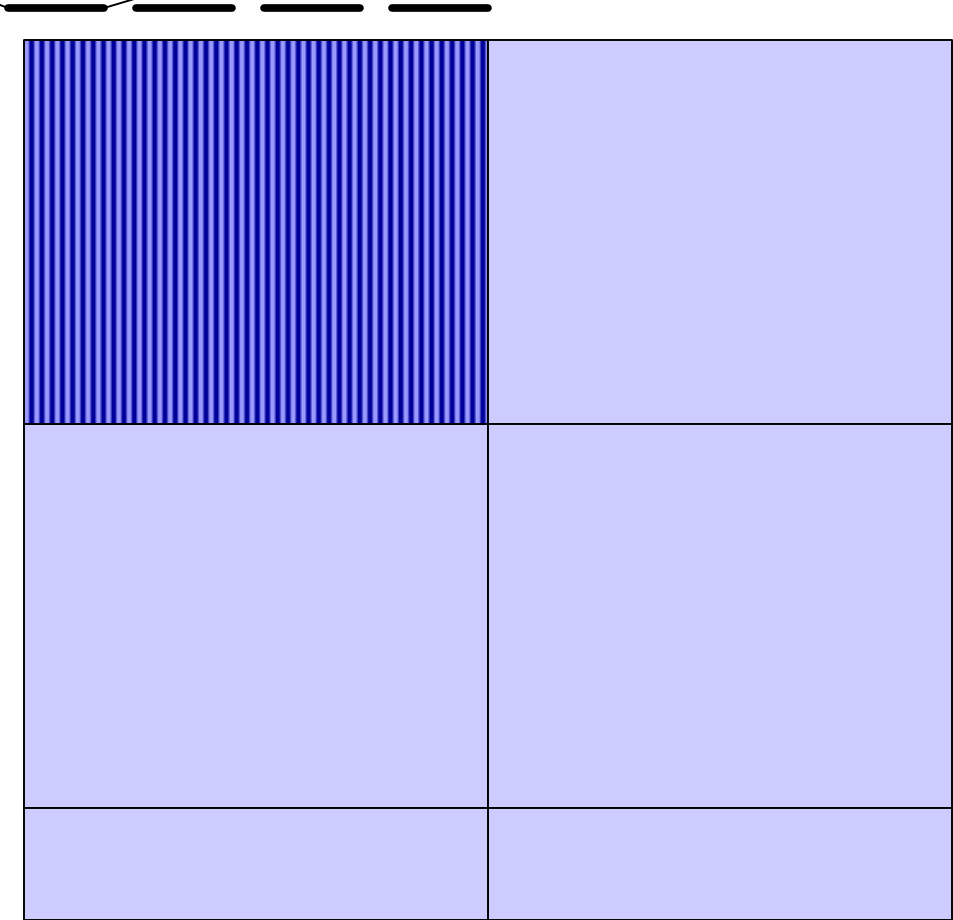
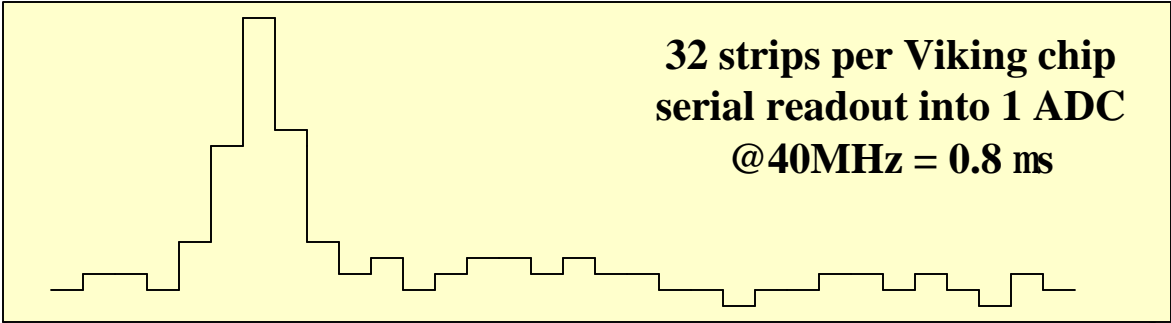


Experimental Method



Silicon mstrip Detectors (S1, S2)
(1.28 cm long vertical strips at 50 mm pitch)



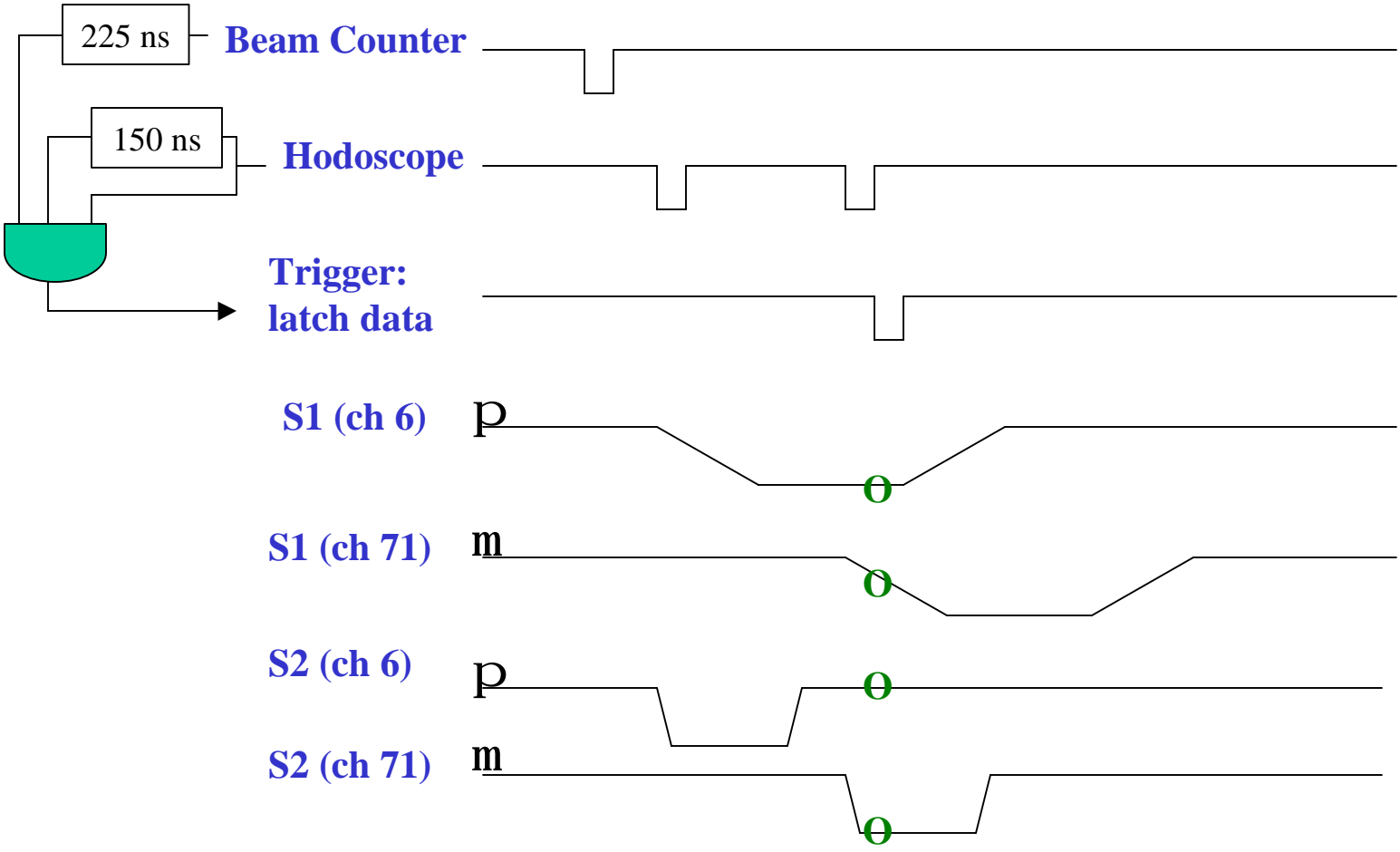


Sample & Hold Readout System

Simple

Standard

Cheap



Two Run Scenarios

Dedicated

H10 in DC mode => 10 GeV protons
 H5 replaced with thin septum
 $1.6 \times 10^{-6} \pi^+$ /pot
 3 TP on target => 800 hrs

Parasitic

25 GeV protons
 Bent Crystal Extraction (34% eff)
 $3 \times 10^{-6} \pi^+$ /pot
 5% of 60 TP => 1600 hrs

For Dedicated Run ... inst. rates

Entering Ring

4×10^6 part/s

Detector

5.7×10^5 part/s

200 Hz/strip

Prescale in trigger
or data storage

Triggers

$p p$

9×10^4 s⁻¹

111 μ s/SSD

50 MB/s

$p m$

455 s⁻¹

22 ms/SSD

0.25 MB/s

Offline

$(p m)$ +vetoes

21 s⁻¹



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 $D_r < 2\text{mm}$ to enrich p m 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)*

- **m => enn ($\tau = 64$ ms)**

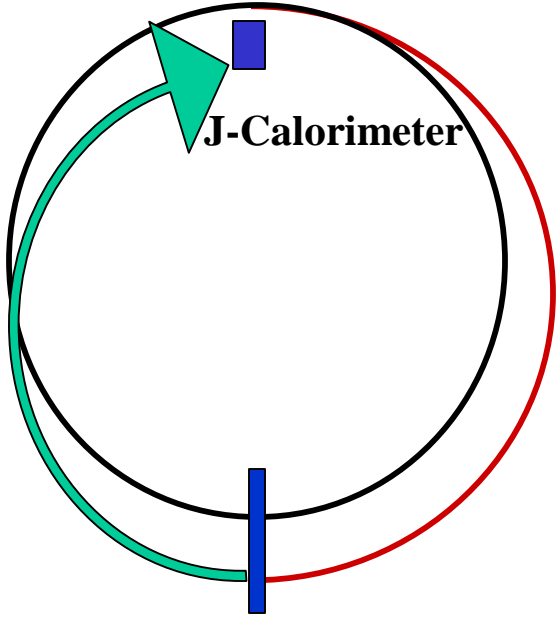
*injected m (1%) and p => mn
< 10^{-4} of good p- m events
rejected by g-2 calorimeters*

- **p => en (BR = 1.2×10^{-4})**

*low tail out to ~ 5 mm
calorimeter at inner J-Veto*

Some Background Configurations

$p^- \rightarrow e n$

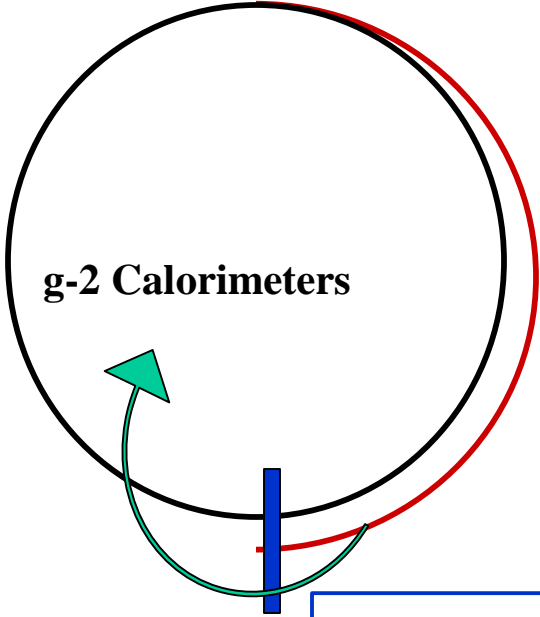


5 mm endpt ($q=70 \text{ MeV}/c$)



SR shrinks it 2 mm

$p^- \rightarrow mn$



$m^- \rightarrow enn$

Schedule

- Summer 2000 Test individual SSD's at CERN
- Spring 2001 Do tests at end of g-2 run (fast extraction)
- Insert 2 SSD's in rigid frame with removable "degrader"**
p-inj, low intensity, no quads, no kicker
No degrader: m- m, p J-veto Degrader: m- J-veto, p p
- Summer 2001 Test of crystal extraction for Slow Beam
- 2001 Build mosaic of SSD
Customize VA readout (chip run)
Tests of detector at CERN test beam
- 2002 Engineering run - parasitic with E949
Crystal extraction: slow beam down V-line
Final 5x5 SSD configuration with degrader in ring
- 2002 Physics run - parasitic or dedicated

Responsibilities

Beamline and Ring	BNL
SSD and readout electronics	CERN, Minnesota
Active Vetoes and Scint Trigger	Illinois, Tokyo IT
Feedthrus and positioners	Tokyo IT, Heidelberg, BNL
DAQ and g-2 electronics	Existing (Minnesota, BU)
Field Measurements	Yale, Heidelberg, BNL
Orbital dynamics, Monte Carlo Analysis	Cornell, Yale, NYU, Minn, BU, and all the rest

Some overlap between g-2, NuMass, MuLan, EDM

Overlap between NuMass and EDM is good for both groups

maintenance of magnet, shift running, sharing test runs

EDM is staged - last stage not until NuMass is over

Construction of new detectors for NuMass is done by

new collaborators (CERN, Tokyo) or

doubles up on existing infrastructure

e.g. scintillators (Illinois)

g2 electronics (BU), Viking readout & DAQ (Minnesota)

MuLan: test runs in 2001, 2002. Physics run 2003

JMU, LBL responsibilities. Also seeking new collaborators