How to measure g-2 with 15 GeV muons

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Yale

Present situation

BNL experiment	0.001 165 920 80	(63)	0.54 ppm
	Phys. Rev. D 73, 072003-1 (2006)		
theory	0.001 165 917 95	(59)	0.51 ppm
exp - theory	0.000 000 002 85	(86)	

de Raphael, Miller, Roberts — Reports on Progress in Physics

S. Eidelman — ICHEP conference, July 2006

2.44 ± 0.74 ppm

3.3 sigma

Can we do 10 x better .... ± 50 ppb ?

f = a (e/2r mc) B   Measure f , know B, calculate a

f is independent of particle energy

error in f $\Delta f = \frac{\sqrt{2}}{T \sqrt{N}}$ proportional to 1 / T

$\Delta a / a = \Delta f / f = \frac{\sqrt{2}}{f T \sqrt{N}} = \frac{\sqrt{2}}{n \sqrt{N}}$

n = number of cycles

muon lifetime	2.2	μs
at 3.1 GeV	64	μs
at 15 GeV	320	μs

At 15 GeV, more cycles to measure .... more accuracy for same cou

g-2 period	1.5 Tesla	4.4	μs
	3.0 Tesla	2.2	μs

Storage ring requirements

Need to focus the particles

know the magnetic field to better than 50 ppb

Muons are spread in radius .... field should be same at all radii

3.1 GeV .... magic energy ..... use uniform magnetic field

electric quadrupole focusing

at 3.1 GeV electric field does not affect g-2 frequency

snags: lifetime only 64 μs

cannot increase B .... electric field gets too large

Build an AG ring in which mean field is independent of radius

calibrate B with protons in flight

15 GeV ..... lifetime = 320 μs x 5

increase B x 2

⟹ x 10

Design of AG Ring

Mean field independent of radius (momentum) $R \propto p$

Momentum compaction factor $\alpha = (p / R).\, dR / dp = 1$

Well-known formula $\alpha = 1 / Q_h^2$

Courant & Snyder, Annals of Physics (1958)

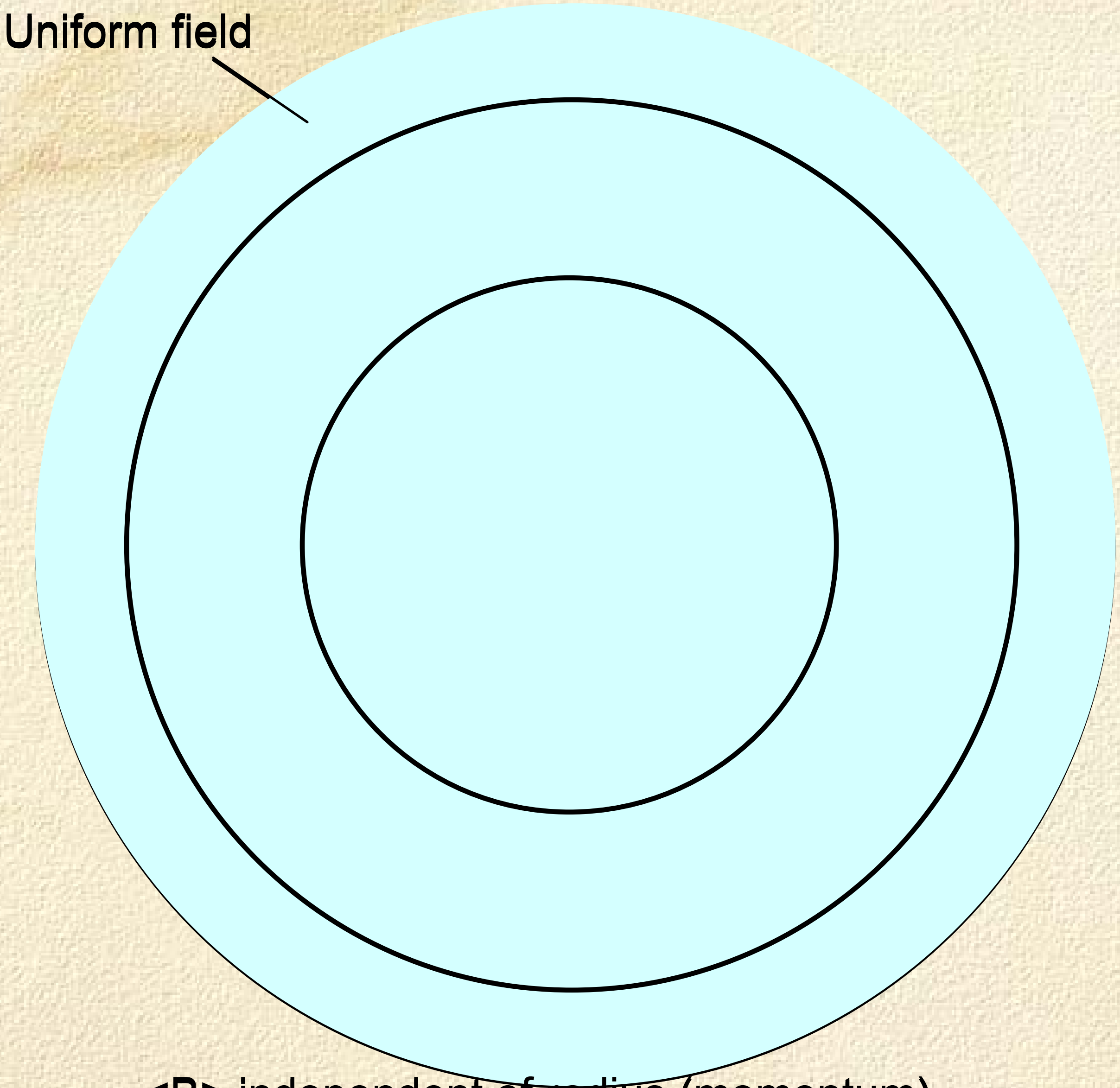
Example: weak focusing $Q_h = \sqrt{(1 - n)}$

$\alpha = 1 / (1 - n)$

If $\alpha = 1$, $Q_h = 1$

horizontal resonance

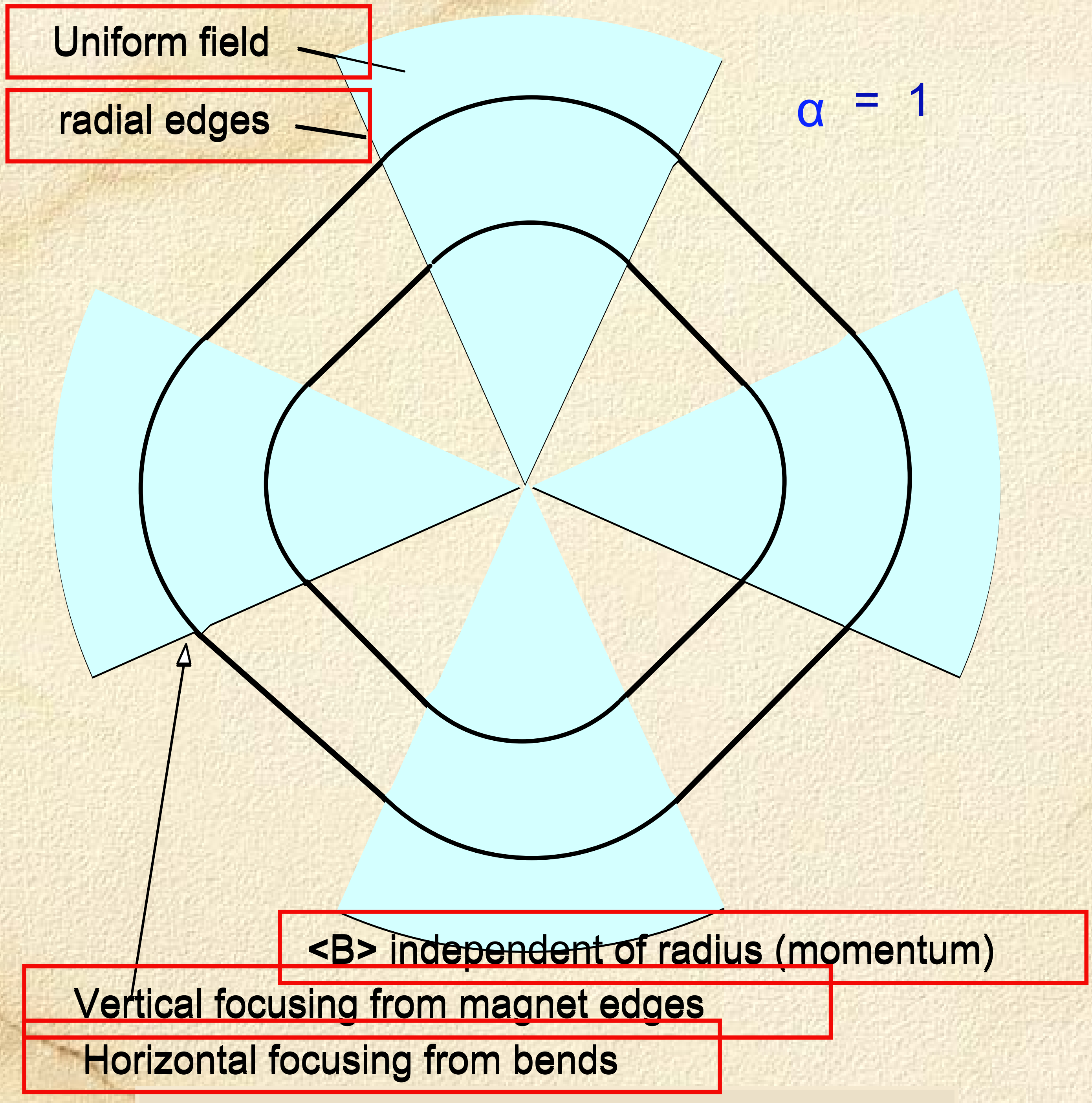
Experts say you cannot have $\alpha = 1$



<B> independent of radius (momentum)

No vertical focusing

Use electric quadrupoles - magic energy

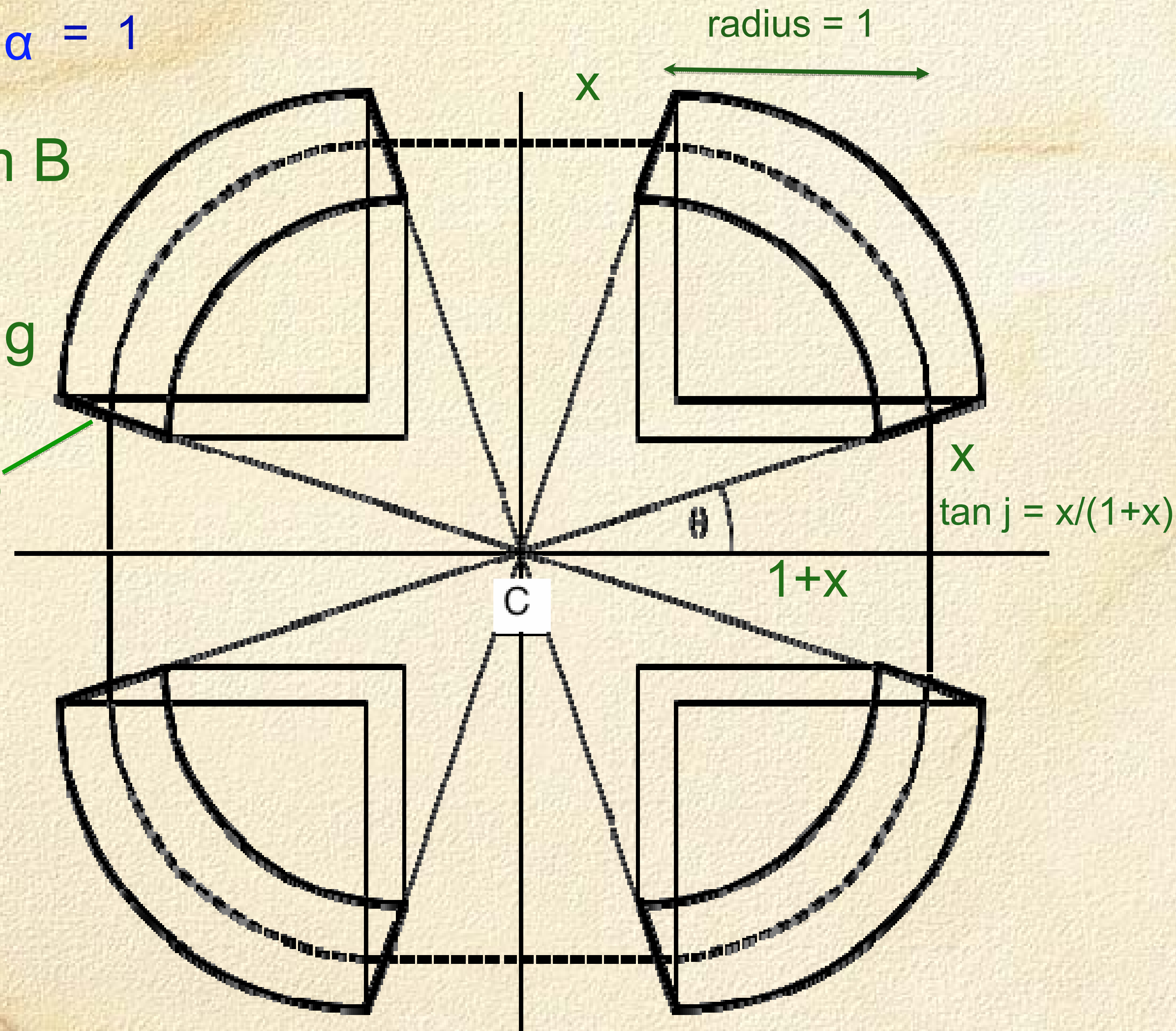

Uniform field
radial edges
α = 1
<B> independent of radius (momentum)
Vertical focusing from magnet edges
Horizontal focusing from bends

<B> is same for all radii

uniform B

edge focusing

line extrapolates to center point



Calculate horizontal tune Q_h

$$\begin{vmatrix} 1 & 2x \\ 0 & 1 \end{vmatrix}$$

XY

$$\begin{vmatrix} 1 & 0 \\ T & 1 \end{vmatrix}$$

Y

T = tan j = x/(1+x)

$$\begin{vmatrix} C & S \\ -S & C \end{vmatrix}$$

YZ

N=no. of sectors

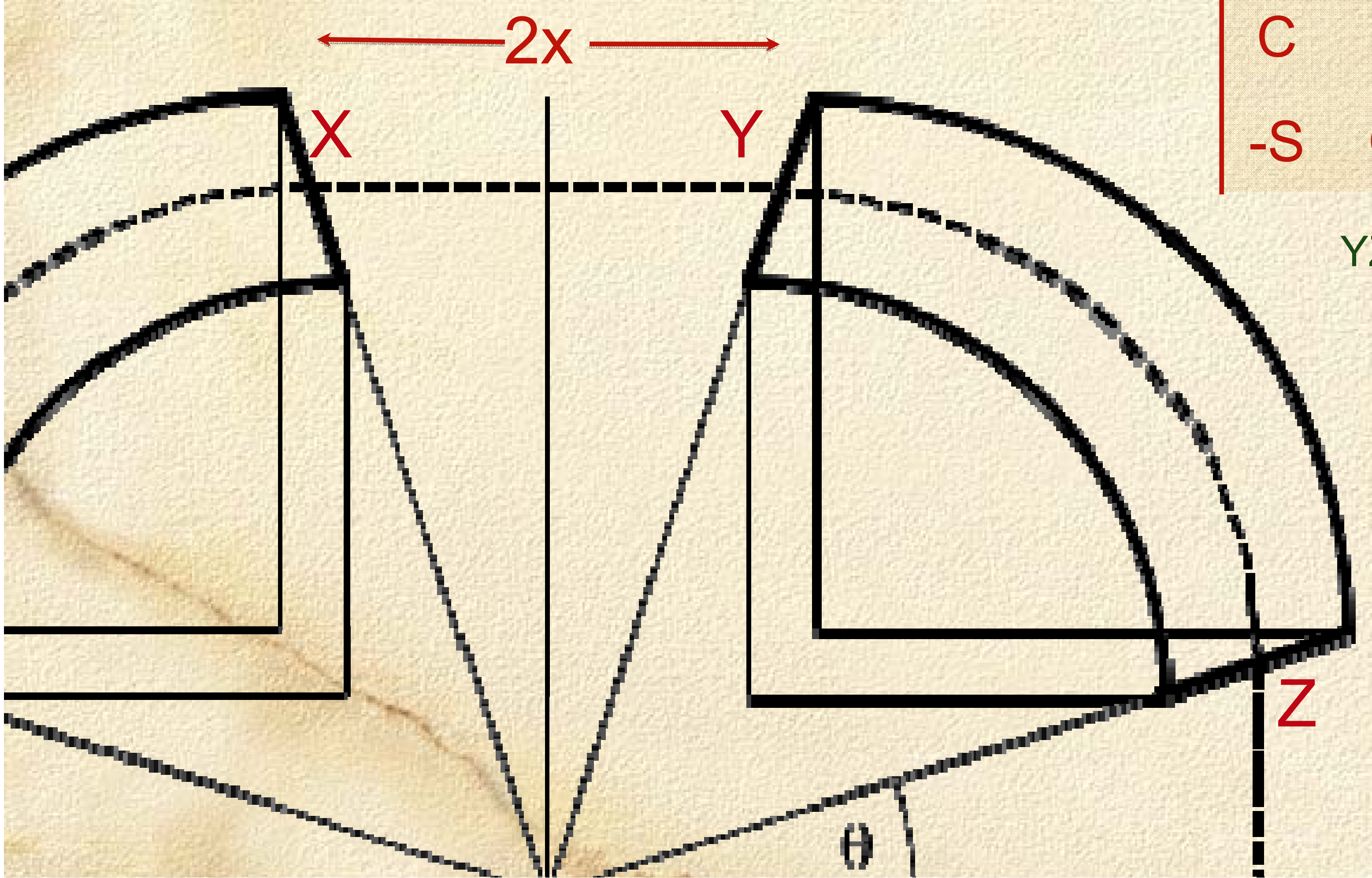
z = 2r/N

C=cos z

S=sin z

$$\begin{vmatrix} 1 & 0 \\ T & 1 \end{vmatrix}$$

Z



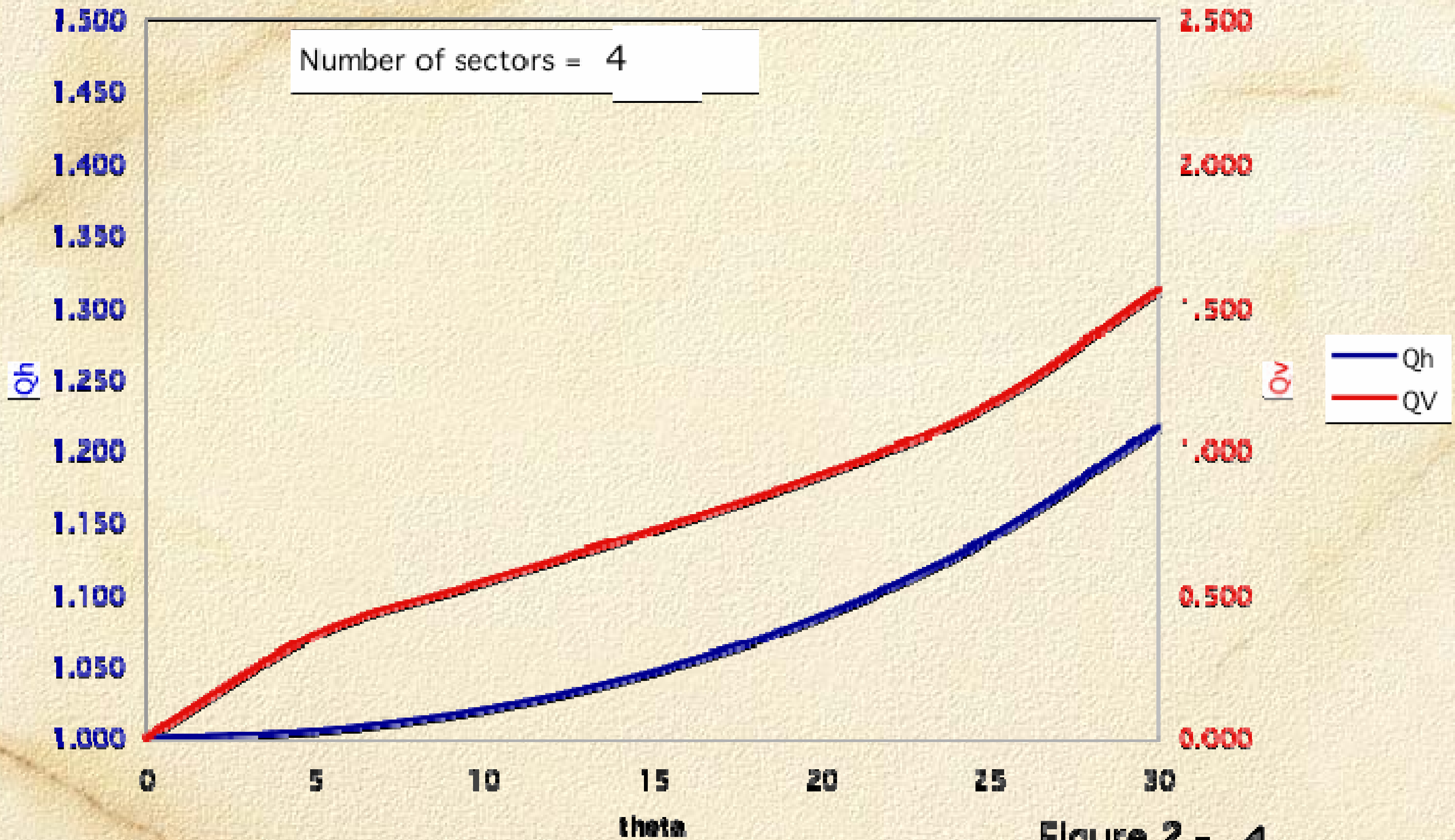
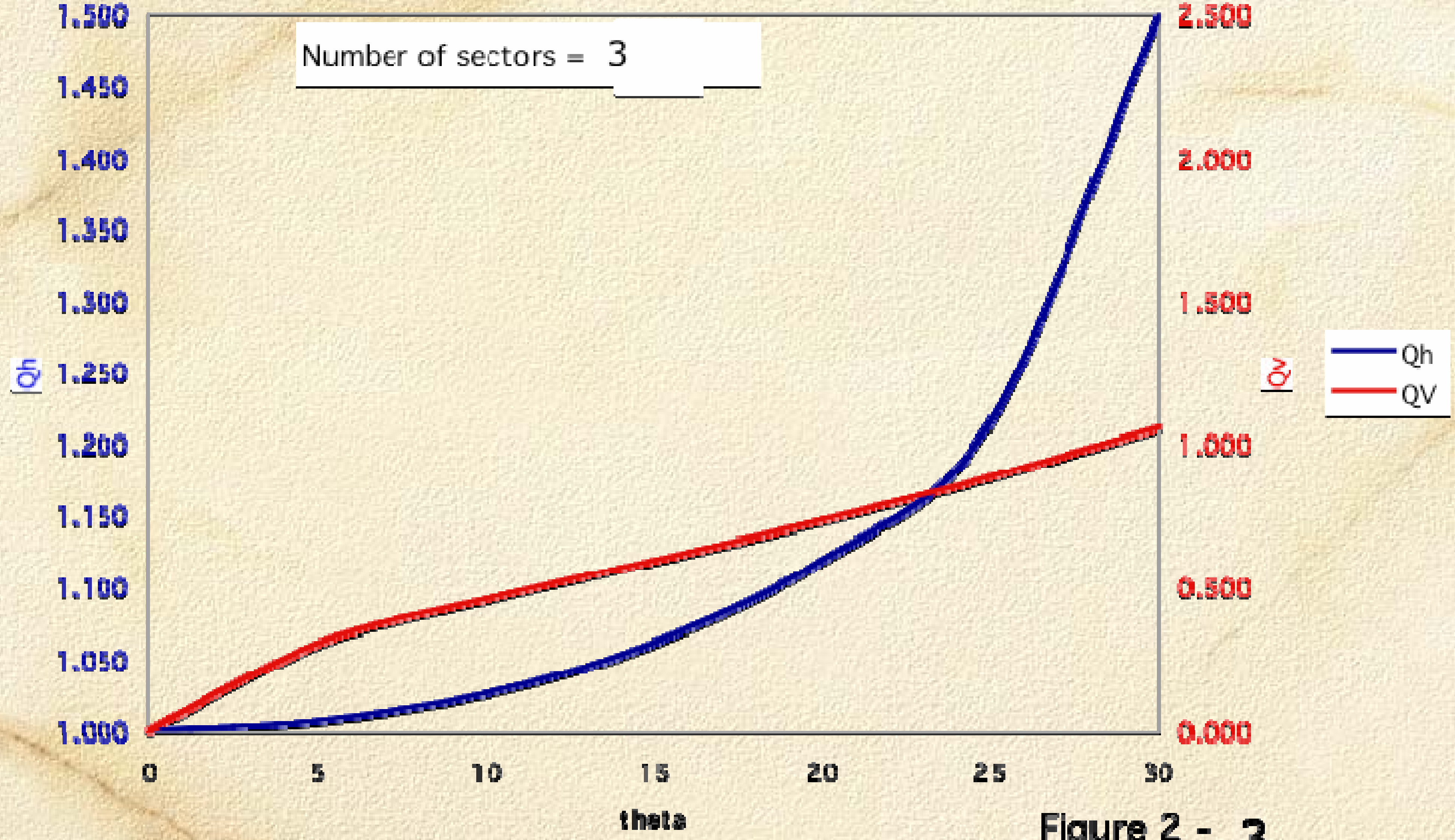

Number of sectors = 4
1.500
1.450
1.400
1.350
1.300
1.250
1.200
1.150
1.100
1.050
1.000
Qh
2.500
2.000
1.500
1.000
0.500
0.000
Qv
0
5
10
15
20
25
30
theta
Qh
QV

Figure 2 - 4



Number of sectors = 3
1.500
1.450
1.400
1.350
1.300
1.250
1.200
1.150
1.100
1.050
1.000
Qh
2.500
2.000
1.500
1.000
0.500
0.000
QV
0
5
10
15
20
25
30
theta
Qh
QV

Figure 2 - 3

To measure magnetic field

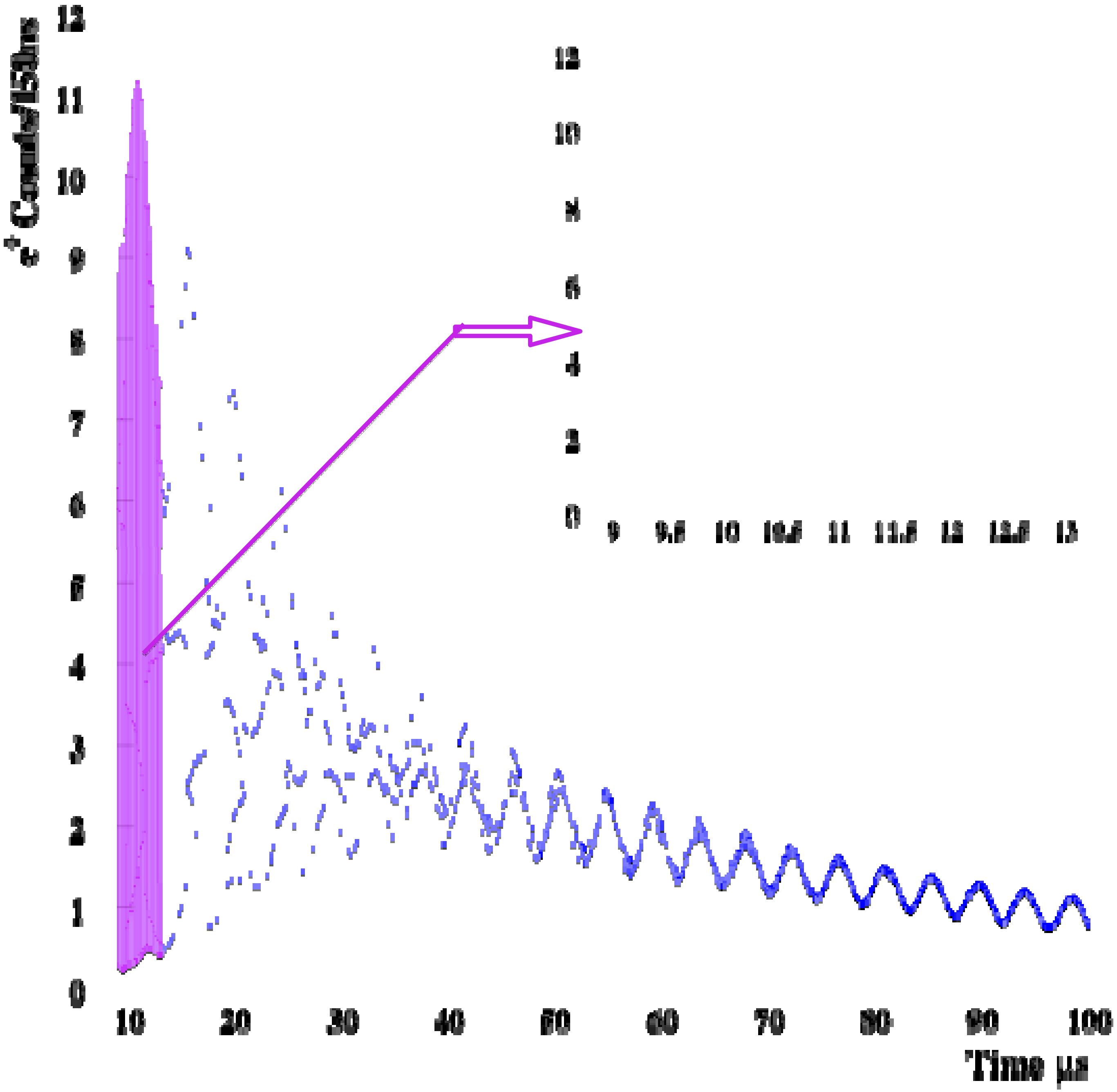
cannot use NMR probes because of azimuthal gradients

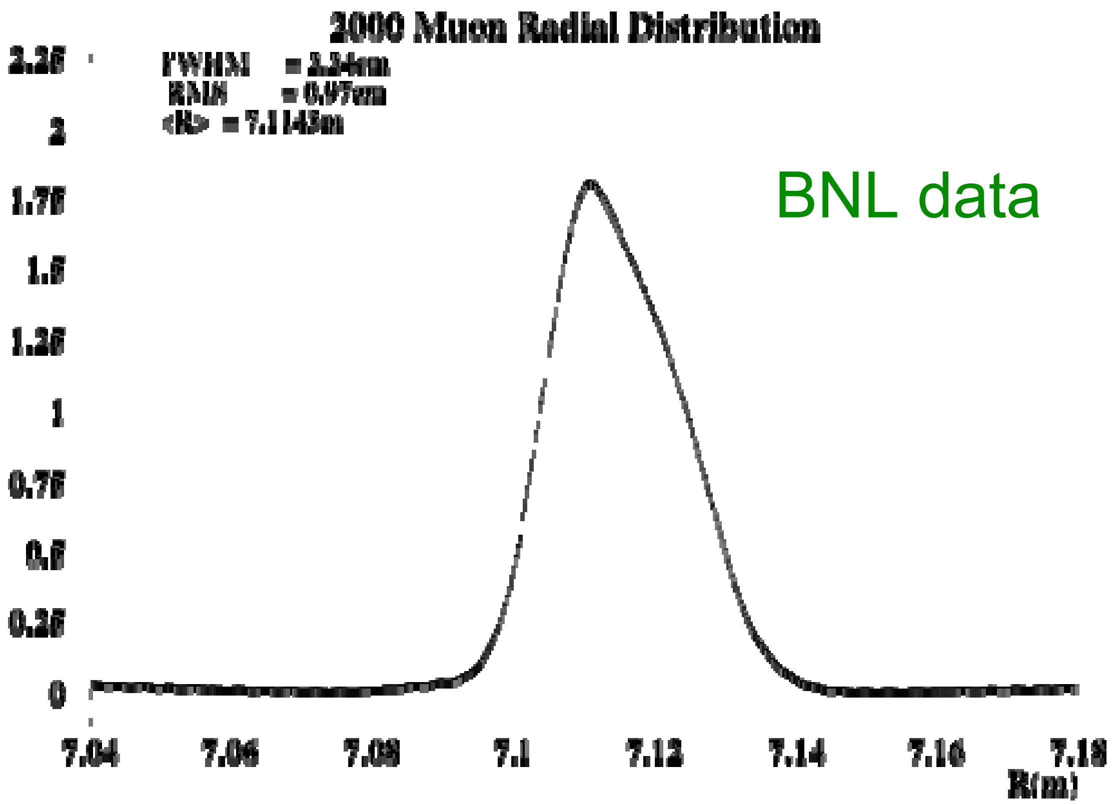
1) locate muons in radius

2) inject 15 GeV polarised protons on the same track

Locate muons in radius

BNL data





particles are bunched ...... we can measure their radius ... very precise

for muons

for protons

Inject polarised protons ...... on the same track

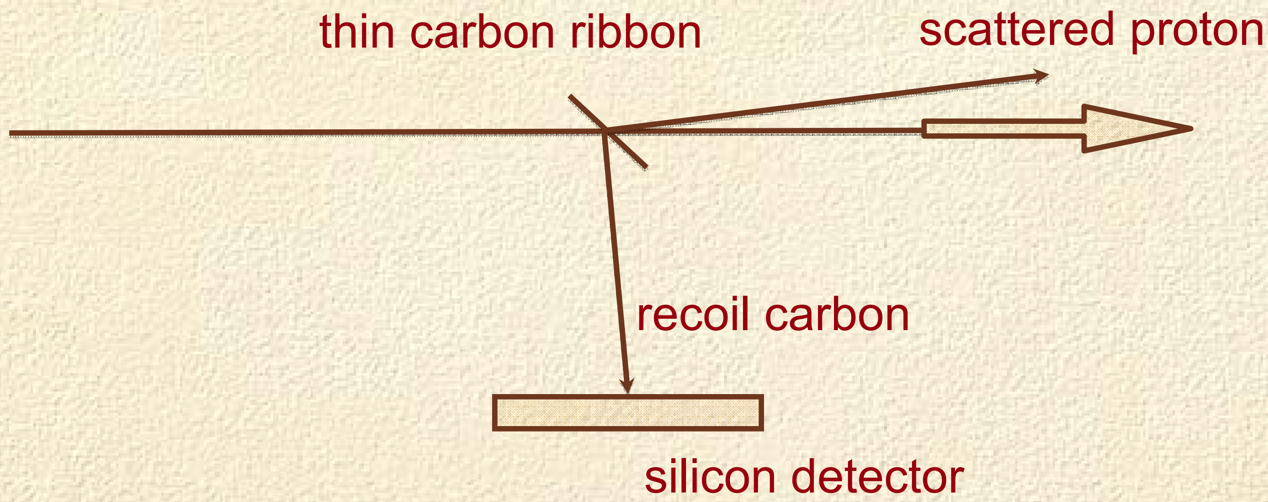
To measure magnetic field

inject transversely polarised protons of same momentum

particles of same momentum have to follow the same orbit

rotation frequency determines the orbit

15 GeV polarised protons used in RHIC



protons precess in horizontal plane

counters above and below measure up/down asymmetry

Asymmetry ~ 0.006 counting rate 1 MHz

We are using g-2 of proton to measure the magnetic field B

a = 1.789 284 739 (30 ppb)

		1.5 T	4 T
f_s = (1+a) eB/2**r** mc		62 MHz	
f_a = a eB/2**r** mc		42 MHz	112 MHz
g-2 period		25 ns	9 ns
10 million cycles	n	250 ms	90 ms
counts/fill	N	2.5 10^5	10^5
asymmetry A		0.006	

DB / B = Df / f = √2/nA√N = 50 ppb in one fill

Dp/p ~ 10^{4} proton beam is only 1 mm radially

all protons see same field

no wash out in 10 million cycles

We are measuring the ratio

$$\frac{\text{muon anomalous moment}}{\text{proton anomalous moment}}$$

NO messy corrections

diamagnetism of water molecule

paramagnetic salts

vacuum chamber walls

Measuring proton radius

protons are bunched ...... measure rotation frequency

$Dp/p \sim 10^{-4}$ width of beam $\sim$ 1 mm

small phase space

scan in radius to map field vs R

automatically averages in azimuth

no calibration or corrections

pitch correction is very small

tweak field with pole face windings to get B independent of R

apply vertical electric field to move protons up/down

1 kV/cm would move the median plane up 1 cm

$B = 4.5$ T $\langle B \rangle = 3.8$ T

bend radius 12 m

straight sections 4.3 m

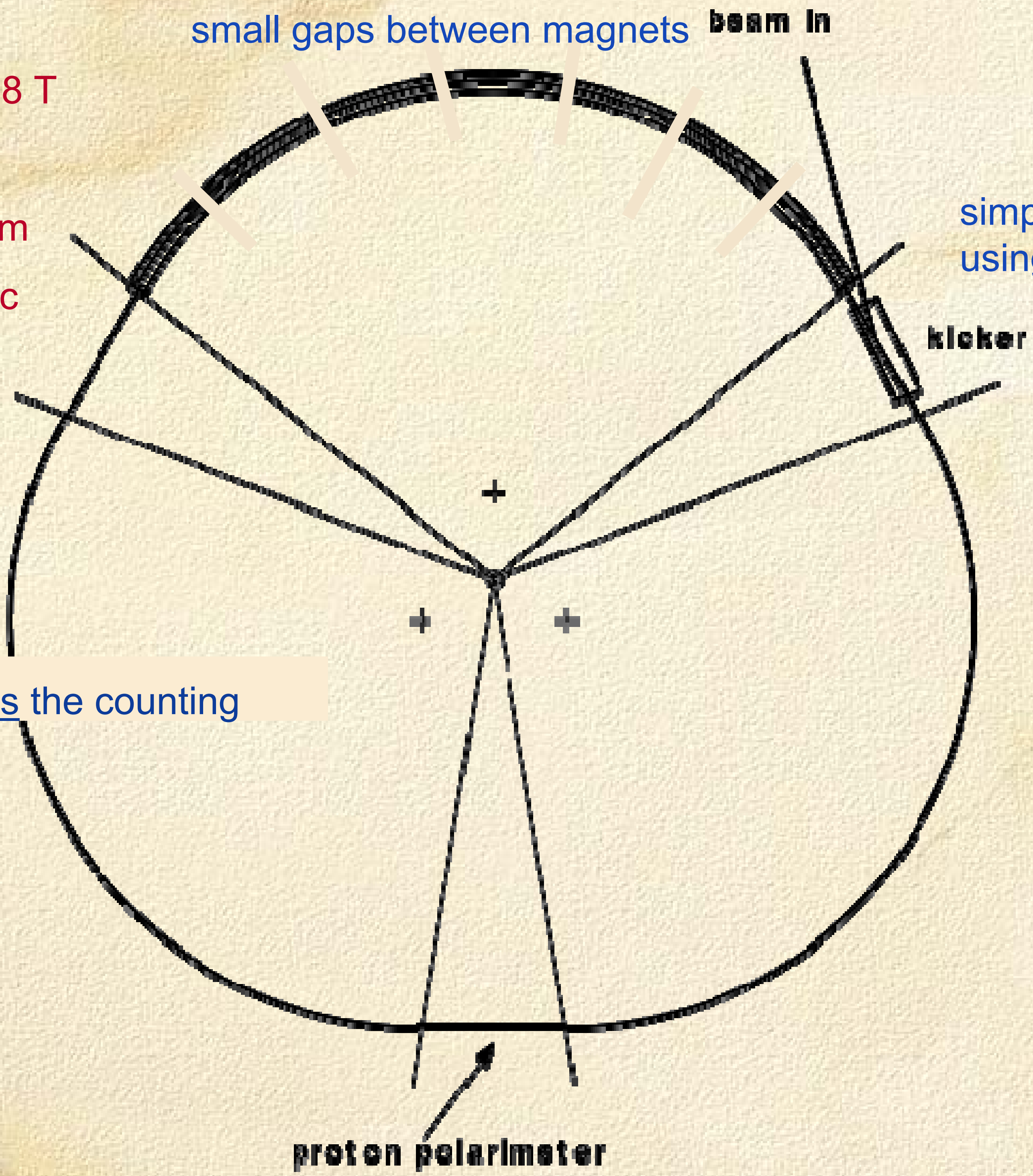
momentum 15 GeV/c

Q_h 1.025

Q_v 0.4

small gaps between magnets

simple kicker using ferrite



longer lifetime reduces the counting rate

less signal overlap

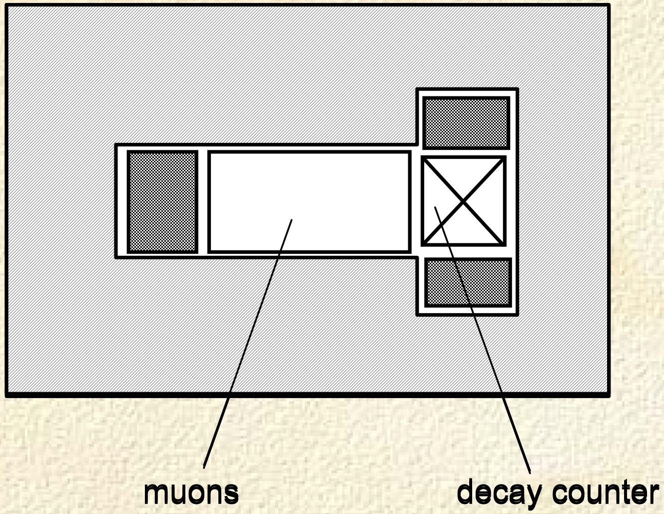
less residual flash

Challenges

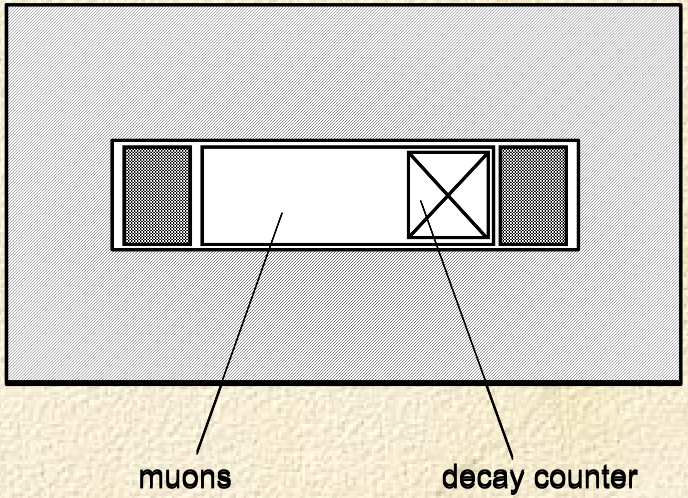
how high can we get the magnetic field

field stability

rapid switching from muons to protons



where to put decay electron counters



muon distribution in vertical plane ..... pitch correction $\sim$ 20 ppb

15 GeV muon source .... 5×10^{10} per year

plus polarised protons

Why bother ??

Another nail the coffin of the standard model

Test the next theory

Supersymmetry $$\delta a_\mu = 1.2 \ ppm \times \frac{\tan \beta}{M^2}$$

M is in units of 100 GeV

current value $$M^2 = 0.5 \tan \beta$$

e.g. $\tan \beta = 20$, $M = 320$ GeV

current limits
1σ

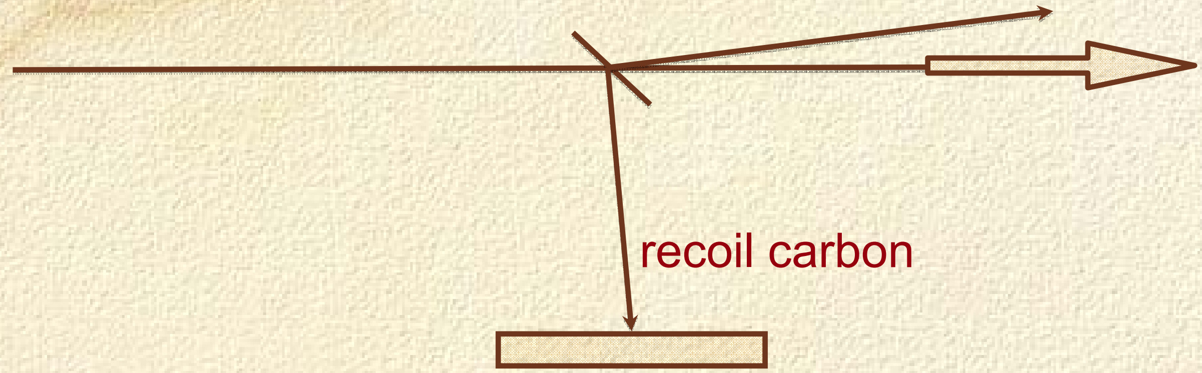
$$0.38 < \frac{M^2}{\tan \beta} < 0.70$$

Nuclear Instruments and Methods, A 523 251 (2004) *hep-ex/0307024*

Advantages

- no electric quadrupoles
- no trolley
  - calibration
  - correction for diamagnetism in water
  - paramagnetism in surrounding materials
- no inflector to cancel the field in the magnet at injection
- simple kicker using ferrite
- higher energy ... e g 15 GeV
  - increased accuracy
  - longer lifetime reduces the counting rate
  - less signal overlap
  - less residual flash
- higher magnetic fields
  - increased accuracy

Proton polarimeter



counters above and below measure up/down asymmetry

Asymmetry $\sim$ 0.01

Measure say 10^6 events

$N A^2 = 100$

10^6 precession cycles

$Df / f \sim 0.1$ ppm

Vertical questions

For muons

where is the median plane ?

amplitude of vertical oscillations ?

Hard to relate to the trolley map ! ! !

Protons

protons have the same median plane as muons

inject protons with small vertical angle .... is <B> the same ?

map <B> vs vertical amplitude

We know more about the protons than the muons !

Easier to relate proton data to what we know about the muons

Apply vertical electric field to move protons up/down

1 kV/cm would move the beam up 1 cm

$B = 4.5$ T $\langle B \rangle = 3.8$ T

bend radius 12 m

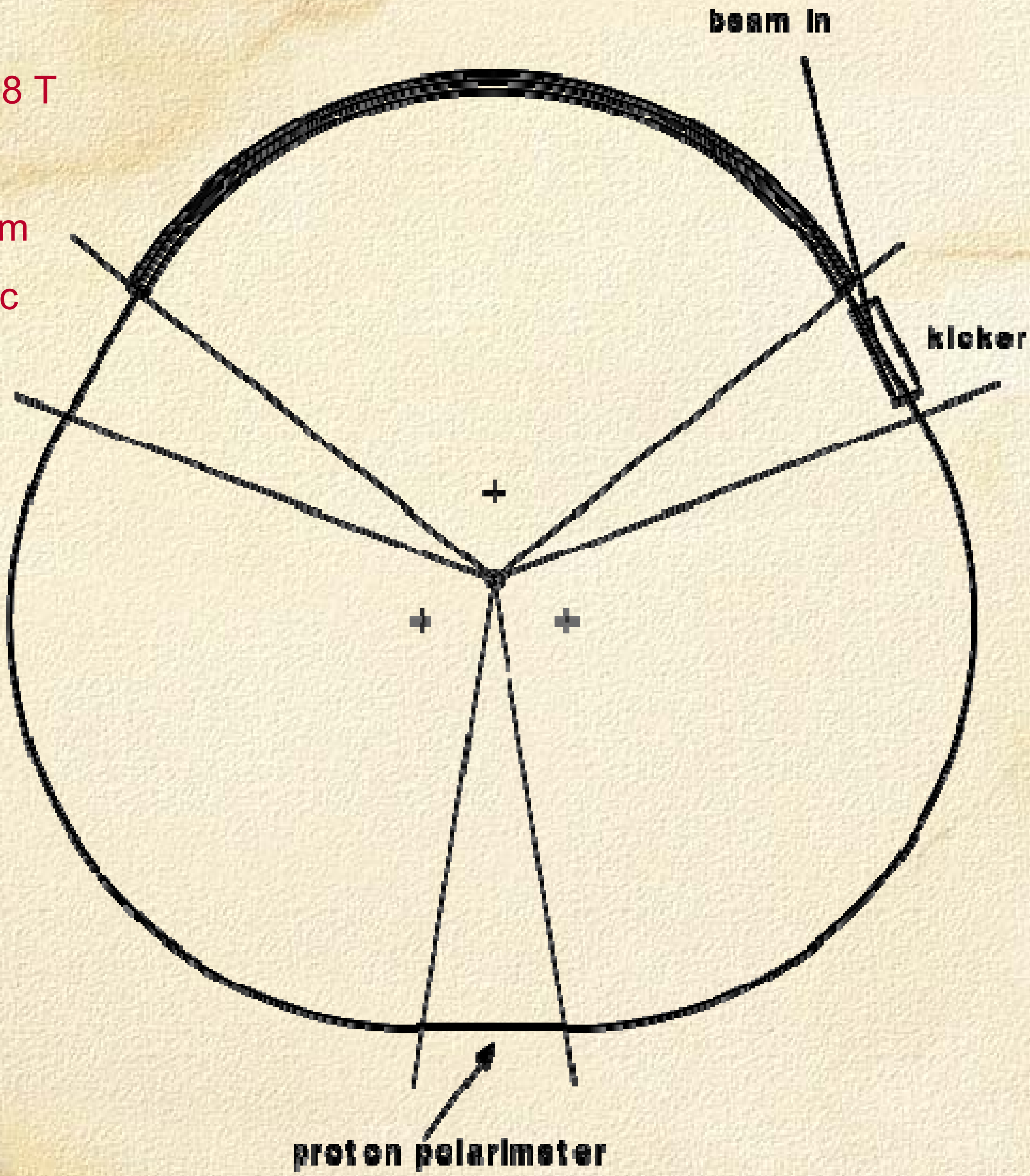
straight sections 4.3 m

momentum 15 GeV/c

Q_h 1.025

Q_v 0.4

Think about it



Measuring proton radius

protons are bunched ...... measure rotation frequency

$Dp/p \sim 10^{-4}$

small phase space

width of beam $\sim$ 1 mm

measure 10,000 turns .... 3 ms ..... error in radius < 0.1 mm

Better than the trolley ! ! !

scan in radius to map field vs R

- automatically averages in azimuth
- no calibration or corrections
- pitch correction is very small

tweak field with pole face windings to get B independent of R

- Is B then independent of z ?
- No ! $d^2 B/dz^2 = 0$, so dB/dz is constant .... but may not equal zero
- B can vary linearly with z .... but error is opposite above and below mid-plane

What you get with option key

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Ω≈ç√∫˜µ≤≥÷

σ Δ ψ η γ φ θ π χ Λ λ δ φ

π

ε β

σ Δ ψ η γ φ θ π χ Λ λ δ φ

∝

ε ∝ σ_x σ_θ ∝ ²

σ_θ ——> t

$\beta_\perp$ γ