MUON POLARIZATION.

- WHY ?
- POLARIZATION FIGURE OF MERIT
- SCENARIOS
- MONITORING
- CONCLUSIONS

see also
- Palmer Sessler Tollestrup
- Rossmanith
- Fernow Gallardo Fukui
- Raja , Raja Tollestrup
- Keil
- AB νfact'99 , "Prospective Study".

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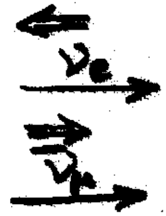
http://alephwww.cern.ch/~bdl/mu
/nufacpol

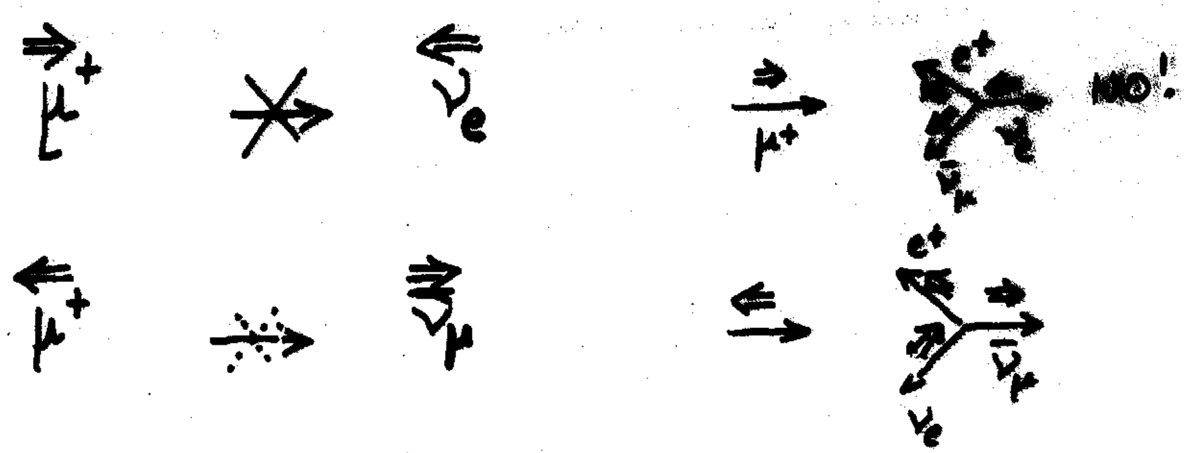
WHY ?

- ν_e is Left-handed
- $\bar{\nu}_\mu$ is Right-handed



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

- LONG BASELINE EXPTS DETECT ν's EMMITTED AT ≃ ZERO DEGREE

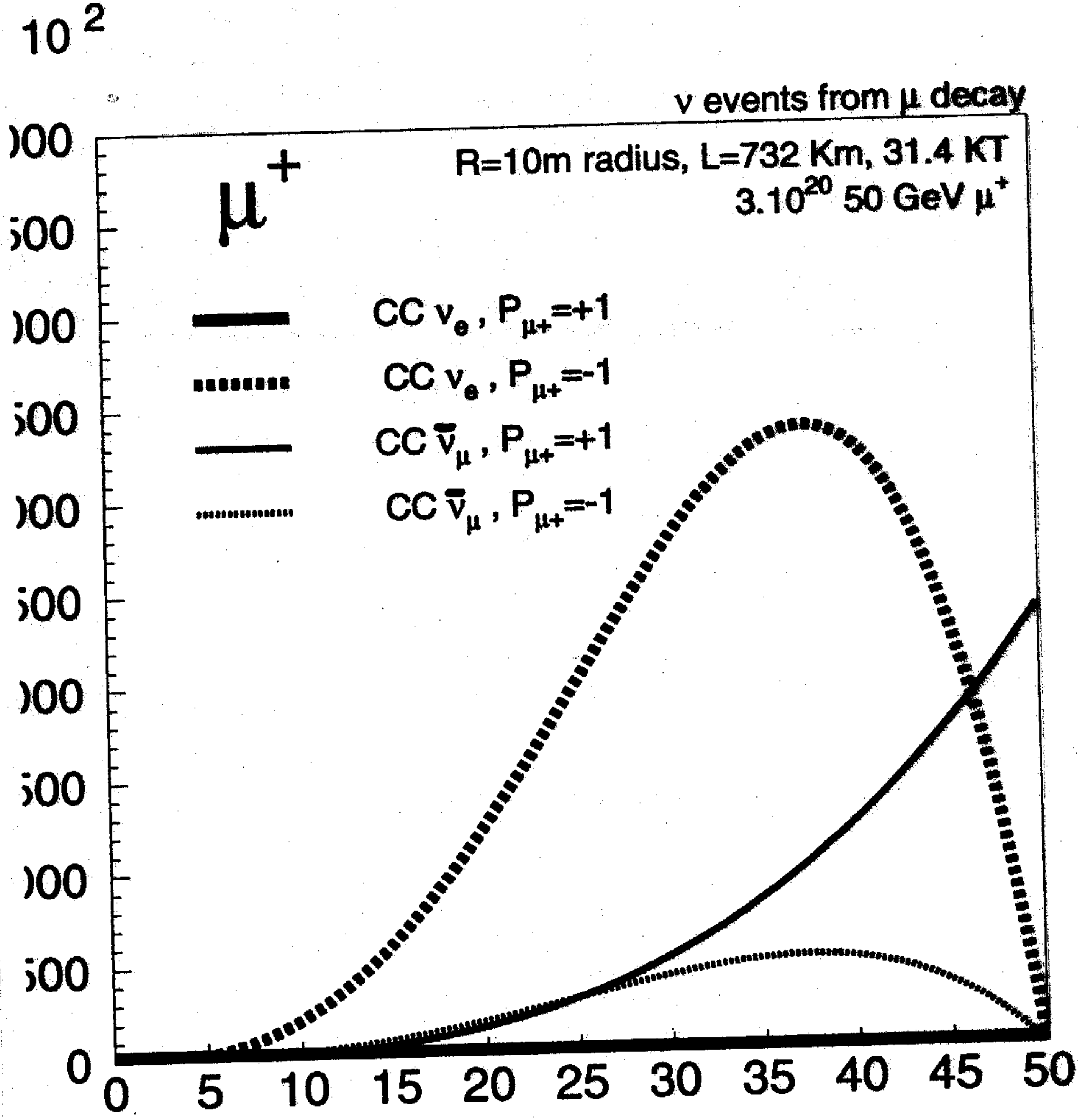


⇒ MUON POLARIZATION CONTROLS $\nu_e / \bar{\nu}_\mu$!

- <u>MUST</u> BE MONITORED

- IMPORTANT TOOL FOR CONTROLE OF BACKGROUND CALCULATIONS FOR eg

$$\mu^+ \underset{\text{decay}}{\rightarrow} \nu_e \underset{\text{oscillation}}{\rightarrow} \nu_\mu \underset{\text{detection}}{\rightarrow} \mu^-$$



10 2
ν events from μ decay
R=10m radius, L=732 Km, 31.4 KT
3.10^20 50 GeV μ+
μ+
CC νe , Pμ+=+1
CC νe , Pμ+=-1
CC ν̄μ , Pμ+=+1
CC ν̄μ , Pμ+=-1
000
500
000
500
000
500
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500
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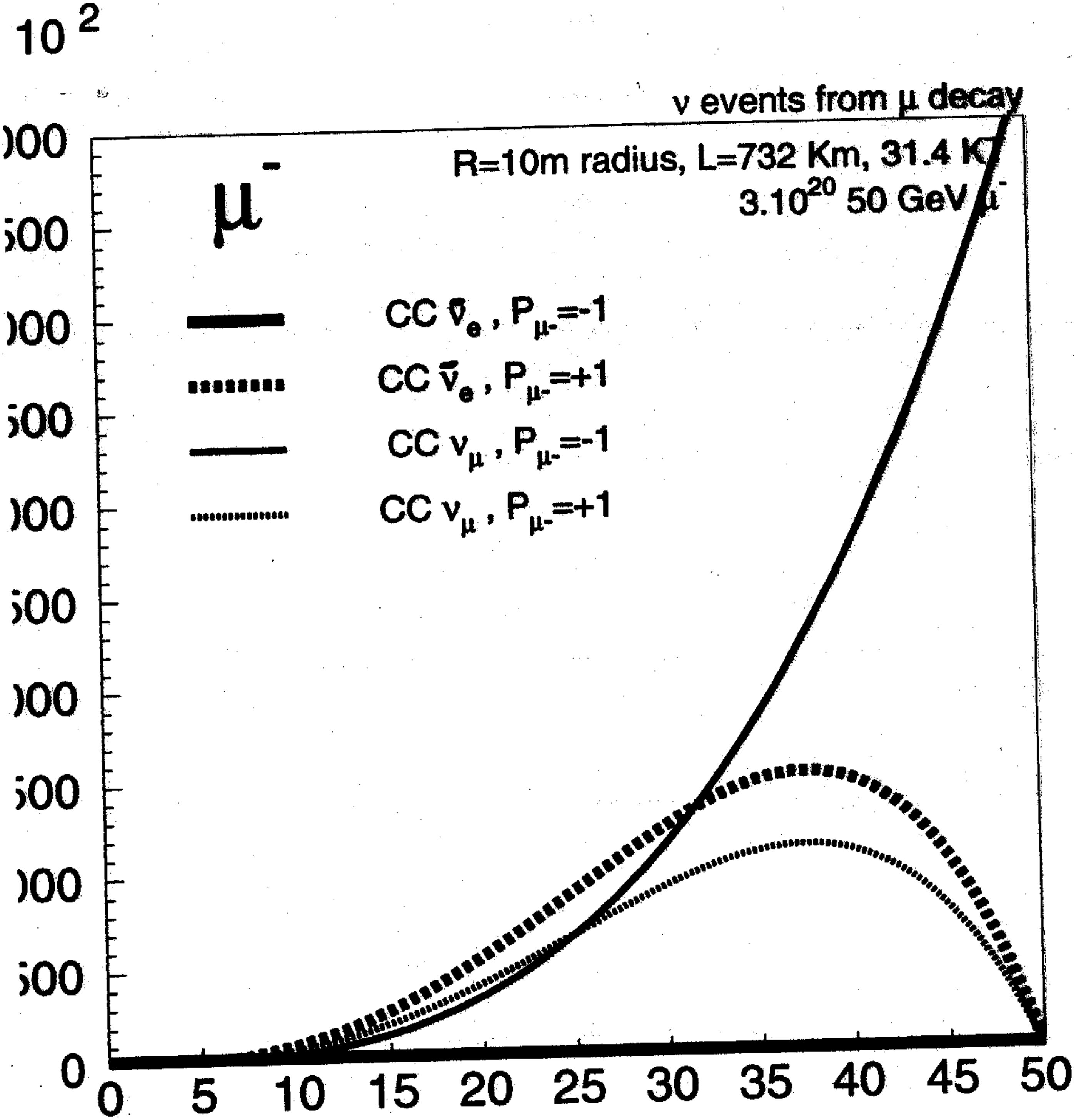
500
0
0 5 10 15 20 25 30 35 40 45 50



10 2
ν events from μ decay
R=10m radius, L=732 Km, 31.4 K
3.10^20 50 GeV μ-
μ-
CC ν̄e , Pμ-=-1
CC ν̄e , Pμ-=+1
CC νμ , Pμ-=-1
CC νμ , Pμ-=+1
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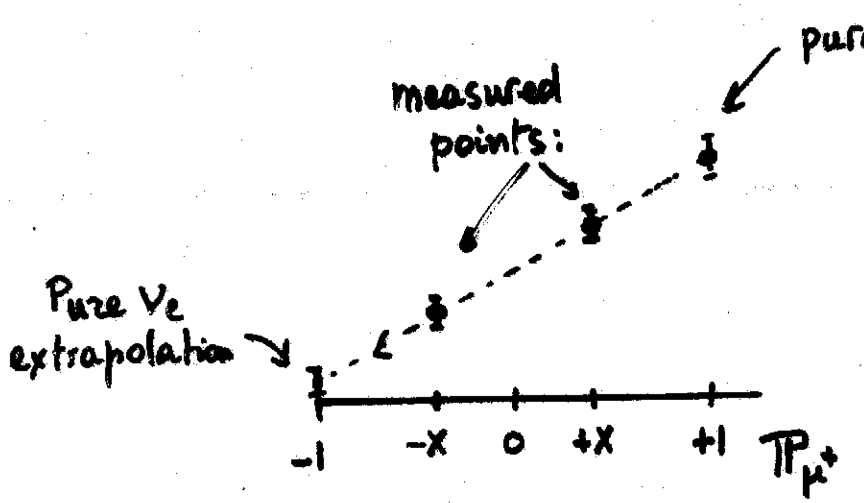
0
0
5
10
15
20
25
30
35
40
45
50

POSSIBLE USE

- COMPARE EVENT RATE FOR $\overrightarrow{\mu}^{\pm}$ and $\overleftarrow{\mu}^{\pm}$
  (SIGNAL!?)

$\Rightarrow$ EXTRACT PURE ν_e (SIGNAL!) EVENT RATE

AND PURE ν_μ



$\Rightarrow$ This type of events comes from $\bar{\nu}_\mu$ interactions!

- THIS WILL BE PRECIOUS TO DEMONSTRATE EXISTENCE OF A SIGNAL INDEPENDENTLY OF BACKGROUND SIMULATIONS ON THE WRONG ν COMPONENT

- $\mu^+ \leftrightarrow \mu^-$ SWITCH CANNOT BE USED SINCE IT IS ALREADY USED TO DEMONSTRATE MATTER OSCILLATIONS OR CP VIOLATION!

T, CP violation beyond wrong sign

ex $\theta_{12} = 23°$ $\theta_{13} = 5°$ $\theta_{23} = 45°$ $L = 7300$ km

$\Delta m^2_{12} = 10^{-4}$ $\Delta m^2_{23} = 3\,10^{-3}$

10 GeV ν's formulae from hep-ph 0002 108, Cervera et al. to be verified! (validity?)

(preliminary numbers)

(%)	$P_{\nu_e \to \nu_\mu}$	$\bar{\nu}_e \to \bar{\nu}_\mu$	$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$
$A=0$ $\delta=0$	1.56	1.56	1.35	1.35	1.56	1.56
$A=0$ $\delta=90°$	2.01	0.89	0.89	2.01	0.89	2.01
$A=A_m$ $\delta=0$	2.79	0.06	2.98	0.04	2.79	0.06
$A=A_m$ $\delta=90$	2.34	0	3.44	0.12	3.44	0.12

T violation !

Q. can this be seen in μ^- beam ?

(A: yes of course, if P = -1)

Q: can this be used [illegible]

Is MUON Polarization useful?

Alain Blondel + Mario Campanelli

Treat one example, PRELIMINARY, stat. only

Principle of Experiment:
. take half data with +P, half with -P
. “ “ “ “ μ^+ “ “ μ^-

Take detector and data of super ICARUS
Bueno/Campanelli/Rubbia, hep-ph 0005007

4 event classes: $e^\pm$, right sign μ, wrong sign μ, NC

Fit for δ while leaving all other parameters free,
see if error on δ is reduced when $|P|$ ↗

Input Parameters

Δm^2_{12}= 10^{-4}
Δm^2_{23}= 3.5 10^{-3}ev^2
θ_{12}=45°
θ_{23}=45°
$\sin^2 2\theta_{13}$= 0.05
δ=0 or $\pi/2$

L= 2900 km
10 ktons fiducial

2 10^{21} useful muons (5 10^{20} for each sign-polarity)

detector classes:
1. "electrons": any event with an electron (no energy cut)
2. "right sign muon": event with muon (P>2 GeV) of beam sign
3. "wrong sign muon": event with muon (P>2 GeV) of sign opposite beam
4. "NC": all other events.

Decays in flight of hadrons -> muons are included
no background for electrons
no systematic errors on beam (yet)
matter density is left as free parameter in the fits

Some numbers

Surprise: there is a big δ–effect in electron event numbers

$\mu^- (\to \bar{\nu}_e \ \nu_\mu)$

ELECTRON CLASS:

	δ=π/2		δ=0
P=0	**59550**	**(-510)**	**60060**
P=-1	**6003**	**(-604)**	**6607**
P=+1	**113100**	**(-400)**	**113500**

Kills anti-ν_e ⟶ (P=-1)

δ=π/2 decreases the $\nu_\mu \to \nu_e$ oscillation.

Some numbers

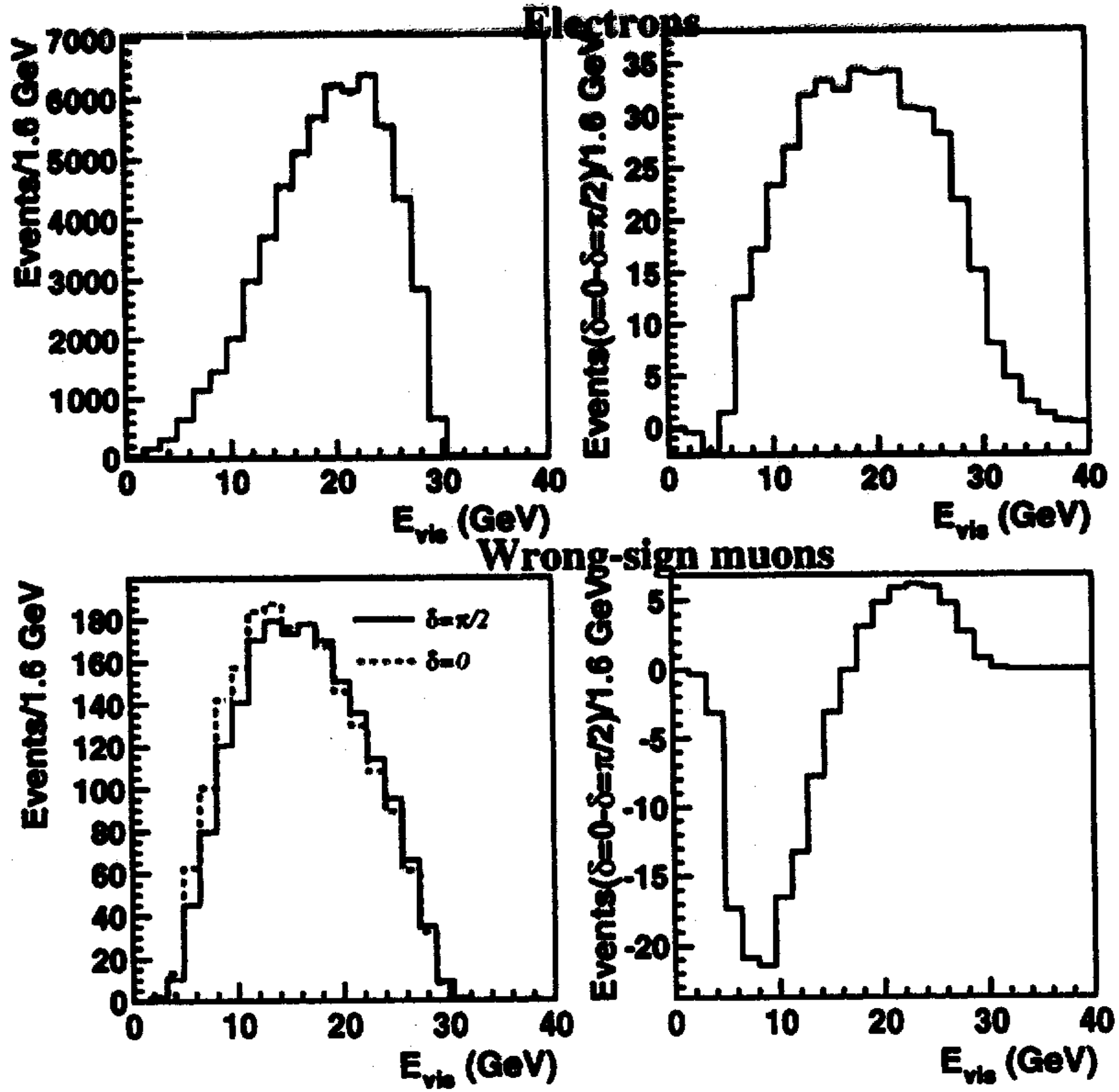
Surprise: there is no big δ–effect in wrong sign muon event numbers

$\mu^+ (\to \nu_e \, \bar{\nu}_\mu)$

	WRONG SIGN MUON CLASS:		
	$\delta=\pi/2$		$\delta=0$
P=0	1919	(+43)	1876
P=-1	3795	(+83)	3712
Kills ν_e ⟶ P=+1	41	(-)	41

BUT $\delta=\pi/2$ modifies the shape of the $\nu_e \to \nu_\mu$ oscillation.

No polarisation



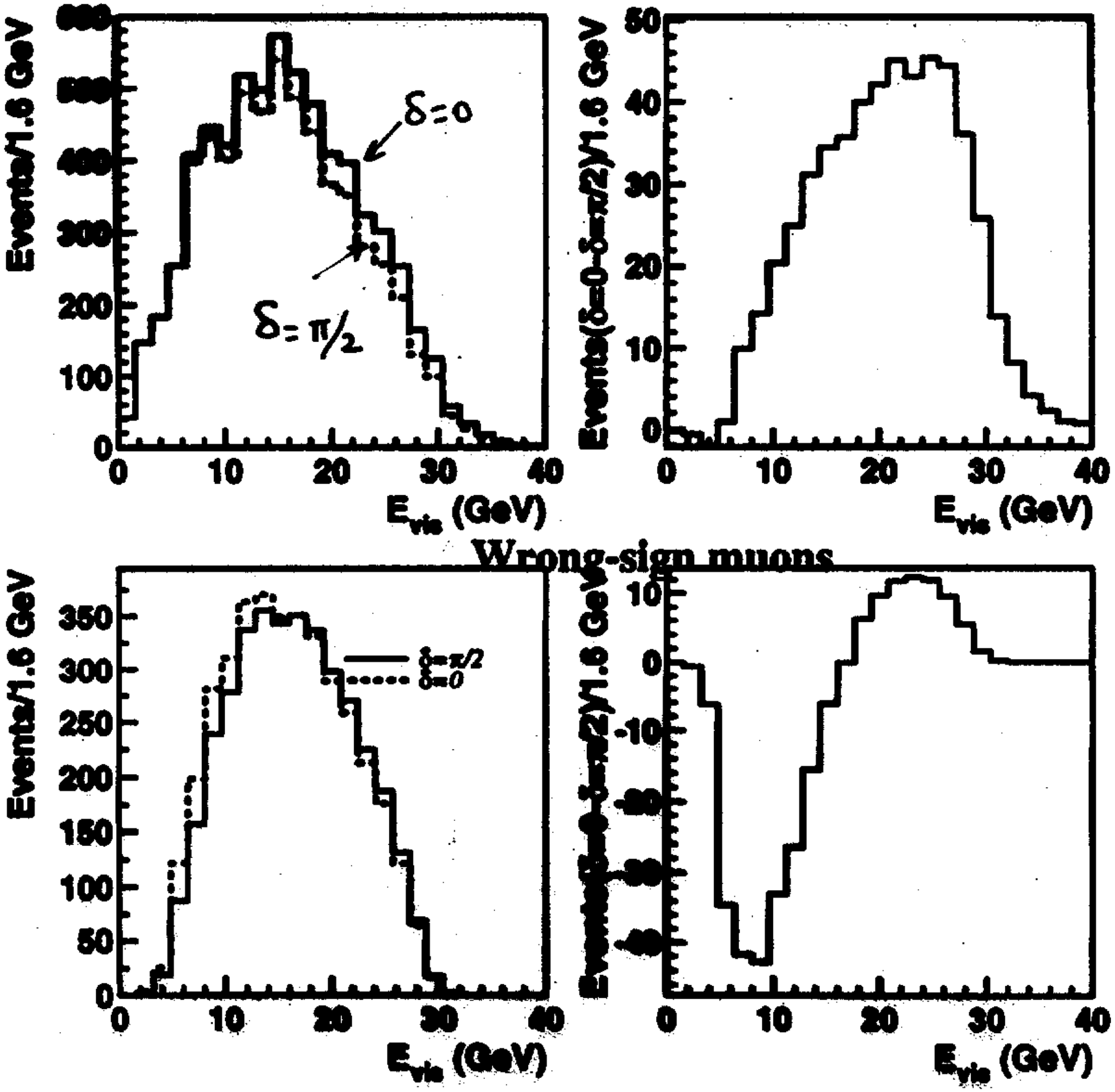
Negative polarisation(100%)

δ=0 − δ=π/2

μ−, P=−1

kills $\bar{\nu}_e$

"electron" events



μ+, P=−1

more $\bar{\nu}_e$

"Wrong sign muons" events

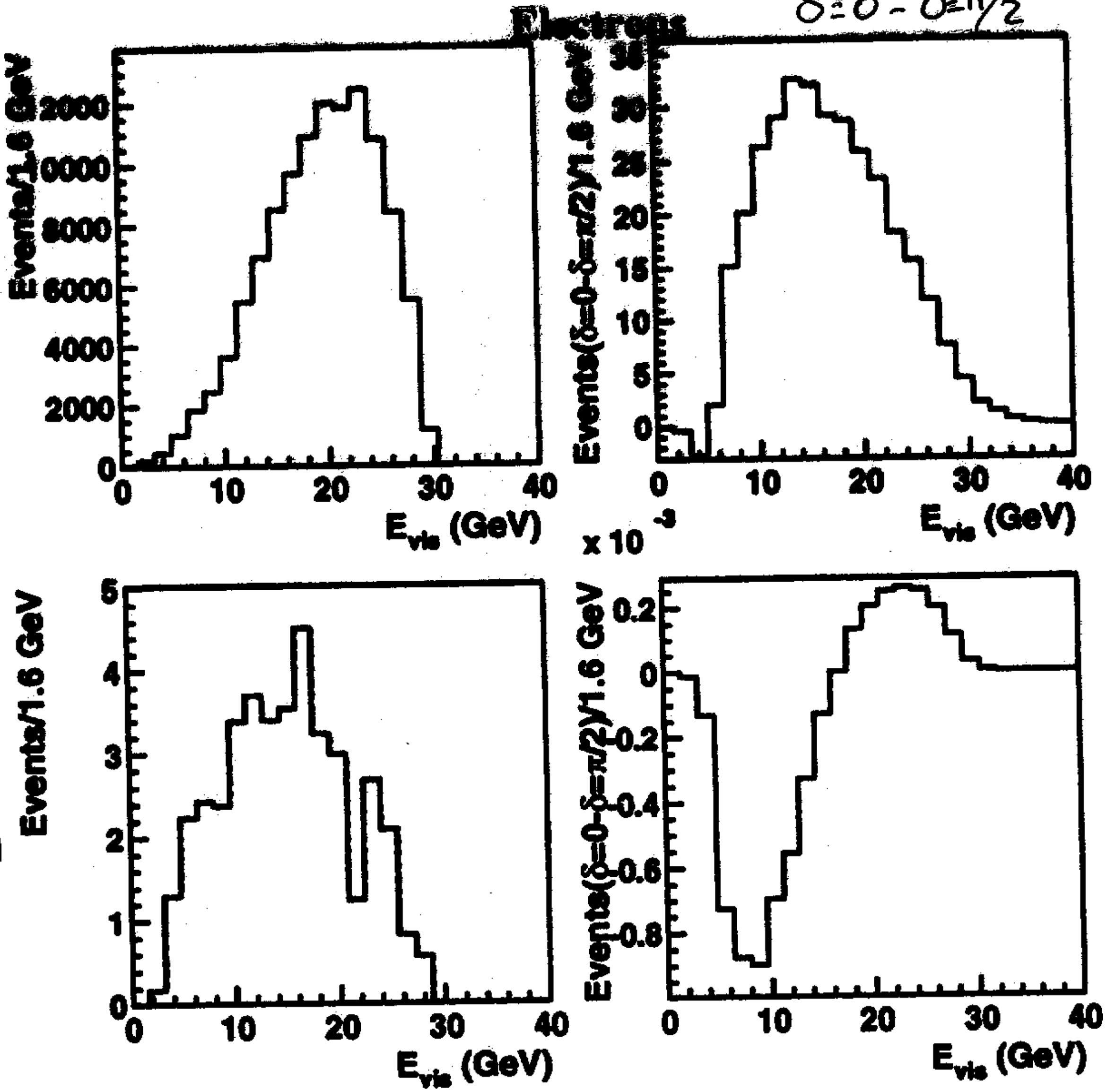
Positive polarisation (100%!)

$\delta = 0 - \delta = \pi/2$

μ−, P=+1

more ν_e

"election" events

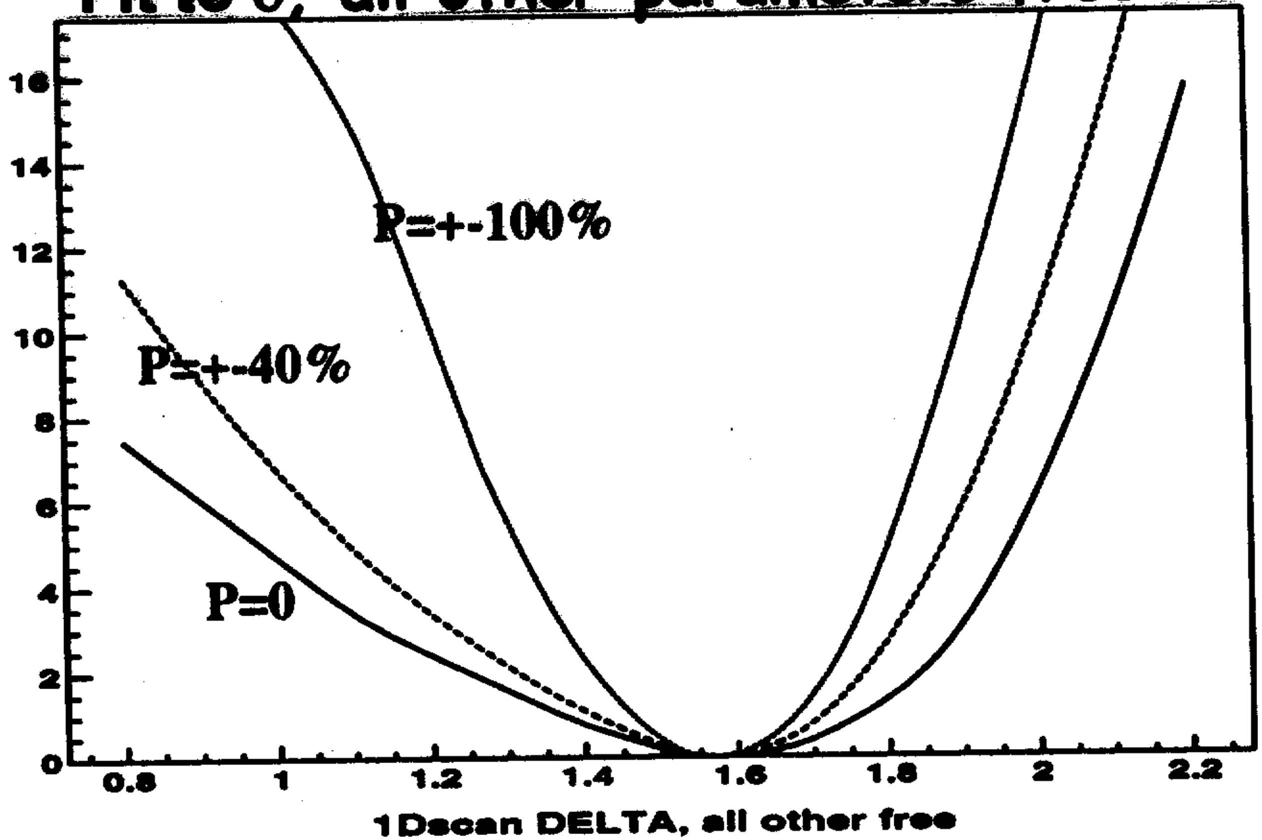


μ+, P=+1

[kills ν_e]

"wrong sign muon" events

Fit to δ, all other parameters free



P = 0 :	$\delta = 1.57 \pm 0.20$
P= ±40%	$\delta = 1.57 \pm 0.15$
P= ±100%	$\delta = 1.57 \pm 0.10$

±40 % polarisation is equivalent, for this example, to increasing the muon flux by 1.77

⇒ IT APPEARS THAT BEAM POLARIZATION INCREASES STATISTICAL SENSITIVITY

Q. IS THIS FROM T-VIOLATION
OR FROM BETTER SIGNAL/B ratio
in CP VIOLATING OBSERVABLE ?

⇒ IF THIS BRINGS VALUABLE INSIGHT / CROSS CHECKS ON GOLDEN MEASUREMENT

OR NEW MEASUREMENT

IS GOOD THOUGH ADMITTEDLY NOT EARTH-SHAKING.

POLARIZATION FIGURE OF MERIT

measure N_{+P} N_{-P}

FORM $$A_m = \frac{N_{+P} - N_{-P}}{N_{+P} + N_{-P}} \simeq |P| \frac{N_{+1} - N_{-1}}{N_{+1} + N_{-1}} \simeq |P| A_{true}$$

$$\Delta A_m = \frac{1}{\sqrt{N_{+P} + N_{-P}}}$$

$$\Delta A_{true} = \frac{1}{|P| \sqrt{N_{+P} + N_{-P}}} = \frac{1}{\sqrt{P^2 N}}$$

$\Rightarrow$ figure of merit = $P^2 N$ or $\int P^2(t) \, I(t) \, dt$

$$P_{eff} = \sqrt{\frac{\int P^2 I}{\int I}}$$ "effective Polarizatio

POLARIZATION SCENARIOS.

1. DO NOTHING [= FERMILAB STUDY]

   $P_{eff} \simeq 0.$ $\langle P \rangle = 0 \pm 10^{-4}$ [if no losses]

   ⇒ Need to measure Polarization.

2. BE CAREFUL [= PRESERVE WHAT YOU HAVE]

   $P_{eff} = 0.25$ (or 0.15?)

   ➡ Adjust RLA energies and # turns to inject longitudinal polarization in a BOW-TIE Ring

   [Alternative to BOW-TIE: 2π-ring and $E = 45.311$ GeV $\pm 10^{-3}$ and RF $Q_s > \frac{\Delta p}{p}$]

3. BE PROACTIVE [= ENHANCE WHAT YOU HAVE]

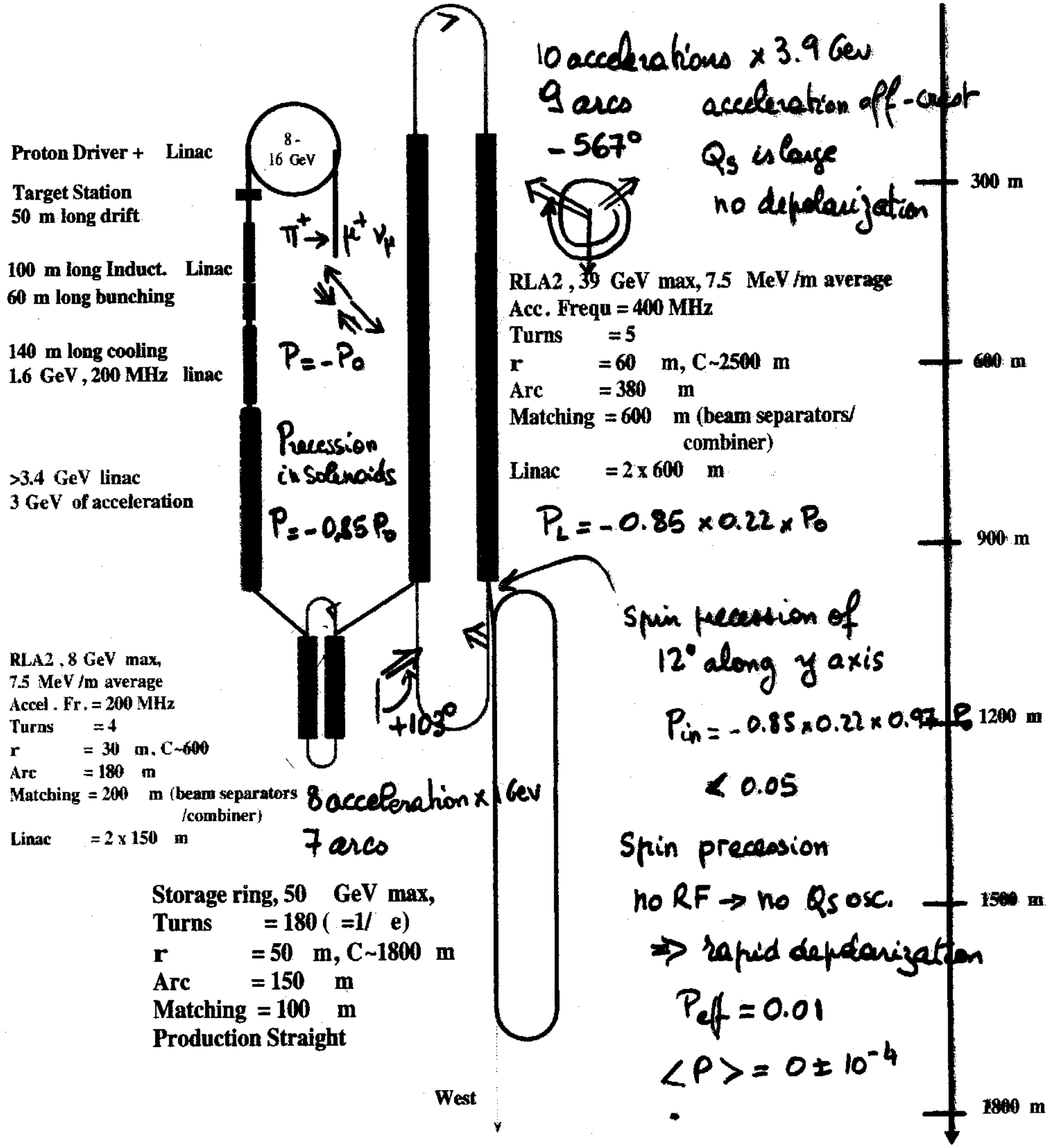
   $P_{eff} = 0.38$

   ➡ 1st phase rotation after target to monochromatize pions. no loss of I.

➡ momentum cut on muons ↗ $P_{eff} = ?$

($P \nearrow$ $I \searrow$)

SCENARIO 1.



NB $P_0 =$ 27% (Palmer Sessler Tollestrup → Pais
AB

? 18.5% Fernow Gallardo Fukui → HAYAKAWA)

WITH SOME CARE ....

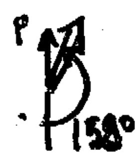
8 x 3.875

7 arcs

−517° (net = − 359°)

$P = -0.85\, P_0$

$P = 0.85\, P_0$



x 2 GeV

8 accelerations

7 arcs

$P = -0.85\, P_0 \cdot 0.97$

Spin precession at 50 GeV

$\Rightarrow P_{eff} = \frac{1}{\sqrt{2}} \cdot 0.85 \times 0.97$

$Q_s = 0.04$, no depolarization

at 45.311 ± $2\,10^{-4}$!

$\Rightarrow P_{eff} = 0.85 \cdot 0.97 \cdot P_0$

or BOW.TIE: (RF not needed)

$\Rightarrow P_{eff} = 0.8\, P_0$

P_0 can be improved (Palmer) by

1. monochromatization of π's

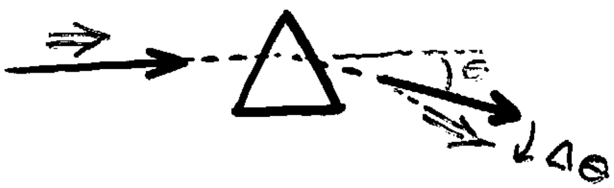
   (first phase rotation BEFORE decay tunnel) no loss (rather gain?) of intensity

2. Culling of muons [see older muon collider studies
   – Loss of Intensity]

- this requires that the beam remains bunched
- AND that experiments time the events to $\simeq \pm 5$ ns
  OK...? ICANOE?
- AND that polarization is measured for each time slot
  (OK)

DEPOLARIZATION IN FRONT-END

OCCURS BECAUSE OF SPIN PRECESSION.



$$\Delta\theta = \frac{g-2}{2} \cdot \frac{E_\mu}{m_\mu} \cdot \epsilon$$

$$\Delta\theta = \frac{E_\mu}{(E_0 = 90.6223\ \text{GeV})} \cdot \epsilon$$

- 500 m of 1.5 T solenoid for $P_\perp^{max} = 60$ $P_L = 200$

41 loops! $\Rightarrow \Delta\theta = \frac{g-2}{2} \cdot \frac{E_\mu}{m_\mu} \cdot 41 \times 2\pi = 0.57 = 33°$

$$P = P_{init} \times \cos(33°) = 0.85 \times P_{init}$$

- this does not include solenoid reversals and may be pessimistic

- muons dont depolarize in matter. (QED conserves helicity!)

confirmed by Fernow - Gallardo -

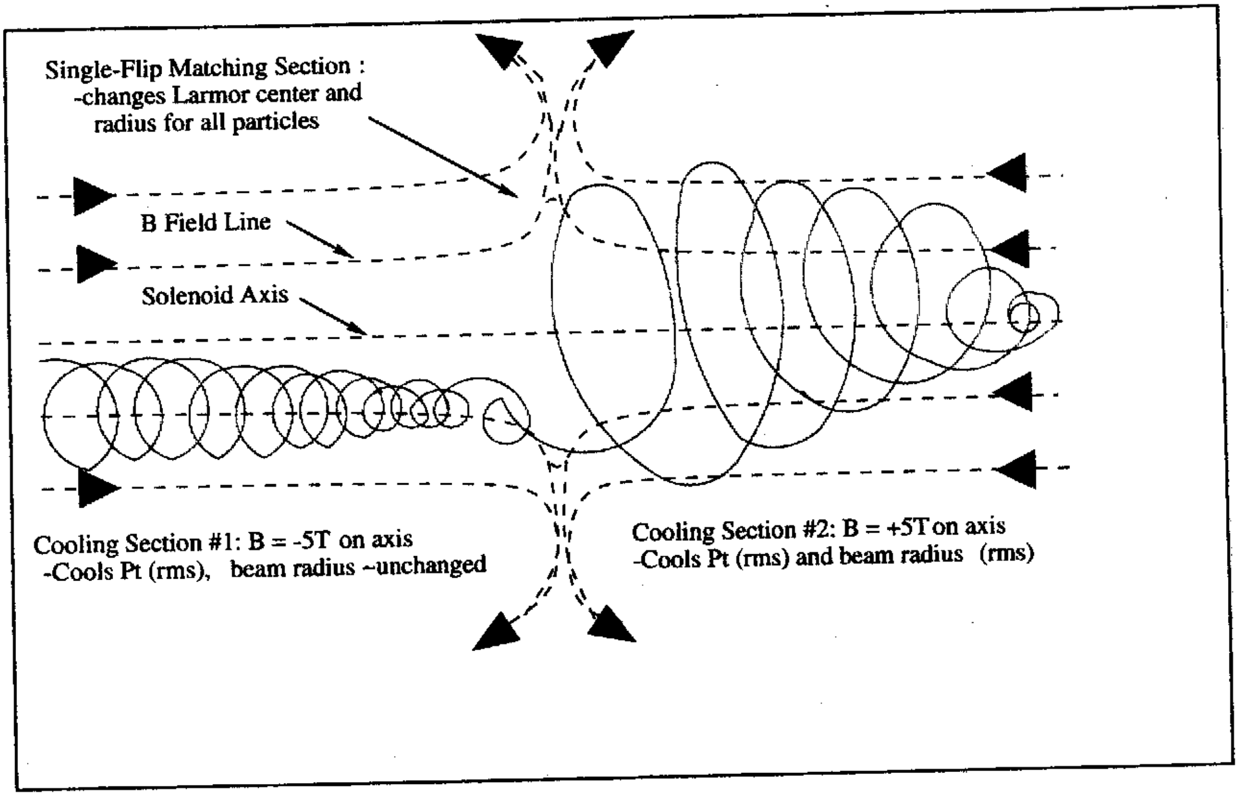
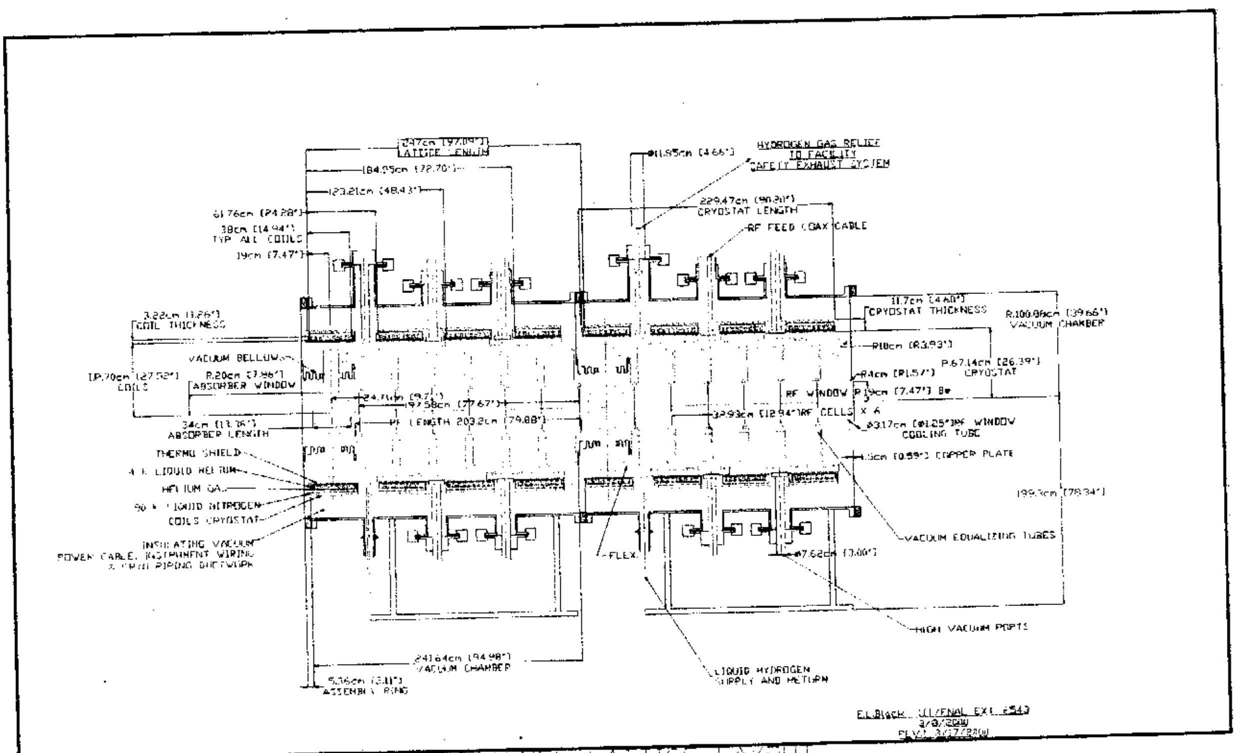


Illustration of particle motion in a single flip channel

While both designs have adequate performance for an entry-level neutrino factory, both fall short of the PJK benchmark. In both cases, the performance of the cooling channel is limited by the parameters of the input beam provided at the end of the buncher. We expect that ongoing work on tuning and optimization will improve the muon yield by a substantial factor.



V.B. CHANNEL LATTICE LAYOUT

SPIN-PRECESSION in RLA's

$$\Delta\theta_{spin} = \frac{g-2}{2} \cdot \frac{E_\mu}{m_\mu} \cdot \Delta\theta_{muon}$$

$$\Delta\theta_{spin} = \frac{E_\mu}{90.6223} \Delta\theta_{muon}$$

$$\Rightarrow \quad \Delta\theta_{spin} = \sum_{arcs} \frac{E_{arc}}{90.6223} \times \pi \times (\pm 1)$$

with two RLA's with $\begin{cases} E_o \text{ at the start} \\ N_1 \times \Delta E_1 \text{ Linacs} \quad (N_1 - 1 \text{ arcs}) \\ N_2 \times \Delta E_2 \text{ Linacs} \quad (N_2 - 1 \text{ arcs}) \end{cases}$

$$P_L = P_o \times \cos(\Delta\theta_{spin})$$

$$\Delta\theta_{spin} = \frac{\pi}{90.6223} \Big[N_1 E_0 + \frac{N_1(N-1)}{2} \Delta E_1$$

$$\pm \left(N_2 (E_o + N_1 \Delta E_1) + \frac{N_2 (N_2 - 1)}{2} \Delta E_2 \right) \Big]$$

add transferlines kicks
Solve for $N_1, \Delta E_1$ $N_2, \Delta E_2, E_o$ such that

$$\Delta\theta_{spin} = 0 \text{ Mod}(\pi \text{ or, better, } 2\pi)$$

A Few Solutions for non depolarizing acceleration

(acceleration off crest ⇒ $Q_s \gtrsim \frac{\Delta P}{P}$)

$N_{arcs} = N_{accelerations} - 1$

OUT of LINAC	RLA 1	RLA 2	Sign	E_{top}	$\Delta\theta$ (rad)	$\cos\theta$
E_0	$N_1 \times \Delta E_1$	$N_2 \times \Delta E_2$	+/-			
3.	8 × 1	10 × 3.9	⊖	50	-8.09	-0.24
3	8 × 1	10 × 2.74	⊖	38.4	(2π) -6.28	+1.0000
3	8 × 1.13	12 × 2.77	⊖	45.311	(3π) -9.42	-1.000
3	8 × 2.0	8 × 3.875	⊖	50 GeV	(2π) -6.27	+1.0000
3	12 × 2.2	—		29.4 GeV	6.28	+1.000
2	9 × 2.0173	—		20.156	3.1416	-1.000
3	16 × 1.11	—		20.76	6.28	+1.000

<u>NB</u> FFAG provides flexibility of ≠ turns for spin reversal.

1ST PHASE ROTATION

- Polarization of μ^+ from π^+ decay is $\simeq -28\%$
- it is correlated with μ^+ momentum for monochromatic π^+

⇒ π monochomatization (a.k.a 1ST Phase Rotation
+ DRIFT (momentum → time)

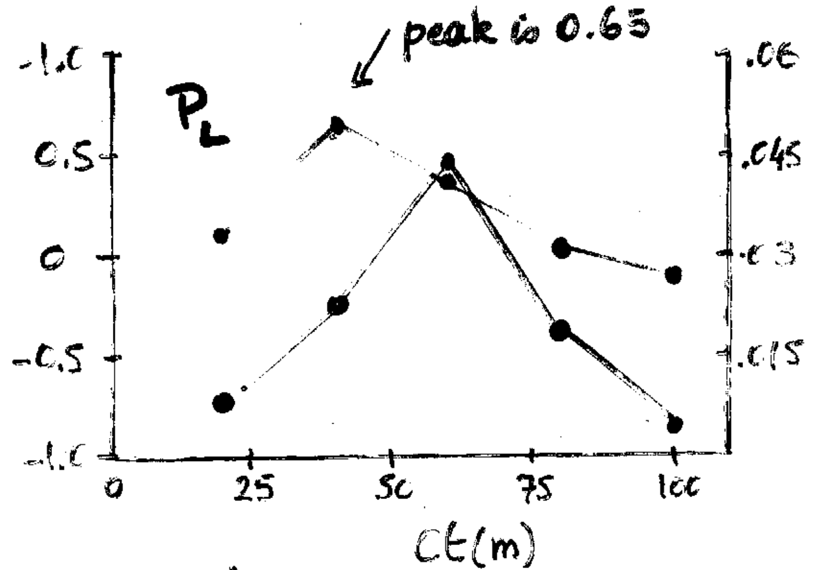
can be used to ANALYSE the spins

THIS DOES NOT CHANGE $\langle P \rangle$!

PJK

$\langle P \rangle \simeq .3$

P



μ/p/…

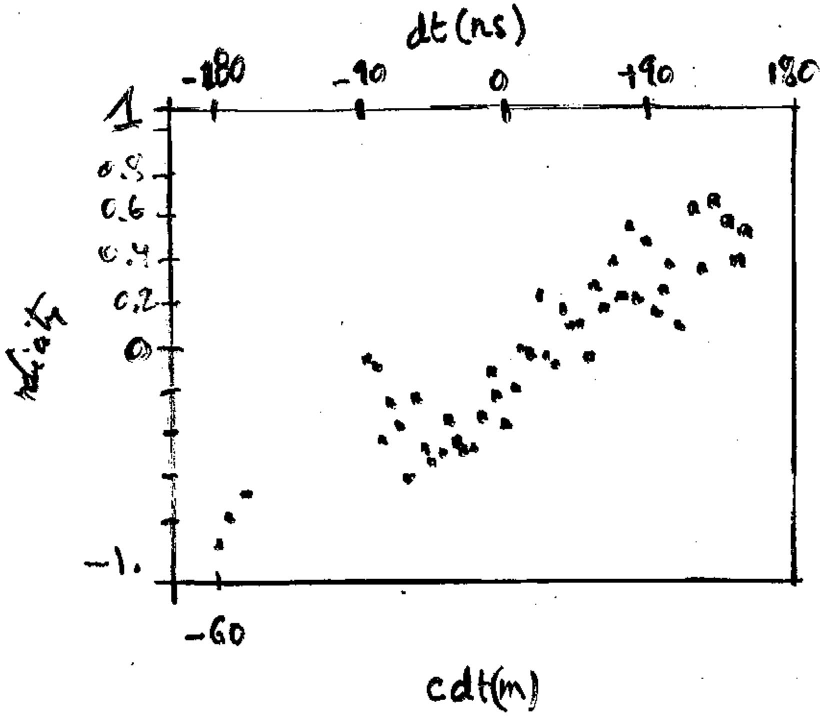
$P_{eff} = 0.40$ from the graph

(0.48 from the report ?)

⇒ NO 1ST PHASE ROTATION → $P_{eff} \simeq 28\%$ $P^2 = 0.08$

WITH 1ST PHASE ROTATION → $P_{eff} \simeq 40\%$ $P^2 = 0.16$ } 2.

Gallardo/Fernow/Fukui : muon polarization in ICOOL



$\langle P \rangle = 0.154$

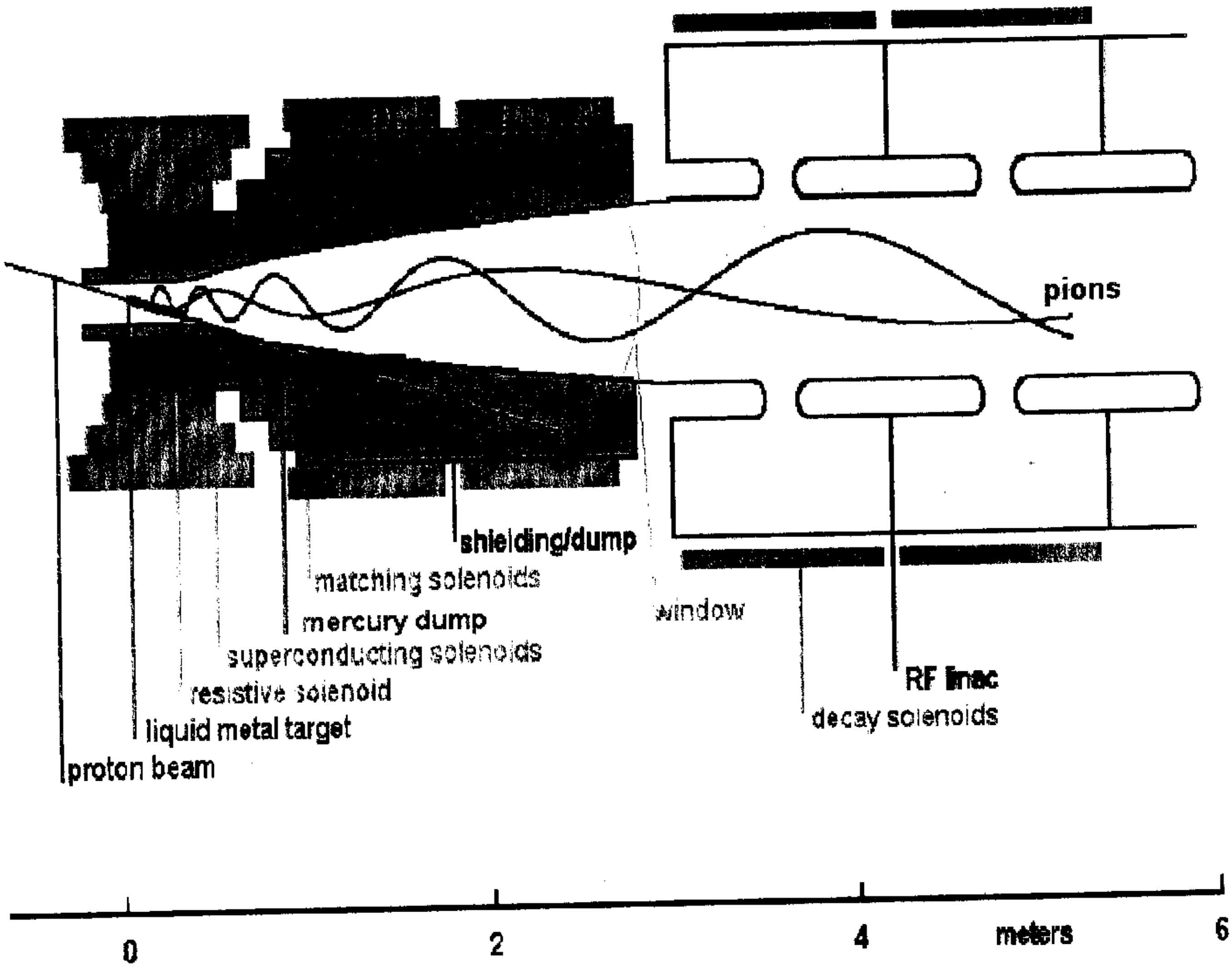
$(P_0 = 0.195)$ (?)

$\sqrt{\langle P^2 \rangle} = 0.38$

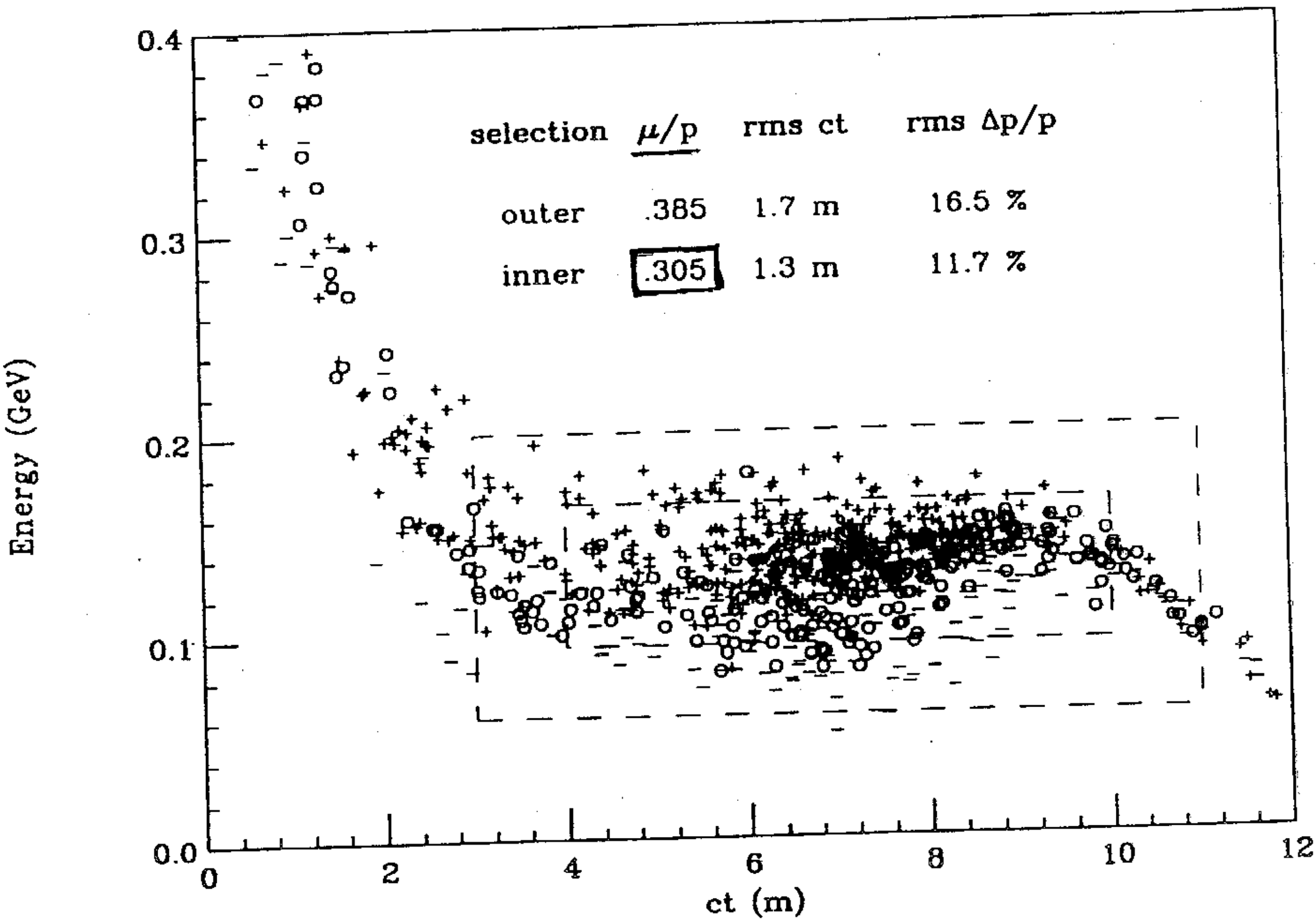
Polarization } is time-dependent
and RATE! }

⇒ must be measured bunch by bunch! Intensity and Polarization

Overview of Targetry for a Muon Collider



- 1.2×10^{14} $\mu^{\pm}$/s via π-decay from a 4-MW proton beam.
- Proton pulse $\approx$ 1 ns rms for a muon collider.
- Mercury jet target.
- 20-T capture solenoid followed by a 1.25-T π-decay channel with phase-rotation via rf (to compress energy of the muon bunch).

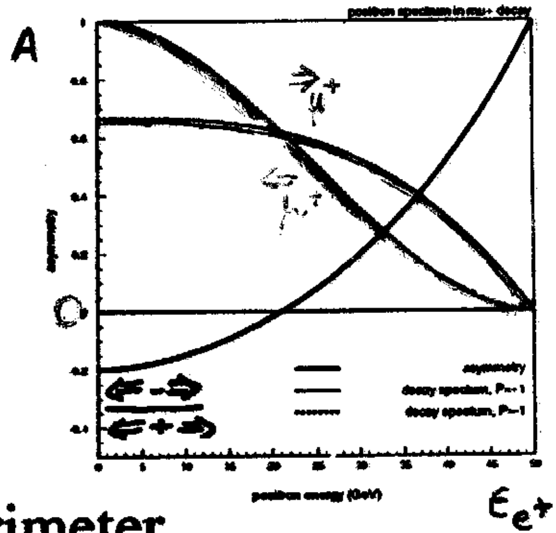

selection μ/p rms ct rms Δp/p
outer .385 1.7 m 16.5 %
inner .305 1.3 m 11.7 %
Energy (GeV)
ct (m)
0.0
0.1
0.2
0.3
0.4
0
2
4
6
8
10
12

ENERGY CALIBRATION

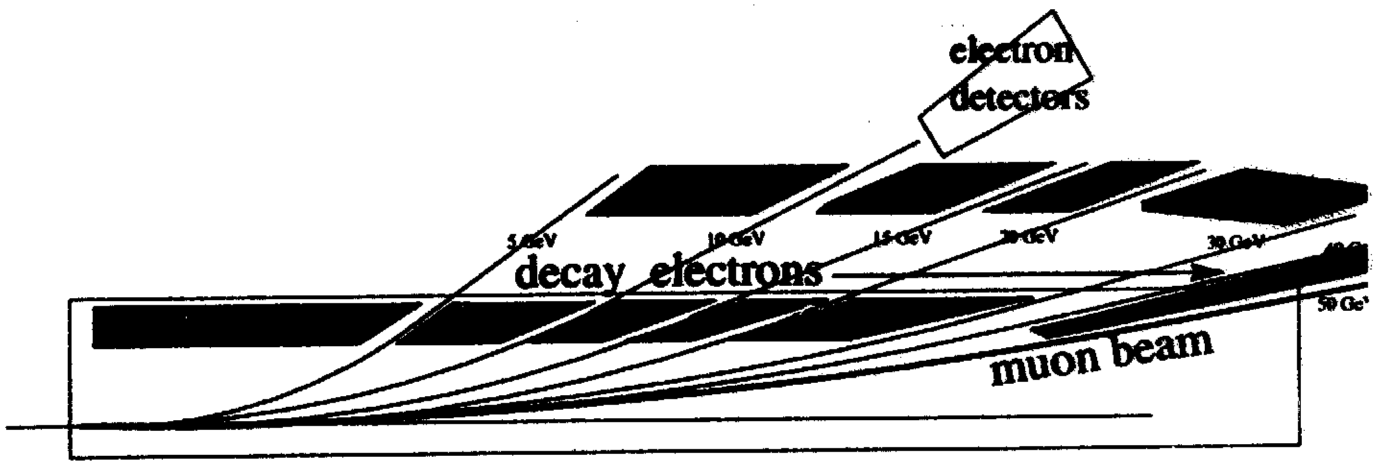
At every turn, 10^9 muons decay.
Spectrum of the decay electrons depends on muon helicity:

Muon polarisation precesses spin tune:

$$\nu = \frac{g_\mu - 2}{2}\frac{E_{beam}}{m_\mu} = \frac{E_{beam}(GeV)}{90.6223(6)} \simeq 0.55$$



muon polarimeter

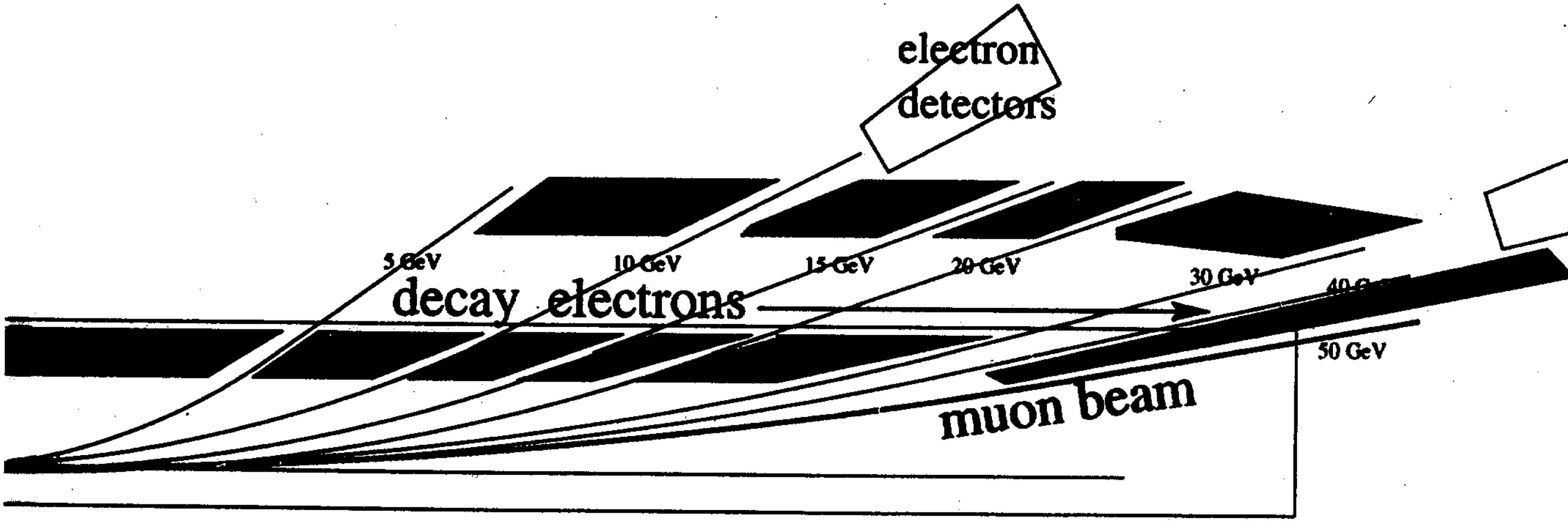


First magnet after straight section

Possible setup of a muon polarimeter. Decay electrons of different energies can be filtered by angular analysis, using slits in the shielding, in the first bend after a straight section. Best asymmetry in 30-40 GeV region. [E_μ = 50 GeV]

A.B CERN 99-02
(Prospective study)

muon polarimeter



First magnet after straight section

SPIN PRECESSION:

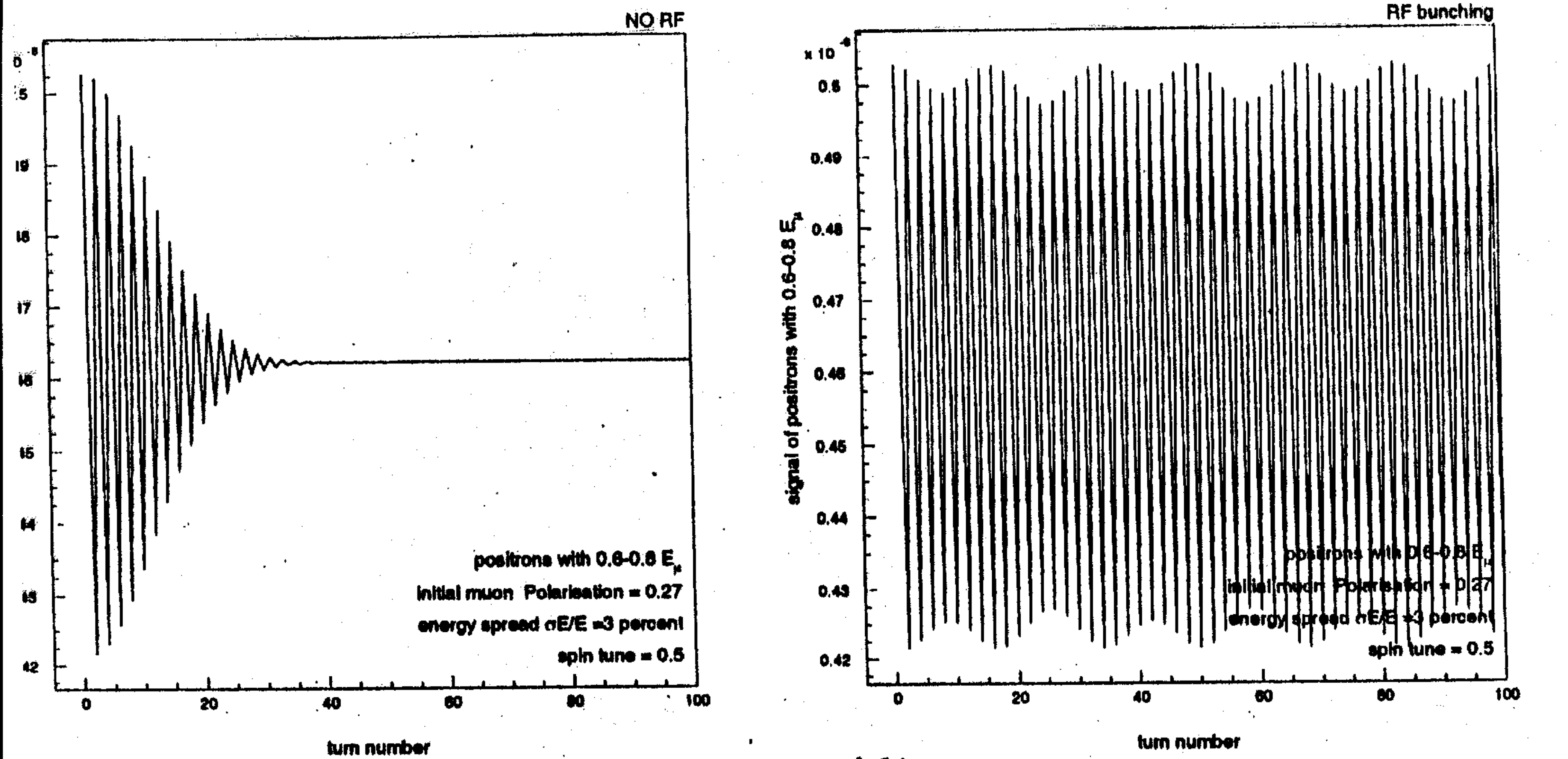
$$\nu = \frac{g-2}{2}\,\frac{E_\mu}{m_\mu} = \frac{E_\mu}{90.6223} \simeq 0.5 \text{ @ } 45\,\text{GeV}$$

if $\nu \neq 0.5$ $\quad \Rightarrow \Leftarrow \Rightarrow \Uparrow \Downarrow \Nearrow \Swarrow \Rightarrow$

$$\langle P^2 \rangle = |P|^2 \cdot \langle \cos^2\theta \rangle = 0.5\,|P|^2$$

$$\Rightarrow \quad P_{eff} \simeq 0.7\,|P|$$

$$\nu = 0.5000 \pm (\lesssim 10^{-3}) \Rightarrow \quad P_{eff} = |P|$$



RF with $Q_s \gtrsim \Delta p/p$ eliminates depolarization. True in RL

g. 3. *Oscillation with turn number in a fill of the number of electrons in the energy nge 0.6-0.8 E_μ (normalised to the total number of muon decays during the given rn). The oscillation amplitude is a measure of the beam polarisation, its frequency neasure of the beam energy, and, if their is no RF bunching, its decrease with ne is a measure of energy spread. The muon lifetime corresponds here to 300 rns. The beam energy is $E_\mu = 45.311 GeV$, the energy spread is 3×10^{-2}. On the t, there is no bunching RF in the muon storage ring, on the right there is RF*

DEPOLARIZATION CAN BE AVOIDED

- WITH BOW TIE
- WITH RF-BUNCHING, $Q_s \geq \frac{\Delta p}{p}$

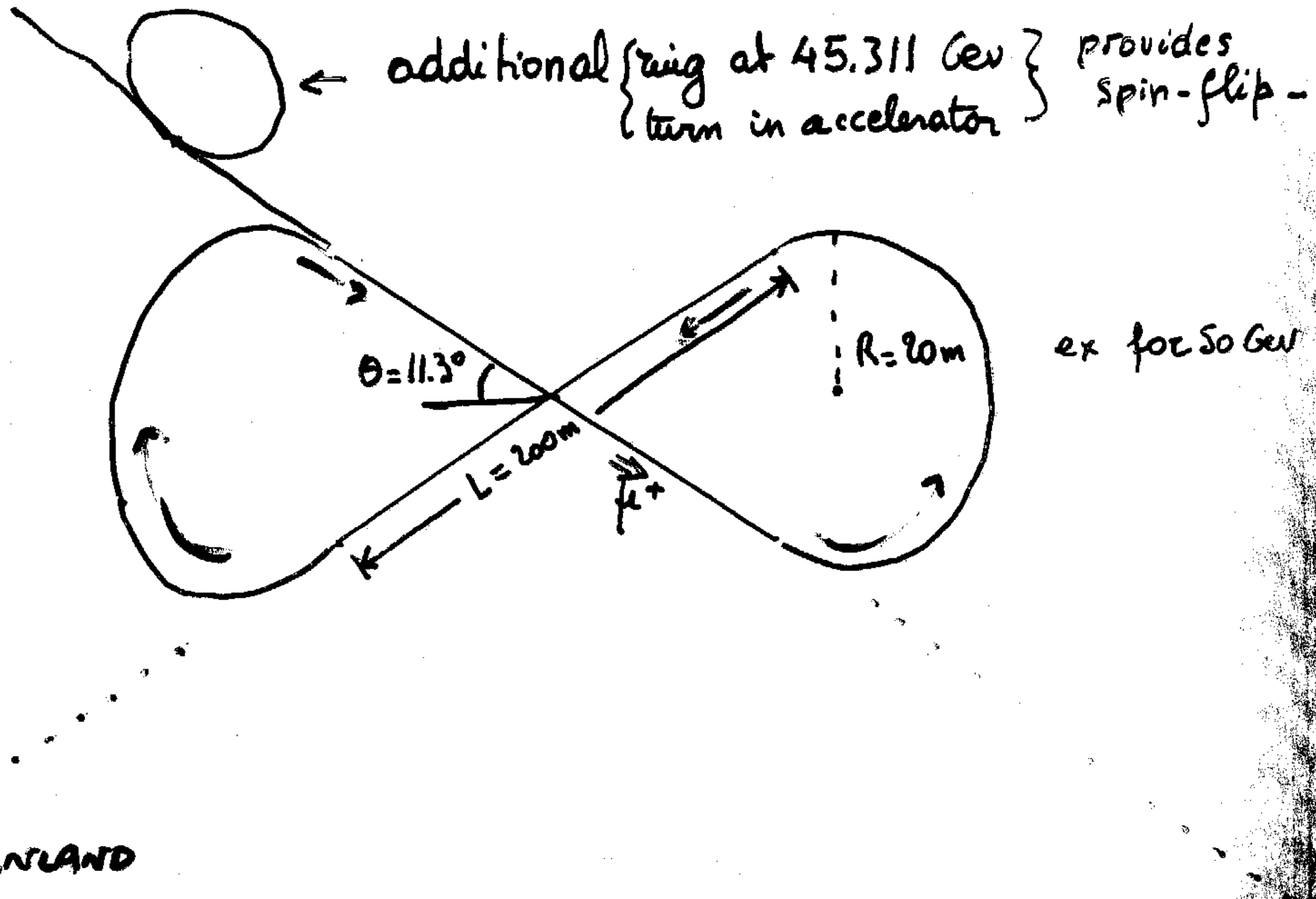
PRECESSION LOSES 30% OF POLARIZATION if

- CAN BE AVOIDED WITH BOW-TIE $E \neq 45.311 \pm 2\,10^{-4}$!

TROMBONE OR TRIANGLE:
THIS ASSUMES NO
RE-BUNCHING
(NO RF IN STORAGE
RING)

DESIGN A STORAGE RING

WITH <u>NO</u> SPIN PRECESSION !



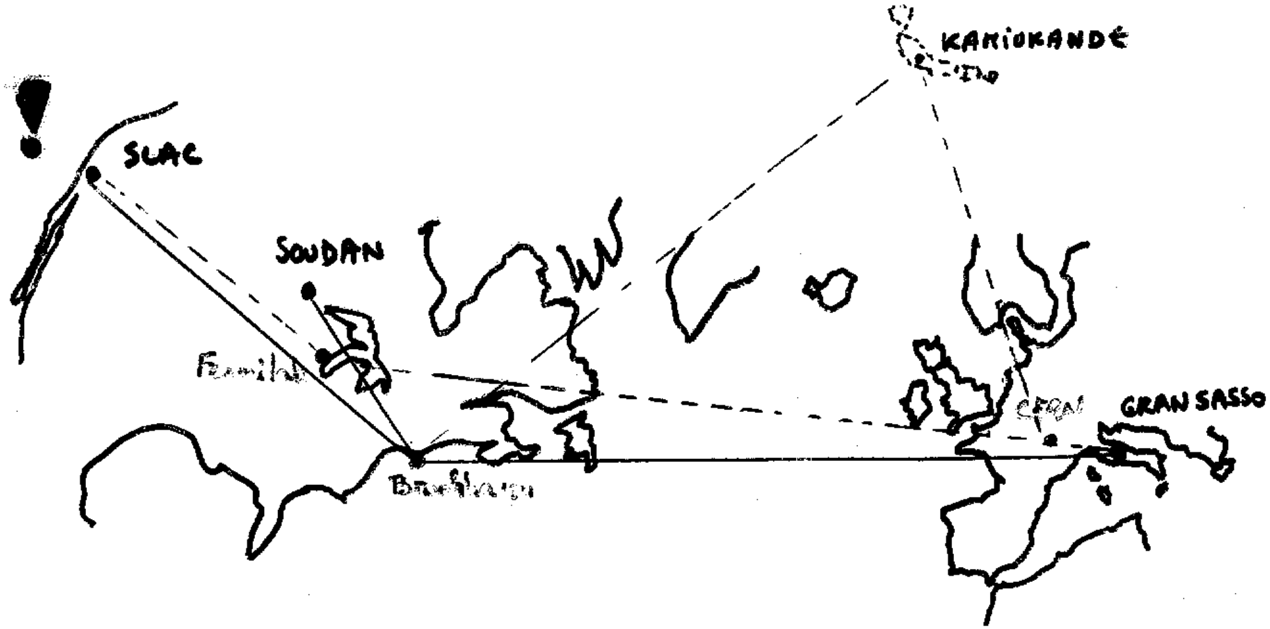
- POLARIZATION IS PRESERVED FOR ALL ENERGIES

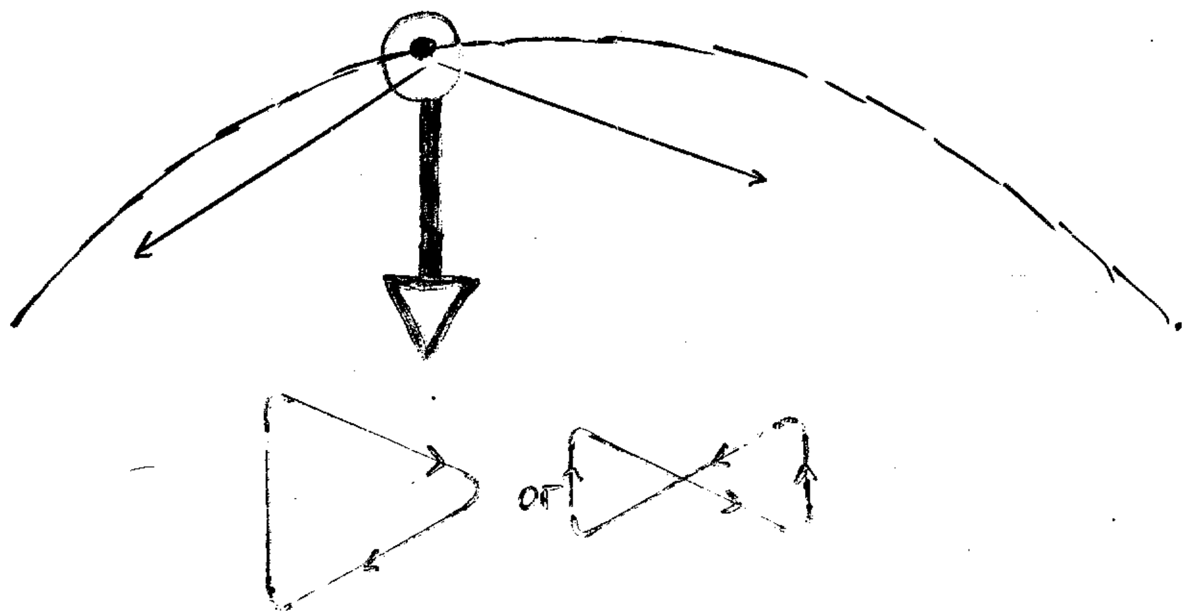
BUT ⇒ NO ENERGY CALIBRATION !

⇒ NO REGULAR SPIN FLIP.

⇒ NO DEPOLARIZATION !

A WORLD MACHINE!





Triangle or "Bowtie"

CONCLUSIONS

- MUON POLARIZATION CONTROLS ν_e / ν_μ ratio

  ⇒ { IMPROVES STATISTICAL POWER
  ALLOWS VALUABLE CROSS-CHECKS

- BY BEING CAREFUL AN EFFECTIVE POLARIZATION OF [.15 → .25] SHOULD BE EASY TO KEEP

- WITH MORE EFFORT

  $P_{eff} \rightarrow 0.4$

  { • 1ST PHASE ROTATION
  • CULLING OF μ's
  • Bunch by bunch (5 ns) recording of intensity / Polarization

- RING @ 45.311 ($\pm < 10^{-3}$) - DIFFICULT
  BOW-TIE - BETTER
  } keep it all

- POLARIZATION MEASUREMENT FROM DECAY $e^{\pm}$ SEEMS QUITE FEASIBLE.
  (MUST BE FIT IN 1ST MAGNET AFTER STRAIGH

- LOOKS LIKE A COST-EFFECTIVE WAY TO IMPROVE PHYSICS OUTPUT