Muon Channeling and the Need to Investigate Negative Particle Channeling and Collimation

Dick Carrigan
Fermilab

Channeling 2008, Erice, Italy

October, 2008

Landscape for TeV-scale channeling

"Recent" developments

- collimation
- volume reflection, capture
  - Vorobiev & Taratin
  - RHIC
  - Tevatron
  - famous CERN H8
- short crystals

LHC collimation

- protons from 1-7 TeV
  - very active …

Everything else

- extraction, e. g. at LHC
- collimation at an ILC, e+-
  - but really not so hard,
    - also later
- muon collider
  - even further away
  - Fermilab 99/069 study
    - crystal collimation
    - not appropriate
  - but may be different at
    - high energy

Update on Tevatron crystal collimation studies

History

2005 – Reproduced RHIC results with "O" crystal

2007 – tried 3 mm, 150 μrad bend, problems -…

2008 – "O" back, better goniometer, instrumentation

Mokhov

T980 – CCE Crystal Collimation Experiment

Fermilab, LARP, CERN, BNL, INFN, IHEP, PNPI, JINR,
RINP-BSU, Chicago, …

several phases over 2008-2010 for collimation in 1, 2 planes,
possible single particle, simulation, etc.

linked with SPS collimation experiment
artificial halo, single particle, …

Oct. 29 half day workshop at Fermilab on channeling collimation
in conjunction with LARP CM11 and **session here today**

Dean Still and others have made significant progress in Sept, Oct.

Crystal collimation at LHC: Ralph Assmann's concerns (from Channeling 2006)

Crystals are an interesting advanced technology for phase 2 of LHC collimation. To evaluate benefit in detail the following information is required:

- How to handle different LHC energies from 450 GeV to 7 TeV?
- Probability spectrum for proton deflections (channeling and others). **Include all effects down to 10^{-5} probability**!
- Sensitivity to beam angle and angular spread?
- Number, opening (impedance) and locations of absorbers. Damage limit of crystal for instantaneous shock beam impact (expect ~3MJ, 0.2×1.0 mm, 200 ns).
- Damage limit of crystal for integrated dose (expect $\sim 5\times10^{16}$ p/year at 7 TeV).
- Handling of crystal during normal operation: 500 kW power impact.
- Requirements for alignment and operational set-up (tolerances, time, …)?

(missing from list – crystal questions)

Recent LHC incident may increase emphasis on collimation even more!

Incomplete TeV-scale channeling topics

Negative particle channeling and bending

hadrons, relation to e^- and channeling radiation

not important for LHC collimation – pp collider

Muon channeling for futuristic possibilities

(collimation for muon colliders – Tollestrup)

Negative particle channeling

early eighties thinking:

large discrete angular deflections like external beam.

collimation is different

any kick, provided it is more than multiple scattering

multi-pass channeling helps.

high energy helps

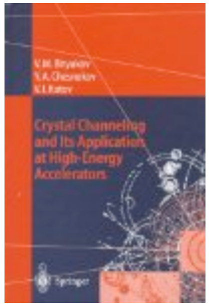
We need more information on negative channeling, negative bending!

Could one channel and collimate antiprotons at the Tevatron?

Could one collimate e^+/e^- at ILC?

In TOTEM, etc. at LHC could one deflect negative particles such as antiprotons?

Functional form of planar dechanneling



Biryukov
Chesnokov
Kotov

$$\lambda_D = 1.62 \frac{\psi_{cp}^2}{\left\langle \Theta^2 \right\rangle_c}$$

where

ψ_{cp} is planar critical angle

$\langle\theta^2\rangle_c$ is the mean square mult scat angle in channel

(see Feldman & Appleton, PRB8, 935 (1973), Carrigan FN-454,

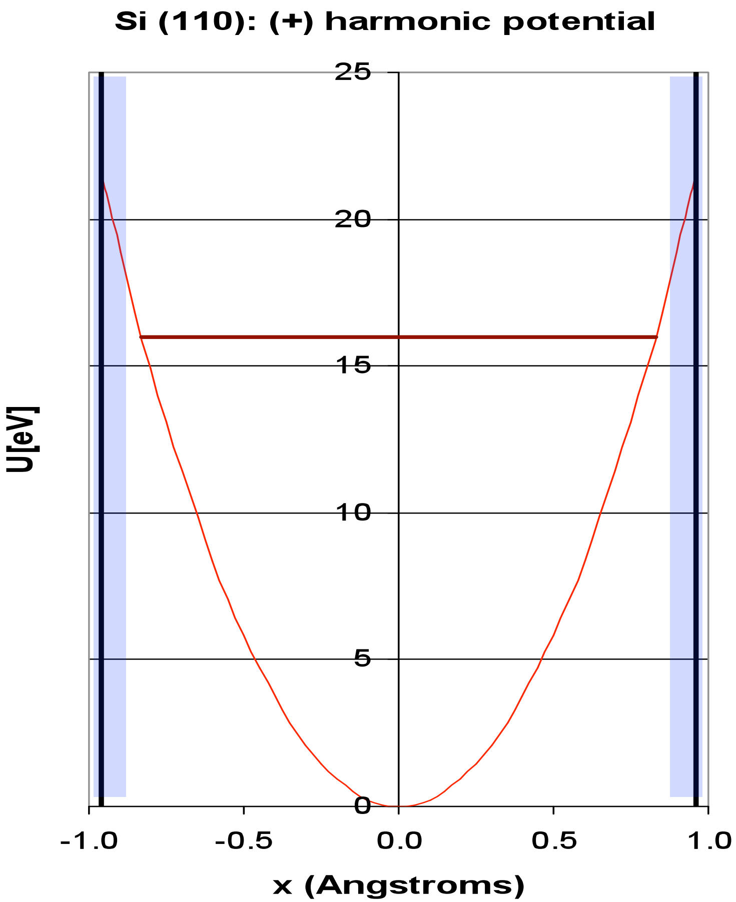
Biryukov, Chesnokov, and Kotov (BCK))

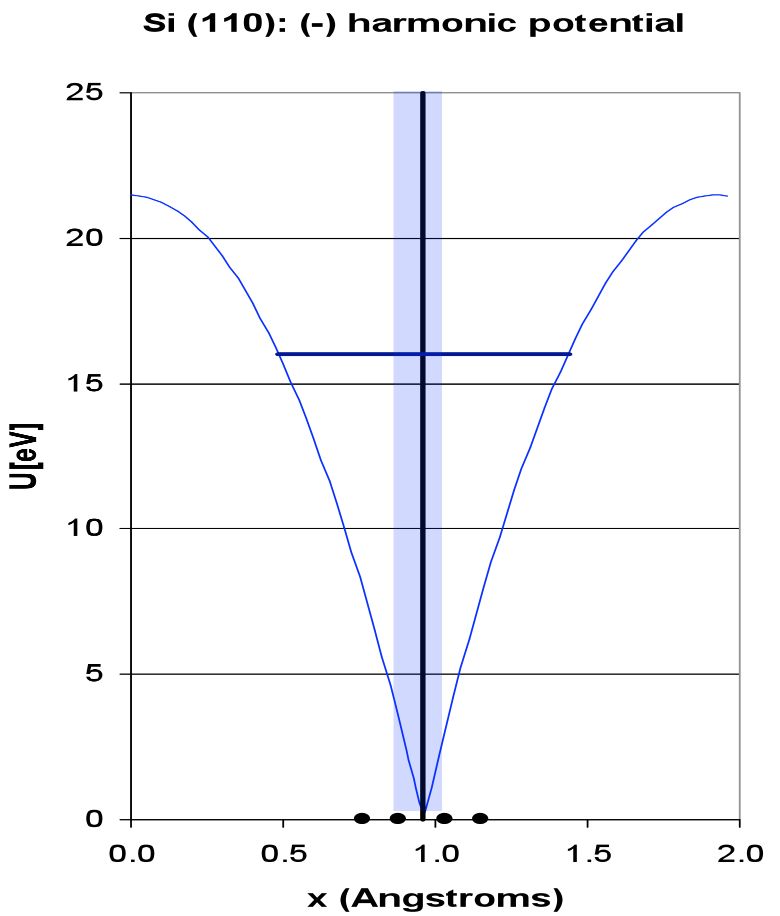
For (+) BCK treatment (1.50) leads to:

$$\lambda_D = \frac{256}{9\pi^2} \frac{pv}{\ln(2m_e c^2\gamma / I) - 1} \frac{a_{TF} d_p}{Z_i r_e m_e c^2}$$

λ_D= 51 cm for (+) @ 1 TeV (roughly ~ E - note log term, ~20% effect)

Potentials for + and – particles to get ψ_p



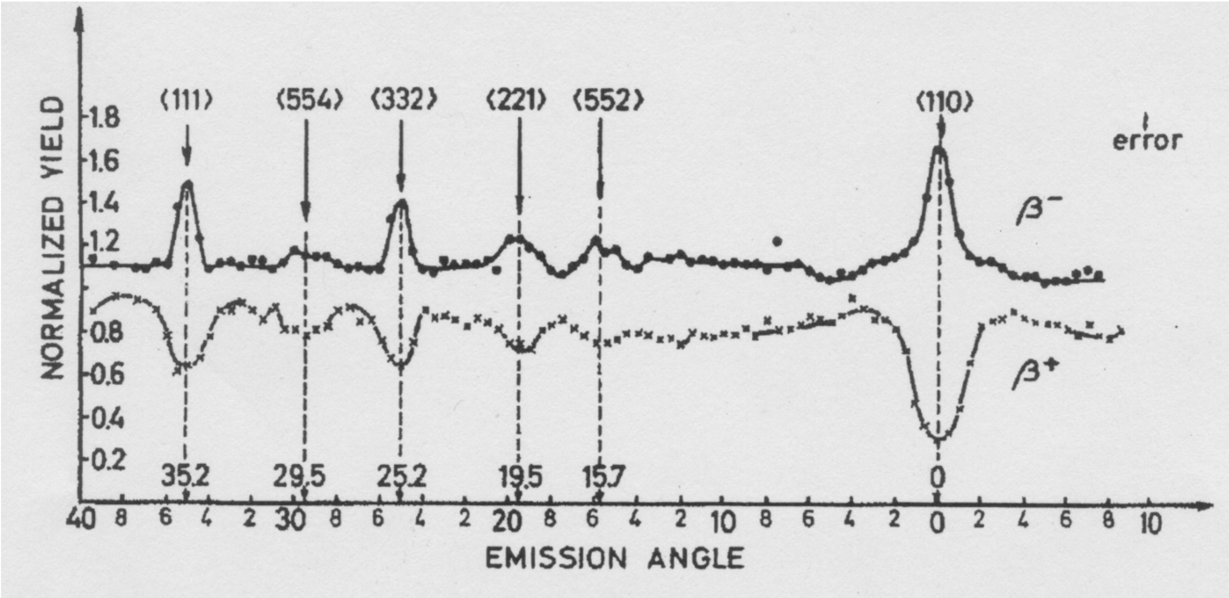


[see, e. g., Taratin and Vorobiev, Phys. Lett A119, 425 (1987)]

Some Aarhus +/- results showing $\psi^- < \psi^+$

Implanted radioactive ^{64}Cu in a Cu crystal –

(E. Uggerhoj, Andersen, Can. J. Phy. **46**, 543 (1968))



U. Uggerhoj

Antiproton Channeling at 1.4 MeV (U. Uggerhoj, et al , NIMB207, 402 (2003))

For antiproton axial channeling find critical angle is about 0.6 of the critical angle for protons. Agrees with theoretical calculations

Negative hadronic channeling

Then for

$$\lambda_D = 1.62 \frac{\psi_{cp}^2}{\left\langle \Theta^2 \right\rangle_c}$$

Where $\langle\Theta^2\rangle_c$ follows from

$$\frac{\left.\frac{d^2\Omega}{dx}\right|_e}{\left.\frac{d^2\Omega}{dx}\right|_n} = \frac{\left.\frac{d^2\Omega}{dx}\right|_+}{\left.\frac{d^2\Omega}{dx}\right|_-} = \frac{(m_e / 2M_i E)(4\pi e^4 / m_e v^2) NZL_e}{(M_t / M_i E)(4\pi Z^2 e^4 / M_t v^2) NL_n} = \frac{L_e}{2ZL_n} \Rightarrow \frac{X_0^n}{X_0^e}$$

where L_i are the log terms in multiple scat. Set $L_n/L_e = 2$.

Get for 1 TeV as an approximation neglecting details of nuclear density.

$$\lambda_- = \left(\frac{\psi_-}{\psi_+}\right)^2 \frac{\lambda_+}{2Z(L_n/L_e)} = \left(\frac{0.48\ A}{0.83\ A}\right)^2 \frac{51\,cm}{2*14*2} = 3\ mm$$

Negative hadronic channeling - continued

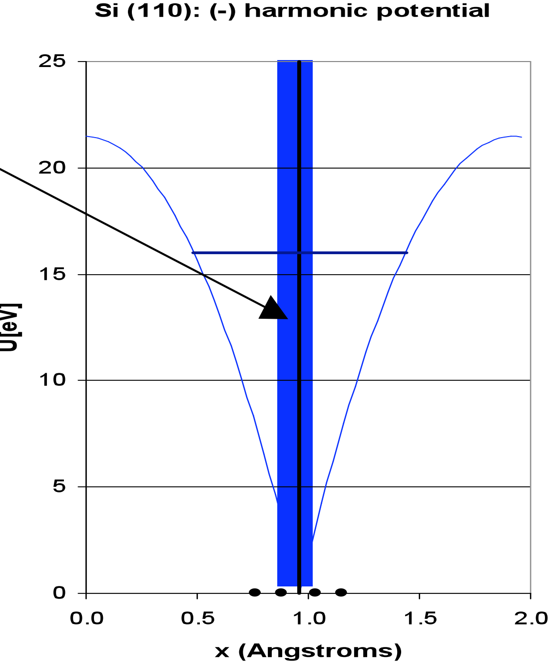
But - potential well is not filled with ions, only $\pm u_T$

a weighting might be

$$Z^{-}_{eff} = \frac{2u_T Z + 2\left(d_p/4 - u_T\right)}{d_p/2}$$

so that Zeff = 3 rather than 14 for 1 TeV Si(110)

giving λ-(1 TeV) ~ 14 mm

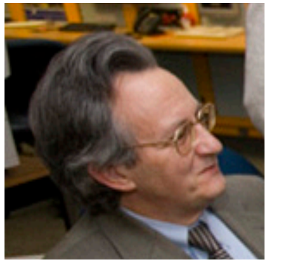


Of course, particle more in center of channel, …

This range (3 to 14 mm) is short but have used:

3 mm strip crystals

Quasimosaic crystals (.03, 1 mm at CERN H8, H4)



Scandale-H4,H8

Straight crystal dechanneling for negative particles

Going beyond hand waving (or hand wringing) need:

- a diffusion model treatment for the negative particle case
- or a simulation ala CATCH or BINCOL

Would like array of (+/-)

$E = 0.07, 0.4, 1, 7$ TeV

$R = 0.1, 0.25, 0.5\ R_T$

Little experimental information on straight negative hadronic dechanneling

Bending of negative particles

The critical bending or Tsyganov radius is:

Tsyganov

$$R_T \approx \frac{pv}{\pi N d_p Z e^2} = \frac{pv(GeV)}{5.7 GeV/cm[Si(110)]}$$

At +1 TeV in Si is ~175 cm (BCK 2.17). For the negative case,

the effective d_p could be smaller and R_T larger

The bending dechanneling length is:

$$\lambda_D(pv, R) = \lambda_{D,0}\left(1 - \frac{R_T}{R}\right)^2$$

If R >> R_T then for negative particles λ_D(pv, R) will be the negative particle dechanneling length, so **it will be short**

Negative particle bending measurements do give a tool to measure dechanneling in principle

Negative hadron bending

Bak et al. did studies of negative particle axial deflection at 10 - 12 Gev with pions [S. Anderson et al., Nucl. Phys. B167, 1 (81), J. Bak, et al., Nucl Phys. A389, 533(82)]

Schiott simulated their data using BINCOL in Carrigan and Ellison (*Relativistic Channeling*, NATO 165, Plenum (87)). Saw only small effects on order of critical angle.

I extract an upper limit on the bending dechanneling length of O(2 mm) from Baurichter et al. studies of negative π^- axial deflection at 200 Gev. [A. Baurichter et al., NIM **B119**, 172 (1996)]

~0.6 < λ_- < 3 mm from the formula and the ansatz for the <u>planar</u> case.

H4, H8 (Bolognini thesis-fig. 4.21a) gives O(1 mm) @150 GeV for (111) in a quasi mosiac crystal

Negative particle volume reflection

Taratin

Taratin and Vorobiev (1987)

In computer model positive particle

deflect ~$2\psi_{cp}$ away from bend

negative particle somewhat less.

Biryukov [2006 – EPAC, Phys. Let B645, 47 (2007)]

Tevatron simulations for proton and antiprotons.

Antiproton effect nearly as strong as proton in volume reflection

Maisheev – analytic treatment

[PRST 10, 084701 (2007)]

This can be used to extrapolate to different energies, radii

Angles for positive case are 1.8 times larger than negative.

For a contrary view on (-) case see

Kovalev arXiv:07073935v2, arXiv:0712.0858v1

No experiments have been reported but CERN H4 now has info

Negative volume capture

Volume capture deflects in the direction of the bend

Volume capture is a feeding-in process that follows reversibility

- This means it will be characterized by a feeding-in length
  - functionally similar to a dechanneling length
- since negative particle dechanneling is stronger
  - feeding-in will be stronger
  - but once in a channel particle will also dechannel faster

The theory of negative particle volume capture has apparently not been discussed

- However simulations such has Biryukov's should implicitly contain it.

No experiments have been reported

[discussions of positive particle volume capture have been given by
Sumbaev (circa 79), Samsonov (C&E-87), and BCK sec 2.3.1]

Studying negative particle channeling

Tevatron – anti protons (Dean Still)

Still

- prefer <1 mm thick crystal, 5 mm might work
- redo proton, antiproton helices locally at E0 (goniometer)

  or remove proton store. Both need serious setup
- need a nearby antiproton downstream collimator, detector – something exists at E0 for Tevatron

Fermilab Meson Area Beams

Meson test beam – a problem is energy fairly low

MIPP – also a problem with low beam energy

Other possibilities for negative particle channeling

CERN

H4- this last summer did 150 GeV negative π, k, μ mesons

used thin crystals (~1 mm thick). Also used H8 in fall 2007

Serpukhov

lower energy beams than CERN

KEK

ATF – Endo et al, expression of interest – with 1.3 GeV tightly focused electron beam

problem – channeling radiation

Muon channeling

Does high energy muon channeling answer fundamental questions?

Not really!

Point is that dechanneling length does not depend on nuclear interactions

L_{col} (Si) = 30 cm, L_+[Si(110)] ~ 51*E(TeV) cm, equal at ~0.6 TeV

L_-[Si(110)] ~ 3 mm*E(TeV).

nuclear density higher for negatives $O(d_p/4u_T)$ or factor of 6

L_{col} is still 100 times longer at 1 TeV, 15 times at 7 TeV

weakly interacting particle does not teach anything

Critical energy for muons in Si is 470 GeV

Bremsstrahlung cross section

$$\sigma_\mu = \sigma_e \left(\frac{m_e}{m_\mu} \right)^2$$

so much less radiation/unit length

but negative muons in high Z^2 region

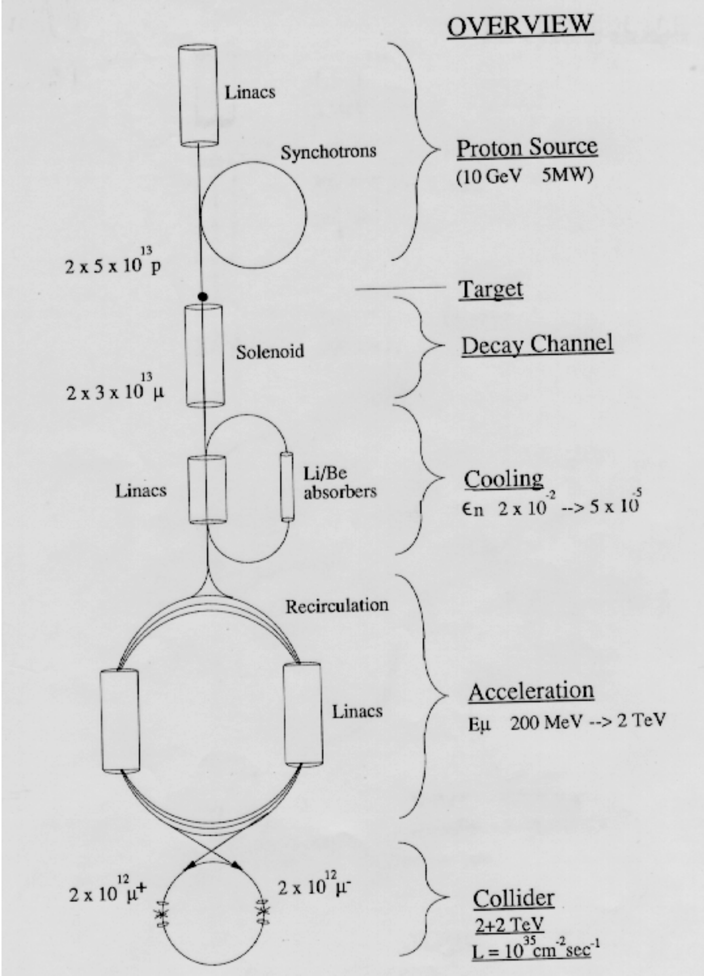
Muon channeling - continued

Potentially might be interesting for
collimation in a **futuristic** muon collider
or neutrino factory

50 on 50 GeV "low" energy muon colliders
collimation <u>no challenge</u> (see Drozhdin et al. FERMILAB-Conf – 99/069)

But for higher energies more of a problem
short quasimosiac bends using axial channeling might begin to be useful

Available information
little experimental muon channeling data,
mostly from pion implantation
no theoretical evaluations?



Muon channeling experiments

Particle identification

use a hadron absorber in front of detector

typically 8 – 10 nuclear interaction lengths or 1.5 m iron.

At 50 GeV: Θ_{ms} = 800 μrad compared to $\boldsymbol{\psi_{cp}}$ = 28 μrad

Muon beams

Muon beams are tertiary beams

process is p >> pions >> muons and neutrinos

(450 GeV) (50 GeV) (<25 GeV)

Need space for pion decay

but even an ordinary pion beam has some muon contamination

But want information at TeV scale!

Rate lower at higher energy, but for channeling may be OK

Muon experiments at CERN?

per Gatignon: M2/COMPASS @ 160 GeV/c has $2E^8$/spill (+, /3 for -),

Θ ~600 μrad, σ ~ 20 mm

I hear that in the H4 run @CERN this summer the beam was 50% muons

Summary

Negative hadronic channeling studies interesting for:

planar and axial cases for normal bending

volume reflection

volume capture

Short crystals via anticlastic or quasimosaic techniques important

Muons:

difficult experimentally but H4 ran last summer @ CERN

not clear there is much interesting channeling physics

no mid-range applications

For more Fermilab channeling information see:

Channeling home:

http://home.fnal.gov/~carrigan/Channeling/Channeling_master.htm

Channeling Formulary:

http://home.fnal.gov/~carrigan/Channeling/Channeling_formulary.htm

Questions?

Negative hadron and e^+/e^- channeling?

e+/e- channeling

- channeling radiation impact must be considered
- crystal lengths must be short
- not so much dependence on charge
- little of no experimental information at high energy,
  particularly for bending

e^+/e^- dechanneling lengths (microns, normalized to 1 GeV)

Critical energy for e^+/e^- in Si is 53 MeV but not so significant for channeled particle

Process	e^+ dechan (microns)	e^- dechan (microns)	Energy MeV	Comment	Author
Planar theory	500 700	 130 qua, 13 pure	1000 1000	Si(110),1/2 Si(110),1/e	Belosh. & Trik Belosh. & Kom.
Planar experiment	1100 (60 – oc len)	660 (36) 88 (31) 23 (28)	54 350 1200	Si(110),1/e Si(110),1/e Si(110),1/e	Livermore Komaki Adejshvili
Axial theory		13 18	1000	Si<111>,? Si<111>,1/2	Muralev Taratin & Vorob
Axial experiment		32 (39)	1200	Si<111>,1/e	Adejshvili

Problems: **Old and incomplete data!** consistency, agreement of experiments (angular divergence), too little data, statistical estimates on data, theory challenges but some recent work at 5 GeV for undulator possibility (Korol et al. Physics/0412101 v1)

Summary of coherent bend effects

Effect	Angle dist	Deflection	Magnitude	Comment
Volume reflection	$\Theta_d \sim \varphi_c \sim 1/(p\beta)^{1/2}$	Away from bend	Strength same as channeling	Cumulative with beam passes
Volume capture	Up to full bend	Toward bend	$w_s \sim const \frac{R}{(p\beta)^{3/2}}$	Small at high energy
Miscut	Lowers deflection	Toward bend	0 to full deflection	
Relaxed bend		Smaller bend		Ruled out by whole arc distribution
Something else				Keep an open mind

Electrons

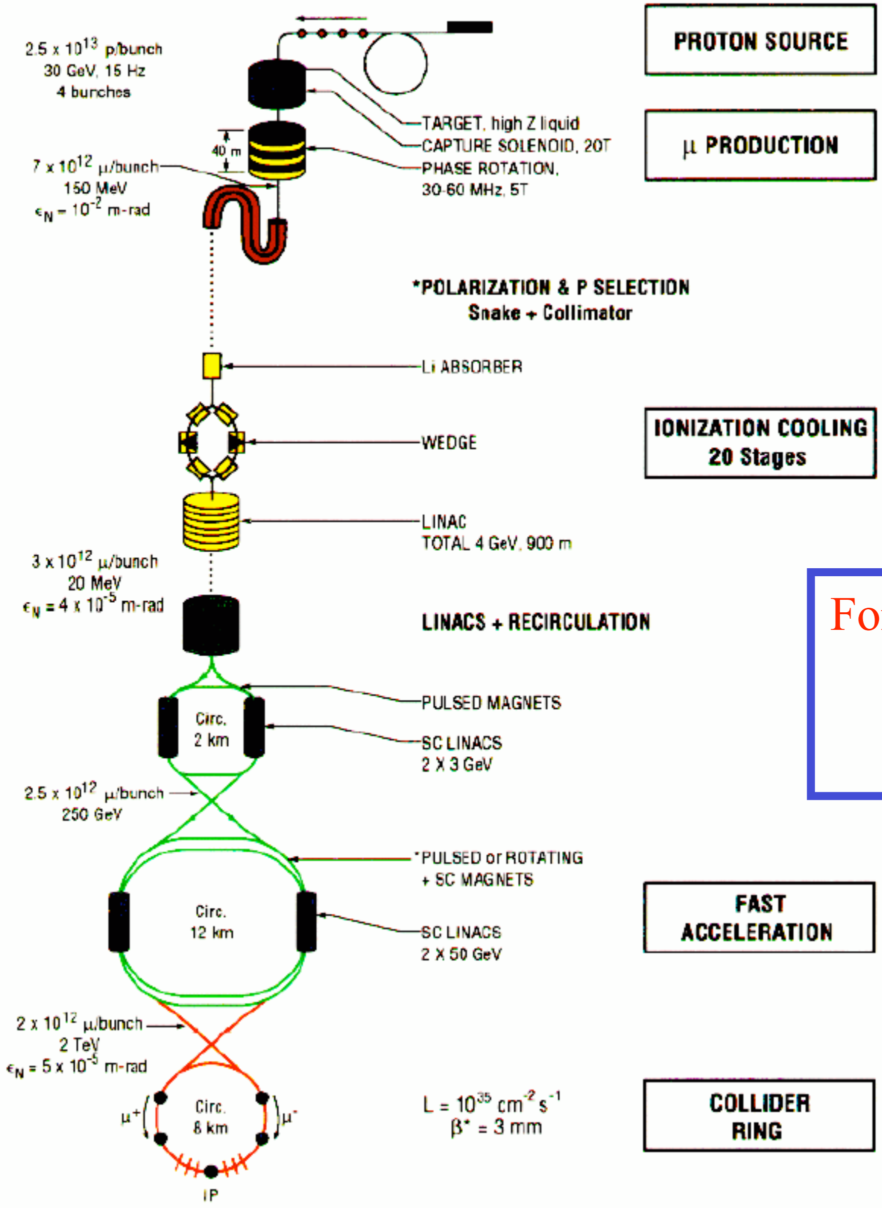
with innovative short bends might be able to do electron bending

this is a regime where GeV scale machines could contribute

electron/positron dechanneling below 1 GeV down to 10 – 20 MeV

old information may not be consistent

Muon collider schematic (taken from Bruce King-BNL, 4th International Conference on the Physics Potential and Development of mu+mu- Colliders, San Fransisco, 1997.)



Very intense

Large aperture

Six degrees of freedom
Does it work?

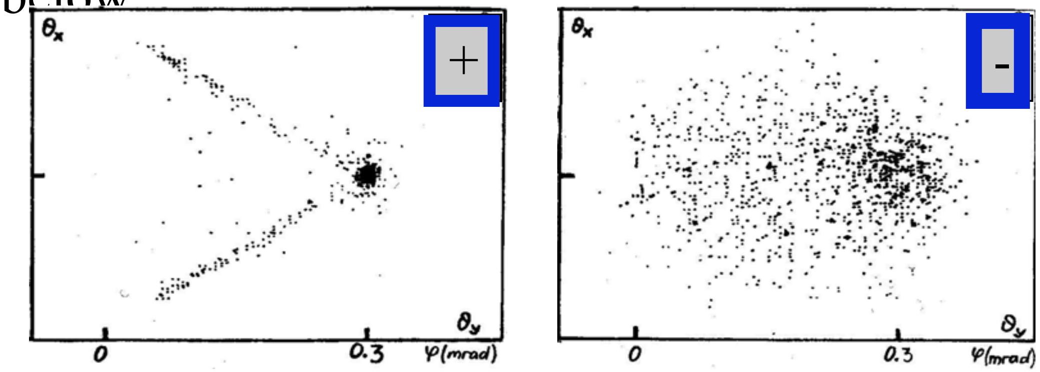
For channeling collimation: problem is large decay emittance of muon

Very fast, large aperture

Negative hadron and e^+/e^- channeling -continued

Taratin & Vorobiev, Phys. Lett. A119, 425 (1987) also discuss negative bending **simulation**.

More recently Greenenko and Shul'ga [NIM B90, 179 (94)] studied negative deflection with a **simulation** program. For **axial** channeling at 400 GeV they saw deflection at the same scale as the Schiott simulation. Their distributions for 100 GeV hadrons bent in a 3 cm crystal are shown below:

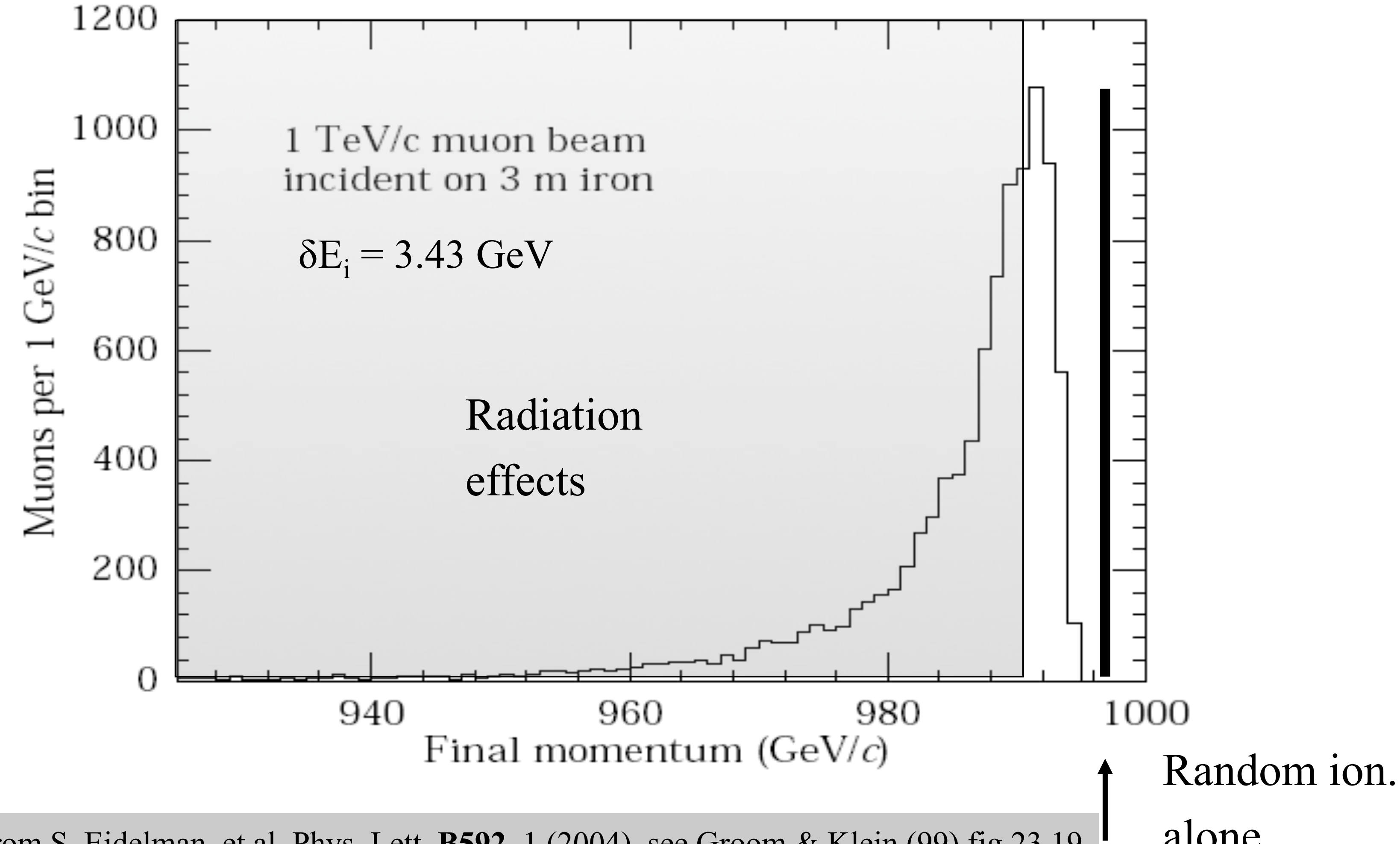


Note that the negative deflection is of the same order as the positive case but very diffuse. Volume reflection or capture?

$\Theta_b = 0.3$ mrad, $\psi_{ca} = 0.04$ mrad

$\Theta_{axis} = 0.3$ mrad

Muon energy loss – small!



From S. Eidelman, et al, Phys. Lett. **B592**, 1 (2004), see Groom & Klein (99) fig 23.19