Università degli Studi di Ferrara

Crystals for Muon Collider beams

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Outline

- Coherent phenomena in crystals

- Crystal-assisted beam manipulation in accelerators
  - Beam halo collimation
  - Beam halo extraction
  - Beam focusing
  - Beam shadowing

Wide energy range, experiments from MeV to TeV

- Possible application in muon colliders
  - Proton LINAC (5GeV-10GeV)
  - Muon before acceleration (339MeV/c)
  - BIB (low energy particles)
  - Primary beam (high energy particles)

Only suggestions: prompt for discussion with beam experts!!

Coherent effects in crystals

- E.m. processes: occuring for charged particles or high-energy photons

PROS

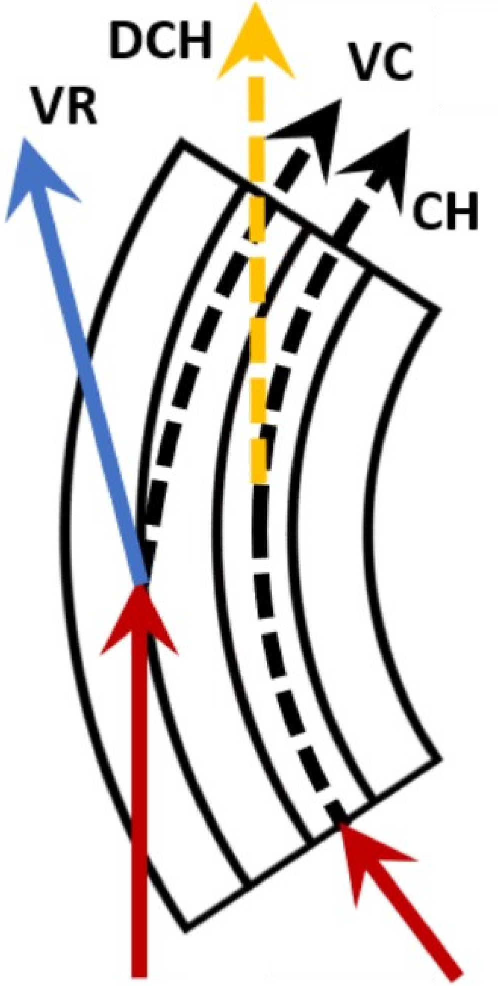
- High steering power up to hundreds of Tesla dipole
- Low material budget ($<0.1X_0$)
- Zero power consumption
- Selective interaction with discrete section of beam/ halo

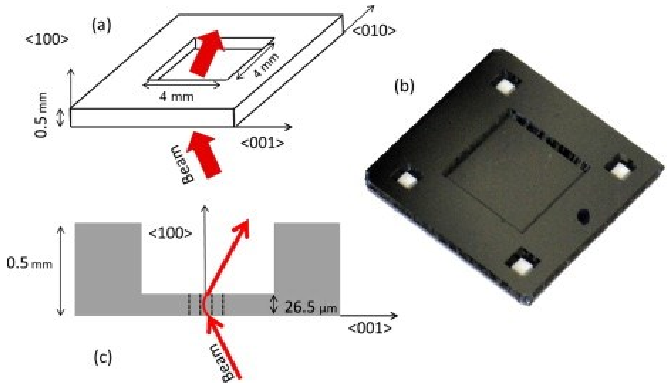
CONS

- Require precise alignment between particles and crystal
- Parameters scale typically with E or $E^{1/2}$
- For some effects lower efficiency in negative charged particles

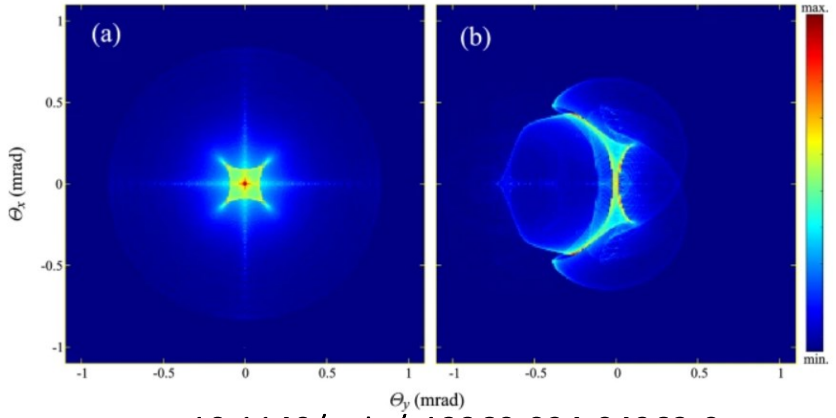
Coherent effects in crystals

- Bent crystal:
  - Channeling: crystals acts as a “waveguide” for particles impacting within critical angle.
  - Volume reflection: particles are “reflected” by critical angle
- Dynamical effects in short crystals:
  - Beam mirroring
  - Rainbow scattering





10.1016/j.physletb.2014.04.062



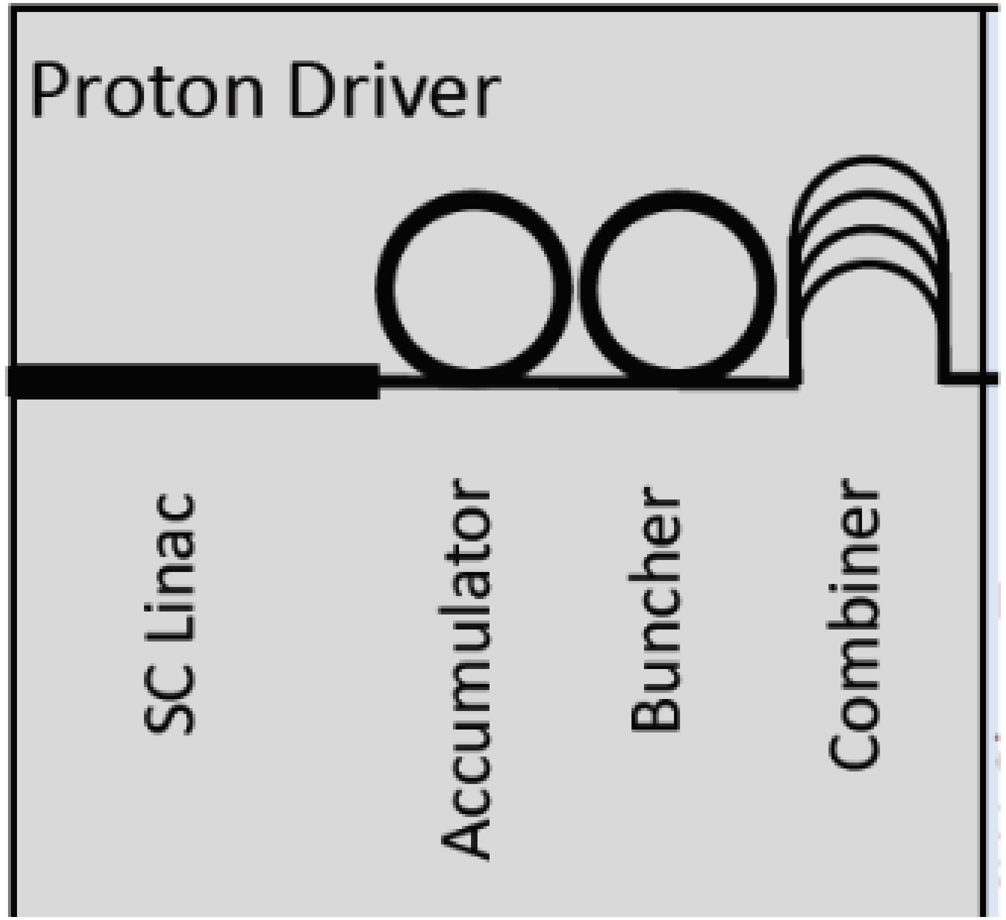
10.1140/epjp/s13360-024-04963-0

Application in accelerators

- Beam halo collimation (tested with protons and ions at LHC)
- Beam halo extraction (employed years at U70 accelerator)
- Beam focusing: both long (meters) and short (cm) focusing length
- Beam shadowing: currently developing crystal to assist Mu2e proton beam extraction

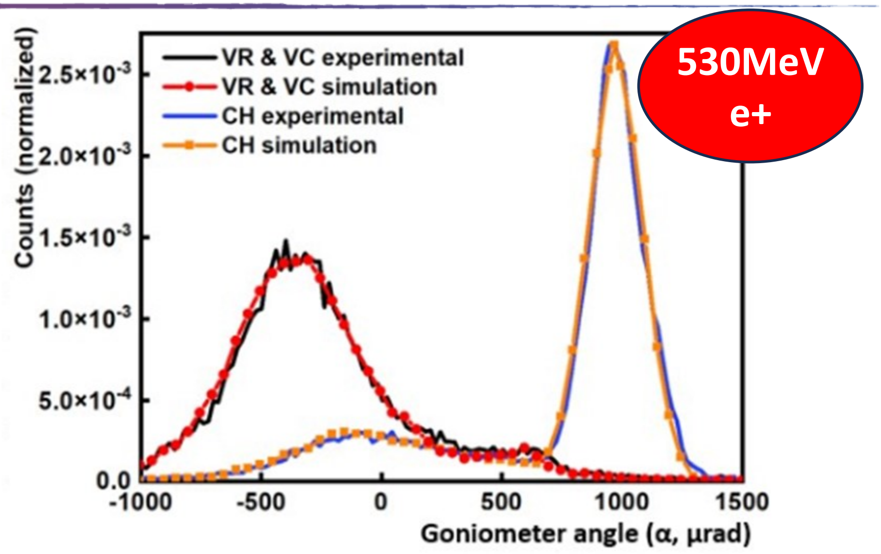
Applications at LINAC

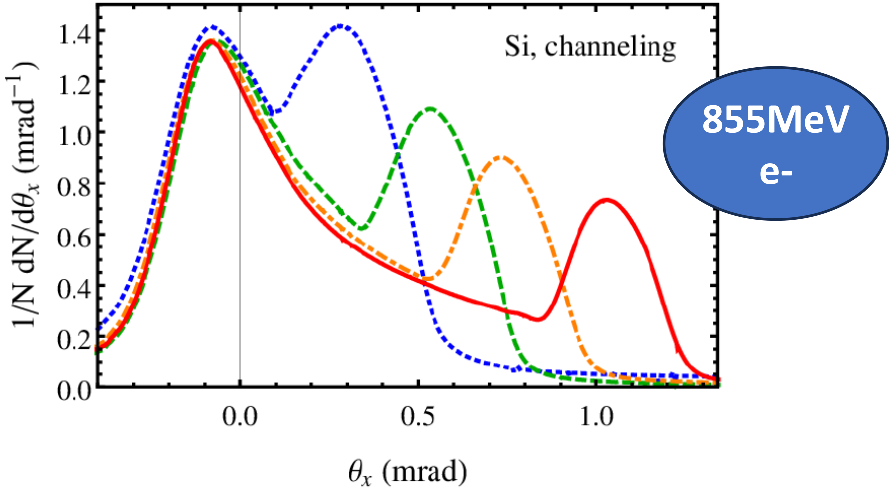
- 5GeV (or 10 GeV) protons are well suited for planar channneling
- Bent crystal can assist collimation of beam
- Beam shadowing of delicate portion of insertion devices to reduce beam losses



End of cooling

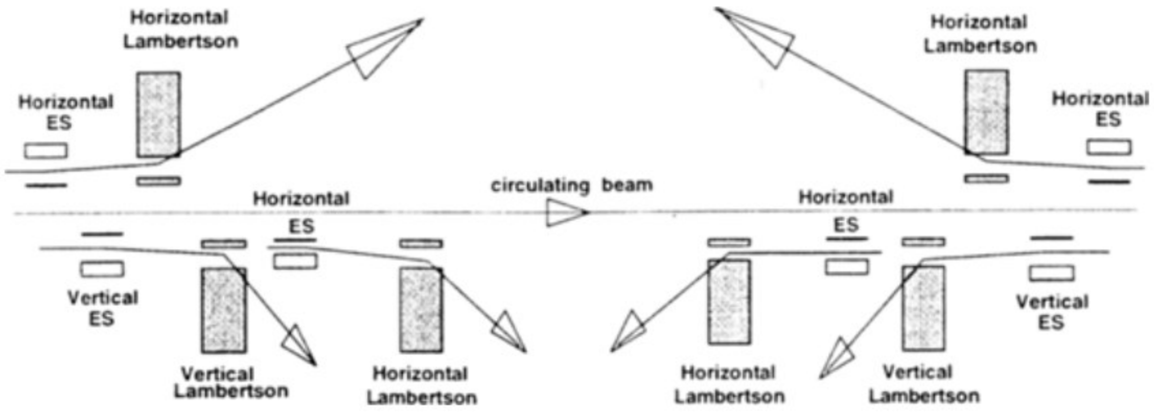
- Particle energy 339MeV
- Thin crystals (15-30μm thickness) to redirect halo particles into accelerator stage
  - Planar channeling
  - Axial channeling
  - Volume reflection
- Mirroring with shorter crystals (≈1μm)



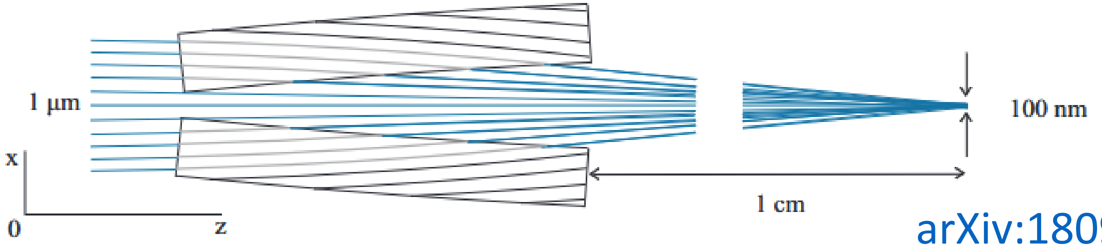


Primary beam manipulation

- Collimation of beam (like LHC)
- Beam extraction
- Beam shadowing (i.e. in assistance of electrostatic beam scraping)
- Beam focusing



[10.1063/1.56430](https://doi.org/10.1063/1.56430)



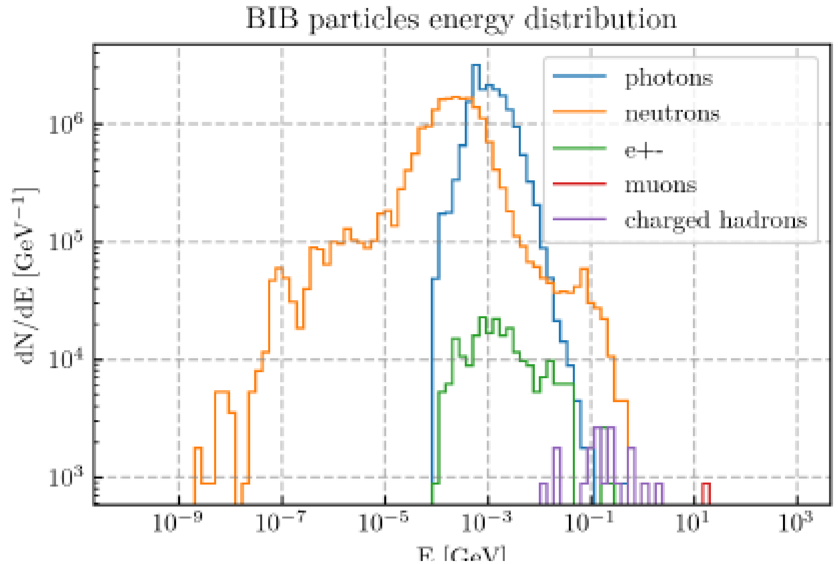
[arXiv:1809.06164](https://arxiv.org/abs/1809.06164)

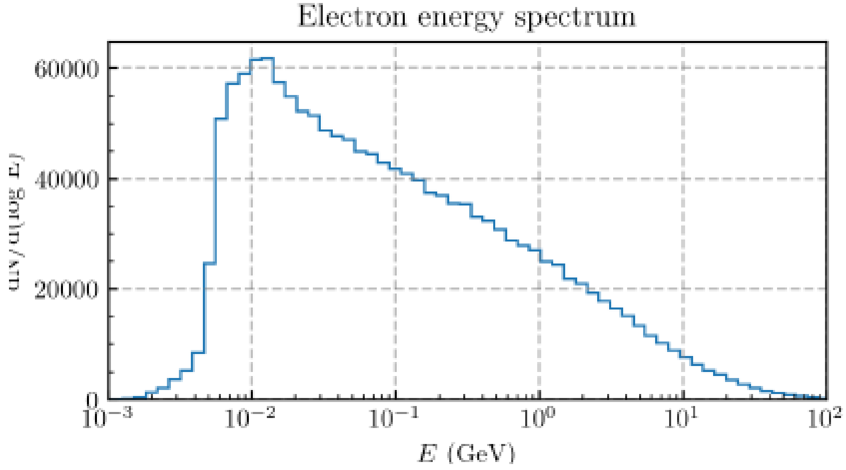
Crystal application with BIB

- Low energy and large energy spread are detrimental to crystals applications (also low efficiency for diffraction of photons and neutrons)

- 2 MeV mirroring with very thin crystals (100 nm) was already performed experimentally, but strict energy spread condition

- For incoherent e+/e- pairs, (higher energy) channeling in bent crystal might be of assistance (see slide 7)





D. Calzolari, ICHEP 2024

Conclusions

- Different kind of coherent effect in crystals can be optimized
- Each application strongly depends on beam parameters and requirements in each portion of the muon collider machine
- Strong inputs are well accepted to design suitable crystal-assisted schemes

Thank you

International MUON Collider Collaboration

MuCol

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Backup slides

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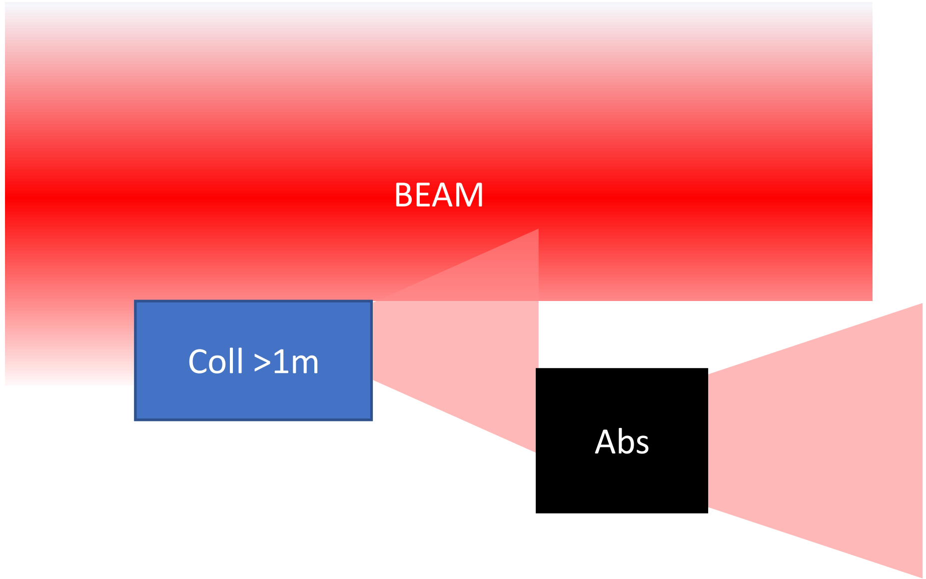
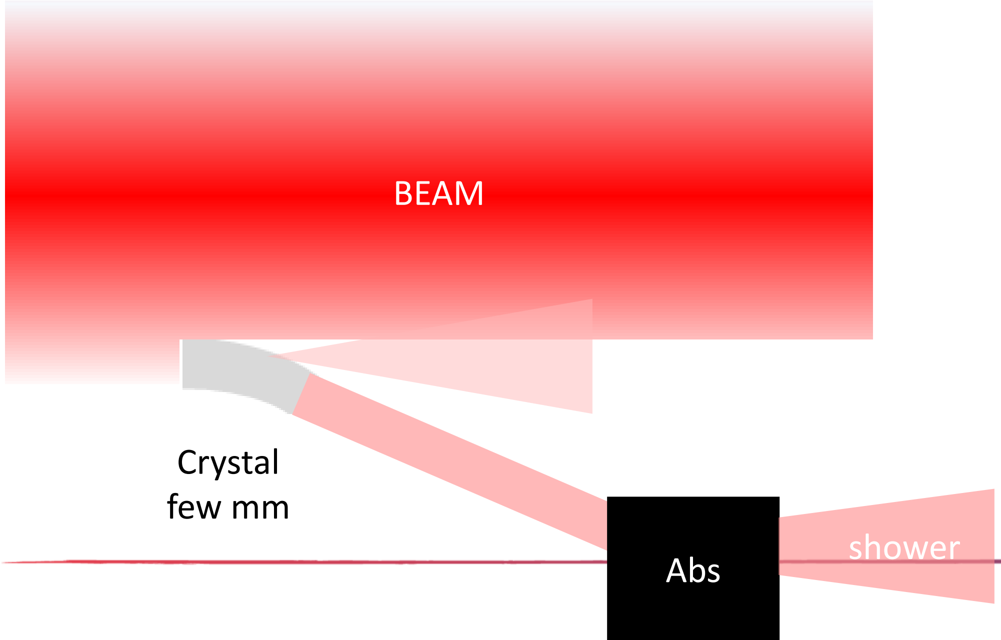
Crystal-assisted beam collimation

- Unavoidably particles diverge from desired trajectory and form **a halo around beam**
- Traditional approach stops the halo with a series of amorphous absorber
- Cons: development of showers in collimators





- Channeled particles in bent crystal while being steered avoid strong scattering: shower development strongly suppressed
- High efficiency in removing halo from beam in controlled manner

Crystal-assisted beam manipulation

Past uses:

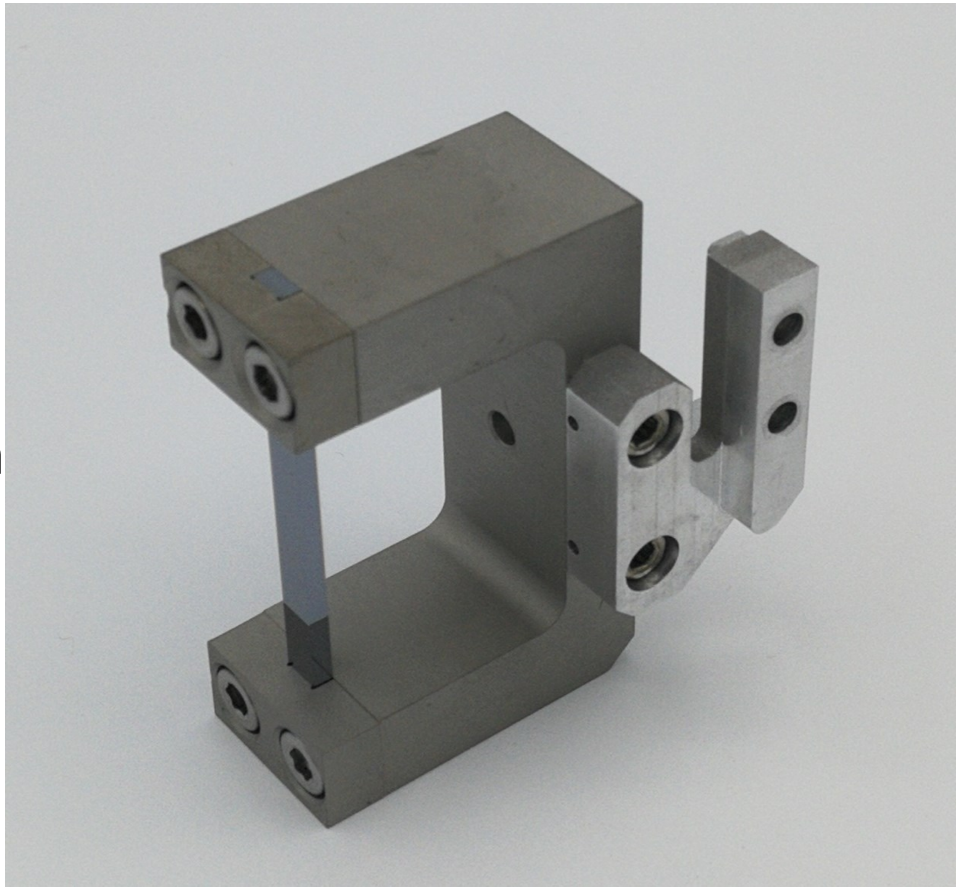
- U70 proton beam extraction
- Spin precession measure of Σ+ baryons at FERMILab

Present and Past Proposal

- UA9: SPS collimation, septum shadowing, extraction
- CRYSBEAM: LHC beam extraction
- SELDOM: charmed baryons spin precession
- SHERPA: positron slow extraction at LNF
- DESY electron baem extraction

Current R&D

- LHC ion beam collimation

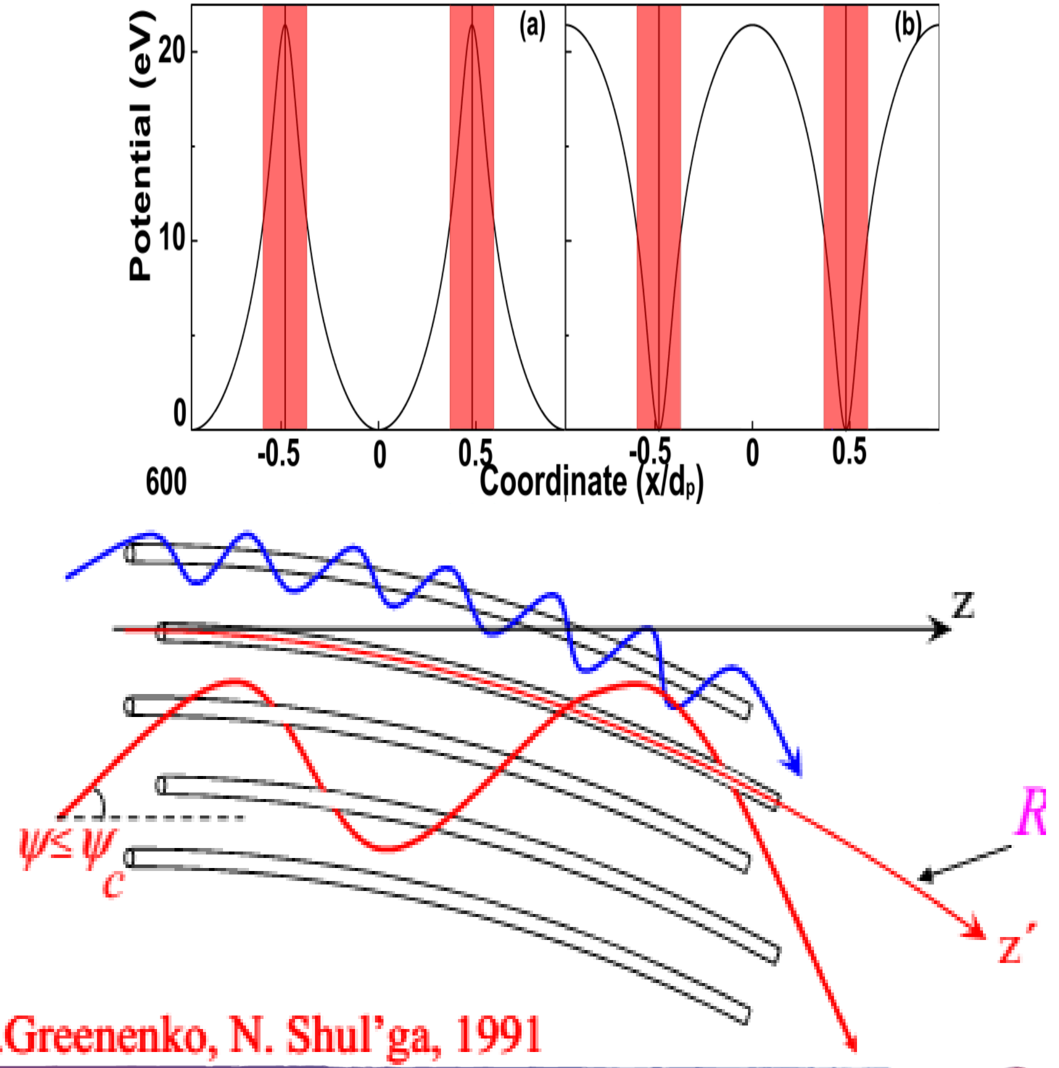


“INFN KE4350/EN/HL-LHC” between INFN and CERN was signed: 4 *crystals collimators* have been already provided to CERN **by INFN Ferrara**

Negative particle steering

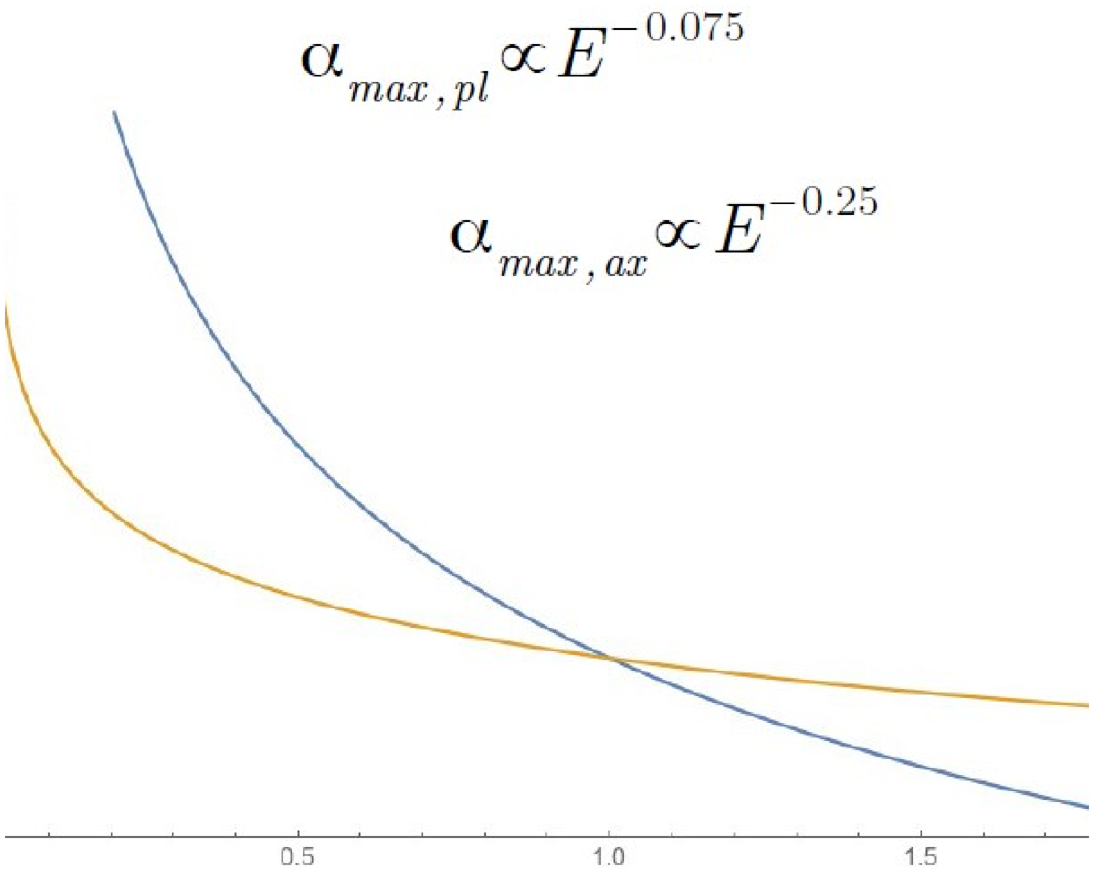
- Planar channeling is significantly less efficient for negative particles, as incoherent scattering with atomic nuclei is enhanced instead of being suppressed.

- Axial Stochastic Deflection was first proposed by A.A. Greenenko and N.F. Shul'ga in 1991
- Experimentally observed by H8-RD22/UA9 collaboration at CERN in 2008 for protons and in 2009 for π⁻ mesons
- The mechanism involve over-barrier motion: particles scattering converge stochastically along the axis direction. Efficient for both positive and negative particles



Axial Stochastic Deflection and Planar channeling

- Negative particles in planar channeling exploit weaker potential and more incoherent nuclear scattering wrt positive case
- Stochastic axial deflection has the potential to steer efficiently both negative and positive particles
- Maximum deflection angle scale with different power law:
  $E^{-0.075}$ (planar) vs $E^{-0.25}$ (axial)



Comparison of planar and axial stochastic deflection at 1 TeV

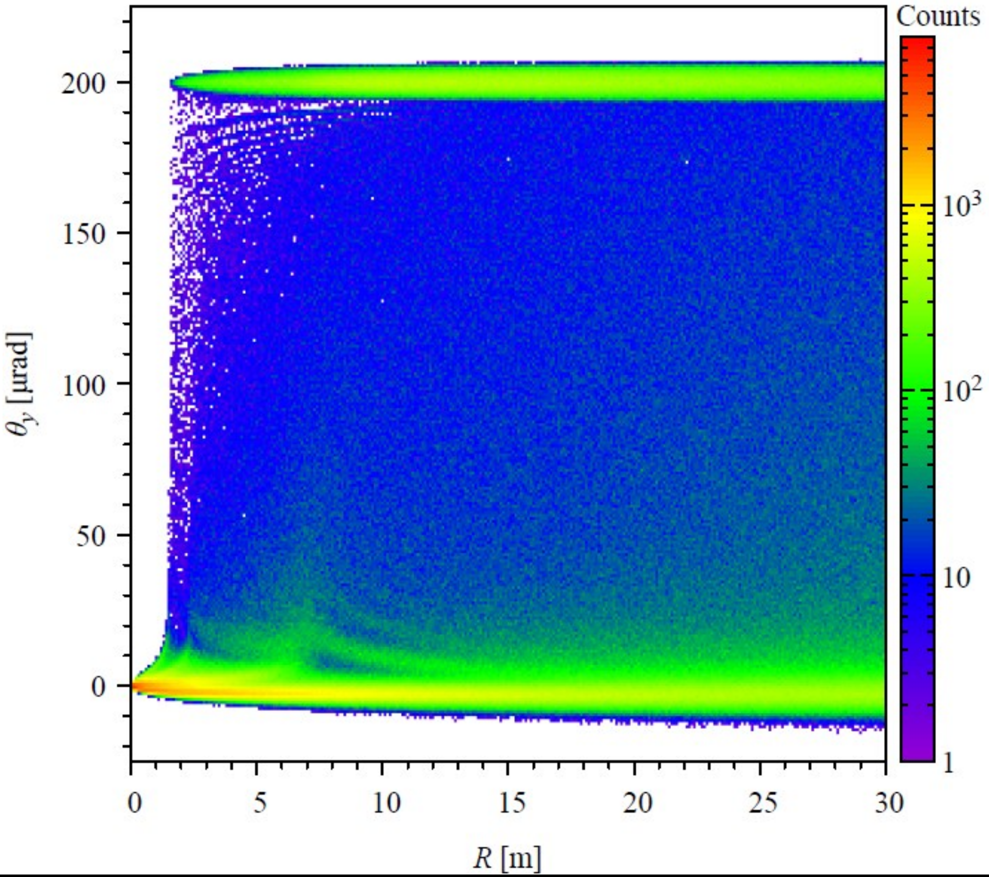
- A large simulation campaign has been carried out with both muon and anti-muon of 1 TeV/c momentum

- Optimal radius of curvature has been obtained for deflection angles from 2 μrad up to 200 μrad

- Cases for 200μrad, 50μrad are presented as example in this work

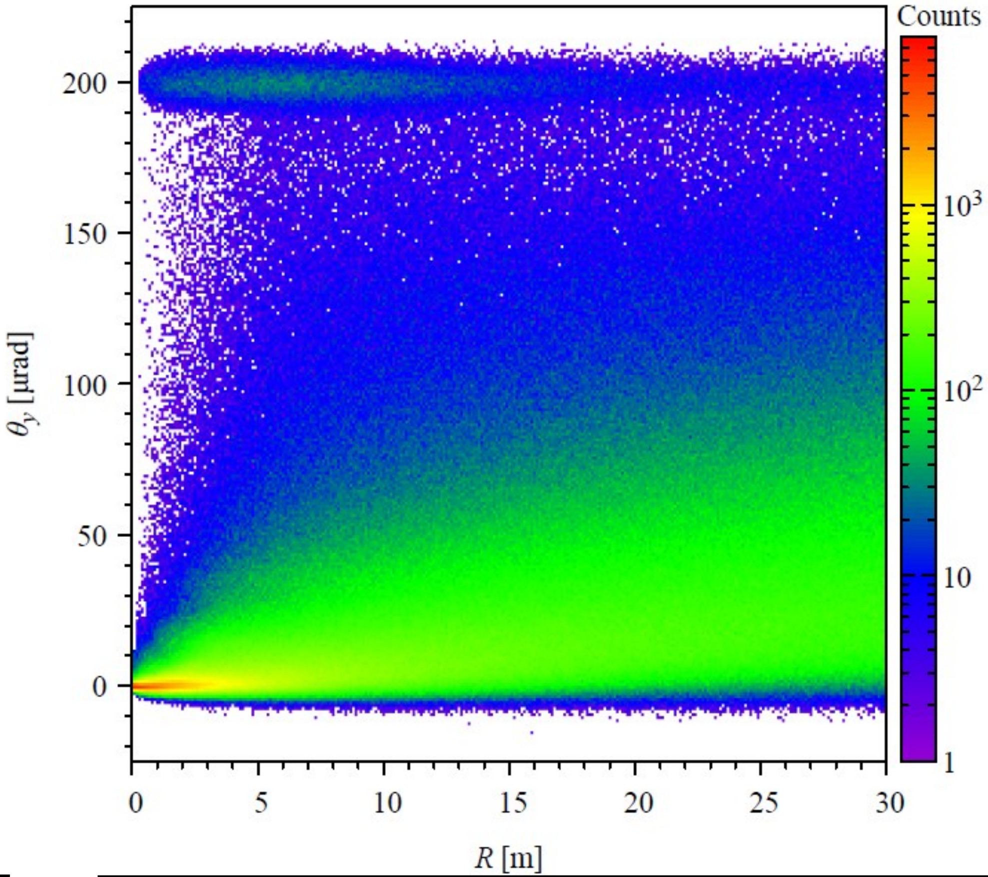
Large angle deflection μ- (200μrad)

(111) plane



Better single pass efficiency with planar channeling

<110> axis

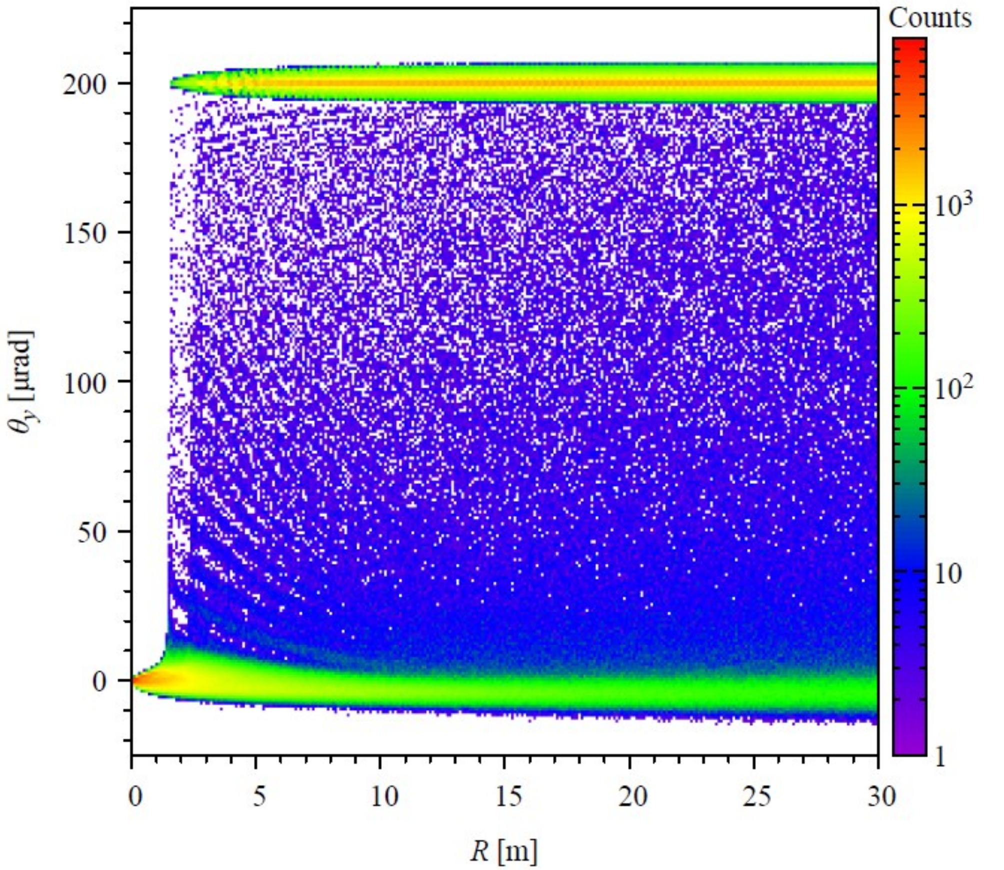


Optimal radius of curvature for R ~6-7m

Courtesy of I. Kyryllin

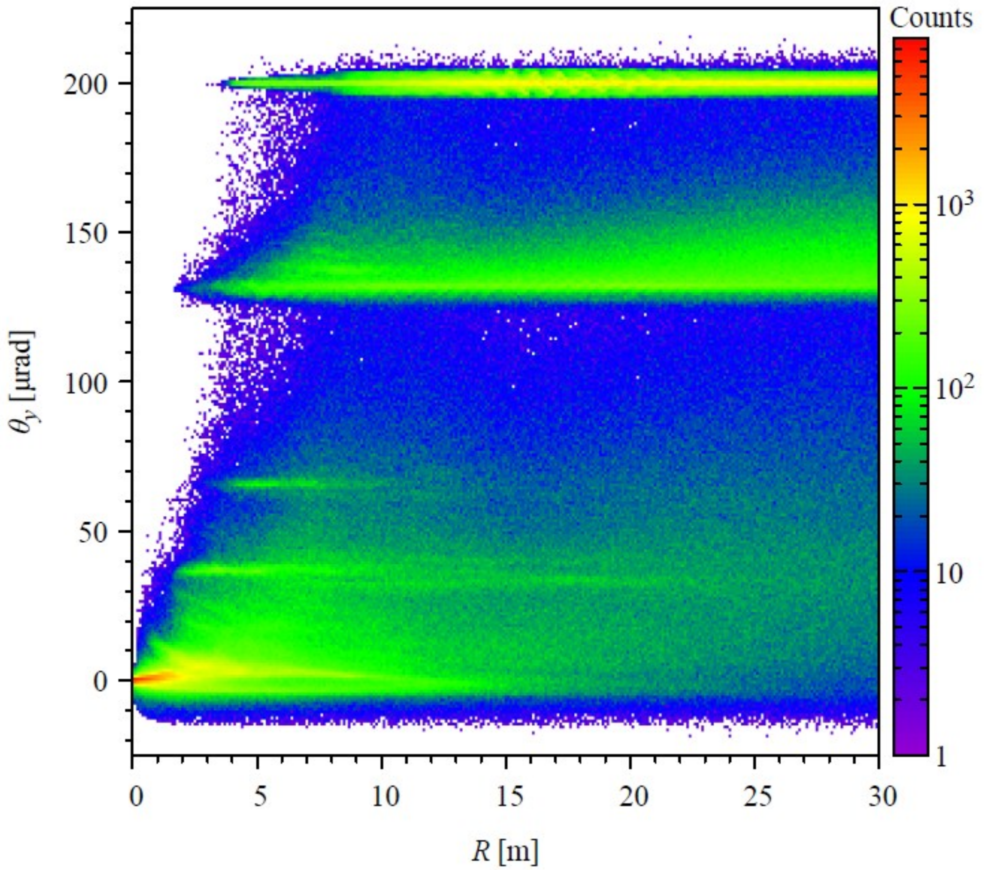
Large angle deflection μ+ (200μrad)

(111) plane



Better single pass efficiency with planar channeling

<110> axis

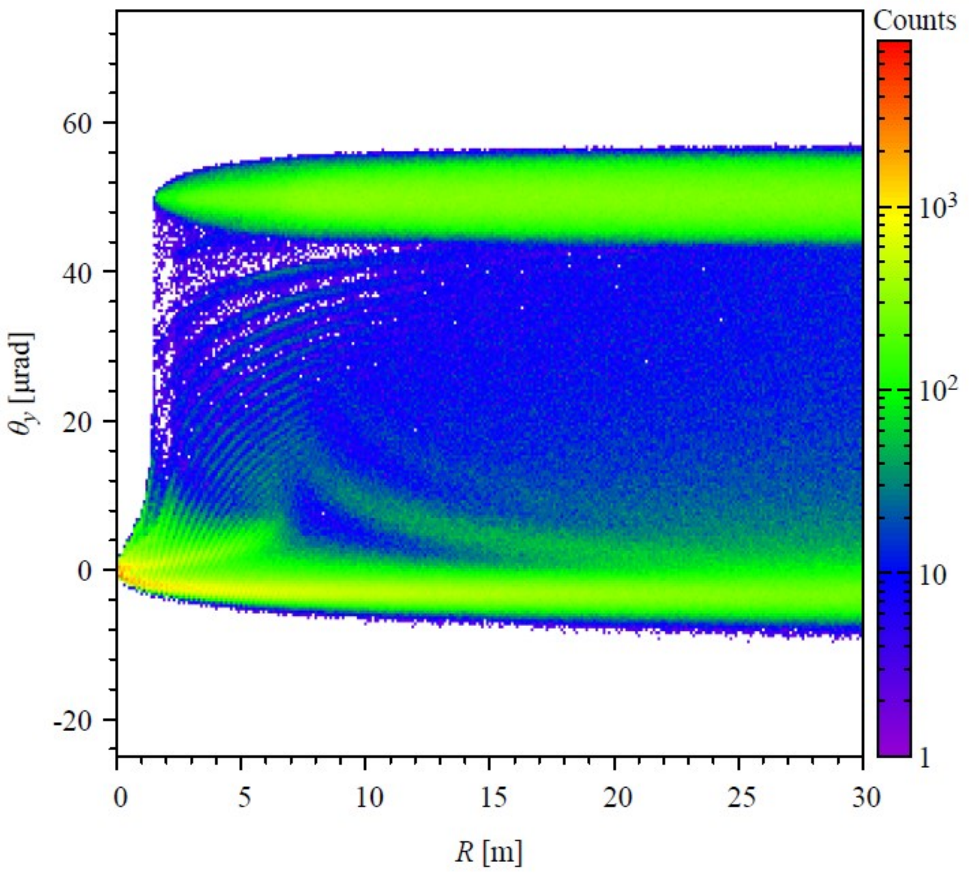


Optimal R between 15-20m

Courtesy of I. Kyryllin

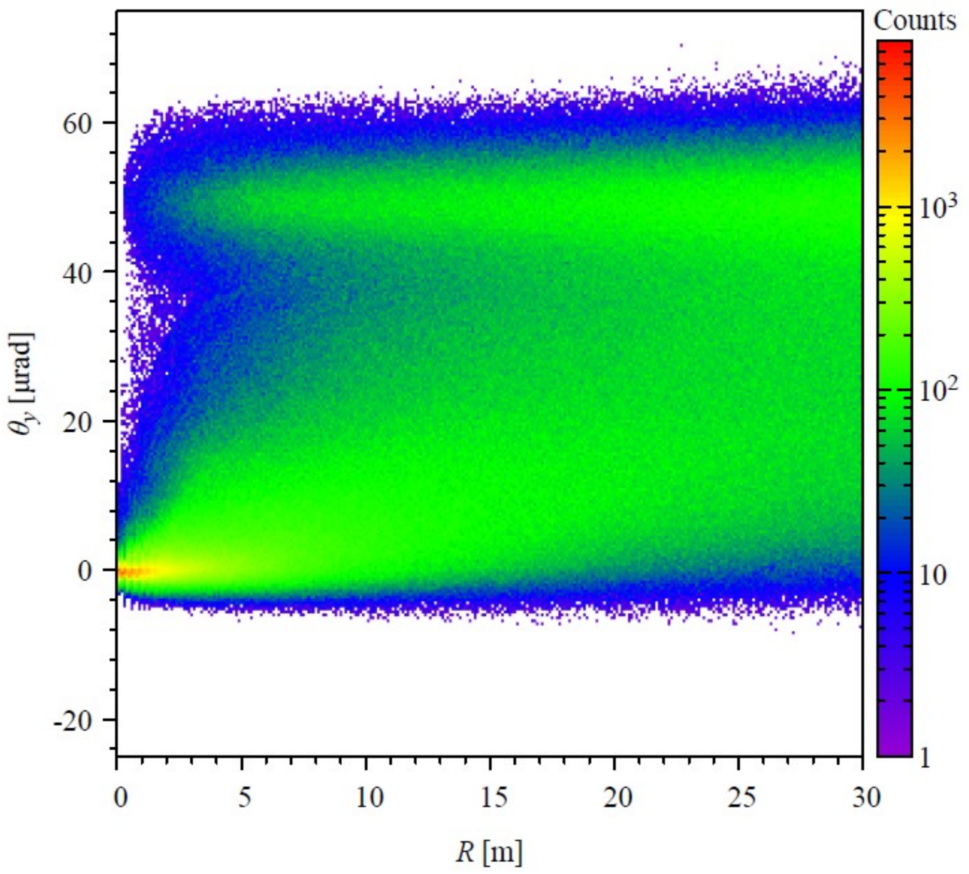
Small angle deflection μ- (50μrad)

(111) plane



Better single pass efficiency with planar channeling

<110> axis

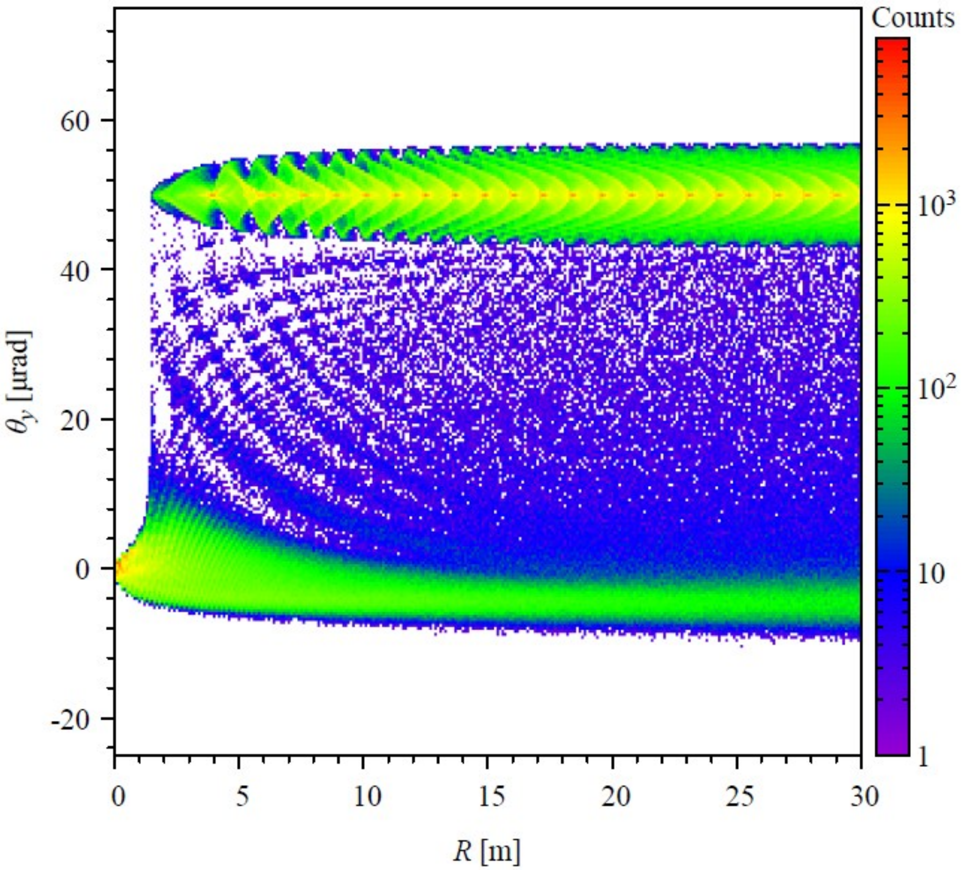


Optimal R between 20-25m

Courtesy of I. Kyryllin

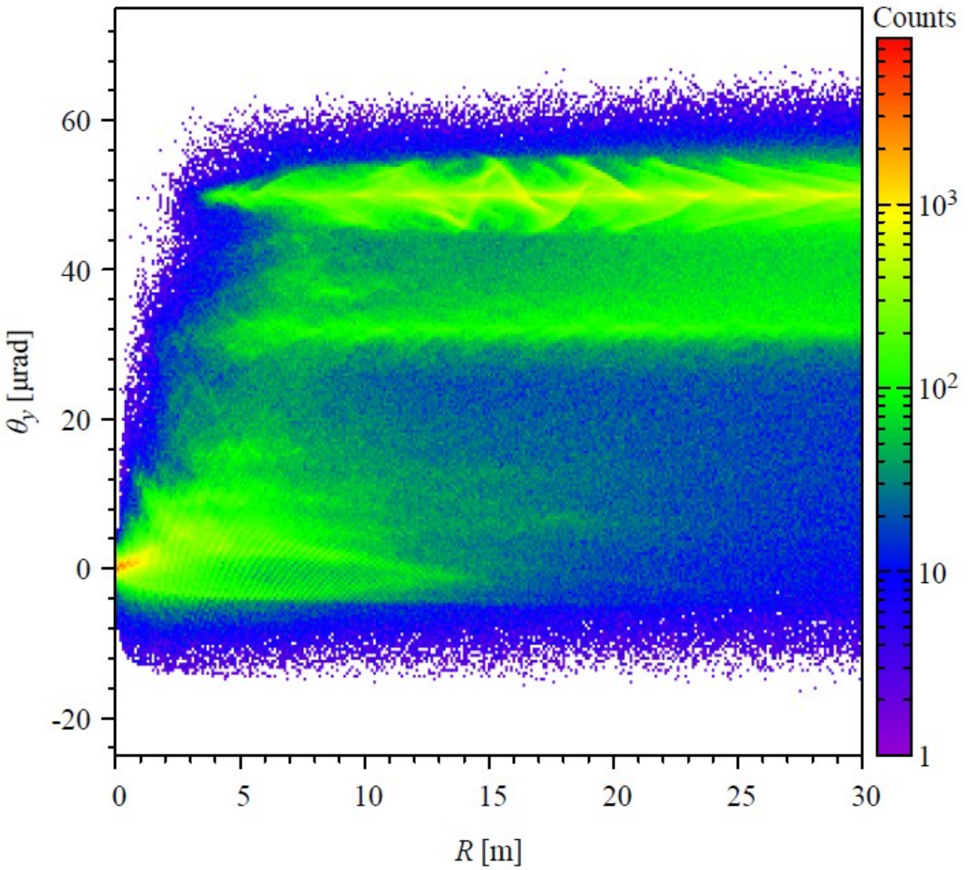
Small angle deflection μ+ (50μrad)

(111) plane



Better single pass efficiency with planar channeling

<110> axis

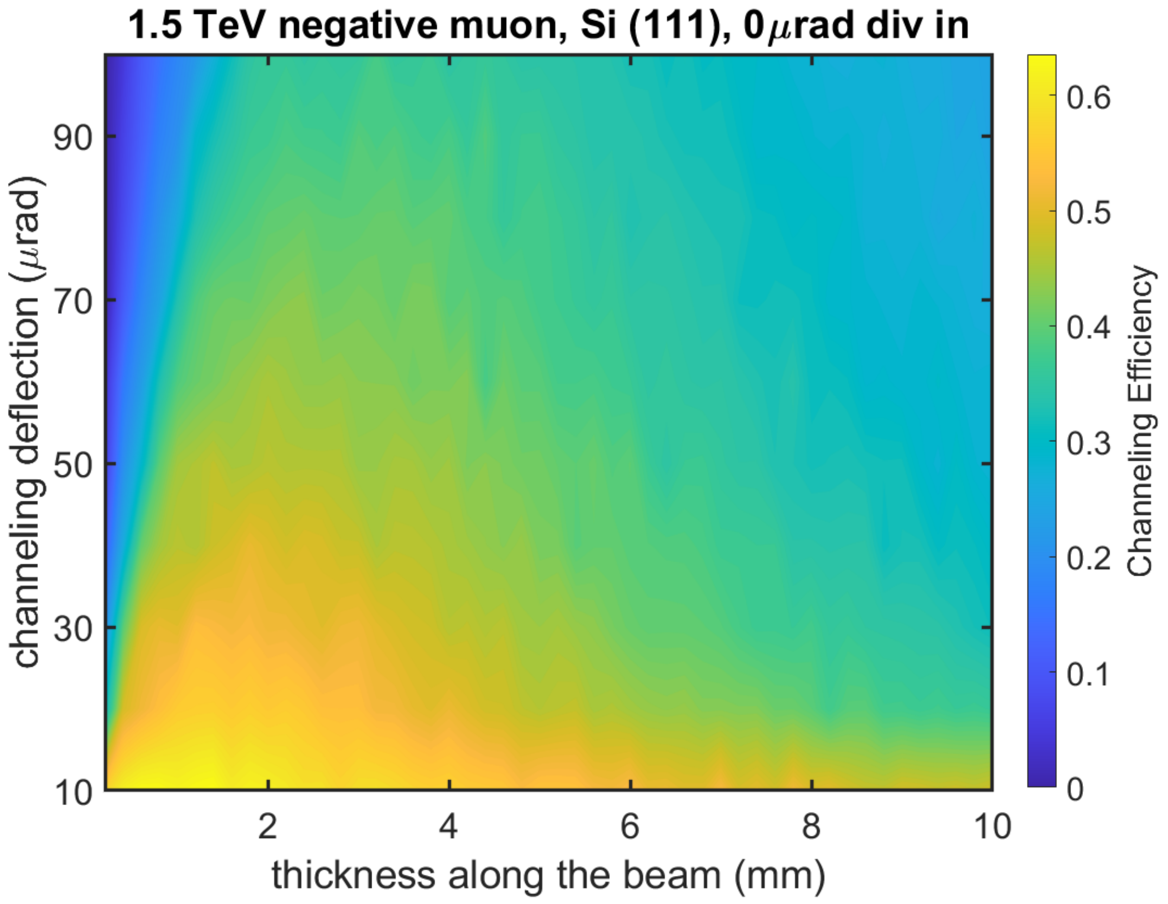


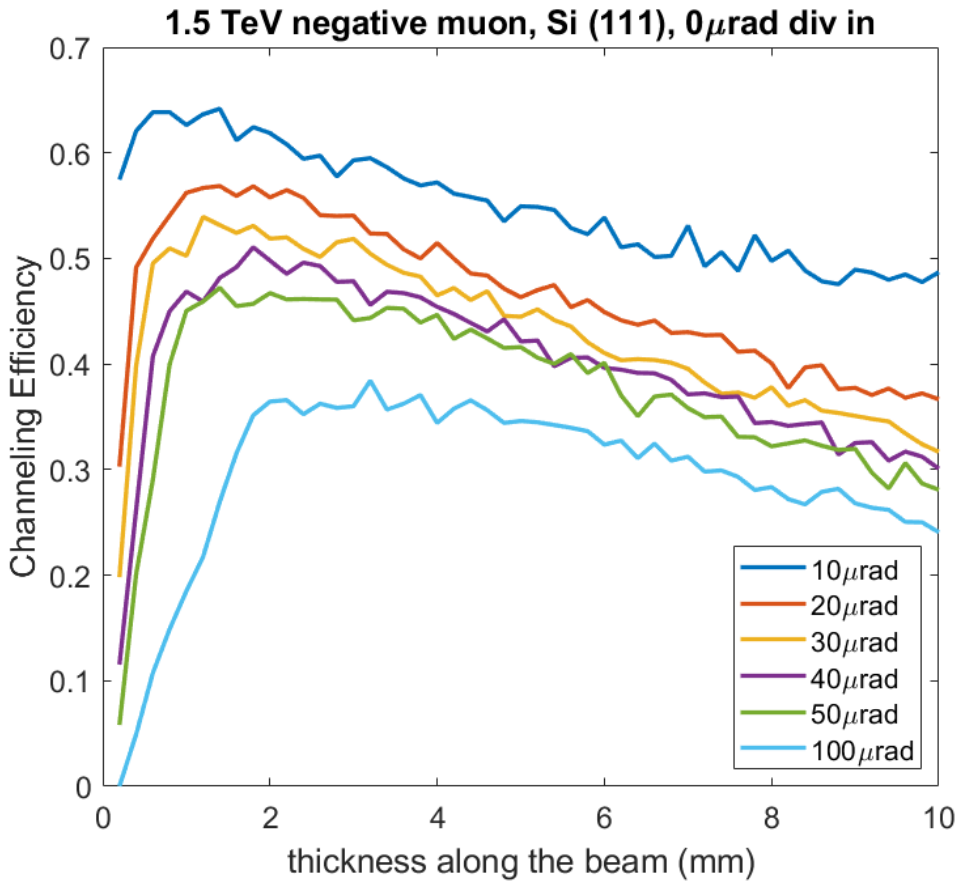
Optimal R between 15-20m

Courtesy of I. Kyryllin

μ- planar channeling efficiency 1.5TeV

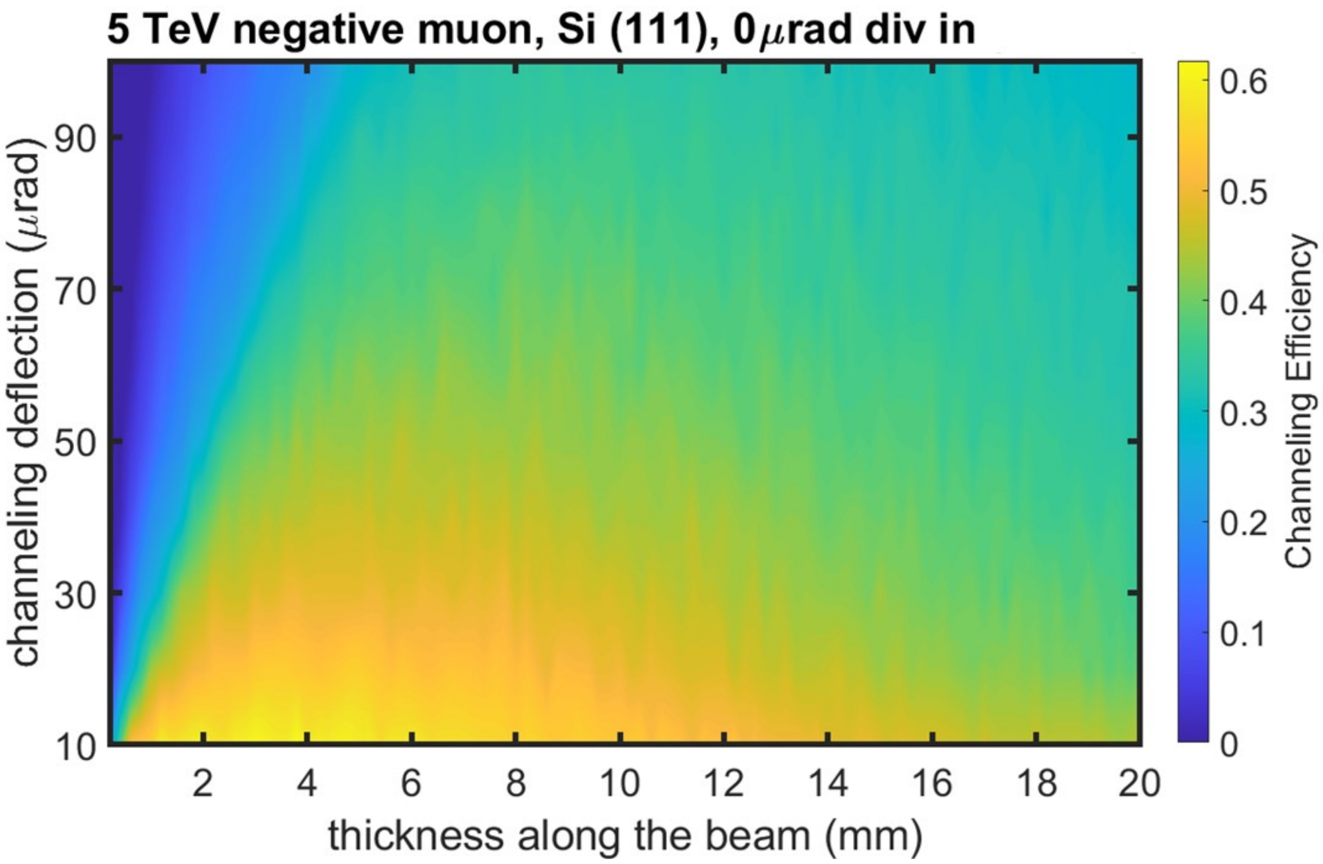
1mm<Optimal crystal length <2mm, possible increase with multi-turn efficiency

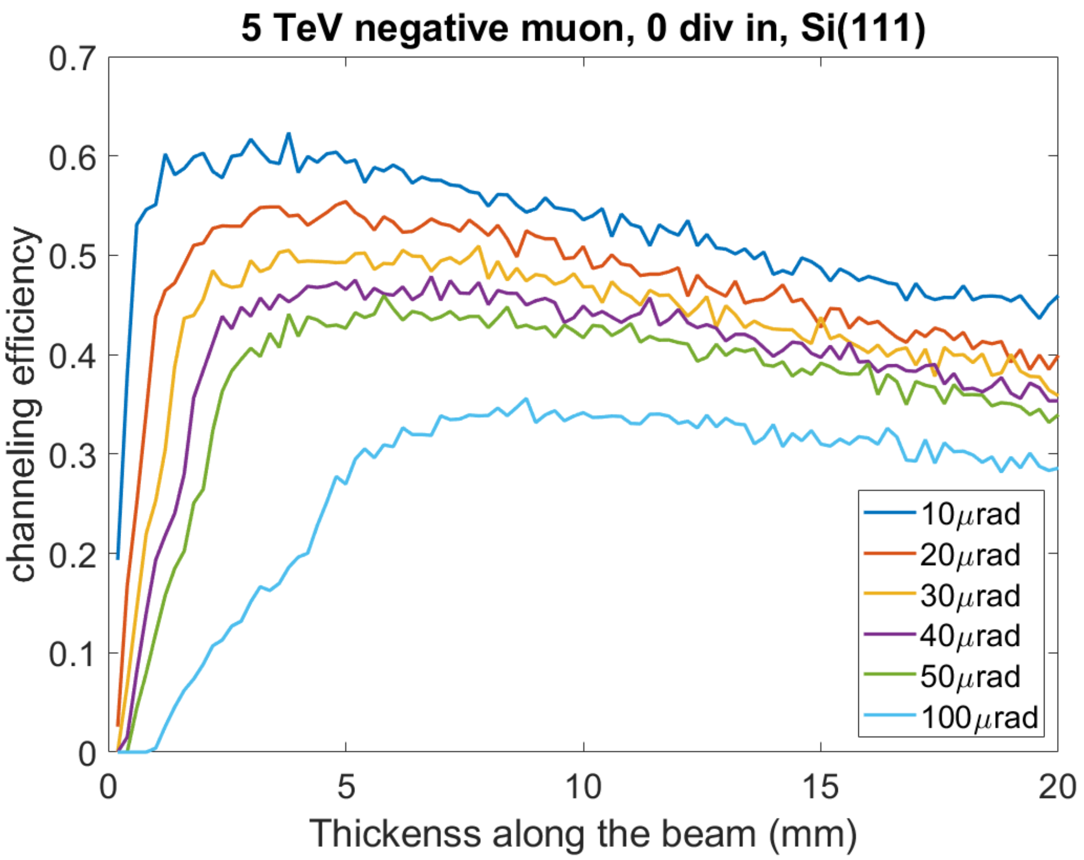




μ- planar channeling efficiency 5TeV

2mm<Optimal crystal length <5mm, possible increase with multi-turn efficiency





Conclusion

- Comparison of axial stochastic deflection and planar channeling as steering mechanism for TeV muon was carried out. Planar channeling was more efficient option as we reach multi-TeV scale

- Optimal single pass efficiency condition was obtained for 1.5 TeV and 5 TeV negative muon case.

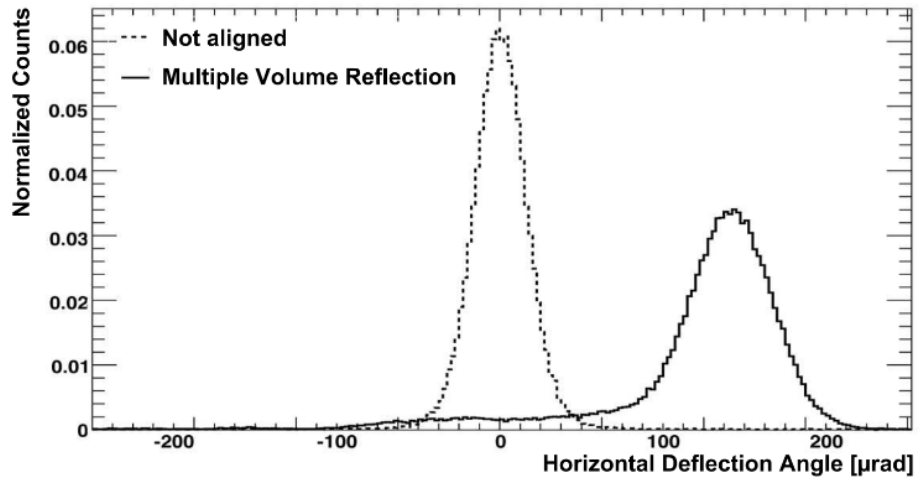
- Future study of volume reflection phenomena such as Multiple Volume Reflection in One Crystal and Multiple Volume reflection in a series of aligned bent crystals.

Multiple Volume Reflection

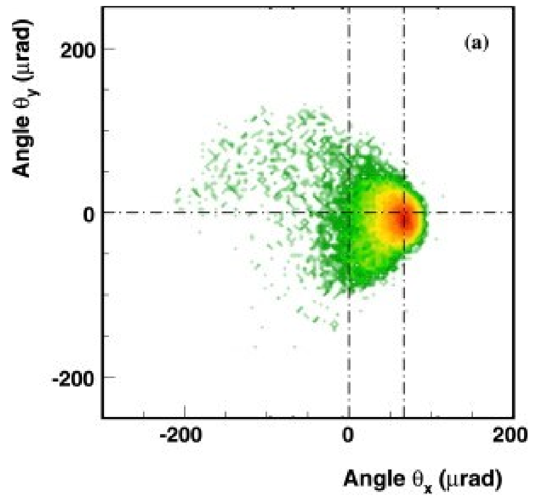
- Volume reflection deflects small angle, but a series of crystals can add up steering with high efficiency

- This can provide deflection comparable with channeling, with good efficiency for both negative and positive particles

- Or near axial alignemtn, multiple volume reflections can occur in a single crystal (MVROC)



10.1088/1748-0221/7/04/P04002



10.1016/j.physletb.2009.11.026