Multistrip crystals for collimation of Tevatron circulating beam

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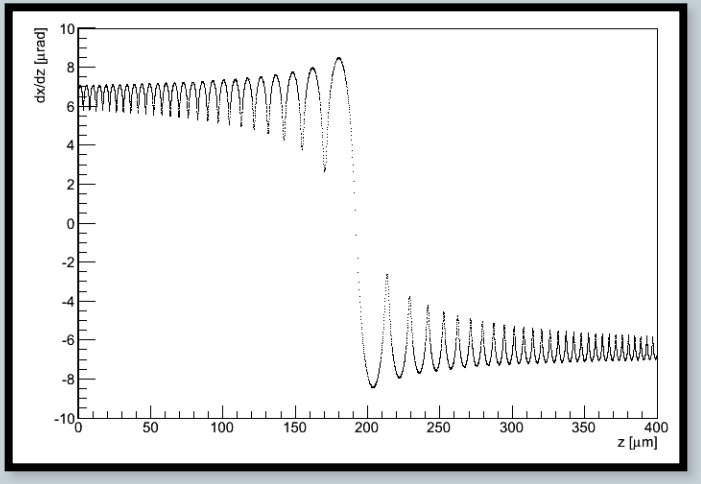
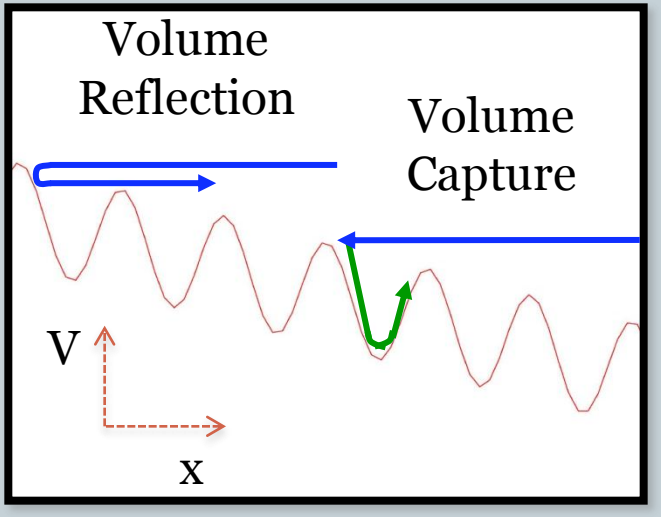
Summary

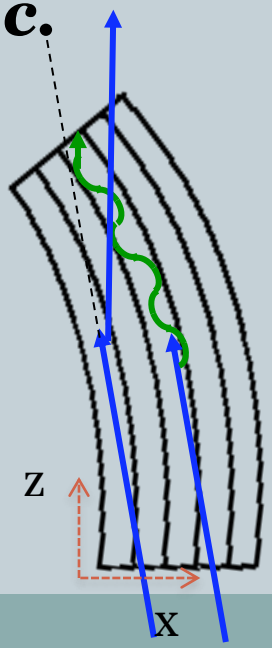
- Volume Reflection Effect
- Collimation Experiment
- MST Fabrication
- MST Characterization
- MST Emulation
- MST Test @ H8 line – SPS
- MST & Negative Particles
- Conclusion

Volume Reflection (VR)

Particles whose **trajectories becomes tangent to crystalline** planes inside the volume of a bent crystal **are deflected by a quantity which tends to** $\theta_{VR} \approx$ ***10μrad @ 400 GeV/c.***







Deflection **efficiency** of volume reflection **is limited only by the** concurrent process of **volume capture (VC).**

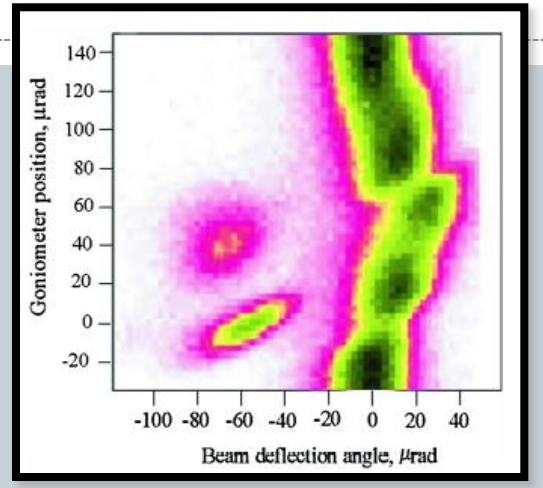
[1] A. M. Taratin and S. A. Vorobiev, Phys. Lett. A 119, 425 (1987).

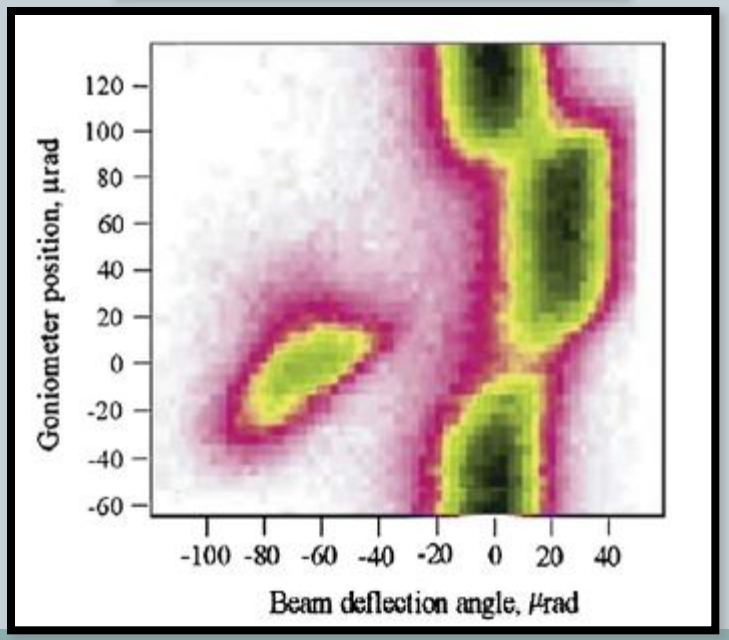
Double Volume Reflection

Two crystals can be properly aligned to produce double volume reflection effect [1].

In the pictures two alignment settings are shown.

Deflection Angle: 23.2 μrad
Deflection efficiency: **96.7%**

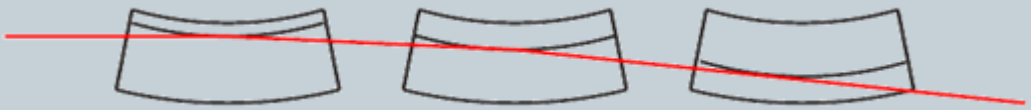




[1] W. Scandale et. al, Physics Letters B 658, 109 (2008).

Multiple Volume Reflection (MVR)

A series of aligned crystals provide increase of deflection angle [1].

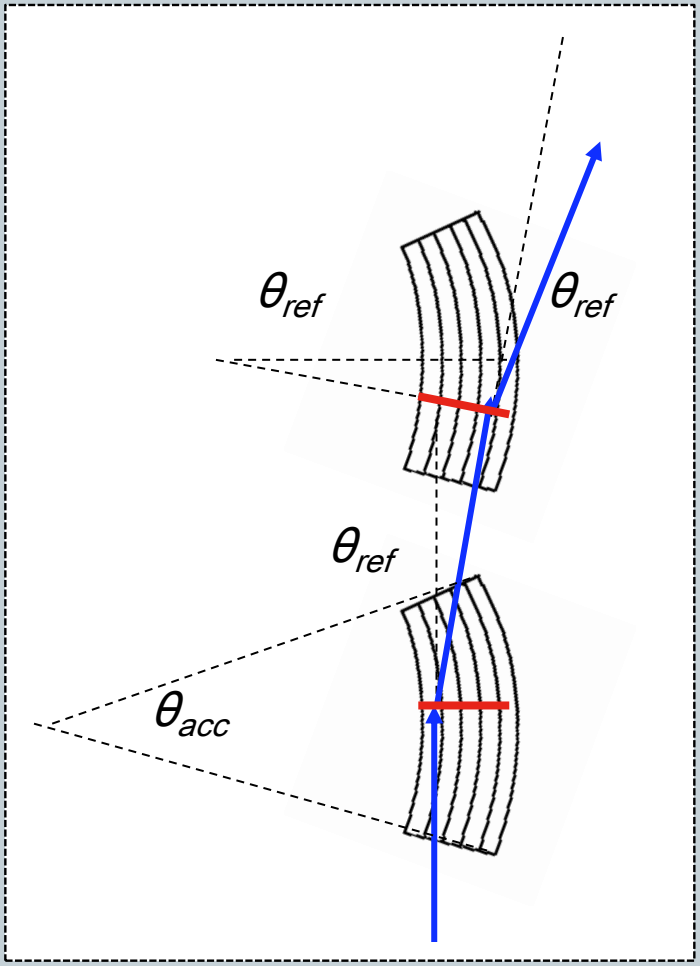


A multistrip is a technique to fabricate a crystal for multiple VR

$$\theta_{ref} = 8.9 \quad mrad$$

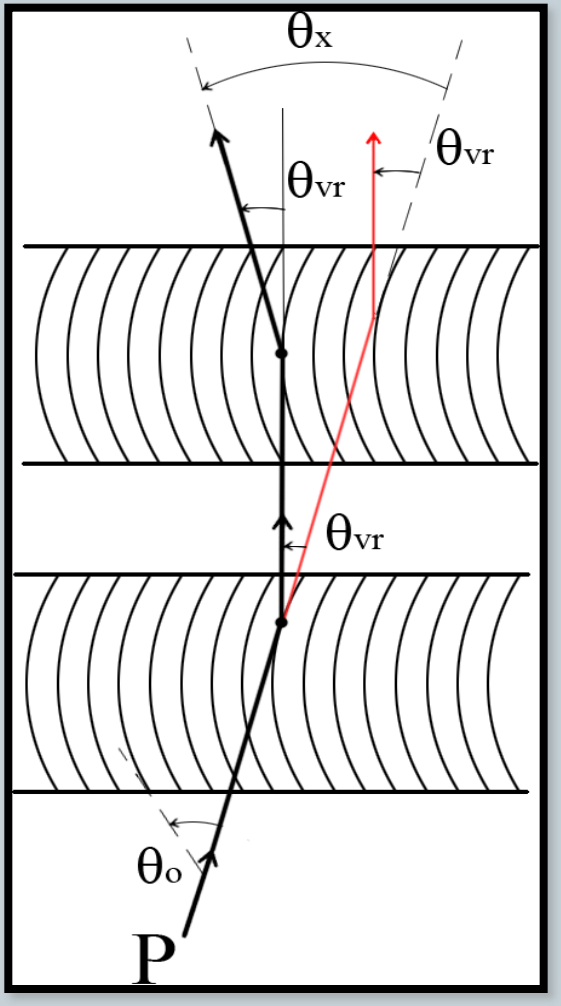
$$\theta_{acc} \sim 250 \quad mrad$$

$$\theta_{ref} << \theta_{acc}$$

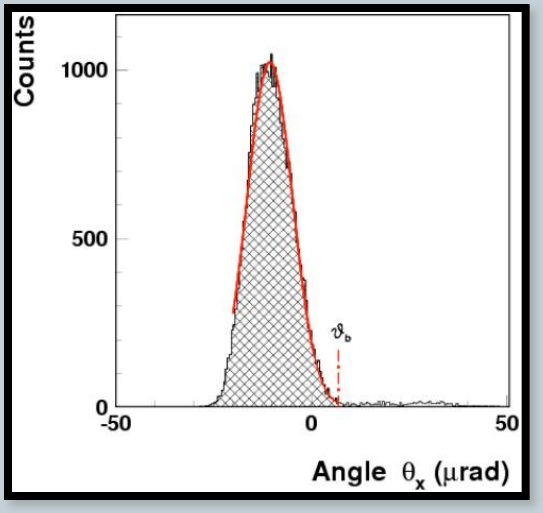


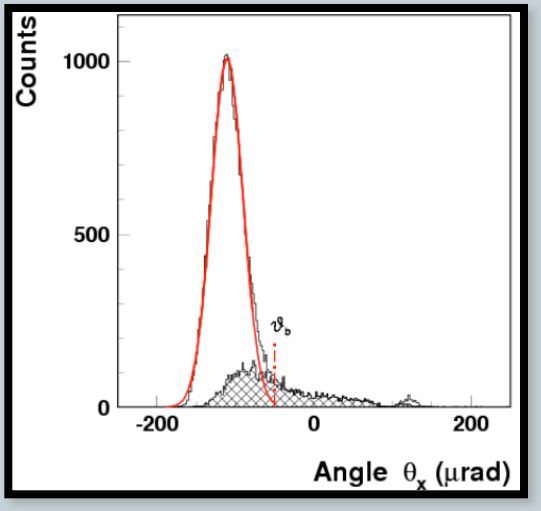
[1] W. Scandale et. al, PRL 102, 084801 (2009).

MVR assistance by Volume Capture (VC)



VC assists volume reflection leading to increase of deflection efficiency [1].

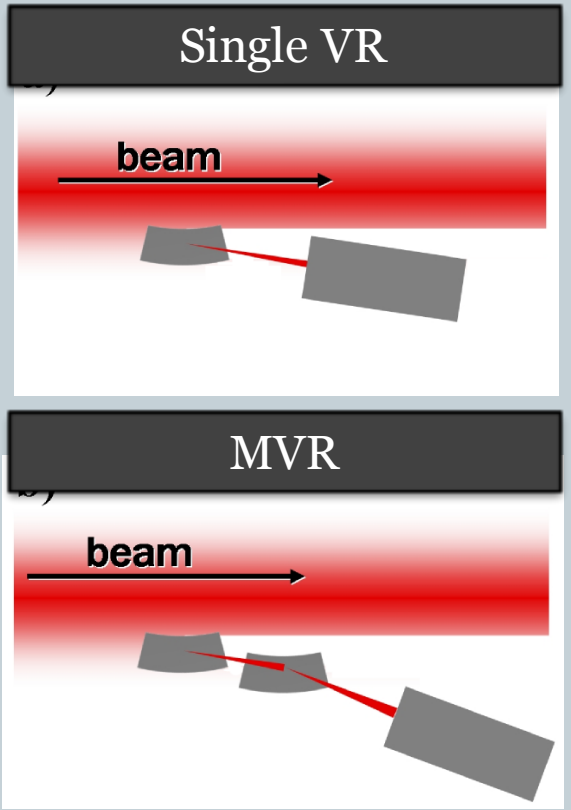




Deflection efficiency: **98% VS 79%** expected for twelve aligned strips.

[1] W. Scandale et. al, Physics Letters B 688 (2010) 284–288.

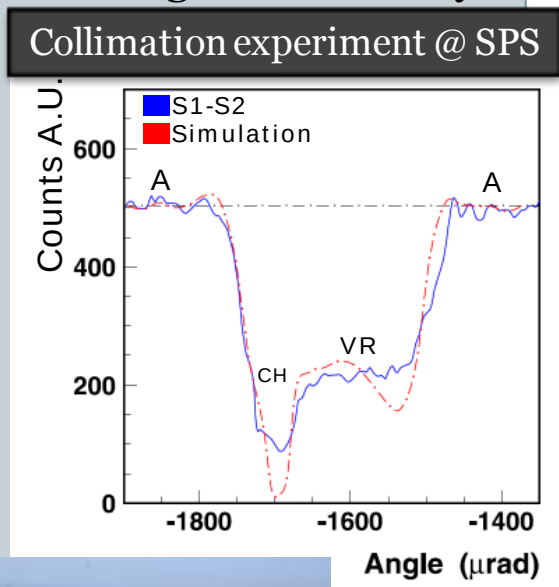
Collimation Experiment



MVR effect could be used to deflect particle at higher angle than single VR [1] (n-times angle of single VR depending on strip number), but with higher efficiency than channeling.

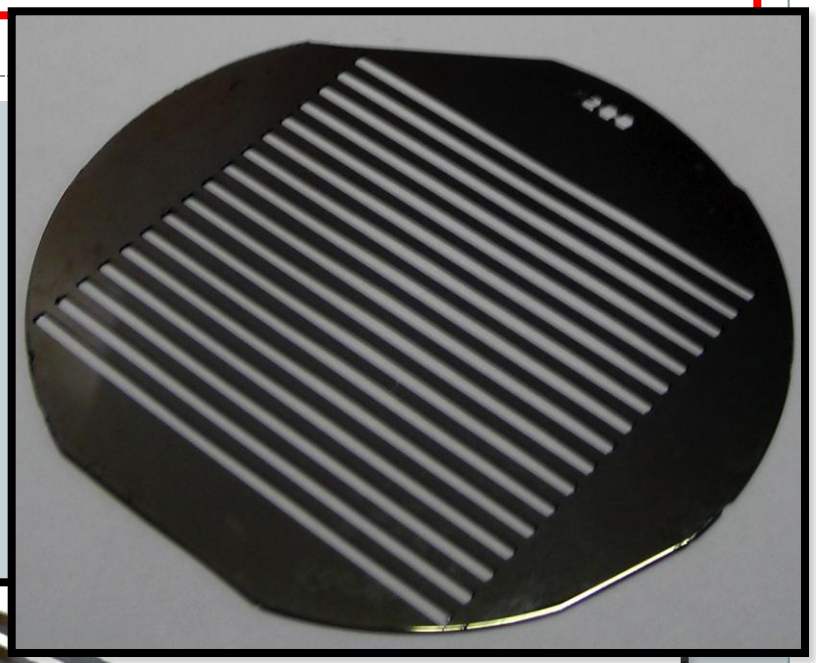
Possibility to use crystal as primary deflector has been already demonstrated [1] at the SPS with channeling and single volume reflection.

Collimation experiments have been proposed [2] for the 1 TeV/c circulating proton beam of Tevatron accelerator.



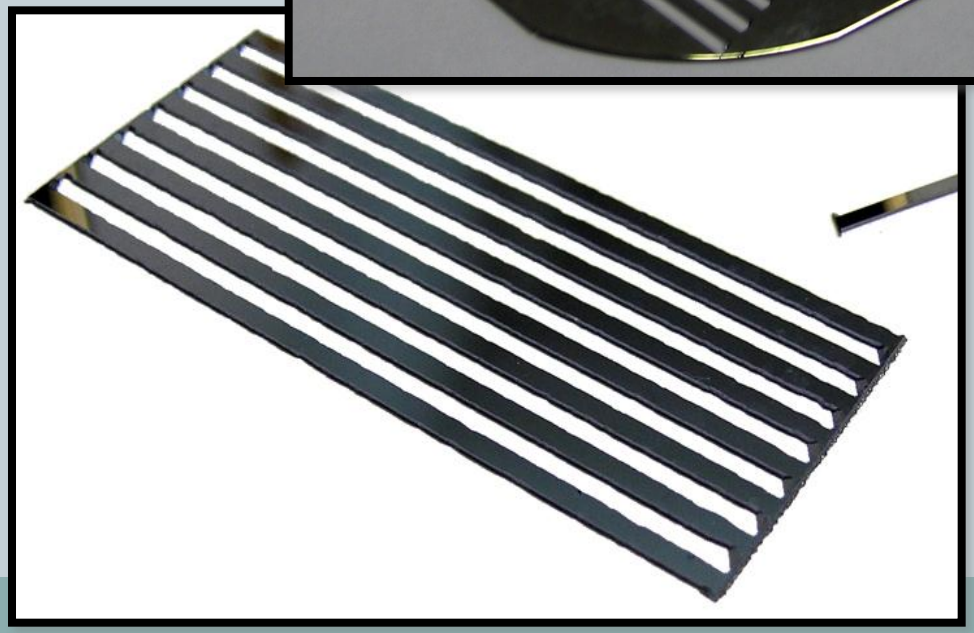
[1] W. Scandale et. al, Physics Letters B 692 (2010) 78-82.
[2] N. V. Mokhov, "Recent developments in crystal collimation at the Fermilab Tevatron (T-980)".

Multristrip (MST)

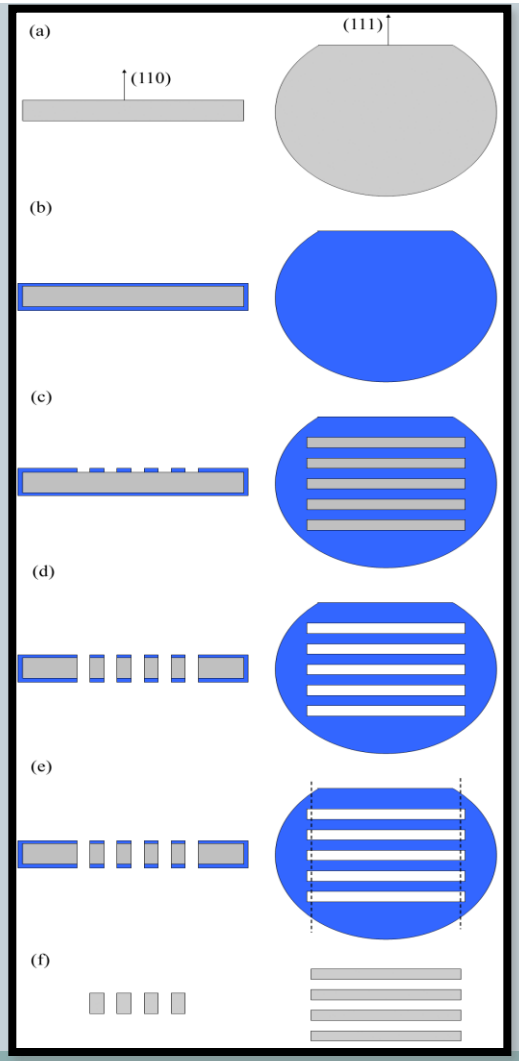


Starting Material
- (110) silicon 4” wafers
- flatness: 300 nm over 26x9 mm^2

Geometrical Properties
- 0.3 x 50 x 31 mm^3
- 16 1 mm-thick strips spaced by 1 mm
- common Si frame



Multistrip Fabrication



a) Starting material: (110) silicon wafer, off-axis: 120 μrad

b) LPCVD deposition of silicon nitride thin layer

c) Silicon nitride patterning

d) Etching of Si in KOH solution, silicon nitride acts as masking layer

e) Silicon strips release

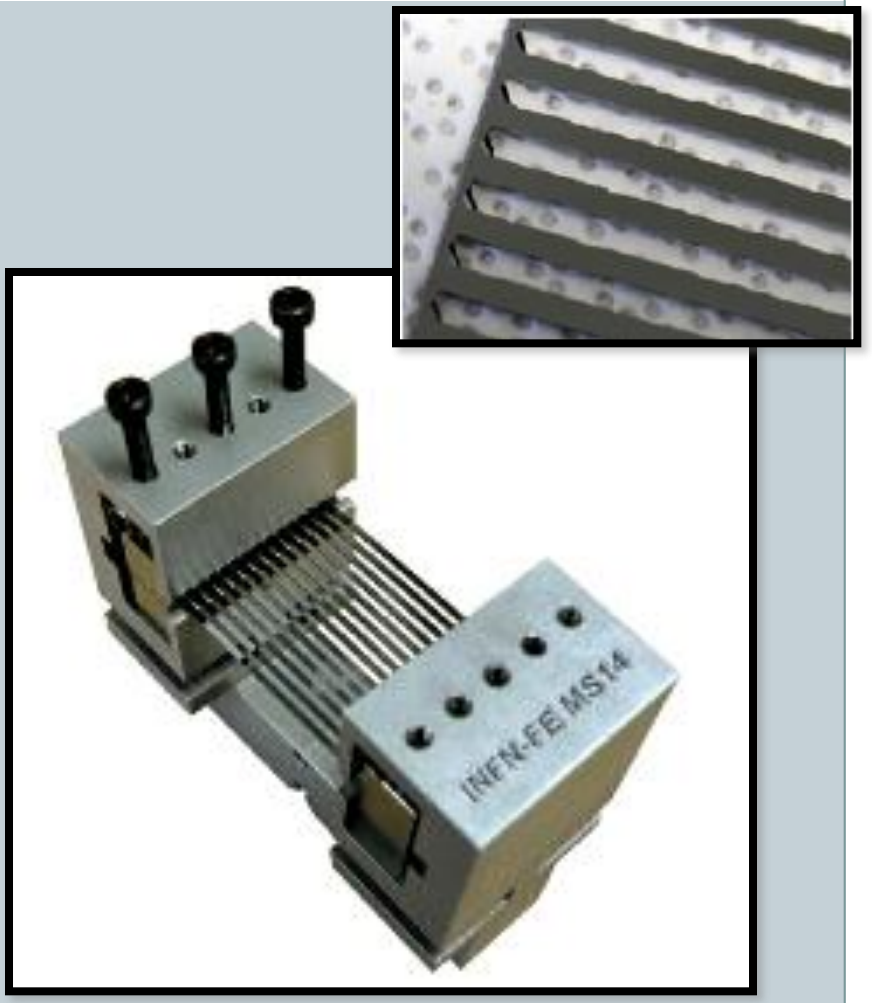
f) Removal of silicon nitride

[1] S. Baricordi et. al., J. Phys. D: Appl. Phys. 41 245501 (2008).

Multristrip (MST)

Primary crystal bending is achieved by **clamping the frame between stainless steel gauges [1]** of flatness less than 150 nm over as wide an area as 10x40mm^2

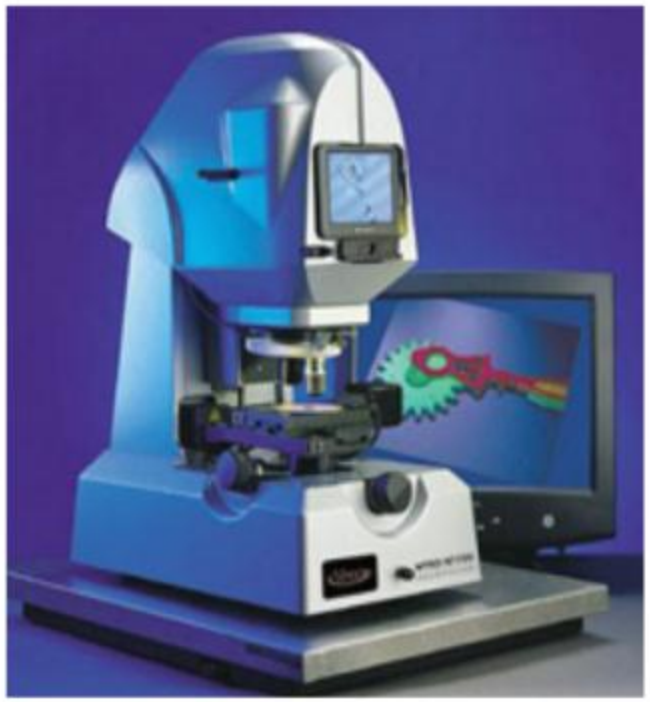
Secondary anticlastic deformation is used to steer the particles through MVR [2]



[1] R.S.I. 81, 066106 (2010)
[2] V. Guidi et. al., J. Appl. Phys. 107, 113534 (2010).

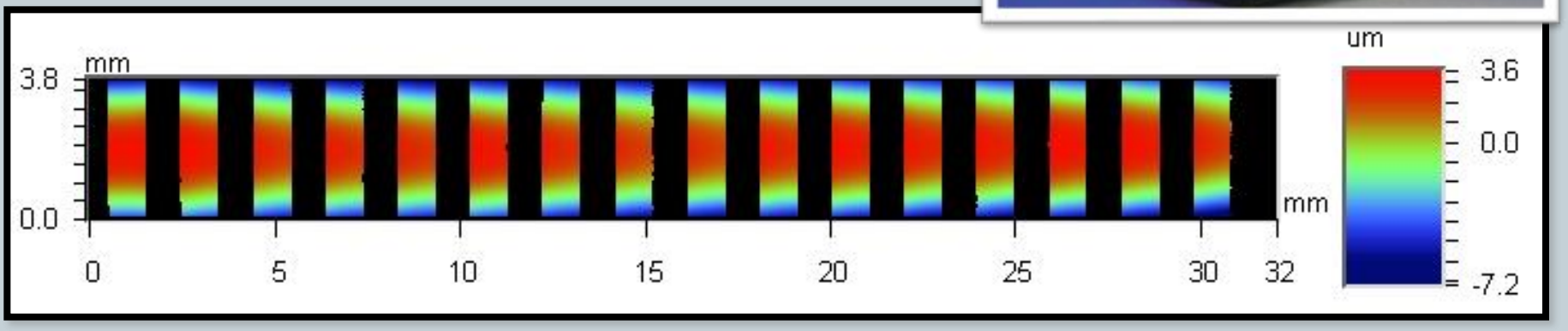
Interferometric Characterization

Veeco NT1100 Optical Profilometer
-horizontal resolution~1 μm
-vertical resolution ~2 nm

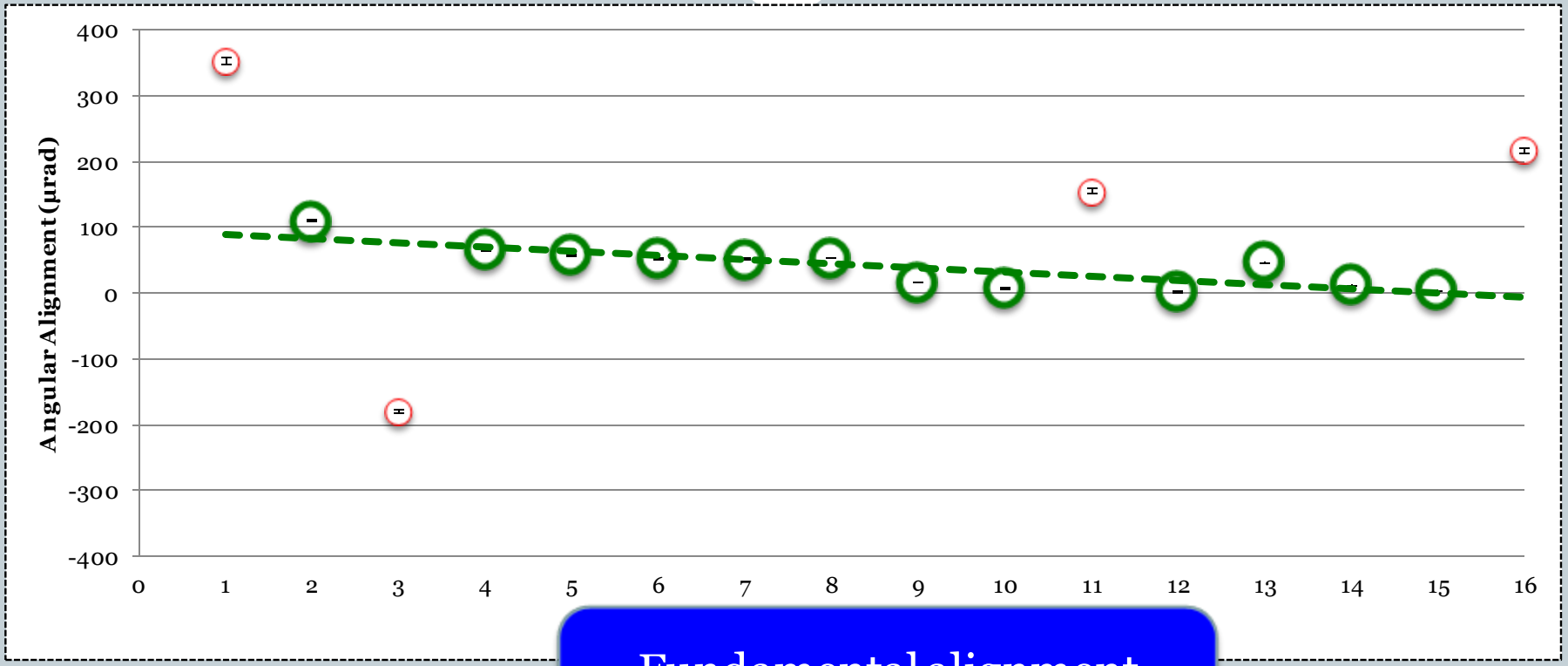


Important information were acquired from the analysis of the interferometric data:

- **reciprocal alignment** of the strips (to evaluate MVR behaviour)
- **height difference** of the strips (for collimation purpose)
- **strip length** (to calculate bending radius)



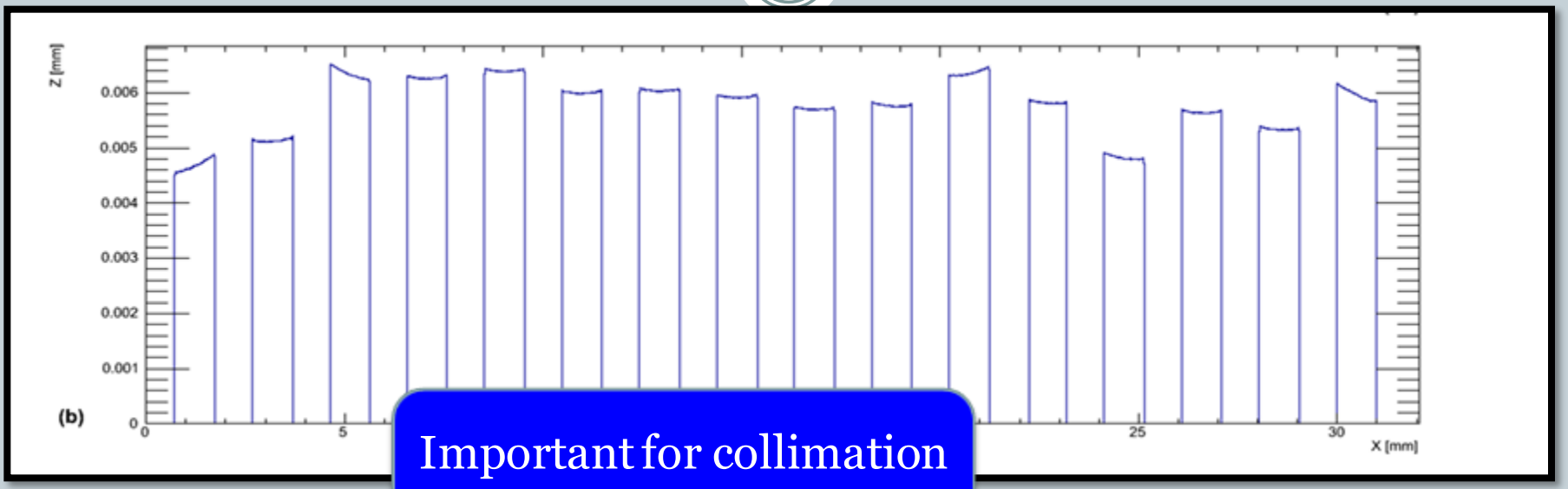
Strip Angular Alignment (μrad)



Fundamental alignment property for a MST crystal

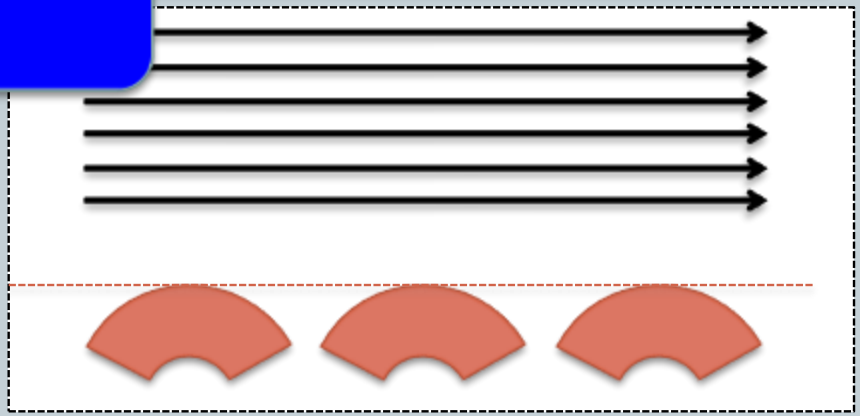
- Twelve strips contr
- Reciprocal alignme r distribution with a pendency of 6.4 ± 0.5 μrad.

Strip Z-Length (μrad)



Important for collimation experiments

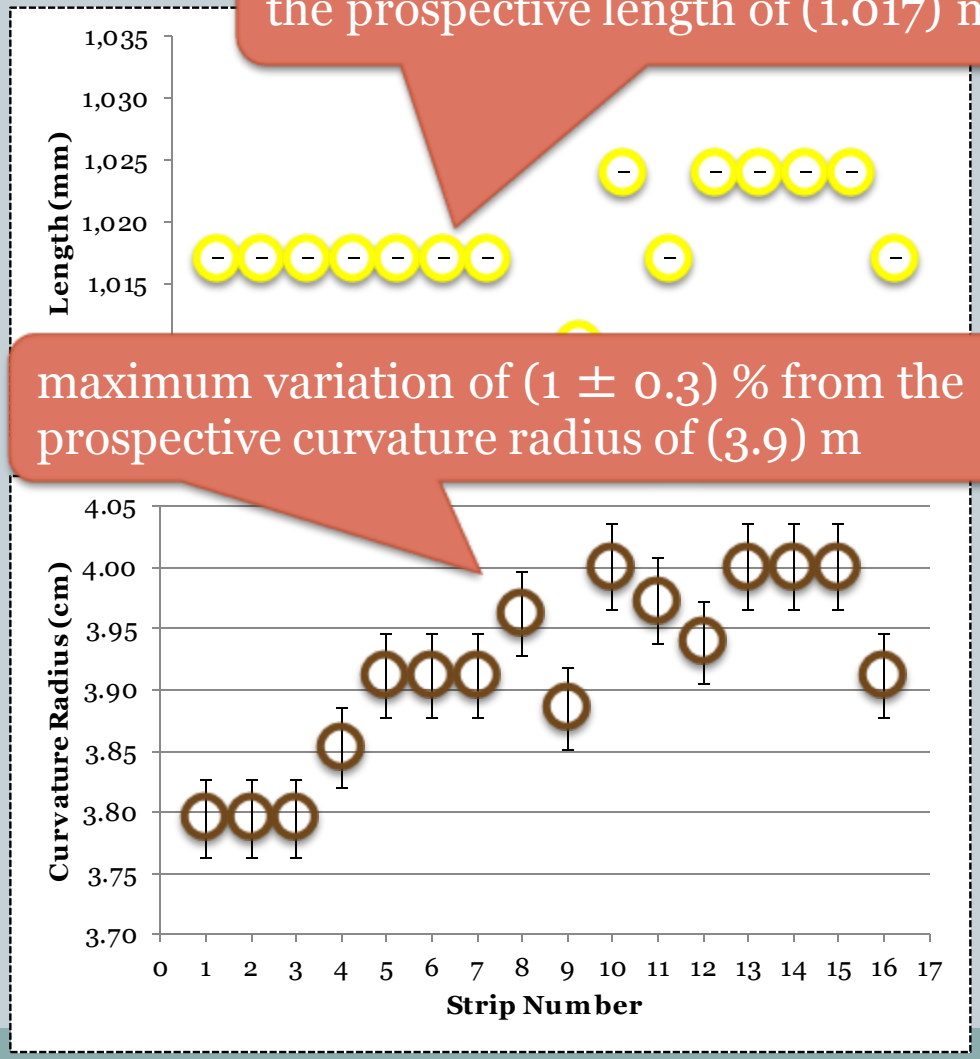
Distribution of the position of the strip faces fall inside a range of 5 μm.



Strip Length and Curv

acceptance angle of the strips is approximately the same

maximum variation of (1 ± 0.5) % from the prospective length of (1.017) mm

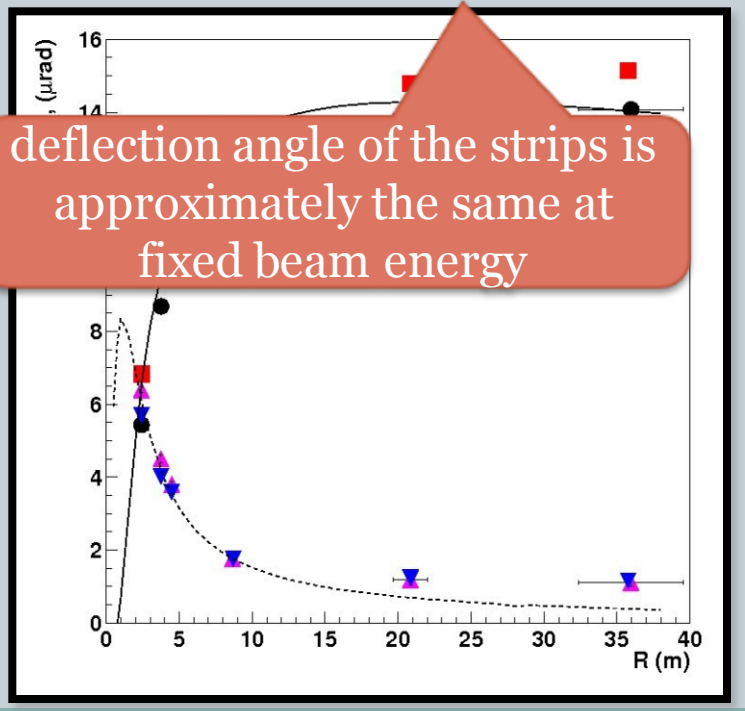


$$q_{acc} = L / R$$

$$q_{defl} = f(R, E)$$

maximum variation of (1 ± 0.3) % from the prospective curvature radius of (3.9) m

deflection angle of the strips is approximately the same at fixed beam energy



Emulation Software (EMUMVR)

Specific C++ Monte Carlo emulation software (EMUMVR) has been developed for MST crystals.
Crystal is treated as a **black box**. We suppose to know what happens inside it and we give a probability of success to every phenomenon as a function of beam energy, crystal radius and penetration depth.
Channeling, volume reflection, dechanneling and volume capture phenomena are considered in the simulation. Code core is based on theoretical equations and experimental data.

Critical Angle & Efficiency

$$\theta_c^b = \theta_c \left(1 - \frac{R_c^b}{R}\right)$$

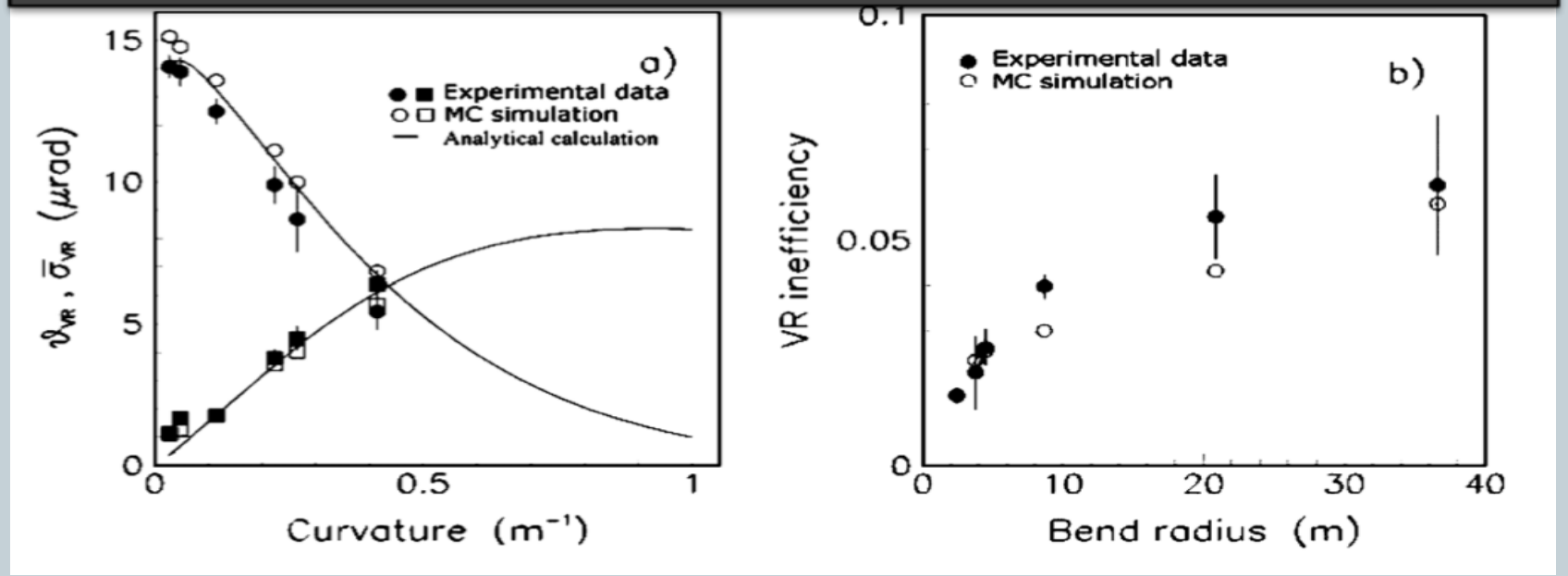
$$C_{eff}^{max}(R) = C_{eff}^{max}(\infty)\left(1 - \frac{R}{R_c}\right)$$

Energy Scaling

$$\theta_c = \sqrt{\frac{2U(x_c)}{pv}} \qquad R_c = \frac{pv}{U'(x_c)}$$

Emulation Software (EMUMVR)

Deflection Angle & Inefficiency [1]

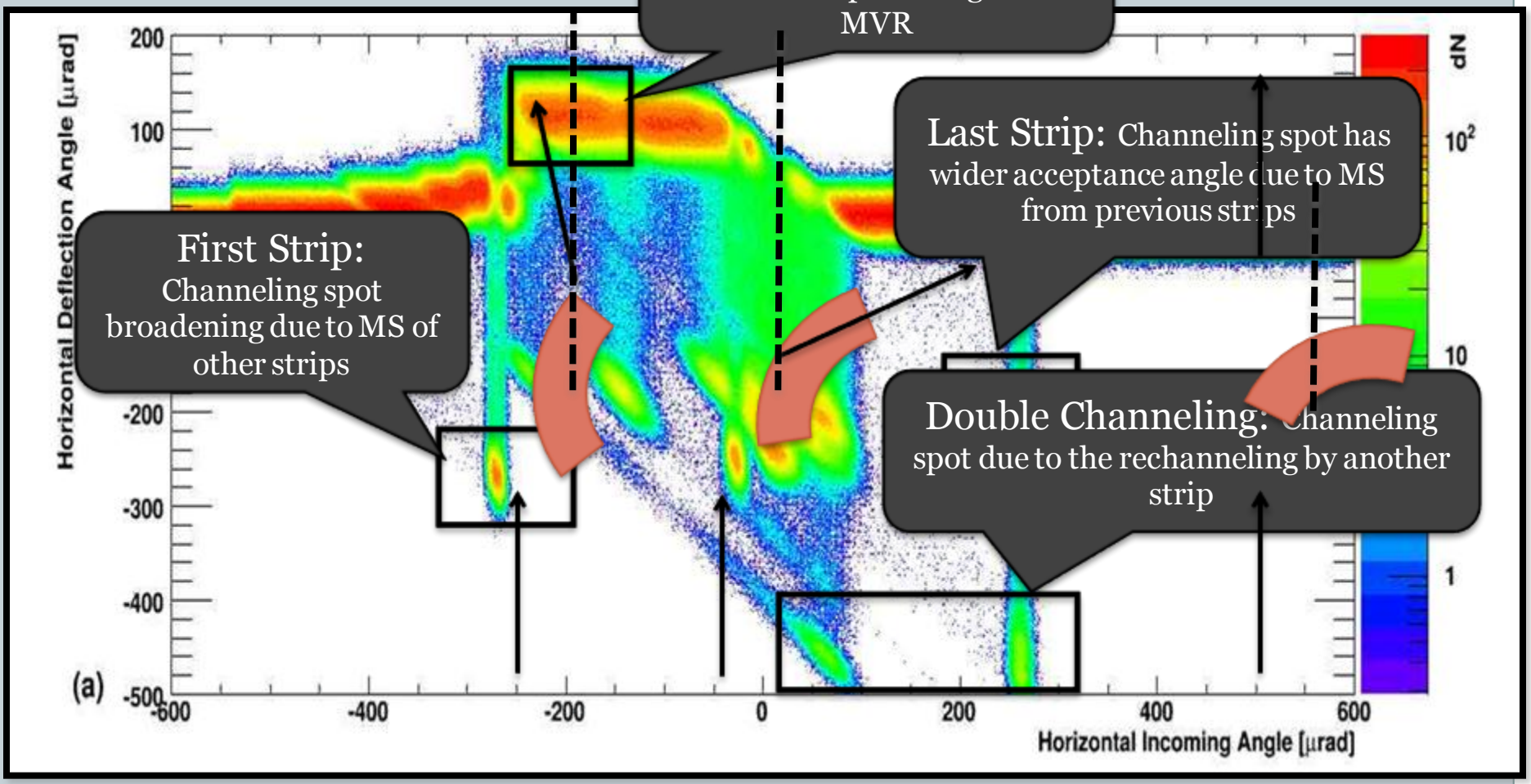


Energy Dependence [2]

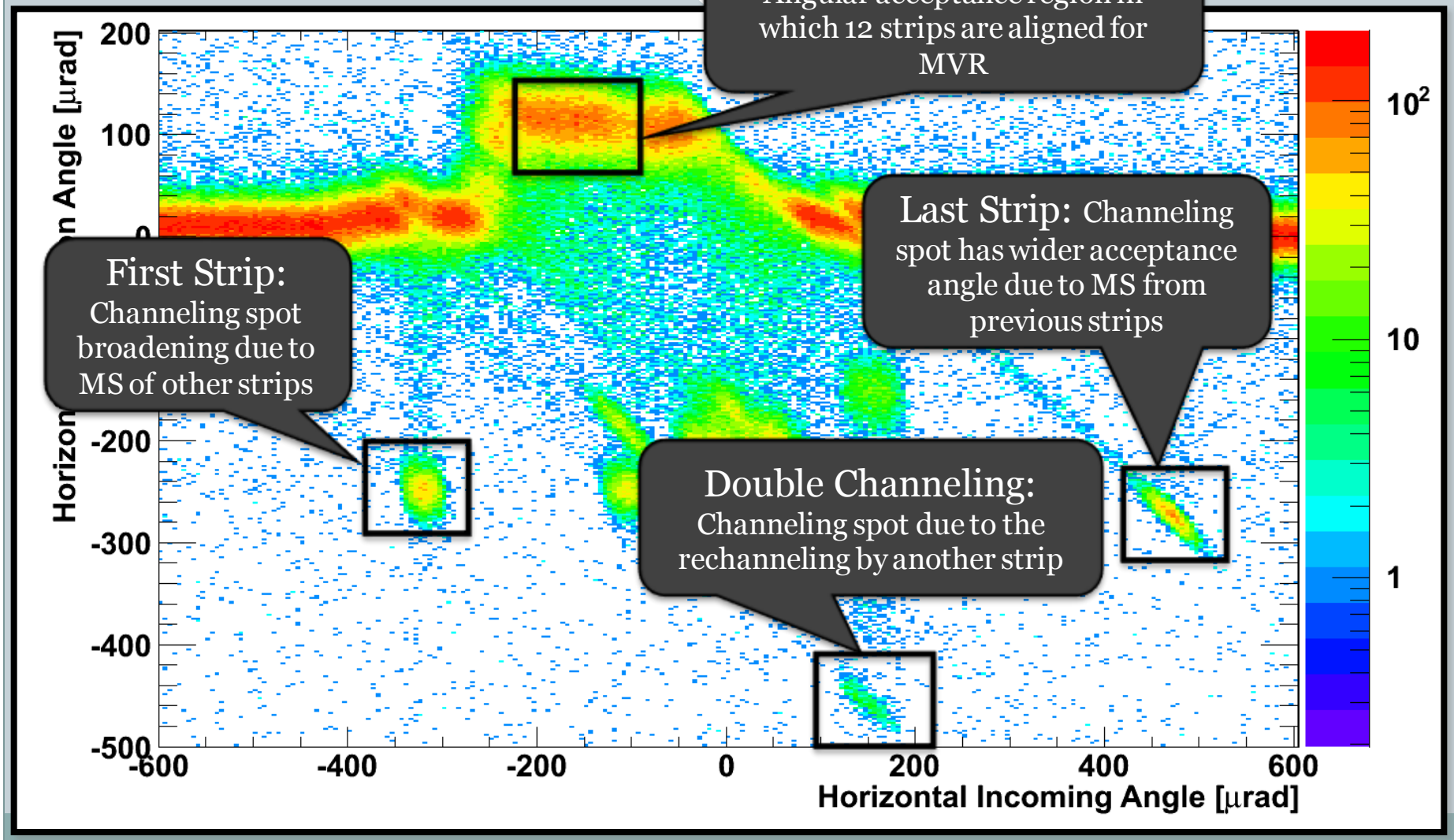
$$\alpha_{VR}(E) = \alpha_{VR}^{exp}(400) * \theta_c(E[\text{GeV}])/\theta_c(400)$$

[1] W. Scandale et. al, PRL 101, 234801 (2008).
[2] S. Hasan, NIM A 617, 449–452, (2010).

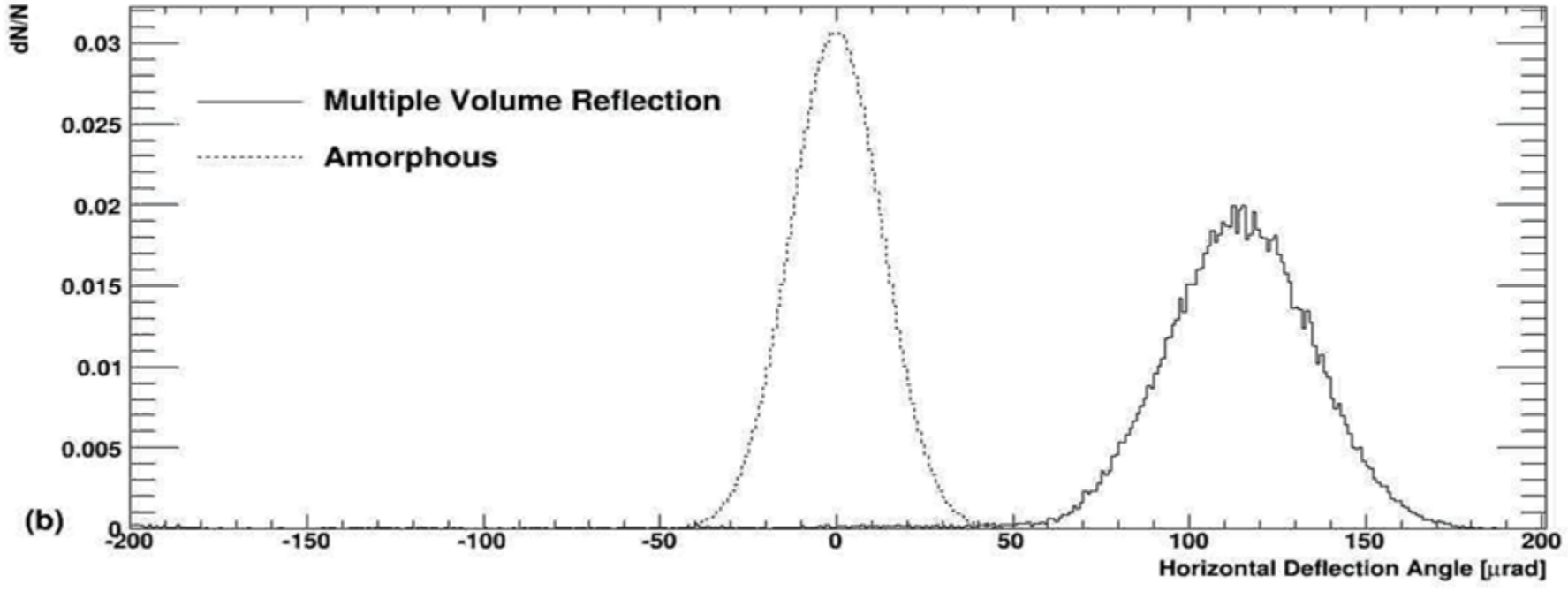
MST Angular Scan Emulation @ 400 GeV/c



MST Angular Scan Experiment @ H8 SPS

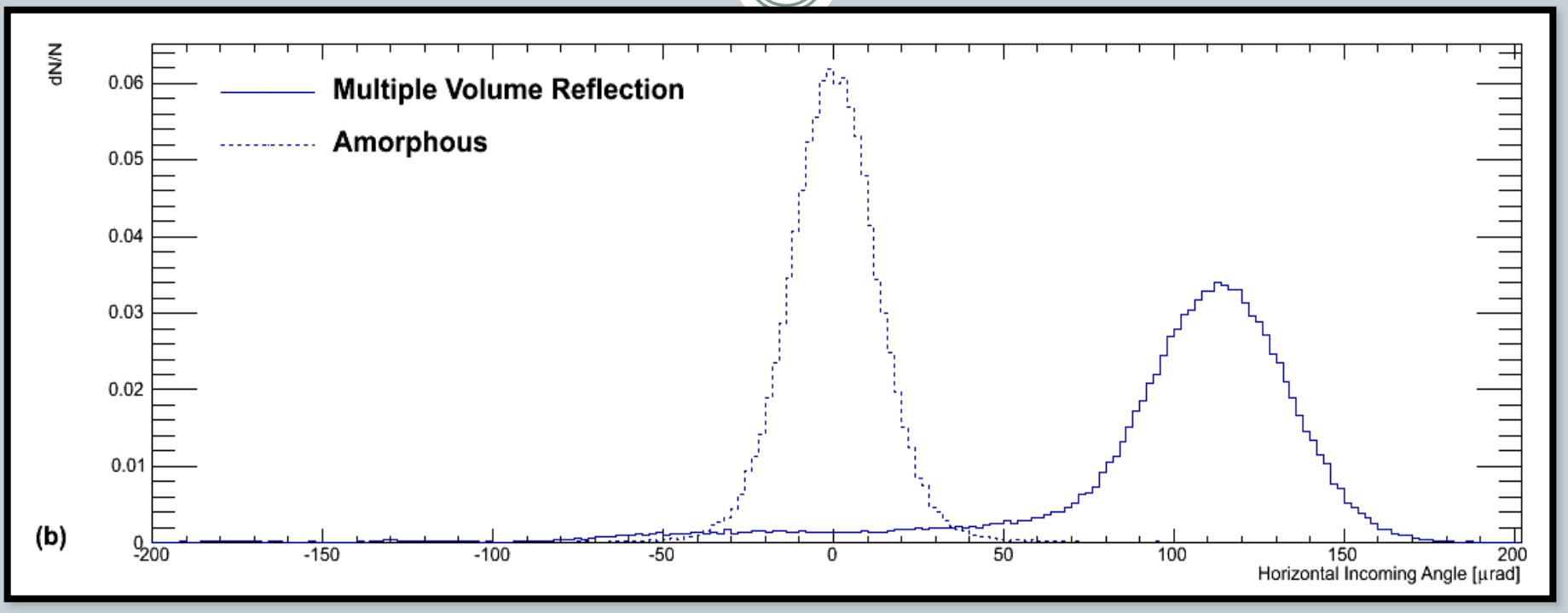


MVR Emulation @ 400 GeV/c



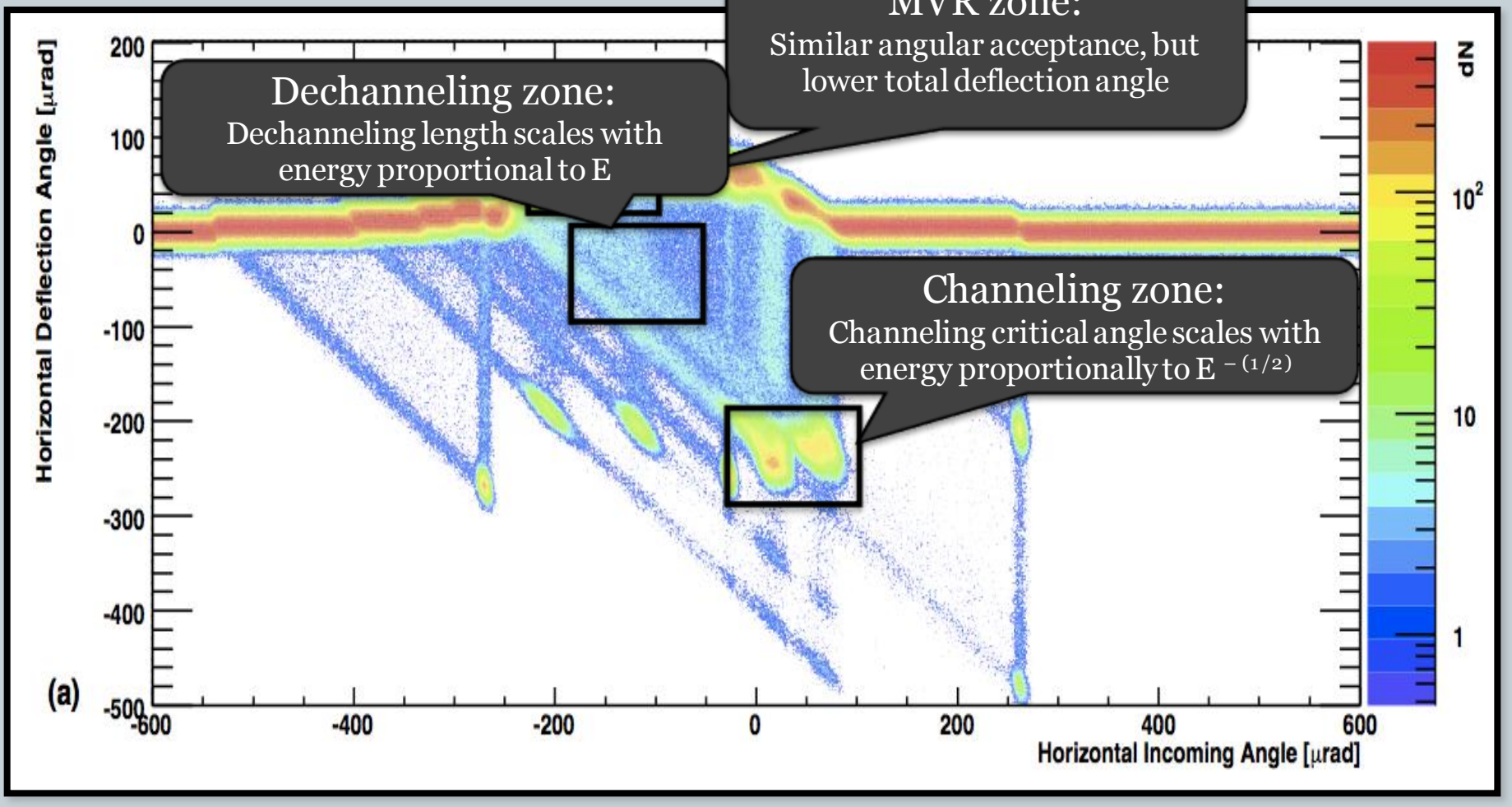
Quantity	Experiment	Emulation
Efficiency		(98.4 ± 0.1) %
Mean deflection angle		(114.1 ± 0.1) μrad
Standard deviation		(20.2 ± 0.1) μrad

MVR Experiment @ H8 SPS line

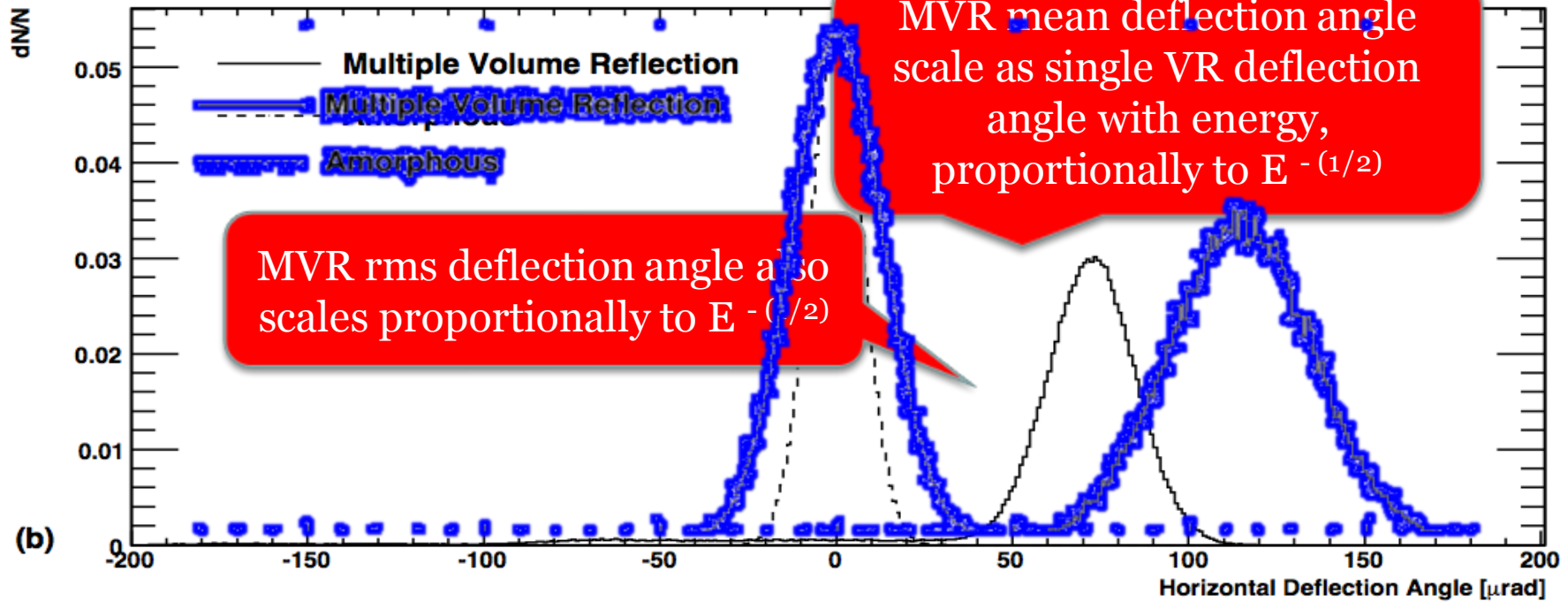


Quantity	Experiment	Emulation
Efficiency	(96.0 ± 0.5) %	(98.4 ± 0.1) %
Mean deflection angle	(112.2 ± 0.1) μrad	(114.1 ± 0.1) μrad
Standard deviation	(21.4 ± 0.1) μrad	(20.2 ± 0.1) μrad

MST Angular Scan Emulation @ 1 TeV/c



MVR Emulation @ 1 TeV/c



MVR mean deflection angle scale as single VR deflection angle with energy, proportionally to $E^{-(1/2)}$

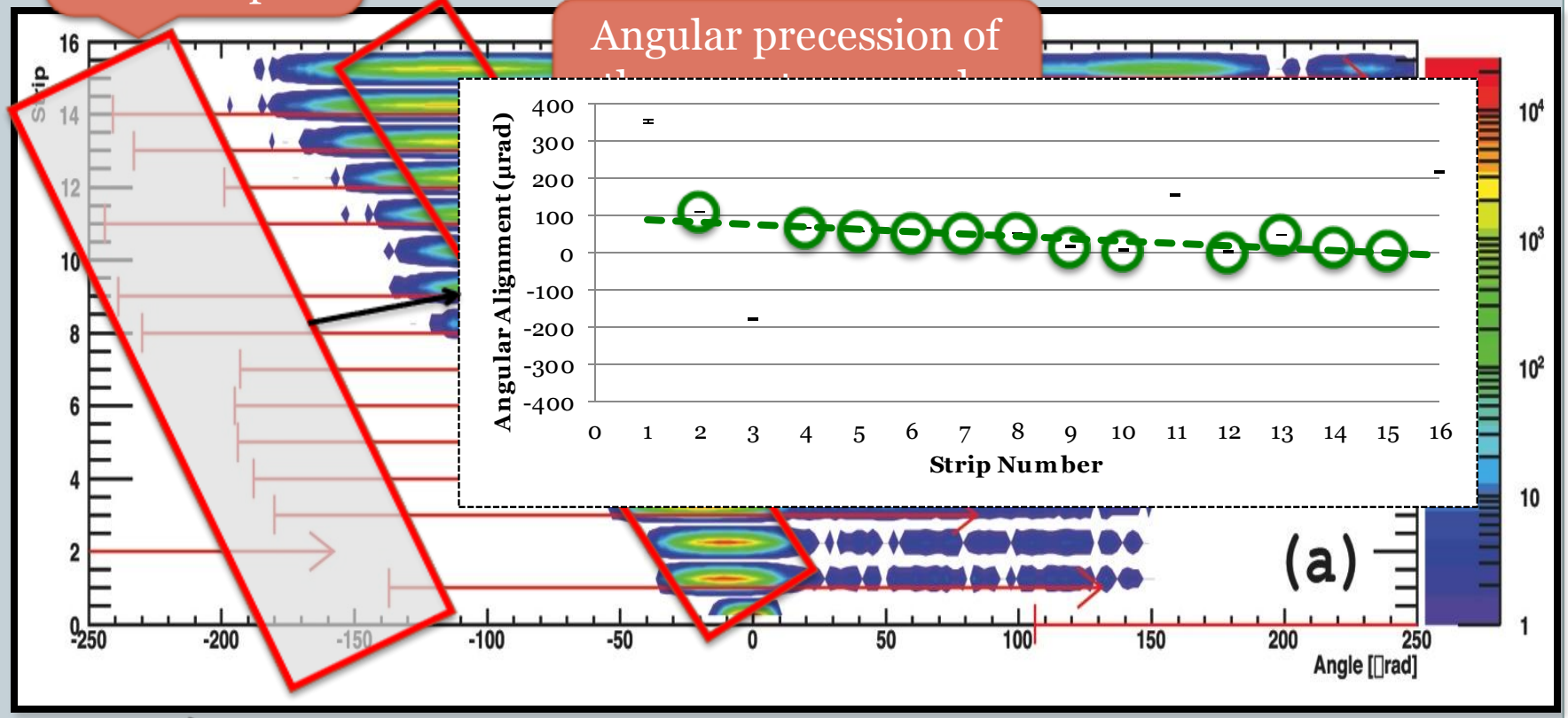
MVR rms deflection angle also scales proportionally to $E^{-(1/2)}$

Quantity	Emulation@400GeV/c	Emulation@1TeV/c
Efficiency	(98.4 ± 0.1) %	(94.8 ± 0.5) %
Mean deflection angle	(114.1 ± 0.1) μrad	(72.3 ± 0.1) μrad
Standard deviation	(20.2 ± 0.1) μrad	(12.5 ± 0.1) μrad

Motion inside MST @ 400 GeV/c

Angular alignment of the strips

Angular precession of



$q_{vr} = 8.9\,\mu rad$

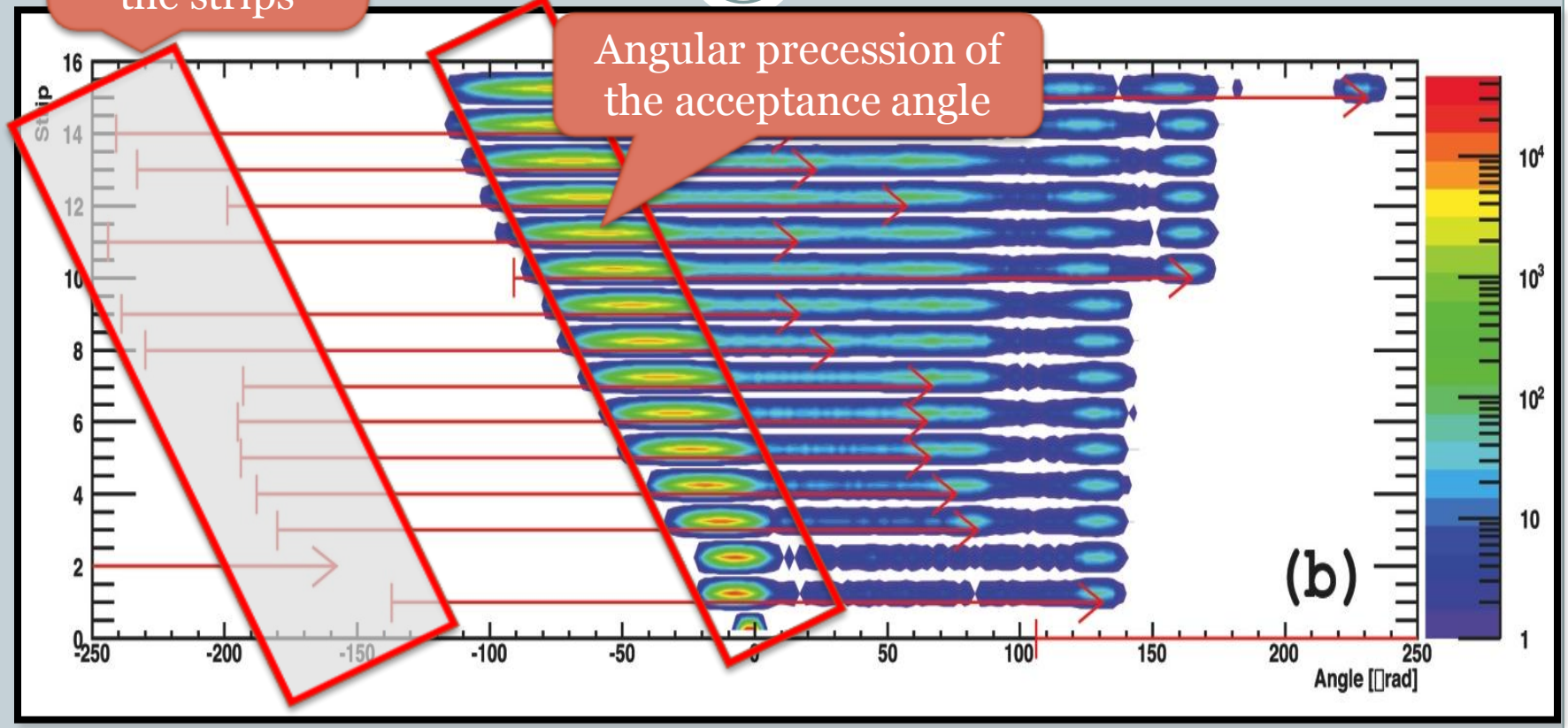
$q_{strip} = 6.4\,\mu rad$

single strip VR angular acceptance

Motion inside MST @ 1 TeV/c

Angular alignment of the strips

Angular precession of the acceptance angle



$q_{vr} = 5.6\,\mu rad$

$q_{strip} = 6.4\,\mu rad$

single strip VR angular acceptance

Volume Reflection of Negative Charged Particles

VR was experimentally observed with 150 GeV/c π^- [1]. It occurs with smaller deflection angle than for positive particles.

A negative particle has a small transverse velocity between the crystal planes where the electric field of the planes has a wide minimum. Therefore, the trajectory parts with small transverse velocities are longer for negative particles. So, the deflection to the crystal bend side acquired outside the turning area, which reduces the VR deflection angle, is larger for negative particles.

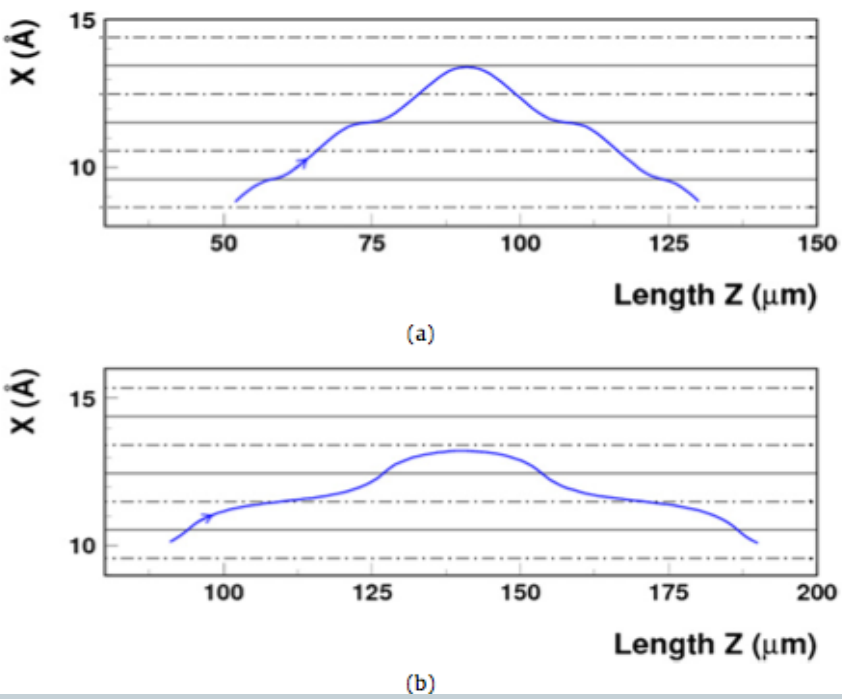
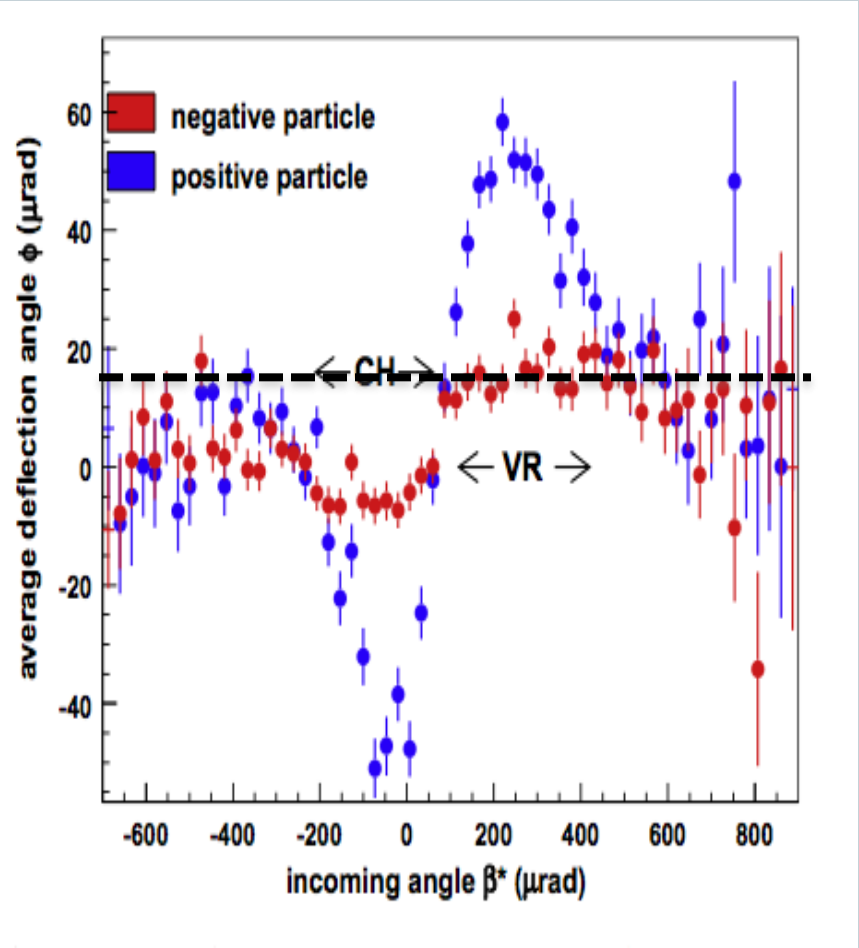


Table 1
Channeling and VR parameters for 150 GeV/c π^- in (111) and (110) Si.

Crystal	θ_c (μrad)	R (m)	θ_{vr} (μrad)	P_{vr} (%)	P_d (%)
(111) Si, QM2 experiment		12.92 ± 0.09	14.64 ± 0.12	82.74 ± 0.28	30.24 ± 0.38
Simulation	18.34		16.6 ± 0.07	78 ± 0.13	30.11 ± 0.15
Theory			14.28		
(110) Si, ST10 experiment		22.79 ± 0.22	11.53 ± 0.23	76.75 ± 0.32	28.81 ± 0.47
Simulation	17.39		12.84 ± 0.11	74.77 ± 0.14	28.67 ± 0.14
Theory			11.81		

[1] W. Scandale et. al, Physics Letters B 681 (2009) 233–236.

Volume Reflection experiment @ 13 GeV/c



Channeling and Volume reflection effects have been recently observed on PS-CERN with 13 GeV/c π+ and π- beam [1].

Use of MST crystal can provide multiplication of the single VR deflection angle.

[1] S. Hasan et. al, NIM B 269 (2011) 612–621.

Conclusion

- Interferometric measurements could provide useful off-beam information on MST samples.
- Test beam @ 400 GeV/c proton beam showed capability to deflect a proton beam of 112 μrad with an efficiency up to 96%;
- EMUMVR code made using interferometric has been validated with experimental data and have showed a prediction accuracy of deflection angle and efficiency higher then 95%;
- Emulation @ 1TeV/c proton beam highlights the possibility to use MST in the Tevatron for collimation experiments with an efficiency up to 96 %.
- Experiment @ 13 GeV/c shows the possibility to use MST as a deflector of negative particle beam. Further investigation are needed to develop analytic description of volume reflection process with other particles.

Thank you for the attention!