A Crystal Routine for Collimation Studies in Circular Proton Accelerators

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Acknowledgments:

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Introduction

Motivations

Experience in other machines shows that understanding of crystal collimation requires, in addition to a good modelling of crystals, full simulation of the accelerator (multi-turn tracking, collimators, aperture, ...)

Main tool used:

- ✓ Collimation version of `SixTrack` coupled with aperture model of the machine

→ *prediction of expected beam loss pattern*

Main requirements for such simulations:

- ➢ Accurate and very fast routines due to the high-statistics needed

→ *10-20M particles tracked for 200/2000 turns, depending on crystal orientation*

- ➢ Good description of nuclear events "dangerous" for the cleaning performance of collimation systems

→ *Basic limitation at the LHC: particles that lose energy at the primary stage and lost in the dispersion suppressor*

Crystal routine

Crystal routine originally written by I. Yazinin, and implemented in `SixTrack` *by V. Previtali*

Pure ***Monte Carlo emulator*** *of various interactions*

no solving of eq. of motion

fast high-statistics simulations

"All" **physics process** known in bent crystals
well described in literature

Free parameters were tuned on experimental data
taken on the CERN-SPS extraction line H8
in the framework of the H8RD22 Collaboration

Mainly composed of two blocks:

- Treatment of **coherent process** in bent crystals
- **Scattering routine** for nuclear point-like interactions

The scattering routine is called:

- Each time a proton is out of any coherent process
- When protons are trapped in between planes, but with cross sections rescaled on the average nuclear density seen

Solid routine used to design the present LHC Collimation system, constantly benchmarked and upgraded, described in: C. Tambasco, CERN-THESIS-2014-014

An overview on the physics and benchmarking of the coherent part is given in the next

Treatment of coherent process

Input: *crystal **length** and **bending** radius, **x, x'** and **energy** of the impinging proton*

Are then estimated as first: θ_c^s, θ_c^b, R_c based on theoretical approach given in [1]

Together with: P_{VC}, θ_{VR}, σ_{VR} based on theoretical approach given in [2, 3, 4]

Probability to get trapped in between crystalline planes given by: $P_{CH} = \frac{\sqrt{\theta_c^{b2} - \theta_{in}^2}}{\theta_c^s}$

- Obtained through parametric study with respect to what achieved with analytical codes

Dechanneling process treated as exponential decay of trapped particles:

- Characteristic **electronic dechanneling** length given by theory in [1]
- 10% of captured particles is assumed undergoing **nuclear dechanneling (a_{TF}/d_p~0.1)**. Characteristic length is extrapolated by fine tuning w.r.t. [5]

Coherent process implemented: CH, DC, VC, VR, DC after VC

Crystal imperfections that can be taken into account: ***miscut angle, amorphous layer***

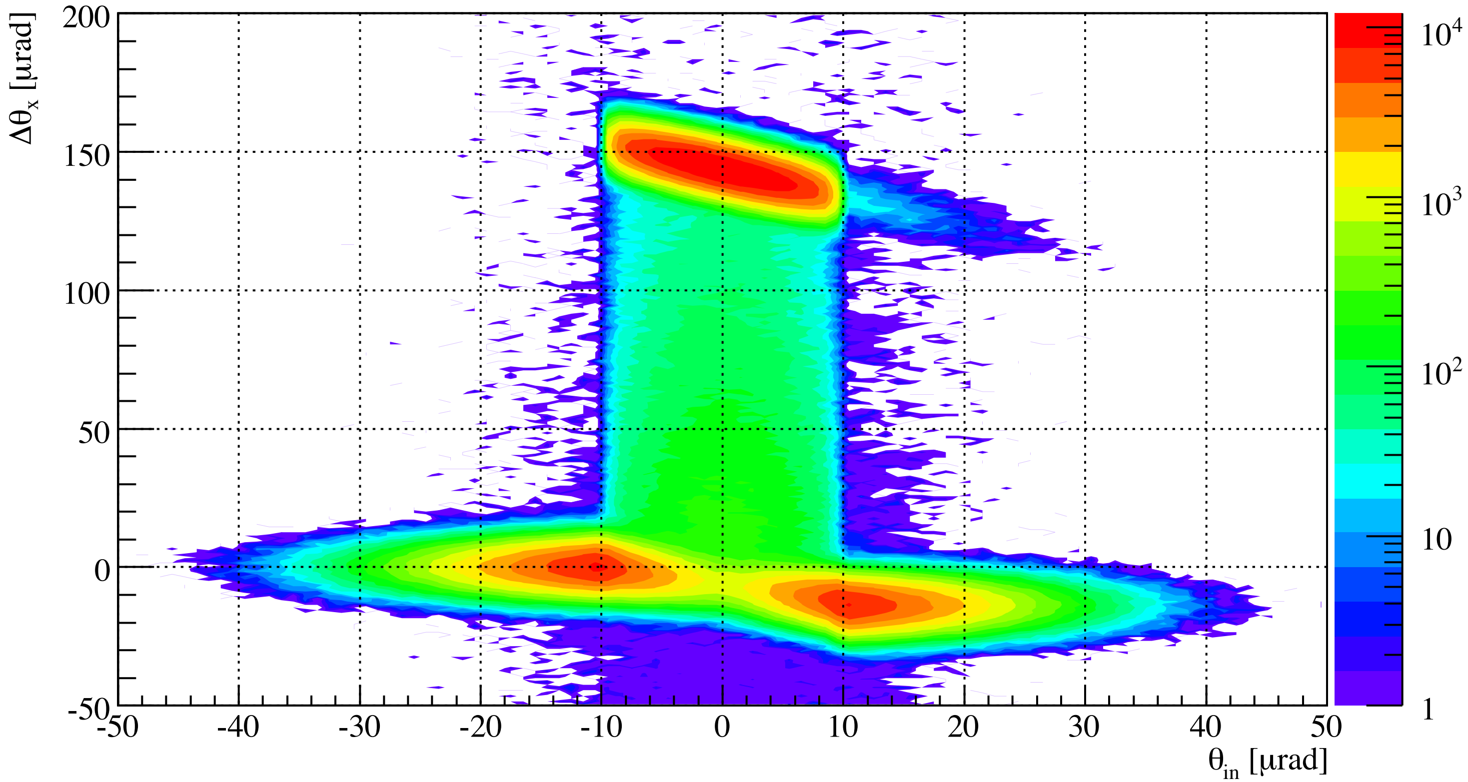
[1] V.M. Biryukov, Y.A. Chesnokov, V.I. Kotov., ``Crystal channeling and its application at high energy accelerators", Springer, 1996.
[2] W. Scandale et. al., PRL 101, 234801 (2008)
[3] A. M. Taratin and W. Scandale, NIM B 262 (2007) 340-347
[4] Yu. A. Chesnokov, V. A. Maisheev and I. A. Yazyninn, arXiv:0808.1486v1
[5] W. Scandale et. al., PLB 680 (2009) 129-132

Outline

Benchmarking with experimental data at 400 GeV

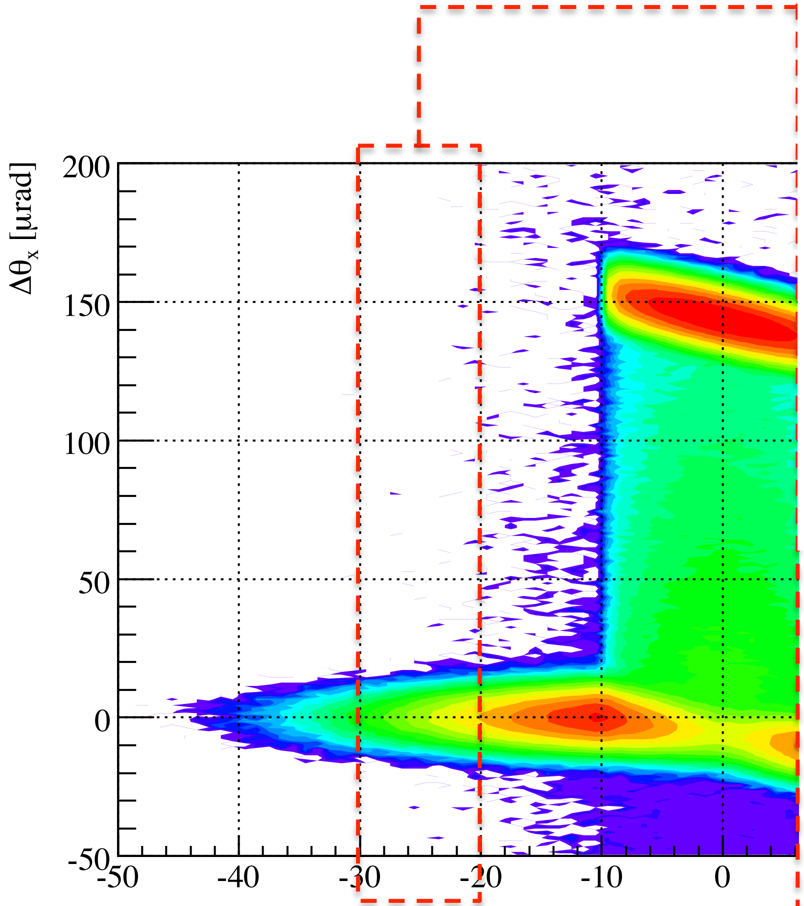
Deflections

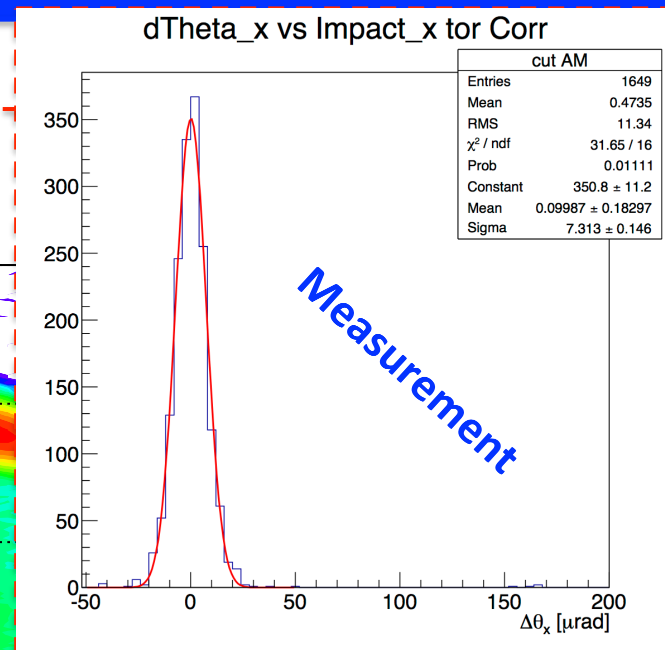
Simulated deflection as function of the incoming angle at 400 GeV,
for silicon crystal 2mm long and ~144μrad bent, using gaussian beam with σ_x=1mm, $\sigma_{x'}$=10μrad

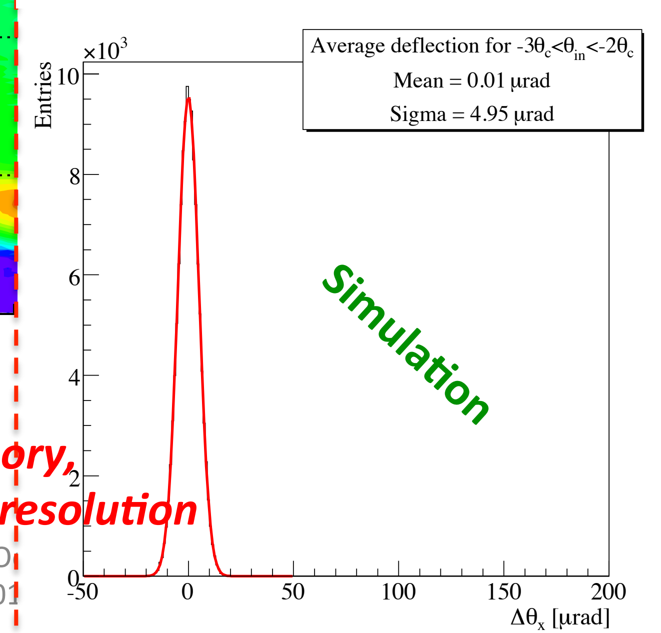


Analysis performed with same tools for simulated and experimental data, used and developed in collaboration with R. Rossi.

Deflections

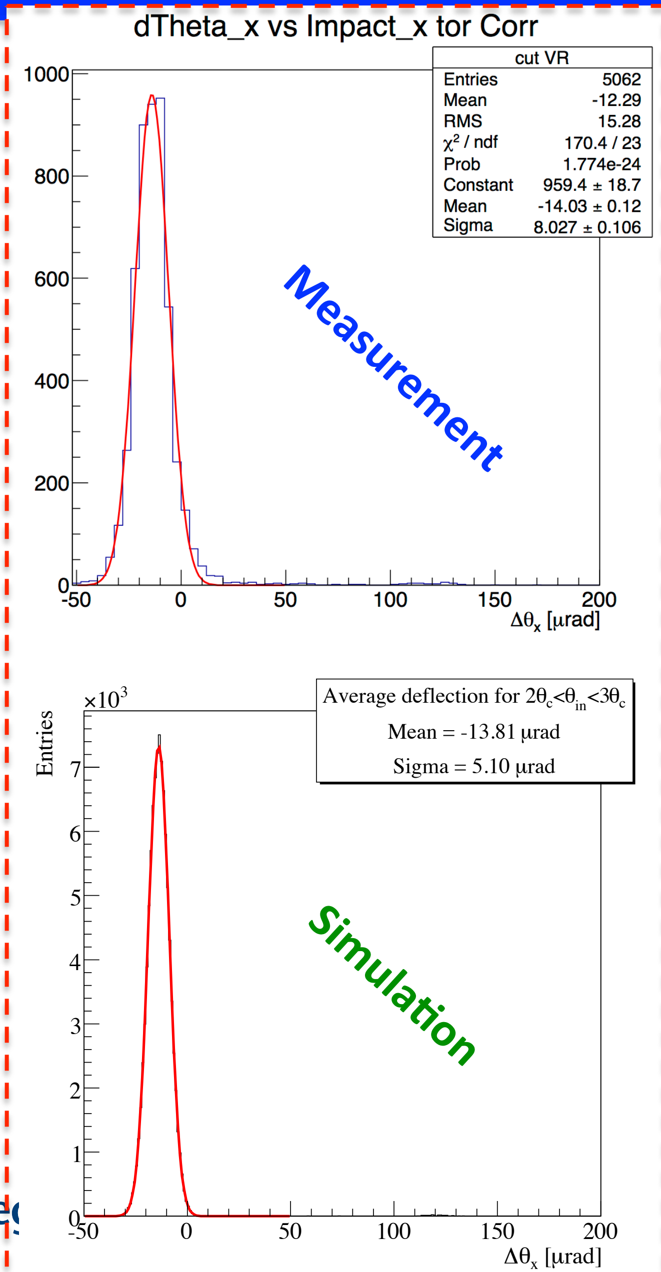


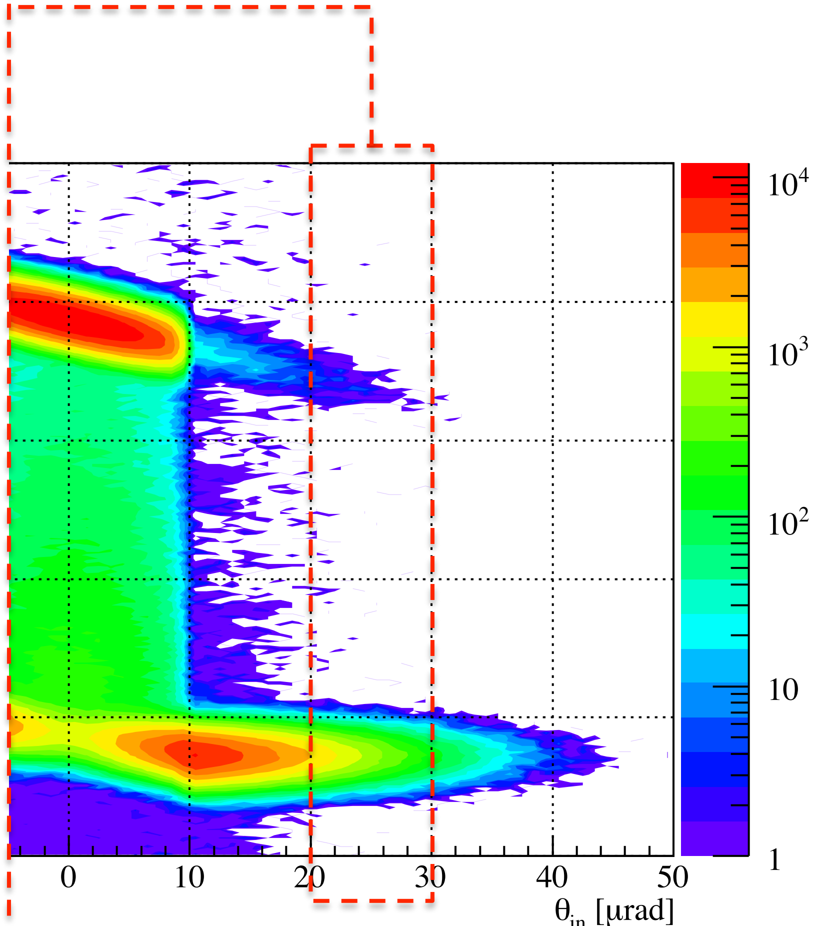




Simulated sigma in agreement with Molière theory,
Measured scattering may be influenced by exp. resolution

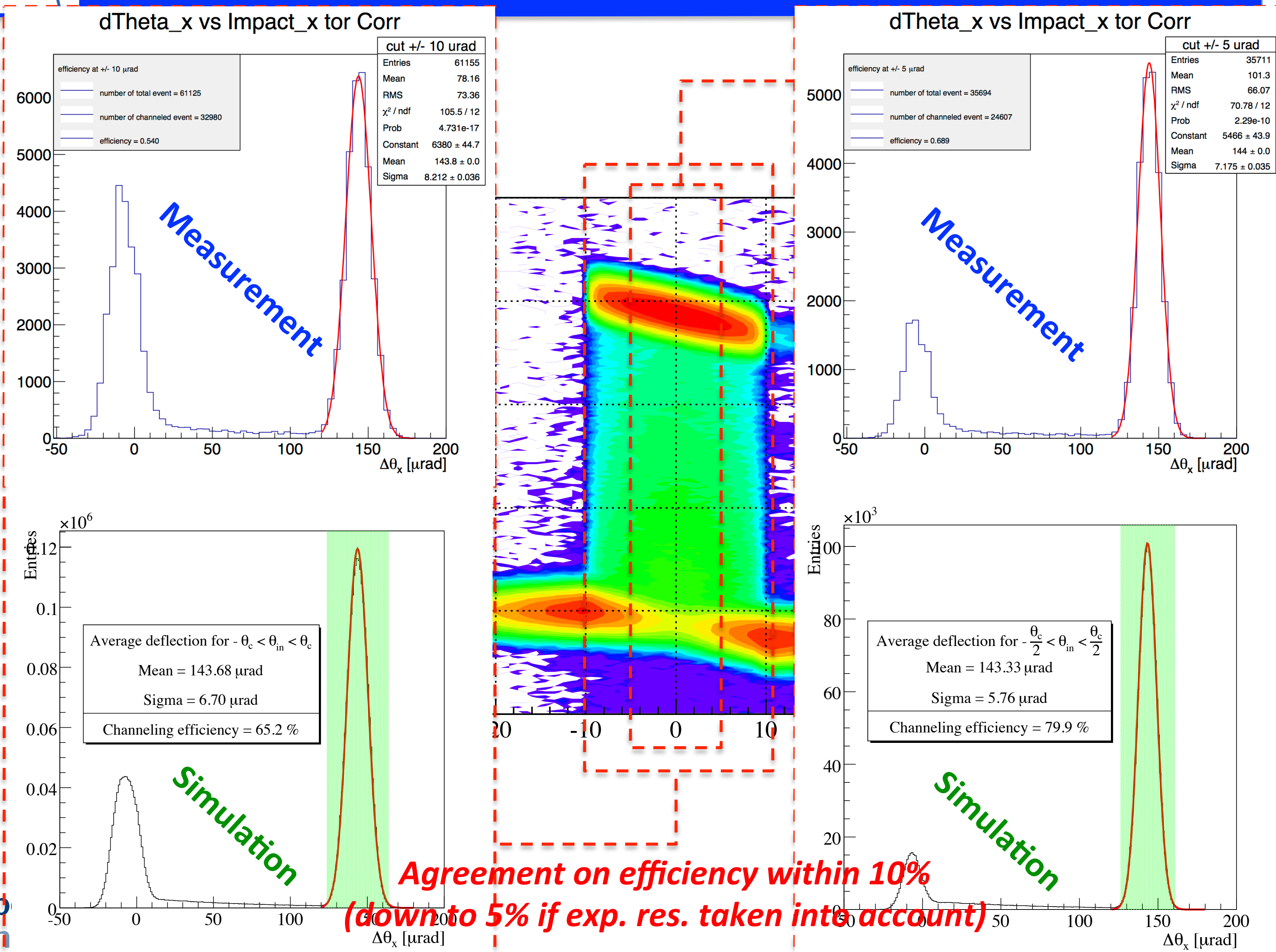
Deflections





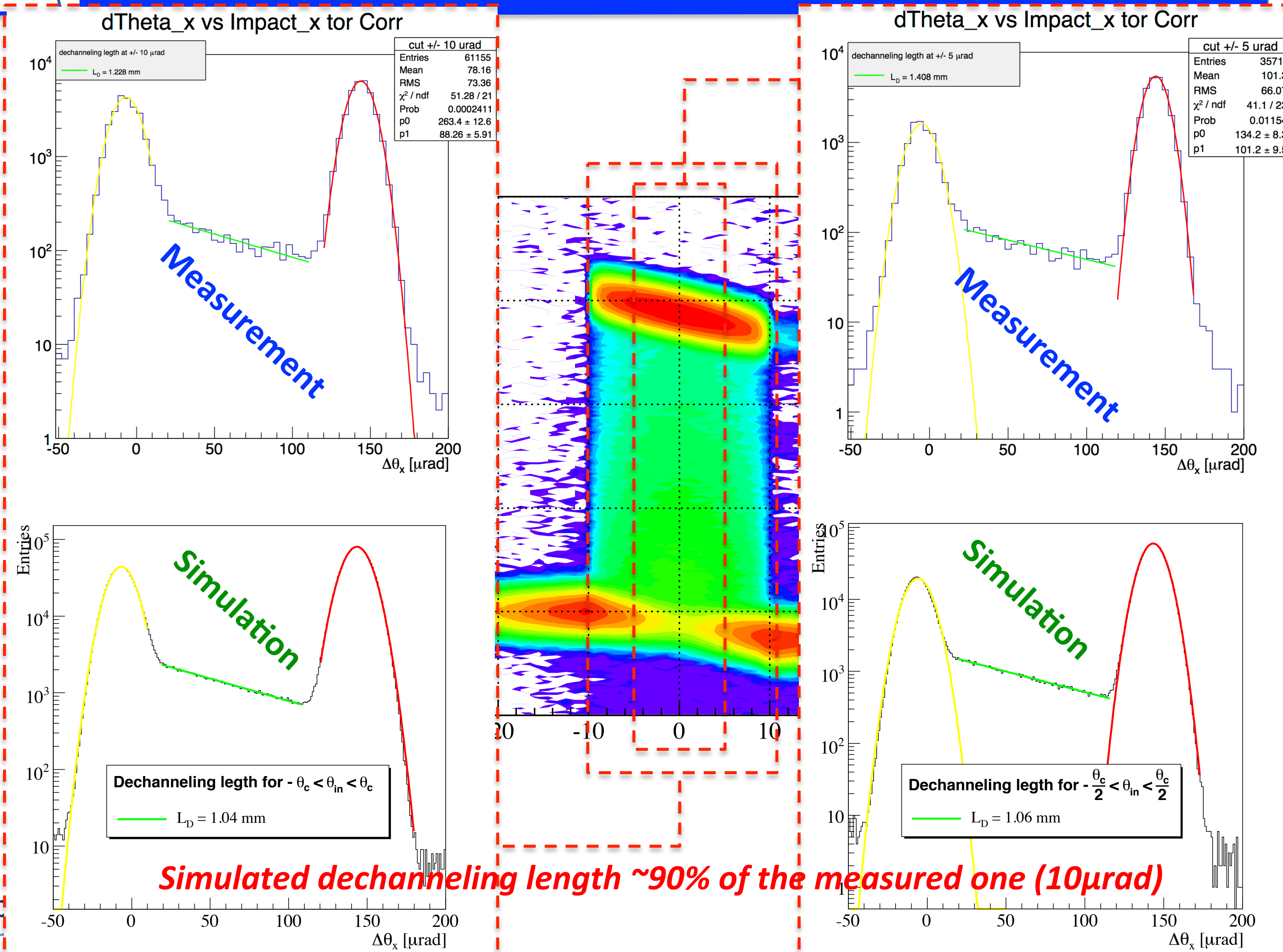
Good agreement on the mean,
Sigma may be influenced by exp. resolution

Deflections



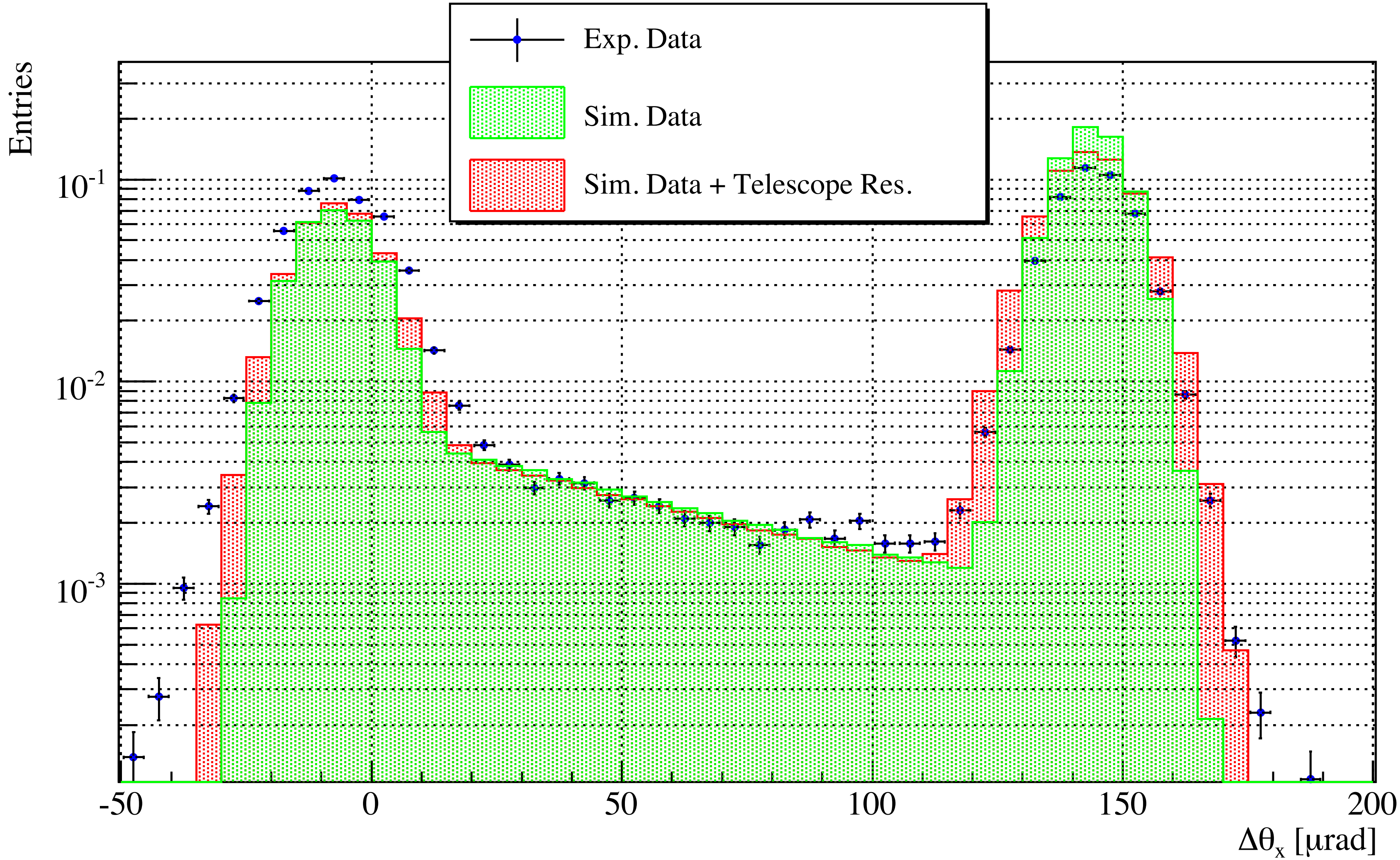
Agreement on efficiency within 10%
(down to 5% if exp. res. taken into account)

Deflections



Simulated dechanneling length ~90% of the measured one (10μrad)

Global comparison

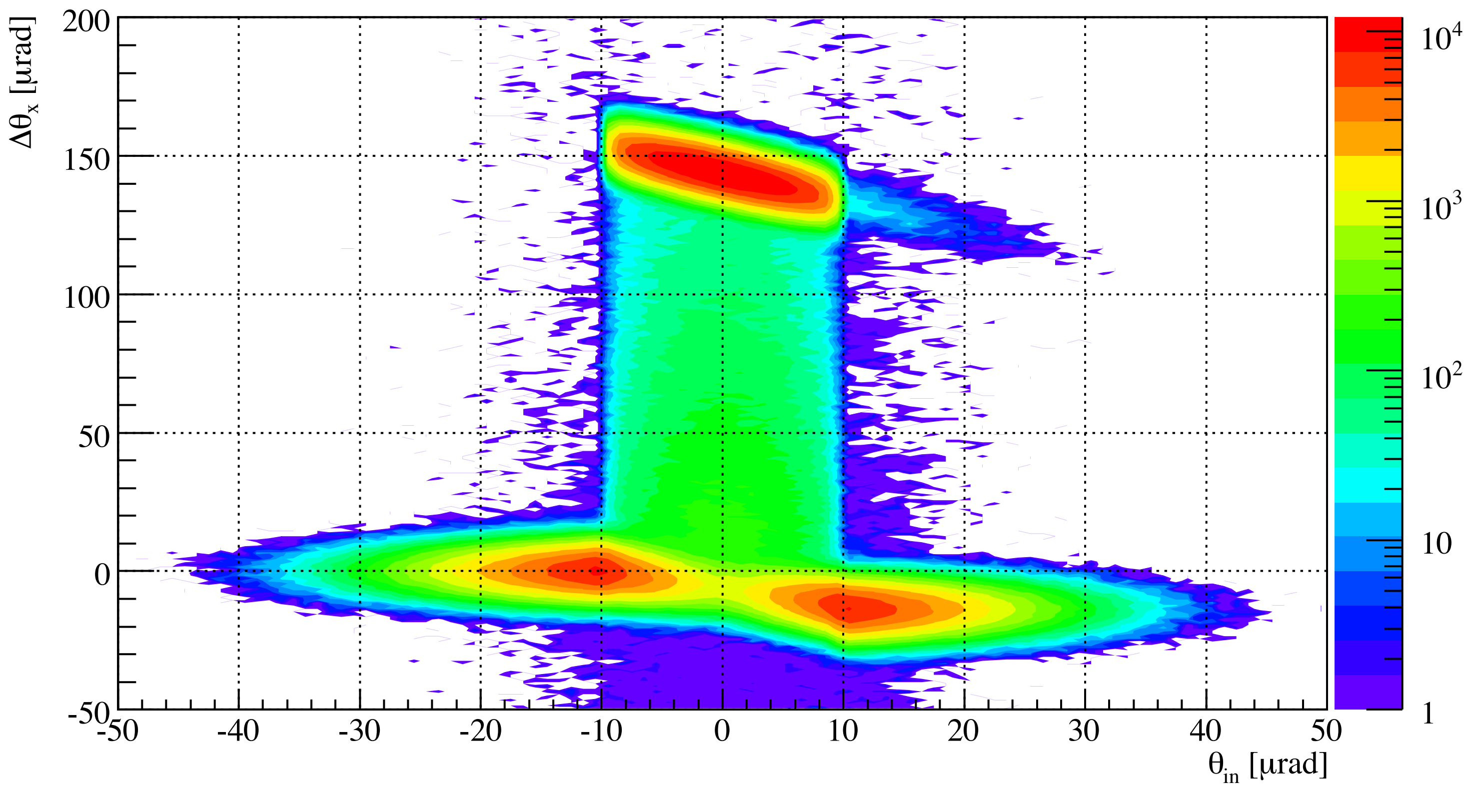


Angular cut ±10μrad, similar results with ±5μrad but more prominent effects of resolution

<u>Very good overall agreement between experimental and simulated data!</u>

Transitions

Simulated deflection as function of the incoming angle at 400 GeV,
for silicon crystal 2mm long and ~144μrad bent, using gaussian beam with σ_x=1mm, $\sigma_{x'}$=10μrad



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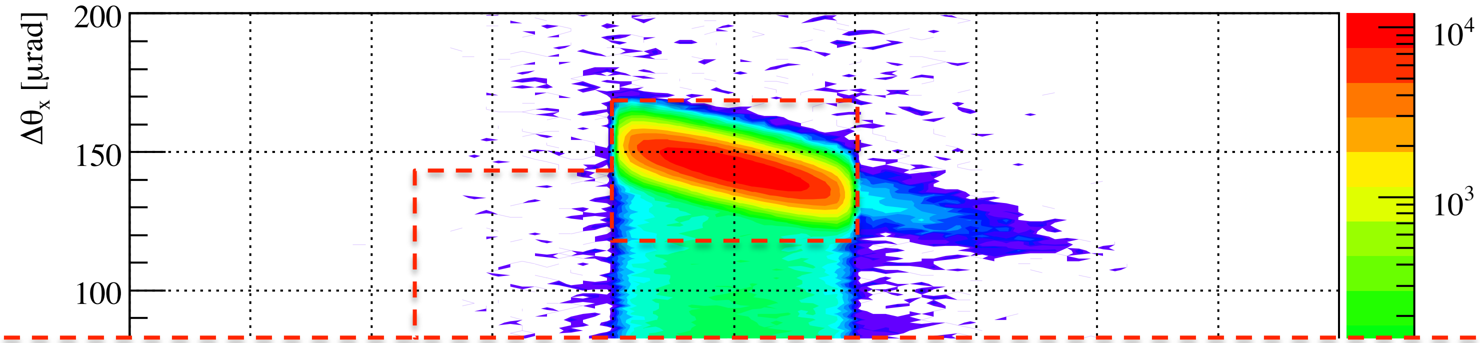

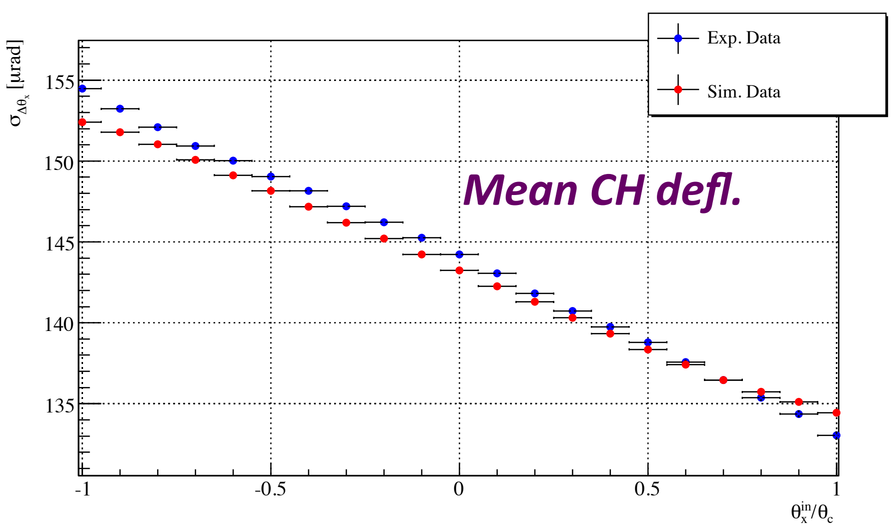

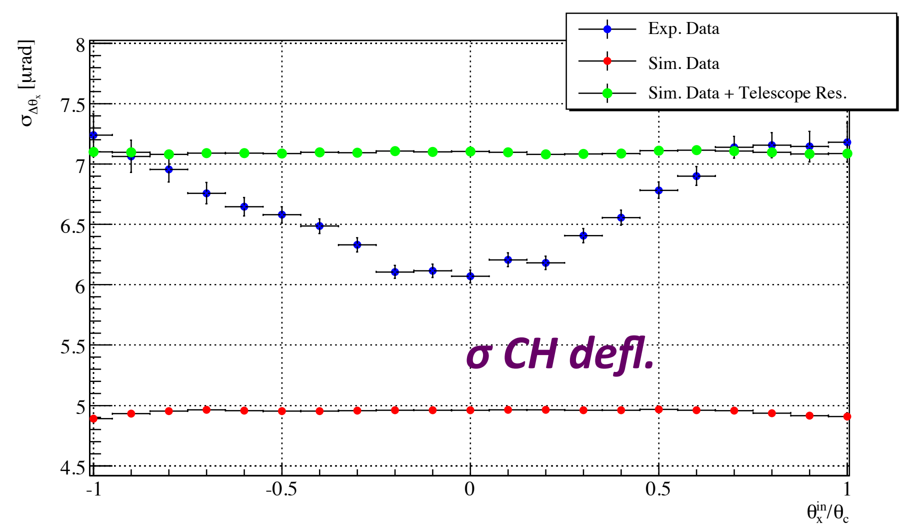

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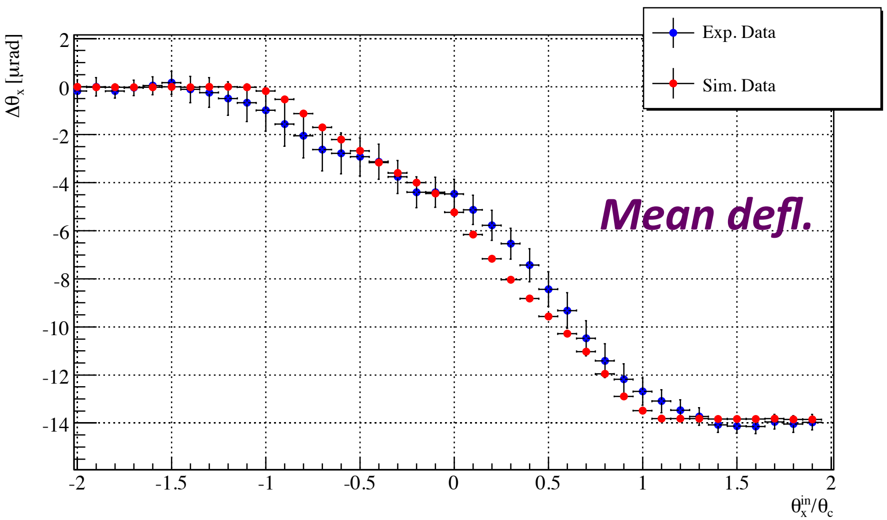
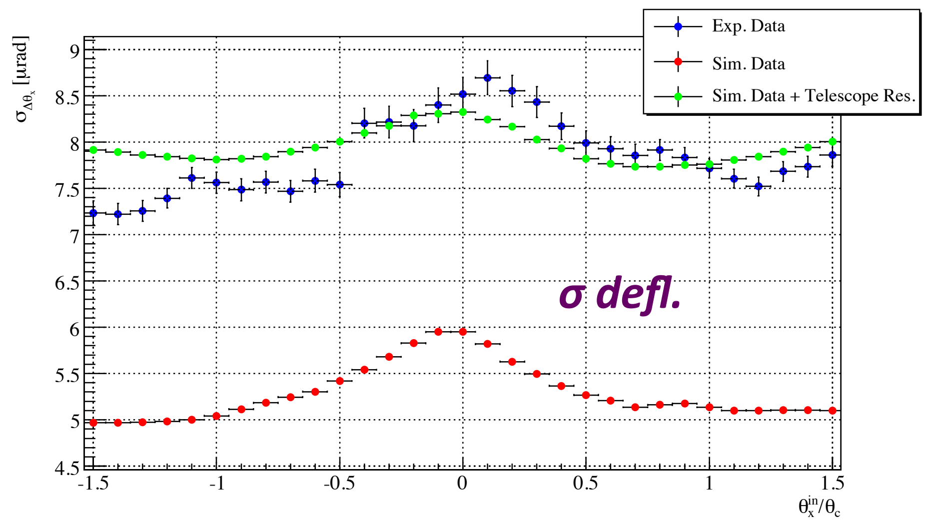
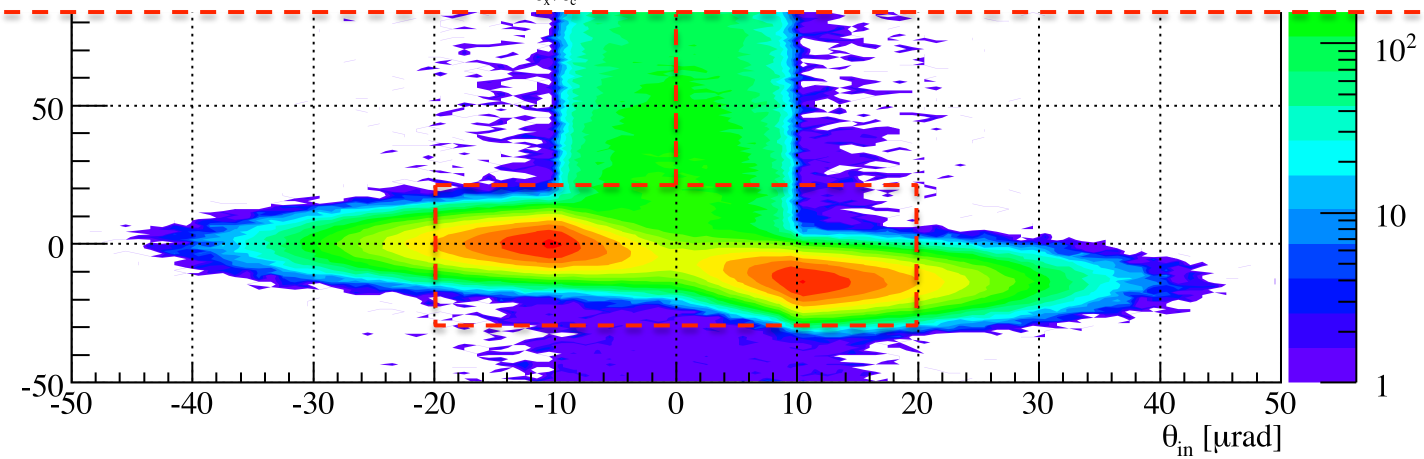
Transitions







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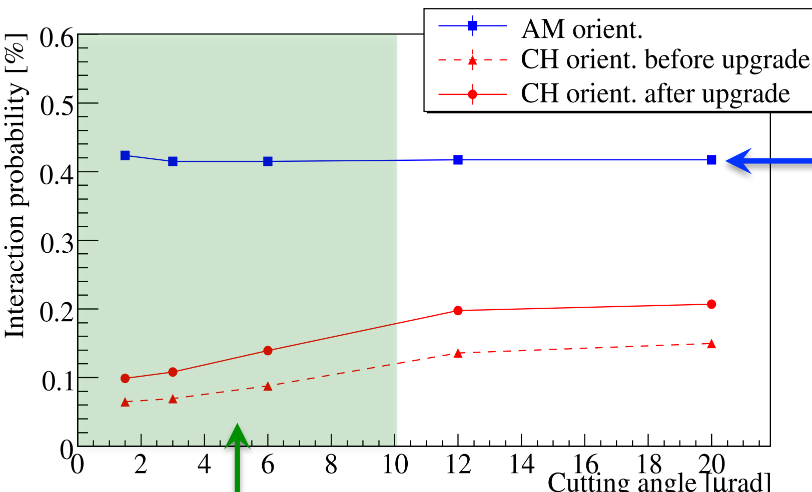
Nuclear interactions rate

Comparison made w.r.t: W. Scandale et al., "Probability of inelastic nuclear interactions of high-energy protons in a bent crystal", NIMB 268 (2010)

Simulation

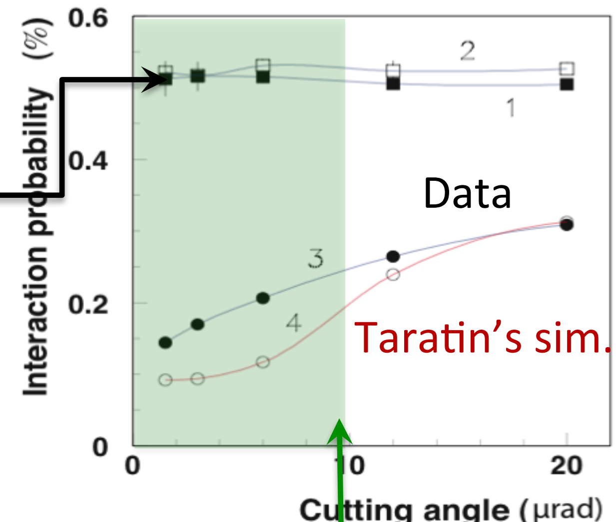


$P = \sigma \cdot \rho \cdot l$

Glauber's app.
σ = 0.504 b

P.D.G. app.
σ = 0.430 b

Measurement



Most interesting range for collimation purpose

Angular divergence of intercepted LHC/SPS beam halo << θ_c

θ_c at 400 GeV ~ 10 μrad

Occurrence of nuclear interactions for channeled protons is now taken into account by using cross sections rescaled by the average nuclear density seen

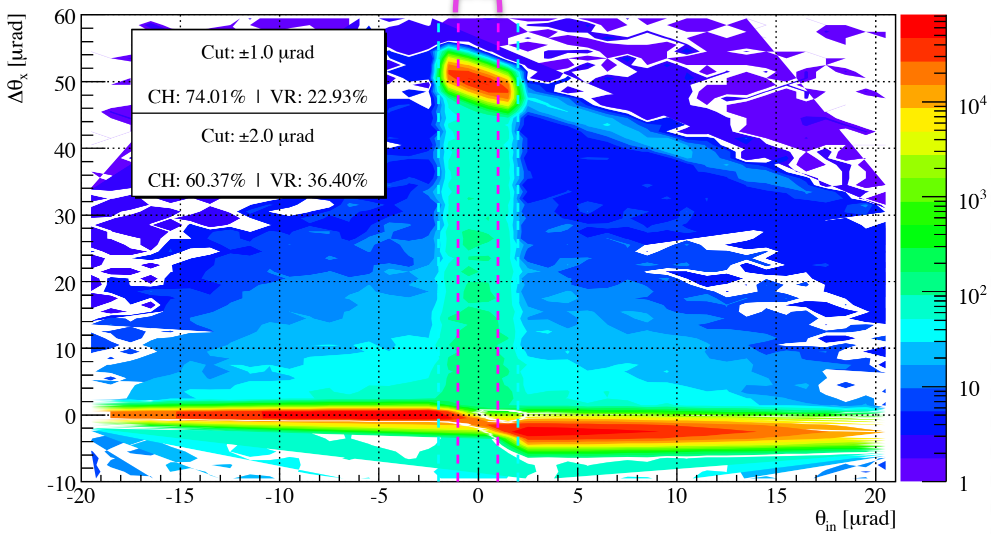
Outline

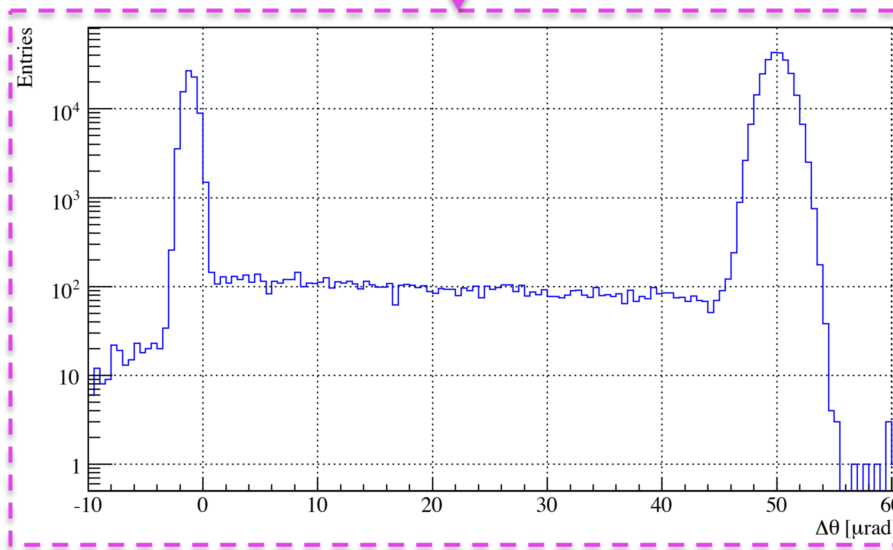
Examples of what expected at 7 TeV

Deflections & efficiency

Simulated deflections & efficiency for crystals installed in the LHC: 4 mm long, 50 μrad bending

Gaussian beam of 7 TeV with σ_x=1mm, $\sigma_{x'}$=10μrad.

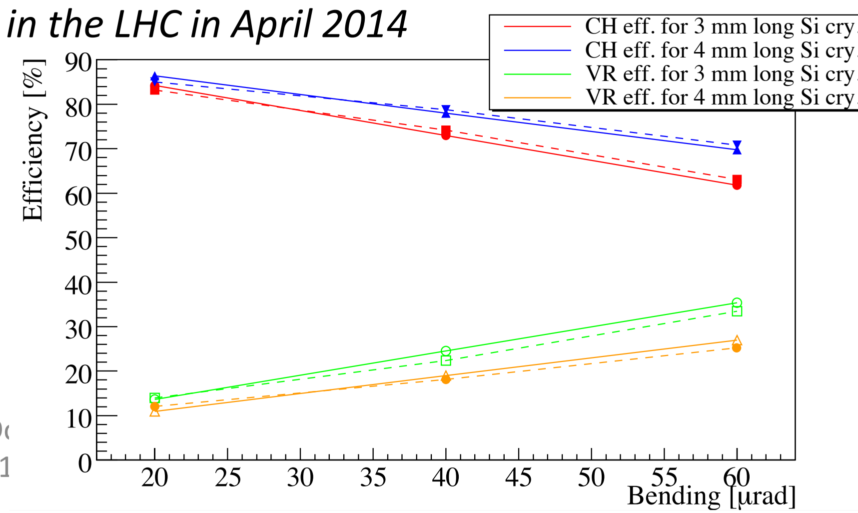




Parametric comparisons made with respect to Taratin's code at 7 TeV for studies related to the choice of crystals installed in the LHC in April 2014

7 TeV beam with a uniform distribution ±1 μrad.
Trend of CH & VR efficiency are compared.

Dashed line: **Fully analytical crystal simulator**
Solid line: **Crystal emulator in SixTrack**



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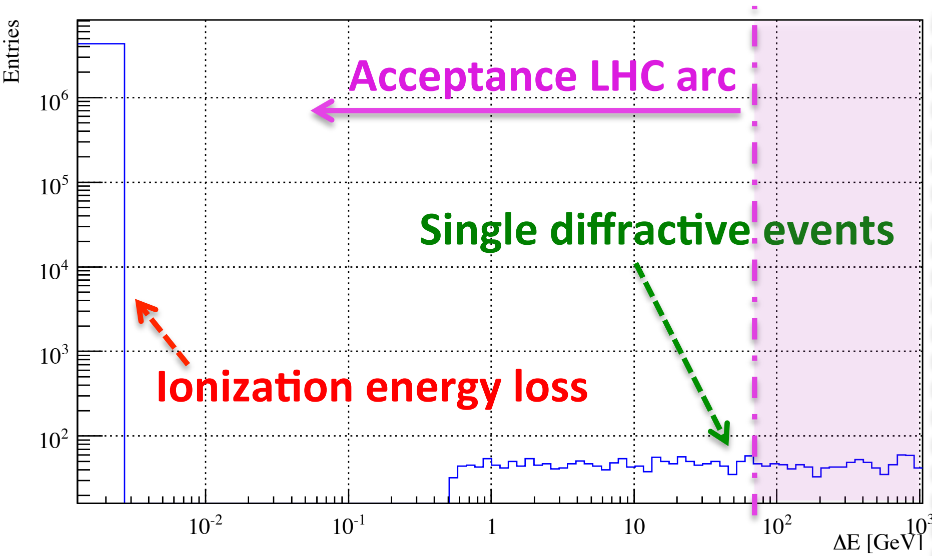
Energy loss

Energy loss related to single pass simulations of LHC crystals performances in the previous slide



Dominant process in the range

$$M_0^2 < M^2 < 0.15\,s$$

$$M_0 = (m_p + m_\pi) \approx 1\,\mathrm{GeV/c^2}$$

Phenomenological parameterization based on:
K.Goulianos. *Physics Letters B*, 358:379–388, 1995

$$\sigma_{pp}^{SD}(s) = 4.3 + 0.3 \ln s$$

Random generated energy loss:

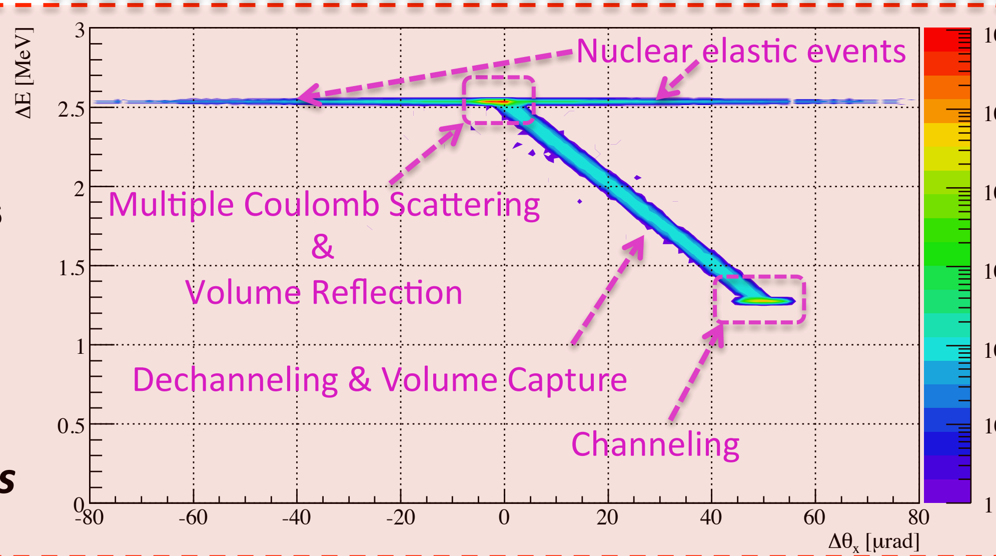
$$E_{out} = E_{in}\left(1 - \frac{\exp\left(\mathrm{Rnd}()\,\log(0.15s)\right)}{s}\right)$$

Ionization energy loss given by Bethe-Bloch plus probability of losses in the Landau tail

At 7 TeV ionization losses lead to: $\frac{\delta p}{p} \sim 10^{-6}$

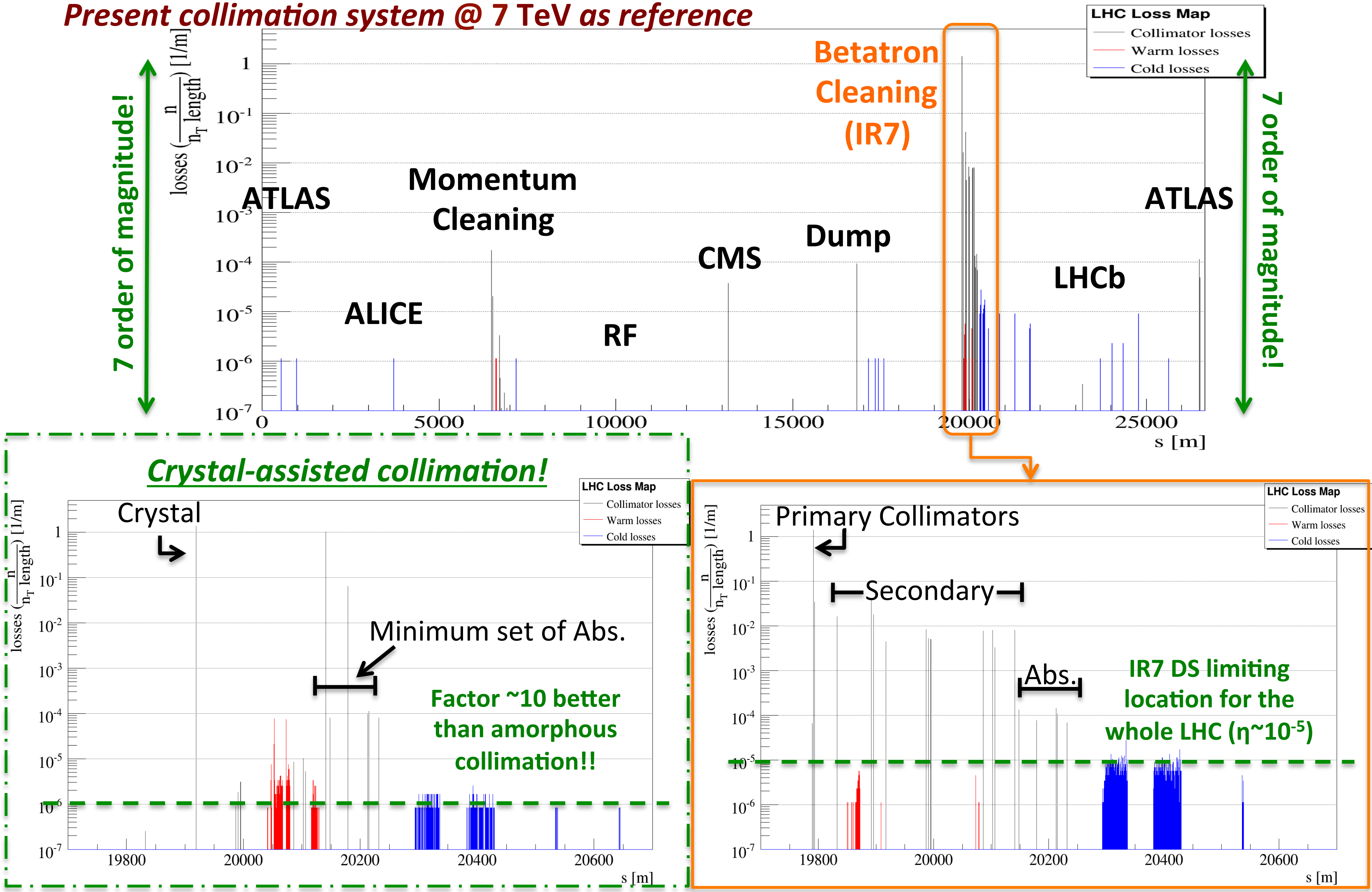
Acceptance of the LHC arc: $\frac{\delta p}{p} \sim 10^{-2}$

Marginal role in the dynamic of beam losses



Expected loss-maps in the LHC

Present collimation system @ 7 TeV as reference



Conclusions

Conclusions

Recent code development focused on improving aspects relevant for the LHC case, addressing:

- ✓ Channeling, dechanneling, volume reflection and volume capture models
- ✓ Topology, energy loss, rate of nuclear point-like interactions with very low probability
- ✓ Scaling with energy of any interaction implemented

Single pass benchmarking performed with respect to:

- Experimental data at 400 GeV taken on the H8-SPS extraction line in the framework of the UA9 Collaboration
- State-of-the-art crystal simulation tools for higher energies

Multiturn benchmarking performed with respect to:

- Experimental data at 120&270 GeV taken on the SPS in the framework of the UA9 Collaboration. (not shown here)

This simulation setup provides to date the only way to simulate loss maps around the ring of complex machines like the SPS and the LHC, taking into account:

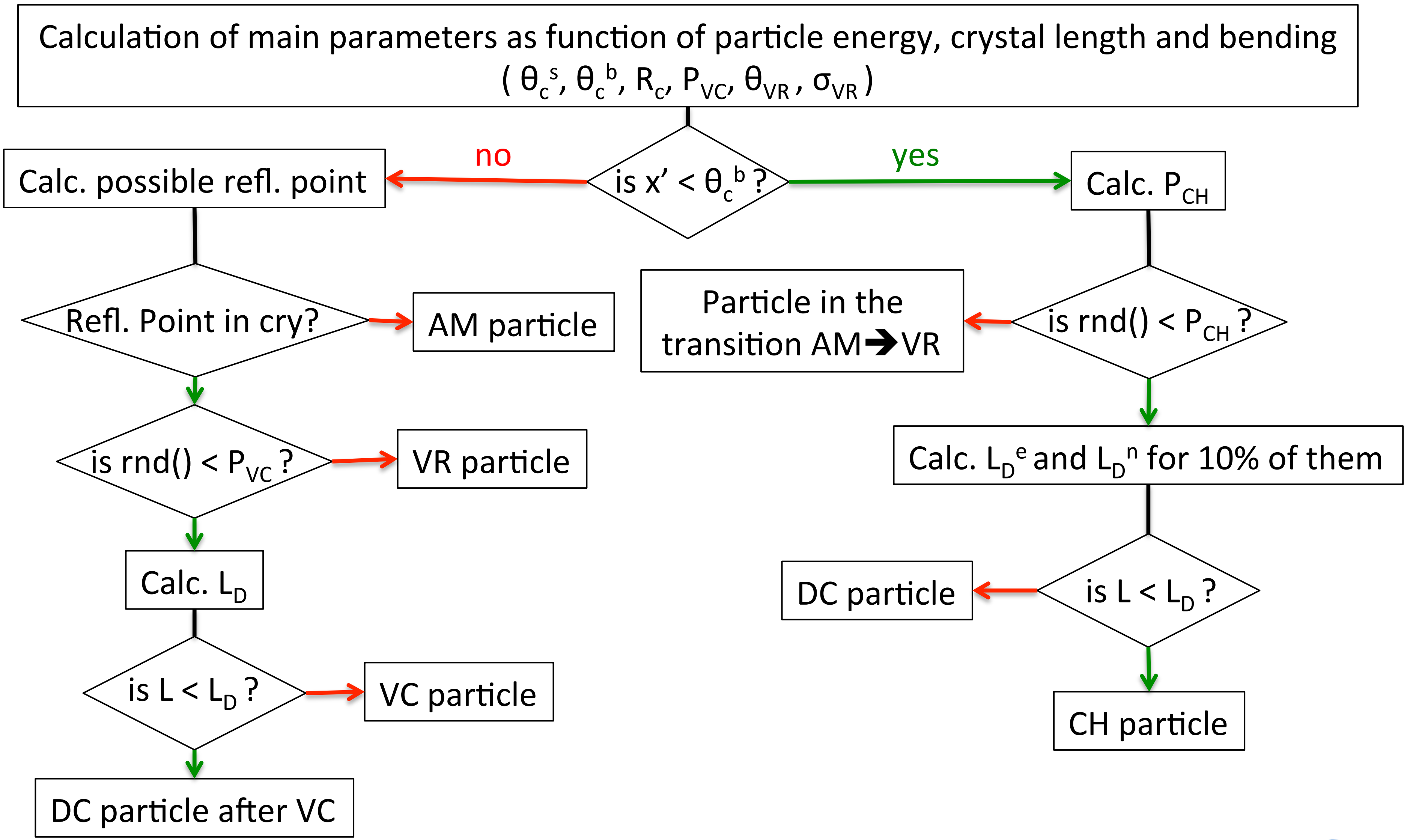
- ➢ Proton-crystal interactions
- ➢ Complete collimation layouts
- ➢ Aperture models and accurate 6D particle tracking

Making us confident that this tool is adequate for predictions of crystal collimation performance in LHC

Outline

Backup

Crystal routine



Resume table

415	CUT	Telesc. MCS included	VR/AM peak	CH peak	CH rate	DC rate	L_D
	[urad]		[urad]	[urad]	[%]	[%]	[mm]
Experiment	5	yes	-4.5 σ 9.3	144.0 σ 7.2	68.9	4.76	1.23
Simulation	5	no	-6.3 σ 5.9	143.3 σ 5.8	79.9	5.30	1.04
Simulation	5	yes	-5.9 σ 8.1	143.3 σ 7.7	69.8	5.18	1.06
Experiment	10	yes	-5.9 σ 9.5	143.8 σ 8.2	54.0	5.13	1.41
Simulation	10	no	-6.6 σ 7.5	143.7 σ 6.7	65.2	5.15	1.06
Simulation	10	yes	-6.0 σ 8.1	143.5 σ 8.8	62.0	5.10	1.09