Recent developments and applications of the crystal channeling at the Large Hadron Collider

Stefano Redaelli, BE-ABP, on behalf of WP5

European Physics Society: Conference on High Energy Physics — HEP 2019
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Acknowledgements

Collimation results are presented of behalf of the HL-LHC WP5 (collimation upgrade)
— Most plots/analyses prepared by D. Mirarchi, M. D'Andrea, R. Rossi
— See details on our study at the Crystal Collimation Day: https://indico.cern.ch/event/752062

CERN groups involved in these crystal studies: BE-ABP, EN STI, EN SMM
(support from many: vacuum, diagnostics, operations, services…)

Funding of LHC crystal installation: LHC Collimation Project CERN, HiLumi HL-LHC PROJECT

UA9 collaboration: UA9

Physics Beyond Collider: Physics Beyond Colliders

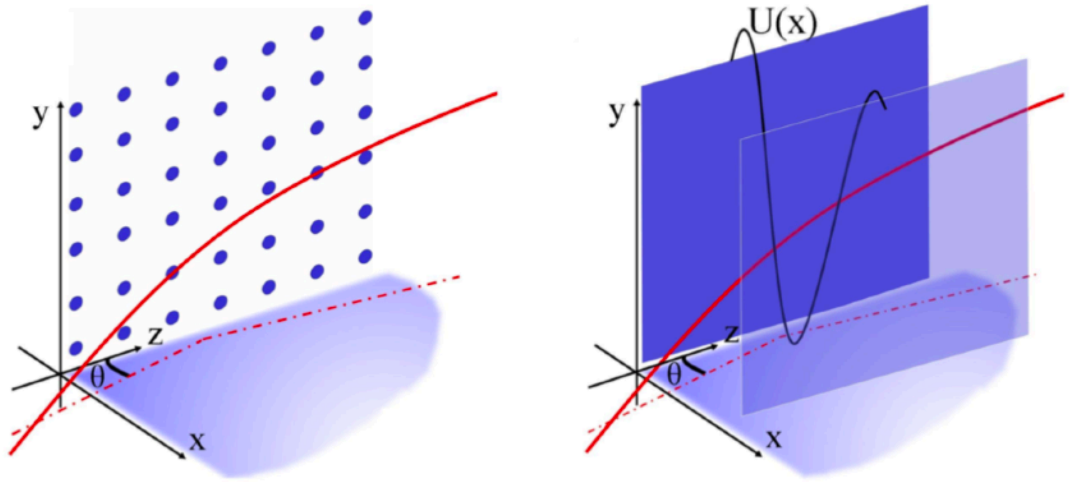
Work on high-β^* run: D. Mirarchi, R. Bruce, M. D'Andrea, H. Morales, S. Redaelli, A. Masi, M. Di Castro, P. Serrano, M. Butcher, with ATLAS-ALFA and TOTEM

Recent PhD thesis works at CERN (simulations and/or measurements):

V. Previtali: CERN-THESIS-2010-133 (2010, PhD)
D. Mirarchi: CERN-ACC-2015-0143 (2015, PhD)
R. Rossi: CERN-THESIS-2017-424 (2014, PhD);
P. Schoofs: CERN-THESIS-2014-131 (2014, PhD, FLUKA team)

Planar channeling in bent crystals

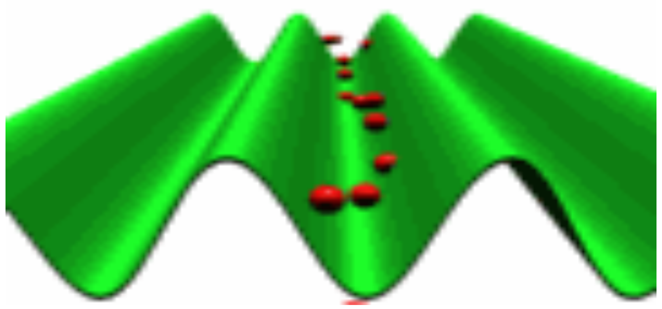
Pure crystals with regular lattices



*If the protons **have** $p_T < U_{max}$*

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

Critical angle



LHC 450 GeV	=	9.4 µrad
LHC 6.5 TeV	=	**2.4 µrad**
FCC-hh 50 TeV	=	0.9 µrad

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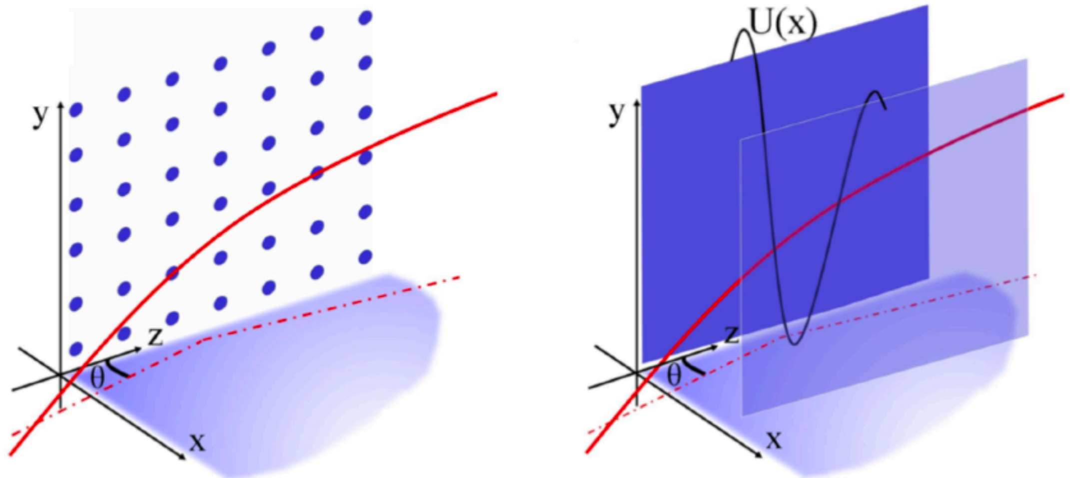

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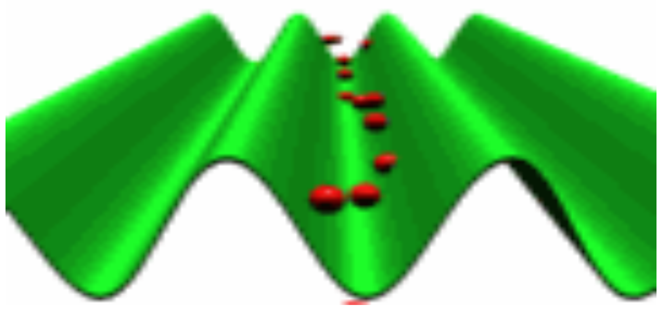
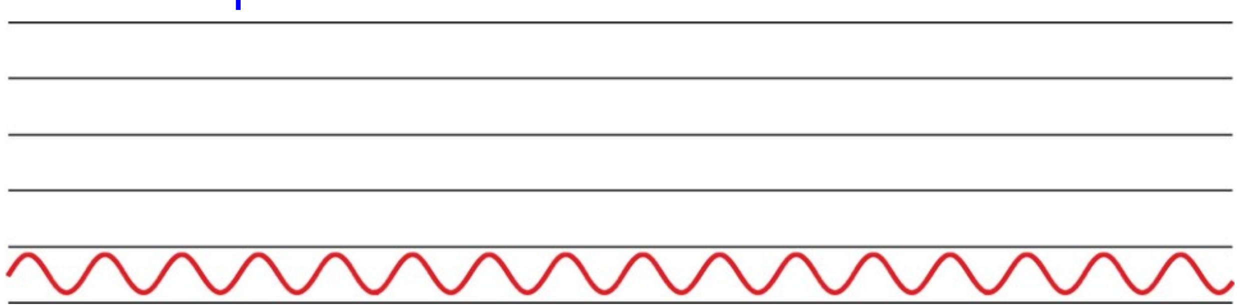
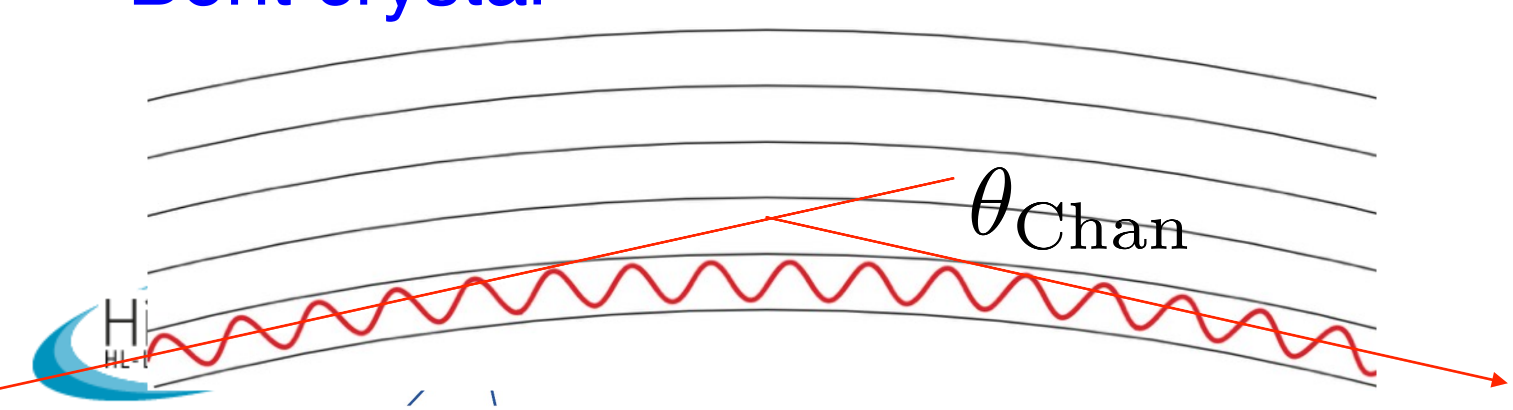


LHC 450 GeV	=	9.4 μrad
LHC 6.5 TeV	=	**2.4 μrad**
FCC-hh 50 TeV	=	0.9 μrad

Straight crystal: hadron oscillate, “trapped” between planes



Bent crystal

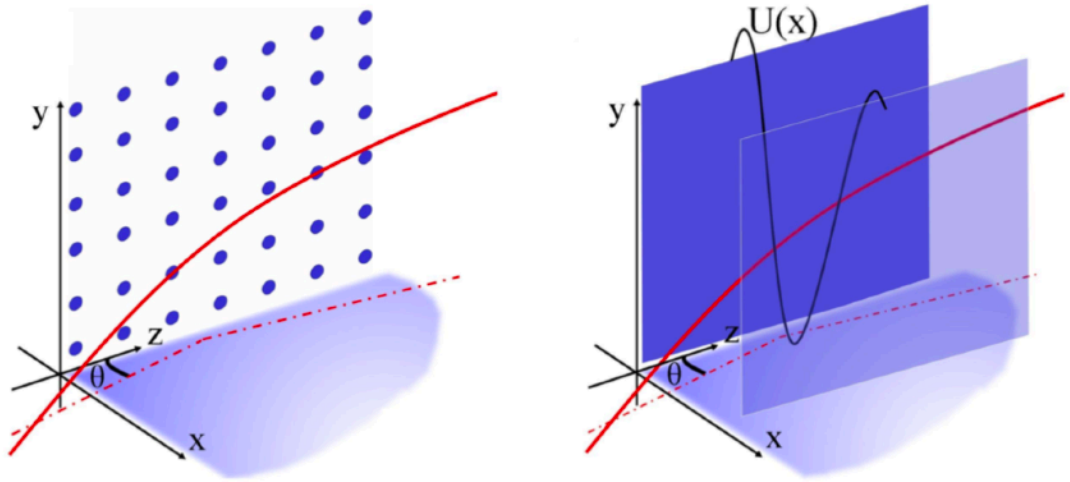


Mechanical bending of crystal produces a net kick of trajectories of the particles trapped between planes.

Equivalent magnetic field for **50μrad** at **7 TeV** proton beams: **310 T** (4 mm crystal)

Planar channeling in bent crystals

Pure crystals with regular lattices



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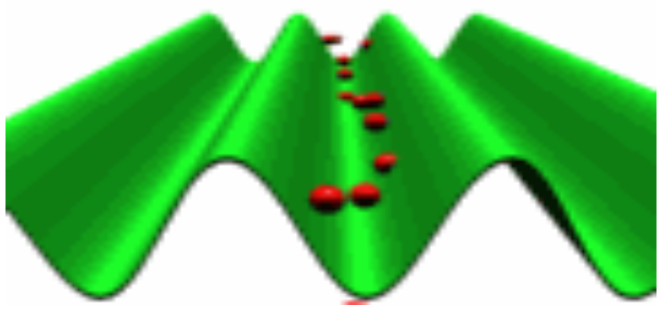
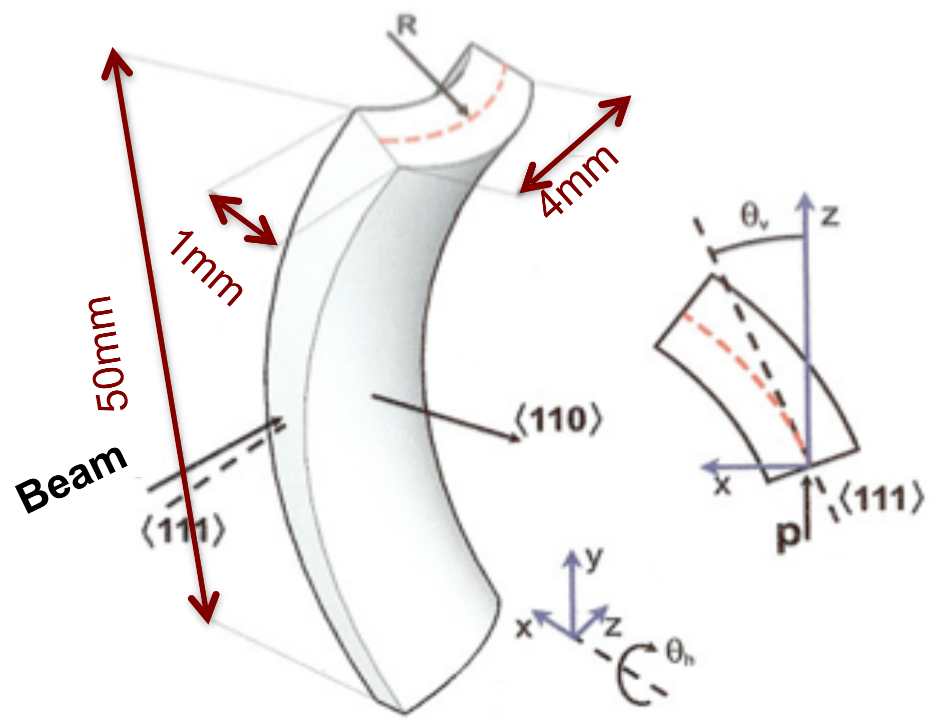


LHC 450 GeV = 9.4 μrad
LHC 6.5 TeV = **2.4 μrad**
FCC-hh 50 TeV = 0.9 μrad

LHC design parameters for **Silicon crystals**



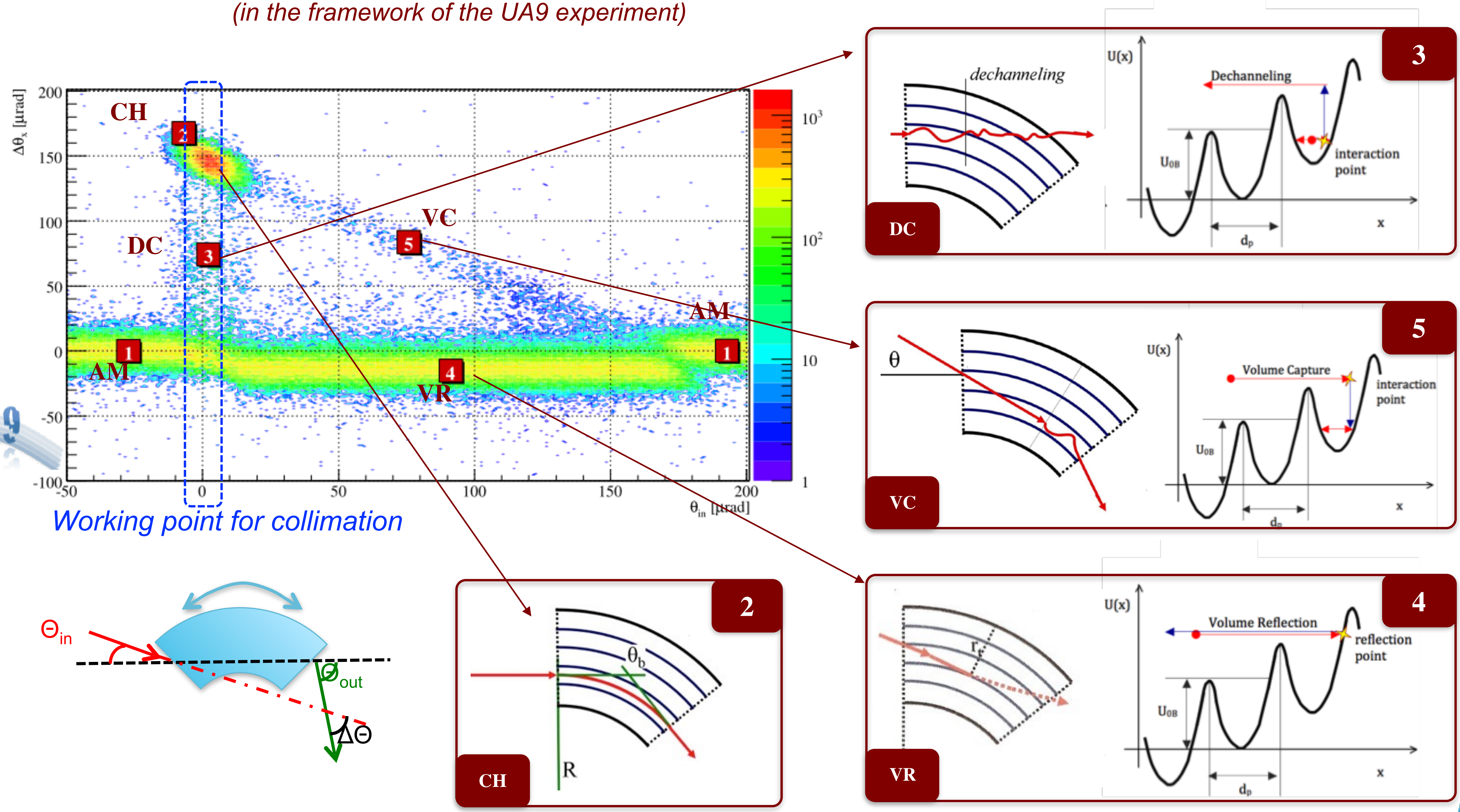
Bending 50μrad

Mechanical bending of crystal produces a net kick of trajectories of the particles trapped between planes.

Equivalent magnetic field for **50μrad** at **7 TeV** proton beams: **310 T** (4 mm crystal)

Coherent interactions in bent crystals

***From test beam** on the CERN-SPS extraction line H8:*
(in the framework of the UA9 experiment)



See for an extensive overview Phys. Rept. 815 (2019) 1-107

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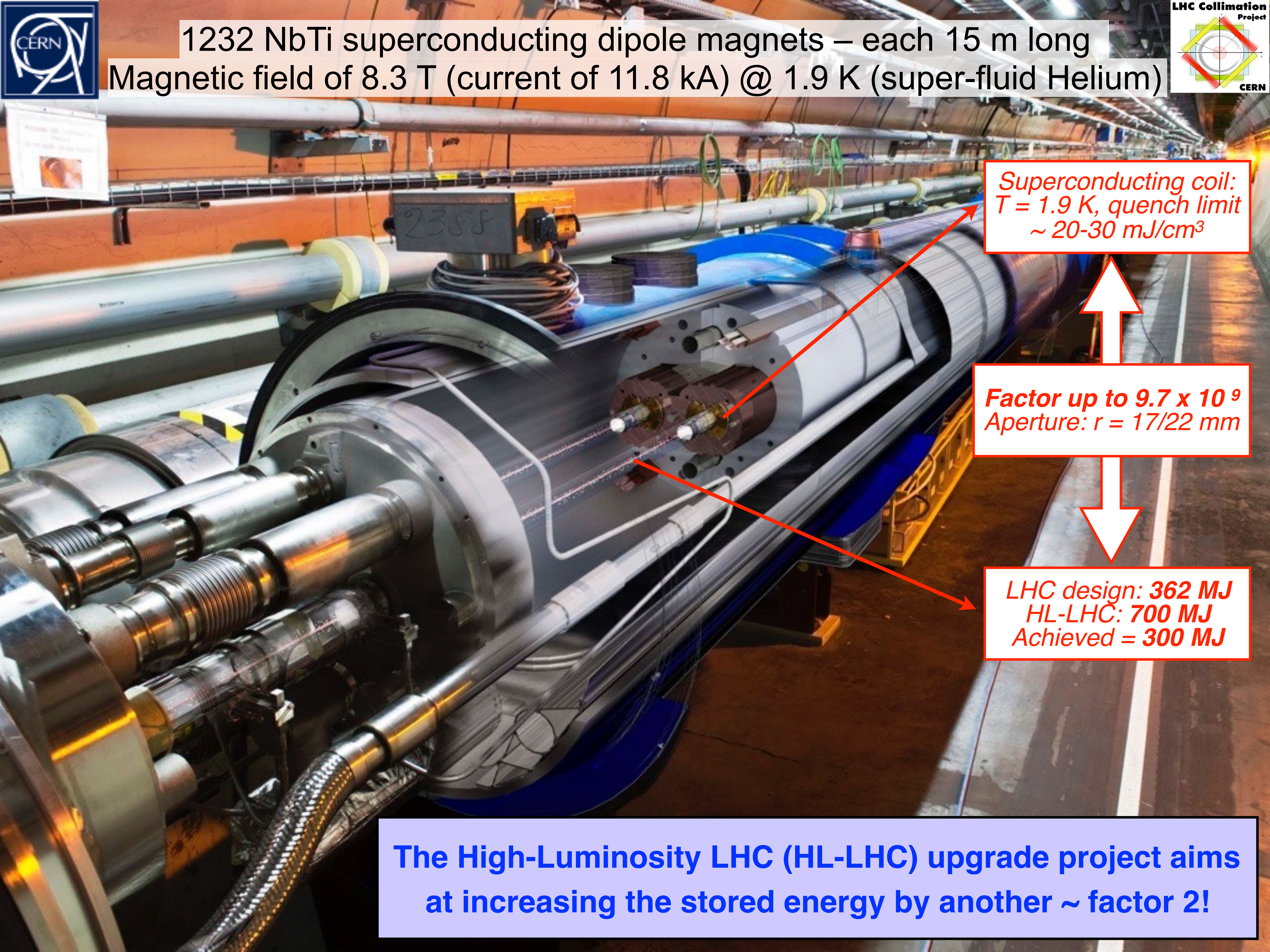
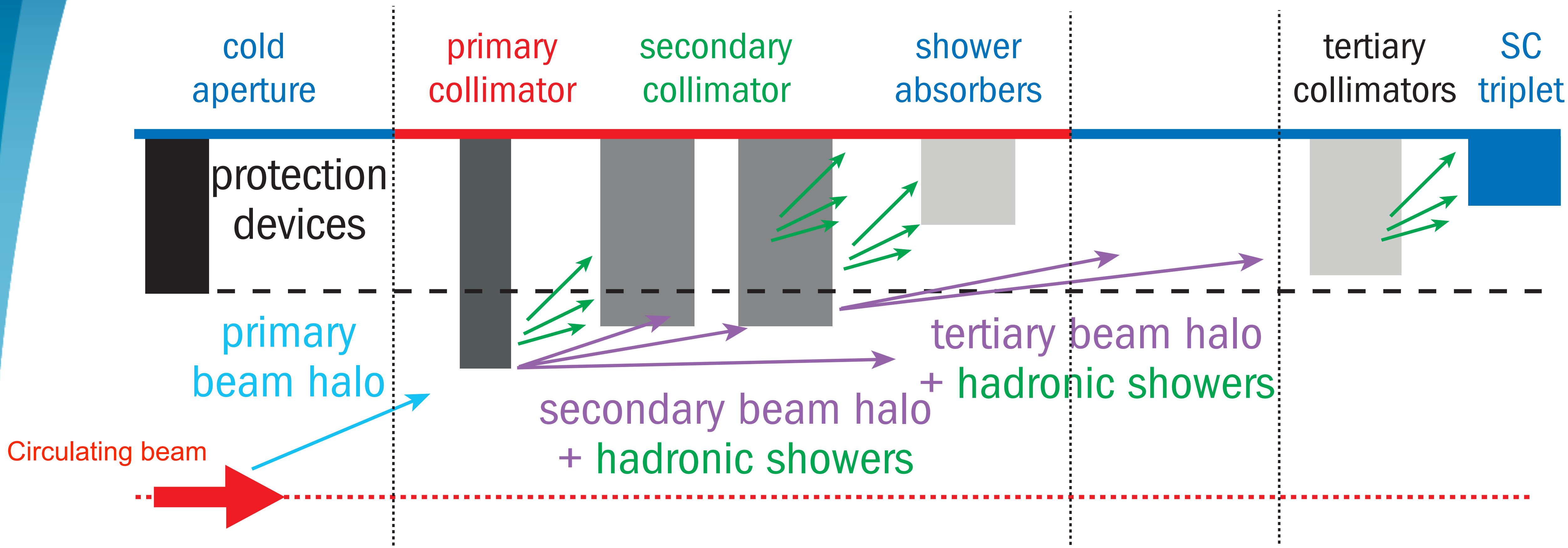
1232 NbTi superconducting dipole magnets – each 15 m long

Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)



The High-Luminosity LHC (HL-LHC) upgrade project aims at increasing the stored energy by another ~ factor 2!

LHC multi-stage collimation



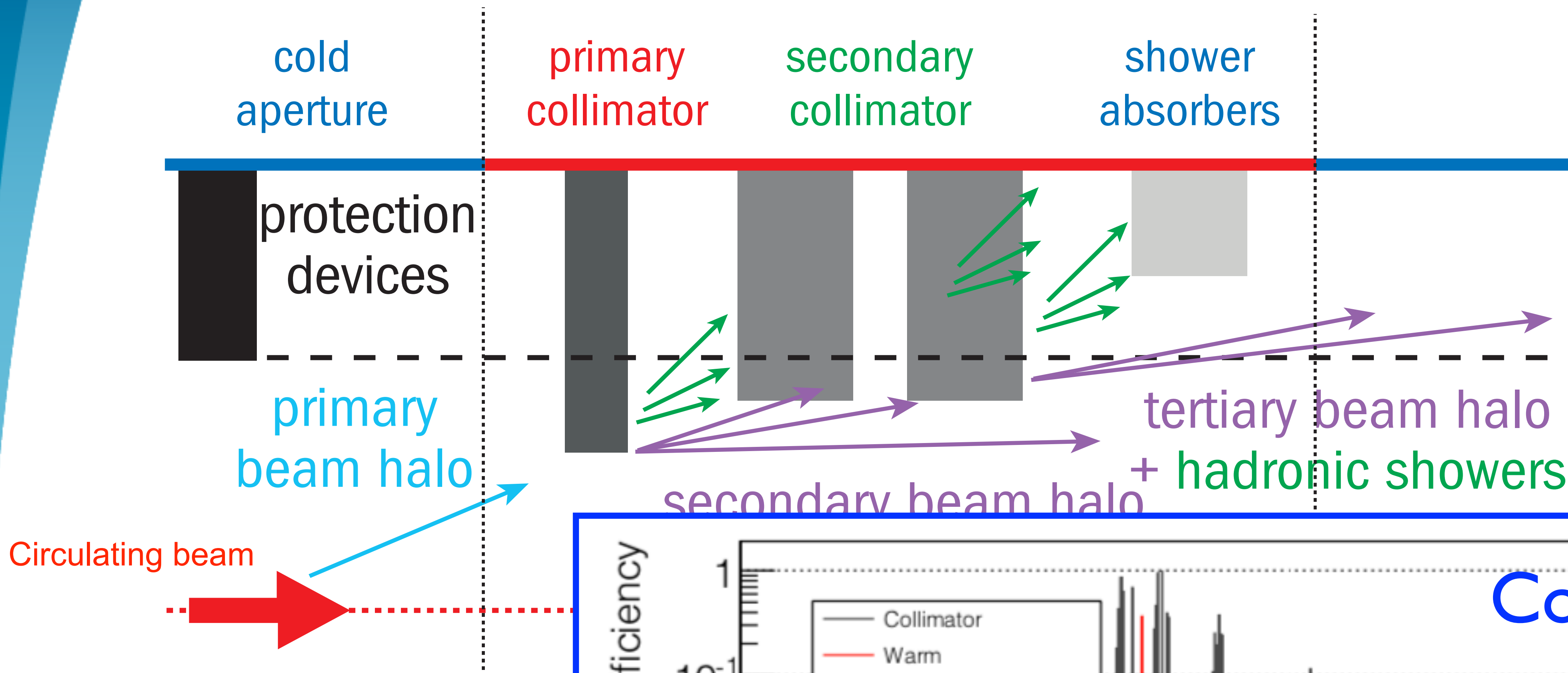
Three-stage cleaning in warm **cleaning insertions**: betatron (IR7) and off-momentum (IR3); local "tertiary" collimators at inner triplet.

Well-defined *collimation hierarchy* that integrates injection and dump protection collimators (as well as Roman pots). **Five stages**!

Machine aperture sets the scale for collimation hierarchy

Critical beam-based alignment to determine local orbit and beam size.

LHC multi-stage collimation

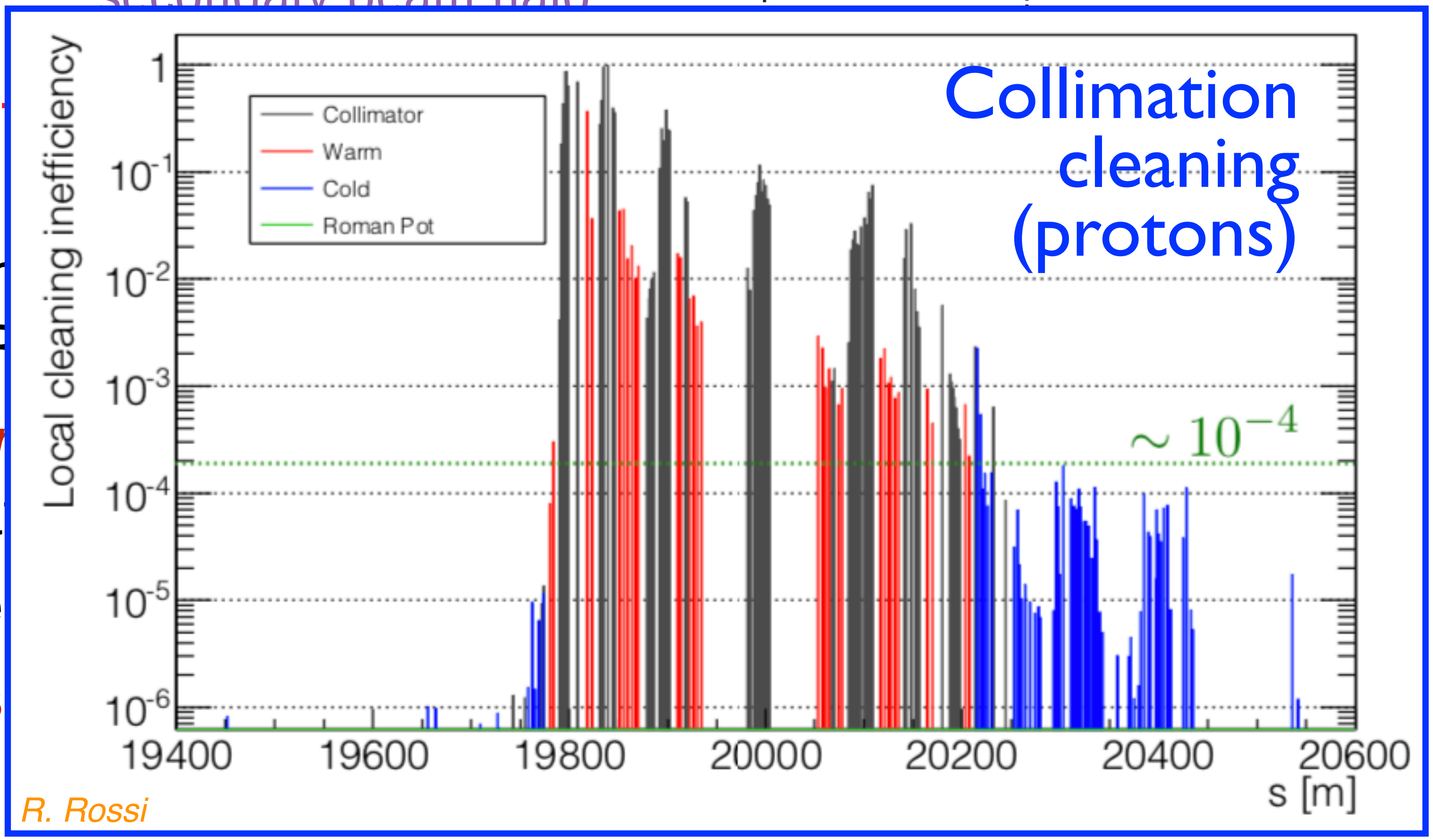


Three-stage clear
off-momentum (IF

Well-defined *colli*
protection collima

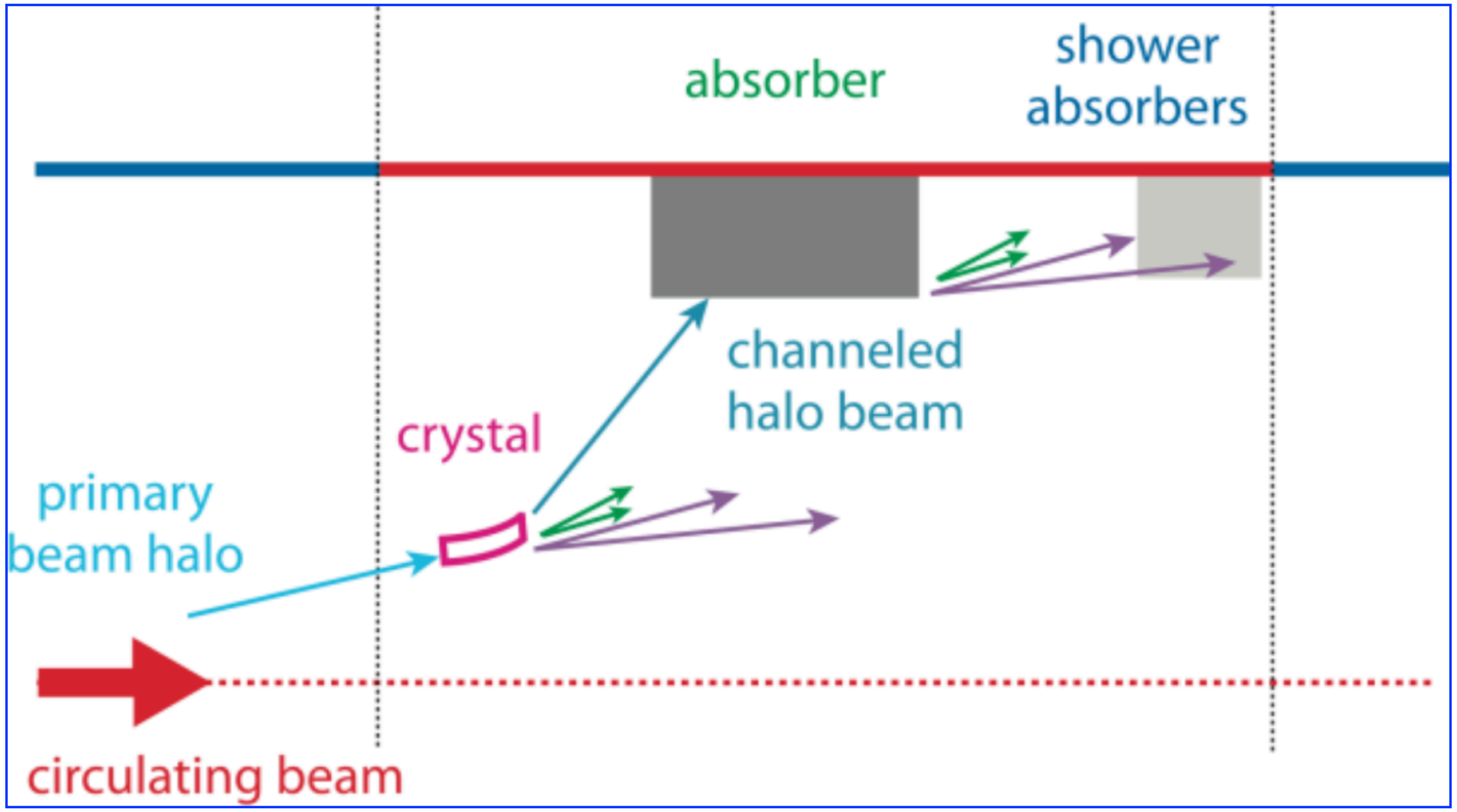
Machine aperture

Critical beam-bas



The crystal collimation concept

(replacing the 3-stage system for betatron cleaning)



<u>Crystal-based betratron halo cleaning</u>

- — Bent crystal replaces horizontal and vertical primary collimators
- — A single massive absorber (per plane) intercepts the channeled halo
- — Potentially needs some additional shower absorbers downstream

Promises: Improvement of cleaning, with fewer collimators, in particular for <u>heavy ion beams</u> (suppress of fragmentation/dissociation!)

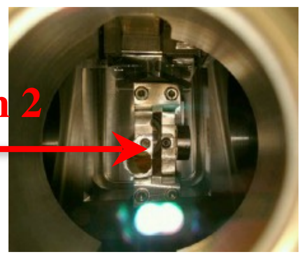
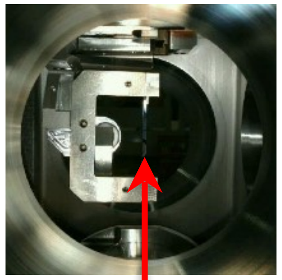
Challenges: Quality and performance of crystal assembly
Angular control within sub-micro radiants
Safe and efficient disposal of channeled halo

LHC layouts for beam tests

Four crystals installed in the LHC: two per beam, one per plane

Same specifications for all crystals, two **different producers** and **technologies**

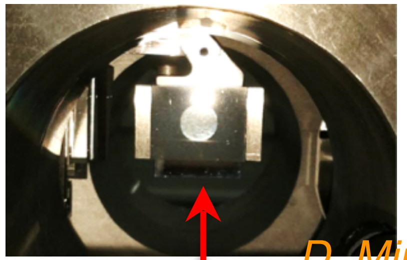
TCPCH.A5R7.B2

PNPI

Pics. courtesy of Y. Gavrikov

TCPCV.A6R7.B2



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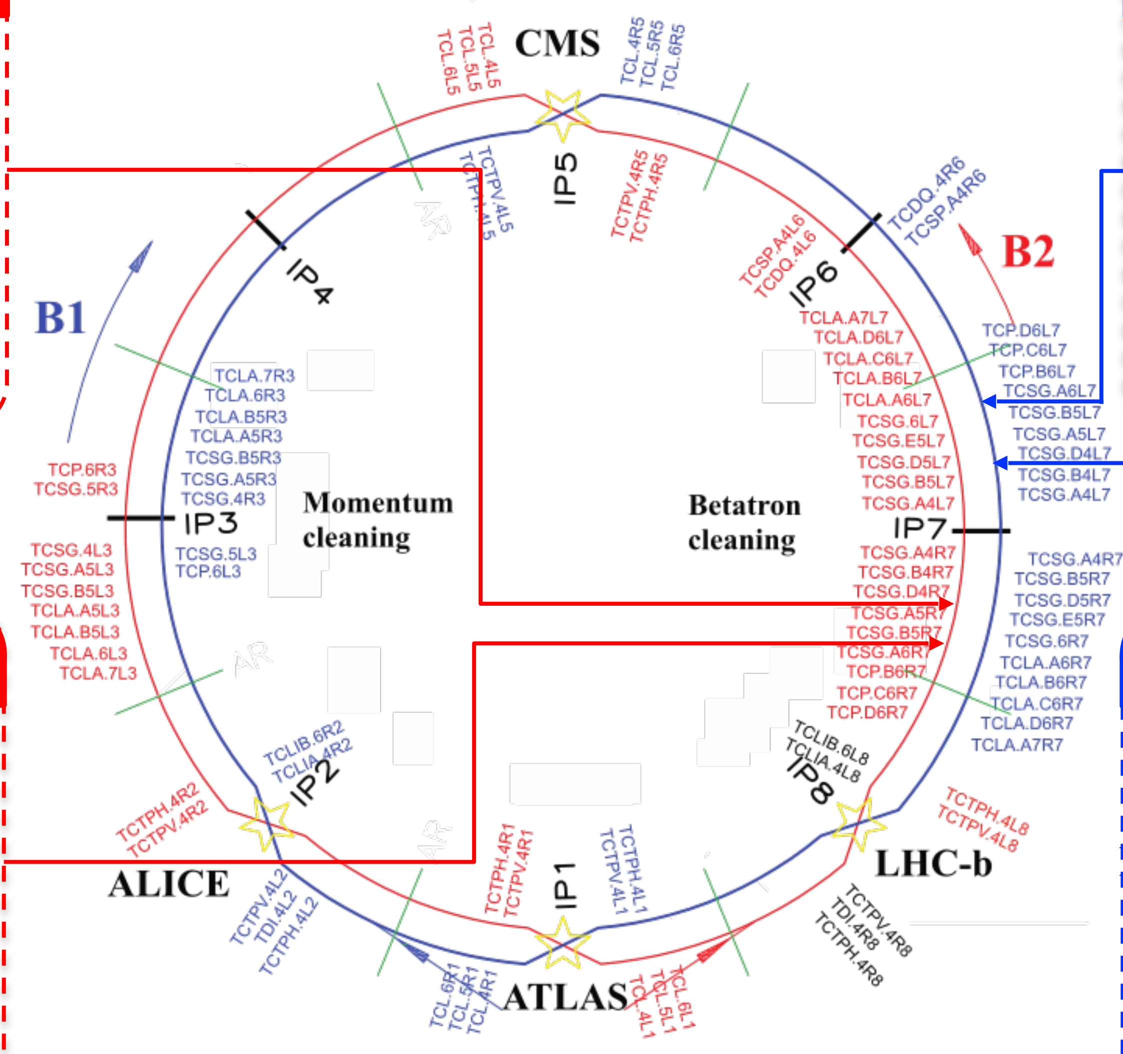

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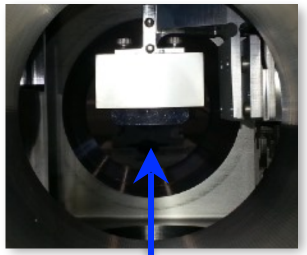

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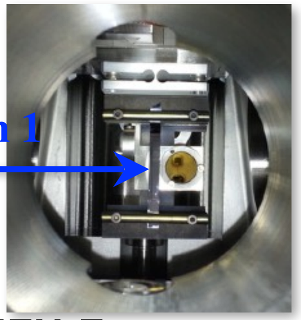
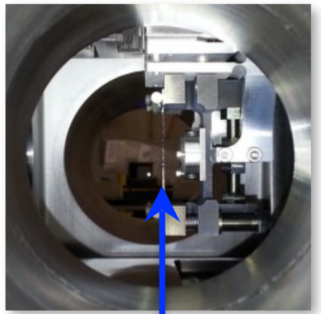
TCPCH.A4L7.B1

INFN-Fe

Complete layout : both beams and planes — allow thorough investigations and **operational** tests

LHC layouts for beam tests

Four crystals installed in the LHC: two per beam, one per plane

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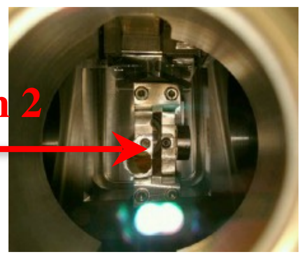
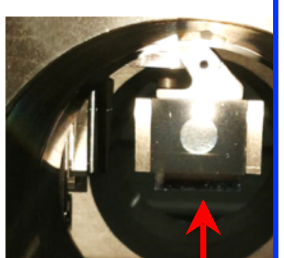


PNPI

Pics. courtesy of Y. Ga

TCPCV.A6R



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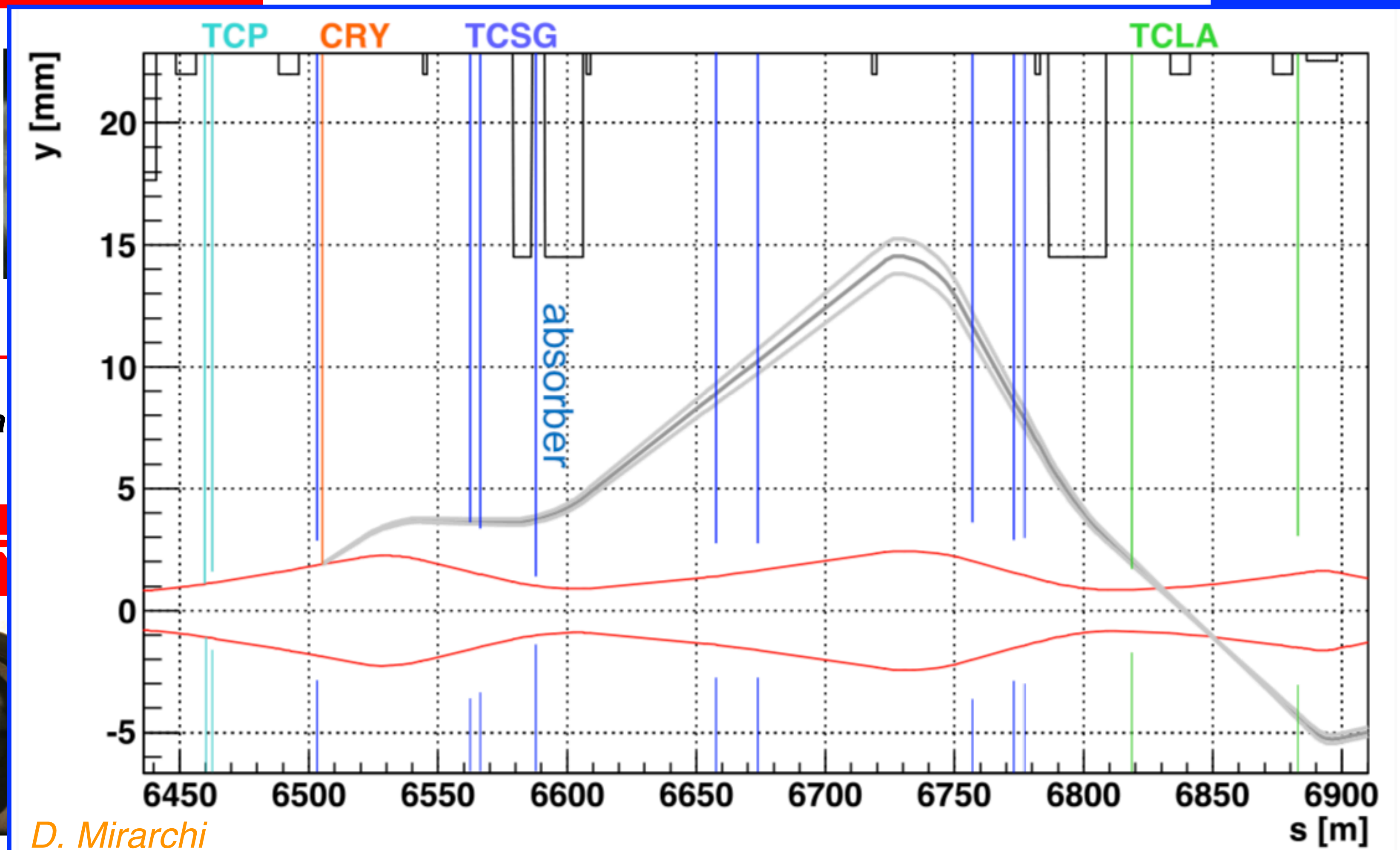
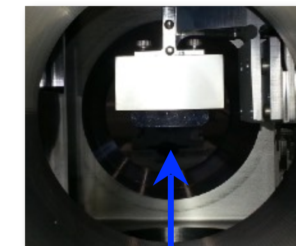
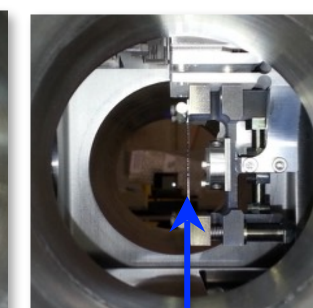


TCPCV.A6L7.B1



PCH.A4L7.B1



INFN-Fe

TCP = primary collimator
TCSG = secondary collimator
TCLA = shower absorber

Complete layout : both beams and planes — allow thorough investigations and **operational** tests

History of beam tests: key milestones

2015

- Installation on beam 1 only (horizontal and vertical)
- **Observation p channeling** at the LHC: **450 GeV and 6.5 TeV**
- **Observation Pb channeling** at the LHC: **450 Z GeV**

2016

- **Continuous** channeling during **energy ramp**
- **First** assessment of **cleaning performance** with p beams
- **First observation Pb channeling** at the LHC: **6.37 Z TeV**

2017

- Added 2 crystals on beam 2 (horizontal and vertical)
- **Channeling of Xe at 450 Z GeV 6.5 Z TeV**, together with assessment of cleaning performance

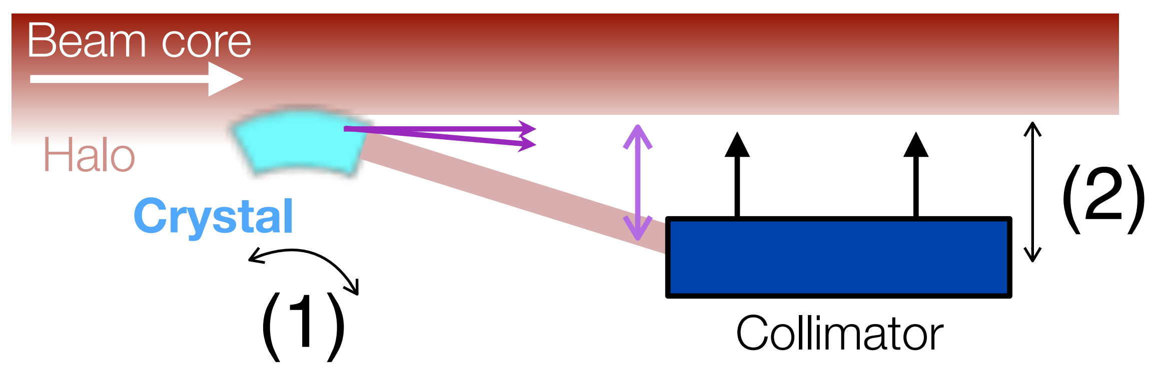
2018

- **Continuous** channeling during **squeeze** and **collision**
- **First** operational use in a **physics run**
- **Operational tests** with **6.37 Z TeV Pb** beams with high intensity

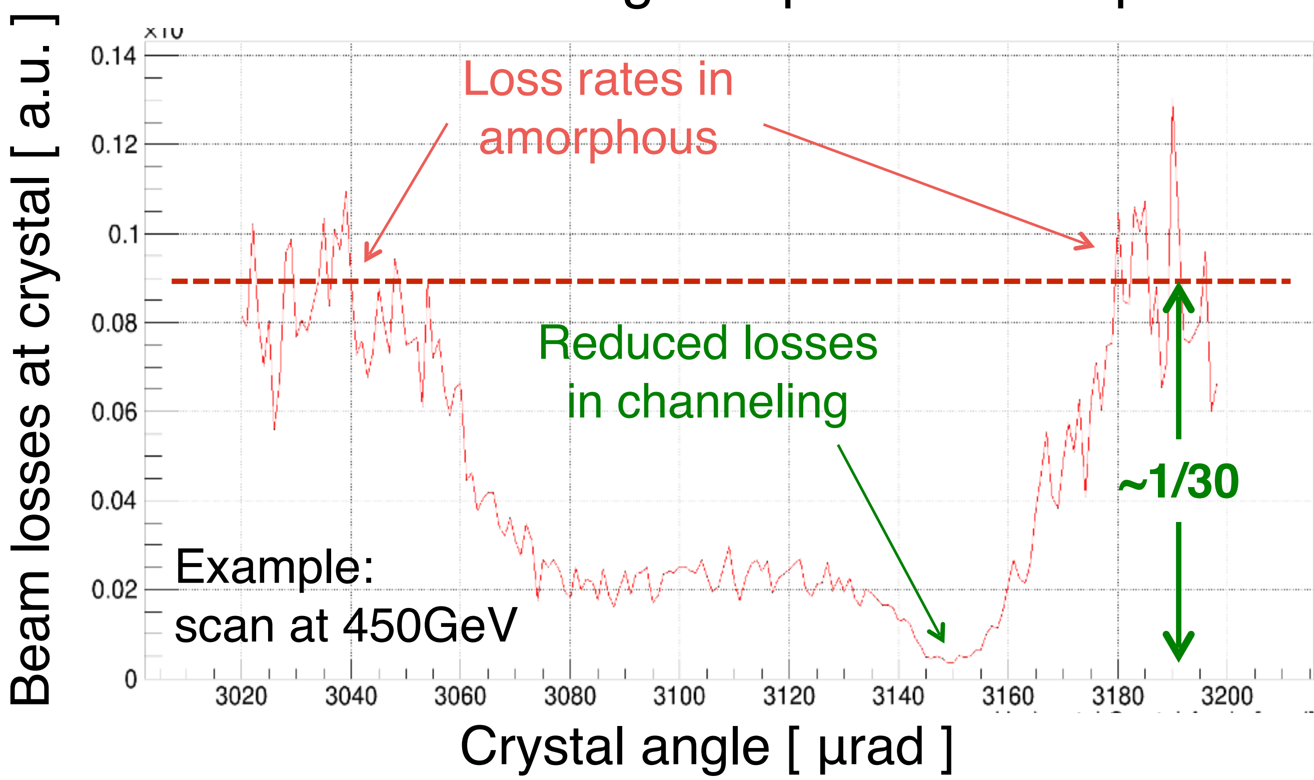
Total "Machine Development" (MD) time: 58h with protons, 34h with ions

Channeling observations at 6.5 TeV

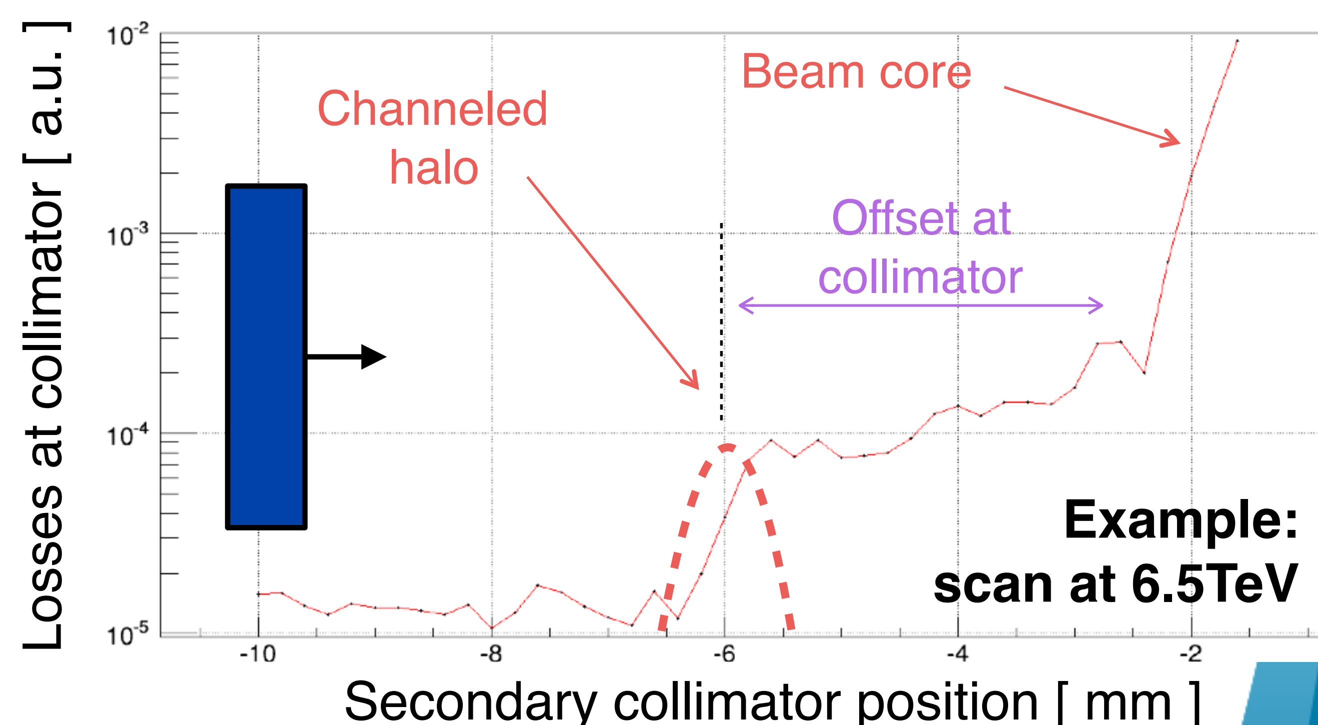
Key measurements: crystal angular scans and linear collimator scans



(1) **Angular scan**: strong reduction of local losses in channeling compare to amorphous.



(2) **Linear collimator scan**: measures the profile of the channeled halo.



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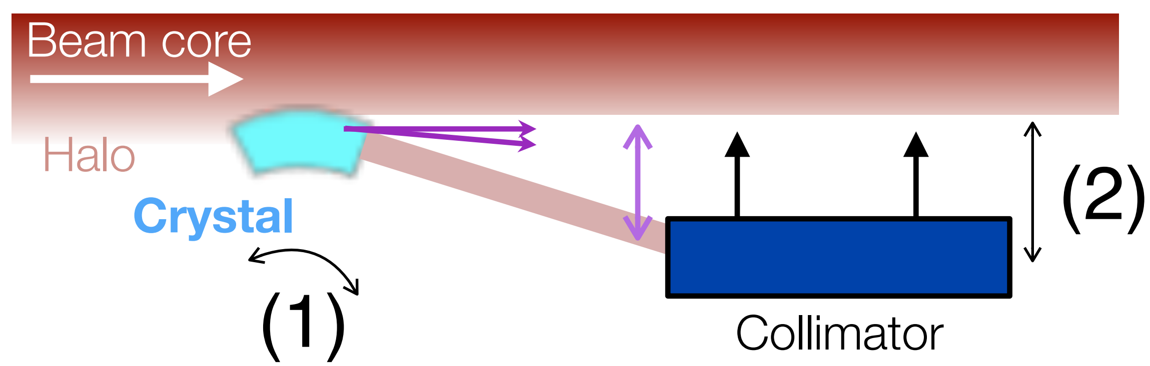

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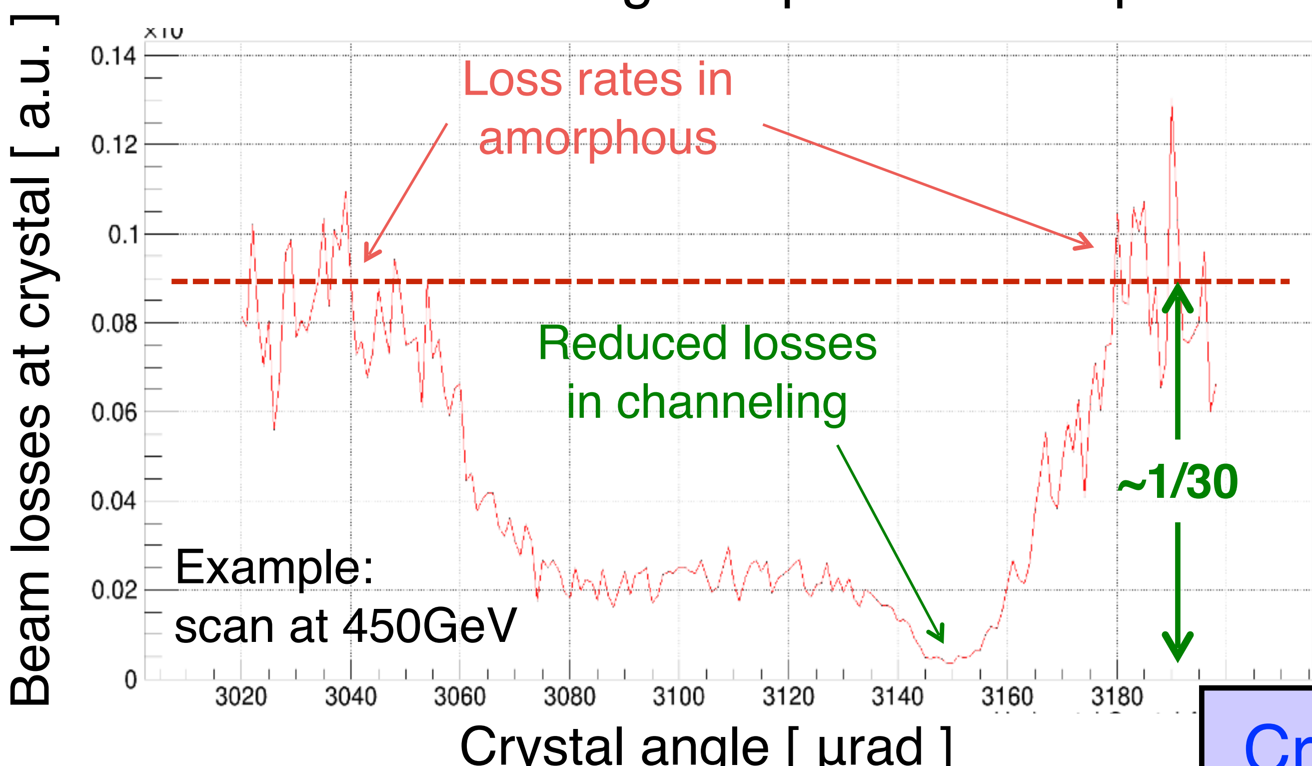

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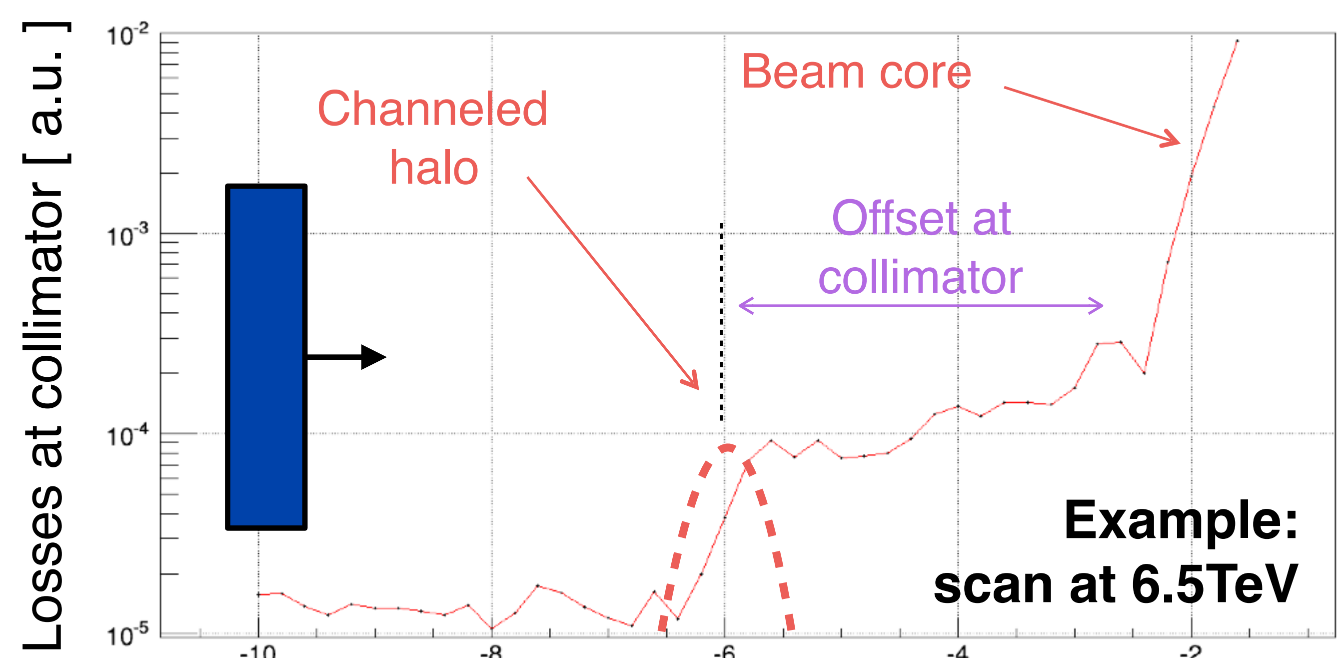
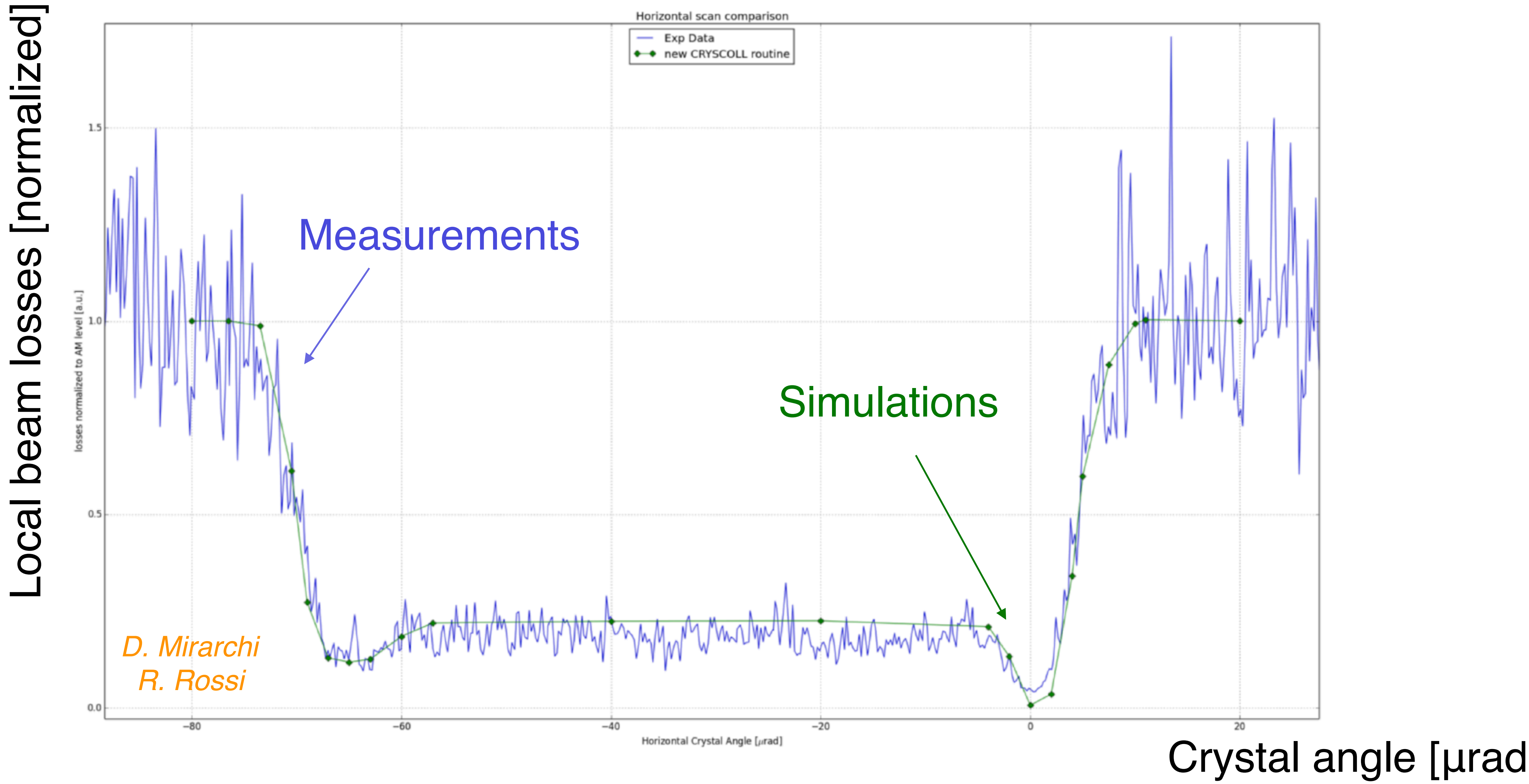


Critical: Achieved the required angular control of better than ~1 μrad (A. Masi *et al.*)

Measurements and simulations, 6.5 TeV



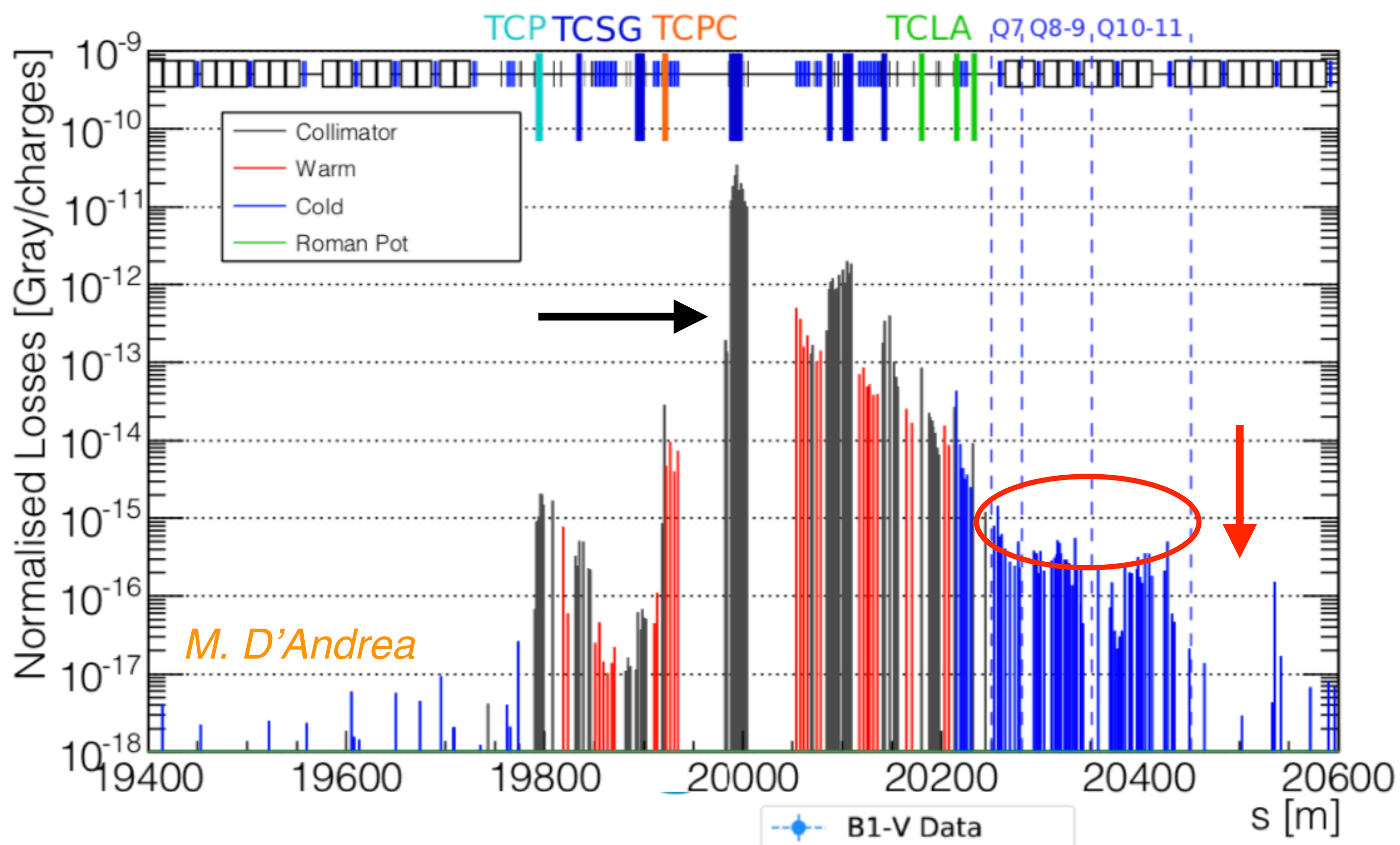
Comparison: beam losses downstream of crystal in an angular scan vs simulated nuclear interactions in the crystal.

Experimental input from measurements: crystal bending angle (65μrad).

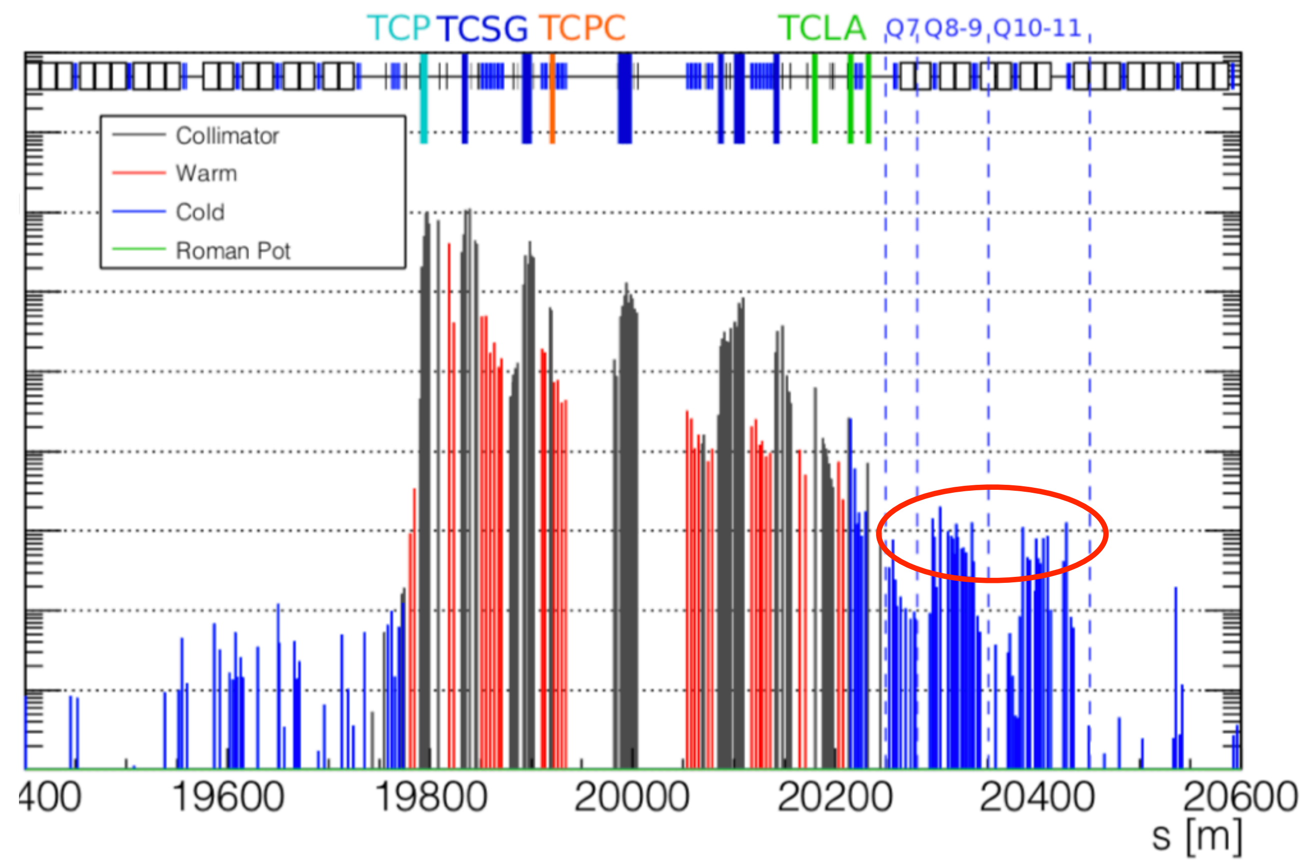
See CERN Yellow Book CERN-2018-011-CP for details on simulation tools.

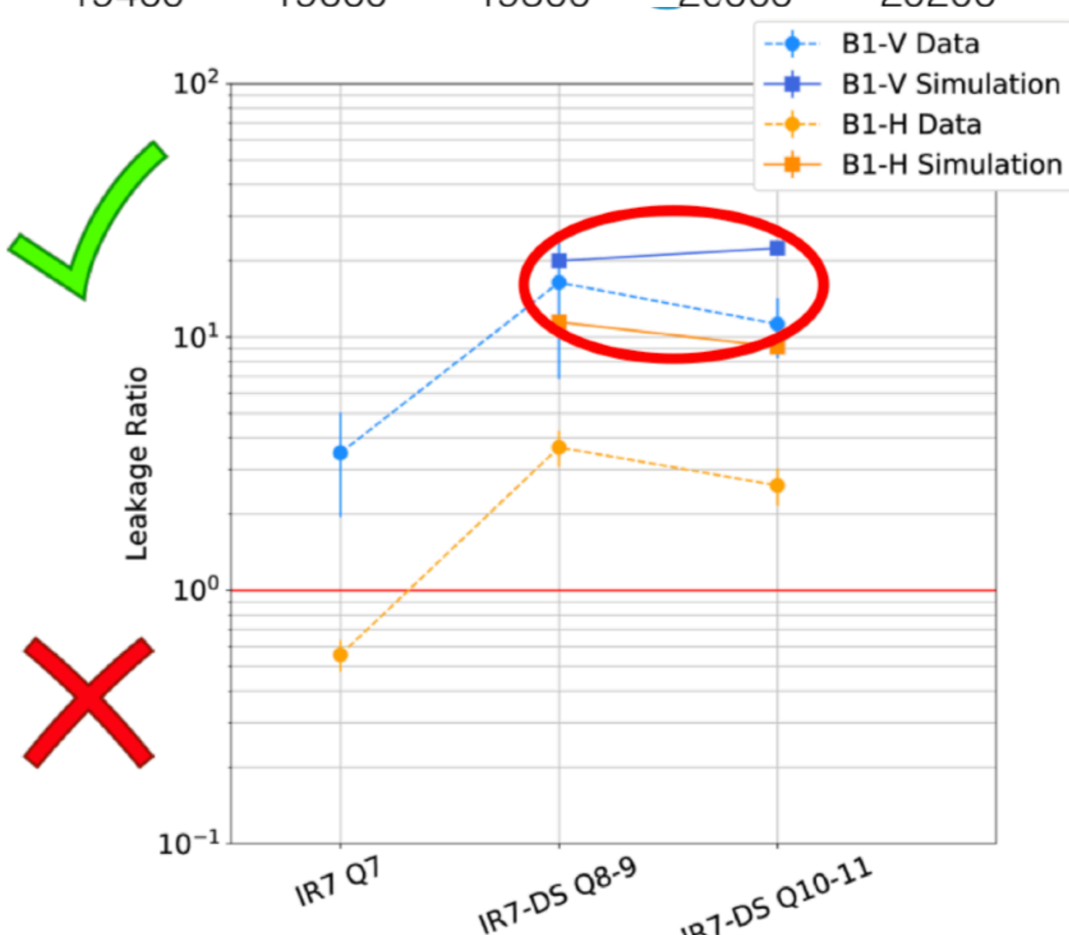
Collimation cleaning for proton beams

Crystal collimation



Conventional collimation

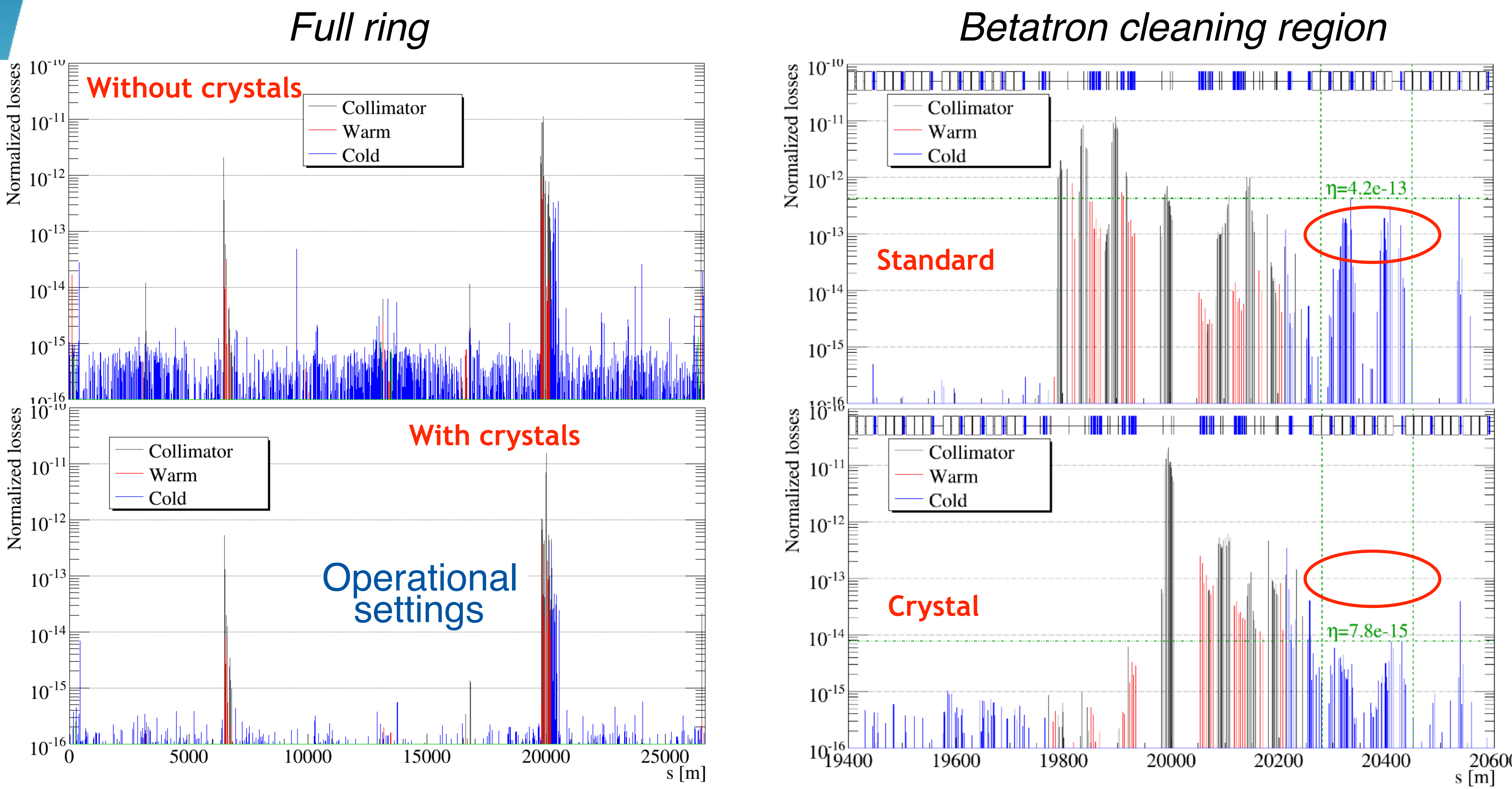




- Achieved up to a factor ~10 cleaning improvement at critical locations
- For protons, this is a "demonstrator setup", compatible only with low beam intensities
- HL-LHC: design losses of ~1MW require a dedicated beam absorber!

  Not considered for cleaning upgrade!

Collimation cleaning for Pb ion beams

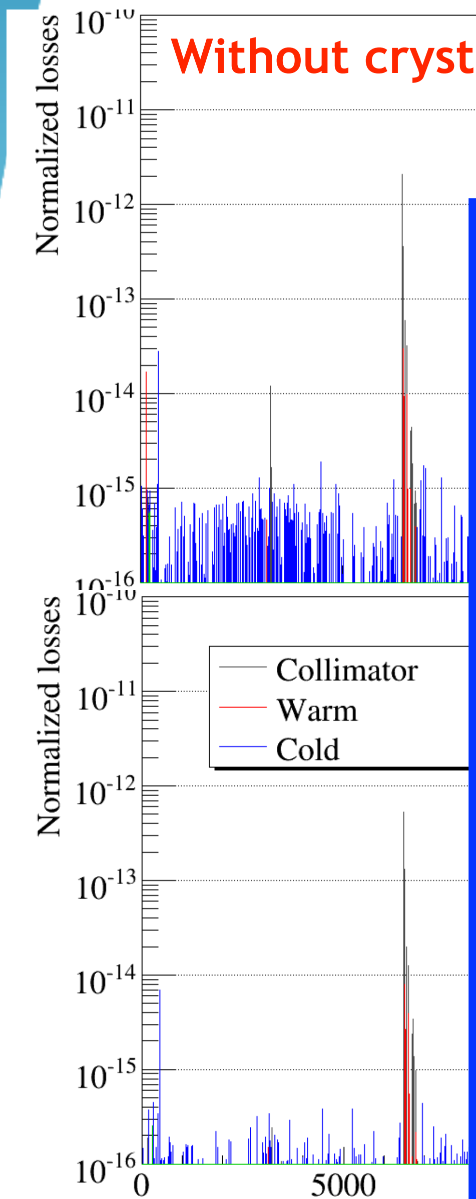


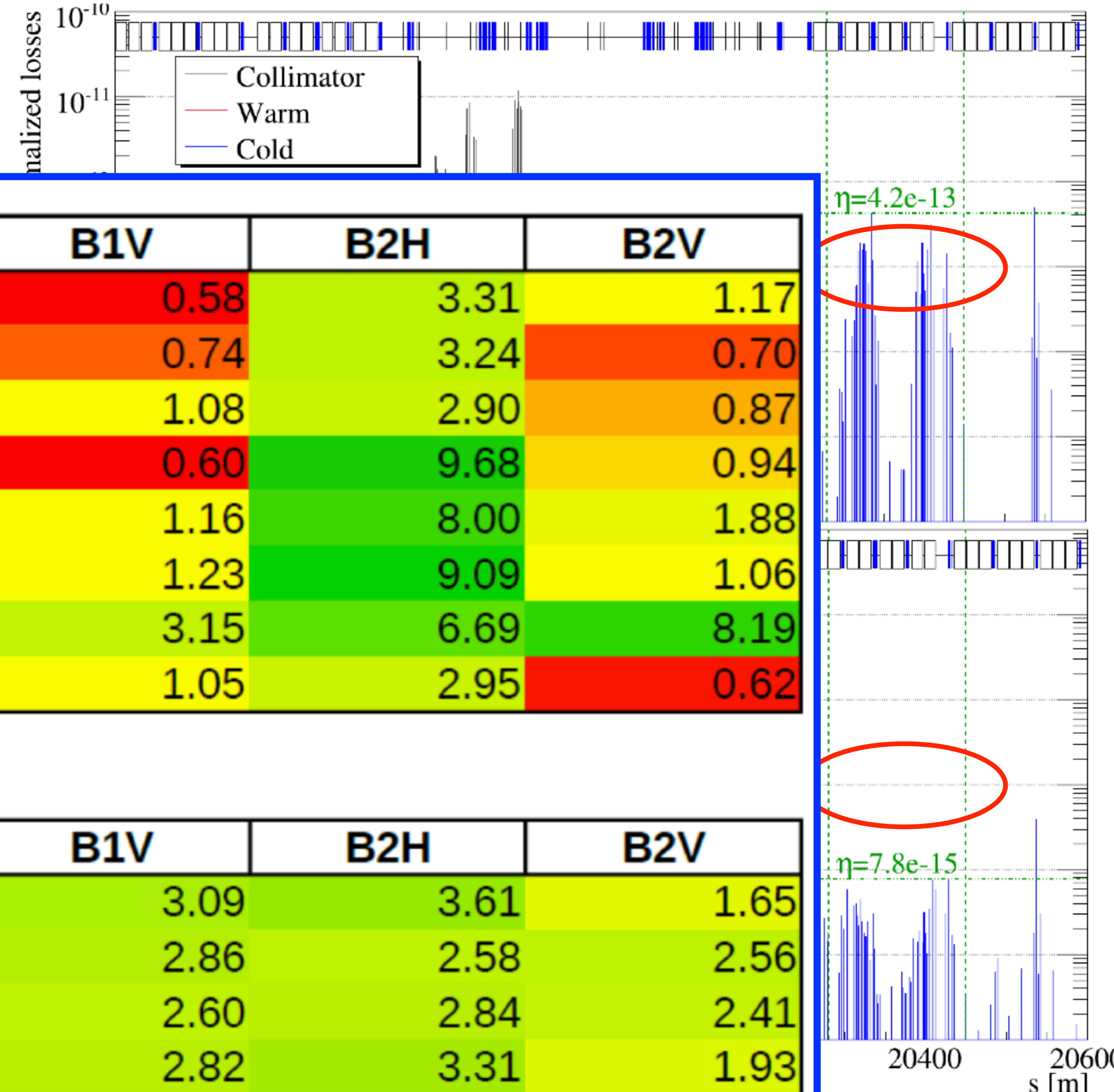
- Overall reduction of losses around the ring.
- Tested with high ions intensities (~600 bunches)!
- Cleaning improvement up to a **factor 7** (more with optimised settings).
- Not the same improvement with all crystals — to be understood.

(measurements available for a broad variety of settings)

Collimation cleaning for Pb ion beams

Full ring | *Betatron cleaning region*





MD

	B1H	B1V	B2H	B2V
cry w/ TCLAs @ 10	8.26	0.58	3.31	1.17
cry w/ TCLAs @ 9	5.81	0.74	3.24	0.70
cry w/ TCLAs @ 8	5.65	1.08	2.90	0.87
cry w/ TCLAs @ 7	8.29	0.60	9.68	0.94
cry w/ all @ 6	10.16	1.16	8.00	1.88
cry w/ all @ 7	4.14	1.23	9.09	1.06
cry w/ all @ 8	5.12	3.15	6.69	8.19
cry w/ all @ 9	5.41	1.05	2.95	0.62

Operational settings

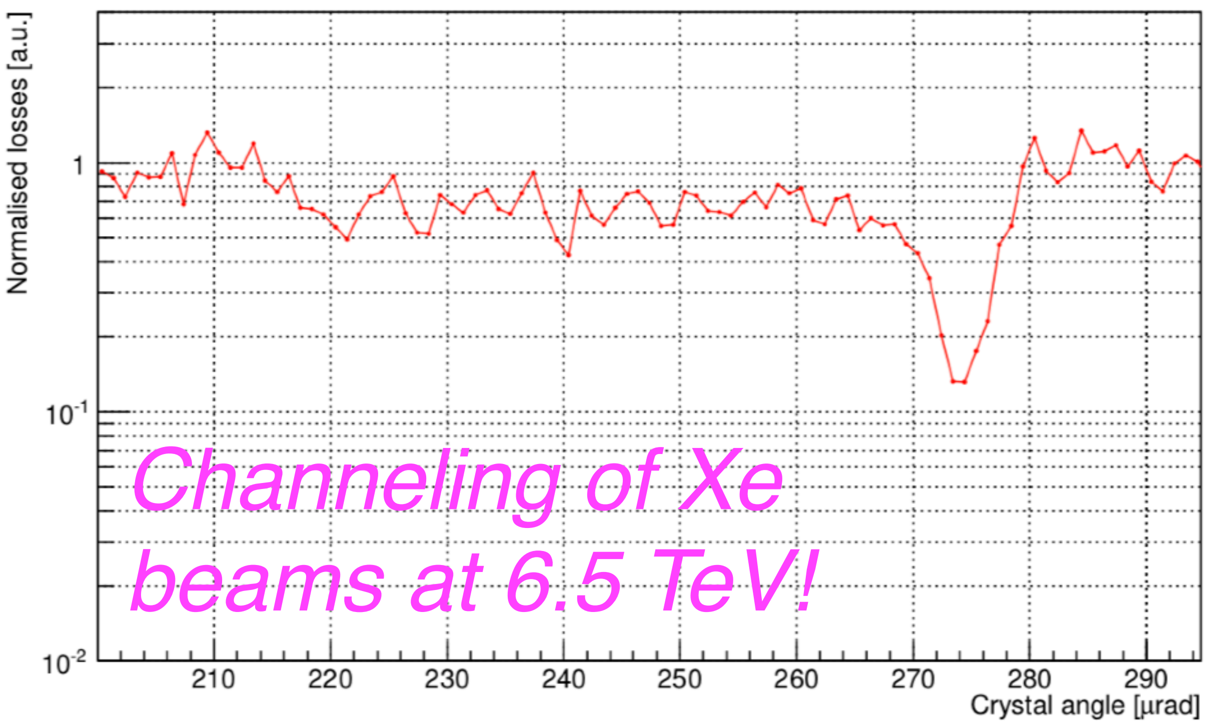
	B1H	B1V	B2H	B2V
cry w/ TCLAs @ 10	7.50	3.09	3.61	1.65
cry w/ TCLAs @ 9	6.16	2.86	2.58	2.56
cry w/ TCLAs @ 8	5.71	2.60	2.84	2.41
cry w/ TCLAs @ 7	6.02	2.82	3.31	1.93

- Overall reduction of losses around the ring.
- Tested with high ions intensities (~600 bunches)!
- Cleaning improvement up to a **factor 7** (more with optimi
- Not the same improvement with all crystals

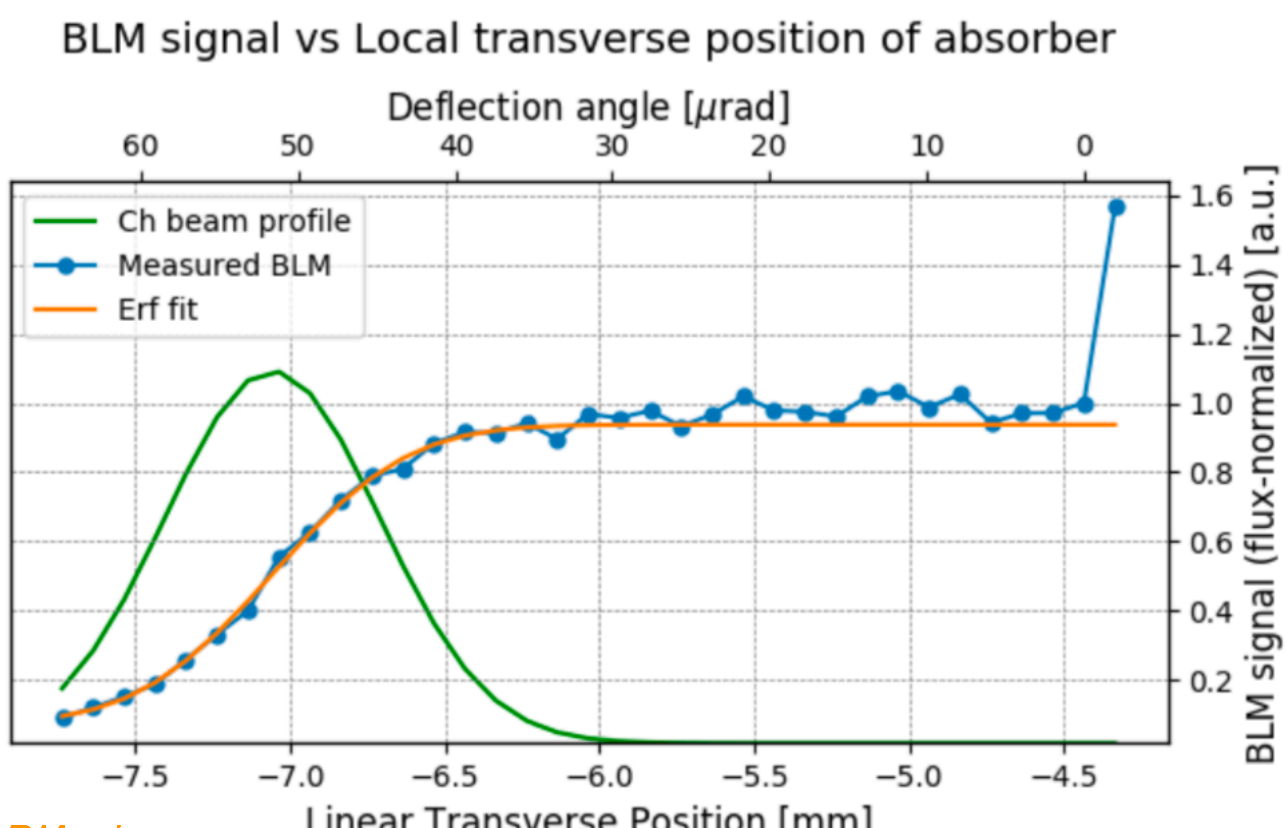
(measurements avail ... ty of settings)

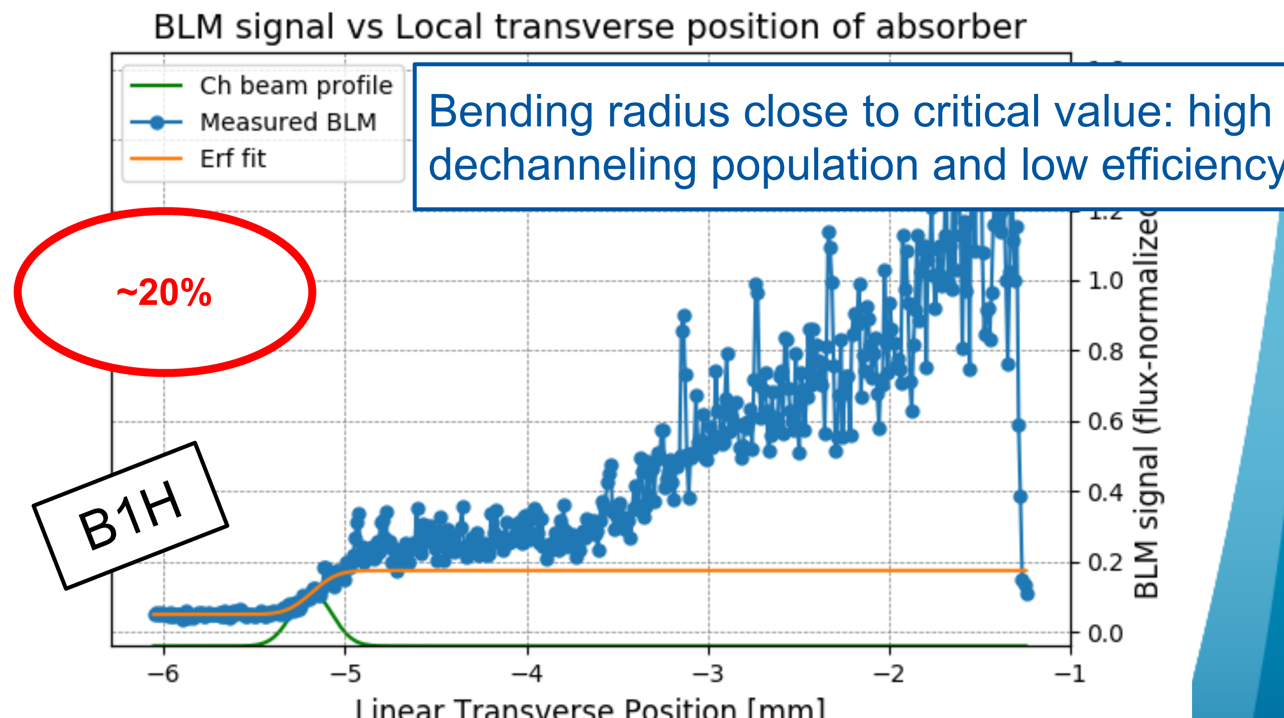
Being considered for the HL-LHC upgrade!

Other measurements of channeling



- Very extensive set of measurements
- Energies up to 6.5 TeV
- Proton, lead and xenon beams
- Continuous channeling during dynamics machine phases (energy ramp, optics changes)
- Channeling of secondary beam halos





M. D'Andrea

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2018 special run "high-β^*" at 450 GeV

Challenges for total p-p cross section measurements

- Short run of only a few days, at injection energy ($s^{1/2}$ = 900 GeV)
- New optics with large colliding beam sized in ATLAS/CMS
- Roman pots of ATLAS-ALFA and TOTEM as close as possible to the beam
- High background rates observed in beam tests, putting in question the feasibility of this run in 2018.

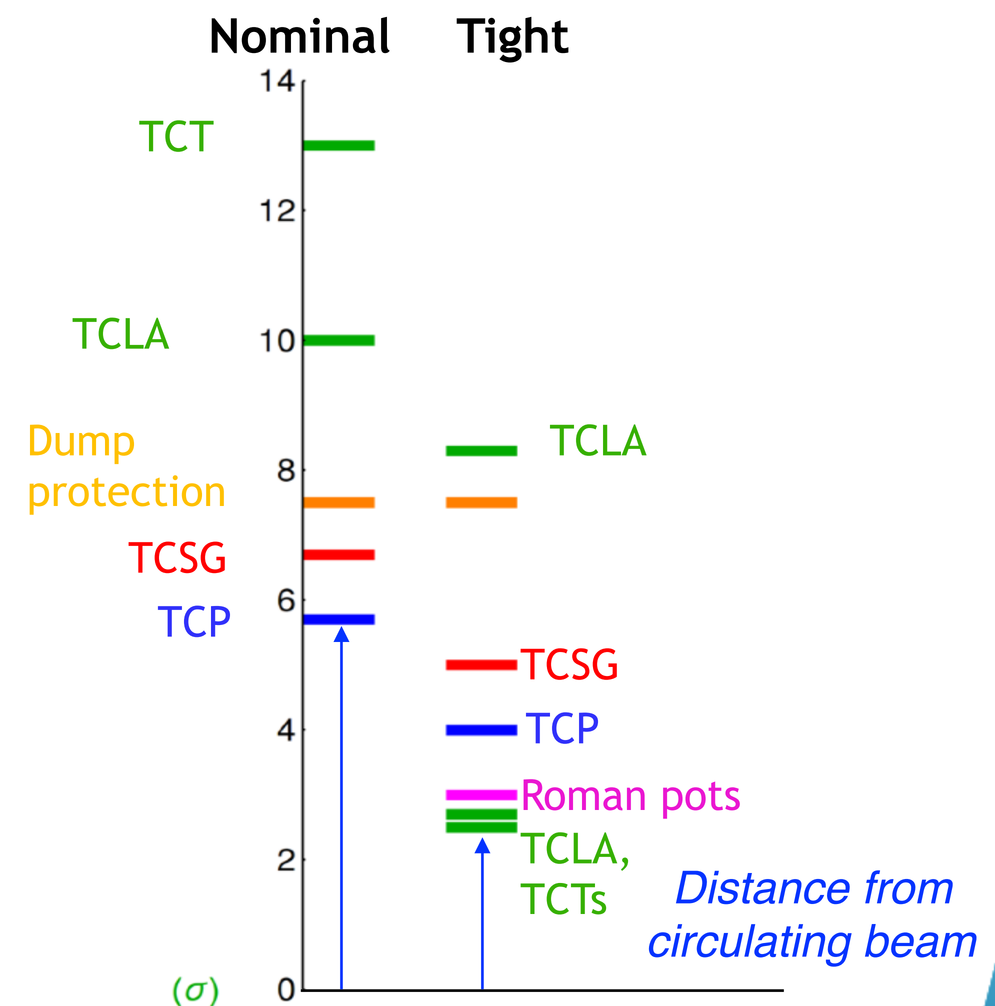
Note: low beam intensities planned for this run!

Two collimation schemes proposed:

1. "Tight settings" scheme with tungsten collimators protecting the pots
2. Crystal collimation at tight settings

Both requiring complex operational procedures.

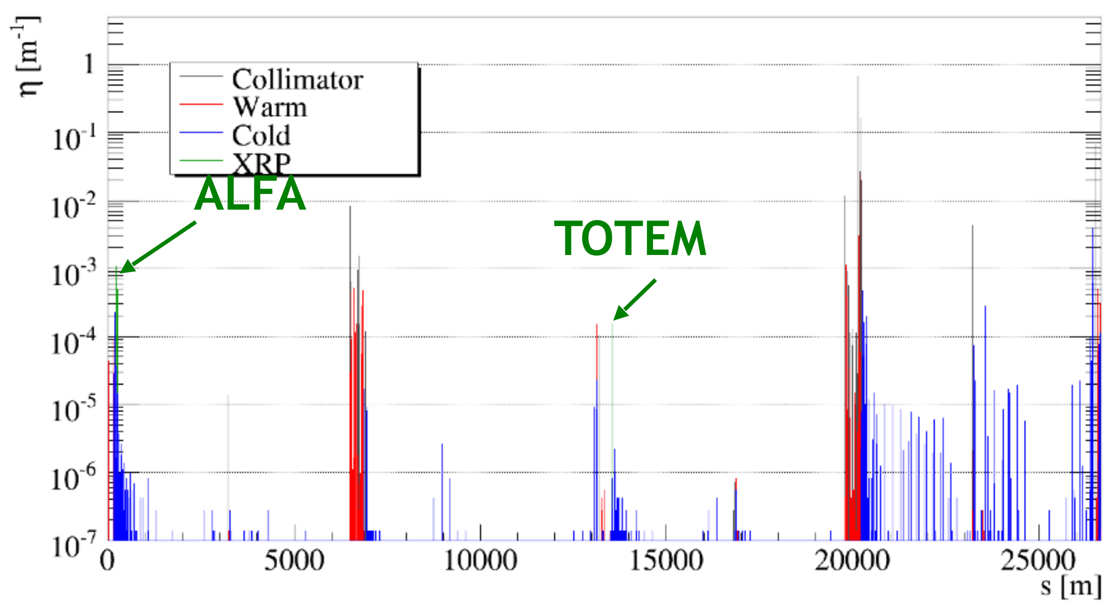
Primary stage at 2.5 σ
Secondary stage at 2.7 σ
Roman Pots at 3 σ
Tightest collimation ever in the LHC!



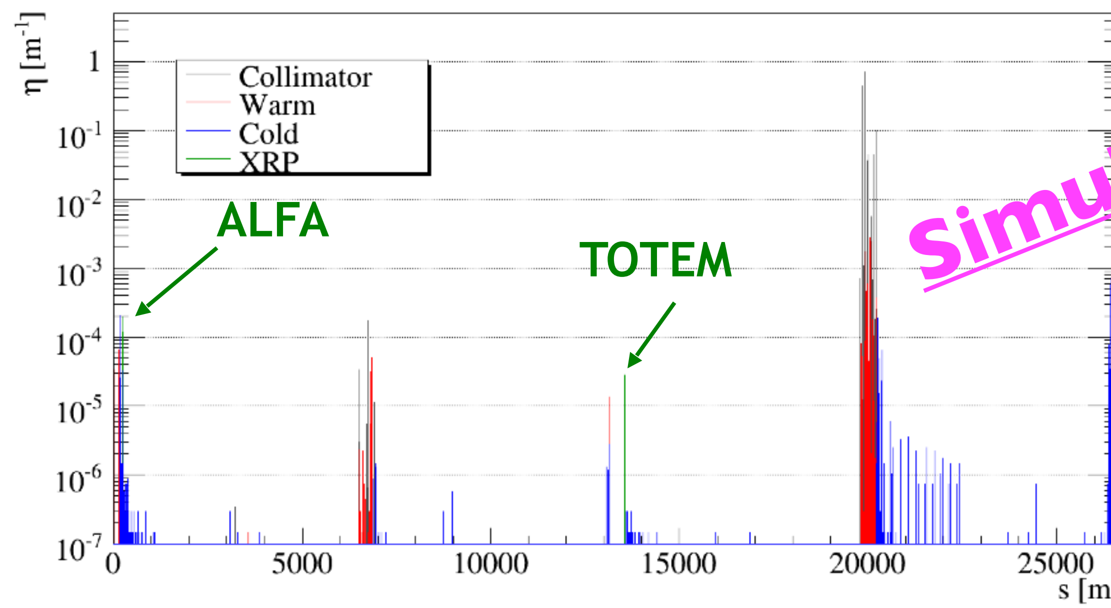
R. Bruce

Reduced background with crystals

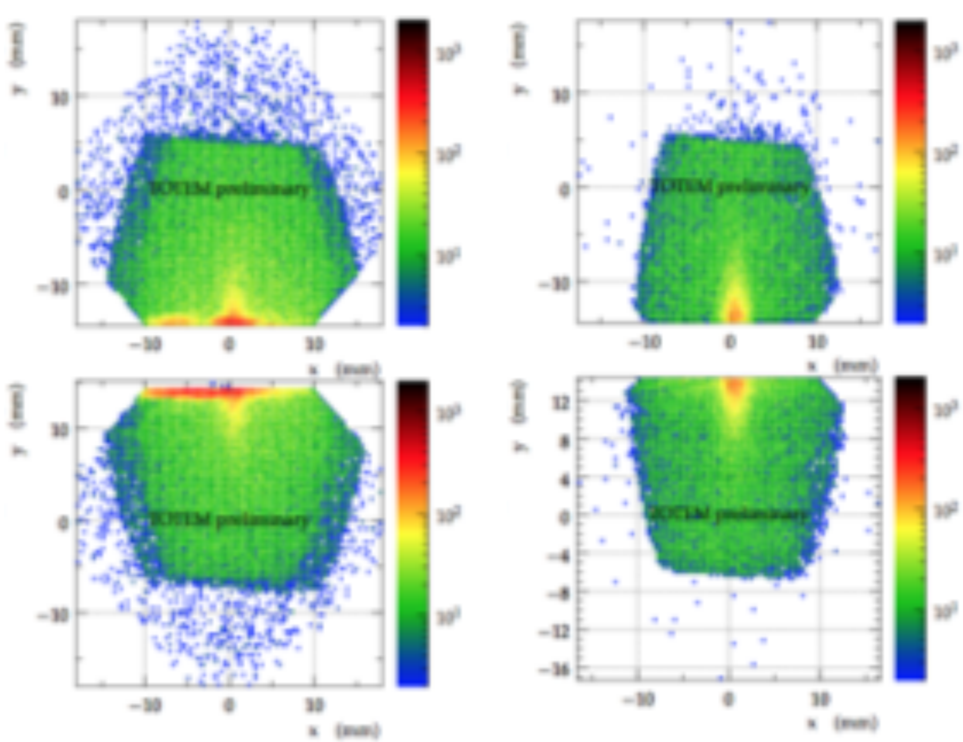
Conventional collimation



Crystal collimation



Standard **Crystal**



Courtesy of TOTEM (preliminary)

With crystal collimation:

— Significant background suppression for TOTEM!

Much simplified analysis, lower data rejection.

— ATLAS-ALFA: <u>problematic</u> distributions at some pots

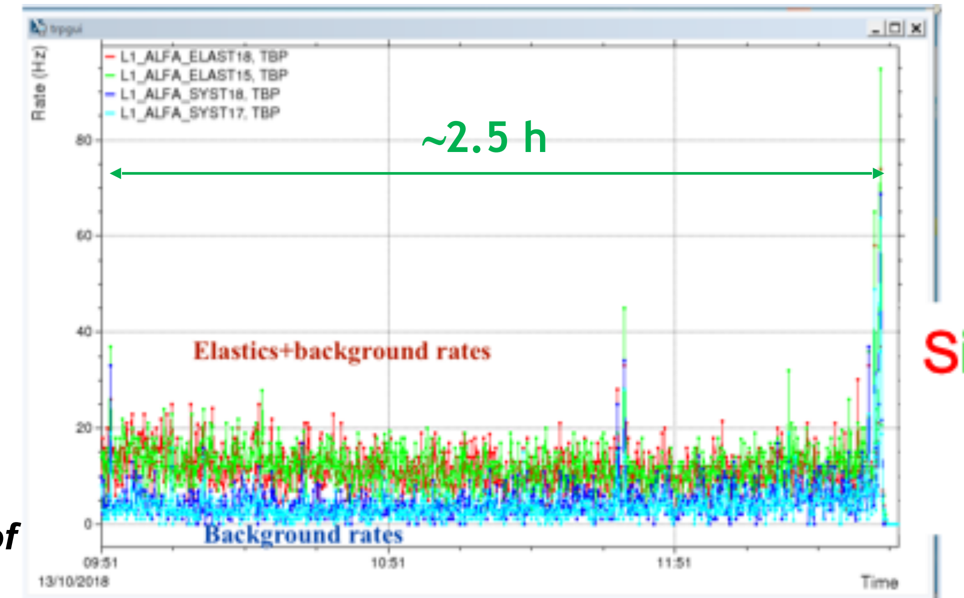
Understood later in simulations how to fix this, but not in time for the short data taking period.

— Both experiments acknowledged a significant bckg reduction as a function of time, with no need for frequent re-shaping of beam halos!

Background evolution in time

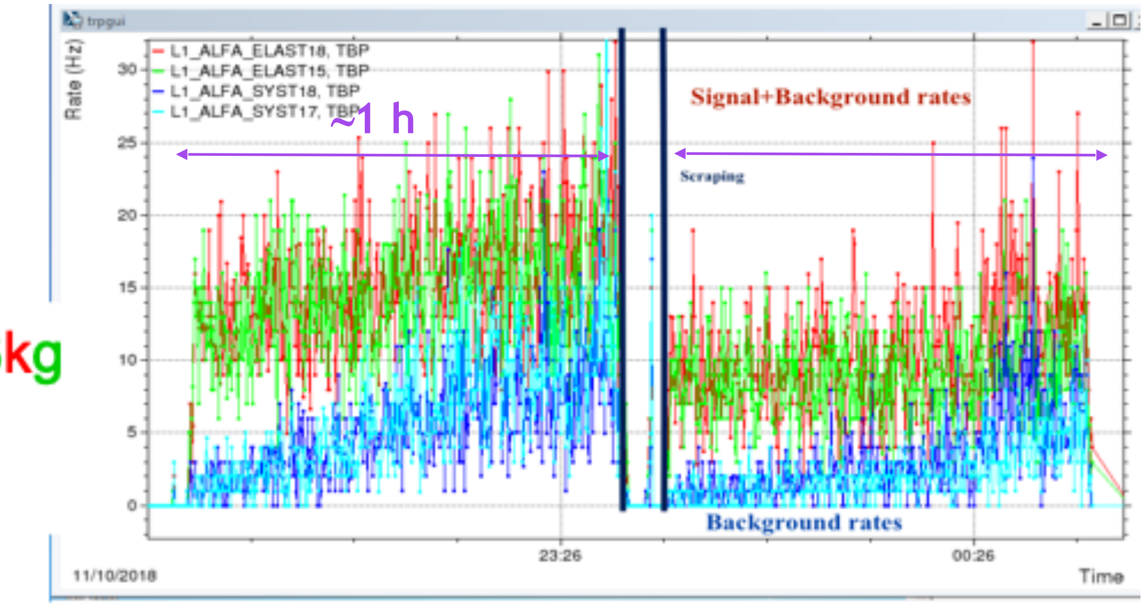
Crystal collimation

Standard collimation

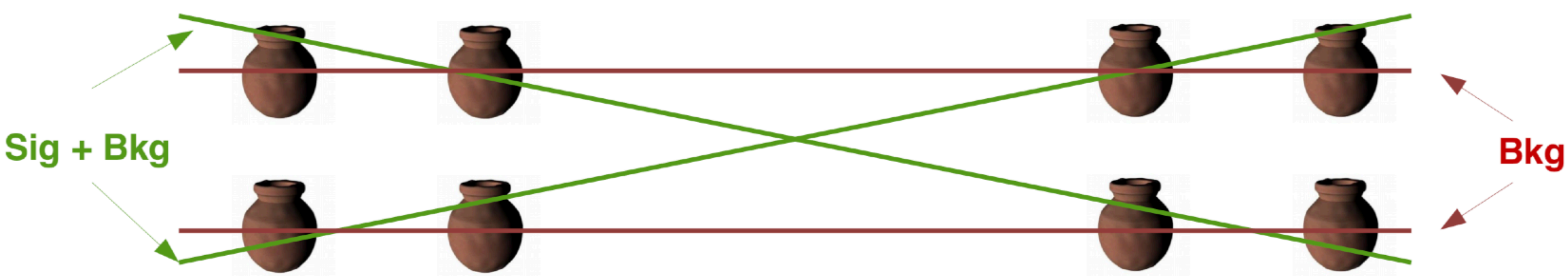


Signal+Bkg

Bkg



Courtesy of ATLAS (preliminary)



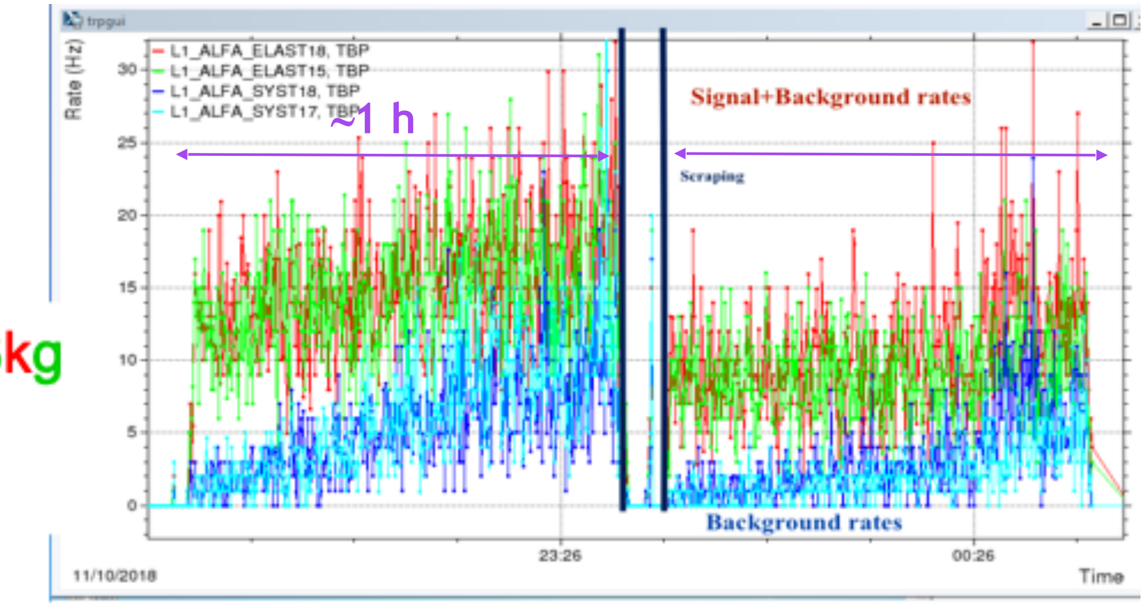
Scheme by C. Schwicz

Background evolution in time

Crystal collimation

Courtesy of ATLAS (preliminary)

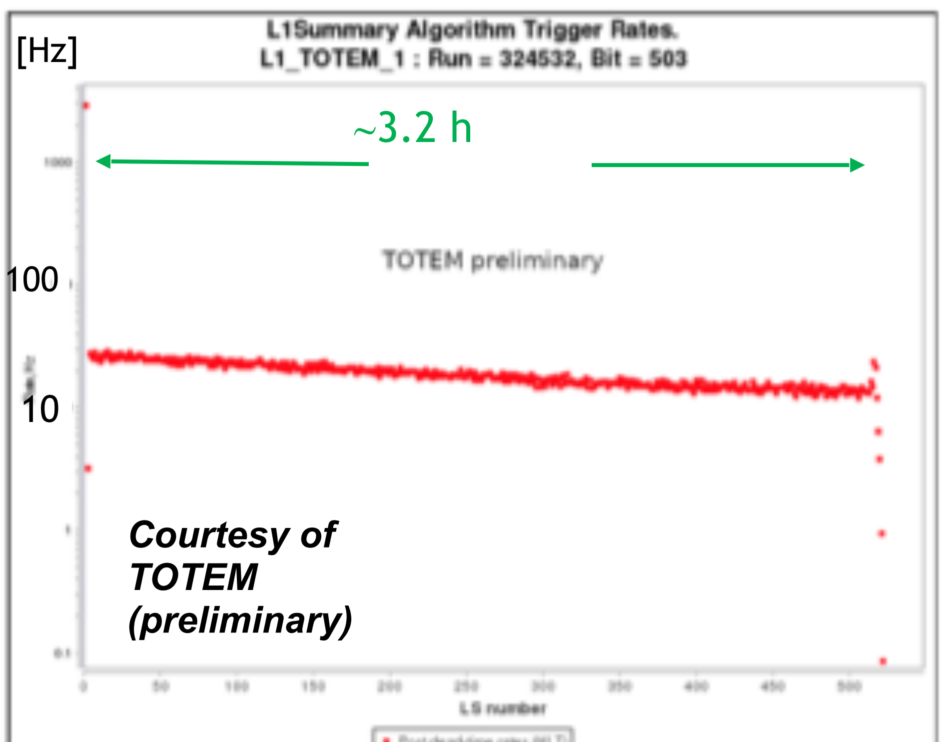
Standard collimation



Signal+Bkg

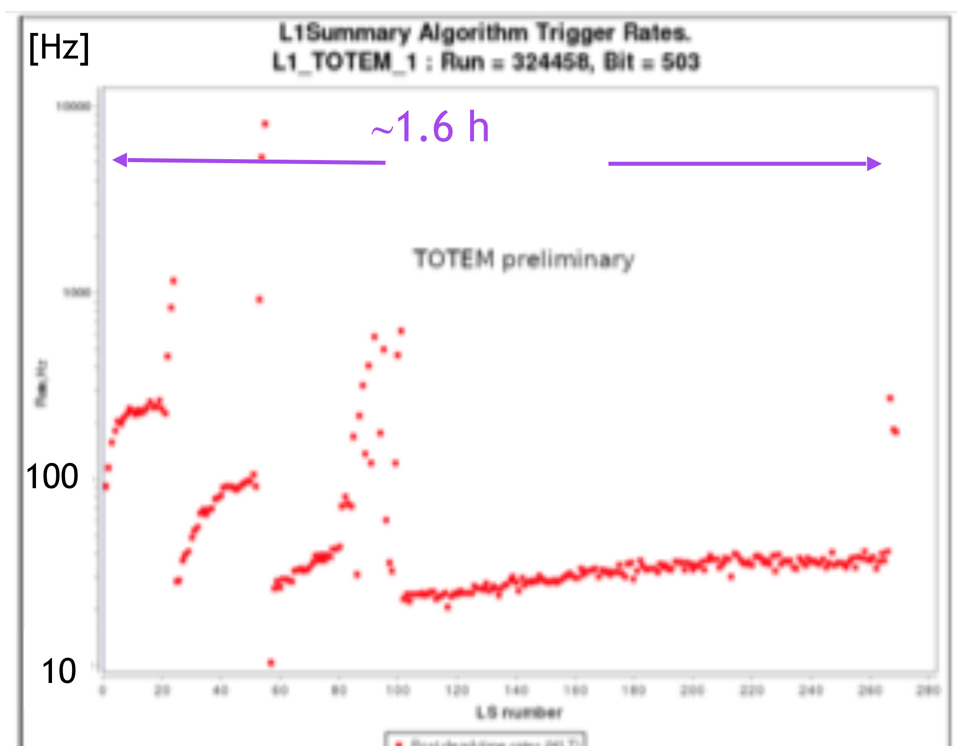
Bkg

Crystal collimation



Courtesy of TOTEM (preliminary)

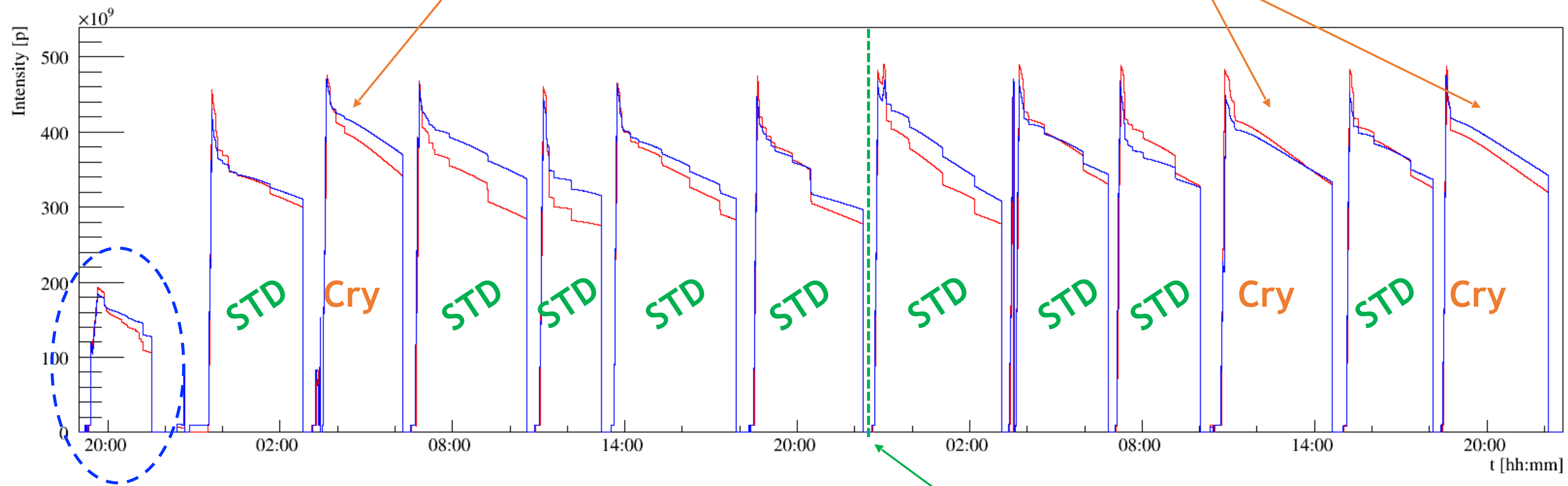
Conventional collimation



Overall view of the high-β^* run

No need for frequent scraping when crystal collimation is used!

D. Mirarchi



1 setup fill: confirmed alignment STD and Cry coll.

Re-align needed for STD
Bad bkg to TOTEM following fills

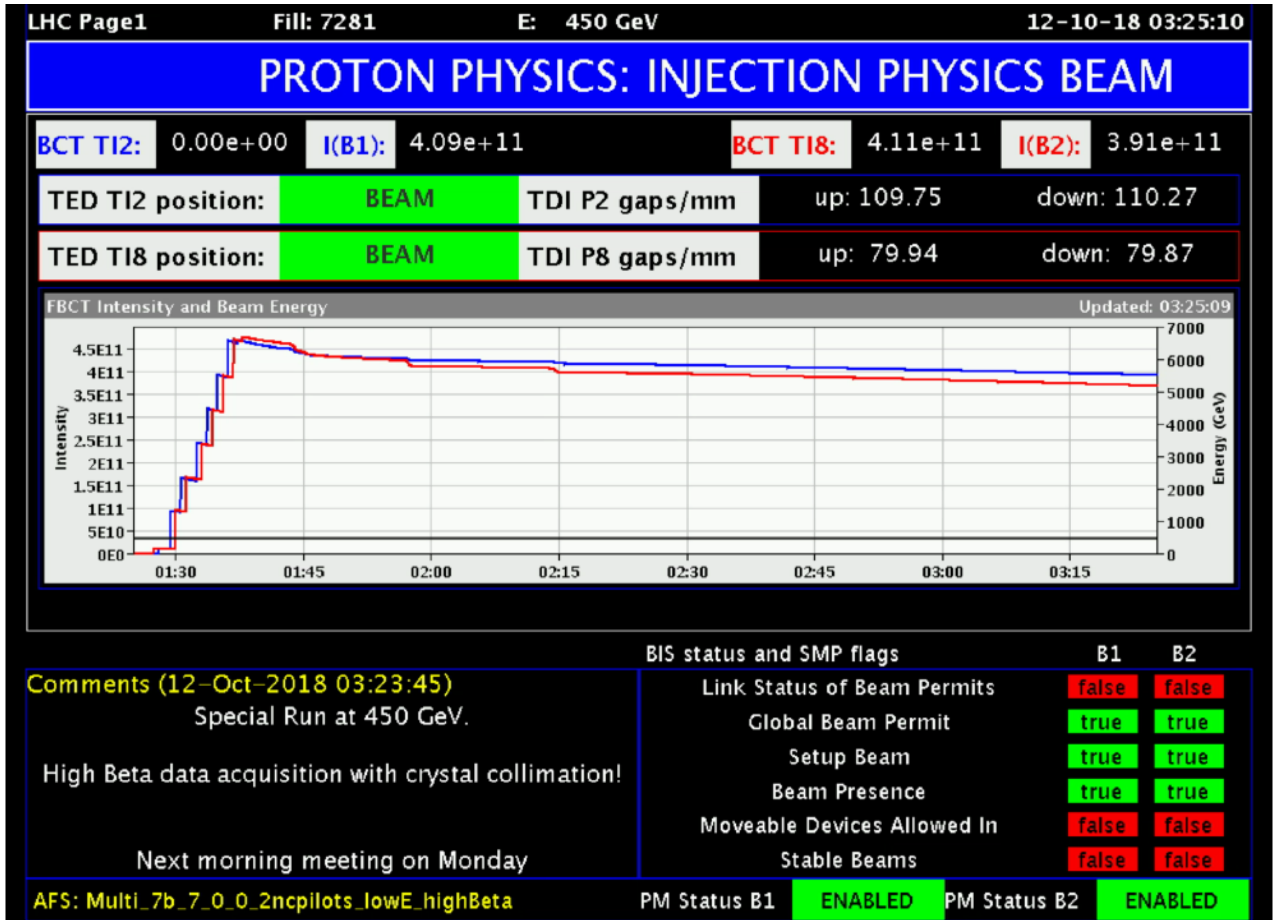
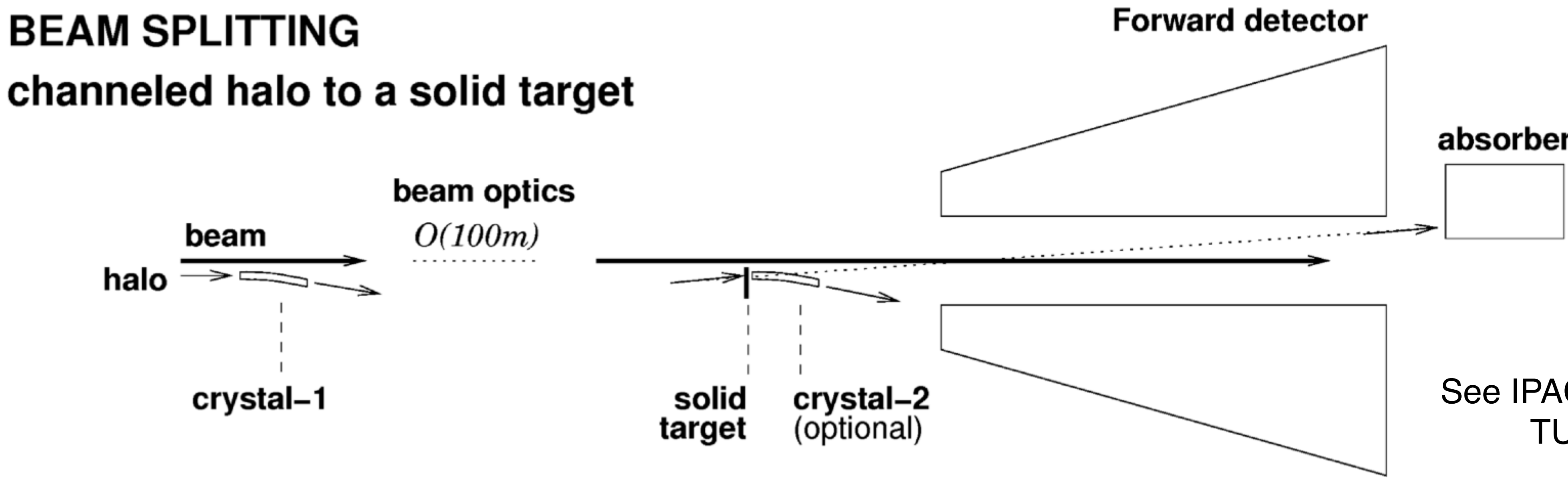


Table of contents

Scheme for halo splitting and fixed targets



See IPAC2018 proceedings, TUPAF045 (link)

Basic idea:

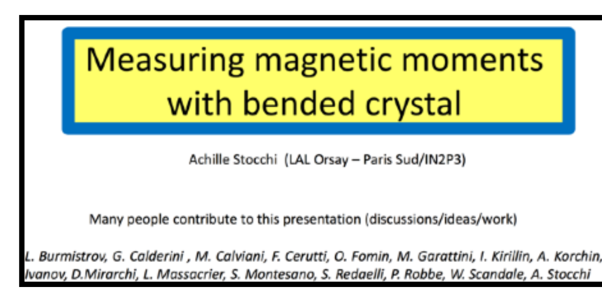
— A crystal inserted in the transverse collimation hierarchy can deflect part of the beam (secondary or tertiary) halos, otherwise disposed of by the collimation system

— Further downstream, this “split halo” impinges onto an in-beam-vacuum fixed target

— Additional absorbers downstream needed to intercept the collision products

— **“Double-crystal setup”: a second crystal is attached to the target to study the magnetic and electric dipole moment precession of short lived barions (Lambda_c)**

Studies are part of the PBC study at CERN: see PBC-FT (“LHC fixed target”) working group.


Measuring magnetic moments with bended crystal

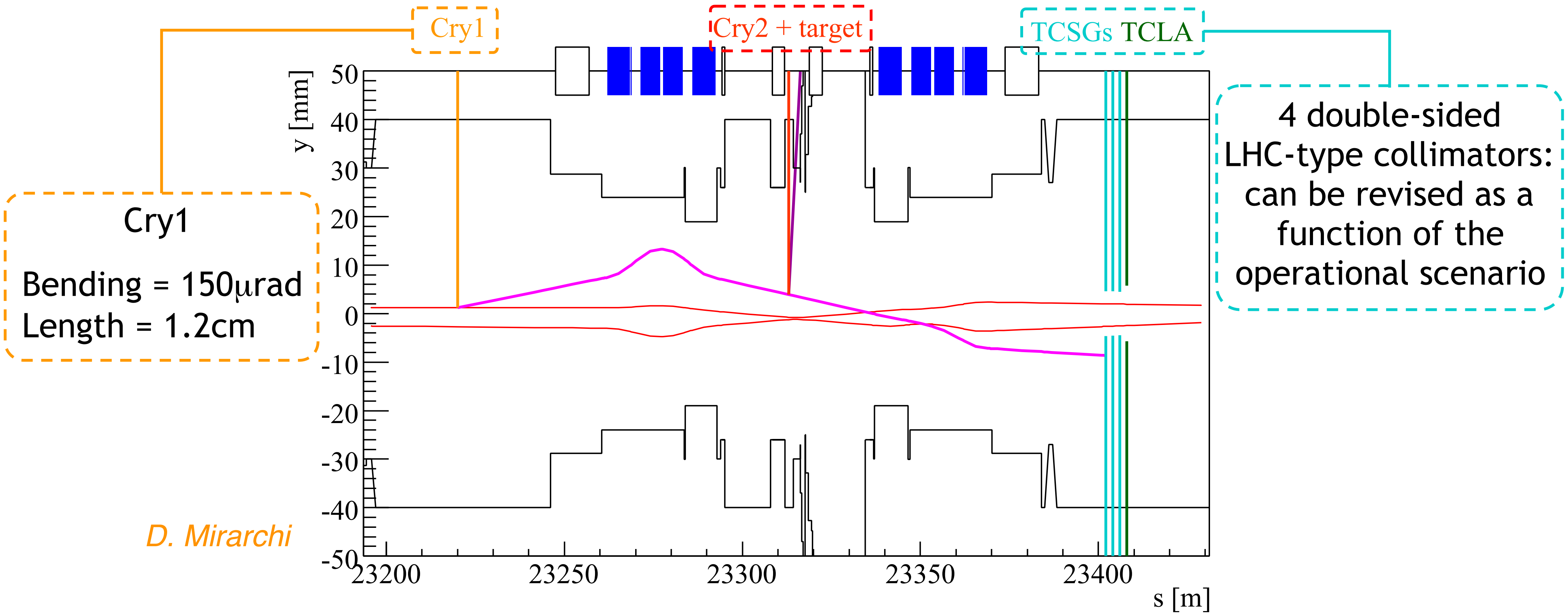
Achille Stocchi (LAL Orsay – Paris Sud/IN2P3)

Many people contribute to this presentation (discussions/ideas/work)

L. Burmistrov, G. Calderini , M. Calviani, F. Cerutti, O. Fomin, M. Garattini, I. Kirillin, A. Korchin, Y. Ivanov, D.Mirarchi, L. Massacrier, S. Montesano, S. Redaelli, P. Robbe, W. Scandale, A. Stocchi

See also: Eur.Phys.J. C77 (2017) no.12, 828

Layouts in LHC IP8 (LHCb)



5 mm long target made of W at 2.4 m from IP8; Cry2 bending angle = 14 mrad, length = 7cm.

— Being studied with the UA9 collaboration and the SELDOM team. Under evaluation by LHCb (not yet approved).

— The PBC-FT team is actively working on a final assessment of achievable protons on target for measurements of MDM and EDM. WG summary document out this summer.

— Some members of ALICE Collaboration are studying a similar layout, with a conventional target and no second crystal (see ESPP proposal: **https://cds.cern.ch/record/2671944**) Interested also in using this concept with heavy ion beams,

— Studying also alternative layouts in the LHC ring, see for example IR3 (arXiv:1906.08551).

Conclusions

- Reviewed the main results obtained with bent crystals at the high-energy frontier at the LHC.
  - A 4-crystal scheme was available during the LHC Run II at 6.5 TeV.
  - Extensive beam tests were done: proton beams, Pb ion beams, Xe ion beams.
  - Driven by the study of upgraded beam halo collimation.
- Very promising results obtained for beam halo cleaning.
  - Observation of channeling at unprecedented beam energies, showing that we master the technology to control angles with the required accuracy.
  - Promising performance with heavy ion beams, being considered for the upgrade!
- In 2018, we had a first operational use of crystal collimation in a physics run, to reduce backgrounds for the p-p cross section
  - High-β^* run in 2018 profited from the availability of crystals for low backgrounds.
- Simulations combining crystal interactions, optics, aperture and scattering in other collimators are well advanced (for protons).
  - Various developments ongoing for ions.
- Promising results obtained motivated new ideas!
  - New idea of halo splitting being considered for LHC fixed-target implementations.