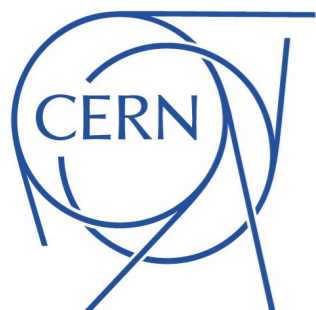


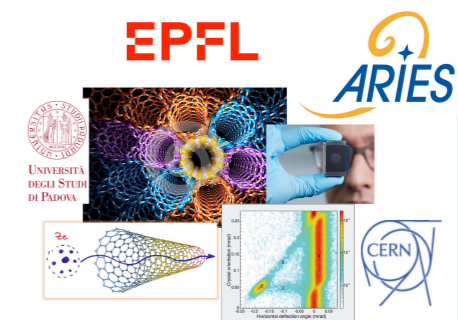
# Application of Crystals for Beam Collimation at the Large Hadron Collider (LHC)

Stefano Redaelli, BE-ABP, on behalf of HL-LHC WP5

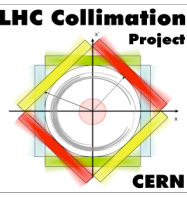


ACN2020: "Applications of Crystals and Nanotubes for Accelerations and Manipulations"

10-11 March, 2020 — EPFL, Lausanne (CH)



# 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 2018 Crystal Collimation Day: <https://indico.cern.ch/event/752062>

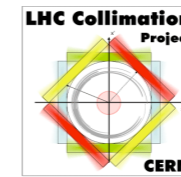
CERN groups involved in these crystal studies:

(support from many: vacuum, diagnostics, operations, services...)



EN  
SMM

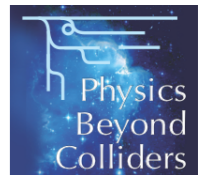
Funding of LHC crystal installation:



UA9 collaboration:



Physics Beyond Collider:



Work on high- $\beta^*$  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

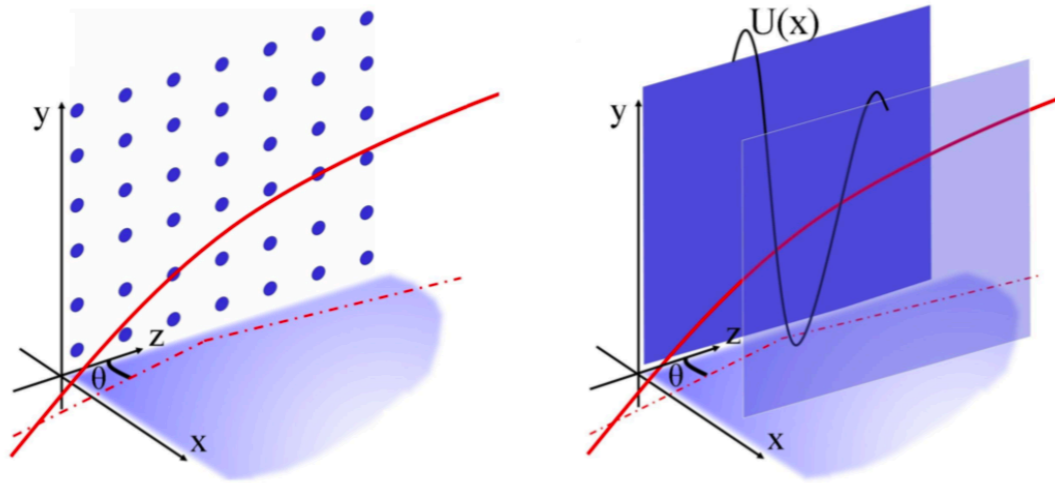
Recent PhD thesis works at CERN (simulations and/or measurements):

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



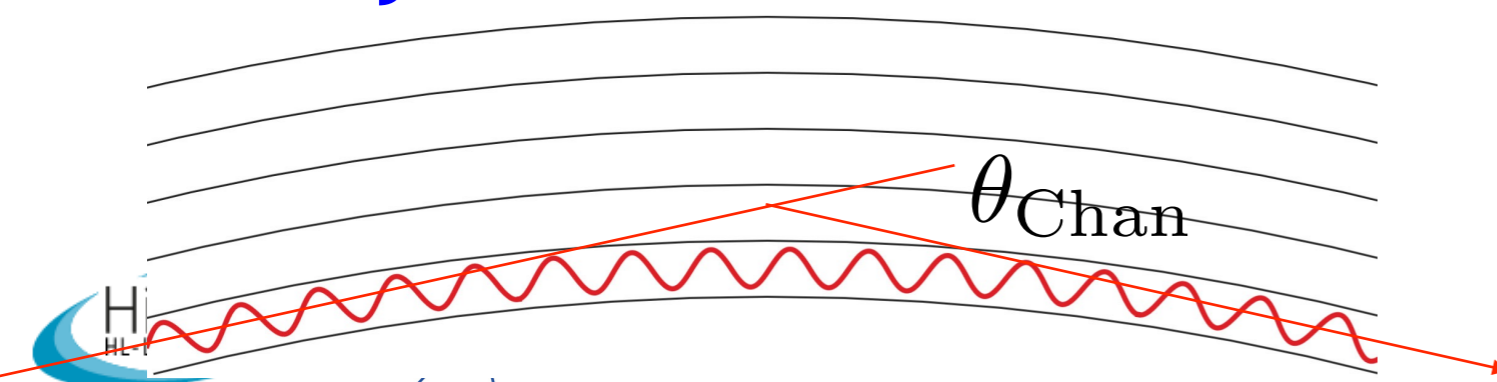
# Planar channeling in bent crystals

Pure crystals with regular lattices



*Straight crystal: hadron oscillate, “trapped” between planes*

**Bent crystal**

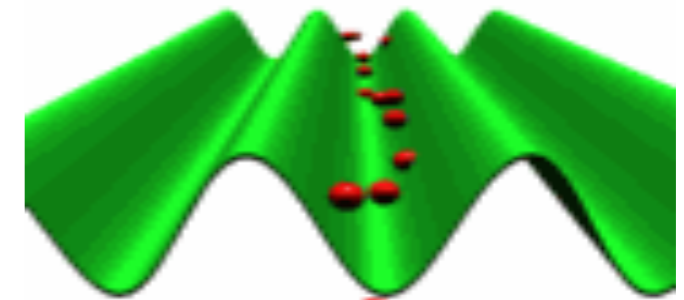


If the protons have  $p_T < U_{max}$



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

Critical angle



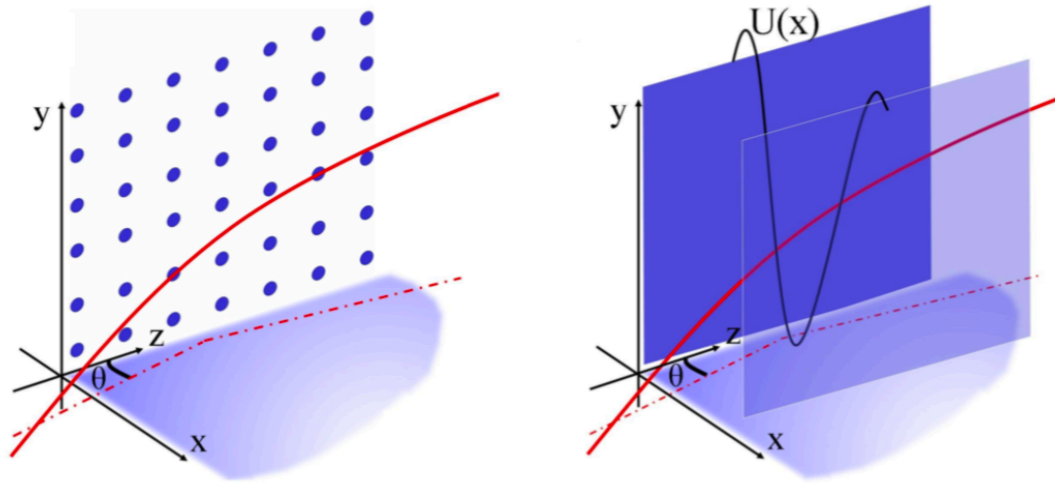
LHC 450 GeV	=	9.4 $\mu$ rad
LHC 6.5 TeV	=	<b>2.4 <math>\mu</math>rad</b>
FCC-hh 50 TeV	=	0.9 $\mu$ rad

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

Equivalent magnetic field for **50 $\mu$ rad** at **7 TeV** proton beams: **310 T** (4 mm crystal)

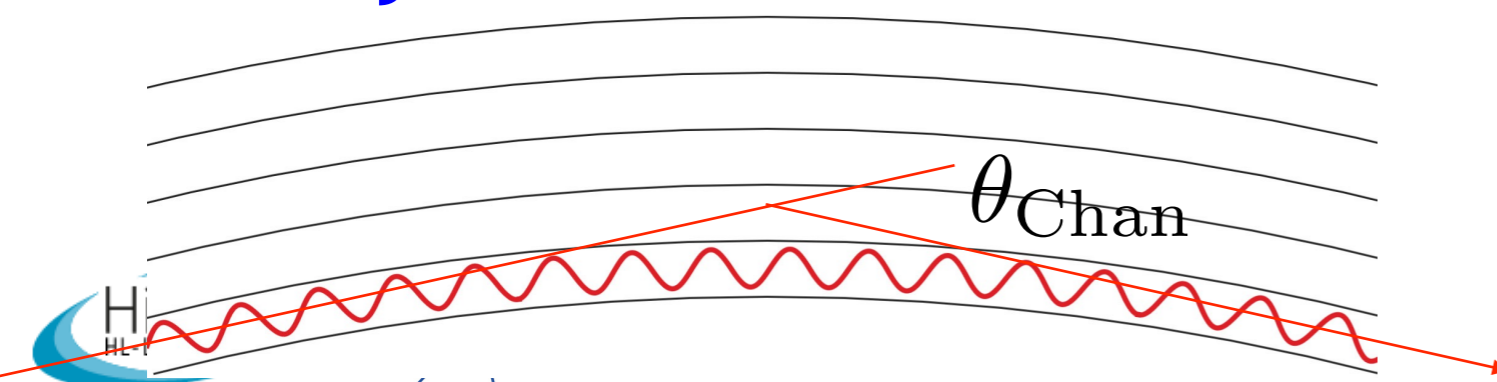
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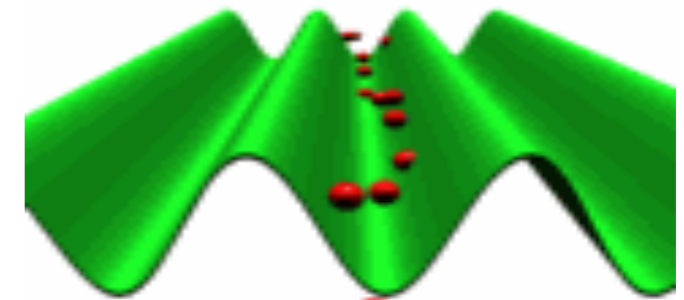


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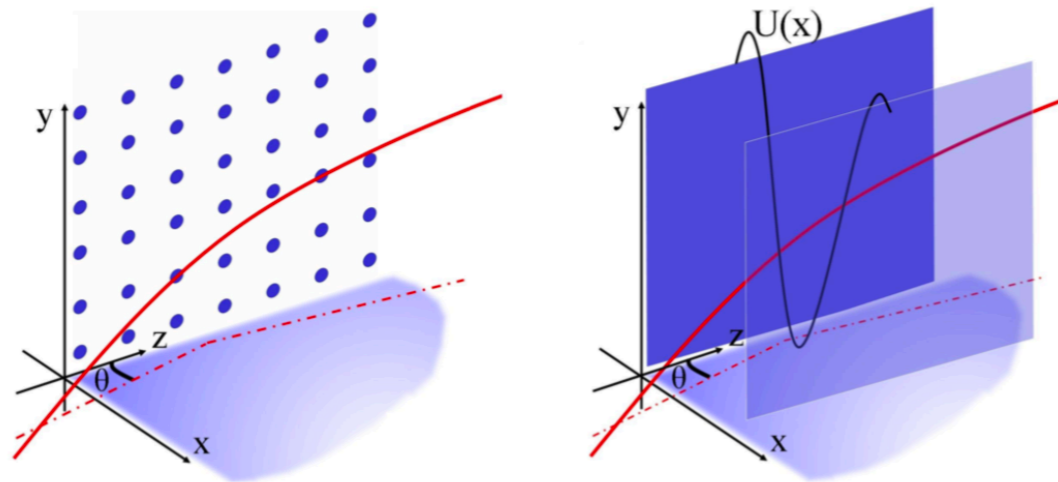
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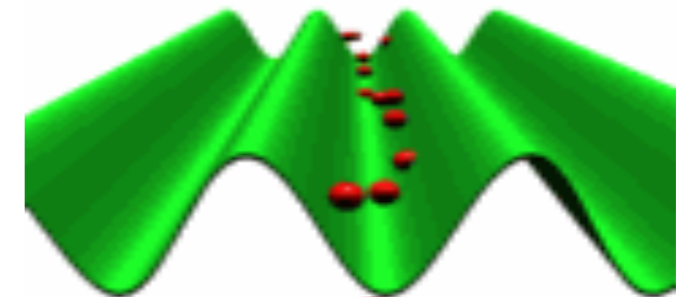


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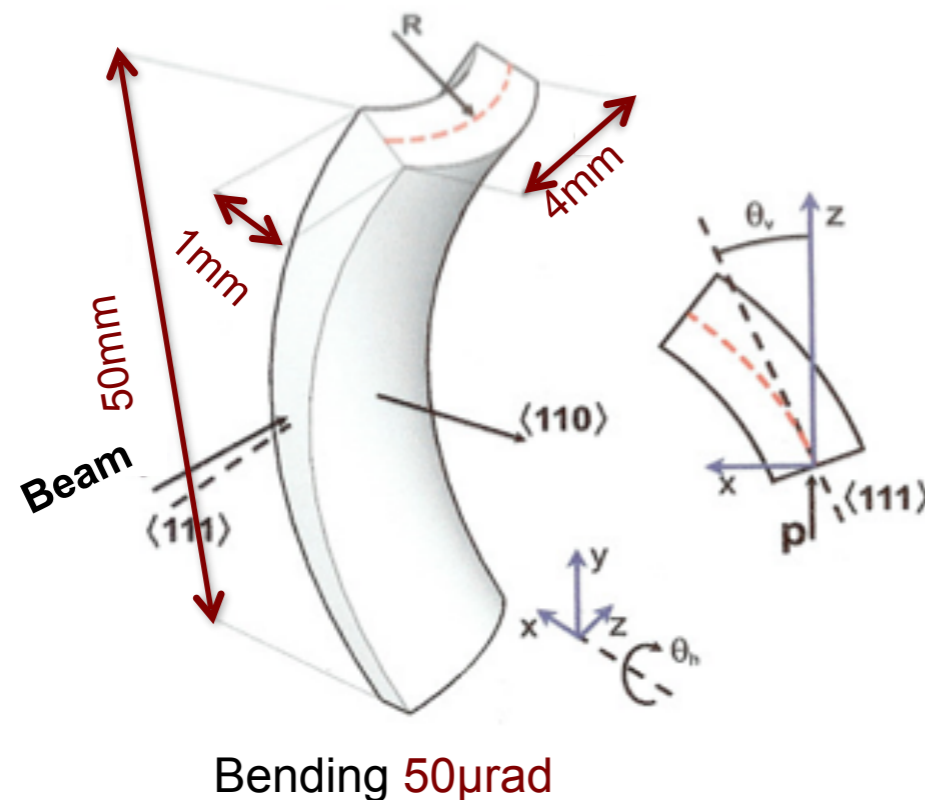
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LHC design parameters for **Silicon crystals**

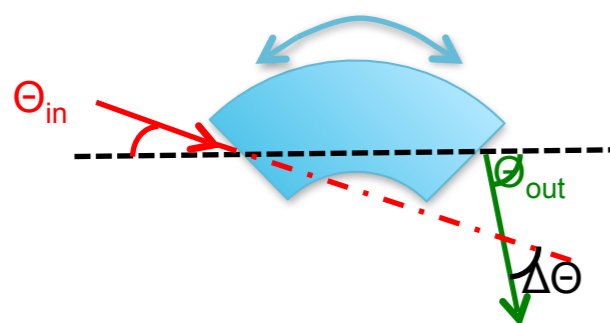
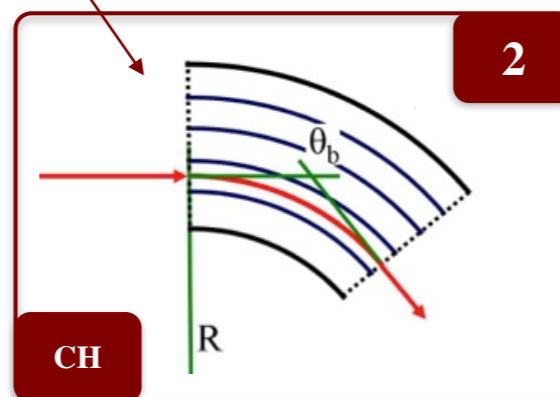
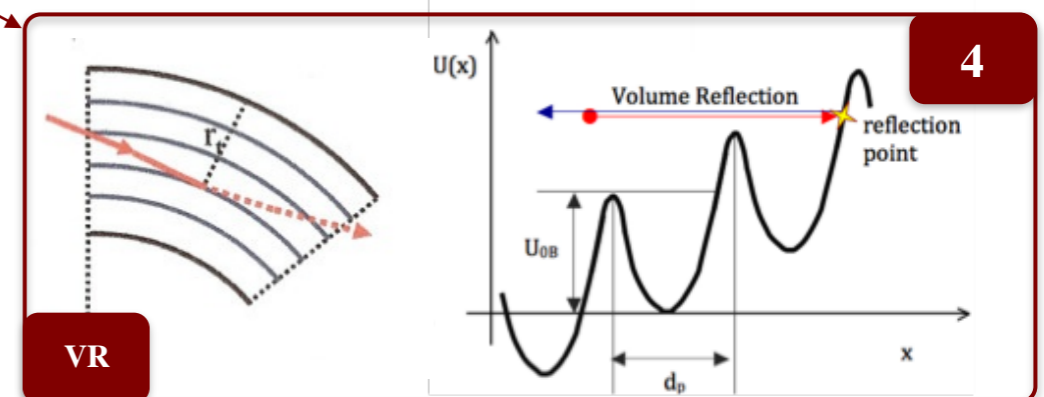
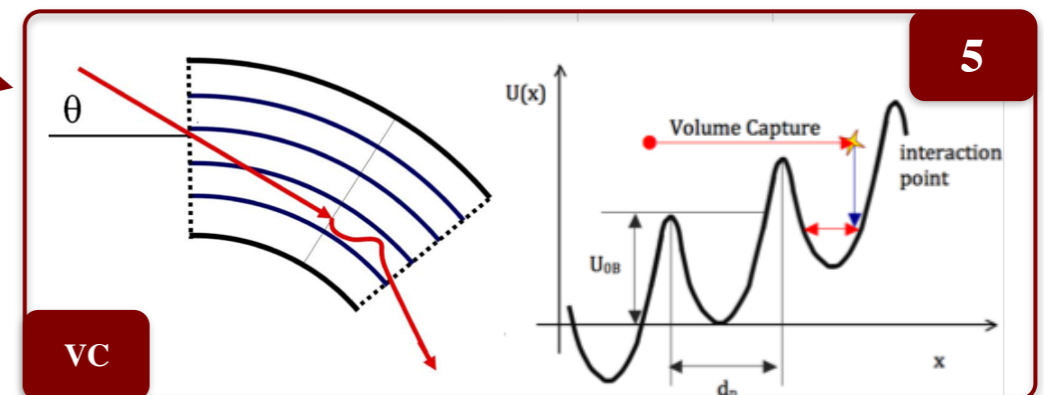
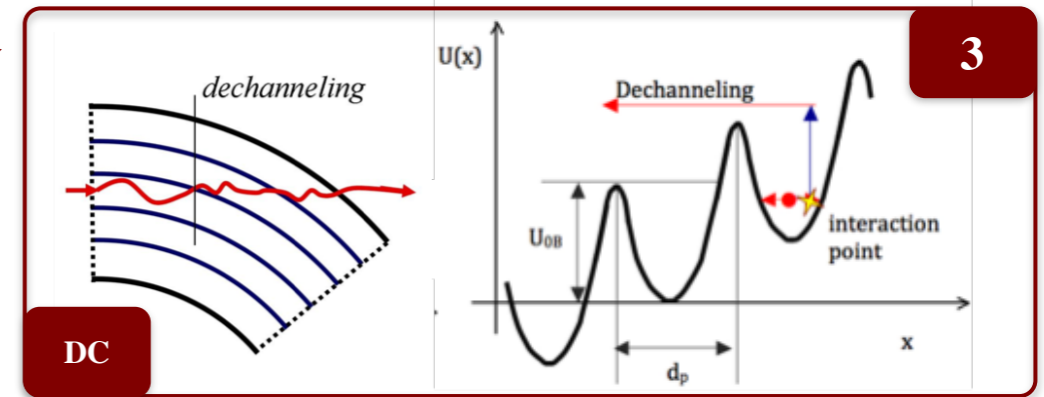
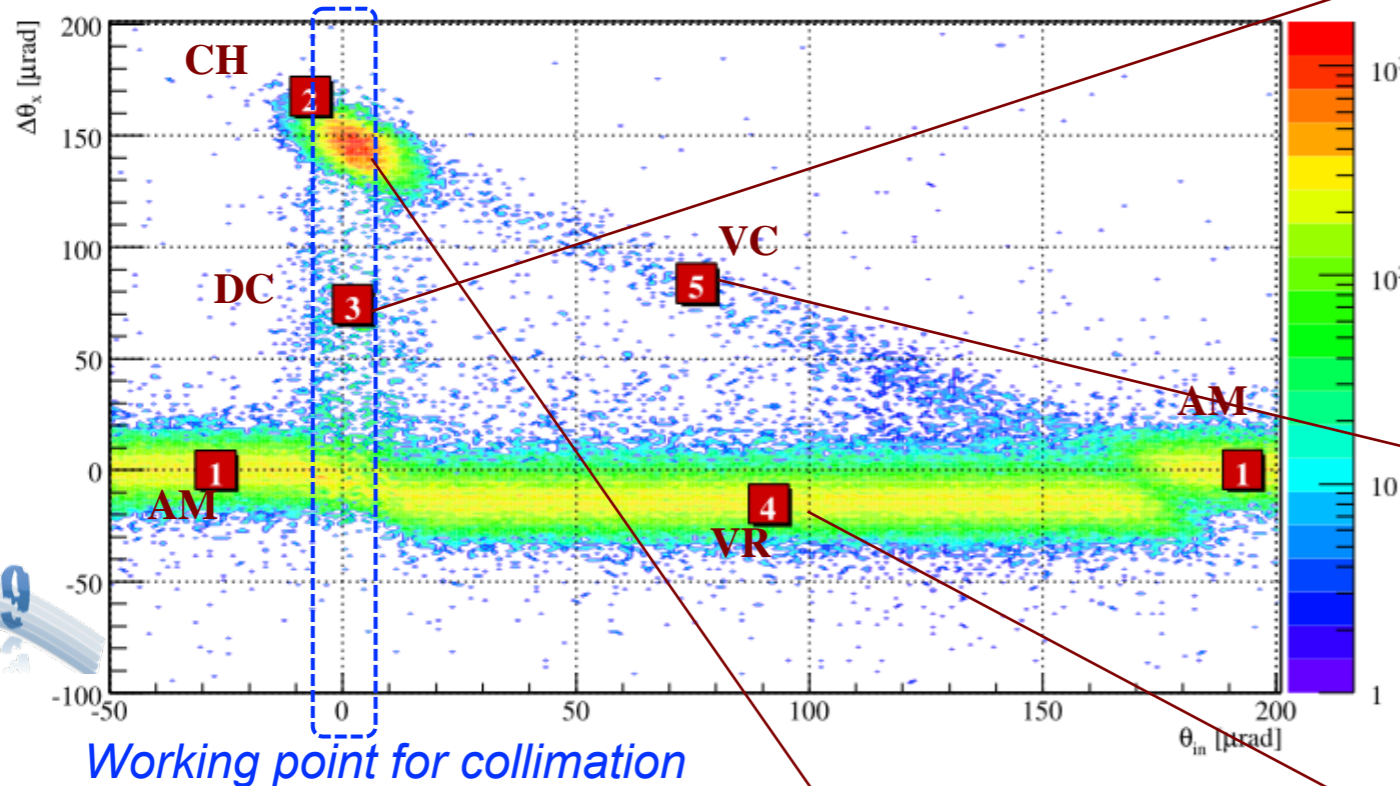


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# Coherent interactions in bent crystals

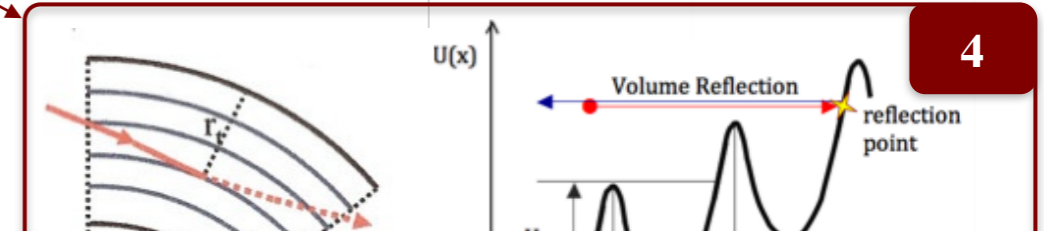
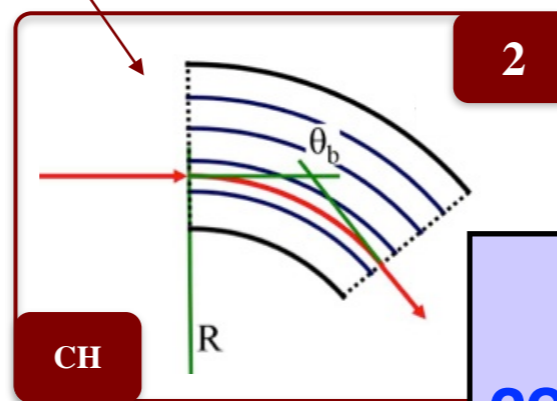
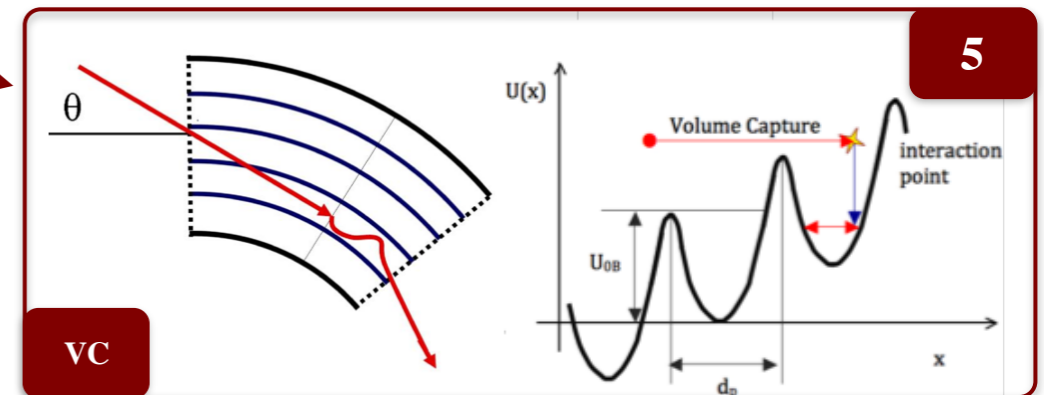
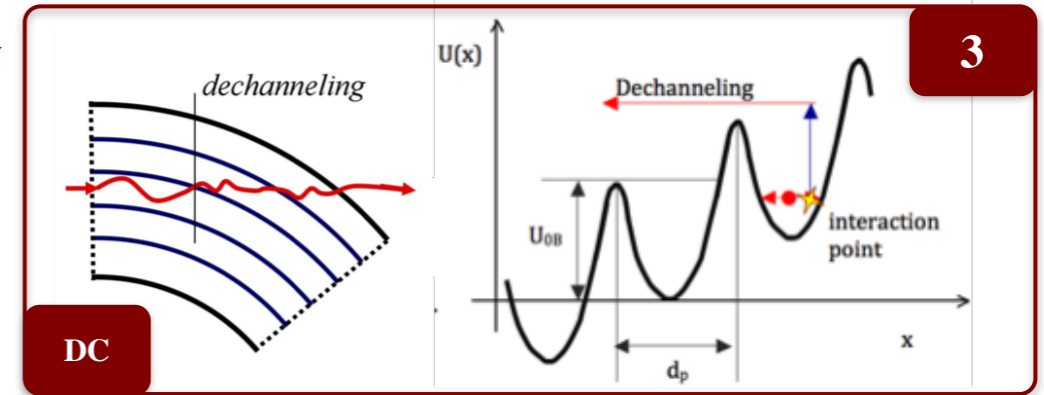
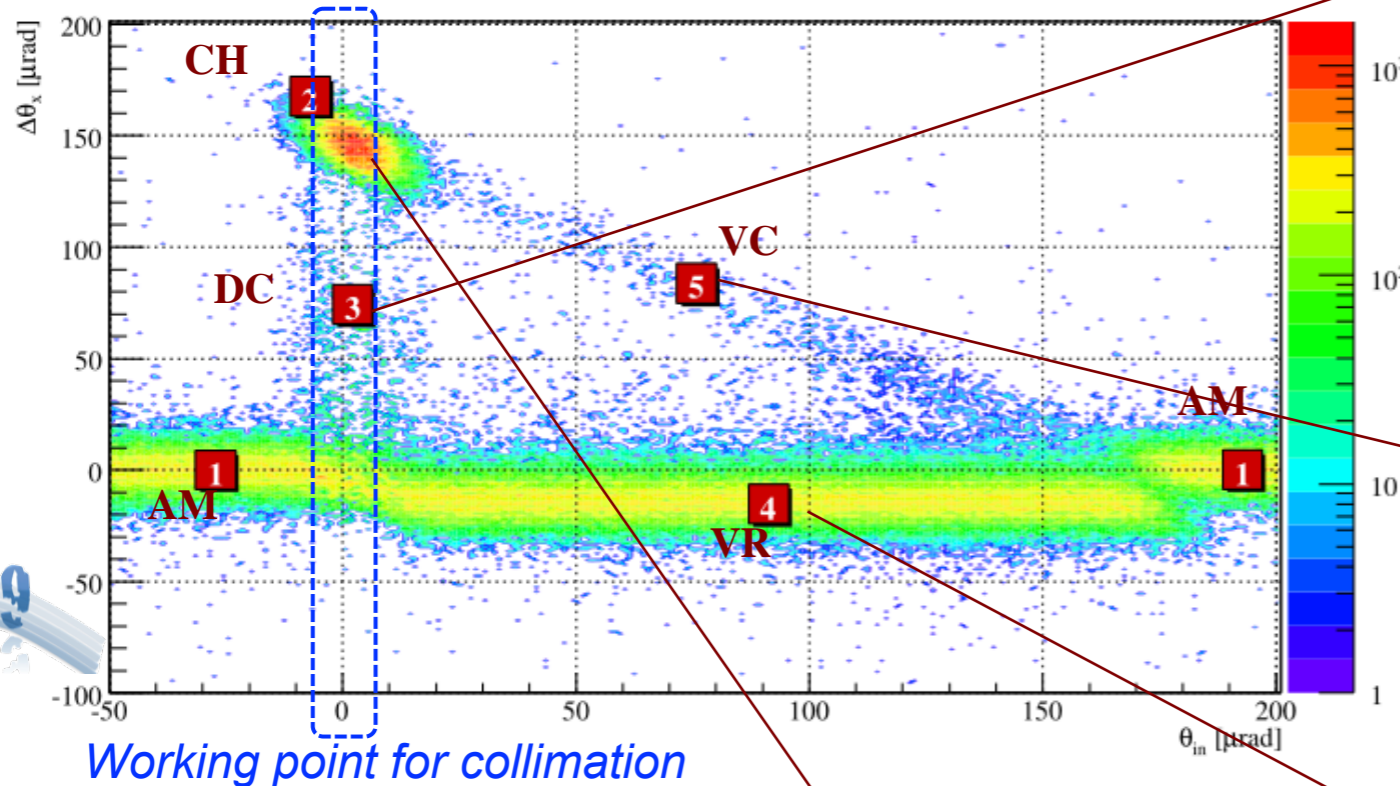
From test beam on the CERN-SPS extraction line H8:  
(in the framework of the UA9 experiment)



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

# Coherent interactions in bent crystals

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



The application to LHC beam collimation rely on “crystal channeling”

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

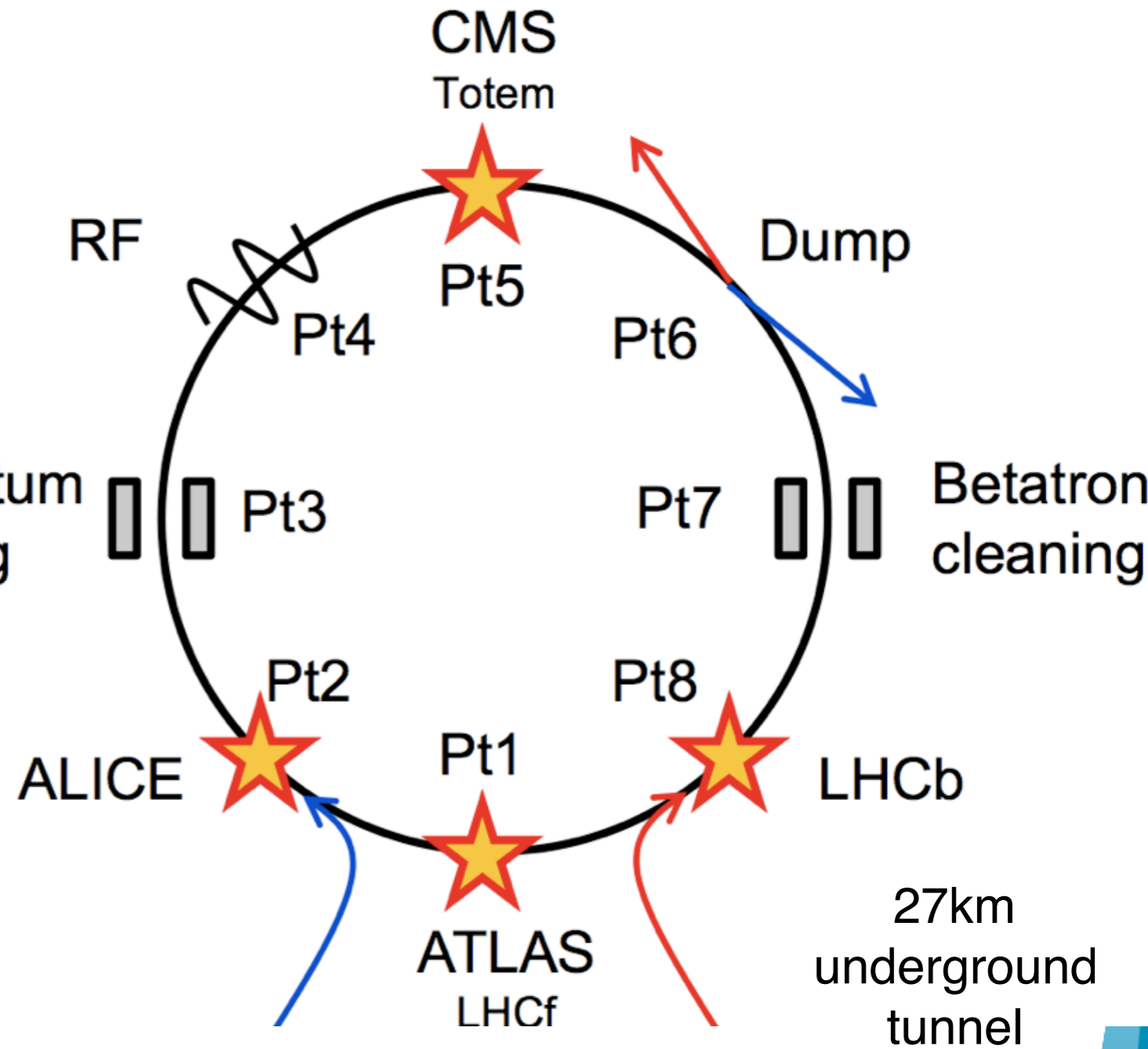
# Table of contents

- **Introduction**
- **Crystal collimation at the LHC**
  - LHC collimation challenges
  - Crystal collimation layouts
  - Highlight results from LHC Run II
- **Low-background run in 2018**
  - 450 GeV run for Roman pot physics
  - Crystal collimation to optimise backgrounds
- **Crystals for LHC fixed-targets**
- **Conclusions**

# The Large Hadron Collider

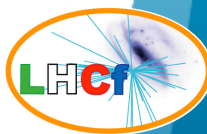
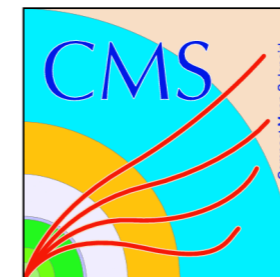
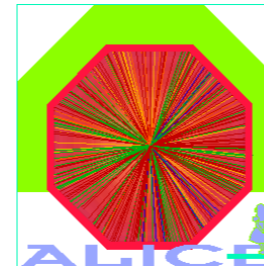
## LHC Layout

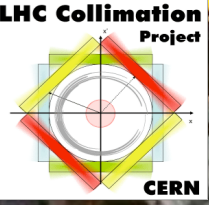
- 8 arcs (~3 km)
- 8 straight sections (~700 m)
- Two-in-one magnet design
- 4 interaction points (IPs):  
IP1, IP2, IP5, IP8
- IP2/IP8: beam injection
- IP6: beam dump region
- IP4: RF (acceleration)
- IP3/IP7: beam cleaning



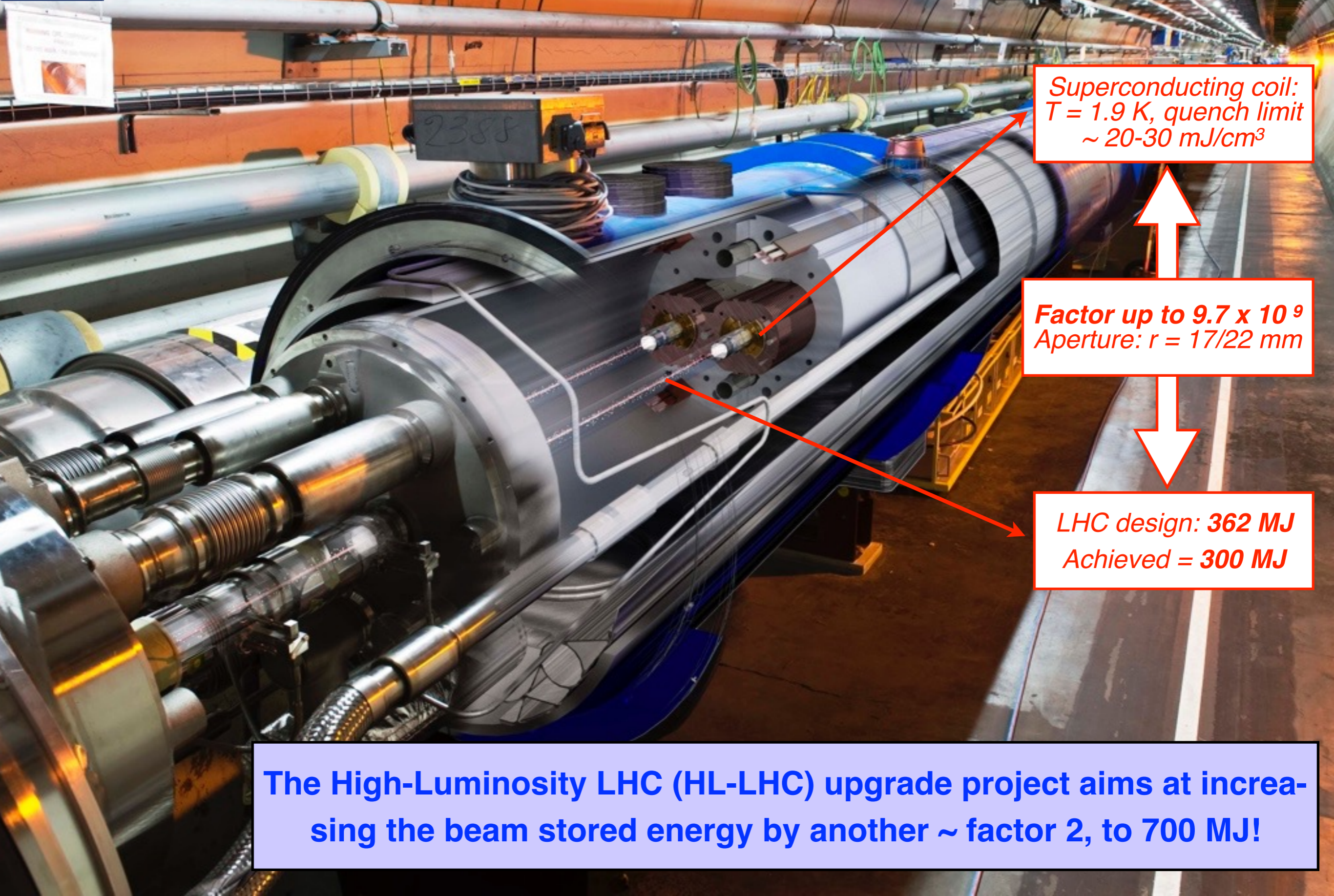
### Nominal LHC parameters

Beam injection energy (TeV)	0.45
Beam energy (TeV)	7.0
Number of particles per bunch	$1.15 \times 10^{11}$
Number of bunches per beam	2808
Max stored beam energy (MJ)	362
Norm transverse emittance ( $\mu\text{m rad}$ )	3.75
Colliding beam size ( $\mu\text{m}$ )	16
Bunch length at 7 TeV (cm)	7.55





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)



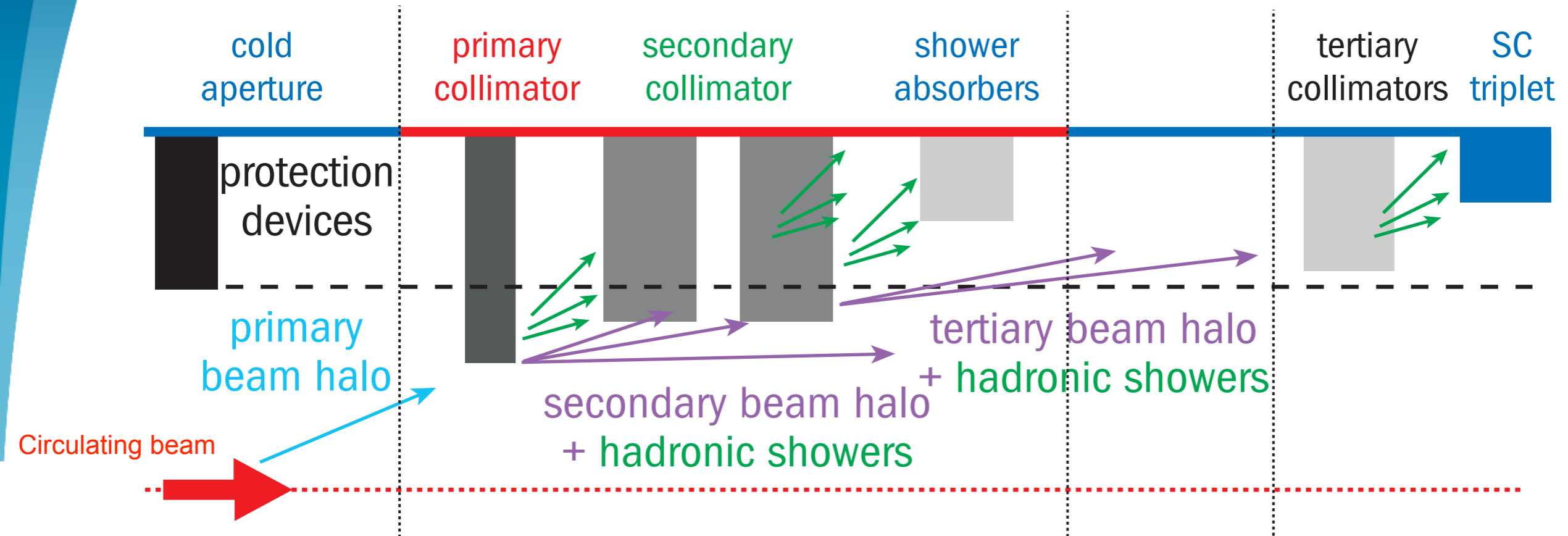
*Superconducting coil:  
 $T = 1.9\text{ K}$ , quench limit  
 $\sim 20\text{-}30\text{ mJ/cm}^3$*

*Factor up to  $9.7 \times 10^9$   
Aperture:  $r = 17/22\text{ mm}$*

*LHC design: 362 MJ  
Achieved = 300 MJ*

**The High-Luminosity LHC (HL-LHC) upgrade project aims at increasing the beam stored energy by another  $\sim$  factor 2, to 700 MJ!**

# LHC multi-stage collimation



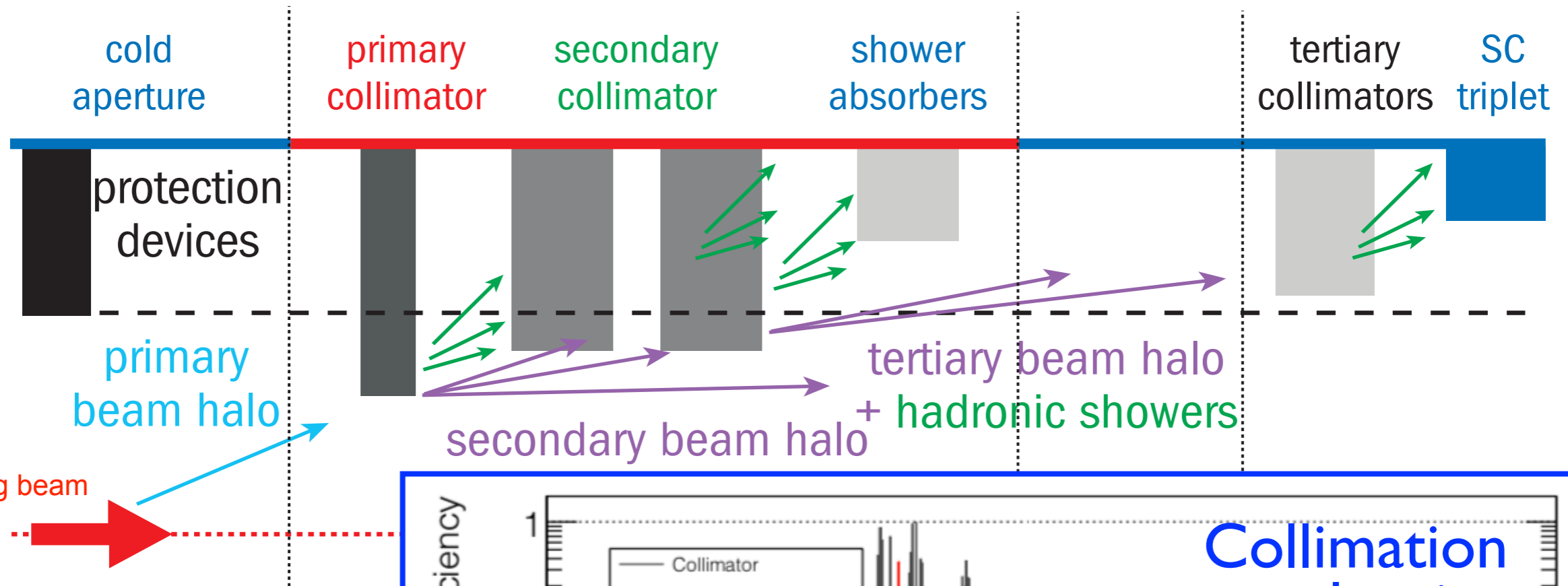
Three-stage cleaning in warm **cleaning insertions**: betatron (IR7) and off-momentum (IR3); local “tertiary” collimators at inner triplet.

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

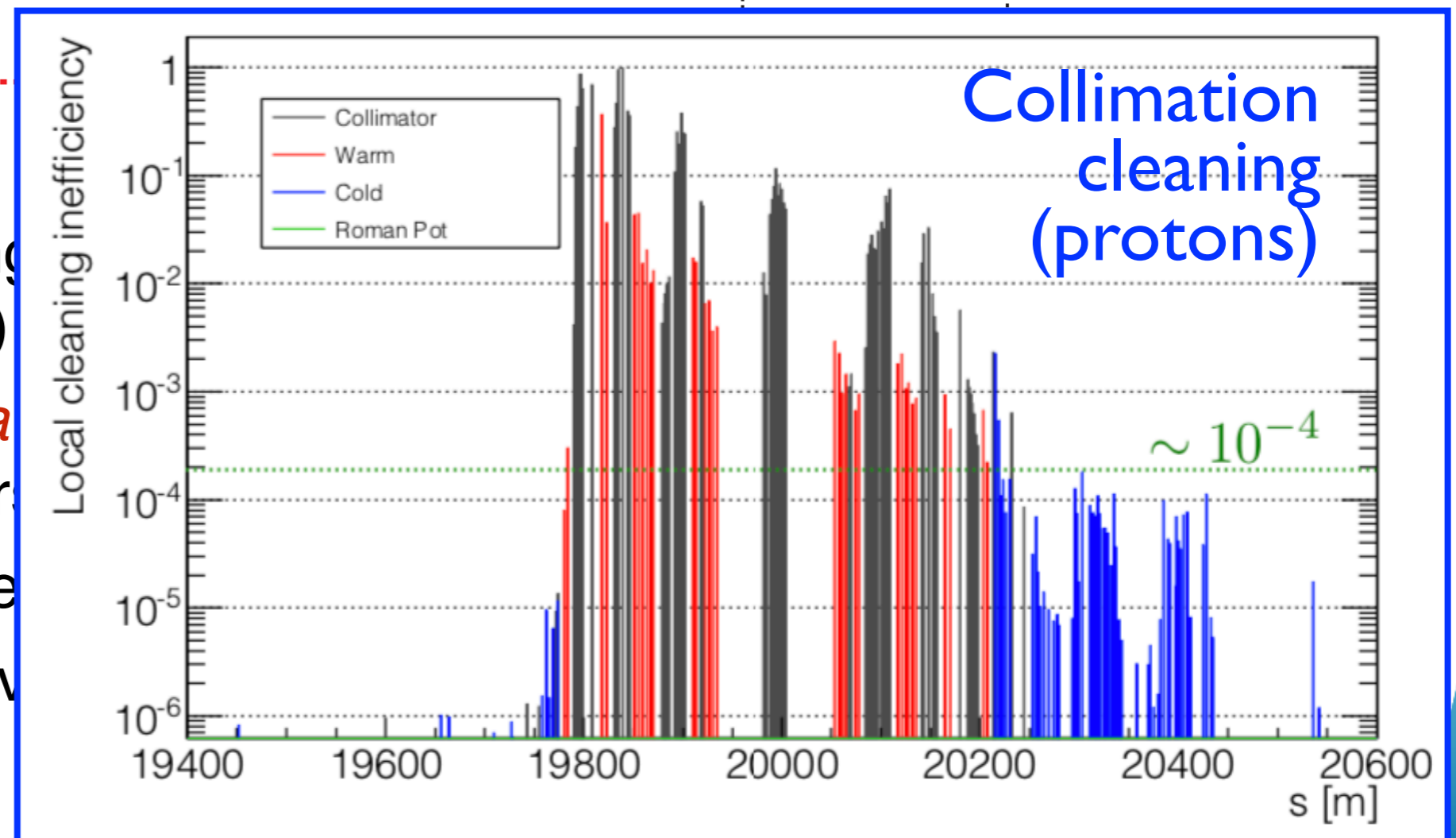
Machine aperture sets the scale for collimation hierarchy

Distributed losses over many collimators to dispose safely of total losses.

# LHC multi-stage collimation

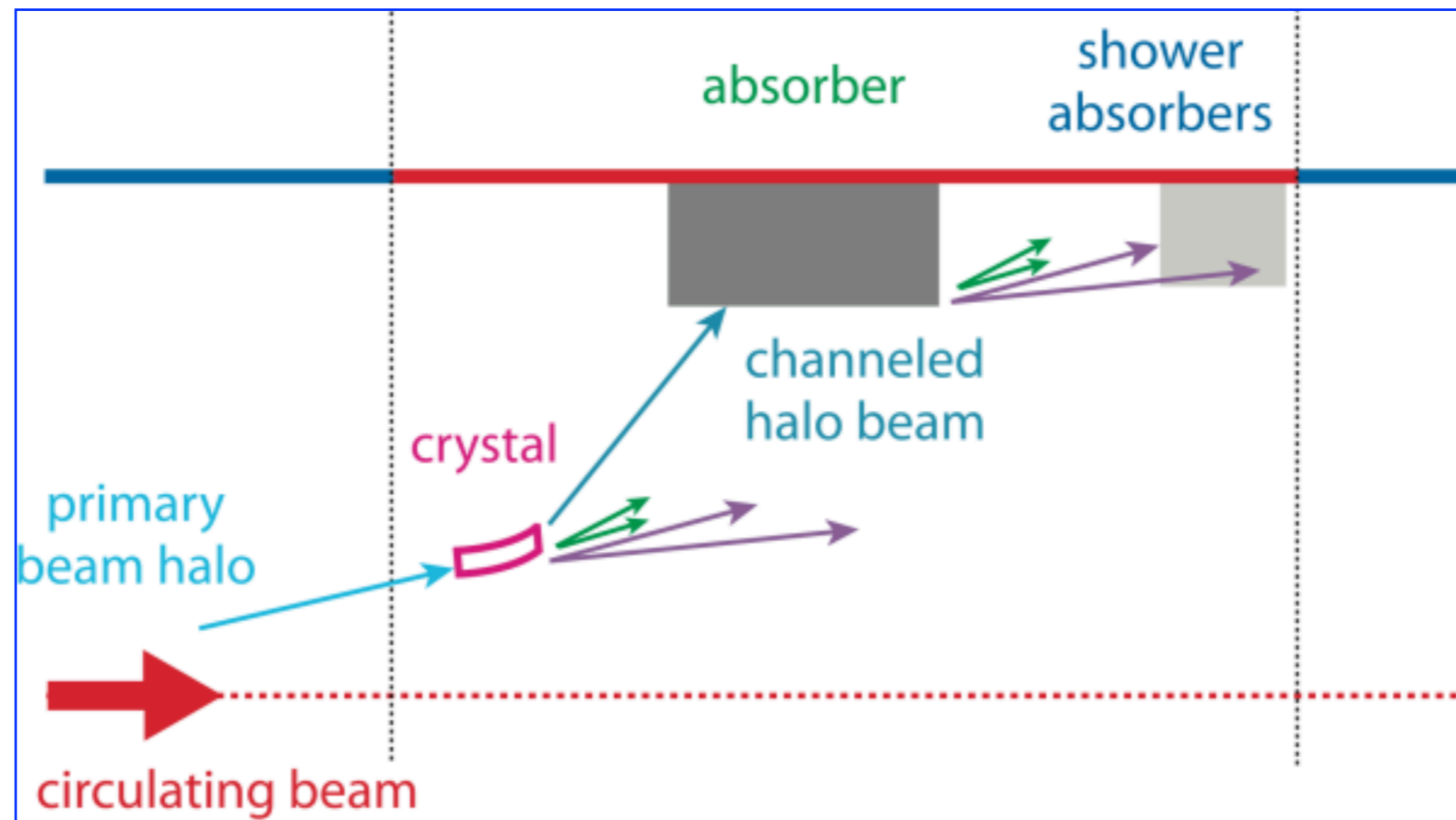
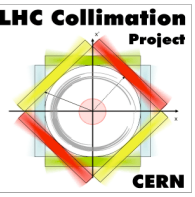


Three-stage cleaning  
off-momentum (IR3)  
Well-defined *collima*  
protection collimator  
Machine aperture se  
Distributed losses ov



# The crystal collimation concept

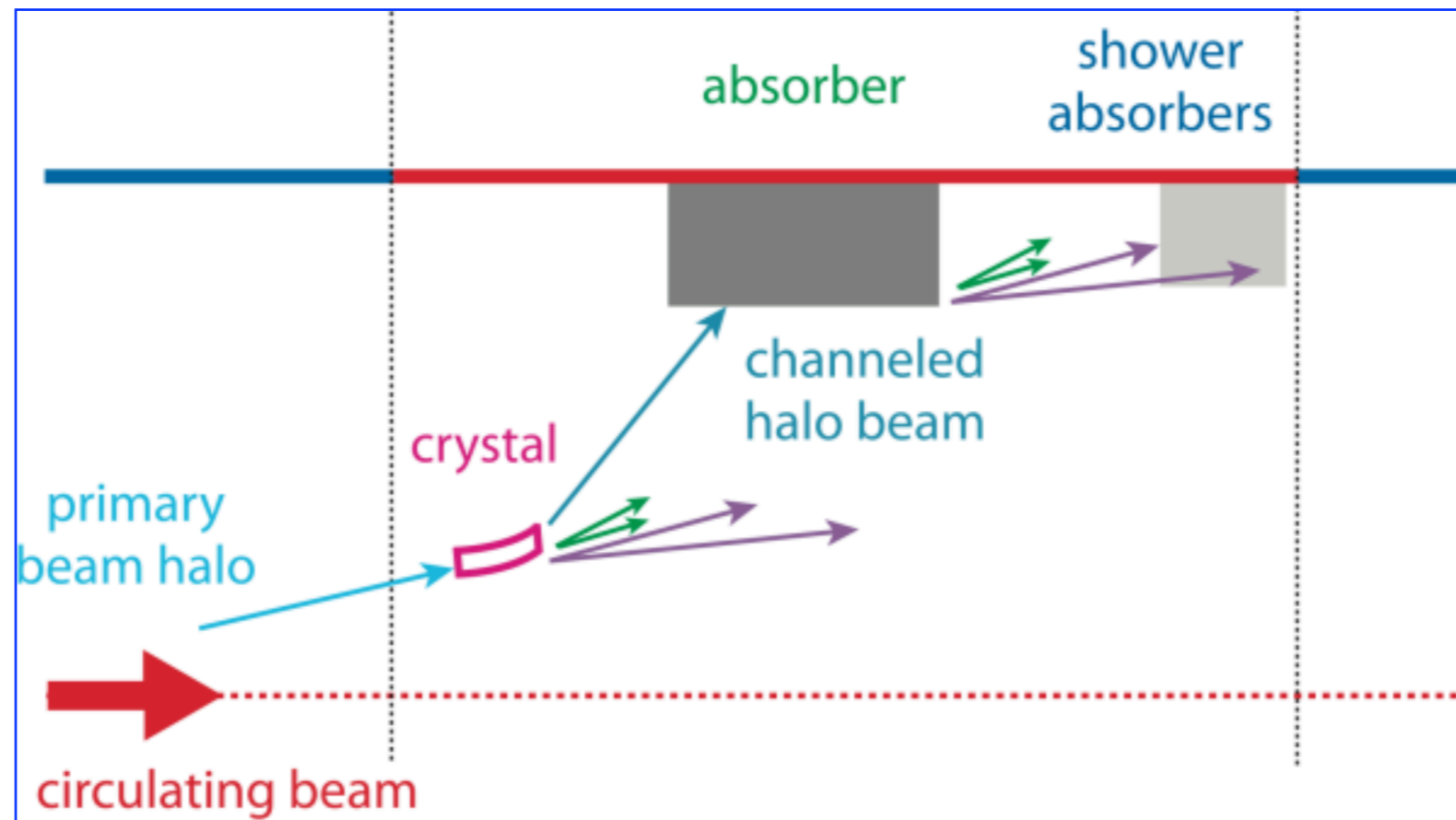
(replacing the 3-stage system for betatron cleaning)



*The rest of the hierarchy (protection, inner triplet, etc...) remains needed!*

# The crystal collimation concept

(replacing the 3-stage system for betatron cleaning)



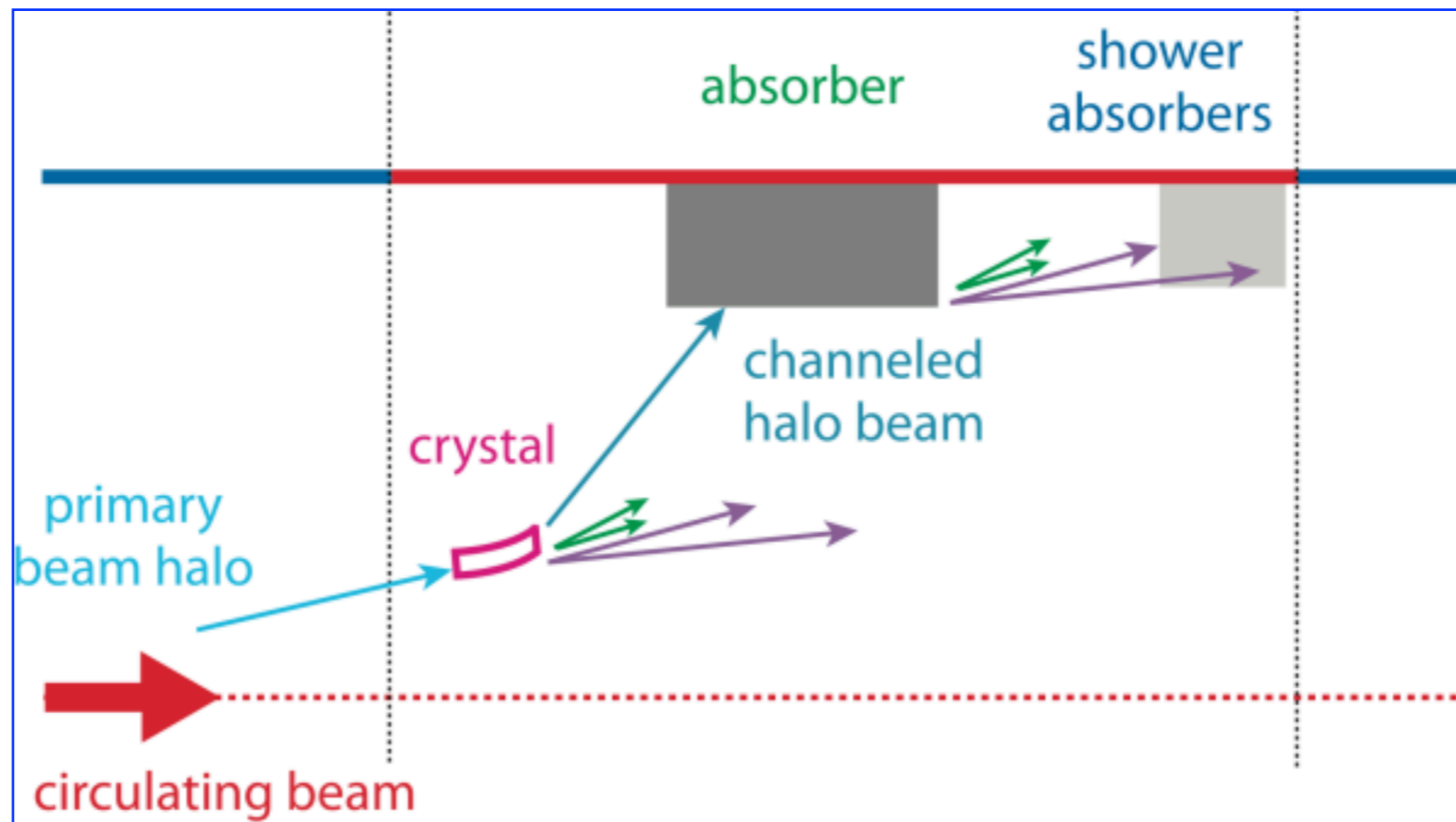
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## Crystal-based betatron halo cleaning

- Bent crystal replaces horizontal and vertical primary collimators
- A single massive absorber (per plane) intercepts the channeled halo
- Needs additional shower absorbers, but “cleaner” disposal of primary losses

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(replacing the 3-stage system for betatron cleaning)



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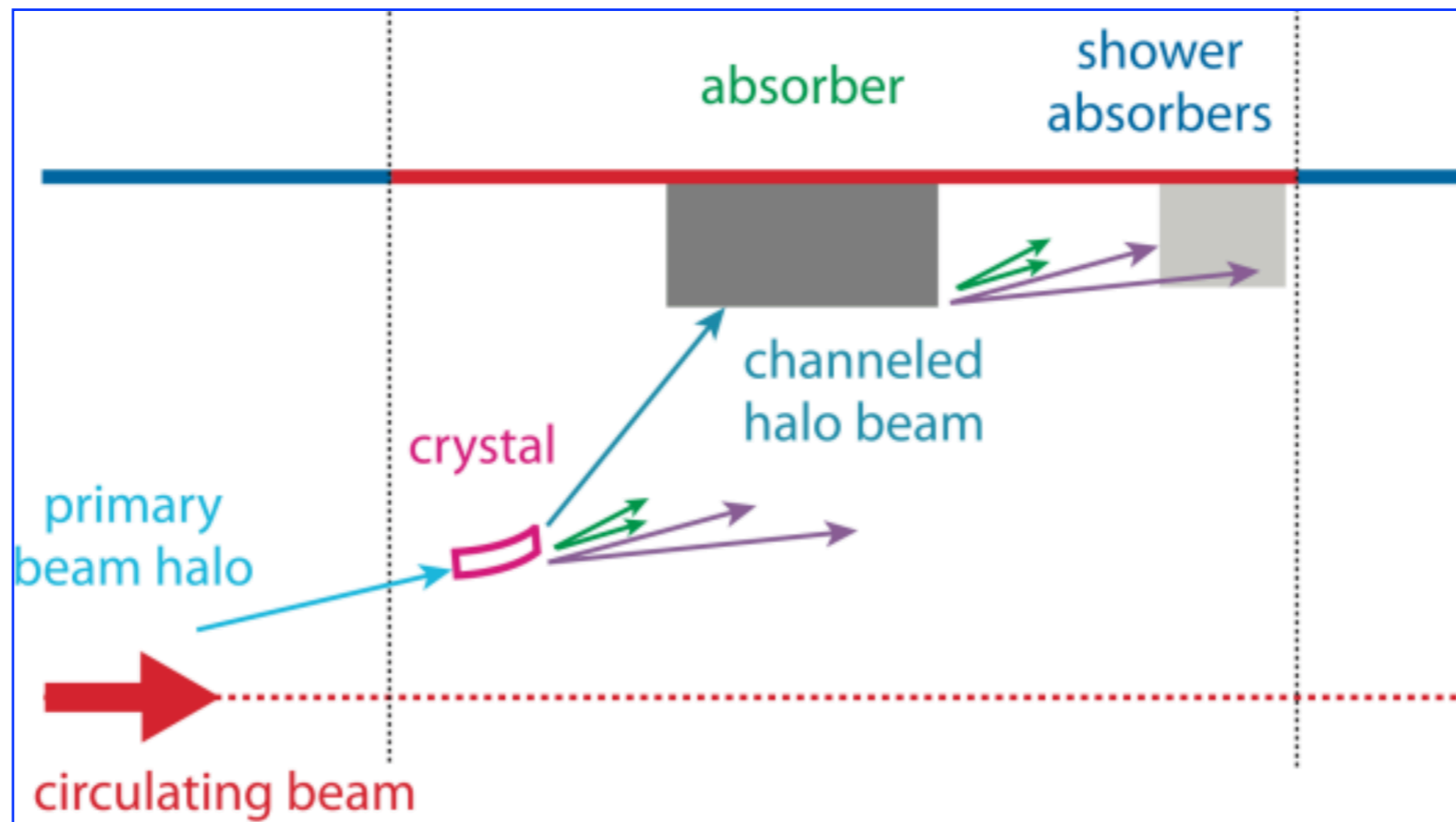
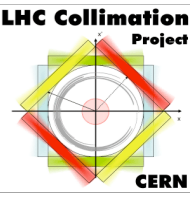
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**Promises:** Improvement of cleaning, with fewer collimators, in particular for heavy ion beams (suppress of fragmentation/dissociation!)

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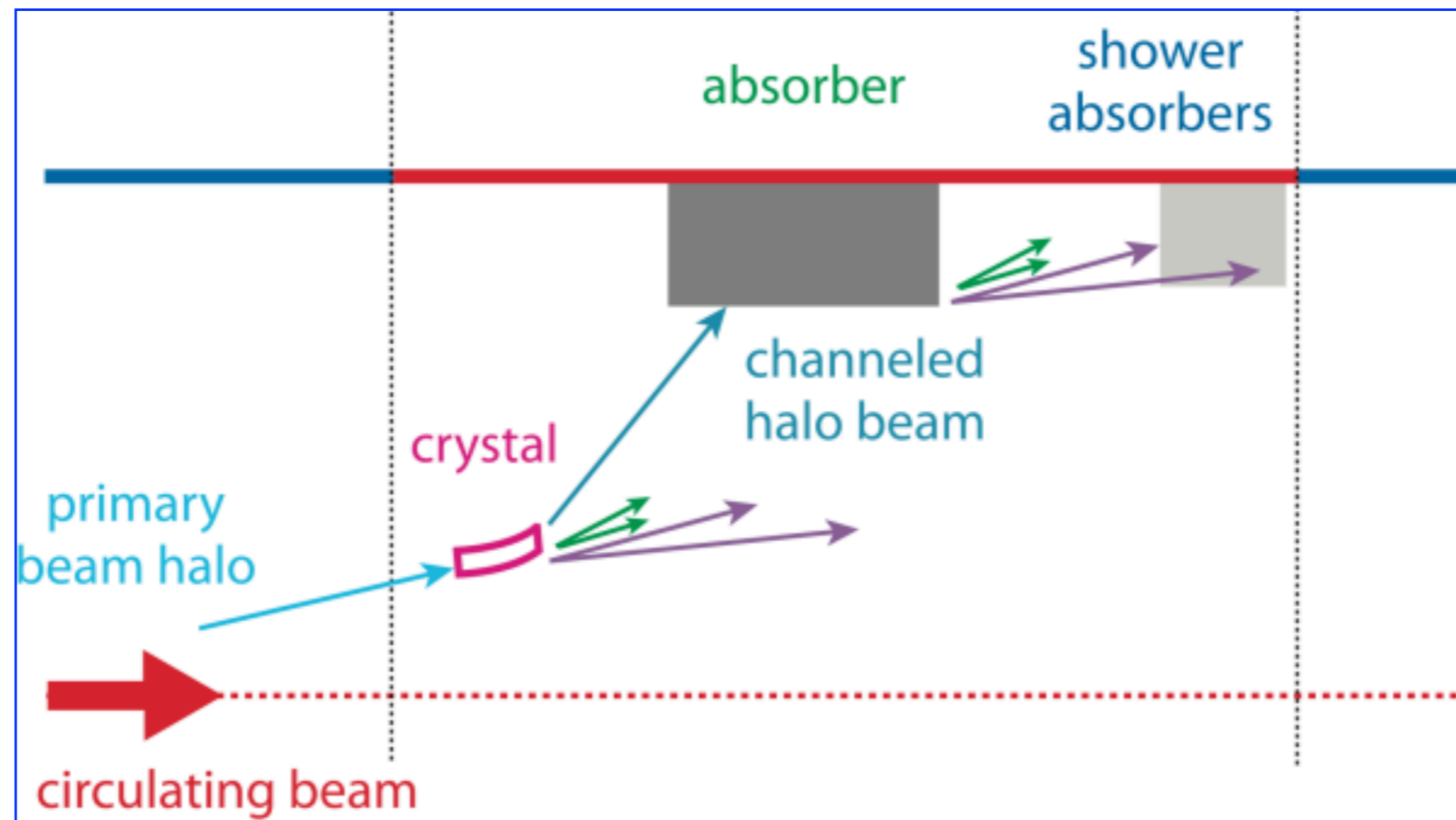
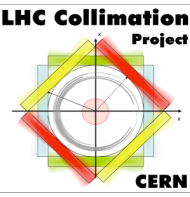
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**Promises:** Improvement of cleaning, with fewer collimators, in particular for heavy ion beams (suppress of fragmentation/dissociation!)

**Challenges:** Quality and performance of crystal assembly (new energy regime)  
Angular control within sub-micro radiants  
Safe and efficient disposal of channeled halo

# The crystal collimation concept

(replacing the 3-stage system for betatron cleaning)



*The rest of the hierarchy (protection, inner triplet, etc...) remains needed!*

## Crystal-based betatron halo cleaning

- Bent crystal replaces horizontal and vertical primary collimators
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Improvement of cleaning with fewer collimators in particular for

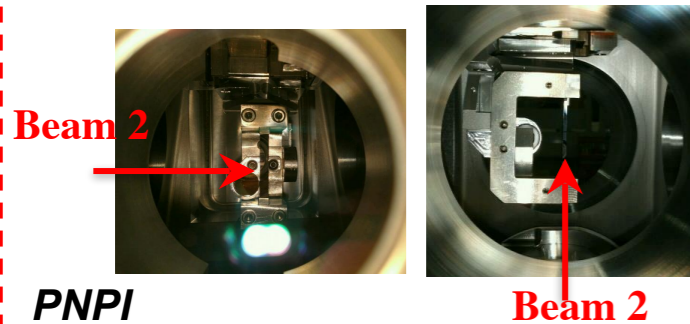
## Challenges:

Qu Decision to install a **crystal collimation test stand** as part of the LHC collimation betatron system to assess performance benefit and operational aspects with **LHC conditions**.

# LHC crystal collimation layouts

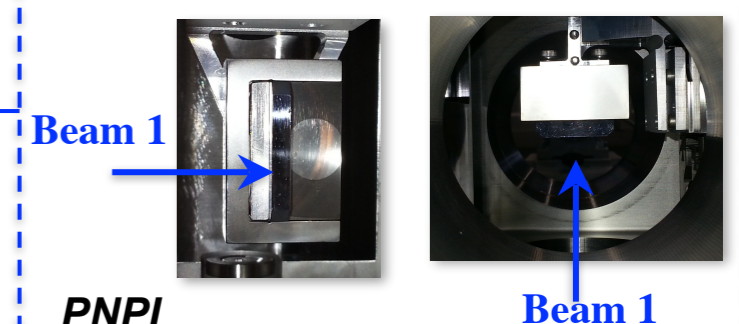
Four crystals installed in the LHC: two per beam, one per plane. Provided and validated by the UA9 collaboration. 2 producers: PNPI (3 crystals) and INFN-Fe (1).

**TCPCH.A5R7.B2**

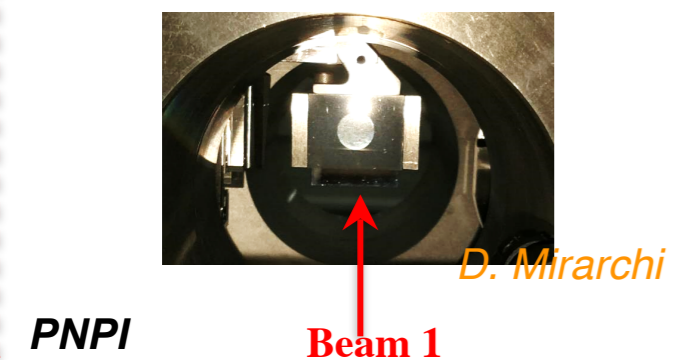


Pics. courtesy of Y. Gavrikov

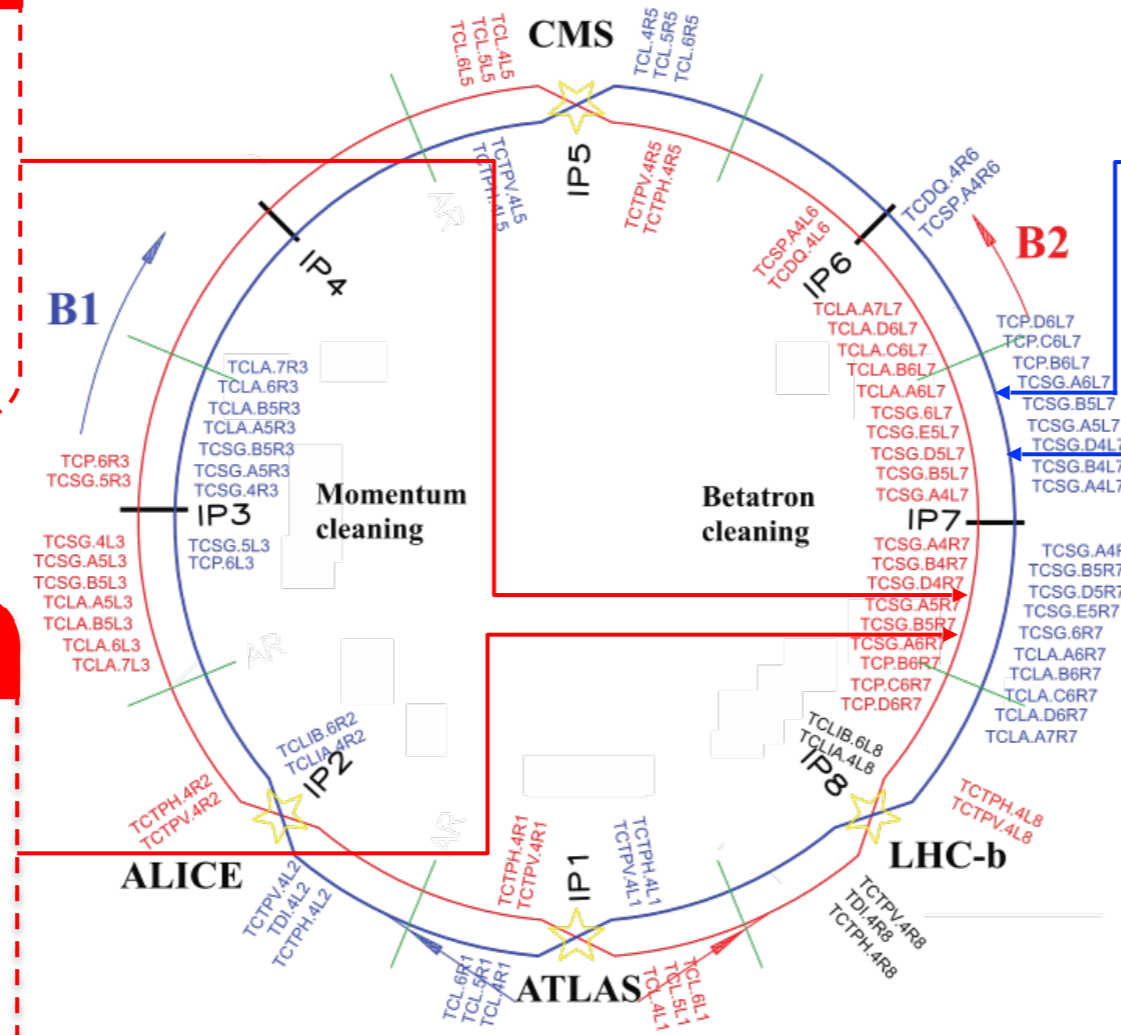
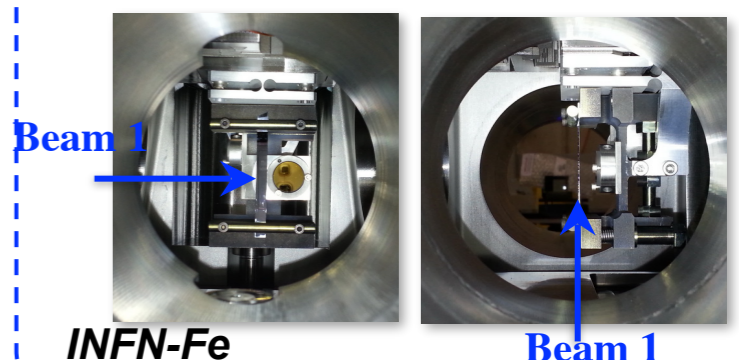
**TCPCV.A6L7.B1**



**TCPCV.A6R7.B2**



**TCPCH.A4L7.B1**

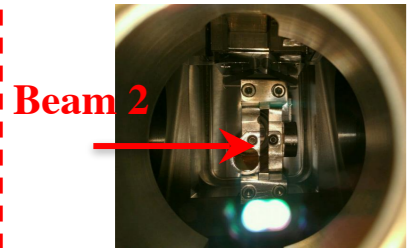


**Complete layout : both beams and planes** — allow thorough investigations and **operational** tests

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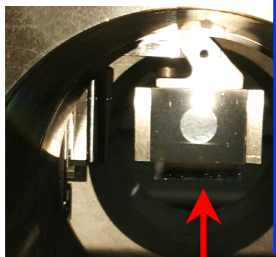
TCPCH.A5R7.B2



PNPI

Pics. courtesy of Y. Gao

TCPCV.A6L7.B1

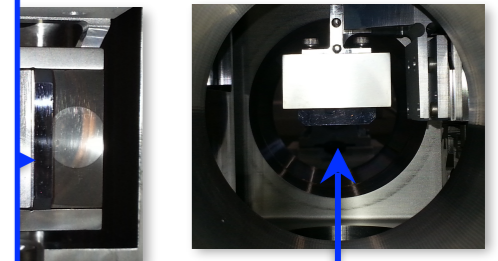


PNPI

Beam 1

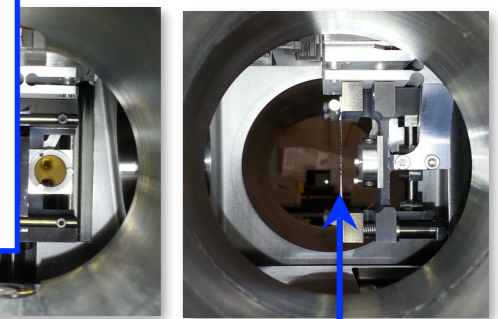
D. Mirarchi

TCPCV.A6L7.B1



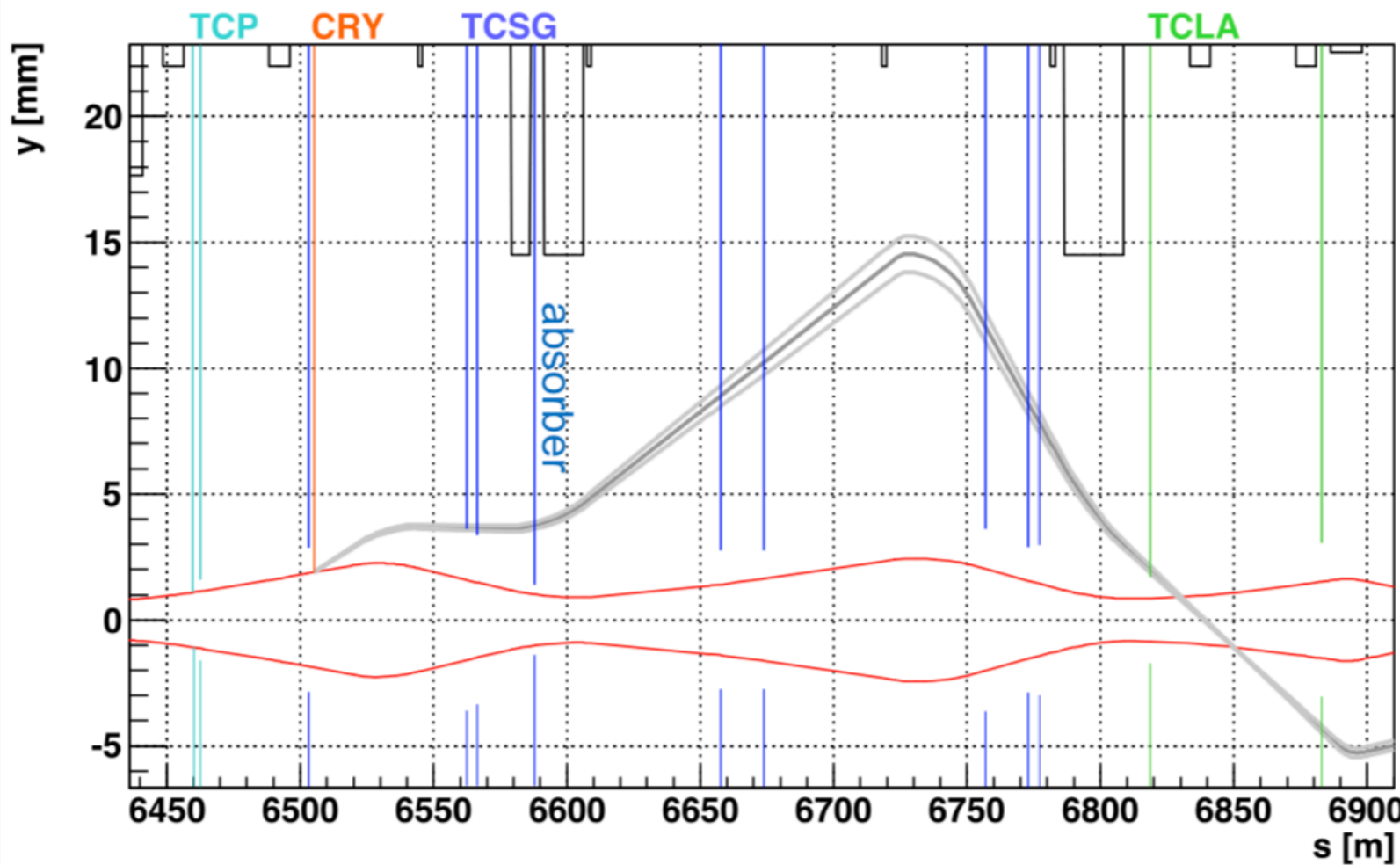
Beam 1

PCH.A4L7.B1



Beam 1

INFN-Fe



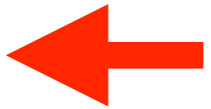
TCP = primary collimator  
TCSG = secondary collimator  
TCLA = shower absorber

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

# LHC beam tests: key milestones

2015

- Available: two crystals 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**

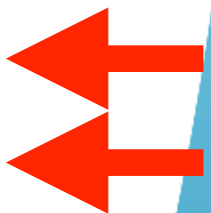


2017

- 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



*Beam tests carried out in the scope of the Collimation activities, as machine tests.  
Total “Machine Development” (MD) time: 58h with protons, 34h with ions*

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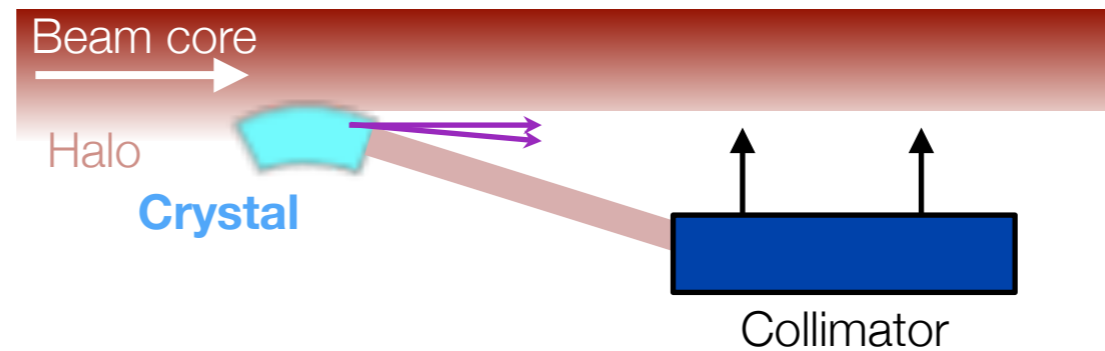
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Decision to include crystal collimation as part of the HL-LHC upgrade baseline: endorsement in “Cost&Schedule” review 2019, followed by approval by CERN Council (Dec. 2019).

# Channeling observations at 6.5 TeV

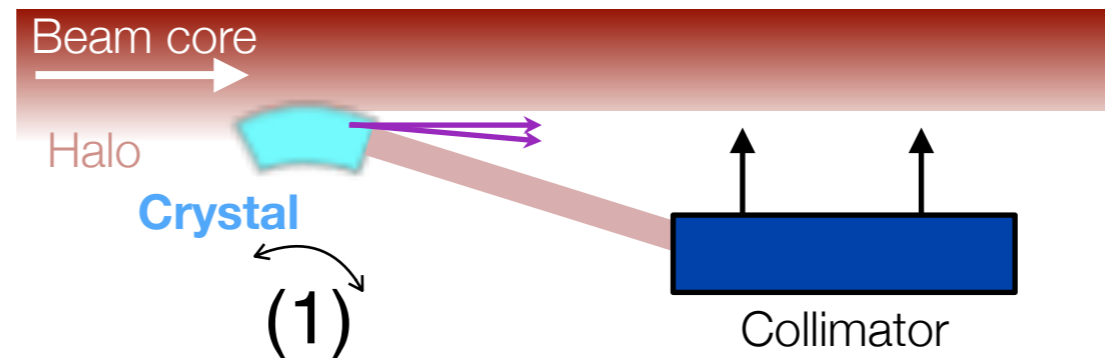
Key measurements: crystal angular scans and linear collimator scans



*Established in other circular accelerators, in particular: useful operational experience at the SPS (UA9 setup).*

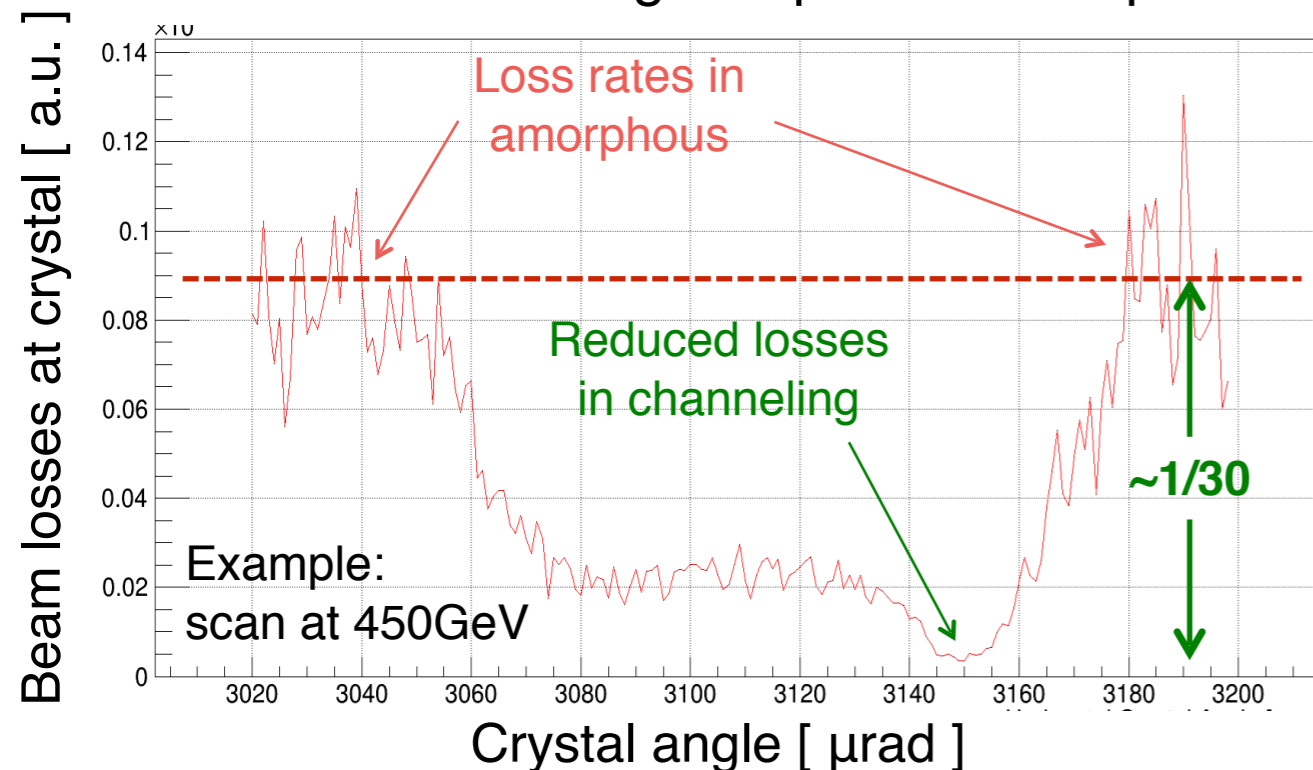
# Channeling observations at 6.5 TeV

Key measurements: crystal angular scans and linear collimator scans



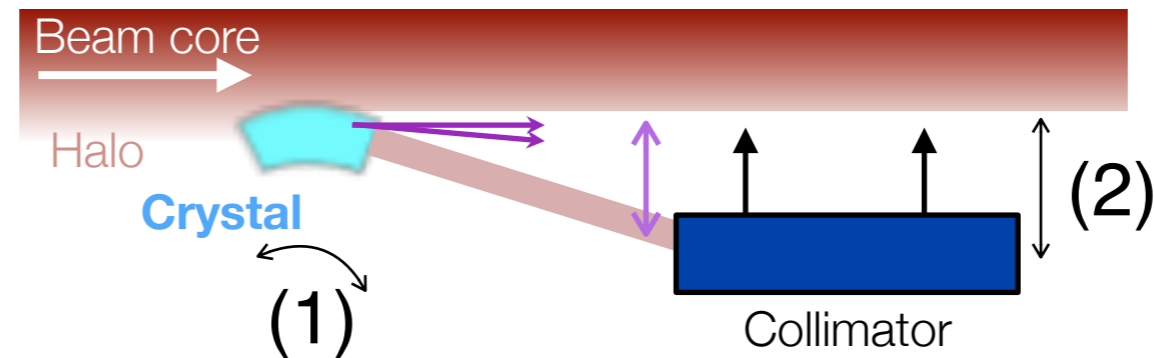
*Established in other circular accelerators, in particular: useful operational experience at the SPS (UA9 setup).*

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



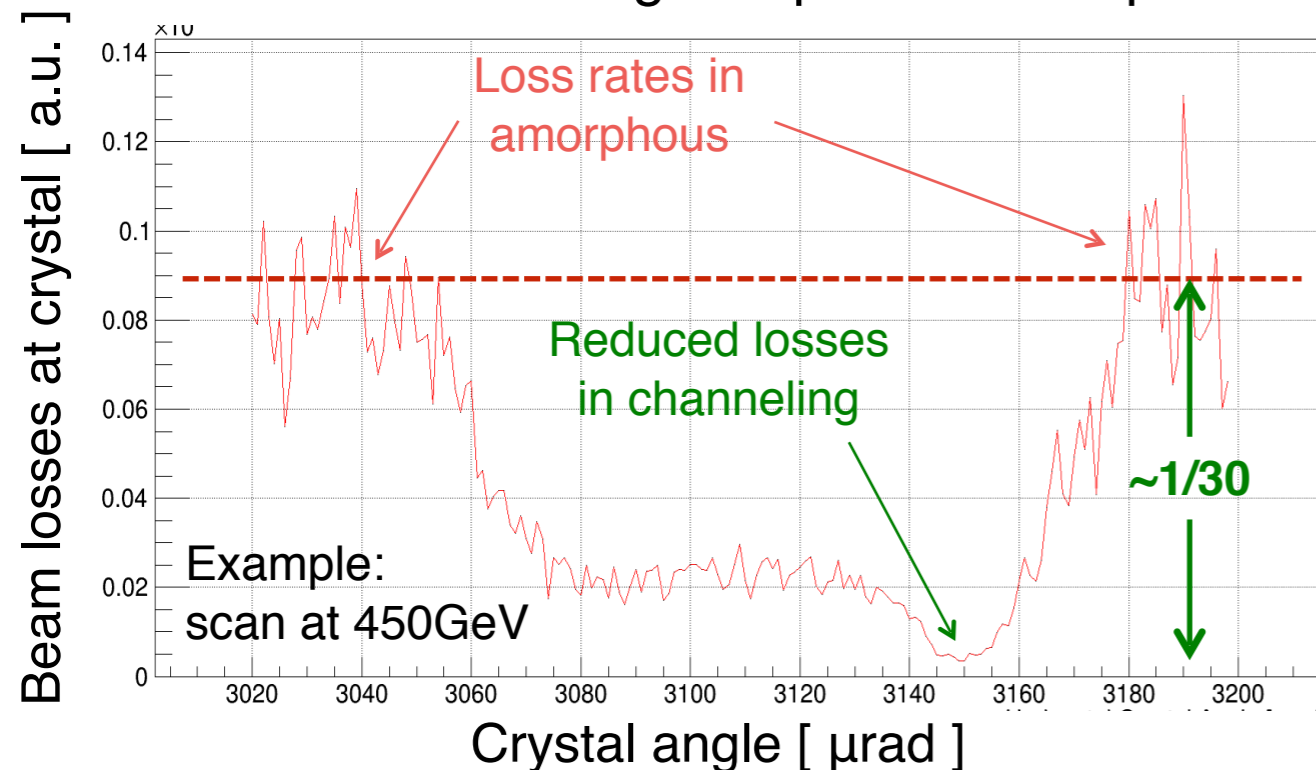
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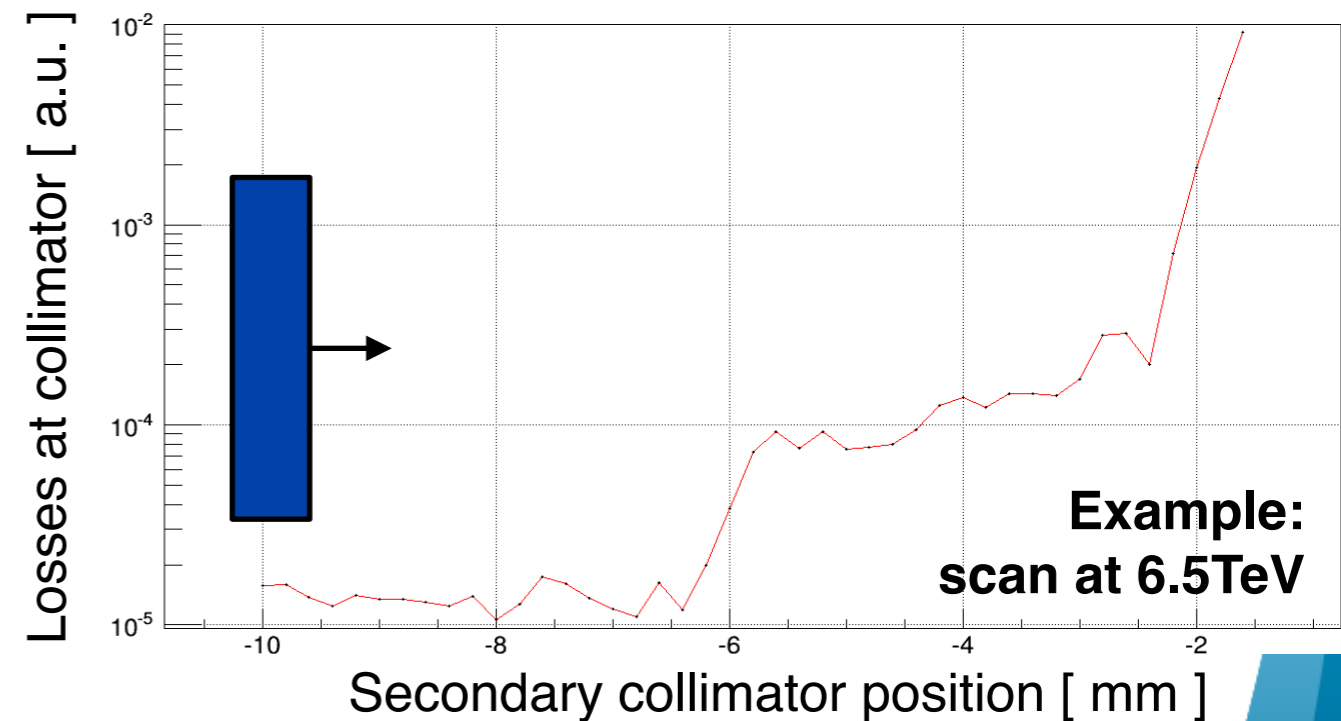


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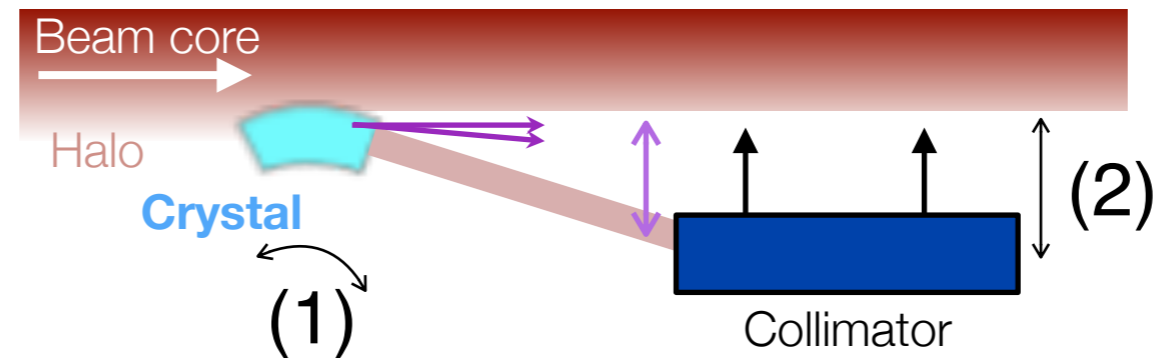


(2) **Linear collimator scan:** measures the profile of the channeled halo.



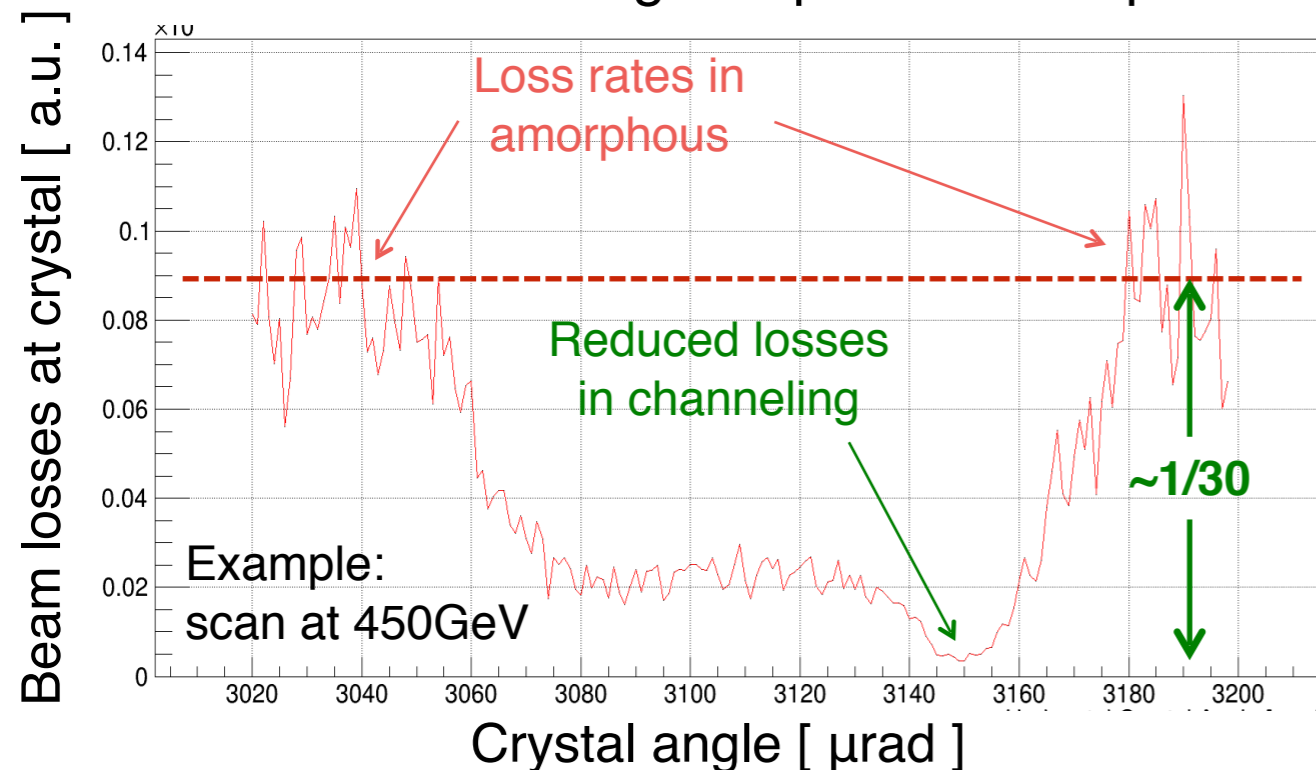
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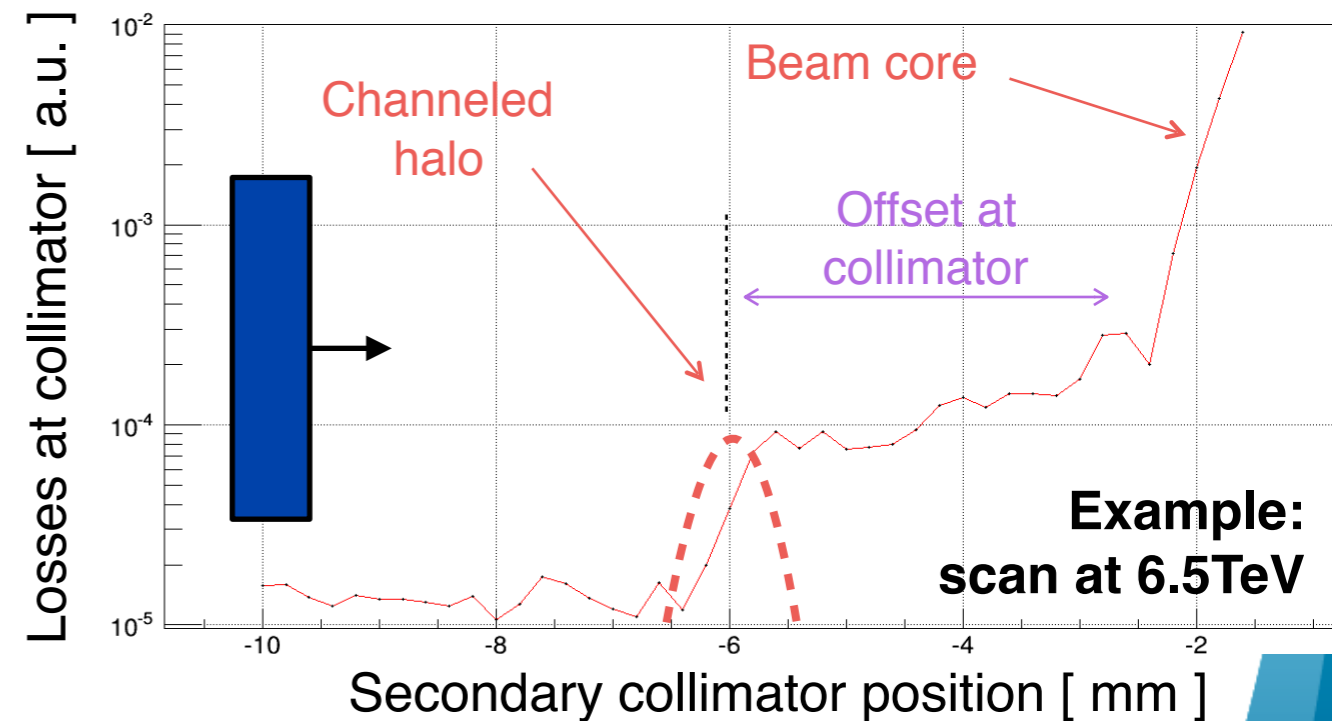


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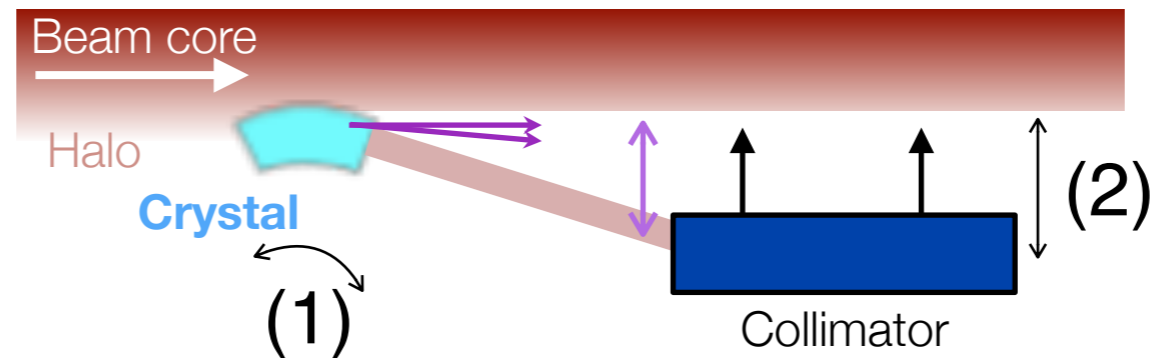


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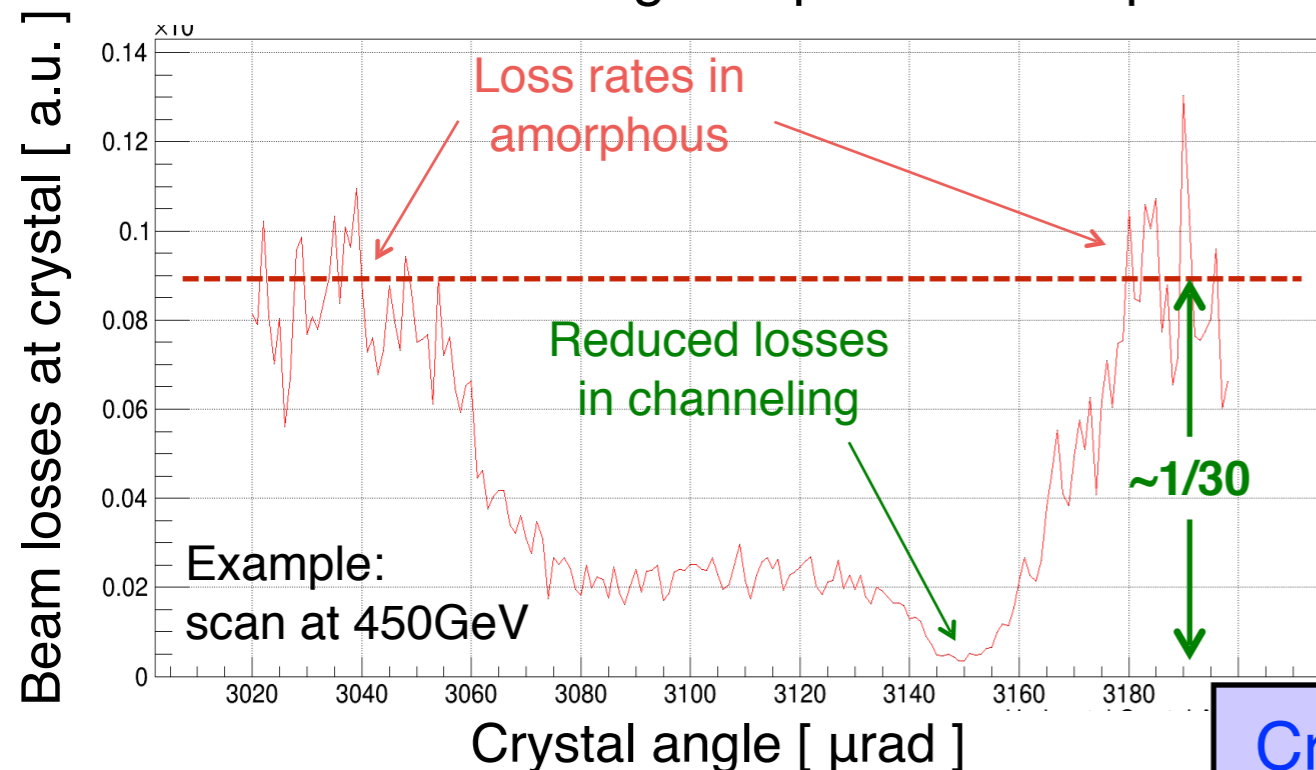
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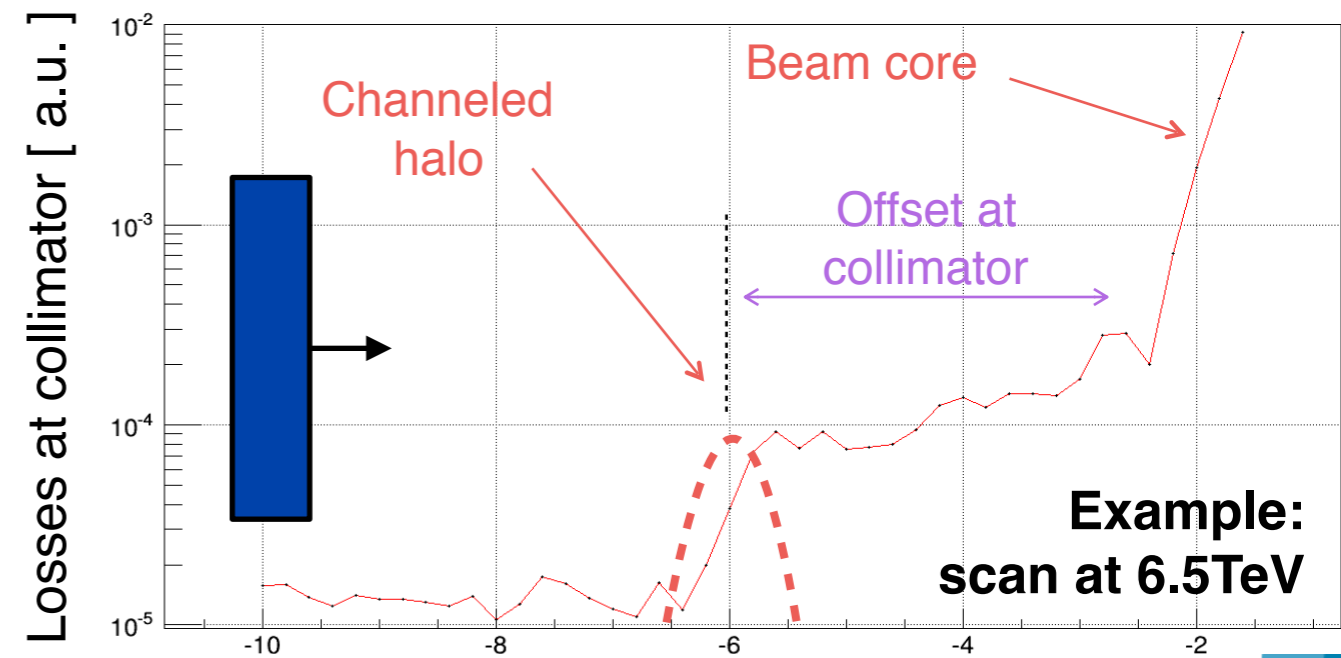


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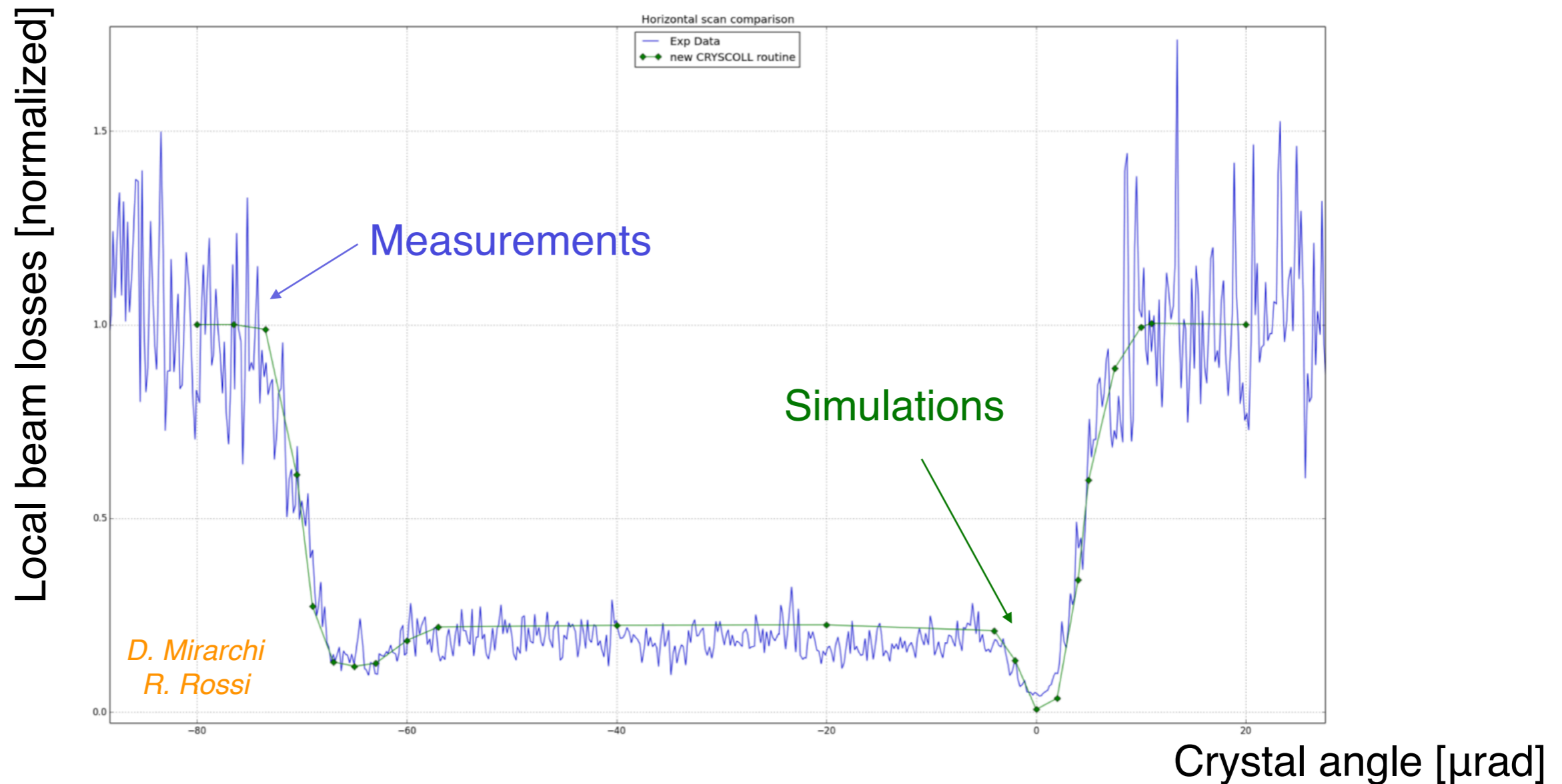


(2) **Linear collimator scan:** measures the profile of the channeled halo.



Critical: Achieved the required angular control of better than  $\sim 1 \mu\text{rad}$  (A. Masi *et al.*)

# Measurements and simulations, 6.5 TeV

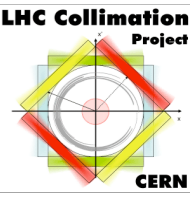


Comparison: beam losses downstream of crystal in an angular scan vs simulated nuclear interactions in the crystal.

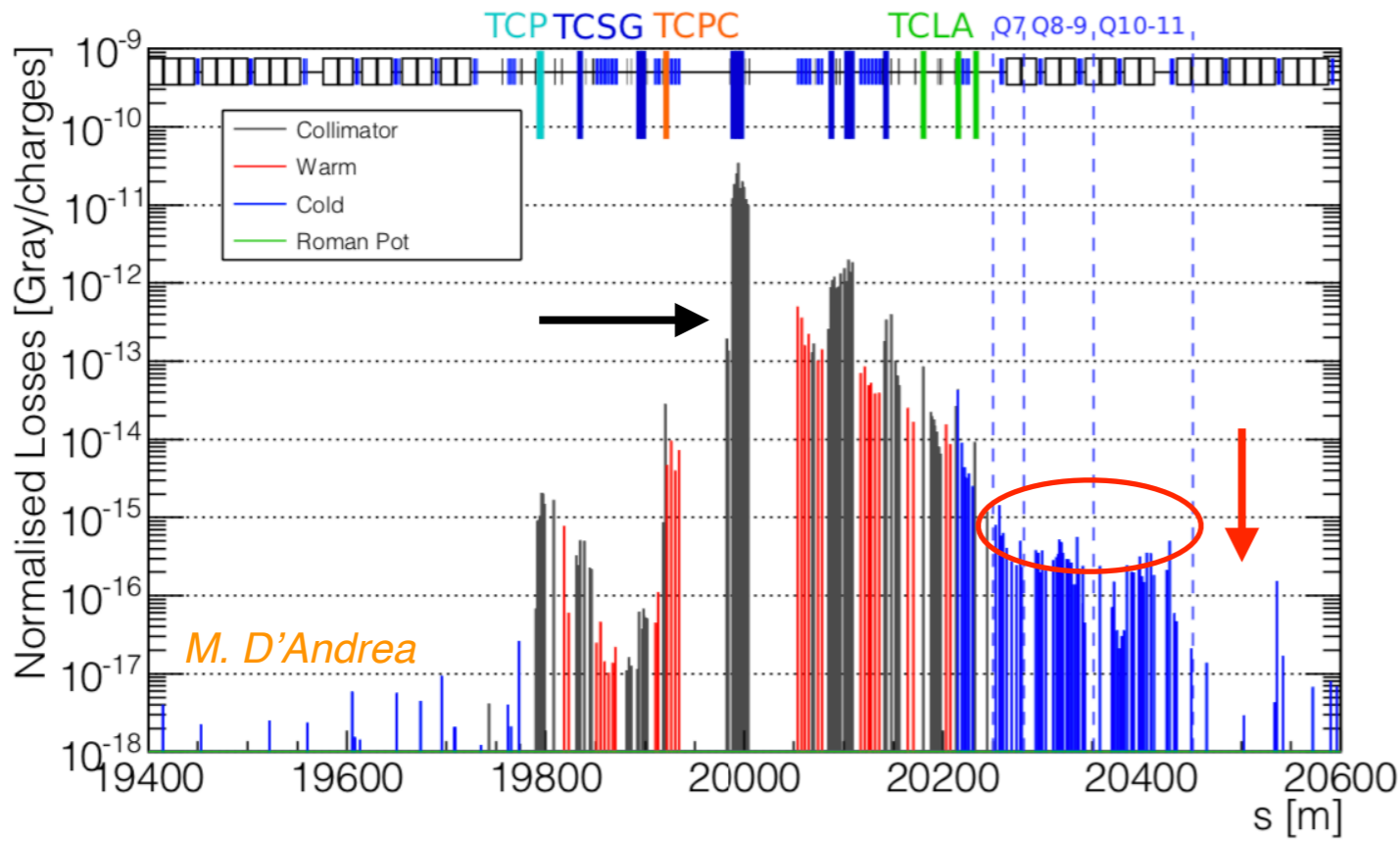
Experimental input from measurements: crystal bending angle ( $65\mu\text{rad}$ ).

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

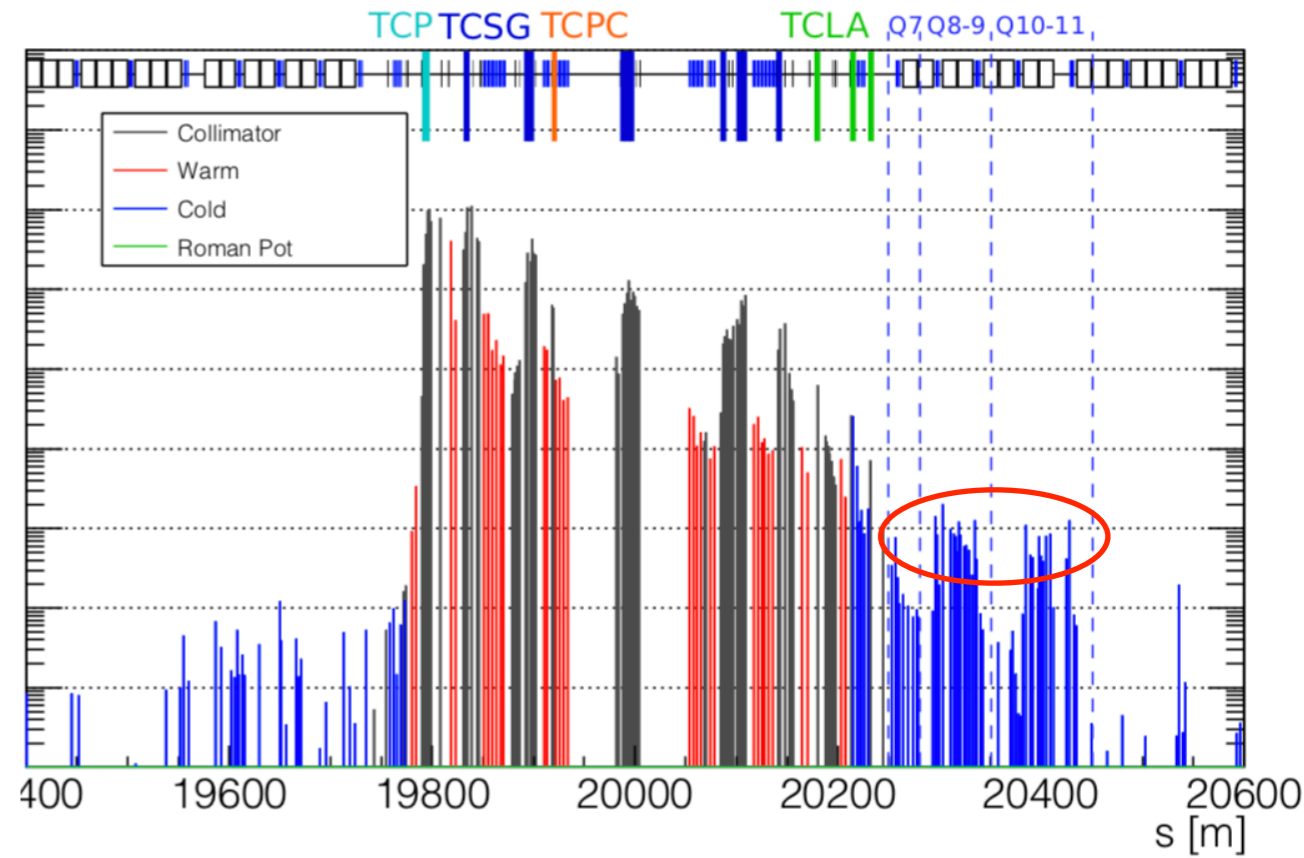
# Collimation cleaning: 7 TeV proton beams



## Crystal collimation

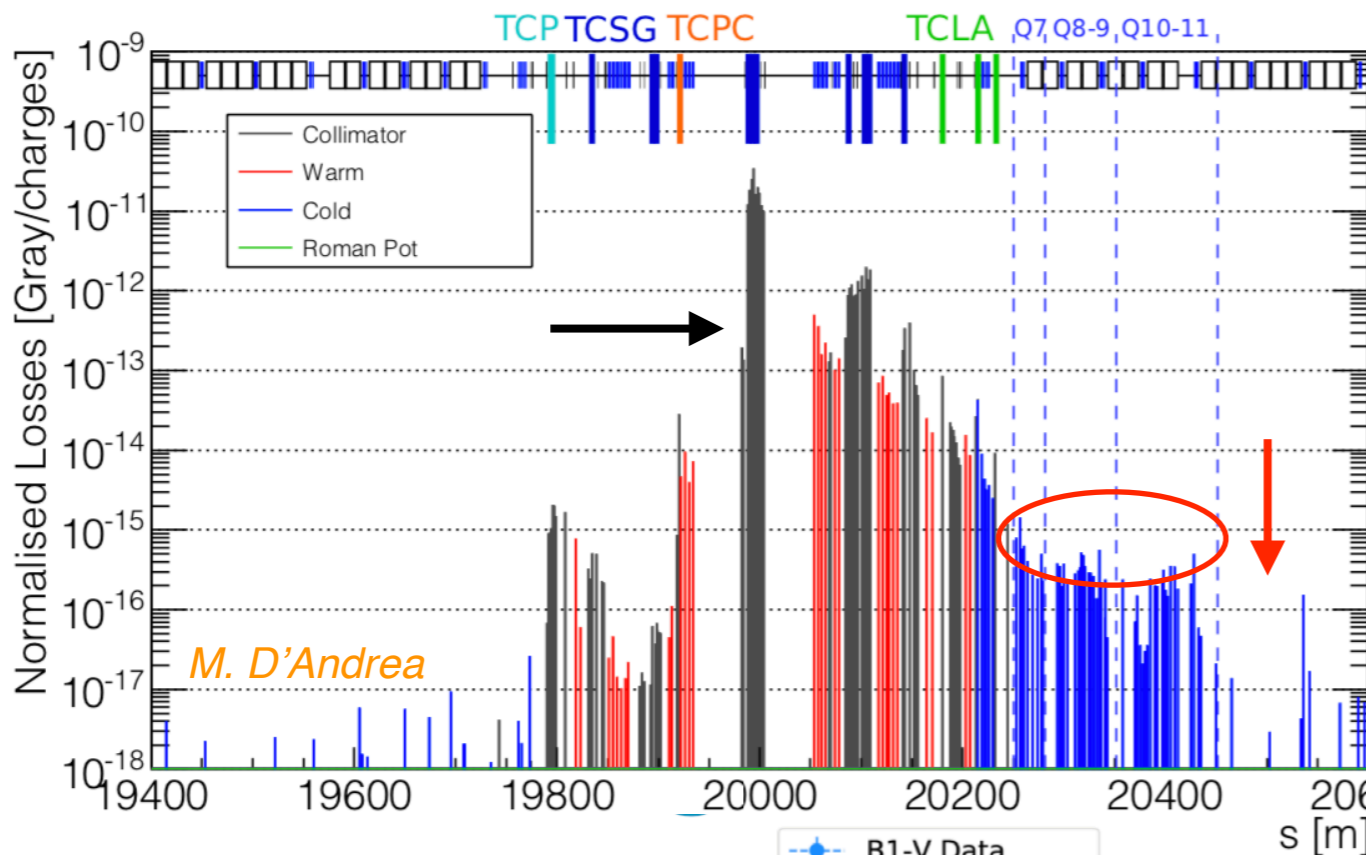


## Conventional collimation

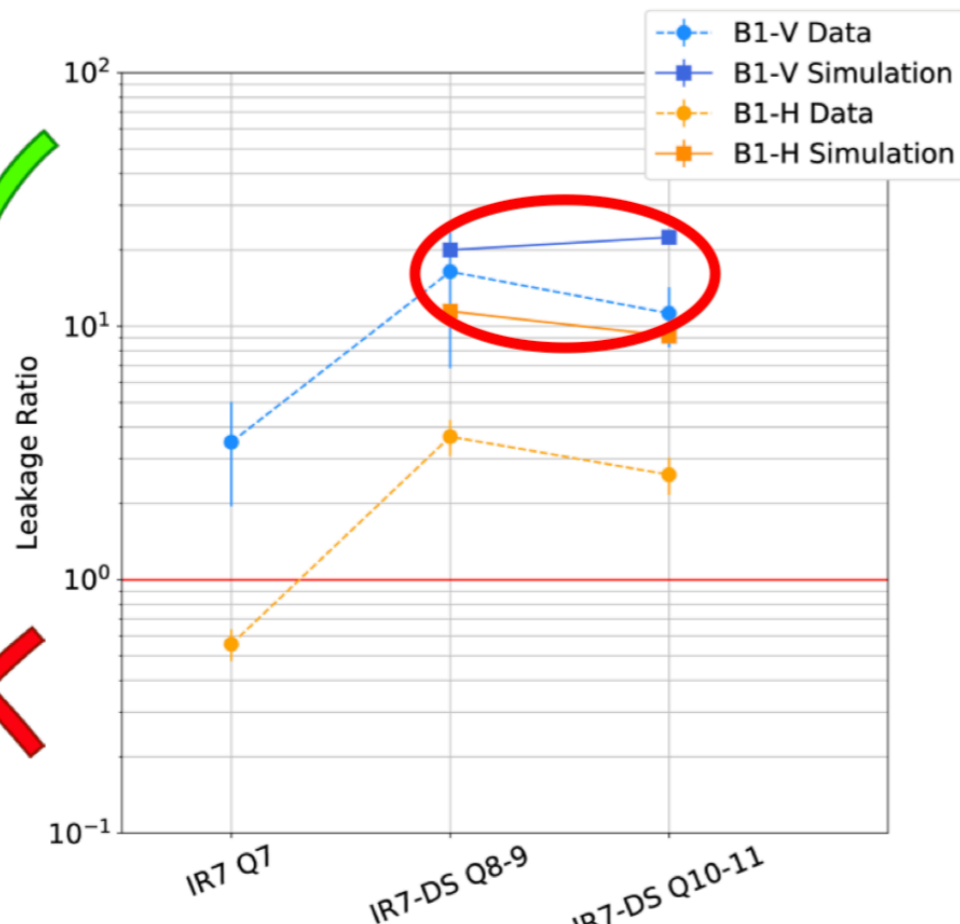
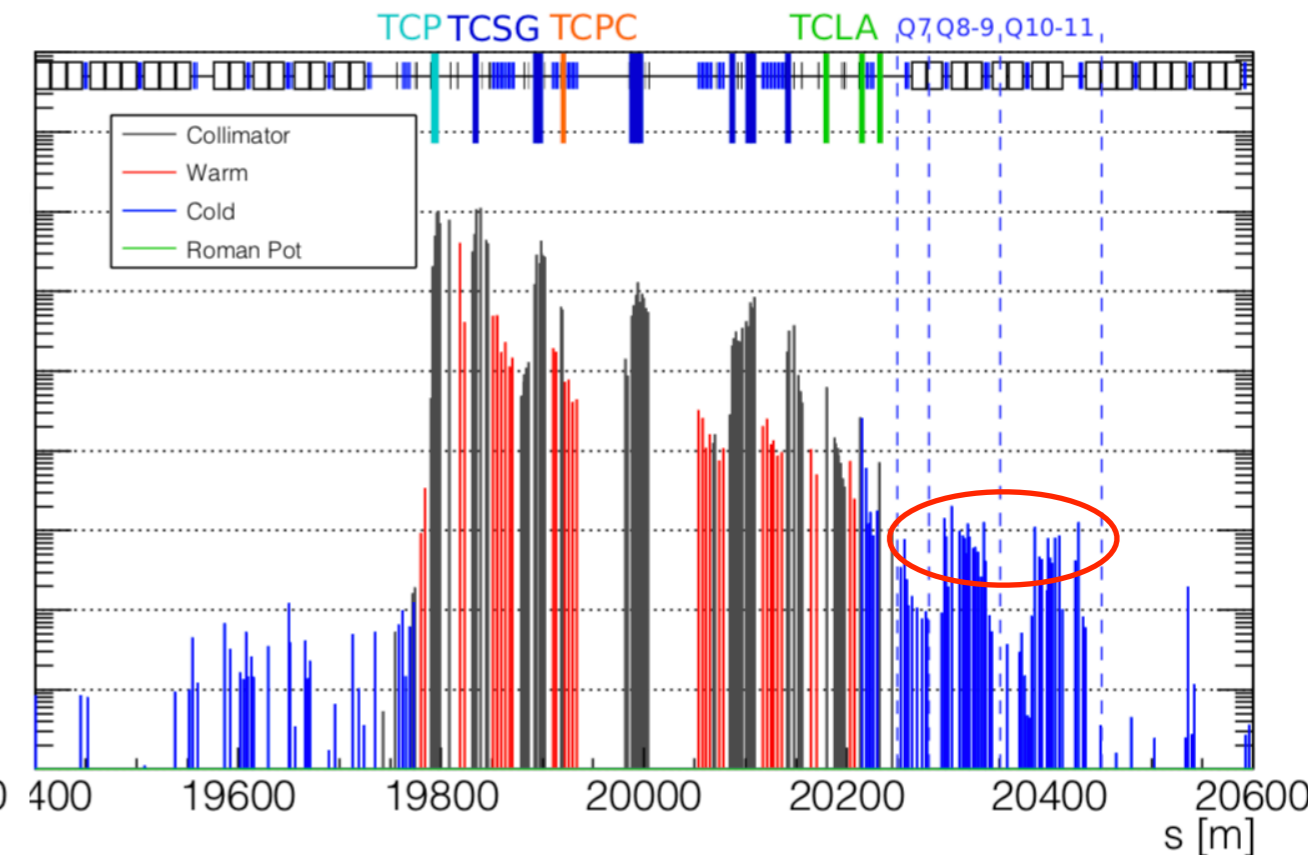


# Collimation cleaning: 7 TeV proton beams

## Crystal collimation



## Conventional collimation



- Achieved up to a factor  $\sim 10$  cleaning improvement at critical locations
- For protons, this is a “demonstrator setup”, compatible only with low beam intensities
- HL-LHC: design losses of  $\sim 1\text{MW}$  on a  $\sim \text{mm}^2$  require a dedicated beam absorber!  
*Not considered for cleaning upgrade!*

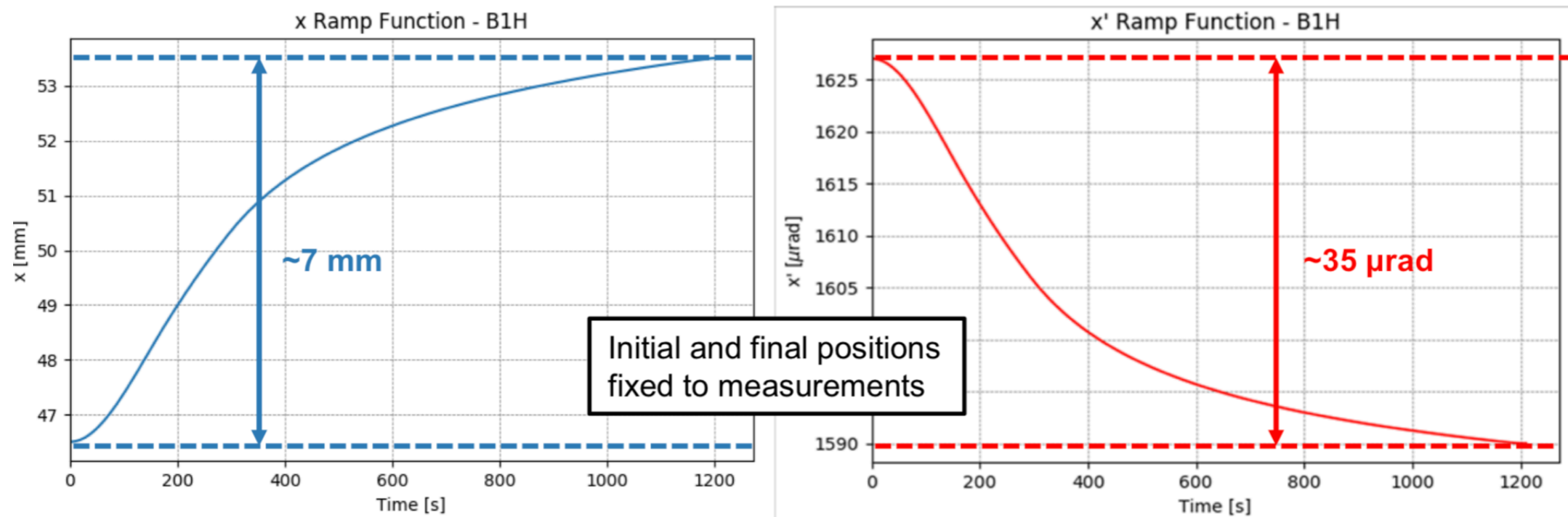
# Continuous channeling in energy ramp

## Challenges:

- shrinking of beam size and change in angular distribution due to adiabatic dumping
- change in critical angle (from  $\sim 10 \mu\text{rad}$  to  $\sim 2 \mu\text{rad}$ ) and acceptance

Functions need to be prepared to move the crystals: same formula used for standard collimators, but adapted also for rotational stage

$$x(t) = x_c - \left[ n_{inj} + \frac{n_{ft} - n_{inj}}{\gamma_{ft} - \gamma_{inj}} (\gamma(t) - \gamma_{inj}) \right] \left[ \tilde{\sigma}_{inj} + \frac{\tilde{\sigma}_{ft} - \tilde{\sigma}_{inj}}{\gamma_{ft} - \gamma_{inj}} (\gamma(t) - \gamma_{inj}) \right] \frac{1}{\sqrt{\gamma(t)}}$$



**Achieved thanks to a goniometer based on interferometry, developed at CERN (EN/SMM group), providing a sub- $\mu\text{rad}$  angular accuracy.**

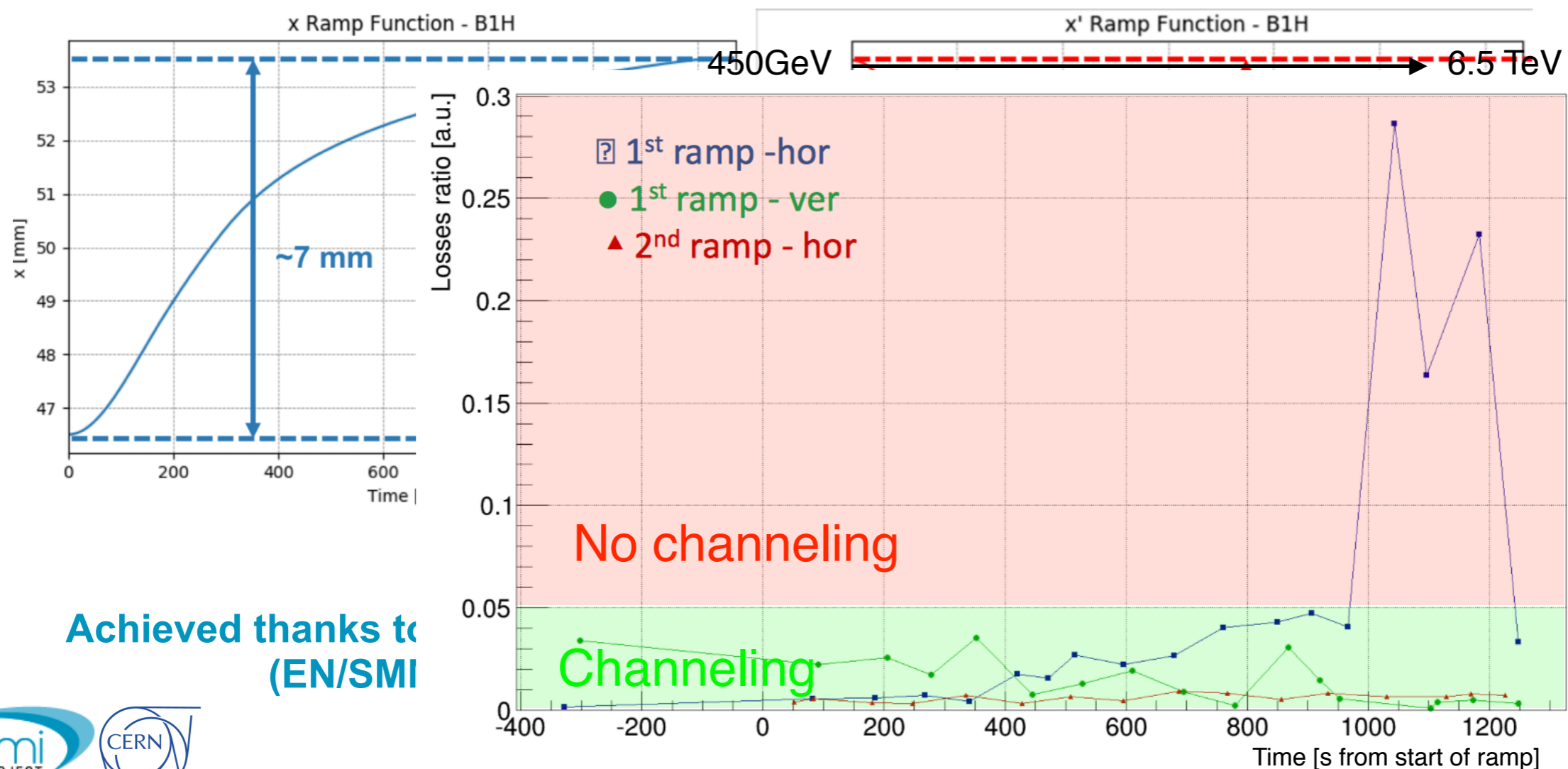
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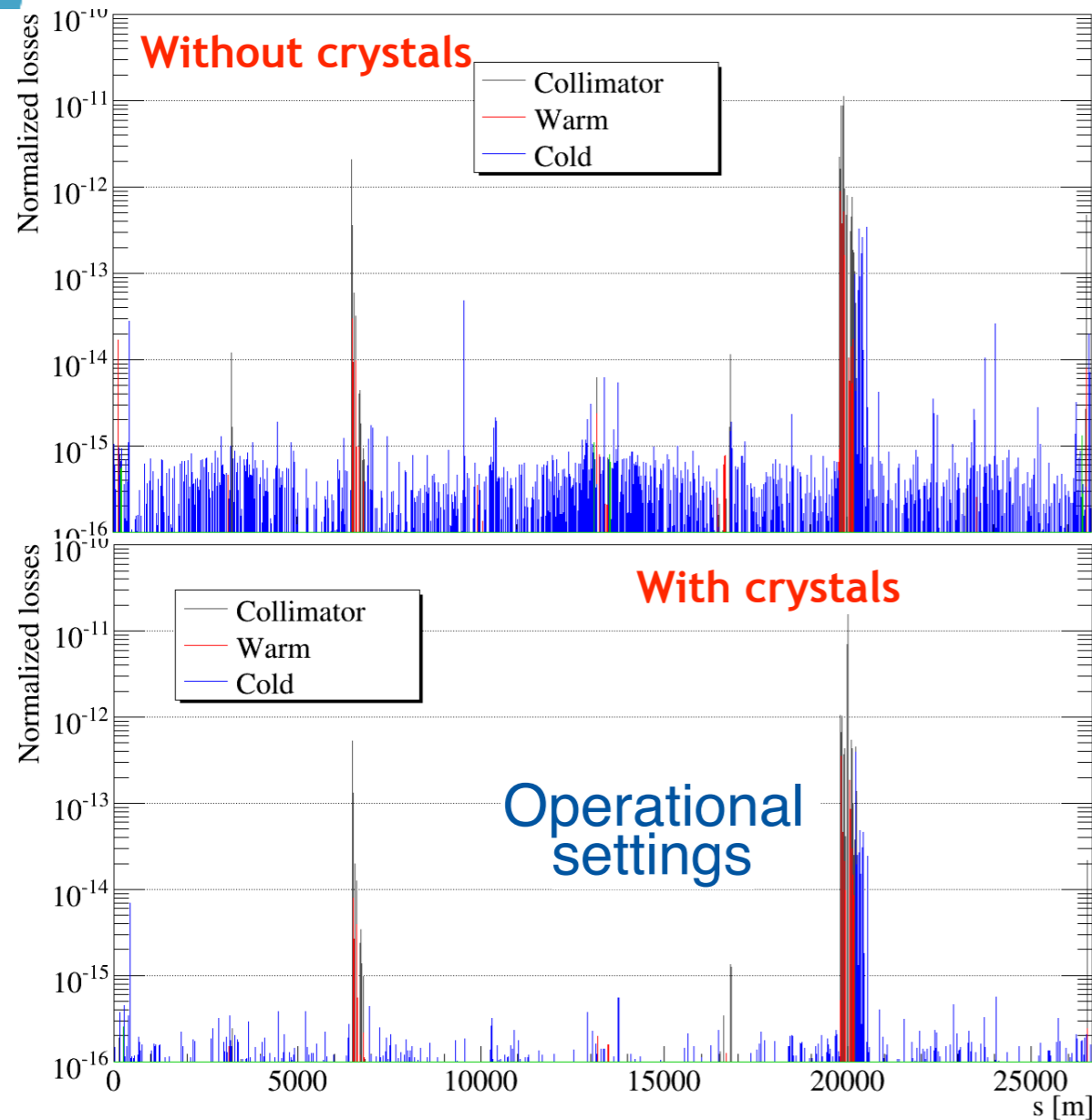
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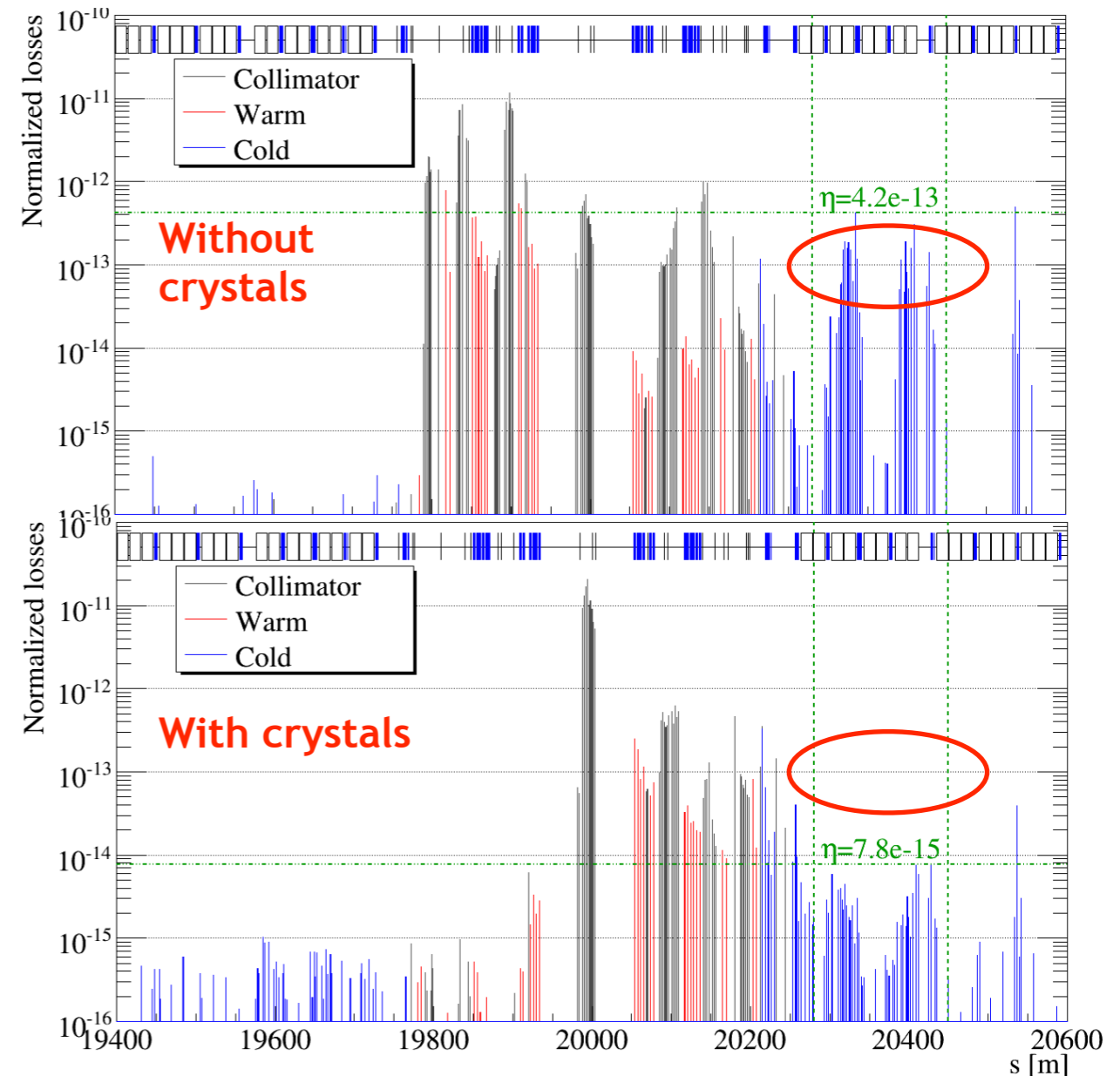
Achieved thanks to  
(EN/SMI)

# Collimation cleaning: 6.37 Z TeV Pb beams

*Full ring*



*Betatron cleaning region*

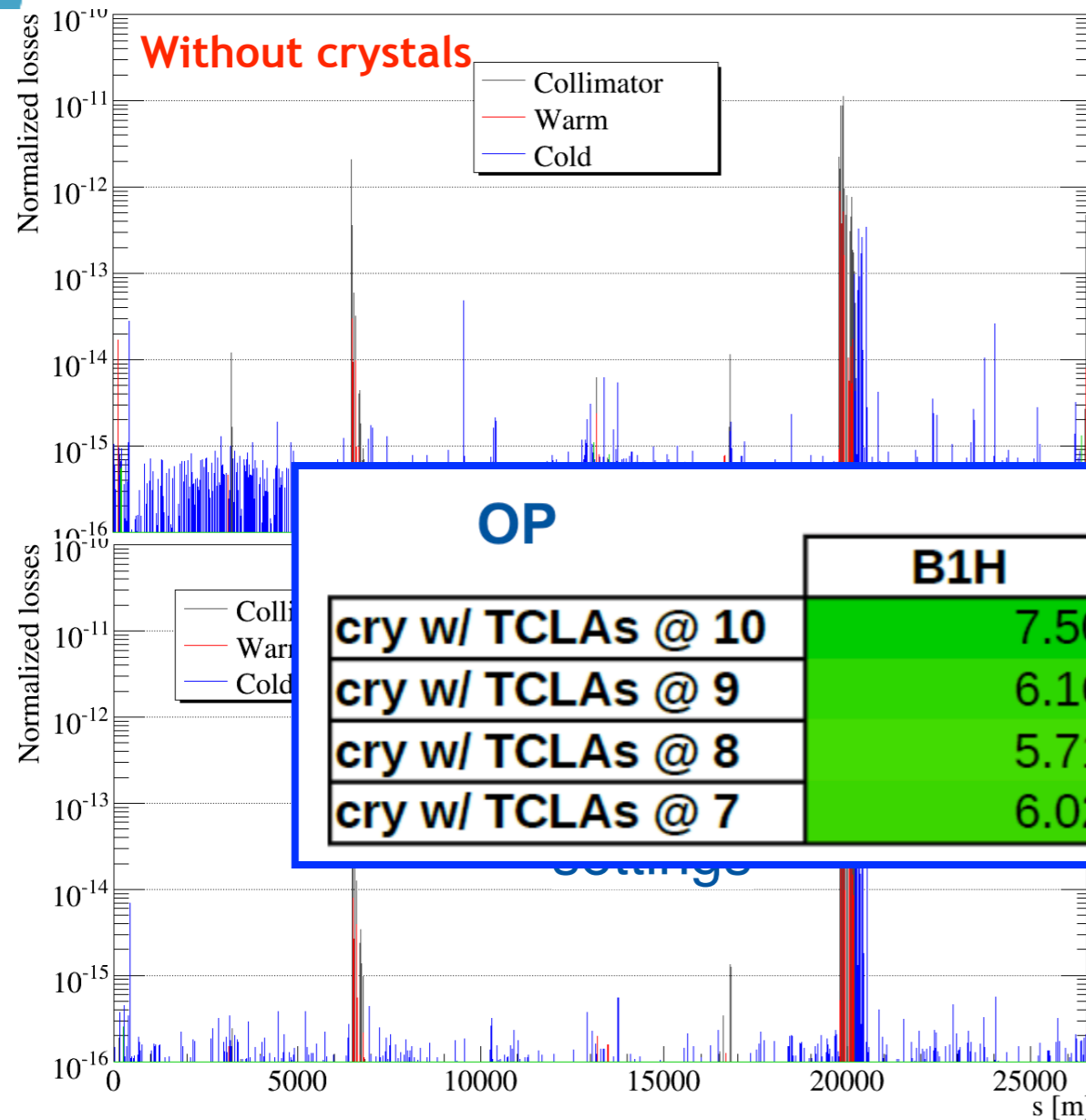


- Overall reduction of losses around the ring with crystal added to system.
- Tested with high ions intensities (~600 bunches)!
- Cleaning improvement up to a **factor 7** (more with optimised settings).
- Not the same improvement with all crystals — to be understood.

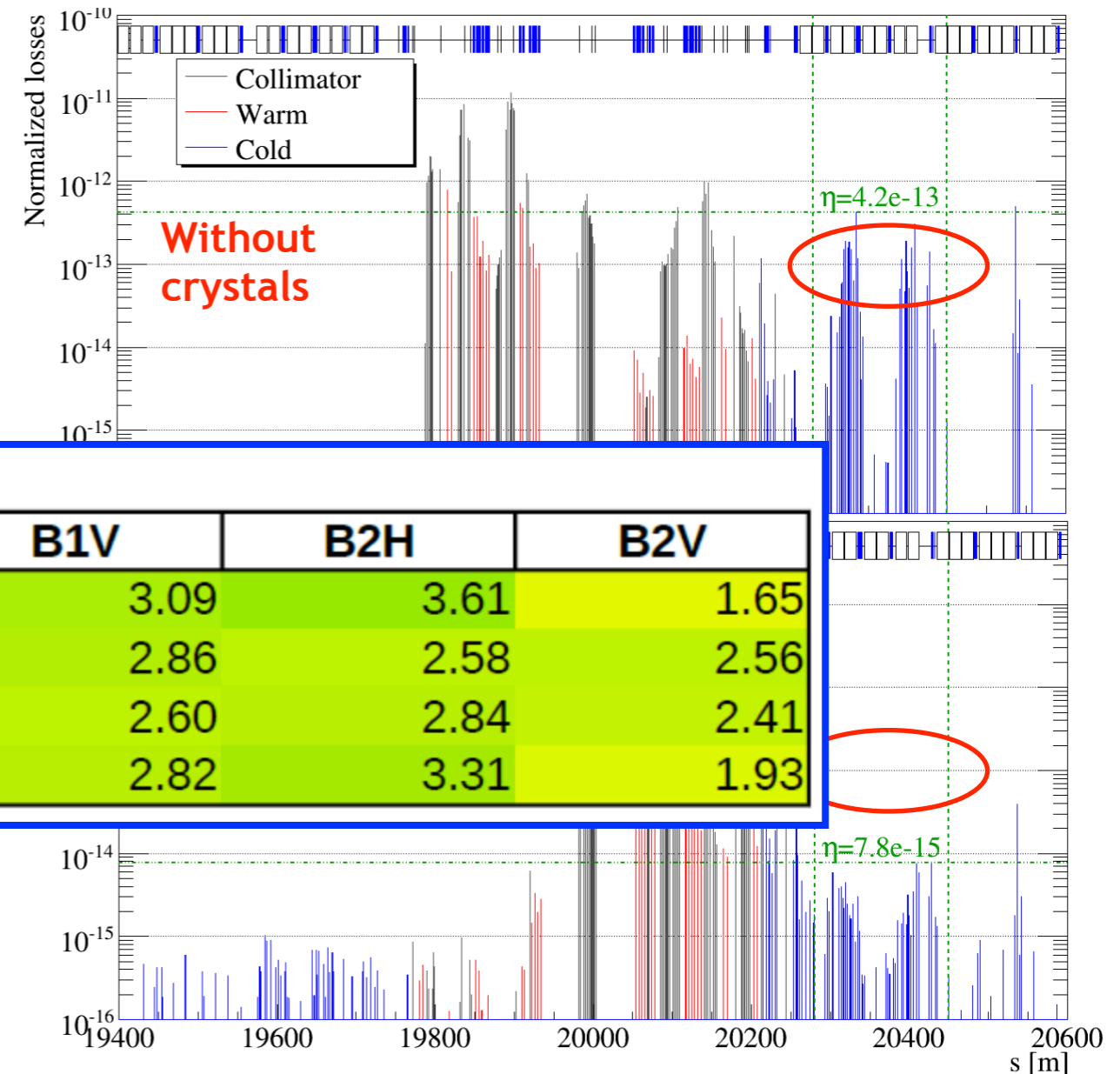
*(measurements available for a broad variety of settings)*

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Full ring



Betatron cleaning region

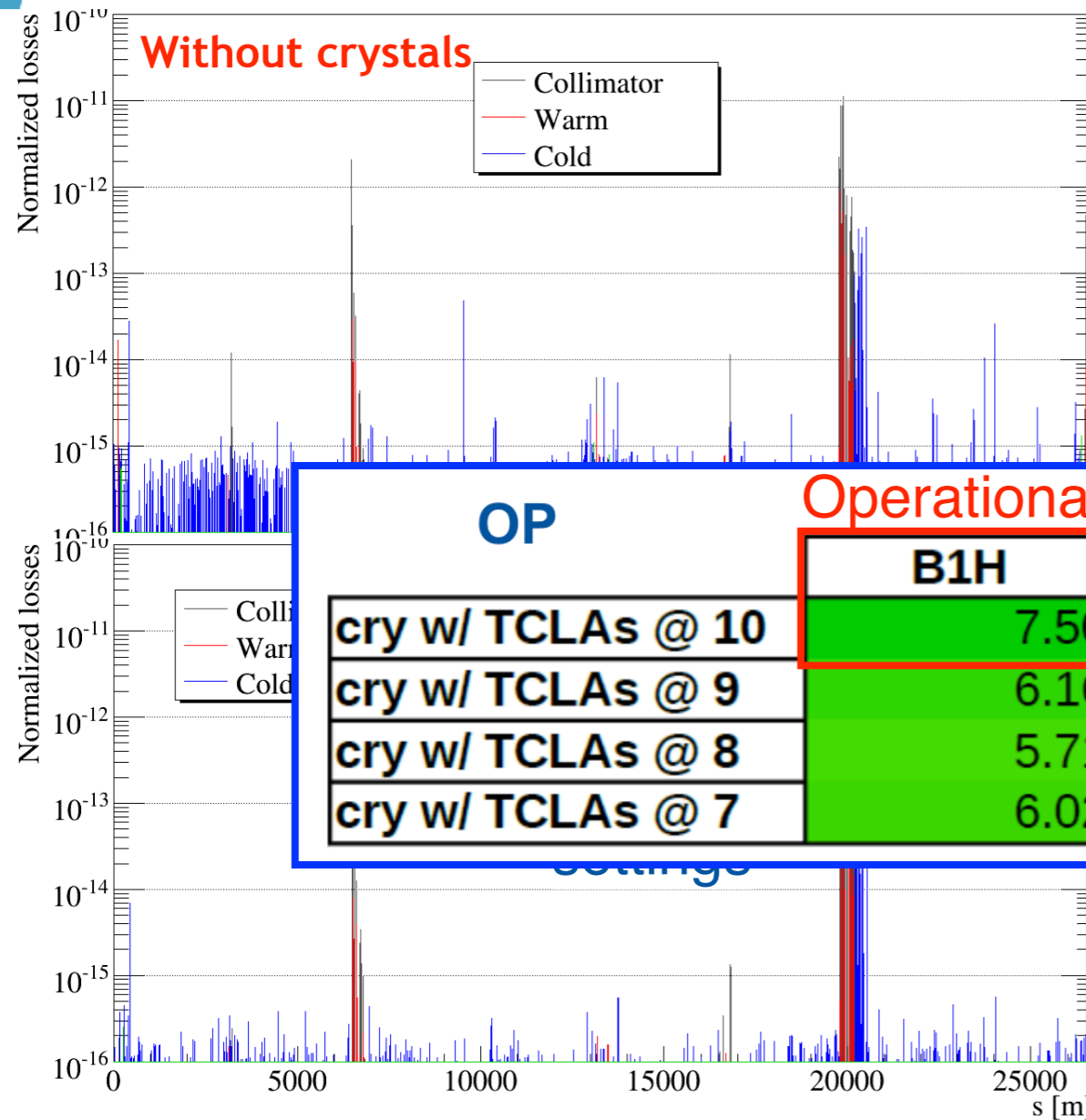


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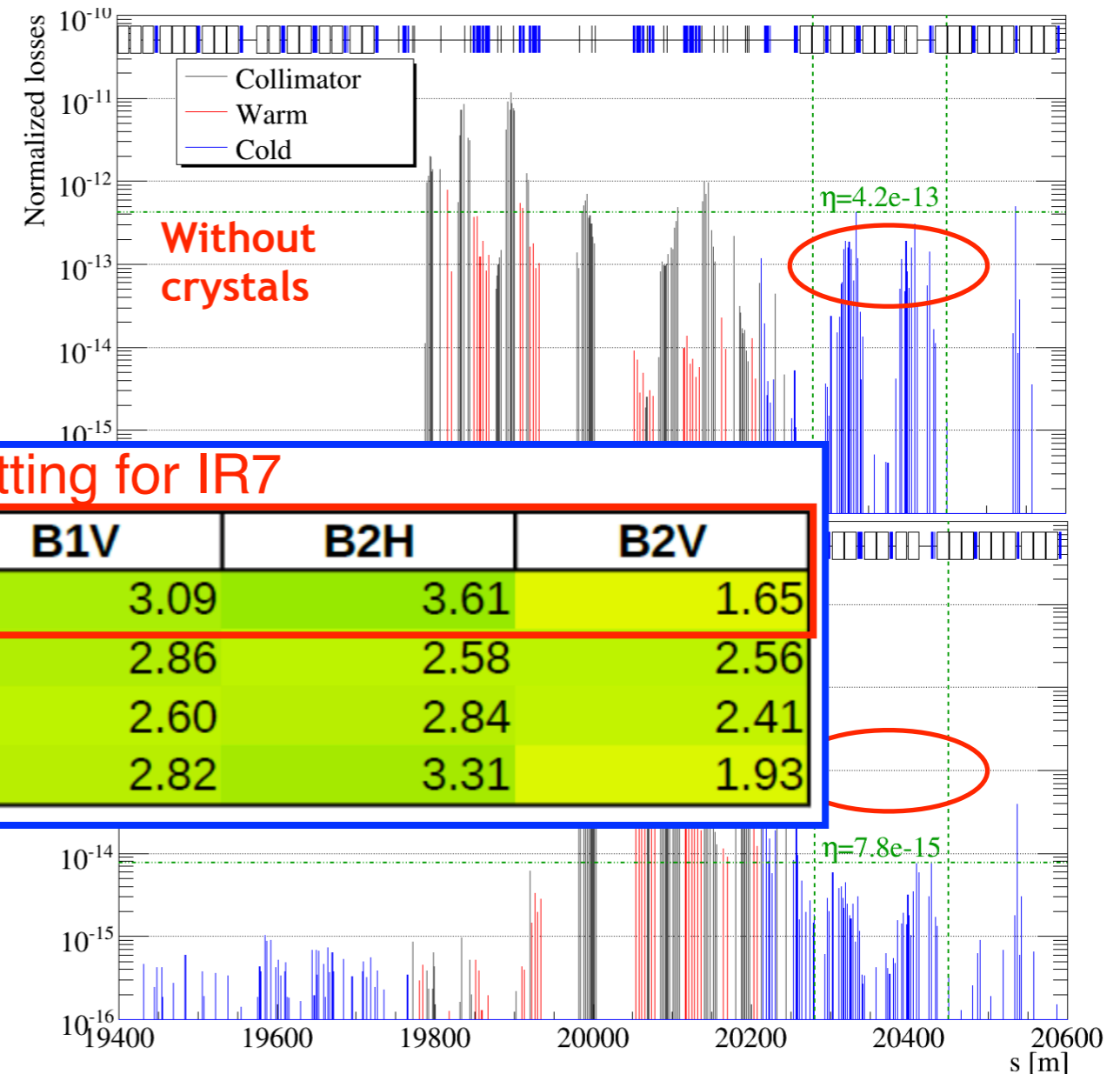
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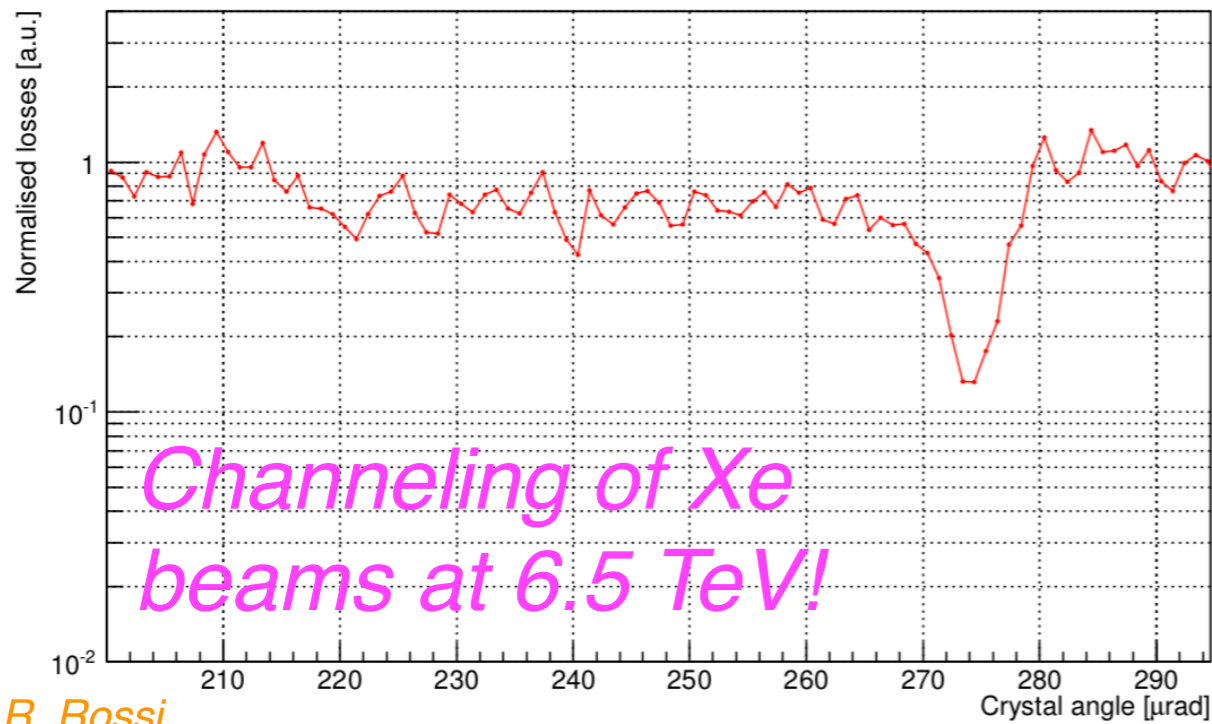
Betatron cleaning region



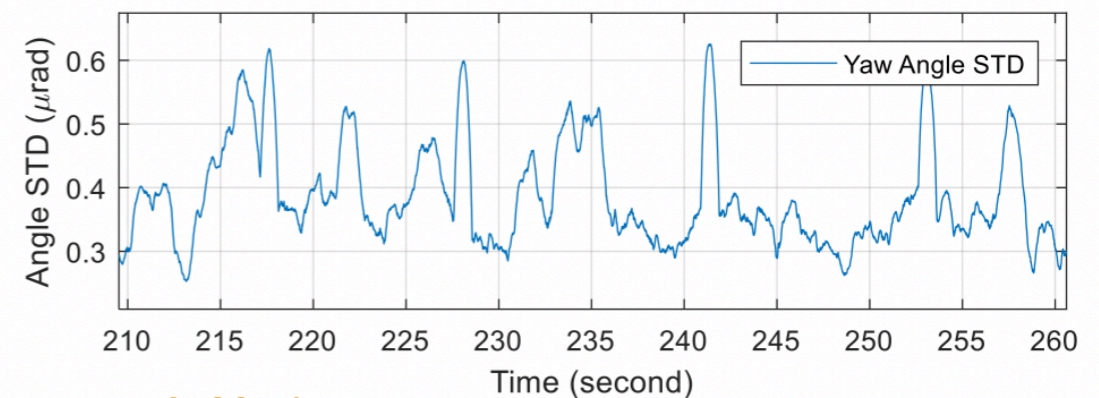
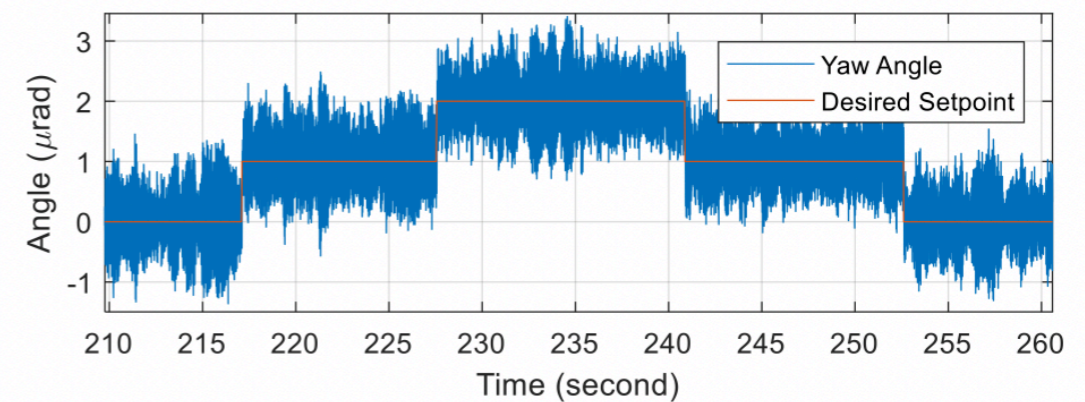
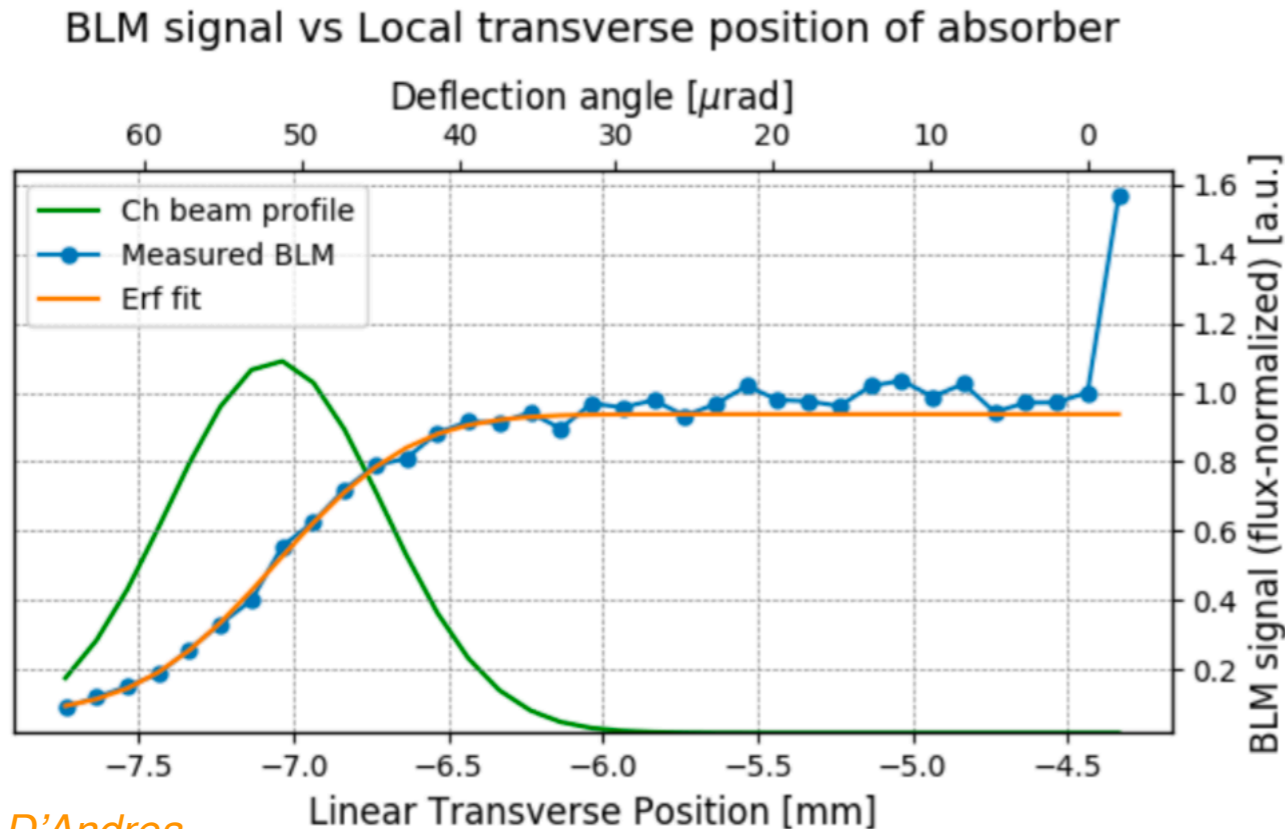
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(measurements available for a broad variety of settings)

# 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
- Sub- $\mu\text{rad}$  control of crystal angles

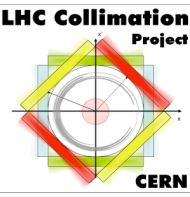


A. Masi

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- **Introduction**
- **Crystal collimation at the LHC**
  - LHC collimation challenges
  - Crystal collimation layouts
  - Highlight results from LHC Run II
- **Low-background run in 2018**
  - 450 GeV run for Roman pot physics
  - Crystal collimation to optimise backgrounds
- **Crystals for LHC fixed-targets**
- **Conclusions**

# 2018 special run “high- $\beta^*$ ” at 450 GeV

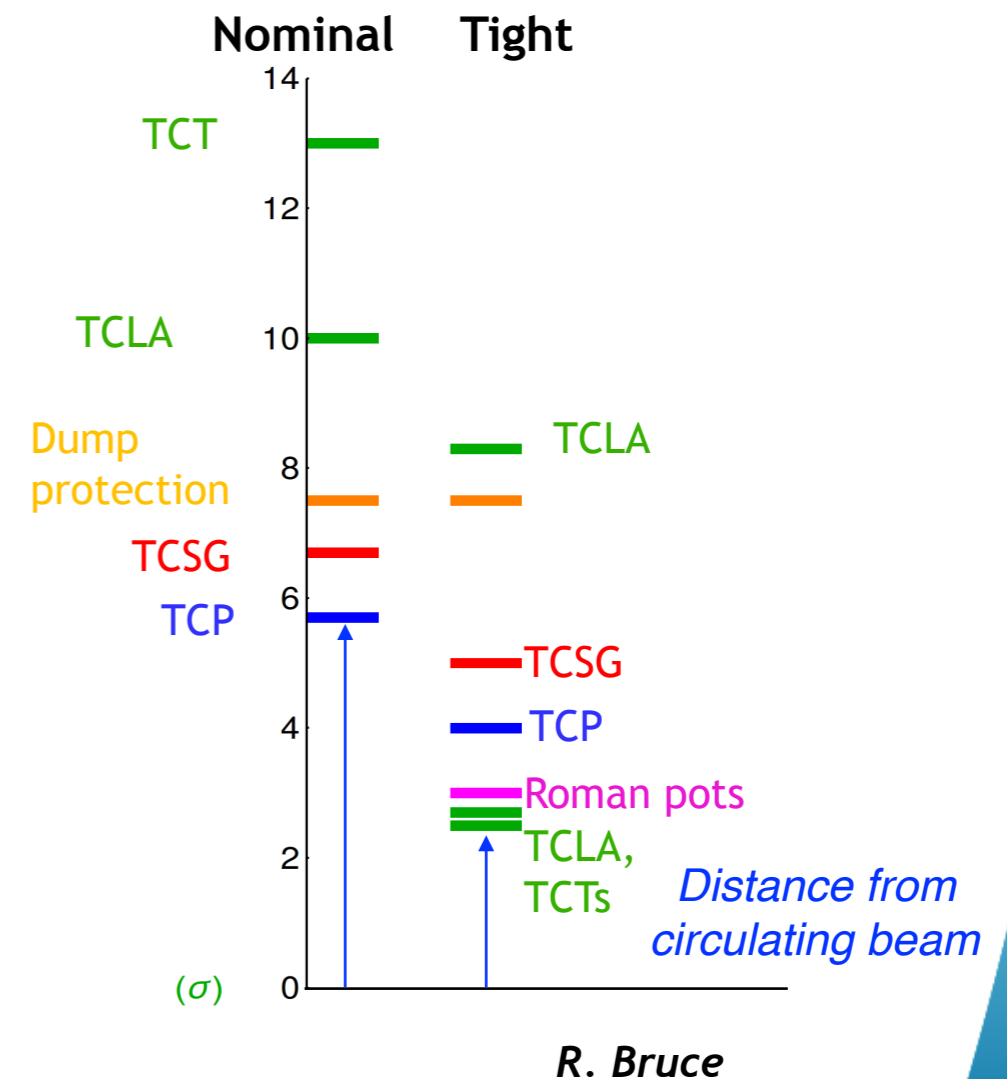


## Challenges for total p-p cross section measurements

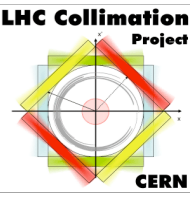
- **Short run** of only a few days, at injection energy ( $s^{1/2} = 900$  GeV)
- **New optics** with large colliding beam sized in ATLAS/CMS
- Roman pots of ATLAS-ALFA and TOTEM as **close** as possible to the beam
- **High background** rates observed in beam tests, putting in question the feasibility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

*Note: low beam intensities planned for this run!*

Primary stage at  $2.5 \sigma$   
Secondary stage at  $2.7 \sigma$   
Roman Pots at  $3 \sigma$   
*Tightest collimation ever in the LHC!*



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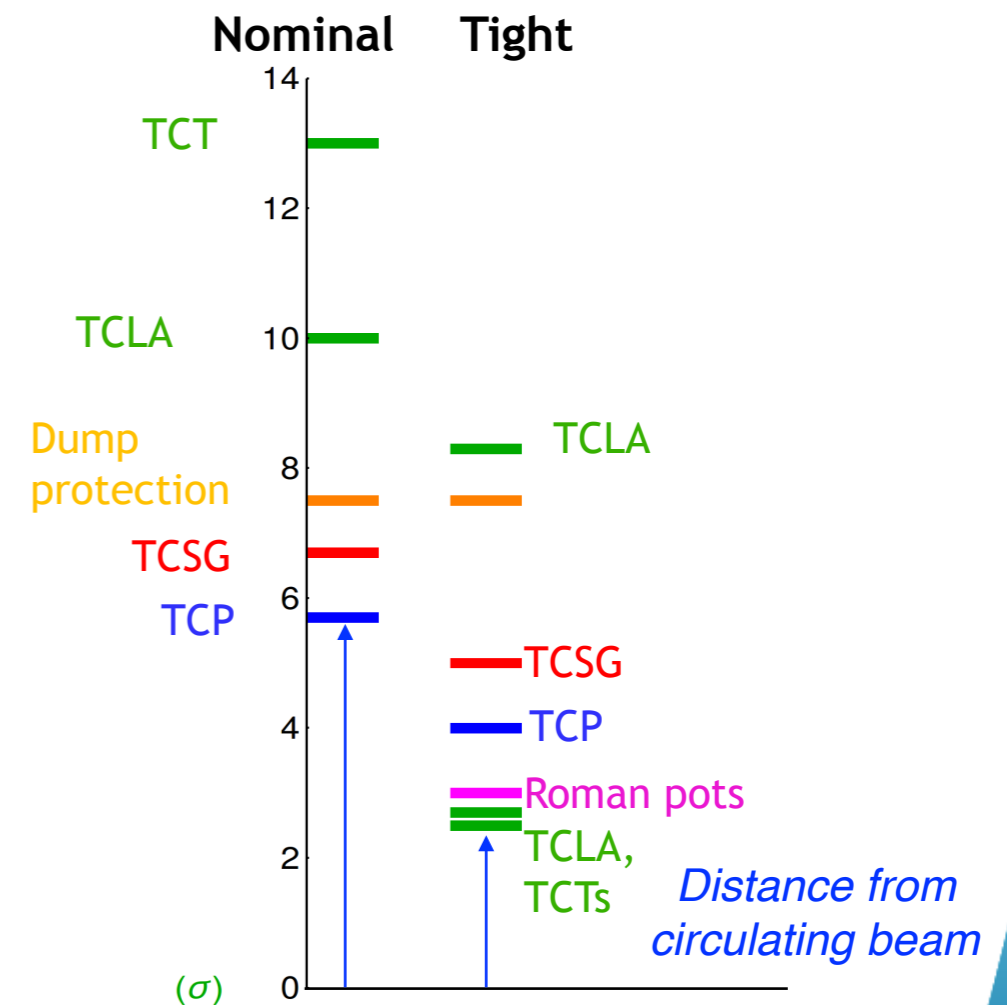
*Note: low beam intensities planned for this run!*

## 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.

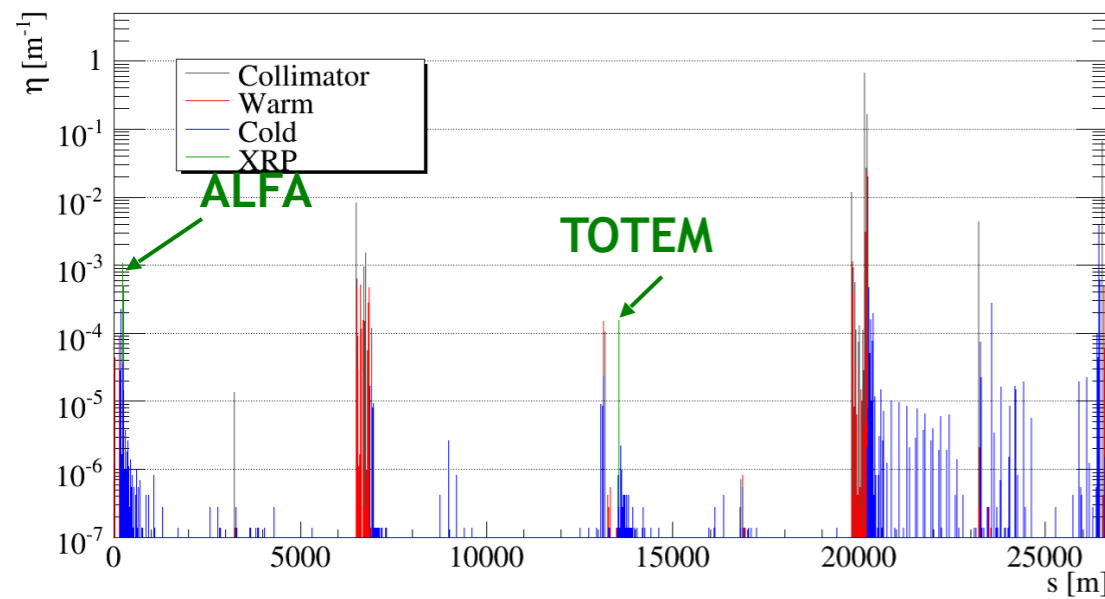
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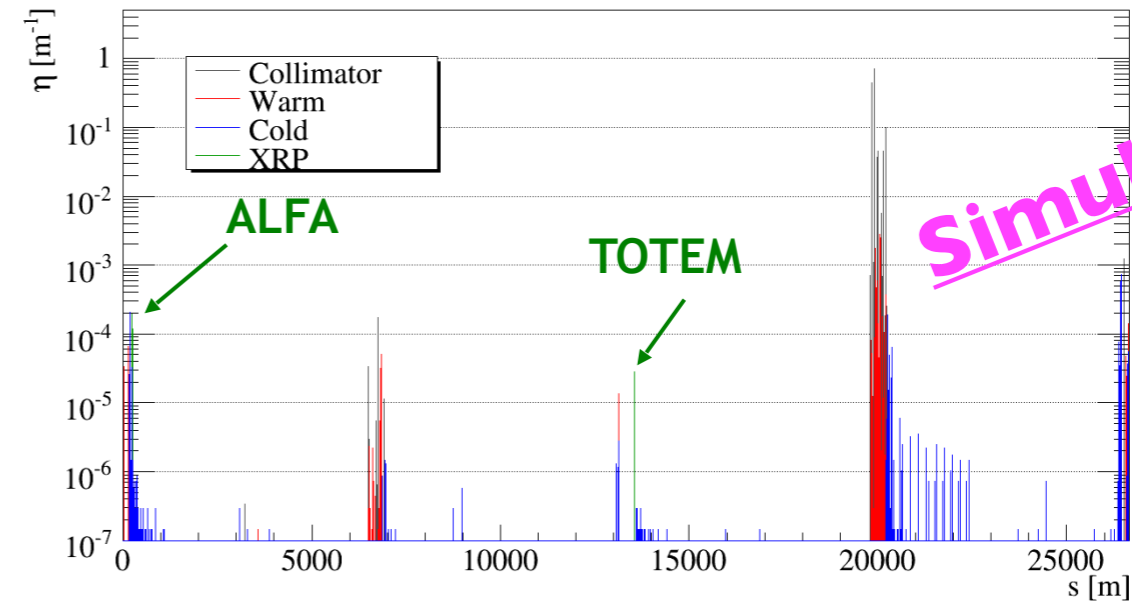
R. Bruce

# Reduced background with crystals

Conventional collimation



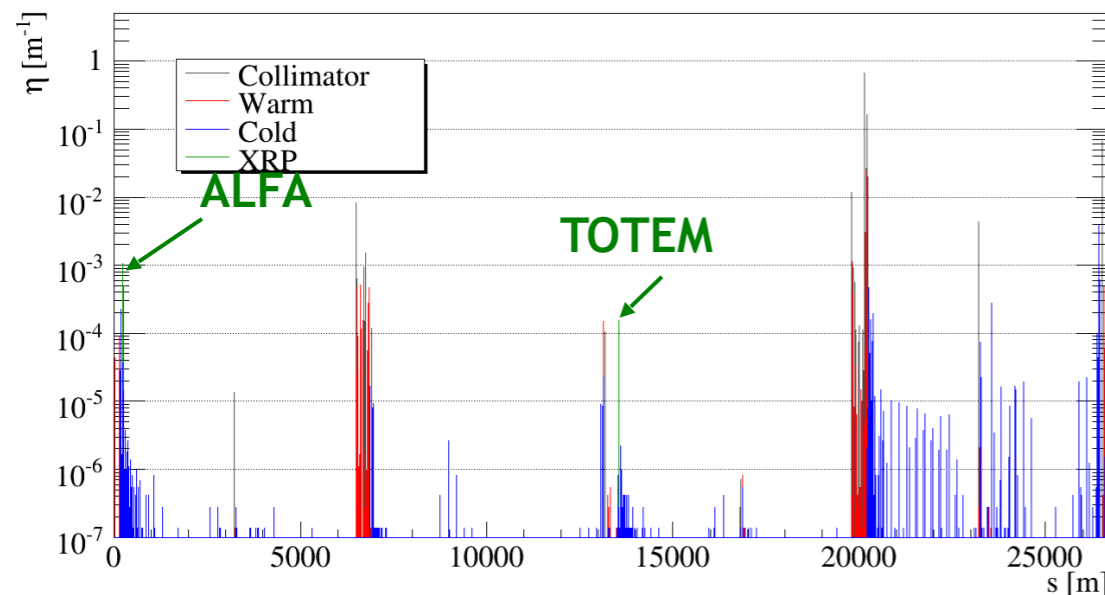
Crystal collimation



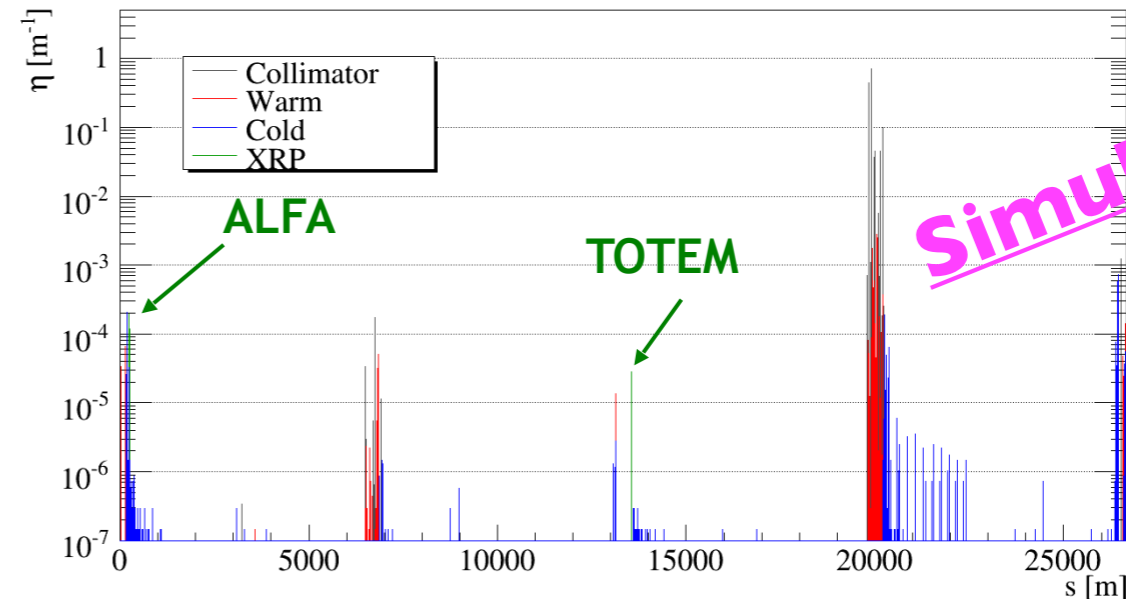
Simulations

# Reduced background with crystals

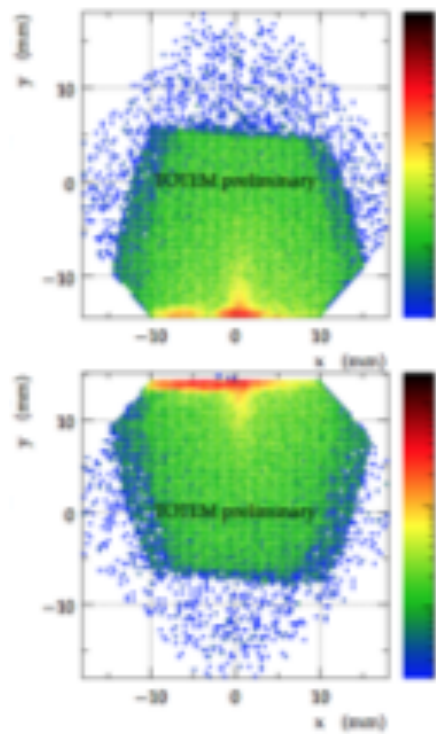
Conventional collimation



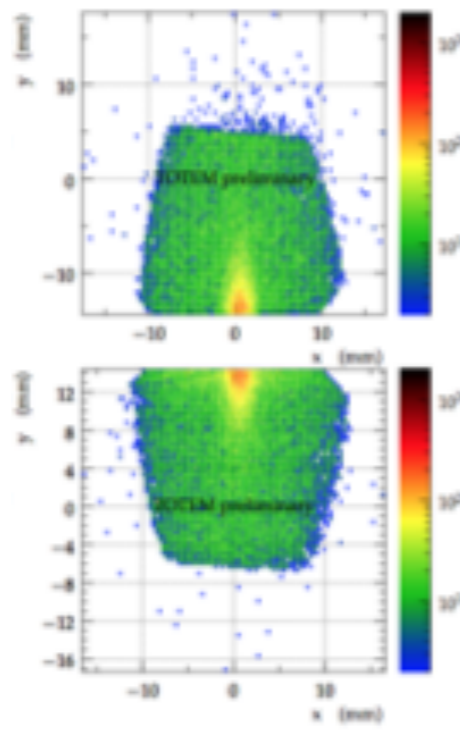
Crystal collimation



Standard



Crystal



## With crystal collimation:

- Significant background suppression for TOTEM!  
*Much simplified analysis, lower data rejection.*
- ATLAS-ALFA: problematic 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!

Courtesy of TOTEM (preliminary)

# Background evolution in time

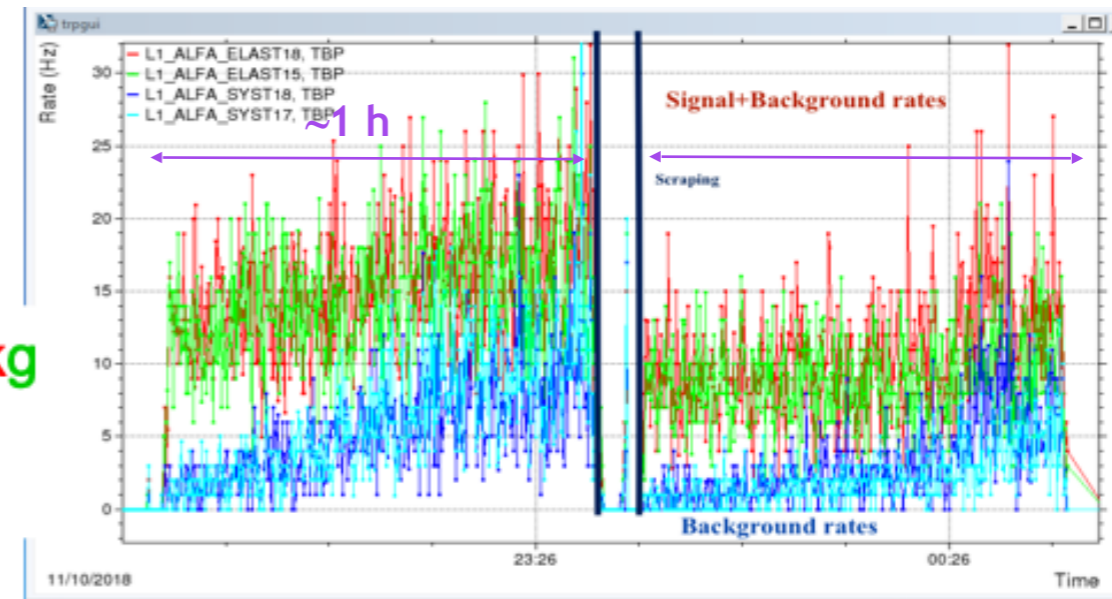
Crystal collimation



Signal+Bkg

Bkg

Standard collimation



Sig + Bkg

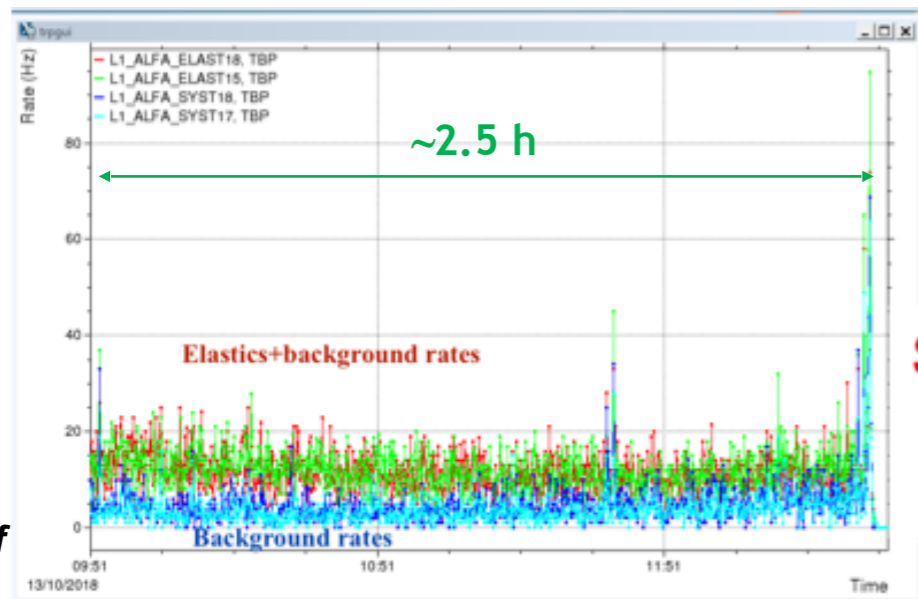
Bkg

Scheme by C. Schwicz

Courtesy of  
ATLAS  
(preliminary)

# Background evolution in time

Crystal collimation

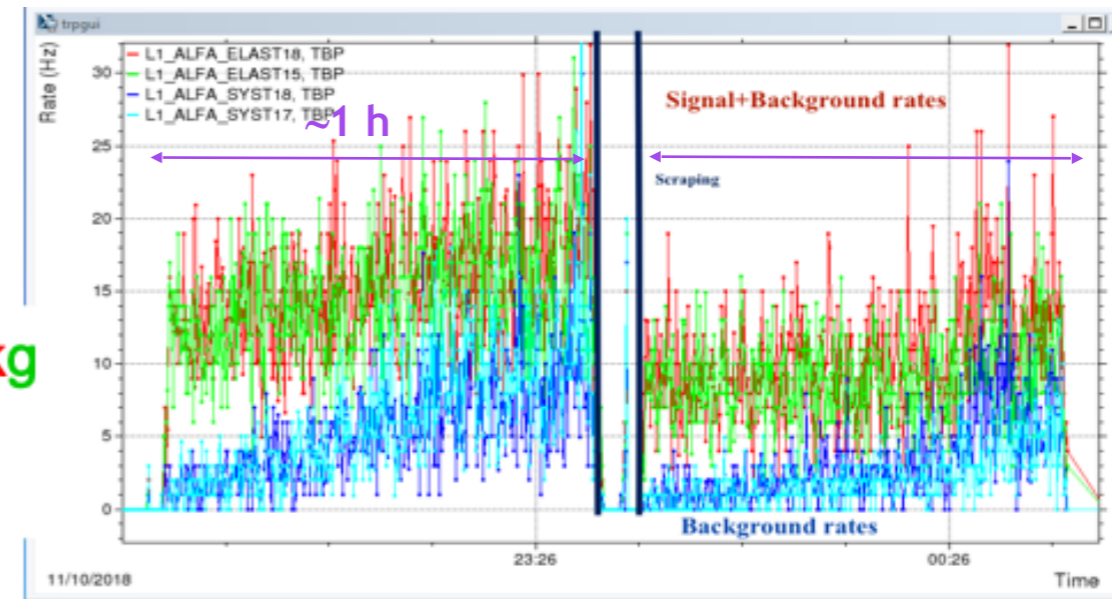


Signal+Bkg

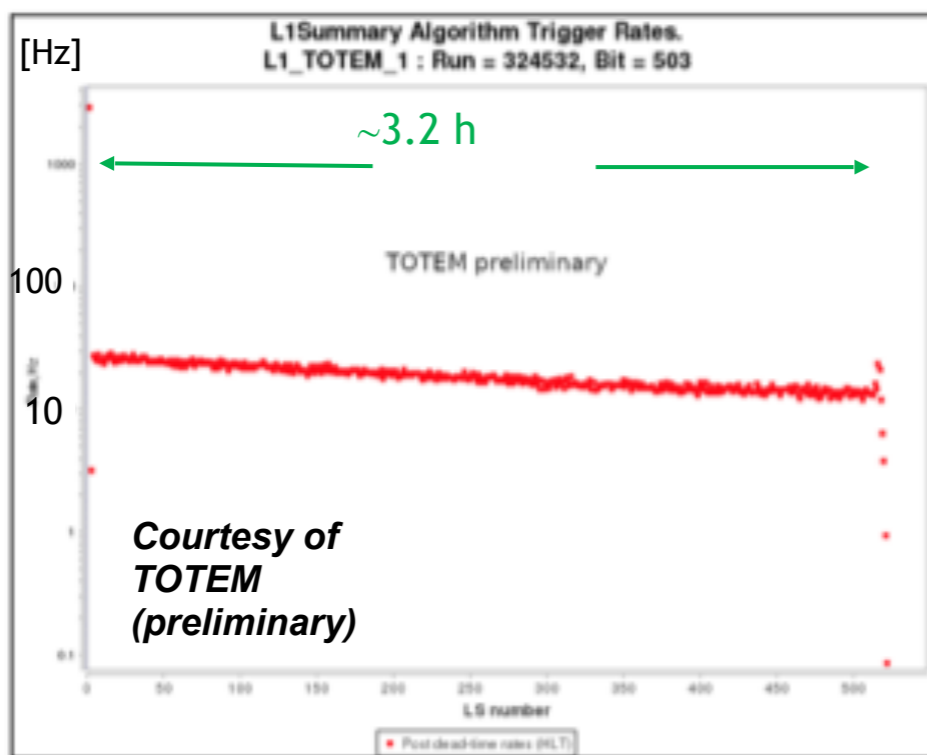
Bkg

Courtesy of  
ATLAS  
(preliminary)

Standard collimation

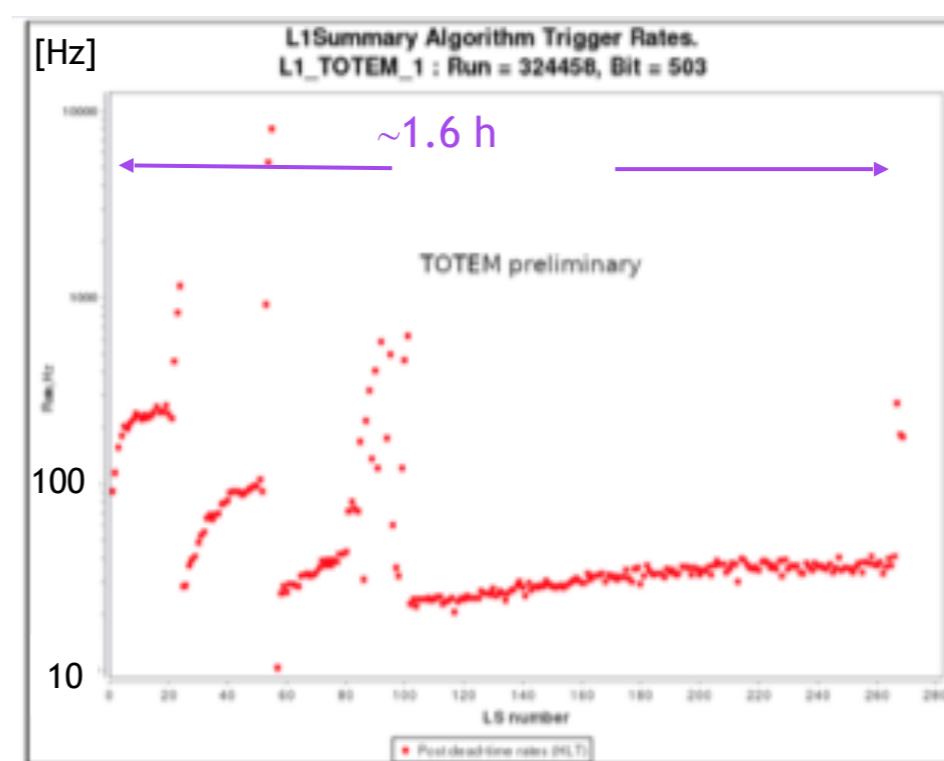


Crystal collimation



Courtesy of  
TOTEM  
(preliminary)

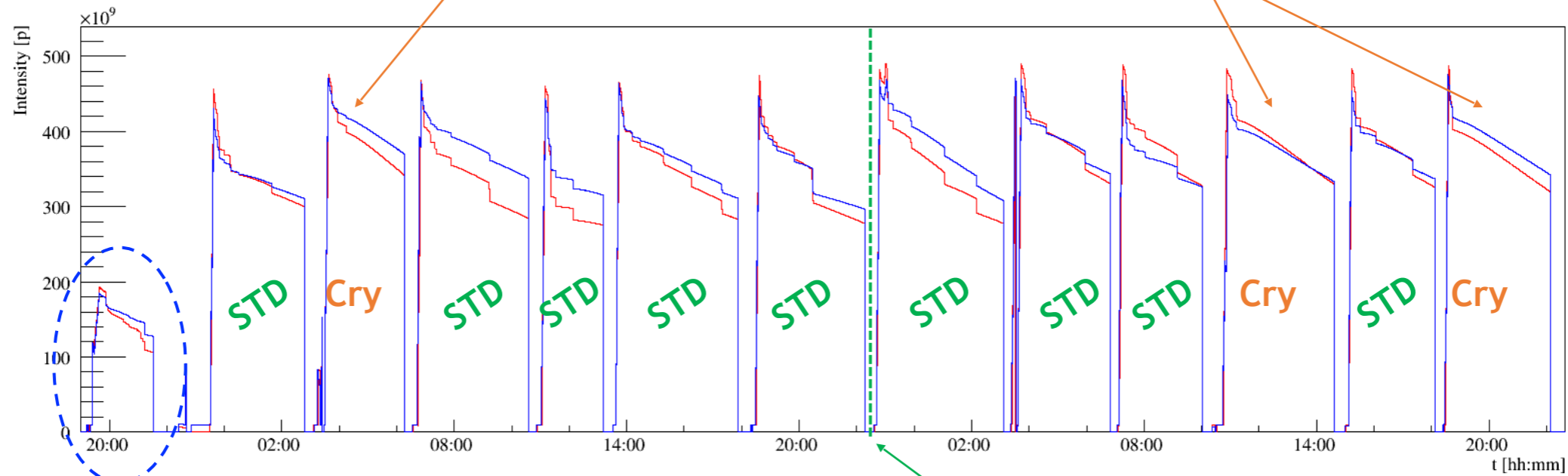
Conventional collimation



g

# Overall view of the high- $\beta^*$ run

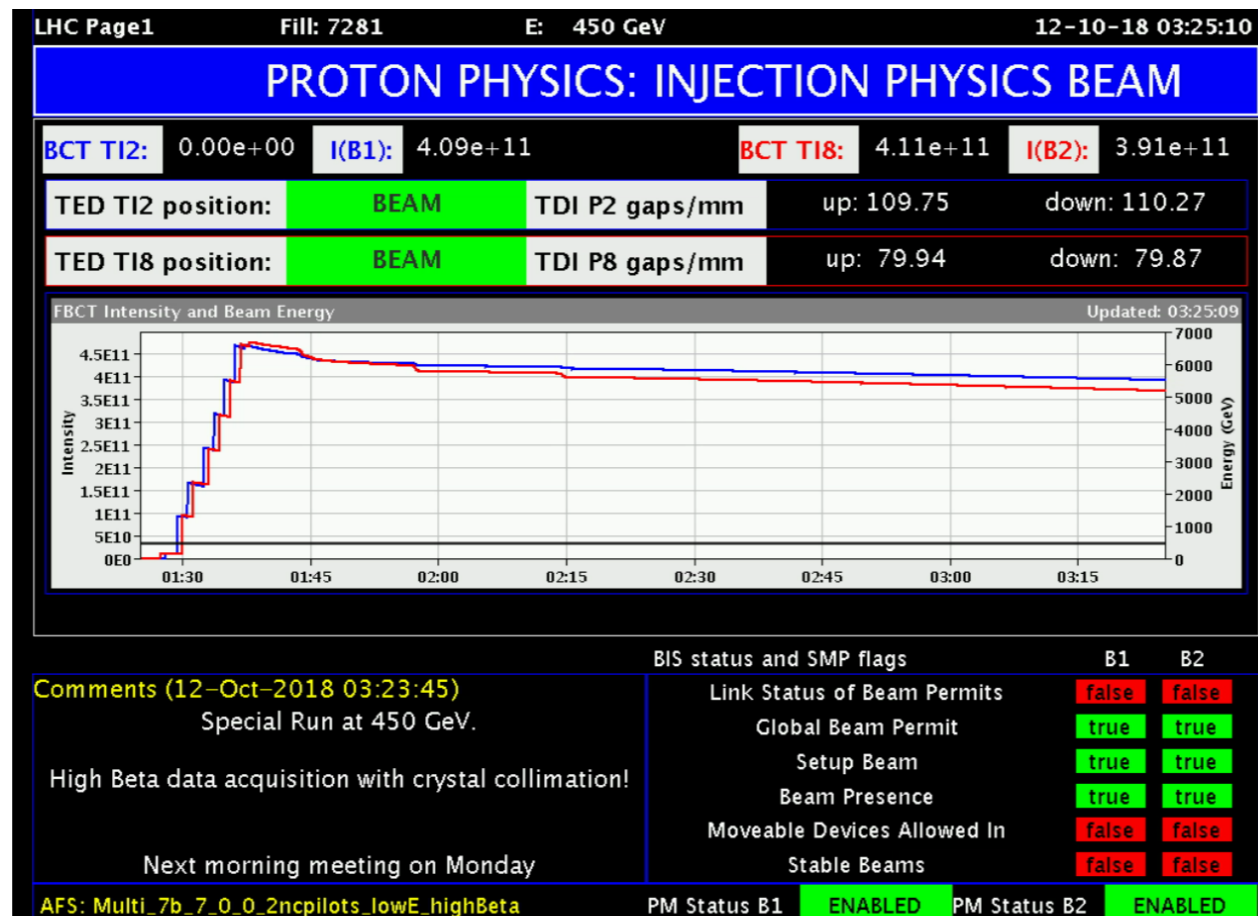
No need for frequent scraping when crystal collimation is used!



D. Mirarchi

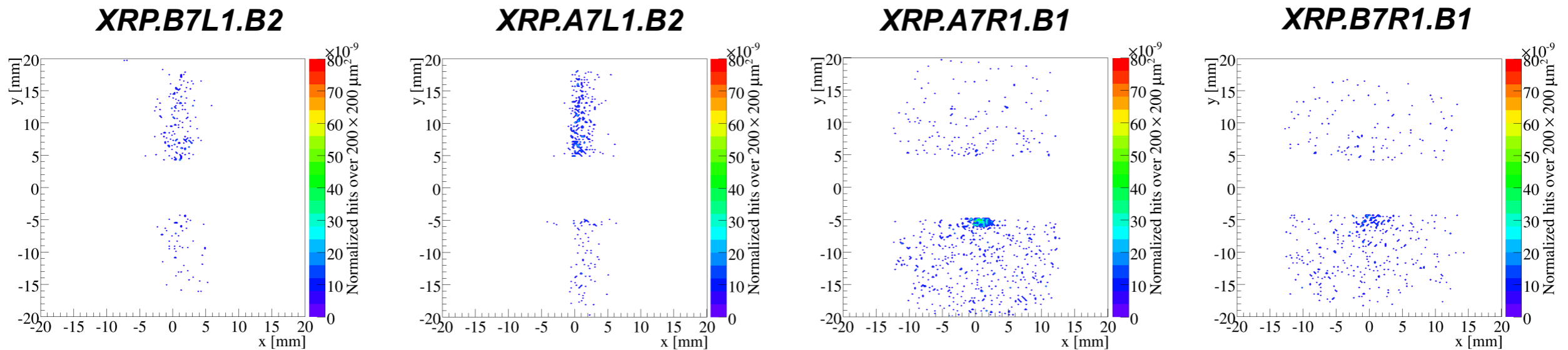
1 setup fill: confirmed alignment STD and Cry coll.

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



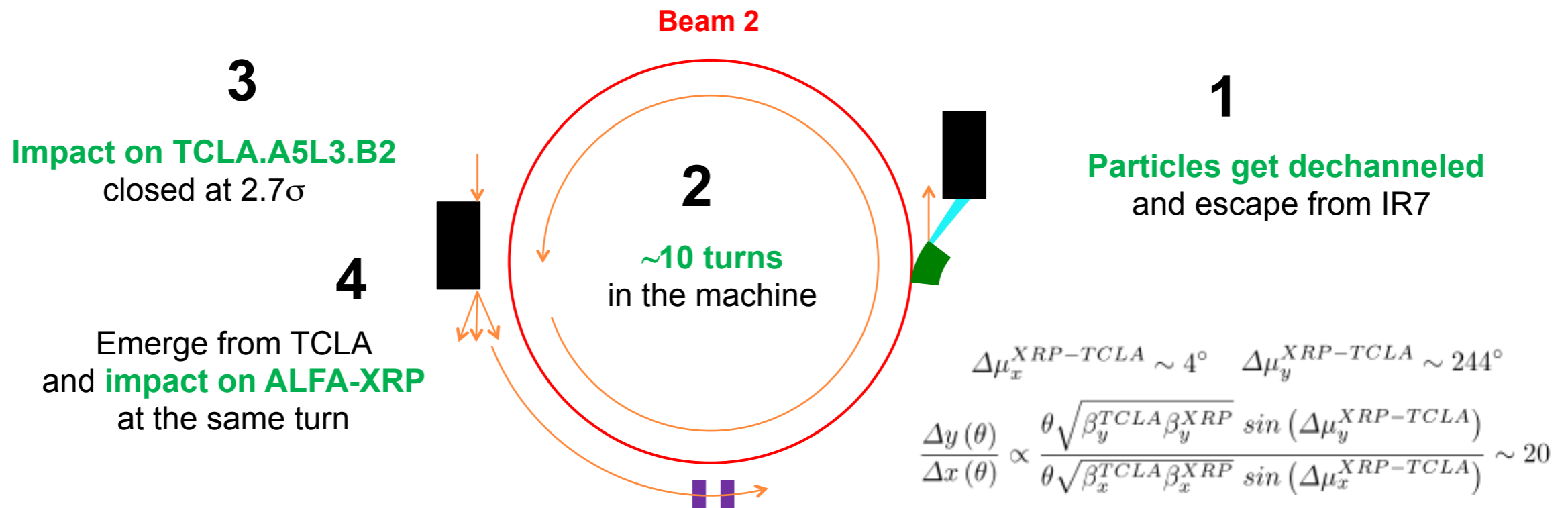
# Understanding ALFA background in simulations

Very high statistics needed:  $96 \times 10^6$  p simulated



- History of each particle reconstructed to understand the hit pattern:

D. Mirarchi



Exciting experimental observation that crystals clean the halo “faster”, i.e. over fewer turns.

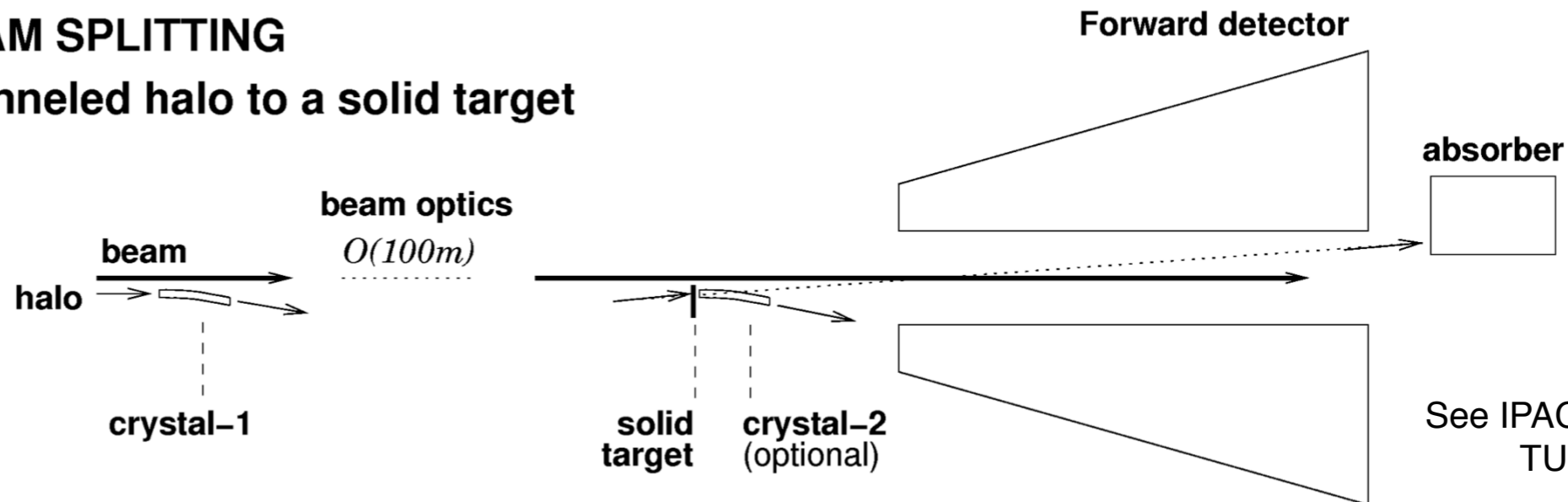
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# Scheme for halo splitting and fixed targets

## BEAM SPLITTING

channeled halo to a solid target



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

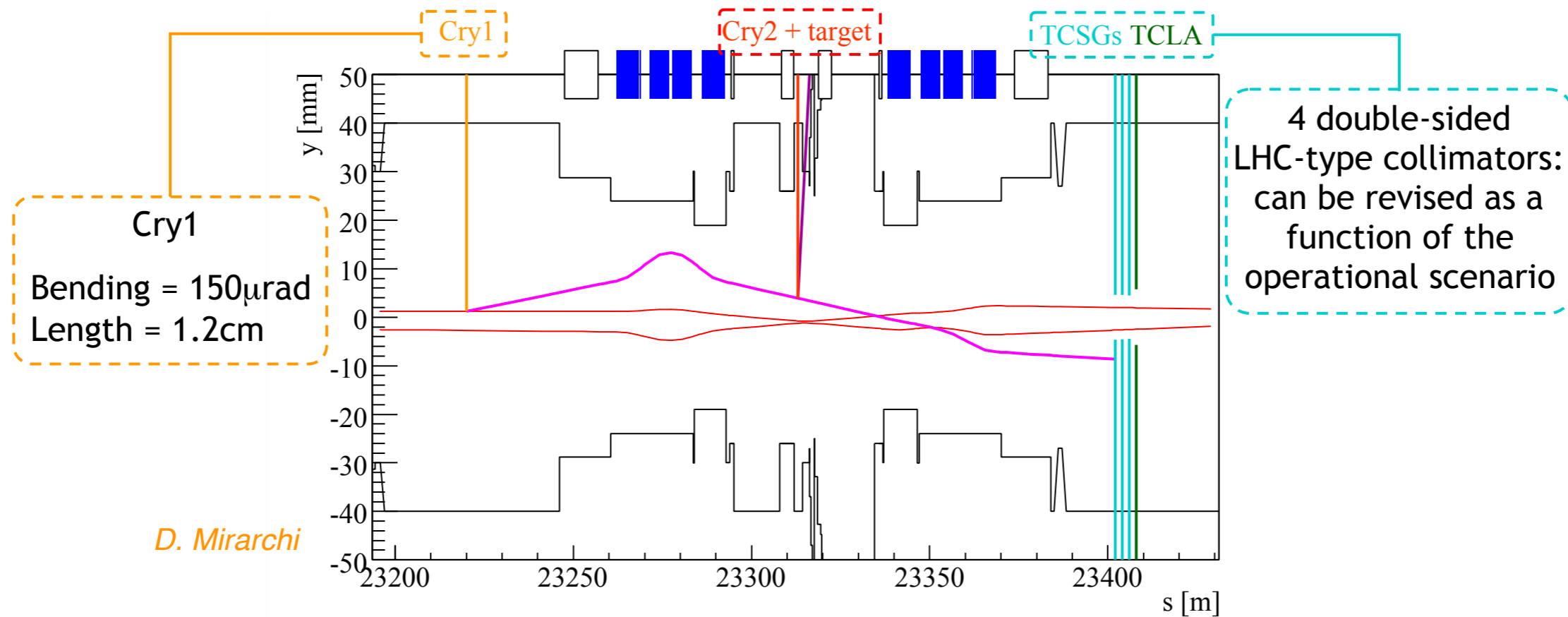
Achille Stocchi (LAL Orsay – Paris Sud/IN2P3)

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 = 7 cm.

- Being studied with the UA9 collaboration and the SELDOM team. Under evaluation by LHCb (not an approved experiment).
- The PBC-FT team is actively working on a final assessment of achievable protons on target for measurements of MDM and EDM. WG final report: CERN-PBC-REPORT-2019-001.
- 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).

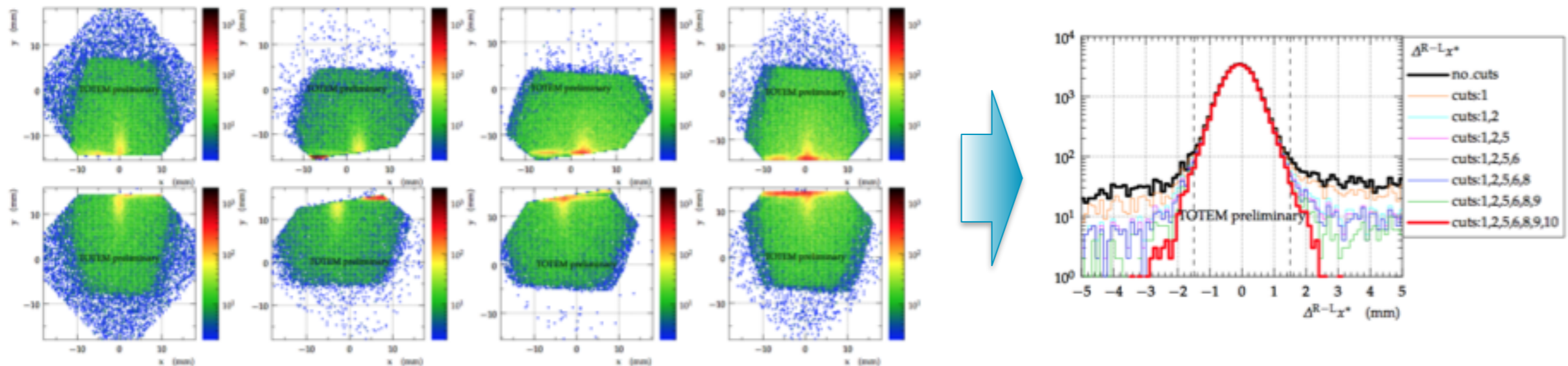
# Conclusions

- Reviewed the application of bent crystals at the high-energy frontier at the LHC: **crystal collimation of hadron beams**
  - A 4-crystal scheme was available during the LHC Run II at 6.5 TeV.
  - Extensive beam tests were done: proton, Pb, Xe; different energies.
- Very promising results for ion beam cleaning motivated the **integration of crystal collimation in the upgrade baseline**.
  - Observation of channeling at unprecedented beam energies, showing that we master the technology to control angles with the required accuracy.
  - Significant improvement of performance with heavy ion beams!
- **2018: first operational use of crystal collimation in a physics run, to reduce backgrounds for the p-p cross section measurements**
  - High- $\beta^*$  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: “PBC-FT”!

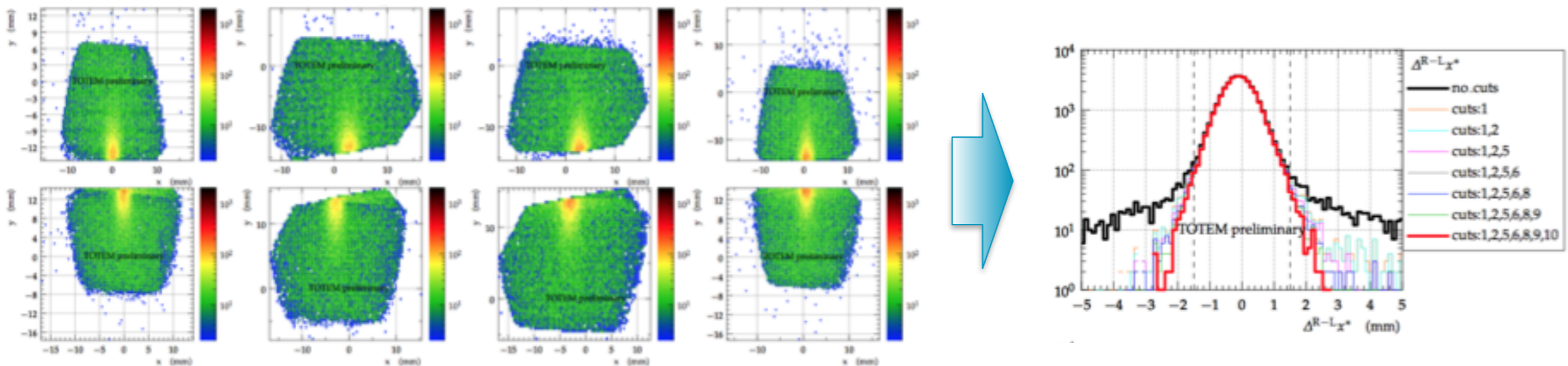
# *Reserve slides*

# TOTEM data quality (preliminary)

- Standard collimation: background at sensor edges, removed with full off-line cut



- Crystal collimation: no background evident, removed with first off-line cut



COURTESY OF J. CASPAR

# Evolution of LHC layouts

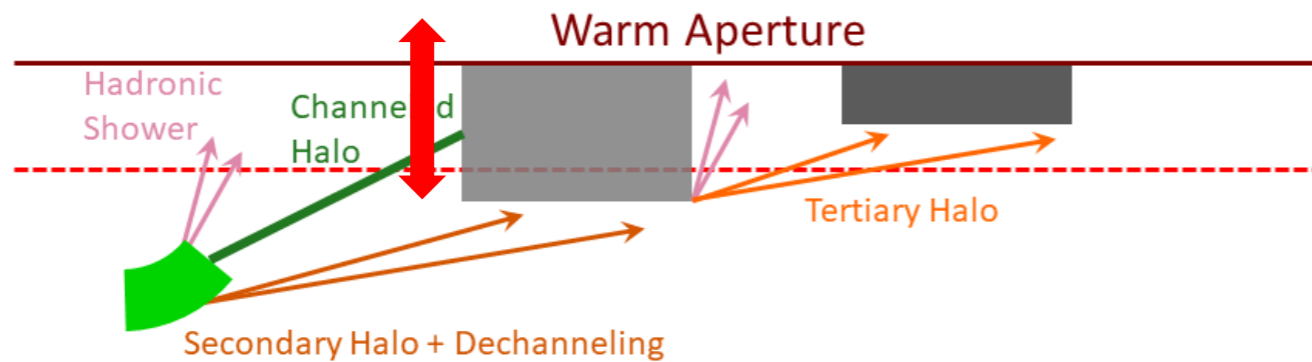
Four crystals installed in the LHC: two per beam, one per plane

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

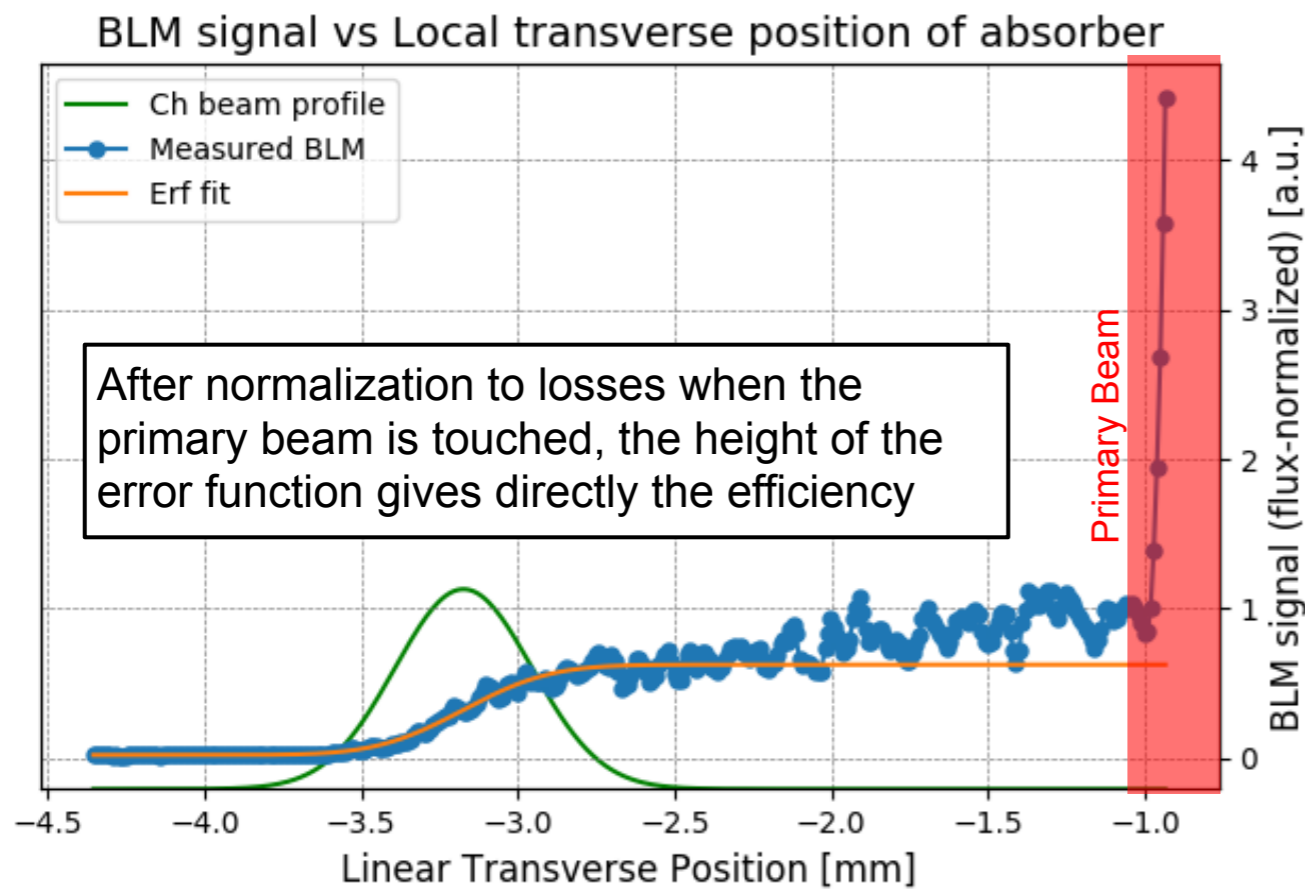
	Beam 1		Beam 2	
	Horizontal	Vertical	Horizontal	Vertical
2015 2016	Strip-INFN	QM-PNPI	N.A.	N.A.
2017	Strip-INFN	QM-PNPI	QM-PNPI	QM-PNPI
2018	Strip-INFN	QM-PNPI	Strip-PNPI	QM-PNPI

Complete layout to allow thorough investigations and operational tests

# Details of crystal linear scans



The absorber is retracted and inserted until it touches the primary beam, with the crystal in channeling orientation



Distance between channeled and primary beam is converted into deflection angle using the transfer matrix

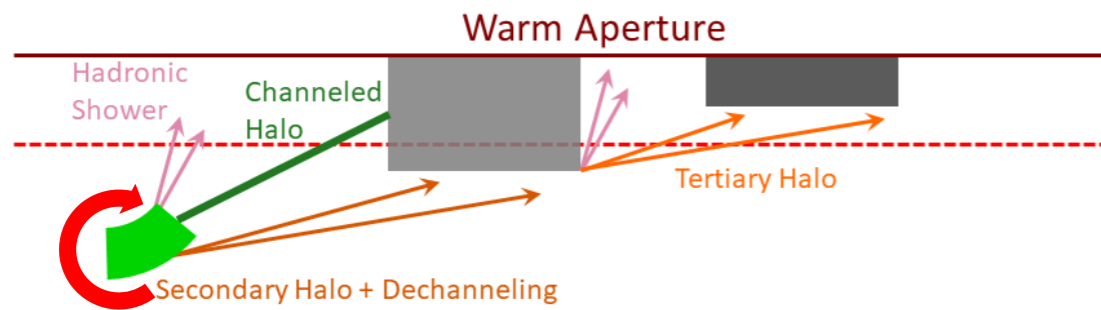
## What we look at:

- losses at the absorber as a function of its transverse position

## What we look for:

- multiturn channeling efficiency
- characterization of channeled beam and crystal bending angle

# Details of crystal angular scans



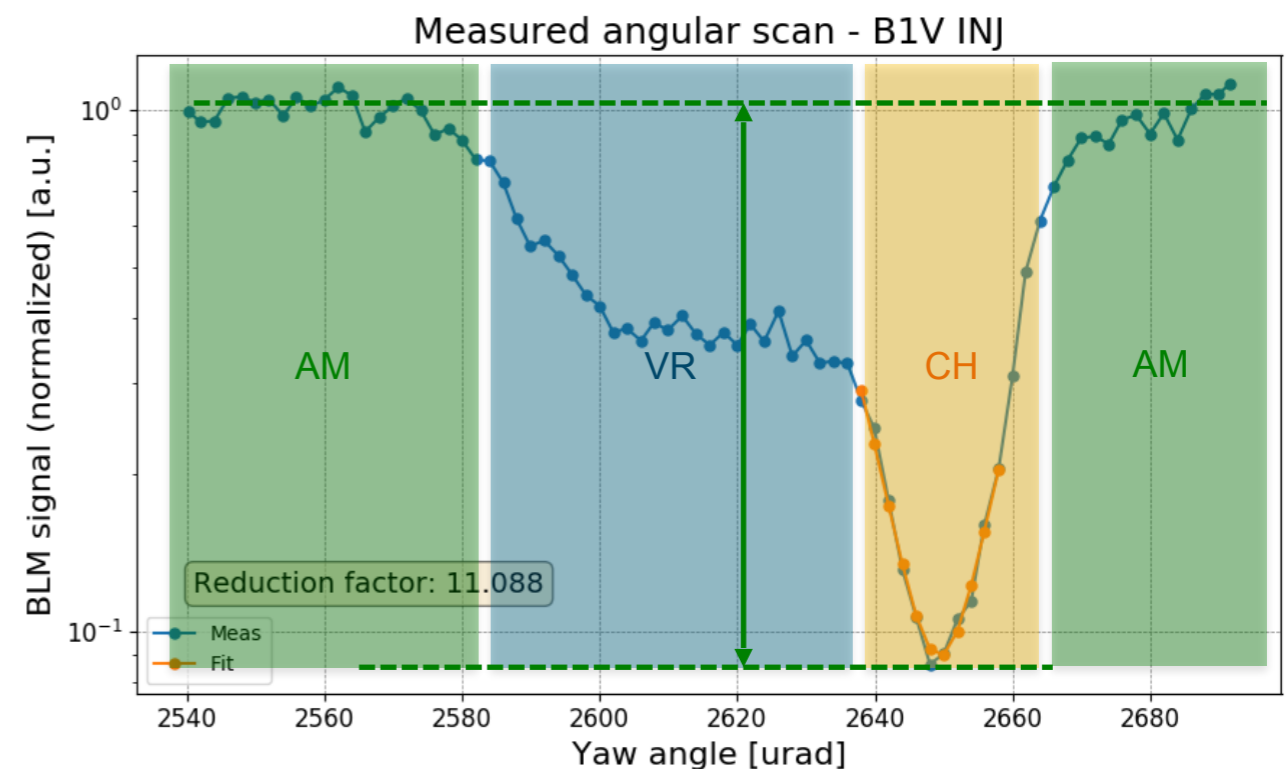
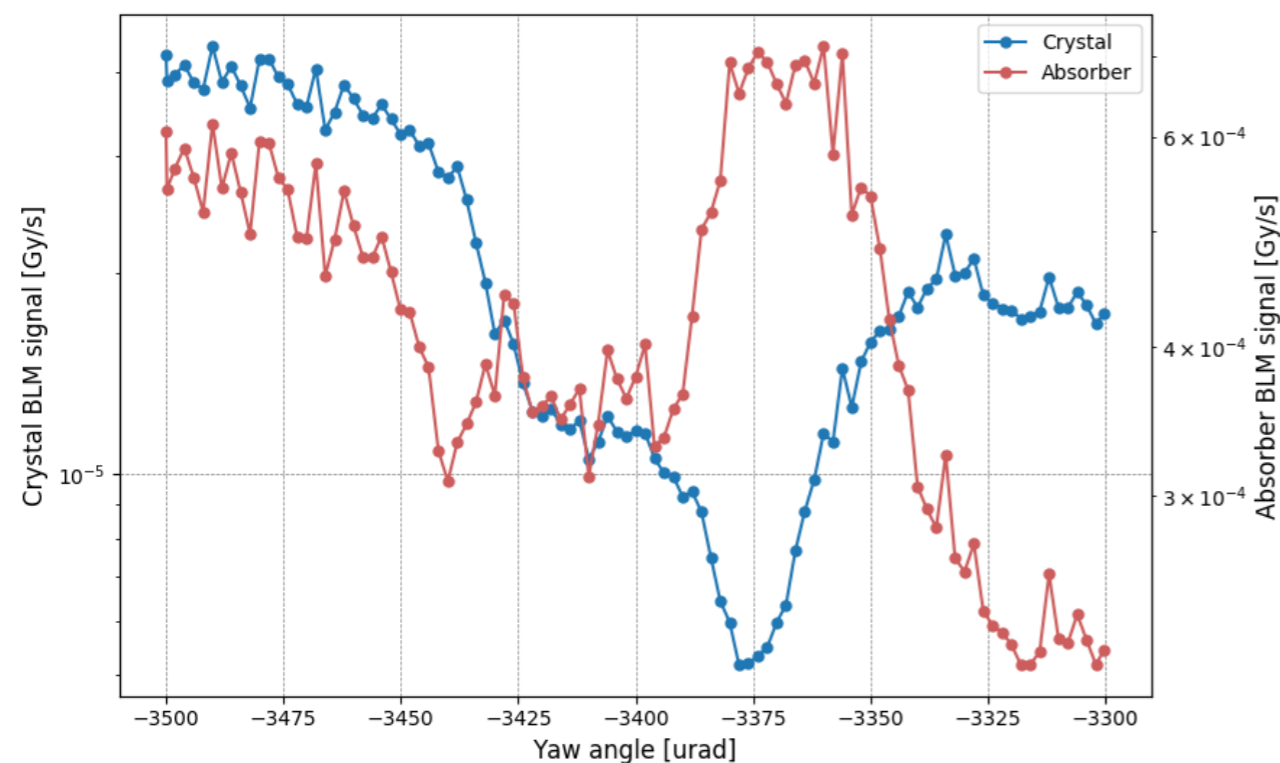
The crystal device is aligned to the beam halo and rotates around its axis

## What we look at:

- decreased losses at the crystal
- increased losses at the absorber

## What we look for:

- optimal channeling orientation
- reduction factor



Background subtracted, normalization to lost particles flux and amorphous level

# Motivation for the double-crystal setup

Use bent crystals for measuring the magnetic moment of the charmed charged hadrons starting from  $\Lambda_c^+$  ( $ct_0(\Lambda_c^+) \sim 60\text{mm}$ )

The same technique could be also used to measure the magnetic moment of the lepton  $\tau$

Anomalous magnetic moment of charmed and/or beauty quarks may account for the compositeness of those quarks

PBC kickoff, Sep. 2016:

## 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

Magnetic moment of channeled particles should precess in a bent crystal

$$\vartheta_{spin} = \frac{g-2}{2} \gamma \vartheta_{crystal}$$

See V.G. Baryshevskii, Pis'ma Zh. Tekh. Fiz.5, 182 (1979) and 757 (2016) 426-9.

PLB

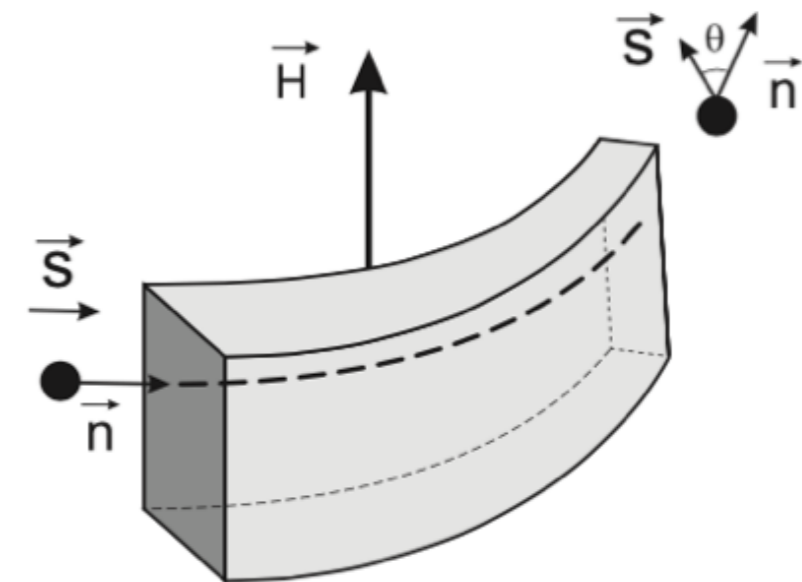


Figure 1. Spin rotation in a bent crystal