Crystal collimation for lead ion beams

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Acknowledgments:
UA9 Collaboration that provided the crystals installed in the LHC
R. Losito (EN), S. Gilardoni, M. Calviani, I. Lamas (EN-STI),
A. Masi, M. Di Castro, M. Butcher, P. Serrano, C. Dionisio (EN-SMM)
that provided hardware and controls of LHC goniometers

International Review of the HL-LHC Collimation System,
12th February 2019, CERN

Outline

I. Crystal channeling

II. Beam Collimation at the LHC

III. Main challenges and milestones achieved

IV. From MD to Operations

V. Conclusions

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4. ***From MD to Operations***
5. ***Conclusions***

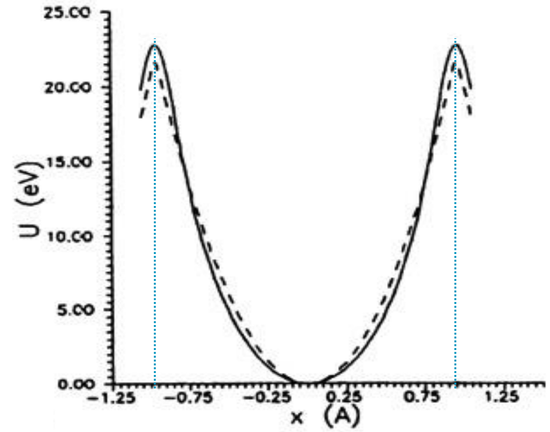
Planar channeling

Potential between a **particle** and an **atom** described by the **Thomas-Fermi model**: $V(r) = \frac{Z_i Z e^2}{r}\Phi(\frac{r}{a_{\mathrm{TF}}})$

Continuous approximation (small θ_{imp}):

$$U_p(x) = Nd \iint_{-\infty}^{+\infty} V(x,y,z)dydz$$

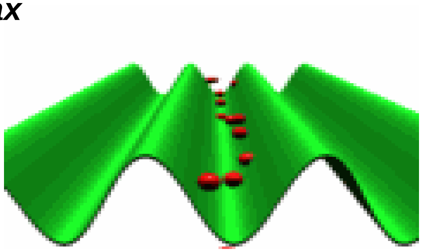
Potential seen by protons from crystalline planes



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

Critical channeling angle

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



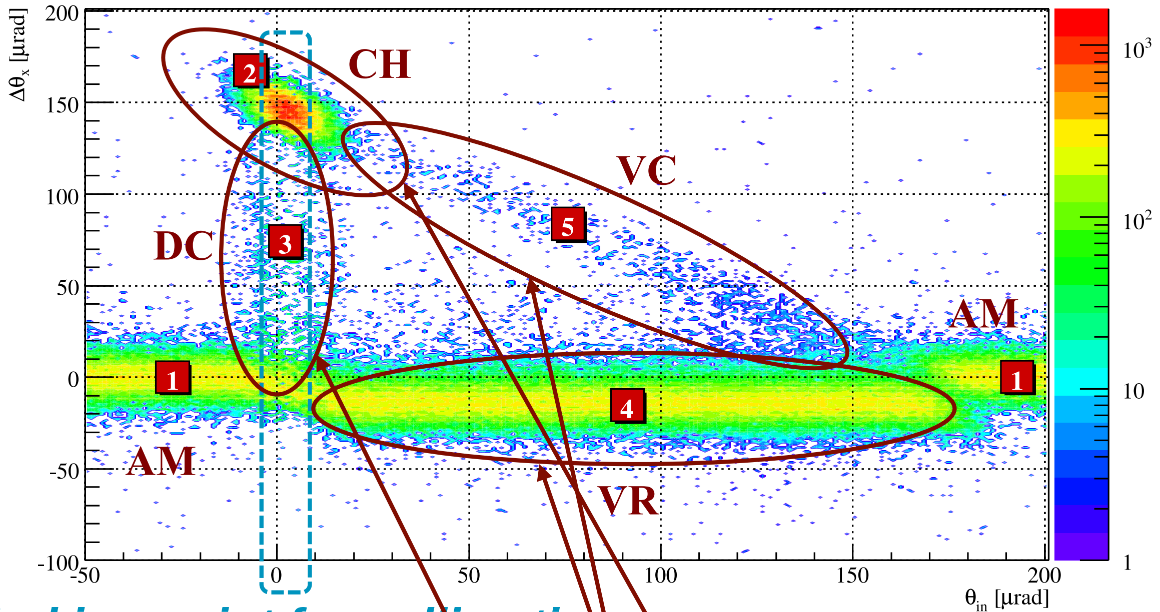
Forced to oscillate in a relatively empty space

***Typical values** at energies of our interest:*

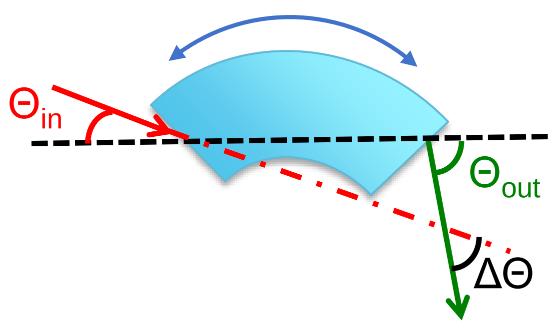
Case	Energy [GeV]	θ_c [μrad]	λ [μm]
SPS coast	120	18.3	33.0
SPS coast	270	12.2	49.6
H8	400	10.0	60.3
LHC inj.	450	9.4	64.0
LHC top	6500	2.5	243.2
LHC top	7000	2.4	252.3

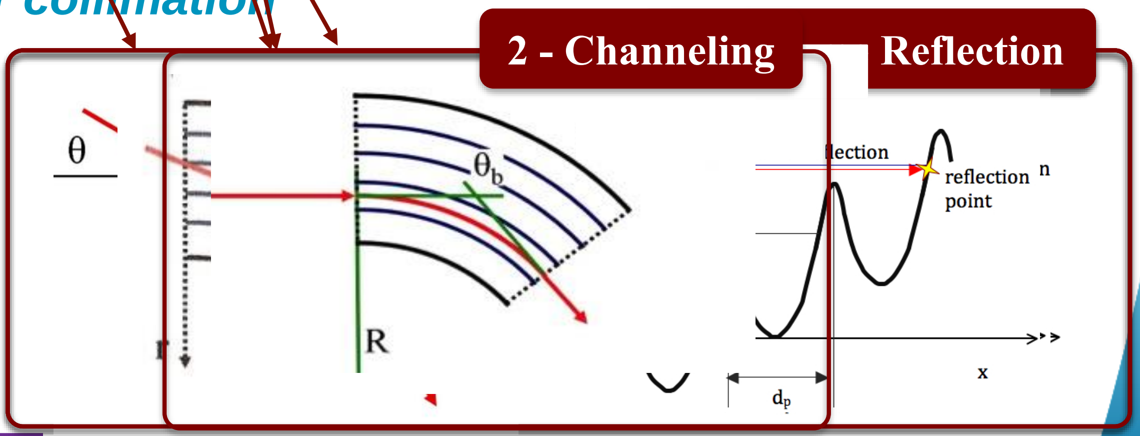
Coherent processes in bent crystals

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



Working point for collimation





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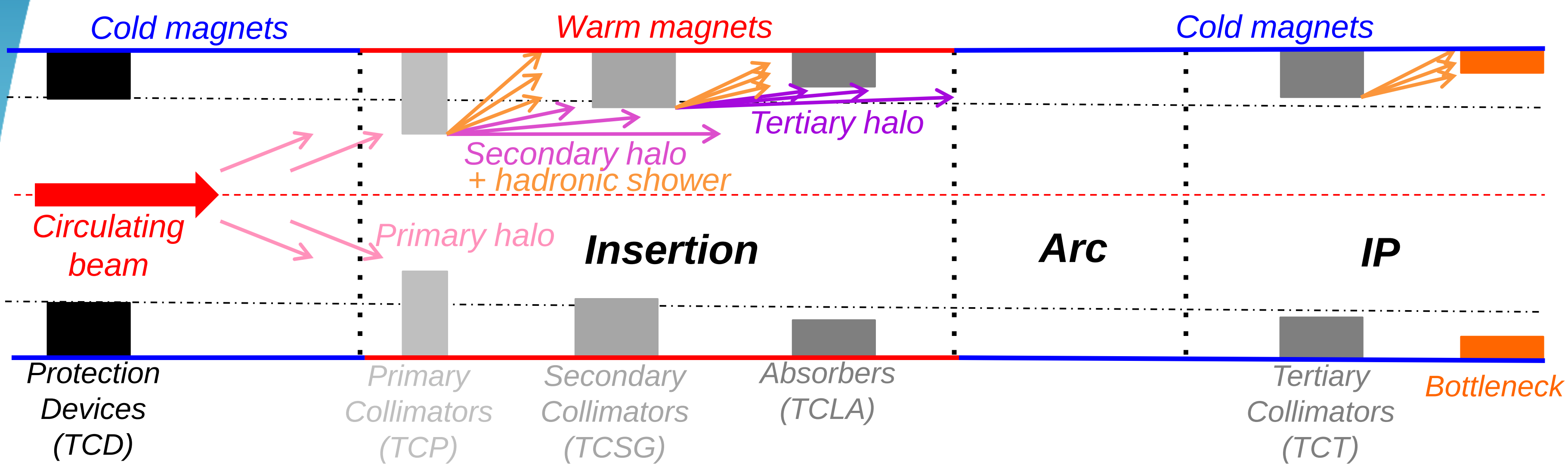
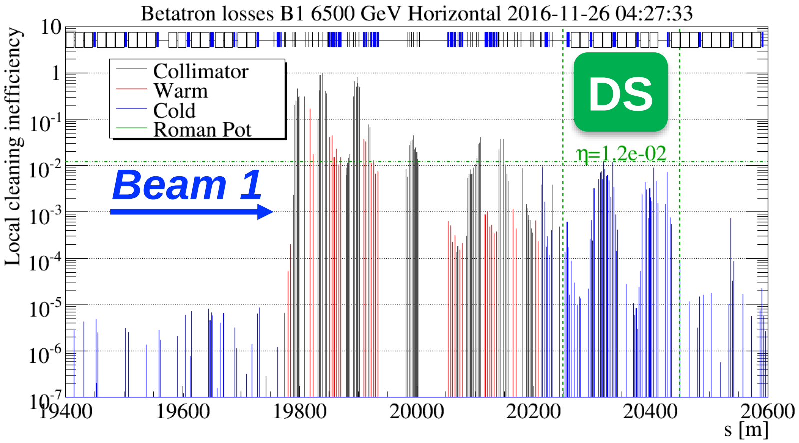
Present Collimation



Main limitations:

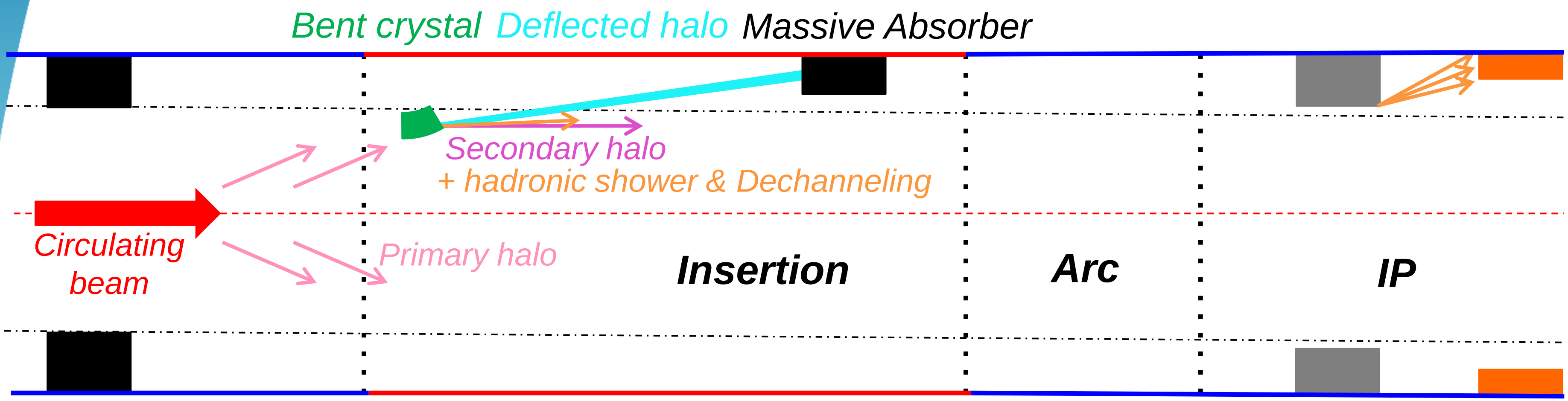
IR7 betatron cleaning insertion



- **Protons** collimation:
  - **Single diffractive** events
    - ✓ *Small deflection*
    - ✓ *Non-negligible δp/p*

- **Lead ions** collimation:
  - **Fragmentation and dissociation**
    - ✓ **Cleaning efficiency** reduced to $\mathbf{10^{-2}}$ (10^{-4} with protons)

Crystal Collimation



Main promises:

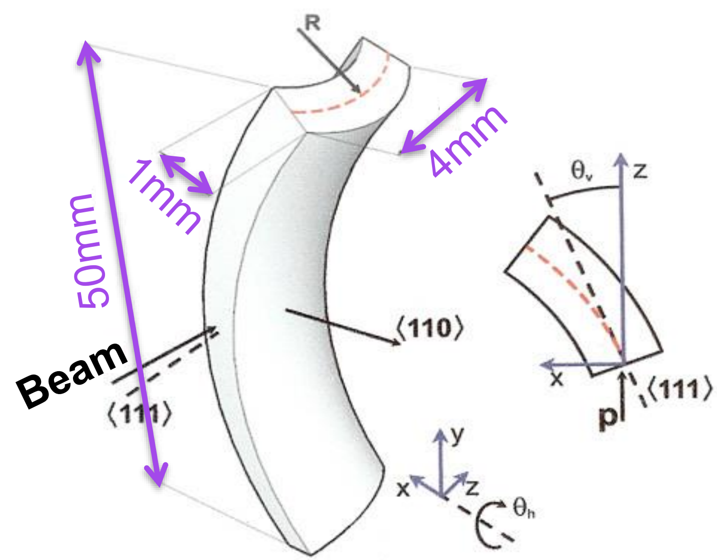
- ✓ Reduction of **inelastic interactions**

Reduced off-momentum losses in DS

- ✓ **Similar performance with p and Pb**

Significant improvement w.r.t. present

LHC design parameters



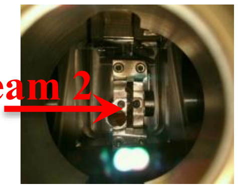
Bending **50μrad** ≡ B ≈ 310 T @ 7 TeV!

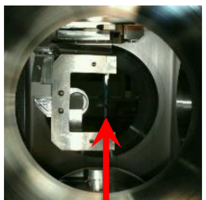
Present layout

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

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

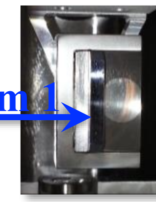
TCPCH.A5R7.B2

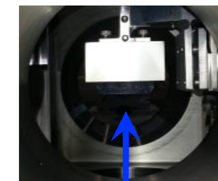




PNPI

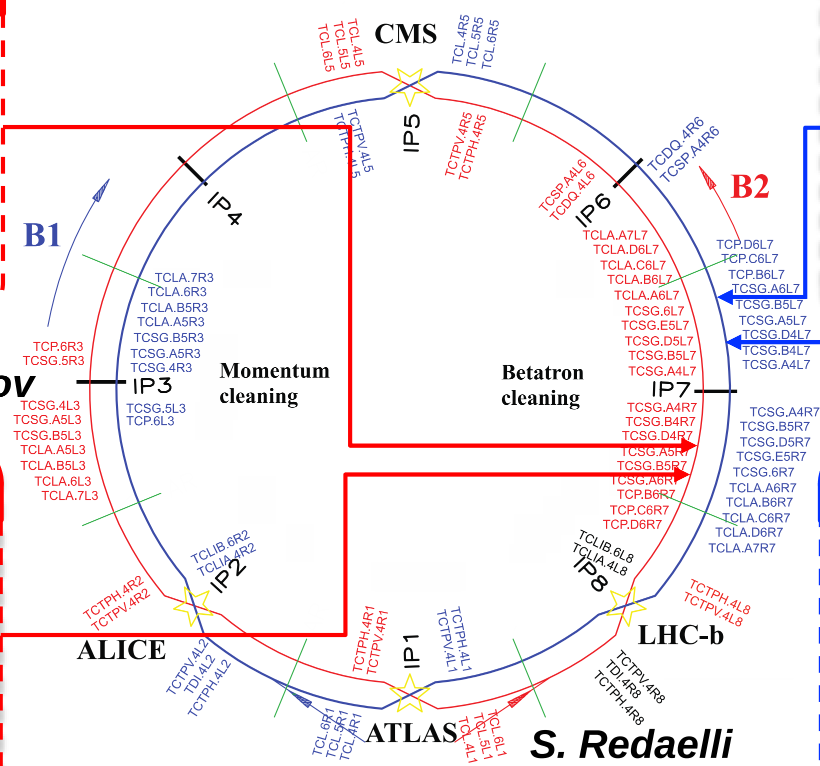
TCPCV.A6L7.B1





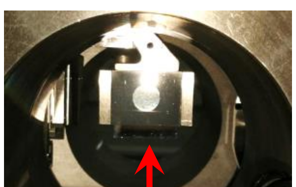
PNPI

Pics. Courtesy of Y. Gavrikov



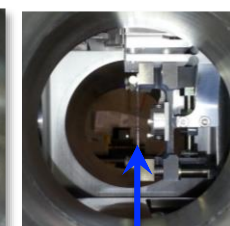
S. Redaelli

TCPCV.A6R7.B2



PNPI

TCPCH.A4L7.B1



INFN-Fe

Complete layout to allow thorough investigations and **operational** tests

Outline

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Main challenges

- **Completely different** method of **beam collimation:**
  - **Positive results** obtained by **UA9** in tests at the **SPS** (coasting beams)
  - **Negative results** obtained at **Tevatron** and **RHIC**

- **Crucial** to perform **tests under LHC conditions** before relying on this innovative collimation approach:

1. Demonstration of **stable channeling** at **LHC energies**
2. Demonstration of **stable channeling** during **dynamic LHC phases**
3. Demonstration of **improved cleaning performance** w.r.t. the present system

Milestones achieved

2015

- **First p channeling** at the LHC: **450 GeV and 6.5 TeV**
- **First Pb channeling** at the LHC: **450 Z GeV**

2016

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

2017

- **First channeling of Xe at 450 Z GeV 6.5 Z TeV**, together with assessment of cleaning performance

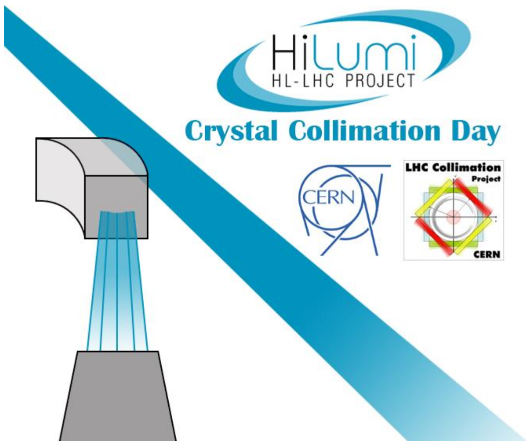
2018

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

Total MD time: 58h with p, 34h with ions

Crystal collimation day

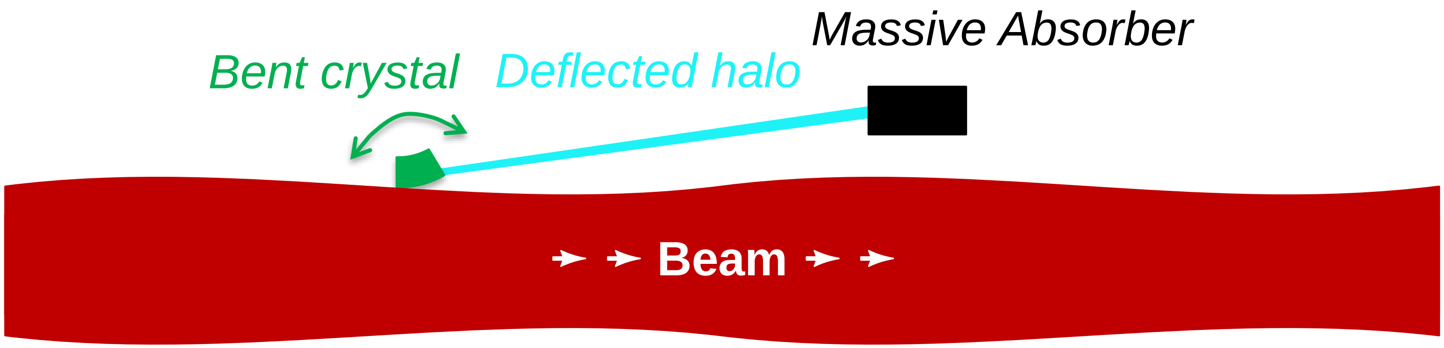
- **Dedicated workshop** in the framework of the **8th HL-LHC Collaboration Meeting**



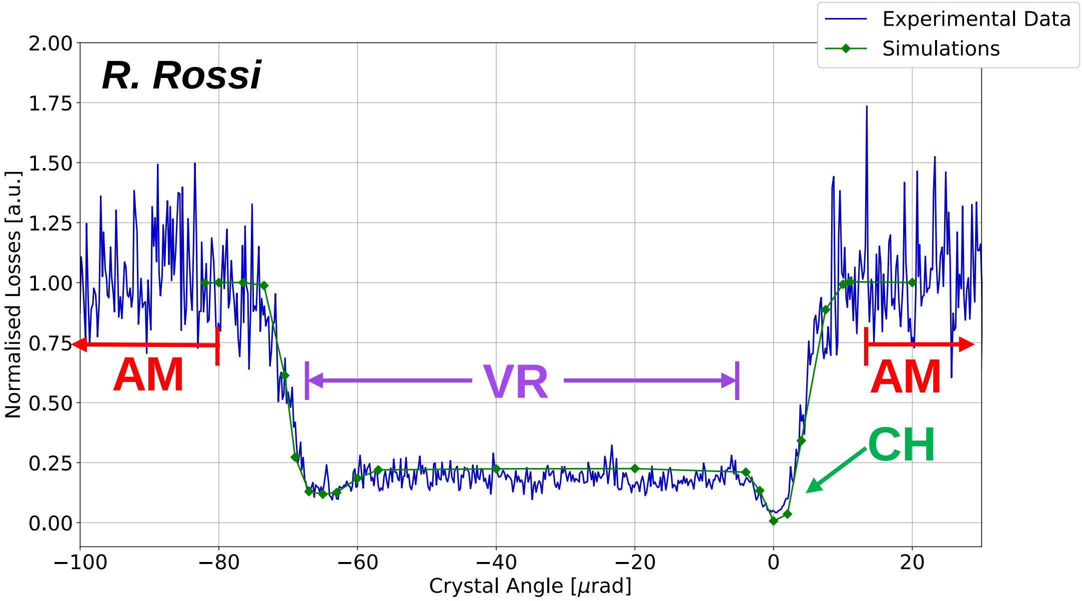
CERN, 19th October 2018

- **Extensive overview** from **beam dynamics** to **hardware readiness** (Indico link)

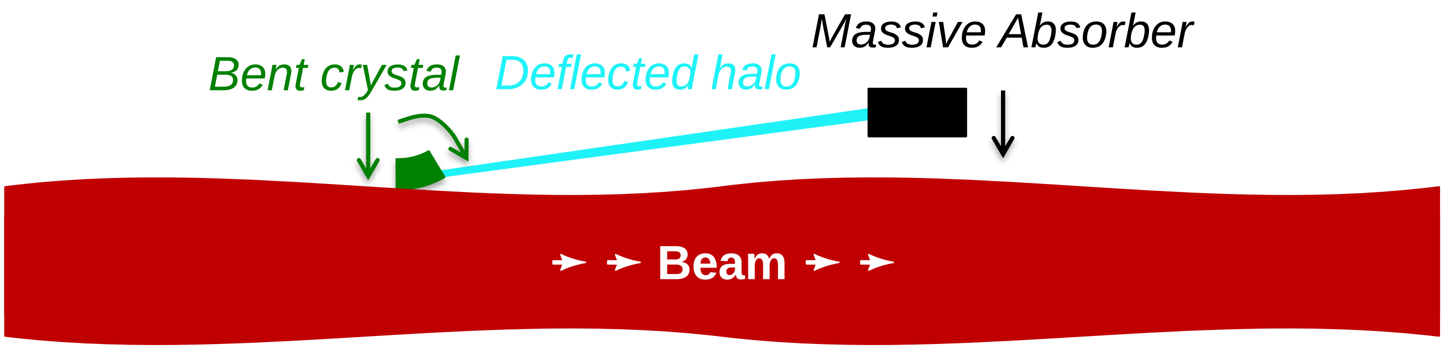
First Channeling of p at 6.5 TeV



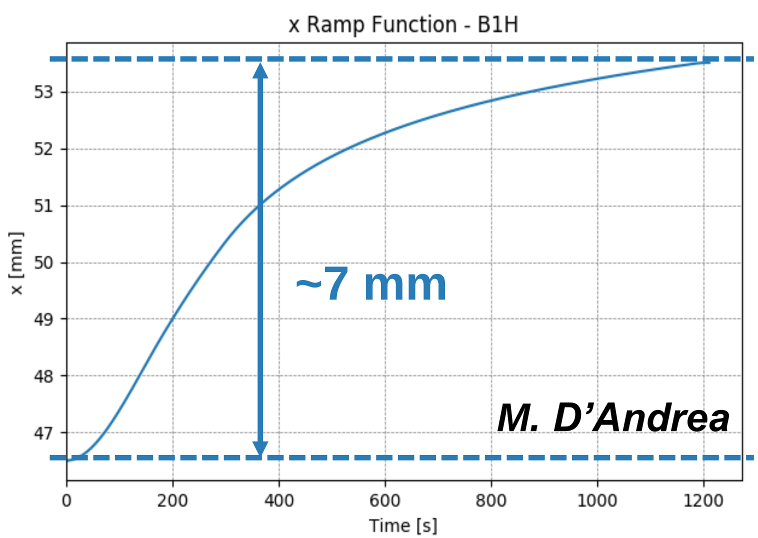
Angular scan: *monitoring of losses at the crystal location as a function of its angle*

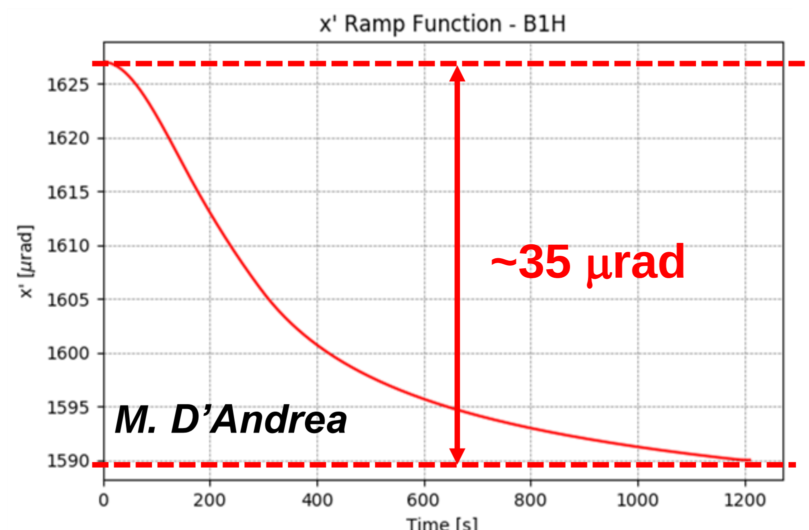


Channeling during energy ramp



- Example of **linear** and **angular** functions used to follow adiabatic dumping





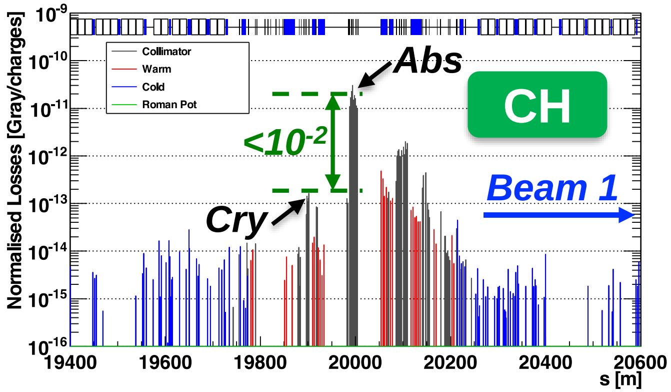
θ_c ~ 10 µrad
450 GeV

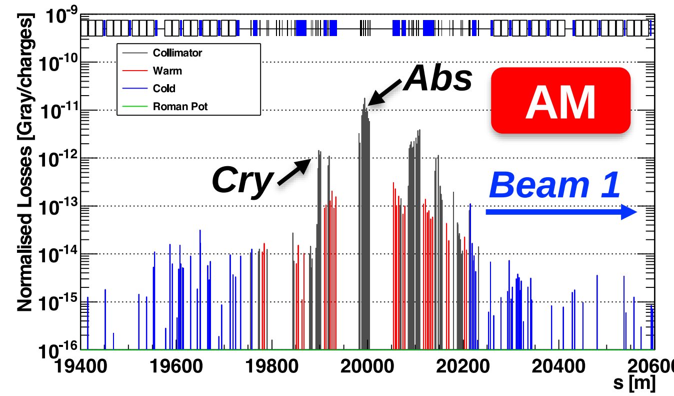
θ_c ~ 2.5 µrad
6.5 TeV

Channeling during dynamic phases

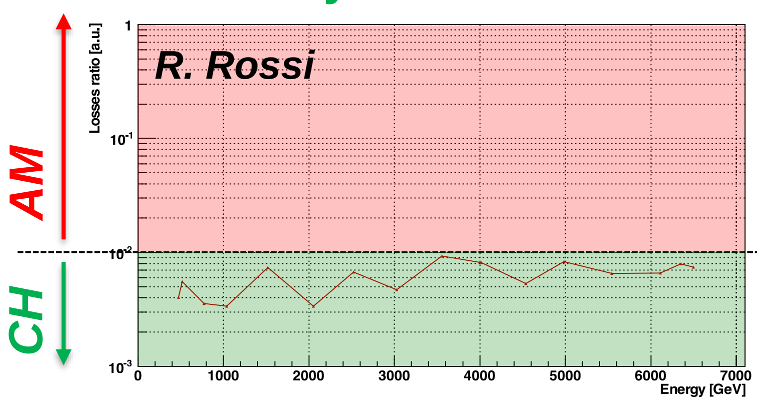
- **Channeling** conditions assessed by means of continuous loss maps

→ Observable: ratio of **losses at absorber w.r.t. at crystals**

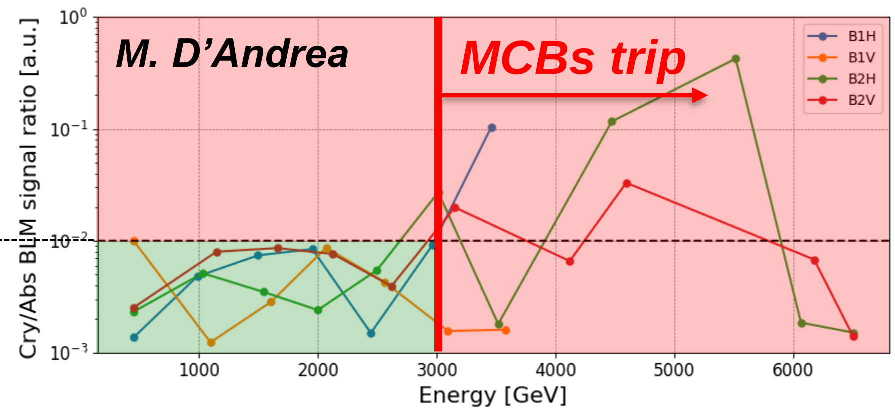




Only B1H in 2016



All 4 crystals in 2018!

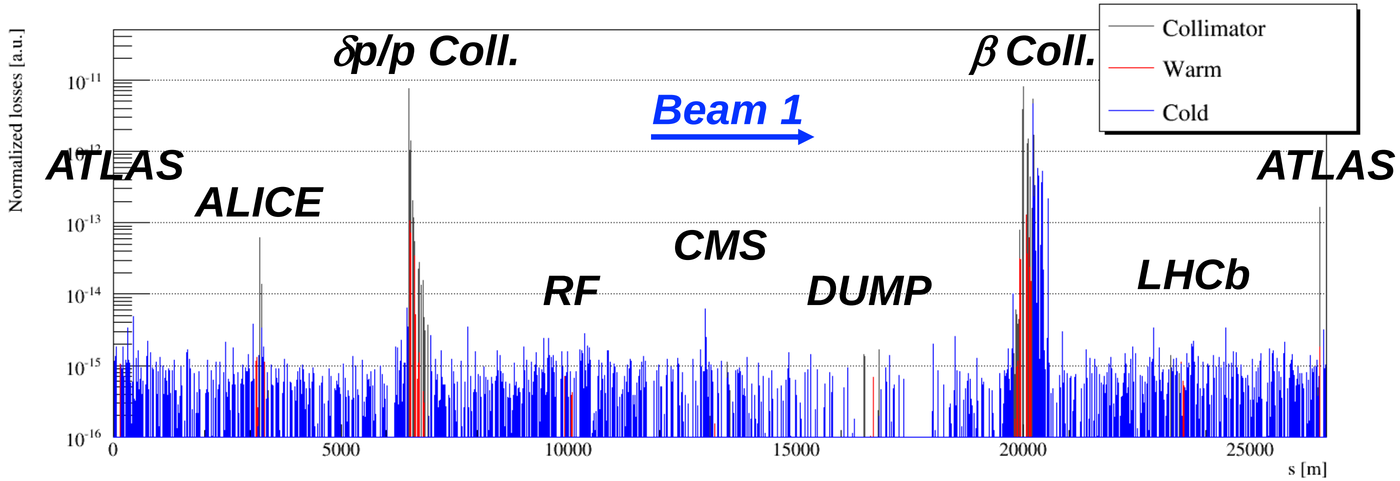


- **Same results** during **squeeze**, **collapsing separation** and **orbit corrections**

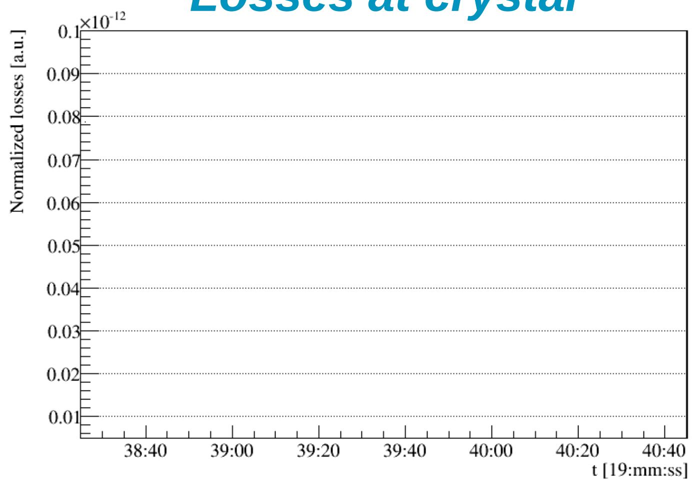
→ Good control of **channeling** during **dymanic phases achieved!**

Loss pattern with Pb at 6.37 Z TeV

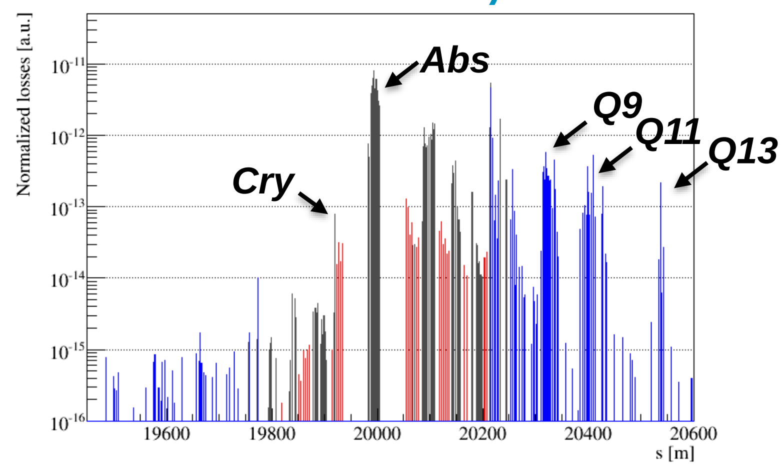
Example of **global** and **local losses** during an **angular scan (0.2 μrad/s)**



Losses at crystal

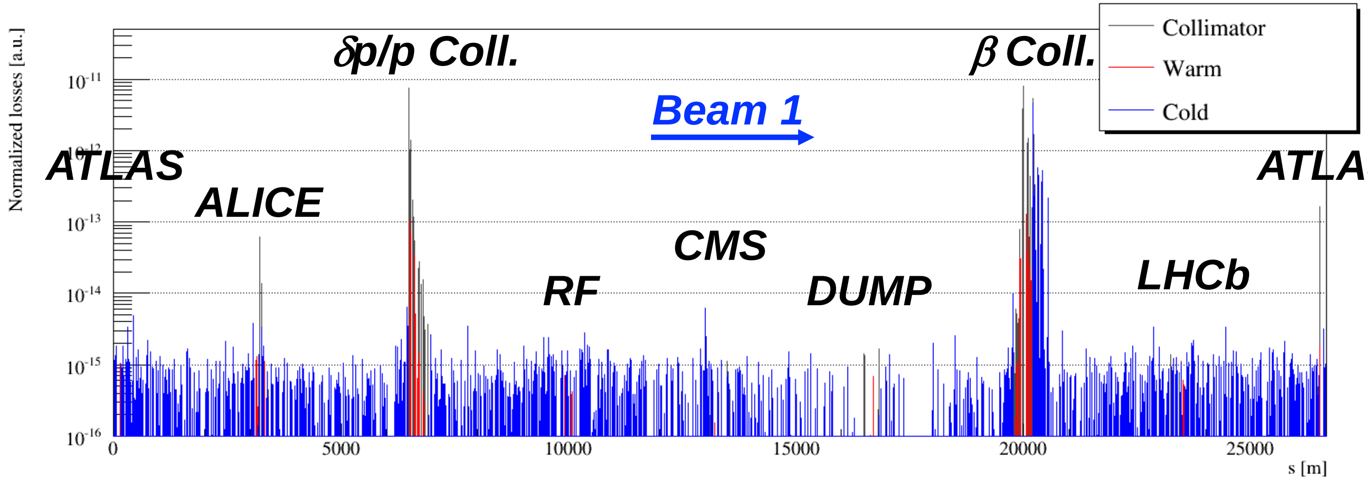


Losses in the β Coll.

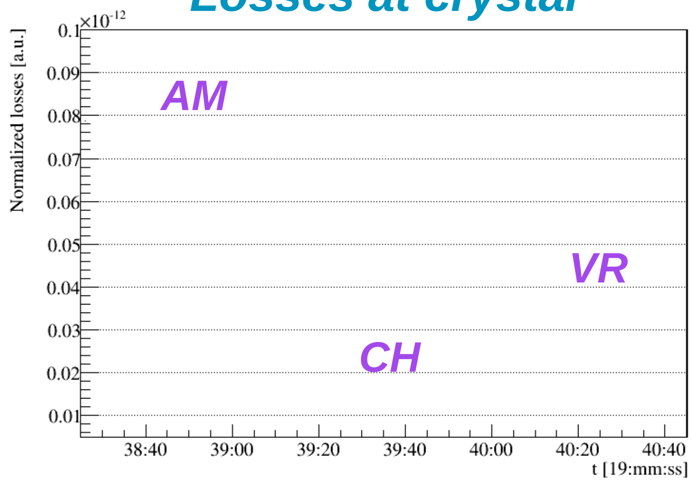


Loss pattern with Pb at 6.37 Z TeV

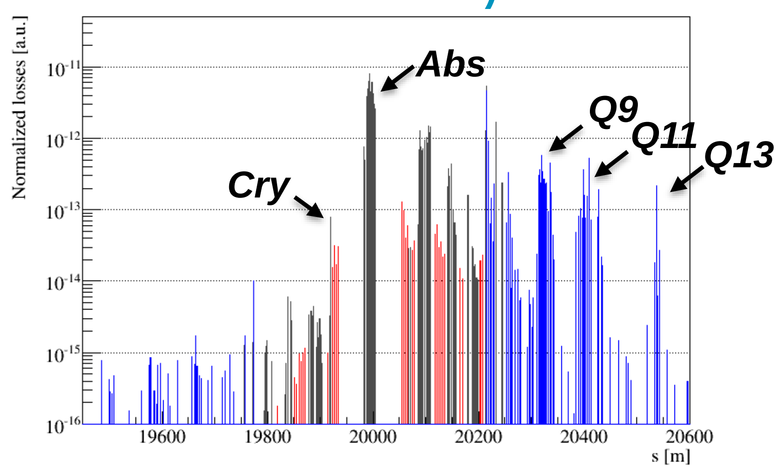
Example of **global** and **local losses** during an **angular scan (0.2 μrad/s)**



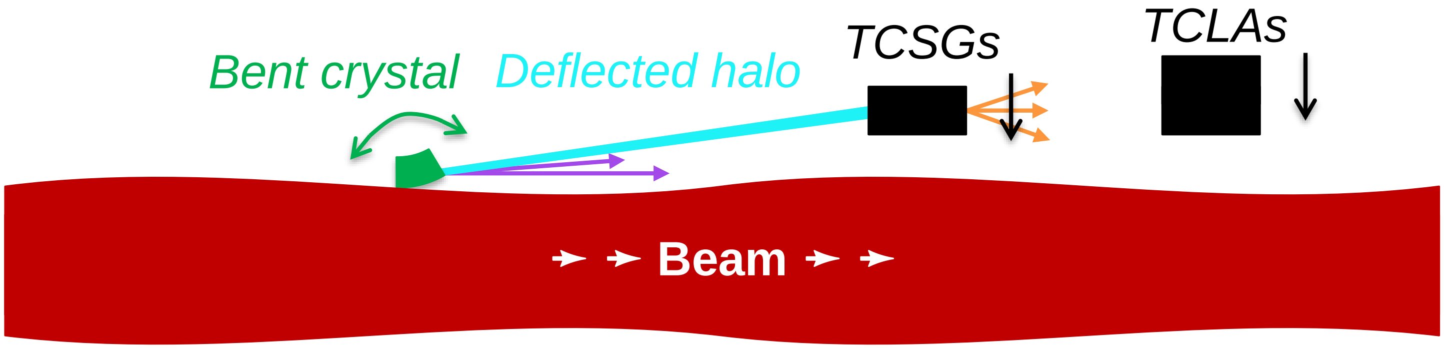
Losses at crystal



Losses in the β Coll.

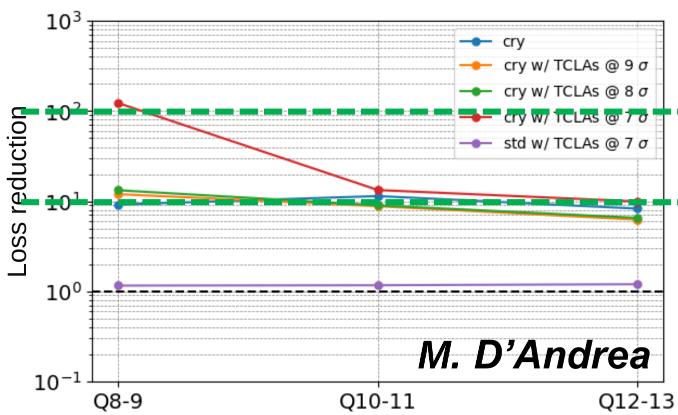


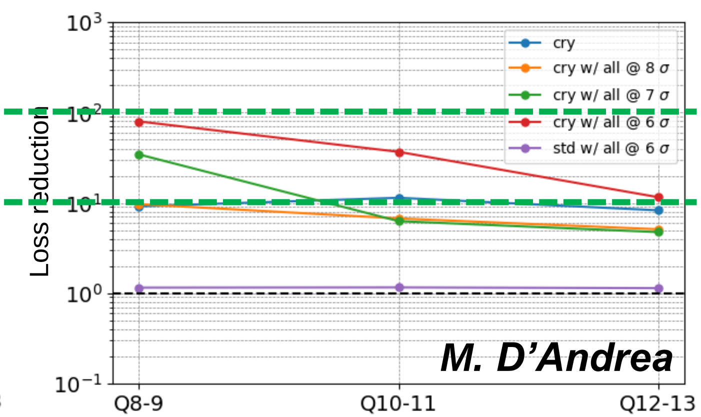
Cleaning inefficiency with ion beams



- Extensive set of **Loss Maps to study** contribution of:

Fragments from TCSGs **Fragments from crystal / DC**





Up to x100 better with tight settings

x10 better cleaning with OP settings

Consistent results with **Xe beams**

- **Up to a factor 10 also with p**, but major upgrade of **absorbers needed**

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Operational tests with Pb beams

- **Adiabatic insertion of crystals** in present collimation scheme

  → **Standard system** fully **in place** with **crystals** placed **0.25σ tighter than TCPs**

- **All 4 crystals inserted** at top energy during intensity ramp up tests

  → Maximum stored intensity **648 bunches**

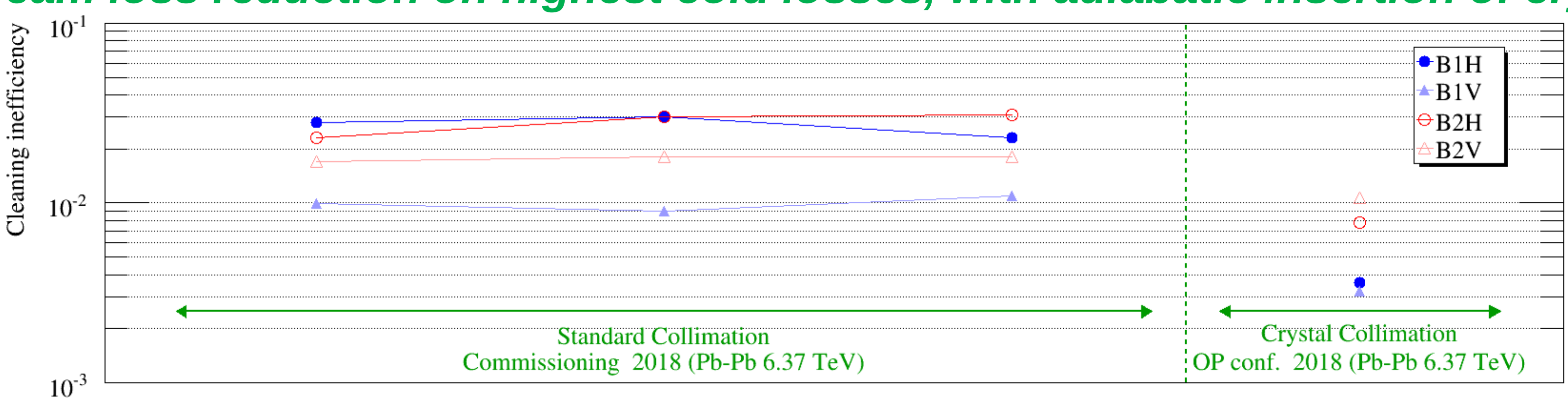
  Stable channeling kept for 2-3 hours

- Constant **monitoring of temperature** sensors on goniometers

  → **No temperature increase** observed

  Final assessment on-going by impedance team

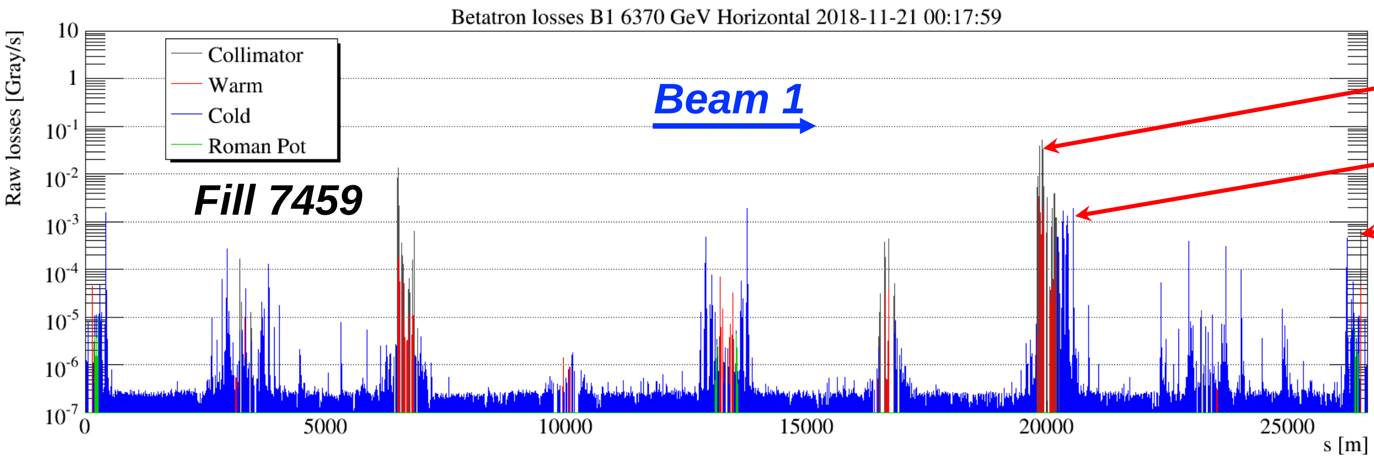
Beam loss reduction on highest cold losses, with adiabatic insertion of crystals



Heavy ions run limitation in 2018

- **7 dumps occurred during Pb-Pb run in 2018** with similar signature: (14.5% fills)

Horizontal orbit oscillations leading to dump on loss thresholds



Limiting locations:

TCSG.A5L7.B1

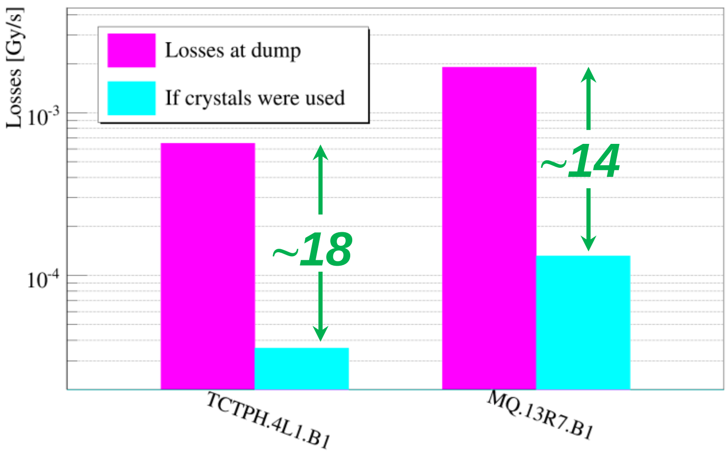
MQ.13R7.B1

TCTPH.4L1.B1

Losses above BLM threshold (set at quench level)

- Could crystal mitigate these dumps?

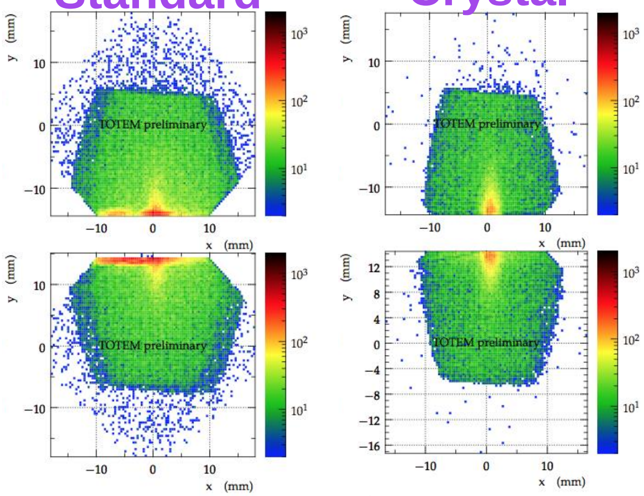
Measured >10 times less losses on limiting locations using crystals!



First physics run using crystals!

- **First ever data tacking using crystal collimation** during high-β* at 450 GeV!
  - **Very challenging** conditions for collimation required to **suppress background**
- **Both** standard and crystal collimation **schemes prepared for operations**
  - Fully automated **insertion of crystals directly in channeling** deployed
- Feedback **from experiments using crystals**:
  - Significant **background suppression**
  - **No need of scraping** during the fill

*Better **data quality***
*and more **integrated lumi!***



Courtesy of TOTEM

- **Future plans:**
  - **High-β* run** at intermediate energies **may be requested** in Run3/HL-LHC
  - **Preference of using crystal** collimation scheme during data tacking
  - **Partially stripped ions** in the LHC?

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Conclusions

- **Good operational experience** achieved in Run2 and **first use during physics**
  - **Stable channeling** and **improved cleaning** demonstrated along **entire cycle**
  - **Goniometers** hardware and controls **provided required stability**

- **Viable option** to **mitigate** of possible **limitations** with **heavy ion beams**
  - Present **secondary collimators** can **safely absorb channeled halo**
  - **Consolidation of controls** needed to deploy **limit functions during ramp**

- **Goniometer** with **upgraded angular controller redundancy** being prototyped
  - Final assessment on impedance on-going

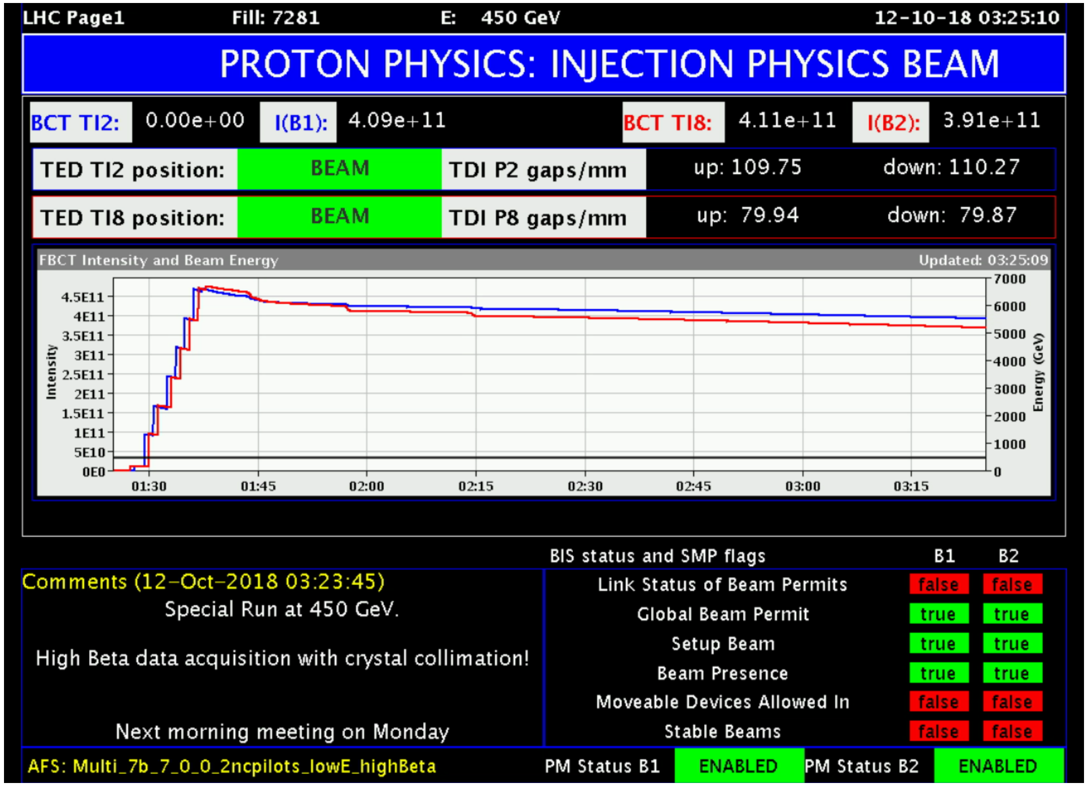
- Ideal system would need **8 crystals to constraint orbit drifts**
  - **Considered as future implementation**
  - **In-kind contribution from Russia** being considered

HiLumi
HL-LHC PROJECT

LHC Collimation Project
CERN

MANCHESTER 1824
The University of Manchester

Thank you for your attention!



CERN

Outline

Backup

Present layout

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

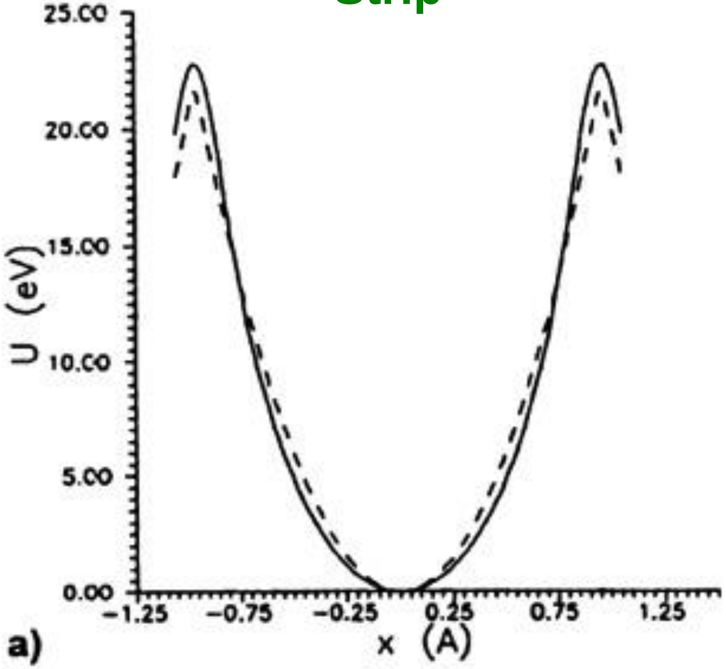
Same design **specifications** for all crystals, two **different producers** and **technologies**

	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

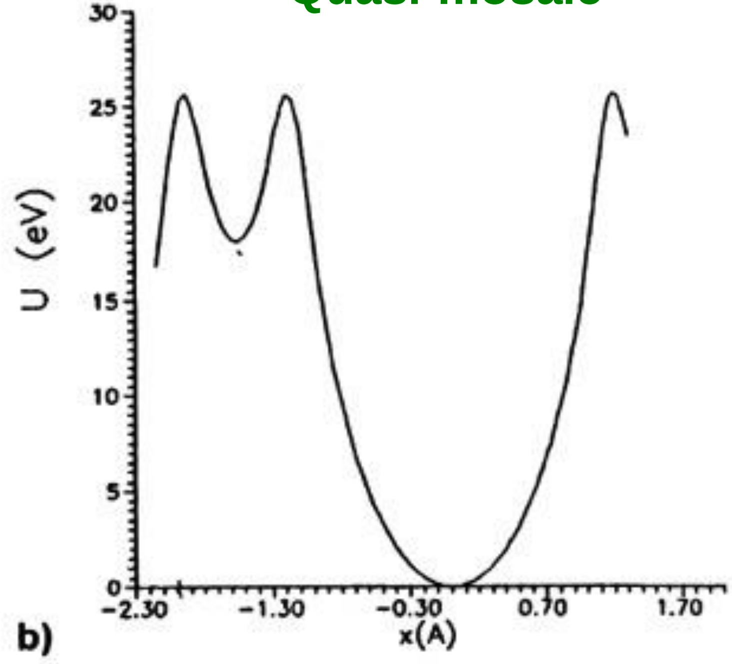
Complete layout to allow thorough investigations and **operational** tests

Strip / QM

Strip



Quasi-mosaic



Layout design goals and constraints

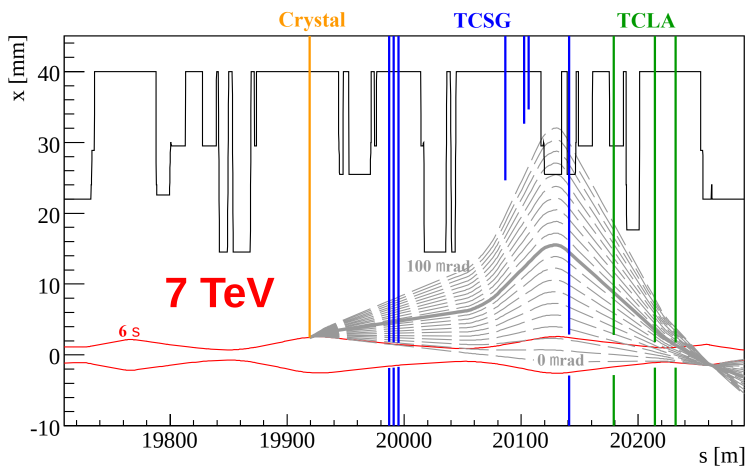
- Demonstration of **crystal channeling** with good efficiency **throughout the entire cycle**
- Demonstration that crystal collimation can **improve the cleaning efficiency**
- Minimize the **impact on the present IR7 layout**
  - Fully operational for standard operations
- **Machine geometry** and an optimized design of the **goniometers**
  - Horizontal/vertical crystal in the internal/top side of the machine
- **Space availability** in connection with required **optics parameters**
  - Slots already equipped with collimator supports
- **Radiation doses** to personnel

Main steps

Tight connection between longitudinal position, collimator settings and crystal parameter:

1. Identification of **suitable locations based on space availability and optics**

2. Sub-set chosen on **semi-analytical studies**



Main considerations:

- **α ~ 0**
  - Easier to follow energy ramp
- **Angular cut** applied by TCSG
  - Constraints on crystal bending

3. 6D tracking simulations using **SixTrack**

4. Definition of **location**, crystal **parameters** and **layout** configuration

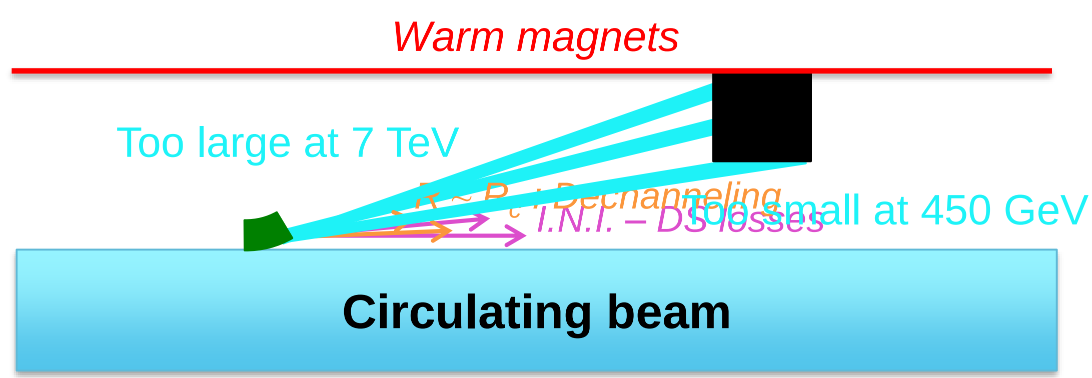
All details in Eur. Phys. Jour.C 77.6 (2017): 424

Crystal parameter optimization

- Optimization of **length** and **bending** requires **compromises between opposite needs:**
  - ✓ **Channeling efficiency**/**inelastic interaction rate** → "**long**/**short**" crystals
  - ✓ **Large impact parameter on the absorber**/**safe margins** → "**large**/**small**" bending

- **Several combination tested** and final subset chosen for SixTrack simulations

R [m]		Bending [µrad] 40	Bending [µrad] 50	Bending [µrad] 60
Length [mm]	3	✗	✗	✗
Length [mm]	4	✗	✓	✗
Length [mm]	5	✗	✗	✗



Bending angle of 50 µrad
Length of 4.0 mm

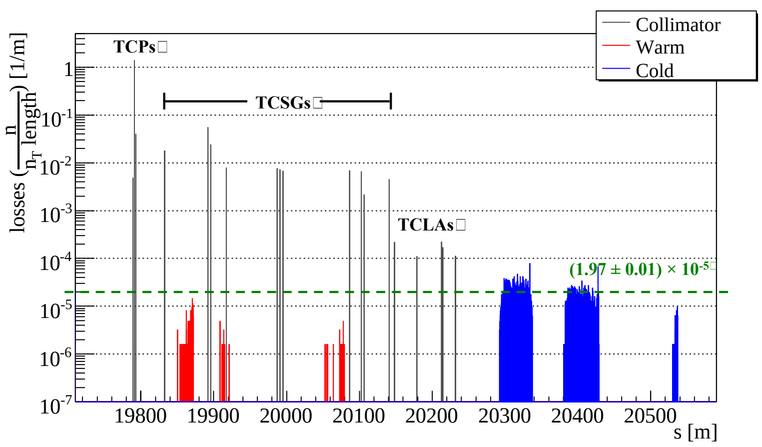
All details in Eur. Phys. Jour. C 77.6 (2017): 424

Expected performance

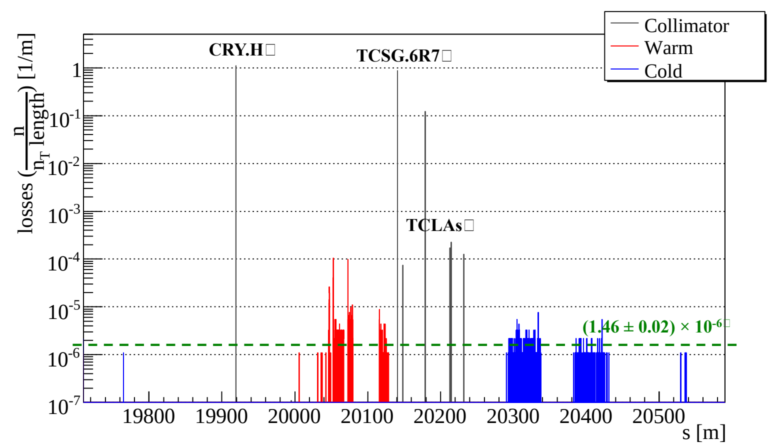
- **Comparative assessment of performance** between standard and crystal collimation at every fixed point fo the cycle
- **IR7-DS limiting location** in terms of cleaning performance for both systems

→ ***Cleaning performance*** *defined as* ***average level of losses in the IR7-DS***

Present collimation



Crystal collimation



Factor ~ 10 better cleaning w.r.t. present system expected **with crystals collimation**

Plans for possible operational deployment

Main challenge: safe disposal of **channeled beam on absorber**

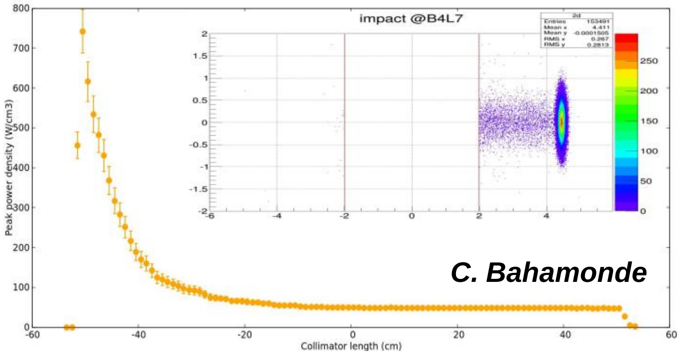
Failure design scenario: τ = 0.2 h for 10 s

HL-LHC proton beams

A mini dump would be required
~1 MW over few mm^2

Layout adequate for safe operations with ions!

HL-LHC heavy ion beams

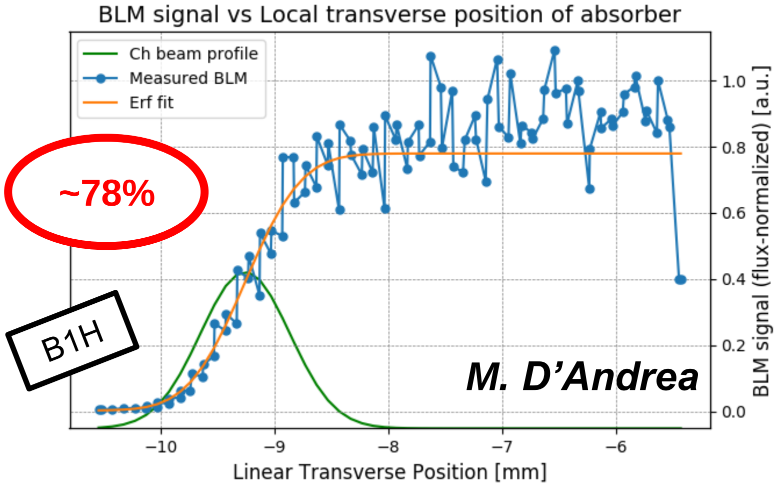


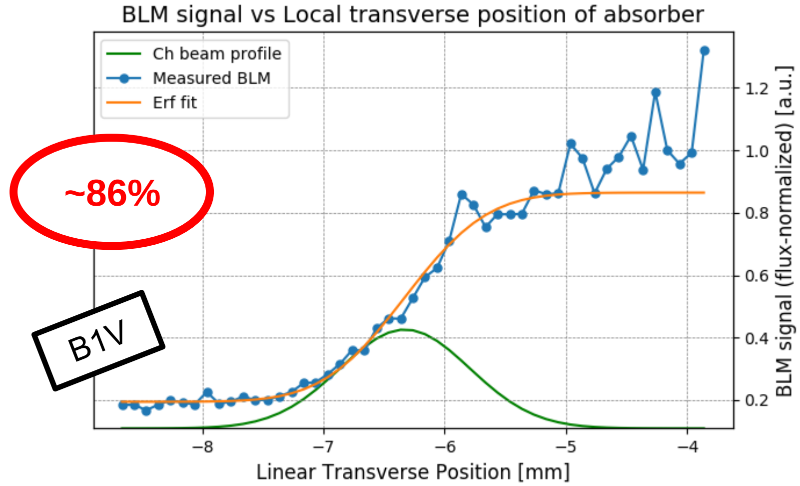
Peak power density < 1 kW/cm^3

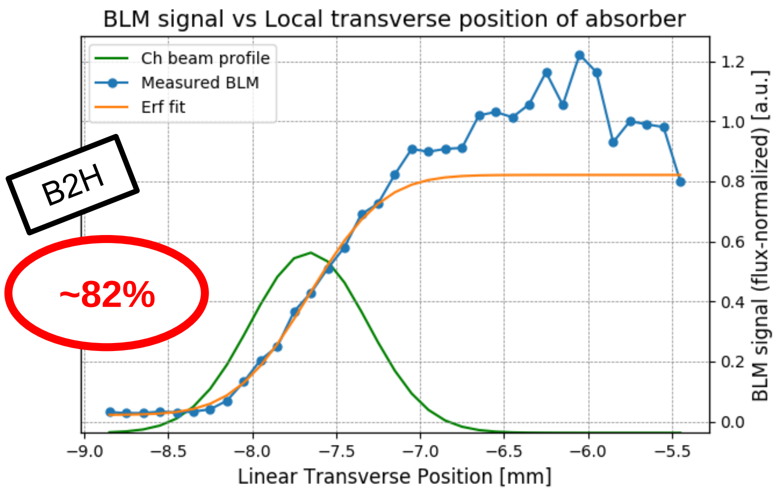
- **New interlock strategy** implemented to allow tests with high intensity Pb beams
- **End of Fill tests in 2018** heavy ions run to reproduce results obtained with Xe beams
- **If improved cleaning confirmed** and machine performance limited by present collimation

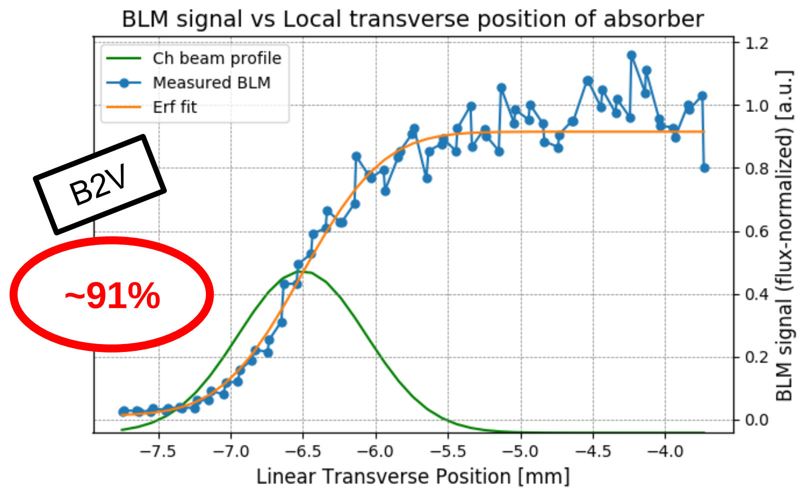
→ **Adiabatic insertion of the crystal in the present collimation hierarchy**

Multiturn channeling efficiency at 450 GeV

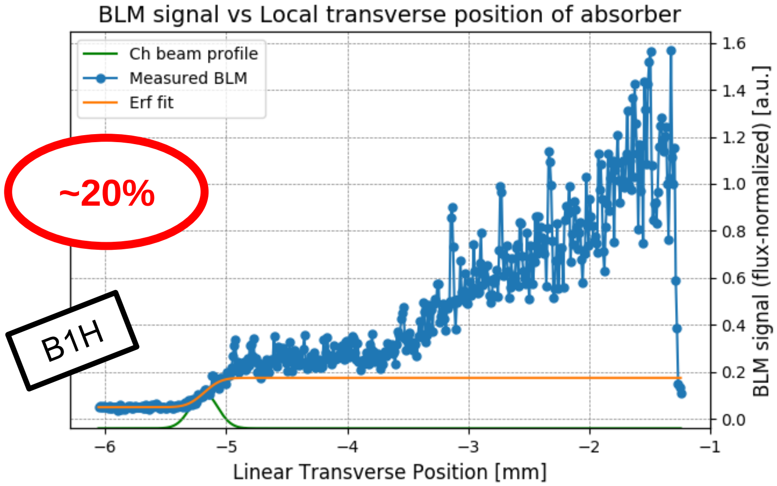


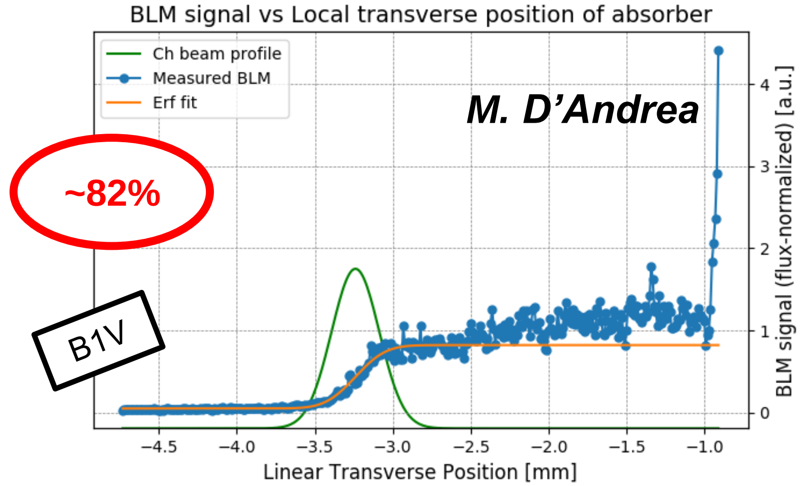


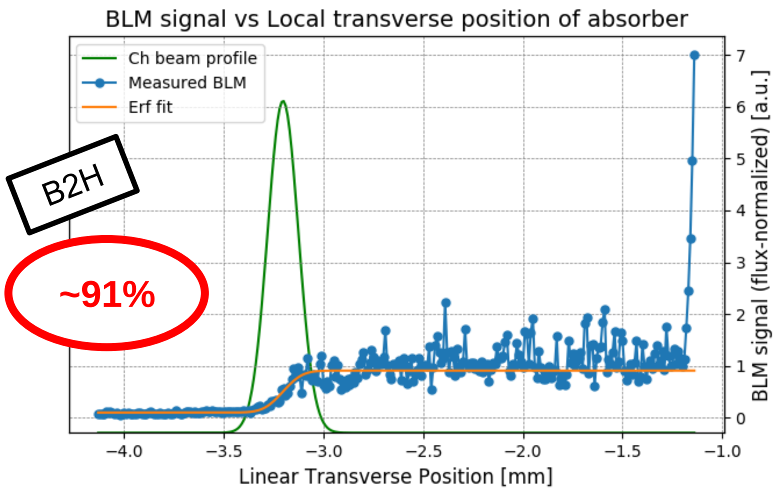


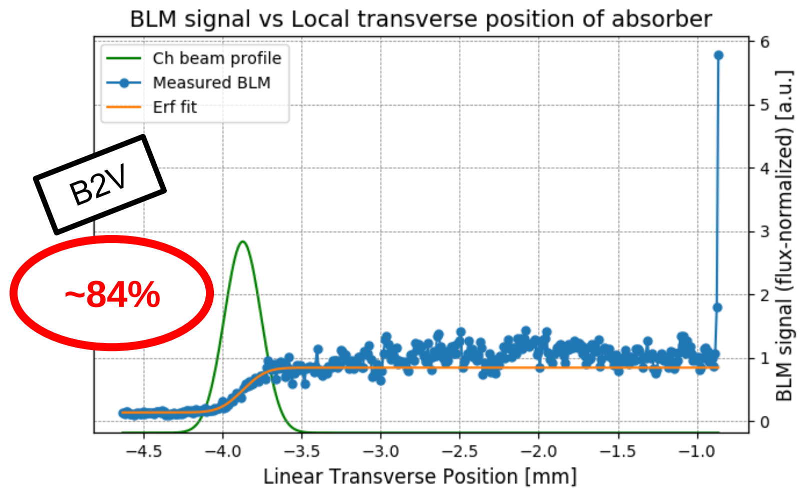


Multiturn channeling efficiency at 6.37 Z TeV

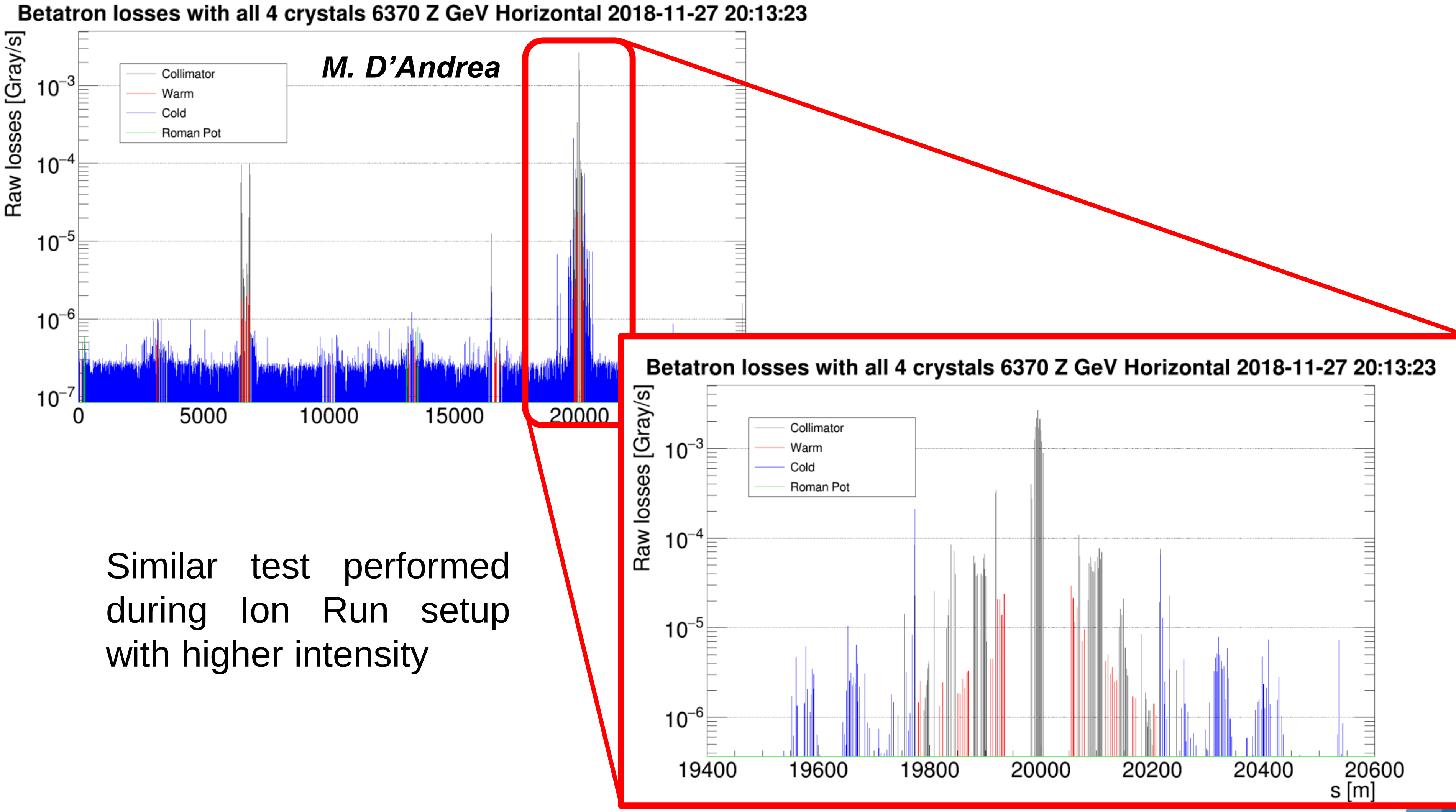








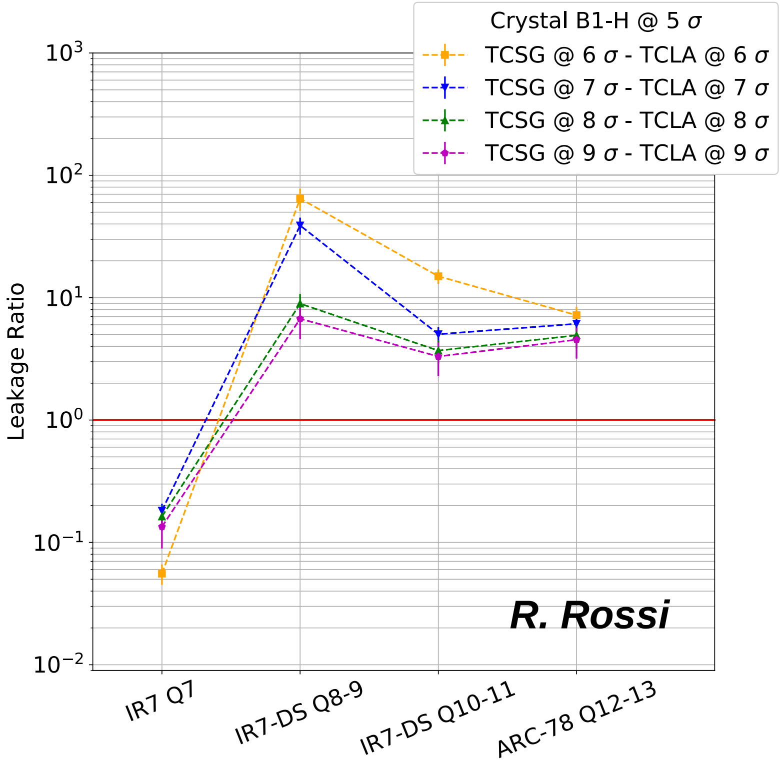
Continuous high losses



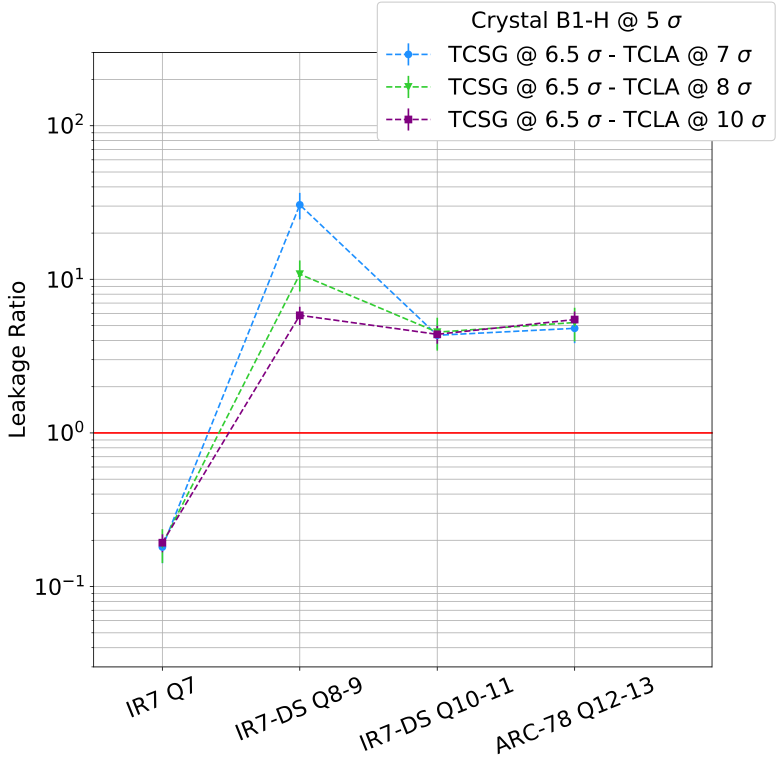
Similar test performed during Ion Run setup with higher intensity

Cleaning performance with 6.5 Z TeV Xe beams

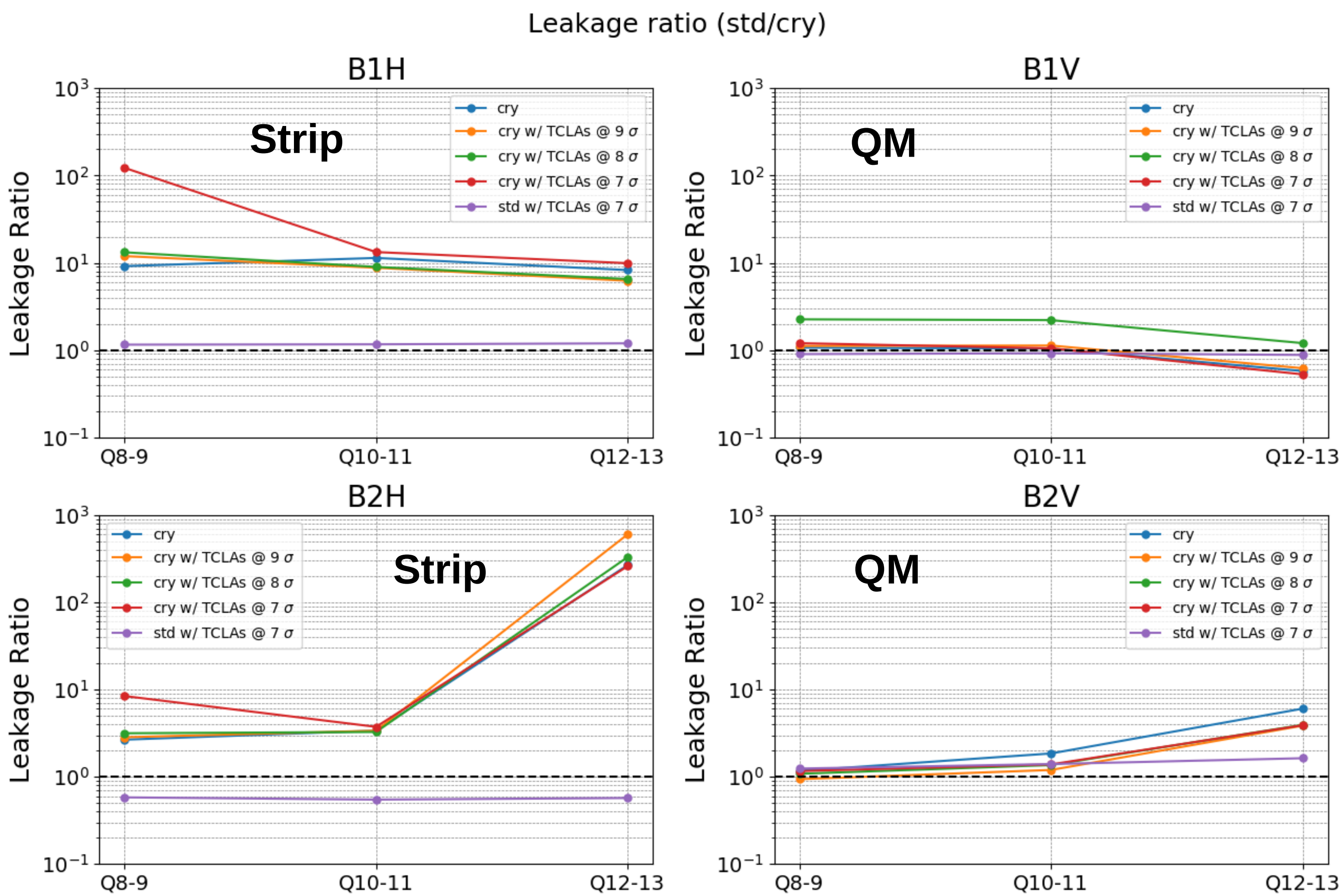
Fragments from crystal / DC



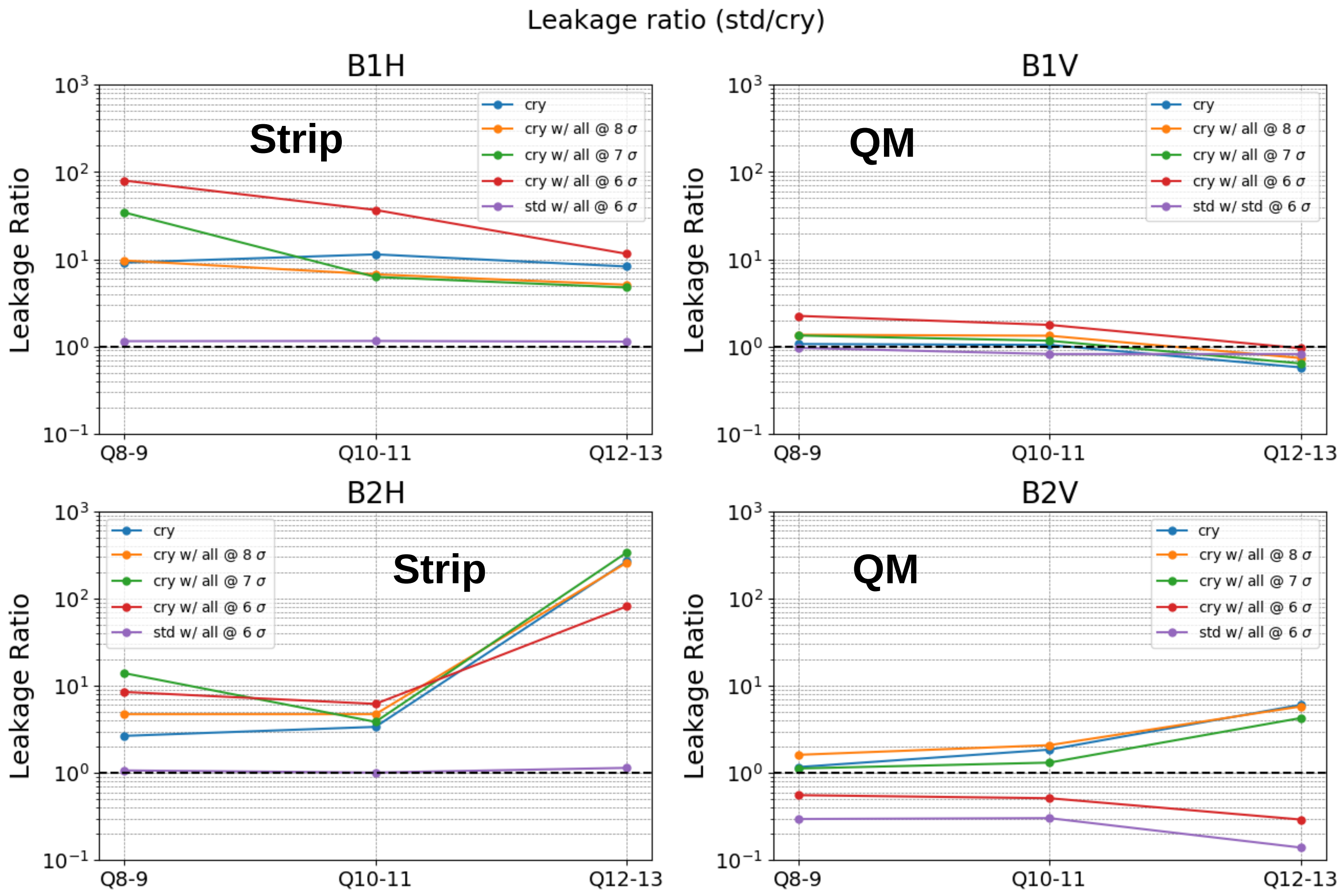
Fragments from TCSGs



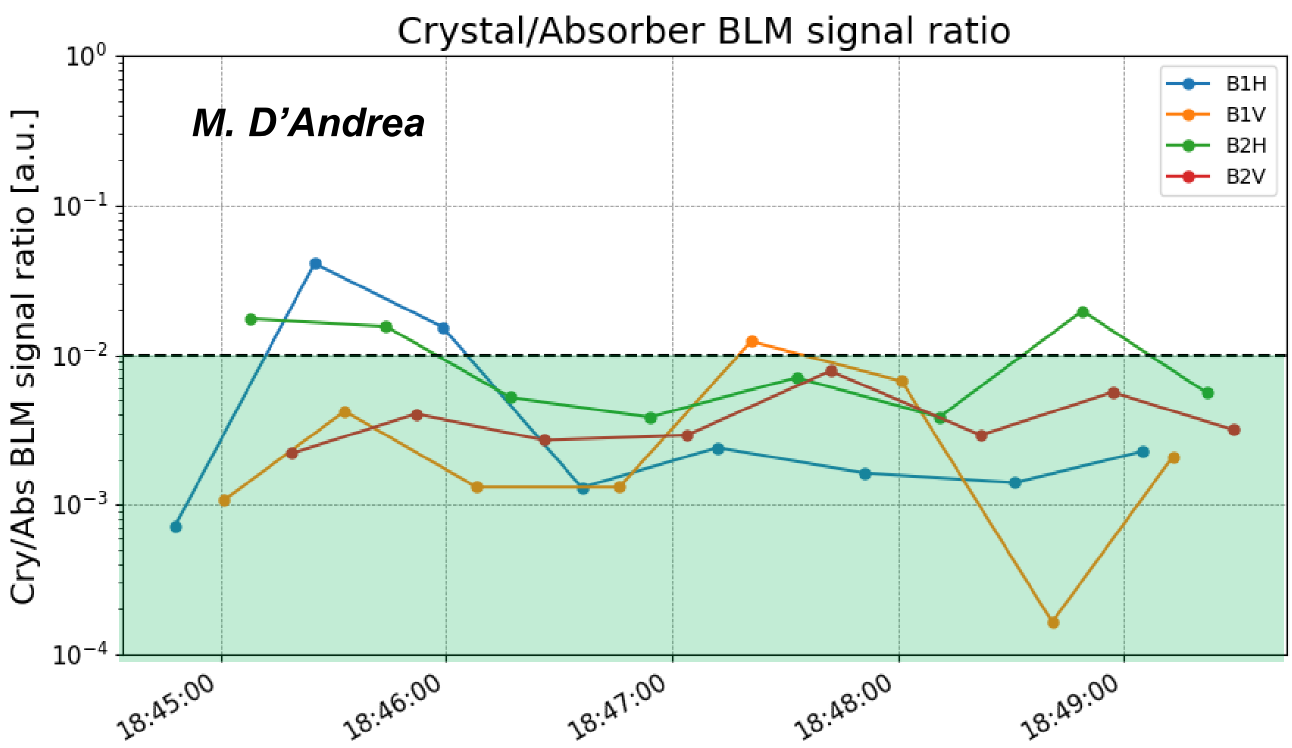
MD 6.37 Z TeV Pb beams (TCLA scan)



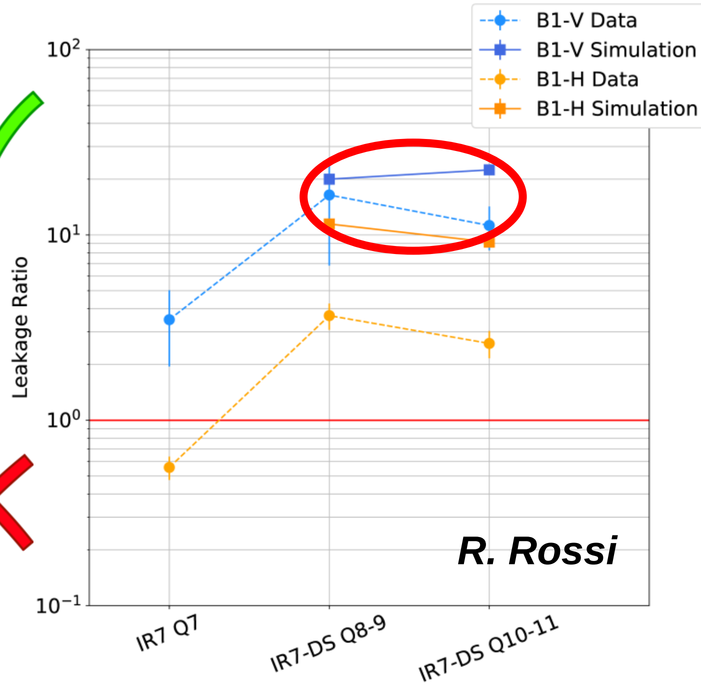
MD 6.37 Z TeV Pb beams (TCSG+TCLA scan)



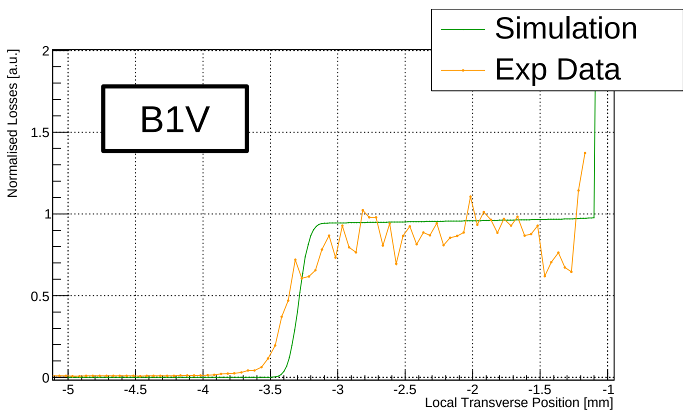
Channeling during Squeeze

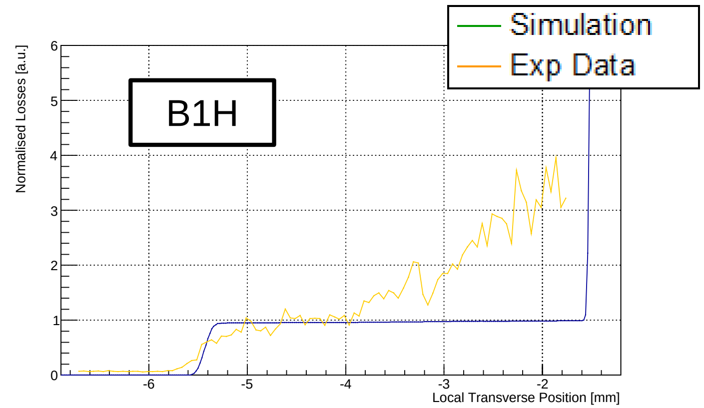


Cleaning efficiency with protons



- Significant improvement (factor ~10) observed in the DS for B1V
- Analogous results observed for B2V
- No significant improvement observed on B1H (possibly due to high dechanneling)
- Comparison with simulation shows good agreement for B1V and a significant difference for B1H
- No analytical description for bending radius close to critical value: not reproducible in simulations



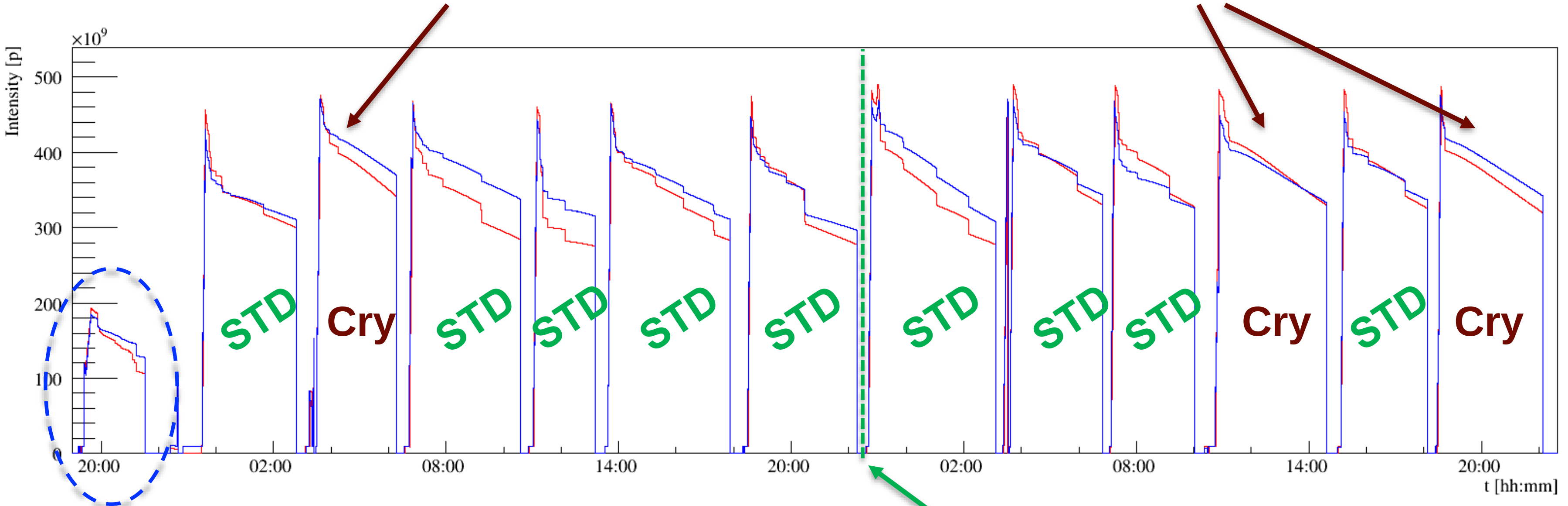


Overview high-β* run

- **Promising results obtained during initial tests**

→ Decided to have the **crystals as a viable option** for the real physics run

NO NEED TO SCRAPING WITH CRYSTAL

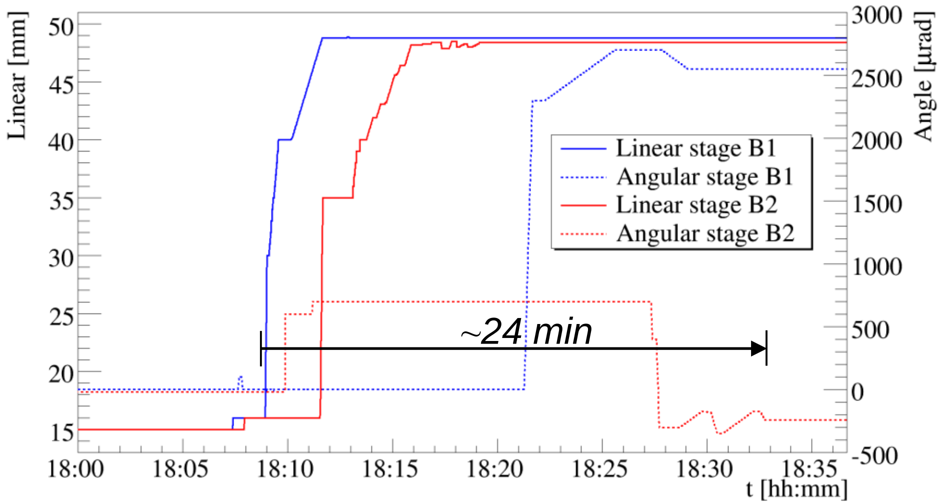


1 setup fill: confirmed alignment STD and Cry coll.

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

Operational performance

- **Setup** of the crystal collimation scheme took **less than 25 min** during initial setup fill!

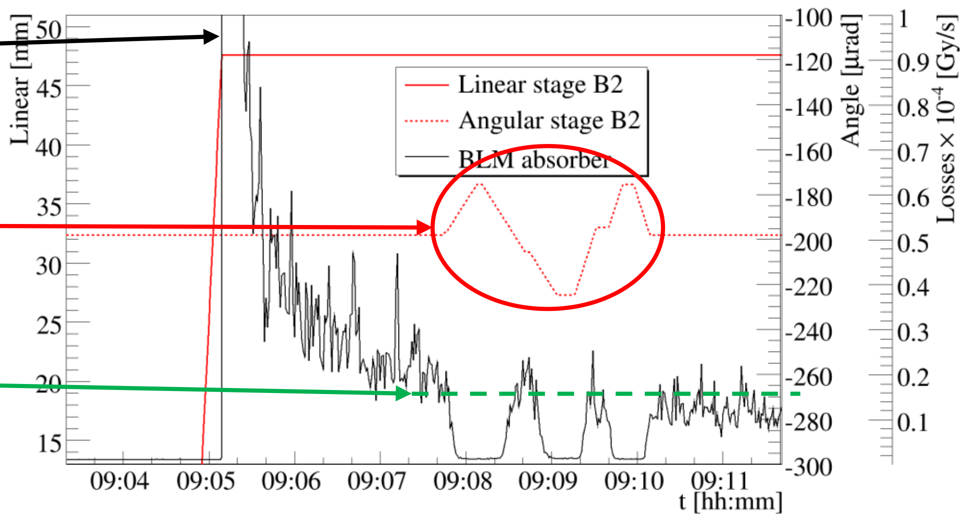


- **Crystals inserted through automated sequences directly in channeling orientation during operations!**

Beam touched as expected

Quick angular scan around channeling in the shadow of XRPs insertion

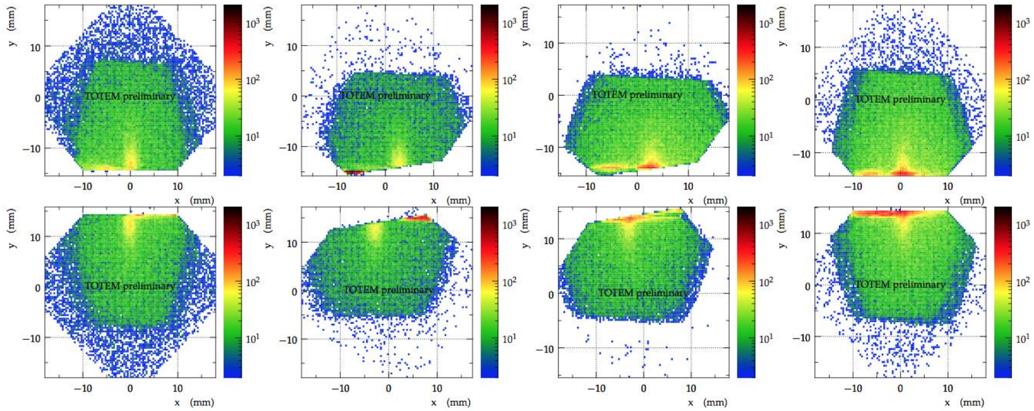
Crystals where inserted in channeling

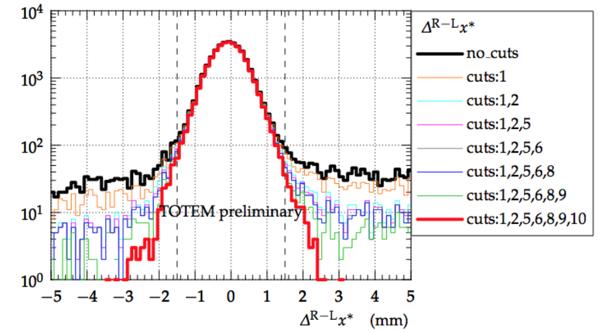


Data quality from TOTEM

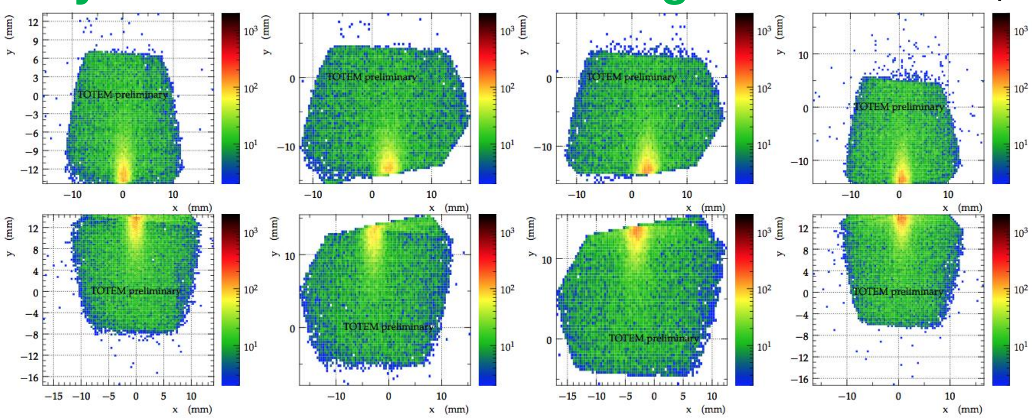
PRELIMINARY DATA COURTESY OF J. CASPAR FOR THE TOTEM COLLABORATION

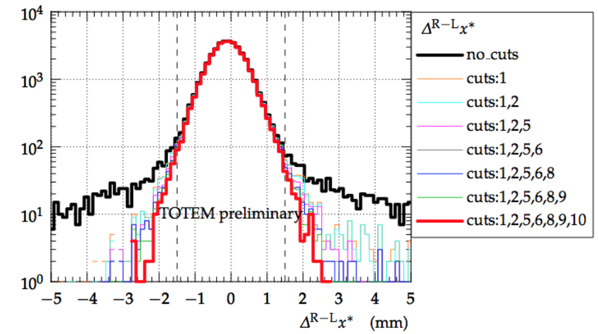
- **Standard collimation: background** at sensor edges, removed with **full off-line cut**





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



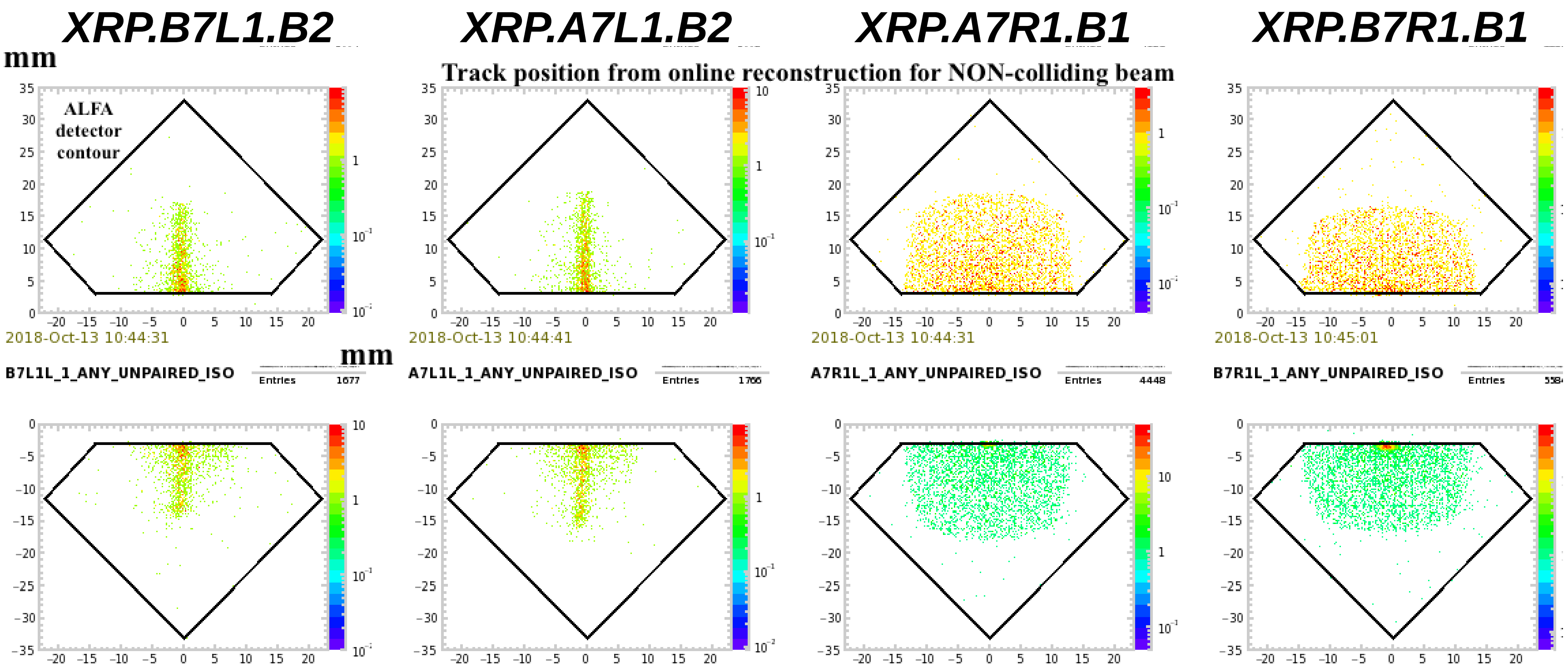


Data quality from ALFA

PRELIMINARY DATA COURTESY THE ATLAS-ALFA COLLABORATION

- **Potentially problematic background distributions** with crystal collimation

  → Signal from non colliding bunches similar to elastic scattering signature

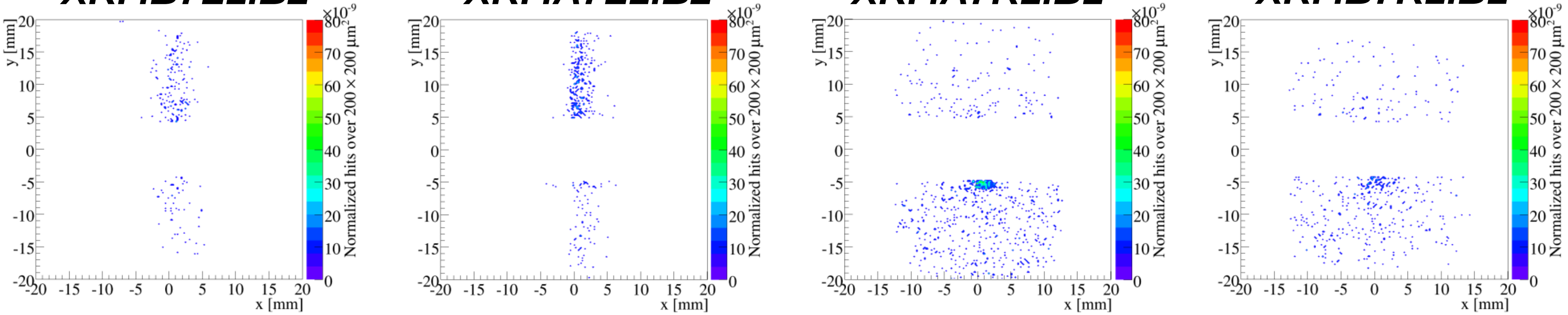


Off-line analysis show that data collected could be used (LPC 29/10/18)

Understanding ALFA background

Very high statistics needed: 96×10^6 p simulated

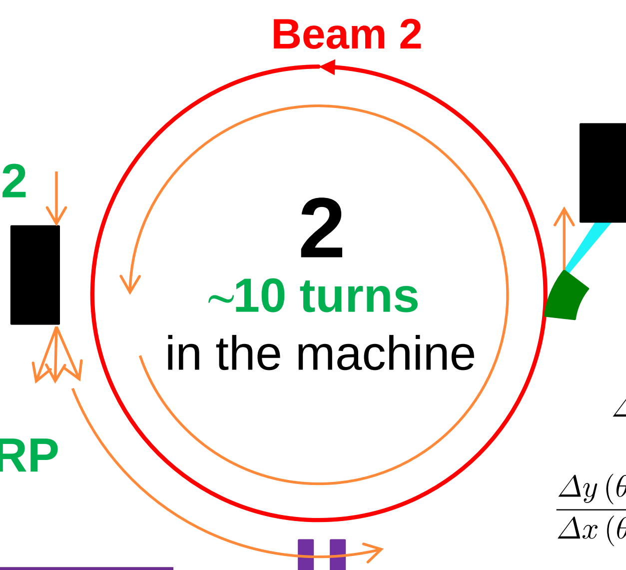
XRP.B7L1.B2 ***XRP.A7L1.B2*** ***XRP.A7R1.B1*** ***XRP.B7R1.B1***



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

1

Particles get dechanneled and escape from IR7



3

Impact on TCLA.A5L3.B2 closed at 2.7σ

4

Emerge from TCLA and **impact on ALFA-XRP** at the same turn

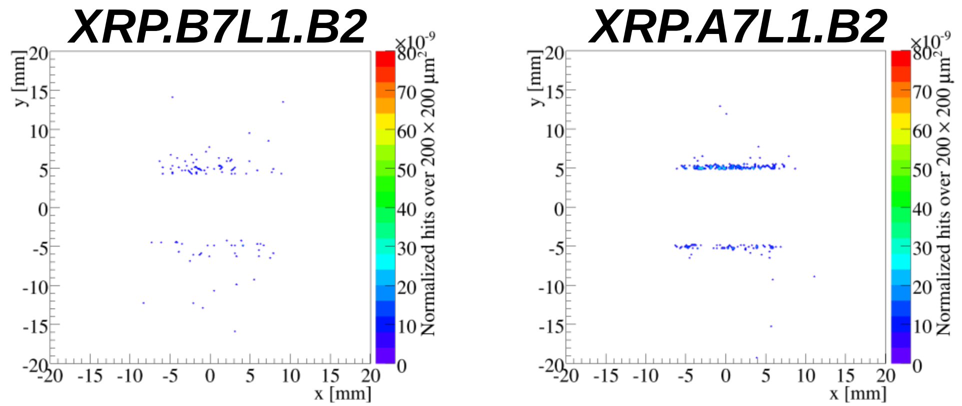
$$\Delta\mu_x^{XRP-TCLA} \sim 4^\circ \qquad \Delta\mu_y^{XRP-TCLA} \sim 244^\circ$$

$$\frac{\Delta y(\theta)}{\Delta x(\theta)} \propto \frac{\theta\sqrt{\beta_y^{TCLA}\beta_y^{XRP}}\ sin\left(\Delta\mu_y^{XRP-TCLA}\right)}{\theta\sqrt{\beta_x^{TCLA}\beta_x^{XRP}}\ sin\left(\Delta\mu_x^{XRP-TCLA}\right)} \sim 20$$

Fixing ALFA background

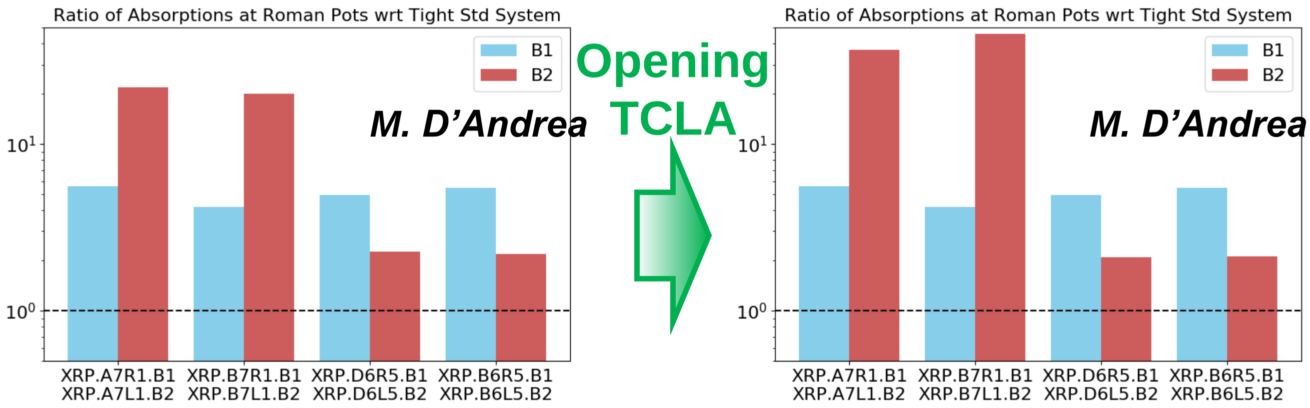
- Simulations performed with **TCLA.A5R3.B2 opened at 13 σ** as all other TCLAs in IR3

Background distribution at problematic ALFA-XRP after TCLA retraction



- **No changes** of distribution **in other pots** observed and even **larger gain in bkg rate** expected:

Expected gain with respect to standard collimation (tight settings - 2.5 σ)

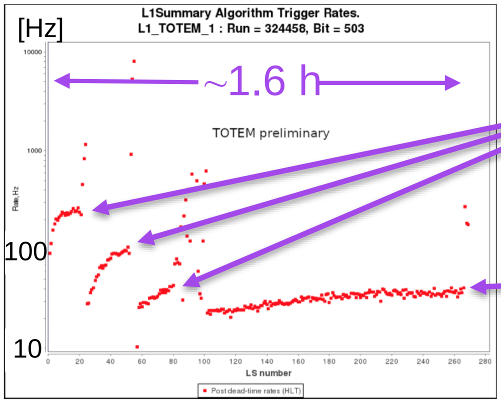


Potentially problematic background at ALFA could have been easily fixed!

Background rate from TOTEM

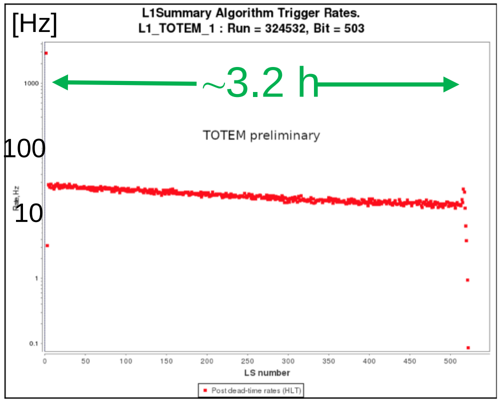
PRELIMINARY DATA COURTESY OF J. CASPAR FOR THE TOTEM COLLABORATION

• Standard collimation:



- Frequent initial scraping needed to achieve a reasonable rate
- Regular scraping needed due to the increasing ra

• Crystal collimation:

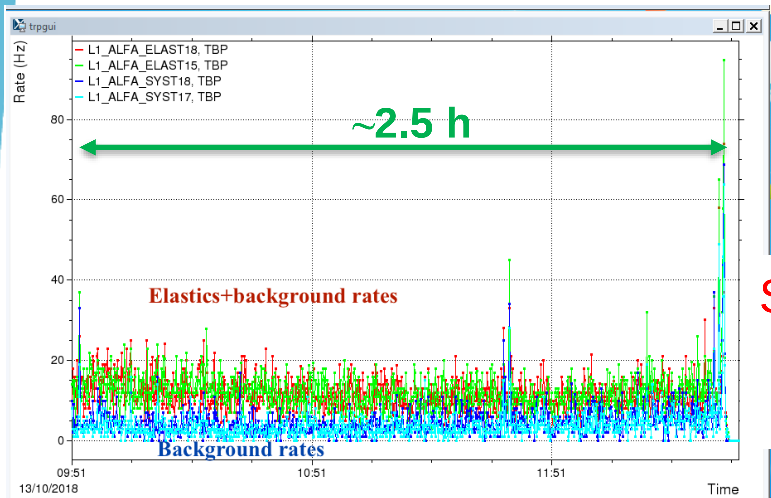


- No need of scraping
- Trigger rate follow luminosity

Background rate from ALFA

PRELIMINARY DATA COURTESY THE ATLAS-ALFA COLLABORATION

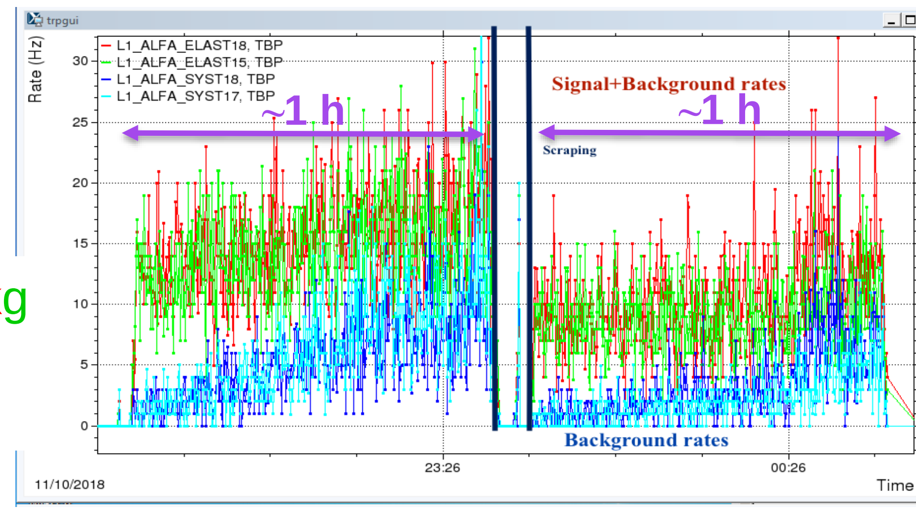
Crystal collimation



Signal+Bkg

Bkg

Standard collimation



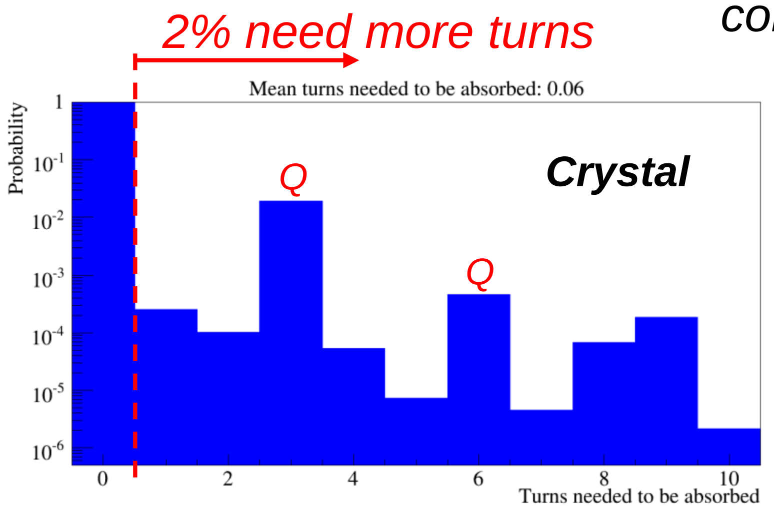
Same observations as for TOTEM: no need of scraping with crystals

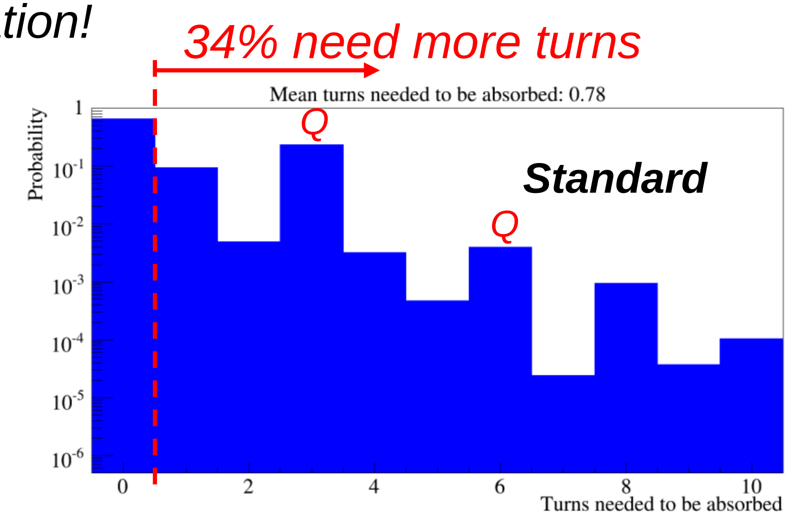
Understanding background rate

- **Two working hypothesis:**
  1. **Background with crystals is so low that the is below BLM sensitivity**
     → Inputs from experiments needed, agreed at last Collimation Working Group
  2. **Faster halo removal with crystals, able to digest larger diffusion rate**
     → Evaluate the number of turns needed to remove a particle, using simulations

- **"Observable": number of turns between the hit on primary stage and absorption/lost**

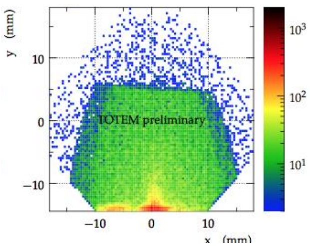
98% (66%) of particles absorbed in IR7 at the same turn in case of crystal (standard) collimation!

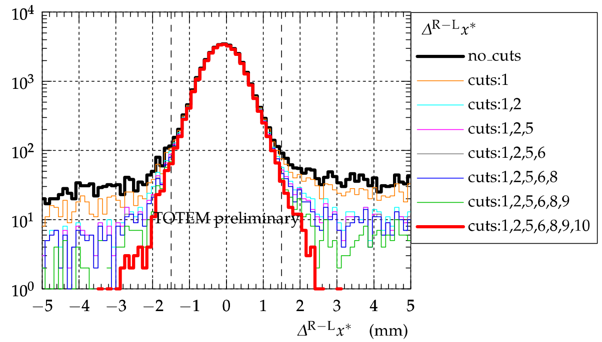




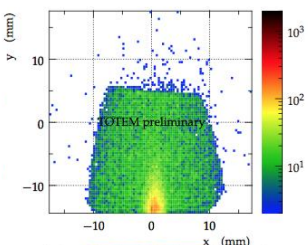
Bad background from TOTEM

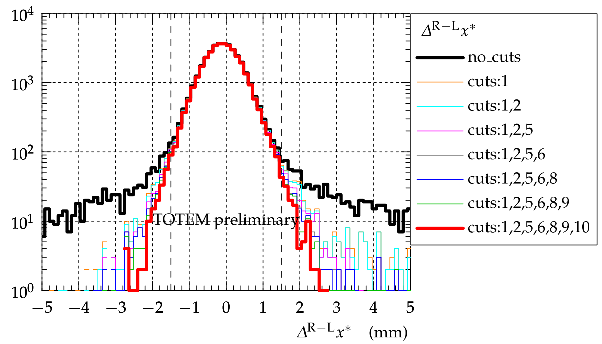
PRELIMINARY DATA COURTESY OF J. CASPAR FOR THE TOTEM COLLABORATION



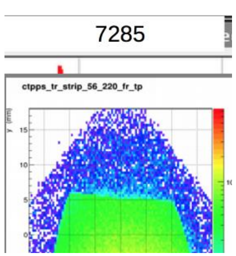


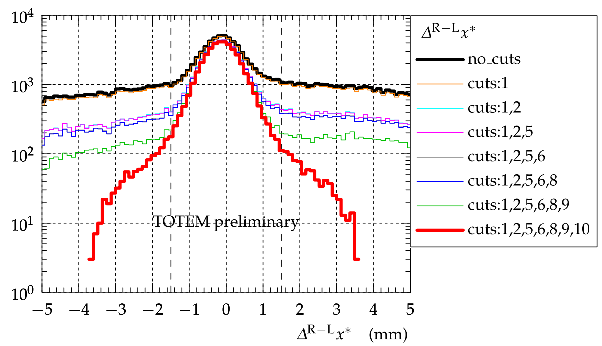
- fill 7280 – standard collimation working well
  - background present (black curve has tails)
  - but treatable with offline cuts (red curve does not have tails)





- fill 7281 – crystal collimation
  - very little background present – most of it removed with the first offline cut





- fill 7286 – standard collimation with large background
  - even with all offline cuts background cannot be eliminated (red curve has significant tails)

Crystal irradiation history

Facility	IHEP U-70	SPS North Area – NA48	HiRadMat
Reference	Biryukov et al., NIMB 234, 23-30	Biino et al., CERN-SL-96-30-EA	IPAC13 (THPFI059)
Year			2012
Beam	70 GeV protons	450 GeV protons	440 GeV protons
Irradiation	• 50 ms spills of 10^{14} p • one spill every 9.6 s • several min of irradiation	• 2.4 s spills of 5×10^{12} p • one spill every 14.4 s • one year irradiation (2.4×10^{20} p/cm^2 in total)	• 7.8 μs pulses of 3.2×10^{13} p • Several shots
Findings	channelling efficiency unchanged	channelling efficiency reduced by 30%	no visual damage, change in channelling efficiency to be evaluated

Moreover…

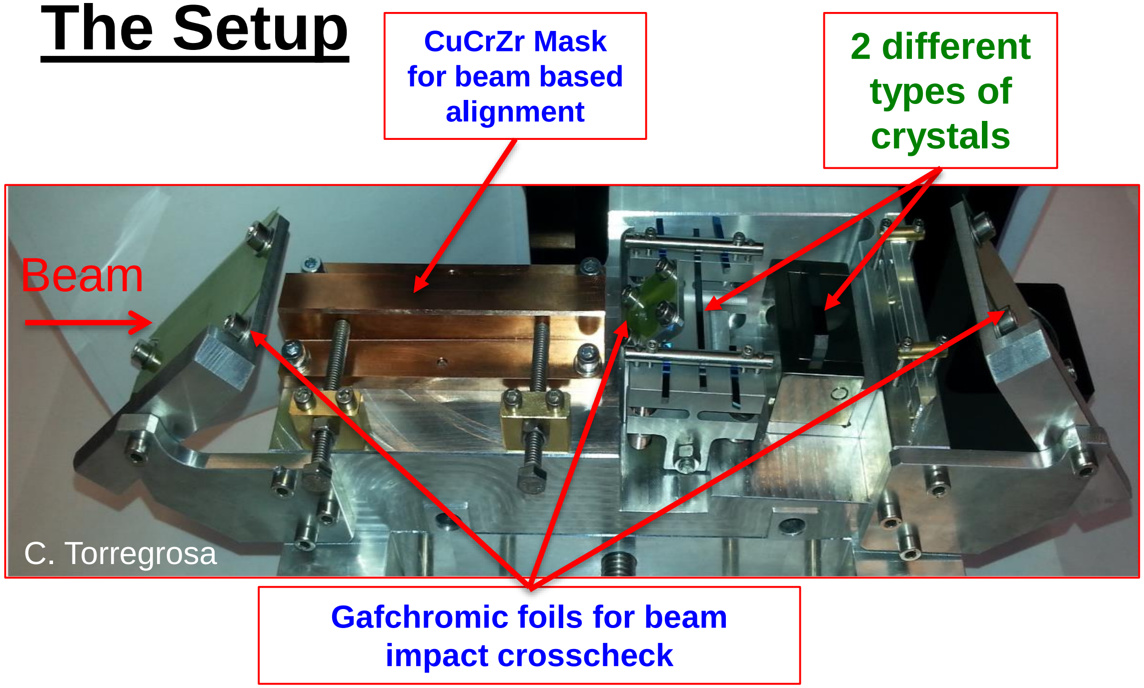
- UA9 tested several bent silicon crystals for collimation MDs in SPS and LHC
- Crystals have been irradiated for years during MD operations
- Crystals suffered some accidental beam impacts
- Crystals have shown always the same performances (angle and efficiency)
- Crystals did not show macroscopic damages

M. Garattini at CWG #234

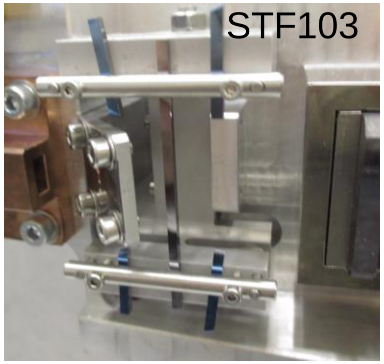
HiRadMat irradiation test

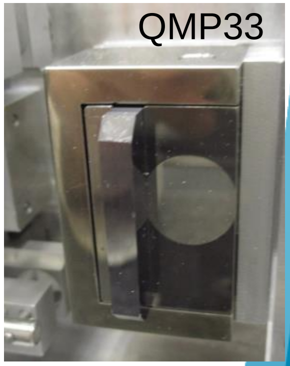
- E = 440 GeV
- 3 shots with 216 bunches (~2.5e13 ppp)
- 1 shot with 288 bunches (~ 3.2e13 ppp)
- ~0.3 x 0.3 mm size at 1σ

The Setup



No macroscopic damages after irradiation

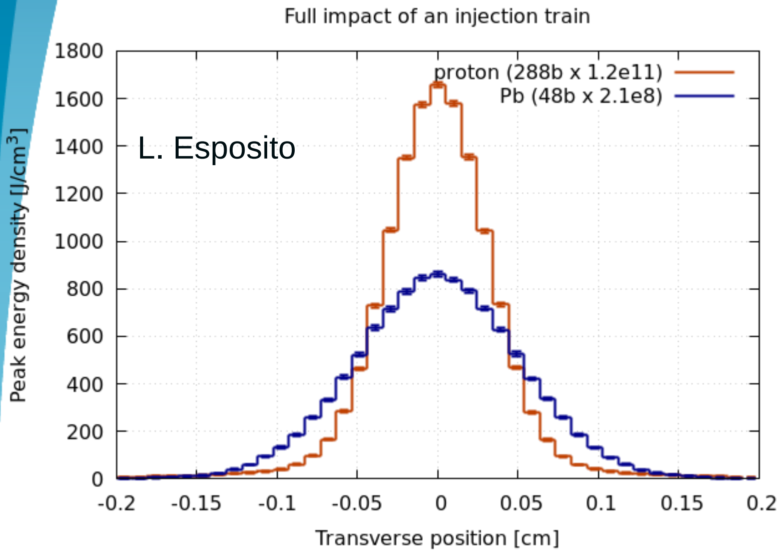




M. Garattini at CWG #234

Energy deposition

Accidental impact on crystal at injection



	Protons	**Pb**
Energy [GeV]	450	450 Z
#bunches	288	48
#particles/ bunch	1.2E11	2.1E8
Norm. emit. [μm]	1.3	1.5

- Impact of a full injection train on TCPCV.A6R7.B2 (smaller $\beta_x \cdot \beta_y$)
- Crystal assumed as amorphous
- Same optics for the injection of proton and Pb

Remark on induced energy densities:

- Due to small dimensions of the crystal (4 mm thick) peak energy density dominated by ionising energy loss of impacting protons
- Electronic stopping power of protons in silicon only varies by 10% between 440 GeV and 7 TeV → a test in HiRadMat with 288 bunches at 440 GeV allows also for conclusion valid at higher energies
- For an asynchronous beam dump at top energy few bunches are expected to be lost on the crystal

M. Garattini at CWG #234

Channeling efficiency

2 LHC crystals irradiated in HiRadMat and tested before and after in H8

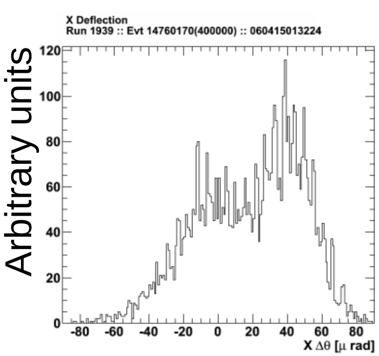
- 1st crystal full analysis: angle and efficiency measurement

Crystal	Θ_{CH} (before) (±1 μrad)	Eff. (before) (±2 %)	Θ (after) (±1 μrad)	Eff. (after) (±2 %)
STF103	55 (400 GeV p+)	75 (400 GeV p+)	54 (180 GeV π+)	69 (180 GeV π+)

Crystal of the same kind of the STF103, tested at different energies but not irradiated

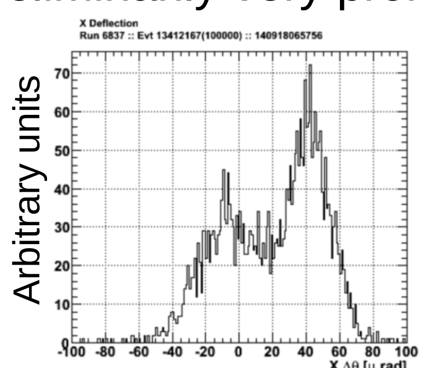
Crystal	Θ_{CH} (400 GeV p+) (±1 μrad)	Eff. (400 GeV p+) (±2 %)	Θ_{CH} (180 GeV π+) (±1 μrad)	Eff. (180 GeV π+) (±2 %)
STF105	51	74	52	64

- 2nd crystal under analysis, but preliminarily very promising

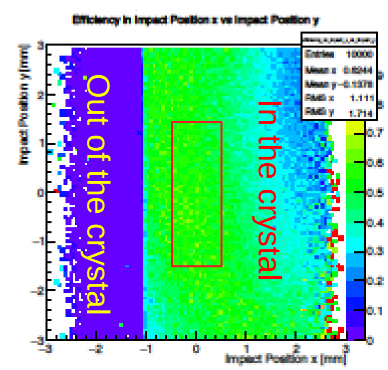


Crystal before HiRadMat

On-line plots



Crystal after HiRadMat



CH efficiency 2D map

M. Garattini at CWG #234