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Shanghai, China

Simulations and measurements of collimation cleaning with 100MJ beams in the LHC

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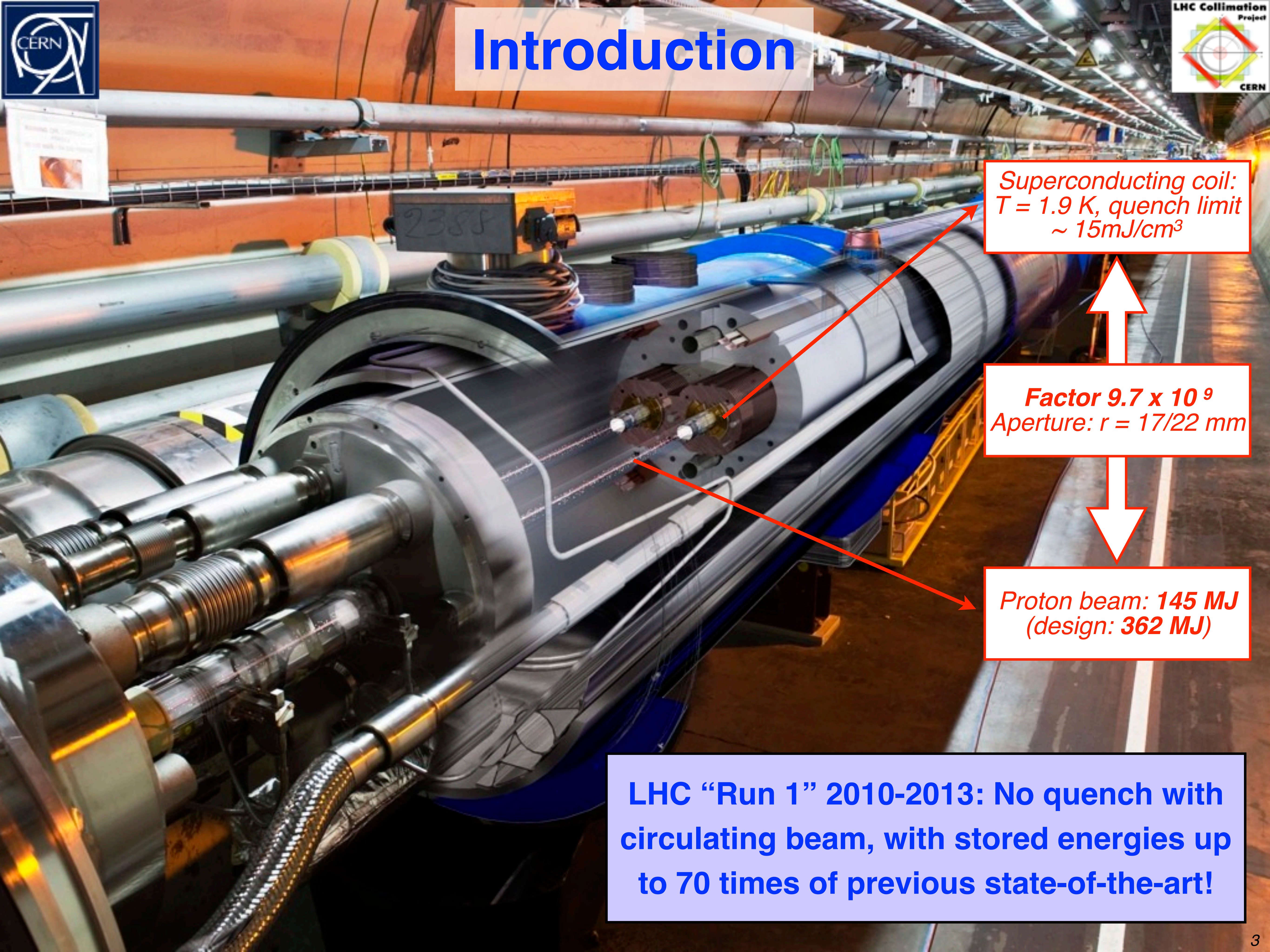
CERN, Geneva, Switzerland

Outline

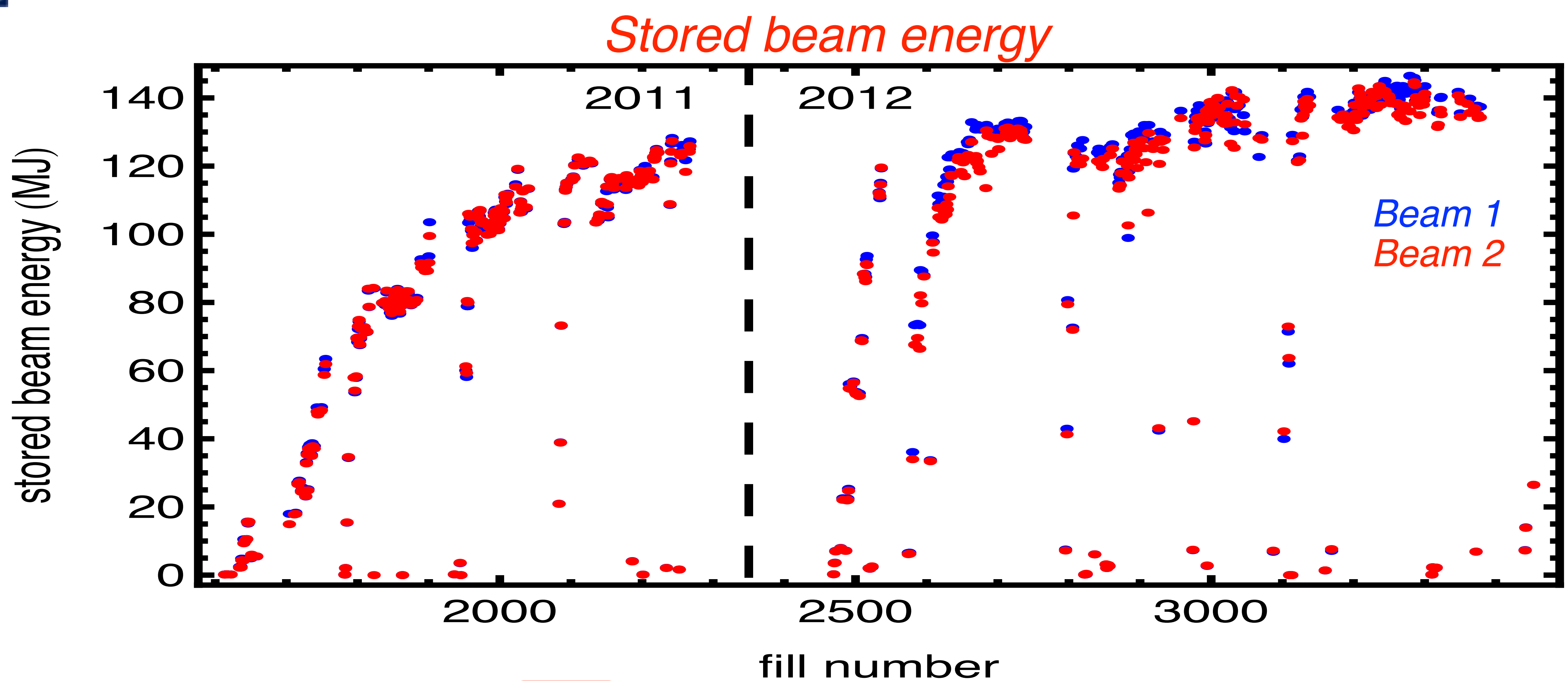
- Introduction
- Cleaning simulation setup
- Comparison with measurements
- Advanced simulations
- Conclusions

Introduction



LHC "Run 1" 2010-2013: No quench with circulating beam, with stored energies up to 70 times of previous state-of-the-art!

Some numbers from 2011-12 operation

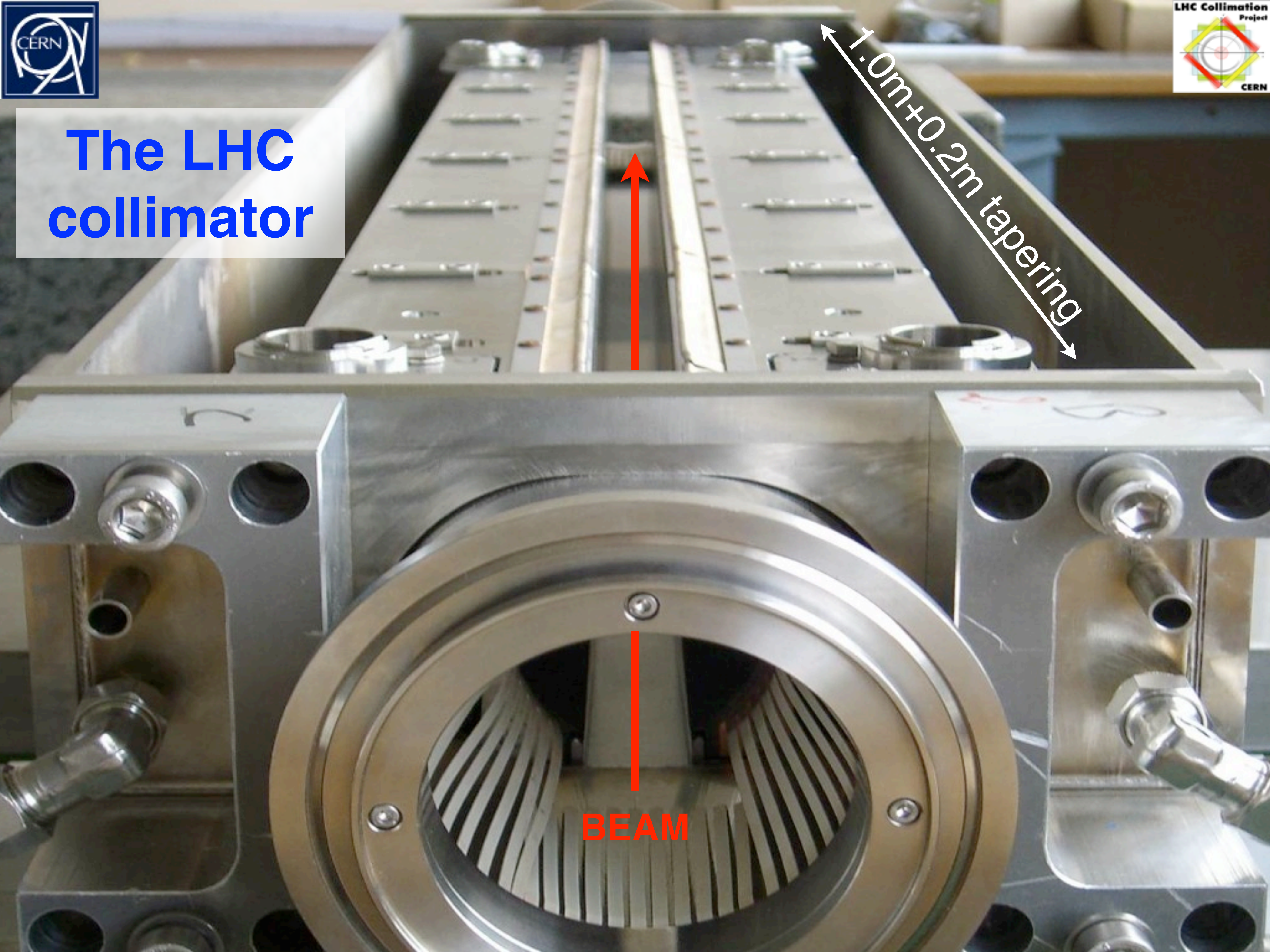


R. Bruce

	2011	2012	Nom.
E (TeV)	3.5	4	7
Number of bunches	1380	1380	2808
Average bunch intensity [10^{11}]	1.2	1.4	1.15
Peak total beam intensity [10^{11}]	2290	2290	3230
Horizontal and vertical β^*in IR1/5 [m]	1.5, 1.0	0.6	0.55
Peak stored energy [MJ]	128	146.5	362
Peak luminosity [10^{34}cm^{-2}s^{-1}]	0.35	0.77	1.0
Transv. normalized emittance [μm]	2.0	2.0	3.75
Primary collimator (TCP) cut (σ)	5.7	4.3	6.0
Secondary collimator (TCS) cut (σ)	8.5	6.3	7.0
Shower absorber (TCLA) cut (σ)	17.7	8.3	10.0
Tertiary collimator (TCT) cut (σ)	11.8	9.0	8.3

*Simulations presented here refer to the **2011 LHC machine configuration**. Cleaning for the “relaxed collimator settings”.*

The LHC collimator



LHC collimation system layout

Two warm cleaning insertions, 3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

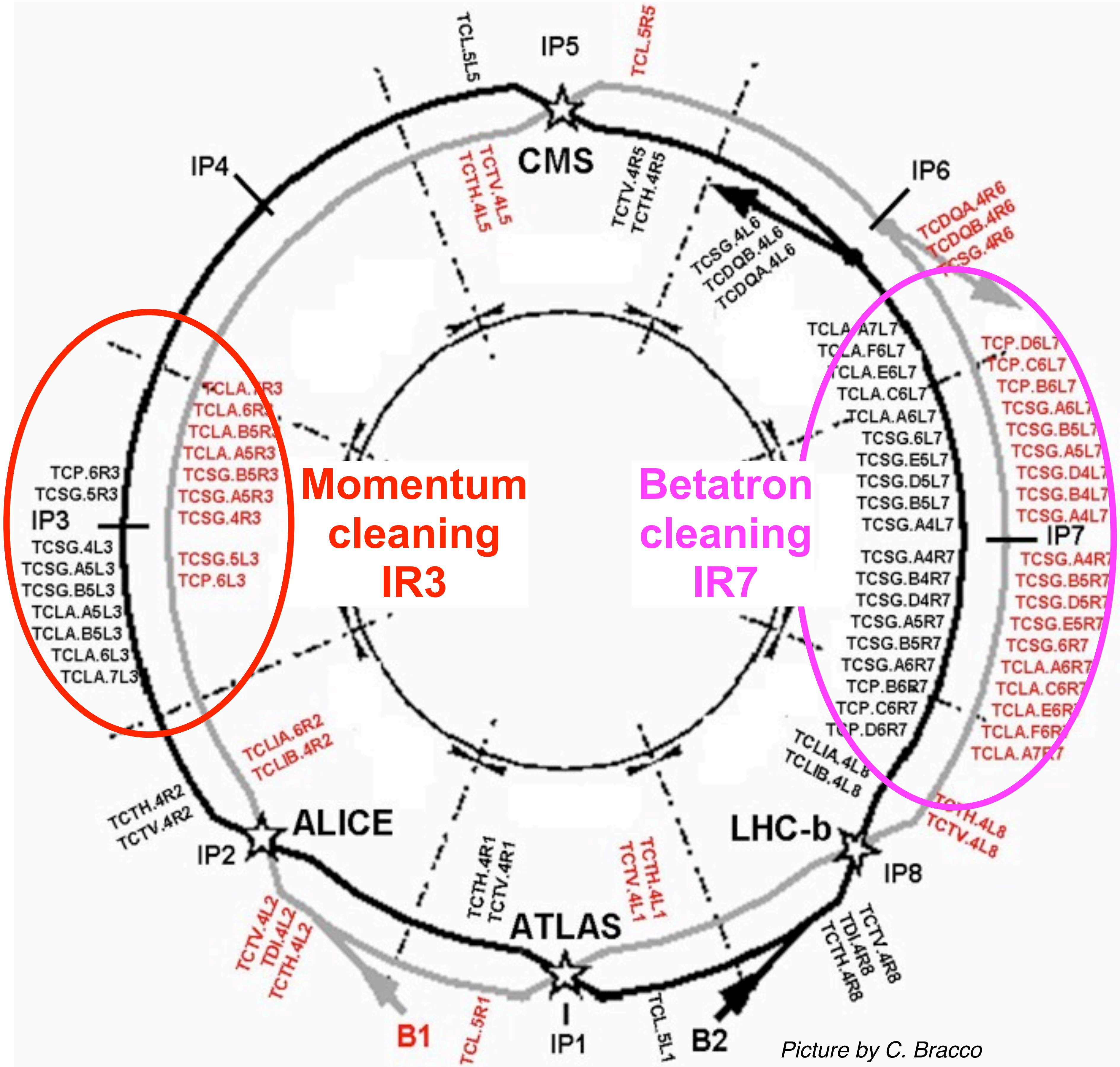
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

Transfer lines (13 collimators)
Injection and dump protection (10)

Total of 108 collimators (100 movable). Two jaws (4 motors) per collimator!



Picture by C. Bracco

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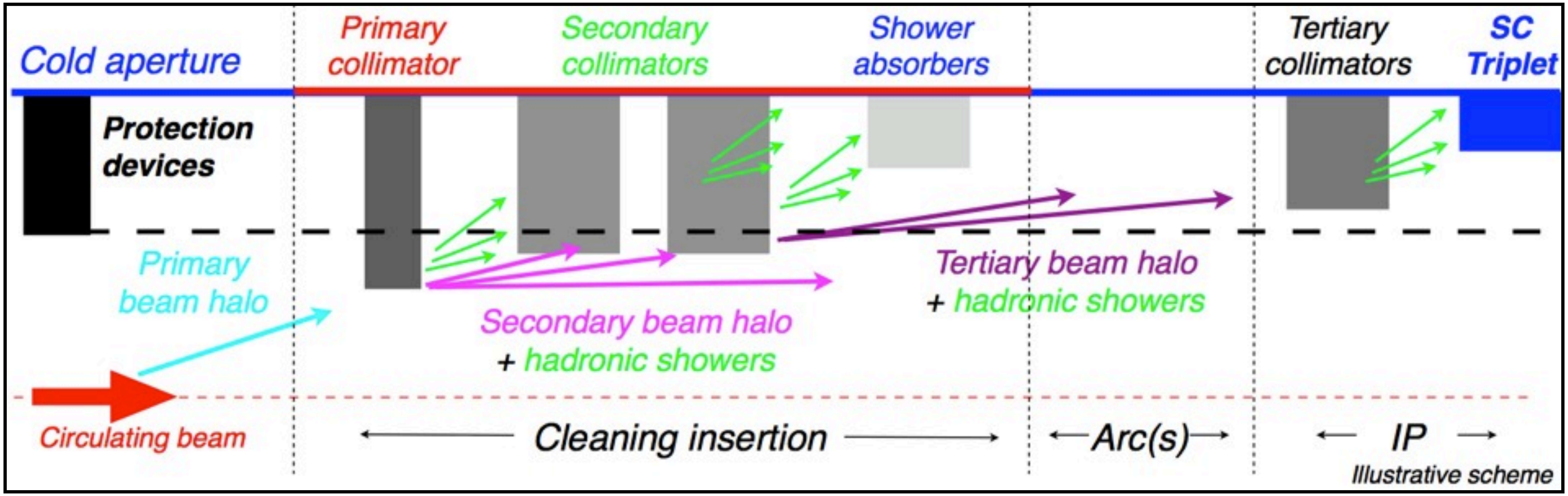
- ☑ **Cleaning simulation setup**
- ☑ Comparison with measurements
- ☑ Advanced simulations
- ☑ Conclusions

LHC collimation: simulation challenges

- Model precisely the **complex** and **distributed collimation** system
  - → *44 collimator per beam along 27 km; **multi-stage cleaning**;*
  - → *2 jaw design for 3 collimation planes: horizontal, vertical and skew;*
  - → *impact parameters in the sub-micron range;*
  - → *beam proton **scattering** with different collimator materials.*
- **Collimation** is designed to provide cleaning efficiencies > 99.99%
  - → *need **good statistical accuracy** at limiting loss locations;*
  - → *simulate only halo particles that interact with collimators, not the core.*



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- **Collimation** is designed to provide cleaning efficiencies > 99.99%
  - → *need **good statistical accuracy** at limiting loss locations;*
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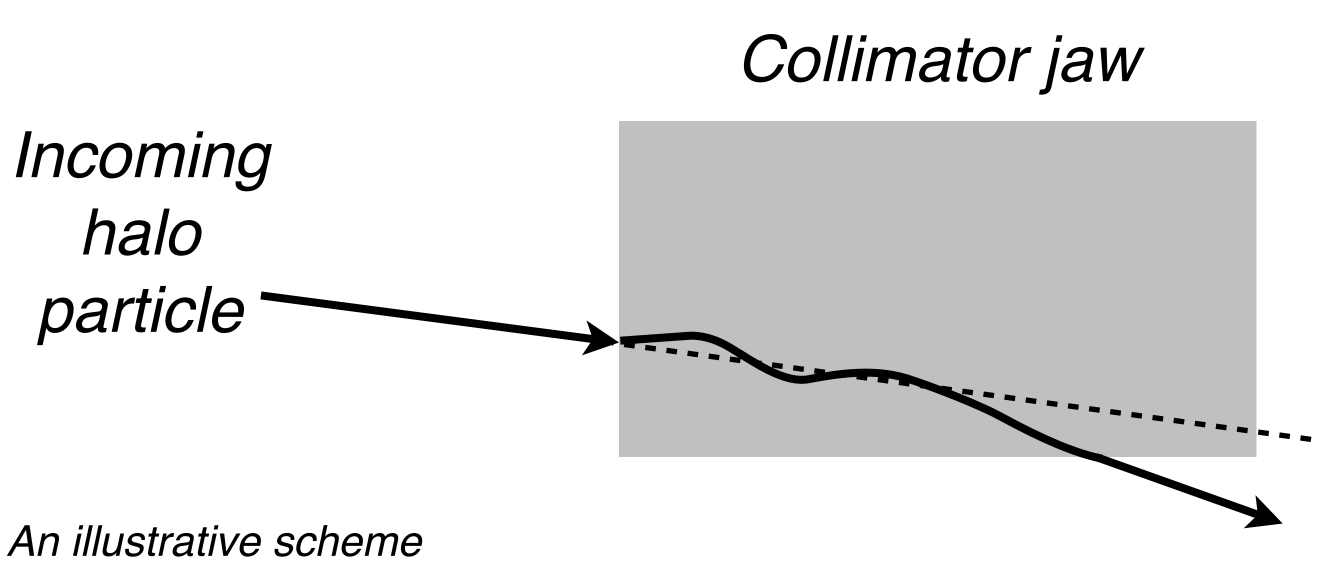
- Detailed description of the **LHC aperture** all along the 27 km
  - → *10 cm binning, i.e. 270000 check points.*
- Accurate tracking of particles with large **orbit** and **energy deviations**
  - → *need state-of-the-art tracking tools.*
- At the scale of 7 TeV beam sizes (~200 microns), small errors matter!
  Need to **model the relevant imperfections**
  - → *Jaw flatness of the order of 40 microns;*
  - → *Jaw positioning (gap/angles);*
  - → *Machine optics and orbit errors.*

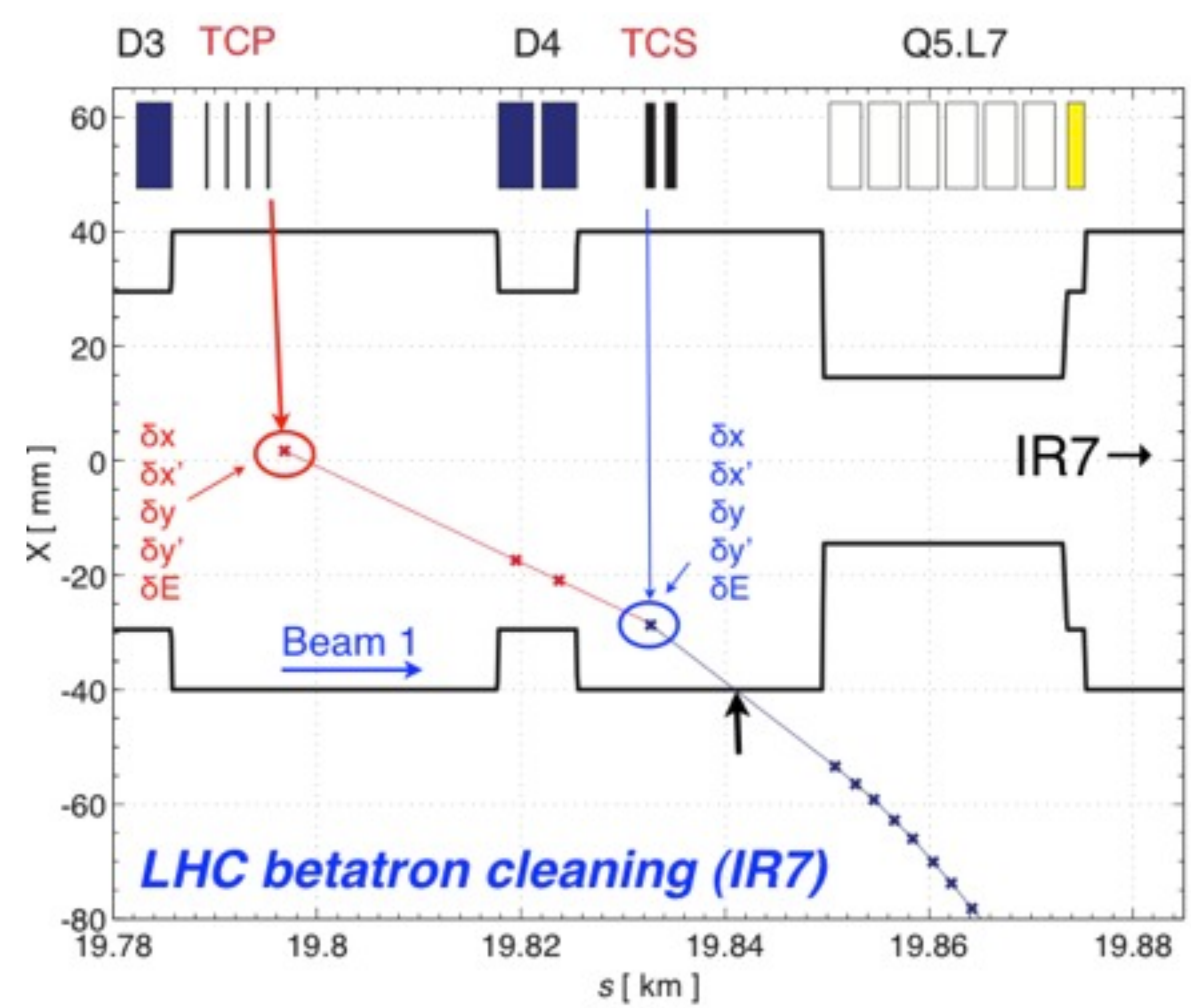
Simulation tools

Accurate tracking of halo particles 6D dynamics, chromatic effects, δp/p, high order field errors, ...	**SixTrack**
Detailed collimator geometry Implement all collimators and protection devices, treat any azimuthal angle, tilt/flatness errors	
Scattering routine Track protons inside collimator materials	**K2**
Detailed aperture model Precisely find the locations of losses	**BeamLossPattern**

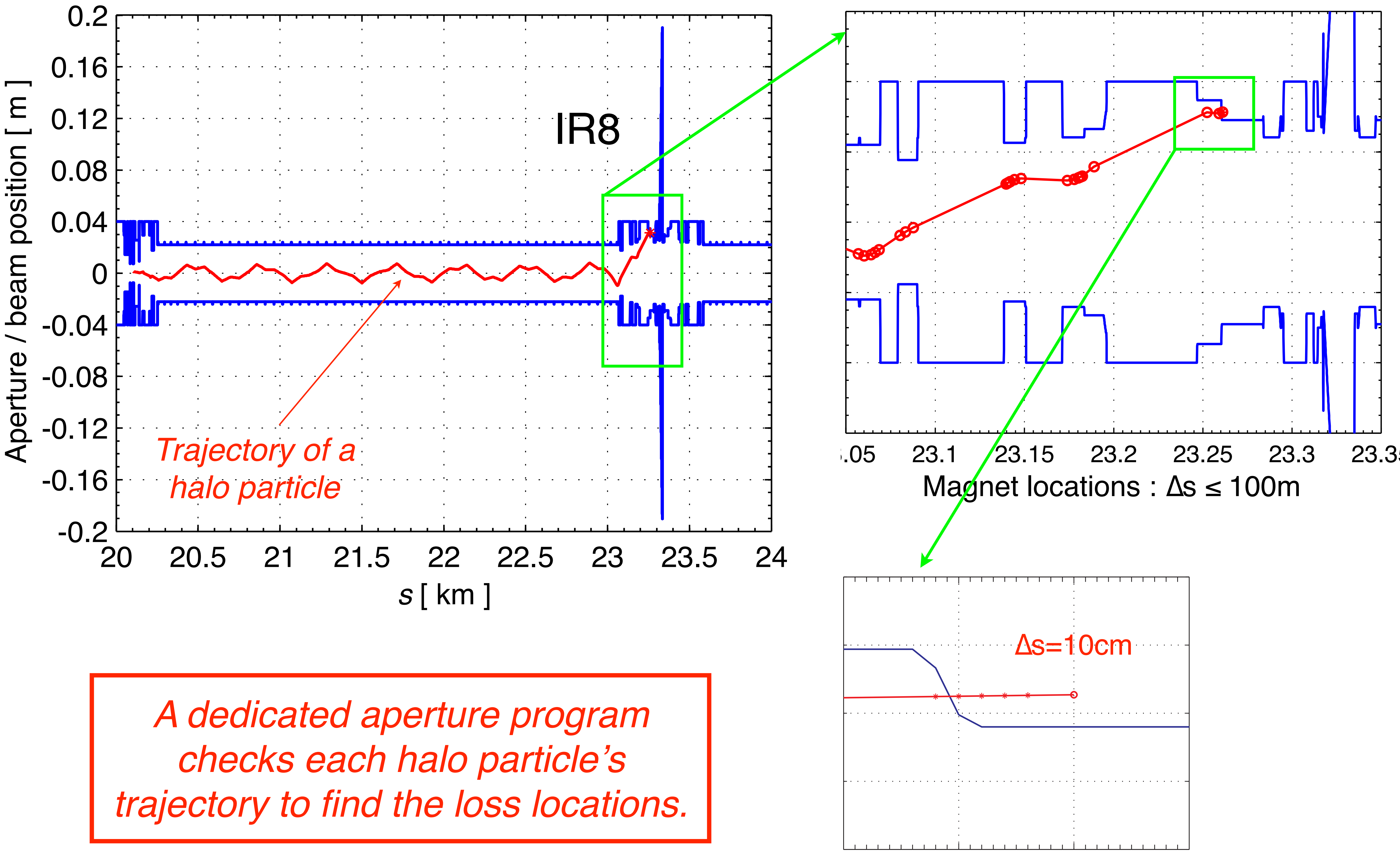
All combined in a simulation package for collimation cleaning studies: G. Robert-Demolaize, R. Assmann, S. Redaelli, F. Schmidt, **A new version of SixTrack with collimation and aperture interface**, PAC2005



An illustrative scheme



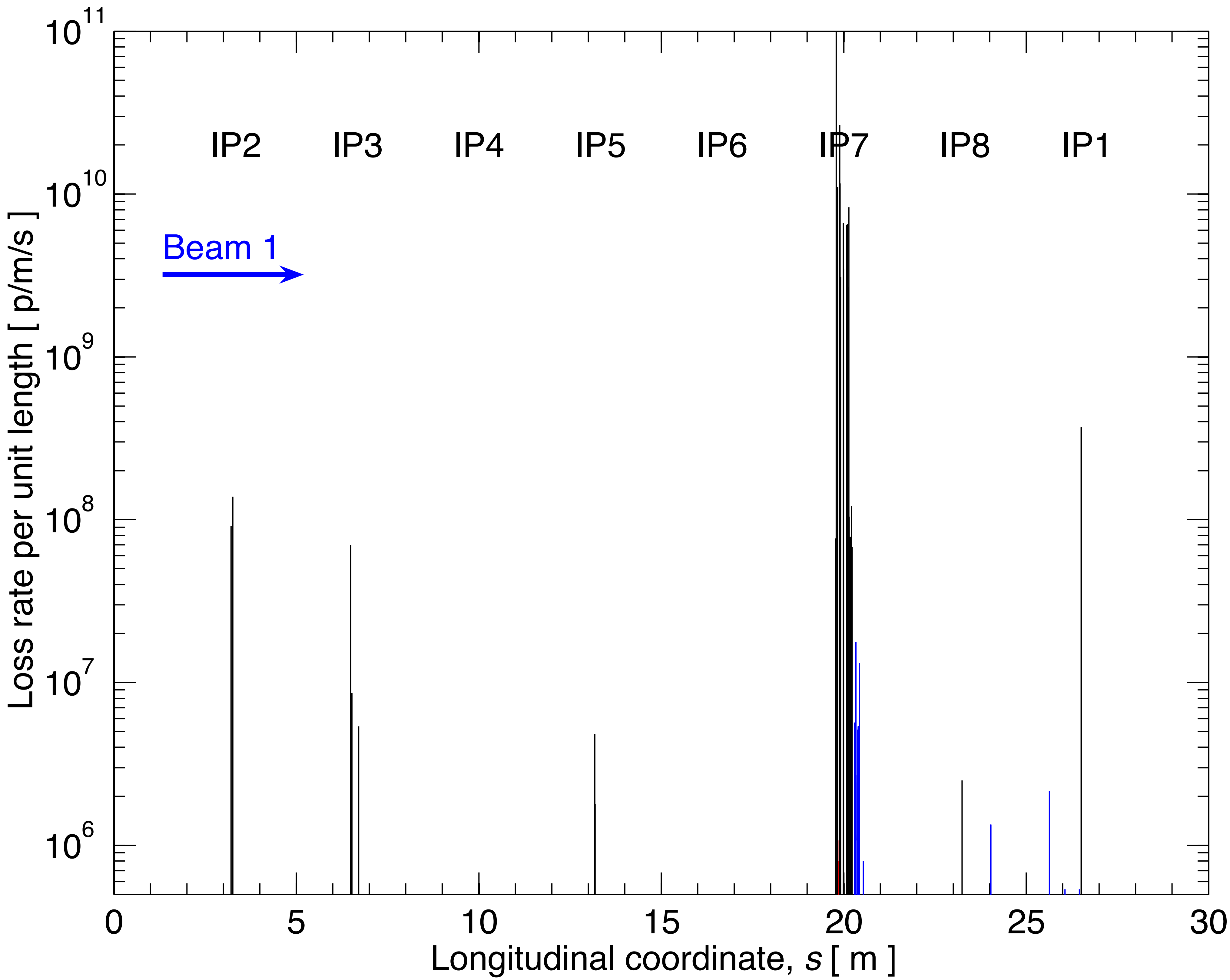
Example: trajectory of a halo particle



Interpolation: Δs=10cm
(270000 points!)

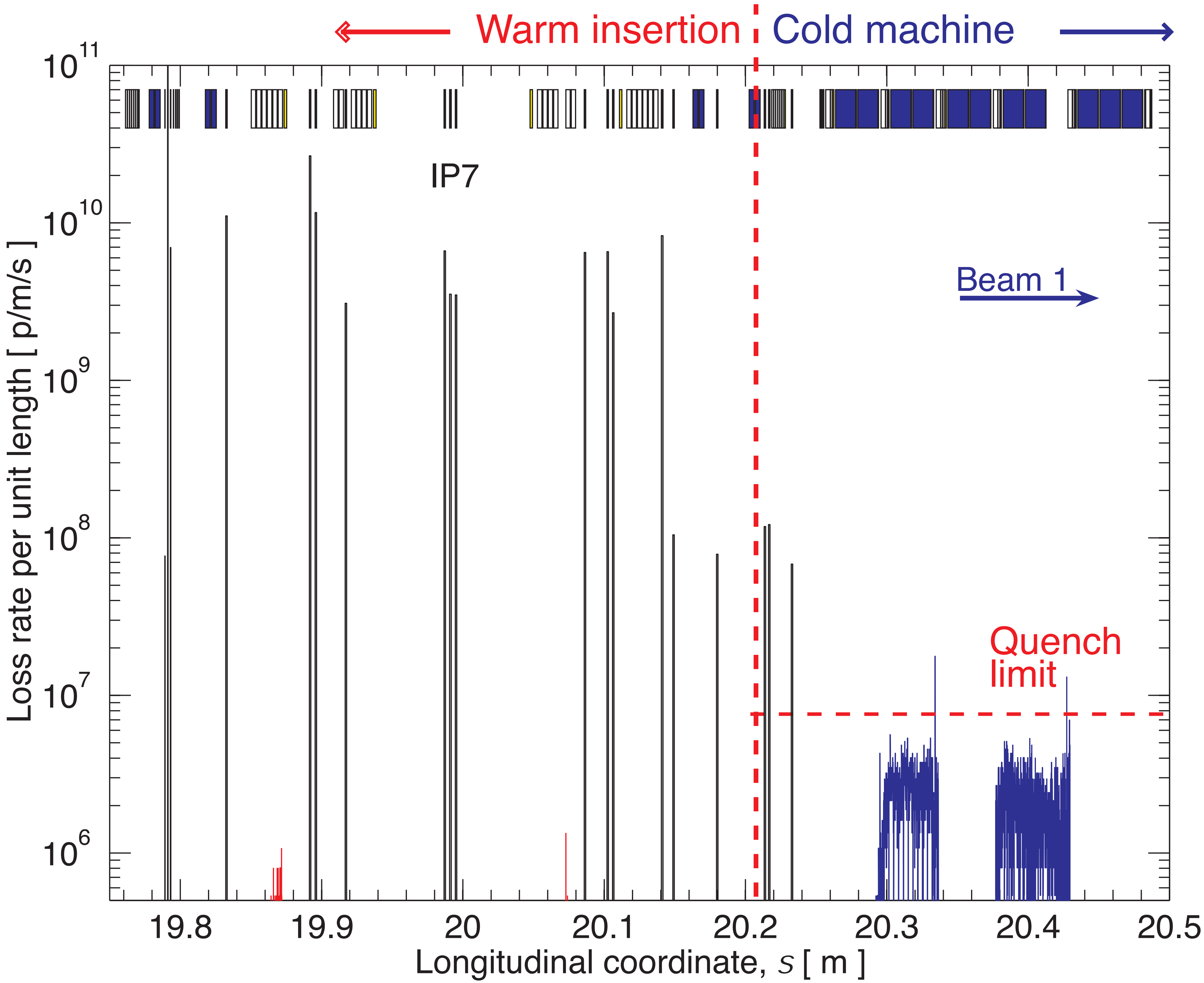
A dedicated aperture program checks each halo particle's trajectory to find the loss locations.

Example of simulated "loss map"



Nominal 7 TeV case, perfect machine

Example of simulated "loss map"



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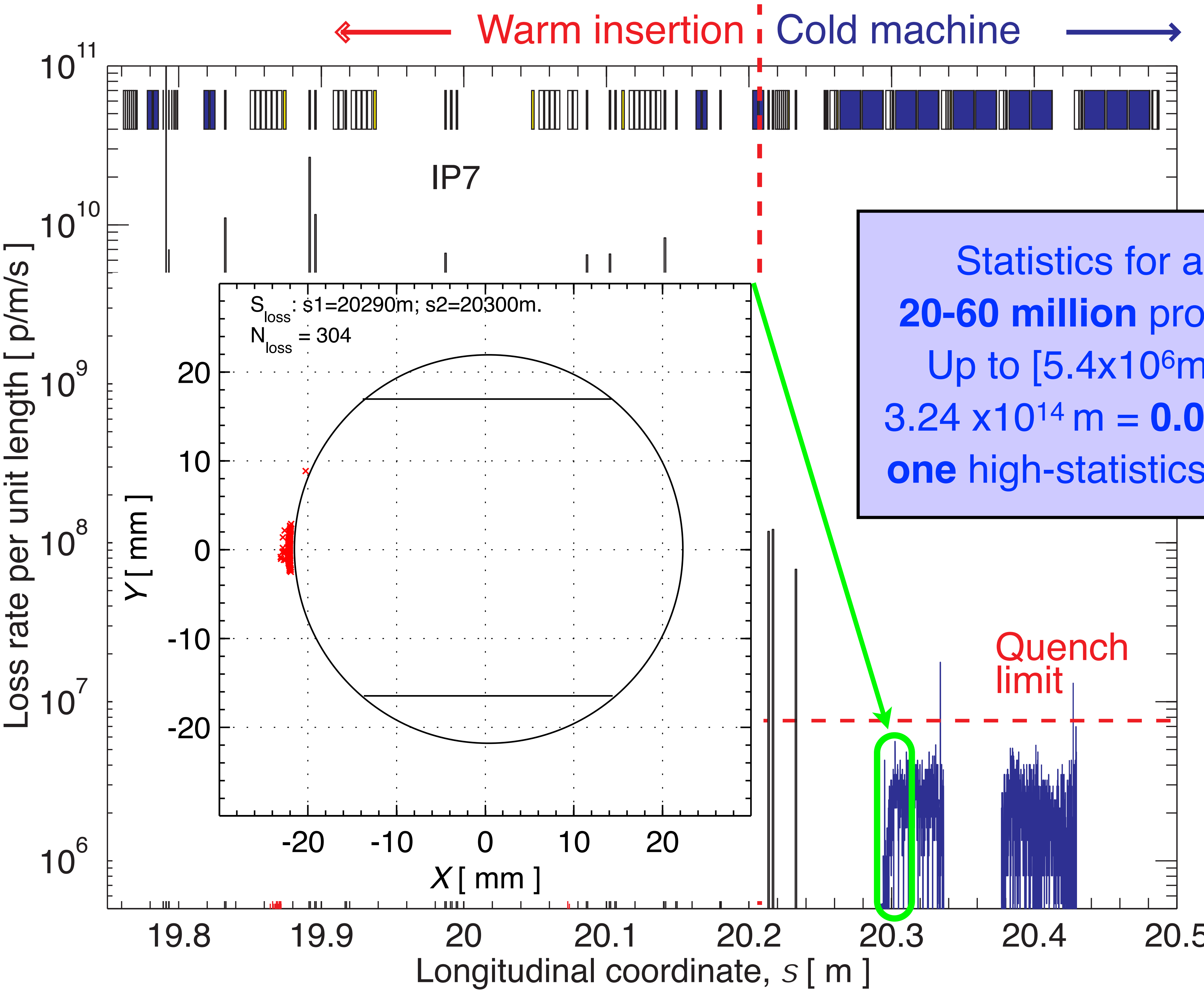
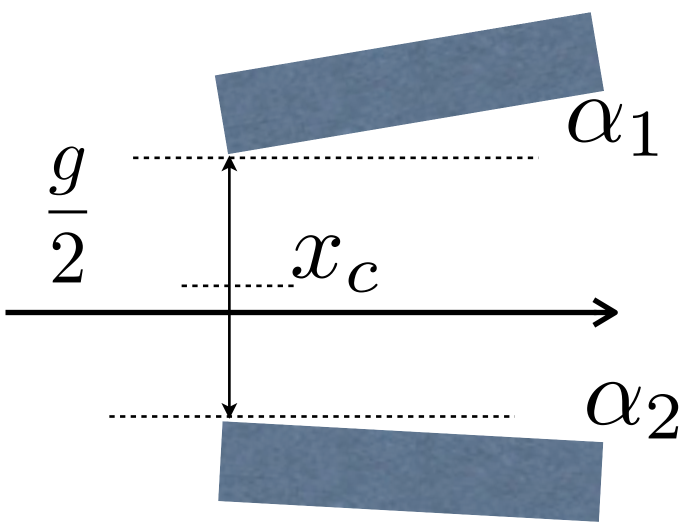


Nominal 7 TeV case, perfect machine

Statistics for a typical case:
20-60 million protons, **200 turns**.
Up to [5.4×10^6m] x [60×10^6p] =
3.24×10^{14} m = **0.034 lightyears** for
one high-statistics simulation case!

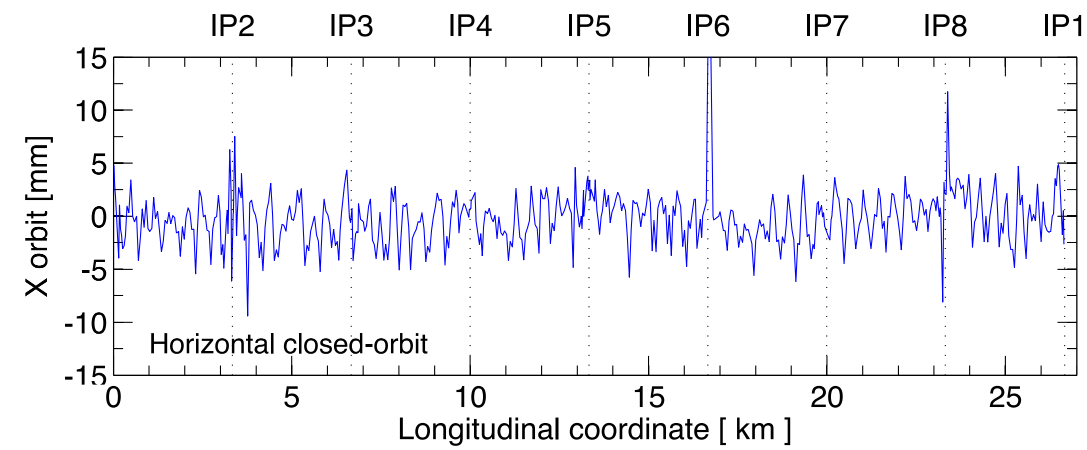
Error models for cleaning simulations

Collimator positioning with respect to the beam



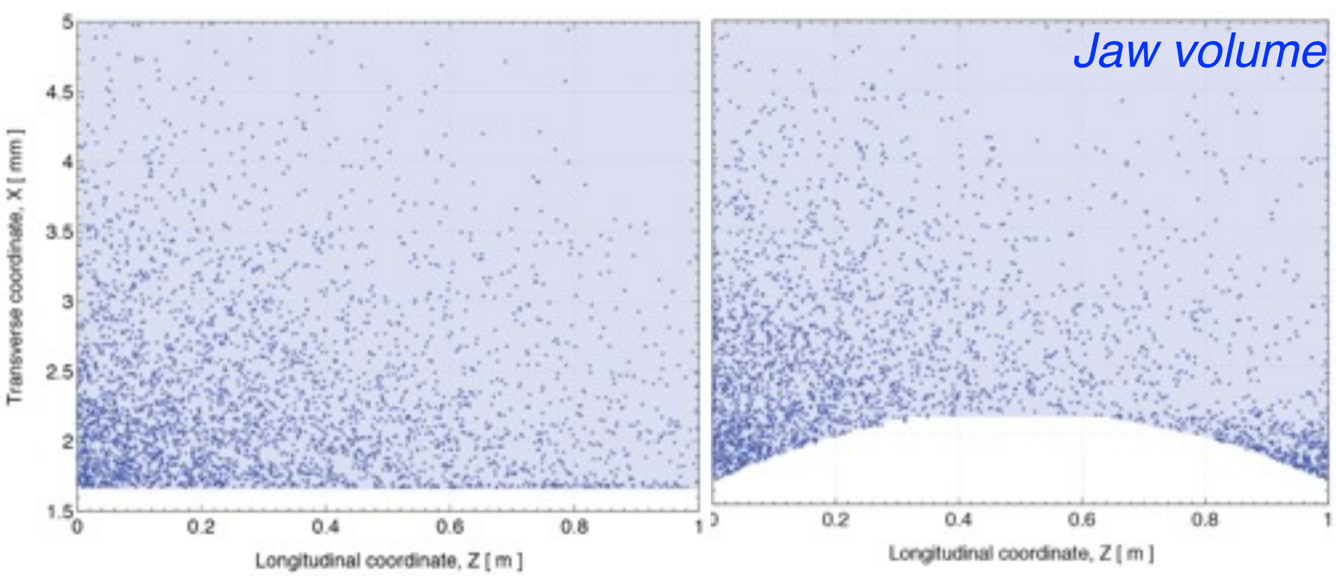
Can apply random errors to collimator geometry.
Typical RMS values:
Collimator centre = 50µm
Gap = 0.1 σ
Jaw tilt angle = 200 µrad

Closed-orbit errors around the ring



Design value: +/- 3-4mm peak-to-peak

Collimator jaw flatness



5th order polynomials to fit measured flatness of all Carbon collimators: ≥ 40 µm

Machine aperture misalignments

Element type	Description	Design		Measured	
		$\sigma_{\Delta x}$ [mm]	$\sigma_{\Delta y}$ [mm]	$\sigma_{\Delta x}$ [mm]	$\sigma_{\Delta y}$ [mm]
MB	main dipole	2.40	1.56	1.83	1.10
MQ	arc quadrupole	2.00	1.20	1.36	0.76
MQX	triplet quadrupole	1.00	1.00	1.53	1.53
MQWA	warm quadrupole	2.00	1.20	0.67	0.41
MQWB	warm quadrupole	2.00	1.20	0.67	0.41
MBW	warm dipole	1.50	1.50	1.96	1.49
BPM	beam position monitor	0.50	0.50	1.36	0.76

In addition, all optics and multipole errors well established for the standard MADX / sixtrack interface can be applied.

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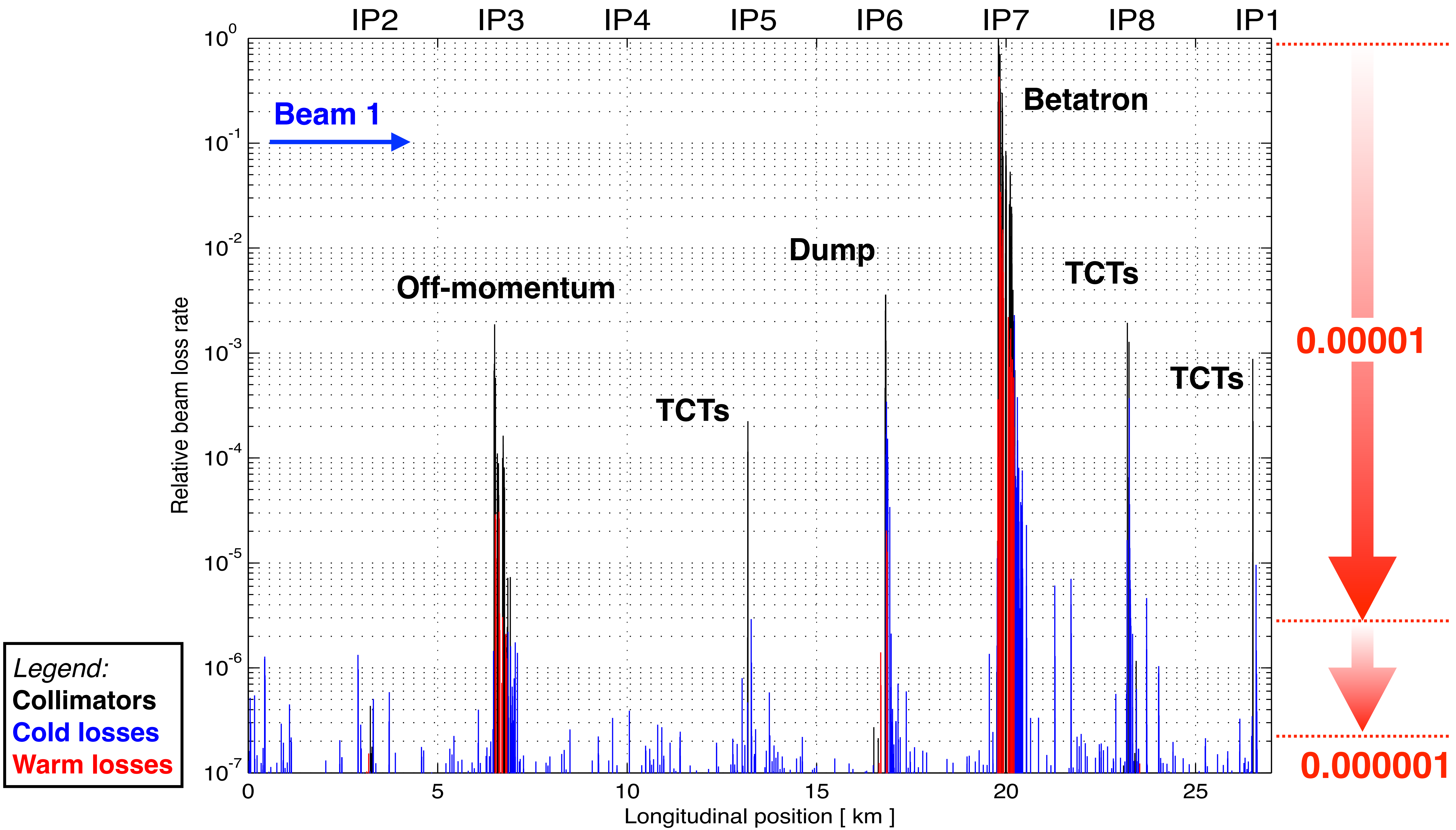
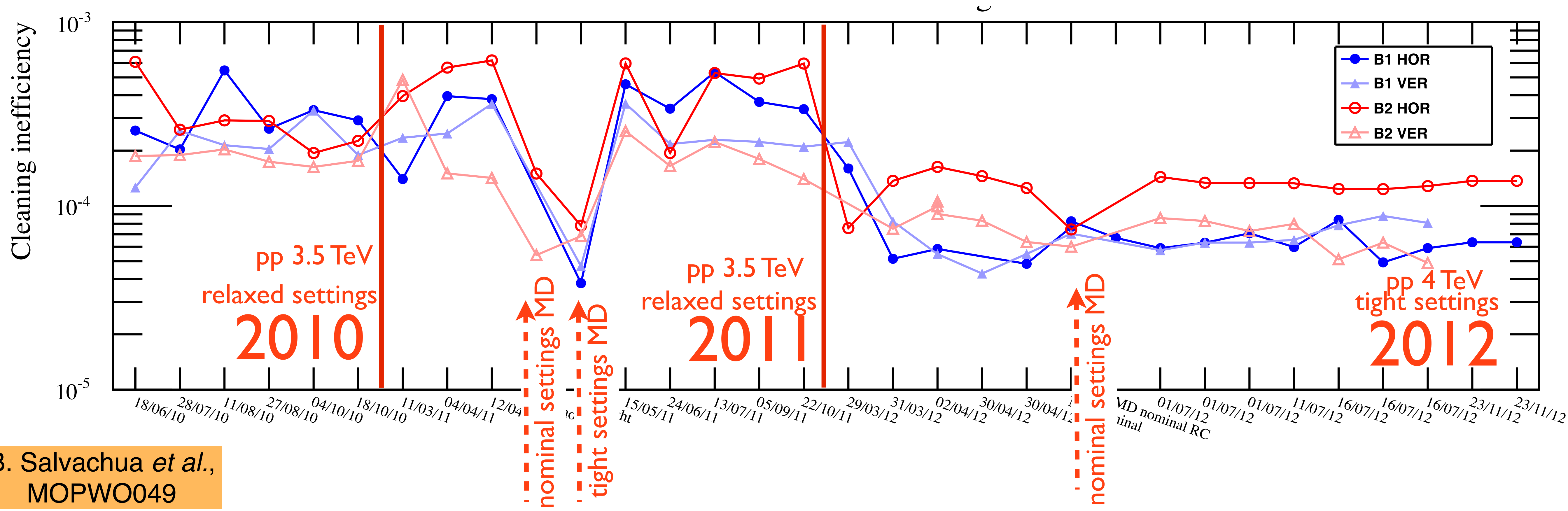
Betatron cleaning at 3.5TeV, β^*=1.5m



Beam losses increased artificially: crossing 3rd order resonance or white noise from damper.

Local cleaning calculated as ratio of local BLM signal to highest loss at the primary collimators.

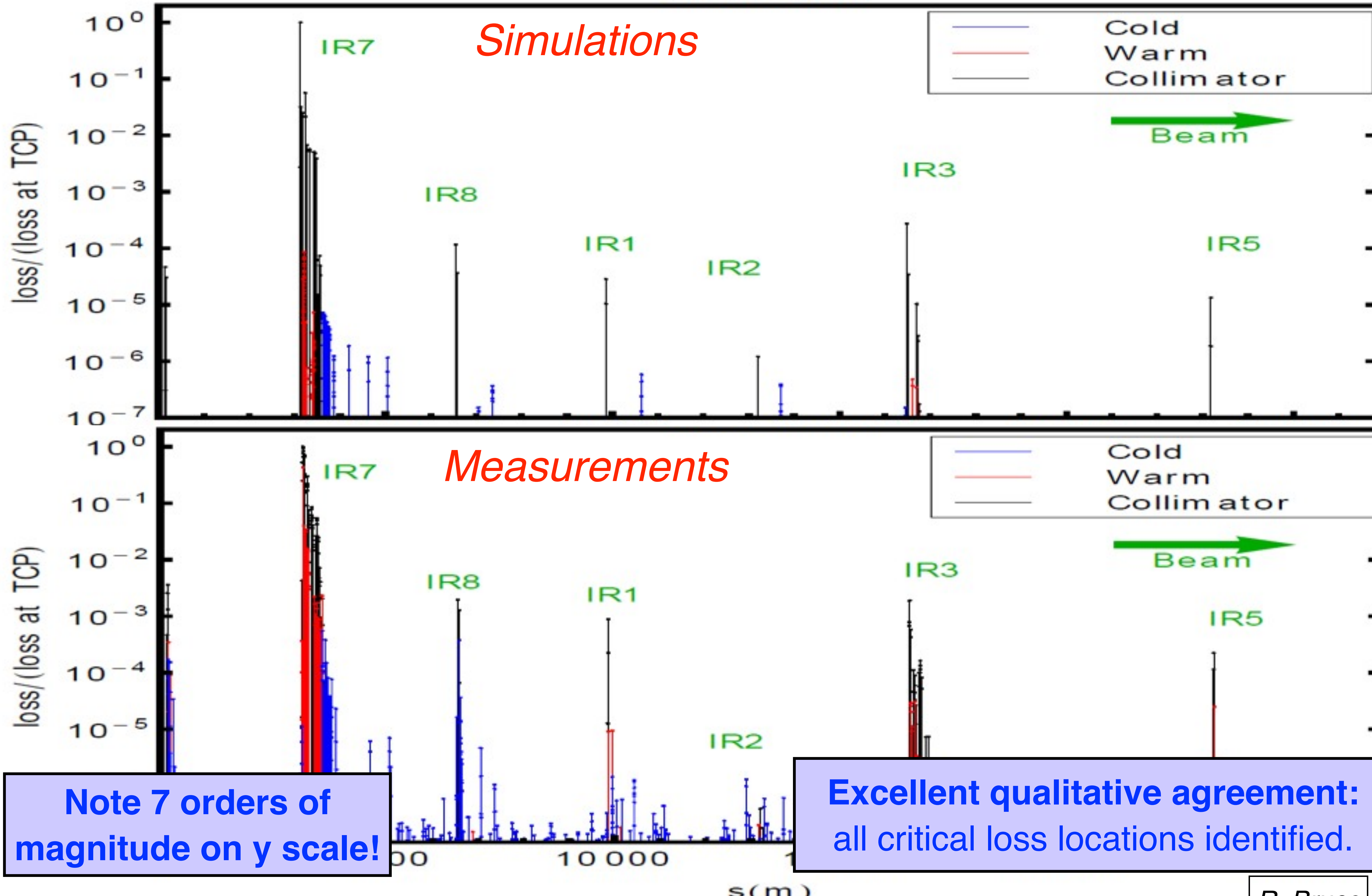
Collimation cleaning in 2010-12



B. Salvachua *et al.*, MOPWO049

- The loss maps are regularly performed to **validate the system functionality**.
  Shown here: cleaning at the highest COLD loss location of the ring (DS in IR7)
- **Excellent stability** of cleaning performance observed!
  Steps in the graph determined by changes of collimator settings.
- However, a certain **spread in measurements** for the "same" configuration adds uncertainty to the measurements, to betaken into account in the coparison.
- In the following, use average of several loss maps done in 2011
  (7 cases that should give the same cleaning).

Comparison - full ring at 3.5 TeV

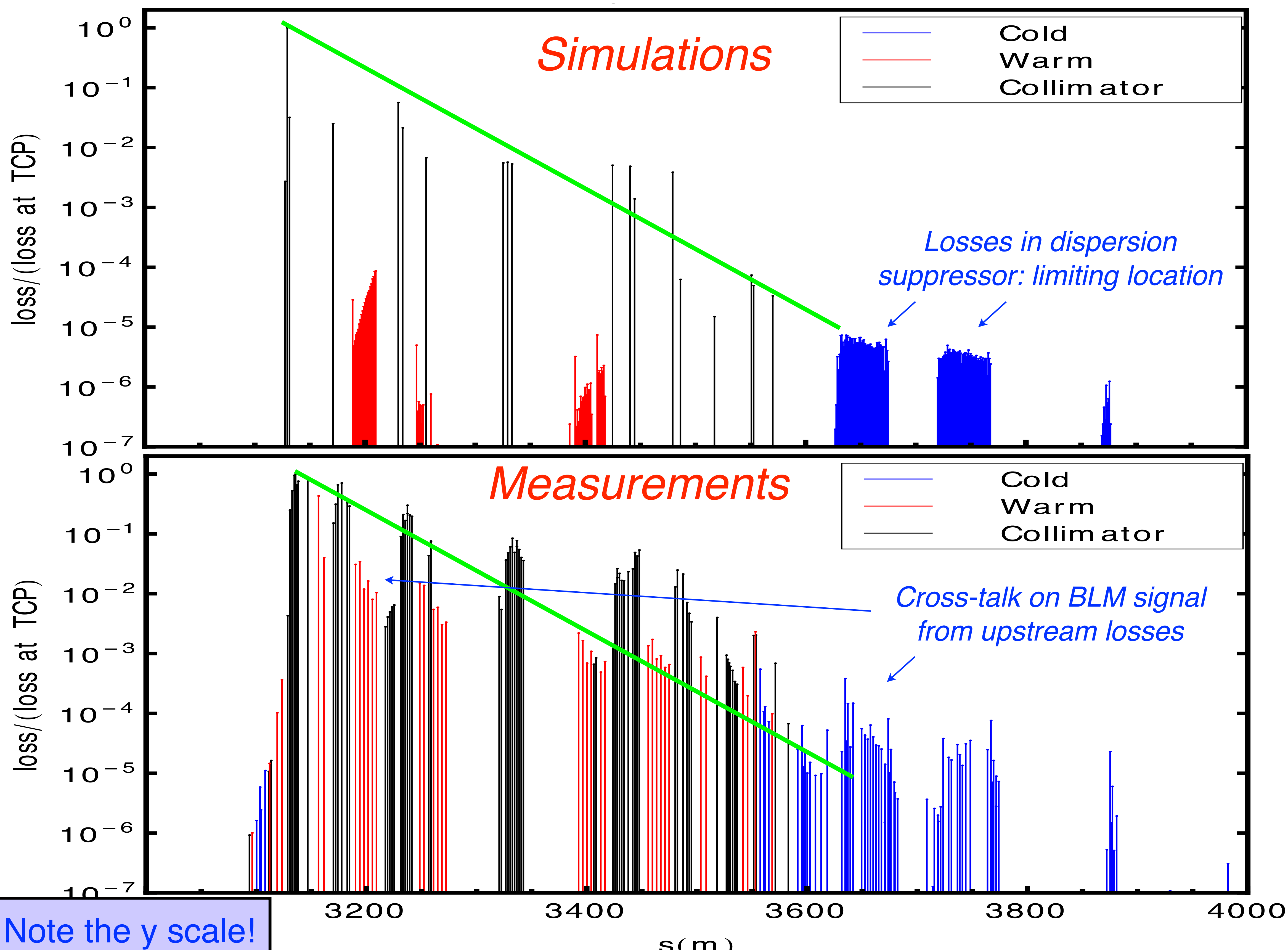


Note 7 orders of magnitude on y scale!

Excellent qualitative agreement: all critical loss locations identified.

R. Bruce

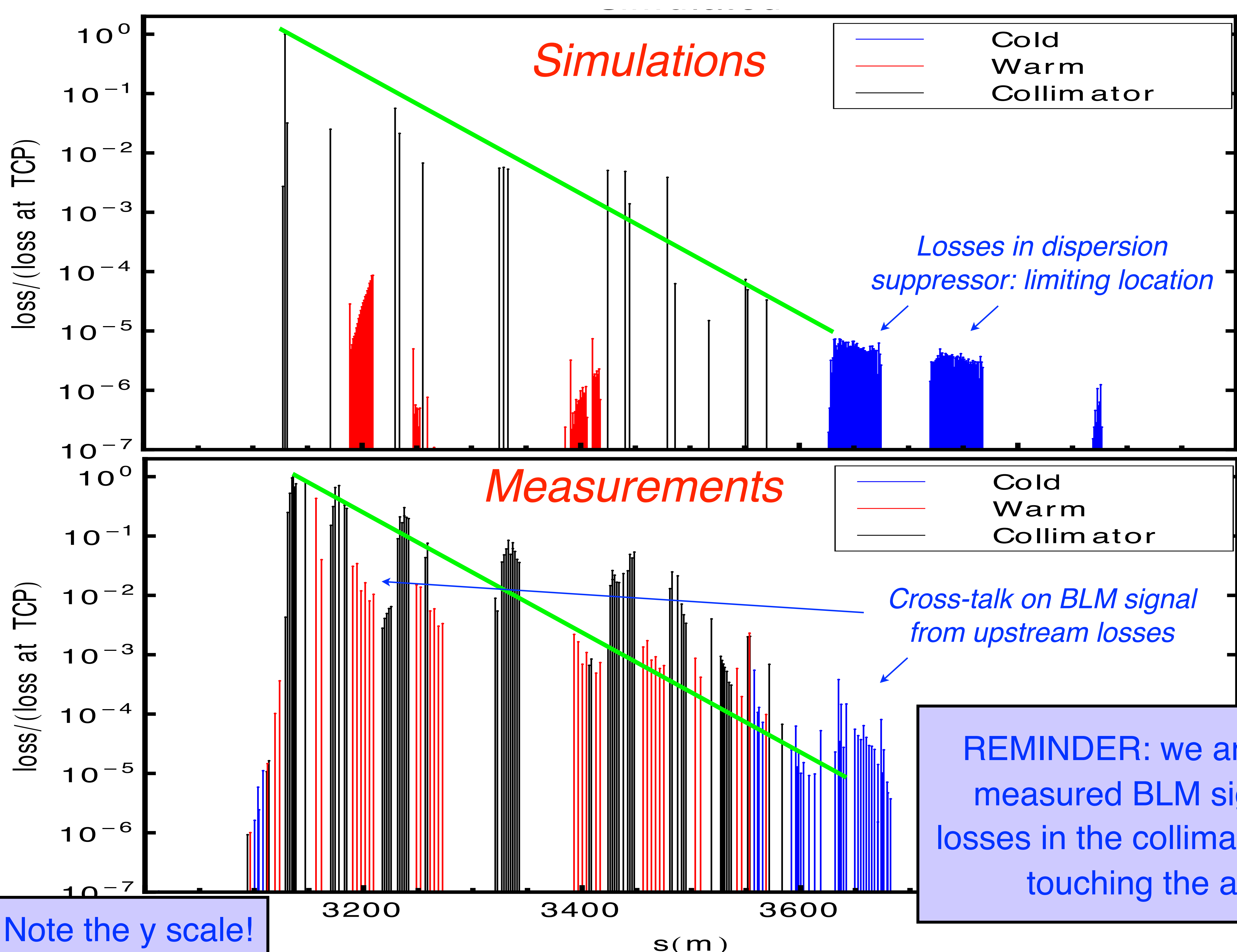
Comparison in the betatron cleaning



R. Bruce

Note the y scale!

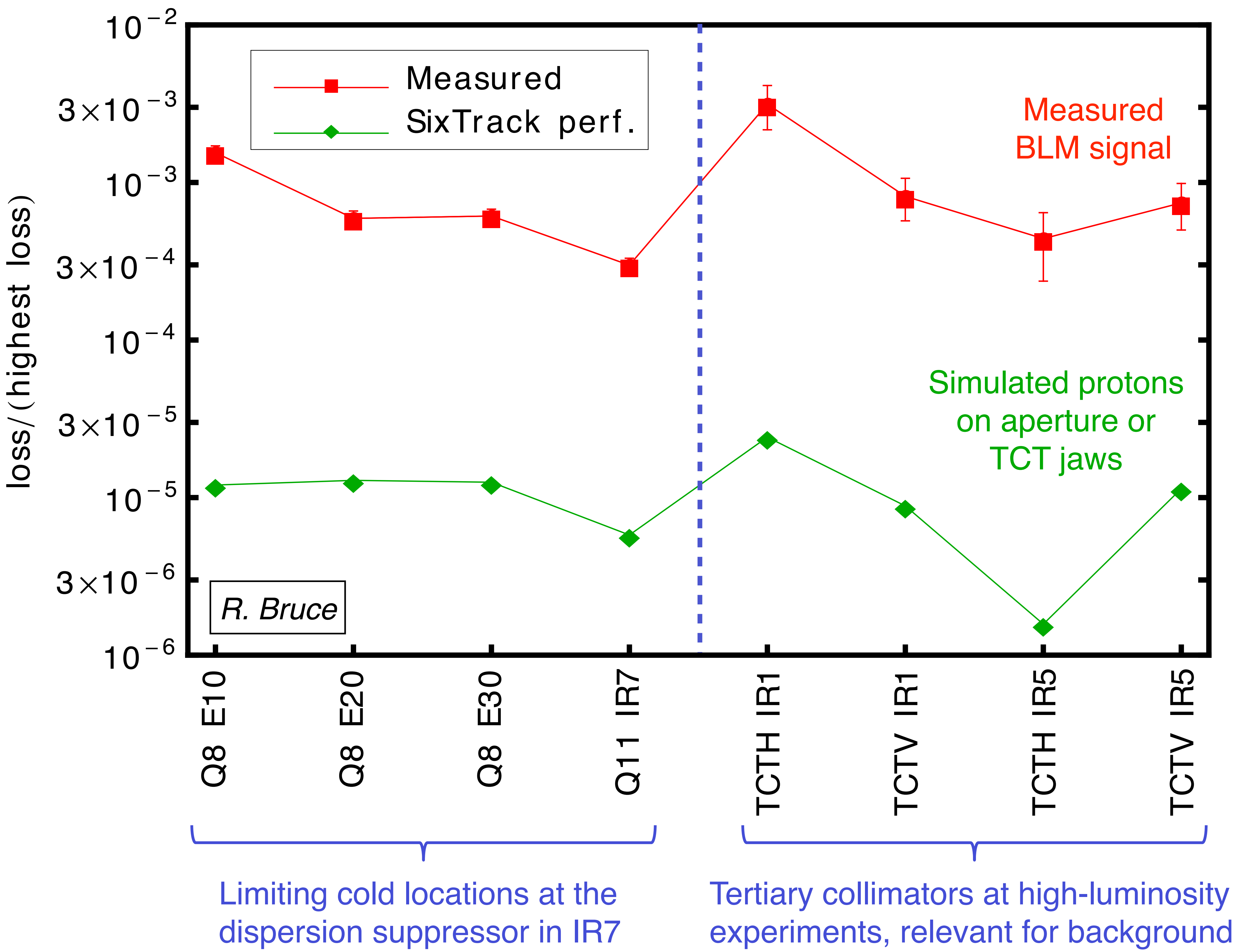
Comparison in the betatron cleaning



REMINDER: we are comparing measured BLM signal against losses in the collimators or protons touching the aperture !

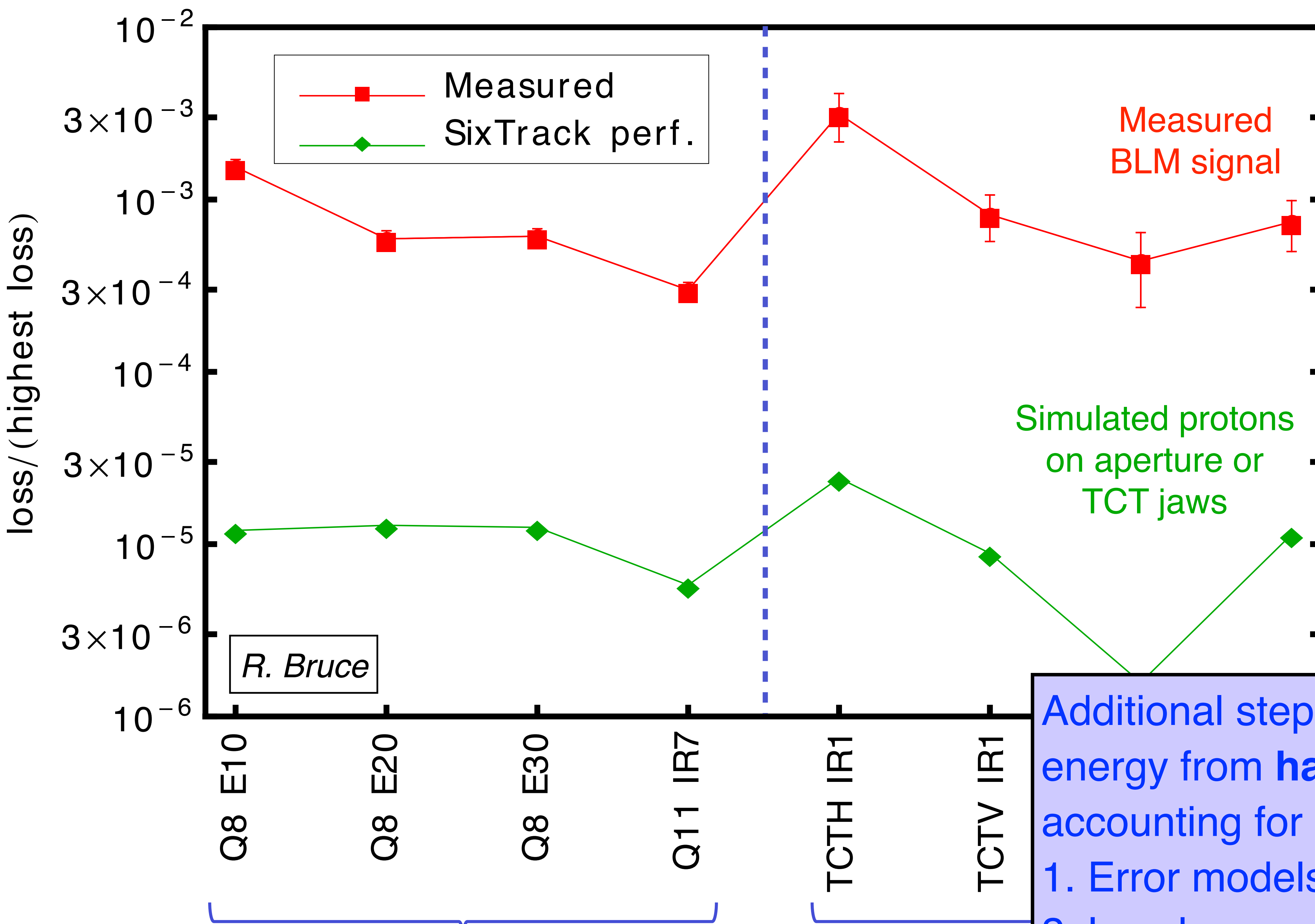
Note the y scale!

Signal at selected loss locations (B1,H)



- SixTrack results summed over 2m interval upstream of each BLM in the IR7 DS
- For TCTs, dividing losses at TCP by losses at TCT
- Measured: 2011 average, normalized to TCP

Signal at selected loss locations (B1,H)



Limiting cold locations at the dispersion suppressor in IR7

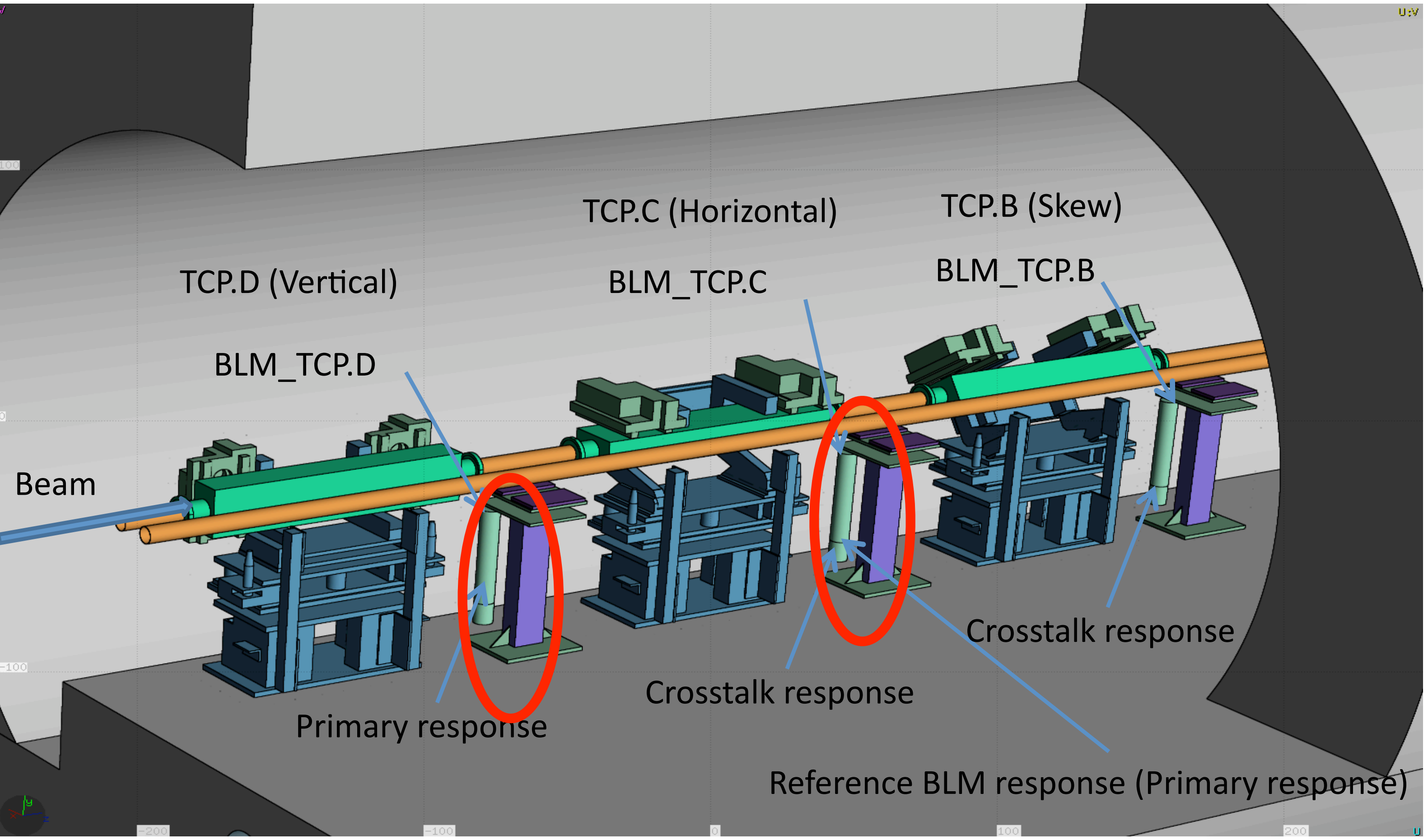
Tertiary collimato... experiments, rele...

- SixTrack results summed over 2m interval upstream of each BLM in the IR7 DS
- For TCTs, dividing losses at TCP by losses at TCT
- Measured: 2011 average, normalized to TCP

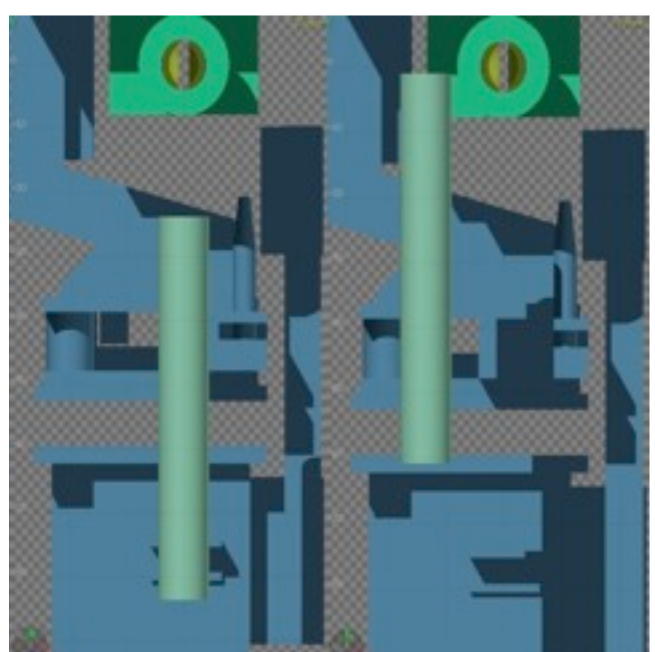
Additional step: simulate deposited energy from **hadronic showers**, accounting for

1. Error models affecting collimation
2. Local geometry and BLM layout
3. Collimator materials
4. Details of impact parameters

Energy deposition and BLM response



E. Skordis for the FLUKA team



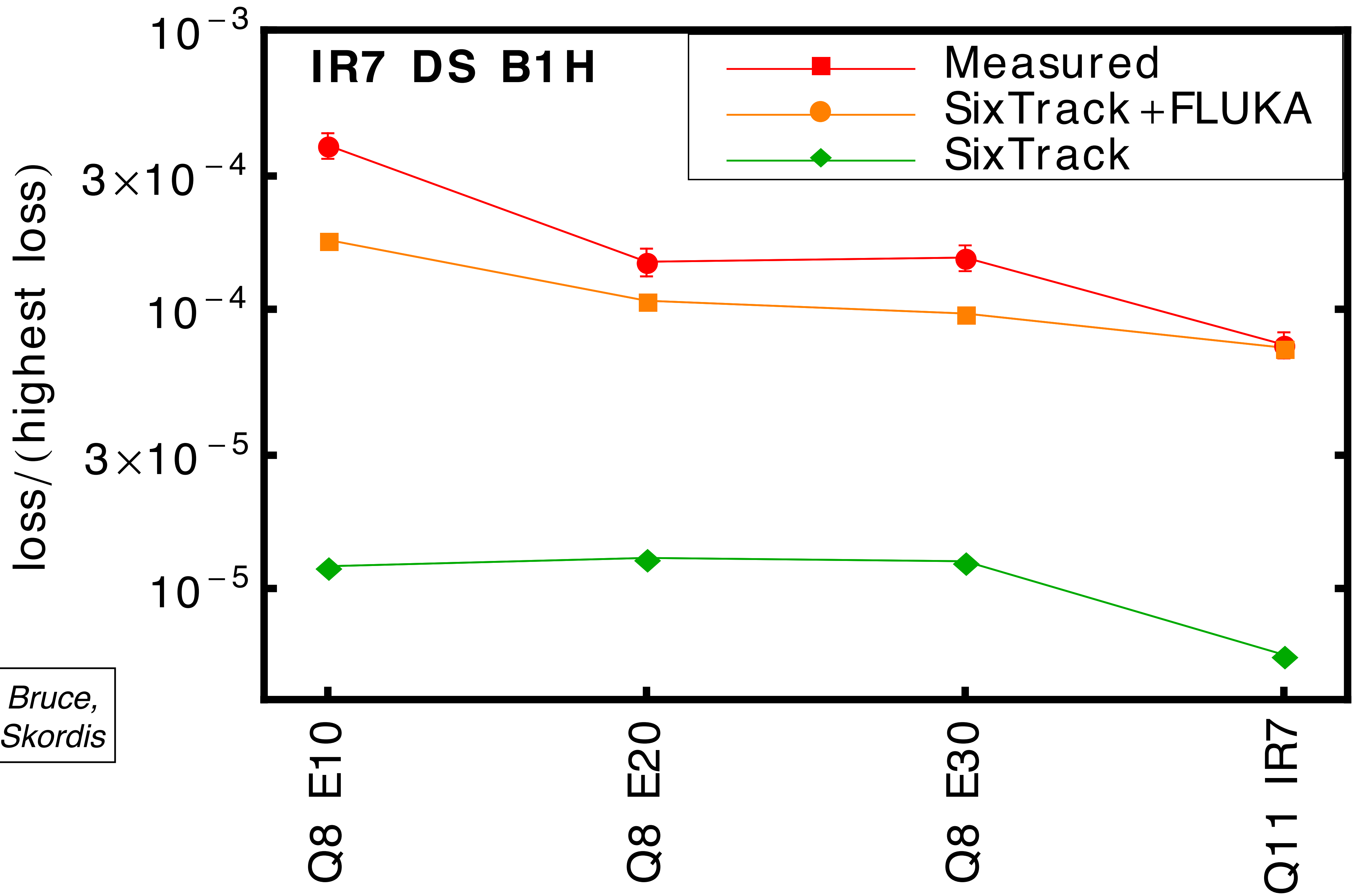
Improved normalization of the BLM for cleaning estimates takes into account TCP response on incoming beam losses.

Primary collimators: BLM response			
	BLM_TCP.D	BLM_TCP.C	BLM_TCP.B
TCP.C (Horizontal)	0.01	**1**	2.53
TCP.D (Vertical)	**0.58**	1.80	2.13

*Modelling the local BLM geometry - never identical - and **collimator material** crucial for final results!*

Tertiary collimators in IR1		
	BLM_H1	BLM_V1
TCT_H1	**6.90**	1.07
TCT_V1	0.41	**3.31**

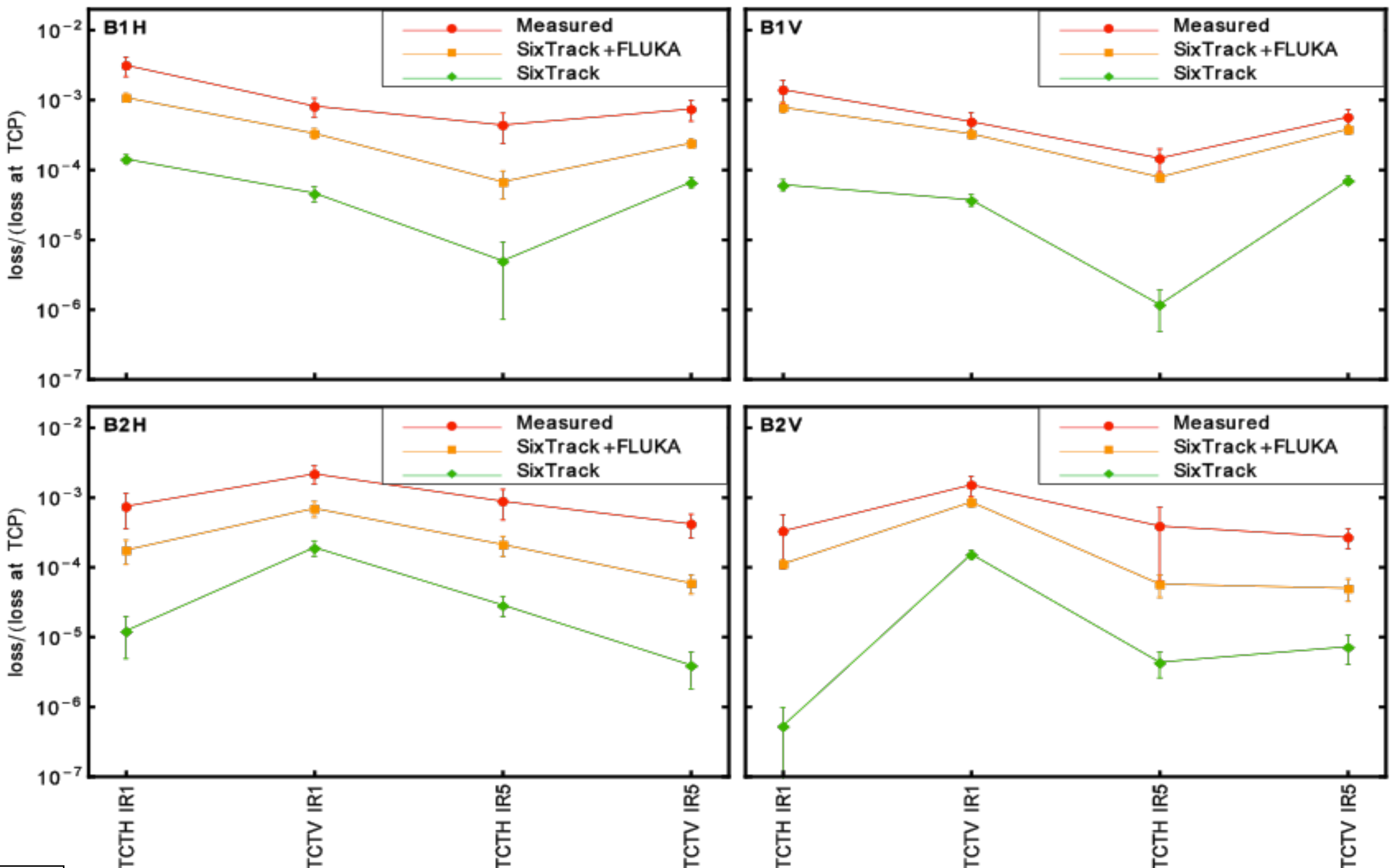
Improved estimates



R. Bruce, E. Skordis

Note:
Simulation sources: protons impinging on a few tens of microns on TCP surface.
*Simulation output: energy deposited in a 50 cm long BLM at **500 meters** from the source!*

Comparison at the tertiary collimators



R. Bruce, E. Skordis

Measurements underestimated by factor 1.5-4! *Note that background beam losses are not taken into account.*

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Advanced collimation studies reported at IPAC13

E. Quaranta *et al.*, MOPWO038	CLEANING INEFFICIENCY OF THE LHC COLLIMATION SYSTEM DURING THE ENERGY RAMP: SIMULATIONS AND MEASUREMENTS
A. Marsili *et al.*, MOPWO041	SIMULATIONS AND MEASUREMENTS OF PHYSICS DEBRIS LOSSES AT THE 4 TEV LHC
L. Lari *et al.*, MOPWO046	SIMULATIONS AND MEASUREMENTS OF BEAM LOSSES AND THE LHC COLLIMATORS DURING BEAM ABORT FAILURES
V. Previtali *et al.*, MOPWO044	NUMERICAL SIMULATION OF A HOLLOW LENS AS A SCRAPING DEVICE FOR THE LHC
E. Quaranta *et al.*, MOPWO037	SIXTRACK SIMULATION OF OFF-MOMENTUM CLEANING IN LHC
D. Mirarchi *et al.*, MOPWO035	LAYOUTS FOR CRYSTAL COLLIMATION TESTS AT THE LHC

Conclusions

- Presented simulations and measurements of **collimation cleaning** for the 3.5 TeV LHC (2011 run).
- An **excellent qualitative agreement** is found when loss locations along the 27 km ring are considered.

  Most critical loss locations predicted by simulations are confirmed.
  Great success for the design of the collimation system!
- Presented a first attempt to **compare quantitatively** simulations and measurements. This required energy deposition studies (FLUKA).

  *Measurements at critical locations are reproduced within **factors 1.5-4.0** when imperfections and details of local layouts are taken into account.*
- Proton losses can be predicted very well - we are confident that our tools are ready for **LHC upgrade challenges**.
- Development of tools continues to address **new simulation setups**: hollow e-lens, fast failures, crystal collimation, cleaning during energy ramp, physics debris cleaning,...

  I encourage to visit our posters on these topics!

(Some) collimation people

Reserve slides

Cleaning during 4 TeV energy ramp

Simulation challenges:

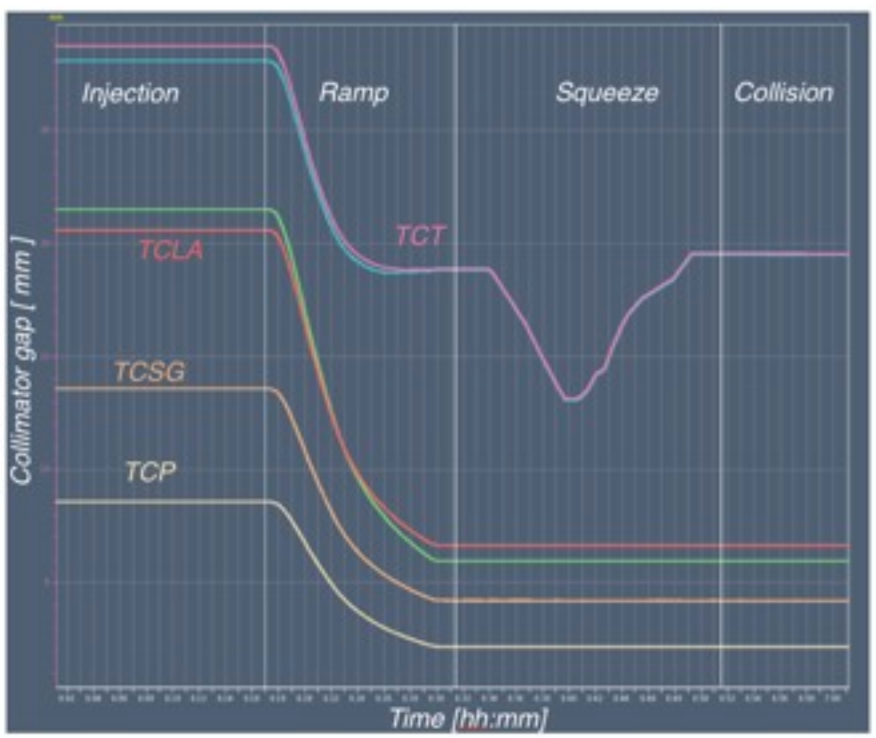
- Modelling physics of p-collimator interaction at different energies.
- Implementation of different collimator gaps.

Measurement challenges:

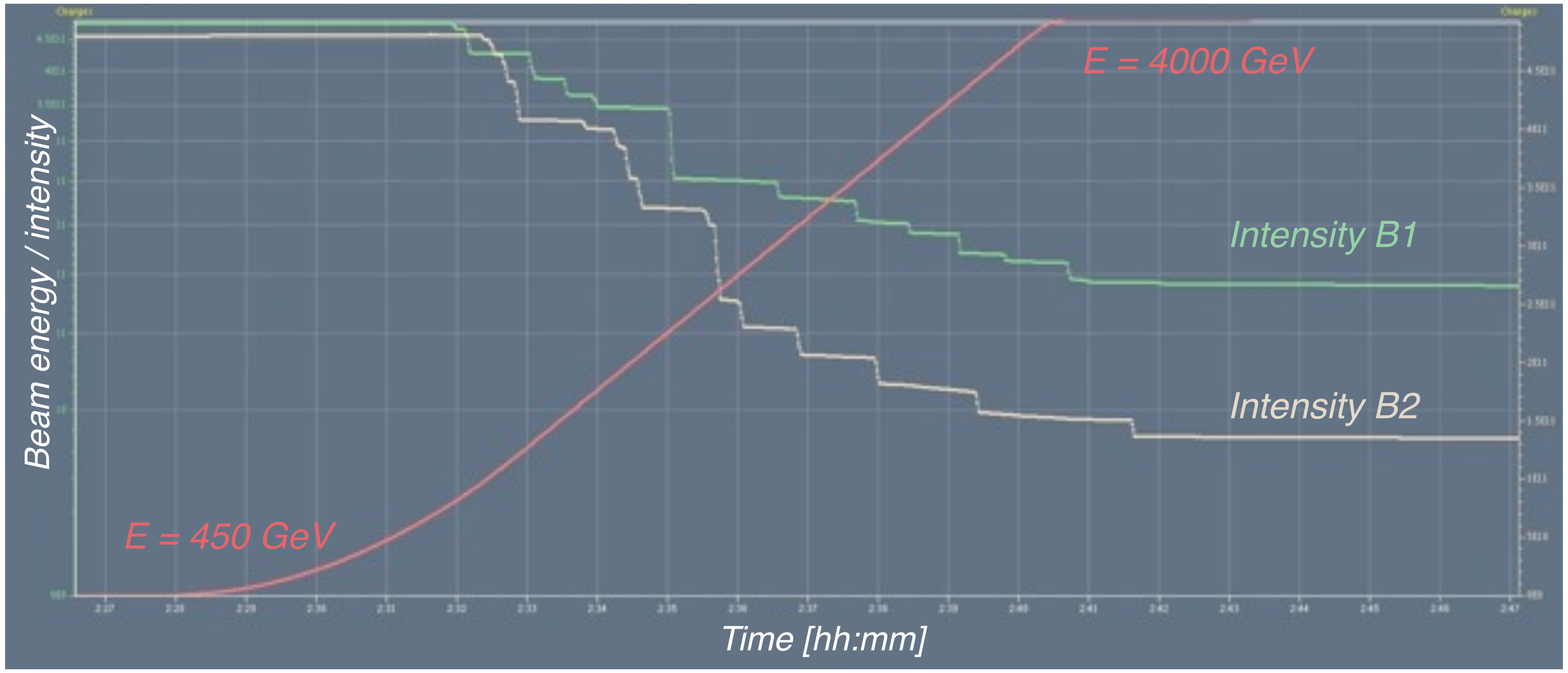
- Controlled losses of individual bunches at selected energies.
- Balance losses: good cleaning accuracy versus risk of dumping.

Important to address scaling of models to unknown energy ranges above 4 TeV → dedicated beam tests in 2012 during 4 TeV energy ramp

Collimator settings in [mm]



Collimator settings [mm]



E. Quaranta *et al.*, MOPWO038

Thanks to the ADT team for controlled losses.

Very good agreement - note the 6 orders of magnitude on y scale!

Cleaning during 4 TeV energy ramp

Simulation challenges:

- Mode
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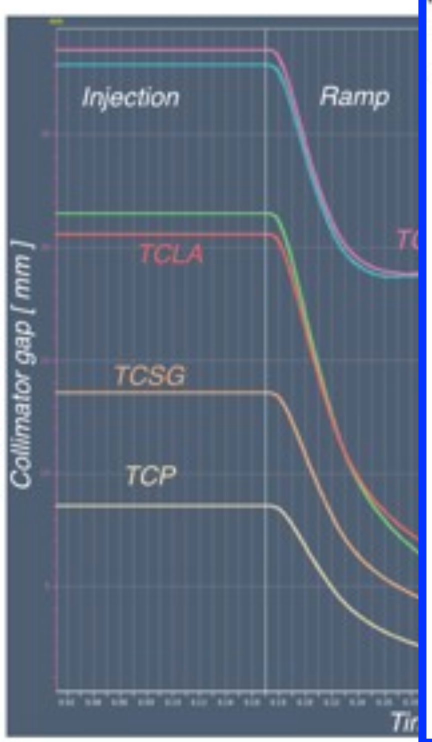

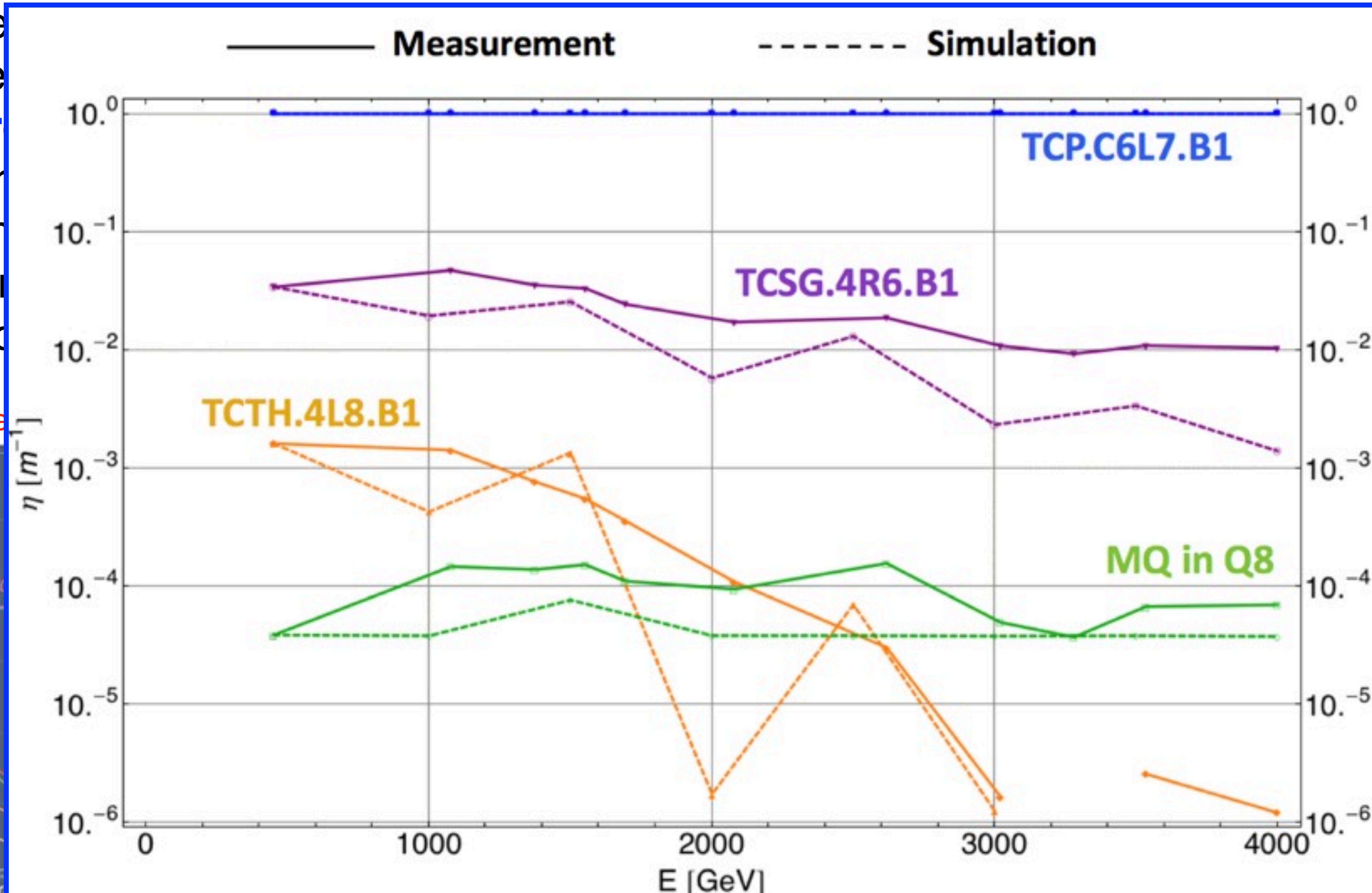

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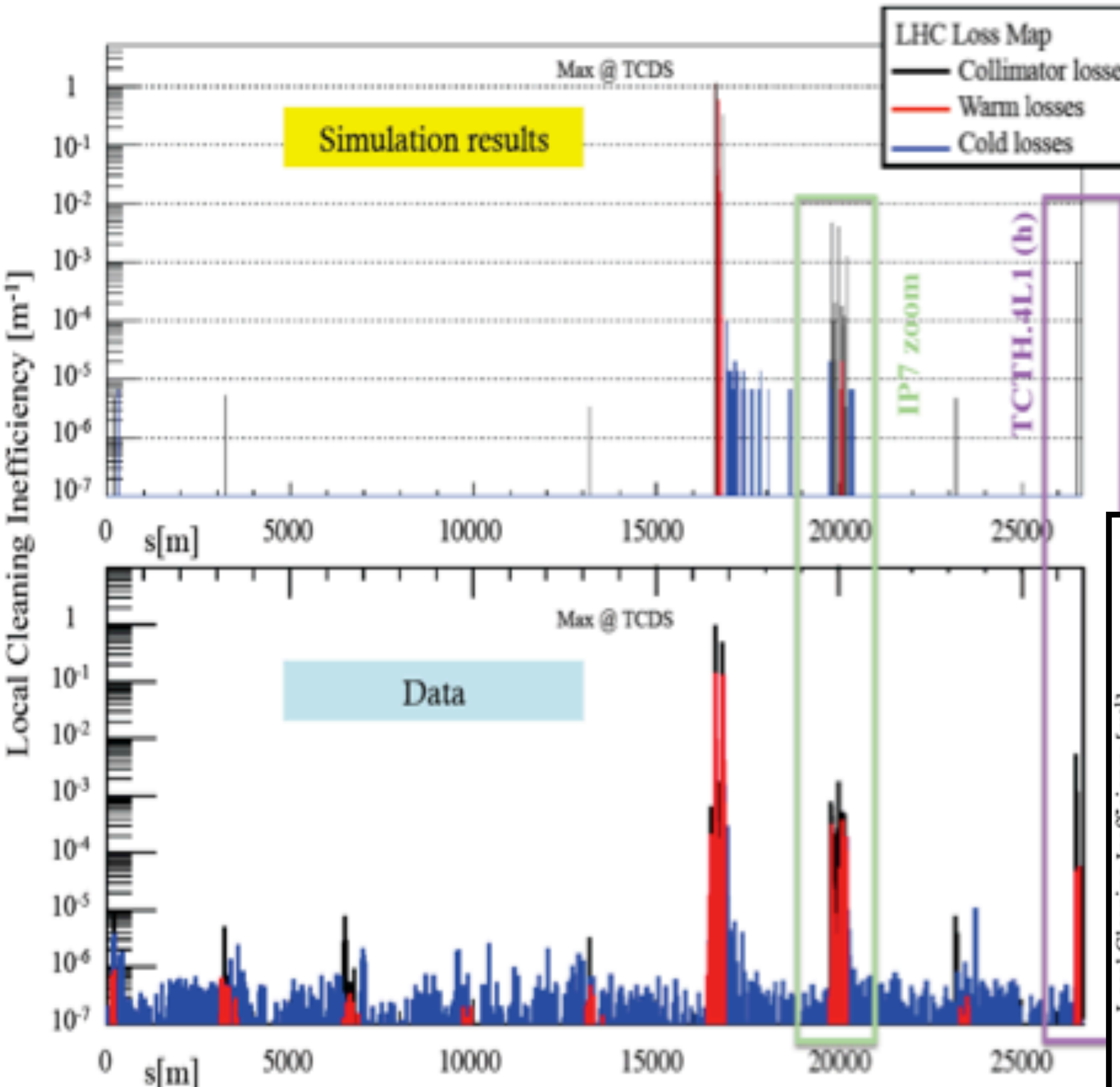
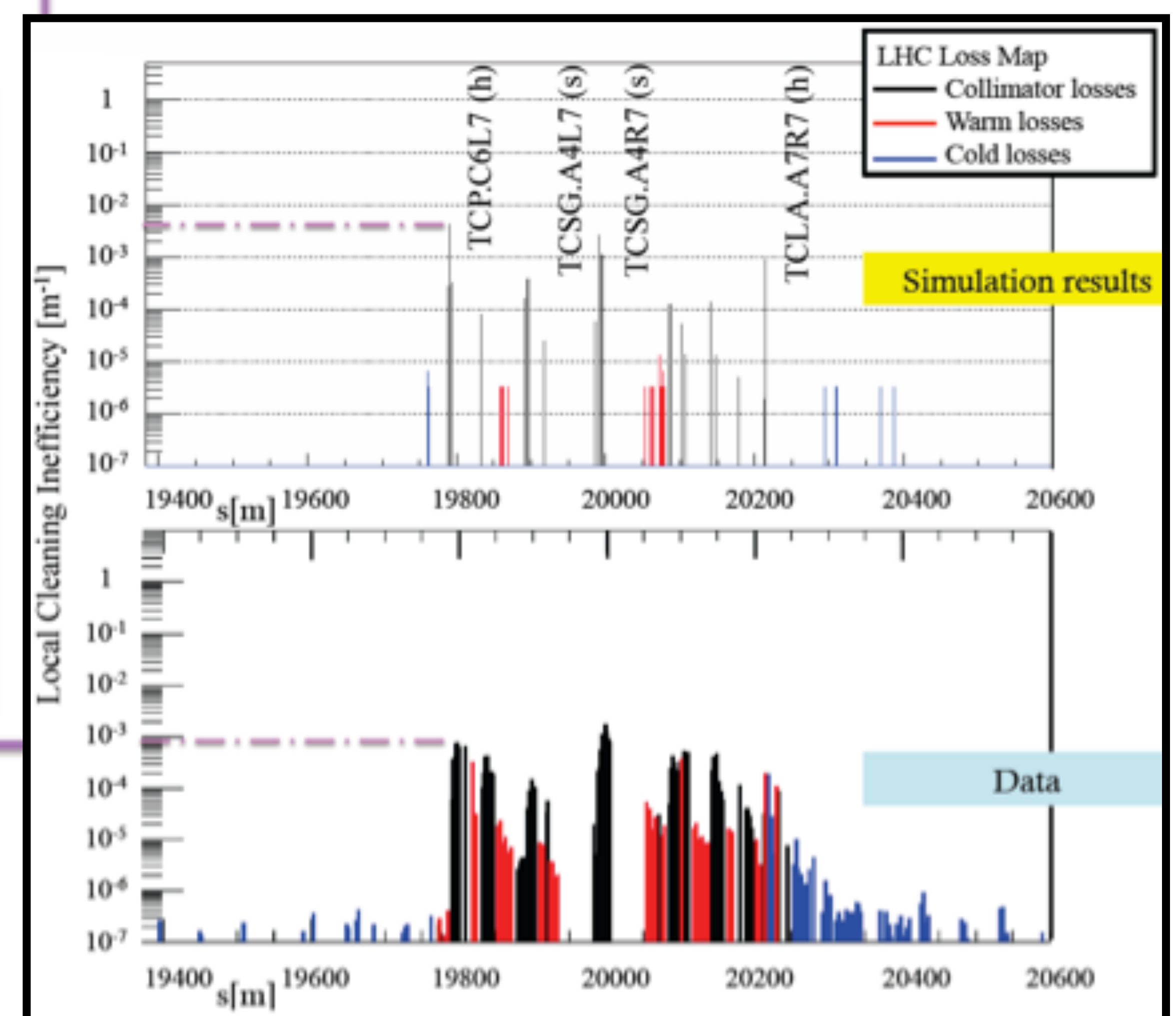
Fast failures and collimator errors

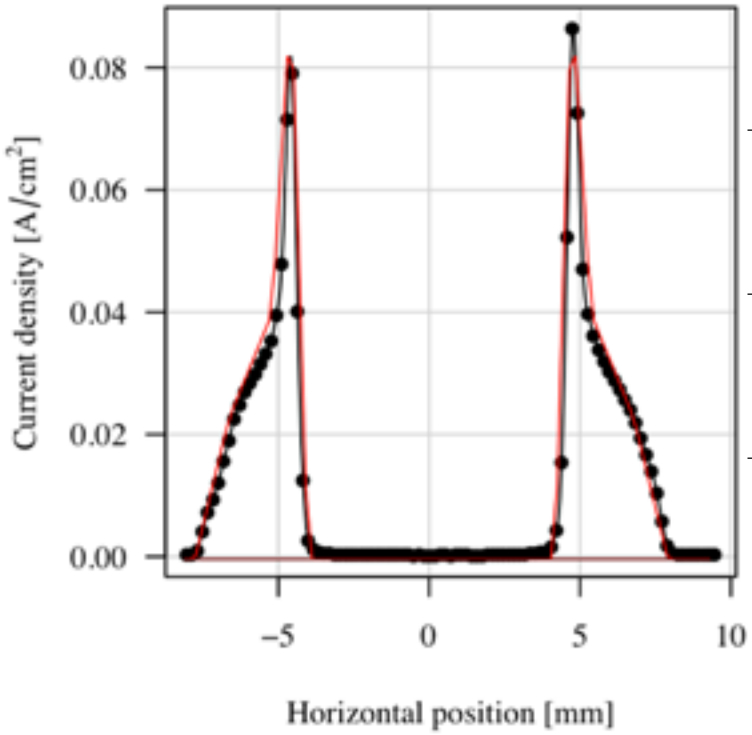


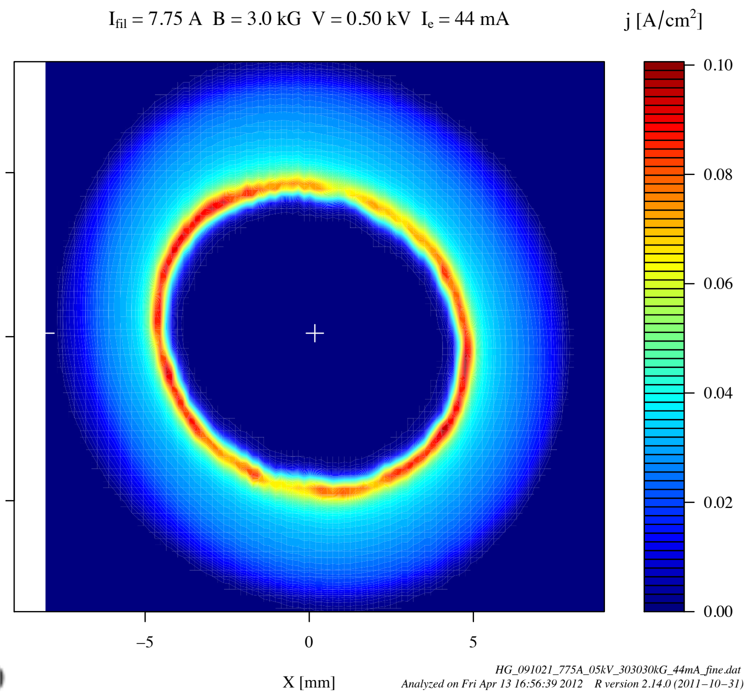
Time-dependent profile of the dump kicker rising field implemented to address beam losses in case of asynchronous beam dumps.
Promising comparison with beam data.

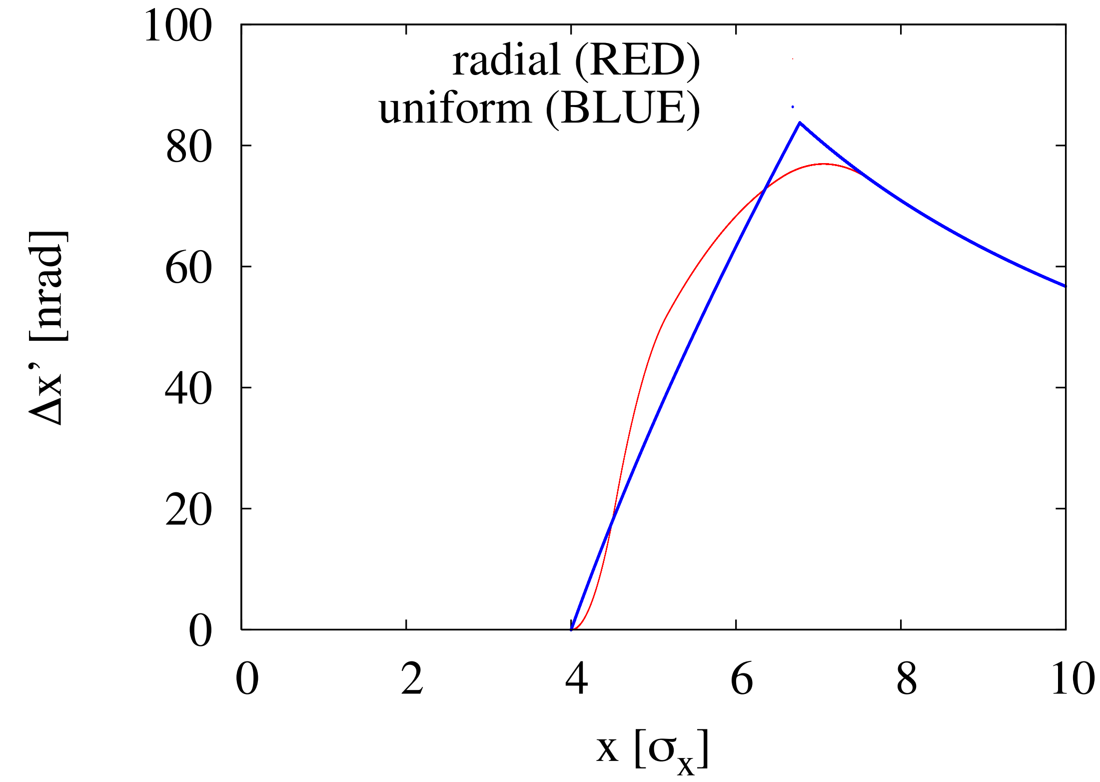


L. Lari *et al.*, MOPWO046

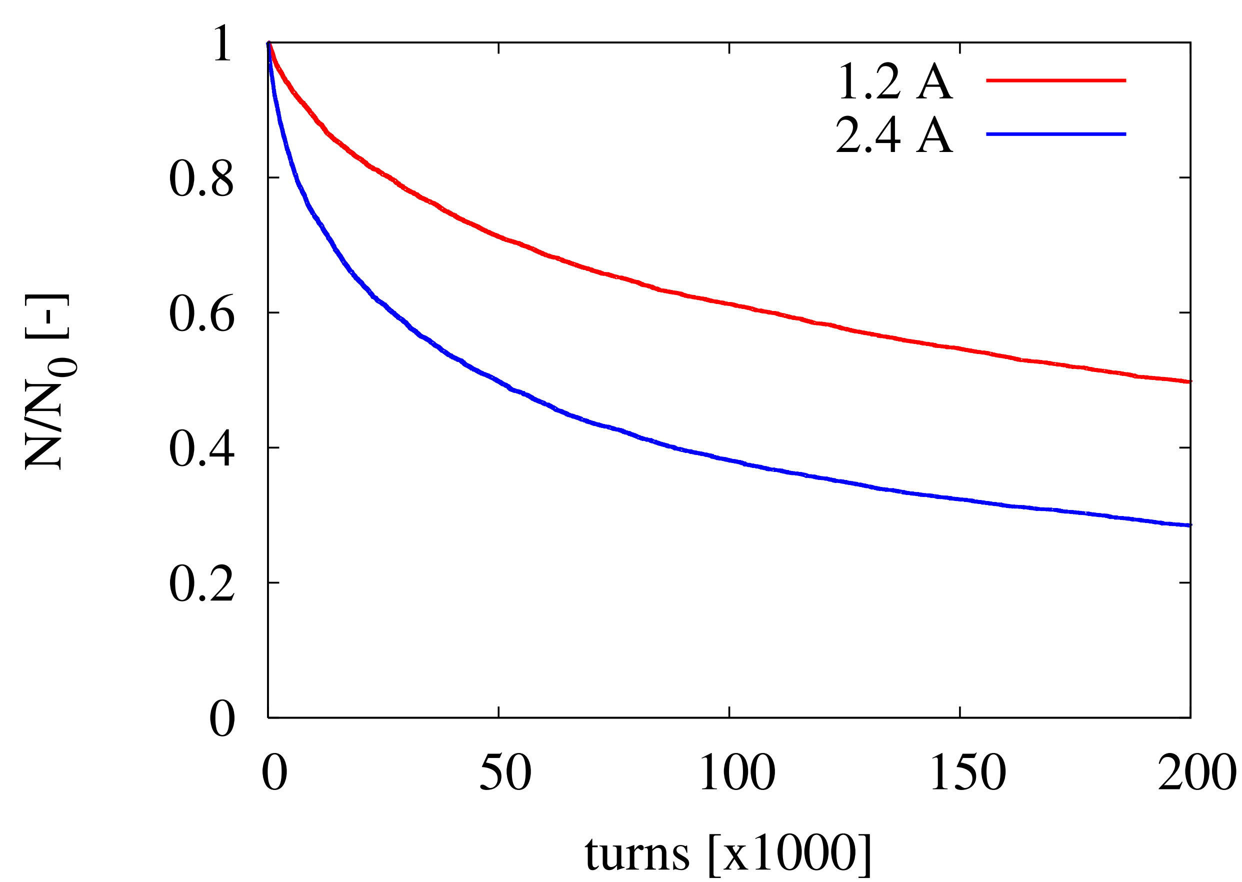
Cleaning with hollow e-lens





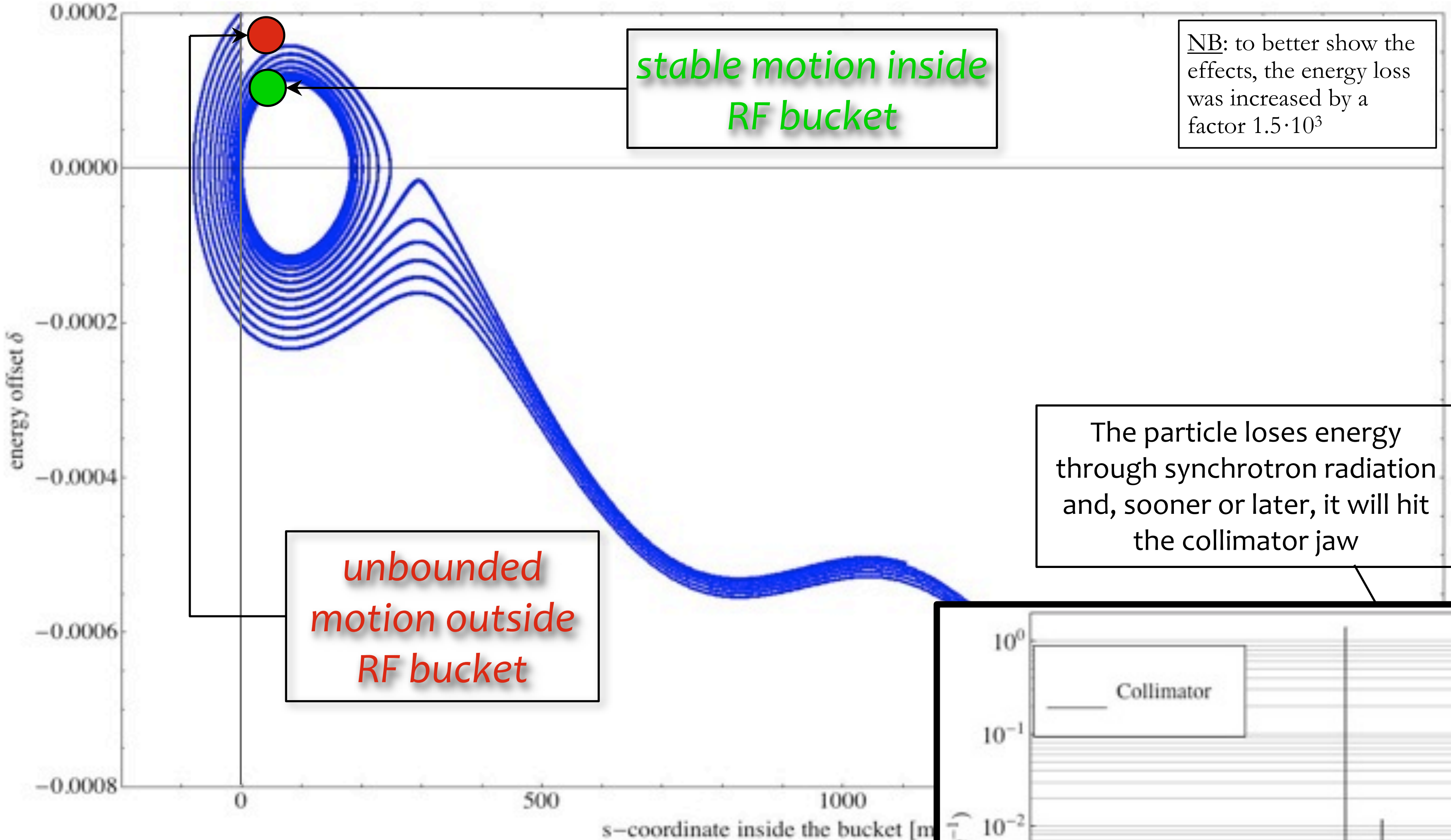


Measured profile of Tevatron e-lens implemented in the SixTrack collimation routine to simulate **efficiency of halo removal** and effect on **impact parameter** on primary collimators.

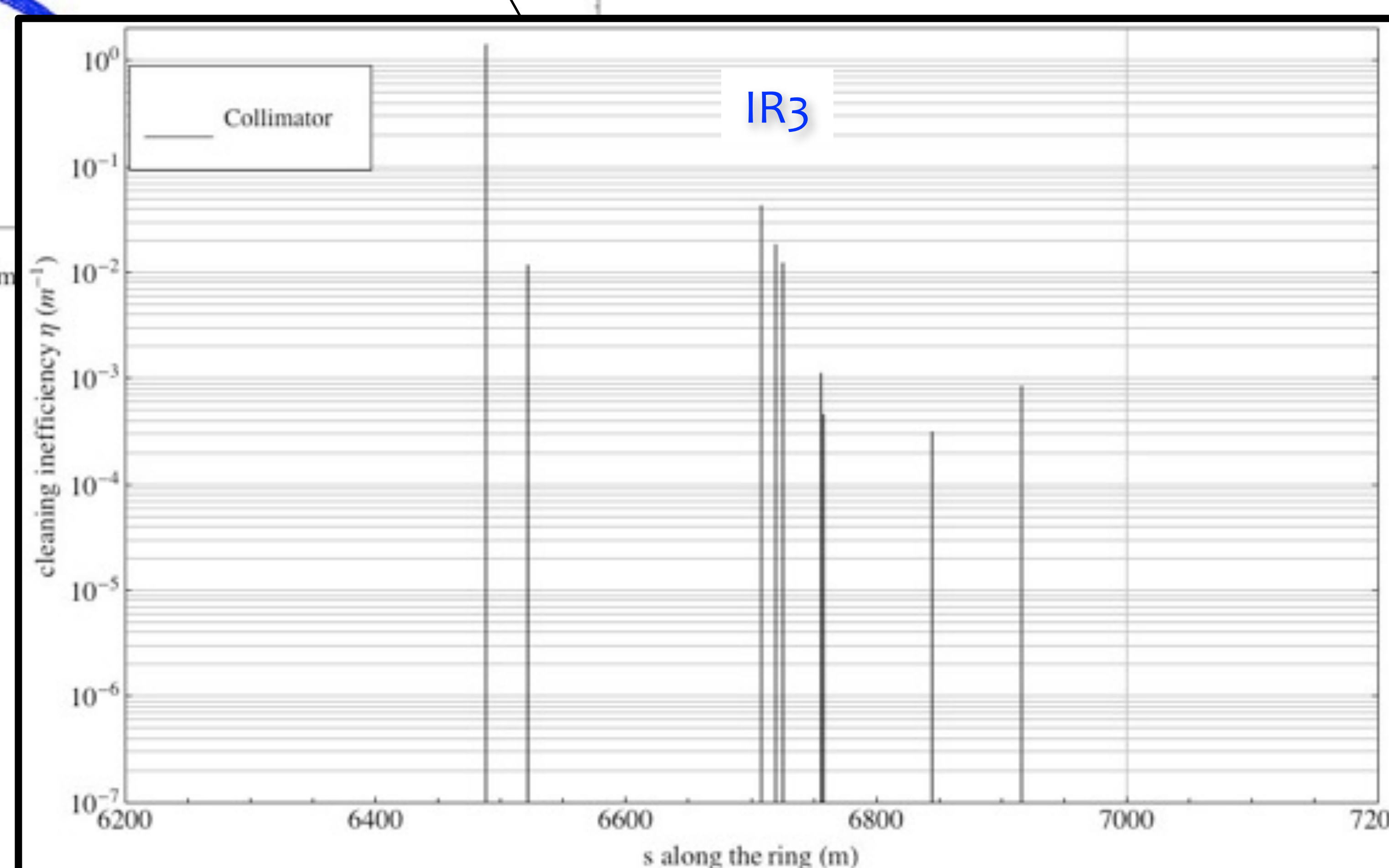


V. Previtali *et al.*, MOPWO044

Outlook - Momentum cleaning



Particles outside the RF bucket lose energy due to synchrotron radiation emission and are lost on the primary collimators in IR3.

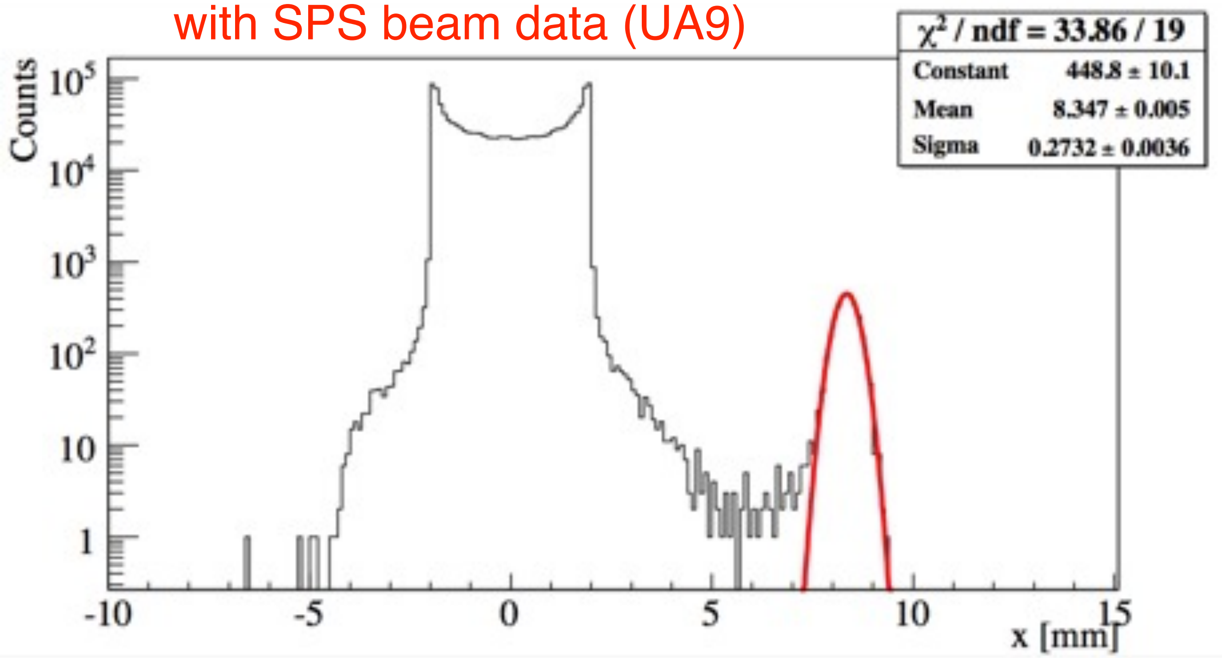


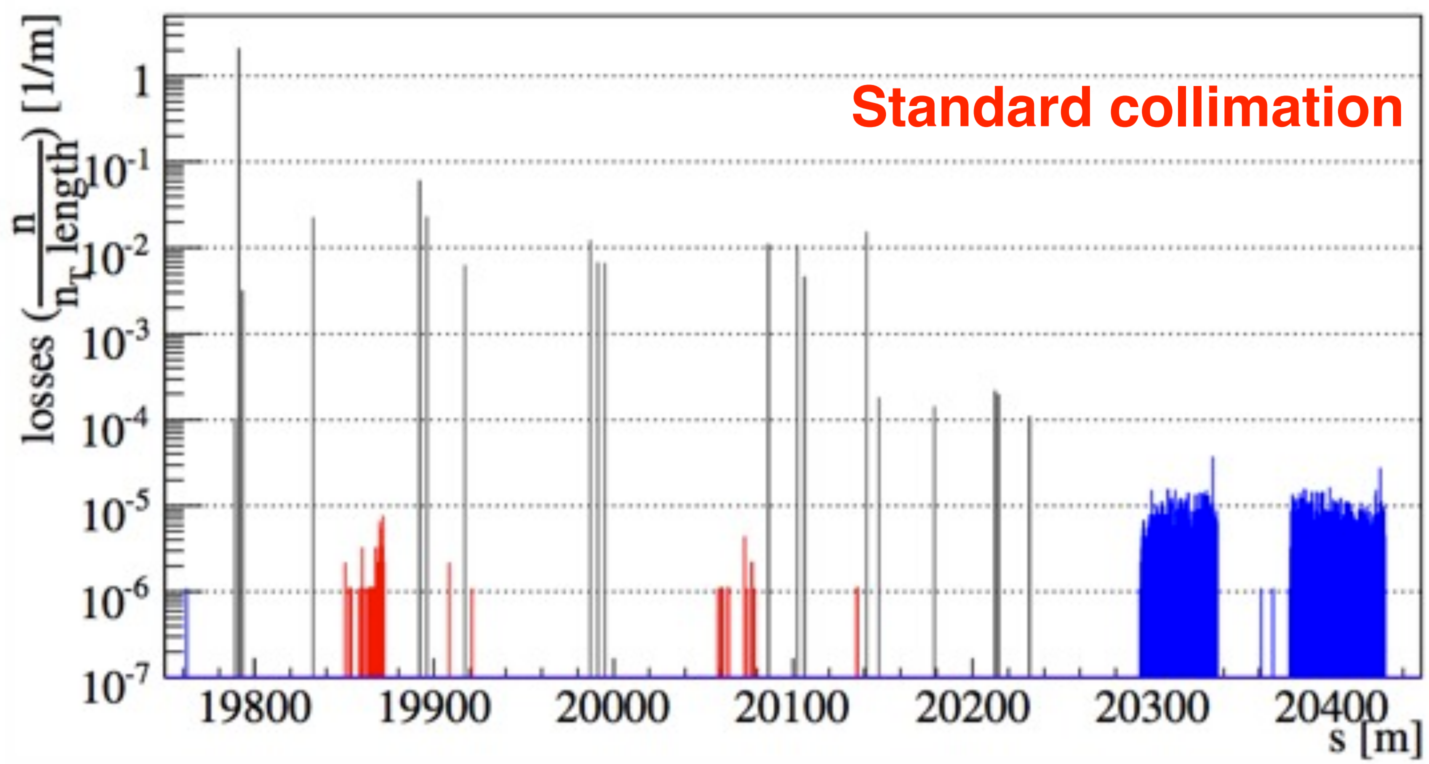
Primary source of losses in IR3 at 7TeV.
Modelled for the first time.

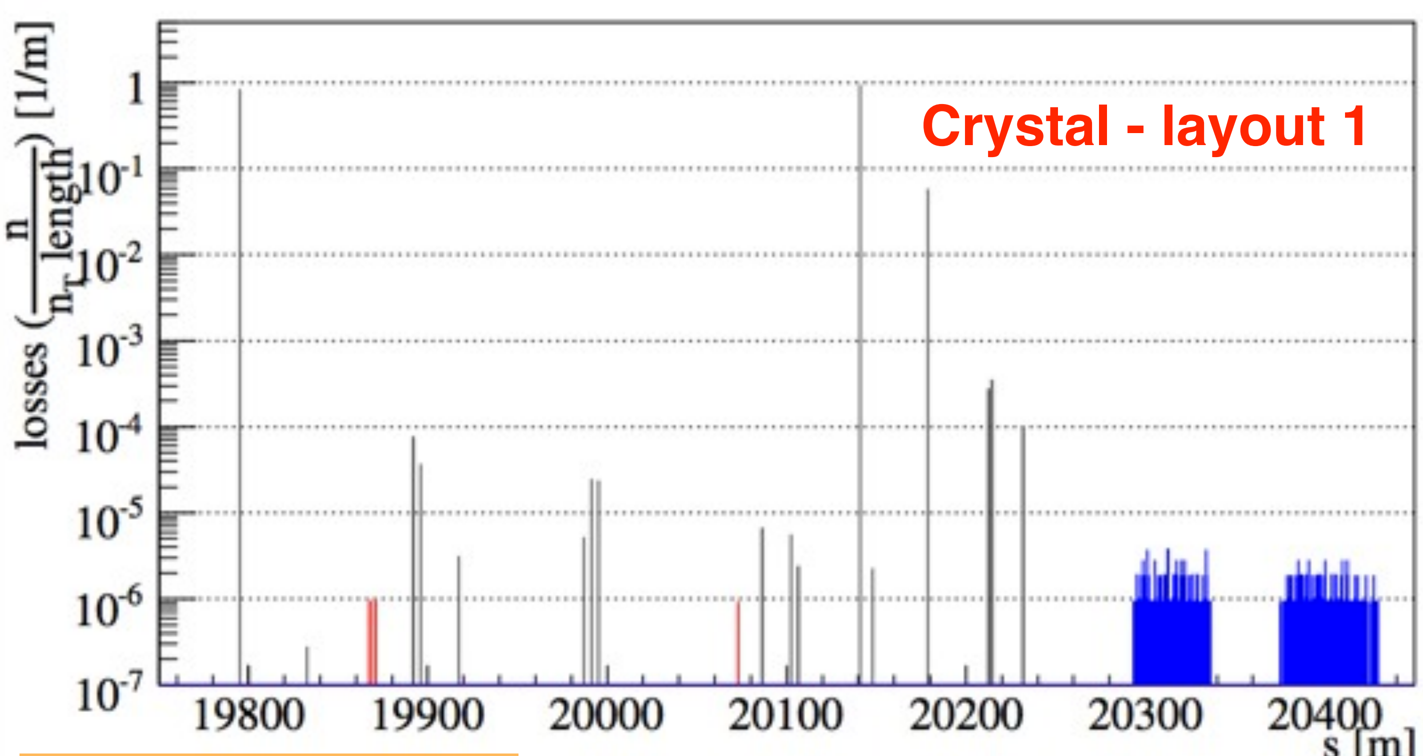
E. Quaranta *et al.*, MOPWO037

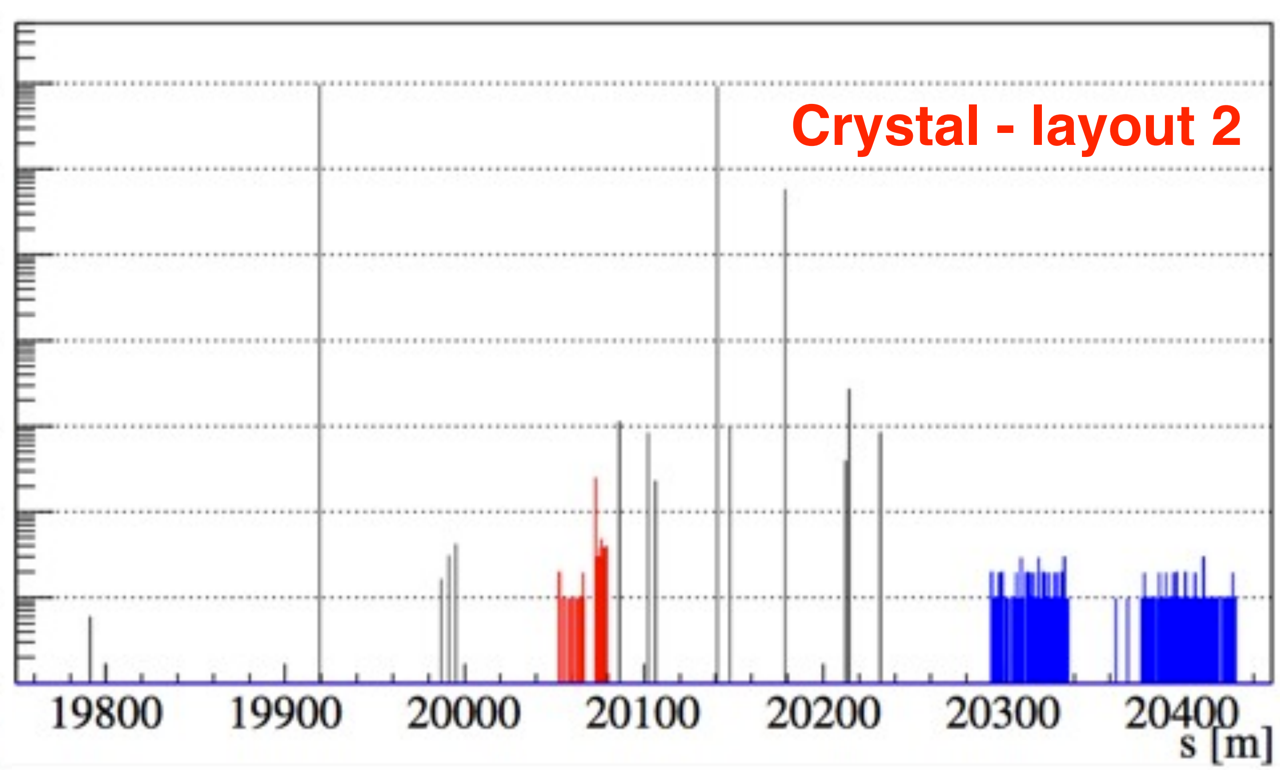
Crystal-collimation cleaning

Crystal routine benchmarked with SPS beam data (UA9)





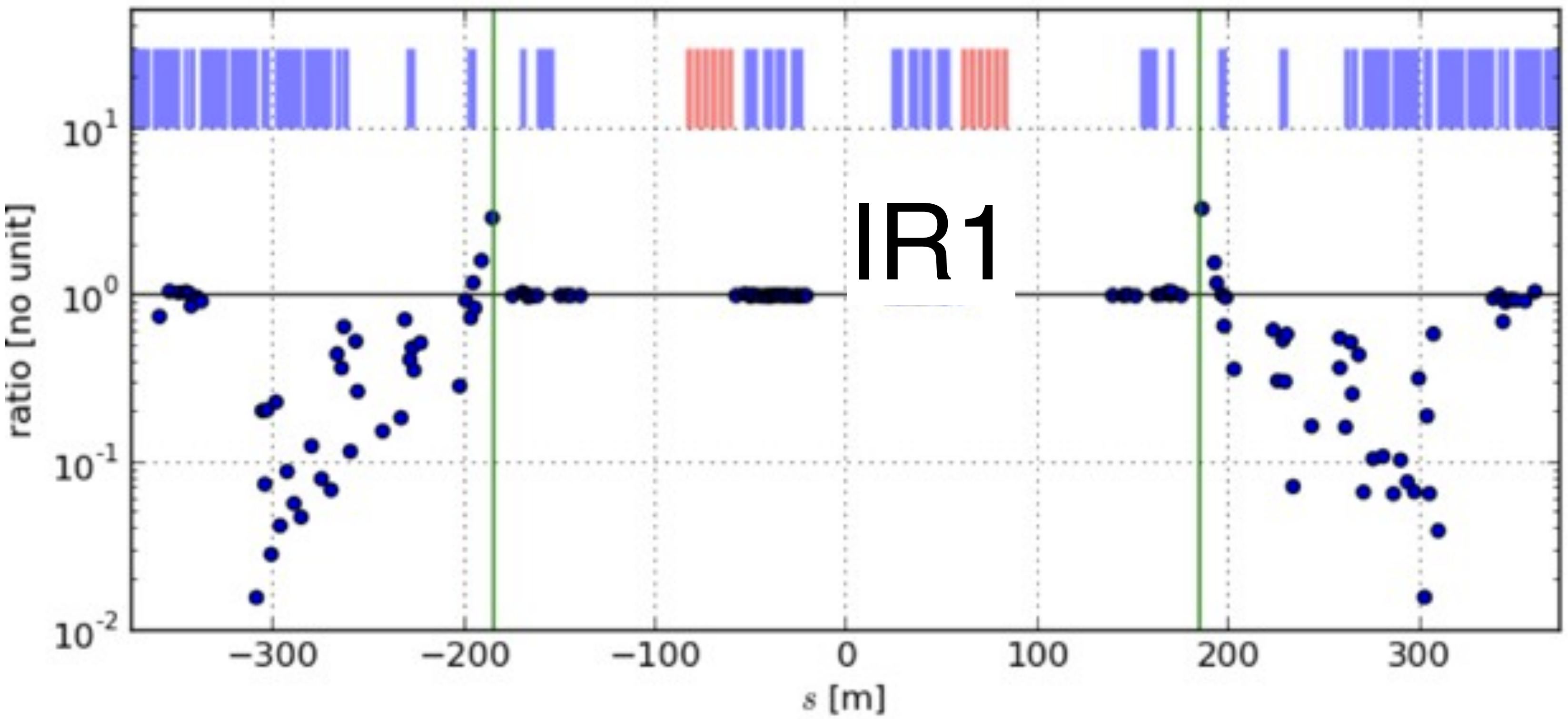




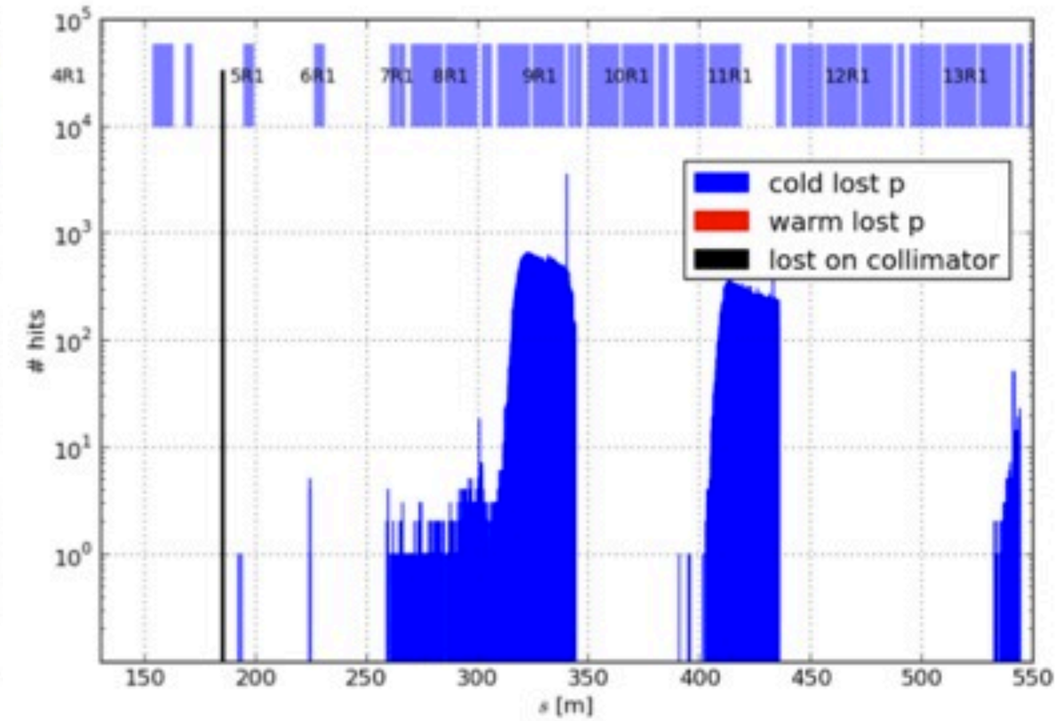
D. Mirarchi *et al.*, MOPWO035+THPFI064

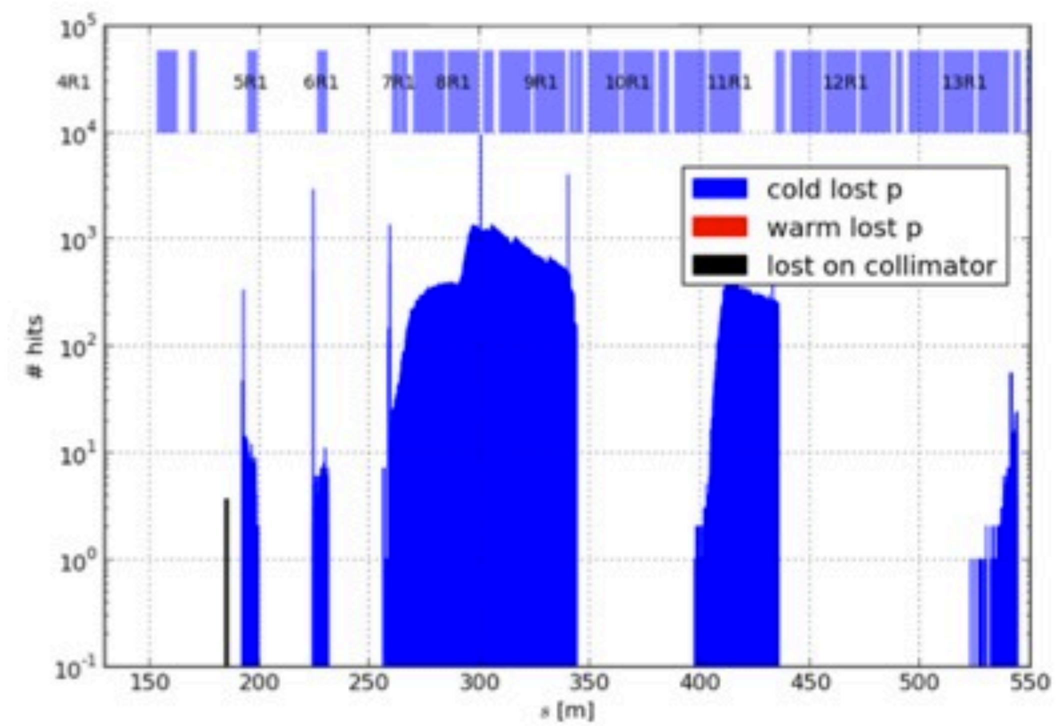
Simulations of physics debris losses

Measured losses: ratio TCL_{out}/TCL_{in}



SixTrack simulations



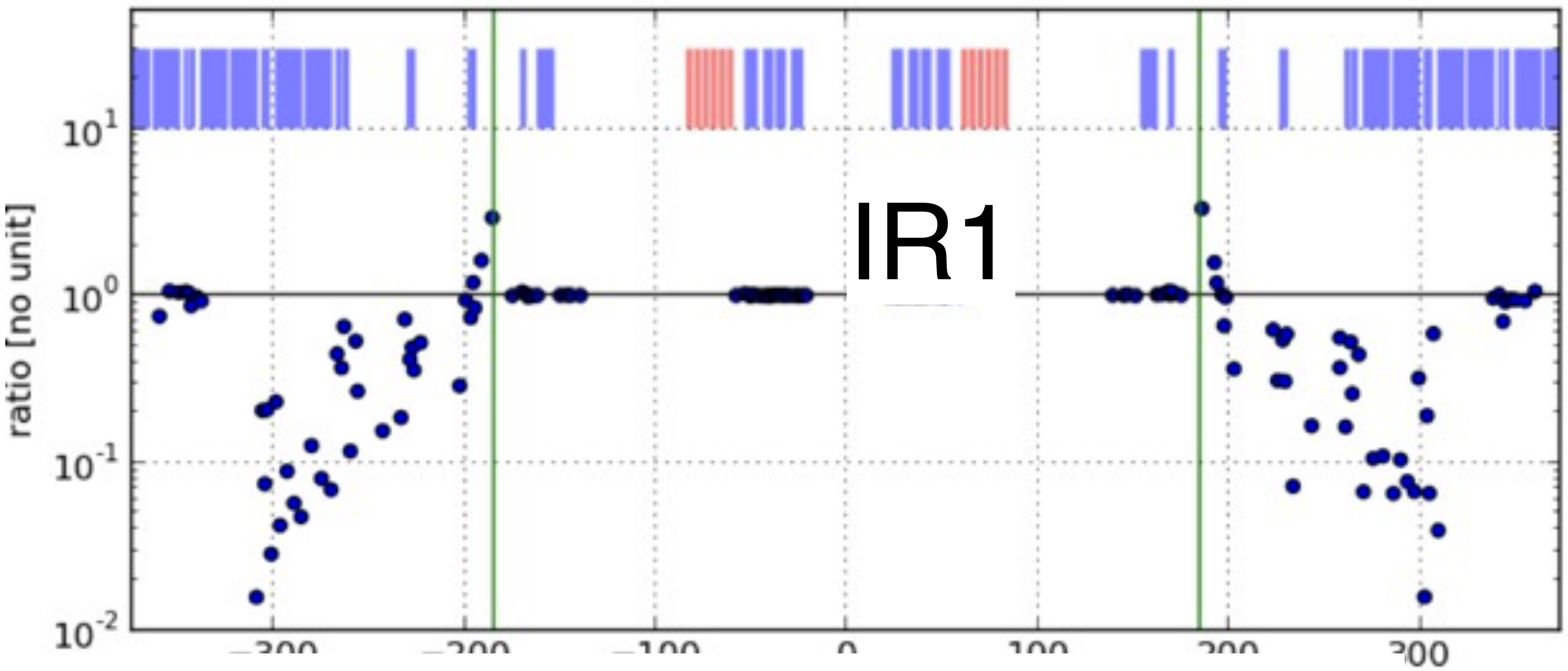


TCL collimators in IR1/5: catch physics debris losses and protect the matching sections.
We track for many turns the protons that experience collisions (distributions generated with FLUKA).

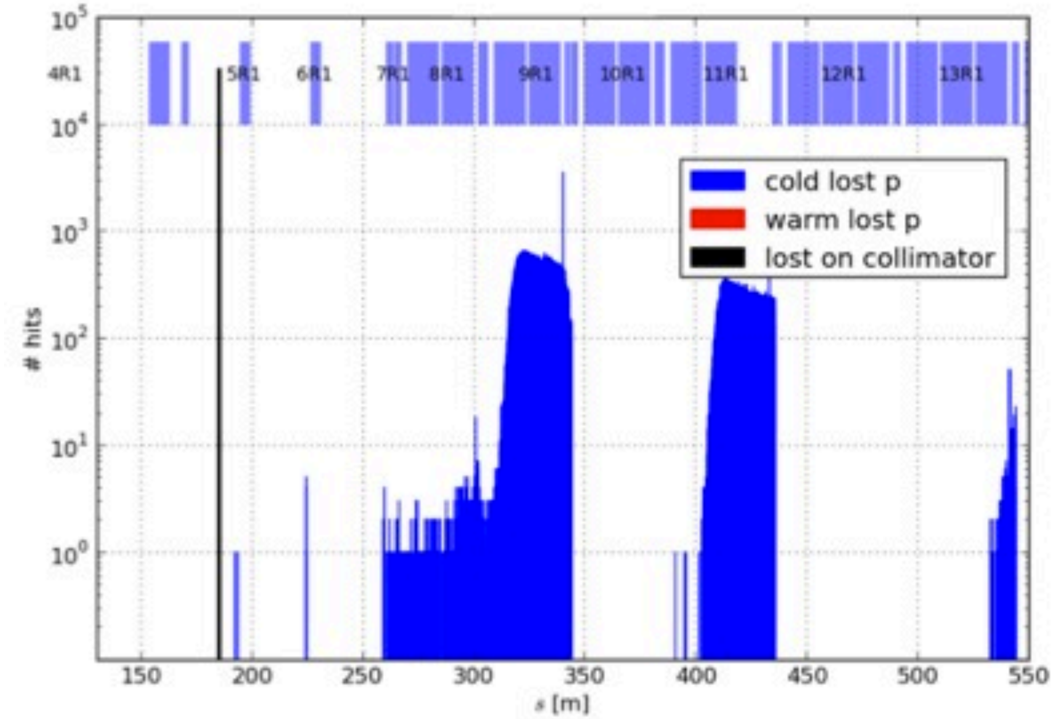
A. Marsili *et al.*, MOPWO041

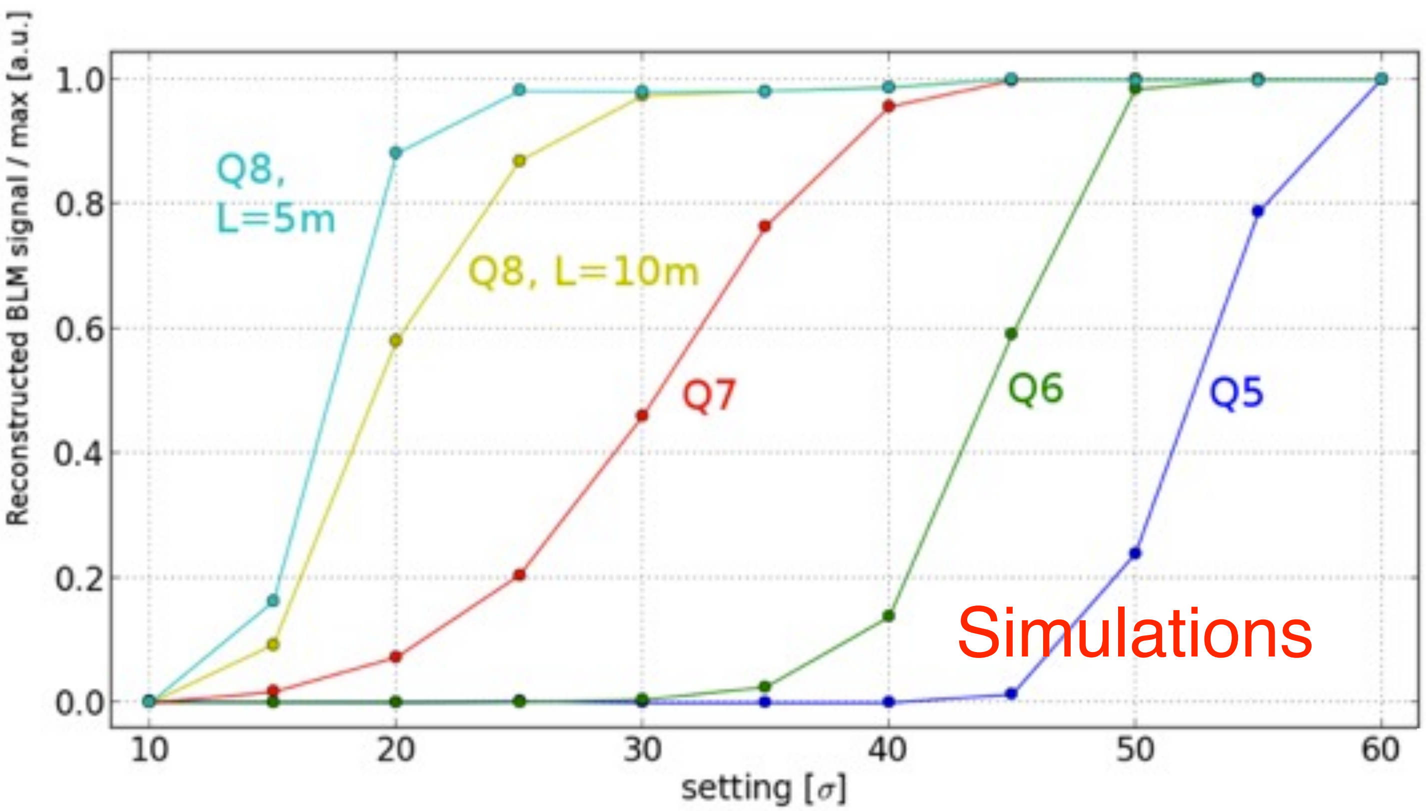
Simulations of physics debris losses

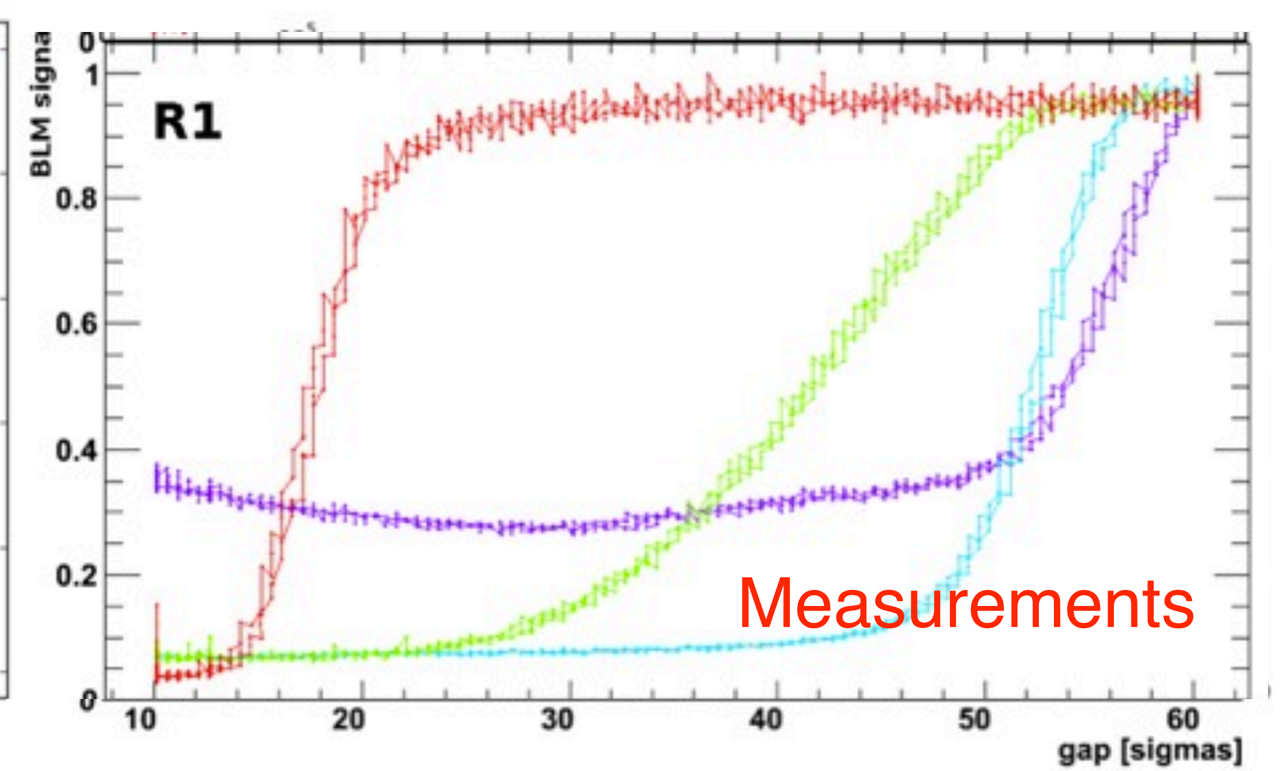
Measured losses: ratio TCL_{out}/TCL_{in}



SixTrack simulations

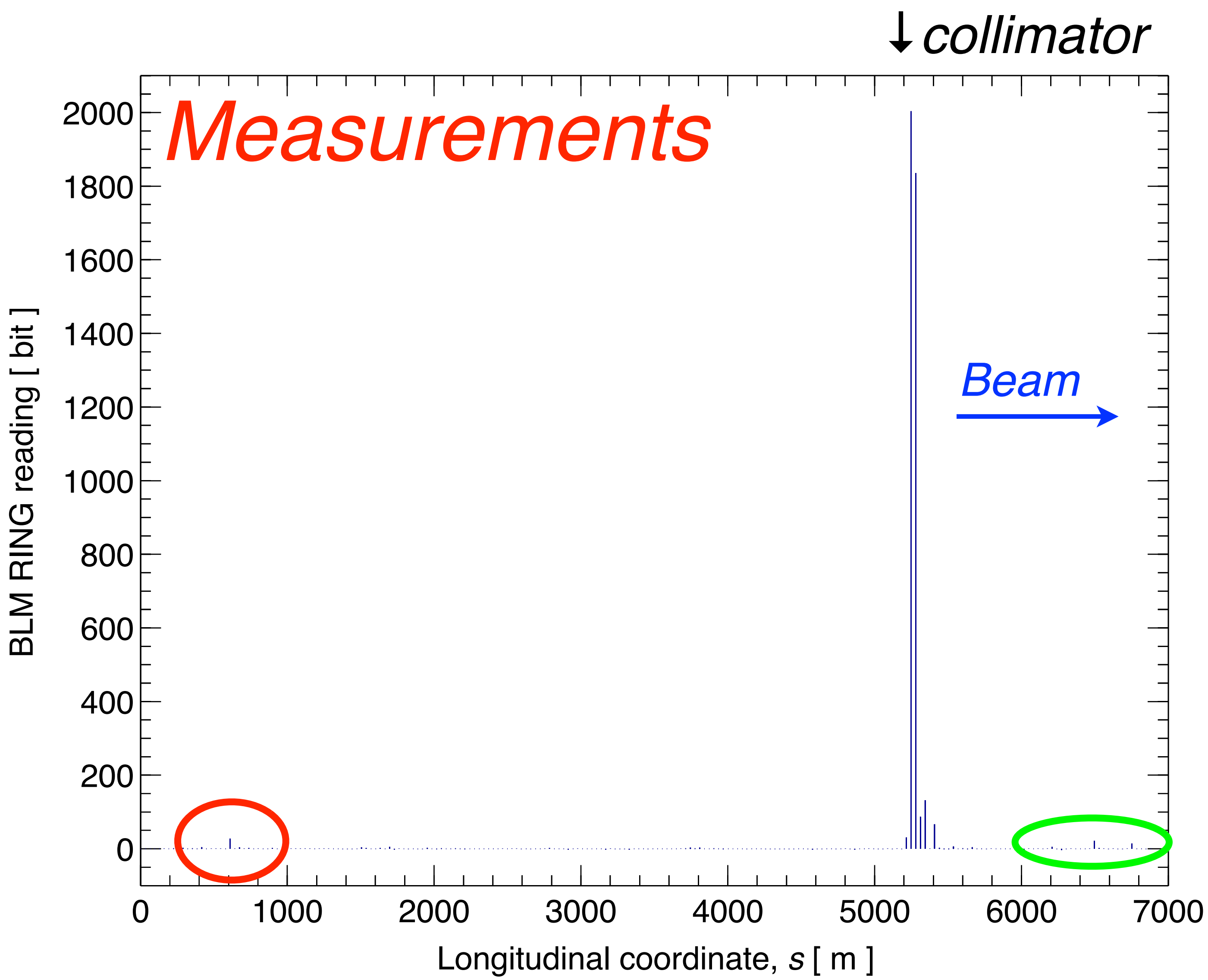


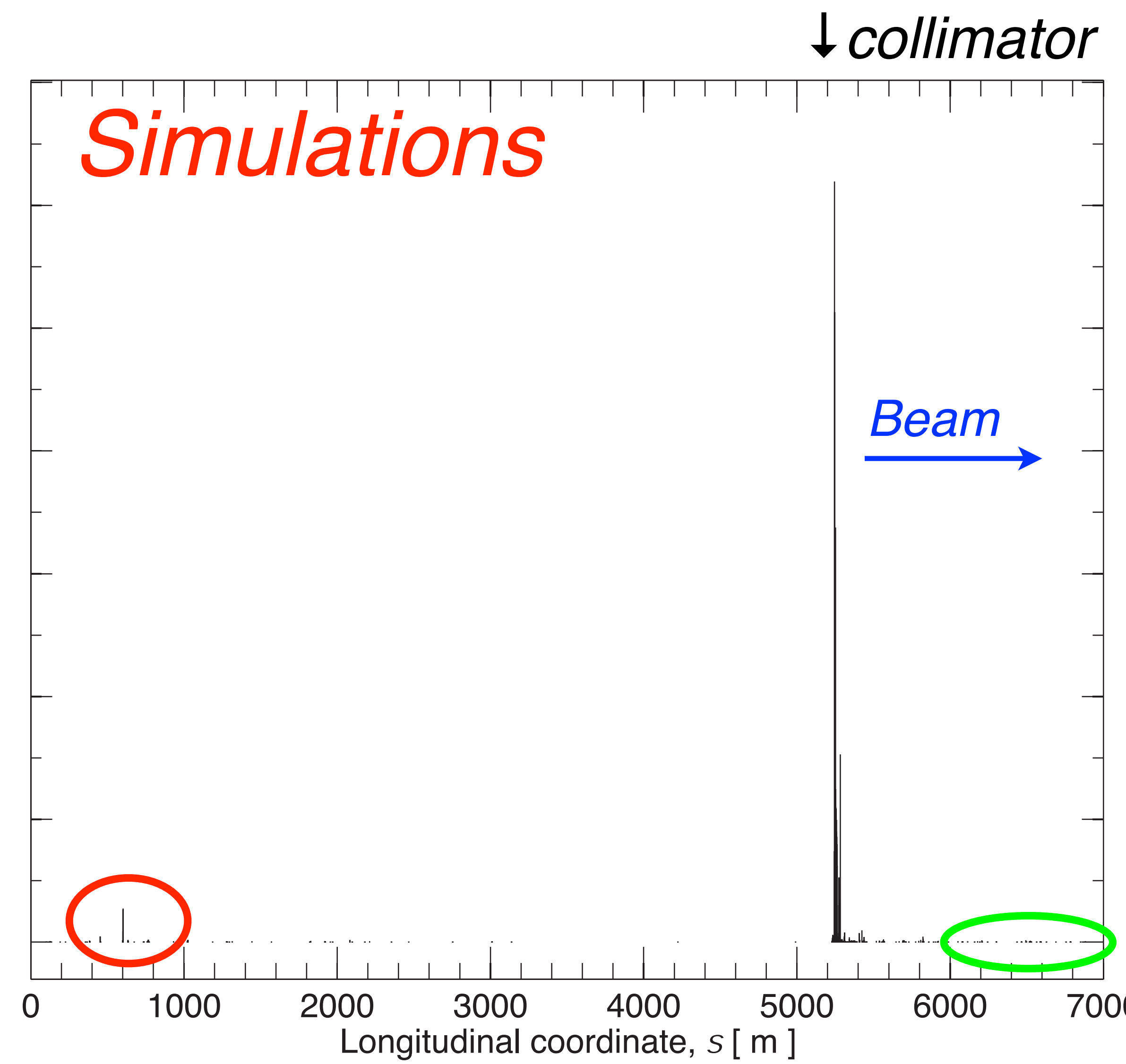




A. Marsili *et al.*, MOPWO041

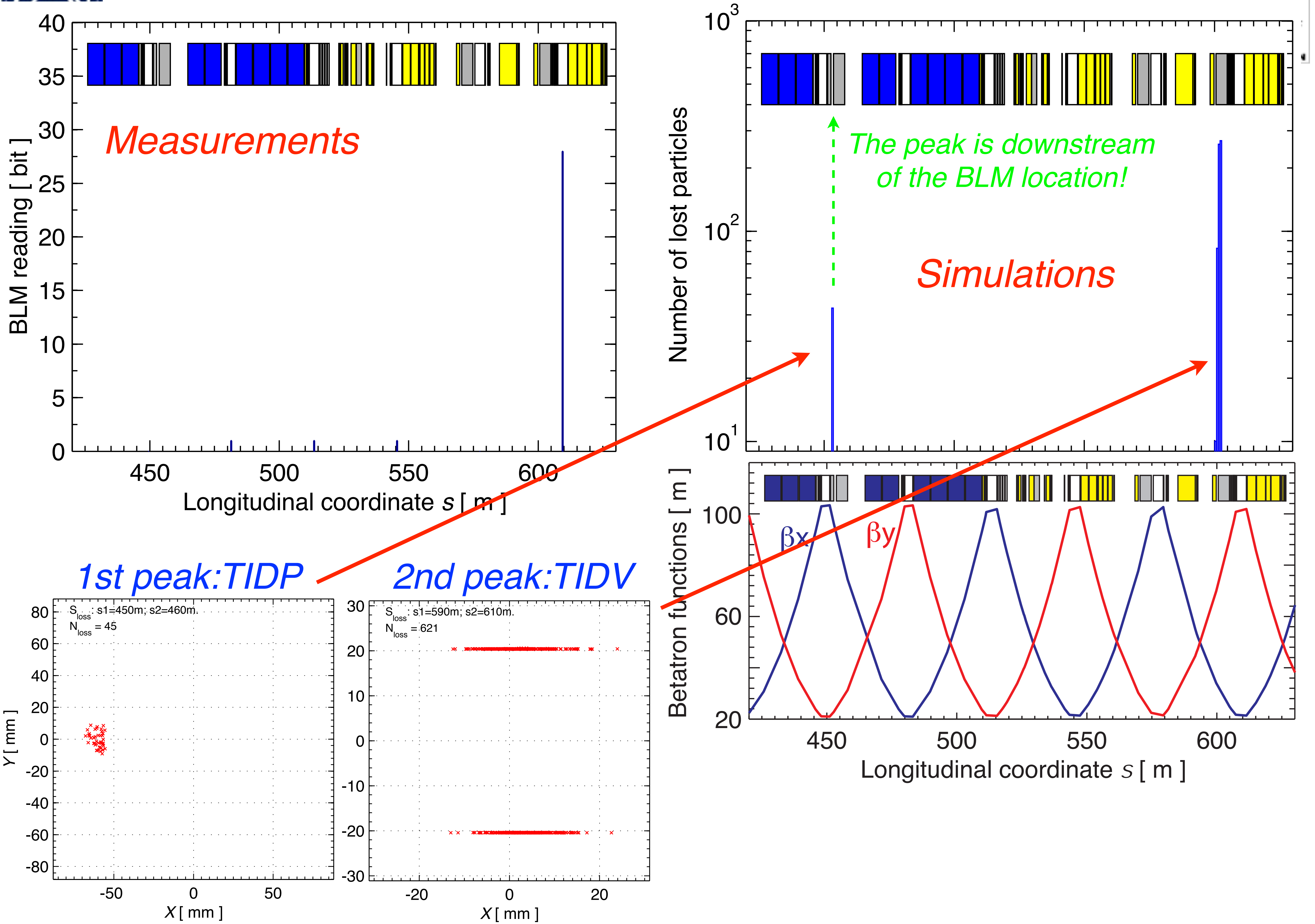
Comparison at the CERN-SPS (i)



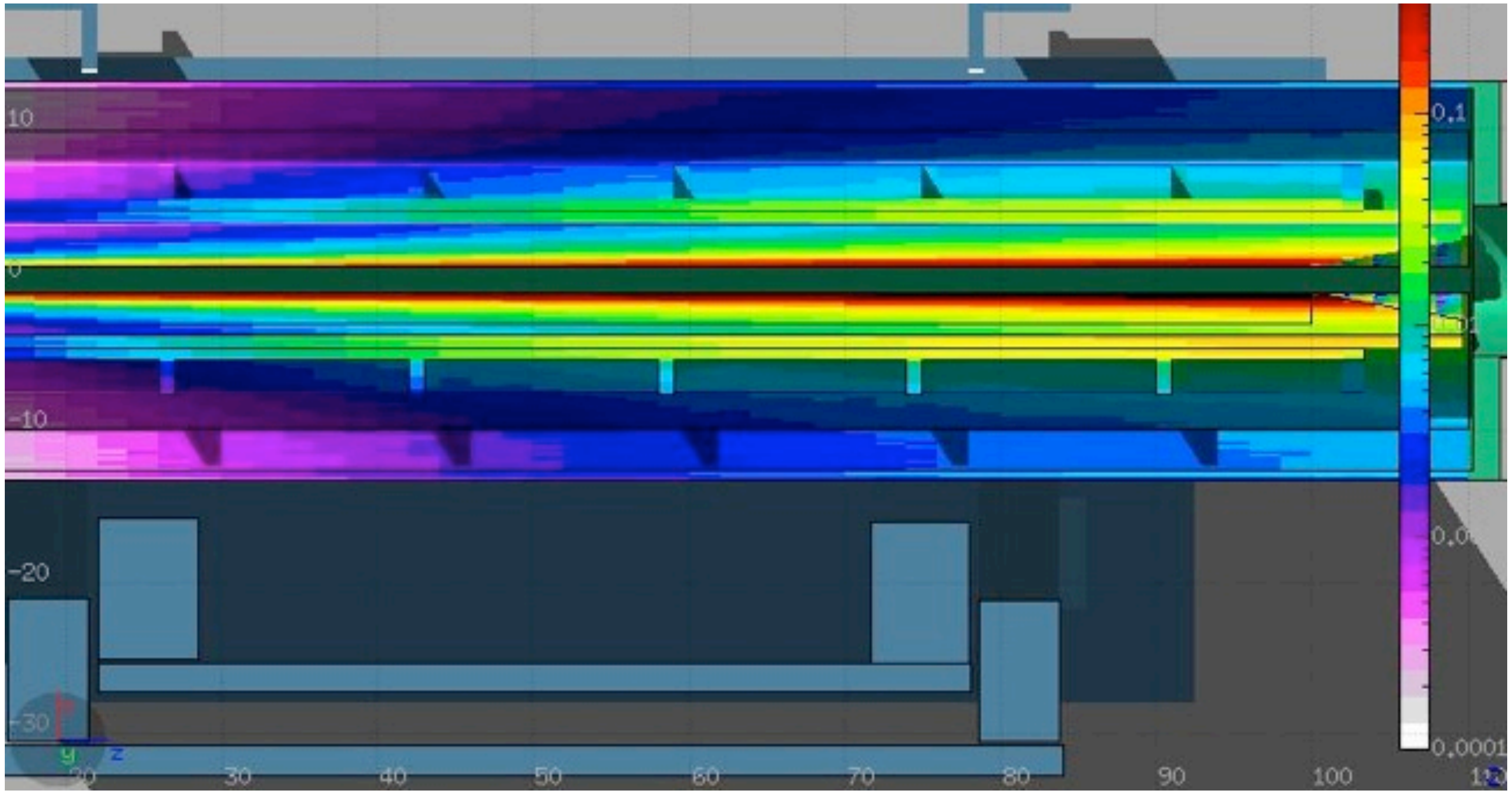


Overall loss pattern along the full ring is correctly predicted!

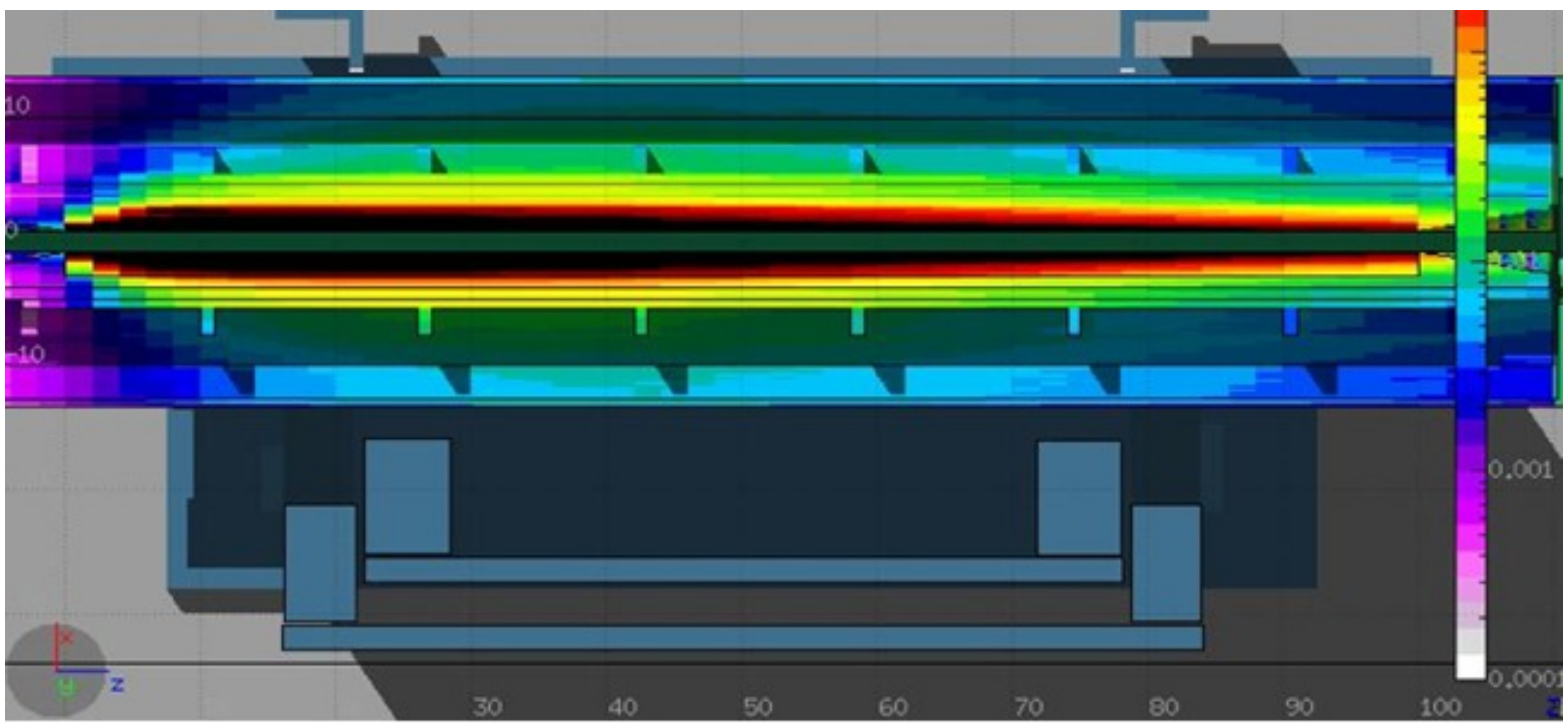
- ➘Main losses immediately downstream of the collimator
- ➘Next significant peak at an SPS collimator, >2.5km downstream!


Measurements
BLM reading [bit]
Longitudinal coordinate s [m]
Simulations
The peak is downstream
of the BLM location!
Number of lost particles
Betatron functions [m]
βx
βy
Longitudinal coordinate s [m]
1st peak:TIDP
Sloss: s1=450m; s2=460m.
Nloss = 45
Y [mm]
X [mm]
2nd peak:TIDV
Sloss: s1=590m; s2=610m.
Nloss = 621
X [mm]

Different shower development



Carbon composite for primary collimators



Tungsten for tertiary collimators: higher Z cause showers to be more contained in collimator volume → larger BLM signal

E. Skordis

Effect of collimation imperfections