LHC Optics Measurements and Corrections Review

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LHC aperture checks

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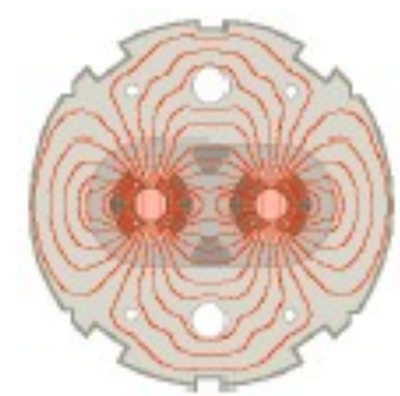


Outline

- Introduction
- LHC aperture in run 1
- Plans and tools for post-LS1
- Conclusions

References

Recent presentations on aperture

- G. Müller, **LBOC, Nov. 22nd, 2011**: IR2 aperture
- R. Bruce, **LBOC, Oct. 11th, 2011**: IR1+IR5 aperture; **LBOC, Mar. 8th, 2011**, 450 GeV aperture;
  LSWG, **May15th, 2012**: MD results.
- J. Wenninger, **LMC, Nov. 2nd, 2011**, IR2 aperture (β^*=1.0m)
- S. Redaelli, **LMC, Aug. 31st, 2011**: IR1/5 aperture at 3.5 TeV (β^*=1.5m); **LBOC, Feb. 8th, 2011**, Squeeze baseline
  LBOC Mar. 27th, 2012: Summary of 2012 results.

References to published papers/notes:

PAC2009: S. Redaelli, I. Agapov, R. Calaga, B. Dehning, M. Giovannozzi, F. Roncarolo, R. Tomas, "First beam-based aperture measurements for arcs and insertions of the LHC"

Evian2010 (Jan.): M. Lamont, G. Müller, S. Redaelli, M. Strzelczyk, "Betatron squeeze: status, strategy and issues"

IPAC2010: C. Alabau Pons, M. Giovannozzi, G. Müller, S. Redaelli, F. Schmidt, R. Tomas, J. Wenninger, "LHC aperture measurements"

HB2010: S. Redaelli, X. Buffat, M. Lamont, G. Müller, R. Steinhagen, J. Wenninger, "Commissioning of ramp and squeeze at the LHC"

IPAC2011: R. Assmann, M. C. Alabau Pons, R. Bruce, M. Giovannozzi, G. Müller, S. Redaelli, F. Schmidt, R. Tomás, J. Wenninger, D. Wollmann, "Aperture determination in the LHC based on an emittance blowup technique with collimator position scans"

ICALEPCS2011: G.J. Müller, K. Fuchsberger, S. Redaelli, "Aperture meter for the LHC"

CERN ATS notes: CERN-ATS-Note-2011-110 MD, 2011-117 MD, 2013-026 MD, + note in preparation for IR2.

IPAC2012: S. Redaelli et al., "Aperture measurements in the LHC insertion regions"

Introduction

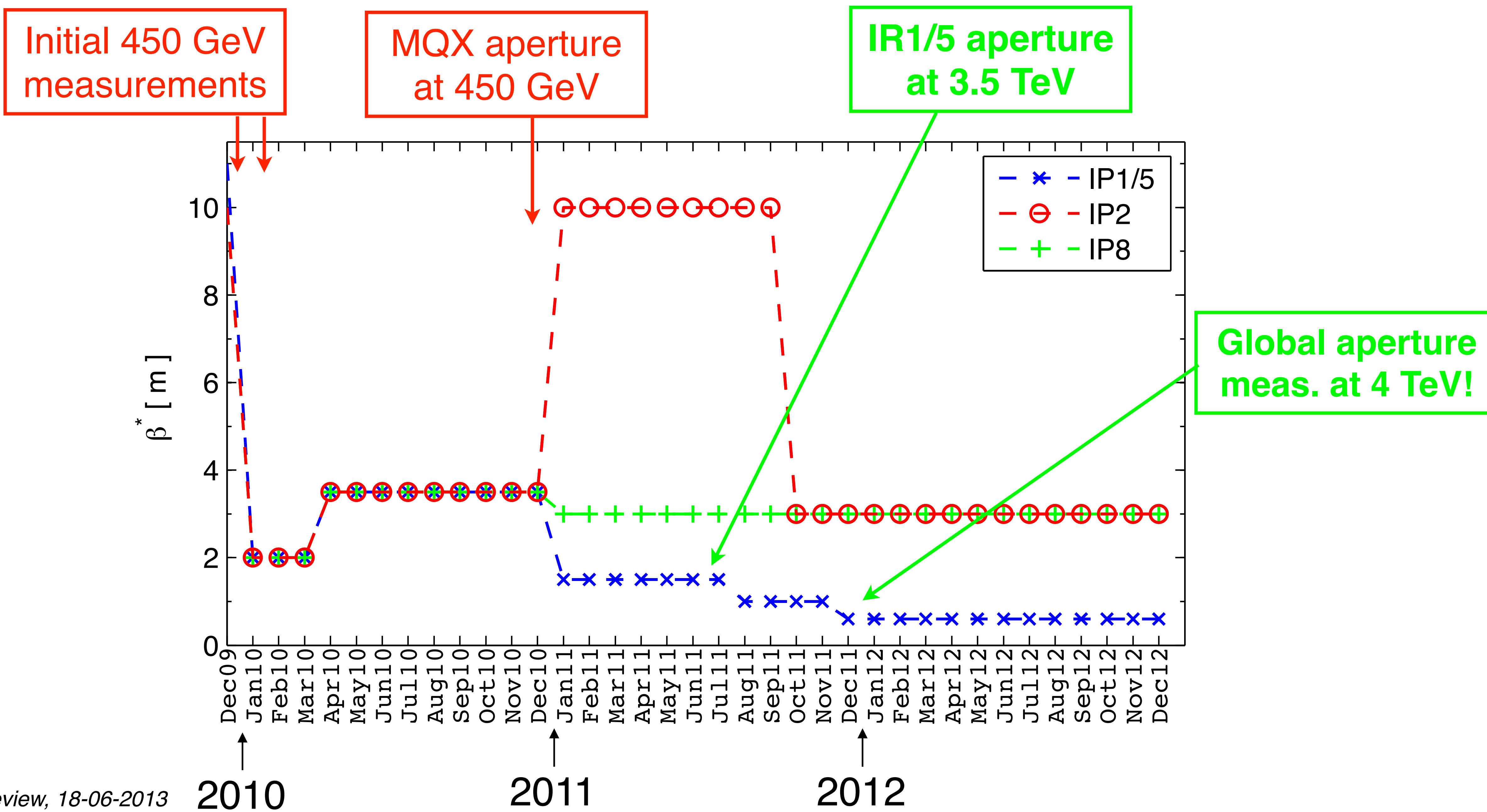
The knowledge of the **machine aperture**

(1) is essential to operate safely the collider and

(2) determines the collider performance in terms of β^* reach!

The smallest available aperture sets the scale for collimator settings; the triplet aperture fixes the minimum β^*.

Beam-based aperture measurements and checks allow achieving a precise knowledge!



Aperture definitions

Aperture ("aperture model") of an accelerator is a concept used to defined the normalized transverse (x,y) space available for the beam, for a given machine configuration (given energy, optics, orbit, etc.). *The minimum normalized aperture bottleneck is what matters in most cases.*

Global machine aperture (per plane, per beam):

$$A_\sigma = \min_{s_i} \left[\frac{A_{\mathrm{mm}}(s_i)}{\sigma(s_i)} \right]$$

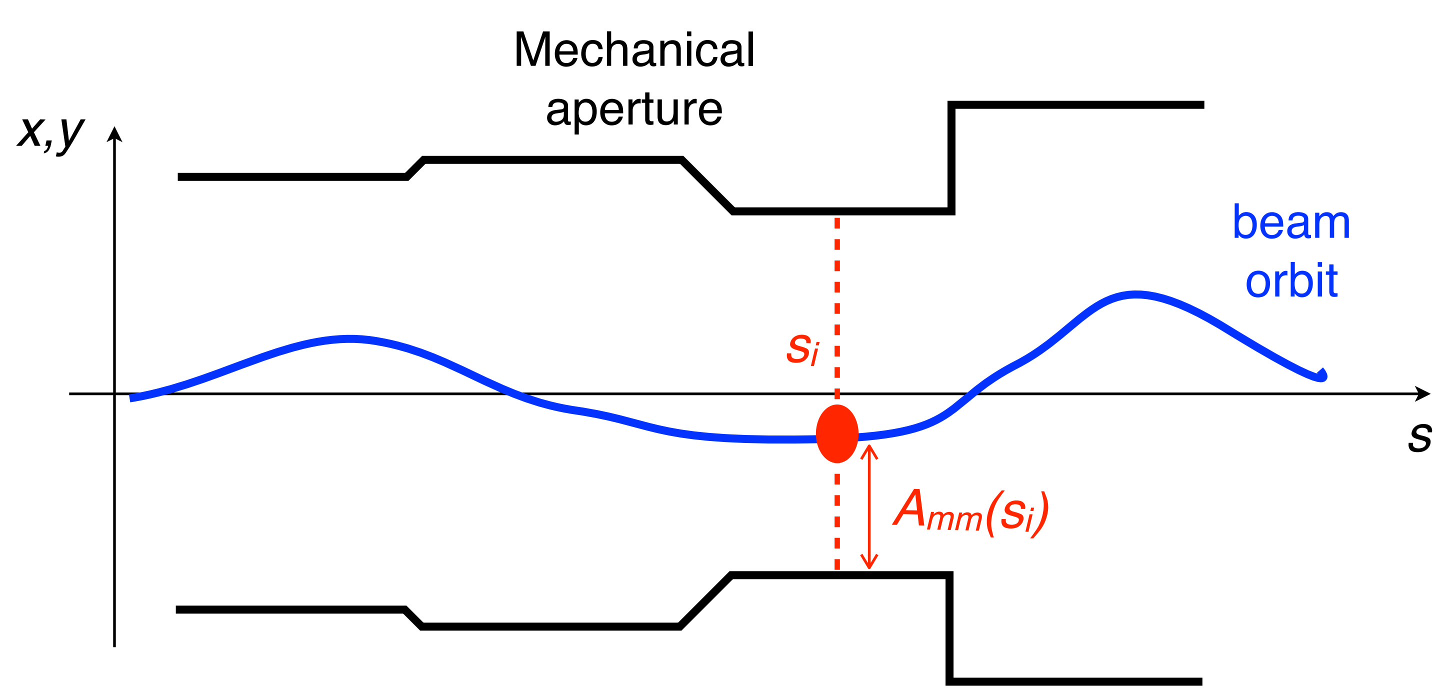
- The definition of aperture requires the knowledge of the mechanical aperture of all accelerator's lattice elements AND of the relevant beam parameters.
- LHC design phases: the aperture was simulated with various error assumptions.
- **Beam-based measurements** are now used to determine the performance reach!
- For convenience, expresses in units of beam size (relative to collimator gaps).

A_σ depends on energy, optics, orbit and errors (β-beating, ...):

- Location of aperture bottlenecks might be different for each configuration.

- amplitude of normalized aperture might change accordingly.

Need to be defined for all relevant phases of the operational cycle.



Aperture measurements in 2012-13

- **Global aperture 450 GeV**:	March 19th, 2012. Beam blowup with TCP collimator scans.
- **Global aperture at 4 TeV, 60 cm**:	March 23rd, 2013. Beam blowup with TCT collimator scans.
- **Aperture checks with loss maps**:	April 4th, 2012. Loss maps with different TCT settings.
- **Asymmetric aperture checks in IR1/5**:	April 22nd, 2012. TCT scans with different crossing angles.
- **IR8 aperture at 450 GeV**:	November 29th, 2012. Classical bump method with envelope shaped by TCP's.
- **IR2 aperture at 4 TeV**:	January 17th, 2013. TCT scan as in IR1/5. Also off-momentum.

Note:

Important to measure/verify the aperture in **three conditions**:

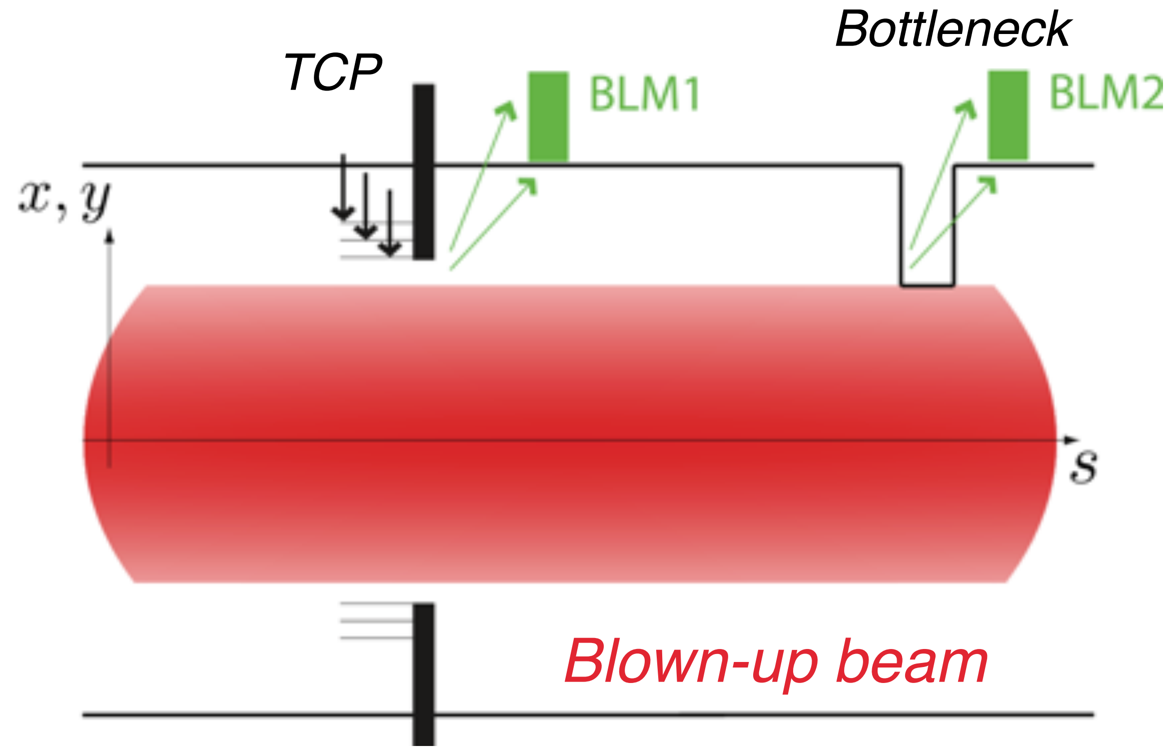
- Injection;
- Squeezed separated;
- Squeezed colliding (with orbit settings for optimized luminosity).

(Assuming the present operational cycle with separated ramp and squeeze)

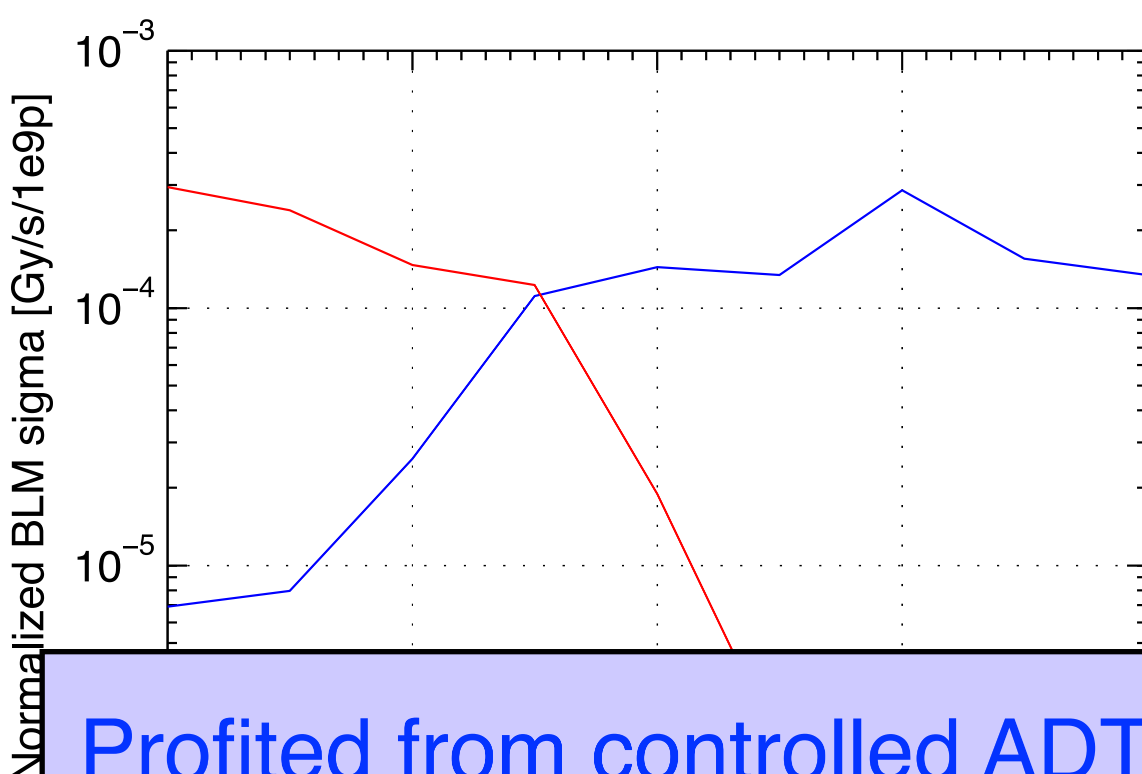
Local scans at bottlenecks useful for recentring orbit - never needed it to do it.

450 GeV aperture measurements

Since 2008, we have used and compared several different methods:
- Trajectory oscillations (sector tests)
- Close orbit oscillations, local bumps
- Emittance blowup with aperture kicker
- Beam blow-up with collimator scans
(Ralph A. et al, IPAC2011)
Focused on the blow-up method since 2011.

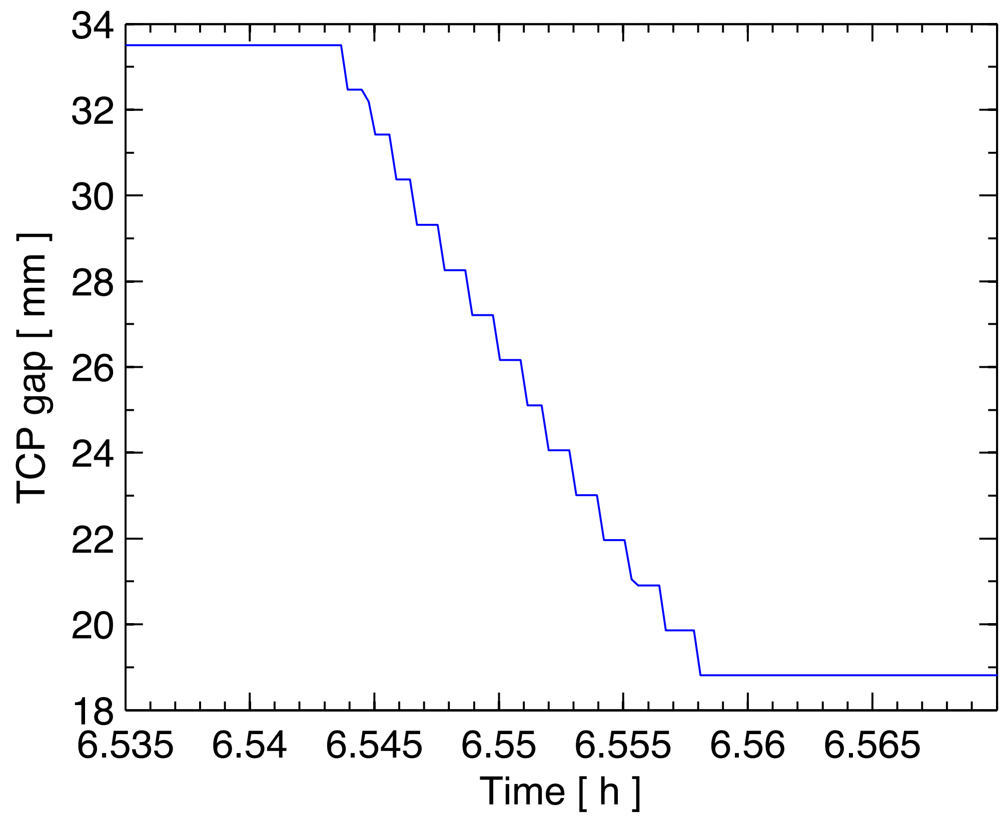


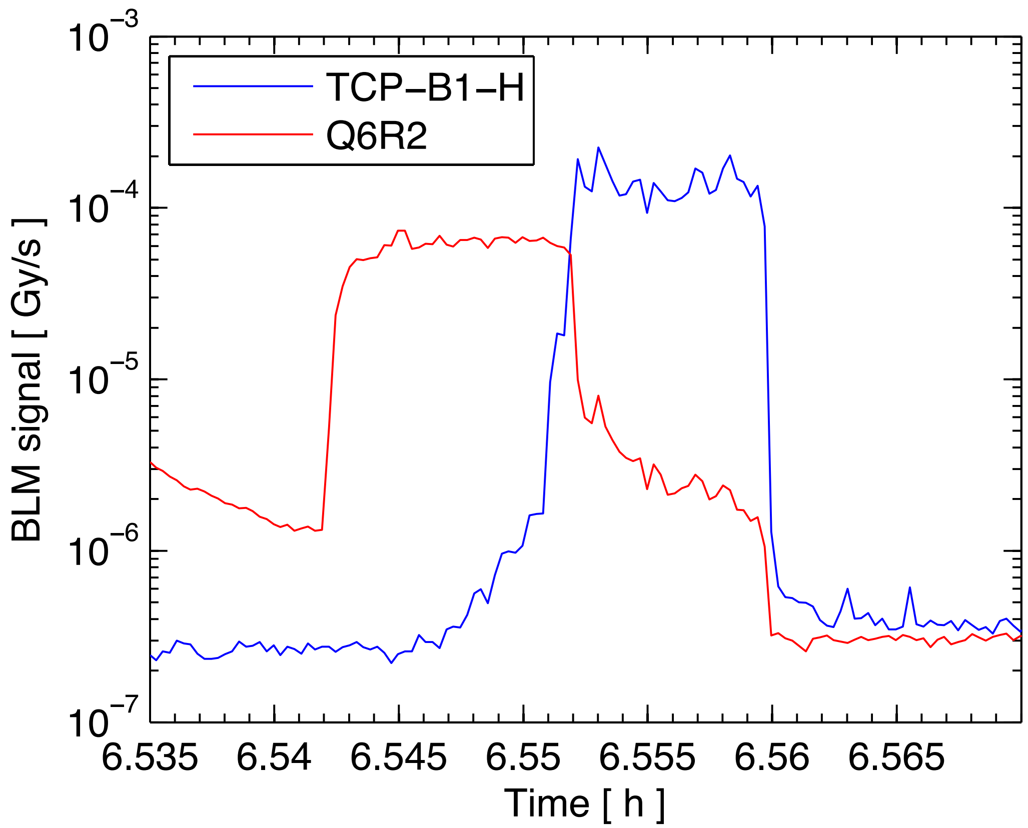
Steps to perform measurements
0. Beam based alignment of TCP collimators
1. Emittance blow-up to find bottleneck (coll. open)
2. Perform a collimator scan and repeat blow-up
3. When losses move to the TCP, the ***precise*** *knowledge of* ***collimator gap*** *gives the* $\mathbf{N_\sigma}$
4. Can be used for approximated LOCAL measurements with orbit bumps
Refined calculations use normalized BLM

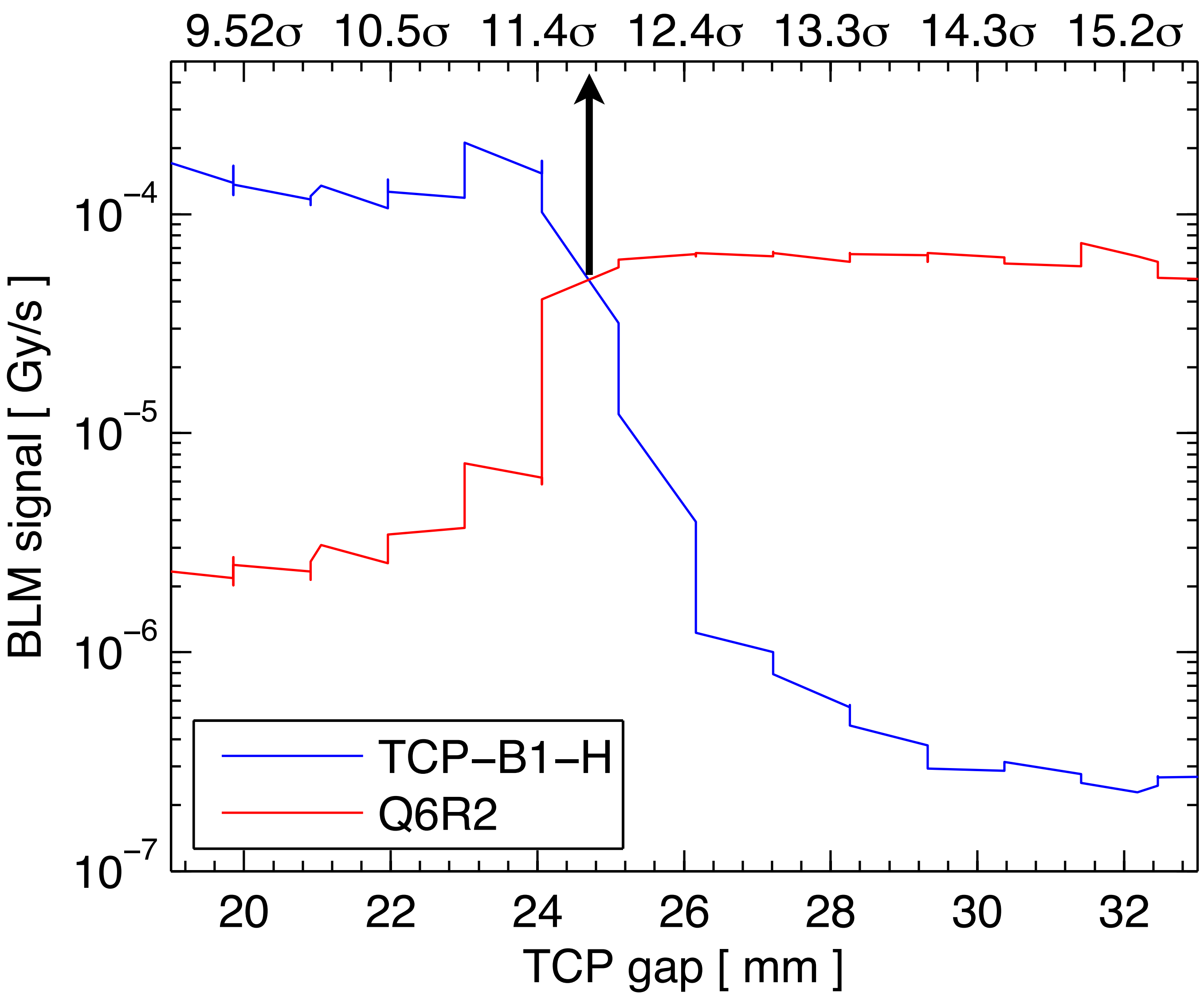


Profited from controlled ADT blow-up deployed in 2012!

Example of injection measurements







This opened the possibility to perform controlled global measurements at top energy!

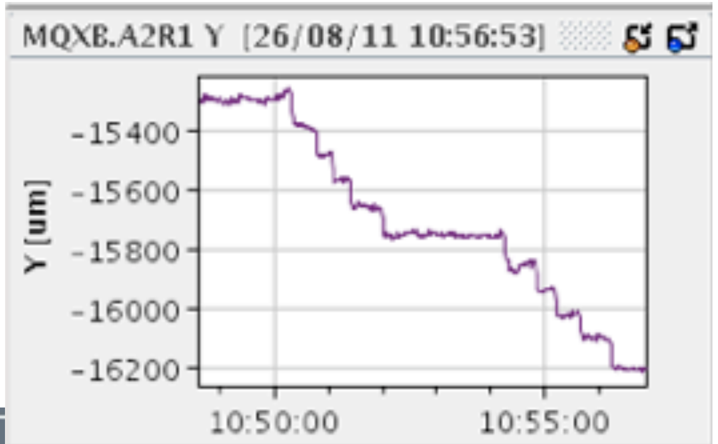
Aperture measurements at top energy

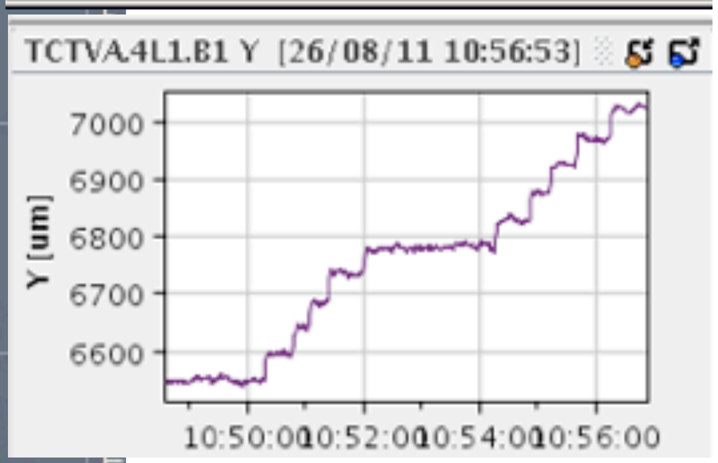
Procedure established to determine optimum tertiary collimator (TCT) settings.

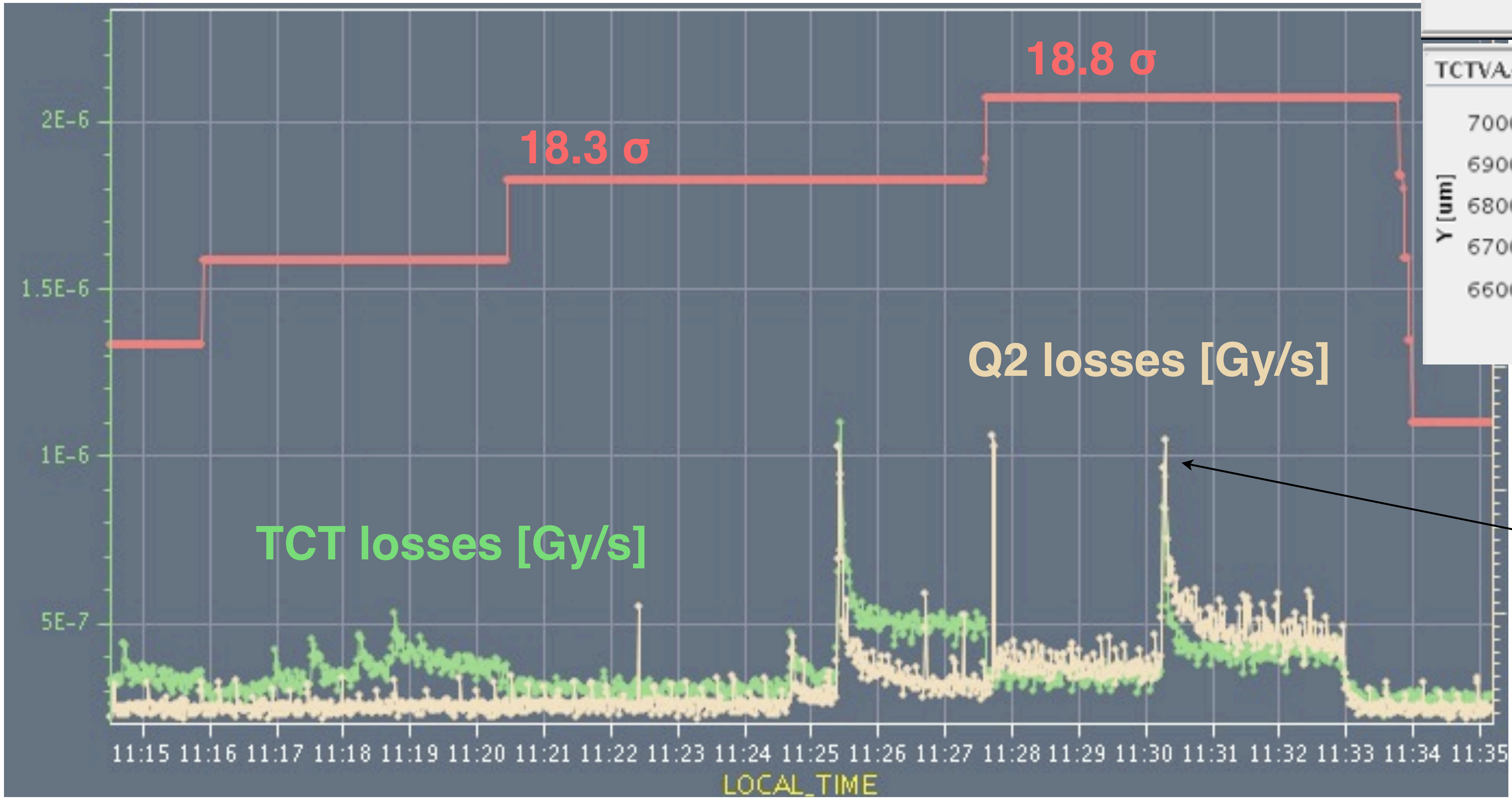
Centre around orbit the TCTs that protect the triplet and open them in steps until triplet aperture is "exposed":

1. *Add a local bump until the beam touches the TCT*
2. *Open TCT by 0.5 sigma (250-320µm in H-V)*
3. *Increase bump by 0.25 sigma*
4. *Check relative height of BLM spikes: TCT vs MQX (Q2)*

Orbit at TCT and Q2







Loss spikes while the orbit is increased, touching TCT or MQX

LHC injection aperture

Global aperture 2012

	H [σ]	V [σ]
B1	**11.5 (Q6R2)**	**12.5 (Q4L6)**
B2	**12.5 (Q5R6)**	**13.0 (Q4R6)**

Beam-based centre shifts

	H [mm]	V [mm]
B1	**0.00** (Q6R2)	**-0.80** (Q4L6)
B2	**0.50** (Q5R6)	**0.25** (Q4R6)

Global aperture 2010

	H [σ]	V [σ]
B1	**12.5 (Q6R2)**	**13.5 (Q4L6)**
B2	**14.0 (Q5R6)**	**13.0 (Q4R6)**

Global aperture 2011

	H [σ]	V [σ]
B1	**12.0 (Q6R2)**	**13.0 (Q4L6)**
B2	**12.5 (Q5R6)**	**13.0 (Q4R6)**

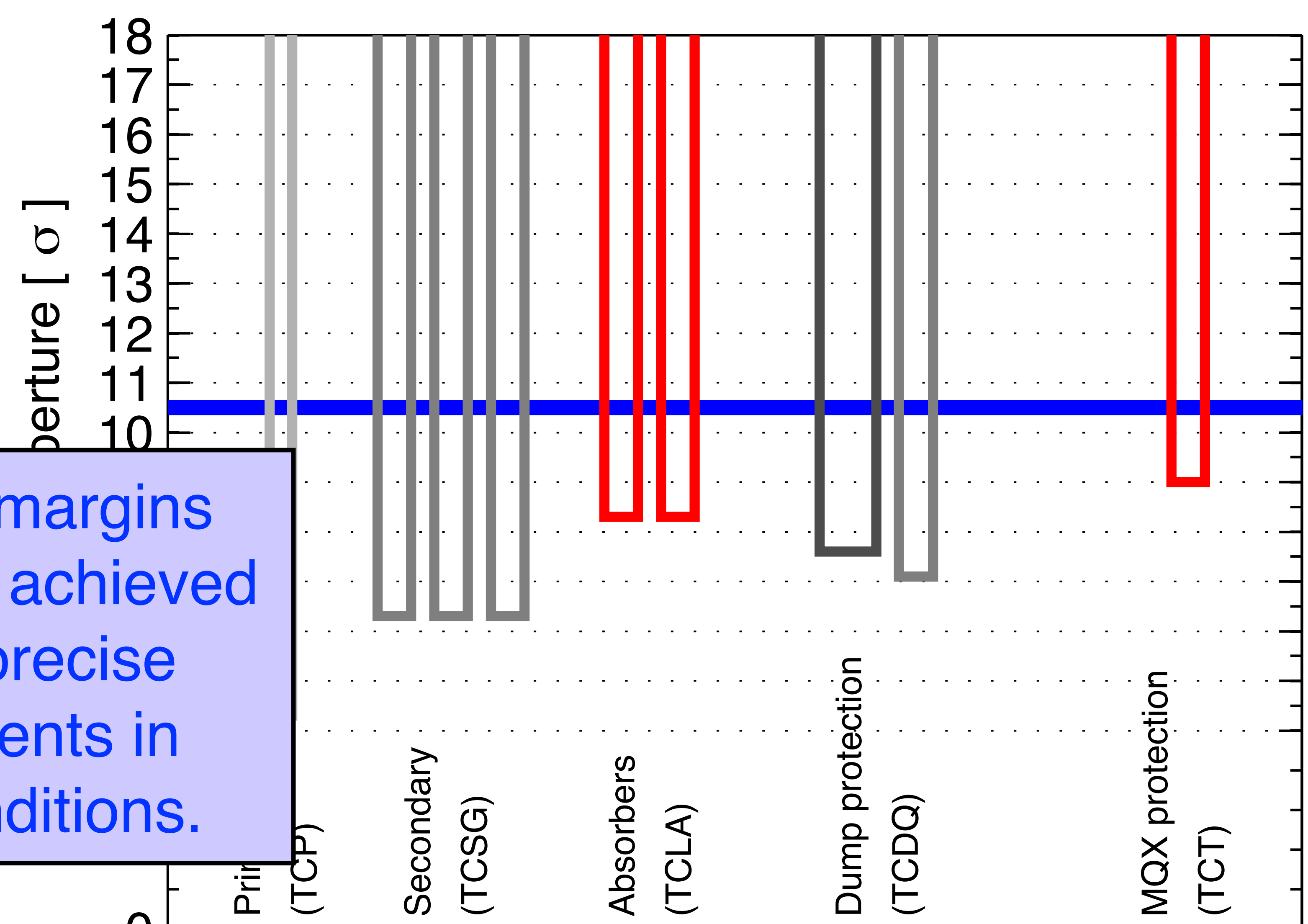
Same locations found in the last years for the bottlenecks.
We are loosing 0.5-1.0 sigmas per year. Check with the SU team?

Aperture at 4 TeV, $\beta^* = 60$ cm

(Separation = 650 μm, crossing = 145 μrad)

	H [σ]	V [σ]
B1	**11.5 - 12.0 (Q2-L5)**	**11.0 - 11.5 (Q3-L1)**
B2	**11.5 - 12.0 (Q3-R1)**	**11.0 - 11.5 (Q3-R1)**

Checks in collision with luminosity bumps indicated that ~0.5 sigma was lost!



Minimum aperture in collision conditions: 10.5 sigmas

Such small margins could only be achieved thanks to precise measurements in physics conditions.

Outline

- ☑ Introduction
- ☑ LHC aperture in run 1
- ☑ **Plans and tools for post-LS1**
- ☑ Conclusions

Plans for post-LS1 operation

1. Aperture measurements will be **crucial** for the operation after LS1!
   - *Important to re-assess the injection aperture (all machine is being opened!)*
   - *Need to ensure in all phases that the machine will be safe.*
   - *Requirements on triplet measurements depend on the choice of beta*.*
2. Checks during **sector tests** in available arcs might be useful.
3. Solid experience gained so far - we base future program on that!

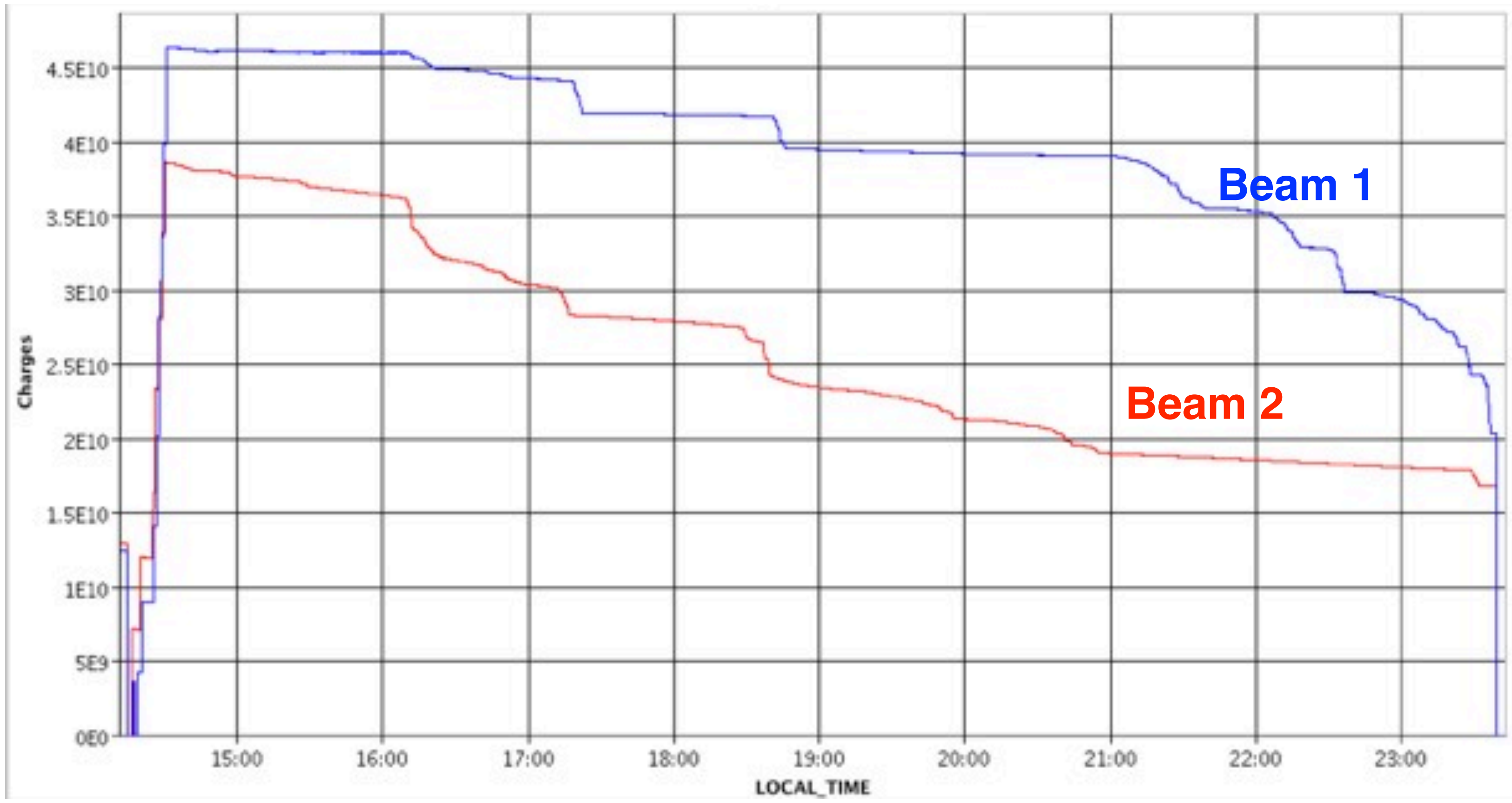
   Fit the measurements in the commissioning plan, recalling that:
   - *Preliminary checks can be done "quickly" **but***
   - ***Main measurements** must be scheduled after **nominal machine** is established:*

     Final orbit reference with nominal bunches, IR bumps. Optics corrections IN.
4. Orbit re-centring in bottlenecks to gain up to ~1σ to be foreseen.
5. Need to update/re-think the procedures for **measurements at top energy**! *In my opinion we should foresee to check aperture at 6.5 TeV!*
6. Implications of various proposals on the table must be studied

   - Smaller beta at injection, final beta* in case of combined ramp&squeeze...*

“Gentle” measurements at 4 TeV

Beam intensity during global measurements at 4 TeV in 2012



With controlled blow-up, we achieved precise measurements with MINOR beam losses!
Beam dumped after about 8h of measurements at top energy.

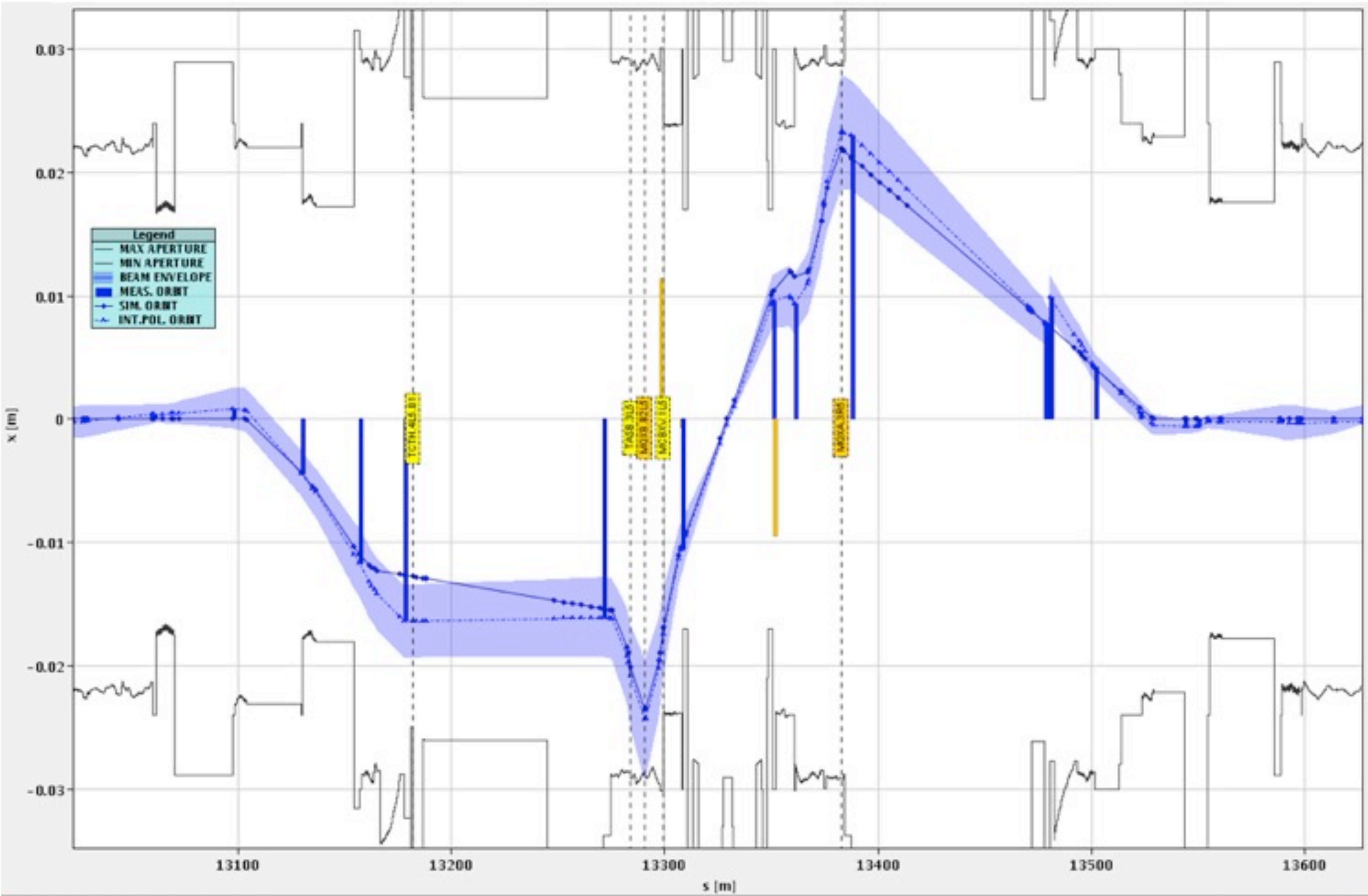
But*:*
In some cases collimators and aperture are close to the beam orbit - we can never exclude fast beam losses like asynchronous dump.
Very small probability with many bunches in the machine, but...

Also note that our knowledge of the machine keeps improving, so it is legitimate to ask whether we really need measurements at top energy.

Comments on tools

1. Aperture measurements rely on collimator scans
   - *Need tools to efficiently centre collimator around the orbit (see next talk): will be available with minor changes.*
   - *Need to know precisely the collimator gaps: also available.*
2. Some automated analysis tools might be useful but I do not consider this to be essential for startup.
3. Question: do we want to be ready for automatic aperture scans?
   - *"Hot topics" before first commissioning, then forgot about it!*
   - *Do we want to be prepared for efficient measurements in case of several bottlenecks occur in the arcs?*
4. The **ApertureMeter** is an important tool that should in my option be maintained!

IR5 aperture at 3.5 TeV



Part of PhD work of G. Müller.

Remarkable result!
Interesting prospect for check related to machine protection.

Conclusions

- **The experience with LHC aperture in run1 was reviewed!**

  Measurements are done at injection and top energy (since mid 2011).

  The LHC aperture is excellent and this allowed to achieve β^*=60cm.
  A beam-based understanding of the aperture was crucial to achieve this result.

- **We established several methods to measure the aperture in the "units" that we need.**

  Methods rely on various types of collimator scans to achieve directly the aperture and protection settings in sigma units used for collimator gaps!

  Important work on controlled beam blow-up allows measurement at top energy.

- **Plans for post-LS1 commissioning discussed (first thoughts)**

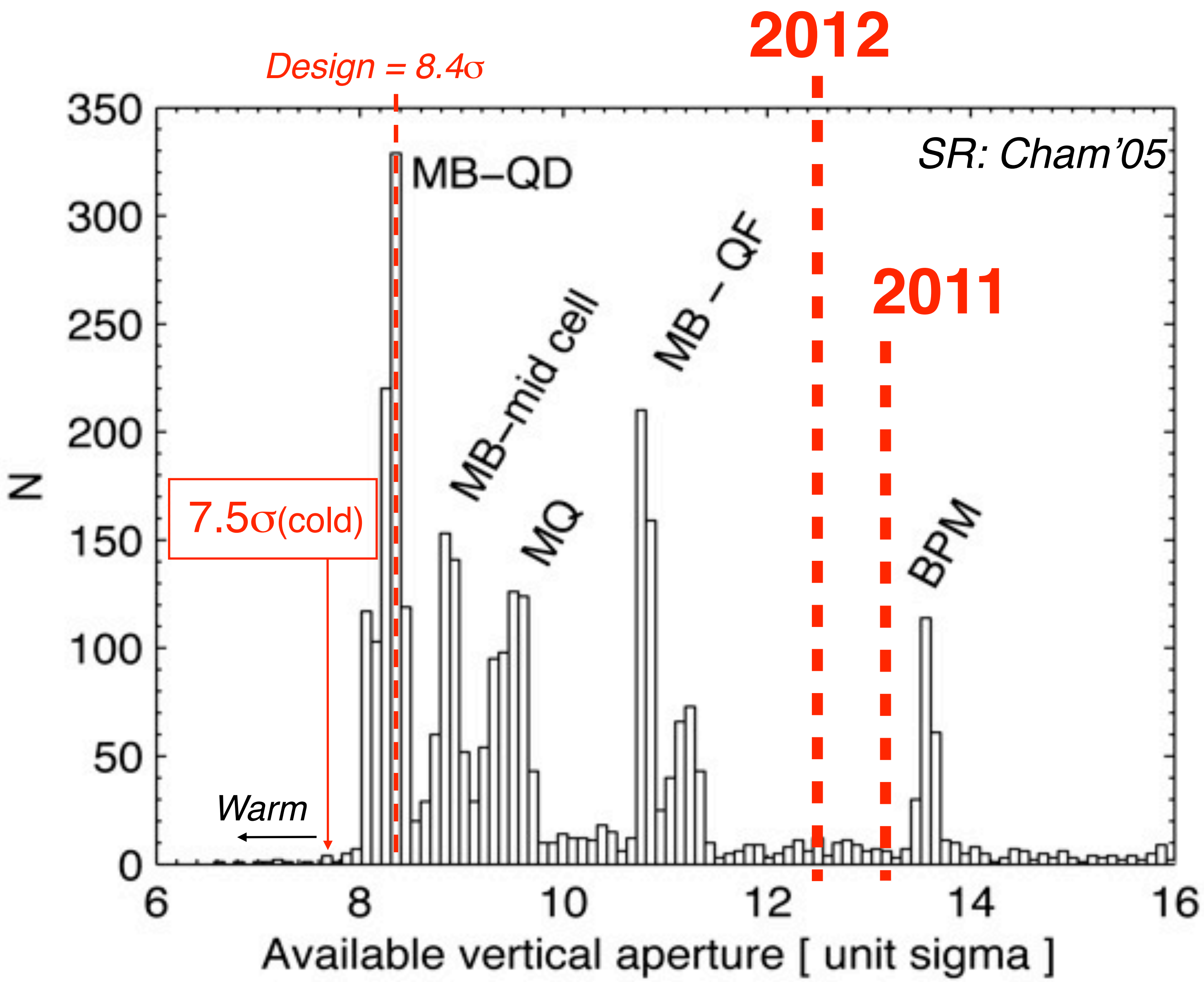
  The requirements will be similar to what we have done so far (see 2012 case).
  Need to be very careful with measurements at top energy!
  No strong requirements in terms of new tools, some improvement welcome.
  Important to keep alive the ApertureMeter.

- **New operational scenarios will require new measurements**

  More details local triplet aperture at injection if smaller beta considered*
  Foresee some checks at flat-top in case of combined R&S
  IR8 aperture for different crossing / separation planes...

Reserve slides

Comments on injection aperture



Tolerance table

Closed orbit	± 4 mm
Beta-beat	± 20 %
Spurious dispersion	27% D_{nom}^{Arc}
Mechanical tolerance	1-2.5 mm
Alignment	1.0.-1.6 mm

Achieved and surpassed the **nominal injection aperture** (170 μrad crossing angle, 3.5 μm emittance)

... and we have some margins that we could profit from (used already aperture for relaxing injection protection; injection at **smaller β***, change crossing plane in IR8? ...)