What did we learn about halo population during MDs and regular operation?

Review of the needs for a hollow e-lens for the HL-LHC

October 6th, 2016

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with input from:

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- Beam distribution & diffusion measurements
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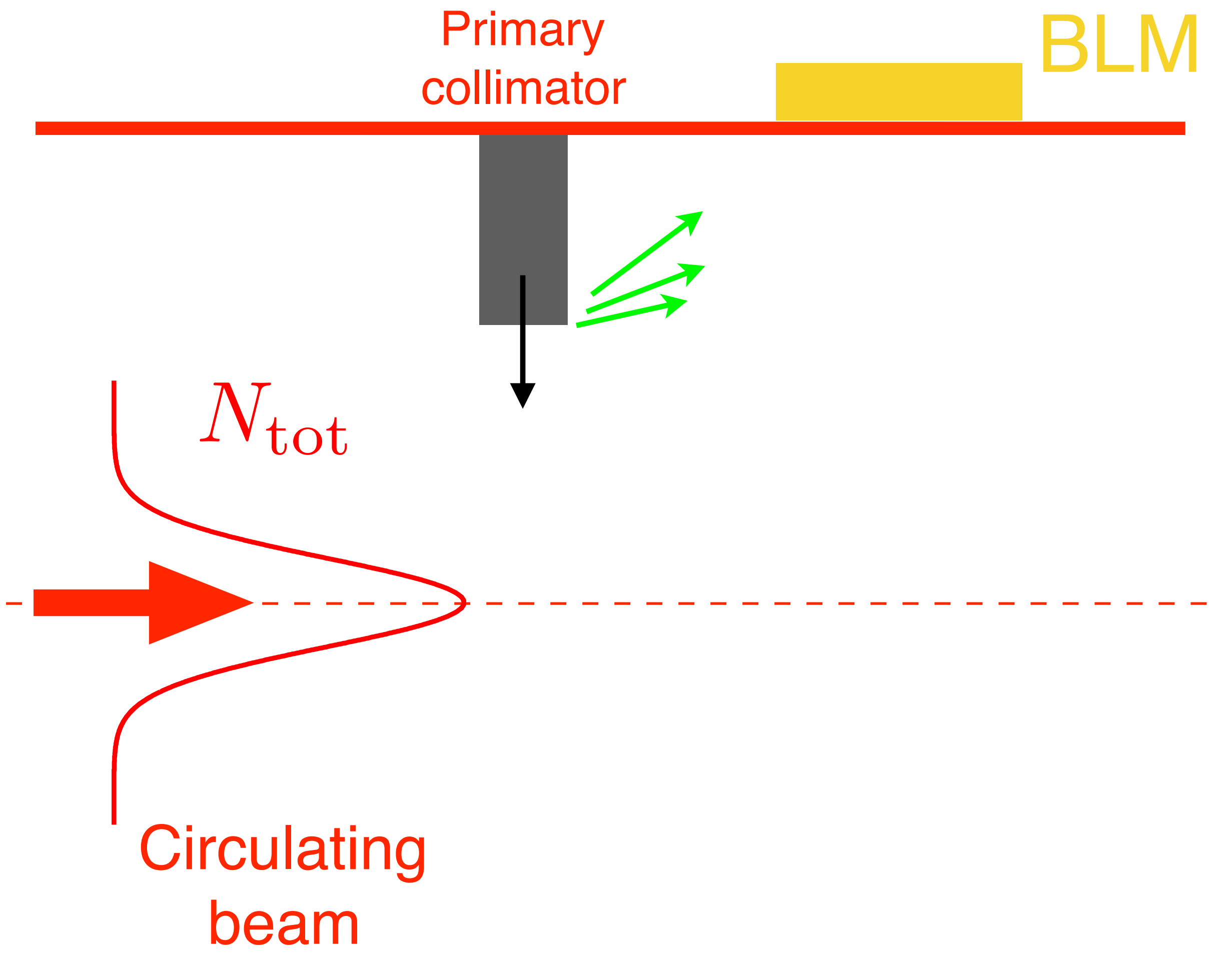
Introduction

- Collimator scans are a useful diagnostic tool to gain insight into the properties of a beam
    - Tried and tested techniques already used in other accelerators
    - The time evolution of losses gives information on halo diffusion and population.
    - Beam intensity and beam loss measurements provide information on beam distribution

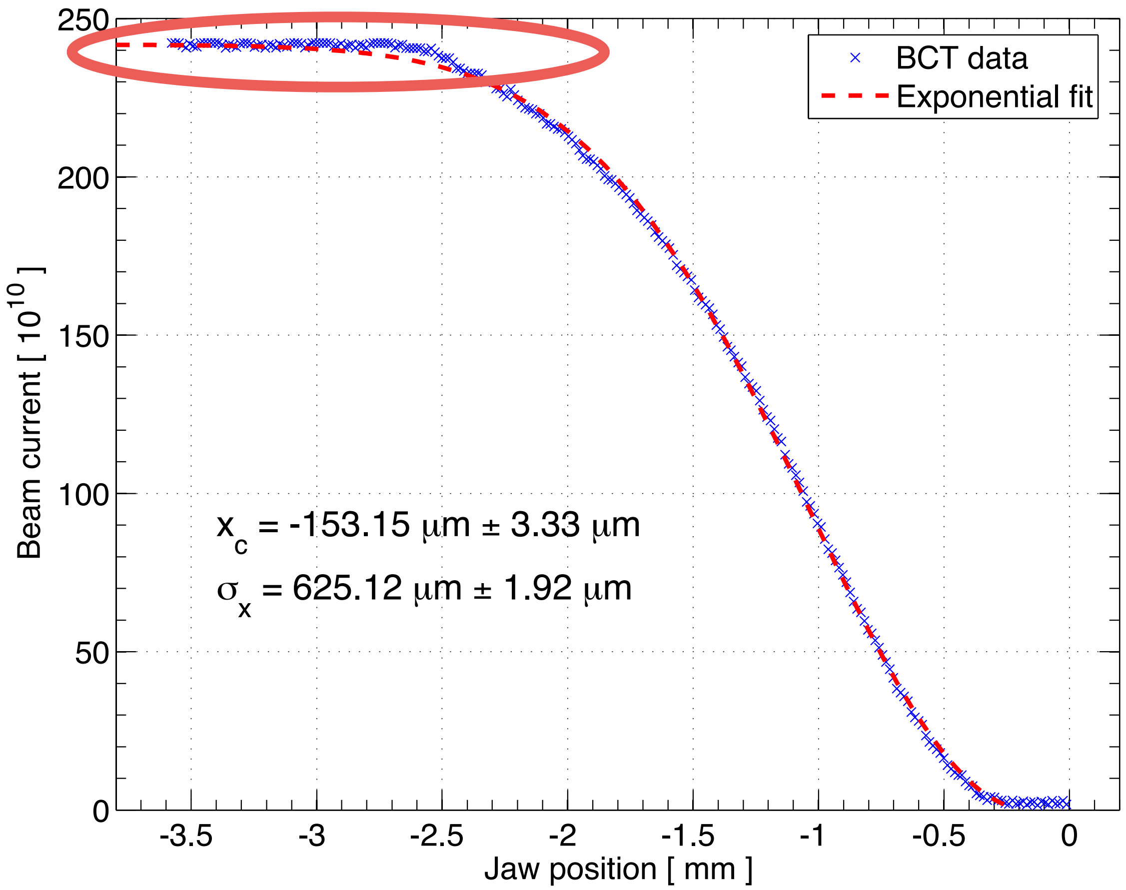
- Several measurements performed over 2011-2016 during dedicated MDs and in standard operation.

- This talk will review the results obtained, and try to extrapolate towards HL-LHC parameters to understand whether assumptions related to beam halo are valid.

Collimator scan technique



SPS collimator scan - full scraping

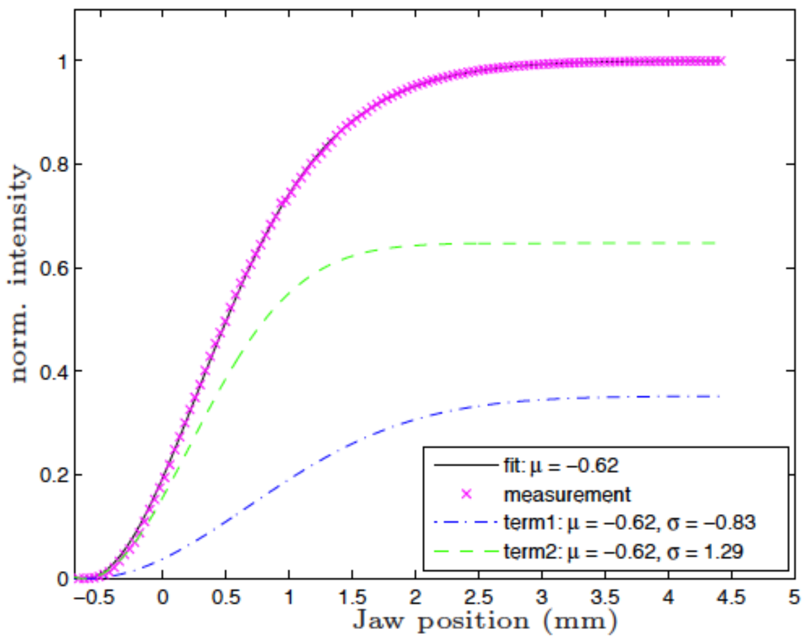


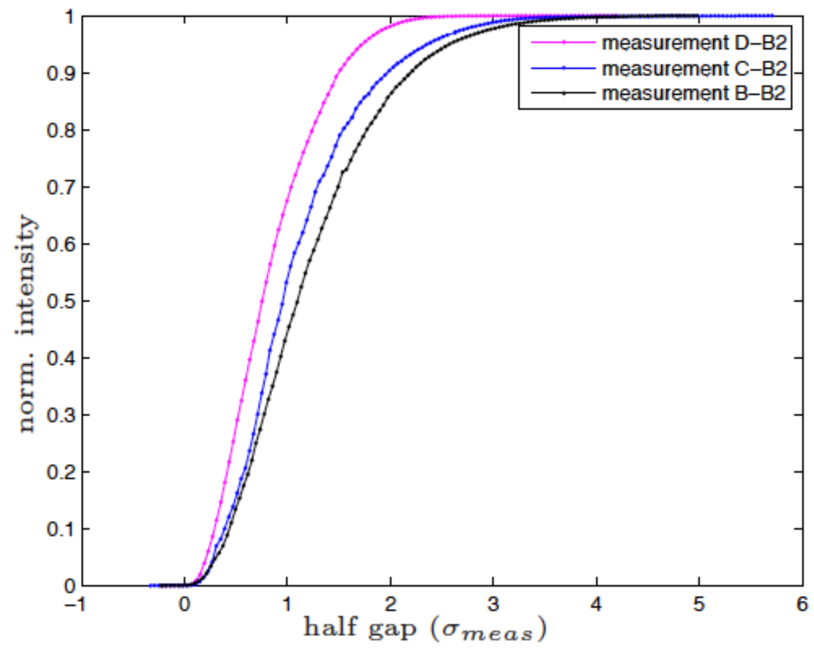
- Idea:
  - Move collimator jaw(s) into the beam in 5-20 um steps.
  - Record losses: shower from the jaw/beam interaction or beam intensity.

Done with primary collimators (TCP): robust, in warm insertion, hor/ver/skew.

Beam distribution

- Dedicated full scrapings of B1+B2, H/V/S done at 450 GeV in 2011:

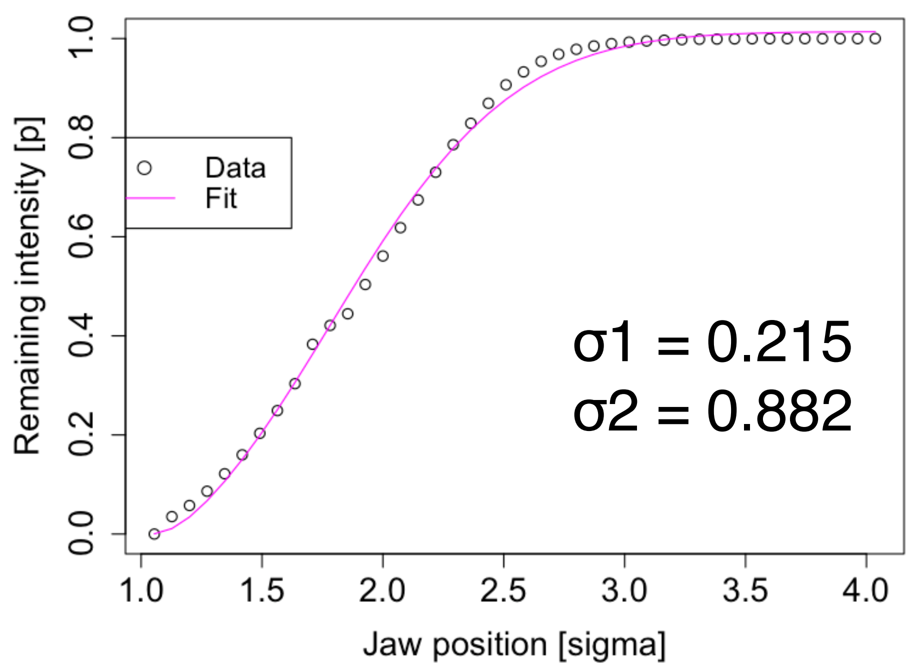




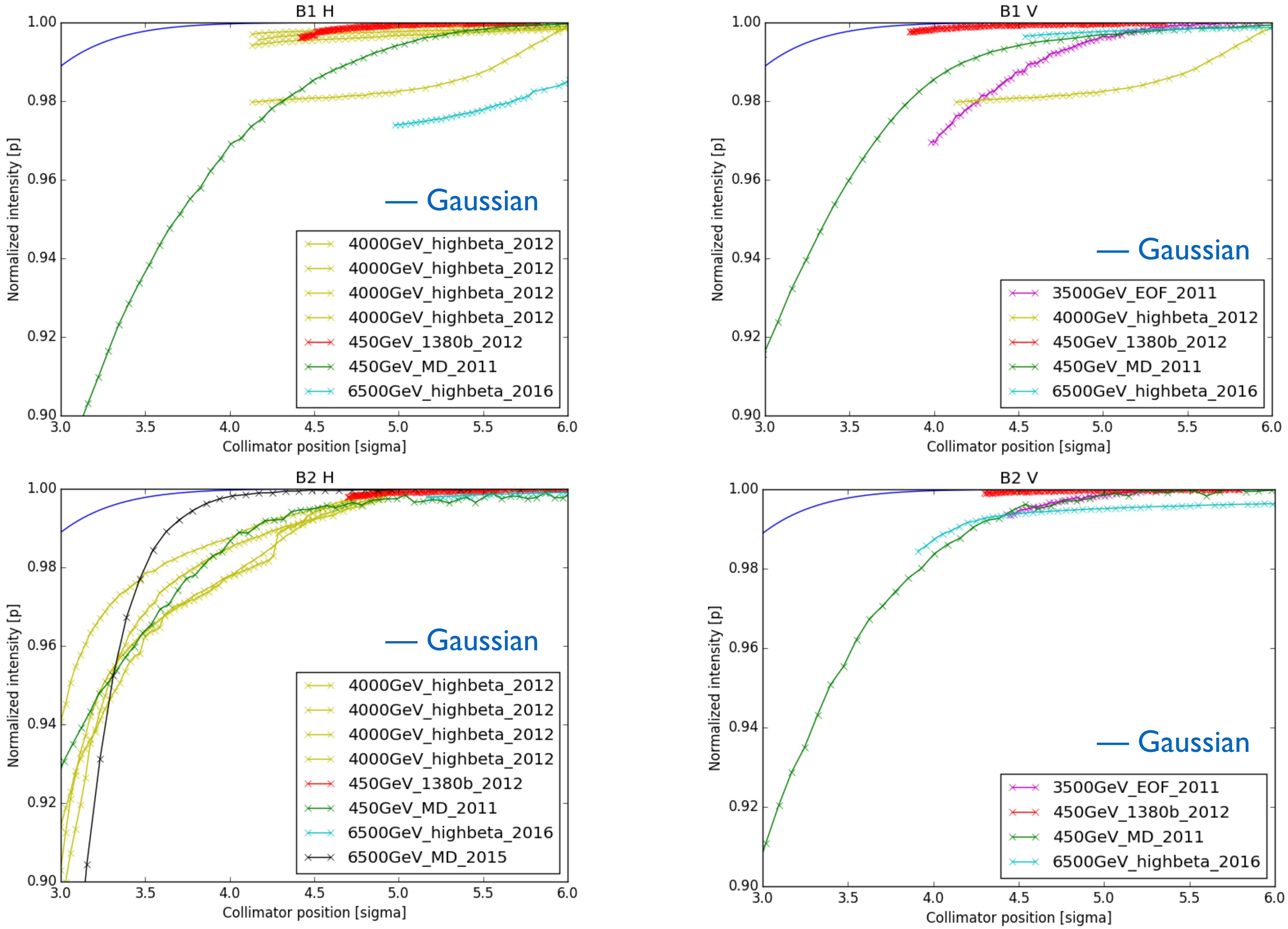
F. Burkart
Masters thesis

Double-Gaussian fit required due to larger tails

- Also done for B2 H at 6.5 TeV:



Single beam: Halo population



- Around 5% of the beams is in the tails (> 3.5 sigma), compared to 0.22% for Gaussian
- Factor 22 difference: **scaling to HL-LHC parameters = 33.6 MJ vs 1.48 MJ**
- No apparent correlation with energy

Beam diffusion

- Macroscopic particle motion can be considered to be a stochastic diffusion process due to spikes and dips in loss rates decaying in time as 1/sqrt(t)
- Diffusion model: the temporal losses observed during a collimator scan can be related to the particle flux at a certain collimator position (action) via a diffusion constant.

$$L = -D \times [\partial_J f]_{J=J_c}$$

- The diffusion constant can be obtained empirically by fitting the losses via:

$$\partial_J f_I(J_c, t) = -A_i + 2(A_i - A_c) P\left(\frac{-J_c}{w}\right) - \frac{2A_i(J_{ci} - J_c)}{\sqrt{2\pi} w} + \frac{2(A_i J_{ci} - A_c J_c) e^{[-(J_c/w)^2/2]}}{\sqrt{2\pi} w}$$ (Inward step)

$$\partial_J f_O(J_c, t) = -2A_i P\left(\frac{J_{ci} - J_c}{w}\right) + 2(A_i - A_c) P\left(\frac{-J_c}{w}\right) + 2 \frac{A_i J_{ci} - A_c J_c}{\sqrt{2\pi} w} e^{[-(J_c/w)^2/2]}$$ (Outward step)

where: $w \equiv \sqrt{2Dt}.$

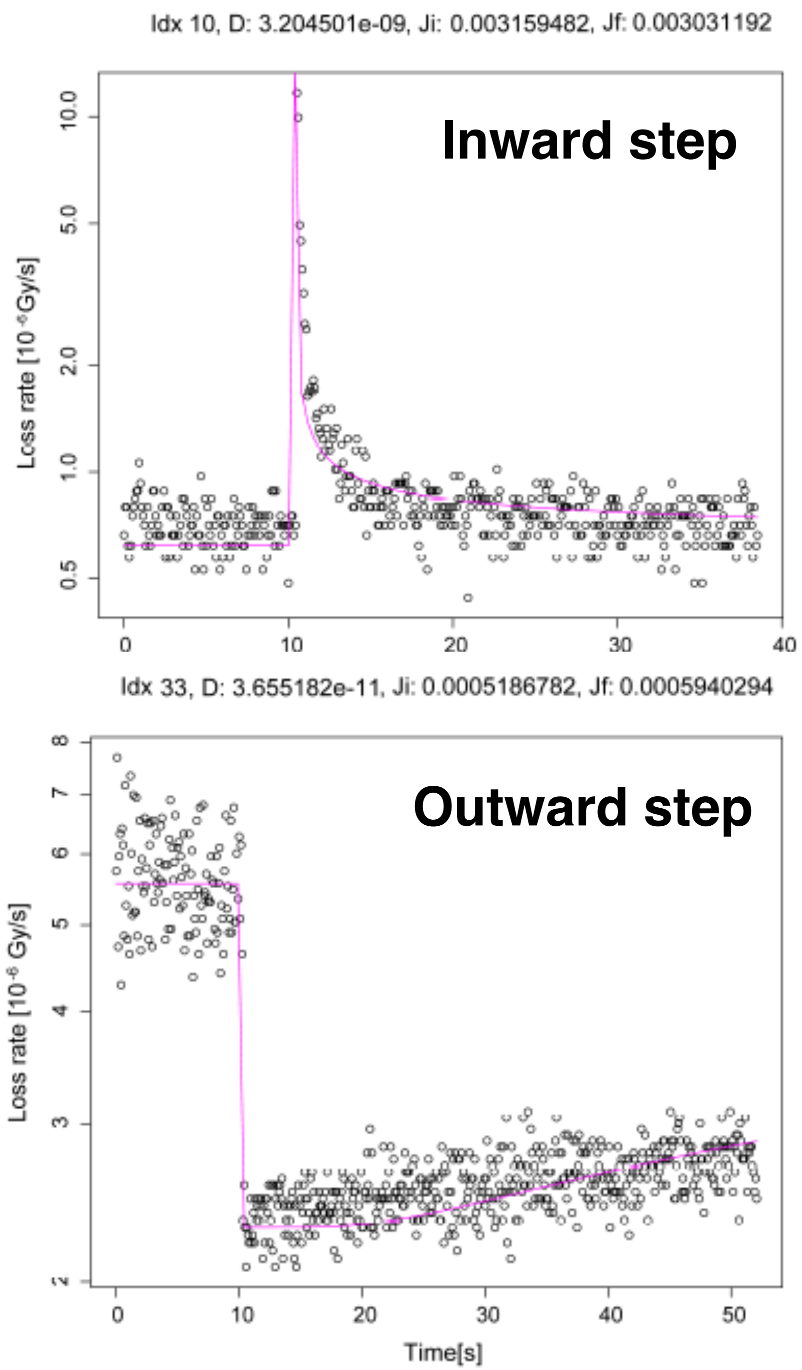
A is the slope of the distribution function

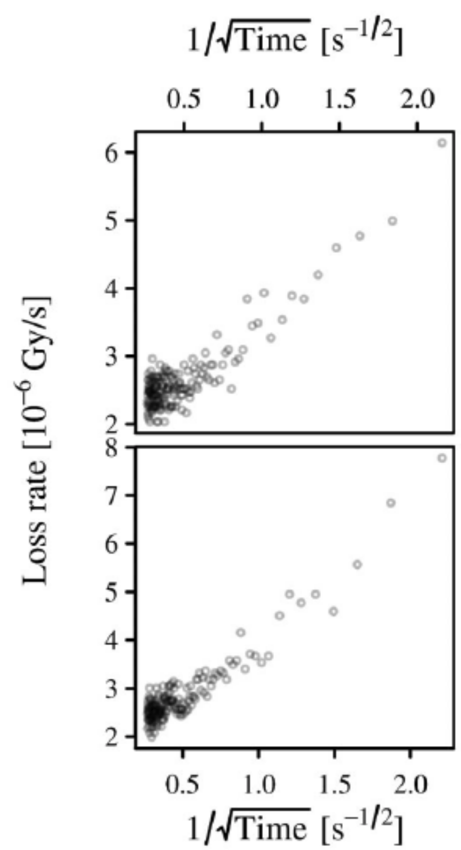
P(x) is the cumulative Gaussian distribution

Developed by G. Stancari for use at Tevatron

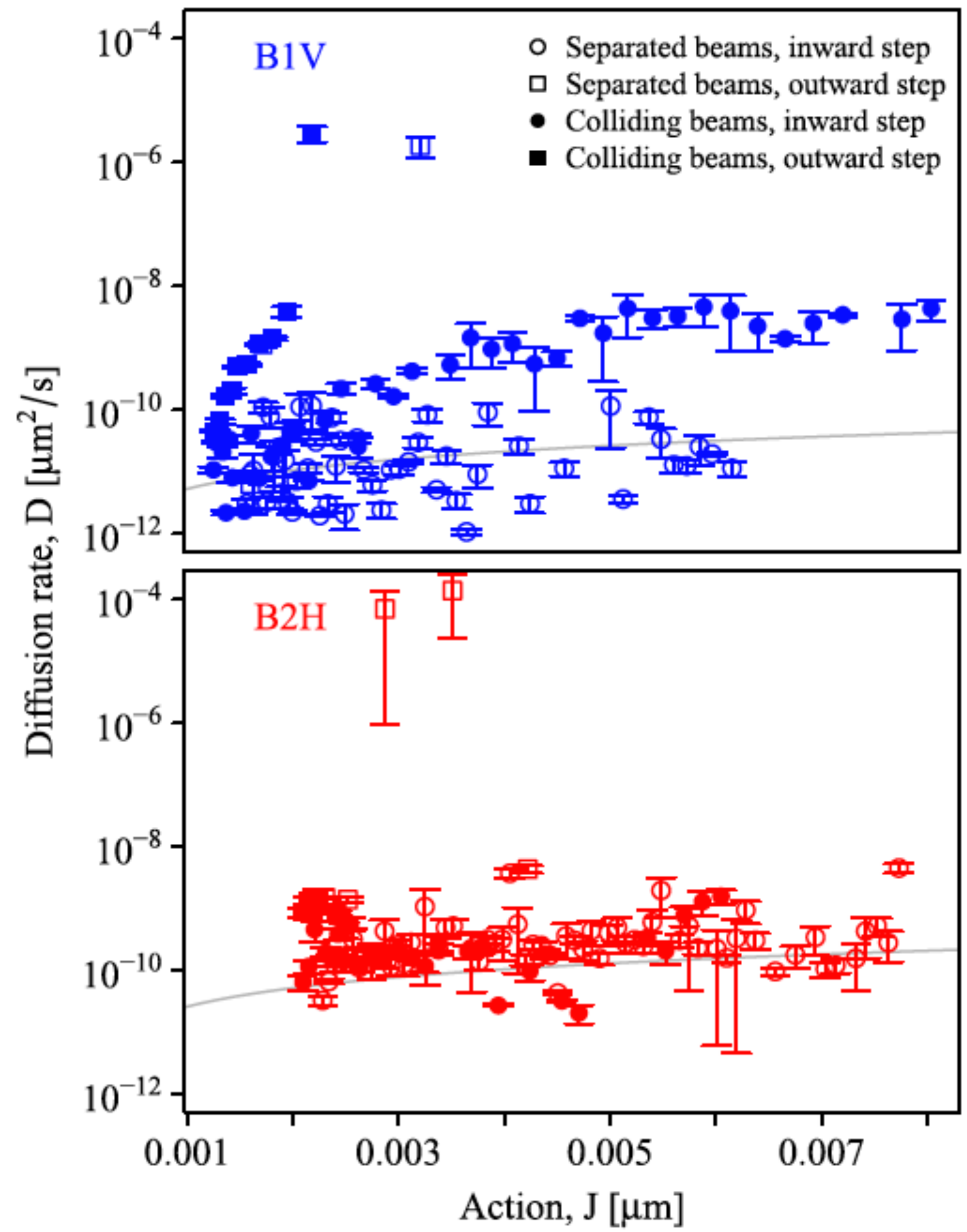
Single beam: diffusion at 4 TeV

- First such MD held in the LHC was in 2012, drawing on the experience in the Tevatron (sampled 7 down to 2 sigma)
- Done with separated & colliding beams with 1 nominal bunch





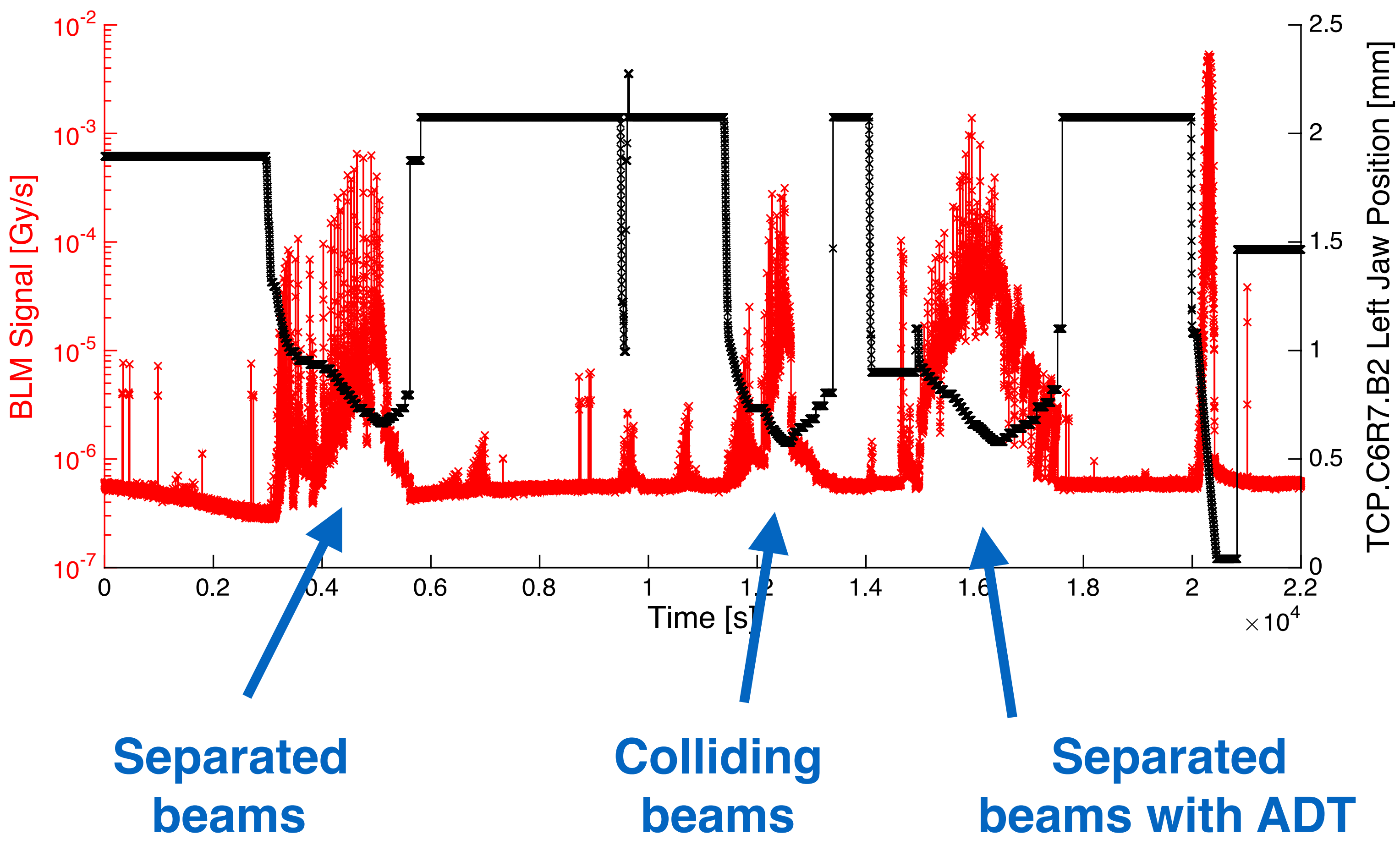
Gray line: diffusion expected from core emittance growth rates

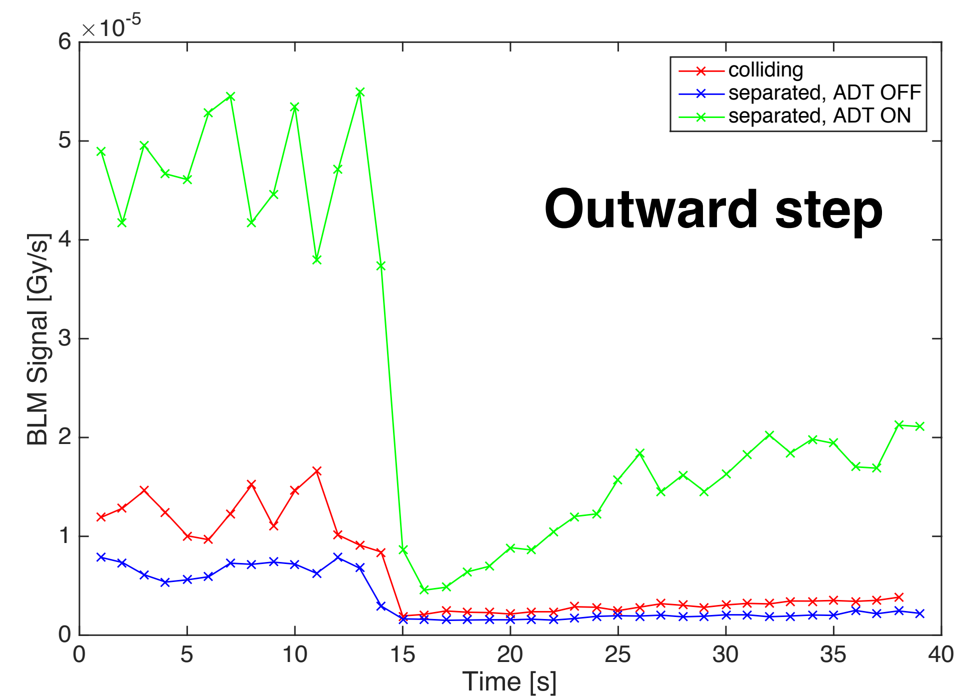


Diffusion is enhanced with collisions in B1 V, no effect for B2 H

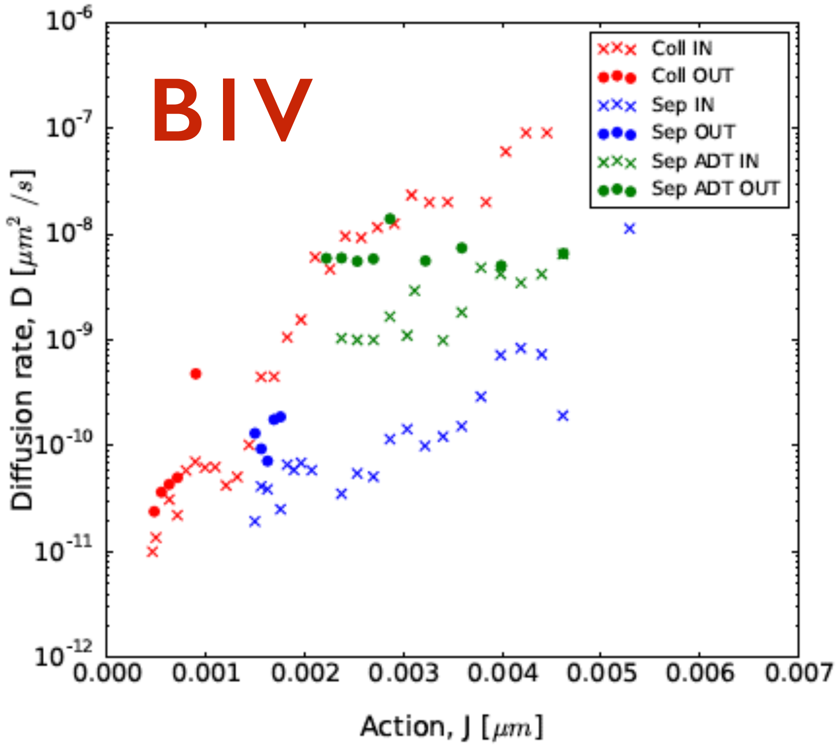
Single beam: diffusion at 6.5 TeV

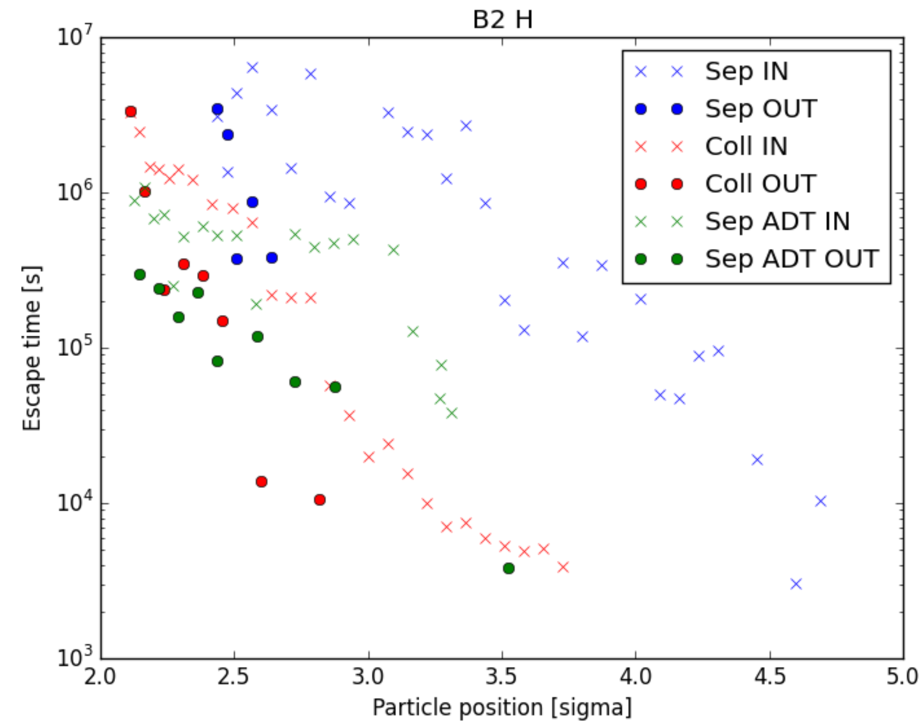
- Dedicated MD performed at 6.5 TeV with separated and colliding beams
    - Sampled range from 7 to 2 sigma
    - Measurements done with 100 Hz BLM data
- Performed scraping also with gentle ADT transverse blow-up running to evaluate effect on diffusion





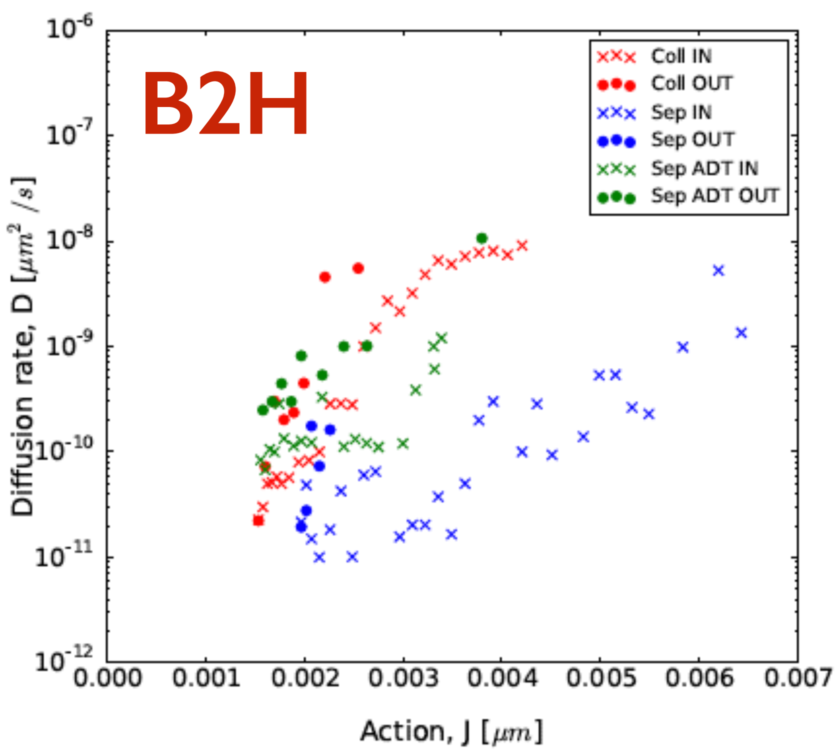
Single beam: diffusion at 6.5 TeV

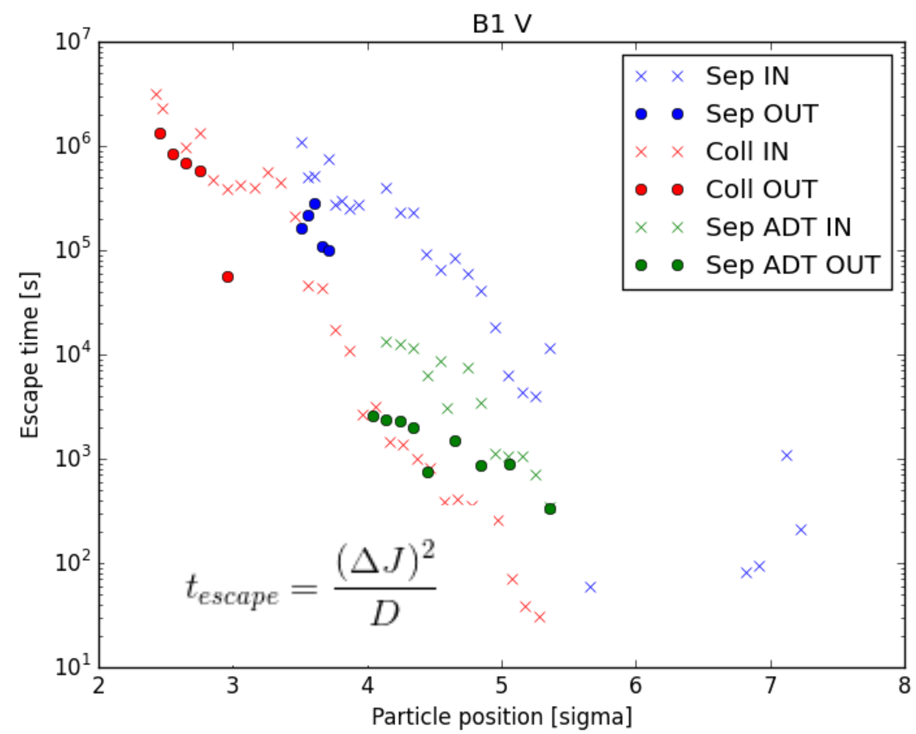




TCP

at 6σ

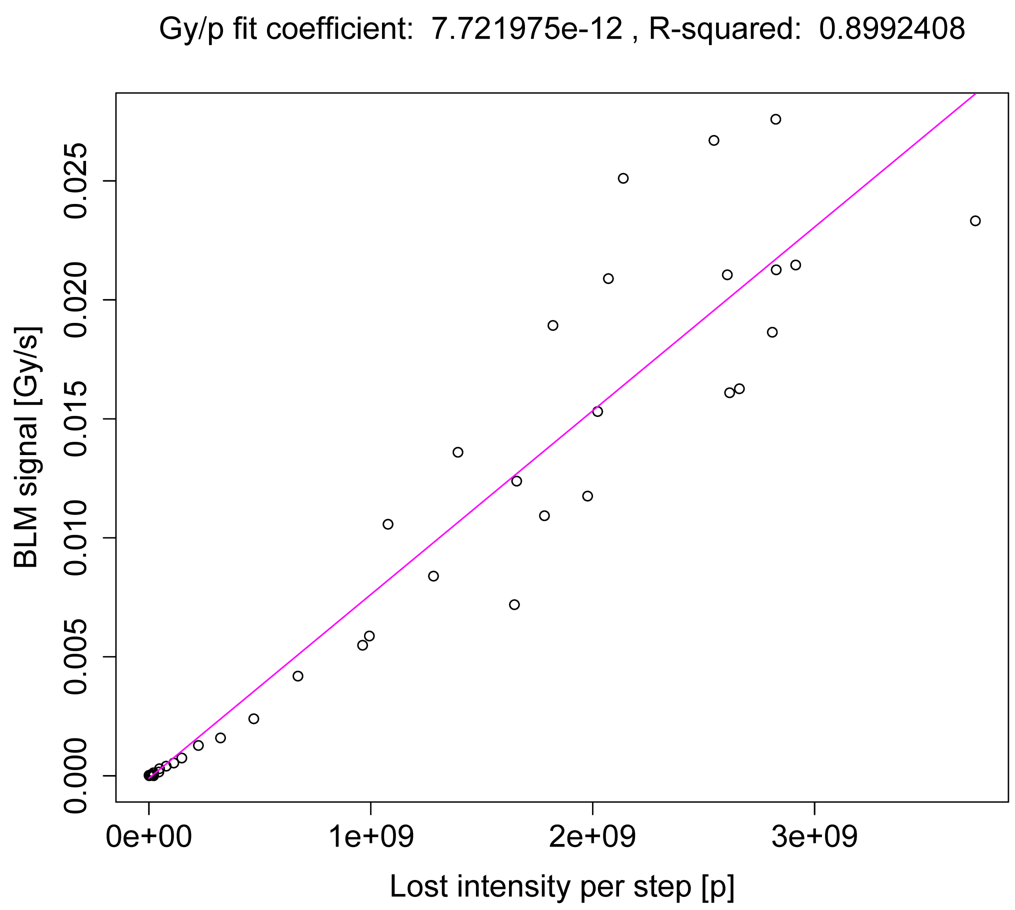


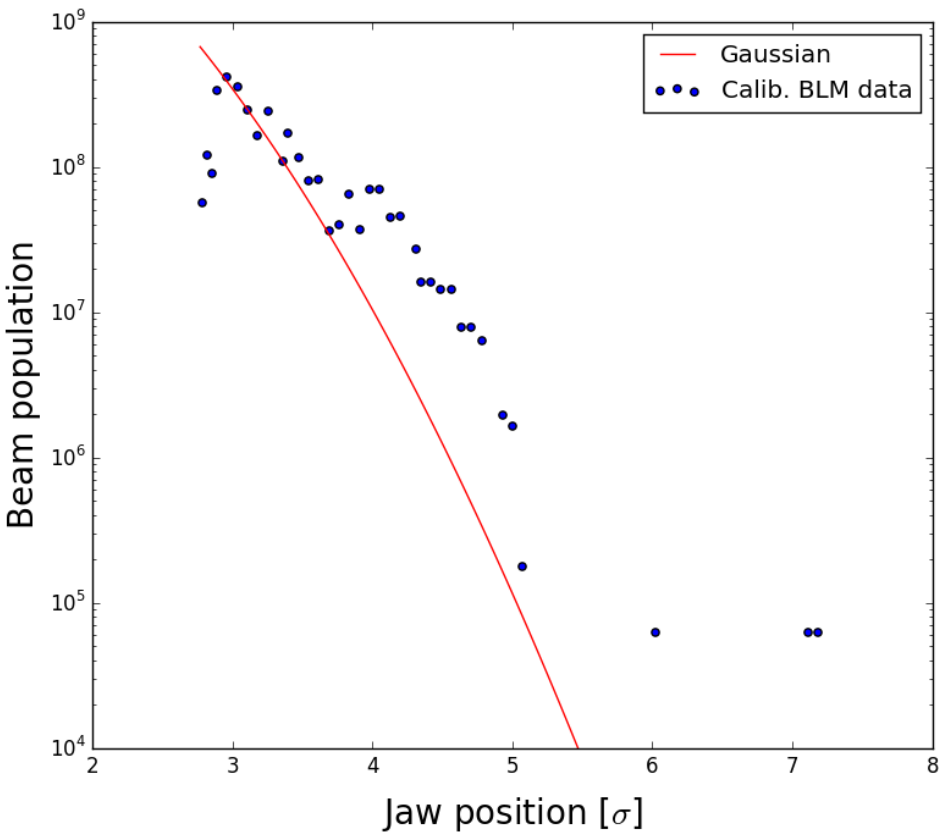


- Difference between inward and outward steps possibly due to different population being sampled.
- Difference between H & V could be due to off-momentum component (only left jaw used).

Single beam: diffusion at 6.5 TeV

- We can calculate the halo population for a given sigma value by using a calibration factor on the BLM spikes during the scraping exercise.
- Advantage: more sensitive to losses than BCT particularly at large amplitudes.

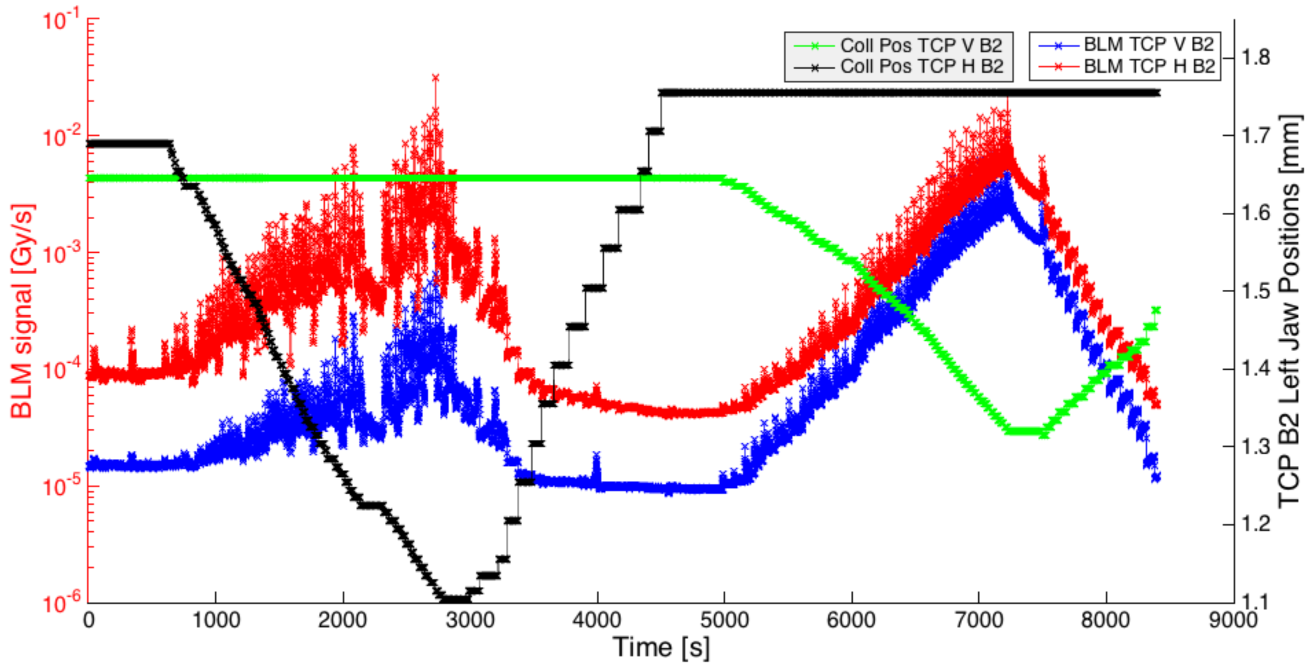


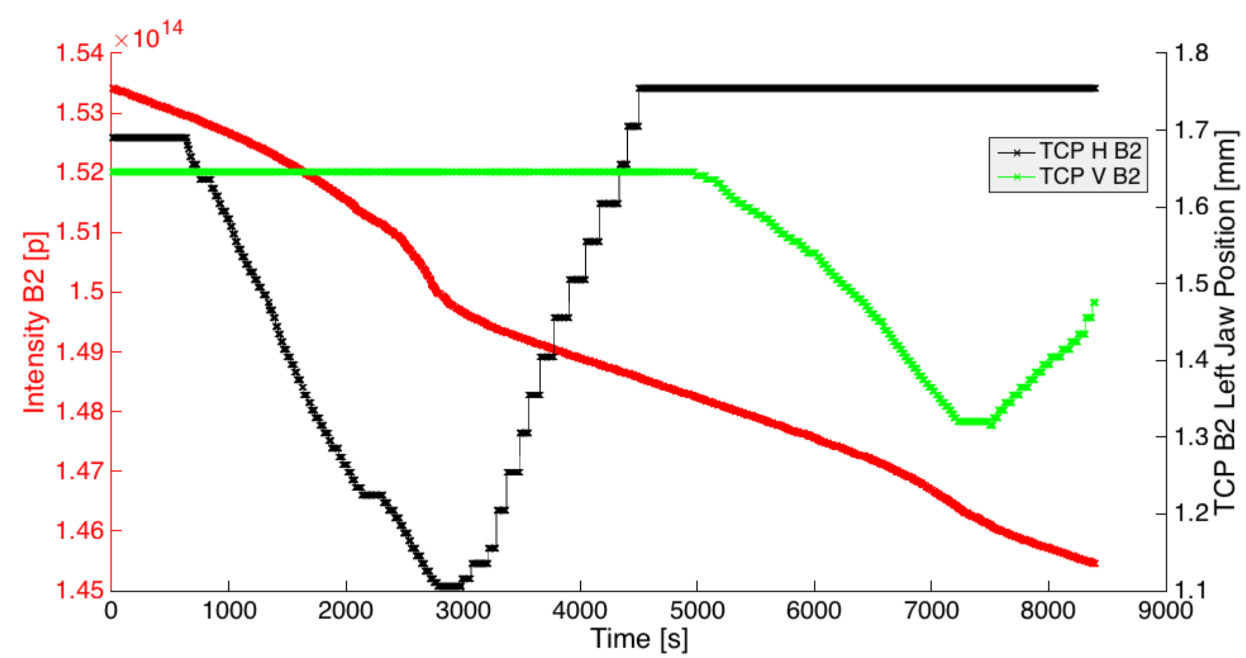


Physics beam: diffusion at 6.5 TeV

- Two End of Fill (EoF) studies were performed in May and July with 300b and 2076b respectively after 6.5 and 20 hours of stable beams.
  - 30 MJ and 172 MJ of stored energy respectively!
- The measurements could only be done in collisions (standard physics resumed after)
- Challenging conditions (jaw could not be moved in further than 3 sigma for MP reasons), but demonstrated feasibility of diagnostic technique!

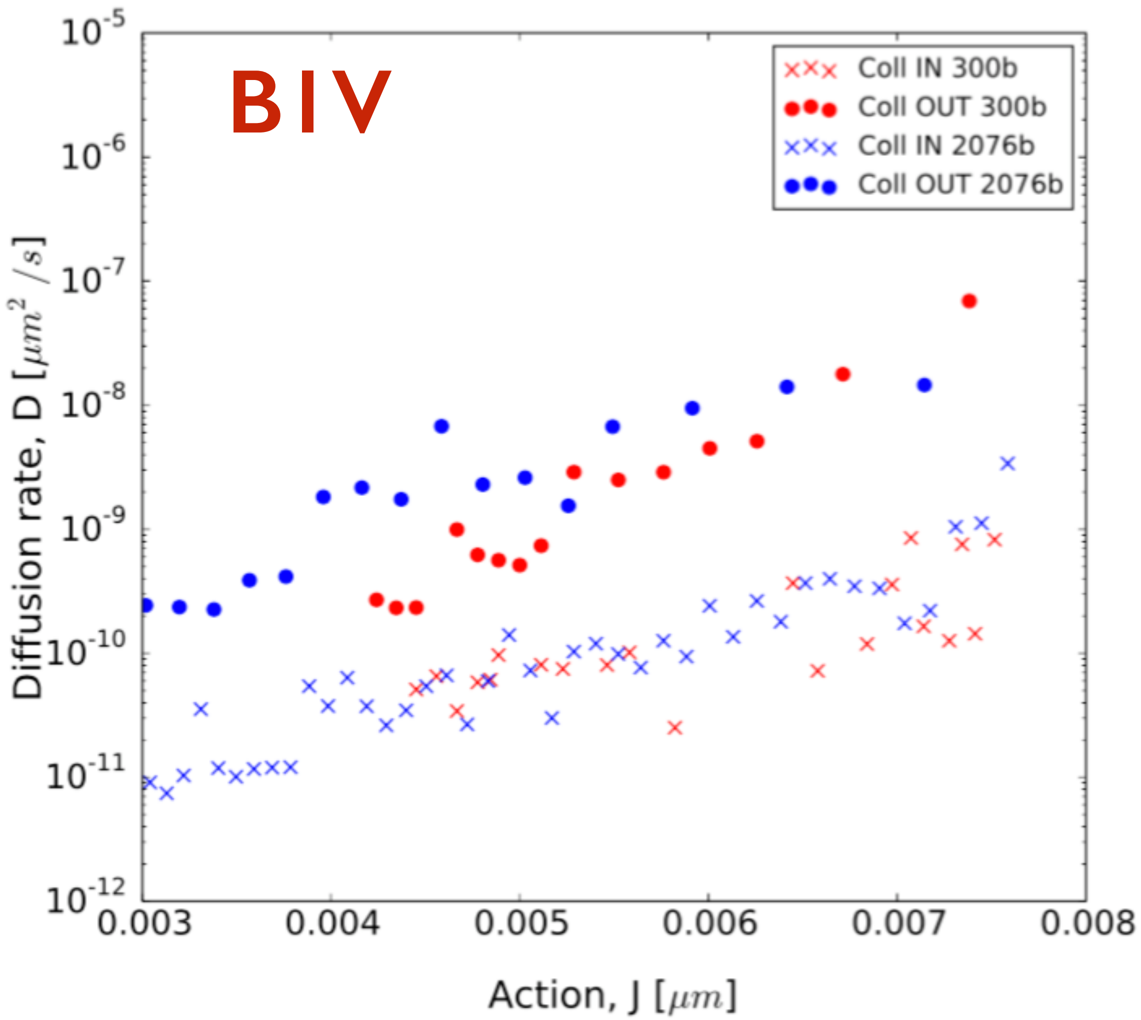
2076b

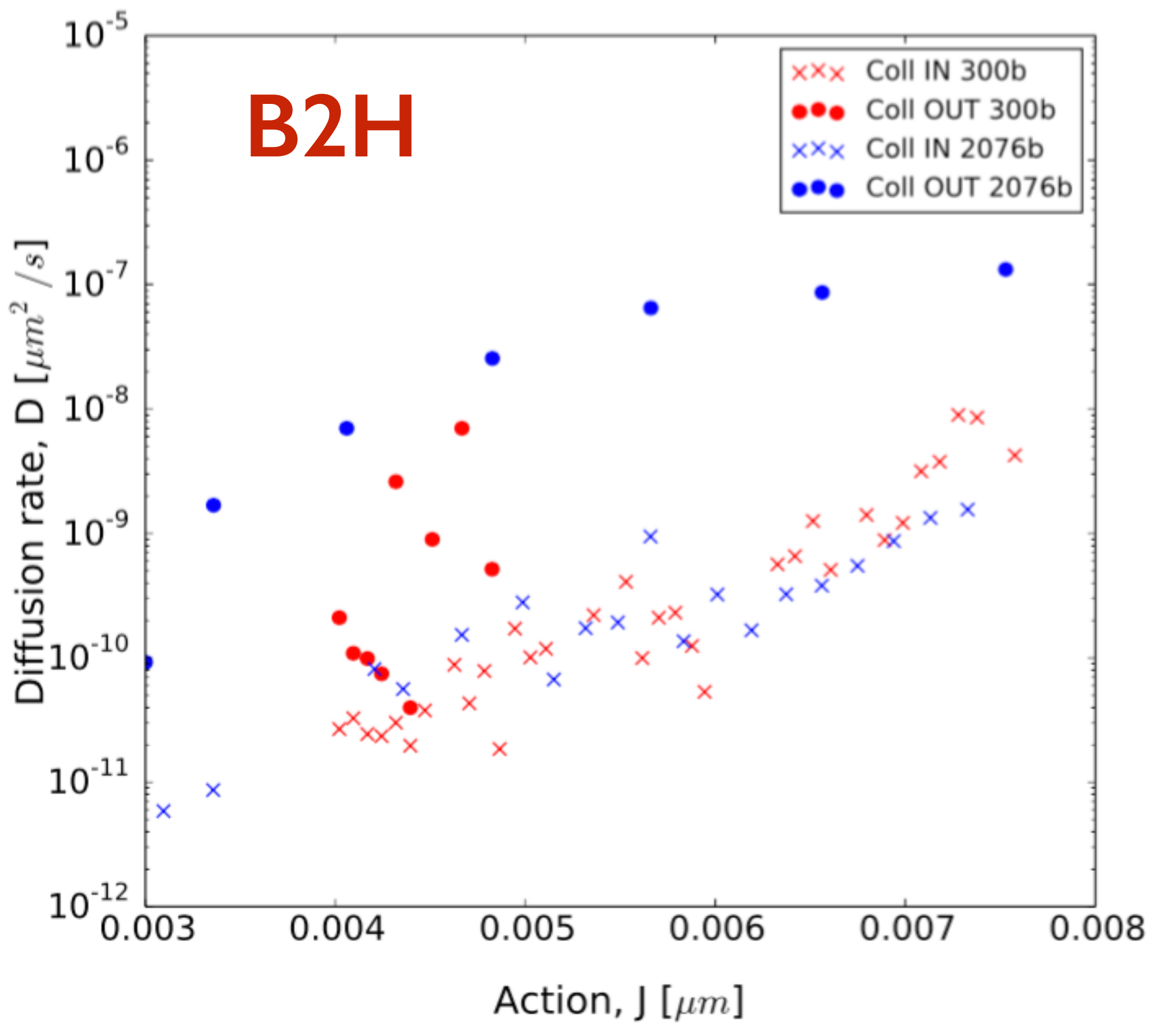




Physics beam: diffusion at 6.5 TeV

300b & 2076b



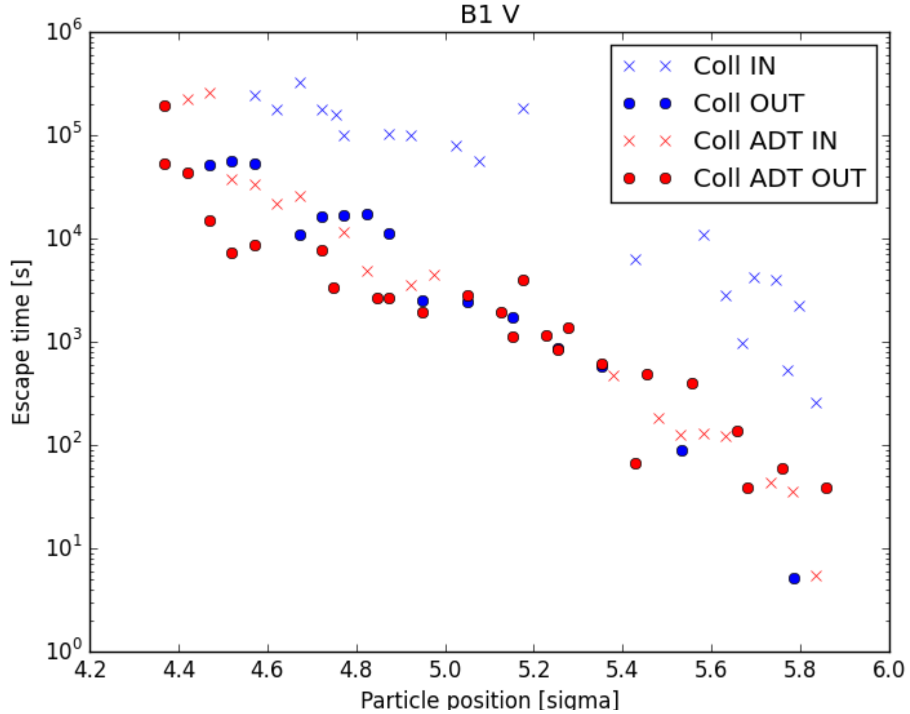


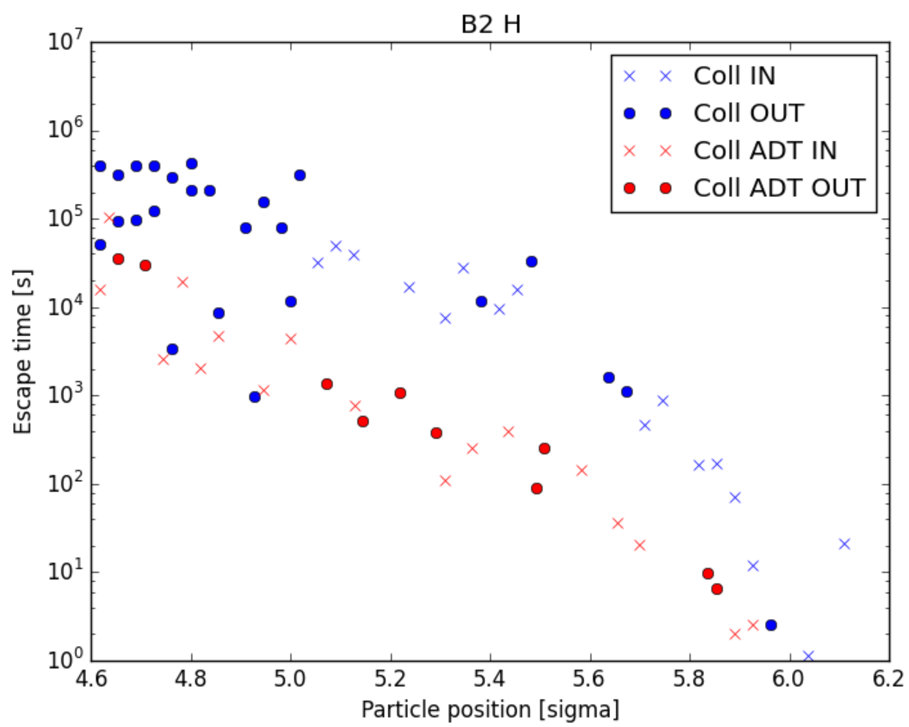
- Very reproducible results from one intensity to another!

Physics beam: Particle escape time

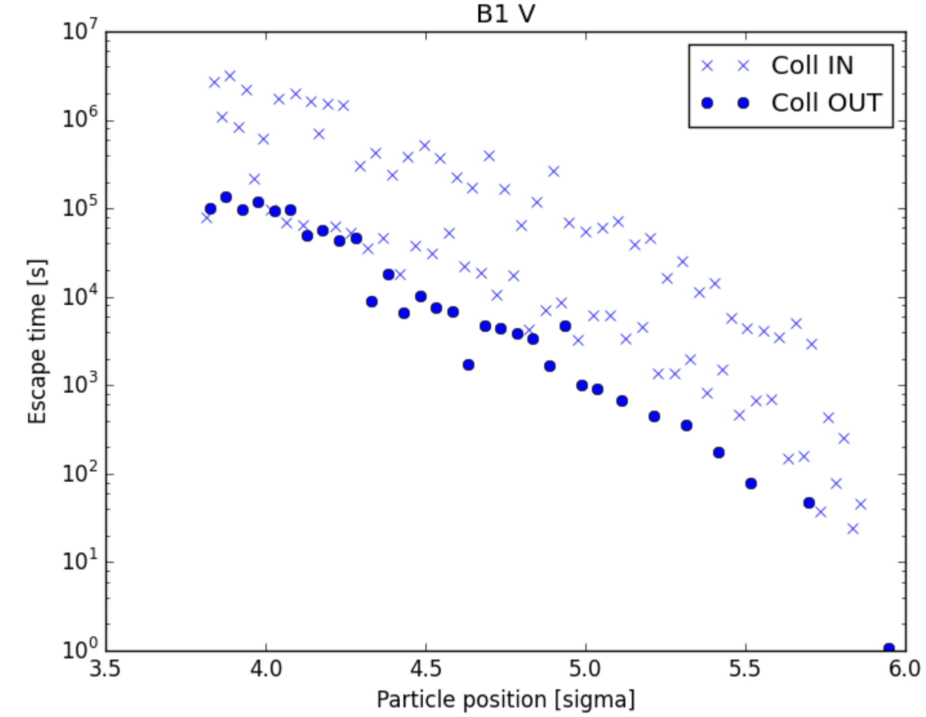
LHC Collimation Project

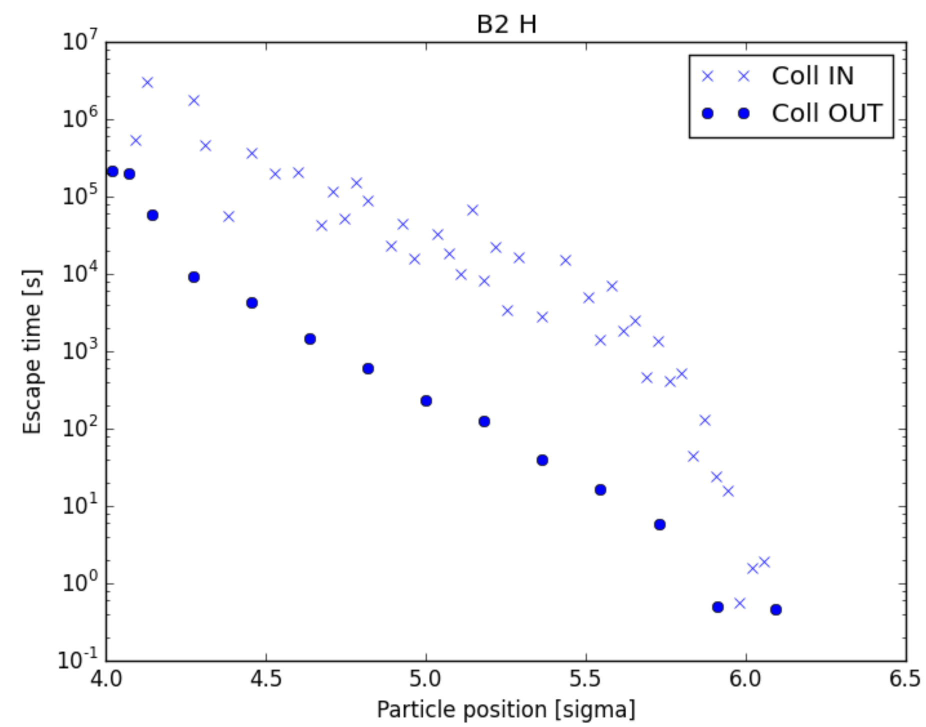
300b





2076b



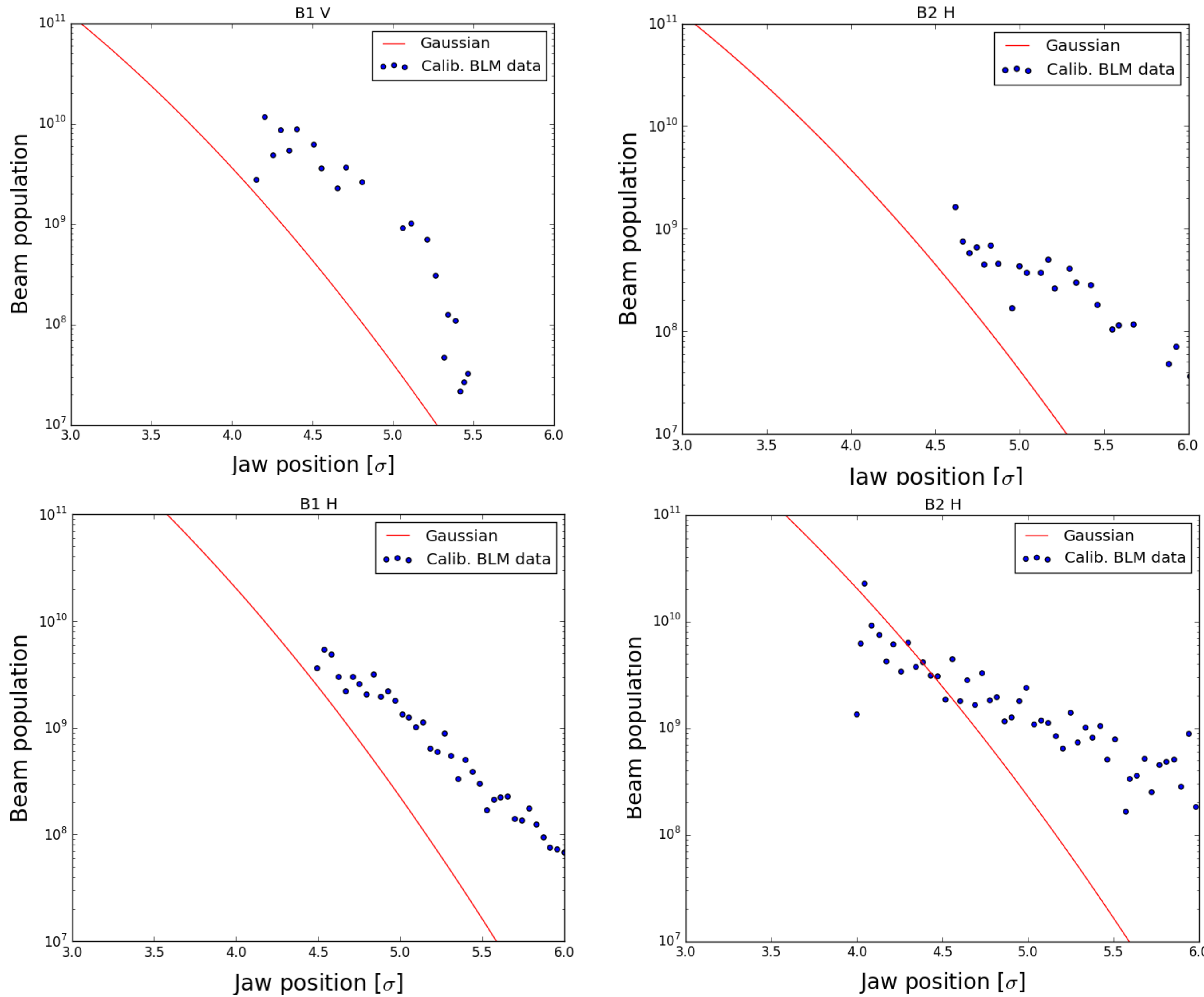


TCP at 6σ

Physics beam: halo population

300b:

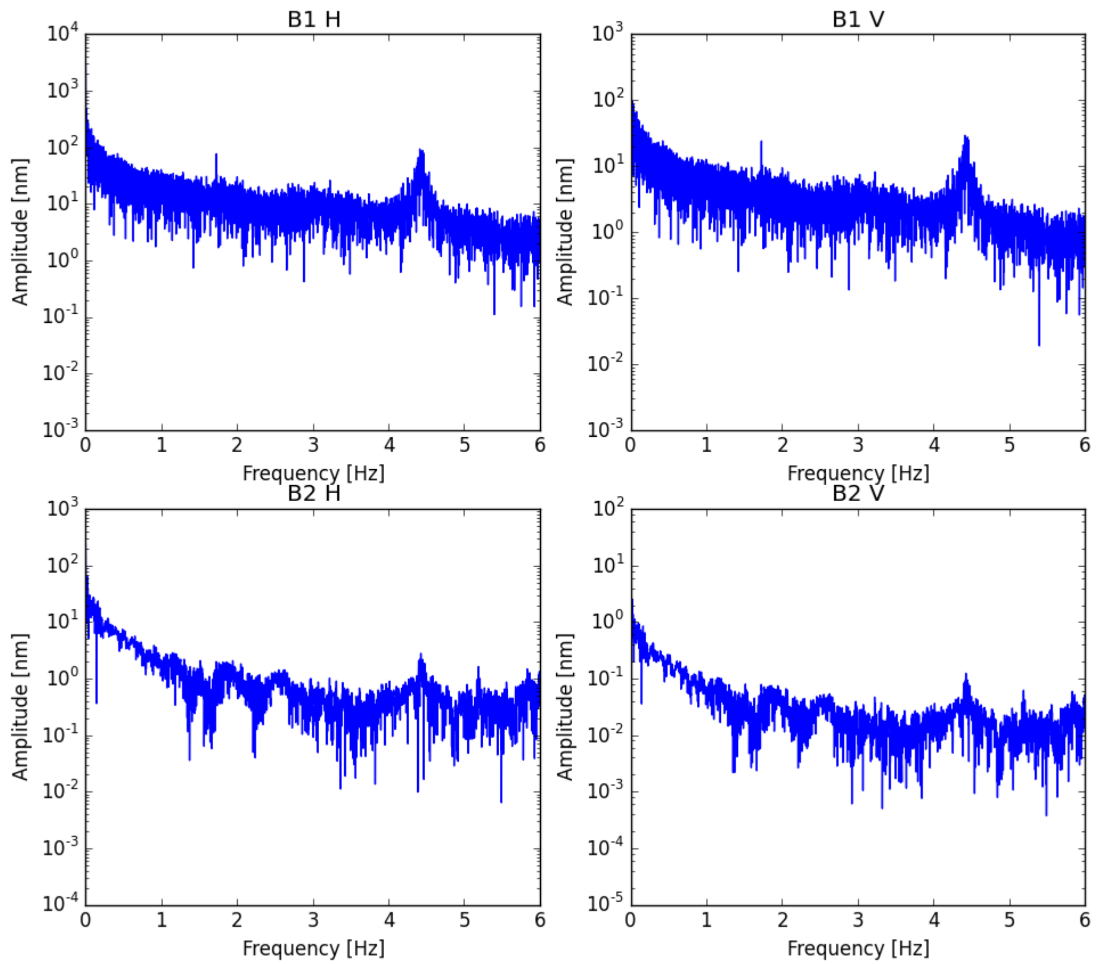
2076b:



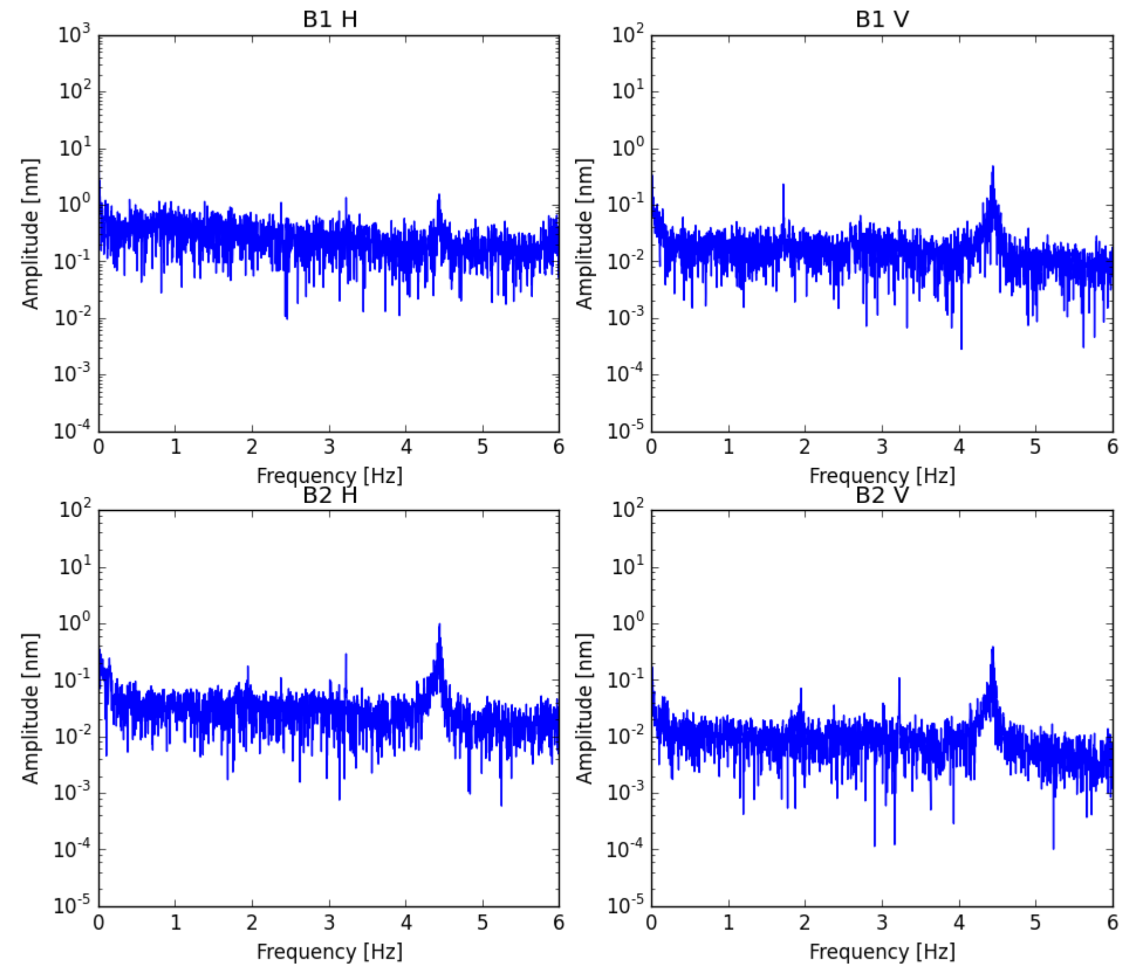
Frequency analysis of beam losses

- The time structure of losses with tight collimator settings is a sensitive probe of beam vibrations.

2076 b with TCP @ 3 sigma



2076 b with TCP @ 5.5 sigma

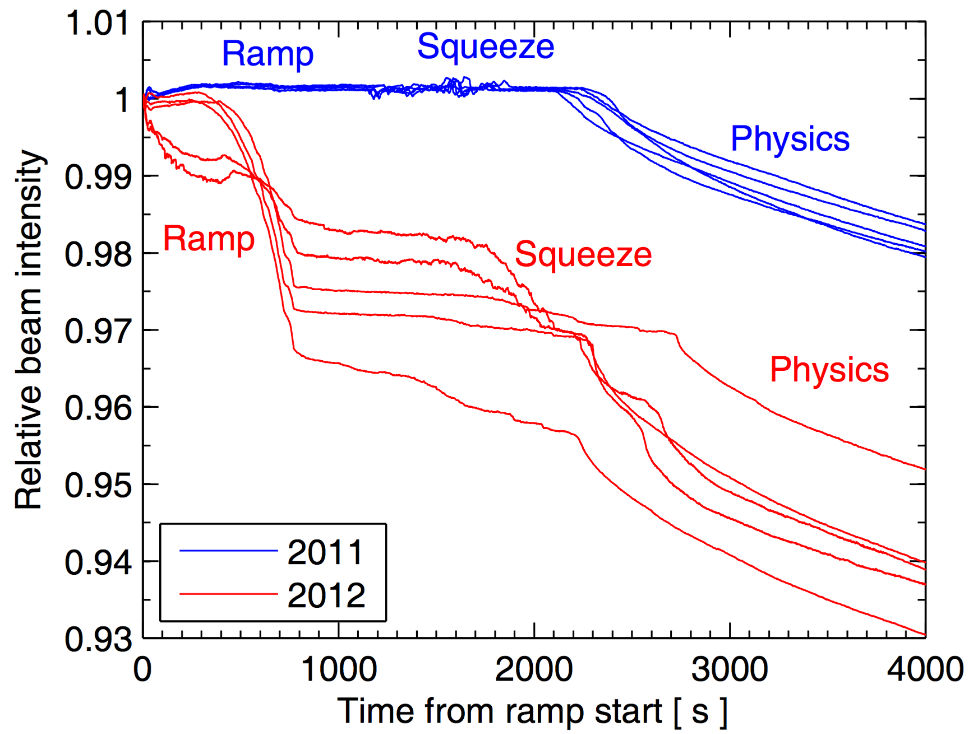


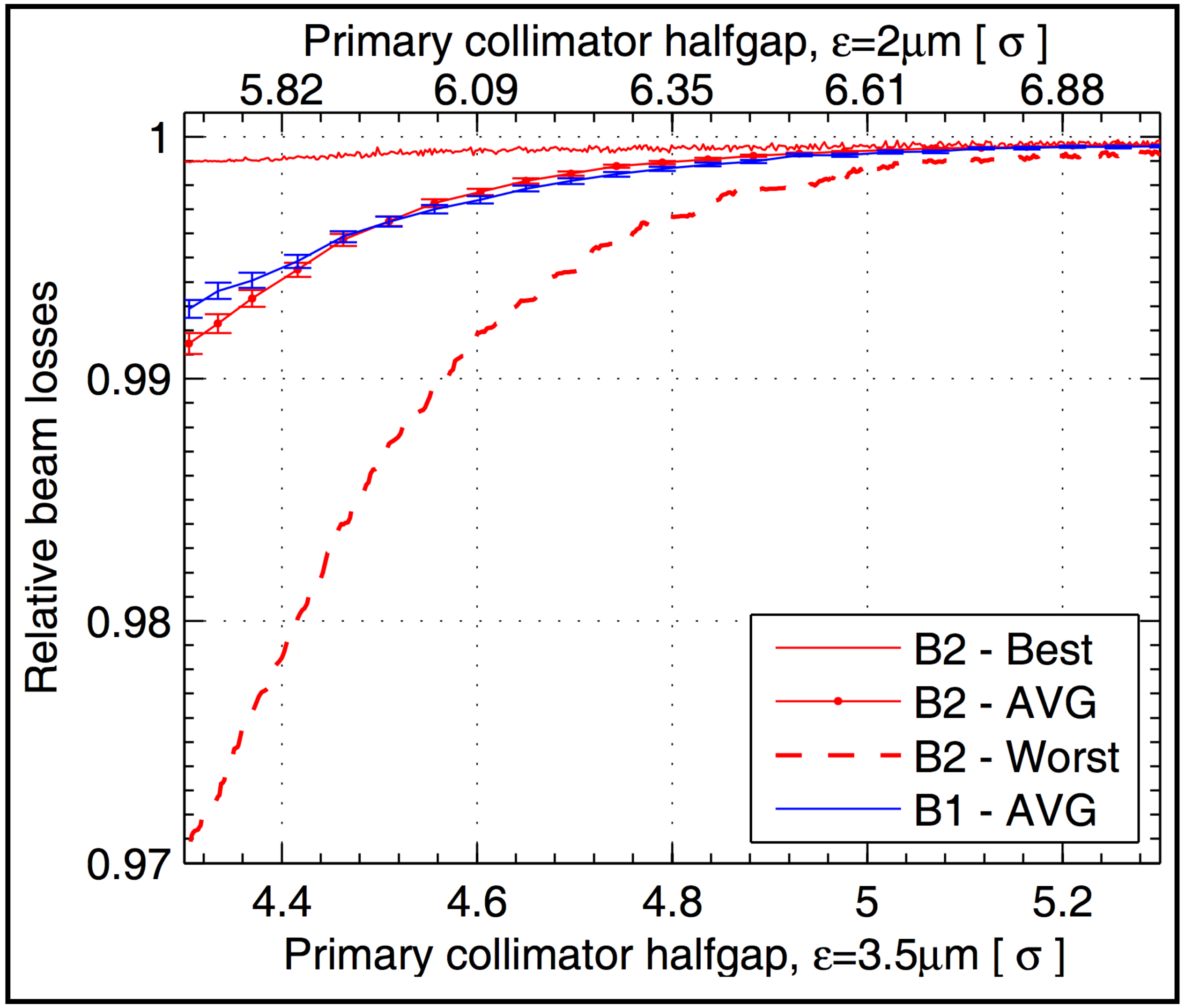
- A distinctive peak is observed at 4.6 Hz, similar to what was seen at 4 TeV (also seen at Tevatron: corresponded to mechanical vibrations of compressors in Central Helium Liquefier).

- Amplitudes in standard physics are lower as jaw is further away.

Observations in operation

Losses in the ramp (2012)





EXPERIENCE WITH HIGH-INTENSITY BEAM SCRAPING AND TAIL POPULATION AT THE LARGE HADRON COLLIDER

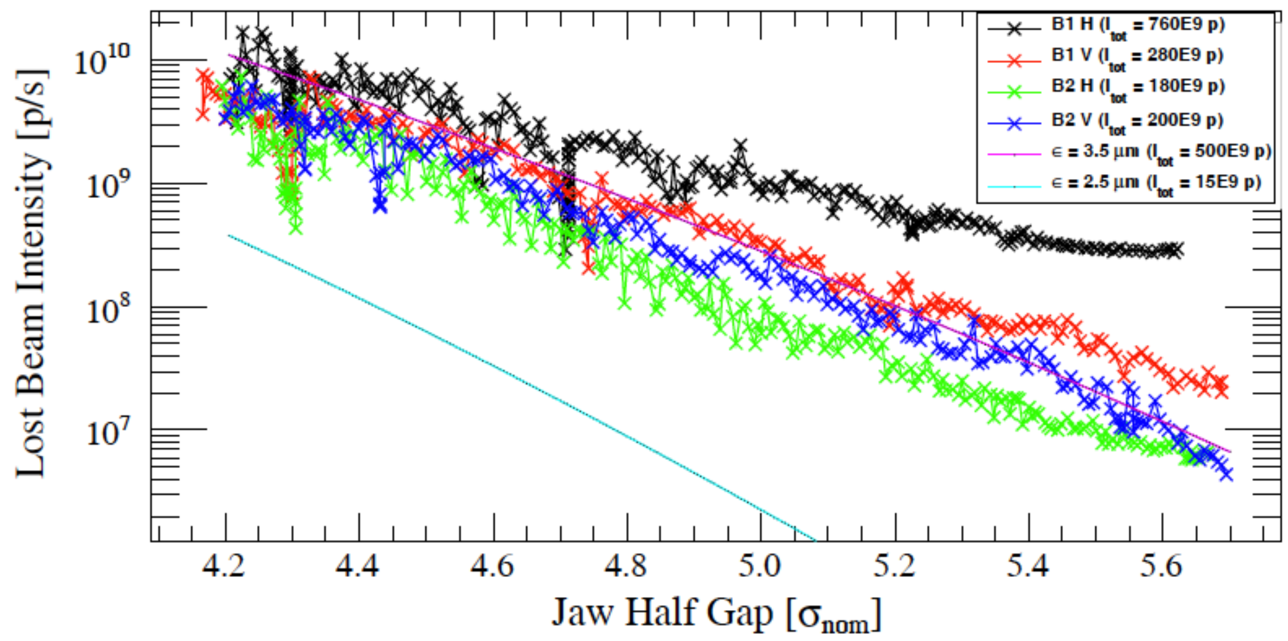
S. Redaelli, R. Assmann, F. Burkart, R. Bruce, D. Mirarchi, B. Salvachua, G. Valentino, D. Wollmann, CERN, Geneva, Switzerland

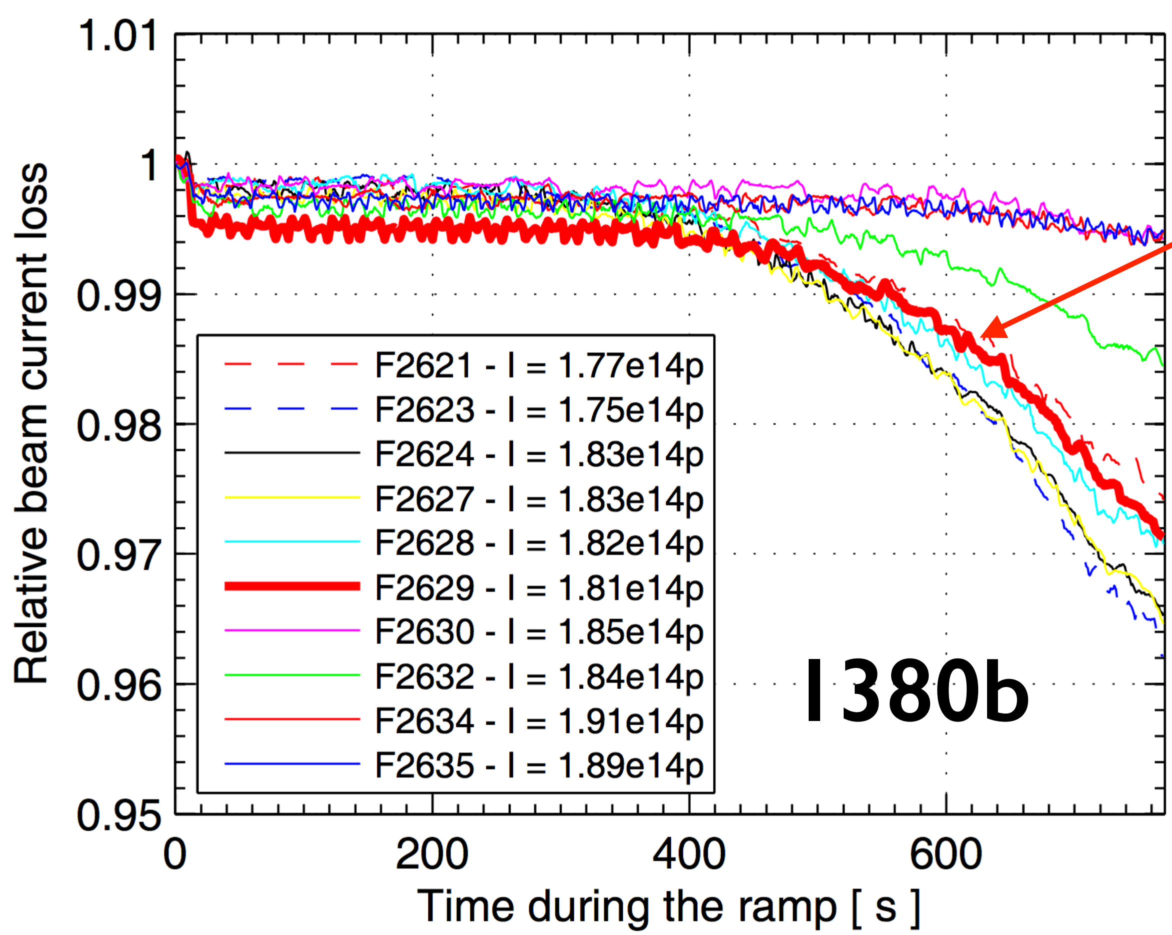
Qualitatively different loss behaviour between 2011 and 2012:
    "tight" collimator settings deployed to fit 60 cm β* at 4TeV.
Primary cut: 5.7σ - 4.3σ (ε=3.5μm) during the ramp.
"Slow" losses at the end of the ramp; sensitive on orbit jitters in the squeeze.

Observations in operation

LHC Collimation Project
CERN

- Observed losses appearing in the last 200 s of the ramp
- Significant losses started below 5 nominal sigma (or 6.6 real sigma)
- A single measurement was carried out on May 15th 2012 to understand to what extent these ramp losses are related to the tail population at injection
- Scraped down to ~4.2 nominal sigma in H and V





Transverse tails scraped at injection - no difference in losses (note - low statistics: tried only once).

Beam tails are therefore repopulated during the ramp

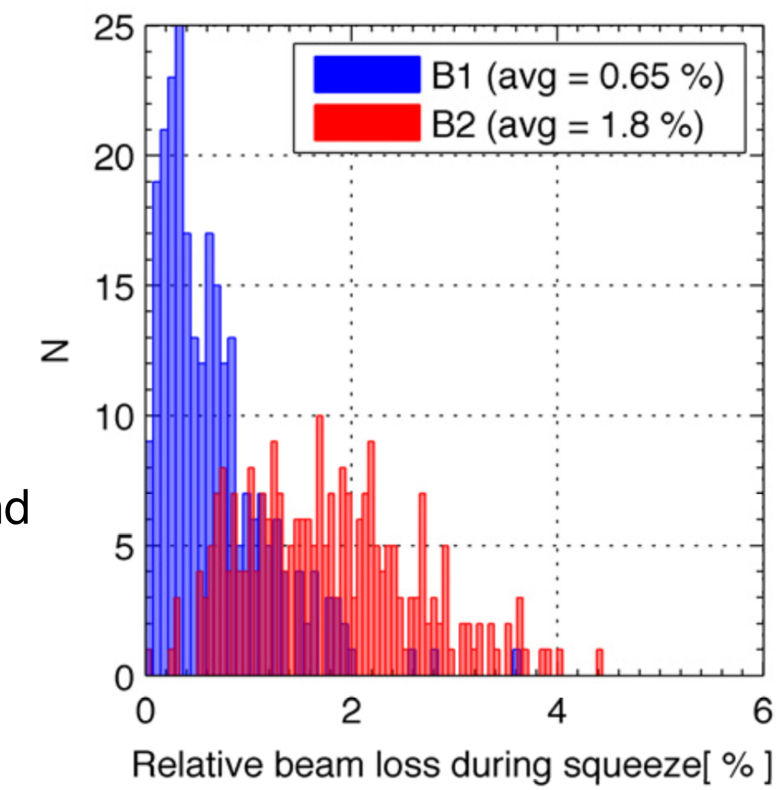
S. Redaelli

Observations in operation

Losses in the squeeze (2012)

- No changes in IR7, so losses at TCP are driven by local orbit jitters
- Maximum orbit drifts at TCPs wrt absolute reference from collimator alignment are around 0.36 nom sigma (H) and 0.43 nom sigma (V)

Data from 65 squeezes



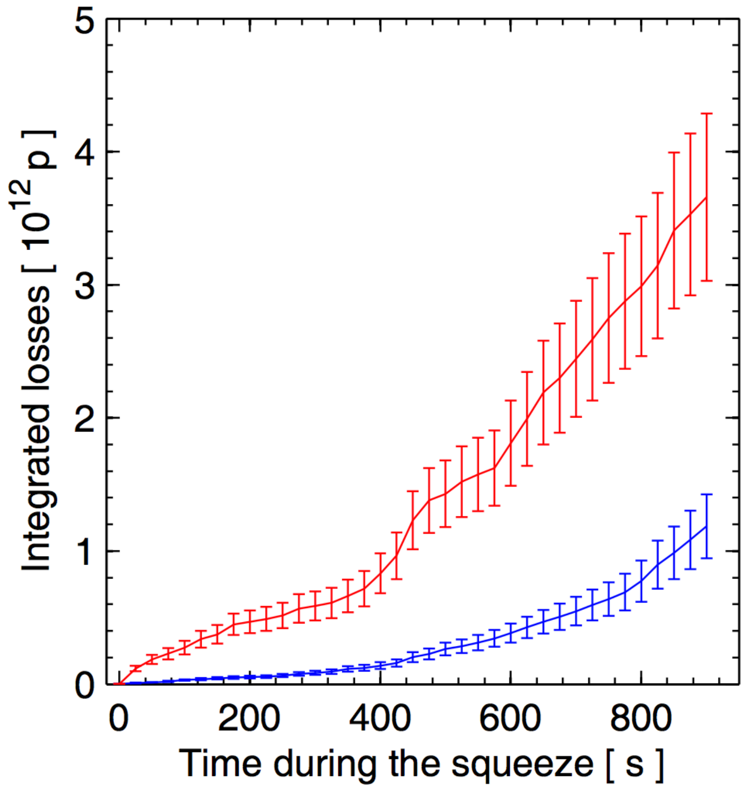
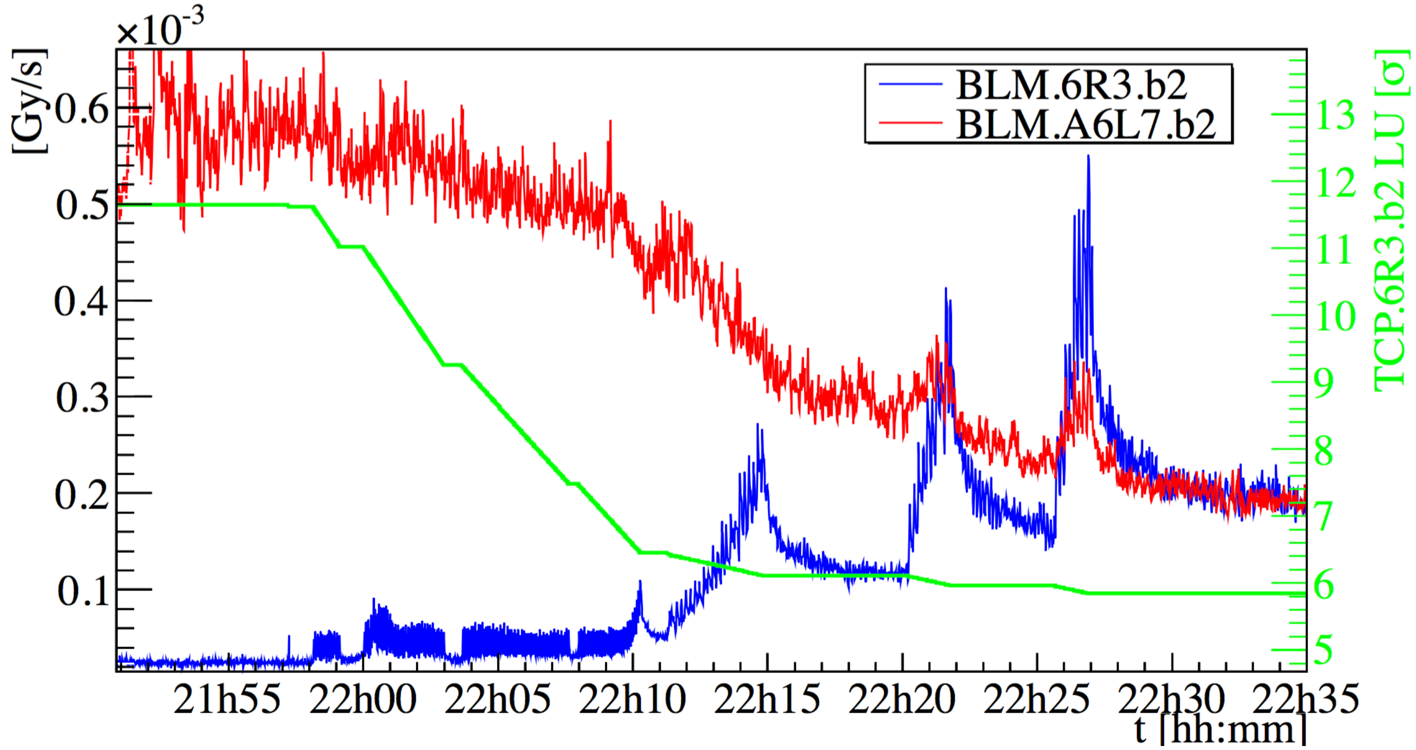


Table 1: Tail populations measured in ramp and squeeze of standard physics fills in 2012.

	Ramp		Squeeze	
	B1	B2	B1	B2
Percent losses	0.7 %	0.9 %	0.7 %	1.8 %
Amplitude, σ_{nom}	4.3-5.7	4.3-5.7	4.0-4.3	3.9-4.3

S. Redaelli

Observations in operation

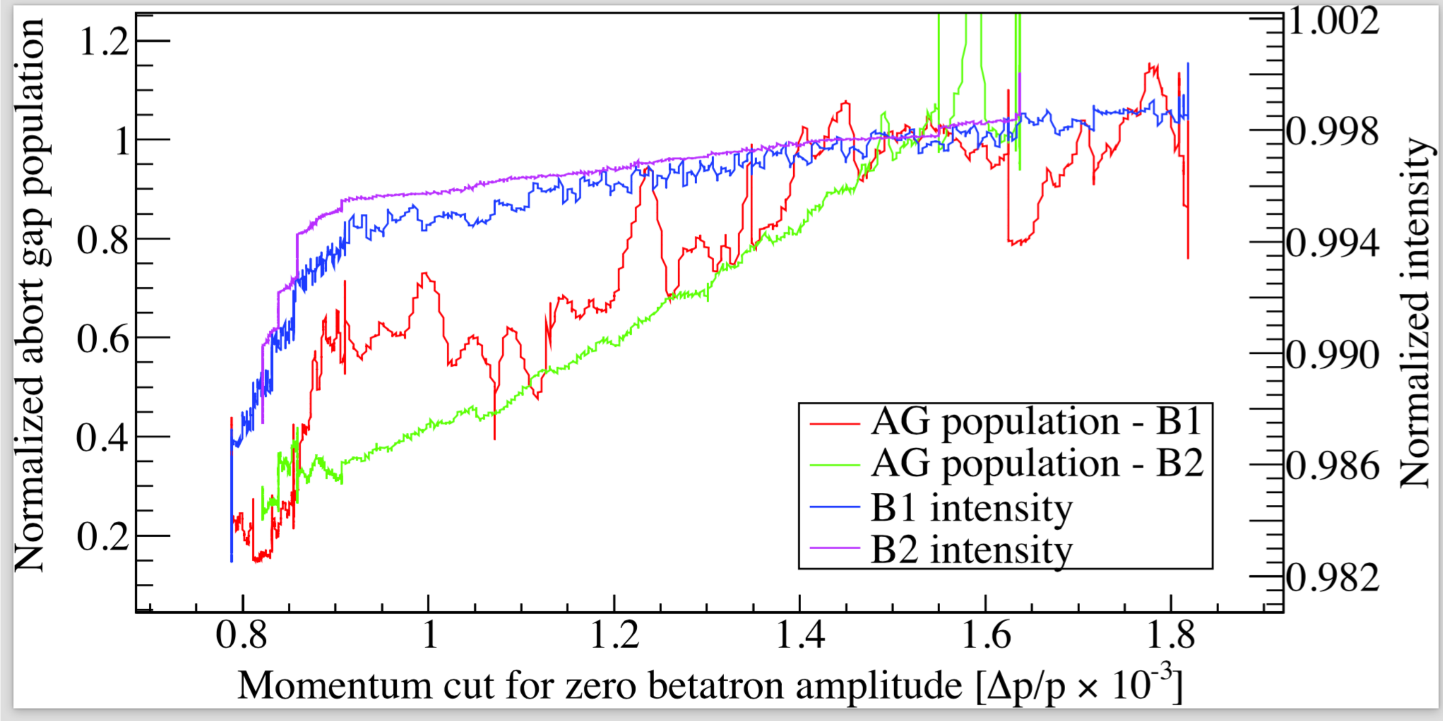


Off-momentum tail population

End-of-fill study in 2012: 400 bunches at 25ns spacing.

D. Mirarchi

- TCP jaw on negative off-momentum side closed from 12 to 6 nominal sigma
- Disregarding initial beam loss rate in collision, only a fraction of a percent of beam is found in the Δp/p range between 0.8E-3 and 1E-3



Conclusions

- **Reviewed the experience** in operation and with dedicated collimator scans for halo measurements at the LHC
  - Scans provide good diagnostics for precise measurements below 5 sigma
  - Several measurements performed at different energies and beam conditions
- **Halo population:** in a majority of cases, the beam tails above 3.5 sigma are more populated than a standard Gaussian by a factor 20.
- **Diffusion speed and escape times** provide valuable input for HEL operation in HL-LHC.
- Bunch-by-bunch analysis of latest scraping MD with 2076b ongoing
  - Look forward to additional measurements now that diamond BLMs are available!

References

- *Beam Loss and Beam Shape at Collimators*, F. Burkart, CERN-THESIS-2012-046 + IPAC'11 paper
- *Meausrements of transverse beam halo diffusion rates in the LHC with collimator scans*, G. Stancari et al., FERMILAB-FN-0950-APC
- *Beam diffusion measurements using collimator scans in the LHC*, G. Valentino et al., *Phys. Rev. ST Accel. Beams, **16** 021003 (2012)*
- *Collimation down to 2 sigma in special physics runs in the LHC*, H. Burkhardt et al., IPAC'13
- *Experience with high-intensity beam scraping and tail population at the Large Hadron Collider*, S. Redaell et al., IPAC'13
- *Diffusion and halo population measurements with collimator scans at 6.5 TeV*, G. Valentino et al., CERN-ACC-NOTE-2016-0010.