LHC Emittance Preservation during the 2012 Run

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Reminder: 2011 Results

LHC

1. No measureable blow-up from injection process
   - Sensitivity: ± 10 %

2. Blow-up during injection plateau → bunch-by-bunch differences, smallest effect on total emittance blow-up
   - Consistent with IBS simulations
   - 0 – 10 %, different for different batches

Measured again in 2012
Tried RF batch-by-batch blow-up

3. Significant blow-up during the ramp
   - > 20 % for 1.6 μm

Tried higher damper gain in 2012

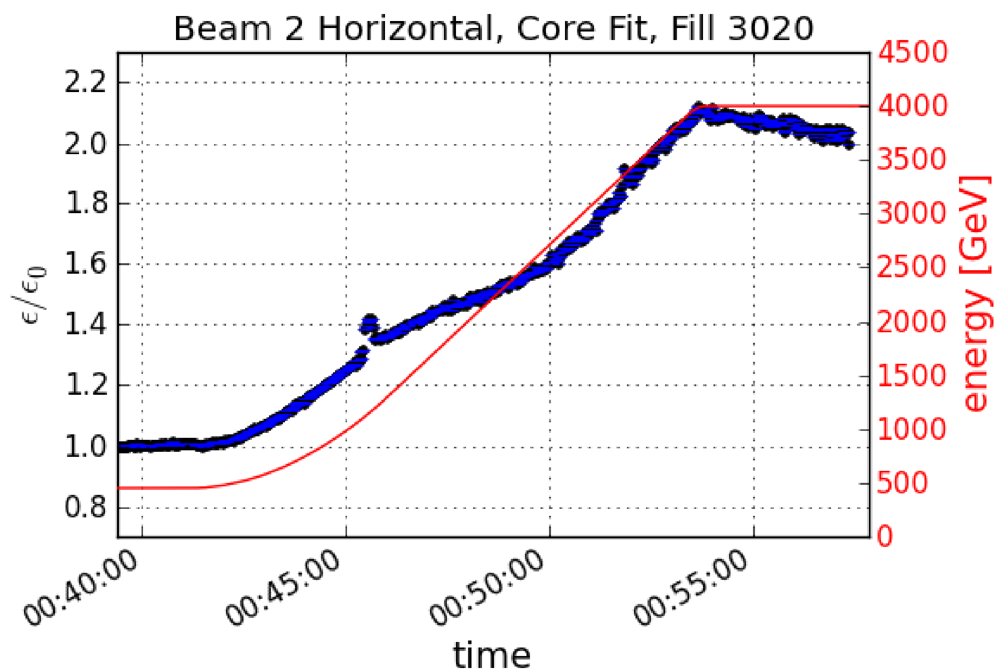
4. Blow-up during the squeeze for beam 1, horizontal plane
   - > 20 %

5. Absolute emittance growth through cycle independent of bunch intensity and emittance
   - $\Delta\varepsilon$ ~ 0.5 – 0.6 μm for convoluted, averaged emittance from luminosity

Emittance Measurement Situation (1)

- Cannot measure physics beams through the LHC cycle:
  - Indirect measurement of convoluted emittance through luminosity and luminous region at the end of cycle
- 2012 wire scanners:
  - Can we trust the beam size from the wire scanners? See later…
  - Intensity limit even lower since switch to spare system after TS3: can only measure 2.7 x 10^{13} at 450 GeV and 3.1 x 10^{12} at 4 TeV
  - One wire broken: no more measurements for physics injection since fill 3287 (14.11.2012)
- 2012 BGI
  - BGI not bunch-by-bunch, calibration with wire scanner and BSRT
  - Only beam 2 working, since June 2012 data for most fills
  - Energy dependent calibration not satisfying yet

Ramp with BGI: beam 2 H, fill 3020, 1374 bunches



Emittance Measurement Situation (2)

- 2012 BSRT:
  - Calibrated with wire scanner
  - Since September 2012 only beam 1 working
  - Expert fast scan available since May 2012 (scans on demand)
    - scans 3 - 4 bunches per second, 1380 bunches in ~ 7 min
  - New server with fast scan available since October 2012 (fully automatic scans)

- General issue:
  - Optics measurement in IP4: beta-beat values with large errors
    - due to BPM errors and systematic errors from the MQYs
      - Analysis takes this into account and leaves out BPMs with larger error
      - Procedure needs to be optimized, no reasonable ramp data yet
  - Eventually repeated with k-modulation during MD II (fill 2778, 24.6.2012)
    - Smaller errors!
    - Beta functions at injection energy, flattop energy and after squeeze

Emittance Measurement Errors

- Emittance from Wire Scanners
  - Transverse profiles are fitted offline to the core (80%) with a Gauss function.
  - Beam sizes are averaged over in and out wire scan and if applicable over one batch
  - Beta functions are measured with k-modulation
  - Error bars include beta function error, fitting error and error from averaging.
  - Error on beam size from wire scanner might be large: see later in this talk

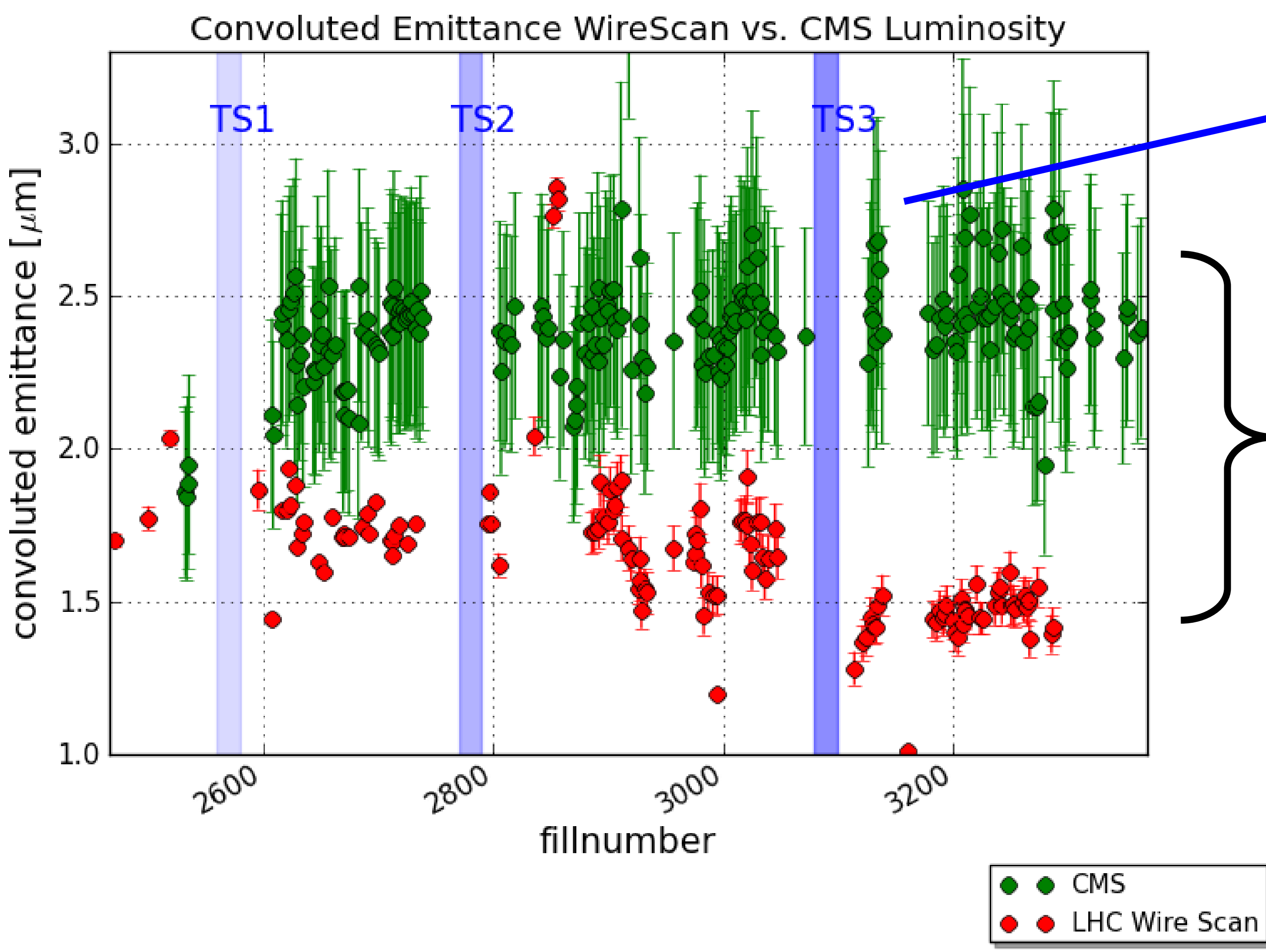
- Emittance from luminosity or luminous region
  - Luminosity: convolutes beams and planes
  - Luminous region: convolutes beams and assumes round beams
  - Uncertainties due to β^* and crossing angle

- Emittance from BSRT
  - Systematic error from optical magnification
  - Energy dependent systematic error from imaging

2012 – Overall Results

- Comparison of wire scans in LHC with emittance from luminosity
  - Convoluted emittance $\varepsilon_{conv} = \frac{1}{2}\sqrt{(\varepsilon_{1H}+\varepsilon_{2H})(\varepsilon_{1V}+\varepsilon_{2V})}$
    - ❑ ± 15 % error on beta function and ± 5 % error on crossing angle

Total emittance growth with Q26 optics in SPS ~ 0.7μm



After TS3: changed to spare wire scanners in LHC and Q20 optics in SPS

Total emittance growth with Q20 optics in SPS ~ 1μm

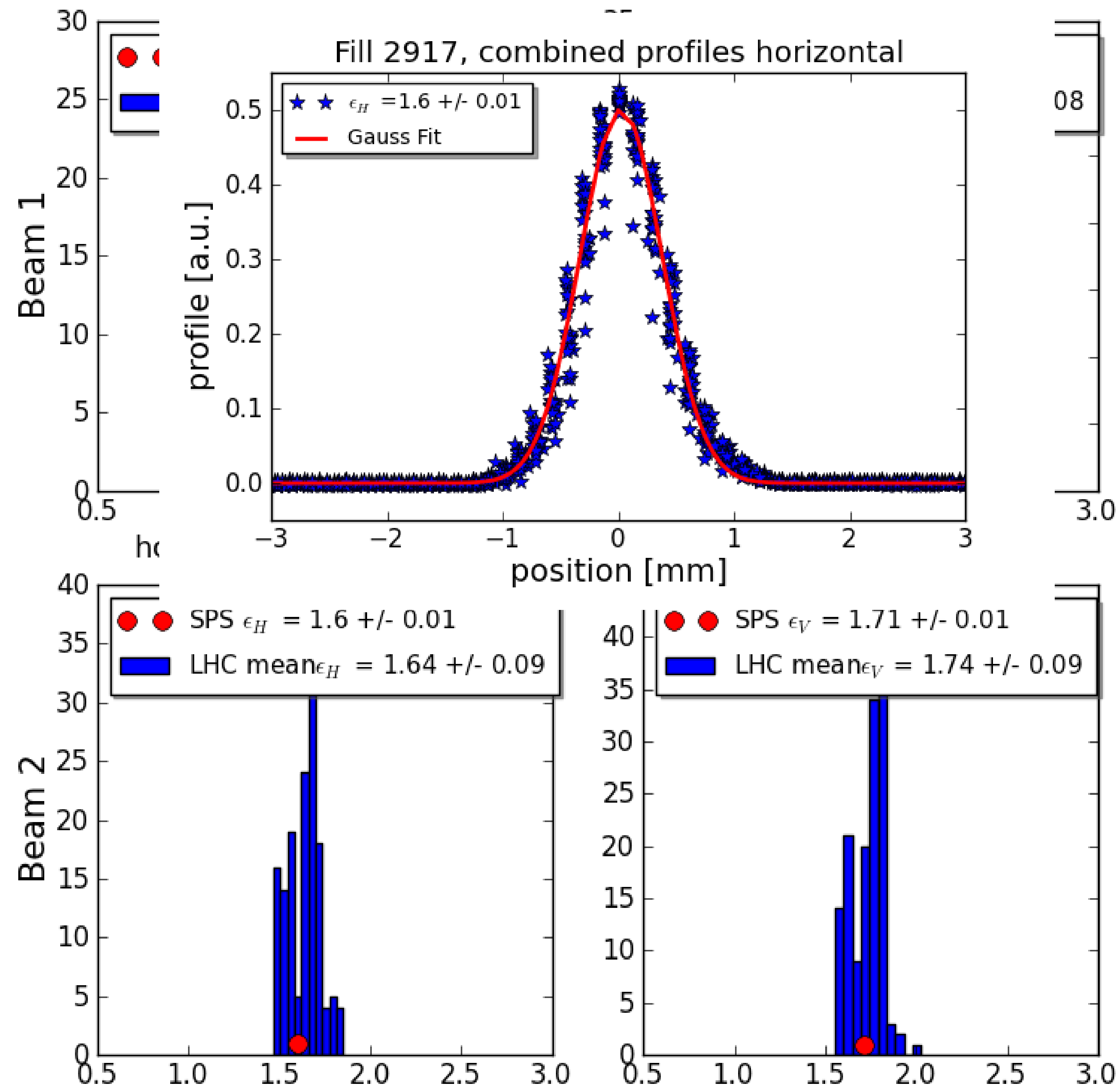
- Same results for emittance from luminous region

Injection: Emittance Preserved Like in 2011

- Wire scan of LHC beam at SPS extraction vs. wire scan at LHC injection
  - first batch, 144 bunches
  - LHC bunch-by-bunch measurement
  - Increased SPS accuracy: combine profiles of several scans for fit

➔ No mismatch at injection

Emittances are conserved within measurement accuracy between SPS extraction and LHC injection

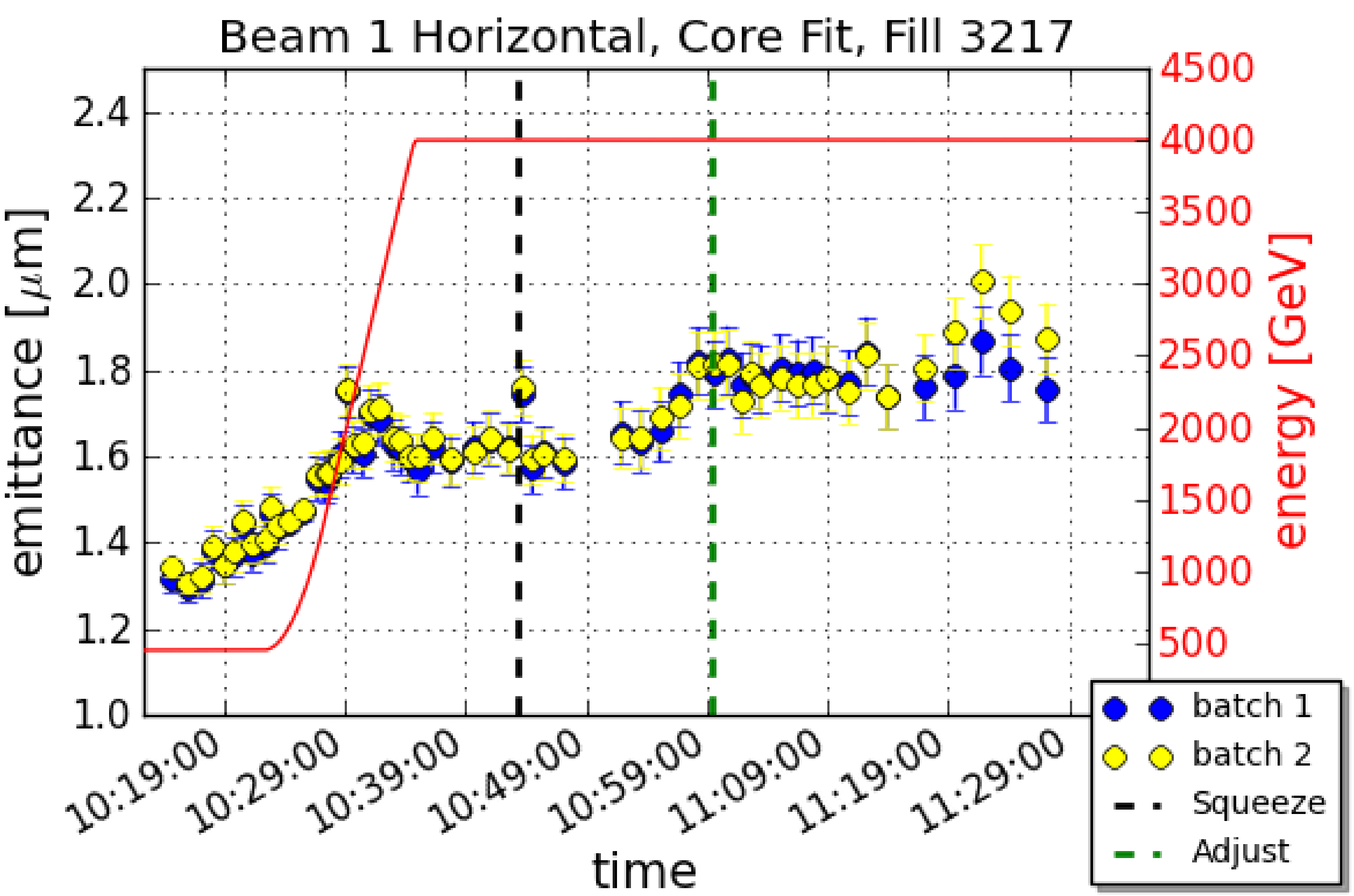


SPS in red, LHC in blue.
SPS average over all bunches (not bunch-by-bunch)

Similar results for other fills

Emittance Evolution Through Cycle

- Measured test cycle with 2 x 6 nominal 50 ns bunches with wire scanners
- Emittance growth mainly during the injection plateau and the ramp
  - Also **blow-up at the end of the squeeze** observed at the end of 2012 run



Each point is average over 6 bunch batch.

Only batch 2 colliding in ATLAS and CMS

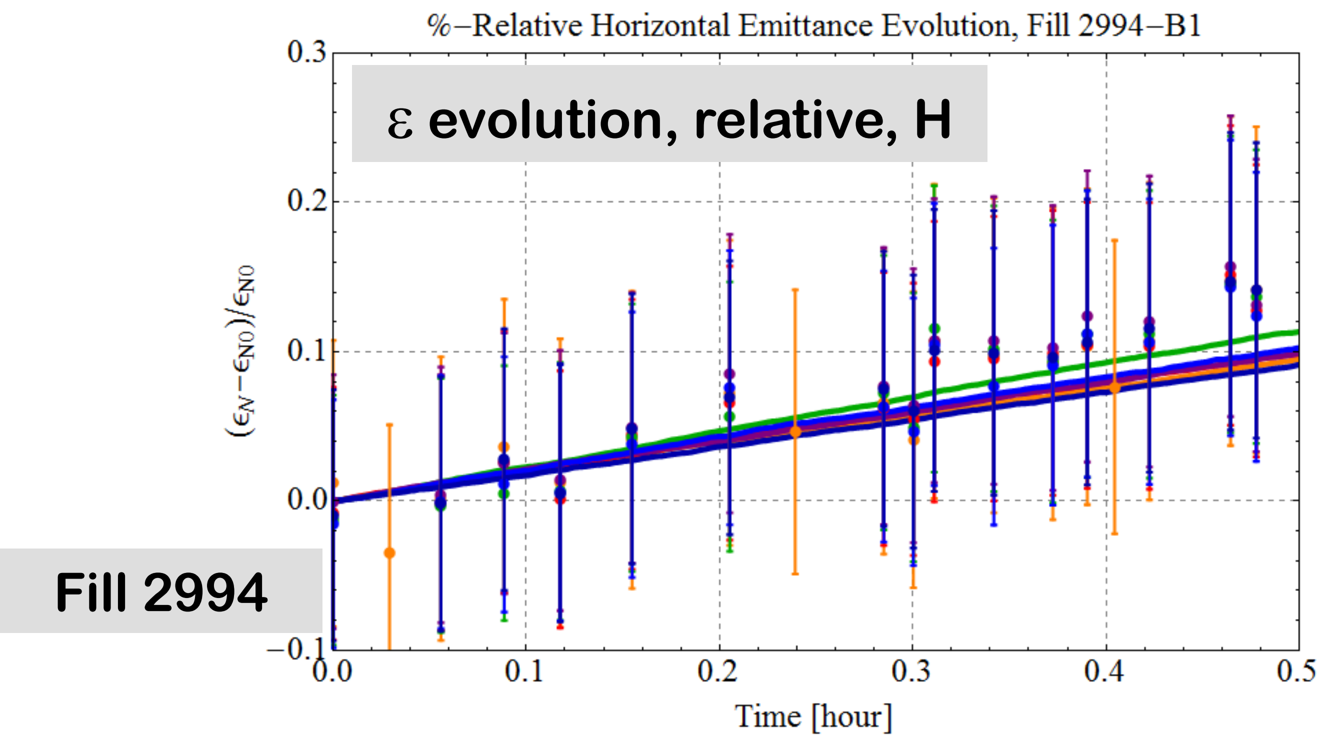
Discrepancy between wire scans and ATLAS data, but within errors ok:

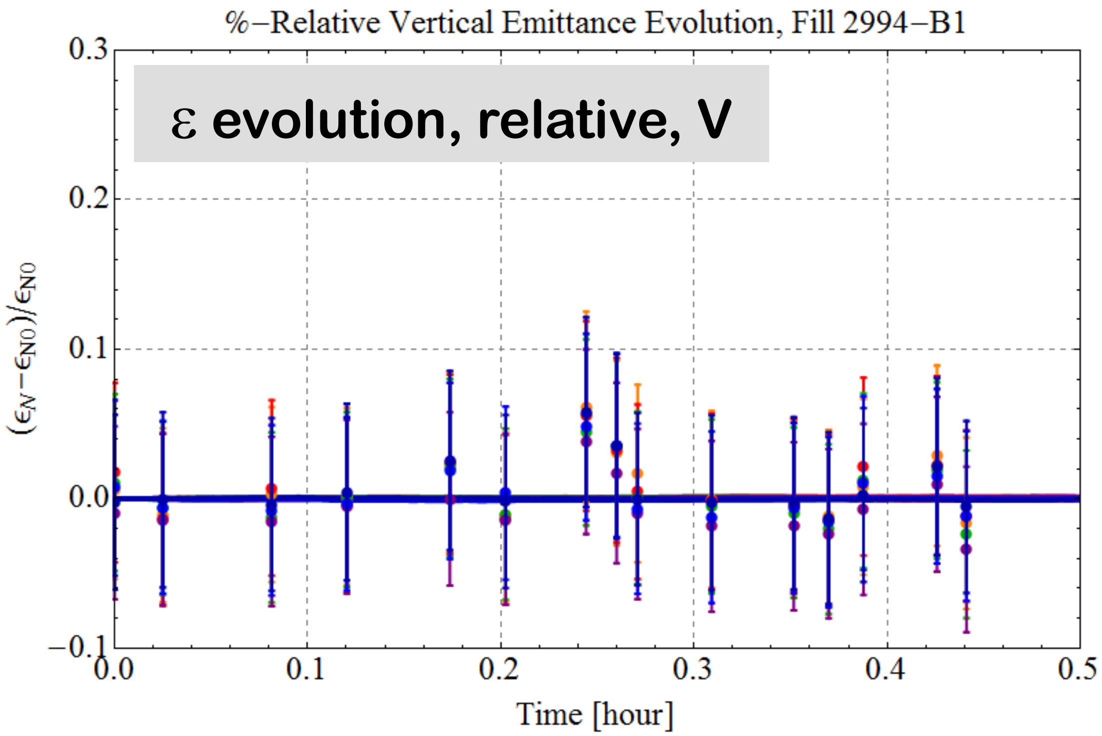
- **Total growth from wire scanners until collision: ~ 0.48 $\pm$0.06 μm (35 %)**
- **Convoluted emittance from ATLAS luminosity – LHC injection: ~ 0.72 $\pm$ 0.34 μm (50 %)**

SOURCES OF EMITTANCE GROWTH AND SOLUTIONS

Growth at 450 GeV vs. IBS Simulations 2012

- Measurements of 6 nominal 50 ns bunches at 450 GeV with wire scanners
  - Compared to IBS Simulations with same initial conditions
- Emittance growth well predicted with IBS, but slightly faster than simulation





- Possible reason for slightly faster growth: 50 Hz noise, see later

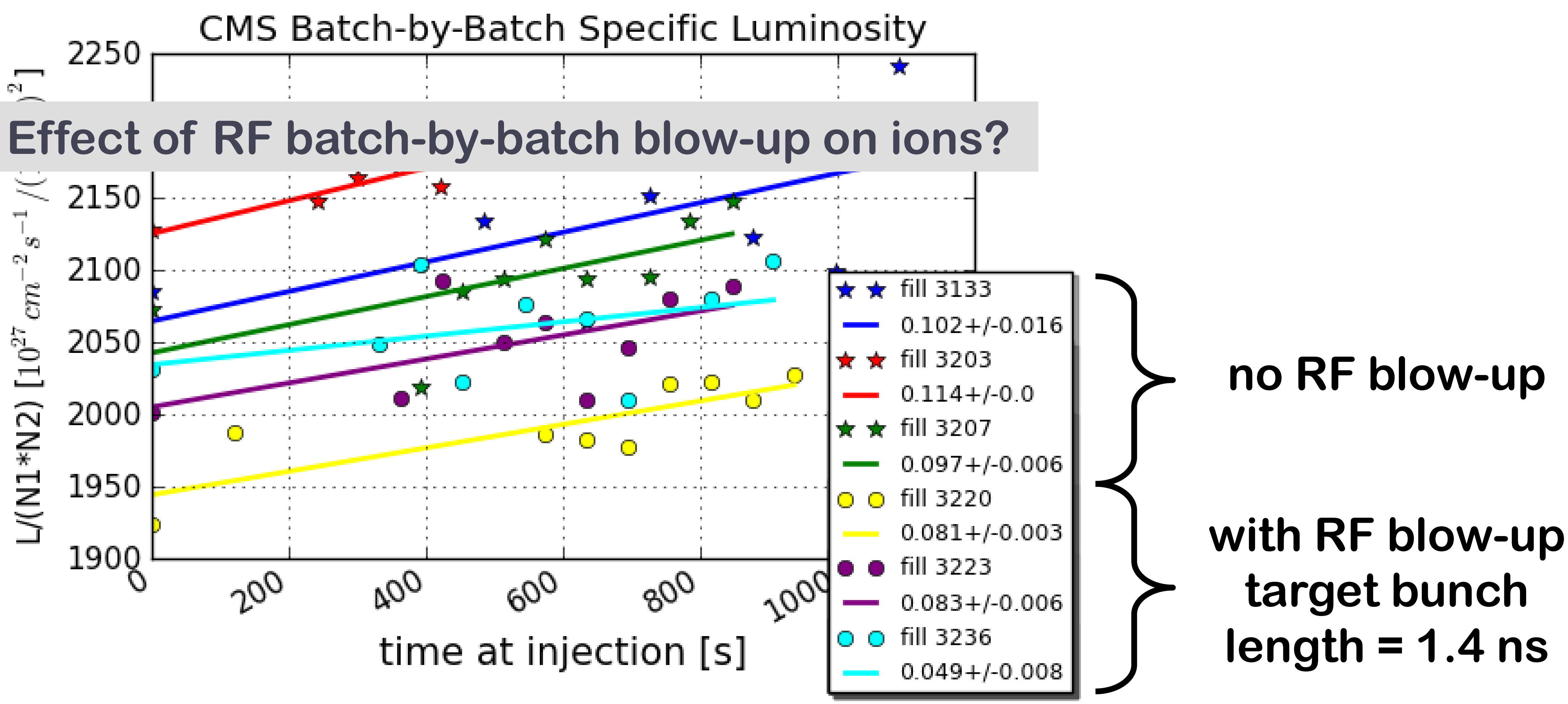
- **Possible solution for effects from IBS: longitudinal batch-by-batch blow-up**

RF Batch-by-Batch Blow-Up

- Effects at injection introduce batch-by-batch differences in specific luminosity
- RF batch-by-batch blow-up was introduced operationally 25.10.2012 (fill 3220)
  - Expectation: reduce batch-by-batch luminosity differences

P. Baudrenghien
T. Mastoridis

CMS specific luminosity per batch vs. injection time:



Effect of RF batch-by-batch blow-up on ions?

- Average slope slightly smaller for fills with longer bunches, but **NO clear improvement**
- Also still other source of batch-by-batch differences: 50 Hz noise

Noise Studies at 450 GeV

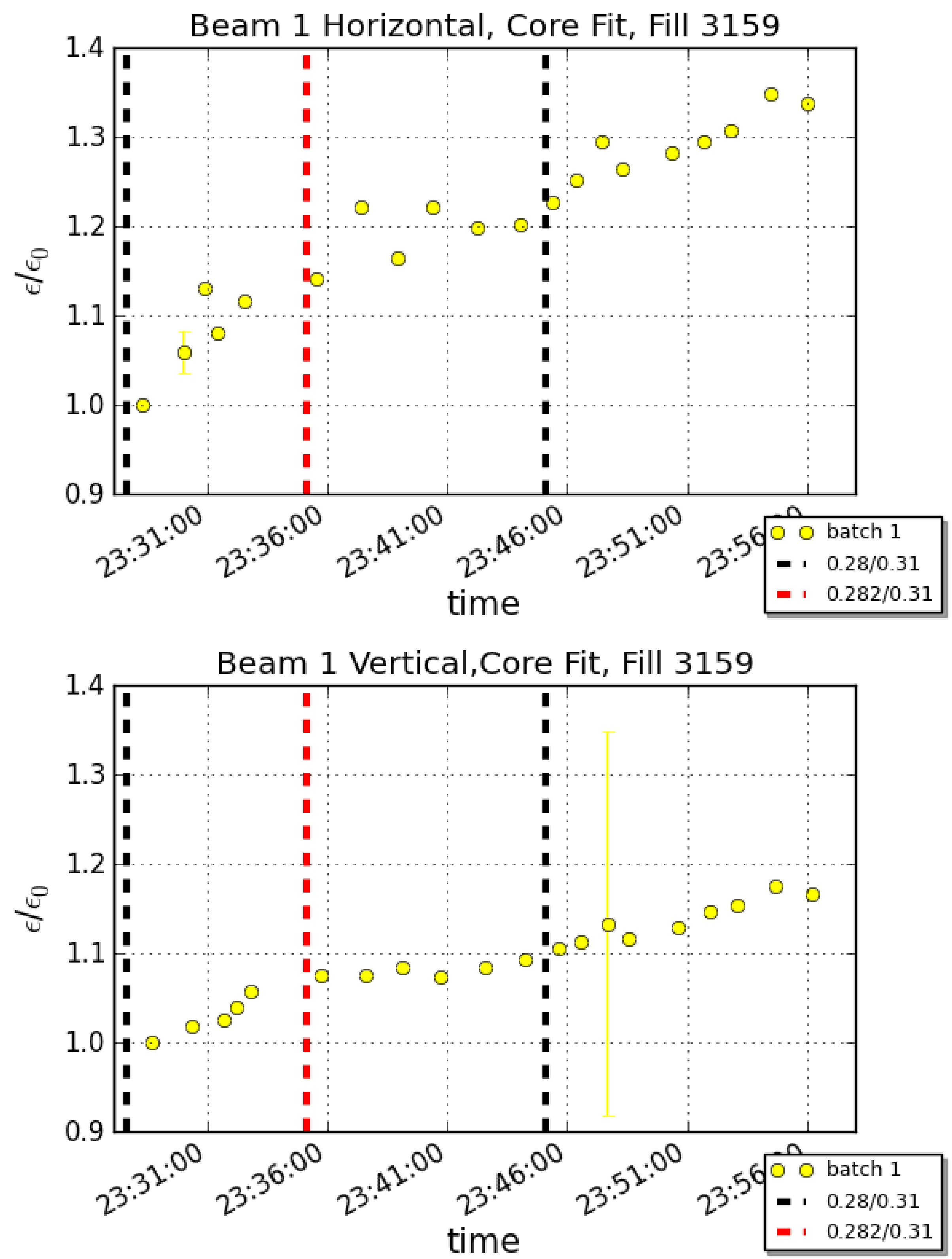
Tune 0.28 sits on top of 50 Hz line

- Test: 2 x 6 nominal 50 ns bunches
  - 10 min @ nominal tune
  - 10 min @ 0.282/ 0.31
  - 10 min @ nominal tune

- **Changing horizontal tune: effect on both planes**
  - More easily visible in V
  - Coupling between H and V for this fill not negligible
  - Effect in H superimposed by IBS, therefore less visible

Staying on the nominal 50 Hz horizontal tune leads to emittance growth in the transverse planes.

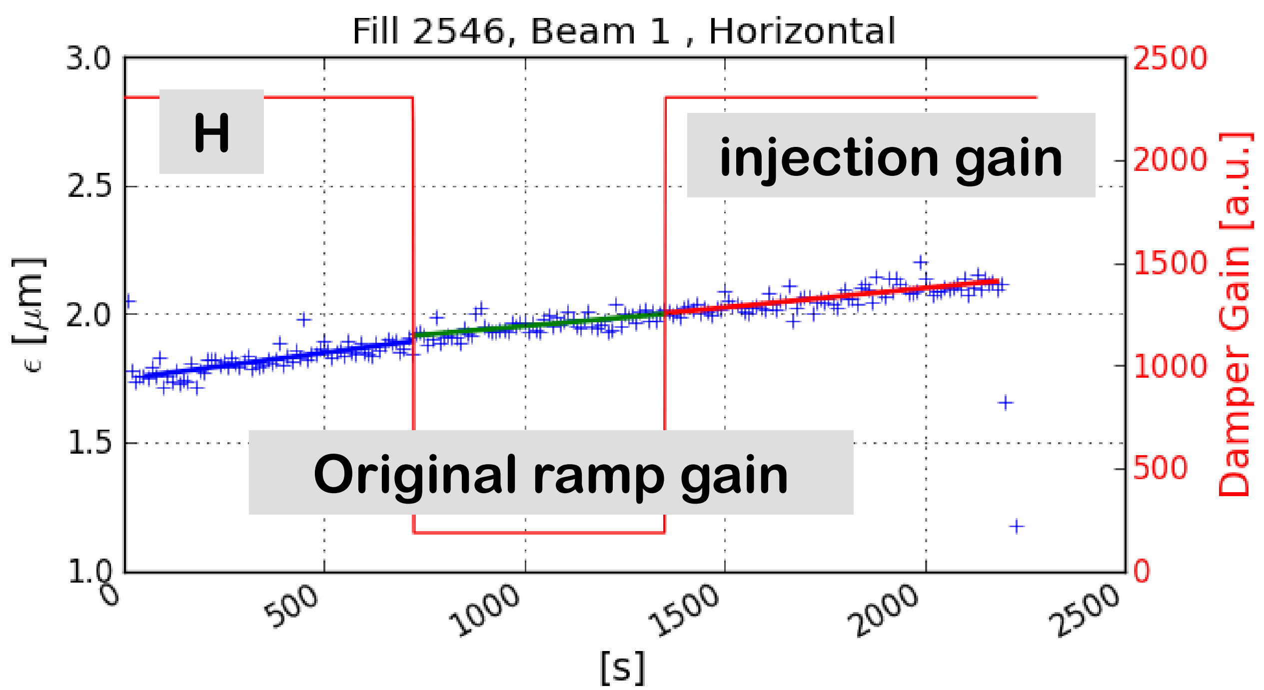
Test ramp recently at slightly different H tune: No evident improvement on ε growth

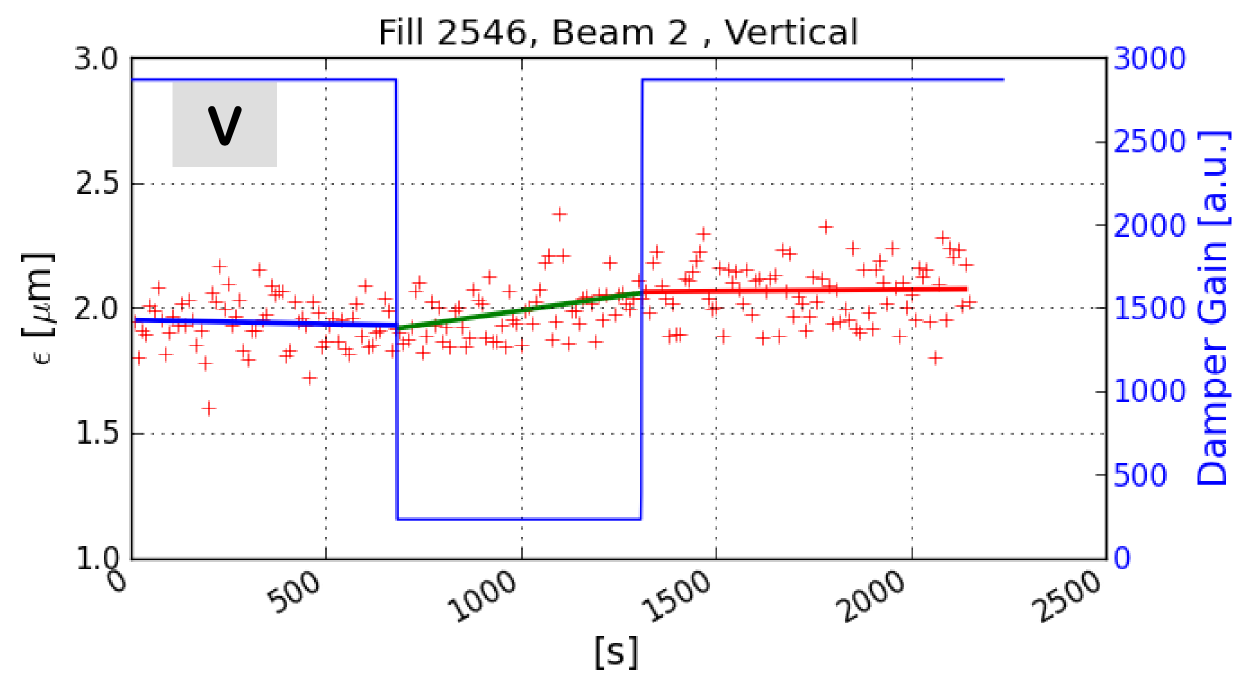


Wire scan measurements averaged over 6 bunches.

Transverse Damper Gain at 450 GeV

- Higher damper gain reduces/removes growth
  - Results from MD I, emittance measurements from BSRT
  - Changed the transverse damper gain at injection energy in both planes
- Horizontal plane: growth due to IBS and noise
- Vertical plane: growth due to noise



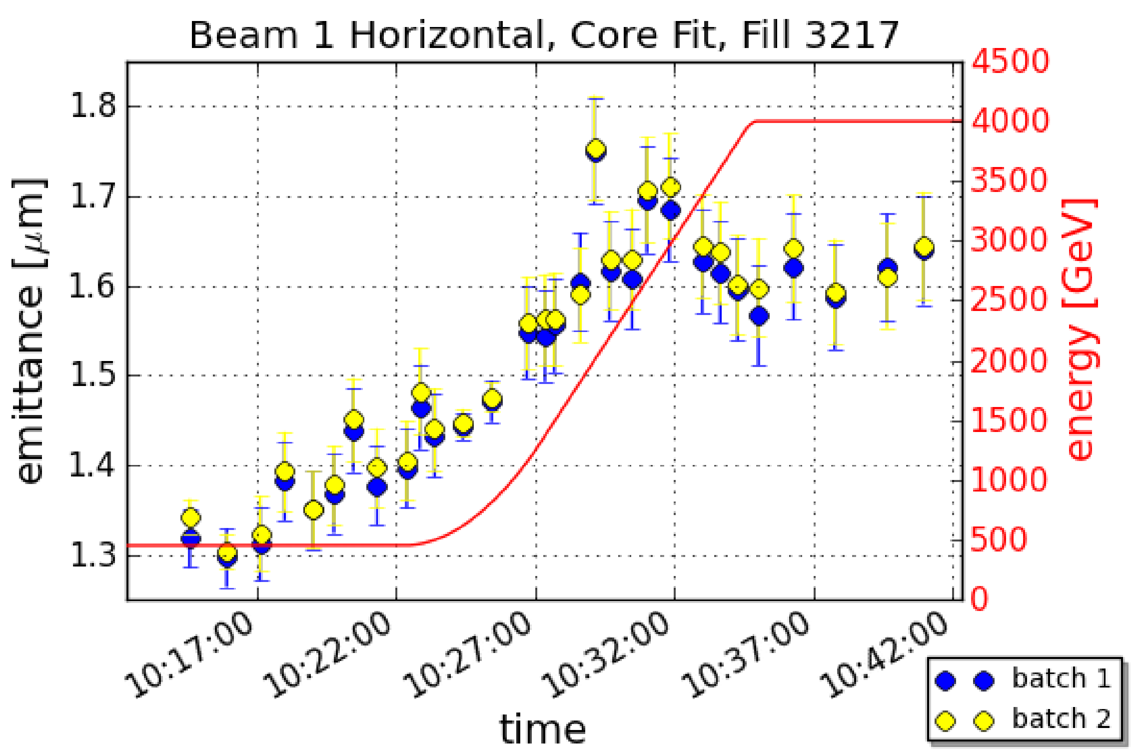


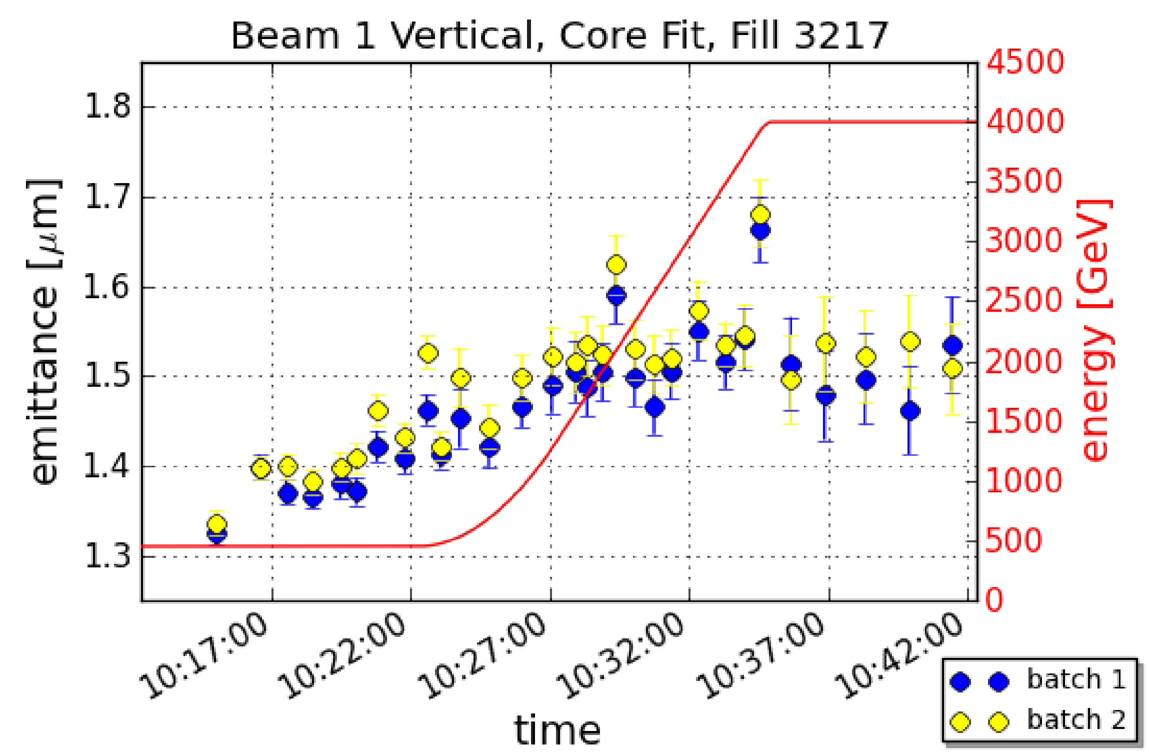
BSRT measurements and linear fits for the different segments

Does higher damper gain also help against blow-up during the ramp?

Ramp (1)

- Fill 3217: 2 x 6 nominal 50 ns bunches
  - Preliminary…missing beta functions through the ramp





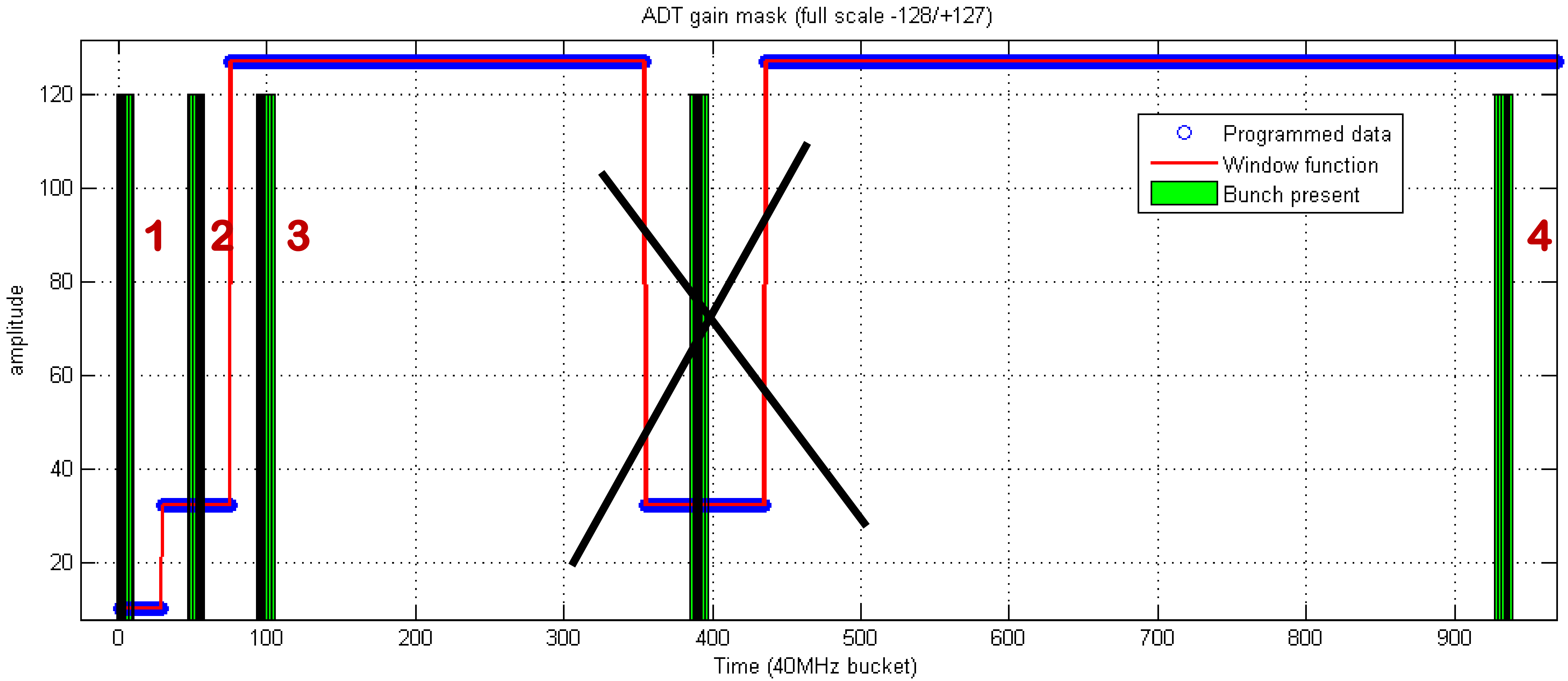
Averaged emittances per batch. Similar for beam 2.

- Emittance growth through the ramp:
  - Beam 1: horizontal = 0.18 $\pm$0.10 μm (~ 13 %) vertical = 0.12 $\pm$ 0.06 μm (~ 8 %)
  - Beam 2: horizontal = 0.30$\pm$0.08 μm (~ 19 %) vertical = 0.07 $\pm$ 0.02 μm (~ 5 %)

- Analyzed many fills - all look similar
  - Average blow-up through the ramp: 20 % (depending on the wire scanner settings)
  - Smaller blow-up in the vertical plane than in the horizontal plane

Ramp (2) – Effect of Damper Gain

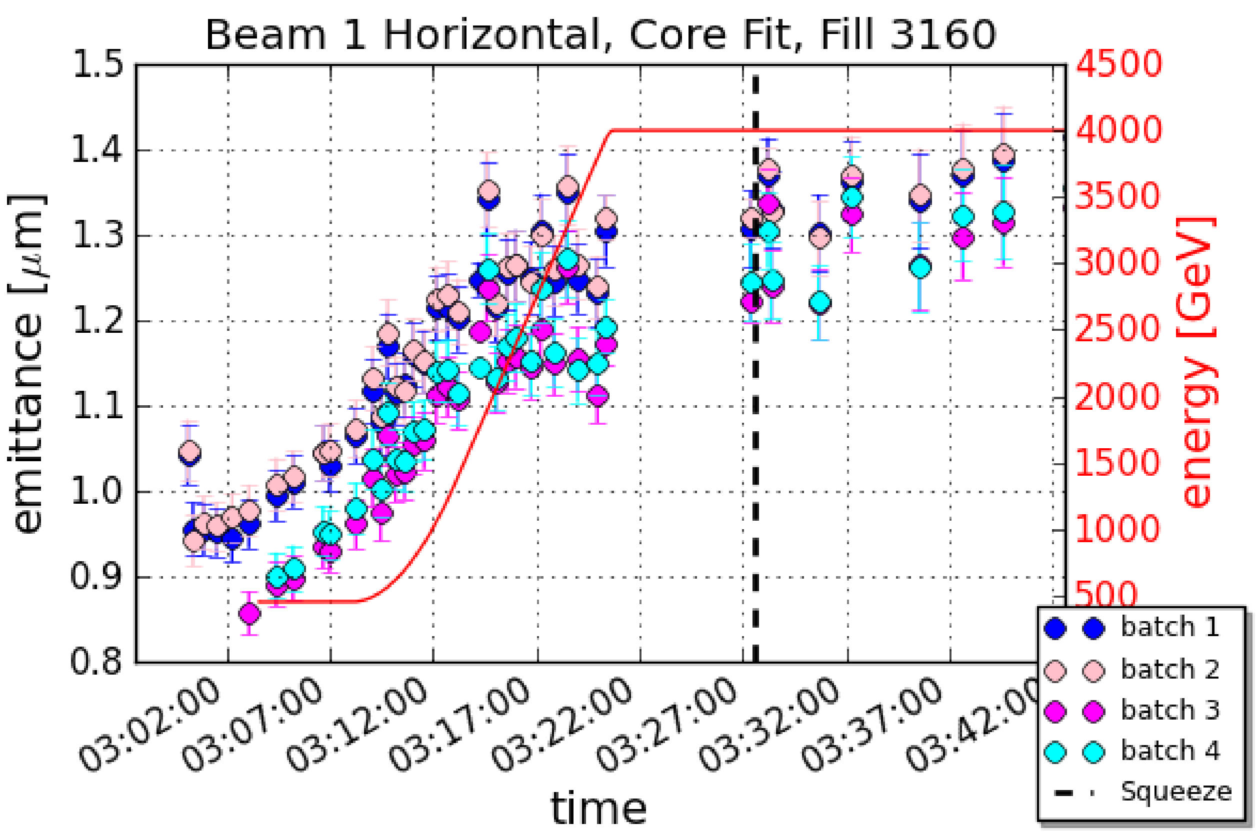
- Results for growth with increased damper gain:
  - Batch 1: very low gain bunches, sacrificial (lower than operational gains)
  - Batch 2: low gain bunches (~ nominal prepare ramp low gain)
  - Batch 3 and 4: high transverse damper gain (127/128 at start of ramp)

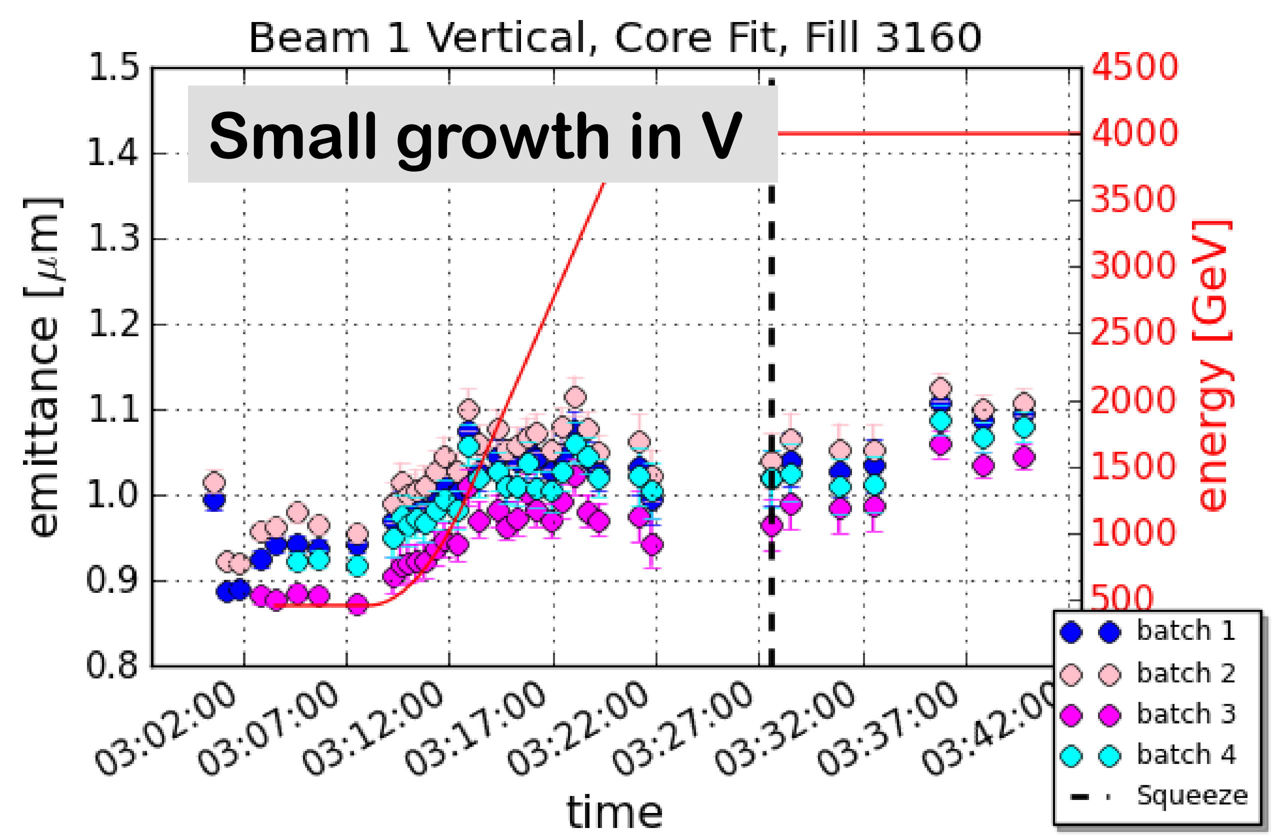


ADT gain modulation for the 4 injected batches during the ramp.

Ramp (3) – Effect of Damper Gain

- Results of ramp of batches with different damper gains:



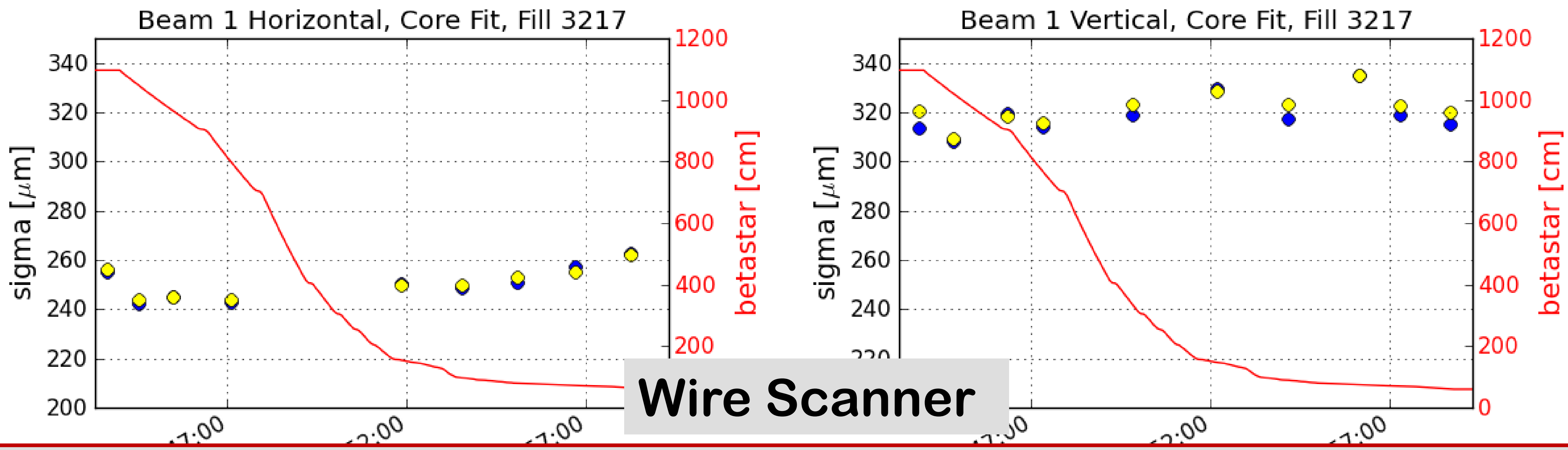


B1 Horizontal	Growth during ramp [μm]
Batch 1	0.24 ± 0.08 (23 %)
Batch 2	0.25 ± 0.06 (23 %)
Batch 3	0.26 ± 0.05 (27 %)
Batch 4	0.27 ± 0.07 (27 %)

No significant difference of blow-up for different damper gains.

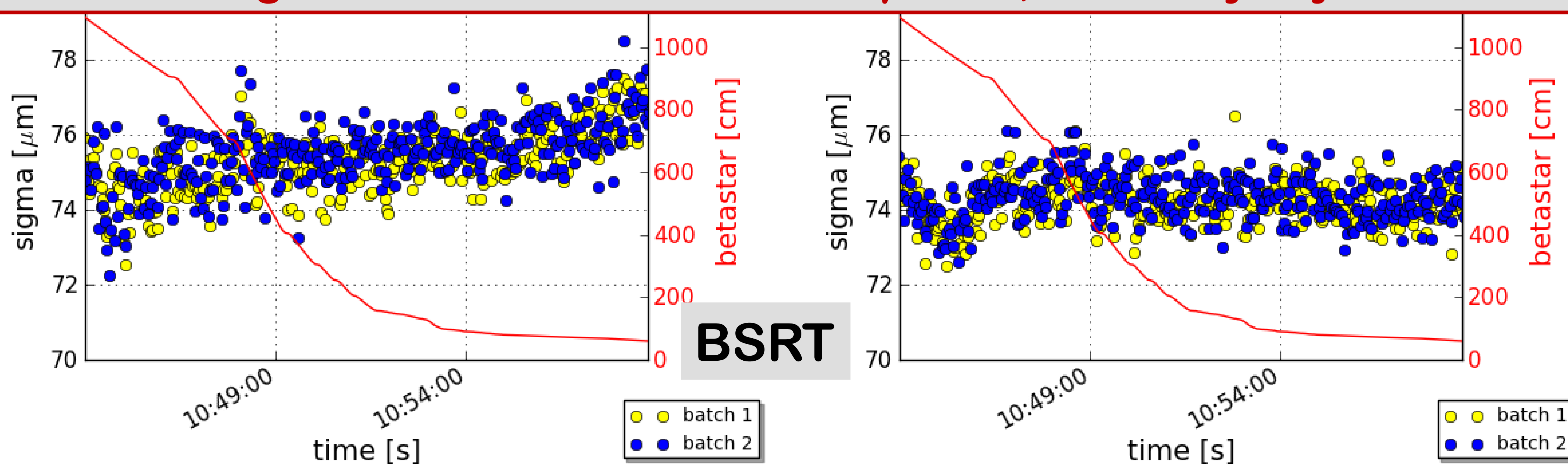
Squeeze (1)

- Measured 2 x 6 nominal 50 ns bunches
  - Display only beam sizes



V: no emittance growth

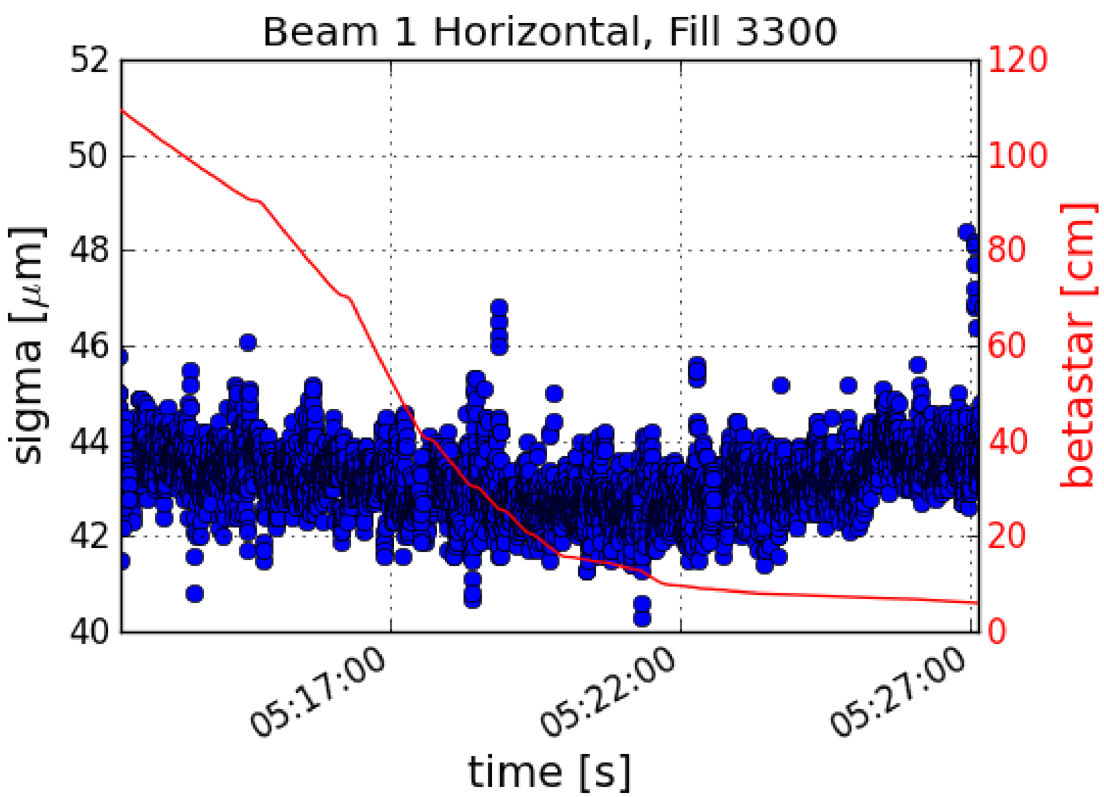
H: sometimes growth towards the end of squeeze, not always by same amount

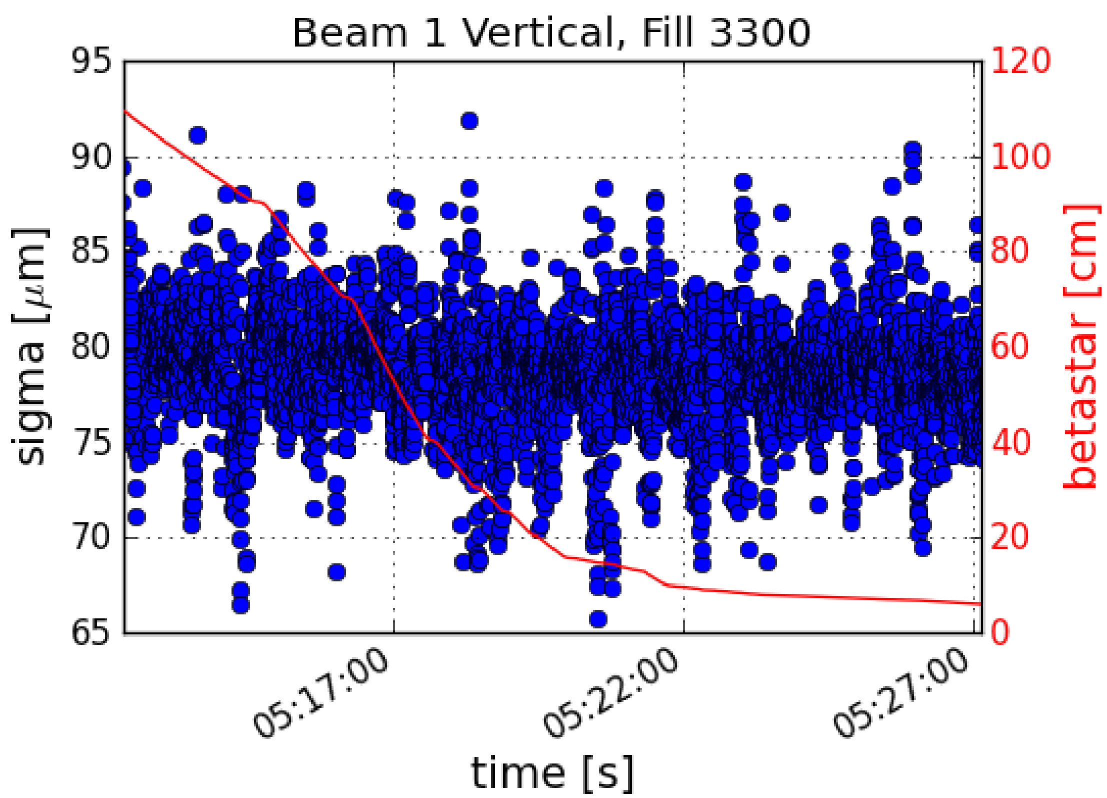


Squeeze (2)

For completeness:

- Similar results for physic fills:
  - Analyzed BSRT beam 1 data for squeezes of 1368 bunches (no data for beam 2!)

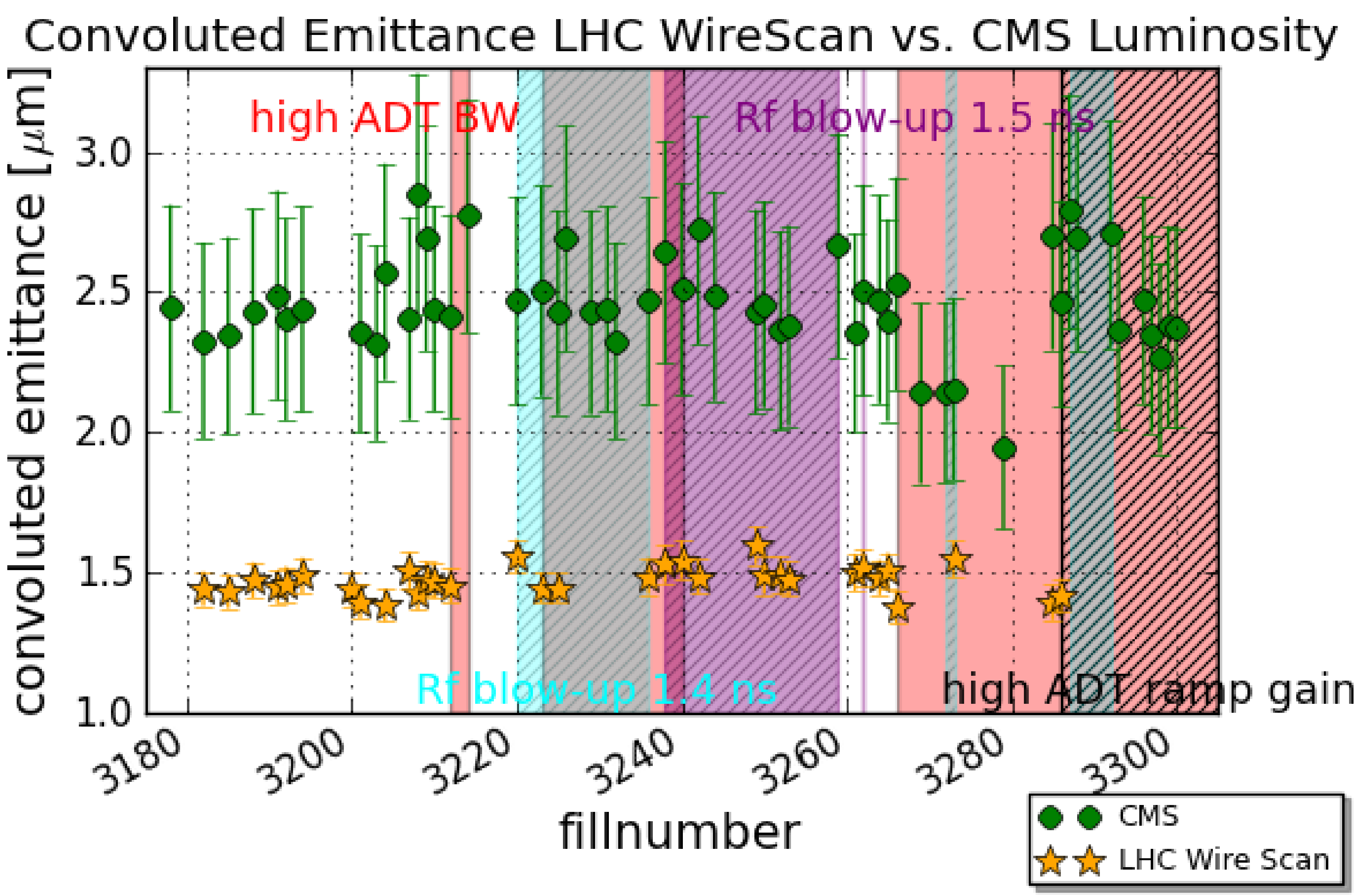




Any Measures That Help Against ε Growth?

After TS3 several potential measures became operational:

- RF batch-by-batch blow-up operational since fill 3220
- Since fill 3286 higher ADT gain for the ramp
  - Gated BBQ operational since fill 3287
- ADT wideband settings from flattop to start of stable beams

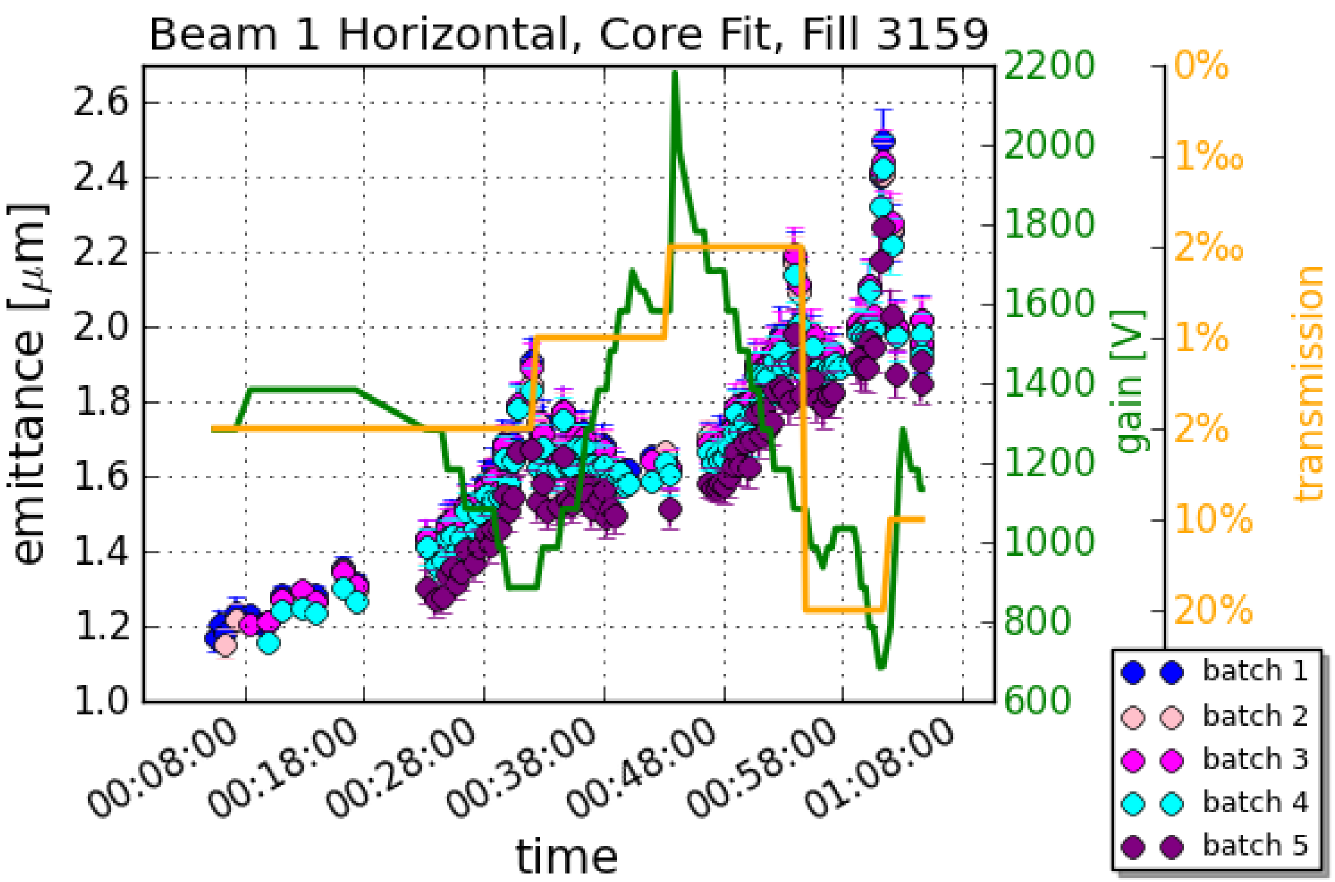


→ No evident improvement of average emittance at collision for any measures taken so far

→ but peak bunch-by-bunch luminosity could be increased with higher damper gain

Issue: Accuracy of Wire Scanner

- Test with 5 x 6 nominal 50 ns bunches
  - Change filters and voltage of wire scanners at 450 GeV in all planes
    - B1 H displazed as an example, the other planes show the same results
    - Beam size evolution at 4 TeV similar



The resulting error on the measurement is therefore:

At injection up to **0.5 μm instead of ~ 0.1 μm** (from averaging and betas).

At flattop up to **0.8 μm instead of ~ 0.1 μm.**

Still investigating the best working point of the wire scanners.

Not sure which settings give the 'REAL' beam size!

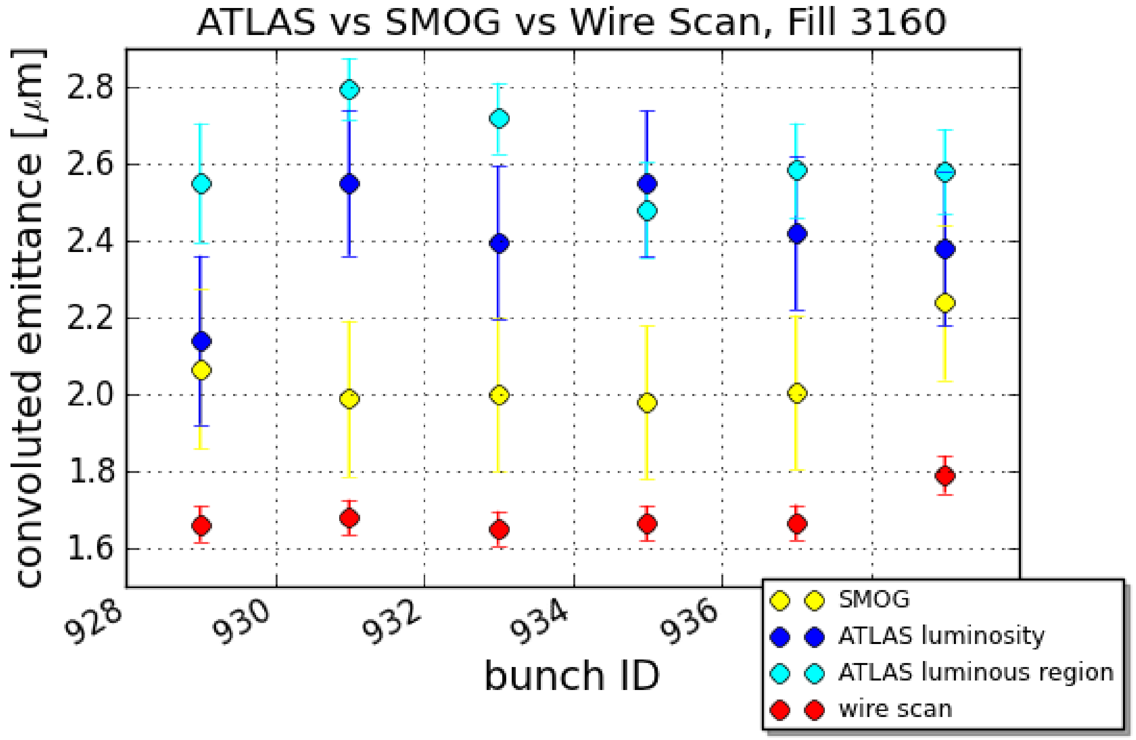
- The wire scanner photomultipliers are satu
  - we are not talking about ADC saturation (easy
  - All profiles still look Gaussian

Comparison of SMOG, ATLAS and WS

- For MD fill 3160 bunch-by-bunch data for head on colliding bunches:
  - Compare emittance from luminosity, luminous region, SMOG and wire scanner at same timestamp
    - SMOG: measurements in all 4 planes, errors include systematic, statistical and 15 % β* error
    - ATLAS luminosity: measurement in 1 plane, errors include 15 % β* error and 10 % crossing angle error
    - ATLAS luminous region: measurements in 2 planes, errors include statistical and 15 % β* error

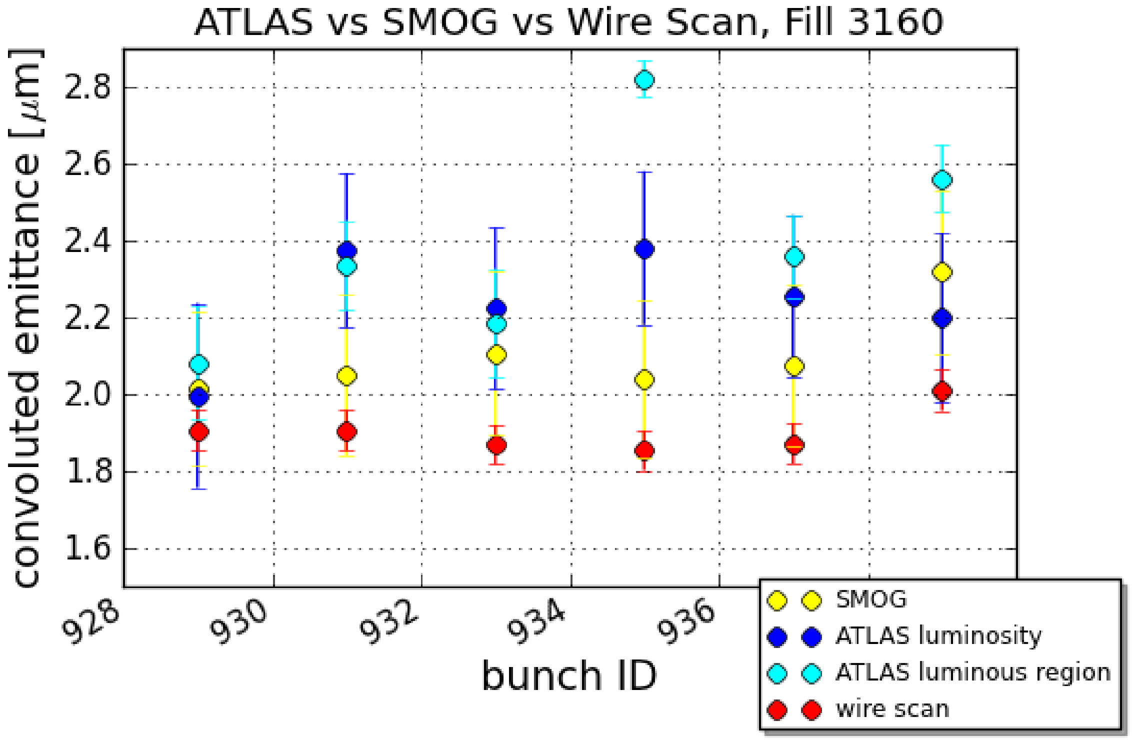
B1 0.2 % filter
B2 1 % filter

04:42 start of SMOG injection



measurement with different wire scanner setting 05:04

B1 1 % filter
B2 10 % filter

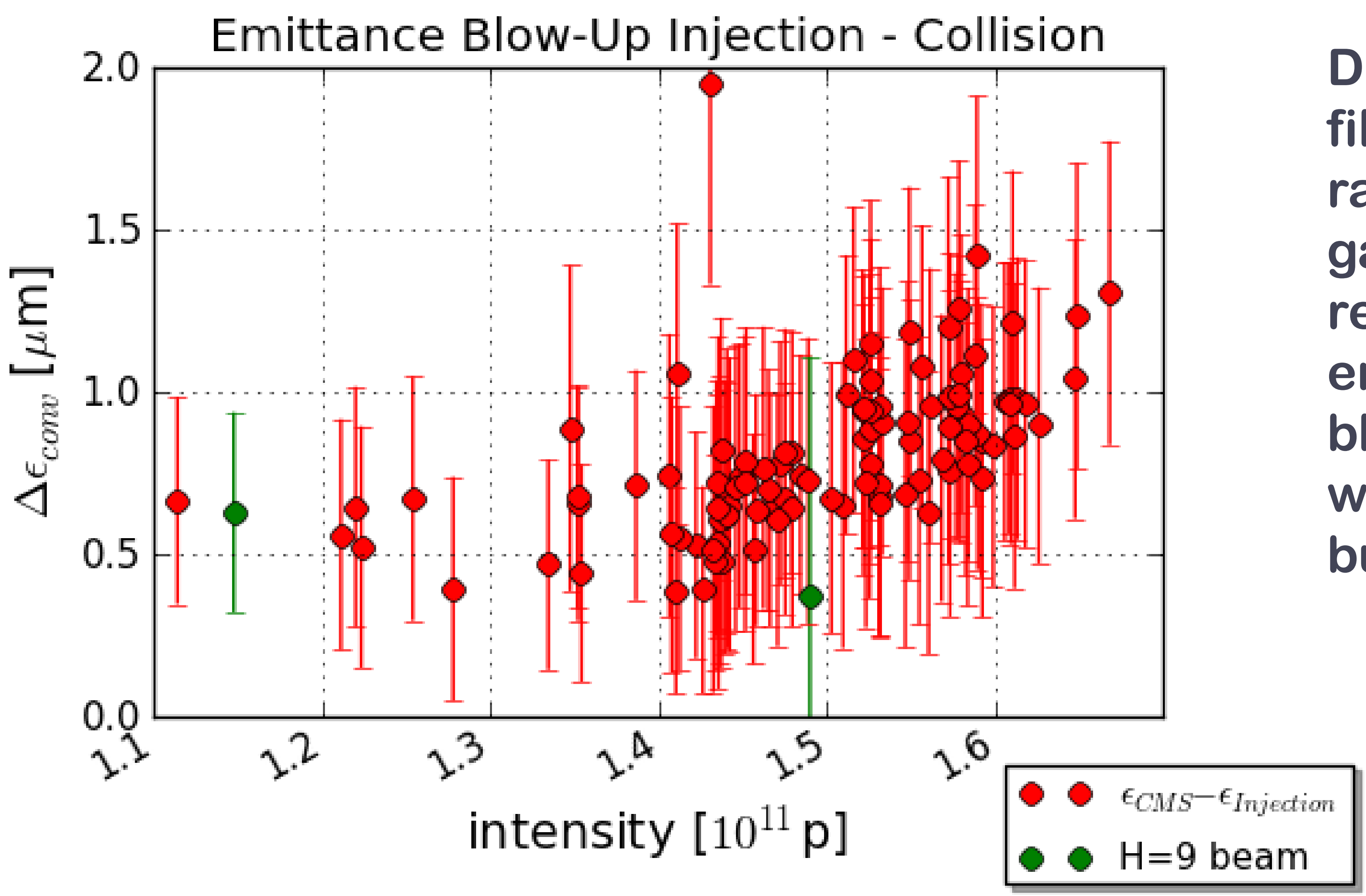


Large difference between wire scans and data from experiments!

Wire scanner rather too small beam sizes.

Emittance Blow-Up vs. Bunch Intensity

- Emittance blow-up in 2012 from LHC injection to collision
  - Convoluted emittance from CMS peak luminosity
  - Convoluted emittance from wire scanner at LHC injection (first 144 bunch batch)
  - Bunch intensity measured with FastBCT



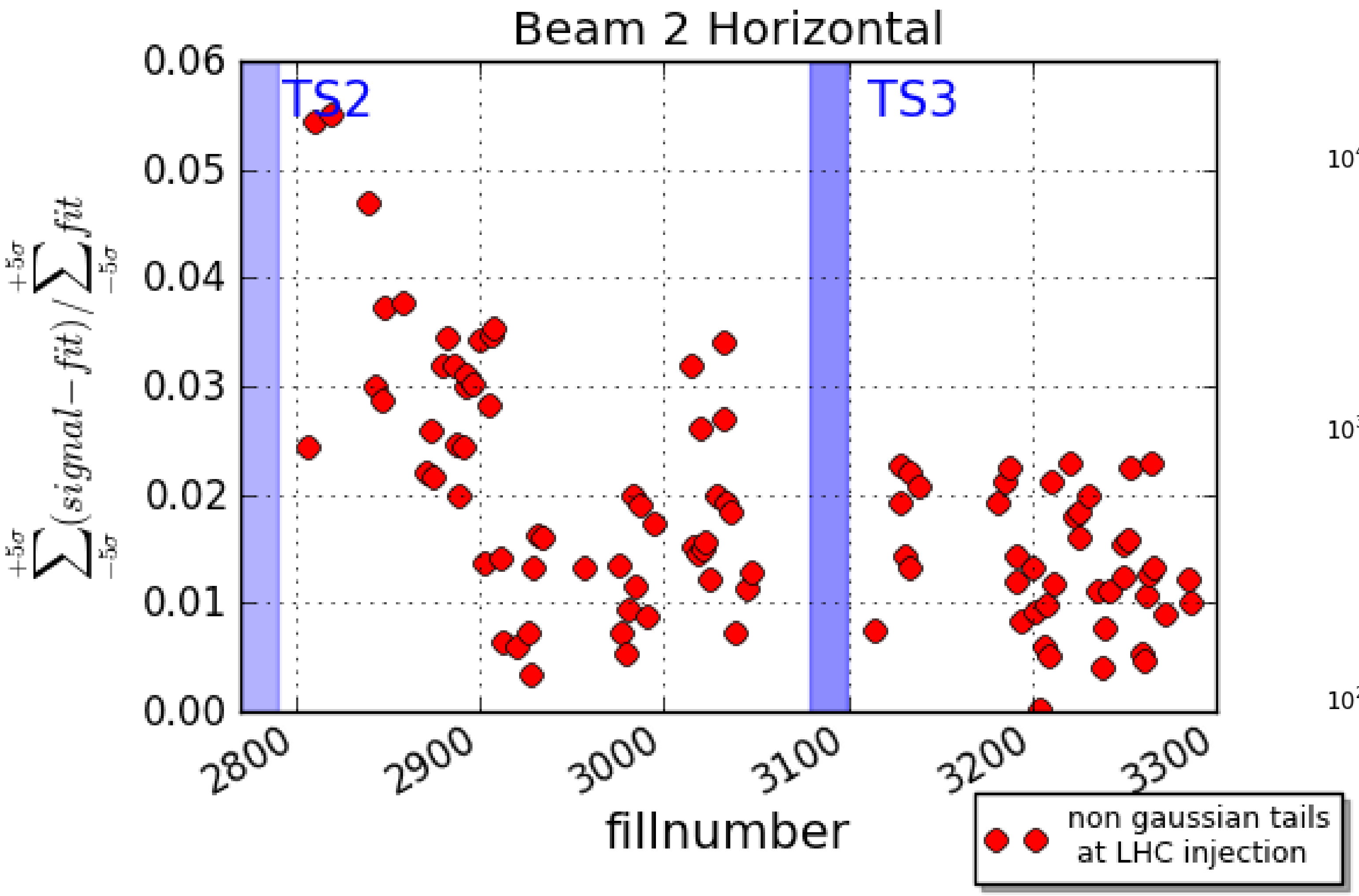
During 25 ns fills: higher ramp damper gain possibly reduced emittance blow-up, but was also lower bunch intensity

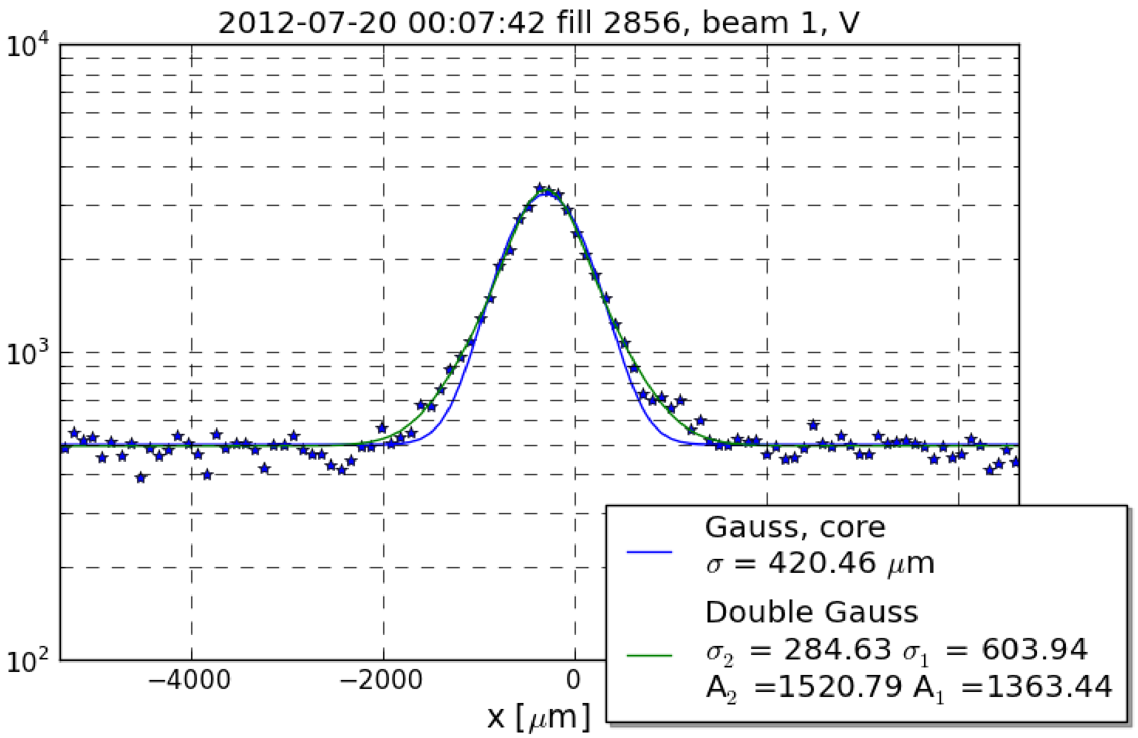
Emittance growth larger for very high bunch intensities.

Tails: Can We Measure Them?

- Behavior of tails through cycle not clear yet, needs to be studied in detail
- But we have a way of quantifying them
- We can “see” the tails

- Evolution in LHC tail population at injection over the year for B2H:
  - Calculated from transverse profiles measured with wire scanners





Tail population estimate: difference of wire scanner signal with Gauss fit.

Instrumentation Wish List for After LS1

…the same almost as we had for 2012

- Need reliable instrument to monitor emittances through the LHC cycle
- Wire scanners with higher intensity limit
  - Need to be able to scan 288 bunches at injection
  - Thinner wires?
- BSRT for all beams and planes
- BGI for all beams and planes
  - To analyze physics fills
  - Especially the ramp
- New device to measure physics fill → BGV: Beam-Gas Imaging Vertex Detector
  - Two times more bunches after LS1

Conclusion

- Still very difficult to measure emittances and emittance blow-up
  - Still not sure about the wire scanner results
  - Emittances from luminosity results are most reliable

- Need reliable and accurate transverse profile measurement systems after LS1

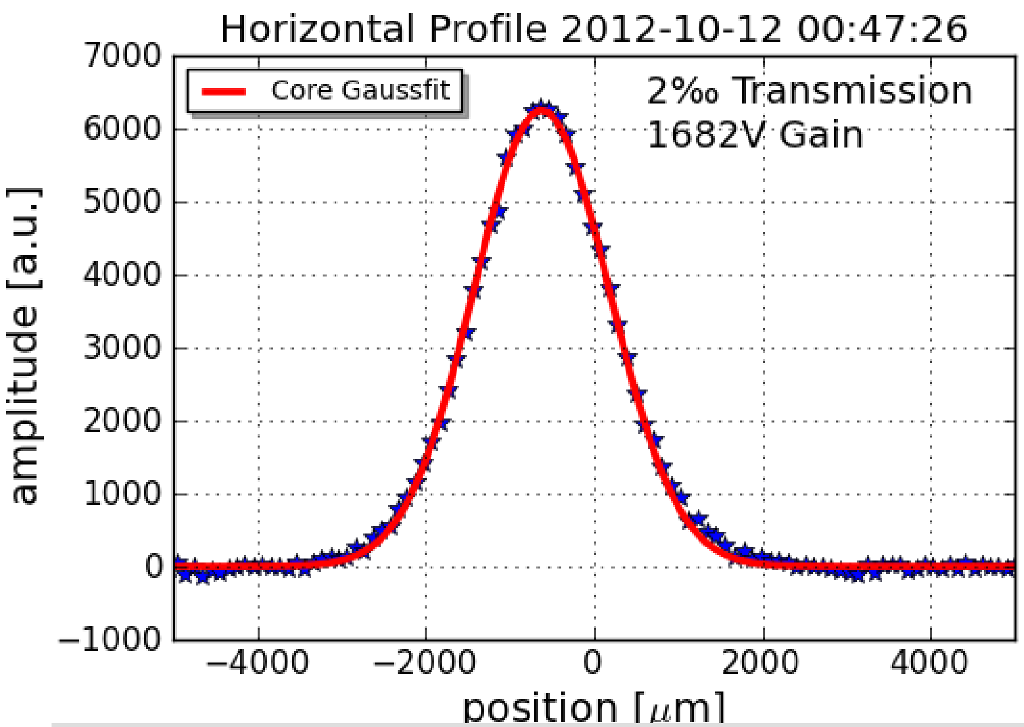
- Emittance blow-up situation in 2012 similar to 2011
  - Significant blow-up from injection and ramp. Sometimes at the end of squeeze.
  - Clear sources are IBS and 50 Hz noise. Sources for the ramp unknown.

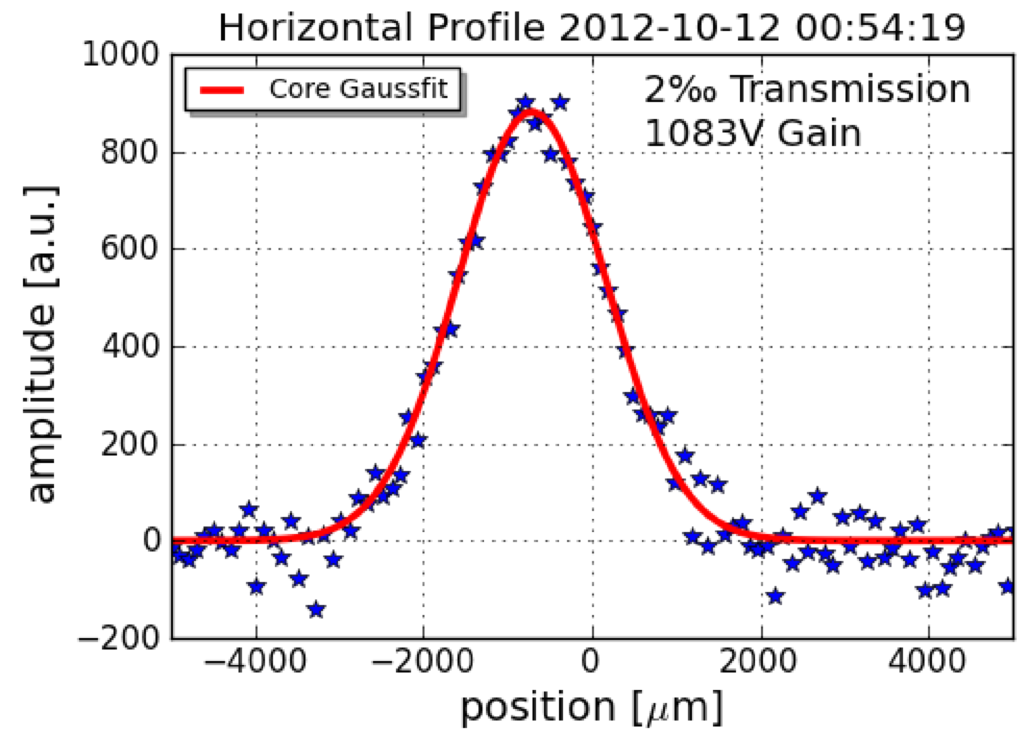
- Absolute emittance growth through cycle **$\Delta\varepsilon \sim$ 0.7 – 1 μm** for convoluted, averaged emittance from luminosity

- Any potential mitigation like RF batch-by-batch blow-up and higher transverse damper gain have NOT yet lead to significant improvement of emittance blow-up

EXTRA SLIDES

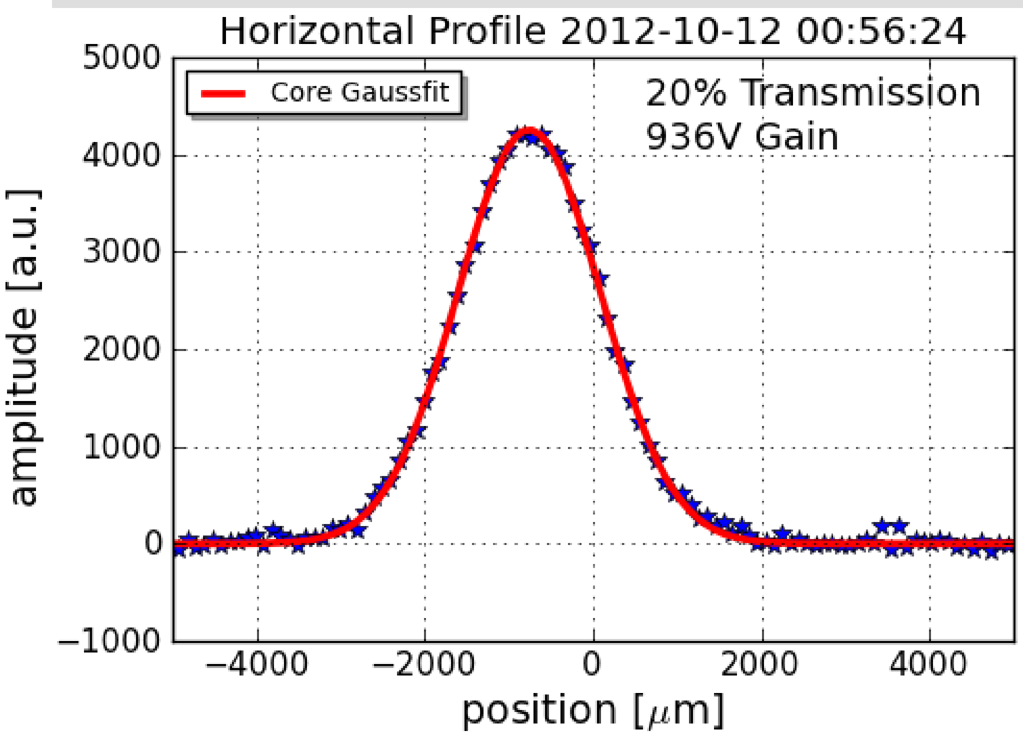
Issue: Accuracy of Wire Scanner

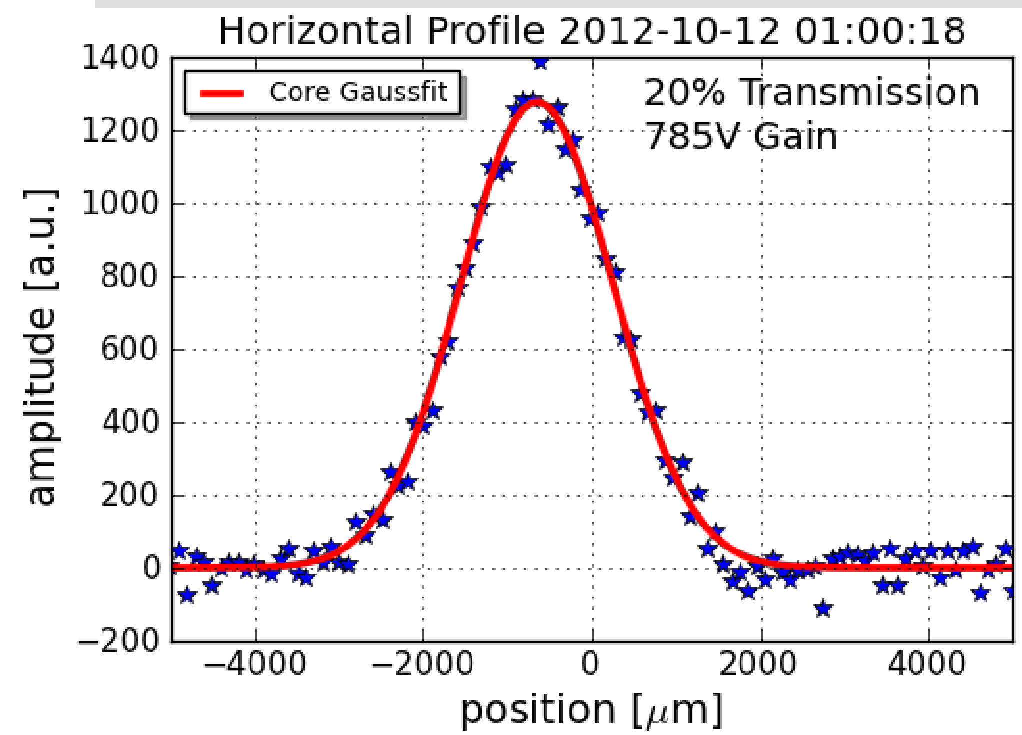




High gain (low and high transmission)

Low gain (low and high transmission)





– **All profiles still look Gaussian**