Transverse Emittance through the Cycle – Update

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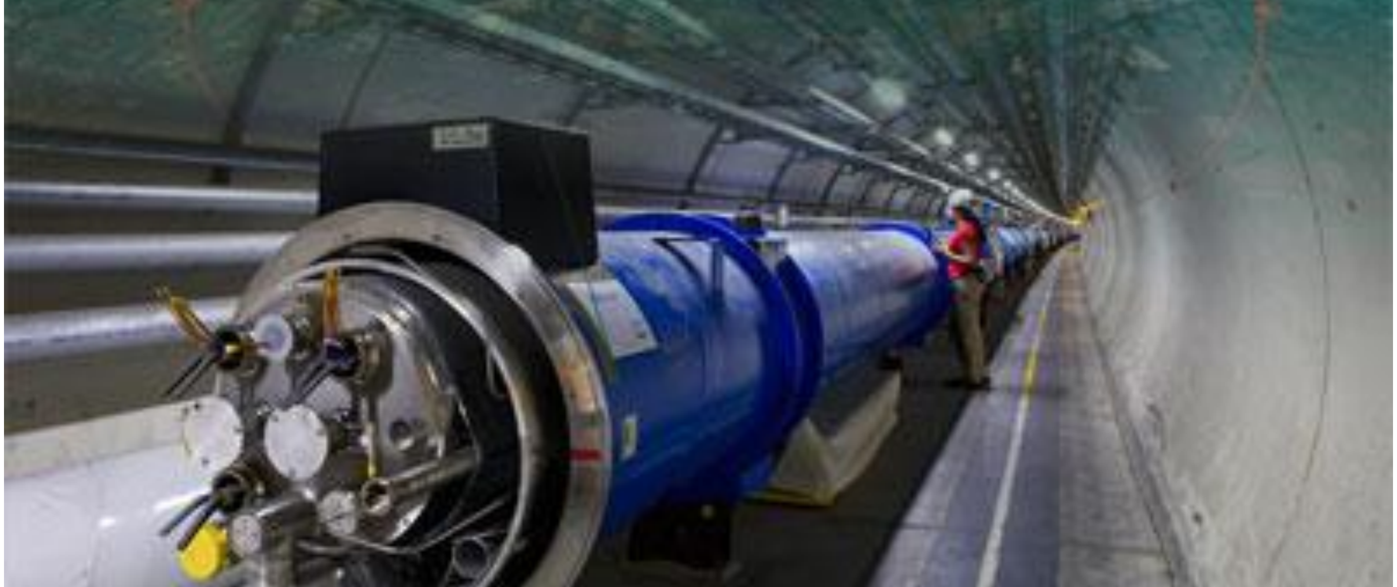
Thanks to G. Arduini, A. Langner, Y. Papaphilippou, G. Papotti, M. Schaumann and R. Tomas

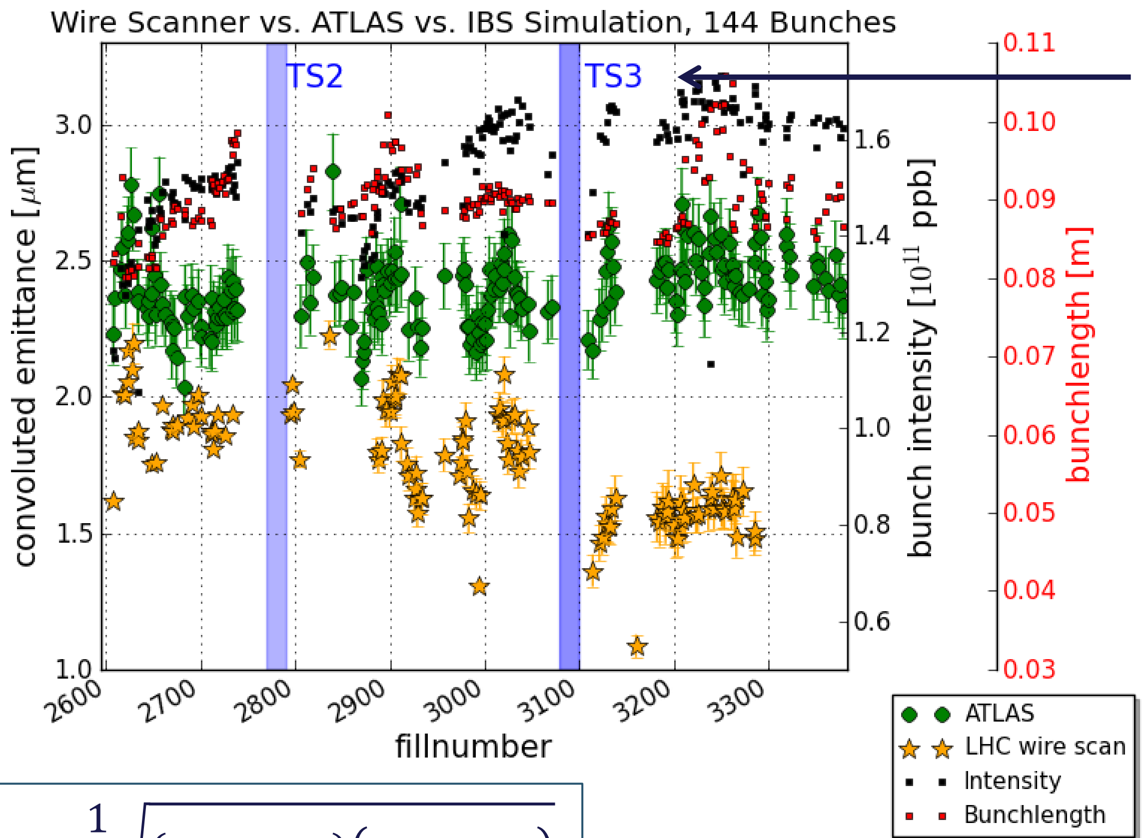


Motivation: 2012 Emittance Blow-up

- Overall average transverse normalized emittance blow-up through the LHC cycle:
  - ~ 0.4 – 0.9 μm from injection into the LHC to start of collision (convoluted ε) for the first injected batch of 144 bunches per beam

<u>Convoluted ε:</u>

- Collision values from ATLAS bunch luminosity (similar for CMS values)
- Injection values from LHC wire scanners
- Average of first 144 bunch batch



After Technical Stop 3 (TS3): very high brightness beams from the LHC injectors lead to even larger emittance growth!

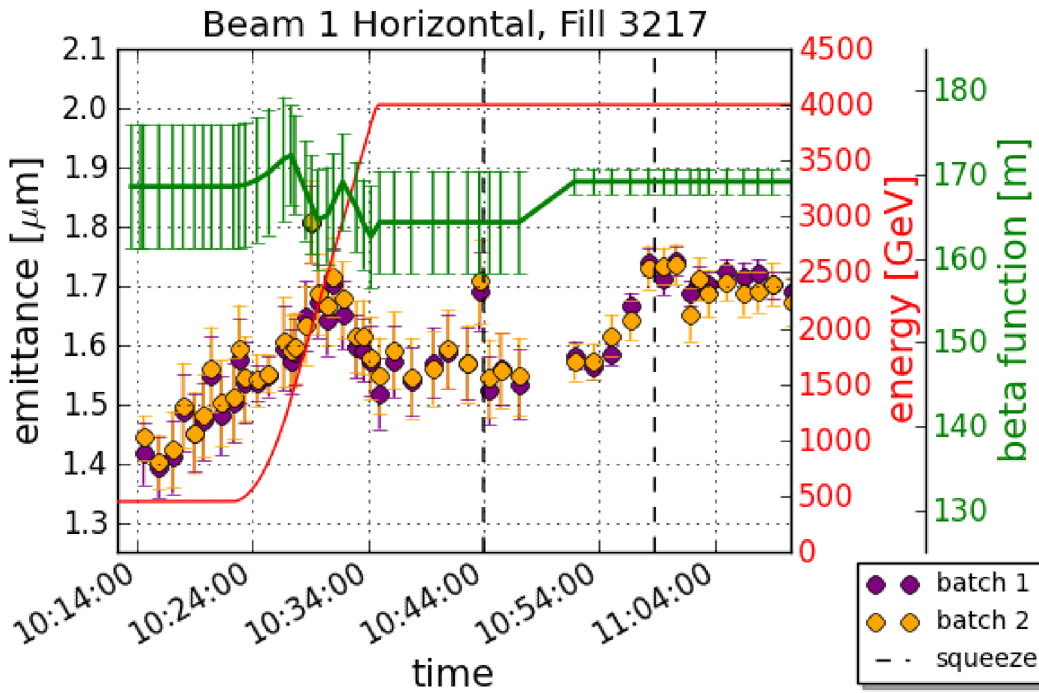
$$\varepsilon = \frac{1}{2}\sqrt{(\varepsilon_{1x} + \varepsilon_{2x})(\varepsilon_{1y} + \varepsilon_{2y})}$$

Instrumentation and β Measurements

- 2012 available transverse profile monitors through the cycle:
  - ONLY WIRE SCANNERS!
    - Could only measure low intensity test fills, no physics fills
    - Influence of gain and filters on obtained beam sizes, not possible to obtain optimum settings and thus optimum beam sizes values [1]
    - Transverse beam sizes obtained from 5 parameter Gauss fit of the core of the profile (80 % intensity cut)
- β functions from turn-by-turn phase advance measurement [2]
  - At injection, at discrete energies during the ramp, at flattop energy and after the β* squeeze
    - Linear interpolation between the measurement points
  - Values transported to location of wire scanners and experiments
- Example: Fill 3217 (25. Oct. 2012)
  - 2 batches of 6 bunches, 50 ns bunch spacing
  - Bunch intensity ~ 1.6 x 10^{11} ppb, (4 σ) bunch length ~ 1.2 ns
    - Caveat: fill after LHC octupole polarity swap, thus large growth during β* squeeze!

Emittances through the 2012 LHC Cycle

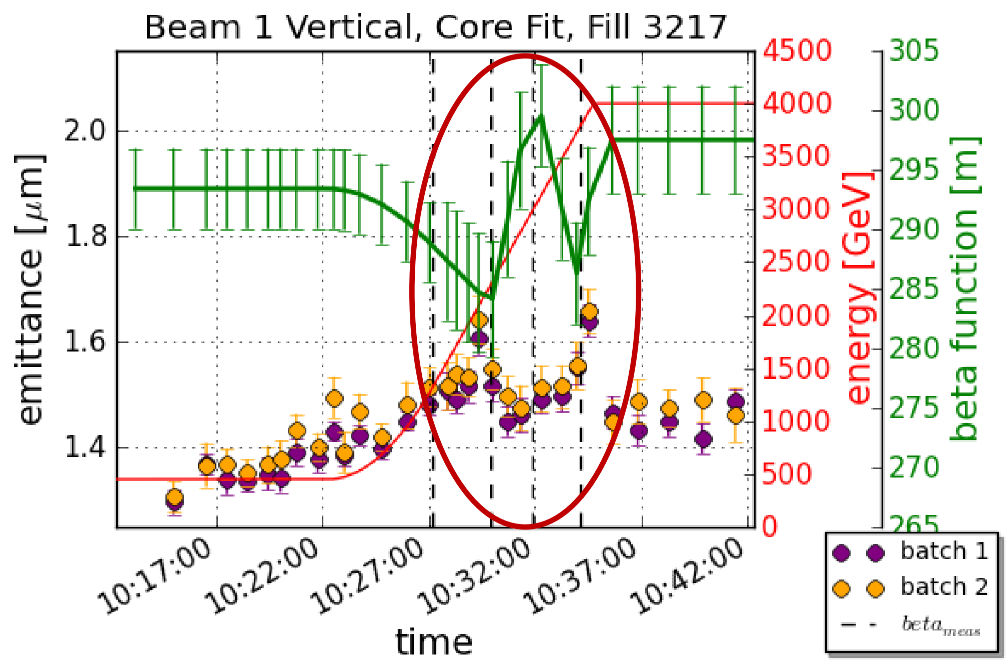
- Conclusions from wire scanner measurements:
  - Emittances are mainly growing during injection plateau and ramp
  - Sometimes shrinking emittances during the ramp (beam 1)
  - Sometimes large blow-up at the end of squeeze

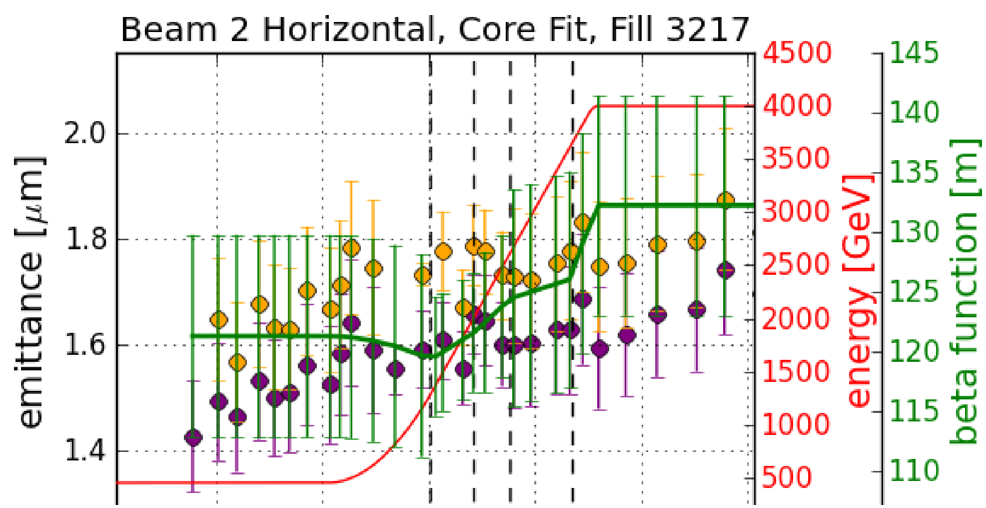


- Sources of emittance blow-up:
  - Injection: intra beam scattering (IBS) and 50 Hz noise [1]
  - Ramp: probably only IBS
    - Growing- shrinking emittances due to non-monotonic changes of optics at wire scanners
  - Squeeze: probably beam instabilities
  - Blow-up in the vertical planes at injection and ramp from coupling

Non-Physical Emittance Evolution during Ramp

- New beta function analysis for values through the ramp
- Growing- shrinking emittances due to non-monotonic changes of optics at wire scanners
  - Same for B1H
  - Not enough β measurements to remove all "non-physical" points
- Monotonic growth of beta function at wire scanner
  - ➔ No shrinkage!
  - Same for B2V





IBS during the LHC Ramp

- Comparison of emittance measurement during the ramp with wire scanners and IBS simulations with MADX [3]

Beam 2:

Simulation matches measurement!

Bunch lengths and intensities similar for both batches, but different initial emittances

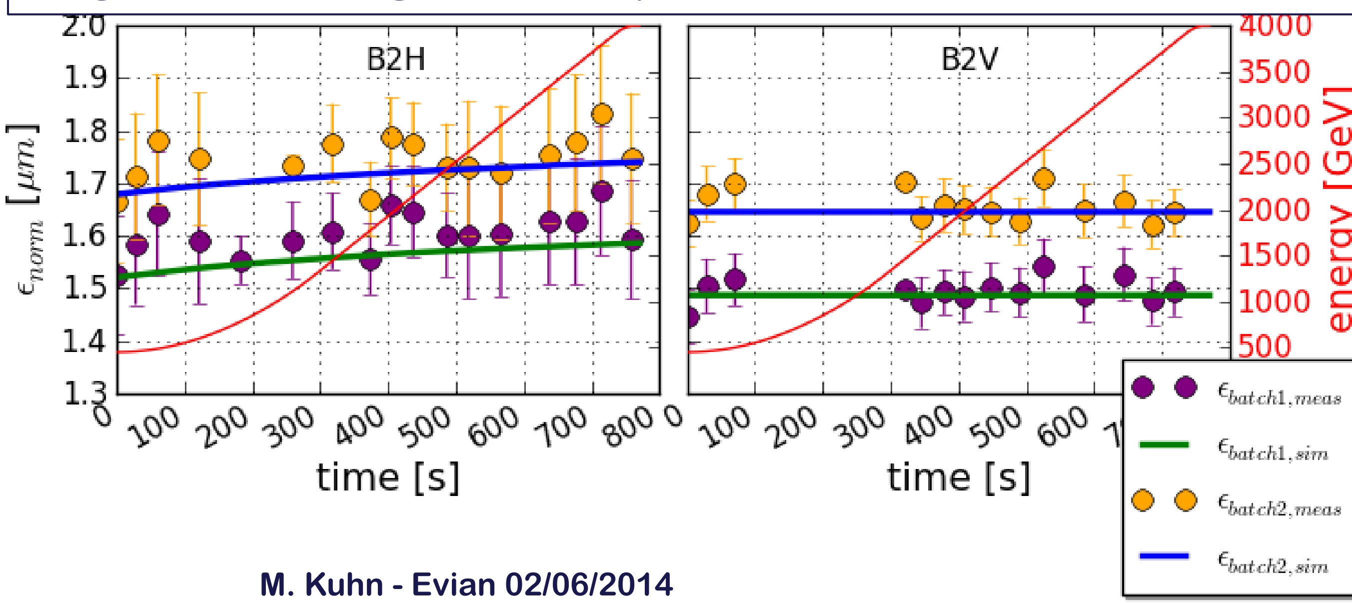
↓

Almost same growth in IBS simulation (4 - 5 %)

IBS Simulation LHC Ramp Fill3217, Normalized Emittances

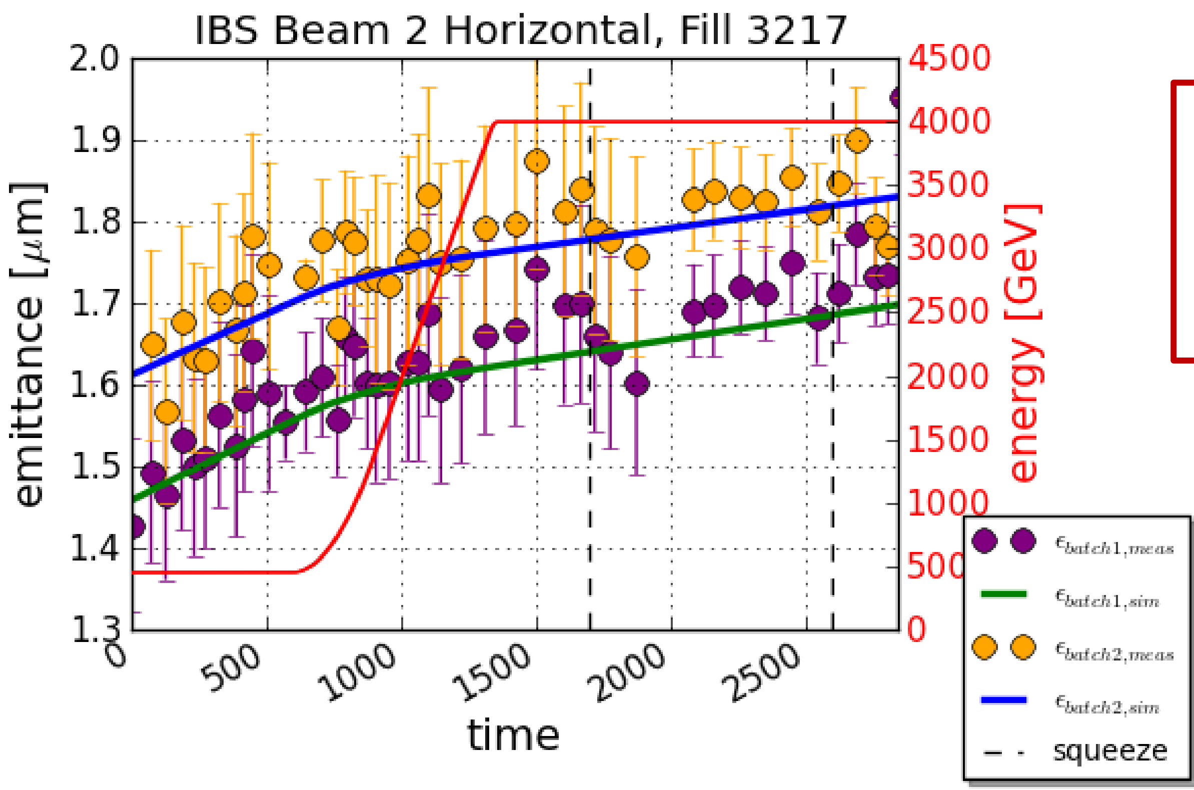
Emittance growth in the horizontal planes during the LHC energy ramp probably only from IBS

- For test fills ~ 3 - 5 % growth through the ramp depending on initial beam parameters
- First guess for physics fills: ~ 3 - 5 % (≤ 0.1 μm) growth through the ramp



IBS during the LHC Cycle

- Example: Fill 3217 beam 2 horizontal
  - Monotonic optics changes for B2H during the LHC cycle
  - Linear interpolation of β gives reasonable values and thus emittances
- Full IBS simulation during the entire LHC cycle compared to wire scanner measurements



IBS simulations and wire scanner measurements for B2H compatible!

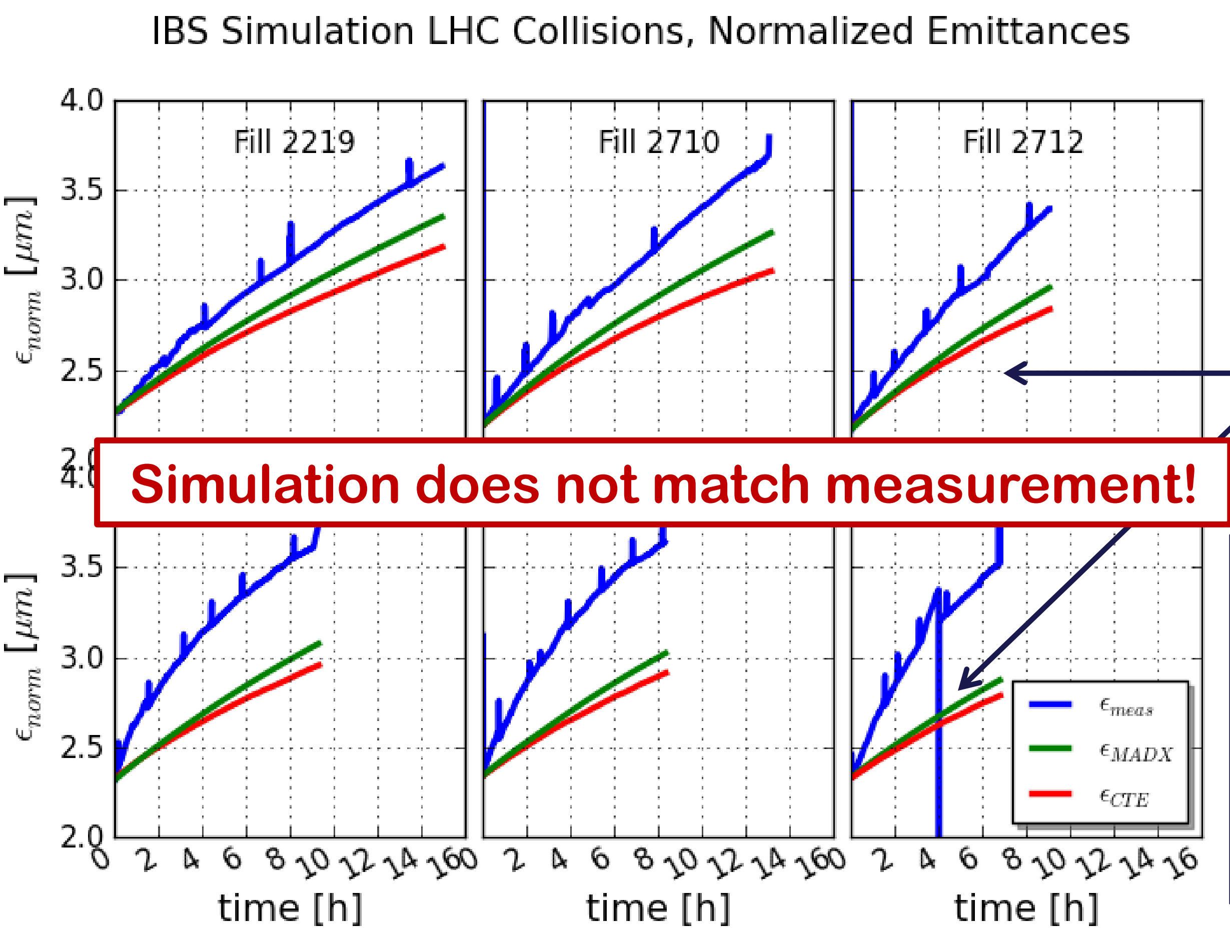
IBS during Stable Beams (1)

- Comparing emittances of "good" fills to IBS simulations
  - from 2011 and 2012 (before and after octupole polarity switch)
  - Long fills with stable bunches (cleaned data)
  - Caveat: large uncertainty about initial horizontal emittance!

2011/ beginning of 2012

ε_{conv} from luminosity vs. simulated ε_H from MADX and CTE

End of 2012



For later fills:

- larger ε_0
- Different growth

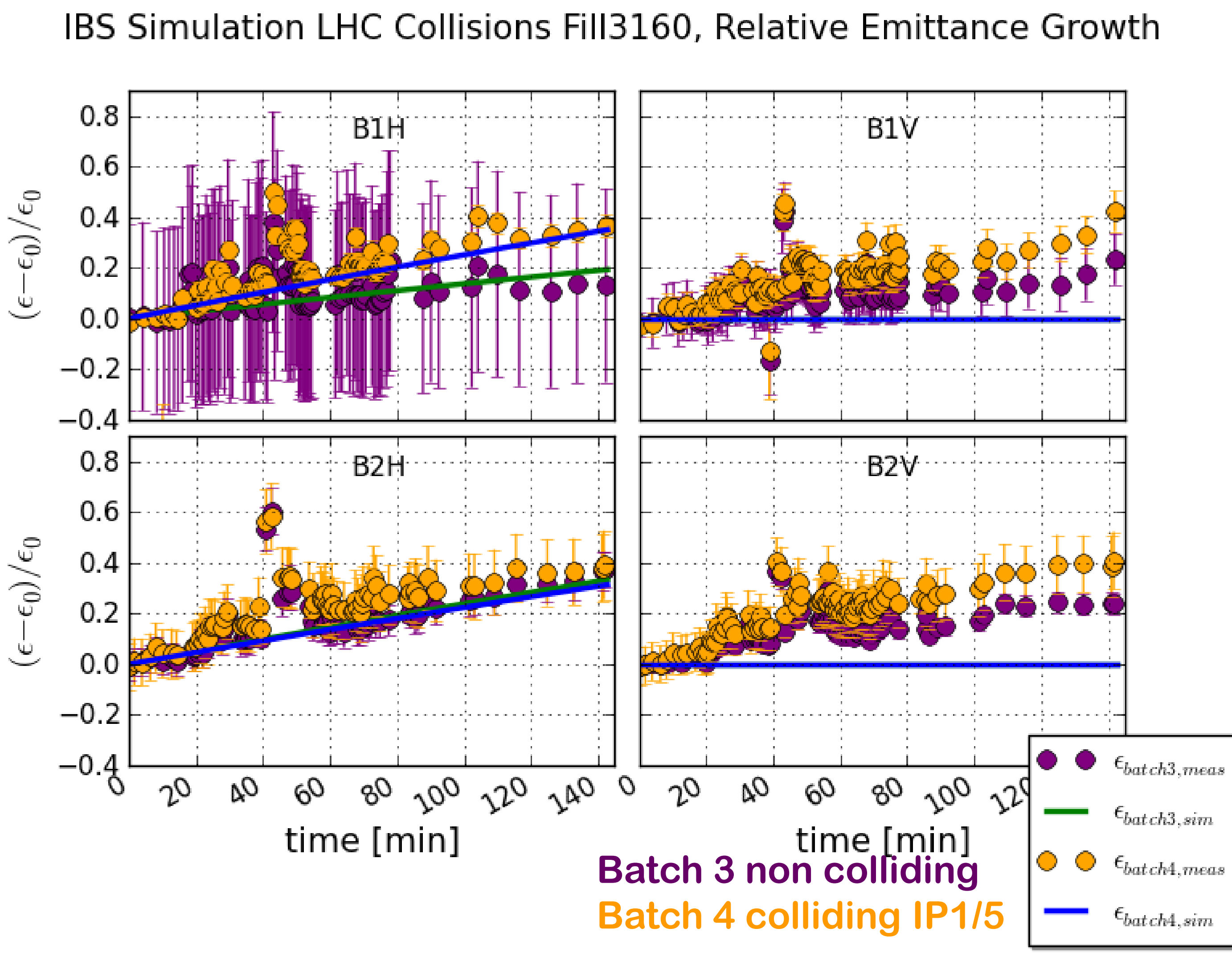
Measured blow-up ~ 2x larger than IBS simulated horizontal growth!

IBS during Stable Beams (2)

- Comparing emittances of MD Fill 3160 to IBS simulations (MADX)
  - Caveat: only 2 h stable beams, short bunch length, small emittance

Horizontal:
Simulation matches measurement!
For this fill almost 40 % blow-up in only 2 hours!

Vertical:
What causes the blow-up?
Almost the same growth as in horizontal plane.



Batch 3 non colliding
Batch 4 colliding IP1/5

Outlook LHC Run 2

- Simulated emittance growth for beams in 2015
  - 20 min ramp to 6.5 TeV (RF 6 - 12 MV, 95 % transmission)
    - assuming injection and flattop plateau length are the same as in 2012
- Estimated emittance blow-up in the horizontal plane from IBS during cycle and collisions (similar as in 2012):

		Nominal beam	High brightness beams
Beam Parameters	$\varepsilon_{x,y}$(inj./coll.) [μm]	2.4 / 2.7	1.3 / 1.7
	Bunch length [ns]	1.25	1.25
	Bunch intensity [10^{11} ppb]	1.3 / 1.2	1.3 / 1.2
Horizontal ε growth from IBS	During cycle	~ 5 % (≤ 0.15 μm)	~ 20 % (≤ 0.3 μm)
	During 8 h stable beams	~ 15 % (≤ 0.4 μm)	~ 40 % (≤ 0.7 μm)

➔ **High brightness beams will suffer severely from IBS!**

Emittance Measurement Puzzle

- Large discrepancy between wire scanner and ALTAS/CMS/LHCb emittances during collisions
  - Measured emittance with wire scanners during collisions at test fills
  - Compared to emittance from ATLAS/CMS luminosity (e.g. Fill 3217)

Fill 3217	Wire scanner	ATLAS	CMS
ε_{conv} [μm]	1.84 ± 0.06	2.33 ± 0.12	2.63 ± 0.14

➔ **Wire scanner results much smaller than ATLAS/CMS results!**

  - Also compared to LHCb emittances measured with beam-gas interactions (SMOG [4], Fill 3160)

➔ **LHCb delivers smaller or larger emittances, depending on the beam and plane with a difference up to 0.6 μm**

- Mostly emittance values from LHCb are smaller than ATLAS/CMS values and larger than the wire scanner ones

New IR4 Optics for LHC Run 2

- At 6.5 TeV beam sizes will be very small: affects emittance measurement accuracy!
- Increase β at transverse profile monitors to increase beam size
  - Option max: overall new optics, ATS-compatible [5,6]
- **Expected beam size improvements** with new optics:
  - At 6.5 TeV with 1.7 μm emittance
    - In 2012 measured beam sizes 200 - 400 μm at 4 TeV with WS

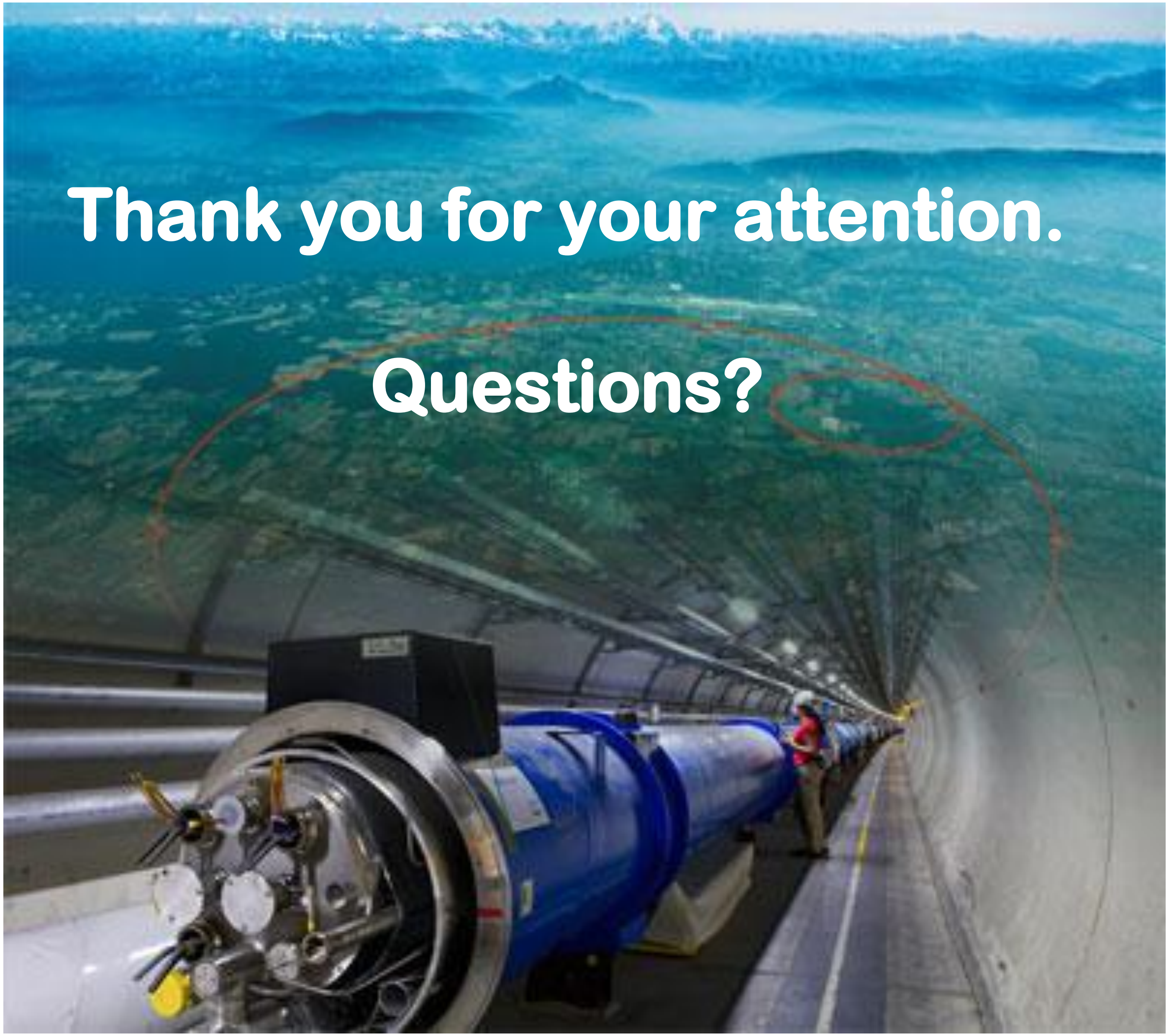
σ [μm]	B1H	B1V	B2H	B2V
Wire Scanner	201 → 217	266 → 289	**174 → 213**	315 → 320
D3 (BSRT)	206 → 222	230 → 271	**177 → 219**	287 → 297
BGI	277 → 282	**153 → 229**	259 → 279	228 → 251

➔ Advantages:

- Wire Scanner and BSRT better measurement accuracy
- BGI possible applicability during Run 2

Plans For the Start Up in 2015

- Essential: optics measurements with AC dipole and k-modulation
  - Tools will be available
- Calibration of all transverse profile monitors at the start of Run 2!
  - Quantify wire scanner photomultiplier saturation
  - Cross calibration: wire scanner, BSRT, BGI, BGV
    - BGV: demonstrator Beam Gas Vertex Detector for LHC beam 2
- Comparison of wire scanner, luminosity and SMOG during Van der Meer scans at the beginning of Run 2
- Measurements with few bunches during the entire cycle including stable beams
  - Comparison of wire scanner, BSRT, BGI and BGV if possible
- Lumi scans at the end of physics fills if possible (as in 2011)


Thank you for your attention.
Questions?

Literature

[1] M. Kuhn, "Emittance Preservation at the LHC," Master Thesis, University of Hamburg/CERN, Geneva, Switzerland 2013.

[2] A. Langner, "Improvements in the Optics Measurement Resolution for the LHC," to be published at IPAC14.

[3] http://mad.web.cern.ch/mad/

[4] C. Barschel, "Precision luminosity measurement at LHCb with beam-gas imaging, " Ph.D. Thesis, RWTH Aachen University, 2013.

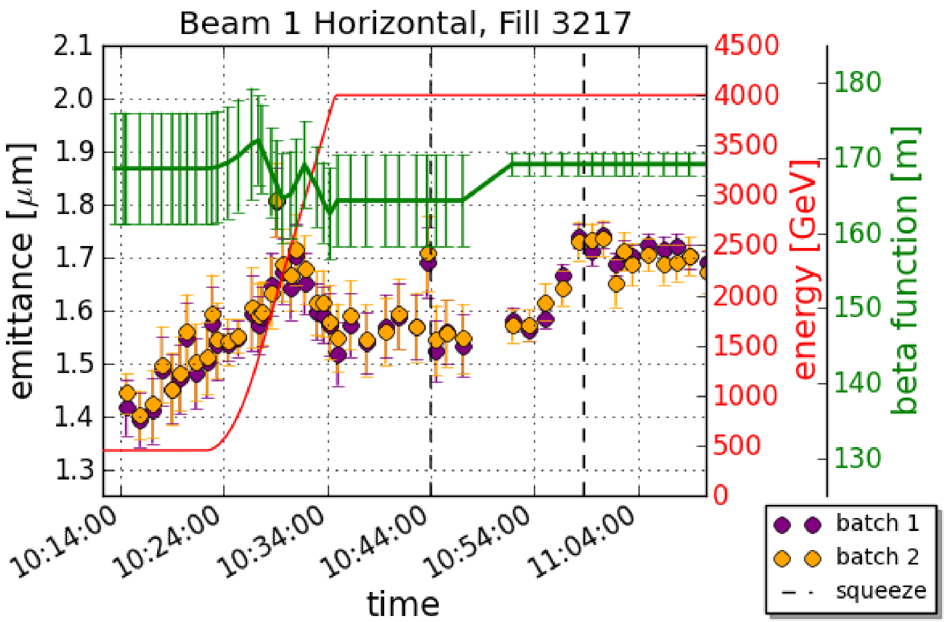
[5] S. Fartoukh, "Optics change requests for Run II and possible options for 2015," LMC Meeting # 179, April 30, 2014.

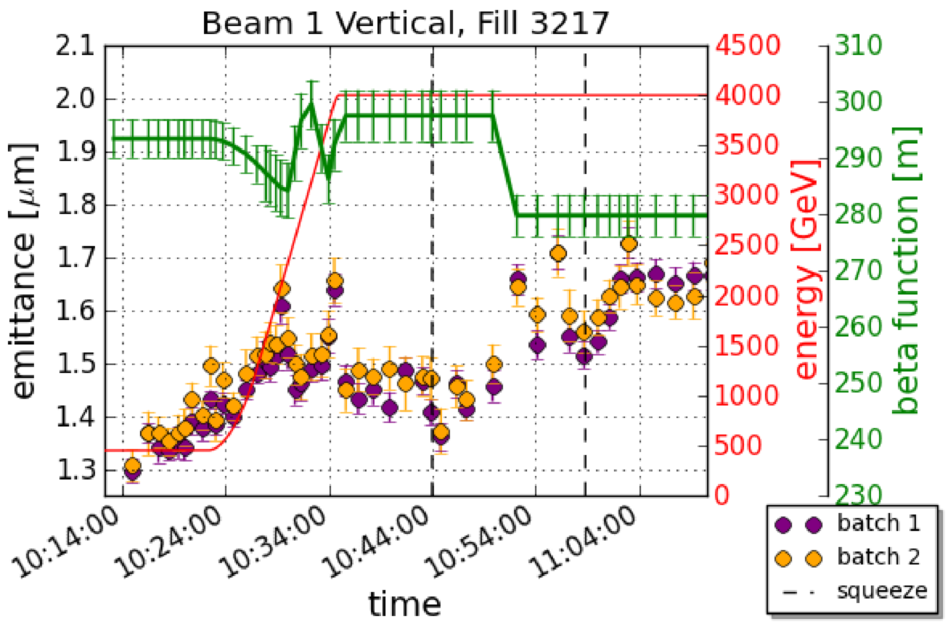
[6] G. Trad, "Implications on beam size measurements in IR4," LBOC Meeting #17, April 15, 2014.

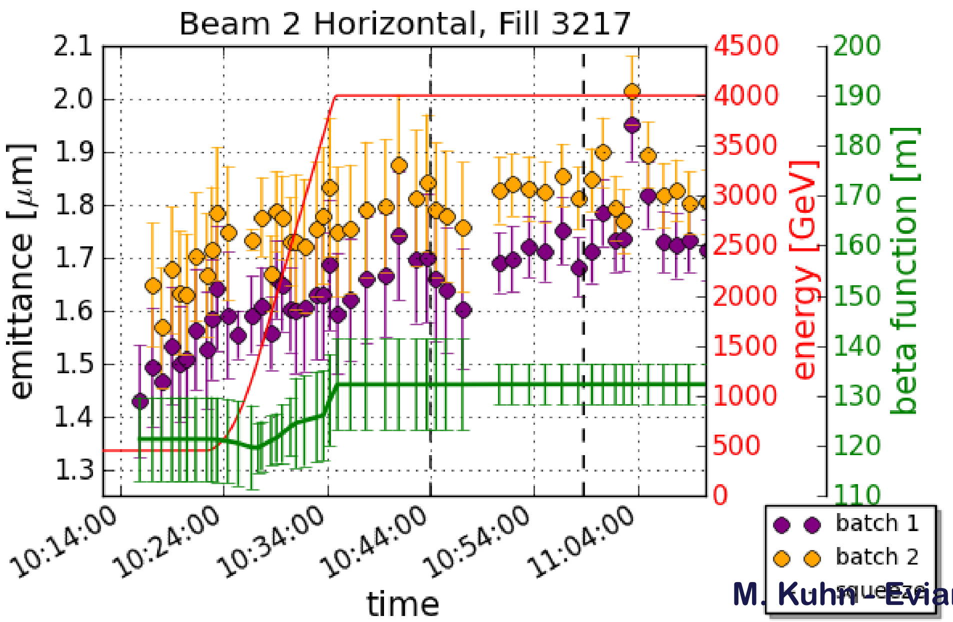
[7] M. Kuhn, "Update on emittance analysis," LBOC Meeting #11, January 28, 2014.

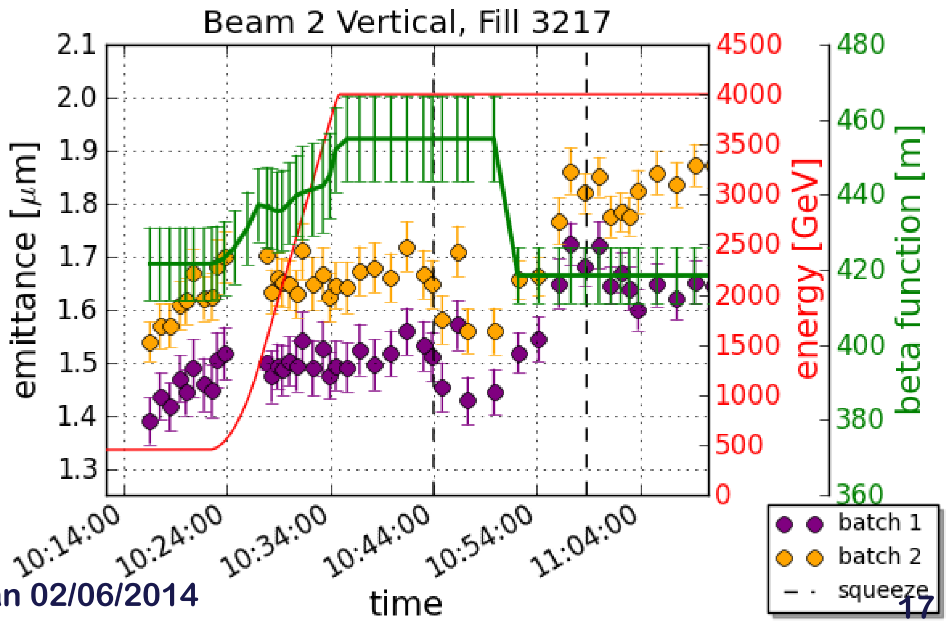
Additional Slides

Emittance through 2012 LHC Cycle

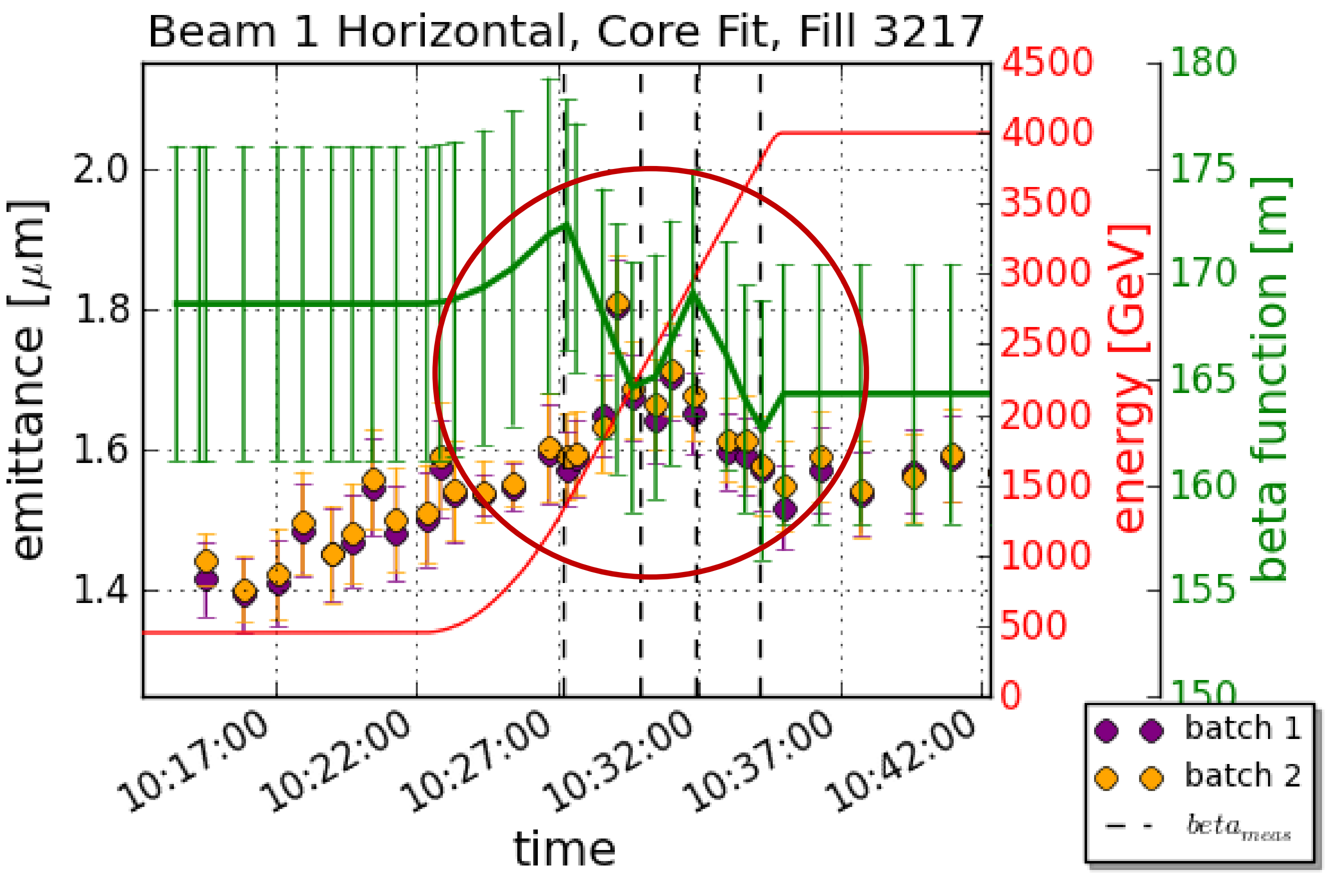








Emittance vs. Beta Function – B1H

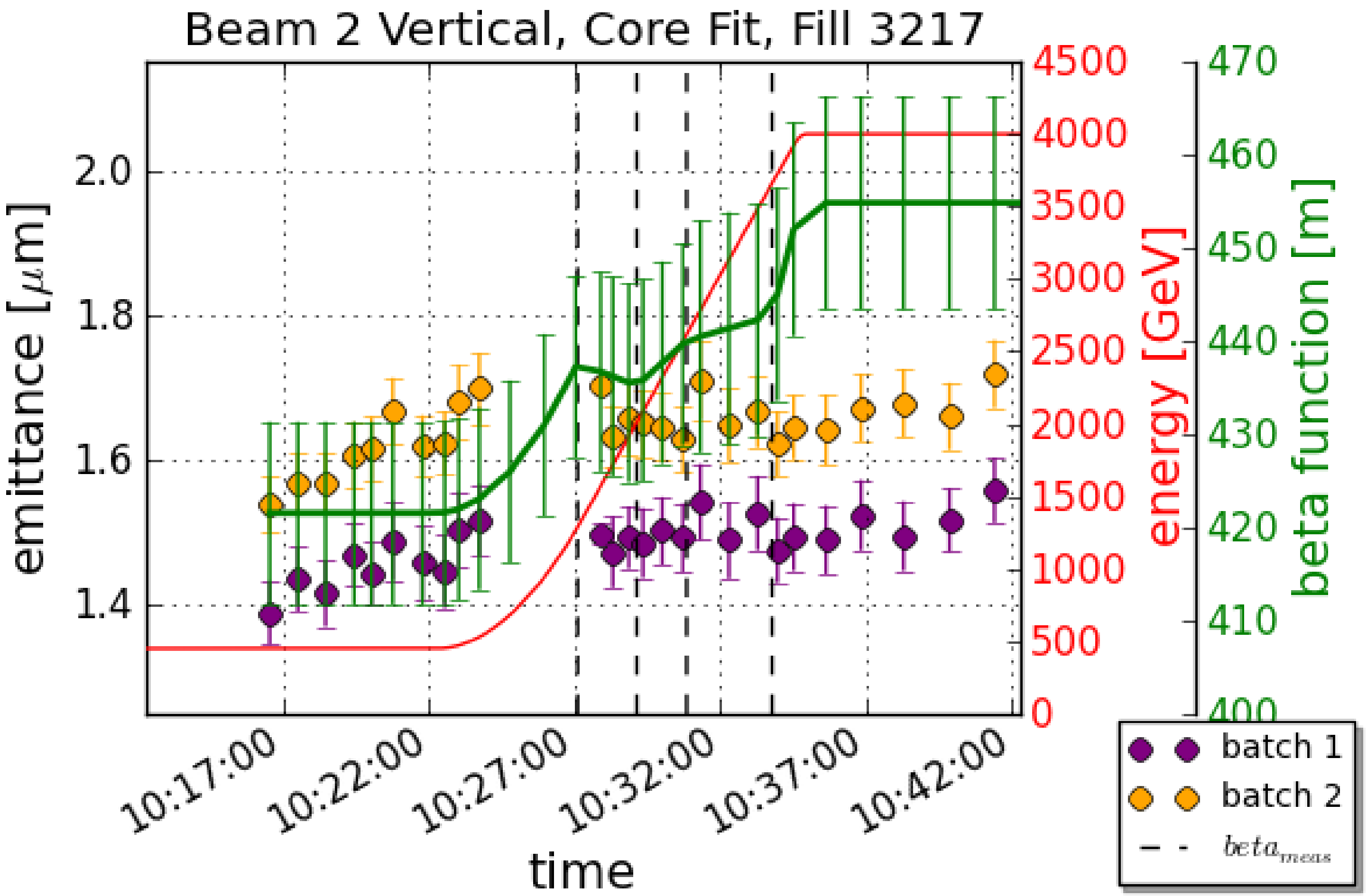


➔ **Growing- shrinking emittances due to non-monotonic changes of optics at wire scanners. Even more obvious for B1 V, next slide.**

– **Not enough beta-measurements to remove all "non-physical" points**

Emittance vs. Beta Function – B2V

- Monotonic growth of beta function at wire scanner
  - ➔ no shrinkage



ATLAS/CMS vs. Wire Scanner

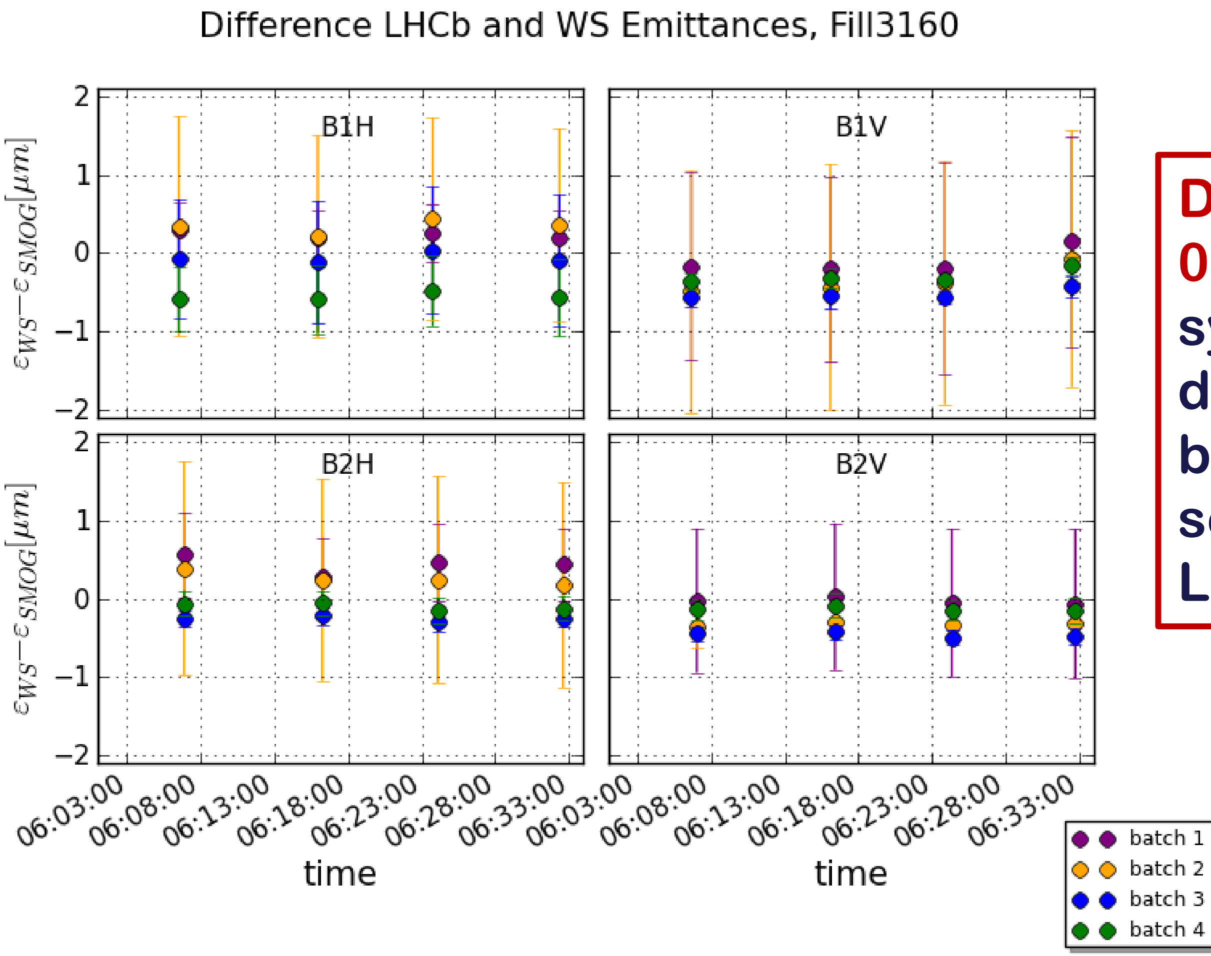
- Example: low intensity test Fill 3217
  - Injection values measured with wire scanners
    - Gauss fit of the entire transverse profile
  - Collision values measured with wire scanners and obtained from ATLAS and CMS bunch luminosity
  - Average value of 6 colliding bunches

	Wire scanner	ATLAS	CMS
Emittance at injection [μm]	1.58 ± 0.06	Measurement not possible	
Emittance at collision [μm]	1.84 ± 0.06	2.33 ± 0.12	2.63 ± 0.14
Emittance growth [μm]	0.25 ± 0.12	0.75 ± 0.18	1.05 ± 0.20
Relative growth	16 %	47 %	66 %

- Wire scanner results much smaller than ATLAS/CMS results!
  - Similar for other test fills measured in 2012

SMOG vs. Wire Scanner

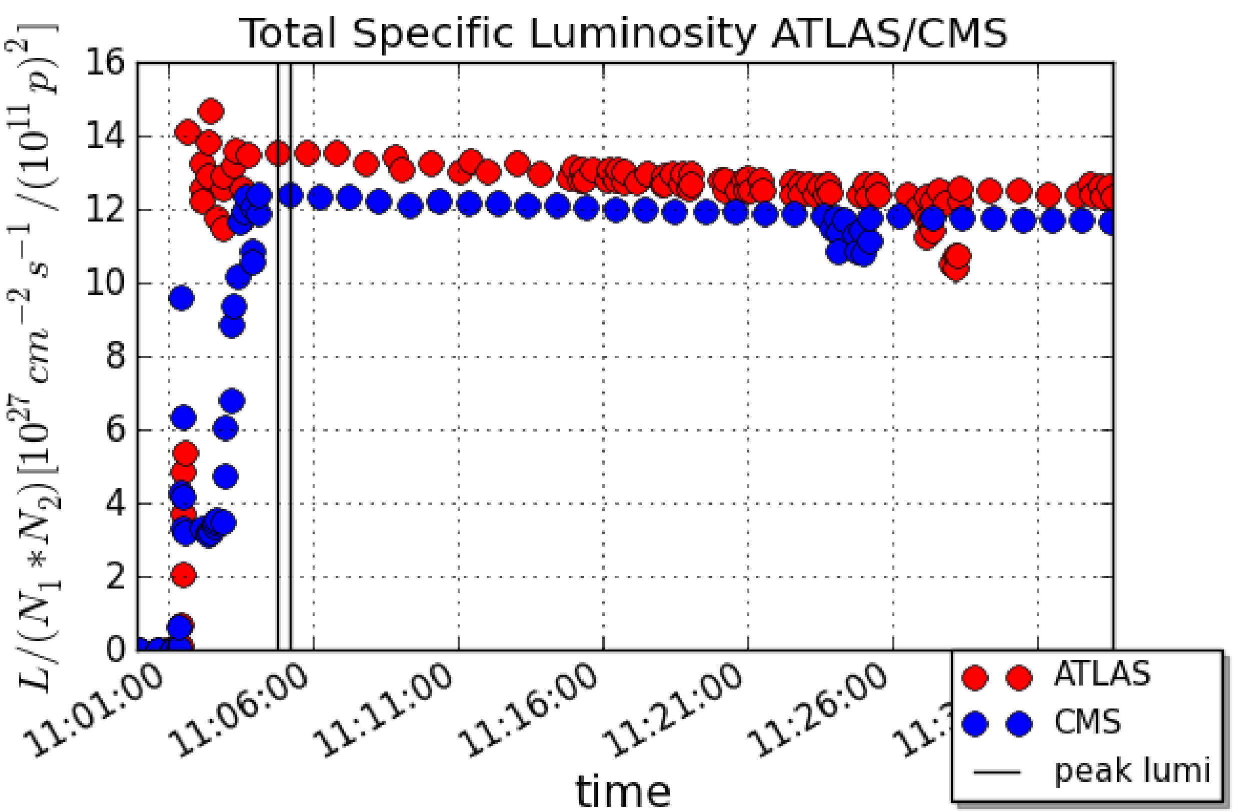
- Measurements during 30 min in collisions with beam gas interactions in LHCb (SMOG) [4] and wire scanners
  - Average emittances of 6 bunches per batch



Discrepancy up to 0.6 μm, but no systematic difference between wire scanner and LHCb emittances!

Fill 3217 ATLAS/CMS Luminosity

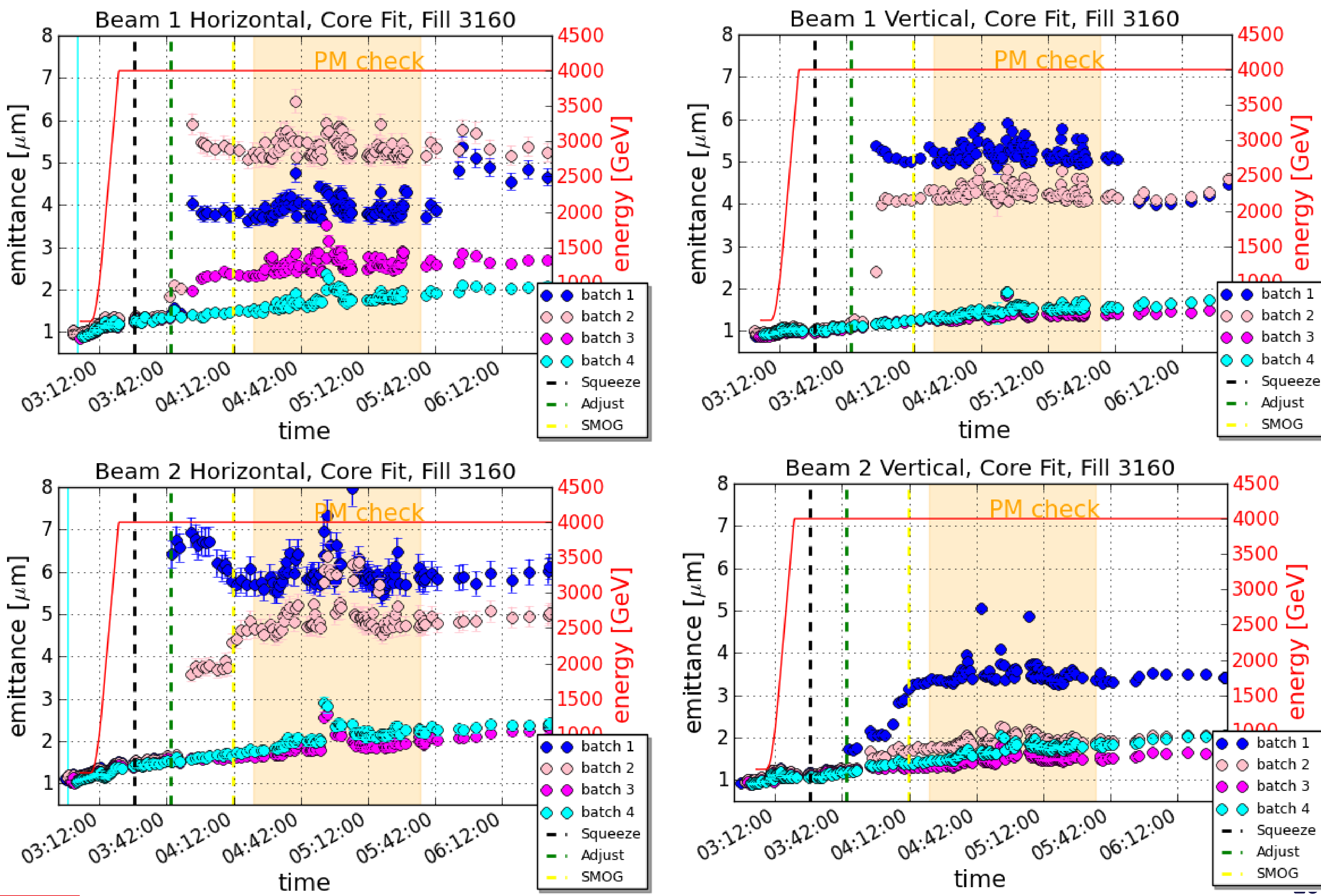
- Rather large discrepancy between ATLAS and CMS emittance values from luminosity
- Closer look at specific luminosity reveals different results for ATLAS and CMS



Fill 3217
6 bunches (batch 2) colliding.

Black line indicates peak luminosity taken for emittance calculation.

Fill 3160 – LHC Cycle



IBS during Stable Beams (2)

- Comparing emittances of “good” fills to IBS simulations
  - from 2011 and 2012 (before and after octupole polarity switch)
  - Long fills with mostly stable bunches (cleaned data)

Fill	Measured growth in 8h	MADX simulated growth in 8h	CTE simulated growth in 8h	
2219	37 %	29 %	25 %	2011
2710 2712	45 % 52 %	33 % 33 %	28 % 28 %	Beginning of 2012
3232 3286 3350	53 % 54 % ~ 54 %	29 % 28 % ~ 28 %	24 % 24 % ~23 %	End of 2012: higher chromaticity and brightness, octupole polarity switch
mean	**~ 50 %**	**~ 30 %**	**~ 25 %**	

Simulation does not match measurement!
Measured blow-up is almost twice as larger as simulated horizontal growth from IBS!

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  - Caveat: only 2 h stable beams, short bunch length, small emittance

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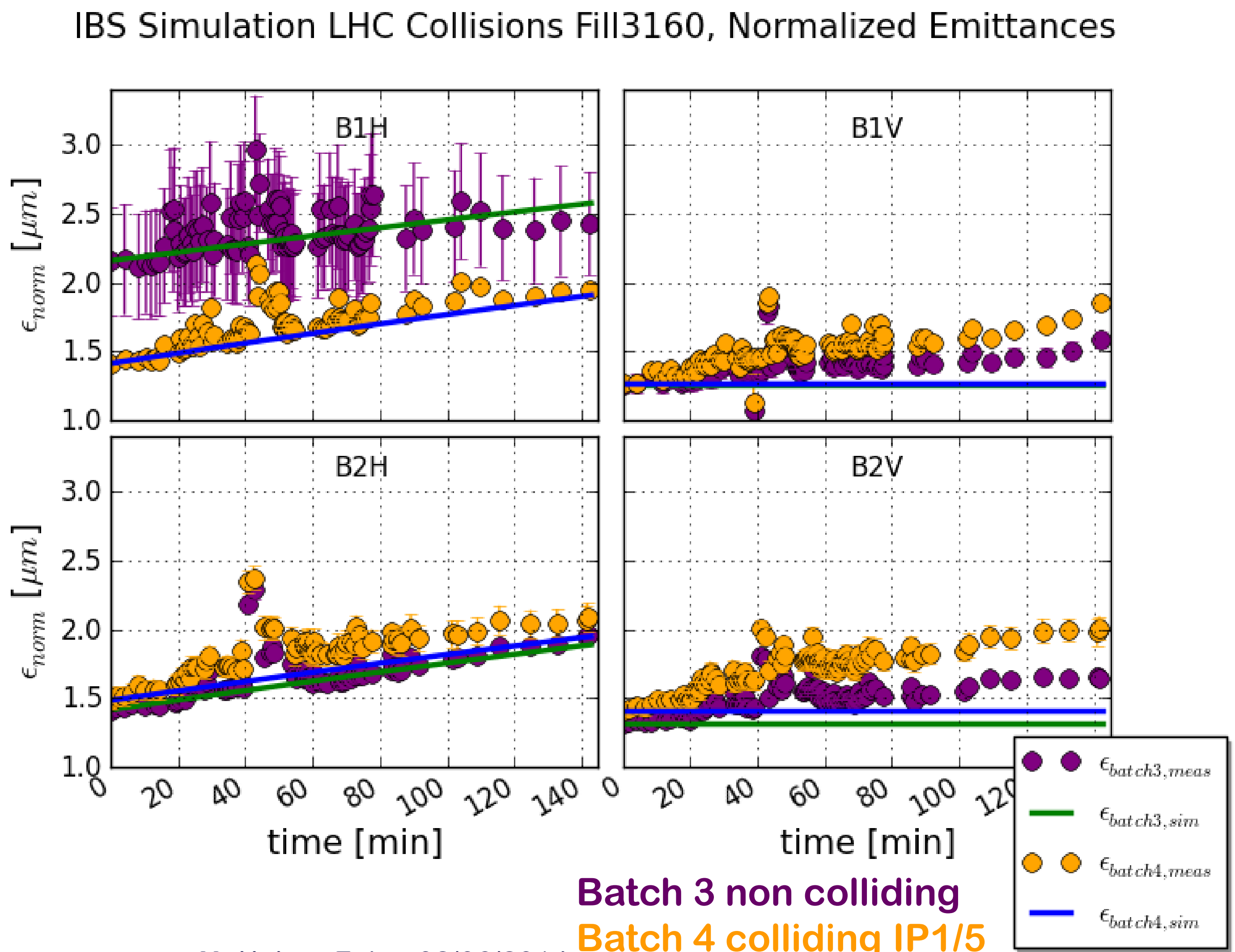

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σ [μm]	B1H	B1V	B2H	B2V
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→ Advantages:

- WS and BSRT better measurement accuracy
- BGI possible applicability during Run 2