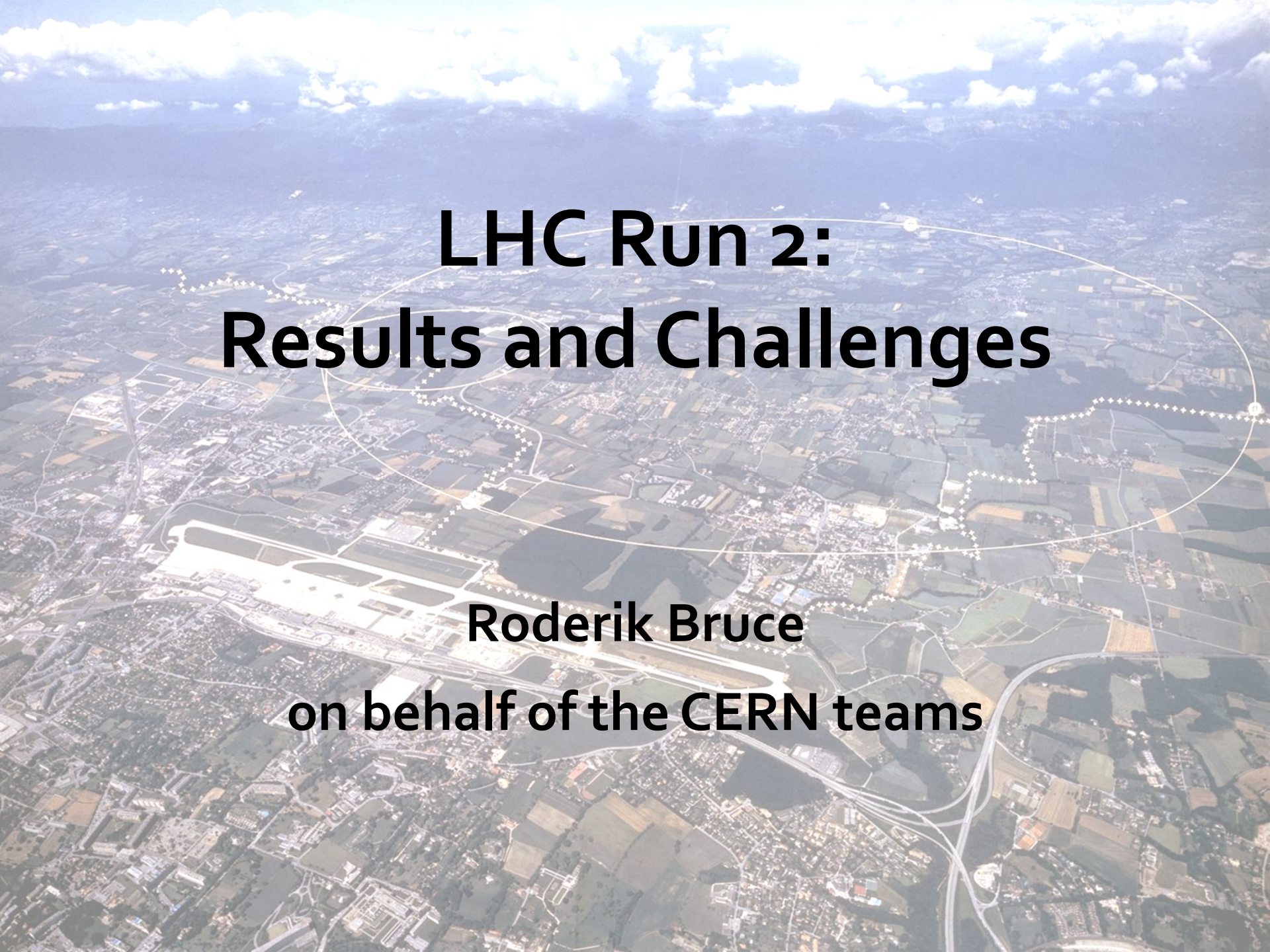


LHC Run 2: Results and Challenges

Roderik Bruce

on behalf of the CERN teams

Acknowledgements

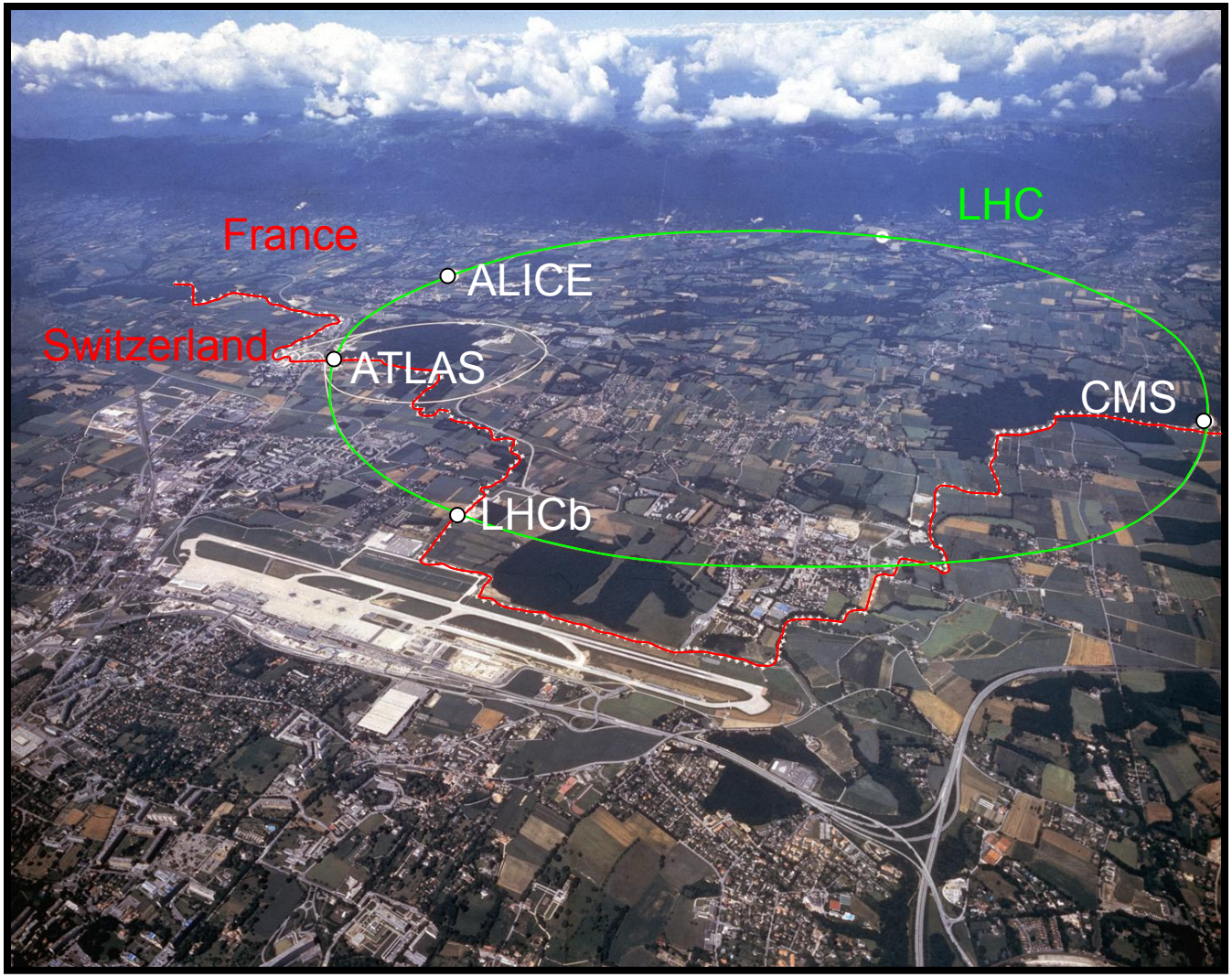
- A big thanks to all colleagues involved across various teams!
- Special thanks for material and discussions
  - G. Arduini, B. Auchmann, J. Boyd, O. Bruning, L. Carver, M. Crouch, H. Damerau, R. de Maria, S. Gilardoni, M. Giovannozzi, W. Hofle, G. Iadarola, J. Jowett, K. Li, M. Lamont, A. Lechner, E. Metral, D. Mirarchi, T. Pieloni, S. Redaelli, G. Rumolo, B. Salvant, C. Schwick, G. Valentino, D. Valuch, J. Wenninger
- Apologies for topics not covered…

Outline

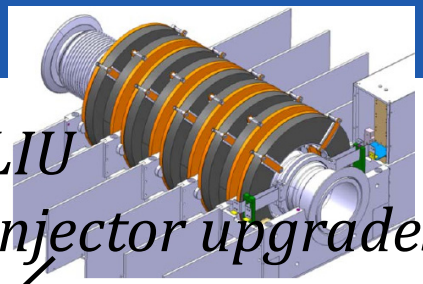
- Introduction: LHC, general goals from Run 2
- Recent highlights from luminosity production
- Beams from injectors
- 2015: commissioning year
- 2016: production year
- Outlook & conclusions

The Large Hadron Collider

- 27 km synchrotron, built to collide 7 TeV proton beams at 4 experiments
- About 1 month per year: heavy-ion collisions



Where are we now?



We are here

Construction
Accident Recovery
Run 1
3.5-4 TeV, 50 ns
Long shutdown 1
Run 2
6.5 TeV, 25 ns
Long shutdown 2
Run 3
Long shutdown 3

2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

Goals for Run 2

- Main physics goals for Run 2 (2015-2018):
  - Measurement of standard model physics including W, Z, top
  - Study of the Higgs boson (decays, spin/parity)
  - Searches for new particles beyond the standard model (supersymmetry etc)
- Main accelerator goals for Run 2:
  - Increased beam energy compared to Run 1
  - Go to 25 ns bunch spacing to decrease pileup (was 50 ns in Run 1)
  - Collect > 100 fb^{-1} of data (got ~30 fb^{-1} in Run 1)
  - In 2016: Collect > 25 fb^{-1}

Outline

- Introduction: LHC, general goals from Run 2
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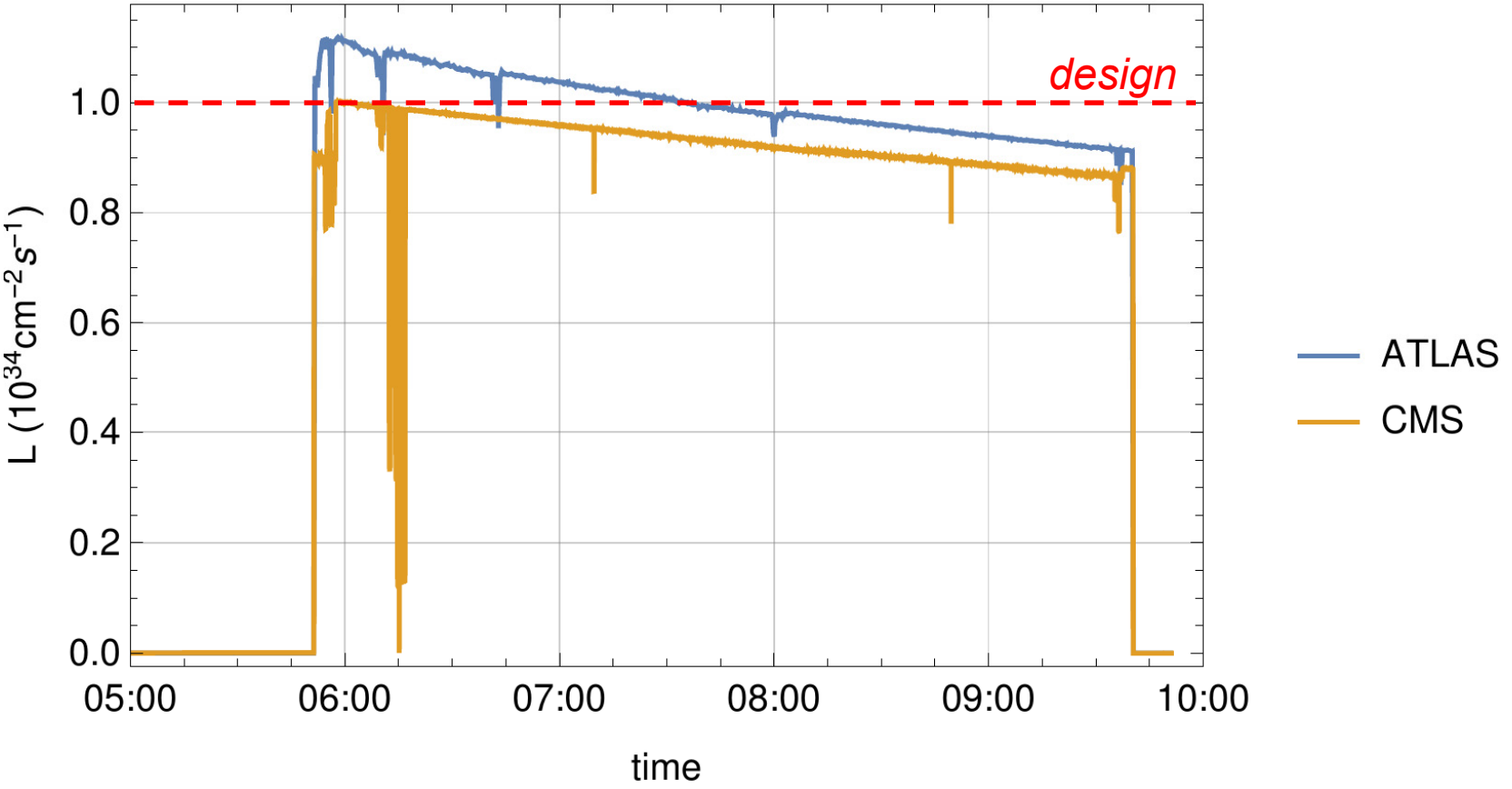
Fill from July 2, 2016

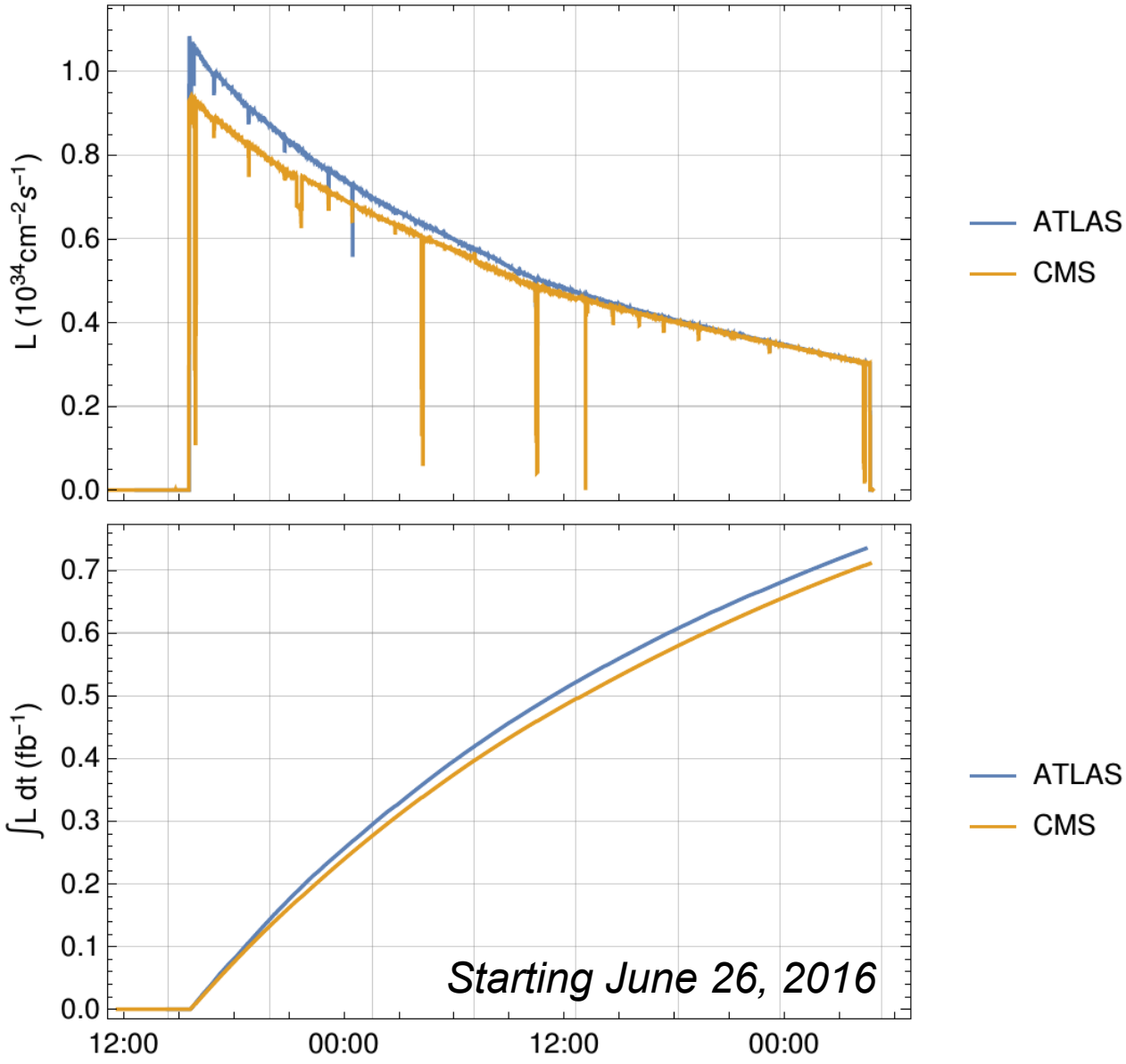
- Luminosity production going quite well at the moment
- **Last week, LHC design luminosity 10^{34} cm^{-2} s^{-1} reached and surpassed for the first time ever!**



Nominal luminosity reached

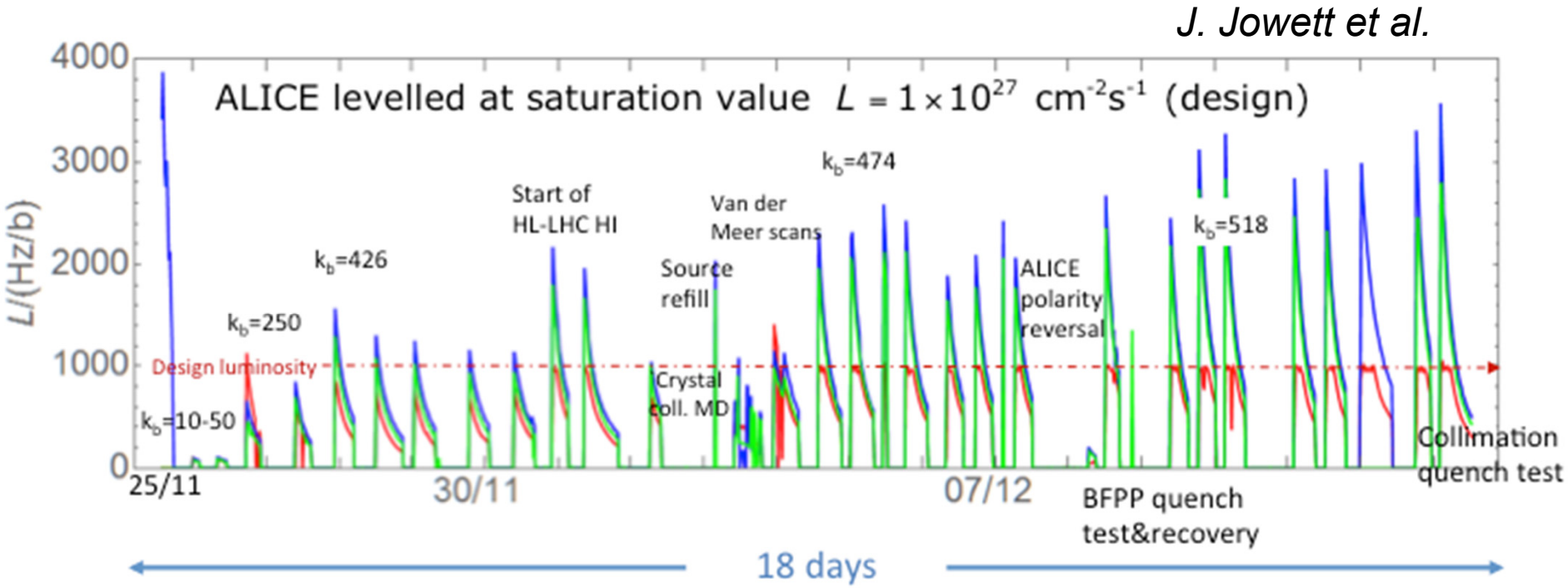
Other recent records

- Other recent records:
  - 0.74 fb^{-1} produced in one fill, 37 h
  - More than 2 fb^{-1} in one week



LHC heavy-ion highlights

- Pb-Pb run at end of 2015. p-Pb planned for end of 2016



- In 2015, **about 3 times design luminosity (Pb-Pb) achieved** thanks to excellent injector performance (higher bunch charge)

Outline

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- Beams from injectors
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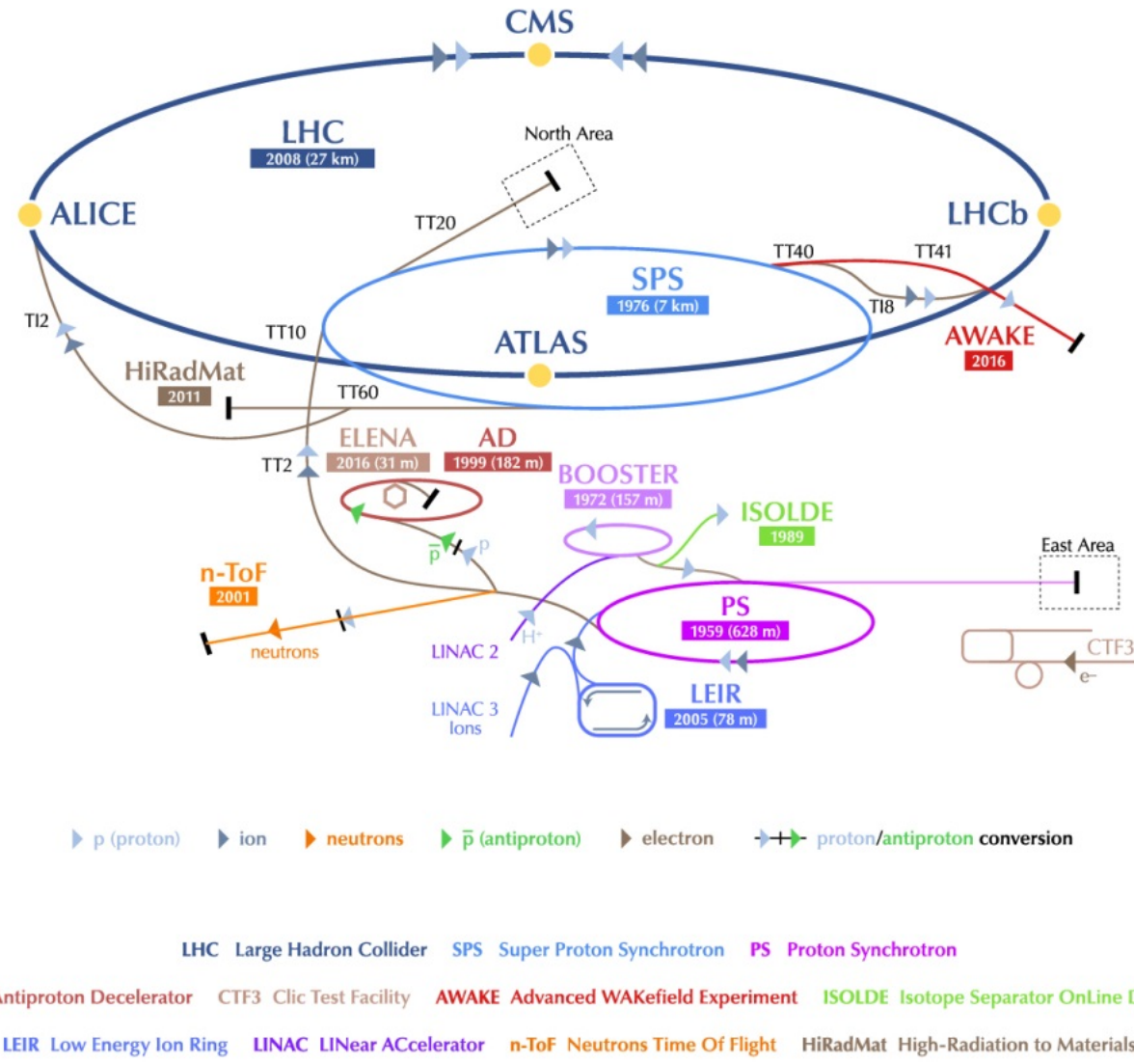
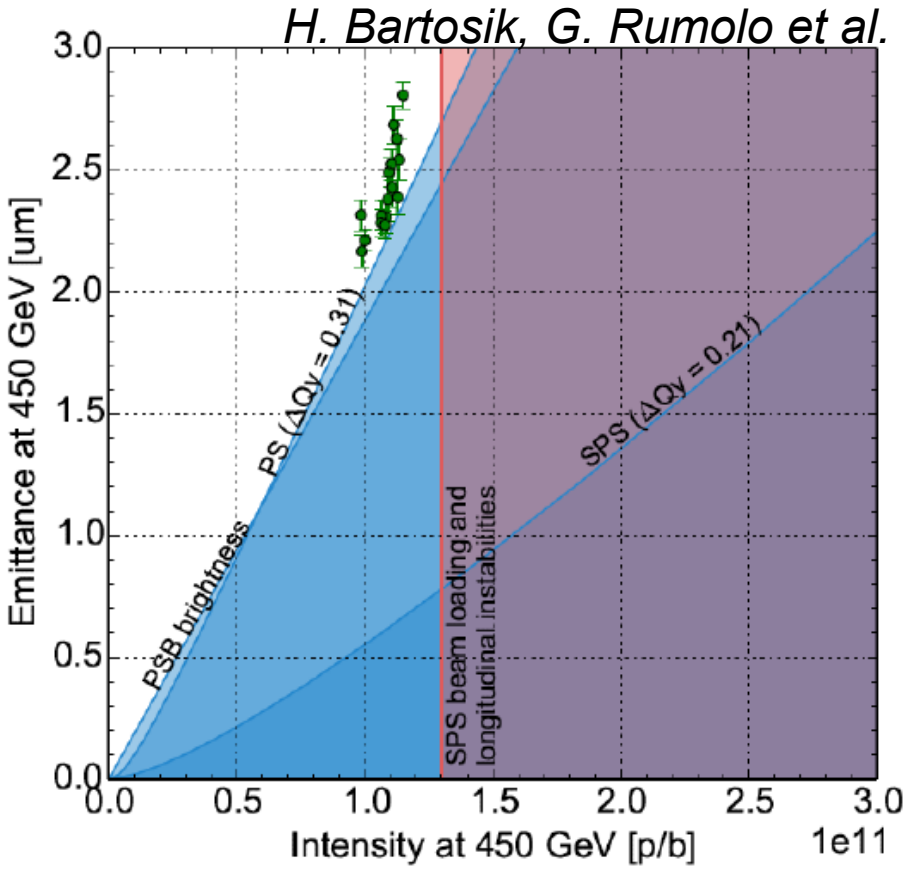
CERN accelerator complex

- LHC last in a chain of accelerators
  - Transverse emittance given by PS Booster
  - Longitudinal train structure given by the PS
  - SPS creates bunch structure for injection into the LHC



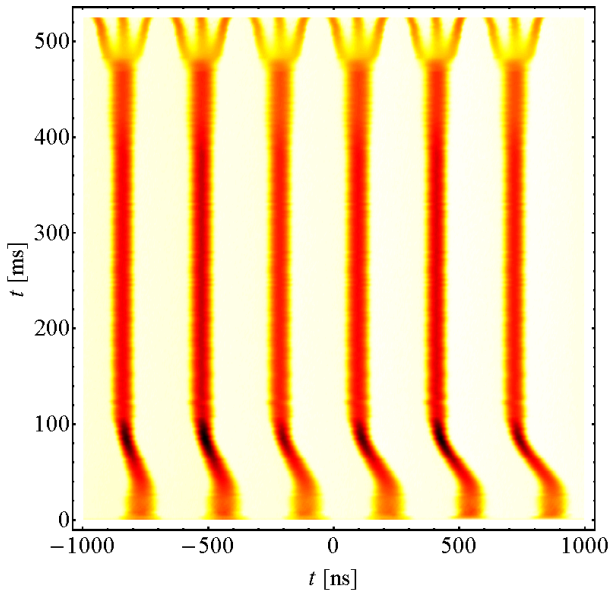
Beam from the injectors

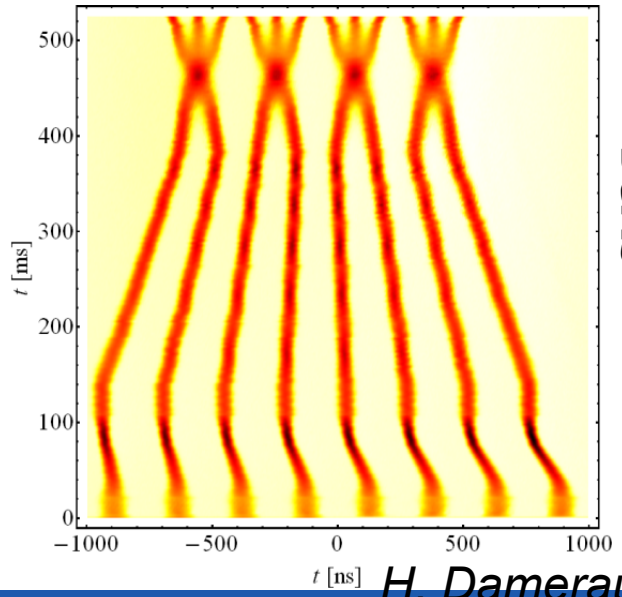
- Limitations in the injector chain define the LHC beams



Production schemes for LHC beams

- Standard 25 ns scheme used so far
- Alternative scheme: BCMS (**B**atch **C**ompression, **M**erging & **S**plitting)
- Different RF manipulations in the PS





H. Damerau et al.

LHC beam menu from the injectors

- BCMS gives higher brightness (smaller emittance and same bunch intensity), but also fewer bunches per train.
  - Potentially higher luminosity if emittance can be kept in LHC, but watch out with beam stability and lifetime

	Standard 25 ns	BCMS
Bunch population	~1.2e11	~1.2e11
Transv. emittance	2.5 μm	1.8 μm
Max. n.o. bunches	2748	2268

H. Bartosik, G. Rumolo et al.

- Further alternative schemes under study
  - 80 bunches, 8 bunches 4 empty, 50 ns …
- Several further HB talks on LHC injectors: C. Bracco, E. Metral, E. Shaposhnikova, H. Bartosik, S. Machida, K. Li, E. Benedetto

Outline

- Introduction: LHC, general goals from Run 2
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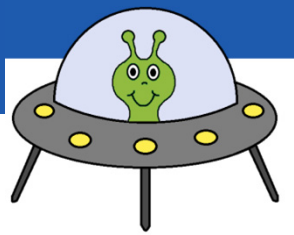
LHC in 2015

- Commissioning year, relaxed parameter set
  - main priority to get back after shutdown and commission 6.5 TeV beam energy and 25 ns bunch spacing

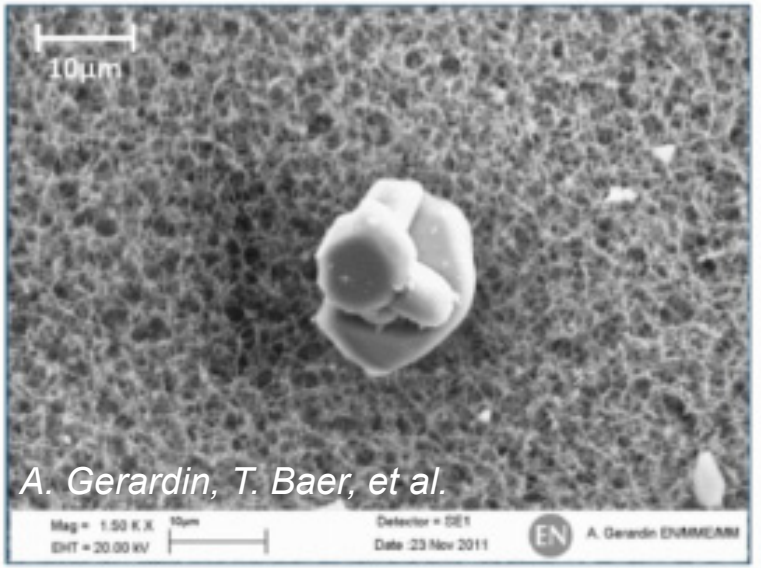
3rd June: First Stable Beams

- Some issues encountered
  - Non-radiation hard electronics in quench-protection system: fixed
  - Non-conformities on absorber for injection protection (TDI): fixed
  - ULO (unidentified lying object). Aperture restriction in one specific magnet, bypassed with orbit bump: fixed

UFOs



- UFOs (unidentified falling object): Believed to be falling dust particles hit by the beam.
  - Induced losses could cause beam dump or quench
  - 2015 : 18 dumps, 3 quenches due to UFOs
  - Conditioning with time

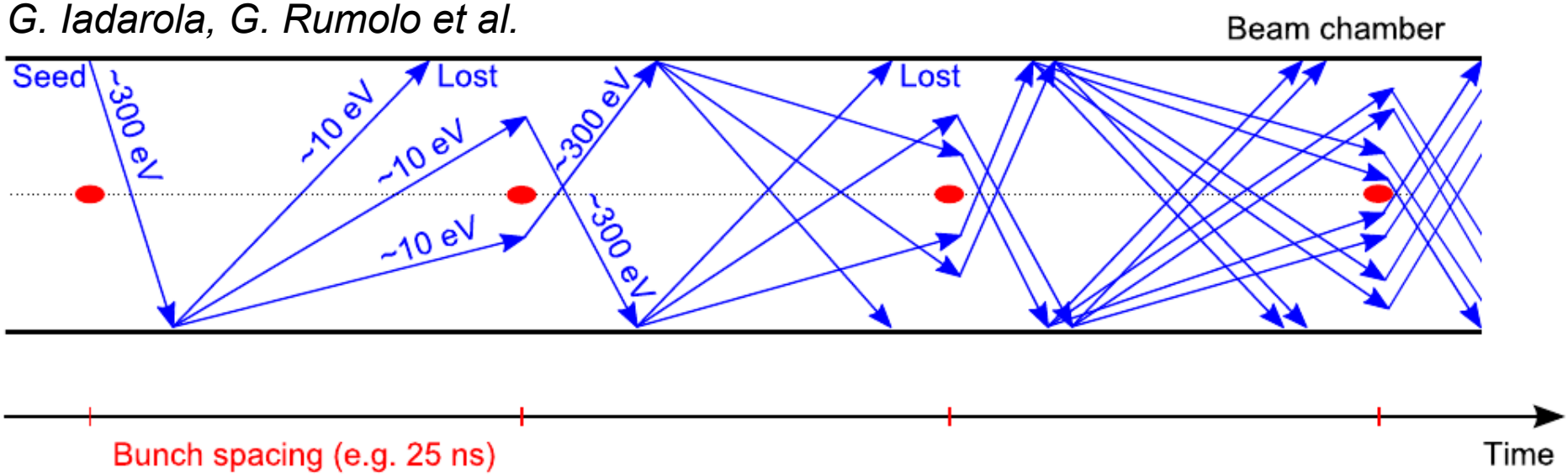


T. Baer CERN-THE

Electron cloud (1)

- Electrons accelerated by passing bunches => secondary electrons emitted when hitting the chamber
  - Possible avalanche effect when secondary electrons are accelerated

G. Iadarola, G. Rumolo et al.

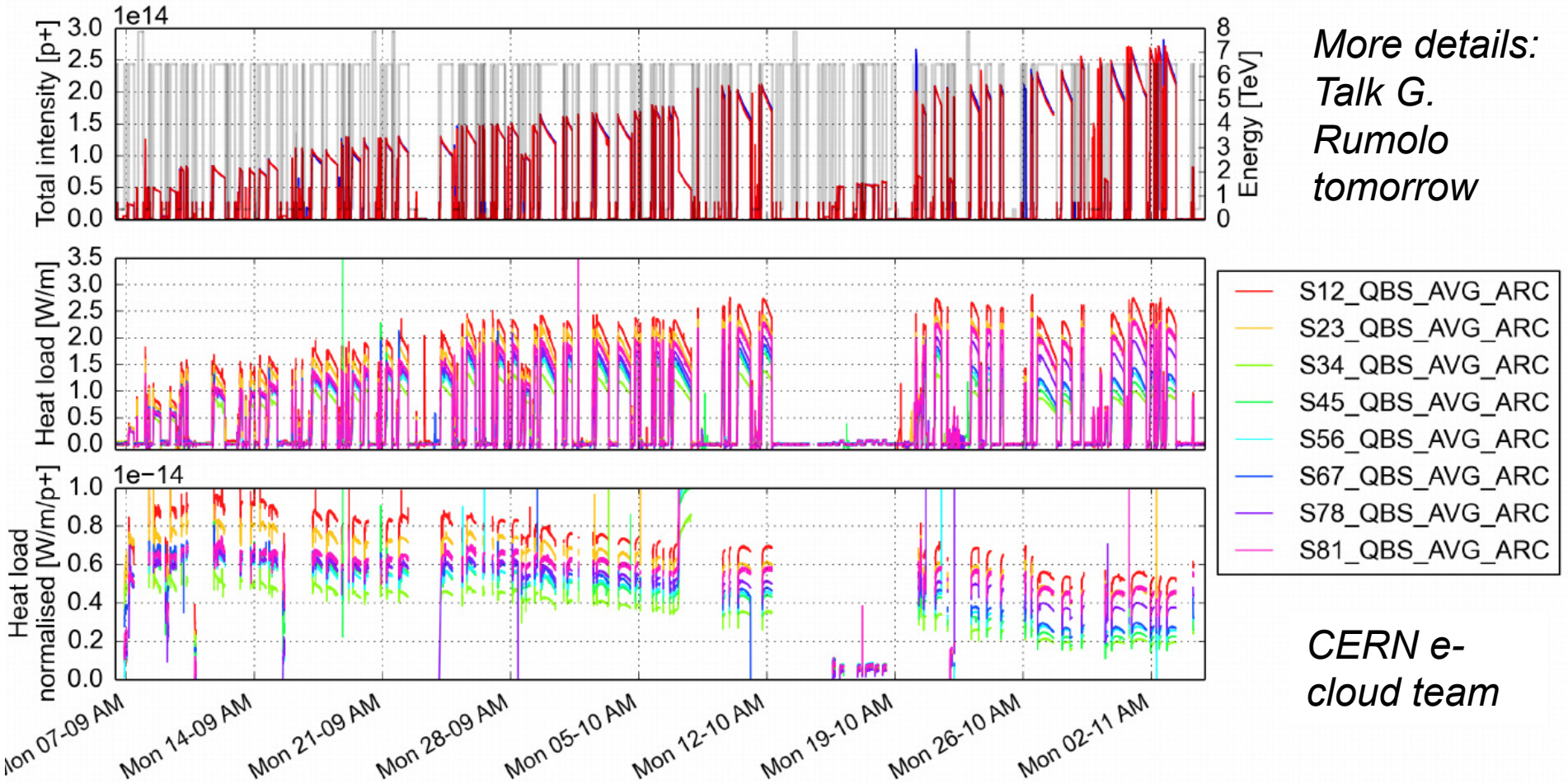


- Possible consequences: heat load on chamber wall, instabilities, vacuum degradation, emittance blowup …

Electron cloud (2)

- Main limitation for LHC: heat load to cryogenics
  - Transients at injection, ramp, beam dump. Working close to cooling power limit
  - Main limit on the number of bunches achieved in 2015
  - Some issues also with vacuum spikes at injection kicker
- Conditioning observed with time – "scrubbing"

Electron cloud (3)



More details: Talk G. Rumolo tomorrow

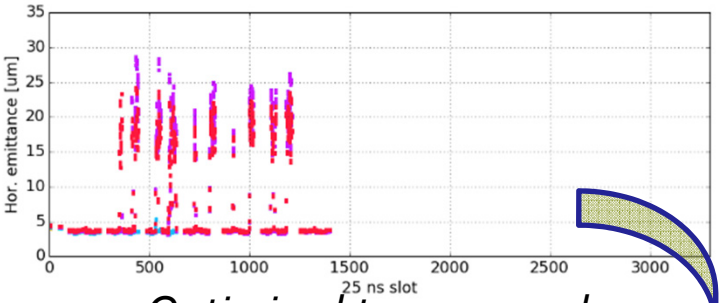
CERN e-cloud team

- Different heat loads in different machine sectors – not well understood.

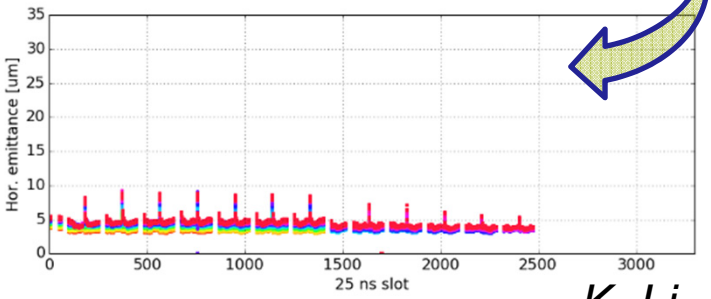
Fighting instabilities

- Main sources of instabilities: electron cloud and impedance
- LHC experience: Beams stable through the cycle (after scrubbing) with
  - High chromaticity
  - High octupoles
  - High transverse damper gain
  - Change of working point at 450 GeV
- Beam-induced heating not an issue anymore: significant effort done to minimize impedance and fix non-conformities

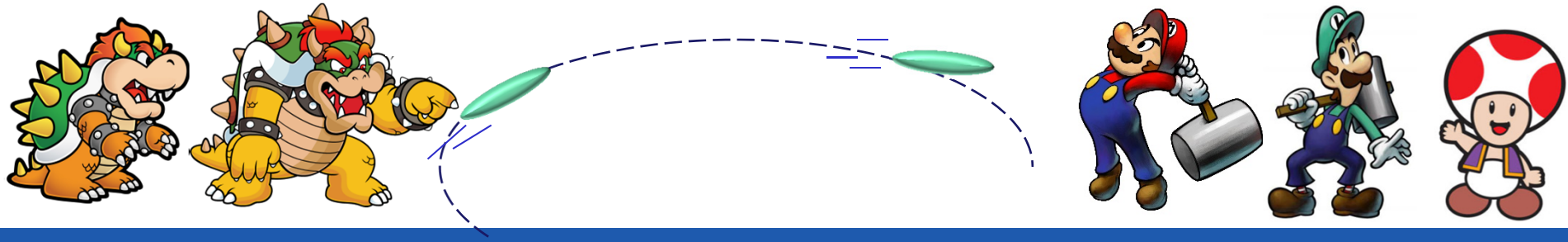
Impedance team
More details: talk E. Metral



Optimized transverse damper

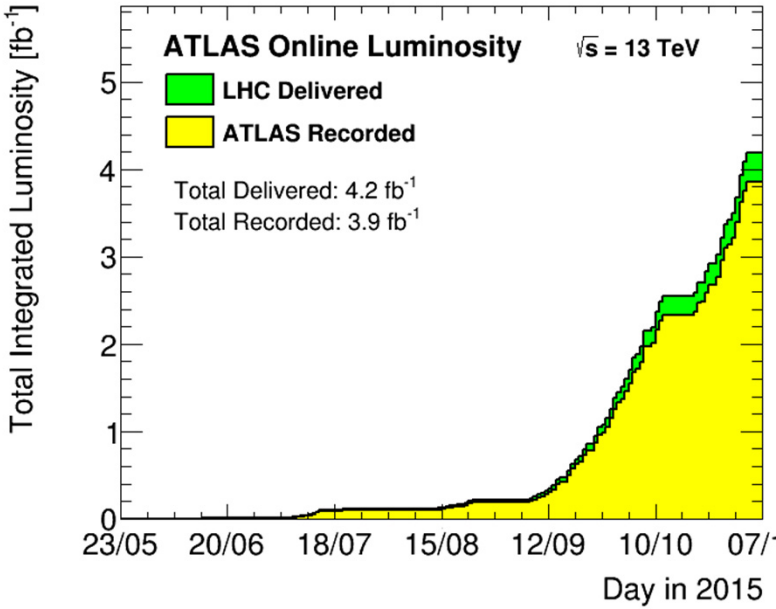


K. Li



2015 achievements

- Main achievements
  - Successfully established 6.5 TeV and 25 ns beams
  - Achieved 2244 bunches (2748 possible)
  - Peak luminosity of about 5 x 10^{33} $cm^{-2}s^{-1}$ (half of nominal)
  - Peak production: ~1 fb^{-1} of data/week
  - Physics: Accumulated 4.2 fb^{-1} of data



- 2016
  - Production year: must significantly increase luminosity (compare goal of more than 100 fb^{-1} in Run 2)
  - Try to push the limitations encountered in 2015

Pushing luminosity

Higher intensity

Increase bunch intensity

Increase number of bunches

$$\mathcal{L} = \frac{N_1 N_2 f_{\mathrm{rev}} k_B}{4\pi\beta^* \epsilon_{xy}} F$$

Smaller β*

Smaller emittance

Smaller beam size

Increase F: shorter bunches, smaller crossing angle

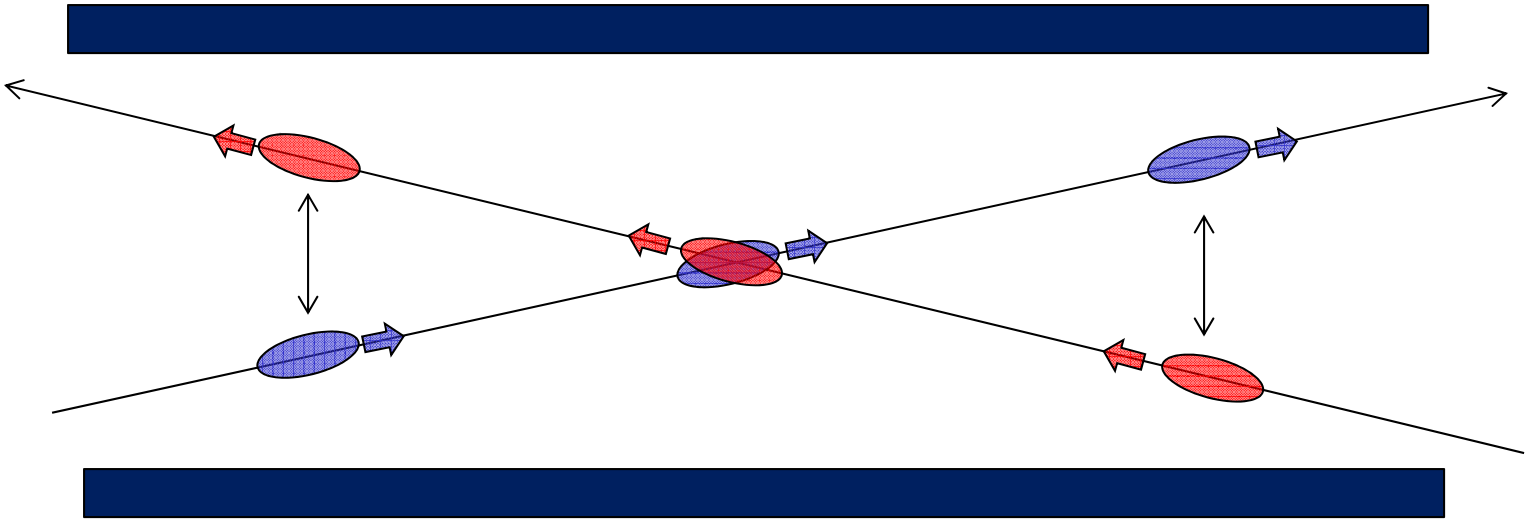
$$\frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

Intensity and emittance

- Through scrubbing and gradual intensity increase, try to approach the limit of 2748 bunches
  - Temporary issue: vacuum leak on SPS dump. Limit on train length: 96 bunches to ensure dump is not damaged. Spares in preparation
  - Presently limited to 2076 bunches in the LHC
  - Close to cryogenic limit: even without SPS dump issue, not much margin due to e-cloud
- Smaller emittance from BCMS is promising option, in particular while number of bunches is anyway limited
  - Ongoing efforts to understand emittance blowup during LHC cycle
- Bunch intensity: gradual increase recently, now close to limit

Increasing geometric factor

- Fewer collisions when bunches are not fully overlapping



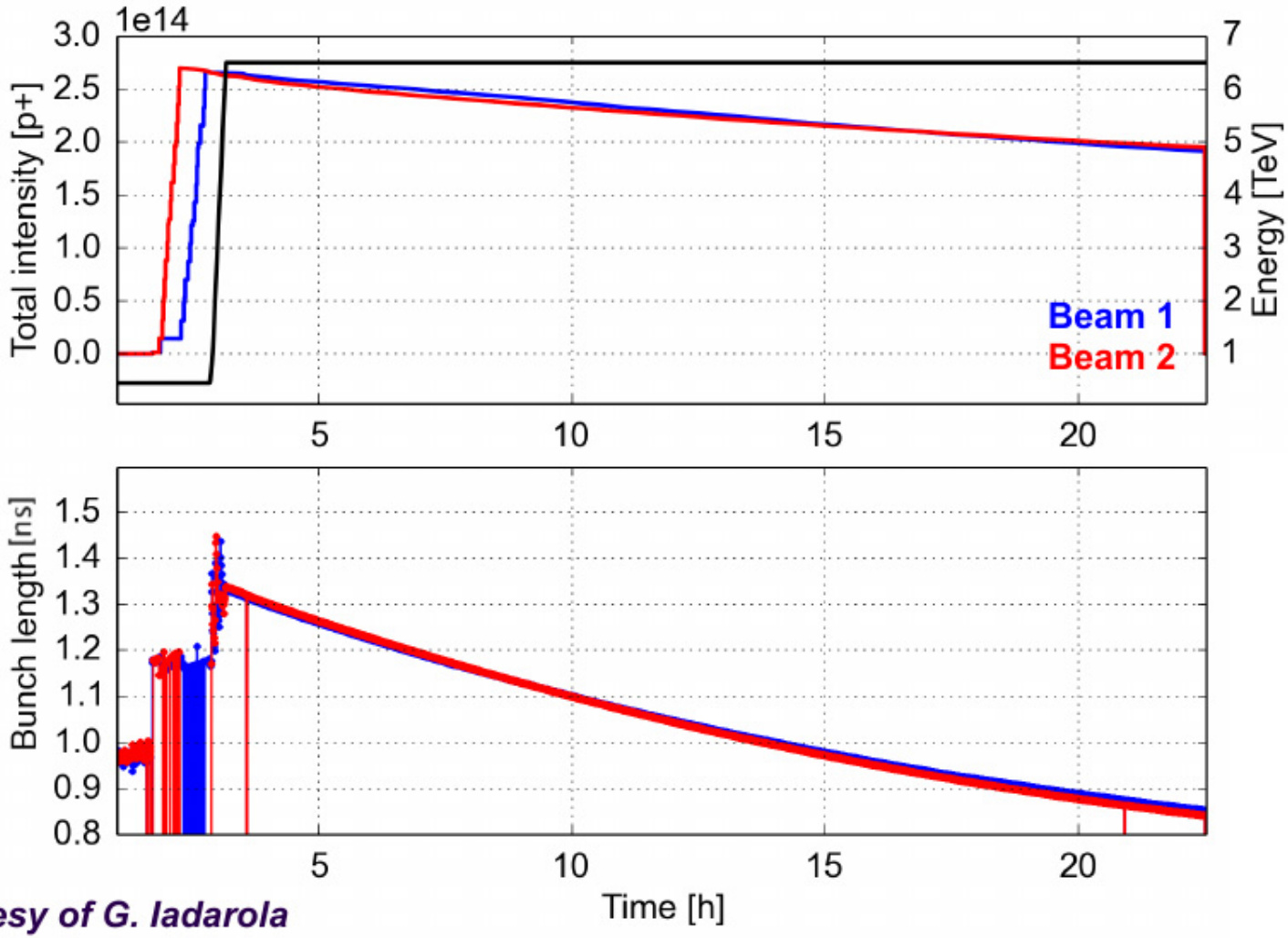
- Decrease bunch length and/or crossing angle to minimize effect
  - Crossing angle gives normalized beam-beam separation: dynamic aperture and beam lifetime sets lower limit

Decreasing bunch length

- Limited by electron cloud effects and longitudinal instabilities
  - Presently at ~1.12 ns bunch length at 4 σ (8.4 cm at 1 σ) at start of fill after gradual decrease
  - Not yet down at nominal ~1 ns (7.5 cm).
- Bunch length shrinks due to synchrotron radiation
  - Consider longitudinal blowup to stay stable - ongoing efforts in RF team

Shrinking bunch length

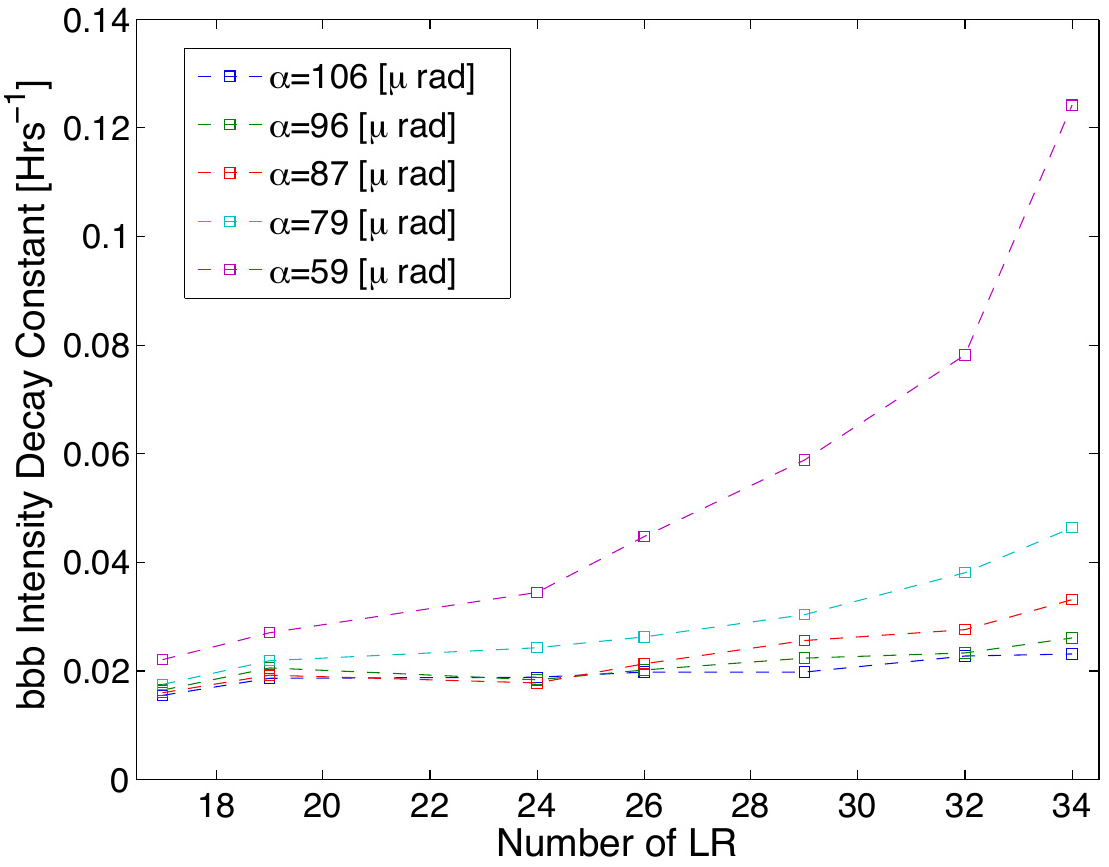
Clear measurements of bunch length shrinking due to synchrotron radiation in proton machine



Courtesy of G. Iadarola

Beam-beam studies

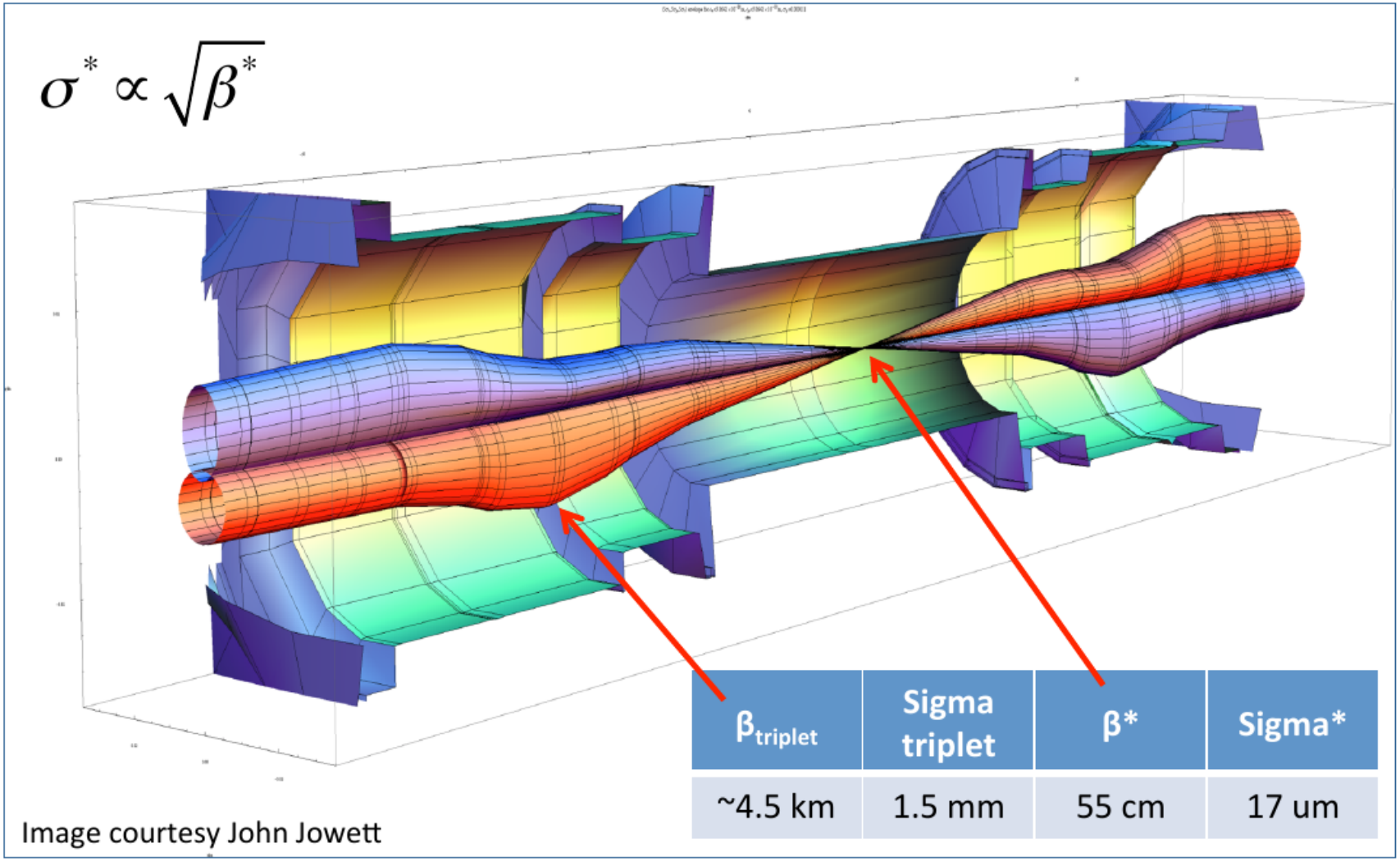
- Crossing angle limited by beam-beam considerations
- LHC operating with a beam-beam parameter of ~0.007 in 2016 with good lifetime. Head-on presently not a limitation
- Main concern: reduction of dynamic aperture from long-range encounters
  - Dedicated experiments have demonstrated possibility to reduce IR1/5 beam-beam separation from 11 σ to 10 σ in 2016
  - Possibilities to go down further under study



CERN beam-beam team
More details: talk T. Pieloni on Thursday

Reducing β*

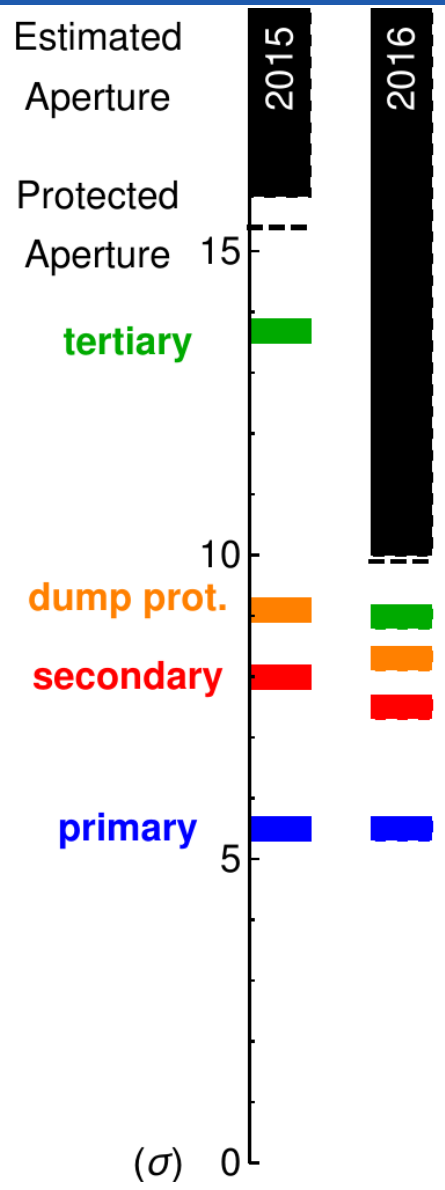
- β* in LHC so far limited mainly by aperture considerations



$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

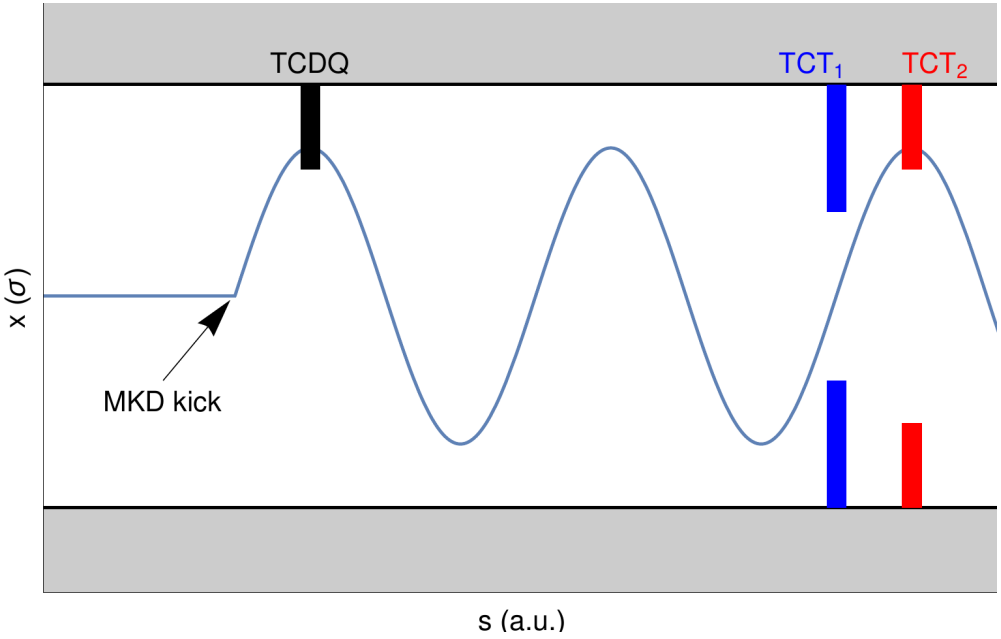
Ways of reducing β*

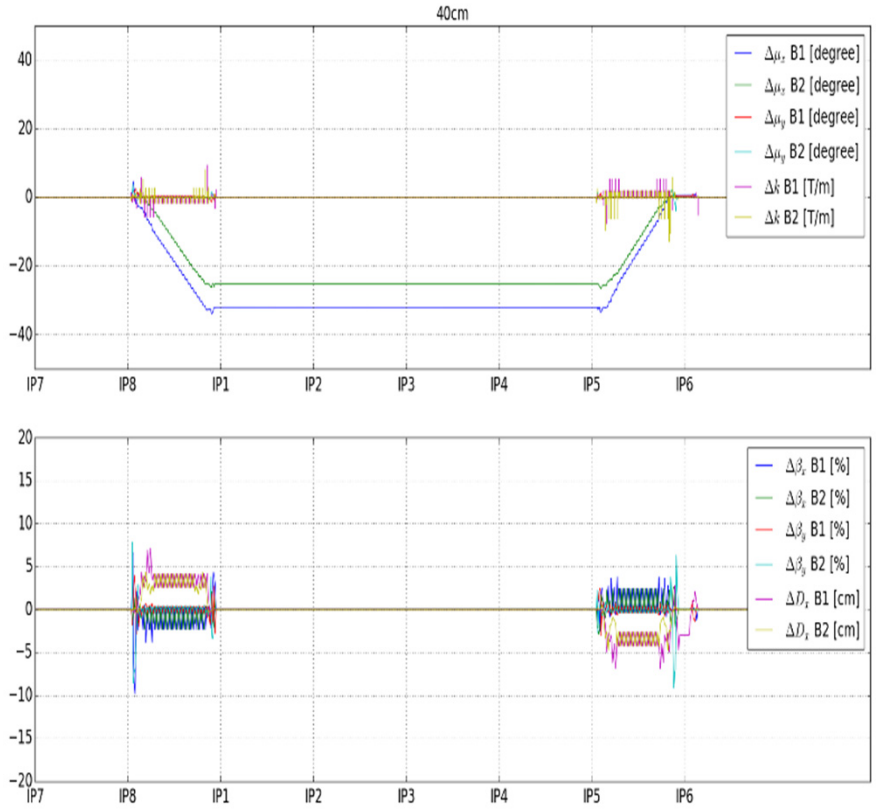
- β*: several ways to reduce.
  - Decrease beam-beam separation and crossing angle so that less aperture is required
  - Optimize collimation system to protect smaller aperture
    - Much tighter settings in 2016 based on extensive experimental and theoretical studies
  - Large part of previous margin for protection against asynchronous beam dumps.
    - Reduction possible relying on special phase advance in optics



Gain in margin from phase advance

- "Good" phase advance protects against damaging impacts from miskicked beam during asynchronous beam dumps

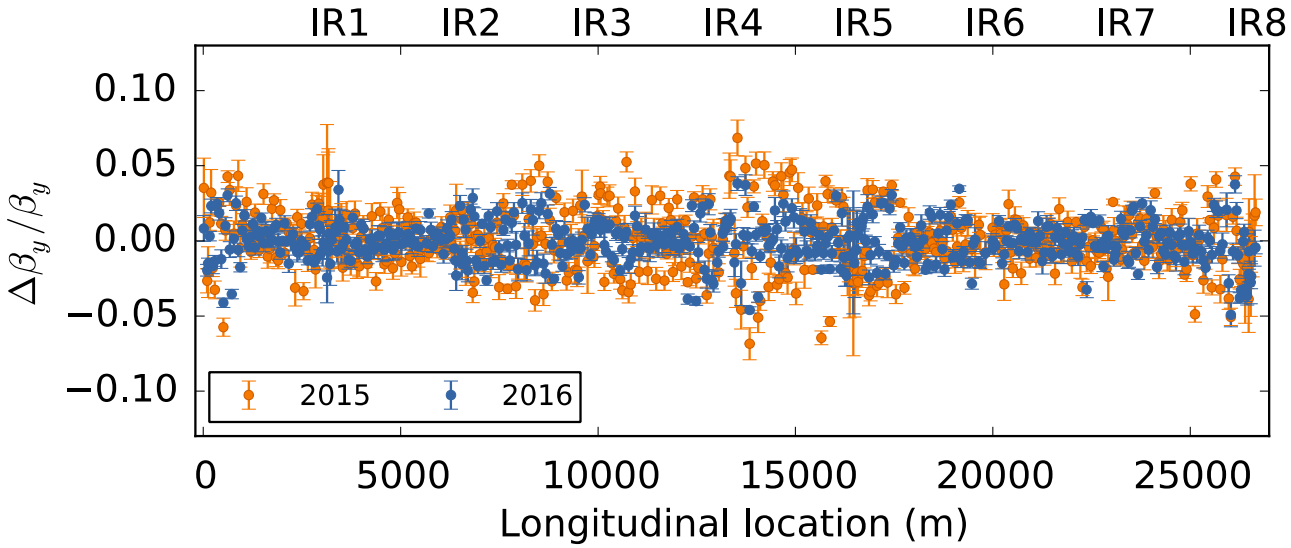




- Using the tighter collimation hierarchy, new optics, and tighter beam-beam separation => **2016 baseline is β*=40 cm**
(compare nominal 55 cm, 80 cm in 2015)

Achieved optics correction

- Peak beta beat below 5%
  - Essential for the machine performance

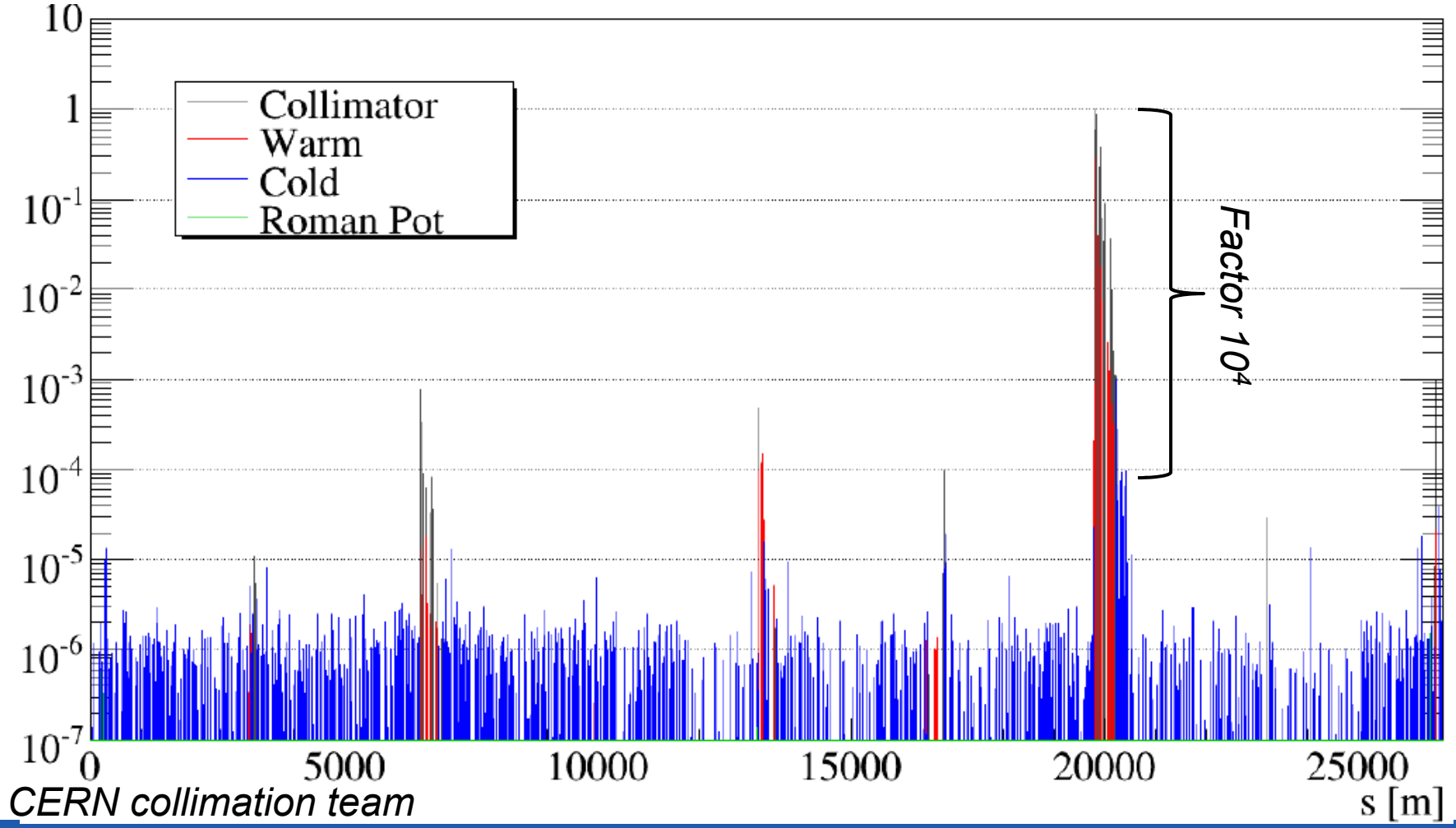


Optics Measurements and Corrections (OMC) team

- Correction strategy
  - Local correction of strongest quadrupole errors
  - Global correction

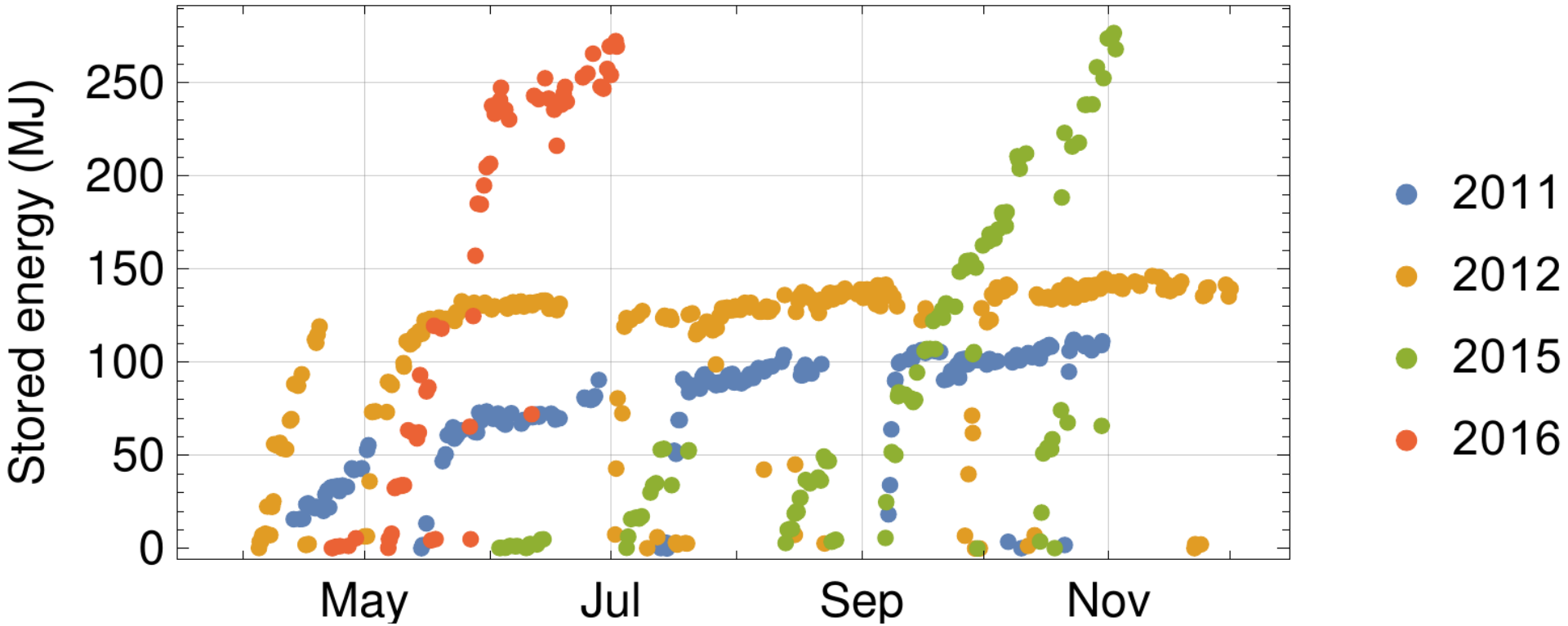
Achieved beam cleaning

- Collimation working well with tighter settings
  - Qualified cleaning performance for high intensity



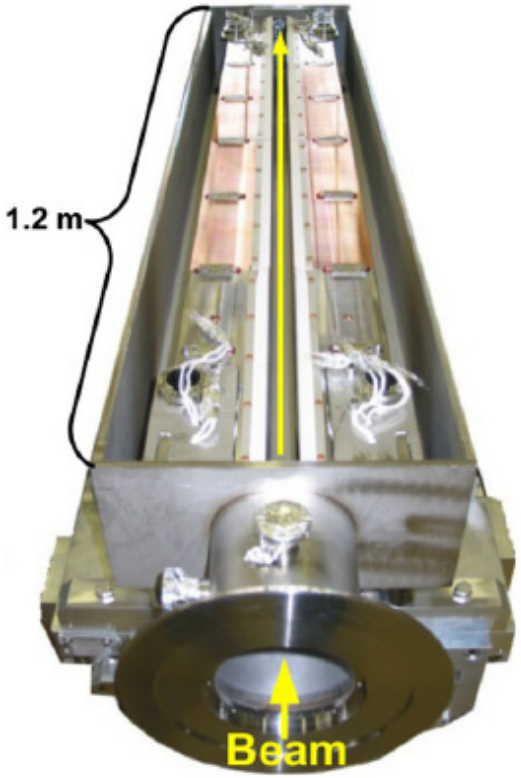
LHC stored energy per beam

- Quick rampup to ~250 MJ stored energy
- LHC beams highly destructive



Collimator gaps

- Opening of primary collimator: 2.2 mm
- More details: talk S. Redaelli on Wednesday



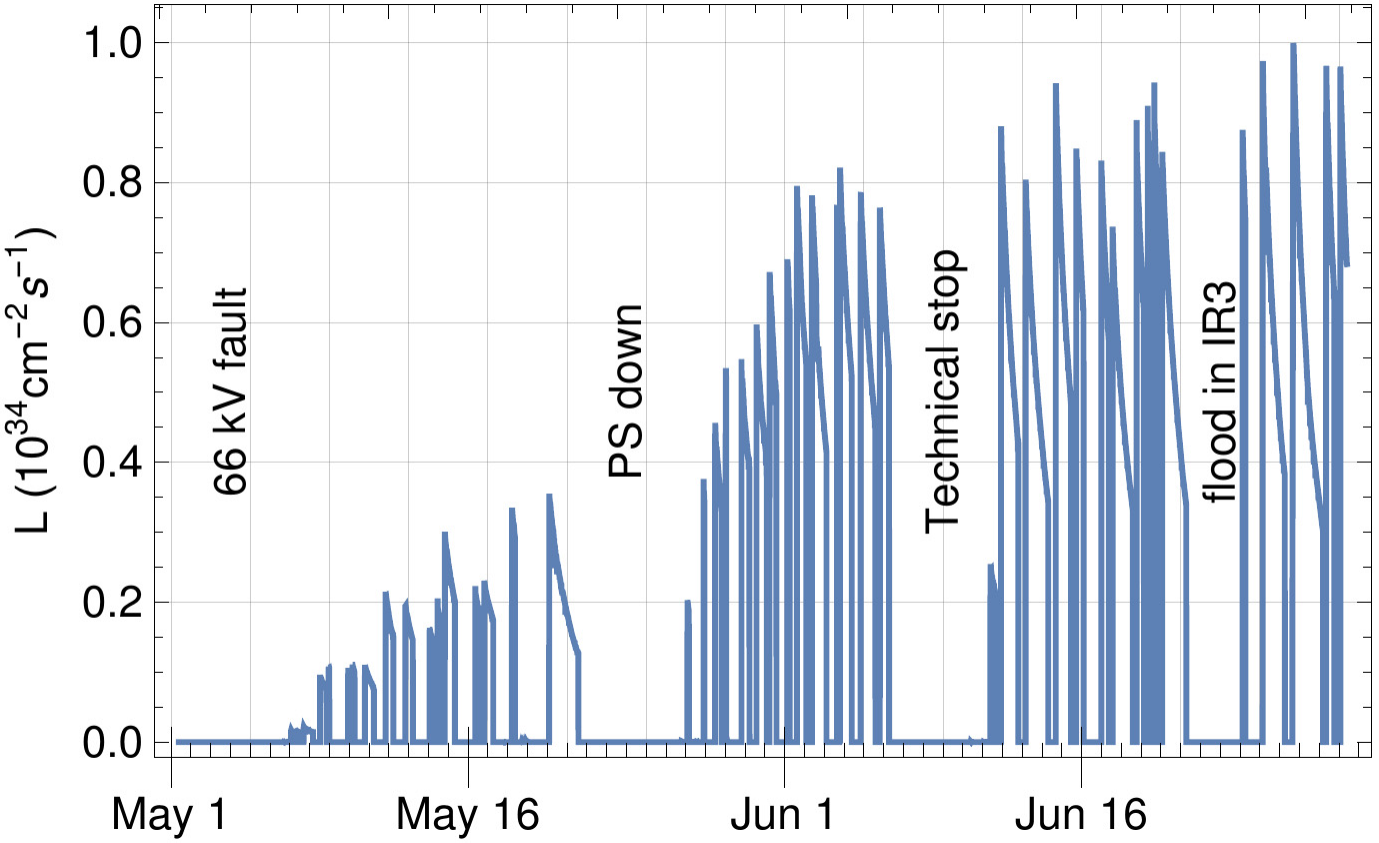
250 MJ,
2.2 mm full gap

2016 technical issues

- Technical issues earlier in 2016 caused downtime, e.g.
  - PS main power supply (main failed, shortly after spare failed) → 6 days
  - 66 kV transformer fault (not caused by weasel – was a marten) → 6 days
  - Further issues: SPS beam dump, water on collimator cable connectors …

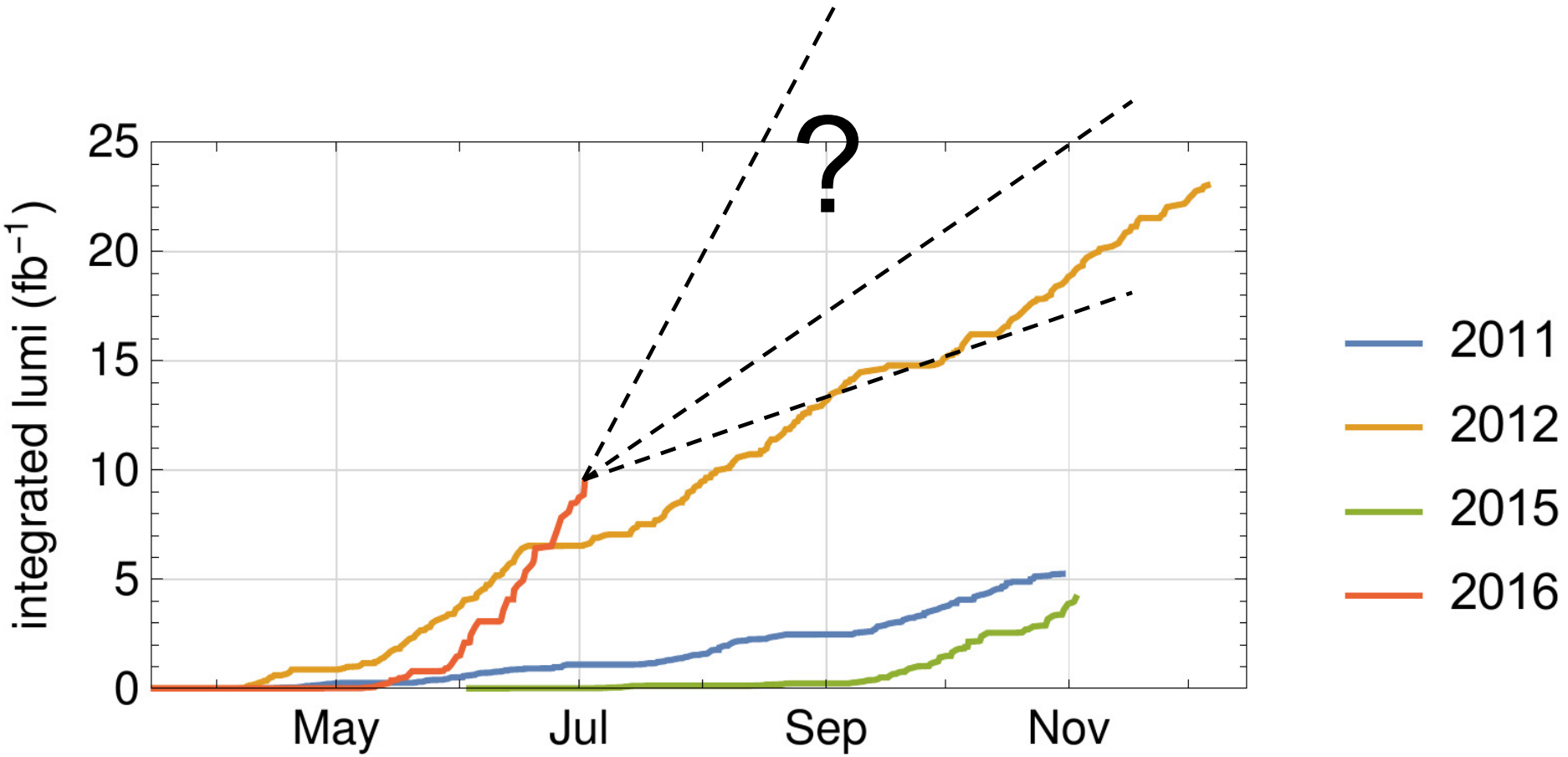
Recent availability

- Recently excellent availability and reliability from all systems: cryogenics, power converters, RF, diagnostics, collimation… …. …
- Excellent machine stability (optics, orbit…)
- Record: spent 75% of time doing physics during 1st week of June



Status of 2016 luminosity production

- Luminosity goal of >25 fb^{-1} in 2016 : on a good track
  - 9.5 fb^{-1} so far (July 3) - Compare: 4.2 fb^{-1} delivered in 2015



Availability

- A good machine availability is key to success
- Most important parameter to maximize: *integrated* luminosity
  - Need to maximize the time spent in physics operation
  - Need to minimize unforeseen beam dumps, downtime and time spent preparing the beams
- Need both good reliability of all systems, a healthy set of operational parameters (avoid instabilities, large beam losses etc.), and good operational efficiency
  - Several efforts made to minimize time outside physics, e.g. combined ramp and squeeze. Efforts continued on many fronts

Achieved parameters so far (p)

	Run 1			Run 2		
	2010	**2011**	**2012**	2015	2016 (so far)	**Design**
Energy [TeV]	3.5	3.5	4.0	6.5	6.5	7.0
Bunch spacing [ns]	150	50	50	25	25	25
No. of bunches	368	1380	1380	2244	2076	2808
Stored energy per beam (MJ)	23	112	143	277	272	362
β* [m]	3.5	1.0	0.6	0.8	0.4	0.55
Max. **p/bunch** [10^{11}]	1.2	1.45	1.7	1.2	1.25	1.15
Normalized **emittance** [μm]	~2.0	~2.4	~2.5	~3.5	~3.2	3.75
Peak **luminosity** [10^{33} $cm^{-2}s^{-1}$]	2.1	3.7	7.7	5.0	10.6	10.0

Outlook on the rest of Run 2

- Goal for Run 2: Produce >100 fb^{-1}
  - Continued efforts for higher luminosity and availability
- Possible performance improvements
  - Push emittance (BCMS?), while remaining stable
  - Push electron cloud limits: increase number of bunches
  - push bunch length
  - Further decrease β* (collimation, beam-beam, optics). Flat optics?
- Increase energy
  - 7 TeV would probably require hundreds of additional training quenches. More tests in 2016-2017 Christmas stop for better estimates

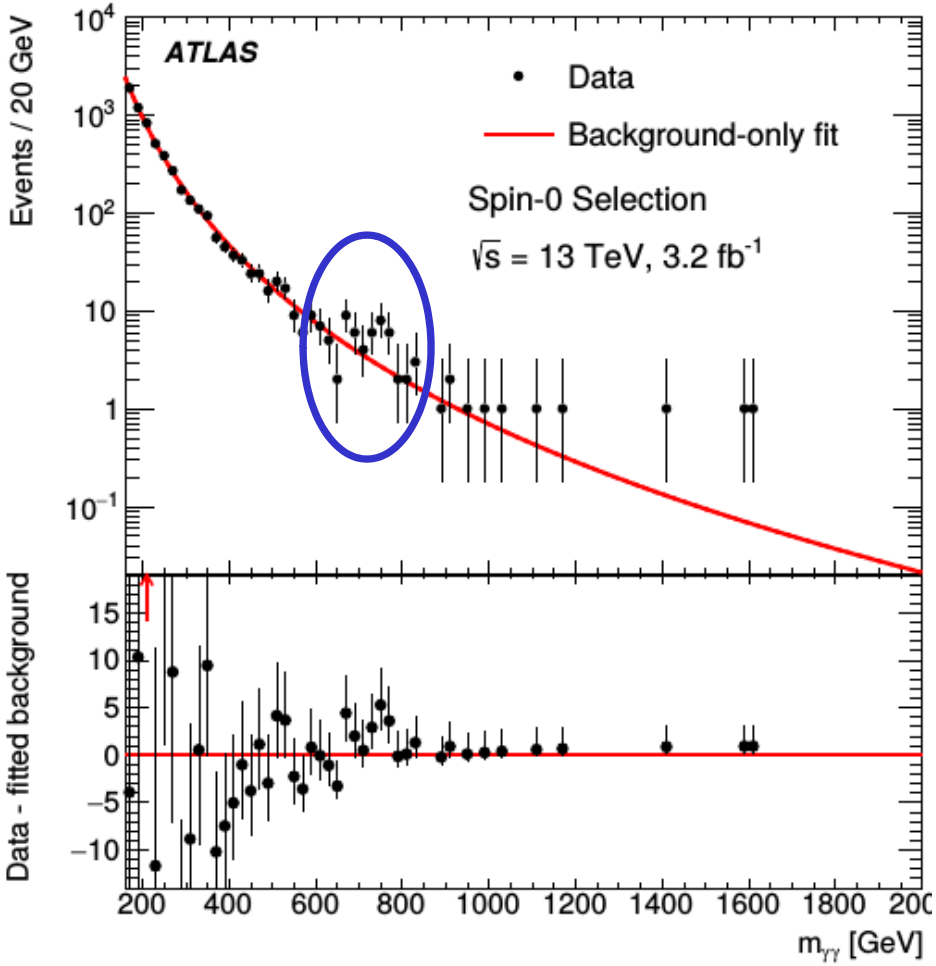
A. Verweij

Summary

- LHC back after long shutdown at higher energy (6.5 TeV)
- 2015 commissioning year, 2016 production year
- Strong push in performance 2016
  - Sub-nominal β^*=40 cm
  - Excellent availability recently
  - Just reached nominal luminosity for the first time
  - Luminosity production on a good track
- Challenges ahead:
  - Push the limits of electron cloud and maintain high availability
  - Explore means of further increasing luminosity
- Hope for exciting physics ahead → 1 more slide…

Final slide: news from the experiments

- Recent results submitted for publication, based on 2015 data:
  arXiv:1606.03833,
  arXiv:1606.04093
- CMS: "A modest excess of events over the background-only hypothesis is observed for mX ≈ 750 GeV"
- Is this a statistical fluctuation or something interesting?
  - More LHC data needed
- **Exciting times ahead!**



for your attention!