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LHC Operation at 6.5 TeV: Status and Beam Physics Issues

Giulia Papotti

for the LHC team

thanks in particular to M. Lamont and J. Wenninger

additionally, with material from:

A. Apollonio, X. Buffat, S. Danzeca, A. Gorzawski, M. Hostettler, G. Iadarola, J. Jowett, T. Persson, A. Romano, C. Schwick, J. Wenninger

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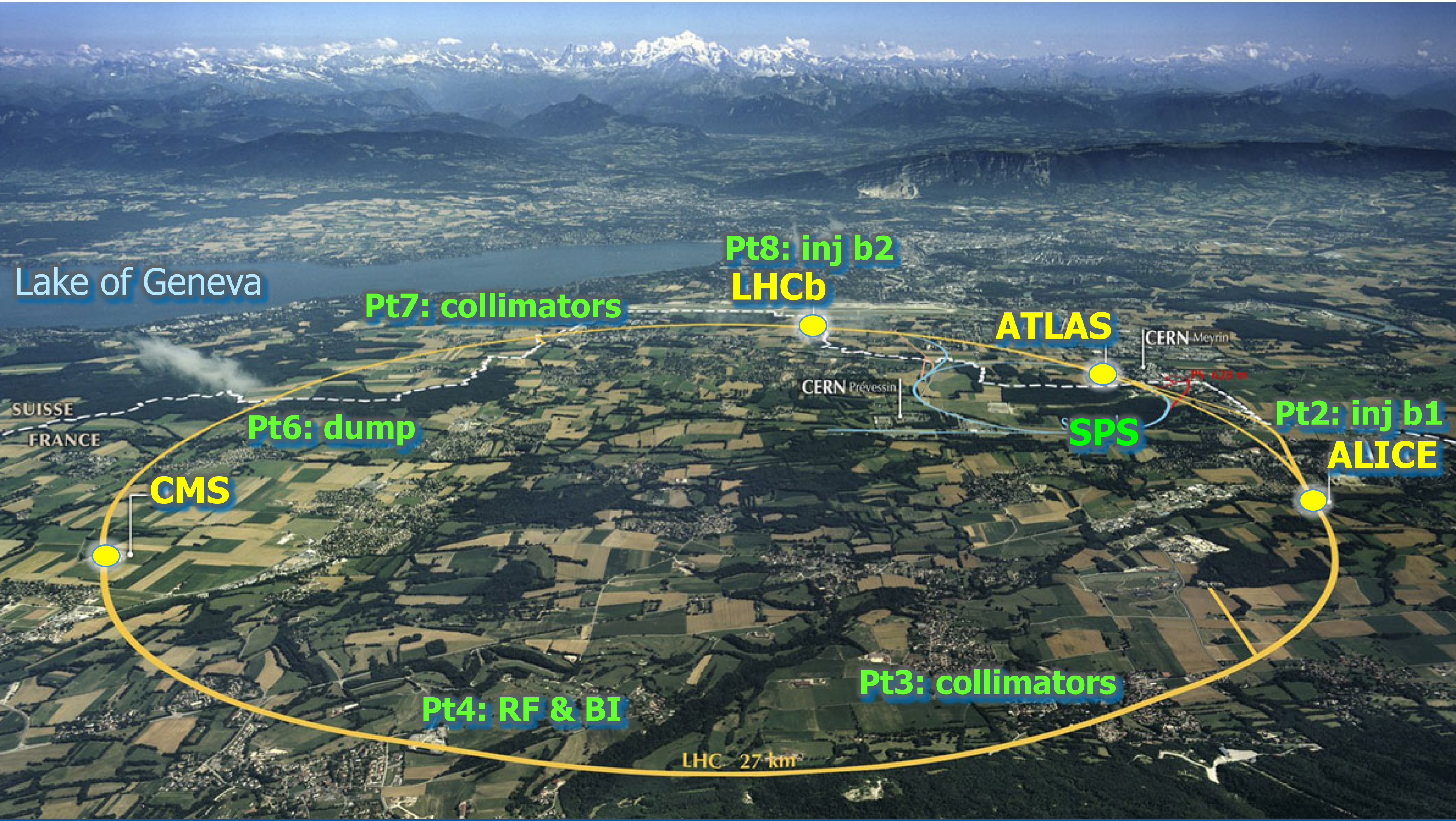
outline

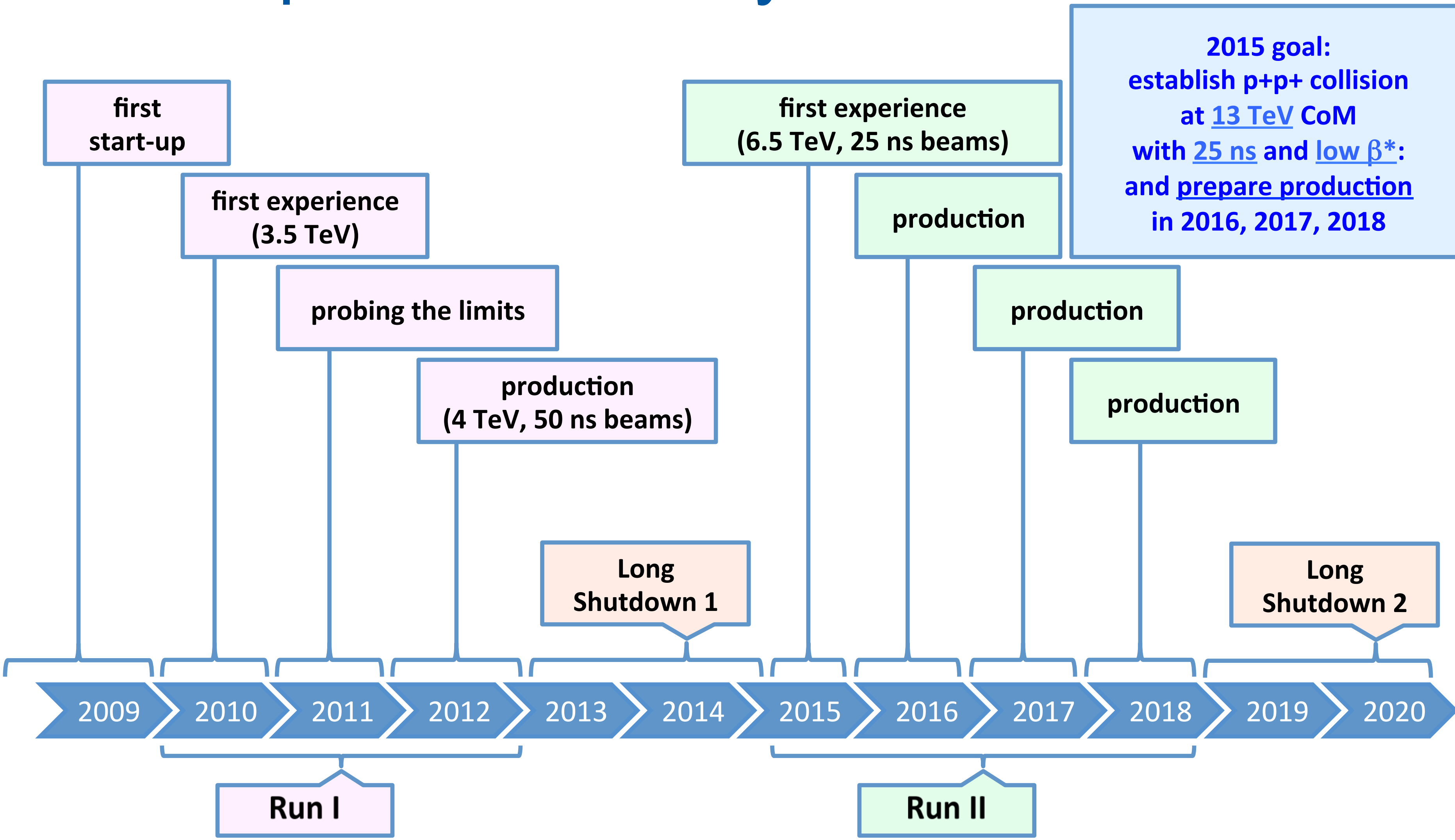
- introduction & history
- 2015-2016 performance
- some details on some limitations
  - electron cloud, Unidentified Falling Objects, Radiation to Electronics
- some highlights
  - optics corrections, crossing angle reduction, luminosity leveling
- latest news & outlook

giulia.papotti@cern.ch

the Large Hadron Collider



LHC operation history



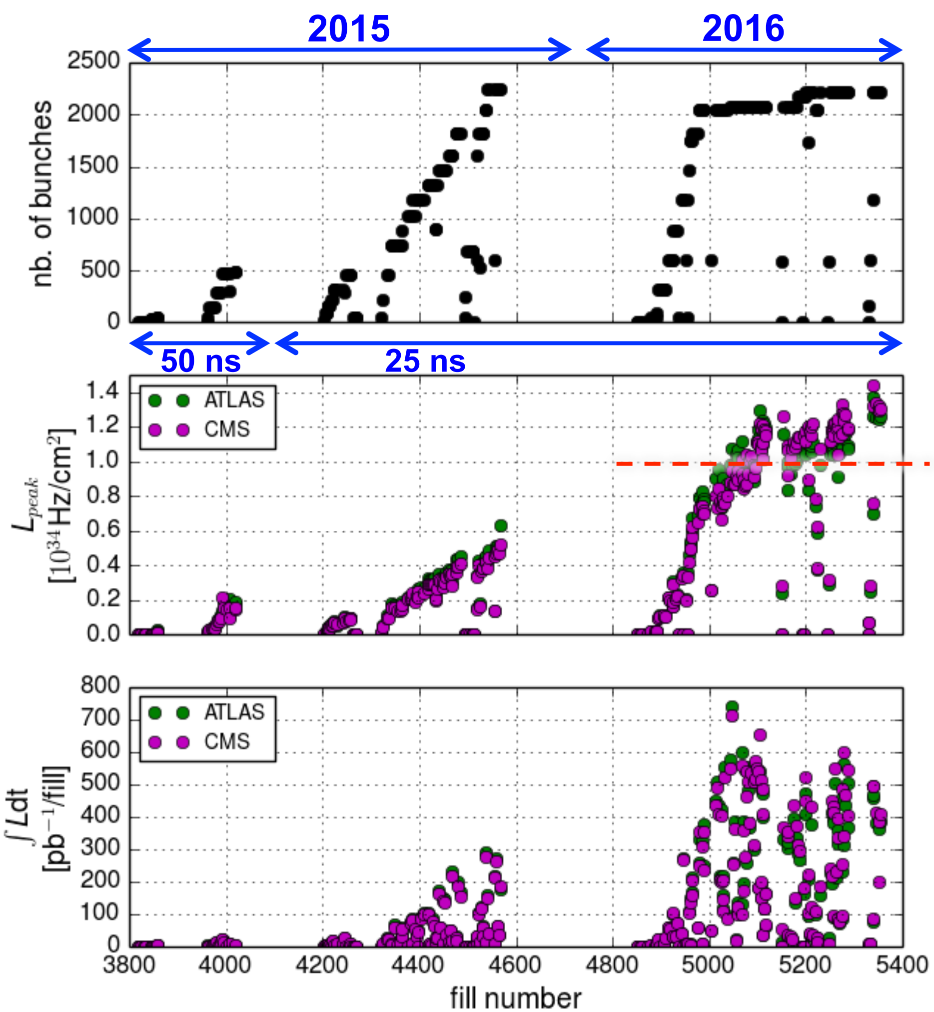
giulia.papotti@cern.ch

peak luminosity

$$L = \frac{k N_b^2 f \gamma}{4\pi \beta^* \varepsilon_N} F$$

	2015	2016	Design Report
energy [TeV]	6.5	6.5	7
bunch spacing [ns]	25	25	25
β^* [cm]	80	40	55
ε_N[mm mrad] at start of fill	3.5	2	3.75
N_b, bunch population [10^{11} p/bunch]	1.15	1.1	1.15
k, max. number of bunches	2240	2220	2808
max. stored energy [MJ]	270	260	360
peak luminosity [10^{34} cm^{-2}s^{-1}] in IP1/5	~0.5	**~1.4**	1
pile-up	18	41	20

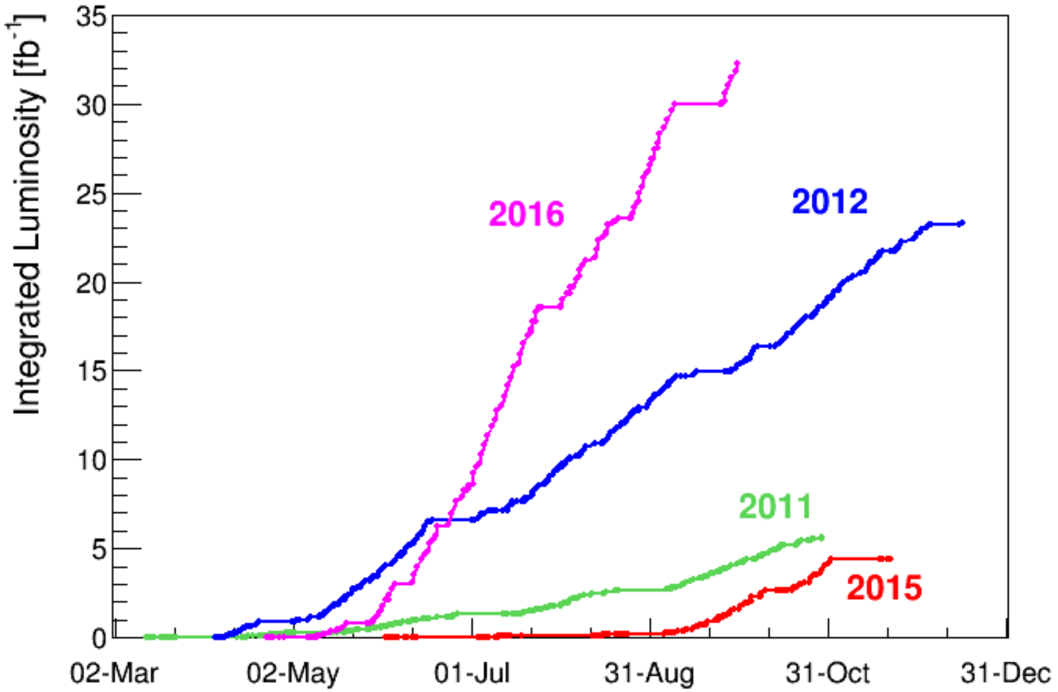
performance per fill



- 2015
  - slow ramp up
    - 50 ns first, 3 weeks of scrubbing
    - difficult August with UFOs and radiation to electronics
  - reached
    - 25 ns, nominal bunch intensity
    - 2244 bunches/ring (e-cloud)
    - 1 fb^{-1}/week at the end
- 2016
  - number of bunches /injection limited to 96 by SPS dump
    - max 2220 bunches/ring
  - consistently high peak and integrated luminosity per fill

giulia.papotti@cern.ch

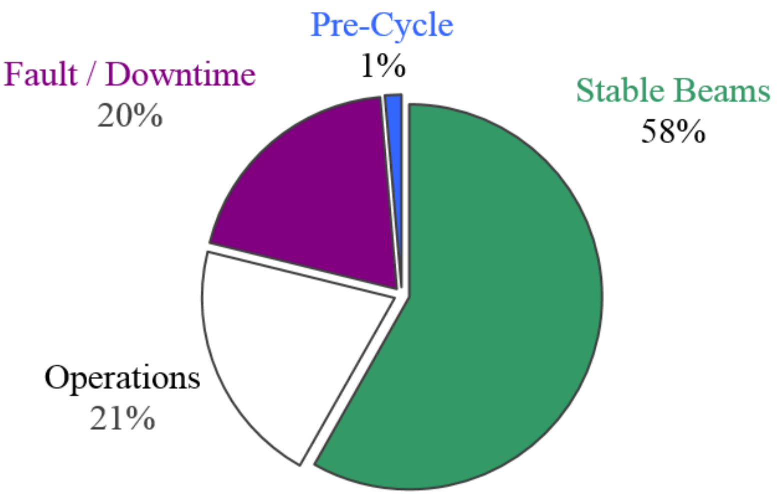
put in perspective



- latest figures for 2016: ~33 fb^{-1}
  - target for 2016 was 25 fb^{-1}
  - max. luminosity delivered in 7 days: 3.3 fb^{-1} (ATLAS)

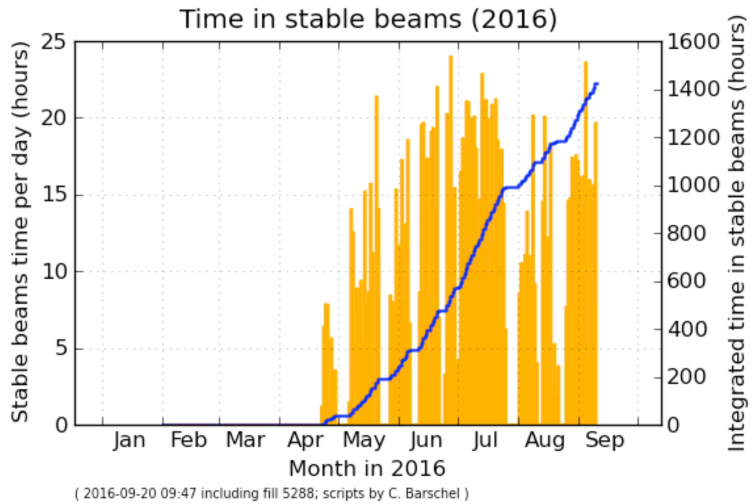
recent physics efficiency

- improved operational efficiency
  - combine ramp and squeeze
  - shorten precycle (lower energy)
  - minimum turn around <3 h
- improved system availability
  - cf ~33-35% in stable beams of the previous years



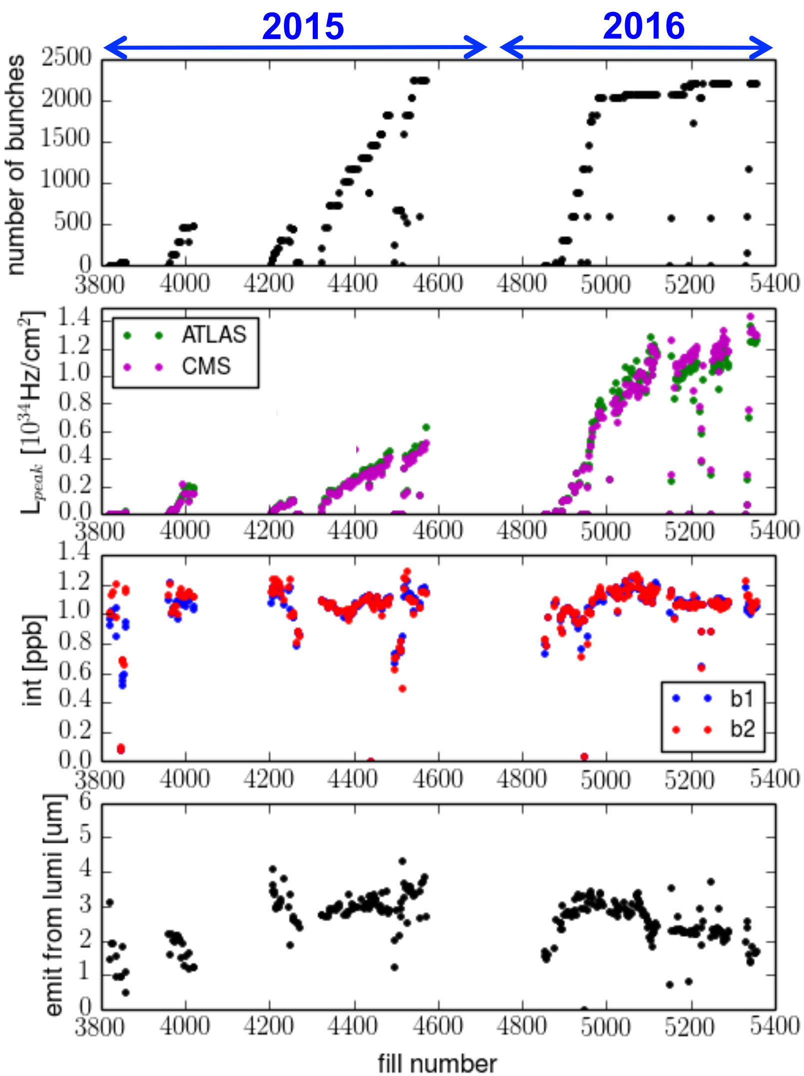
over 79 summer days , physics production only (no commissioning, MD, …)

A. Apollonio

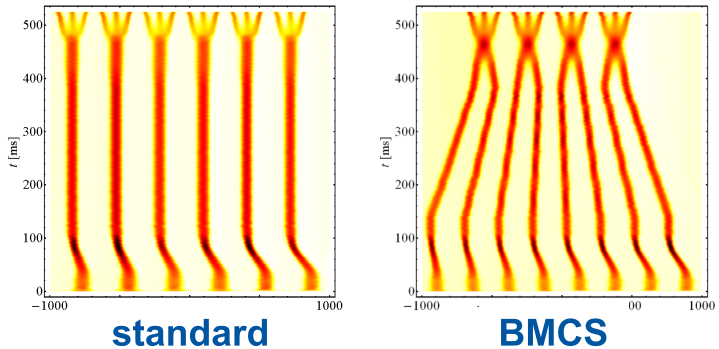


- 96 fills in physics
  - 46 OP dump, 47 aborted by faults
  - 7 suspected radiation induced
- optimize fill length and dump time
  - good luminosity lifetime

beam parameters



- recently intensity /bunch limited to 1.1e11 ppb
  - outgassing from ceramic connection in LHC injection kicker
- smaller emittance and high brightness from BCMS beams
  - Batch Compression, Merging and Splitting
  - 2 um into collision, cf 3.75 um nominal



2016 limitations

- SPS beam dump: replace during winter stop
- LHC injection kicker: add pumping during winter stop

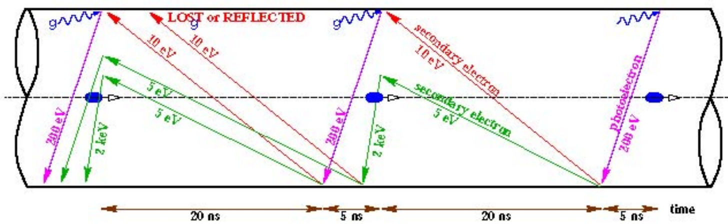
- potential inter-turn short in sector 12
  - being monitored
  - lowered Beam Loss Monitor thresholds to play it safe
  - replace during the winter stop

- electron-cloud
- Unidentified Falling Objects
- Radiation to Electronics (R2E)

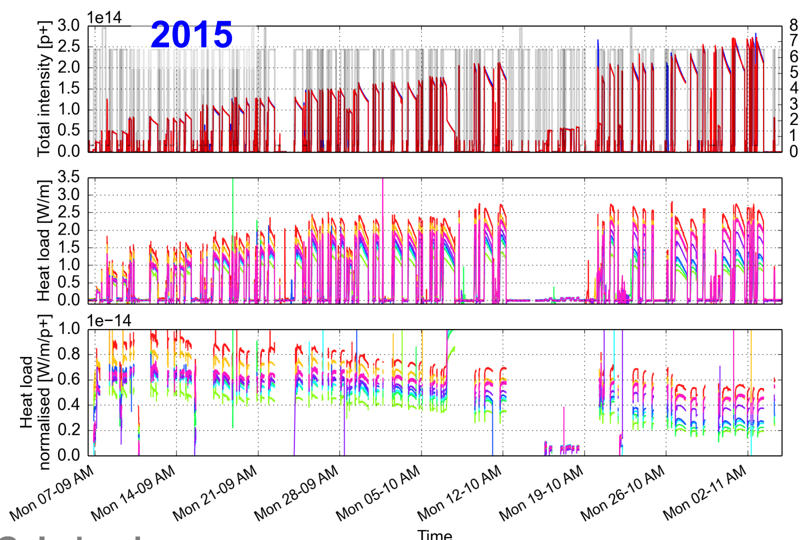
electron cloud

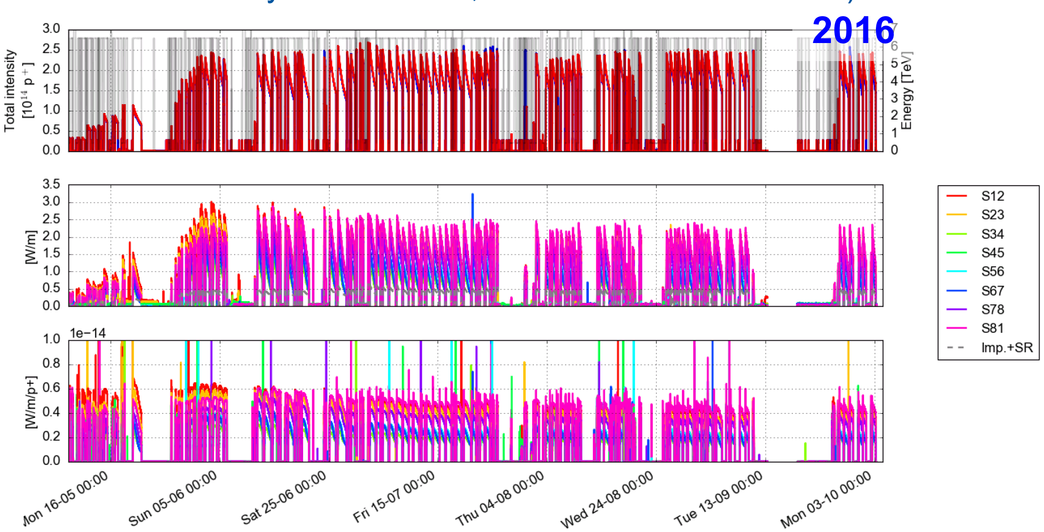
- SEY>threshold: avalanche effect (multipacting)
  - effect depends on bunch spacing and population
  - SEY decreases with accumulated dose: “scrubbing”
- e-cloud effects observed in LHC with bunch trains
  - vacuum pressure rise, heat load on cryogenic systems
  - beam size growth, single- and multi-bunch instabilities

Secondary Emission Yield



- anticipated & confirmed to be a challenge with 25 ns
- 2015: lived at the heat-load limit
- 2016: still significant heat-load within cryogenic limits, little improvement over the year
  - scrub with physics asap (12 h dedicated scrubbing at the flat bottom)
  - no impact of cryogenics on operations (dynamics well handled by feed-forward, released interlocks levels)

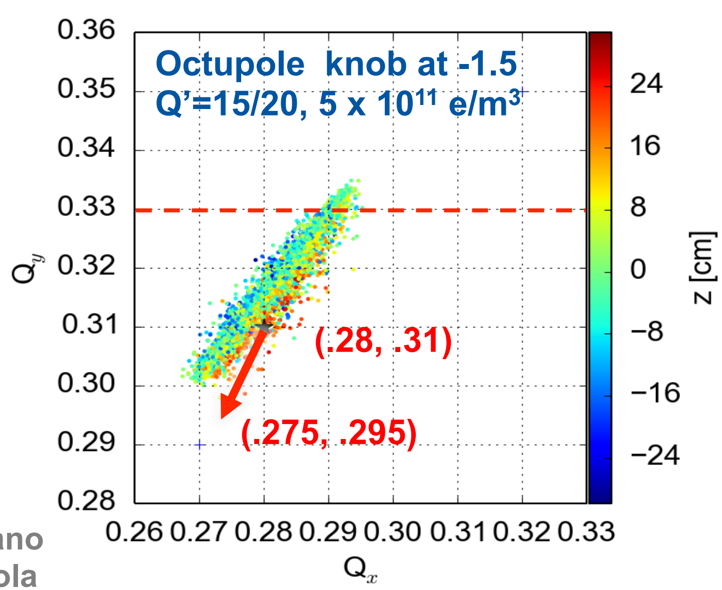


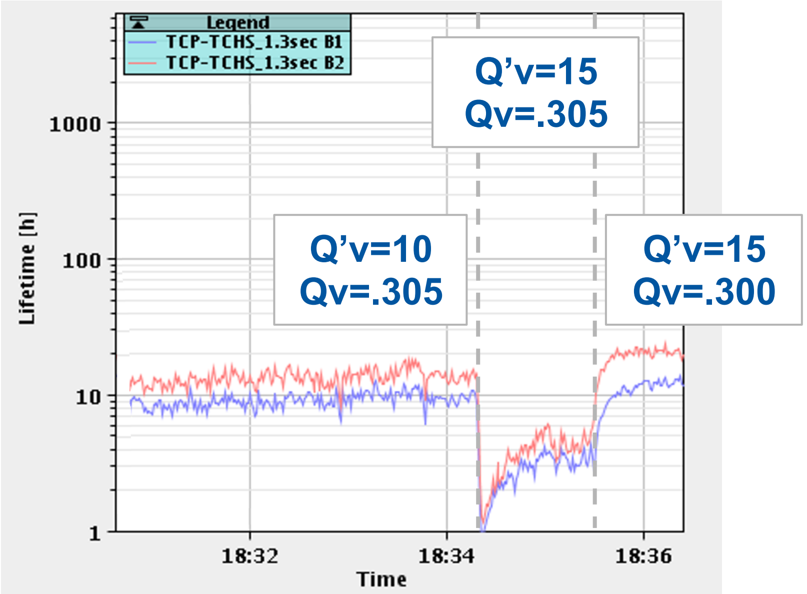


G. Iadarola

e-cloud and beam dynamics

- full suppression of the e-cloud not achieved
  - scrubbing provided sufficient mitigation against beam degradation at 450 GeV
- thus run the machine in the presence of the e-cloud
- slightly changed working point at injection to better accommodate large tune footprint from Q’, octupoles and e-cloud
  - for beam stability at 450 GeV: high Q’, high octupoles, full transverse damper

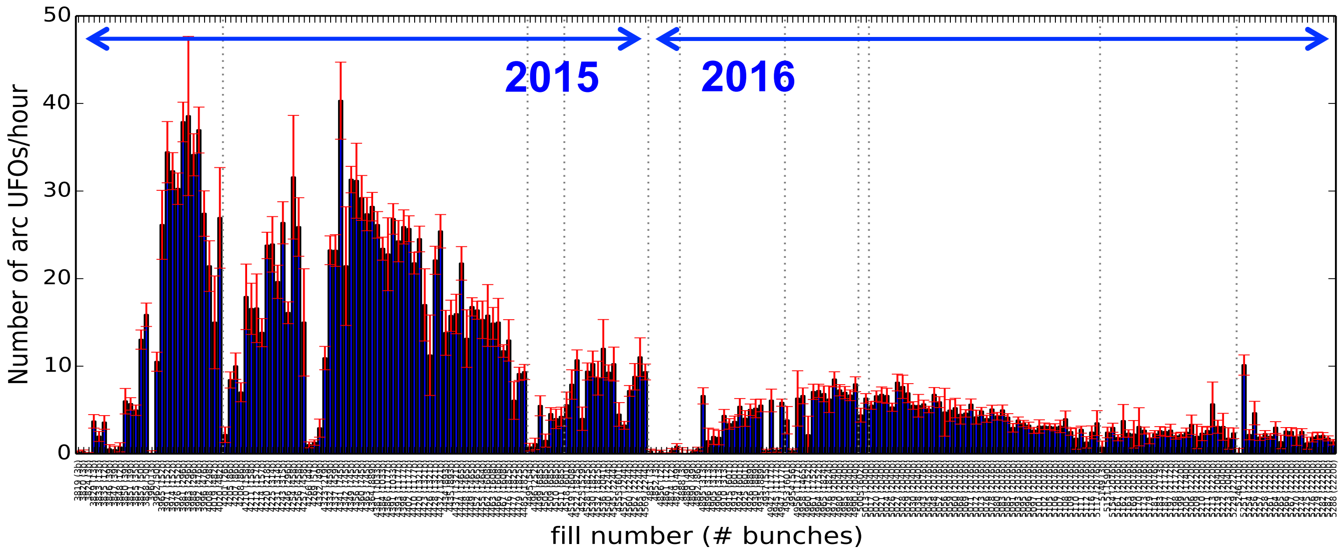




A. Romano
G. Iadarola

Unidentified Falling Objects (UFOs)

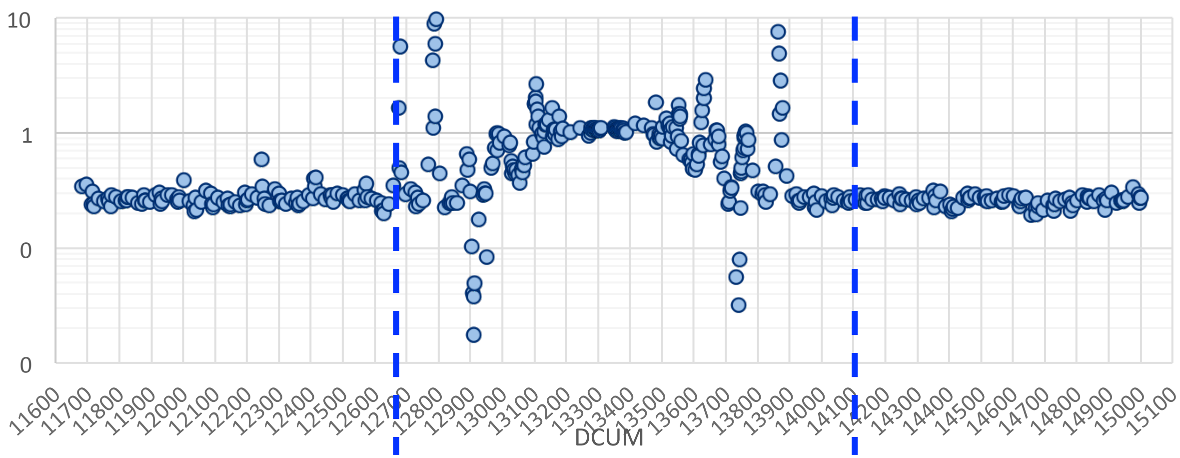
- fast loss events (ms timescale) due to dust particles falling into the beam
  - feared for availability at high energy operation: less margin for magnets, more losses per event
- 2015: 17 dumps + 3 beam-induced quenches
  - up to 5 events in 2 days!
- 2016 so far: 13 dumps + 3 beam-induced quenches
  - loss monitor thresholds increased to allow few quenches per year
    - most beam dumps would not have quenched
- conditioning with beam time confirmed
  - very high rates observed at start 2015, now settled at ~2 arc UFOs/hour in stable beams
  - deconditioning did not take place after year end stop



Radiation to Electronics (R2E)

- failure rates proportional to radiation levels
  - IP: rad level mainly from integrated luminosity
  - arc: rad level mainly from beam-gas interaction, thus integrated intensity
- 2016: 3 radiation-related dumps up to 20 fb^{-1}, expected ~1 dump/fb^{-1}
  - arc radiation levels per unit luminosity are lower than in 2015
    - can be due to the lower vacuum pressure in the arc, or to the higher luminosity per proton (smaller beta*), analysis ongoing
    - very clean machine, luminosity losses are burn-off dominated, less e-cloud

loss ratio 2016 vs 2015 per fb^{-1} (over 20 fb^{-1})



16L5 **IR5** **16R5**

IP: ratio is 1
arc: ratio is 0.3

S. Danzeca

some highlights

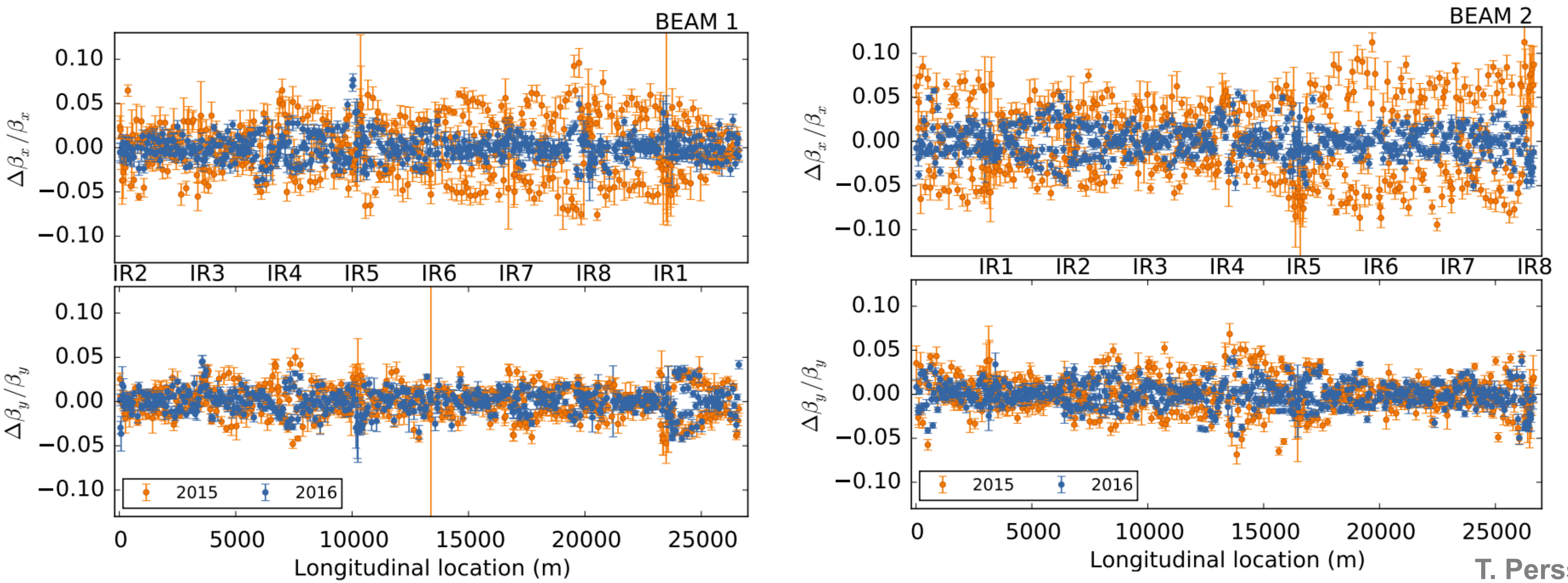
- optics corrections
- crossing angle reduction
- luminosity leveling

giulia.papotti@cern.ch

record optics corrections

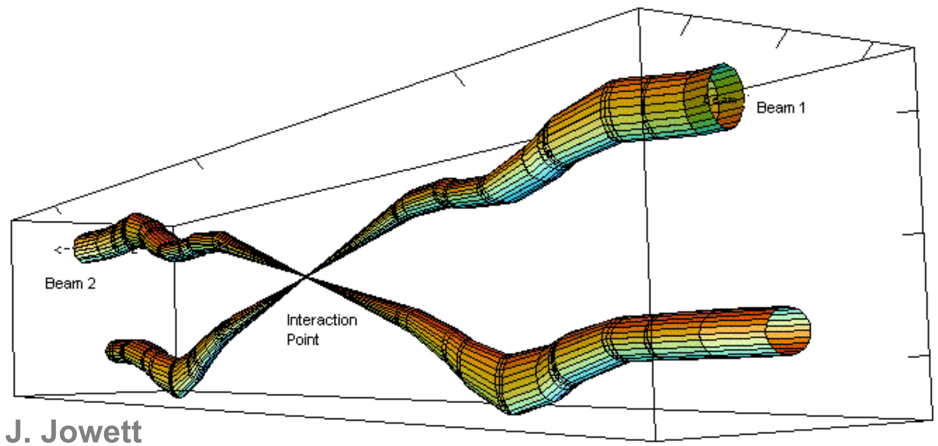
- rms beta-beating at the interaction point: <1%
  - also control of longitudinal position of beta function waist (after 2015 experience)

IP	Beam	β_x^* [cm]	β_y^* [cm]
1	1	39.8 ± 0.5	40.1 ± 0.1
1	2	39.8 ± 0.1	40.1 ± 0.1
5	1	39.9 ± 0.2	40.1 ± 0.1
5	2	39.5 ± 0.1	39.6 ± 0.2



T. Persson

crossing angle reduction



J. Jowett

Relative beam sizes around IP1 (Atlas) in collision

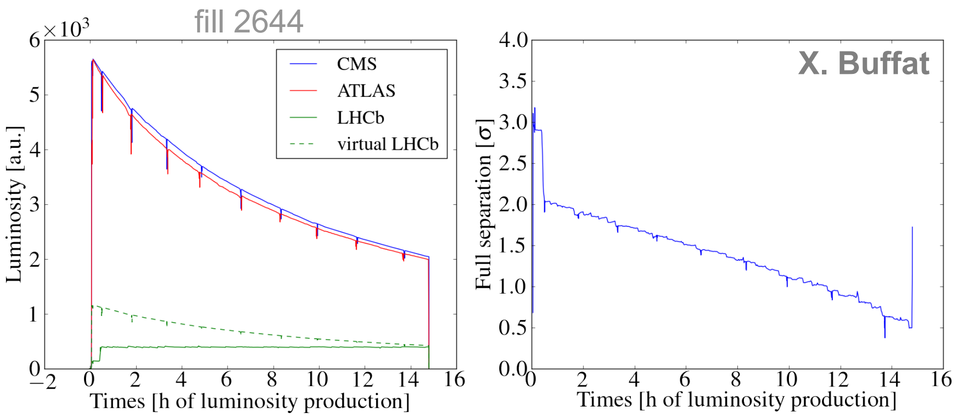
$$L = \frac{k N_b^2 f \gamma}{4\pi \beta^* \varepsilon_N} F$$

$$F \propto \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\frac{\varphi}{2}\right)^2}}$$

- crossing angle required because of bunch trains
  - otherwise parasitic collisions not in the center of detector
  - negative impact on luminosity… keep it as small as possible
- constraint: minimum beam separation
  - big beam emittance or small beta* require bigger crossing
- reduced crossing angle a couple of weeks ago
  - machine setup for standard, but use BCMS
  - could reduce a bit the margins
  - plan it well: validation overhead not to dominate!

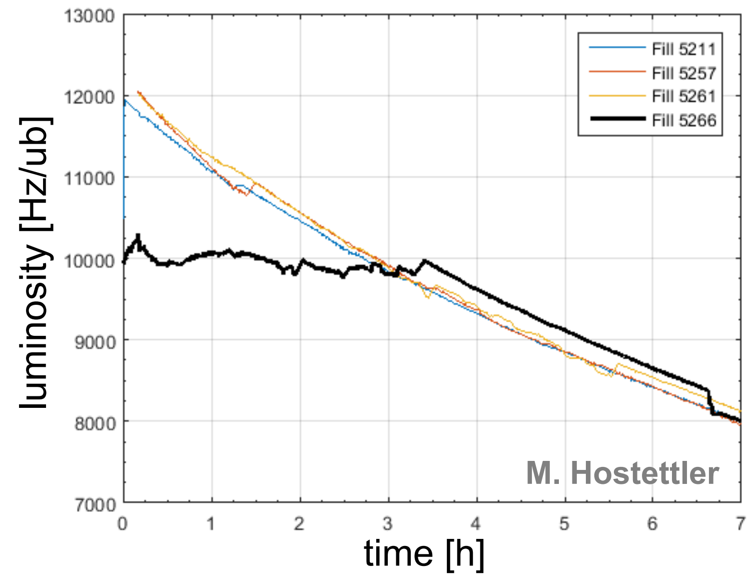
beam size [μm]	3.5	2.5
separation [σ]	10.5	9
ϕ [μrad]	370	280
F	0.59	0.70
L_{pk} [10^{34}cm^{-2}s^{-1}]	1.27	1.5

luminosity leveling by separation



$$\frac{\Delta x}{\sigma_x} = \sqrt{-4\log\frac{L}{L_0}}$$

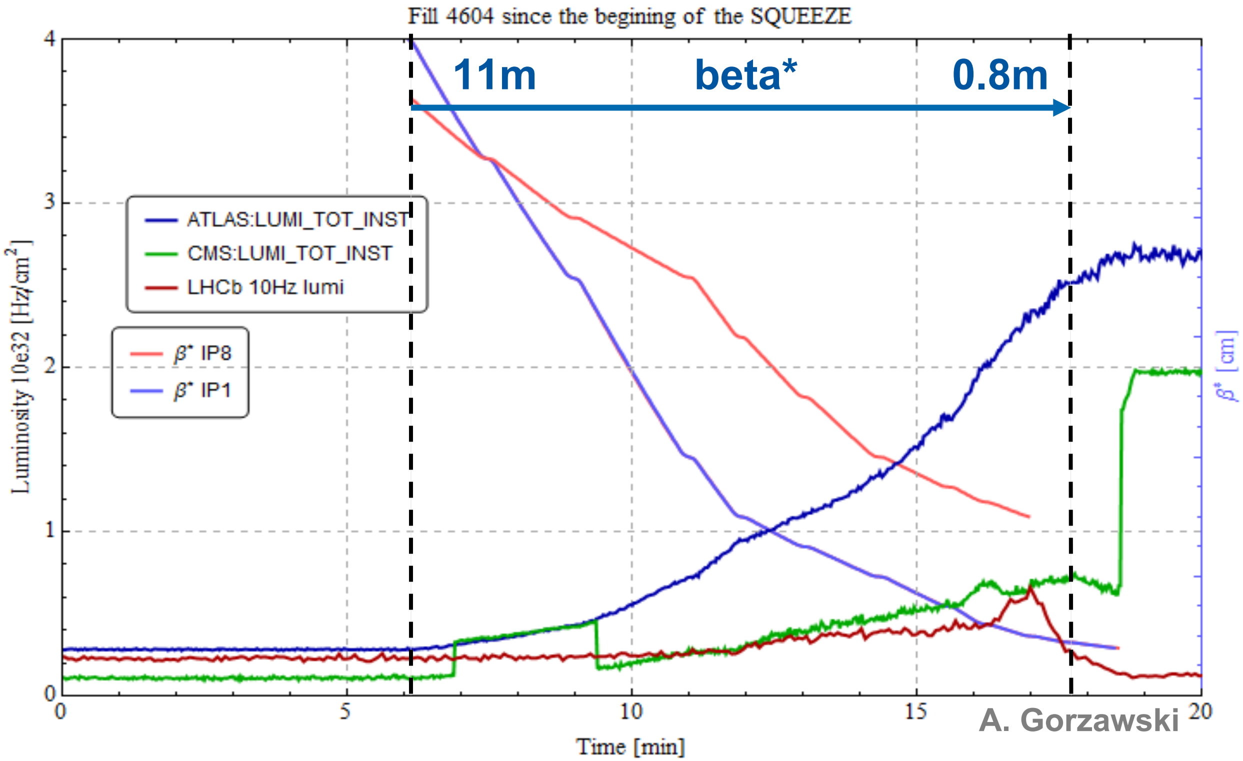
- routine for LHCb and ALICE
  - while ATLAS and CMS fully head-on
- tried few weeks ago also on ATLAS and CMS
  - all 4 experiments were leveled



giulia.papotti@cern.ch

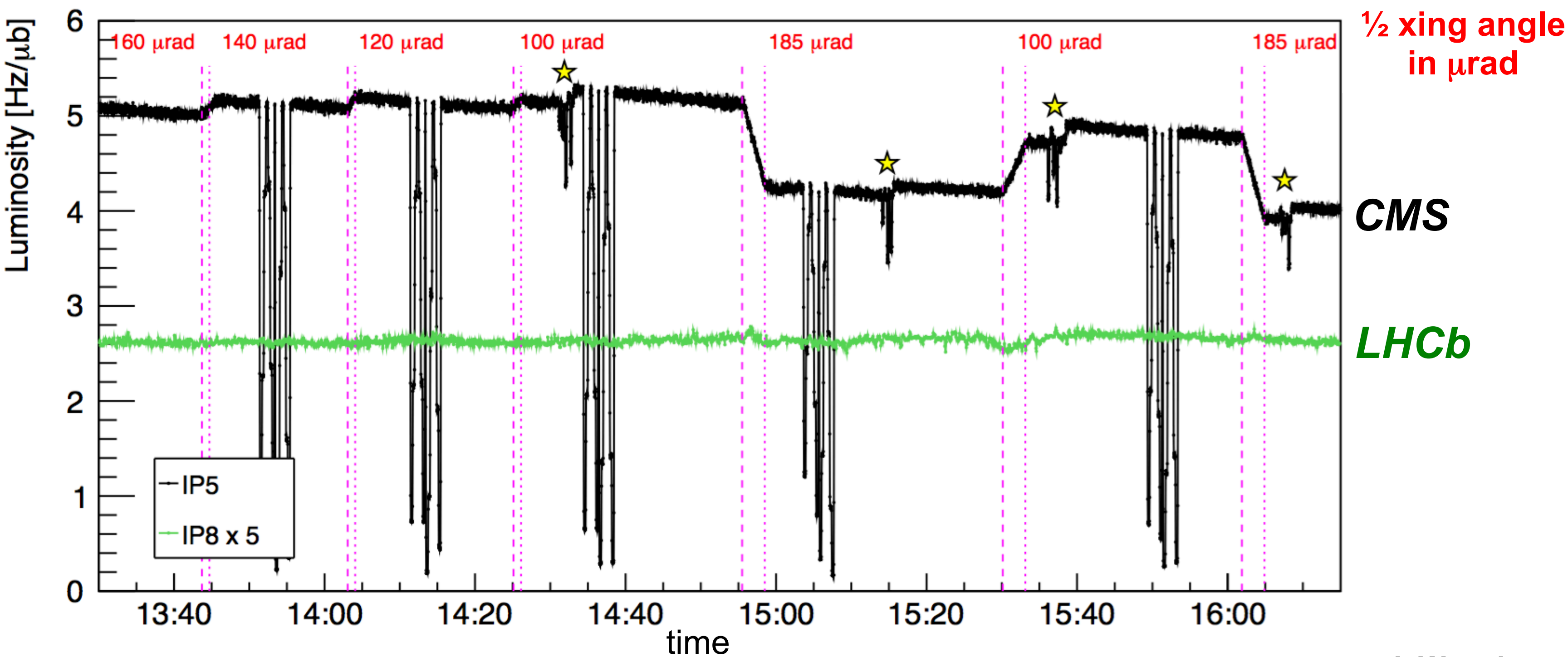
luminosity leveling with β*

- reduce β* in steps while keeping beams in collisions
  - machine study in 2015
  - more to do with controls than beam physics



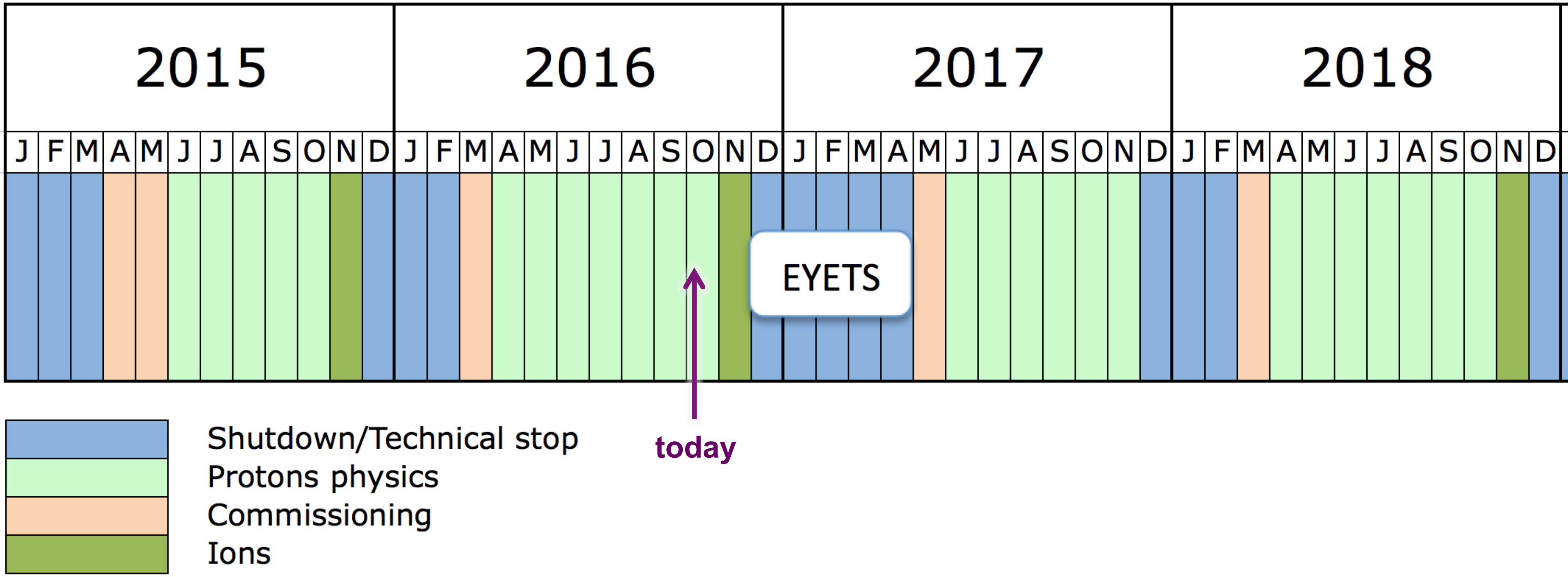
luminosity leveling by crossing angle

- reduce crossing angle in steps while keeping beams in collisions
  - machine study in 2016
- plot of CMS and LHCb luminosity evolution
  - CMS luminosity is levelled
  - LHCb (and ALICE) are separated and luminosity remains well inside a ±10% band



J. Wenninger

Run 2 schedule



- Extended Year End Technical Stop (20 weeks)
  - driven by CMS experiment pixel upgrade
  - push 2 sectors towards 7 TeV, to gain knowledge on how long it takes to reach higher energy
- ~40-45 fb^{-1}/year in 2017 and 2018 (tbc)
  - max peak luminosity ~1.7e34 $cm^{-2}s^{-1}$, limited by inner triple cooling

projections until LS2

- BCMS or not?
  - BCMS: low emittance, thus low crossing angle: higher luminosity/bunch pair
    - TDI limits on number of bunches/SPS transfer: less bunches/ring
    - less electron-cloud thanks to the shorter trains
  - standard beams: +30% bunches, but higher emittance: likely less luminosity
    - less pile-up
  - choice requires input from experiments
- if pile-up is an issue, level down
- need to start the year with the correct parameter set!
  - commissioning and validation are non-negligible overhead
- availability is the key to good integrated luminosity!
  - max peak luminosity is limited
  - 2016, 2017, 2018: similar run length

giulia.papotti@cern.ch

conclusions

- 2015 well invested to prepare excellent production in 2016
  - machine magnetically reproducible, magnets well behaved
  - peak performance above design: reached 1.35 10^{34} $cm^{-2}s^{-1}$
    - squeeze further, bright beams from injectors
  - still some margin for improvement in Run 2
- good delivery of integrated luminosity: >30 fb^{-1} in 2016
  - improved availability
  - electron cloud conditioning very slowly
  - fortunately: UFOs have conditioned down, R2E below expectations

- the LHC has moved from commissioning to exploitation
  - enjoying the benefits of the decades-long international design, construction, installation effort: the foundations are good
  - huge amount of experience & understanding gained and fed-forward
- astounding results and progress represent a phenomenal ongoing effort by all the teams involved

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