LHC machine configurations in Run 2

(with focus on collimation and β*)

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with input from N. Fuster Martinez, P. Hermes, A. Mereghetti, D. Mirarchi, S. Redaelli, B. Salvachua

Outline

- Recap of Run 2 machine configuration evolution
- Summary of Run 2 aperture measurements
- Evolution year by year, and reasoning behind changes for
  - Collimator settings
  - β*
- Conclusions

Main run 2 configuration changes

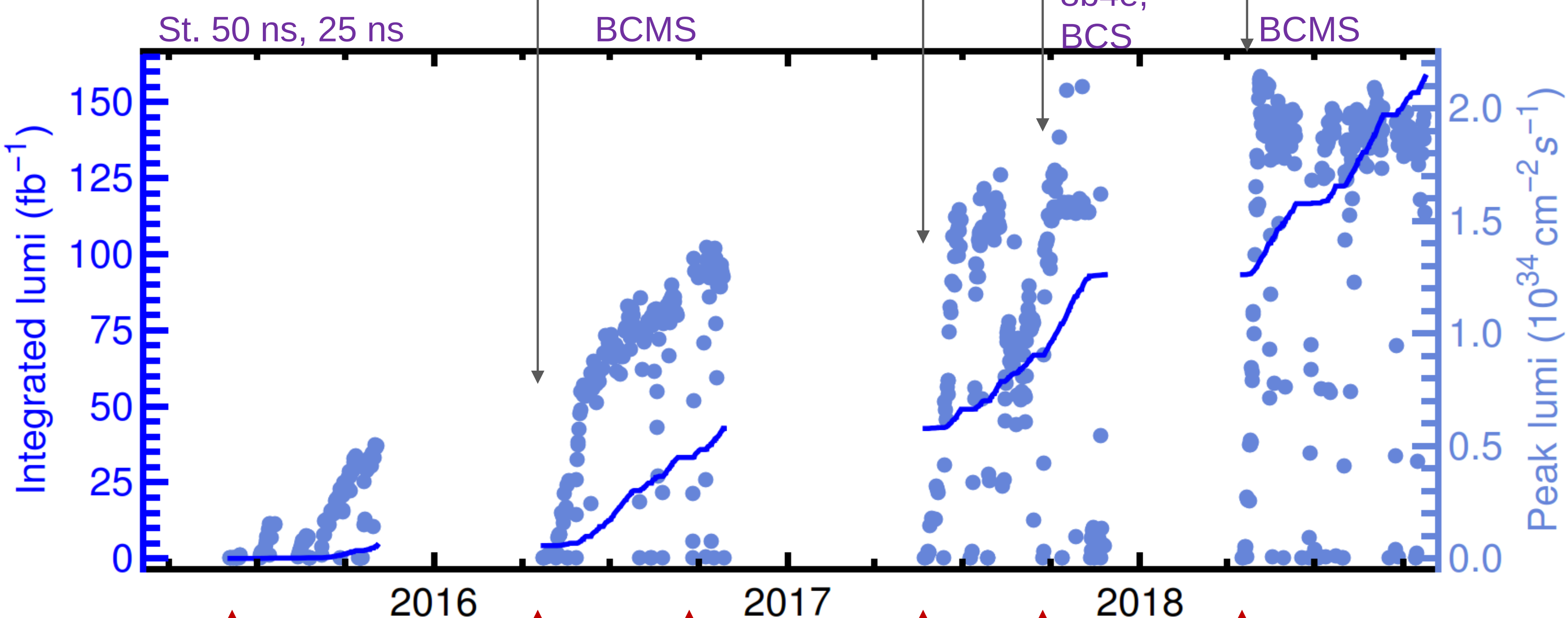
More details: Talk B. Salvachua

Combined ramp & squeeze
Matched MKD-TCT phase

RF full detuning
ATS optics
Crossing anti-leveling

Separation leveling

β*-leveling



β*=80 cm, 150 µrad

β*=40 cm, 185 µrad

140 µrad

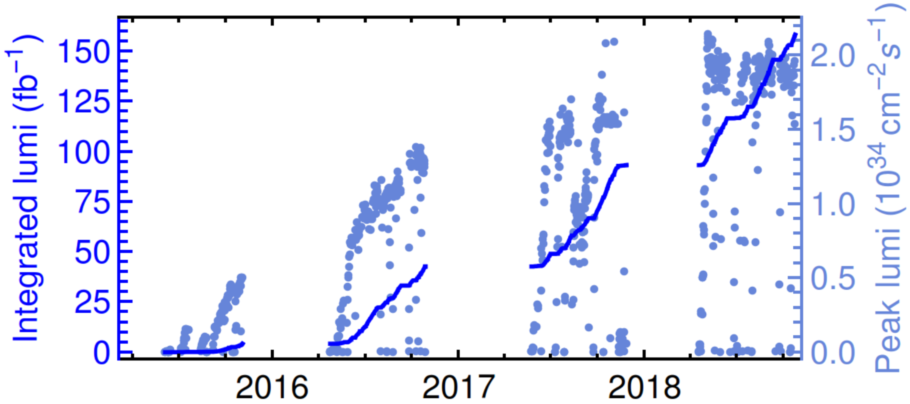
β*=40 cm, 150→120 µrad

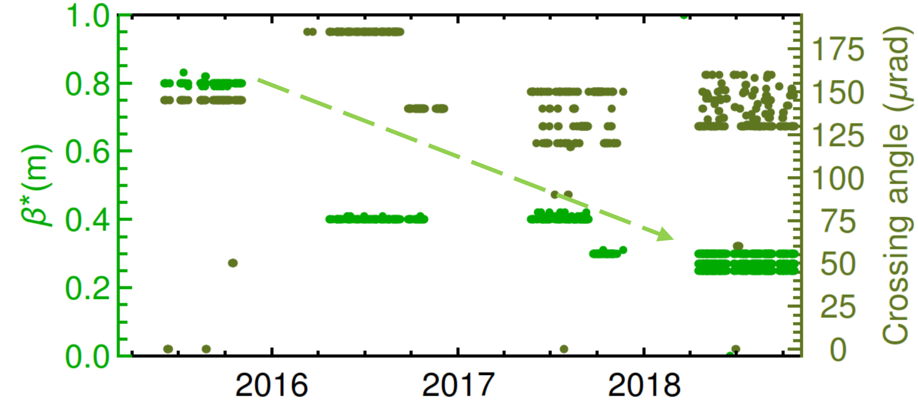
β*=30 cm

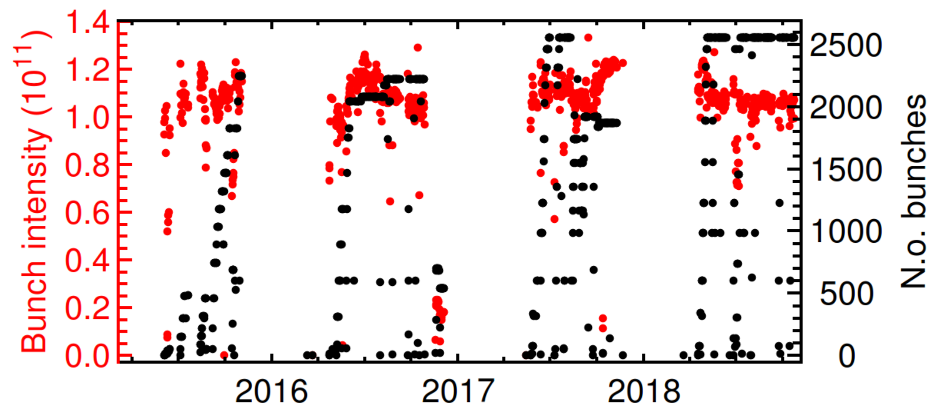
β*=30→25 cm, 160→130 µrad

Evolution of key parameters

- Starting from a careful approach in 2015, ramping up to excellent performance
  - Regularly operating at twice the LHC design luminosity
- Steady decrease of β* over the years
  - Key to increased peak performance with total intensity almost flat in the last years







Comparison: 2018 vs LHC design

- Some keys to good peak performance:
  - Small emittance
    - See talks H. Bartosik, S. Papadopoulou
  - Small β* at collision point
    - Focus of this talk

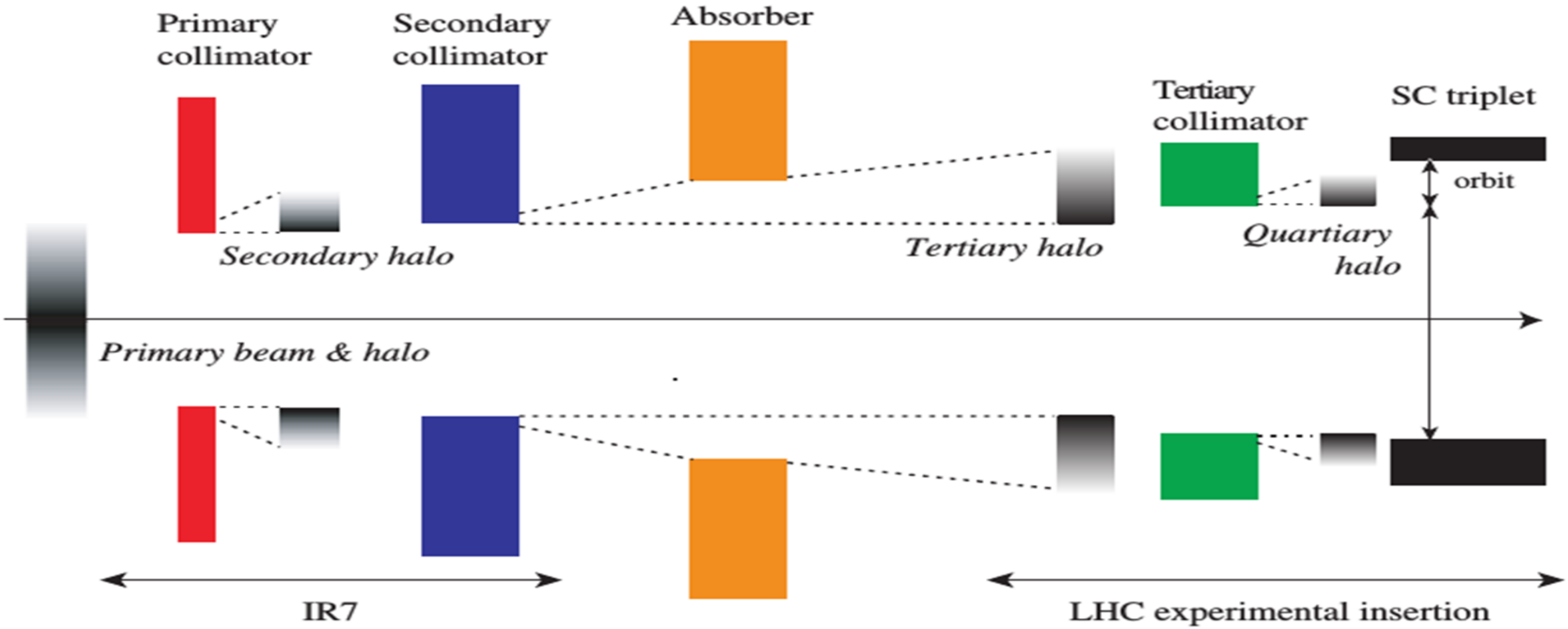
Parameter	2018	LHC Design
Energy [TeV]	6.5	7.0
No. of bunches	2556	2808
Max. stored energy per beam (MJ)	312	362
β* IR1/5 [cm]	**30→25**	**55**
Half crossing angle IR1/5 [μrad]	160→130	142.5
Normalized beam-beam separation	10.6→7.9	9.4
p/bunch (typical value) [10^{11}]	1.1	1.15
Typical normalized emittance [μm]	**~1.9**	**3.75**
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	**2.1**	**1.0**

Machine configuration aspects

- **Several aspects of machine configuration covered in other talks**
  - Beam characteristics: beam types, bunch intensity, emittance → H. Bartosik, S. Papadopoulou
  - Optics → T. Persson
  - RF settings → H. Timko
  - Chromaticity, octupoles → X. Buffat
  - Heavy-ion configurations → J. Jowett
  - β*
  - Collimator settings

  } This talk (β*, Collimator settings)

Collimator settings and aperture



- Collimation hierarchy sets lower limit for protection of aperture
- All elements (e.g. triplet) must have larger apertures (in σ)
- Beam size increases in triplet when β* is squeezed
- Smaller β* usually requires larger crossing angle

=> smaller normalized aperture in σ to be protected at smaller β*

Ways to push aperture limit

- Tighter collimators => protect smaller normalized aperture
- Smaller normalized beam-beam separation => smaller crossing angle and more aperture at any given β*
- Better knowledge of the aperture allows a smaller margin on the aperture
  - Used to squeeze in Run I, now aperture "goldmine" is depleted

Strategy in Run 2 (first two points)

Aperture measurements

- Crucial to know aperture well for correct determination of machine settings that ensure protection

- Detailed aperture measurements part of standard commissioning
  - Limited precision due to variations in closed orbit and machine movements
  - Some minor differences expected between the years

- Measured aperture used to verify calculation parameters for predicting the aperture in new, untested configurations
  - MAD-X aperture module – accurate 2D calculation, but need to tune many input parameters for various sources of imperfections
  - “Scaling” of aperture – fast and straight-forward method, but risk of errors if aperture bottleneck is purely horizontal or vertical

Collision apertures in Run 2

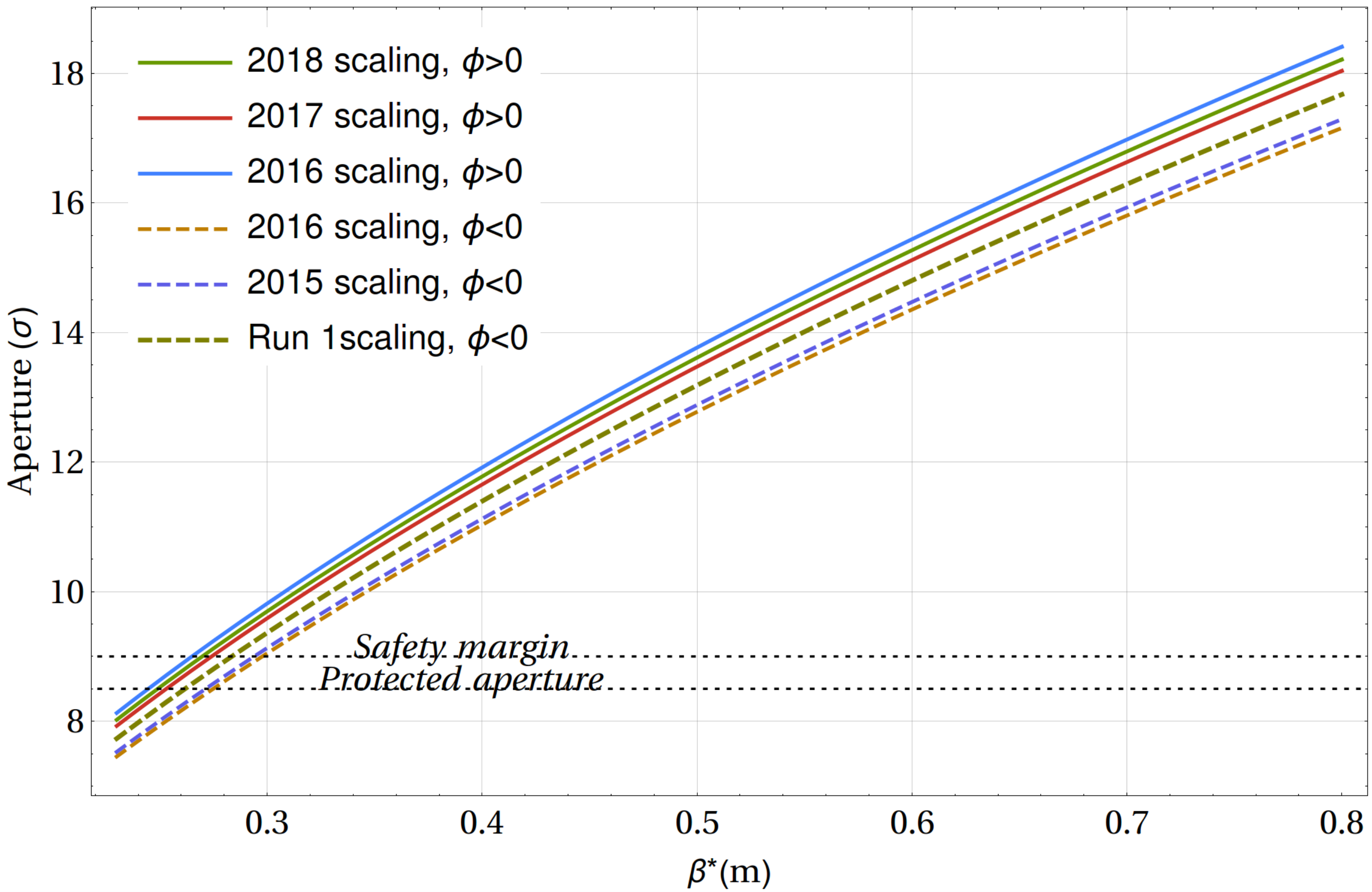
	B1H	B1V	B2H	B2V
2015, 80 cm, -145 μrad	18.2 (D1/Q3R5)	15.7 (D1/Q3L1)	16.2 (D1/Q3R1)	15.7 (D1/Q3R1)
Predicted 2015	16.0			
2016, 40 cm, -185 μrad	10.6 (D1/Q3R5)	9.9 (D1/Q3L1)	11.5 (D1/Q3R1)	10.4 (D1/Q3R1)
Predicted 2016	10.2			
2017, 40 cm, +185 μrad	10.9 (D1/Q3R5)	12.0 (D1/Q3L1)	12.9 (Q2R5)	11.4 (D1/Q3R1)
2017, 40 cm, +150 μrad	11.5 (D1/Q3R5)	12.4 (D1/Q3L1)	14.0 (Q2R5)	12.0(D1/Q3L1)
Predicted 2017a	11.6			
2017, 30 cm, +150 μrad	10.6 (D1/Q3L1 & D1/Q3R5	11.1 (Q2R5 & Q3/D1 L1)	10.9 (D1/Q3R1)	10.5 (D1/Q3R1)
Predicted 2017b	10.0			
2018, 30 cm, +160 μrad	10.5 (D1/Q3L1)	10.5 (D1/Q3L1)	10.0 (D1/Q3R1)	10.5 (D1/Q3R1)
Predicted 2018a	9.6			
2018, 25 cm, +145 μrad	9.2 (D1/Q3L1)	9.2 (D1/Q3L1)	>12	10.5 (D1/Q3R1)
Predicted 2018b	9.4			

All in σ for 3.5 μm emittance

All apertures predicted within 0.5 σ

Crossing plane aperture at top energy

- Calculating aperture as function of β* using scaling for fixed BB-separation
- Aperture measurements with beam largely consistent



Aperture scaled from worst measurement every year. Assuming varying crossing angle – 9.2 σ beam-beam separation for ε=2.5 μm

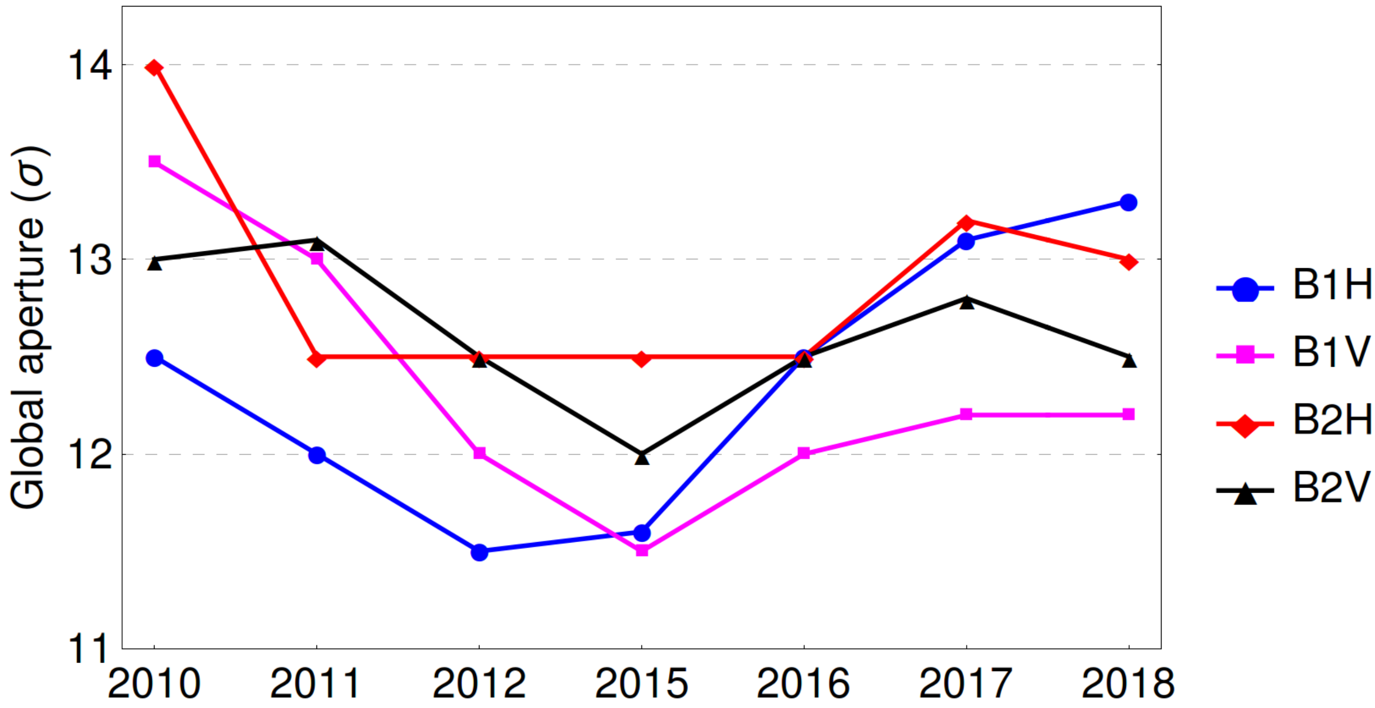
Lessons learned on aperture

- Asymmetry in aperture between IR1 crossing angle signs
  - Gained about 2 σ in the crossing plane of IR1 with positive crossing angle
    - limitation moves to other plane. Gain on limit about 1 σ
  - Crossing changed to distribute radiation in triplet. Change back to negative polarity in Run 3?
    - so far produced with positive polarity: 115 fb^{-1} at 6.5 TeV,
      with negative polarity: 45 fb^{-1} at 6.5 TeV + 30 fb-1 at ≤ 4TeV

- CMS IP shift bump predicted to cause significant degradation of vertical aperture in MAD-X calculations
  - Not observed in measurements – shadowed by IR1 crossing plane
  - Global LHC measurements: No effect seen in tests down to -2 mm at β^*=40 cm
  - Operated with CMS bump at -1.8 mm in 2018

Injection aperture

- Injection aperture measured in the commissioning of every year
- See some variations and improvement over the years, in particular B1H
- Some variations of the bottleneck locations – see backup
  - Probably several bottlenecks at similar apertures



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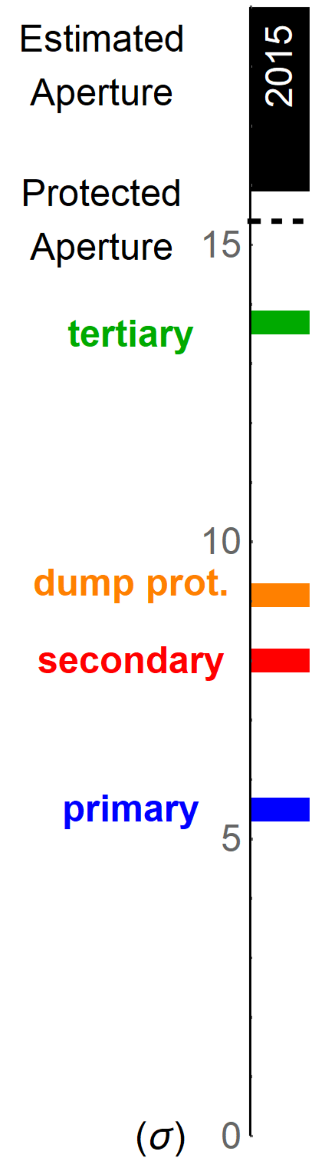
2015

- First year after LS1 – concerns for losses, stability and protection of aperture
  - Higher beam energy (6.5 TeV vs 4 TeV) and lower quench limit
  - Shorter 25 ns bunch spacing
  - Loss spikes and instabilities

- Strategy
  - Put focus on feasibility, stability and ease of commissioning. Allow comfortable margins for operation and avoid introducing too many untested features at once
  - Main priority: Get LHC running 25 ns at 6.5 TeV
  - Performance should not be main focus, but we should also not be overly pessimistic
  - Prepare for production and higher performance in 2016

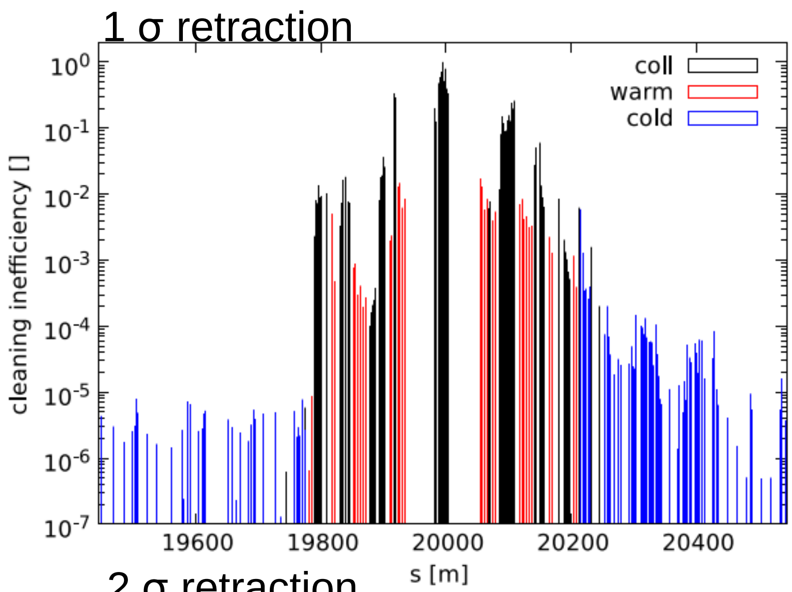
2015

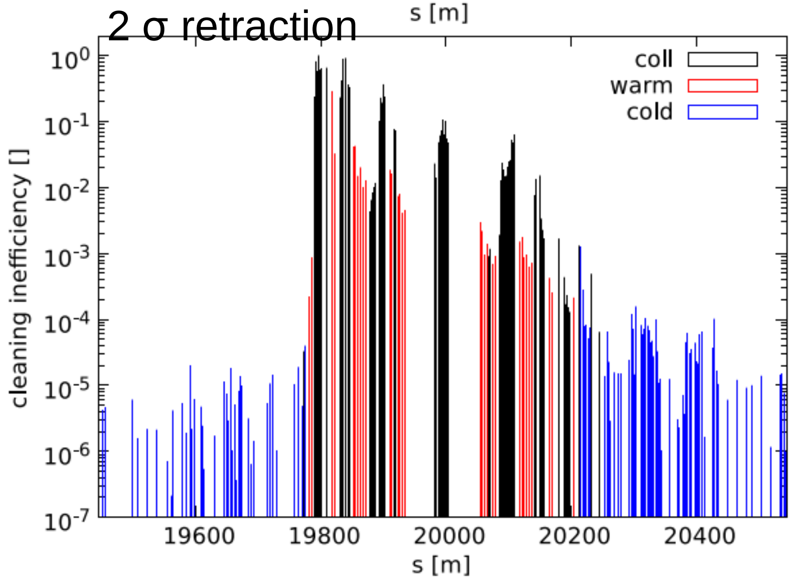
- Collimator settings
  - Kept IR7 settings from 2012 in mm
  - Well-proven long-term stability and cleaning
  - Cleaning predicted to be satisfactory at 6.5 TeV
- Start carefully with comfortable margins on aperture, orbit, optics, beam-beam
- Protection of aperture: added 2 σ extra margins on top of assumption as in Run 1 [see PRSTAB 18, 061001 (2015)]
  - Risk of damage to TCTs and triplet during asynch dump driving choice of settings
- Started with conservative value of β^*=80 cm and 11 σ beam-beam separation (150 μrad)



Development during 2015

- Started thinking of how to push performance
- MDs on tighter collimation hierarchy
  - Found that impedance and stability of cleaning hierarchy were acceptable when moving in TCSGs to 2 σ retraction from TCP
  - Found a hierarchy breakage at 1 σ retraction
- MDs by beam-beam team showed possibility of reduced beam-beam separation
  - 10 σ for 3.75 μm

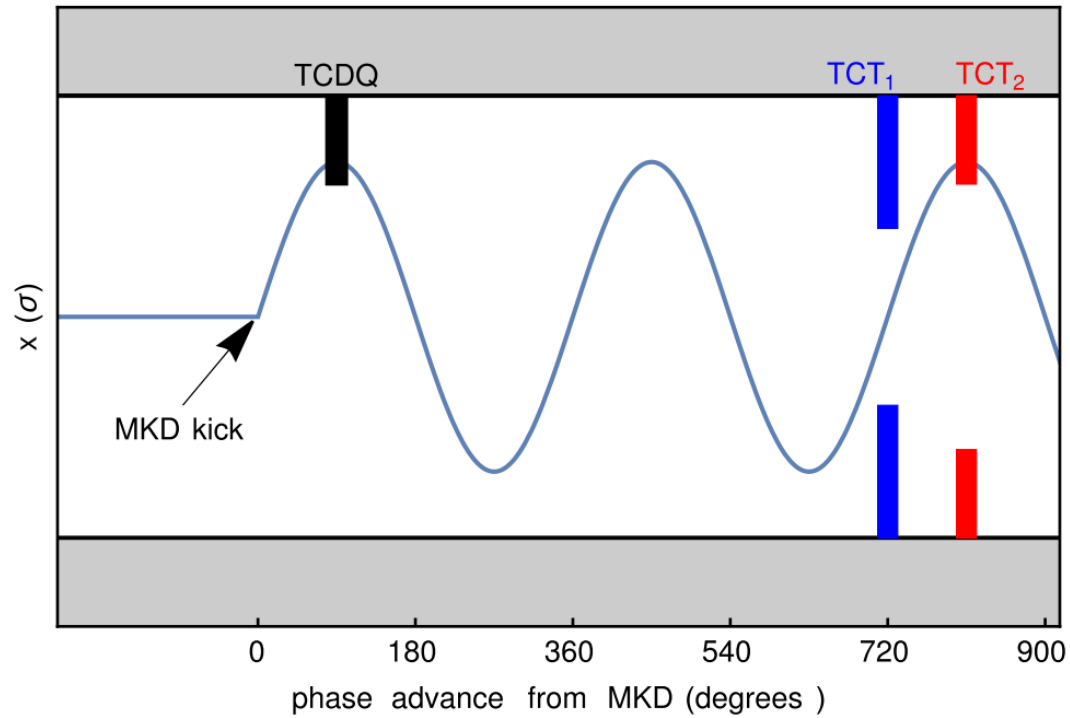




A. Mereghetti et al.

Reducing TCDQ-TCT margin

- Relatively large margin of 4.6 σ taken between TCDQ and TCT in collimation hierarchy in 2015
  - Ensure that the TCTs and the triplet aperture just behind never risk to be damaged during an asynchronous beam dump

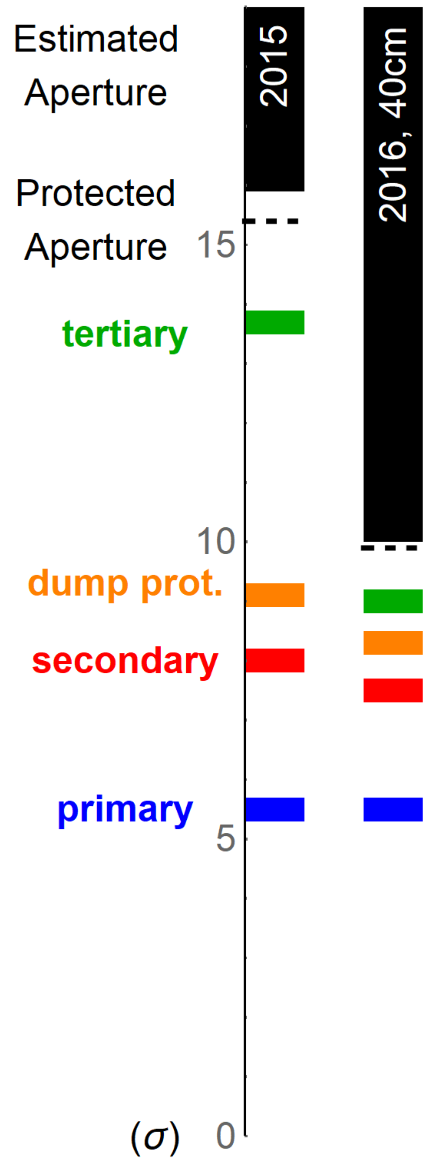


- Possible to reduce margin by demanding that TCTs / triplets should be close to the minimum of the oscillating miskicked beam
  - Triggered design of new optics for 2016 (R. de Maria et al.), demanding MKD-TCT phase stays below 30 deg
- MDs on aperture measurements at smaller β*

2016 configuration

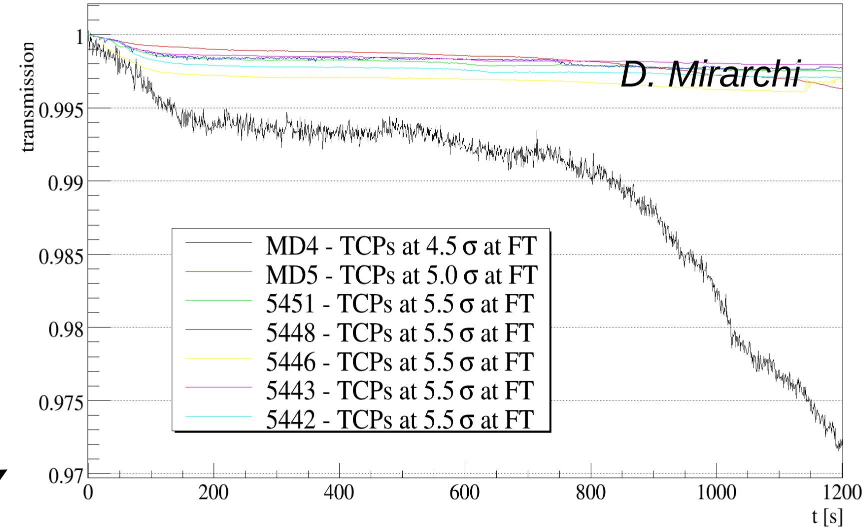
- Reduced margins in collimation hierarchy, in particular reducing TCDQ-TCT margin to 0.9 σ
  - Could maybe have been reduced even more, but didn't do it due to fear of causing higher experimental background
  - Started developing new software interlocks on phase (power converter interlock) and BPMs in IR6 and at TCTs to ensure operation within acceptable interval
    - Using built-in BPMs at collimators

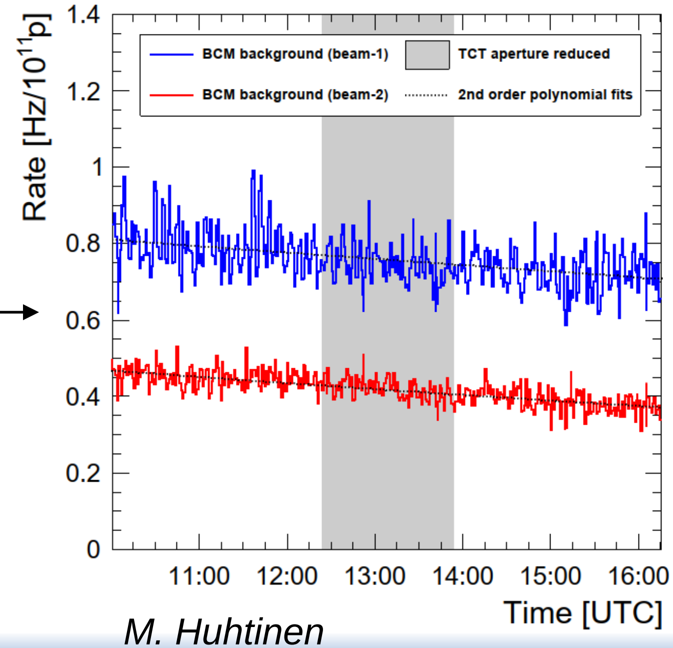
- Could go to β*=40 cm and 10 σ beam-beam separation (185 µrad)
  - First time that LHC operated below the design value β*=55 cm
  - Production year – start pushing performance



Developments in 2016

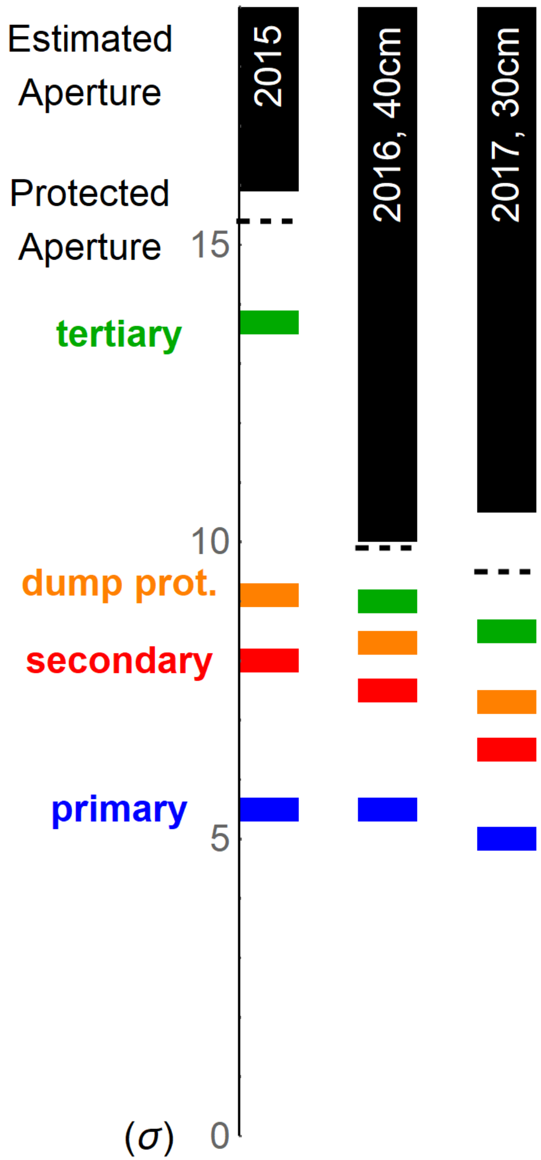
- Studies by beam-beam team: Reduced crossing from 185 urad to 140 urad
  - 9.3 σ for BCMS emittance 2.5 μm
  - Gave additional aperture margin – further reduction of β*?
- Campaign of MDs in view of reduced β* in 2017
  - Tighter TCP setting by 0.5 σ
  - Tighter collimation hierarchy – TCSG retraction of 1.5 σ acceptable
  - Tighter TCT setting did not show effect on experimental background
  - Aperture measurements
- Development of new ATS optics with matched MKD-TCT phase (S. Fartoukh)





2017

- Implemented tighter IR7 settings
- Started close to 2016 configuration: β*=40 cm, but with new ATS optics
  - Optics commissioned down to 30 cm to prepare future reduction
  - Asymmetric TCDQ setting required
- Pushed after TS2 to β*=30 cm, based on measurements and simulations.
  - Kept same crossing angle of 150 μrad – decrease in normalized beam-beam separation
  - Helped in recovering performance during the "16L2 period"

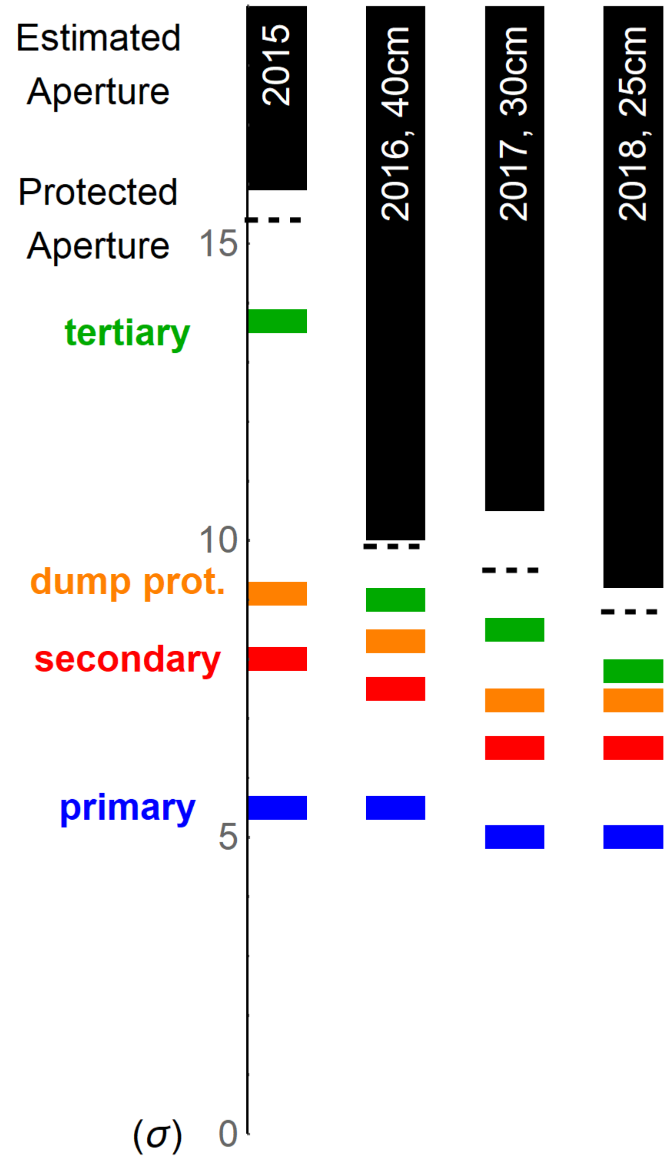


2018

- No large margins left to gain on collimators – already pretty tight
  - Primary half gaps of less than 1 mm
  - Still some room to move in tertiaries and allow smaller aperture

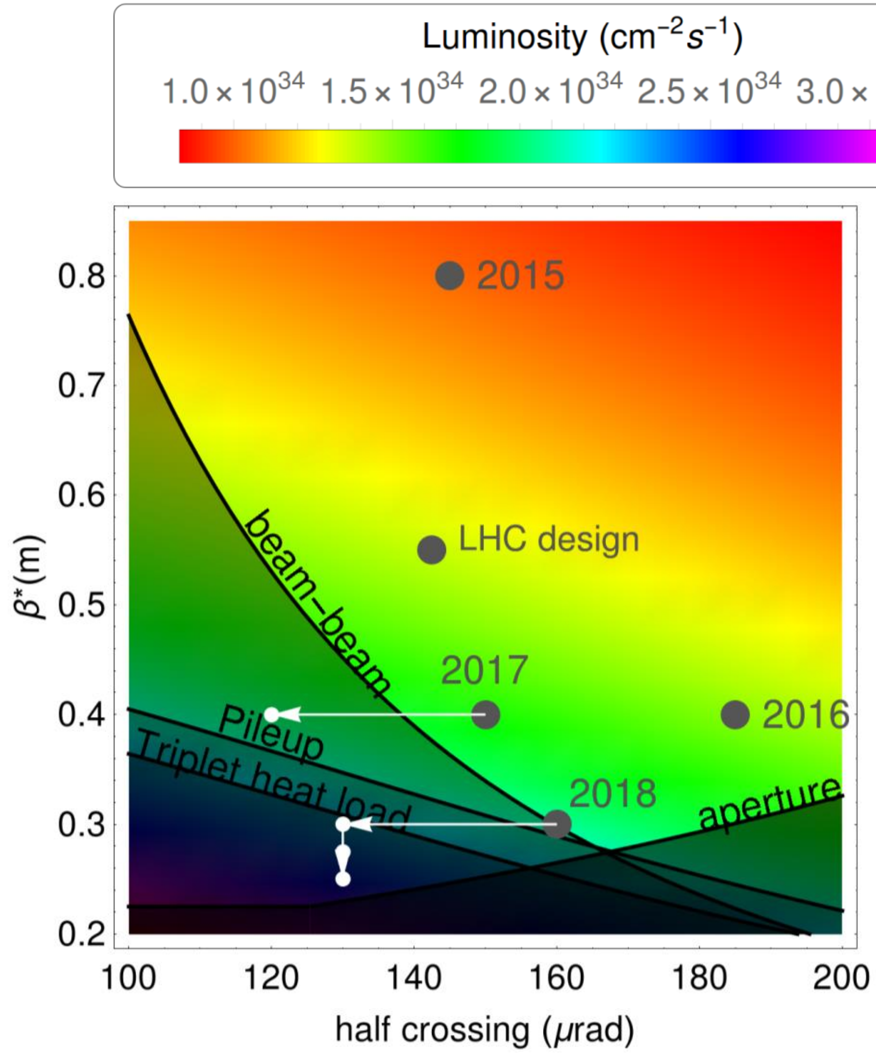
- Largely kept 2017 collimator settings
  - Needed to introduce tilt on TCSG to avoid hierarchy breakage even at 1.5 σ retraction

- Potential room to reach 27.5 cm – still started at 30 cm, but with additional β*-leveling down to 25 cm



Parameter space for Run 2 operation

- Explored a wide parameter space in Run 2
- Leveling pushes configuration later in fill when intensity-dependent constraints are relaxed
- Have gone a long way since LHC design!



Assumptions

For lumi calculation:
2544 bunches
1.1E11 p/bunch
1.9 μm emittance
8 cm bunch length

Beam-beam:
10.6 σ, for 1.9 μm

Aperture:
8.5 σ protected,
+0.5 σ margin,
positive IR1 crossing

Max pileup = 60

Triplet - max. lumi:
2.2E34 cm^{-2} s^{-1}

For visibility, including only starting configuration for each year

Conclusions

- Explored a large parameter space for the Run 2 machine configurations
- Pushed towards higher performance every year
  - Relied on good knowledge of the aperture
  - Aperture measurements part of standard commissioning
- Collimators continuously tightened during Run 2
  - Can now protect aperture that is close to the LHC design value
  - Used MD results to determine the next machine configuration
- Pursued options to improve machine performance while staying safe and not reducing machine availability
- Achieved β^* less than half of the LHC design value
  - Reduced β^* by more than factor 3 since 2015

Thanks for the attention.

Questions?

Backup

Summary of Run 2 collimator settings

Collimator	2015	2016	2017a	2017b	2018
TCP IR7	**5.5**	**5.5**	**5.0**	**5.0**	**5.0**
TCSG IR7	**8.0**	**7.5**	**6.5**	**6.5**	**6.5**
TCLA IR7	**14.0**	**11.0**	**10.0**	**10.0**	**10.0**
TCP IR3	15.0	15.0	15.0	15.0	15.0
TCSG IR3	18.0	18.0	18.0	18.0	18.0
TCLA IR3	20.0	20.0	20.0	20.0	20.0
TCSP IR6	**9.1**	**8.3**	**7.3**	**7.3**	**7.3**
TCDQ IR6	**9.1**	**8.3**	**7.3**	**7.3**	**7.3**
TCT IR1/5	**13.7**	**9.0**	**9.0**	**8.5**	**8.5→ 7.8**
Aperture 1/5		***9.9***	***9.9***	***9.5***	***8.8***
β* IR1/5	***80 cm***	***40 cm***	***40 cm***	***30 cm***	***30 cm → 25 cm***
TCT IR2	**37.0**	**37.0**	**37.0**	**37.0**	**37.0**
TCT IR8	**15.0**	**15.0**	**15.0**	**15.0**	**15.0**

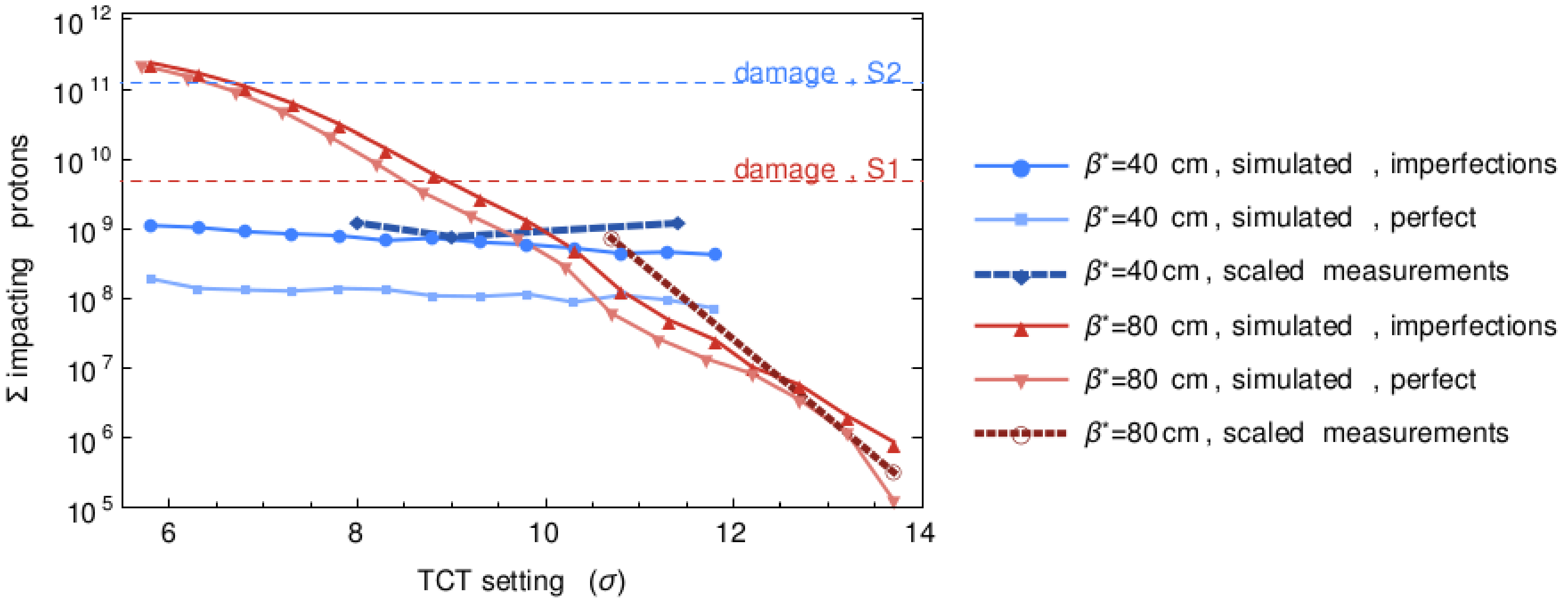
Settings in σ with ε=3.5 μm

Injection apertures in Run 2

	B1H	B1V	B2H	B2V
2015	MBRC.4R8: 11.6	Q6L4: 11.5	Q4L6: 12.5	Q4R6: 12.0
2016	MBRC.4R8: 12.5	Q6L4: 12.0	TCDQM.4L6: 12.5	Q4R6: 12.5
2017	Q6R2: 13.1	Q4L6: 12.2	Q6L8: 13.2	Q4R6: 12.8
2018	Q4R6: 13.3	Q4L6: 12.2	Q4L6 & Q6L8: 13.0	Q4R6: 12.5

2016 beam tests of asynch dump

- MDs: Verified experimentally TCT losses during asynchronous dump tests in different optics



- As expected, do not see dependence on TCT setting at 40 cm
  - TCT still intercepts secondary beam out-scattered in IR6 – more spread out → not problematic