Potential and Limitations of High Brightness Beams in the LHC and its Injectors

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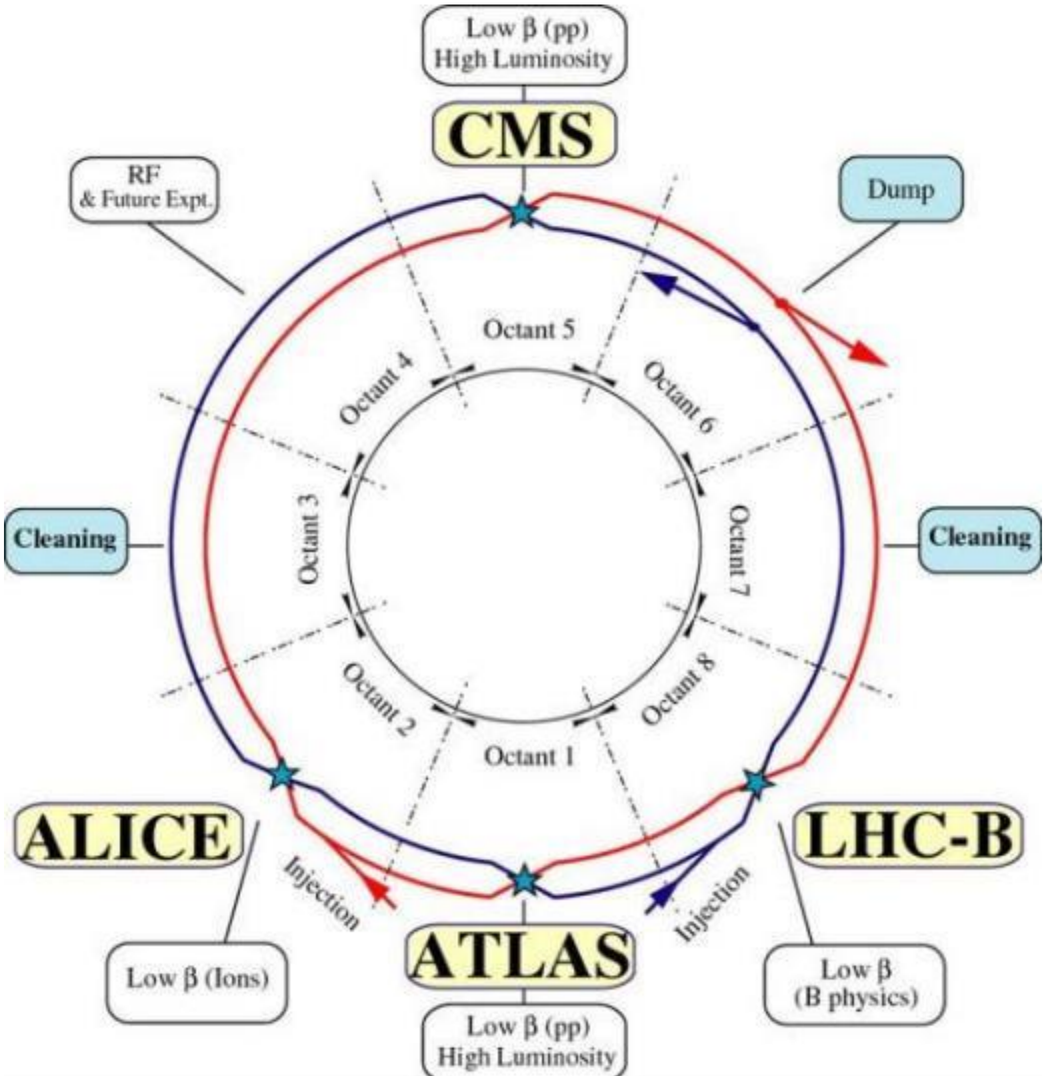
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

LHC layout and planning



Year		TeV	L_{nom}	fb^{-1}
2011	RunI 50ns	7	20%	5.6
2012		8	75%	30
2013	LS1	splice consolidation, R2E, bpm collimators		
2014				
2015	RunII 25ns	13 -> 14		
2016				
	EYETS	SPS CC		
2017	RunII		1x	150
2018				
2019	LS2	LIU, cryo P4, 11T, Exp. upgrade phase I		
2020	RunIII 25ns	14	2x	
2021				
2022				300
2023	LS3	HL-LHC upgrade, Exp. upgrade phase II		
2024				
2025				
2026	RunIV 25ns	14	5x or 7x	250/ year
….				

High Luminosity LHC

Outline

High intensity and high brightness beams are a key ingredient to fulfill the LHC and HL-LHC goals.

Content:

- LHC Intensity and brightness limitations
- LHC injector beam production reach
- Experiment constraints and physics run conditions
- Parametric analysis of luminosity expectations

The focus of the talks is on pp runs, although the LHC has also a very ambitions heavy ion physics program.

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MOPAB43, P. Hermes

High Luminosity LHC

LHC Beam current limitations

O. Bruning, R. Assmann, E. Métral

LHC nominal: 1.1 10^{11} ppb, 2748 bunches, about 0.5 A.

HL-LHC baseline: 2.2 10^{11} ppb, 2748 bunches, about 1 A.

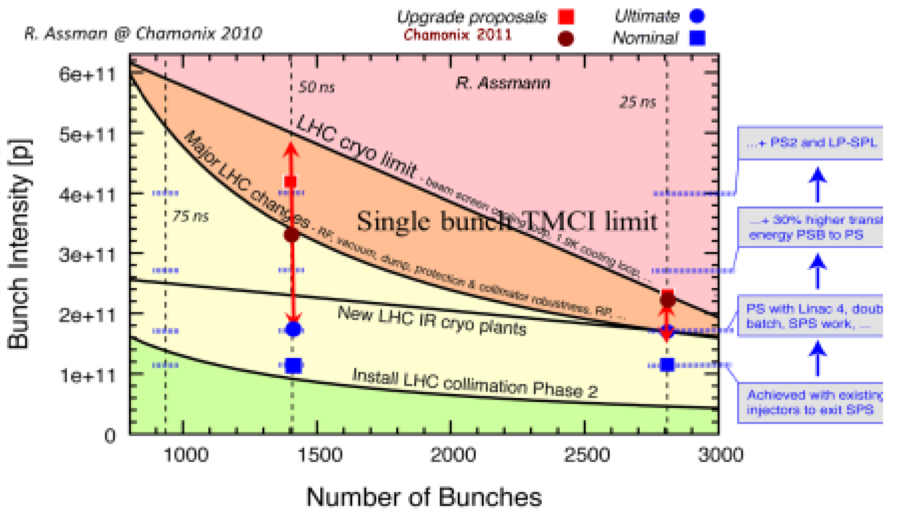
e-cloud to be solved by scrubbing the dipoles below SEY 1.3 and increase cooling capacity and/or apply coating in the standalone quadrupoles.

Couple bunch instability stabilized by the damper.

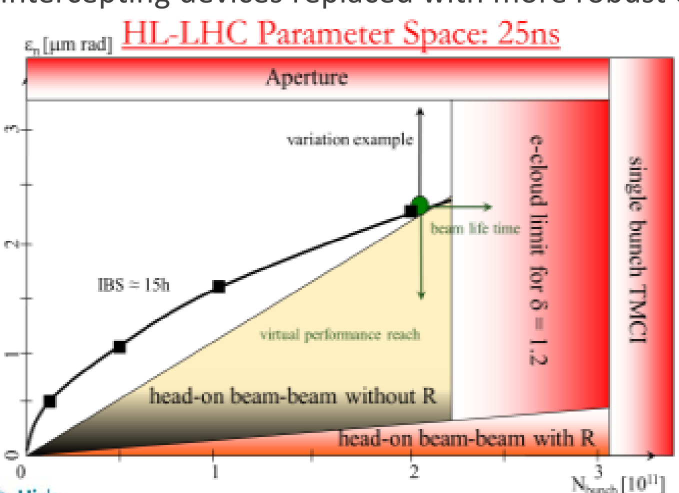
Single bunch instability threshold far in the present model (with metallic collimator) or stabilized by head-on tune spread.

Intercepting devices replaced with more robust ones.

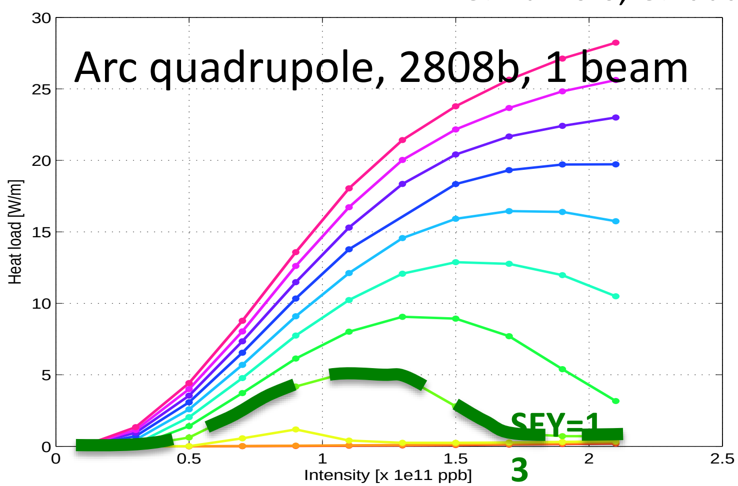
Summary of LHC Intensity Limits (7 TeV)



O. Bruning, E. Métral et al.



G. Rumolo, G. Iadarola



Understanding intensity limitations in the LHC is constantly evolving.

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WEO2AB02, M. Sapinski; bunches, about 1 A.

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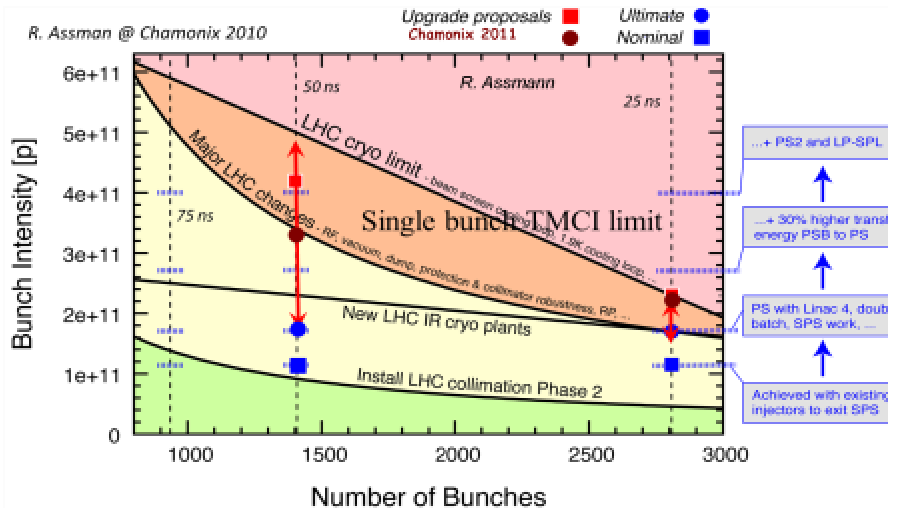

G. Rumolo, G. Iadarola

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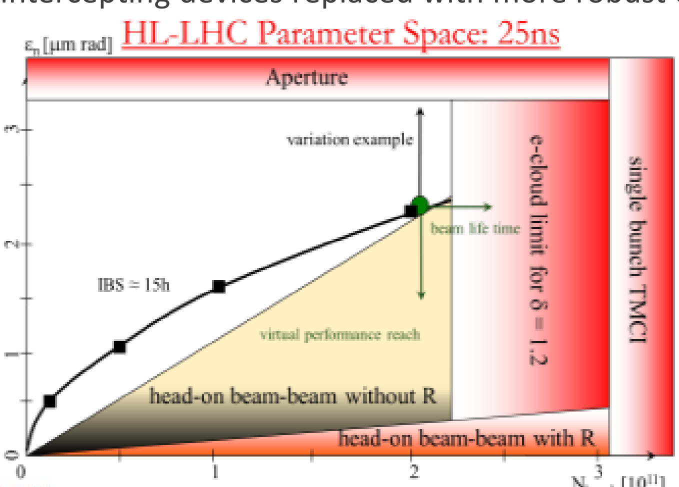

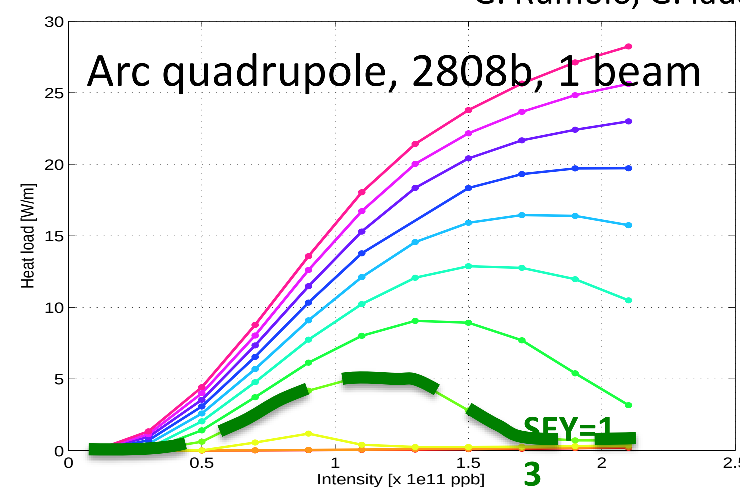

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THO4LR03, H. Timko

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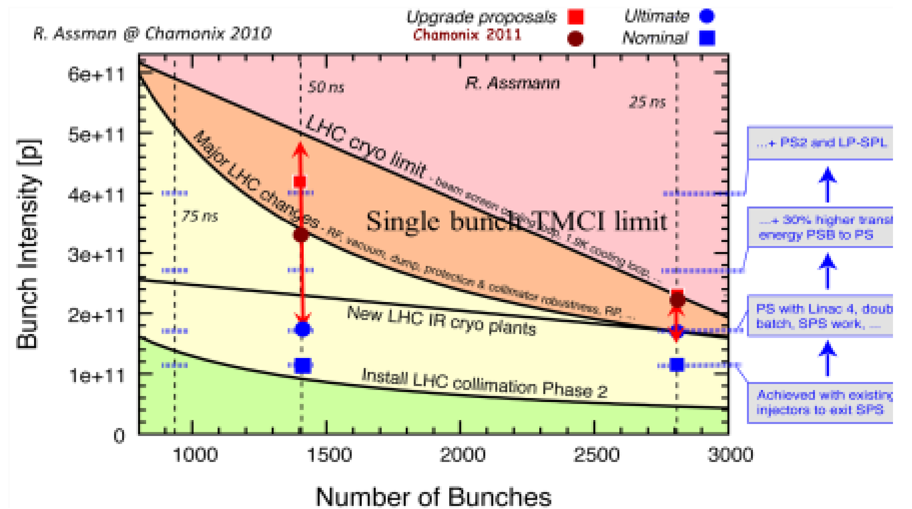

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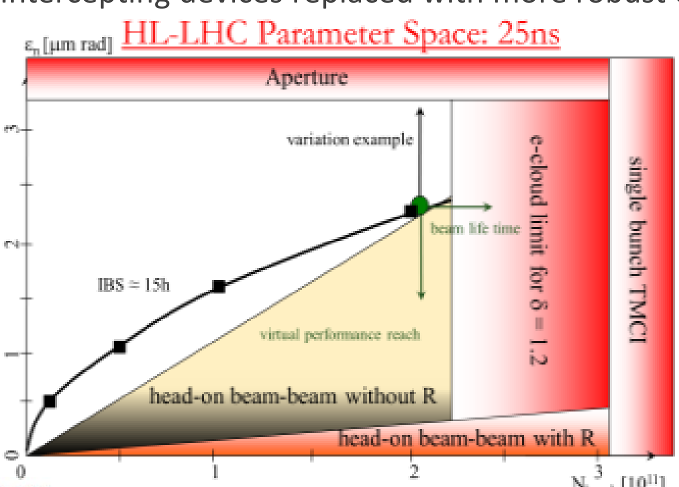
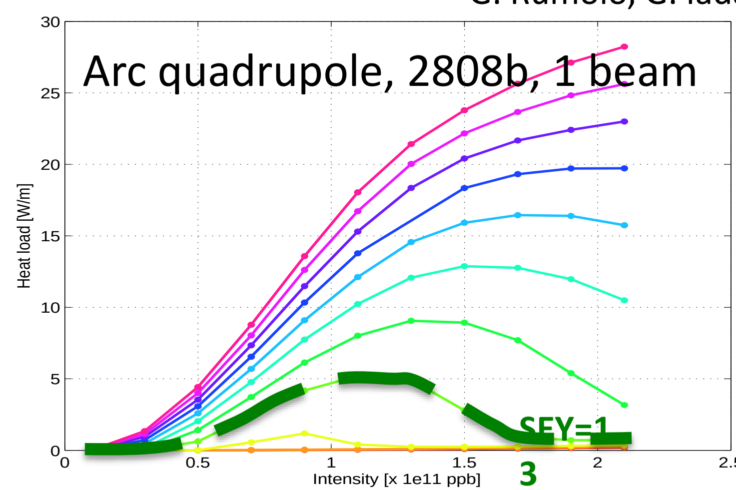


G. Rumolo, G. Iadarola



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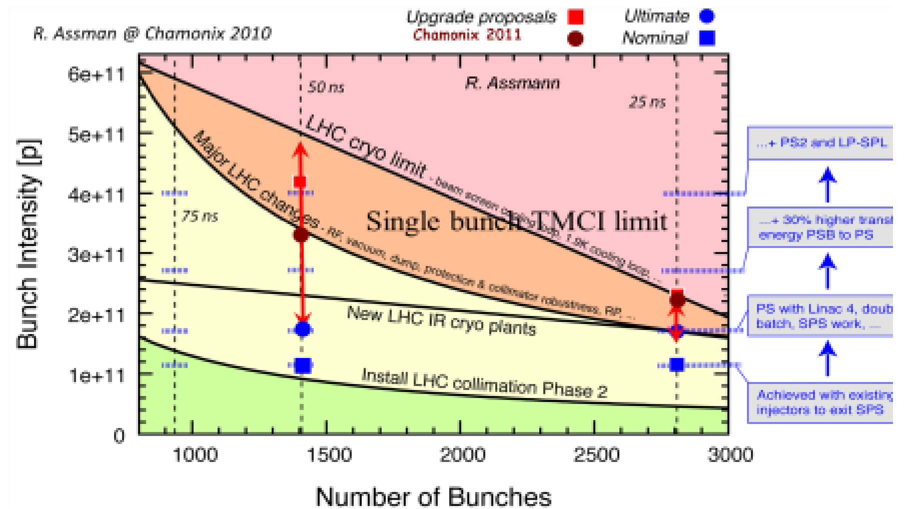

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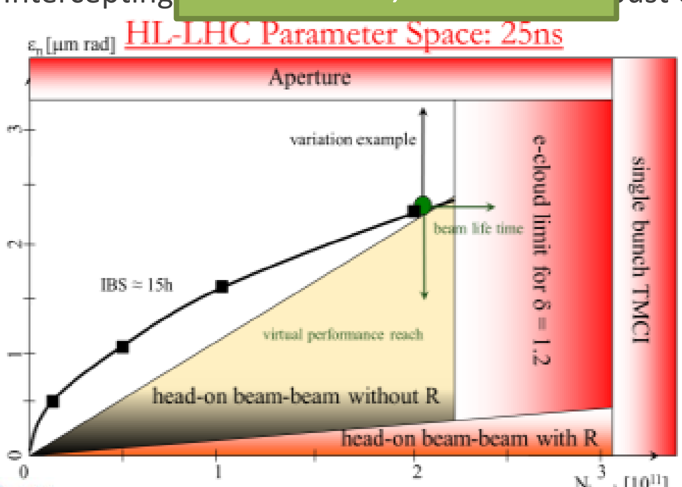
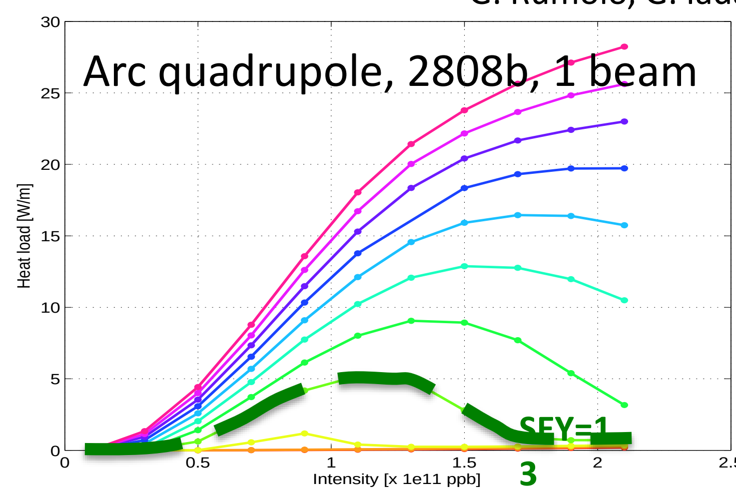


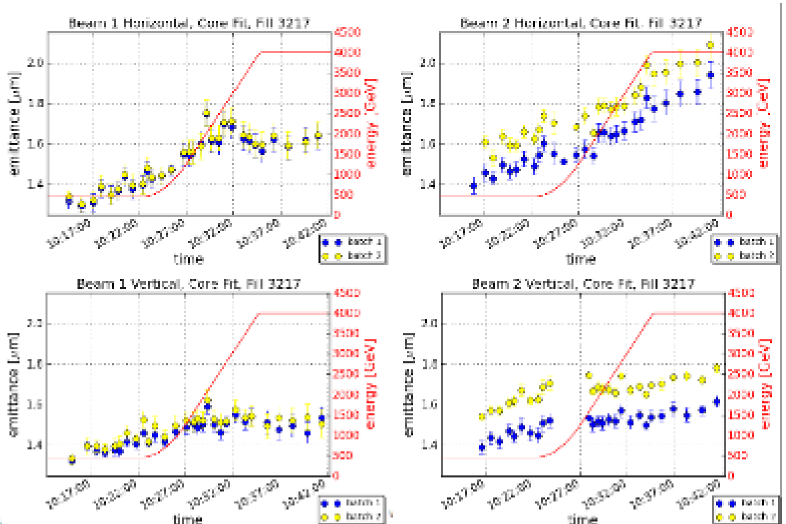
G. Rumolo, G. Iadarola



Understanding intensity limitations in the LHC is constantly evolving.

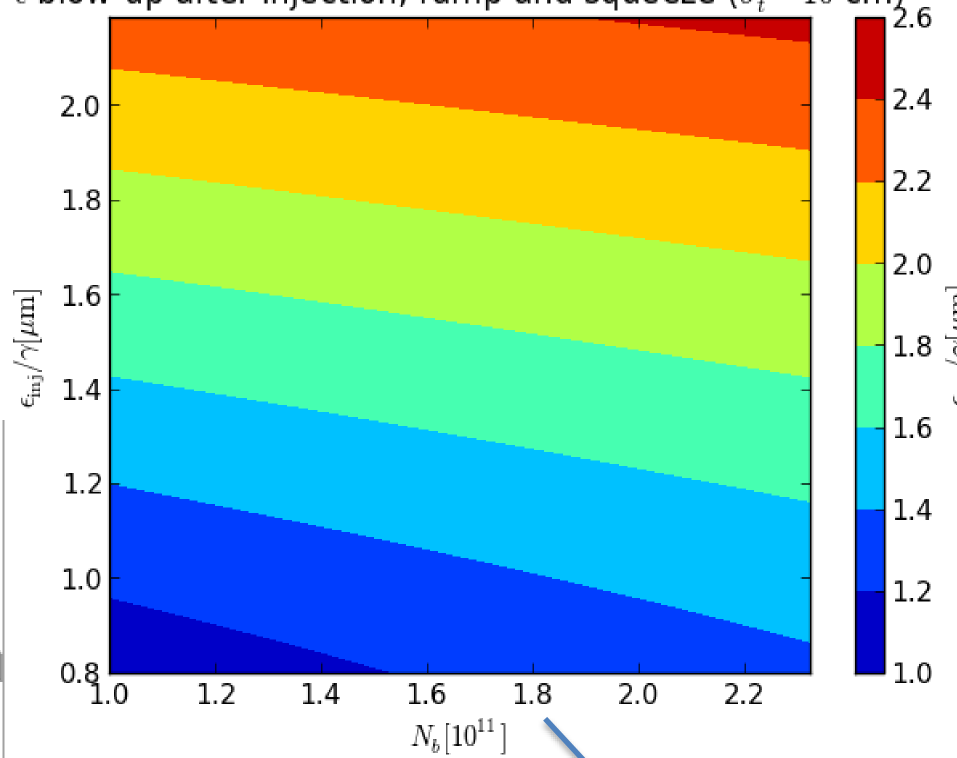
LHC Injection to Collisions

- **5% intensity** loss assumed during the cycle such that average lifetime >20h and never below 0.5 h to be compatible with collimators
- **10 % emittance blow-up + IBS** in H plane and
  - additional source in the vertical plane 40h.
  - control of the blow-up due to electron clouds
  - 10 cm bunch length to reduce IBS.



R. Tomas, O. Dominguez

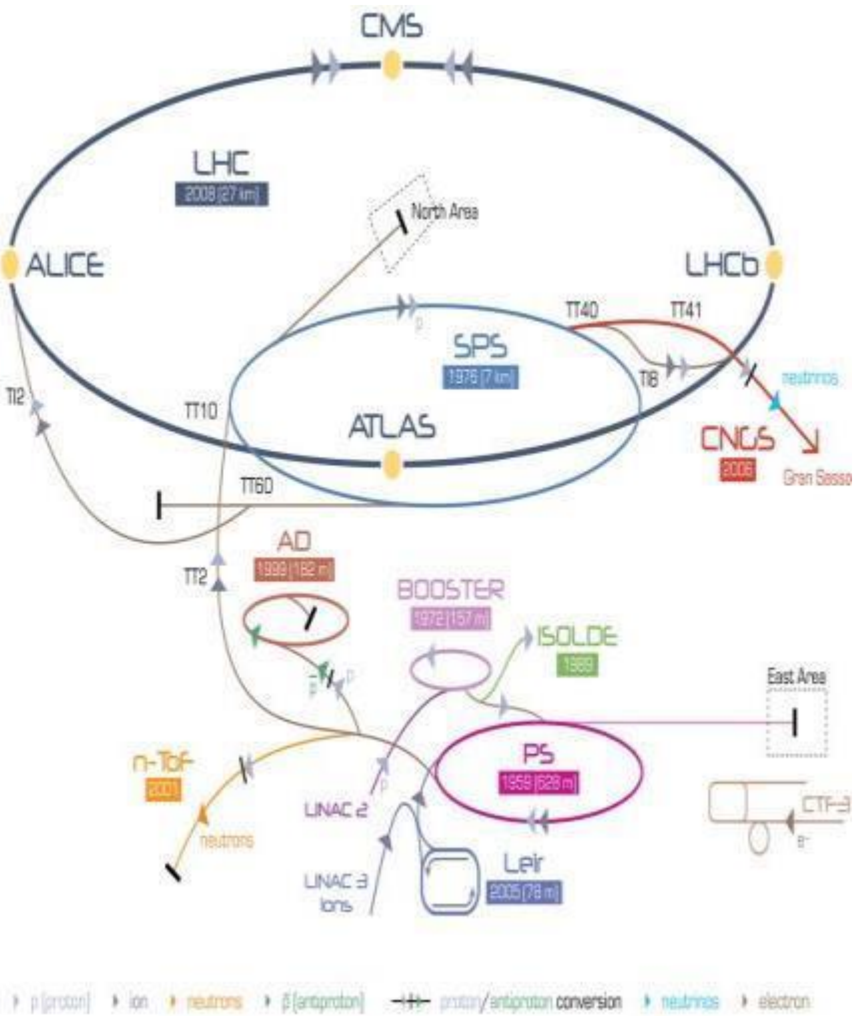
IBS blow-up model



$$\epsilon_{col} \approx 1.1\ \epsilon_{inj} + 0.2\ N_b / \epsilon_{inj}\ [10^{11}/\mu m]$$

Assumed for both plane for simplicity

LHC injectors after LS1

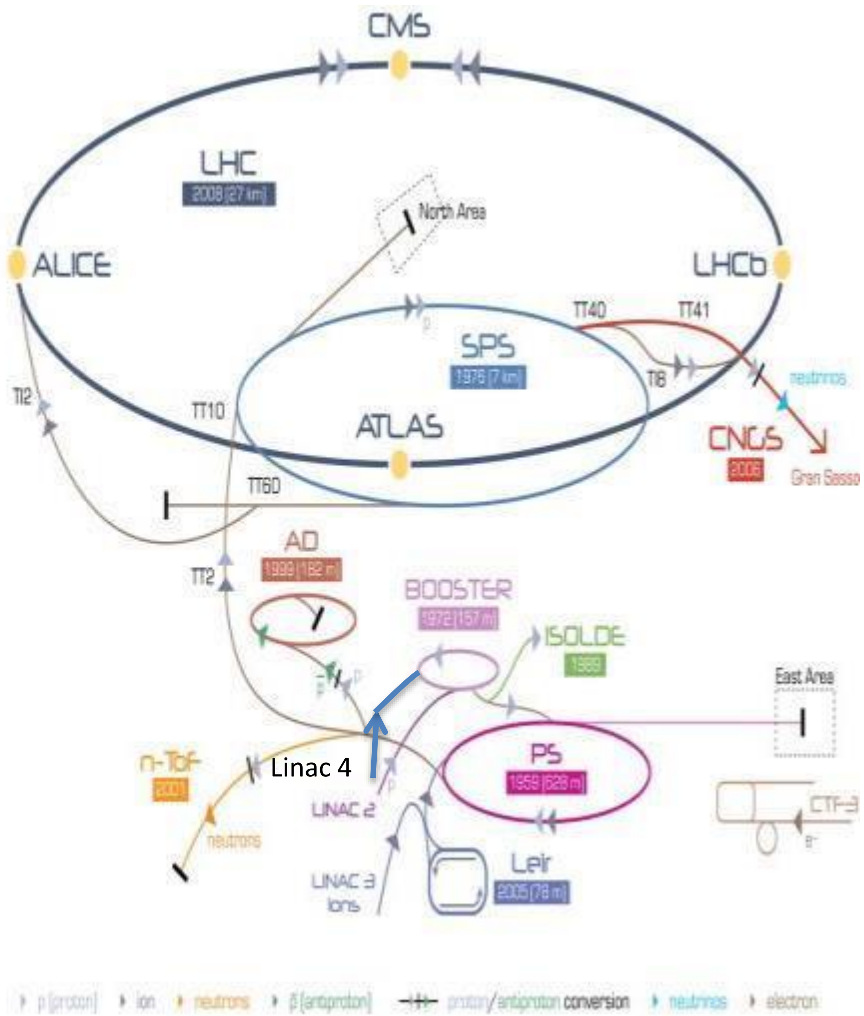


G. Rumolo et al. for the LIU team

	E	K_b	N_b	ε_T/γ
	[GeV]		[10^{11}]	[μm]
Linac2 to PSB	0.05*	1/ring	19.2	1.5
PS inj.	1.4*	2+4	18.2	1.6
PS ext.	26	72	1.4	1.6
SPS ext.	450	4x72	1.4	1.9
LHC inj.	450	2748	1.3	2.4
LHC physics	7000	2748	1.2	2.7

* Kinetic Energy

LHC injectors after Upgrade (LIU) in LS2



G. Rumolo et al. for the LIU team

	E	K_b	N_b	ε_T/γ
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Linac4 to PSB	0.16*	1/ring	29.6	1.5
PS inj.	2*	2+4	28.1	1.6
PS ext.	26	72	2.3	1.6
SPS ext.	450	4x72	2.2	1.9
HL-LHC inj.	450	2748	2	1.9
HL-LHC target			2.32	2.2
HL-LHC physics	7000	2748	1.9	2.3
HL-LHC target			2.2	2.5

* Kinetic Energy

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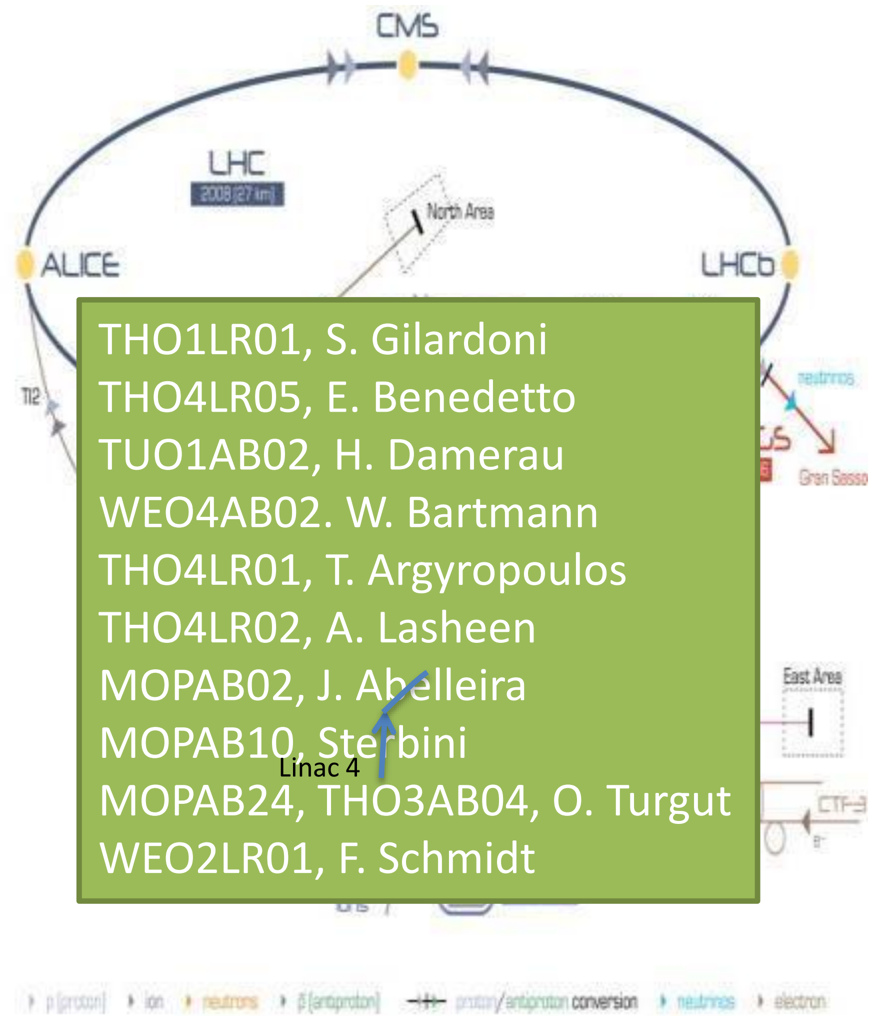

THO1LR01, S. Gilardoni
THO4LR05, E. Benedetto
TUO1AB02, H. Damerau
WEO4AB02. W. Bartmann
THO4LR01, T. Argyropoulos
THO4LR02, A. Lasheen
MOPAB02, J. Abelleira
MOPAB10, Sterbini
MOPAB24, THO3AB04, O. Turgut
WEO2LR01, F. Schmidt

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Standard beam production

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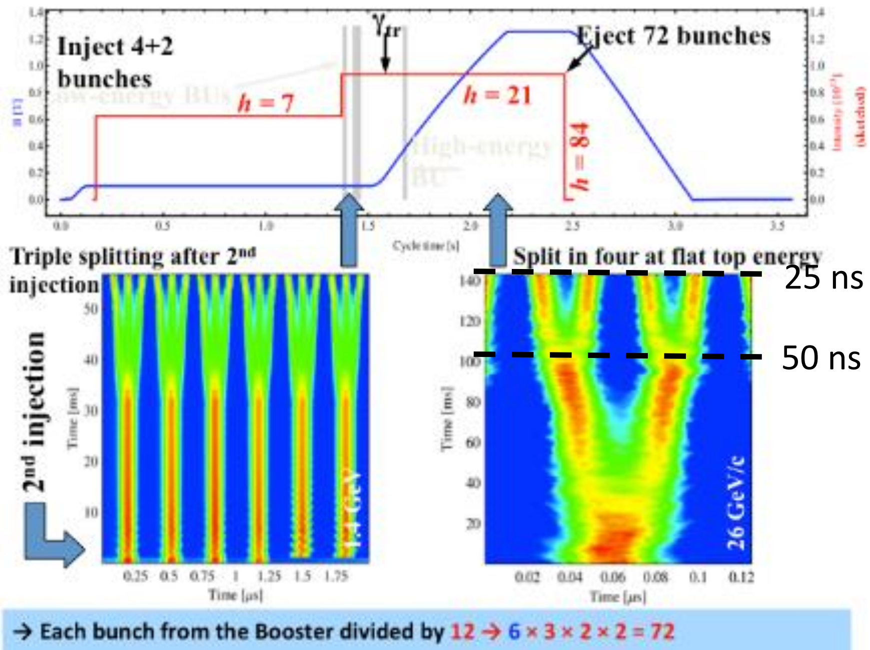
<u>Standard scheme:</u>

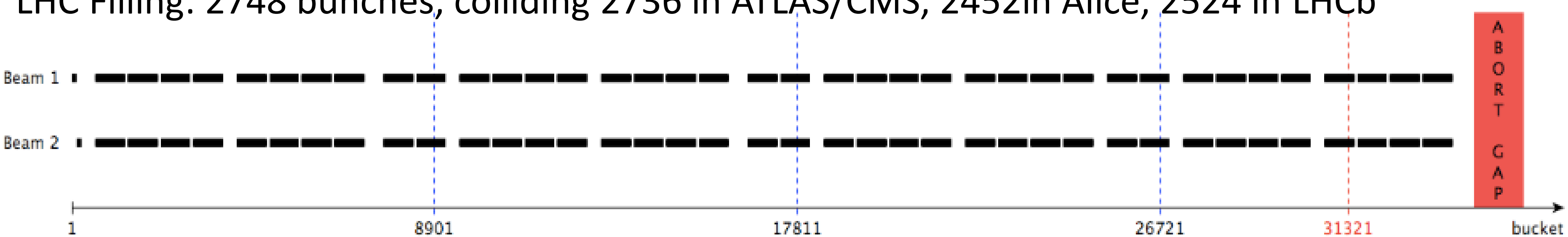
(maximum number of bunches in LHC)



		k_b	N_b	ε_T/γ
			$[10^{11}]$	[μm]
LHC inj.	STD <LS2	2748	1.3	2.4
LHC physics			1.24	2.7
LHC inj.	STD >LS2	2748	2	1.9
LHC physics			1.9	2.3

B. Gorini

LHC Filling: 2748 bunches, colliding 2736 in ATLAS/CMS, 2452in Alice, 2524 in LHCb



BCMS beam production

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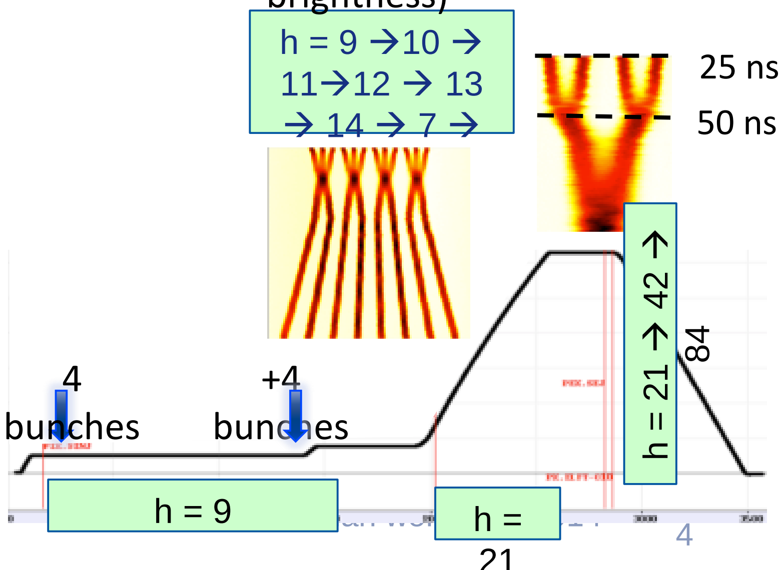
BCMS scheme:

(less bunches in LHC but higher brightness)



PS batches with 48 (24) bunches for 25ns (50ns)

		k_b	N_b	ε_T/γ
			$[10^{11}]$	[μm]
LHC inj.	STD <LS2	2748	1.3	2.4
LHC physics			1.24	2.7
LHC inj.	STD >LS2	2748	2	1.9
LHC physics			1.9	2.3
LHC inj.	BCMS <LS2	2508/ 2592	1.3	1.28
LHC physics			1.24	1.6
LHC inj.	BCMS >LS2	2508/ 2592	2	1.38
LHC physics			1.9	1.8

LHC Filling: 2604 bunches, colliding 2592 in ATLAS/CMS, 2288 in Alice, 2396 in LHCb

LHC pp operational constraints

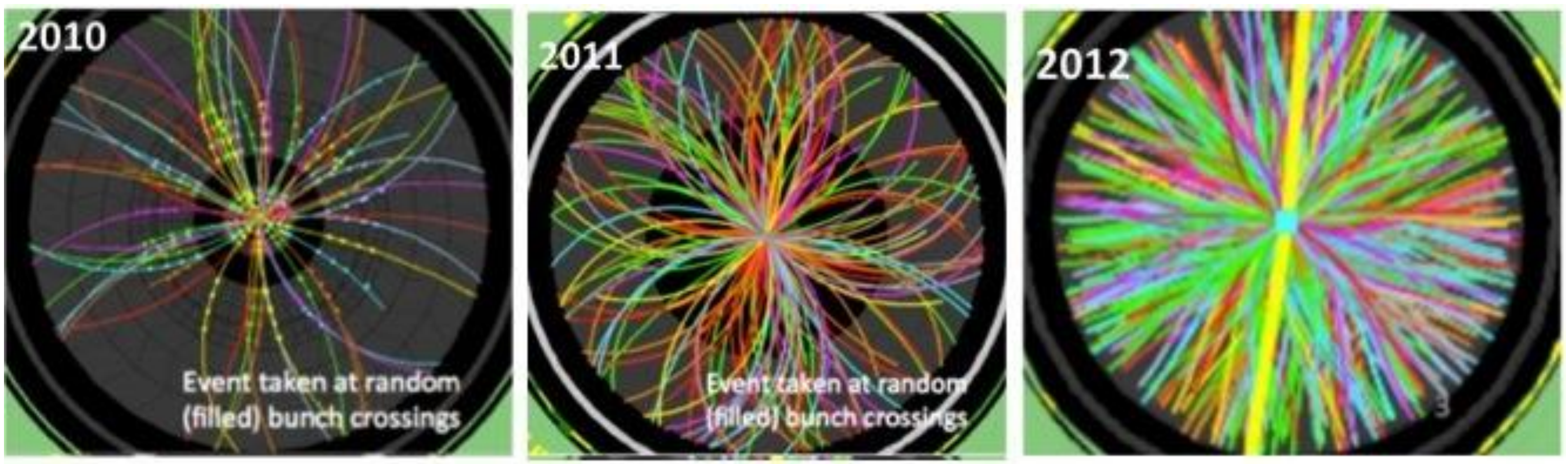
Average pile-up limit for ATLAS and CMS:

- ATLAS/CMS LHC: 50 event/crossing
- ATLAS/CMS HL-LHC: 140 to 200 events /crossing
- LHCb HL-LHC: 4.5 events /crossing

Max luminosity for:

LHCb LHC: 4 to 6 10^{32} $cm^{-2}s^{-1}$
Alice LHC: 5 10^{29} to 2 10^{30} $cm^{-2}s^{-1}$
Alice HL-LHC: 2 10^{31} $cm^{-2}s^{-1}$.

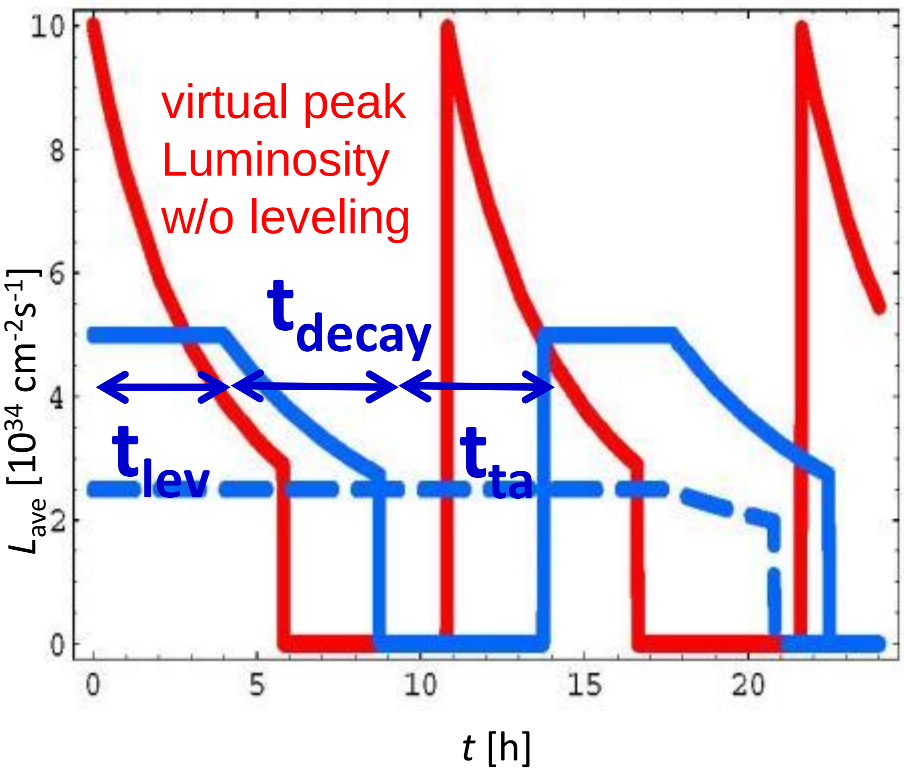
ATLAS event reconstruction



Scheduled Physics Time: 160 days with 50% physics efficiency (RunI: 53%)
Average fill duration: 6.1h on average of Run I due to mainly faults.

High Luminosity LHC

Luminosity evolutions LHC



F. Zimmermann

Lumi evolution model with burn-off for performance with optimal fill length evaluation

$$\frac{dN}{dt} = -\frac{N}{\tau} = -n_{\mathrm{IP}}\sigma L_{\mathrm{lev}} \qquad \tau = \frac{N}{n_{\mathrm{IP}}\sigma L_{\mathrm{lev}}};$$

$$L_{\mathrm{virt}} = k\, L_{\mathrm{lev}} \quad t_{\mathrm{lev}} = \tau\left(1 - \frac{1}{\sqrt{k}}\right) = \tau K$$

$$t_{\mathrm{decay}} = \frac{\tau}{1+K}\left(-K + \sqrt{K^2 + (K+1)\frac{t_{\mathrm{ta}}}{\tau}}\right);$$

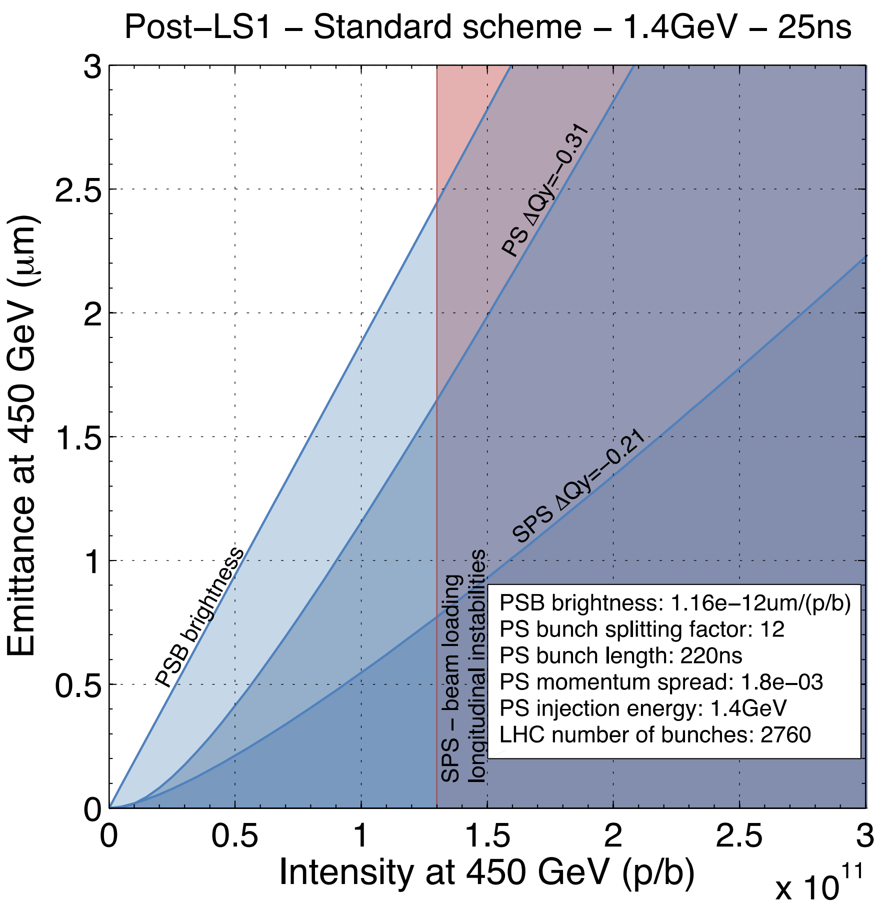
$$L_{\mathrm{ave}} = L_{\mathrm{lev}}\frac{t_{\mathrm{lev}} + \frac{t_{\mathrm{decay}}\tau}{t_{\mathrm{decay}}+\tau}}{t_{\mathrm{lev}} + t_{\mathrm{decay}} + t_{\mathrm{ta}}}$$

Levelling is key ingredient for HL-LHC and maybe be even needed for LHC.

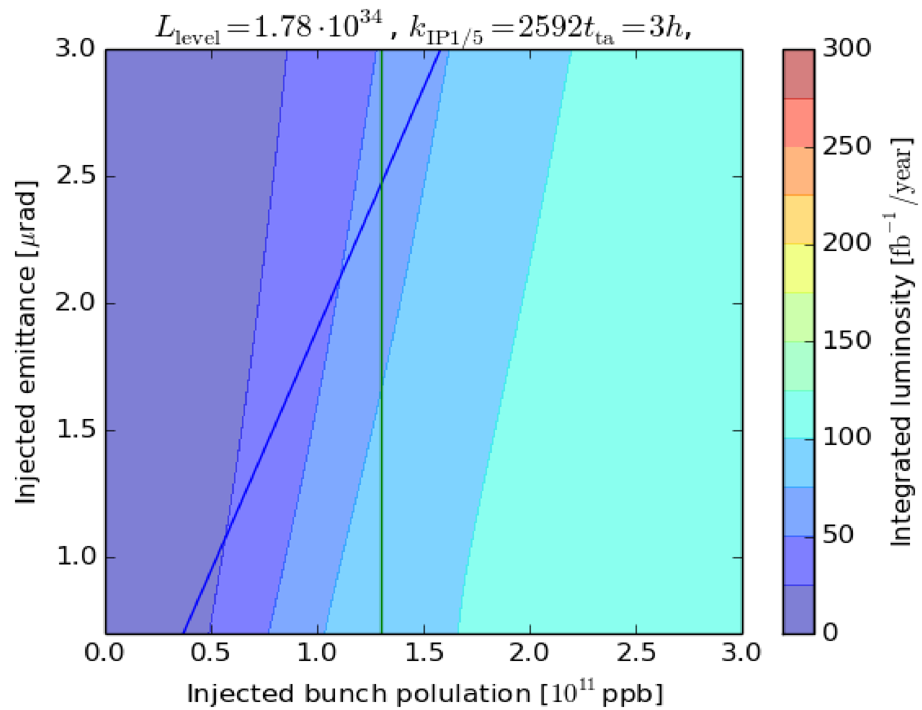
High Luminosity LHC

Post-LS1 Standard beams

Injector brightness curves



LHC Integrated luminosity expectations



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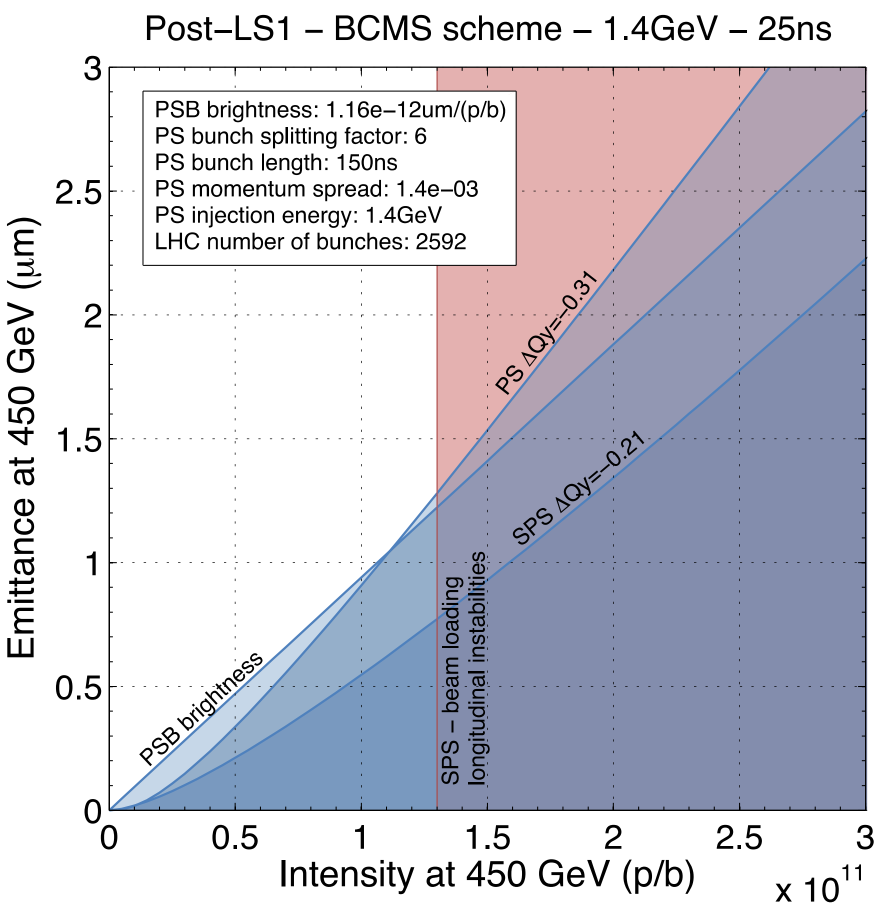
Post-LS1: BCMS beams

Injector brightness curves



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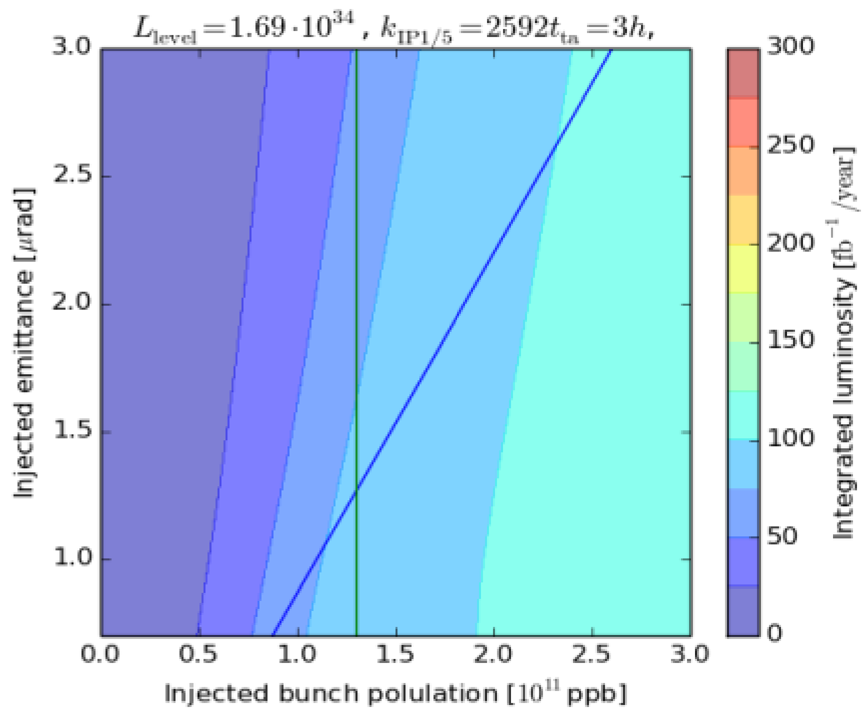

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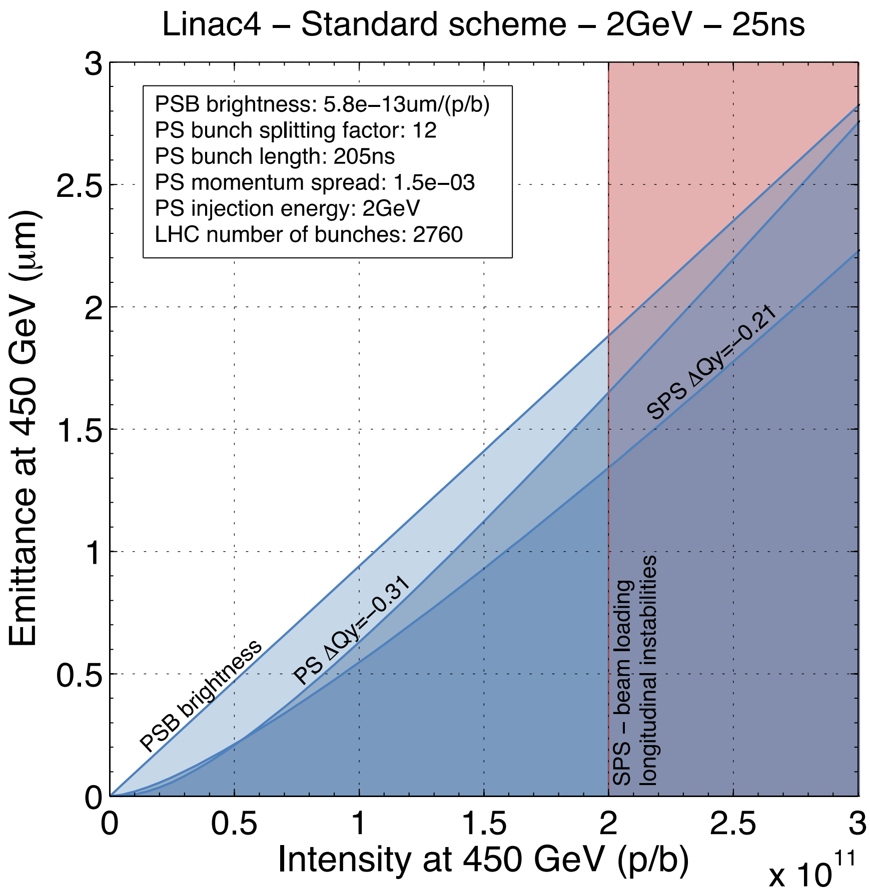
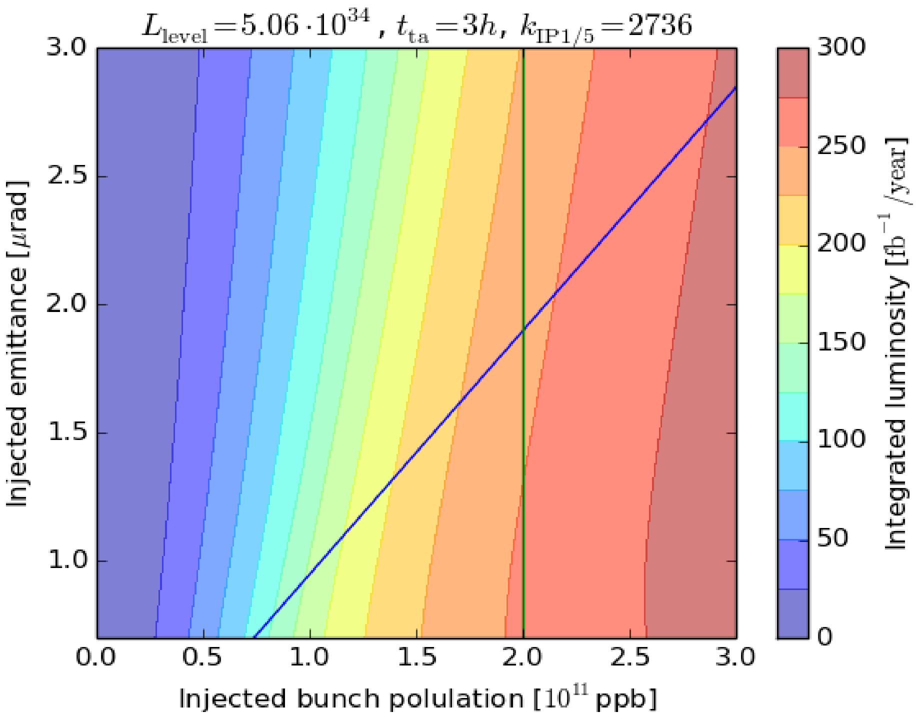
Post-LS2: Standard Beam

Injector brightness curves



LHC Integrated luminosity expectations



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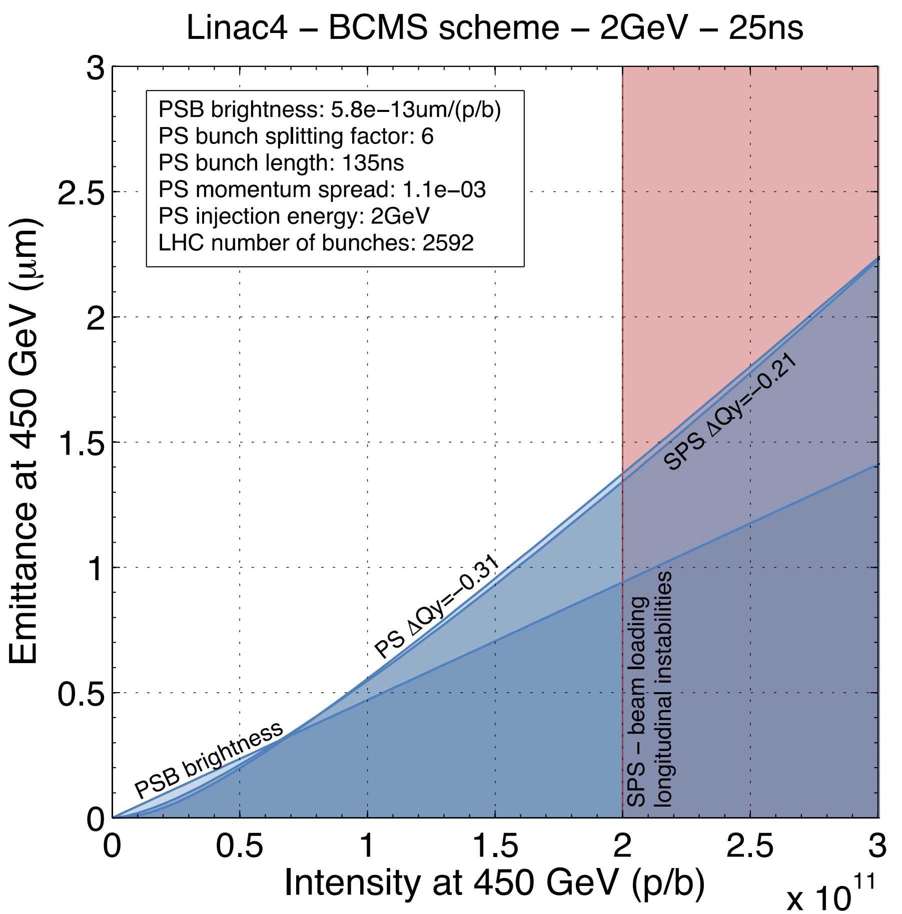

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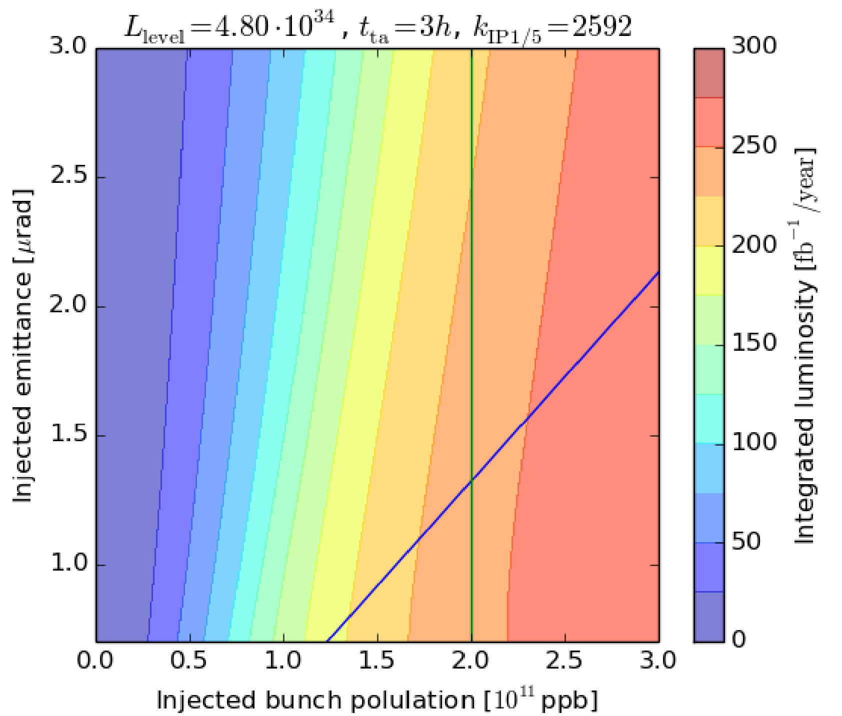

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Daily integrated luminosity estimates

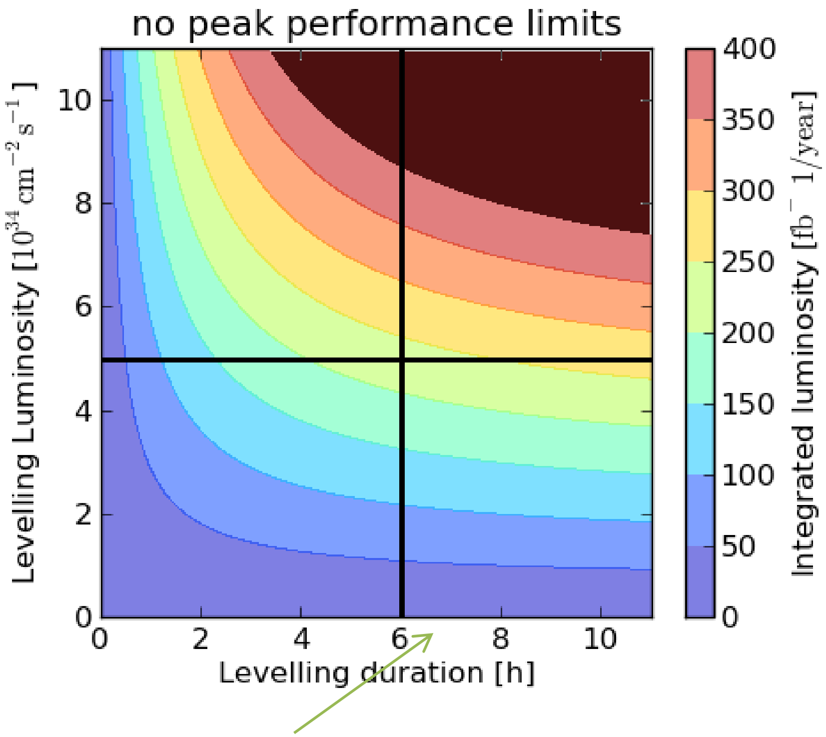
	Bunch Spacing	Bunch Population	Emit. Coll.	Pile-up Max/Lev	Daily Lumi [fb^{-1}]	Fill duration (levelled time) [h]
LHC 6.5 TeV β*=60cm	25 ns	$1.2 \cdot 10^{11}$	2.8 μm Std	30/50	0.58	10.1
			1.7 μm BCMS	50/50	0.78	7.5
	50 ns	$1.6 \cdot 10^{11}$	2.0 μm Std	76/50	0.53	8.1(5.6)
			1.6 μm BCMS	95/50	0.52	7.8(4.4)
HL-LHC 7 TeV β*=15cm	25 ns	$1.9 \cdot 10^{11}$	2.3 μm Std	419/140	2.99	7.2(5.7)
			1.9 μm BCMS	510/140	2.93	7.8(6.7)
	25 ns	$2.2 \cdot 10^{11}$	2.5 μm Std	517/140	3.17	8.6(7.3)
	50 ns	$3.5 \cdot 10^{11}$	3.0 μm Std	517/140	1.75	15(14.1)

Differential model including IBS, radiation damping, noise sources.
G. Arduini

High Luminosity LHC

HL-LHC Performance reach

- Assuming 80 days of successful fills limited by leveled luminosity and fill durations, how much luminosity may we integrate in one year?



Average fill duration 2012

Simplest model that bounds integrated performance:
run at max allowed luminosity for half of the scheduled physics until a failure occurs.

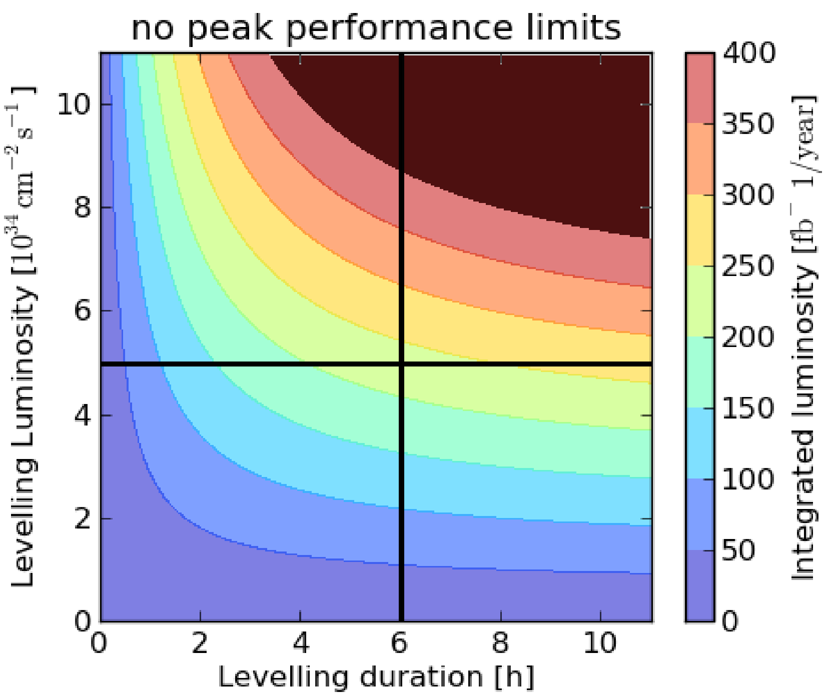
$$L_{\mathrm{lev}} \sim n_{\mathrm{pileup}} \cdot n_{\mathrm{bunches}}$$

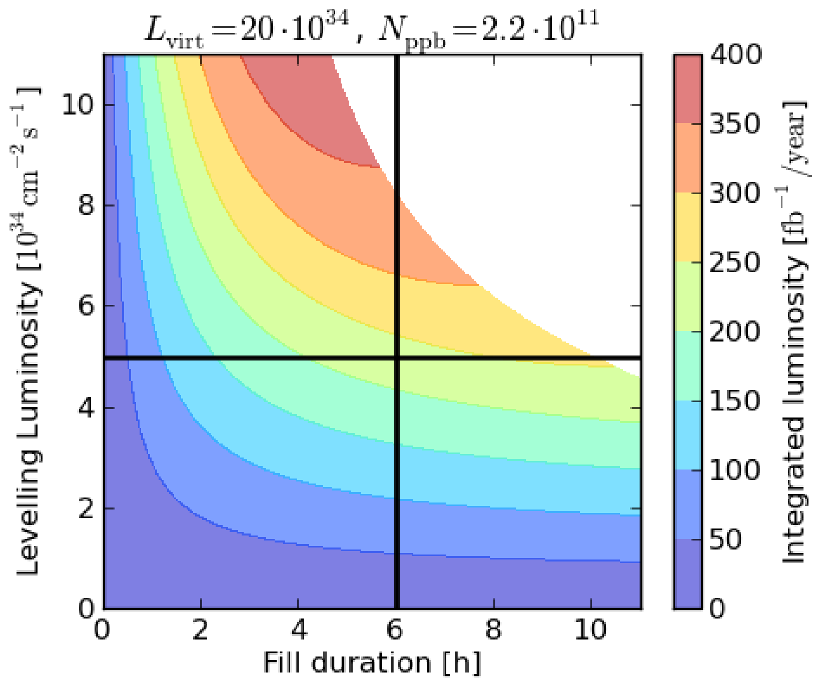
$$L_{\mathrm{int}} = 0.5\, t_{\mathrm{phys}} L_{\mathrm{lev}} \frac{t_{\mathrm{fill}}}{t_{\mathrm{fill}} + t_{\mathrm{turnaround}}}$$

High Luminosity LHC

HL-LHC Performance reach

- Assuming 80 days of successful fills and a given peak luminosity how much luminosity may we integrate in one year?



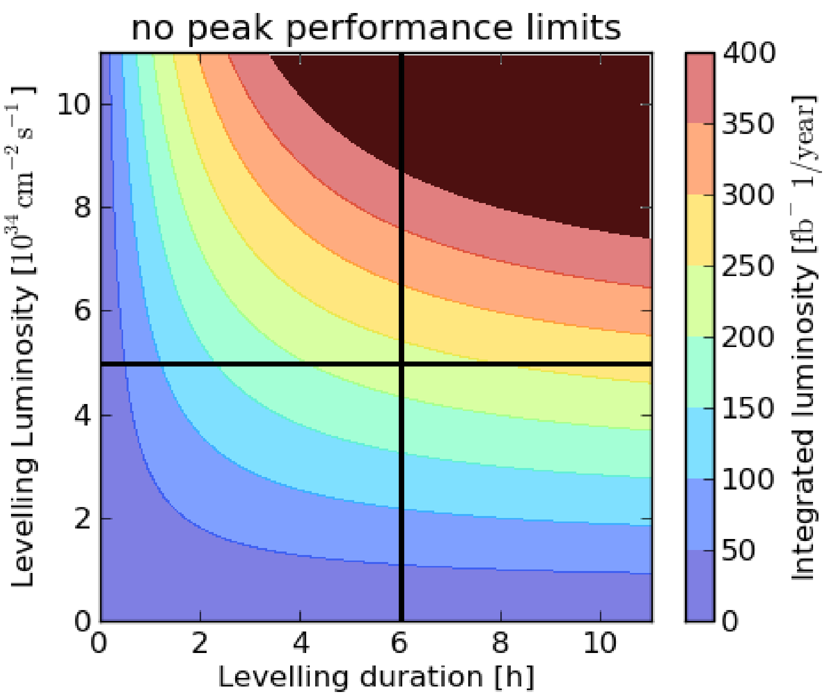


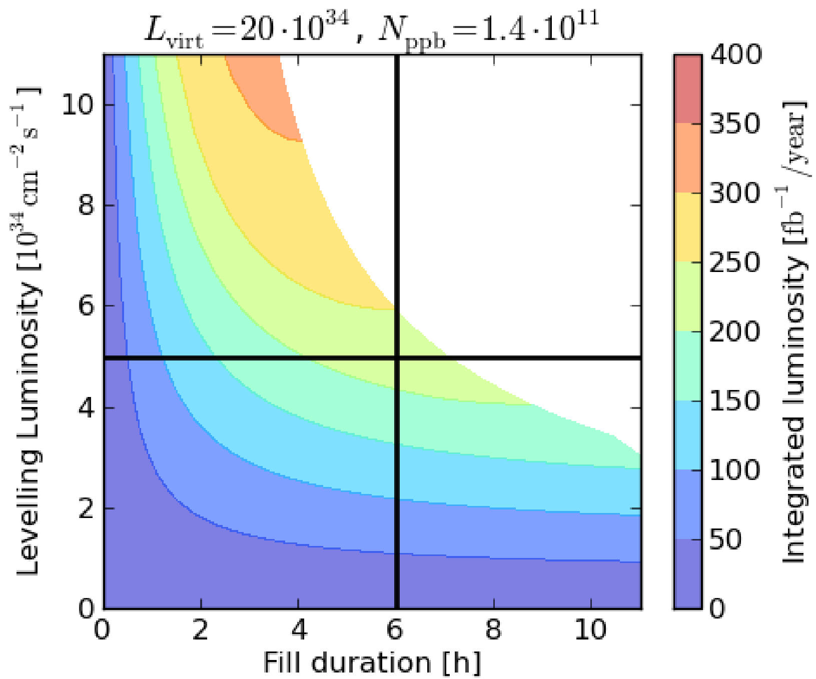
→ Virtual luminosity must be much larger than levelled luminosity to exploit the parameter space, provided reliability will improve.

→ Virtual luminosity is proportional to brightness, but…

Performance reach

- Assuming 80 days of successful fills and a given peak luminosity how much luminosity may we integrate in one year?

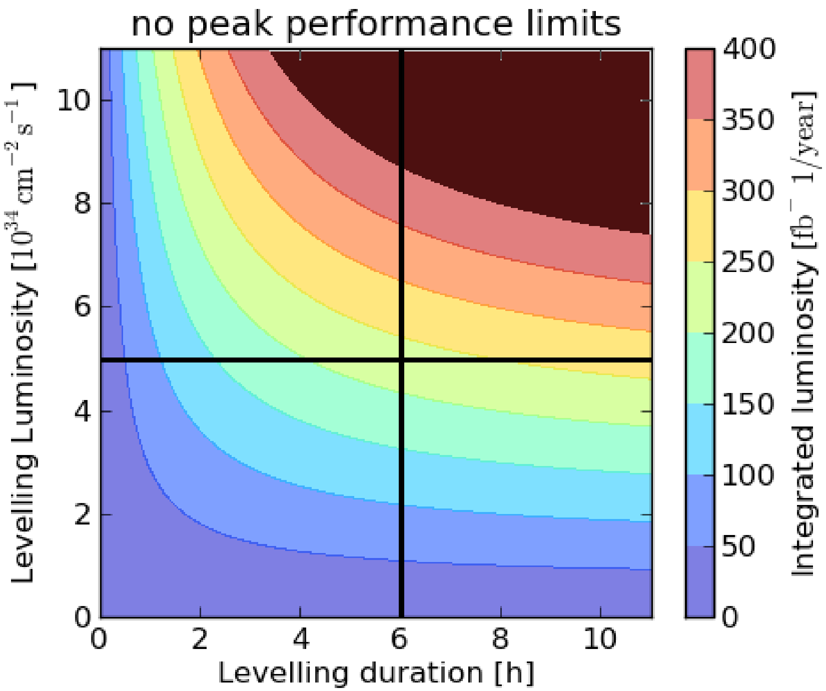


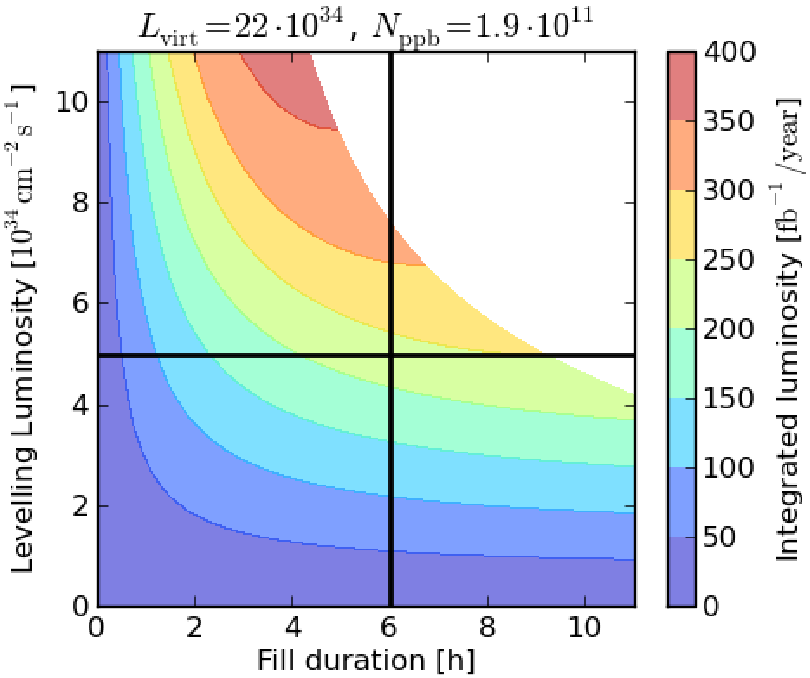


→ … for the same virtual luminosity, the decreasing intensity is less efficient,

Performance reach

- Assuming 80 days of successful fills and a given peak luminosity how much luminosity may we integrate in one year?





→ or even increasing virtual luminosity at the cost of some intensity is not equivalent.

Conclusion

- The LHC and HL-LHC relies on high brightness to fulfil their goals, thanks the upgrade plans and the progress in understanding and circumventing limitations.
- At constant brightness, larger intensity offer the best reach when coupled with long fill thanks to larger luminosity lifetimes that fights against the turnaround time loss.
- Conversely if unexpected beam dumps are very frequent, brightness through low emittance is competitive, if it also contributes to increase reliability.
- However, the brightness gain with emittances is easily lost in integrated luminosity if it comes with less colliding bunches even for large brightness increase and
- strong emittance reduction are also lost early due to IBS.