Integrated performance of the LHC at 25 ns

without and with LINAC4

J. Wenninger

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25 ns @ SPS

Beam type	Scenario	N_{bunch} [10^{11}]	ε^* [μm]	Limit
BCMS	**Achieved**	1.15	1.39	--
BCMS	No upgrade	1.3	1.28	PS/SPS
BCMS+L4	Linac 4	1.3	1.28	PS/SPS
Standard	**Achieved**	1.2	2.6	--
Standard	No upgrade	1.3	2.44	SPS
Standard+L4	**Linac 4**	1.3	**1.65**	SPS

- Only standard beam gains with Linac4.
- Limits after LS1:
  - *Brightness in the PS (BCMS),*
  - *RF in the SPS (all).*

See presentation by G. Rumolo

25 ns @ LHC collisions

Beam type	N_{bunch} [10^{11}]	ε* [μm]	k	β* [cm]	½ Xing angle [μrad]
BCMS (+L4)	1.25	1.65	2590	40 / 50	150 / 140
Standard	1.25	2.9	2740	50	190
Standard+L4	1.25	2.0	2740	40 / 50	150 / 140

- N_{bunch} and ε* : values for LHC collisions.
- From SPS extraction to LHC collision:
  - *Assumed emittance blow up of 15% on top of IBS - optimistic wrt 2012 (~ 30% observed),*
    - *E-cloud-driven and additional 2012-like blow up under control,*
  - *Transmission of 96% (~ 2012 values).*
- Crossing angles: deduced from an analysis by R. Bruce.
- Filling scheme variations may affect k at the level of ~5%.

Pile-up & luminosity limits

- A maximum average pile-up of *45 events per crossing* is used as upper limit (given as rough guideline for 2015).
  - *Based on a visible cross-section of 85 mb @ 6.5 TeV.*
  - *For simplicity it is assumed that we can also level at a pile-up of 45.*

- The cooling of the triplet sets a limit to the maximum achievable luminosity of ***~1.75 ×10^{34} cm^{-2}s^{-1}*** ±10-20%.
  - *We will have to explore the limit in 2015+.*
  - *Further reduction of limit due to e-could heat load?*
  - *A study will be launched to analyze all possible limitations in the triplet (starting with the limiting heat-exchanger).*

L. Tavian @ Evian 2012

Intensity & brightness limitations

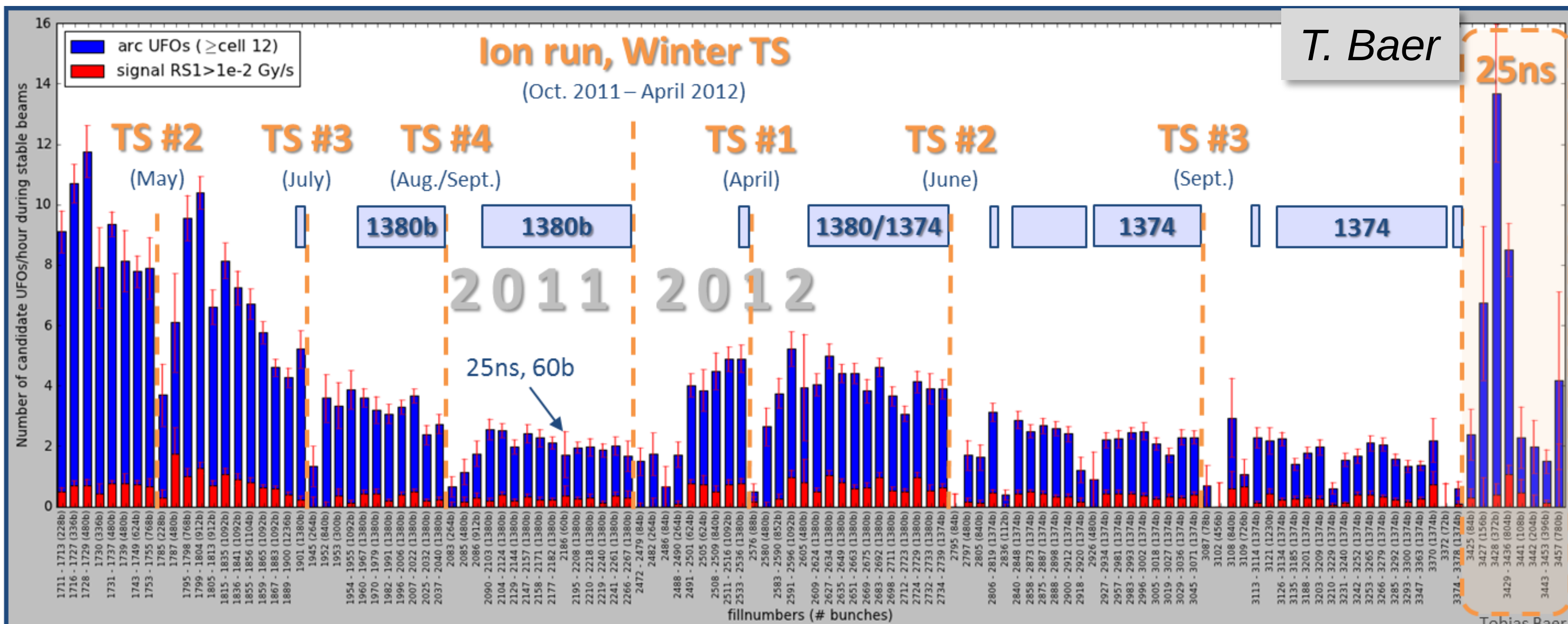
- The intensity/brightness may be limited by instabilities.
  - *25 ns up to 1.3E11 ppb just at the edge?*
  - *Stabilized by head-on beam-beam if needed, but implies more complicated operation.*

- Other possible limitations to intensity:
  - *heating*,
  - *e-cloud*,
  - *UFOs*.

  - more experience must be collected in 2015+.

UFOs

- Extrapolation from 2012 to 7 TeV: ~100 beam dumps from UFOs
- UFO rate depends on bunch spacing, stronger with 25 ns.
  - *But: fast conditioning observed over a few fills in 2012 – there is hope !*
- We have to expect serious deconditioning after LS1.
- Current status of quench test analysis (LBOC meeting 22.10): we may have extra margin (x 2) at 4 TeV for UFO timescales. To be confirmed.
- Clear picture only after 2015.



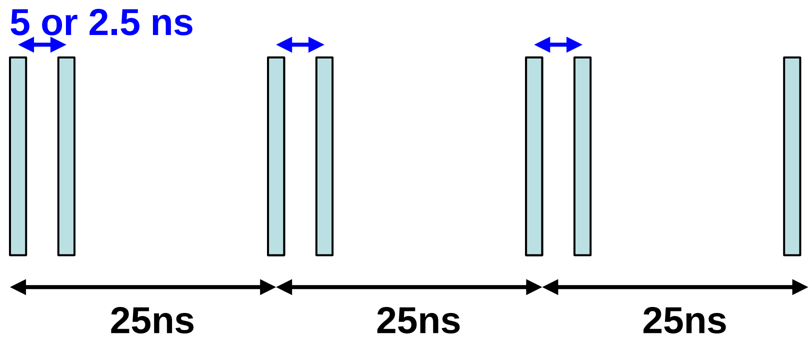
E-cloud in 2012

- Scrubbing
  - Demonstrated to be efficient at 450 GeV
  - It lowers e-cloud in dipoles, less evident in quadrupoles (due to a significantly lower threshold SEY)
- Despite 2-beam-50 ns operation in triplet for ~ 2 years (high electron dose), e-cloud still present in triplets.
  - SEY ~1.2-1.3 – deduced from heat-load & simulations.
- Significant increase of heat load (~ factor 4) in arcs during ramp.
  - From e-cloud in the dipoles. No change in quadrupoles.
  - Does not decrease over time at flattop (no scrubbing at flattop ?)
  - Underlying mechanism to be understood

G. Rumolo at al

E-cloud for 2015

- Available cooling power in the arcs (~ 250 W / ½ cell) will possibly limit (initial) operation at 6.5 TeV.
  - Limitations in SAMs will be lifted during LS1.
- Projection of CURRENT situation to 2015: limitation to ≈ ½ number of bunches at 25 ns (~1400).
- Idea to enhance scrubbing at 450 GeV to remove e-cloud in the dipoles "completely" with dedicated scrubbing beam.
  - Use doublet beam : **5 – 20 ns or 2.5 – 22.5 ns spacing**
  - Implications and issues (BI, RF, ADT) under investigation. Report at the next LHC Beam Operation Committee (5^{th} November).



Run length & overheads

- A run length of 160 days (high int pp) per year is assumed.
- Periods of reduced luminosity are embedded in our runs. Such periods include:
  - *Initial intensity ramp up – few weeks. Likely to improve every year up to an incompressible minimum.*
  - *Ramp up after technical stops: ~ 2 days.*

>> this reduces the integrated luminosity by 5-10%

- β^* leveling setup may be required (and learning curves).
  - *Important to train asap – LHCb !*
- And one should not forget all the special runs like high-beta, LHCf etc that eat up additional few % of the proton runs.

Availability in 2012

- The 2012 run can be split into 3 blocks.
  - *On a per-physics-fill basis we had:*

Stable beams	Faults	Turn-around = the 'rest'
6.1 hours	4.8 hours	5.5 hours

⇔ 36% stable beams fraction / <u>physics efficiency</u>

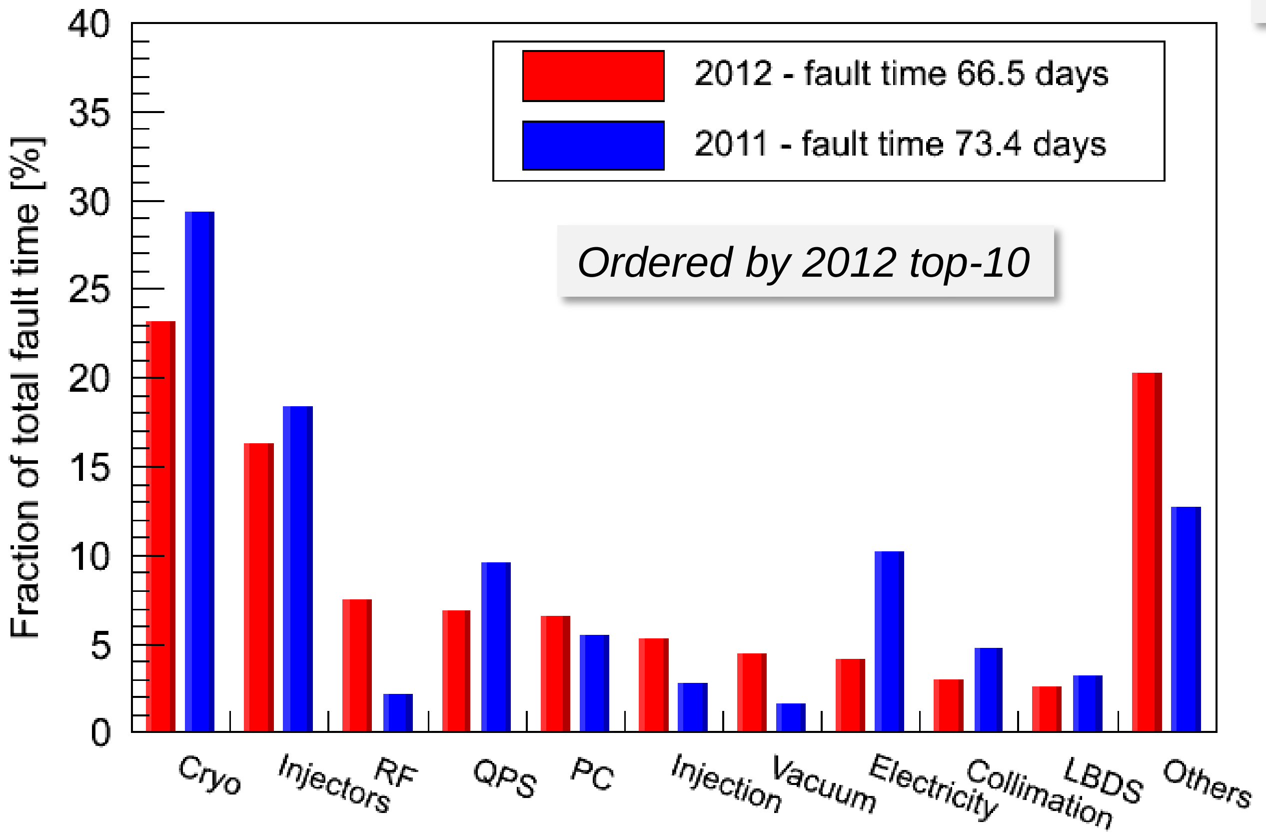
- The blue turn-around box also accounts for
  - *Test cycles (Q/Q' measurements, FB tests, loss maps, high beta setup…) and lost cycles.*
  - *'Short' tests that were inserted in a standard cycles.*
  - *A certain number of pre-cycles.*
  - *Etc…*
  - ***<u>Minimal / best turn-around time ~ 2.2 hours.</u>***

This will always be required !

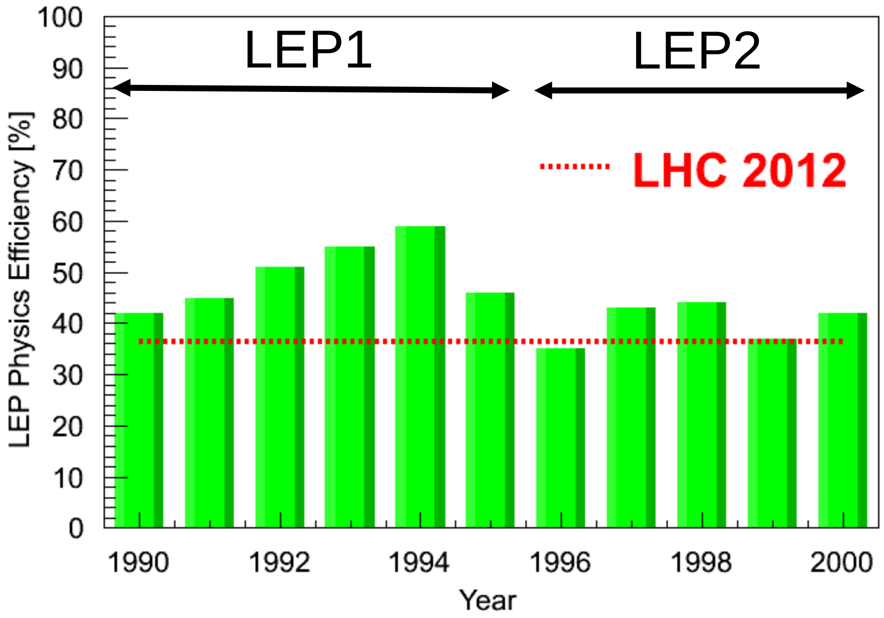
Failure breakdown

- Cryo + injectors account for ~1/3 of fault time in 2012.
  - *Typical SPS efficiency:85 ± 5%.*

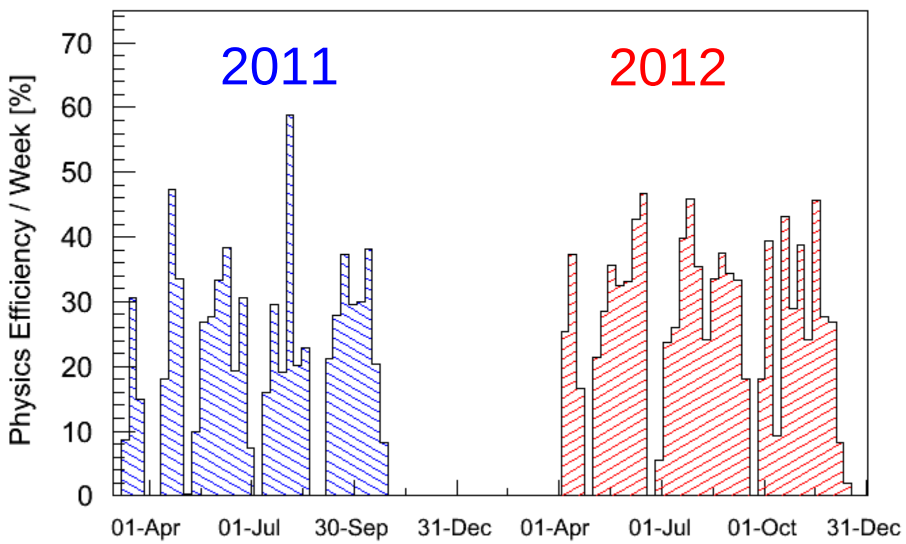
A. Macpherson



Physics Efficiency of LHC & LEP



- LEP1 reached physics efficiencies > 50% (1992-1994).
  - Simpler machine, long fills.
  - LEP2 had short(er) fills – similar to LHC.



- With one exception, best LHC weeks achieved ~45% physics efficiency. Do it more often...

Availability Modeling - future

- Our current accounting of faults & 'turn-around' is rather coarse.
- There is an ongoing effort between AWG (Availability WG) and OP to improve the modeling and information on the different phases.
- Aim to build a tool that combines
  - *Cycle information (beam modes, intensity, energy),*
  - *Post-mortem information*
  - *Fault information,*
  - *Etc*

  … to provide a better model for faults and for 'the rest'.

Work in progress

Availability assumption

- What we know:
  - *The cycle length increases by ~20 minutes.*
- Baseline assumption for performance:
  - *Everything remains the same except for cycle length,*
  - *Assume that in 'Turn-around' there are ~2 cycles → 40 minutes,*

Stable beams	Faults	Turn-around = the 'rest'
6.1 hours	4.8 hours	6.2 hours

⇔ 35% stable beams fraction

- Many uncertainties ⇔ assumptions optimistic for 2015? No point in speculating too much.
- Baseline for analysis: stable beams efficiency of 35%.

Luminosity model

- A simple luminosity model is used for 6.5 TeV, based on 2012 observations during collisions.
- Ingredients:
  - *Burn-off (σ = 105 mb),*
  - *Single beam lifetimes,*
  - *Emittance growth.*

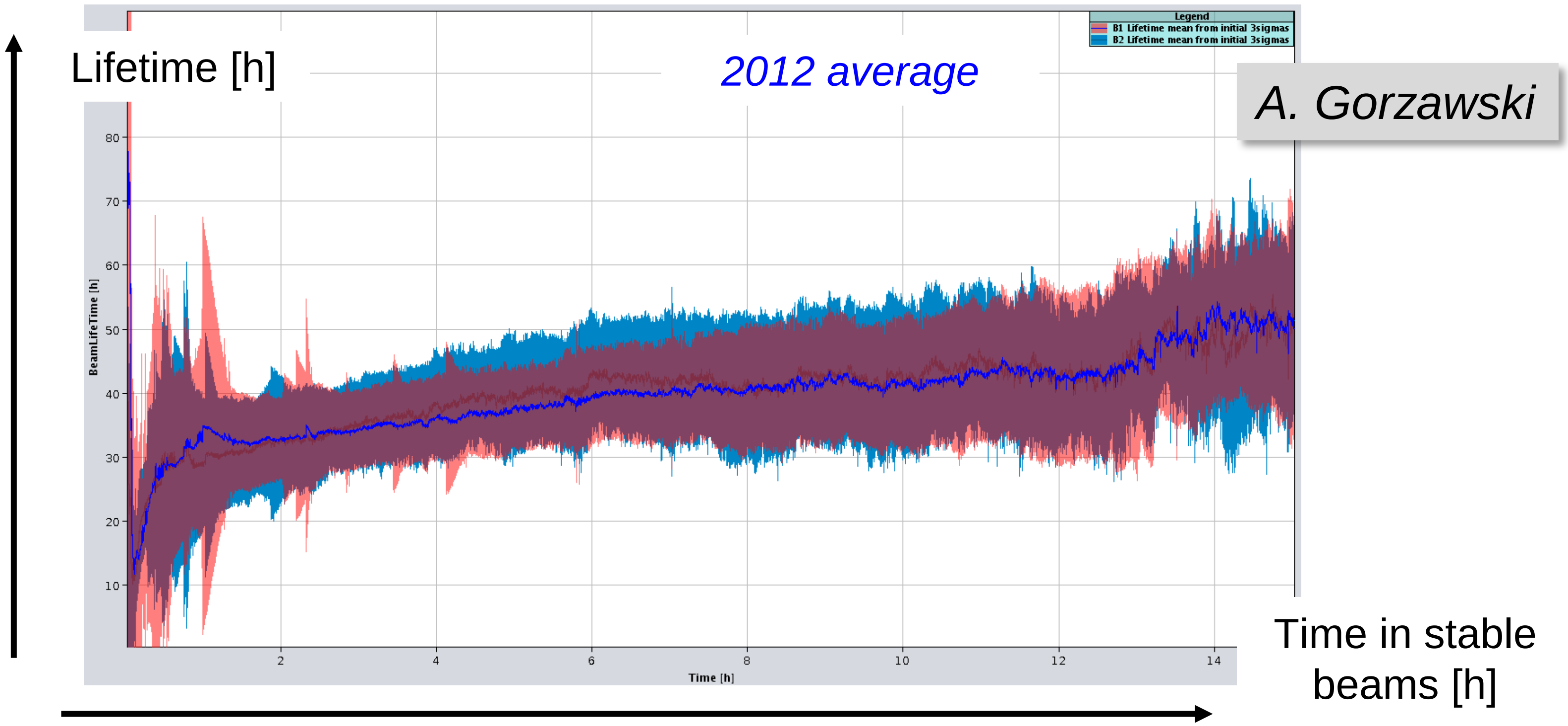
Model dependence of predictions can be > 10%

- Cross-checked with:
  - *Simple analytic approach (simple closed formula) for exponential fill length distribution and constant averaged luminosity lifetime (CERN-ATS-Note-2013-033 PERF).*
  - *Monte-Carlo approach (A. Apollonio).*

Intensity lifetime

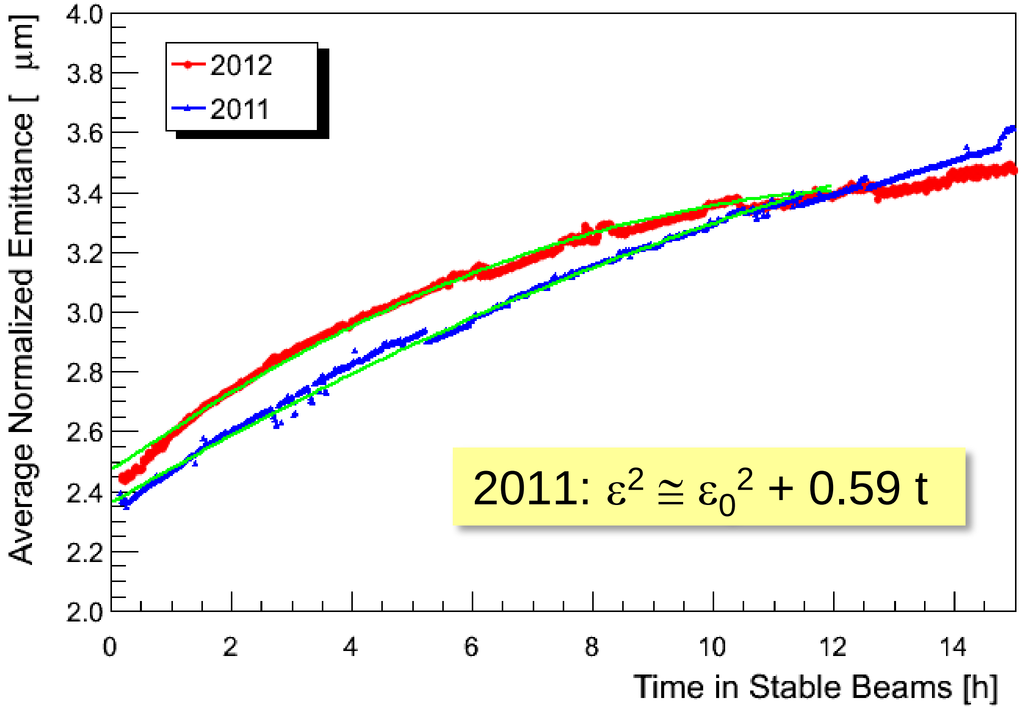
- 2012 beam intensity lifetimes:
  - $\tau \approx$ 25-40 hours in collision (includes burn-off)
  - Before collision tricky to obtain due to large influence of tails in the squeeze.

→ assume 60 hours average intensity lifetime without burn-off.



Emittance growth

- Significant 'effective' emittance growth is observed in collision (from luminosity evolution) at 3.5/4 TeV.
  - *Origin of growth not understood. IBS is not sufficient, need an extra 20 h emittance growth time (→ G. Arduini).*
  - *Growth was steeper in 2011.*
  - *2012 evolution is used to model the luminosity at 6.5 TeV, corrected for radiation damping.*



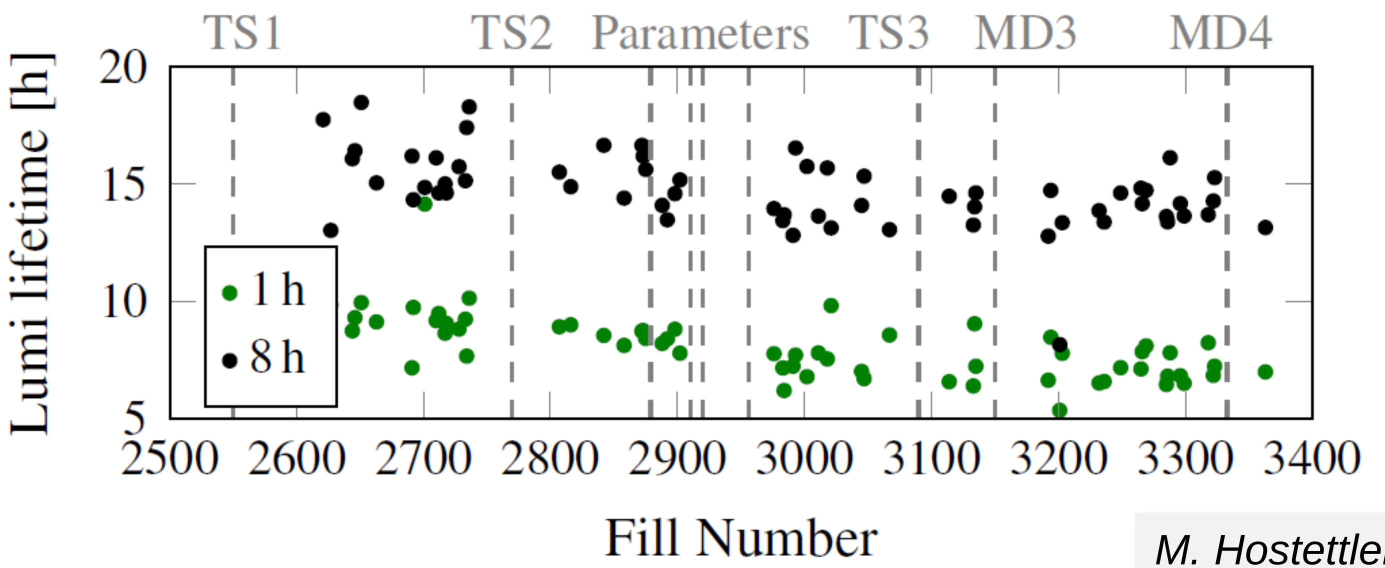
2011: β* 1 m

2012 : after MO polarity switch

A. Gorzawski

- 2012 run experience @ 4 TeV:
  - *$\tau \approx$ 6-8 hours – first hour,*
  - *$\tau \approx$ 12-15 hours – after 8 hours.*

Reproduced by the model

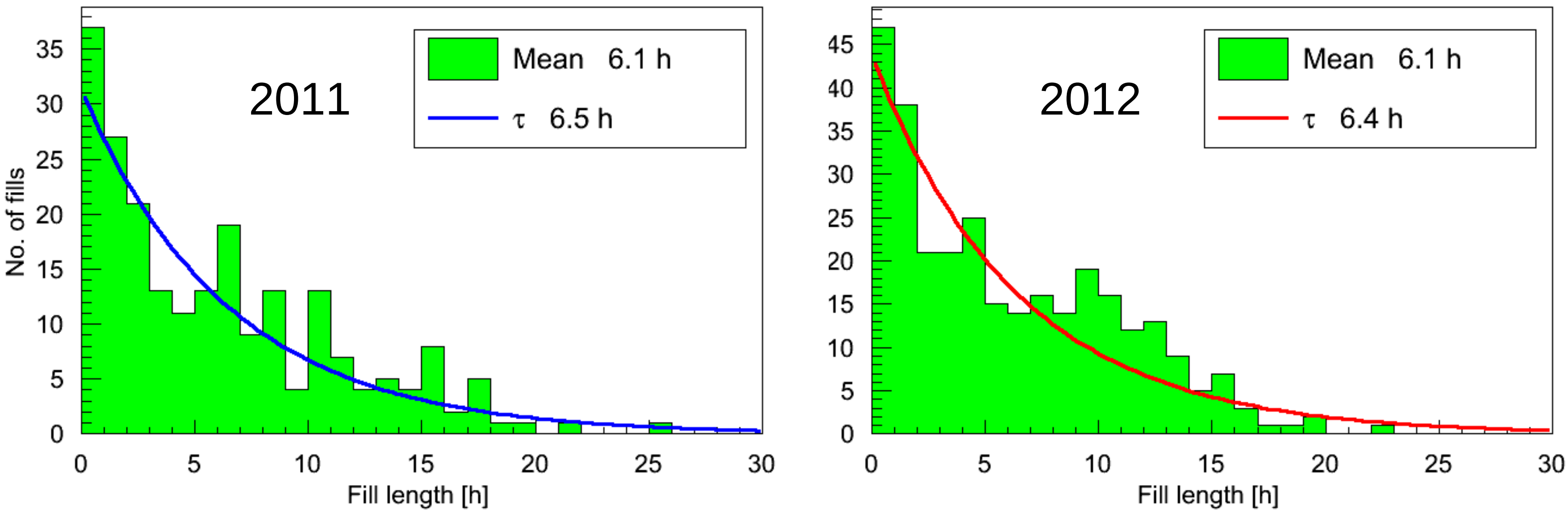


M. Hostettler, G. Papotti

- Luminosity lifetime from burn-off @ 2×10^{34} cm^{-2}s^{-1} + 6.5 TeV :
  - $\tau \approx$ 12 hours.

Fill length

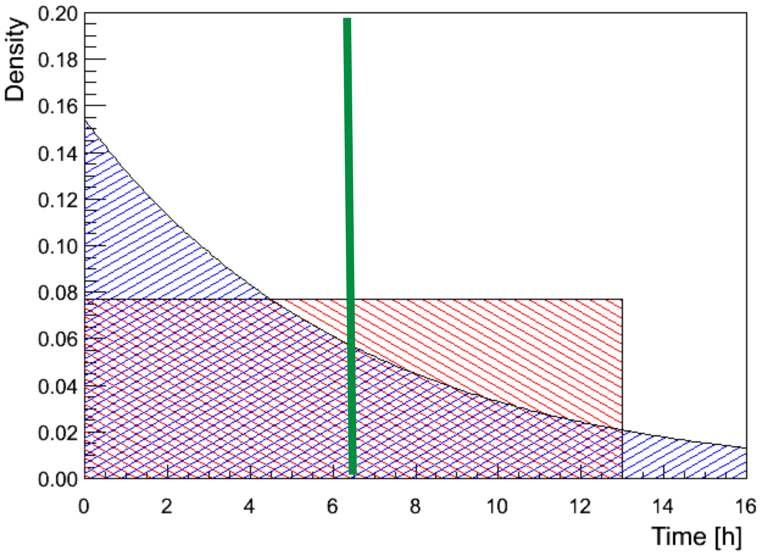
- Fill lengths in 2011 and 2012 $\approx$ exponentials.
  - *~30% of the fills are dumped by OP.*



- An exponential fill length distribution is used for the performance figures quoted in the next slides.

Distributions

- Effect of the fill length distribution:
  - *Exponential (truncated @ 20 hours), flat, delta – mean length 6.5 h in all cases.*



Distribution	Rel. Int. L
Exponential	1
Flat	~1.1
Delta	~1.2

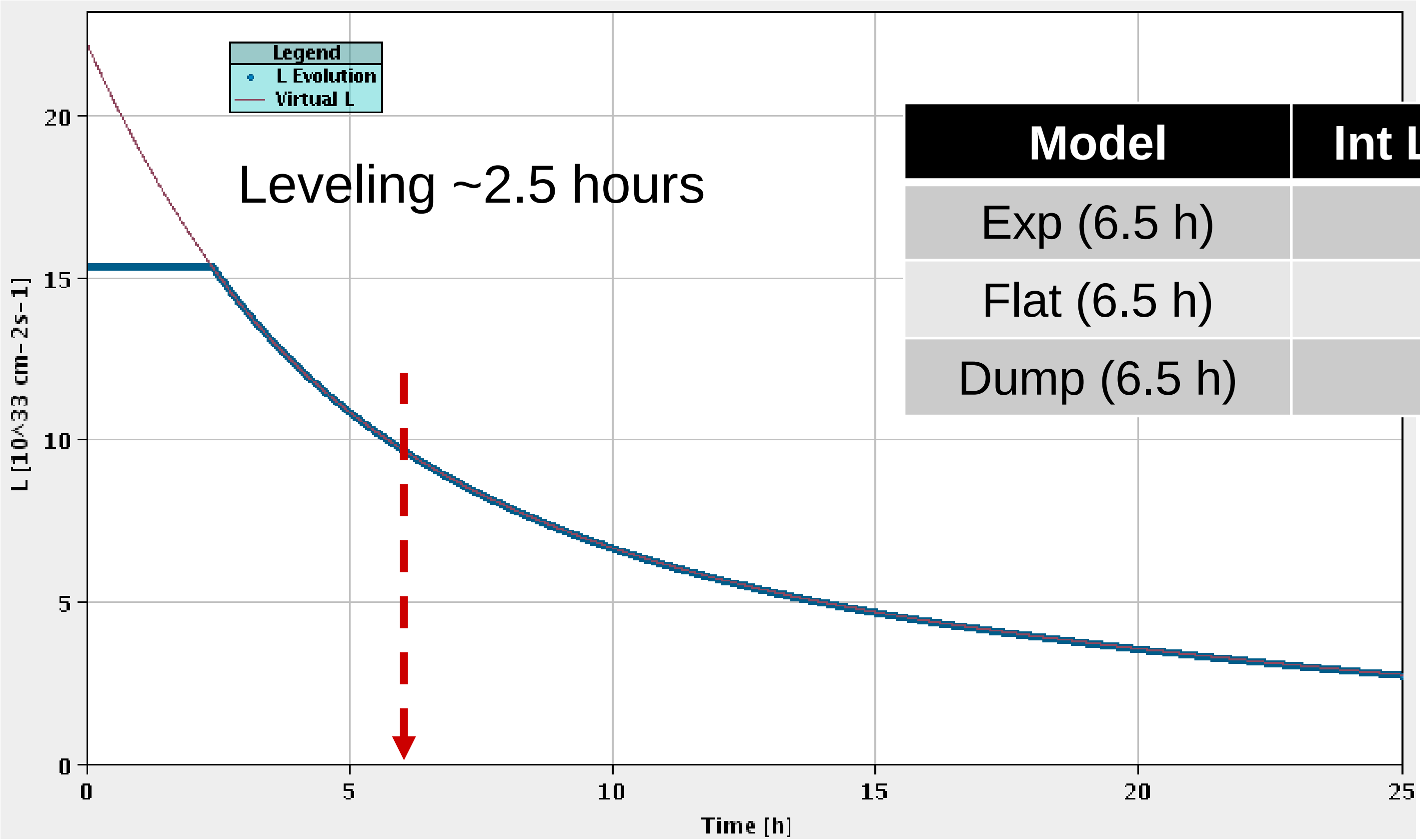
Depends on lifetime assumptions

- Distribution for 2012 is a mixture of:
  - *Exponential – faults (~2/3),*
  - *Flat + smeared delta from OP dumps (1/3).*

+5-10% wrt exponential

BCMS example

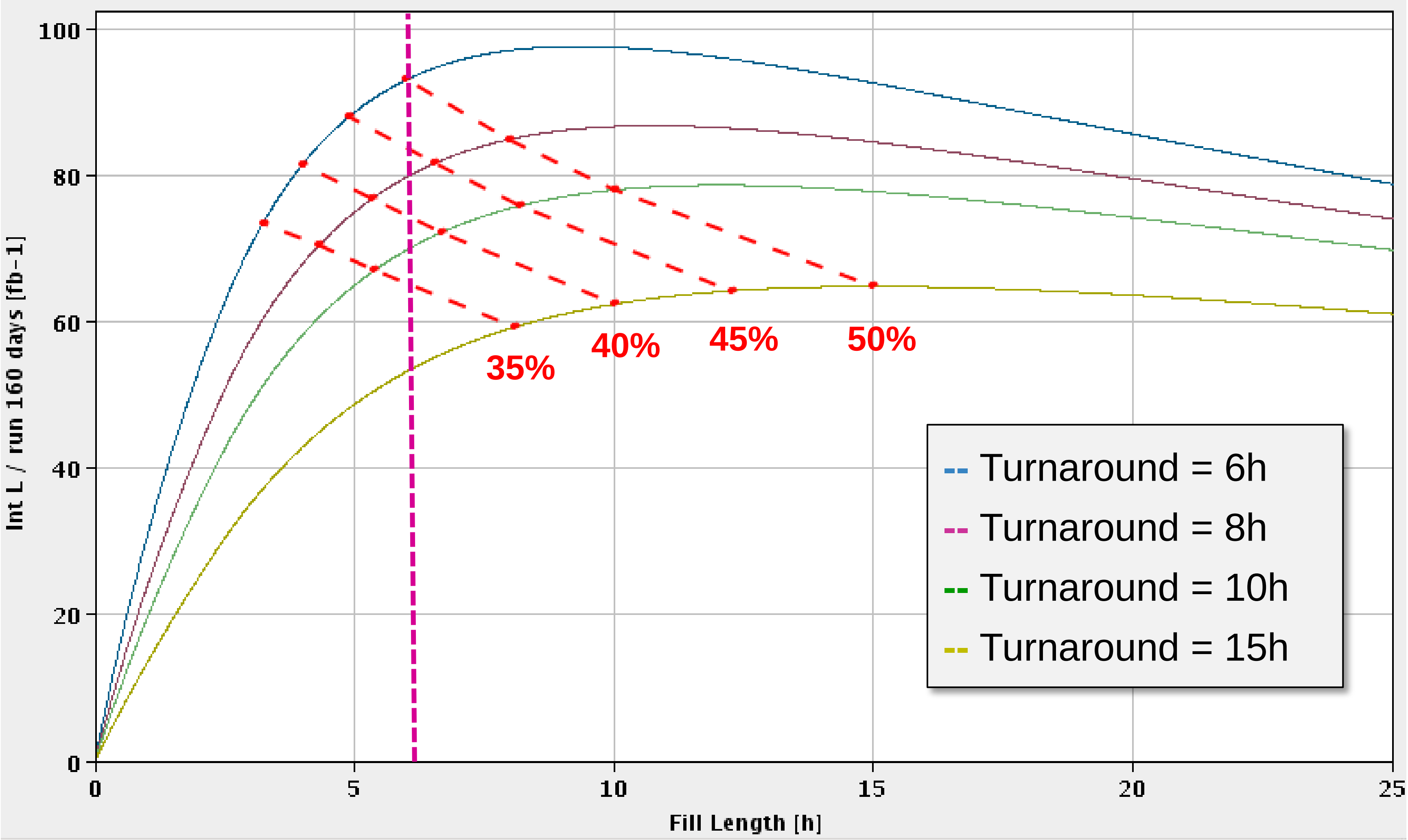
	N_{bunch} $[10^{11}]$	ε^*_l [µm]	k	β* [cm]	½ Xing [µrad]
BCMS (w/wo L4)	1.25	1.65	2590	40	150



Model	Int L/fill (pb^{-1})
Exp (6.5 h)	259
Flat (6.5 h)	283
Dump (6.5 h)	306

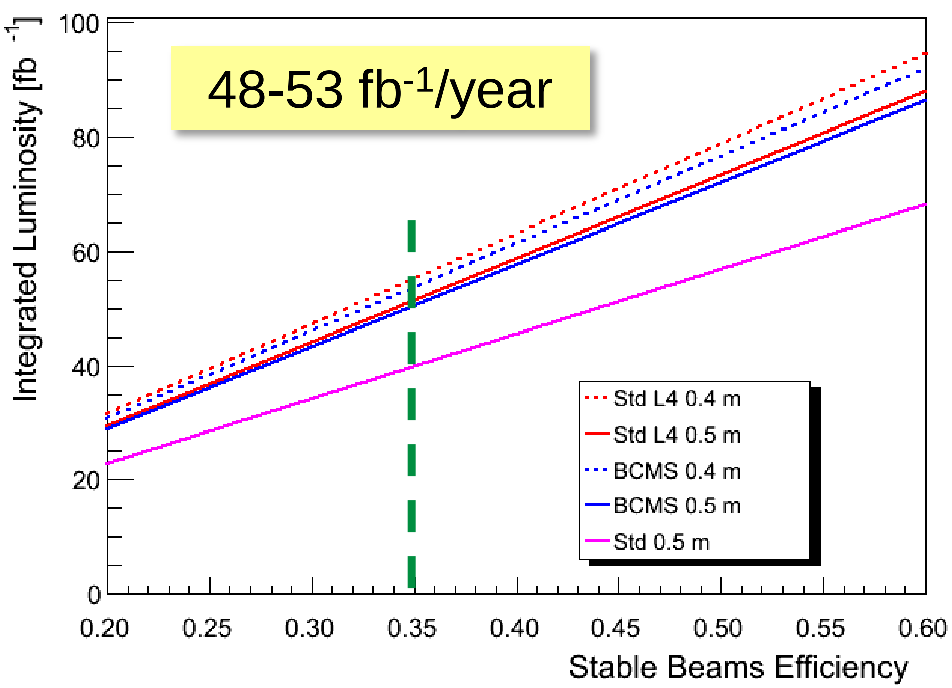
Optimum fill length – BCMS example

- The 6.5 hours dump time is not too far from the optimum ~ 8-10 h.



Comparison – exponential model

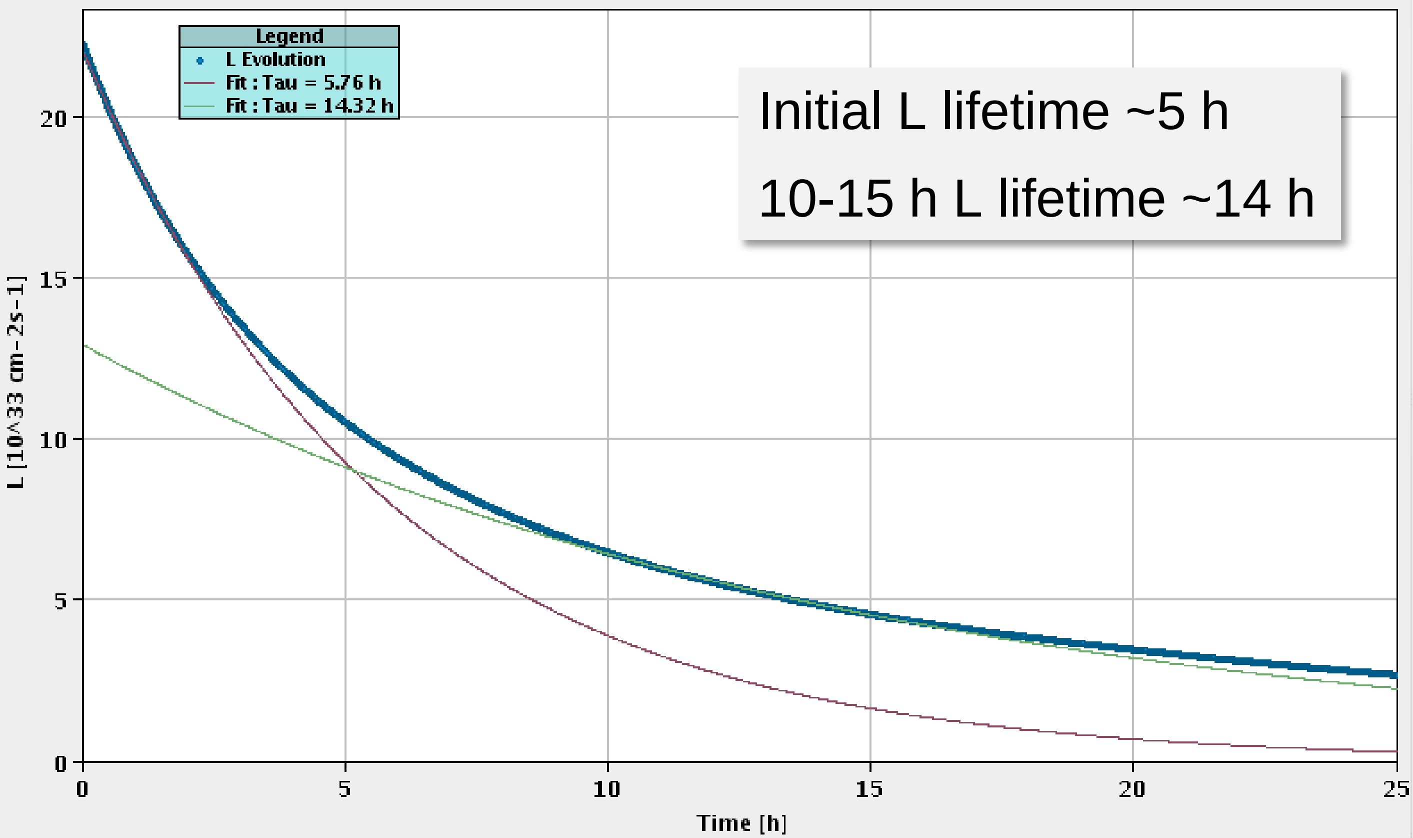
Beam	β* (m)	Leveled L (10^{34} cm^{-2}s^{-1})	Peak L (10^{34} cm^{-2}s^{-1})	Leveling time (h)
Standard L4	0.4	**1.65**	2.1	~1.6
BCMS	0.4	**1.54**	2.2	~2.5
Standard L4	0.5	**1.65**	1.9	~0.7
BCMS	0.5	**1.54**	2.0	~1.6
Standard	0.5	**1.65**	1.2	--



- BCMS & standard are very close in performance.
- Leveled L ~at the triplet limit, peak lumi BCMS / L4 above limit.
- With 2011 emittance model, values increase ~2%.

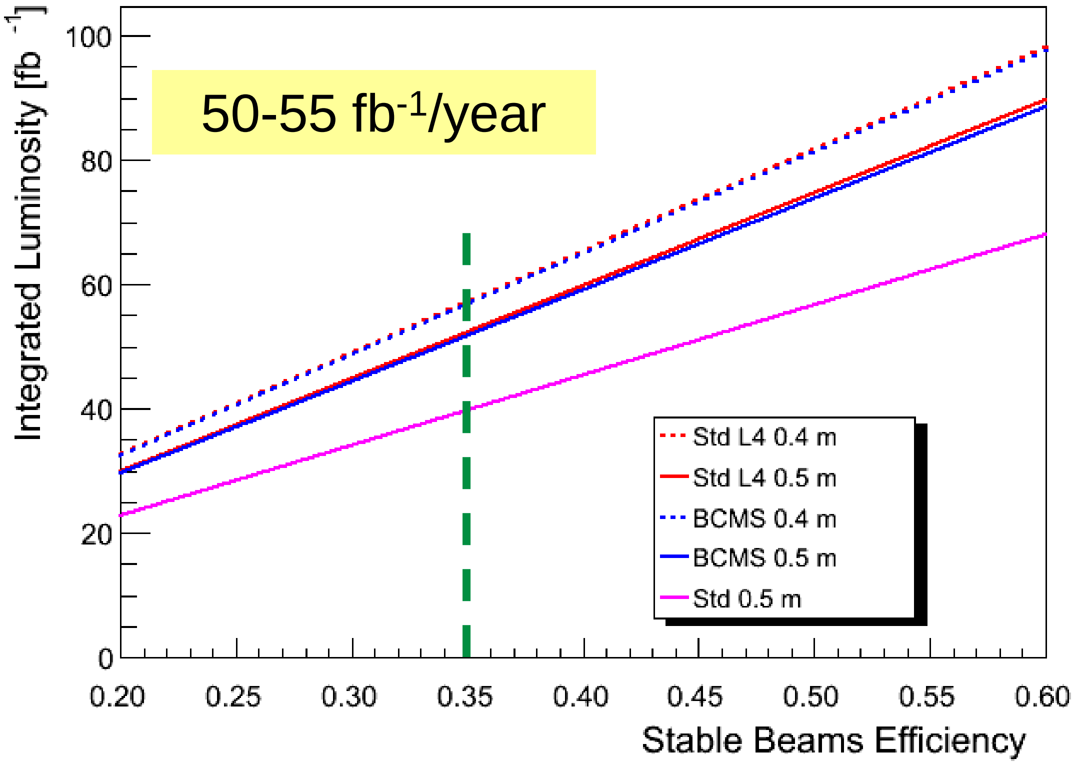
Add 5-10% to account for mixed fill length distribution

	N_{bunch} [10^{11}]	ε^*_l [μm]	k	β* [cm]	½ Xing [μrad]
BCMS (w/wo L4)	1.25	1.65	2590	40	150



Performance – no leveling

- Modest gain of a few fb^{-1} due to short leveling time & low(er) initial lifetime.
- BCMS and Standard+L4 have again similar performance, but higher pile-up with BCMS.
- Peak pile-up ~66 for BCMS and β* = 0.4 m.



Monte-Carlo Model

- Monte-Carlo model by A. Apollonio, developed for HL-LHC, to model luminosity (simplified), failures and turn-around. Applied to 25 ns operation post-LS1:
  - *30% fills dumped by operation,*
  - *6.2 hours of turn-around,*
  - *Fault time modeled by 4 LogNormal distributions.*
- Results are consistent in the range of ~45 fb^{-1}.
- The increased impact of UFOs (~100 dumps/year) can lower the integrated luminosity by 15% for the current BLM thresholds.

Summary (1)

- The expected integrated luminosity per year for 25 ns is in the range of 45-55 fb^{-1} for a 2012-like efficiency.
  - *For 5 ½ years of operation until LS3 → 250-300 fb^{-1}.*
  - *Before L4 : use BCMS – with L4: use standard beam.*
  - *Unknowns on limitations, emittance, efficiency – 10% level effects – situation will be clearer end 2015.*
  - *Peak luminosity close to / above expected triplet limitation !!!!*
- With L4 the standard 25 ns beams and the BCMS beams have very similar performance.
  - *Bonus for standard 25 ns: lower pile-up (~10%).*
  - *The emittances that are eventually achieved may make the difference – easier for standard (larger ε) ?*

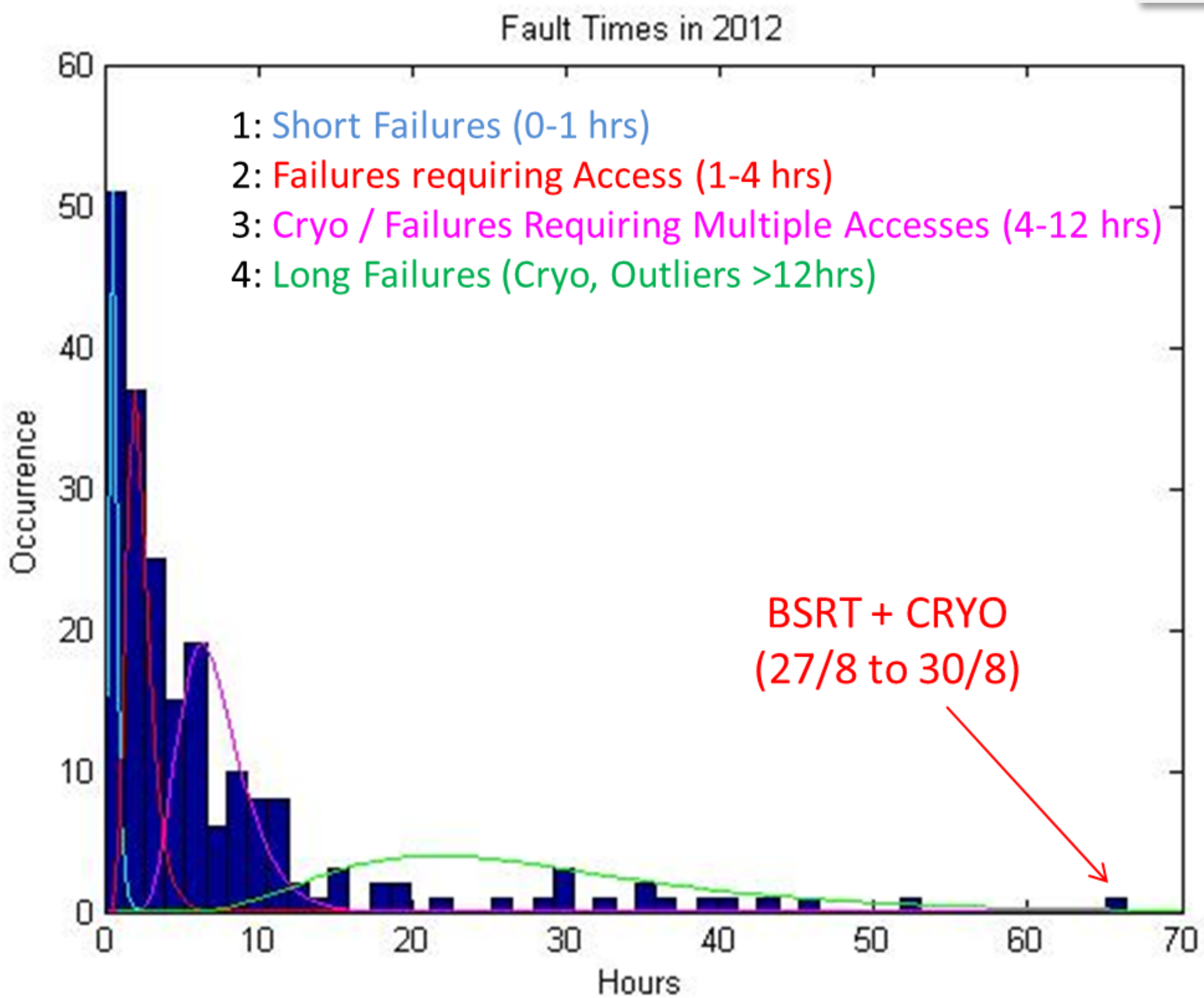
Summary (2)

- To be sure to reach/exceed 300 fb^{-1} by LS3 we should aim to improve the average physics efficiency of the LHC from ~35% to at least 40%.
  - *Concerted long term effort !*
  - *Could reduce peak L / pile-up and compensate with efficiency if we get too close to detector damage.*
- To reach luminosities of 2.5 10^{34} $cm^{-2}s^{-1}$ as quoted in reference figures β^* needs to be pushed further, emittances lowered etc.

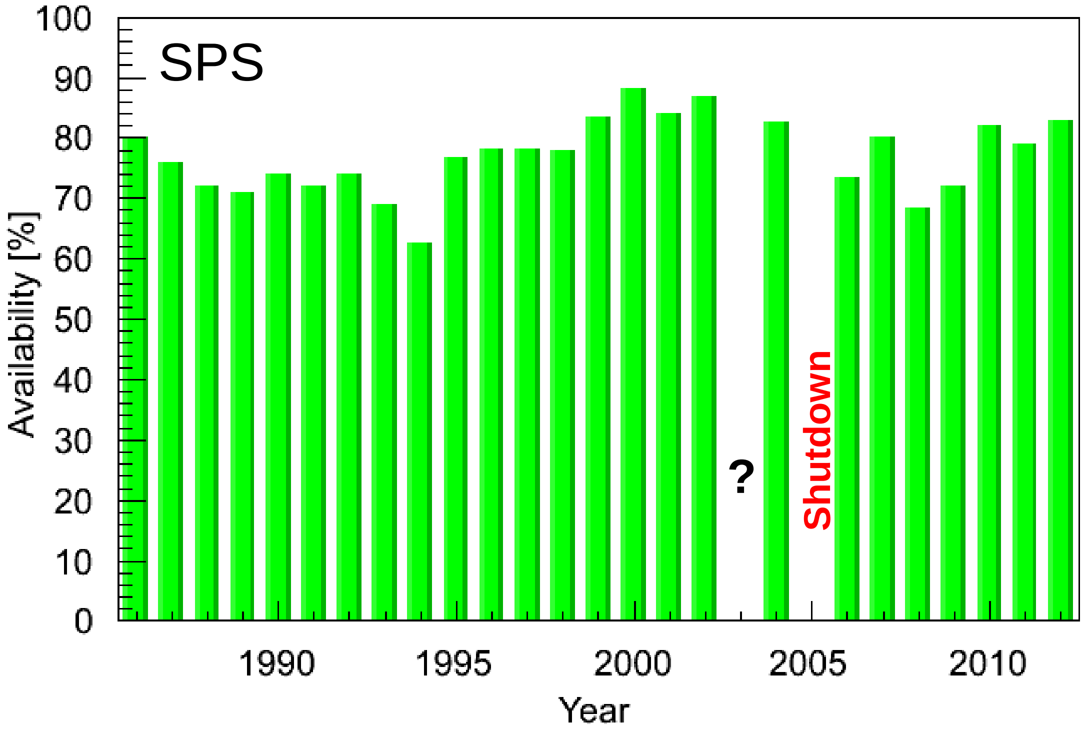
High-Luminosity LHC and Availability

Fault time distributions in 2012 (4 logn):

A. Apollonio



SPS efficiency (fixed target)



Summary: β*-reach

50 ns, 2.5 um	beta* crossing (cm)	beta* separation (cm)	Half crossing angle (urad)	BB sep (sigma)
mm scaled, no BPM	47	49	129	9.3
mm scaled, BPM	39	39	141	9.3
2 sig retraction, no BPM	42	43	136	9.3
2 sig retraction, BPM	35	33	150	9.3

50 ns, 1.6 um	beta* crossing (cm)	beta* separation (cm)	Half crossing angle (urad)	BB sep (sigma)
mm scaled, no BPM	43	49	108	9.3
mm scaled, BPM	35	39	119	9.3
2 sig retraction, no BPM	38	43	115	9.3
2 sig retraction, BPM	31	33	127	9.3

25 ns, 3.75 um	beta* crossing (cm)	beta* separation (cm)	Half crossing angle (urad)	BB sep (sigma)
mm scaled, no BPM	60	49	180	12
mm scaled, BPM	52	39	194	12
2 sig retraction, no BPM	55	43	189	12
2 sig retraction, BPM	46	33	205	12

Updates after MD?

25 ns, 1.9 um	beta* crossing (cm)	beta* separation (cm)	Half crossing angle (urad)	BB sep (sigma)
mm scaled, no BPM	49	49	141	12
mm scaled, BPM	42	39	154	12
2 sig retraction, no BPM	45	43	149	12
2 sig retraction, BPM	37	33	163	12

Summary: β*-reach in crossing plane