Future Wishes and Constraints from Experiments at LHC

- Aspects related to beam-beam -

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Input from all experiments and machine, thanks to
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Outline

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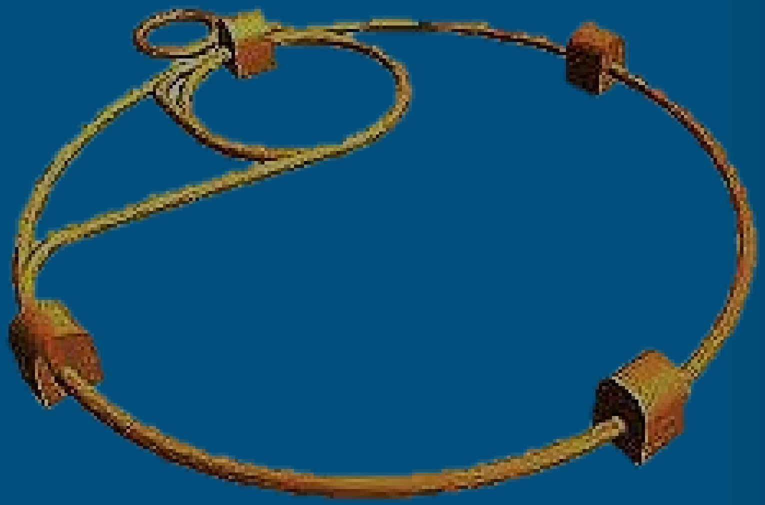
  1. Introduction: Review and maximizing physics
  2. Motivations for limiting luminosity / luminosity control
     - Pileup is very similar to an “allergy”
  3. Overview of the future high-lumi pp-scene
  4. Global requirements and constraints from experiments on luminosity control
  5. Methods of luminosity control and main implications for experiments
  6. Summary

- *Disclaimer:*
  - *Only speak about high luminosity proton-proton program*
  - *Internal discussions in experiments on the future running conditions is ongoing*
    ➔ *Many ideas and works in progress*
  - ➔ *This presentation is an illustration of the principles (requirements) qualitatively*
  - ➔ *Plots serve as illustrations, not ultimate performance*

Definition: μ *is everywhere average number of visible minimum-bias interactions per crossing*
“pileup” is average number of interactions in visible crossings ($\mu/1\text{-}e^{\mu}$*,* $\mu >> 1$ ➔ $\mu \sim$ *pileup…)*
Both quantities refer to a fraction of the total inelastic cross-section which depends on acceptance

Introduction -- Review 2010 - 2012



- Why bother with beam-beam?

Introduction -- Review 2010 - 2012

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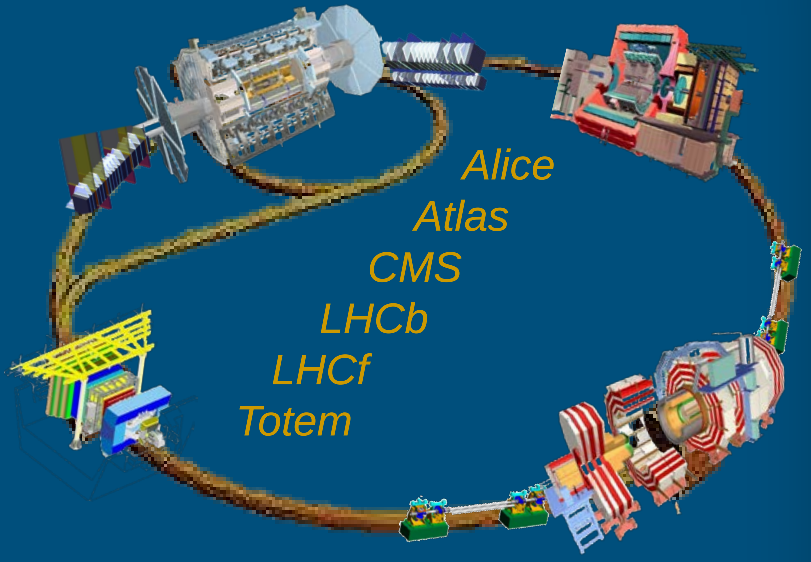
  - Six different experiments with different objectives



Introduction -- Review 2010 - 2012

- Why bother with beam-beam?
  - Six different experiments with different objectives

Introduction -- Review 2010 - 2012

- Why bother with beam-beam?
  - Six different experiments with different objectives
  - Four experiments at three wildly different luminosities
    - $2*10^{30} – 8*10^{33}$ cm^{-2}s^{-1}
  - Tight collimator settings in two IPs
  - Luminosity levelling at intermediate luminosity
  - Luminosity levelling at low luminosity
  - 50ns collision scheme with different number of colliding bunches in the IPs
  - One IP shifted by 11.25m with respect to nominal IP
  - Non-colliding bunches
  - Collision scheme with nominal bunches against enhanced satellites from injectors in 50ns gaps
  - Spectrometer magnets, polarity changes, and the entailing complicated long-range cases
  - Tilted 20^{o}-crossing scheme in one IP
  - ……

  ➔ All at the same time!

  ➔ Rapidly evolving requirements in 2010 – 2012

  ➔ Preparing for collisions and maintaining it stable not an easy task

  ➔ Understanding [origin of] instabilities very challenging

➔ Done successfully providing extremely clean environment

Physics at 13 TeV

- Physics goal 2015 – 2021:
  - "Standard model precision physics"
    - ➢ Search for new physics at higher mass scale in a multitude of channels
    - ➢ Measure Higgs-like boson properties
  - Of course continued direct searches for new particles

➔ Statistics and ultra high data quality

- Note: 8 TeV → 13 TeV natural effect:
  - Minimum-bias cross-section and the associated pileup increases by O(15%)
  - Interesting high-p_T physics goes up by a factor 2
    - High-p_T physics is a small fraction of the minimum bias cross-section
  - Expected overall multiplicity increases O(10%) at $|\eta|<2.4$, O(20%) in LHCb

➔ At equivalent number of bunches and luminosity, events get O(25%) more busy in Atlas/CMS and up to O(40%) in LHCb.

➔ Good confidence on 'guesstimates' but nevertheless unknown domain

- Assume Bunch Compression Merging Scheme:

(25ns-BCMS used in all examples by default unless stated otherwise)

	# bunches	N_{bunch} [10^{11}]	ε_{coll}[μm]
25 ns BCMS (48 bunches/PS batch)	2520	1.15	1.9
50 ns BCMS (24 bunches/PS batch)	1260	1.6	1.6

- Assume n_{bb}(IP1,2,5)=2500 and n_{bb}(IP8) = 2400 for 25ns-BCMS

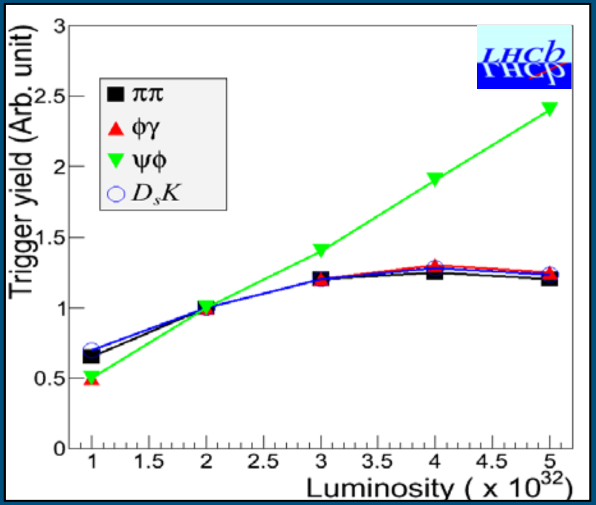
Maximizing Physics

- Stating the trivial:
  - (Peak) instantaneous luminosity isn't all
  - And nor integrated luminosity
    - Depends on machine stability and luminosity lifetime
  - Not even recorded integrated luminosity with good data quality is enough
  - Effective – as in usable for physics - instantaneous luminosity is a key parameter
    - Physics selection efficiency and background rejection depends on experiment resolution as a function of the physics and pileup

    ➔ Physics yield

➔ Usable recorded good data quality integrated luminosity is the key : "Integrated yield"

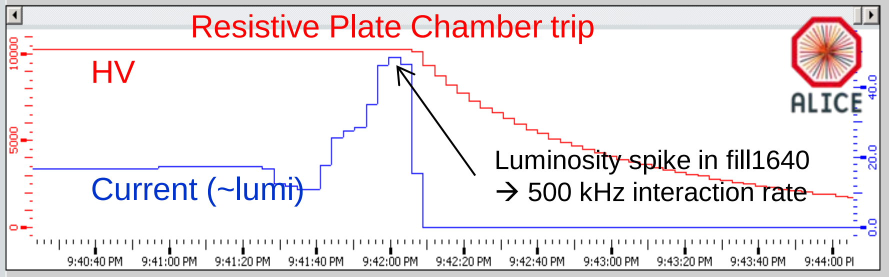
- Can be different for different analyses depending on type of final state and complexity
- Challenge is to find the proper instantaneous luminosity and trigger as the best compromise for all analyses



➔ Whichever mode of operation we chose, it has to be the one which maximizes this obviously

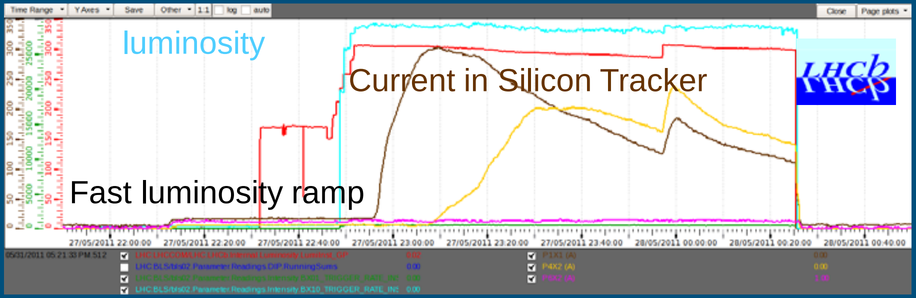
Motivations for Luminosity Control 1

- Possible reasons for luminosity control as the more general case of “levelling”
  - Instrumental limitation or instantaneous damage (Alice gaseous detectors)
    - HV trips impacts data taking efficiency (integrated luminosity) and data quality



Detector limitations

  - Ageing
    - Assumed to be ~linear in instantaneous / integrated luminosity but largely an unknown until it has been measured
    - Replacement program in place based on experience and expected performance
  - Detector conditioning
    - LHCb experienced a phenomenon in this category in 2011 at every beginning of fill



  - Detector performance
    - Degradation in signal yield (spill-over/out-of-time pileup, deadtime, etc)
    - Spill-over (out-of-time pileup) effect is an important parameter in all experiments

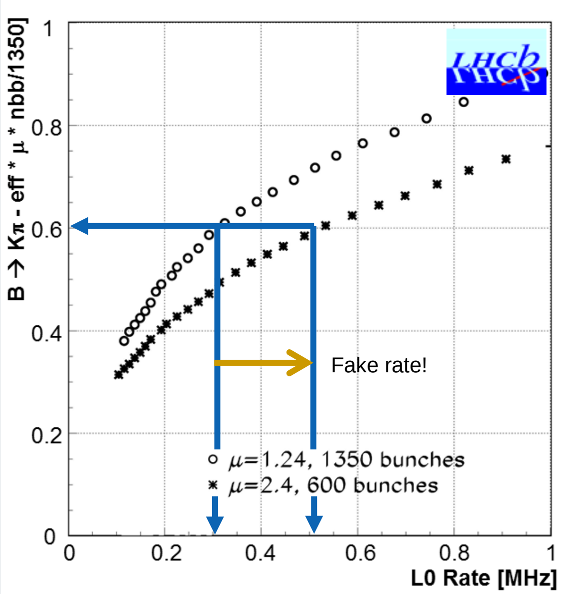
Motivations for Luminosity Control 2

- Cont’d: Possible reasons for luminosity control

Readout limitations

  - <u>Event size limitation in readout</u>
    - ~proportional to pileup + spill-over + background
    - Truncation or deadtime (Alice TPC 100μs gating)
  - <u>Trigger rate limitation</u>
    1. Increase in physics cross-sections
    2. Increase in combinatorics from pileup and spill-over
       - ➔Increases fake rates
       - ➔Increases CPU time in the High-Level Trigger processing
  - <u>Bandwidth limitation in readout</u>
    - Combined effect of trigger rate and pileup

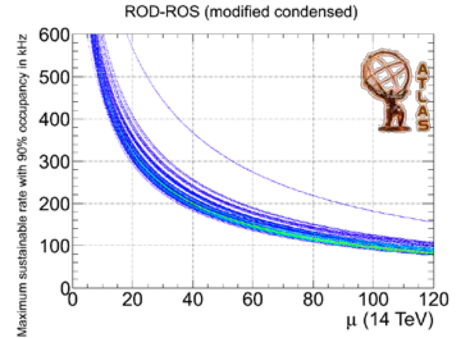
B→ Kπ efficiency at the same luminosity



Processing limitations

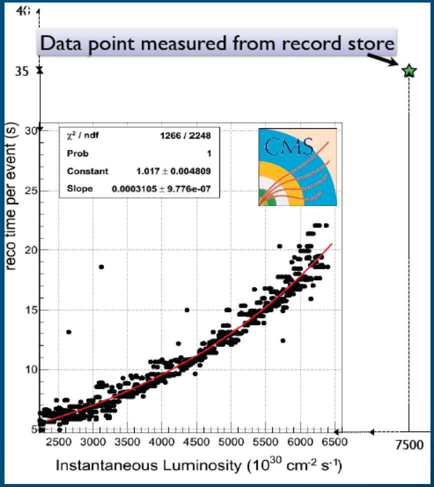
  - <u>Offline processing time</u>
    - Combinatorics in reconstruction

E.g. Bandwidth limitation in Atlas SCT readout with 128 RODs



100 kHz → <μ>~87 corresponding to:
- 3.2e34 $cm^{-2} s^{-1}$ at 25ns
- 1.6e34 $cm^{-2} s^{-1}$ at 50ns

CMS Offline reconstruction

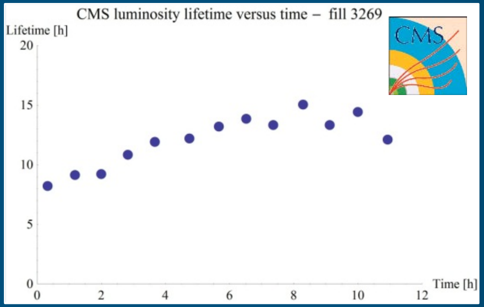


Motivations for Luminosity Control 3

- Cont'd: Possible reasons for luminosity control

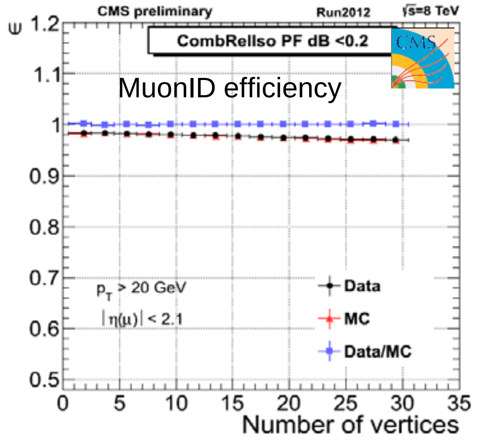
Machine limitations

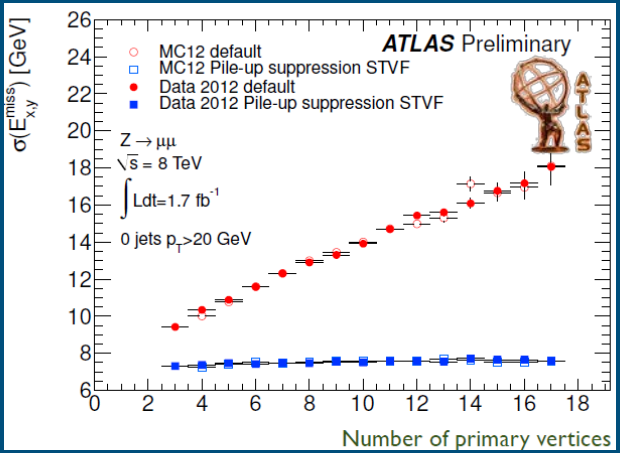
- Machine limitation
  - Luminosity debris
  - Run2: L_{peak} (max) ~ 1.7*10^{34} $cm^{-2}s^{-1}$ ± 20% due to the cryogenic limits in IR1/5
- Maximizing integrated luminosity
  - Potential gain in integrated luminosity by potentially reducing emittance growth and collimation burn-off at peak

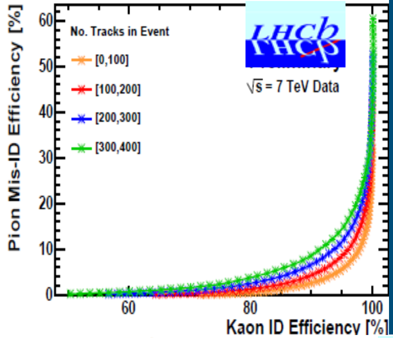


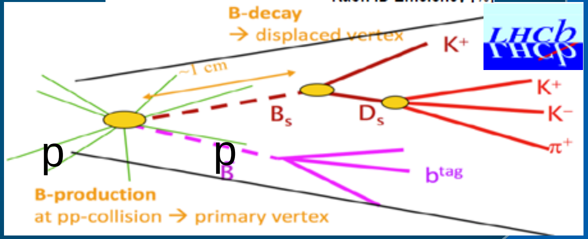
Physics limitations

- Impact on physics
  - Loss of resolutions with higher pileup (vertex, b-tag, tracking, momentum, energy [particle, jet, missing], part. ID, etc)
    ➔ Enormous amount of work has gone into improving and optimizing stability as function of pileup
  - Systematic errors in precision measurements sensitive to changing pileup, trigger, ageing etc (LHCb)
    ➔ Stable running conditions over months

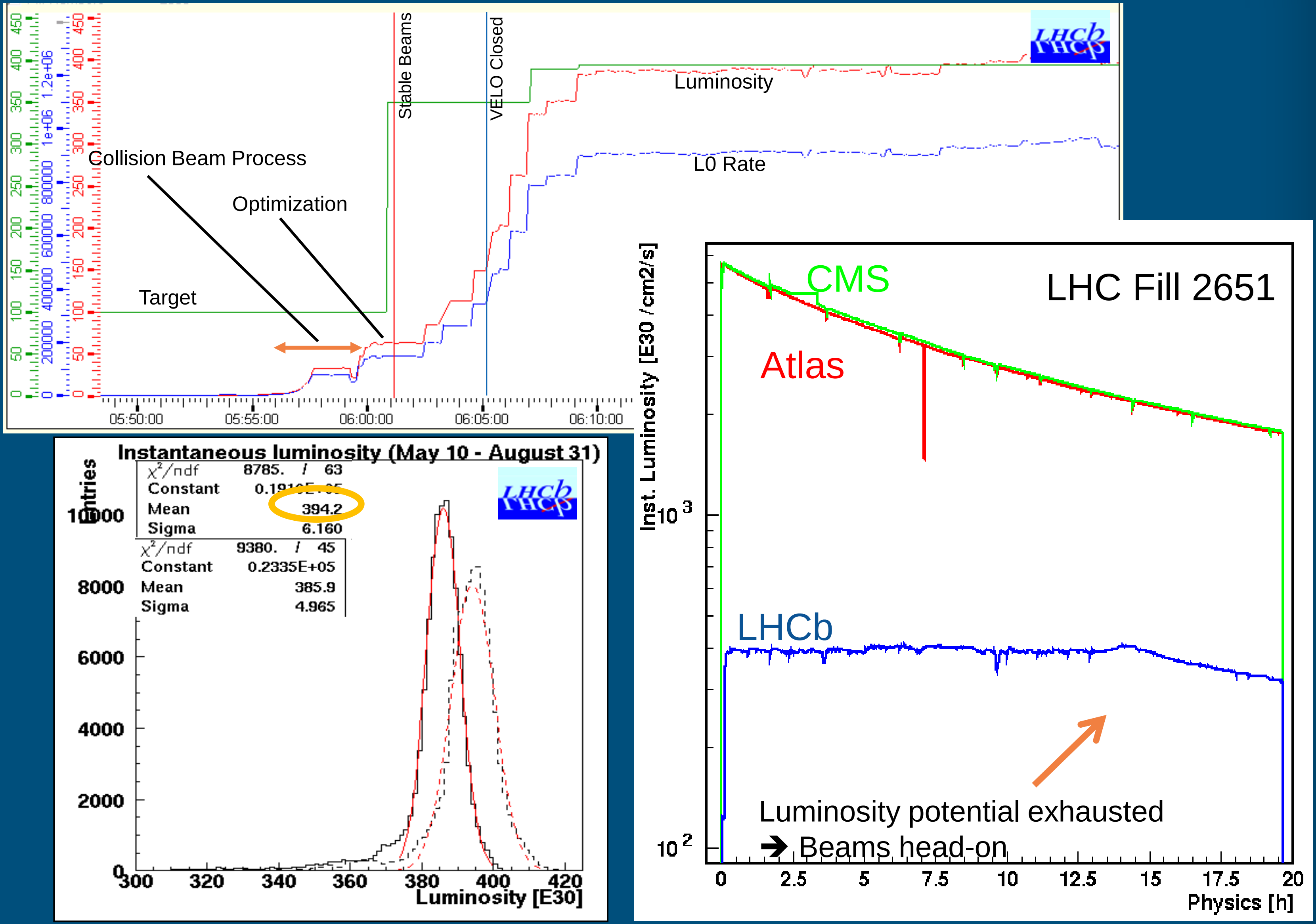








Luminosity Control Illustrated (LHCb)



Luminosity potential exhausted
➔ Beams head-on

95% of the total integrated luminosity was recorded within 3% of the desired luminosity 2011-2012

Future High-Lumi pp Scene (25ns default)

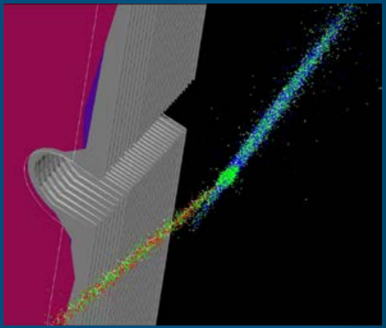
- 25ns is strongly requested by Alice, Atlas, CMS, LHCb and TOTEM
  - ➔ Time should not be spent on 50ns optimization
  - ➔ “Do what it takes” to move to 25ns even at the expense of integrated luminosity in 2015
- 50ns will imply levelling in Atlas/CMS in Run2 and less integrated luminosity for IP1,5,8
  - Caveat: that 25ns is destined to work…

	LS1 2013 2014	RUN2 2015 2016 2017	LS2 2018	RUN3 2019 2020 2021	LS3 2022	2023 -
LHC	Splice and magnet training (Luminosity debris limitation?)	**25ns - BCMS: Lpeak ~ 1 - 2 * E34 @ 13 TeV** #bunches ~2500 **Lint ~ 100 /fb**	Injector upgrade	**Lpeak ~ 2 - 2.5 E34** #bunches ~ 2800 **Lint ~ 300 /fb**	Triplets+crab	**Lpeak ~ 2 * E35** **Lint ~ 3000 /fb**
ATLAS	Trigger consolidation: 100 kHz Increased readout bandwidth Additional pixel detector layer	**Max L ~ 2 * E34 (μmax ~ 60)** At 50ns-BCMS levelling required	Muon inner endcap replacement Hi-precision CALO L1 trigger Fast tracking in L2 trigger Topological L1 trigger	**Max L ~ 2 - 3 * E34 (μmax ~ 55 - 85)**	Major detector upgrade	**Level L ~ 5 * E34 (μ ~ 135)** (Max L ~ 6 - 7 * E34 (μmax ~ 190))
CMS	Detector/trigger consolidation	**Max L ~ 2 * E34 (μmax = 60)** At 50ns-BCMS levelling required	Pixel upgrade (2016-2017) HCAL upgrade L1 Trigger upgrade (2016)	**Max L ~ 2 - 3 * E34 (μmax ~ 55 - 85)**	Tracker and forward upgrades Trigger upgrade	**Level L ~ 5 * E34 (μ ~ 135)**
LHCb	Trigger consolidation New HLT farm	**Level L ~ 4 - 6 * E32 (μ ~ 1.0 - 1.6)** **Lint ~ 5 - 6 /fb**	Upgrade to 40 MHz readout Major detector upgrade	**Level L ~ 1 - 2 * E33 (μ ~ 2.6 - 5.2)** **Lint ~ 20 /fb**	Consolidation	**Level L ~ 2 * E33 (μ ~ 5.2)** **Lint ~ 50 /fb**
Alice	DAQ/trigger consolidation	**Level L~4*E30 (μ ~ 0.01) : 3/pb barrel trigger** **Level L~2*E31 (μ ~ 0.05) : 15/pb μ-arm trigger** (If 50ns: 45 isolated main-main collisions)	Detector upgrade (Si-tracker, TPC with GEMs, electronics upgrade)	**Level L ~ 2 * E31 (μ ~ 0.05)**	N/A	**Level L ~ 2 * E31 (μ ~ 0.05)**
TOTEM	Relocation, pixel tracker + TOF	**Run together with CMS at high lumi** Pots inserted at 5σ(H) and 3σ(V) w.r.t TCTs (~O(1	N/A	**Run together with CMS at high lumi**	N/A	N/A
LHCf	GSO crystal scintillators Radiation damage after 1/fb	**Run in parallel with Atlas at "low pileup" in 2015 up to radiation damage (TS1/TS2).**	N/A	N/A	N/A	N/A

Global Constraints on Luminosity Control

- Prerequisites for luminosity control, ideally…
  - Should be local
    - Controlling luminosity in one IP should have minimal impact on the other IPs
  - Should be individual
    - It is not excluded that even Atlas and CMS may benefit from a decoupled luminosity occasionally
  - Should have minimal operational overhead
    - Re-commissioning, verification…
  - Should not limit flexibility for other configurations
    - VDM scans, etc
  - Should be 'safe' to allow full control in Stable Beams
    - Acting on detector states involves downtimes of O(5) min in all experiments
    - The protection system of each experiment should be developed and tuned to ensure that the detector is protected against too high luminosity or instrumental failure in the levelling
  - Should be relatively fine adjustable <5% and stable (robust)
    - To LHCb the stable running conditions is of particular important – systematics is affected by pileup, and same trigger – precision measurements
    - Optimal running at the limit of the capacity of the trigger/readout introduces dead-time with varying luminosity
  - Should be remote controllable real-time (experiment)
  - Should have minimal effect on machine / beam stability
    - Instabilities are also very costly from integrated luminosity point of view (cmp. 2011 and 2012)
  - The levelling parameter(s) and related quantities should be measurable and monitored
    - Allow in-depth analysis offline

Global Constraints on Luminosity Control

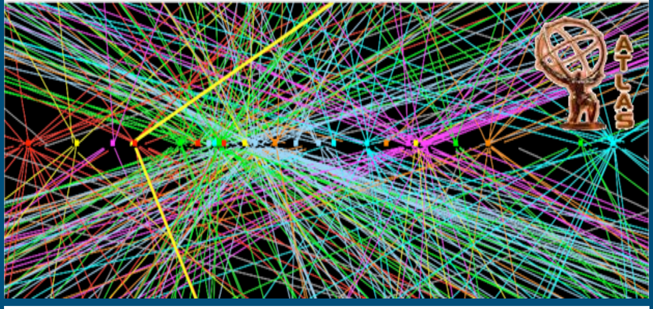


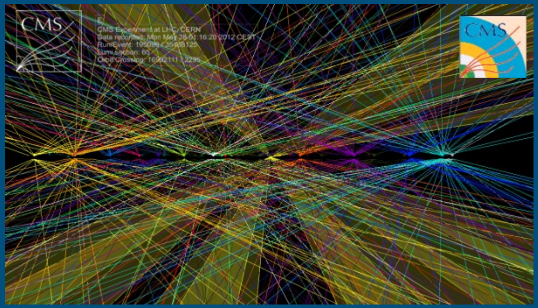
- Should have minimum impact on the luminous region
  - Length/width/position and minimal movement
  - Parameters should be known in advance for correct simulation

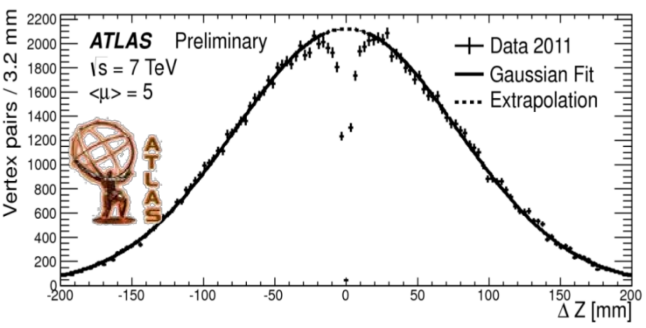
➔ Atlas,CMS,LHCb,TOTEM all depend critically on the length of the luminous region

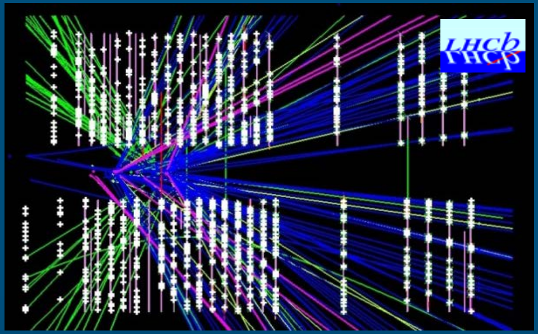
- ➢ Luminous region should be long and stable to dilute the interactions
- ➢ Current ~45-50mm is OK for μ~30-35 but 10-15% increase would improve
- ➢ Find good compromise between luminous region and geometric factor for luminosity
- ➢ Vertex detector acceptance introduces inefficiencies if too long
- ➢ LHCb could benefit from a shift of luminous region upstream (by separation in crossing plane)
- ➢ Studies are underway

➔ LHCb is also sensitive to transverse size ($\Sigma_{x,y}$ ~ O(70 μm)) and limited variation









Methods of Pileup/Luminosity Control

$$L = \frac{n_{bb} * N^2 * frev}{A} * \mathrm{R}(\beta^*, \theta, \sigma_z, \phi_P, \delta_s, \delta_c, \Delta t)$$

- Ways of controlling luminosity (experiment prejudice)
  - Higher bunch crossing frequency (not levelling but as means to reduce pileup)
    - At the same luminosity, reduces pileup by n_b'/n_b per crossing but increases stored energy by $\sqrt{(n_b'/n_b)}$ ….
    - However, no improvement as all crossings take place at the same place and are integrated over 25ns
    - Complete remake of entire electronics!...
  - Cogging (shifting beams longitudinally, Δt)

    👎 Violates the requirement of local and individual control and moves around the luminous region longitudinally
  - Crossing angle θ

    👎 Short and varies length of luminous region

    👎 Collimator and orbit management complicated – even safety aspects to do in Stable Beams

    👎 Limited lever arm

Methods of Pileup/Luminosity Control

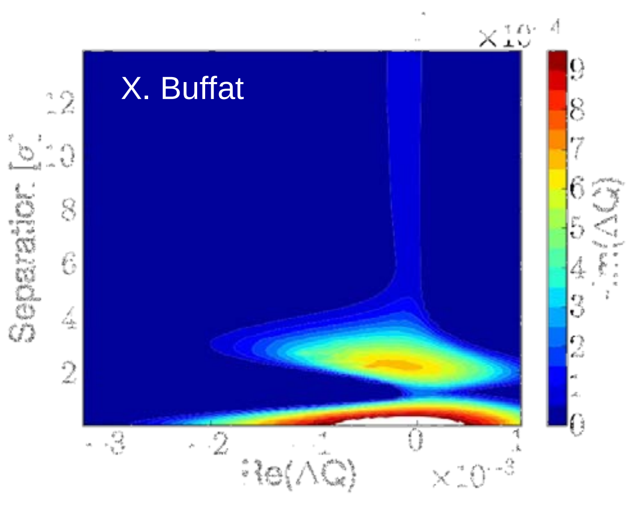
- Bunch rotation with crab cavities (ϕ)
  - 👎 Leveling by crab cavity leads to short and varying length of luminous region
  - ● Stability?
  - ➔ Crab cavities for maximum luminosity is of course vital
  - ➔ Crab cavities maximizes the luminous region longitudinally

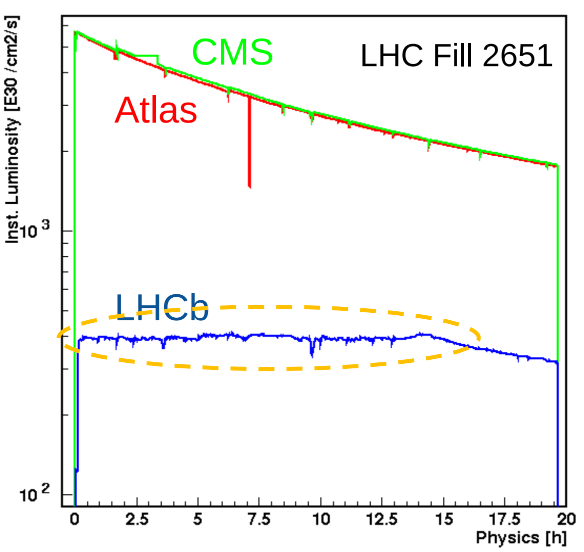
- Piwinski angle ϕ_P (Angle θ + bunch length σ_z)
  - 👎 Angle by external means complicated (as above)
  - 👍 Angle by crab cavity
  - 👍 Compensation for length shortening of luminous region by σ_z
  - 👎 Not local
  - 👎 Limited lever arm

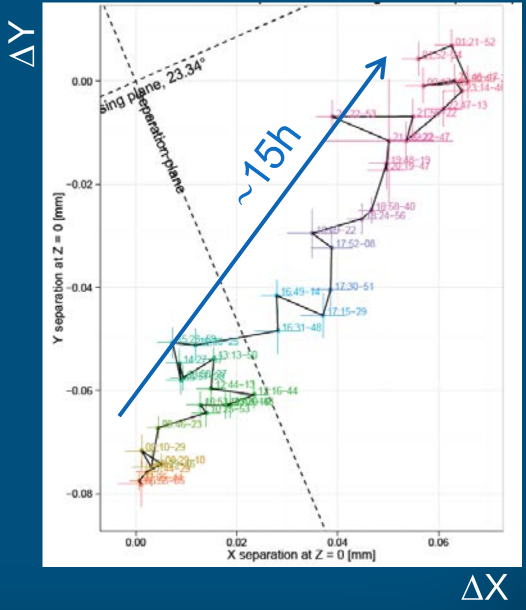
$$L \propto \frac{1}{\sqrt{1+[\frac{\theta\sigma_z}{2\sigma_{x,y}}]^2}}$$

Methods of Pileup/Luminosity Control

- <u>Separation orthogonal to crossing plane</u>
  - 👍 Simple operational scheme
  - 👍 Stable luminous region both longitudinally and transversally
  - 👍 Infrastructure in place
  - 👎 Orbit effects have direct impact on luminosity in an uncontrolled manner
    - ➔ Bunch rattling
  - 👎 Lack of damping is a concern
  - ➔ 2011-2012 experience: origin of instabilities difficult to understand
    - ➔ Impact on integrated luminosity
    - ➔ Levelling by separation always blamed….







Methods of Pileup/Luminosity Control

- Examples of use of separation in the future:
  - Alice @ Run2/3 (β^*=10m and level at $4*10^{30}$ $cm^{-2}s^{-1}$ / $2*10^{31}$ $cm^{-2}s^{-1}$):

    ➔L(head-on) ~ $1*10^{33}$ $cm^{-2}s^{-1}$ (Accidental head-on will lead to dump)

    ➔Separation ~ 5σ / 4σ
  - LHCb @ Run2 (Level at 4 – 6 $*10^{32}$ $cm^{-2}s^{-1}$)
    - IP8 peak luminosity with β^*= 10m and tilted crossing (resulting angle = 340mrad): 9 $x10^{32}$ $cm^{-2}s^{-1}$
    - Leveling lifetime: 8.5h to exhaustion as compared to ~14h now assuming same luminosity lifetime of ~10h

    ➔β^* ~ 5m for 12h "leveling lifetime" ➔ $L_{head-on}$ ~ 1.9 * 10^{33} cm^{-2}

    ➔Separation ~ 2 – 2.5σ → 0σ
  - LHCb @ Run3- (Level at 1 - 2 * 10^{33} $cm^{-2}s^{-1}$)
    - β^* ~ 3m for 12h "leveling lifetime" ➔ $L_{head-on}$ ~ 5 * 10^{33} $cm^{-2}s^{-1}$ (head-on likely to lead to dump by triplet BLM)
    - Separation ~ 2.5σ → 0σ
  - Atlas/CMS @ Run2 (Level at e.g. 1 * 10^{34} $cm^{-2}s^{-1}$, pileup limitation at 60, in case of 50ns BCMS)
    - β^* ~ 0.4m ➔ Separation ~ 1.3σ → 0σ
    - Orbit variation of ±1um at IP changes luminosity/pileup by ±8%

Methods of Pileup/Luminosity Control

- beta* control
  - 👍 Stable luminous region longitudinally (except for h-glass effect) and limited variation transversally
  - 👍 Flat beams head-on in crossing plane – alternative crossings in IP1(V) / IP5(H) should provide beam stability
    - ➔ Potential benefit with small and stable transversal size of lumi region
  - 👍 More immune to orbit variations
  - 👍 No accidental head-on's
  - 👎 Beam-beam tune shift may be at the limit with head-on collision in 3 IPs
    - ➔ High pileup MDs shows no limit yet at 0.05 with two IPs (G. Trad)

Questions

- Possible to have tolerance on collimator settings (limited movement) vertically in IP5 and IP8 during beta-squeeze (?)
- What about IP1 with presumable tighter settings horizontally as protection against asynchronous dumps?
- Collimator needs to follow change of orbit during beta-squeeze, use collimators with BPMs?

- Pure smooth control of β^*?
- Alt. progressive beta squeeze + separation ($<1\sigma$) in plane orthogonal to crossing plane to stay at optimal luminosity
  - Interpolation is possible for optics and collimators to avoid setup and validation?

Methods of Pileup/Luminosity Control

- Examples of use of dynamic β^* in the future:

  - LHCb @ Run2 (Level at 4 – 6 $*10^{32}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
    - $\beta^*_{crossing}$ ~ 20m ➔ $\beta^*_{\perp}$ ~ 30(20)m → 3m

    ➔ Inject at larger beta* ~ 20m ? What about triplet aperture with tilting at injection?
  - LHCb @ Run3 - (Level at 1 - 2 * 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
    - β^* ~ 3m ➔ $L_{head\text{-}on}$ ~ 5 * 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (head-on likely to lead to dump by triplet BLM?)
    - $\beta^*_{crossing}$ ~ 3m ➔ $\beta^*_{\perp}$ ~ 30m → 3m

  - Atlas/CMS @ Run2 with 50ns-BCMS and $\beta^*_{crossing}$ ~0.4m
    - E.g. assume limit is $1*10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, that is pileup of 60 as limit ➔ $\beta^*_{\perp}$ ~ 1.6m → 0.4m
    - Assume a luminosity lifetime equal to running at peak ➔ Levelling for 4.7h (potentially more by less growth)

  - TOTEM: Beta* levelling adds complication as they have to correct for optics

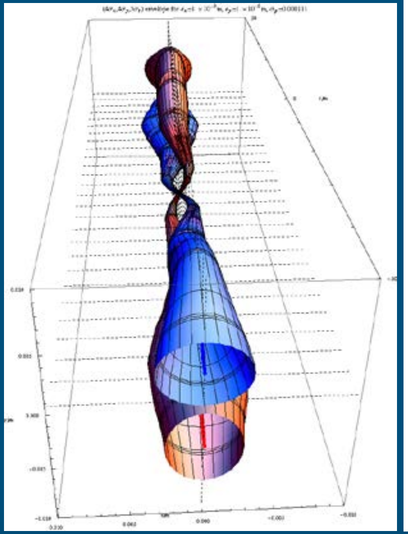
Other requirements

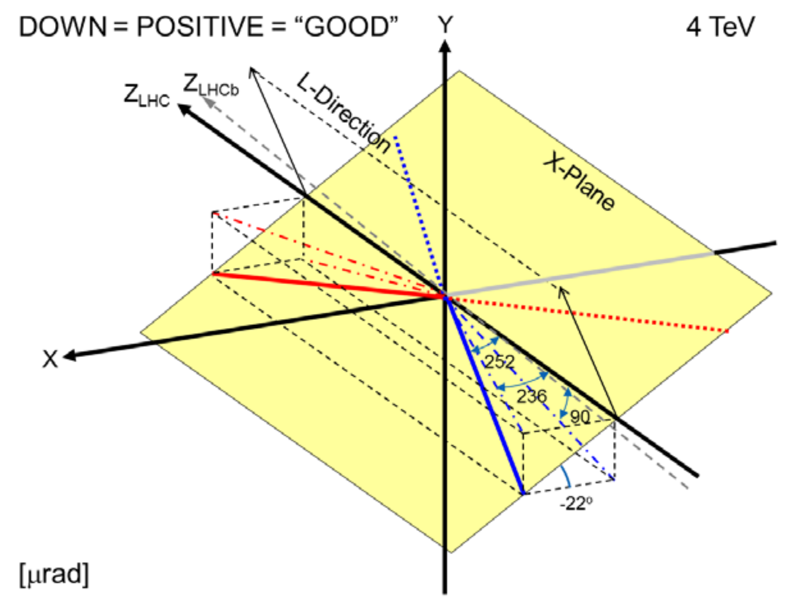
"Miscellanea"

- Atlas/CMS/Alice
  - Ideally a few non-colliding bunches
    - Physics background and luminosity subtraction
  - ➔ A reduced injection with shifted train, the loss in number of colliding bunches to be checked

- LHCb
  - LHCb operating with vertical external crossing angle to maintain tilted crossing scheme
    - Same boost vector amplitude in both polarities
  - LHCb polarity swaps as now
  - LHCb gets non-colliding bunches by construction

- Alice
  - Alice polarity reversals





Conclusions 1

All:

- 25ns is a must
  - No optimization at 50ns in 2015, take the time to make 25ns work instead
  - We'll all be commissioning the new trigger in 2015 for 25ns operation
- Longitudinal luminous region should be long and stable

Atlas + CMS +TOTEM:

- A priori, levelling is not expected to be needed for Run2 (Run3)
  - Assumes 25ns operation
  - ➔ Vital for physics
- ➔ Preparations for levelling should be made for Run2 already
  - Problems with 25ns
  - Trigger preparation insufficient (alternative is reoptimization with unavoidable efficiency loss in some channel(s))
  - LHC going beyond 2E34 (e.g. improved emittance control, miracles in bunch intensity, etc…)
  - The unexpected!
  - Levelling is also needed for HL-LHC – operational experience
- Wish for a handful of non-colliding bunches

LHCb:

- Luminosity control required in all cases
  - ➔ Physics optimization
- Tilting and polarity swaps as now

Alice:

- Take pp data during good fraction of the year with levelling (separation OK)

Conclusions 2

LHCf

- Will only run for a limited period in 2015
- Need special run very early during commissioning of 50ns
- Take data at low pileup in parallel with Atlas up to 1 /fb

- Seems important to have the levelling by β* option for IP1/5/8
  - ➔ Could LHCb be development platform?
  - ➔ Leveling by separation exist by default…

- Disfavors the availability of a mixed scheme only
  - I.e some IPs with one type of leveling and other IPs by a different method of levelling
  - ➔ Problem of disentangling detrimental effects

- Implications of squeeze and collide scheme for stability
  - 10-15min of collisions lost (3m → 0.4m)
  - Any hopes we can do this in Stable Beams?

- Experience from 2010 – 2012
  - Beam instabilities very costly
  - Levelling and beam stability is a delicate issue…
  - More monitoring and faster analysis needed
  - Levelling is vital to the experiment(s) once we are at the limit (optimum)

- Expected performance and physics are driving the upgrades

Abstract

Luminosity control as the more general version of ‘leveling’ has been at the heart of the success for LHCb, and to a large extent also for Alice, throughout Run I. In the case of LHCb this has consisted of a semi-automatic procedure driven by a continuous and automated online analysis of the experiment data taking conditions in the LHCb data acquisition system. The actual control of the luminosity was achieved with the simple concept of adjusting the transversal overlap of the two beams at the interaction points.

With the increasing energy and potential luminosity in LHC, luminosity control may be required by all the experiments at some point in the future as a means of controlling the pileup conditions and trigger rates, but possibly also as a way of optimizing the integrated luminosity. A number of reasons calls for considering other options for controlling the luminosity. In order to evaluate the consequences of the different options, this presentation reviews the motivation for the luminosity control from the experiments’ point of view and the running conditions for the experiments in the future, aiming at giving a guidelines for the requirements both in terms of luminosity and luminous region management.