CERN Accelerator School
Chavannes de Bogis, Switzerland
8 November 2013

Luminosity

Giulia Papotti (BE-OP-LHC)

acknowledgements to
W. Herr, J. Wenninger, M. Ferro-Luzzi, W. Kozanecki

main references

- W. Herr, B. Muratori, many many luminosity lectures at previous CERN Accelerator Schools
- M. Ferro-Luzzi, “A novel method for measuring absolute luminosity at the LHC”, CERN-PH seminar, 29 August 2005
- J. Wenninger, “Luminosity diagnostics”, CAS on Beam Diagnostics, Dourdan (France), June 2008
- P. Grafstrom and W. Kozanecki, “Luminosity determination at proton colliders”, to be submitted to Prog. Part. Nucl. Phys.

CONVENTION FOR THE ESTABLISHMENT OF A EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

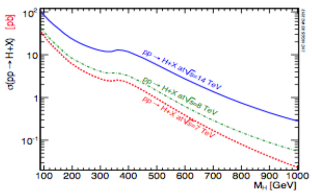
Paris, 1st July, 1953
as amended on 17 January 1971

ARTICLE II : Purposes

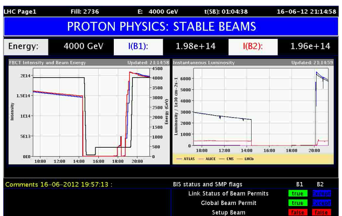
1. The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available.
2. The Organization shall, in the collaboration referred to in paragraph 1 above, confine its activities to the following:
   a. the construction and operation of one or more international laboratories (hereinafter referred to as "the Laboratories ") for research on high-energy particles, including work in the field of cosmic rays; each Laboratory shall include:
      i. one or more particle accelerators;
      ii. the necessary ancillary apparatus for use in the research programmes carried out by means of the machines referred to in (i) above;
      iii. the necessary buildings to contain the equipment referred to in (i) and (ii) above and for the administration of the Organization and the fulfilment of its other functions;
   b. the organization and sponsoring of international co-operation in nuclear research, including co-operation outside the Laboratories; this co-operation may include in particular:
      i. work in the field of theoretical nuclear physics;
      ii. the promotion of contacts between, and the interchange of,

accelerator or collider?

- at CERN: many accelerators and one collider
  - see R. Alemany, "Overview of the CERN Complex", these lecture series
- at high energy to produce heavier particles or probe smaller scales
  - lighter particles were studied in older machines
  - some events only possible at higher energies
    - see P. Sphicas, "Standard Model and Beyond", these lecture series
- particle colliders use two beams
  - higher energy by colliding two beams ($p_1 = -p_2$) than by using a fixed target ($p_2 = 0$)
    - see W. Herr, "Relativity", these lecture series



$$E_{cm} = \sqrt{(E_1 + E_2)^2 + (\vec{p}_1 + \vec{p}_2)^2}$$



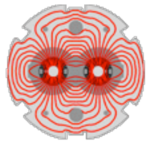
- need many interactions to explore and prove rare events
  - luminosity measures the number of events for the experiments

→ figures of merit of a collider: energy E_{cm} and luminosity L

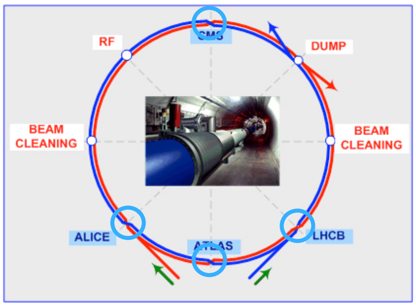
LHC
E_{cm} = 14 TeV
L = 10^{34} $cm^{-2}s^{-1}$

LHC layout

- choice of beam particle:
  - for a discovery machine need hadrons
  - use proton-proton to have many events

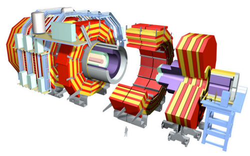


➔ same particle in the two beams: need two rings
  - 2-in-1 magnet design
  - common vacuum chamber in 4 interaction points only

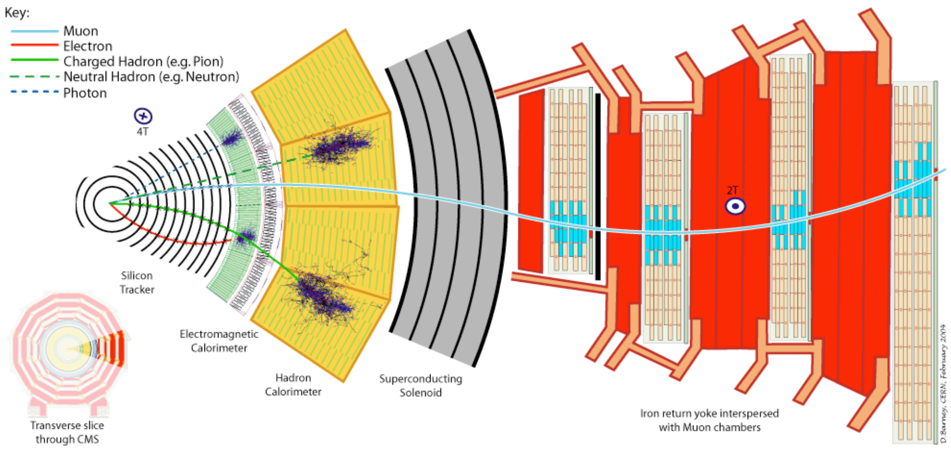


- note: also single ring and linear accelerators exist
  - e.g. SppS @ CERN
  - e.g. SLC @ SLAC

diversion: a CMS slice



or "what the experiments do with the collisions"



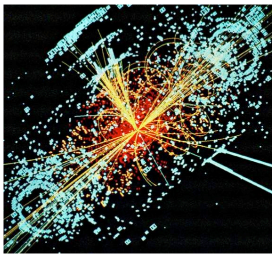
…but that is another story and shall be told another time

outline

- (motivation)
- luminosity
  - definition and derivation from machine parameters
  - head-on and offset collisions
  - reduction factors
    - crossing angles and crab cavities, hourglass
  - lifetime, contributions
  - luminosity scans and luminosity levelling
- integrated luminosity and ideal run time
- measurements and optimizations
  - vdM scans, high beta runs

- no linear colliders
- no single ring colliders
- no leptons
- no fixed target
- no coasting beams

definition: cross section



- *process*: a particle encounters a target
  - e.g. another beam
  - the encounter produces a certain final state composed of various particles (with a certain probability)
- *cross-section* σ_{event} expresses the likelihood of the process
  - σ_{event} represents the "area" over which the process occurs
  - units: [m^2]
    - in nuclear and high energy physics: 1 barn (1 b = 10^{-24} cm^2)

L: definition

$$R = \frac{dN}{dt} = L(t)\sigma_{event}$$

- luminosity L relates cross-section σ and event rate R = dN/dt at time t :
  - quantifies performance ("brilliance") of collider
  - relativistic invariant and independent of physical reaction

$$N = \sigma_{event} \int L(t)\,dt$$

- accelerator operation aims at maximizing the total number of events N for the experiments
  - σ_{event} is fixed by nature
  - aim at maximizing ∫L(t)dt

- units : [m^{-2} s^{-1}]
  - ∫Ldt is frequently expressed in $pb^{-1} = 10^{36}$ cm^{-2} or $fb^{-1} = 10^{39}$ cm^{-2}
- e.g.: today ATLAS+CMS have 1400 Higgs events in total
  - in ~30 fb^{-1} each: 6.1 fb^{-1} in 2011, 23.3 fb^{-1} in 2012

LHC
N = 5
σ_{event} = 0.5 fb = 10^{-39} cm^2
∫L(t) dt = 10 fb^{-1}

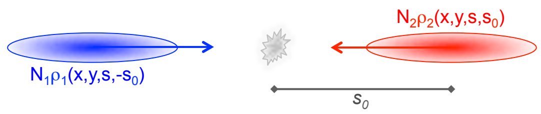
other circular colliders

Machine	Beam type	Beam energy [GeV]	Luminosity [cm^{-2} s^{-1}]
ISR	p p	31	>$2x10^{31}$
LEP I	e+ e-	45	$3x10^{30}$
LEP II	e+ e-	90-104	10^{32}
KEKB	e+ e-	8 x 3.5	$2x10^{34}$
SppS	p anti-p	270	$6x10^{30}$
TEVATRON	p anti-p	980	$2x10^{32}$
LHC	p p	7000	10^{34}

L from machine parameters -1-

- intuitively: more L if there are more protons and more tightly packed

$$L \propto N_1 N_2 \Omega_{x,y}$$



$$L \propto N_1 N_2 K \int_{x,y,s,s_0} \rho_1(x,y,s,-s_0)\rho_2(x,y,s,s_0)\, dx\, dy\, ds\, ds_0$$

- K = 2 *c*: kinematic factor (see W. Herr, "Relativity", these lecture series)
- N_1, N_2: bunch population
- $\rho_{1,2}$: density distribution of the particles (normalized to 1)
- x,y: transverse coordinates
- s: longitudinal coordinate
- s_0: "time variable", $s_0 = c\,t$
- $\Omega_{x,y}$: overlap integral

L from machine parameters -2-

- for a circular machine can reuse the beams f times per second (storage ring)
- for k colliding bunch pairs per beam
- for uncorrelated densities in all planes $\rho(x,y,s,t) = \rho_x(x)\rho_y(y)\rho_s(s-vt)$

$$L = 2fkN_1N_2 \int_{x,y,s,s_0} \rho_{1x}(x)\rho_{1y}(y)\rho_{1s}(s-s_0)\rho_{2x}(x)\rho_{2y}(y)\rho_{2s}(s+s_0)\, dx\, dy\, ds\, ds_0$$

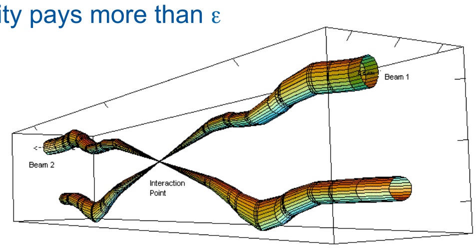
- for Gaussian bunches $\rho_u(u) = \frac{1}{\sigma_u\sqrt{2\pi}}\exp\left\{-\frac{(u-u_0)^2}{2\sigma_u^2}\right\}$ $u = x, y$
- for equal beams in x or y ($\sigma_{1x} = \sigma_{2x}$, $\sigma_{1y} = \sigma_{2y}$)
- can derive a closed expression: $L = \frac{kN_1N_2f}{4\pi\sigma_x\sigma_y}$

LHC
k = 2808
N_1,N_2 = 1.15 10^{11} ppb
f = 11.25 kHz
σ_x, σ_y = 16.6 μm
L = 1.2 10^{34} $cm^{-2}s^{-1}$

- f: revolution frequency
- k: number of colliding bunch pairs at that Interaction Point (IP)
- N_1, N_2: bunch population
- $\sigma_{x,y}$: transverse beam size at the collision point

need for small β*

- expand physical beam size $\sigma_{x,y}$: $\sigma_x^* = \sigma_y^* = \sqrt{\frac{\beta^* \varepsilon}{\gamma}}$ ➔ $L = \frac{k N_1 N_2 f \gamma}{4\pi \beta^* \varepsilon}$
  - * means "at the IP"
- conserve low ε from injectors
  - explicit dependence on energy (γ)
- design low β* insertions
  - limits by triplet aperture, protection by collimators
  - in nominal cycle: "squeeze"
- intensity pays more than ε



Relative beam sizes around IP1 (Atlas) in collision

LHC
β* = 18 ➔ 0.55 m
ε = 3.75 μm
γ = 7463
$\sigma_{x,y}$ = 16.6 μm

reduction factors (F)

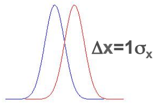
transverse offsets

crossing angles and crab cavities

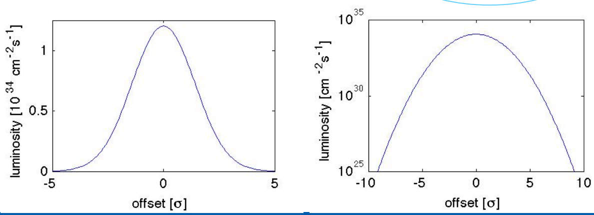
hourglass effect

transverse offsets

- in case the beams do not overlap in the transverse plane (e.g. in x)



- more generally $L = \frac{kN_1N_2f}{4\pi\sigma_x\sigma_y} \exp\left\{-\frac{\Delta x^2}{4\sigma_x^2} - \frac{\Delta y^2}{4\sigma_y^2}\right\}$ F

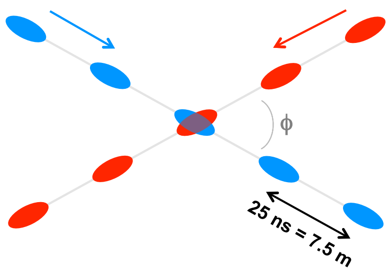


Δx	F
0	1
1 σ	0.779
2 σ	0.368
3 σ	0.105
4 σ	0.018
5 σ	0.002

crossing angles -1-

- to avoid parasitic collisions when there are many bunches
  - otherwise collisions elsewhere than in interaction point only
    - common vacuum pipe is 120 m long, CMS 21 m long

- luminosity is reduced as the particles no longer traverse the entire length of the counter-rotating bunch



$$L = \frac{kN_1N_2f}{4\pi\sigma_x\sigma_y} \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2}\right)^2}}$$ F

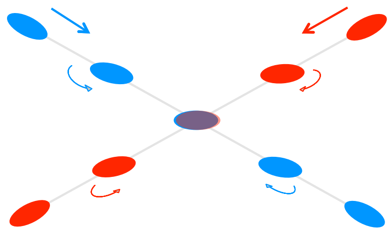
$\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2}$ is called the Piwinski angle

valid for small ϕ and $\sigma_s >> \sigma_x, \sigma_y$

LHC
ϕ = 285 μrad
σ_s = 7.5 cm
F = 0.84

crossing angles -2-

- for very small β^*, need big crossing angle: big reduction in L
  - e.g. for LHC upgrade (HL-LHC): β^* = 15 cm, ϕ = 590 μrad, F ~ 0.35
    - see T. Pieloni, "Beam-beam effects at the LHC", these lecture series
- "crab crossing" scheme being considered
    - see F. Bordry, "Exploitation of LHC and future colliders", these lecture series

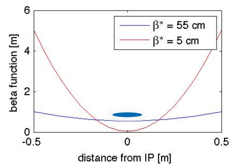


- use fast RF cavities for bunch rotation (transverse deflection)
  - used at KEKB, but with leptons and "global" scheme
  - at LHC, need "local" scheme due to collimators, need compact cavities
    - feasibility to be demonstrated, studies on-going

hourglass effect 

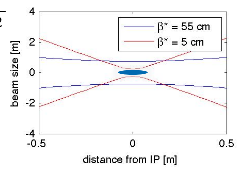
- β depends on longitudinal position s
  - see B. Holzer, chapter on Insertions in "Transverse Beam Dynamics II", these lecture series

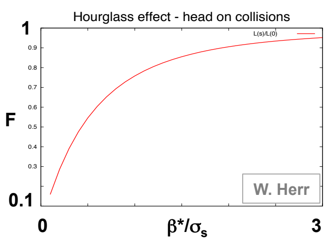
$$\beta(s) \approx \beta^*\left(1+\left(\frac{s}{\beta^*}\right)^2\right)$$



- then beam size $\sigma_{x,y}$ depends on s
  - if $\beta^* \sim \sigma_s$, bunch samples bigger β than β^*
  - if $\beta^* >> \sigma_s$, effect is negligible

$$\sigma_{x,y}(s) \approx \sigma^*_{x,y}\sqrt{1+\left(\frac{s}{\beta^*_{x,y}}\right)^2}$$





- L reduction is non-negligible for long bunches and small β

LHC	HL-LHC
β^*/σ_s > 7	β^*/σ_s ~ 2
F ~ 1	F ~ 0.90

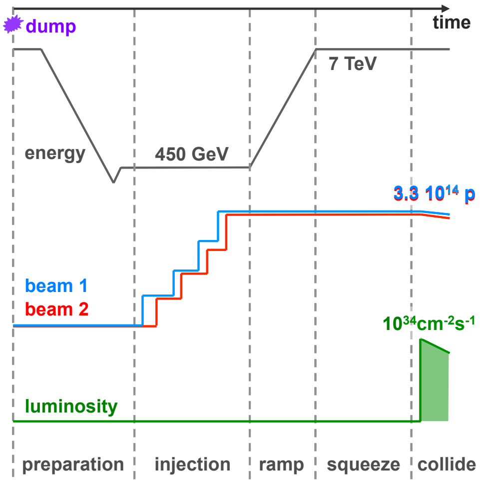
planned vs achieved

Parameter	2010	2011	2012	Nominal
beam energy [TeV]	3.5	3.5	4.0	7.0
bunch spacing [ns]	150	75 / 50	50	25
k [no. bunches]	368	1380	1380	2808
N_b [10^{11} p/bunch]	1.2	1.45	1.6	1.15
ε [mm mrad]	2.2	2.3	2.5	3.75
β^* [m]	3.5	1.5 → 1	0.6	0.55
half crossing angle [μrad]	100	120	145	142.5
L reduction factor	~1	0.95/0.91	~0.8	~0.84
L [$cm^{-2}s^{-1}$]	2×10^{32}	3.5×10^{33}	7.7×10^{33}	10^{34}

L evolution during a fill

natural decay, components
luminosity levelling

diversion: what is a fill?



- fill: a complete machine cycle
  - includes all phases needed to get to luminosity production
  - customarily: starts at dump
  - also called “luminosity run”
    - note: “LHC run 1” is 2010-13
- need time to prepare before producing luminosity!
  - ramp-down, inject, ramp, squeeze…
  - efficiency is not 100%, even with 100% availability!

jargon: “turn-around (time)”: from dump to start of next collisions (min: 2h08’)

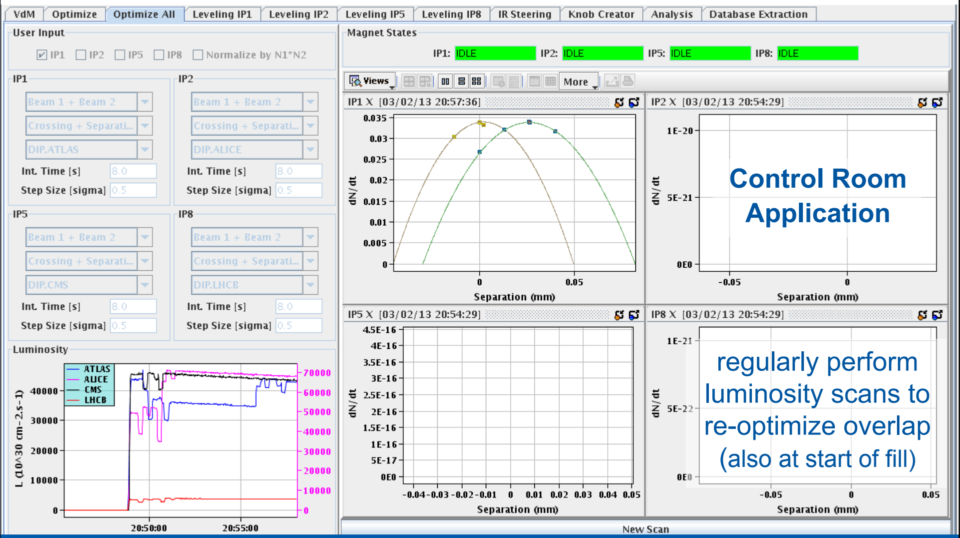
2012	typ time
prep	>50’
inj	~60’
ramp	~15’
squ.	~20’
coll.	0-20 h

L natural decay during a fill

$$L = \frac{k N_1 N_2 f \gamma}{4\pi \beta^* \varepsilon} F$$

- not changing during the fill:
  - γ (set by magnetic field in bends)
  - f (set by beam energy and tunnel length)
  - β^* (set up during beam commissioning, compromise between aperture, collimator settings, tolerances)
  - k (set at injection)
- changing during a fill (and naming only a few causes):
  - ε increases
    - Intra Beam Scattering (τ_x ~105 h, τ_s ~63 h)
    - noise in power converters (at LHC: small!)
  - N_1, N_2 decrease
    - luminosity burn-off (i.e. particle loss from collisions, e.g. τ ~ 45 h)
    - scattering on residual gas (extremely good, τ_{gas} >100 h)
  - F changes
    - imperfect overlap from orbit drifts, can be corrected by orbit corrections

luminosity scans



max peak L is not all…

- might need luminosity control
  - if too high can cause high voltage trips then impact efficiency
  - might have event size or bandwidth limitations in read-out
  - too many simultaneous event cause loss of resolution
- ...experiments also care about:
  - time structure of the interactions: *pile up* μ
    - average number of inelastic interactions per bunch crossing

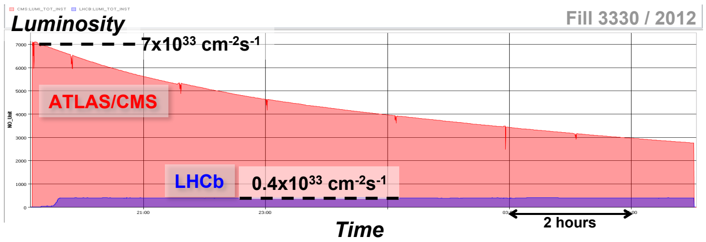
$$\langle R \rangle = \left\langle \frac{dN}{dt} \right\rangle = \mu f$$

	design	2010	2011	2012	HL-LHC
μ	21	4	17	37	140

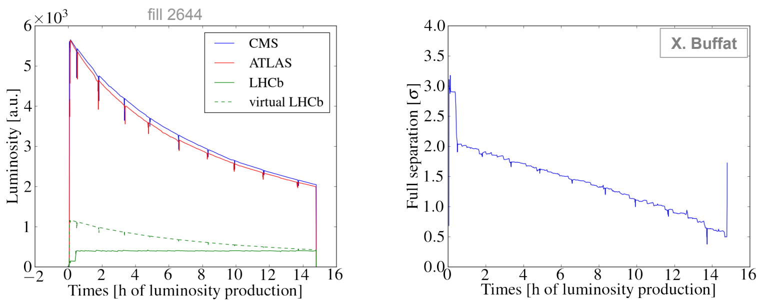
  - spatial distribution of the interactions: *pile-up density*
    - e.g. HL-LHC: accept max pile up density of 1.3 events/mm
  - quality of the interactions (e.g. background)
    - no problems at the LHC so far
  - size of luminous region
    - e.g. need constant length (input to MonteCarlo simulations)

L levelling

- maintain the luminosity constant over a period of time (i.e. the fill)
  - stay as long as possible at the maximum value that experiment can manage (which is lower than what the machine could provide)
- performed in 2010-2011-2012 for LHCb and ALICE
  - need to limit pile-up (thus luminosity per bunch pair)
  - e.g. μ < 2.1 at LHCb in 2012
  - done by transversely offsetting the beams at the IP



L levelling by separation

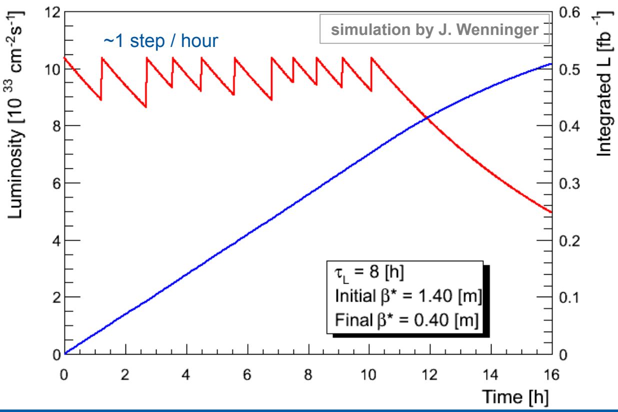


$$\frac{\Delta x}{\sigma_x} = \sqrt{-4\log\frac{L}{L_0}}$$

- worked beautifully in run 1 for LHCb and ALICE
  - while ATLAS and CMS fully head-on
- can't use it for all experiments at the same time
  - Landau damping from beam-beam helps stability
- might need different solutions for run 2 or HL-LHC

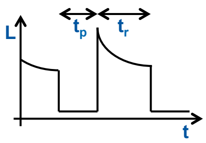
L levelling with β*

- reduce β* in steps while keeping beams in collisions
- tested successfully in 2012 Machine Developments



ideal run time -1-

- so far talked about instantaneous L
- but need integrated luminosity $N \propto \int L(t)\,dt$
  - gives the number of events
- need to account for extra time to prepare a fill (t_p)
  - inject, ramp, squeeze, ...
  - plus downtime (an accelerator is a very complex system!)



- exercise: assume exponential decay for L: $L(t) = L_0 e^{-\frac{t}{\tau}}$
- calculate optimum run time (t_r) to maximize the average luminosity <L>

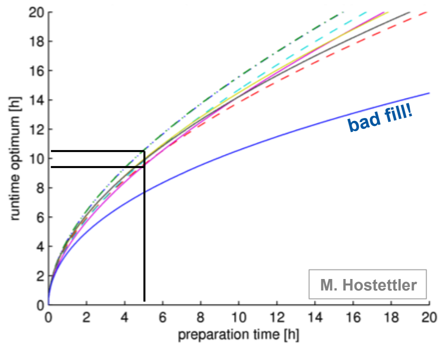
$$\langle L \rangle = \frac{\int_0^{t_r} L(t)\,dt}{t_r + t_p}$$

- need
  - good peak luminosity L_0
  - good luminosity lifetime τ
  - short preparation time
    - "turnaround": jargon for "from dump to stable beams"
  - good machine availability (little downtime, that goes into average preparation time)

LHC
τ ~ 15 h
t_p ~ 5 h
t_r ~ 10 h

ideal run time -2-

- from 2012 data
  - based on more complicated and accurate model for L decay
  - numerical integration to find optimum t_r
- derive optimum fill length: good agreement with previous simple model

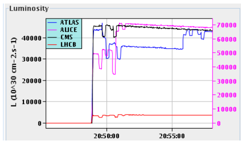


t_p	2.5 h	5 h	10 h
opt t_r	7 h	10 h	15 h

L measurements

calibration
van der Meer scans
high beta runs

L measurements



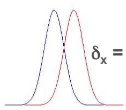
- relative and absolute L
  - relative: based on an arbitrary scale
    - good enough to monitor variations
      - e.g. for optimizing the rates in CCC
  - absolute: mandatory to measure a process cross section
    - reminder: $N = \sigma_{event} \int L(t)\,dt$
    - needs to be calibrated at some point in time
- calibrations
  - from machine parameters
    - not directly from $\varepsilon_{x,y}$, β^*, $N_{1,2}$, ... (gives 5-10% precision only)
  - from optical theorem
  - from reactions with well known cross sections
    - "easy" for lepton machines

vdM scans

- recall: $L_b = f N_1 N_2 \Omega_x \Omega_y$
  - assumes uncorrelated densities in all planes
- key: calculate overlap from ratio of rates
  - by measuring rates for different overlaps and integrating over the whole range
  - can measure rates R in arbitrary units!

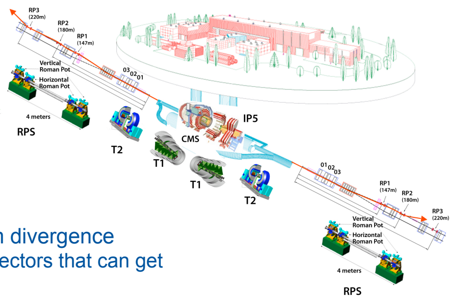
$$\Omega_y = \frac{R_y(0)}{\int R_y(\delta_y)\,d\delta_y}$$

- what it takes
  - accurate bunch-by-bunch intensities
  - dedicated fill: no crossing angle, few bunches
  - scans in x, y to get the overlaps Ω_x, Ω_y
    - need a few steps of δ_y for $\int R_y(\delta_y)\,d\delta_y$

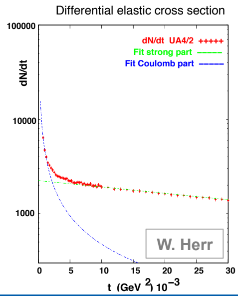


- first done by S. van der Meer at the ISR (1968) in one plane
  - generalized to bunched beams by C. Rubbia at SppS

high beta runs

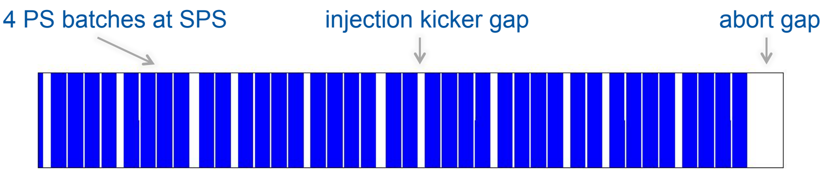


- optical theorem allows to link:
  - total cross section
  - forward elastic scattering
- “forward” means “at small angle”
  - use high β* optics to get small beam divergence
    - use Roman Pots: include silicon detectors that can get as close as 1-4 mm to the beam
    - e.g. TOTEM experiment at LHC pt 5
  - use small emittance beams
- can also study the Coulomb region, t → 0
  - t = squared momentum transfer in particle scattering
  - see W. Herr, “Relativity”, these lecture series
  - Coulomb scattering can be computed reliably
    - don’t need to measure the inelastic rate
  - need β* ~2.5 km at LHC
  - e.g. ALFA experiment at ATLAS



filling schemes

- motivation: different luminosity targets from the 4 experiments
  - filling schemes tailored to give different number of colliding pairs
- ATLAS, ALICE, CMS located at the IP symmetry point, LHCb is 11.25 m away
- 2.5 ns buckets, h = 35640, 25 ns minimum bunch spacing
- for a filling scheme we can chose:
  - bunch spacing: 25ns, 50ns, 75ns, 150ns, or >250ns
  - number of PS batches (1-4, dynamic), number of PSB rings
  - injection bucket



50 ns, 1380 bunches/ring
(1377 collide at ATLAS and CMS, 1274 at LHCb)

wrap-up

bunch spacing
filling schemes

crossing angle
hourglass effect
offset collisions

luminosity scans

$$L = \frac{kN_1N_2f\gamma}{4\pi\beta^*\varepsilon}F$$

turnaround time
preparation time

collider
rates, events

squeeze
levelling by β^*
levelling by offset

van der Meer scans
high beta runs

cross section
pile-up
30 fb^{-1}, 700 Higgs events