CERN Accelerator School
Prague, Czech Republic
10 September 2014

Luminosity

Giulia Papotti (CERN, BE-OP-LHC)

acknowledgements to:
W. Herr, W. Kozanecki, J. Wenninger

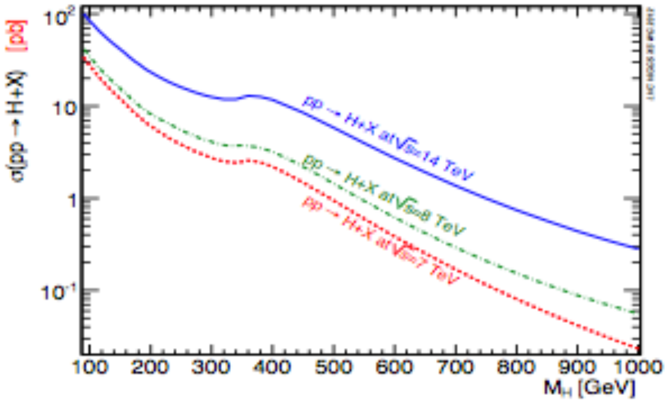
and with material by:
X. Buffat, F. Follin, M. Hostettler

Bibliography

- W. Herr and 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 published in Prog. Part. Nucl. Phys.
- A. Chao and M. Tigner, “Handbook of accelerator physics and engineering”, World Scientific, 2002.

collider

- at high energy to probe smaller scales or to produce heavier particles
  - lighter particles were studied in older machines
    - "to boldly go where no man has gone before"
  - some events only possible at higher energies
  - collider as last stage of the accelerator chain
    - e.g. at CERN: Linac+PSB+PS+SPS+LHC



- particle colliders use two beams
  - higher available energy by colliding two beams ($-\underline{p}_1 = \underline{p}_2$, $E_1 = E_2 = E+m_0$)
  - than using a fixed target (p_2=0, E_2=m_0)
    - see *W. Herr, "Relativity"*

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

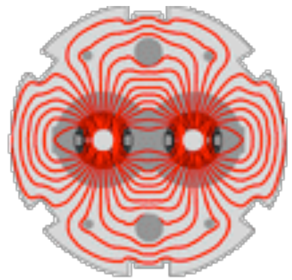
- need many interactions to explore and prove rare events
  - luminosity measures the number of events for the experiments

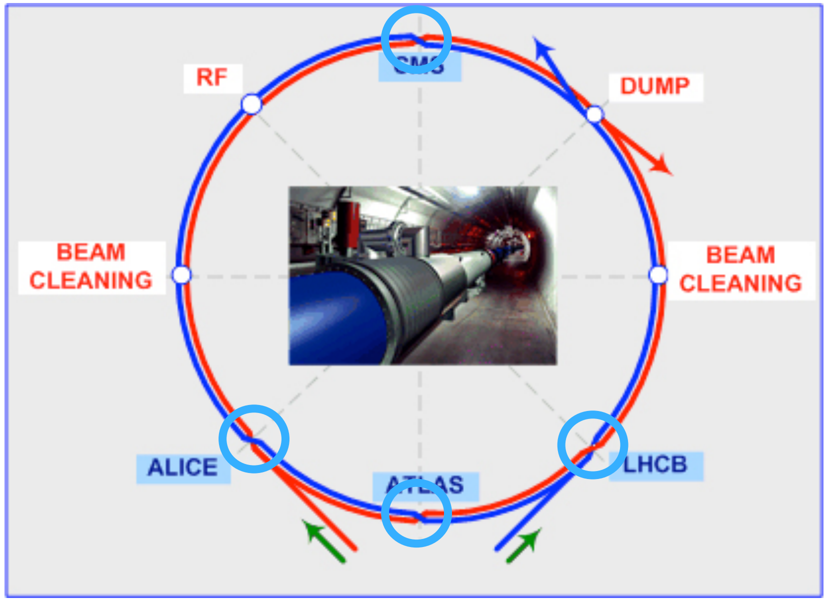
➔ figures of merit of a collider: energy E_{cm} and luminosity L

e.g.: the Large Hadron Collider

- main example in this lecture
- choice of beam particle:
  - for a discovery machine, need hadrons
  - use proton-proton to have many events

➔ same particles to counter-rotate: need two rings
  - 2-in-1 magnet design

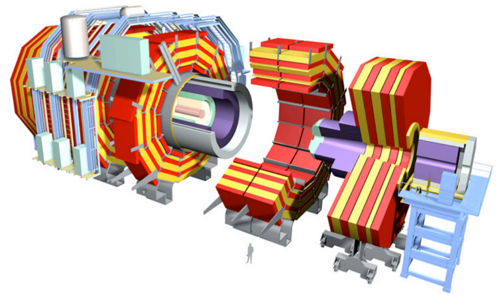




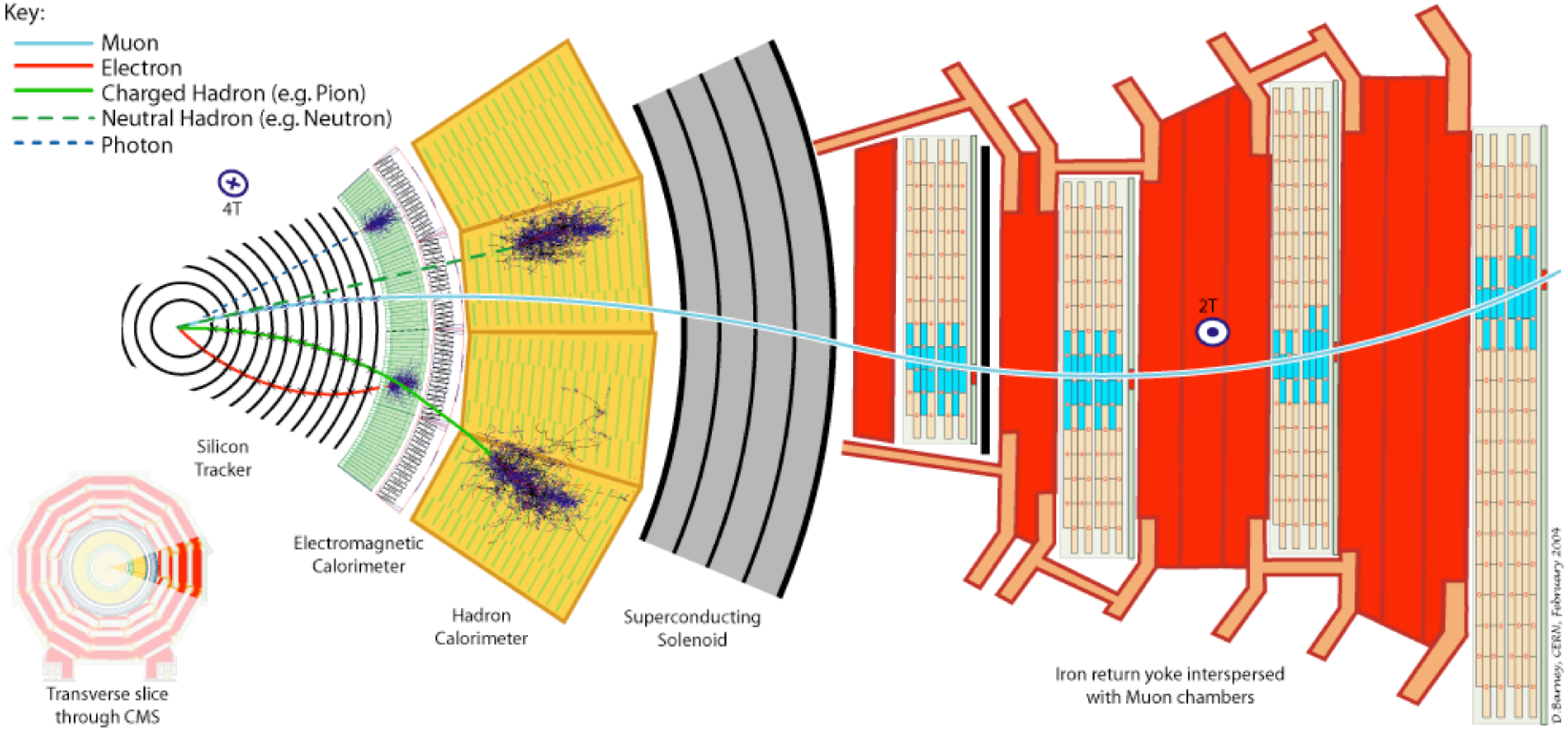
- LHC layout
  - 8 arcs and 8 straight sections (SS)
    - 4 SS for machine equipment
    - 4 SS for experiments
      - Alice, ATLAS, CMS, LHCb
  - common vacuum chamber in 4 interaction points only
  - note: also single ring colliders exist
    - e.g. SppS, LEP, Tevatron

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

diversion: a CMS slice



or "what the experiments do with the collisions"



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

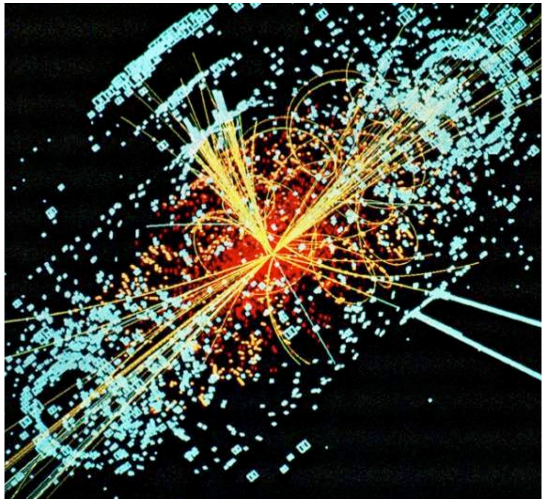
outline

- (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
- linear colliders

- 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)

definition: Luminosity (L)

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

- 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 $\int L(t)dt$

- units : [m^{-2} s^{-1}]
  - $\int Ldt$ is frequently expressed in $pb^{-1} = 10^{36}$ cm^{-2} or $fb^{-1} = 10^{39}$ cm^{-2}
- e.g.: from LHC run 1, ATLAS+CMS got 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 = 0.5 10^{-39} cm^2
$\int L(t)\, dt$ = 10 fb^{-1}

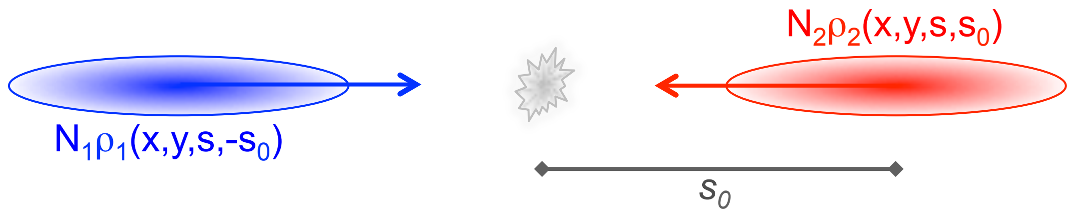
circular colliders

Machine	Years in operation	Beam type	Beam energy [GeV]	Luminosity [cm^{-2} s^{-1}]
ISR	1971-’84	p p	31	>$2x10^{31}$
LEP I	1989-’95	e+ e-	45	$3x10^{30}$
LEP II	1995-2000	e+ e-	90-104	10^{32}
KEKB	1999-2010	e+ e-	8 x 3.5	$2x10^{34}$
SppS	1981-’84	p anti-p	270	$6x10^{30}$
TEVATRON	1983-2011	p anti-p	980	$2x10^{32}$
LHC	2008-?	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"*)
- 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: $\rho_u(u) = \frac{1}{\sigma_u\sqrt{2\pi}}\exp\left\{-\frac{(u-u_0)^2}{2\sigma_u^2}\right\};$ $u = x,y$ $\qquad \int_{-\infty}^{+\infty} e^{-at^2} = \sqrt{\frac{\pi}{a}}$
- 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
$\sigma_x, \sigma_y = 16.6\ \mu$m
$L = 1.2\ 10^{34}\ cm^{-2}s^{-1}$

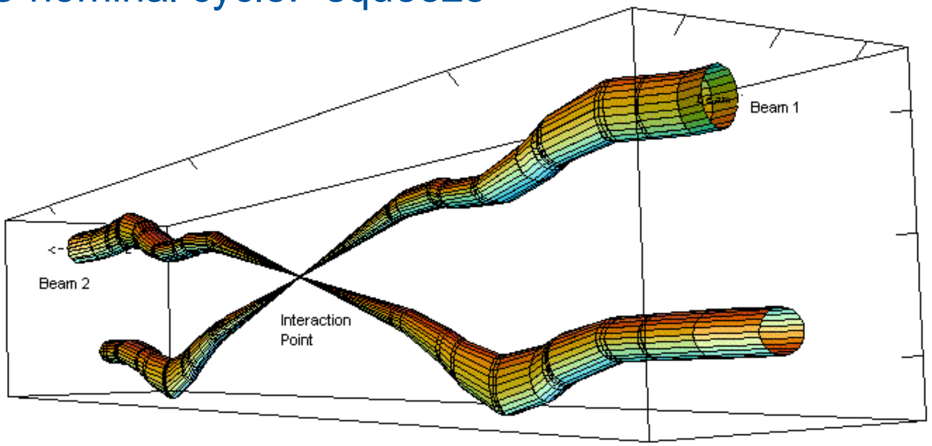
- f: revolution frequency
- k: number of colliding bunch pairs at that Interaction Point (IP)
- N_1, N_2: bunch population
- $\sigma_{x,y}$: transverse beam size at the collision point

need for small β*

- expand physical beam size $\sigma_{x,y}$:
  - * means "at the IP"

$$\sigma_x^* = \sigma_y^* = \sqrt{\frac{\beta^* \varepsilon}{\gamma}} \rightarrow L = \frac{kN_1N_2 f\gamma}{4\pi\beta^*\varepsilon}$$

- try and conserve low ε from injectors
  - explicit dependence on energy (γ)
- intensity pays more than ε and β*
- design low β* insertions
  - limits by triplet aperture, protection by collimators
  - in LHC nominal cycle: "squeeze"



Relative beam sizes around IP1 (Atlas) in collision

LHC
$\beta^* = 18 \rightarrow 0.55$ m
$\varepsilon = 3.75$ μm
$\gamma = 7463$
$\sigma_{x,y} = 16.6$ μm

reduction factors (F)

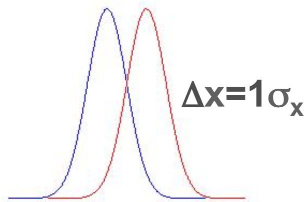
transverse offsets

crossing angles and crab cavities

hourglass effect

transverse offsets -1-

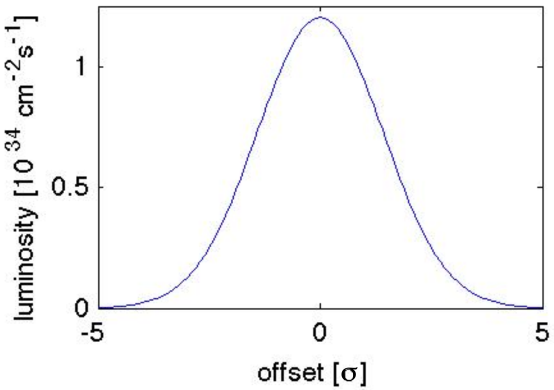
- in case the beams do not overlap in the transverse plane (e.g. in x)

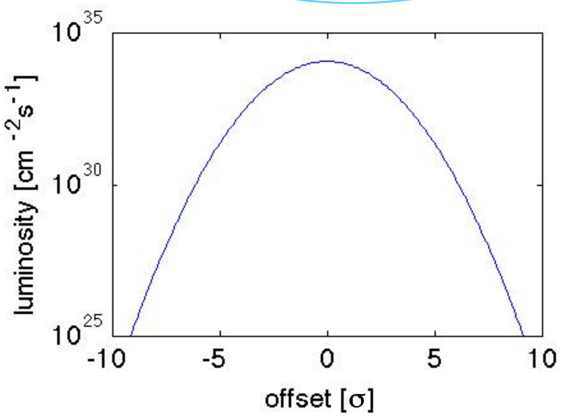


- more generally

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

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

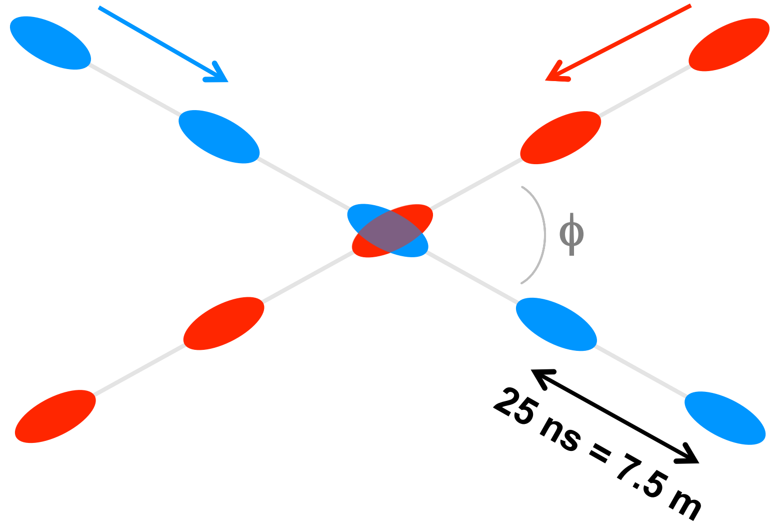
transverse offsets -2-

- more general expression including different beam sizes:
  - $\sigma_{1x} \neq \sigma_{2x}$, $\sigma_{1y} \neq \sigma_{2y}$

$$L = \frac{kN_1N_2f}{2\pi\sqrt{(\sigma_{x,1}^2+\sigma_{x,2}^2)(\sigma_{y,1}^2+\sigma_{y,2}^2)}}\exp\left\{-\frac{(\Delta x)^2}{2(\sigma_{x,1}^2+\sigma_{x,2}^2)}-\frac{(\Delta y)^2}{2(\sigma_{y,1}^2+\sigma_{y,2}^2)}\right\}$$

crossing angles -1-

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

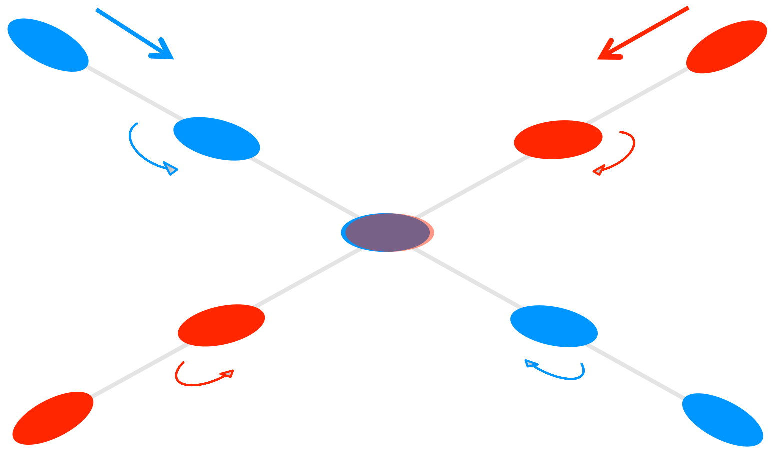
$\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2}$ is called the Piwinski angle

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
- "crab crossing" scheme being considered

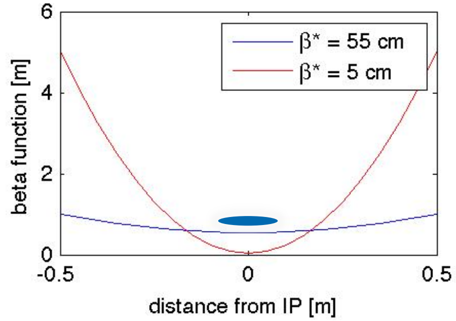


- use fast RF cavities for bunch rotation (transverse deflection)
  - used at KEKB, but with leptons and "global" scheme
  - at LHC, need "local" scheme due to collimators, need compact cavities
    - feasibility to be demonstrated, studies on-going

hourglass effect 

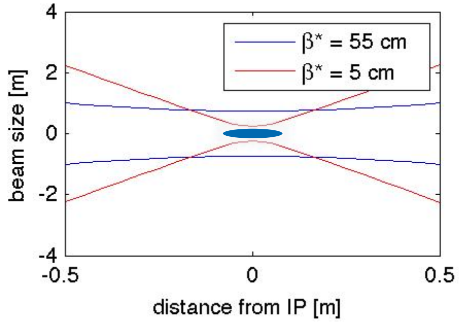
- β depends on longitudinal position s
  - see *B. Holzer*, chapter on *Insertions* in *"Transverse Beam Dynamics"*

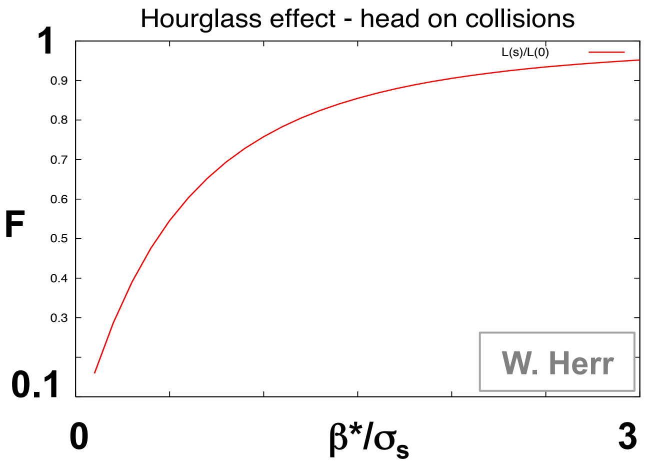
$$\beta(s) \approx \beta^* \left(1 + \left(\frac{s}{\beta^*}\right)^2\right)$$



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

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





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

LHC	HL-LHC
$\beta^*/\sigma_s > 7$	$\beta^*/\sigma_s \sim 2$
F ~ 1	F ~ 0.90

LHC parameters

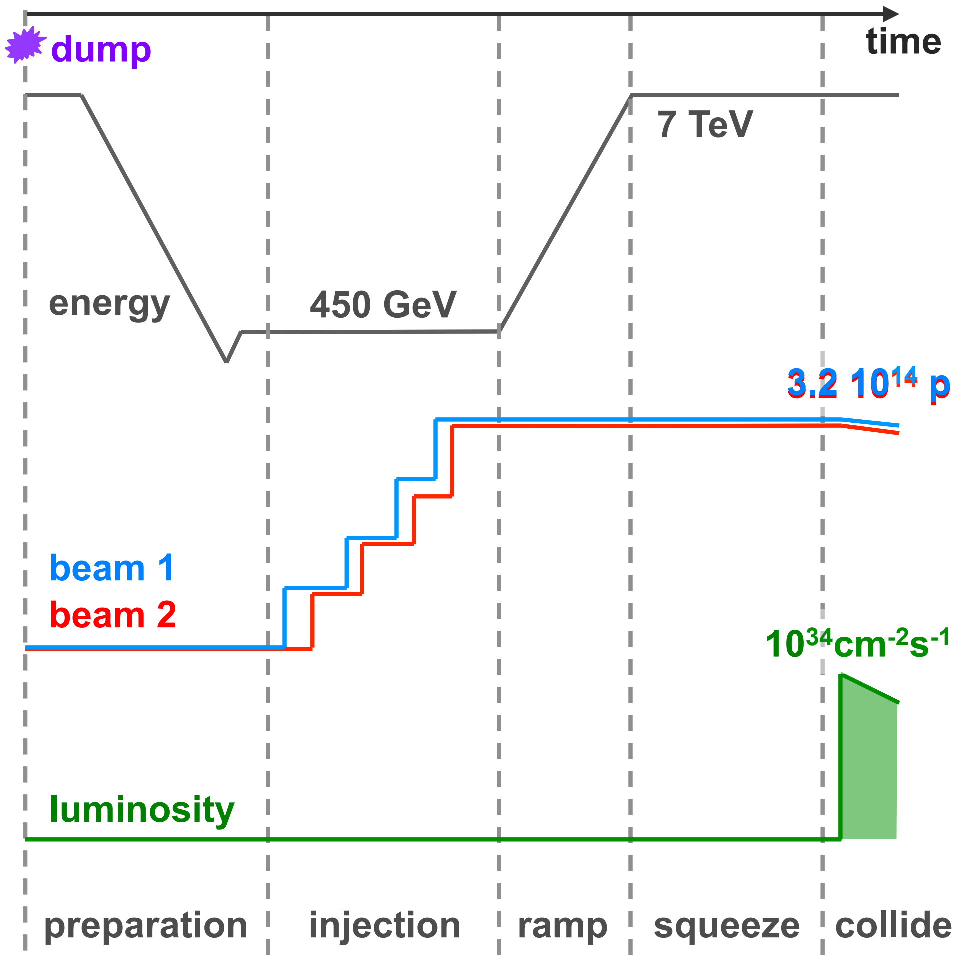
Parameter	Nominal	2010	2011	2012
beam energy [TeV]	7.0	3.5	3.5	4.0
bunch spacing [ns]	25	150	75 / 50	50
k [no. bunches]	2808	368	1380	1380
N_b [10^{11} p/bunch]	1.15	1.2	1.45	1.6
ε [mm mrad]	3.75	2.2	2.3	2.5
β^* [m]	0.55	3.5	1.5 → 1	0.6
half crossing angle [μrad]	142.5	100	120	145
L reduction factor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

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!

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

L natural decay during a fill

$$L = \frac{kN_1N_2 f\gamma}{4\pi\beta^*\varepsilon}F$$

- 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)
    - with a couple of exceptions…
  - k (set at injection)

- changing during a fill (and naming only a few causes):
  - ε increases
    - Intra Beam Scattering
    - noise in power converters
  - N_1, N_2 decrease
    - luminosity burn-off (i.e. particle loss from collisions)
    - scattering on residual gas
  - F changes
    - imperfect overlap from orbit drifts, can be corrected by orbit corrections

LHC
$\tau_{IBS,x}$ ~ 105 h
$\tau_{IBS,s}$ ~ 63h
$\tau_{B.O.}$ ~ 45 h
τ_{gas} > 100 h

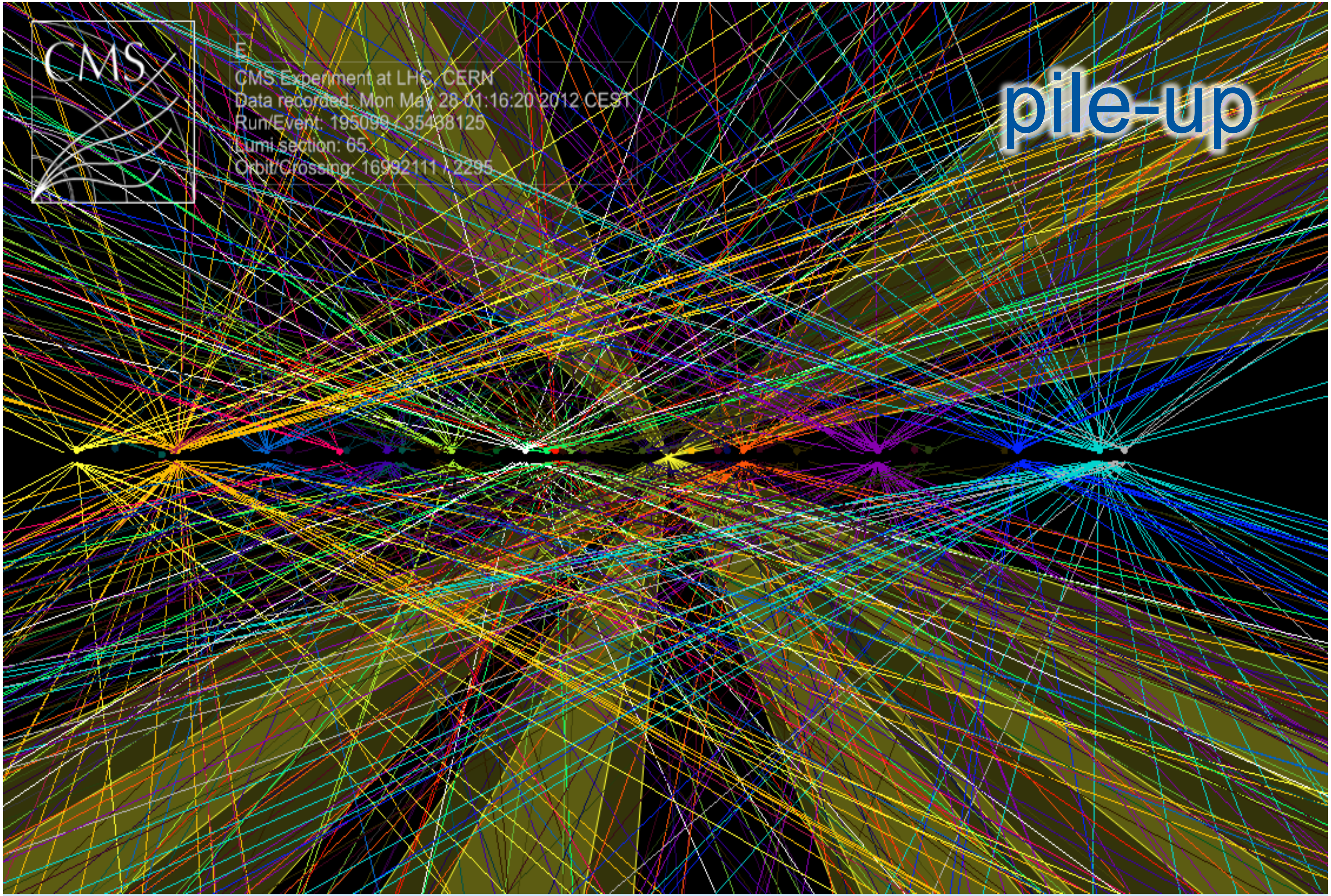
max peak L is not all…

- experiments 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)
  - size of luminous region
    - e.g. need constant length (input to MonteCarlo simulations)


CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
pile-up

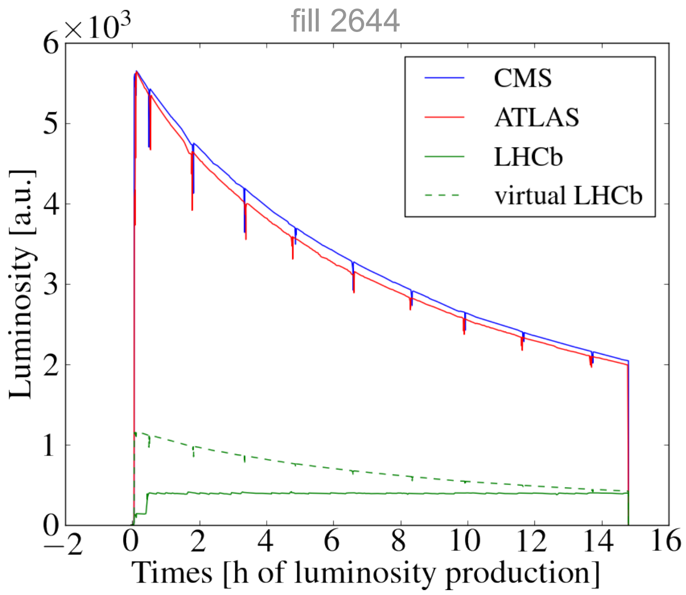
L levelling

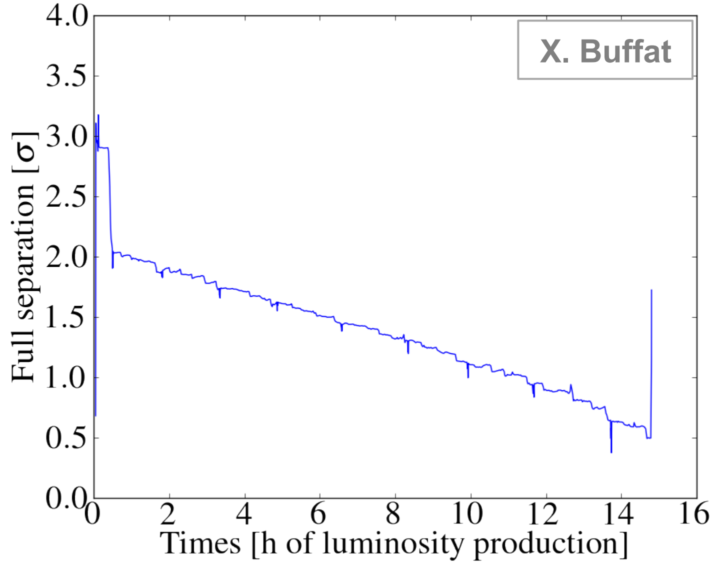
- some experiments need to limit the pile-up
  - thus luminosity per bunch pair
    - e.g. $\mu < 2.1$ at LHCb in 2012

- stay as long as possible at the maximum value that experiment can manage
  - which is lower than what the machine could provide
- maintain the luminosity constant over a period of time (i.e. the fill)

- possible techniques:
  - by transversely offsetting the beams at the IP
  - by β^*
  - …

L levelling by separation



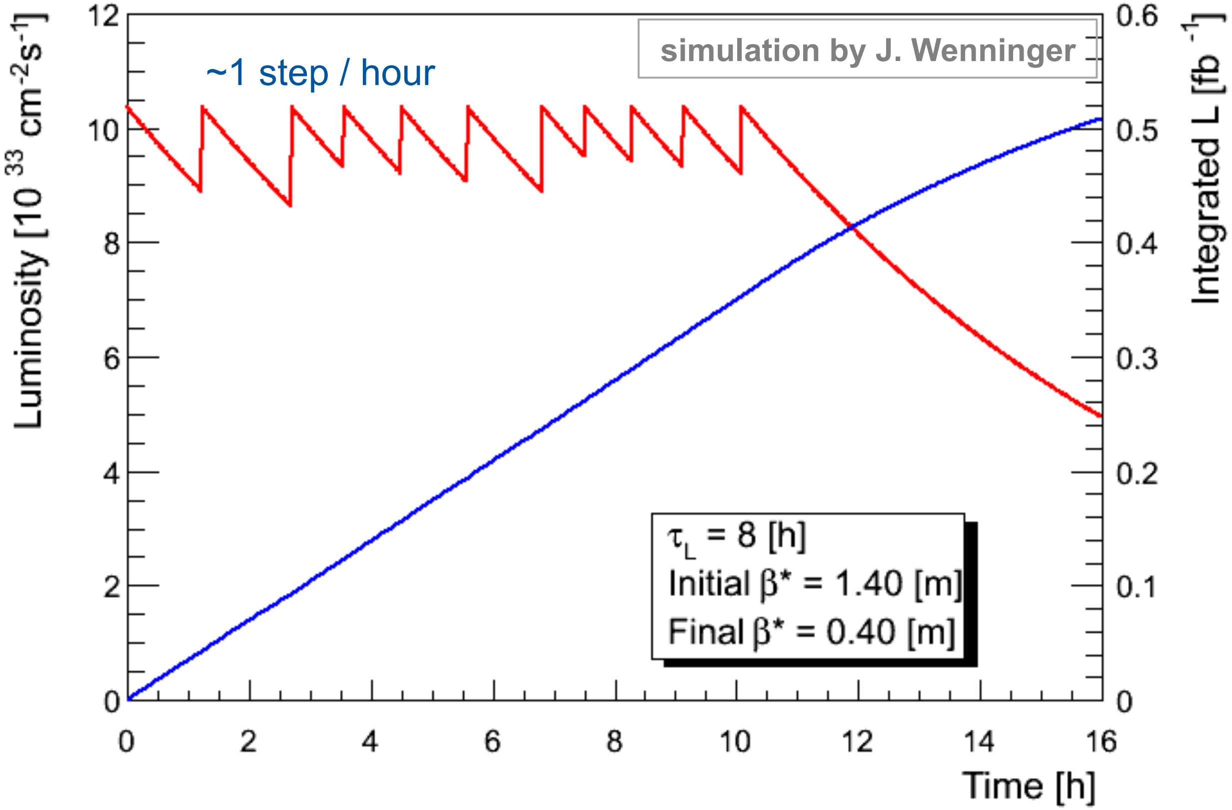


$$\frac{\Delta x}{\sigma_x} = \sqrt{-4\log\frac{L}{L_0}}$$

- worked beautifully in LHC 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

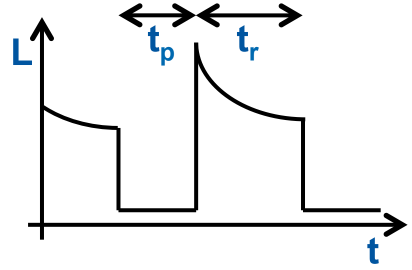
L levelling with β^*

- reduce β^* in steps while keeping beams in collisions
- tested successfully at LHC in 2012 Machine Developments
  - more to do with controls than beam physics



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>

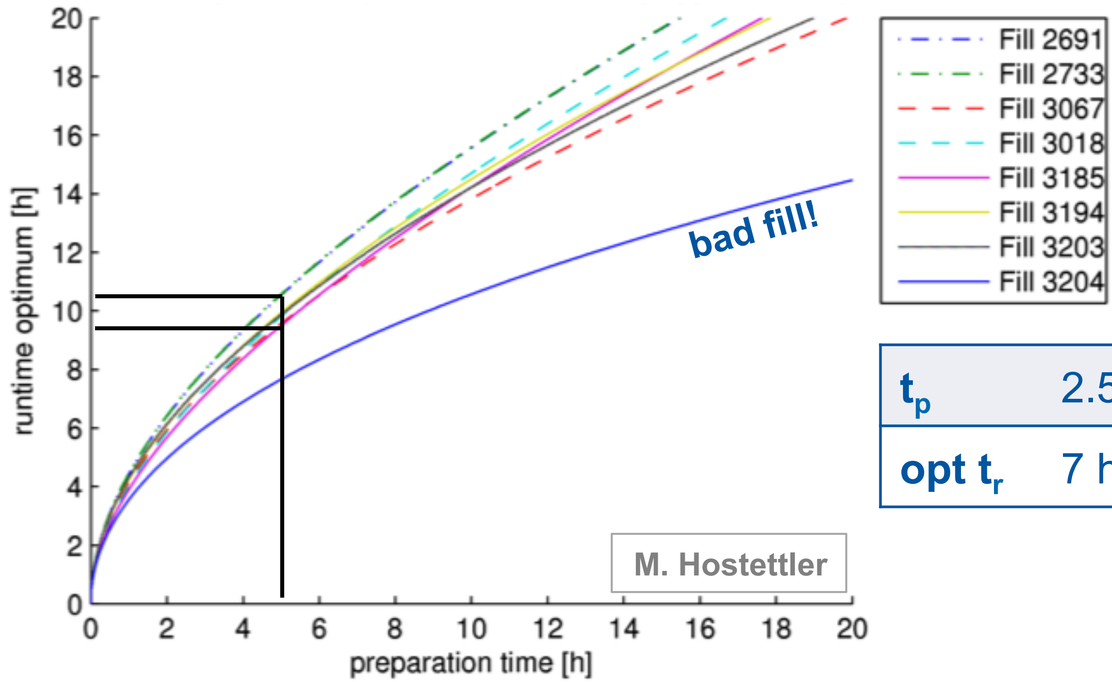
$$\langle L \rangle = \frac{\int_{t_r} L(t)\,dt}{t_r + t_p}$$

- 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 LHC 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

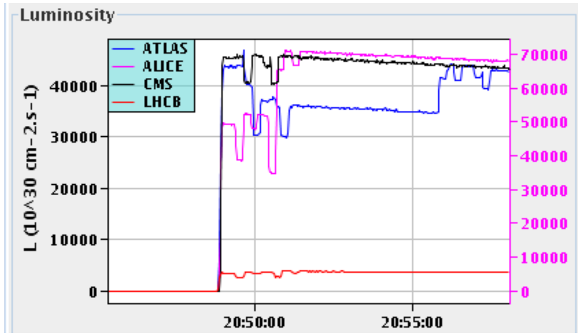
L calibration

van der Meer scans

high beta runs

BhaBha scattering

L measurements



- relative and absolute L
  - relative: based on an arbitrary scale
    - good enough to monitor variations
      - e.g. for optimizing the rates in the control room
  - 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

vdM scans

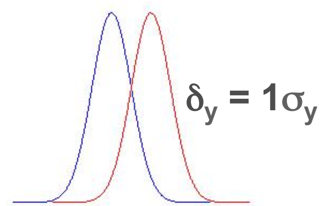
- first done by S. van der Meer at the ISR (1968) in one plane
  - generalized to bunched beams by C. Rubbia at Sp$\bar{p}$S

- recall: $L_b = f N_1 N_2 \Omega_x \Omega_y$
  - assumes uncorrelated densities in all planes

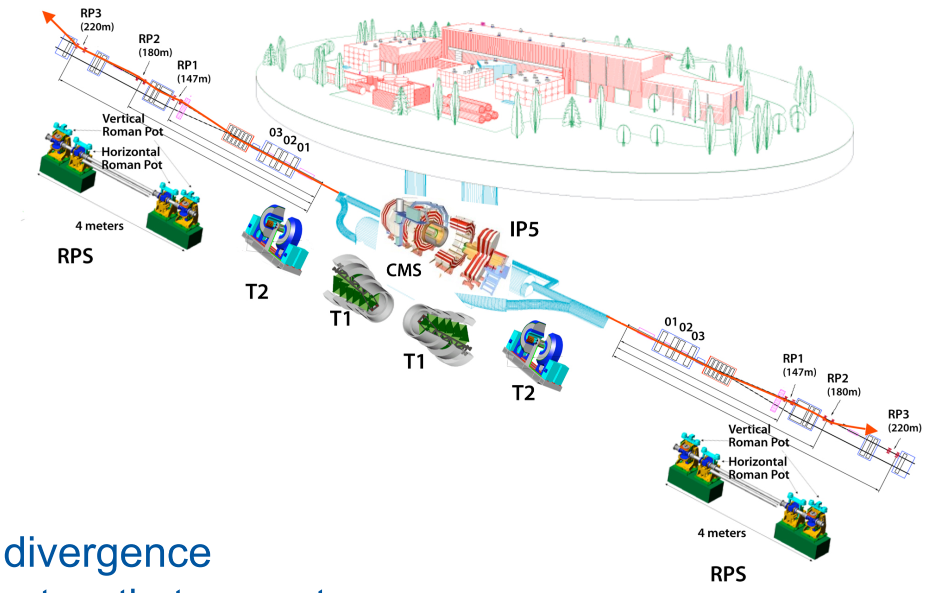
- key: calculate overlap from ratio of rates
  - by measuring rates for different overlaps and integrating over the whole range
  - can measure rates R in arbitrary units!

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

- 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 $\int R_y(\delta_y)\, d\delta_y$



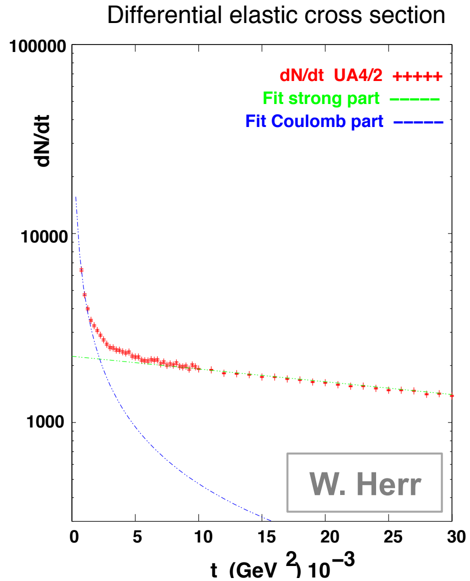
high beta runs



- optical theorem allows to link:
  - total cross section
  - forward elastic scattering

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}\left(\frac{d\sigma_{el}}{dt}\right)_{t=0}$$

- “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
  - use small emittance beams



- can also study the Coulomb region, t ➔ 0
  - t = squared momentum transfer in particle scattering
  - see *W. Herr, “Relativity”*
  - 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

from known cross section

- use reactions with well known cross sections
  - σ can be calculated with high precision
  - high event rates for low statistical error
  - background processes identified and/or subtracted

$$L(t) = \frac{R}{\sigma} = \frac{dN/dt}{\sigma}$$

- lepton machines: e^+e^- elastic scattering (Bhabha scattering)

$$e^+e^- \rightarrow e^+e^-$$

  - have to go to small angles ($\sigma \propto \Theta^{-3}$)

$$\sigma = k\left(\frac{1}{\theta^2_{\min}} - \frac{1}{\theta^2_{\max}}\right)$$

  - small rates at high energy ($\sigma \propto 1/E^2$)

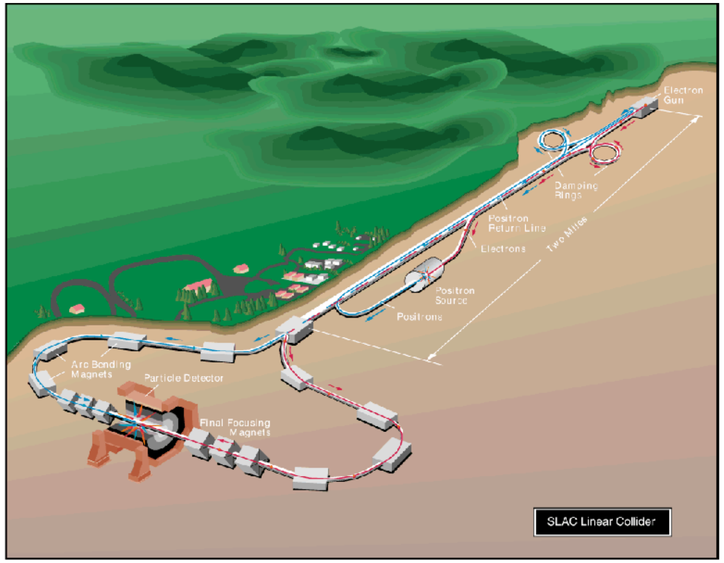
linear colliders

disruption, pinch effect

enhancement factor

beamstrahlung

linear colliders



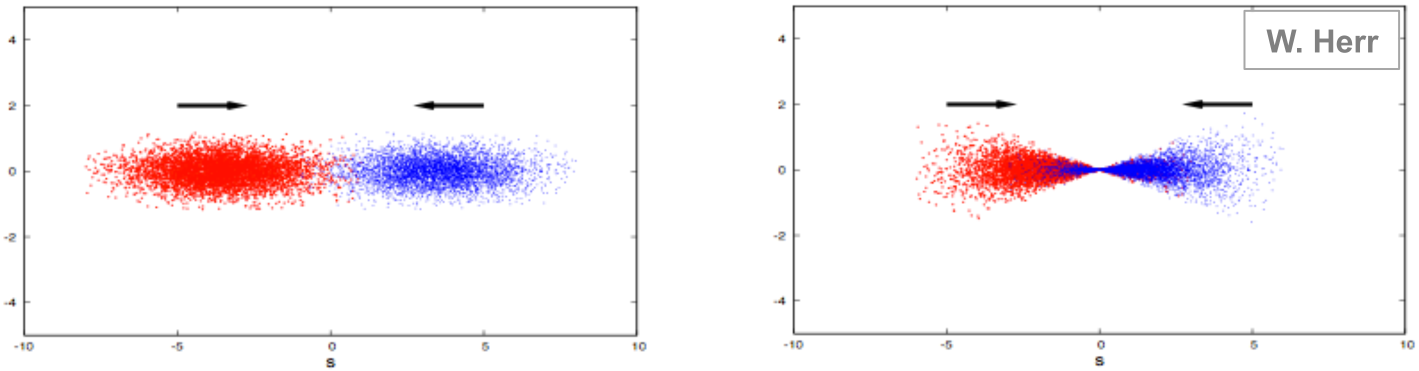
- e.g.:
  - SLC at SLAC, operated in the 90's
  - being designed: CLIC and ILC
- with electron-positron collisions (e+e-)

- linear: particles collide only once
  - from "revolution" to "repetition" frequency (f_{rep})
    - e.g. 120 Hz at SLC, 5 Hz at ILC, 50 Hz at CLIC
  - thus need bright, intense beams to reach high luminosity

- intense beams cause intense electromagnetic fields affecting the particles in the opposing beam
  - disruption effects
  - beamstrahlung effects

disruption effects -1-

- strong field by one beam bends the opposing particle trajectories
- quantified by disruption parameter $$D_{x,y} = \frac{2 r_e N \sigma_s}{\gamma \sigma_{x,y} \left(\sigma_x + \sigma_y \right)}$$
- nominal beam size is reduced by the disruptive field (*pinch effect*)
  - additional focusing for the opposing beam



- r_e: electron classical radius
- N: bunch population
- $\sigma_{x,y,s}$: beam size at the collision point
- γ: relativistic factor

disruption effects -2-

- define an "enhancement factor" H_D: $$H_D = \frac{\sigma_x \sigma_y}{\bar{\sigma}_x \bar{\sigma}_y}$$
- so luminosity can be re-written:

$$L = \frac{N_1 N_2 k f_{rep}}{4\pi \bar{\sigma}_x \bar{\sigma}_y} \rightarrow L = \frac{H_D N_1 N_2 k f_{rep}}{4\pi \sigma_x \sigma_y}$$

- for round beams ($D_x=D_y$) and weak disruption (D<<1):

$$H_D = 1 + \frac{2}{3\sqrt{\pi D}} + O(D^2)$$

  - beyond D<<1, need simulations

- D: disruption parameter
- $\sigma_{x,y}$ [$\overline{\sigma_{x,y}}$]: transverse beam size at the collision point [resp.: effective beam size]

beamstrahlung

- disruption at the interaction point is a strong bending:
- results in synchrotron radiation (*beamstrahlung*)
  - causes spread of centre-of-mass energy
  - high energy photons increase detector background

- quantified by beamstrahlung parameter Y

$$Y = \gamma \frac{\langle E + B \rangle}{B_C} \approx \frac{5}{6} \frac{r_e^2 \gamma N}{\alpha \sigma_s \left(\sigma_x + \sigma_y \right)}$$

- with $B_C \equiv \frac{m^2 c^3}{e\hbar} \approx 4.4 \cdot 10^{13} \mathrm{Gauss}$

wrap-up

turnaround time
preparation time

bunch spacing
filling schemes

crossing angle
hourglass effect
offset collisions

luminosity scans

$$L = \frac{kN_1 N_2 f \gamma}{4\pi \beta^* \varepsilon} F$$

beamstrahlung
disruption
pinch effect

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