Optimisation of LHC beam conditions

by Helmut Burkhardt / CERN BE/ABP for the LHC team

- **short introduction with few words on the LHC status** (more by S. Myers in plenary)
- **with main parameters, beam-beam effects**
- **experimental conditions : luminosity, background, knowledge of IP parameters**
- **luminosity : optimisation and normalisation**

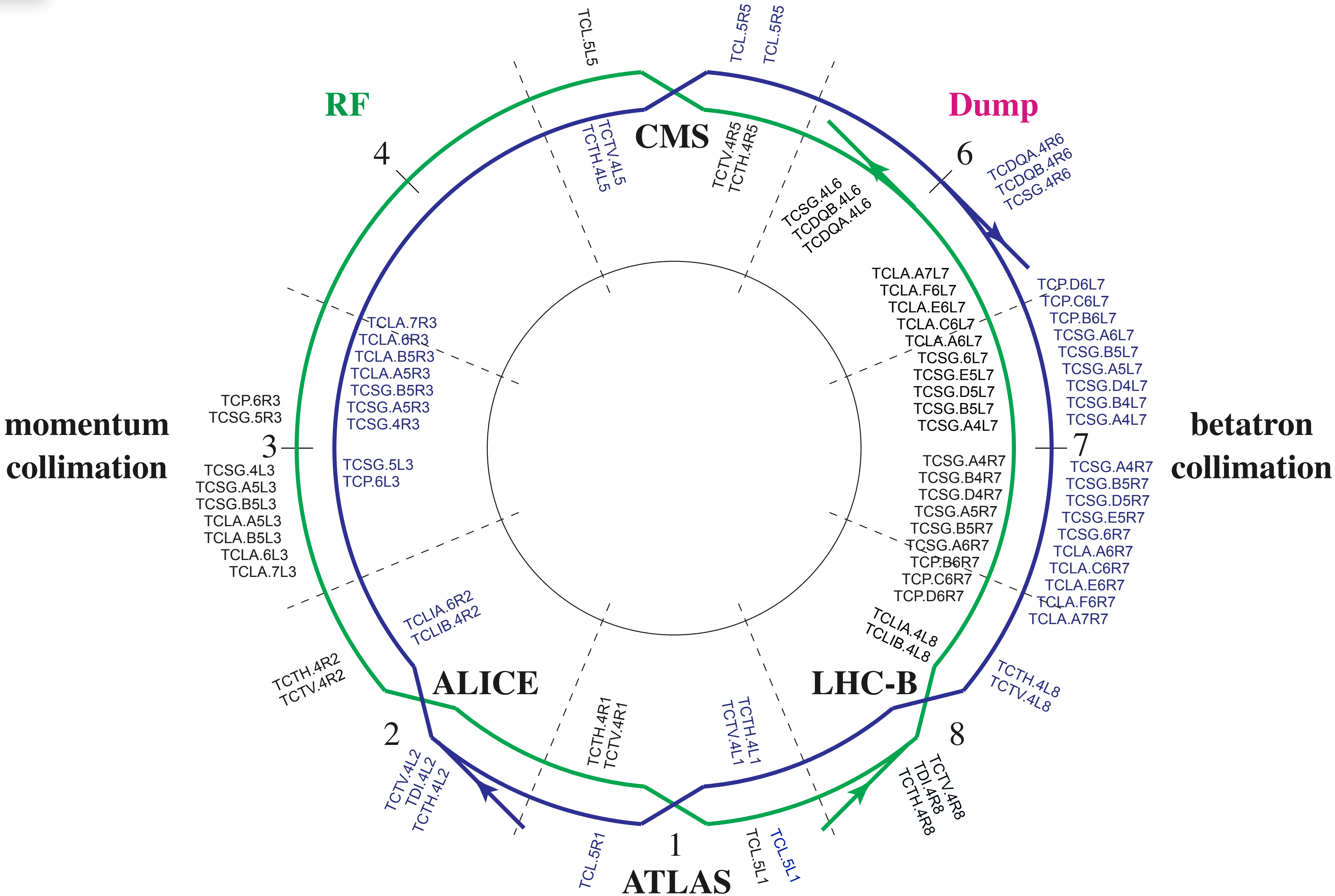
Reporting from the machine team - on work done in close collaboration with the experiments

Related meetings at CERN, - machine + experiments (#machine people < #institutes in experiments) :

LBS LHC Background Study Group; dealing with beam conditions for Expts., open WG, chaired by me

LPC LHC Programme Coordination, chaired by M. Ferro-Luzzi (next speaker)

Layout of the LHC



94 collimators (phase 1)

Few words on the LHC status

LHC :
End of 2009 first collisions, mostly at injection energy 2x450 GeV

2010 : commissioning and first year of operation with collisions at high energy;

- **already 350 nb^{-1} delivered** per experiment
- **main LHC challenge : damage potential,**
- **enormous stored energy :** nominal is 10 GJ in magnets, 362 MJ in beam
- currently 2.5 GJ in magnets, 0.5 MJ in beam
- next : double intensity 24+24 bunches; run like that during August

	LHC design	July 2010
Momentum at collision, TeV/c	7	3.5
Luminosity, $cm^{-2}s^{-1}$	1.0E+34	1.6E+30
Dipole field at top energy, T	8.33	4.17
Number of bunches, each beam	2808	12
Particles / bunch	1.15E+11	0.9E+11 (up to 1.3E+11)
Typical beam size in ring, µm	200 – 300	300-500
Beam size at IP, µm	17	59

LHC fill 1233 from last week-end

Stable beams for 19 hours (18/07 10:57 to 19/07 5:59)**; initially L = 1.65e30 cm-2s-1;** 70nb-1 from this fill

Luminosity by request reduced for ALICE, earlier in this fill also for LHCb

1.2e12 total beam intensities; 13 bunches; 8+8 colliding each experiment; β*=3.5 m

Factors needed to go to nominal : #bunches 2808/8 = 351 ; β* 3.5/0.55 = 6.4; Eb 7/3.5 = 2; Intensity (1.15/0.9)^2 = 1.6 together 7300 which gets us to 1.2e34 cm-2s-1 (extra 20 loss in crossing angle)

Filling pattern and collisions

Reference numbers, nominal LHC

f_{RF} = 400.7896 MHz

λ_{RF} = 0.748 m or 2.4951 ns

35 640 RF buckets

Bunches spaced by multiples of 25 ns or 10 buckets, allowing for a maximum of 3564 bunches

Gaps required for kicker timing with
a 119 bunch abort gap ~ 3 μs
Inject batches of
2, 3 or 4 x 72 bunches
1 batch = 72 bunches
total 39×72 = **2808 bunches**

A full LHC turn is 88.9244 μs

Figure from M. Ferro-Luzzi LPC 19/07/10

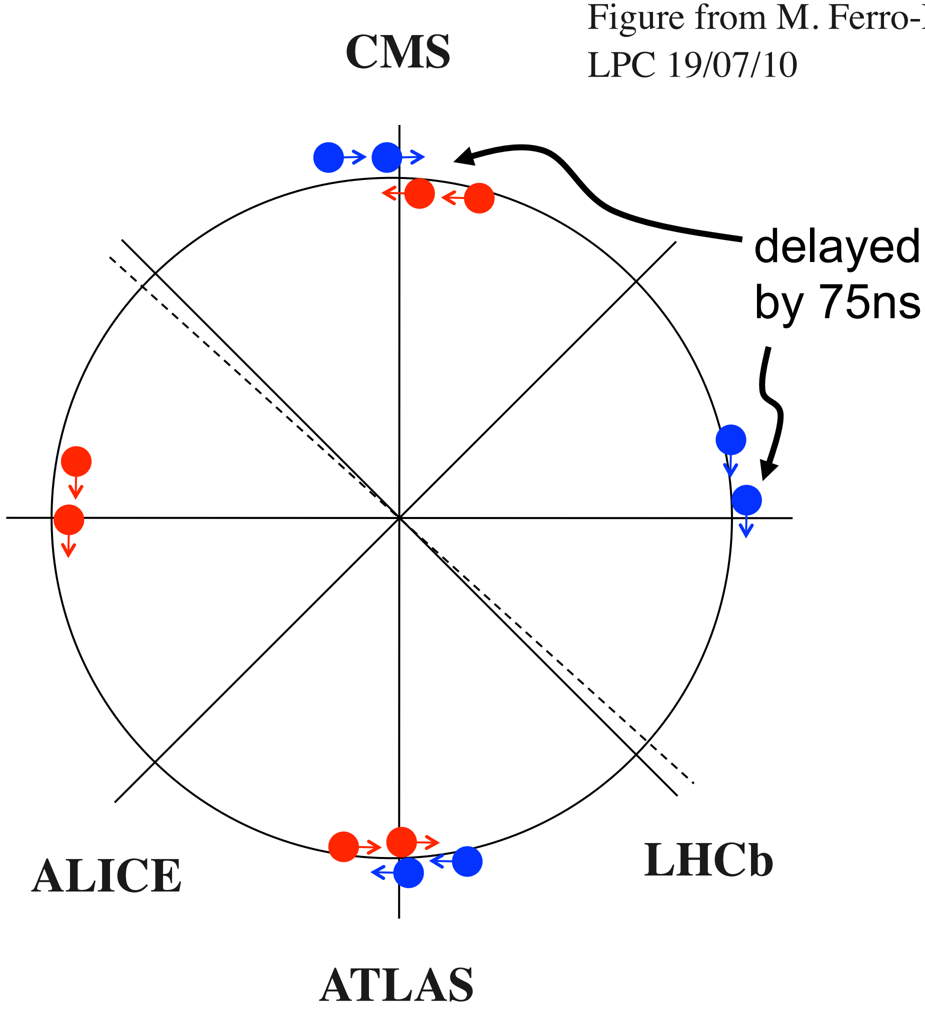
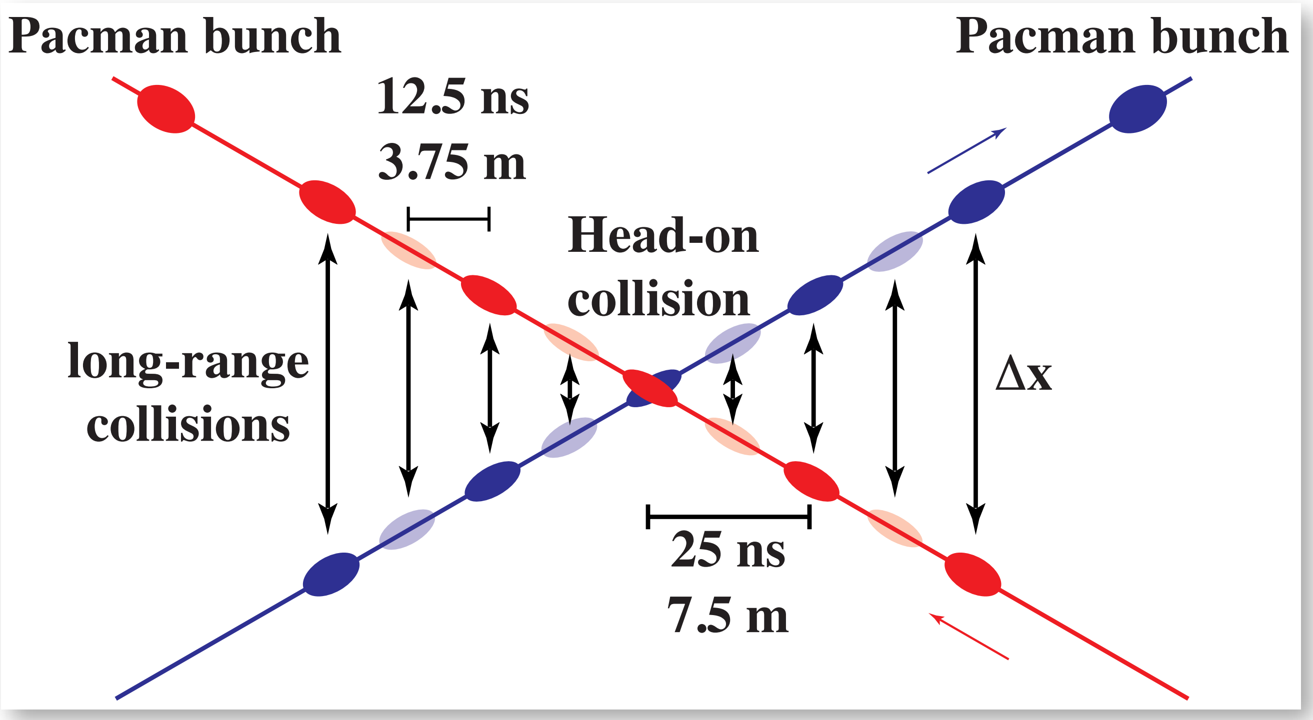


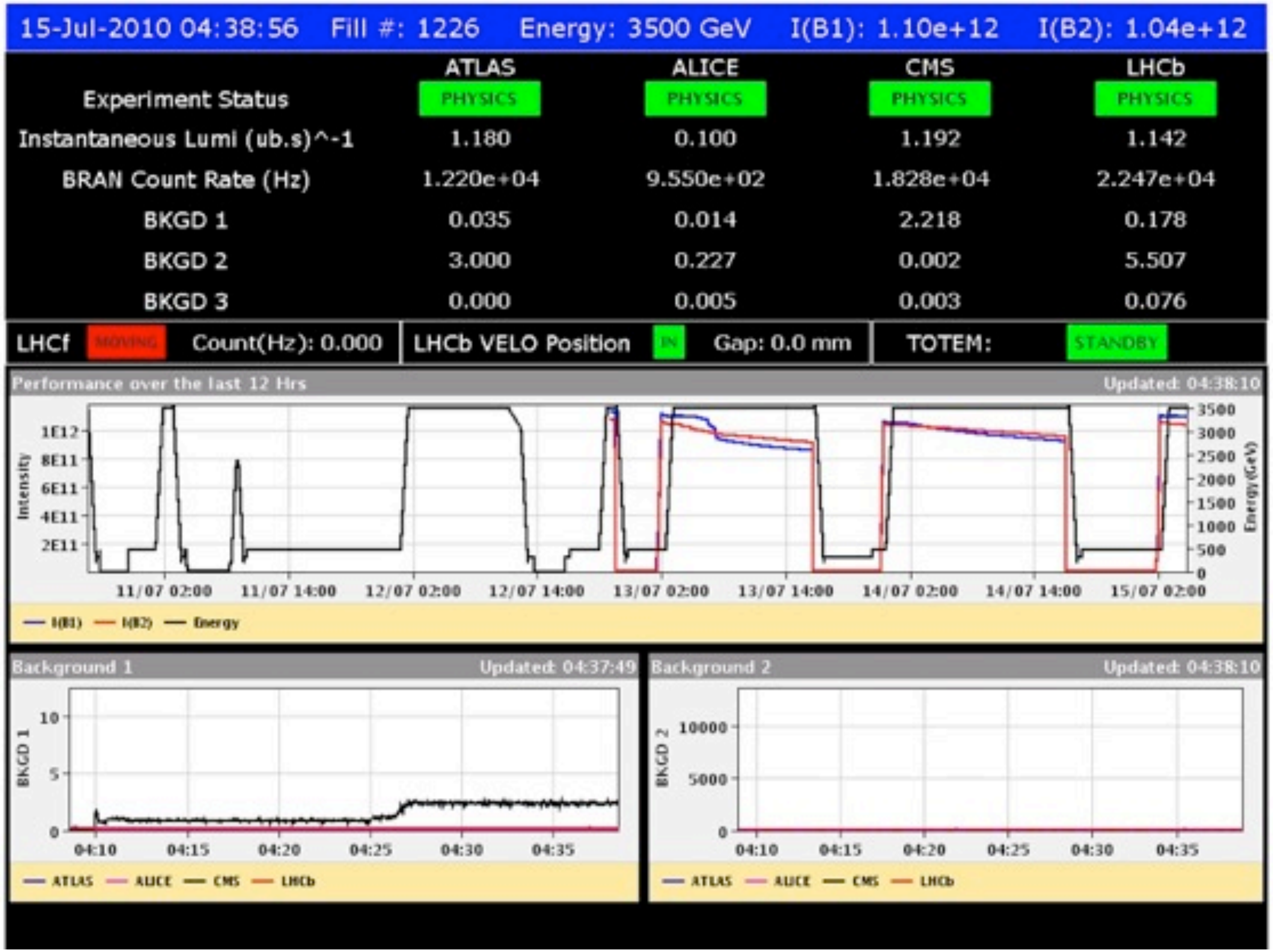
Illustration of collisions from few bunches as relevant for current operation

Crossing angle required for many bunches

Crossing angle needed for bunch spacing below 21×25 ns to avoid encounters closer than ~ 6 σ
Angle scales with σ or $1/\sqrt{\beta^*}$ and $1/\sqrt{E_b}$
Nominal angle at 0.55 m, 7 TeV is ± 142.5 μrad
2×15 parasitic crossings ±58m from IP at 7.5 – 13 σ
Maximum is 156 bunches without crossing angle
In 7/2010 : β* = 3.5 m, 3.5 TeV, 100 μrad in 1&5



Signal exchange and status pages



Automatic exchange of data :

Luminosity, backgrounds - from the experiments

Machine : settings and measurements of beam parameters, currents ..

Basis for optimisation and essential for luminosity optimization and calibration scans.

Main machine induced background sources

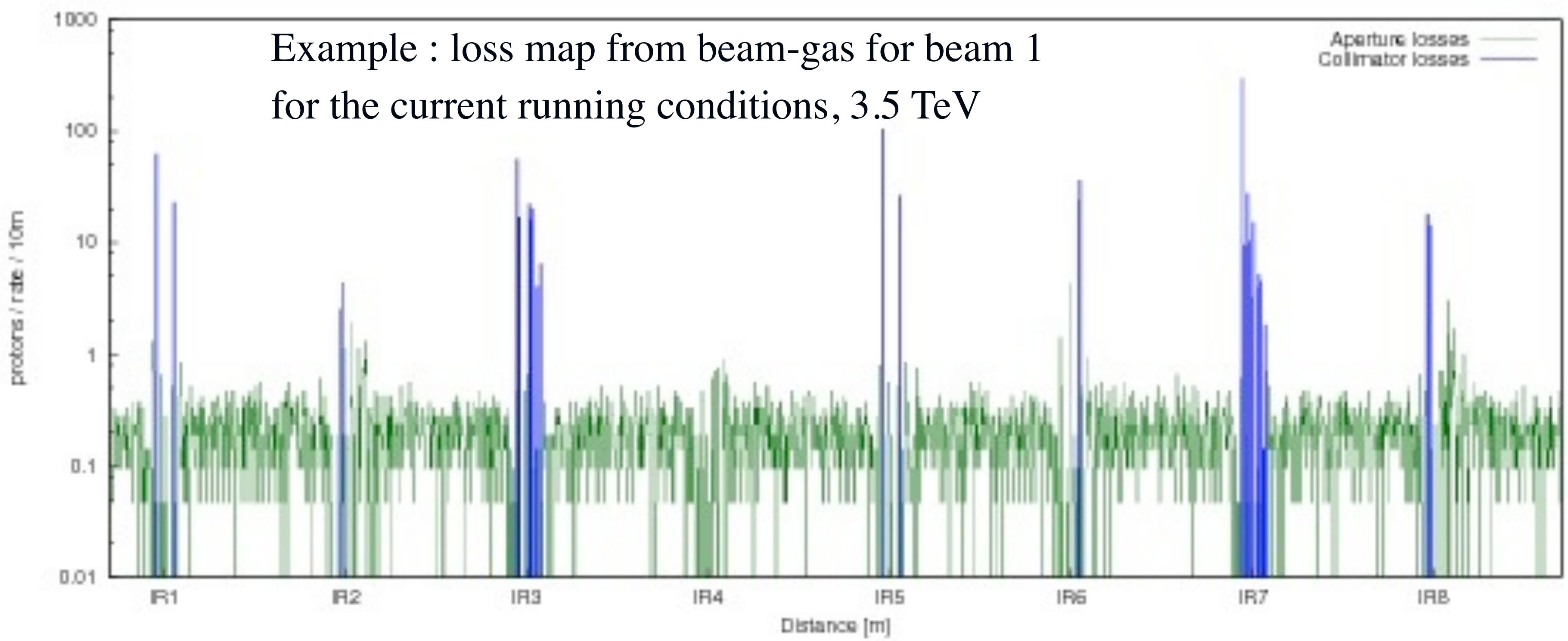
and how to distinguish between them (in practice not always obvious)

1. Beam gas scattering on residual gas, always present; pressure and intensity dependent
2. Halo - losses by slow drift, on primary, secondary, tertiary collimators ; lifetime - collimation dependent
3. Collision related - only there when in collisions; depending in separation in IPs
   "signal" if originating by collisions at the IP
   "collision - cross talk" background - if generated in other IPs

Simulations

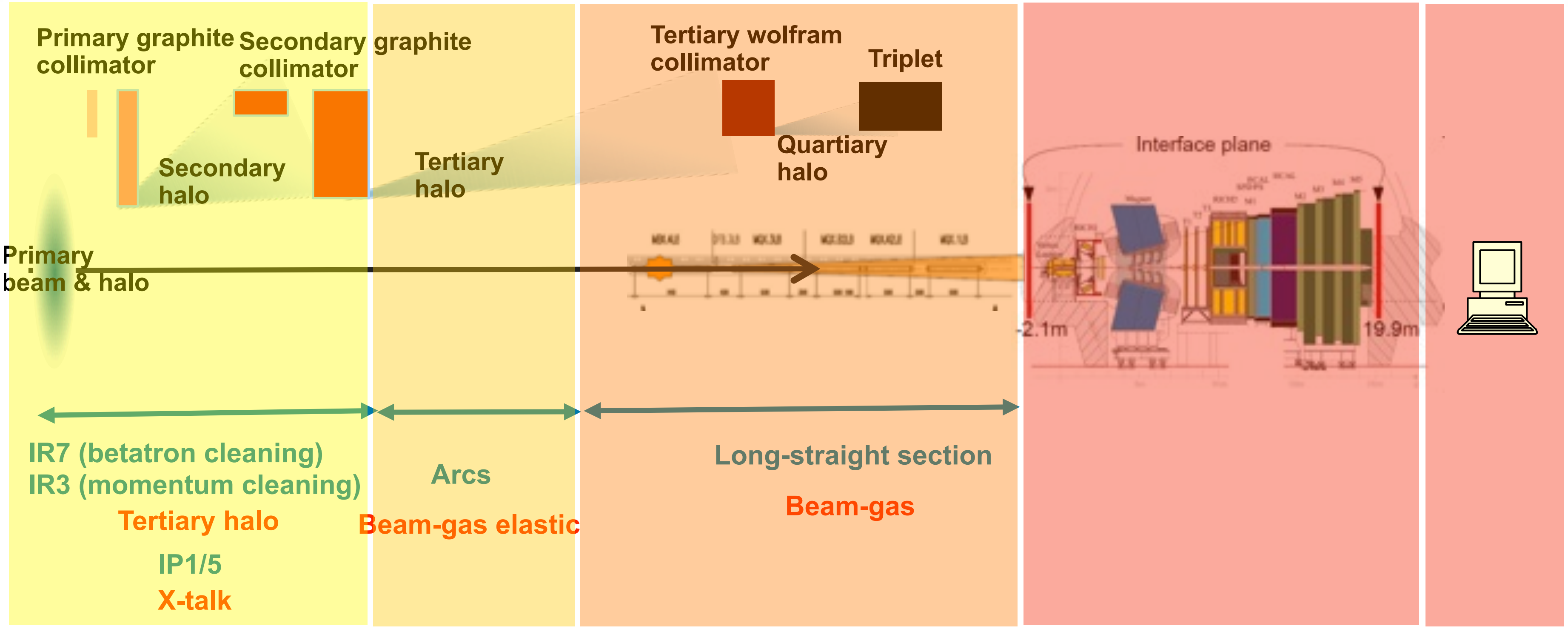
we are providing rather complete sets of simulations for all known sources
for different running scenarios and energies
For details see http://project-lhc-bkg-sim.web.cern.ch

Example : loss map from beam-gas for beam 1
for the current running conditions, 3.5 TeV



Halo part by the collimation team (A. Rossi et. al.)
Beam gas with input from the vacuum group and cross talk; PhD student Yngve Levinsen
Geometry and secondaries around IPs up to experiments : Rob Appleby (2&8), Roderik Bruce (1&5)
with lots of help from the experiments - who use this as input for detector simulations
including Nikolai Mokhov, Vadim Talanov, ..

Background Sources & Simulations



Loss maps prepared by Collimation Team

Beam-gas losses and IP X-talk provided by Y.Levinsen and H.Burkhardt (BE/ABP) with input from Vacuum group

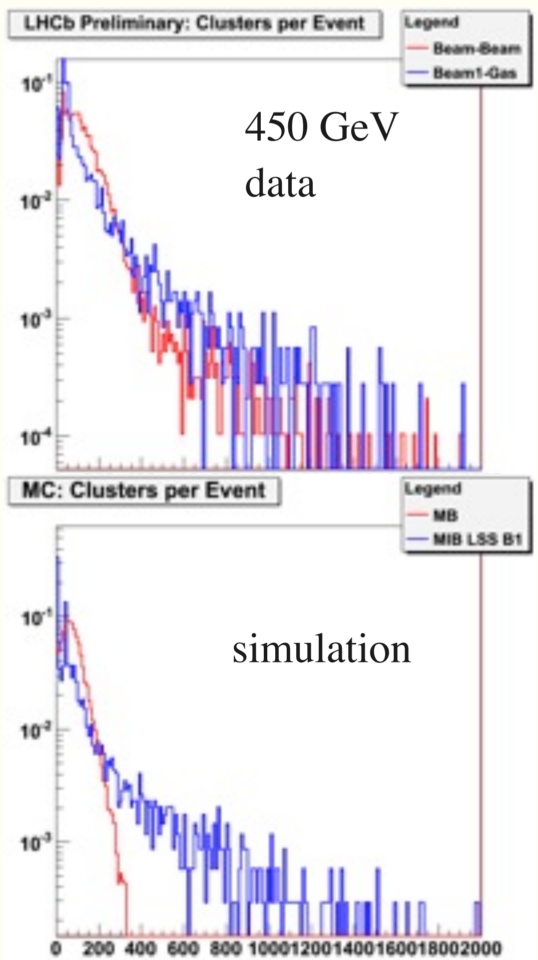
Losses in LSS and cascade and transport to interface plane by R. Appleby (EN/MEF)

Transport, cascade and detector response using in Gauss (special generator) and Boole by M. Lieng and V. Talanov for BLS

Analysis of LHCb response and impact using Brunel and DaVinci by M.Lieng

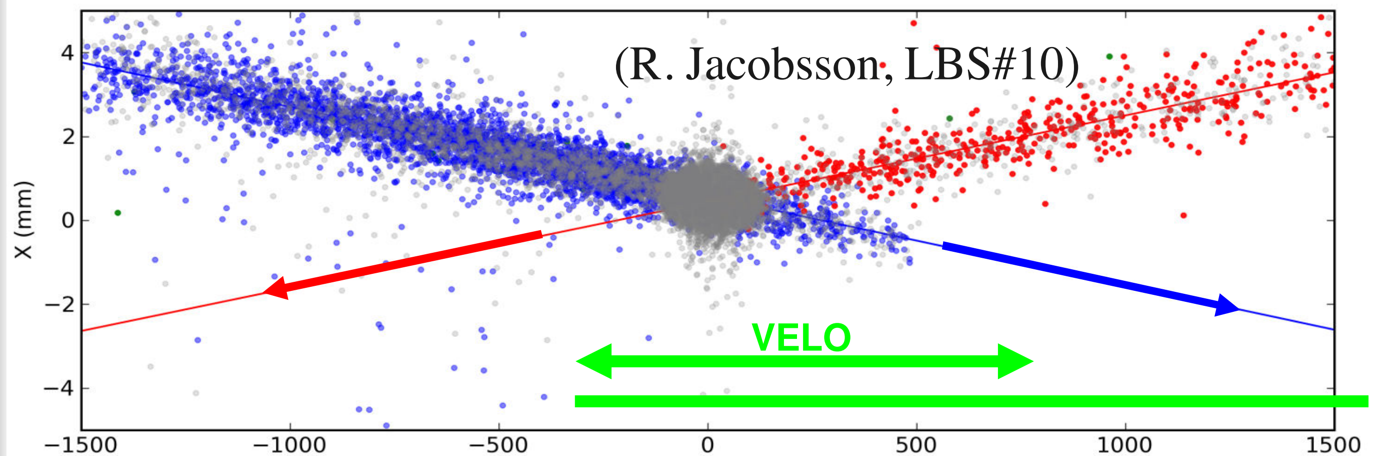
Slide from Gloria Corti / LHCb, LBS#12

Current backgrounds



at least on some occasions, a good agreement between data and simulation in shape and magnitude was seen

Current background levels are typically very low and to some extend welcome to see the beam

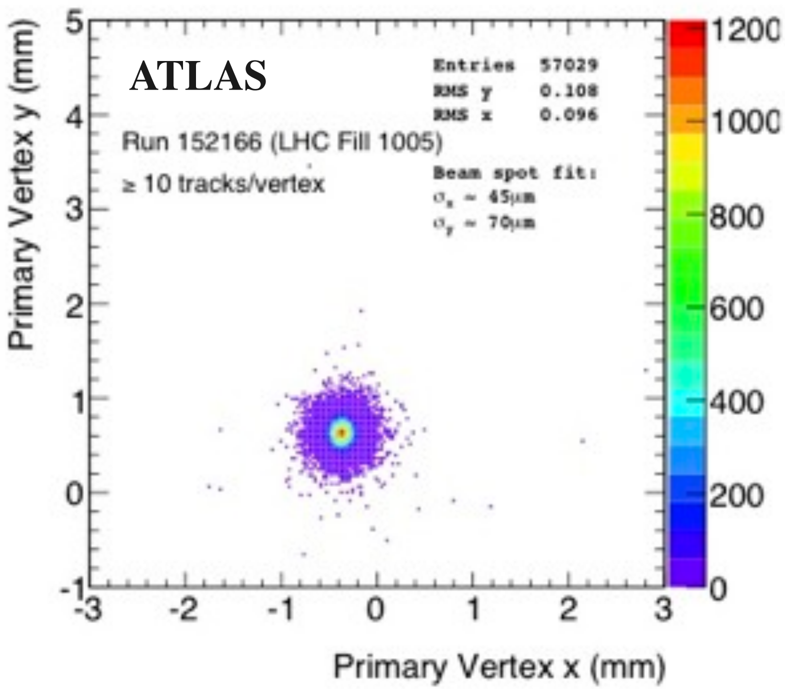


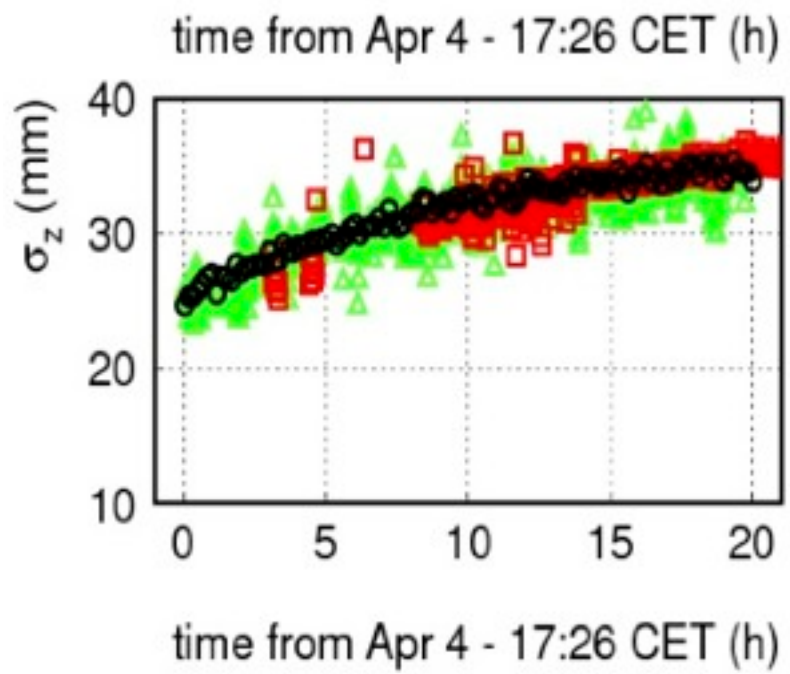
- We still have a **very** long way to go
- nearly 4 orders of magnitude in peak luminosity
- Backgrounds may increase faster

Example beam gas : intensity limit now 1.2×10^{12} @ 3.5 TeV. Nominal is 3.2×10^{14} at 7 TeV / beam
in addition to the factor of 300 in intensity we may get a factor of 100 in dynamic pressure increase
together this is would be an increase of 3×10^{4}

IP parameters, vertex information from experiments

vertex distributions and positions in x, y, z; measured by the experiments; [IPAC'10 paper with ATLAS]





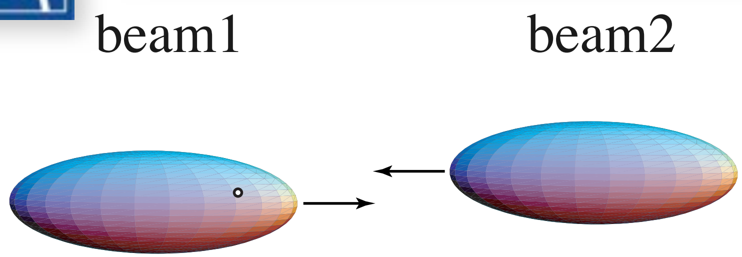
Longitudinal and transverse beam sizes are also measured on the machine side - wire scanners, synchrotron light monitors

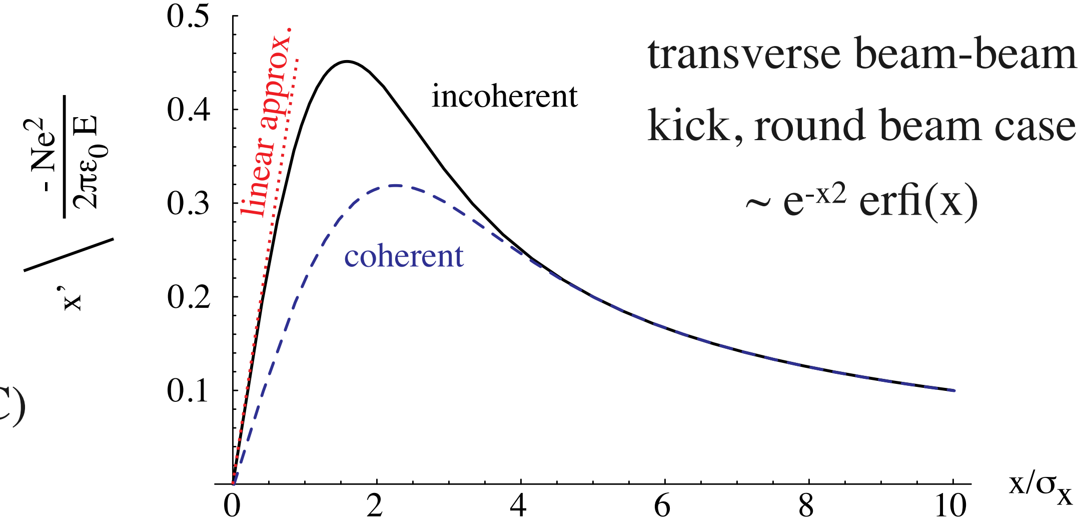
Was already very useful for cross calibration of instruments

Can be expected to further gain interest for the detailed fill analysis as a basis to understand the emittance and luminosity evolution during a fill and for orbit optimisation around IPs

Possible to locate beam-pipe and screen by secondary interactions ; can help for re-alignment and to gain space for reducing the beam pipe radius

Beam-beam effects





transverse beam-beam kick, round beam case

$\sim e^{-x^2}\,\mathrm{erfi}(x)$

separation in σ

for small x approx. linear kick x' ∝ x

like quadrupole but **same in both planes**,

defocusing if beam1, 2 have same charge (LHC)

and focusing for opposite charge (e+e-, $\mathbf{p\bar{p}}$)

tune shift from linear kick

$$\Delta Q_x = -\frac{\beta_x}{4\pi}\frac{\Delta x'}{x}$$

this maximum tune shift - effective for particles at the bunch centre - is used to quantify the beam-beam effect.

N = bunch population,

r_c = classical particle (e, p) radius

$$\xi_{x,y} = \frac{r_c\ N\,\beta^*_{x,y}}{2\pi\,\gamma\,\sigma_{x,y}\,(\sigma_x+\sigma_y)}$$

LEP

$\xi_{x,y} \sim .03$ - $.08$

LHC round beams, const ε_N $\quad \sigma_{x,y} = \sqrt{\beta_{x,y}\,\epsilon_N/\gamma}$

$$\xi = \frac{r_c\,N}{4\pi\,\epsilon_N}$$

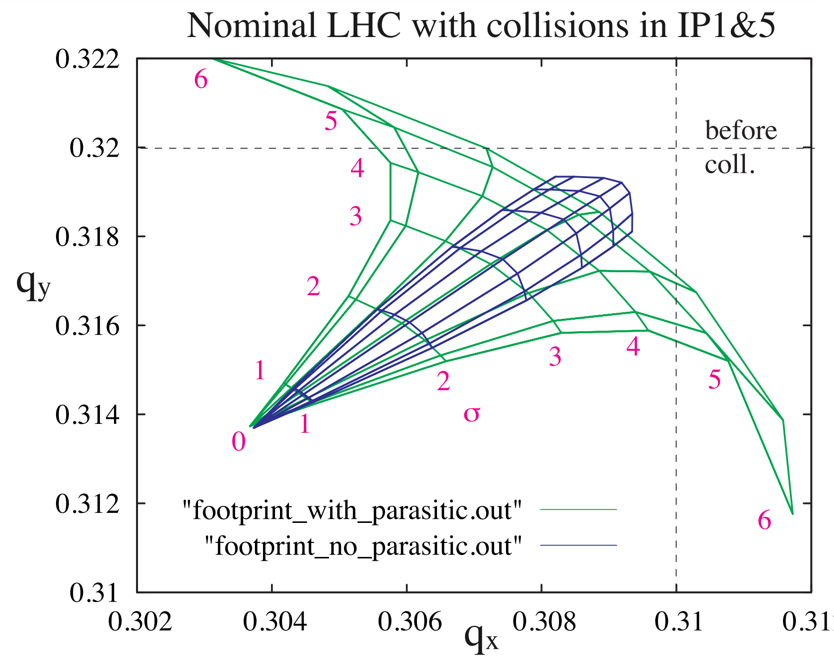
N	ξ
5×10^{9}	0.000163
4×10^{10}	0.00130
1.15×10^{11}	0.00374

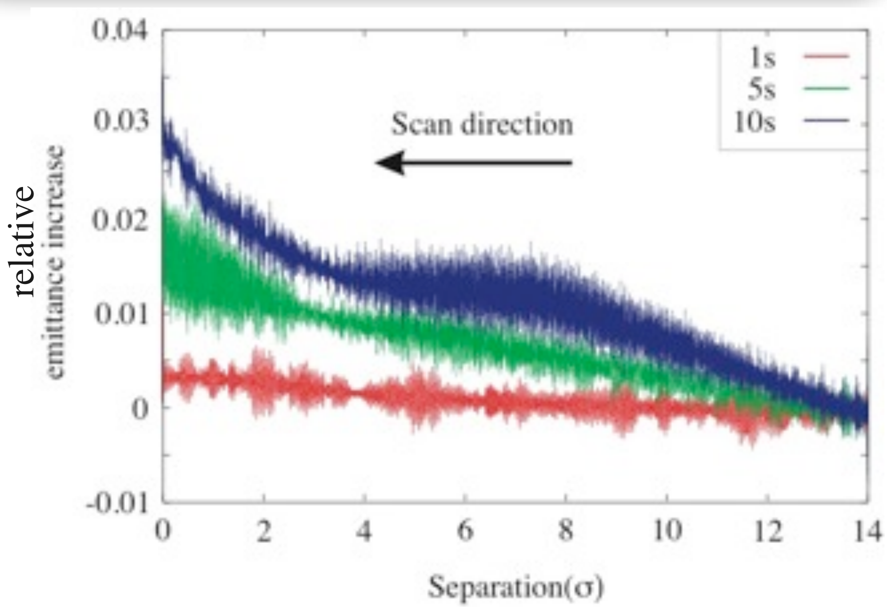
at the design emittance

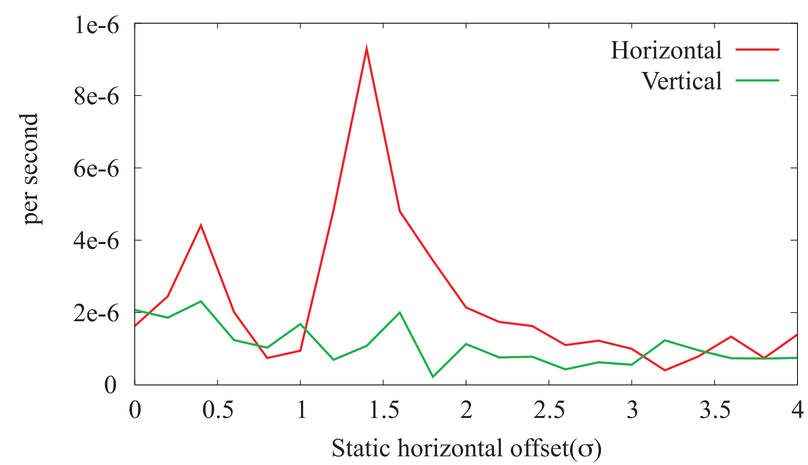
Parasitic b.b., speed to go into collisions & emittance increase

Parasitic beam-beam effects. Can be completely avoided up to 156 bunches.
Then gradually becoming an issue. Gain first experience on this in the 2009 / 2010 run
Nominal, IP1/5 : each 30 parasitic collisions ~ 9σ
Parasitic b.b. effects reduce with fewer bunches or increased crossing angle

Simulation : IP5 colliding. IP1 going into collision by ramping down the horizontal separation







close to head on beam-beam : peaks in blow up at 0.5 and 1.5 σ

Some ref.

W. Herr, M. Zorzano LHC Project Report 462 ; Tatiana Pieloni thesis

Figures above from S. M. White, H. Burkhardt, S. Fartoukh, T. Pieloni, *Optimization of the LHC Separation Bumps Including Beam-Beam Effects WE6PFP018*, PAC'09

Luminosity, general concept

general case, integrated luminosity from single collision of two bunches

$$\mathcal{L}_{sc} = N_1\, N_2 \int dt\, d^3\mathbf{x}\, \rho_1(\mathbf{x},t)\, \rho_2(\mathbf{x},t) \sqrt{(\mathbf{v}_1 - \mathbf{v}_2)^2 - \frac{(\mathbf{v}_1 \times \mathbf{v}_2)^2}{c^2}}$$

kinematic factor from C. Møller, 1945

formulas for special cases are rather straight forward to derive, see also W. Herr et al. CAS 2003

some examples given here.

For head-on collisions "√" $= |v_1 - v_2| \approx 2c$, the differential luminosity can be written as :

$$\mathcal{L} = 2f\, N_1 N_2 \int \rho_1(x,y,s_1)\, \rho_2(x,y,s_2)\, dx\, dy\, ds\, d(\beta ct), \text{ where } s_1 = s+\beta ct \text{ and } s_2 = s-\beta ct$$

Event rate for process with cross section σ $\quad \dot{n} = \mathcal{L}\sigma$

Luminosity reduction by the hourglass effect

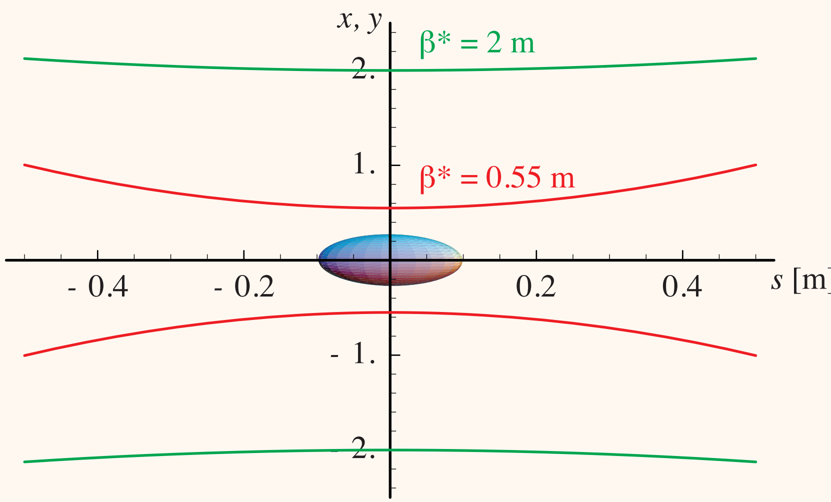
Hourglass effect. Relevant when β* is decreased close to the bunch length σ_z. Define $r = \beta^* / \sigma_z$. Luminosity gets reduced. For round beams the factor is

$$H(r) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-s^2}}{1 + s^2/r^2}\, ds = \sqrt{\pi}\, r\, e^{r^2}\, \mathrm{Erfc}(r)$$

LHC values

$\sigma_z = 7.55$ cm

β^*	r	$H(r)$
10.	132.	0.999972
2.	26.5	0.999289
1.	13.2	0.997174
0.55	7.28	0.990833



LHC : negligible effect for β* > 2m and still small for nominal β*

Luminosity with crossing angle

Factor from crossing angle in one plane (x) : $S = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z}{\sigma_x} \tan \frac{\Phi}{2}\right)^2}}$

σ_x [μm]	σ_z [mm]	$\Phi/2$	S	
59.3	0.0755	100	0.992	3.5 TeV, $\beta^* = 3.5$ m, July 2010
16.6	0.0755	142.5	0.840	7 TeV, $\beta^* = 0.55$ m, nominal

small effect

Both angle and separation : the reduction can be written as the product of three factors S · U · T where

crossing angle

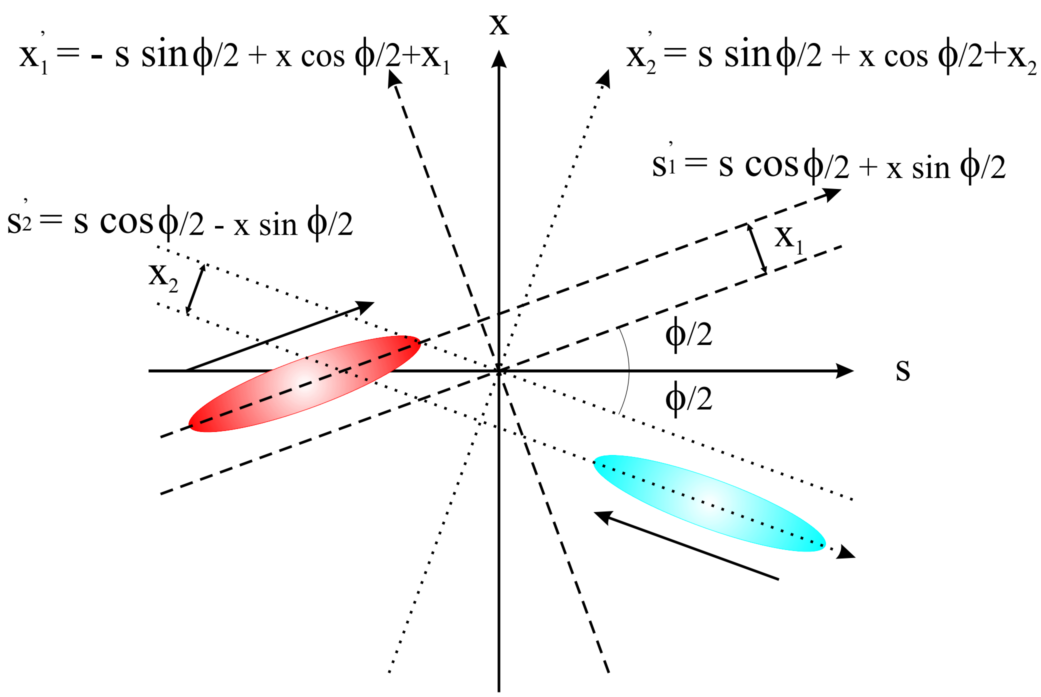
$$S = \frac{1}{\sqrt{1 + \frac{\sigma_{1s}^2+\sigma_{2s}^2}{\sigma_{1y}^2+\sigma_{2y}^2}\left(\tan\frac{\phi_y}{2}\right)^2 + \frac{\sigma_{1s}^2+\sigma_{2s}^2}{\sigma_{1x}^2+\sigma_{2x}^2}\left(\tan\frac{\phi_x}{2}\right)^2}}$$

separation

$$T = e^{-\frac{\delta x^2}{2(\sigma_{1x}^2+\sigma_{2x}^2)} - \frac{\delta y^2}{2(\sigma_{1y}^2+\sigma_{2y}^2)}}$$

both

$$U = e^{S^2 \frac{\sigma_{1s}^2+\sigma_{2s}^2}{2}\left(\frac{\delta x \tan\frac{\phi_x}{2}}{\sigma_{1x}^2+\sigma_{2x}^2} + \frac{\delta y \tan\frac{\phi_y}{2}}{\sigma_{1y}^2+\sigma_{2y}^2}\right)^2}$$

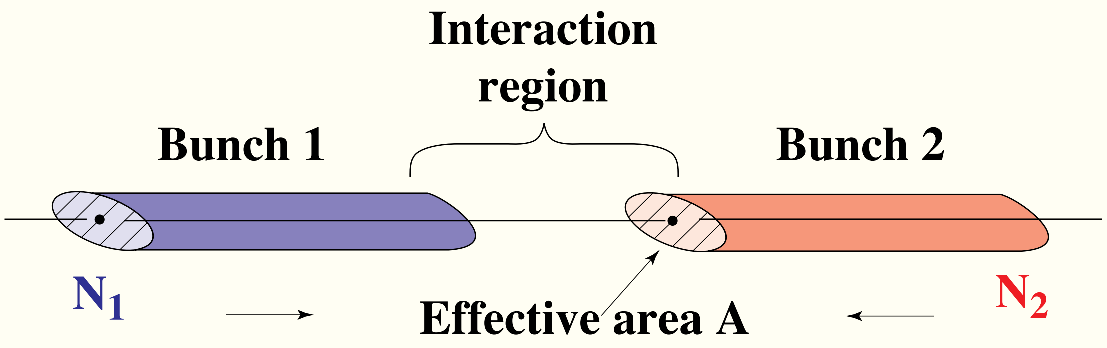


courtesy Simon White

Absolute Luminosity Normalization

Luminosity from bunch crossings at frequency $f = f_{rev}\, n_b$

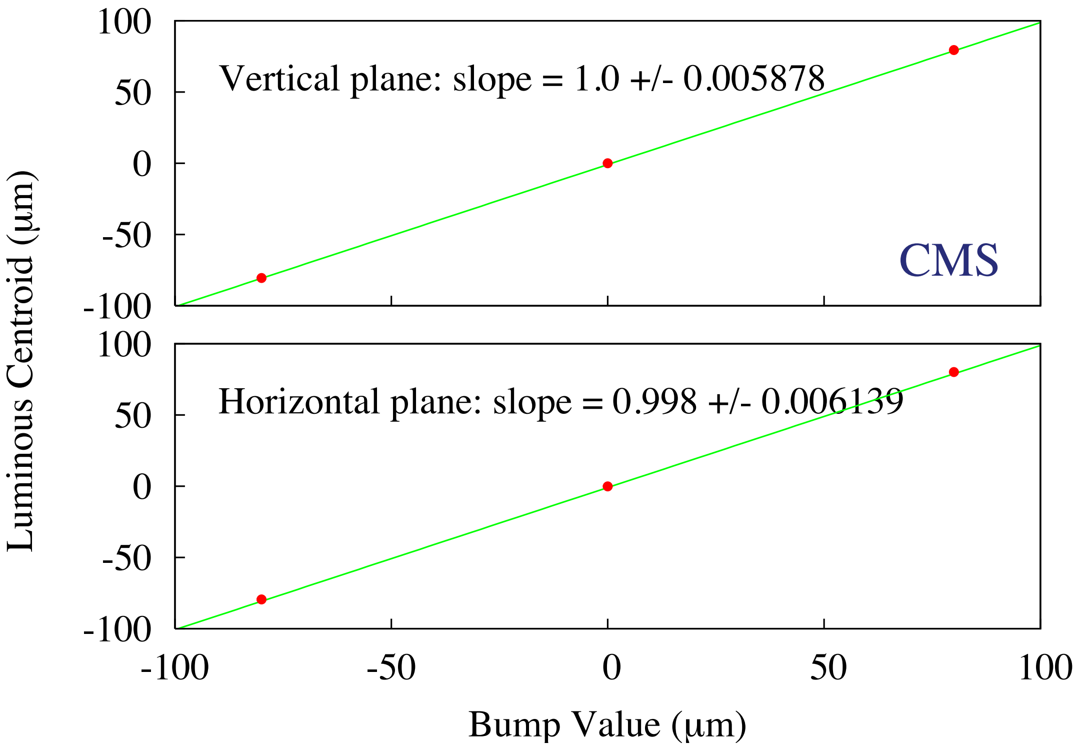
$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

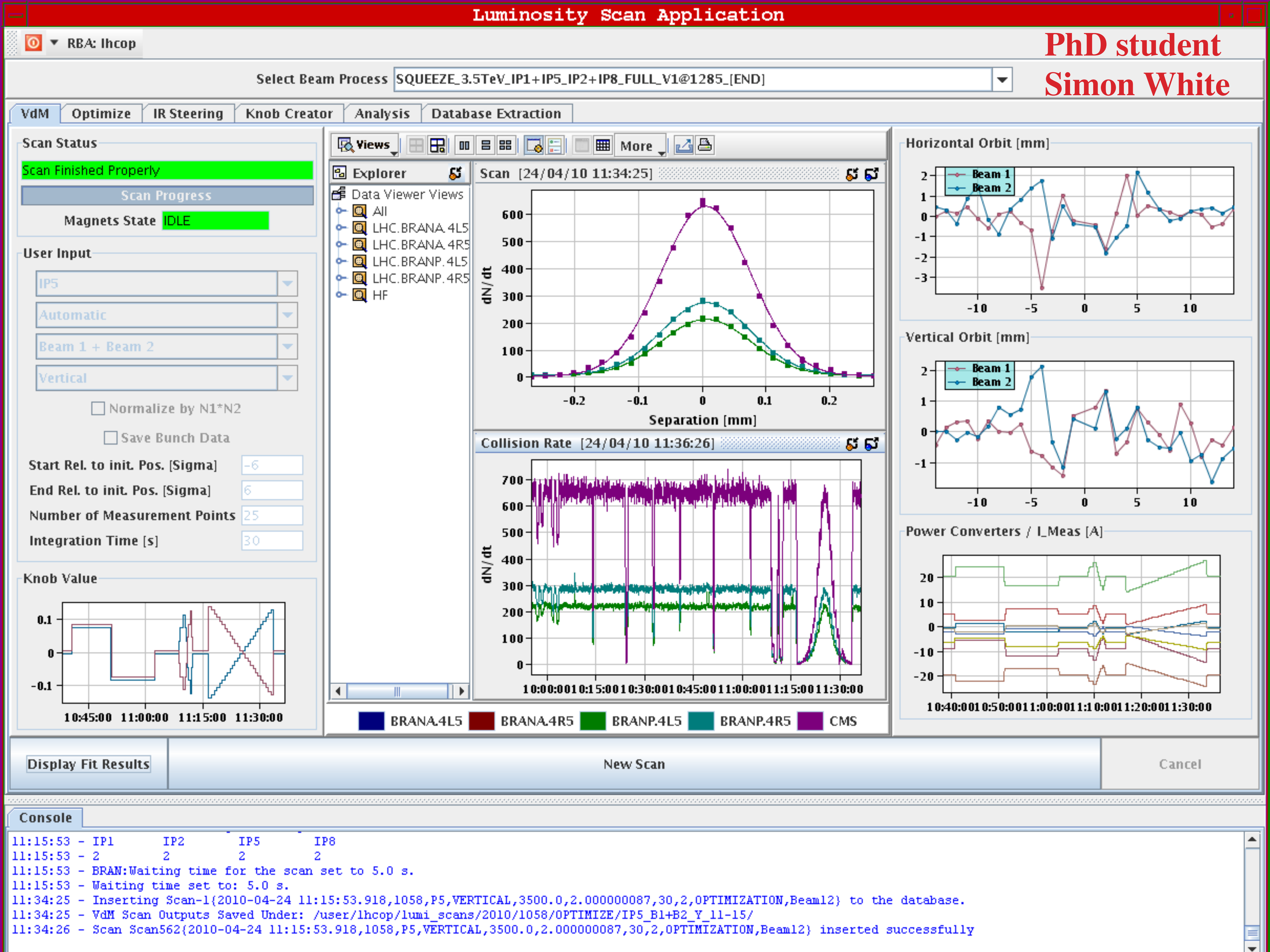


for Gaussian bunches with rms sizes $\sigma_x\ \sigma_y$ $\mathbf{A} = 4\pi\sigma_x\sigma_y$

The overlap area is directly measured in separation scans , pioneered by Simon Van der Meer @ ISR

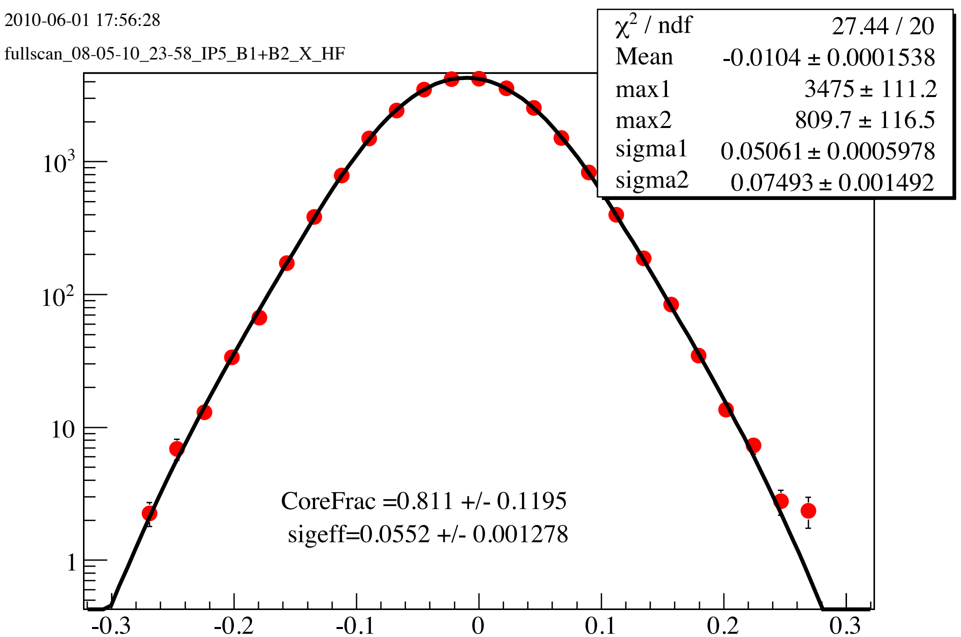
length scale calibrated
displacing both beams
+ vertex info from detectors

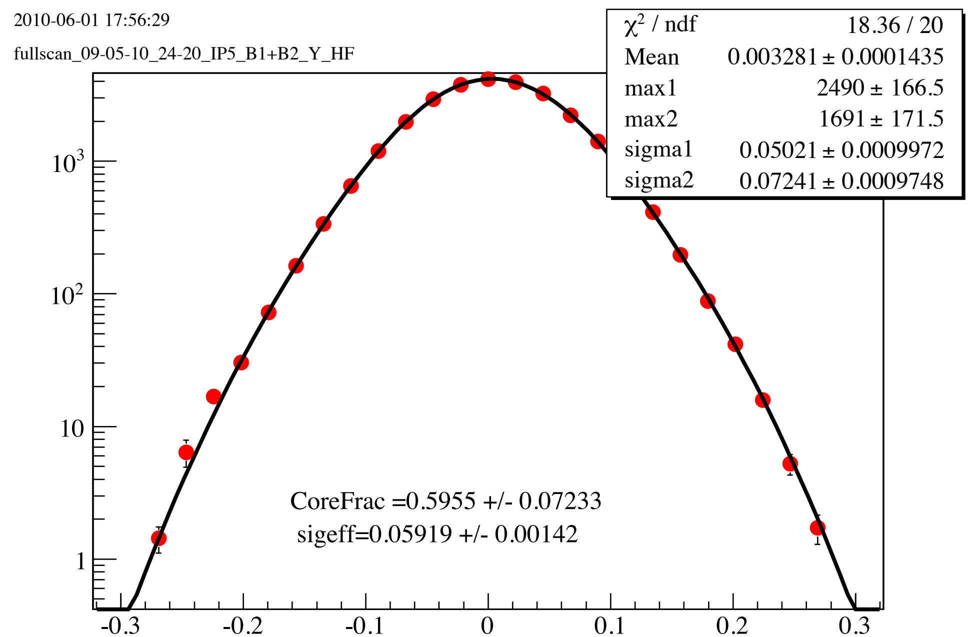



Luminosity Scan Application
RBA: lhcop
PhD student
Simon White
Select Beam Process
SQUEEZE_3.5TeV_IP1+IP5_IP2+IP8_FULL_V1@1285_[END]
VdM
Optimize
IR Steering
Knob Creator
Analysis
Database Extraction
Scan Status
Scan Finished Properly
Scan Progress
Magnets State
IDLE
User Input
IP5
Automatic
Beam 1 + Beam 2
Vertical
Normalize by N1*N2
Save Bunch Data
Start Rel. to init. Pos. [Sigma]
-6
End Rel. to init. Pos. [Sigma]
6
Number of Measurement Points
25
Integration Time [s]
30
Knob Value
Views
More
Explorer
Data Viewer Views
All
LHC.BRANA.4L5
LHC.BRANA.4R5
LHC.BRANP.4L5
LHC.BRANP.4R5
HF
Scan [24/04/10 11:34:25]
dN/dt
Separation [mm]
Collision Rate [24/04/10 11:36:26]
BRANA.4L5
BRANA.4R5
BRANP.4L5
BRANP.4R5
CMS
Horizontal Orbit [mm]
Beam 1
Beam 2
Vertical Orbit [mm]
Power Converters / I_Meas [A]
Display Fit Results
New Scan
Cancel
Console
11:15:53 - IP1 IP2 IP5 IP8
11:15:53 - 2 2 2 2
11:15:53 - BRAN:Waiting time for the scan set to 5.0 s.
11:15:53 - Waiting time set to: 5.0 s.
11:34:25 - Inserting Scan-1{2010-04-24 11:15:53.918,1058,P5,VERTICAL,3500.0,2.000000087,30,2,OPTIMIZATION,Beam12} to the database.
11:34:25 - VdM Scan Outputs Saved Under: /user/lhcop/lumi_scans/2010/1058/OPTIMIZE/IP5_B1+B2_Y_11-15/
11:34:26 - Scan Scan562{2010-04-24 11:15:53.918,1058,P5,VERTICAL,3500.0,2.000000087,30,2,OPTIMIZATION,Beam12} inserted successfully

First extended scans : beams very clean

Example for illustration from online data sent by CMS to the CCC
Showing a scan by +/- 3 nominal sigma for CMS in LHC fill 1089
2e10 protons / bunch; single colliding pair





Fits well by a double gaussian. Low background. No extended tails.

Offline analysis and discussion on the systematic errors :
done by the experiments; next talk and papers at this conference
Overall uncertainty from first scans ~ 11%, dominated by the uncertainty in the intensity determination

Luminosity scans - which precision could be reached ?

- **the first experience from the scans (~ two per experiment) done so far was very promising**

  two different types of uncertainties
- **intensity "N1 × N2"; 3-4 % from BCT specification JJ. Gras et al. Beam Instrum. group**
- **luminous region "$\sigma_x \times \sigma_y$"; very clean nearly Gaussian beams, fitting very well, 3-4 %**

  together we can hope to get down to 5%

Is there an interest to push this further ?

What might be the ultimate precision ?

What about 1% as for the ISR ? G. Carboni et al., Nucl. Phys. B 254 (1985) 697; K. Potter CAS'92

Would certainly required much more work and probably extra instruments

One idea :

Intensity normalisation by proton counting (for example with diamond detectors) **when slowly scraped off :**

40 MHz × 100 sec = 4×10^9 protons

Further information, bibliography - with authors from the machine

Documentation of details in forthcoming PhD thesis :

Simon White, Determination of the Absolute Luminosity in the LHC; Autumn 2010

Yngve Levinsen, Study of LHC Experimental Conditions and Machine Induced Detector Backgrounds; Autumn 2011

H.B. and Per Grafstrom; Absolute Luminosity from Machine Parameters, LHC Report 1019 May 2007

IPAC2010 proceedings :

First Luminosity Scans in the LHC, MOPEC014

Beam-gas Loss Rates in the LHC, TUPEB072

Dependence of Background Rates on Beam Separation in the LHC, TUPEB073

Characterization of Interaction-Point Beam Parameters .. in the ATLAS Detector at the LHC, MOPEC008

Concluding remarks

The LHC performs very well in the early physics operation

Single beam parameters (intensity, b.b. tune shift) reached nominal parameters

The increase in single bunch intensities was rather fast and smooth

Beam-beam effects rather complex and potential limitation - some worry on triggering coherent oscillations, otherwise rather better than expected

Next : increase the number of bunches - mostly a challenge for beam-protection including beam-dump and collimation

but also : improved and tighter control of many parameters and tolerances, decrease differences between beams and bunches; identify and reduce any sources of blow up pick-up and vibrations

Optimization tools : lumi scans, tunes (and b1, b2 tune split), minimize optics errors like beta beating, transverse damper, ...

Backup Slides

Beam-beam kick

Gaussian beams of elliptical cross section, beam-beam deflection angle and kicks using Basetti-Erskine function f_{BS}

$$\theta_{0\pm} = \frac{N_{\mp} e^2}{2\pi\,\epsilon_0\;E_{\pm}\;(\sigma_{x\mp} + \sigma_{y\mp})} = \frac{2 N_{\mp} r_c}{\gamma_{\pm}\;(\sigma_{x\mp} + \sigma_{y\mp})}$$

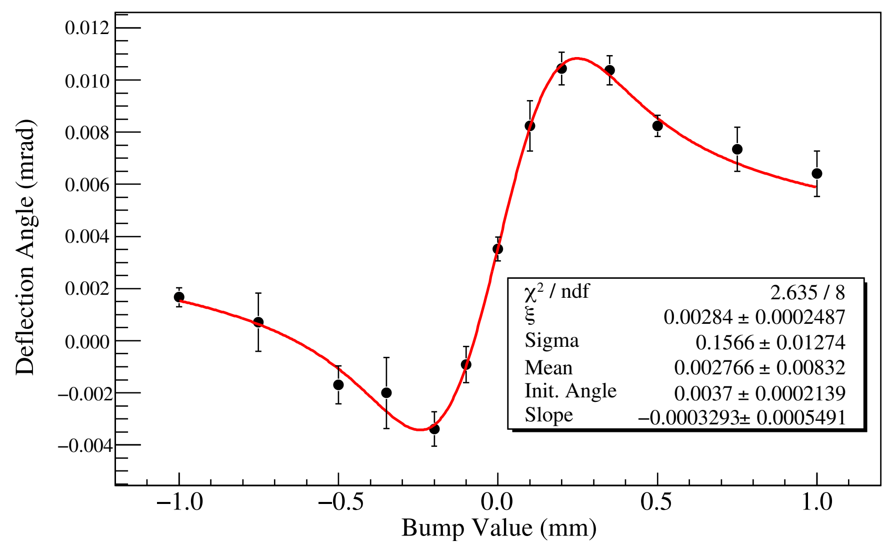
$$\Delta x'_{\pm} - i\Delta y'_{\pm} = -\theta_{0\pm}\; f_{\mathrm{BS}}(x_{\pm} - \overline{x}_{\mp}, y_{\pm} - \overline{y}_{\mp}; \sigma_x^{\mp}, \sigma_y^{\mp})$$

Round gaussian beams, $\sigma_x = \sigma_y = \sigma_r$ ~ the case of the LHC

$$\theta_0 = \frac{N e^2}{2\pi\,\epsilon_0\;E\;(\sigma_x + \sigma_y)} = \frac{N e^2}{2\pi\,\epsilon_0\;E\;2\,\sigma_r} = \frac{N r_c}{\gamma\,\sigma_r}$$

$$\Delta r' = -\frac{N\,e^2}{2\pi\epsilon_0\,E}\,\frac{1 - \exp\frac{-r^2}{2\sigma_r^2}}{r} = -2\,\sigma_r\;\theta_0\,\frac{1 - \exp\frac{-r^2}{2\sigma_r^2}}{r}$$

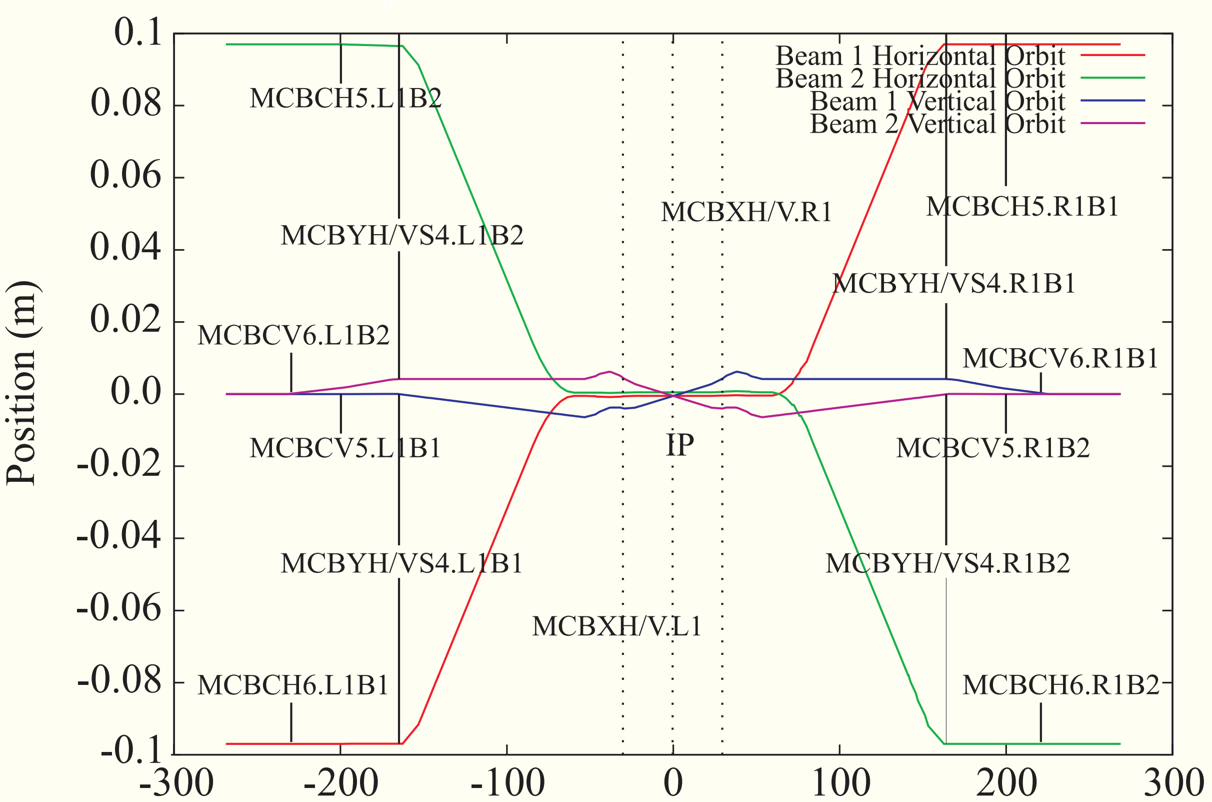
60 μrad LEP2, measurable, deflection scans
1.4 μrad for nominal LHC parameters
visible in RHIC :



A. Drees, S. White, et al. IPAC 2010

IR-bumps

two types of magnetic separation bumps :
parallel separation to avoid collisions in beam preparation, off in physics
crossing angle to avoid parasitic collisions, always required for > 156 bunches
IR1 : horizontal separation and vertical crossing angle
IR5 : vertical separation and horizontal crossing angle



courtesy Simon White

orbit corrector magnets used in the IP bumps

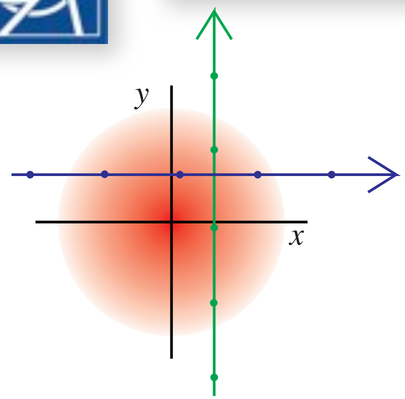
MCBX in triplet - important for crossing angle and aperture at injection

collapse bump by combination of MCBC, MCBY and MCBX
or ramp down MCBX first

Separation scans, optimization with MCBC, MCBY on one beam

Luminosity scans and absolute luminosity

(pioneered by Van der Meer @ ISR)

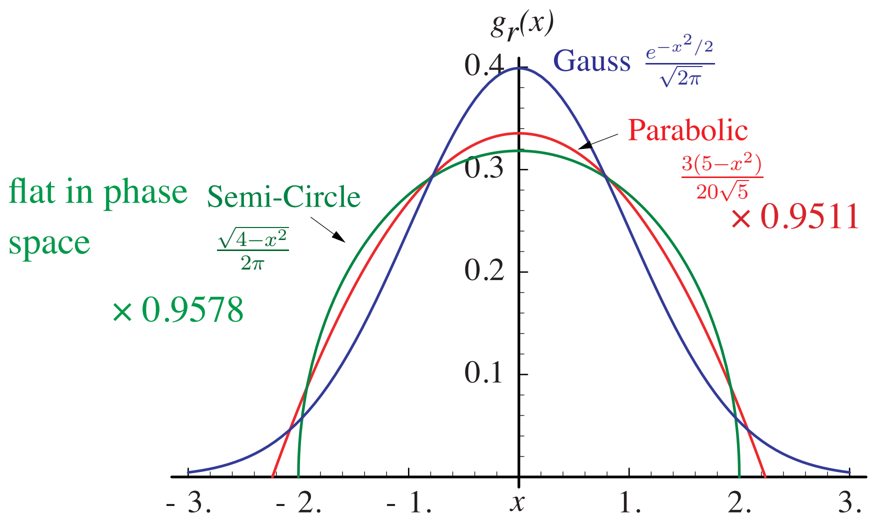


Orthogonal x, y scans to determine $\sigma_{x,y}$*

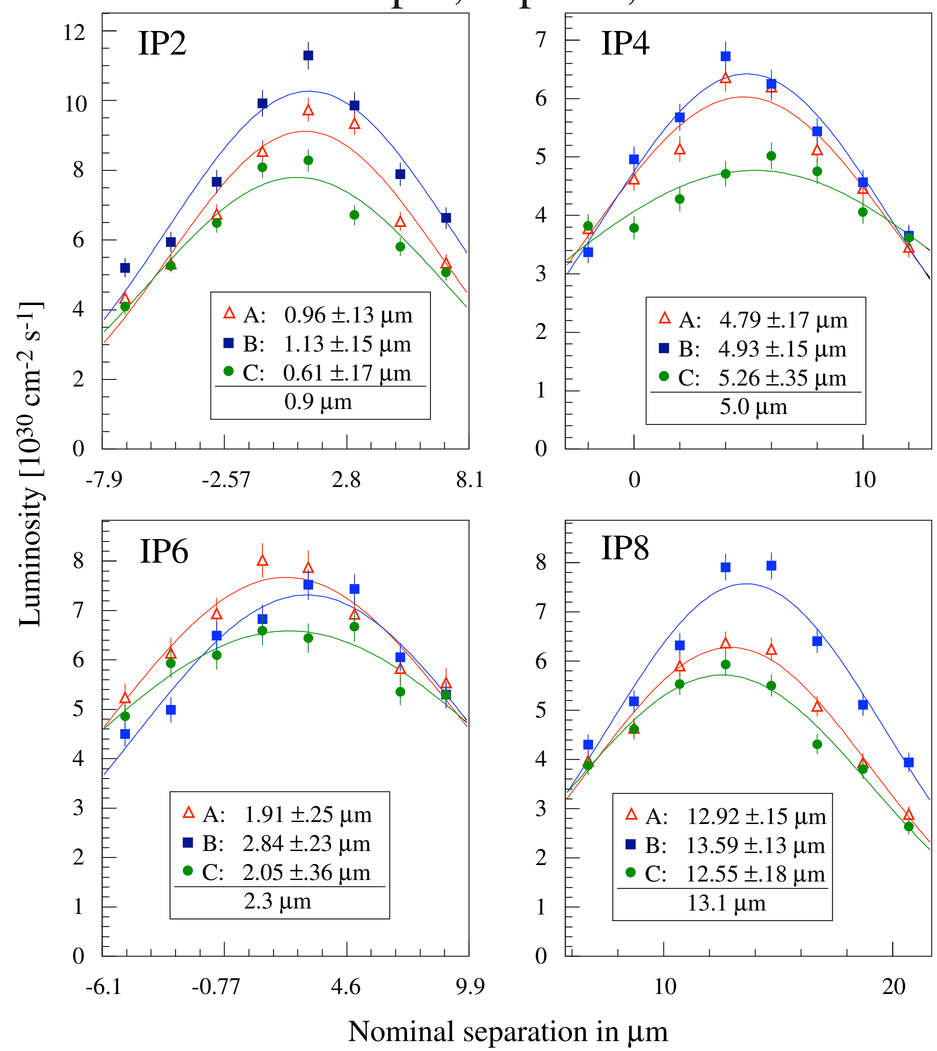
$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi\, \sigma_x\, \sigma_y}$$

$$\frac{\mathcal{L}}{\mathcal{L}_0} = \exp\left[-\left(\frac{\delta x}{2\sigma_x}\right)^2 - \left(\frac{\delta y}{2\sigma_y}\right)^2\right]$$ gaussian beams

Exact shape
extreme cases



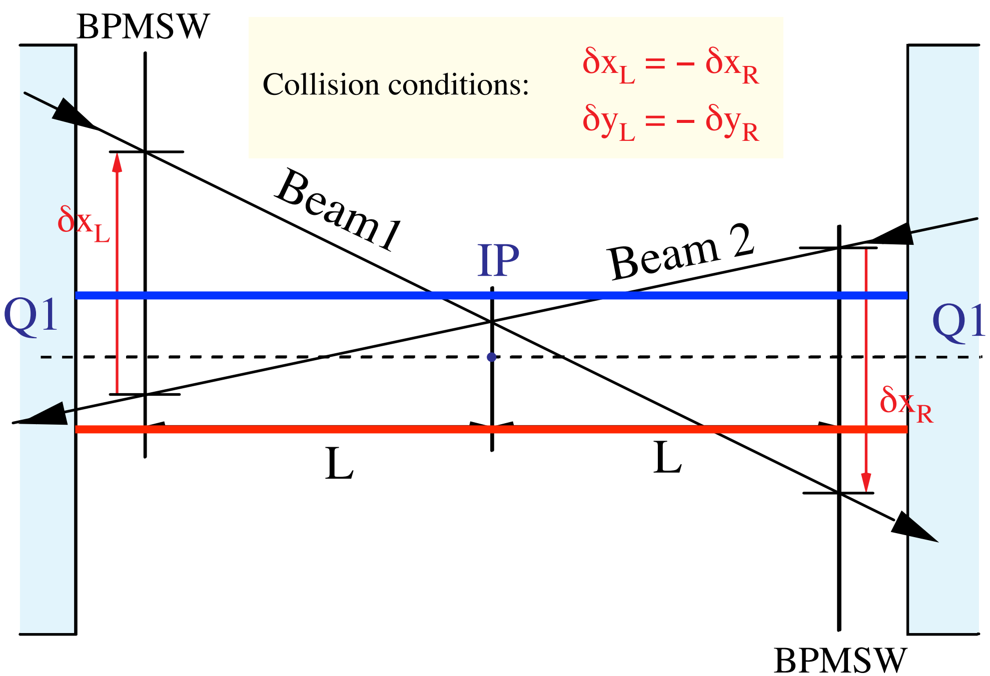
LEP example, V-plane, 3 bunches



studied by Simon White - as PhD thesis.
principle : H.B. and Per Grafstrom; LHC Report 1019 from 23 May 2007 http://cdsweb.cern.ch/record/1056691
and H.B., R. Schmidt, *Intensity and Luminosity after Beam Scraping*, CERN-AB-2004-032

Get LHC beams colliding : BPM resolution

adjust orbits such, that the beam 1 and 2 difference left/right of the IP is the same
beams must then collide. This is independent of mechanical offsets and crossing angles



nominal beam sizes at the IP			
	450GeV	3.5 TeV	5 TeV
β* [m]	σ* [μm]	σ* [μm]	σ* [μm]
11	293	105	88.0
3	153	54.9	45.9
2	125	44.8	37.5
1	88.4	31.7	26.5

$\frac{\delta x}{\sigma_x}$	$\frac{\delta y}{\sigma_y}$	$\mathcal{L}/\mathcal{L}_0$
0	0	1.0000
0.1	0	0.9975
0.2	0	0.9901
0.3	0	0.9778
0.4	0	0.9608
0.5	0	0.9394
0.5	0.5	0.8825
1	0	0.7788
1	1	0.6065
2	0	0.3679
2	2	0.1353

measured with special (beam-) directional strip-line couplers BPMSW, at about L = 21 m left and right of the IP in front of Q1 in each IR. Resolution each plane $\delta_{\mathrm{IP}} = \sigma_{\mathrm{BPM}}$

Expected resolution for small separation and 0 crossing angle ; in each plane.

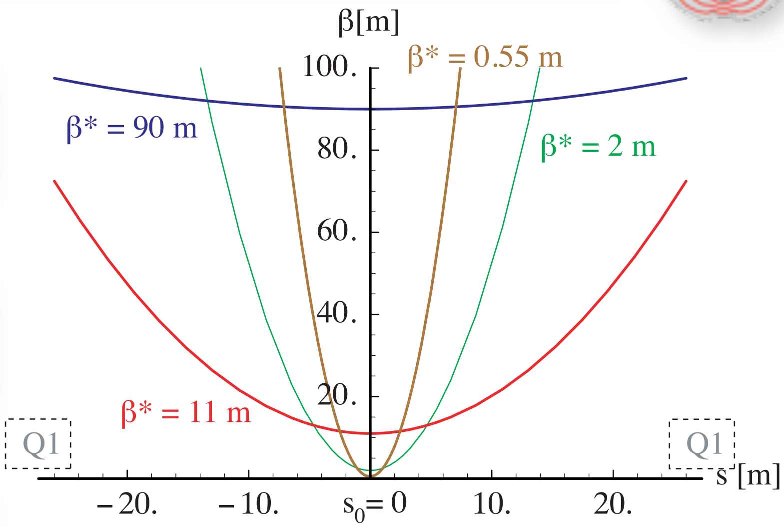
~ 50 μm using selected, paired electronics ; otherwise ~ 100 - 200 μm
beam 1 and beam 2 have separate electronics

~ 10 μm with extra BPMWF button pick-ups. Installed in 1&5, for large bunch spacing, EDMS doc 976179

Low β insertion ; LHC

the β-function in a field free region has a form of a parabola with

$$\beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*}$$

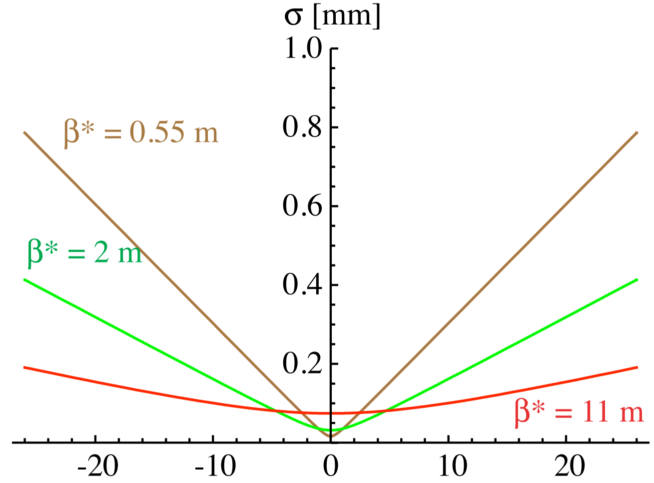


the beam size of a beam of emittance ε in a dispersion free region is

$$\sigma = \sqrt{\beta\,\varepsilon}$$

and the angular beam size divergence

$$\sigma' = \sqrt{\frac{\varepsilon}{\beta}}$$



the beam size increases about linearly from the IP to the first quadrupole, by a factor s / β* (for s >> β*)

--> aperture limit for low β*

LHC triplet aperture currently 70 mm (50 mm with screen)

upgrade studies --> 130 mm aperture, NbTi

for the nominal emittance

$\varepsilon_N = 3.75\ \mu m$, $\varepsilon_N = \varepsilon\,\beta\,\gamma$

$\varepsilon = 0.503$ nm at 7 TeV