Luminosity Scans at the LHC

Outline:

- Introduction
- Beam Dynamics Considerations
- Optimal Conditions and Limitations
- Procedure and Proposal

S. White
LHC Lumi Days Workshop
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Introduction

• **Method pioneered at ISR by S. Van Der Meer (1968):**
⇒ S. Van Der Meer, "Calibration of the effective beam height in the ISR"
⇒ **1% precision** K. Potter, "Luminosity measurements and calculations"
⇒ **Conditions different from LHC: Continuous beam, displacement calibrated with scraper** K. Potter, S. Turner, "High Precision Scrapers for ISR Luminosity Measurements"

• **More recently done at RHIC with conditions similar to the LHC:**
⇒ **Latest results (2009): about 7% precision. Beam conditions not optimized, strong beam-beam, hourglass** K. A. Drees, S. White, "Vernier scan results from the first RHIC proton run at 250 GeV"

• **Initially (officially) proposed for the LHC in 2007:**
⇒ H. Burkhardt, P. Grafstrom, "Absolute Luminosity from Machine Parameters"
⇒ **Original idea was to give a first calibration with ~10% precision** S. White et al., "Luminosity Optimization and Calibration at the LHC"
⇒ **Reach percent level with other methods (TOTEM/ATLAS-ALFA, see previous talks)**
⇒ **Worked better than expected**

Formalism

- **General expression of the luminosity:** $$L_0 = \frac{N_1 \, N_2 \, n_b \, f}{A_{\text{eff}}}$$

- **Regardless of the beam density distribution (uncorrelated x/y distributions):**

$$L(\delta x, \delta y) = L_0 \; F(\delta x, \delta y) = L_0 \; F_x(\delta x) \; F_y(\delta y)$$

- **Effective area given by:** $$A_{\text{eff}} = \frac{\int_{-\infty}^{+\infty} F_x(\delta x) \, d\delta x}{F_x(0)} \; \frac{\int_{-\infty}^{+\infty} F_y(\delta y) \, d\delta y}{F_y(0)}$$

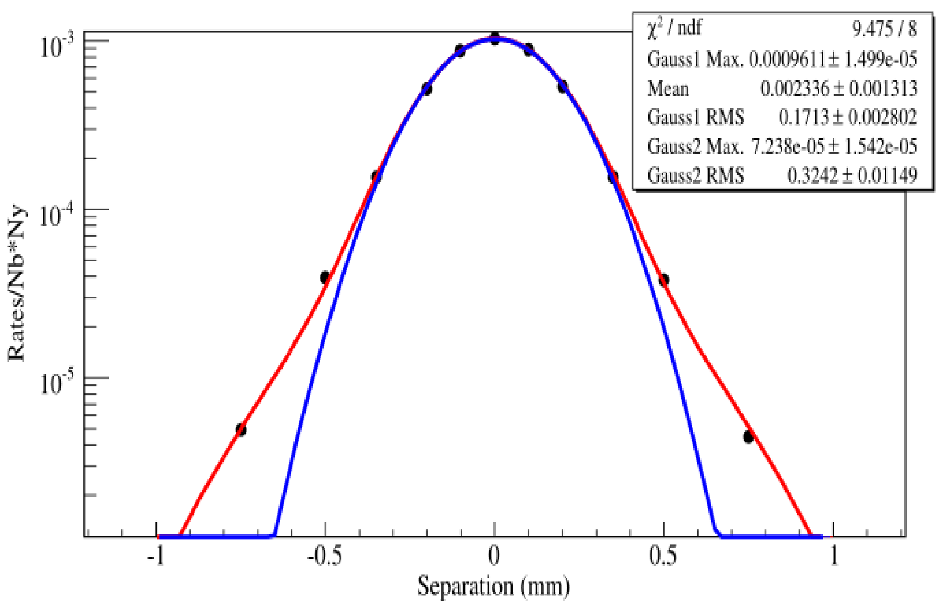
- **Perfect Gaussian:** $$F(\delta x, \delta y) = \exp\left[-\frac{\delta x^2}{2\,(\sigma_{x1}^2 + \sigma_{x2}^2)} - \frac{\delta y^2}{2\,(\sigma_{y1}^2 + \sigma_{y2}^2)} \right]$$

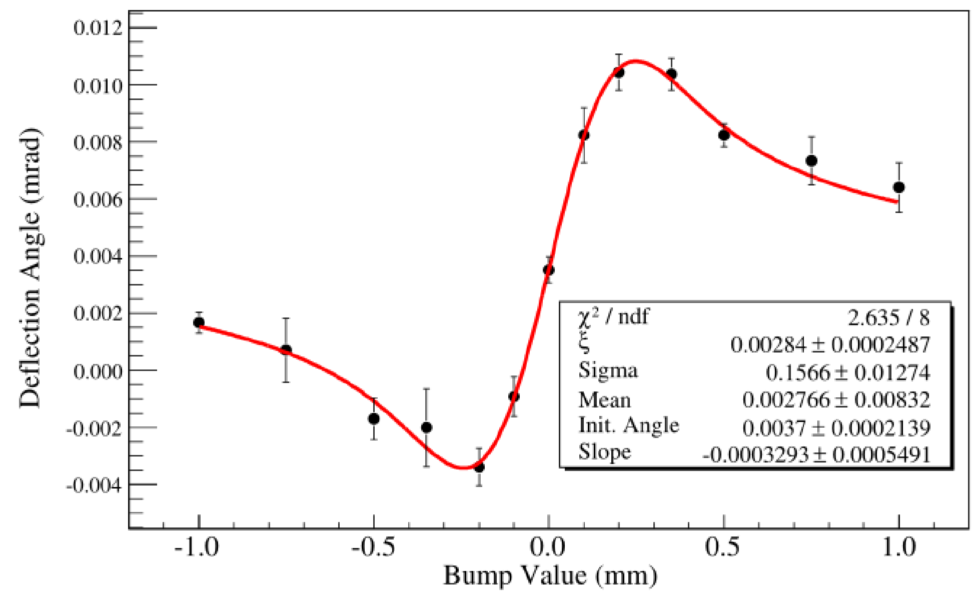
- **Effective sizes and area:** $$A_{\text{eff}} = 2\,\pi \sqrt{\sigma_{x1}^2 + \sigma_{x2}^2} \sqrt{\sigma_{y1}^2 + \sigma_{y2}^2} = 2\,\pi\,\sigma_{x\text{eff}}\,\sigma_{y\text{eff}}$$

RHIC Scans

- **Measurements done in 2009:**

⇒ No crossing angle, about 100 bunches, strong beam-beam and hourglass effects.
⇒ Reached ~7 % precision dominated by the knowledge of the bunch current and the beam displacement
⇒ Conditions similar to the LHC: excellent collaboration helped preparing the LHC start-up (software, procedure)





Measurements done in 2009. 250 GeV RHIC proton run with A. Drees. Presented at IPAC10

2010 LHC Beam Parameters

Two sets of scans performed in 2010 with different parameters:

• **April-May 2010 (first attempt):**
⇒ $\beta^* = 2$ m
⇒ No external crossing angle (internal crossing angle in ALICE and LHCb)
⇒ Low bunch intensity ~ 2.0×10^{10} p/bunch
⇒ One bunch crossing per IP (except first CMS scan)

• **October 2010:**
⇒ $\beta^* = 3.5$ m
⇒ External crossing angle in all IPs of ~ 100 μm
⇒ Higher bunch intensity ~ 8.0×10^{10} p/bunch
⇒ Several bunch crossing per IP

⇒ Better beams conditions and instrumentation for the October scans
⇒ Systematic uncertainty dominated in both cases by the bunch current knowledge

Impact of the Beam Parameters

These beam parameters can have an effect on the luminosity:

- **Crossing angle:** $$\frac{L}{L_0} = \left(\sqrt{1 + \frac{\sigma_{1s}^2 + \sigma_{2s}^2}{\sigma_{1x}^2 + \sigma_{2x}^2} \left(\tan \frac{\varphi}{2} \right)^2} \right)^{-1}$$

- **Hourglass effect (β*):** $$\frac{L}{L_0} = \int \frac{1}{\sqrt{\pi}} \frac{e^{-t^2}}{\sqrt{(1 + t^2/t_x^2)\ (1 + t^2/t_y^2)}} dt$$

- **Coupling + elliptical beams:** $$\frac{L}{L_0} = \left(\sqrt{1 + \frac{(\sigma_{1\xi}^2 - \sigma_{1\eta}^2)\ (\sigma_{2\xi}^2 - \sigma_{2\eta}^2)}{(\sigma_{1\xi}^2 + \sigma_{2\xi}^2)\ (\sigma_{1\eta}^2 + \sigma_{2\eta}^2)} \sin^2(\phi_2 - \phi_1)} \right)^{-1}$$

- **Bunch intensity: beam-beam effects scale with the bunch intensity**

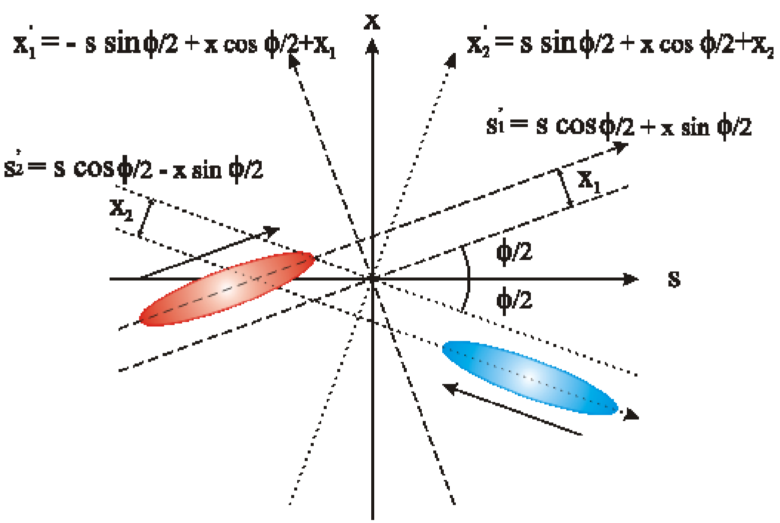
⇒ All these effects will have an impact on the determination of the effective beam size but are small or can be minimized under certain conditions

Crossing Angle

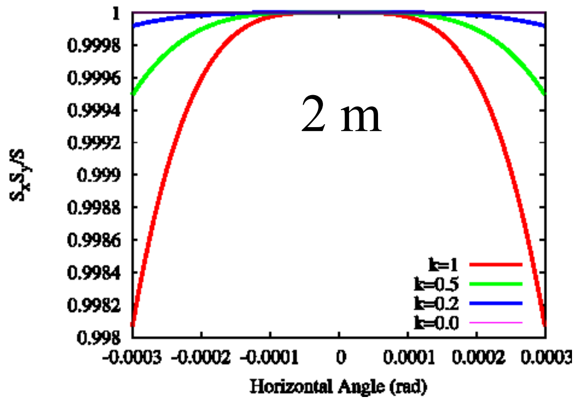
- **In case the crossing angle and the separation are in the horizontal plane:**

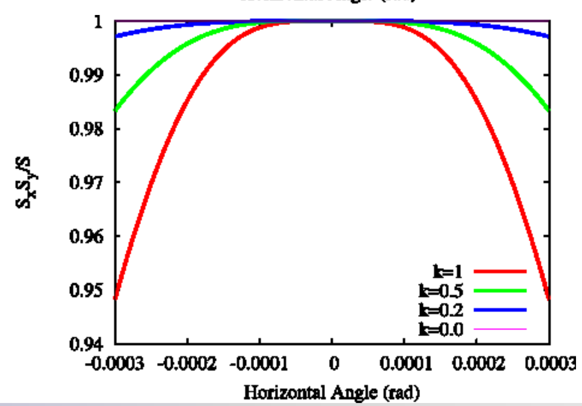
$$\frac{L}{L_0} = \left(\sqrt{1 + \frac{\sigma_{1s}^2 + \sigma_{2s}^2}{\sigma_{1x}^2 + \sigma_{2x}^2} \left(\tan \frac{\varphi}{2} \right)^2 } \right)^{-1} \exp\left[- \frac{\delta x^2}{2\,(\sigma_{1x}^2 + \sigma_{2x}^2)} \right] \exp\left[S^2 \frac{\sigma_{1s}^2 + \sigma_{2s}^2}{2} \left(\frac{\delta x \; \tan(\varphi/2)}{\sigma_{1x}^2 + \sigma_{2x}^2} \right)^2 \right]$$

$$F(\delta x) = \exp\left[- S^2 \frac{\delta x^2}{2\,(\sigma_{1x}^2 + \sigma_{2x}^2)} \right] \Rightarrow \sigma_{\mathrm{eff}} = \frac{1}{\sqrt{2\pi}} \frac{\int_{-\infty}^{+\infty} F(\delta x)\, d\delta x}{F(0)} = \frac{\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}}{S}$$



Rotated coordinate system to compute the overlap integral





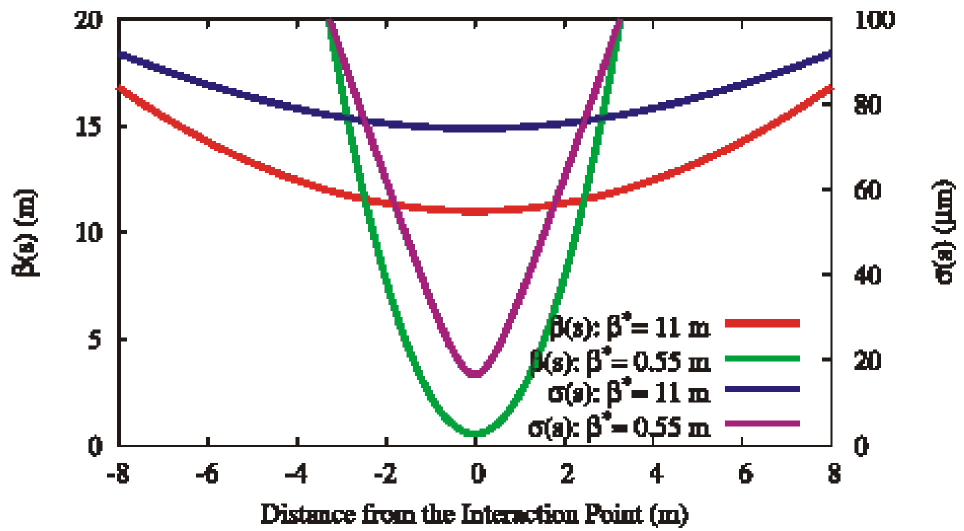
⇒ **When the scan is performed in the crossing angle plane no additional systematic uncertainty**

⇒ **When the scan is not performed in the crossing angle plane (tilted angle) the error remains negligible with actual beam parameters**

Hourglass Effect

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

$$\sigma(s) = \sigma^* \sqrt{1 + \frac{s^2}{\beta^*}}$$



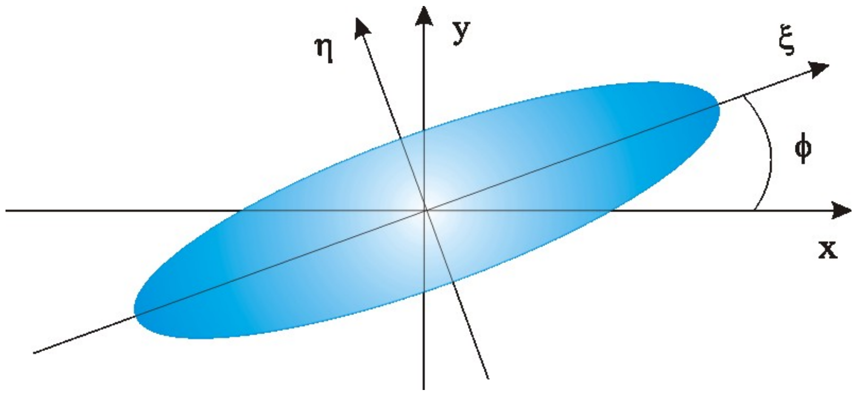
- **Effect becomes relevant when β^* equal or smaller than σ_s**
- **⇒ Include dependency in the overlap integral**

- **Round beams approximation:** $$\frac{L}{L_0} = \sqrt{\pi}\; t_r\, e^{t_r^2}\, \mathrm{erfc}(t_r) \quad \text{where} \quad t_r^2 = \frac{2\beta^{*2}}{(\sigma_{1s}^2 + \sigma_{2s}^2)}$$

β* [m]	t_r	$H(t_r)$
10	132	0.999972
2	26.5	0.999289
1	13.2	0.9971774
0.55	7.28	0.990833

⇒ 2010 beam parameters negligible effect
⇒ 2011 beam parameters, in case we run at 1.5 m effect remains negligible
⇒ At the level of 1% for nominal LHC beam parameters: keep β* not too small

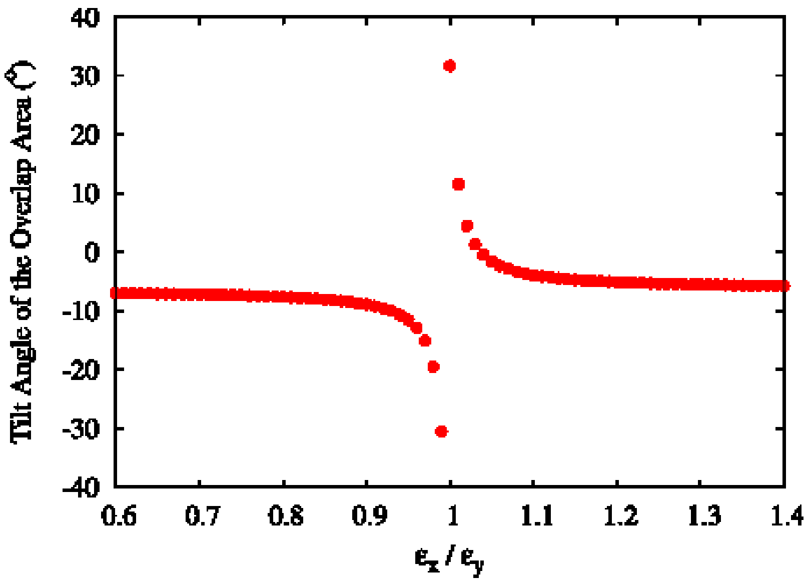
Linear x-y Coupling

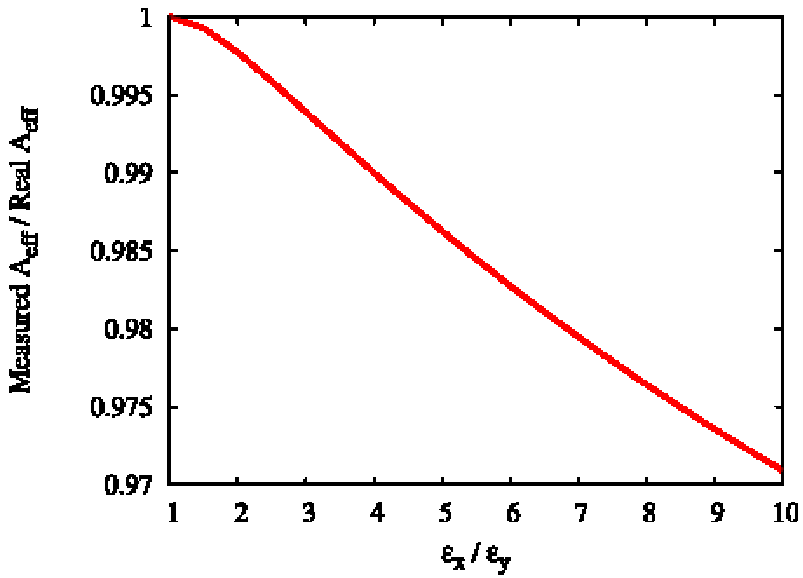


$$\tan 2\phi = \frac{2\sigma_{xy}}{\sigma_{xx} - \sigma_{yy}}$$

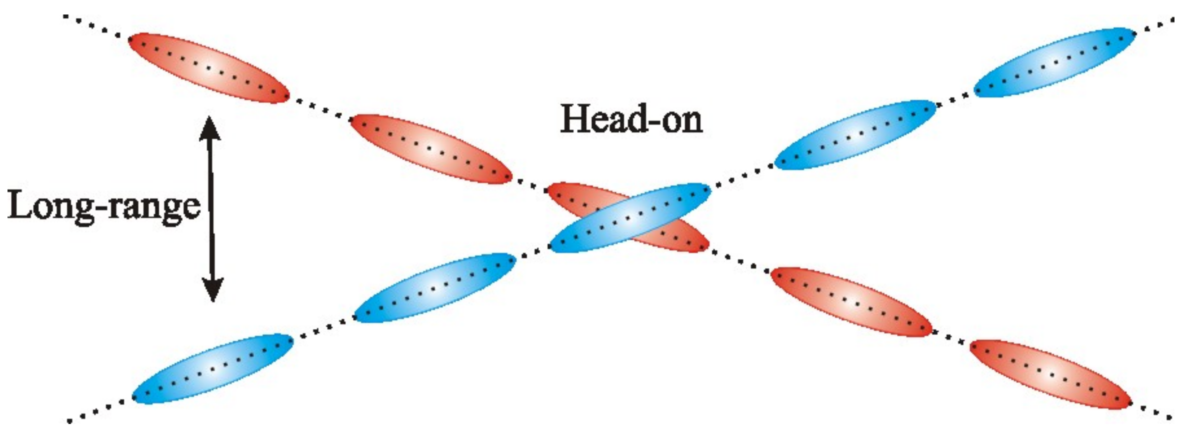
$$A_{\mathrm{eff}} = 2\pi\sigma_{\xi}\sigma_{\eta}$$

• **Tilt angle determined from emittance and optics measurements. Undefined for round beams. For round beams no error from coupling** ($\sigma_x = \sigma_y = \sigma_\zeta = \sigma_\eta$).





• **If significant perform raster scan to measure the beam sizes along the ellipse axes**



Beam-beam interactions at the LHC can be separated into two families:

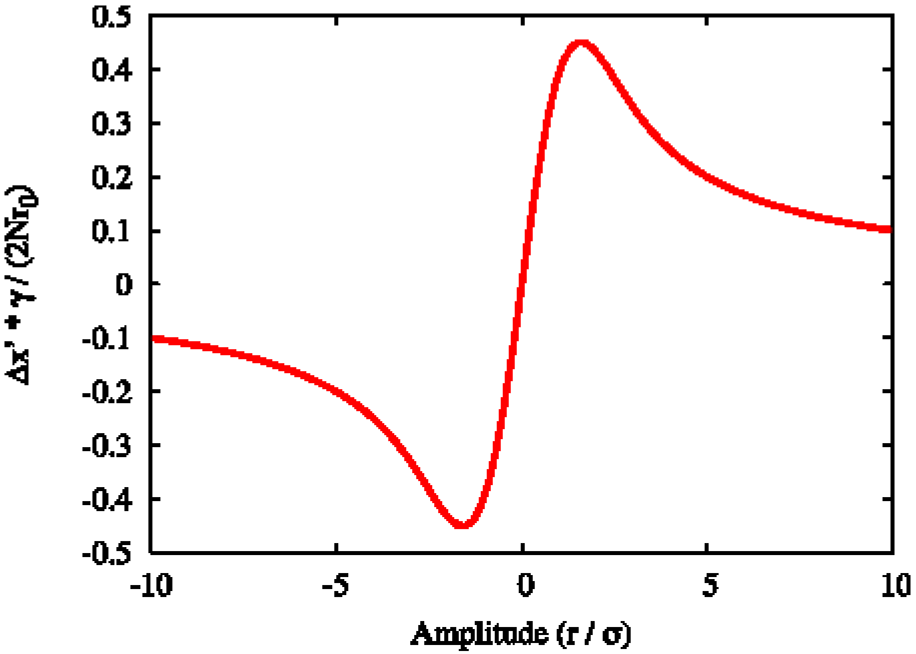
- **Head-on interactions:** central collisions
- **Long-range interactions:** away from the IP, only present for large number of bunches / small bunch spacing

- **For round Gaussian beams ($\sigma_x = \sigma_y = \sigma$), the beam-beam deflection angle depends on the radial separation *r*:**

$$\Delta r' = \frac{2 N r_0}{\gamma} \frac{1}{r} \left[1 - \exp\left(- \frac{r^2}{2 \sigma^2} \right) \right]$$

- **For the LHC the beam-beam parameter does not depend on the energy or β*:**

$$\xi = \frac{r_c N}{4 \pi \varepsilon_N}$$



Effects on Beam Parameters

- **Head-on beam-beam will perturb the lattice as a function of the separation:**

⇒ β-function (1%), tune and closed orbit will vary during the scan

⇒ Emittance blow-up? (T. Pieloni, W. Herr, Ji Qiang). No evidence during RHIC scans with strong beam-beam

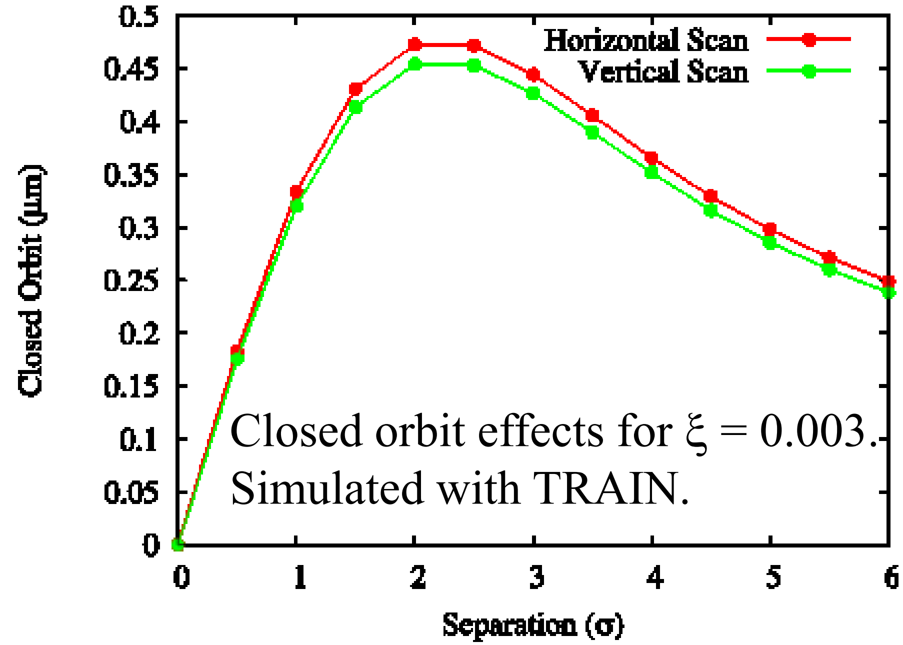
⇒ Tails, bad lifetime

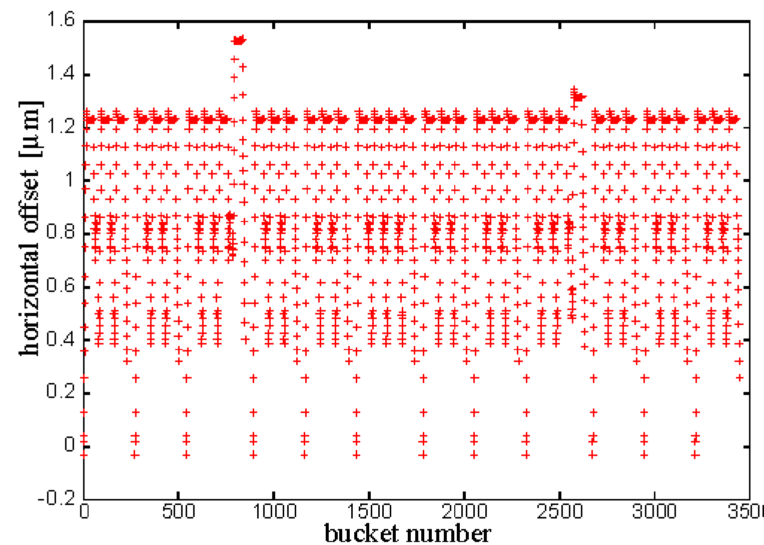
⇒ All these effects are small for LHC tunes but should be avoided if possible: reduce N/ε_N

- **Long-range interactions. Not all bunches experience the same number of interactions along the trains:**

⇒ Spread in tune, closed orbit, etc… along the bunch trains (PACMAN effect)

⇒ Should be avoided: reduce the number of bunches / increase bunch spacing





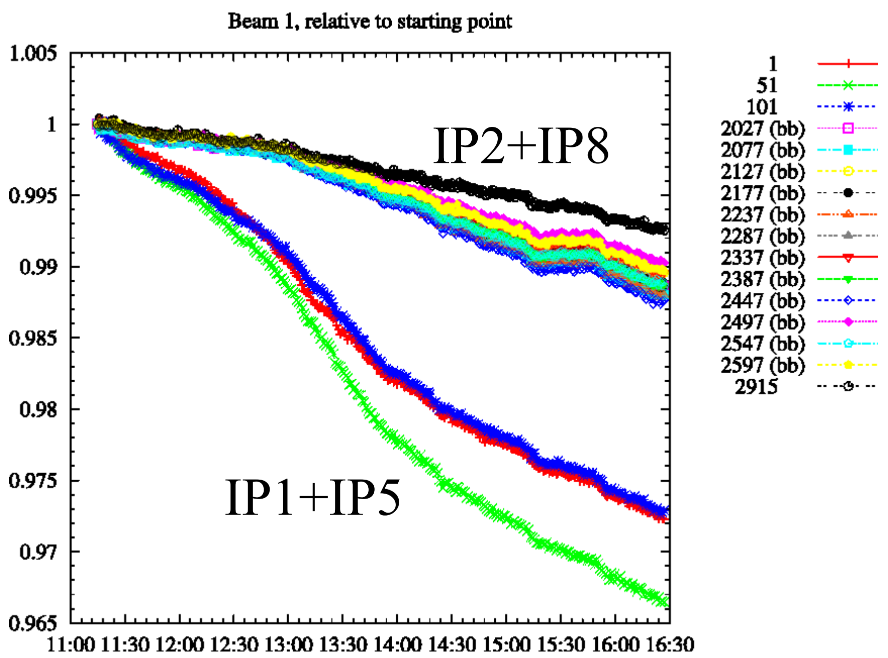
Offsets from long range (H. Grote)

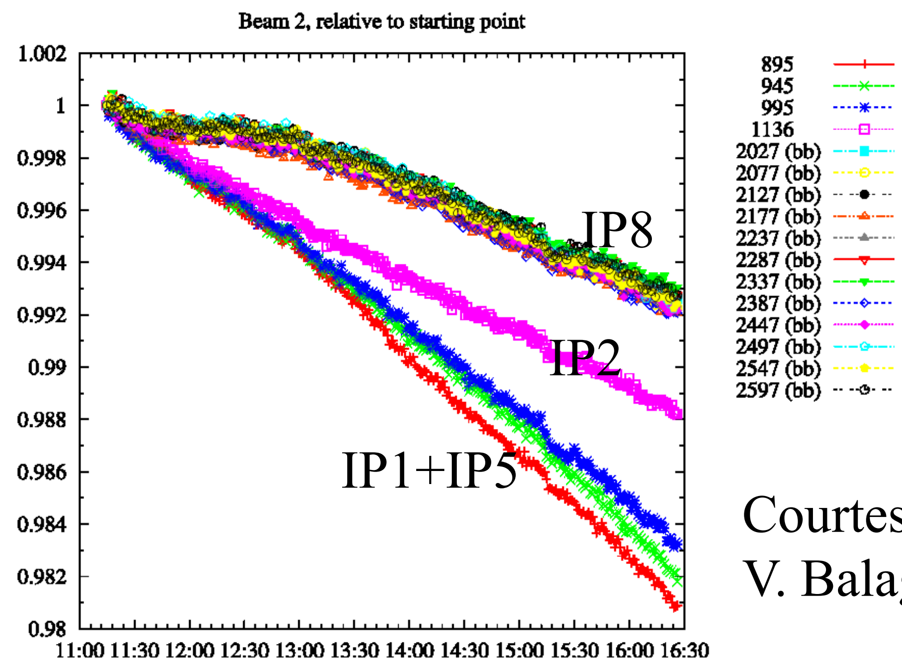
Some Observations

- **October set-up:**

⇒IP1 and IP5 share bunches: 2 head-on collisions

⇒ IP2 and IP8 private bunches: 1 head-on collision





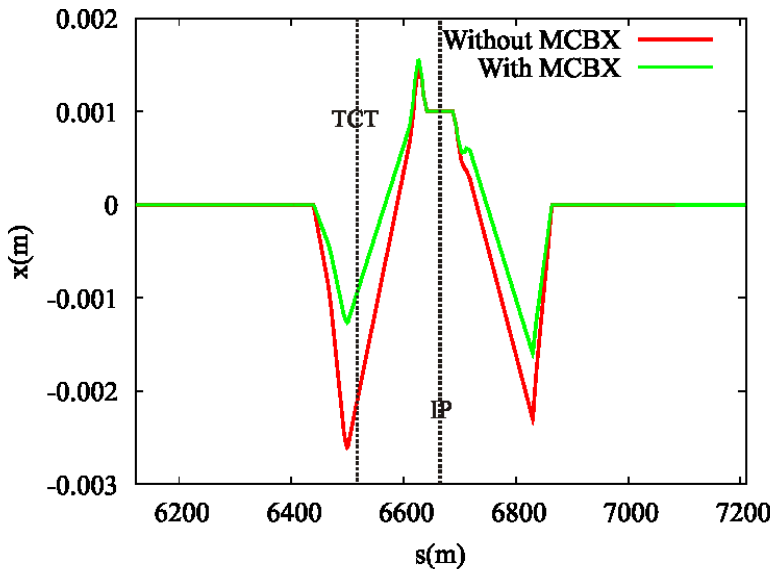
Courtesy of V. Balagura

- **Bunch intensity over the fill:**

⇒ IP1 and IP5 have higher losses than IP2 and IP8

⇒ Beam-beam effects are present and indirectly observed. Building tails?

How the Scans are Done



Example of an IP bump with and without MCBX:

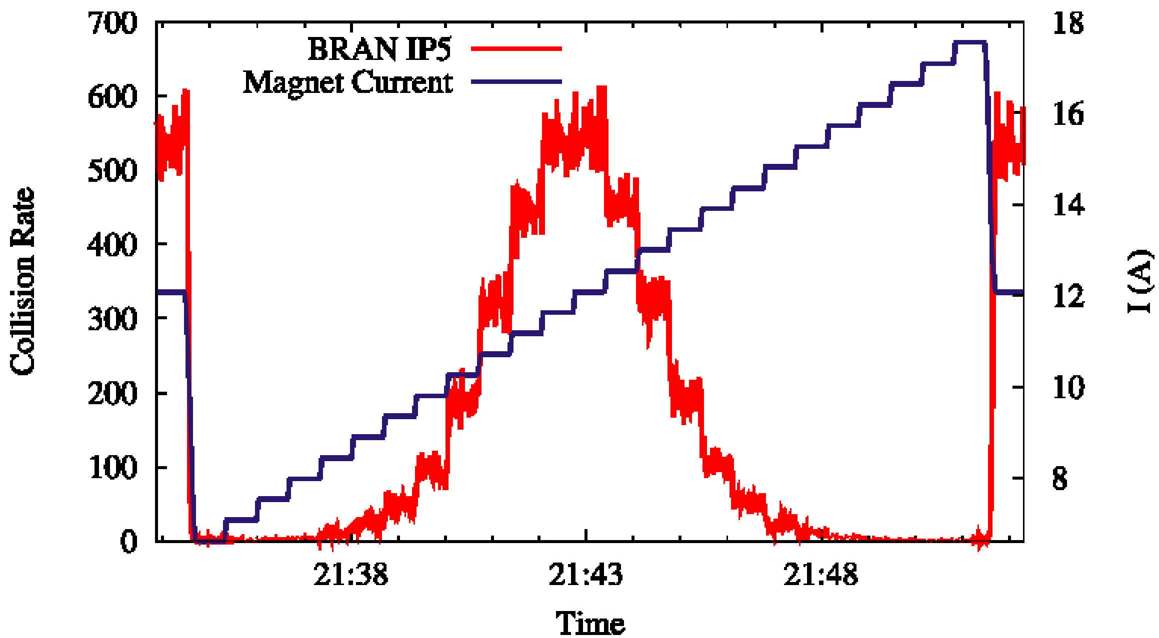
⇒ Creates a large offset in the TCT region

⇒ This offset can be reduced by using MCBX

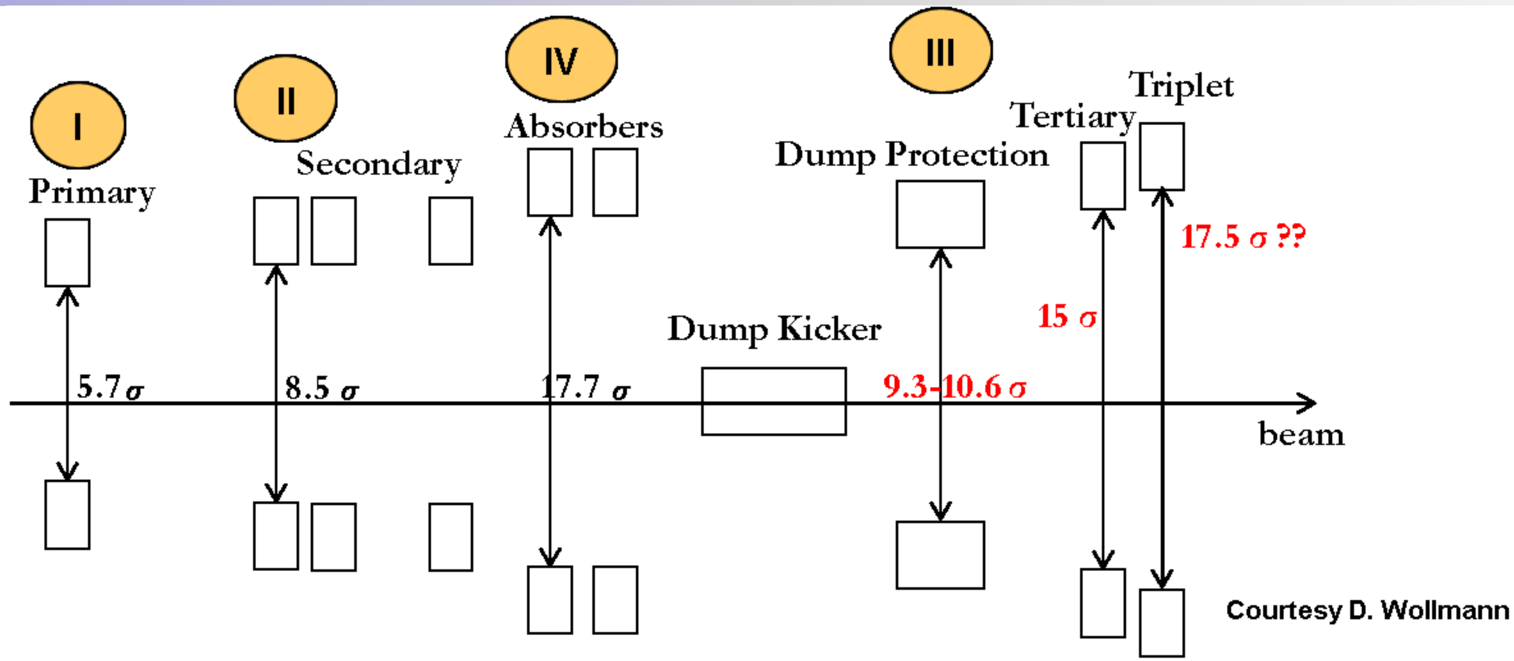
⇒ Split the amplitude between beams

⇒ Characterize performance of the magnets: MCBX subject to large hysteresis. Not used for precision measurements

- Move the beams stepwise across each other and measure the collision rates as a function of the beam displacement. Repeat in both planes to compute the effective overlap area
- Synchronization and data exchange with experiment software based. Done online



Limitations - Orbit



• **Hierarchy between cleaning stages must be preserved to guarantee protection - limits orbit variation:**

⇒ An IP closed orbit bump will distort the orbit at the TCT and in the triplets.

⇒ It is mandatory to respect the TCT/triplets and dump protection/TCT margins to safely perform the scans. These margins depend on the optics: more aperture in the triplets for zero crossing angle / higher β^*

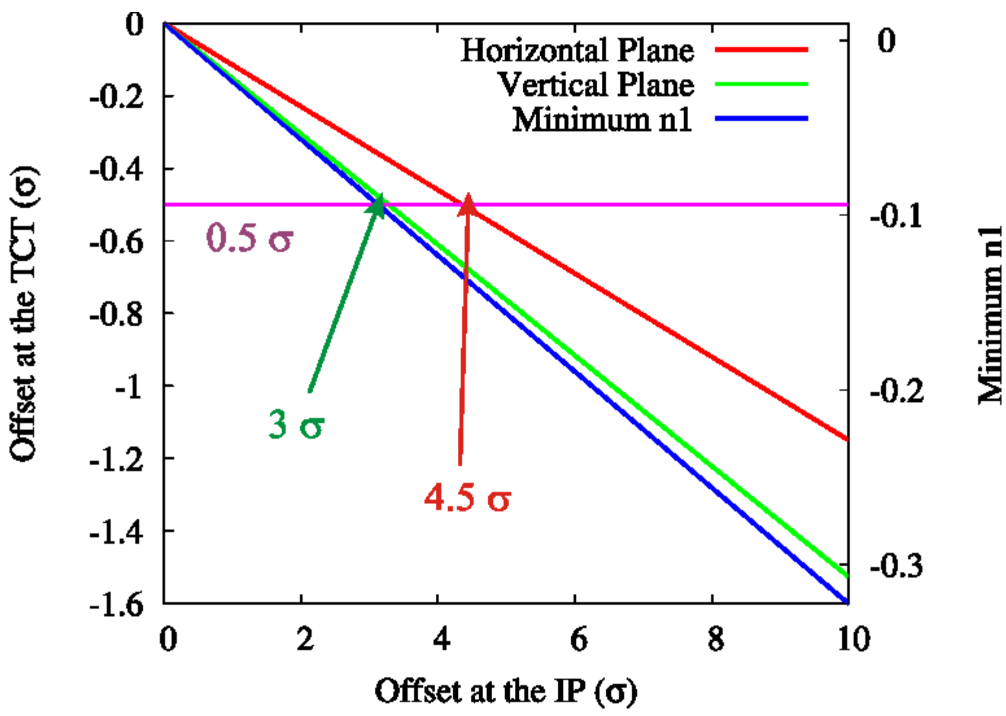
• **Outcome of Evian:**

⇒ MUST move the TCT with the beam: gives more margin dump protection/TCT

⇒ Does not prevent from breaking the TCT/triplet margin: requires detailed study for each scenario

Triplet Protection

- **Evian (R. Bruce): Proposal for 2011 running (to be decided in Chamonix): β*=1.5 m, intermediate settings, margins: 1.5 σ aperture-TCT, 2.1 σ TCT-TCDQ.**
- **Condition for triplet shadowing:** $$|\Delta x_{TCT}[\sigma]| < n\sigma_{QX} - n\sigma_{TCT}$$
- **In addition leave 1σ for operation (orbit drift, optimization, etc….)**



- **MADX estimates for IP5 (preliminary):**
  ⇒We barely have space for the double beam scans: justifies the statement to move the TCTs with the beam
  ⇒ Aperture reduction (n1) due to orbit changes in the triplets seems reasonable?
  ⇒ Providing the TCTs are moved with the beam there should be room for calibration scans even at 1.5 m
  ⇒ More systematic studies required to really assess the limits

Limitations - Intensity

- **Bunch intensity:**

⇒Calibration switch low/high sensitivity ~ 4.0-5.0x10^{10} p/bunch

⇒ Changing gain during the fill show be avoided

⇒ Working away from the switch low/high bunch intensity should not be an issue. Low intensity done for ions

⇒ No hard limits, low bunch intensity is preferable to minimize beam-beam effects

- **Total intensity:**

⇒ ATLAS requests wire scanners

⇒ Evian (F. Roncarolo):

⇒ 2010 SW interlock set to 2.0x10^{13} p (quench protection)

⇒ Quench tests: could go up a factor 3 at 3.5 TeV, relaxed interlock? Damage limits?

⇒ Providing low bunch intensity, lot of margin on the number of bunches

Optimal Beam Conditions (VDM Method)

- **Use the standard optics:** reduced set-up time and operation overhead. Physics optics: comparison CMS/ATLAS more relevant (β^* checks), higher rates, hourglass still small

- **Low bunch intensity:** minimize beam-beam effects, pile-up (ideally 2.0-4.0x10^{10} p/bunch)

- **No crossing angle:** no real gain in terms of systematic uncertainty but would simplify the picture and could provide additional information on satellite bunches (IP1+IP5 zero net angle)? Avoid main/satellite collisions at large separation

- **Relatively high number of bunches (< 156, crossing angle):** reduce the uncertainty on the beam current. Independent calibration/bunch

- **Low emittance (take what comes out of the injector):** keep luminosity per bunch high enough. Controlled blow-up in the injectors could be the source of non-Gaussian tails. Round beams

Procedure and Proposal

- The procedure and software are well established and fully commissioned. To be developed:

⇒ Automated length scale
⇒ Displacement of the TCT with the beam
⇒ More flexibility?

- Proposal for next year:

⇒ Dedicated fills with optimized beam conditions to be discussed in joint machine + experiments meetings. Machine protection, efficiency and operation overhead to be considered.

⇒ End of fill scans (conditions to be defined with MP) could help understanding the systematic uncertainty and would provide additional information.

- The 2010 experience was very instructive and results went beyond expectations. With additional efforts and dedicated beam conditions it should be possible to do even better.

References

• **Luminosity derivations:**

⇒ W .Herr, B. Muratori, "Concept of luminosity"

⇒ M. A. Furman, "Hourglass Effects for Asymmetric Colliders"

⇒ Y. Cai, "Luminosity of Asymmetric e+e- Collider with Coupling Lattices"

⇒ S. White, "Determination of the Absolute Luminosity at the LHC"

• **Beam-beam effects:**

⇒ W. Herr, "Beam-beam Interactions"

⇒ T. Pieloni, "A Study of Beam-beam Effects in Hadron Colliders with a Large Number of Bunches"

⇒ T. Pieloni, W. Herr, Ji Qiang, "Emittance Growth due to Beam-Beam Effects with a Static Offset in Collision in the LHC"

⇒ H. Grote and W. Herr et al., "Contributions of the SL Division to the Workshop on Beam-beam Effects at Fermilab"