ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Swiss Accelerator Research and Technology

Beam-beam effects in Van der Meer scans: COMBI and TRAIN beam-beam corrections

T. Pieloni and C. Tambasco (EPFL)

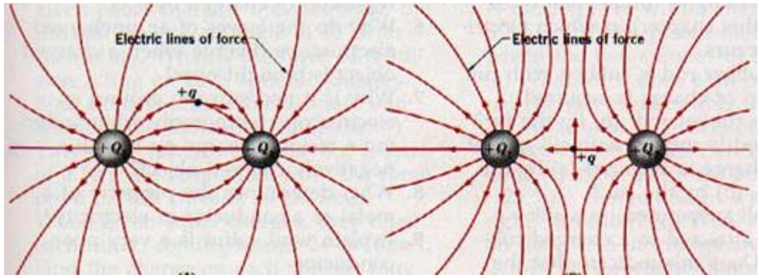
Acknowledgements: W. Kozanecki and V. Balagura
X. Buffat, W. Herr, R. Tomas, H. Burkhardt, J. Wenninger (CERN)

4-5 June 2019, Lumi-days 2019

Beam-Beam electro-magnetic interactions

A Beam is a collection of charges
(protons in the LHC)

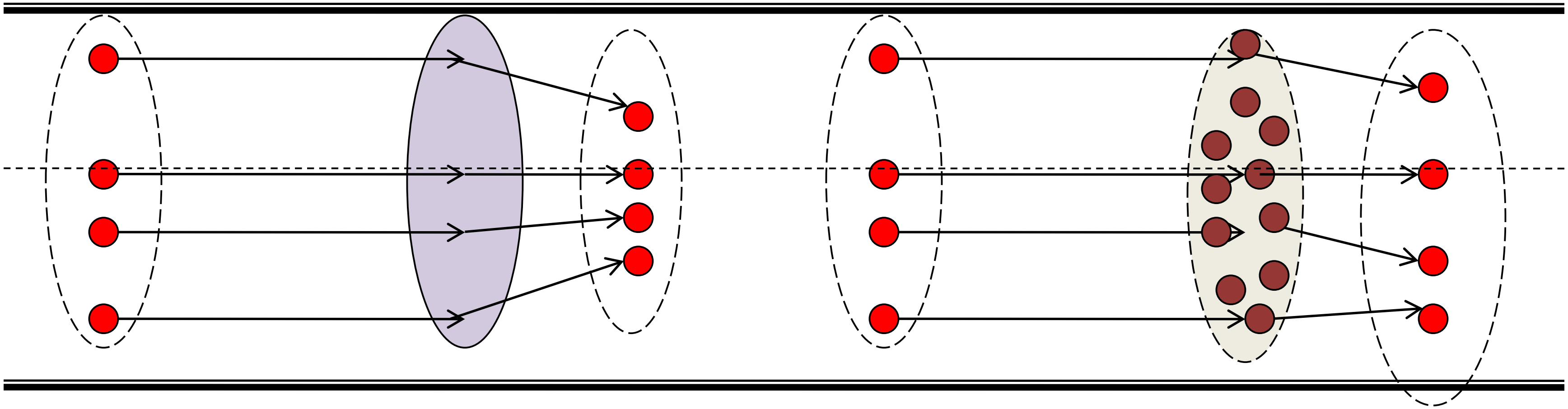
→ represents an electromagnetic potential for other charges (opposite beam)



Single particle motion (**incoherent**) and whole bunch motion (**coherent**) is distorted

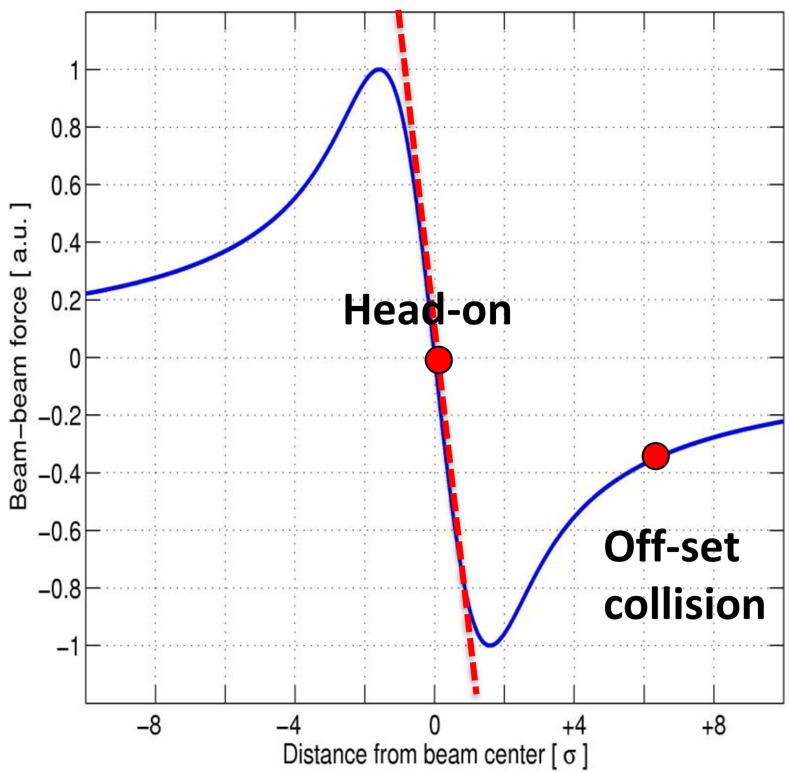
Focusing quadrupole

Beam-beam effects



Each beam acts on opposing particles like a non-linear electromagnetic lens..

Beam-beam Force for Gaussian beams



If we assume Gaussian distributions and in round approximation ($\sigma_x=\sigma_y$) The beam-beam force can be expressed as:

$$F \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right]$$

$$\mathcal{L} \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b$$

The force at small distances can be linearized and the proportional factor is the so called beam-beam parameter ξ → strength of the beam-beam force

$$F \propto -\xi \cdot r \qquad \xi \propto \frac{N_p}{\epsilon}$$

No-crossing angle (i.e. in VdM)

For VdM 2012 we have ξ = 0.0025
Physics Fills is different (larger and depends on β* and x-ing angles)
LHC Largest in MDs or in 2012 physics RUN.

Beam-beam effects:

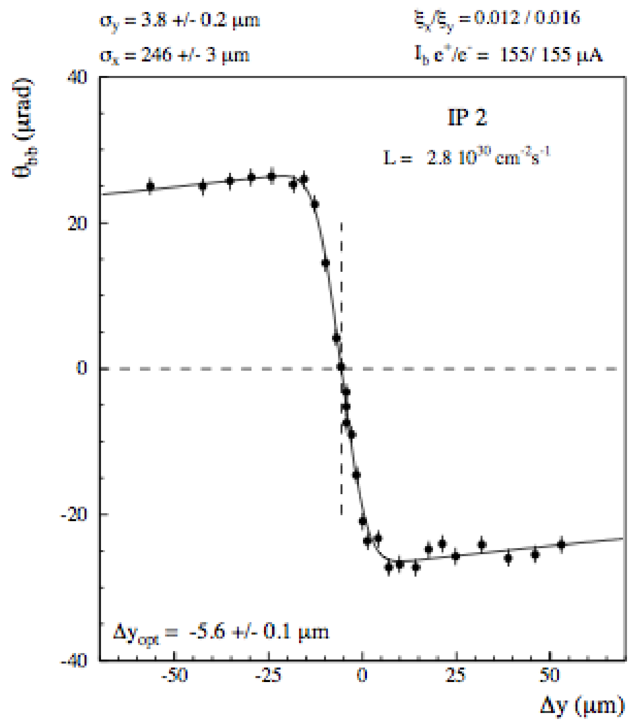
- Orbit effect → changes the orbit of the whole bunch
- Changes of focusing properties → dynamic beta, beta beating or “beam size” effect
- Detuning with amplitude → changes betatron frequencies “tunes” of particles
- Particle losses
- Emittance blow up
- Coherent oscillations and modes
- …

Beam-beam effects:

- Orbit effect → changes the orbit of the whole bunch
- Changes of focusing properties → dynamic beta, beta beating or “beam size” effect
- Detuning with amplitude → changes betatron frequencies “tunes” of particles
- Particle losses
- Emittance blow up
- Coherent oscillations and modes
- …

Angular deflection and Orbit effect

- Well understood effect
- Several models (formula, MADX, TRAIN, COMBI)
- Several observations



LEP measurement
J. Wenninger, SL Note 96-01 (OP)

Beam-beam angular kick:

$$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

Closed Orbit effect:

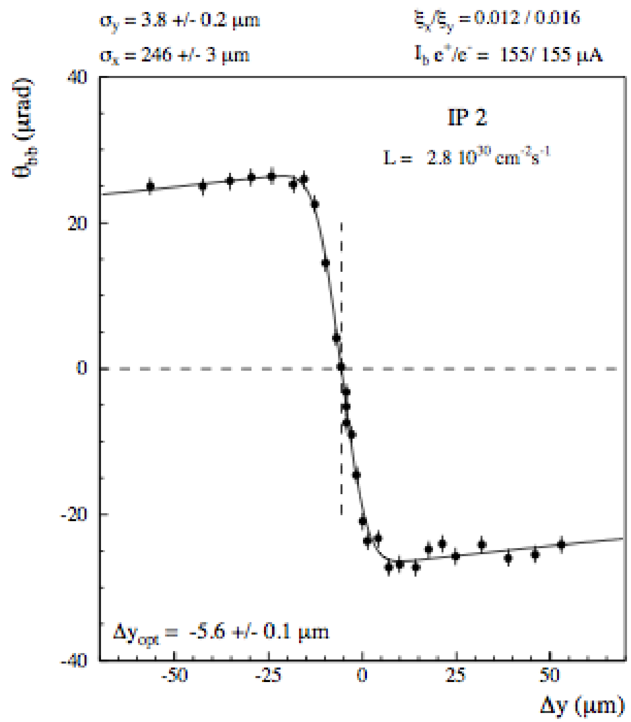
$$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

Some material available

Bunch Train working Group LEP
M. Venturini and W. Kozanecki, SLAC-PUB-8700
S. White PHD Thesis
CERN-ACC-2017-185 Arek & MIchi

Angular deflection and Orbit effect

- Well understood effect
- Several models (formula, MADX, TRAIN, COMBI)
- Several observations



[LEP measurement](#)
[J. Wenninger, SL Note 96-01 (OP)](#)

Beam-beam angular kick:

$$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

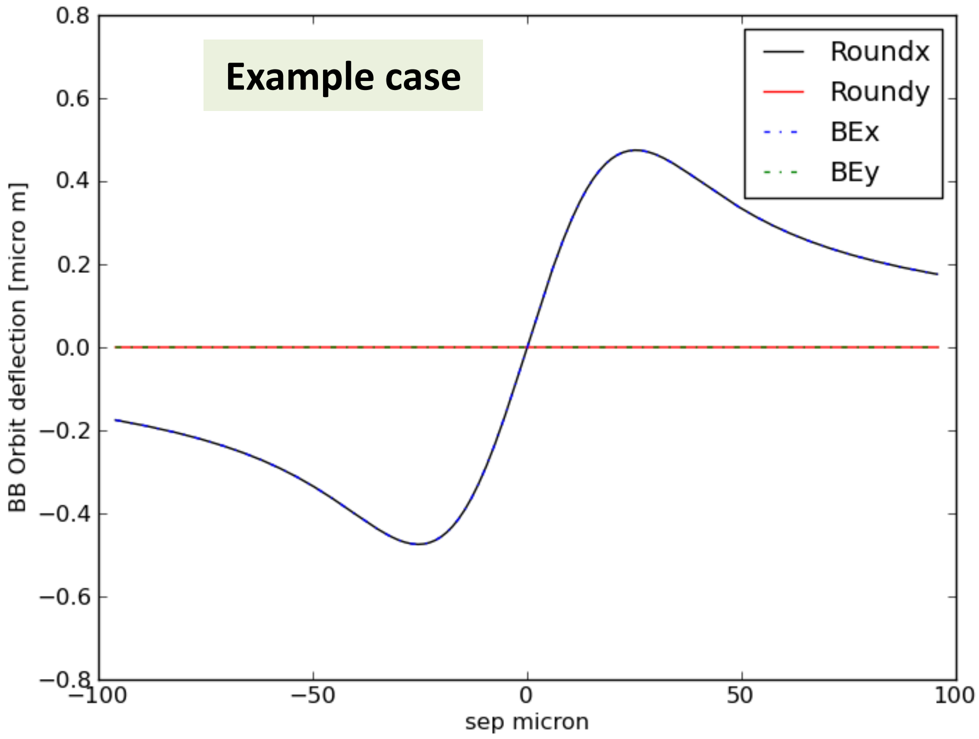
Closed Orbit effect:

$$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

Depends on the beam-beam parameter and the tune and propagates to other IPs

Orbit Correction

- Orbit effect propagates from one experiment to the other
- Needs to be accounted for in overlap integral of the two beams during VdM scans → adds an extra separation to the beam
- Effect depends on beam brightness (beam-beam parameter ξ)

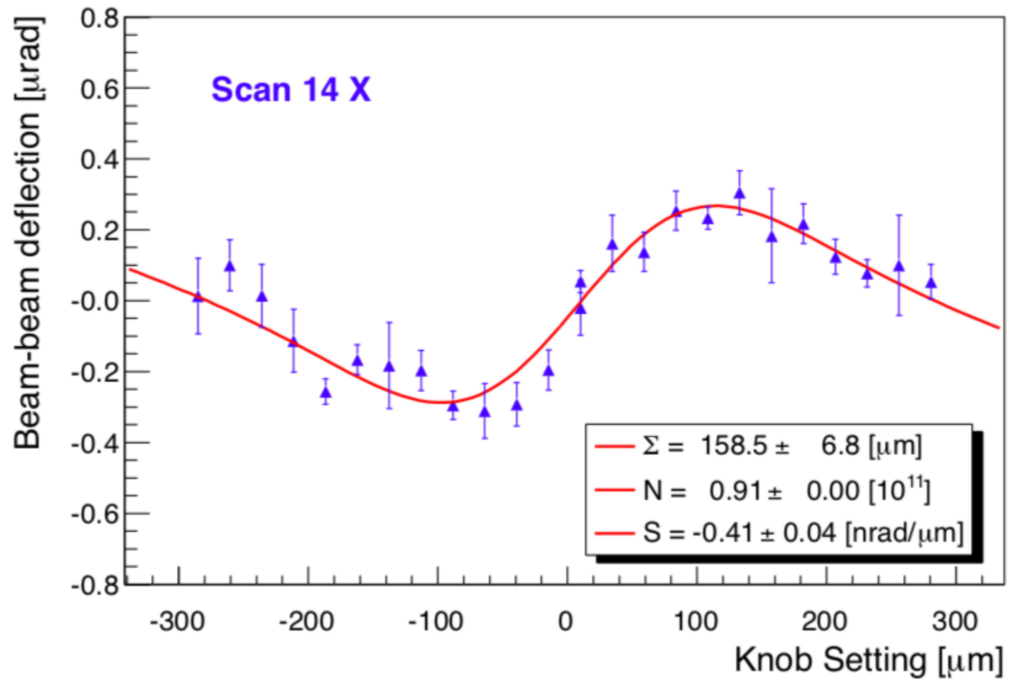


Python routine available to all experiments (W. Kozanecki and T. Pieloni)

BBScan.py: to test the BB routine, available for estimates
BB.py: calculation routine uses Bassetti-Erskine general formula and computes kicks and orbit effects
BassErsk: to calculate the electric fields Ref. CERN-ISR-TH/80-06.

Orbit Correction Data benchmark

- Beam-beam deflection angle as a function of the beam 1 luminosity knob for the VdM scan no. 14 in ATLAS (fill 3311 2012)
- Corrections match well with LHC observations



(a) Horizontal Plane

Measurements in VdM
CERN-ACC-NOTE-2013-0006
J. Wenninge, Kozanecki, Pieloni

Dynamic beta effect linear approximation

- Beam-beam collision changes the optical properties of the machine (beta functions)
  @ the IP → β^* dynamic beta
  @ around the machine β beta beating

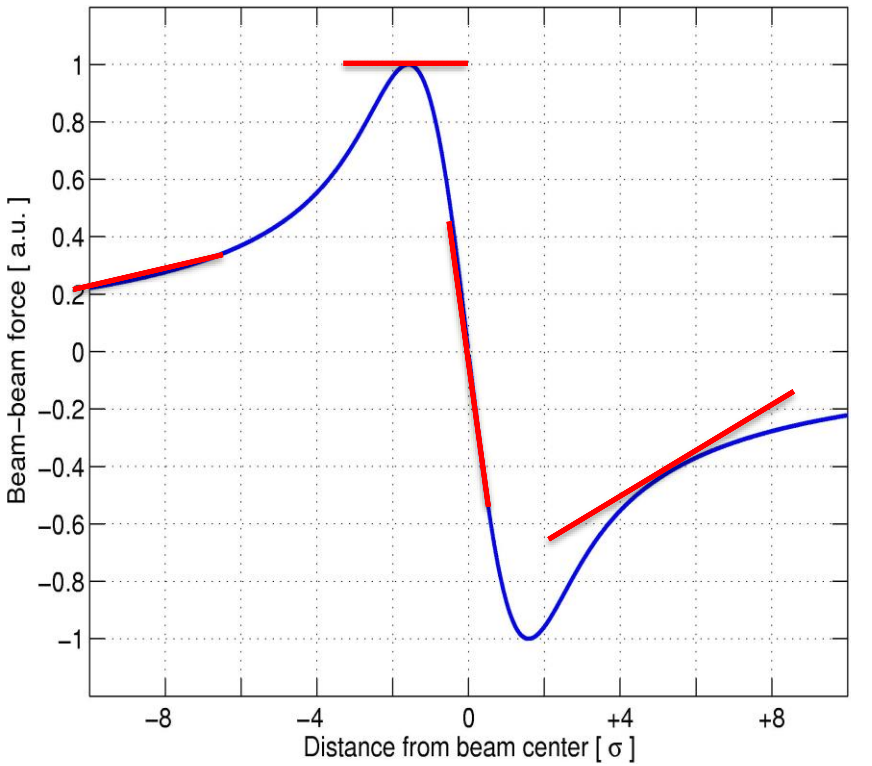
- In first approximation this can be treated with linearized formalism

- Beam-beam force linearized and impact is like a quadrupole magnet with changing strength depending on the offset

- First order correction to the optical function

→ tune shift and change in beta function

Beam-beam force linearized



[BEAM-BEAM EFFECTS AND DYNAMIC β* W. Herr Lumi-days 2012]

Dynamic beta effect linear approximation

Tune change:

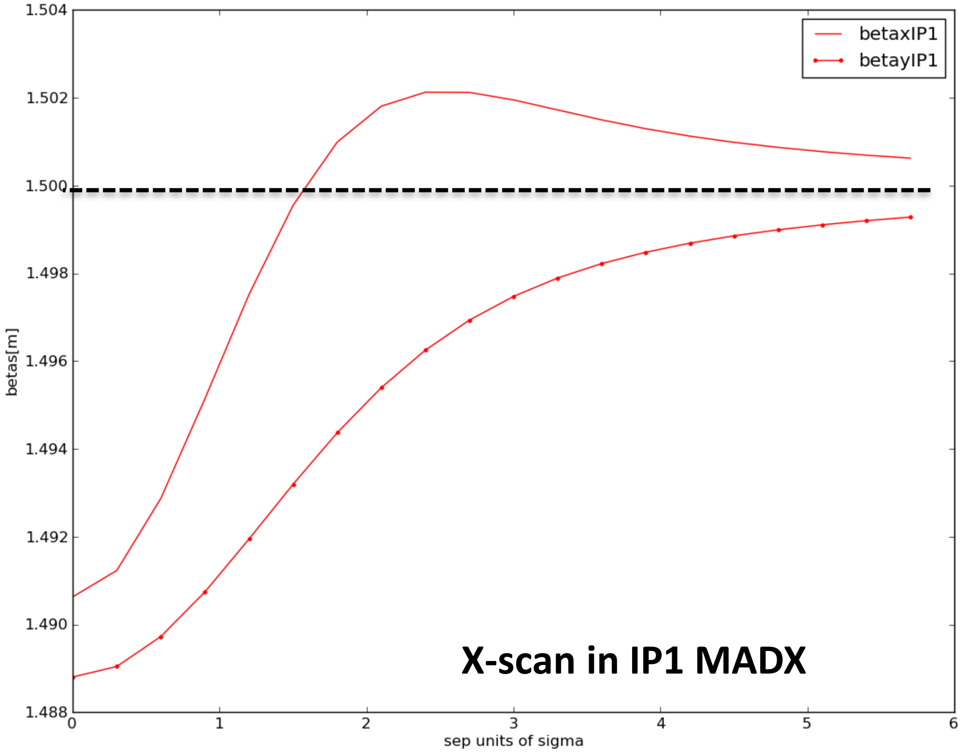
$$cos(2\pi(Q + \Delta Q)) = cos(2\pi Q) - \frac{\beta_0^* \cdot 4\pi\xi}{\beta^*} sin(2\pi Q)$$

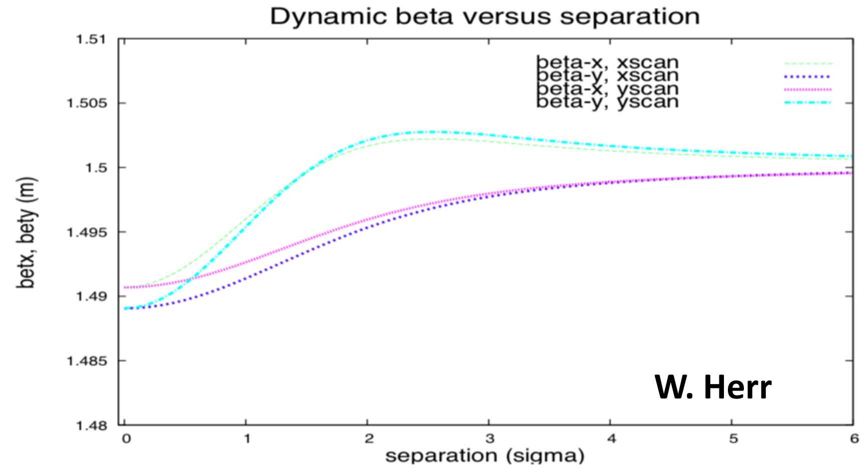
β-function change:

$$\frac{\beta^*}{\beta_0^*} = \frac{1}{\sqrt{1 + 4\pi\xi cot(2\pi Q) - 4\pi^2\xi^2)}}$$

Or one can compute it with models: MADX

Dynamic beta effect during Van der Meer scans



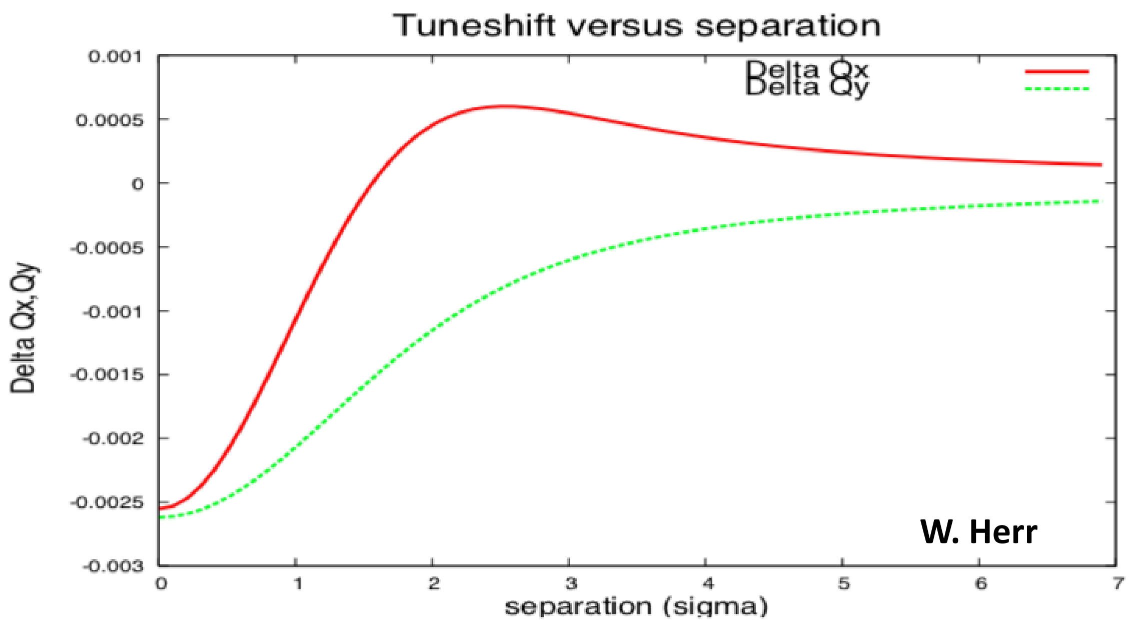


Single particle effects (MADX type)
Example case ξ=0.0025
At IP1 around 0.7 % effect on beta function

The beam-beam parameter ξ changes as a function of separation
→ impact on beta function depends on separation

Also the betatron frequency changes→ Tunes

Tune shifts during Van der Meer scans

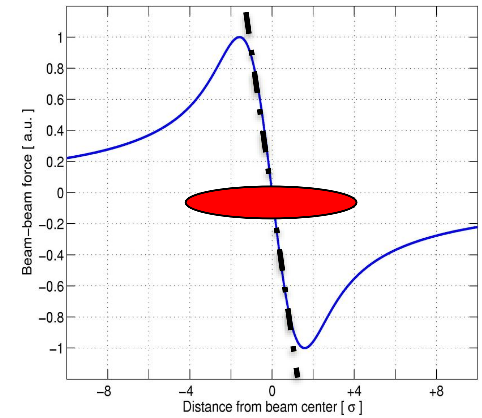


Tune shift at zero separation is equivalent to the beam-beam parameter $\xi = 0.0025$

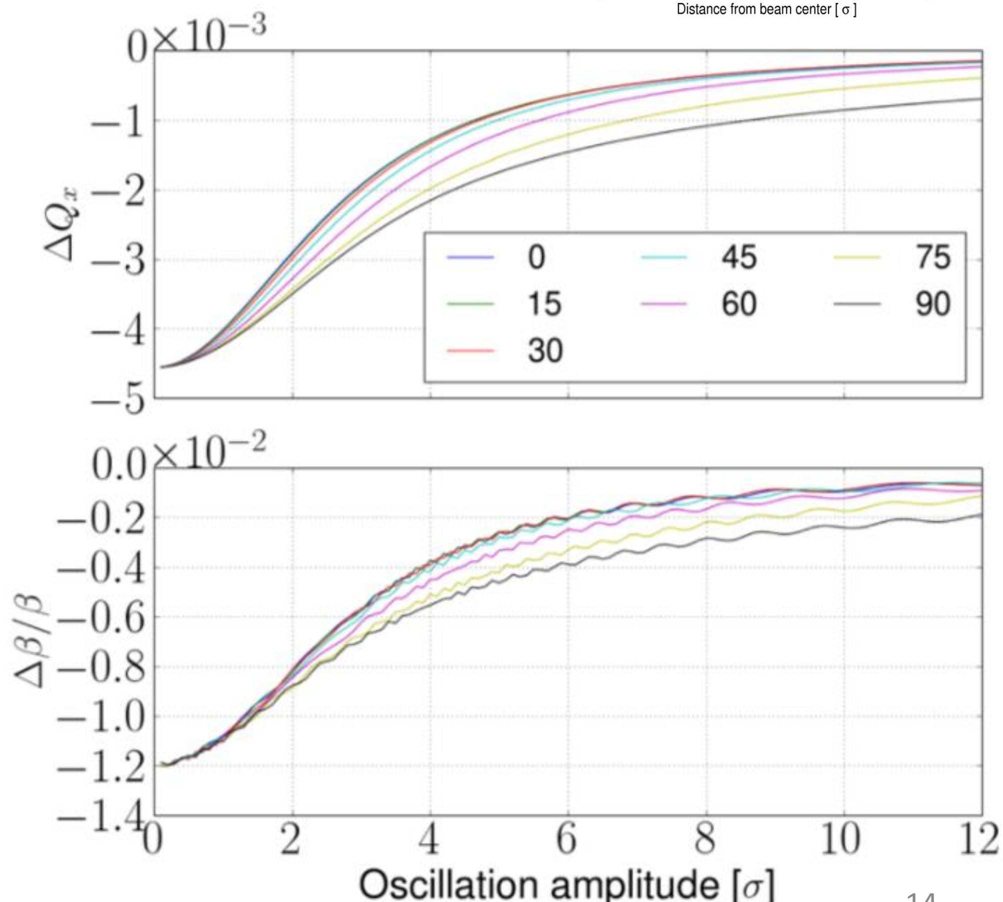
All particles receive the same kick as in a quadrupole magnet but in reality this is not true! There is a dependency on the particle amplitude of oscillation.

Now to improve precision, higher order effects can be taken into account !

Multi particle effects HEAD-ON collision



- Not all particles oscillate at small amplitudes → they sample different parts of the force
- Effect depends on the amplitude of oscillation → this results in a tune shifts and "dynamic beta" change that depends on the particle amplitudes
- Tune spread and "dynamic beta spread"
- For HO collision Maximum effect for small amplitude particles, weaker for large amplitude particles
- Very different for offset collision

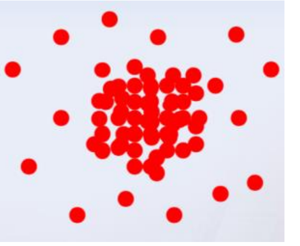


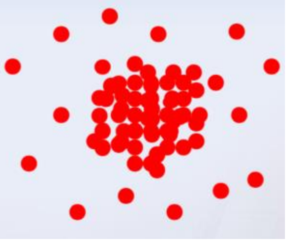
[P. Goncalves, CERN-THESIS-2017-161](#)
[Dynamic Beta and beta-beating](#)

COMBI code

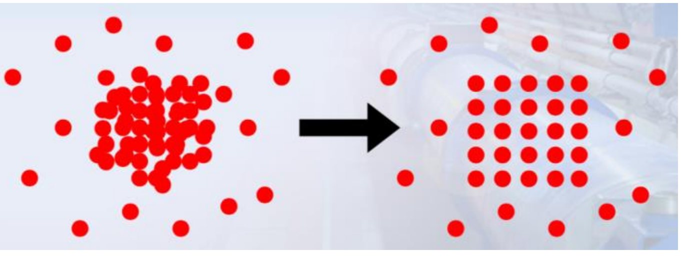
Each bunch is described by its particle distribution (can be Gaussian… anything) in 4D or 6D with N macro-particles

each macro-particle has an intensity of $Int/N_{macro\text{-}particles}$





1) Beam-beam kick assumes Gaussian (rms and centroid of distribution as x and σ)
2) Hybrid Fast Multiple Method: no assumptions on particle distributions



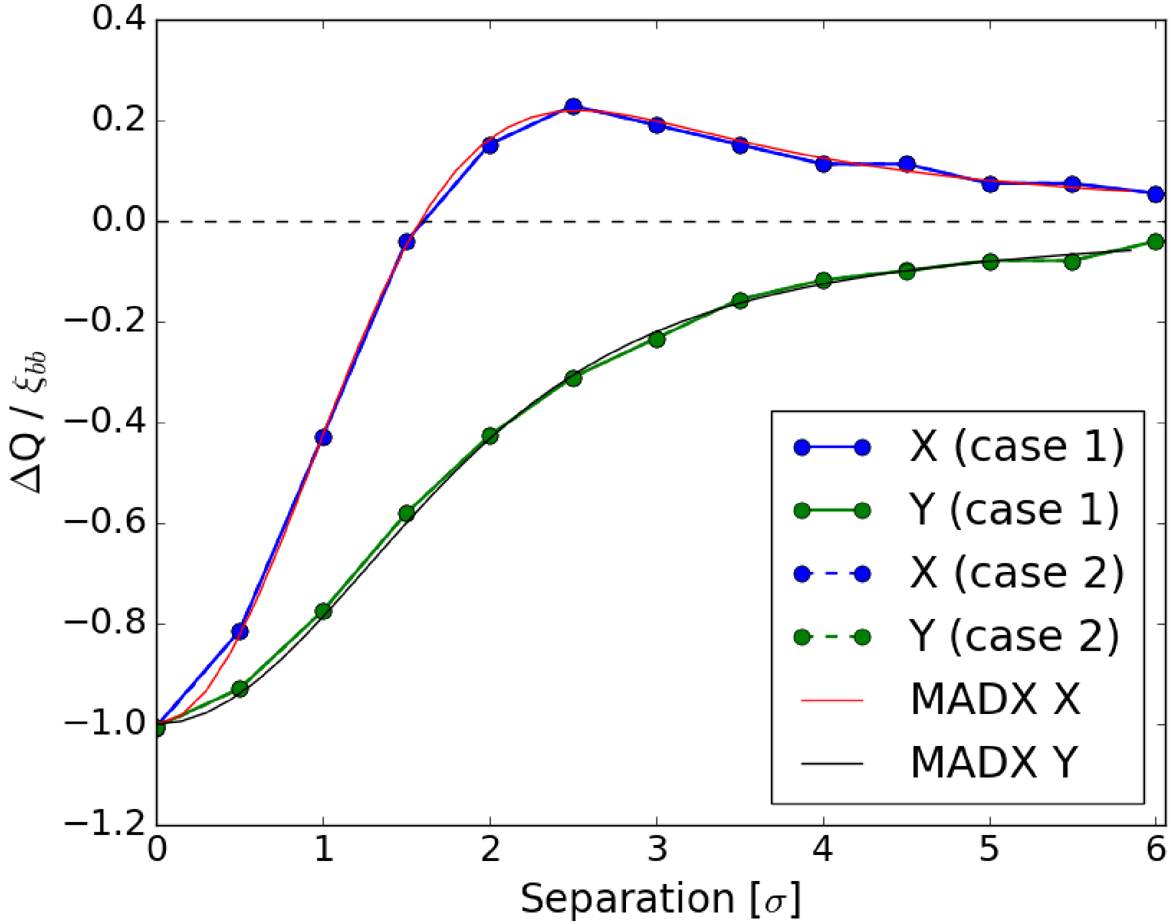
At each interaction the particle coordinates x' and y' are up-dated with incoherent BB kick

Parameters

- Intensities 0.85 10^{11} protons per bunch
- Emittance 4 μm
- β^* = 1.5 m @ ATLAS and CMS
- Energy 3.5 TeV
- 1 σ beam = 40 μm
- Horizontal scan in IP1

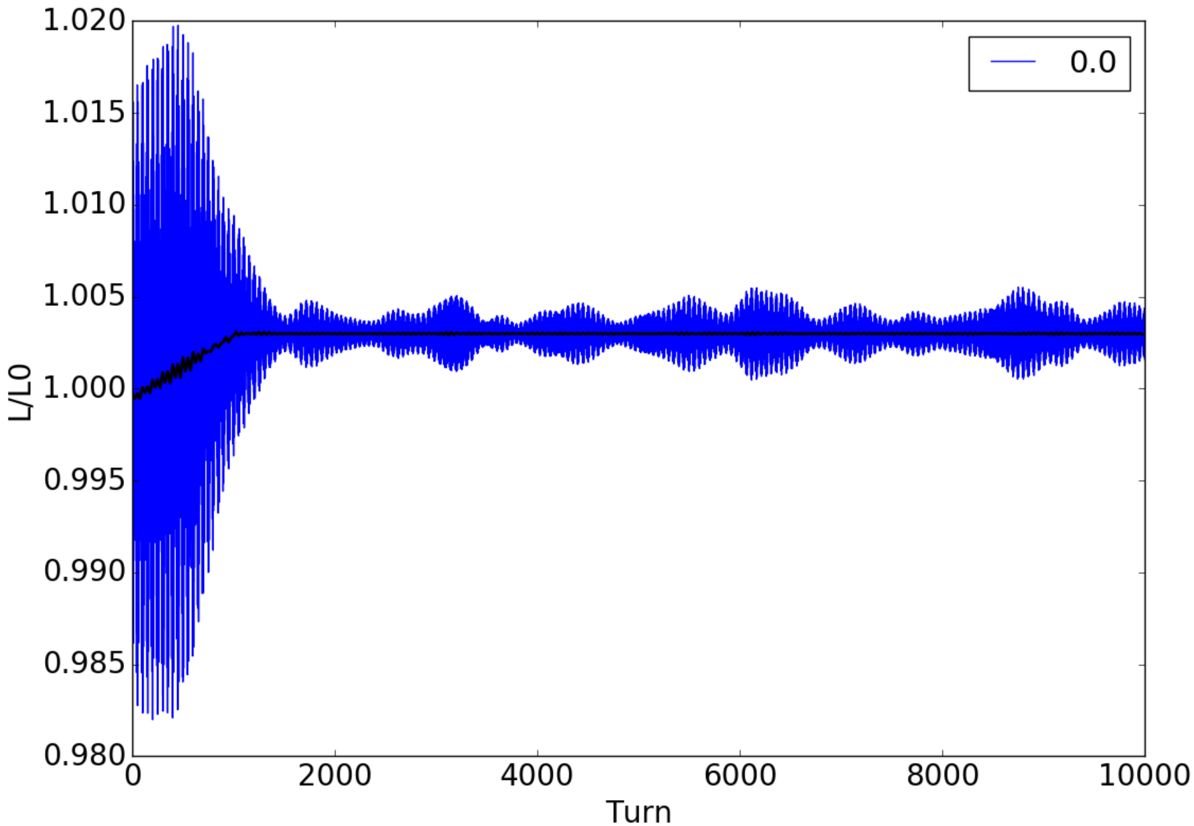
Kicks are produced by the distribution of opposite bunch and can be computed using Gaussian approximation or HFMM method

Tune shifts COMBI incoherent vs MADX results



Comparison of COMBI tune shift for linear incoherent beam-beam interaction a la MADX versus MADX→ always looking at zero amplitude particle
→ Need to evaluate the sigma change → beta effect for completeness

How to see below a 1% effect COMBI

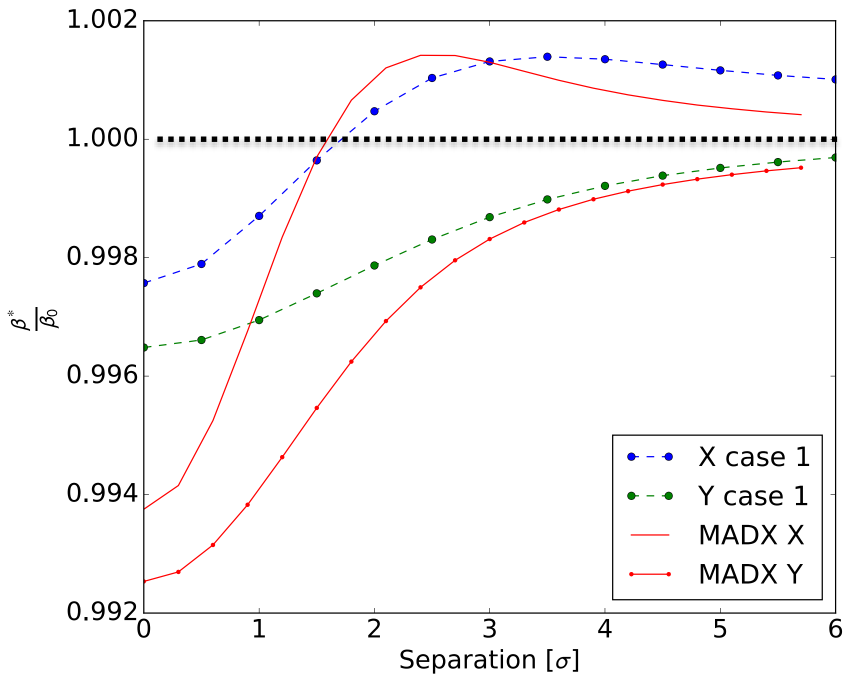


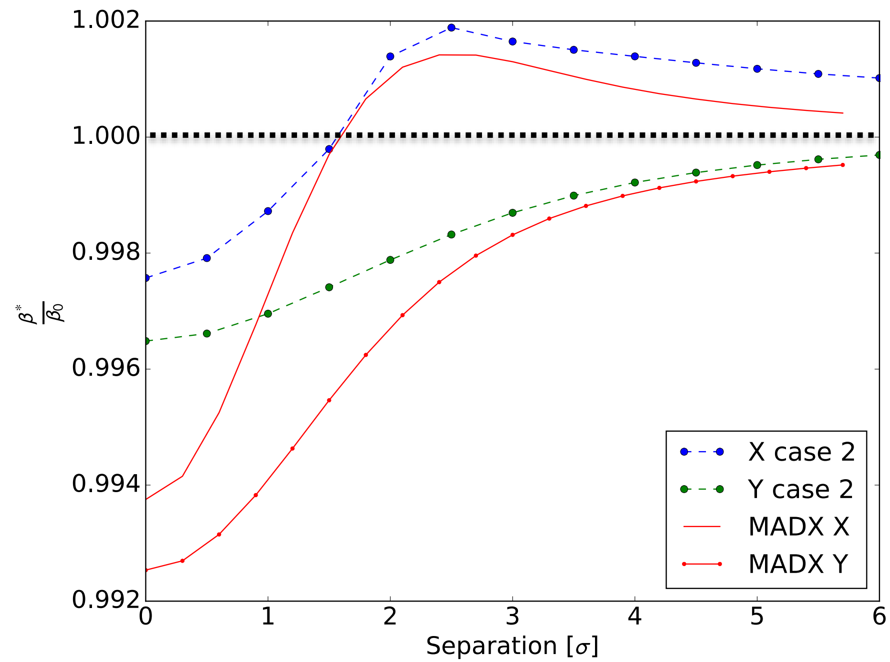
We turn on beam-beam adiabatically, skip first 2500 turns where equilibrium is found → average sliding window to reduce noise level (10^6 macro-particles, 1 IP) σ is the RMS of particle distribution→ allows for effects below 1% level in lumi ratios

“Dynamic beta” COMBI versus MADX

Case 1 → bbkick –coherent dipolar kick
Case 2 → bbkick

COMBI “beta change” is computed from beam size effect $\beta^* = \sigma^2 / \varepsilon$

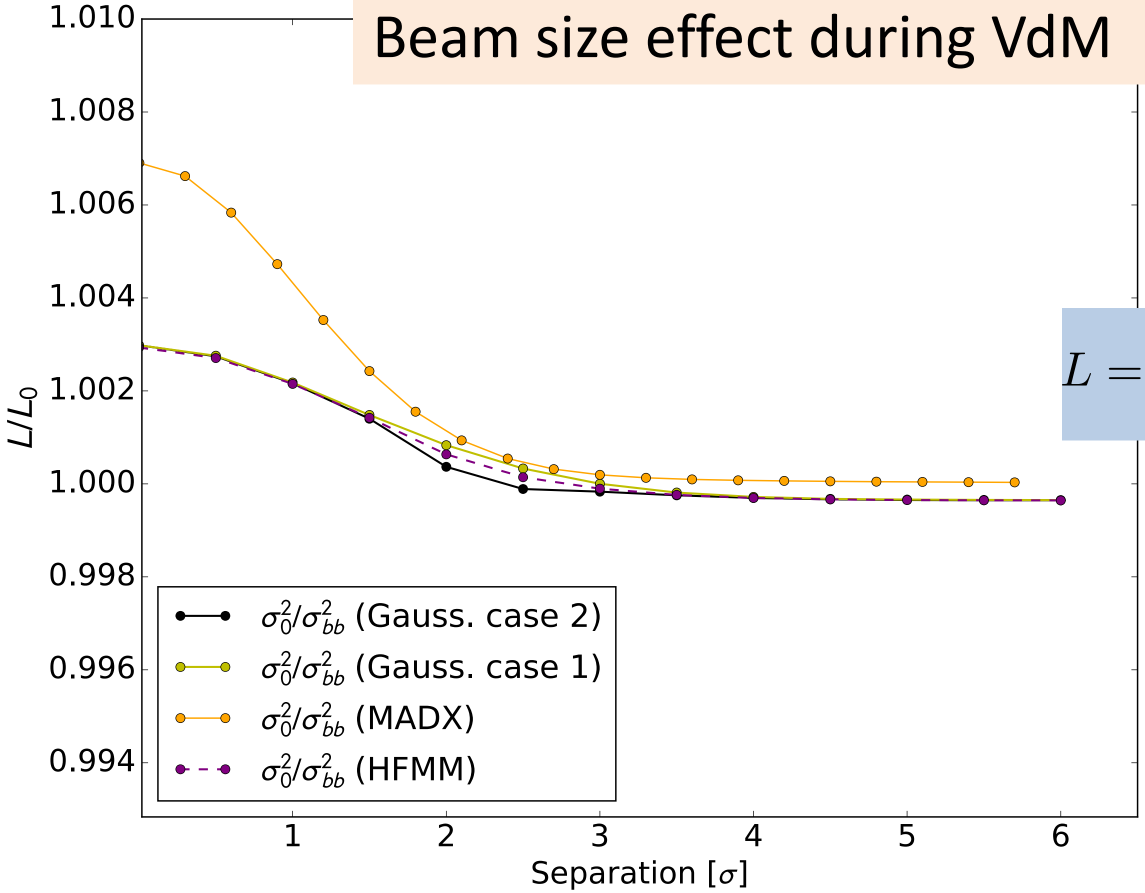




They should not be the same as for the case of the incoherent kick of beam-beam

MADX vs COMBI corrections to Luminosity

Beam size effect during VdM



$$L_0 = \frac{N_p^2 f}{4\pi\sigma_x\sigma_y} \cdot \exp(-\frac{sep^2}{4\sigma_x^2})$$

$$L = \frac{N_p^2 f}{4\pi\sigma_{x,bb}\sigma_{y,bb}} \cdot \exp(-\frac{(sep + Orb_{bb})^2}{4\sigma_{x,bb}^2})$$

If we assume:

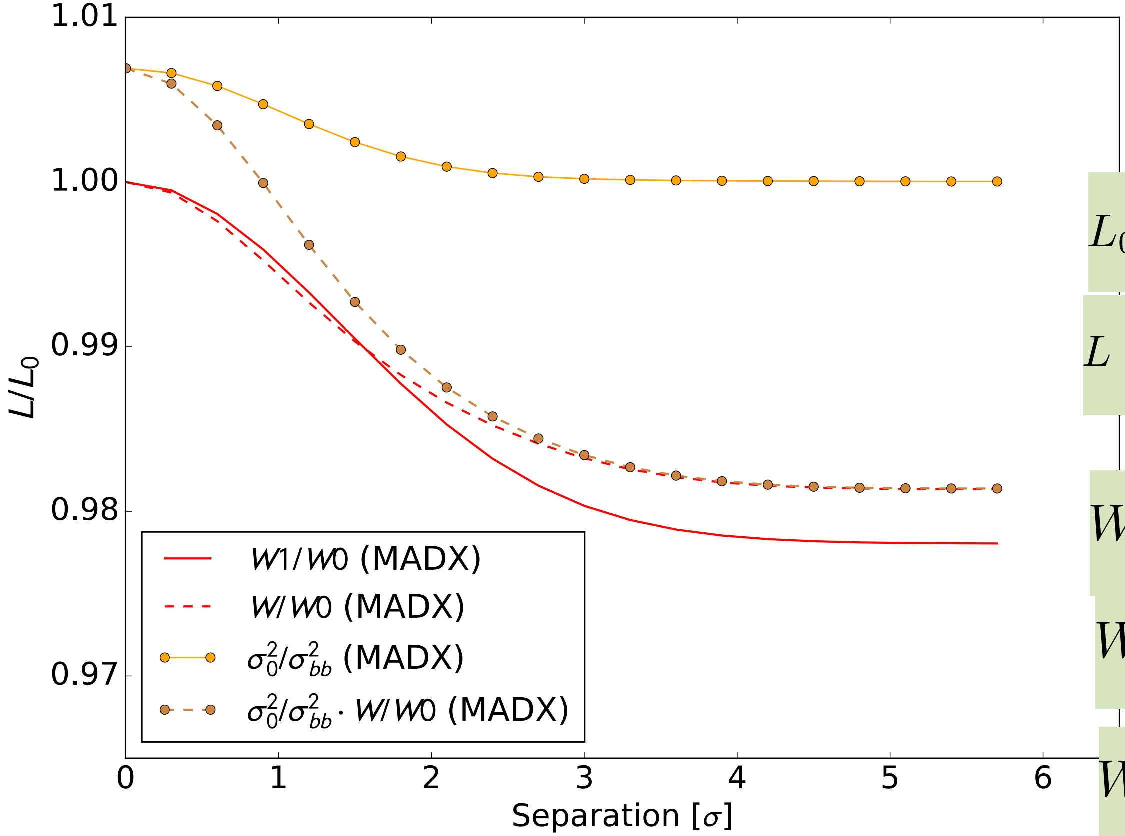
- Gaussian distributions
- No orbit effects from BB

→ the impact on Luminosity can be expressed as:

$$\frac{L}{L_0} = \sigma_0^2/\sigma_{bb}^2$$

Not all particles see the same effect → reduced sigma effects respect to MADX

MADX corrections to Luminosity



If we assume:

- Gaussian distributions
- Yes orbit effects from BB

→ the impact on Luminosity can be expressed as:

$$L_0 = \frac{N_p^2 f}{4\pi\sigma_x\sigma_y} \cdot W_0$$

$$L = \frac{N_p^2 f}{4\pi\sigma_{x,bb}\sigma_{y,bb}} \cdot \exp(-\frac{(sep + Orb_{bb})^2}{4\sigma_{x,bb}^2})$$

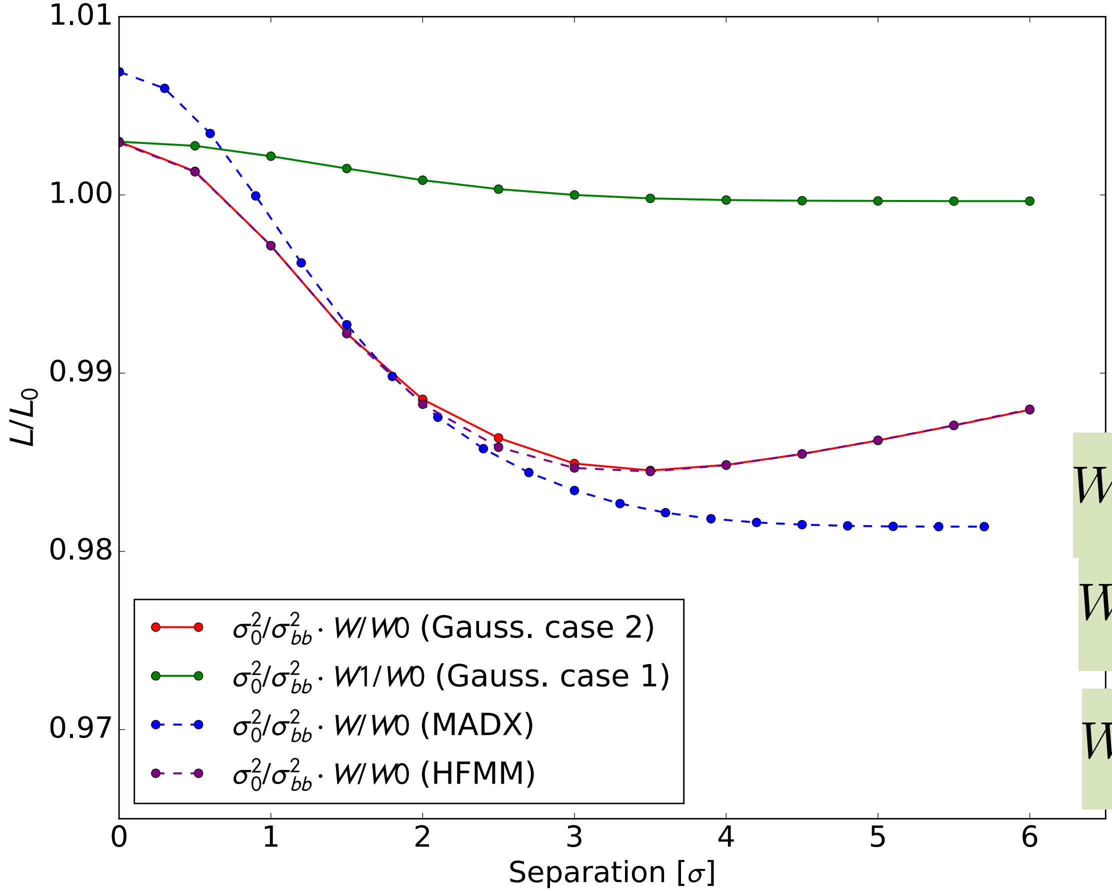
$$W = exp(-\frac{1}{4\sigma_{x,bb}^2} \cdot (Orb_{bb} + sep)^2)$$

$$W_0 = exp(-\frac{1}{4\sigma_0^2} \cdot sep^2)$$

$$W_1 = exp(-\frac{1}{4\sigma_0^2} \cdot (Orb_{bb} + sep)^2)$$

Orbit effects are computed and added as reduction factors defined as W

MADX vs multi-particle COMBI



Gaussian versus non-Gaussian beam-beam kick

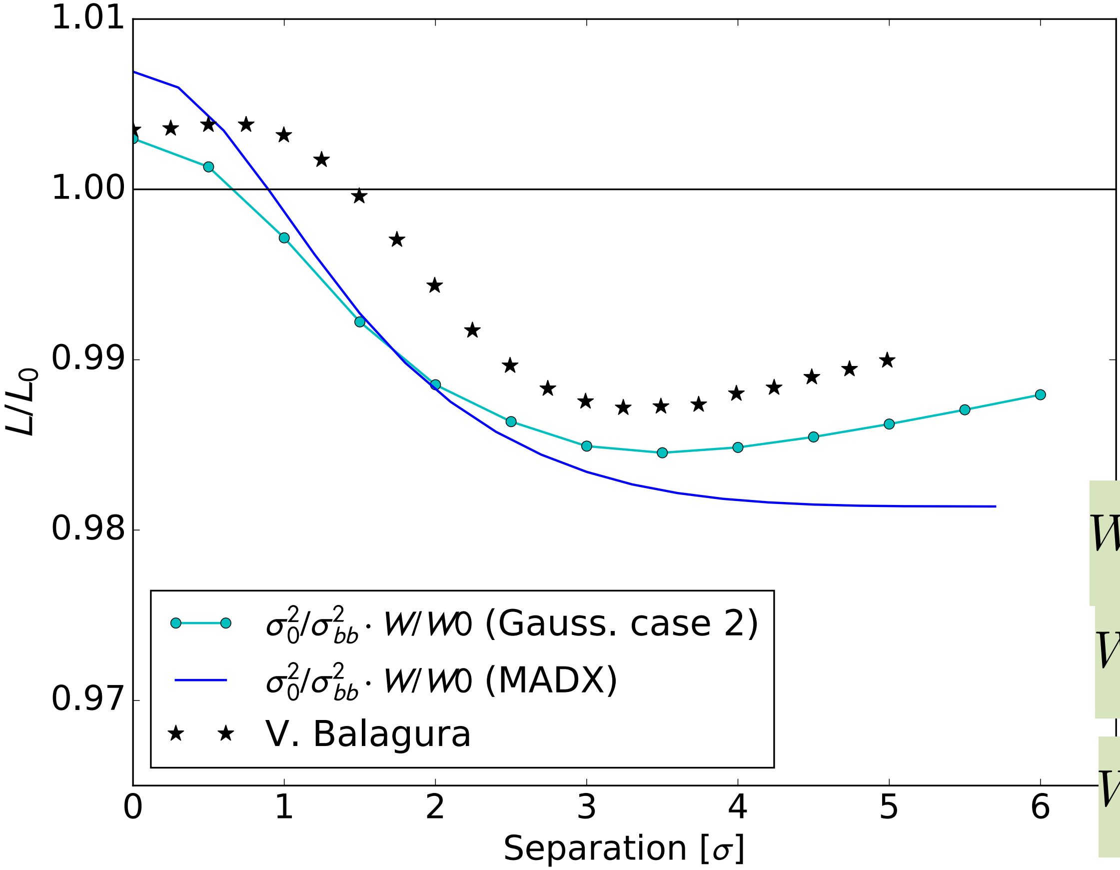
$$W = exp(-\frac{1}{4\sigma_{x_{bb}}^2} \cdot (Orb_{bb} + sep)^2)$$

$$W_0 = exp(-\frac{1}{4\sigma_0^2} \cdot sep^2)$$

$$W_1 = exp(-\frac{1}{4\sigma_0^2} \cdot (Orb_{bb} + sep)^2)$$

Overall effect changes because of particle distribution, no big impact if HFMM is used for the force calculation

COMBI vs V. Balagura results



Vladik uses an integrator for Lumi calculations
We used so far Luminosity equations for Gaussian distribution but with beam-beam effects distributions deviates from Gaussian.

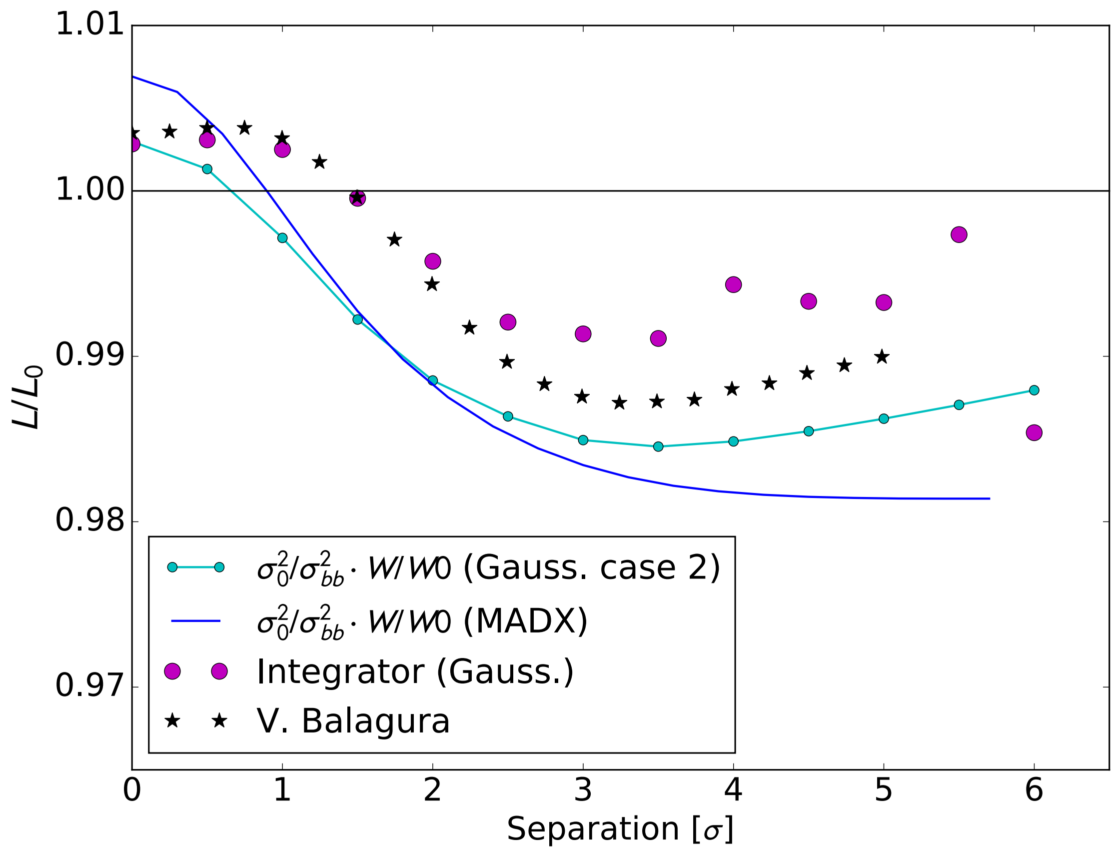
$$W = exp(-\frac{1}{4\sigma^2_{x_{bb}}} \cdot (Orb_{bb} + sep)^2)$$

$$W_0 = exp(-\frac{1}{4\sigma_0^2} \cdot sep^2)$$

$$W_1 = exp(-\frac{1}{4\sigma_0^2} \cdot (Orb_{bb} + sep)^2)$$

Integrator to compute overlap integral shows different effect respect to luminosity formulas for Gaussian beams

COMBI versus V. Balagura



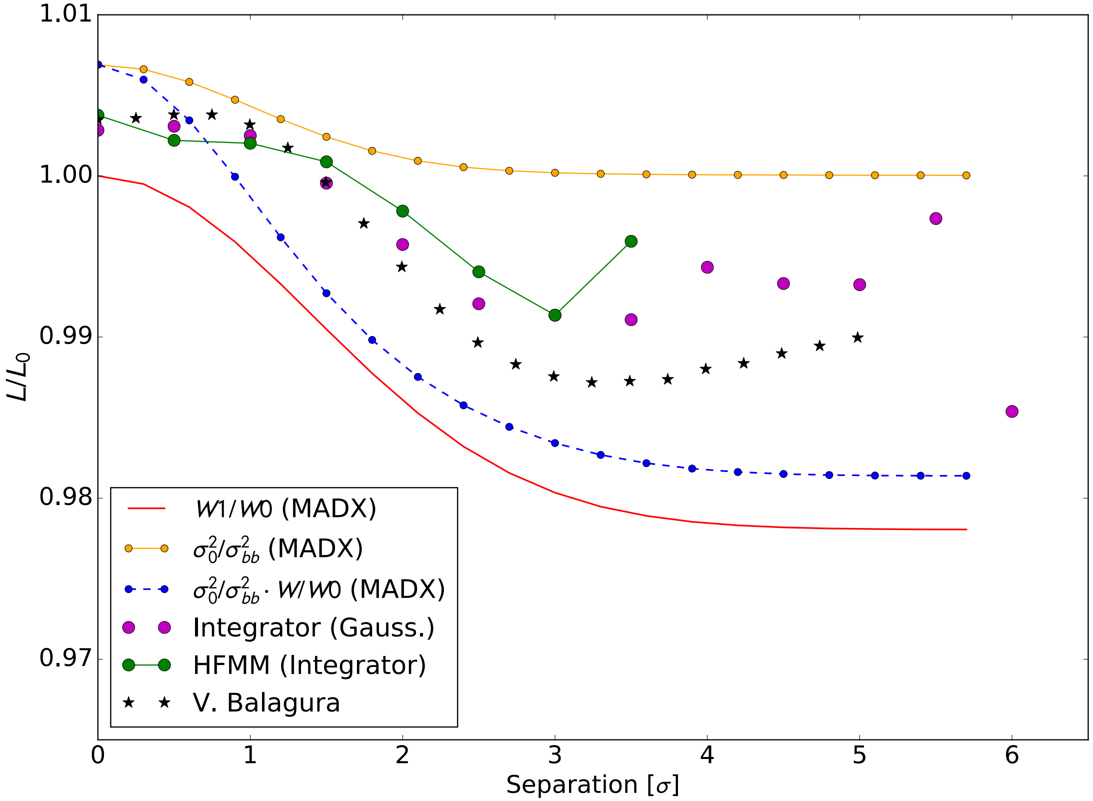
Vladik uses an integrator for Lumi calculations
We used so far Luminosity equations for Gaussian but beams are not really Gaussian

→ Developed simulations to compute overlap integral
J. Villarreal EPFL

→ Still some convergence issues (working on it)

Beams profiles are not Gaussian →Luminosity formulas for Gaussian profiles do not hold
Get luminosity from overlap integral of modified distributions
Results become more compatible with Balagura

COMBI versus V. Balagura



If distributions are not Gaussian→ how will a consistent beam-beam kick will affect the results?

→ **Beam-beam simulations with HFMM calculations**

Changes are not important if we take a correct computation for the beam-beam force due to the modified distribution

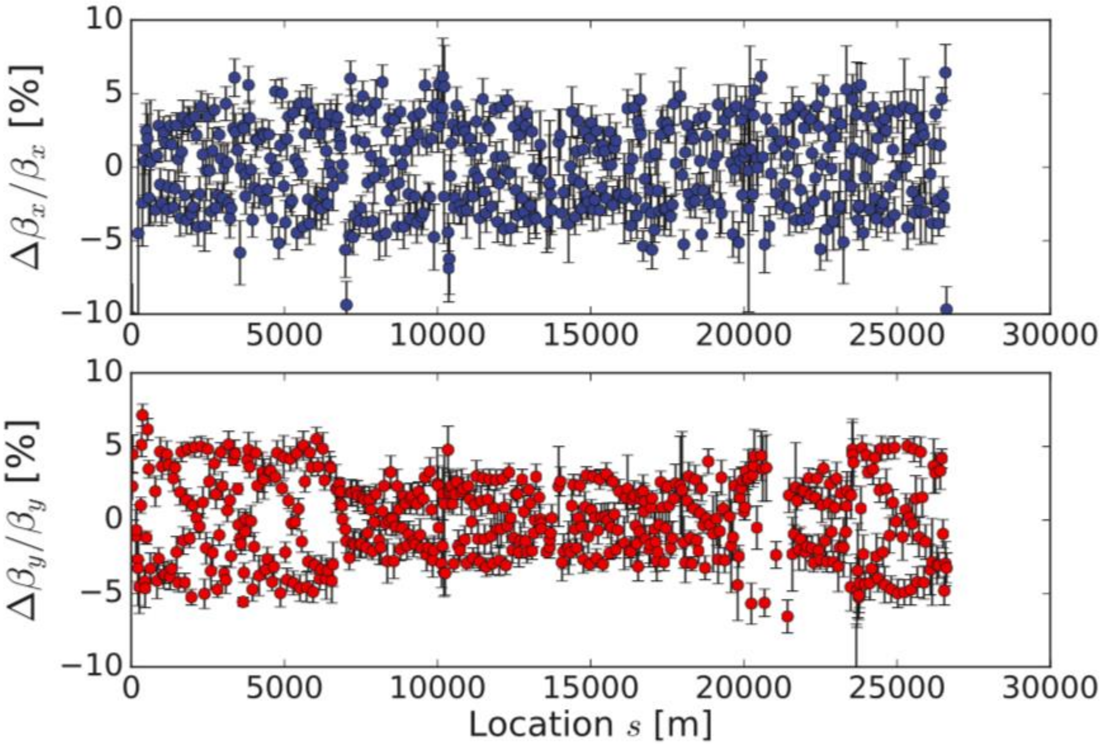
Summary

- Beam-beam effects modify the overlap integral of the two colliding beams during VdM scans with not negligible impact to the luminosity precision measurements
  - “dynamic beta” (beam size effect)
  - Orbit effect
- Past corrections were based on small amplitude particle approximation and frozen Gaussian distributions
- Different particles depending on their amplitude of oscillations sample different parts of the BB force which also couples x-y planes
- Higher order effects can be quantified with multi-particle simulations
- Distributions are modified and become non Gaussian → Luminosity formulas not valid to compute the correct overlap integral
- Results are qualitatively consistent with findings by Balagura but significant differences still need to be understood
- **If this is confirmed it implies that all Luminosity calibrations since 2012 are biased by an over correction of the order of 1%**

On-going work and outlook

- Improve integrator convergence for large separations
- Compare effects COMBI vs Balagura of beam size effects, overlap integrals, beam spectra.
- Multiple IP simulations and distribution impact from “HO” collisions in other IPs
- Build an effective parameterization (does it scale with ξ ?) that can be used by all experiments at all VdM scans
- Combined effects of long-range and head-on beam-beam effects (TRAIN and COMBI combined C. Rongrong EPFL student)
- Testing the effect in RUN III (X. Buffat and R. Tomas) ?

We always looked at larger beam-beam effects if we can measure at the detector 1% effect this will be a beautiful experimental evidence



[PHYS. REV. ACCEL. BEAMS 20, 101002 (2017) CERN-ACC-2017-151]

Measurement of beta beating due to beam-beam collision for ξ = 0.02 at IP1 for a beam oscillating at 2 σ amplitude → expected maximum effect 6-7 %

Beam-Beam deflection angles and orbit in the LHC: model for round and non-round beams

Deflections: $$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

$$\left\{ \begin{array}{l} \Sigma_{12} = 0 \\ \Sigma_{11} > \Sigma_{22} \\ \Sigma_{11} = \sigma_{x^1}^2 + \sigma_{x^2}^2 \\ \Sigma_{22} = \sigma_{y^1}^2 + \sigma_{y^2}^2 \end{array} \right.$$

Bassetti-Erskine formula:

$$F_0(x, y, \Sigma) = \frac{\sqrt{\pi}}{\sqrt{(\Sigma_{11} - \Sigma_{22})}}[w(\alpha_1) - w(\alpha_2) \cdot \exp(-\frac{1}{2}(\Sigma_{11}^{-1} x^2 + \Sigma_{22}^{-1} y^2))]$$

$$\alpha_1 = \frac{x + iy}{\sqrt{2(\Sigma_{11} - \Sigma_{22})}} \qquad \alpha_2 = \frac{(\Sigma_{22} x + i\Sigma_{11} y)}{\sqrt{2\Sigma_{11}\Sigma_{22}(\Sigma_{11} - \Sigma_{22})}}$$

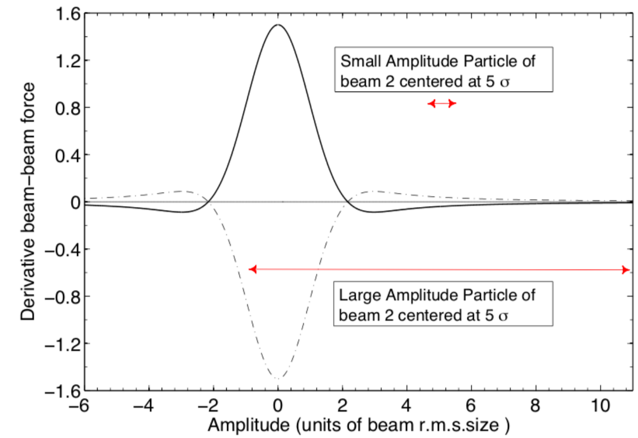
$$w(z) = exp(-z^2)erfc(-iz)$$

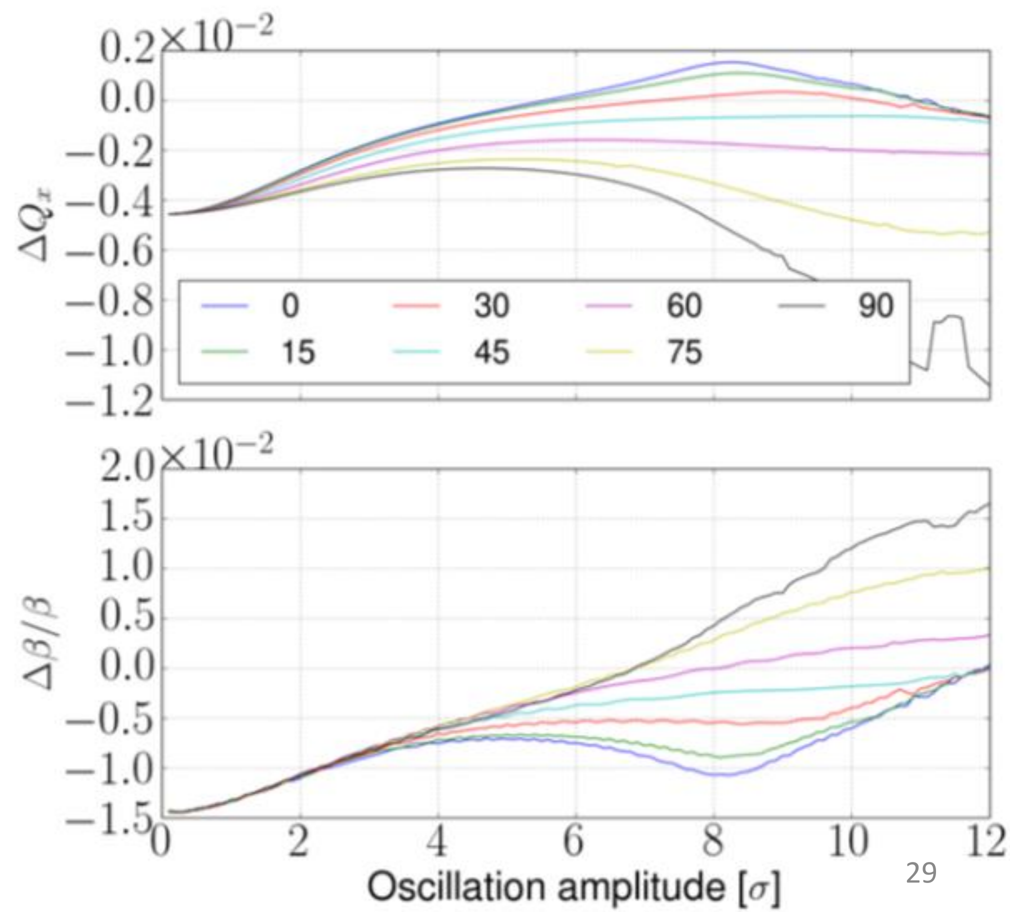
Closed Orbit effect: $$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

Multi particle effects
Head-ON and LONG-RANGE collision

- Not all particles see the same beam-beam effect

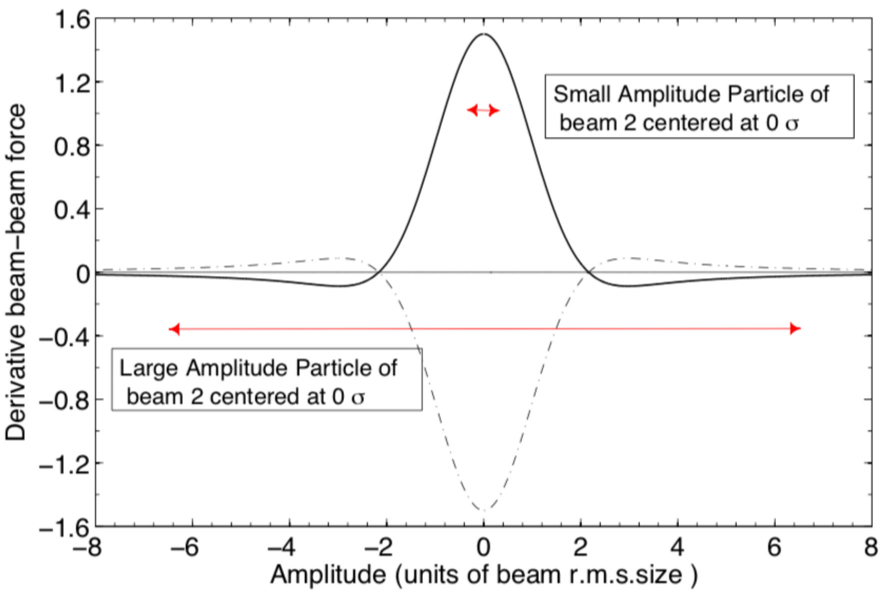
- Effect depends on the amplitude of oscillation → this results in a tune spread and a “sigma effect”





Tune spread and "dynamic beta" spread effect

Zero separation



6 σ separation