Future Circular Collider Technical and Financial Feasibility Study
2d FCC Energy Calibration, Polarization and Mono-chromatisation workshop

Opposite sign dispersion and collision offsets at the interaction points

FCC EPOL WORKSHOP

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https://indico.cern.ch/e/EPOL2022

remote participation possible

Opposite sign dispersion - LEP

The **impact on the center-of-mass energy** of **opposite sign dispersion** – more generally of **dispersion differences** – of the beams at the IP was identified at LEP in 1995.

- LEP had switched to operation with short bunch trains in 1995.
- This scheme involved separation of the trains (4 trains of 3 bunches) in the vertical plane by electrostatic separators installed in the straight sections on either side of each IP.
- The separation bumps generated by design a **dispersion difference at the IP of up to 2 mm between e+ and e- beams** (for β^* = 5 cm).

Details on the derivation of the equations – for **head-on collisions**:

Influence of Dispersion and Collision Offsets on the Centre-of-Mass Energy at LEP

CERN SL/Note 95-46 (OP)

J.M. Jowett, J. Wenninger, J. Yamartino*

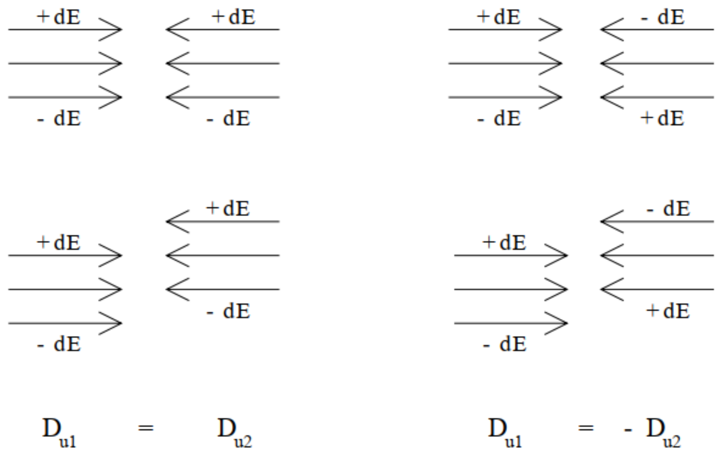
Opposite sign dispersion and CM energy

While the impact of dispersion on the **CM energy spread** depends on

- the **dispersion** at the IP (D_{ui}),
- the **beam energy spread** ($\sigma_\varepsilon = \sigma_E/E_0$),
- the **betatronic beam size** at the IP (σ_u),

… the CM energy shift depends also on

- the **separation of the two beams** (total separation = $2u_0$).



$$\Delta E_{CM} = -2u_0 \frac{\sigma_E^2 (D_{u1} - D_{u2})}{E_0(\sigma_{B1}^2 + \sigma_{B2}^2)}$$

I =1,2 labels the two beams
u = x,y labels the planes

$$\sigma_{E_{CM}}^2 = \sigma_E^2 \left[\frac{\sigma_\epsilon^2 (D_{u1} + D_{u2})^2 + 4\sigma_u^2}{\sigma_{B1}^2 + \sigma_{B2}^2} \right]$$

$$\sigma_{Bi}^2 = \sigma_u^2 + (D_{ui}\sigma_\epsilon)^2$$

Total beam size

for head-on collisions !

Opposite sign dispersion and CM energy

Separation between the two beams

Lower energy spread helps

Only the difference in dispersion matters, not the average value !

$$\Delta E_{CM} = -2u_0 \frac{\sigma_E^2 (D_{u1} - D_{u2})}{E_0(\sigma_{B1}^2 + \sigma_{B2}^2)}$$

$$\sigma_{E_{CM}}^2 = \sigma_E^2 \left[\frac{\sigma_\epsilon^2 (D_{u1} + D_{u2})^2 + 4\sigma_u^2}{\sigma_{B1}^2 + \sigma_{B2}^2} \right]$$

To control the impact on ECM:

- Minimize the dispersion @ IP
- No beam offset (at least on average)

Dispersion @ FCCee IPs

Simulations on machine errors + correction at the time of the publication of the paper on energy calibration resulted in a **typical IP dispersion of 10 μm** with **peaks of 30 μm** (by beam).

Going back to the CM energy error:

$$\Delta\sqrt{s} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0 \sigma_u^2} \quad \rightarrow \quad |\Delta\sqrt{s}| = 96\ |u_0|\ [\mathrm{keV/nm}]$$

for $\Delta D^* = 1$ μm, $\sigma_E/E = 0.13\%$

For **$\Delta D^* = 10$ μm**, the CM error is **~1 MeV/nm**, i.e., the uncertainty on / average separation must be below **$u_0 < 0.1$ nm to limit the systematic errors < 100 keV.**

- Even closer to 0.01 nm for $\sigma \sim 20$ nm → at the level of a % of the beam size.

A **measurement** and a subsequent **correction of ΔD*** is the key to **relax the tolerances** on control of the beam separation → **an uncontrolled bias of the beam separation at a very small level (<% of beam size) can generate an uncontrolled CM energy bias**.

Objectives to minimize the CM energy uncertainty

Minimize (zero on average !) the collision offsets at the IP

Measure and minimize (opposite sign) dispersion at the IP

Luminosity scan – beam separation corrections

Beam separation scans to minimize collision offsets are a **simple tool to optimize the luminosity (beam overlap)**.

- Luminosity versus beam separation in selected plane.

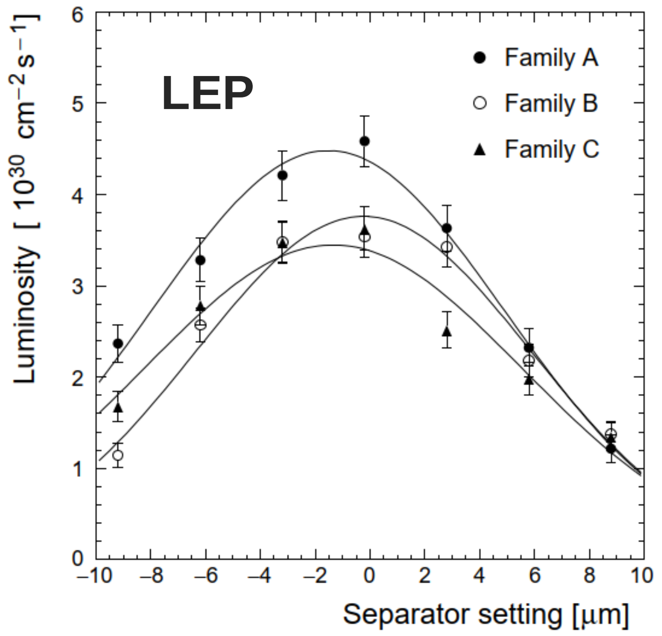
Scans must be performed regularly to ensure no offsets develop; frequency depends on the machine stability.

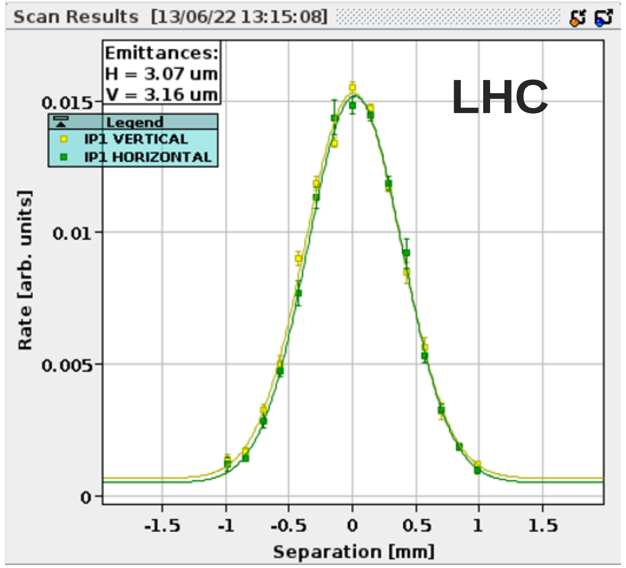
- Stability probably more critical for large machine due to the larger number of orbit drift sources !

This method was adequate for LEP1 (45 GeV), scans were performed at the beginning of physics data taking periods and repeated every few hours. The same applies at LHC.

- But the tolerance on offsets were/are quite relaxed compared to FCCee energy calibration needs !

Neither LEP nor LHC aim(ed) to control of the average offset at a level below ~0.1σ – impact on luminosity negligible.





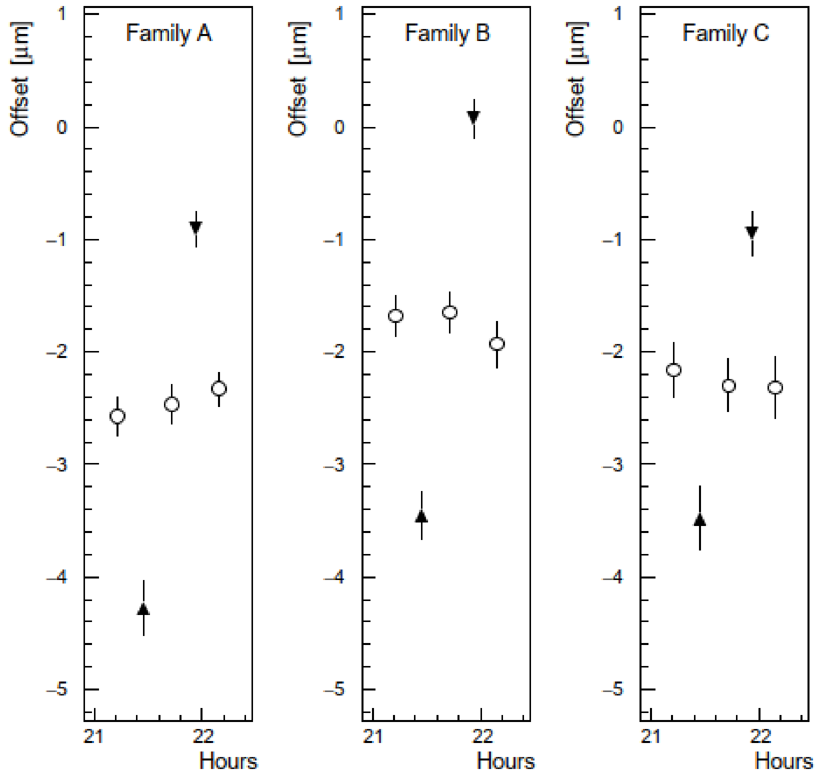
IP Dispersion @ LEP

At LEP1 the **dispersion differences at the IPs** were measured by applying a **RF frequency change** (→ change of dp/p) and measuring the change of the optimum separation settings using a luminosity scan.

- Direct access to the difference in dispersion at IP.
- Insensitive to the same sign dispersion (as beam movement is the same for e+ and e-).

	ΔD_y^* (mm)			
	IP2	IP4	IP6	IP8
Measurement	2.0 ± 0.4	-2.0 ± 0.7	1.8 ± 0.8	-1.5 ± 0.7
Theoretical prediction	1.8	-2.8	1.9	-1.9

Measured and predicted IP opposite sign vertical dispersion

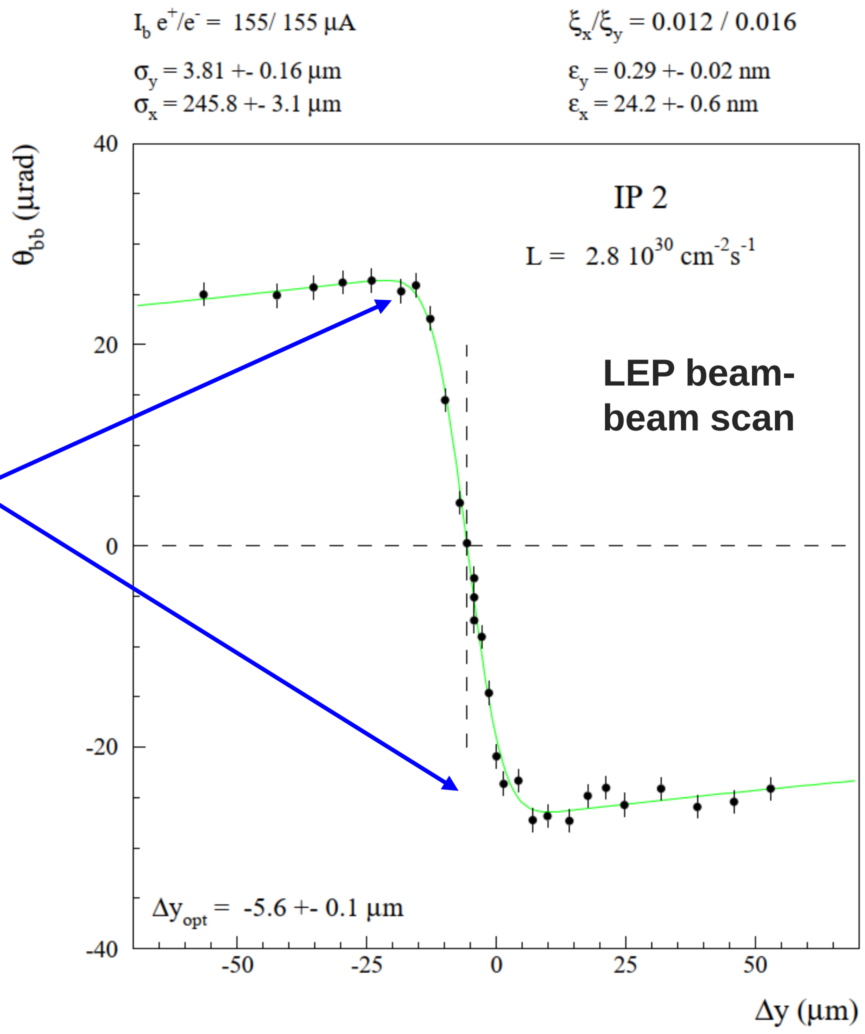


Example of separation scan optimum settings for **dp/p = 0** (circles) and **dp/p > or < 0**, (triangles). For the 3 bunches in the train.

Beam-beam deflection scan – beam separation correction

Beam-beam deflection scans – pioneered at SLC – **are an alternative to luminosity scans** to measure and correct beam separation offsets.

- In general, much faster to acquire an orbit reading than to integrate some luminosity.
  - But also more indirect: beam angle and not luminosity.
- BB scans however require to scan over a much **larger separation**, typically **±3σ with respect to expected optimum**: reach the **kink** of the deflection curve.

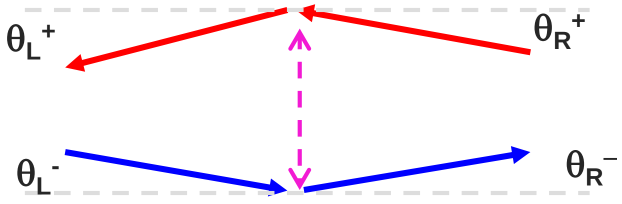


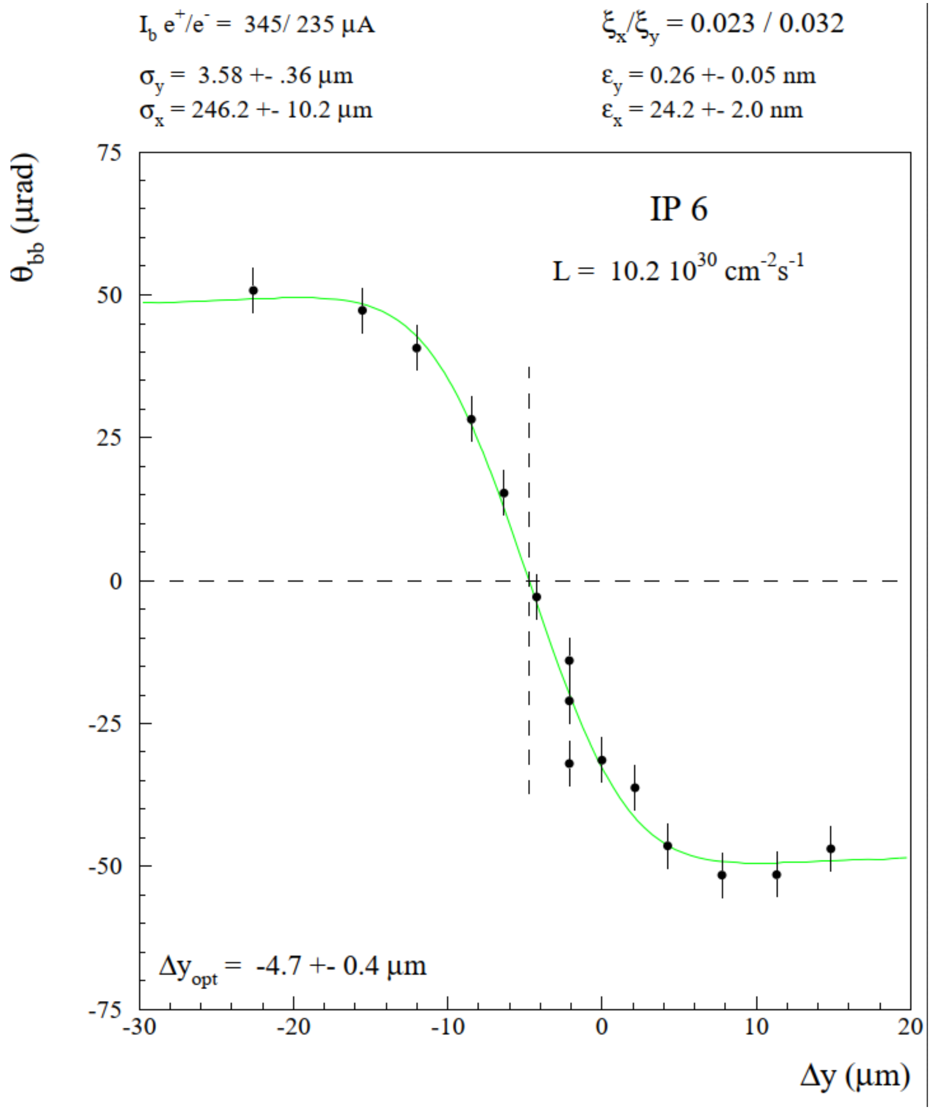
Beam-beam deflection

A clean and quite bias-free method relies on reconstructing the **difference in deflection between the e+ and e- beam**, i.e.:

$$\theta_{bb} = (\theta_L^+ - \theta_R^+) - (\theta_L^- - \theta_R^-)$$

L,R = left/right side of IP
+,- = e+ / e- beam





The **angles θ** are reconstructed using **2 BPMs** on either side of the IP (1 BPM is not sufficient !).

- Only the relative angle changes are relevant, absolute angles / offsets of the angles are irrelevant.
- In the plot to the right the **fitted offset** of θ_{BB} has been **removed**.

Impact of beam-beam kicks

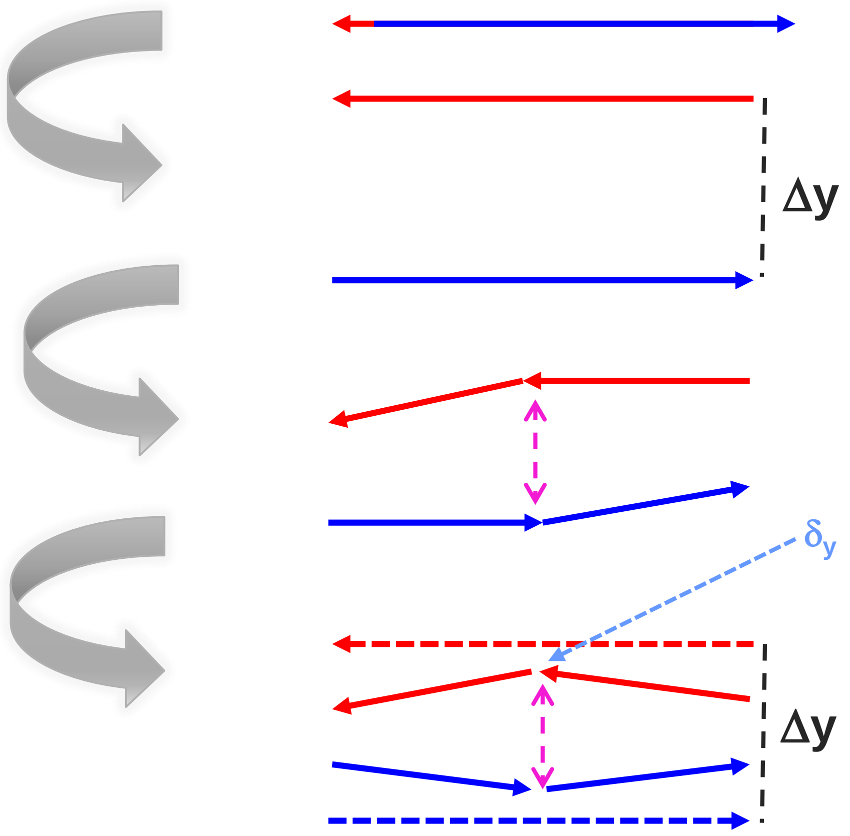
The naïve picture of scanning the beam by applying a separation at the IP must be corrected due to the presence of the coherent BB kick – valid for luminosity and beam-beam kick scans.

Apply a separation δ of the beams at IP

Beam-beam kick due to the separation δ

The beam-beam kick induces a **closed-orbit change** δ_y, leading to an **effective separation** that is **smaller than Δy** (for an attractive bb force and fractional Q in [0,0.5]).

$$\delta_y = \theta_{bb} \frac{\beta^*}{2 \tan \pi Q}$$



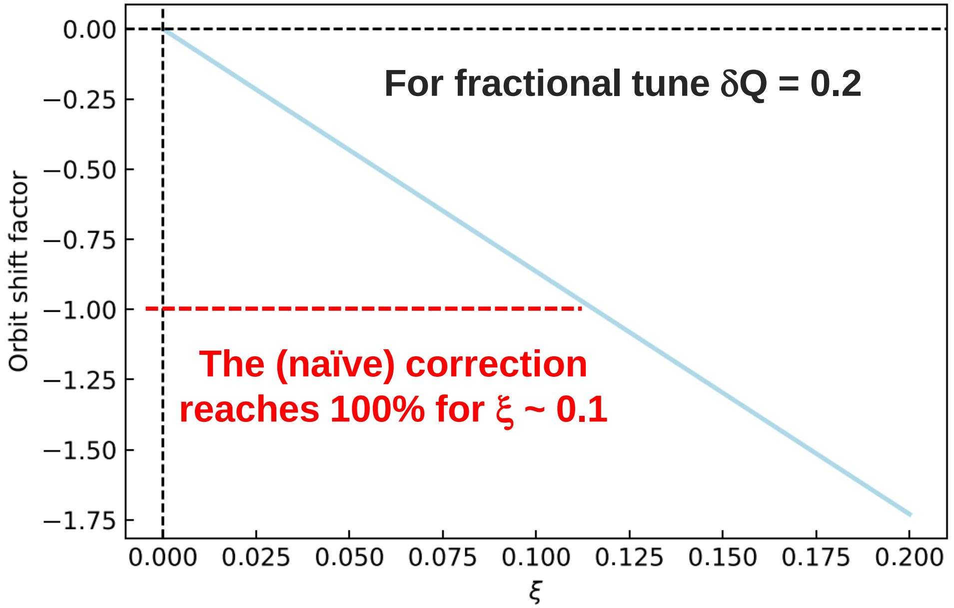
This first order estimate is only valid for $\delta \ll \Delta y$, small BB kick.

Impact of beam-beam kicks (2)

The beam-beam kick induces a change of the externally imposed separation Δy.

With a beam-beam kick(*) $\theta_{bb} = \frac{-4\pi\xi}{\beta*}\Delta y$

The orbit change at the IP is $\delta_y = \theta_{bb}\frac{\beta*}{2\tan\pi Q} = \boxed{\frac{-2\pi\xi}{\tan\pi Q}}\Delta y$



For large BB tune shifts, a self-consistent calculation is required for the real separation $\mathbf{\Delta y_s}$:

$$\Delta y_s = \Delta y - \frac{2\pi\xi}{\tan\pi Q}\Delta y_s$$

$$\Delta y_s = \Delta y/(1 + \frac{2\pi\xi}{\tan\pi Q})$$

for ξ ~0.1, $\Delta y_s \sim \Delta y/2$

Those estimates do not consider dynamic beta-beat… leading to a change of ξ and $\beta*$.

Not to forget, IP-to-IP cross-talk !

(*) assuming we are in the linear regime

Minimizing the separation

Separation optimization by **luminosity** scans has the advantage of relying on the primary observable – **the luminosity** – to define the optimum.

- High accuracy (statistics) and low systematics (very tiny beam movements),
- Modest scan range of 0.5-1σ could be sufficient.

Separation optimization by **BB kick reconstruction** requires much **larger amplitudes (±3σ)** and does not use the primary observable which is the luminosity.

- Bias from BPM system cannot be excluded.
- Realistic simulations of such scans required to better evaluate possible biases.

The impact of the BB kick (and dynamic beta) on the applied separation leads to a deformation of scan curve but should not affect the optimum (i.e head on) setting.

A **realistic BB tracking simulation** must be performed to get a better **understanding of the dynamics** of luminosity and BB separation scans – as a function of the BB tune shift.

IP dispersion measurements @ FCC-ee

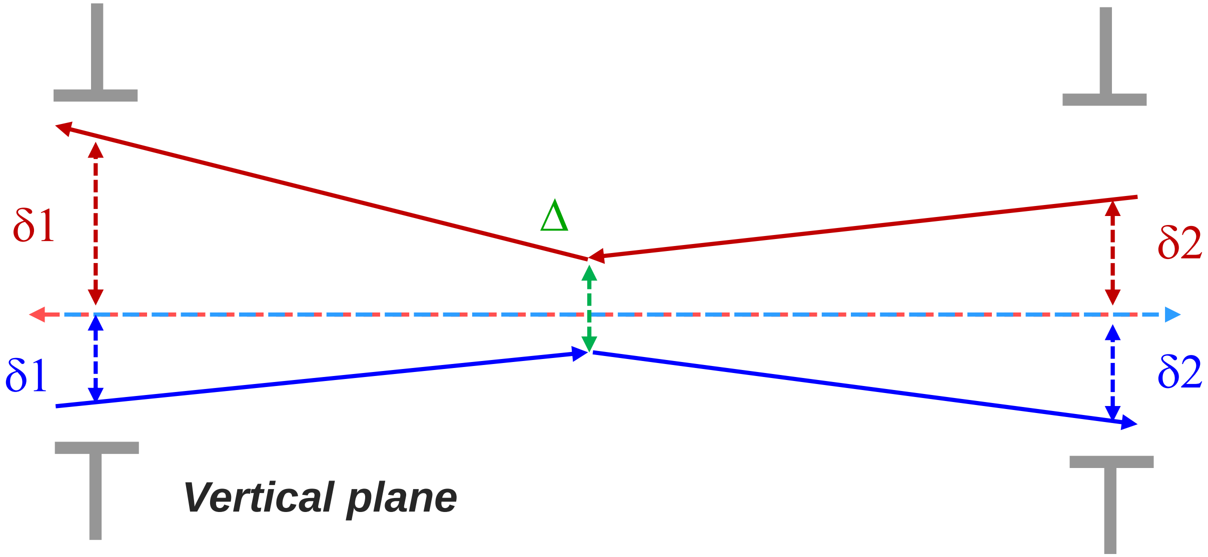
For an energy change of **dp/p = ±0.1%** and **ΔD* = 10 μm**

→ The separation change at the IP is **Δy = 10 nm – without BB !** – **measurable with a separation scan** since we must be able to control the separation << 1 nm.

The BB kick due to such a change is $y' = \frac{-4\pi\xi}{\beta^*}\Delta y$

→ y_s' = -6 μrad for ξ = 0.1, β* = 1 mm (self-consistent).

At the first **BPMs** (~2 m), the **displacement due to the BB kick is ~12 μm** to which one must add the shift due to the **local dispersion at the BPM** → no direct extraction of the dispersion from the BPM readings.



δ2, δ1, δ2, δ1, Δ receive contributions from the local dispersion and from the BB kick @ IP.

IP dispersion measurements

To **disentangle** position shift due to local dispersion @ BPMs from the BB kick, one must subtract a **reference without the BB kick.**

- Assumes that non-colliding and colliding bunches have the SAME dispersion: to what level is that statement true? Cannot answer at this stage → have to study.

A few **non-colliding bunches** in the filling scheme – preferably of **same intensity** than the colliding bunches to limit systematic errors – could provide that **reference**.

- Reconstruct the BB kick due to the IP separation shift by subtracting at each BPM the readings of the non-colliding bunches → still requires to disentangle effect of BB kick to obtain the dispersion.
- Systematic effects difficult to assess at this stage, but at equal intensity they could be minimized.

If a measurement of the angle y' with an **accuracy of 1 μrad** (or better) is achievable, **ΔD*** could be **determined to within ~1 μm** directly from the BB kick (no scanning).

For a short-term BPM accuracy of **0.1 mm**, **ΔD* can be determined << 1 μm.**

Dispersion measurement

Direct measurement: the **shift** in **optimum separation** at the IP with dp/p offset can be determined with the **luminosity** or the **BB kick** **separation scans**. The difference in optimum defines the opposite sign dispersion.

- Accuracy of scans – which should be high – will define accuracy on dispersion together with dp/p range. For dp/p ~ $\pm$0.1%, a measurement of ΔD^* to 1 μm or less should be feasible.

Indirect measurement: avoid the optimization scan of the direct measurement but extracting the dispersion from a reconstructed BB kick after applying a dp/p change.

- Requires a reference measurement of the dispersion at the BPMs, obtainable from non-colliding bunches.
  - Need an excellent understanding of the BB kick to be able to infer the initial perturbation from the dispersion.

Summary

Scans of the optimum separation – whether by luminosity of BB kick – will be important to minimize the collision offsets feeding into the CM energy error.

- Advantage of luminosity: it is a direct indicator of optimum overlap; scans require a smaller range.

With either scan method the opposite sign dispersion can be measured.

- Once the dispersion is determined, a correction should be attempted to better control the CM energy uncertainty and relax tolerances on the knowledge of the separation.

A determination of the dispersion directly from the BB kick – without any scan – may also be possible.

- Large corrections due to the BB kick must be considered.
- This method could on the other hand provide a **fast method to set an upper bound to the dispersion or ensure the stability of the dispersion**.

A lot of work ahead of us to control this uncertainty !!