Centre-of-mass energy shifts in Z pole run

Alain Blondel as member of EPOL group

Resonant depolarization frequency → $< E^{+}_{b} >$, $< E^{-}_{b} >$ → $E_{CM}\,(IP_{1,2,3,4})$

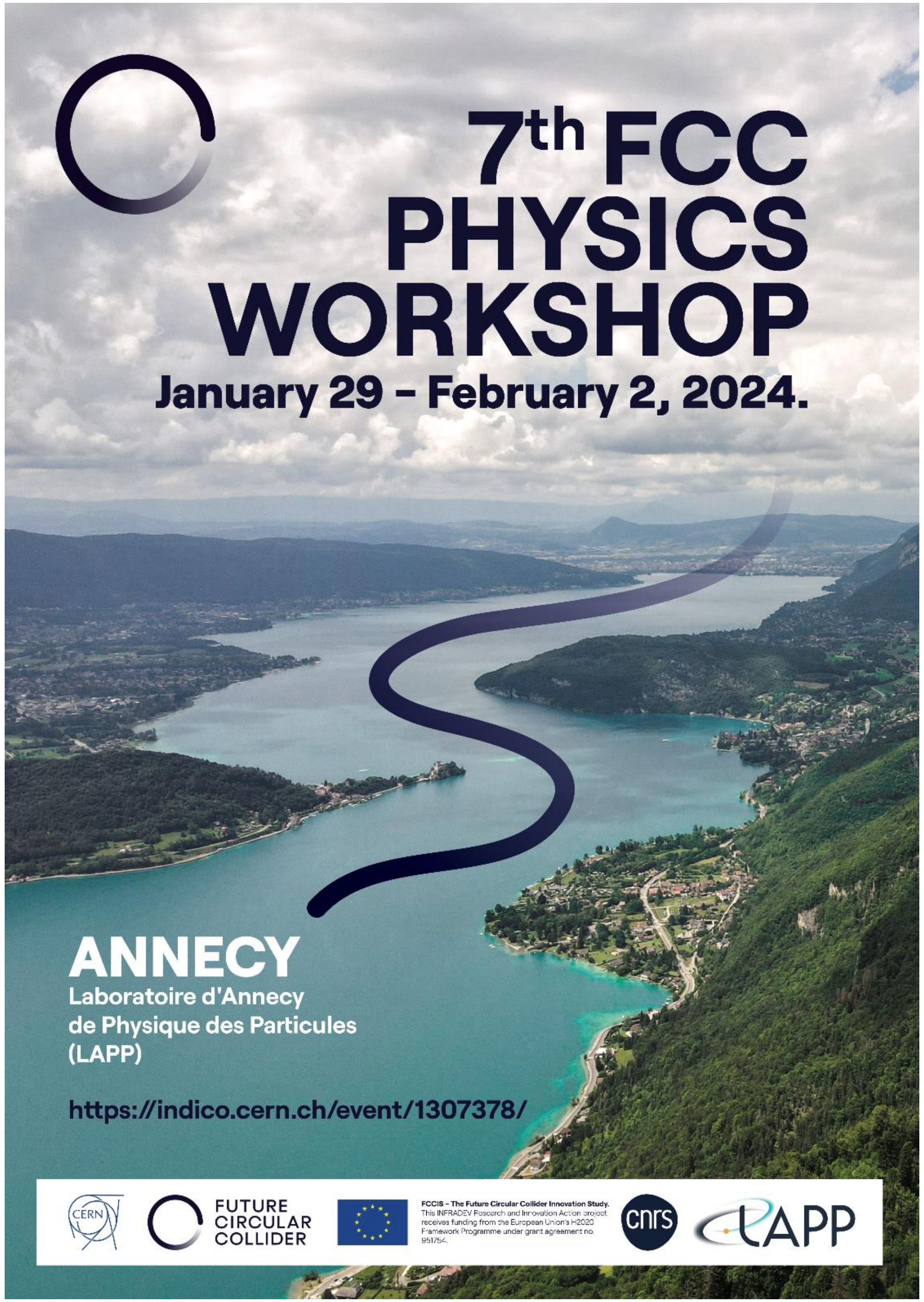
-- Energy gains and losses in the ring
-- Beam Collision Offsets X Opposite Sign Vertical Dispersion (OSVD)
-- EM attraction between bunches

and their monitoring/measurement methods

Error budget on E_{CM} : << 100 keV absolute, ~<4keV point-to-point

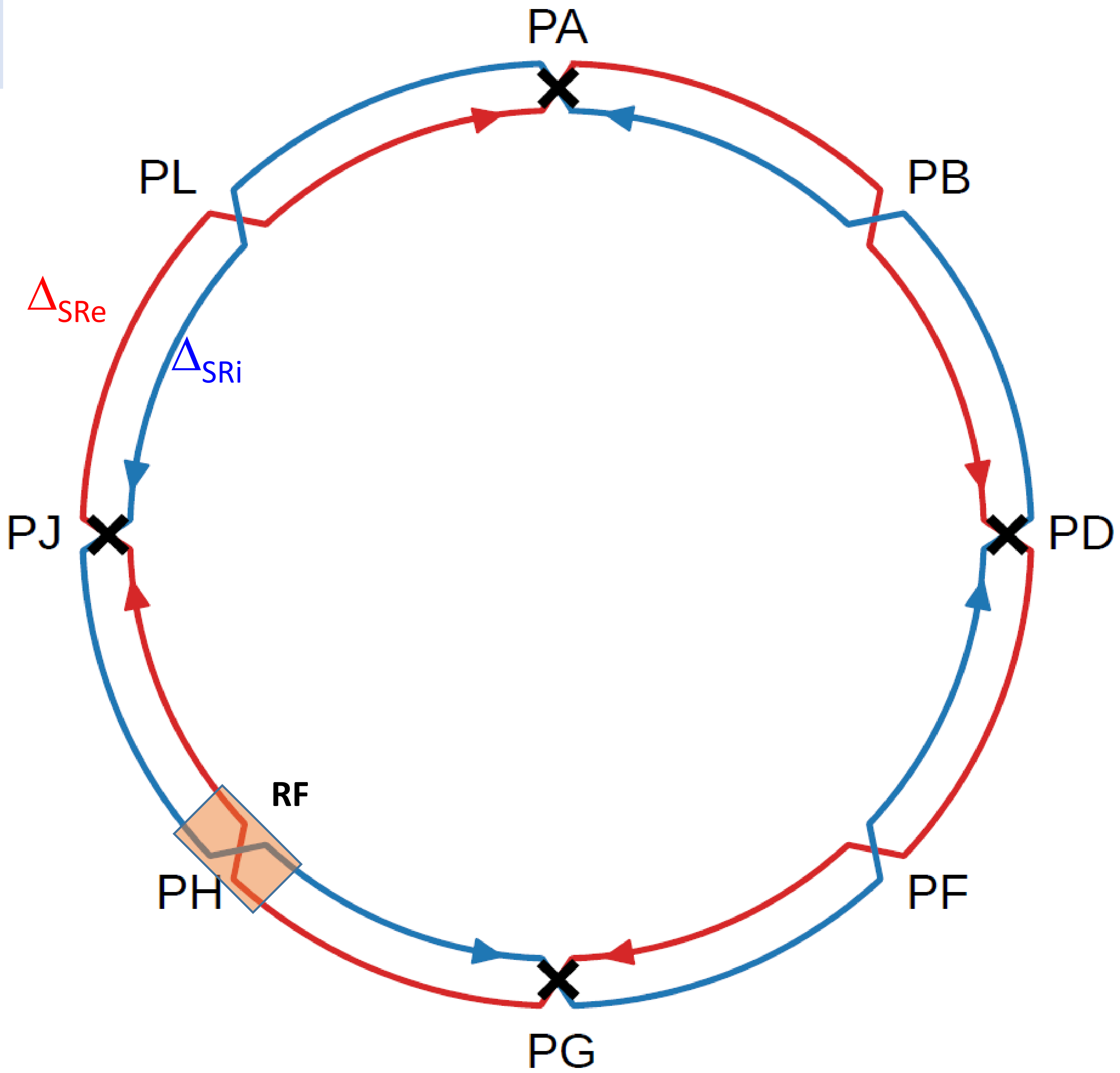
PROGRESS_REPORT January 2024 Annecy based on June 2023 London

GO TO PAGE 5, 6-9



Orders of magnitude, basics

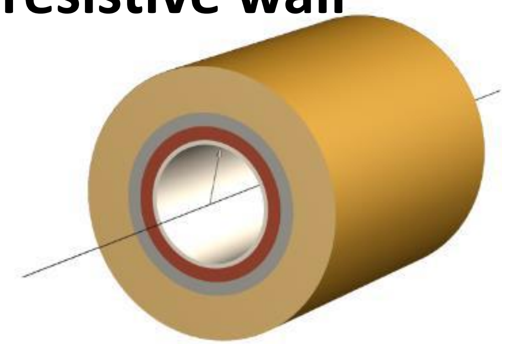
the average energies E_0 around the ring
are determined by the magnetic fields and
RF frequency
➔same for colliding or non-colliding beams
-- measured by resonant depolarization
-- can be different for e^+ and e^-
ESSENTIAL TO HAVE ALL RF IN ONE POINT

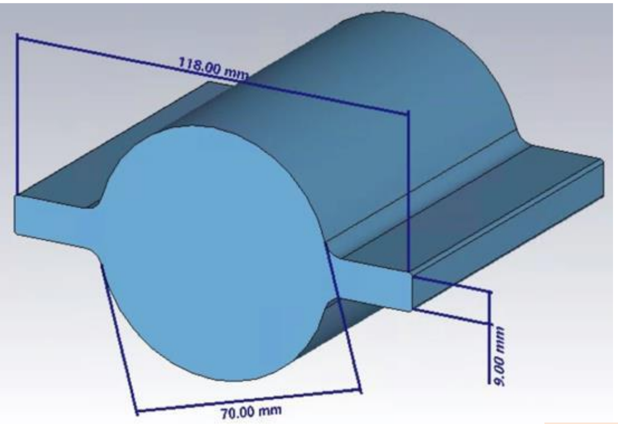


Orders of magnitude, Longitudinal Impedance

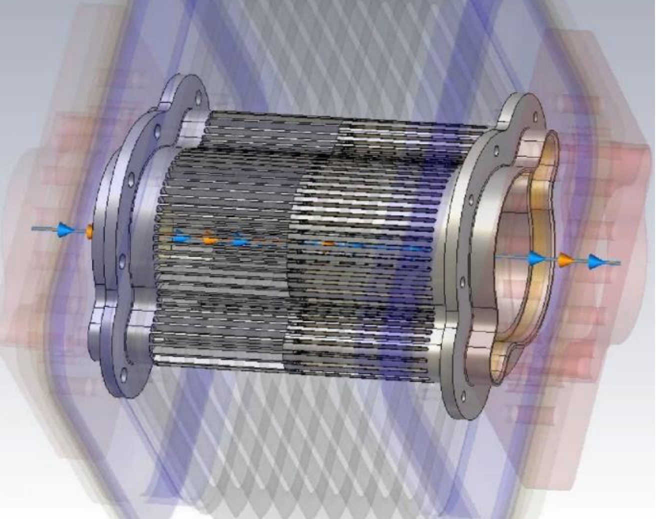
Emanuela Carideo, EPOL workshop 2

resistive wall

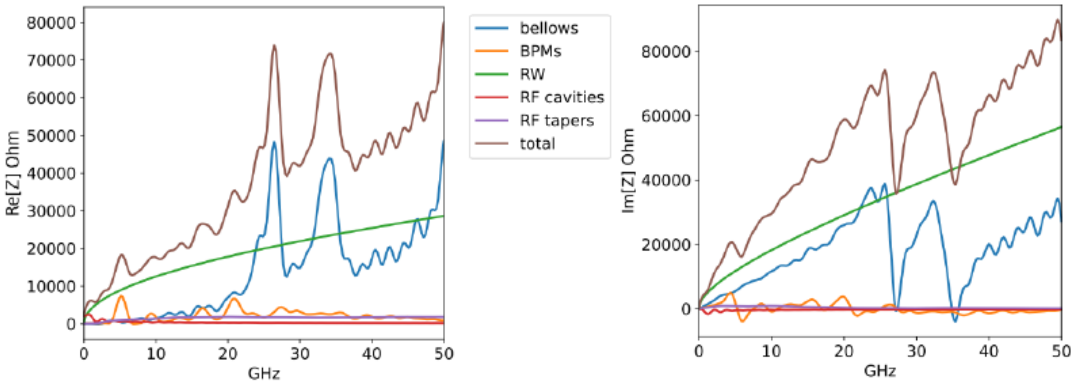




Bellows



Total impedance: longitudinal



Uniformly distributed depends on bunch length!

The main sources of longitudinal impedance, responsible of the energy change, are the RW and the bellows, which are distributed uniformly around the machine → there is no strong localized impedance that can change the bunch energy (and its

The bunch lench increases for colliding beams ➔ energy losses decrease.

	Pilot bunch (3×10^{10} ppb)	Nominal intensity (2.6×10^{11} ppb)	Nominal intensity and beamstrahlung (2.6×10^{11} ppb)	SR
Energy spread	0.039 %	0.045 %	0.143 %	0.039 %
Energy loss	0.8 MeV	4.2 MeV	~ 1.6 MeV	39 MeV
Bunch length	5 mm	8.3 mm	17.2 mm	4.4 mm

From EPOL Workshop I (2017)

3. **From spin tune measurement to center-of-mass determination** $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

3.1 Synchrotron Radiation energy loss (10 MeV @Z in 4 'arcs') calculable to < permil accuracy

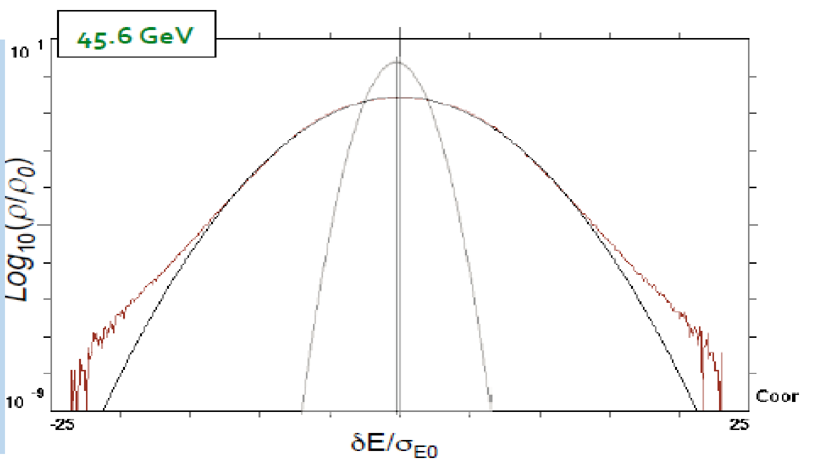
3.3 Beamstrahlung energy loss (0.62 MeV per beam at Z pole), compensated by RF (Shatilov)

3.4 layout of accelerator with IPs between two arcs well separated from single RF section

3.5 E_b^+ vs E_b^- asymmetries and energy spread can be measured/monitored in expt:

e+e- → μ+ μ- longitudinal momentum shift and spread (Janot)

D. Shatilov: beam energy spectrum without/with beamstrahlung

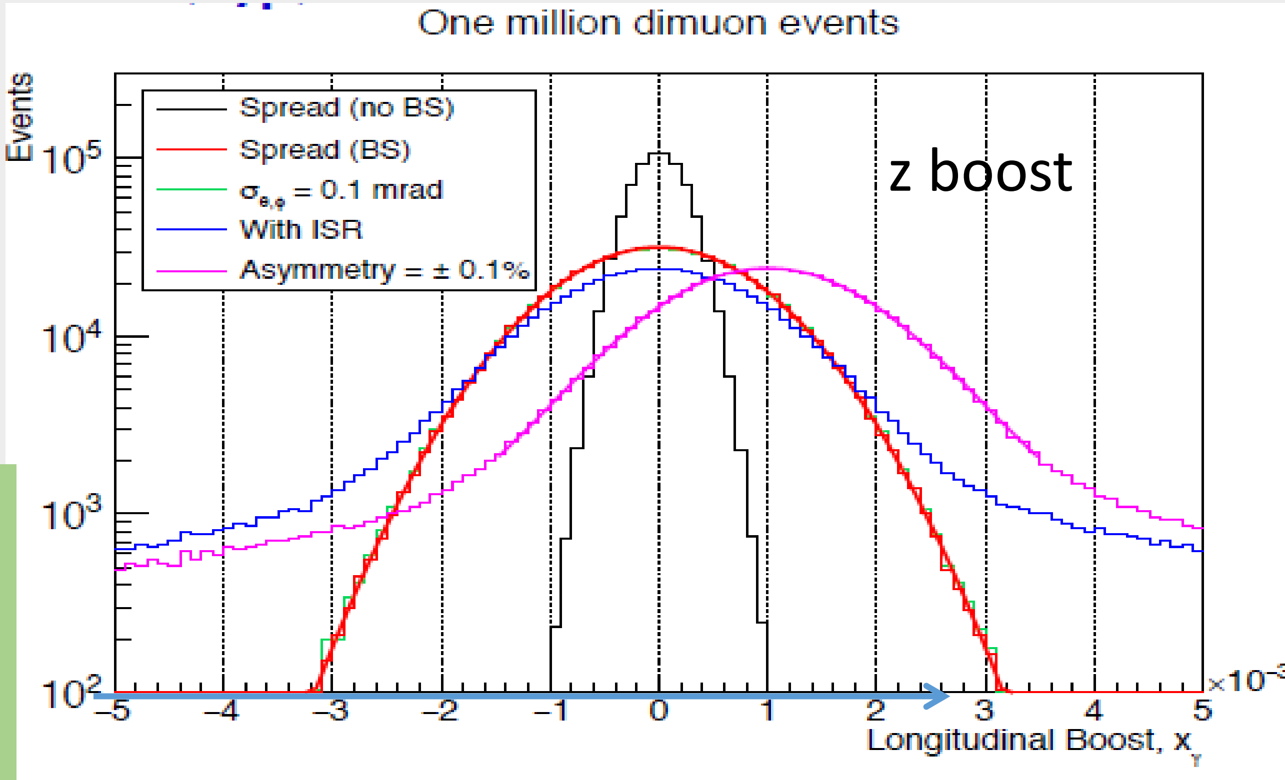


P. Janot: 5 min/exp @Z ➔ 10^6 μ+ μ- /expt →

→ 50 keV meast both on σ_{ECM} and $E^+ - E^-$

→ and beam crossing angle α (error negl.)

→ also monitor relative ECM (p-t-p!)



Orders of magnitude – ECM and Boosts

in this slide, many simplifying assumptions
-- ΔBS same for all IP
-- energy losses same for all arcs, include SR and Long. Impedance
-- γ^4 effect ignored
-- E_0 measured by Resonant depolarization

$\Delta_{RF} = 4\Delta_{SRi} + 4\Delta_{SRe} + 4\Delta_{BS}$

$E^-_J = E_0^- + \Delta RF/2 - \Delta_{SRi} - \Delta_{BS}/2$

$E^+_J = E_0^+ + \Delta RF/2 - 4\,\Delta_{SRi} - 3\,\Delta_{SRe} - 7\Delta_{BS}/2$

$E^+_J + E^-_J = E_0^+ + E_0^- + \Delta RF - 5\,\Delta_{SRi} - 3\,\Delta_{SRe} - 4\Delta_{BS}$

$E^+_J + E^-_J = E_0^+ + E_0^- + \Delta_{SRe} - \Delta_{SRi}$

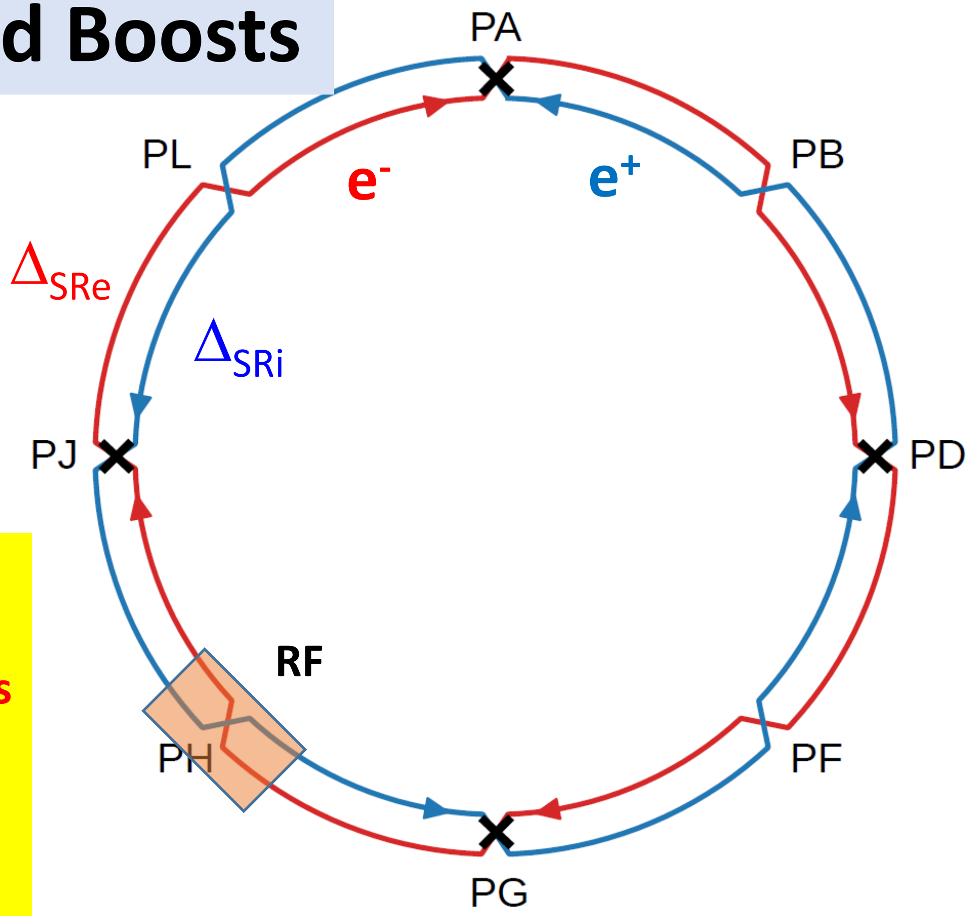
$E^-_A = E_0^- + \Delta RF/2 - 2\Delta_{SRi} - \Delta_{SRe} - 3\Delta_{BS}/2$

$E^+_A = E_0^+ + \Delta RF/2 - 3\,\Delta_{SRi} - 2\,\Delta_{SRe} - 5\Delta_{BS}/2$

$E^+_A + E^-_A = E_0^+ + E_0^- + \Delta RF - 5\,\Delta_{SRi} - 3\,\Delta_{SRe} - 4\Delta_{B}$

$E^+_A + E^-_A = E_0^+ + E_0^- + \Delta_{SRe} - \Delta_{SRi}$

-- ECM shift due to SR in $\neq$ ext
-- all Ecm are the same
-- boosts measure the energy losses
-- differences between the rings will show up.
-- assumes BS energy loss before collision is on average half of full beamstrahlung



Boost(J) = $E^-_J - E^+_J = E_0^- - E_0^+ + 3\,\Delta SRi + 3\,\Delta SRe + 3\,\Delta BS$ ➔ measures ¾ of E losses in J and G

Boost(A)= $E^-_A - E^+_A = E_0^- - E_0^+ + \Delta SRi + \Delta SRe + \Delta BS$ ¼ in A and D

(other two ibid with reverse sign)

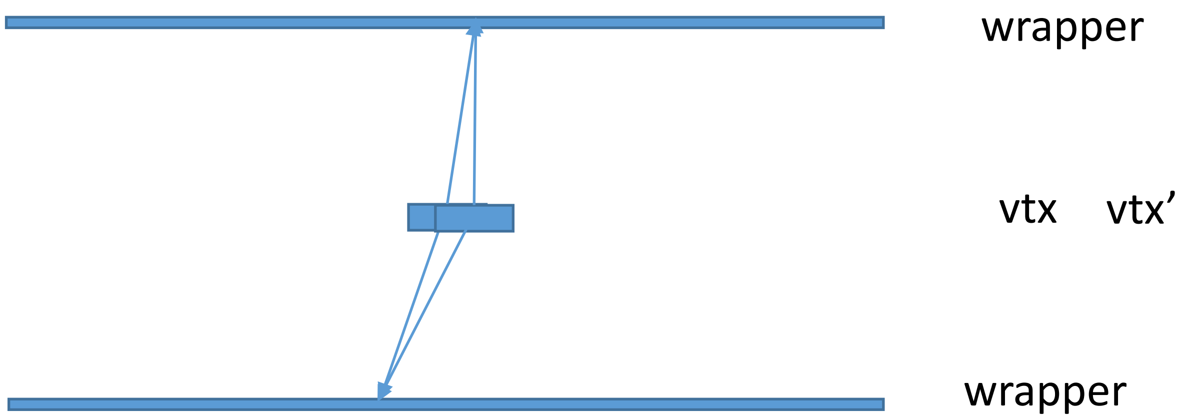
considerable information contained in the boosts measured by the experiments!

About the boost measurement using dimuons

refer to Patrick's presentation in London, based on measurement of the acollinearity in $Z \rightarrow \mu\mu$ events
This is a beautiful and potentially very powerful method. The statistical precision will be quickly sufficient.
A fundamental difficulty is that many sources of misalignment exist that affect the measurement of track angles.

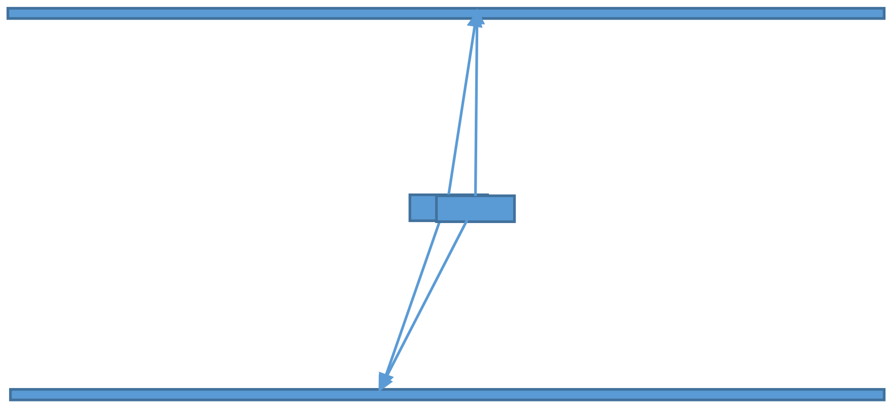
Example of a difficulty:

the internal alignment of the detector leads to systematic uncertainties in the track angle measurements -- we are not measuring the angle directly, but basically from the position of a set of space points. A relative shift of the vertex detector assembly wrt the outer part (wrapper) of the tracker by only 30 microns ➔ **acollinearity shift by 30microrad**.
This is very similar to a longitudinal shift in CM boost of 1.5 MeV!. The slight difference can be observed by analysis of the dilepton sample, but can also be mimicked by a small deformation of the outside detector, in which one encap has a slightly larger diameter than the other.



In other words, the 'global' in-situ alignment require a 'global' fit to a great many sources of misalignment simultaneously, and it is not guaranteed that there will not remain blind directions.

The need of cosmic muons

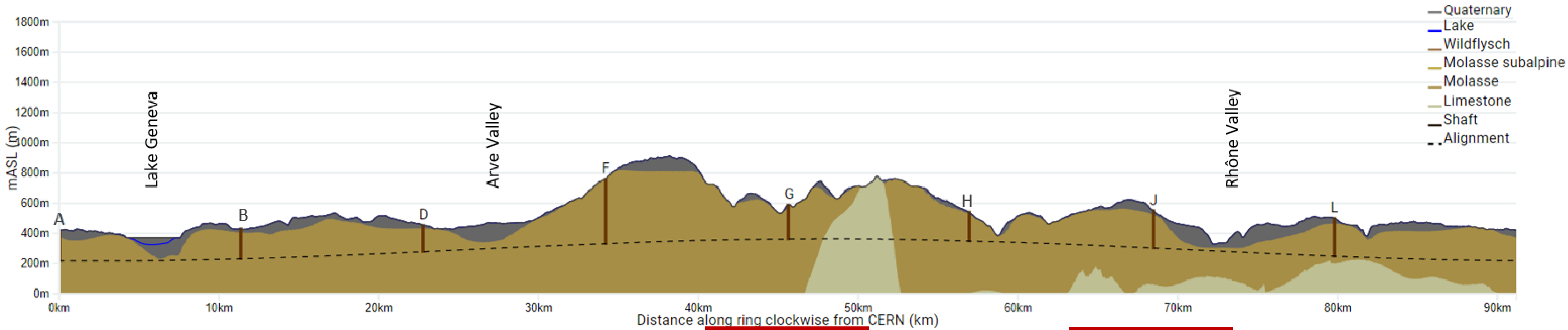


This type of misalignment cannot be eliminated using tracks originating from the vertex, **traditionally this is constrained by using cosmic tracks that are going through all the detectors of concern.**
The FCC caverns are far deeper (over 200m) than CMS (~70m), ATLAS (~57m) or even ALEPH (125m) (see next slide)

The smallness of the vertex detector and the depth of the caverns both reduce the number of useful cosmic muons.
Energy of the muons has to be >~5 GeV at entrance into detector. Each muon will provide an alignment constraint equivalent to ~3-5 microns on the relative longitudinal position of the vtx detector.

A few 100 cosmics will be sufficient to efficiently constrain the longitudinal boost below micron level.
In order to obtain a precision of 5keV on the longitudinal boost as desirable for the Z mass measurement around O(>100’000) useful muons might be necessary. Is this possible? **TO BE FOLLOWED!**
Hope to improve also with the dimuon 3D boost measurement and constraints.
The availability of both, cosmics and in-situ alignment, is precious redundancy and should be pursued

From T. Watson’s talk



PA	PB	PD	PF	PG	PH	PJ	PL
201 m	201m	181 m	400 m	226m	235m	253 m	250m

MAD-X simulation

A. Blondel, J. Keintzel, T. Persson, D. Shatilov

ECM and Boosts for Z-Mode

- **PH: 0.1 GV, 400 MHz** cavity
- ≲ 0.62 MeV beamstrahlung losses per beam and IP (simulations)
- 40 MeV radiation losses per revolution

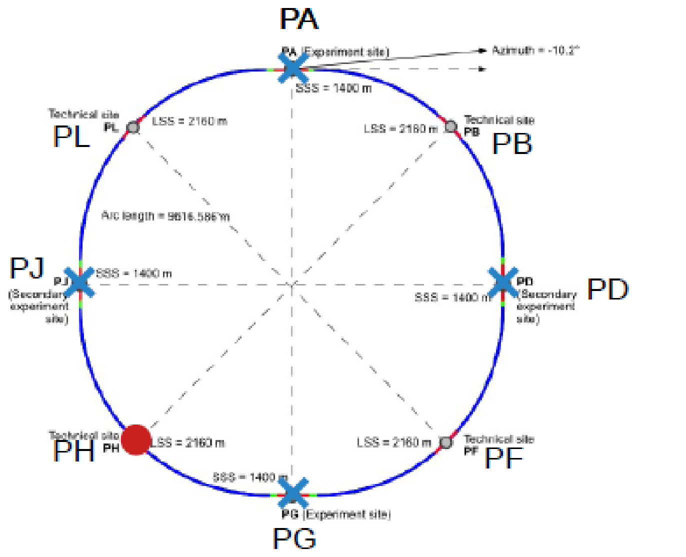
One 8 h shift will give 5 keV precision

Sum of losses close to sum of absolute boosts

Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

1 RF → almost constant ECM

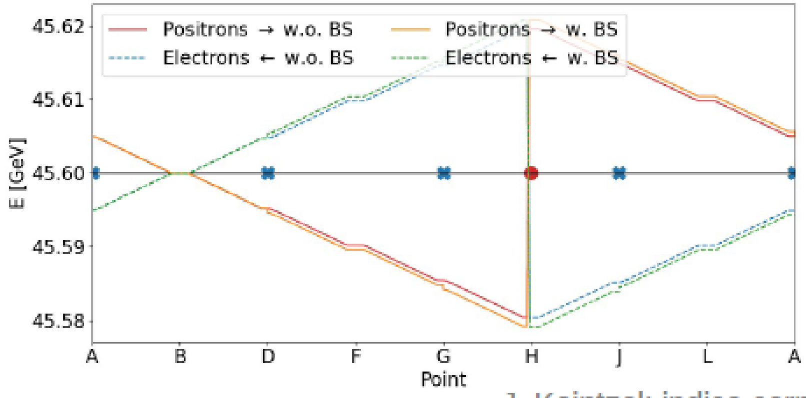
IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439

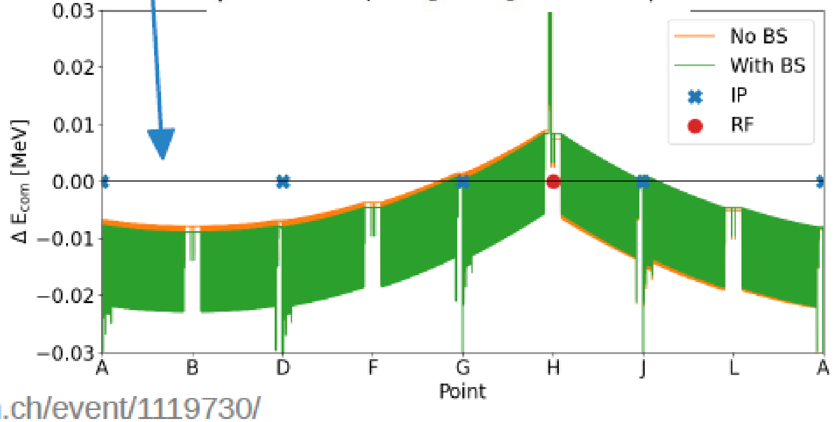


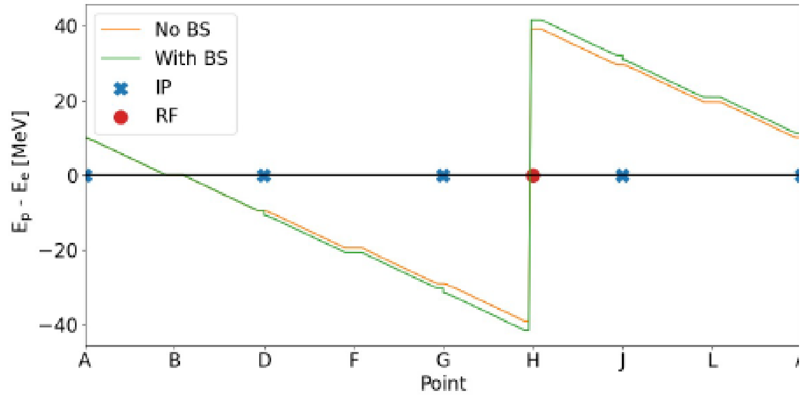
Boost: + for e+; - for e-

$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{e+}E_{e-}}\cos\alpha/2$$







J. Keintzel: indico.cern.ch/event/1119730/

No longitudinal impedance included yet

$$\sqrt{s} = 2\sqrt{E_b^+ E_b^-}\cos\alpha/2,$$

Exact numbers not final!

IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439

sum of |boosts| is indeed 2X energy losses! (41.48 MeV x 2)

-- The centre of mass energy is equal to the 'zero' value with great precision, (8 keV) even with beamstrahlung included
-- to be checked: the average energy that is given by resonant depolarization is not exactly E_0 but close
-- this is due to the virtue of having only one RF section.
-- the boosts are large and not as symmetric as expected. 3B(A)=-3B(D) = B(J)=-B(G) ; ➔ to be understood in detail why.

Every 8 minutes the boosts are measured with a precision of 50 keV. 5keV per shift.... 0.5 keV for 30days of run.
Applying the constraints can fix the energy loss model effectively.

THE GRAND TEST IN FINE: ALL MEASURED Z MASSES SHOULD BE THE SAME

Constraining distributed energy losses

Jorg Wenninger

Boosts at the IPs – measurable with muon pairs provides 4 constraints on e+/e- difference.

Synchrotron tune: constraint on total energy loss + effective RF voltage.

High resolution orbit difference measurements:

- Bunches with different charges → impedance losses.
- Tapering on and off differences to observe the energy loss sawtooth ?
  - May not be trivial to switch on the fly with circulating beam.

→ boosts, Qs and orbit differences will depend on beam intensity via both beamstrahlung and variation of impedance, which somewhat compensate eachother
→ Important to check, since pilot bunches will have different behaviour than colliding ones!
→ (of course on <average energy> this is all compensated by the RF!

	Pilot bunch (3×10^{10} ppb)	Nominal intensity (2.6×10^{11} ppb)	Nominal intensity and beamstrahlung (2.6×10^{11} ppb)	SR
Energy spread	0.039 %	0.045 %	0.143 %	0.039 %
Energy loss	0.8 MeV	4.2 MeV	~ 1.6 MeV	39 MeV
Bunch length	5 mm	8.3 mm	17.2 mm	4.4 mm

Algorithm for disentangling of SR and coherent losses

Two beam Energies in a detector E_e, E_p depend on beam currents ***I*1, *I*2** (coherent losses) and on SR losses. These dependences can be parametrized via simple power law:

$$E_e = E1 + a1 \cdot (I1)^{\alpha} + b1 \cdot (E1)^{\beta}$$
$$E_p = E2 + a2 \cdot (I2)^{\alpha} + b2 \cdot (E2)^{\beta}$$

- where ***E*1, *E*2** - RD-energies; ***I*1, *I*2** – beam currents; α, β – the coherent and the SR power law degrees $\boldsymbol{a1}$, $\boldsymbol{a2}$, $\boldsymbol{b1}$, $\boldsymbol{b2}$ – unknown fit coefficients.

In our MC simulation we chose α=1, β=4. Power law index α can be measured/fitted by interpolation of the closed orbit shift dependence on the current in high dispersion places near RF straight section (Jorg's remark at august 2022 EPOL meeting).

Energy boost: $E_e - E_p = E1 - E2 + a1(I1)^{\alpha} - a2(I2)^{\alpha} + b1(E1)^{\beta} - b2(E2)^{\beta}$

N equations: *n*=1, 2, ..., *N* with known *E*1, *E*2; *I*1, *I*2; α, β; and with unknown linear fit coefficients $a1$, $a2$, $b1$, $b2$. The reconstructed c.m. energy is a sum of beams energy:

$$E_{cm} = E_e + E_p = E1 + E2 + a1(I1)^{\alpha} + a2(I2)^{\alpha} + b1(E1)^{\beta} + b2(E2)^{\beta}$$

Ivan Koop

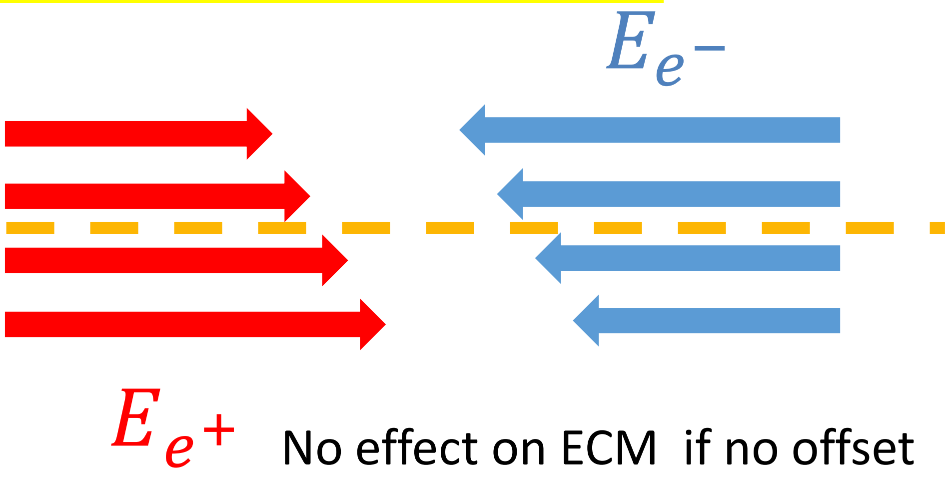
Concludes that the energy losses can can be fit to extremely high accuracy. (and for instance the power law E^4 verified by fitting the exponent)

Work in progress!..

e.g. need cosmics or some other method to constrain the boost measurements.

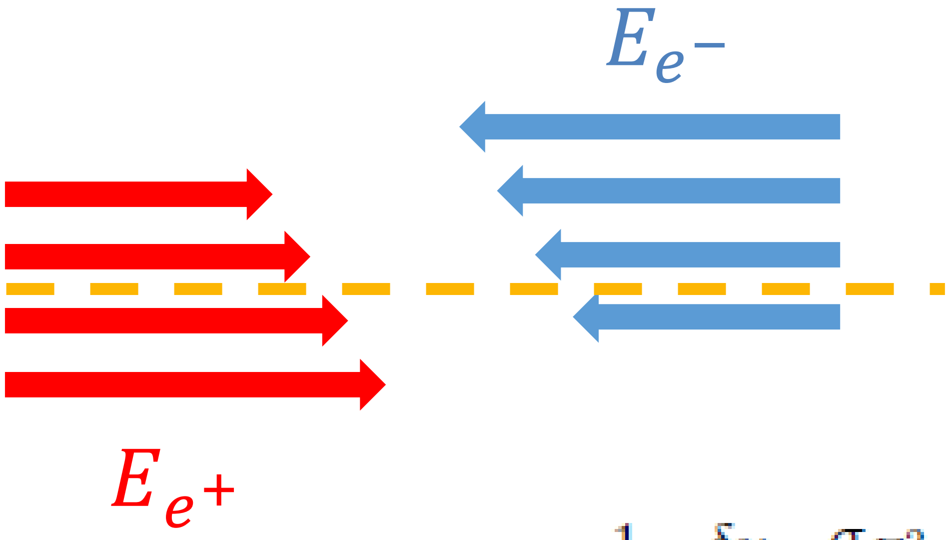
From beam energy to E_{CM}

opposite sign dispersion



No effect on ECM if no offset

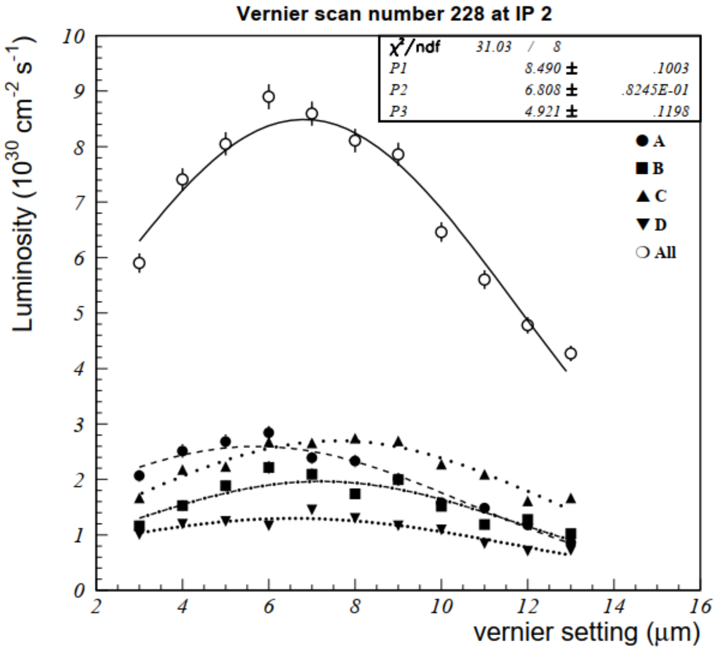
NB energy spread is reduced.

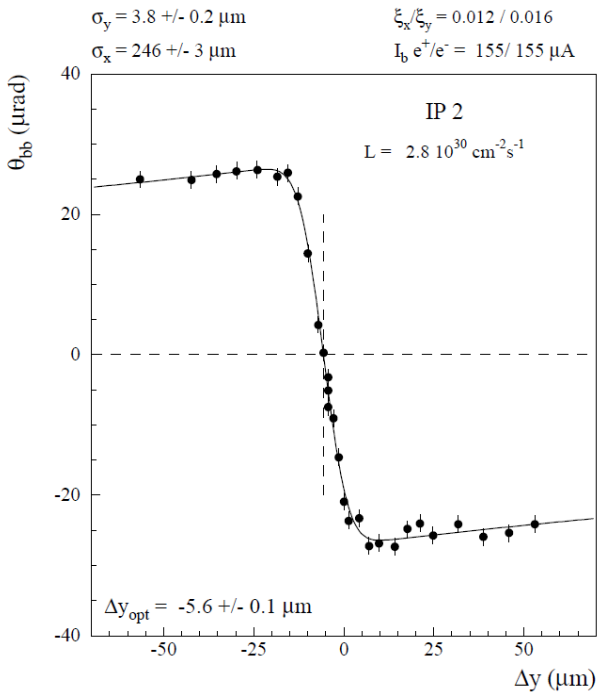


ECM lowered: $$\Delta E_{\rm CM} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_{E_b}^2}{E_b} \cdot \Delta D_y^*$$

Experience from LEP: Vernier scans

Relative position of beams measured to +- 80 nanometers from one scan





precision requires going far from maximum

➔ loose beam?

Try beam-beam deflection?

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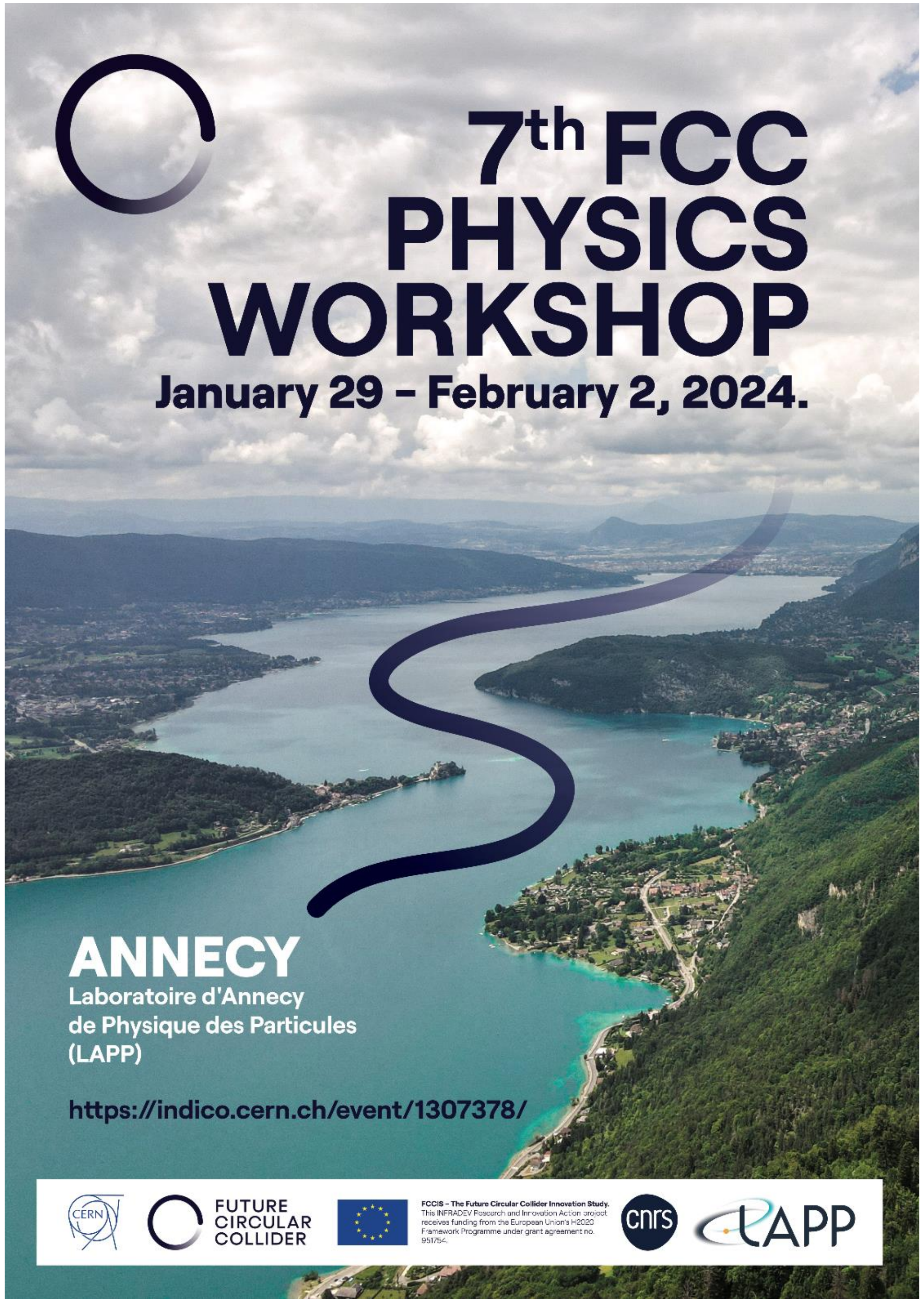


vernier scans

arXiv:1909.12245

7.2 Dispersion at the IP

For beams colliding with an offset at the IP, the CM energy spread and shift are affected by the local dispersion at the IP. For a total IP separation of the beams of $2u_0$ the expressions for the CM energy shift and spread are [72]

$$\Delta\sqrt{s} = -2u_0 \frac{\sigma_E^2 (D_{u1} - D_{u2})}{E_0(\sigma_{B1}^2 + \sigma_{B2}^2)} \quad (90)$$

$$\sigma_{\sqrt{s}}^2 = \sigma_E^2 \left[\frac{\sigma_\epsilon^2 (D_{u1} + D_{u2})^2 + 4\sigma_u^2}{\sigma_{B1}^2 + \sigma_{B2}^2} \right] \quad (91)$$

D_{u1} and D_{u2} represent the dispersion at the IP for the two beams labelled by 1 and 2. σ_E is the beam energy spread assumed here to be equal for both beams and $\sigma_\epsilon = \sigma_E / E$ is the relative energy spread. σ_{Bi} is the total transverse size of beam (i) at the IP,

$$\sigma_{Bi}^2 = \sigma_u^2 + (D_{ui}\sigma_\epsilon)^2 \quad (92)$$

with σ_u the betatronic component of the beam size.

If the beam sizes at the IP are dominated by the betatronic component which is rather likely, the energy shift simplifies to

$$\Delta\sqrt{s} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0 \sigma_u^2} \quad (93)$$

where $\Delta D^* = D_{u1} - D_{u2}$ is the difference in dispersion at the IP between the two beams. This effect applies to both planes (u = x,y). In general due to the very flat beam shapes the most critical effect arises in the vertical plane.

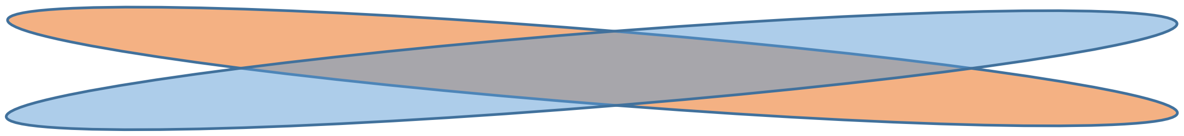
For FCC-ee at the Z we have in vertical direction:

- Parasitic dispersion of e+ and e- beams at IP 10um
  the difference is $\Delta D_y^* = 14\mu m$.
- Sigma_y is 28nm
- Sigma_E is 0.132%*45000MeV=60MeV
- **Delta_ECM is therefore 1.4MeV for a 1nm offset**
- Note that we cannot perform Vernier scans like at LEP, we can only displace the two beams by ~10%sigma_y
- Assume each Vernier scan is accurate to 1% sigma_y, we get a precision of 400 keV.
  the process should be simulated
- we need 100 beams scans to get an E_{CM} accuracy of 40keV – suggestion: vernier scan every hour or more.
- It is likely that Vernier scans will be performed regularly at least once per hour or more. (→100 per week) we end up with an uncertainty of ~10keV over the whole running period. ***(provided no systematic effects show up)***
- **The dispersion must be measured as well; this can be done by using the vernier scans with offset RF frequency**
- this would lead to lots of Vernier scans!

critical effect is in the vertical plane, but horizontal plane should be investigated as well

CONJECTURE:

Because the beams are crossing each other at an angle in the horizontal plane, horizontal dispersion or offsets are not relevant



every x slice of one beam crosses every x slice of the other

Check this is correct!

Dispersion at IP

Separation between the two beams

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

CM energy shift due **to combination of beam offsets and dispersion** @ IP.

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

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

To control the impact on ECM:

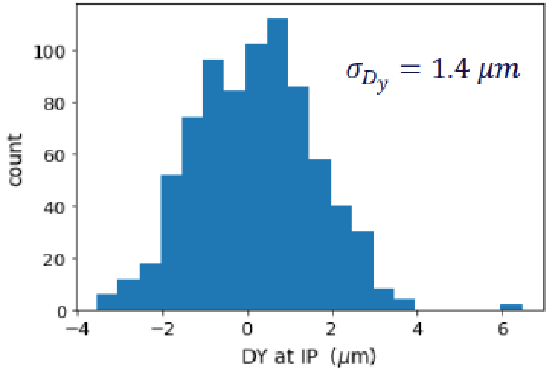
- Minimize the dispersion @ IP
- No beam offset (at least on average)

Latest set of simulations of machines with errors & corrections reach now **smaller residual D_y**:

- From rms D_y **~10 μm** to rms **~1 μm** → good news !
- Impact of solenoid (X → Y) on D_y to be considered.

Control of dispersion requires first a robust way to **measure the IP dispersion** – complex to perform on colliding beams due to the strong BB effect → need proper simulation of the process to include dynamic effects – Lifetrack etc.

Knobs to correct dispersion at IP – work started.



M. Hofer, T. Charles

This is good news because effect (problem) is 10 times smaller than we thought.... 40keV→ 4 keV (stat!) but we wont believe it until we measure it! (How do we measure vertical dispersion at IP?)

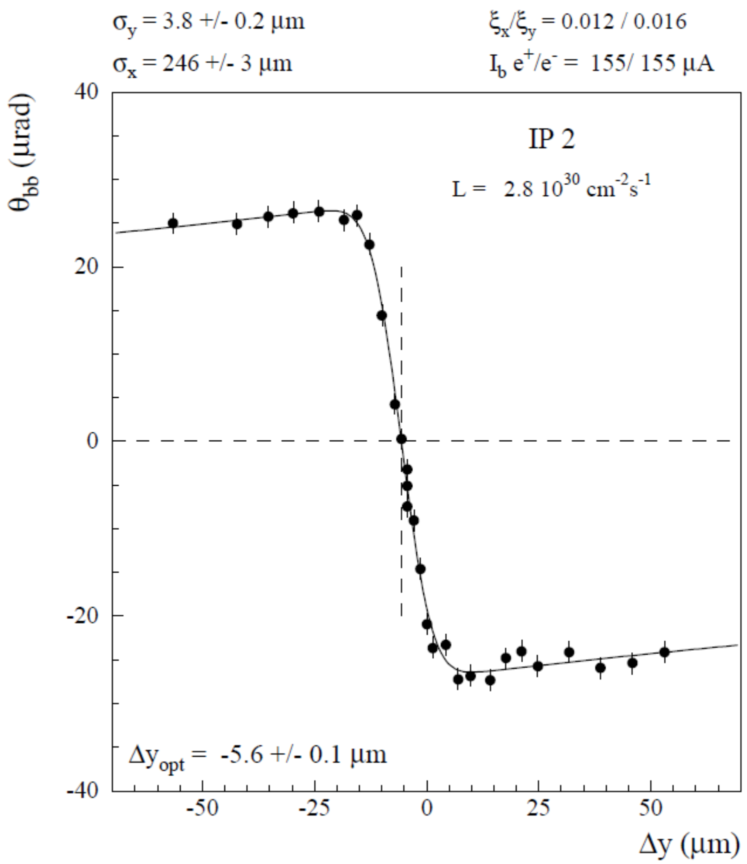
beam-beam deflection scans
already used at SLC, KEK and LEP, and now at SuperKEKb

Luminosity Optimisation Using Beam-beam Deflections at LEP

C. Bovet, M.D. Hildreth, M. Lamont, H. Schmickler, J. Wenninger,
CERN, Geneva, Switzerland

CERN-SL-96-025
https://inspirehep.net/literature/420668

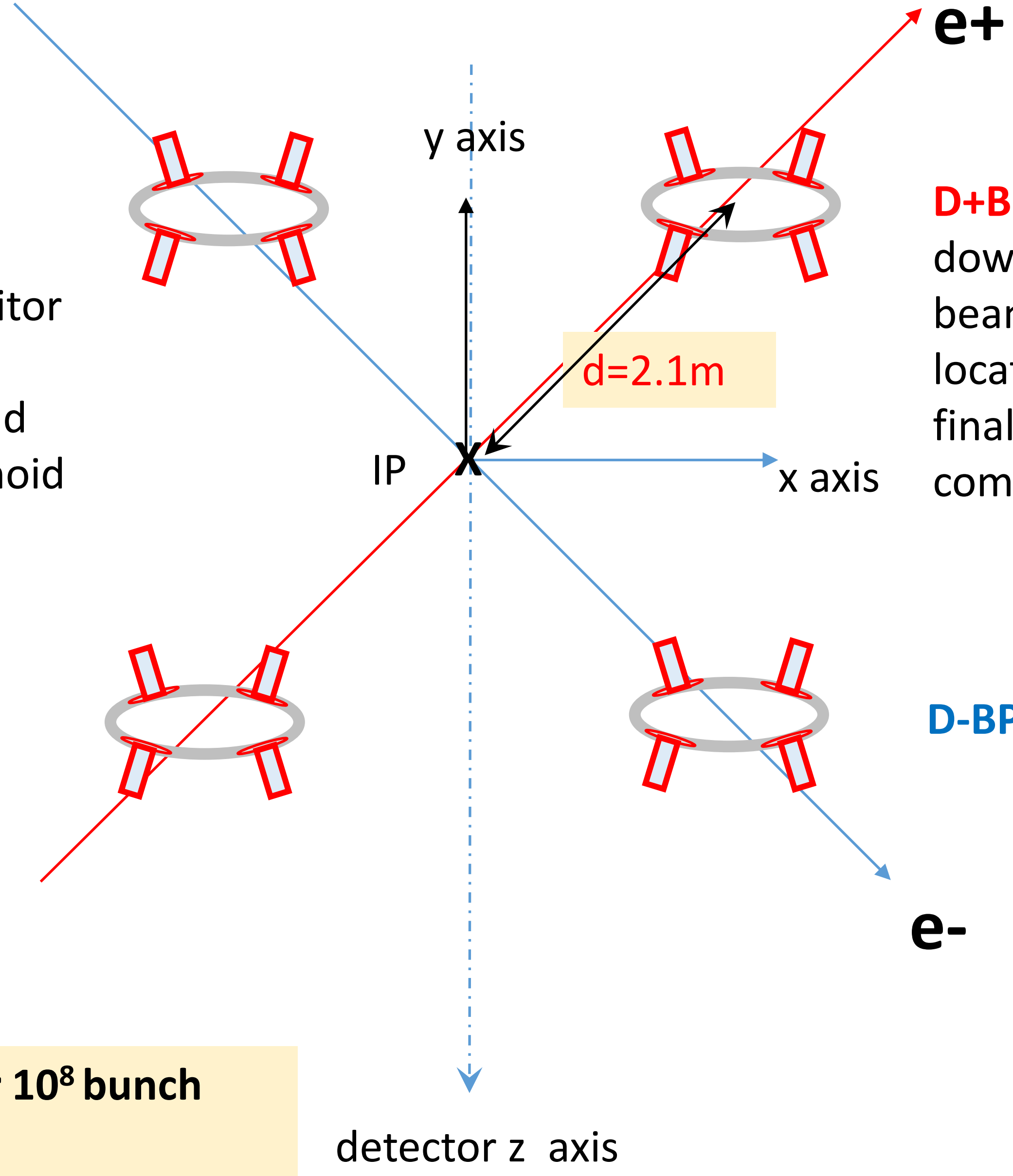
Uncertainty on Δy_{opt} = -5.6±0.1 μm
is 1/40 of the vertical beam size 3.8±0.2 μm
which was itself measured in the process



beam-beam deflection measurement at FCC-ee as if in « squished perspective » looking from behind detectors endcaps

U-BPM
upstream electron
beam position monitor
located between
final focus quads and
compensating solenoid

U+BPM

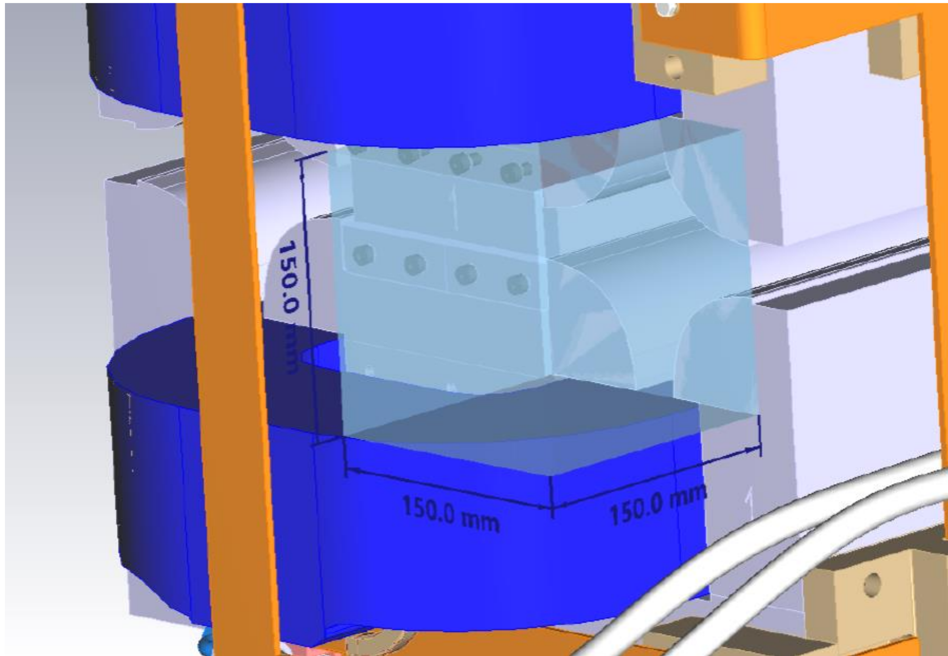


D+BPM
downstream positron
beam position monitor
located between
final focus quads and
compensating solenoid

D-BPM

BPM precision over 10^8 bunch passages is ~1µm

BPM in arc magnets



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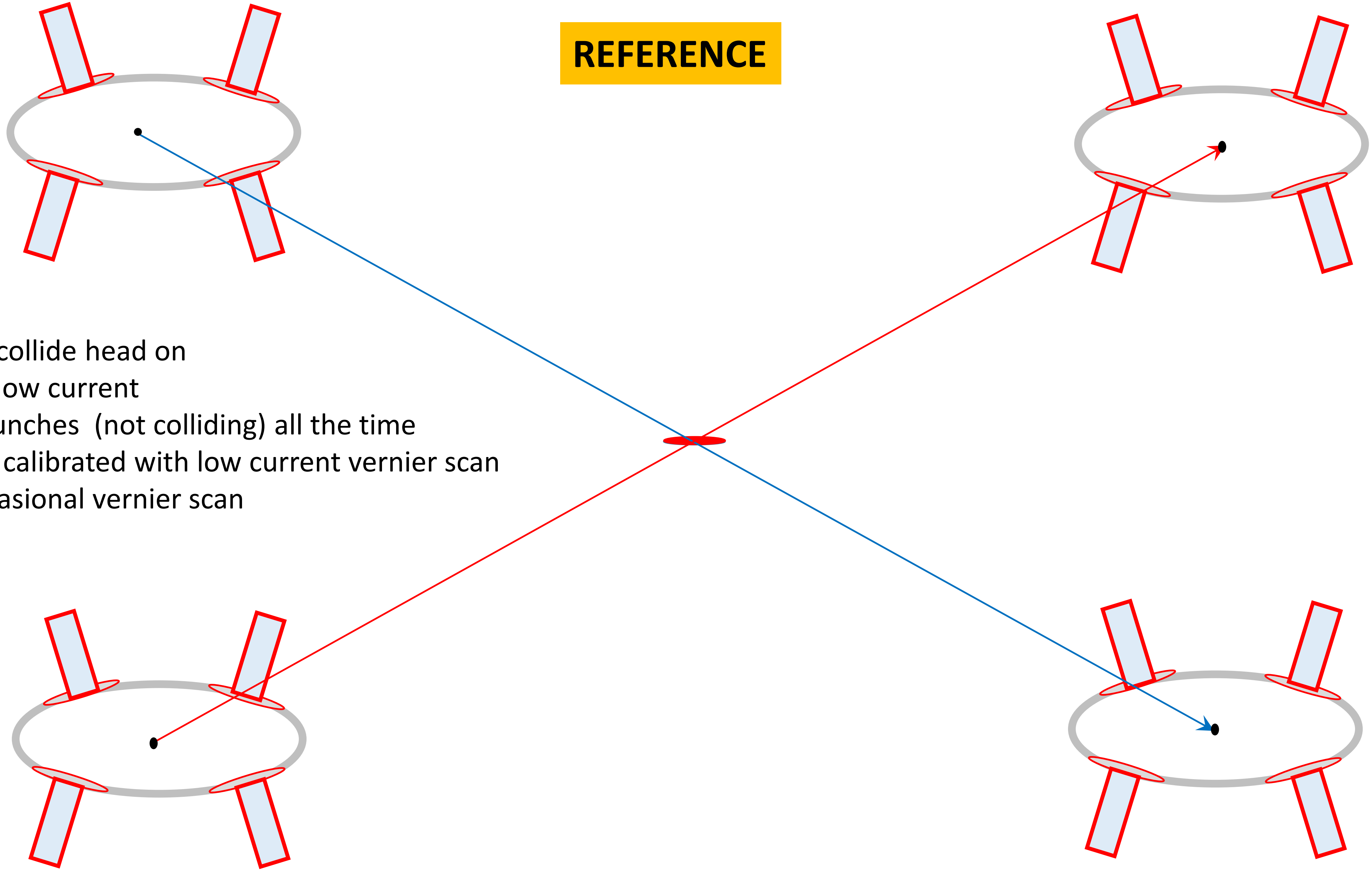


1. beams collide head on
   -- or at low current
1’. pilot bunches (not colliding) all the time
1’’ can be calibrated with low current vernier scan
1’’’ or occasional vernier scan

COLLISION OFFSET

2. **offset by $\delta_y = 0.1\sigma_y$ (=3.5nm)**

➔ opposite kick by 4μrad

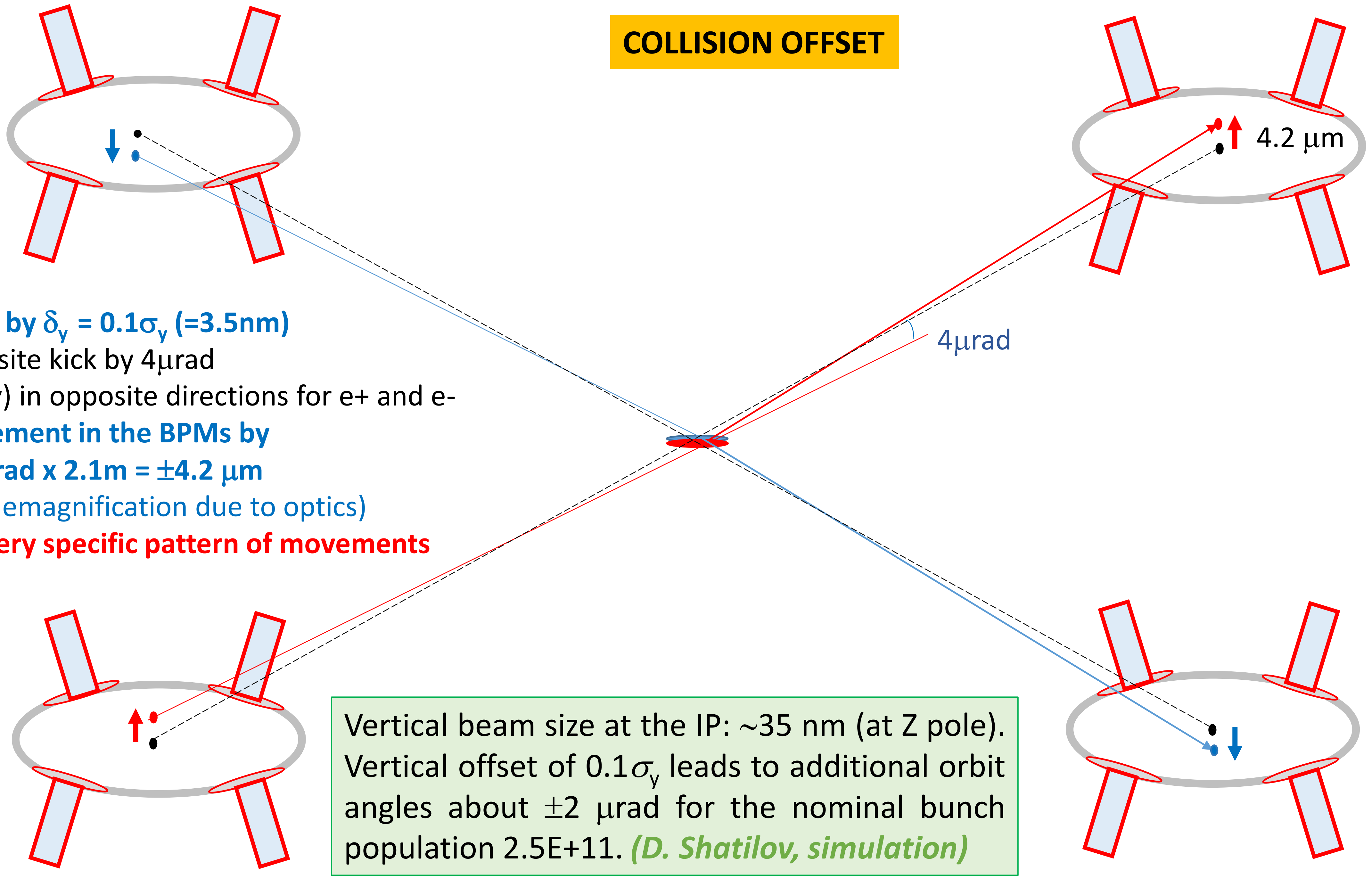
(Shatilov) in opposite directions for e+ and e-

➔ **movement in the BPMs by**

± 2 μrad x 2.1m = ±4.2 μm

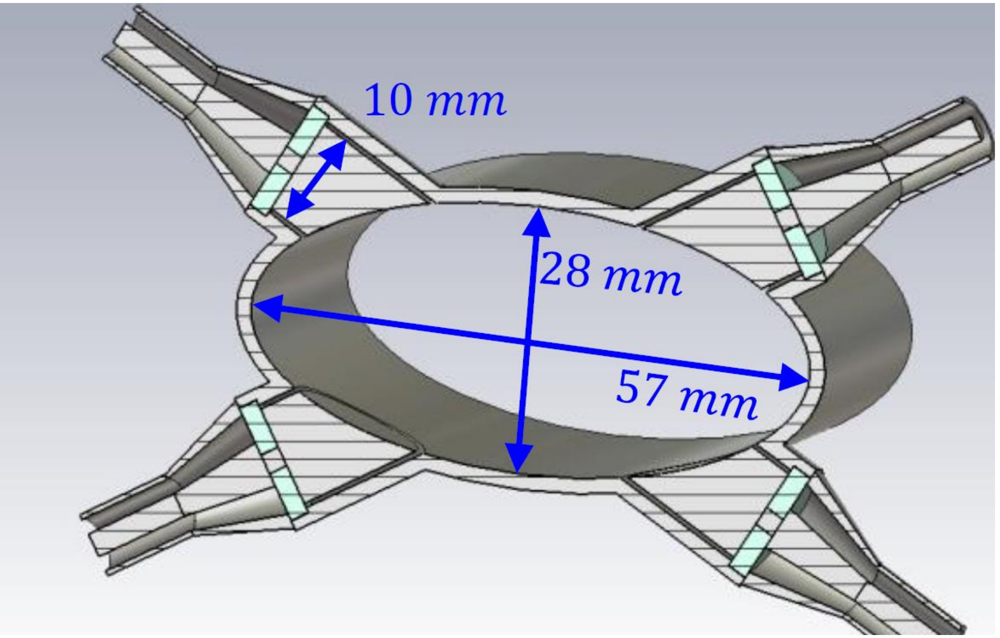
(x1000 demagnification due to optics)

with a very specific pattern of movements

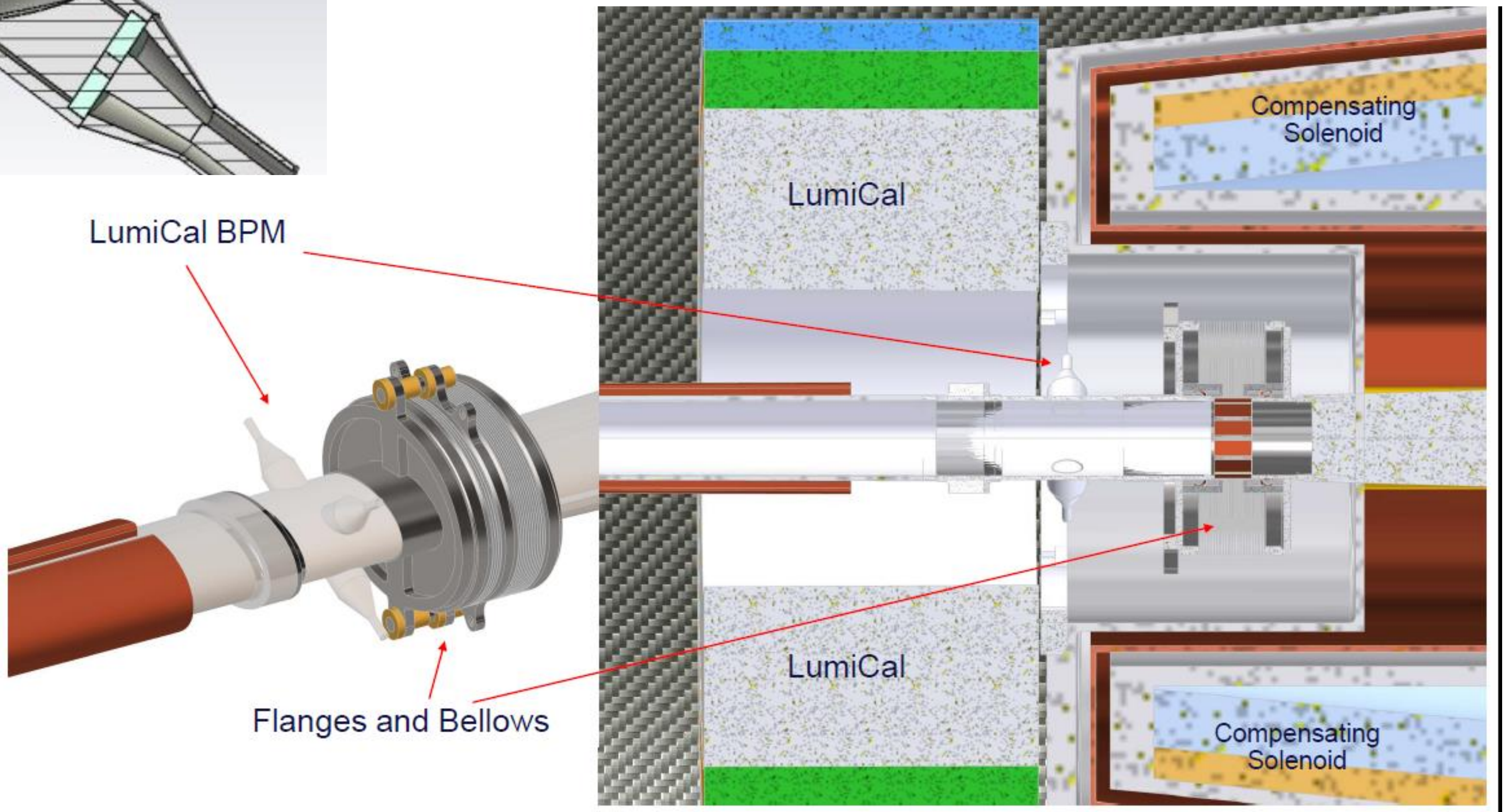


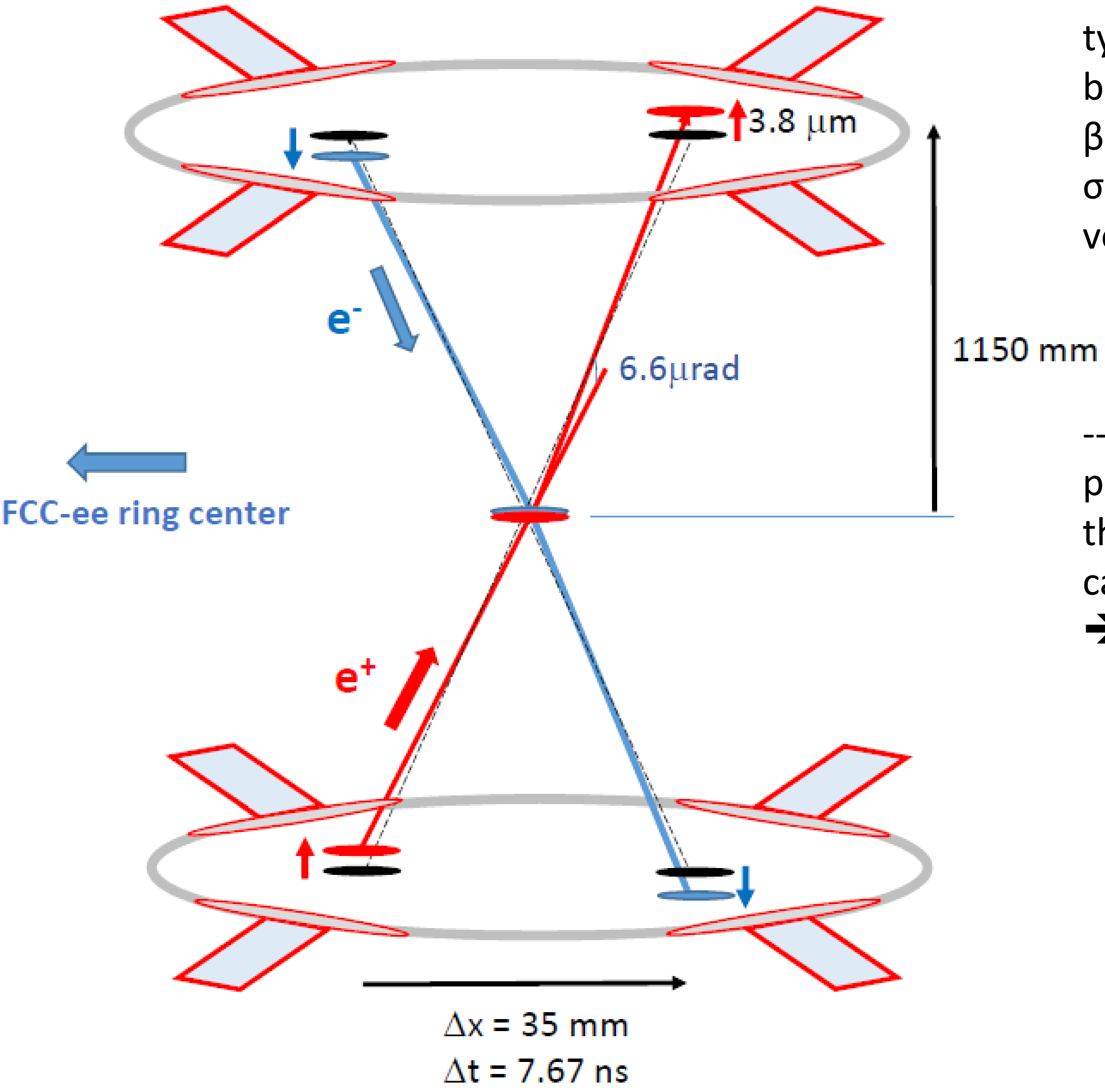
Vertical beam size at the IP: ~35 nm (at Z pole). Vertical offset of $0.1\sigma_y$ leads to additional orbit angles about ±2 μrad for the nominal bunch population 2.5E+11. ***(D. Shatilov, simulation)***

GOOD NEWS: THE LCAL BPM



M. Wendt proposed LumiCal BPM pickups
Wendt@fccweek2023
-- 1.15 m away from the interaction point
-- both e+ and e- measured in the same device!
-- ideal place to measure relative beam-beam motion accurately.





typical FCC-ee parameters of
beam-beam tune shift $\xi y = 0.14$,
$\beta * y = 0.8$ mm and
$\sigma y = 30$ nm,
vertical collision offset of 3nm ($0.1\sigma_y$)

➔ beam-beam deflection of 6.6μrad,
or 3.8μm in each of the four BPMs

-- Assuming BPM resolution of 1μm for 10^8 bunch passages, (3 seconds for 10^4 bunches) of each beam, the relative difference of 7.6 μm btw e+ and e- bunches can be measured with a precision of 1μm

➔ precision of 0.4~nm on the collision offset
($1.3\ \%$ of σ_y)

Measurement of opposite sign vertical dispersion (OSVD) at the IP

to close the loop one needs to measure the OSVD at the IP for the colliding beams.

The OSVD can be directly estimated by varying both beam energies with a modification of the revolution frequency.
However, although this method was successful at LEP, the feasibility of performing this procedure on colliding beams remains to be demonstrated. Furthermore, this could lead to a cross-talk between the IPs, due to their individual collision offsets and OSVD, which remains to be investigated.
-- Non-dispersive collision knobs need to be designed
-- procedure needs to be simulated
-- suggested that one could take advantage of tidal effect which is in fact a continuous

For a modification of the energy by 10^{-3}, the above measurement of collision offsets with a precision of 0.4nm corresponds to a measurement of the combined effect of collision offsets and OSVD on the centre-of-mass energy with an accuracy of 20 keV every 30 minutes.
If a four times smaller relative excursion of energy of 2.5×10^{-4} is preferred, the same result will be obtained after 16 such measurements, providing a precision of 20 keV on the centre-of-mass energy every 8 hours, which would constitute a perfectly acceptable solution.

It has recently been proposed to use the horizontal orbit correctors to modify the path length, as an alternative to adjusting the RF frequency. This technique could only be performed on non-colliding pilot bunches. It would therefore be necessary to assume that these pilots possess the same OSVD as the colliding bunches.

Measurements of offsets and Opposite Sign Vertical Dispersion (OSVD)

Purely statistical and preliminary arguments:

OFFSETS:

Four measurements of 4.2 micron displacement with 1 micron precision can be made with 10^8 bunch passages (assume 10000 bunches in each beam)

→ **every 3 seconds**

→ **measurement of beam beam offset with precision of 0.1 * 35nm / 4.2 / √4 = 1/80 of beam size or ~0.4nm**

NB no need of a scan in principle **if a good and stable reference can be demonstrated.** **CAN WE USE THE PILOT BUNCHES?**

LEP did not have pilot bunches, but maybe we can use them? (there is a debate on this)

Pilot bunches would provide 10^8 bunch measurements in 2 minutes (only 250 bunches of each beam)

Even better use a second set of (unpolarized) pilot bunches with full intensity. How many are needed?

Question is asked (to M. Wendt) about impact of bunch length which is different of pilot and colliding bunches

OSVD (this requires simulation of a 4IP machine because the beam beam effect will result in cross-talk between IPs)

we cannot really measure the dispersion at IP directly,

but the beams will move in opposite directions upon a change of RF frequency

→ we measure the opposite sign vertical dispersion (OSVD) this way!

Assuming that a relative momentum change of 10-3 is feasible, this measurement corresponds to a measurement of opposite sign vertical dispersion D*y(e+)-D*y(e-) with a precision of 0.4 micrometer.

Potential is great but the devil is in the details

OSVD and collision offsets -- status

THIS IS VERY PROMISING:

possible shift in energy (or absence thereof) with a precision **of $\pm$ 20 keV each time the dispersion measurement is done.**

If the pilot bunches can be used as reference because it saves large scanning across the beams

➔ from a combination of 'beam-beam offset scans' (Vernier or Van der Meer scans)
and direct beam-beam collision offset measurements
we have two methods providing <u>potentially</u> a large sample of measurements with a precision of O(20keV)
-- more simulations needed to ascertain feasibility of IP dispersion measurement

Energy shifts from EM interaction between the bunches

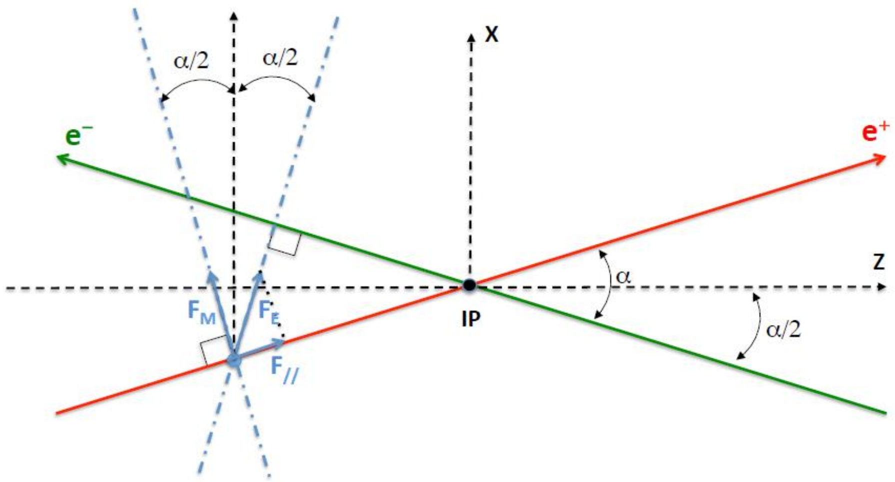


Figure 48. Schematic view of the electric and magnetic attractive Lorentz forces $\vec{F}_E$ and $\vec{F}_M$ acting on each positron from the opposite electron bunch, upon bunch crossing at the interaction point (IP). Similar forces from the positron bunch affect each electron. The beam crossing angle is denoted α. The Z axis is the bisecting line of the two beam axes at the interaction point, the X axis is orthogonal to the Z axis such that the horizontal (X, Z) plane contain the two beam axes.

This was discussed already in the EPOl paper Section 7.5.2 and 8.1.

The critical point is that

the EM forces being conservative, they do not modify the centre-of-mass energy,

they modify both :

the beam energies and the crossing angle

net effect is about 60 keV correction

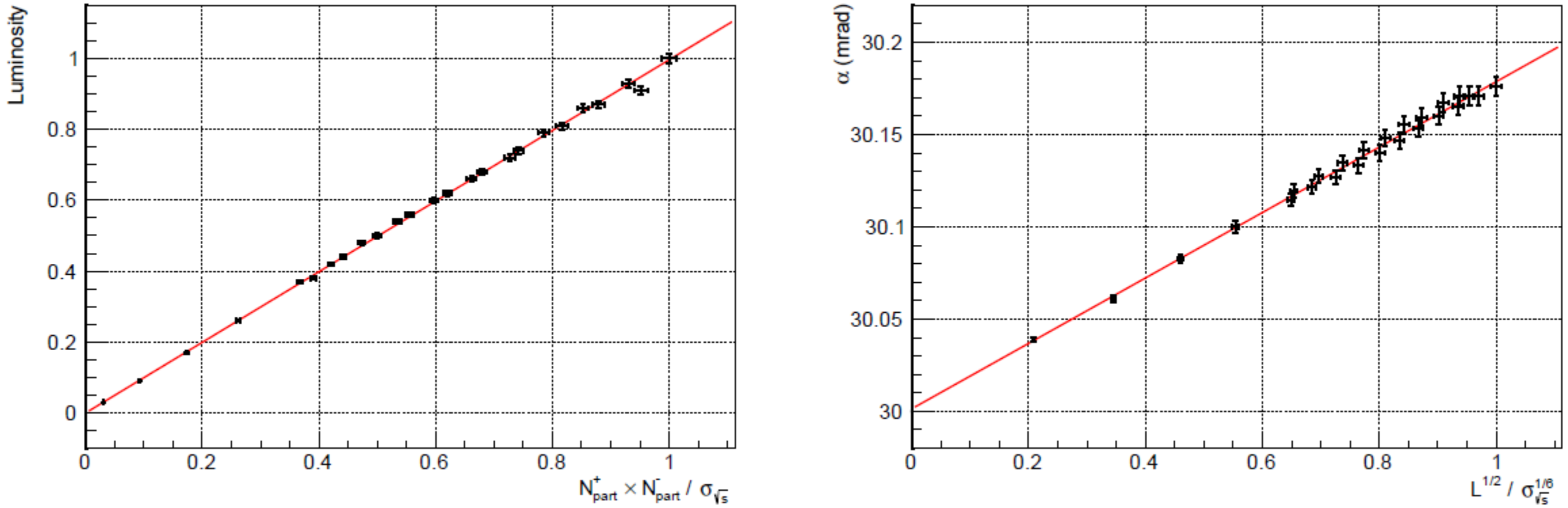
$$\sqrt{s} = 2\sqrt{E_1 E_2}\cos{\alpha/2} = 2\sqrt{|p_{Z,1}p_{Z,2}|},$$

“The determination of the average centre-of-mass energy therefore requires

1. **the average beam energy from pilot bunches with resonant depolarization**
   (+ correction for energy losses as above)
2. **the measurement of the crossing angle in collision**
3. **the determination of the crossing angle increase due to beam-beam effects”**

With 10^6 dimuon events, expected to be recorded in ~10 minutes at the Z pole (exp)
the crossing angle (taken as the peak of the fitted Voigtian function) can be determined
with a sub-microrad *statistical* precision: α= 29.9998 0.0003 mrad

It is proposed is to perform in each filling a progressive mesurement of crossing angle with increasing beam charges



it is also shown that the result can be obtained from the natural variation of intensity during each fill.

NB Issues of stability and systematics are really crucial here
➔ more understanding/discussion needed!

Figure 56. Left: Luminosity $\mathcal{L}$ as a function of $N^+_{\text{part}} \times N^-_{\text{part}}/\sigma_{\sqrt{s}}$. Right: Beam crossing angle α (in mrad) as a function of $\mathcal{L}^{1/2}/\sigma^{1/6}_{\sqrt{s}}$. Both plots are obtained from the `Lifetrac` simulation code for bunch populations varying from 10% to 100% of the nominal FCC-ee value at the Z pole (keeping $e^{\pm}$ bunch populations within ±5% from each other). The luminosity $\mathcal{L}$, the $e^{\pm}$ bunch populations $N^{\pm}_{\text{part}}$, and the centre-of-mass energy spread $\sigma_{\sqrt{s}}$ are normalized to their nominal values. All other parameters are fixed to their nominal FCC-ee values at the Z pole. The uncertainties arise from the limited MC stastistics. The lines show the linear fits to the simulated points: for example, the fitted crossing angle is 30.0013 ± 0.0031 mrad for empty bunches, and amounts to 30.1775 ± 0.0032 mrad for nominal parameters.

Assigning energy shift errors to absolute or point to point (recap from arXiv:1909.12245)

Table 15: Calculated uncertainties on the quantities most affected by the center-of-mass energy uncertainties, under the final systematic assumptions.

Quantity	statistics	$\Delta \mathrm{E}_{\mathrm{CMabs}}$ 100 keV	$\Delta \mathrm{E}_{\mathrm{CMSyst-ptp}}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
$\mathrm{m_Z}$ (keV)	4	100	**28**	1	–
Γ_Z (keV)	7	2.5	**22**	1	**10**
$sin^2\theta_W^{\mathrm{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(\mathrm{M_Z})}{\alpha_{QED}(\mathrm{M_Z})} \times 10^5$	3	0.1	**0.9**	–	**0.05**

the point-to-point uncertainty dominates the physics output. It can be controlled in two ways

1. compare the momentum as measured with the polarimter spectrometer between different energies (monitored constantly at each energy)

➔ Magnet must be very precisely monitored (<10-6) and dedicated monitoring of the main beam after the collision and magnet should be discussed.

➔ this requires dedicated design of polarimeter

2. use the e+e- ➔ μ+μ- events in the detectors to measure ECM for each of the energies.

➔ monitor experimental magnet to (<10-6) precision + QED issues etc..

Assigning energy shift errors to absolute or point to point

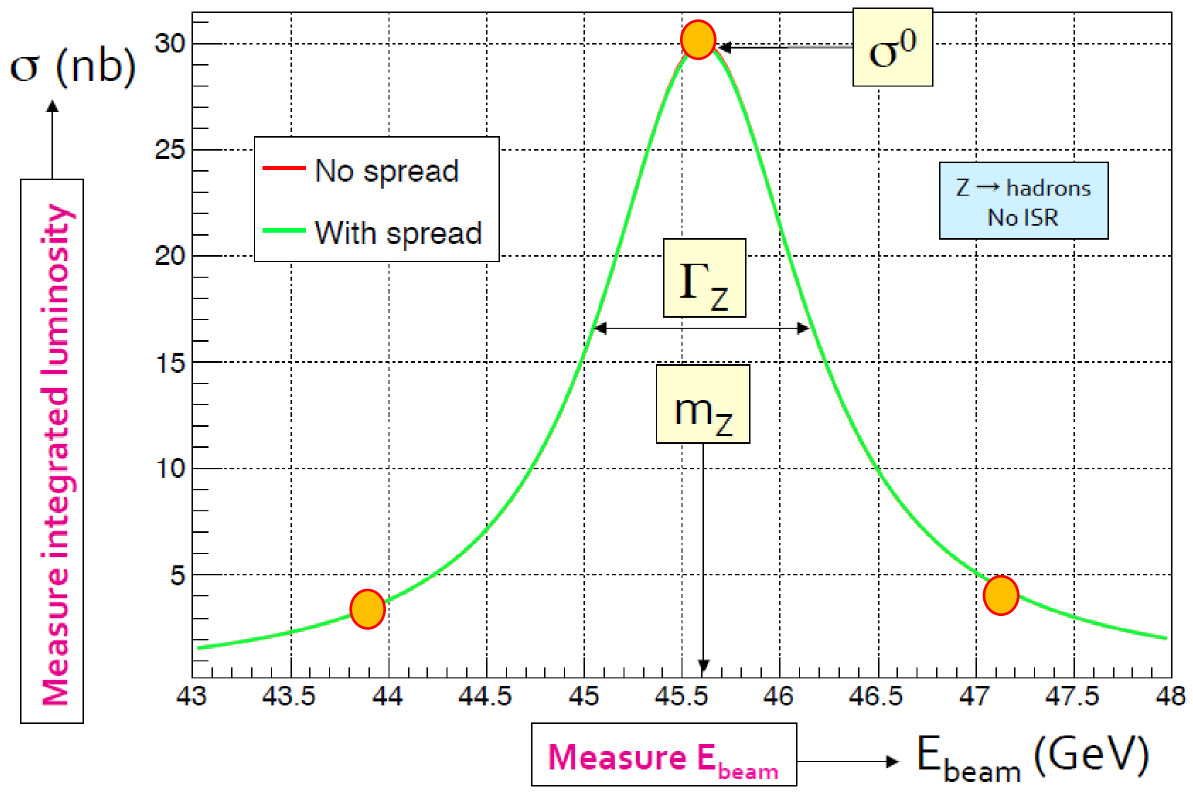
For the Z line-shape measurement (and for asymmetries) the point-to-point errors dominate.

The above error estimates O(20 keV) are really applicable for the Absolute Scale Uncertainty. (in addition to error in RDP→ Ebeam, for which this analysis need to be done too)

The point to point errors are normally much smaller.

➔ keep the running conditions and calibration methods IDENTICAL (as much as possible) for the (typically 3 or 3 groups) of data taken below at and above the Z peak (88,91,94 GeV E_{cm})

Typically:
statistical errors → point-to-point
Method uncertainties → absolute scale



Conclusions : progress, and way forward

We have outlined the main methods and excellent potential precision for the control of energy shifts
It is too early to give new estimates but aim to give new values with significant improvements for the Feasibility Study report.

Progress is ongoing

ENERGY LOSSES

-- the boost measurements in the experiments basically provide measurements of the energy losses at keV levels on daily basis. Uncertainty anlysis to be made including impact of beamstrahlung.

Alignment of inner vs outer central detector to ±0.1 microns is required for 4 keV boost measurement. dimuons? Cosmics?

Collision offsets x OSVD

-- vernier scans and beam beam deflection measurements provide collision offsets and IP dispersion measurements at 20 keV level every time a dispersion measurement is made.

-- new LCAL BPM is a real jewel

-- many questions remain e.g.

-- feasibility and reliability of full charge pilot bunches as reference (impossible, needs to reduce the current.

-- OSVD measurement on colliding beams? resulting beam beam collision offsets in all four experiments at once.

need to design method and knobs and simulate it!

Beam beam transverse attraction

-- beam-crossing angle measurement when bunch charges are increased measures what we need (stability issues?)

Point-to-point uncertainties

These effects will not generate large point-to-point errors provided running conditions are kept identical for the scan points

They will contribute to absolute energy scale error. **All experiments should measure the same Z mass!**

Parameters

FCC-ee collider parameters as of June 1, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum) [b]	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

[a] incl. hourglass.

[b] only the energy acceptance is taken into account for the cross section