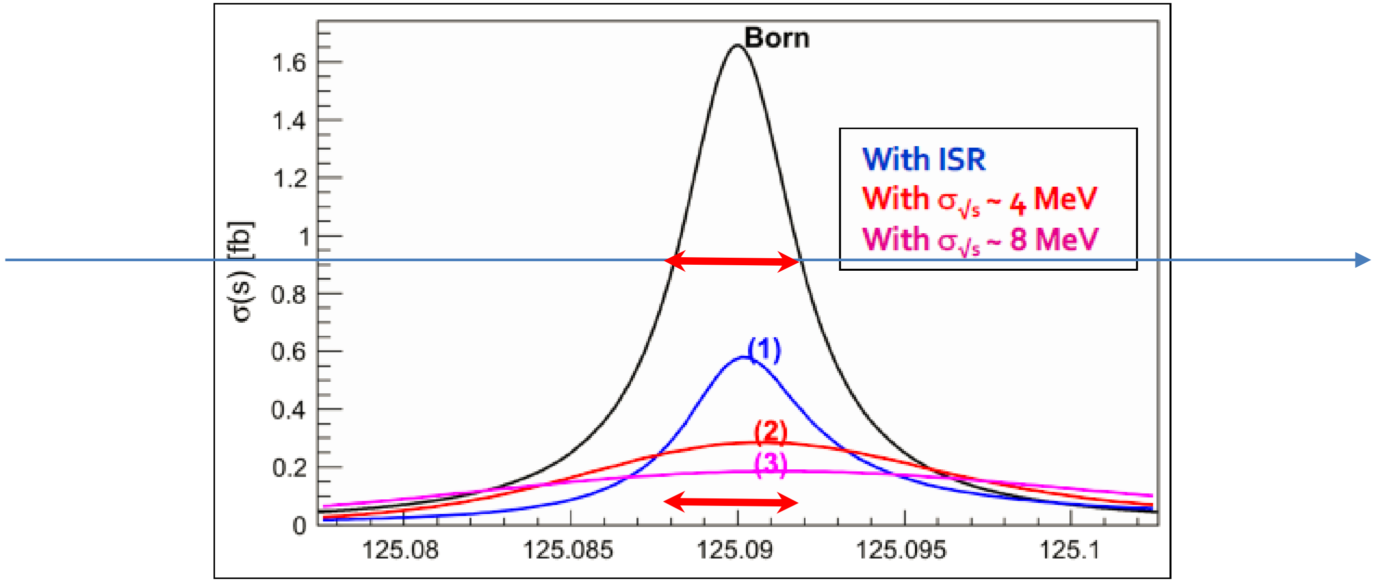
ee→ H run : can we measure monochromatization?



Basic requirements

At any moment during the run:

-- run at nominal centre-of-mass energy that is stable well within Higgs width (±2 MeV OK?)

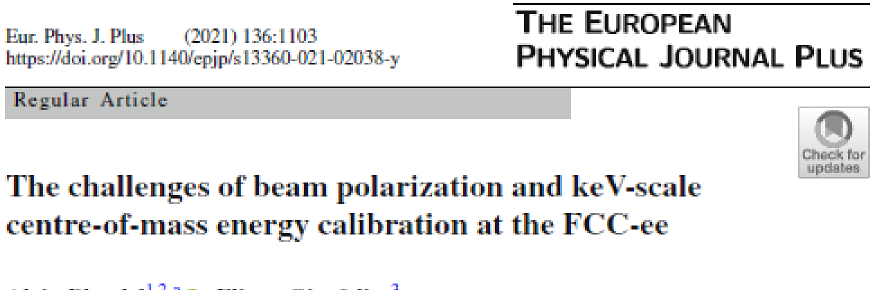
-- know the nominal center of mass energy to much better precision (±1 MeV OK?)

-- know the centre-of-mass energy spread with similar precision (±1 MeV OK?)

references:

arXiv:1909.12245 (The Epol paper)

AB and Eliana Gianfelice http://cds.cern.ch/record/2789651



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THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

The challenges of beam polarization and keV-scale centre-of-mass energy calibration at the FCC-ee

-- know the centre-of-mass energy with precision commensurate to Higgs width (±1 MeV OK?)
NB Higgs total width is 4.2 MeV in minimal Standard Model (assume no new particle anywhere)
this in fact corresponds to an r.m.s. ECM of about 1.8 MeV. (see graph)

➔ this requires use of the transverse polarization and resonant depolarization.

One condition is that the beam energies should be located around the half integer spin tune $\nu_s = E_b / 0.4406486$

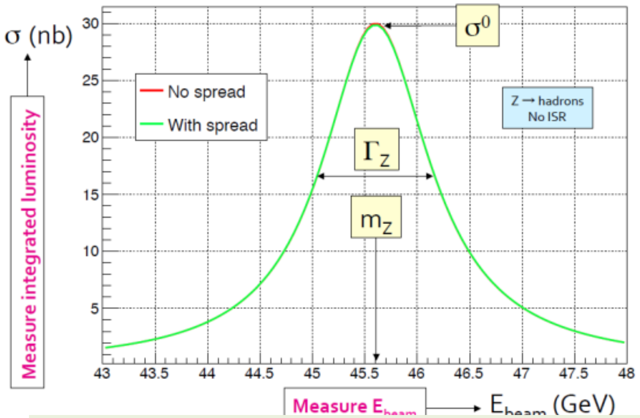
if $m_H = 125.09$ GeV, then: $\nu_s = (m_H/2) / 0.4406486 = 141.938$ which is too close to integer.
-- A possibility is to shift the energies of the two beams in opposite way by $\Delta\nu_s$ = + and - 0.5,
to 141.438 and 142.438 (Oide)
(There might be an elegant way to combine this with OSVD)

➔ then we should use the same method as for the Z run which should be somewhat easier since the **polarization time is ~5 times shorter (125/91)^5**

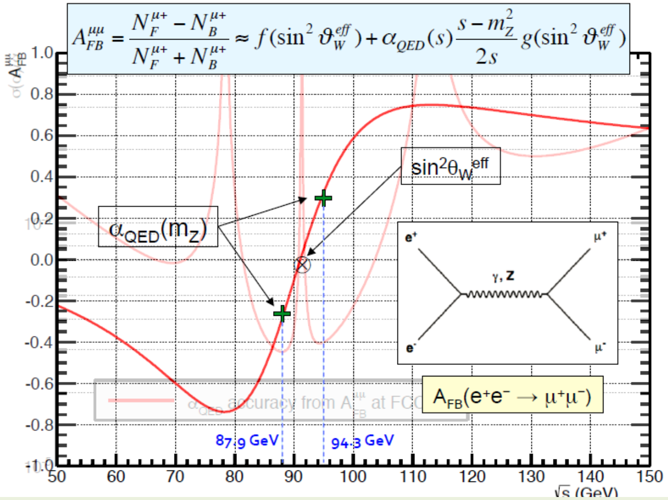
Precision at time of measurement will be similar (±100 keV) as for the Z run and should be sufficient

However it is important that it is tracked very well....

Physics: scan points and output quantities



Z line shape → m_Z and Γ_Z



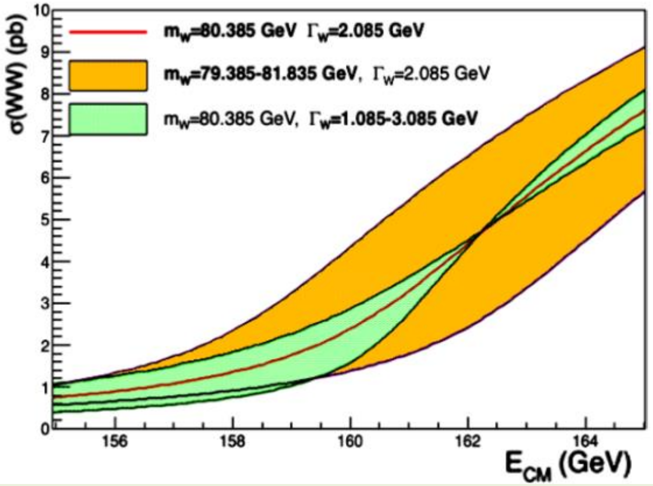
at the same time $A_{FB}^{\mu\mu}(\sqrt{s})$ → $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$

Use half integer spin tune energies for Z line shape, lucky:
ν= 99.5, 103.5, 106.5/107.5
and
W W threshold ν= 178.5, 184.5

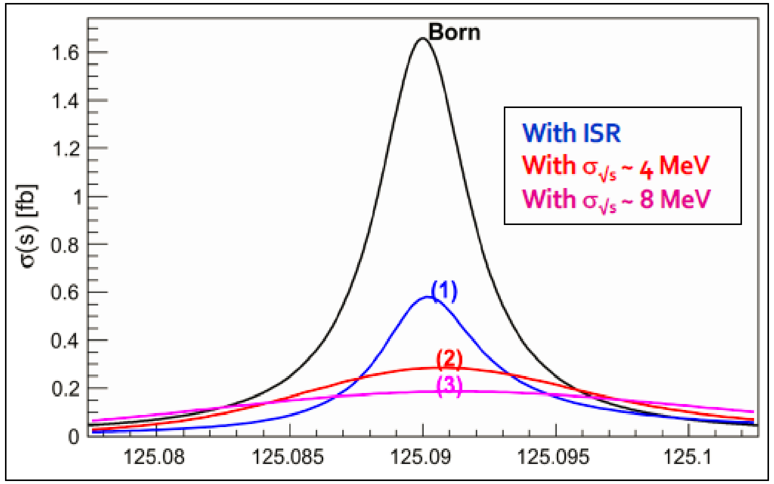
for the Higgs, bad luck!
ν = m_H/2/.4406486 (1) = 141.94
--too close to integer for polarizazion–
→ 141.44 for e+ and 142.44 for e-

at Z: 200 'pilot' bunches will be stored at the beginning of fills with polarization wigglers ON, for about 1 hour to develop about 5-10% transverse polarization.

After a first energy calibration, the full luminosity run will comprise regular calibrations (1/10 min) on pilot bunches.



WW threshold → m_W and Γ_W



Higgs s-channel production need to know E_{cm} σ_{ECM} → $y_e=m_e$?

A moving target

At any moment during the run:

-- run at nominal centre-of-mass energy that is stable well within Higgs width (±2 MeV OK?)

> Large machines like FCC-ee will be subject to earth tides with circumference changes by $\Delta C \simeq \pm 2\,\mathrm{mm}$ for C of 100 km [22, 66, 67]. For a momentum compaction factor of $\chi \simeq 10^{-5}$ the corresponding energy changes reaches $\pm 2 \cdot 10^{-3}$ or $\pm 90\,\mathrm{MeV}$ around the Z

This requirement is more stringent than that for the Z line shape scan where the requirement is well within the center-of-mass energy spread (so that it does not worsen it) of O(80 MeV)
The full swing at the Higgs will be ±125 MeV... for each beam, i.e. ±250 MeV for E_{CM}
This corresponds to a maximum variation of 125 MeV per hour, or ~2 MeV per minute.

This will require **i) a good model of the FCC-ee machine and its energy variations**
-- benchmarked at the Z pole with great precision
and a correction mechanism using the RF frequency (or otherwise)
ii) corrected by e.g. beam position monitors, if valid at that precision.
iii) also use the 'spectrometer' function of the polarimeters in an operational way.
iv) beam energy measurements by RDP might need to be performed as often as possible (more than 10 minutes?)
.

→ it is essential that the ee→ H measurement is performed after the Z line shape run and the possibility of stabilizing the energy to the Higgs width precision is developed and tested

Measuring the centre-of-mass energy spread (I)

A discussed in arXiv:1909.12245 the centre-of-mass energy spread σ_{ECM} cannot be measured from the bunch length when using crab-waist crossing. Method to measure σ_{ECM} from spread in the measured boost of μ+μ- pairs was devised (ILC, Janot)

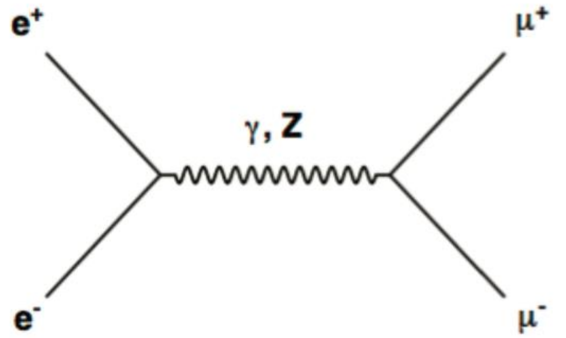
However that analysis was made without taking into account the possibility of intentional dispersion along one or several phase-space parameter(s) (e.g. z, time, other coordinates like x,y,x',y'?) of the particle energies in view of monochromatization. Here I assume only one phase space coordinate (monochromatization coordinate, x_m)
The average boost varies with the monochromatization coordinate position and integrating it leads to a measurement of the **centre-of-mass energy spread in absence of monochromatization. BAD**

We are saved by the fact that the beam is artificially spread around for the monochromatization coordinate x_m
if we are able to measure x_m for events (e.g. μ+μ- pairs) used to measure the energy spread,
with a precision better than the beam size in that coordinate, we can isolate the energy spread in each bin of x_m

If several coordinates are used to create the monochromatization bias, the analysis should be developed in multidimension, so as to gain maximally from it. This goes beyond the scope of this presentation, but multidimensional analysis (sometimes dubbed as AI) is of common use in particle physics.

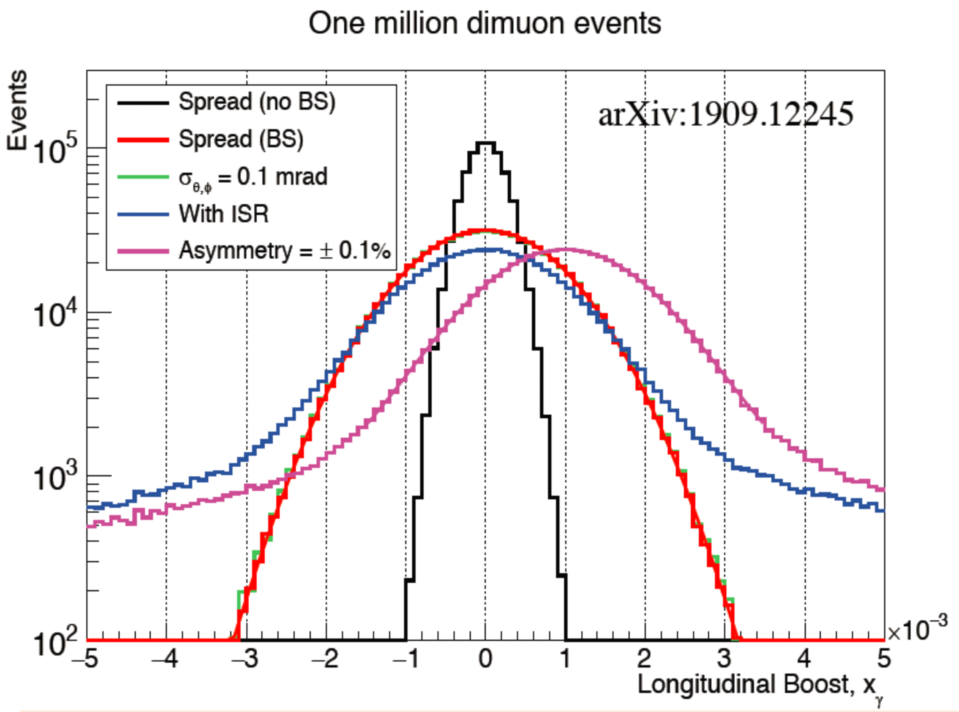
A thousand recipes to use up dimuon events at the FCC-ee

P. Janot

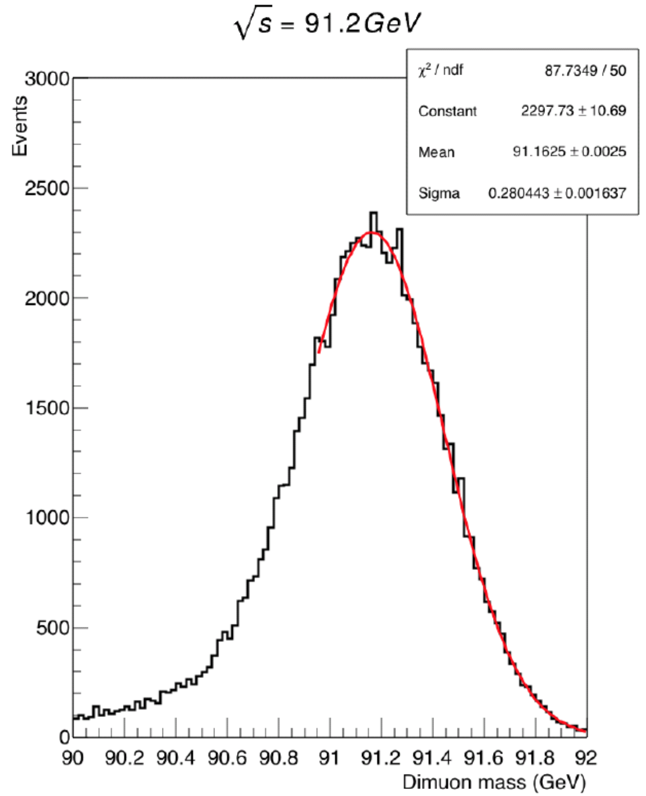


E,P conservation –> allow E_{CM} and P_{CM} on event-per-event basis.

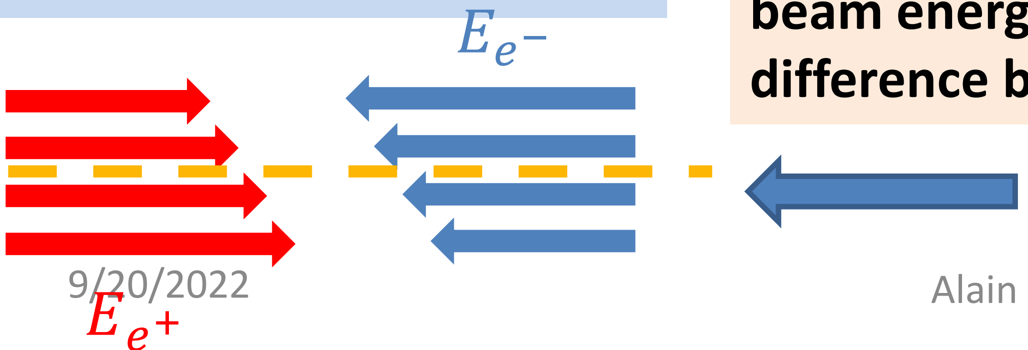
10^6 evts/5 min/expt @Z
~10^4 evts/5 min/exp @H
→Determine ECM, ECM spread and collision angle, in addition to $A_{FB}^{\mu\mu}(\sqrt{s})$!
(also: control of ISR spectrum)



The measurement of CM boost distribution allows control of beam energy spread as well as the difference between e+ vs. e- energies.



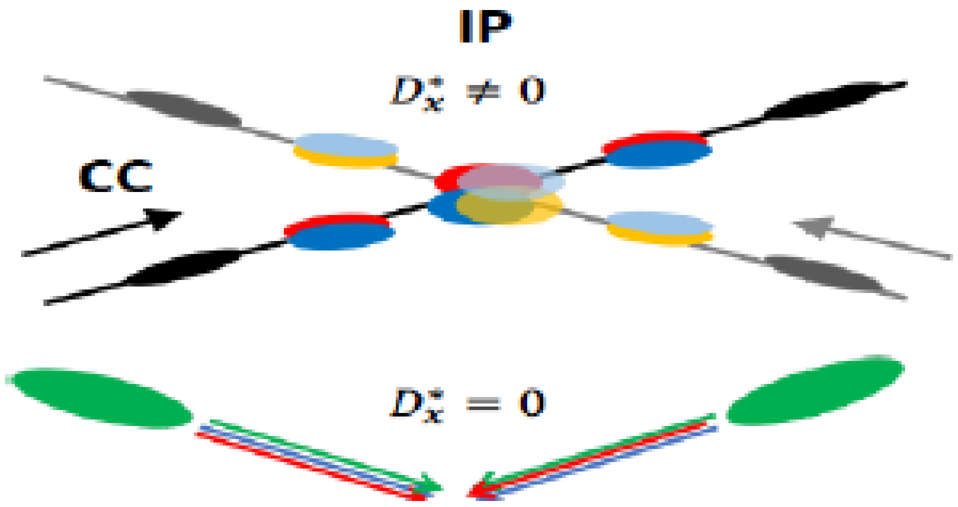
±2.5 MeV ECM meast in 30 seconds of data
~40keV per day at each scan point….
challenge for QED calculations!

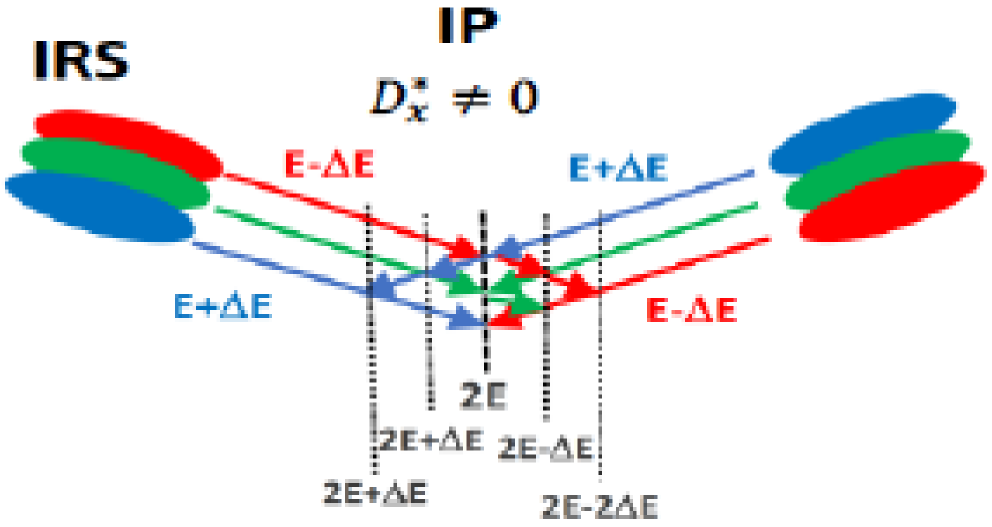


Very useful also for control of Monochromatization!

Monochromatization in FCC-ee

Given the **FCC-ee IR design**, two **monochromatization schemes** are possible. **Crossing angle** monochromatization scheme featuring **IP dispersion of opposite signs** for the colliding beams with **crab crossing** (**CC**) and without or **integrated resonances scan** (**IRS**).

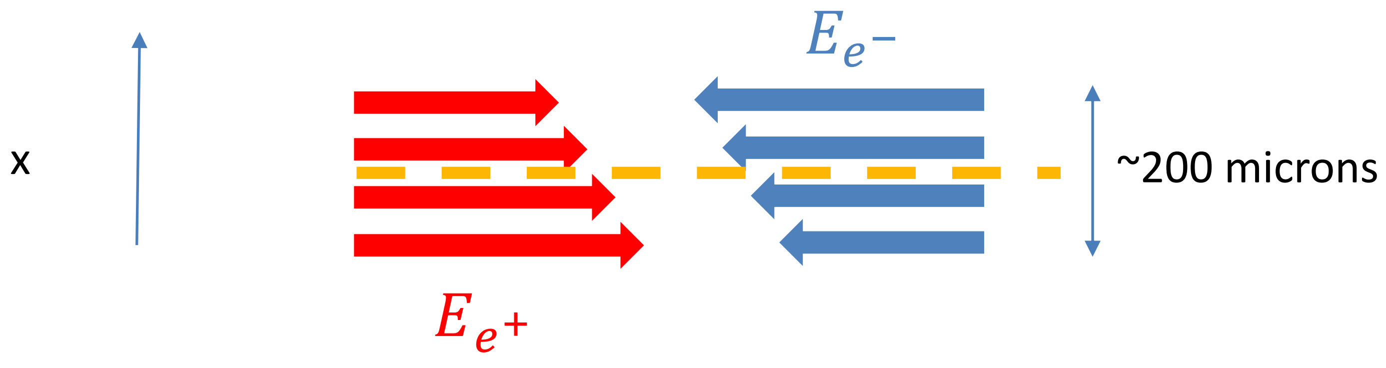




Measuring the centre-of-mass energy spread

In the EPJ paper (**AB and Eliana Gianfelice**) http://cds.cern.ch/record/2789651, we assume that x_m is the horizontal coordinate x (we know this would work if beams are colliding head-on without crossing angle, but this not the preferred scheme). In this case we could have the following situation.

The beam is artificially spread around x for the monochromatization (σ_x ~ ±100 μm) while the detector should be able to measure the production point of each event with a precision of ±3μm inn the x,y and z directions



Monochromatization $D_x(e+) = - D_x(e-)$

<ECM>(x) ~constant

σ_{ECM} (x)~constant ~ <σ_{ECM} (x)>

Boost measurement:

<(E(e+)-E(e-)> ∝ x (D_x(e+)-D_x(e-))

rms((E(e+)-E(e-))(x) ~constant << <rms((E(e+)-E(e-))>

this is very elegant: we can measure from the {boost of the muon pairs vs. x} the true energy spread *and* verify the variation of boost across the beam crossing point -- this is the very principle of monochromatization.
NB we can and should also maybe verify the ECM is constant vs x, s, t Detailed analysis is needed to ascertain the errors.

FCC

Precision of energy spread measurement at $\sqrt{s}$ = 125 GeV

At the Z this measurement would be very fast, especially since the width of the distribution is quite narrow. every 5 minutes a measurement with error of +- 50 keV. However, with monochrmatization the width of the distribution is much smaller (10 MeV vs 50 MeV)
→ high precision but deconvolution of experimental resolution is more critical.

For experimenters: need to check that the resolution on acollinearity is sufficient
requirement will be of O (4 MeV/50 GeV=0.08mrad)
i.e. ~10 times more accurate than for Z measurements

At 125 GeV the conditions are less favorable.

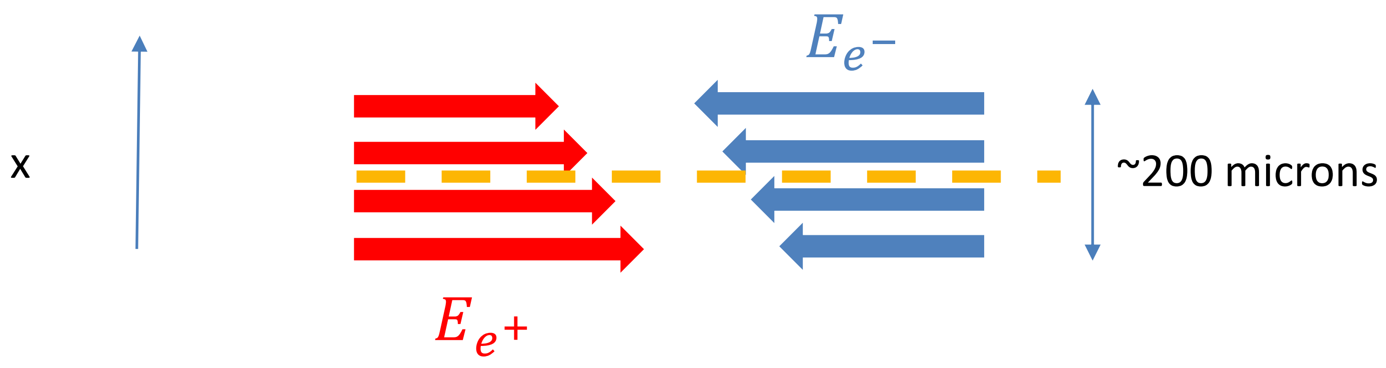
1. **the luminosity is 20 times smallet than at the Z**
2. **the cross-section is 100 times smaller**

For a luminosity of 2.1035/cm2/s and a high-mass muon pair cross section of 10pb, the ECM spread should be measurable with a relative precision of better than 10% in 20 equally populated *x*-bins in less than about 3 h; measuring ECM in each of so many bins with a precision of ±2 MeV will take a few days.

➔ **these long times are OK if the system works, they are too slow for development**

The monochromatization scheme should be developed while running at the Z

For the s-channel Higgs production



Monochromatization

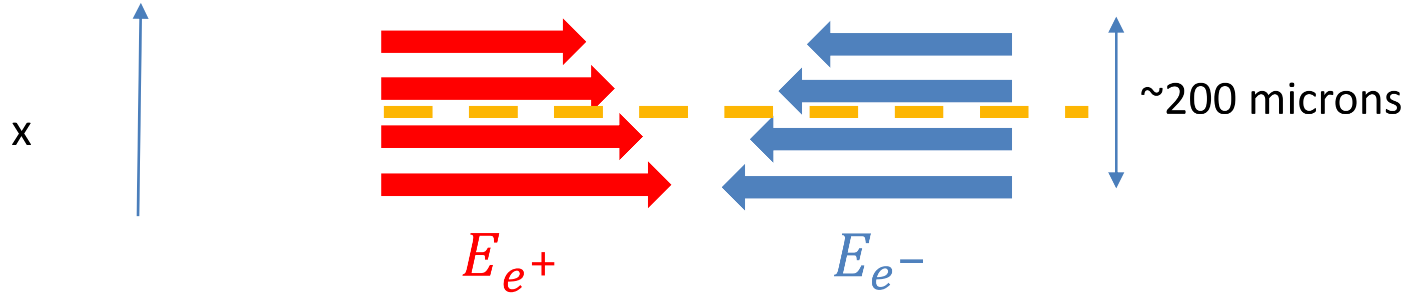
<ECM>(x) ~constant

σ_{ECM} (x)~constant ~ <σ_{ECM} (x)>

Boost measurement:

<(E(e+)-E(e-)> $\propto$ x (D_x(e+)-D_x(e-))

rms((E(e+)-E(e-))(x) ~constant < <rms((E(e+)-E(e-))>



Chromatization along x axis:

across the x axis:

<ECM>(x) ~ x (Dx(e+)+Dx(e-))

σECM (x)~constant < <σECM (x)>

Boost measurement:

<(E(e+)-E(e-)> (x)

Rms((E(e+)-E(e-))(x) ~constant ~<Rms((E(e+)-E(e-))>

“Measure” ECM on evt by evt basis

Measurement uncertainty in x for muon pairs ≈ 3microns/sin(phi)
Investigate other variables (z or time coordinates)

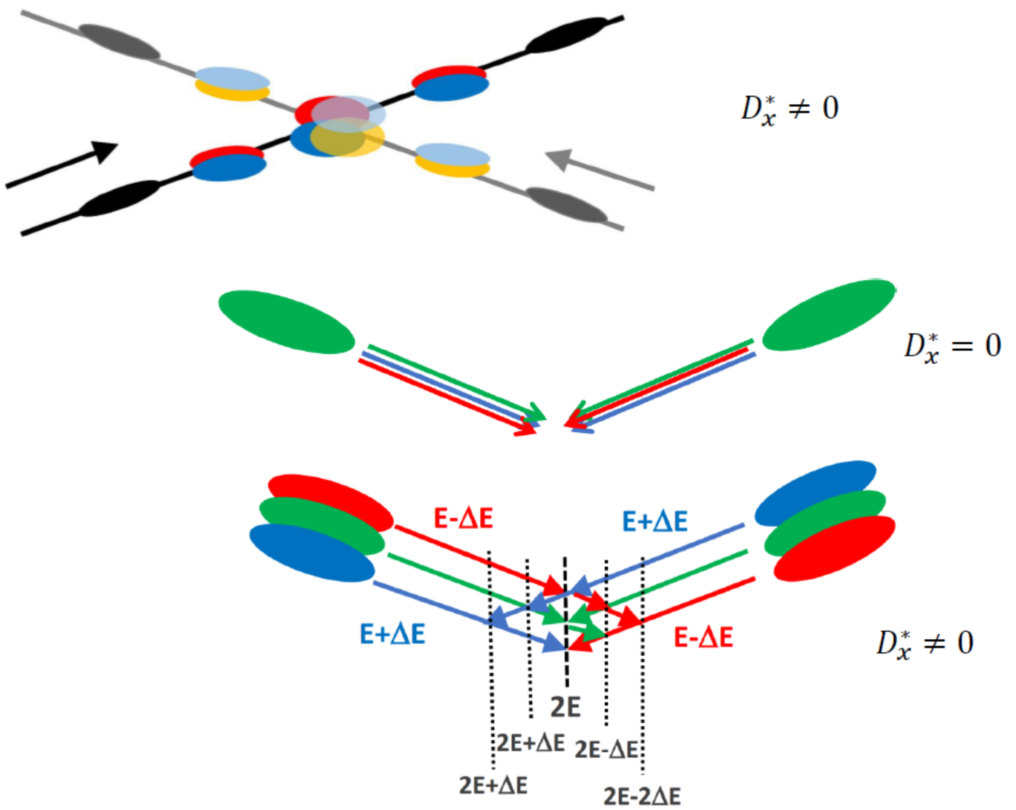
three scenarios for FCC

baseline with crab cavities 1.

optimized by Alan

2.

alternatives with crossing angle 3.



its also possible to envisage monochromatization
or chromatization
along z or time axes,
experiments should be able to measure these quantities on an event by event basis.

D_x results in a distribution of events in z
is it possible to create a E dependence upon time? Harder particles early in one bunch and late in the other?

For the scheme where different values of ECM are spread along the *x*-axis the boost remains constant along the *x*-direction, while the average energy varies.
In either case, the measurements of the variation of the centre-of-mass boost, ECM and ECM spread across the bunch will verify the proper realization of monochromatization; this is essential for the interpretation of the e+e− → *H* physics result.

Luminous region 'vertex size' in x,y,z,t for various ECM points at FCC-ee

		L. A. evt precision				
Ebeam (GeV)	45.6		80	120	175	182.5
σ_x (µm)	6.4		13.0	13.7	36.6	38.2
σ_y (nm)	28.3		41.2	36.1	65.7	68.1
σ_z (mm)	12.1		6.0	5.3	2.62	2.54
Vertex σ_x (µm)	4.5	**3**	9.2	9.7	25.9	27.0
Vertex σ_y (nm)	20	**3000**	29.2	25.5	46.5	48.2
Vertex σ_z (mm)	0.30	**0.003**	0.60	0.64	1.26	1.27
Vertex σ_t (ps)	28.6	**3**	14.1	12.5	6.2	6.0

σ_x is increased to $\geq 100\mu m$ for the D_x scheme

however the longitudinal coordinates (z, t) are also well possible and have not been exploited so far.

Courtesy of Emmanuel Perez

https://github.com/HEP-FCC/FCCeePhysicsPerformance/tree/master/General#vertex-distribution

next steps

Specify the requirements from the experiment on
-- ECM stability,
-- ECM measurements and
-- Centre-of-mass energy spread measurement

It seems possible (but not easy) to get in the right ball park with the techniques used for the Z pole
see **arXiv:1909.12245;** but we should go through the exercise to make sure we are not forgetting anything.

The muon-pair analysis needs to be investigated, it looks like this can provides an excellent monitoring.
at 125 GeV the large amount of radiative Z-return may limit the number of events that are really useable.
also need to check that the acollinearity measurement is precise enough given the narrower energy spread.
Also, because of the narrower energy spread, the detector resolution requirement probably needs to be tightened

Alternative schemes using longitudinal coordinates, z and time could complement/improve the x-axis monochromatization sch
it should be checked that the resulting monochromatization and measurements are feasible.
The y coordinate seems hopeless, but other coordinates (x', y') might work and should be investigated.

Operational considerations are important: thanks to the high event rates at the Z, it appears that t
the Z run will be an ideal place to test and measure the monochromatization.
➔ **Some time should be allowed in the run plan to develop the monochromatization scheme at the Z before the Higgs run.**

next steps

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