FUTURE
CIRCULAR
COLLIDER

FCC-ee Energy Calibration and Polarization Status

**D. Barber, M. Benedikt, A. Blondel*, A. Bogomyagkov, F. Carlier, E. Gianfelice-Wendt,
A. Faus-Golfe, M. Hofer, J. Keintzel, I. Koop, M. Koratzinos, P. Janot,
H. Jiang, A. Martens, N. Muchnoi, S. Nikitin, K. Oide, T. Persson, T. Pieloni, P. Raimondi,
R. Tomàs, D. Sagan, D. Shatilov, J. Wenninger*, G. Wilkinson, Y. Wu, and F. Zimmermann**

2d FCC Polarization Workshop (EPOL) 2022
Joint EIC-FCC Working Meeting on e+/e- Polarization
19th September 2022

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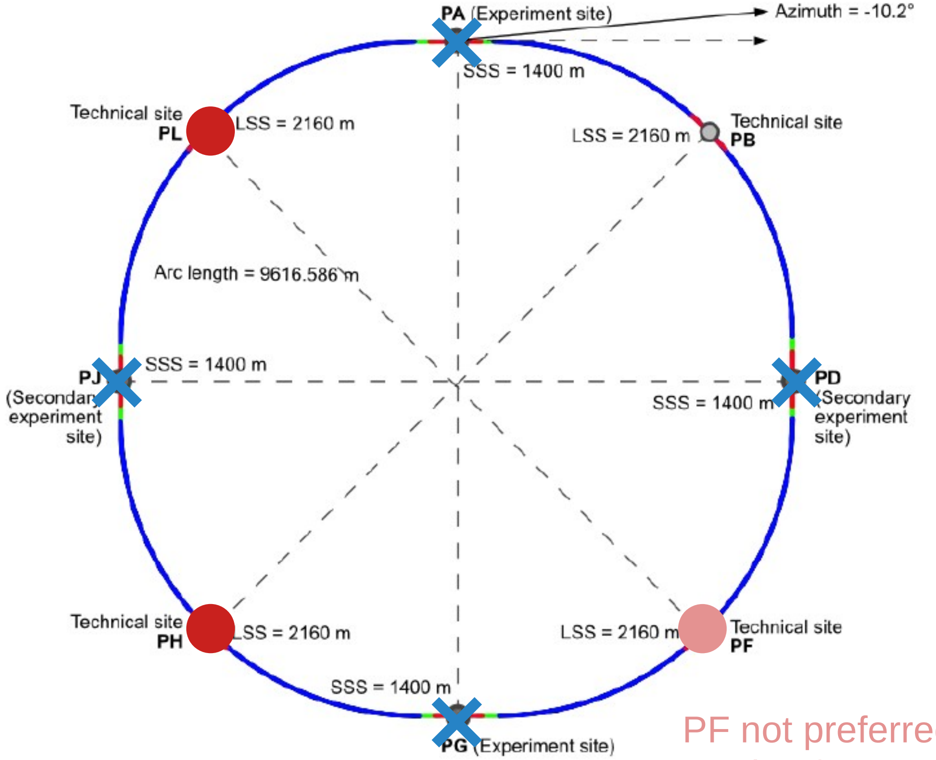
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Overview FCC-ee

- Higgs and electro-weak factory
- 4 different beam energies
- New “lowest risk” 4 IPs scenario (✕)
  - Perfect symmetry
  - Perfect 4-fold superperiodicity
- 1 or 2 RF-sections (●)
- High precision physics experiments
- → **Up to few keV statistical precision achievable**

First set of results obtained in the FCC Design Study:

Polarization and Centre-of-mass Energy Calibration at FCC-ee, **arXiv:1909.12245**



PF not preferred section for RF

Energy calibration and polarization working group
With regular meetings since October 2021:
indico.cern.ch/category/8678
What have we achieved and what are the next steps?

What do we want to measure at which precision?

A. Blondel

Precision Measurements

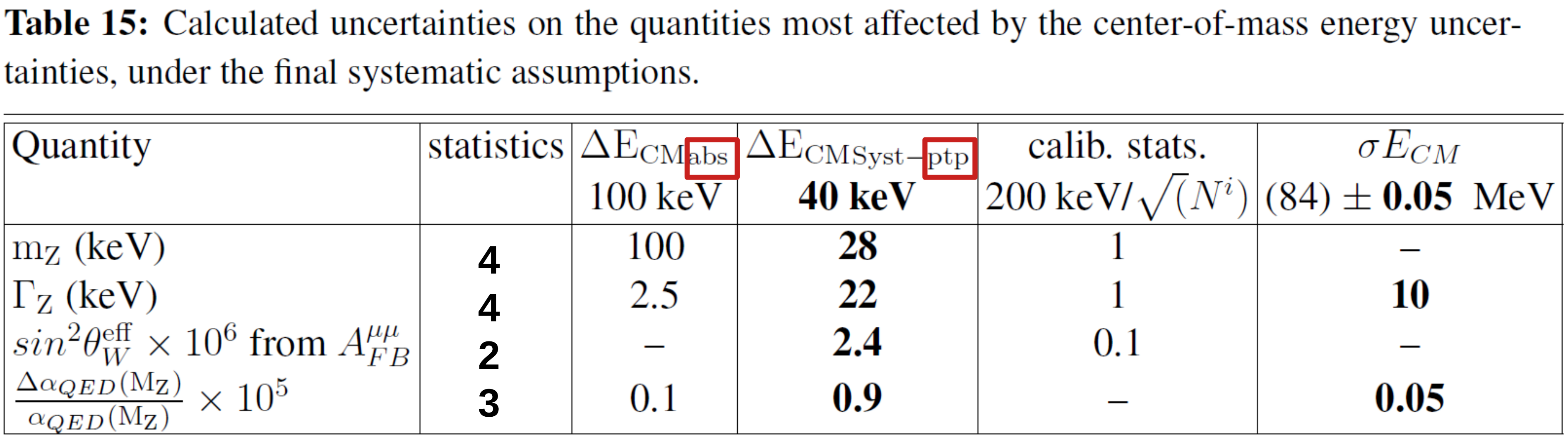


Table 15: Calculated uncertainties on the quantities most affected by the center-of-mass energy uncertainties, under the final systematic assumptions.

	Quantity	statistics	$\Delta E_{CM abs}$ 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
Z	m_Z (keV)	**4**	100	**28**	1	–
	Γ_Z (keV)	**4**	2.5	**22**	1	**10**
	$sin^2\theta_W^{\text{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	**2**	–	**2.4**	0.1	–
	$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	**3**	0.1	**0.9**	–	**0.05**
WW	*)			**300 keV**	**150 keV**	
	m_W(MeV)	**0.200**	**(?)**	**75 keV?**		
	Γ_W (MeV)			(75?)	small	OK

abs: absolute scale error

ptp: point-to-point errors

*) further clarification/documentation needed for W uncertainties in WW studies (threshold meast, direct reconstruction)

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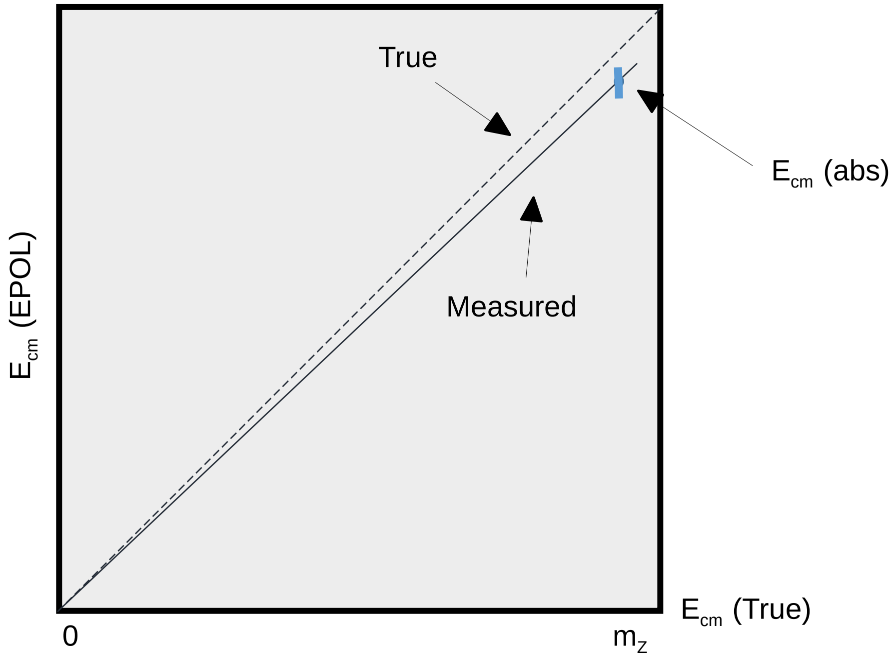
Uncertainties

Absolut scale error (abs)

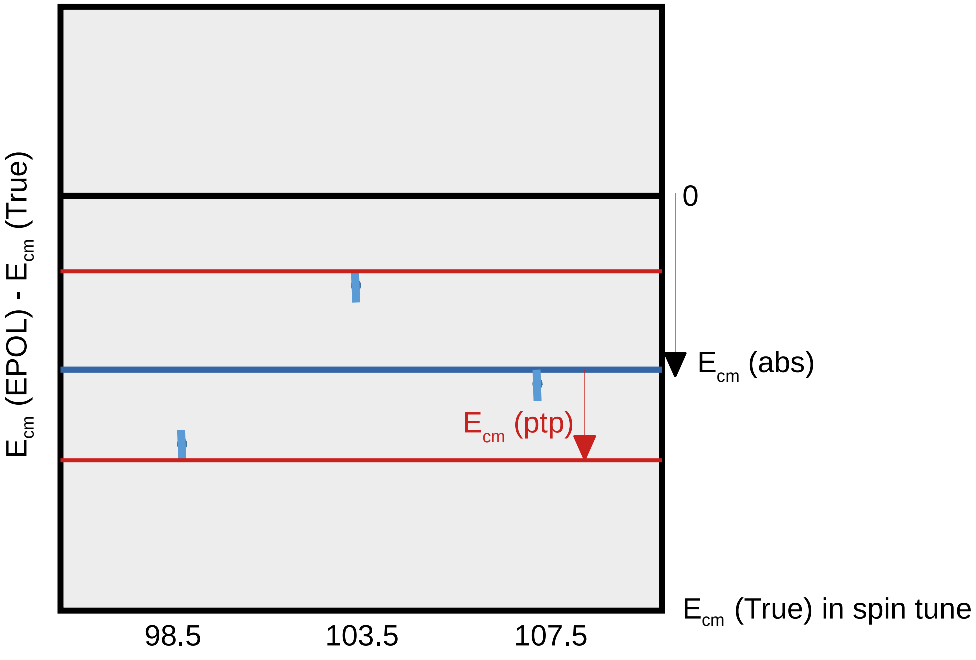


Absolute scale of correspondance between true E_{cm} and the EPOL group estimate

➔ large effect on Z,W mass, small on Z,W width

From: electron mass error, systematic error in RF frequency, or systematic IP dispersion/offset, systematic shift of depolarization wrt resonance, unforeseen energy losses etc.

Point-to-point errors (ptp)

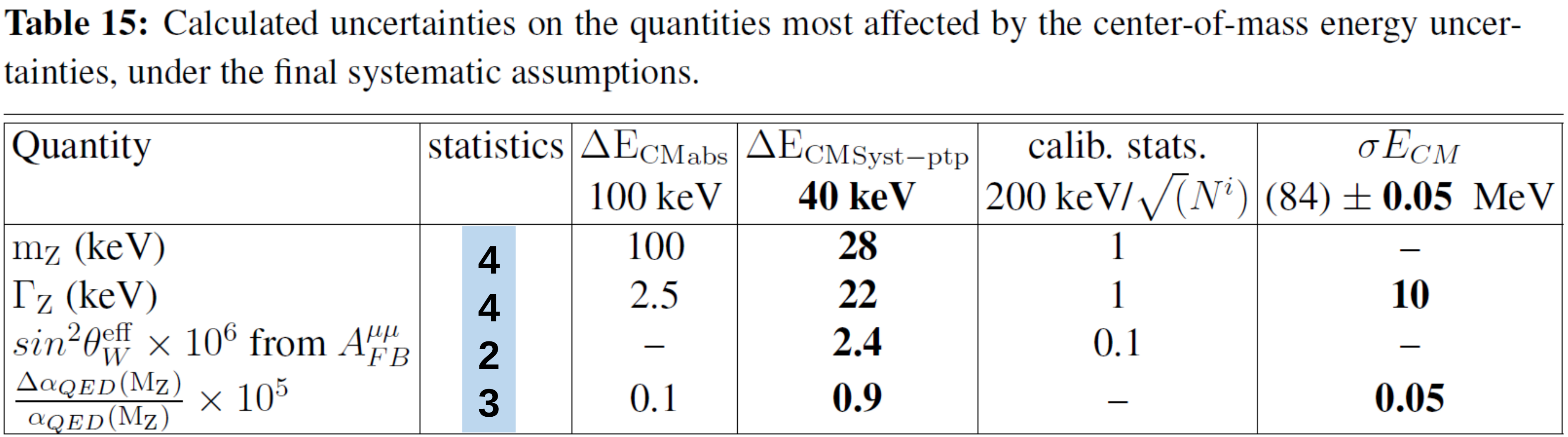


Point-to-point differences in EPOL calibration

➔ dominant effect on Z and W width, m_W/m_Z, A_{FB}

From: spin tune dependence of RDP vs E(true) due to interferences with underlying resonances, variability of running conditions wrt IP effects or ground motion, non-linearity of energy losses, etc.

Precision Measurements



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Z

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WW

*)			**300 keV**	**150 keV**	
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Γ_W (MeV)			(75?)	small	OK

Statistical precisions

4 keV at Z

100 keV per W

Aim for same order of magnitude for systematic precision

*) further clarification/documentation needed for W uncertainties in WW studies (threshold meast, direct reconstruction)

EPOL working group aims at reducing the systematic error on the E_{CM} measurement

A. Blondel

E_{CM} Uncertainties

$$\frac{\Delta m_{\rm Z}}{m_{\rm Z}} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}+\sqrt{s_-})}{\sqrt{s_+}+\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling},$$

$$\frac{\Delta\Gamma_{\rm Z}}{\Gamma_{\rm Z}} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling},$$

$$\Delta A^{\mu\mu}_{\rm FB}({\rm pole}) = \frac{\partial A^{\mu\mu}_{\rm FB}}{\partial\sqrt{s}}\left\{\Delta(\sqrt{s_0}-0.5(\sqrt{s_+}+\sqrt{s_-}))\right\}_{\rm ptp-syst} \oplus_i \frac{\partial A^{\mu\mu}_{\rm FB}}{\partial\sqrt{s}}\left\{\frac{\Delta\sqrt{s^i_{0,\pm}}}{\sqrt{N^i_{0,\pm}}}\right\}_{\rm sampling},$$

$$\frac{\Delta\alpha_{\rm QED}(m^2_{\rm Z})}{\alpha_{\rm QED}(m^2_{\rm Z})} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling},$$

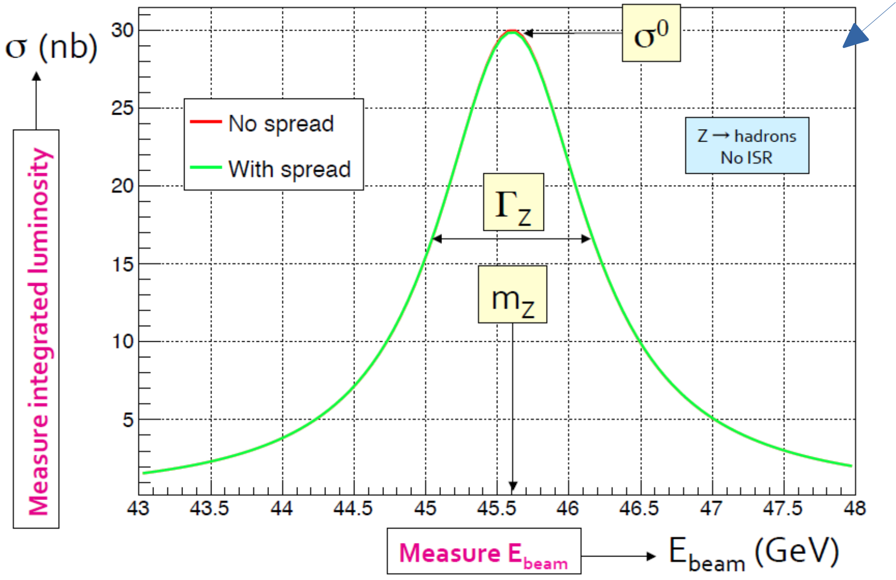
$$\text{with } \frac{\partial A^{\mu\mu}_{\rm FB}}{\partial\sqrt{s}} \simeq 0.09/{\rm GeV}$$

Error categories:
- abs: dominant for Z and W mass
- ptp: dominant for ΓZ, ΓW and AFB (peak and off-peak)
- sampling: negligible for 1 measurement / 15 mins=1000s → 10^4 measurements
- **syst: systematic uncertainty aimed to be reduced to ~4 keV and ~100 keV for Z and W mass**

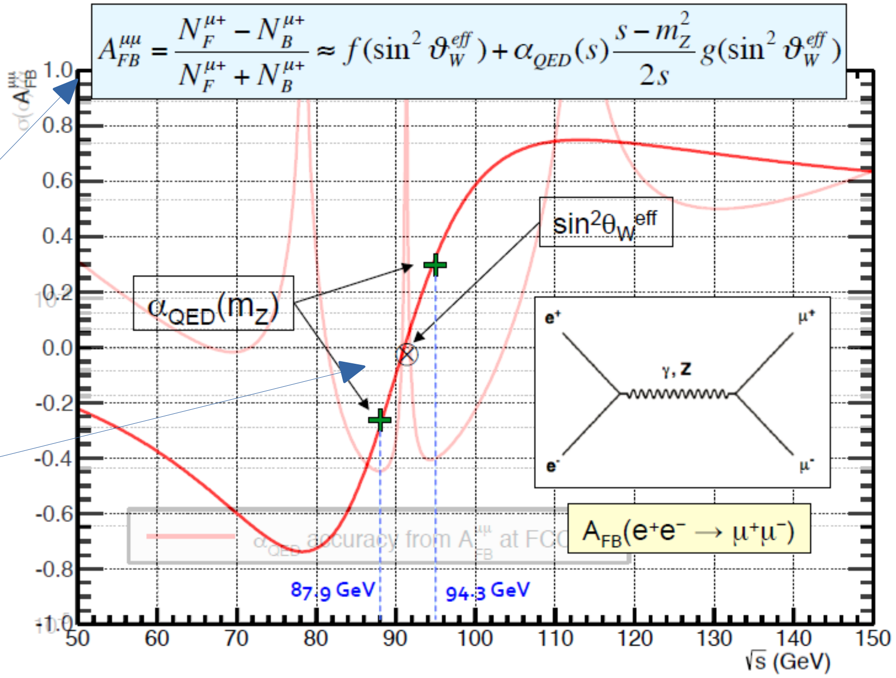
A_{FB} Forward-Backward Assymmetry

A. Blondel

Scan Points



Z mass and width

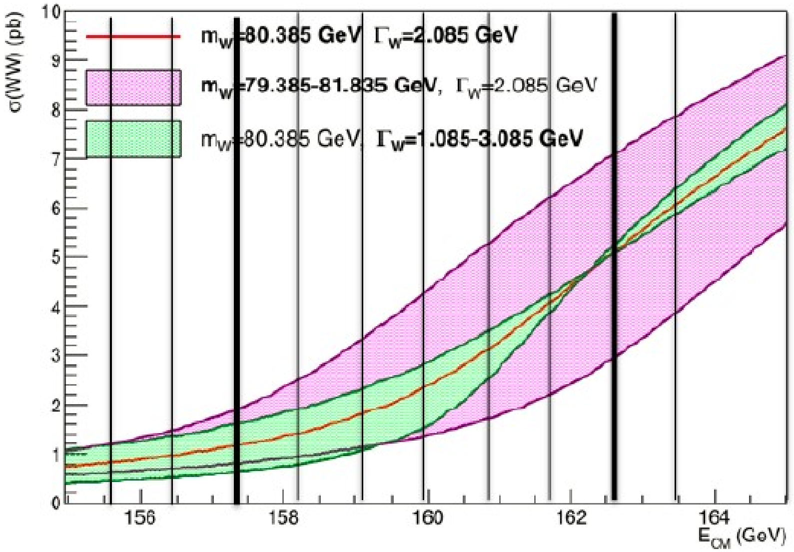


$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2\vartheta_W^{eff}) + \alpha_{QED}(s)\frac{s - m_Z^2}{2s} g(\sin^2\vartheta_W^{eff})$$

Forward-Backward Assymmetry links the weak coupling with the EM-coupling

To measure the slope around the Z resonance at E_{CM} = 91 GeV, a scan at different energies is proposed

Scan point	$\sqrt{s}$ (GeV)	E_b (GeV)	Spin tune
$\sqrt{s_-}$ A	87.69	43.85	99.5
$\sqrt{s_-}$ Request	87.9	43.95	99.7
$\sqrt{s_-}$ B	88.57	44.28	100.5
$\sqrt{s_0}$	91.21	45.61	103.5
$\sqrt{s_+}$ A	93.86	46.93	106.5
$\sqrt{s_+}$ Request	94.3	47.15	107.0
$\sqrt{s_+}$ B	94.74	47.37	107.5



W mass and width have presenlty rather large uncertainties → aim to be reduced

How do we obtain the E_{CM}?
What have we already achieved?

F. Carlier, E. Gianfelice-Wendt, T. Pieloni, Y. Wu

Polarization and Spin Tune

- Lepton beams polarize naturally transversely over time → Sokolov-Ternov-Effect
- Depolarization naturally from synchrotron radiation, resonances, etc.
- Maximum polarization at about 92.4 % in lepton storage rings

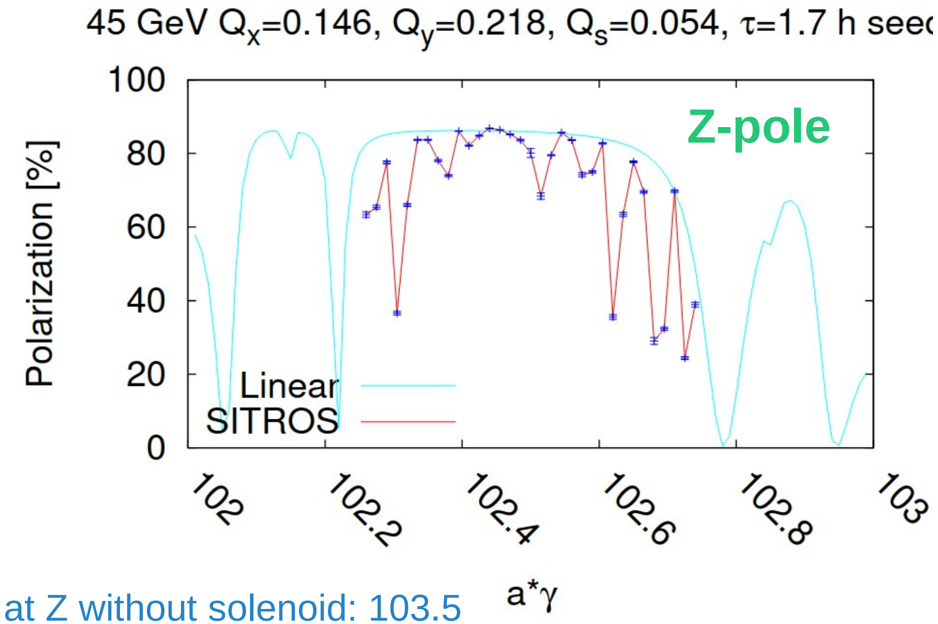
$$\underbrace{\tau^{-1}}_{\text{Effective polarization rate}} = \tau_{bks}^{-1} + \underbrace{\tau_{dep}^{-1}}_{\text{Depolarization rate}}$$

Baier-Katkov-Strakhovenko polarization rate

$$\tau_{bks}^{-1} = \frac{5\sqrt{3}}{8}\frac{\hbar r_e \gamma^5}{m_e C}\oint ds \frac{1-\frac{2}{9}(\hat{n}_0(s)\cdot\hat{s})^2}{|\rho(s)|^3}$$

Polarization direction in ŷ for planar ring

Strong unexpected resonance found for SITROS simulations



aγ at Z without solenoid: 103.5

E. Gianfelice-Wendt,
indico.cern.ch/event/727555/contributions/3468285, 2019.

- Resonances with transverse and longitudinal axis

Q_x … horizontal tune
Q_y … vertical tune
Q_s … synchrotron tune
m_i, k … integer
a … gyromagnetic moment
γ … relativistic gamma

$$\underbrace{a\gamma}_{\text{Spin tune for ideal machine}} + \underbrace{m_x Q_x + m_y Q_y}_{\text{Transverse planes}} + \underbrace{m_s Q_s}_{\text{Longitudinal plane}} = k$$

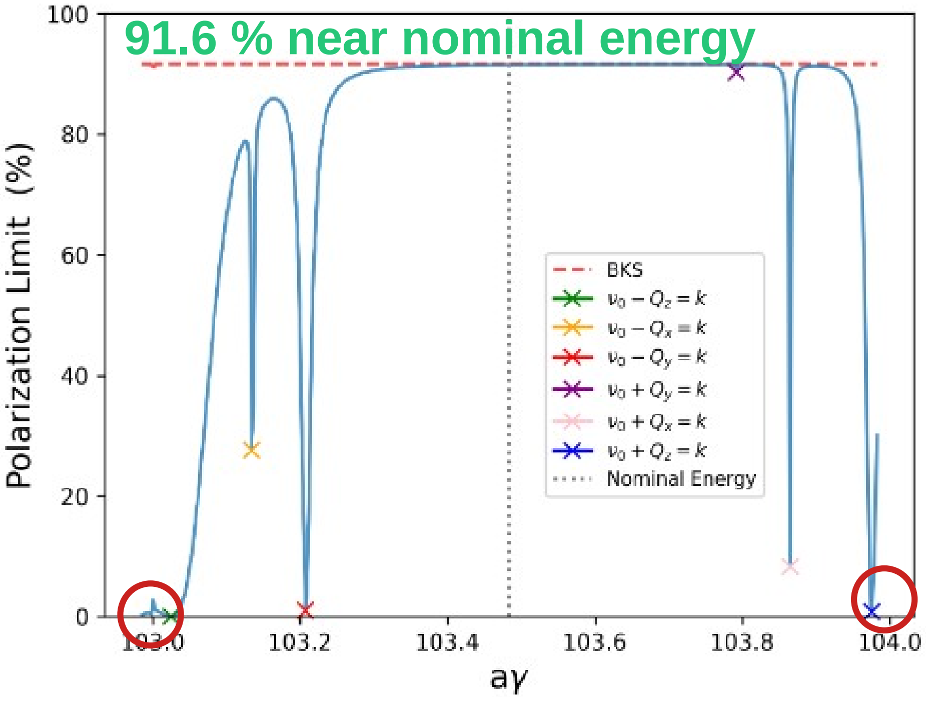
Y. Wu: indico.cern.ch/event/1119730/

F. Carlier, T. Pieloni, Y. Wu

Error Sensitivity

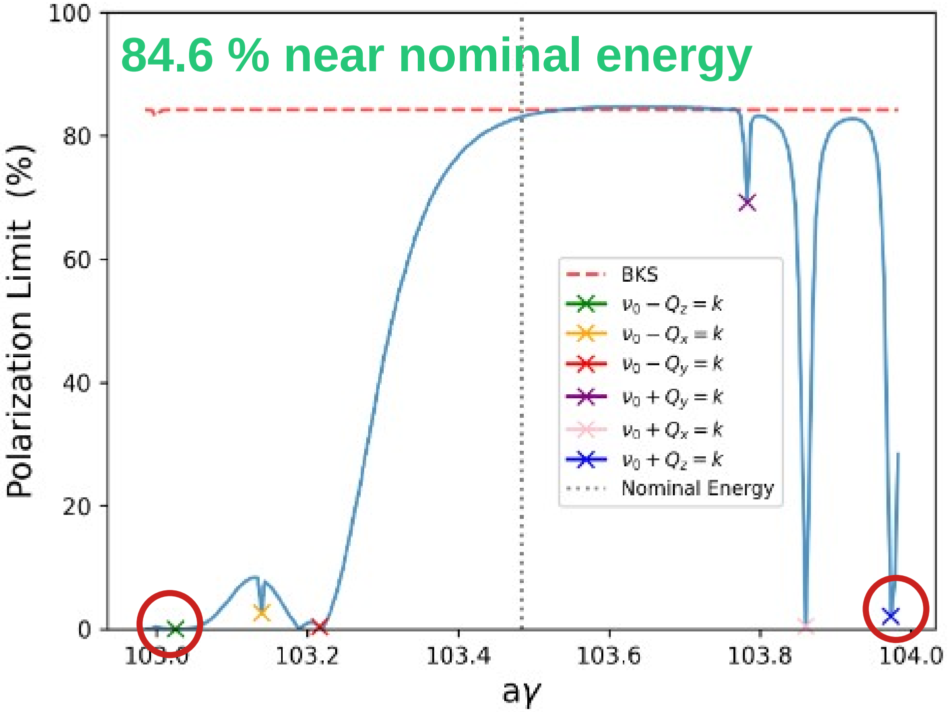
- Resonances enhanced with increasing closed orbit, shown for Z-pole
- More misalignments can reduce maximum polarization → orbit corrections essential

$(\Delta y)_{\mathrm{rms}} = 43.7\ \mu\mathrm{m}$



91.6 % near nominal energy

$(\Delta y)_{\mathrm{rms}} = 148\ \mu\mathrm{m}$



84.6 % near nominal energy

Misalignment errors in Dipoles, quadrupoles Sextupoles

Q_x = .139 Q_y = .219
Q_s = 0.025

Small emittances and large Q_s –> Resonances with the longitudinal plane dominating and symmetric ± Q_s

Y. Wu: agenda.infn.it/event/21199/

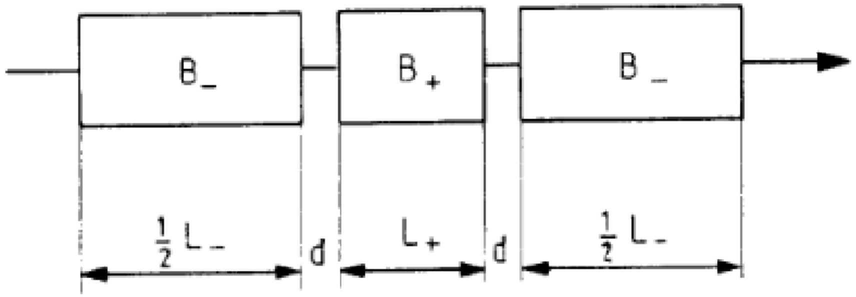
M. Hofer, K. Oide

Wigglers I

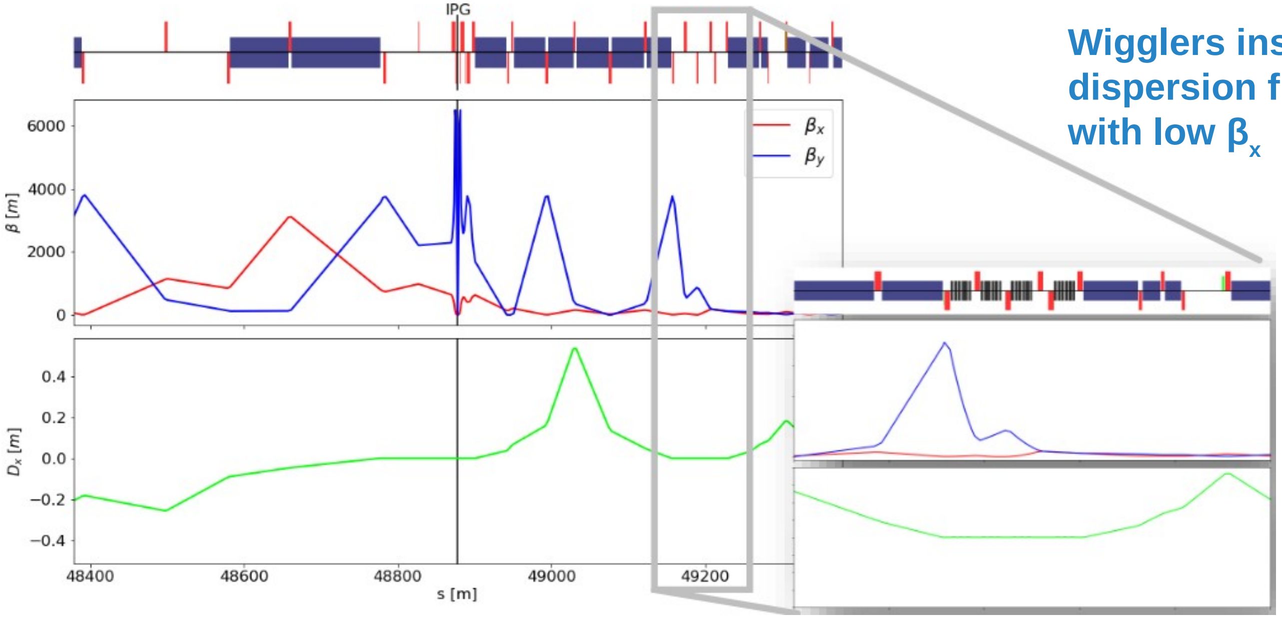
- Very long natural polarization time in FCC-ee
- Wigglers improve polarization time significantly

$$\left(\frac{\sigma_E}{E}\right)^2 \propto \frac{E^4}{\gamma^3 \tau_p \Delta E_{loss}} \qquad r = \frac{B_+}{B_-} = \frac{L_-}{L_+}$$

Follow 3 three-block design from LEP



Parameter	FCC-ee	LEP
Number of units per beam	24	8
B_+ [T]	0.7	1.0
L_+ [mm]	430	760
r	6	2.5
d [mm]	250	200
Crit. Energy of SR photons [keV]	968	1350



Wigglers installed in dispersion free section with low β_x

Polarization time decreases from 248 h to 12 h

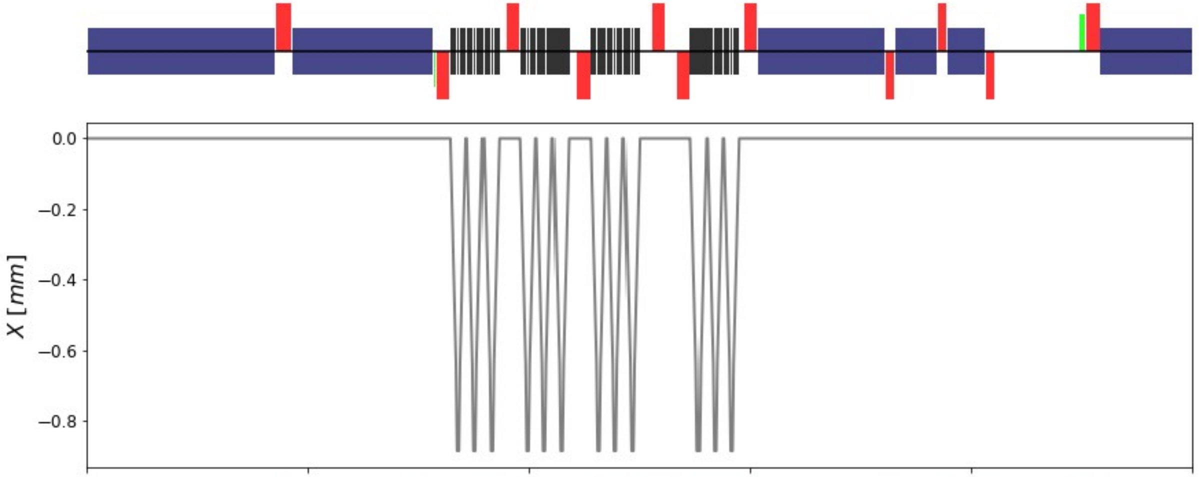
Energy spread increases from 17 MeV to 64 MeV

M. Hofer: indico.cern.ch/event/1080577/

M. Hofer, K. Oide

Wigglers II

- Operational scenario:
  - Inject few pilot bunches
  - Use wigglers to reach ~5 % polarization
  - Switch wigglers off
  - Inject all bunches
  - Measure polarization to retrieve energy



- Caveat of wigglers:
- Orbit generates synchrotron radiation
- Photons with critial energy O(MeV)
- → Can generate neutrons
- Radiation protection challenges

M. Hofer: indico.cern.ch/event/1080577/

Resonant depolarization together with polarimeter

Determining average energy

Measurement of photons from e+e- –> μ+μ-(γ)

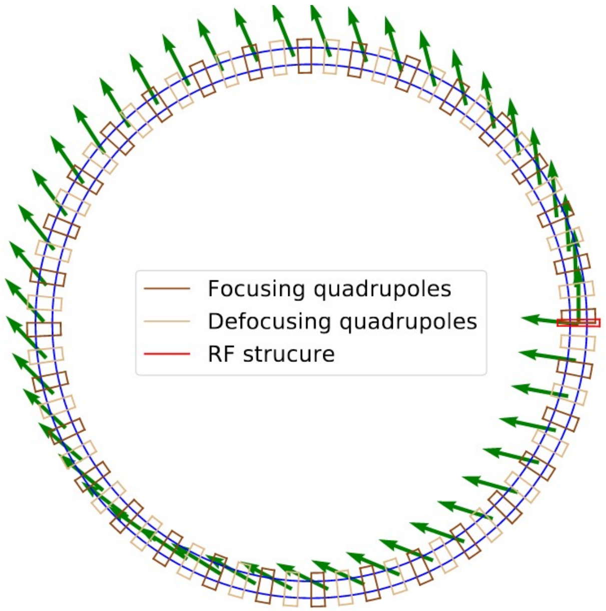
Determining boosts

A. Bogomyagkov, V. Caudan, E. Gianfelice-Wendt

Energy from Spin Tune

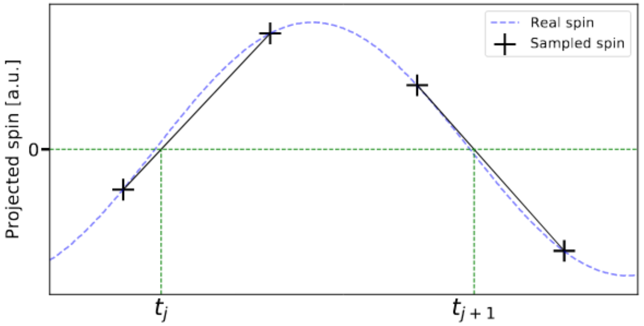
- Using resonant depolarization and polarimeter to determine average beam energy
- Promising simulations performed for simple FODO cell lattice with 100 m circumference

Precession of spin over one revolution in ideal machine with spin tune of about 0.25



E … energy
m … mass
c … speed of light
ν … spin tune
a … anomalous magnetic dipole moment

$$E = mc^2 \left(\frac{\nu}{a} - 1 \right)$$



$$\nu_j \approx \frac{1}{2(t_{j+1} - t_j)} \frac{1}{f_{\mathrm{rev}}}$$

Spin tune measurement might not be exact beam energy measurement

Various contributions on the average beam energy estimated

synchrotron oscillations	ΔE/E	$-2\ 10^{-14}$
Energy dependent momentum compaction	ΔE/E	10^{-7}
Solenoid compensation		$2\ 10^{-11}$
Horizontal betatron oscillations	ΔE/E	$2.5\ 10^{-7}$
Horizontal correctors*)	ΔE/E	$2.5\ 10^{-7}$
Vertical betatron oscillations **)	ΔE/E	$2.5\ 10^{-7}$
Uncertainty in chromaticity correction	$O(10^{-6})$ ΔE/E	$5\ 10^{-8}$
invariant mass shift due to beam potential		$4\ 10^{-10}$

E. Gianfelice, I. Kopp, N. Muchnoi, S. Nikitin, J. Wenninger

Resonant Depolarization

- Spin precession frequency Ω given by energy

ω_0 … revolution frequency
ay … ~ spin tune

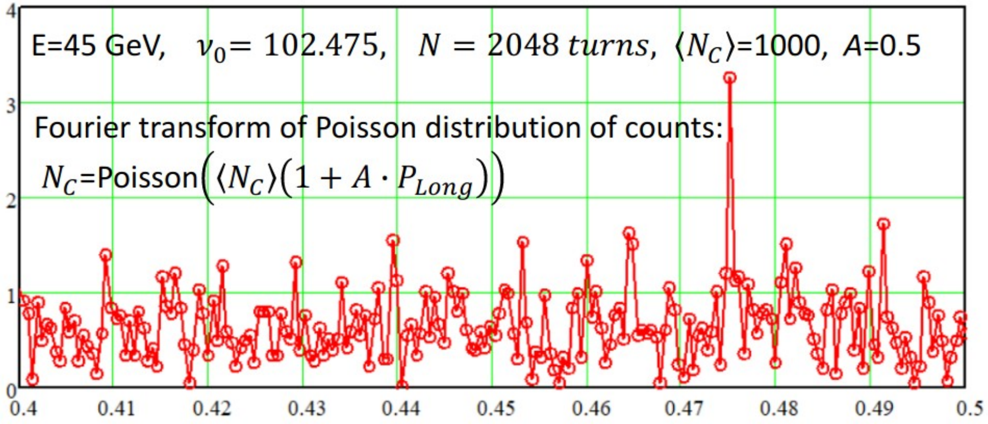
$$\Omega = \omega_0 \left(1 + a\gamma\right)$$

- Measuring depolarizing frequency Ω
- Resonant depolarization by RF kicker with ω_d
- Resonant condition given by $\Omega = n\omega_0 \pm \omega_d$
- Technique used in various machines
- Measured precision of a few keV

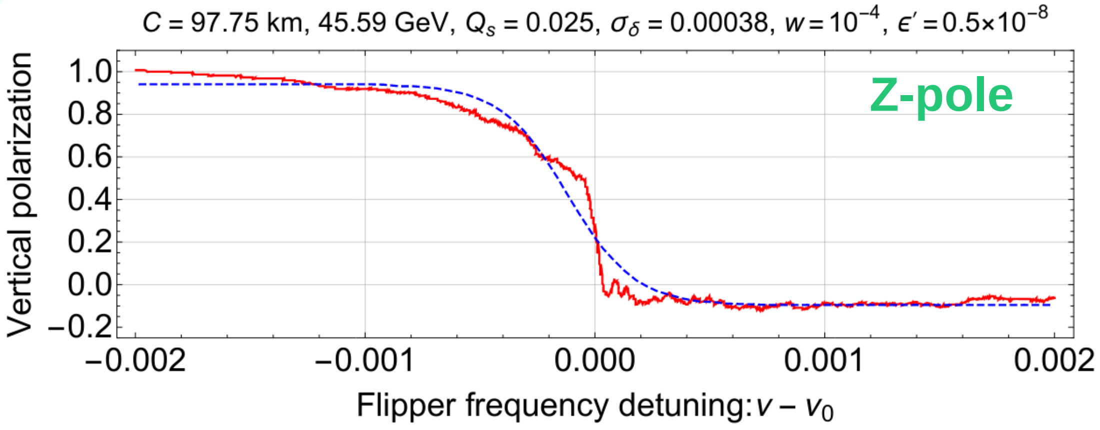
Simulations for FCC-ee
Sweep through driving frequencies (260 s duration)

E. Gianfelice, The polarization code challenge, FCC November Week 2020.
N. Muchnoi, FCC-ee polarimeter, arXiv:1803.09595, 2021.
S. Nikitin, Possible beam studies at VEPP-4M, FCC November Week 2020.
FCC-ee polarization workshop, 18-27 October 2017.

Fourier transformation of counted electrons with high energy loss



Specify depolarizer for FCC-ee ongoing

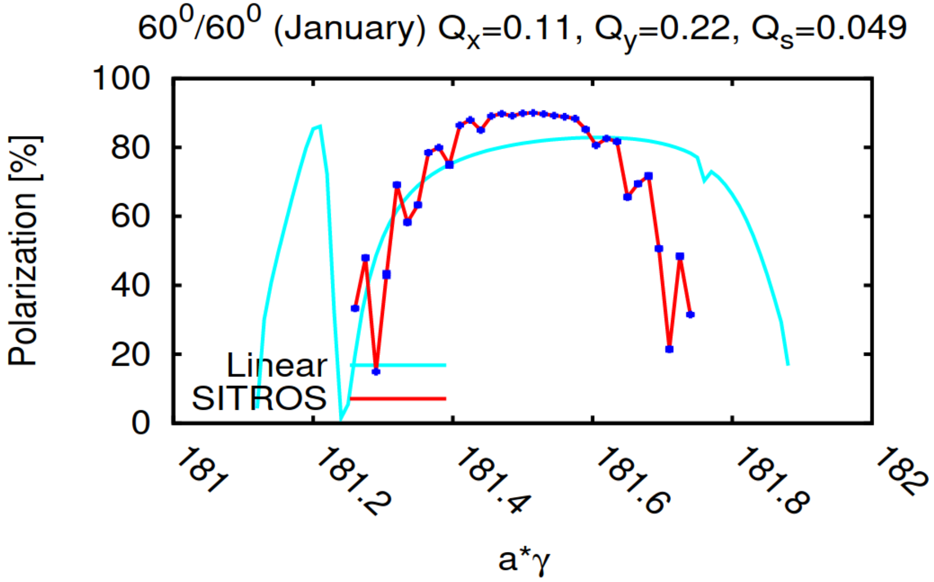


I. Koop, indico.cern.ch/event/1147611/ , 2022.

E. Gianfelice-Wendt, I. Kopp

Polarization at W-pole

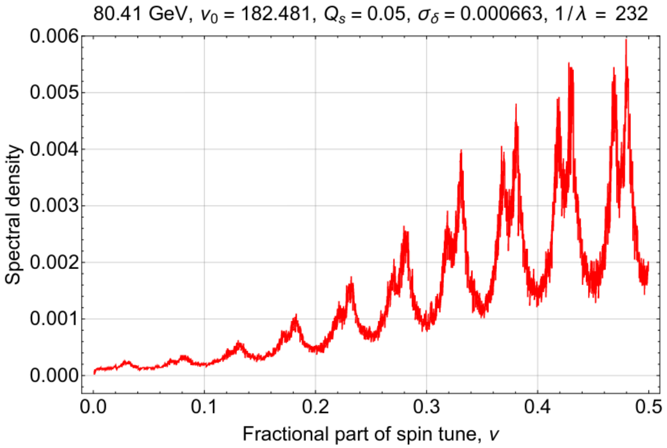
- Same errors as for Z-pole gives sufficient polarization for W
- Sweeping as at Z does not work as Qs sidebands too strong



ay at W without solenoid: 181.55

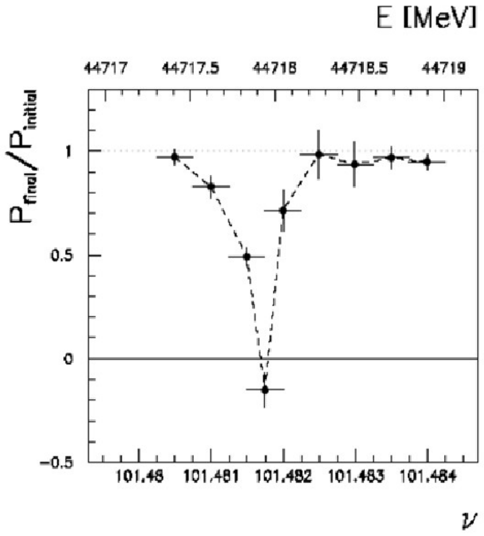
Polarization after applying misalignment errors and correction of vertical dispersion

Large synchrotron sidebands after Fourier transform caused by large energy spread

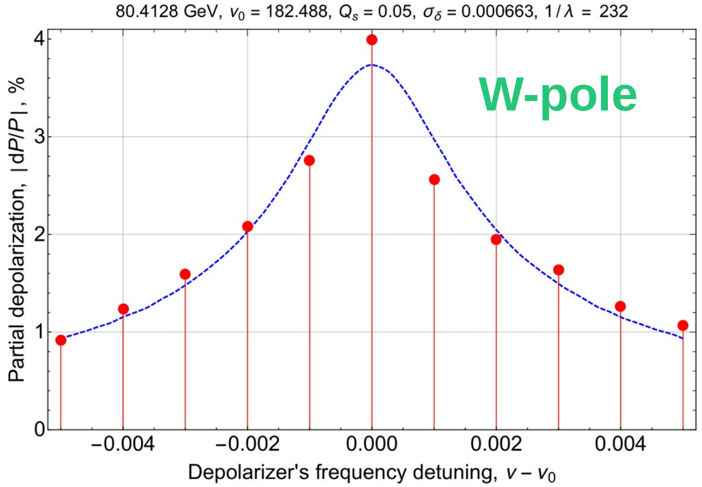


Several short depolarization steps required instead of one long sweep, similar to LEP

A. Blondel et al., arXiv:2019.12245, 2019.



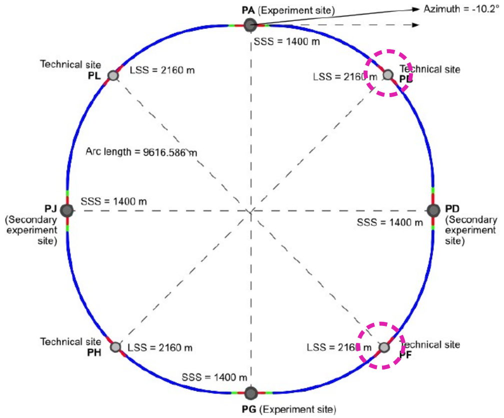
Measurements at LEP Shorter depolarization steps to improve precision



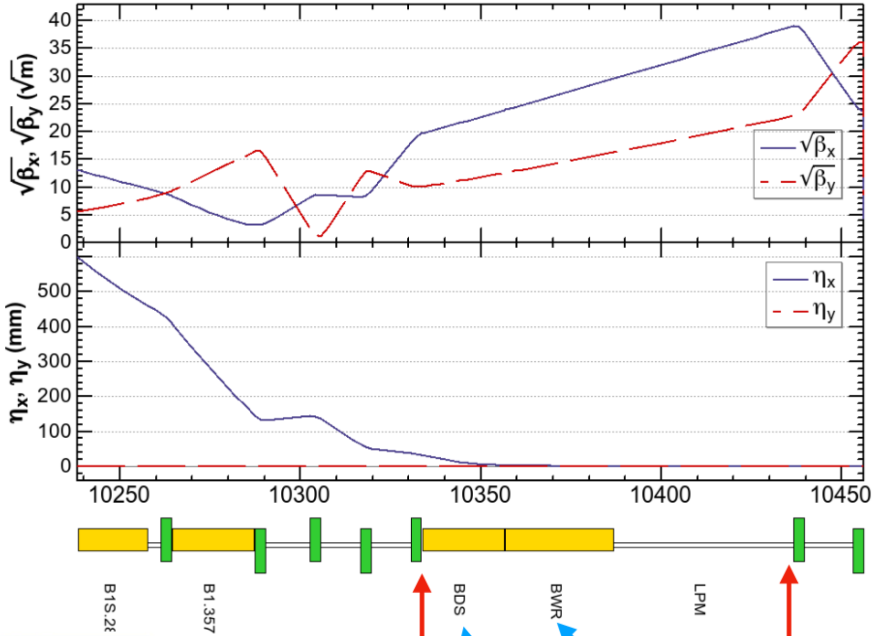
M. Hofer, A. Martens, N. Muchnoi, K. Oide, J. Wenninger

Polarimeter

- One polarimeter per beam
- First definition of specifications
  - 2 mrad angle
  - 100 m drift space
  - 2 m space for LIR (monitoring of location to be designed)



Polarimeter implemented in straight section without IP or RF



0.2 mrad

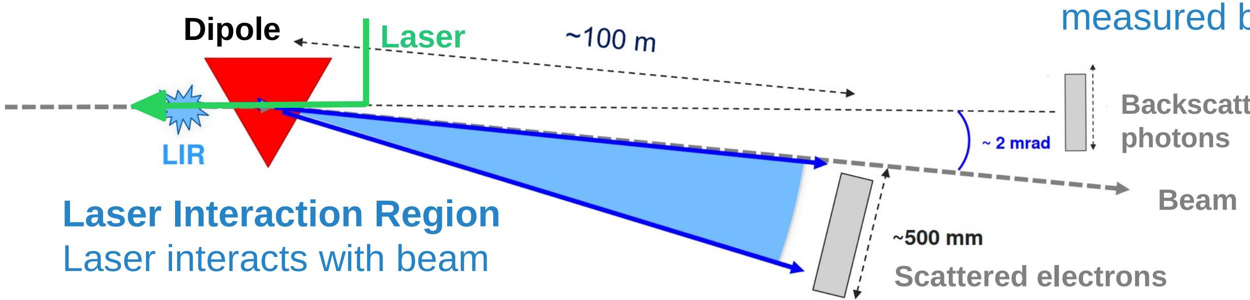
2.17 mrad

Laser

Polarimeter

$L \approx 100$ m

Allows measurement of three coordinates of beam polarization


Dipole

Laser

~100 m

LIR

~ 2 mrad

Backscattered photons

Beam

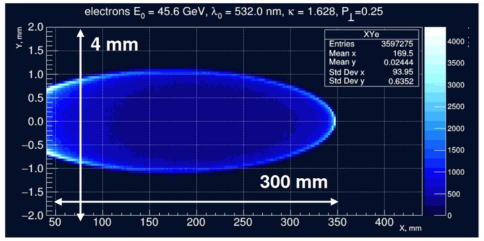
~500 mm

Scattered electrons with minimum energy

Laser Interaction Region

Laser interacts with beam

Scattered electrons to be measured by Si pixel detector



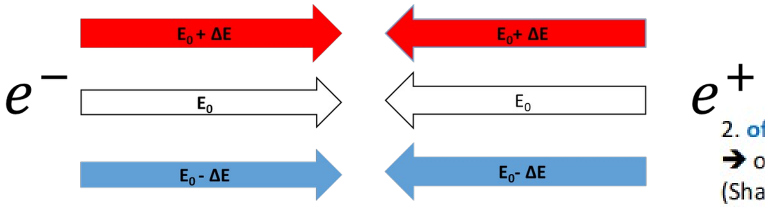
M. Hofer and J. Wenninger: indico.cern.ch/event/1108961/
N. Muchnoi: indico.cern.ch/event/1119730/
K. Oide: indico.cern.ch/event/1162192

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

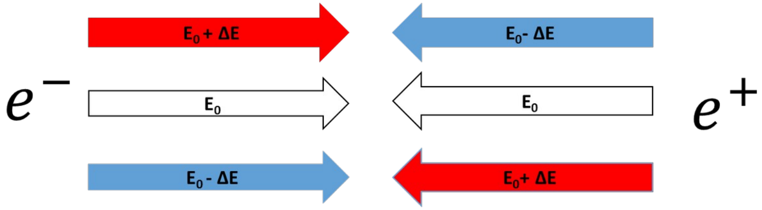
From Average Energy to ECM

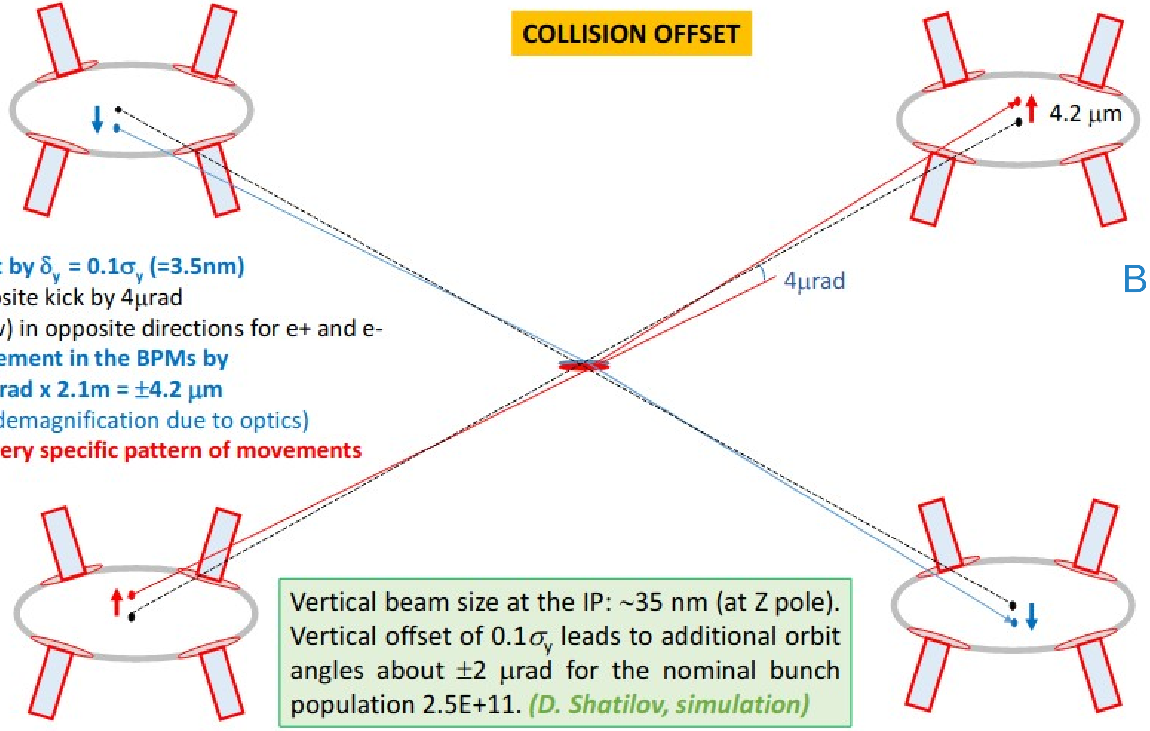
- ECM depends on many factors (collision offsets, dispersion, beamstrahlung, radiation losses, ...)

Same sign dispersion at the IP leads to change of ECM



Opposite sign dispersion helps reducing ECM spread
→ **Monochromatization**



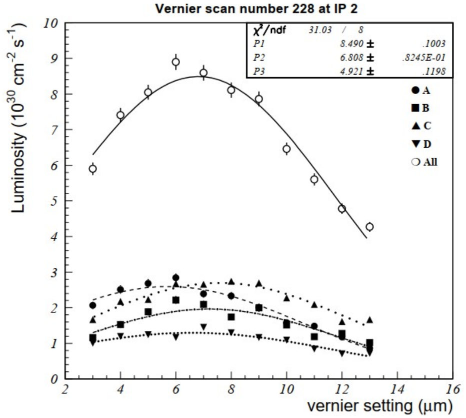


2. offset by $\delta_y = 0.1\sigma_y$ (=3.5nm)
➔ opposite kick by 4µrad (Shatilov) in opposite directions for e+ and e-
➔ movement in the BPMs by ± 2 µrad x 2.1m = ±4.2 µm (x1000 demagnification due to optics)
with a very specific pattern of movements

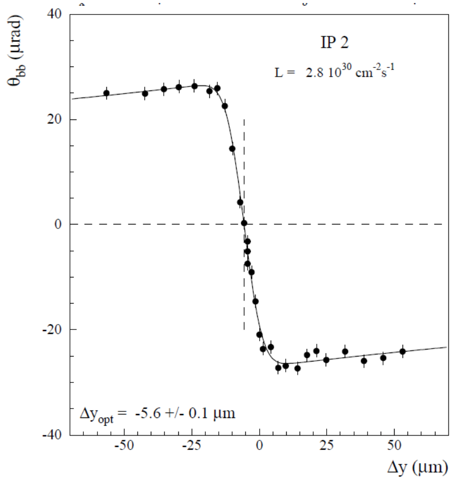
Vertical beam size at the IP: ~35 nm (at Z pole). Vertical offset of $0.1\sigma_y$ leads to additional orbit angles about ±2 µrad for the nominal bunch population 2.5E+11. *(D. Shatilov, simulation)*

A. Blondel: https://indico.cern.ch/event/1064327/

Vernier-scans performed at LEP



Beam-beam deflection at LEP

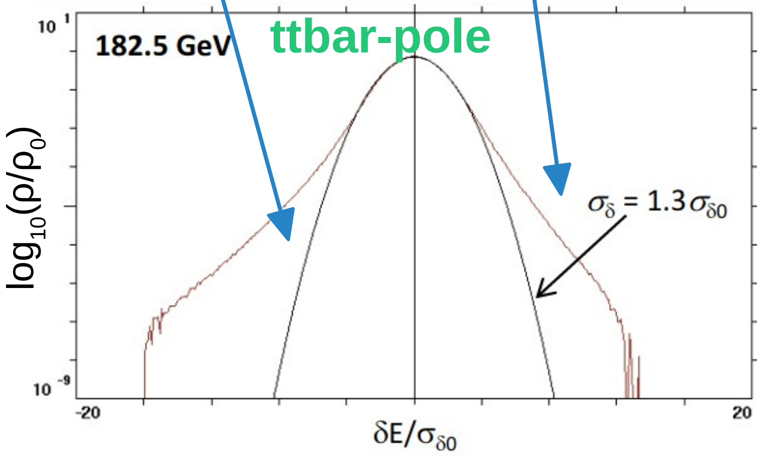


A. Blondel, P. Janot, D. Shatilov

Beamstrahlung and Boosts

- Beamstrahlung (BS): crossing bunches interact with force field created by the other bunch
- Dominant effect: increased energy spread
- **Does not shift peak energy**

Beam energy spectrum with and without beamstrahlung

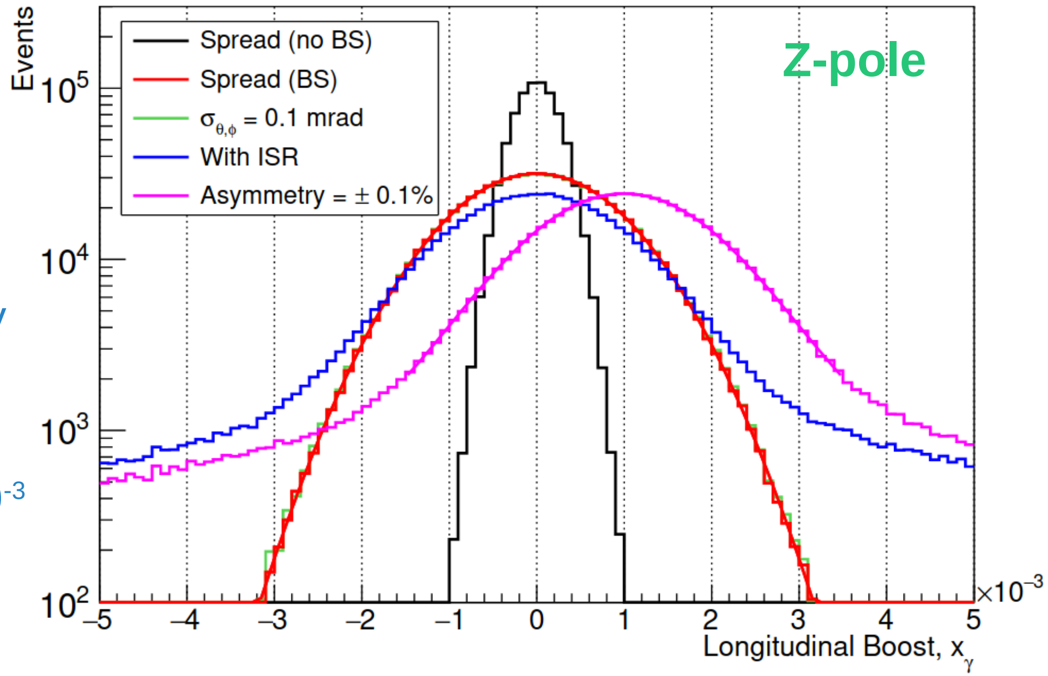


Black: no beamstrahlung
Red: + beamstrahlung
Green: + angular resolution
Blue: + photon emission
Pink: + asymmetry between electron and positron energy

Only asymmetric energies shift the center of the energy spectrum for dimuon events

Measuring 10^6 dimuon events yields precision of 10^{-3}
5 min measurements at FCC Z-mode gives boost precision of 50 keV and one 8 h shift will give 5 keV

Statistics of 1 million dimuon events at Z-pole
e+e- –> μ+μ- (γ)
(γ)… Initial-State-Photon (ISR)



A. Blondel et al., arXiv:2019.12245, 2019.

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

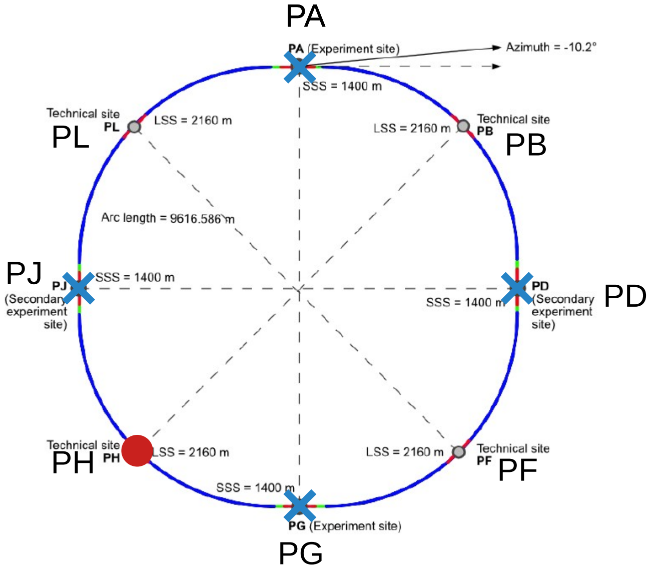
ECM and Boosts for Z-Mode

- **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

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



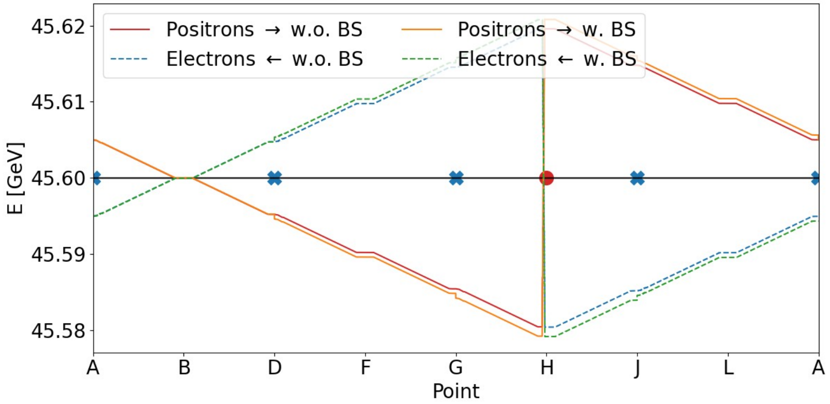
Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

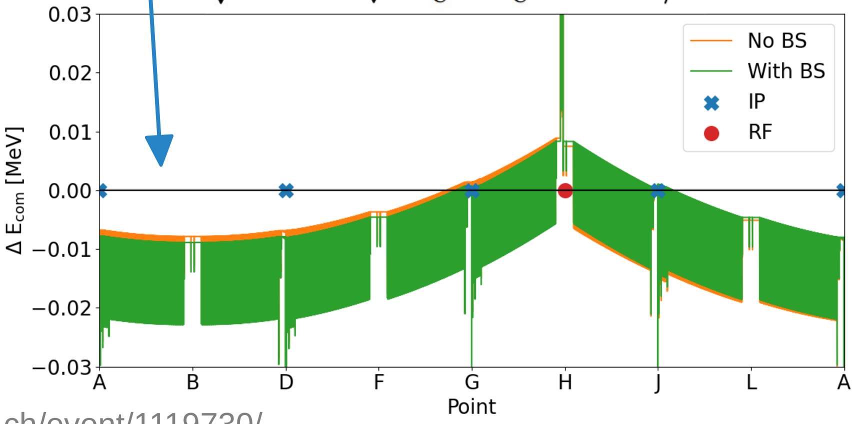
1 RF → almost constant ECM

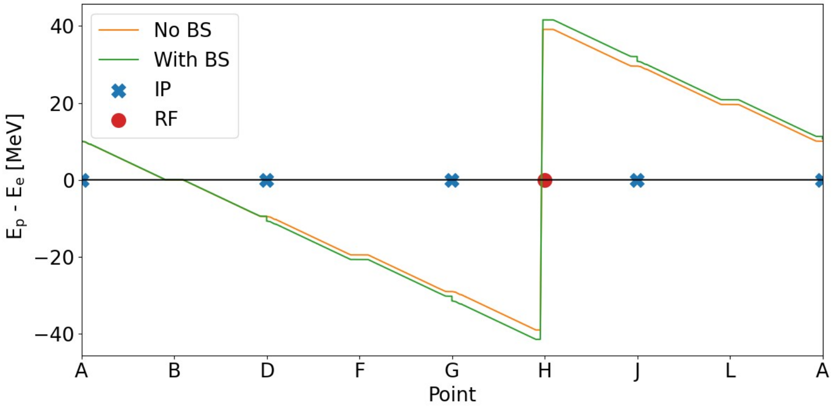
$$\Delta E \propto \gamma_{\text{rel}}^4$$

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

Boost: + for e+; - for e-







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

What are the goals for the EPOL team and this workshop?

Structure of the EPOL Team

A- Simulations of polarization and spin-tune to beam energy relationship
    -- simulations of spin polarization in realistic machine (also able to calculate emittances, luminosity)
    -- res. depolarization at Z and WW threshold
    -- design and integration of wigglers, RF kickers, in FCC-ee
B. Simulation of the relationship between beam energies and centre-of-mass energy
    -- studies of operation scenarios
    -- control of offsets and vertical dispersion
    -- Impact and control of energy losses: Synchrotron rad., Beamstrahlung, impedance, etc.
C. Polarimeter design and performance
    -- now working to build a global collaboration
    -- Aim to provide integration of polarimeters,
    -- conceptual design and cost estimate of polarimeter for FCC FS
D. Measurements in Particle Physics Experiments
    -- use of dimuons and other processes to determine centre-of-mass energy spread, boost, at and within IP
E. Monochromatization
    -- new ideas for monochromatization in other dimensions than horizontal (x) axis. (time, z)
        -- what its the limit?

Detailed descriptions from October 2021 recalled, including additions and corrections resulting from work that has already been done

Full lists to be completed by participants during this workshop and aimed to be summarized in one document

A. Blondel

WG1: Simulations of spin-tune to beam energy relationship

-A1a- Benchmarking of BMAD with SITROS

-A1b- Implementation of FCC-ee optics in existing code (BMAD) to evaluate, both at first order (“SLIM” or improved version with thick lenses) and with multi-turn spin tracking, the relationship between nominal energy, ECM, the polarization level, and of the (calculated) spin tune of the two beams (also the beam energies at the position of the LBIP of the respective polarimeters, see below).

-A2- implementation of polarization calculations and procedures in the MADx simulation code for FCC-ee. Benchmark against the BMAD implementation.

-A3- Simulation of the resonant depolarization process in view of establishing the depolarizer parameters, the depolarization procedures. Study the possible deviations from the relationship between the calculated spin tune and measured resonant depolarization frequency. This relationship might be affected by interference with various single particle and collective oscillations. Establish the accuracy reachable for the resonant depolarization at the Z pole (ECM=88-95 GeV), WW threshold (ECM=158-164 GeV) and single-Higgs energies (ECM= m_{Higgs}).

-A4- Effect of imperfections: simulate, one at the time, the various imperfections affecting the accelerator -- polarization is particularly sensitive to effects generating vertical dispersion, x-y betatron coupling and any spurious spin rotation -- and any residual effect on the above relationships; beam energy itself is particularly sensitive to the main magnetic field and ground motion. Systematic study of absolute and point-to-point ECM errors.

-A5- Spin and energy correction knobs and procedures establish the list and suggest an ordering of required correction procedures, acting on each beam individually (individual energy tuning, spin matching, vertical dispersion) or for both beams (main dipole, RF shift).

A. Blondel

WG1: Possible new additions

-A6- Study sensitivity of RDP upon polarization level and polarimeter statistical precision

- -- possibility to save on ‘wiggler on’ time at beginning of fills?

-A7- Study sensitivity of spin precession measurement to the effects that might affect the RDP measaurement

- -- requirement on polarimeter statistical precision
- -- impact of 3D measurement on precision and ambiguities
- -- suggestion were made
  - -- (ref LEP) to perform RDP in small steps
  - -- (from BINP group) perform RDP sweep in both directions: increasing and decreasing frequency.

-A8- Possibility to identify/measure energy biasing effects from their spin tune or orbit correction dependence

- -- arrange running mode accordingly? (the scan points do not need to be at the same energy all the time)
  i.e. e.g. alternate 103.45 and 103.55
- -- create artificial resonances and calculate/measure the possible shift?

-A9- Compare beam energies obtained from RDP to spin precession energies and to other direct measurements of energy from

- -- polarimeter-spectrometer
  - -- E_{cm} measurement in the detectors
  - -- undulator measurement (P. Raimondi)

WG2: Simulation of the relationship between beam energies and centre-of-mass energy

A. Blondel

-B1- Collision effects on centre-of-mass energy: opposite sign horizontal and vertical dispersion combined with collision offsets, leads to a shift in centre- of-mass energy. Possible remedies are as follows
-- detection of the offset by detection of induced vertical or horizontal excitation
-- detection and measurement of the offset and its sign by use of low angle radiative Bhabha scattering or beamstrahlung
-- measurement of the horizontal or vertical dispersion
-- detection and measurement by experiment of position dependence of average ECM or CM boost upon one of the axes at the interaction point.
NB contrary to the deviations in the spin-tune to energy relation, the relation between collision offsets and dispersion and the resulting energy shifts does not have a hidden ECM dependence other than the randomness of imperfections.

-B2- Design and performance of the low angle/beamstrahlung monitors
These are low angle calorimeters in a region where a considerable amount of soft radiation will be present from the collision point. This is also related to the MDI work.

-B3- Monitoring of opposite sign dispersion and possible offsets in the PP detectors
This was done using large angle muons in the EPOL paper [2], for the primary sake of measuring the ECM spread. Work should be extended to the detection of the effects listed in B1 above, and of the monochromatization (see point E below)

-B4- Beam energy losses around the ring
One of the sources of uncertainties on ECM is the proper calculation of the energy loss of the beams around the ring (saw-tooth). This can be calculated from the orbit but can also be monitored from
-- the energy difference between e+ and e- particles resulting in a well-measured CM boost in the experiments.
-- the measurement of the beam energy in the polarimeter/spectrometers
-- and other means of control such as beam positions in dispersion regions etc.

WG2: Possible new additions

-B5- Collision effects on centre-of-mass energy: opposite sign horizontal and vertical dispersion combined with collision offsets, leads to a shift in centre- of-mass energy. Possible remedies are as follows
-- detection of the offset by detection of induced vertical or horizontal kicks (beam-beam deflection)
-- measurement of the horizontal or vertical dispersion **by beam-beam deflection vs RF shifts**
-- detection and measurement by experiment of position dependence of average ECM or CM boost upon one of the axes at the interaction point.
NB contrary to the deviations in the spin-tune to energy relation, the relation between collision offsets and dispersion and the resulting energy shifts does not have a hidden ECM dependence other than the randomness of imperfections.

-B6- Design and performance of the low angle/beamstrahlung monitors
Probably not the main monitoring method, but there is a lot of information there.

A. Blondel

WG3: Polarimeter design and performance

The two compton backscattering polarimeter/spectrometer devices are little experiments of their own. They study the recoil photon e+(or e-) as well as the backscattered photon. In principle this device can be used to extract all three components of the polarization vector at the location of the interaction point of the laser with the beam (LBIP). The polarization transverse to the accelerator plane can be obtained both from the photons and the charge lepton. The end-point of the recoil lepton provides a measurement of the beam momentum at the LBIP, which can be used as a precious relative monitor of the beam energy with potentially different point-to-point systematics than the RDP measurement.

-C1- Bibliography
retrieve documentation on historical examples of backscattered laser compton polarimeters:
LEP, Hera, SLC, ILC etc. Review existing work ongoing on EIC and FCC-ee.

-C2-Possible collaboration
review possible groups involved in polarimeter activities globally, establish contact and organize possibly kick-off meeting.

-C3- Overall specifications
We assume that the design will be based on N. Muchnoi design as in arXiv:1803.09595v1 arXiv:1909.12245v1
-- define possible beam-laser interaction points specifying requirement on available space for laser injection, laser collision point, detection of scattered photon and electron.
-- given the foreseen use, define electron bunch populations, beam sizes, specify desirable photon spot size and intensity. (uses are: depolarization of pilot bunches, measurement of polarization of colliding bunches, beam energy measurement)
-- Compare to past and existing designs
-- Specify parameters of the laser (wavelength, repetition rate, intensity, instantaneous and average power, precision of laser polarization)
-- specify size and rates, resolution and accuracy for the detectors of scattered photons and electrons

A. Blondel

WG3: Polarimeter design and performance (Ctd.)

-C4- Insertion in the storage ring
define location and study synchrotron radiation exposure; design laser ports and mirrors, beam exit ports; consider transverse mode coupling to circulating beams and sources of heating; propose detailed design.

-C5- Laser light box: compile desired polarization states for the laser, design laser light box accordingly, controls and monitoring in synchronization with accelerator bunches

-C6- Detector
1. Photon counter design photon counter for detection of transverse movement of backscattered photon beam, foresee electronics able to deal with pilot bunches and colliding bunches. Arrange movable SR shielding and data acquisition
2. Spectrometer and electron counter
Specify the spectrometer magnet, measurement and control of relevant magnetic field
Design electron detector – preferably as one single mechanical unit with photon detector. Specify precision or measurement of construction accuracy and stability.
Design electronics as above, data acquisition and the possible need for online processing

-C7- Overall data acquisition and operator interface
describe possible operation mode, operator interface for input and output of results. Possibly connect with other polarization-related operation systems (spin correctors, injection etc.)

WG4: Measurements in Particle Physics Experiments

A. Blondel

-D1- muon pairs will provide measurements of the distribution of i) ECM boost, ii) ECM value; possibly as a function of the coordinates (x, z, t – it is assumed that vertical coordinate cannot be distinguished) of interactions. It was already shown in [2] that one can extract the ECM energy spread, the average $<E_{e+} - E_{e-}>$, the collision angle and possibly monitor the relative ECM between the scan points of the Z resonance or WW threshold, or[3] on the Higgs resonance. The following remains to be determined
-- possibility to evaluated the opposite sign dispersion and ECM spread in the horizontal plane (x- dependence of longitudinal boost distribution)
-- possibility to evaluate opposite sign dispersion in the longitudinal plane (z and t dependence of longitudinal boost distribution)

-D2- Independent ECM determination and point-to-point uncertainty
The muon pairs and possibly the Bhabha scattering events might be able to provide a measurement of ECM. Evaluate the precision that can be achieved for the ECM relative and absolute measurements. This point requires
-- understanding of the QED corrections to ECM and their ECM dependence.
-- understanding of the stability of the momentum and energy determinations.
-- detector magnetic field stability and small corrections related to the change in magnetic fields of the accelerator components when changing the ECM setting.
-- possible calibration of detector magnetic system using fixed candles such as J/□, K_s decays etc.

-D3- Application to the monochromatization scheme
Investigate the possibility to use the above studies for
-- a demonstration of the monochromatization scheme at the Z pole energy taking advantage of the high statistics of dimuons, and evaluation of the performance and monitoring precision.
-- monitoring of the monochromatization if running at the H(125) energy.

-D4- Tracking of the overall ECM calibration results
The participation of experimenters in the EPOL group is essential to understand the nature of the sources of ECM uncertainty and variability, and monitor progress by evaluating their impact on the uncertainties on the precision measurement.

WG4: Possible new additions

-D5- Precision required on measurement of polarization of the colliding beams for cross-section and asymmetry measurements

-- on Z scan
-- at WW energies

-D6- timing precision in view of measurements of boost and energy spread within the beam collision parameter space

A. Blondel

WG5 : Monochromatization

at this point the work package job description does not exist

-- suggest that some discussion time be devoted to draft one and discuss it.

FUTURE
CIRCULAR
COLLIDER

A lot of fun ahead of us!

Energy calibration and polarization
indico.cern.ch/category/8678

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R. Tomàs, D. Sagan, D. Shatilov, J. Wenninger*, G. Wilkinson, Y. Wu, and F. Zimmermann**

2d FCC Polarization Workshop (EPOL) 2022
Joint EIC-FCC Working Meeting on e+/e- Polarization
19th September 2022

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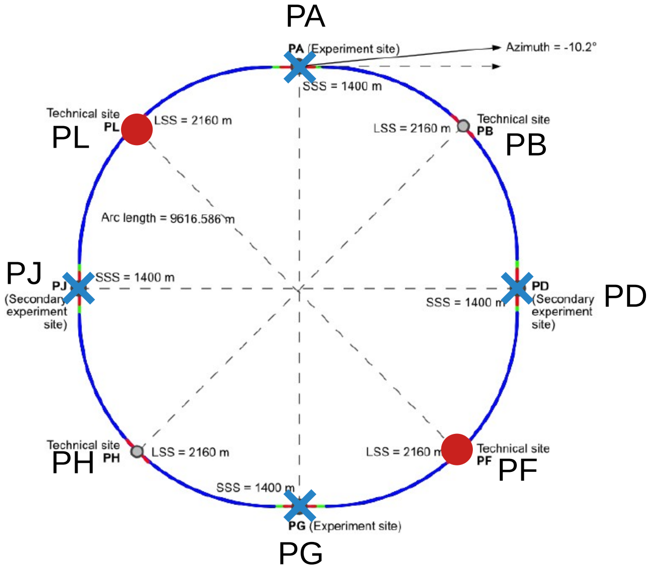
ECM and Boosts for ttbar-Mode

- PH: 5 GV, 400 MHz cavity and PL: 6.7 GV 800 MHz cavity
- 14 MeV beamstrahlung losses per beam and IP (simulations)
- 10 GeV radiation losses per revolution

Different ECM and boosts at the IPs result from, radiation losses and BS

BS small impact on boosts

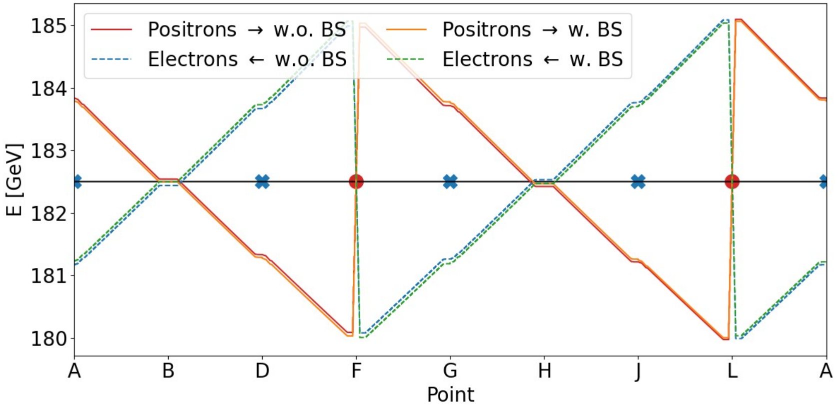
IP	ΔECM [MeV]	Boost [GeV]
PA	12.663	2.574
PD	11.043	- 2.455
PG	- 46.531	2.573
PJ	- 48.155	- 2.454

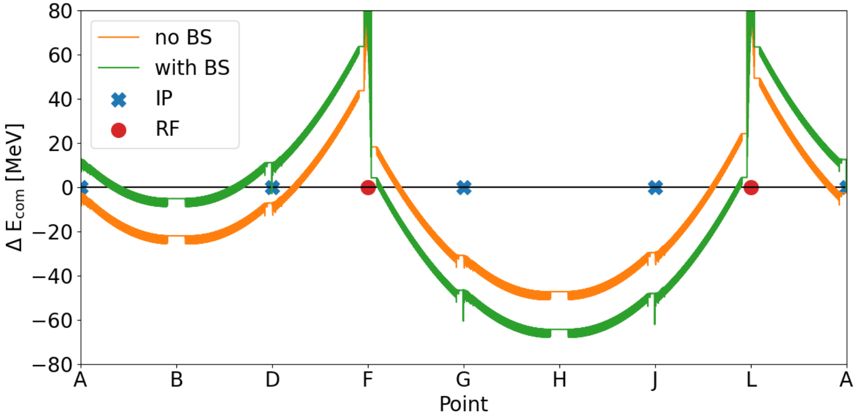


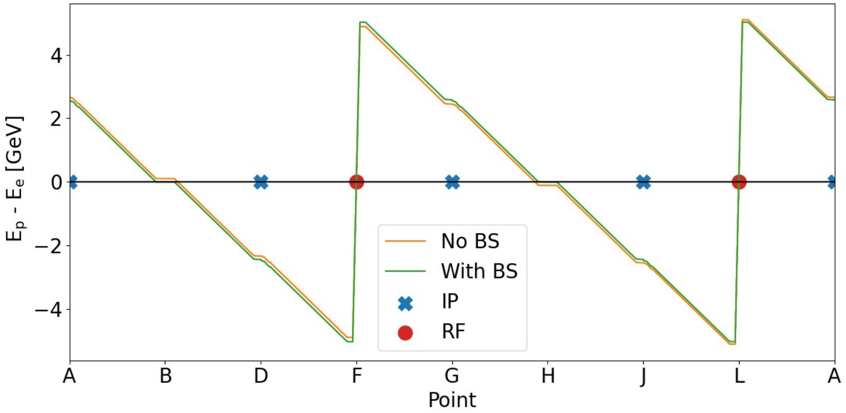
Boost: + for e+; - for e-

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

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







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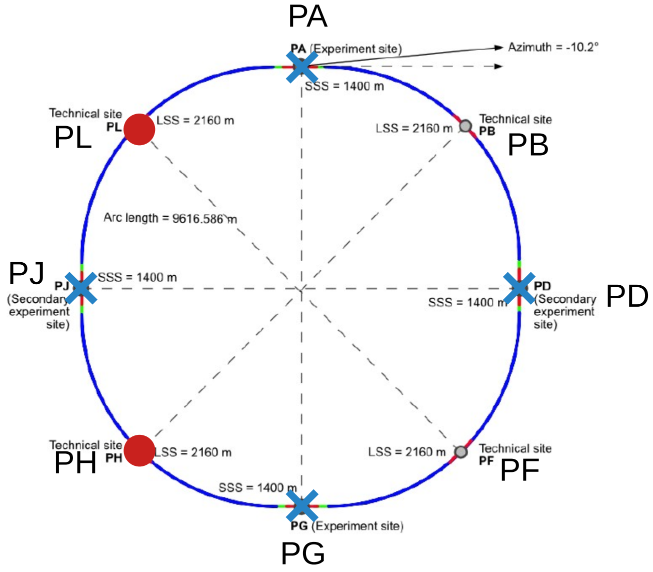
ECM and Boosts for ttbar-Mode

- **PH: 5 GV, 400 MHz** cavity and **PL: 6.7 GV, 800 MHz** cavity
- ≲ 14 MeV beamstrahlung losses per beam and IP (simulations)
- 10 GeV radiation losses per revolution

IP	ΔECM [MeV]	Boost [GeV]
PA	42.813	5.187
PD	- 30.176	0.157
PG	34.236	- 4.873
PJ	-152.467	- 0.233



Boost: + for e+; - for e-

Different ECM and boosts at the IPs result from asymmetric RF placement, radiation losses and BS

BS small impact on boosts

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

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