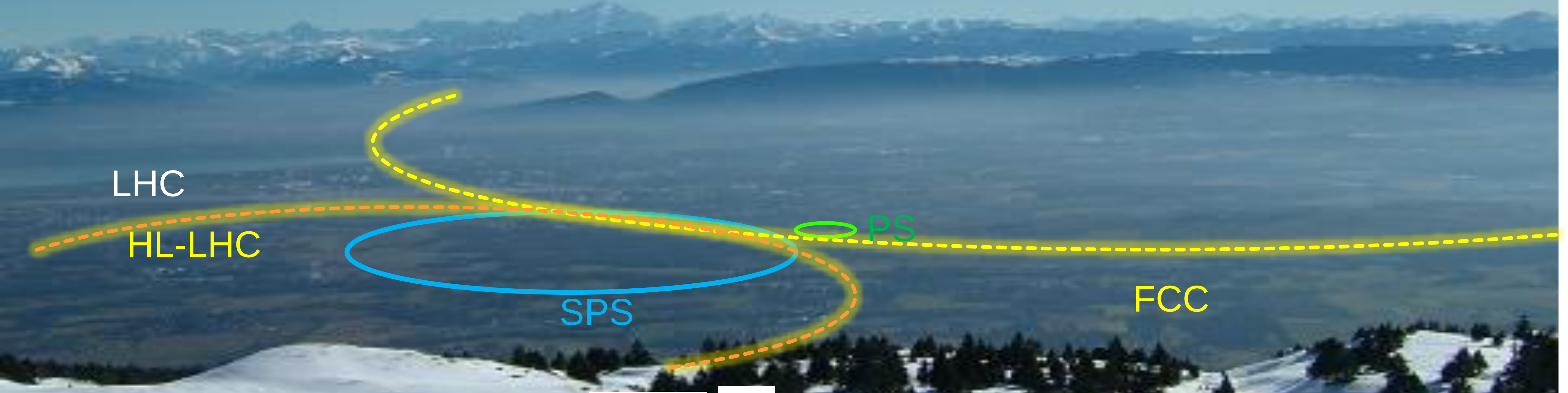
Future Circular Collider Feasibility Study

FCCee Centre-of-mass calibration and Polarization, Monochromatization (EPOL)



http://cern.ch/fcc

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photo: J. Wenninger

FCC Feasibility Study – coordination team and contact persons

EU Projects
NN

Collaboration building
Emmanuel Tsesmelis

Communications
Panagiotis Charitos, James Gillies

Study Support and Coordination
Study Leader: Michael Benedikt
Deputy Study Leader: Frank Zimmermann

Study Support Unit
IT: Sylvain Girod
Procurement: Adam Horridge
Quality control: NN
Resources: Sylvie Prodon
Scheduling, quality mangement: NN
Secretariat: Julie Hadre

Physics, Experiments and Detectors
Patrick Janot
Gavin Salam

- **Physics programme** – Matthew McCullough, Frank Simon
- **Detector concept** – Mogens Dam
- **Physics performance** – Patrizia Azzi, Emmanuel Perez
- **Software and computing** – Gerardo Ganis, Clément Helsens

Accelerators
Tor Raubenheimer
Frank Zimmermann

- **FCC-ee collider design** – Katsunobu Oide
- **FCC-hh design** – Massimo Giovannozzi
- **Technology R&D** – Roberto Losito
- **FCC-ee booster design** – Antoine Chancé
- **FCC-ee injector** – Paolo Craievich, Alexej Grudiev
- **FCC-ee energy calibration polarization** – Alain Blondel, Jorg Wenninger
- **FCC-ee MDI** – Manuela Boscolo, Mike Sullivan

Technical Infrastructures
Klaus Hanke

- **Integration** – Jean-Pierre Corso
- **Geodesy & survey** – Hélène Mainaud Durand
- **Electricity and energy management** – Jean-Paul Burnet
- **Cooling and ventilation** – Guillermo Peon
- **Cryogenics systems** – Laurent Delprat
- **Computing and controls infrastructure, communication and network** – Dirk Duellmann
- **Safety** – Thomas Otto
- **Operation, maintenance, availability, reliability** – Jesper Nielsen
- **Transport, installation concepts** – Cristiana Colloca

Host State processes and civil engineering
Timothy Watson

- **Administrative processes** – Friedemann Eder
- **Placement studies** – Johannes Gutleber, Volker Mertens
- **Environmental evaluation** – Johannes Gutleber
- **Tunnel, subsurface design** – John Osborne
- **Surface sites layout, access and building design**

Organisation and financing models
Paul Collier (interim)

- **Project organisation model**
- **Financing model** – Florian Sonnemann
- **Procurement strategy and rules**
- **In-kind contributions**
- **Operation model** – Paul Collier, Jorg Wenninger

Alain.Blondel@cern.ch , Jorg.Wenninger@cern.ch

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Beam Energy Calibration, Polarisation, Monochromatisation

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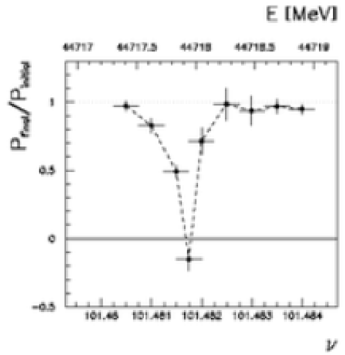


Meetings related to the Beam energy calibration, polarisation, and monochromatisation (EPOL) work package, joint with the FCC accelerator design study.

December 2021

09 Dec FCC-FS EPOL group meeting 3

November 2021

18 Nov FCC-FS EPOL group meeting 2

October 2021

07 Oct FCC-FS EPOL group meeting 1

June 2021

24 Jun Feasibility Study Work Package on Center-of-mass Energy, Polarization and Monochromatization

The work done in the FCC design study is summarized in the following paper:

Polarization and Centre-of-mass Energy Calibration at FCC-ee

The FCC-ee Energy and Polarization Working Group:
Alain Blondel,[1,2,3] Patrick Janot,[2] Jörg Wenninger[2] (Editors)
Ralf Aßmann,[4] Sandra Aumon,[2] Paolo Azzurri,[5] Desmond P. Barber,[4]
Michael Benedikt,[2] Anton V. Bogomyagkov,[6] Eliana Gianfelice-Wendt,[7]
Dima El Kerchen,[2] Ivan A. Koop,[6] Mike Koratzinos,[8] Evgeni Levitchev,[6]
Thibaut Lefevre,[2] Attilio Milanese,[2] Nickolai Muchnoi,[6] Sergey A. Nikitin,[6]
Katsunobu Oide,[2] Emmanuel Perez,[2] Robert Rossmanith,[4] David C. Sagan,[9]
Roberto Tenchini,[5] Tobias Tydecks,[2] Dmitry Shatilov,[6] Georgios Voutsinas,[2]
Guy Wilkinson,[10] Frank Zimmermann.[2]

arXiv:1909.12245
subm to PRAB

Some references (not a complete set!):

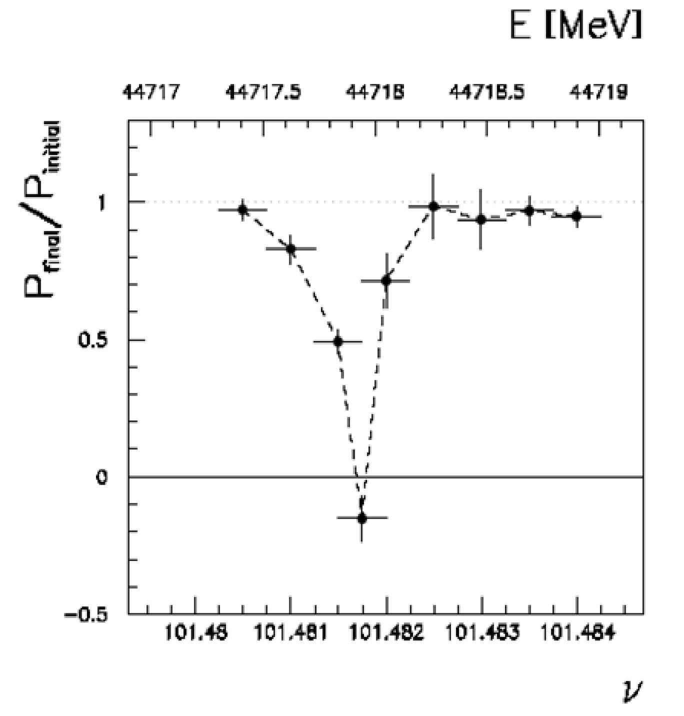
B. Montague, Phys.Rept. 113 (1984) 1-96;
Polarization at LEP, CERN Yellow Report *88-02;*
Beam Polarization in e+e-, AB, CERN-PPE-93-125 Adv.Ser.Direct.High Energy Phys. 14 (1995) 277-324;
L. Arnaudon et al., Accurate Determination of the LEP Beam Energy by resonant depolarization,
Z. Phys. C 66, 45-62 (1995).
Spin Dynamics in LEP http://dx.doi.org/10.1063/1.1384062
Precision EW Measts on the Z Phys.Rept.427:257-454,2006 arXiv:0509008v3
D.P. Barber and G. Ripken ``Handbook of Accelerator Physics and Engineering" World Scientific (2006), (2013)
D.P. Barber and G. Ripken, Radiative Polarization, Computer Algorithms and Spin Matching in Electron Storage Rings arXiv:physics/9907034

for FCC-ee:

First look at the physics case of TLEP arXiv:1308.6176, **JHEP 1401 (2014) 164** DOI: 10.1007/JHEP01(2014)164
M. Koratzinos FCC-ee: Energy calibration IPAC'15 arXiv:1506.00933
E. Gianfelice-Wendt: Investigation of beam self-polarization in the FCC-ee arXiv:1705.03003
October 2017 EPOL workshop: https://indico.cern.ch/event/669194/
AB, P. Janot, J. Wenninger et al Polarization & Centre-of-mass Energy Calibration @ FCC-ee **arXiv:1909.12245**
AB, E. Gianfelice-Wendt, The challenges of beam polarization and keV-scale center-of-mass energy calibration at the FCC-ee, *Eur. Phys. J. Plus* 136 (2021) 1103

See also slides (attached) summarizing the work done during the FCC Design Study and the resulting to-do list.

Beam Polarization can provide two main ingredients to Physics Measurements



LEP ±200keV
VEPP4M: ±6keV on J/psi mass

1. Transverse beam polarization provides beam energy calibration by resonant depolarization

$$\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$$

→ low level of polarization is required (~10% is sufficient)

→ at Z & W pair threshold comes naturally $\sigma_E \propto E^2/\sqrt{\rho}$

→ at Z use of asymmetric wigglers at beginning of fills since polarization time is otherwise very long (250h→ ~1h)

→ should be used also at ee → H(126)

→ use 'single' non-colliding bunches and calibrate continuously during physics fills to avoid issues encountered at LEP

→ Compton polarimeter for both e+ and e-

→ should calibrate at energies corresponding to half-integer spin tune

→ must be complemented by analysis of «average E_beam-to-E_CM» relationship

For beam energies higher than ~90 GeV can use ee → Z γ or ee → WW events to calibrate E_{CM} at ±1-5 MeV level: m_H (5 MeV) and m_{top} (20 MeV) measts

Beam Polarization can provide two main ingredients to Physics Measurements

2. Longitudinal beam polarization provides chiral e+e- system

-- High level of polarization is required (>40%)

-- Must compare with natural e+e- polarization due to chiral couplings of

or with final state polarization analysis for CC weak decays (... and top)

-- **Physics case** for Z peak is very well studied and m...

$A_{LR} = A_e$, $A_{FB}^{Pol}(f)$ etc… (CERN ...

figure of merit is $L.P^2$ --> mu... a factor ~10 in lumi.

self calibrating polari... requires controlled e+ and e- polarization

at high stat... the role of A_{LR} (Tenchini)

-- ... ection (by up to ~30%)

... ark couplings? final state analysis does as well (Janot **arXiv:1503.01325)**

enhance signal, subtract/monitor backgrounds, for ee→WW , ee →H

-- requires High polarization level and often both e- and e+ polarization

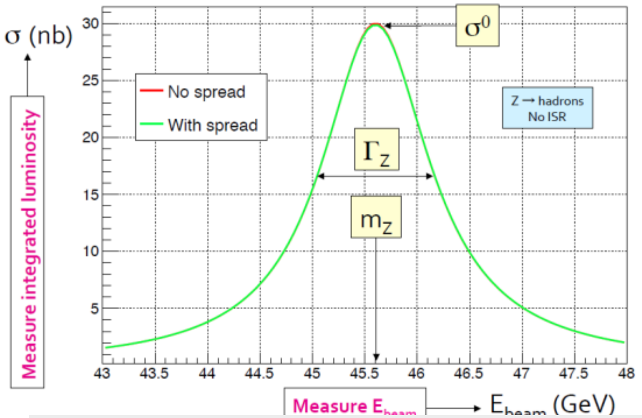
➔ **not interesting If loss of luminosity is too high**

-- Obtaining high level of polarization in high luminosity collisions is delicate in top-up mode

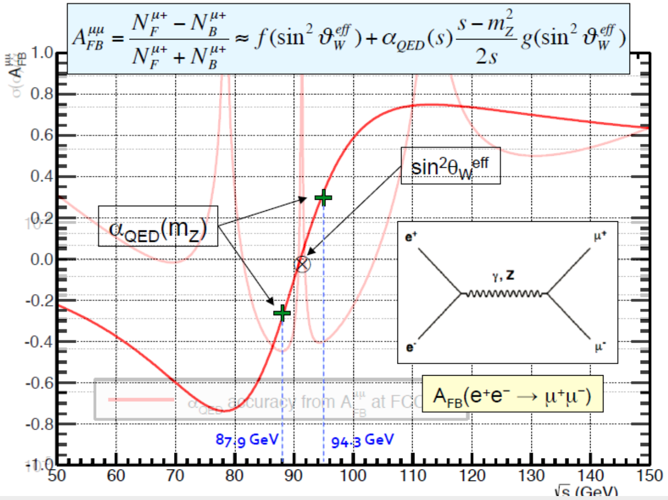
DECIDED to FOCUS ON TRANSERSE POLARIZATION FOR ENERGY CALIBRATION

As far as we could check, there is no physics that can be done with longitudinal polarization that cannot be done without, given enough luminosity. ➔ lower priority, but if someone interested?

Physics: scan points and output quantities



Z line shape → m_Z and Γ_Z



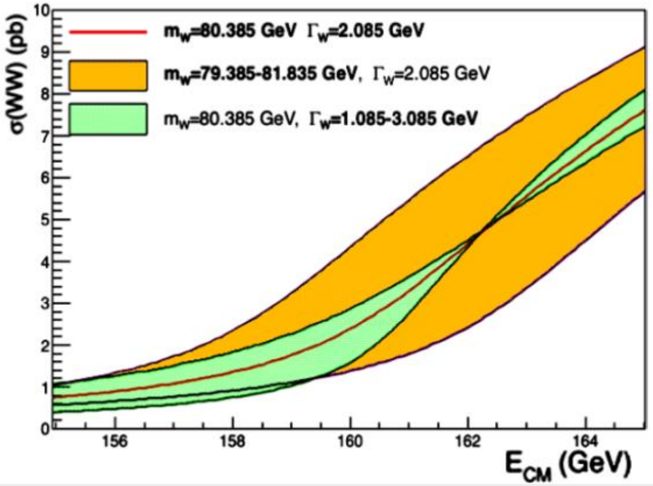
at the same time $A_{FB}^{\mu\mu}(\sqrt{s})$ → $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$

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

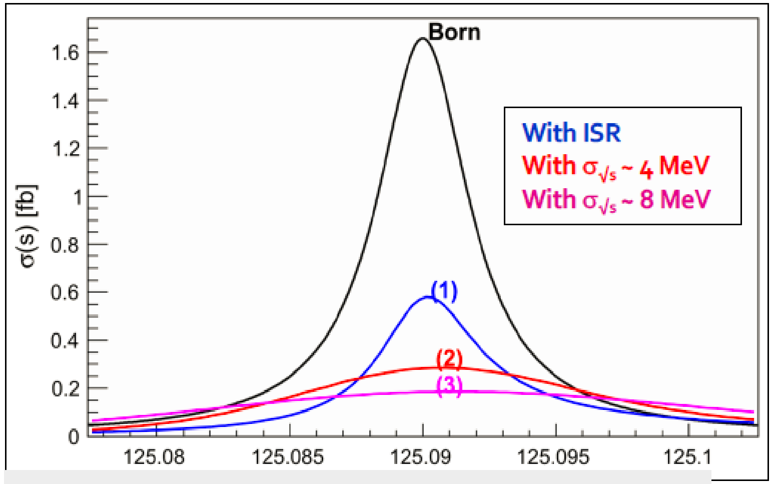
for the Higgs, bad luck!
ν = m_H (125.1)/2/.4406486 (1) = 141.95
--too close to integer for polarization–
→ 141.45 for e+ and 142.45 for e-

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} and σ_{ECM}

Systematic error evaluation out of the Design Study

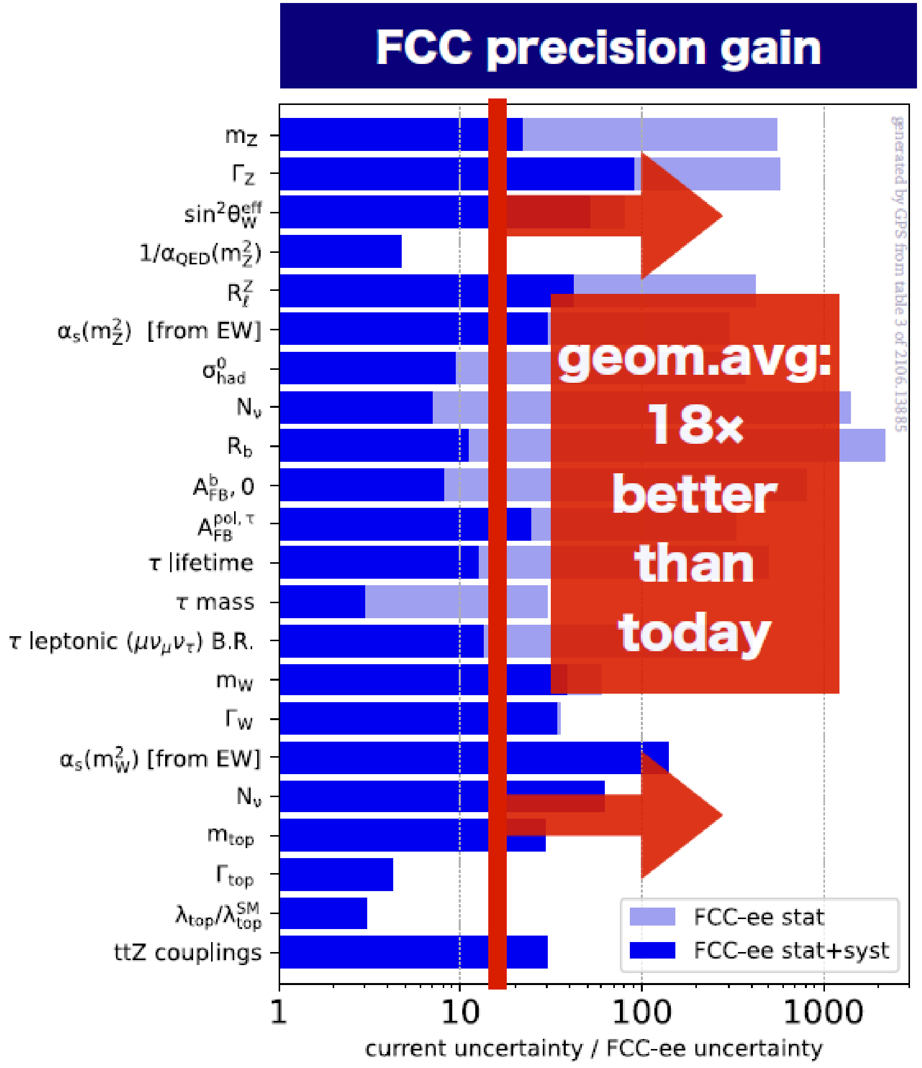
Table 15: Calculated uncertainties on the quantities most affected by the center-of-mass energy uncertainties, under the final systematic assumptions.

Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	7	2.5	**22**	1	**10**
$sin^2\theta_W^{eff} \times 10^6$ 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**

Point-to-point uncertainty dominates the physics output.

More optimistically O(10 keV) was estimated by M. Koratzinos

Statistical errors might reduce with 4IP.



current uncertainty / FCC-ee uncertainty

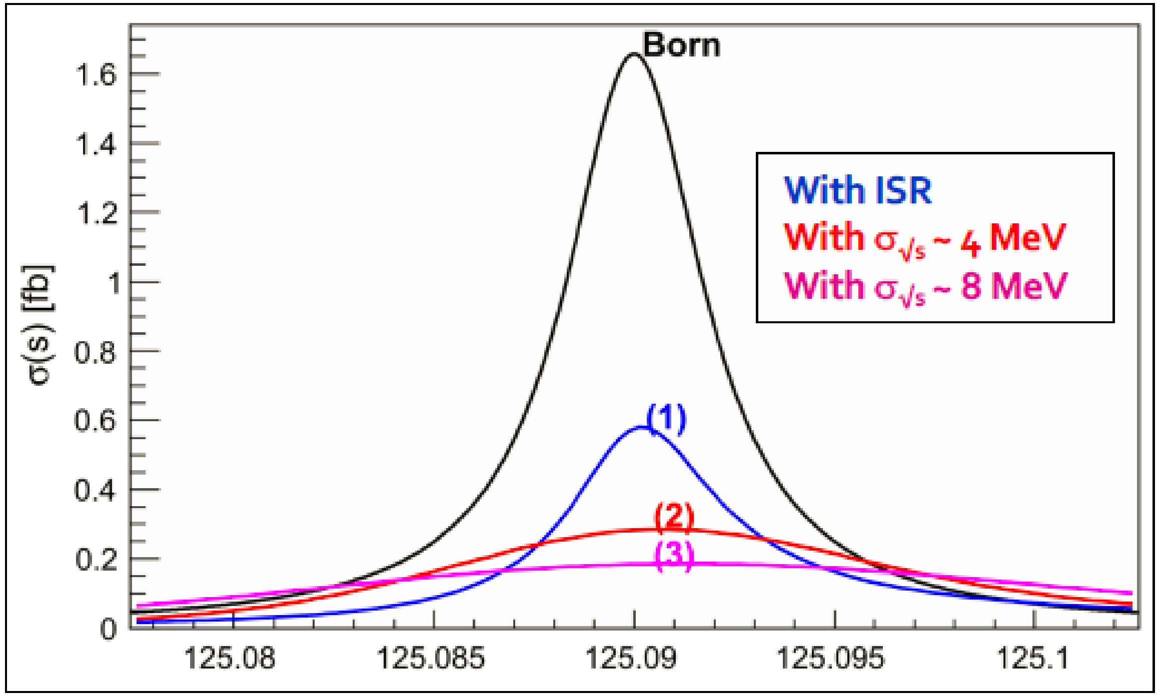
Two messages

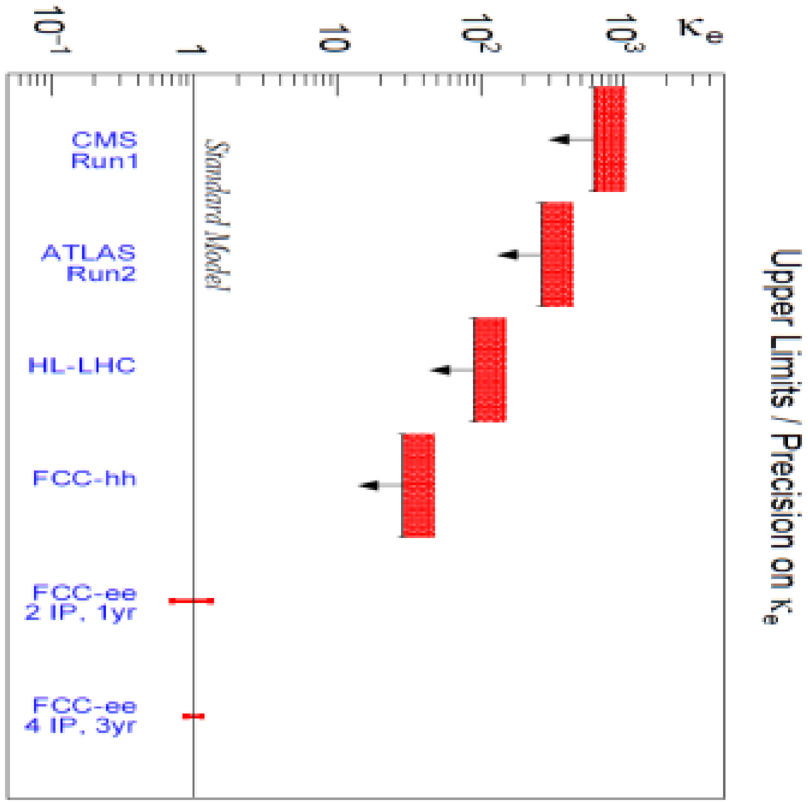
- with a rough estimate for systematics, FCC brings a big step forward (geom.avg. $= \times$ 18, across $\gtrsim$ 20 observables)
- still huge scope for thinking about how to improve systematics (gain of up to further $\times$ 100 in some cases)

This is the fun part for us as physicists!

The studies should be done now as they will impact accelerator and detector design

Something unique!





HUGE CHALLENGE

e+e- → H @ 125.xxx GeV requires

-- Higgs mass to be known to ~2 MeV from 240 GeV run

-- **Huge luminosity**

-- **monochromatization** (opposite sign dispersion using magnetic lattice) to reduce σ_{ECM}

-- **continuous monitoring and adjustment of E_{CM}** to MeV precision (transv. Polar.)

-- an extremely sensitive event selection against backgrounds

FCC

NEW

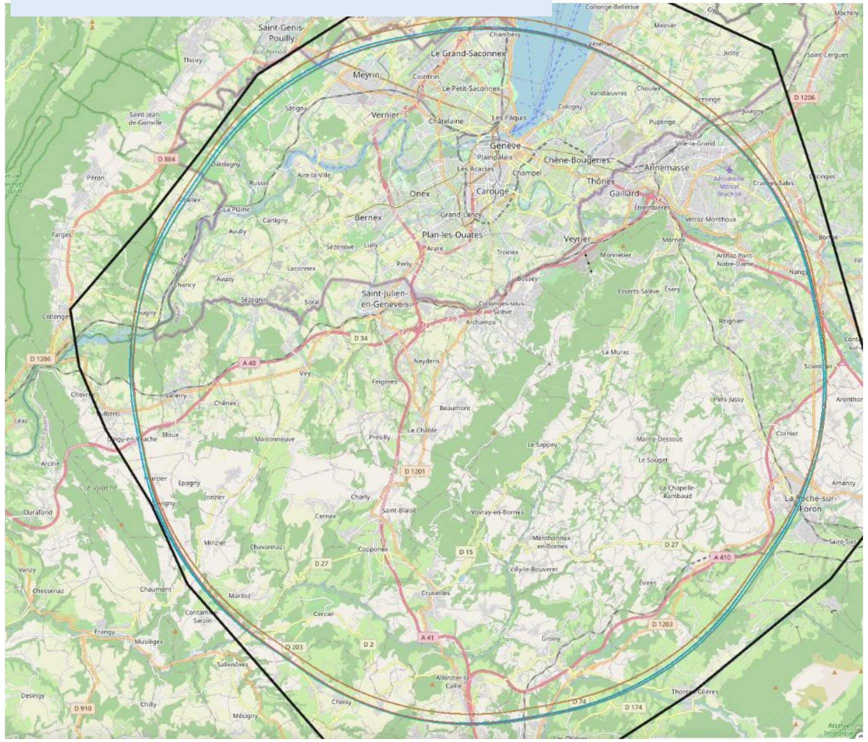
The requirements for the Higgs s-channel experiment (ee→ H) have been developed in the recent paper (AB, EG). They are very similar to those for the Z and W threshold scans but have some notable differences:

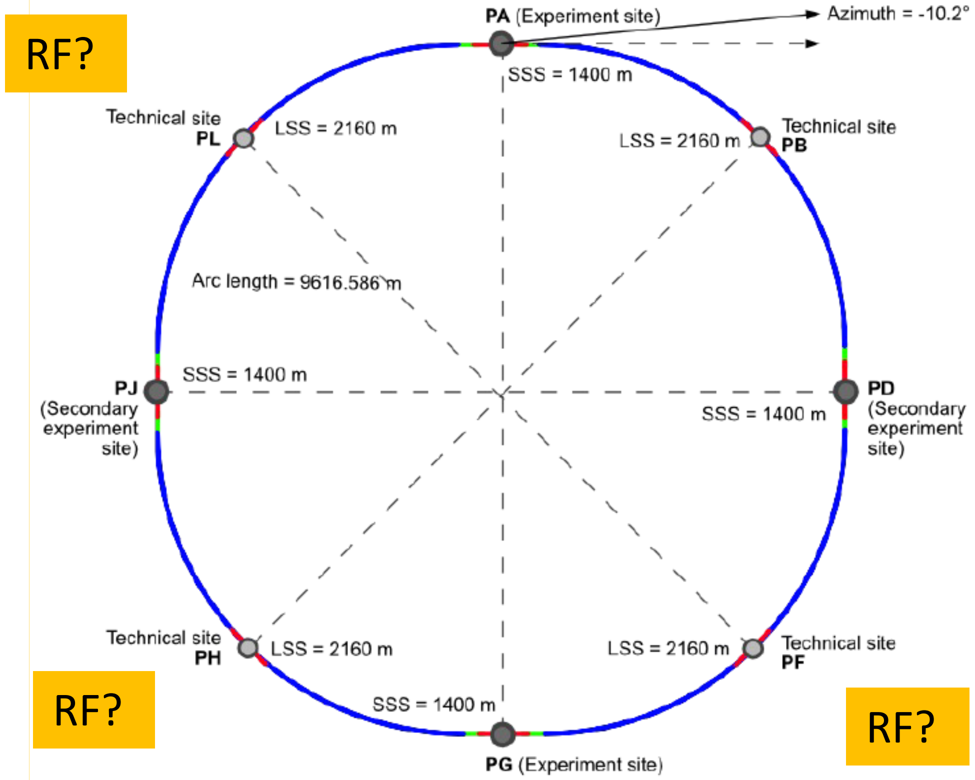
1. the centre-of-mass energy (ECM) has to be set at the Higgs mass within the Higgs width
   Γ_H = 4.2 MeV but this is the full width ⇔ this corresponds to an r.m.s. of Γ_H**/2.3** = ±1.8 MeV)
2. however we do not need to measure the luminosity averaged ECM to a precision that is much better than that
   say ±0.5 MeV (TBD)

experiment:	setting precision	ECM measurement requirement
Z and W run	± 50 MeV	**a few keV (Z), a few 10 keV (WW)**
ee→ H	**±1.8 MeV**	±0.5 MeV

can be done, requires the Z machine, but after the ZH run → RF placement !

New FCC Layout





-- Study has converged on **1 baseline layout** (and 2 fallback solutions)

-- 8 pits (was 12) total circumference of 91.173km (was 97km in CDR)→ cost savings. Luminosity smaller by ~10%

-- Consistent with ee (2 or 4IP), hh; flexibility. Optimization of 4IP parameters under study for realistic machines.

-- Placement of RF stations has made considerable progress (point B unpractical, L,H preferred, F possible)

-- 1 RF point for Z, WW, HZ, (eeH) acceleration of e+ and e- in separate RF cavities (low gradient, high current) eliminate uncertainties on E_{cm} due to beam energy losses (synchtron radiation, beamstrahlung)

-- 2 RF points (HZ), tt (E_{cm} = 340-365) e+ and e- acceleration in the same RF cavities (low current, high gradient)

➔ centre of mass boosts!

From beam energy to E_{CM}

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

Energy gain (RF) = losses in the storage ring
Synchrotron radiation (SR)
beamstrahlung (BS)

$\Delta_{RF} = 2\Delta_{SRi} + 2\Delta_{SRe} + 2\Delta_{BS}$

at the Z (O of mag.):

$\Delta_{SR} = 2\Delta_{SRi} + 2\Delta_{SRe}$ =39 MeV

$\Delta_{SRe} - \Delta_{SRi} \approx \alpha/2\pi\ \Delta_{SR}$ = 0.20 MeV

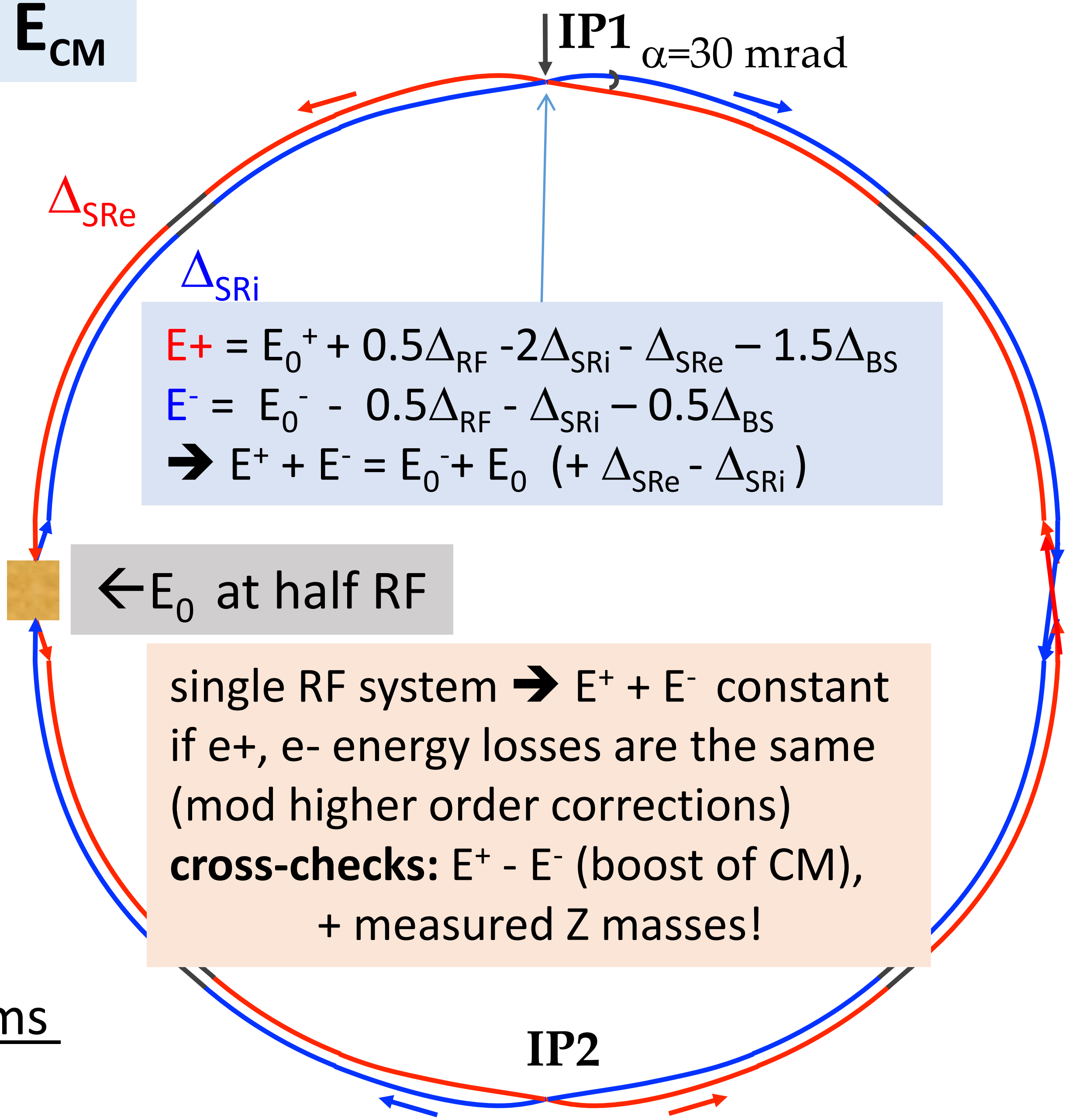
Δ_{BS} = 0 up to 0.62 MeV

the average energies E_0 around the ring are determined by the magnetic fields

➔ same for colliding or non-colliding beams

-- measured by resonant depolarization

-- can be different for e^+ and e^-



$E+ = E_0^+ + 0.5\Delta_{RF} - 2\Delta_{SRi} - \Delta_{SRe} - 1.5\Delta_{BS}$

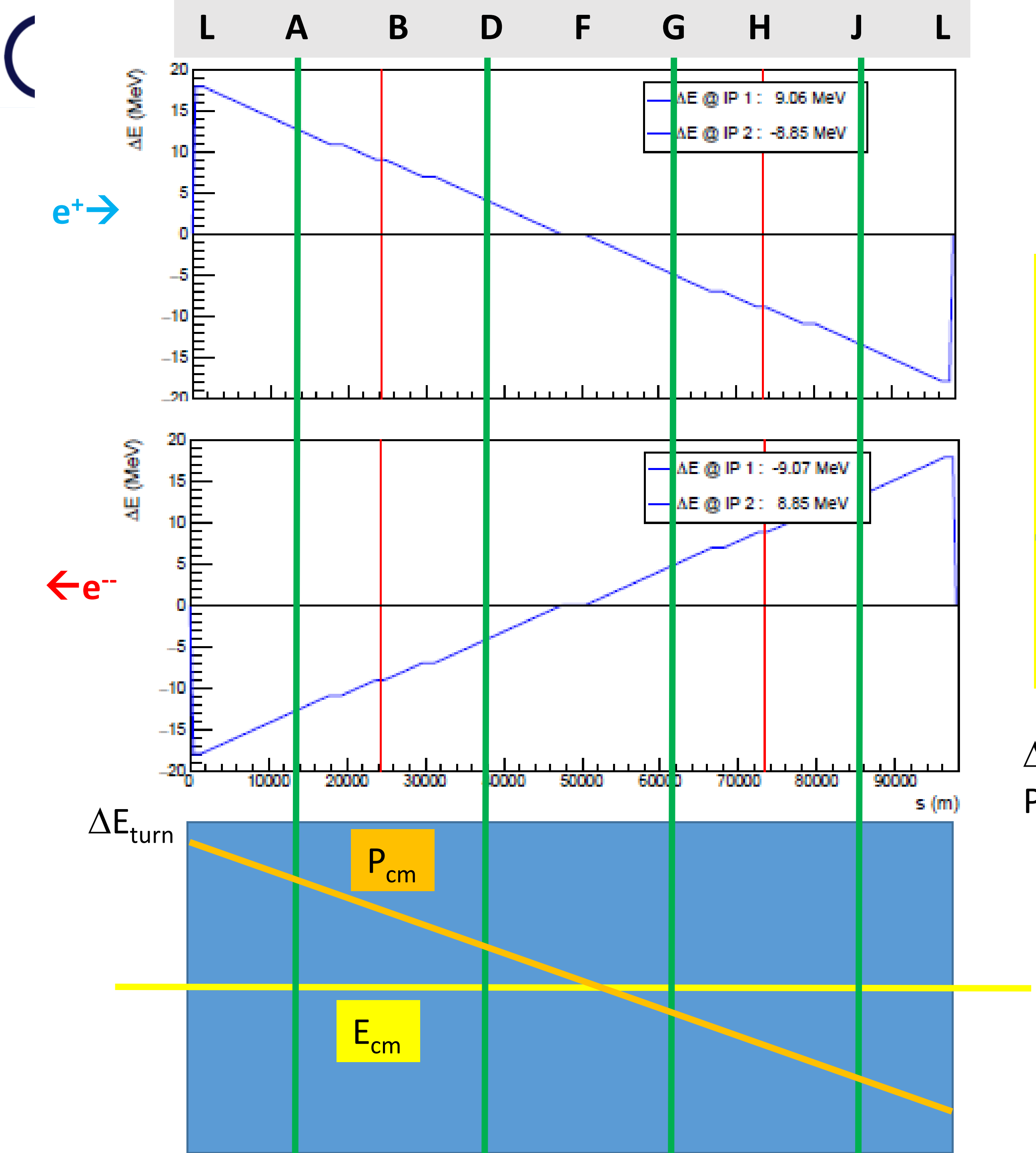
$E^- = E_0^- - 0.5\Delta_{RF} - \Delta_{SRi} - 0.5\Delta_{BS}$

➔ $E^+ + E^- = E_0^- + E_0 \; (+\Delta_{SRe} - \Delta_{SRi})$

← E_0 at half RF

single RF system ➔ $E^+ + E^-$ constant if e+, e- energy losses are the same (mod higher order corrections)

cross-checks: $E^+ - E^-$ (boost of CM), + measured Z masses!



1 single RF point for e- and e+)
good for Z, eeH, WW and even ZH if wanted

Approximate energy loss per turn (91.3km machine)

E_{cm}	E_{beam}	ΔE_{turn} (GeV)	maximal boost P_{cm}
91	45	0.039	0.030
125	62.5	0.140	0.105
160	80	0.374	0.280
240	120	1.89	1.420
350	175	7.98	
365	182.5	10.0	

UPGRADE

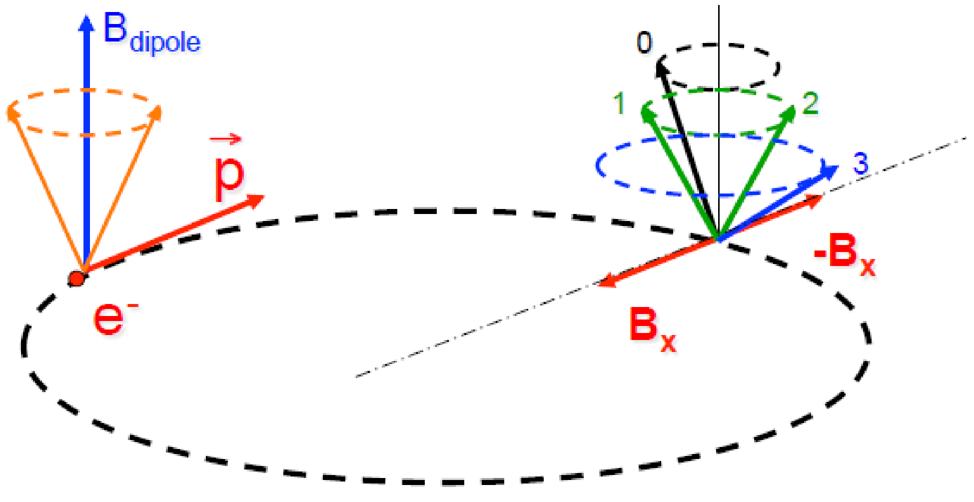
scaling law: E^4/ρ : increase of 6% with new 91.3km layout

$\Delta E_{cm} = \Delta E_{e+} + \Delta E_{e--} = \{0,0,0,0\}$

$P_{cm} = \Delta E_{e+} -- \Delta E_{e--} = \{ ¾\, \Delta E_{turn} , ¼\, \Delta E_{turn} , -¼\, \Delta E_{turn} , ¾\, \Delta E_{turn} \}$

with a single RF location and two or four experiments
all IP have the same energy (within small corrections)
different c.m. boost OK
Boosts will be very well measured at all energies with μ+μ- events and serve as a measure of the beam energy loss!

RESONANT DEPOLARIZATION



Once the beams are polarized,
an RF kicker at the spin precession frequencv
will provoke a spin flip and complete
depolarization
Simulation of FCC-ee by I. Kopp:

spin precession (ν is the *spin tune*)

$\delta\theta_{spin} = (g-2)/2 \;.\; E/m \; \delta\theta_{trajectory}$

$= \nu \;.\; \delta\theta_{trajectory}$

$\nu = E_{beam} / 0.4406486$

$= 103.5$ at the Z peak

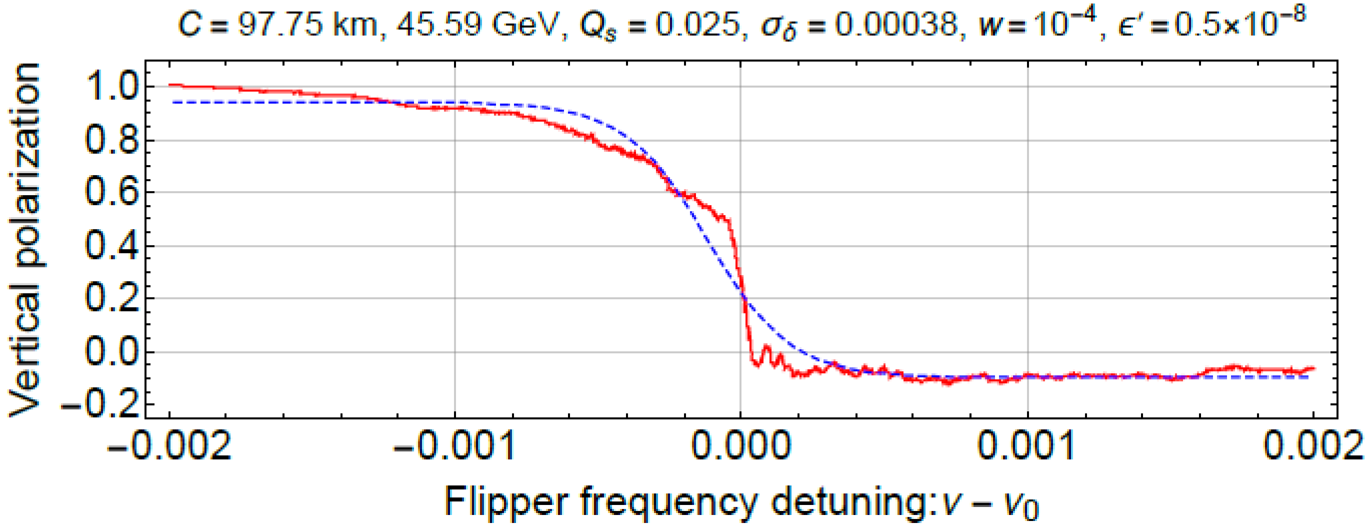
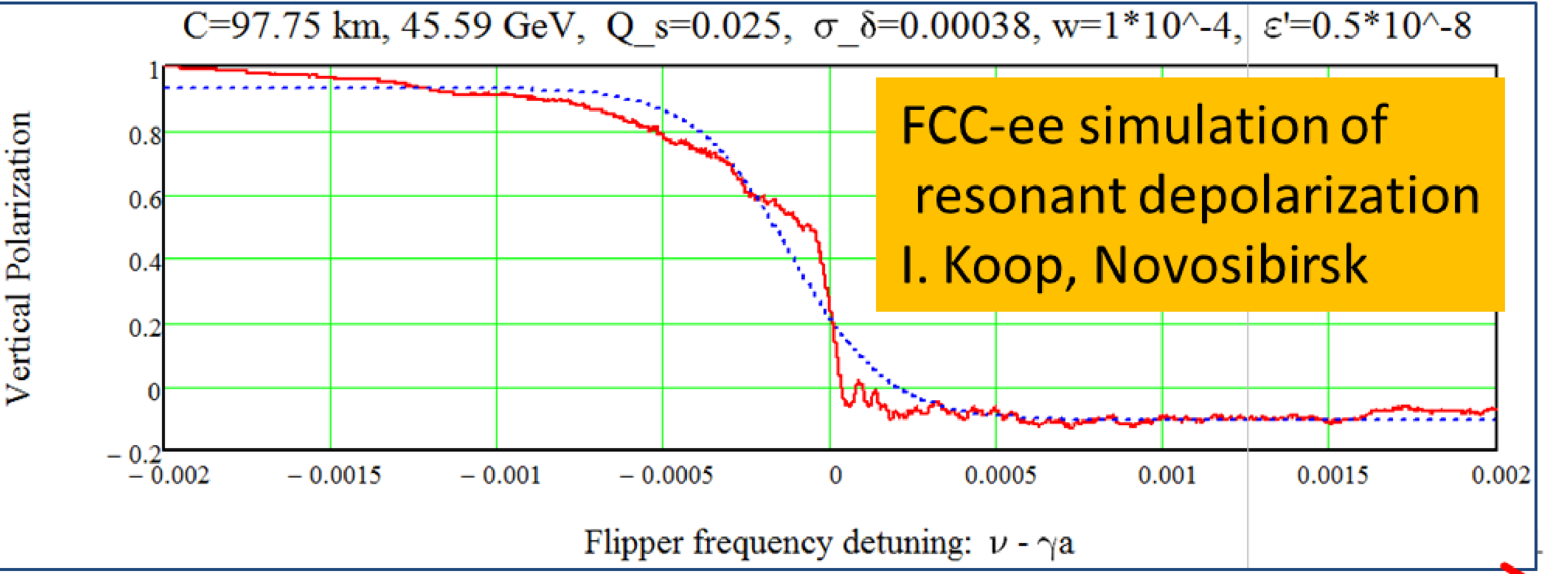
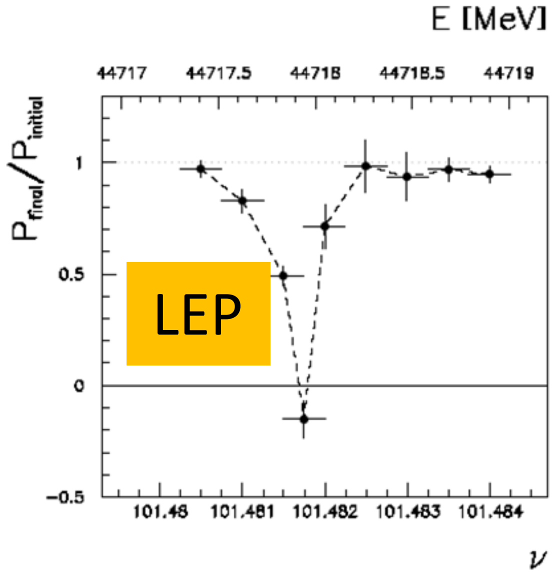


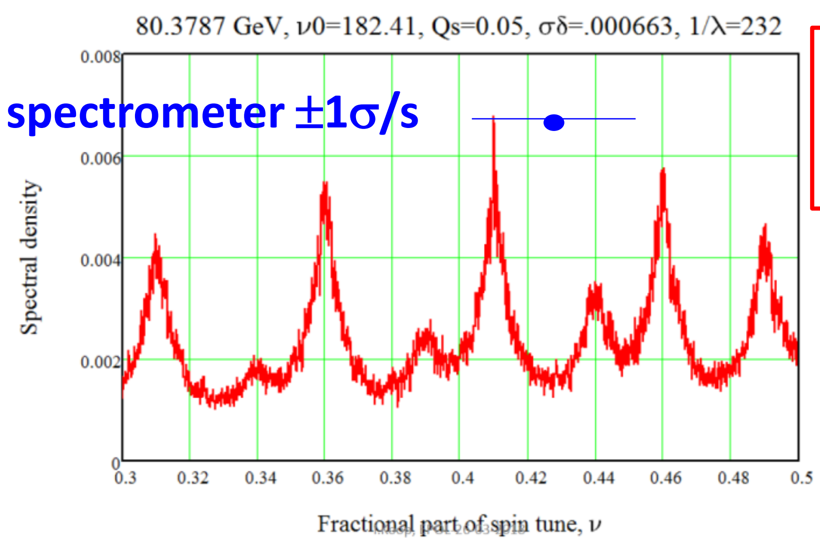
Figure 39. Simulation of a frequency sweep with the depolarizer on the Z pole showing a very sharp depolarization at the exact spin tune value.



260 seconds sweep of depolarizer frequency

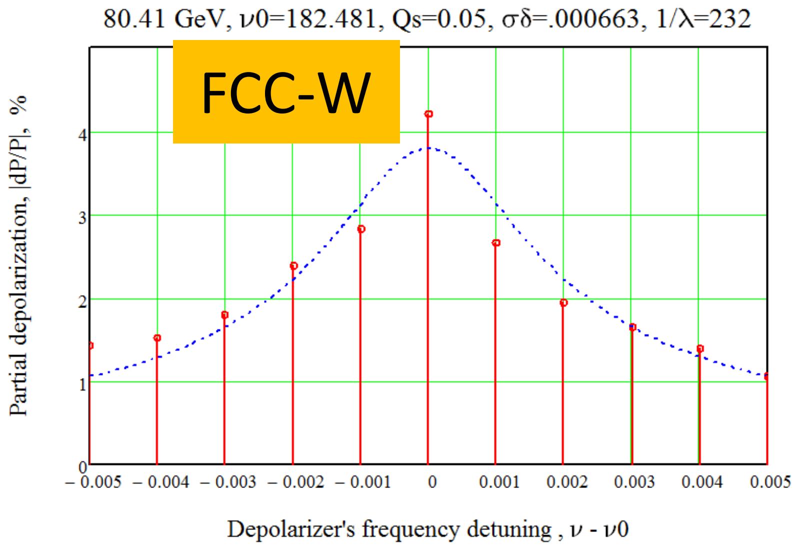


long sweep works well at the Z. Several depolarizations needed: eliminate Qs side band and 0.5 ambiguity
Less well at the W: the Qs side bands are much more excited because of energy spread, need iterations with smaller and smaller sweeps – work in progress. see *I. Koop* presentations at FCC weeks.



← Fourier analysis shows the side band situation at W.

First attempt at 'LEP' multiple sweep technique →



FCC-ee Beam Polarization and Energy Calibration

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

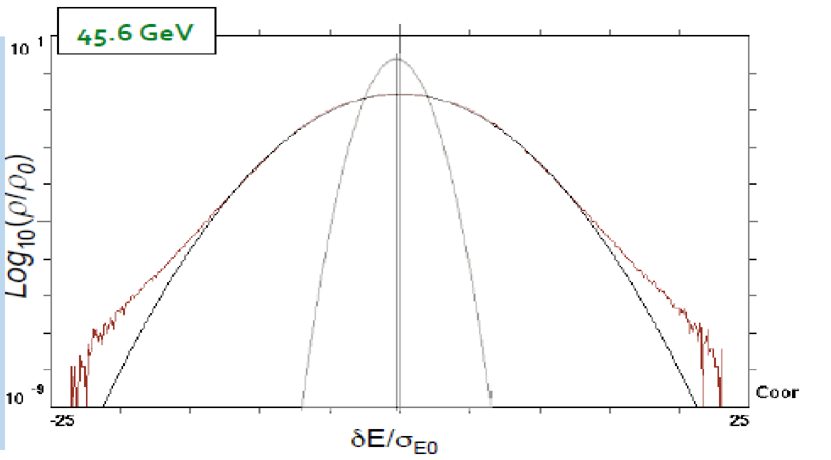
3.3 Beamstrahlung energy loss (<0.62 MeV per beam at Z pole), compensated by RF (Shatilov)

3.4 layout of accelerator with **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

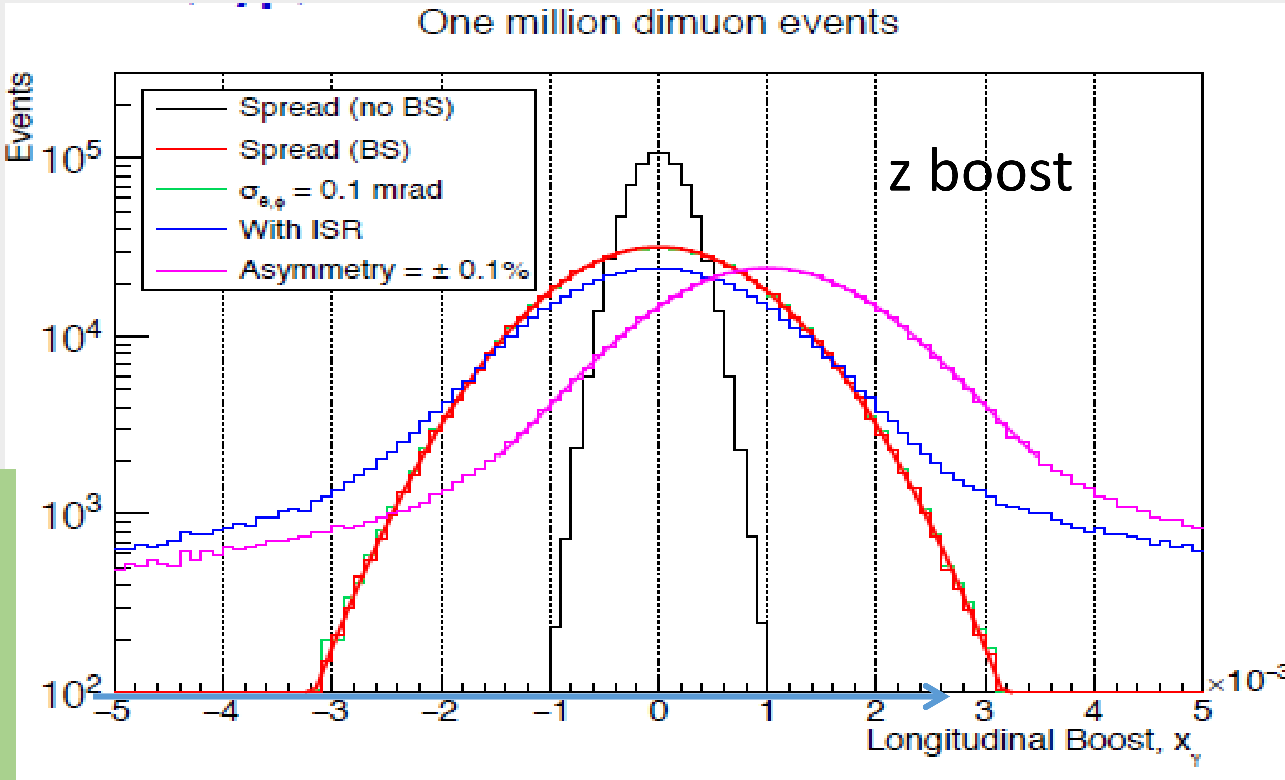


5 min/exp @Z ➔ 10^6 μ+ μ- /expt →

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

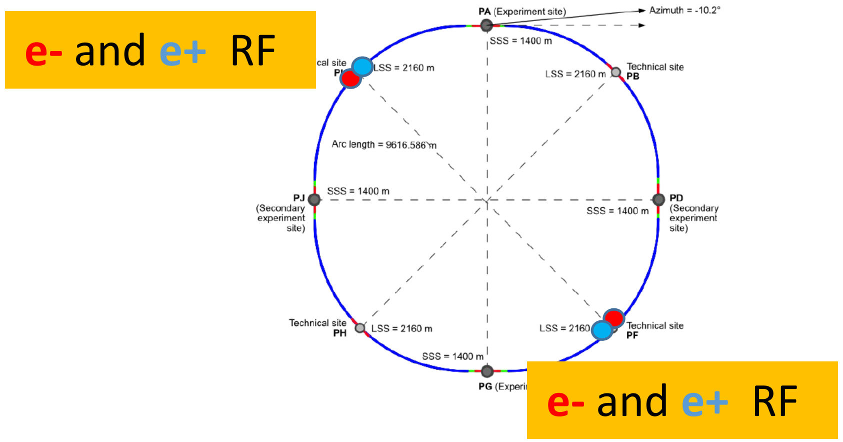
→ and beam crossing angle α (error negl.)

→ also 300keV (stat) on relative ECM (p-t-p!)

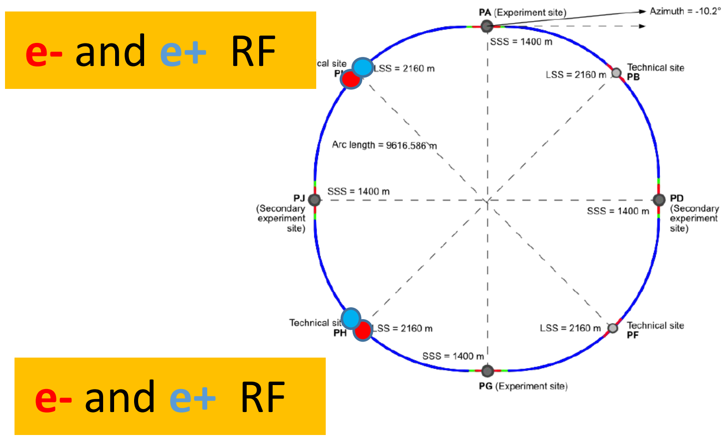


For the high energies (possibly ZH, then top energies)

C



D

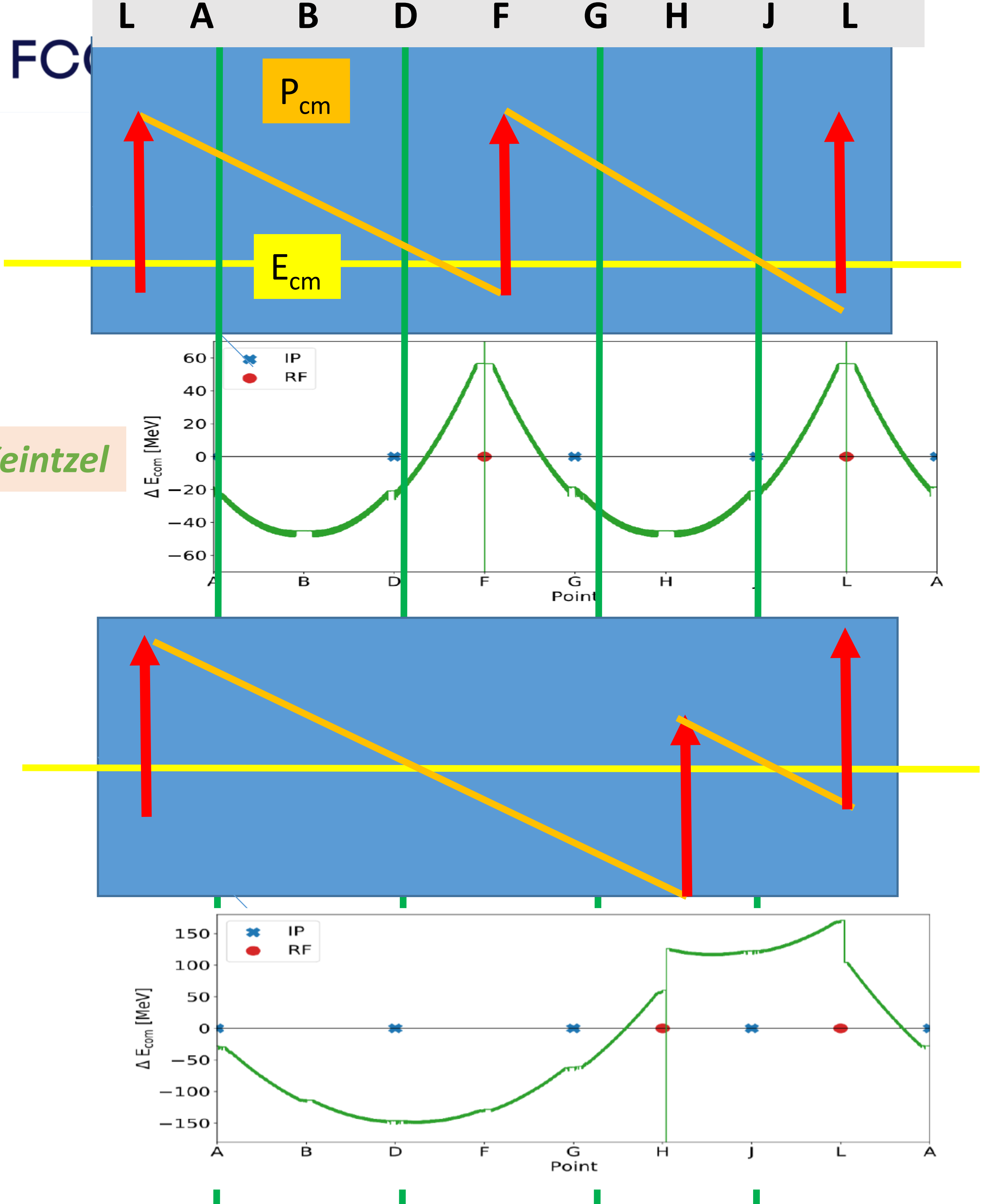


After an upgrade, the FCC-ee will have two RF stations with RF shared between e+ and e-
→ same energy gain for e+ and e- at two different places.

Question from Klaus Hanke: (for local practicality)

Do we need the scenario C or can we live with scenario D (easier for logistics)?

Answer next pages



J. Keintzel

scenario C 2 RF stations for both e+ and e-
for top energies (shared RF) here points F and L

Energy loss per turn (91.3km machine)

E_{cm}	E_{beam}	ΔE_{turn} (GeV)	maximal boost P_{cm}	
91	45	0.039	0.030 MeV	
350	**175**	**7.98**	**C: 2.0 GeV**	**D: 4 GeV**
365	**182.5**	**10.0**	**C: 2.5 GeV**	**D: 5 GeV**

scaling law: E^4/ρ : increase of 6% with new 91.3km layout

$\Delta E_{cm} = \Delta E_{e+} + \Delta E_{e--}$ = {-19,-21,-19,-21} MeV

$P_{cm} = \Delta E_{e+} -- \Delta E_{e--}$ = {¼ ΔE_{turn} , - ¼ ΔE_{turn} , ¼ ΔE_{turn} , - ¼ ΔE_{turn} }

scenario D: 2 RF stations for both e+ and e-
for top energies (shared RF) here points H and L

$\Delta E_{cm} = \Delta E_{e+} + \Delta E_{e--}$ = {-28,-146, -61, +123} MeV

$P_{cm} = \Delta E_{e+} -- \Delta E_{e--}$ = { ½ ΔE_{turn} , 0 , - ½ ΔE_{turn} , 0 }

all IPs have the same energy (C: +- 2MeV D: +- 135 MeV)
but D leads to different (large) c.m. boost
C is a bit nicer but both C and DOK!

Goals of the EPOL feasibility study

1- For centre-of-mass energy calibration:

o confirm the technical feasibility and the performance of the scheme proposed in [2], by sufficient level of simulations; **in particular complete the study of the depolarization method and its precision at the W energy.**

o **The existing simulation codes for luminosity and polarization must be unified, while calculating both the spin tune and the IR centre-of-mass energy.** The relationship between these two quantities and its sensitivity to tuning knobs, centre-of-mass energy and various imperfections should be investigated and if possible mitigated.

o The mitigation of collision effects such as **opposite sign dispersion** should be developed.
Should verify that Polarization at IP is 0 within precision required for cross-section and $A_{FB}^{\mu\mu}$

o **The design and implementation of the instrumentation must be completed and costed;** this includes **e+ and e- polarimeter/spectrometer, wigglers, depolarization kicker** and possibly additional IR instrumentation such as beamstrahlung or **low angle radiative Bhabha monitors.**

o The simultaneous and coordinated operation of the accelerator, of the continuous polarization and depolarization measurements, and of the beam monitoring devices, should be analysed in order to ensure a precise extrapolation from beam energies to the knowledge of centre-of-mass energy and energy spread.

o The contributions of the particle physics experiments to the determination of the centre-of-mass energy and its spread should be quantified and integrated in analysis and operation.

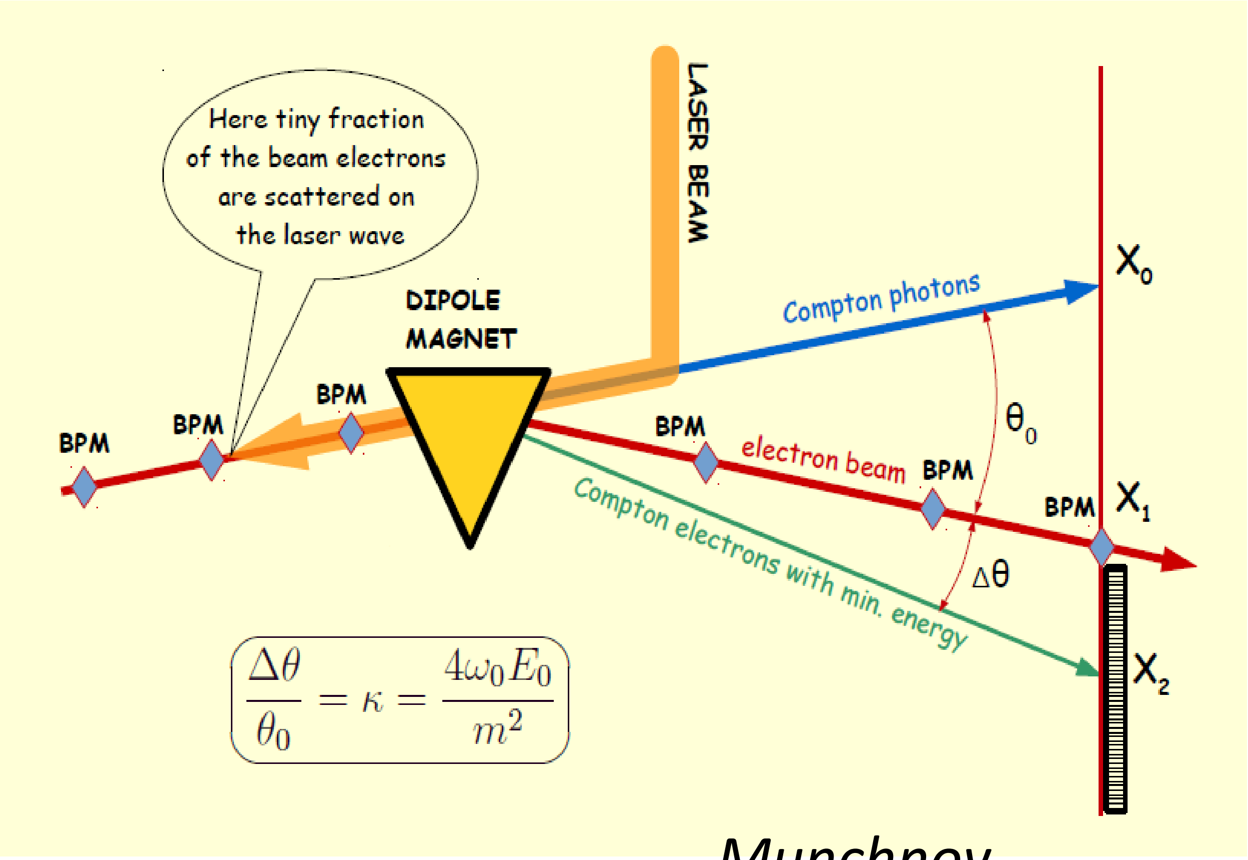
Hardware requirements: polarimeters

2 Polarimeters, one for each beam

Backscattered Compton γ +e $\rightarrow$ γ + e **532 nm (2.33 eV) laser; detection of photon and electron.**

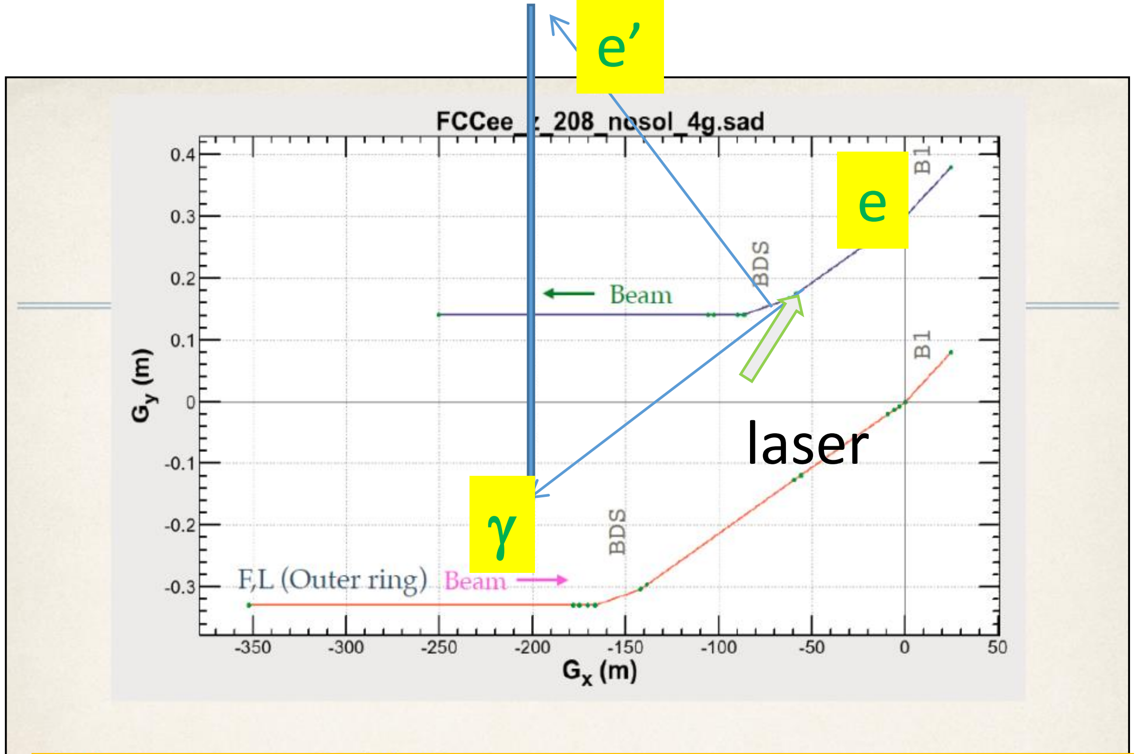
Change upon flip of laser circular polarization → beam Polarization ±0.01 per second

End point of recoil electron → beam energy monitoring ± 4 MeV per second



$$\frac{\Delta\theta}{\theta_0} = \kappa = \frac{4\omega_0 E_0}{m^2}$$

Munchnoy



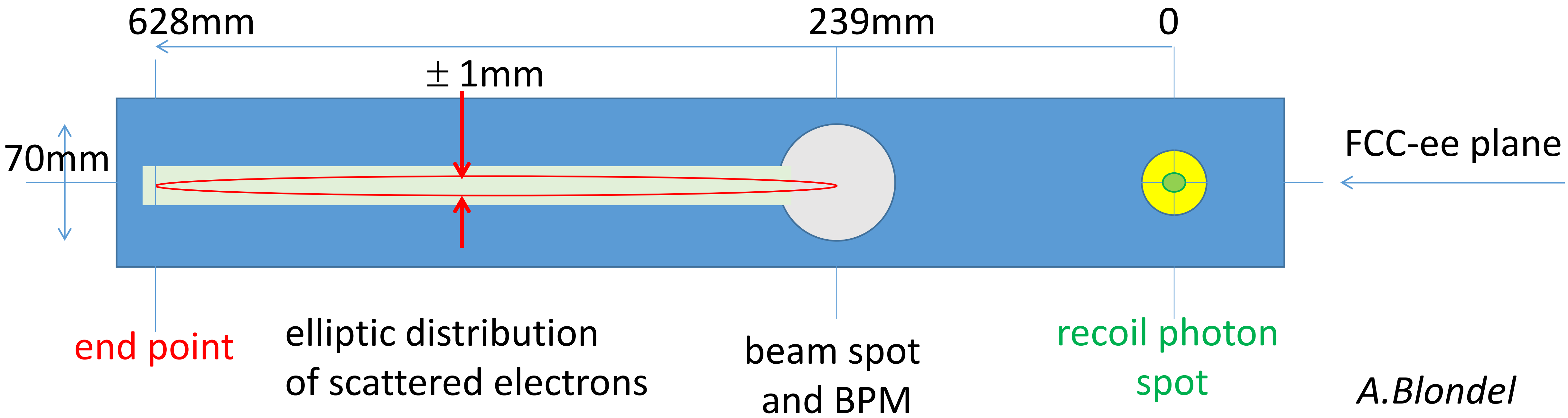
install photon-electron IP on inner ring in points H and F *(Oide)*

polarimeter-spectrometer situated 100m from end of dipole.

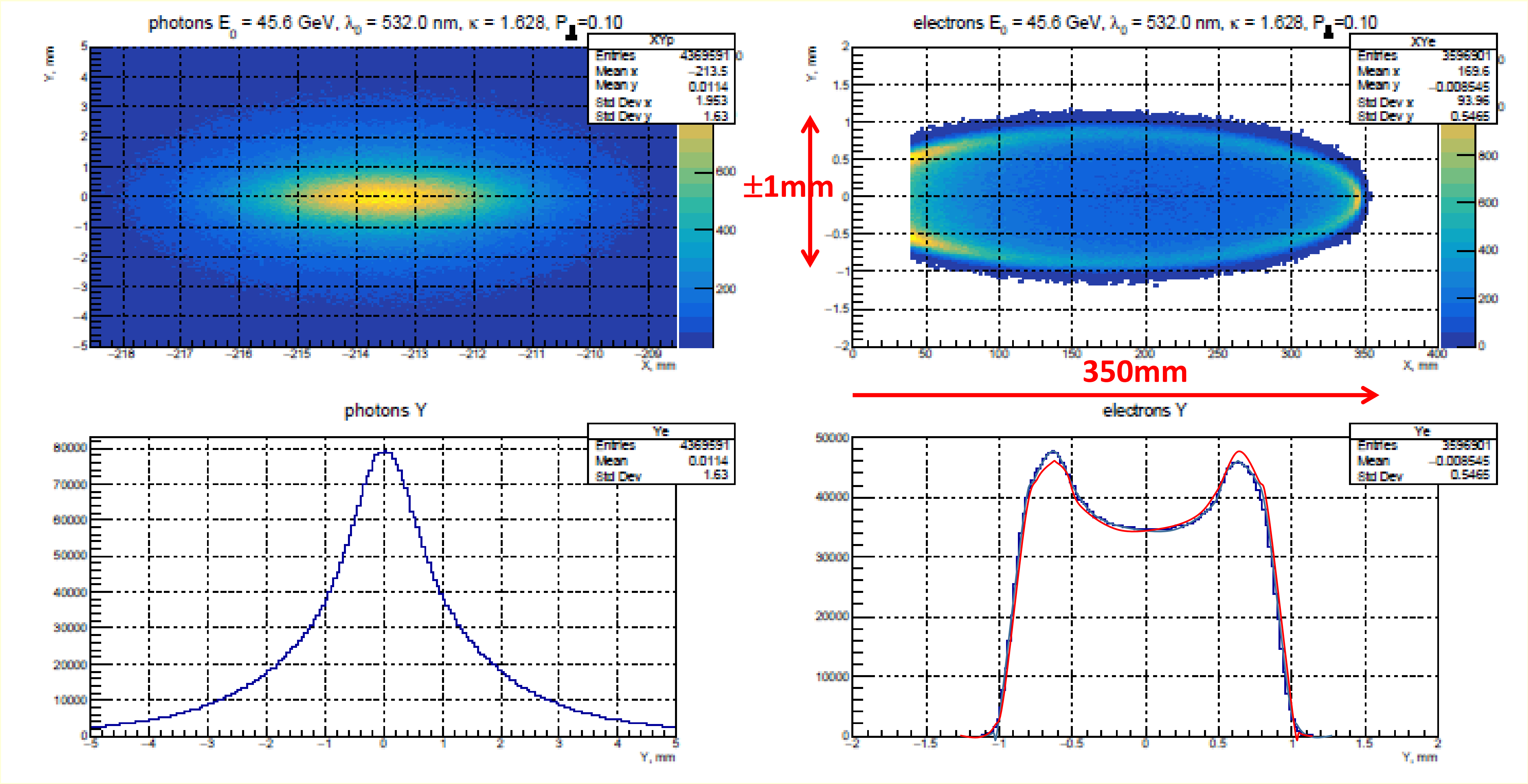
Using the dispersion suppressor dipole with a lever-arm of **100m** from the end of the dipole, one finds
-- minimum compton scattering energy at 45.6 GeV is 17.354 GeV
-- distance from photon recoil to Emin electron is 0.628m

	laser (eV)	beam (GeV)	mc2(MeV)	B field	R	LM	theta	L	true beam
	2.33	45.6	0.511	0.013451	11300	24.119	0.002134	100	45.60005
nominal kappa = 4. E_laser.Ebeam_nom/mc2	1.627567296								
true kappa = 4. E_laser.Ebeam_true/mc2	1.627568924								
nominal Emin	17.35445561								
true Emin	17.35446221								
position of photons	0								
nominal position of beam (m)	0.239182573								
true position of beam (m)	0.239182334	2.39182E-07							
nominal position of min (m)	0.628468308								
true position of min (m)	0.628468069	2.39182E-07							

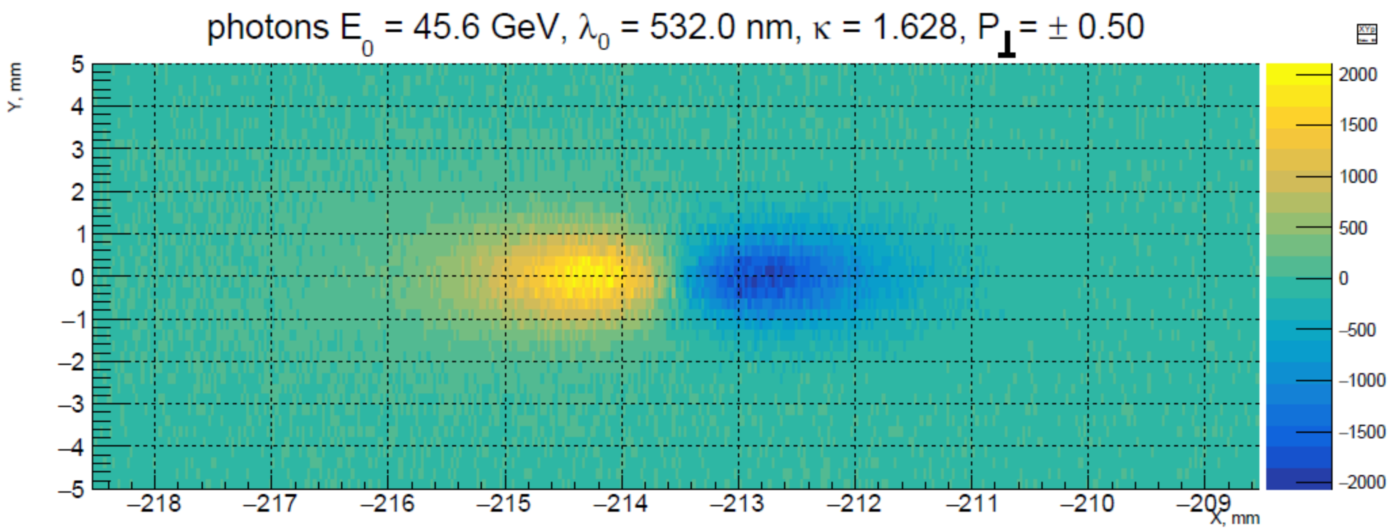
mouvement of beam and end point are the same:
0.24microns for $\delta Eb/Eb=10^{-6}$ ($\delta Eb=45keV$)

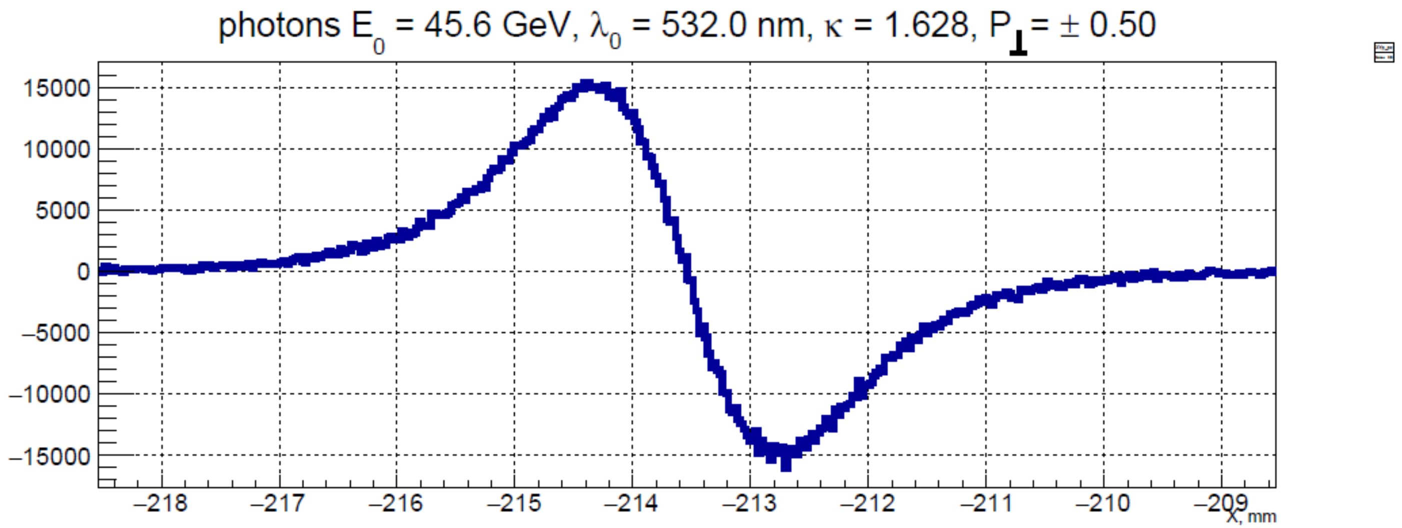


A.Blondel


photons E0 = 45.6 GeV, λ0 = 532.0 nm, κ = 1.628, P⊥=0.10
XYp
Entries 4369591
Mean x −213.5
Mean y 0.0114
Std Dev x 1.953
Std Dev y 1.63
Y, mm
X, mm
electrons E0 = 45.6 GeV, λ0 = 532.0 nm, κ = 1.628, P⊥=0.10
XYe
Entries 3596901
Mean x 169.6
Mean y −0.008545
Std Dev x 93.96
Std Dev y 0.5465
±1mm
350mm
photons Y
Ye
Entries 4369591
Mean 0.0114
Std Dev 1.63
Y, mm
electrons Y
Ye
Entries 3596901
Mean −0.008545
Std Dev 0.5465
Y, mm

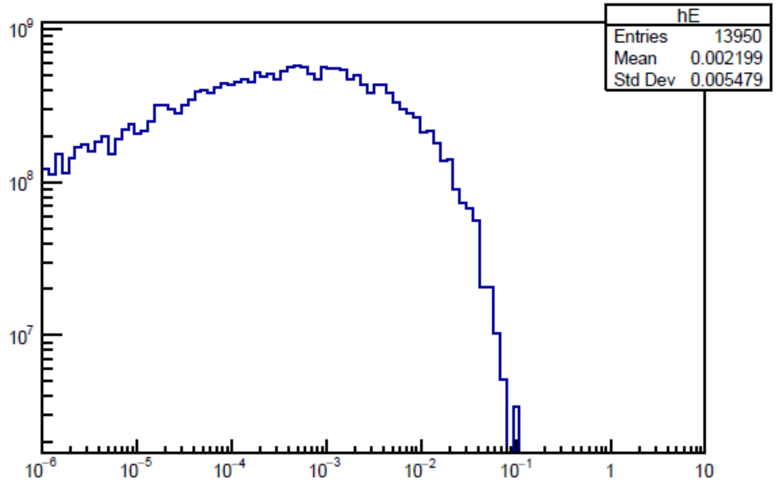
Munchnoi

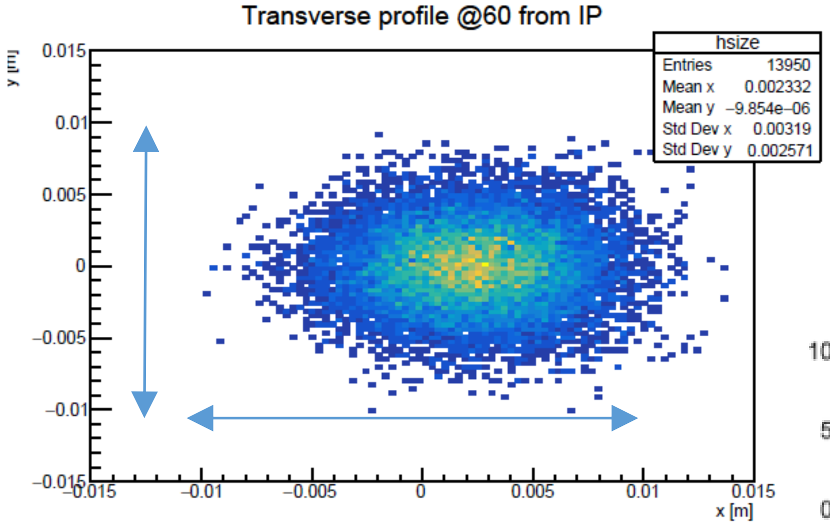




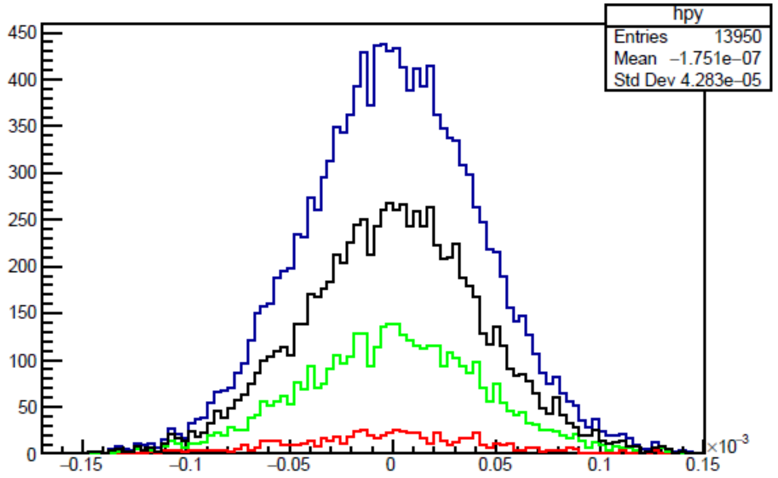
Spoiler : the polarimeter can measure the third component of polarization: Px from the horizontal movement of the recoil photons upon flip of circular polarization of the laser. (Precision ans sensitivity remain to be determined)

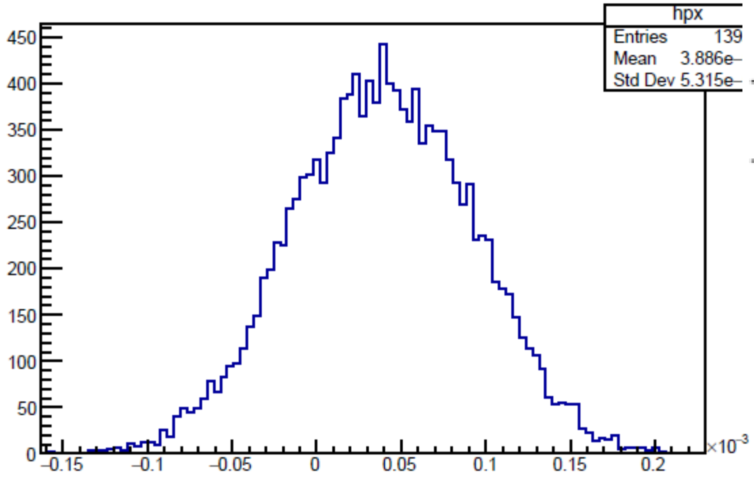
Beamstrahlung/radiative Bhabha monititor: ongoing work by Andrea Ciarma



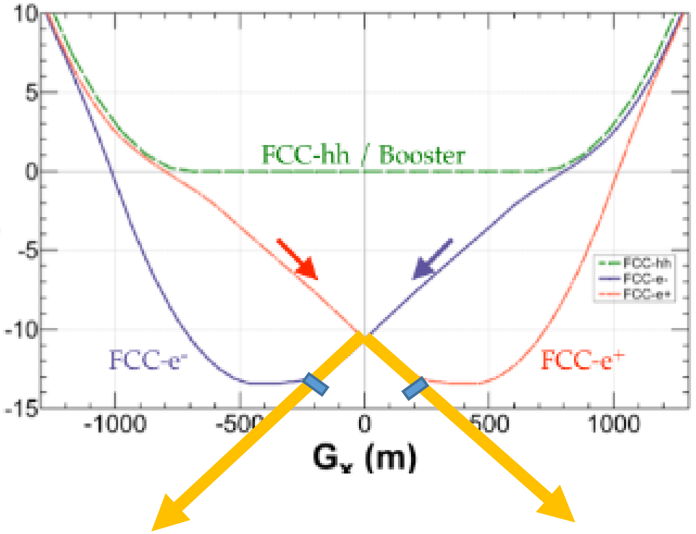


Offset = 0.0 sigma_y





± 1 cm spot of beamstrahlung photons



detect photons at exit from bending magnet in a deteector system that is all to be designed!

Goals of the EPOL feasibility study

DRAFT for comments

2. For monochromatization:

- The schemes of combination of schemes able to provide monochromatization should be investigated quantitatively to establish the feasibility of useful monochromatization.
- At the same time the experimental working group should explore further the optimization of purity and efficiency for the selection of Higgs s-channel production, possibly taking into account the specific beam set-ups.
- Realistic implementation scenarios should be proposed and analyzed with the tools developed above.
- The monitoring developed at the Z and W energies for ECM determination should be adapted for the Higgs s-channel production and possible additional actions to be foreseen should be identified and studied.

  -- might need to run beams with different energies to reach exactly ECM = m_{Higgs}

  -- need to measure energy spread in each point of the luminous region (with e.g. large angle dimuon events)

Organizational matters

-- participants
mailing list (CERN e-group) has been collected,

-- regular zoom meetings https://indico.cern.ch/category/8678/
should be short and lead to discussion of most important items
propose **every two weeks on Thursday at 16:30 CERN time** (nice time for California, Europe Russia ... not so nice for Japan) **Next meetings 9 December, 13 January, 27 January**

Work has already started and we plan to contribute to the next FSR with
-- better understanding of requirements on the accelerator and experiments
-- costed estimates for the polarimeters, wigglers, depolarizer, beamstrahlung monitor

Lots of very interesting work to do -- Join us!

contacts: Angeles Paus-Golfe, Aurélien Martens, AB

FCC-FS EPOL group meeting 3

Thursday 9 Dec 2021, 16:30 → 18:45 Europe/Zurich

Description The FCC technical and financial feasibility study comprises a work package (EPOL) on precision determination of the centre of mass en FCCee. using resonant depolarisation of the beams, in conjunction with precise measurement of the energy spread and other parameter physics events in the detectors, and other beam diagnostics in particular to control the collision parameters. Specific equipment involve polarimeters for both beams, polarisation wigglers, and depolarising RF kickers. The possible mono-chromatization of the beams in view measurement of the e+ e- —> H (125) process will also be studied and special requirements investigated.

Short group meetings are foreseen at 16:30 on Thursday typically every two weeks.

Videoconference FCC-FS EPOL group meeting

16:30 → 16:40 **Welcome, Introduction** 10m
Speakers: Alain Blondel (Universite de Geneve (CH)) , Jorg Wenninger (CERN)

16:40 → 16:50 **RF locations, CM energies and boosts** 10m
Speaker: Jacqueline Keintzel (CERN)

16:50 → 17:10 **The FCC-ee polarimeters: design and rates** 20m
Speaker: Nickolai Muchnoi (Budker INP)

17:10 → 17:30 **Laser possibilities for the FCC-ee polarimeter** 20m
Speaker: Aurelien Martens (IJClab Orsay)

17:35 → 17:45 **status of simulation studies at EPFL** 10m
Speakers: Tatiana Pieloni (EPF Lausanne) , Yi Wu (EPFL)

17:50 → 18:00 **First look at monochromatization optics** 10m
Speaker: Angeles Faus-Golfe (IJClab IN2P3 CNRS-Université Paris-Saclay (FR))

18:05 → 18:10 **Actions, agenda for next meetings** 5m