FCC-ee centre-of-mass energy calibration, polarization and monochromatization

Beam Energy Calibration, Polarisation, Monochromatisation

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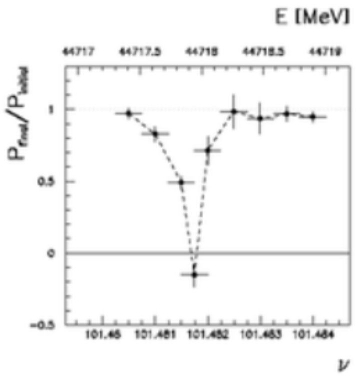


Meetings related to the Beam energy calibration, polarisation, and monochromatisation (EPOL) work package, joint with the FCC accelerator design study.

https://indico.cern.ch/category/8678/

May 2022

- 19 May FCC-FS EPOL group meeting 10
- 05 May FCC-FS EPOL group meeting 9

Group meets ~once / 2 weeks.
Next meeting: thursday 9 June
EPOL Workshop 19-30 September 2022

FCC Feasibility Study – coordination team and contact persons

FCC

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

- **EU Projects** – NN
- **Collaboration building** – Emmanuel Tsesmelis
- **Communications** – Panagiotis Charitos, James Gillies

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

Here we are:

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

Joint physics+accelerator WG

Works packages

A- Simulations of spin-tune to beam energy relationship

-- EPFL group obtained funding from CHART for a student and a postdoc (stdies started -- Yi Wu)

-- Ivan Koop now concentrating on res. dep at WW threshold (Qs is now 0.075, *good*!)

B. Simulation of the relationship between beam energies and centre-of-mass energy.

-- Impact of energy losses (Jacqueline Keintzel)

-- control of offsets and vertical dispersion (Wenninger, Oide, Shatilov, AB)

-- Studied the beamstrahlung monitor but does not work in a circular machine (Shatilov)

-- Studies will continue to implement beam deflection scans (AB-Oide-Shatilov-Wenninger)

C. Polarimeter desing and performance

-- now working to build a global collaboration (IJCLAB (Martens), BINP (Muchnoi), CERN (Lefevre), -- others?)

-- Aim to provide integration of polarimeters, wigglers, RF kickers in FCC-ee

-- conceptual design and cost estimate of polarimeter for FCC FS

D. Measurements in Particle Physics Experiments

-- not much work done beyond design study, needs to restart soon, very precious information from dimuons

E. Monochromatization

Angeles Faus, Jorg Wenninger, Pantaleo Raimondi, Frank Zimmermann, Dmitry Shatilov

-- new ideas for monochromatization in other dimensions than horizontal (x) axis. (time, z)

-- what its the limit?

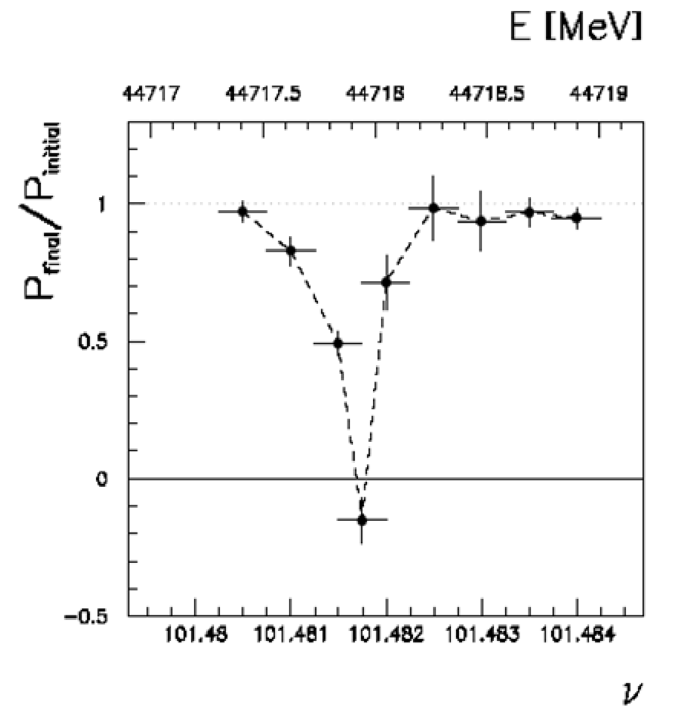
EPOL sessions at this FCC week

Wednesday			Thursday			
Parallel 1 Campus Cordeliers room 155 p.	Parallel 2 Campus Cordeliers room 75 p.	Parallel 3 Réfectoire Cordeliers room 100 p.	Parallel 1 Campus Cordeliers room 470 p.	Parallel 2 Campus Cordeliers room 155 p.	Parallel 3 Campus Cordeliers room 75 p.	Parallel 4 Réfectoire Cordeliers room 100 p.
FCC hh accelerator	PED: EPOL	FCCIS WP3 Placement	Reserve	PED/ACC: FCCee EPOL	TI Geodesy alignment	Technology
Chairperson	Chairperson	Chairperson	Chairperson	Chairperson	Chairperson	Chairperson

1. **Wednesday 9:00-10:30**
   -- FCC-ee EPOL The center-of-mass energy calibration and polarization working group (Alain Blondel)
   -- enter-of-mass energy and boosts for various RF-configurations (Jacqueline Keintzel)
   -- Polarimeter & wiggler integration status (Katsunobu Oide)
   -- 3D Polarimeter performance and laser control (Aurelien Martens)

2. **Thursday 9:00-10:30**
   -- Simulations of the Spin Polarization for the Future Circular Collider e+e- using Bmad (Yi Wu)
   -- Study of the depolarization process, possible biases (Ivan Koop)
   -- Control of beam-beam offsets and related ECM biases (Blondel/Oide/Shatilov)
   -- Progress in monochromatization (Angeles Faus-Golfe)

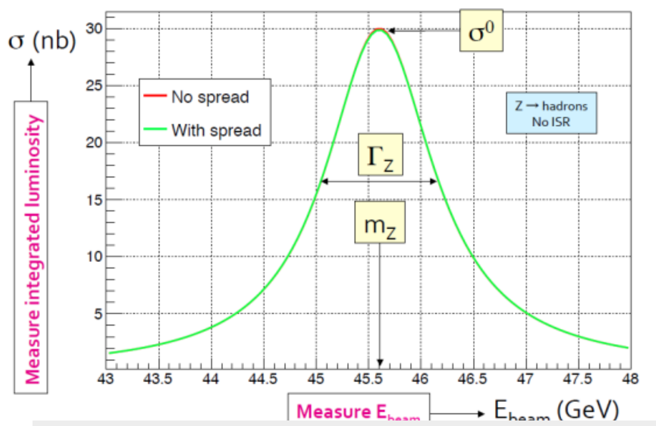
Transverse beam polarization provides beam energy calibration by resonant depolarization



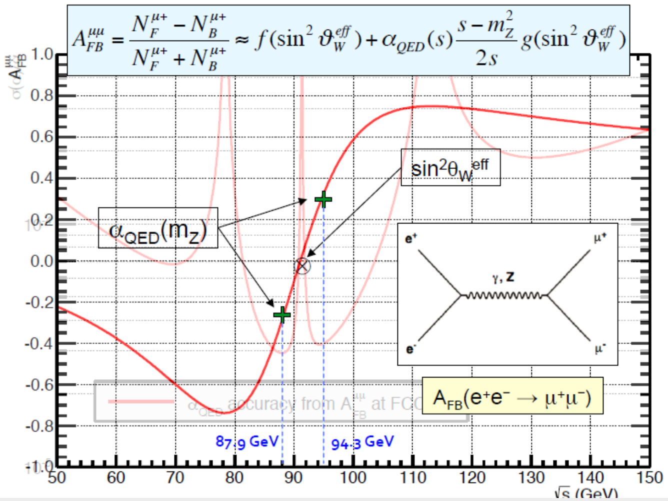
→ low level of polarization is required (~10% is sufficient)
→ at Z & W pair threshold comes naturally $\sigma_E \propto E^2/\sqrt{\rho}$
→ at Z use of asymmetric wigglers at beginning of fills
since polarization time is otherwise very long (250h→ ~1h)
→ should be used also at ee $\rightarrow$ H(126)
→ use 'single' non-colliding bunches and calibrate continuously
during physics fills to avoid issues encountered at LEP
→ Compton polarimeters for e+ and e- each
→ 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 $\rightarrow$ Z γ or ee $\rightarrow$ WW events
to calibrate E_{CM} at $\pm$1-5 MeV level: m_H (~3 MeV) and m_{top} (~10-20 MeV) measts

Physics: scan points and output quantities



Z line shape → m_Z and Γ_Z



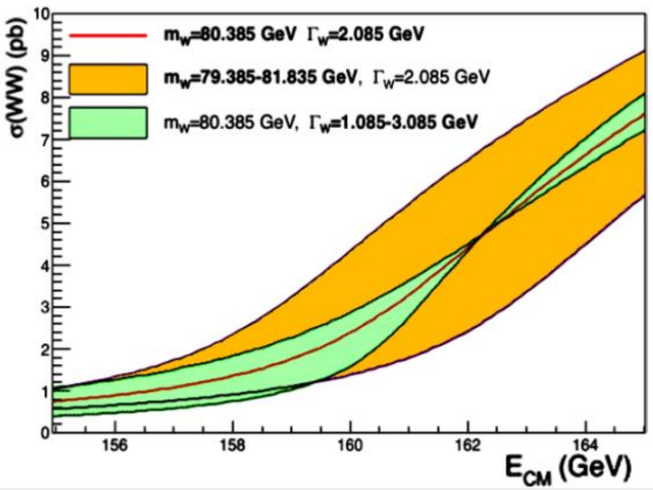
at the same time $A_{FB}^{\mu\mu}(\sqrt{s})$
→ $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$

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

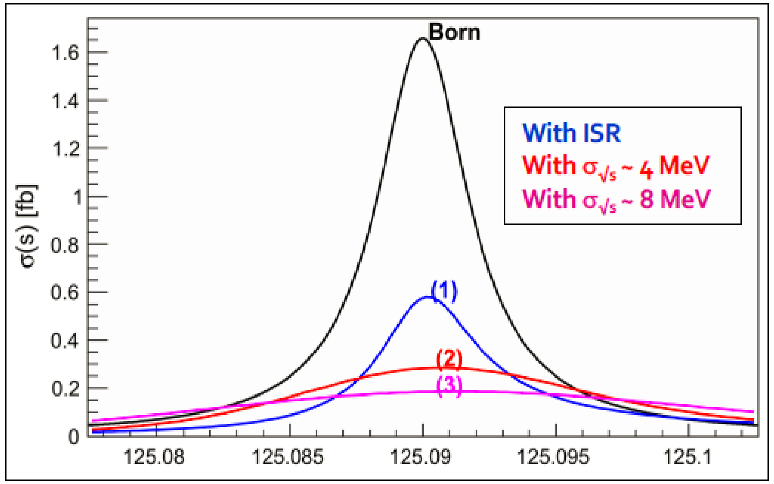
for the Higgs, bad luck!
ν = m_H/2/.4406486 (1) = 141.94
--too close to integer for polarizazion–
→ 141.44 for e+ and 142.44 for e-

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?

First set of results obtained in the FCC Design Study:

Polarization and Centre-of-mass Energy Calibration at FCC-ee, 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	$\Delta E_{\rm CMabs}$ 100 keV	$\Delta E_{\rm CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) $\pm$ **0.05** MeV	stat/present
m_Z (keV)	**4**	100	**28**	1	–	500
Γ_Z (keV)	**4**	2.5	**22**	1	**10**	400
$sin^2\theta_W^{\rm eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	**2**	–	**2.4**	0.1	–	75
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	**3**	0.1	**0.9**	–	**0.05**	15 (qualitiative!)
m_W(MeV)	**0.250**	-- **0.300** --				40

Next challenges for the feasibility study:

-- Ascertain the above with integrated simulations (simulation of polarization and depolarization on real machine)

-- Match systematic errors with statistics.

most relevant targets : **the point-to-point systematics, improve the WW energy**

– these are effects that would lead to a deviation from relation between

-- the spin tune as measured by resonant depolarization

-- and the center-of-mass energy.

-- examples: 1. interference between depolarizing resonances and the induced depolarizing resonance because the spin tune varies with energy.

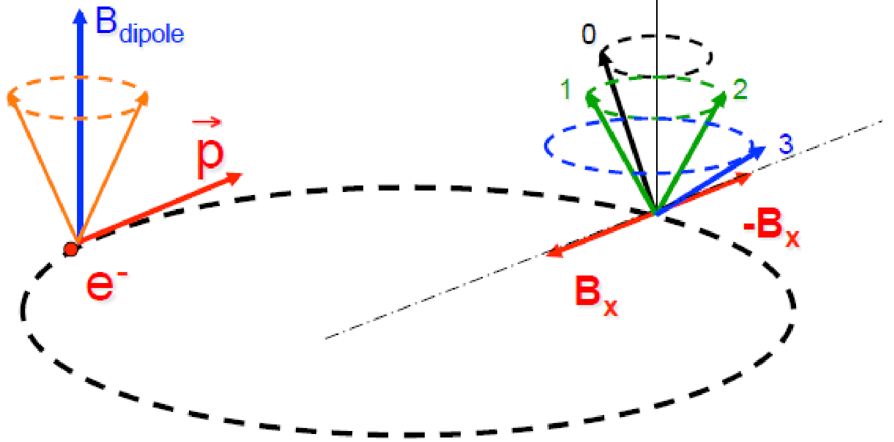
2. effects due to collision offsets folded by opposite sign dispersion

-- designevaluate performance and cost the polarimeter at conceptual level

-- finalize implementation in the realistic machine, study operational aspects

SPIN PRECESSION

RESONANT DEPOLARIZATION



(ν is the *spin tune*)

$\delta\theta_{spin}$ = (g-2)/2 . E_{beam} /m_e $\delta\theta_{trajectory}$

$\delta\theta_{spin} = \nu \cdot \delta\theta_{trajectory}$

ν = E_{beam} / 0.4406486

ν = 103.5 at the Z peak

AMPLIFICATION

➔ high precision

➔ sensitivity to misalignements

-- depolarization

-- spurious spin resonances

Once the beams are polarized, an RF kicker at the spin precession frequency (fractional part thereof) will provoke a spin rotation and depolarization

Simulation of FCC-ee by I. Koop:

can we do as well at W threshold?

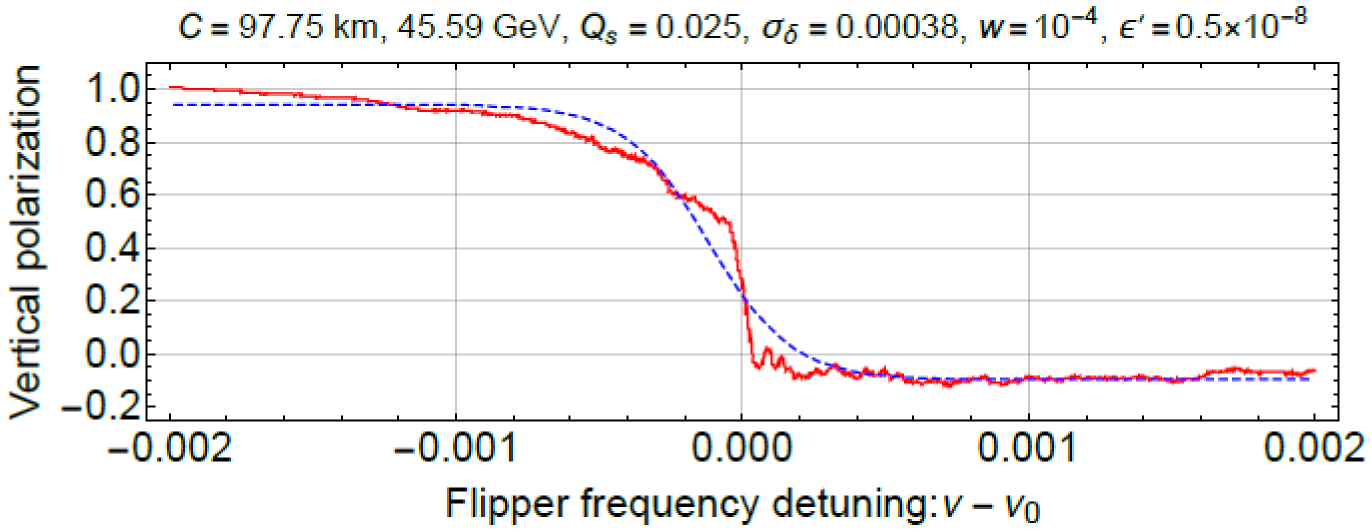


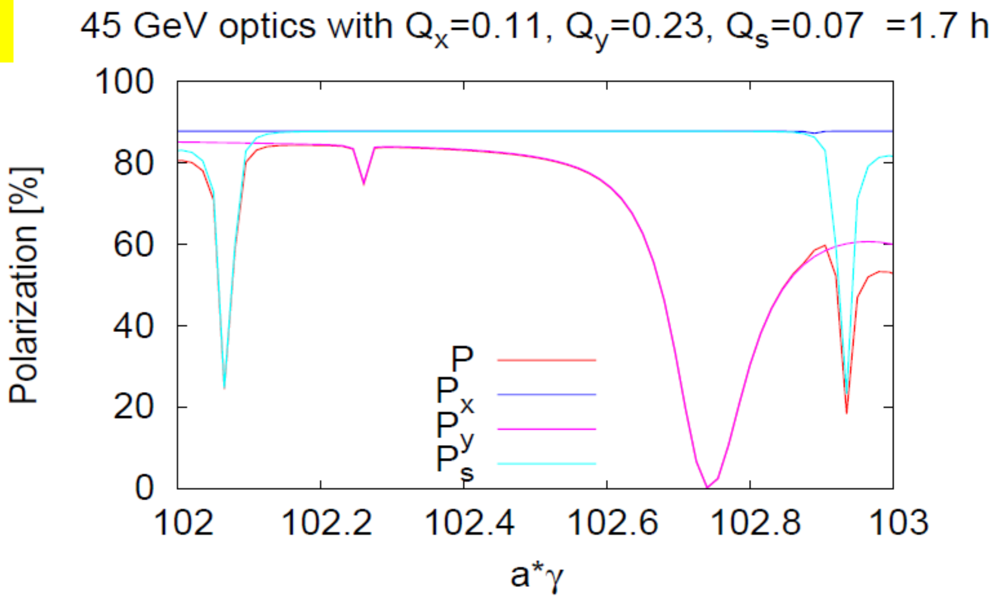
Figure 39. Simulation of a frequency sweep with the depolarizer on the Z pole showing a very sharp depolarization at the exact spin tune value.

Simulations of self-polarization

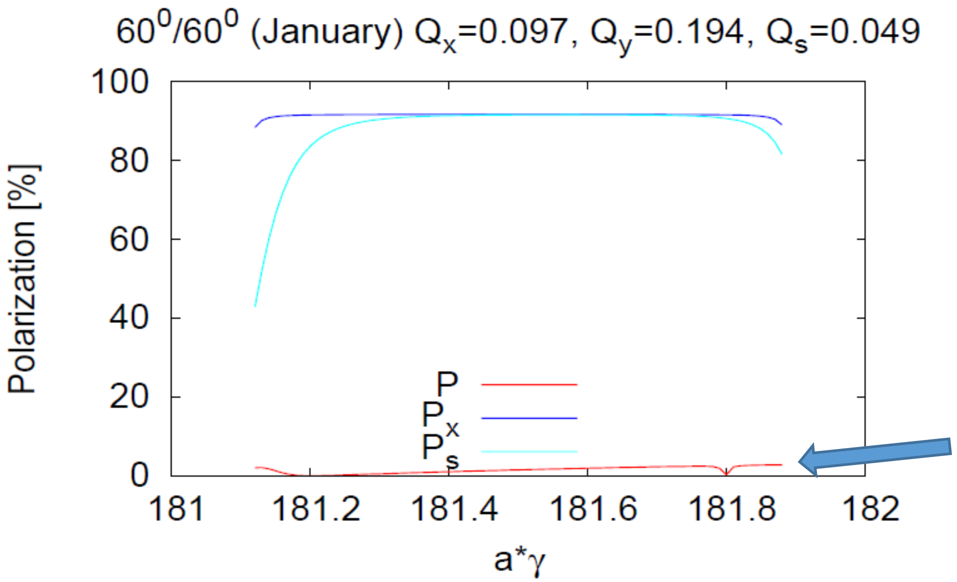
Orbit correction leading to similar values for vertical dispersion and vertical emittance than for the luminosity optimization

E. Gianfelice
arXiv:1909.12245

@ Z

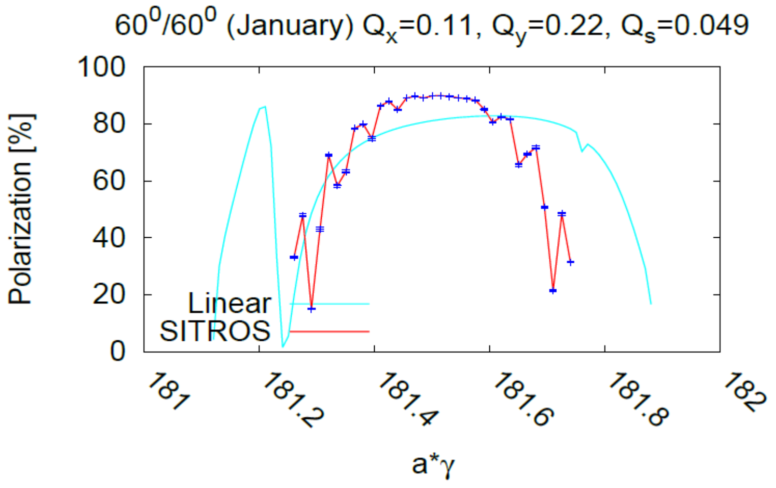


@WW



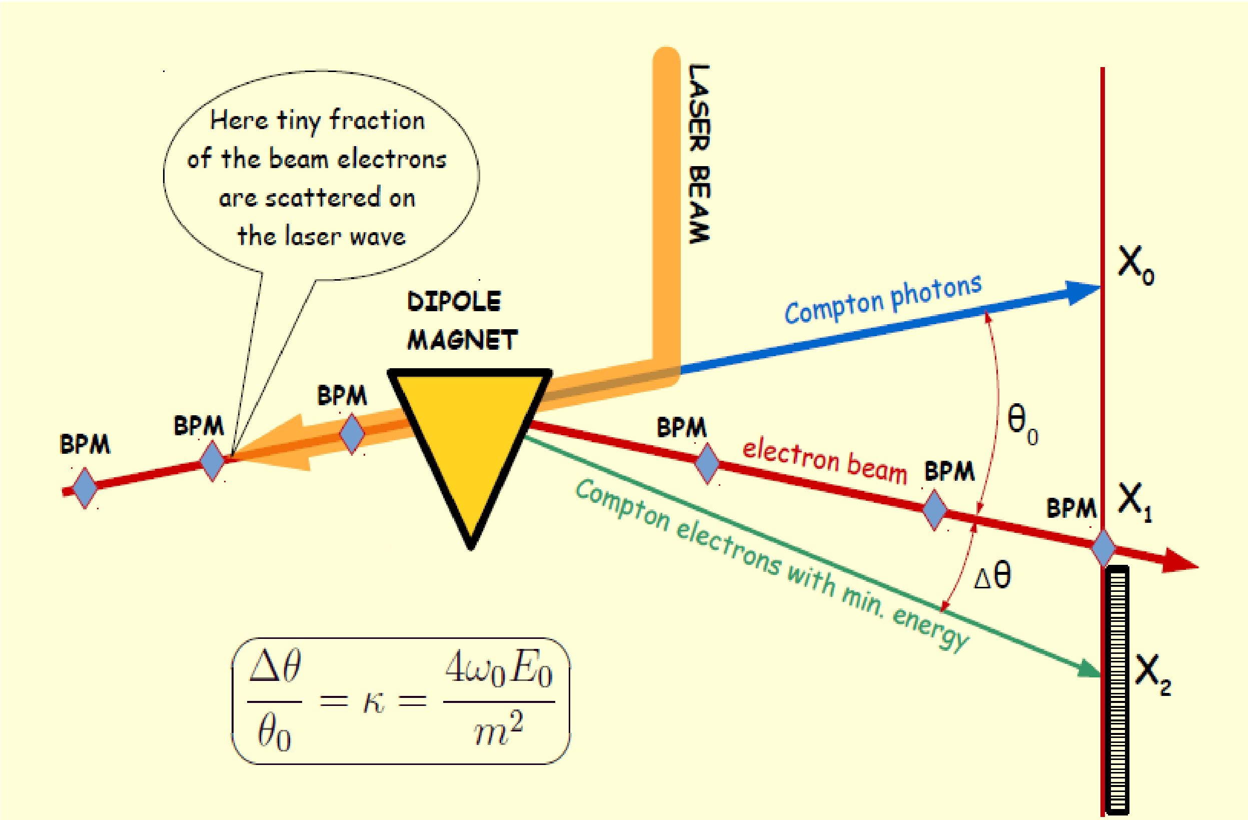
significant impact of spin resonances from vertical orbit @Z **might reduce polarization @W too much**

-- Sufficient level of polarization at Z for machine that is optimized for luminosity.
-- Additional correction of dispersion and
-- harmonic spin matching helps at W *→
-- Effect on resonant depolarization frequency small... but must be simulated
-- These studies will be repeated with simulation on same machine of lumi/polarization ➔ BMAD code by D. Sagan → Yi Wu

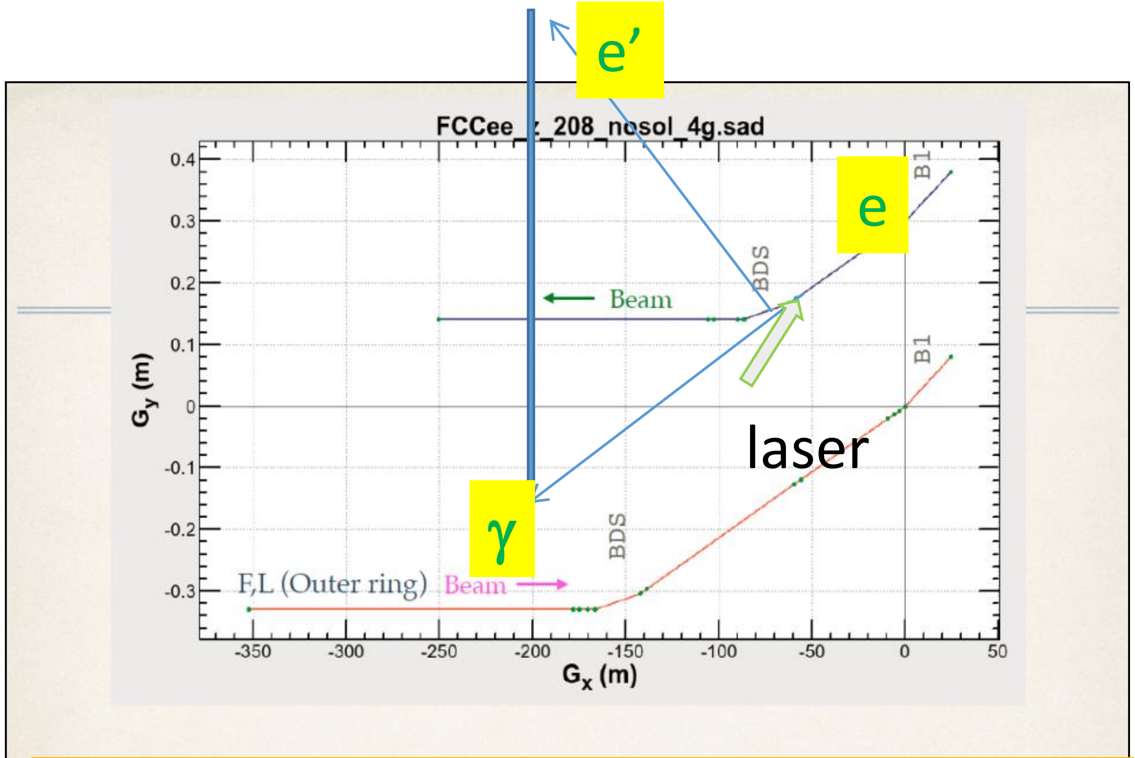


polarimeters

2 Polarimeters, for e+ and e-   Use of both electron and photons recoil →measurement of 3D beam polarization
Backscattered Compton γ +e → 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   (Muchnoi, Aurelien Martens)



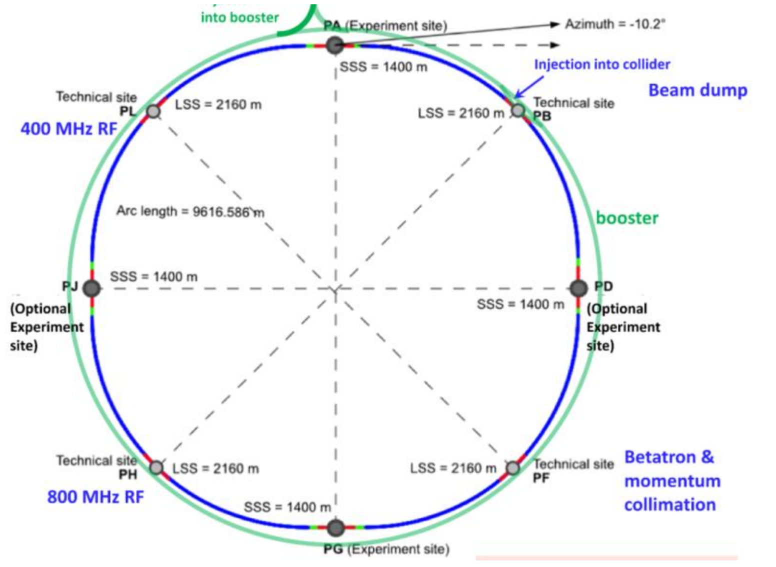
Munchnoy



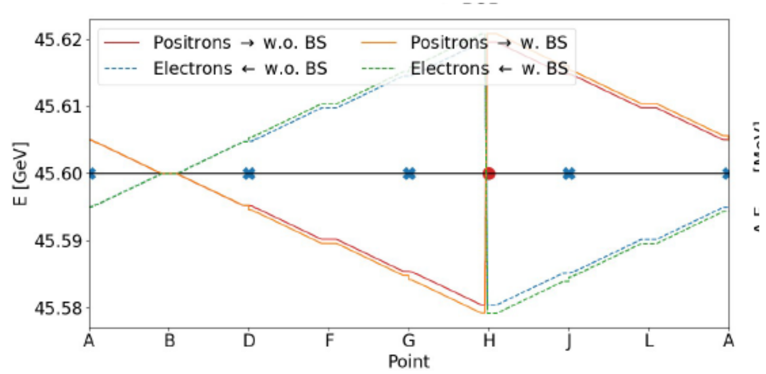
install photon-electron IP on inner ring in RF straights *(Oide)*

Resonant depolarization frequency vs average beam energy?

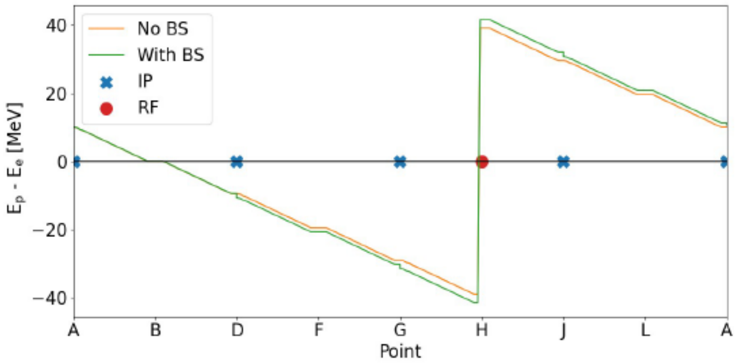
Jacqueline Keintzel



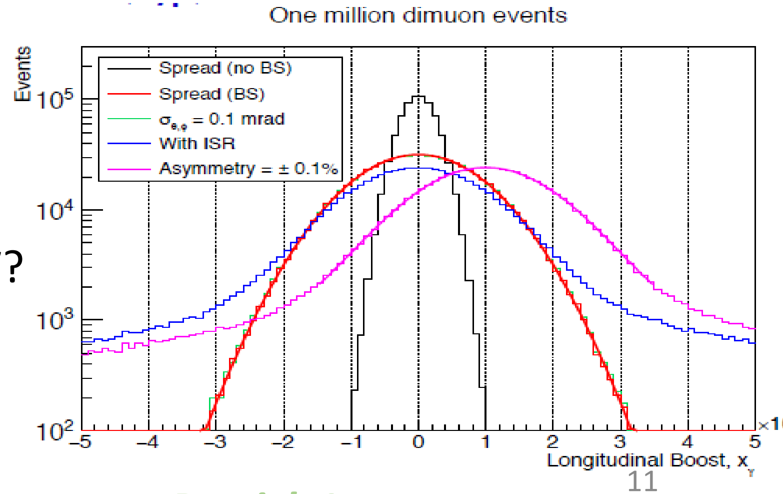
Just because particles have to stay in the ring...
the energy losses (SR, beamstrahlung...) and gains cancel.
IF there is only one RF section for both e+ and e-
➔ **a strong requirement for the Z, W (and ee➔ H) machines**



Boost: + for e+; - for e-



The boosts can be verified with great precision, using muon pairs in the experiments, (±40 keV in 5 minutes). Also, the energy spread can be measured



Patrick Janot

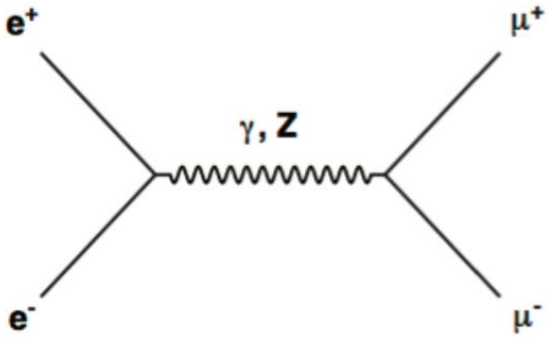
small (8keV) effect comes from $\Delta E \propto \gamma_{\mathrm{rel}}^4$

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

How well does that work for W?

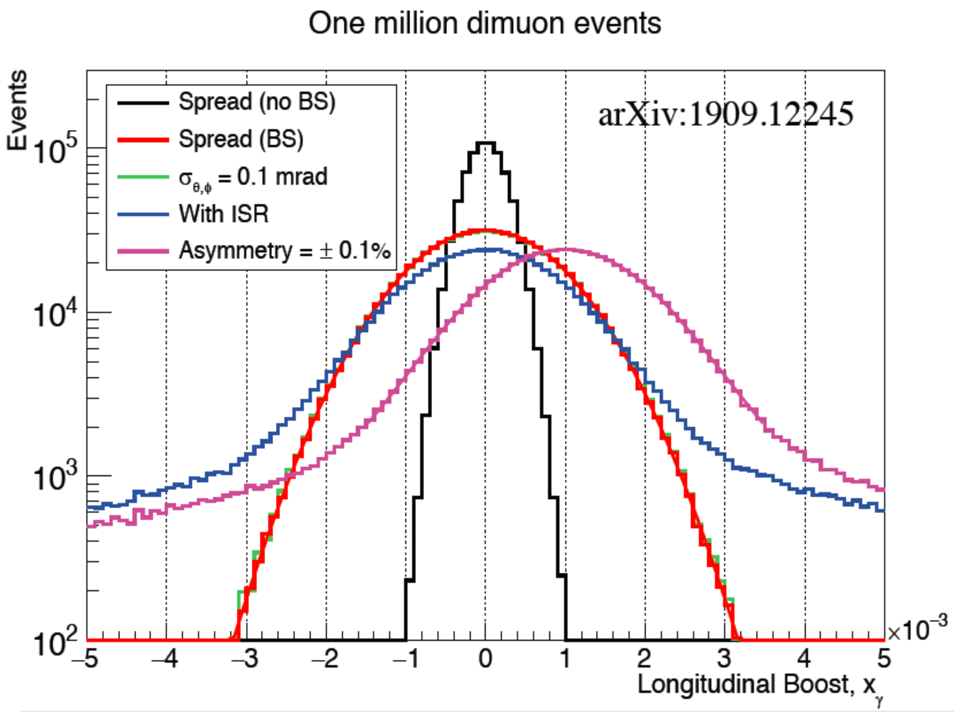
A thousand recipes to use up dimuon events at the FCC-ee

P. Janot

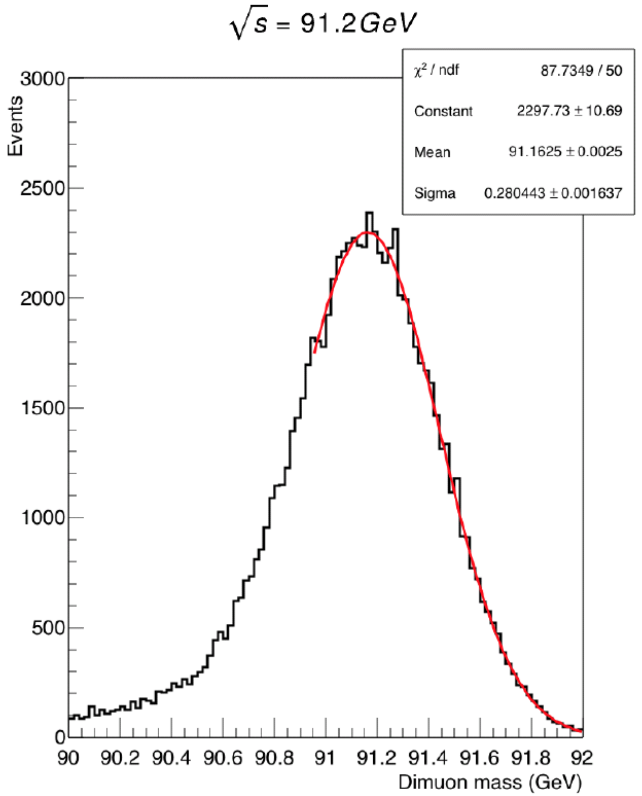


E,P conservation –>
allow E_{CM} and P_{CM}
on event-per-event basis.

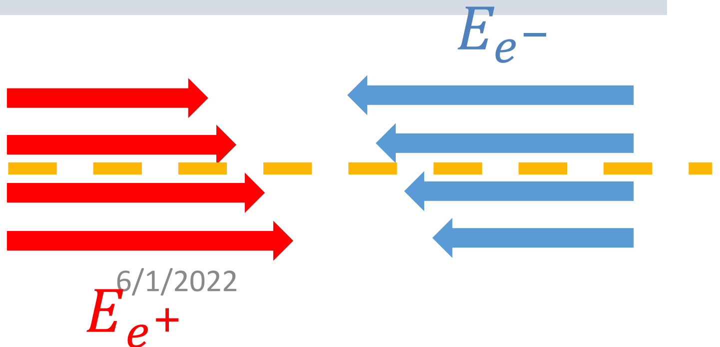
10^6 evts/5 min/expt @Z
~10^4 evts/5 min/exp @H
→Determine ECM, ECM spread and collision angle,
in addition to $A_{FB}^{\mu\mu}(\sqrt{s})$!
(also: control of ISR spectrum)



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



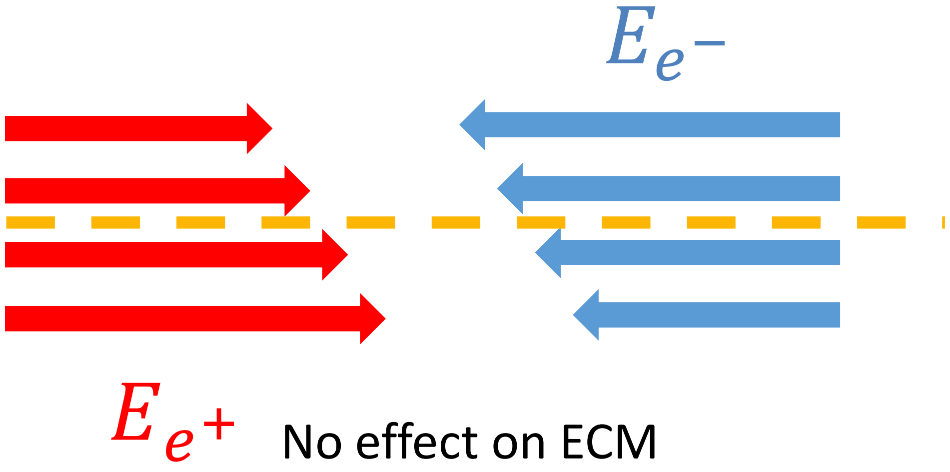
±2.5 MeV ECM meast
in 30 seconds of data
~40keV per day at
each scan point….
challenge for detectors and QED calculations!



Very useful also for control of Monochromatization!

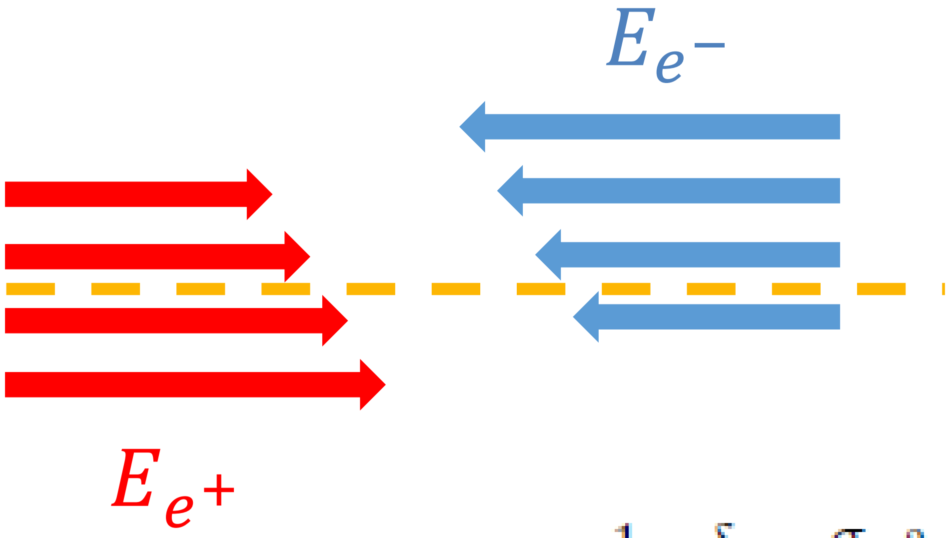
From beam energy to E_{CM}

opposite sign dispersion



No effect on ECM

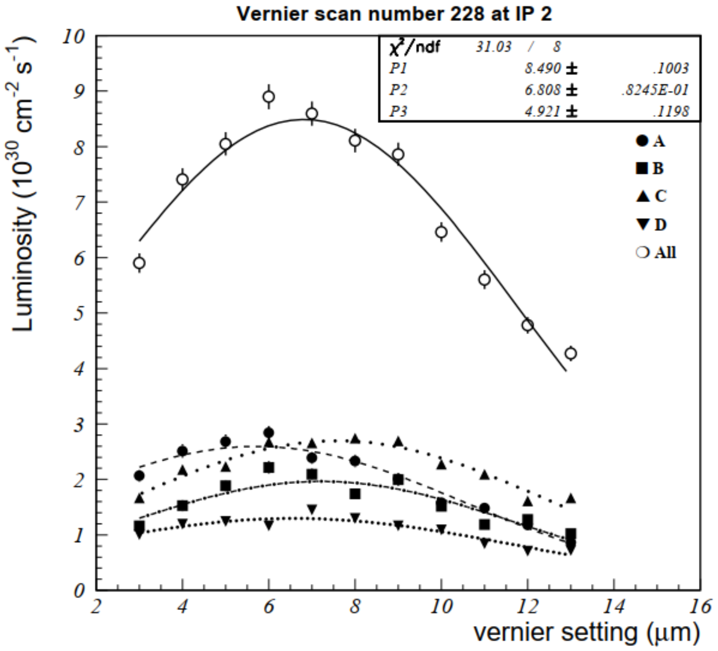
NB energy spread is reduced.

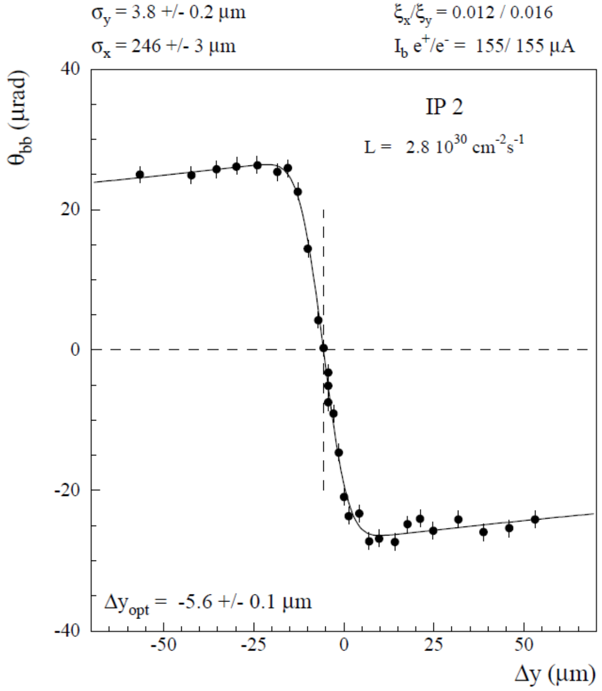


ECM lowered: $$\Delta E_{\mathrm{CM}} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_{E_b^2}}{E_b} \cdot \Delta D_y^*$$

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 deflection scans
First look tomorrow...
Statistics look very good.

Conclusions

Resonant depolarization is a cornerstone of the precision programme of FCC-ee

factor 500-75 more precise than LEP

~40 times more precise than CDF

➔ Improvement by factor 10-1000 on a long list of EW precision measurements.
e.g. W mass down to ±250 keV, Z mass and width ±4 keV, $\sin^2\theta_W^{eff} \pm 2.10^{-6}$ etc..
➔ explore new physics at 10-100 TeV scale, or 10^{-5} mixing with known particles.

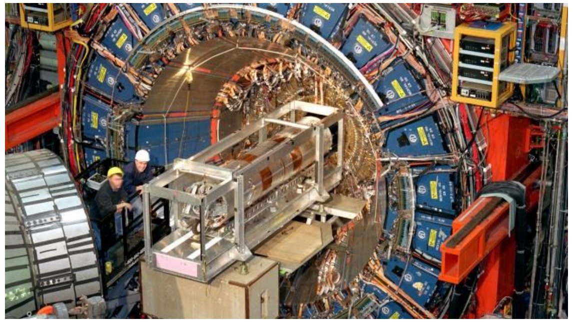
The goal of the group is to demonstrate that a feasible program of measurements and procedures in the operation and data taking of the accelerator will allow a determination of the centre-of-mass energy that matches the precision offered by the high luminosities.

This involves talking in kev and ppm

We are steadily making progress in this direction

There are many important contributions to make and yours will be welcome.

FCC-ee Energy Calibration and Polarization

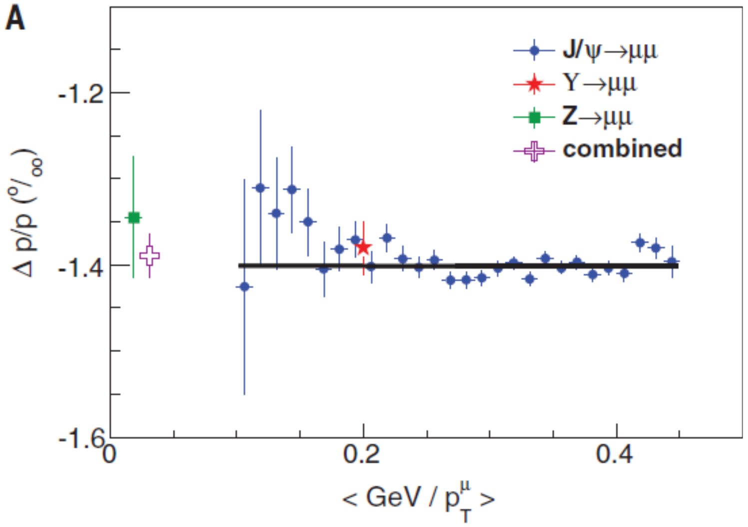


Recent CDF: m_W (MeV)= 80'433.5 ± 6.4 $_{stat}$ ± 6.9$_{syst}$ (10^{-4} precision)
-- « could hint at new physics » and surely created a buzz!
-- precision measurements as broad exploration of new physics in quantum corrections, or mixing (SUSY, Heavy neutrinos, etc..)
(-- questions because inconsistent with previous measurements)

CDF measurement is remarkable in two ways:

1. (after 10 years of work)
systematic errors similar to statistical precision

2. relies for the precise calibration on J/ψ, ϒ, Z masses
all measured in e+e- colliders... (VEPP-4M, Doris, LEP= using resonant depolarization!



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