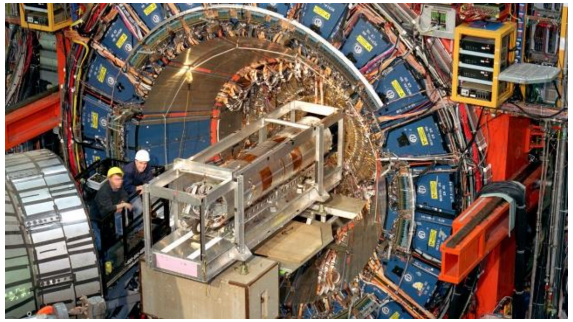
FCC-ee Electroweak Physics

1. Introduction
2. overview of case studies and detector requirements
3. Ongoing: center-of-mass energy calibration

in less than 30 minutes.

About Precision Measurements...



Recent CDF: m_W (MeV)= 80’433.5 $\pm$ 6.4 $_{stat}$ $\pm$ 6.9$_{syst}$ (10^{-4} precision)

-- « could hint at new physics » and surely created a buzz!

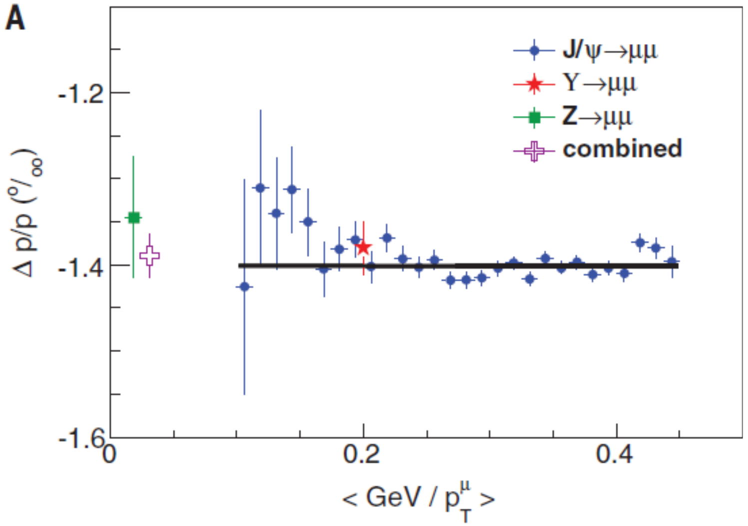
-- precision measurements as broad exploration of new physics in quantum corrections, or mixing (SUSY, Heavy neutrinos, etc..)

(-- 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...
using resonant depolarization!



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

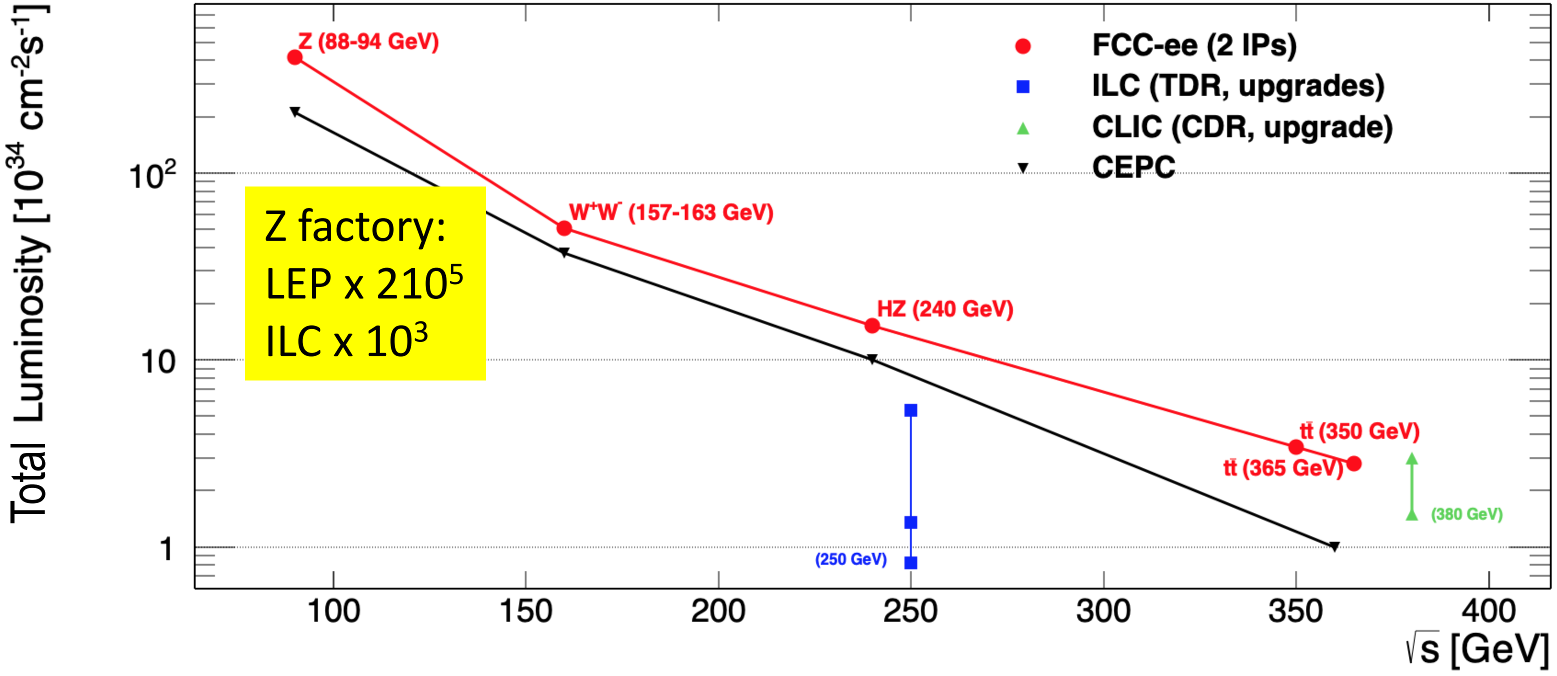
~40 times more precise than CDF

➔ Improvement by factor 10-1000 on a long list of 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.

factor 500 more precise than LEP

FCC-ee

Great energy range for the heavy particles of the Standard Model



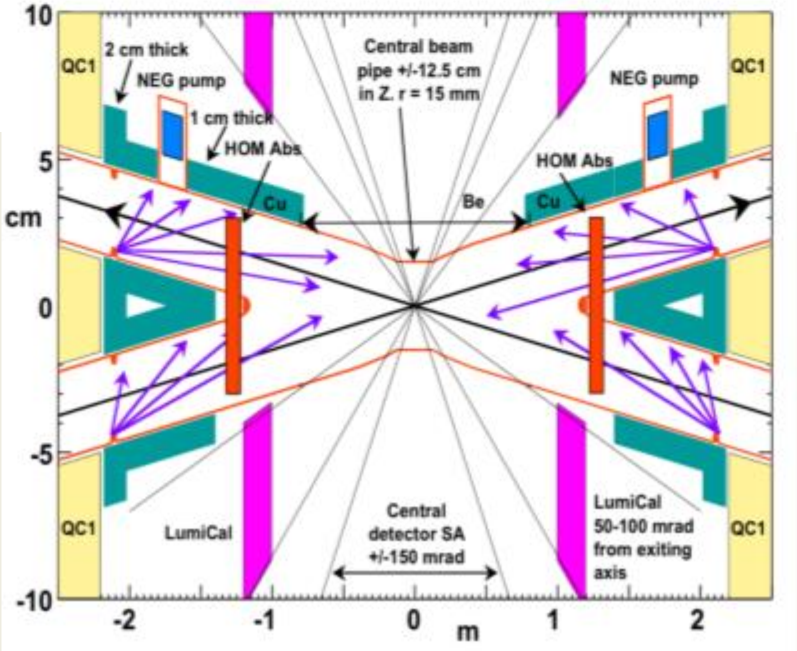
Z factory:
LEP x 210^5
ILC x 10^3

notes:
-- 4IP increases Total Lumi by 1.7
-- 2IP assumed in all numbers below
-- order and duration of Z/WW/ZH can be decided at a later stage
-- ee→ H must be after both Z and ZH and before tt

Event statistics (2IP) for typical run plan:

					E_{CM} errors:
Z peak	**E_{cm} : 91 GeV**	**4yrs**	**5 10^{12} e+e- → Z**	**LEP x 2.10^5**	<100 keV
WW threshold	**$E_{cm} \geq$ 161 GeV**	**2yrs**	**>10^8 e+e- → WW**	**LEP x 2.10^3**	<300 keV
ZH maximum	**E_{cm} : 240 GeV**	**3yrs**	**> 10^6 e+e- → ZH**	**Never done**	1 MeV
s-channel H	***E_{cm} : m_H***	***(3yrs?)***	***O(5000) e+e- → H***	***Never done***	*<< 1 MeV*
$t\bar{t}$	**E_{cm} : $\geq$ 340 GeV**	**5yrs**	**10^6 e+e- → $t\bar{t}$**	**Never done**	2 MeV

FCC-ee experimental conditions



1. By design of the accelerator, low background conditions in the experiments, ~1cm radius beam pipe

2. High luminosity → DAQ rate 100kHz @Z, pile-up $O(10^{-3})$
   No trigger necessary (important for LLP searches)
   low angle upper limit of accelerator elements 100mrad
   beam pipe radius at IP : 10mm

3. High precision E_{CM} calibration O(10-100 keV)
   --@ Z (+WW unlike LEP) resonant depolarization
   -- at higher energies relies on ee→ Zγ , WW

4. Moderate beamstrahlung →measurable, ~Gaussian energy spread

5. New design compatible with 4 IP for FCC-ee → improve total Luminosity (and physics/MW) to match the multiple detector requirements

Motivation for the precision measurements and associated precision calculations

1. Given that the SM is complete with the Higgs discovery, how do we find out:
-- if the Higgs boson is exactly what is foreseen by the standard model?
-- where/what are the new physics phenomena that must be present to explain:
baryon asymmetry
dark matter,
neutrino masses (and other mysteries we don't understand)

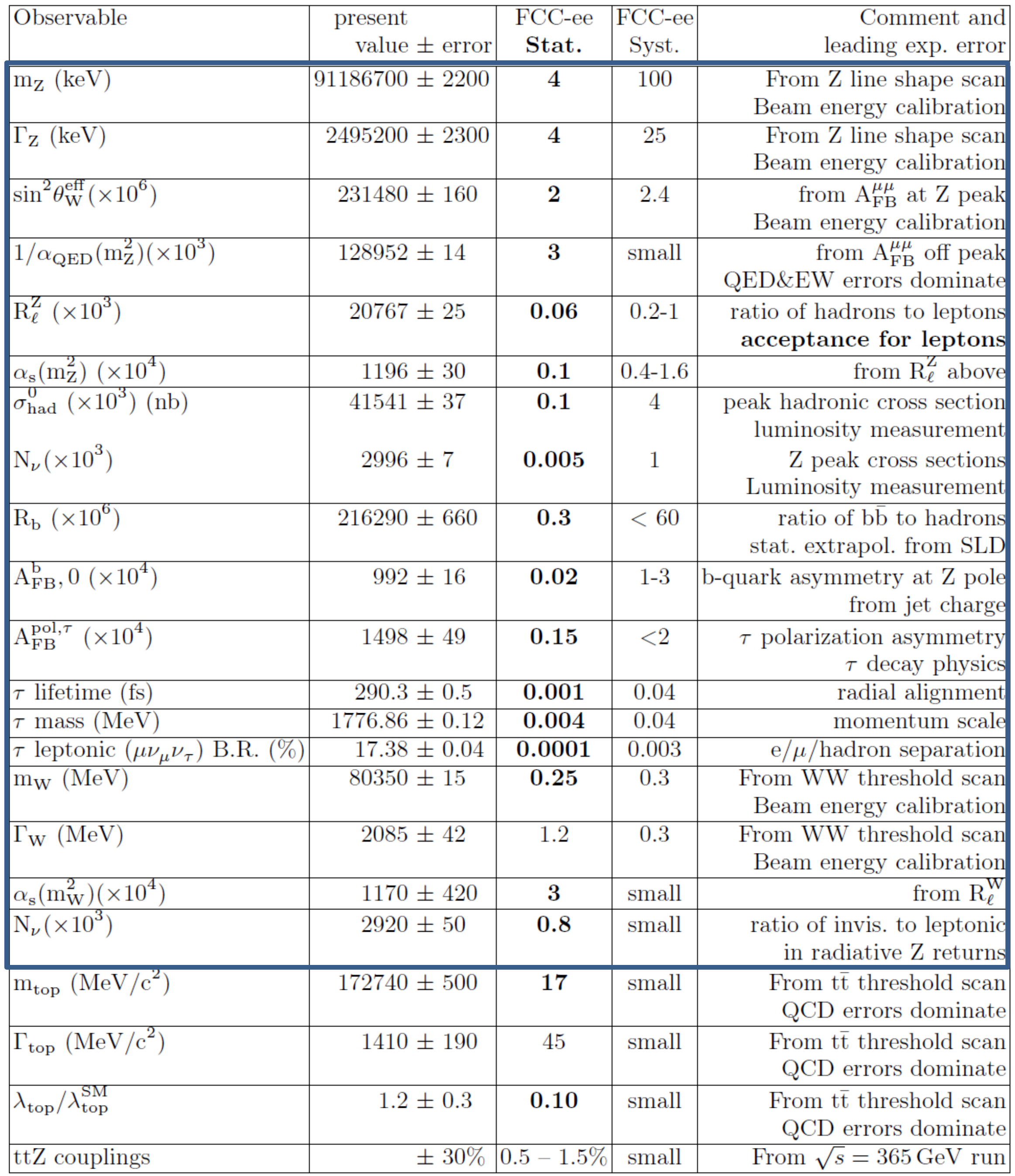
2. A powerful and broadly efficient methods is to perform **precision measurements**
-- many **observables** contain sensitivity to new phenomena, either by loops, direct long distance propagator effects, or mixing with SM coupled particles.
(in addition to a great program of direct searches for feebly coupled particles)
  -- are there any more weakly coupled particles?
    The top quark effect at LEP was 10σ! (➔ there is *not* another t-b quark system)
«T» any SU(2)-violating effect will appear strongly regardless of mass scale

«ν» -- is there mixing ? in particular active-sterile neutrino mixing (ibid)

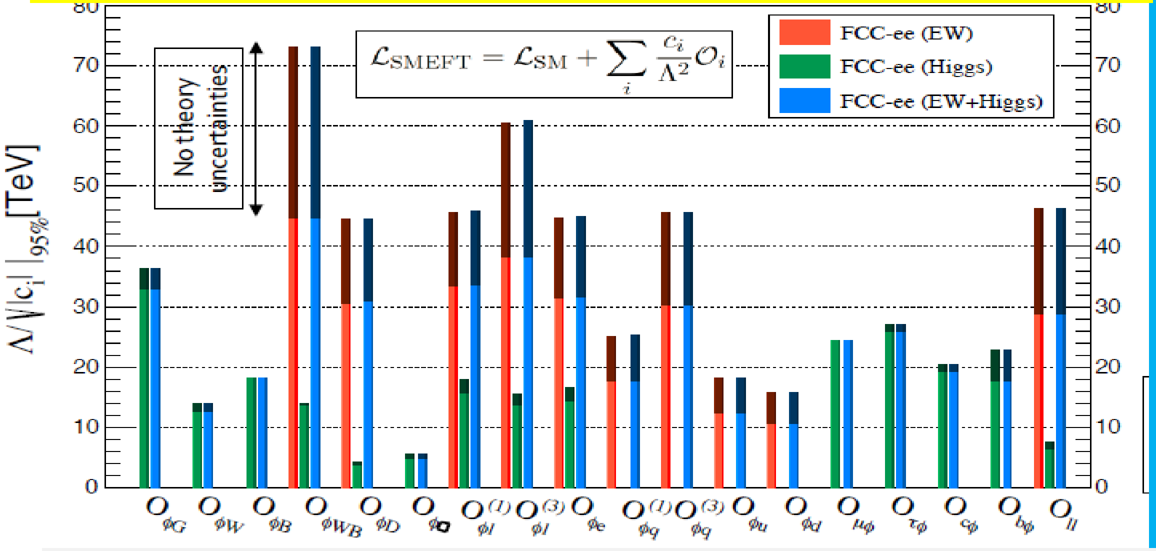
«S» -- high mass SM coupled SU(2)-respecting → (ex: Z' or degenerate SuSy)

EFT 'fits' can accomodate most models of new physics,
Emphasis on different observables depending on the question asked.

Precision EW measurements: is the SM complete?



Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
$R_\ell^Z\ (\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)\ (\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
$\sigma_{\rm had}^0\ (\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$R_b\ (\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^{b},0\ (\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{{\rm pol},\tau}\ (\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run



NP Sensitivity by oblique/vertex loops or mixing

- ***Higgs + EWPO (+ flavours) are complementary***
- top quark mass and couplings essential

(the 100km circumference is optimal for this)

- preliminary systematics

aim at reducing to the level of statistics

- many observables still to be added (flavours)
- complemented by high energy FCC-hh
- ***Theory work is critical and initiated*** *1809.01830*
- *see also recent physics workshop session.*

Status of electroweak precision measurements

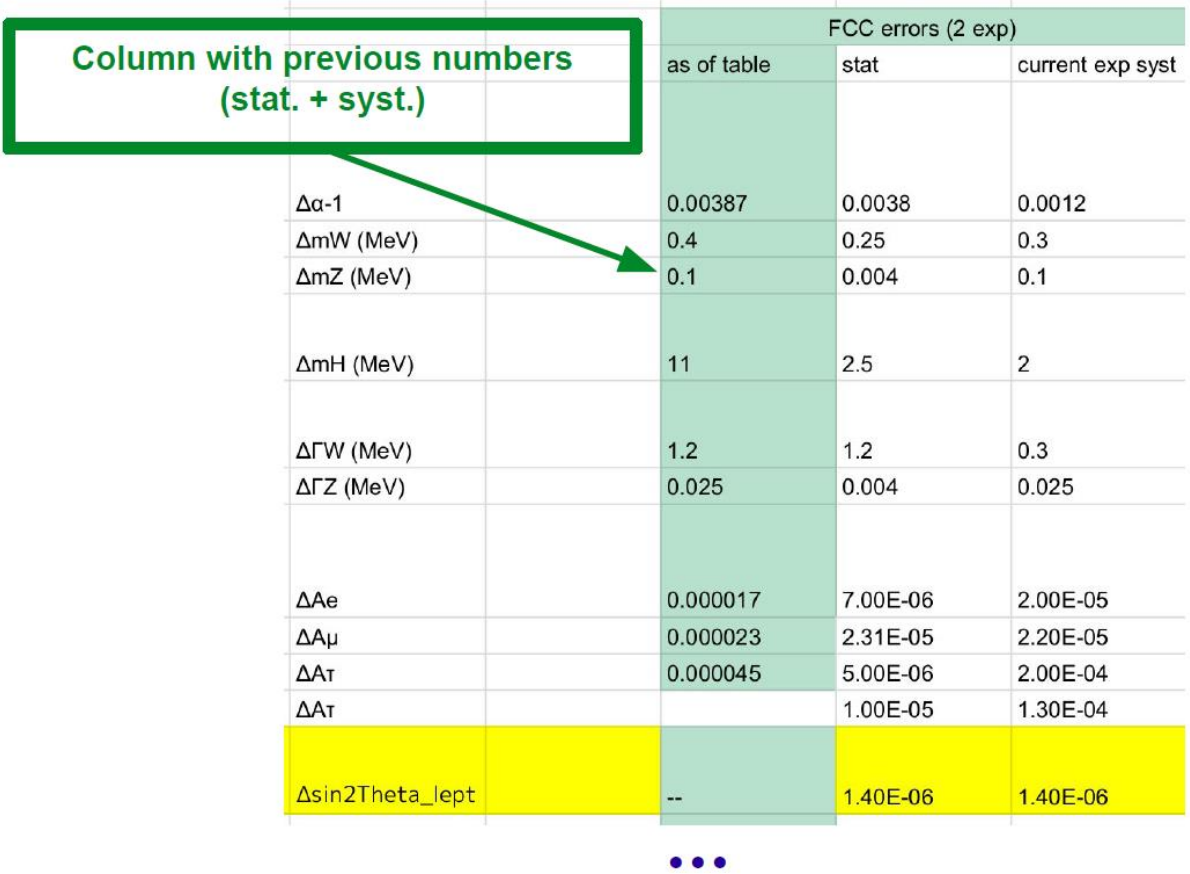
J. Alcaraz (CIEMAT-Madrid)

(Table updates: J.A. + A. Blondel + P. Janot + R. Tenchini)

FCC Physics Workshop
11 February 2022

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
física de pa

Our tables (being updated)



Column with previous numbers (stat. + syst.)

	FCC errors (2 exp)		
	as of table	stat	current exp syst
Δα-1	0.00387	0.0038	0.0012
ΔmW (MeV)	0.4	0.25	0.3
ΔmZ (MeV)	0.1	0.004	0.1
ΔmH (MeV)	11	2.5	2
ΔΓW (MeV)	1.2	1.2	0.3
ΔΓZ (MeV)	0.025	0.004	0.025
ΔAe	0.000017	7.00E-06	2.00E-05
ΔAμ	0.000023	2.31E-05	2.20E-05
ΔAτ	0.000045	5.00E-06	2.00E-04
ΔAτ		1.00E-05	1.30E-04
Δsin2Theta_lept	--	1.40E-06	1.40E-06

• • •

General remarks

It is obvious that once the data arrive (around 204x) a large number of people and significant resources will be devoted to extract the best possible results. (and typically try to reach systematics that are as small as statistics if possible)

The main aim of the physics studies (programme+performance) is to be **proactive** in identifying the key limiting factors and defining **detector requirements or theoretical effort** that will allow to surmount them.

To this effect a process has been proposed
-- defining benchmark measurements (based on physics motivation!)
-- elaborating case studies that lead to detector requirements.

One of the constant issues for the most precise Z pole observables is the event statistics of several 10^{12} events.
-- is full simulation needed?
-- back of envelope / gen. level/ fastsim/ reweighting/ event rotations etc. etc.
-- importance of event generator at appropriate level of detail

A first list of benchmark studies

'line-shape'

1. Towards an ultimate measurement of $R_\ell = \frac{\sigma(\mathrm{Z}\to\mathrm{hadrons})}{\sigma(\mathrm{Z}\to\mathrm{leptons})}$
2. Towards an ultimate measurement of the Z total width Γ_{Z}
3. Towards an ultimate measurement of the Z peak cross section
4. Direct determination of $\sin^2\theta^\ell_{\mathrm{eff}}$ and of $\alpha_{\mathrm{QED}}(m^2_{\mathrm{Z}})$ from muon pair asymmetries
5. Determination of the QCD coupling constant $\alpha_{\mathrm{S}}(m^2_{\mathrm{Z}})$
6. Tau Physics, Lepton Universality, and Lepton Flavour Violation

Tau polarization

7. Tau exclusive branching ratios and polarization observables

HF Electroweak R_b

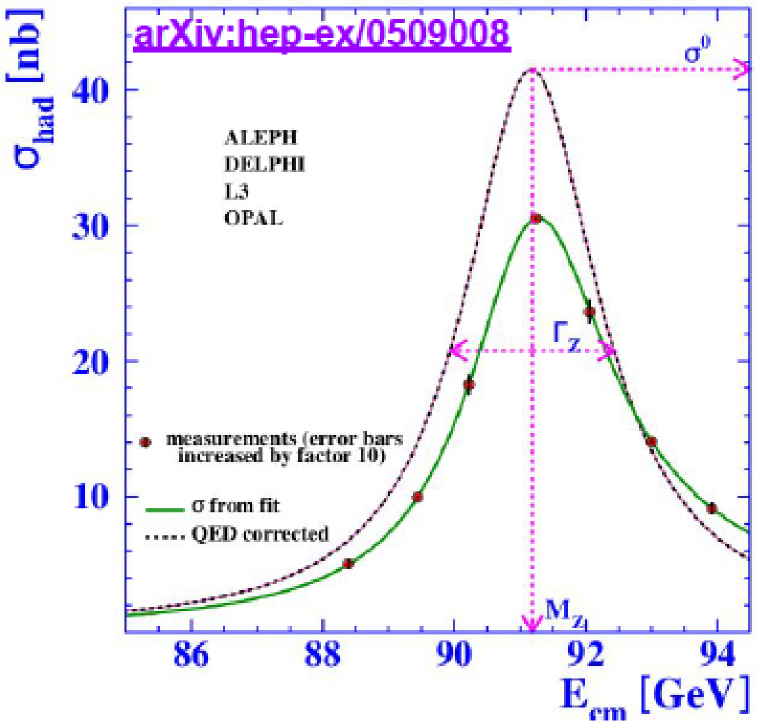
8. Z-pole Electroweak observables with heavy quarks
9. Long lived particle searches

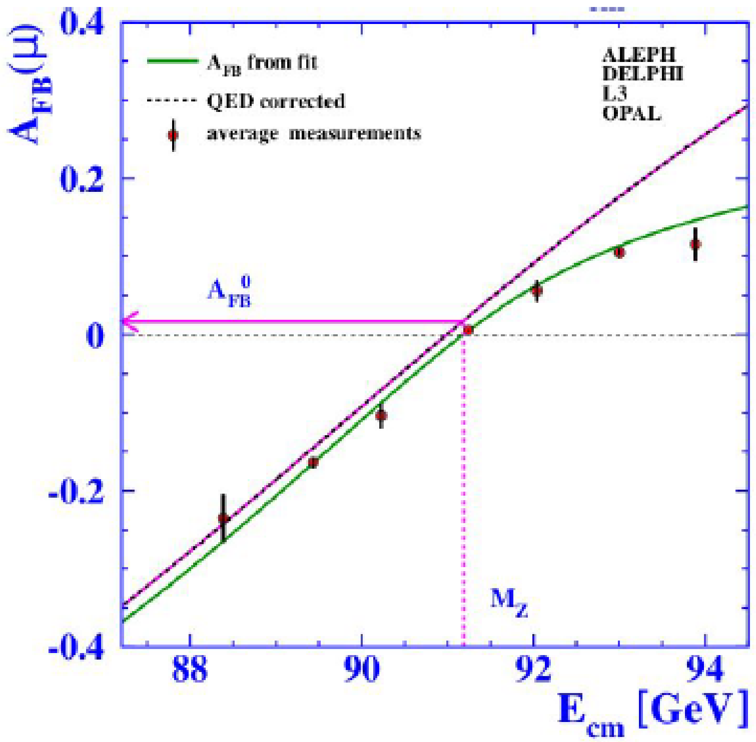
W mass and width, branching ratios

10. Measurement of the W mass

Z lineshape measurements

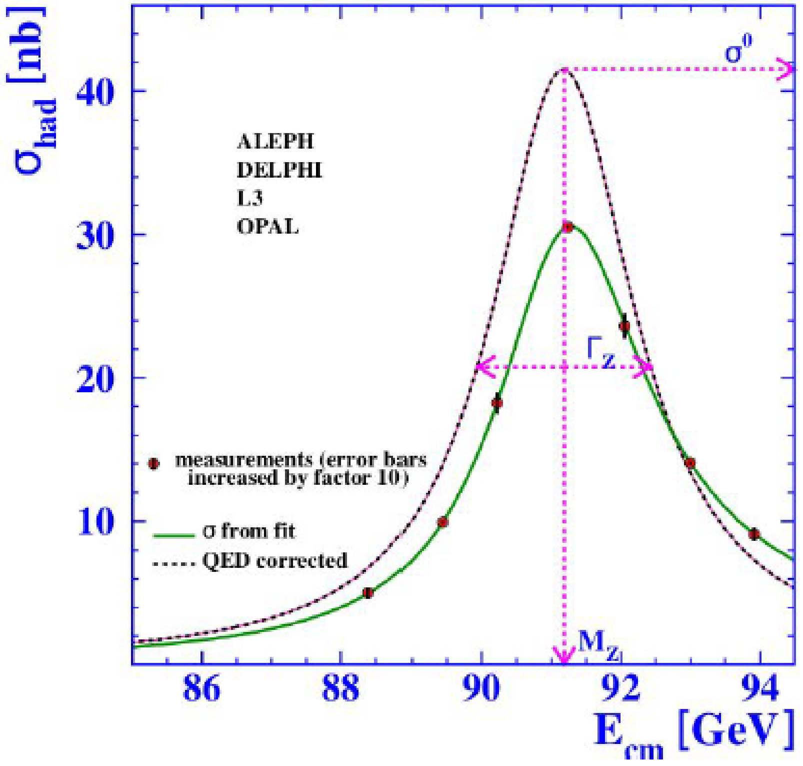
Juan Alcaraz





- Expected precisions in a nutshell:
  - $\approx 10^{-4}$ on cross sections (aimed luminosity uncertainty); possibility to reduce it by an order of magnitude using the measured $\sigma(ee\rightarrow\gamma\gamma)$ as reference
  - $\approx 10^{-6}$ statistical uncertainties ($\approx 1/\sqrt{N}$) on relative measurements like forward-backward charge asymmetries
  - Ultimate uncertainties typically dominated by systematics; precious value of “Tera” Z samples to study / constrain many of those uncertainties

$R_l = \Gamma_{had}/\Gamma_l$



J. Alcaraz, 23 Oct 2020, FCC-ee Z lineshape and EW HF

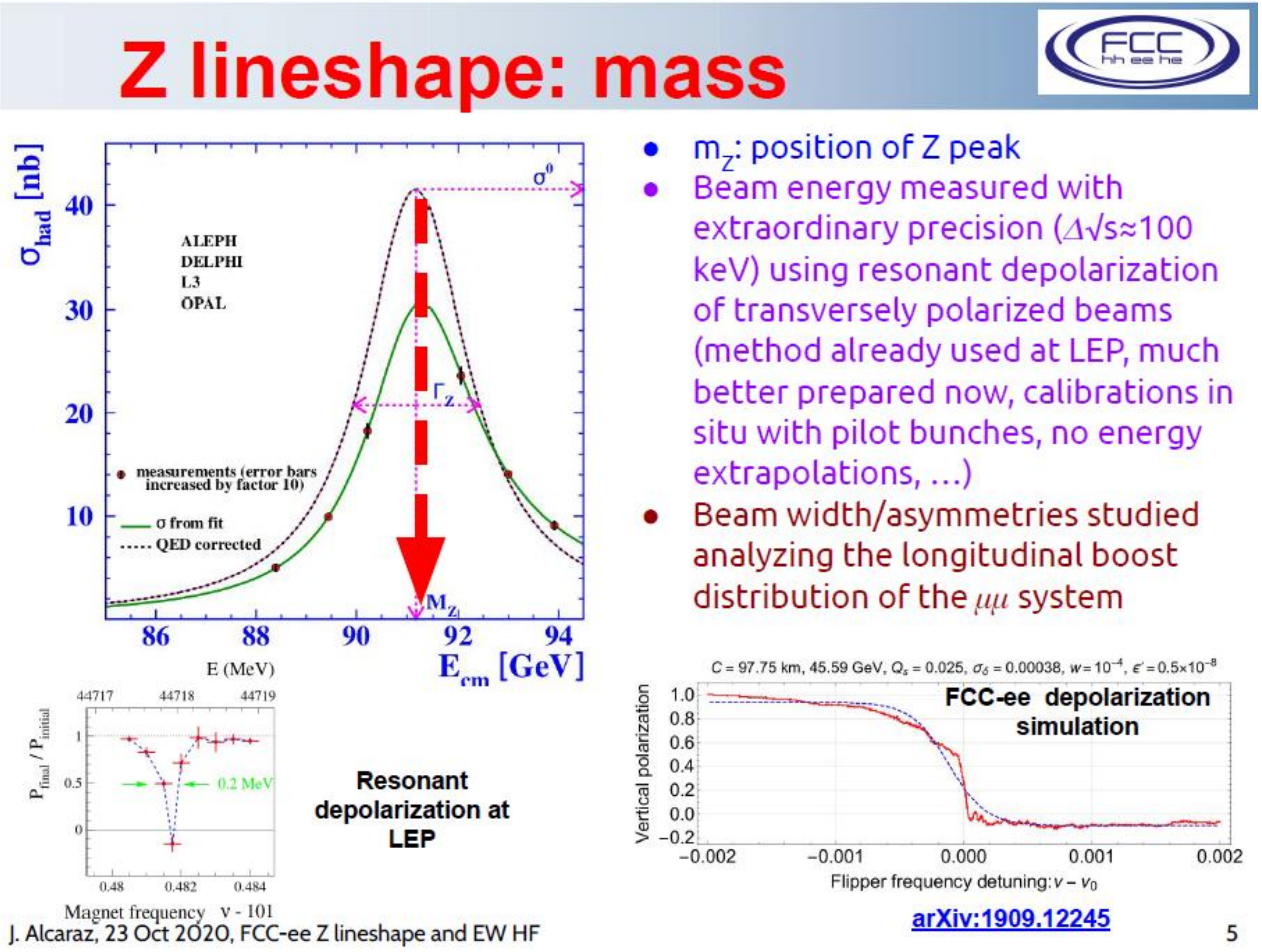
statistical precision 3 10^{-6} for each of $\ell = e, \mu, \tau$
test of universality in NC
test of quark-lepton universality
leads to determination of $\alpha_{QCD}(m_Z)$ with 10^{-4} precision (better?)

at LEP main systematic came from lepton acceptance
(a cosθ cut at 0.95 leads to ~10% event loss for leptons
only 1-2% for hadrons)
Event rotation technique used for hadron successfully (leptons?)

we have requested a low angle limit of 100 mrad
for the accelerator elements (final focus, solenoid compensation)

a clean design of the low angle detector fiducials
(similar to lumi monitor) probably necessary.

level of detail in lepton event generator etc...



Z lineshape: mass

- m_Z: position of Z peak
- Beam energy measured with extraordinary precision ($\Delta\sqrt{s}\approx100$ keV) using resonant depolarization of transversely polarized beams (method already used at LEP, much better prepared now, calibrations in situ with pilot bunches, no energy extrapolations, …)
- Beam width/asymmetries studied analyzing the longitudinal boost distribution of the $\mu\mu$ system

Resonant depolarization at LEP

FCC-ee depolarization simulation

arXiv:1909.12245

J. Alcaraz, 23 Oct 2020, FCC-ee Z lineshape and EW HF

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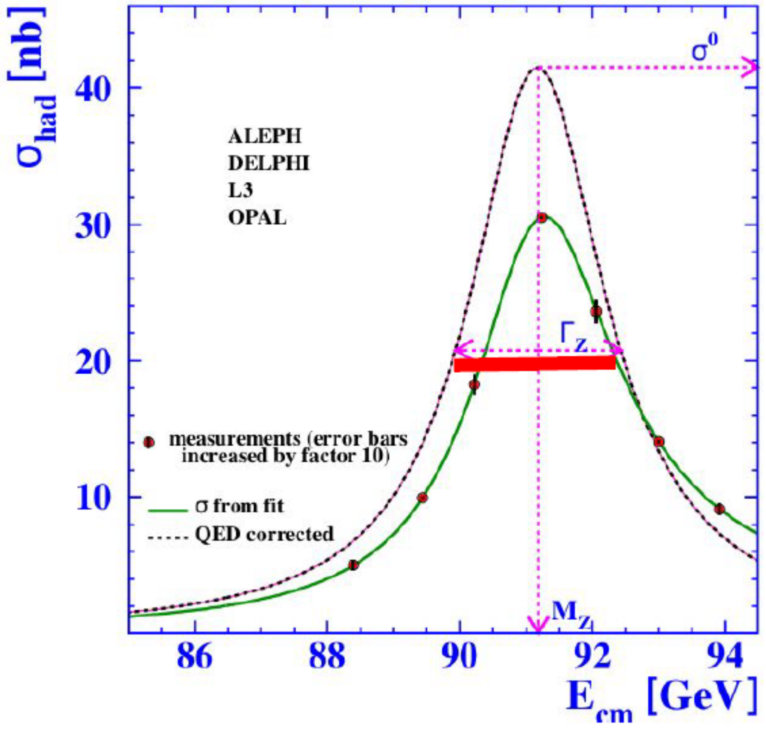
see later...

Γ_Z, N_ν

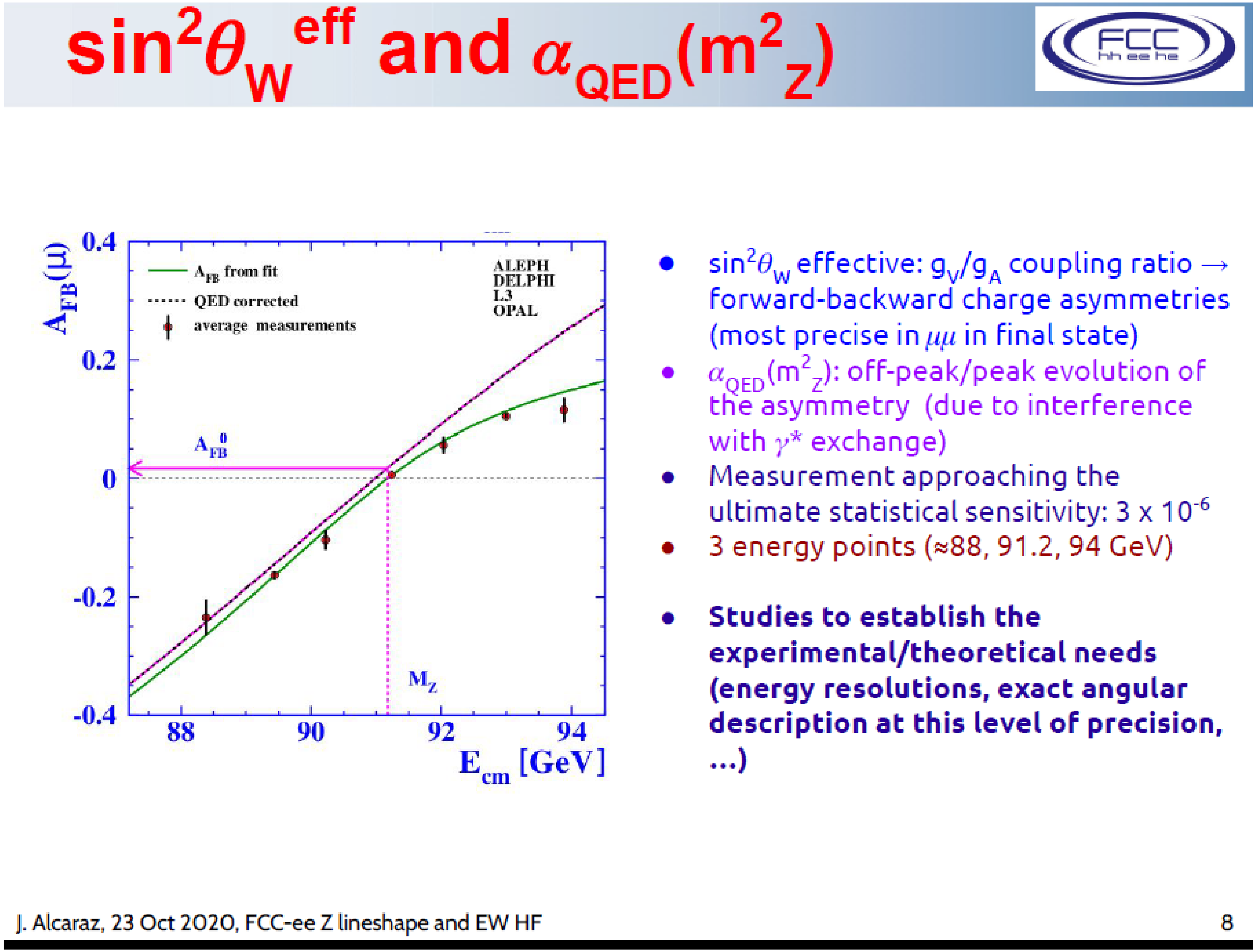


- **Total Z width → basically coming from the visible width of the lineshape**
- **Statistical precision of $\Delta\Gamma_Z \approx 4$ keV** using hadronic lineshape
- Dominant systematics is the "point-to-point" beam uncertainty
- Study the point-to-point changes (3-5 points) using the invariant mass of dimuon events at each energy and realistic conditions at the beam interaction region: **current estimate is $\Delta\Gamma_Z \approx 25$ keV**

- **A precise measurement of N_ν / invisible width requires a measurement of cross sections at the peak, not just Γ_Z → luminosity dependency → ≈ 10 times improvement over LEP (it will be measured with better precision using radiative recoil ratios: $\sigma(\nu\nu\gamma)/\sigma(ll\gamma)$)**

For the width the two-gamma background (non resonant) should be studied. Also event shapes might be slightly affected by the varying ISR across the peak.

Fo the absolute cross-section luminosity is dominant.



$\sin^2\theta_W^{eff}$ and $\alpha_{QED}(m^2_Z)$

- $\sin^2\theta_W$ effective: g_V/g_A coupling ratio → forward-backward charge asymmetries (most precise in $\mu\mu$ in final state)
- $\alpha_{QED}(m^2_Z)$: off-peak/peak evolution of the asymmetry (due to interference with γ^* exchange)
- Measurement approaching the ultimate statistical sensitivity: 3 x 10^{-6}
- 3 energy points (≈88, 91.2, 94 GeV)
- **Studies to establish the experimental/theoretical needs (energy resolutions, exact angular description at this level of precision, ...)**

J. Alcaraz, 23 Oct 2020, FCC-ee Z lineshape and EW HF

this is an easier measurement as many experimental uncertainties vanish

Peak asymmetry measures

$A_{FB}^{\mu\mu} = ¾ \; A_e A_\mu$

where

$A_\ell \equiv (g_{L\ell}^2 - g_{R\ell}^2)/(g_{L\ell}^2 + g_{R\ell}^2)$

$= 2\, g_{V\ell}\, g_{A\ell} / (g_{V\ell}^2 + g_{A\ell}^2)$

and

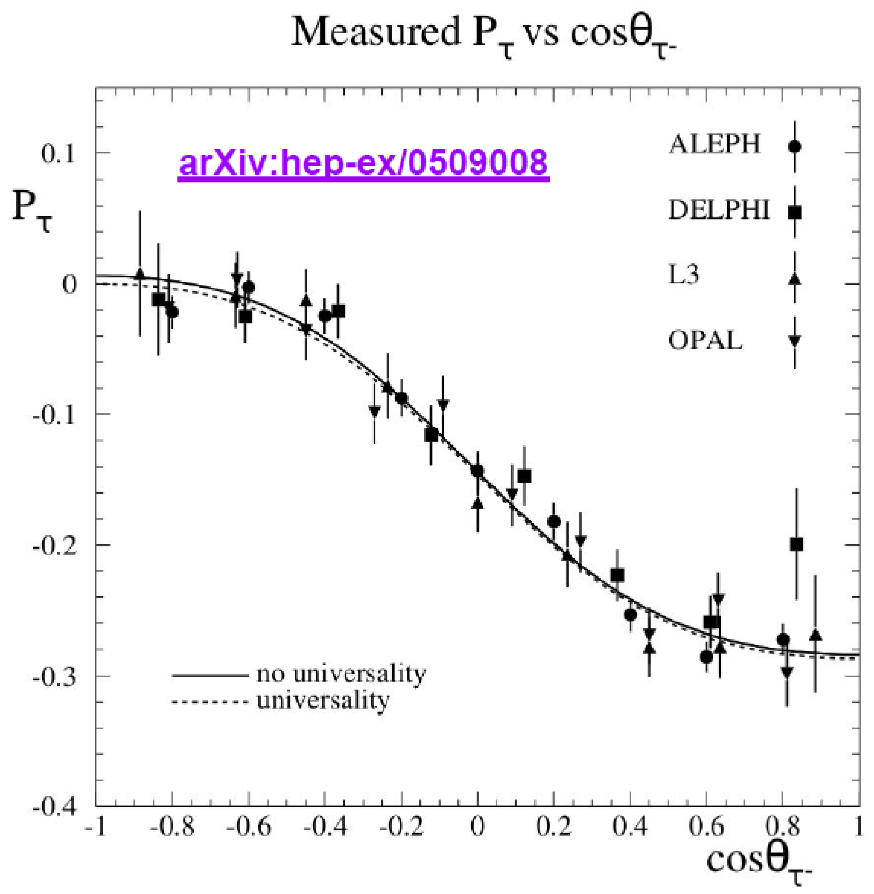
$\sin^2\theta_W^{eff} \equiv ¼\,(1- g_{V\ell}/g_{A\ell})$

this is *not* $1-m_W^2/m_Z^2$ (should better not be used by experiments, just use m_W as relation is sensitive to new physics)

refer to analysis by P. Janot for the extraction of $\alpha_{QED}(m_Z^2)$ arxiv:1512.05544 importance of QED effects on asymmetry and event generator

analysis of asymmetry for e and τ final states of great interest – can we improve precision?

Lepton asymmetries: A_e, A_μ, A_τ

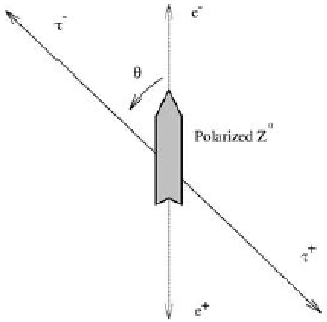

Measured P_τ vs $\cos\theta_{\tau^-}$

arXiv:hep-ex/0509008

$$P(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

- **IMPORTANT: the FCC-ee baseline does not use longitudinal beam polarization:**
  - Although feasible, It would reduce too much the available luminosity
  - Not needed: tau polarization input is enough to measure A_e, thus facilitating precise measurements of the L-R asymmetry parameters for all fermions: A_e,A_μ,A_τ, A_b,A_c

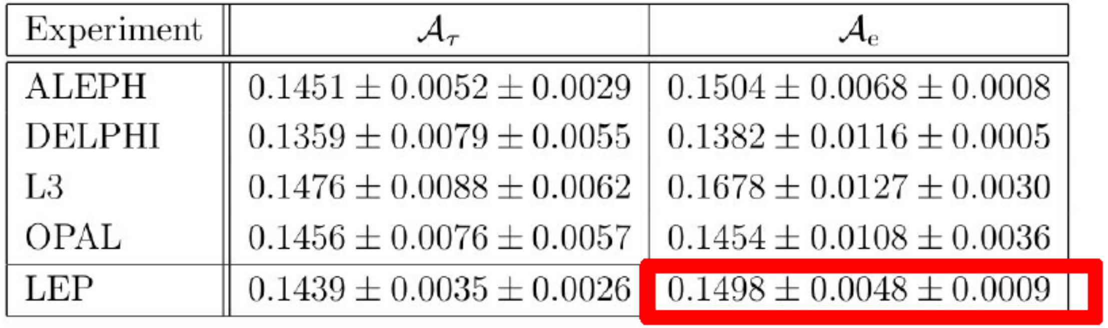
$$A_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$



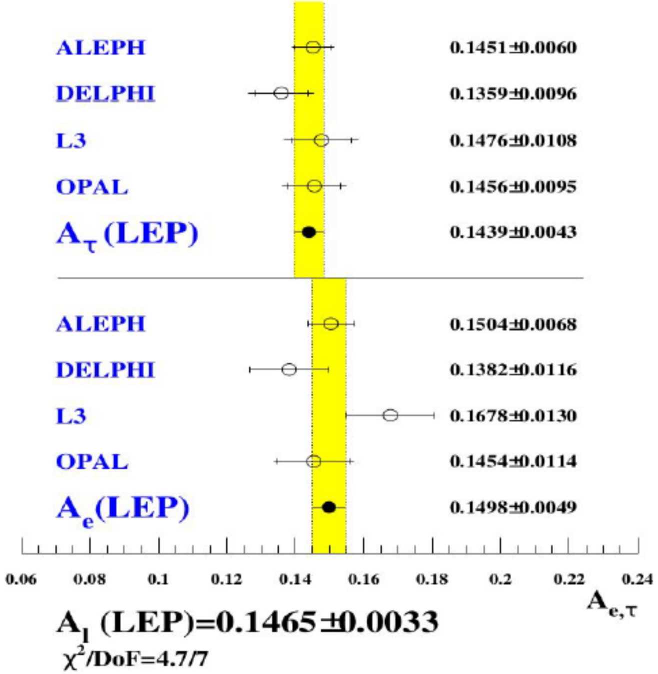
- **A_e = Z polarization**
- **FB tau polarization asymmetry:**

$$\mathcal{P}_\tau^{FB} = -\tfrac{3}{4}\mathcal{A}_e$$

A_e is a safe measurement...



Experiment	$\mathcal{A}_\tau$	$\mathcal{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108 \pm 0.0036$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$	$0.1498 \pm 0.0048 \pm 0.0009$



J. Alcaraz, 11 Feb2022, FCC EW Status

- **The FB tau polarization asymmetry (=$\mathcal{A}_e$) is NOT affected by uncertainties on the knowledge of polarization distributions / migrations (unless they are both F-B asymmetric and charge dependent)**
- **Dominant systematic uncertainty should be non-tau backgrounds: assume an order of magnitude reduction w.r.t. LEP: huge control samples, reduction via cuts, ...**

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Here the uncertainty is clearly detector dependent. Detectors with highly granular EM calorimeter and efficient tracker (TPCs) (ALEPH and DELPHI) fared better that drift chamber + cristal/leadglass blocks.

➔ this measurement is extremely important and should have heavy impact on detector design especially the EM calorimeter (granular rather than high energy resolution.

$R_b \equiv \Gamma(Z \rightarrow \bar{b}b)/\Gamma(Z \rightarrow \text{hadrons})$

Of all FCC-ee measurements this is where the largest relative improvement wrt LEP is expected.
-- factor 500 in statistical precision x a factor 5 in tagging efficiency (85% @ <1% background)

In addition R_b is sensitive to new physics via the vertex correction involving top and thus to e.g. supersymmetry in a different way than the usual self-energy corrections (see next slide)

With $7\ 10^{11}$ $Z \rightarrow \bar{b}b$ events a relative statistical precision of $O(1.5\ 10^{-6})$ is expected (WOW!)

There is a great synergy with the b,c,g tagging undertaken for the Higgs decays by Selvaggi et al. The Z decay should also be used as a calibration.

The measurement is affected by gluon splitting to $\bar{b}b$ in hadronic events, but a lot of information should exist in the data to eliminate uncertainties on tagging efficiency, hemisphere correlations, gluon production and many more. ***How far can we go?***

Also of interest R_c, R_s, etc... where strange particle ID might be more important.

Precision Natural SUSY at CEPC, FCC-ee, and ILC, JJ Fan, M. Rees and Liantao Wang

arXiv:1412.3107v2 figure 5 (top row)

«Higgs and EWPOs are complementary»

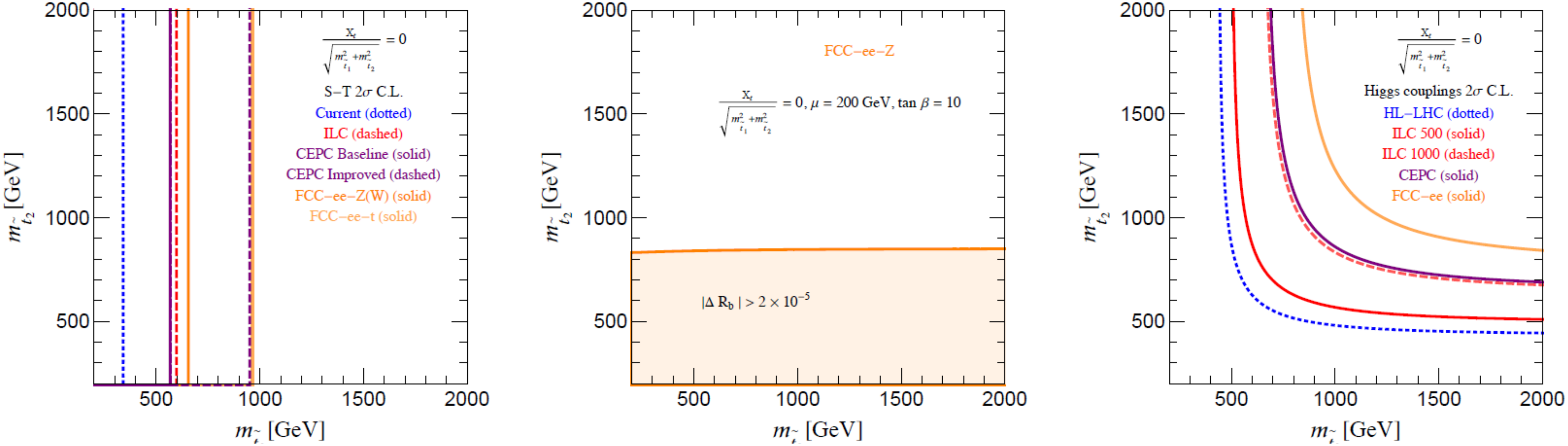
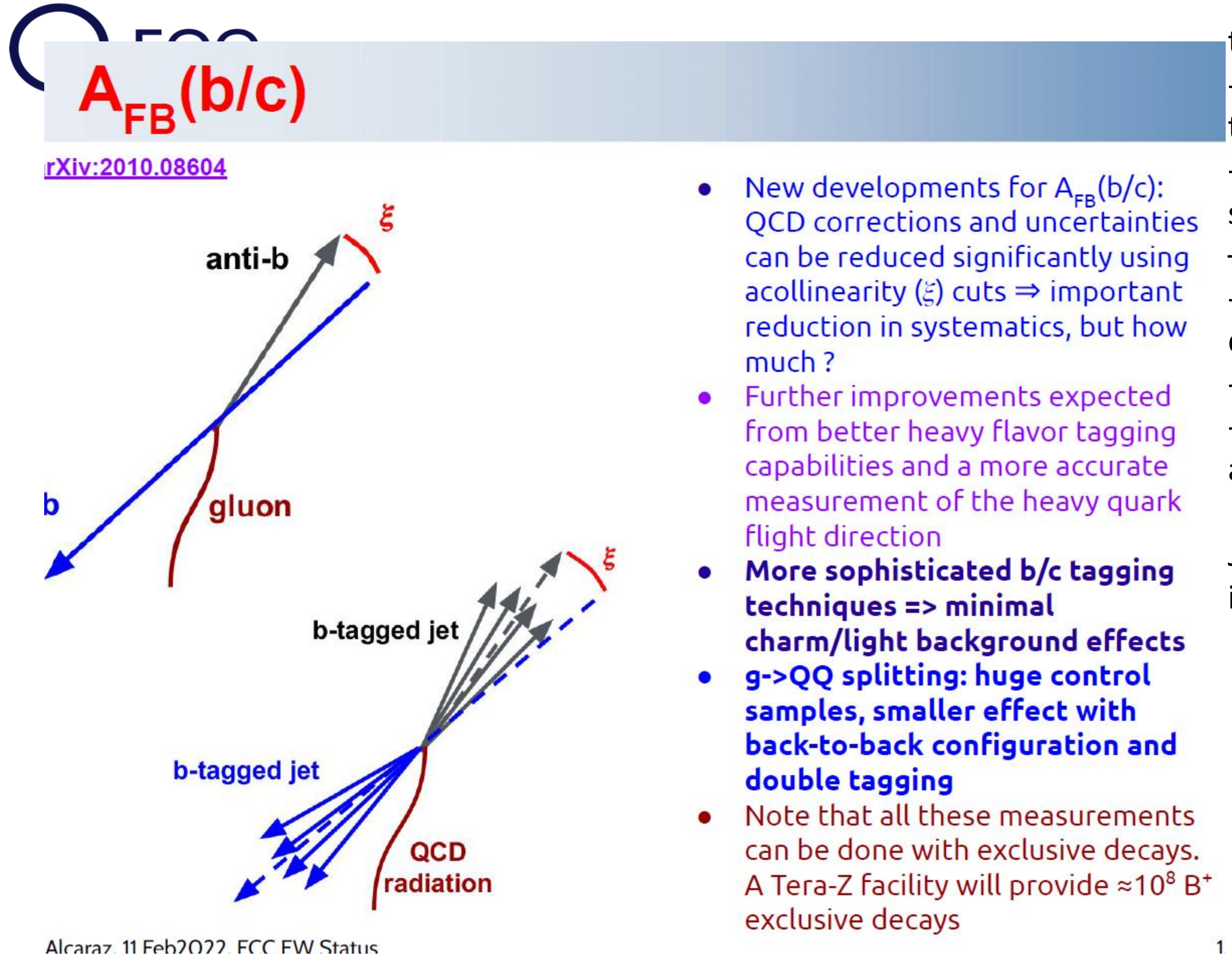


Figure 5. Regions in the stop physical mass plane that are/will be excluded at 2σ by EWPT with oblique corrections (left column), R_b at FCC-ee (mid column) and Higgs couplings (right column) for different choices of $X_t/\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}$: 0 (first row), 0.6 (2nd row), 1.0 (3rd row) and 1.4 (last row). We chose the mass eigenstate with $m_{\tilde{t}_1}$ to be mostly left-handed while the mass eigenstate with $m_{\tilde{t}_2}$ to be mostly right-handed. For non-zero choices of X_t, there are regions along the diagonal line which cannot be attained by diagonalizing a Hermitian mass matrix [32]. Also notice that the vacuum instability bound constrains $X_t/\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim \sqrt{3}$ [76].

" also, b→ sγ could be useful"



A_{FB}(b/c)

rXiv:2010.08604

- New developments for A_{FB}(b/c): QCD corrections and uncertainties can be reduced significantly using acollinearity (ξ) cuts ⇒ important reduction in systematics, but how much ?
- Further improvements expected from better heavy flavor tagging capabilities and a more accurate measurement of the heavy quark flight direction
- **More sophisticated b/c tagging techniques => minimal charm/light background effects**
- **g->QQ splitting: huge control samples, smaller effect with back-to-back configuration and double tagging**
- Note that all these measurements can be done with exclusive decays. A Tera-Z facility will provide ≈10^8 B^+ exclusive decays

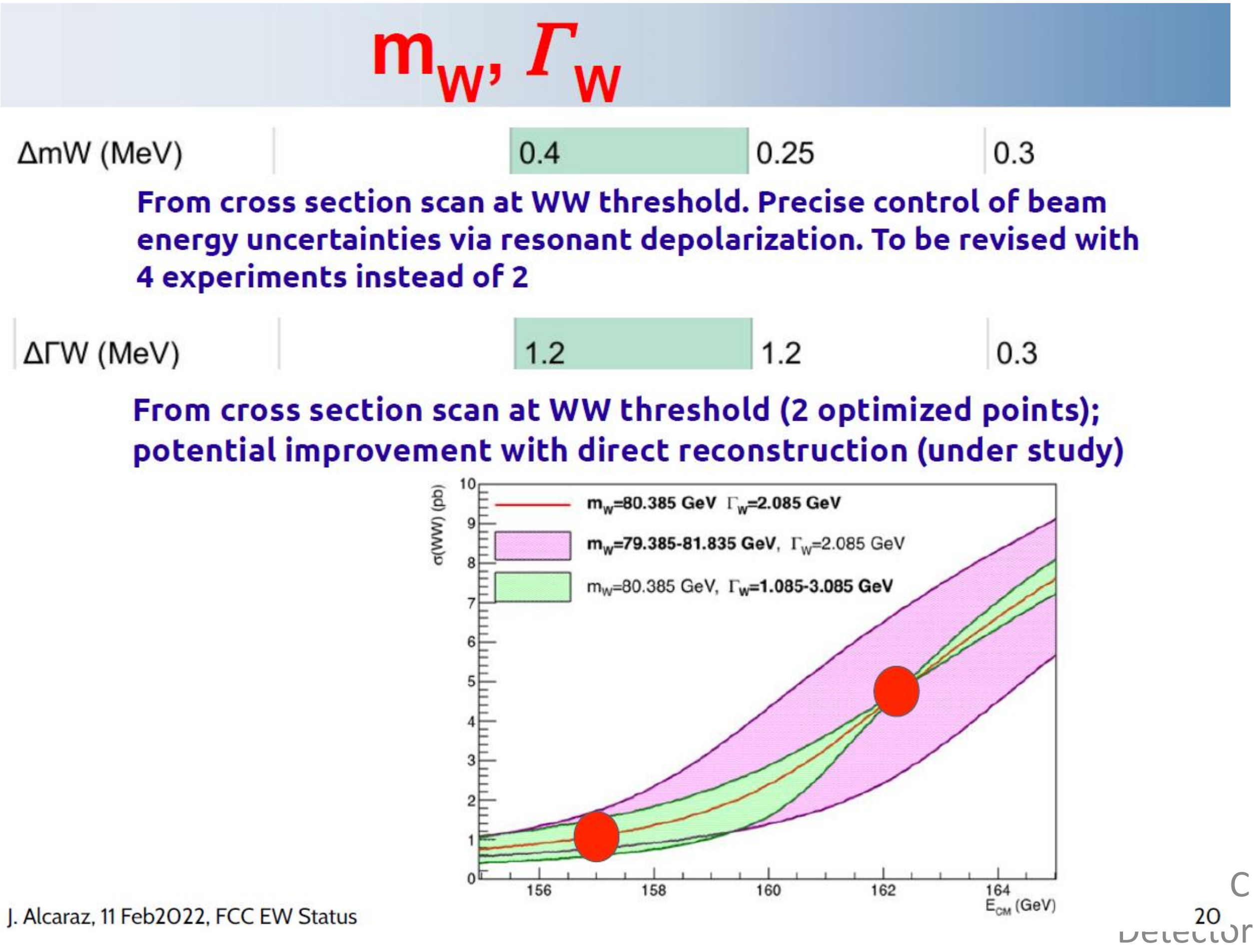
Alcaraz, 11 Feb2022, FCC EW Status 1

this measurement allows
-- in combination with Ae from $P\tau^{FB}$
to extract Ab.
-- or directly to be used as an EWPO
sensitive to similar effects as $\sin^2\theta_W^{eff}$
–some buzz due to present difference with A_{LR}
-- sensitive to gluon emission which
dilutes the forward backward asymmetry.
-- requires charge tagging
-- jet charge was the best charge indicator
at the end of LEP

J. Alcaraz showed that, similarly to R_b, lots of information can be retrieved from the data

W mass, width and branching ratios

-- W mass is the most sensitive quantity when compared with G_F m_Z and $\alpha_{QED}(m_Z)$ but sensitive to errors in the latter or direct comparison with $\sin^2\theta_W^{eff}$ (no sensitivity to error in $\alpha_{QED}(m_Z)$ in this case).



m_W, Γ_W

ΔmW (MeV)	0.4	0.25	0.3

From cross section scan at WW threshold. Precise control of beam energy uncertainties via resonant depolarization. To be revised with 4 experiments instead of 2

ΔΓW (MeV)	1.2	1.2	0.3

From cross section scan at WW threshold (2 optimized points); potential improvement with direct reconstruction (under study)

J. Alcaraz, 11 Feb2022, FCC EW Status

Two techniques

-- total WW cross-section around theshold – Paolo Azzurri)

-- invariant mass reconstruction using constrained kinematic fit for WW threshold or higher energies. (M. Beguin thesis)

-- possibility of measurement of width from mass reco?

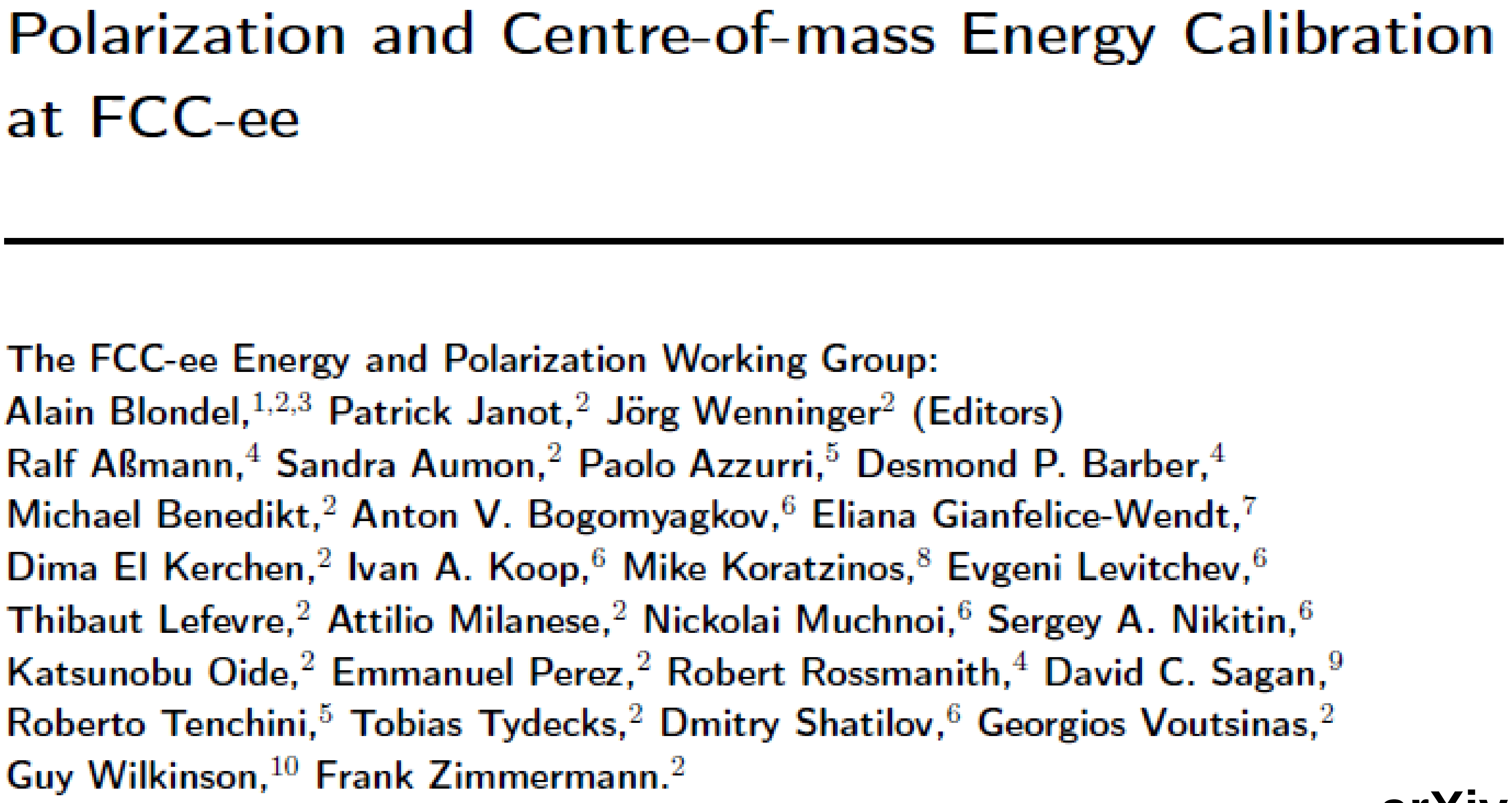
-- precision of resonant depolarization at WW threshold to be improved.

-- measurement of hadronic/leptonic branching ratio provide

-- independent measurement of $\alpha_{QCD}(m_W)$

-- further verifications of charged current interactions direct measurements of Vcs, Vbc and Vbu

FCC-ee beam polarization and centre-of-mass energy calibration



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

Some references (not a complete set!):

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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;
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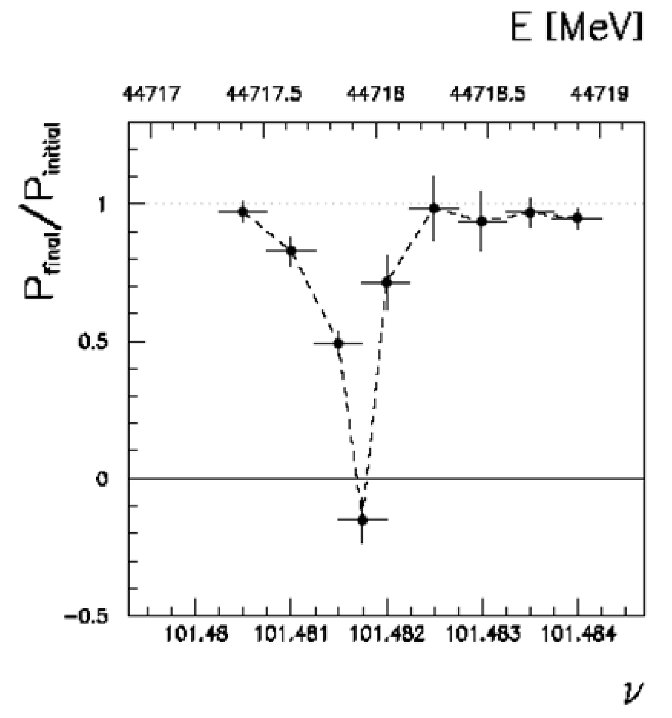
Precision EW Measts on the Z Phys.Rept.427:257-454,2006 arXiv:0509008v3
D.P. Barber and G. Ripken ``Handbook of Accelerator Physics and Engineering” World Scientific (2006), (2013)
D.P. Barber and G. Ripken, Radiative Polarization, Computer Algorithms and Spin Matching in Electron Storage Rings
arXiv:physics/9907034
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**

Beam Polarization can provide two main ingredients to Physics Measurements



1. **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 → 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 cou trons (15%)
or with final state polarization analysis for CC weak deca rized) (tau and top)

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

$A_{LR} = A_e$, $A_{FB}^{Pol}(f)$ etc... (CERN Y.R. 8

figure of merit is L.P^2 --> must not los actor ~10 in lumi.

self calibrating polarization measu es controlled e+ and e- polarization

at high statistics A_{FB}^{Pol} = *A* *of* A_{LR} *(Tenchini)*

-- enhance Higgs cross se ~30%)

top quark c l state analysis does as well (Janot **arXiv:1503.01325)**

enha tract/monitor backgrounds, for ee→WW , ee →H

-- require ation level and often both e- and e+ polarization

➔ ing If loss of luminosity is too high

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

CIDED 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

Requirements from physics

1. Center-of-mass energy determination with precision of << ± 100 keV around the Z peak
2. Center-of-mass energy determination with precision of < ± 300 keV at W pair threshold
3. For the Z peak-cross-section and width, require energy spread uncertainty $\Delta\sigma_E/\sigma_E = 0.2\%$

NB: at 2.3 $10^{36}/\mathrm{cm}^2/\mathrm{s}/\mathrm{IP}$: **full LEP statistics** 10^6 $\mu\mu$ 2.10^7 qq in **6 minutes** in each expt

-- use resonant depolarization as main measuring method

-- use pilot bunches to calibrate during physics data taking: 100 calibrations per day each 10^{-6} rel.

-- long lifetime at Z requires the use of wigglers at beginning of fills

➔ take data at points where self polarization is expected

$$\boxed{\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}} \approx N + (0.5 \pm 0.1) \qquad E_{CM} = \left(N + (0.5 \pm 0.1)\right) \text{ x } 0.8812972 \text{ GeV}$$

Given the Z and W widths of 2 GeV, this is easy to accommodate with little loss of statistics.

It might be more difficult for the Higgs 125.09+-0.2 corresponds to ν_s = 141.94+-022

Simulations of self-polarization level with SITROS

Some results of coupling/dispersion correction

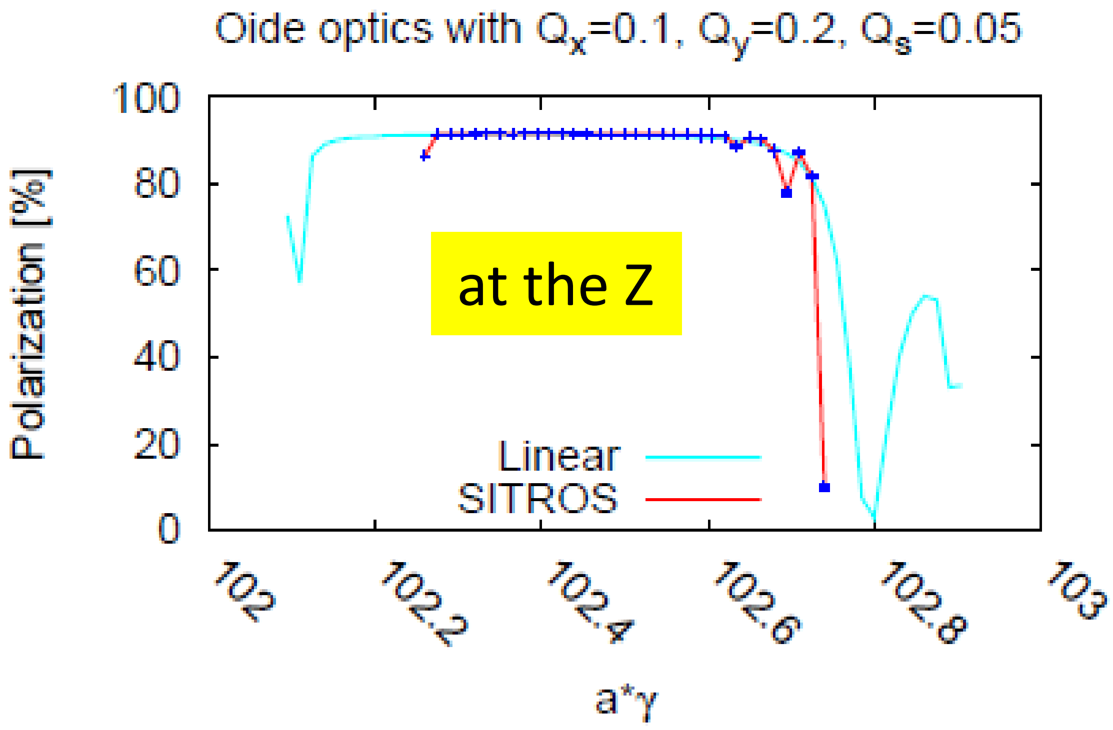
E. Gianfelice

- δy^{Q}_{rms}=200 μm (including doublets)
- 250 μrad quadrupole roll angle (including doublets)
- 1086 BPMs w/o errors
- orbit corrected with 1086 CVs down to y_{rms}=0.05 mm
- coupling/dispersion correction with 289 skew quadrupoles

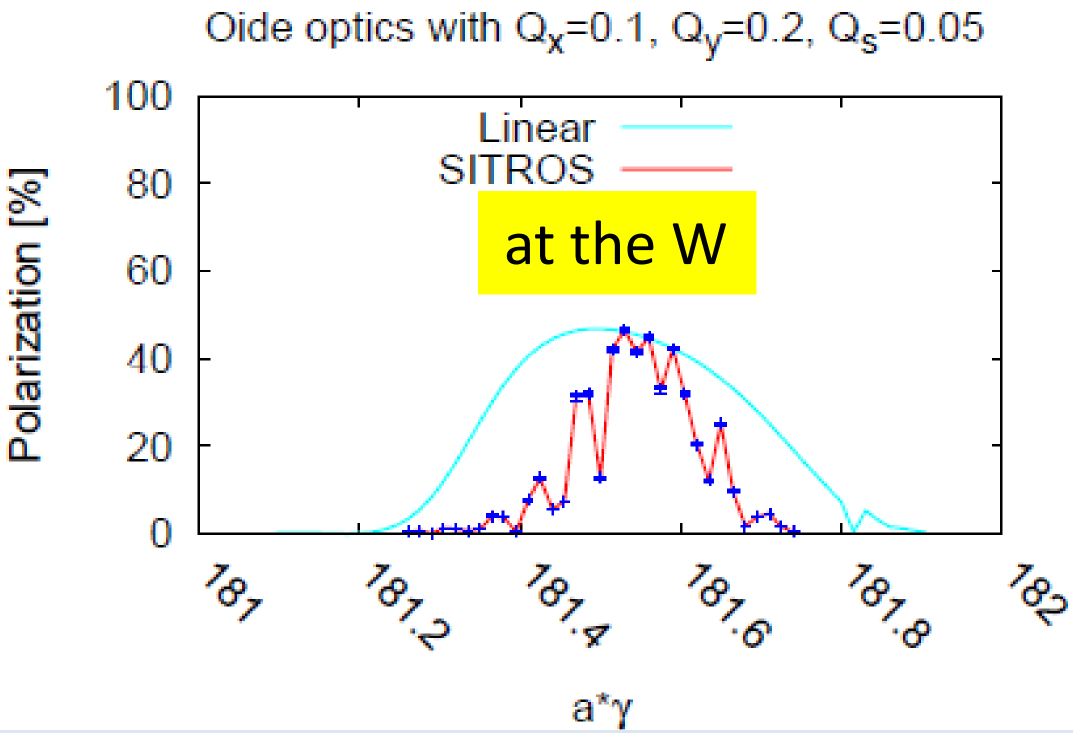
1. orbit and emittance corrections needed for the FCC-ee luminosity seem sufficient to ensure useful levels of polarization

2. HOWEVER: same simulation does not produce luminosity and polarization,

➔ effect of simultaneous optimization could not be simulated



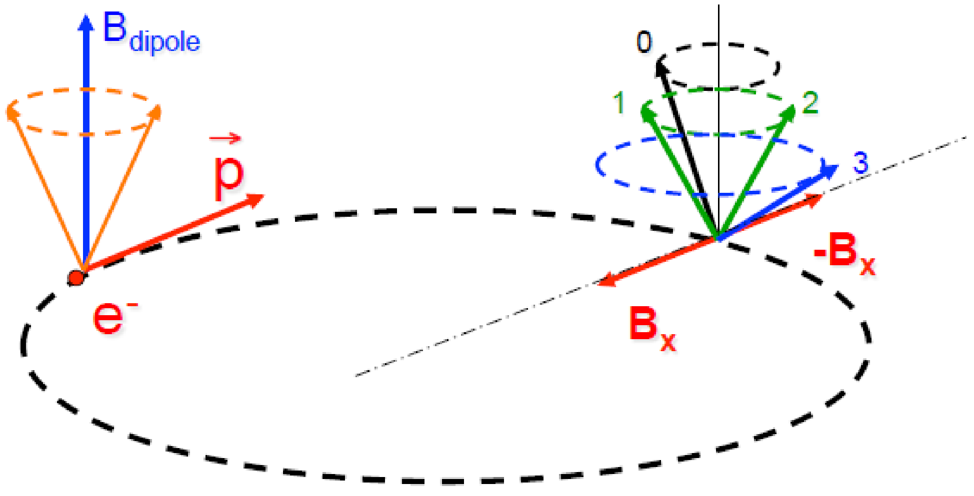
at the Z



at the W

Excellent level of polarization at the Z (even with wigglers) and sufficient at the W $\underline{\sigma_E \propto E^2/\rho}$

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*)

$$\delta\theta_{spin} = (g-2)/2 \; . \; E/m \; \delta\theta_{trajectory}$$
$$= \nu \; . \; \delta\theta_{trajectory}$$
$$\nu = E_{beam} / 0.4406486$$
$$= 103.5 \text{ at the Z peak}$$

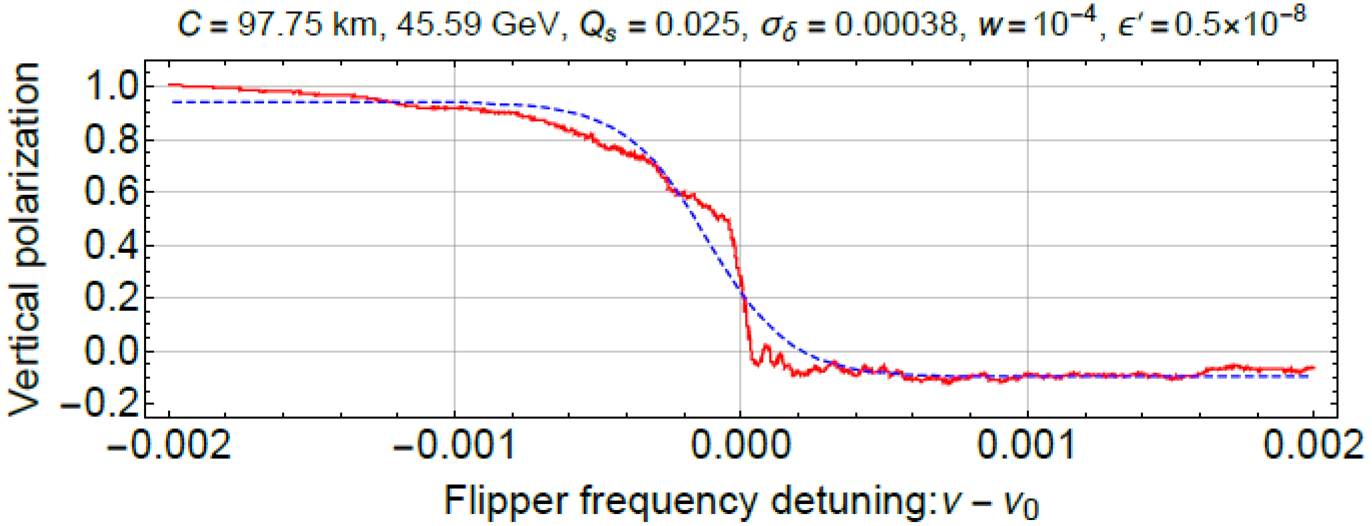
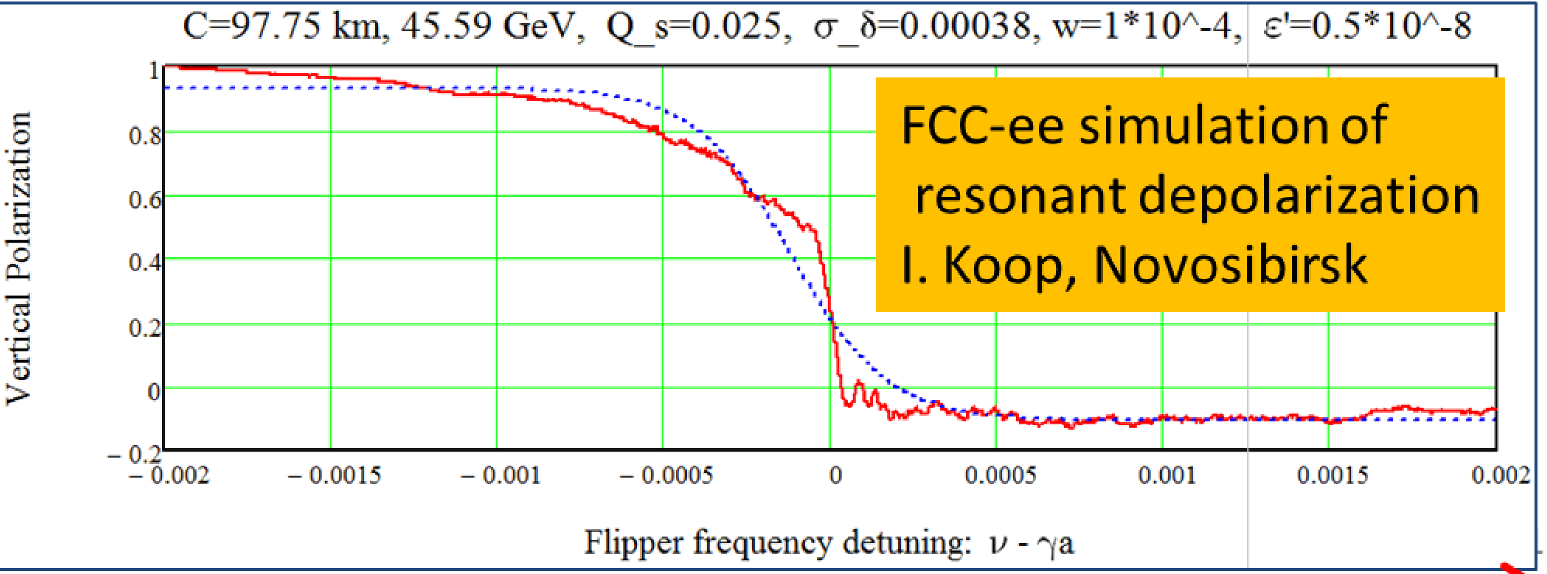
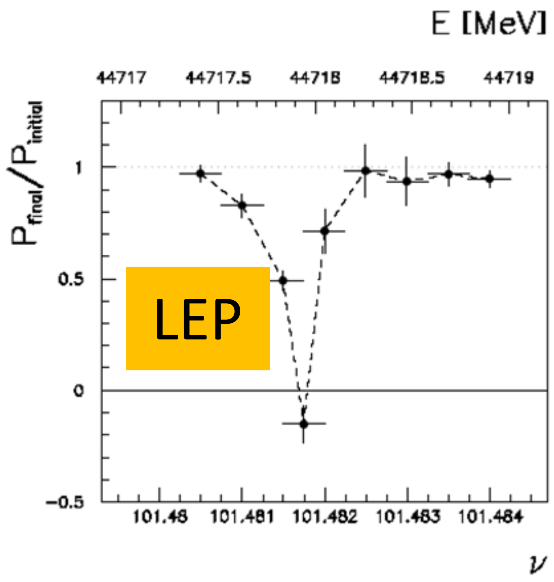


Figure 39. Simulation of a frequency sweep with the depolarizer on the Z pole showing a very sharp depolarization at the exact spin tune value.



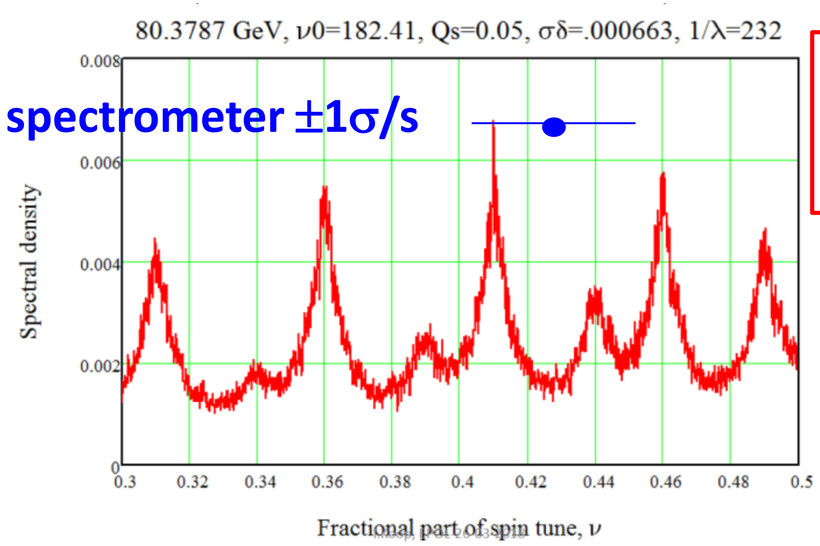
FCC-ee simulation of resonant depolarization
I. Koop, Novosibirsk

260 seconds sweep of depolarizer frequency



LEP

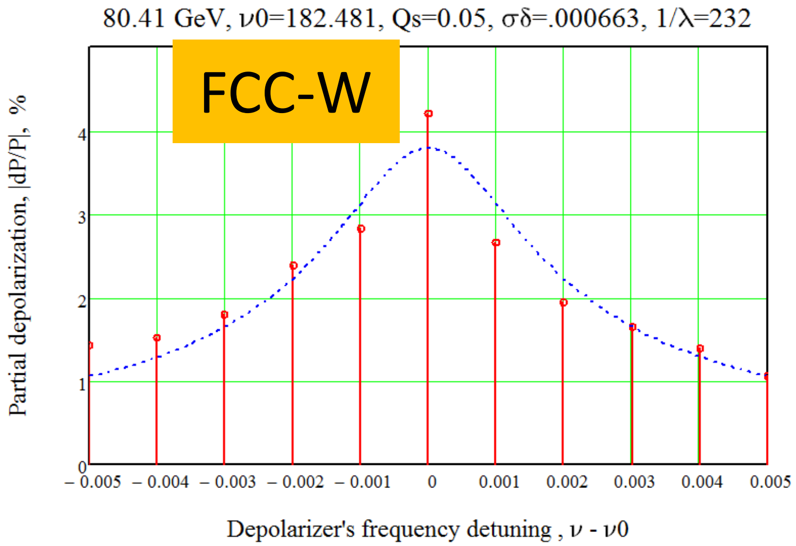
long sweep works well at the Z. Several depolarizations needed: eliminate Qs side band and 0.5 ambiguity
Less well at the W: the Qs side bands are much more excited because of energy spread, need iterations with smaller and smaller sweeps – work in progress. see *I. Koop* presentations at FCC weeks.



spectrometer ±1σ/s

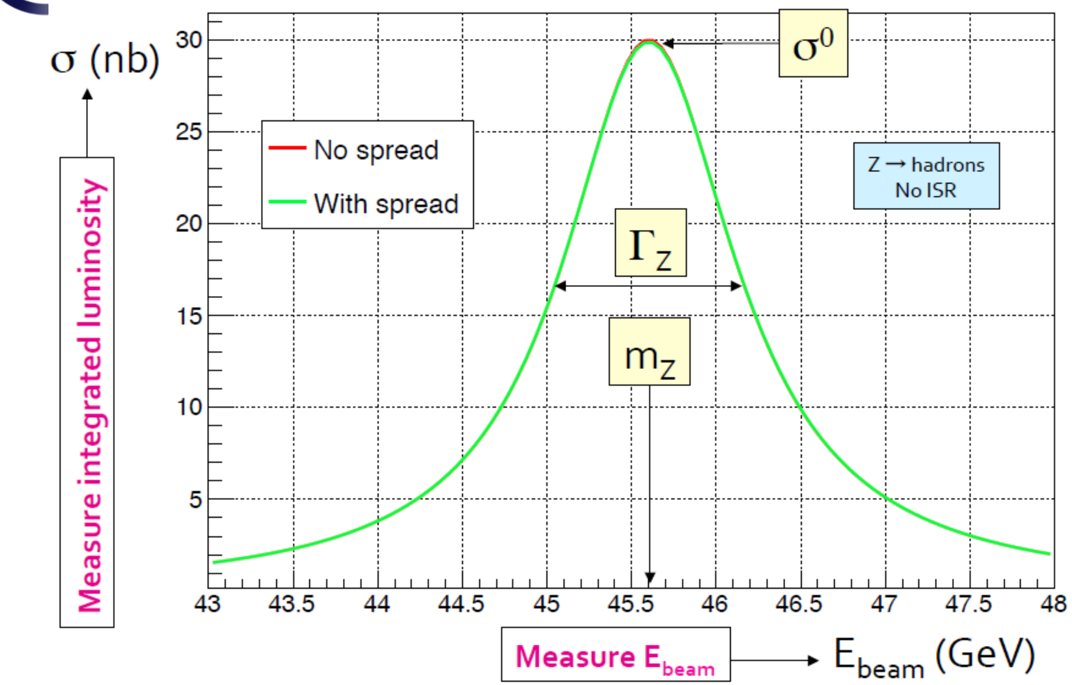
← Fourier analysis shows the side band situation at W.

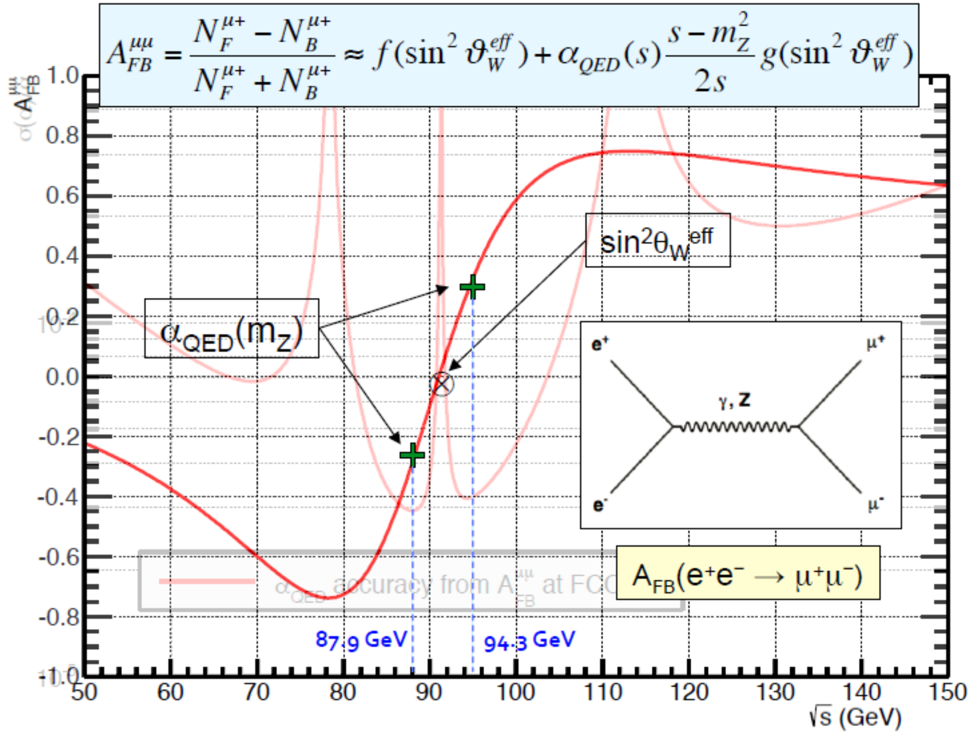
First attempt at 'LEP' multiple sweep technique →



FCC-W

scan points for m_Z and m_W

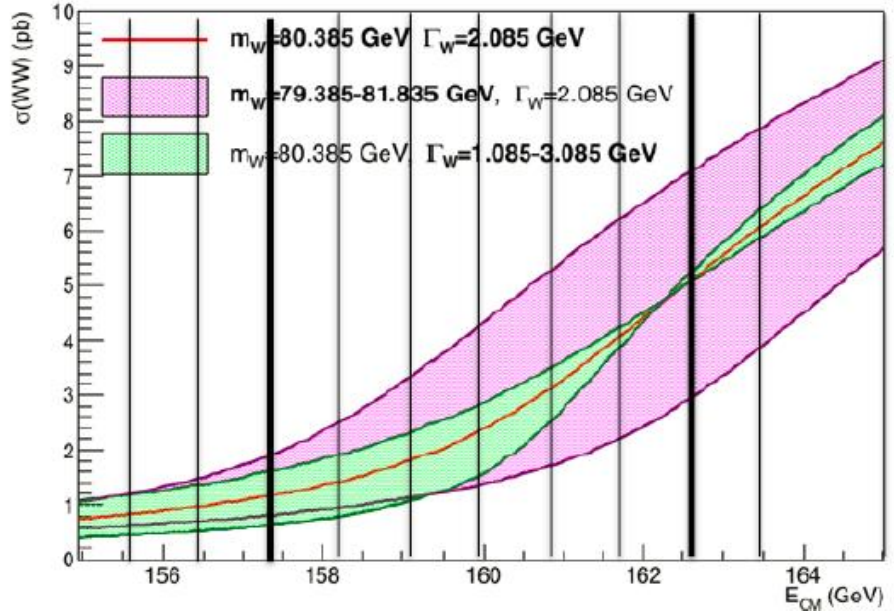




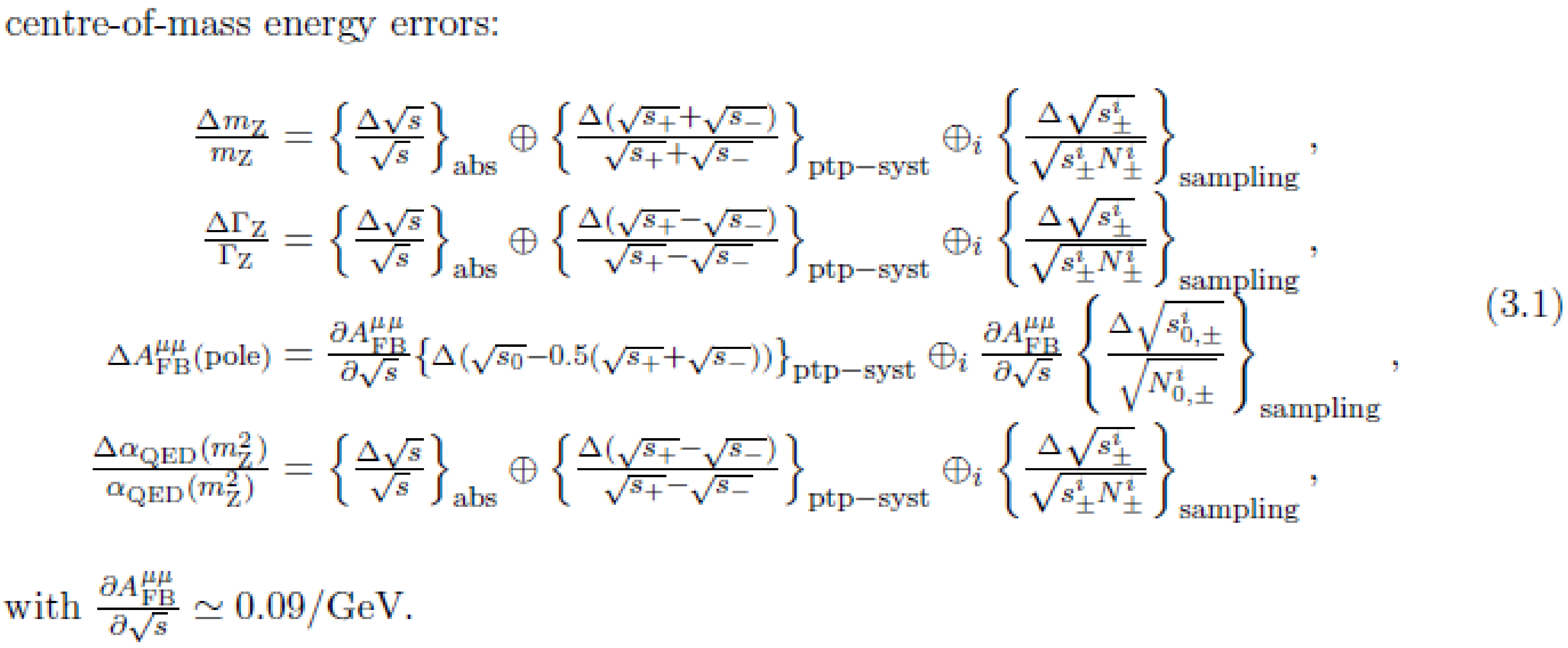
$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2\vartheta_W^{eff}) + \alpha_{QED}(s)\frac{s - m_Z^2}{2s} g(\sin^2\vartheta_W^{eff})$$

Table 3: Center-of-mass energies for the proposed Z scan. The points noted A and B are half integer spin tune points with energies closest to the requested energies.

Scan point	Centre-of-mass Energy	Beam Energy	Spin tune
E_{CM}^- A	87.69	43.85	99.5
E_{CM}^- Request	87.9	43.95	99.7
E_{CM}^- B	88.57	44.28	100.5
E_{CM}^0	91.21	45.61	103.5
E_{CM}^+ A	93.86	46.93	106.5
E_{CM}^+ Request	94.3	47.15	107.0
E_{CM}^+ B	94.74	47.37	107.5



statistical precision at the Z



centre-of-mass energy errors:

$$\begin{aligned}
\frac{\Delta m_Z}{m_Z} &= \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}+\sqrt{s_-})}{\sqrt{s_+}+\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling}, \\
\frac{\Delta\Gamma_Z}{\Gamma_Z} &= \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling}, \\
\Delta A^{\mu\mu}_{\rm FB}({\rm pole}) &= \frac{\partial A^{\mu\mu}_{\rm FB}}{\partial\sqrt{s}}\left\{\Delta(\sqrt{s_0}-0.5(\sqrt{s_+}+\sqrt{s_-}))\right\}_{\rm ptp-syst} \oplus_i \frac{\partial A^{\mu\mu}_{\rm FB}}{\partial\sqrt{s}}\left\{\frac{\Delta\sqrt{s^i_{0,\pm}}}{\sqrt{N^i_{0,\pm}}}\right\}_{\rm sampling}, \\
\frac{\Delta\alpha_{\rm QED}(m_Z^2)}{\alpha_{\rm QED}(m_Z^2)} &= \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\rm abs} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\rm ptp-syst} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\rm sampling},
\end{aligned} \tag{3.1}$$

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

Three categories:

- **Abs**olute dominate for Z and W mass
- **ptp** Point-to-point dominate for Γ_Z & $A_{FB}^{\mu\mu}$ (peak and off-peak)
- Due to **sampling** – turns out to be negligible for 1meast /(15 min= 1000s) → 10^4 measts

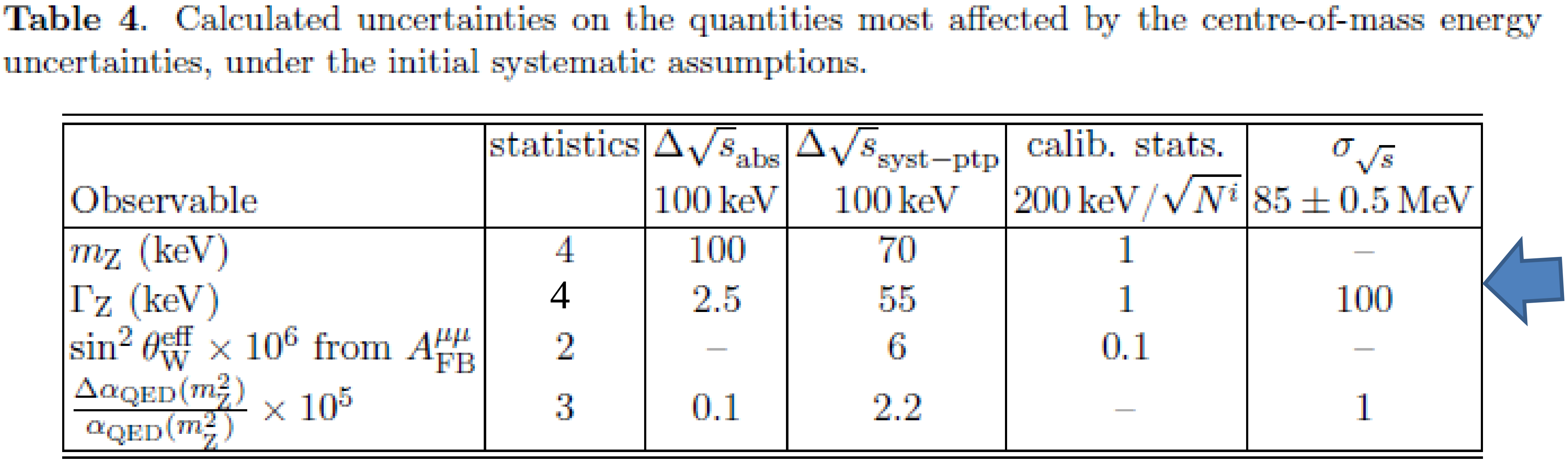


Table 4. Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the initial systematic assumptions.

Observable	statistics	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ 100 keV	calib. stats. 200 keV / $\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 ± 0.5 MeV
m_Z (keV)	4	100	70	1	–
Γ_Z (keV)	4	2.5	55	1	100
$\sin^2\theta_W^{\mathrm{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	6	0.1	–
$\frac{\Delta\alpha_{\mathrm{QED}}(m_Z^2)}{\alpha_{\mathrm{QED}}(m_Z^2)} \times 10^5$	3	0.1	2.2	–	1

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.):

$\Delta_{SR} = 2\Delta_{SRi} + 2\Delta_{SRe}$ =36 MeV

$\Delta_{SRe} - \Delta_{SRi} \approx \alpha/2\pi\ \Delta_{SR}$ = 0.17 MeV

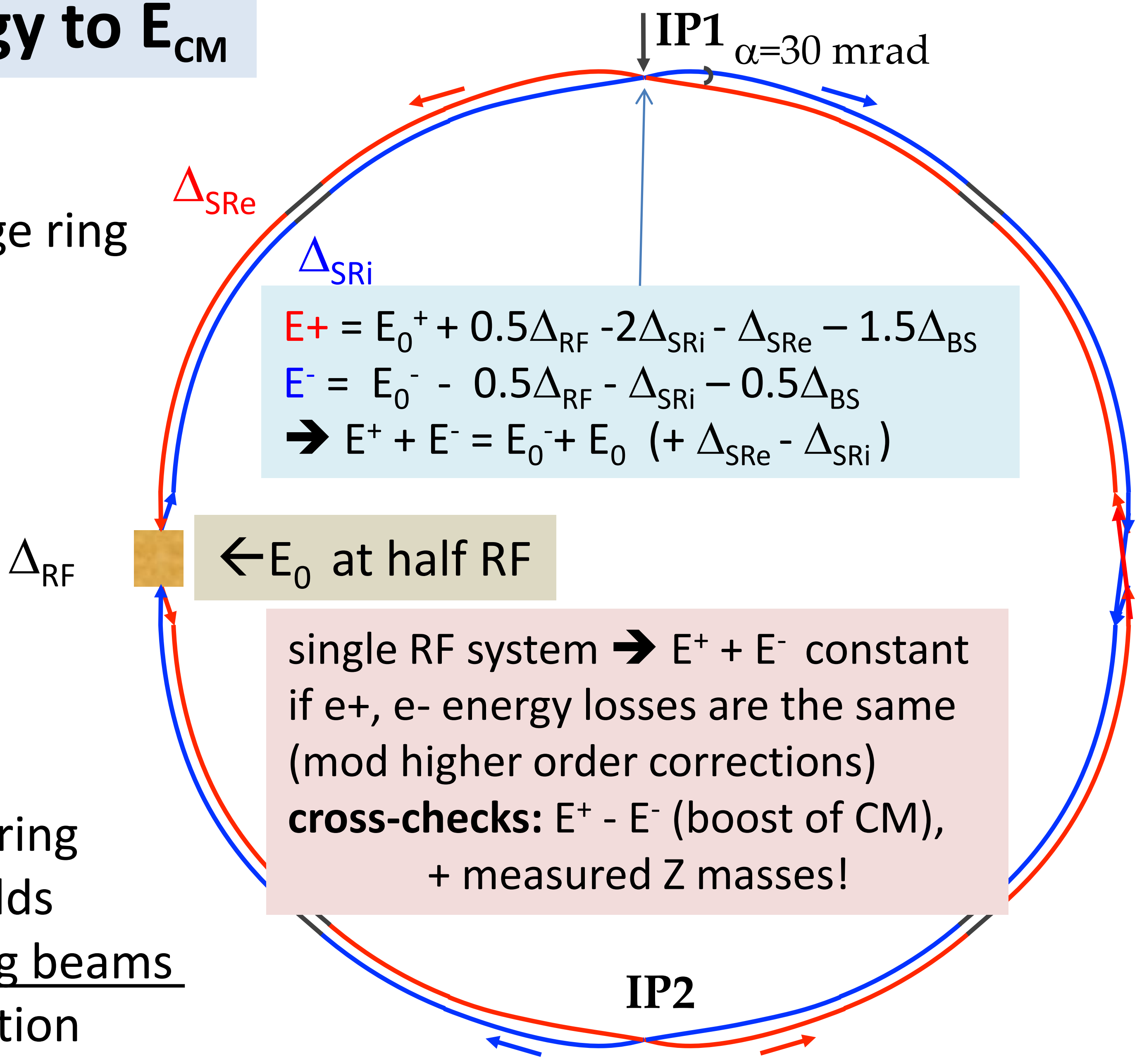
Δ_{BS} = 0 up to 0.62 MeV

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

➔ <u>same for colliding or non-colliding beams</u>

-- measured by resonant depolarization

-- can be different for e⁺ and e⁻



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

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

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

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!

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

ECM and Boosts for Z-Mode

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

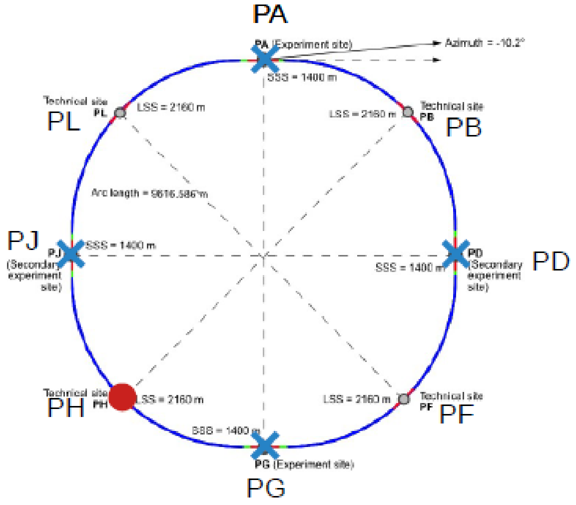
One 8 h shift will give 5 keV precision

Sum of losses close to sum of absolute boosts

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

1 RF → almost constant ECM

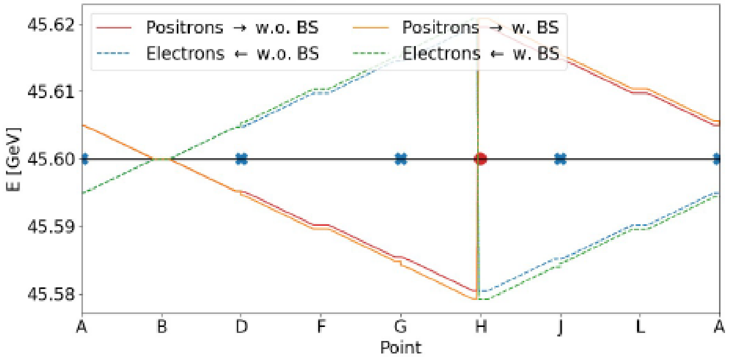
IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439

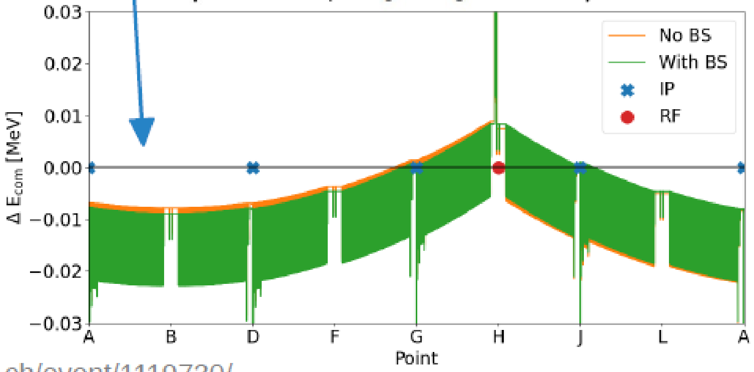


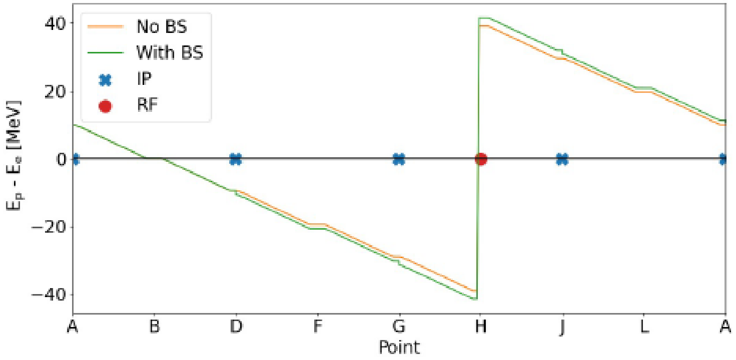
$$\Delta E \propto \gamma_{\mathrm{rel}}^{4}$$

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

Boost: + for e+; - for e-







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

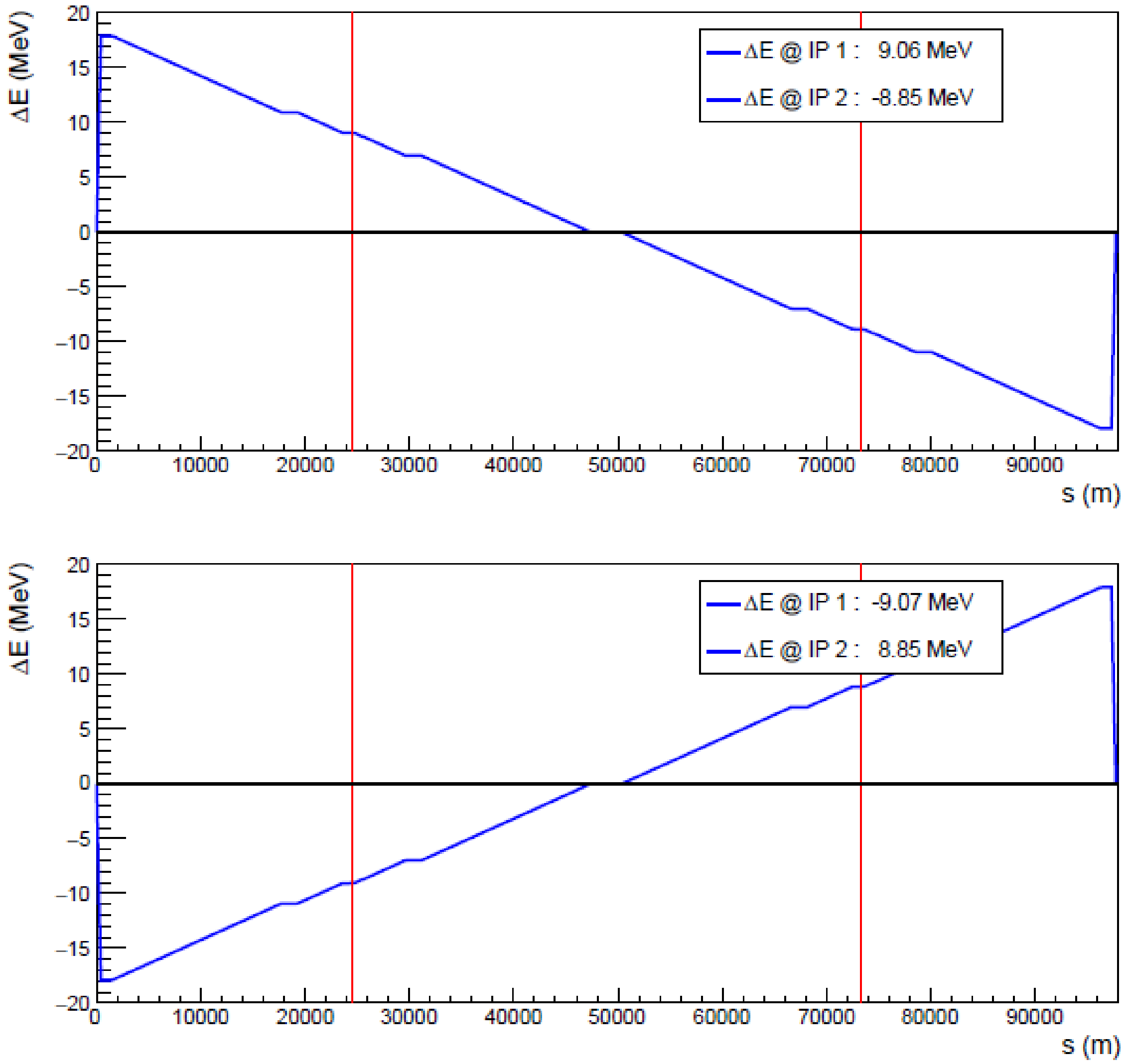


Figure 43. Energy sawtooth at the Z pole for the two beams with a single RF station per beam in the same location (top: beam direction left to right, bottom: beam direction right to left), the vertical axis corresponds to the relative energy offset and the horizontal axis to the longitudinal coordinate. The two IPs are indicated by the red vertical lines.

arXiv:1909.12245

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 (9 MeV @Z in 4 'arcs') calculable to < permil accuracy

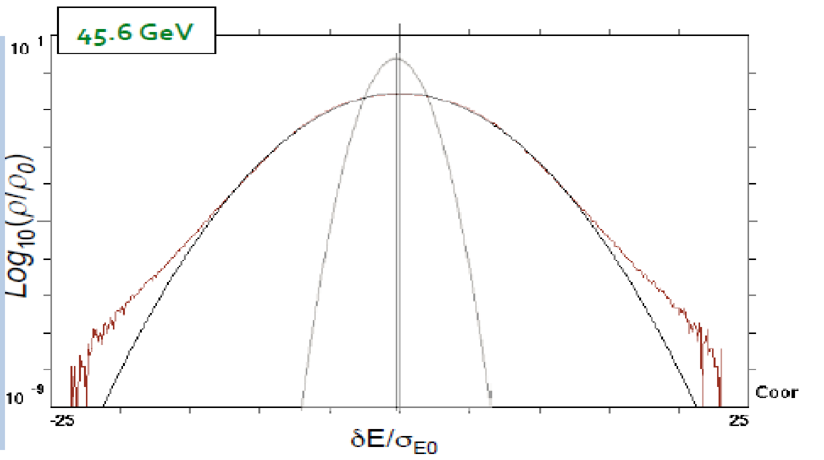
3.3 Beamstrahlung energy loss (0.62 MeV per beam at Z pole), compensated by RF (Shatilov)

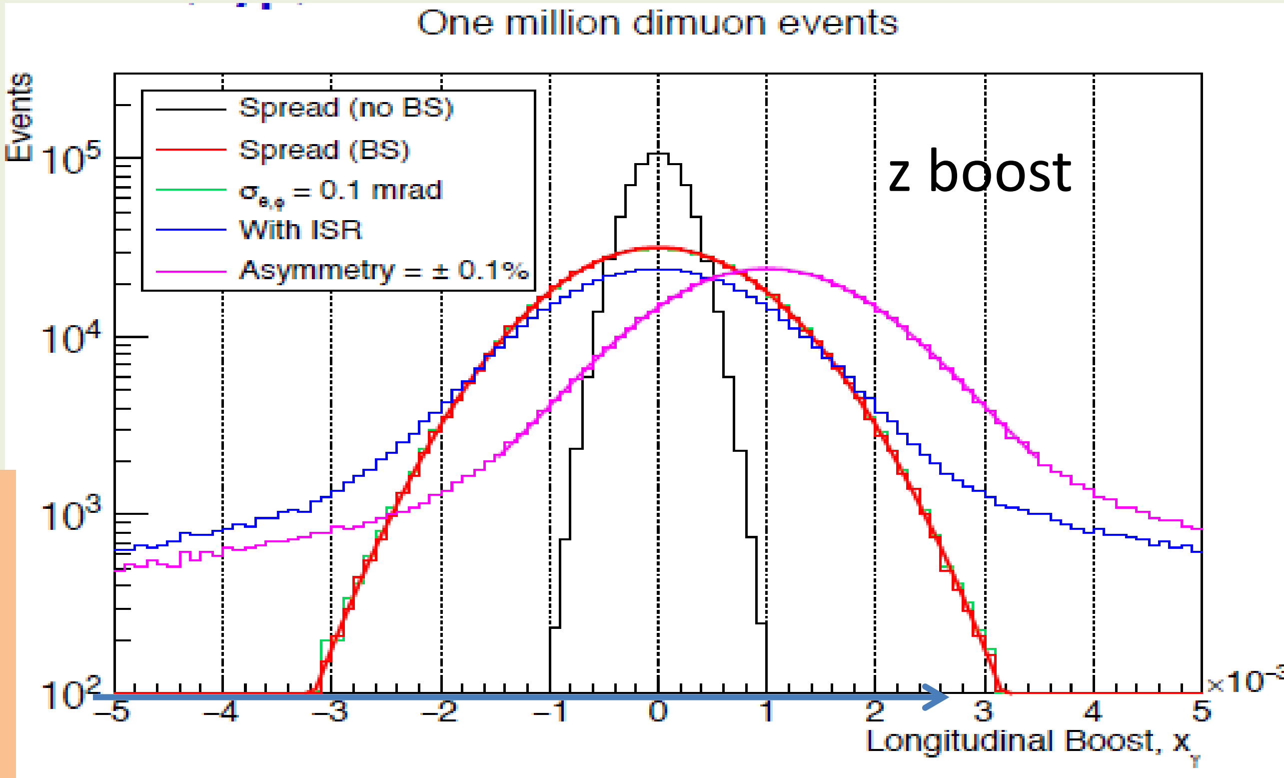
3.4 layout of accelerator with IPs between two arcs well separated from single RF section

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

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

D. Shatilov:
beam energy spectrum without/with beamstrahlung





P. Janot: 5 min/exp @Z ➔ 10^6 μ+ μ- /expt →
→ 50 keV meast both on σ_{ECM} and $E^+ - E^-$
→ and beam crossing angle α (error negl.)
→ also monitor relative ECM (p-t-p!)

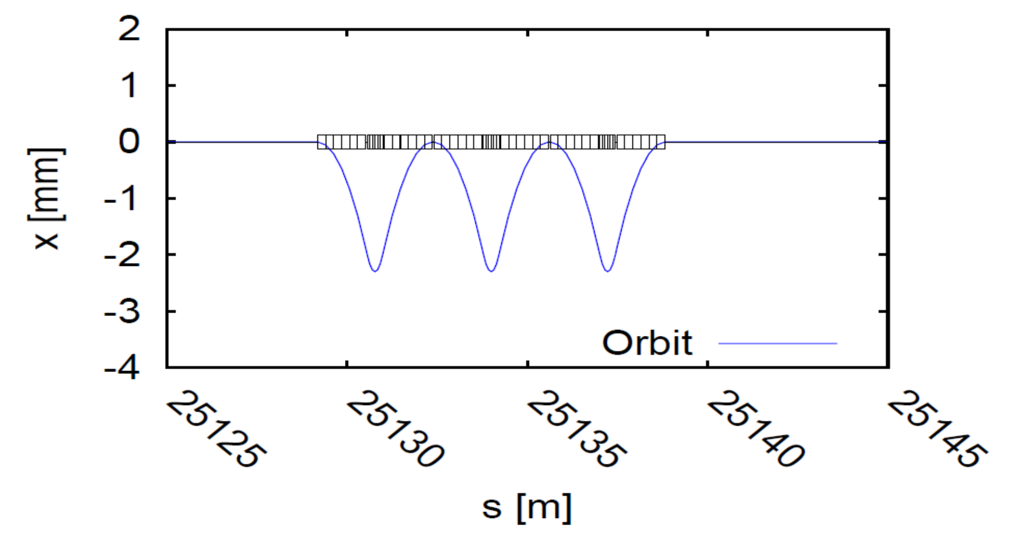
Hardware requirements: wigglers

Given the long polarization time at Z, wigglers will be necessary.
An agreement was reached on a set of **8 wiggler units per beam**

Polarization wigglers

8 units per beam, as specified by *Eliana Gianfelice*

B+=0.7 T L+ = 43cm L-/L+ = B+/B- = 6
at Eb= 45.6 GeV and B+= 0.67 T
=> P=10% in 1.8H σ_{Eb} = 60 MeV E_{crit}=902 keV



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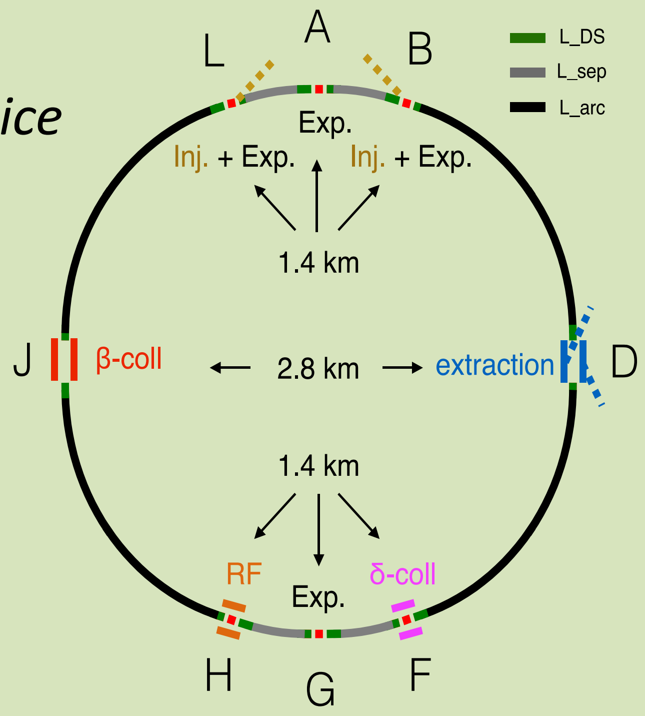
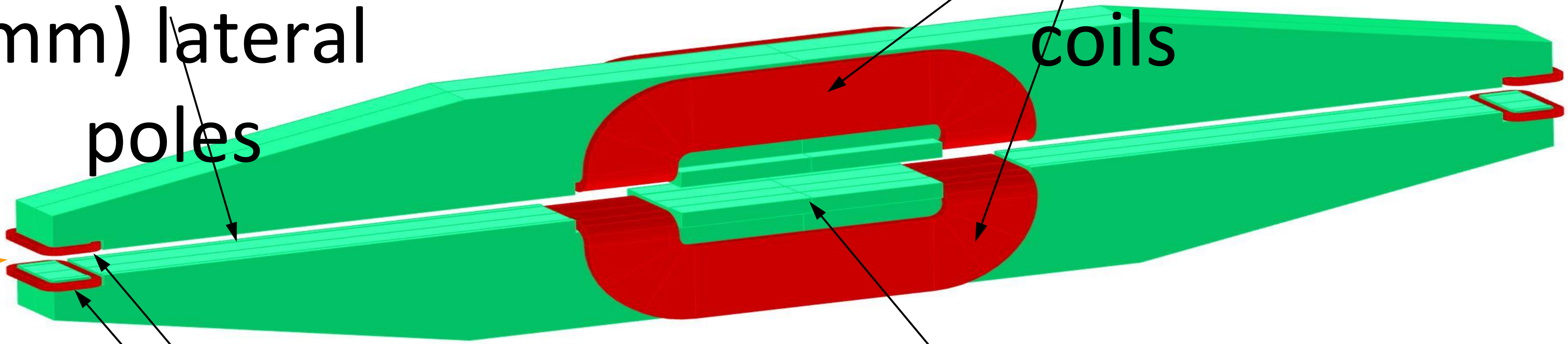


placed e.g. in dispersion-free straight section H and/or

First single pole magnetic concept, keeps some of the ideas of the LEP design, in particular the "floating" poles



narrower (200 mm) lateral poles

central main coils

bear

side trim coils

wider (300 mm) central pole

mass ≈ 4 tons

A. Milanese

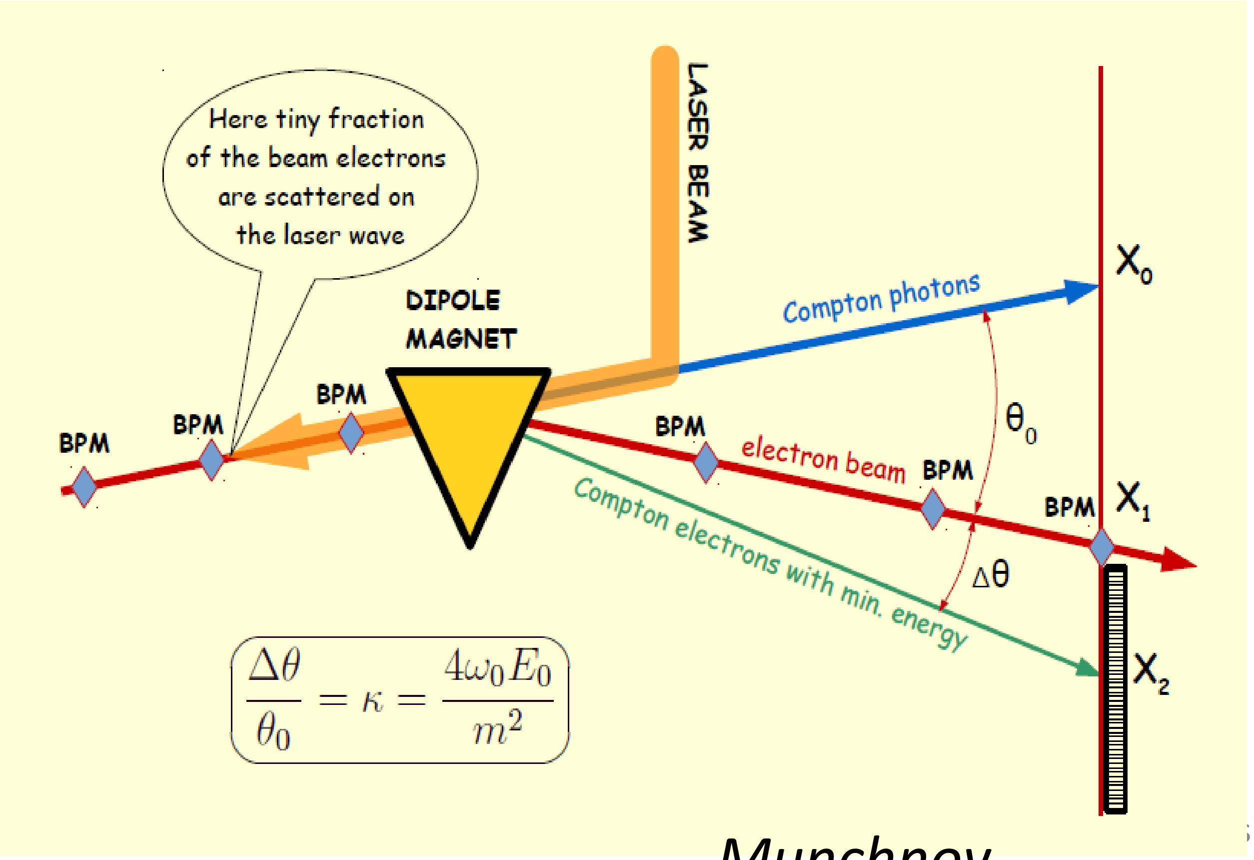
Hardware requirements: polarimeters

2 Polarimeters, one for each beam

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

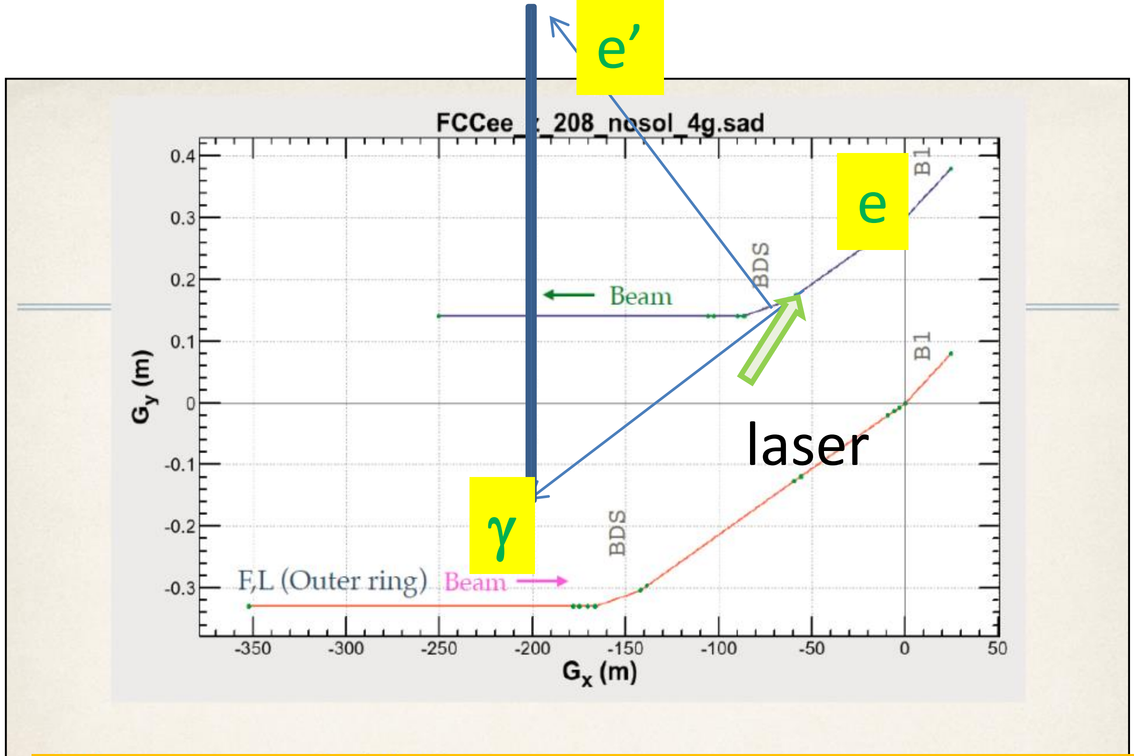
Change upon flip of laser circular polarization → beam Polarization ±0.01 per second

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



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

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

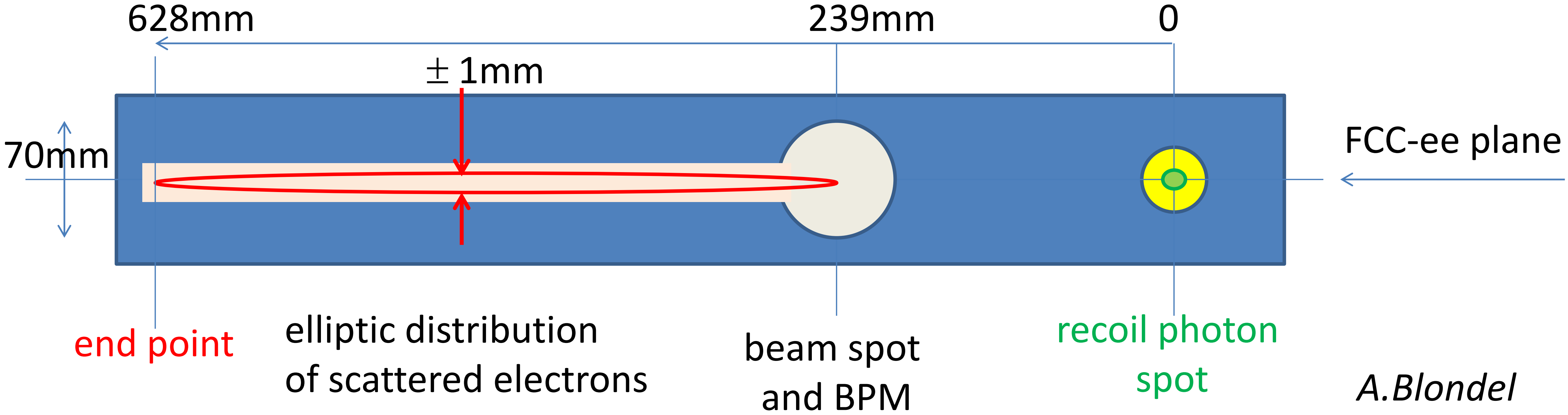
-- minimum compton scattering energy at 45.6 GeV is 17.354 GeV

-- distance from photon recoil to Emin electron is 0.628m

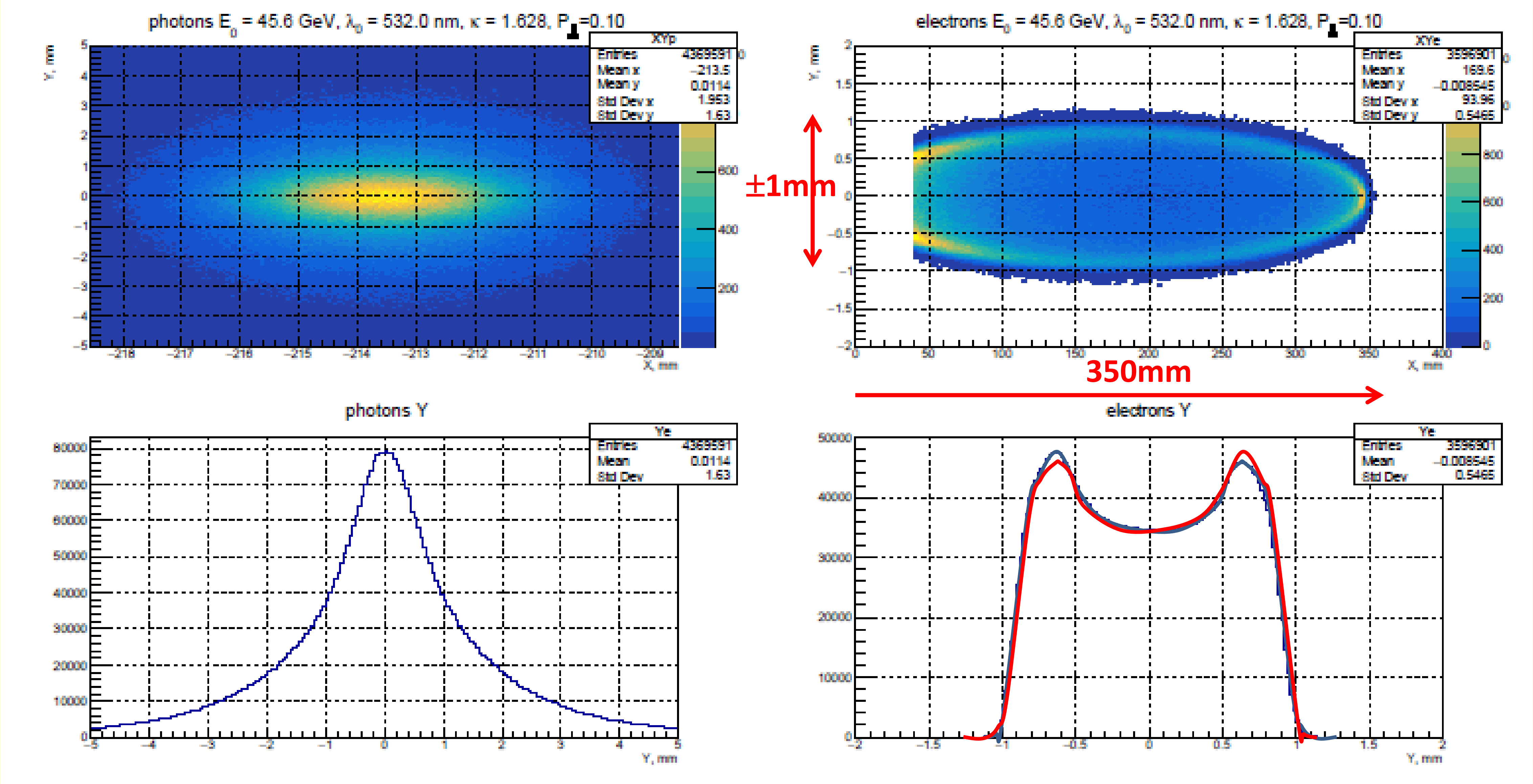
	laser (eV)	beam (GeV)	mc2(MeV)	B field	R	LM	theta	L	true beam
	2.33	45.6	0.511	0.013451	11300	24.119	0.002134	100	45.60005
nominal kappa = 4. E_laser.Ebeam_nom/mc2	1.627567296								
true kappa = 4. E_laser.Ebeam_true/mc2	1.627568924								
nominal Emin	17.35445561								
true Emin	17.35446221								
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 $\delta Eb/Eb=10^{-6}$ (δEb=45keV)

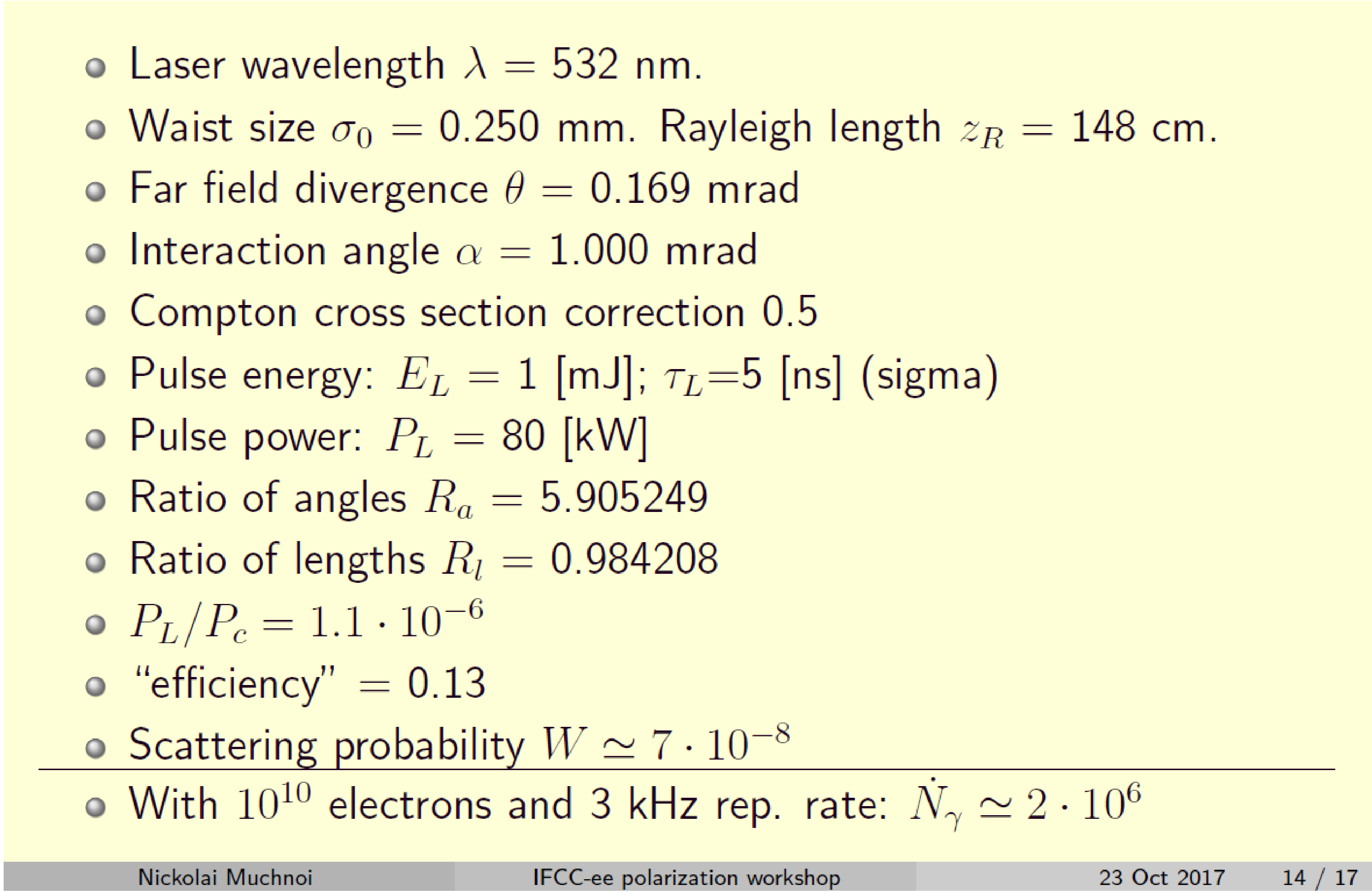


A.Blondel


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
Y, mm
X, mm
±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

Compton Polarimeter: Rates



- Laser wavelength $\lambda = 532$ nm.
- Waist size $\sigma_0 = 0.250$ mm. Rayleigh length $z_R = 148$ cm.
- Far field divergence $\theta = 0.169$ mrad
- Interaction angle $\alpha = 1.000$ mrad
- Compton cross section correction 0.5
- Pulse energy: $E_L = 1$ [mJ]; τ_L=5 [ns] (sigma)
- Pulse power: $P_L = 80$ [kW]
- Ratio of angles $R_a = 5.905249$
- Ratio of lengths $R_l = 0.984208$
- $P_L/P_c = 1.1 \cdot 10^{-6}$
- "efficiency" $= 0.13$
- Scattering probability $W \simeq 7 \cdot 10^{-8}$

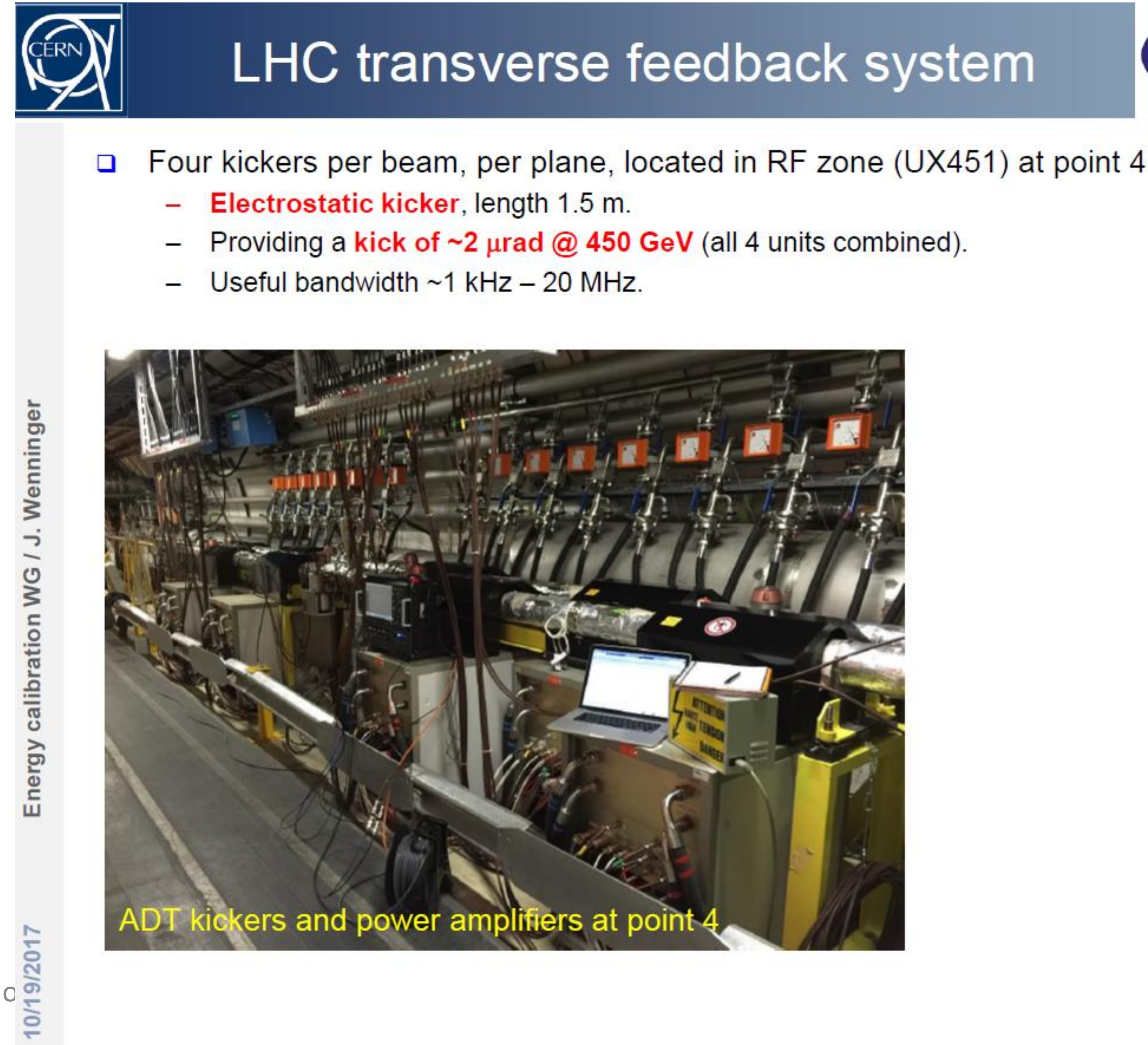
- With 10^{10} electrons and 3 kHz rep. rate: $\dot{N}_\gamma \simeq 2 \cdot 10^6$

Nickolai Muchnoi | IFCC-ee polarization workshop | 23 Oct 2017 | 14 / 17

Depolarization

This is not-so trivial in FCC-ee!
16700 bunches circulate
time-between-bunches = 19ns,
depolarize one-and-only-one
of them.
Kicker must have fast (<9ns) rise.

The LHC TF system works essentially on a bunch by bunch basis for 25ns.
They would provide a transverse kick of up to ~20 mrad at the Z peak with ~10 MHz bandwidth. This is 10x more than what we may need-
➔ **a priori OK !**



LHC transverse feedback system

- ❑ Four kickers per beam, per plane, located in RF zone (UX451) at point 4
  - **Electrostatic kicker**, length 1.5 m.
  - Providing a **kick of ~2 μrad @ 450 GeV** (all 4 units combined).
  - Useful bandwidth ~1 kHz – 20 MHz.

ADT kickers and power amplifiers at point 4

Energy calibration WG / J. Wenninger

10/19/2017

From resonant depolarization to Center-of-mass energy
-- 1. from spin tune to beam energy--

The spin tune may not be en exact measurement of the average of the beam energy along the magnetic trajectory of particles. Additional spin rotations may bias the issue. *Anton Bogomyagkov* and *Eliana Gianfelice* have made many estimates.

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}

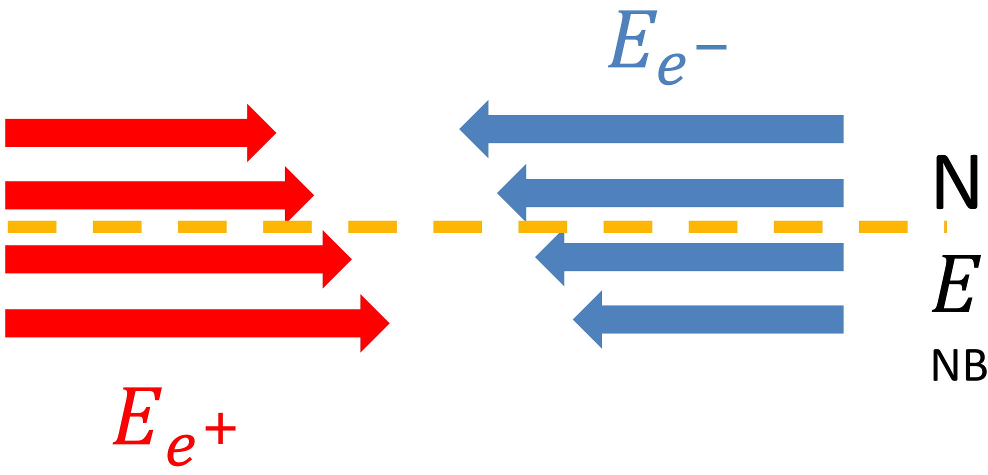
*) 2.5 10^{-6} if horizontal orbit change by >0.8mm between calibration is unnoticed or if quadrupole stability worse than 5 microns over that time. consider that 0.2 mm orbit will be noticed

**) 2.5 10^{-6} for vertical excursion of 1mm. Consider orbit can be corrected better than 0.3 mm.

From resonant depolarization to Center-of-mass energy

2. from beam energy to E_{CM}

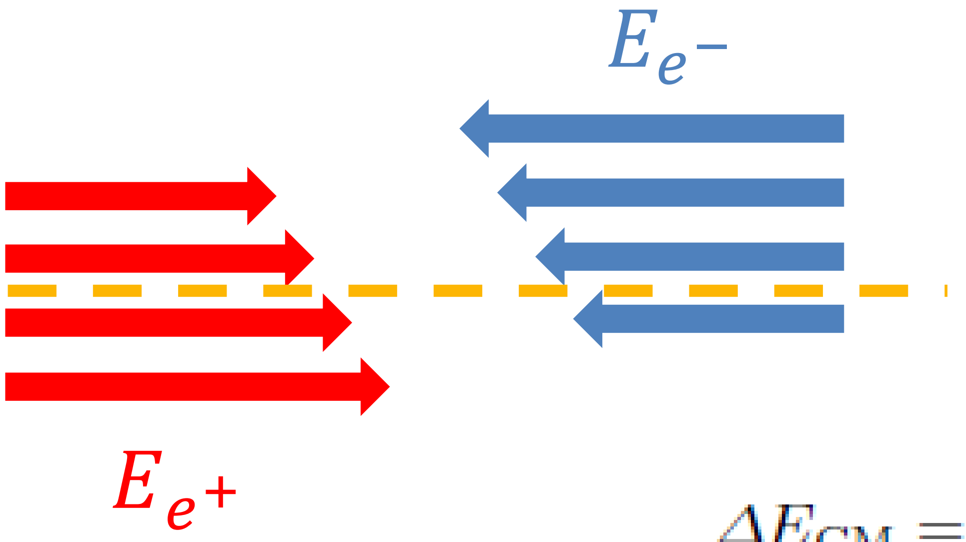
opposite sign dispersion



No effect.

$$ECM = (E_{e^+} + E_{e^-})$$

NB energy spread is reduced.



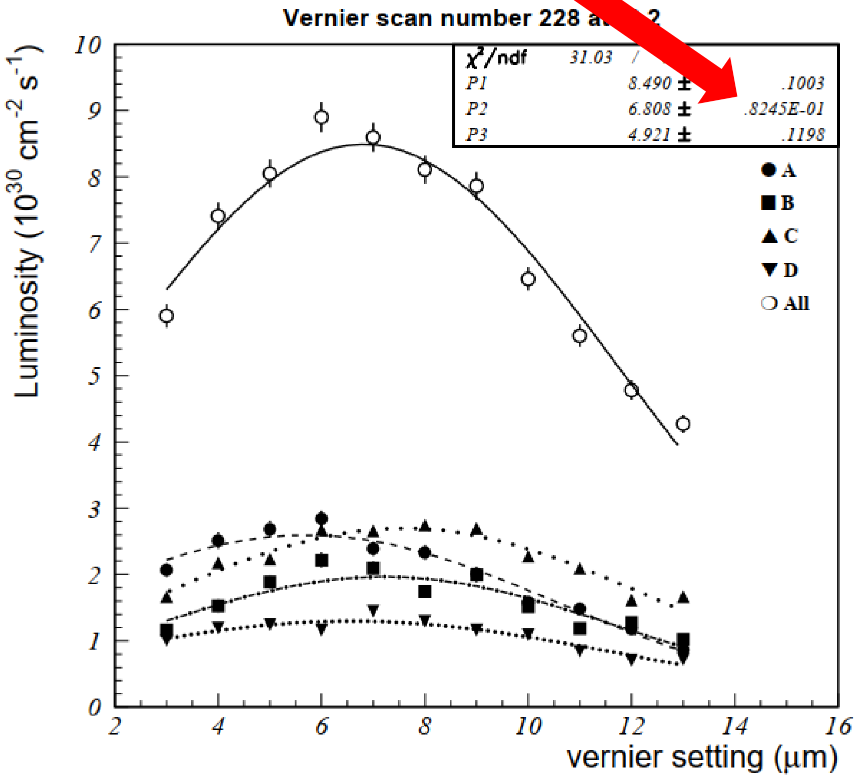
ECM lower than $(E_{e^+} + E_{e^-})$

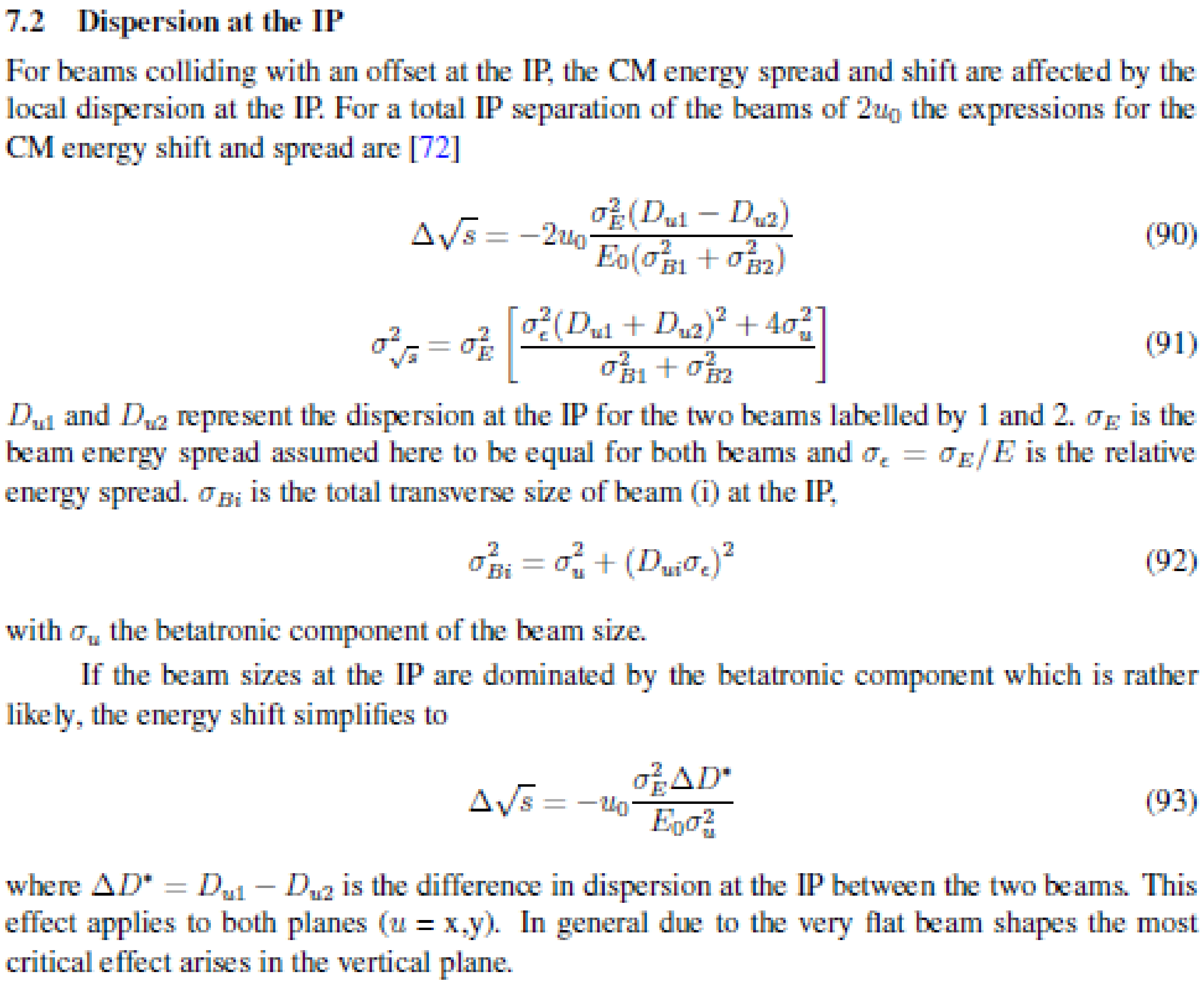
$$\Delta E_{\mathrm{CM}} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_{E_\mathrm{b}}^2}{E_\mathrm{b}} \cdot \Delta D_y^*$$

Experience from LEP – Vernier scans

Van Der Meer today

Relative position of beams measured to 80 nanometers from one scan





7.2 Dispersion at the IP

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

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

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

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

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

with σ_u the betatronic component of the beam size.

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

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

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

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

- Parasitic dispersion of e+ and e- beams at IP 10um
  the difference is $\Delta D_y^* = 14\mu m$.
- Sigma_y is 28nm
- Sigma_E is 0.132%*45000MeV=60MeV
- **Delta_ECM is therefore 1.4MeV for a 1nm offset**
- Note that we cannot perform Vernier scans like at LEP, we can only displace the two beams by ~10%sigma_y
- Assume each Vernier scan is accurate to 1% sigma_y, we get a precision of 400 keV.
  the process should be simulated

- we need 100 beams scans to get an E_{CM} accuracy of 40keV – suggestion: vernier scan every hour or more.
- It is likely that Vernier scans will be performed regularly at least once per hour or more. (→100 per week) we end up with an uncertainty of ~10keV over the whole running period.

- **The dispersion must be measured as well; this can be done by using the vernier scans with offset RF frequency**

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

with the improved systematic error evaluation

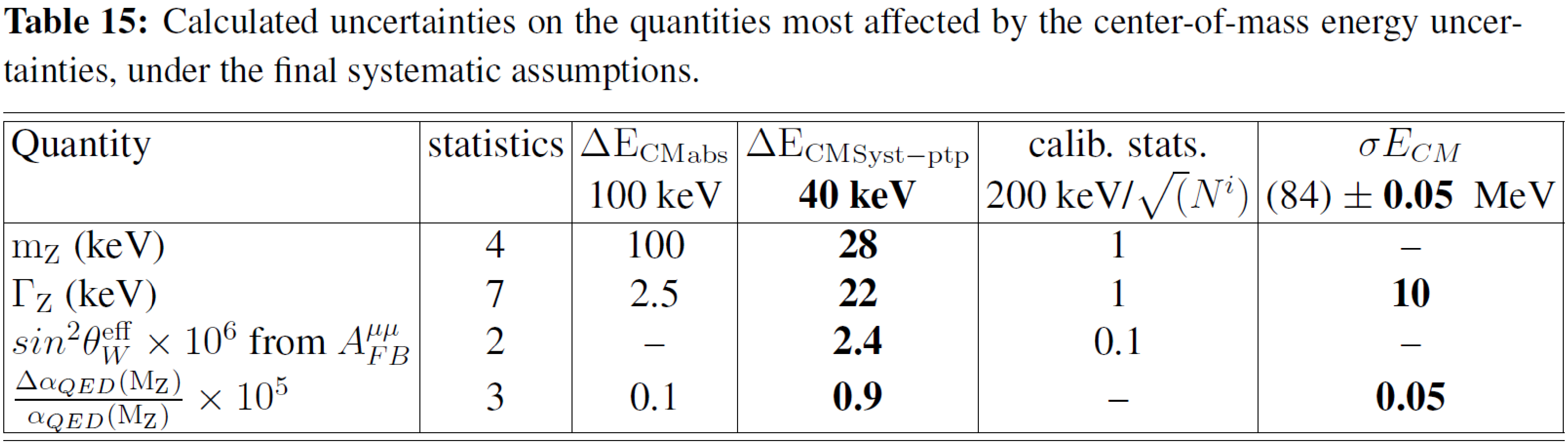


Table 15: Calculated uncertainties on the quantities most affected by the center-of-mass energy uncertainties, under the final systematic assumptions.

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

the point-to-point uncertainty estimate is O(10 keV) (M.K.) It can be controlled in two ways

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

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

➔ this requires dedicated design of polarimeter

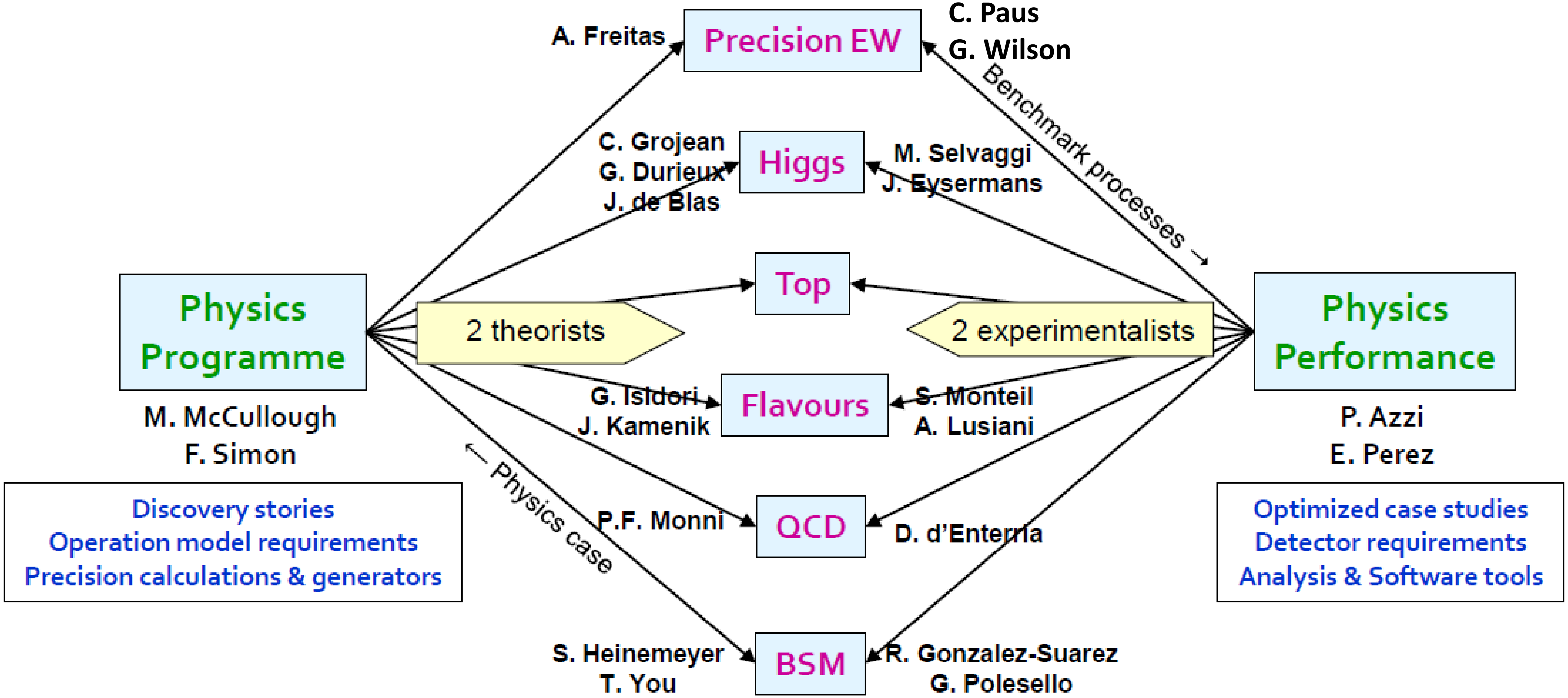
2. use the e+e- → μ+μ- events in the detectors to measure ECM for each of the energies.

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

Conclusions

We had a first look at the determination of centre of mass energy and energy spread in FCC-ee
Results are promising of extraordinary, historical measurements.
This must be improved and secured further towards the TDR

EPOL indico thread



A. Freitas
Precision EW
C. Paus
G. Wilson

Benchmark processes →

C. Grojean
G. Durieux
J. de Blas
Higgs
M. Selvaggi
J. Eysermans

Top

Physics Programme

M. McCullough
F. Simon

2 theorists

2 experimentalists

Physics Performance

P. Azzi
E. Perez

G. Isidori
J. Kamenik
Flavours
S. Monteil
A. Lusiani

← Physics case

P.F. Monni
QCD
D. d'Enterria

S. Heinemeyer
T. You
BSM
R. Gonzalez-Suarez
G. Polesello

Discovery stories
Operation model requirements
Precision calculations & generators

Optimized case studies
Detector requirements
Analysis & Software tools

Physics groups define benchmark measurements
to be picked up by case studies ...
leading to performance evaluation and detector requirements

FCC-ee Detectors

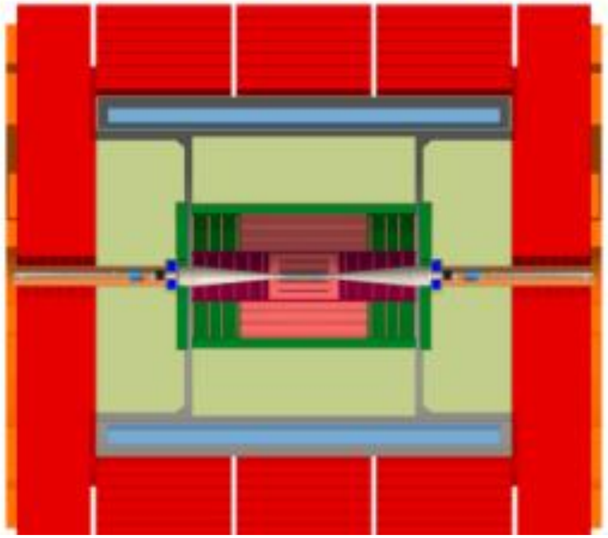
Detectors can be done and work for the FCC-ee, but physics optimization remains to be done.

Two integration, performance and cost estimates:

-- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee

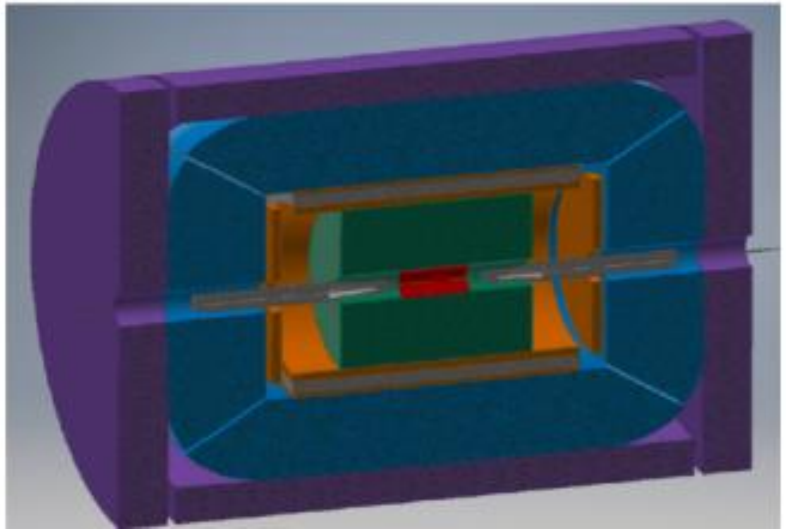
-- IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"



SiD at ILC, CLD at FCC-ee

"IDEA"



- Vertex detector: ALICE **MAPS**
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

IDEA at FCC-ee & CEPC

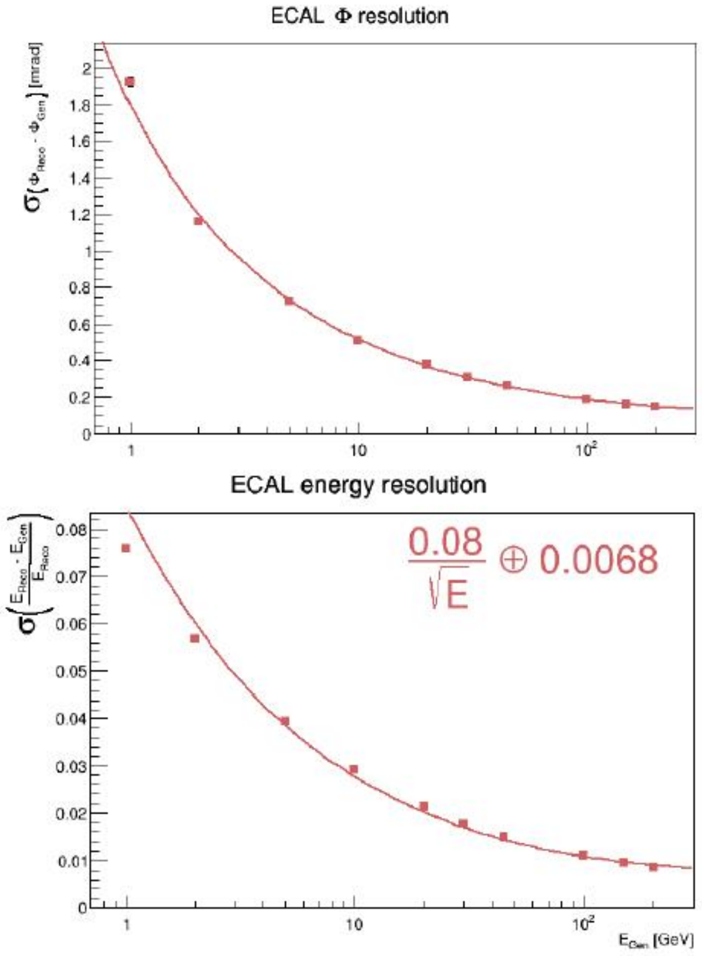
Many challenges to come, mainly because of the Z run.

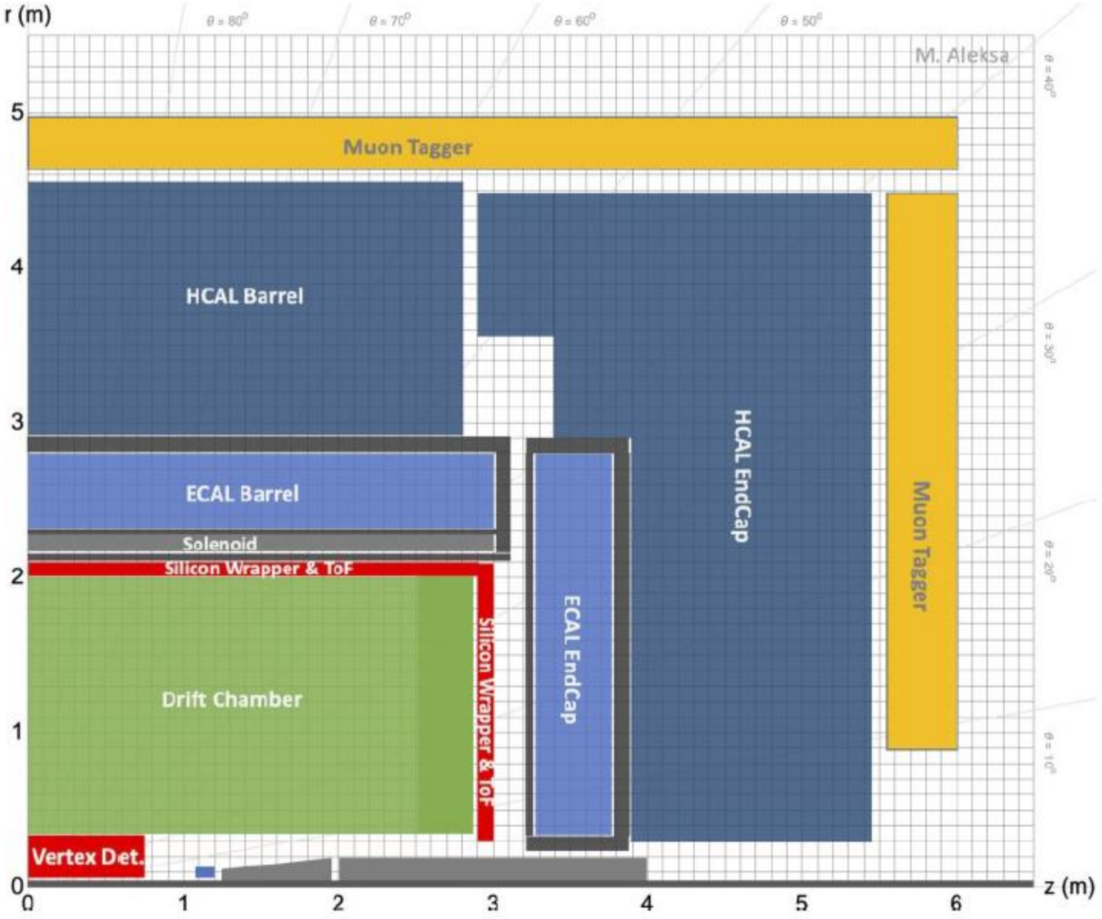
New from the FCC ‘Liverpool’ physics workshop

implementation of Noble Liquid Calorimeter in FCCSW

→ intention to develop an entire detector concept around this key element.

Brieuc François, Weds + Fri





Remember: Detector Concepts must pay attention to *full range* of FCC-ee physics !

The PED ultimate objectives until the next ESU

- Match detectors with the physics opportunities offered by the facility
  - Establish a coherent set of detector requirements from physics studies
    - To fully benefit from statistics, variety of channels, new physics sensitivity
  - Provide a coherent set of detector solutions (or path to solutions)
    - To maximally exploit the new collider layout compatibility with four interaction points
    - To deliver preliminary infrastructure requirements and cost estimates

➛ Physics Programme

➛ Physics Performance

➛ Detector Concepts

- This ought to happen in time for (proto)collaborations to
  - Pick up the wealth of knowledge acquired and common tools developed on the way
  - Present EoI's to the next strategy, and
  - Run away with the project once approved

➛ Software & Computing

- Best would be that at least four (proto)collaborations propose a detector
  - Serious funding will arise at this point
  - More precise costs and demands on infrastructure will be elaborated

SPARES

Our marching orders from ESPP 2020:

“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

Feasibility of the colliders (ee and hh) and related infrastructure.
→ **FCC is the highest priority after HL-LHC for Europe and its international partners (Plan A)**

Physics at FCC-ee

1. HIGGS FACTORY

Higgs provides a very good reason why we need e+e- collider

2. ELECTROWEAK PRECISION (10^{-3} today → 10^{-5})

Z + WW + top required!

Test of the completeness of the SM

Are there further particles with SM couplings?

3. Z FACTORY

($5\ 10^{12}$ Z i.e. $1.5\ 10^{11}$ ee, $\mu\mu$, $\tau\tau$; ~$0.7\ 10^{12}$ uu,dd,ss,cc,bb ; 10^{12} $\nu\nu$)

High statistics for Heavy Flavours, QCD

Search for Feebly Coupled Particles

The place for 'direct discovery'

+ comments on the synergy and complementarity of FCC-ee hh and eh

Status of FCC

-- June 2021 The FCC Feasibility Study (2021-2025) organization was proposed to CERN council, approved unanimously

MTP: 100MCHF/5yrs

-- Council documents :

- Organisational structure of the FCC feasibility study
http://cds.cern.ch/record/2774006/files/English.pdf
- Main deliverables and timeline of the FCC feasibility study
http://cds.cern.ch/record/2774007/files/English.pdf

-- Financial study: “ The focus will be on the tunnel and the first-stage collider (FCC-ee)”

-- Design of FCC-ee and FCC-hh, and their injectors, key technologies, technical infrastructure

-- MDI and Ecm calibration for FCC-ee

-- The physics case and detector concepts will be consolidated for both colliders (FCC-ee and FCC-hh).

-- intermediate review mid 2023, delivery of Feasibility Study Report (FSR) end 2025, (first collisions >2040)

-- Stress the importance of communication towards
scientific community, governments and funding agencies, industries and general public

-- work has started on placement in Geneva area (France and Switzerland)
→ reduce number of surface points to 8
→ layout consistent with later choice of 2 or 4IP for the e+e- collider

-- in parallel, high field magnet R&D for FCC-hh will be carried out with high priority

+120MCHF/6yrs

These events bring both FCC-ee and FCC-hh one step closer to reality

More on TeraZ

The Flavour Factory

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,

FCC-ee(Z): will provide ~10^{12} b pairs. "**Want at least 5 10^{12} Z…"**

- precision of CKM matrix elements
- Push forward searches for FCNC, CP violation and mixing
- Study rare penguin EW transitions such as $b \to s\, \tau^+ \tau^-$, spectroscopy (produce b-baryons, B_s …)
- **Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}**

-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID); a story to be written!

The 3.5 × 10^{12} hadronic Z decay also provide precious input for QCD studies

High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : $10^{-3} \to 10^{-4}$

huge √s lever-arm between 30 GeV and 365 GeV, fragmentation, baryon production ….

Testing running of α_s to excellent precision with hadron production from low energy ($\gamma^*/Z^* + \gamma$) to 365 GeV

And… H→gg is a pure gluon factory (100’000 events)

Centre of mass Energy Calibration: the cornerstone of the precision programme

E. Gianfelice

Large ring→transverse polarization of $e^{\pm}$ up to E_{beam} > 80 GeV $\sigma_E \propto E^2/\sqrt{\rho}$

Resonant depolarization provides high precision E_{beam} $\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)}$

Unique to circular machines (ee and μμ)

Improve over LEP by using pilot bunches + e- and e+ polarimeter

Relationship between ν_s and E_{CM}

- ➔ **CM boost, σ_{ECM}, α_{coll} determined from 10^6 μμ /5min**
- ➔ **Beamstahlung monitor under study etc...**

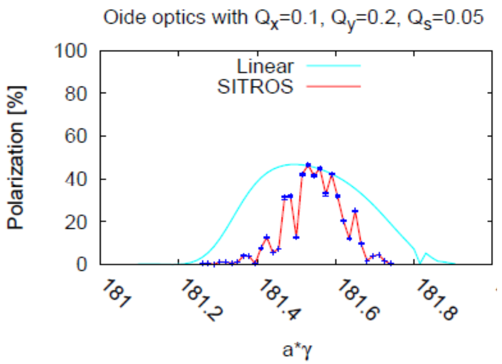
First round of studies (arxiv 1909.12245)

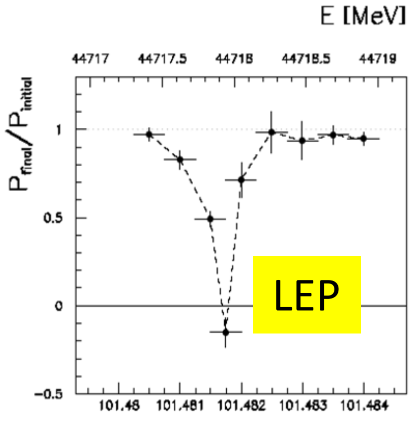
m_Z, Γ_Z, $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$, m_W

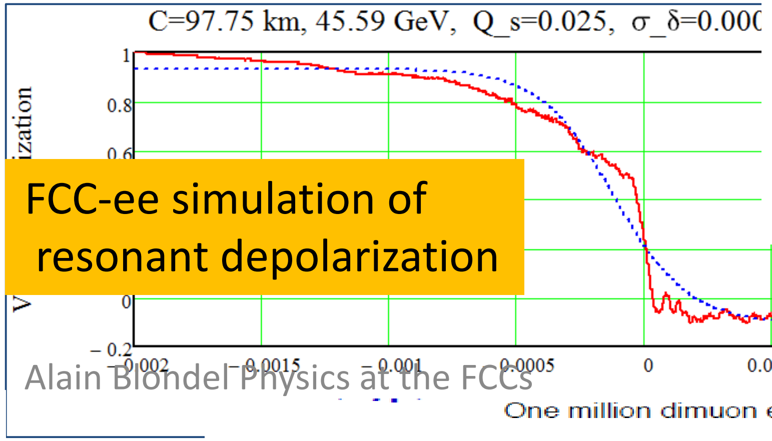
next target: bring syst. closer to stat. errors.

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**

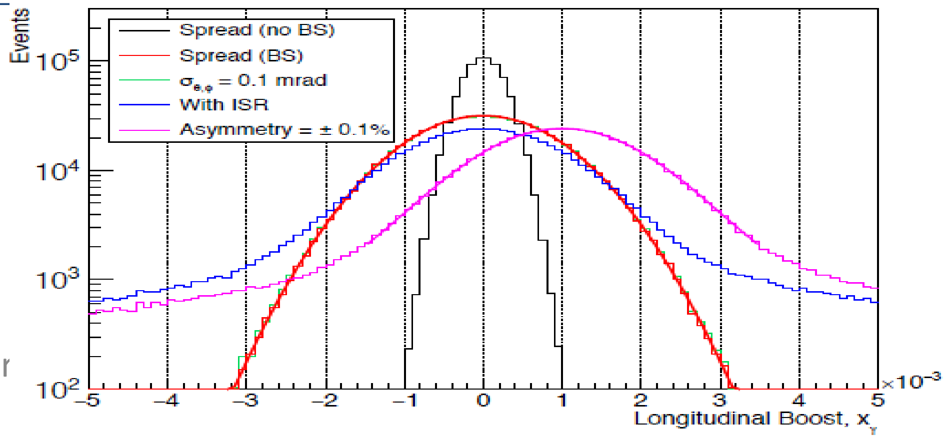
At our luminosity level, longitudinal polarization brings nothing that cannot be done otherwise.







FCC-ee simulation of resonant depolarization



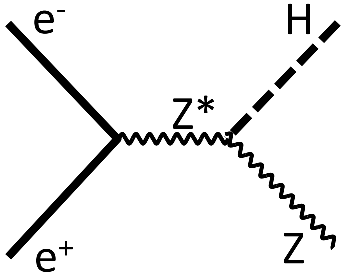
Higgs Physics

e+e- : Z – tagging by missing mass

THE LHC is a Higgs Factory…BUT

$$\sigma_{i\to f}^{\text{observed}} \propto \sigma_{\text{prod}} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H} \;?$$

→ must do physics with ratios

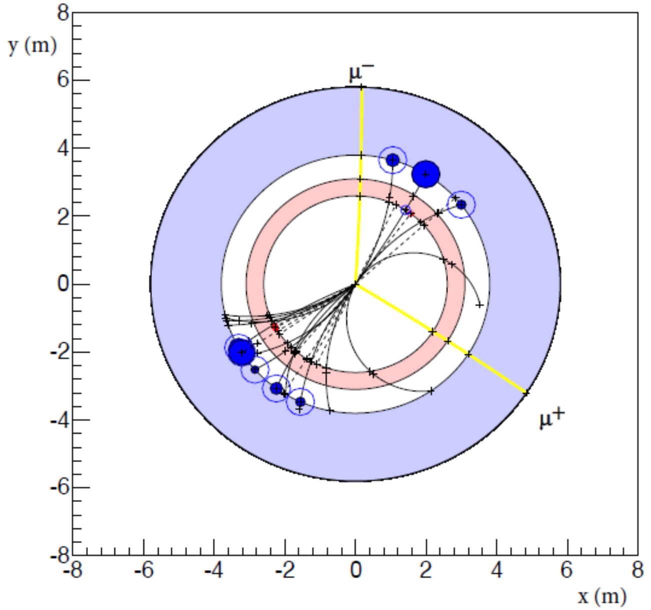


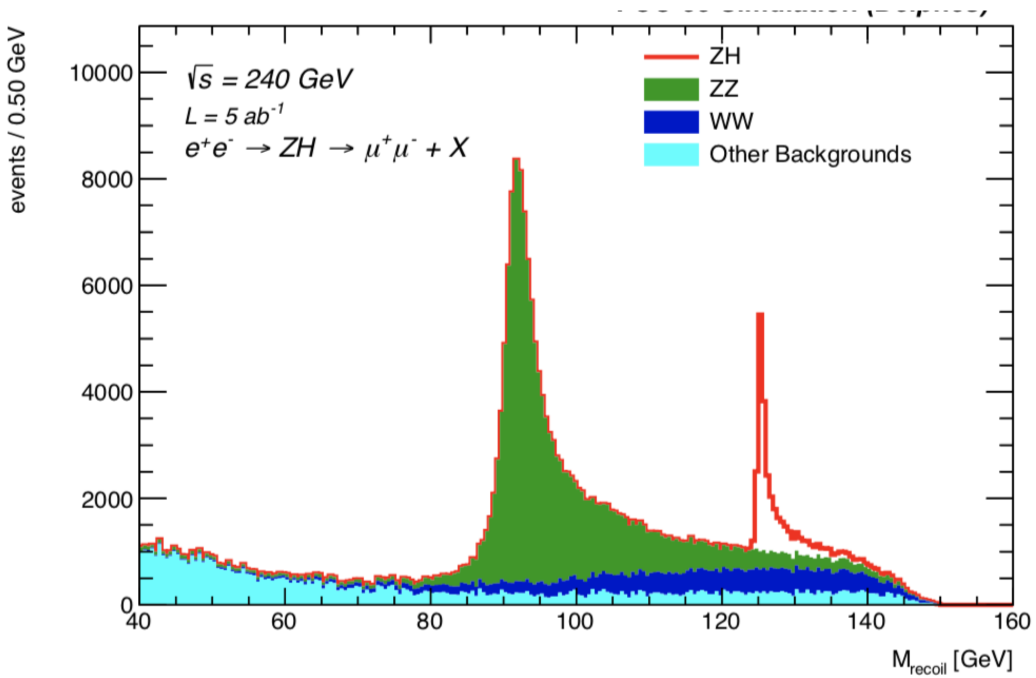
total rate	$\propto g_{HZZ}^2$
ZZZ final state	$\propto g_{HZZ}^4 / \Gamma_H$
➔ measure total width	Γ_H

g_{HZZ} to ±0.2%

empty recoil = invisible width

'funny recoil' = exotic Higgs decay



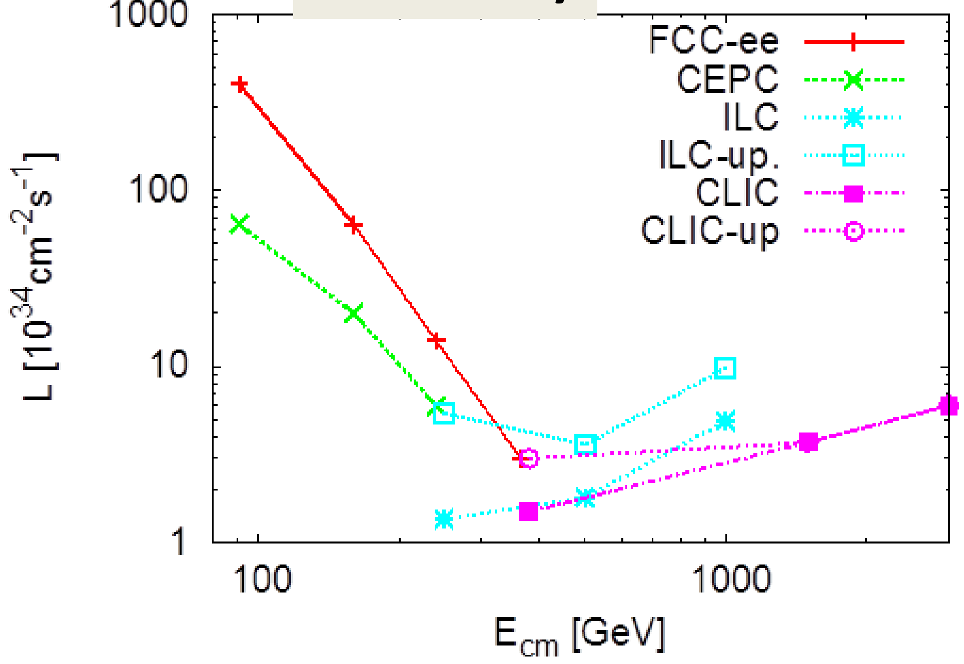


FCC

Circular vs linear complementarity

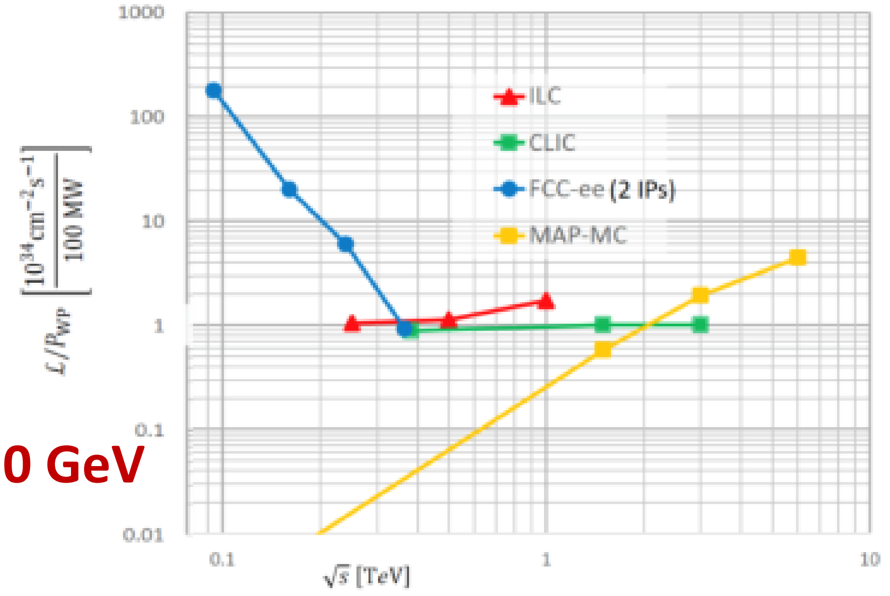
plots from Briefing Book

Luminosity



cross-over ~350 GeV

Luminosity/Power → Energy efficiency



Luminosity vs Energy circular below 365GeV linear above 365 GeV

Efficiency : 9 (5) GJ/Higgs at FCC-ee with 2(4)IP 50GJ/Higgs for ILC250 (first 15 years)

Beam polarization: circular: transverse → ppm beam energy calibration

linear: longitudinal : e- ±80% easy, (e+ ±30% difficult) → additional d.o.f

Monochromatization for e+e- → H (125 GeV)

Long term energy upgrade circular: pp, AA, e-h linear: High energy lepton collisions

Interaction points circular: 2-4 linear: 1 IP (at a time)

Run limited in time by arrival of hadron collider Run is open ended

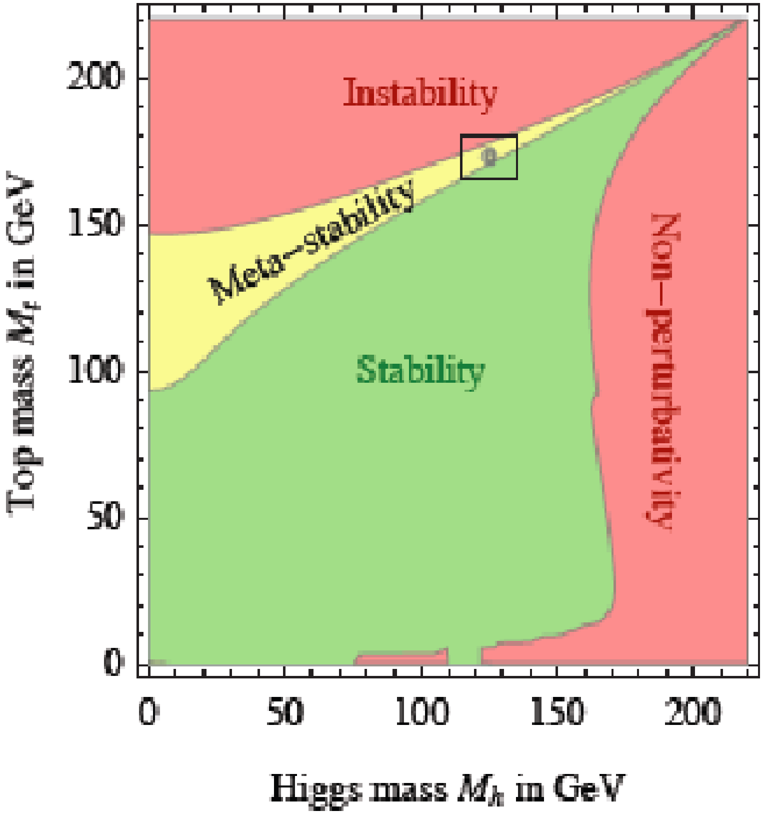
The Standard Model is a very consistent and complete theory.

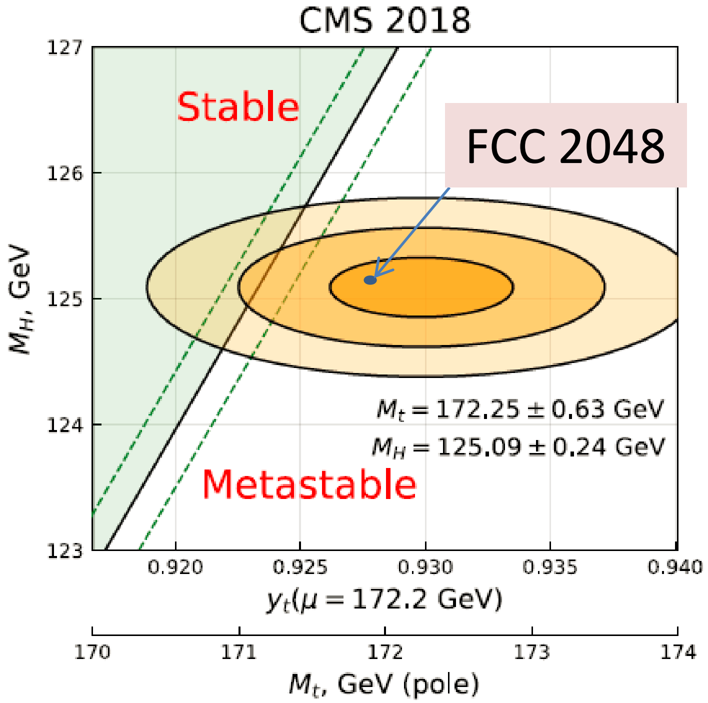
It explains all known collider phenomena and almost all particle physics (except ν's)

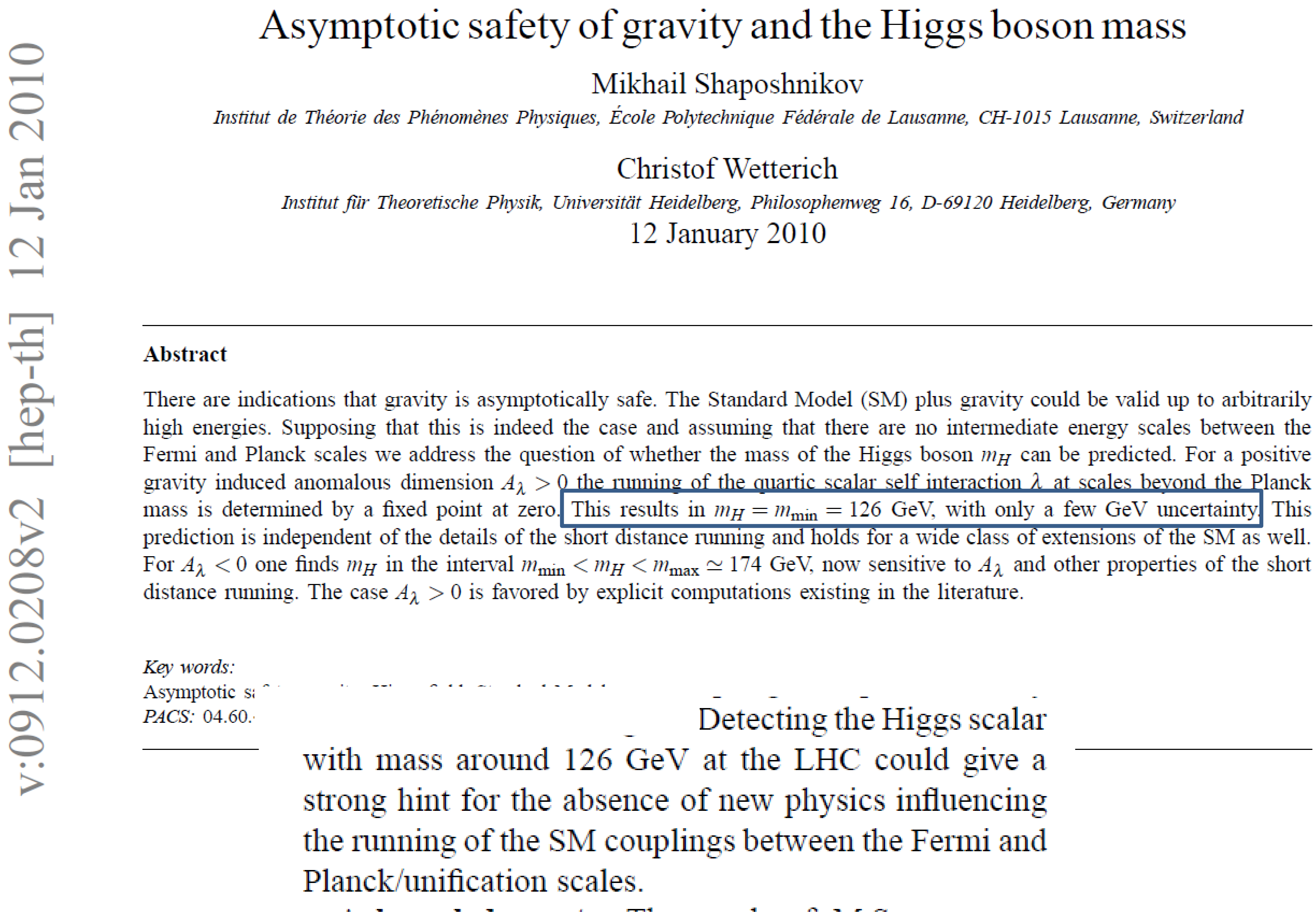
– this was beautifully verified at LEP, SLC, Tevatron and the LHC.

-- the EWPO radiative corrections predicted top and Higgs masses assuming SM *and nothing else*

we can even extrapolate the Standard Model all the way to the the Plank scale :







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Asymptotic safety of gravity and the Higgs boson mass

Mikhail Shaposhnikov
Institut de Théorie des Phénomènes Physiques, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Christof Wetterich
Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

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Abstract

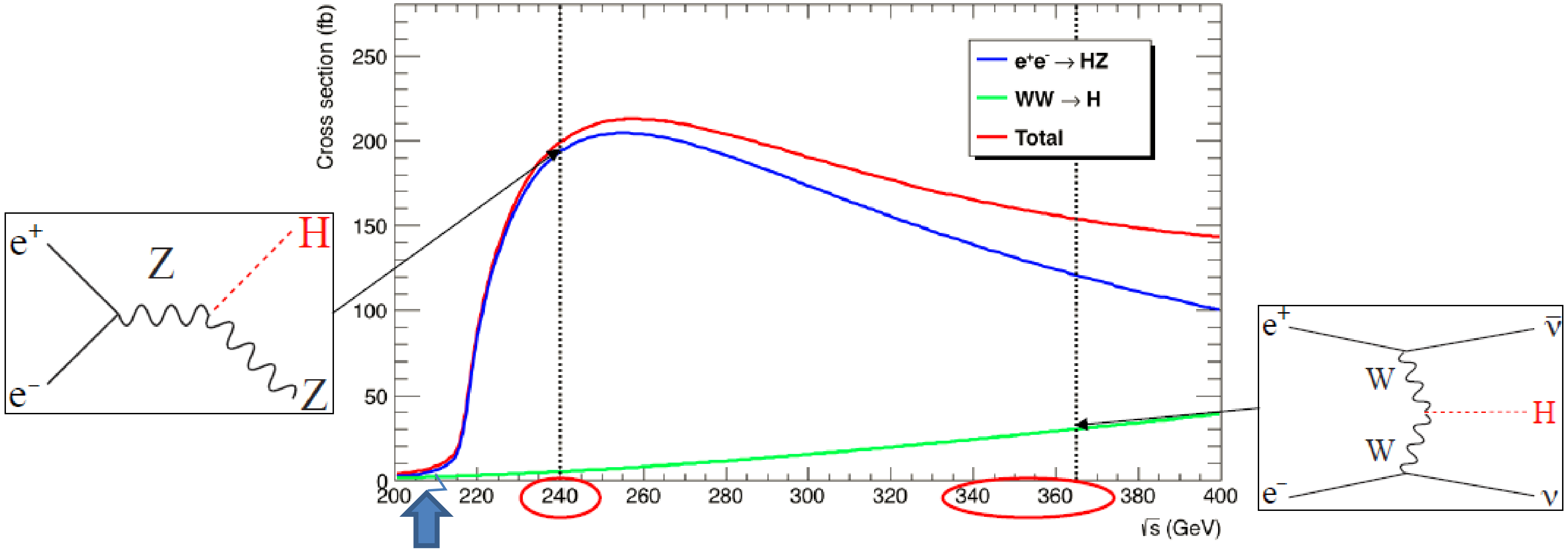
There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. $\boxed{\text{This results in } m_H = m_{\min} = 126 \text{ GeV, with only a few GeV uncertainty.}}$ This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\min} < m_H < m_{\max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Key words:
Asymptotic s
PACS: 04.60.

Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

Is it the end?

Higgs Production



LEP

10^6 e+e- → ZH events with 5 ab-1

- **Target : few per-mil precision, statistics-limited.**
- **Complemented with 200k events at √s = 350 – 365 GeV**

Of which 30% in the WW fusion channel (useful for the Γ_H precision)

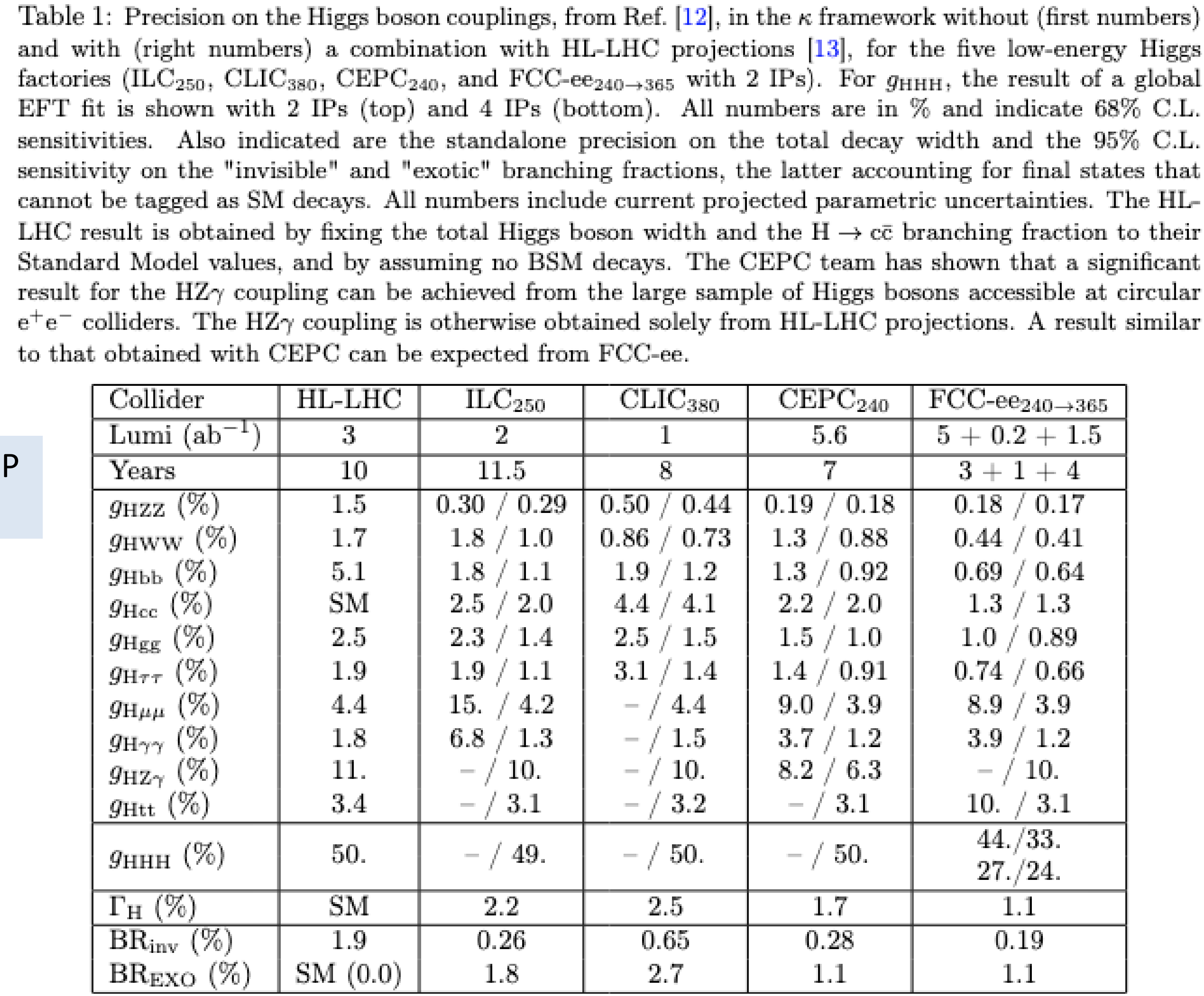


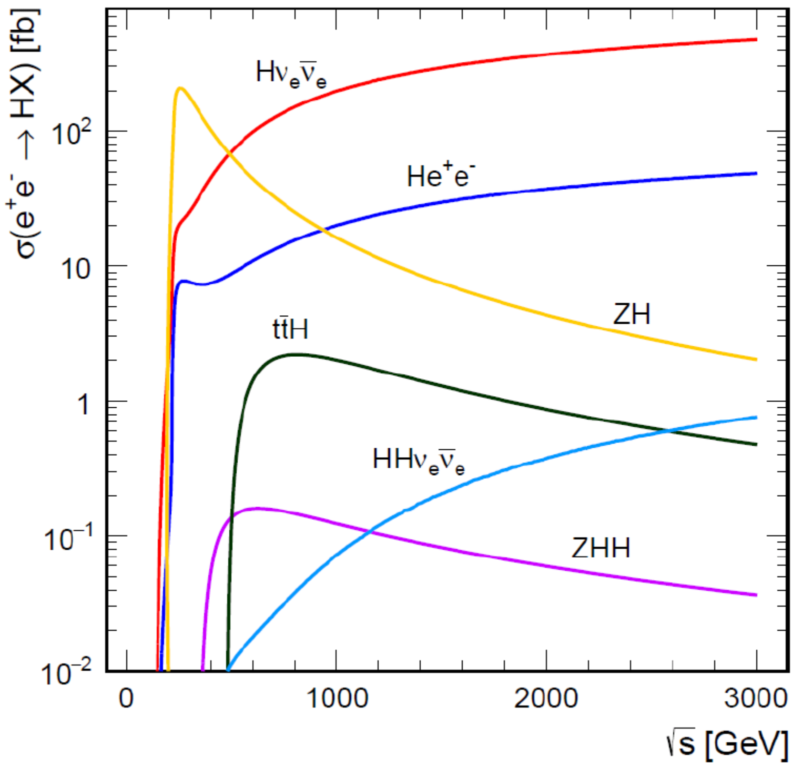
Table 1: Precision on the Higgs boson couplings, from Ref. [12], in the κ framework without (first numbers) and with (right numbers) a combination with HL-LHC projections [13], for the five low-energy Higgs factories (ILC$_{250}$, CLIC$_{380}$, CEPC$_{240}$, and FCC-ee$_{240\to365}$ with 2 IPs). For g_{HHH}, the result of a global EFT fit is shown with 2 IPs (top) and 4 IPs (bottom). All numbers are in % and indicate 68% C.L. sensitivities. Also indicated are the standalone precision on the total decay width and the 95% C.L. sensitivity on the "invisible" and "exotic" branching fractions, the latter accounting for final states that cannot be tagged as SM decays. All numbers include current projected parametric uncertainties. The HL-LHC result is obtained by fixing the total Higgs boson width and the H → c$\bar{\mathrm{c}}$ branching fraction to their Standard Model values, and by assuming no BSM decays. The CEPC team has shown that a significant result for the HZγ coupling can be achieved from the large sample of Higgs bosons accessible at circular e$^+$e$^-$ colliders. The HZγ coupling is otherwise obtained solely from HL-LHC projections. A result similar to that obtained with CEPC can be expected from FCC-ee.

Collider	HL-LHC	ILC$_{250}$	CLIC$_{380}$	CEPC$_{240}$	FCC-ee$_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5	0.30 / 0.29	0.50 / 0.44	0.19 / 0.18	0.18 / 0.17
g_{HWW} (%)	1.7	1.8 / 1.0	0.86 / 0.73	1.3 / 0.88	0.44 / 0.41
g_{Hbb} (%)	5.1	1.8 / 1.1	1.9 / 1.2	1.3 / 0.92	0.69 / 0.64
g_{Hcc} (%)	SM	2.5 / 2.0	4.4 / 4.1	2.2 / 2.0	1.3 / 1.3
g_{Hgg} (%)	2.5	2.3 / 1.4	2.5 / 1.5	1.5 / 1.0	1.0 / 0.89
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2
$g_{\mathrm{HZ}\gamma}$ (%)	11.	– / 10.	– / 10.	8.2 / 6.3	– / 10.
g_{Htt} (%)	3.4	– / 3.1	– / 3.2	– / 3.1	10. / 3.1
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 27./24.
Γ_{H} (%)	SM	2.2	2.5	1.7	1.1
BR$_{\mathrm{inv}}$ (%)	1.9	0.26	0.65	0.28	0.19
BR$_{\mathrm{EXO}}$ (%)	SM (0.0)	1.8	2.7	1.1	1.1

table from ESPP briefing book

High energy Higgs factories: ILC500, CLIC3000, FCC-hh.

FCC-ee + FCC-hh is very competitive



Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT	
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16	ee
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19	
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48	
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96	
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50	
$g_{H\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46	
$g_{H\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43	hh
$g_{H\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32	
$g_{HZ\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70	
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95	
g_{HHH} (%)	27.	10.	9.	±3(stat)±~1.4(syst)	
Γ_H (%)	1.1	1.0	1.6	0.91	ee
BR_{inv} (%)	0.23	0.22	0.61	0.024	hh
BR_{EXO} (%)	1.4	1.4	2.4	1.0	ee

FCC-hh > 10^{10} H produced, +
FCC-ee measurement of g_{HZZ}
→ g_{HHH} , $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, $g_{H\mu\mu}$, BR_{inv}

(*)see M. Selvaggi, 3d FCC physics workshop,
9% precision in 3 years of FCC-hh running, 2004.03505v1

FCC-ee at the intensity frontier

- **TeraZ offers four additional pillars to the FCC-ee physics programme**

Flavour physics programme

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., $b \to s\tau\tau$

QCD programme

- Enormous statistics with $Z \to \ell\ell$, qq(g)
- Complemented by 100,000 $H \to gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
$5 \cdot 10^{12}$ Z is a minimum

Tau physics programme

- Enormous statistics: $1.7\ 10^{11}$ $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons

FCC-ee at the intensity frontier

- **… which in turn provide specific detector requirements**

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

QCD + EW programme

- Particle-Flow reconstruction
- Lepton and jet angular and energy resolution ; Lepton ID

More case studies will lead to more detector requirements

Tau physics programme

- Momentum resolution
  - Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  - Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  - BR measurements, EWPOs, spectral functions

Rare/BSM processes, e.g. Feebly Coupled Particles

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

If all these constraints are met, Higgs and top programme probably OK (tbc)

Precision Natural SUSY at CEPC, FCC-ee, and ILC, JJ Fan, M. Rees and Liantao Wang

arXiv:1412.3107v2 figure 5 (top row)

«Higgs and EWPOs are complementary»

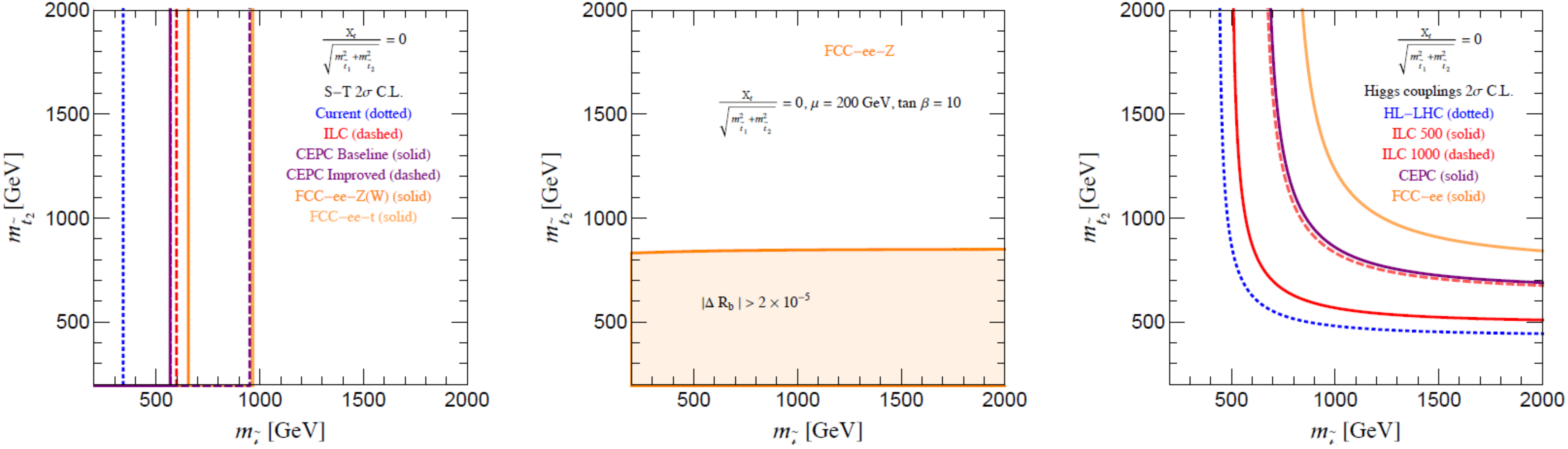


Figure 5. Regions in the stop physical mass plane that are/will be excluded at 2σ by EWPT with oblique corrections (left column), R_b at FCC-ee (mid column) and Higgs couplings (right column) for different choices of $X_t/\sqrt{m_{\tilde{t}_1}^2+m_{\tilde{t}_2}^2}$: 0 (first row), 0.6 (2nd row), 1.0 (3rd row) and 1.4 (last row). We chose the mass eigenstate with $m_{\tilde{t}_1}$ to be mostly left-handed while the mass eigenstate with $m_{\tilde{t}_2}$ to be mostly right-handed. For non-zero choices of X_t, there are regions along the diagonal line which cannot be attained by diagonalizing a Hermitian mass matrix [32]. Also notice that the vacuum instability bound constrains $X_t/\sqrt{m_{\tilde{t}_1}^2+m_{\tilde{t}_2}^2}\lesssim\sqrt{3}$ [76].

" also, b→ sγ could be useful"