Mini workshop: Precision EW and QCD calculations for the FCC studies: methods and techniques

12 Jan 2018, 09:00 → 13 Jan 2018, 19:30 Europe/Zurich

4-3-006 - TH Conference Room (CERN)

Alain Blondel (Universite de Geneve (CH)) , Janusz Gluza (U.Silesia (PL)) , Patrick Janot (CERN)

Description Motivation for the mini-workshop on multiloop/multiscale methods and techniques in the context of precise Z-boson studies

The future 100-km circular collider (FCC, see the web page) will deliver the highest integrated luminosities to study all heavy Standard Model particles with unprecedented precision.

The first step of this collider (FCC-ee) will deliver e+e− collisions to study the Z, W, and Higgs bosons, and the top quark, but also the b and c quarks, and the tau lepton. The number of Z bosons produced by FCC-ee (up to 5×10^12), for example, is expected to be almost six orders of magnitude larger than the
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processes made possible by these large data samples will open opportunities for new physics discoveries, from very weakly-coupled light particles that could explain the yet unobserved dark matter to quantum effects of high-mass scale new physics typically up to 100 TeV. For these quantum effects to be measurable, however, the precision of the theoretical calculations that predict the various observables within the standard model and beyond will have to match that of the experimental measurements, i.e., to improve by one-to-two orders of magnitude with respect to current achievements. This tour-de-force will require complete two- and three-loop corrections to be calculated, and probably the developments of breakthrough computation techniques to keep the time needed for these numerical calculations within reasonable limits.

WELCOME – THIS WORKSHOP IS A VERY IMPORTANT STEP!

The purpose of the mini-workshop is to discuss:

(i) the precision of the theoretical calculations that predict the various observables within the standard model (and beyond) required to match that of the experimental measurements to be made by the FCC-ee,

(ii) the techniques to be applied and/or developed to reach this precision.

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The first step of this collider (FCC-ee) will deliver e+e- collisions to study the Z, W, and Higgs bosons, and the top quark, but also the b and c quarks, and the tau lepton. The number of Z bosons produced by FCC-ee (up to 5×10^12), for example, is expected to be almost six orders of magnitude larger than the number of Z bosons collected at LEP (2×10^7), and orders of magnitude larger than that envisioned with a linear collider (a few 10^9). Furthermore, the exquisite determination of the centre-of-mass energy by resonant depolarization available in the storage rings will allow measurements of the W and Z masses and widths with a precision of a few hundred keV. The high-precision measurements and the observation of rare processes made possible by these large data samples will open opportunities for new physics discoveries, from very weakly-coupled light particles that could explain the yet unobserved dark matter to quantum effects of high-mass scale new physics typically up to 100 TeV. For these quantum effects to be measurable, however, the precision of the theoretical calculations that predict the various observables within the standard model and beyond will have to match that of the experimental measurements, i.e., to improve by one-to-two orders of magnitude with respect to current achievements. This tour-de-force will require complete two- and three-loop corrections to be calculated, and probably the developments of breakthrough computation techniques to keep the time needed for these numerical calculations within reasonable limits.

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(ii) the techniques to be applied and/or developed to reach this precision.

The programme will include detailed presentations on multiloop/multiscale techniques and other methods, identified bottle-necks problems of both present software and analytical/numerical methods, and discussions towards establishing a work plan for future studies.

For general physics studies connected with FCC-ee, you may consider to participate in the 2nd FCC Physcs weeks which will take place at CERN just a week after this event, 15-19 January 2018, see indico.

The Future Circular Colliders
CDR and cost review for the next ESU (2018)

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- *Ultimate goal:* ~16 T magnets
  100 TeV pp-collider (FCC-hh)

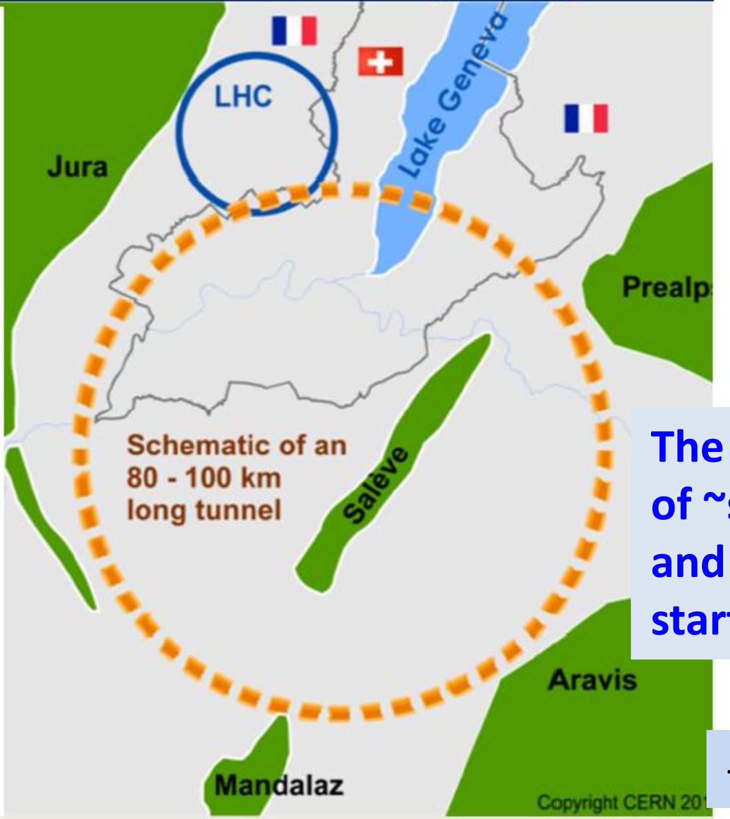
→ defining infrastructure requirements

Possible first steps:

- e^+e^- collider (*FCC-ee*)
  High Lumi, E_{CM} =90-400 GeV
- *HE-LHC* 16T ⇒ 28 TeV
  in LEP/LHC tunnel

Possible add-on:

- *p-e* (*FCC-he*) option



The two first steps are of ~similar cost and lead to similar starting date for FCC-hh

+ FCC-μ+μ- ?

From European Strategy in 2013: "ambitious post-LHC accelerator project"
Study kicked-off in Geneva Feb 2014

FCC CONCLUSIONS

-- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology.

-- Both FCC-ee and FCC-hh have outstanding physics cases

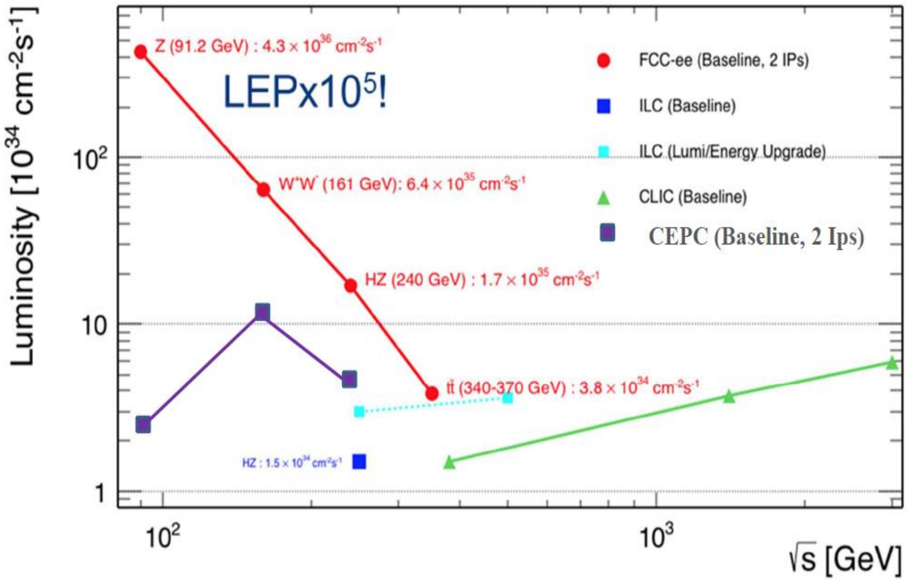
-- each in their own right

-- the sequential implementation of FCC-ee, FCC-hh, FCC-eh would maximise the physics reach

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.

-- the FCC are shaping up as the most natural, complete and powerful aspiration of HEP for its long-term future

The Physics case of FCC-ee and theory uncertainties



In short:

-- very high luminosities for Z, W, H, top

-- unique measurements for H(125)

-- exquisite energy calibration at Z and W

-- clean experimental environment ,

➔ survey of the heavy particles of the SM with unprecedented sensitivity/precision

Physics program: 88 GeV to 365 GeV

First step towards 100 TeV pp collisions

2013 European Strategy: There is a strong scientific case for an electron positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

FCC-hh discovery potential
Highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

FCC-hh physics is dominated by three features:

-- Highest center of mass energy –> a big step in high mass reach!
ex: strongly coupled new particle up to 50 TeV
Excited quarks, Z', W', up to ~tens of TeV
Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV
Sensitivity to high energy phenomena in e.g. WW scattering

-- HUGE production rates for single and multiple production of SM bosons (H,W,Z) and quarks
-- Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau/ZZ$, ttH/ttZ @% level
-- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling
-- detection of rare decays $H\rightarrow V\gamma$ ($V=\rho,\varphi,J/\psi,\Upsilon,Z\ldots$)
-- search for invisibles (DM searches, RH neutrinos in W decays)
-- renewed interest for long lived (very weakly coupled) particles.
-- rich top and HF physics program

-- Cleaner signals for high Pt physics
-- allows clean signals for channels presently difficult at LHC (e.g. $H\rightarrow bb$)

working point	luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	*geom. lumin.*	luminosity/year	physics goal	run time [years]
Z first 2 years	65	*69*	17 ab^{-1}/year	150 ab^{-1}	6
Z later	130	*137*	34 ab^{-1}/year		
W	20	*30*	5 ab^{-1}/year	8 - 10 ab^{-1}	2
H	7	*8*	1.8 ab^{-1}/year	5 ab^{-1}	3
top	2.0	*2.1*	0.5 ab^{-1}/year	1.5 ab^{-1}	3

-- Fantastic step to have achieved a 'guaranteed' baseline for luminosity and performance

-- The experimental set-up is not affected by an increase of the performance

-- no pile up & low backgrounds

➔ any improvement in luminosity/MW improves physics and/or saves running time

➔ improves flexibility of FCC-ee → FCC-hh transition

➔ should be encouraged!

FCC-ee: discovery machine, not «just» measurements!

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

> EXPLORE 10 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass reach)

$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , α_{QED} (m_z), α_s $(m_z; m_W; m_\tau)$

-- Higgs boson couplings and top quark properties

> DISCOVER a violation of flavour conservation or universality

-- ex FCNC ($Z \to \mu\tau$, $e\tau$) in 5 10^{12} Z decays.

+ flavour physics (10^{12} bb events)

> DISCOVER dark matter as «invisible decay» of H or Z

> DISCOVER Right-Handed neutrino(s) or very weekly coupled particle in 5-100 GeV energy scale such as Dark Photons etc…

Precision EW measurements at lepton colliders

Some references:
Snowmass EW report,
ILC 'GigaZ' papers, top talks and papers at LCWS16,17
'First look at physics at TLEP' arxiv:1308.6176
papers at 'physics behind precision' workshop

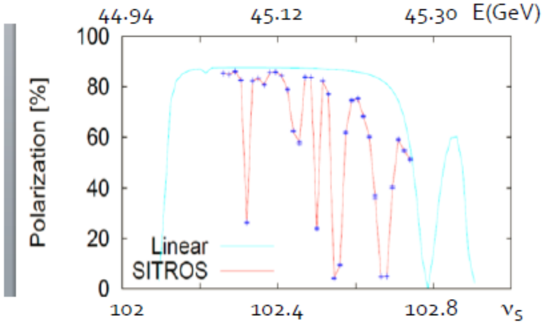
The question: closure of the Standard Model.
-- are there further new particles or phenomena which affect (via loops or otherwise) the relationship between observables?

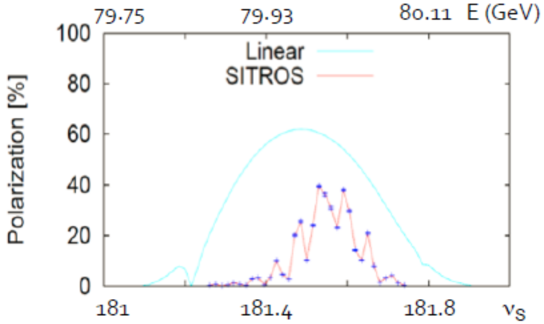
➔ **Is there an intrinsic limit to extract physics due to theoretical calculations?**

observable	Physics	Present precision		FCC-ee stat Syst Precision	FCC-ee key	Challenge
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	**E_cal**	QED corrections
Γ_Z MeV/c2	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	**E_cal**	QED corrections
$R_l = \frac{\Gamma_h}{\Gamma_l}$	α_s, δ_b	20.767 (25)	Z Peak	**0.0001 (2-20)**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak $Z+\gamma$(161 GeV)	**0.00008 (40)** **0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 (66)	Z Peak	**0.000003 (20-60)**	Statistics, small IP	Hem. corr, gluon split. m_b
A_{LR}	**$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)**	**$\sin^2\theta_w^{eff}$** 0.23098(26)	Z peak, **Long. polarized**	$\sin^2\theta_w^{eff}$ **±0.000006**	4 bunch scheme	Design experiment
A_{FB}^{lept}	**$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)**	**$\sin^2\theta_w^{eff}$** 0.23099(53)		$\sin^2\theta_w^{eff}$ **±0.000006**	**E_cal** & Statistics	
M_W MeV/c2	**$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ (T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<0.5 MeV**	**E_cal** & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	**~10 MeV**	**E_cal** & Statistics	Theory limit at 50 MeV?

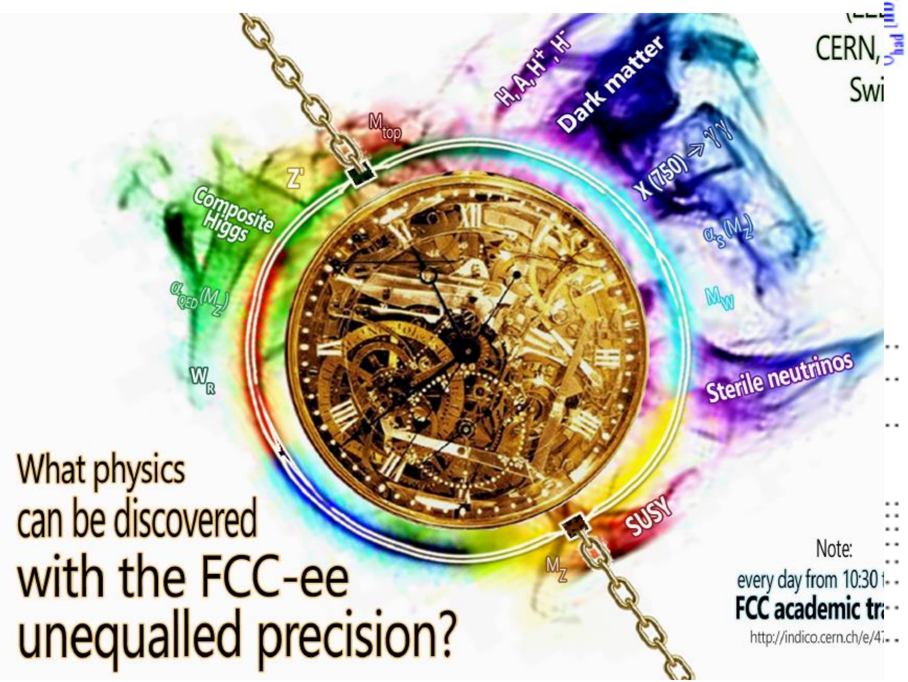
Beam energy calibration

- **Achieve / measure beam transverse polarization**
  - For a few 10's of non-colliding "monitoring" bunches – out of 16000 (Z) or 2000 (W)
    - Excellent polarization level at the Z
    - Enough polarization at the W (~LEP at the Z)



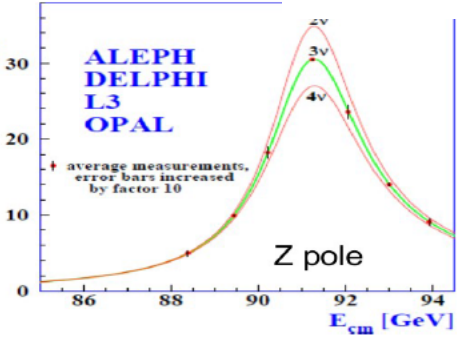


  - Need wigglers to have polarization fast enough during physics run
- **"Continuous" beam energy calibration with resonant depolarization**
  - See backup for an explanation of "resonant depolarization"
  - A unique feature of circular e^+e^- colliders !
    - Demonstrated (and used) at LEP, outside physics runs (extrapolation error 2 MeV)
    - Target precision at FCC-ee is ± 100 keV on $\sqrt{s}$ at the Z pole and WW threshold
      - ➨ Crucial for sensitivity to new physics of the electroweak measurements

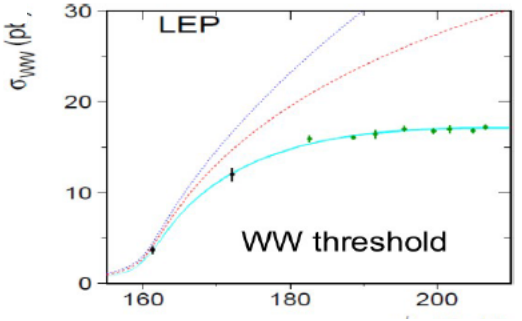


https://indico.cern.ch/event/469561/

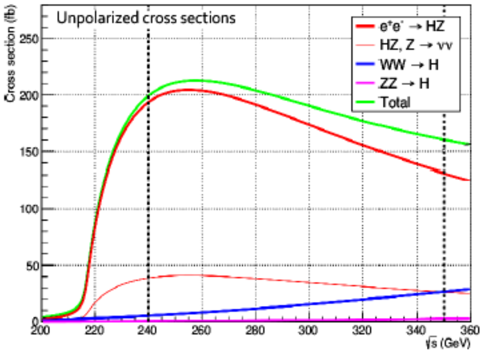
$\sqrt{s}$=91 GeV, 5 10^{12} Zs



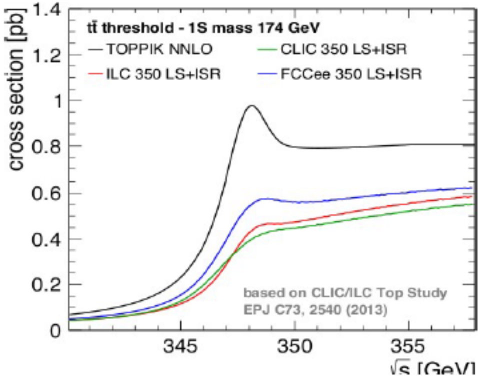
$\sqrt{s}$=161 GeV, 10^8 W's



$\sqrt{s}$=240 GeV, 10^6 H's



350-365 GeV 10^6 tops



Precision Electroweak Measurements depend on theory in many different ways!

QED at measurement level:

Absolute luminosity enters in measurement of
$\sigma^{peak}(m_Z)$ → N_ν ; WW threshold → m_W ; e+e- → ZH (Higgs total width) ; e+e-→ $t\bar{t}$
→ low angle Bhabha + large angle e+e- → $\gamma\gamma$ (*new* thanks to high luminosity, more precise)

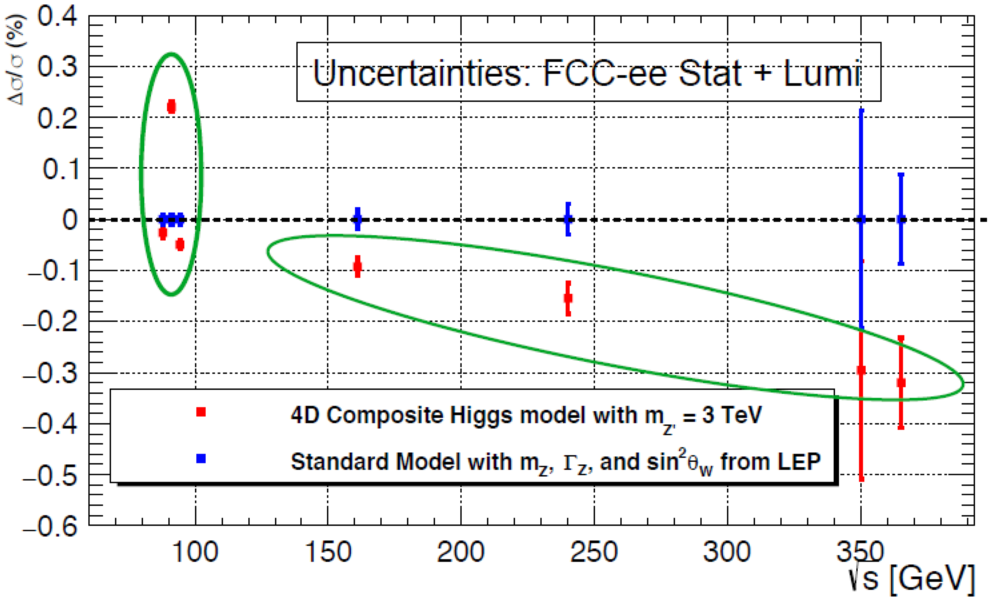
Initial state radiation is crucial for Z line shape, $A_{FB}^{\mu\mu}$, WW, ZH, tt threshold
Shift E_{CM} , changes cross-section and event kinematics. (Presently 300keV effect on m_Z)

Actions : Staszek Jadach, with support from FCC, has set up a web site with up-to-date QED event generators
Maciej Skrzypek is starting work on WW threshold (beyond O(α), exponentiation)
expect precision at O(10^{-4}) for Lumi, Work in Progress for W mass.

Example: Precision needed for $e^+e^- \to \mu^+\mu$

- Cross section : sensitivity to new physics

S. de Curtis et al.

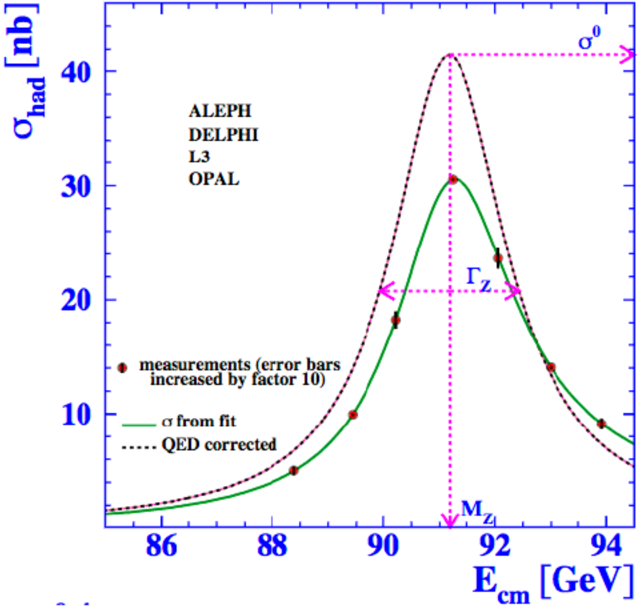


- Z mass and width @ Z pole : predict σ to ~ 5×10^{-5} (also for Bhabha)
  - Reminder : stat + lumi errors ≳ 10^{-3} for Z pole at LEP
- Higher-energy deviations : 10^{-4} precision needed to match stat. errors

Example: Precision needed for $e^+e^- \to \mu^+\mu$

- Cross section : Z mass and width

S. Jadach et al.



(Shown here for $e^+e^- \to$ hadrons)

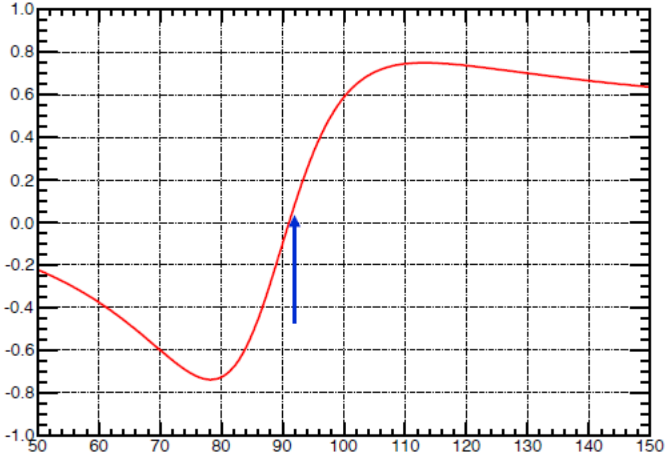
similar improvement needed for e+e- → WW pair threshold for m_W measurement

- ~30% QED corrections (ISR)
  - Current (LEP) precision translates to an uncertainty of 2×10^{-4} on σ
    - ➨ Improvement by a factor ~5 needed

Example: Precision needed for $e^+e^- \rightarrow \mu^+\mu^-$

- Forward-Backward asymmetry : Weinberg angle

A. Blondel et al.



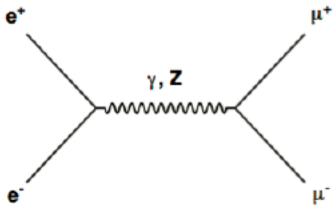
correlation between m_Z and AFB important

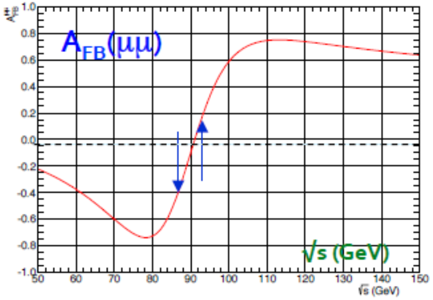
- At the Z pole, $A_{FB}(\mu\mu)$ ~1.6×10^{-2} and $\Delta\sin^2\theta_W$ ~ 0.01 $\Delta A_{FB}/A_{FB}$
- Experimental error dominated by ΔE_{beam} : $\Delta\sin^2\theta_W$ ~ 6 $\times10^{-6}$
  - To match this error, $\Delta A_{FB\,(th)}$ ~ 10^{-5} at the Z pole
    - ➨ LEP theoretical uncertainty is about 10^{-3}

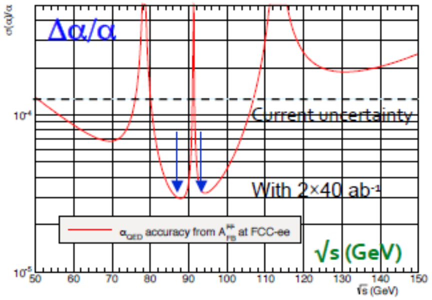
Example: Precision needed for $e^+e^- \to \mu^+\mu^-$

- **Forward-Backward asymmetry : $\alpha_{QED}(m_Z)$**

P. Janot et al.







From γ-Z interference:

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

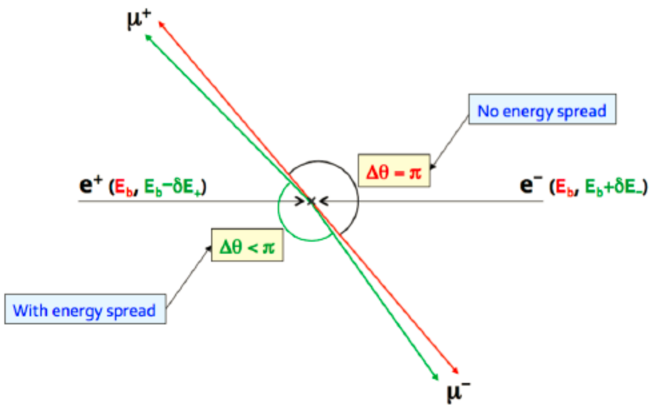
- Measure $\alpha_{QED}(m_Z)$ with A_{FB} at $\sqrt{s}$ = 87.9 and 94.3 GeV
  - To match statistical error
    - Predict AFB with a precision of ~10^{-5} at these energies
    - Predict IFI effects (ISR+FSR interference) to ~ few 10^{-4}

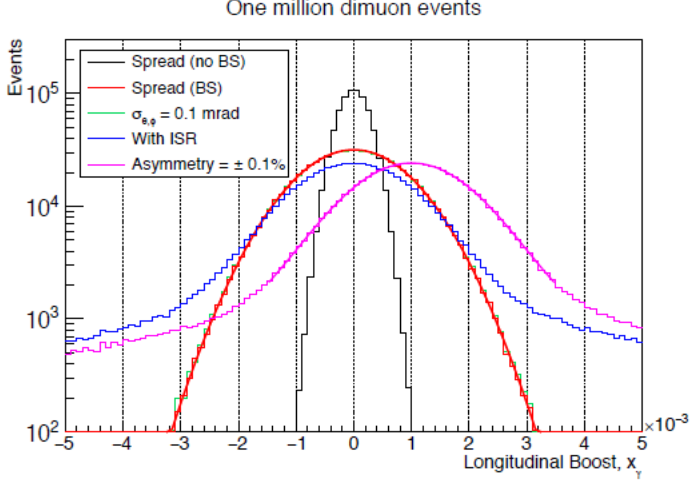
S. Jadach et al.

Example: Precision needed for $e^+e^- \rightarrow \mu^+\mu$

P. Janot et al.

- **Measurement of the beam energy spread**
  - δE_{beam} ~ 0.13% at FCC-ee (Z pole)
    - To be measured with a relative precision of ~0.1%
      - ➨ To match the Γ_Z target uncertainty of 100 keV
  - Determination from the muon angles and (E,p) conservation





  - ISR alters the energy spread determination
    - ISR energy spectrum and angular distribution required with ~% precision

Precision Electroweak Measurements depend on theory in many different ways!

QCD effects at measurement level:

-- value of α_s?

-- gluon radiation, gluon splitting, fragmentation, hemisphere correlations
enter in hadronic quantities $R_{\ell,Z} \equiv \Gamma_{had}/\Gamma_{\ell}$, σ^{peak}_{had} , R_b , WW, etc…
affect efficiencies and jet algorihms.

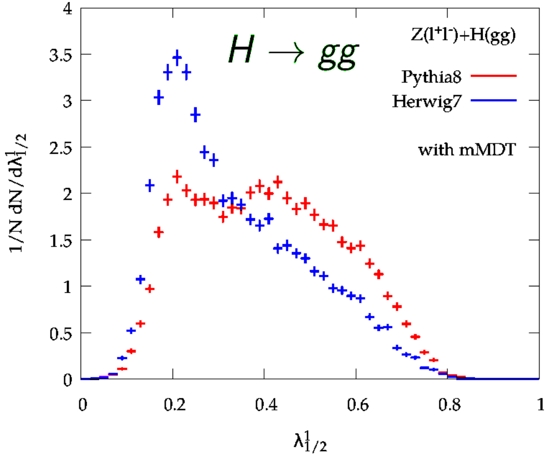
→ 5 10^{12} Z or 10^8 W or Zγ hadronic decays and 10^4 H→gg
with little or no backgrounds and ~4π detector will provide

-- α_s to +- 0.0001-2 (from $R_{\ell,Z}$ or $R_{\ell,W}$ or tau decays)

-- calibration of efficiencies for hadronic decays

-- quark-gluon dynamics

-- quark and gluon fragmentation functions
including into K, p, charm and b-hadrons



Data will provide internally input needed for experimental efficiencies etc…

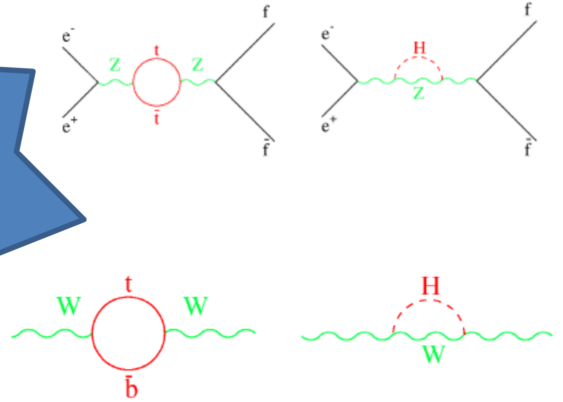
Still: will need QCD event generators with sufficient flexibility to incorporate this knowledge

Physics interpretation of EW precision measurements

Basic inputs
m_Z, $\alpha_{QED}(0)$, $G_F(\tau_\mu)$

Other parameters
$\alpha_{QED}(m_Z)$, $\alpha_s(m_Z)$, m_b, m_{top}, m_H

Electroweak calculation



Also here…

Measured EW observables

fit etc…

5σ?

Predicted EW observables

± **parametric error ($\alpha_{QED}(m_Z)$, $\alpha_s(m_Z)$, m_b, m_{top}, m_H)**

± **calculation error (e.g. missing higher orders)**

under the hypothesis of Standard Model only.

There is new physics !
pattern of deviations may indicate what it is.

pattern of violations from new physics scenarios
RH neutrino(s) ≠ Higgs doublet ≠ new families etc..

The main players

Inputs(2016):

$G_F = 1.1663787(6) \times 10^{-5}$ /GeV^2	from muon life time	$6\ 10^{-7}$
$M_Z = 91.1876 \pm 0.0021$ GeV	Z line shape	$2\ 10^{-5}$
$\alpha = 1/137.035999074(44)$	electron g-2	$3\ 10^{-10}$

EW observables sensitive to new physics:

$M_W = 80.385 \pm 0.015$	LEP, Tevatron	$2\ 10^{-4}$
$\sin^2\theta_W^{eff} = 0.23153 \pm 0.00016$	WA Z pole asymmetries	$7\ 10^{-4}$
$+ \Gamma$ Rb etc...		

Nuisance parameters:

$\alpha(M_Z) = 1/127.944(14)$	hadronic corrections to running alpha	$1.1\ 10^{-4}$
$\alpha_S(M_Z) = 0.1187(17)$	strong coupling constant	$1.7\ 10^{-3}$
$m_{top} = 173.34 \pm 0.76$ GeV	LHC+Tevatron	$4\ 10^{-3}$

$m_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV/c^2 (CMS+ATLAS) $2\ 10^{-3}$

$\Delta\rho \equiv \varepsilon_1$: $\Gamma_\ell = (1+\Delta\rho)\dfrac{G_F\, m_Z^3}{24\pi\sqrt{2}}\left(1+\left(\dfrac{g_{Ve}}{g_{Ae}}\right)^2\right)\left(1+\dfrac{3}{4}\dfrac{\alpha}{\pi}\right)$

ε_3: $\sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \dfrac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,m_Z^2}\,\dfrac{1}{1+\Delta\rho}\,\dfrac{1}{1-\dfrac{\varepsilon_3}{\cos^2\theta_W}}$

δ_{vb}: $\Gamma_b = (1+\delta_{vb})\,\Gamma_d\,(1 - \text{mass corrections } \propto m_b^2/M_Z^2)$

ε_2: $M_W^2 = \dfrac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\sin^2\theta_W^{eff}}\cdot\dfrac{1}{(1-\varepsilon_3+\varepsilon_2)}$

$\sin^2\theta_W^{eff}$ is defined from

$\sin^2\theta_W^{eff} = \dfrac{1}{4}\left(1-\dfrac{g_{Ve}}{g_{Ae}}\right) = \sin^2\theta_W{}^{eff}_{lept}$

obtained from asymmetries at the Z.

also Δr: $m_W^2 = \dfrac{\pi\alpha}{\sqrt{2}\,G_F}\cdot\dfrac{1}{\left(1-\dfrac{M_W^2}{M_Z^2}\right)}\,\dfrac{1}{(1-\Delta r)}$

$\Delta r = \Delta\alpha - \dfrac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\dfrac{\cos^2\theta_W}{\sin^2\theta_W}\varepsilon_3 + \dfrac{c^2-s^2}{s^2}\varepsilon_2$

EWRCs

relations to the well measured

$G_F\ m_Z\ \alpha_{QED}$

at first order:

$\Delta\rho = \alpha/\pi\ (m_{top}/m_Z)^2$

$-\ \alpha/4\pi\ \log(m_h/m_Z)^2$

$\varepsilon_3 = \cos^2\theta_w\ \alpha/9\pi\ \log(m_h/m_Z)^2$

$\delta_{vb} = 20/13\ \alpha/\pi\ (m_{top}/m_Z)^2$

complete formulae at 2d order including strong corrections are available in fitting codes

e.g. ZFITTER , GFITTER

Theoretical limitations
-- present

SM predictions (using other input)

$$M_W = 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo}$$

$$\sin^2\theta^{\ell}_{\rm eff} = 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\rm theo}$$

Parametric uncertainties

Other parameters
$\Delta\alpha_{QED}(m_Z)$, $\alpha_s(m_Z)$, m_b, m_{top} , m_H

FCC-ee will measure

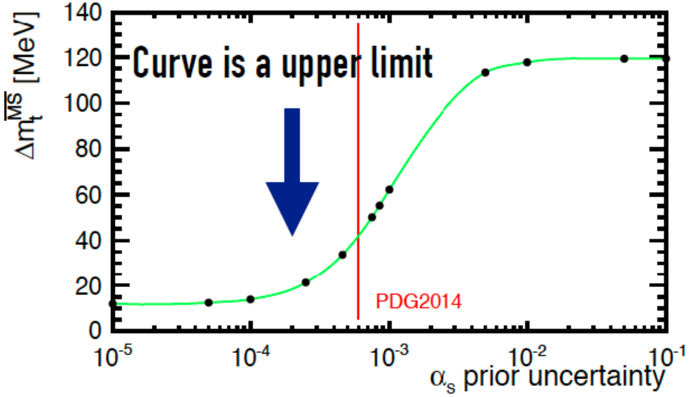
$\alpha_s(m_Z)$ to $\pm < 0.0002$ (see D'Enterria at Berlin and arXiv:1512.05194)
m_{top} to $\pm < 50$ MeV (see P. Azzi / M. Vos/ F. Simon arXiv:1611:03399v1(2016)
m_H to $\pm$ O(10 MeV)
$\alpha_{QED}(m_Z)$ to $\pm$ 3 10^{-5} (P. Azzurri in Berlin, P. Janot , arXiv:1512.05544)
m_b (relevant for H→ bb): ideas for measuring m_b (e.g. measure Z-> bbγ)
had been proposed at LEP should be revisited with benefit of statistics

In addition SuperKEKb will measure more of the {bb} bound state spectrum
and by radiative return the cross-section e+e- → hadrons at low energy.
→ expect $\Delta\alpha_{QED}(m_Z)$ to $\pm$ 5 10^{-5} from that method.

TOP MASS FROM THRESHOLD SCAN

M. Perello', M. Vos (2015)

- Experimental Uncertainties:
  - Beam energy uncertainty of few MeV & beam energy spread: $\Delta m/m$<5MeV
  - α_S: $\Delta\alpha_s$(@FCC)~0.0002 -> $\Delta m/m$ <20MeV
- Theory uncertainties:
  - 1S/PS->$\overline{MS}$@4th loop: $\Delta m/m$~10MeV
  - other scale uncertainties under study



- FCC-ee will measure α_s with unprecedented precision at Z pole and WW threshold runs: $\Delta\alpha_s$ < 0.0002
  - Improved α_s drastically improves correlations m_t, Γ_t and Y_t

With 200 fb-1 and a CLIC-style detector FCC-ee can measure the top quark mass with ~10 MeV statistical accuracy

F. Simon arXiv:1611:03399v1(2016)

Theoretical limitations

FCC-ee

SM predictions (using other input)

$M_W = 80.3593 \pm$ 0.0002 $_t \pm$ 0.0001 $_Z \pm$ 0.0003 $\Delta\alpha_{had}$
$\pm$ 0.0001 $_S \pm$ 0.0000 $M_H \pm 0.0040_{theo}$

0.0005

$\sin^2\theta^{\ell}_{eff} = 0.231496 \pm$ 0.0000015 $\pm$ 0.000001 $_Z \pm$ 0.000006 $_{had}$
$\pm$ 0.0000014 $\pm$ 0.000000 $_H \pm 0.000047_{theo}$

0.000006

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.

BUT can be typically 10 -30 times smaller than present level of theory errors

Will require significant theoretical effort and additional measurements!

the above explains why we want the top running – and high Z statistics.

Freitas, Heinemeyer, Jadach, Gluza … need for 3 loop calculations for the future!

Suggest including manpower for theoretical calculations in the project

Theoretical uncertainties for electroweak and Higgs-boson precision measurements at the FCC-ee

Conveners: A. Freitas[1], S. Heinemeyer[2],
Contributors: M. Beneke[3], A. Blondel[4], A. Hoang[5], P. Janot[6], J. Reuter[7], C. Schwinn[8], and S. Weinzierl[9]

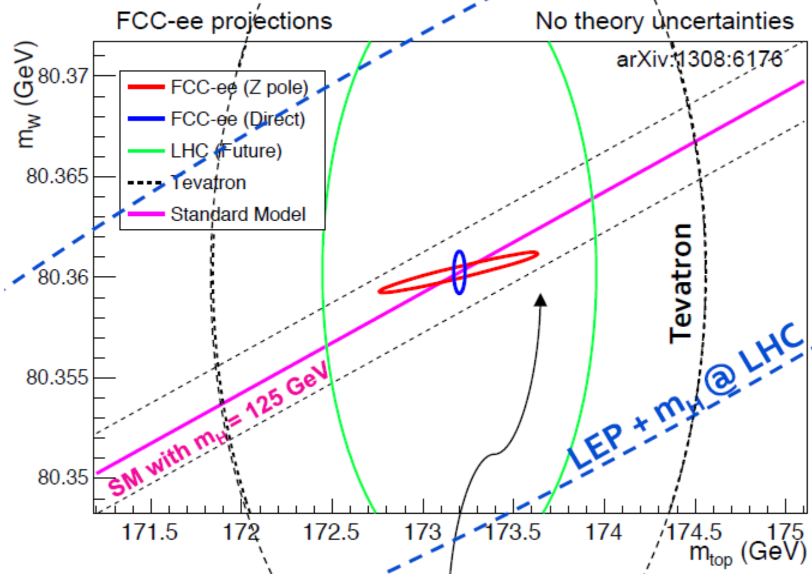
Intrinsic uncertainties: ⇒ always a limiting factor!

DRAFT !

Quantity	FCC-ee	Current intrinsic unc.		Projected unc.
M_W [MeV]	1	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\text{eff}}$ [10^{-5}]	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.2
R_b [10^{-5}]	6	15	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$	7
R_l [10^{-3}]	1	5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$	1.5

Global Fit and sensitivity to new physics

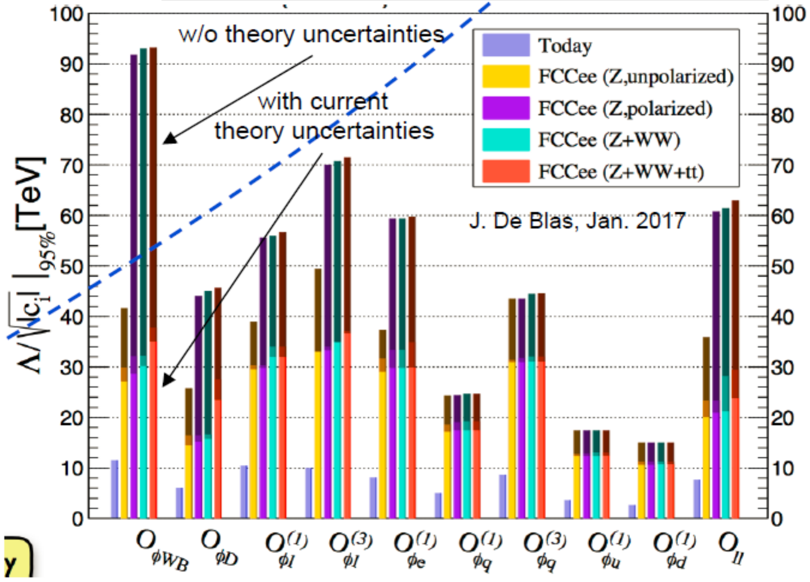
- Combining all EW measurements
  - In the context of the SM … and beyond



Without m_Z (α_{QED})@FCC-ee, the SM line would have a 2.6 (1.8) MeV width

FCC-ee sensitivity severely drops without POLARIZATION + STATISTICS (and improved theory calculations)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

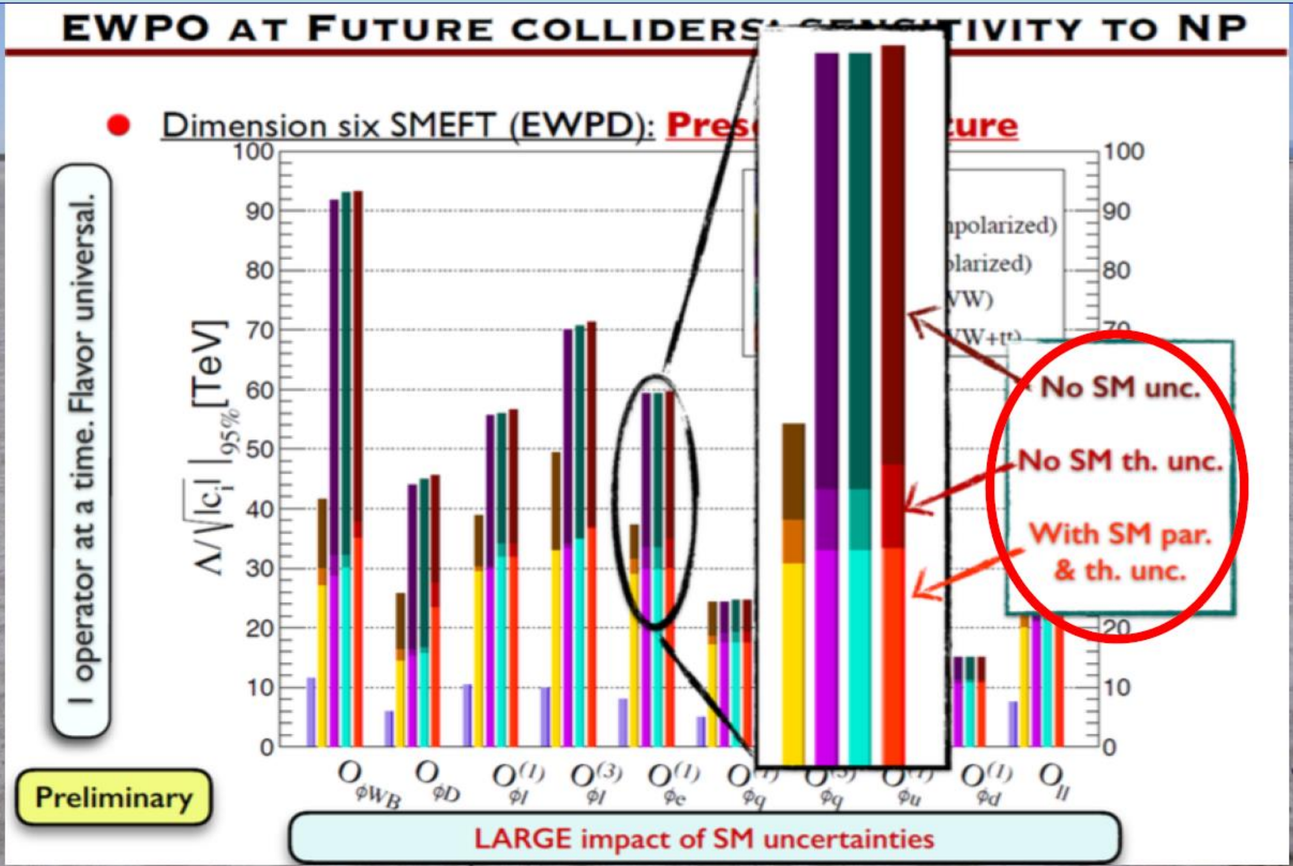


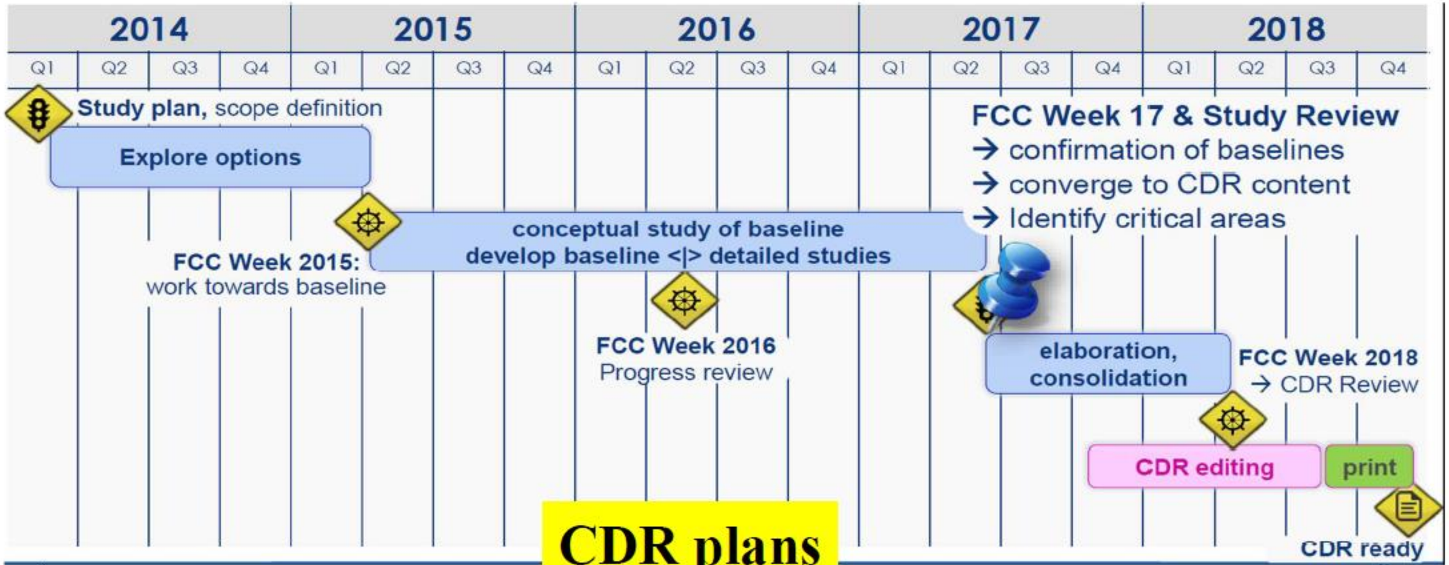
Today: Λ > 5-10 TeV

After FCC-ee: Λ > 50-100 TeV ?

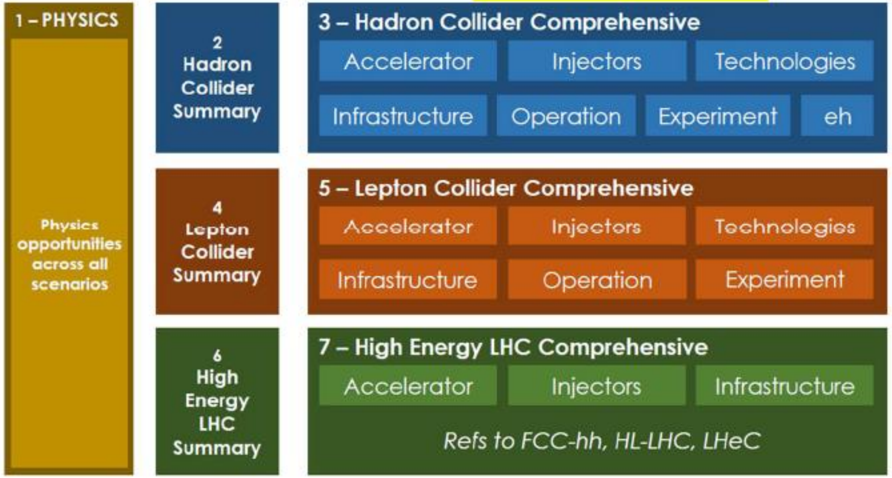
Synergetic with FCC-hh

Important to Control TH and SM Uncertainties





CDR plans



- **Required for end 2018, as input for European Strategy Update**
- **Common physics summary volume**
- **Three detailed volumes FCChh, FCCee, HE-LHC**
- **Three summary volumes FCChh, FCCee, HE-LHC**

Conclusions

Precision measurements of the Higgs, top and Electroweak observables at FCC-ee provide a unique probe in the unknown, complementary and synergetic with FCC-hh

The physics case of FCC-ee is made stronger by robust estimates of theoretical uncertainties.

The high statistics and precision available allows control of parametric uncertainties at FCC-ee e.g. direct determination of $\alpha_{QED}(m_Z)$; as well as lower luminosity meast errors ($ee \rightarrow \gamma\gamma$).

The estimate by S. Heinemeyer et al leads to errors that are of the same order of magnitude as (one is 2.5 times larger than) the target experimental errors. Others are more optimistic. **Only the actual calculations will tell.**

There will be no miracle but for a large amount of work – which equates to discovery potential!

It will be important, *as soon as the project becomes prioritised,* to initiate a training program for students and post-docs to ensure transmission of knowledge from the present experts!

Conclusions(II)

Three years before LEP started (1986 YR) the predicted error on Γ_Z was ~20 MeV!

after LEP predicted the top quark mass from the Z scan (→ Γ_Z to 3 MeV in March 94) ,
t'Hooft and Veltman got the Nobel prize!

It may look like a brick wall but it may be a mine of gold!

Discussion

Precision measurements of the Higgs, top and Electroweak observables at FCC-ee provide a unique probe in the unknown, complementary and synergetic with FCC-hh

The estimate by S. Heinemeyer et al leads to errors that are of the same order of magnitude as (one is 2.5 times larger than) the target experimental errors. This would limit the physics impact of the measurements and demotivate the facility.

This workshop seems to imply that, by 2040, (date when precision measurements will start coming out) the theory is expected to be precise enough not to limit the physics interpretation of the measurements.

➔ IS THIS CORRECT, PARTIALLY or CONDITIONALLY CORRECT?

In any case the conclusions from this workshop should be documented!

Discussion(II)

In any case the conclusions from this workshop should be documented!

There is more than one way to do this.

Proposal to be discussed:

1. produce a single file proceeding out of contributions by all participants (and a few others)

single contributions may be as short as a few pages with an extensive (efficient) list of references. There should be references

2. produce an executive summary making and justifying the most important statements

such as: **'By 2040, when FCC-ee precision measurements will start coming out, the theory will be precise enough not to limit the physics interpretation of the measurements'**

with justification based on the wrkshop contributions, others, and/or references therein.

3. take part in the documentation of these conclusions in the CDR (J. Gluza & F. Piccinini)

Conclusions (III)

4. It will be important, *as soon as the project becomes prioritised,* to initiate a training program for students and post-docs to ensure transmission of knowledge from the present experts!

A good way to initiate this is to already signal and document a set of piecemeal work packages that could be used as a basis for such a proposal.

Some examples

PHYSICS COMPLEMENTARITY

Higgs Physics -- ee → ZH fixes Higgs width and HZZ coupling ,
-- FCC-hh gives huge statistics of ttH, ttZ and HH events for g_{ttH} /g_{ttZ} and Higgs self-coupling

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.5 MeV, m_{top} 10 MeV, etc…)
sensitive to heavy physics up to … 100 TeV
-- FCC-hh gives access to direct observation

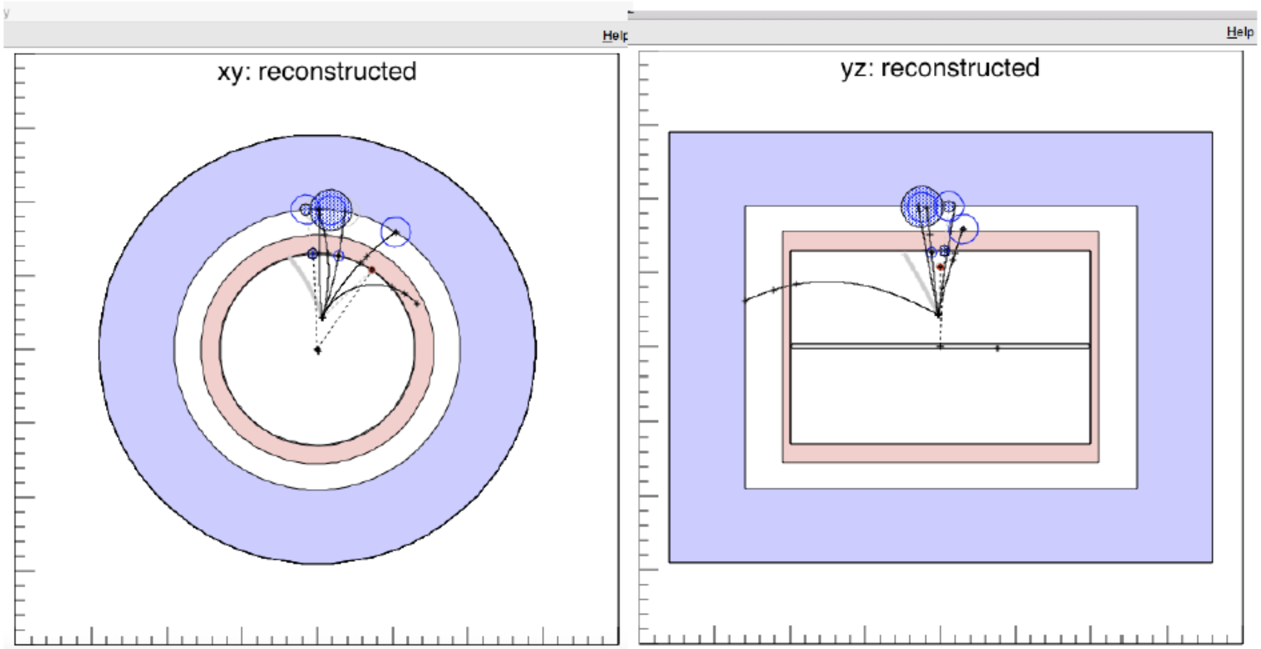
QCD -- ee gives $\alpha_s \pm 0.0002$ in several ways
also H→gg events (gluon fragmentation!)
-- ep provides tructure functions and $\alpha_s \pm 0.0003$
-- all this improves the signal and background predictions
for new physics signals at FCC-hh

Heavy Neutrinos -- ee: powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive

More slides for discussion

Simulation of heavy neutrino decay in a FCC-ee detector

See presentation by O. Fischer.



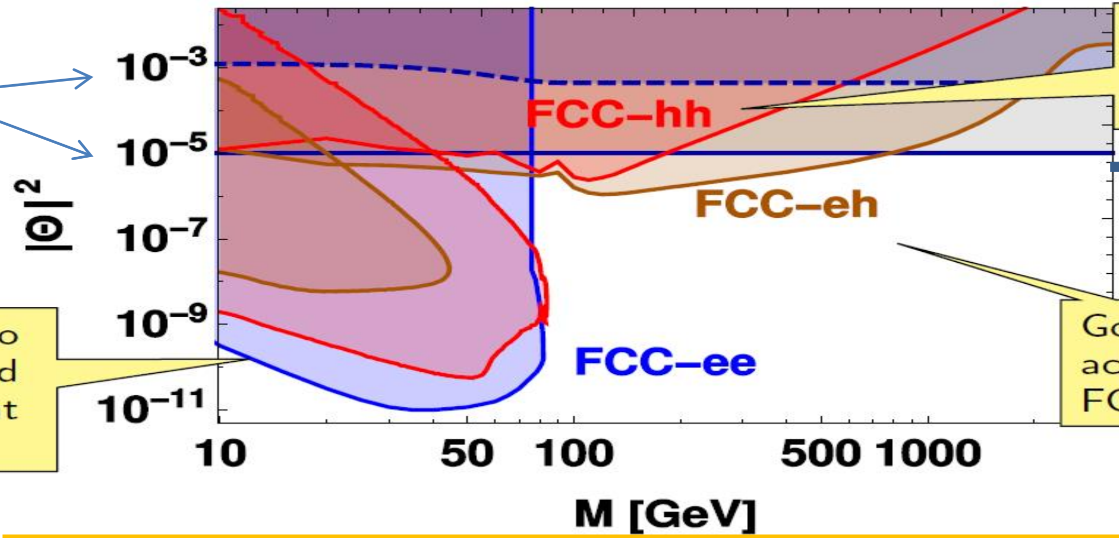
what is the background to this? No trigger needed – we will not lose it!

Summary

Another example of Synergy and complementarity

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO



FCC-hh able to test all flavour combinations.

to > 40TeV

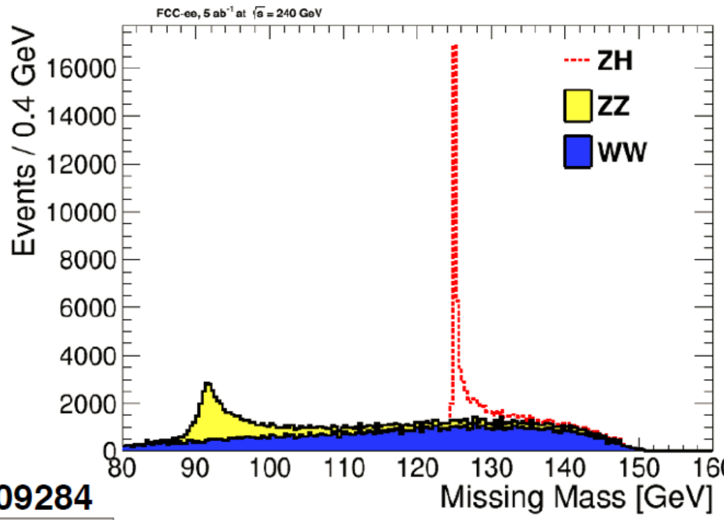
Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

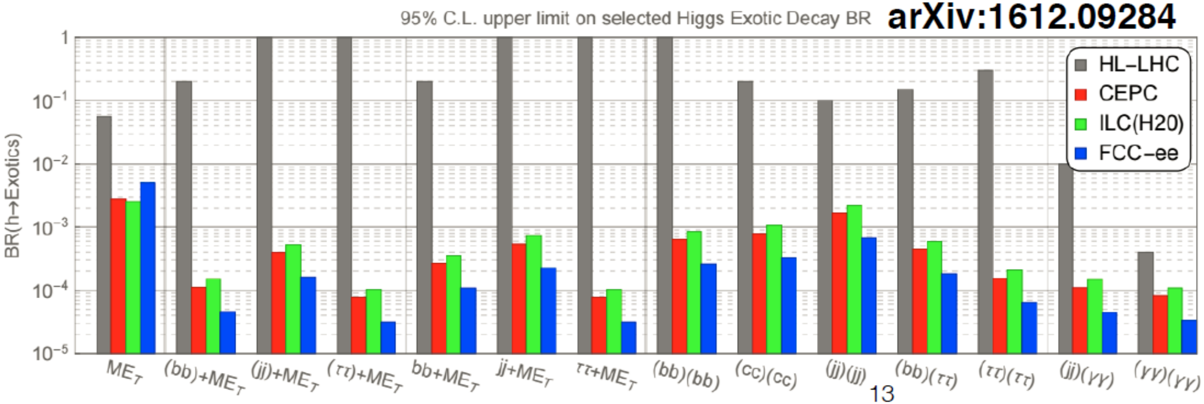
detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

BSM Higgs Studies

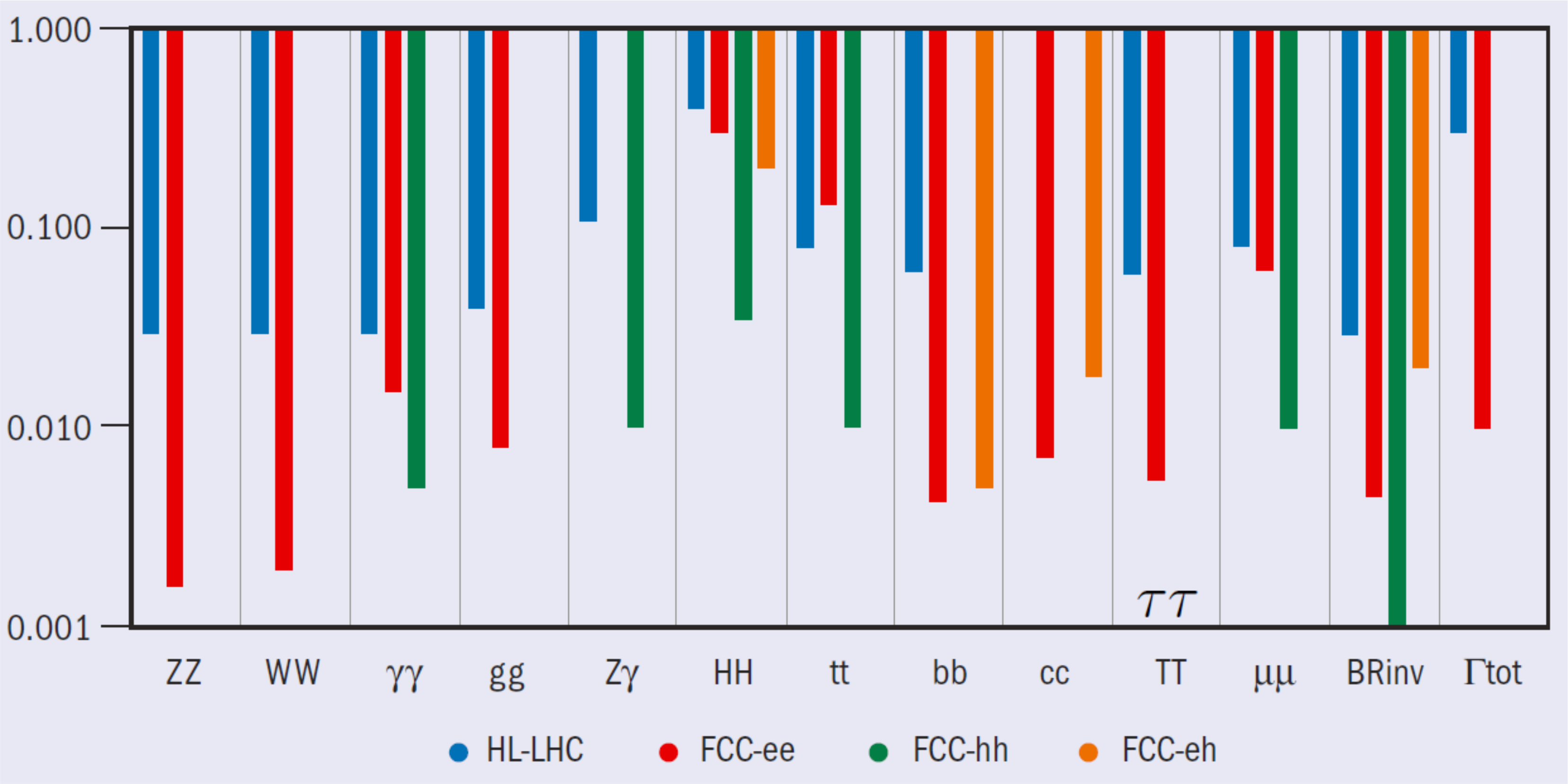
- ➡ **Example: Higgs to invisible decays**
  - follows ZH cross section measurement
  - for visualization BR(H->inv) = 100%
  - 95%CL upper limit using $5ab^{-1}$ is 0.44%
  - study published using leptonic Z decays in Eur. Phys. J. C (2017) 77: 116
  - hadronic Z decays under study. Shows similar performance
- ➡ **Incredible opportunities for BSM Higgs searches**



arXiv:1612.09284



To summarise the Higgs programme...

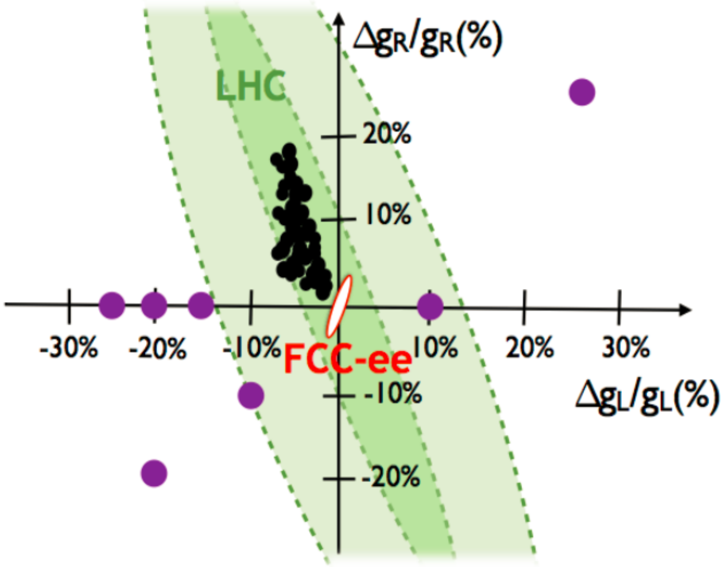


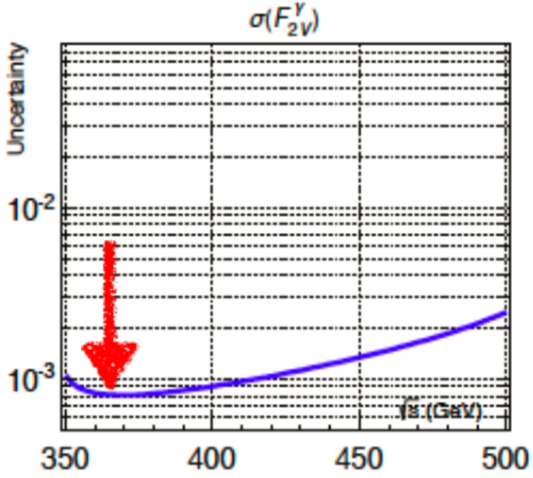
hh, eh precisions assume ee measurements esp. for Htt and HHH

ELECTROWEAK COUPLINGS OF THE TOP QUARK(2)

➤Large statistics and final state polarization allow a full separation of the ttZ/γ couplings with **NO need for polarization in the initial state.**

➤**Optimal $\sqrt{s}$= 365-370 GeV**





- Fit includes conservative assumptions detector performance
- Theory uncertainty on production mechanism dominates

FCC-ee expected precision of order 10^{-2} to 10^{-3}

PHYSICS WITH VERY HIGH ENERGY

e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field, H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann, K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter, C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people suspect that we would be running HL-LHC in that tunnel >**60 years later?**

Let's not be SHY!

CDR Vol. 5 Outline

- Vol. 5 "FCC-ee: Physics & Experiments"
  - Introduction (running plan, history, motivation, …)
  - Electroweak physics with Z's and W's
  - Higgs physics
  - Top quark physics
  - QCD and $\gamma\gamma$ physics
  - Flavours
  - BSM (Physics behind precision, global fits, direct searches)
  - MDI and experimental environment
  - Polarization and beam energy measurement
  - Detector designs
  - Summary and outlook

5 – Lepton Collider Comprehensive

Experiment

- Each of the "physics" sections will contain
  - The theory counterpart (e.g., the quest for precision calculations)
  - The requirements on detectors (geometry, acceptance, resolution, tolerances)
  - The requirements on accelerator (luminosity, polarization, E_{beam} knowledge)

Synergy and complementarity

FCC-ee is a very powerful precision machine covering considerable new territory, with discovery potential in its own right.

There are presently four proposals for e+e- colliders covering the H and top (and Z, WW) {ILC, CLIC} and {FCC-ee, CEPC}.*) There is a consensus that physics needs such a machine
FCC-ee is unique for its precision and luminosity at the W,Z,H.

Only the circular machines come with a tunnel, cryo, etc... for a 100 TeV «ultimate» step
Synergy : cost (ee+hh) < cost (ee) + cost (hh)

The Physics of the hadron collider is quite complementary but in many cases it benefits from the ee measurements in ways that should be quantified further in the 2d Physics Workshop
Complementarity:
Physics (ee+hh+ ep) > Physics(ee) + Physics (hh) + Physics (ep) >> Physics (ee), (hh), (ep)

*) we are starting to work together, but one could do more!

Physics and Experiments Studies Coordination

Physics Studies coordination
A. Blondel, P. Janot (EXP), C. Grojean, M. McCullough, J. Ellis (TH)

EW Physics with Z's and W's	Higgs properties	Top quark physics
R. Tenchini, F. Piccinini	M. Klute, K. Peters	P. Azzi (F. Blekman)
S. Heinemeyer, A. Freitas	S. Heinemeyer, A. Freitas	S. Heinemeyer, A. Freitas

Synergies with FCC-hh physics, LC studies, LEP legacy

QCD and $\gamma\gamma$ physics	Flavours physics	New physics	Global Analysis Synergies
D. d'Enterria	S. Monteil	M. Pierini, C. Rogan	J. Ellis
P. Skands	J. Kamenik	M. McCullough	

Physics software	Online selection & DAQ	Polarization, $\sqrt{s}$ measurement	MDI, Exp'tal environment
C. Bernet, B. Hegner, C. Helsens	C. Leonidopoulos	A. Blondel	M. Boscolo
	E. Perez	J. Wenninger	N. Bacchetta
Synergy with FCC-hh, LC, LHC		*Joint with FCC-ee Accelerator*	*Adapt (to) the interaction region Joint with FCC-ee Accelerator*

Detector designs
A. Cattai, G. Rolandi, M. Dam

Synergy with LC and CEPC
Set constraints on designs to match statistical precision
Propose detector designs

Beam Polarization and Energy calibration

We have concluded that first priority is to achieve transverse polarization
in a way that allows continuous beam calibration by resonant depolarization
(energy measurement every ~10 minutes on 'monitoring' single bunches)

- **This is a unique feature of circular e+e- colliders**
- baseline running scheme defined with monitoring bunches, wigglers, polarimeter
- the question of the residual systematic error requires further studies of the relationship between spin tune, beam energy at IRs, and center-of-mass energy

➔ **target is O(±100keV) at Z and W pair threshold energies (averaged over data taking)**

'Do we want longitudinal polarization'?

➔ **lower priority**

at Z, W, H, top: no information that we cannot obtain otherwise from unpolarized A_{FB} asymmetries or final state polarization (top, tau)

+ too much loss of luminosity in present running scheme to provide gain in precision.