91 GeV revisited: the compelling case for 5×10^{12} Z^0s ('Tera-Z')

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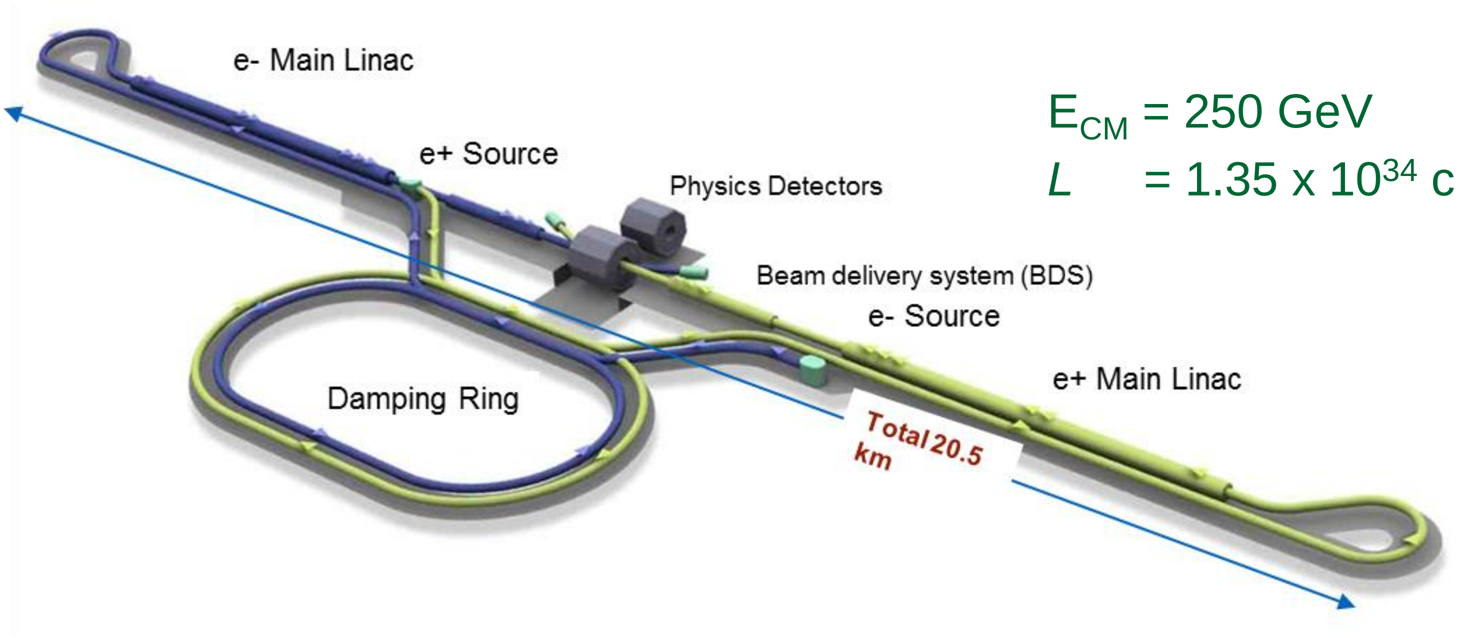
IITM, Chennai, 8/9/23

Seminar outline

- Prologue
- FCC-ee: a Higgs factory par excellence… but very much more
- Déjà vu all again – haven't we been here before ?
- Precision EW physics at the FCC-ee
- FCC-ee as a flavour factory
- Direct searches for New Physics at FCC-ee
- Practicalities: timescale, status and energy use
- Conclusions

“I was the future once” *

For many years, a consensus existed that the next machine should be a linear e^+e^- collider to make precise studies of both the Higgs boson, and also the rich spectrum of SUSY particles that would be found at the LHC.



$E_{CM} = 250$ GeV
$L = 1.35 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

The realisation that the Higgs turned out to be ‘light’ and the lack of any other discovery led to an energy descoping from E_{CM}=500 GeV to 250 GeV. Meanwhile, others began to consider alternative solutions better suited to the new reality.

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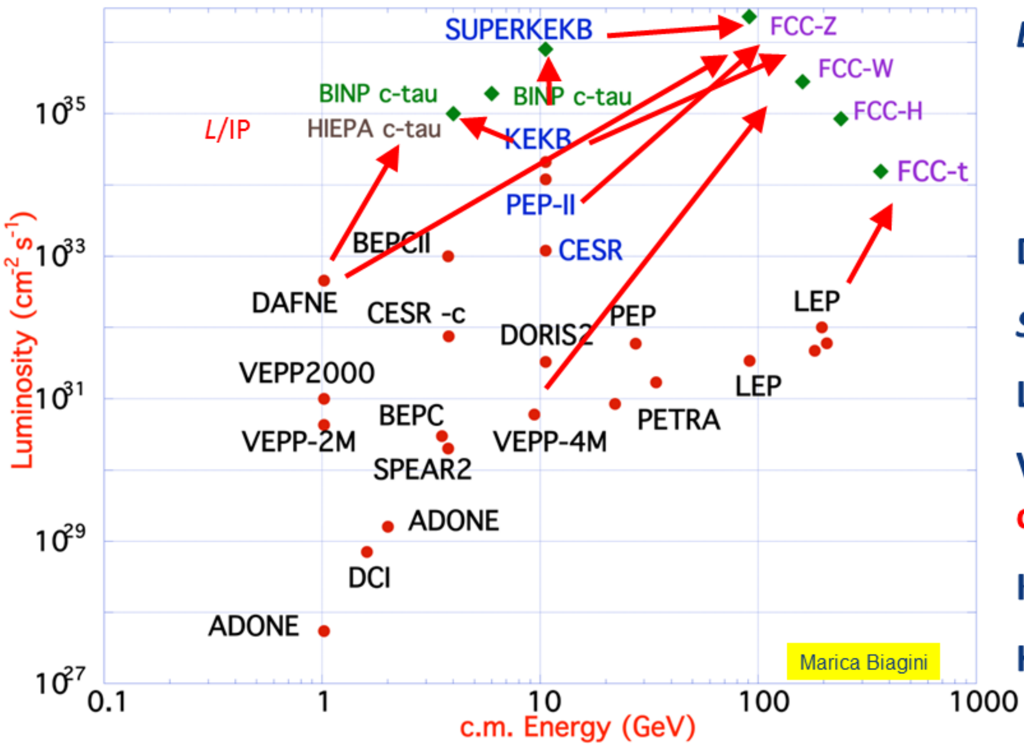
* David Cameron, former British Prime Minister

Going circular

Higher luminosities at E_{CM}~250 GeV can be achieved in a synchrotron, with very high performance achievable by benefitting from advances of recent machines.



B-factories: **KEKB & PEP-II:**
- double-ring lepton colliders,
- high beam currents,
- top-up injection

DAFNE: crab waist, double ring

SuperB-factories, **S-KEKB:** low β_y^*

LEP: high energy, SR effects

VEPP-4M, LEP: precision energy calibration w. res. depolarisation

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

There is also a natural synergy with the push for a very high-energy *pp* collider.

The FCC integrated project at CERN

Build a ~90 km tunnel, to first house FCC-ee: a very high luminosity e^+e^- collider for Higgs physics, and very much more. There will follow FCC-pp: a ~100 TeV hadron collider. e-p collisions also an option (FCC-ep).

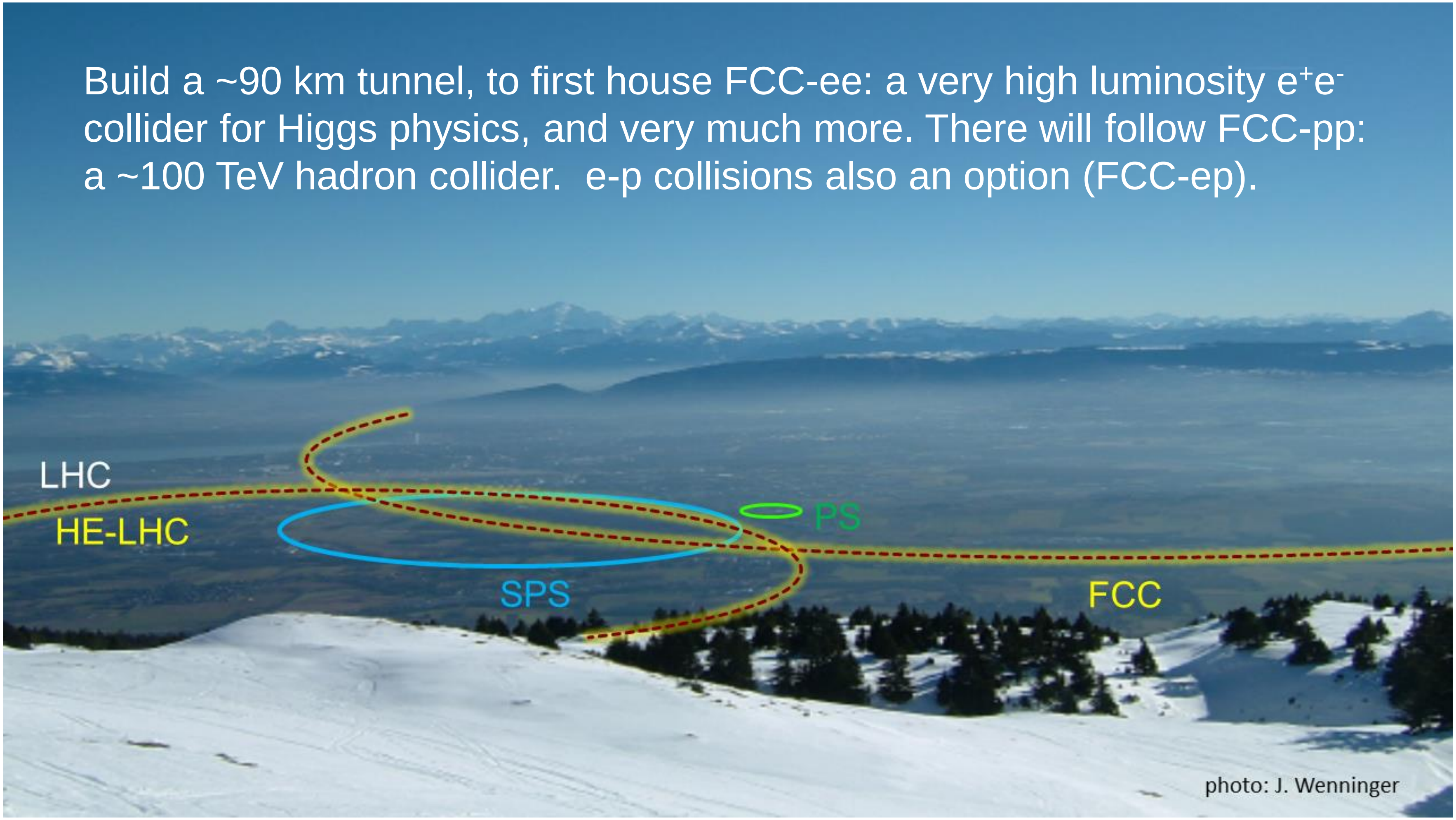


photo: J. Wenninger

The FCC integrated project at CERN

- Conceptual Design Reports published in 2019;
- FCC-hh & future e^+e^- machine given very high priority in European Strategy for Particle Physics Update of 2020;
- Five-year feasibility study now underway (2021-25).

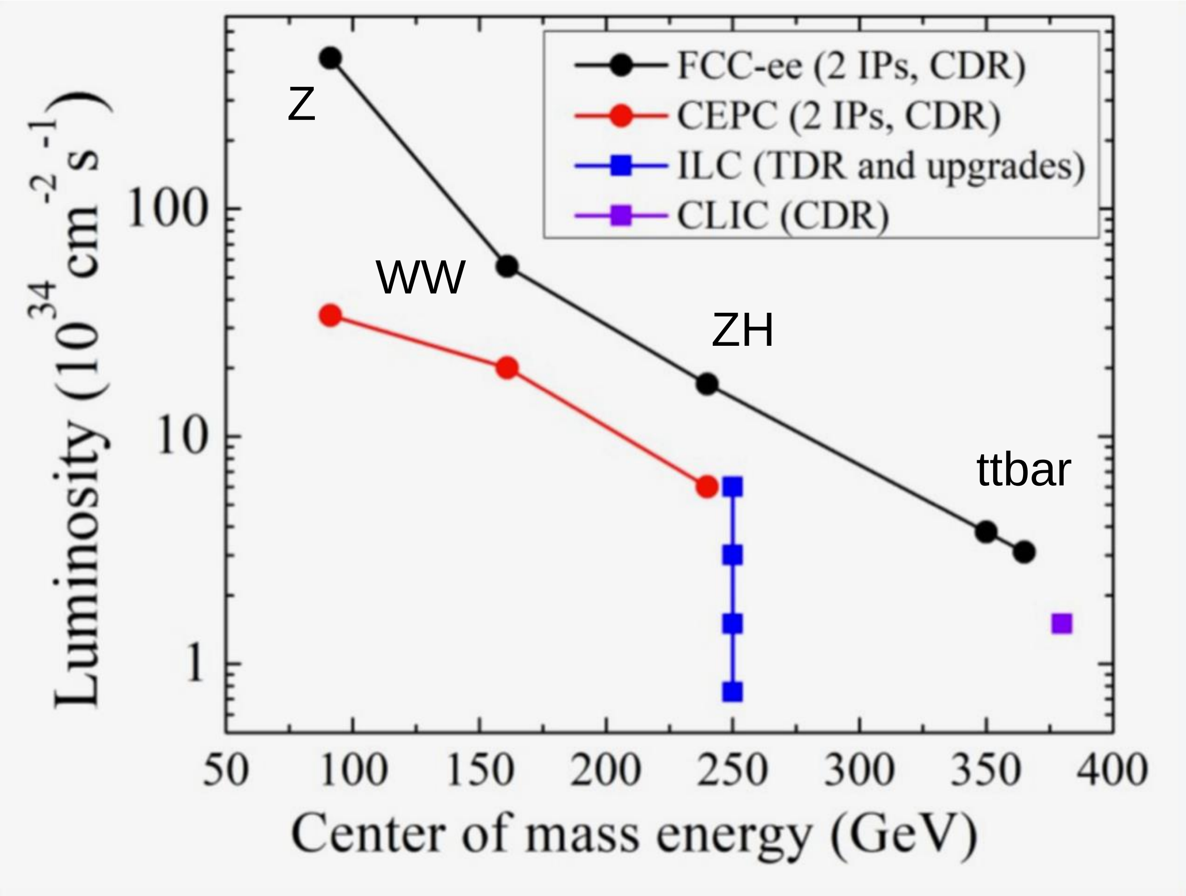
(CDRs link. ESPPU link.)

photo: J. Wenninger

FCC-ee:
a Higgs factory par excellence…
but very much more

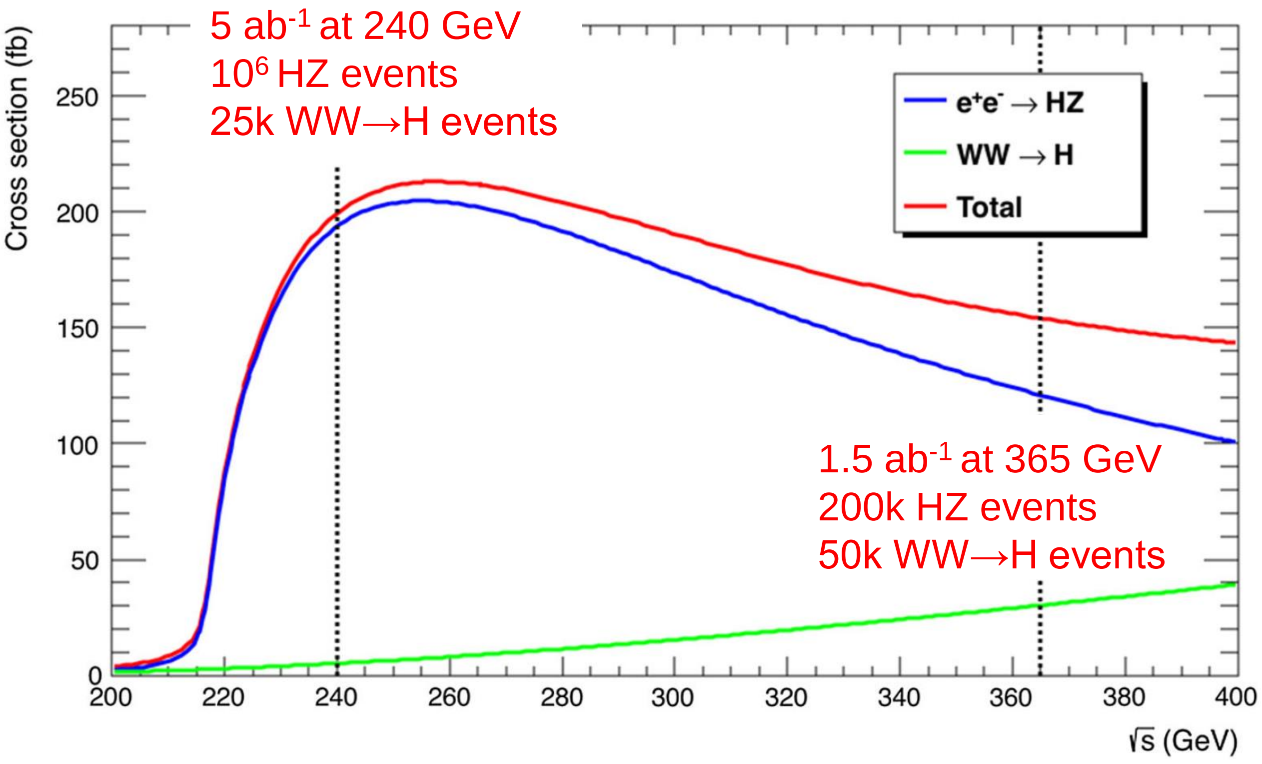
FCC-ee: a Higgs factory par excellence

Primary goal of FCC-ee is Higgs physics, with lumi of ~2 x 10^{35} $cm^{-2}s^{-1}$ at 240 GeV.



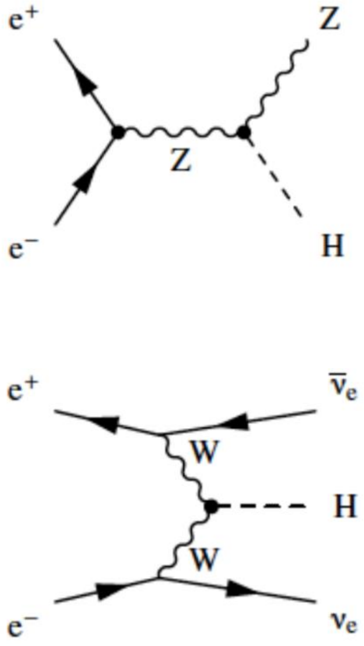
Higgs studies at FCC-ee

Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)% precision. Achieved through operation at two energy points.



5 ab^{-1} at 240 GeV
10^6 HZ events
25k WW→H events

1.5 ab^{-1} at 365 GeV
200k HZ events
50k WW→H events



Higgs studies at FCC-ee

Quantum corrections to Higgs' couplings in SM model are a few %, so essential to reach this level of precision. Note that even FCC-ee is statistically limited !

Overall strategy:

- Count H(→inclusive)Z events, & measure σ_{HZ}, from reconstructing Z & recoiling H system. Extract g_{HZZ} with minimal theory input.

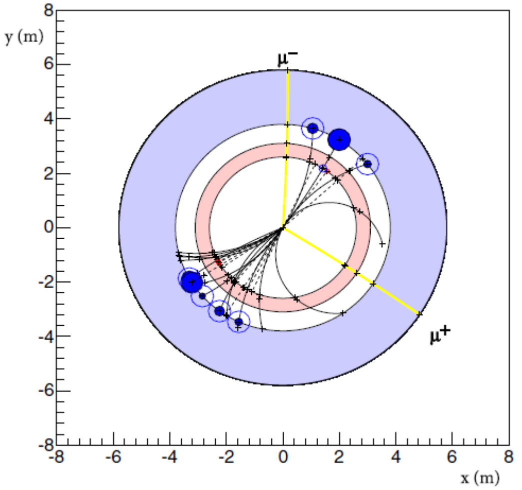
- Count $H(\rightarrow ZZ^*)Z$ events, and measure

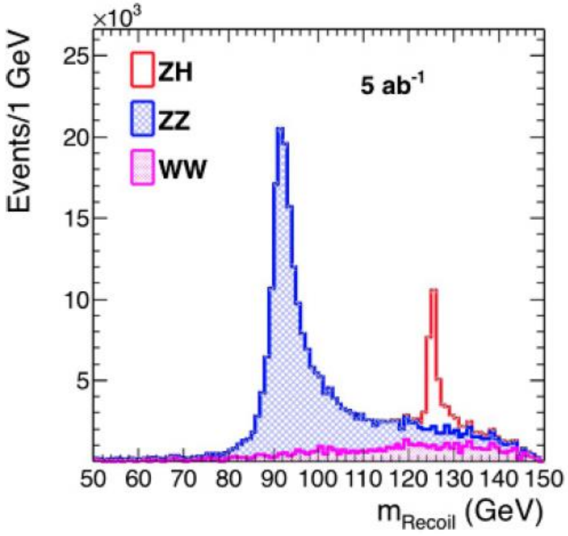
$$\sigma_{HZ} \times \frac{\Gamma(H \rightarrow ZZ^*)}{\Gamma_H} \propto \frac{{g_{HZZ}}^4}{\Gamma_H}$$

  & thus determine Γ_H model independently.

- Reconstructing other final states allow other couplings to be determined, again, in model independent manner.

- Improve further by adding $WW \rightarrow H$ data.





Expected precision on Higgs parameters

FCC-ee provides highly precise model-independent measurements of width & almost all couplings of interest.

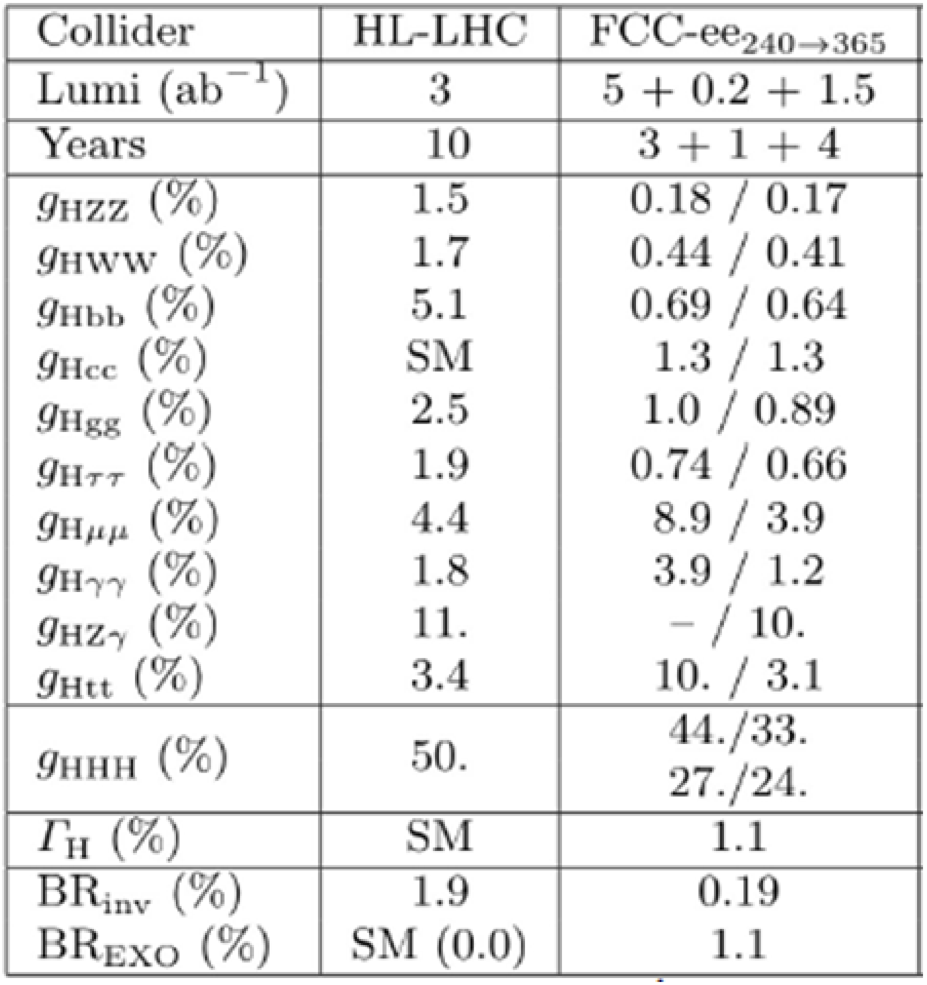
Those beyond energy reach of machine (g_{Htt} & g_{HHH}) can be probed indirectly, with good precision coming from combination with HL-LHC (in time they will be measured very well at FCC-hh).

Other exiting possibilities:

- Access Higgs self-coupling indirectly through precise cross-section measurements;
- Set limits / measure electron Yukawa through Higgs-pole run.

More details in backups.

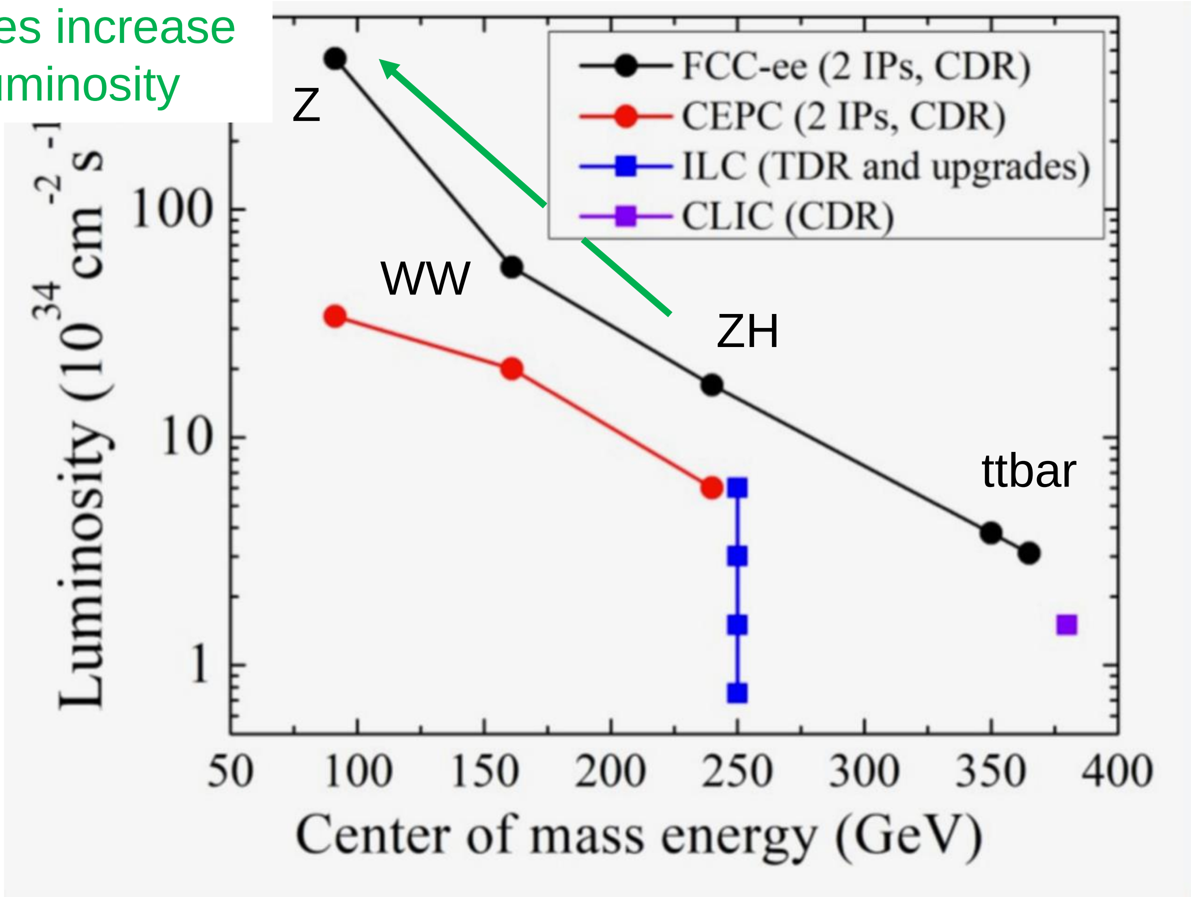
FCC-ee alone / FCC-ee & HL-LHC



Collider	HL-LHC	FCC-ee$_{240\rightarrow365}$
Lumi (ab^{-1})	3	5 + 0.2 + 1.5
Years	10	3 + 1 + 4
g_{HZZ} (%)	1.5	0.18 / 0.17
g_{HWW} (%)	1.7	0.44 / 0.41
g_{Hbb} (%)	5.1	0.69 / 0.64
g_{Hcc} (%)	SM	1.3 / 1.3
g_{Hgg} (%)	2.5	1.0 / 0.89
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74 / 0.66
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9 / 3.9
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9 / 1.2
$g_{\mathrm{HZ}\gamma}$ (%)	11.	– / 10.
g_{Htt} (%)	3.4	10. / 3.1
g_{HHH} (%)	50.	44./33. 27./24.
Γ_{H} (%)	SM	1.1
BR$_{\mathrm{inv}}$ (%)	1.9	0.19
BR$_{\mathrm{EXO}}$ (%)	SM (0.0)	1.1

FCC-ee: not just a Higgs factory

L vs E_{CM} of a synchrotron means that a very high luminosity Higgs factory (240 GeV) will be *an ultra-high luminosity Z factory* (91 GeV). Ditto WW production (161 GeV).



30 times increase in luminosity

FCC-ee: not just a Higgs factory

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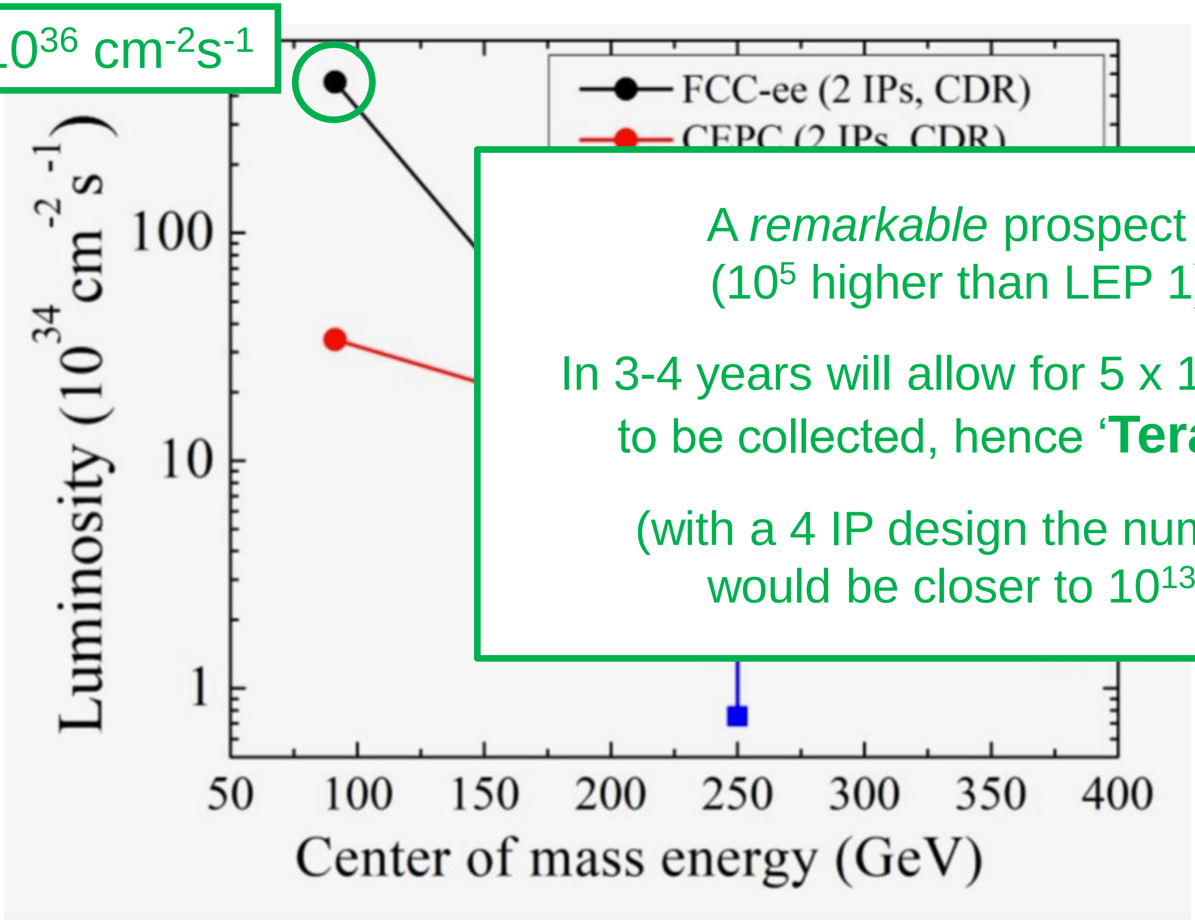
4.6×10^{36} cm^{-2}s^{-1}



A *remarkable* prospect !
(10^5 higher than LEP 1)

In 3-4 years will allow for 5×10^{12} Z^0's to be collected, hence '**Tera-Z**' !

(with a 4 IP design the number would be closer to 10^{13})

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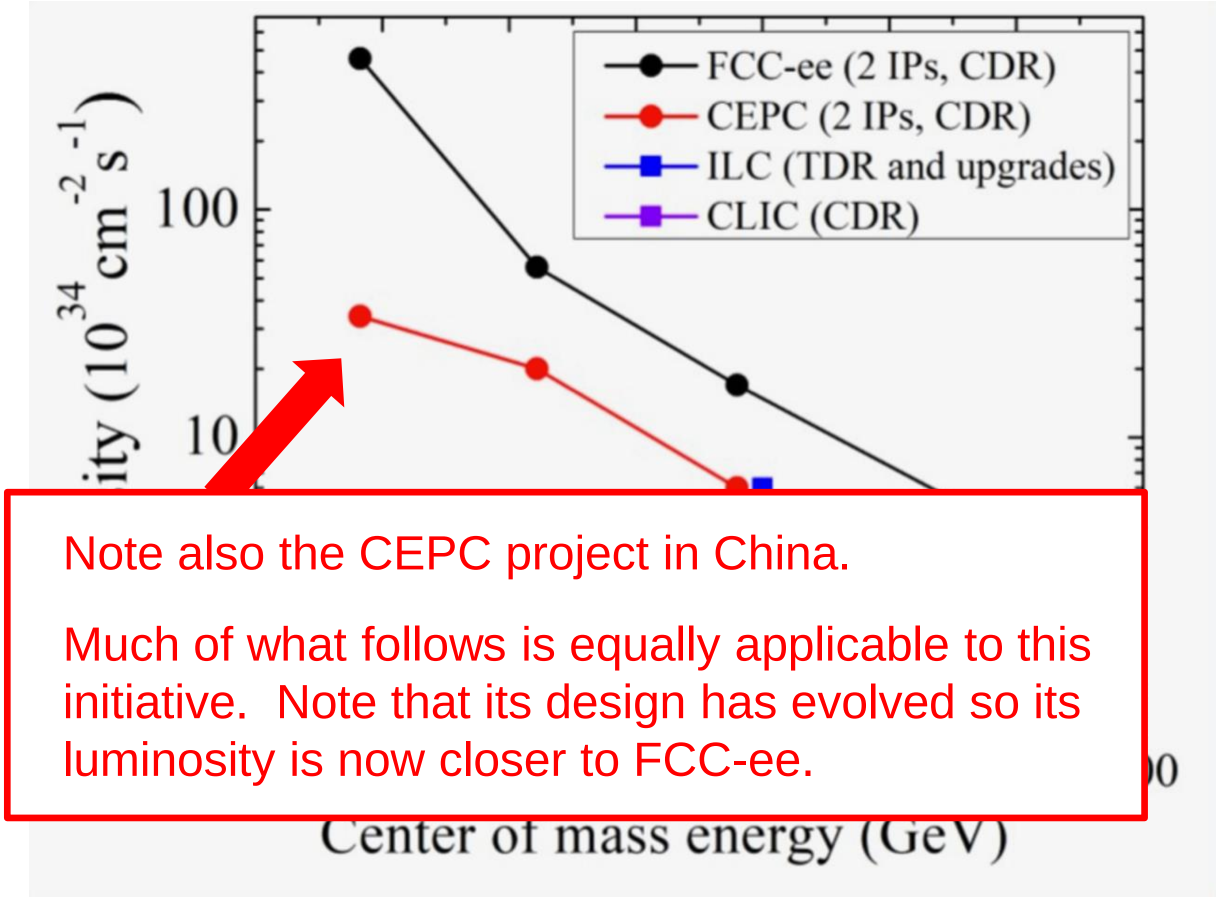
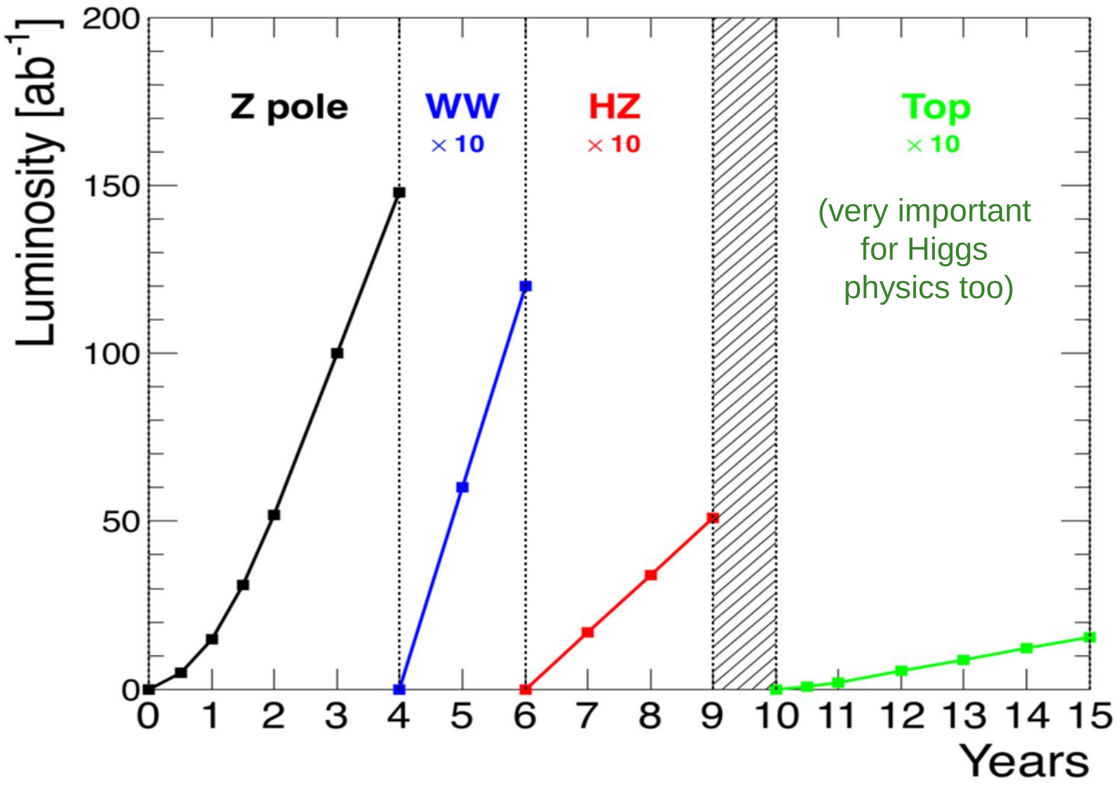


Note also the CEPC project in China.

Much of what follows is equally applicable to this initiative. Note that its design has evolved so its luminosity is now closer to FCC-ee.

FCC-ee: running schedule

Phase	Run duration (years)	Centre-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events



(very important for Higgs physics too)

- Data will not necessarily be collected in this order.
- Duration of certain runs still subject to optimisation.
- Ongoing studies concerning run at E_{CM}=125 GeV.

Déjà vu all over again

Tera-Z sounds fun, but didn't someone measure the properties of the Z once before ?

The LEP legacy

Phys. Rept. 427 (2006) 257

Phys. Rept. 532 (2013) 119

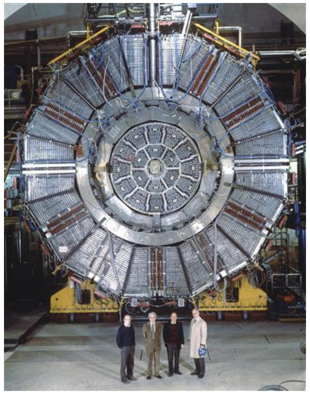
LEP operated at the Z resonance from 1989-1995, with two high statistics scans in 1993 & 1995, and then at & above the W^+W^- threshold (161-210 GeV) up until 2000.

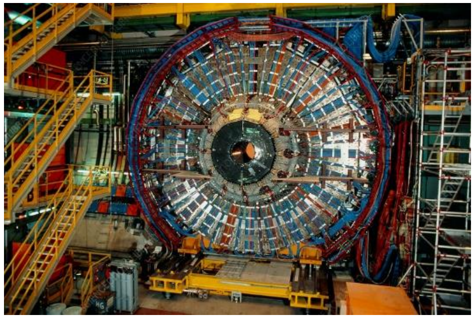
ALEPH
(319 pubs.)

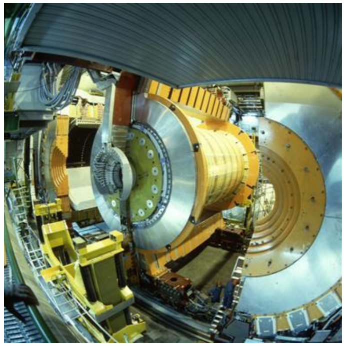
DELPHI
(347 pubs.)

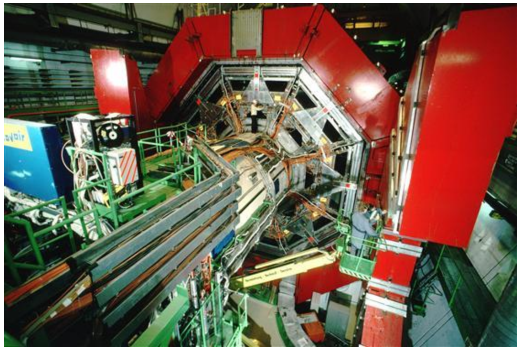
OPAL
(423 pubs.)

L3
(317 pubs.)









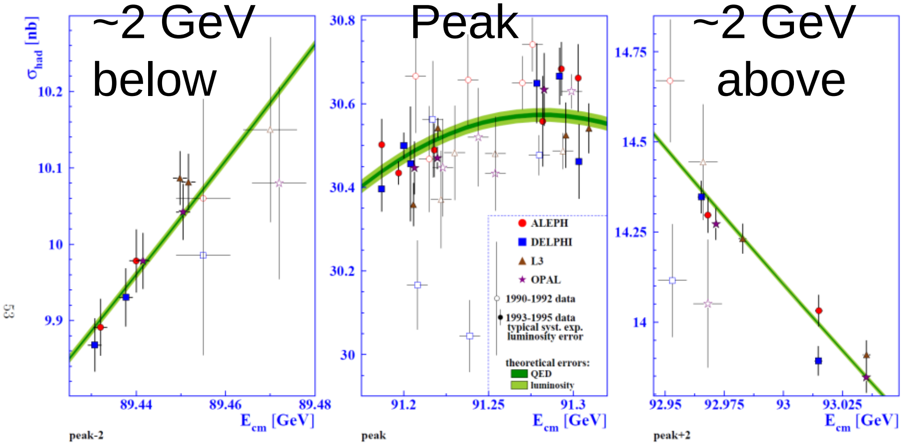
LEP accumulated ~17 million Z^0s and ~40k Ws.
During similar period SLD experiment at SLAC collected ~1 million Z^0s.
Many papers in searches, QCD, b and tau physics, and electroweak (W and Z).

Let's review Z observables, & what we learned from the LEP/SLD measurements.

Key Z^0 observables

Forward-backward asymmetries (& at SLD L-R asymmetries)

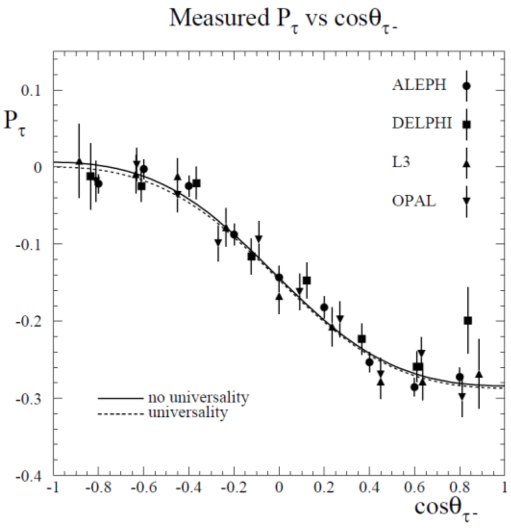
Lepton and inclusive hadron cross-sections

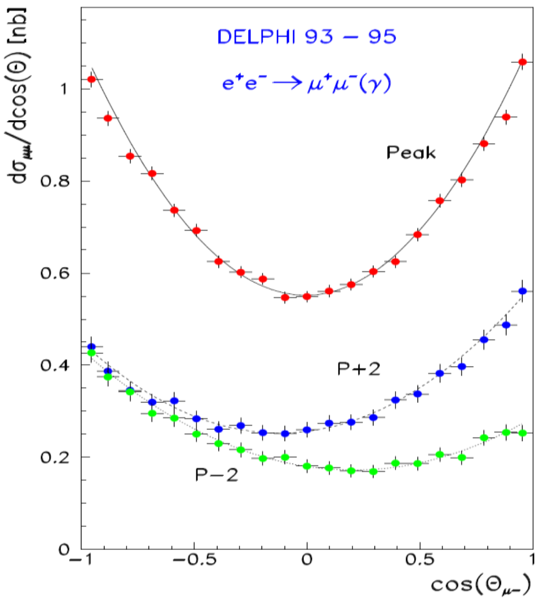

~2 GeV below

Peak

~2 GeV above

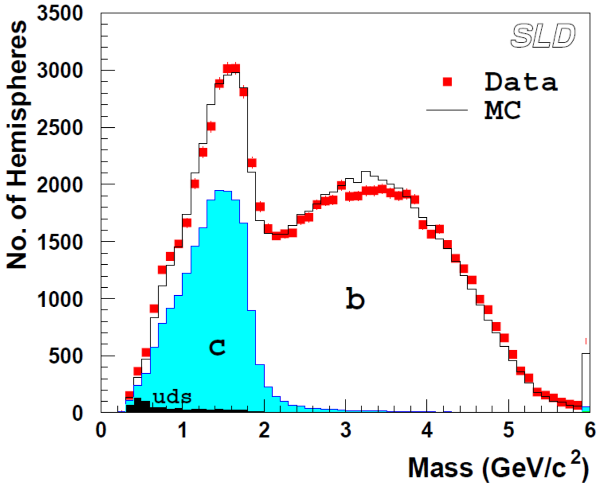
Tau polarisation measurements





Partial width ratios involving heavy flavours

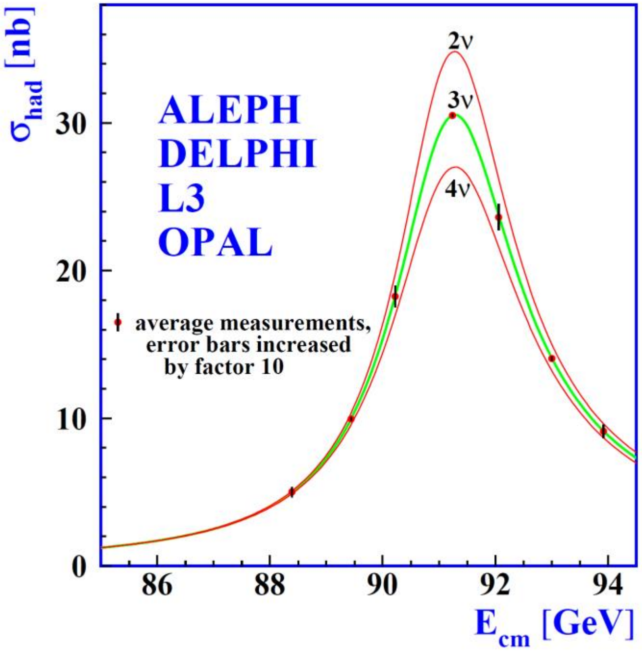
e.g. $R_b = \Gamma_{bbbar}/\Gamma_{had}$



Making use of the observables

- Lineshape parameters *e.g.* M_Z, Γ_Z, and also, number of light neutrinos.

$$\boxed{N_\nu \quad = \quad 2.9840 \pm 0.0082}$$



- Effective vector & axial couplings *e.g.* from forward-backward asymmetries

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$\mathcal{A}_f = 2\frac{g_{Vf}\,g_{Af}}{g_{Vf}^2 + g_{Af}^2}$$

$$g_{Vf} = \sqrt{\rho_f}\left(T_3^f - 2Q_f \sin^2\theta_{eff}^f\right)$$

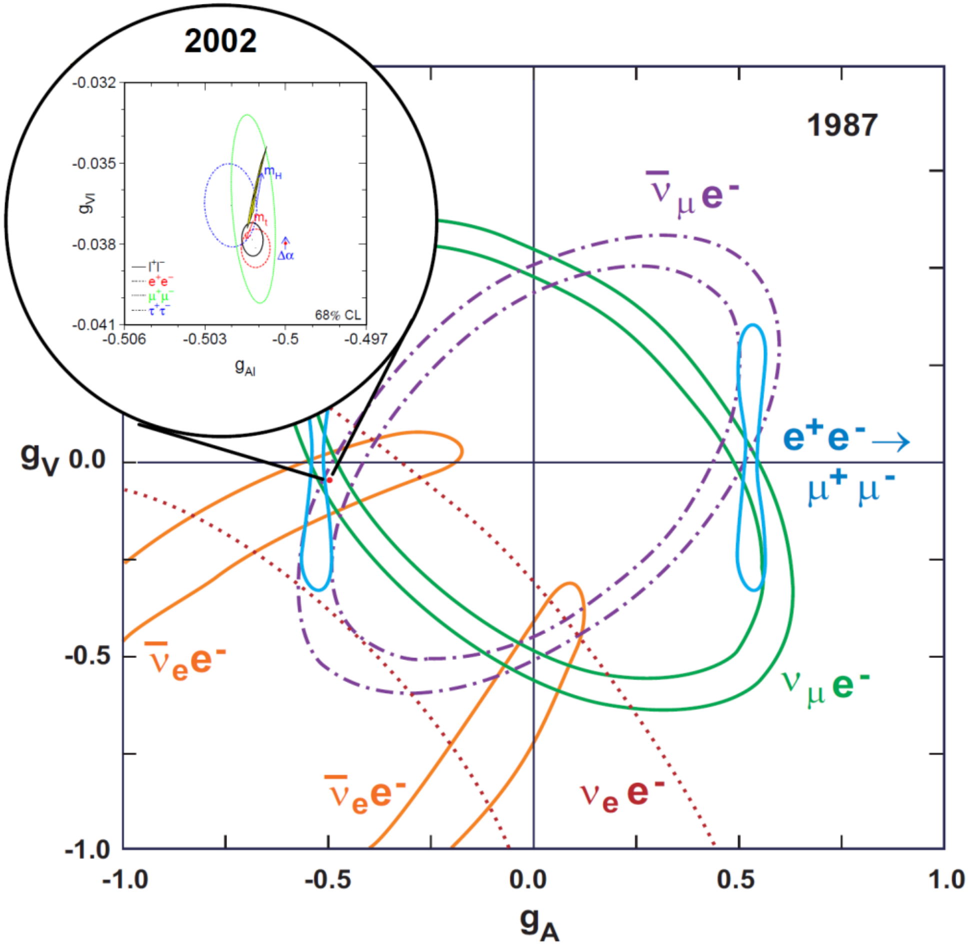
$$g_{Af} = \sqrt{\rho_f}\;T_3^f$$

(ρ_l = 1 in limit EW corrections vanish)

- Testing radiative correction structure of the SM, *e.g.* with S, T, U parameters.

The achievement of LEP & SLD

Dramatic demonstration of the validity of the SM, *e.g.* in the vector & axial couplings.



magnified by
a factor 65

The achievement of LEP & SLD

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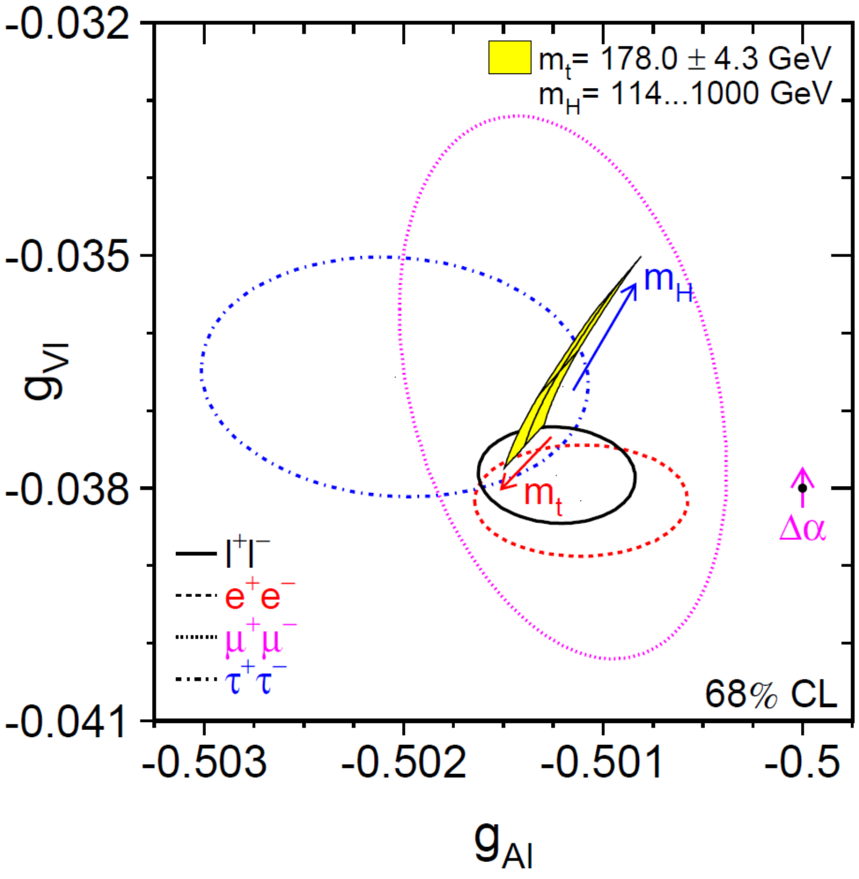
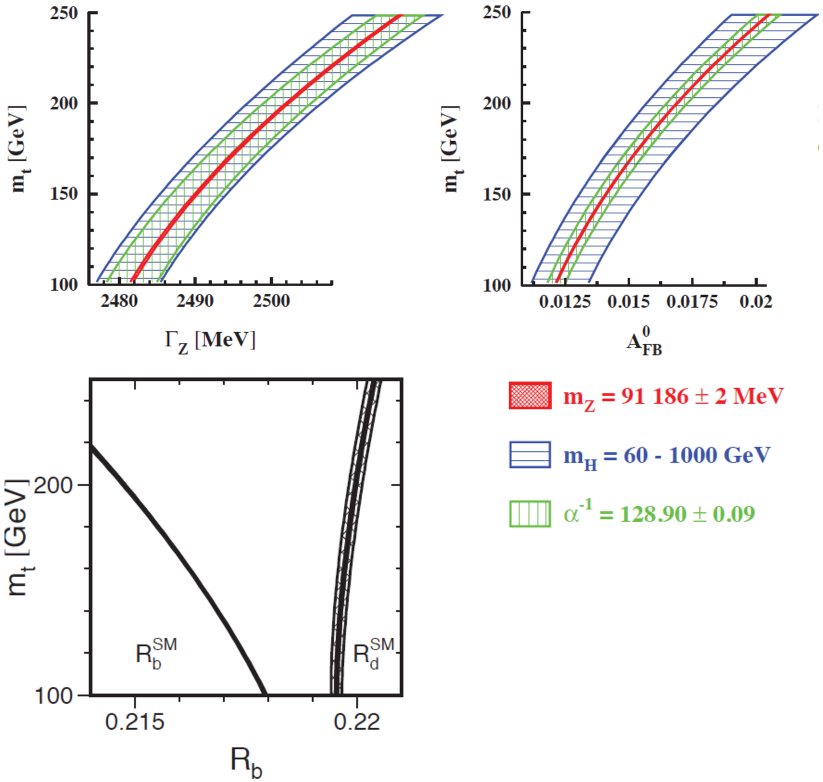
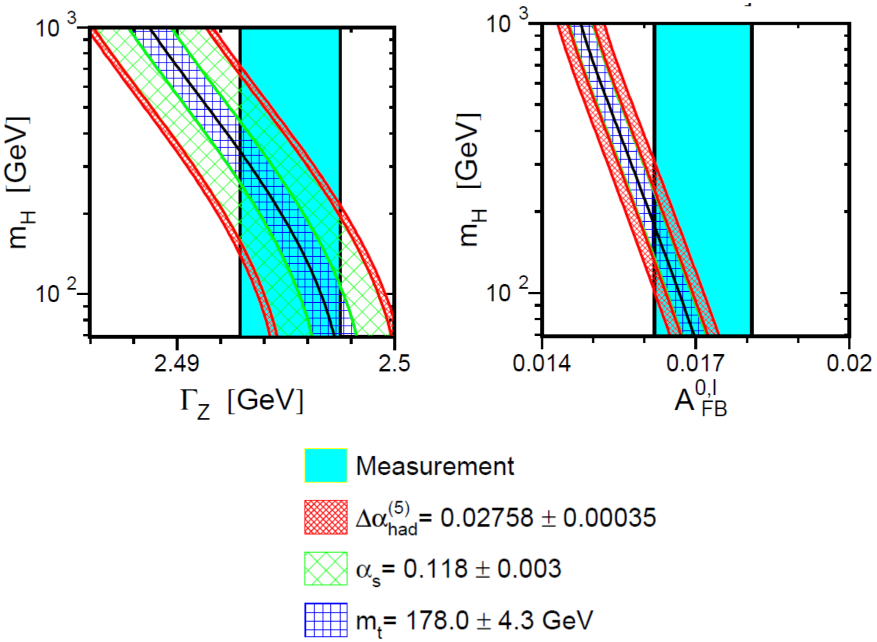


Also high sensitivity to the EW loops giving access to unknown parameters….

Pointing the way to the top and the Higgs

Electroweak corrections present in the observables have a quadratic dependence on the top mass, and a logarithmic dependence on the Higgs.





Pointing the way to the top and the Higgs

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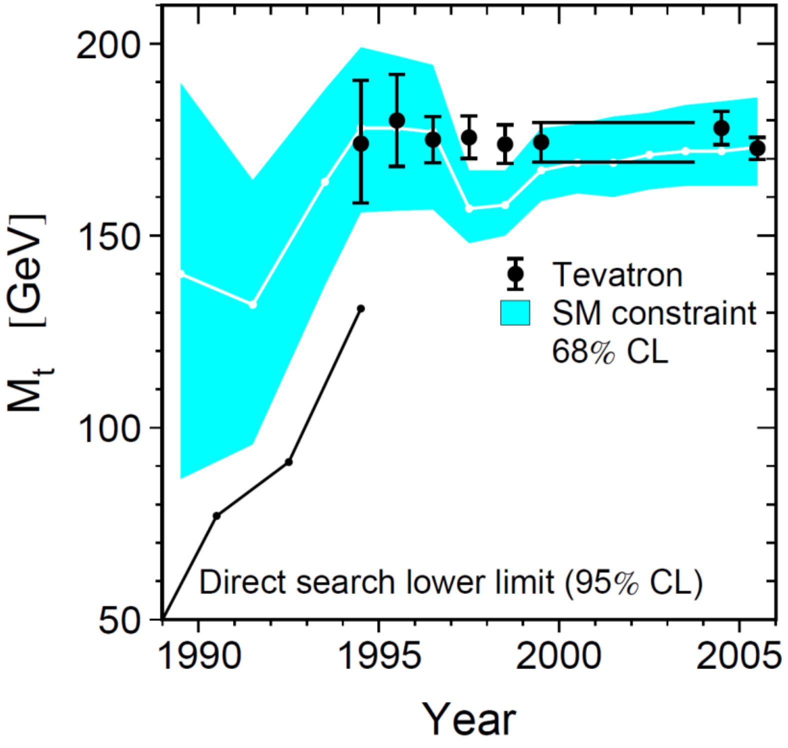
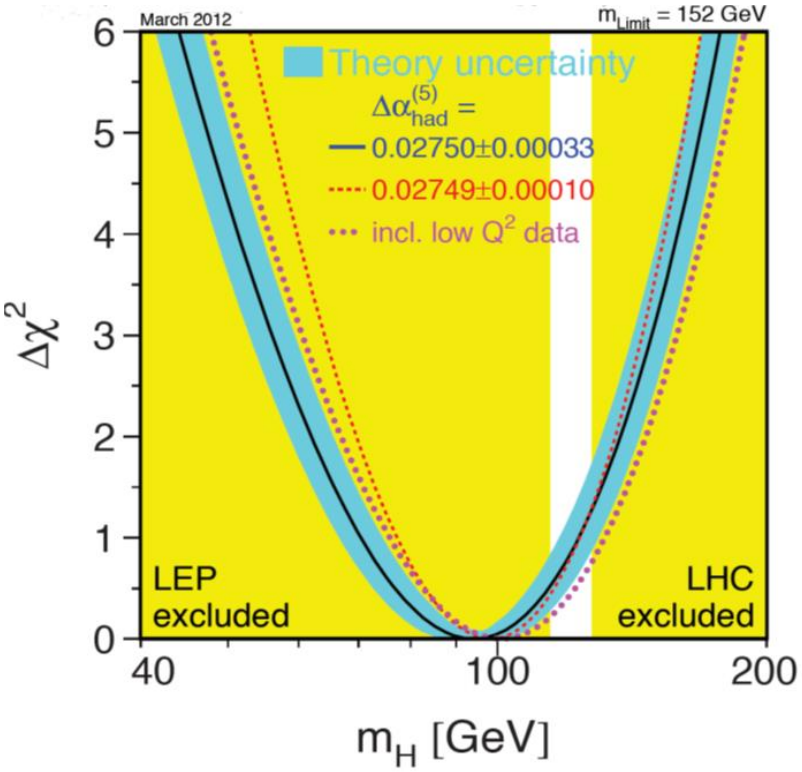


(including LEP2 inputs)



LEP & SLD Z data ‘measured’ top mass well before discovery.

LEP data and SM require something Higgs-like and within LHC reach !

Been there, done that

Why re-measure EW observables at FCC-ee, when we did so already at LEP ?

With the discovery of the Higgs, the SM is now complete, and any set of measurements should be self-consistent. Higher-order corrections in Z^0 (and W) observables offer a powerful probe for inconsistencies !

Moreover, almost all measurement programmes in HEP are based on improving knowledge of things we ‘know’ already – this is fine and well-motivated:

- Higgs programme at ILC/CLIC/FCC-ee aims to improve precision on already studied observables by x2-10 w.r.t. LHC (plus maybe see some processes for the first time, *e.g.* H→ccbar);
- DUNE & HyperK will measure δ_{CP} better by x5 w.r.t. now;
- g-2 will improve $(g-2)_\mu$ by factor of 4;
- Future LHCb upgrades will measure CKM parameters better by x10.

Tera-Z@FCC-ee can improve EW-observable statistical precision by up to ~400. Nowhere else in HEP does there exist the opportunity for such a giant leap forward !

This leap, however, mandates a corresponding improvement in systematic control.

Returning to the Z (& W): precision EW physics at FCC-ee

Challenges of Z-metrology

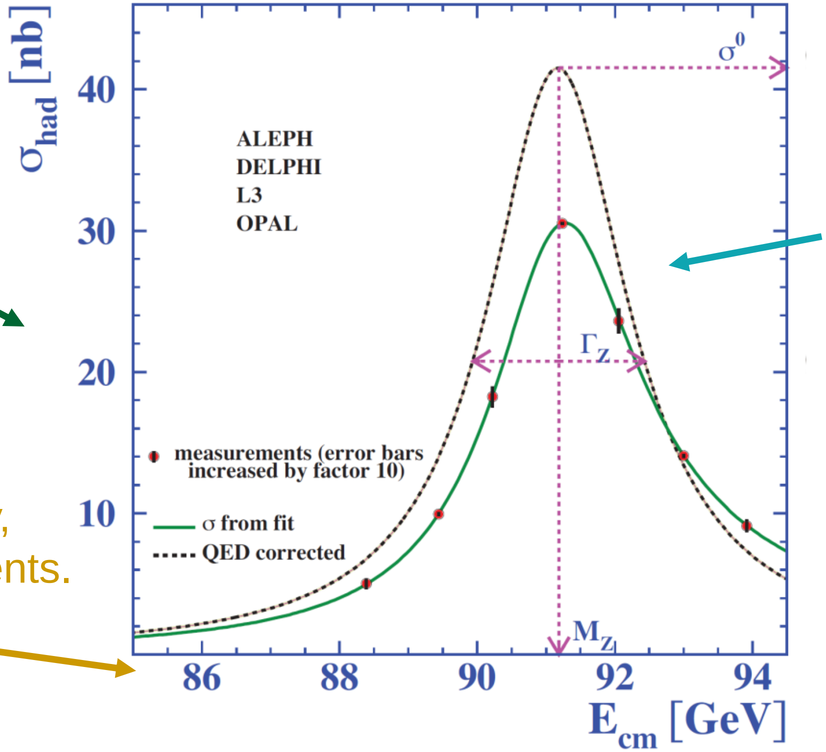
Outlook shortly before LEP turn on: *“The overall conclusion is that at LEP the Z^0 mass and width can be measured with relative ease down to … +/- 50 MeV. A factor of 2-3 improvement can be reached with a determined effort…”* CERN 86-02 ‘Physics at LEP’, ed. Ellis and Peccei.

Vertical-scale uncertainty dominated by luminosity, with largely common uncertainty between experiments.

It was assumed this could be done to ~2%.

Horizontal-scale uncertainty set by knowledge of collision energy, also common between experiments.

It was guessed that ~10 MeV uncertainty *might* be possible.



Also vital Is understanding of shape, in particular effect of QED radiative corrections.

Important, but not discussed further today.

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In fact, the final uncertainties were:

$$\sigma_{M_Z} = 2.1 \text{ MeV}$$

$$\sigma_{\Gamma_Z} = 2.3 \text{ MeV}$$

How did that happen, and what are the consequences for FCC-ee?

Vertical-scale uncer
dominated by lumin
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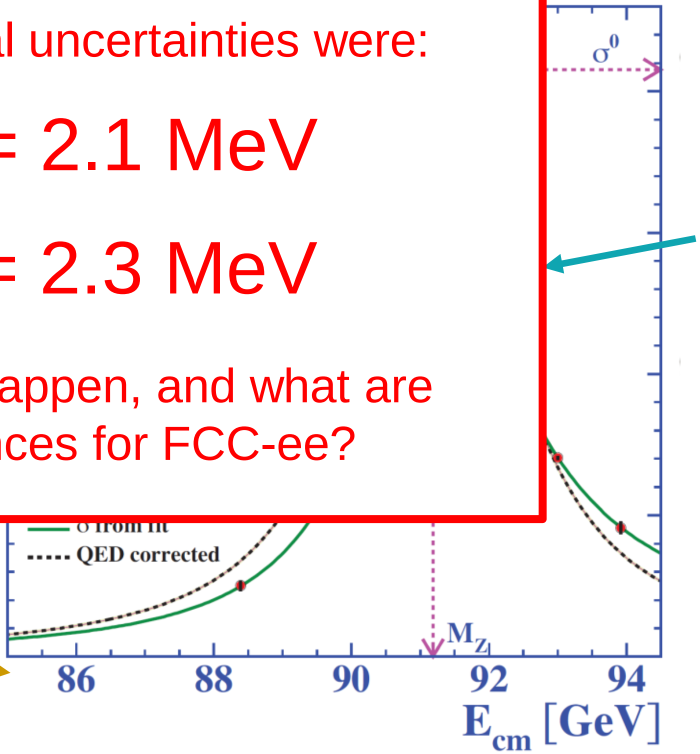

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Luminosity measurement

Lumi measured in QED-dominated low-angle $e^+e^- \rightarrow e^+e^-$ (will remain true at FCC-ee).

LEP was expected to measure lumi to ~2%, but in fact did better than 0.1%.

Two ingredients:

Enormous theoretical work, resulting in a LEP-wide correlated error of 0.06%

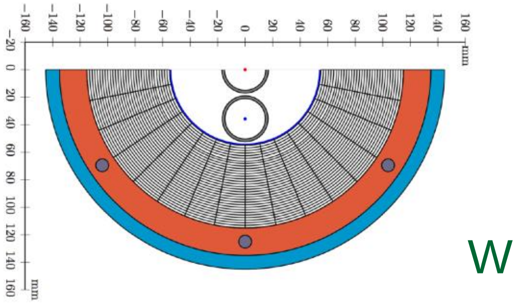
+

Precision luminometers, with 5 μm tolerances & excellent understanding of acceptance

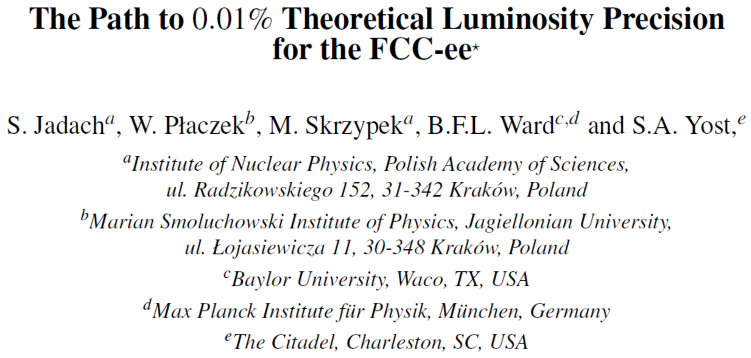
e.g. OPAL achieved ~3 x 10^{-4}

Working goal of FCC-ee studies is to get down to 0.01% absolute, 0.001% relative.

Require next-generation
luminometers with
1 μm tolerances…



…and improved
calculations



The Path to 0.01% Theoretical Luminosity Precision
for the FCC-ee*

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[PLB 790 (2019) 314]

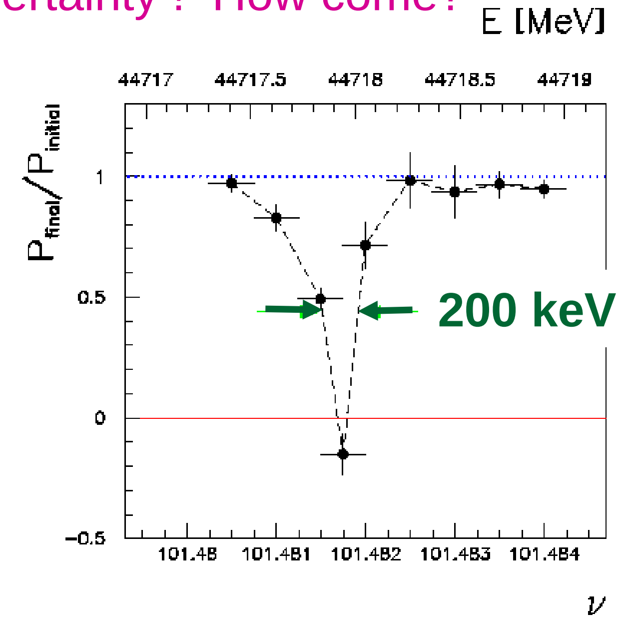
Work already underway !

Collision-energy calibration

Knowledge of collision energy leading systematic in mass and width measurement:

m_Z total uncertainty = 2.1 MeV, of which E_{CM} contribution = 1.7 MeV
Γ_Z total uncertainty = 2.3 MeV, of which E_{CM} contribution = 1.2 MeV

But *much* better than anticipated, and < stat. uncertainty ! How come?



High level of precision achieved through miracle of resonant de-polarisation (RDP), which is unique to circular e^+e^- machines.

- Wait for transverse polarisation to build up;
- Precession frequency, ν_s, directly proportional to E_b :

$$E_b = 2\, v_s\, m_e\, c^2 / (g_e - 2)$$

- Monitor polarisation with Compton scattering from laser whilst exciting beam with transverse oscillating B field. Find frequency at which depol^n occurs.

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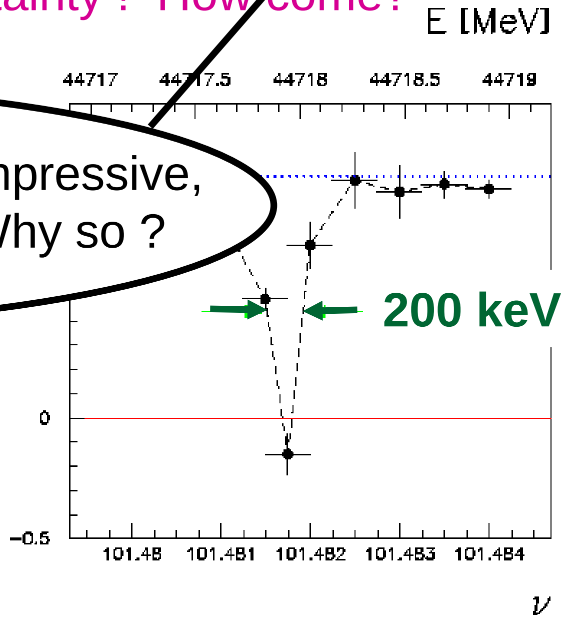
High level of p
miracle
which is

Hang on, these uncertainties, though impressive, are >> intrinsic uncertainty of RDP. Why so ?



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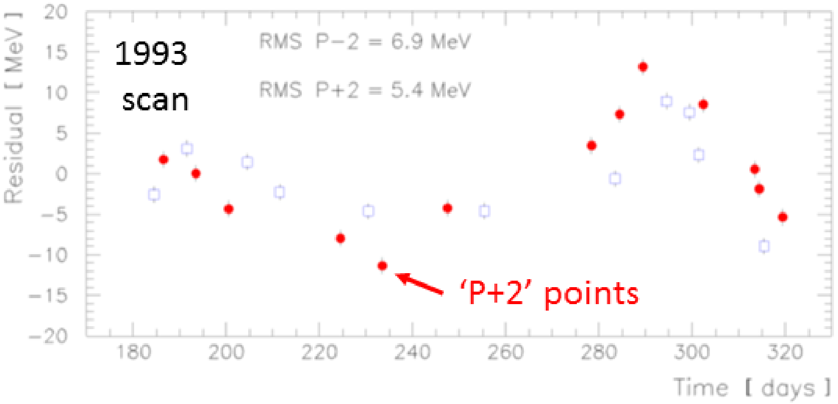
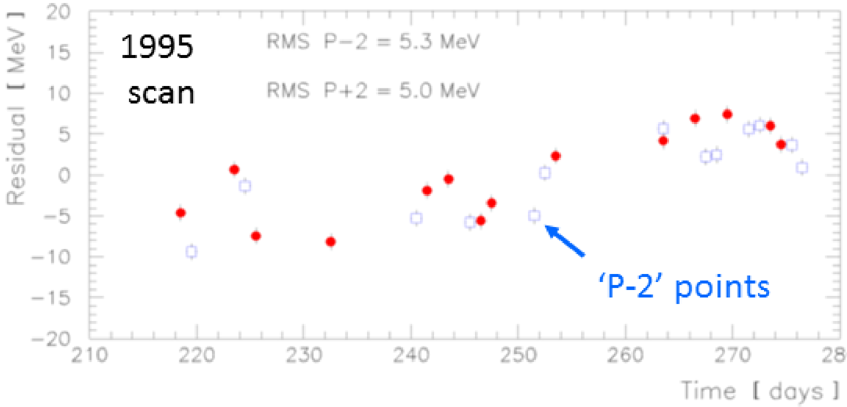
Challenge of E_{CM} calibration at LEP

At LEP RDP could not be performed during physics operation. Time-consuming procedure carried out at the end of certain fills, involving dedicated optics. these measurements showed scatter indicating considerable evolution in E_b.



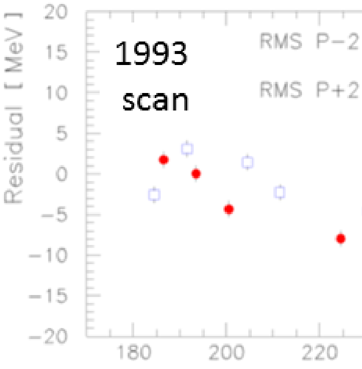


To calibrate the physics data-taking period, necessary to understand and model this evolution – a long and painful process that took many years. Ingredients:

- Bright ideas and machine theory;
- Dedicated instrumentation *e.g.* NMRs in magnets, BPMs *etc.;*
- Lots of machine time for studies (~50 full days in period 1993-2009);
- Mechanisms parameterised in models, used to calibrate physics data periods.

Challenge of E_{CM} calibration at LEP

At LEP RDP co … Time-consuming
procedure carr … ated optics.
these measure … volution in E_b.



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Calibration of centre-of-mass energies at LEP1 for precise measurements of Z properties

The LEP Energy Working Group

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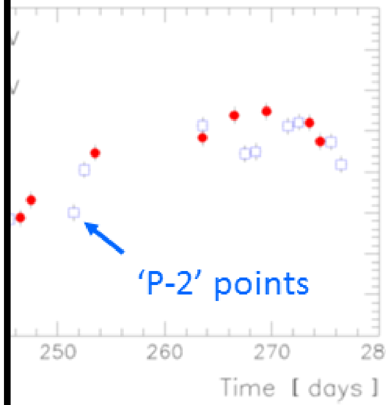
Abstract. The determination of the centre-of-mass energies from the LEP1 data for 1993, 1994 and 1995 is presented. Accurate knowledge of these energies is crucial in the measurement of the Z resonance parameters. The improved understanding of the LEP energy behaviour accumulated during the 1995 energy scan is detailed, while the 1993 and 1994 measurements are revised. For 1993 these supersede the previously published values. Additional instrumentation has allowed the detection of an unexpectedly large energy rise during physics fills. This new effect is accommodated in the modelling of the beam-energy in 1995 and propagated to the 1993 and 1994 energies. New results are reported on the magnet temperature behaviour which constitutes one of the major corrections to the average LEP energy.
The 1995 energy scan took place in conditions very different from the previous years. In particular the interaction-point specific corrections to the centre-of-mass energy in 1995 are more complicated than previously: these arise from the modified radiofrequency-system configuration and from opposite-sign vertical dispersion induced by the bunch-train mode of LEP operation.
Finally an improved evaluation of the LEP centre-of-mass energy spread is presented. This significantly improves the precision on the Z width.

[EPJC 6 (1999) 187]

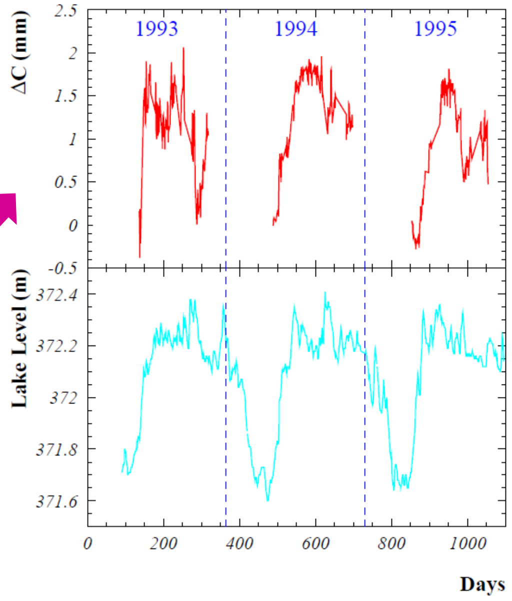


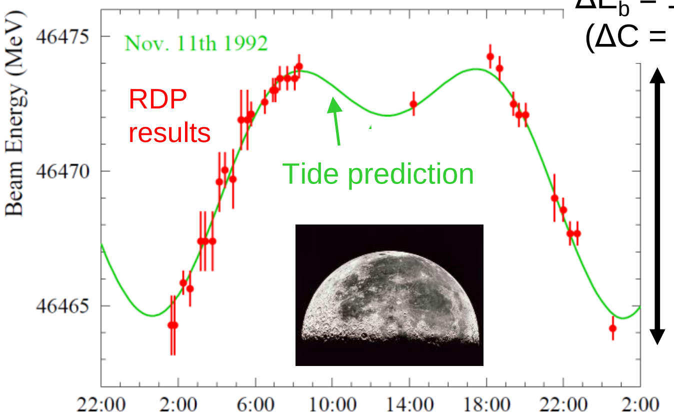
To calibrate the … stand and model
this evolution – … s. Ingredients:

- Bright idea …
- Dedicated … tc.;
- Lots of ma … 93-2009);
- Mechanism … ysics data periods.

Some mechanisms of E_b variation at LEP

Short- (tide) and long- (lake) term ring distortions.

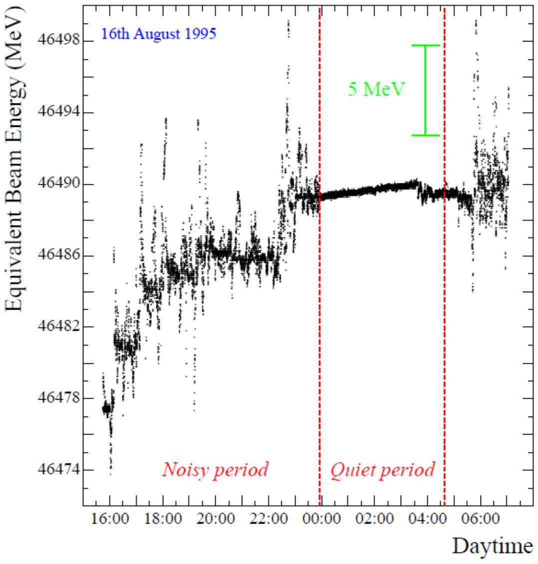


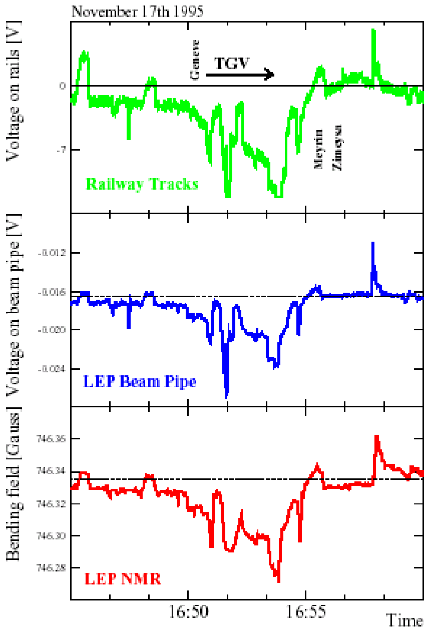


ΔE_b = 10 MeV
(ΔC = 1 mm)

NB at FCC-ee effects will be ~10x larger due to smaller momentum-compaction factor !

Rise of dipole fields stimulated by returning current from trains (TGV).





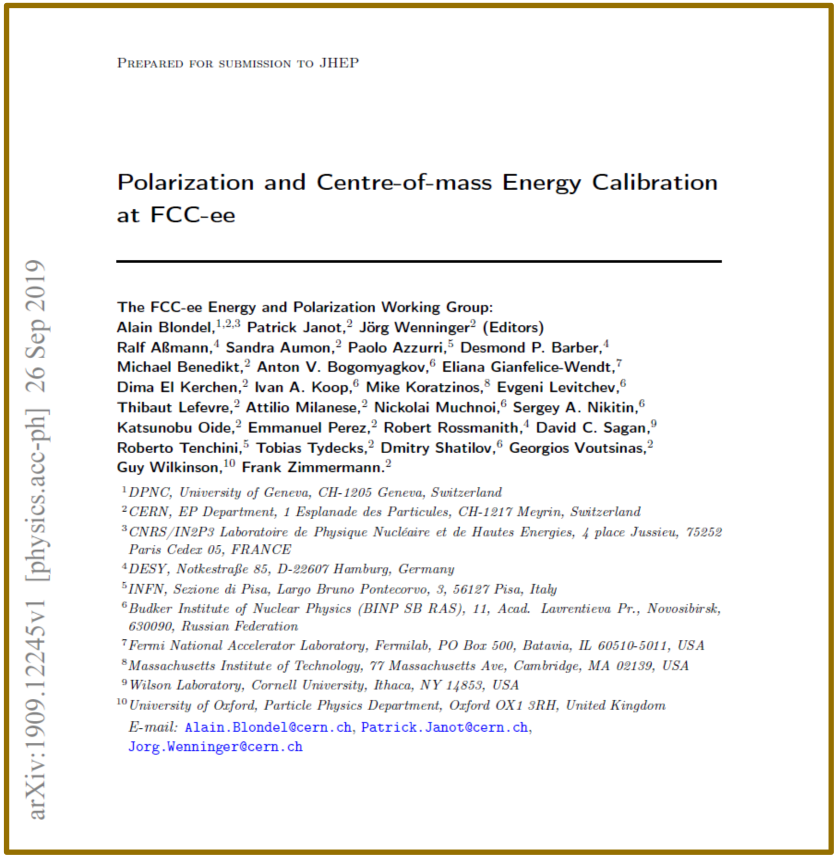
What hope then for E_{CM} calib^{n} at FCC-ee ?

Surely all these effects mean that there can be no big improvements at FCC-ee ?

What hope then for E_{CM} calib^{n} at FCC-ee ?

Surely all these effects mean that there can be no big improvements at FCC-ee ?

Not at all ! In contrast to LEP, build E_{CM} calibration requirements into machine design and planning from start. And already a great deal of thinking has occurred.



PREPARED FOR SUBMISSION TO JHEP

arXiv:1909.12245v1 [physics.acc-ph] 26 Sep 2019

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

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[arXiv:1909.12245]

- Perform RDP ‘continuously’ (~3-4 times per hour). This is done on ~250 out of 16600 non-colliding pilot bunches.

  ➡ Removes to first order all time-dependent effects !!!

- Measure separately for e^+ & e^-.
- Adjust RF frequency at short intervals to suppress tide-like effects.
- Frequent van der Meer scans to suppress dispersion biases at IP.
- Invest in extensive instrumentation and logging of all machine parameters.

E_{CM} uncertainties on lineshape observables

Bottom line – confident that E_{CM} uncertainties will be much smaller than at LEP.

	m_Z	Γ_Z
Statistical uncertainty	4 keV	4 keV
E_{CM}-related systematic (a conservative estimate - we feel we can do better)	100 keV	25 keV

How much better depends on further work, but the goal is to edge as close as possible to the statistical uncertainty for Γ_Z. Already with this level of control, the E_{CM}-related systematics on other observables, *e.g.* $\sin^2\theta_W^{eff}$ from the dimuon forward-backward asymmetry, are as small as we require them to be.

(Not discussed here, but the E_{CM} systematic for quantities such as Γ_Z also receives a contribution from the knowledge of the *energy spread*. This can be quantified in a satisfactory manner from studying the topology of dimuon events.)

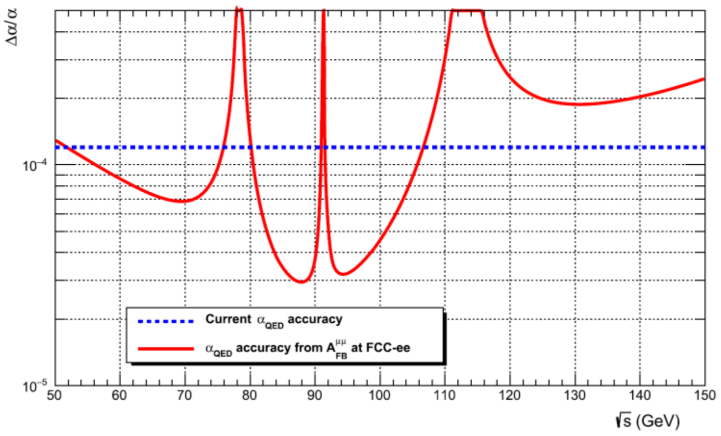
Other Z-related measurements

- **Measurement of $\alpha_{QED}(m_Z^2)$ from forward-backward dimuon asymmetry**

$$A_{\mathrm{FB}}^{\mu\mu}(s) \simeq \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mu} \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{\mathrm{QED}}(s)}{m_{\mathrm{Z}}^{2} G_{\mathrm{F}}\left(1 - 4\sin^{2}\theta_{\mathrm{W}}^{\mathrm{eff}}\right)^{2}} \frac{s - m_{\mathrm{Z}}^{2}}{2s}\right]$$

Choose off-peak energies to allow for factor ~4 improvement in precision.

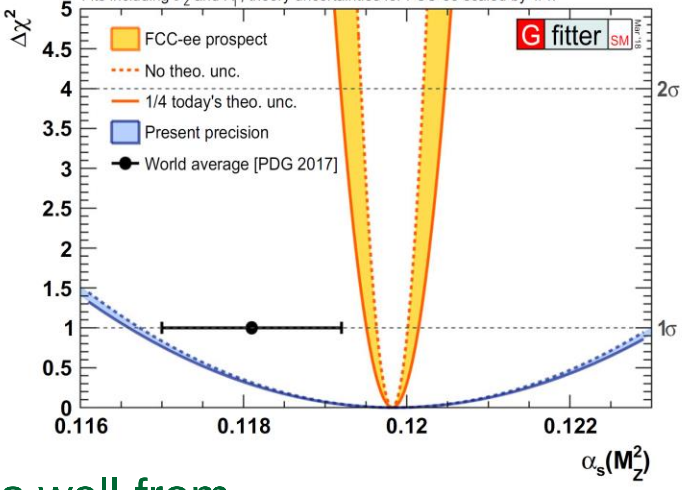
attainable α_{QED} uncertainty with 80 fb^{-1}



- **Improved measurement of $\alpha_{QCD}(m_Z^2)$**

  Expectation from lineshape observables *alone* (not included: τ, W decays, jet rates, event shapes…).

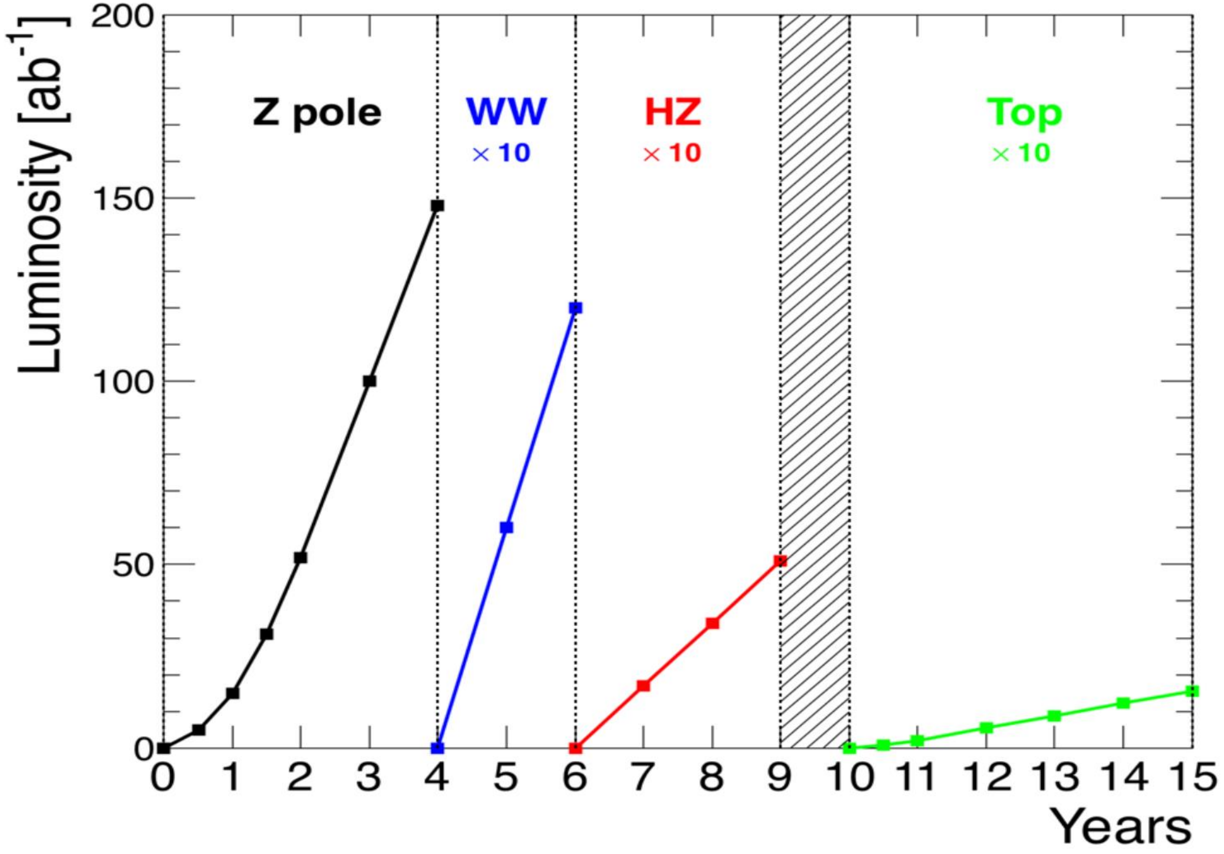
Fits including Γ_Z and R_l^0, theory uncertainties for FCC-ee scaled by 1/4.



- **Improved measurement of N_ν**

  As well as measuring number of neutrino families to 0.001 from lineshape parameters, should be able to do *at least* as well from radiative returns ($e^+e^- \to Z\gamma$, $Z \to \nu\bar{\nu}$) at higher energies (*e.g.* 161 GeV).

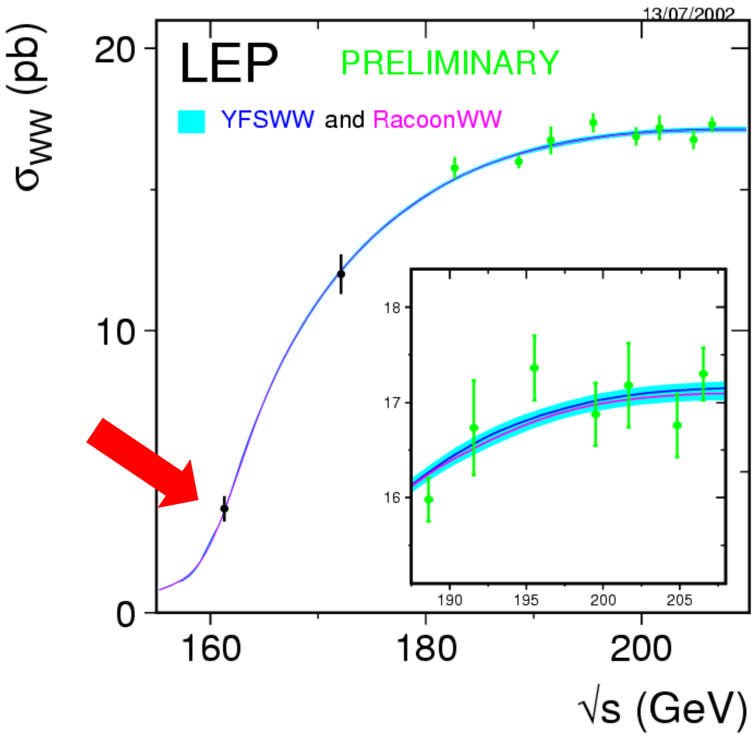
Precision EW physics above the Z

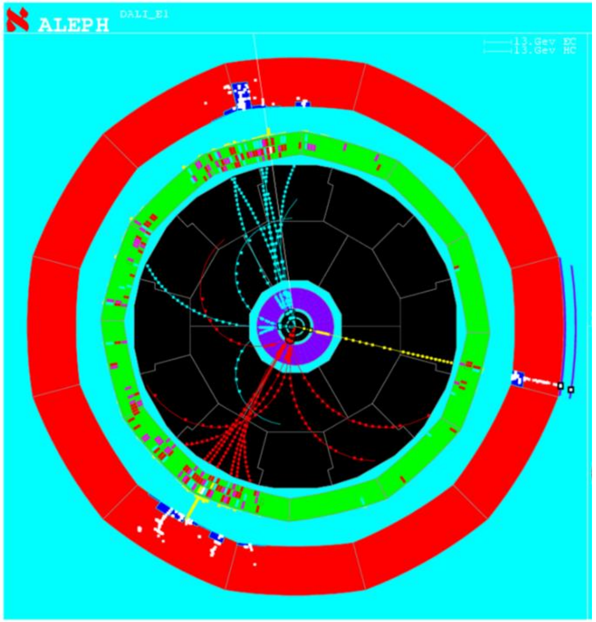


Let us briefly consider EW opportunities at the W^+W^- and ttbar thresholds.

Measuring W mass in $e^+e^- \rightarrow W^+W^-$

Two methods available: measure WW cross-section at threshold, or fully reconstruct event. Former has fewer systematics, and will probably be the method of choice at FCC-ee, but lower statistical uncertainty gave latter higher weight at LEP.





In both cases a leading systematic uncertainty comes from collision energy (yes, that again).

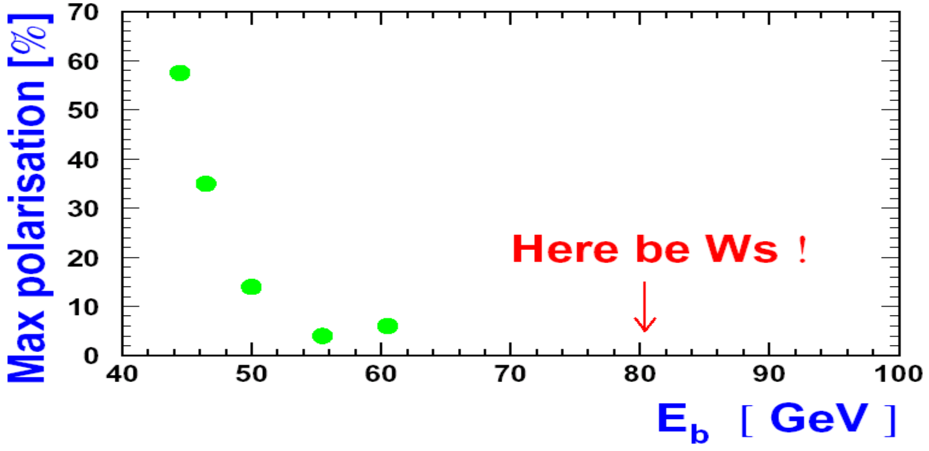
$$\frac{\Delta m_W}{m_W} = \frac{\Delta E_{CM}}{E_{CM}}$$

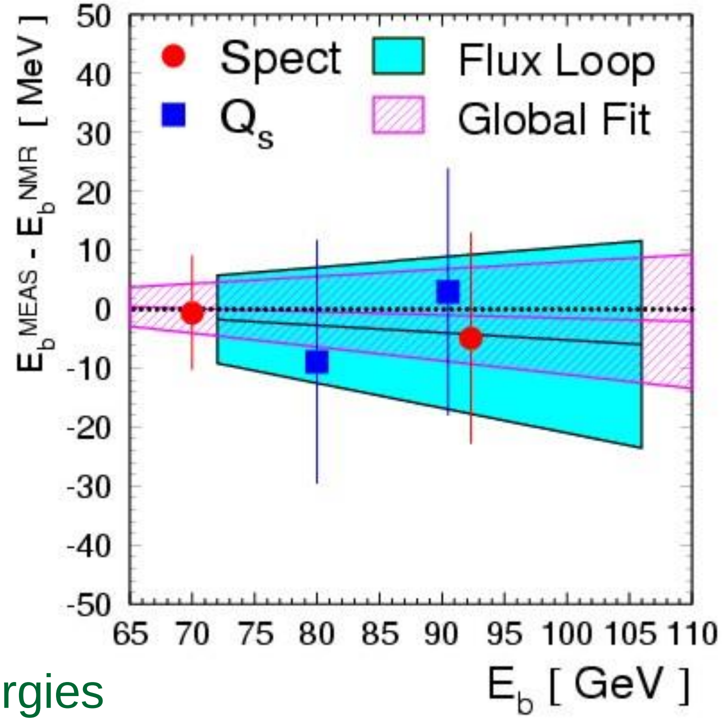
Measuring m_W in $e^+e^- \rightarrow W^+W^-$

$$\frac{\Delta m_W}{m_W} = \frac{\Delta E_{CM}}{E_{CM}}$$

Surely not a problem? Many fewer W's than Z's – statistical precision at LEP a few 10^{-4}, and E_{CM} measured to 2 x 10^{-5} at Z^0. What's the worry ?

Growth of beam spread with energy means depolarising resonances destroy polarisation and make RDP impossible…

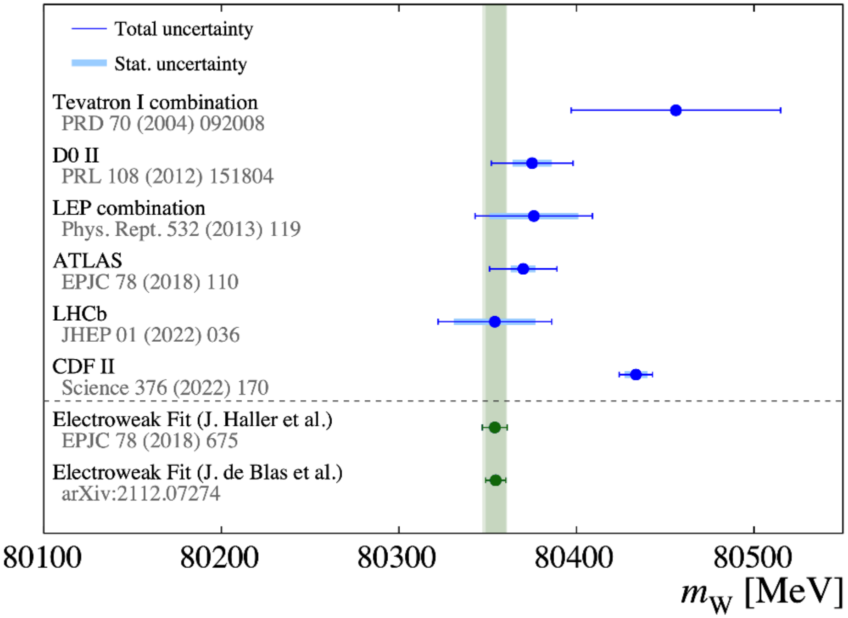




…instead must use a variety of methods (*e.g.* spectrometer) to extrapolate from RDP energies to W^+W^- regime. Very difficult, but it was done [EPJC 39 (2005) 253].

Prospects for m_W at FCC-ee

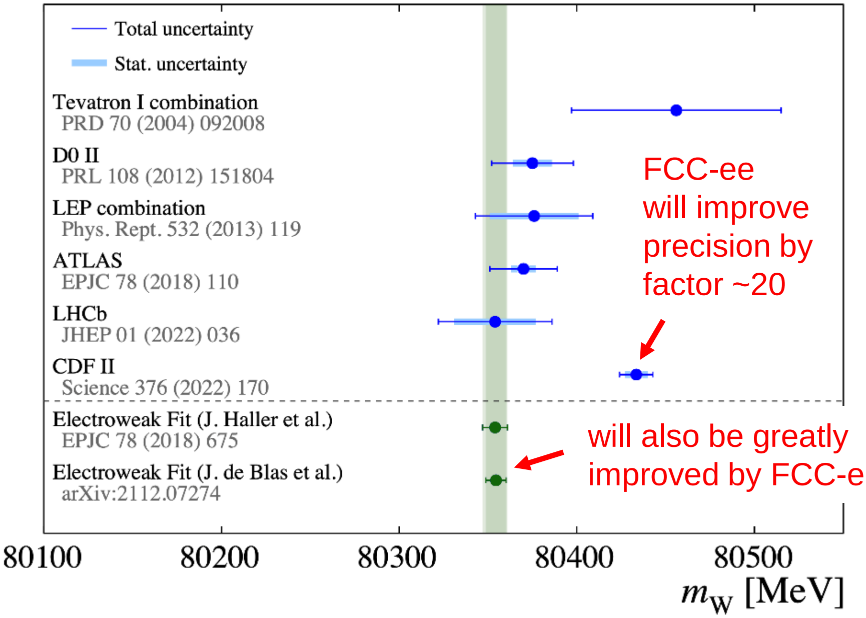
Furthermore, hadron machines now leading way on m_W. And they will improve.



- Yes, but it is exceptionally difficult, particularly at LHC (easier at ppbar).
- Ultimate precision at HL-LHC difficult to assess, but indicative value ~5 MeV (see *e.g.* ATL-PHYS-PUB-2018-026), with best prospects if LHeC operates.

Prospects for m_W at FCC-ee

Furthermore, hadron machines now leading way on m_W. And they will improve.



FCC-ee will improve precision by factor ~20

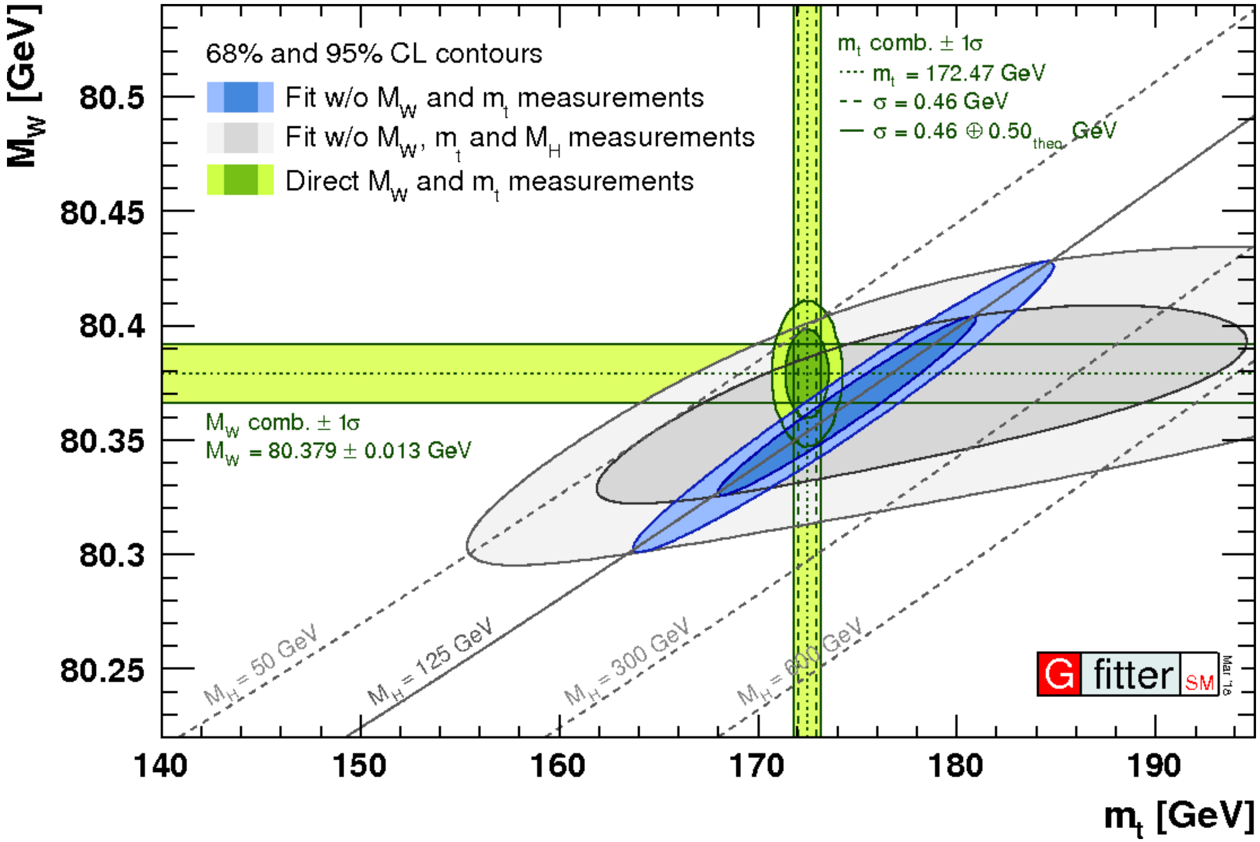
will also be greatly improved by FCC-ee

- Yes, but it is exceptionally difficult, particularly at LHC (easier at ppbar).
- Ultimate precision at HL-LHC difficult to assess, but indicative value ~5 MeV (see *e.g.* ATL-PHYS-PUB-2018-026), with best prospects if LHeC operates.
- But we can do ***much better*** at FCC-ee, since ***polarisation will be possible !*** Because $\sigma_{E_b} \sim E_b^2/\sqrt{\rho}$ where ρ is magnetic bending radius, which is much larger at FCC-ee than LEP.

Goal will be to perform threshold scan of 12 ab^{-1} at 157.5 GeV & 162.5 GeV, with a statistical uncertainty on m_W of 0.5 MeV, and E_{CM}-associated error of ~0.3 MeV.

Improved knowledge of m_W mandatory for vital self-consistency test of SM

Best possible precision on m_W required to perform critical closure test on SM.



Improved knowledge of m_W mandatory for vital self-consistency test of SM

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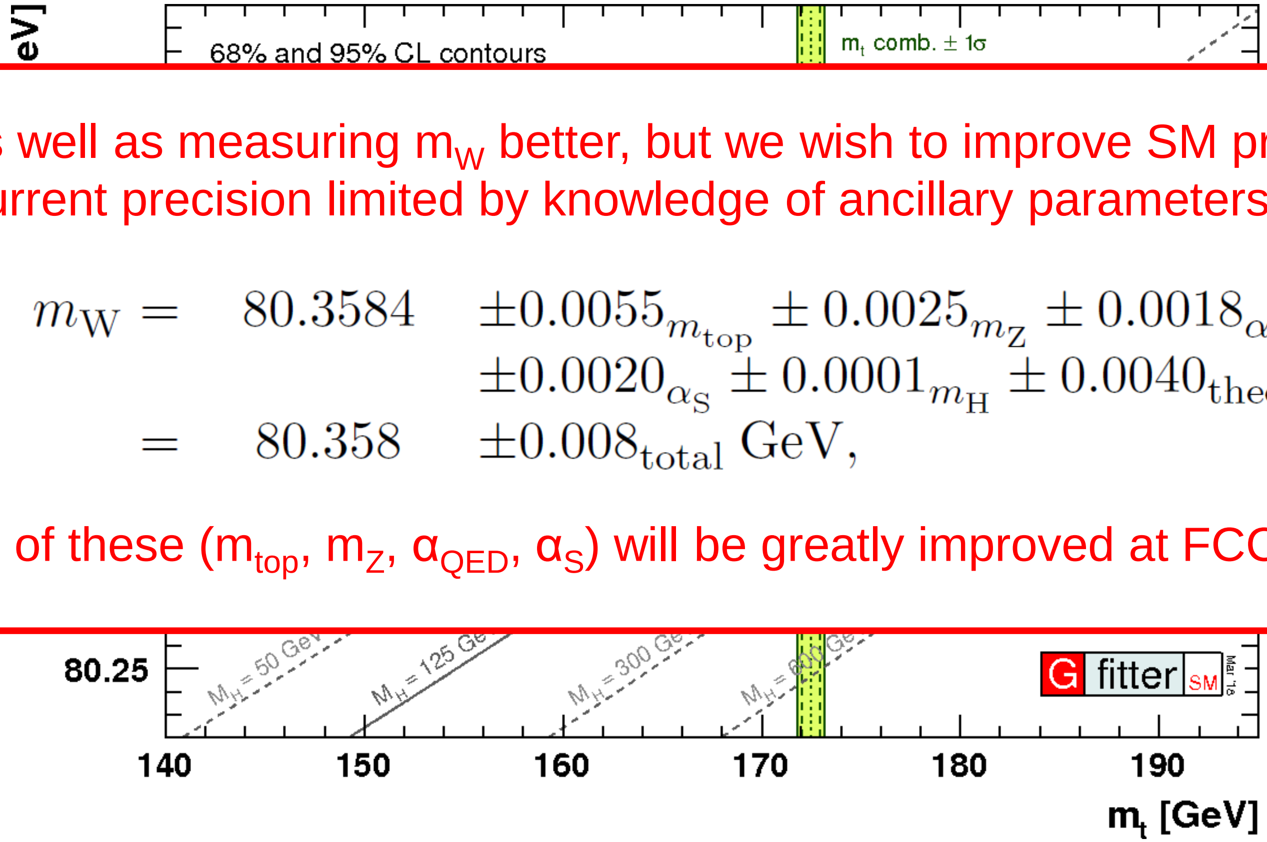


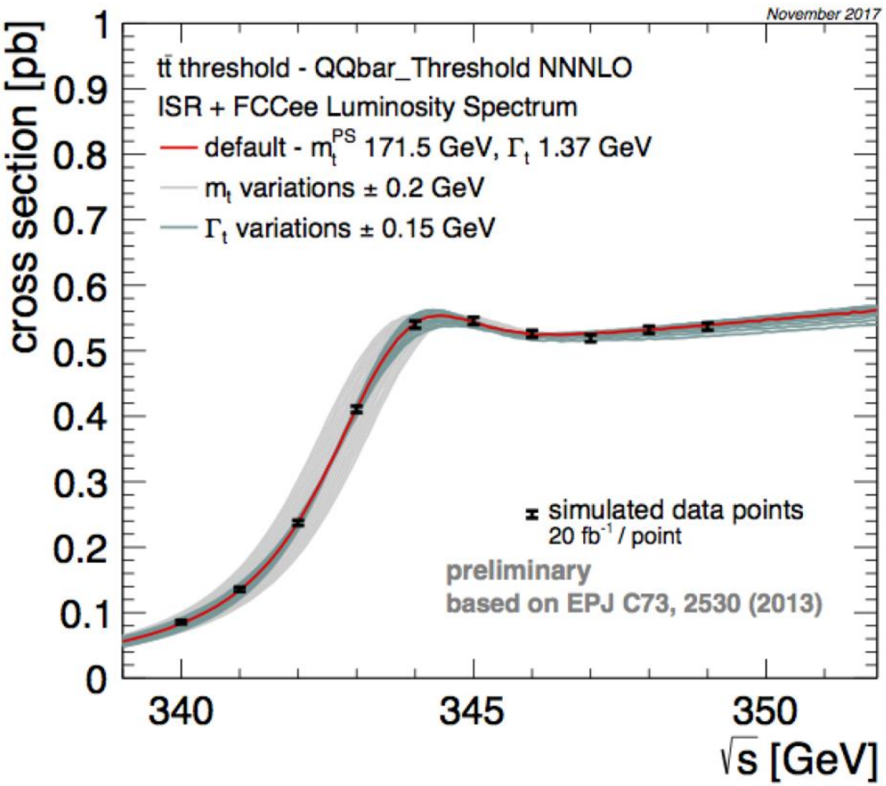
As well as measuring m_W better, but we wish to improve SM prediction. Current precision limited by knowledge of ancillary parameters.

$$\begin{aligned} m_W = \quad & 80.3584 \quad \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \\ & \qquad\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{\text{theory}}\ \text{GeV} \\ = \quad & 80.358 \quad \pm 0.008_{\text{total}}\ \text{GeV}, \end{aligned}$$

All of these (m_{top}, m_Z, α_{QED}, α_S) will be greatly improved at FCC-ee !

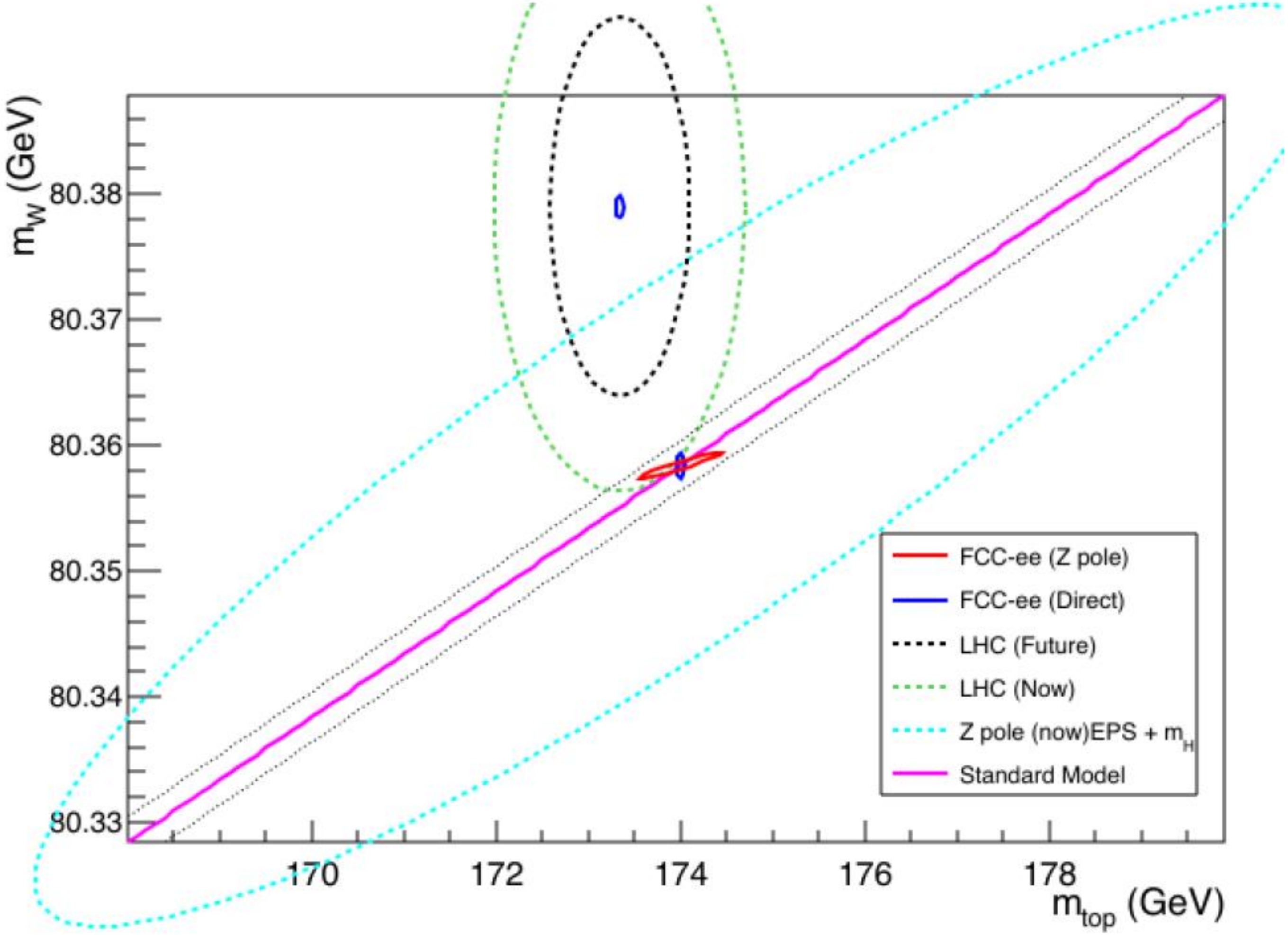
Going to higher energies: m_t

Currently m_t known to ~0.5 GeV. Improved knowledge needed for m_W closure test.

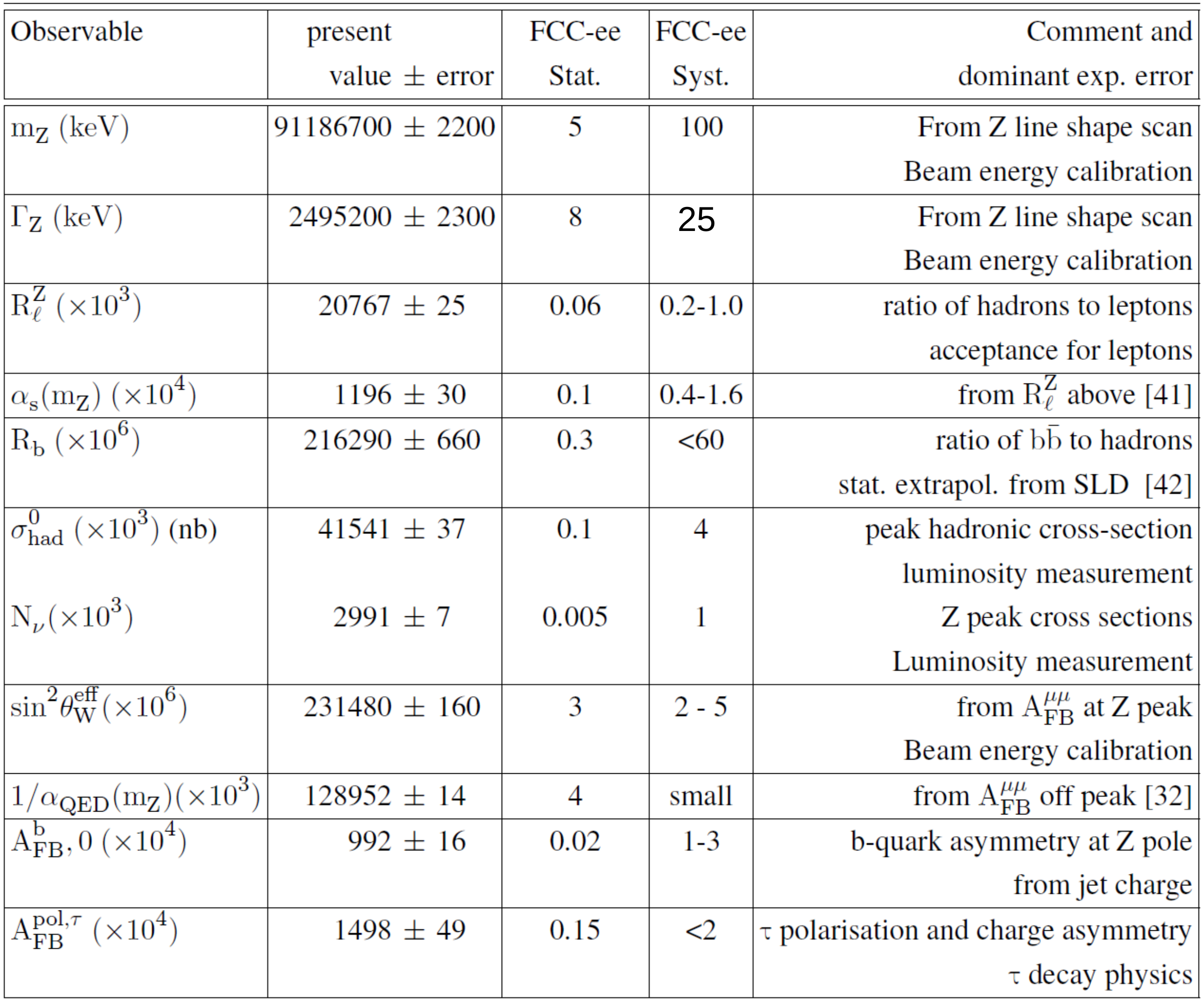


Multi-point threshold scan with 25 fb^{-1} will determine m_t to 17 MeV (& also measure width & top-Yukawa coupling). At these energies RDP is not possible, but sufficient knowledge of E_{CM} will be achievable from reconstruction of WW, ZZ, Zγ events.

Future precision on m_W closure test



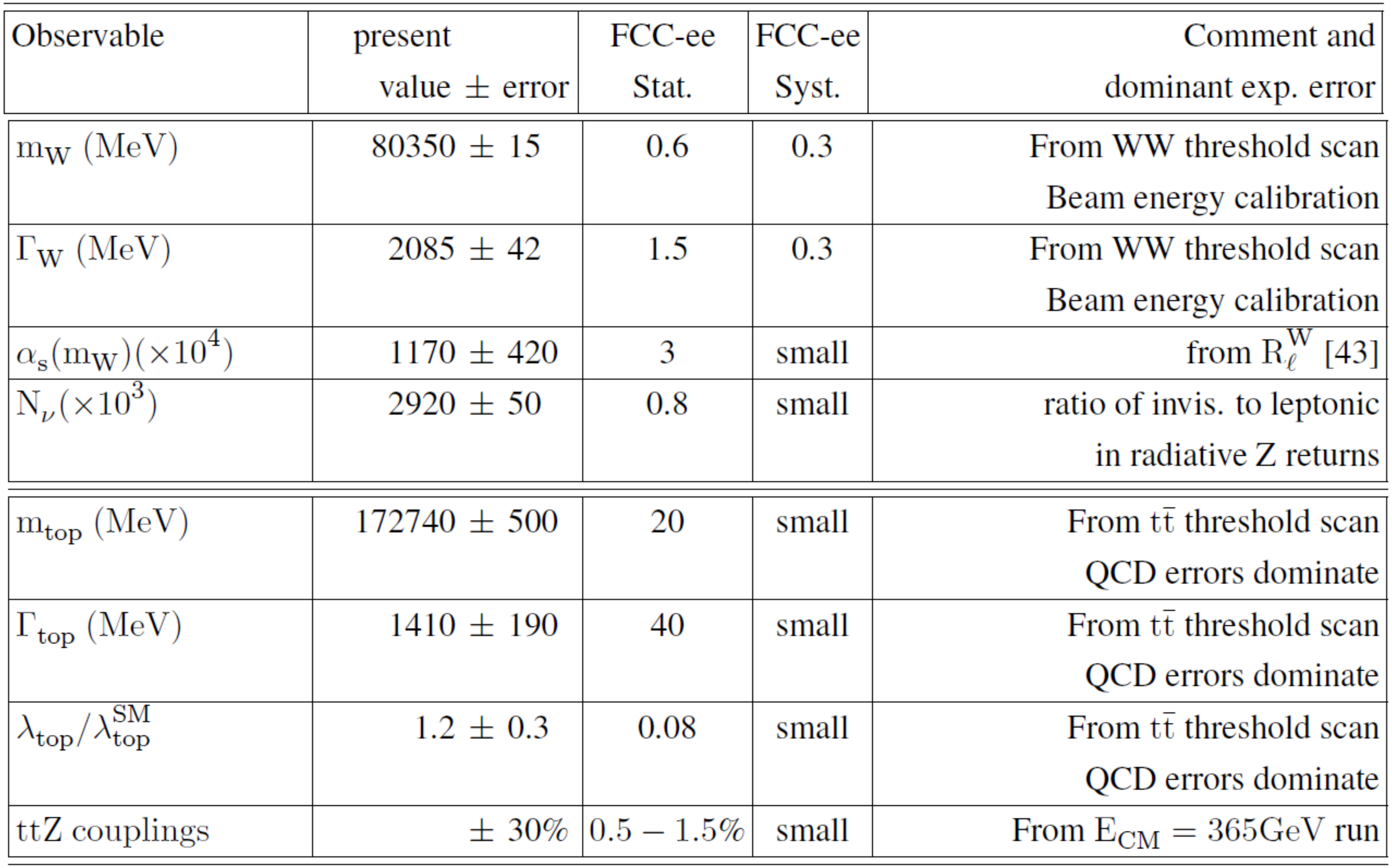
Expected precision on EW observables



Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error	Factor improvement
m_Z (keV)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration	~20
Γ_Z (keV)	2495200 ± 2300	8	25	From Z line shape scan Beam energy calibration	~100
R_ℓ^Z ($\times 10^3$)	20767 ± 25	0.06	0.2-1.0	ratio of hadrons to leptons acceptance for leptons	~20-100
$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R_ℓ^Z above [41]	
R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [42]	>10
σ_{had}^0 ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement	
N_ν($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement	~10
$\sin^2\theta_W^{eff}$($\times 10^6$)	231480 ± 160	3	2 - 5	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	~100
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128952 ± 14	4	small	from $A_{FB}^{\mu\mu}$ off peak [32]	~4
$A_{FB}^{b}, 0$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge	
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics	~20

Conservative estimate of systematics at time of CDR; many will improve.

Expected precision on EW observables



Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error	Factor improvement
m_W (MeV)	80350 ± 15	0.6	0.3	From WW threshold scan Beam energy calibration	~25
Γ_W (MeV)	2085 ± 42	1.5	0.3	From WW threshold scan Beam energy calibration	~25
$\alpha_s(m_W)(\times 10^4)$	1170 ± 420	3	small	from R_ℓ^W [43]	
$N_\nu(\times 10^3)$	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns	~60
m_{top} (MeV)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate	
Γ_{top} (MeV)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate	
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate	
ttZ couplings	± 30%	0.5 – 1.5%	small	From E_{CM} = 365GeV run	

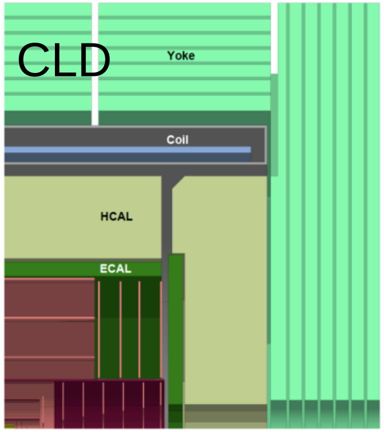
Detector challenges

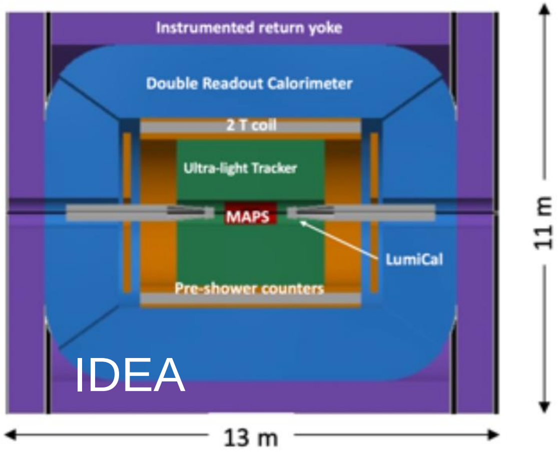
Event rates and radiation challenges modest compared with HL-LHC/FCC-hh.

On the other hand, extreme precision of Tera-Z puts unprecedented demands on stability of detector & operation, resolution of many components *e.g*. luminosity measurement at 10^{-5} (relative), 10^{-4} (absolute), acceptance definition at 10^{-5}.

in contrast, Higgs physics is ‘easy’ !

Early days, but three candidate experiment designs have emerged:


CLD


IDEA


Noble liquid calo based concept

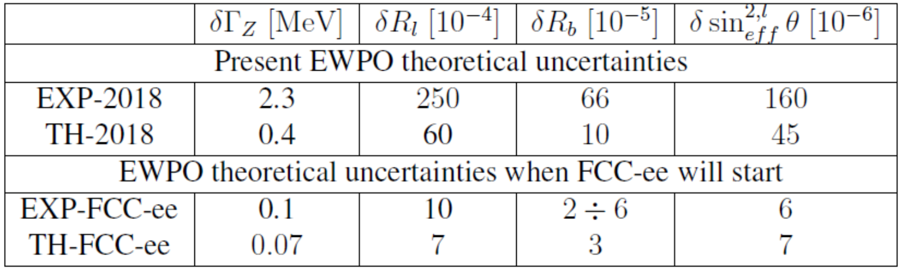
These are not set in stone ! Plenty of room of new ideas, optimisation *etc*.

If we have four IPs rather than two, then the opportunities are even wider, *e.g.* there is no design yet that is optimal for flavour physics (dedicated PID, crystal calo *etc.*).

An exciting challenge for theory too

Foreseen experimental precision will require corresponding advances in theory.

arXiv:1901.02648

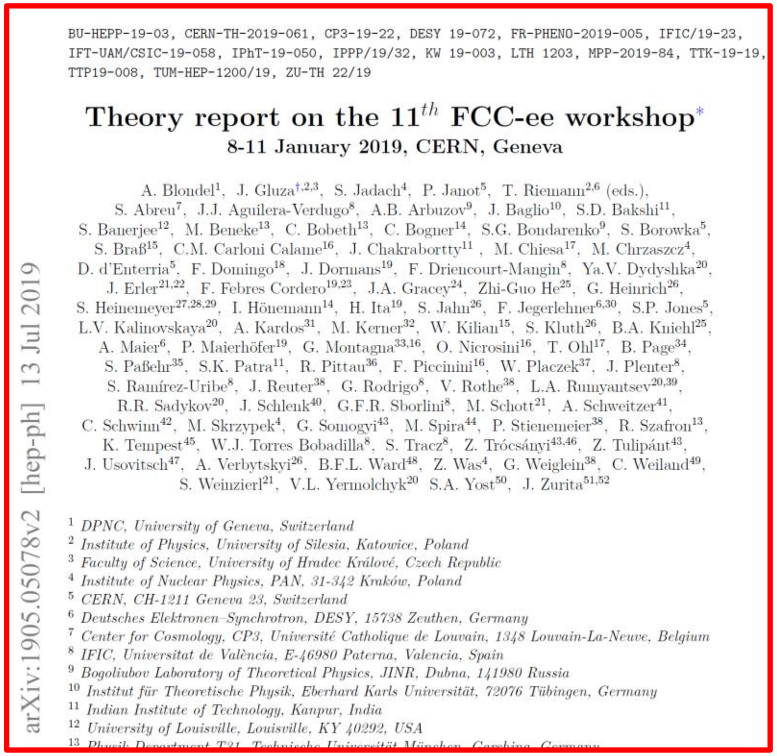


	$\delta\Gamma_Z$ [MeV]	δR_l $[10^{-4}]$	δR_b $[10^{-5}]$	$\delta \sin^{2,l}_{eff}\theta$ $[10^{-6}]$
Present EWPO theoretical uncertainties				
EXP-2018	2.3	250	66	160
TH-2018	0.4	60	10	45
EWPO theoretical uncertainties when FCC-ee will start				
EXP-FCC-ee	0.1	10	$2 \div 6$	6
TH-FCC-ee	0.07	7	3	7

Theory uncertainties assuming
3-loop corrections & dominant
4-loop corrections available.

Does not look impossible, but requires resources (estimated 500 person-years) !

> "We anticipate that, at the beginning of the FCC-ee campaign of precision measurements, the theory will be precise enough not to limit their physics interpretation." J. Gluza



arXiv:1905.05078v2 [hep-ph] 13 Jul 2019

BU-HEPP-19-03, CERN-TH-2019-061, CP3-19-22, DESY 19-072, FR-PHENO-2019-005, IFIC/19-23, IFT-UAM/CSIC-19-058, IPhT-19-050, IPPP/19/32, KW 19-003, LTH 1203, MPP-2019-84, TTK-19-19, TTP19-008, TUM-HEP-1200/19, ZU-TH 22/19

Theory report on the 11^{th} FCC-ee workshop*

8-11 January 2019, CERN, Geneva

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L.V. Kalinovskaya[20], A. Kardos[31], M. Kerner[32], W. Kilian[15], S. Kluth[26], B.A. Kniehl[25],
A. Maier[6], P. Maierhöfer[19], G. Montagna[33,16], O. Nicrosini[16], T. Ohl[17], B. Page[34],
S. Paßehr[35], S.K. Patra[11], R. Pittau[36], F. Piccinini[16], W. Placzek[37], J. Plenter[8],
S. Ramírez-Uribe[8], J. Reuter[38], G. Rodrigo[8], V. Rothe[38], L.A. Rumyantsev[20,39],
R.R. Sadykov[20], J. Schlenk[40], G.F.R. Sborlini[8], M. Schott[21], A. Schweitzer[41],
C. Schwinn[42], M. Skrzypek[4], G. Somogyi[43], M. Spira[44], P. Stienemeier[38], R. Szafron[13],
K. Tempest[45], W.J. Torres Bobadilla[8], S. Tracz[8], Z. Trócsányi[43,46], Z. Tulipánt[43],
J. Usovitsch[47], A. Verbytskyi[26], B.F.L. Ward[48], Z. Was[4], G. Weiglein[38], C. Weiland[49],
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arXiv:1905.05078

FCC-ee as a flavour factory

b physics at the Z pole

Z^0 environment offers many of the benefits of both the Y(4S) and proton-proton.

	Y(4S)	**pp**	**Z**
All hadron species		✓	✓
High boost		✓	✓
Enormous production x-sec		✓	
Negligible trigger losses	✓		✓
Low background environment	✓		✓
Initial energy constraint	✓		(✓)

Enormous luminosity will bring 7.4×10^{11} bbbar pairs, around 30x larger b yield than at Belle II, and a similar number to that produced within LHCb in Run 2.

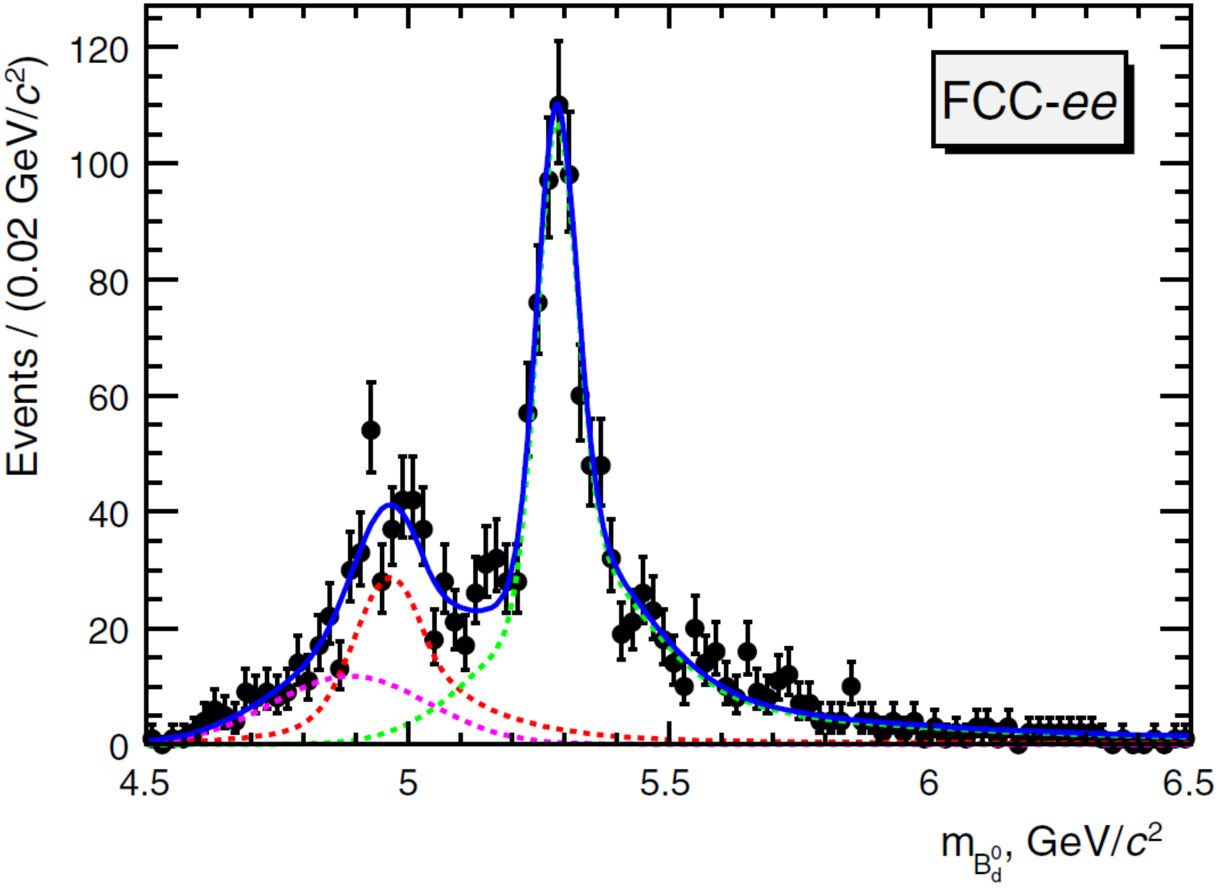
→ high precision b-physics programme complementary to LHCb Upgrades

(NB CEPC, with *current* design, significantly less interesting because of lower lumi)

b physics at FCC-ee

One good example where FCC-ee can shine is in B decays involving taus, where the missing energy makes life extremely difficult at LHCb.

e.g. reconstructing $B^0 \to K^{*0}\tau^+\tau^-$, a priori a very interesting electroweak-penguin mode, and especially so in the light of the current flavour anomalies.



See EPC+ 136 (2021) 837 for a brief overview

b physics at FCC-ee

One good e … involving taus,
where the n … Cb.

e.g. reconst … ctroweak-penguin
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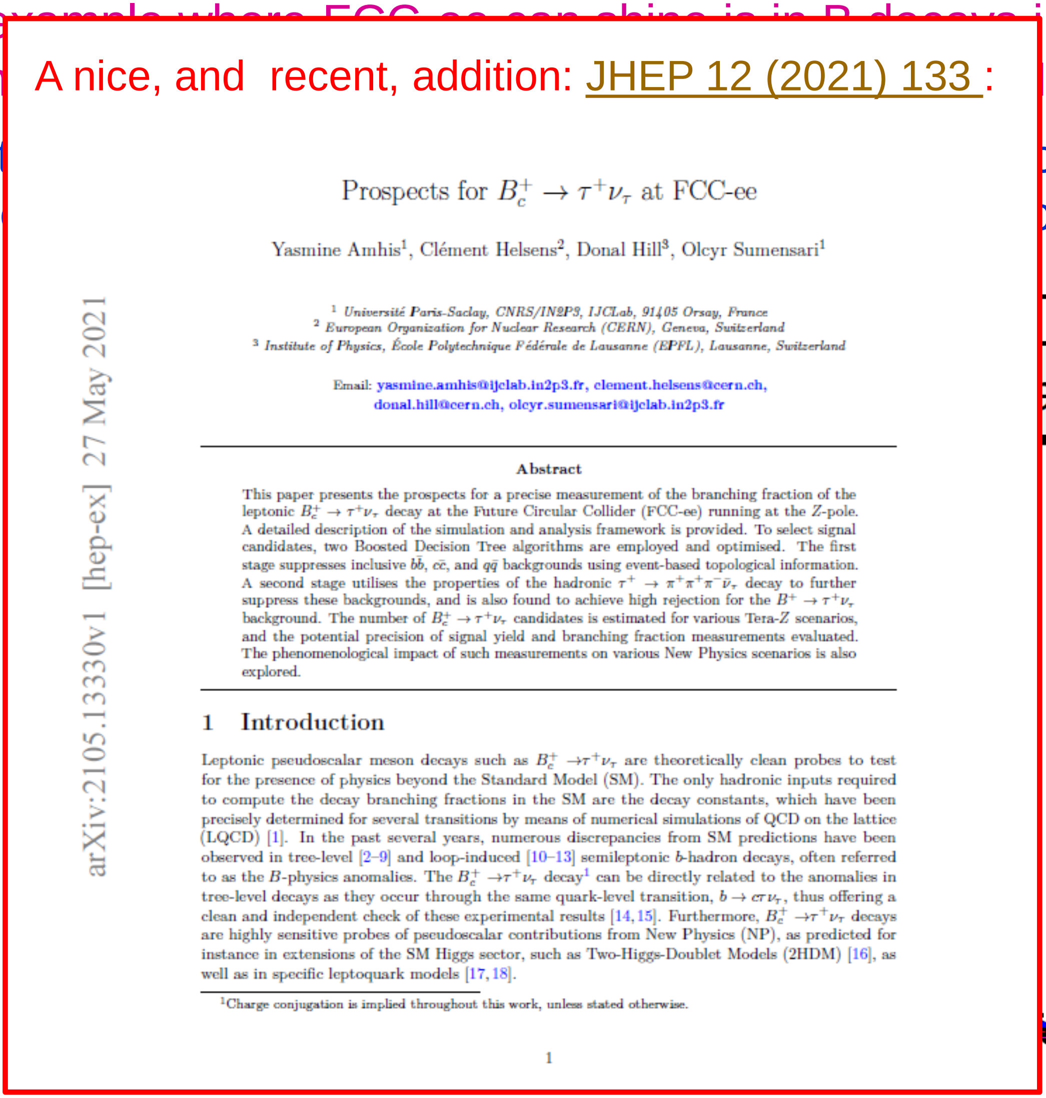

A nice, and recent, addition: JHEP 12 (2021) 133 :

arXiv:2105.13330v1 [hep-ex] 27 May 2021

Prospects for $B_c^+ \to \tau^+\nu_\tau$ at FCC-ee

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Abstract

This paper presents the prospects for a precise measurement of the branching fraction of the leptonic $B_c^+ \to \tau^+\nu_\tau$ decay at the Future Circular Collider (FCC-ee) running at the Z-pole. A detailed description of the simulation and analysis framework is provided. To select signal candidates, two Boosted Decision Tree algorithms are employed and optimised. The first stage suppresses inclusive $b\bar{b}$, $c\bar{c}$, and $q\bar{q}$ backgrounds using event-based topological information. A second stage utilises the properties of the hadronic $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$ decay to further suppress these backgrounds, and is also found to achieve high rejection for the $B^+ \to \tau^+\nu_\tau$ background. The number of $B_c^+ \to \tau^+\nu_\tau$ candidates is estimated for various Tera-Z scenarios, and the potential precision of signal yield and branching fraction measurements evaluated. The phenomenological impact of such measurements on various New Physics scenarios is also explored.

1 Introduction

Leptonic pseudoscalar meson decays such as $B_c^+ \to \tau^+\nu_\tau$ are theoretically clean probes to test for the presence of physics beyond the Standard Model (SM). The only hadronic inputs required to compute the decay branching fractions in the SM are the decay constants, which have been precisely determined for several transitions by means of numerical simulations of QCD on the lattice (LQCD) [1]. In the past several years, numerous discrepancies from SM predictions have been observed in tree-level [2–9] and loop-induced [10–13] semileptonic b-hadron decays, often referred to as the B-physics anomalies. The $B_c^+ \to \tau^+\nu_\tau$ decay[1] can be directly related to the anomalies in tree-level decays as they occur through the same quark-level transition, $b \to c\tau\nu_\tau$, thus offering a clean and independent check of these experimental results [14, 15]. Furthermore, $B_c^+ \to \tau^+\nu_\tau$ decays are highly sensitive probes of pseudoscalar contributions from New Physics (NP), as predicted for instance in extensions of the SM Higgs sector, such as Two-Higgs-Doublet Models (2HDM) [16], as well as in specific leptoquark models [17, 18].

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[1] Charge conjugation is implied throughout this work, unless stated otherwise.

1

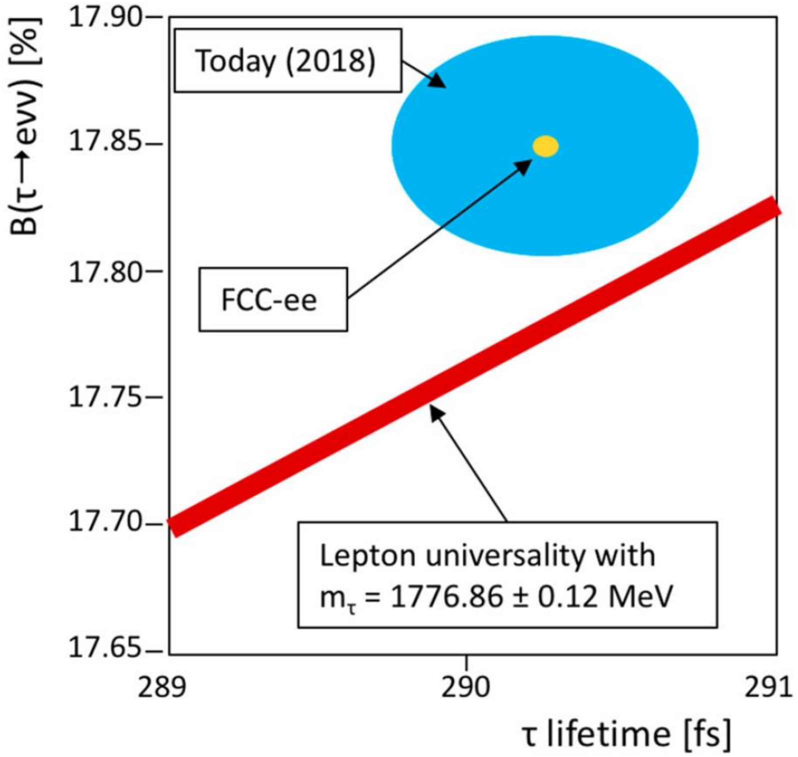
See EPC+ 136 (2021) 837
for a brief overview

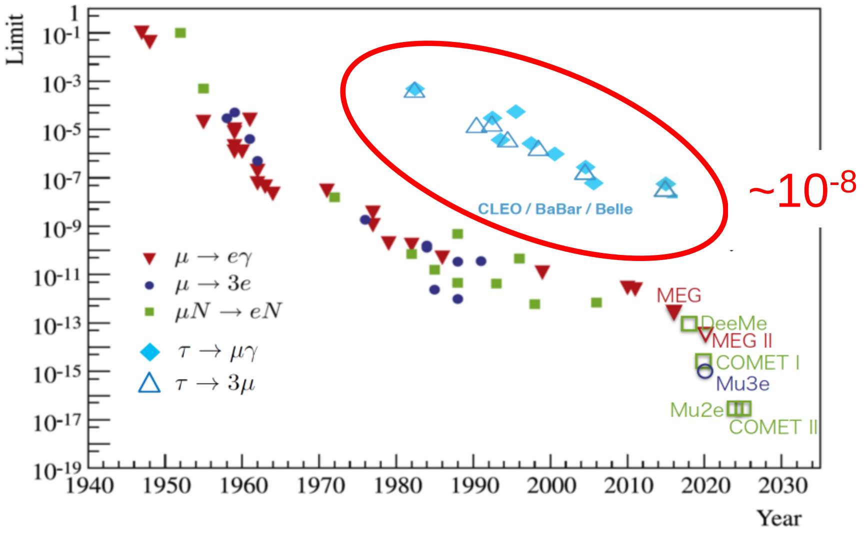
Tau physics at FCC-ee

LEP and the B-factories greatly advanced knowledge of the tau lepton.
Clear opportunity for further strides forward at FCC-ee.

e.g. lepton universality test through measurement of BRs and tau lifetime.

~4x number of tau pairs as expected at Belle II, in (as least) as clean environment





→ world-best sensitivity for wide range of lepton-flavour-violating modes

e.g. $\tau\to\mu\mu\mu$ down to $O(10^{-10})$

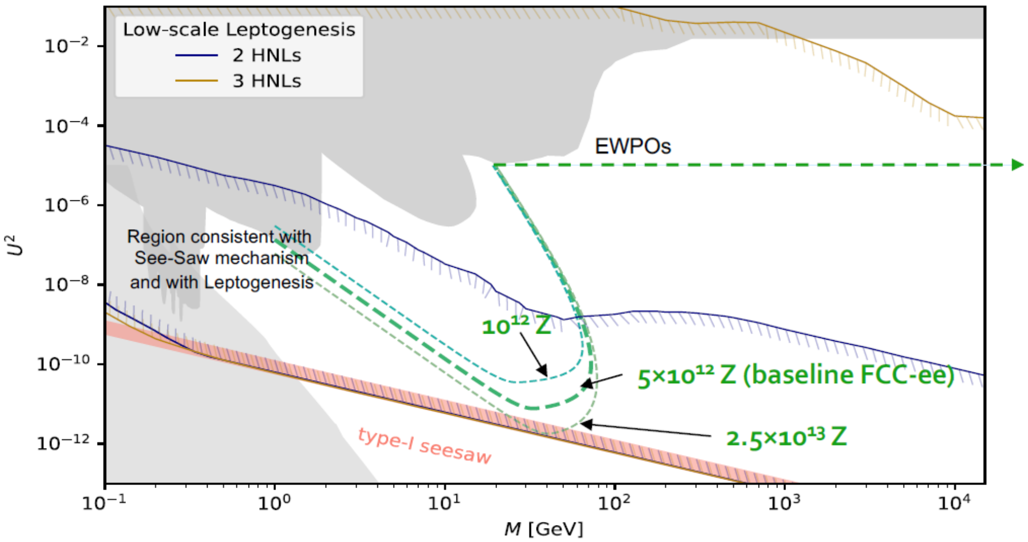
Direct searches at FCC-ee

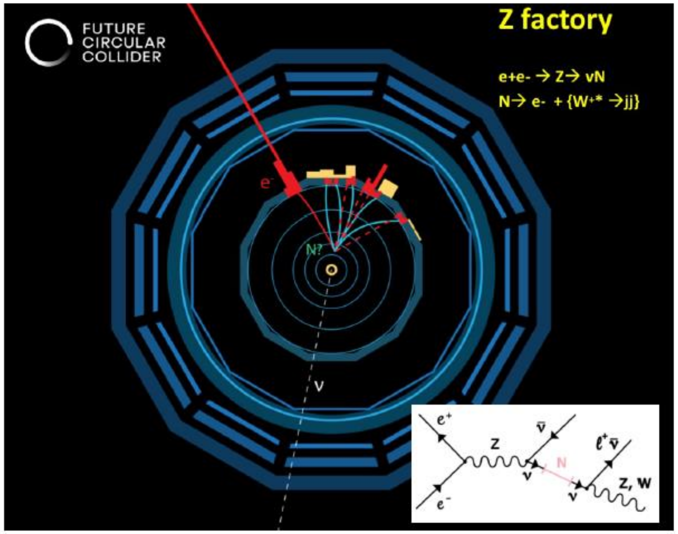
Why 5 x 10^{12} Z^0s ? Direct searches

FCC-ee will be a discovery machine, both through indirect searches (*e.g.* precision EW, Higgs and flavour physics), but also for direct searches for non-SM phenomena.

e.g. exclusion limits for heavy right-handed neutrinos

[also see PRL 127 (2021) 111802]





FCC-ee Z-pole running will have enormous potential in searches for LFV decays, heavy sterile neutrinos, axion-like particles *etc*. In all cases integrated lumi is key !

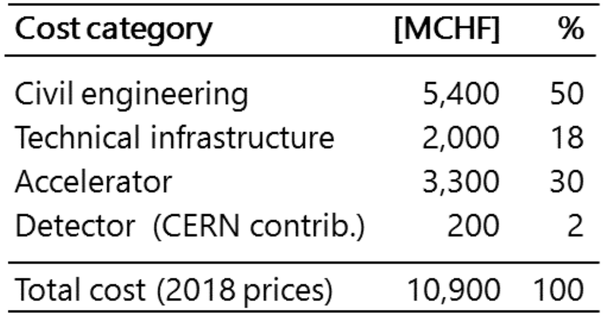
Practicalities

Timescales and finances

Statements of CERN DG in Paris FCC week, June ’22 (and reiterated at London FCC week, June 2023):

“
- If project approved before end of decade → construction can start beginning of 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation ~2070-2090++ ”

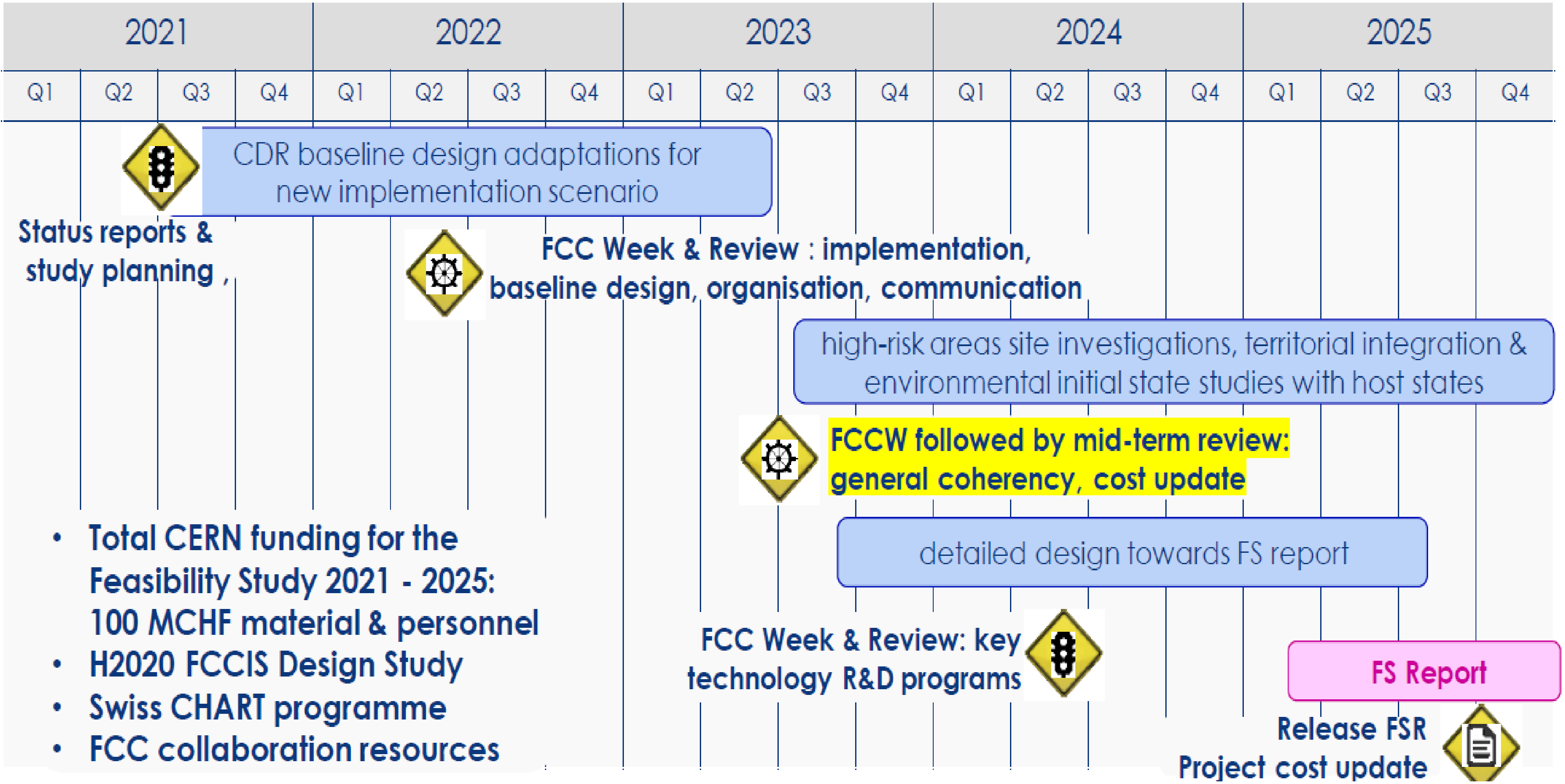
“ Substantial resources (~5 BCHF) needed from outside CERN’s budget… (contributions from non-Member States, special contributions from Host States and other Member States; ongoing discussion with European Commission; private funding?) → discussions started. ”



Cost category	[MCHF]	%
Civil engineering	5,400	50
Technical infrastructure	2,000	18
Accelerator	3,300	30
Detector (CERN contrib.)	200	2
Total cost (2018 prices)	10,900	100

← Reminder of FCC-ee costs (Z, WW and HZ working points, and for two IP configuration)

Feasibility study underway



CDR baseline design adaptations for new implementation scenario

Status reports & study planning ,

FCC Week & Review : implementation, baseline design, organisation, communication

high-risk areas site investigations, territorial integration & environmental initial state studies with host states

FCCW followed by mid-term review: general coherency, cost update

detailed design towards FS report

FCC Week & Review: key technology R&D programs

FS Report

Release FSR Project cost update

- **Total CERN funding for the Feasibility Study 2021 - 2025: 100 MCHF material & personnel**
- **H2020 FCCIS Design Study**
- **Swiss CHART programme**
- **FCC collaboration resources**

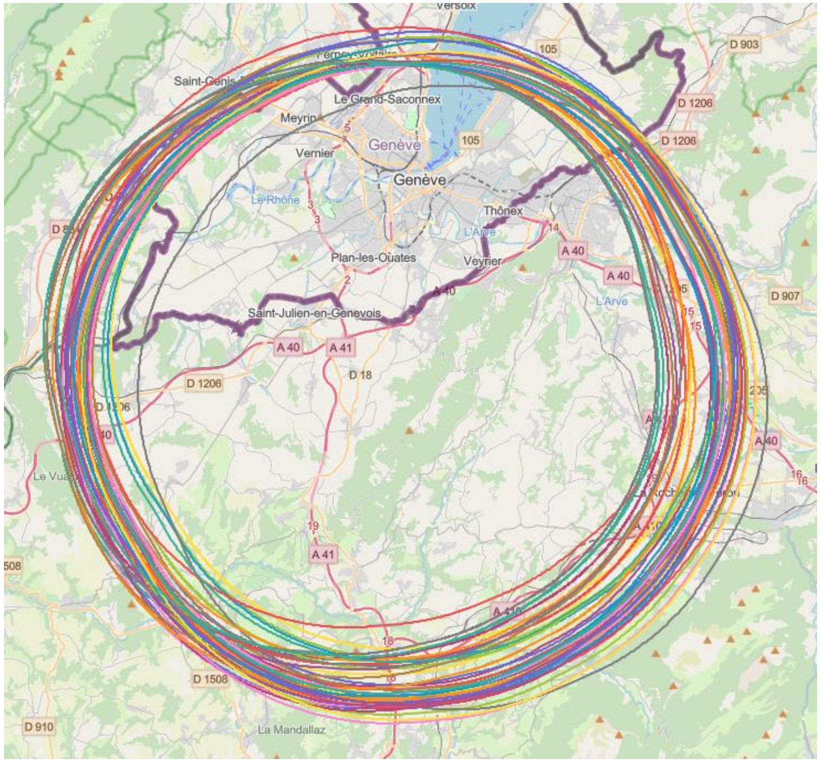
Mid-term review currently underway – report to Council at end of year.

Feasibility study – many issues under consideration

e.g. the exact ring circumference, layout, impact on local communities, and infrastructure needs.

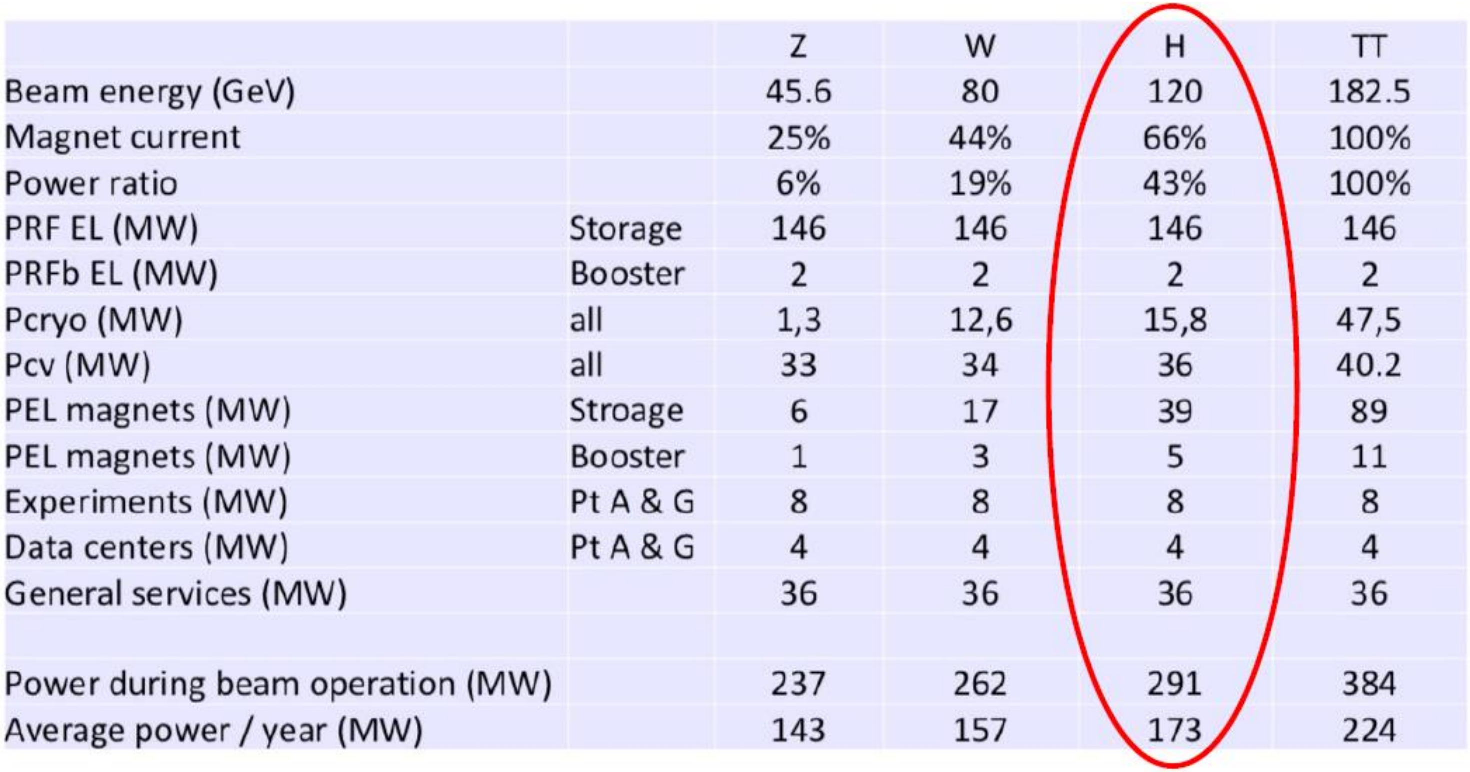
Currently stabilising on a circumference of 91 km, and indeed for a time it was *exactly* 91.2 km (a number that has resonance…).

[Michael Benedikt, ECFA Nov 2022]



Power costs

What is the power budget of FCC-ee, and how does it compare to the competition ?



		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Magnet current		25%	44%	66%	100%
Power ratio		6%	19%	43%	100%
PRF EL (MW)	Storage	146	146	146	146
PRFb EL (MW)	Booster	2	2	2	2
Pcryo (MW)	all	1,3	12,6	15,8	47,5
Pcv (MW)	all	33	34	36	40.2
PEL magnets (MW)	Stroage	6	17	39	89
PEL magnets (MW)	Booster	1	3	5	11
Experiments (MW)	Pt A & G	8	8	8	8
Data centers (MW)	Pt A & G	4	4	4	4
General services (MW)		36	36	36	36
Power during beam operation (MW)		237	262	291	384
Average power / year (MW)		143	157	173	224

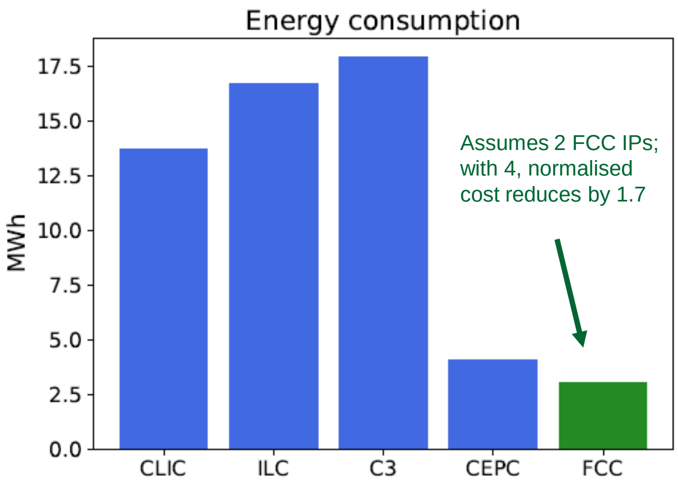
This corresponds to 1.6 TWh/year, to be compared to 1.4 TWh/year for HL-LHC.

As a comparison, P(ILC$_{240}$)=140 MW and P(CLIC$_{380}$)=110 MW. This is not full story ! Both produce 2-4 less Higgs than FCC-ee$_{240}$, with 3-6 times longer running time.

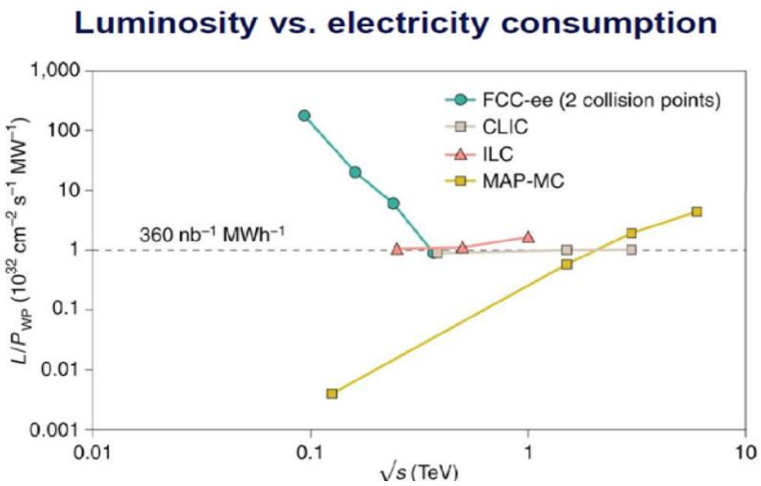
Power costs – a closer look

Normalise energy use by physics outcome, *i.e.* number of Higgs boson, or lumi.

[arXiv:2208.10466]

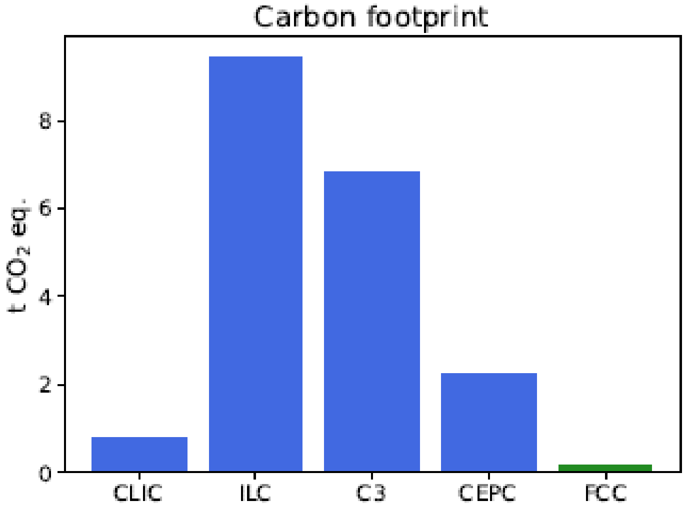


Assumes 2 FCC IPs; with 4, normalised cost reduces by 1.7



[F. Zimmerman]

Comparison in terms of carbon footprint even starker – electricity at CERN almost carbon free.



Nonetheless, important to find ways to decrease overall energy use.

Higher efficiency RF, magnet systems (*e.g.* HTS), cable losses, efficient cooling…

Conclusions

Conclusions

The FCC-ee, though originally a project conceived for Higgs studies, offers extremely exciting opportunities for probing for New Physics through precise studies of the Z, W and top.

Z & W programmes are completely unique to this machine, due to the extremely high luminosity, and the ultra-precise knowledge of the collision energy.

Dominant systematics of LEP programme can be greatly reduced, through machine design, 21st century detector technology and hard work in theory.

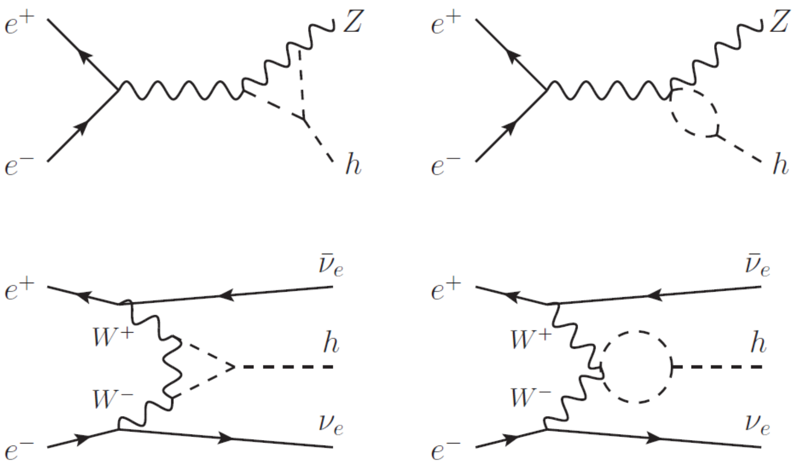
It is serendipitous indeed that a collider project exists which offers this opportunity, alongside a comprehensive programme of Higgs studies.

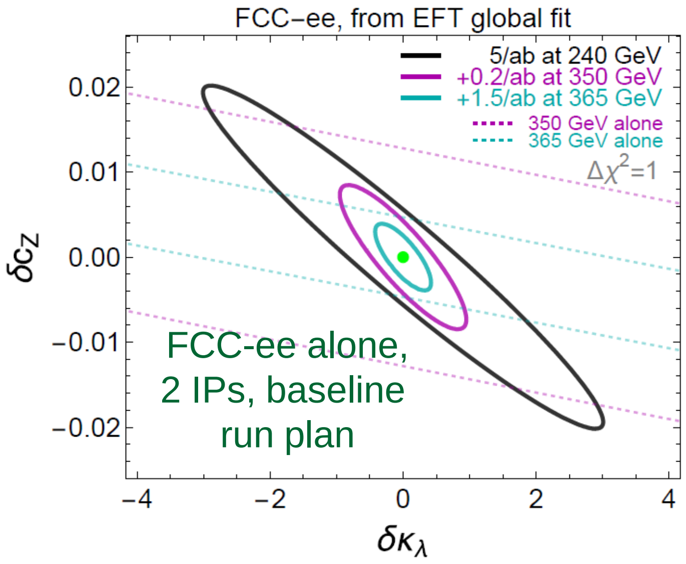
Many opportunities exist for joining the effort to shape the development of the FCC-ee project. All are welcome !

Backups

Higgs self coupling

Discovery of *trilinear Higgs coupling* essential for characterising Higgs potential. FCC-hh can measure it to better than +/-5% through double-Higgs prod^{n}. However, FCC-ee has *indirect* sensitivity through precise x-section measurements.





FCC-ee alone,
2 IPs, baseline
run plan

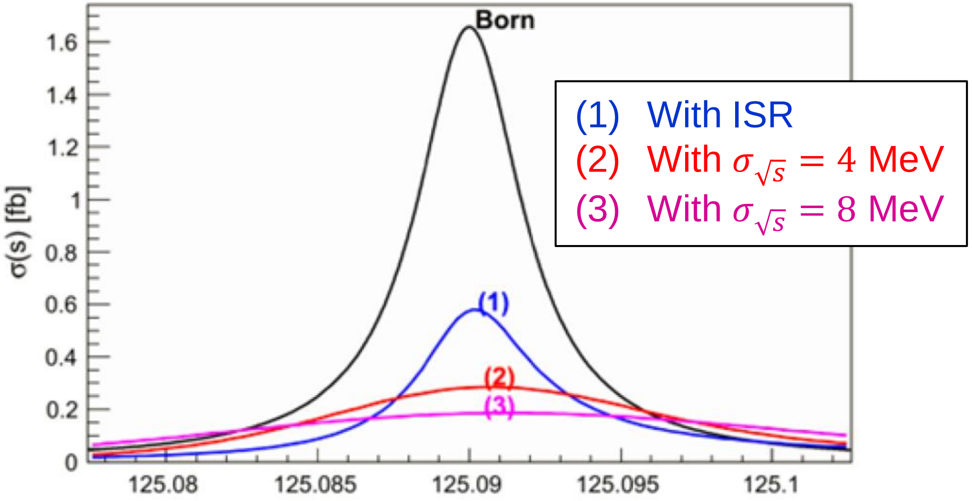
arXiv:1809.10041

Baseline running strategy & 2 IPs gives +/- 42% on κ_λ , & +/ 34% with HL-LHC.

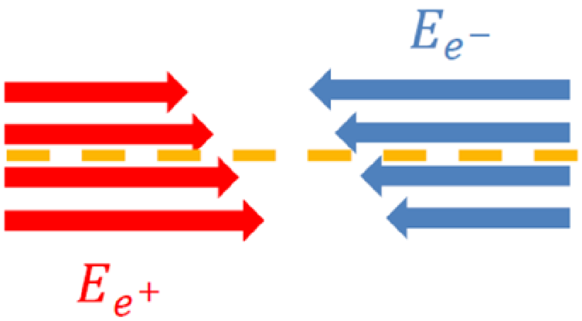
Four IPs or more running time at higher energy would increase sensitivity !

Measuring the electron Yukawa

Intriguing possibility to run at E_{CM}=125 GeV to measure The electron Yukawa through s-channel Higgs production. However the spread of the collision energy in normal operation, ~100 MeV, is large compared to the Higgs width ~4 MeV.



Opposite-sign dispersion

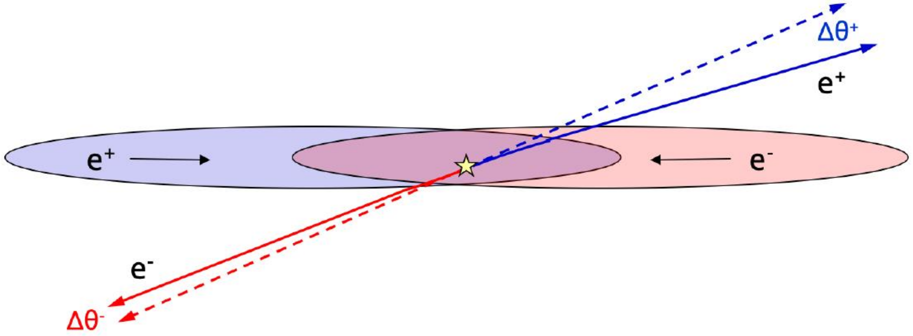


Mitigate problem by introducing opposite sign dispersion and ‘monochromatizing’ the collision energy, but this (in general) comes with a loss of luminosity. It seems that several years would be needed to reach 3σ. Optimisation studies ongoing !

Retrospective improvements

Indeed, new thinking about effects that will be important at FCC-ee, and were supposedly negligible at LEP have had some amusing consequences.

e.g. beam-beam effects modifying acceptance



Studied in Voutsinas *et al.*, PLB 800 (2020) 135078 and found to give a 0.1% bias

Also theoretical improvements in various, components of calculation, which happen all to go in one direction… reduces Bhabha cross-section by 0.048% & reduces overall uncertainty to 0.037% [Janot & Jadach, PLB 803 (2020) 135319].

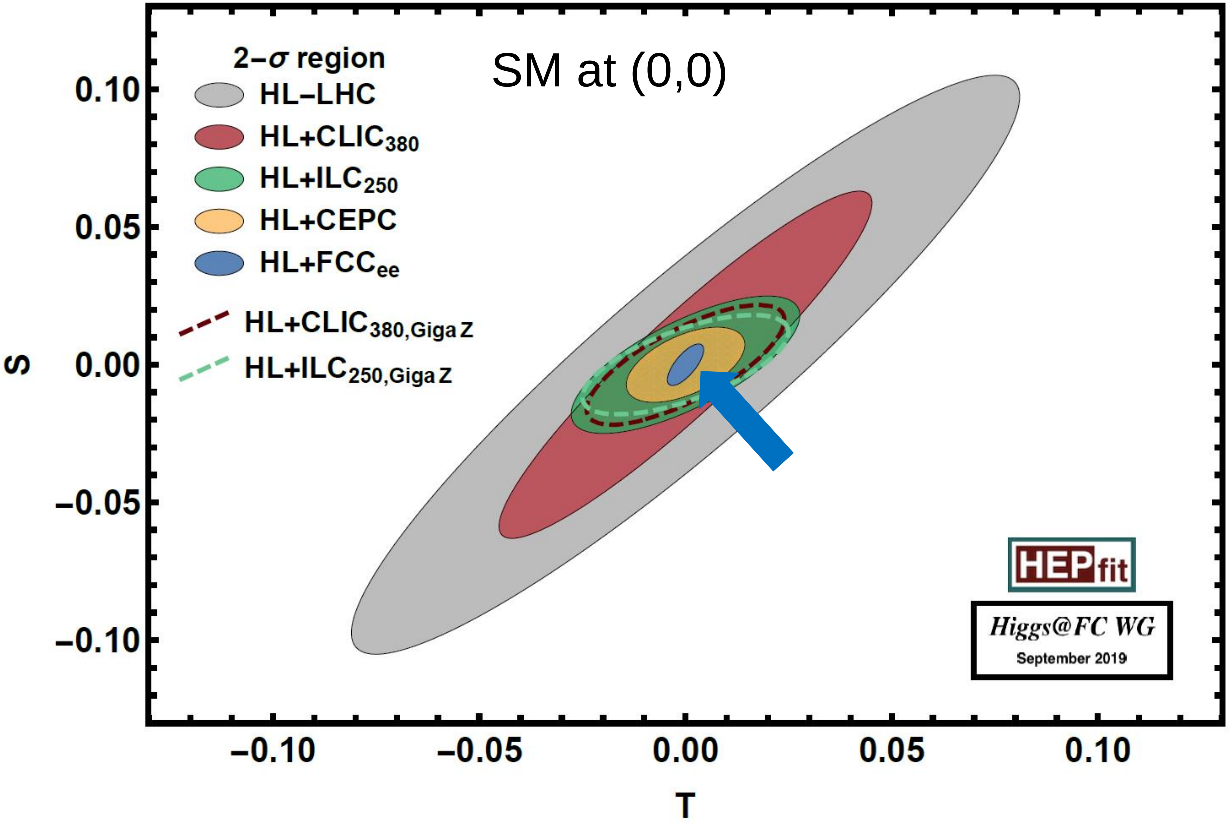
One claimed consequence:

$$N_\nu = 2.9840 \pm 0.0082 \Rightarrow N_\nu = 2.9963 \pm 0.0074$$

"The 20-years-old 2σ tension… is gone" !

Impact of precision EW observables

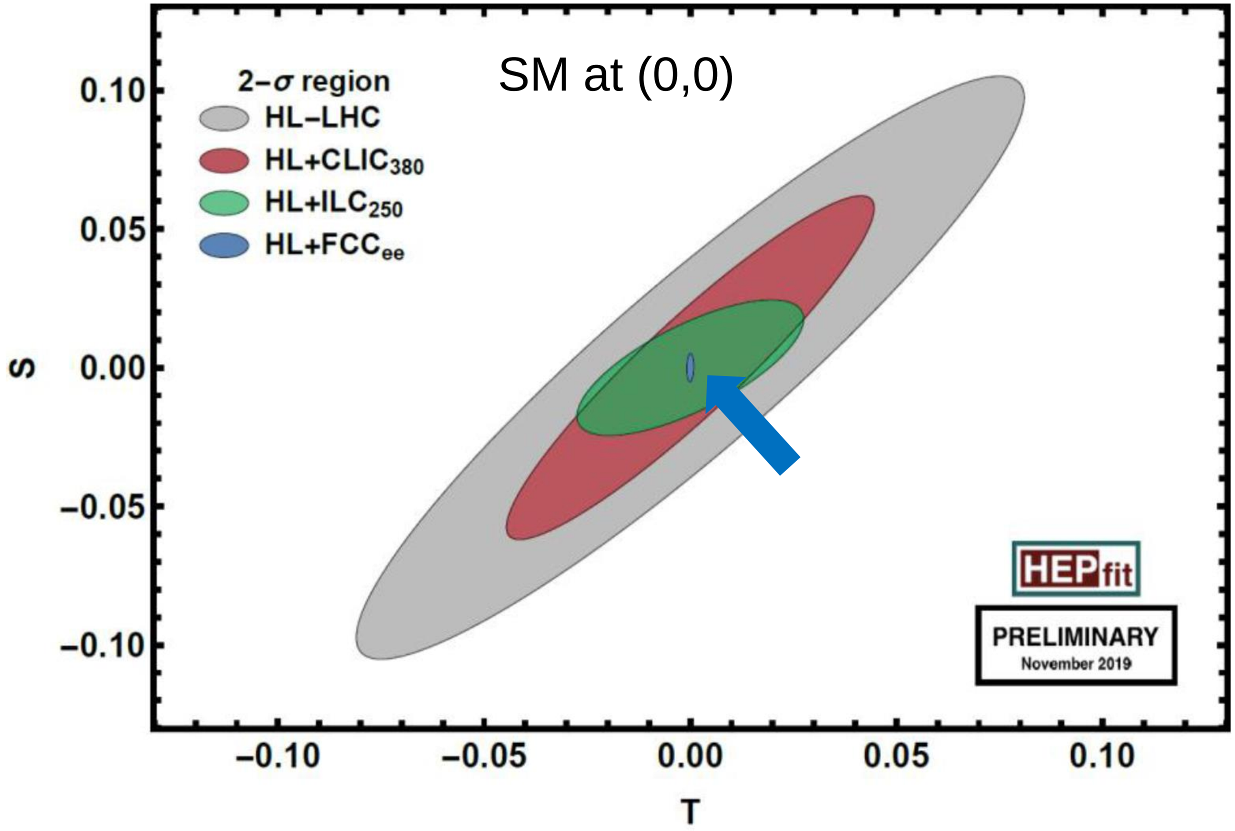
Sensitivity of EW observables to non-SM contributions can be expressed in so-called ‘oblique parameters’ S & T [*e.g.* Peskin & Takeuchi, PRD 46 (1992) 381].



With current estimates of experimental & theoretical uncertainties.

Impact of precision EW observables

Sensitivity of EW observables to non-SM contributions can be expressed in so-called ‘oblique parameters’ S & T [*e.g.* Peskin & Takeuchi, PRD 46 (1992) 381].



SM at (0,0)

Including only uncertainties of a statistical nature, and also including ‘parametric errors’ on m_t, $\alpha_{QED}(M_Z^2)$ *etc.*