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

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University of Oxford
Birmingham HEP seminar
24/2/21

Seminar outline

- Prelude & boundary conditions of talk
- FCC-ee: a multi-purpose machine
- Déjà vu all again – haven't we been here before ?
- Precision EW physics at the FCC-ee
- FCC-ee as a flavour factory
- FCC-ee next step and UK activities
- Conclusions

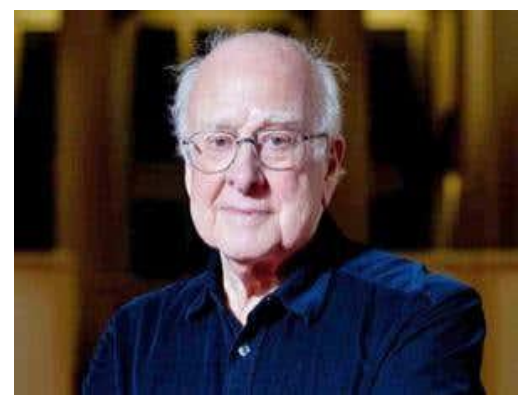
We shall not be talking about

Politics

FCC vs ILC/CLIC
(well, just a bit)

Money and timescale

Higgs prospects



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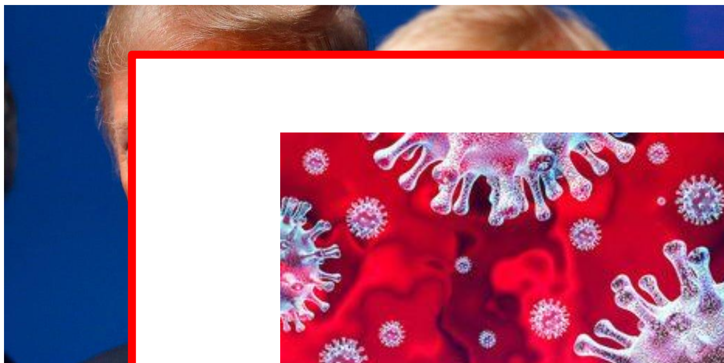

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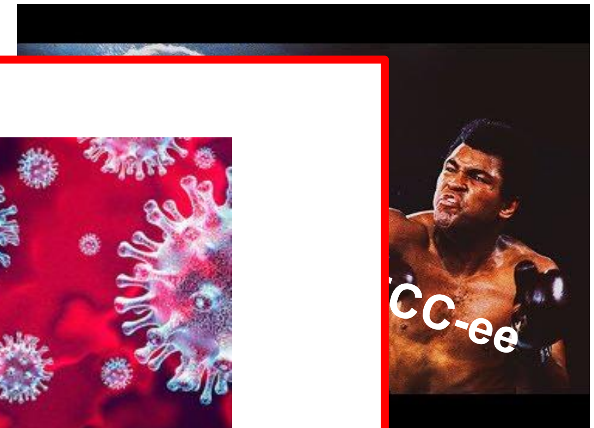

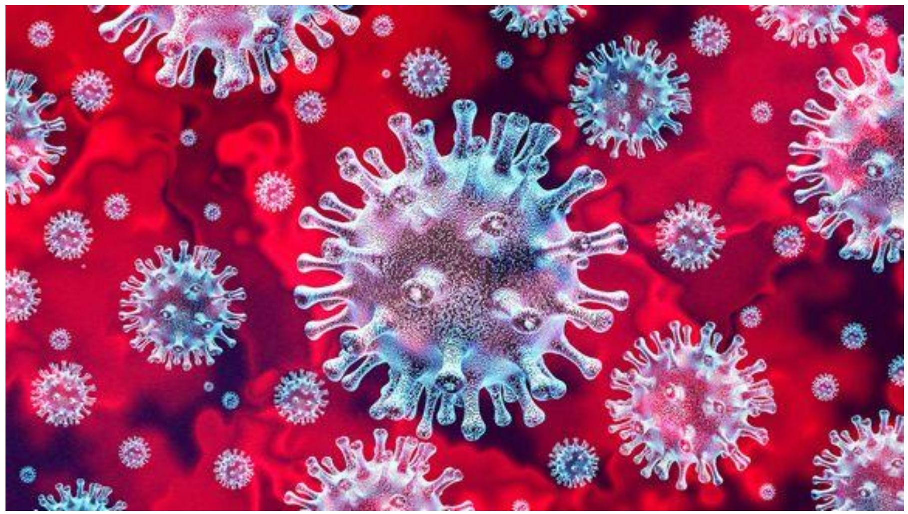

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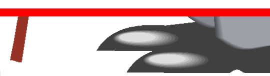

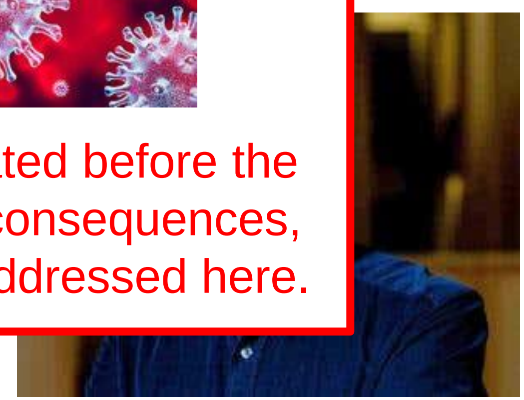

And many of arguments were formulated before the world changed. This may also have consequences, for future of HEP but these wont be addressed here.

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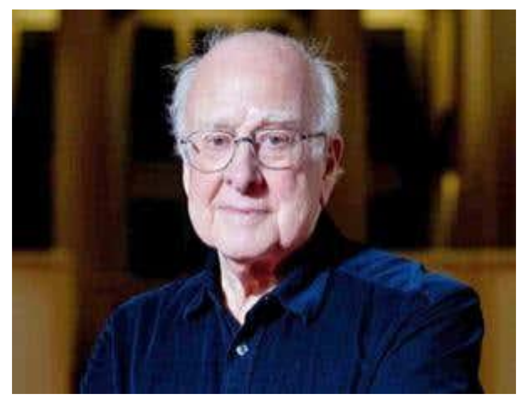


Instead will focus on physics case for precise EW measurements, particularly at Z^0.

What is a ‘precision measurement’* ?

Depends on who is talking – one hears the term in different contexts.

10^{-1}	Higgs B.R.s
10^{-2}	Production x-secs at LHC; many b-physics standard candles
10^{-3}	Higgs mass
10^{-4}	W mass; Z width
10^{-5}	Z mass ← current high-energy brand leader… but we can do still better (on this, and associated observables)
10^{-7}	$(g-2)_\mu$

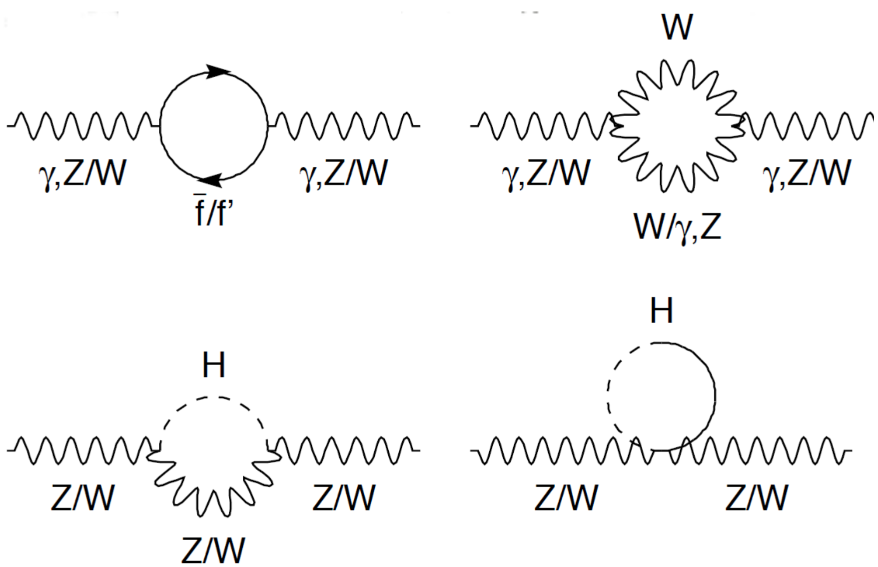
(List restricted to observed particles and phenomena.)

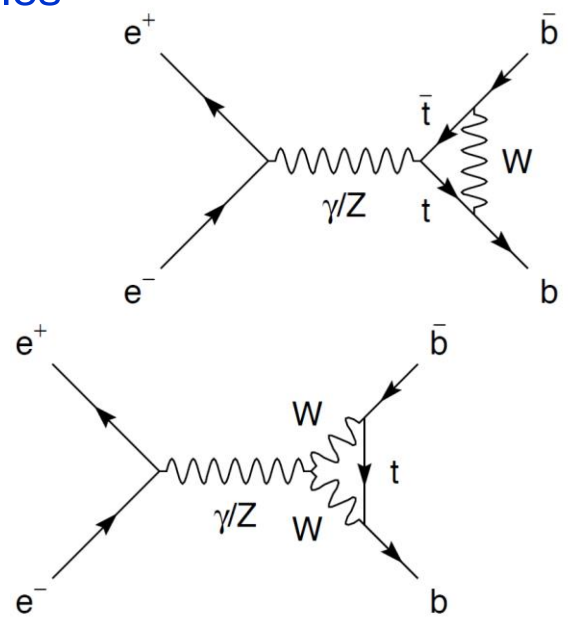
* NB ‘precision’ is not an adjective…

Why do we need precise measurements ?

Precise measurements of observables that are sensitive to loop corrections are a powerful way to probe mass scales that may lie beyond direct searches, and hence look for indications of physics lying beyond the Standard Model.

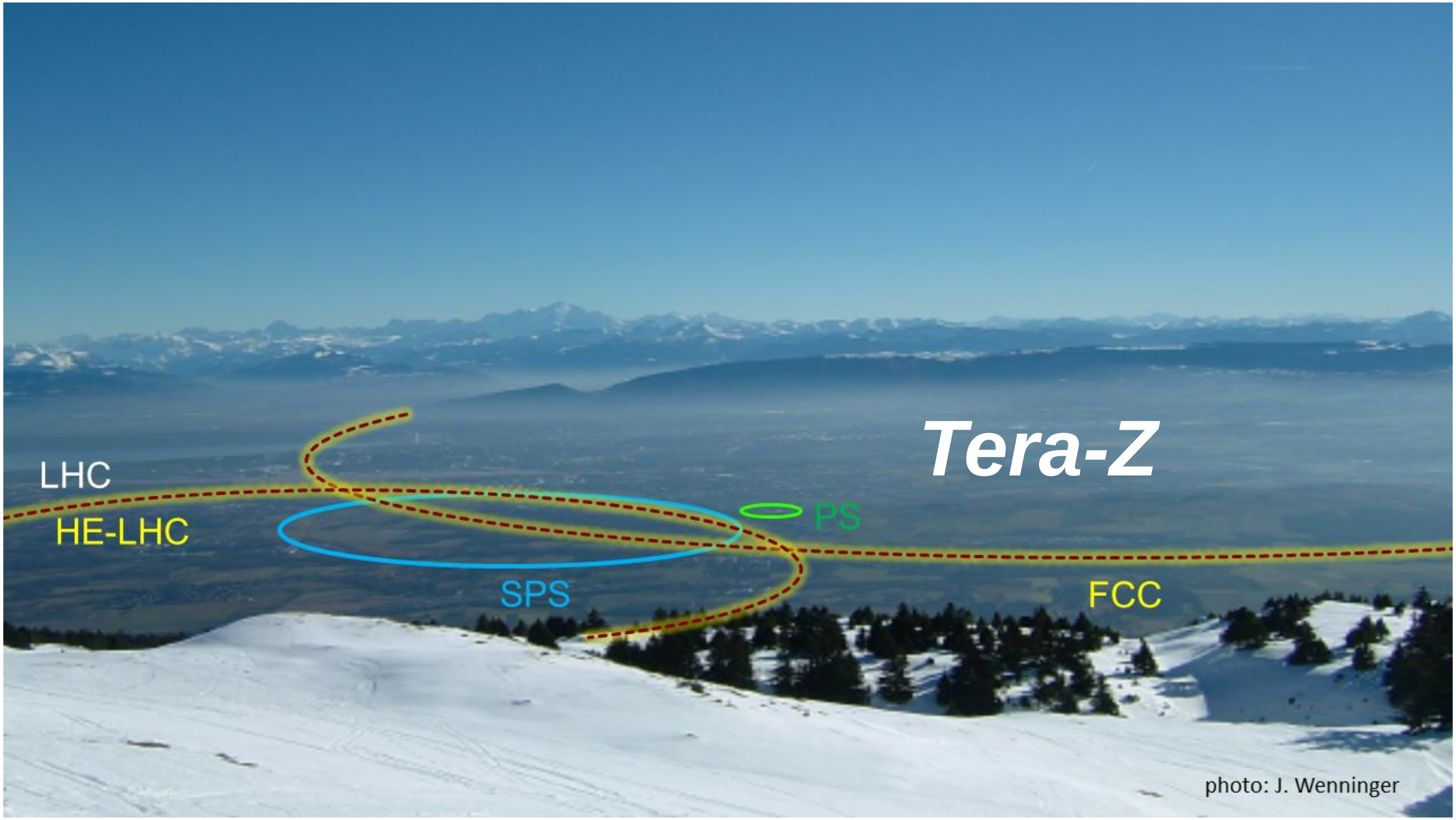
e.g. EW Z & W processes sensitive to massive particles
(here drawn with the SM contributions)





Can pursue this programme in several domains (*e.g.* Higgs, flavour…). Recently an exciting opportunity has arisen to do this very, very well indeed in Z & W physics.

Current & future CERN colliders

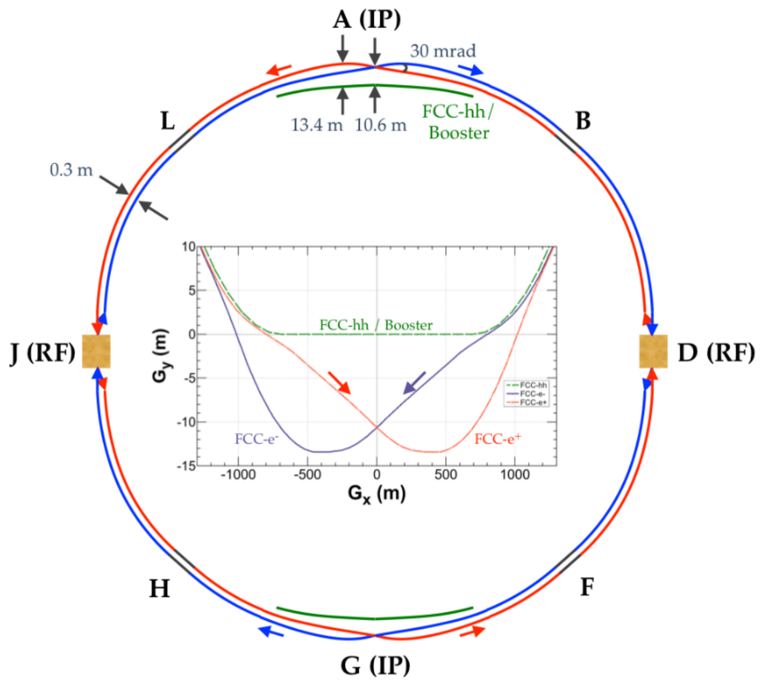


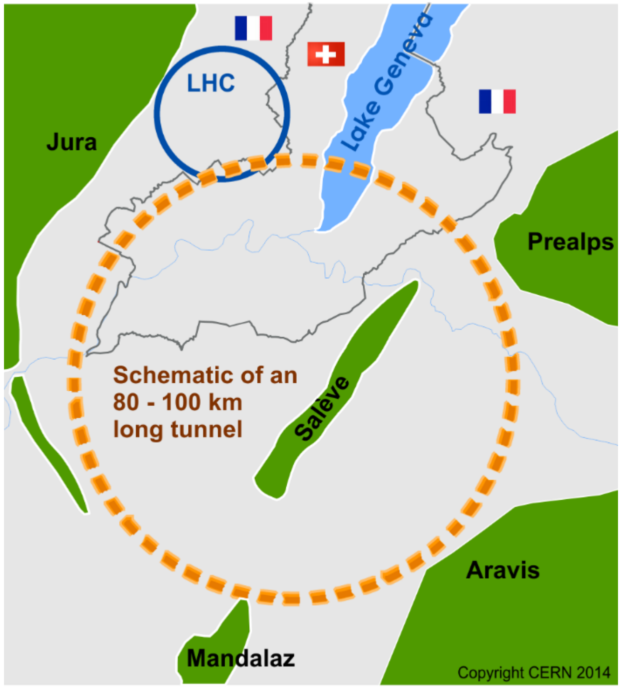
FCC-ee:
a multi-purpose machine

See FCC CDR Vol. 2: A. Abada *et al*., EPJ ST 228 (2019) 261

FCC-ee: a circular Higgs factory

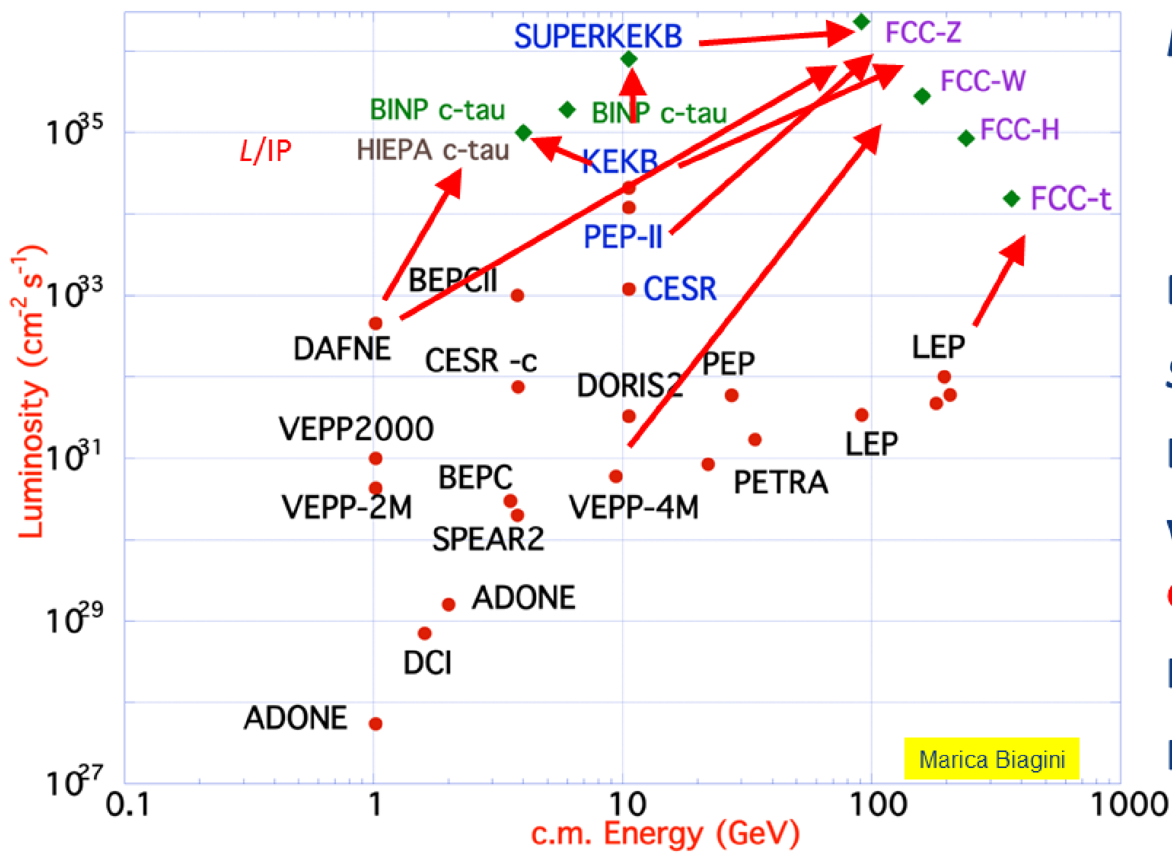
Genesis of FCC-ee: in December 2011, while boarding at LHR, Frank Zimmermann received a phone call from Alain Blondel concerning a possible 120 x 120 GeV e^+e^- Higgs factory in the LEP/LHC tunnel. In time, the concept evolved to a 100 km machine in a new tunnel that could also eventually house a 100 TeV pp collider.





Design luminosity at this energy a few 10^{34} $cm^{-2}s^{-1}$, *ie.* x100 LEP2. Only possible if employ double ring, top-up injection, lower emittance & lower β* than LEP.

Standing on the shoulders of giants



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

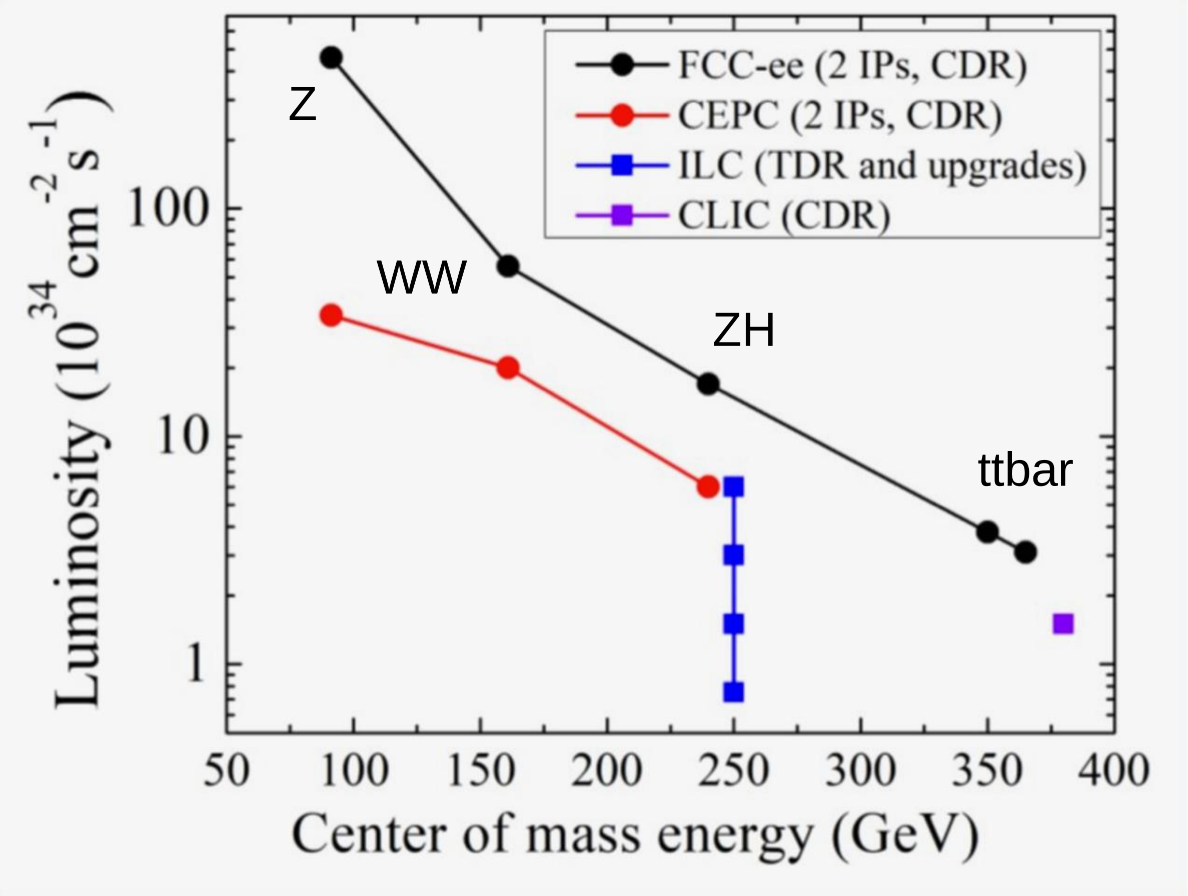
KEKB: *e^+* source

HERA, LEP, RHIC: spin gymnastics

Combining successful ingredients of recent colliders → highest lumis & energies.

FCC-ee: not just a Higgs factory

FCC-ee has great capabilities in Higgs physics, but these do not concern us today.
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).



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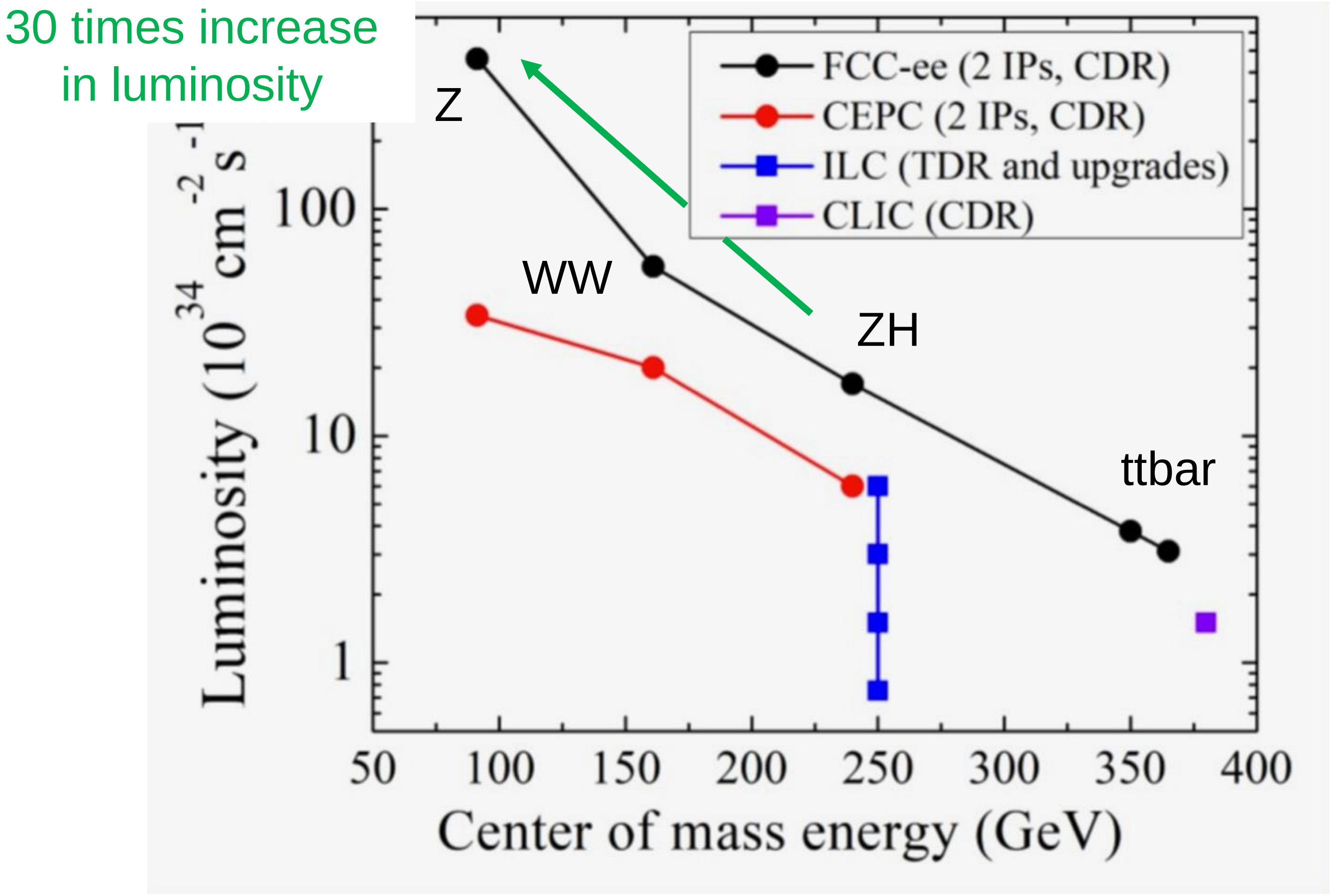

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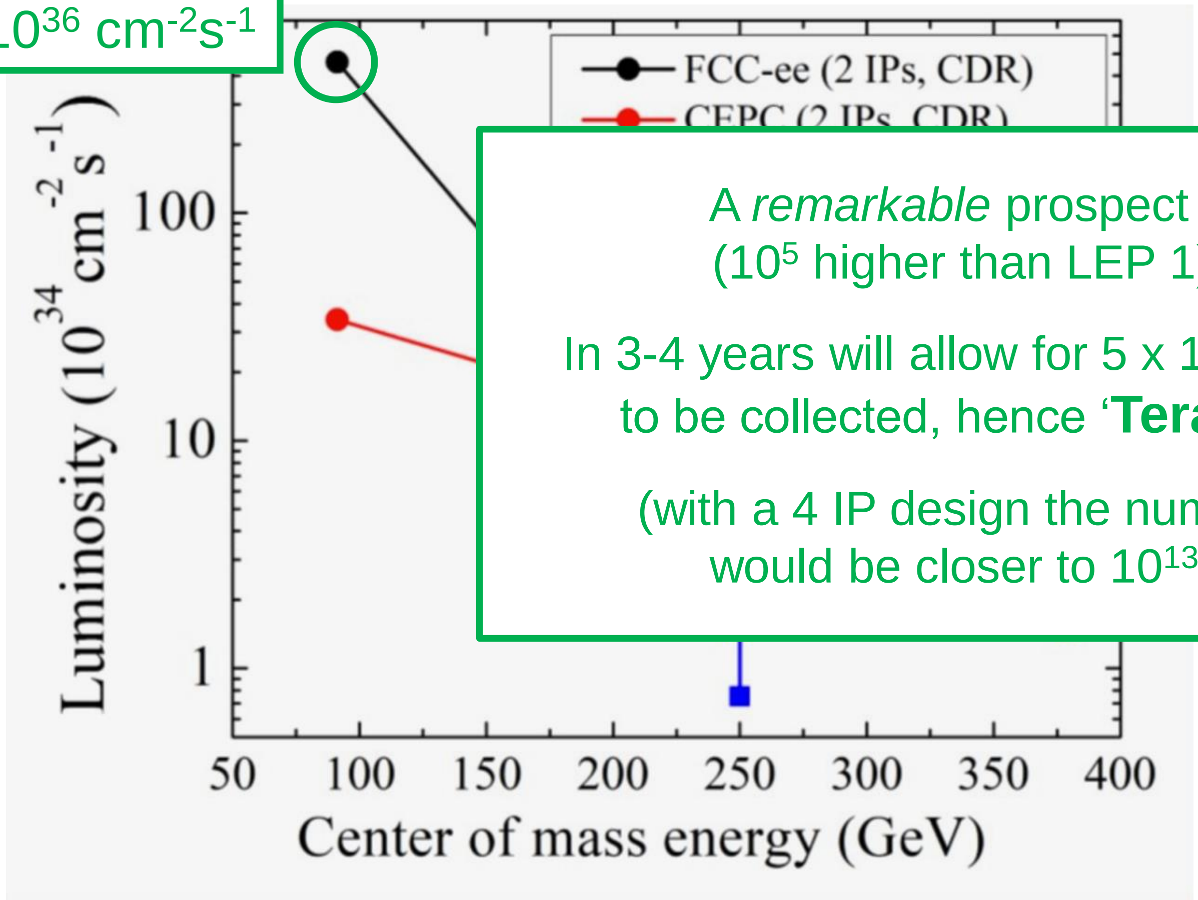
4.6×10^{36} $cm^{-2}s^{-1}$



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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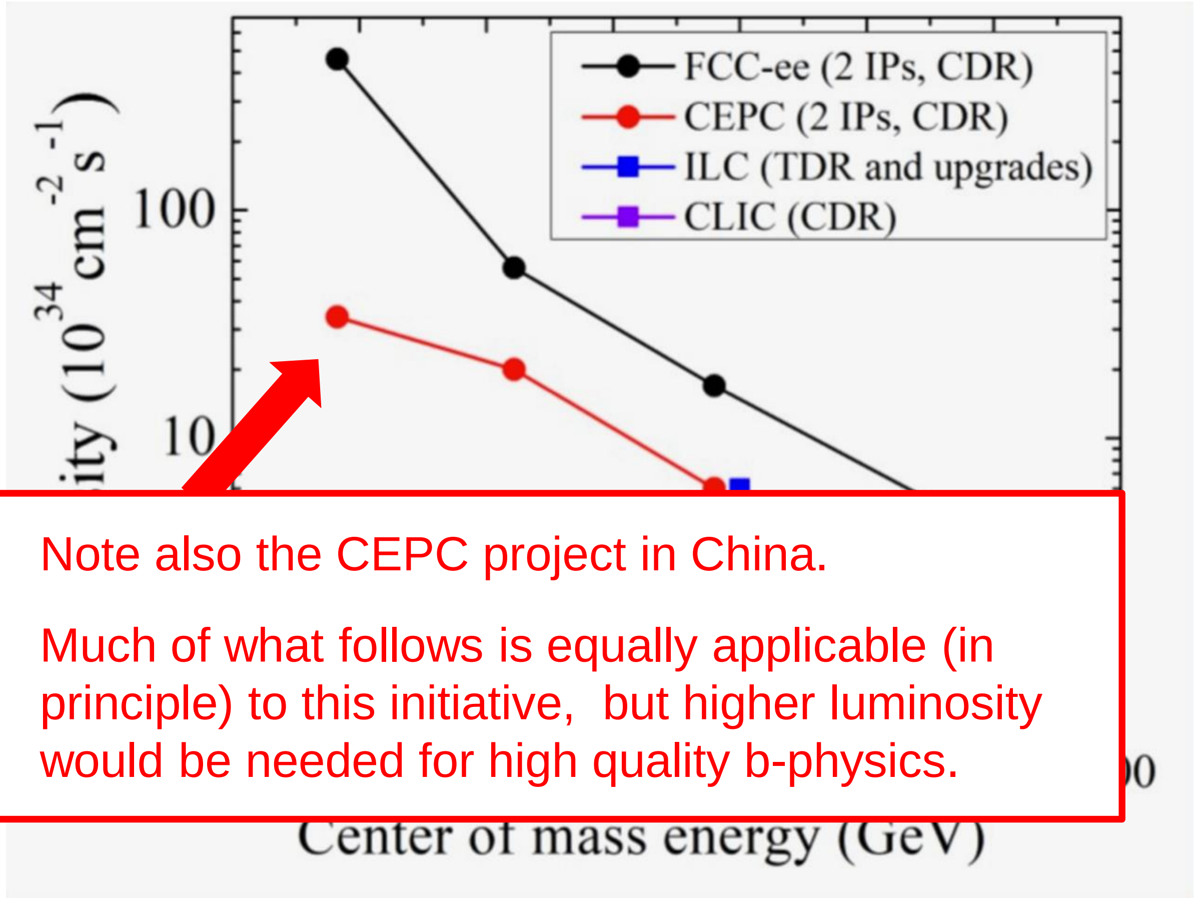
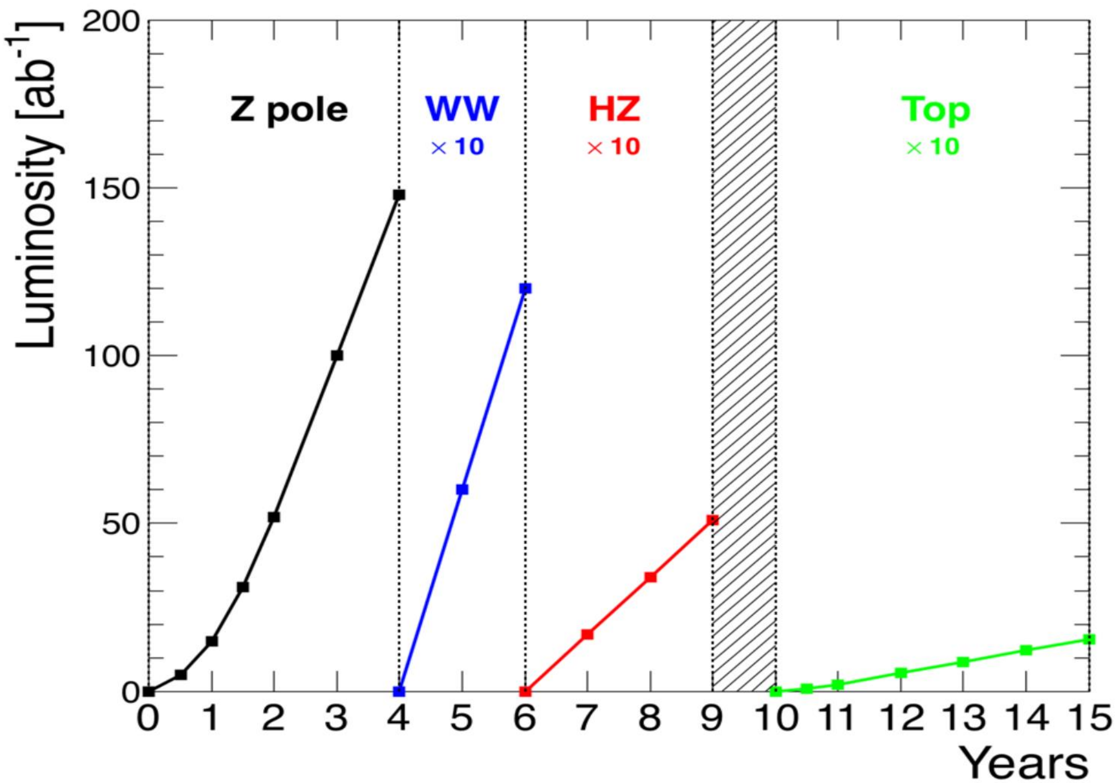


Note also the CEPC project in China.

Much of what follows is equally applicable (in principle) to this initiative, but higher luminosity would be needed for high quality b-physics.

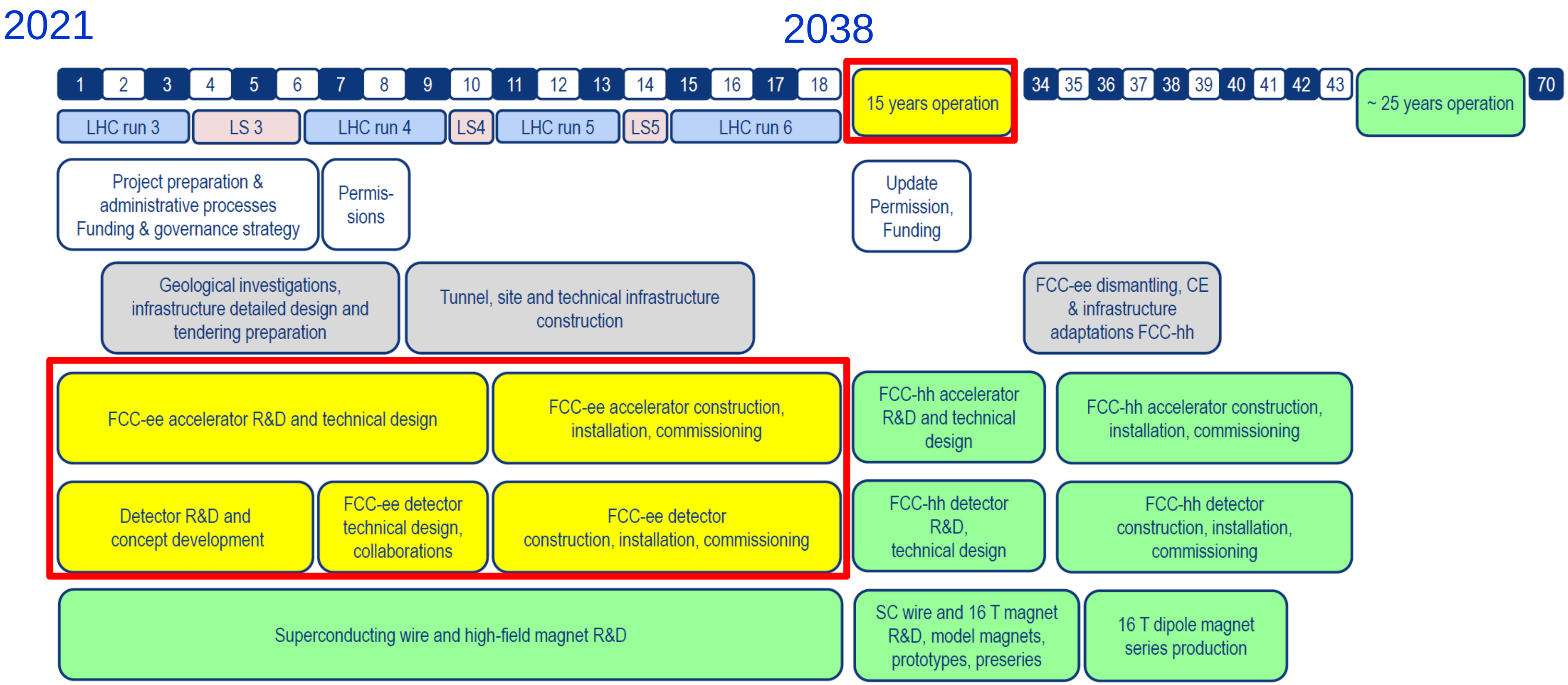
FCC-ee: running schedule

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



Awkward questions (not for today)

When would it start ? Not before late 2030s (CEPC has more aggressive schedule).



How much would it cost ? ~8 GCHF for tunnel (to be re-used by FCC-hh)

~4 GCHF for FCC-ee collider and injector

(~17 GCHF for FCC-hh collider and injector – ouch !)

Déjà vu all over again

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

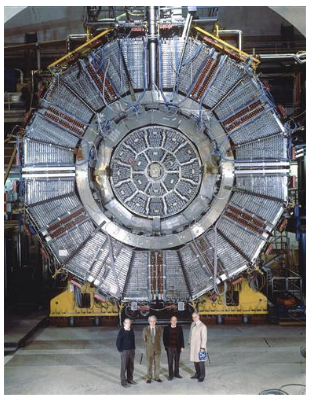
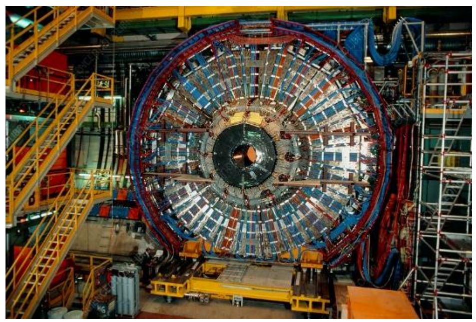
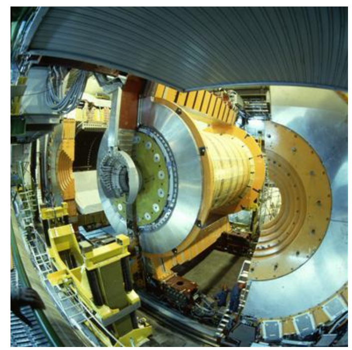
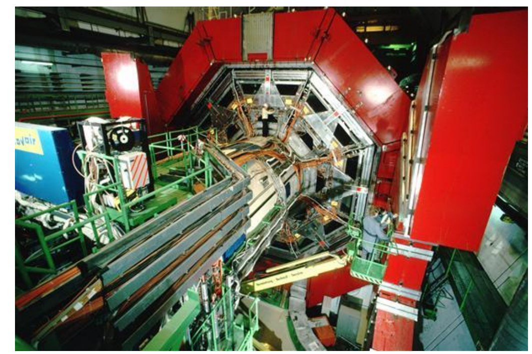
The LEP legacy

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	DELPHI	OPAL	L3
(319 pubs.)	(347 pubs.)	(423 pubs.)	(317 pubs.)

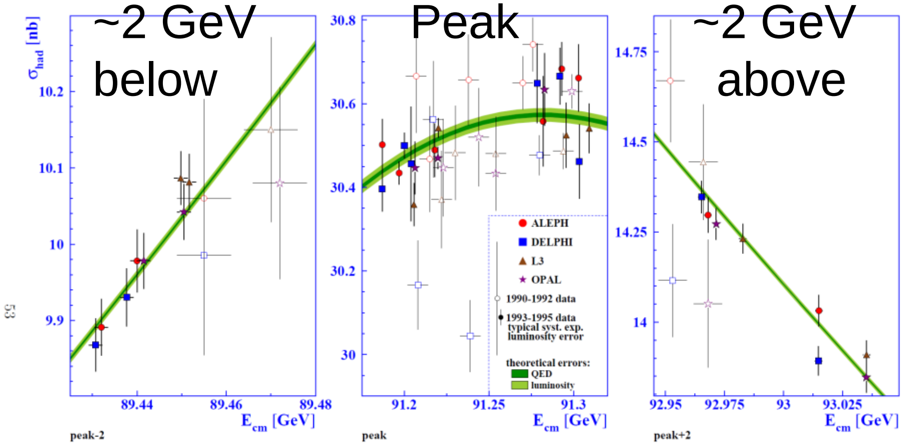
LEP accumulated ~17 million Z^0s and ~40k Ws.
During similar period SLD experiment at SLAC collected ~1 million Z^0s.
Many papers in searches, QCD, b and tau physics, and electroweak (W and Z).

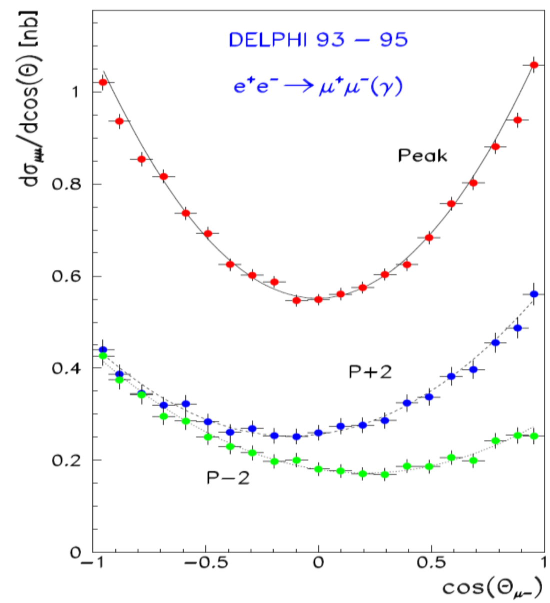
Let's review Z observables, & what we learned from the LEP/SLD measurements.

Key Z^0 observables

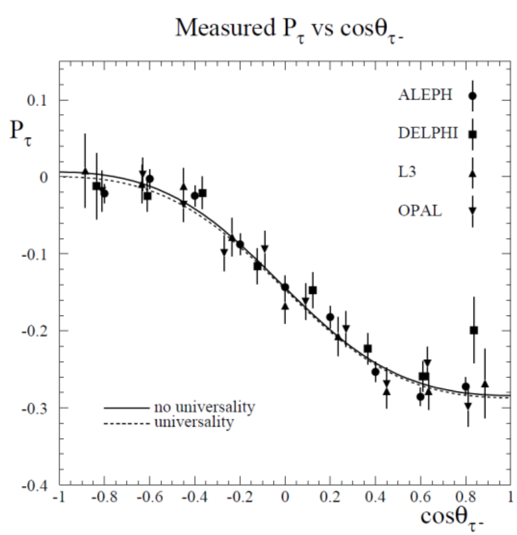
Forward-backward asymmetries (& at SLD L-R asymmetries)

Lepton and inclusive hadron cross-sections



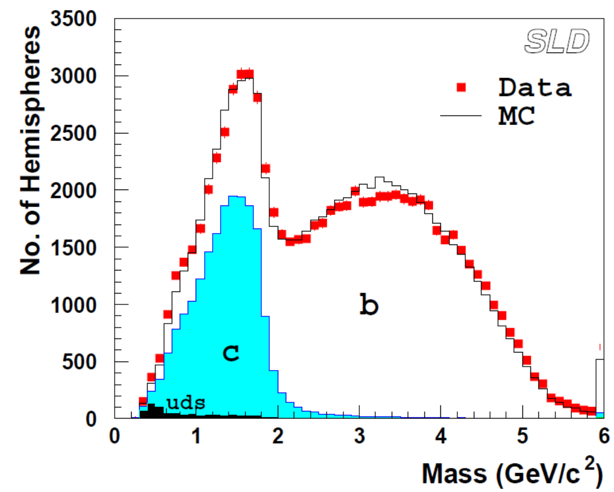


Tau polarisation measurements



Partial width ratios involving heavy flavours

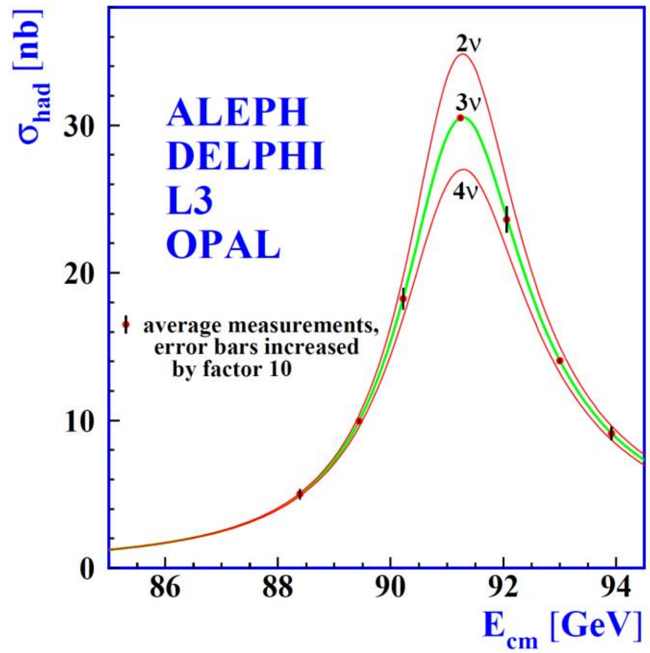
e.g. $R_b = \Gamma_{bbbar}/\Gamma_{had}$



Making use of the observables

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

$$N_\nu = 2.9840 \pm 0.0082$$



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

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

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

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

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

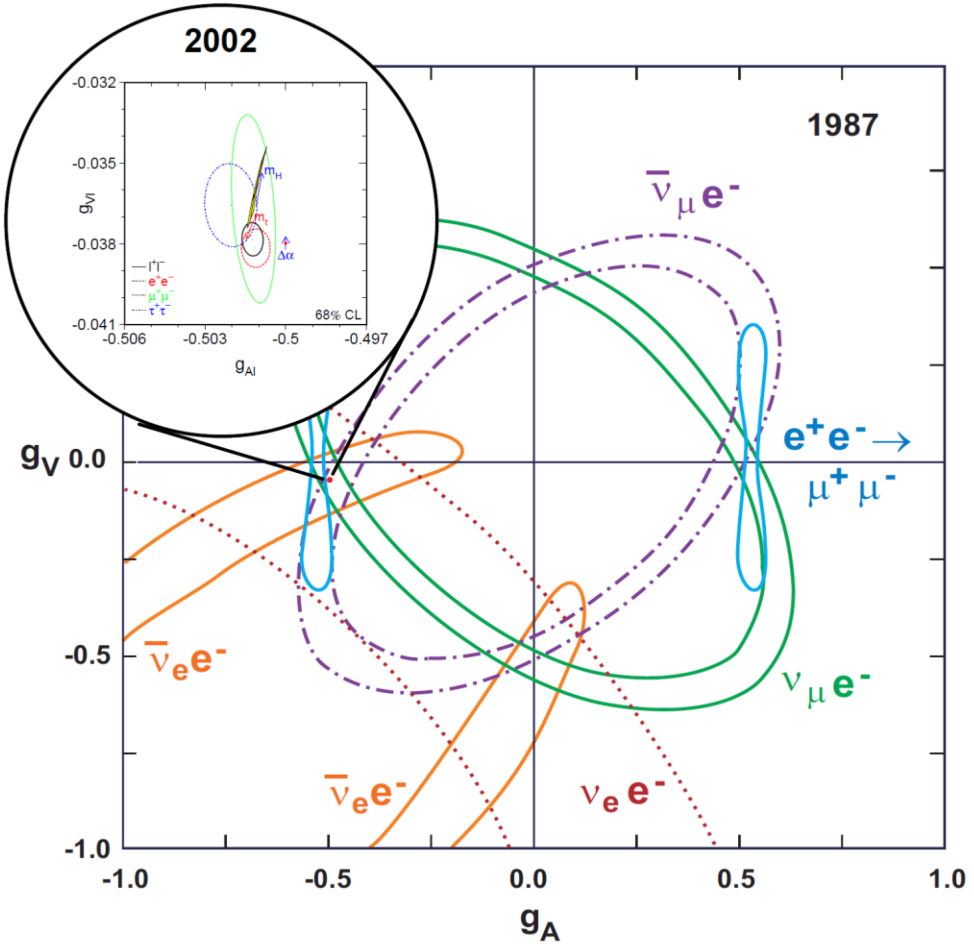
(ρ_l = 1 in limit EW corrections vanish)

- 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



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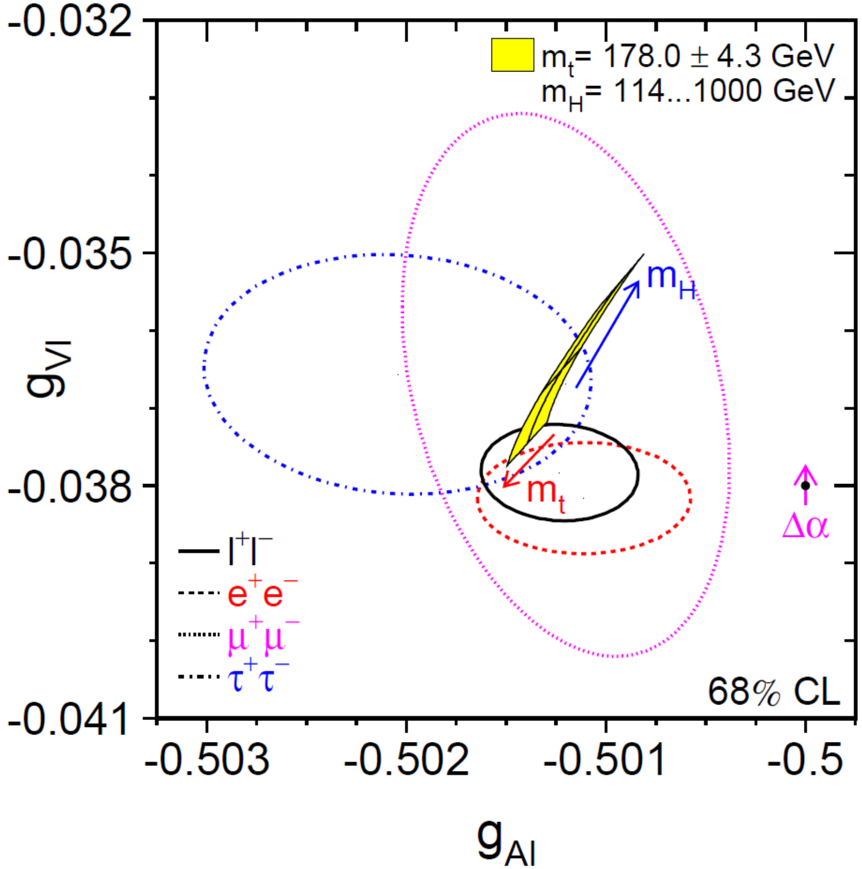
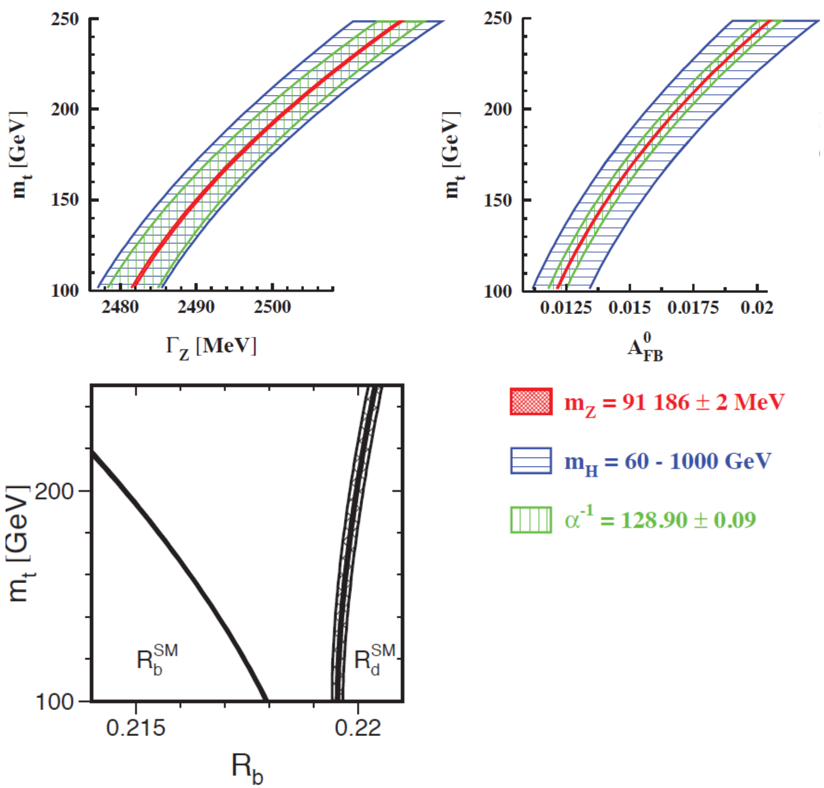
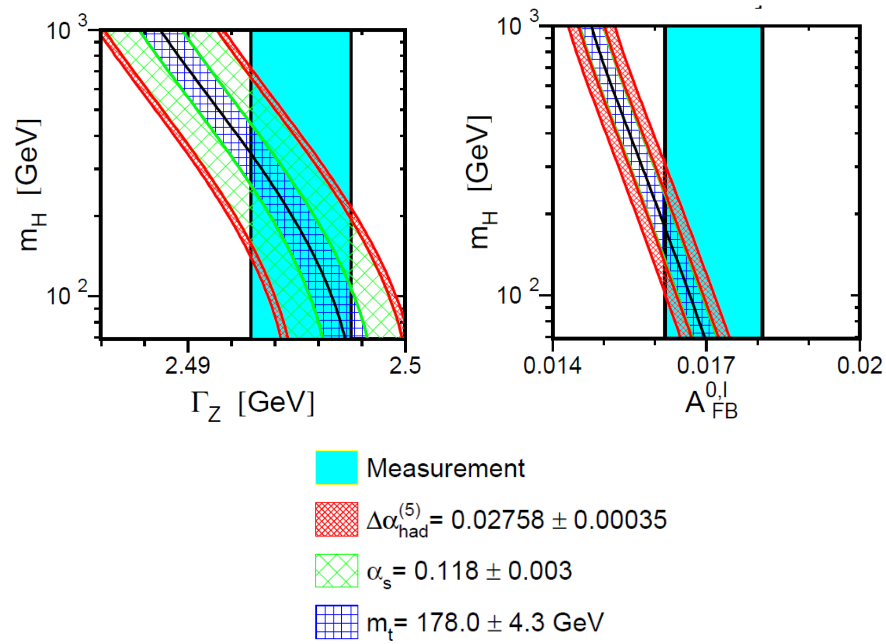


Also high sensitivity to the EW loops giving access to unknown parameters….

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.





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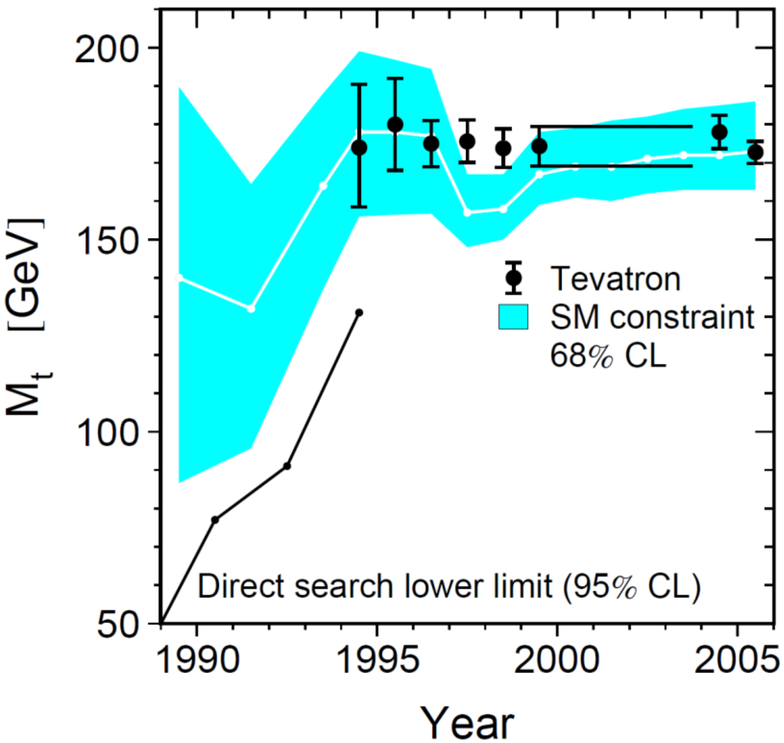
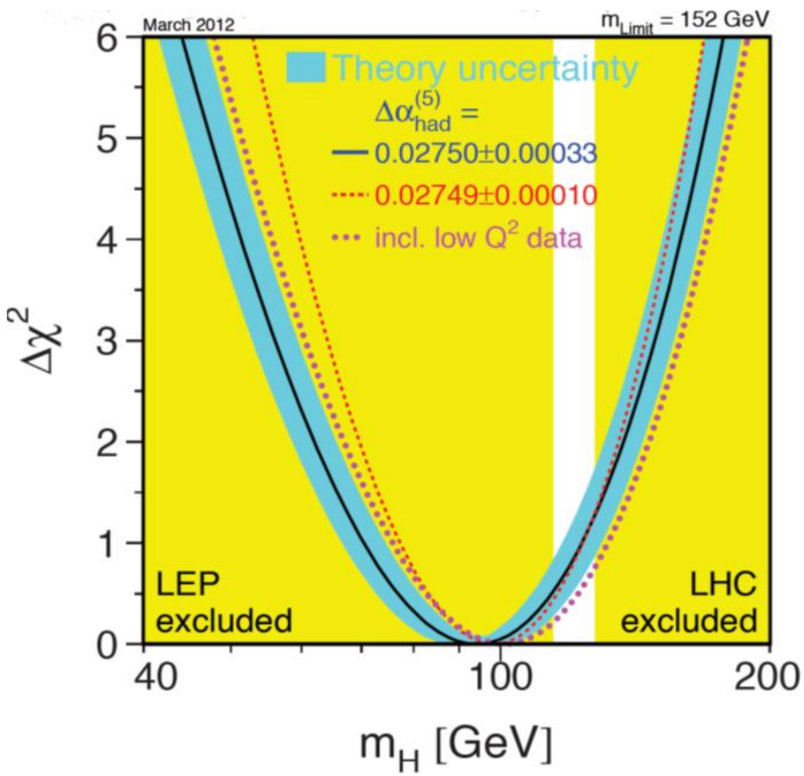


LEP & SLD Z data 'measured' top mass well before discovery.

(including LEP2 inputs)



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 $(g\text{-}2)_\mu$ by factor of 4;
- Future LHCb upgrades will measure CKM parameters better by x10.

However, Tera-Z@FCC-ee can improve EW-observable precision by x20-100+. Nowhere else in HEP does there exist the opportunity for such a giant leap forward !

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

Most of following material can be found in FCC CDR Vol. 1: Abada *et al*., EPJC 79 (2019) 474

Challenges of Z-metrology

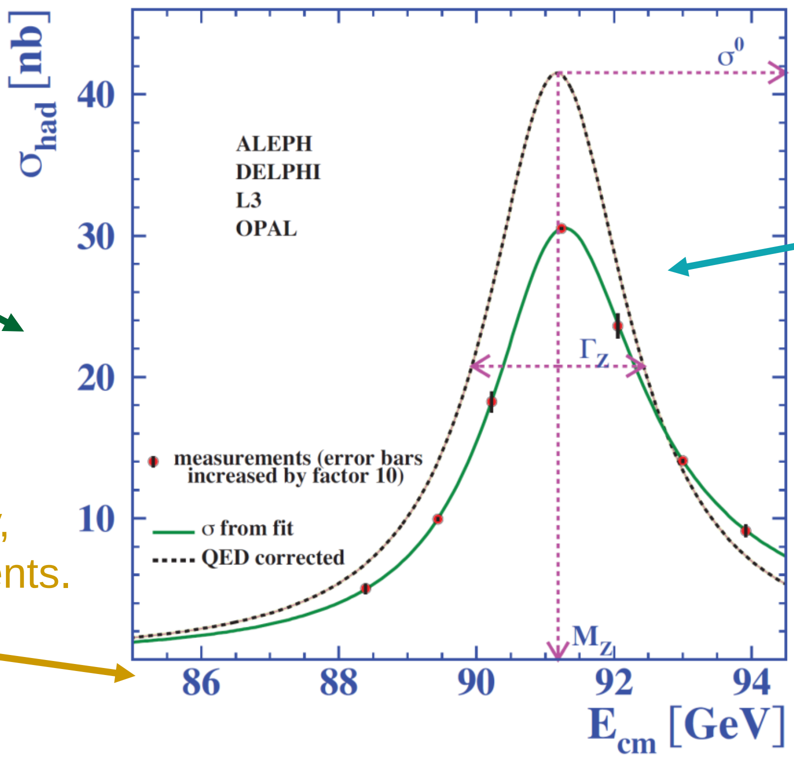
Outlook shortly before LEP turn on: *"The overall conclusion is that at LEP the Z^0 mass and width can be measured with relative ease down to … +/- 50 MeV. A factor of 2-3 improvement can be reached with a determined effort…"* CERN 86-02 'Physics at LEP', ed. Ellis and Peccei.

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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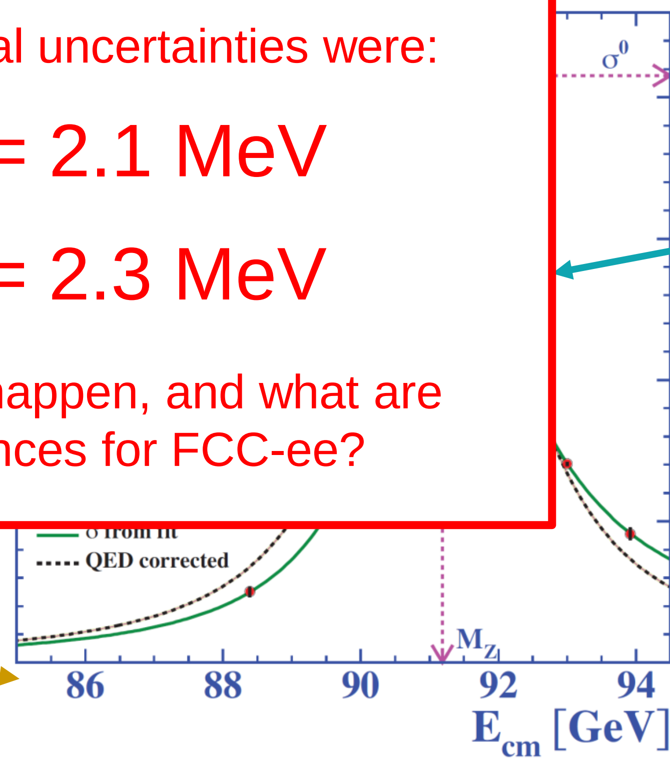
In fact, the final uncertainties were:

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

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

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



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Luminosity measurement

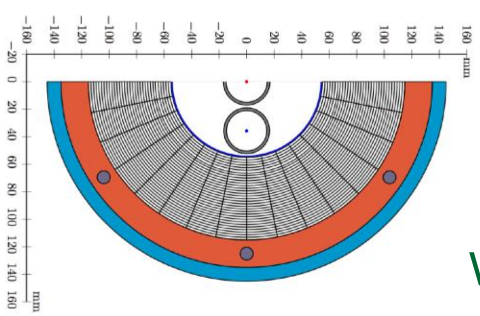
Lumi measured in QED-dominated low-angle $e^+e^- \rightarrow e^+e^-$ (will remain true at FCC-ee).

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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[a]*Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland*
[b]*Marian Smoluchowski Institute of Physics, Jagiellonian University, ul. Łojasiewicza 11, 30-348 Kraków, Poland*
[c]*Baylor University, Waco, TX, USA*
[d]*Max Planck Institute für Physik, München, Germany*
[e]*The Citadel, Charleston, SC, USA*

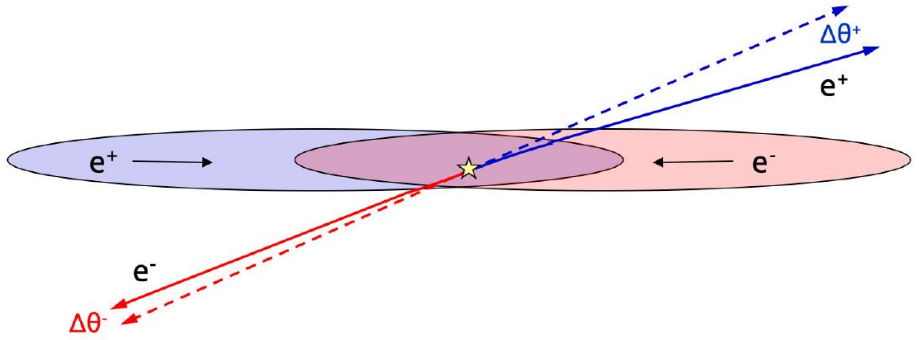
[PLB 790 (2019) 314]

Work already underway !

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, arXiv:1912.02067].

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" !

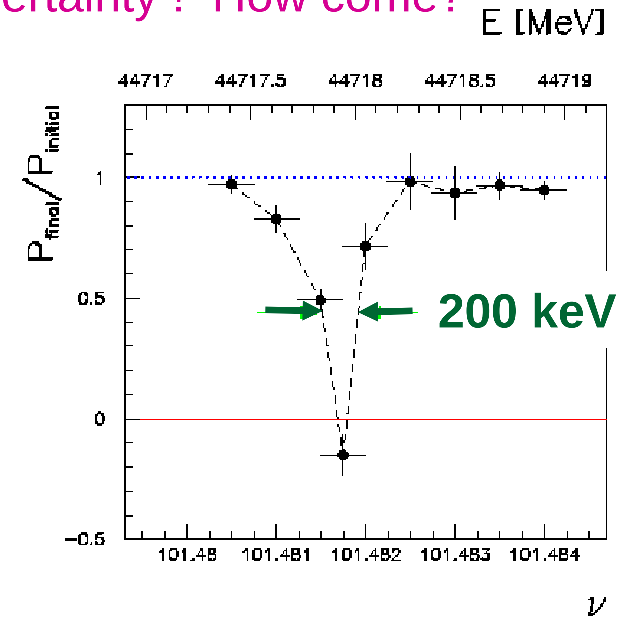
Collision-energy calibration

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 :

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

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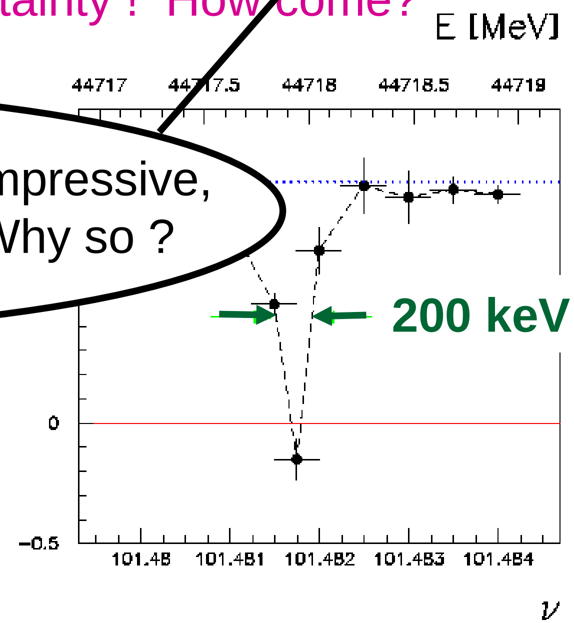
Hang on, these uncertainties, though impressive, are >> intrinsic uncertainty of RDP. Why so ?

High level of p…
miracle…
which is …



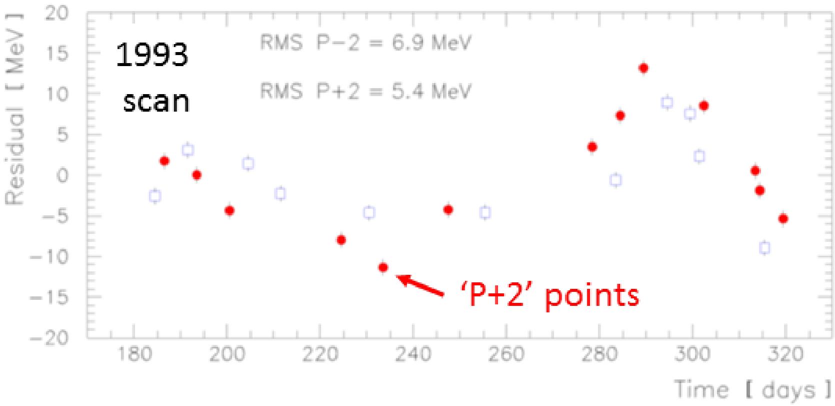
- Wait for transverse polarisation to build up;
- Precession frequency, ν_s, directly proportional to E_b :

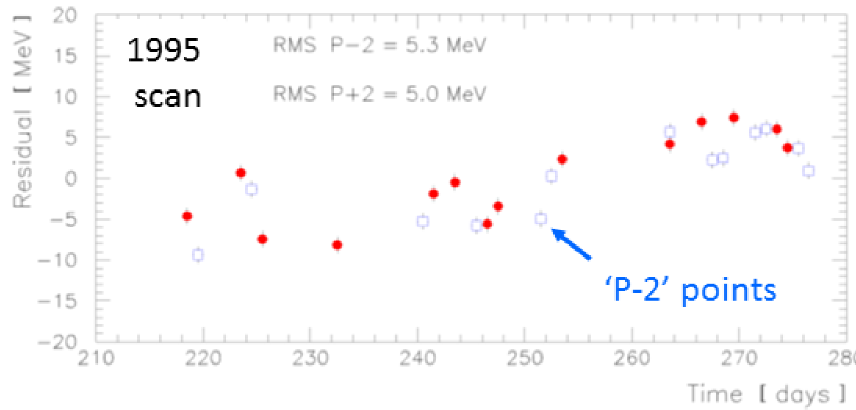
$$E_b = 2\,\nu_s\, m_e\, c^2 / (g_e - 2)$$

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

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.



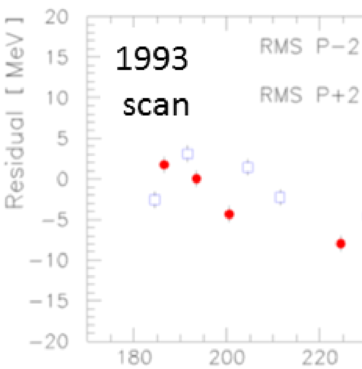


To calibrate the physics data-taking period, necessary to understand and model this evolution – a long and painful process that took many years. Ingredients:

- 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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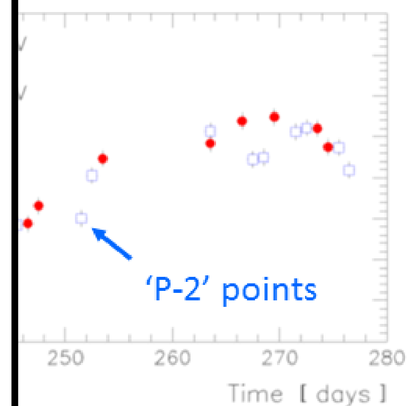
Abstract. The determination of the centre-of-mass energies from the LEP1 data for 1993, 1994 and 1995 is presented. Accurate knowledge of these energies is crucial in the measurement of the Z resonance parameters. The improved understanding of the LEP energy behaviour accumulated during the 1995 energy 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]

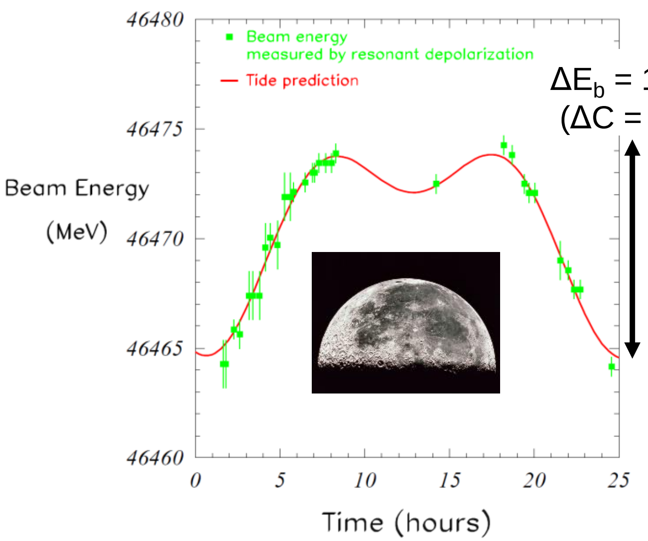


To calibrate the … stand and model this evolution – … s. Ingredients:

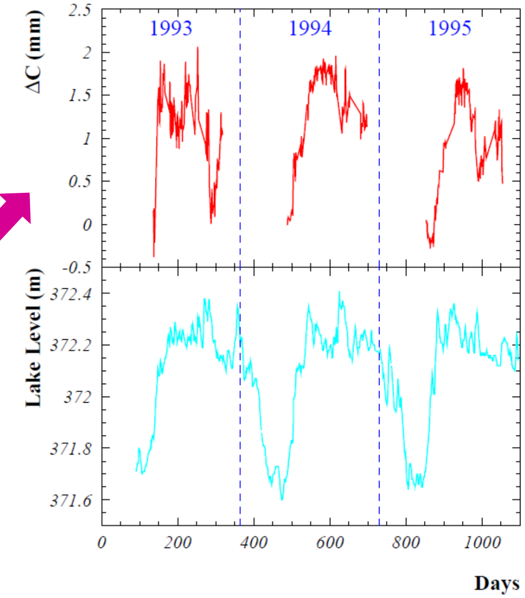
- Bright idea …
- Dedicated … tc.;
- Lots of ma … 93-2009);
- Mechanism … ysics data periods.

Some mechanisms of E_b variation

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

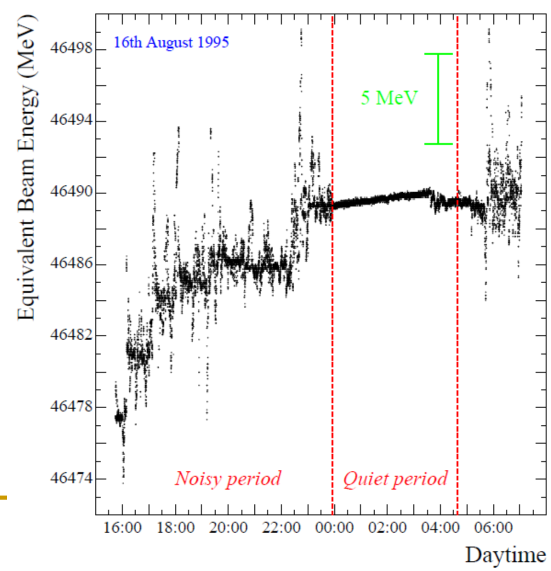


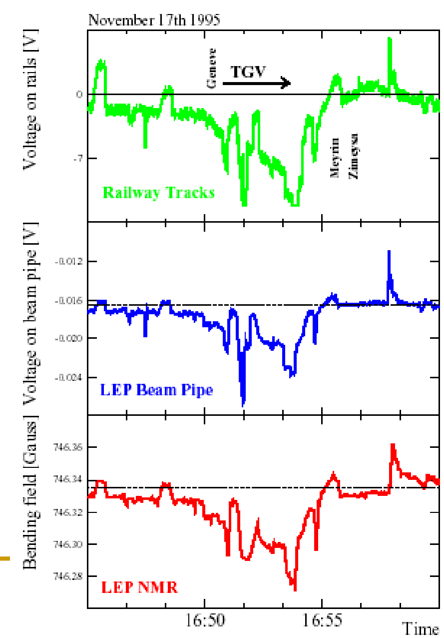
ΔE_b = 10 MeV
(ΔC = 1 mm)



NB at FCC-ee effects will be 30x larger due to different momentum-compaction factor !

Rise of dipole fields due to stimulation from returning current from TGV.





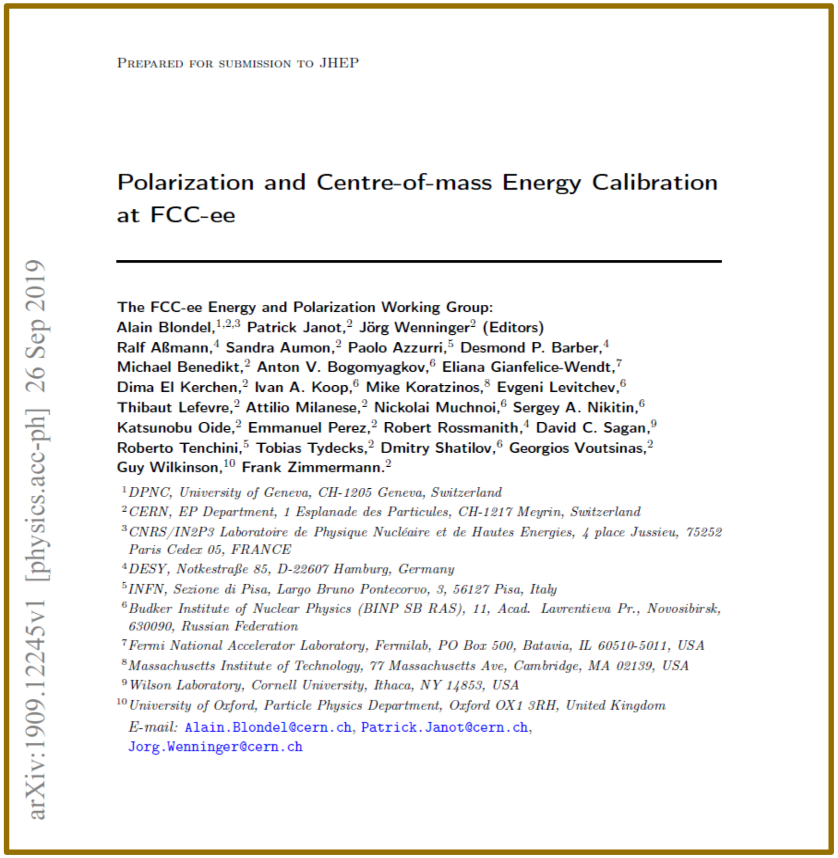
What hope then for E_{CM} calib^n at FCC-ee ?

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

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: reasonable to expect systematic uncertainties of ~100 keV on M_Z and ~25 keV on Γ_Z, which are improvements of 17 and 48 respectively on LEP.

Observable	statistics	$\Delta\sqrt{s}_{\rm abs}$ 100 keV	$\Delta\sqrt{s}_{\rm syst-ptp}$ **40 keV**	calib. stats. $200\,{\rm keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}$ MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{\rm eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**

absolute   point-to-point   beam energy spread

And following experience of LEP, not far-fetched to imagine we will do even better.

(Note, that this uncertainty of Γ_Z is substantially less than is found in tables in the FCC CDR, and is due to subsequent work, particularly on use of dimuons.)

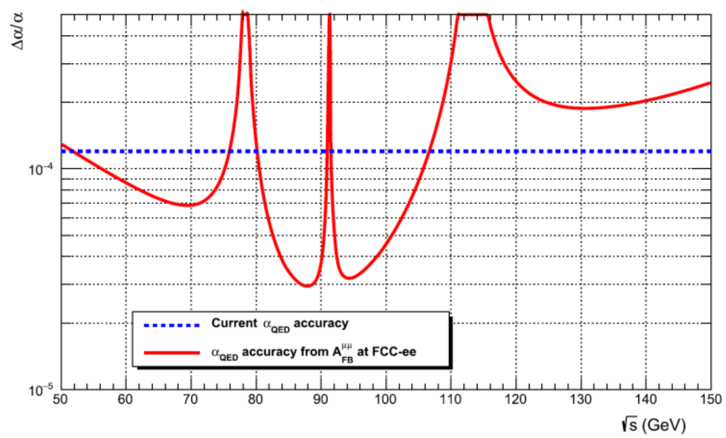
Other Z-related measurements

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

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

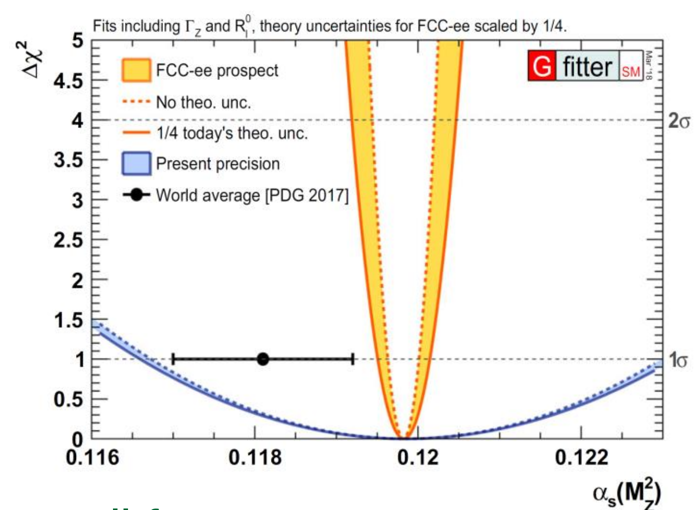
Choose off-peak energies to allow for factor ~4 improvement in precision.

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



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

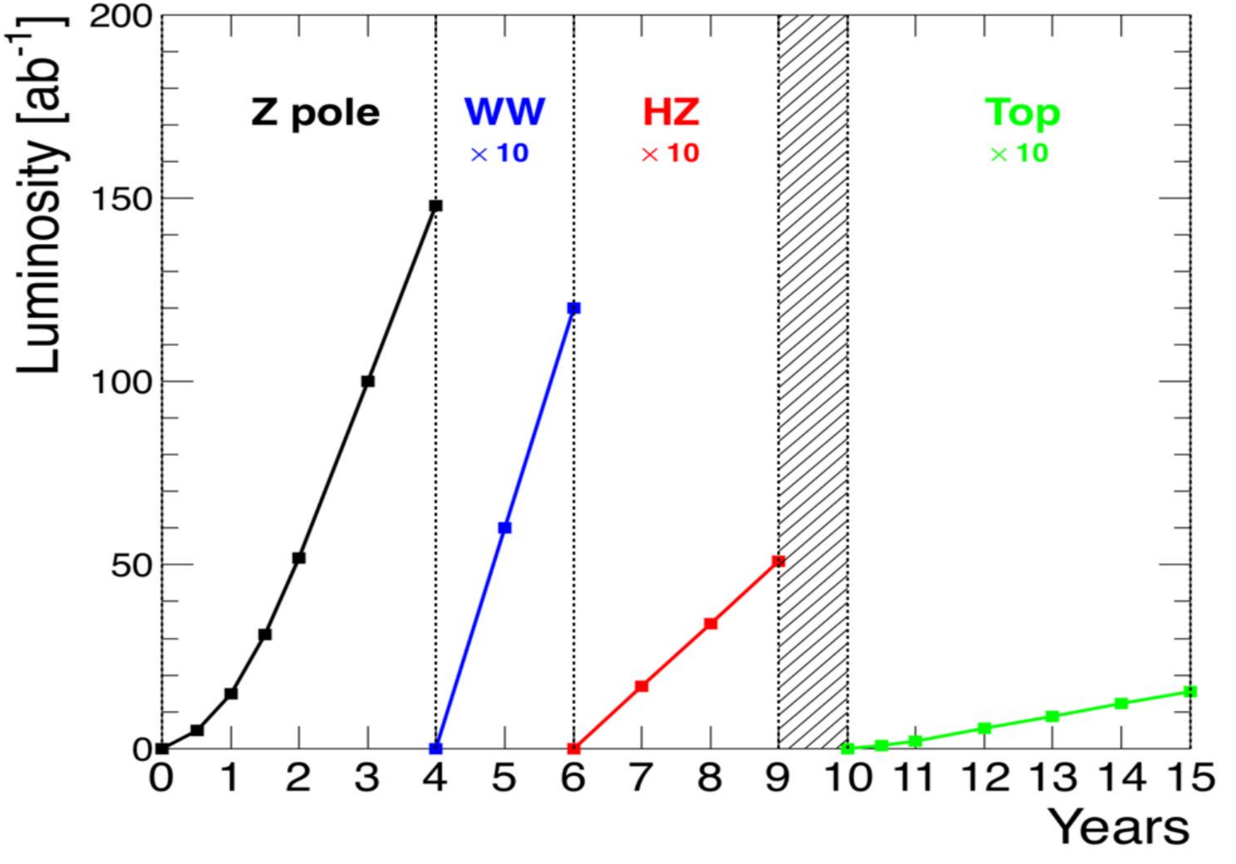
Expectation from lineshape observables *alone* (not included: τ, W decays, jet rates, event shapes…).



- **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 ($e^+e^-\to Z\gamma$, $Z\to\nu\bar{\nu}$bar) at higher energies (*e.g.* 161 GeV).

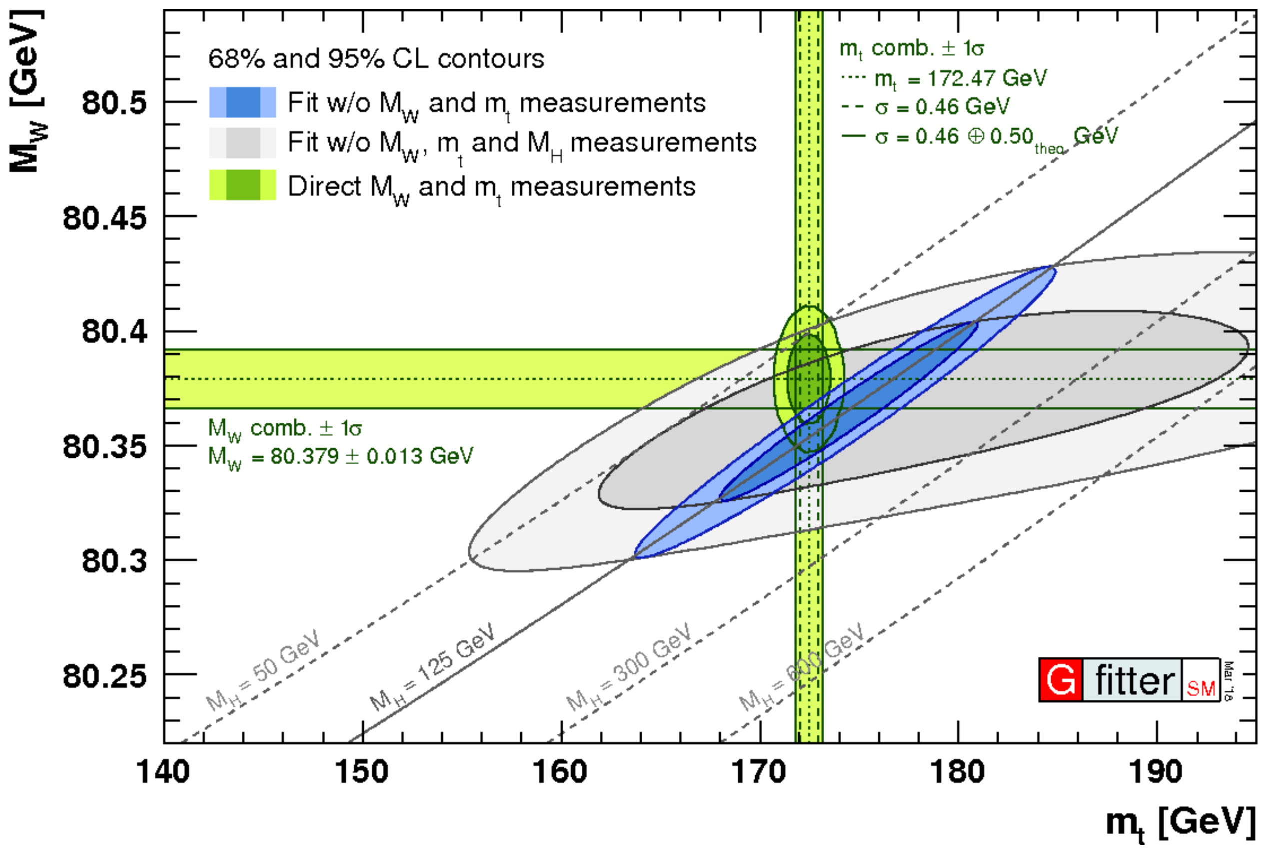
Precision EW physics above the Z



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

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.



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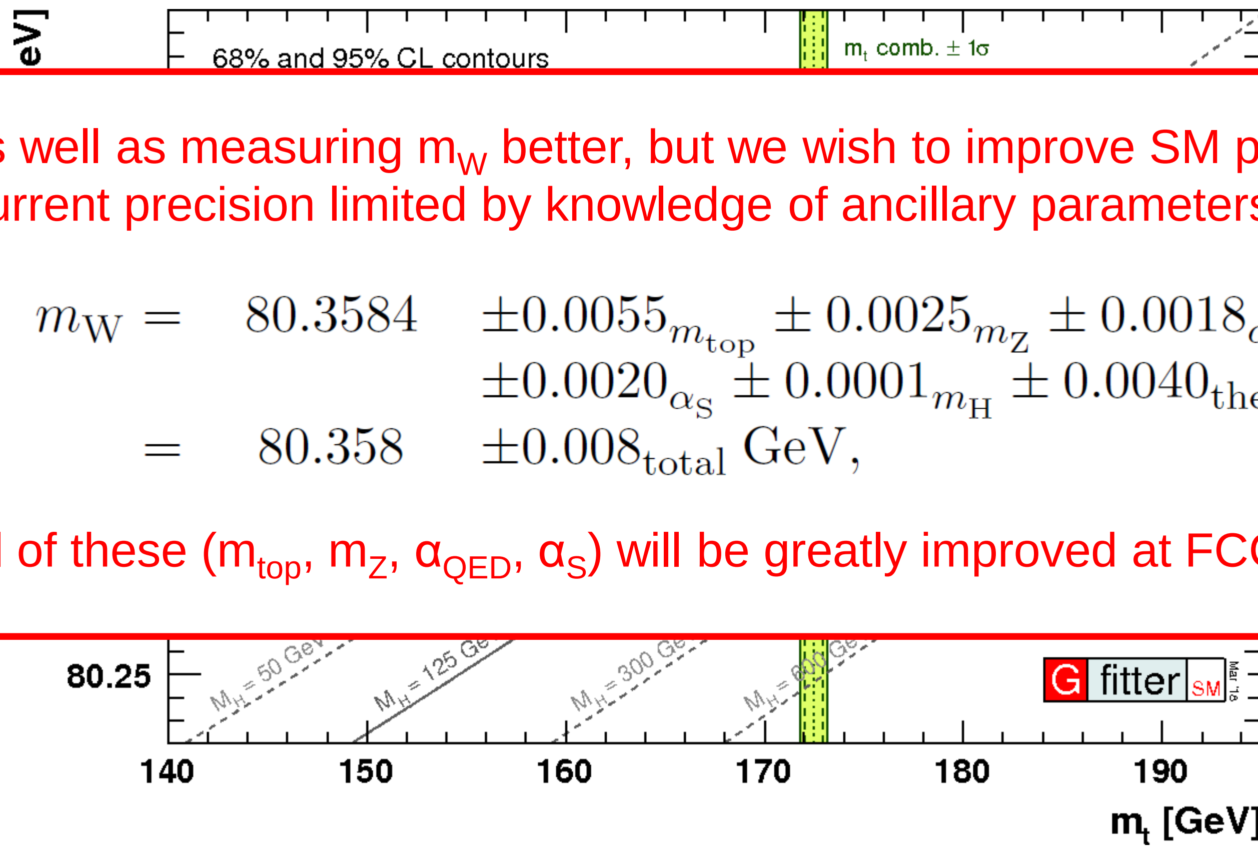


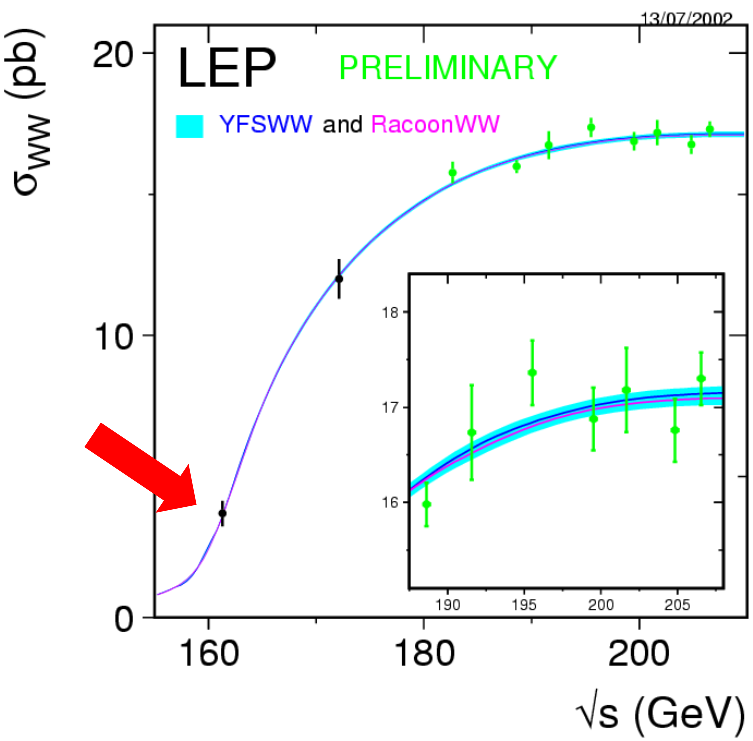
As well as measuring m_W better, but we wish to improve SM prediction. Current precision limited by knowledge of ancillary parameters.

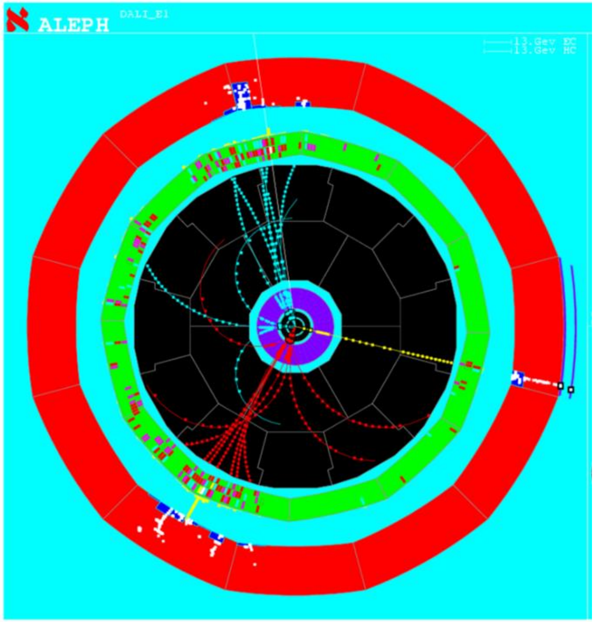
$$\begin{aligned} m_{\mathrm{W}} = \quad & 80.3584 \quad \pm 0.0055_{m_{\mathrm{top}}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{\mathrm{QED}}} \\ & \qquad\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{\mathrm{theory}}\ \mathrm{GeV} \\ = \quad & 80.358 \quad \pm 0.008_{\mathrm{total}}\ \mathrm{GeV},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

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

Measuring m_W 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).

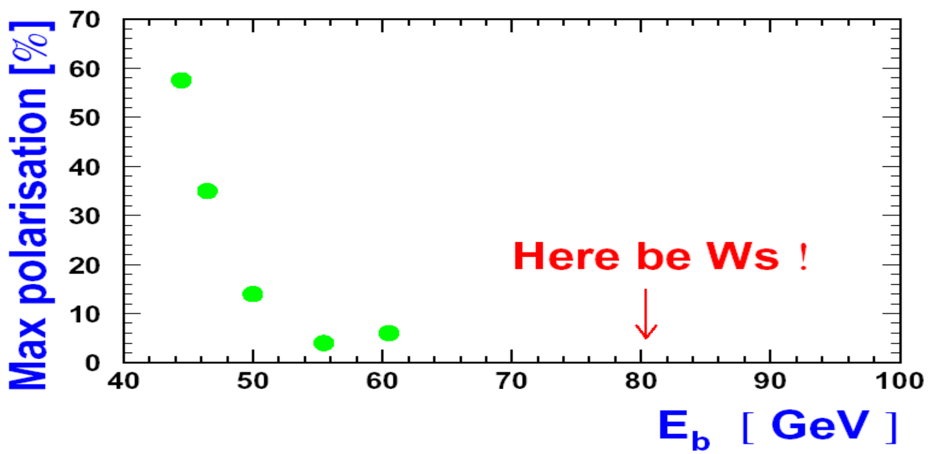
$$\frac{\Delta m_W}{m_W} = \frac{\Delta E_{CM}}{E_{CM}}$$

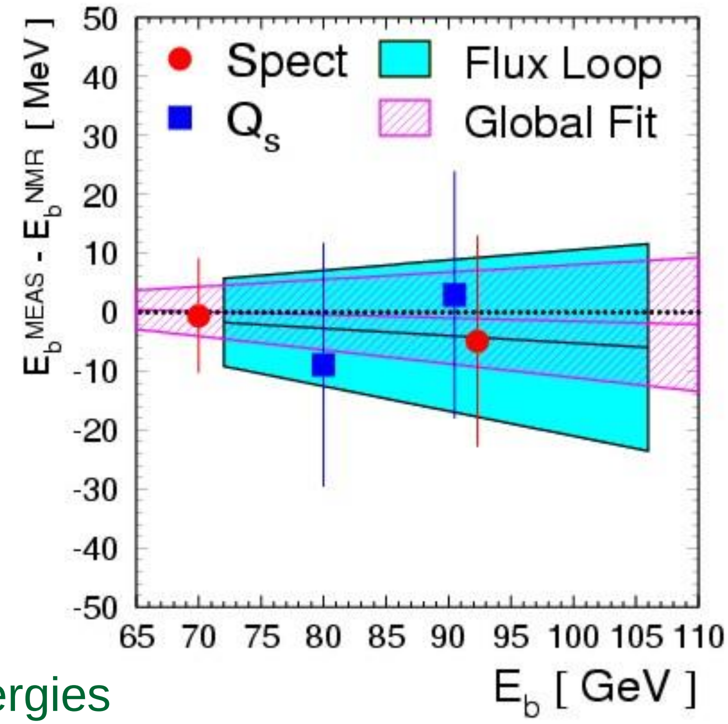
Measuring m_W in $e^+e^- \rightarrow W^+W^-$

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

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…

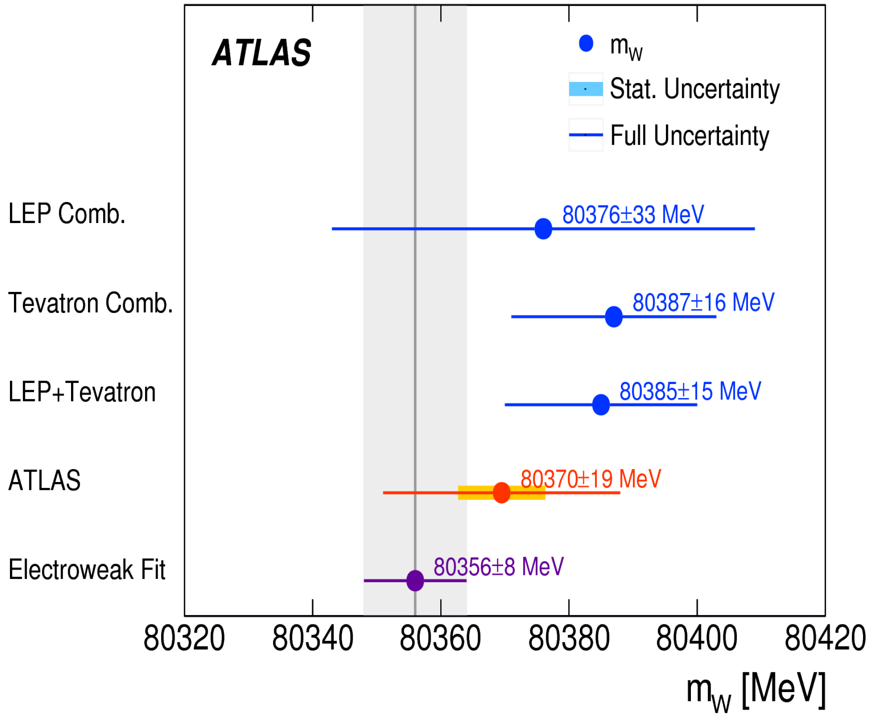




…instead must use a variety of methods (*e.g.* spectrometer) to extrapolate from RDP energies to W^+W^- regime. Very difficult, but it was done [EPJC 39 (2005) 253].

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.

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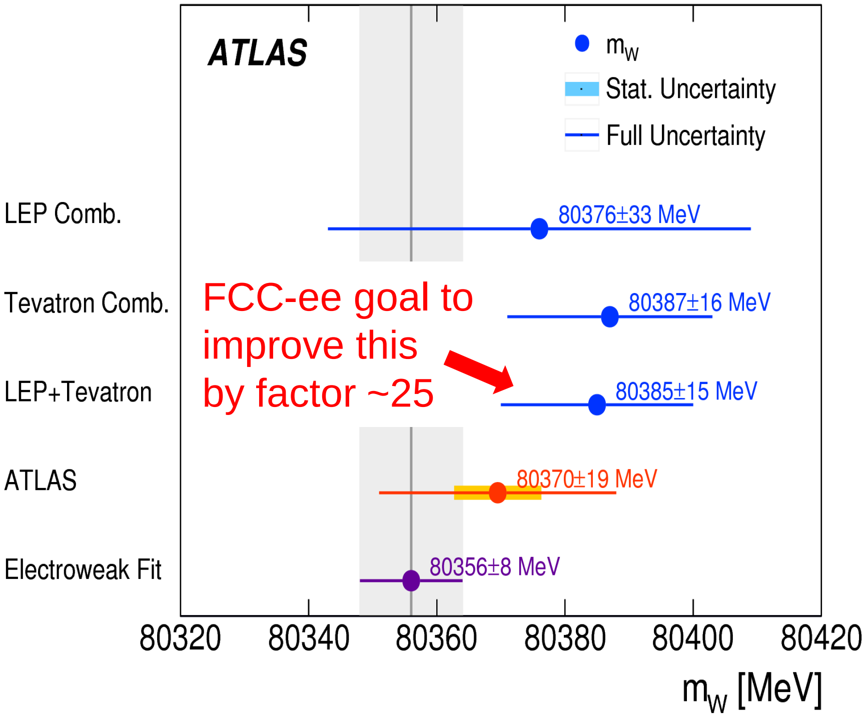
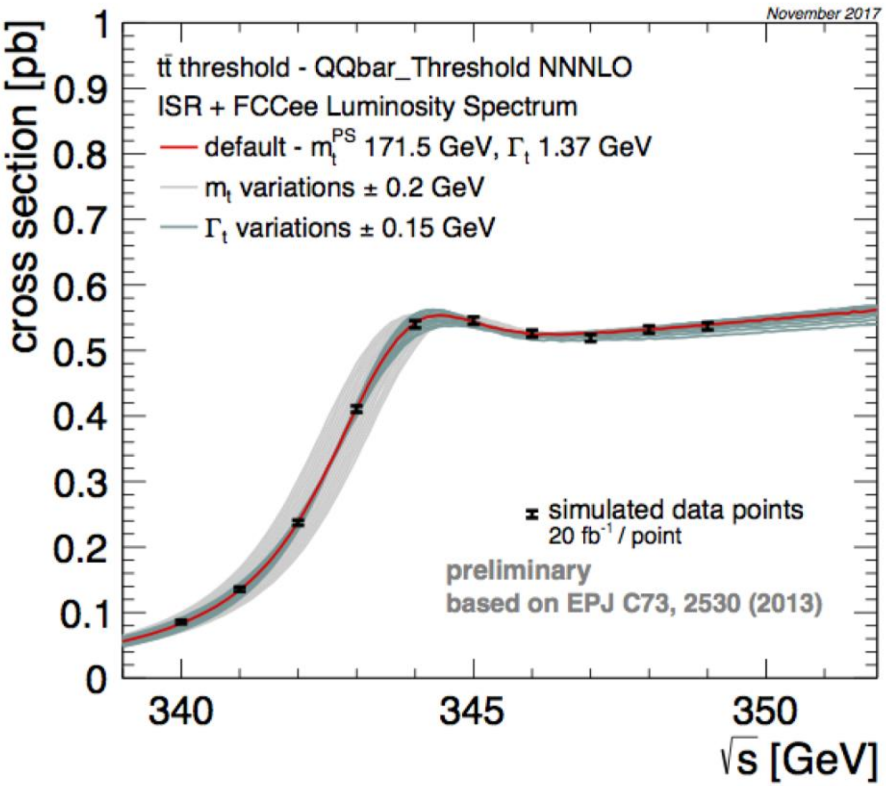


- Yes, but it is exceptionally difficult, particularly at LHC (easier at ppbar).
- Ultimate precision at HL-LHC difficult to assess, but indicative value ~5 MeV (see *e.g.* ATL-PHYS-PUB-2018-026), with best prospects if LHeC operates.
- But we can do ***much better*** at FCC-ee, because ***polarisation will be possible!*** Because $\sigma_{E_b} \sim E_b^4/\rho$ 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.

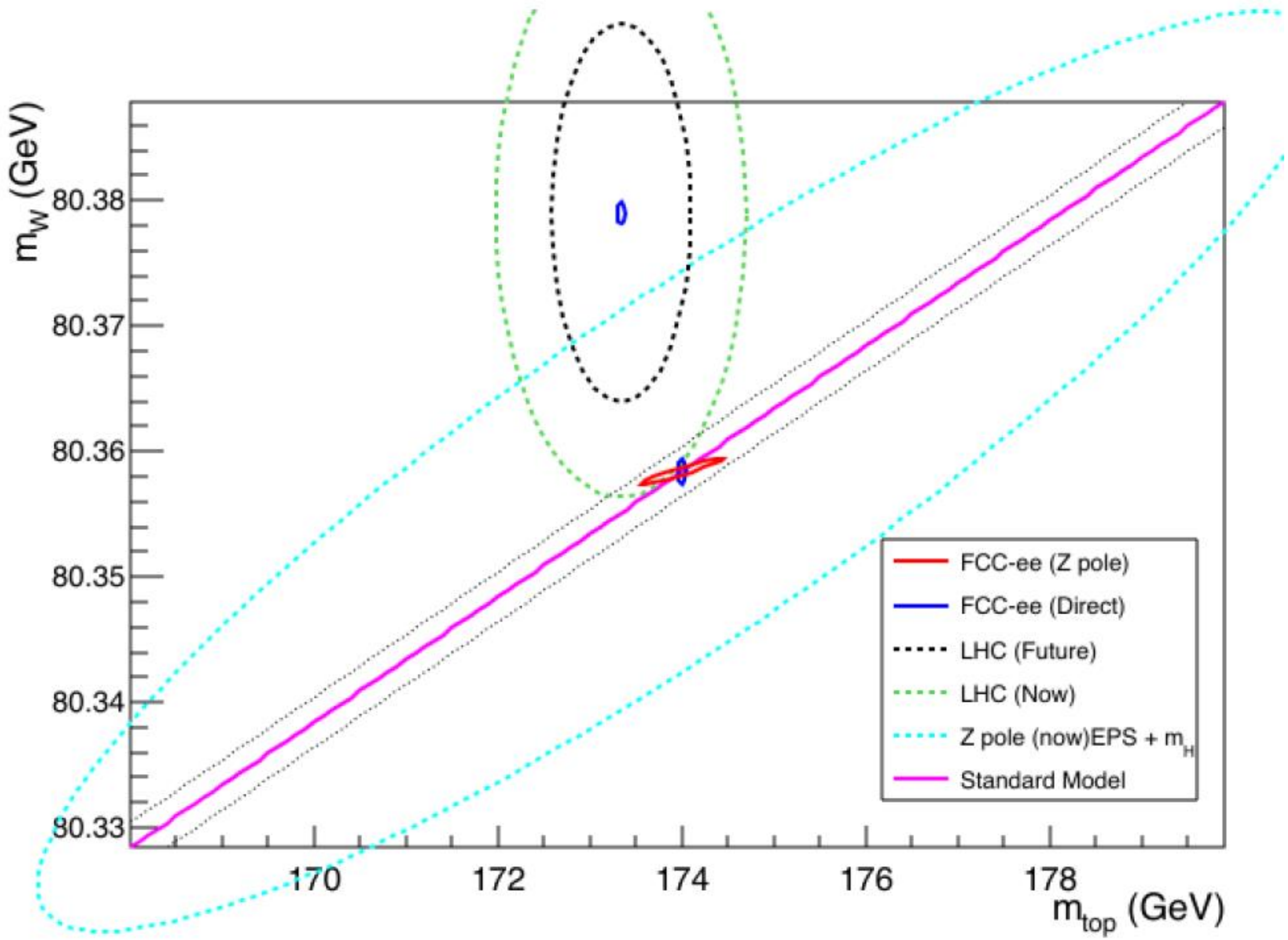
Going to higher energies: m_t

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

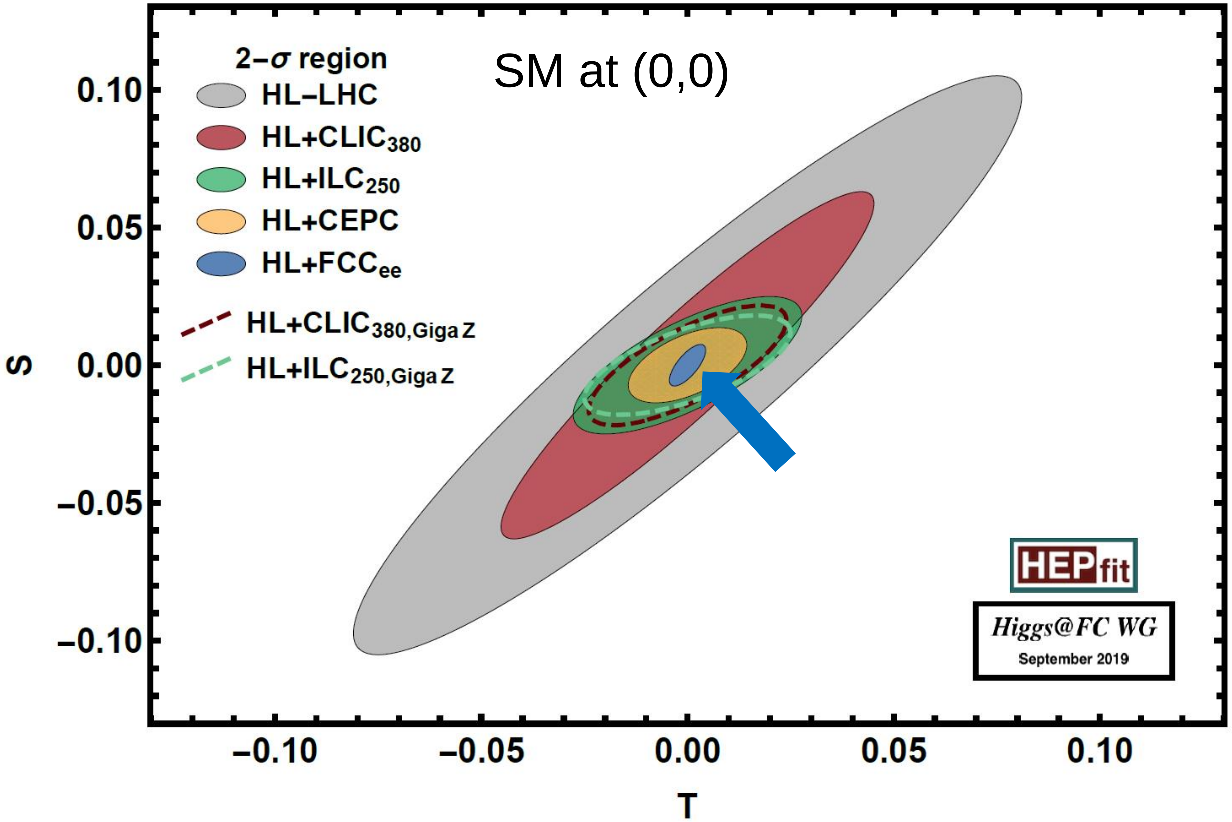
Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error	Factor improvement
m_Z (keV)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration	~20
Γ_Z (keV)	2495200 ± 2300	8	100 → 25	From Z line shape scan Beam energy calibration	~100
R_ℓ^Z $(\times 10^3)$	20767 ± 25	0.06	0.2-1.0	ratio of hadrons to leptons acceptance for leptons	
$\alpha_s(m_Z)$ $(\times 10^4)$	1196 ± 30	0.1	0.4-1.6	from R_ℓ^Z above [41]	~20-100
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	
$N_\nu (\times 10^3)$	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

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	$\pm$ 30%	0.5 – 1.5%	small	From $E_{CM} = 365$GeV run	

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.

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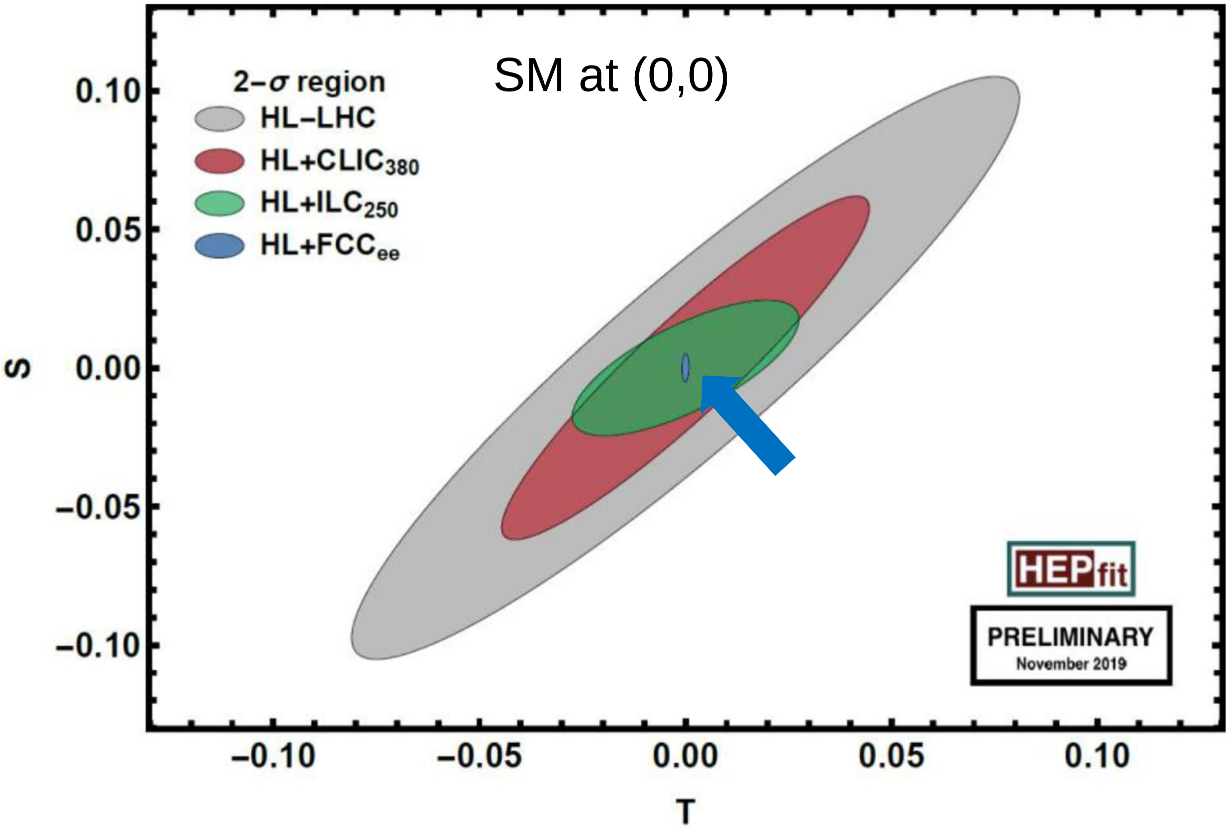


Without certain experimental and theoretical uncertainties (but including those on M_Z, Γ_Z, and including current 'parametric errors' on m_t, $\alpha_{QED}(M_Z^2)$ *etc.*

Detector challenges

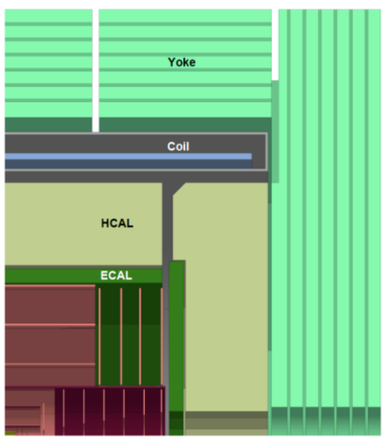
Event rates and radiation challenges modest compared with HL-LHC/FCC-hh.

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}.

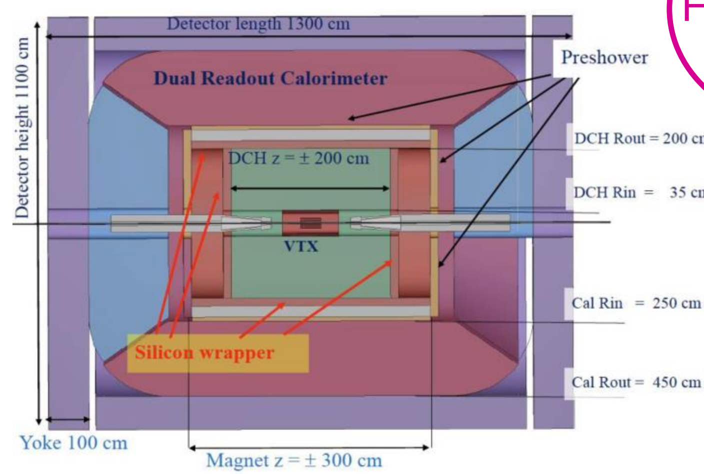
in contrast, Higgs physics is 'easy' !

Early days, but two candidate experiment designs have emerged:

CLD



IDEA



Misc. remarks:

- There may be 4 IPs, so more experiment designs welcome;
- Beampipe radius ~2 cm (3x smaller than LEP) – opportunity for high performance vertex detectors to enhance flavour & EW physics;
- No dedicated hadron PID in current designs (although IDEA drift chamber boasts superlative d*E*/d*x* through cluster counting).

An exciting challenge for theory too

Foreseen experimental precision will require corresponding advances in theory.

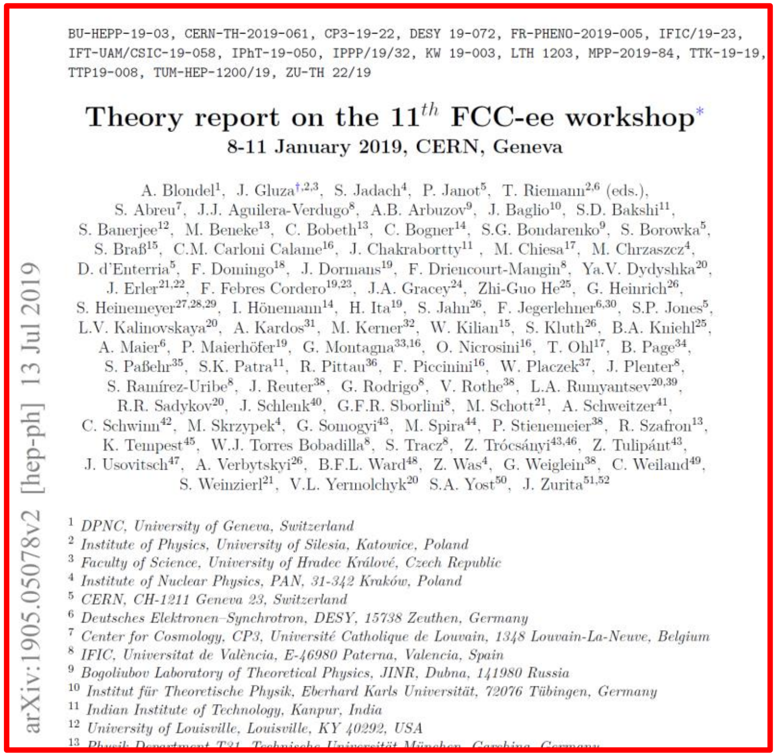
arXiv:1901.02648

	$\delta\Gamma_Z$ [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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Theory report on the 11^{th} FCC-ee workshop*

8-11 January 2019, CERN, Geneva

A. Blondel[1], J. Gluza[†,2,3], S. Jadach[4], P. Janot[5], T. Riemann[2,6] (eds.), S. Abreu[7], J.J. Aguilera-Verdugo[8], A.B. Arbuzov[9], J. Baglio[10], S.D. Bakshi[11], S. Banerjee[12], M. Beneke[13], C. Bobeth[13], C. Bogner[14], S.G. Bondarenko[9], S. Borowka[5], S. Braß[15], C.M. Carloni Calame[16], J. Chakrabortty[11], M. Chiesa[17], M. Chrzaszcz[4], D. d'Enterria[5], F. Domingo[18], J. Dormans[19], F. Driencourt-Mangin[8], Ya.V. Dydyshka[20], J. Erler[21,22], F. Febres Cordero[19,23], J.A. Gracey[24], Zhi-Guo He[25], G. Heinrich[26], S. Heinemeyer[27,28,29], I. Hönemann[14], H. Ita[19], S. Jahn[26], F. Jegerlehner[6,30], S.P. Jones[5], 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], S. Weinzierl[21], V.L. Yermolchyk[20] S.A. Yost[50], J. Zurita[51,52]

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10 Institut für Theoretische Physik, Eberhard Karls Universität, 72076 Tübingen, Germany
11 Indian Institute of Technology, Kanpur, India
12 University of Louisville, Louisville, KY 40292, USA

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 Υ(4S) and proton-proton.

	Υ(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 x 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.

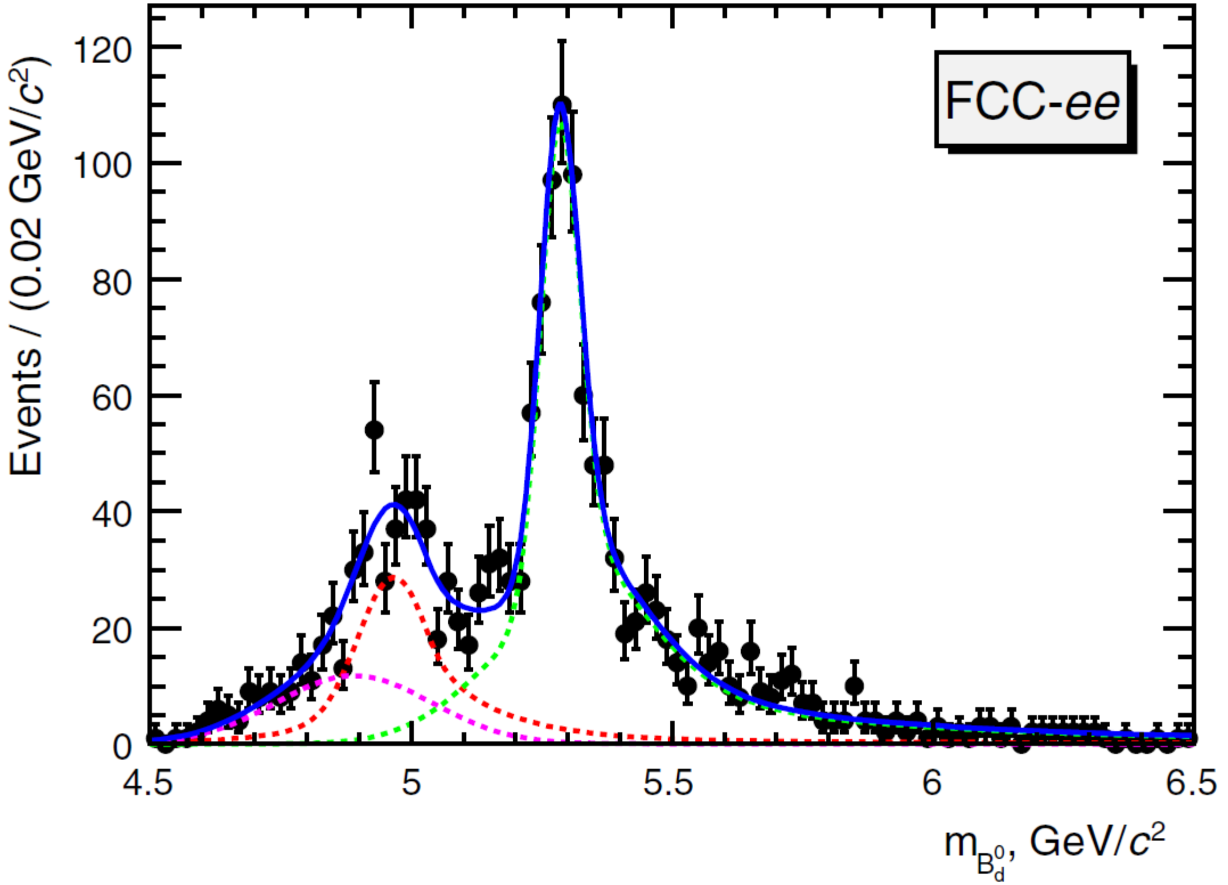
→ high precision b-physics programme complementary to LHCb Upgrades

(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.

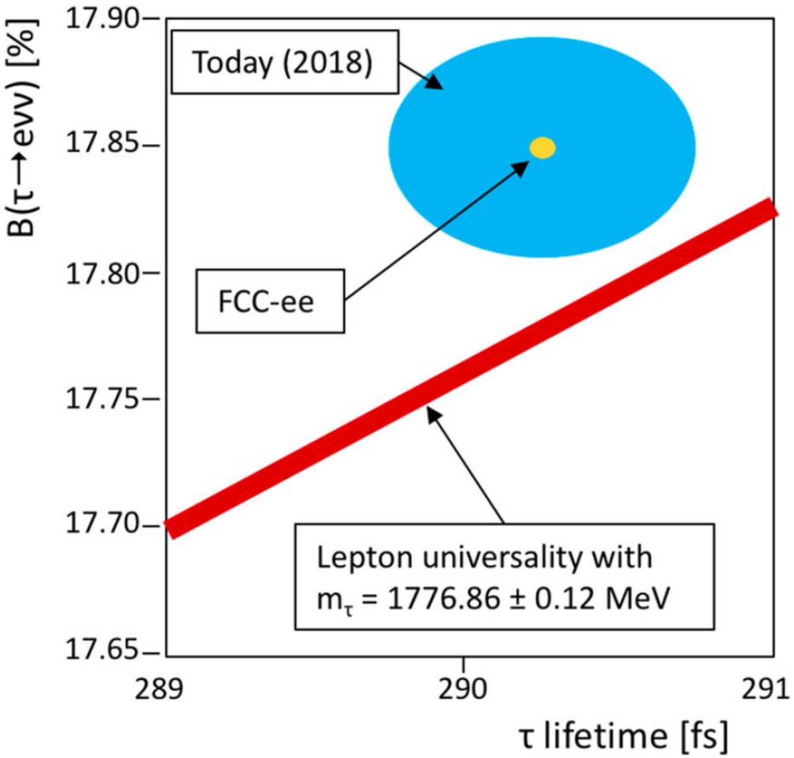
e.g. reconstructing $B^0 \to K^{*0}\tau^+\tau^-$, a priori a very interesting electroweak-penguin mode, and especially so in the light of the current flavour anomalies.



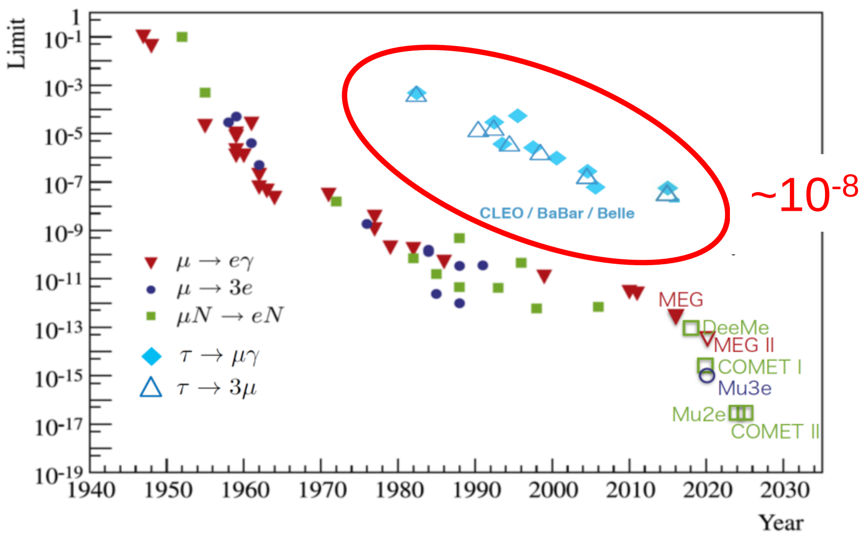
Tau physics at FCC-ee

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. τ→μμμ down to $O(10^{-10})$

FCC-ee next steps and UK activities

Now viewing FCC-ee in the round, *i.e.* considering its potential as a superlative Higgs factory

FCC-ee next steps and UK activities

Last year's report of the European Strategy Update encouraged Europe, and the world, to examine the technical and financial feasibility of a 100 TeV hadron collider (*i.e.* FCC-hh), with an e^+e^- machine (*i.e.* FCC-ee) as a first step.

Executing this charge is a high priority of the new CERN management team. The hadron collider is far away, but the 'technical and financial feasibility' of the tunnel, in particular, needs to be established (or declared impossible) by the time of the next Strategy Update in ~5 years time.

Attention also turning to the detector challenge, with 'CDR++' on similar timescale.

Here we have set up a 'FCC-UK' group, with contacts established in each institute. We had a kick-off meeting in Sept: https://conference.ippp.dur.ac.uk/event/933/ and since then have been preparing inputs for the 'PPAP Roadmap' review.

Clear expertise in several areas: silicon trackers, calorimeters, DAQ, particle ID… Much synergy with linear collider, and this will no doubt be noted in Roadmap.

Obvious statement: developments in Japan cannot be ignored.

FCC-ee next steps and UK activities

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The hadron collider is far away, but the 'tech
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time of the next Strategy Update in ~5 years time.

Your friendly local FCC-UK rep.

Eager for first beams in 2038 !

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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.

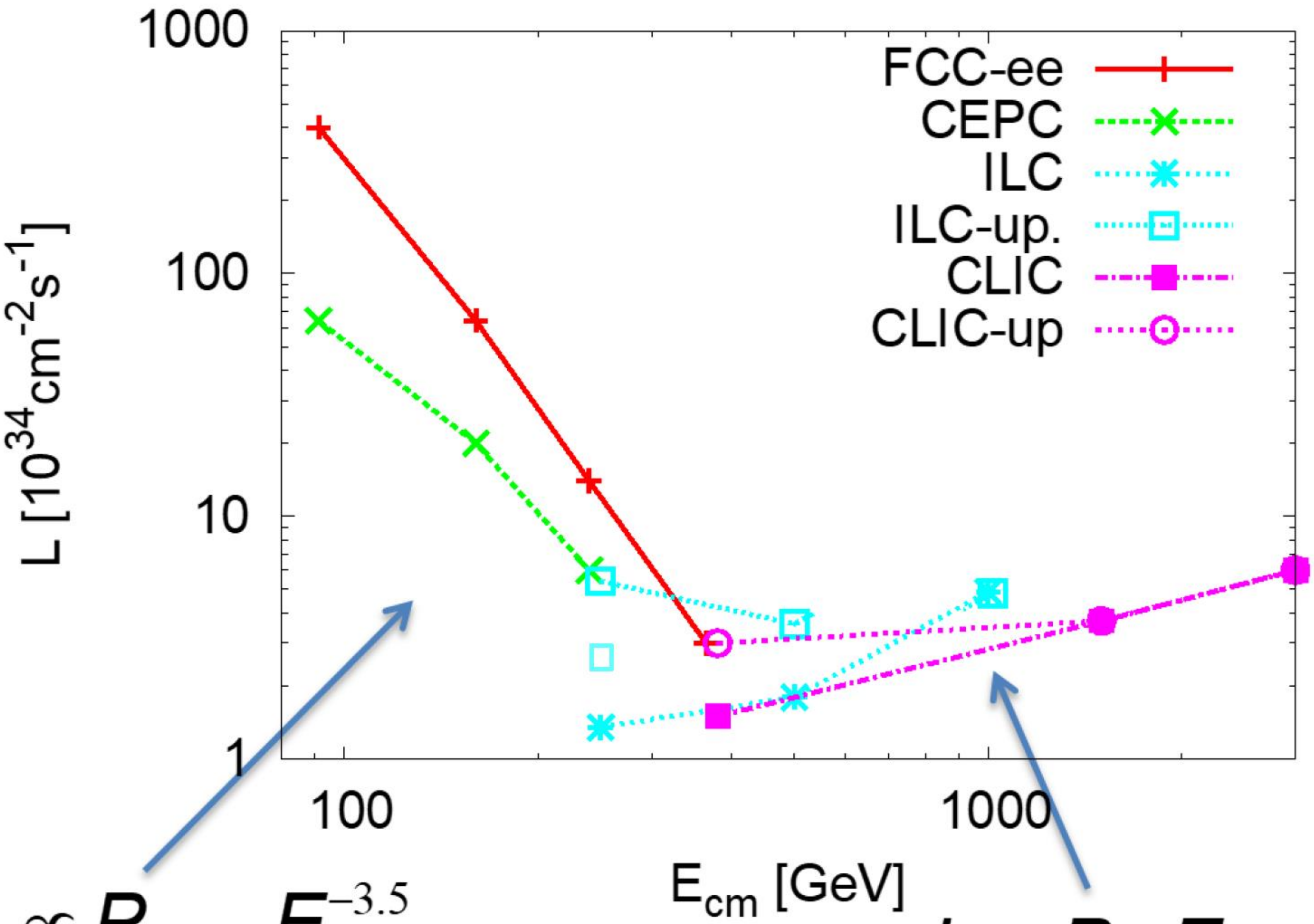
Dominant systematics of LEP programme can be greatly reduced, through machine design, 21st century detector technology and hard work in theory.

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

Luminosity per facility



$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF} E_{cm}$

FCC-ee: vital statistics

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

(Selected) mechanisms of E_b variation

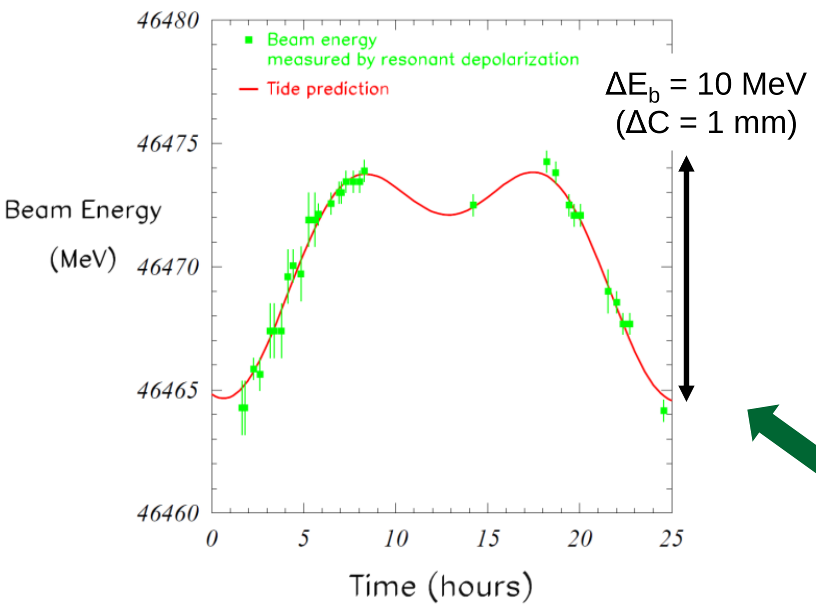
Energy changes can be induced by changes in the ring circumference, as this will lead the beam to sample different fields in the quadrupoles.

$$\frac{\Delta E}{E} = -\frac{1}{\alpha}\frac{\Delta C}{C}$$

α = momentum compaction factor

At LEP 1/α ~ 5000 → even $\Delta C/C \sim 10^{-9}$ (~0.1mm) changes gave noticeable effects.

Short-term drivers of circumference change – earth tides:



Model tracking RDP measurements in dedicated ‘tide experiment’ of 1992

Scary fact: at FCC-ee 1/α 30x larger than LEP, so 300 MeV variations expected !

(Selected) mechanisms of E_b variation

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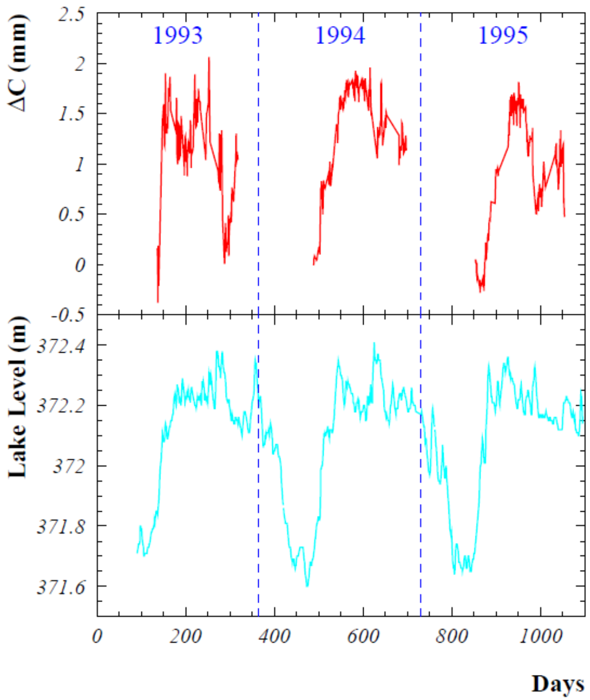
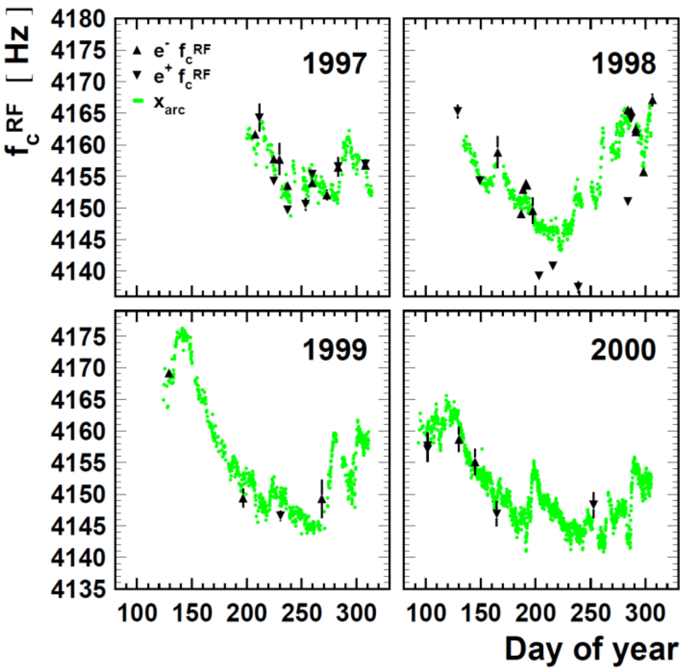
Long-term drivers of circumference change – changing level of Lac Leman:



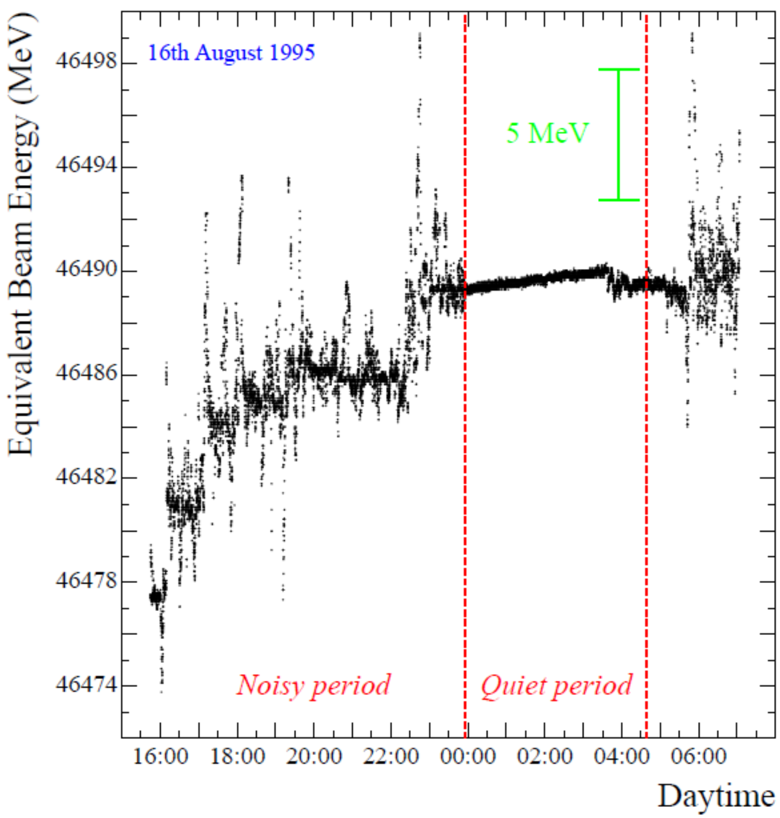


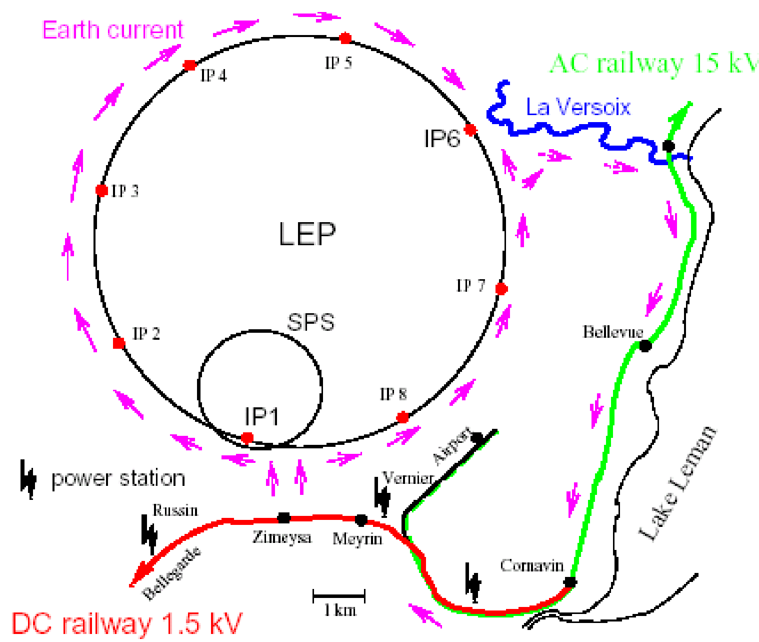
Tracked by BPM data

(Selected) mechanisms of E_b variation

Strange noise and field rises in magnets correlated to time of day and time in fill.

Found to be due to magnets being 'tickled' by current on beam pipe from passing trains.





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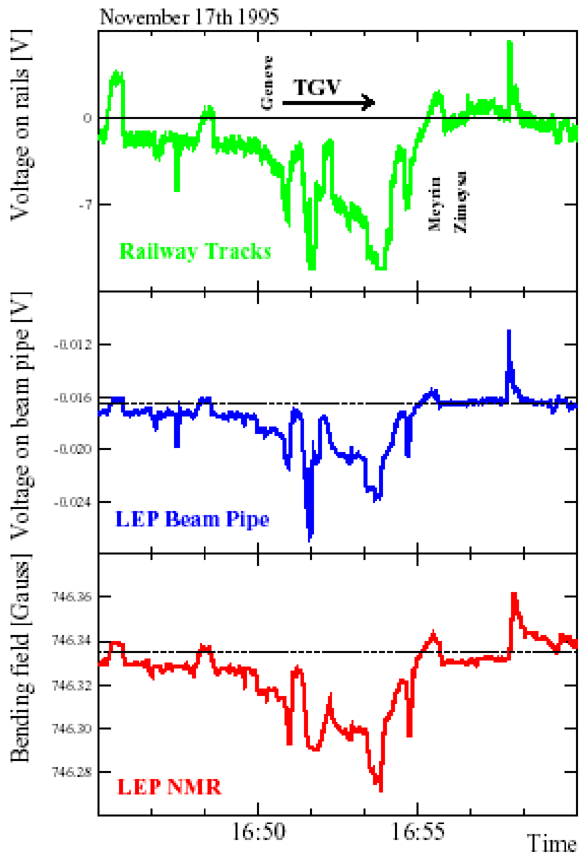

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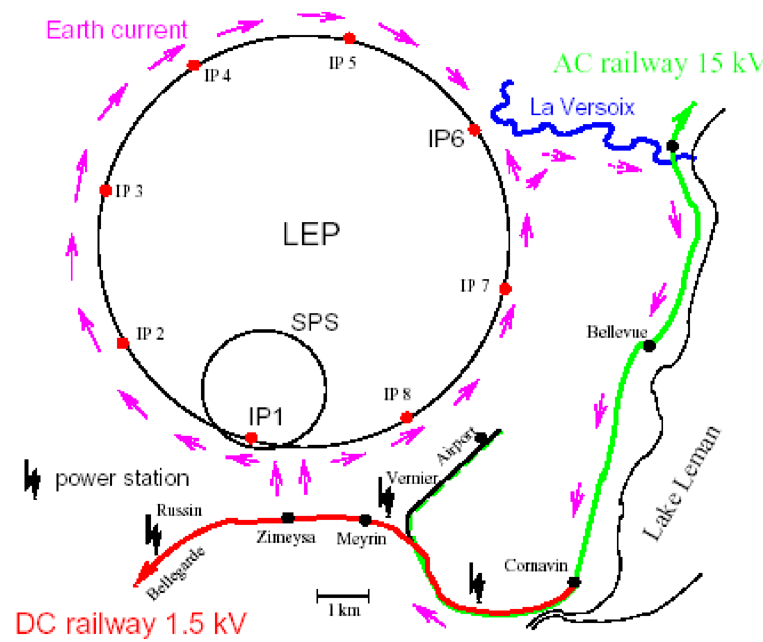
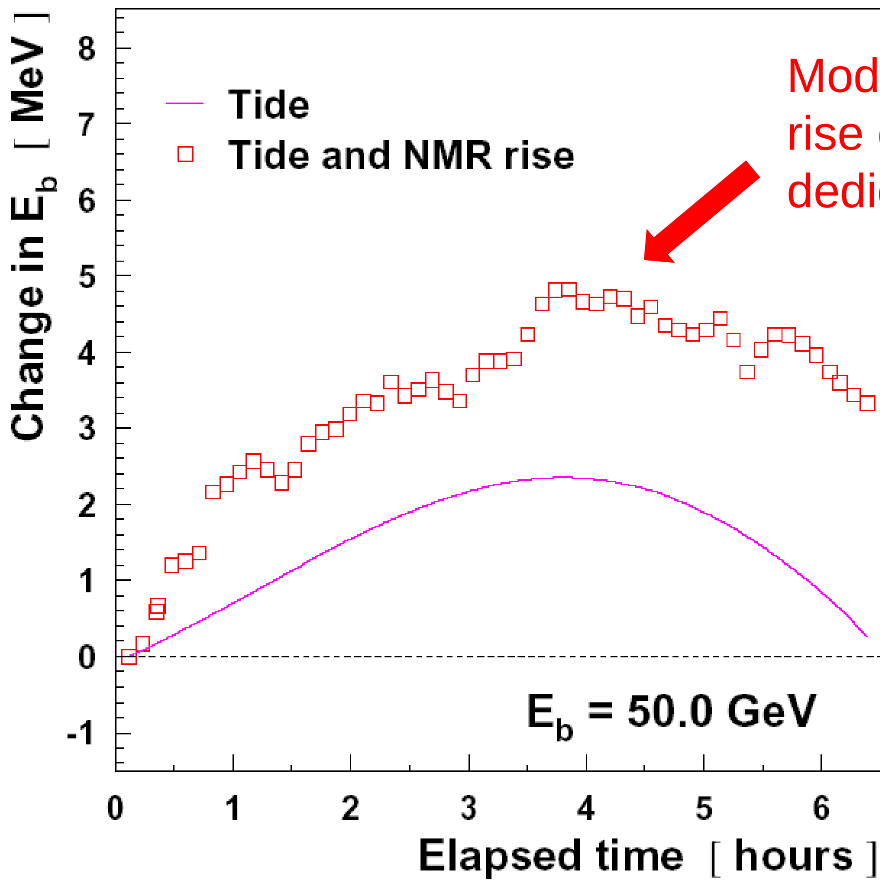


Compelling correlation between current on track, on beam pipe & noise in magnets.

(Selected) mechanisms of E_b variation

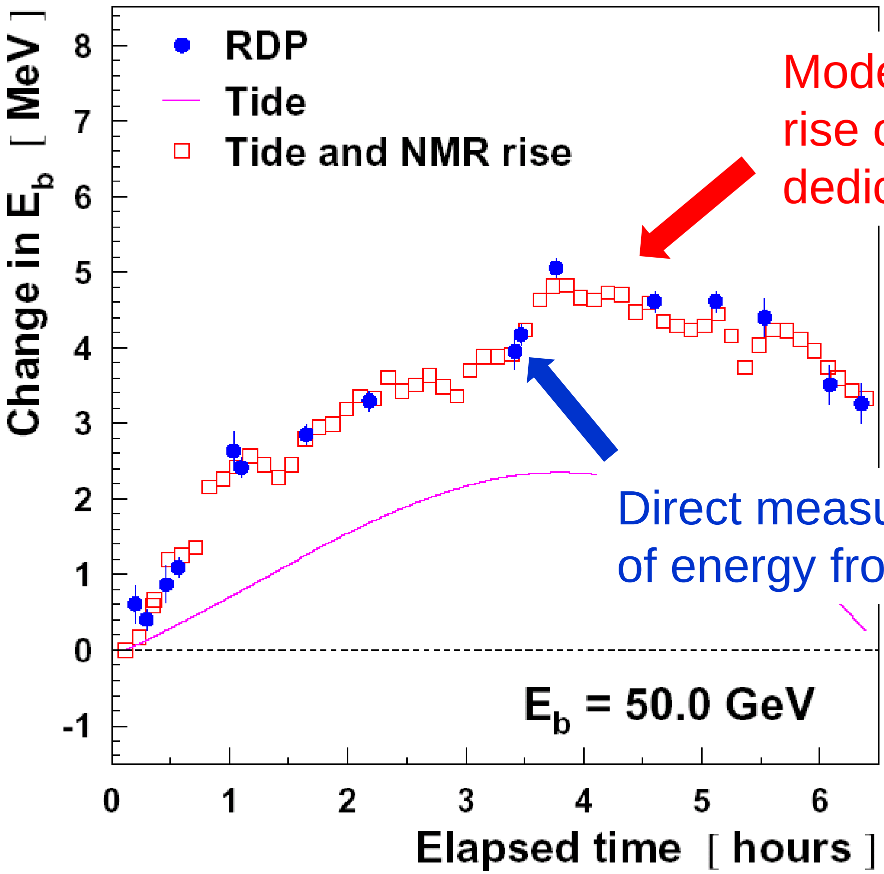
Energy rise modelled with great precision.



Model prediction of energy rise over a fill during a dedicated machine study.

(Selected) mechanisms of E_b variation

Energy rise modelled with great precision, in excellent agreement with RDP.



Model prediction of energy rise over a fill during a dedicated machine study.

Direct measurements of energy from RDP.

Control of beam spread and crossing angle

With the calibration of E_b under control, and other effects relevant for E_{CM} not discussed here (such as IP specific corrections from RF & synchrotron loss), one must worry about other issues, such as finite crossing angle & beam energy spread.

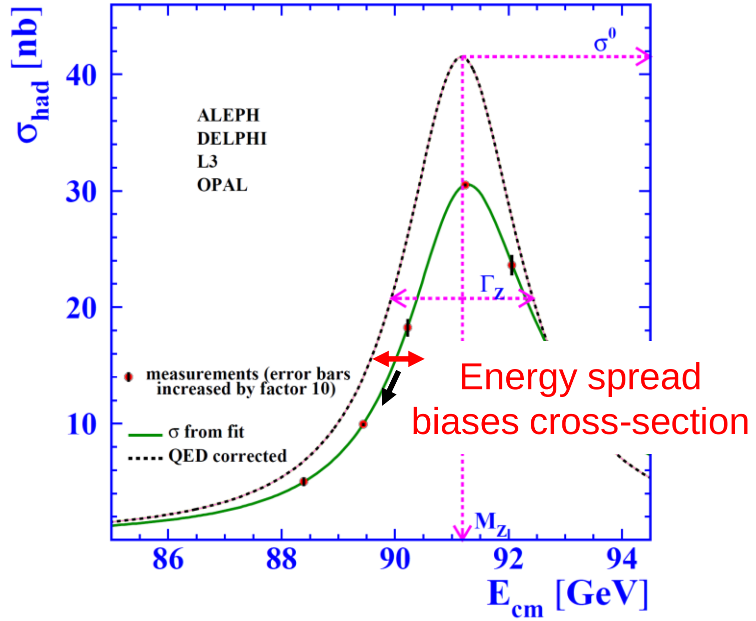
- $$\sqrt{s} = 2\sqrt{E_{e+}E_{e-}}\cos{\alpha/2}$$

Any crossing angle α, will bias E_{CM} and needs to be known.

- Beam energy is not monochromatic, but has a spread of ~50 MeV at Z.

  Spread in collision energy, $\sigma_{E_{CM}}$ will shift cross-section measurements by δ_σ as line shape is (clearly!) not linear.

$$\delta\sigma = -0.5\ \frac{d^2\sigma}{dE^2}\ \sigma^2_{E_{CM}}$$



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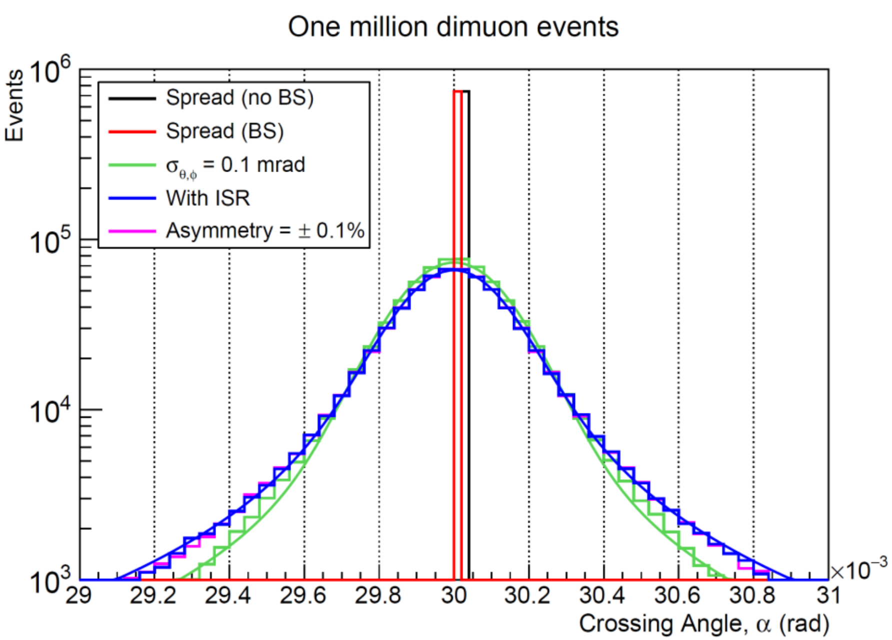
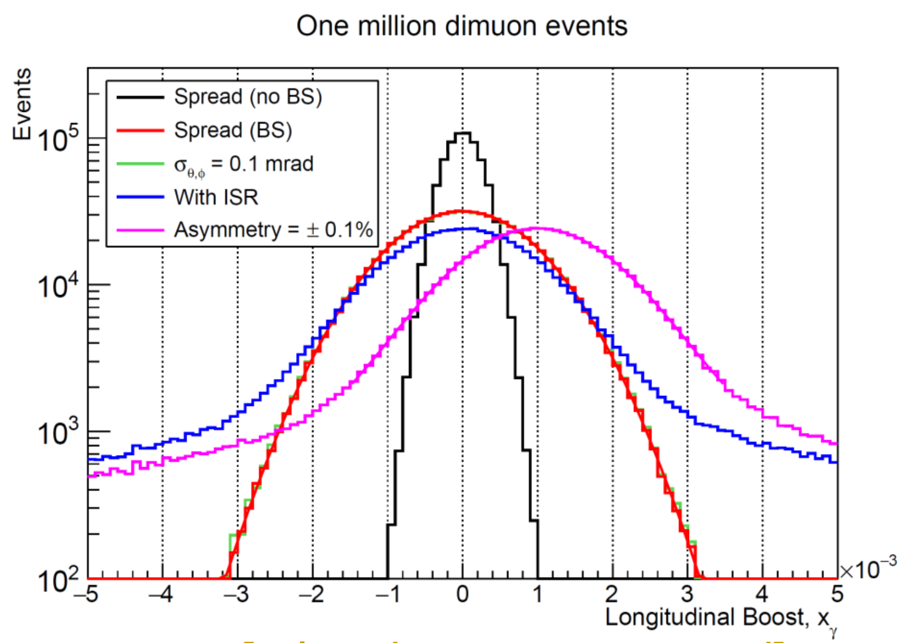
These effects can be controlled to necessary precision through monitoring the topology of $Z \to \mu\mu(\gamma)$ events, of which million will be collected every ~5 minutes.



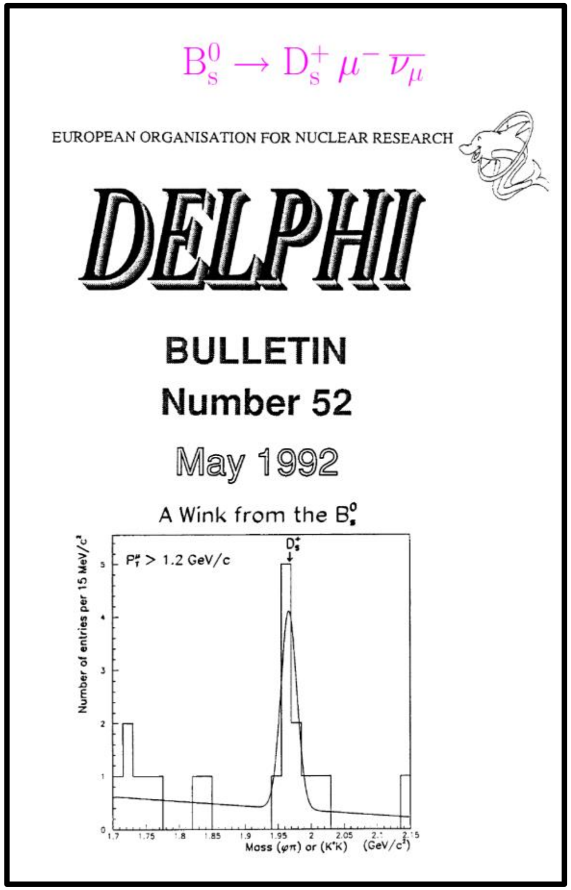


[related to energy spread]

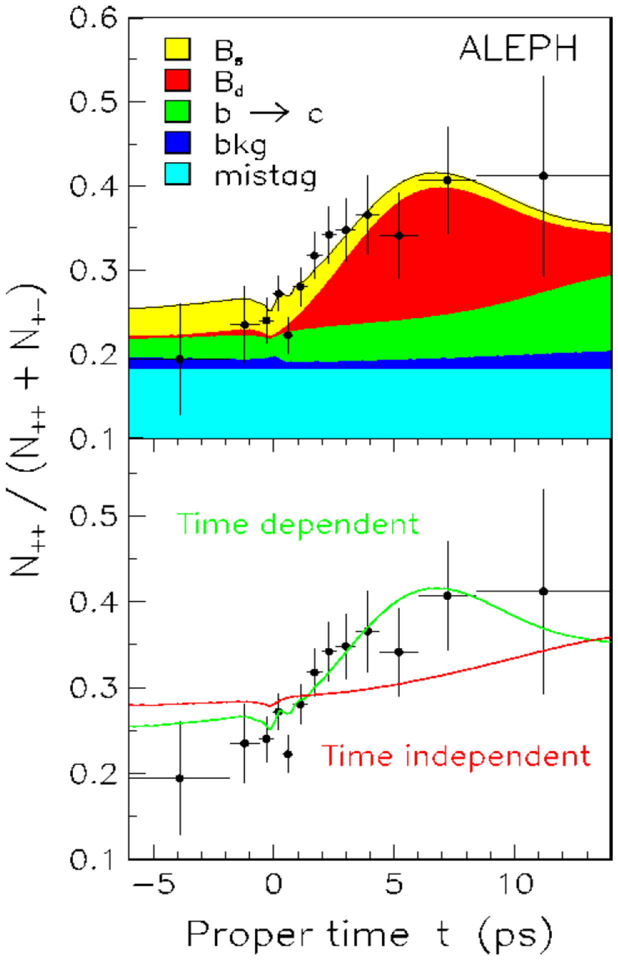
b physics at the Z pole

LEP demonstrated that $e^+e^- \rightarrow Z^0$ is an excellent laboratory for b physics.

e.g. observation of B_s meson



observation of B^0-B^0bar oscillations



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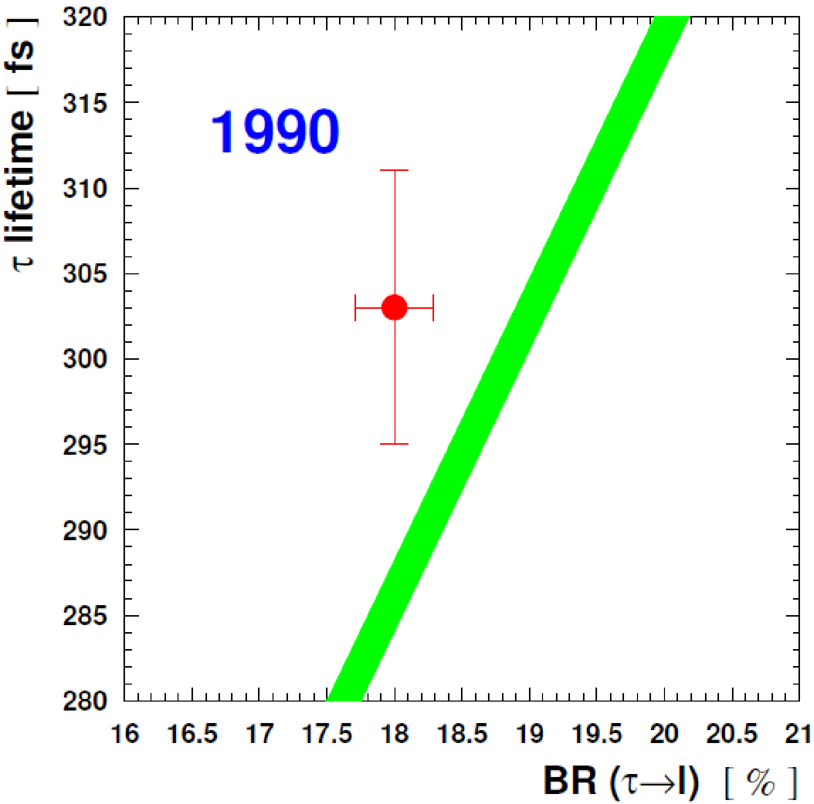
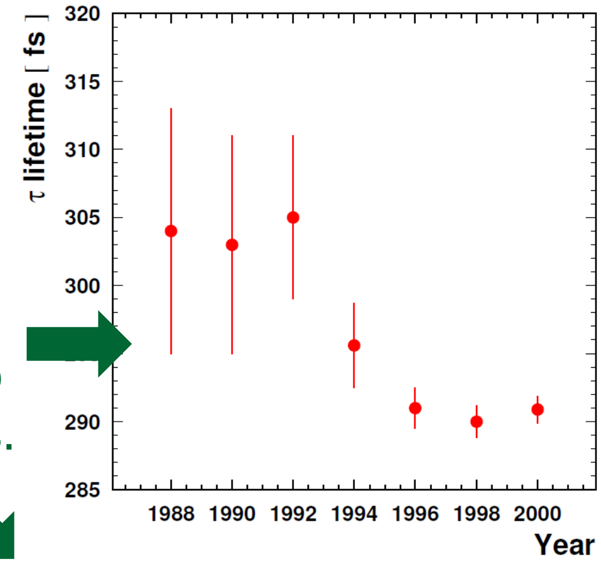
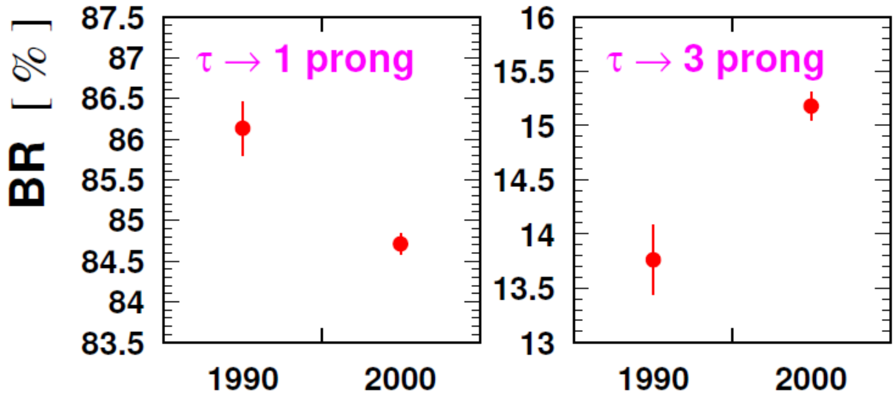
Before LEP – a significant problem….



Impact of LEP on lifetime and branching ratio measurements.





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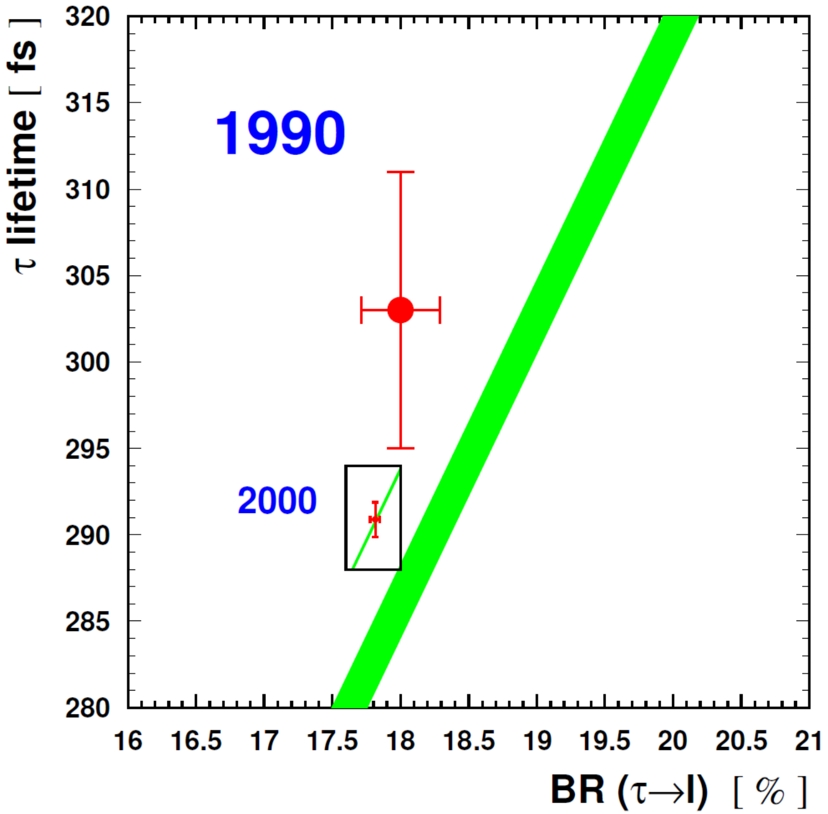
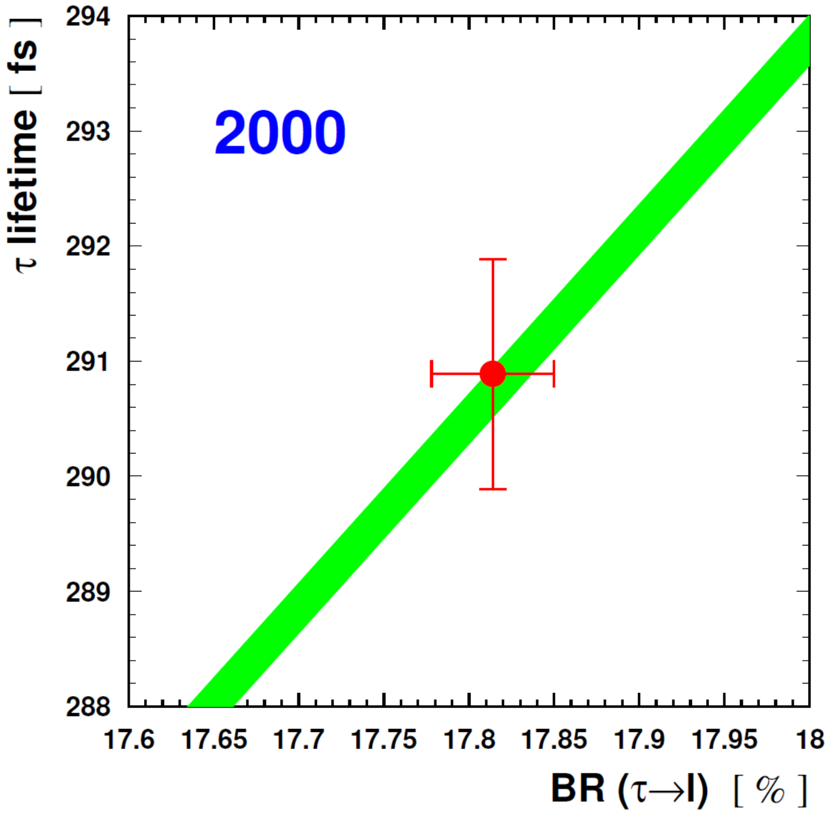


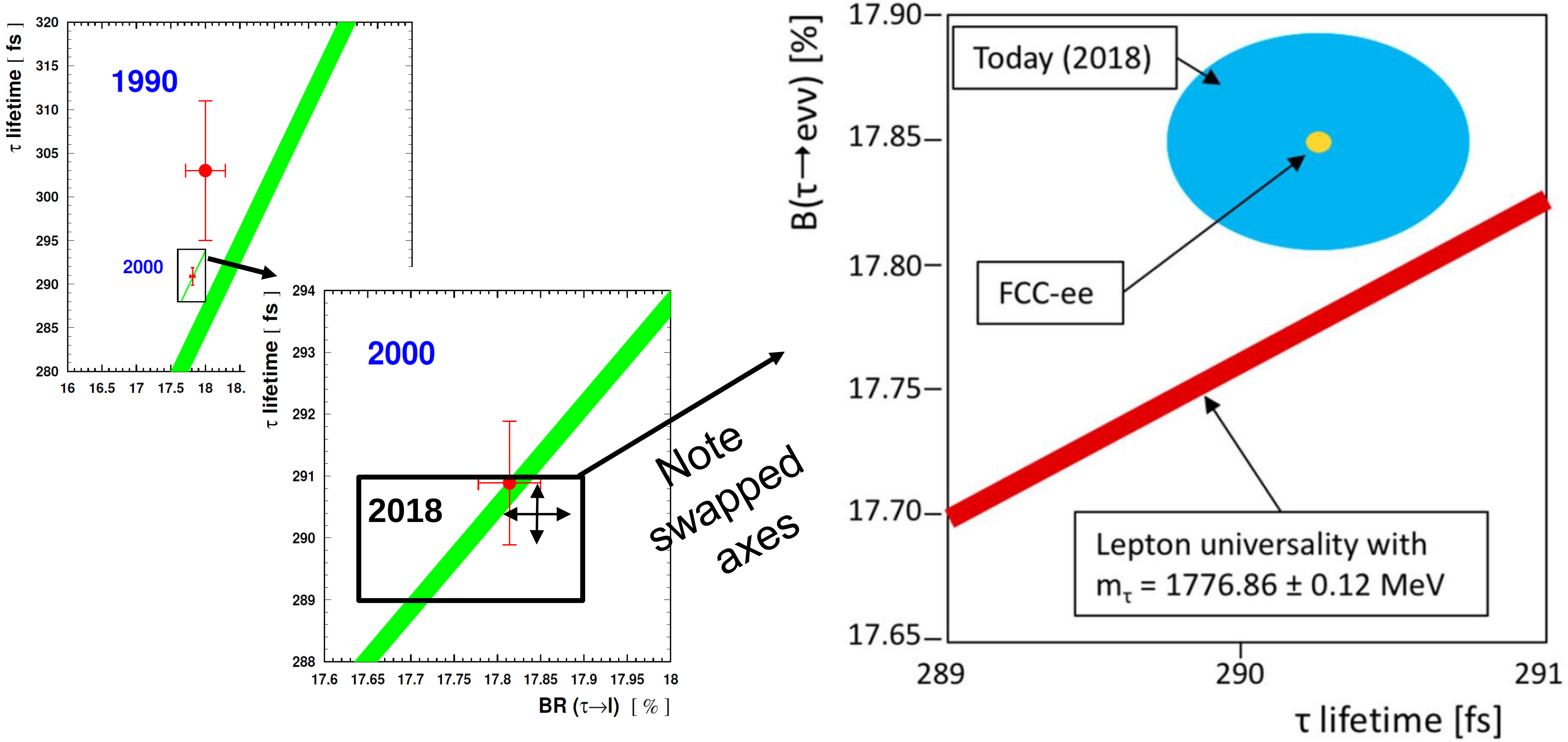
…but precision brings clarity.

(note also the dramatic change in the prediction from BES m_τ measurement)



Tau physics at FCC-ee

Conservatively, order-of-magnitude in lifetime and BRs should be possible (systematics limited), beyond improvements that B-factories made over LEP.



Provides powerful lepton-universality tests (but requires new m_τ measurement).

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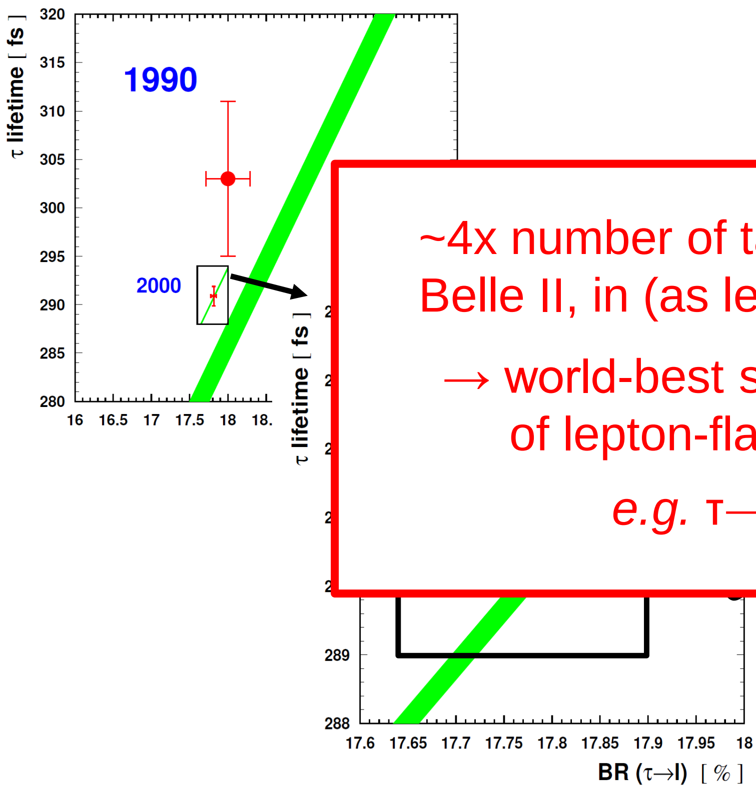

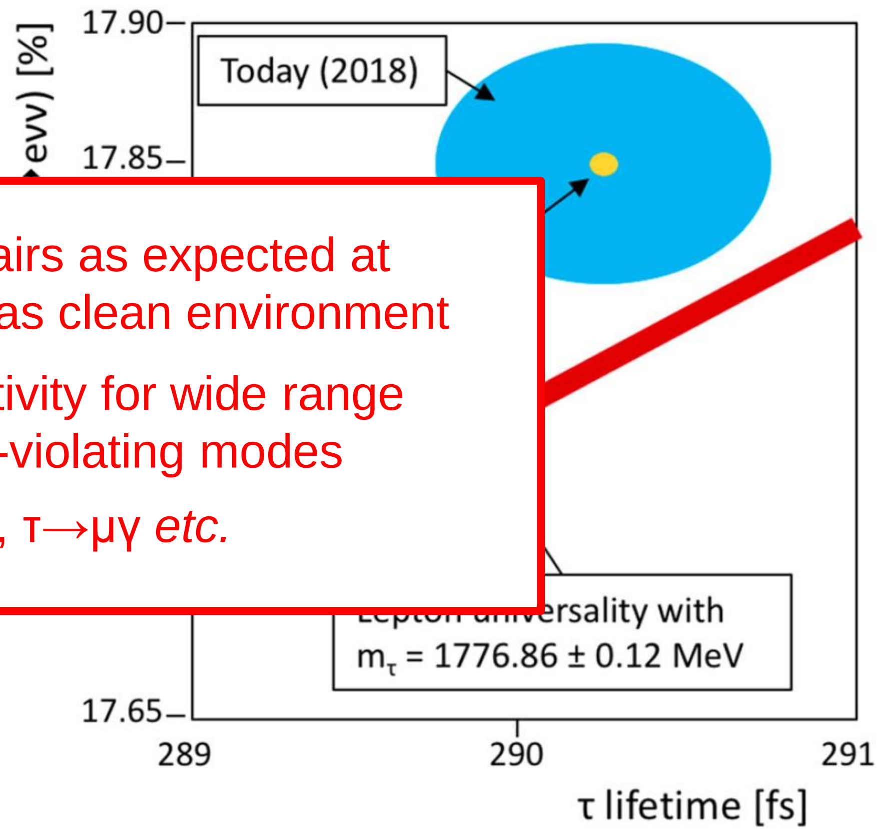

~4x number of tau pairs as expected at Belle II, in (as least) as clean environment

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

e.g. $\tau \to \mu\mu\mu$, $\tau \to \mu\gamma$ *etc.*

Provides powerful lepton-universality tests (but requires new m_τ measurement).

Searches for LFV decays and heavy neutrinos

FCC-ee will have high sensitivity to LFV Z^0 decays. Of particular interest are those involving 3rd generation, *e.g.* $Z^0 \to e\tau$, $\mu\tau$, where current limits are in the $\sim 10^{-5}$-10^{-6} range, & can be greatly improved with 5 x 10^{12} Z^0s [Abada *et al*., JHEP 04 (2015) 051].

Direct searches in $Z^0 \to \nu N$ for heavy right-handed neutrinos N, with masses below M_Z, will also benefit from the enormous number of Z^0s available.