Requirements on FCC-ee from the physics programme

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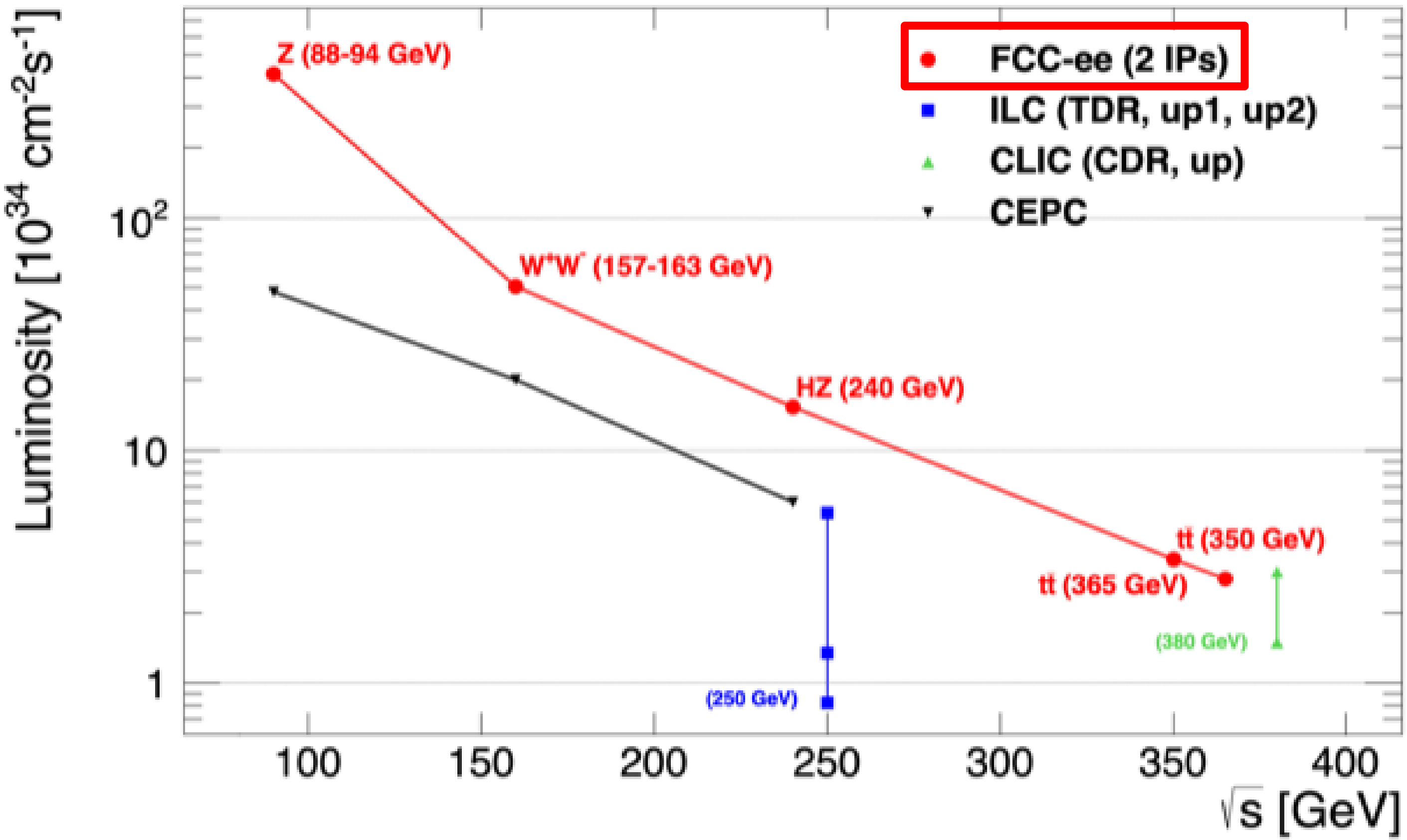
FCC week
28/6/21

Overview

- Run plan: why so many energy points, & why so much data ?
- The compelling case for four interaction points
- E_{CM} calibration: what is required, & what are implications for operation ?
- Monochromotisation: the motivations for & challenges of a run at E_{CM} = 125 GeV
- The machine-detector interface, with some words on beampipe radius

FCC-ee: baseline run plan

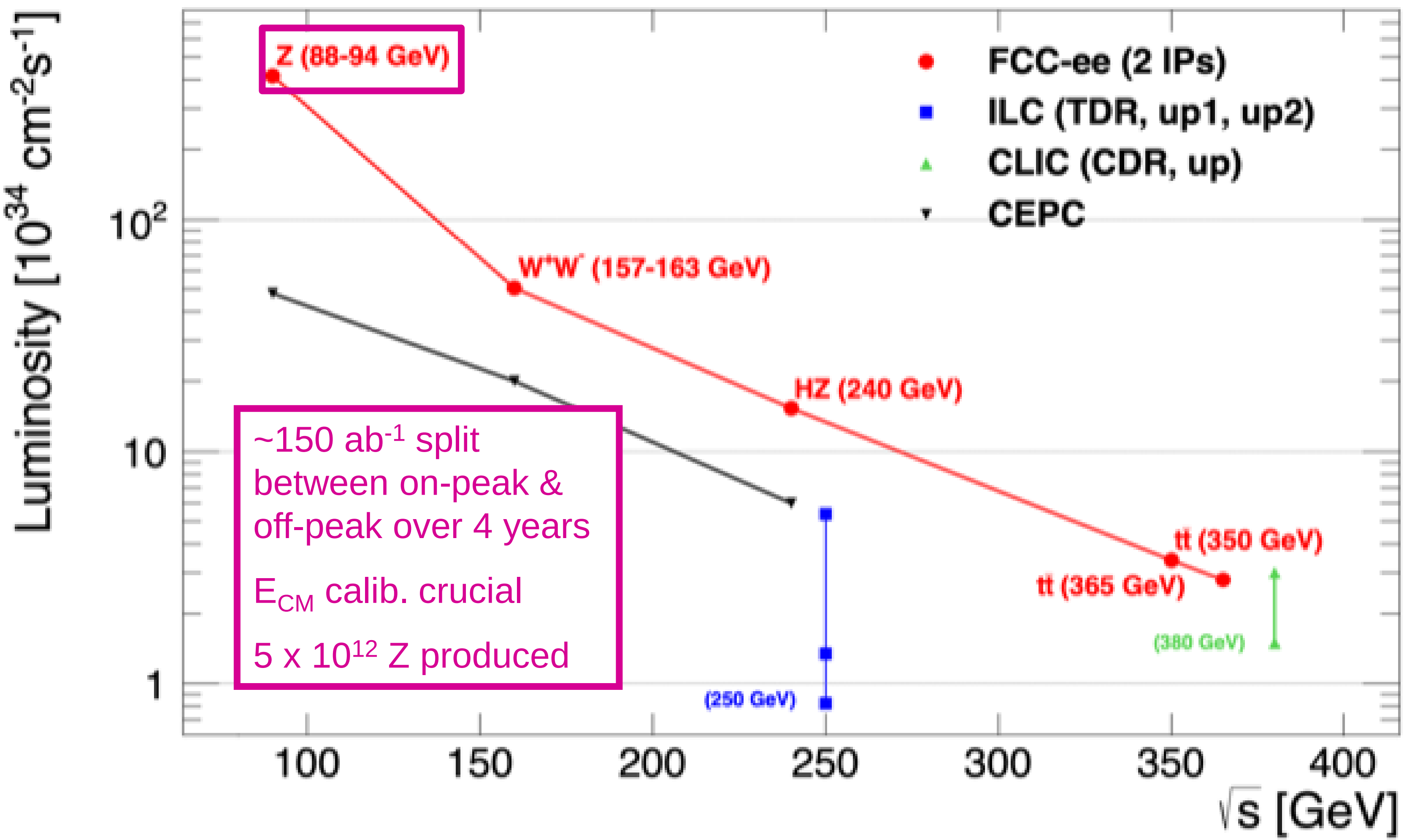
(according to Conceptual Design Report)



Flexibility required (within reason) for order in which each sample is collected.

Here discussion will proceed (mostly) ordered by E_{CM} – this is not a proposal !

FCC-ee: baseline run plan



~150 ab^{-1} split between on-peak & off-peak over 4 years

E_{CM} calib. crucial

5 x 10^{12} Z produced

Why 4 years and ~150 ab^{-1} at & around the Z pole ?

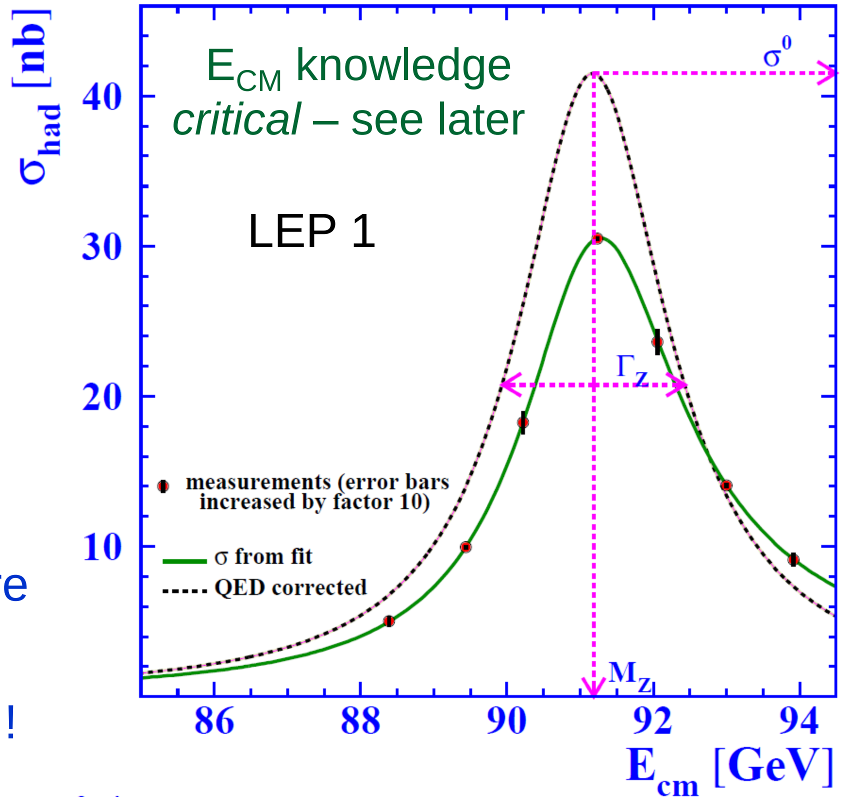
With the discovery of the Higgs, all particles of the SM have now been found.
Very precise measurements of their properties & behaviour, *e.g.* through electroweak observables at (& above) Z pole, will stress-test self-consistency of theory.

A rich array of measurements awaits, for example lineshape parameters:

	LEP uncertainty	Current FCC-ee estimate
m_Z	2200 keV	100 keV (10^{-6} !)
Γ_Z	2300 keV	25 keV (10^{-5} !)

These measurements will unavoidably remain systematics limited (foreseen stat. uncertainty ~4 keV for both), but will require significant time and attention to get right.

Year-1 of Z run will not yield the final result !



Why 4 years and ~150 ab^{-1} at & around the Z pole ?

With … d.
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obse…

A ric…
for e…

m_Z

Γ_Z

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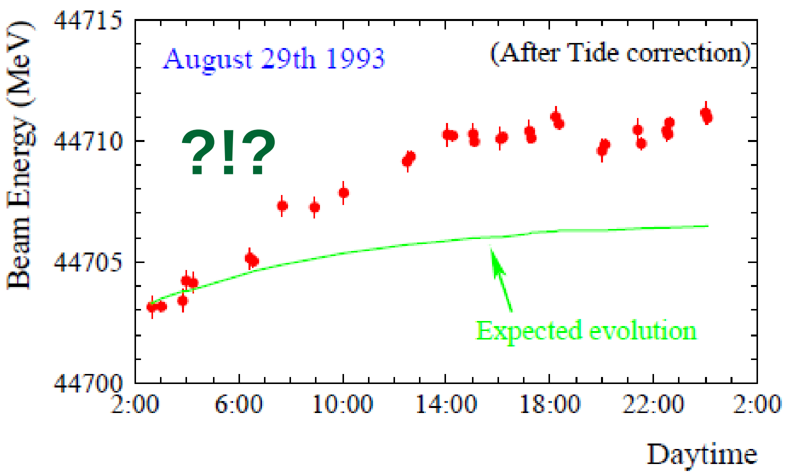
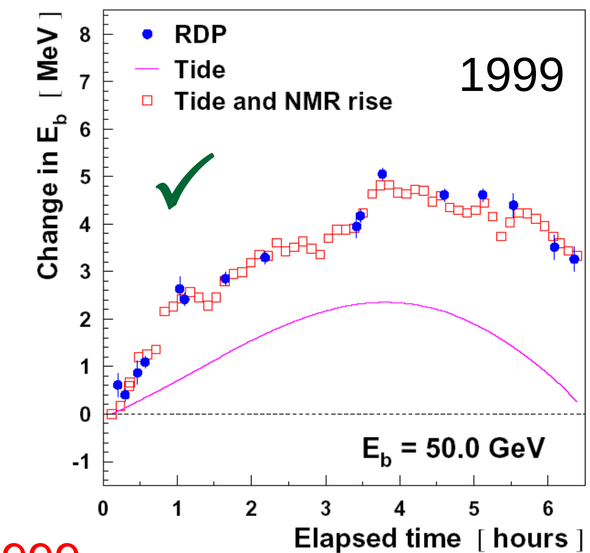
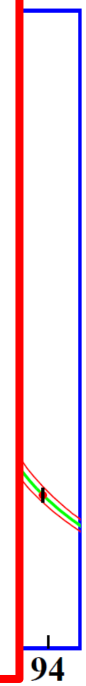
Lessons from history: a puzzling E_b calibration test during 1993 resonance scan required second scan campaign in 1995 to understand…





…with full validation only coming in 1999.

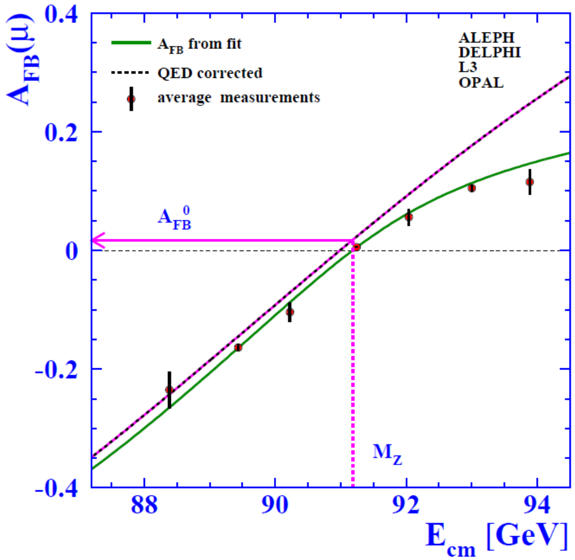


Year-1 of Z run will not yield the final result

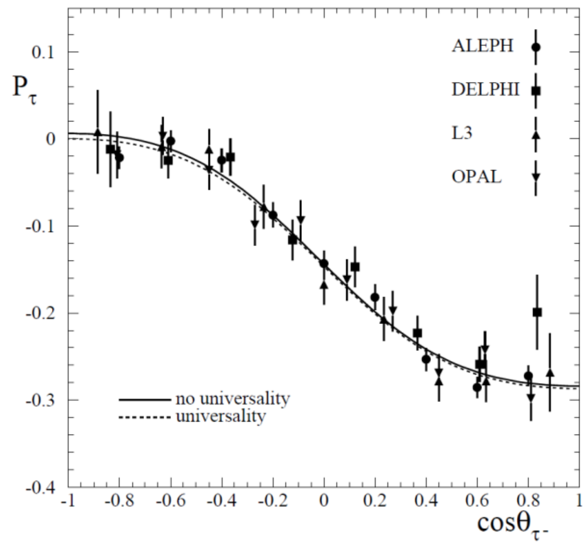
Why 4 years and ~150 ab^{-1} at & around the Z pole ?

Many Z observables have very small intrinsic experimental systematics, which will be further reduced, & may become sub-dominant, with hard work & data-driven studies. *e.g.* forward-backward lepton asymmetries (on-peak & off) (A_{FB}^{ll}), lepton-to-hadron ratios (R_l), tau-polarisation asymmetries ($A_{FB}^{pol,\tau}$), b-specific observables (A_{FB}^{b}, R_b).

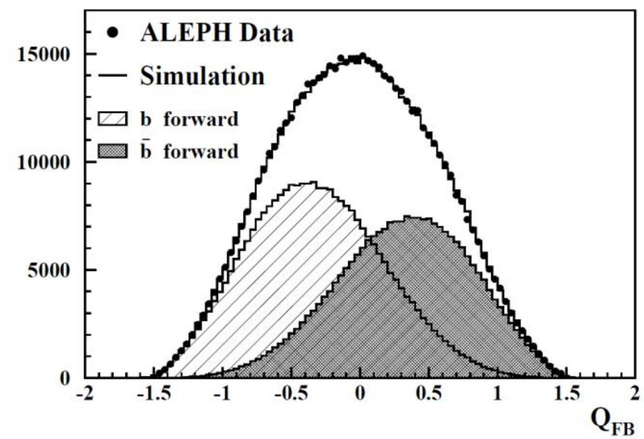
A_{FB} for muons



P_τ vs. $\cos\theta_\tau$



A_{FB} for b production

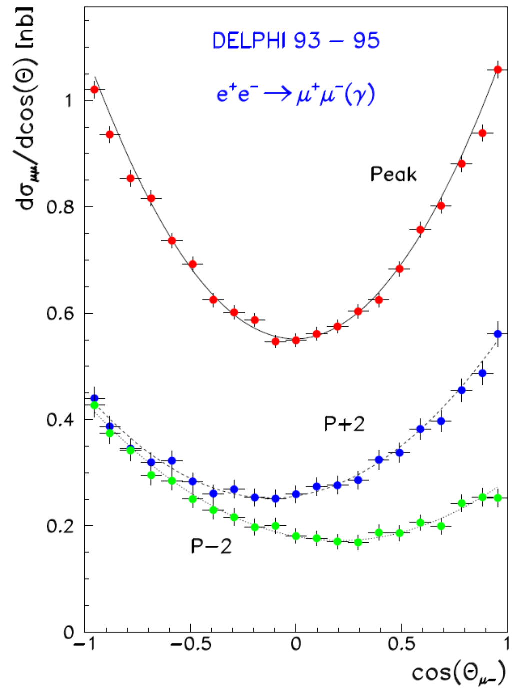


Why 4 years and ~150 ab^{-1} at & around the Z pole ?

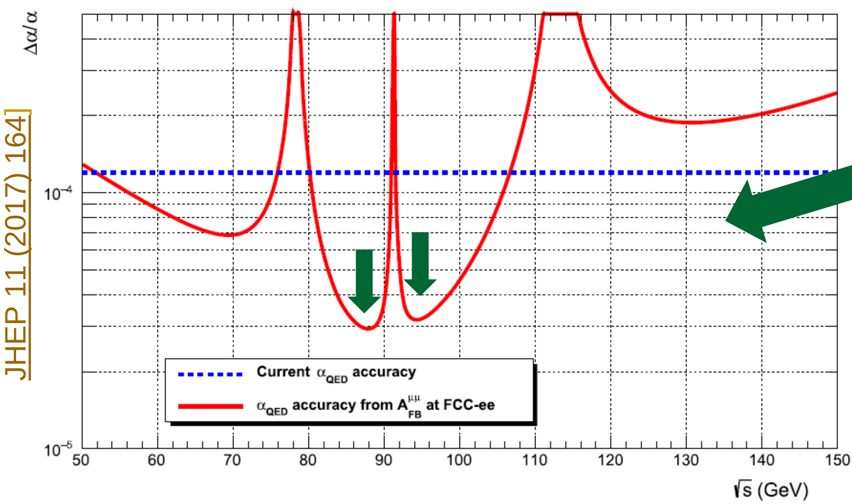
Excellent experimental control of off-peak di-muon asymmetry motivates campaign to collect 50-80 ab^{-1} off peak to gain highest sensitivity to Z-γ interference

$$A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4}\mathcal{A}_e\mathcal{A}_\mu \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{QED}(s)}{m_Z^2 G_F \left(1 - 4\sin^2\theta_W^{eff}\right)^2}\frac{s - m_Z^2}{2s}\right]$$

Allows for clean determination of $\alpha_{QED}(m_Z^2)$, which is a *critical* input for m_W closure tests (see later).



relative α_{QED} uncertainty with 80 ab^{-1}



[JHEP 02 (2016) 053, JHEP 11 (2017) 164]

This dependence, & location of half-integer spin tunes, guides the choice of off-peak energies: 87.8 & 93.9 GeV.

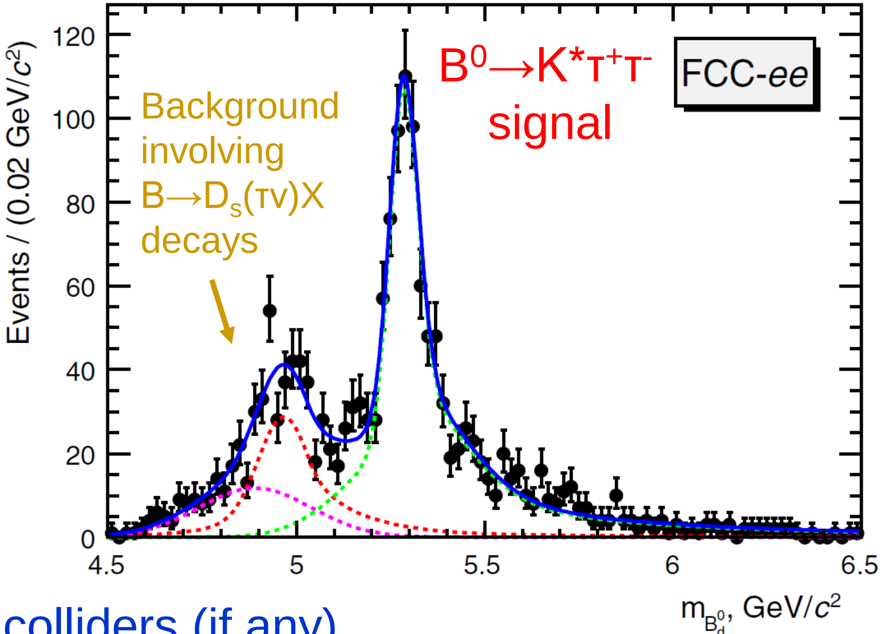
Goal: measure $1/\alpha_{QED}(m_Z^2)$ to +/- 0.003.

Why ~150 ab^{-1} @ Z ? Flavour-physics opportunities

For a flavour physicist *more is never enough* !   There are always important measurements that will remain statistics limited. Baseline will deliver a b sample that will be x15 Belle II (+ B_s, B_c & Λ_b) & *highly* complementary to LHCb upgrades.

A frequently shown plot, but one that's very topical.

(however there are very nice more recent studies, *e.g.* $B_c \to \tau\nu$. See Tues parallel and arXiv:2105.13330)



see *e.g.* arXiv:2106.01259

Unique possibilities at FCC-ee !

- Example of a measurement that LHCb can't really do;
- Z samples achievable at linear colliders (if any) will be too small for frontier b physics, in this mode or in almost any other.

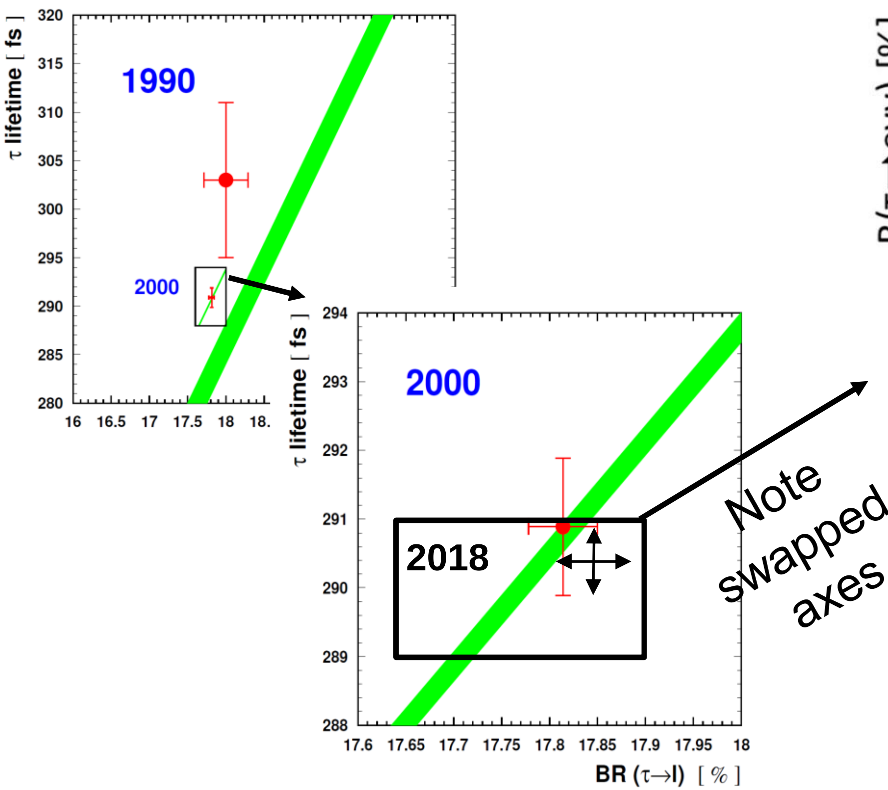
However, no cause for complacency:

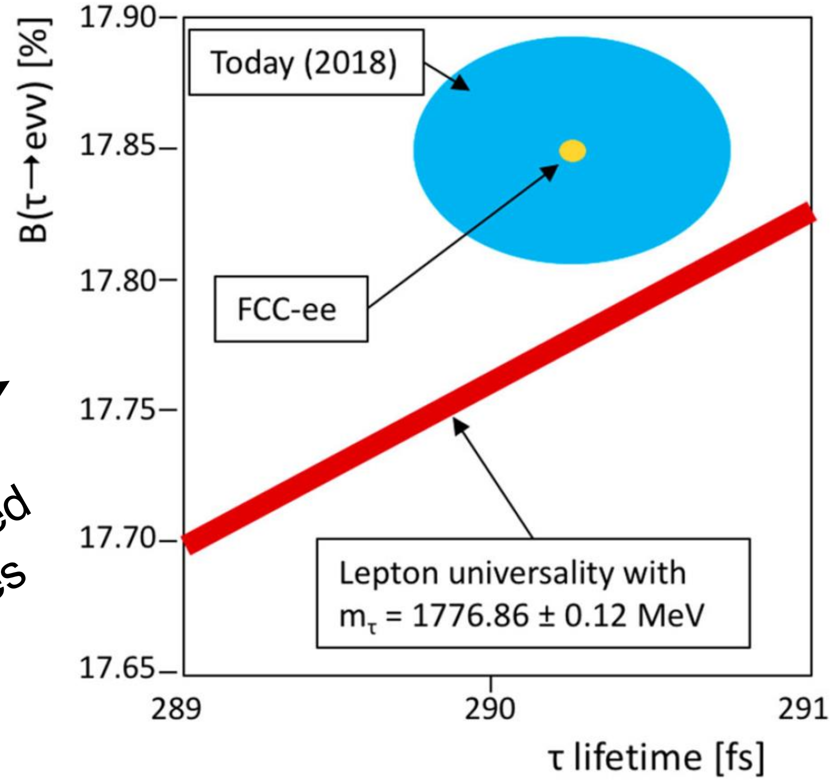
- Having smaller samples would be uncomfortable (& larger would be fantastic!) *c.f.* LHCb has ~5000 decays in the sister $B^0 \to K^*\mu\mu$ study [PRL 125 (2020) 011802].

Why ~150 ab^{-1} @ Z ? Flavour-physics opportunities

Tau physics leadership passed from LEP, to B factories, & then to Belle II.   FCC-ee will deliver 3-4 x more taus than at Belle II, with equally clean environment & boost.

Outstanding opportunities to push lepton-universality tests in muons vs taus (essentially G_F measurement with taus) to new frontier of precision !



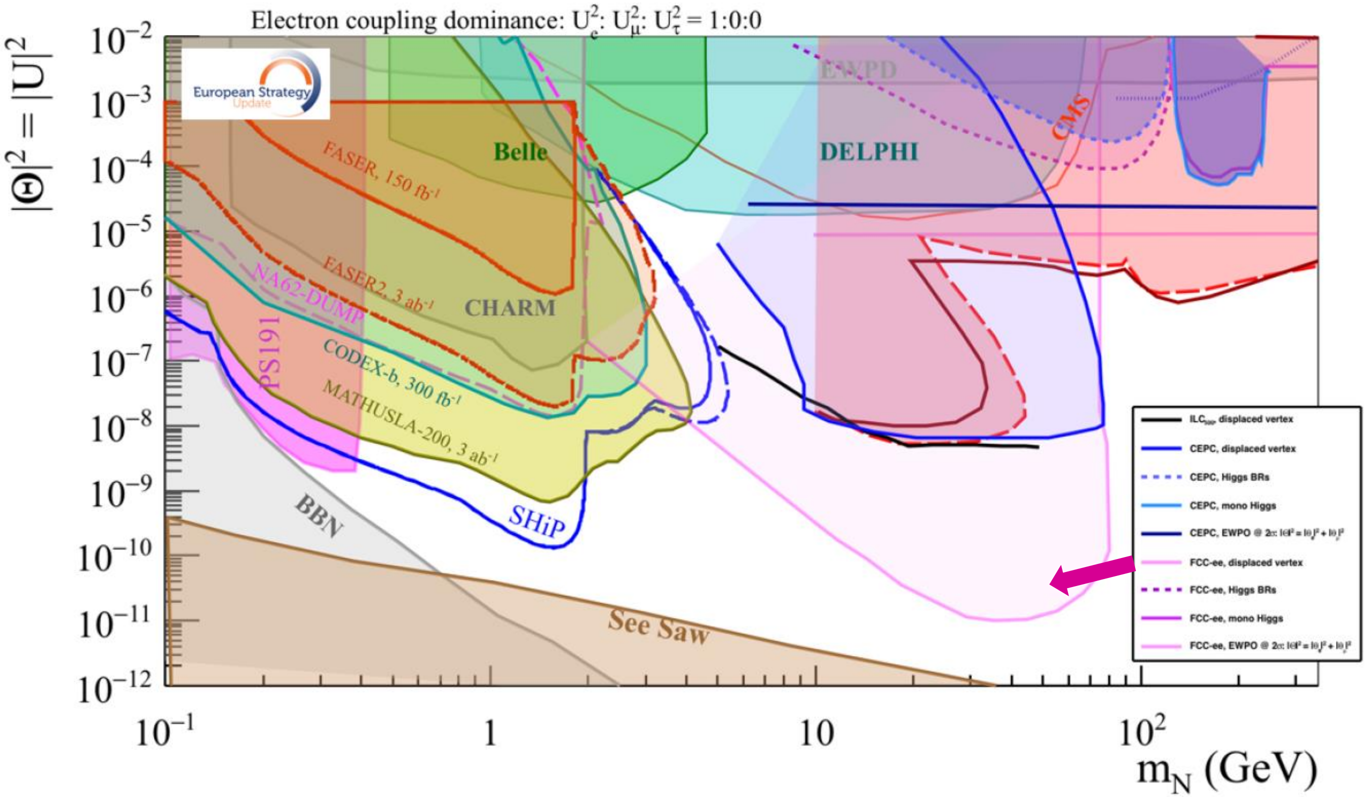


Also probe for LFV in tau decay, *e.g.* $\tau \to \mu\mu\mu$ to 10^{-10} – *very important* in context of hints for lepton-universality violation in LHCb data & elsewhere.

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.

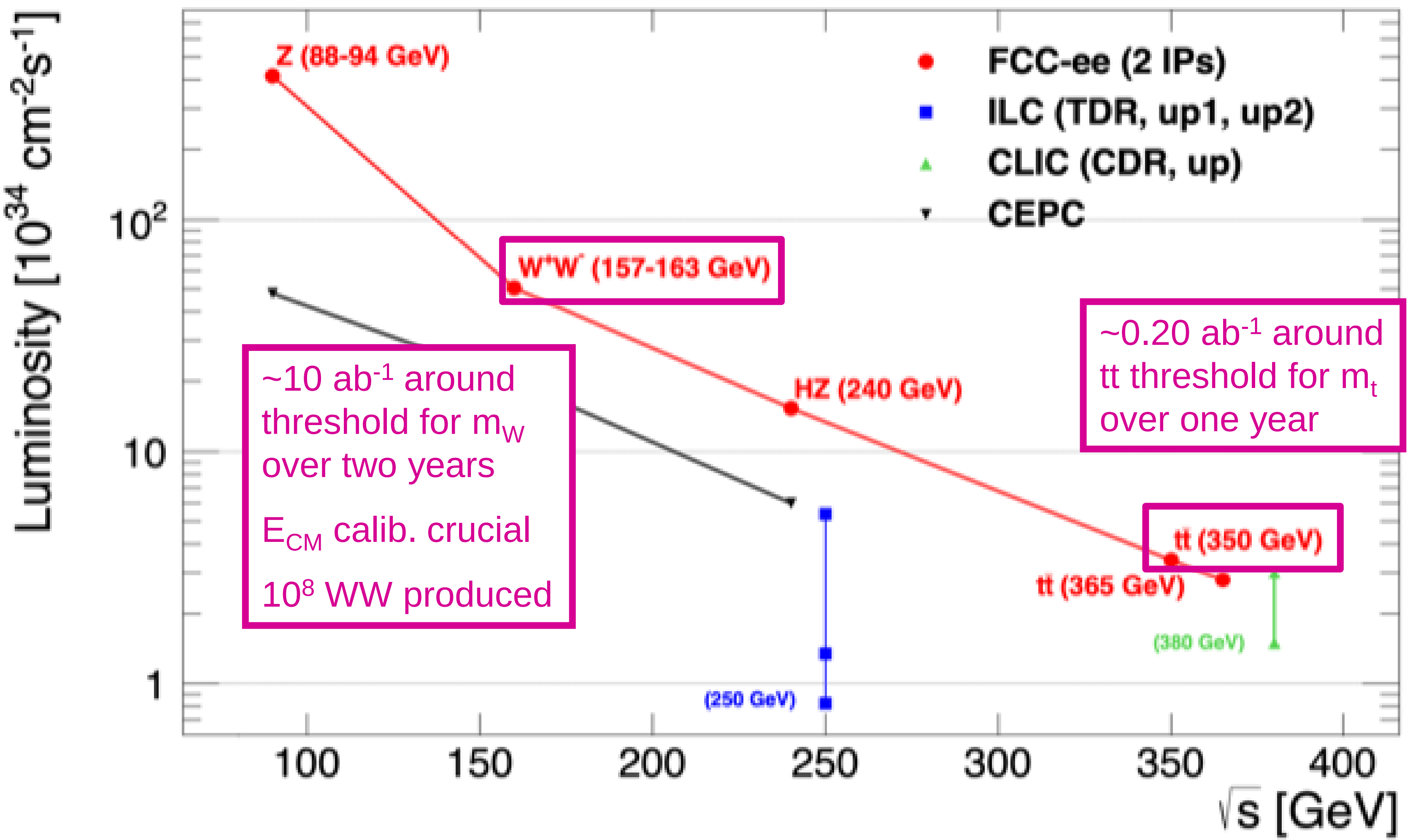
e.g. 90% CL exclusion limits for heavy neutral lepton



[arXiv:1910.11775, arXiv:1612.02728]

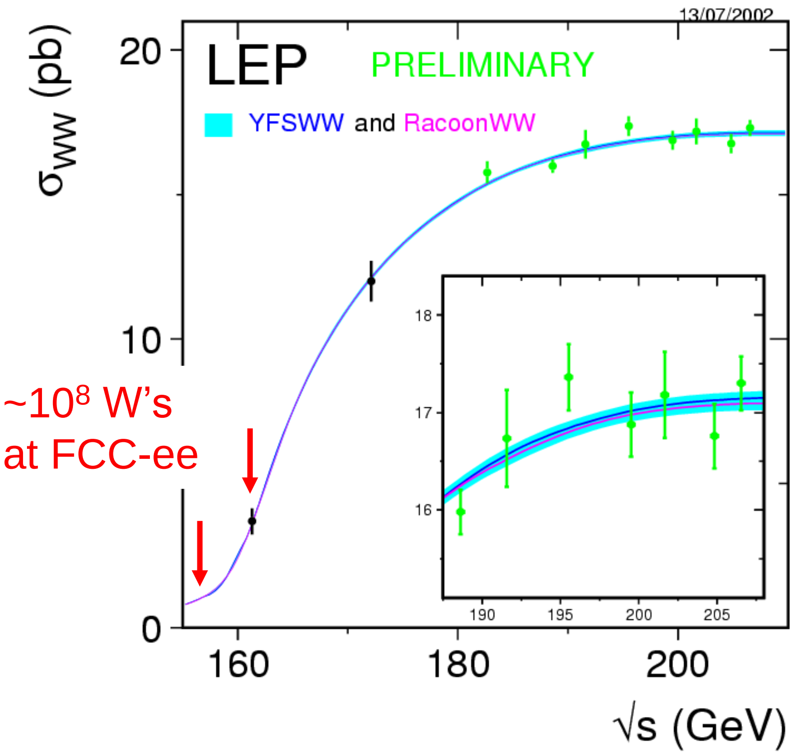
FCC-ee Z-pole running will have enormous potential in searches for LFV decays, heavy sterile neutrinos, axion-like particles *etc*. In all cases integrated lumi is key !

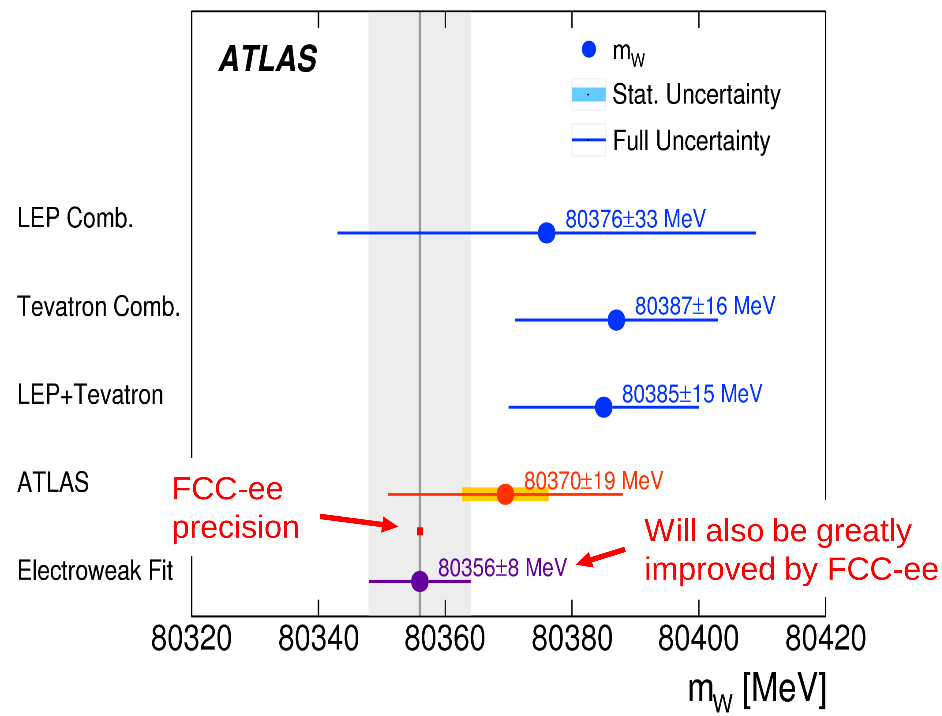
FCC-ee: baseline run plan



Why 2 years and 12 ab^{-1} at W^+W^- threshold ?

Threshold scan of 12 ab^{-1}, taken at 157.5 and 162.5 GeV will yield a statistical precision on m_W of 0.5 MeV. Provided E_{CM} can be controlled at similar, or better, level, this will give order of magnitude improvement on best hopes of LHC.

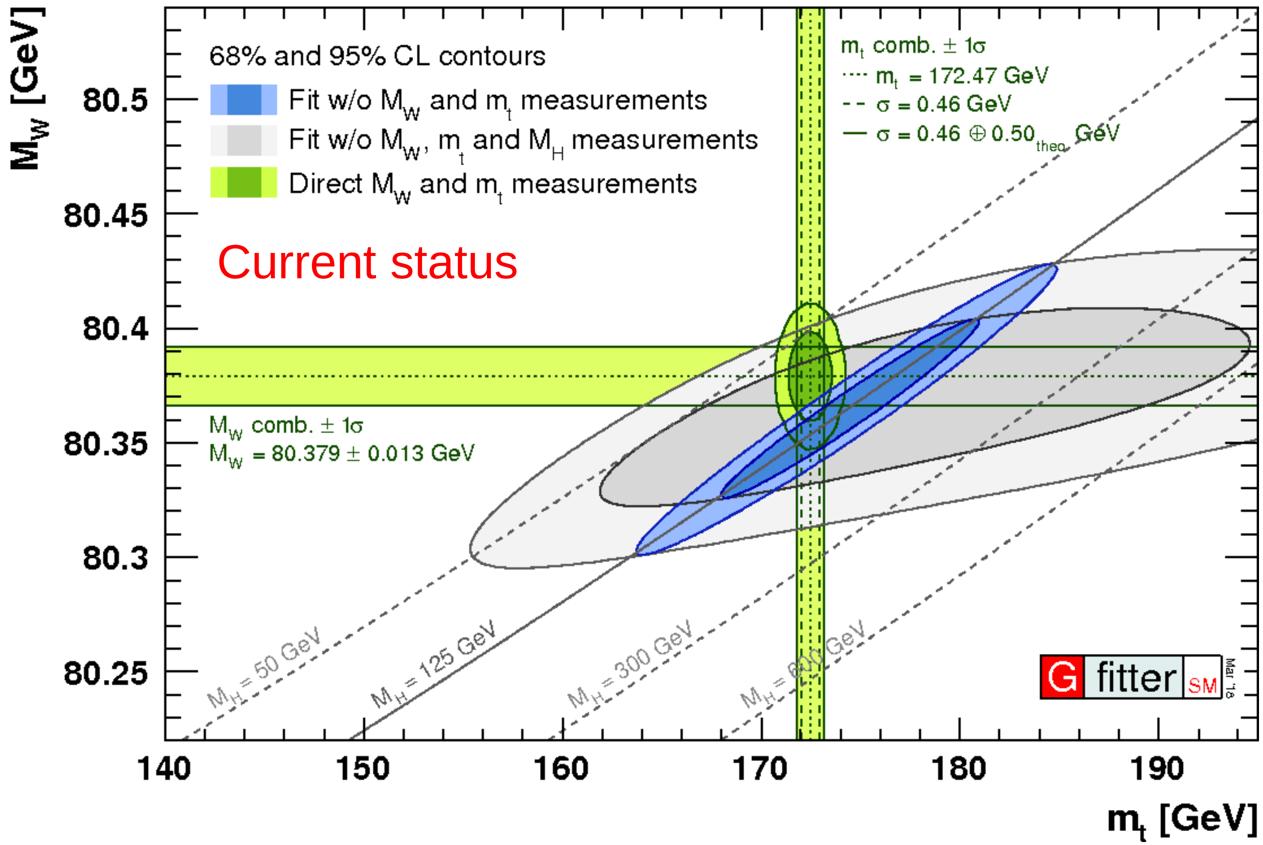




Data very valuable for other studies, *e.g.* V_{cb} from flavour-tagged jets, $\alpha_{QCD}(m_W^2)$ from BRs… Furthermore Zγ return events will provide 10^{-3} determination of N_ν.

Why measure m_W to ~0.5 MeV ?

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



Note, it's not only m_W we need to improve, but also indirect prediction & also m_t.

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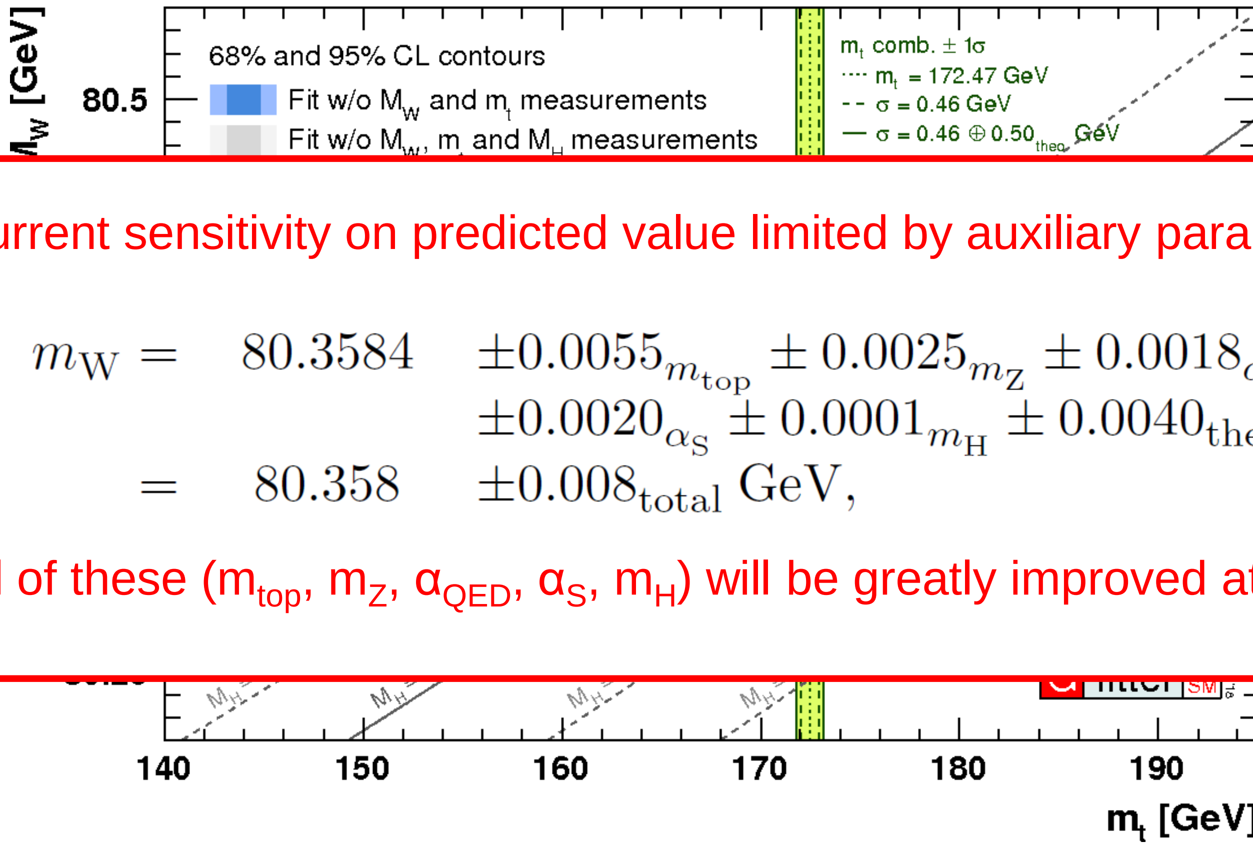


Current sensitivity on predicted value limited by auxiliary parameters.

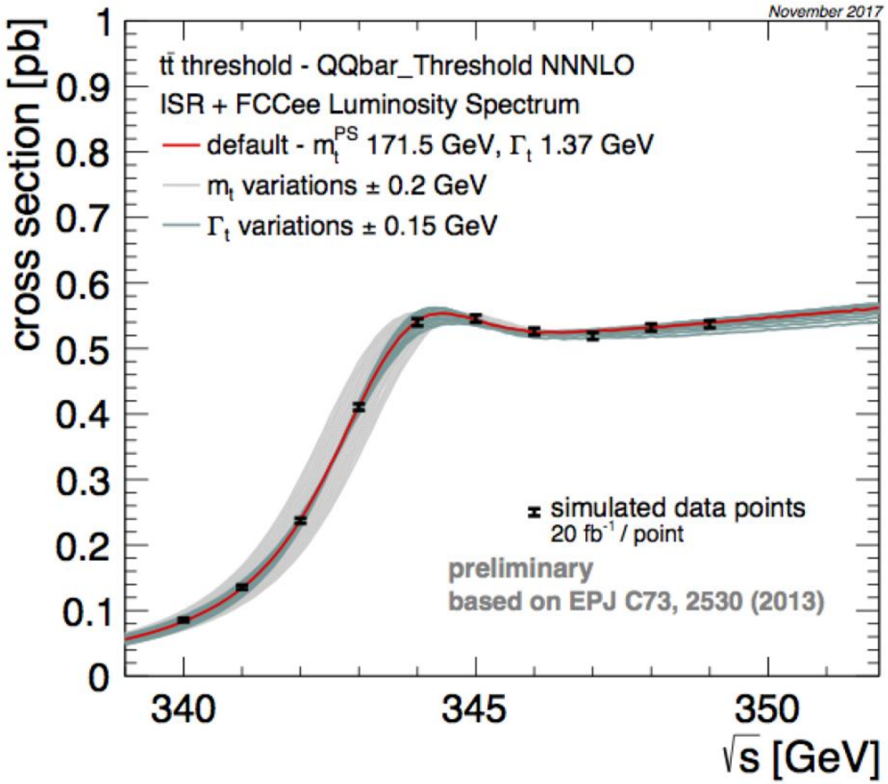
$$\begin{aligned} m_{\mathrm{W}} = \quad & 80.3584 \quad \pm 0.0055_{m_{\mathrm{top}}} \pm 0.0025_{m_{\mathrm{Z}}} \pm 0.0018_{\alpha_{\mathrm{QED}}} \\ & \qquad\qquad \pm 0.0020_{\alpha_{\mathrm{S}}} \pm 0.0001_{m_{\mathrm{H}}} \pm 0.0040_{\mathrm{theory}} \ \mathrm{GeV} \\ = \quad & 80.358 \quad \pm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

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

Note, it's not only m_W we need to improve, but also indirect prediction & also m_t.

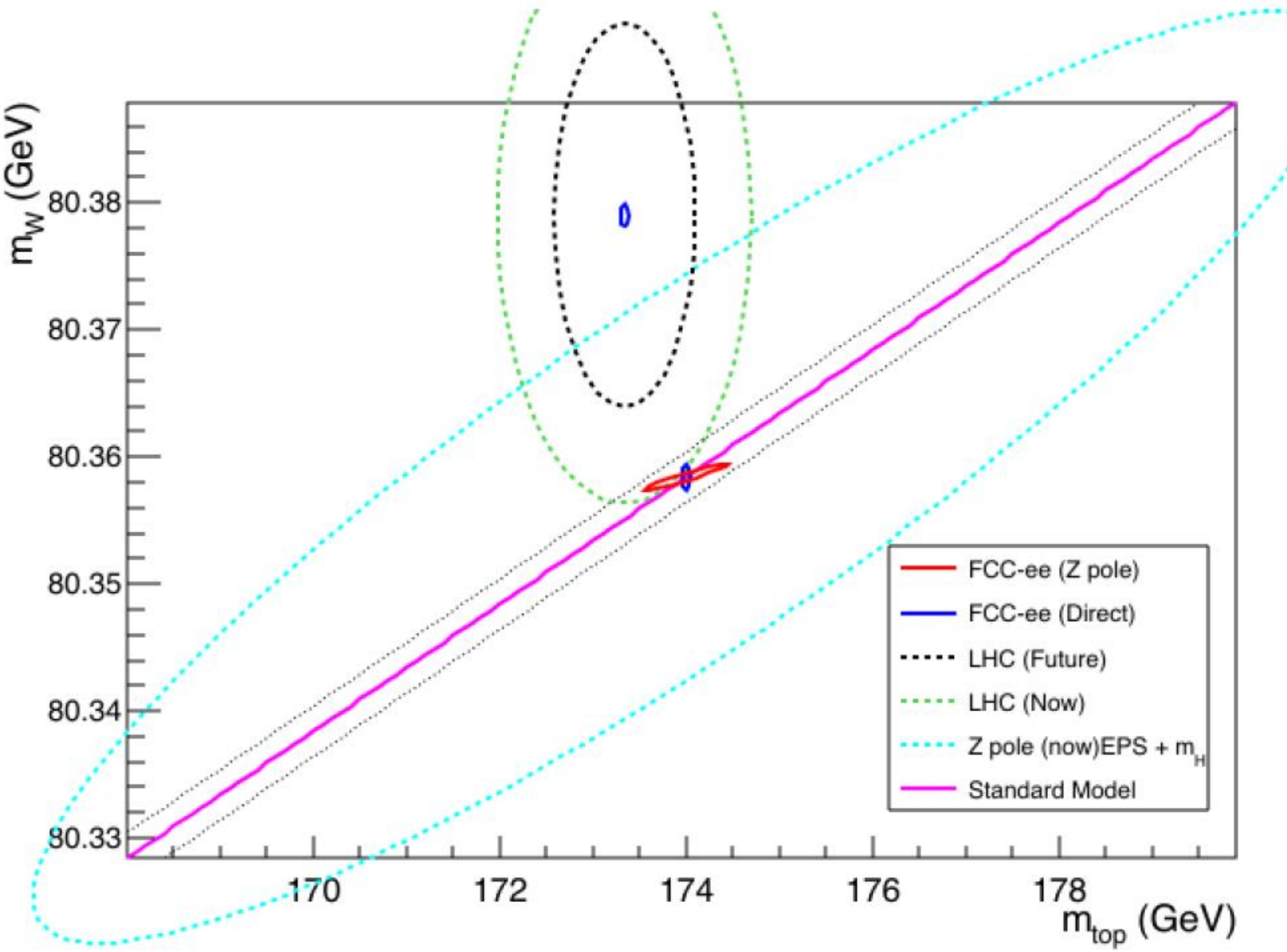
Going to higher energies: m_t

m_t known to ~0.5 GeV. Significant improvement needed for m_W closure test.

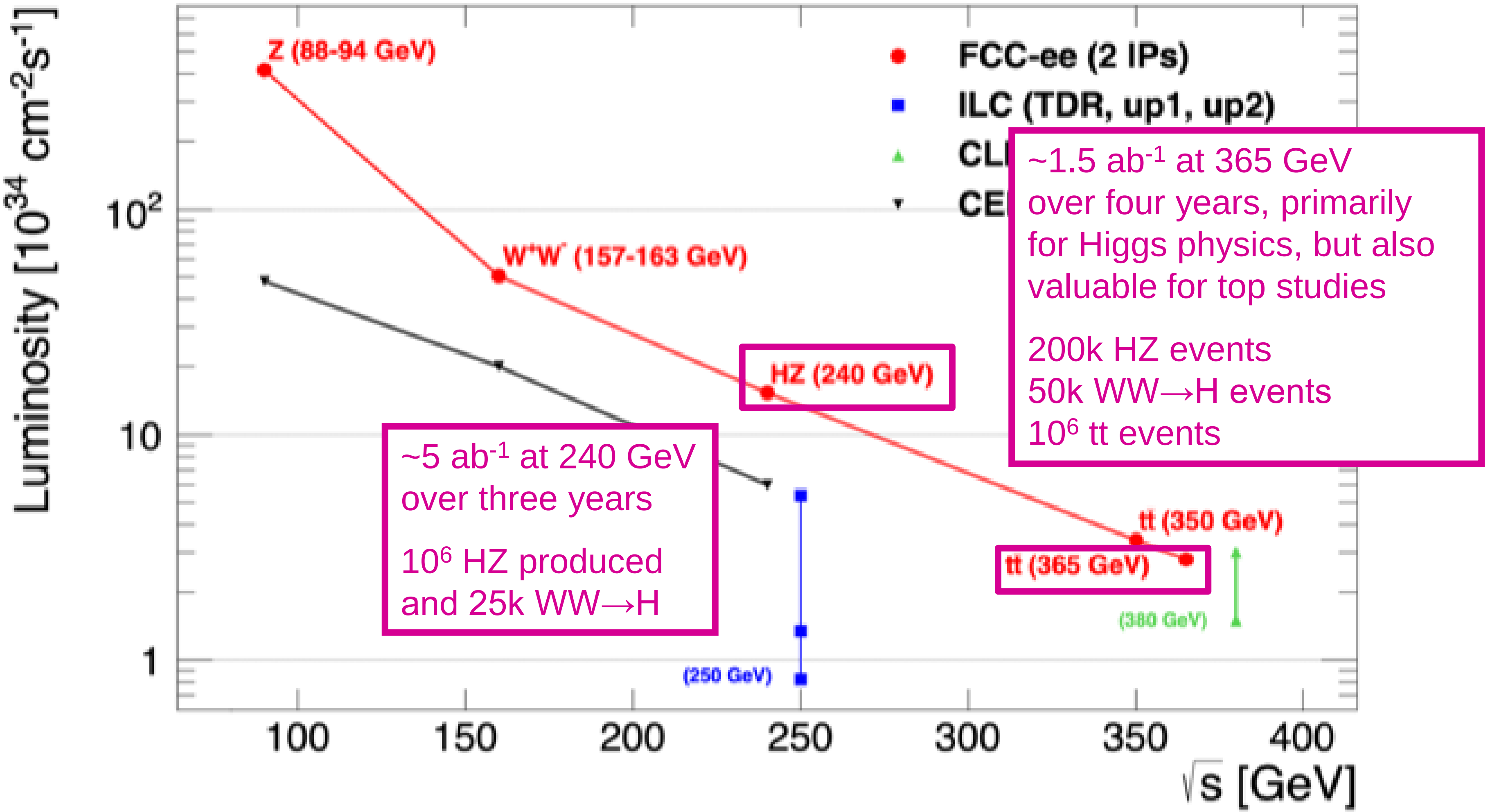


Multi-point threshold scan with 20 fb^{-1} / point will determine m_t to <20 MeV

Status of closure test after Z progamme, W^+W^- and $t\bar{t}$ threshold scans



FCC-ee: baseline run plan



~5 ab^{-1} at 240 GeV over three years

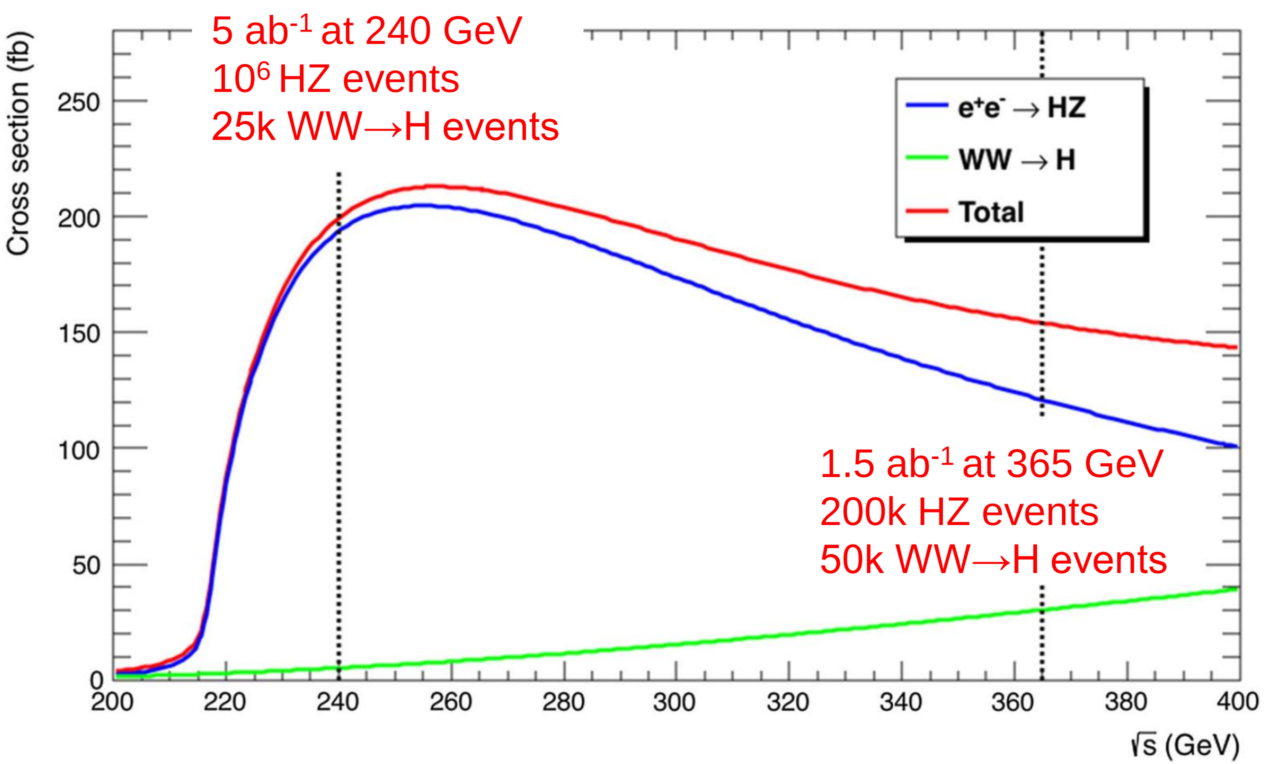
10^6 HZ produced and 25k WW→H

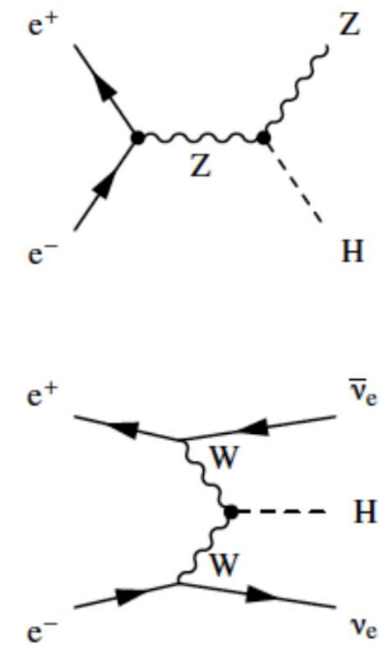
~1.5 ab^{-1} at 365 GeV over four years, primarily for Higgs physics, but also valuable for top studies

200k HZ events
50k WW→H events
10^6 tt events

Why study Higgs at two energies ?

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





Sensitivity to both processes very helpful in improving precision on couplings.

Why study Higgs at two energies ?

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

High precision achievable for all couplings; good complementarity to HL-LHC:

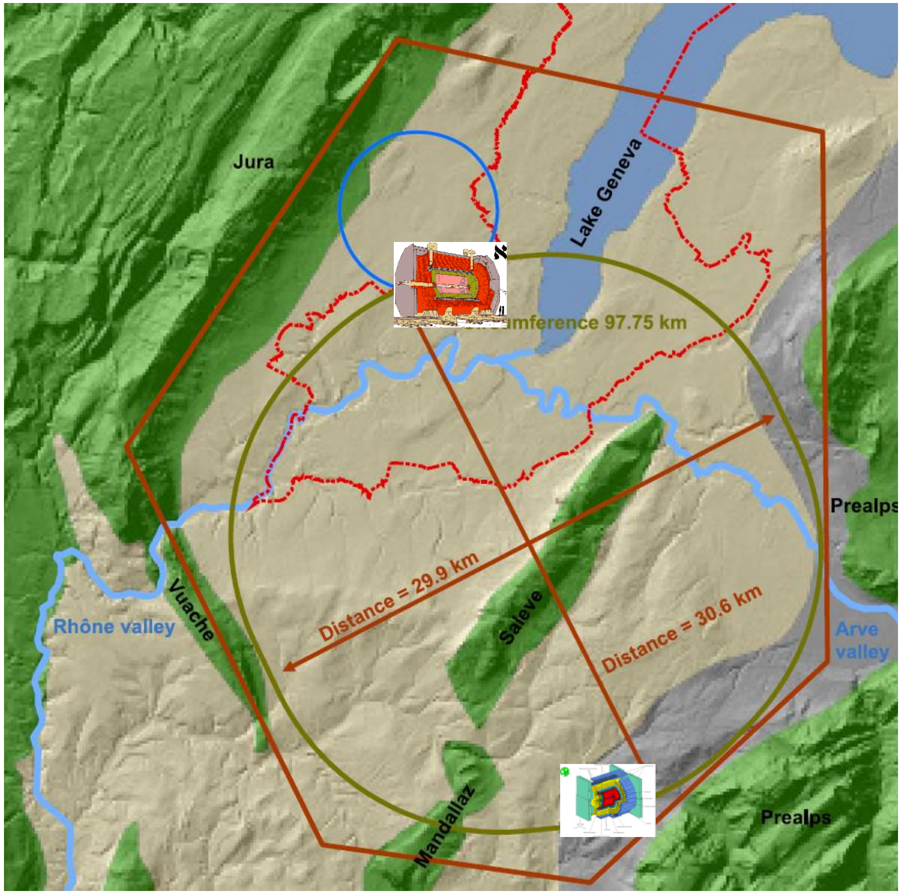
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{Hmm}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	$<$ **1.0**	$<$ **1.0**

Relative duration of 240 vs 365 GeV runs an interesting optimisation question in context of sensitivity to Higgs self coupling (see 2 IP vs 4 IP discussion).

Sensitivity to both processes very helpful in improving precision on couplings.

How many interaction points ?

FCC-ee design as presented in CDR foresees two interaction points.



How many interaction points ?

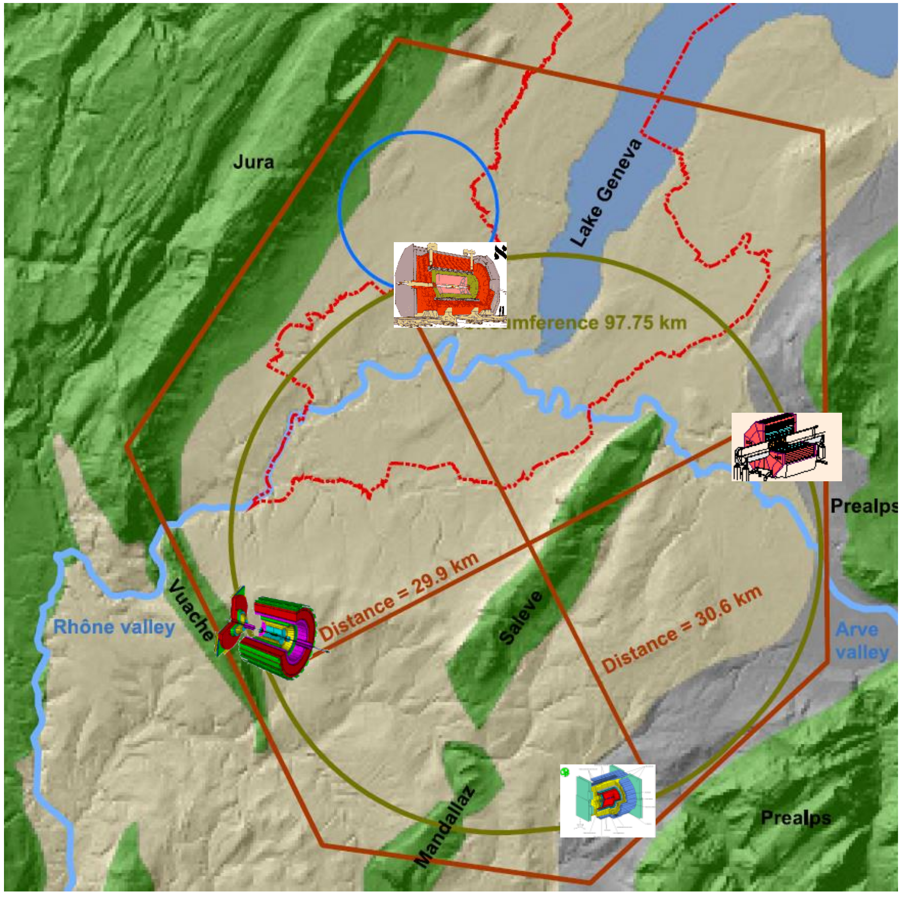
FCC-ee design as presented in CDR foresees two interaction points.

However, there are strong physics-driven arguments for evolving to a four interaction-point layout.

Key points (there are others):

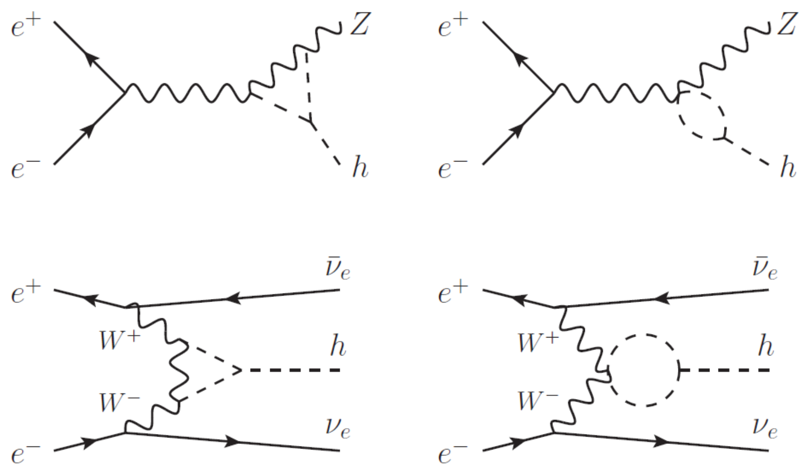
- More data, sooner;
- Systematic robustness with redundancy;
- Better physics coverage.

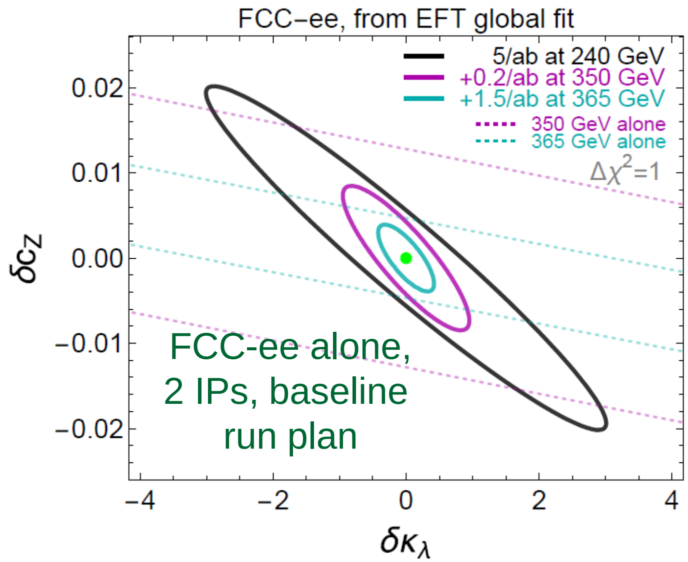
We will restrict ourselves to a single example for each.



Why 4 IPs? More data, sooner

Key example: 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.





[arXiv:1809.10041]

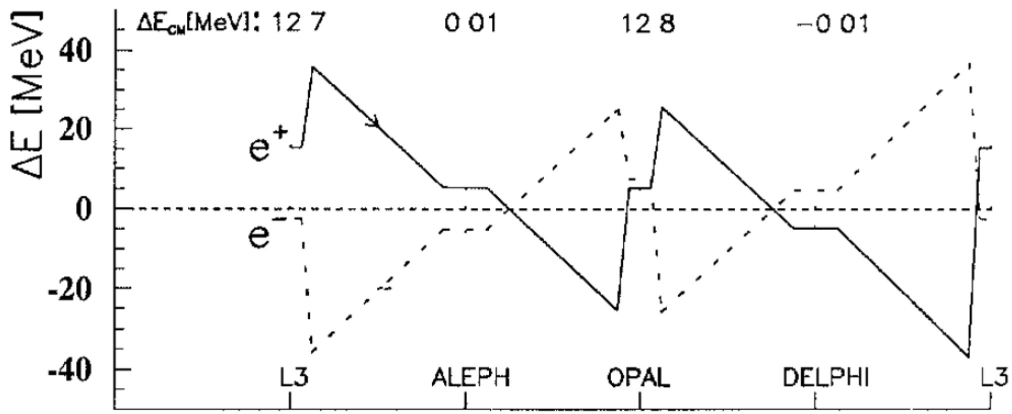
Baseline running strategy & 2 IPs gives +/- 42% on κ_λ , & +/ 34% with HL-LHC.

4 IPs both increases sample sizes, & allows initial stages of FCC-ee programme to be completed earlier, freeing up time for longer high-energy operation.

A very important lever (among several) for enabling discovery before FCC-hh !

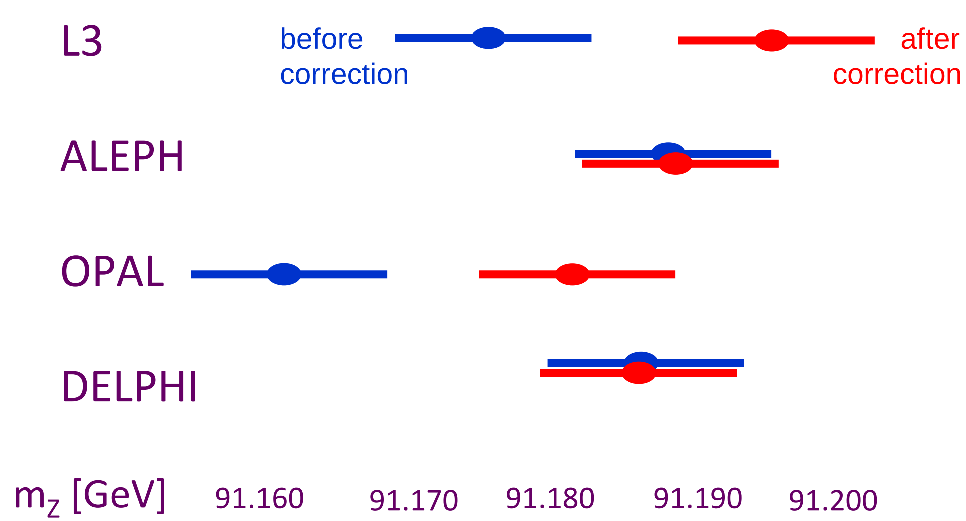
Why 4 IPs? Systematic robustness

With only two experiments, important systematic effects risk being overlooked.



At LEP, it was inspection of 1991 individual m_Z results from each experiment that led to appreciation of effect of `RF sawtooth'

[PLB 307 (1993) 187] .



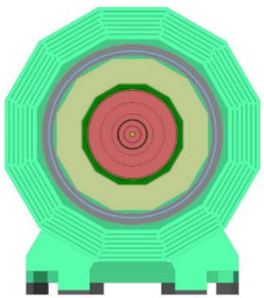
On a ring containing only L3 & OPAL (or ALEPH & DELPHI) this would have been much harder to spot.

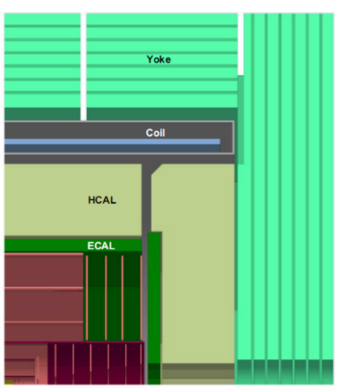
Why 4 IPs? Better physics coverage

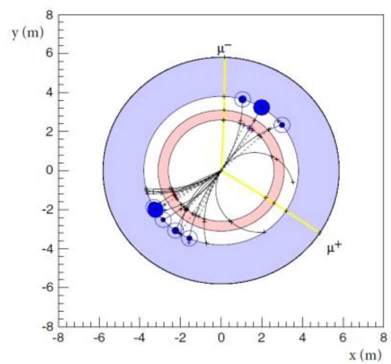
Having four detectors allows for a wide range of technological solutions that can fully exploit wide and rich physics possibilities of FCC-ee programme.

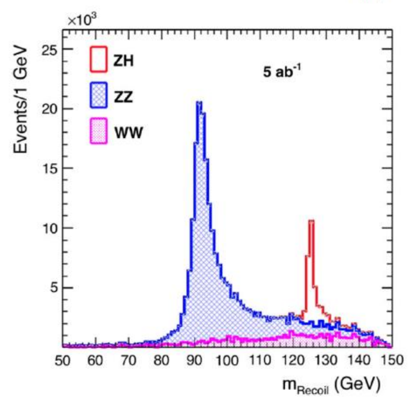
e.g. for flavour physics require PID over wide momentum range and calorimetry with good energy resolution for soft π^0 reconstruction.

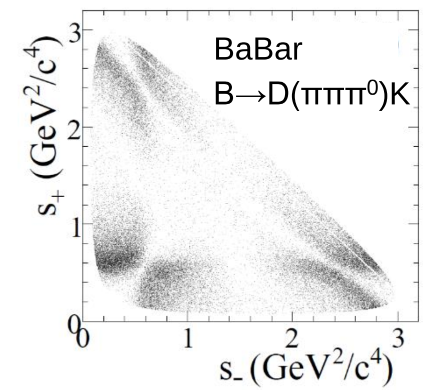
Such a design… …great for this…. …less good for this.



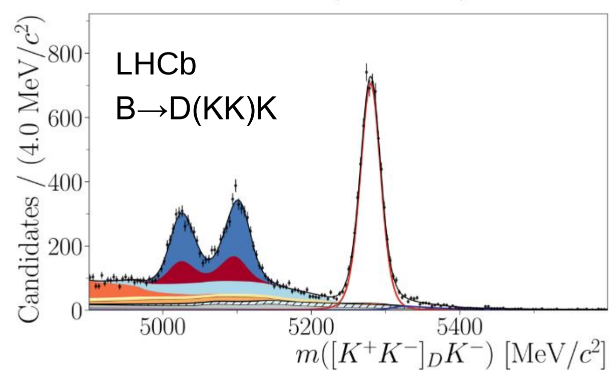








[PRL 99 (2007) 251801]



[JHEP 04 (2021) 081]

Requirements on E_{CM} knowledge

Painstaking work required at LEP to ensure E_{CM} knowledge was sufficient for flagship EW measurements. Even more stringent goals set at FCC-ee.

Uncertainties from E_{CM} *

	m_Z	Γ_Z	m_W
LEP	1.7 MeV	1.2 MeV	9 MeV
FCC-ee (current estimate)	100 keV	25 keV	300 keV

Doesn't look easy !

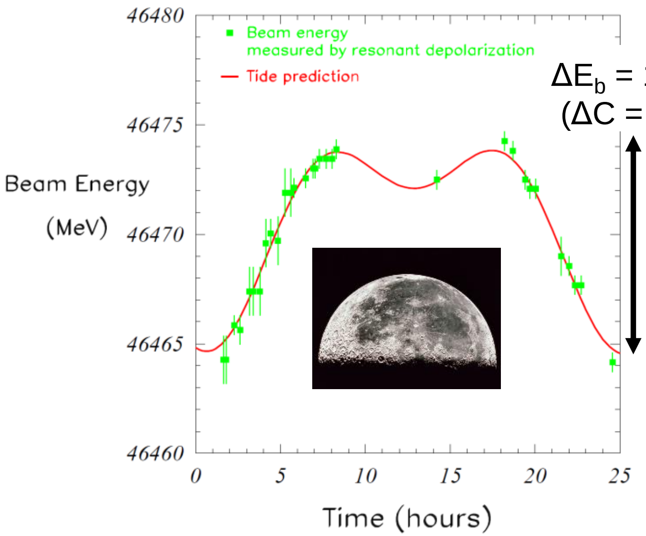
(Control of E_{CM} at this level is also necessary to keep the associated systematic < statistical uncertainty for $\sin^2\theta_W$ from A_{FB} , $\alpha_{QED}(m_Z)$ & many other observables.)

What were the main challenges that existed at LEP ?

- Precise measurement of E_b through Resonant Depolarisation (RDP), but only in a few fills, before or after collisions. E_{CM} knowledge limited by modelling of time evolution between measurements. FCC-ee requires a change of strategy !
- Beam polarisation not available at WW threshold, so RDP not possible. This problem should not exist at FCC-ee thanks to reduced energy spread.

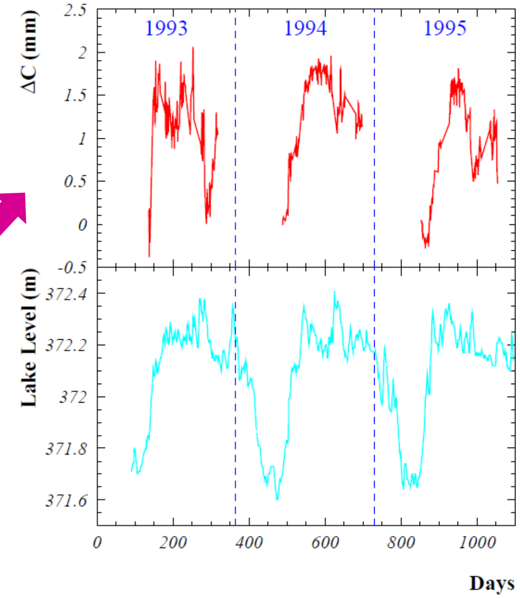
* knowledge of E_{CM} spread also plays a role for FCC-ee Γ_Z & $\alpha_{QED}(m_Z^2)$

Some mechanisms of E_b variation at LEP

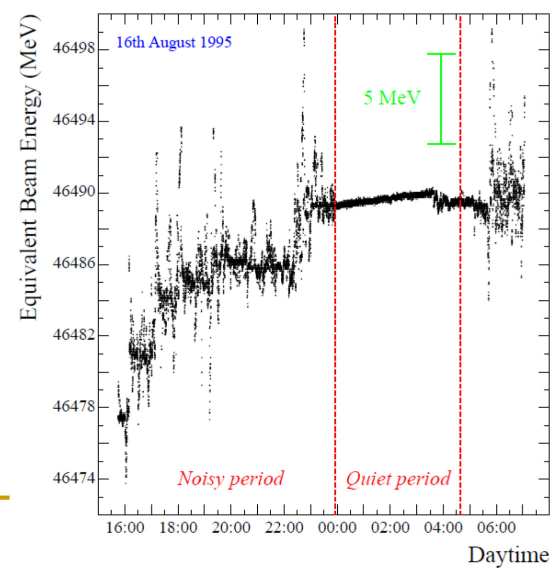


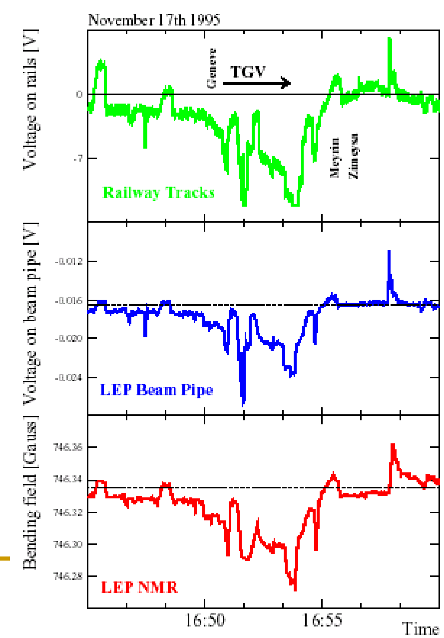
ΔE_b = 10 MeV
(ΔC = 1 mm)

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



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





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

[see arXiv:1909.12245]

Requirements on E_{CM} knowledge

E_{CM} calib. must be a central consideration in FCC-ee design & operational strategy.

- RDP quasi-continuous: perform on pilot bunches for e^- and e^+ several times an hour (overhead: for Z running need to spend ~1 hour at start of fill with wigglers on to allow polarisation to accumulate)

  → removes to 1st order all E_b time-variation issues that plagued LEP.

- f_{RF} change to keep beams centred in quadrupoles to suppress residual tidal effects on E_b; furthermore beam-beam offsets must be minimised to suppress dispersion-induced biases on E_{CM}.

- Investment in instrumentation & detailed logging of all machine parameters. Willingness to devote machine time to calibration studies (at LEP >50 full days taken in this manner from 1993 onwards).

Experiments must do their part: continual accumulation of $Z \rightarrow l^+l^-$ events enables relative energy changes, crossing angle, and energy spread to be monitored.

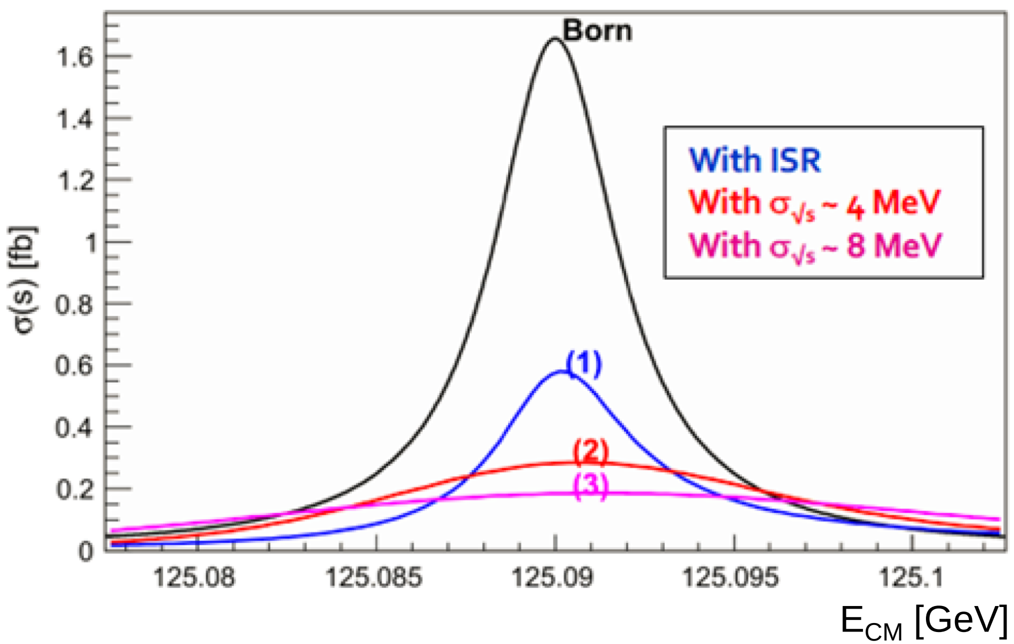
s-channel Higgs production and monochromatisation

An intriguing possibility, under evaluation and not in CDR baseline, is to devote a few years operation at $E_{CM}=m_H=125$ GeV to measure Yukawa coupling to electrons.

But cross-section is tiny…

…& effectively decreased further through ISR and because Higgs width (~4 MeV) small compared to E_{CM} spread.

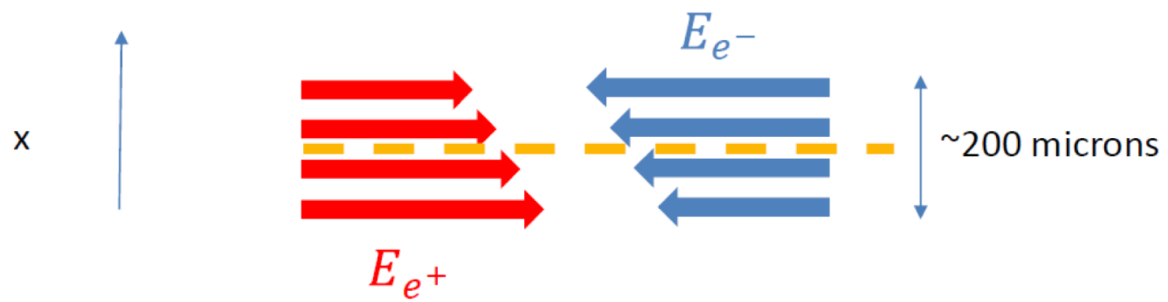
Note that natural E_{CM} spread for colliding beams is ~100 MeV. This must be reduced by < 1/10: the monochromatisation challenge !



Also need good knowledge of m_H (~ Γ_H), good E_{CM} knowledge, & high E_{CM} stability.

The monochromatisation challenge

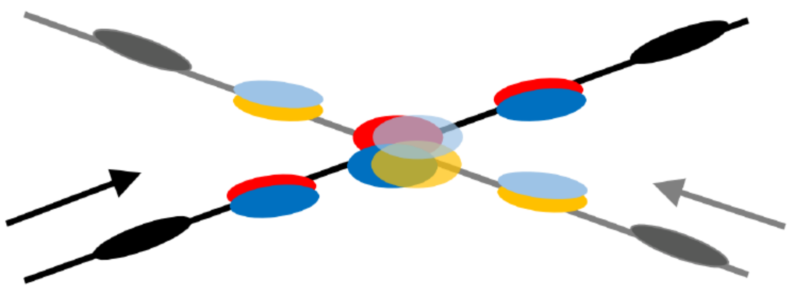
Introduce horizontal dispersion and collide head on to reduce E_{CM} spread.

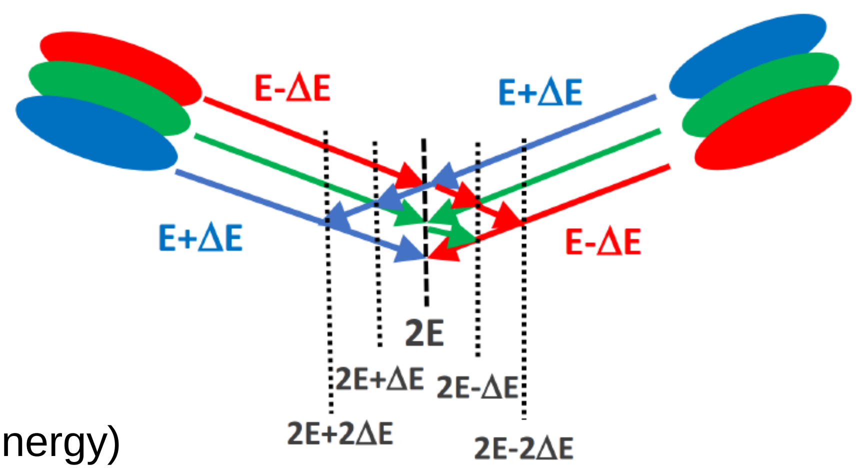


(arrow length ~ energy)

Require crab cavities to achieve head-on collisions

Alternatively live without cavities, and rely on good vertex resolution to account for correlation between x and E_{CM}.

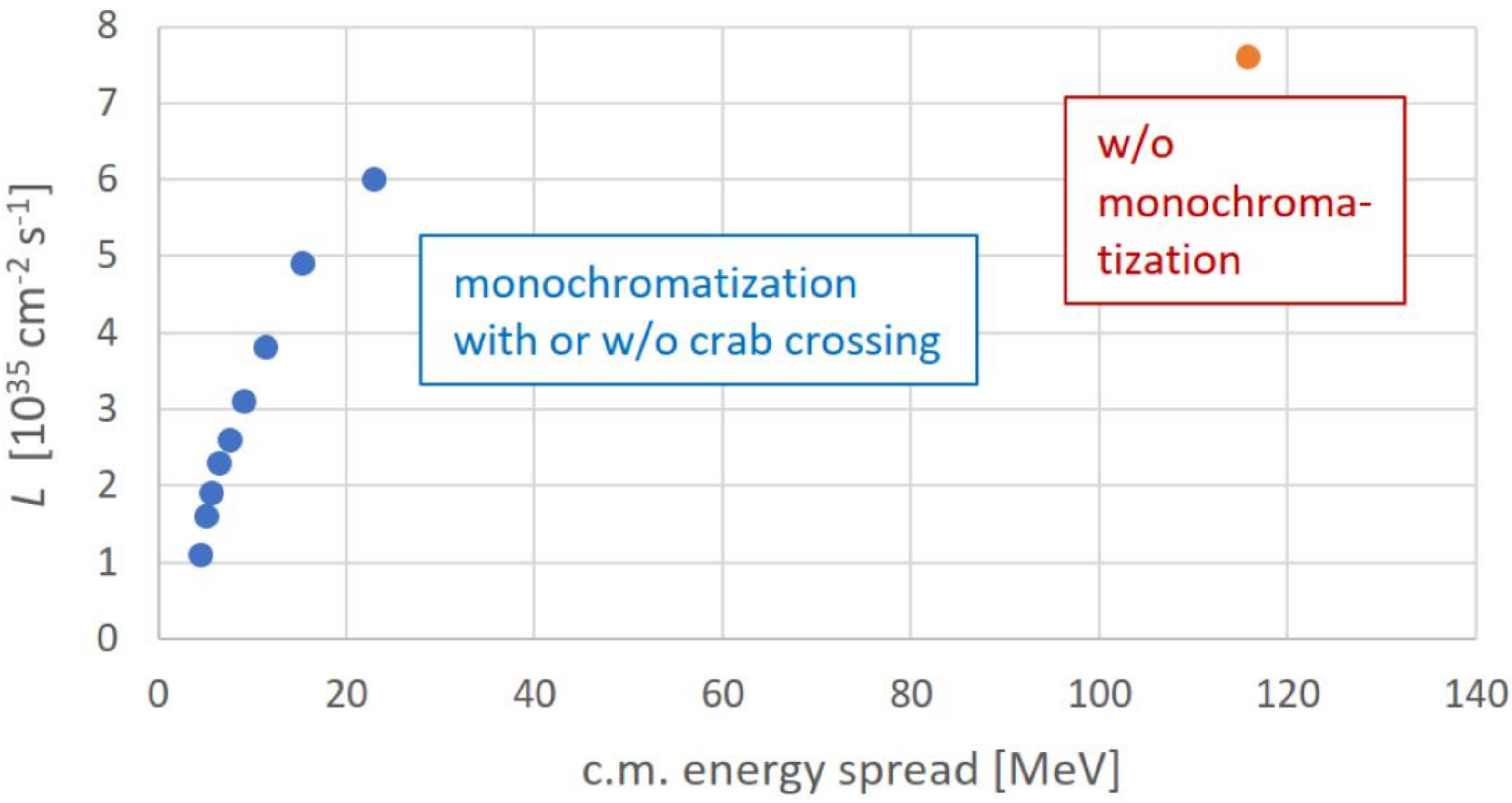




(colour ~ energy)

The monochromatisation challenge

However, dispersion increases horizontal emittance and reduces luminosity.

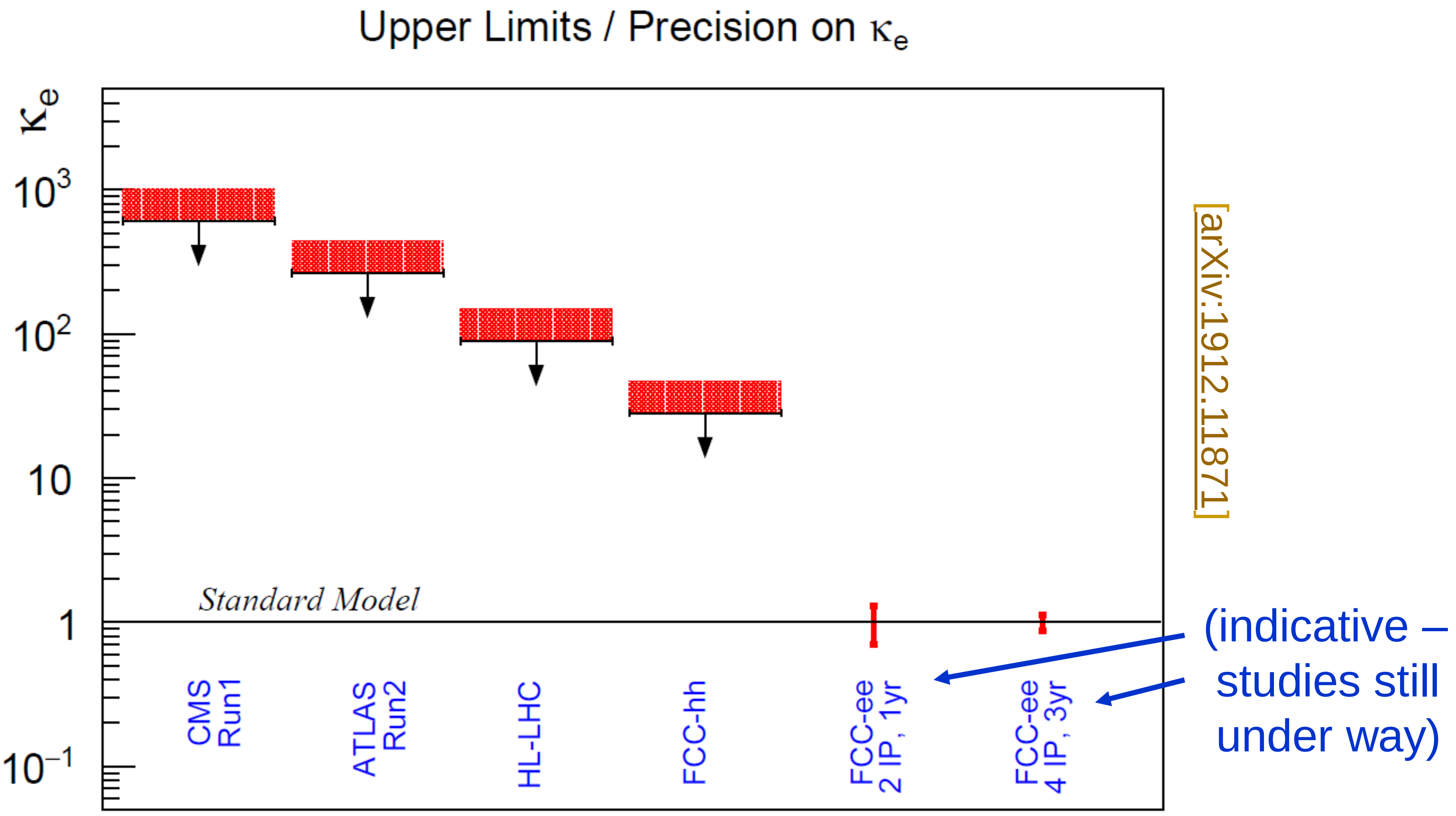


[Faus-Golfe, Garcia and Zimmermann]

An interesting optimisation problem, when event rate is so low.

The monochromatisation challenge

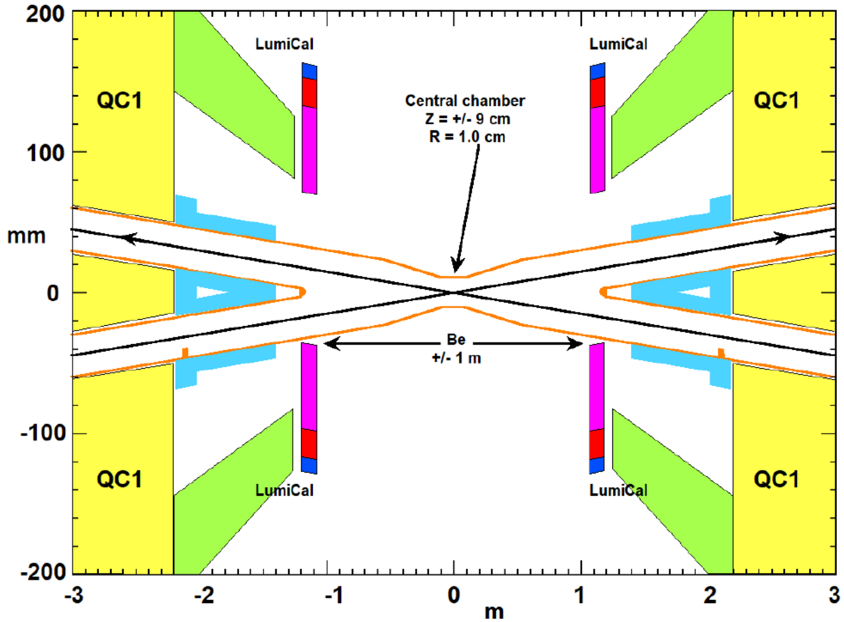
Studies still underway – likely require several years to reach SM value at 3σ. However, can do vastly better than any other machine. Also, motivation for 4 IPs !



Final remark: operation at E_{CM}=125 GeV is also valuable for accumulating radiative returns to the Z and improving sensitivity to the number of neutrino families.

Machine-detector interface

Careful attention must be paid to MDI layout so as not to limit performance.



[arXiv:2105.09698]

Agreed boundaries between machine & detector + conditions largely satisfactory:

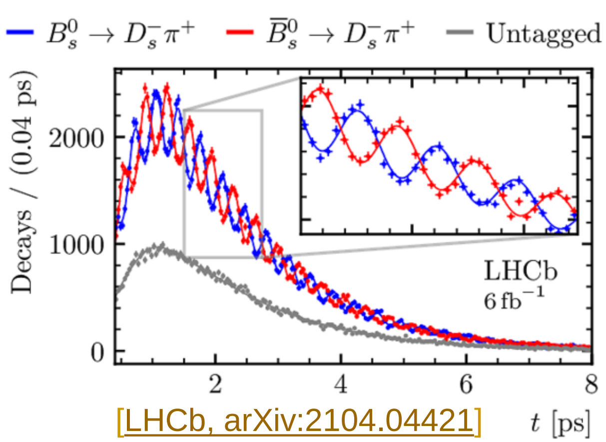
- 2T solenoidal field at Z (possibility of 3T at higher energies under study)
- Low angle acceptance down to 100 mrad. This small value desirable because:
  - Minimises impact on energy-flow measurements;
  - Helps keep systematics manageable for high statistics cross-section measurements.

Beampipe radius

An item where gains can still be made is beampipe radius, as radius of first measured point is crucial in determining secondary vertex resolution.

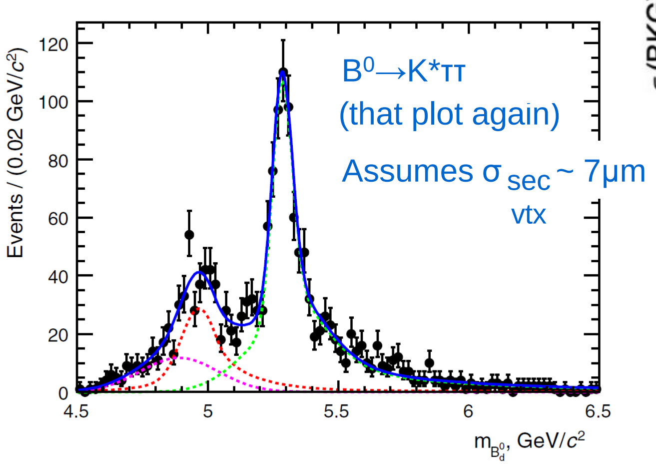
CDR design with r_{bp}=15 mm, and hence r_{first} ~ 17 mm, will limit performance.

Probably OK for B_s physics



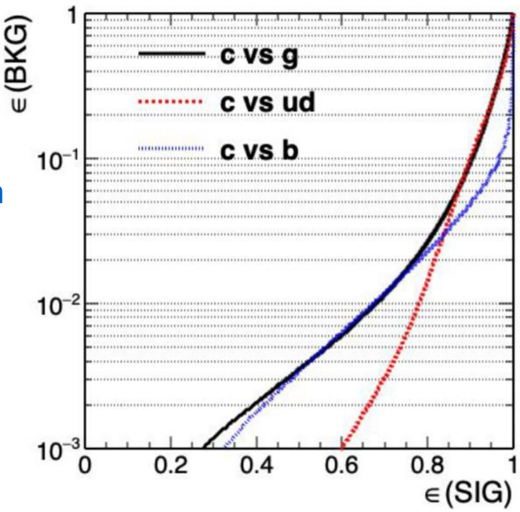
[LHCb, arXiv:2104.04421]

But almost certainly not for reconstruction of decays with neutrinos via vertex constraints



[Monteil, arXiv:2106.01259]

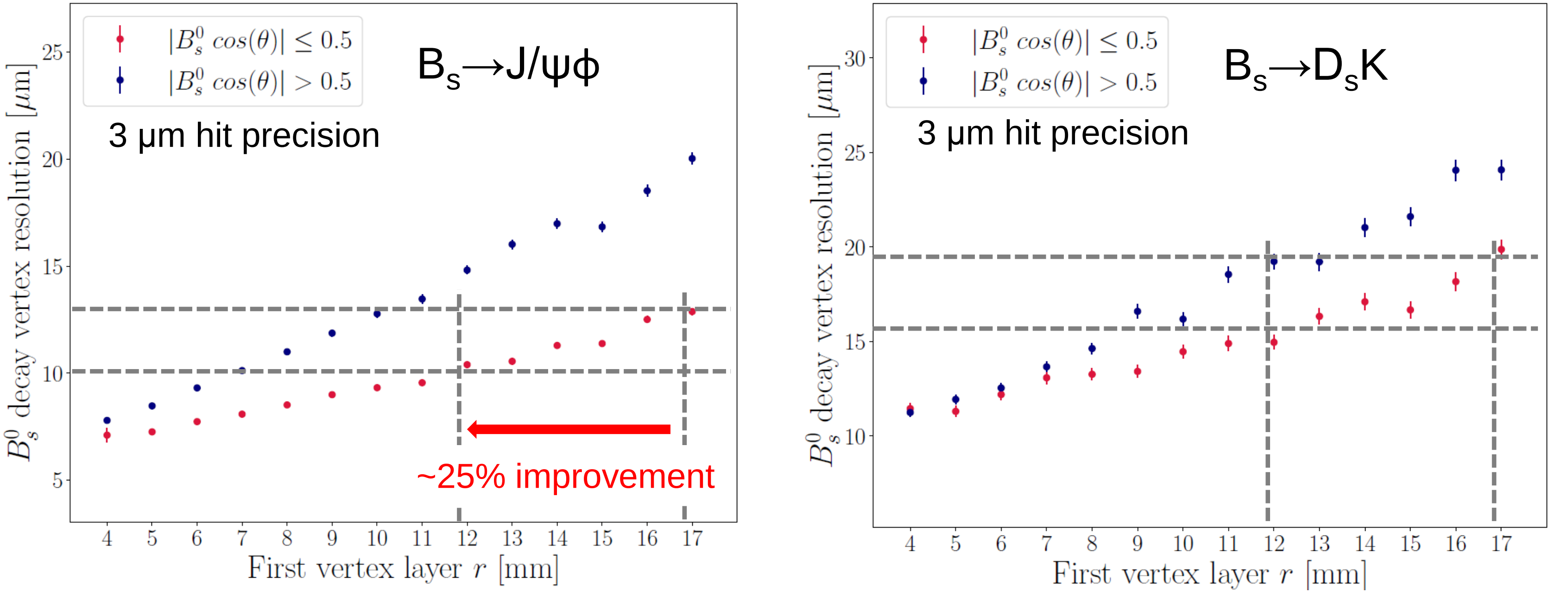
And probably limits charm tagging



[Gouskos & Selvaggi, FCCee Phys Perf meeting, 19/10/20]

Beampipe radius

Variation in secondary-vertex resolution vs r_{first}, for two different decays [Donal Hill]:



News since CDR: updated MDI design incorporating r=10 mm beampipe (see Boscolo *et al.*, arXiv:2105.09698). This is an extremely welcome development ! Let's continue dialogue to optimise performance.

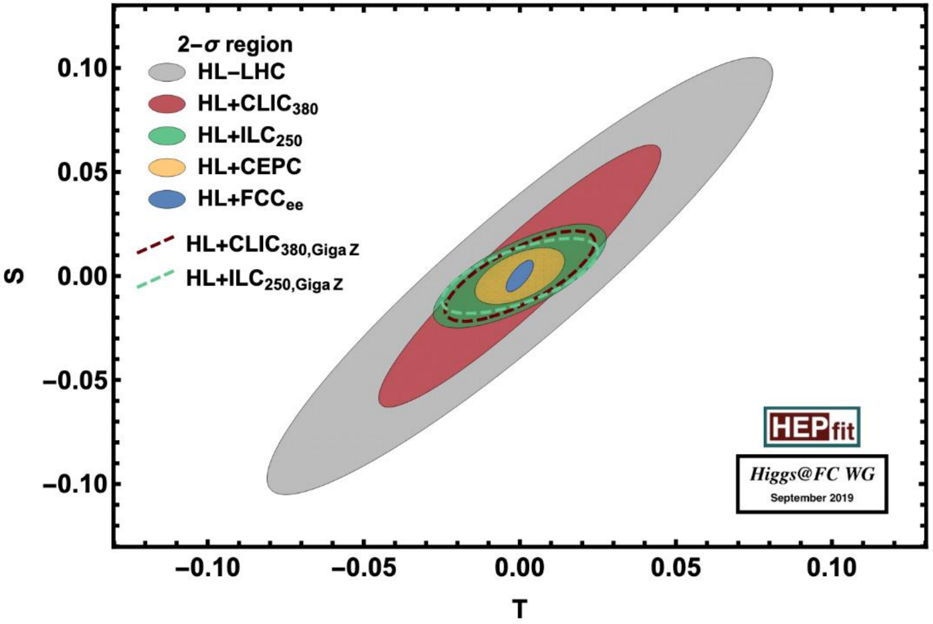
Summary

- Very high luminosities available at FCC-ee over a wide range of energies present enormous discovery potential, through indirect means (*i.e.* super precise measurements of EW, Higgs and flavour observables) and through direct searches;
- There is a growing conviction that four interaction points will add robustness and breadth to the physics programme;
- The opportunity for precise knowledge E_{CM} is a huge asset, and must be intrinsic to machine design and operation plans;
- The merits of an $e^+e^- \rightarrow H$ run are under evaluation. Interest challenges for monochromitisation vs luminosity and ECM calibration;
- The current MDI design is generally good for physics; we welcome continued progress in reducing the beampipe radius, exploring 3T option for high-energy operation, suppressing beam-related backgrounds *etc*.

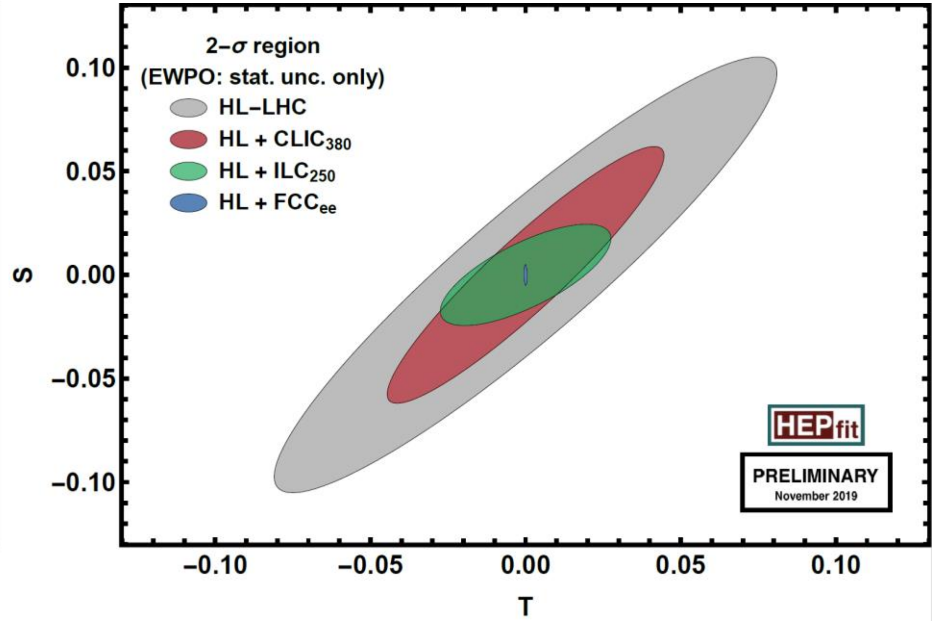
Backups

Expected uncertainty contour for S & T parameters

Constraints on S & T parameters from global fit to EW precision observables.



With naïve estimate of future experimental and systematic uncertainties.



Including statistical and parametric uncertainties only.