Outlook for experimental HEP

or "what to keep an eye on in particle physics between now and 2095"

Lecture II

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Lecture II outline

- The High Luminosity LHC
- Future high-energy e^+e^- colliders
- Towards the highest energies

The High Luminosity LHC

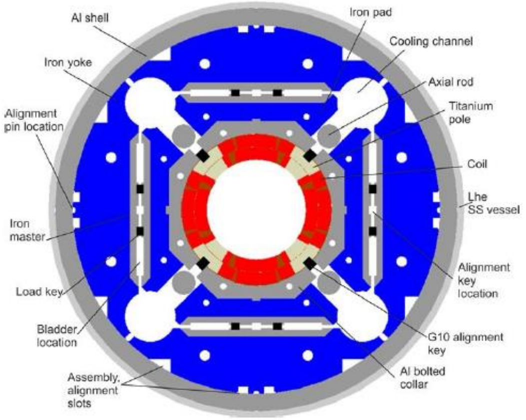
The High-Luminosity LHC (HL-LHC)

HL-LHC is a highly ambitious project to exploit fully the discovery potential of the LHC. Not a modest upgrade, but almost a new machine – the next collider !

When ?	Main work takes place in LS3 (2026-2028), for operation beginning in Run 3 (2029 onwards).
Why then ?	Existing inner triplets at ATLAS and CMS will have reached their estimated lifetime from radiation damage, and will need replacing.
What is the goal ?	Operation at a peak luminosity of 5 x 10^{34} $cm^{-2}s^{-1}$. Enable operation of LHC to continue beyond Run 3 by at least a decade (Runs 4-6). Integrated luminosity 3000 fb^{-1} (or maybe 4000 fb^{-1}) at each of ATLAS and CMS, which is a ~10x increase on what is expected to be collected up to then.

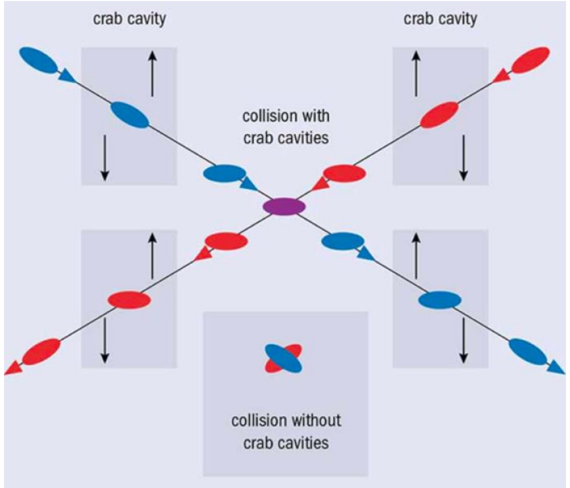
HL-LHC: essential changes to machine

- Reduce β* at ATLAS and CMS. Achieved through new inner triplet made out niobium-tin superconductor (total length 8.4 + 14.3 + 8.4 m).



- Injector upgrade.

- High bunch population, requires larger crossing angle. RF crab cavities are used to ensure a head-on collision.



- Significant increase of shielding, changes of layout, infrastructure *etc.* to cope with increased radiation and collision debris.

HL-LHC: detector ‘Phase-II Upgrades’

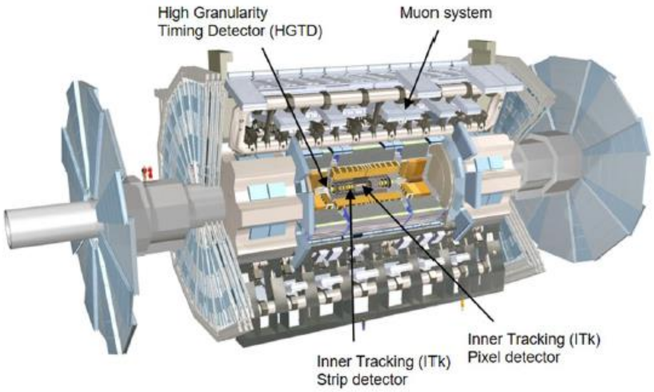
Radiation damage sustained in Runs 1-3, the increased damage foreseen for Runs 4→, and the challenges caused by the increased pileup (up to 140 interactions per crossing) necessitate significant detector replacements / upgrades.

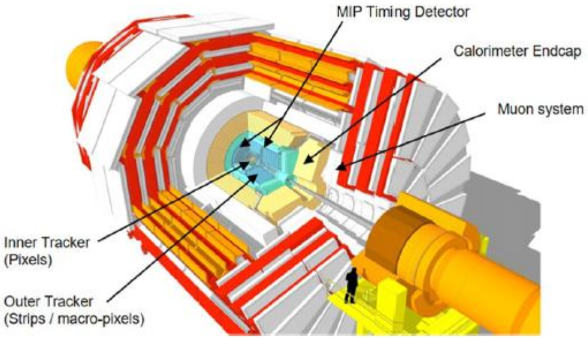
ATLAS

- New: high granularity timing detector and muon detectors.
- Replaced: silicon tracker, trigger system.
- Upgrade: liquid argon & tile calorimeters; muon chambers.

CMS

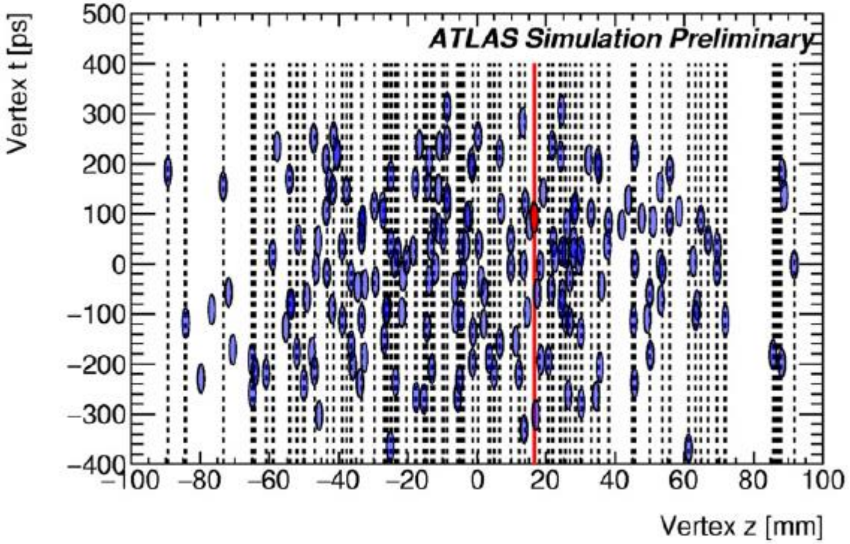
- New: MIP timing detector, and muon detectors.
- Replaced: silicon tracker, end-cap calorimeters, trigger.
- Upgrade: barrel & forward calorimeters; muon detectors.

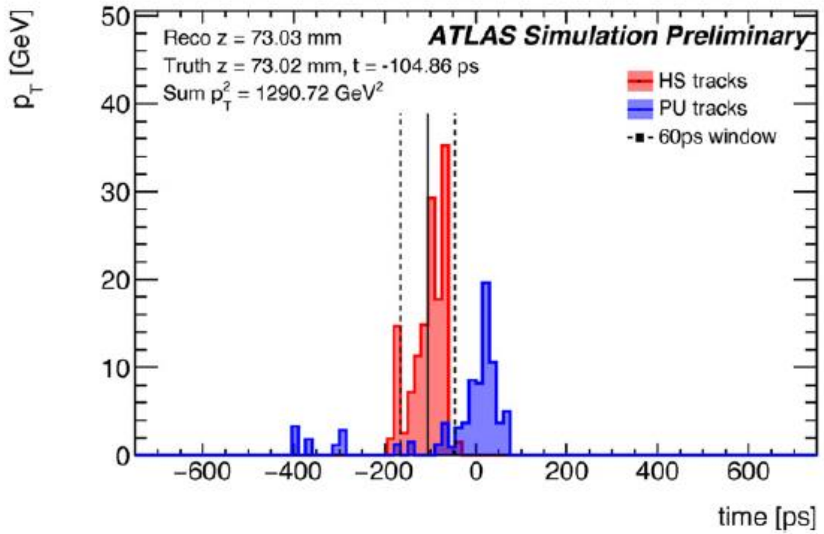




The importance of precise timing

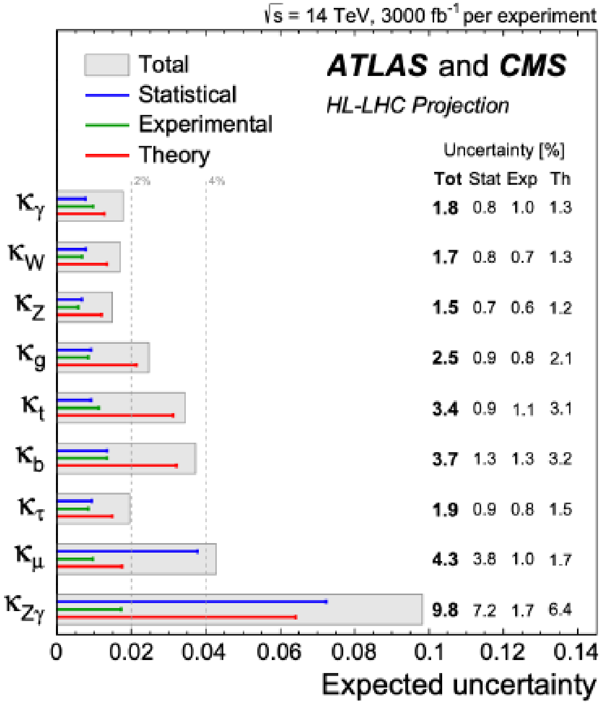
With so much pileup, interactions can occur at the same position in z but at different times. Timing information, with resolution of a few 10s of ps, as provided by the ATLAS HGTD and CMS MIP timing detector, will help mitigate problem.

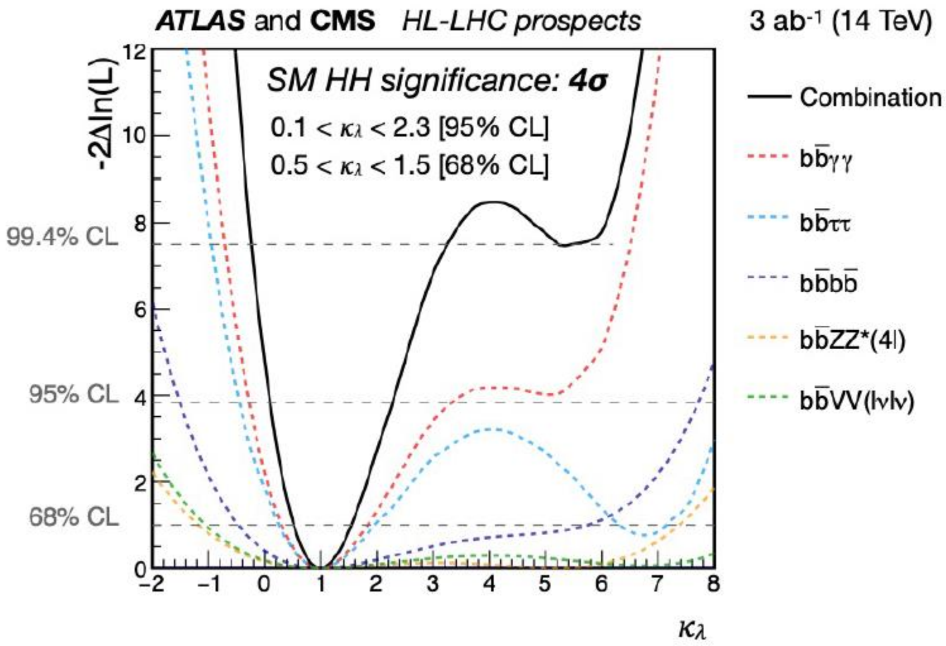




HL-LHC physics reach

- Substantial improvements in search sensitivity, *e.g.* EW SUSY, heavy, resonances, long-lived particles, dark matter….;
- Improved SM, top and flavour physics (see Lecture I) measurements;
- Improvements in knowledge of Higgs' couplings, and 4σ combined ATLAS / CMS sensitivity to di-Higgs production at SM rate.





High-energy e^+e^- colliders

- Physics motivation and the choice of linear vs. circular

- International Linear Collider, and other linear options

- CEPC in China – a brief word

- The Future Circular electron–positron Collider: FCC-ee

Physics motivation and the two options

Future e^+e^- collider is here taken to be a machine of enabling high precision Higgs physics, as well as other studies at the Z pole & higher energies up to 1 TeV or so.

Building such a machine is an acknowledged priority in HEP, *e.g.* recent European Strategy for Particle Physics Update. Two broad options under consideration.

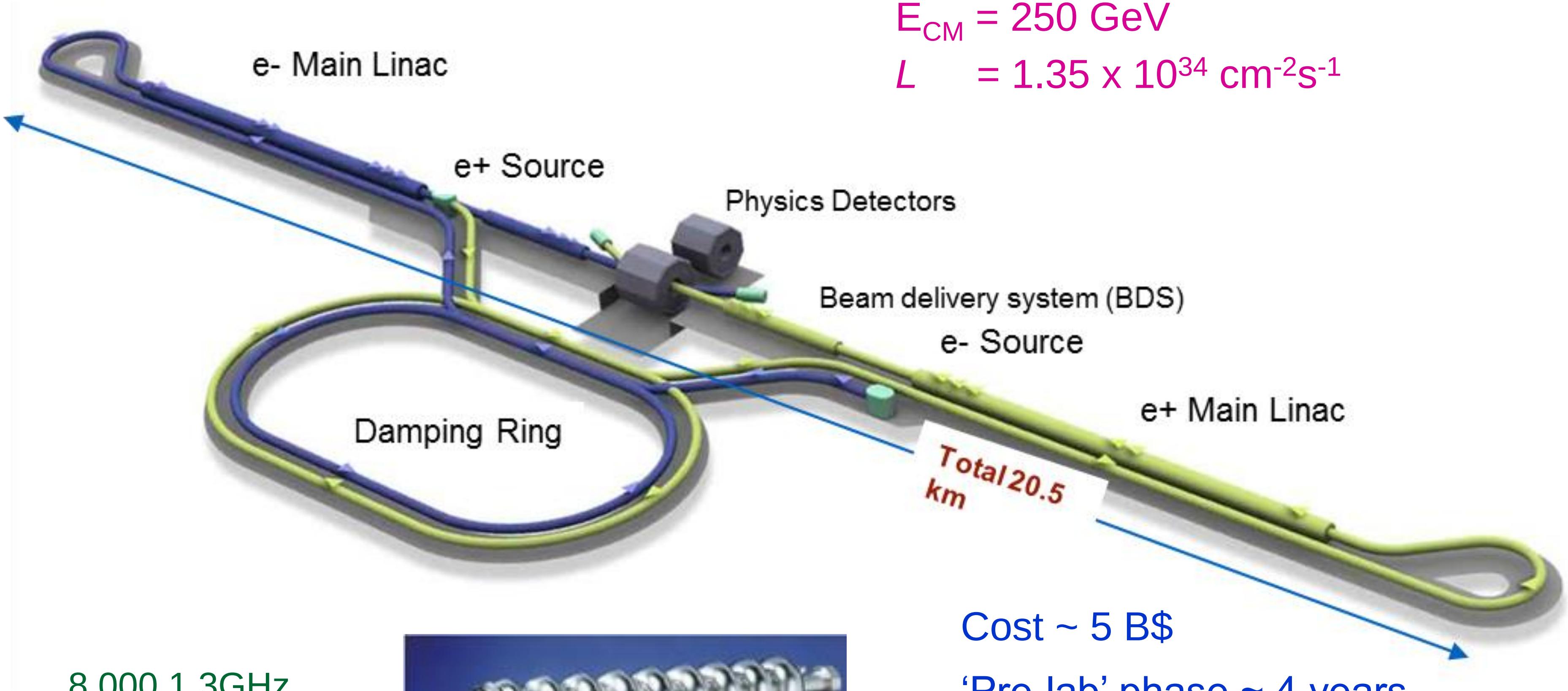
Advantage	Linear	Circular
Best luminosity option for E_{CM}	> 350 GeV	< 350 GeV
Polarisation	Longitudinal (valuable for physics studies)	Transverse (valuable for E_{CM} calibration)
Other		Multiple interaction points (IPs) allow for several detectors

Until, say, five years ago, the linear machine was the clear front runner. Historically this made sense. The Higgs might have been heavier, and the LHC was expected to discover many high-mass SUSY states that would require detailed study.

International Linear Collider - baseline

E_{CM} = 250 GeV

L = 1.35 x 10^{34} $cm^{-2}s^{-1}$



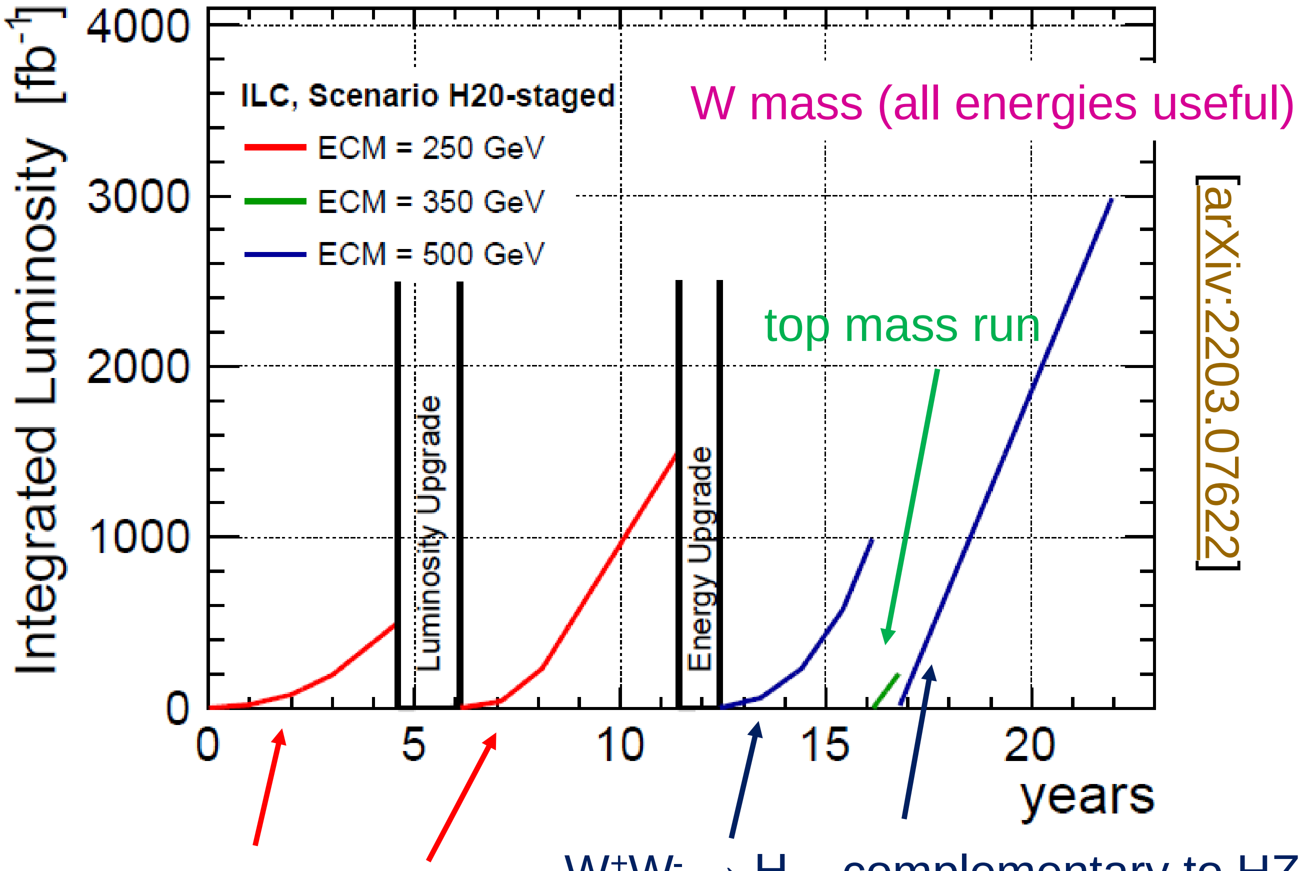
8,000 1.3GHz
SRF cavities @ 2K

Cost ~ 5 B$

'Pre-lab' phase ~ 4 years

Construction + commissioning ~ 10 years

International Linear Collider – possible run plan, involving luminosity and energy upgrades



W mass (all energies useful)

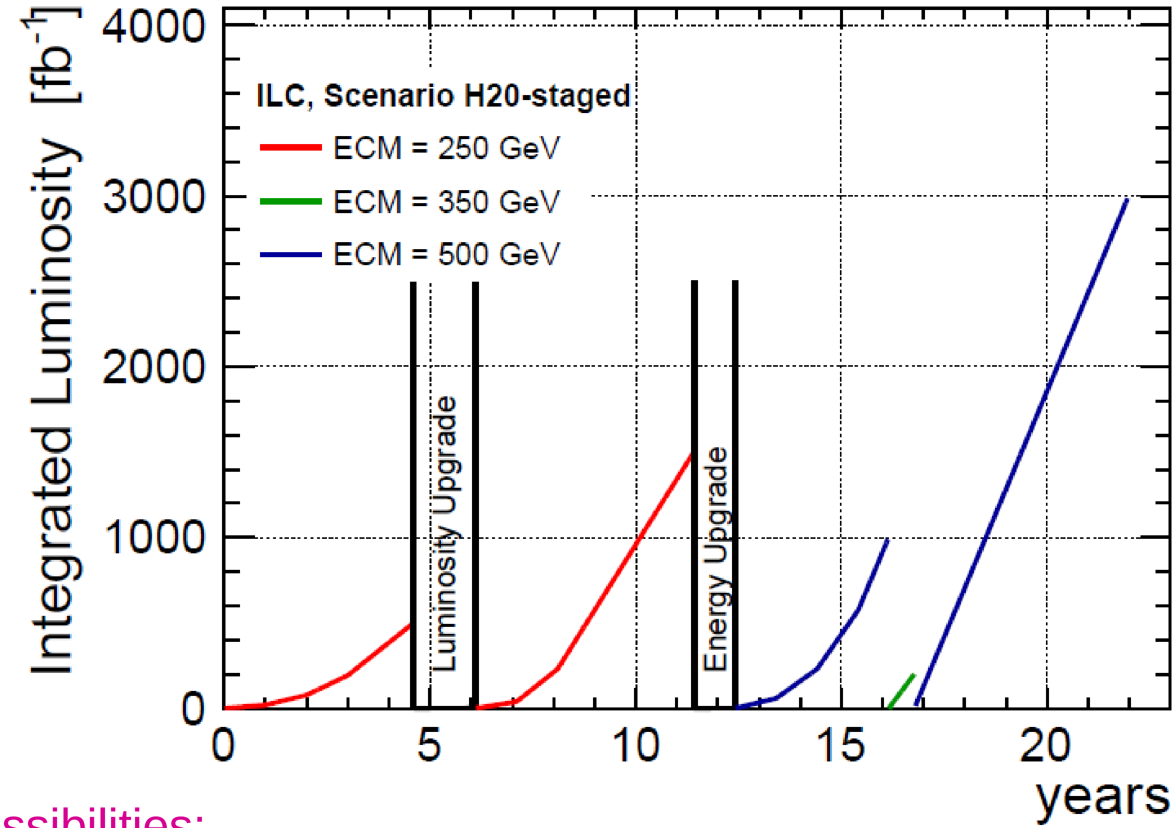
top mass run

[arXiv:2203.07622]

HZ physics – for couplings

$W^+W^- \rightarrow H$ – complementary to HZ, also top Yukawa and some self-coupling sensitivity

International Linear Collider – possible run plan, involving luminosity and energy upgrades



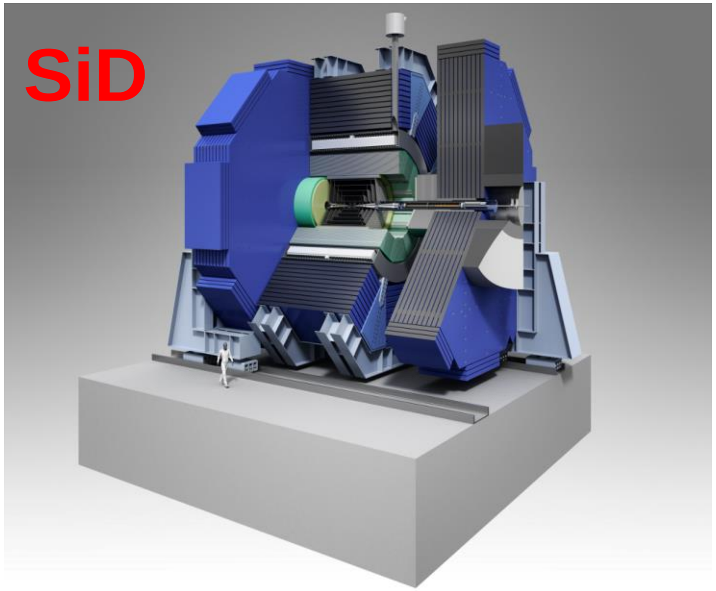
[arXiv:2203.07622]

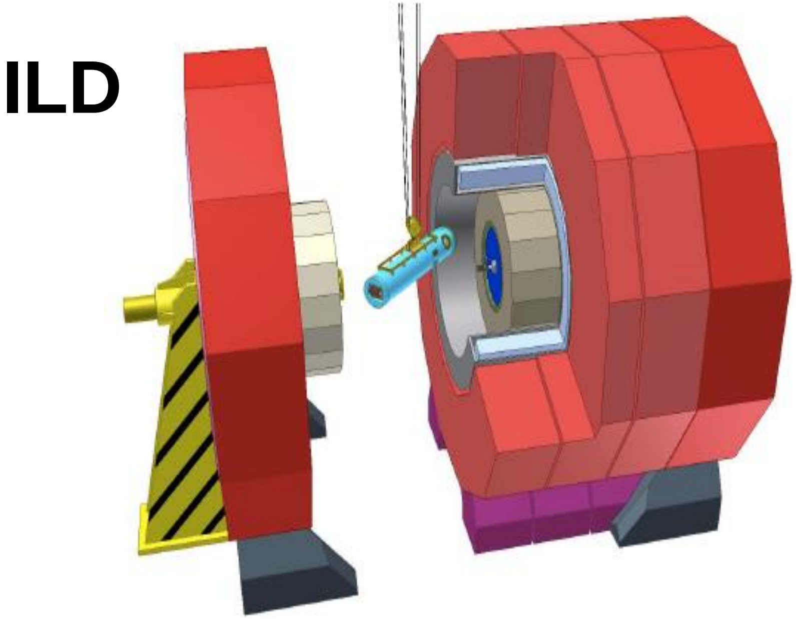
Other possibilities:

- Z pole run: much smaller samples than FCC, but transverse polarisation
- 1 TeV Upgrade: better top Yukawa and Higgs self-coupling sensitivity and discovery / discovery of new particles

International Linear Collider – detectors

Detector studies very mature – ‘push-pull’ operation will allow for two experiments.

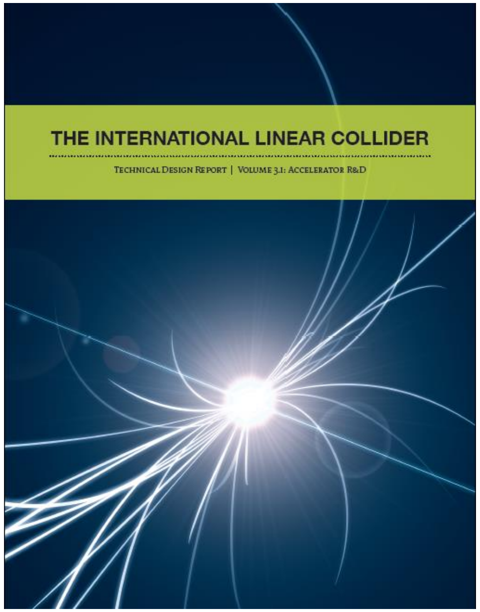




International Linear Collider – status

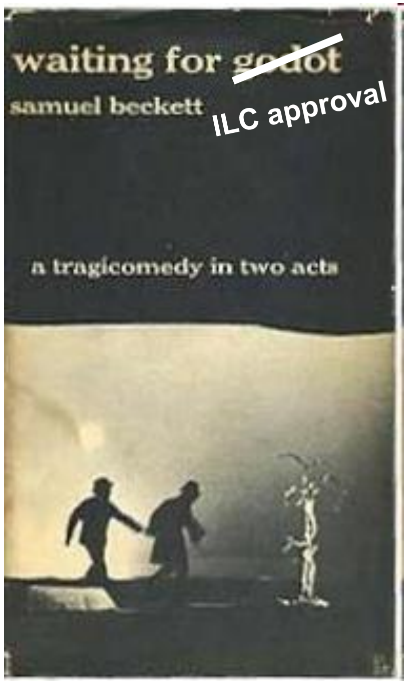
Enormous amount of hard work has been invested in ILC studies, and over many years. The proponents have been waiting a very long time for a green light….

TDR – 2013



Baseline then 500 GeV

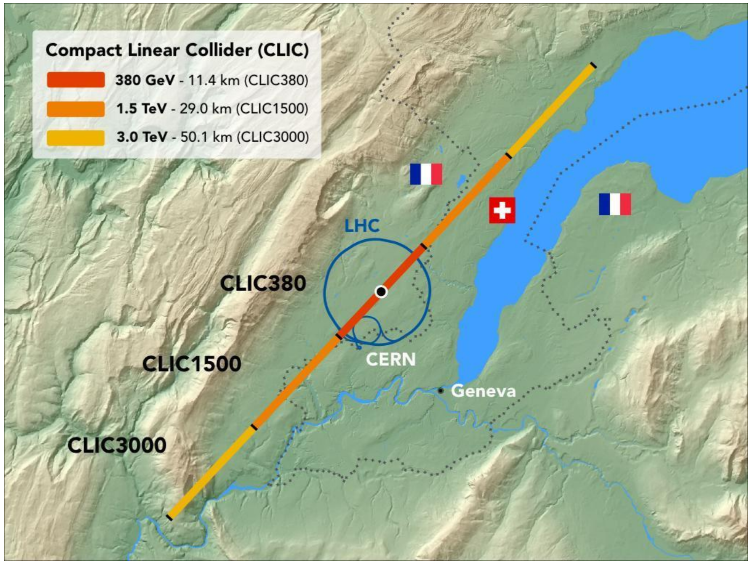
VLADIMIR:
“What are you insinuating? That we've come to the wrong place?”
ESTRAGON:
“He should be here.”
VLADIMIR:
“He didn't say for sure he'd come.”
ESTRAGON:
“And if he doesn't come?”
VLADIMIR:
“We'll come back tomorrow. “
ESTRAGON:
“And then the day after tomorrow.”
VLADIMIR:
“Possibly.”



…maybe we should wait no longer ?

Other linear options

CLIC – CERN ‘plan B’

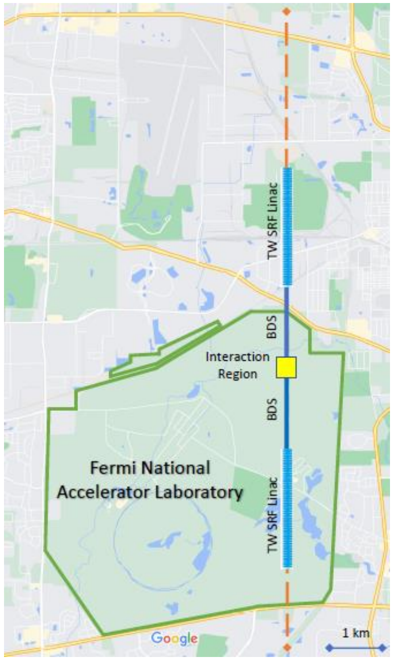


Novel two-beam accelerating technique based on warm cavities.

Upgradable to 3 TeV.

But, unavoidably a post-LHC project.

Alternative RF technologies, e.g. HELEN [arXiv:2203.08211] or `copper-cubed’ [arXiv:2110.15800].



Very early days - a long R&D road required to demonstrate feasibility.

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).

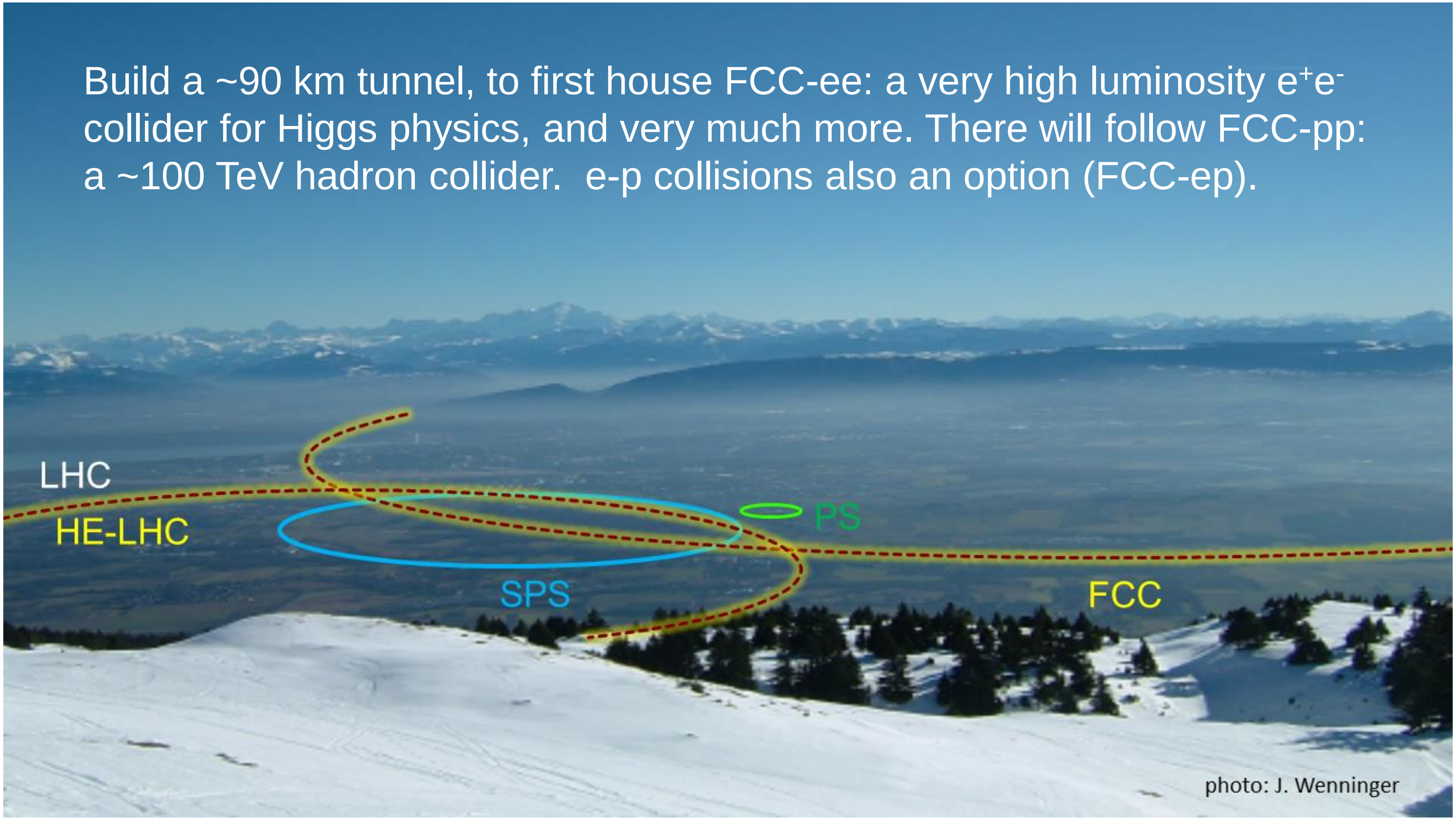


photo: J. Wenninger

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.)

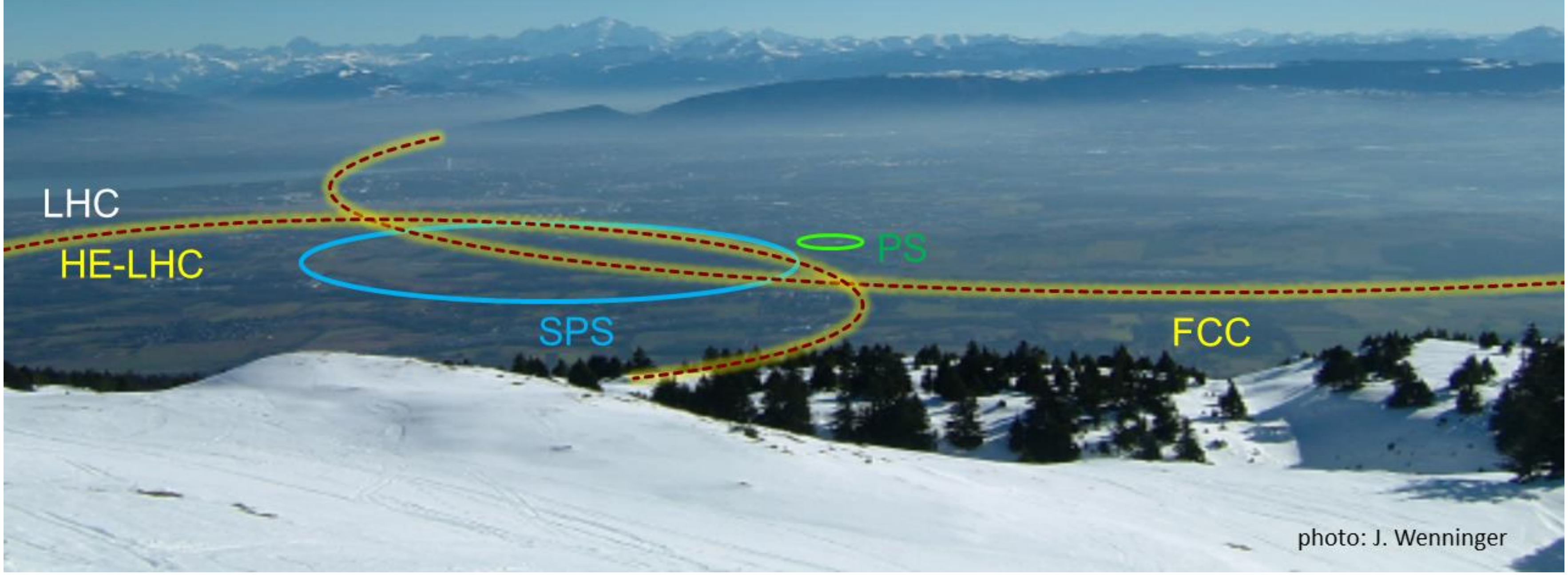


photo: J. Wenninger

Meanwhile, in China…

Circular Electron Positron Collider (CEPC) is a Chinese project, whose main characteristics closely resemble those of FCC-ee. Indeed, over time, it has evolved closer & closer to FCC-ee design.

Operation mode		ZH	Z	W^+W^-	tt
$\sqrt{s}$ [GeV]		~240	~91.2	158-172	~360
L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	CDR (2018)	3	32	10	
	Latest	5.0	115	16	0.5

Ideal Accelerator Roadmap

2016-2021	MOST phase-1 accelerator R&D
2018-2023	MOST phase-2 accelerator R&D
2023-2028	MOST phase-3 accelerator R&D
2022-2023	Accelerator TDR completion
2023-2025	Site selection, engineering design, prototyping and industrialization
2026-2034	Construction and Installation

Accelerator TDR about to be complete, to be followed by two-year accelerator EDR phase.

Its best-case timeline places it ~10 years ahead of FCC-ee, with operation beginning in mid 2030s, but many uncertainties.

Watch closely !

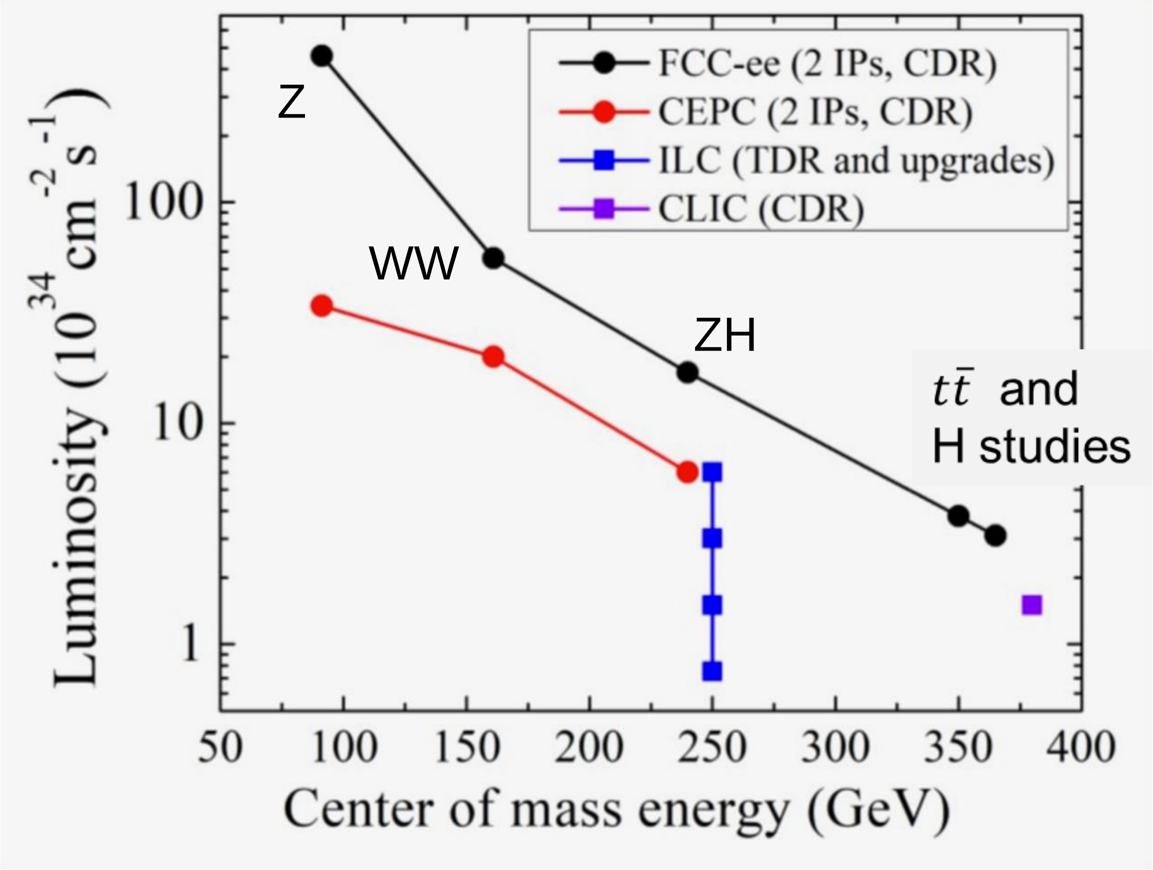
Ideal Detector Roadmap

2016-2021	MOST phase-1 detector R&D
2018-2023	MOST phase-2 detector R&D
2023-2028	MOST phase-3 detector R&D
Now -2024	Seek collaboration, detector R&D
2025-2026	Prepare international collaborations
2027-2028	Detector TDR completed
2028-2034	Detector construction
2033-2034	Installation

For summary see Xinchou Lou presentation at FCC Week 2022, Paris.

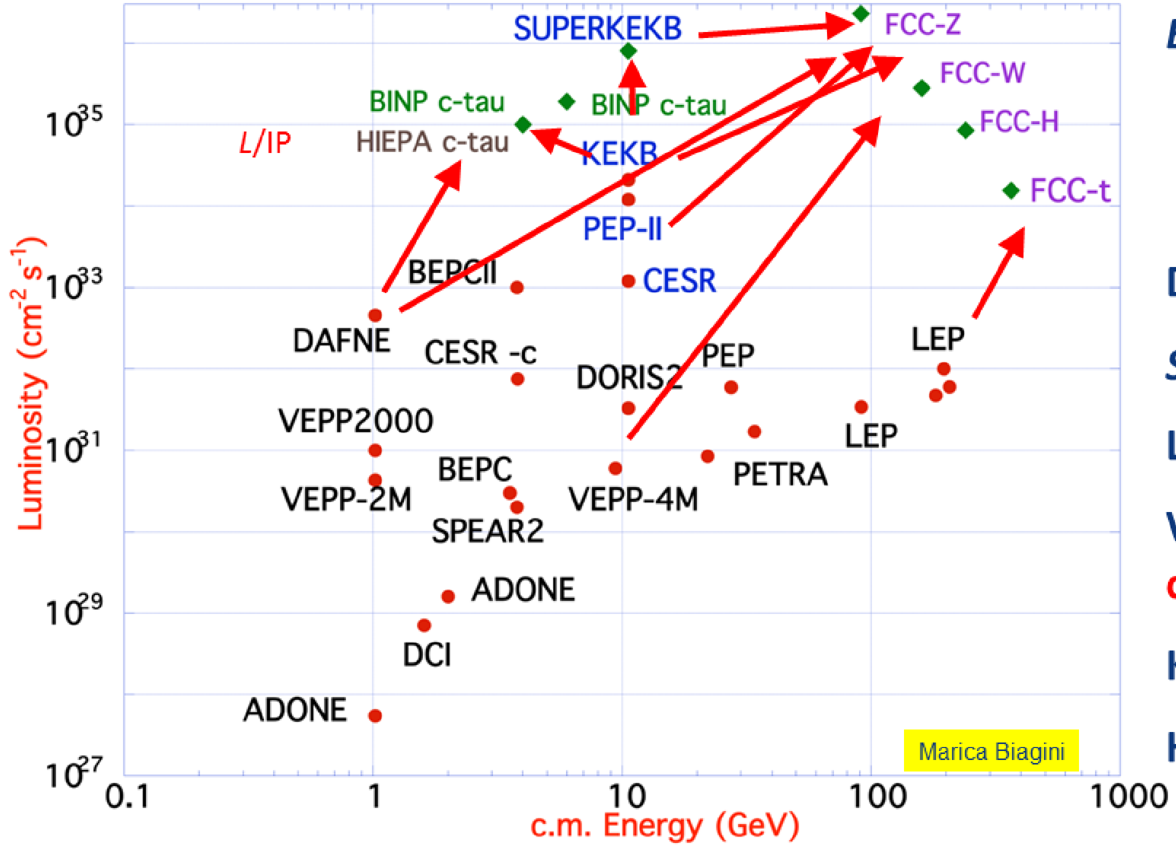
FCC-ee: baseline run plan

(according to Conceptual Design Report)



Enormous luminosities ! How is this achieved ?

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

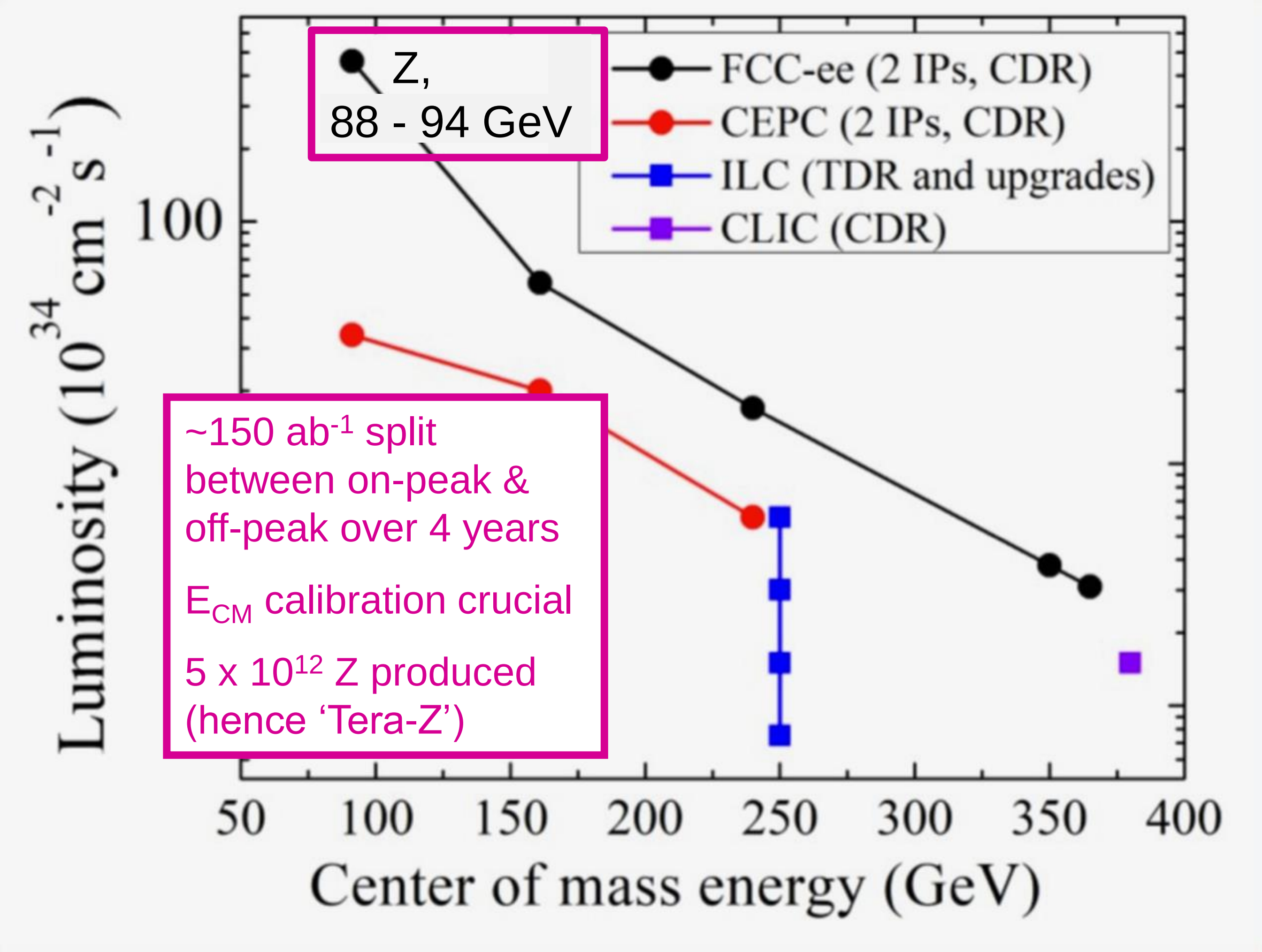
KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

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

FCC-ee: baseline run plan

Let us survey the physics goals at each energy point, starting with the Z. (Actual operation will not necessarily follow this ordering, although there *are* constraints.)



Z,
88 - 94 GeV

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

E_{CM} calibration crucial

5 x 10^{12} Z produced (hence ‘Tera-Z’)

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.

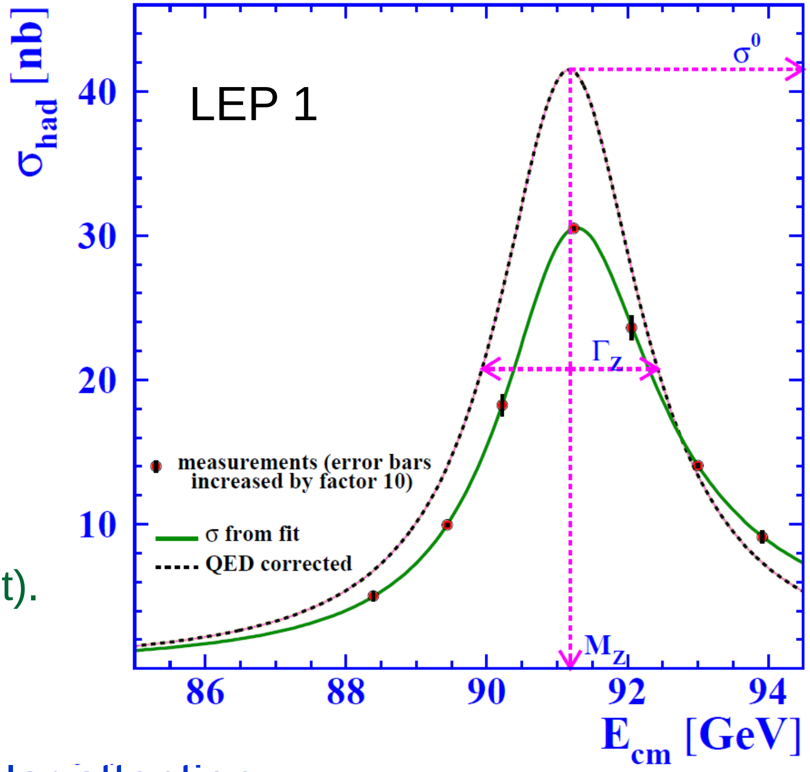
A rich array of measurements awaits, for example lineshape parameters.

Four years will give **~10^5** (sic) more Z's than at LEP. Why not run for less ?

Lesson of LEP is that lineshape scans require time & attention:

- Several years developing the techniques;
- Then two high-precision scan campaigns (the second of which corrected errors in the first).

For sure, not a year-1 measurement !



Moreover, some systematics required particular attention…

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.

	m_Z	Γ_Z
LEP E_{CM} uncertainty	1.7 MeV	1.2 MeV
FCC-ee stat uncertainty	4 keV	4 keV

Doesn't
look easy !

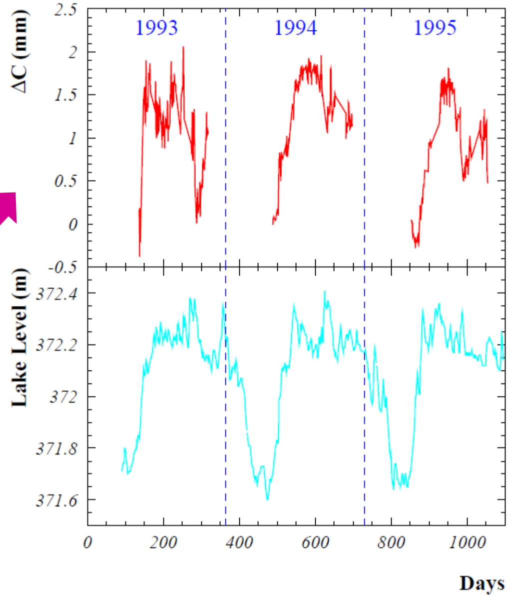
(Control of E_{CM} at this level is also necessary to keep the associated systematic < statistical uncertainty for $\sin^2\theta_W$ from A_{FB} , $\alpha_{QED}(m_Z)$ & many other observables.)

As at LEP, the beam energy can be measured ultra-precisely through the miracle of Resonant Depolarisation (RDP), which relies on the property that the precession frequency of the transverse polarisied beams is proportional to the beam energy.

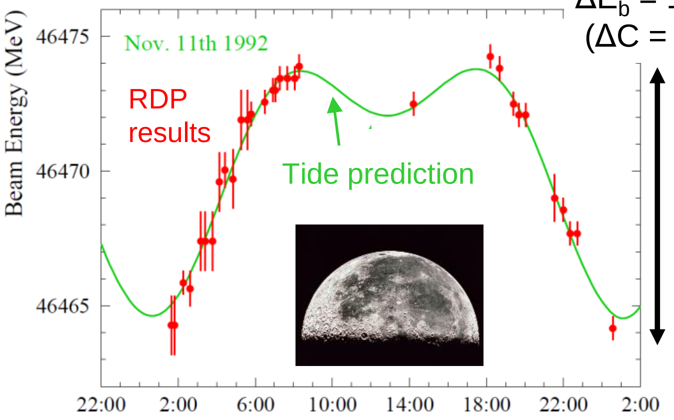
But at LEP, RDP could only be performed in a few fills, before or after collisions. E_{CM} knowledge limited by modelling of time evolution between measurements.

Some mechanisms of E_b variation at LEP

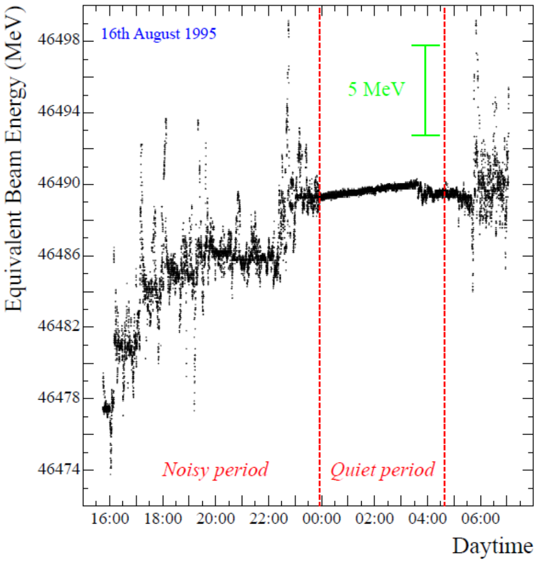
Short- (tide) and long- (lake) term ring distortions.

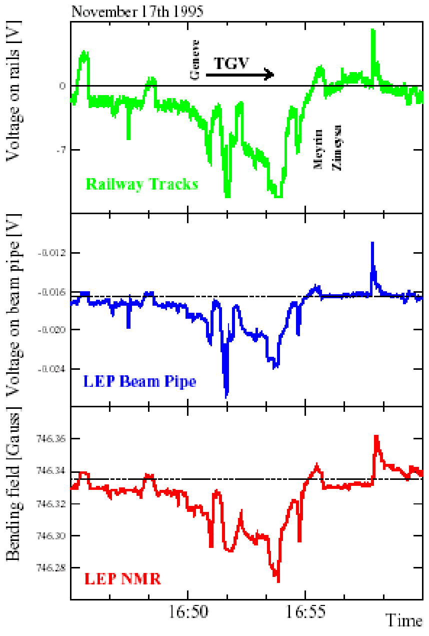


ΔE_b = 10 MeV
(ΔC = 1 mm)



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).

[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 non-colliding pilot bunches for e^- and e^+ several times an hour

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

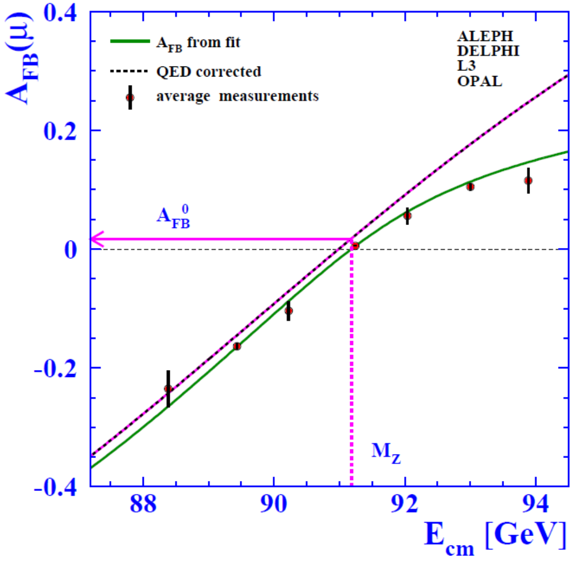
- Change RF frequency to keep beams centred in quadrupoles to suppress residual tidal effects on E_b; furthermore beam-beam offsets must be minimised to suppress dispersion-induced biases on E_{CM}.

With this approach (and taking account of other considerations) there is confidence that E_{CM} systematics can be limited to 100 keV on M_Z and 25 keV on Γ_Z, and the expectation that even better performance will be possible… (work in progress).

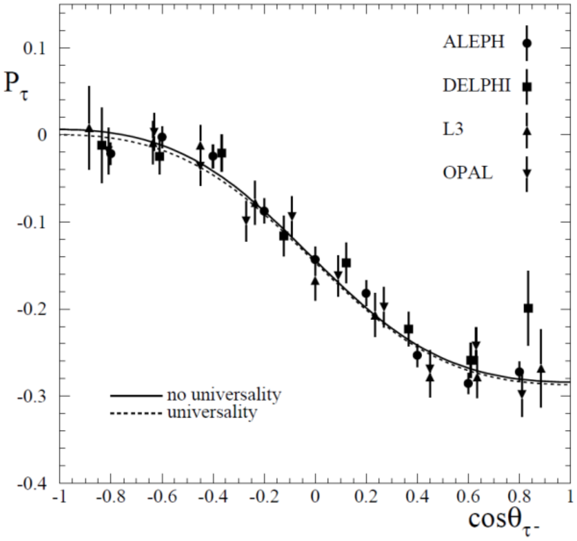
Why 4 years and ~150 ab^{-1} at & around the Z pole ?

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^{ll}_{FB}), lepton-to-hadron ratios (R_l), tau-polarisation asymmetries ($A^{pol,\tau}_{FB}$), b-specific observables (A^{b}_{FB}, R_b).

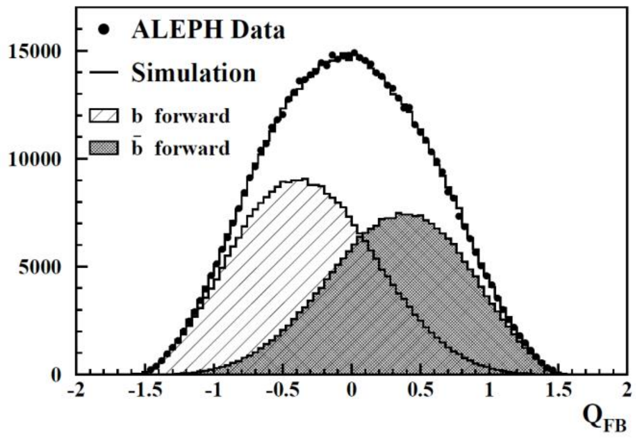
A_{FB} for muons



P_τ vs. cos θ_τ



A_{FB} for b production

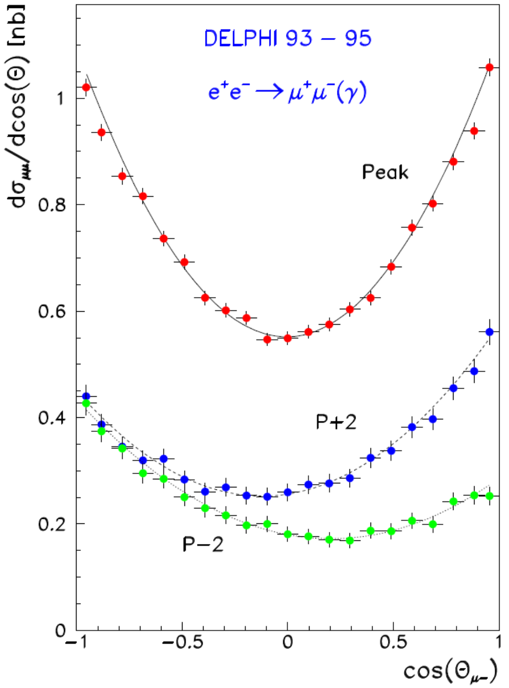


Why 4 years and ~150 ab^{-1} at & around the Z pole ?

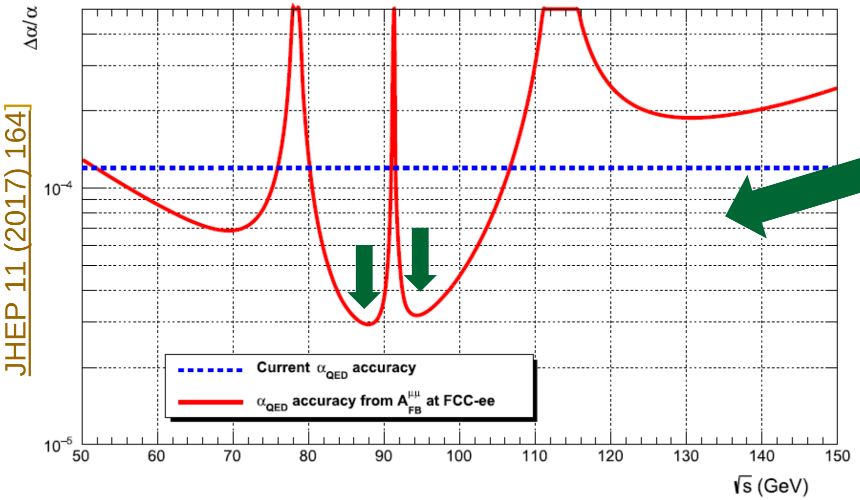
Excellent experimental control of off-peak di-muon asymmetry motivates campaign to collect 50-80 ab^{-1} off peak to gain highest sensitivity to Z-γ interference

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

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.

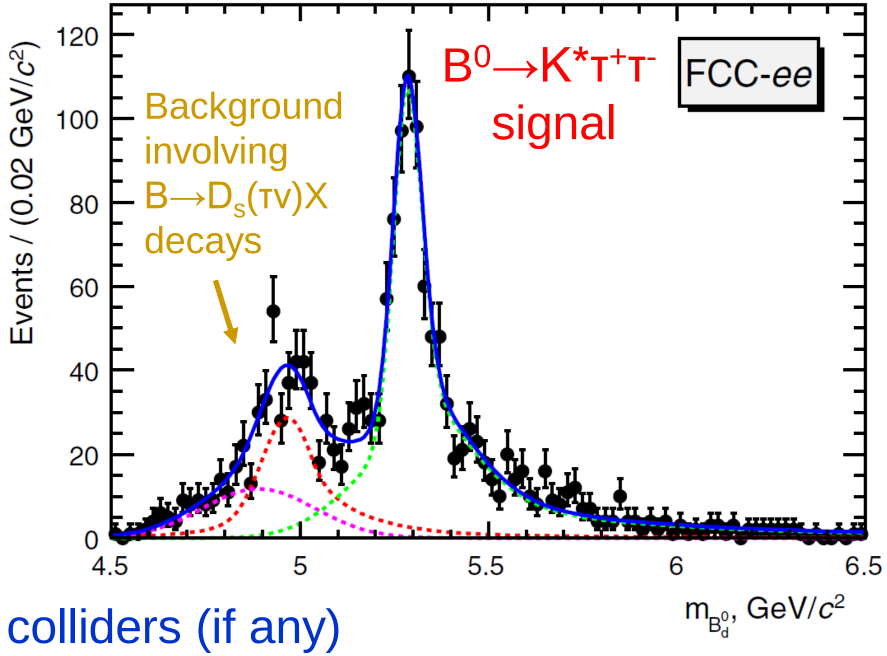
Goal: measure $1/\alpha_{QED}(m_Z^2)$ to +/- 0.003.

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 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.

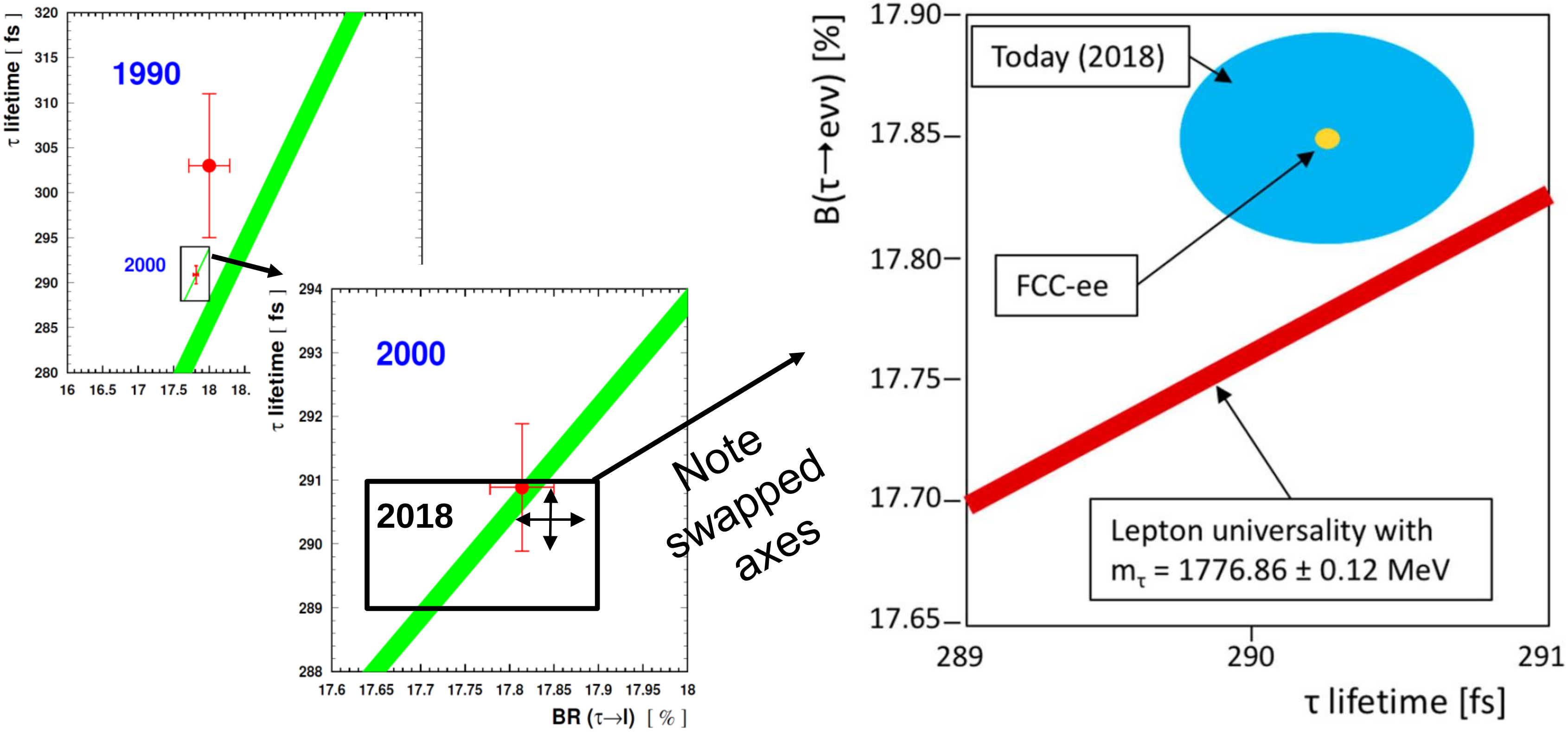
However, no cause for complacency:

- 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 !



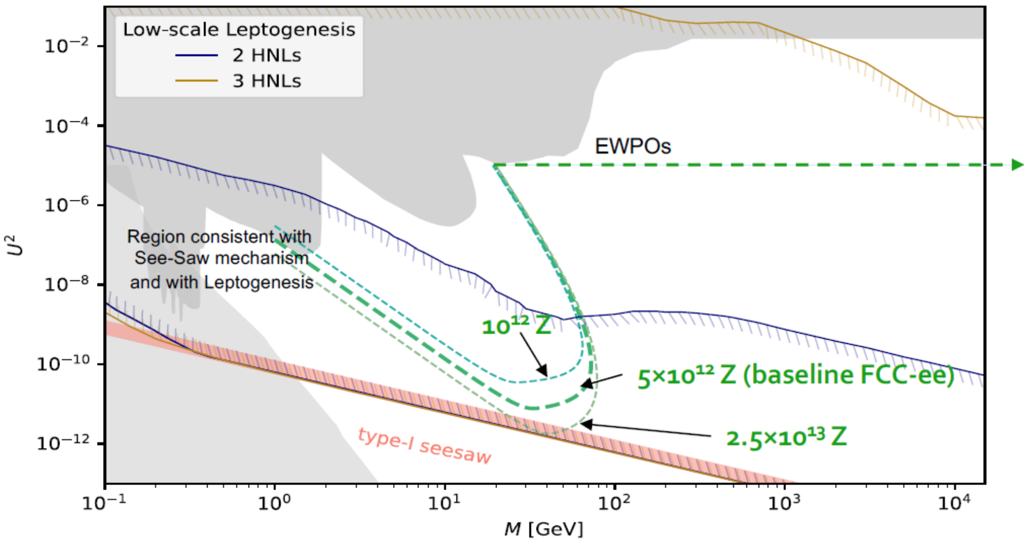
Also probe for LFV in tau decay, *e.g.* $\tau\to\mu\mu\mu$ to 10^{-10} – *very important* in context of hints for lepton-universality violation in LHCb data & elsewhere.

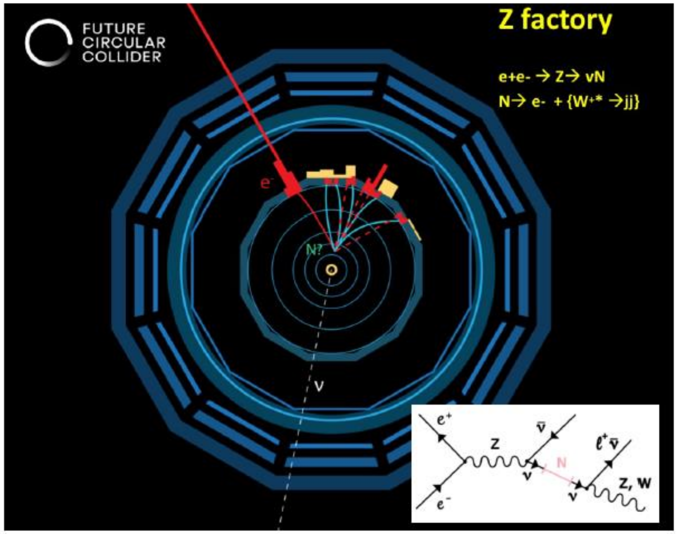
Why 5 x 10^{12} Z^0s ? Direct searches

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. exclusion limits for heavy right-handed neutrinos

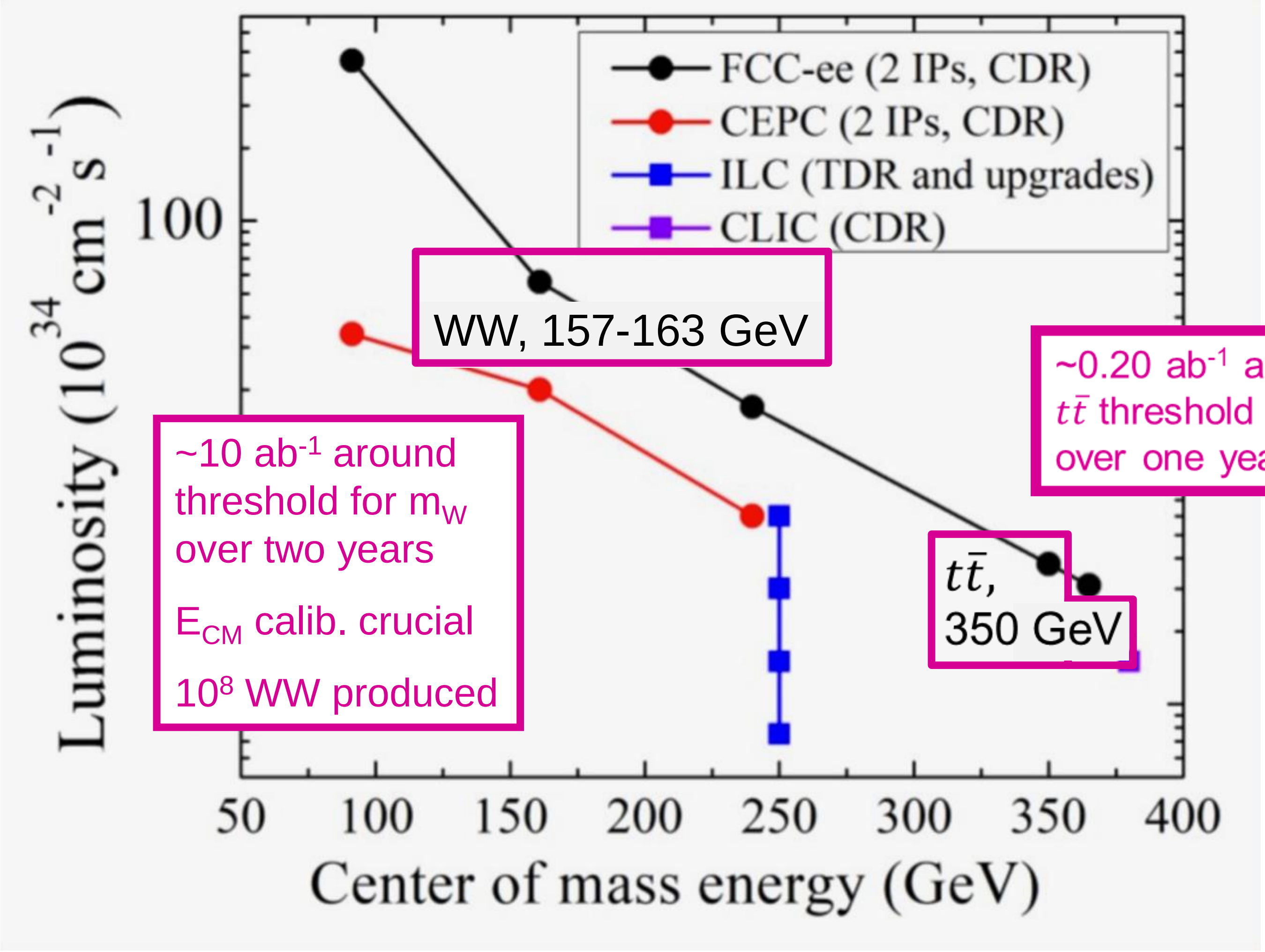
[also see PRL 127 (2021) 111802]





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 !

FCC-ee: baseline run plan



WW, 157-163 GeV

~10 ab^{-1} around threshold for m_W over two years

E_{CM} calib. crucial

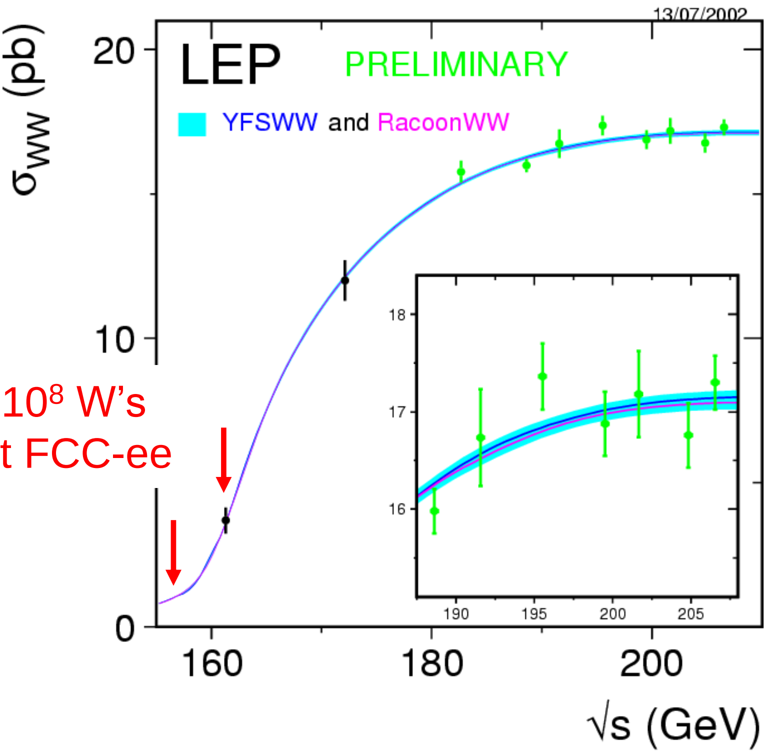
10^8 WW produced

$t\bar{t}$, 350 GeV

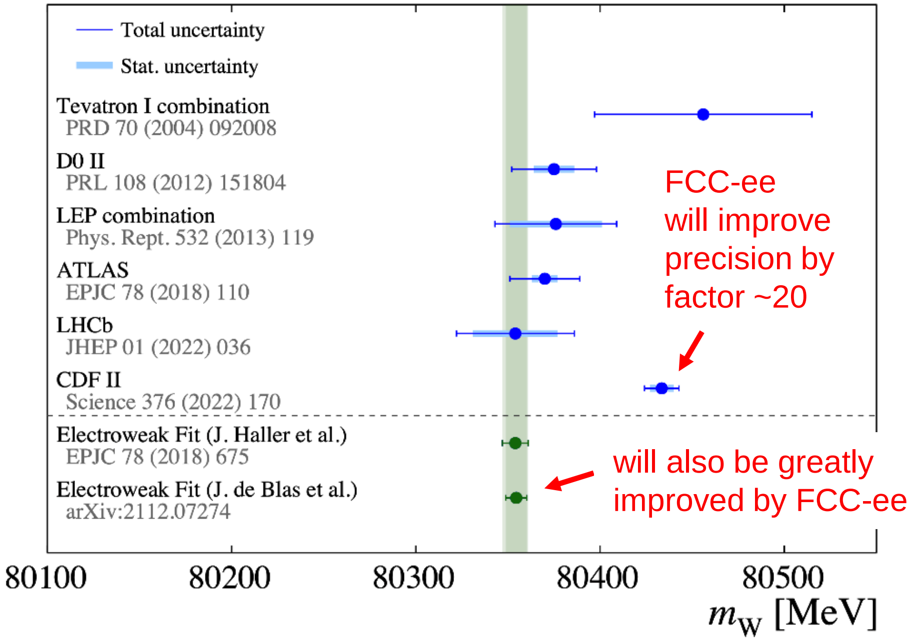
~0.20 ab^{-1} around $t\bar{t}$ threshold for m_t over one year

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.



~10^8 W's at FCC-ee



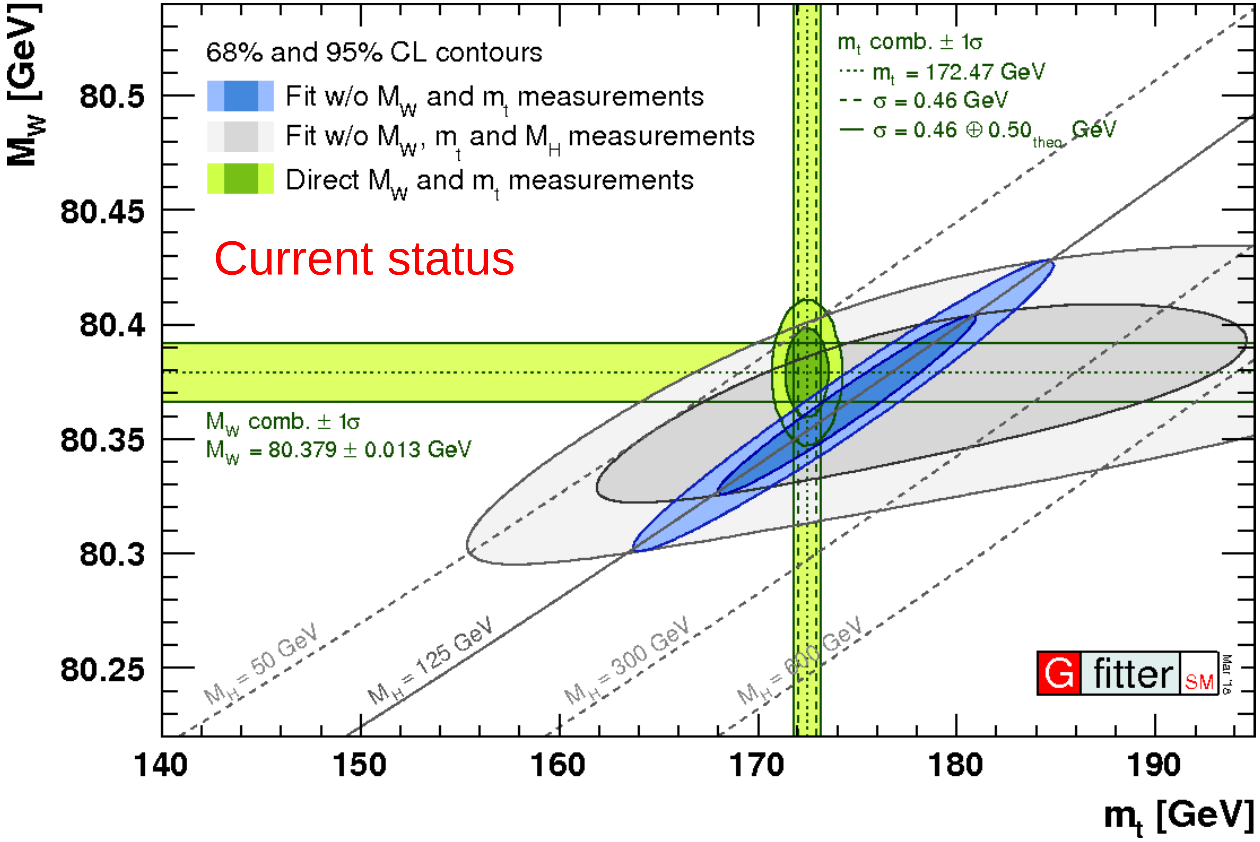
FCC-ee will improve precision by factor ~20

will also be greatly improved by FCC-ee

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 ?

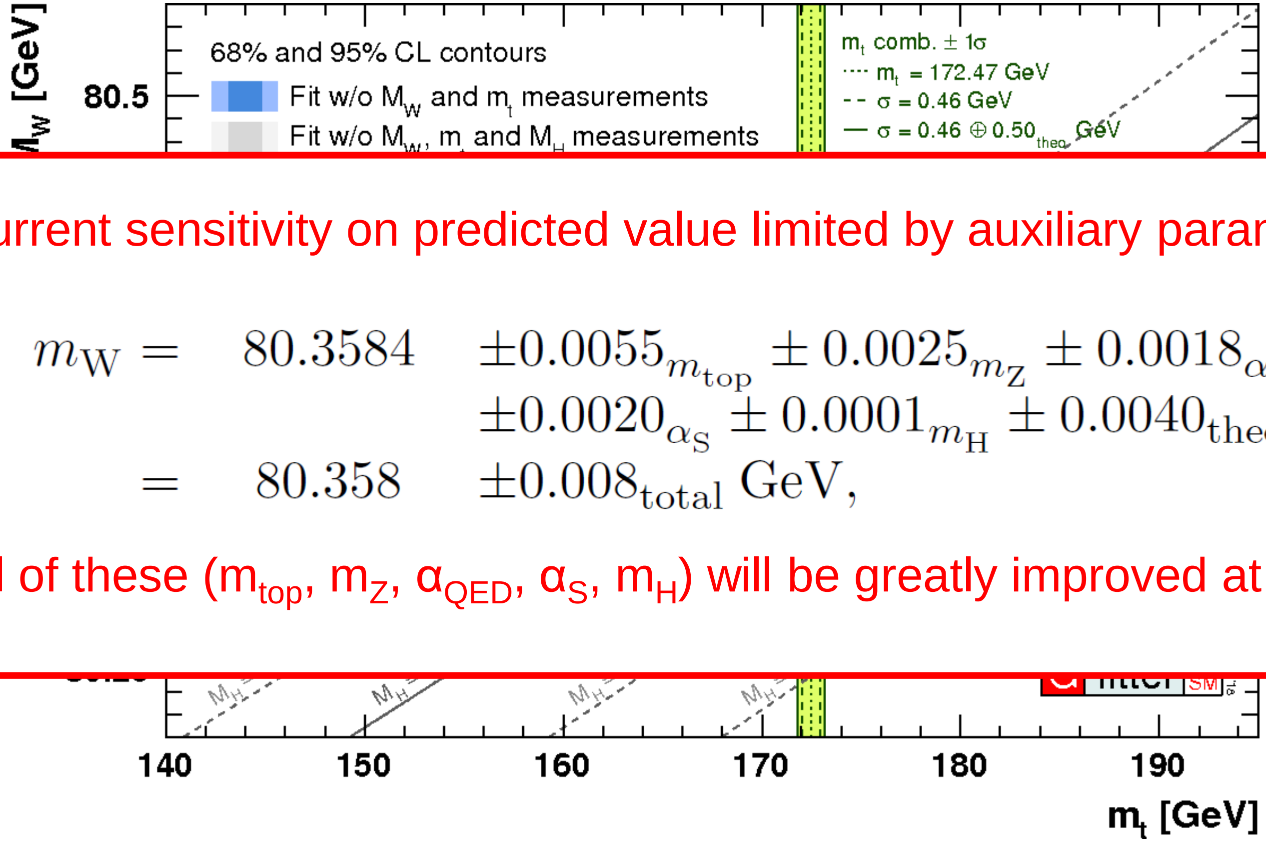
Best possible precision on m_W required to perform critical closure test on SM.



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

Why measure m_W to ~0.5 MeV ?

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



Current sensitivity on predicted value limited by auxiliary parameters.

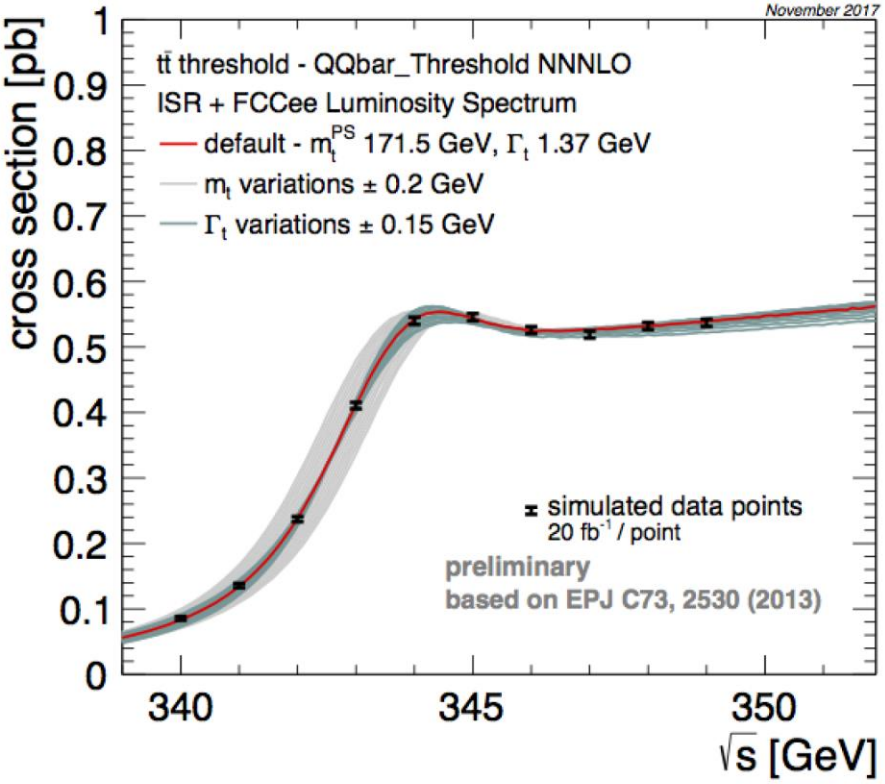
$$\begin{aligned} m_{\rm W} = \quad & 80.3584 \quad \pm 0.0055_{m_{\rm top}} \pm 0.0025_{m_{\rm Z}} \pm 0.0018_{\alpha_{\rm QED}} \\ & \qquad\qquad \pm 0.0020_{\alpha_{\rm S}} \pm 0.0001_{m_{\rm H}} \pm 0.0040_{\rm theory} \ {\rm GeV} \\ = \quad & 80.358 \quad \pm 0.008_{\rm total} \ {\rm GeV}, \end{aligned}$$

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.

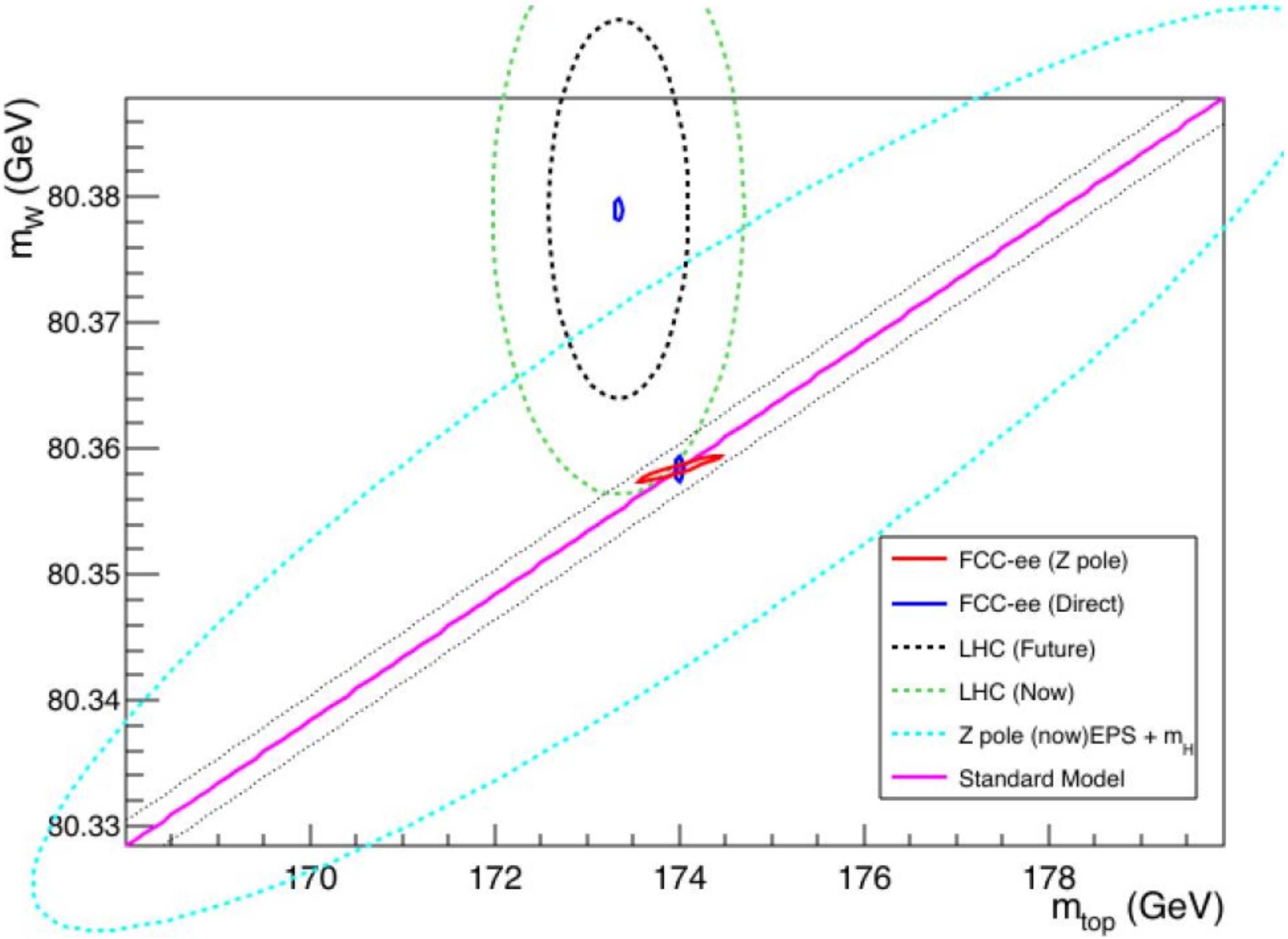
Going to higher energies: m_t

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

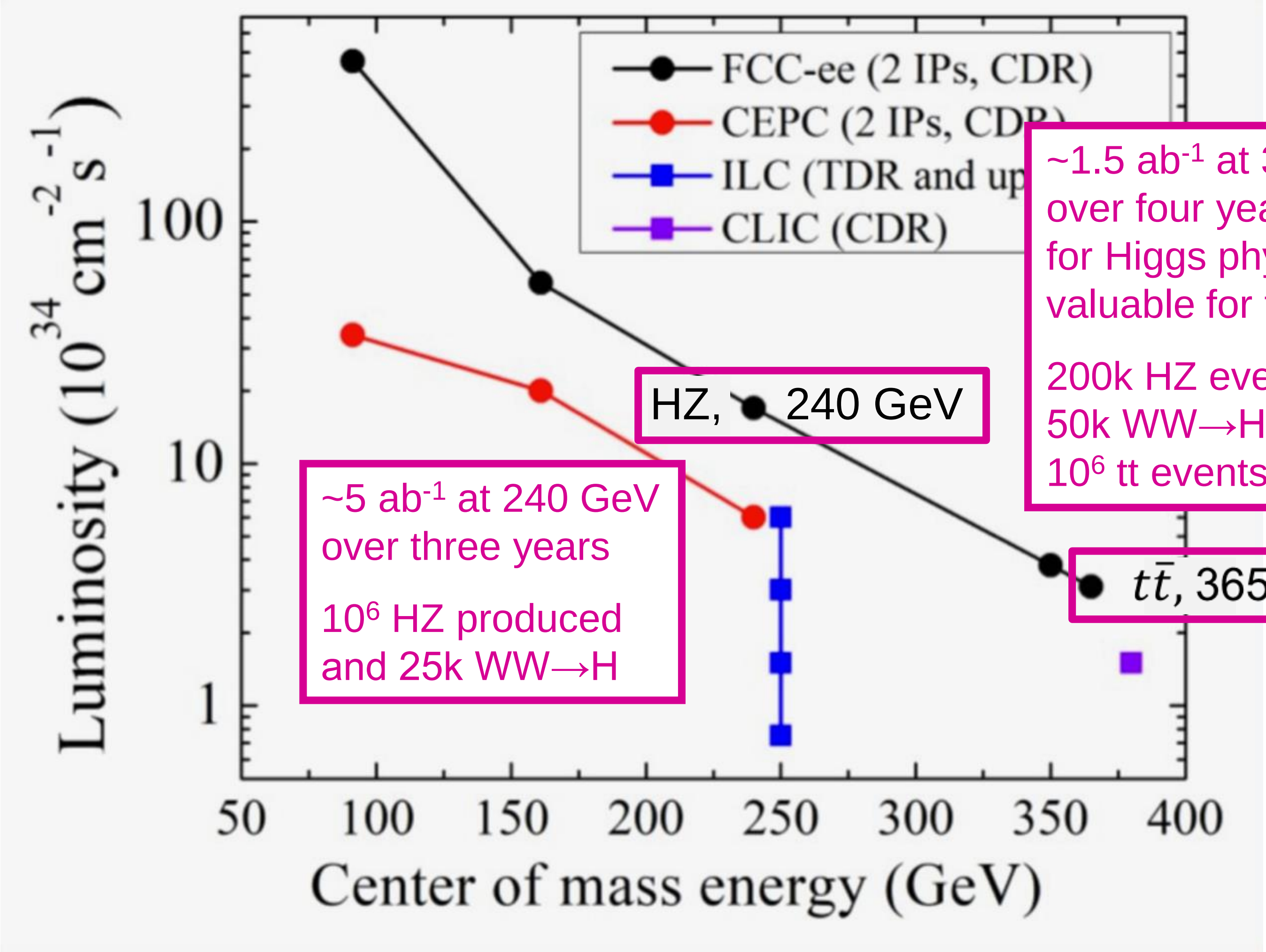


Multi-point threshold scan with 20 fb^{-1} / point will determine m_t to <20 MeV

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



FCC-ee: baseline run plan



HZ, 240 GeV

$t\bar{t}$, 365 GeV

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

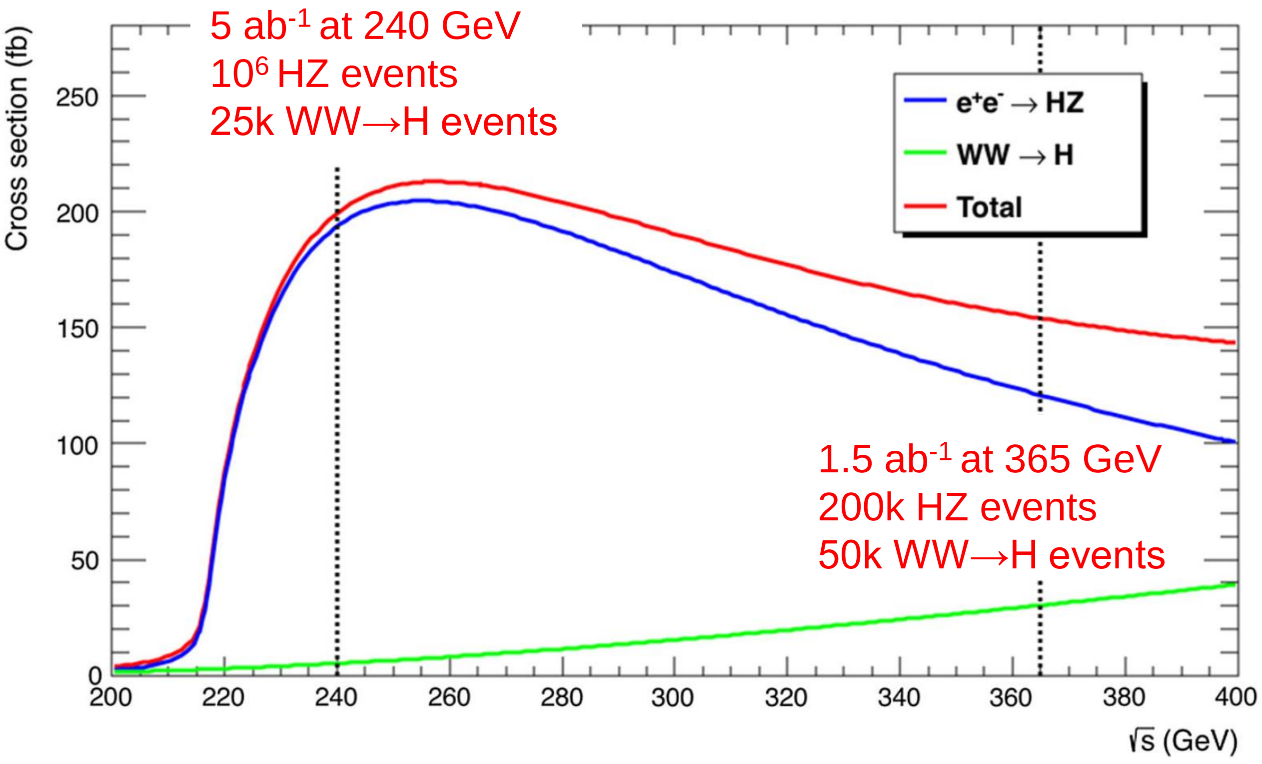
10^6 HZ produced and 25k WW→H

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

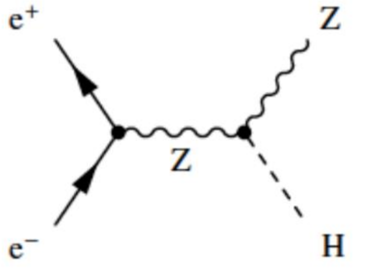
200k HZ events
50k WW→H events
10^6 tt events

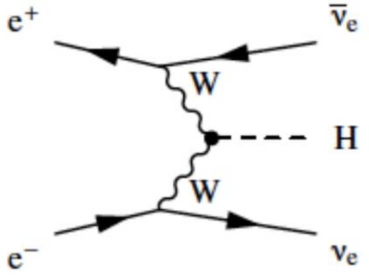
Higgs studies at FCC-ee

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.

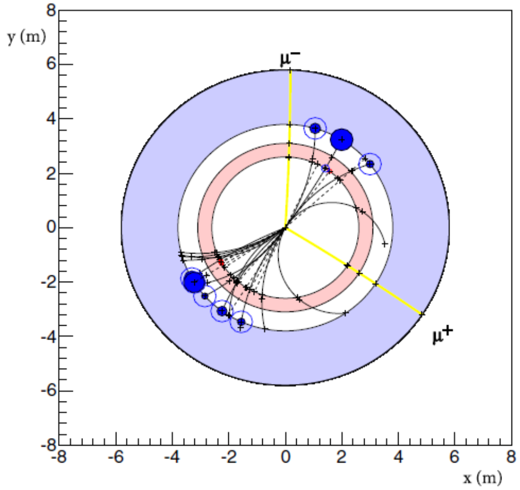
- Count *H*(→*ZZ**)*Z* events, and measure

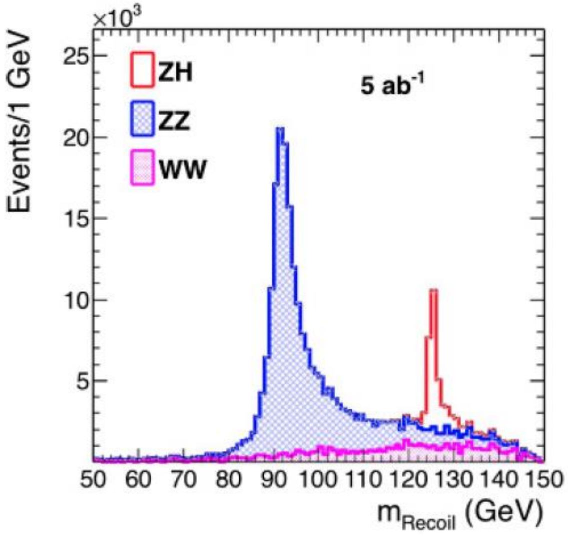
$$\sigma_{HZ} \times \frac{\Gamma(H \to ZZ^*)}{\Gamma_Z} \propto \frac{{g_{HZZ}}^4}{\Gamma_H}$$

  & thus determine Γ_H model independently.

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

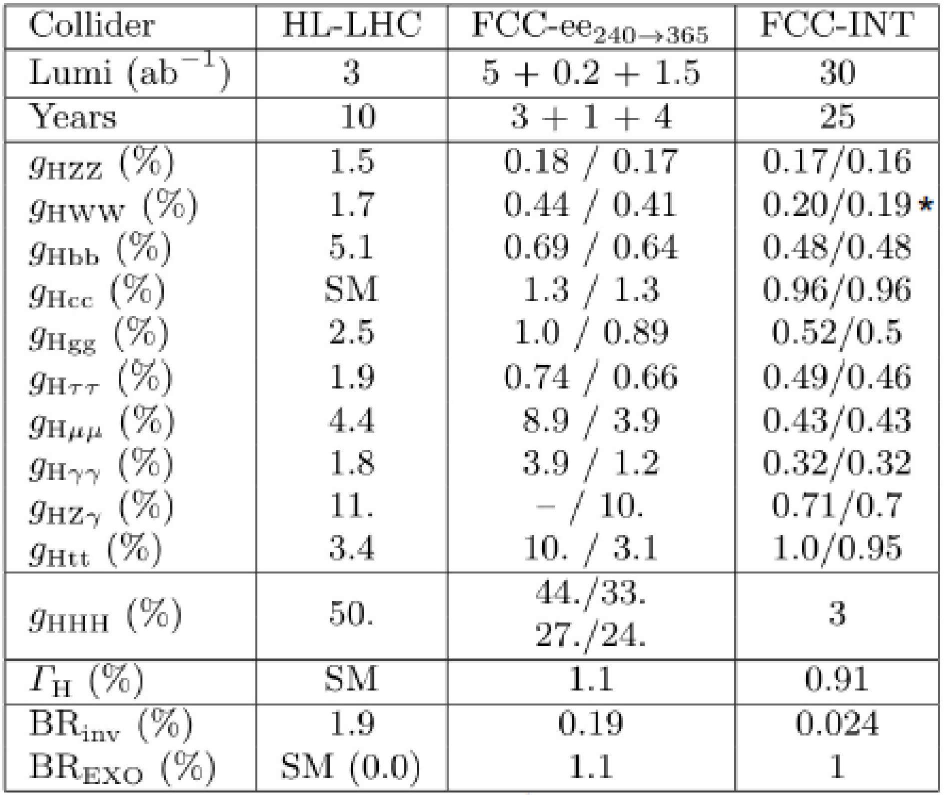
- Improve further by adding *WW*→*H* data.





Higgs studies at FCC-ee (+HL-LHC and FCC-hh)

Instructive to view final precisions from combination of HL-LHC and FCC-ee inputs (and ultimately with FCC-hh). Note that FCC-ee allows HL-LHC specialities (*e.g.* g_{Htt}) to be reinterpreted in a model independent manner.



Collider	HL-LHC	$\text{FCC-ee}_{240\rightarrow365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19 *
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{\text{H}\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{\text{H}\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{\text{H}\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{\text{HZ}\gamma}$ (%)	11.	– / 10.	0.71/0.7
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95
g_{HHH} (%)	50.	44./33. 27./24.	3
Γ_{H} (%)	SM	1.1	0.91
BR_{inv} (%)	1.9	0.19	0.024
BR_{EXO} (%)	SM (0.0)	1.1	1

e^+e^-

pp

e^+e^-

pp

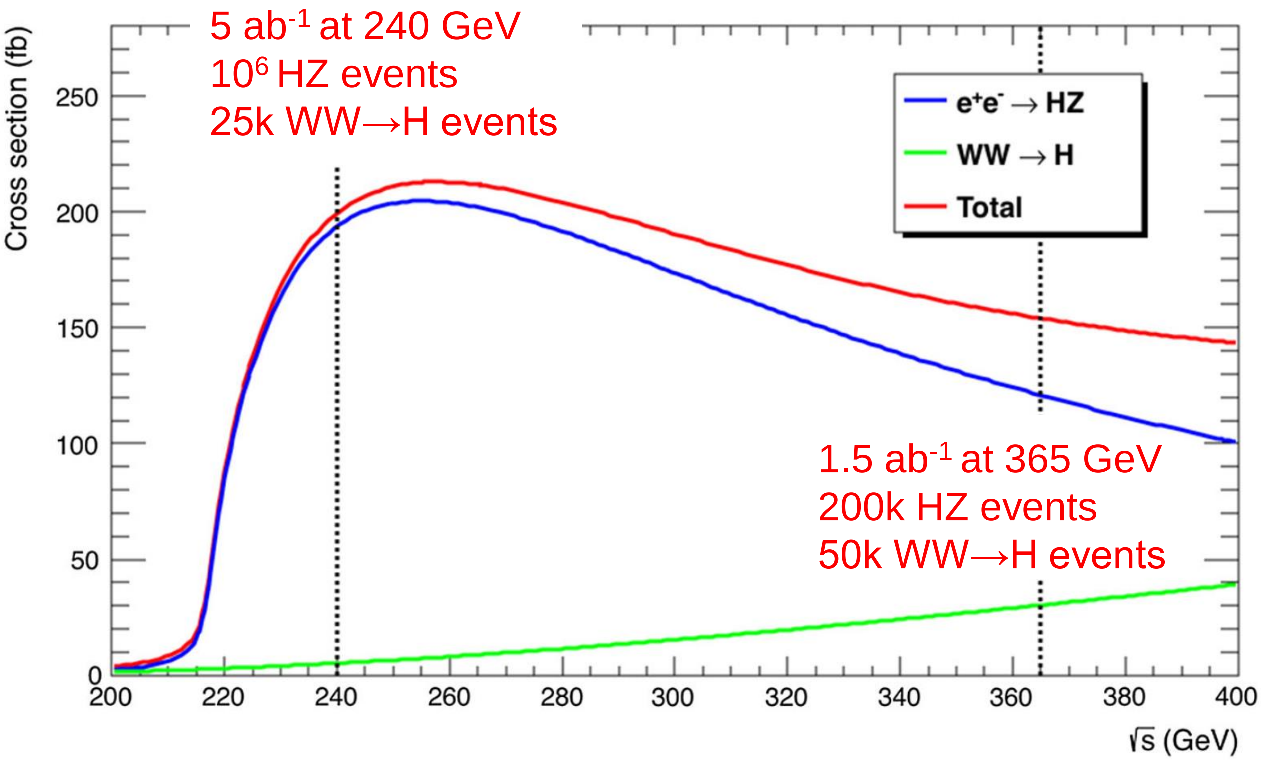
e^+e^-

---

* g_{HWW} includes FCC-eh

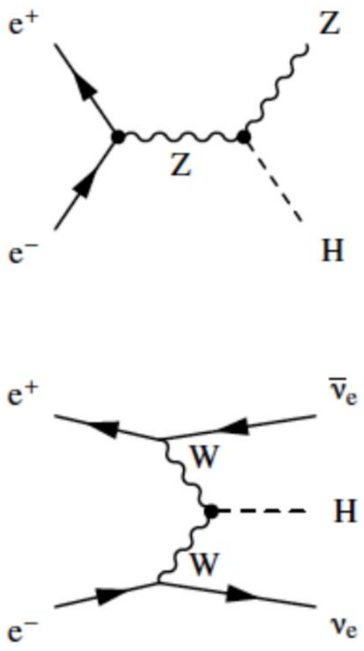
Why study Higgs at two energies ?

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



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

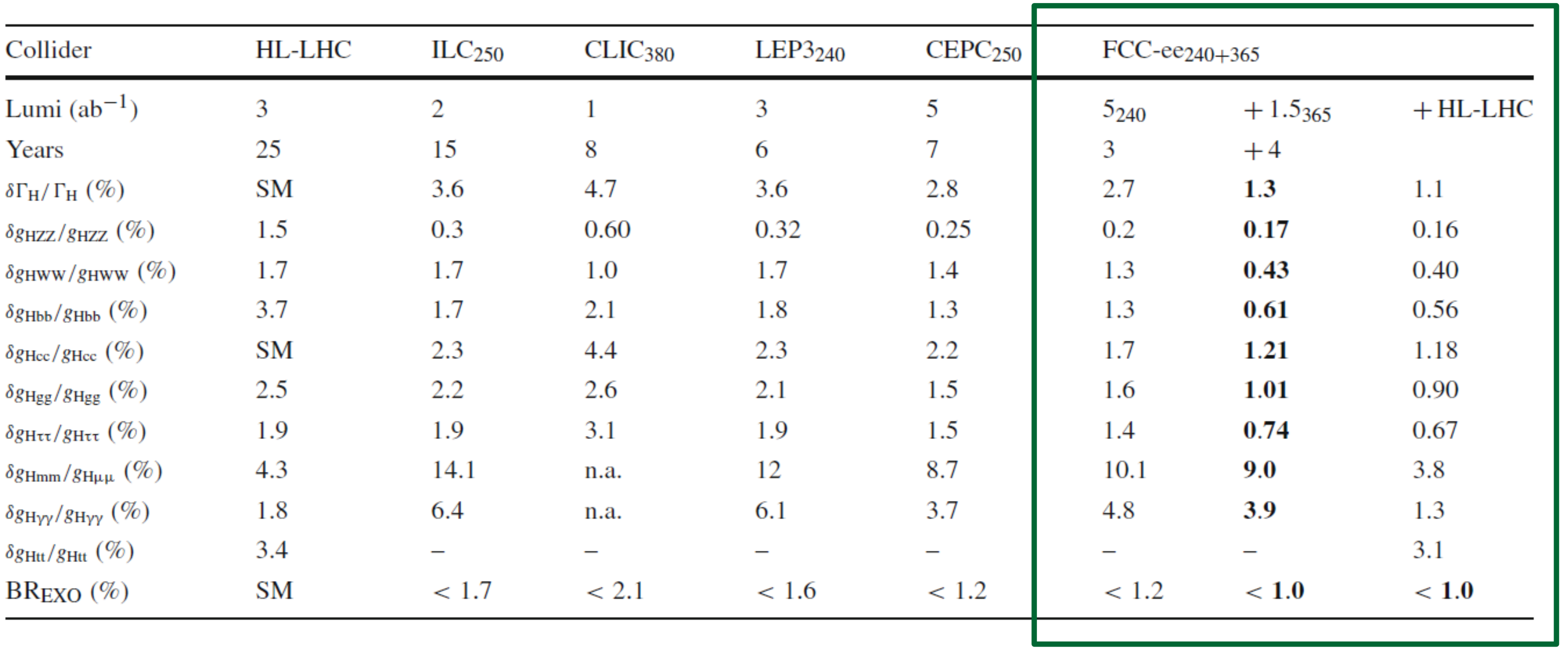


Sensitivity to both processes very helpful in improving precision on couplings.

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

Significant improvements from inclusion of 365 GeV data:

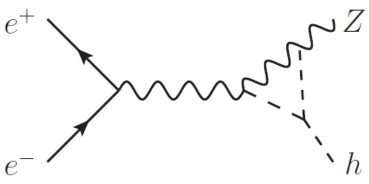


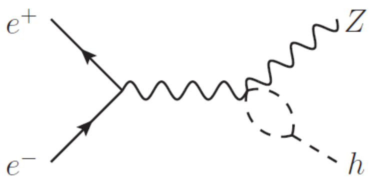
Collider	HL-LHC	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	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**

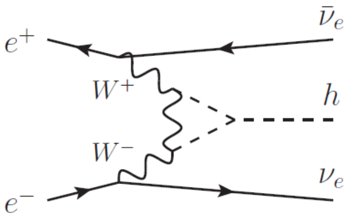
Sensitivity to both processes very helpful in improving precision on couplings.

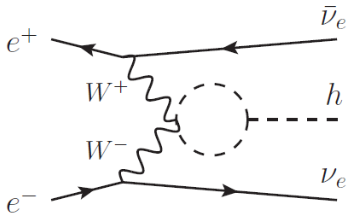
Higgs self coupling

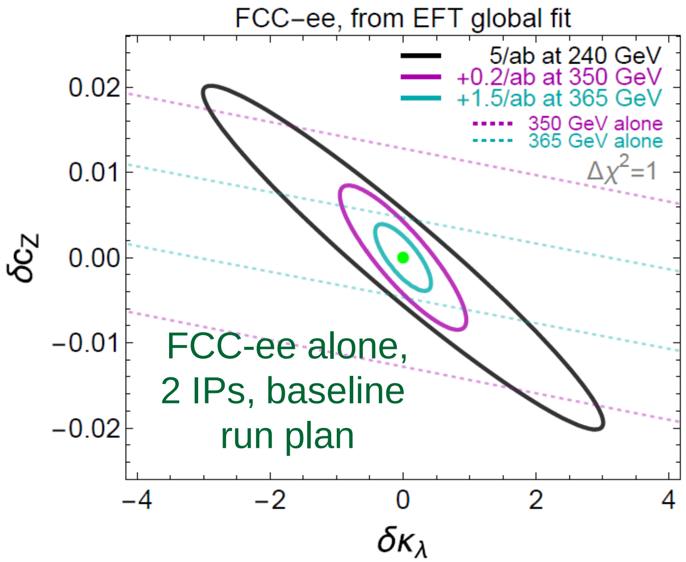
Discovery of *trilinear Higgs coupling* essential for characterising Higgs potential. FCC-hh can measure it to better than +/-5% through double-Higgs prod^{n}. However, FCC-ee has *indirect* sensitivity through precise x-section measurements.











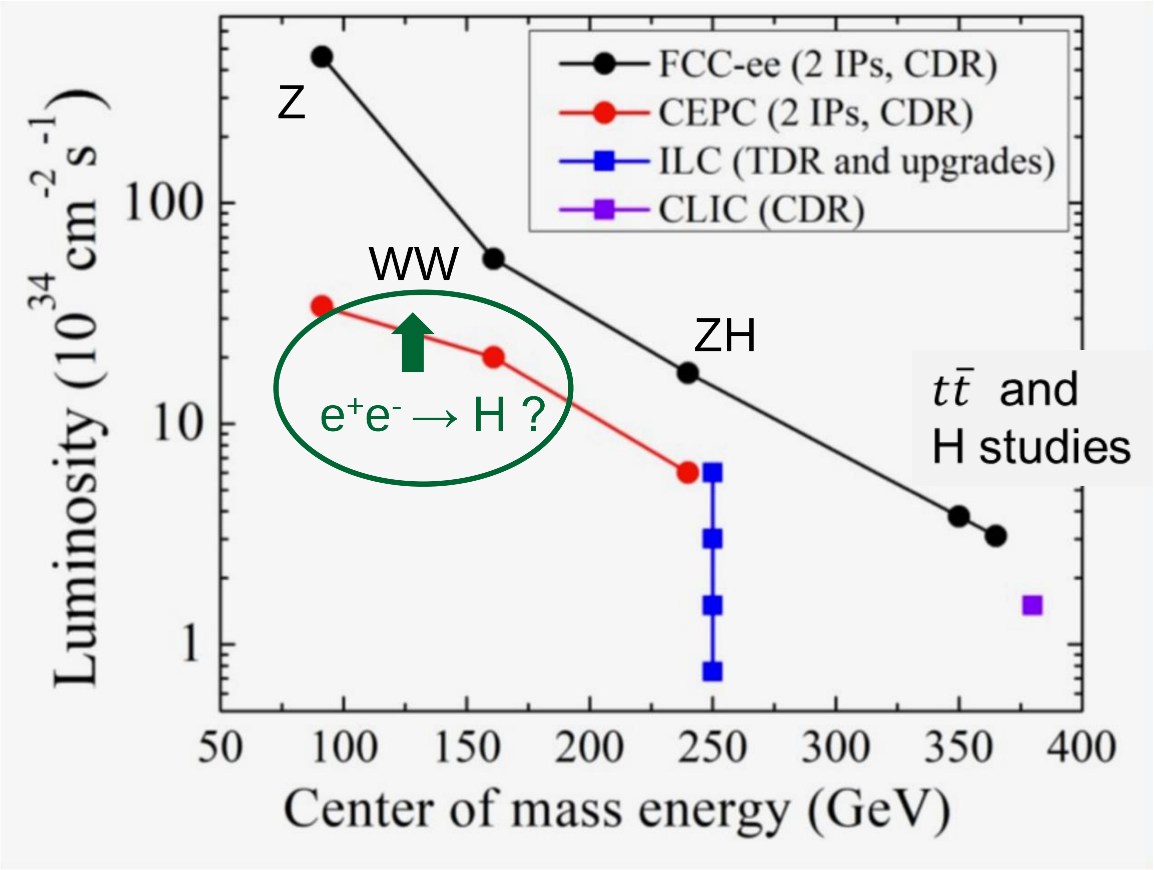
FCC-ee alone,
2 IPs, baseline
run plan

[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 !

Beyond the baseline: Higgs run at 125 GeV ?



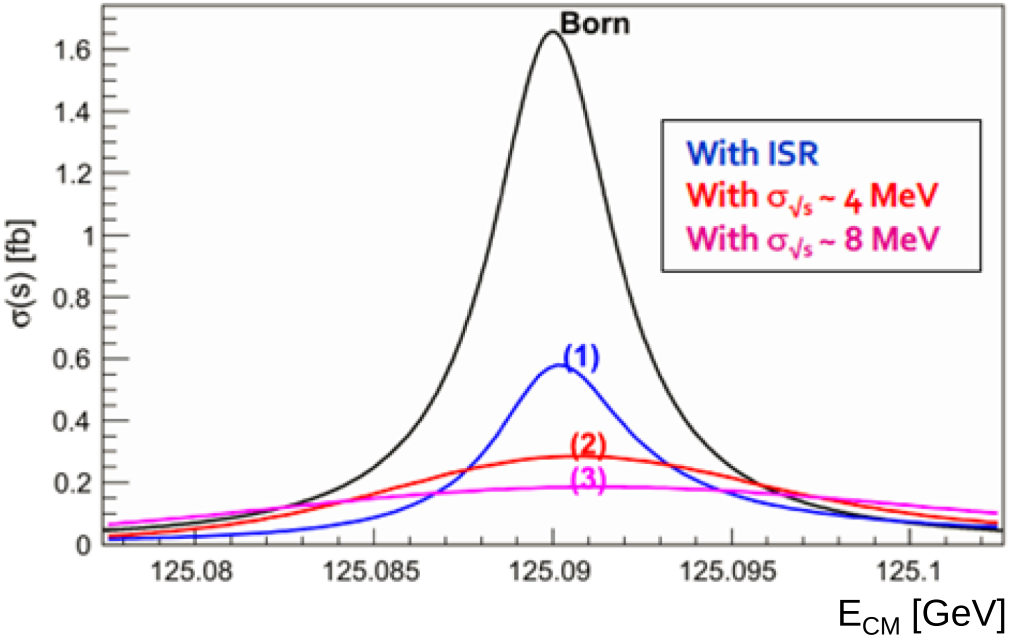
Run at 125 GeV ? s-channel Higgs production and monochromatisation

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.

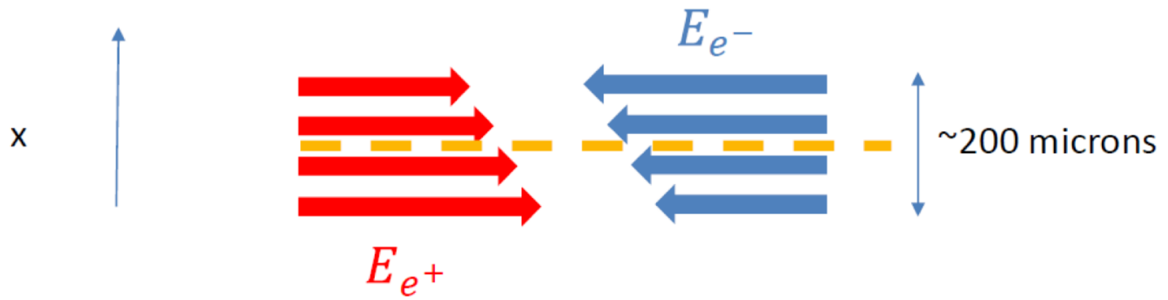
Note that natural E_{CM} spread for colliding beams is ~100 MeV. This must be reduced by < 1/10: the monochromatisation challenge !



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

The monochromatisation challenge

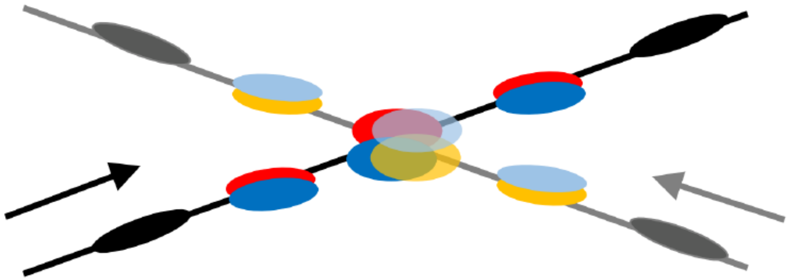
Introduce horizontal dispersion and collide head on to reduce E_{CM} spread.

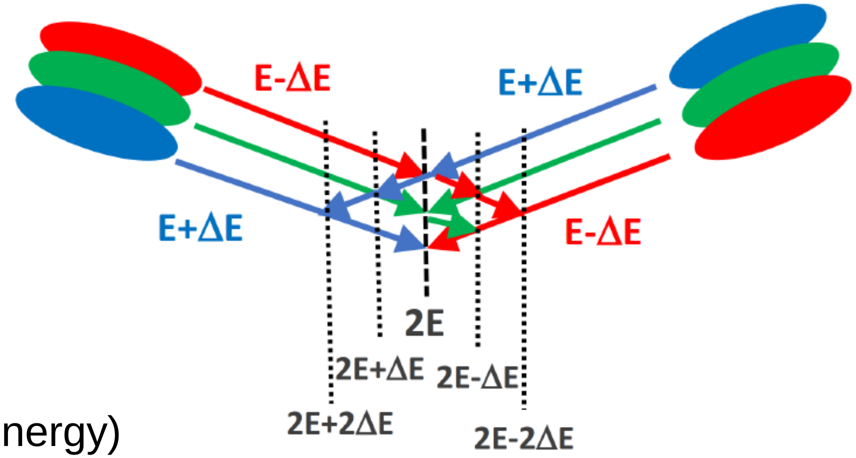


(arrow length ~ energy)

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}.

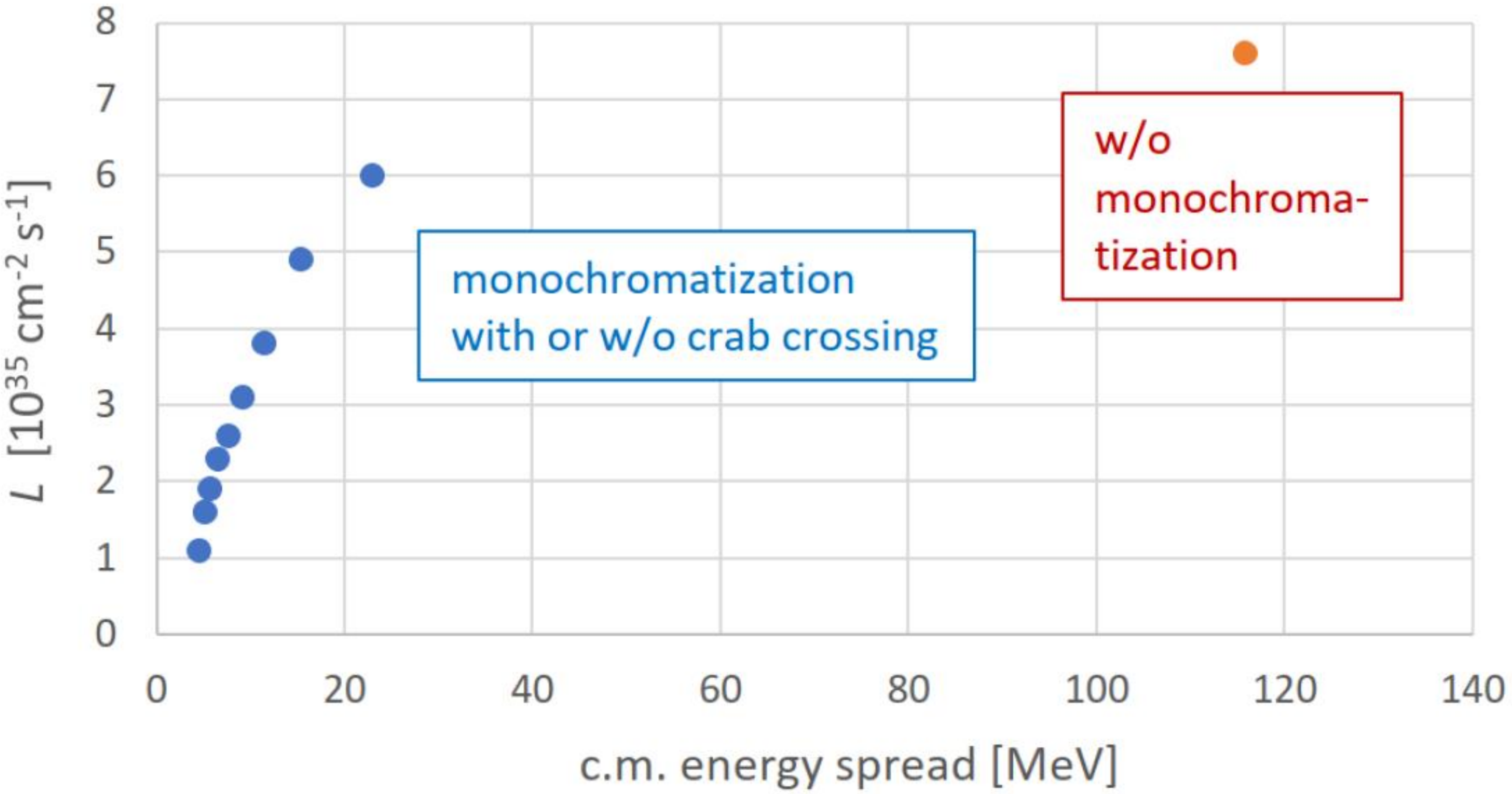




(colour ~ energy)

The monochromatisation challenge

However, dispersion increases horizontal emittance and reduces luminosity.

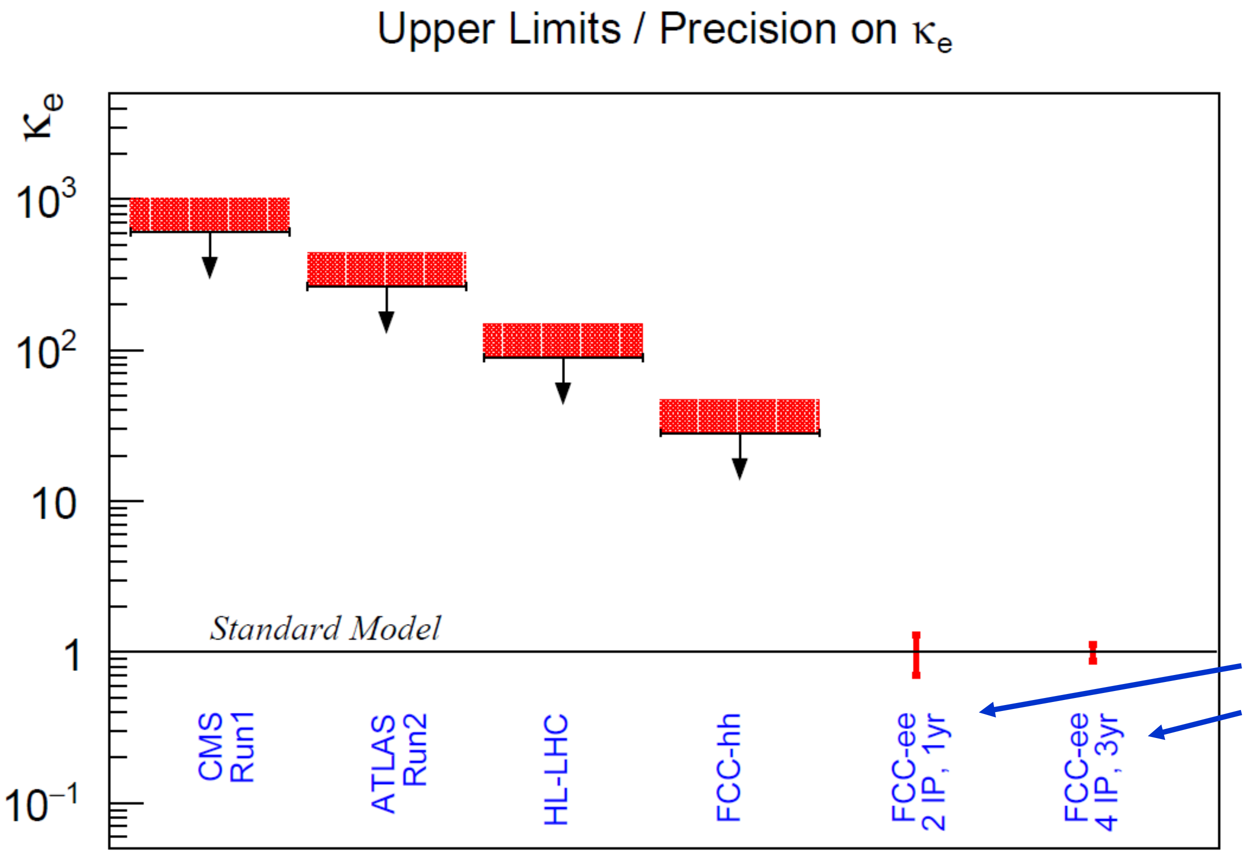


[Faus-Golfe, Garcia and Zimmermann]

Other approaches under consideration, which may retain more luminosity.

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 !



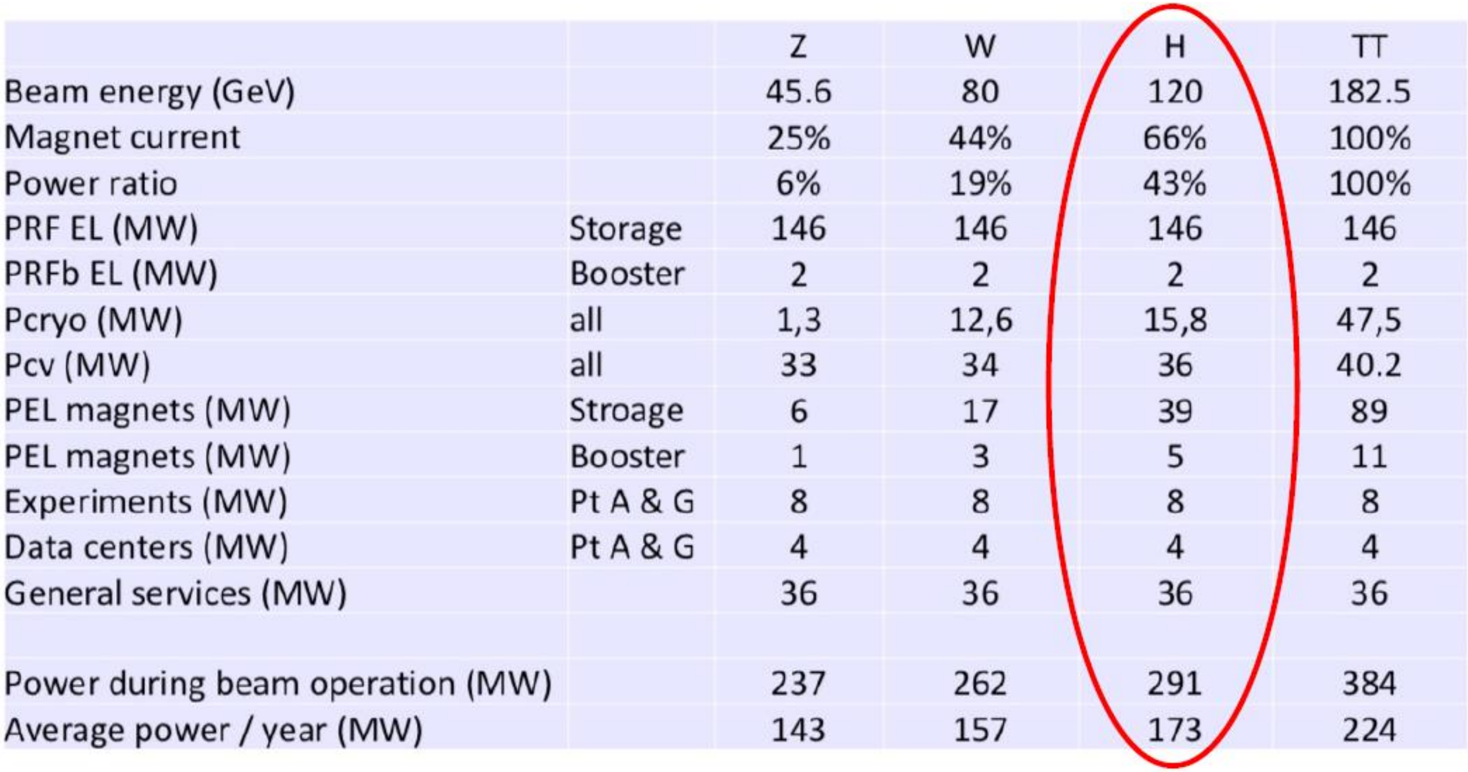
[arXiv:1912.11871]

(indicative – studies still under way)

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.

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

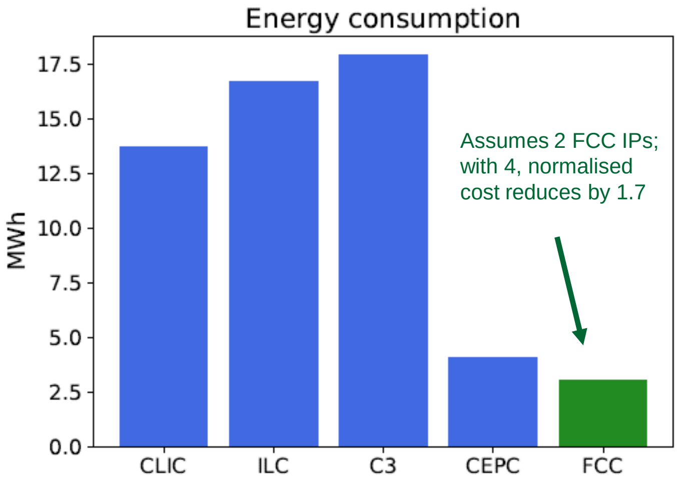
This corresponds to 1.6 TWh/year, to be compared to 1.4 TWh/year for HL-LHC.

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

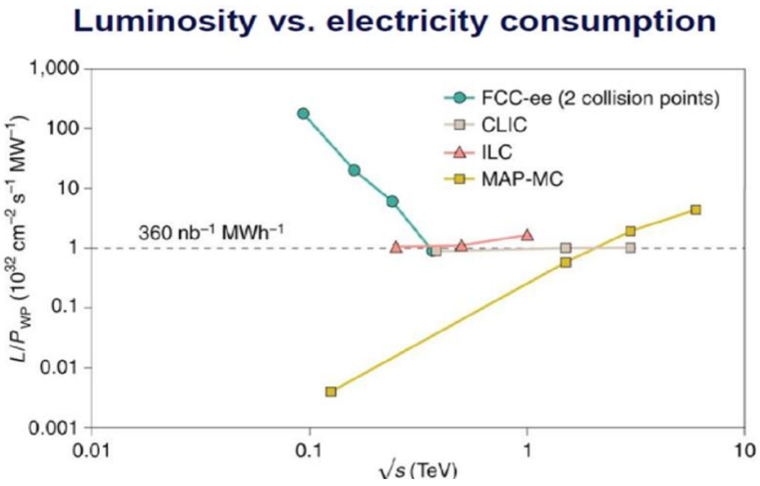
Normalise energy use by physics outcome, *i.e.* number of Higgs boson, or lumi.

[arXiv:2208.10466]



Energy consumption

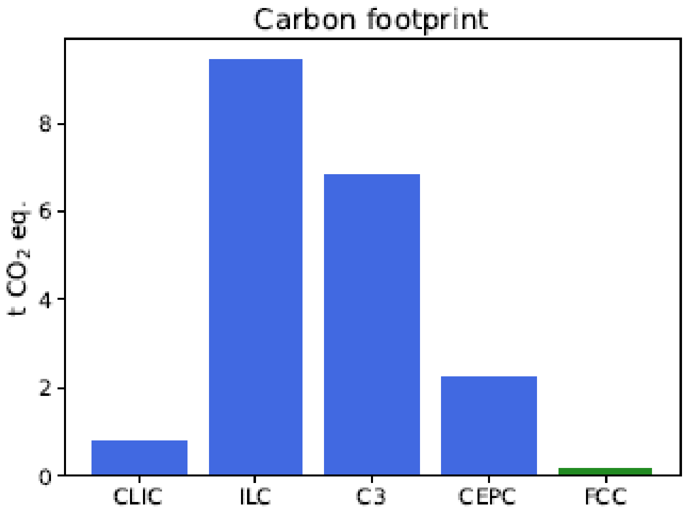
Assumes 2 FCC IPs; with 4, normalised cost reduces by 1.7



Luminosity vs. electricity consumption

[F. Zimmerman]

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



Carbon footprint

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

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

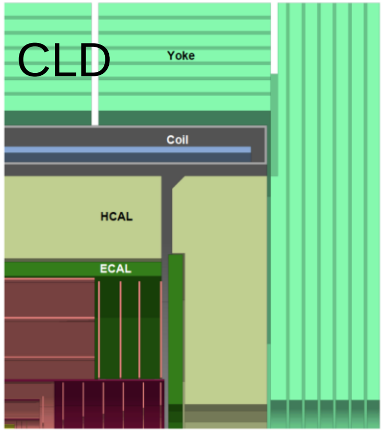
Detector challenges

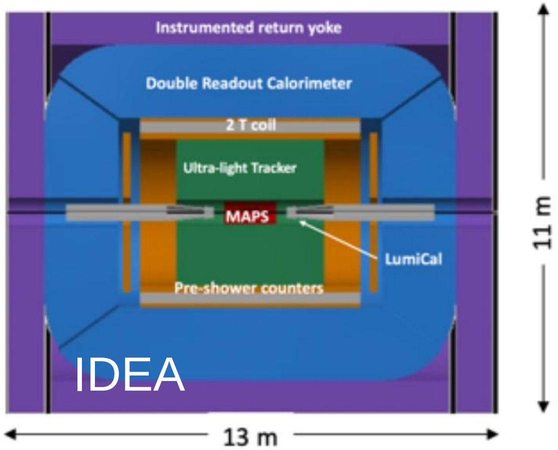
Event rates and radiation challenges modest compared with HL-LHC/FCC-hh.

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:



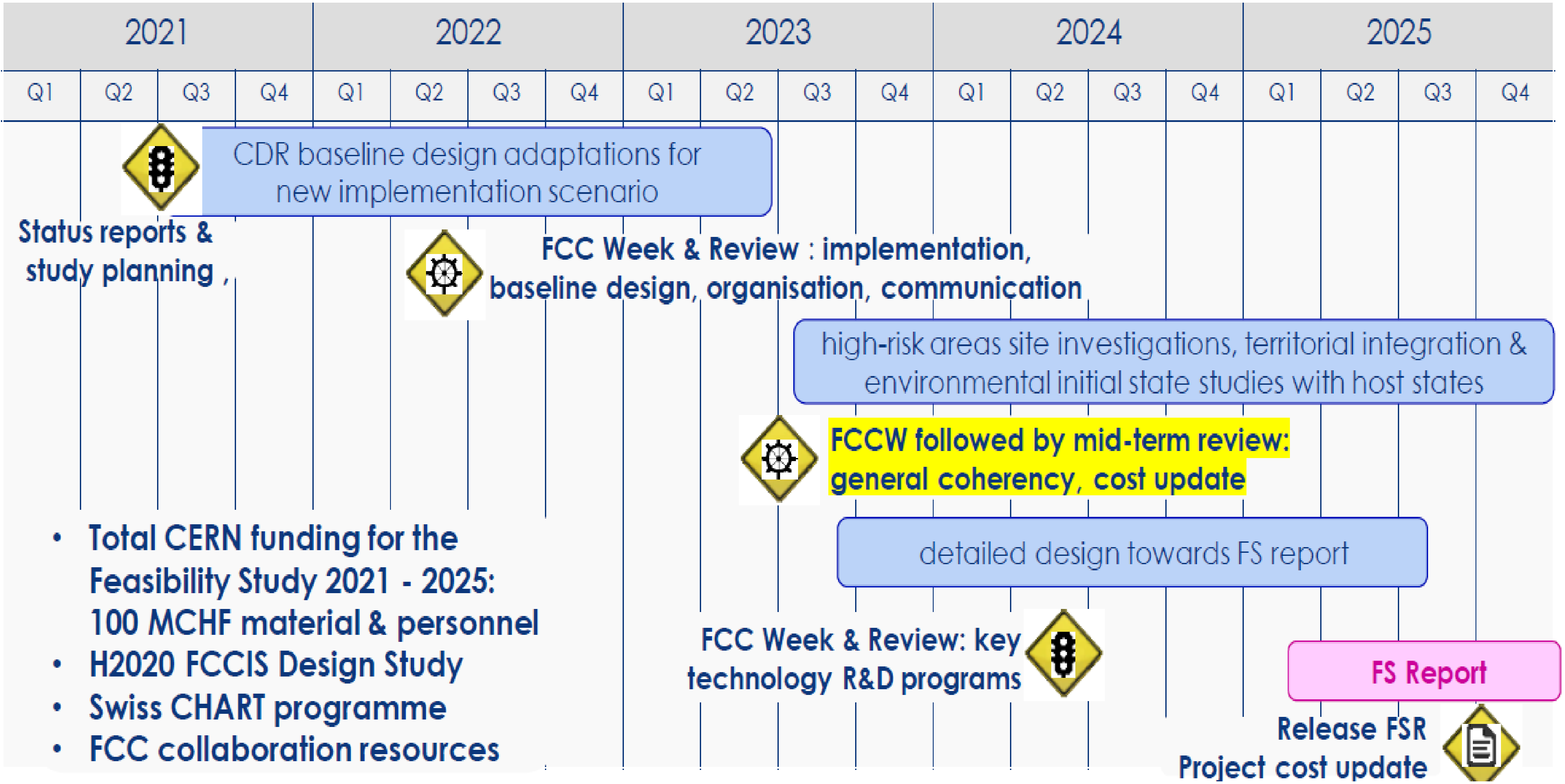


Noble liquid calo based concept

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.*).

Feasibility study underway



2021 | 2022 | 2023 | 2024 | 2025

Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4

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**

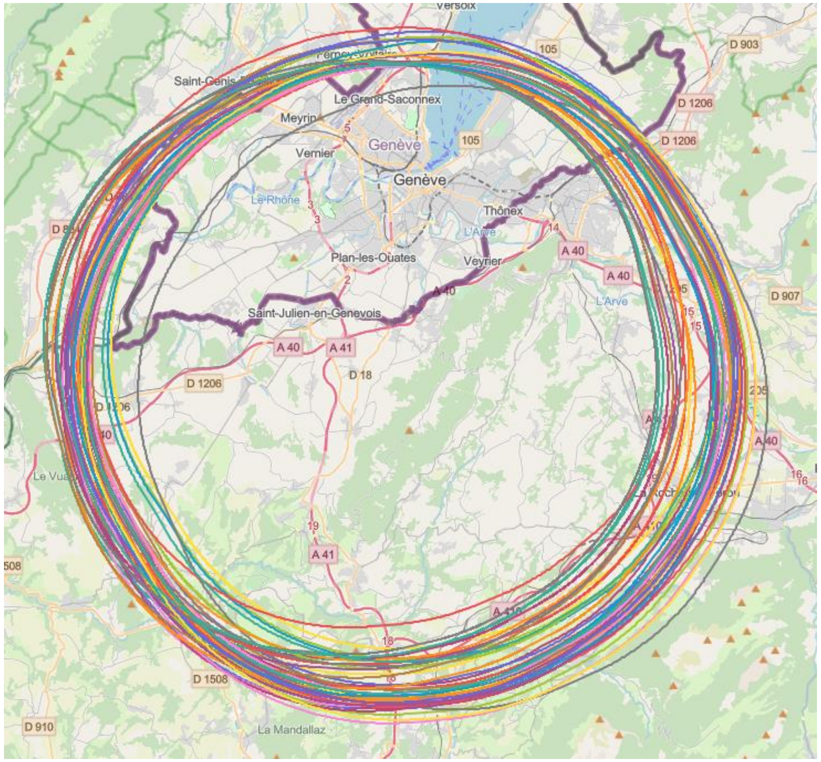
Note mid-term review, in second half of next year.

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]



Timescales and finances

Statements of CERN DG in Paris FCC week (June ‘22)

“
- 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)

The further future – towards the highest energies

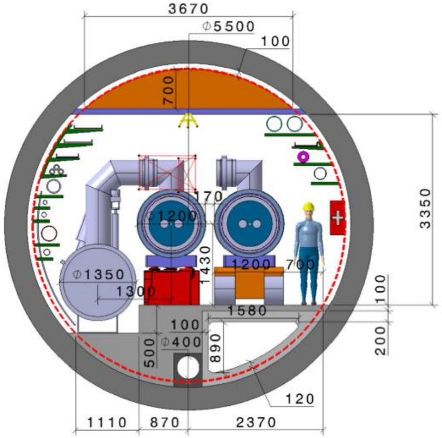
- FCC-hh
- Muon colliders

The further future: FCC-hh

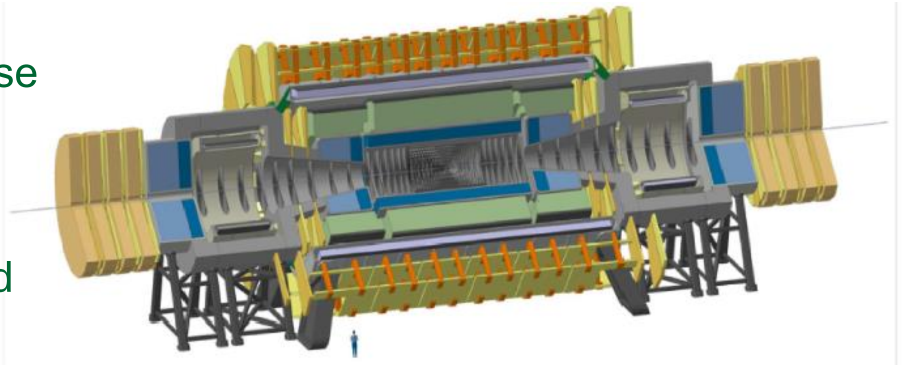
Also SPPC in China

ESPPU: *"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage ."*

FCC-hh will be such a machine, with the aim to collect 20 ab^{-1} per (general purpose) detector over a 25 year period, operating up to 3 x 10^{35} cm^{-2}s^{-1}.



Two 'general purpose detectors', with possibility of two interaction points for more specialised detectors, à la LHC



Extreme challenges include: need for 16 T dipole fields, very high radiation levels, pileup up to 1000, and huge data processing / storing requirements.

FCC-hh: the infinity machine

~30 ab^{-1} at 100 TeV provides astounding physics reach. Jewel in the crown: precision study of the Higgs potential, with self-coupling measured to 3.4 – 7.8%.

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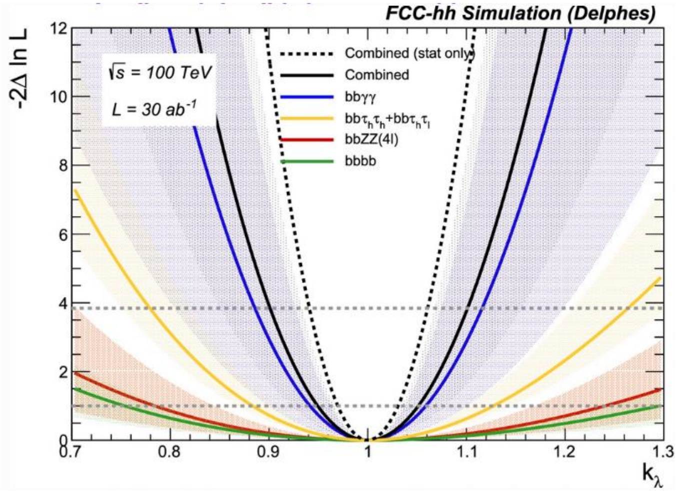
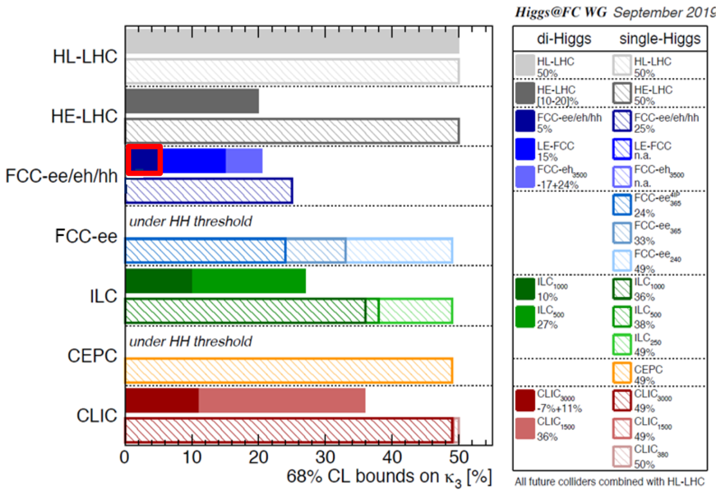
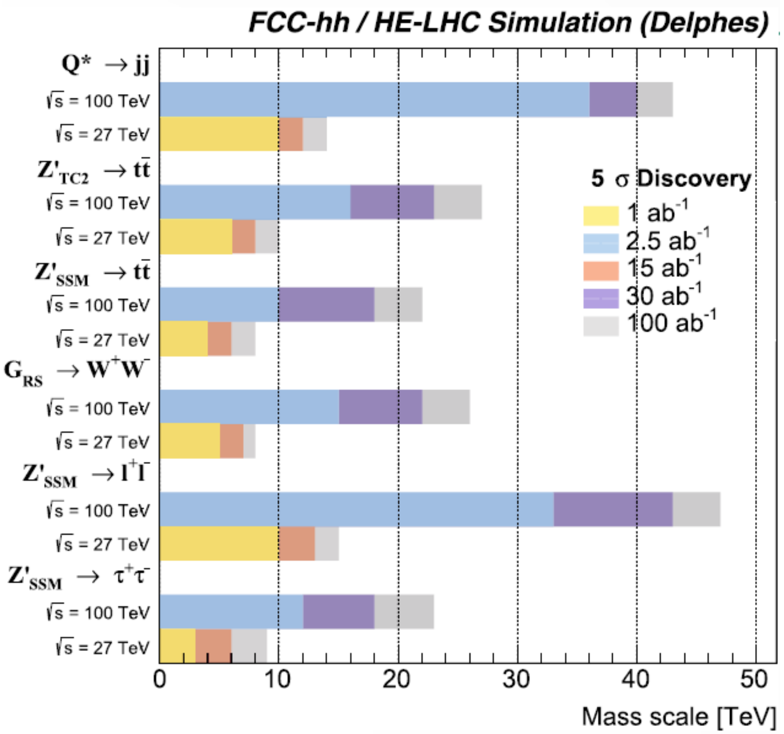


Remarkable direct-search potential

e.g. certain heavy resonances accessible up to beyond 30 TeV





What is the FCC-hh timescale, and why ?

Recall the wise words of the DG in Paris FCC week (June '22)

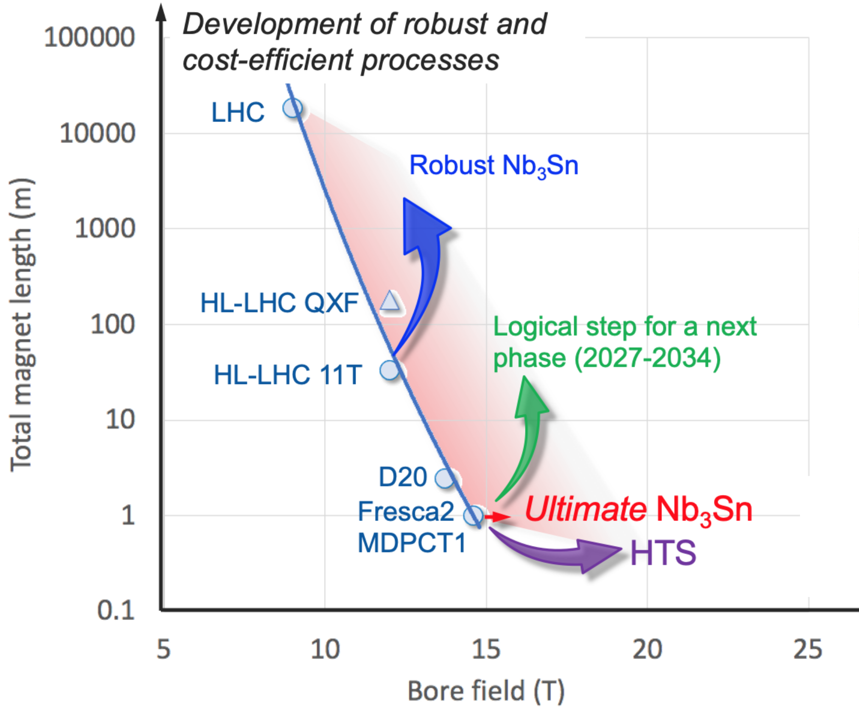
> “ • If project approved before end of decade → construction can start beginning of 2030s
> - FCC-ee operation ~2045-2060
> - FCC-hh operation ~2070-2090++ ”

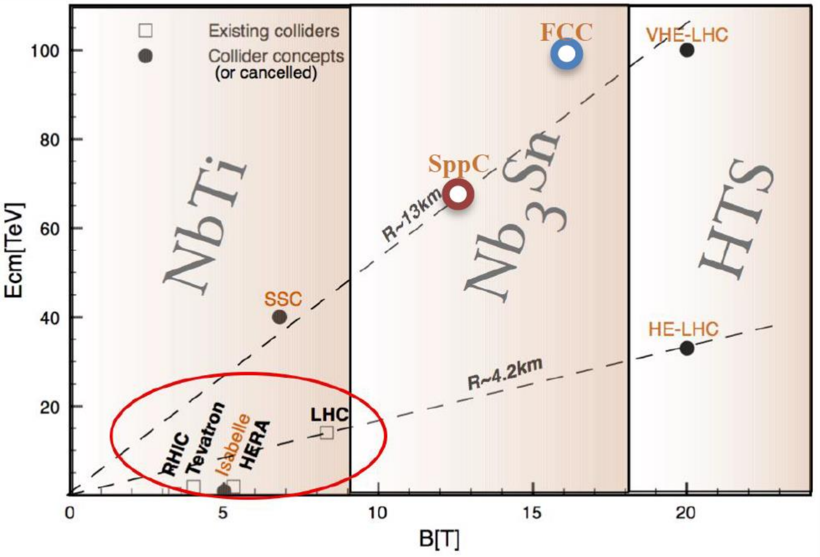
But (say the 'hadron heads'), why not skip FCC-ee and go straight to FCC-hh instead ? Several answers:

1) FCC-ee physics is of very high importance, much of it is unique, and what we learn there will serve as important input to FCC-hh measurements (*e.g.* model-independent Higgs studies);
2) We don't know how to build the magnets;
3) We don't know how to build the detectors;
4) Non-physics fact, but a brutal fact nonetheless: standalone FCC-hh would cost ~24 GCHF. The FCC-ee route is financially more palatable.

FCC-hh: magnet challenges

Require high field magnets that are robust and can be manufactured in bulk.

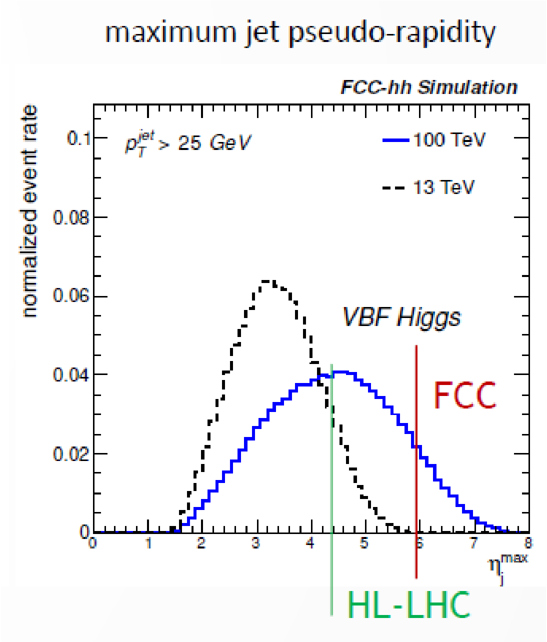


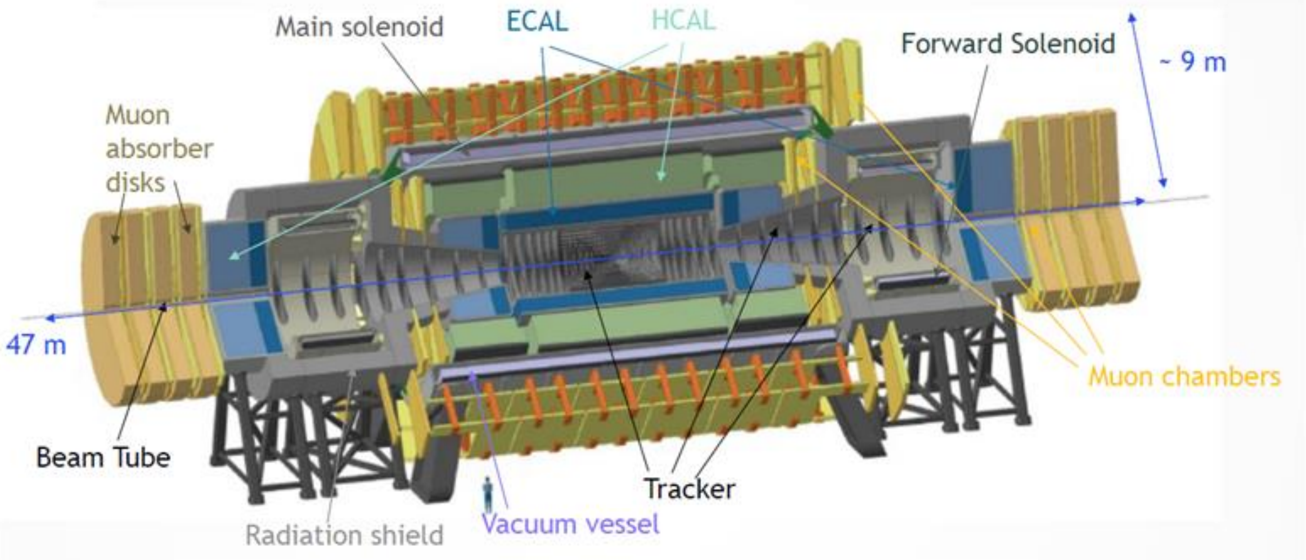


Long term project, with ongoing efforts in Europe, US, Japan & China. *e.g.* CERN is committing 200 MCHF over 10 years, with goals to attain 16T for Nb_3Sn and even higher for high temperature superconductors, with prototypes & industrialisation solutions.

FCC-hh: detector challenges

Detectors will look superficially like those at HL-LHC, with important differences, *e.g.* more physics happens at high rapidity, so forward region more important.

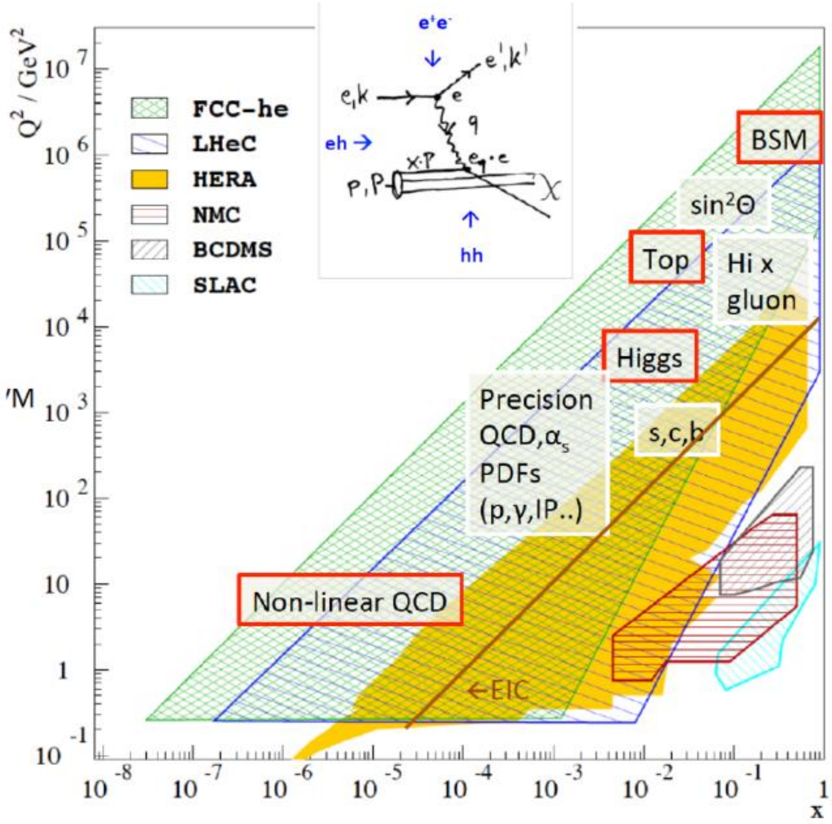




Radiation levels generally 10-30 x worse than HL-LHC, but much bigger for forward calorimeter and innermost tracking layers – beyond capabilities of current technologies ! Long R&D programme required to find solutions – as was the case in the lead up to LHC.

Completing the picture: FCC-eh

Possibility exists to build an Energy Recovery Linac for 60 GeV electrons which would allow for ep collisions, with single dedicated detector.



- Superb microscope for looking deeper into structure of proton, à la HERA. Ever better knowledge of parton distribution functions highly valuable for FCC-hh.
- High sensitivity for certain Higgs and EW studies, *e.g.* g_{HWW}.
- Best reach in certain new particle searches, *e.g.* leptoquarks.

(These possibilities are also being considered for HL-LHC: LHeC.)

Muon colliders – the attractions

Synchrotron radiation $\propto E^4/m^4$, so 10^9 lower than for electrons. Consequences:

- Muon colliders are an attractive route to multi-TeV collisions (and as muons are fundamental particles, such collisions have enormous physics reach);
- Low energy spreads → beams are highly monochromatic;
- Very compact collider, *e.g.* a 10 TeV machine could have a radius of 1.6 km.

Furthermore, s-channel Higgs production is viable (cross section 40,000 times that for electrons), which opens up possibility of running at Higgs pole. However the luminosities and production rate here, or even at 250 GeV are unfavourable compared with an e^+e^- machine. Most attractive scenarios are at higher energies.

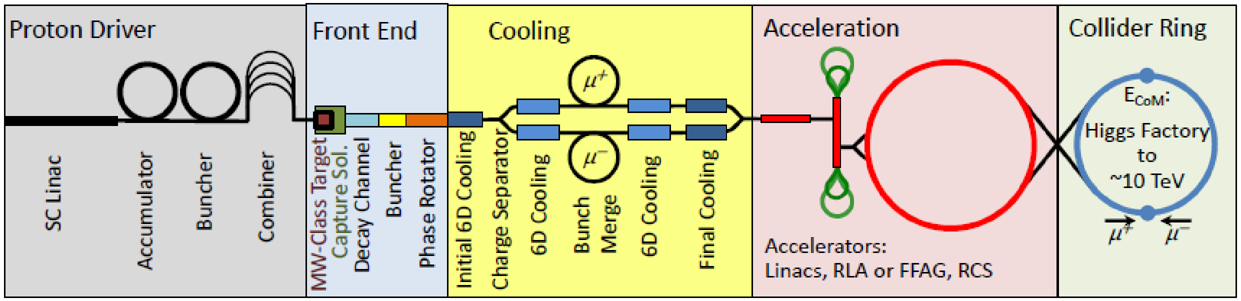
Muon colliders – the challenges

Muon beams are tertiary beams

- Protons → pions → muons
- Requires sophisticated production, capture, manipulation scheme

Muons are born with large phase space

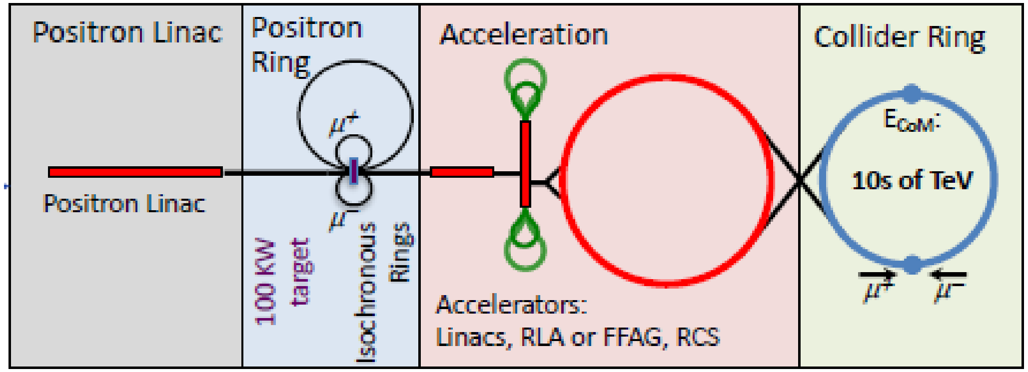
- Must be reduced by many orders of magnitude for a collider



Potentially both these problems can be mitigated by the LEMMA scheme.

Low EMmittance Muon Accelerator (LEMMA)

Produce muon pairs directly from impinging positron beam on electron target.



[NIM A807 (2016) 101]

- Muons produced at low momentum (& phase space) in centre-of-mass frame…
- …but with significant boost in lab frame, with average lifetime of 500 μs.

Significant benefits in terms of cooling needs. Furthermore, fewer muons are needed to reach a given luminosity, which is desirable from radiation aspects.

A promising concept, but intensity required for positron source is very demanding !

Muon colliders – the challenges

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Muons decay

- Everything must be done fast
- Detectors and accelerator must be shielded from decay electrons
- Neutrino flux presents a significant radiation danger

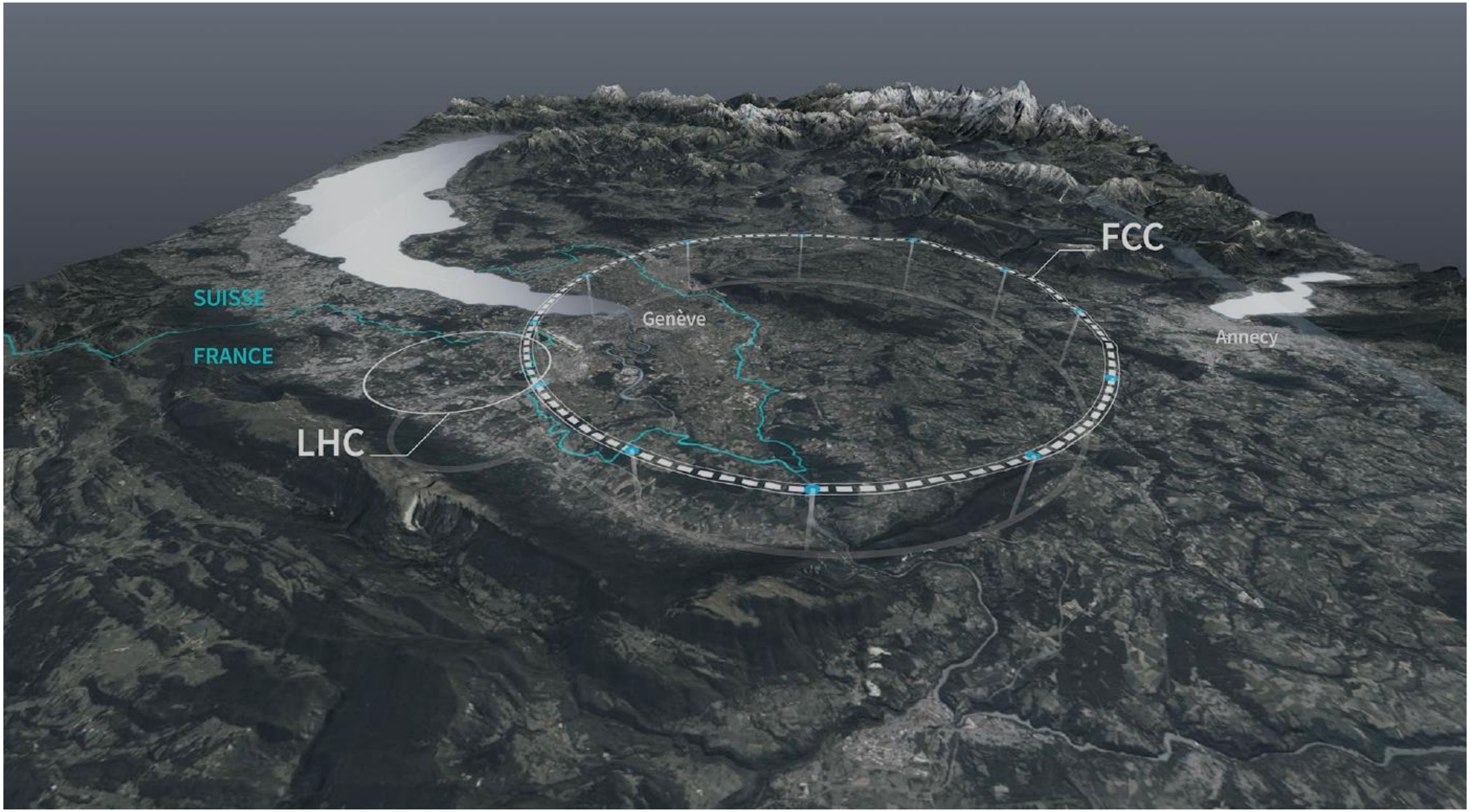
Muon colliders do appear a very interesting route to physics at collision energies of several TeV to 10 TeV, and are being actively evaluated in US [arXiv:2209.01318] and Europe [arXiv:1901.06150]. But unlikely to be viable until second half of century.

Summary

Experimental HEP is at a fascinating stage, with much progress expected in the coming decade and beyond. To single out but two examples, neutrino physics and flavour physics are well placed to make great strides forward.

The collider programme is also at an interesting juncture. The LHC still has an enormous amount to deliver, but a new e^+e^- machine is required to make precise studies of Higgs' properties, and improve our knowledge of other observables in the Standard Model. Even better if building this machine will pave the way for a future discovery programme at very high energy.

The future awaits – let's make it happen !



Backups