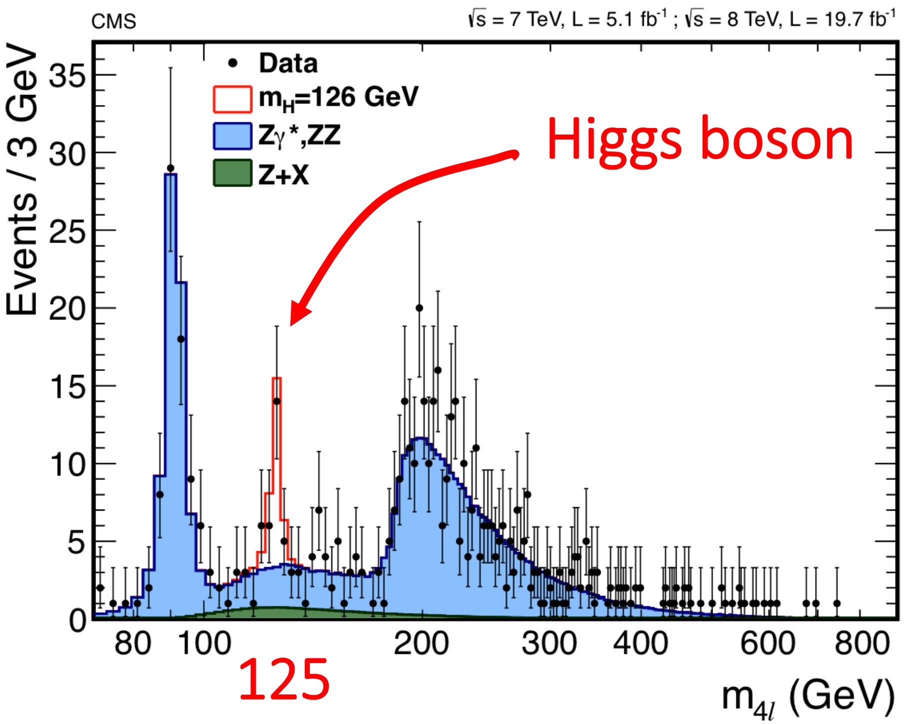
Physics potential of future experiments at FCC

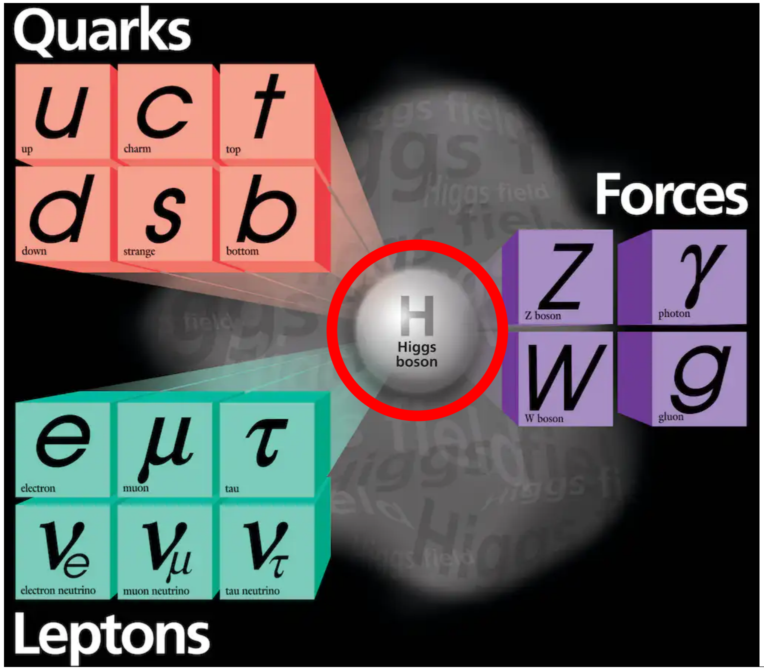
Loukas Gouskos (CERN) on behalf the FCC Collaboration

HEP 2023, Ioannina

The triumph of Standard Model (SM)

- Discovery of the/a (?) Higgs boson (2012)





- SM is now complete
- Higgs boson: Plays a very central role; interacts with all particles

Is that all?

- The big open questions.. that beg for Beyond SM (BSM) physics

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - …

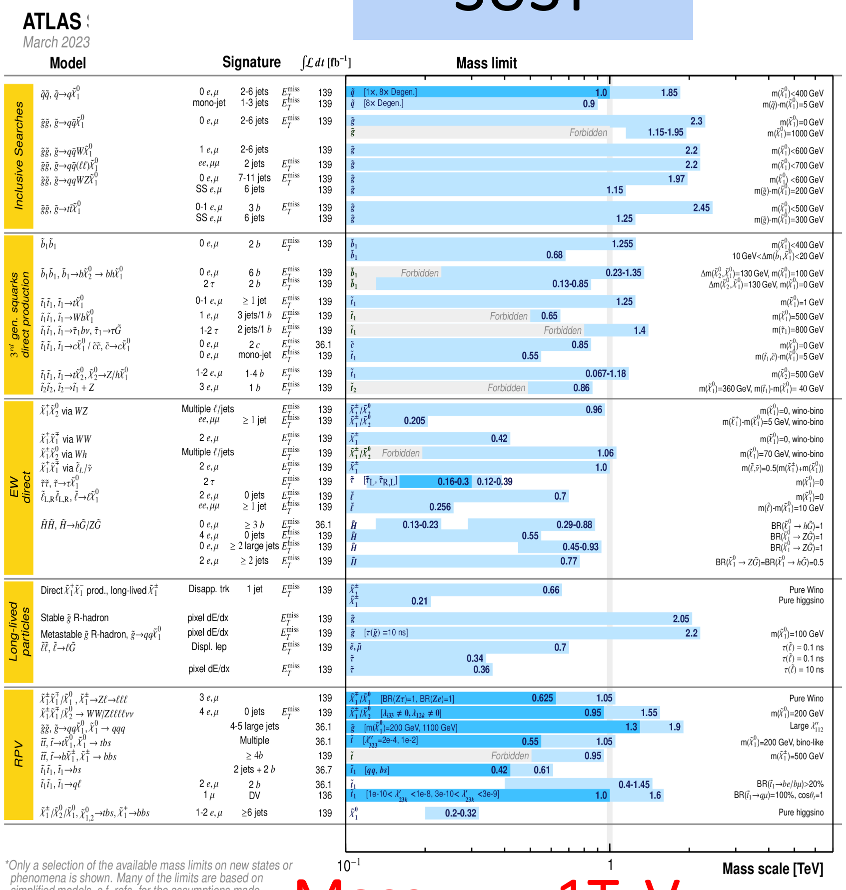
M. Mangano at Higgs Hunting (2019)

- Procedure to address them [at least part of them]
  - Direct BSM searches (SUSY, heavy exotic particles,…)
  - Sensitive tests of SM parameters
    - EWK/top/Higgs properties, Favour physics, …
      - which precision necessary?

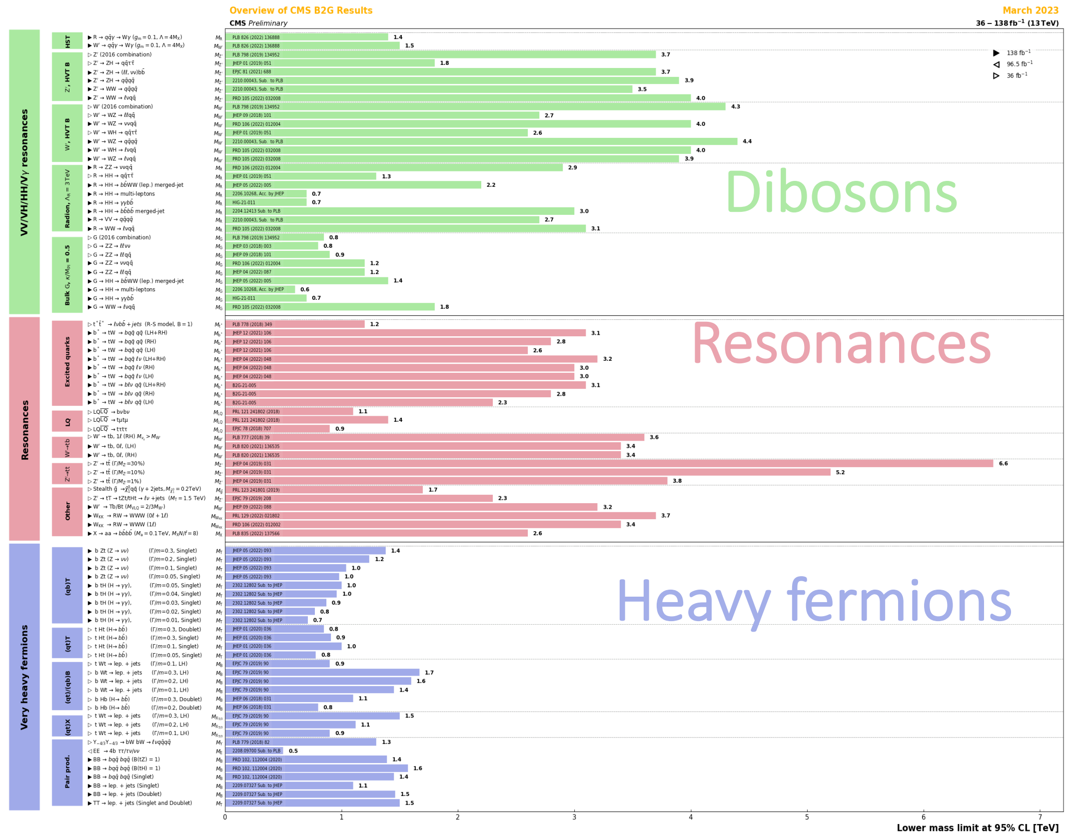
Physics landscape after 10y of LHC

- Plethora of searches for Beyond SM signals exploring energy frontier

SUSY



Heavy resonances



Mass: 1TeV 1TeV 5TeV

- and many many more channels/topologies/signatures

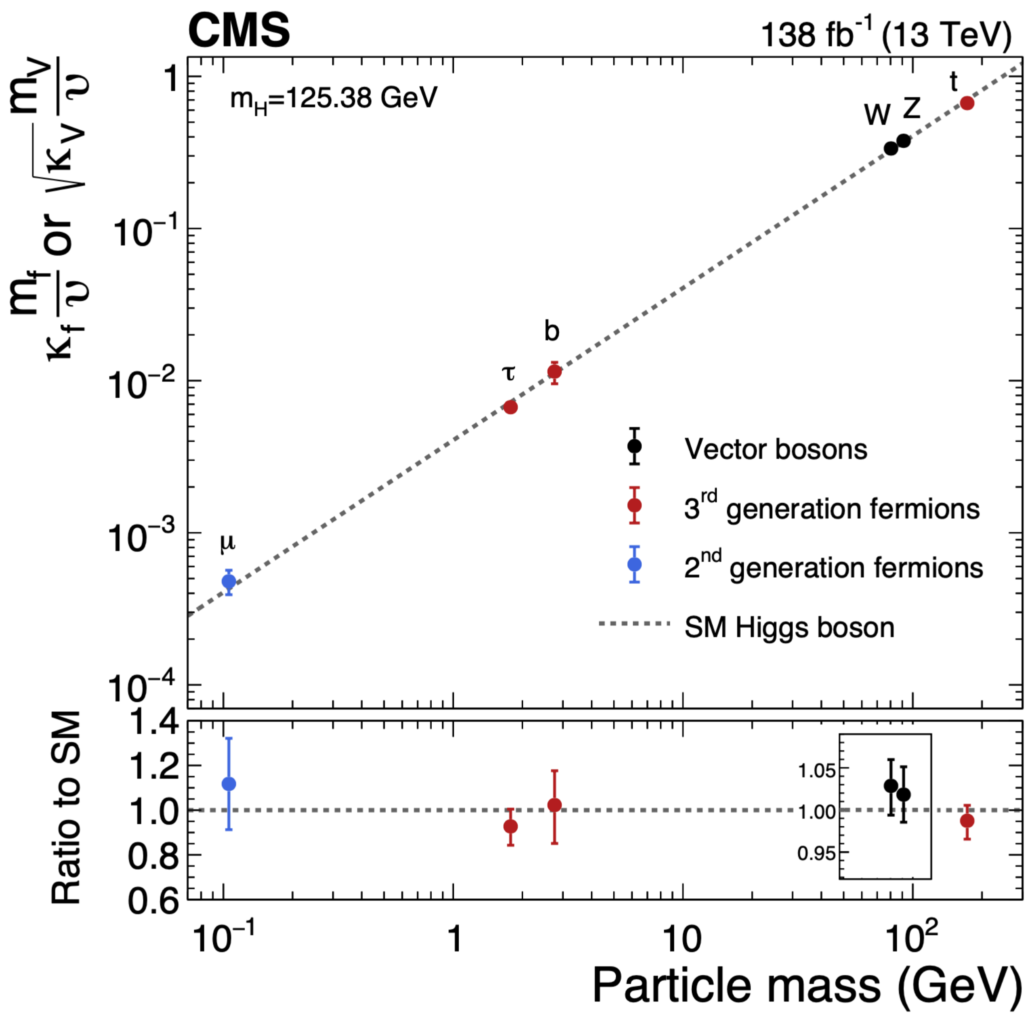
- Nothing came up yet

Physics landscape after 10y of LHC (II)

- A whole new chapter of exploration opened
  - Modifications to Higgs properties → sign of BSM
- Already established:
  - Inclusive rates
  - Couplings to **bosons**
  - Couplings to **3rd-Gen fermions**
- Current focus:
  - Couplings to 2nd-Gen fermions

All-in-all:

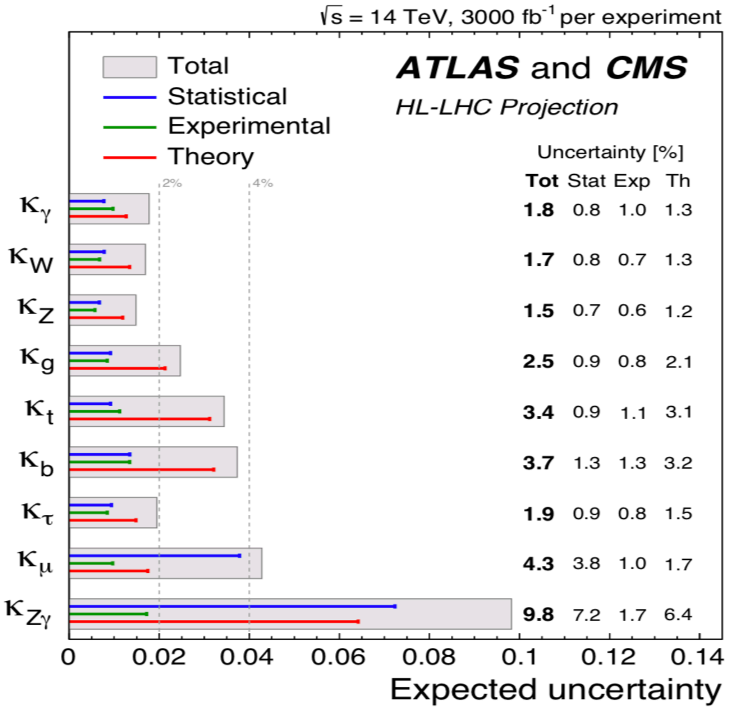
No signs of new physics



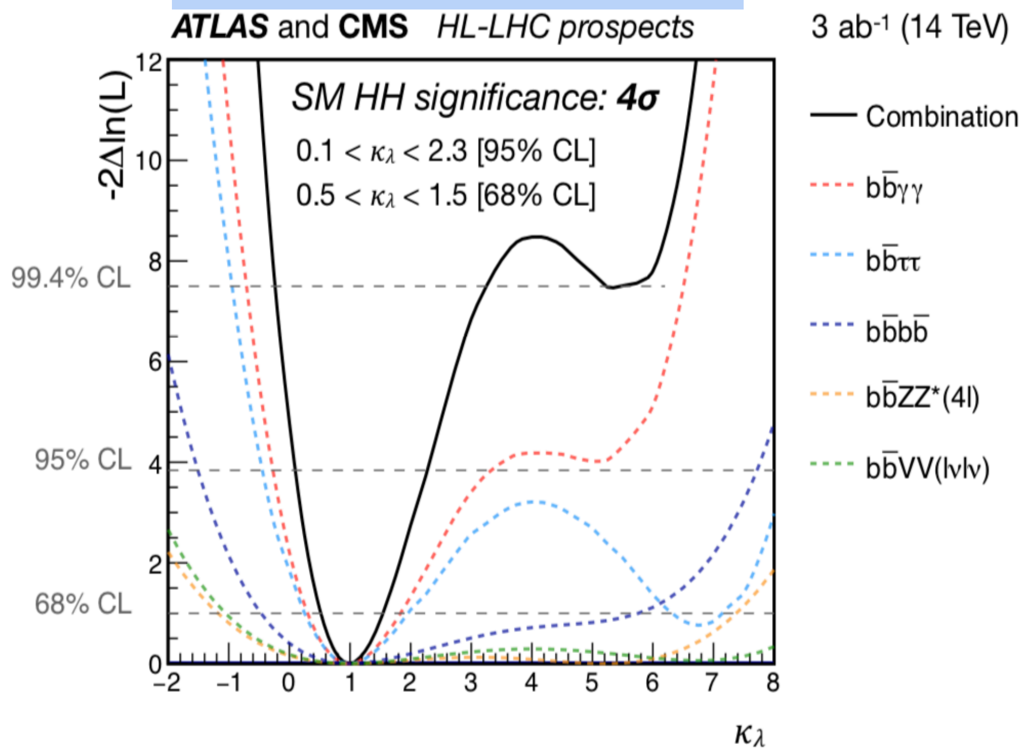
The landscape at the end of HL-LHC

- **Unique situation:** Current results do no concretely point to any BSM scenario/mass scale

Higgs couplings



Higgs-self coupling



+ Probe new resonances (particles) up to ~8 (~4) TeV

HL-LHC: Cannot guarantee definite answers to any of the big open Qs

Shaping the future

- Where is New Physics:
  - **Within LHC reach:** hidden in difficult corners and/or small cross-section
  - **Beyond LHC reach:** very massive new particles

New colliders are necessary to explore the multi-TeV regime

Shaping the future

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- Guiding principles:
  - <u>Sensitive</u> tests of SM parameters
    - NB: “**<u>precision”</u>** not necessarily “**<u>sensitive”</u>**
  - Explore as **<u>broad</u>** as possible set of scenarios
    - all directions impossible
  - Provide **<u>definite answers</u>** to concrete scenarios

No **<u>“guaranteed discoveries”</u>** rather than **<u>“guaranteed deliverables”</u>**

Shaping the future

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  - **Within LHC reach:** hidden in difficult corners and/or small cross-section
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    - all directions impossible
  - Provide **definite answers** to concrete scenarios

No **"guaranteed discoveries"** rather than **"guaranteed deliverables"**

- Typically two approaches [not necessarily mutually exclusive]
  - **Higher precision:** lepton colliders (e+e-)
  - **Larger rate/mass reach:** hadron colliders (pp, ep, HI)

The next collider(s)

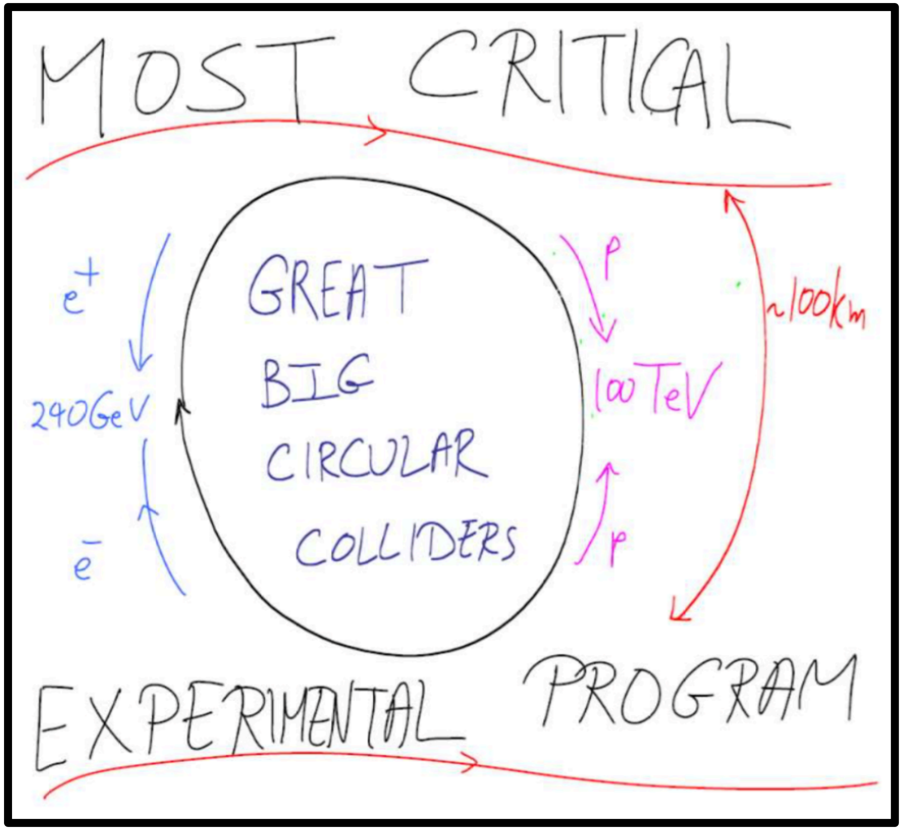
European Strategy update (2013):

"Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update."

European Strategy Group (2020):

"It places priority on the successful completion of the High-Luminosity LHC over the coming decade, and begins to map out the potential landscape for research in Europe in the post LHC era, presenting a vision for both the near- and long-term future. The Strategy update recommends a so-called Higgs factory as the highest priority to follow the LHC, while pursuing a technical and financial feasibility study for a next-generation hadron collider in parallel, in preparation for the long-term."

N. A. Hamed (FCC Week 2019)

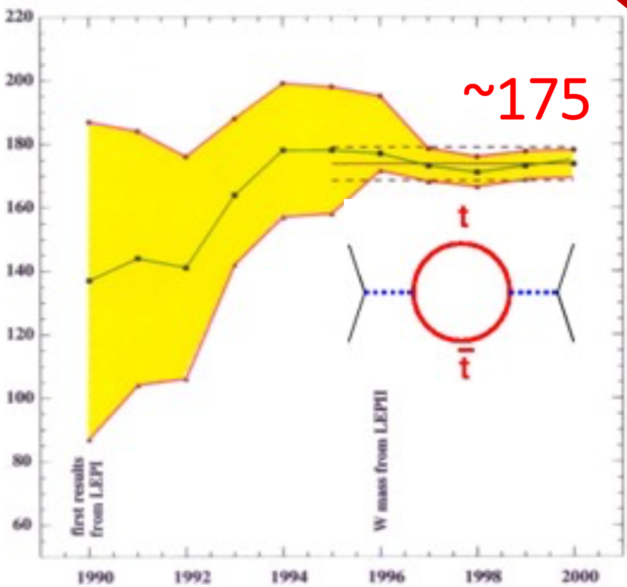


- Exhaustively study the Higgs
- O(10) reach in mass scale

Building on success stories: the “top”

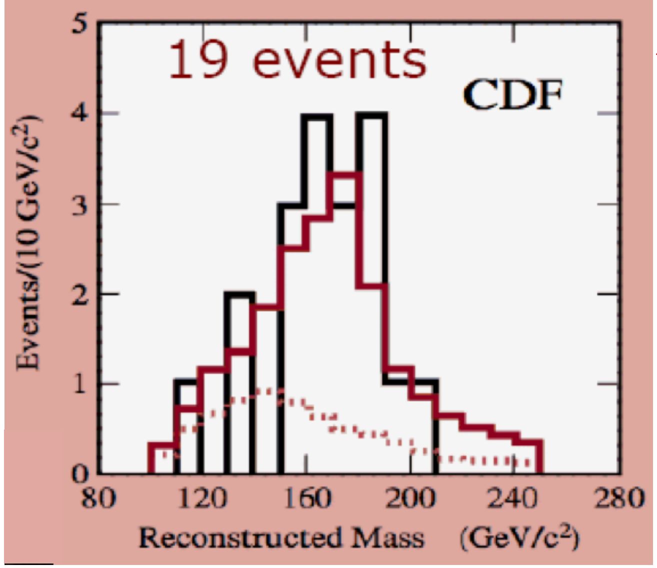
LEP: prediction

Predicted Top mass

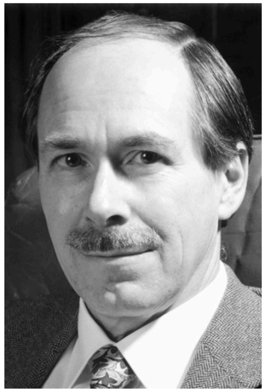


Year

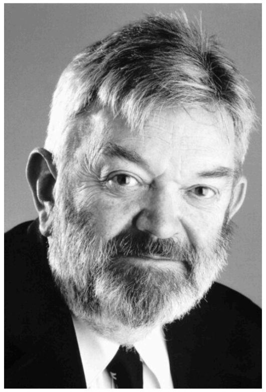
Tevatron: discovery



Nobel Prize (1999)



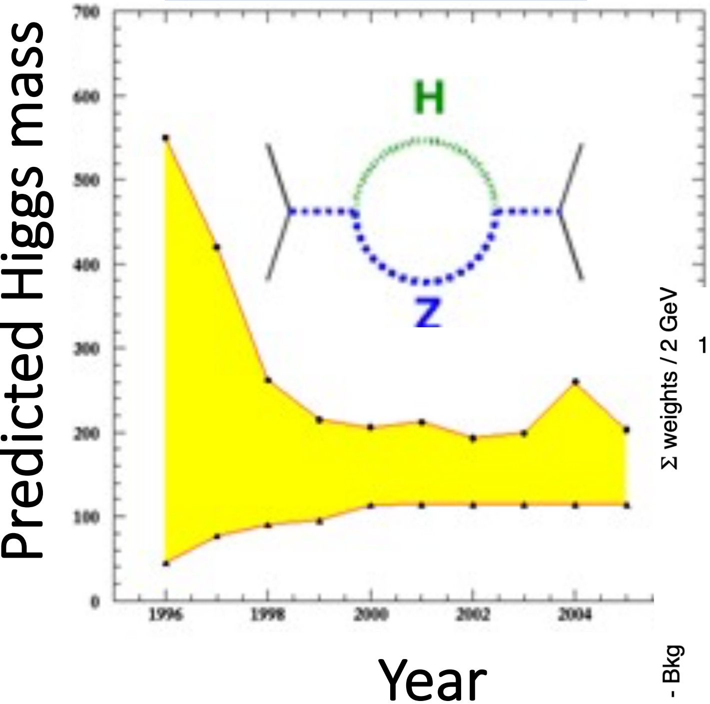
‘t Hooft



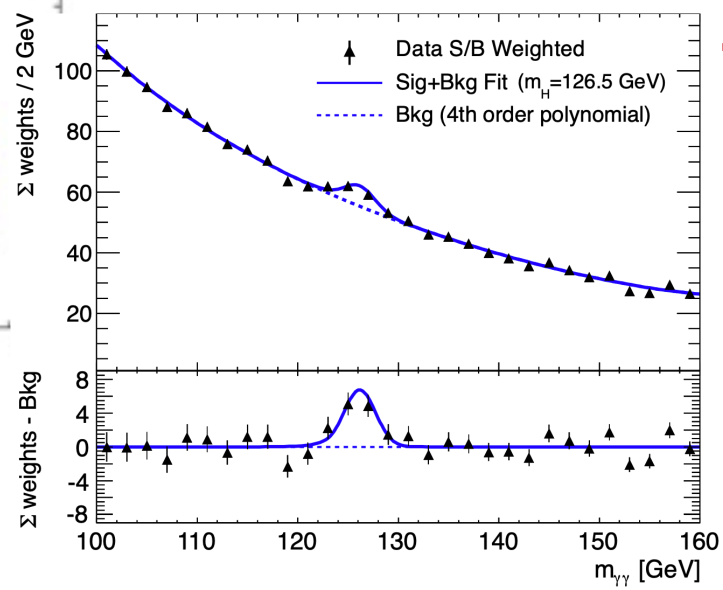
Veltman

Building on success stories: the “Higgs”

LEP: prediction



LHC: discovery



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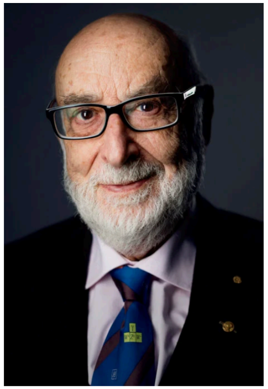
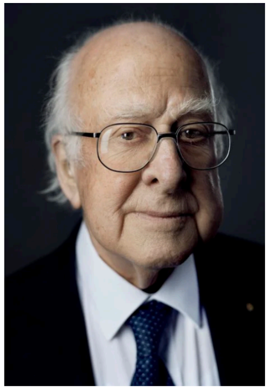


Englert

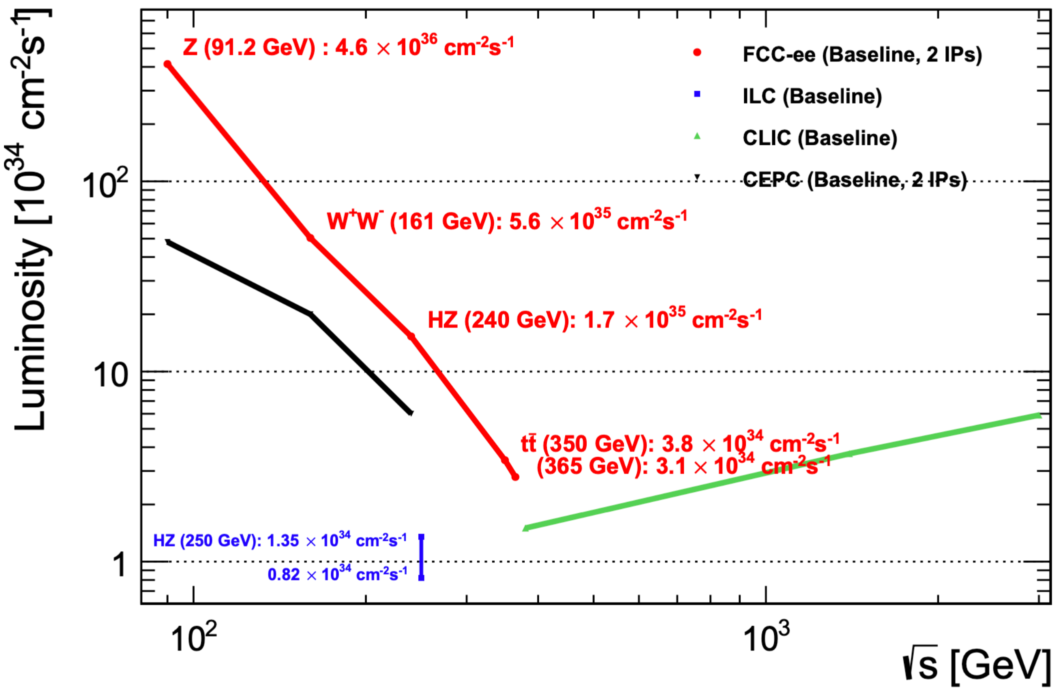


Higgs

The Future Circular Collider (FCC)

- A new 100 km tunnel fitting in Genevois
  - First: **FCC-ee** experiment

Unprecedented luminosity



FCC-ee in numbers(/IP)

- Z-pole: 150 ab^{-1} (5x10^{12} Z)
  - 100K Z/sec
  - LEP: 10^{6} Z events
- WW: 12 ab^{-1}
  - 10K W/sec
- ZH: 5 ab^{-1}
  - 1.5K Higgs/day
- top: 0.2-1.5 ab^{-1}
  - 1.5K top/day

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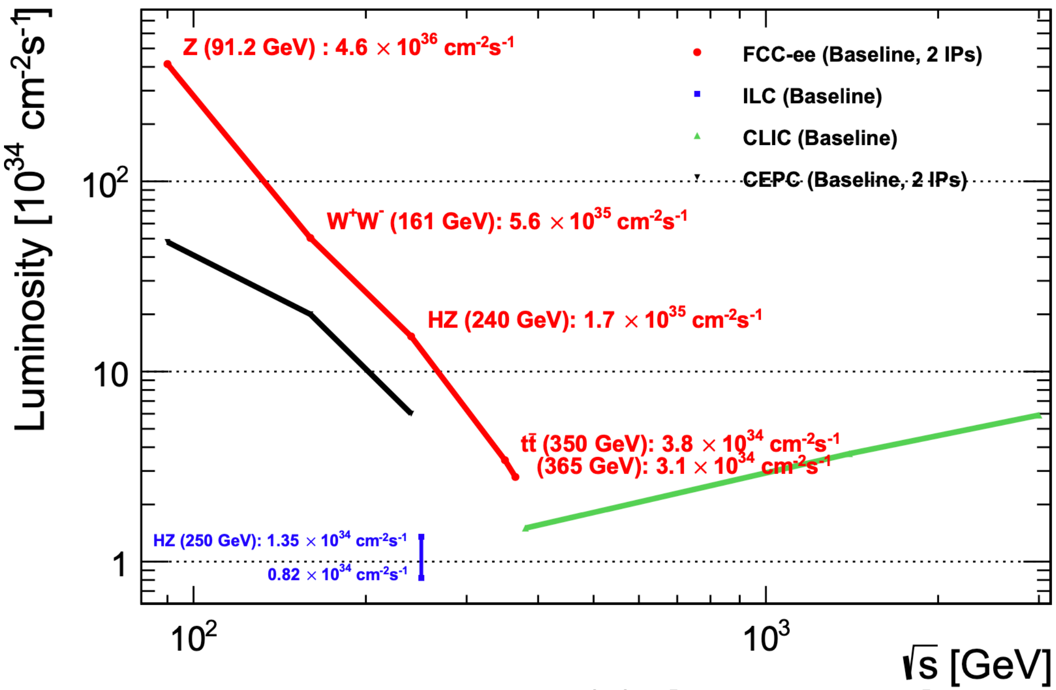

- Ultimate goal: FCC-hh [@100 TeV]
  - Lumi: 30 ab^{-1}
  - HI and e-h options
  - Challenge: The 16T magnets

FCC-ee in numbers(/IP)

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Combination of FCC-ee and FCC-hh produces most of physics

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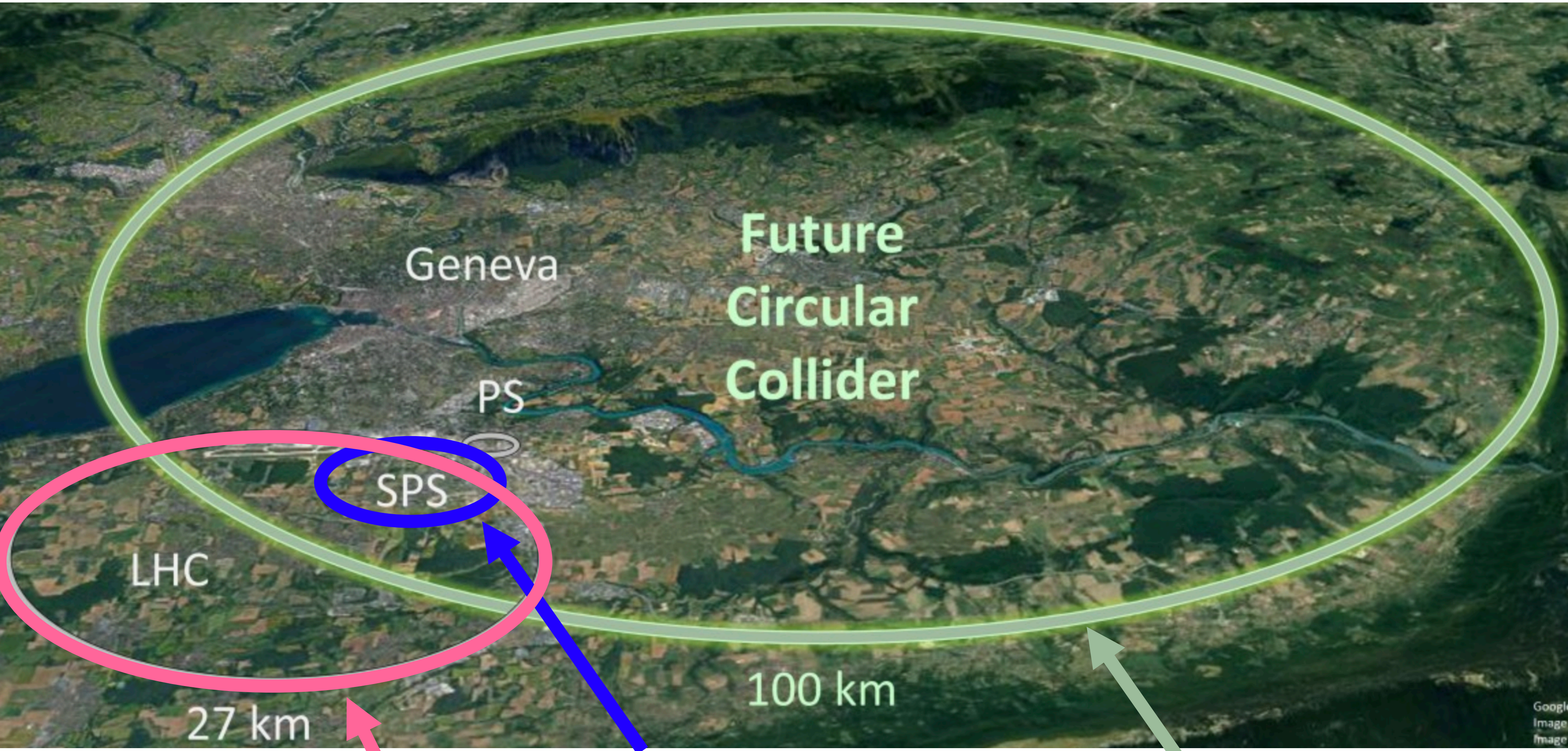


LHC: Higgs discovery and of course LEP

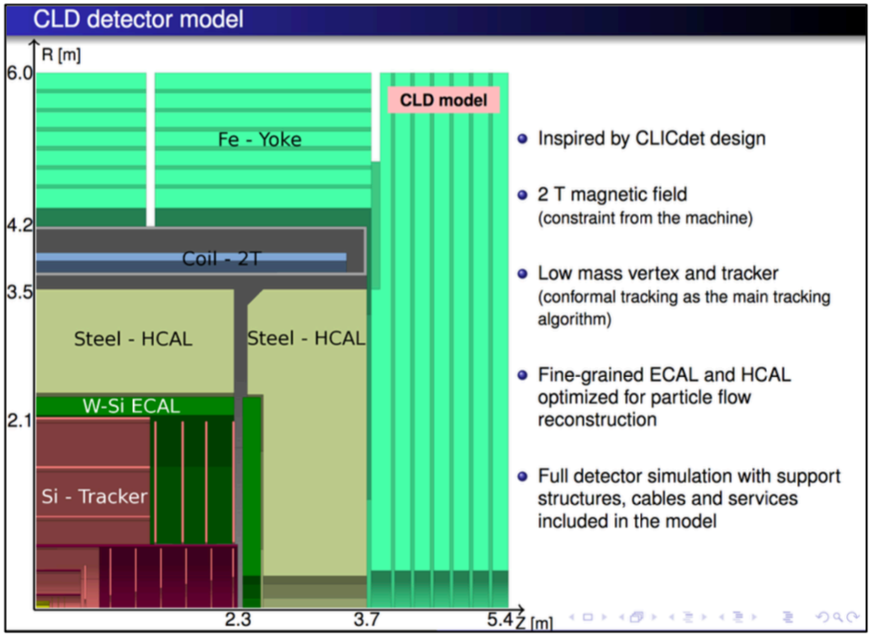
SPS
W/Z discovery

FCC: Answer most fundamental questions about Higgs [at the very least…]

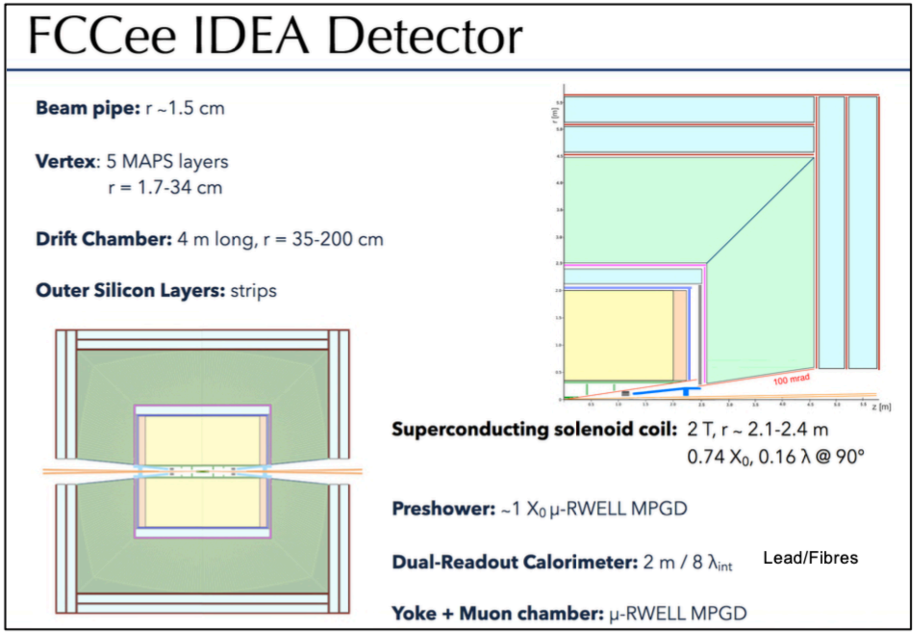
The detector concepts: FCC-ee

- Two complementary detector concepts under study
  - excellent tracking (little material), hadronic resolution, timing info

CLIC detector adapted for FCC-ee



Tailored to FCC-ee



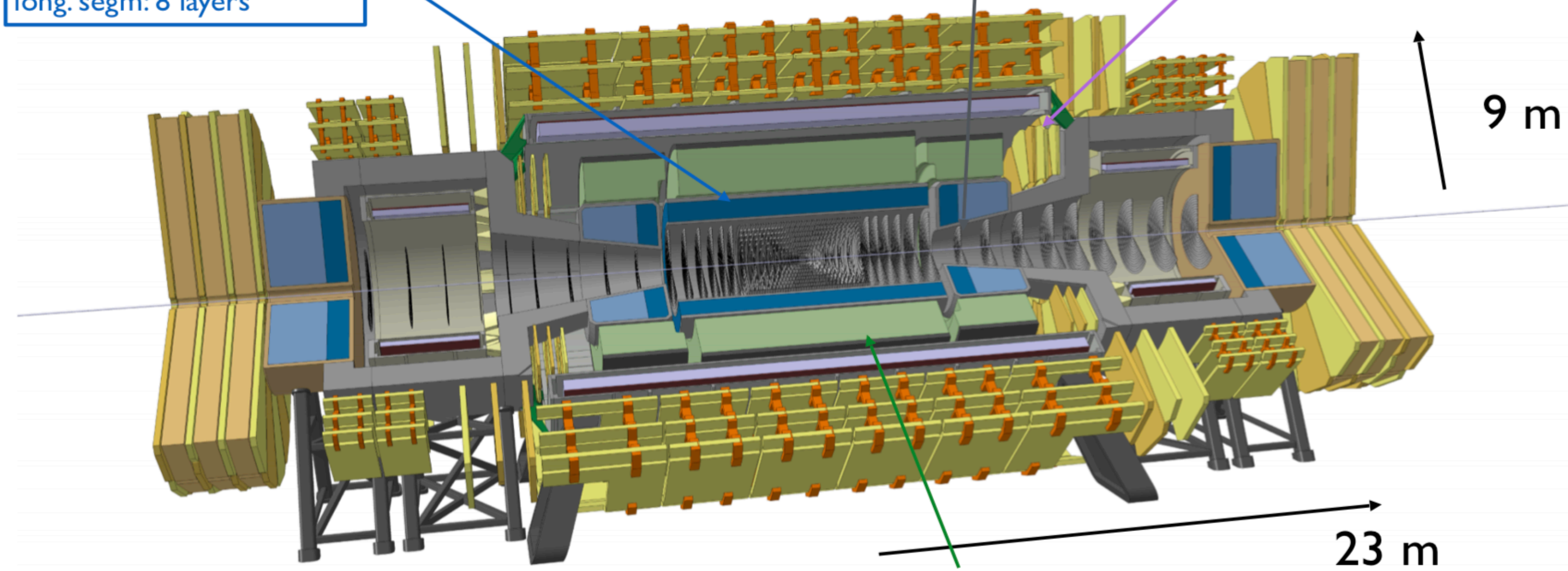
Lot's of important and innovative work to be done in all fronts
- There is more: Possibility for 4 IPs
  [i.e. need for additional detectors - with newer/complementary technologies]

The detector concepts: FCC-hh

Tracker: σ_{p_T}/p_T ~ 20% at 10 TeV (1.5m radius)

Central Magnet + Fwd solenoids 4T

Barrel ECAL: LAr/Pb
σ_E/E ~10%/$\sqrt{E}$ ⊕ 0.7 %
30 X_0
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers



Fwd ECAL: LAr/Cu
σ_E/E ~30%/$\sqrt{E}$ ⊕ 1 %
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

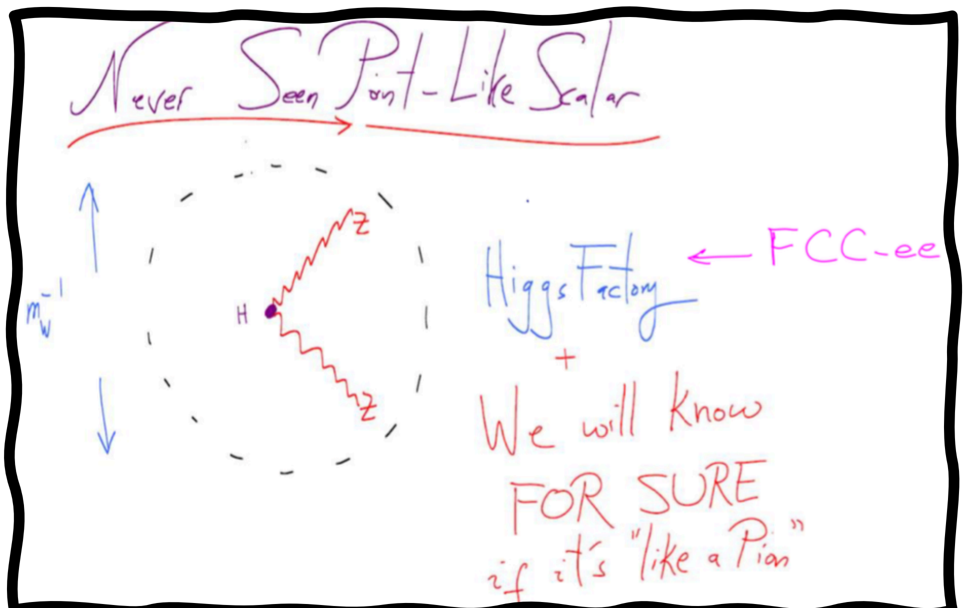
Fwd HCAL: LAr/Cu
σ_E/E ~100%/$\sqrt{E}$ ⊕ 10 %
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
σ_E/E ~50-60%/$\sqrt{E}$ ⊕ 3 %
11 λ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

+
Timing detector w/ resolution ~5ps

Higgs as an exploration tool

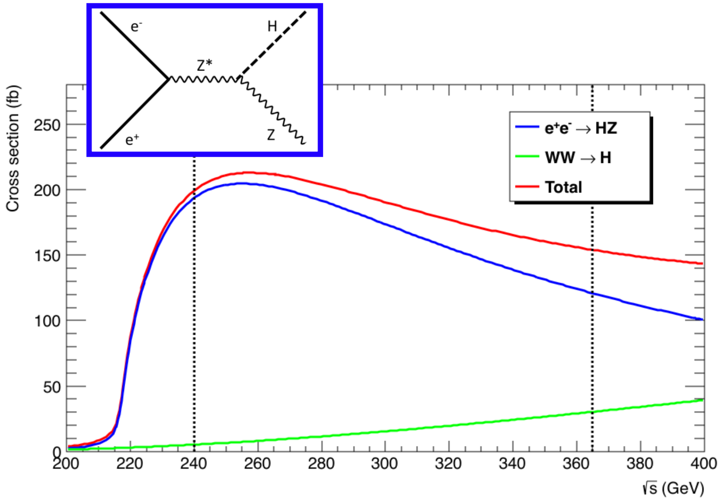
N. A. Hamed (FCC Week 2019)



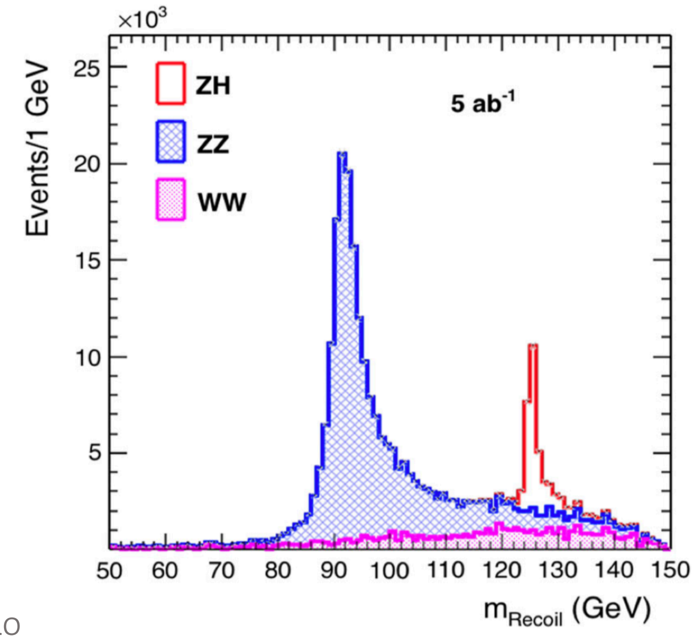
Model-independent measurements

- 1M Higgs @FCC-ee (CM: 240 GeV)
  - Model independent measurement of Higgs-Z coupling
    - using Z→LL, m_{recoil}, E_{beam} constraints

$$m^2_{\text{Recoil}} = s + m^2_Z - 2\sqrt{s}(E_{\ell+} + E_{\ell-})$$



- **First:** measure ZH production
  - rate $\sim g_{HZZ}^2$ → $\delta(g_{HZZ})/g_{HZZ} \sim 0.1\%$
- **Then:** measure ZH(→ZZ)
  - rate $\sim g_{HZZ}^4/\Gamma(H)$ → $\delta(\Gamma(H))/\Gamma(H) \sim 1\%$



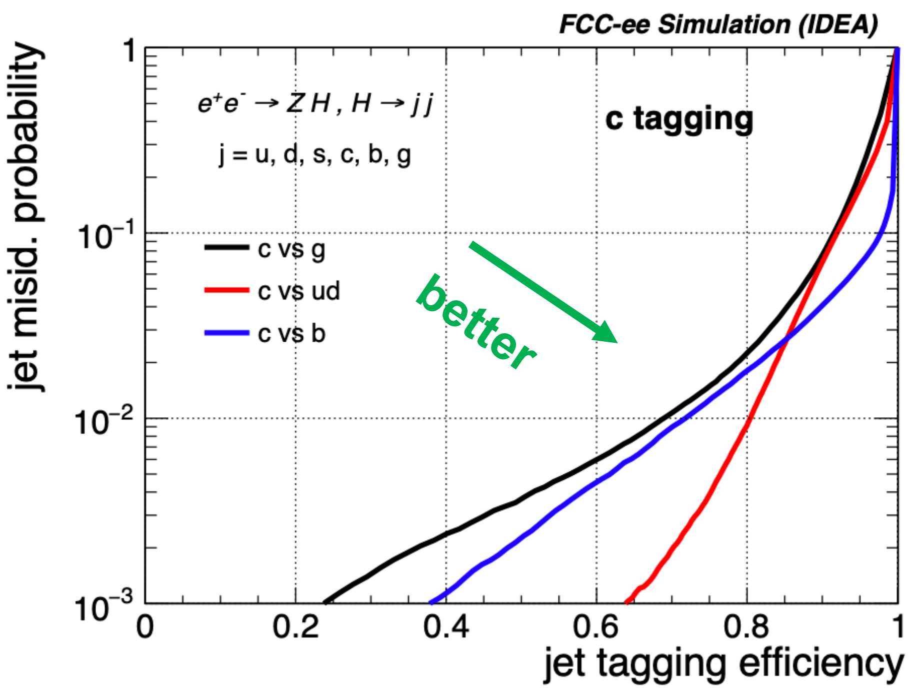
- Unique in e^+e^- machines
- "standard candle" for other Higgs measurements (incl. FCC-hh)

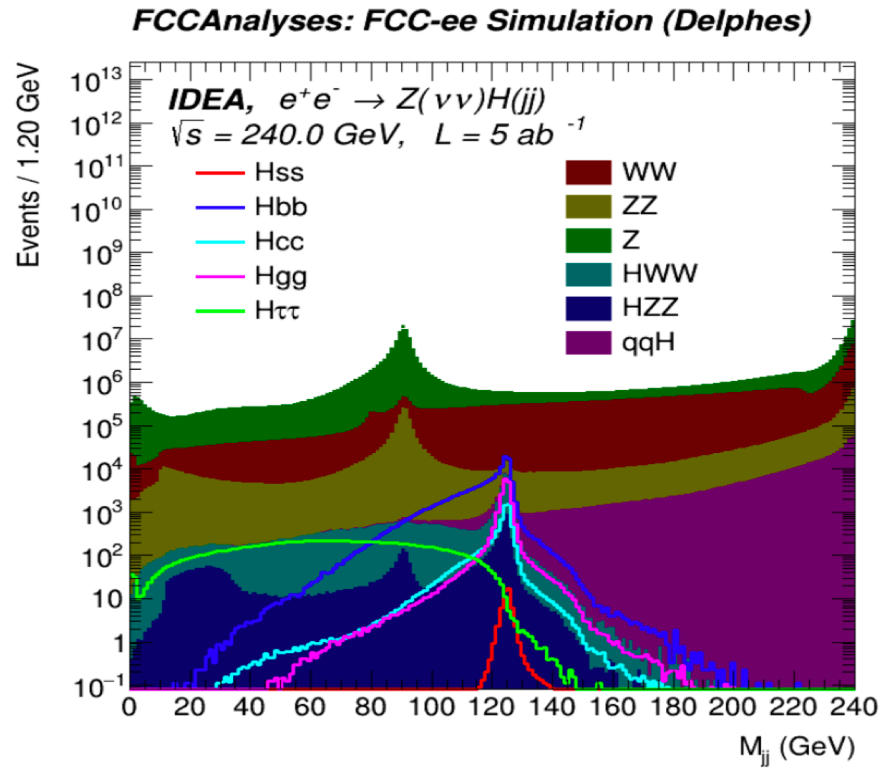
FCC-ee: Higgs couplings (cont.)

- Study additional Higgs decay modes
  - e.g. H→bb, gg, cc, ττ, ss, …
  - key: identification of decay flavor

Signal extraction:
2D fit: m_{rec} vs. m_H

Novel Deep Learning based algorithms under development

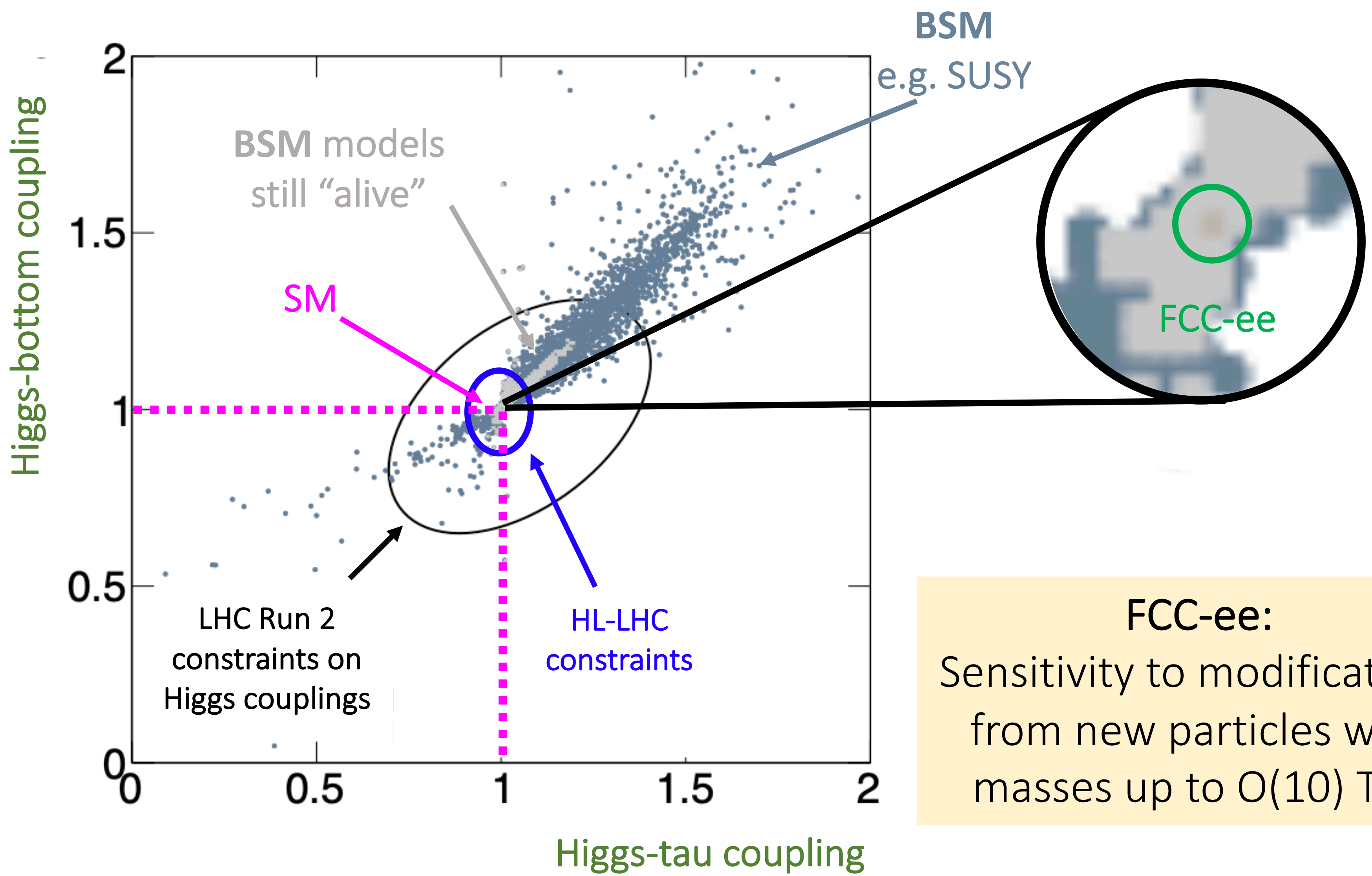




Z(→νν)H(→qq)	bb	cc	ss	gg
δκ/κ (%)	0.2	1.4	50	0.6

***H→ss:** 2σ/IP (all Z decay modes)
1st evidence (i.e. >3σ) with 4IPs

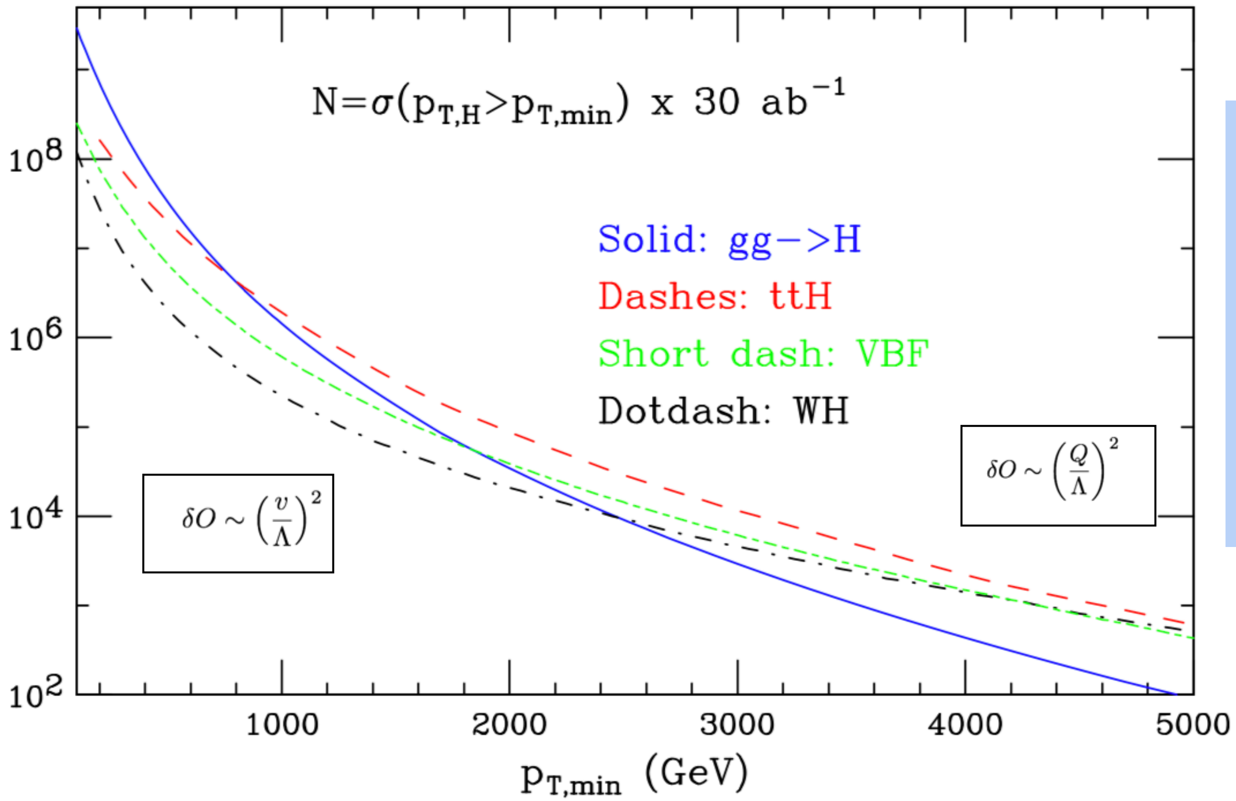
Precision → Sensitivity to New Physics



FCC-ee:
Sensitivity to modifications from new particles with masses up to O(10) TeV

FCC-hh: More on Higgs couplings

- Large statistics:
  - Precise measurement of rare decays (e.g. μμ, Zγ)
  - sensitivity to forbidden channels (e.g. τμ)
- Large kinematic range / probe multi-TeV regime
  - often more sensitive to BSM



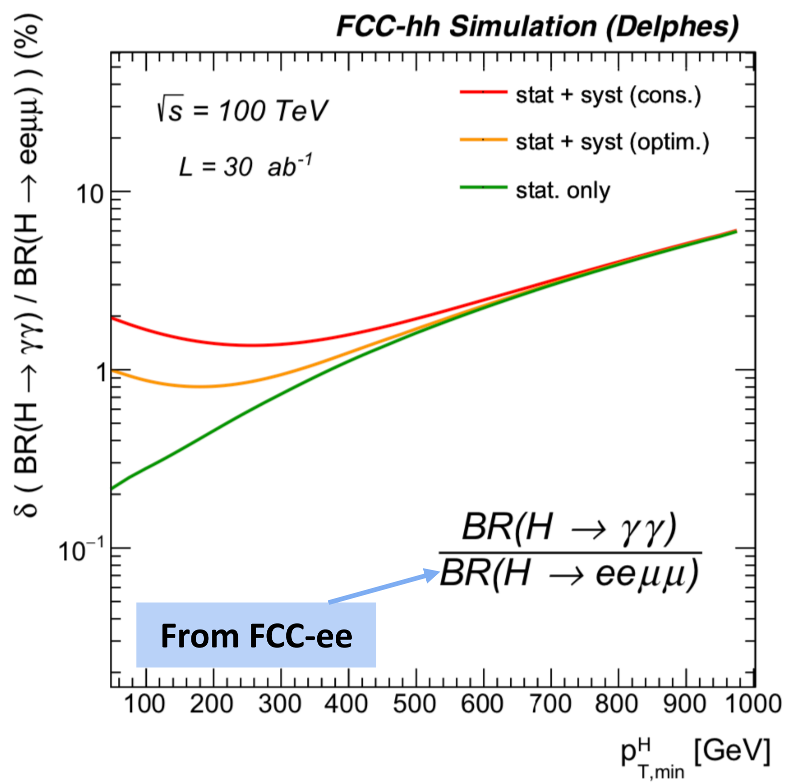
1M Higgs with p_T>1 TeV
- Typically improved S/B
- High p_T(H) regime: indirect probe of BSM
- Heavy new particles running in the loops

FCC-hh: More on Higgs couplings (II)

- General strategy:
  - FCC-ee: H-Z coupling at ~0.1%
  - FCC-hh: Calculate ratios of BRs e.g. BR(H→XX)/(H→ZZ)
    - Cancelation of systematics
    - Powerful probe of BSM: may affect BRs in different ways
  - Then: Extract absolute couplings
    - typically with ~1% precision

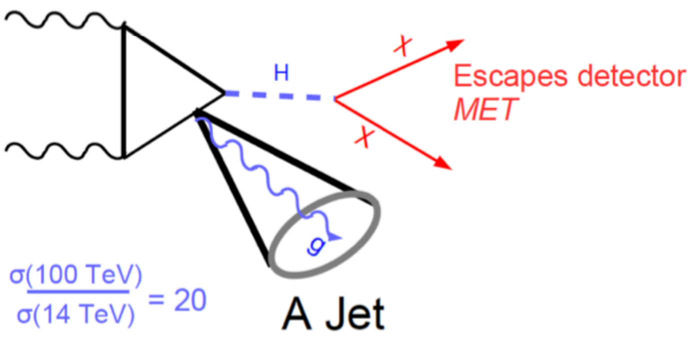
- BR(H→γγ)/BR(H→ZZ*)
  loop vs. tree-level couplings
- BR(H→μμ)/BR(H→ZZ*)
  2nd –Gen vs. Gauge couplings
- BR(H→γγ)/BR(H→Zγ)
  different EW charges in loops

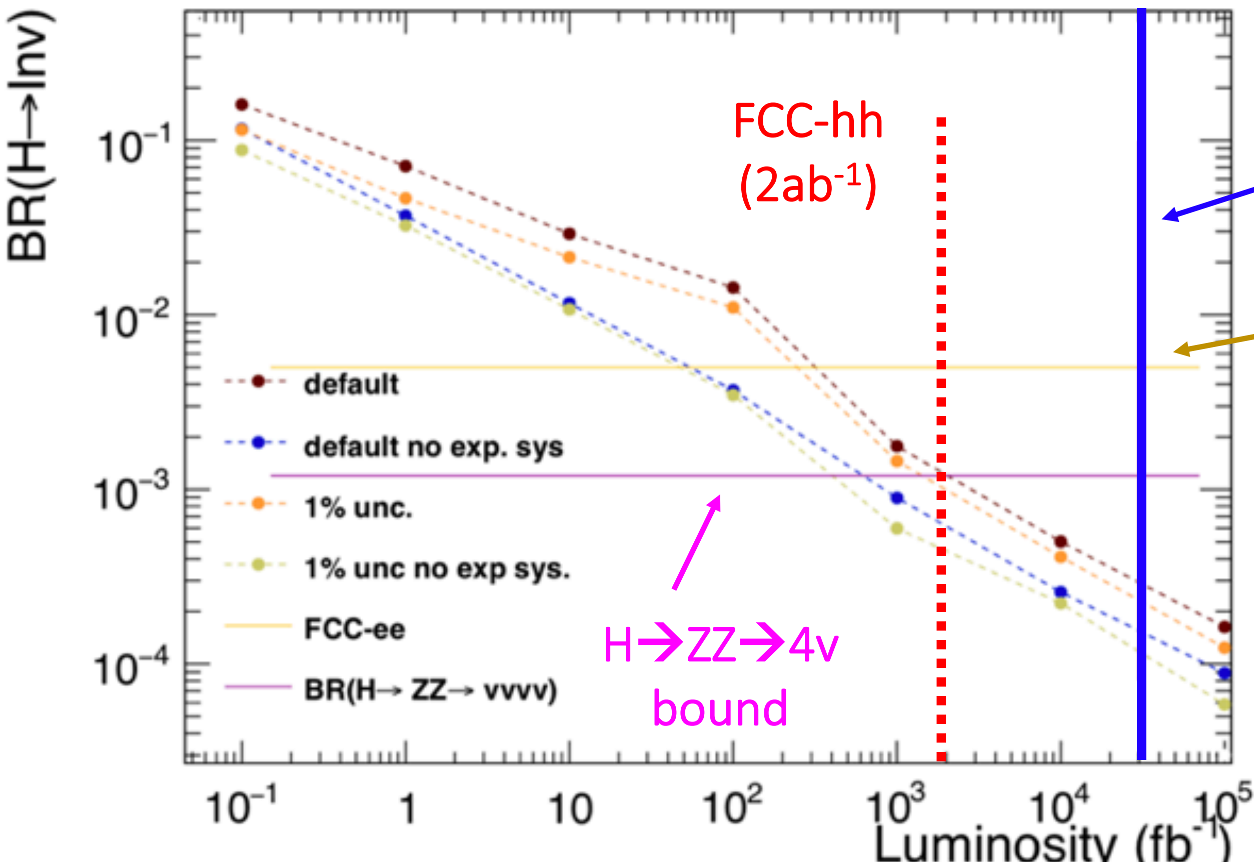
Synergy and **complementarity** between **FCC-ee** and **FCC-hh** physics programs



Higgs→invisible

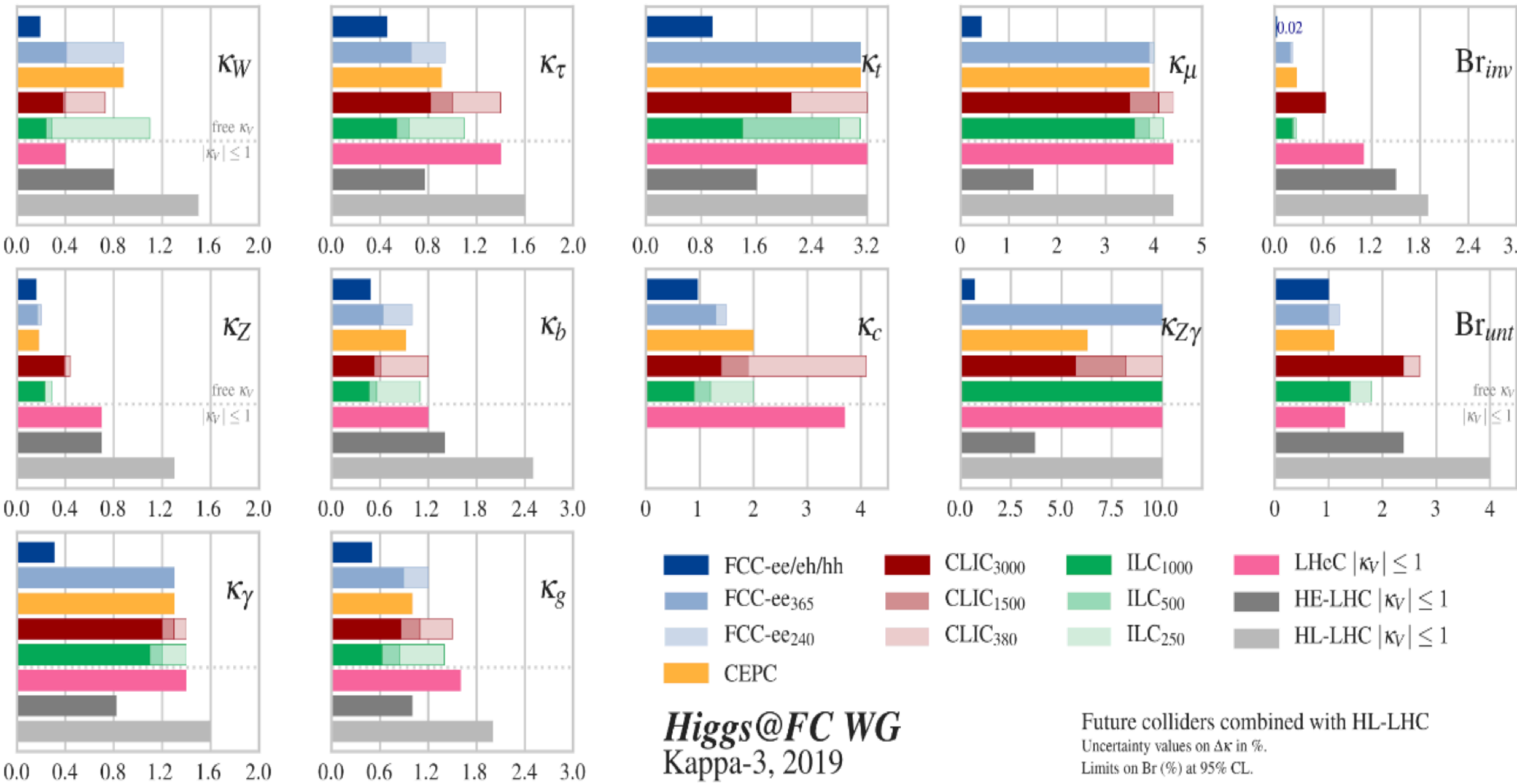
- Portal to Dark Matter (DM)
  - DM only via Higgs decays (?)
- Critical: control of EXP and TH uncertainties @ O(1%)





- Significant improvement wrt HL-LHC and FCC-ee
- **FCC-hh:** Reach neutrino bound already w/ ~2 ab^{-1}

Single-Higgs: Grand summary

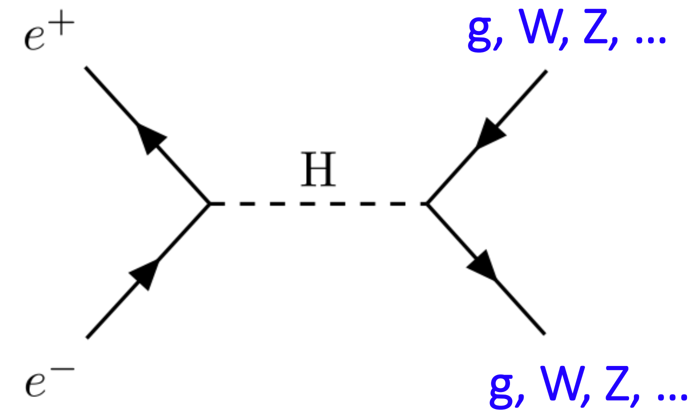


Full FCC program: Best results (by far) for all measurements

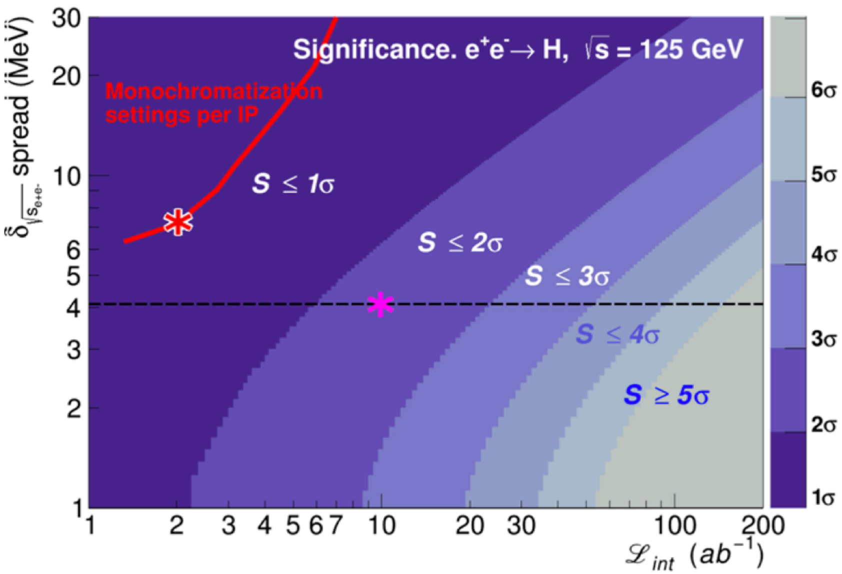
- O(10) improvement compared to HL-LHC
  - all couplings better than 1%; couplings to ZZ/WW and H→inv. at 10^{-3}

Bonus: H→ee unique at FCC-ee

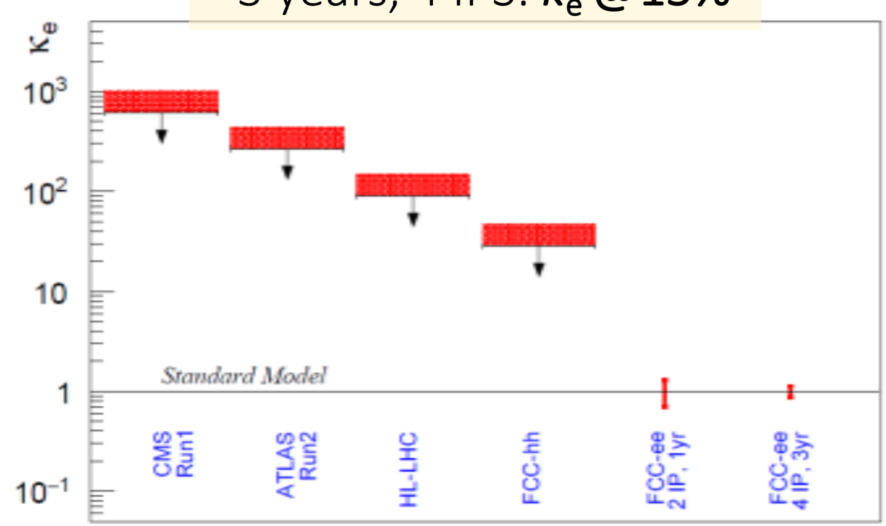
- Extremely challenging: BR(H→ee) ~10^{-9}
- FCC-ee: Resonant Higgs production
  - tiny signal (1.64 fb) vs. huge BKGs
  - but: huge luminosity from FCC-ee
    - 20 ab^{-1}/year/IP → 30K Higgs



- Key points:
  - Beam spread (~MeV) → monochromatization
  - Precise m_H → from ZH run



- 1 year, 2 IPS: **2σ**
- 3 years, 4 IPS: **κ_e @15%**

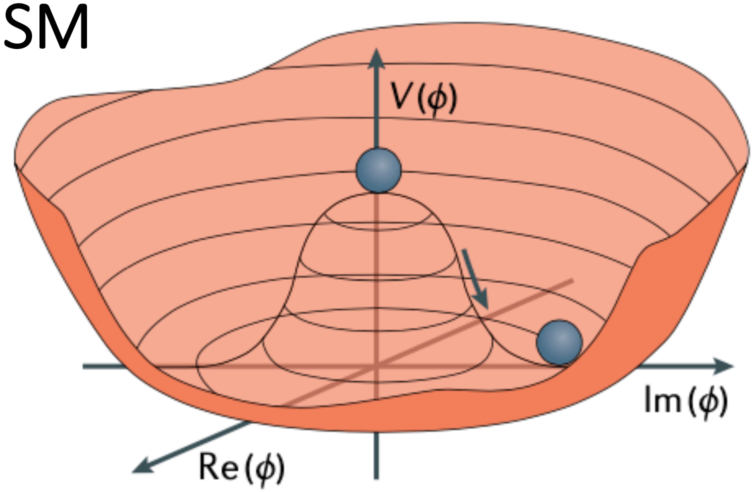


Higgs-pair production

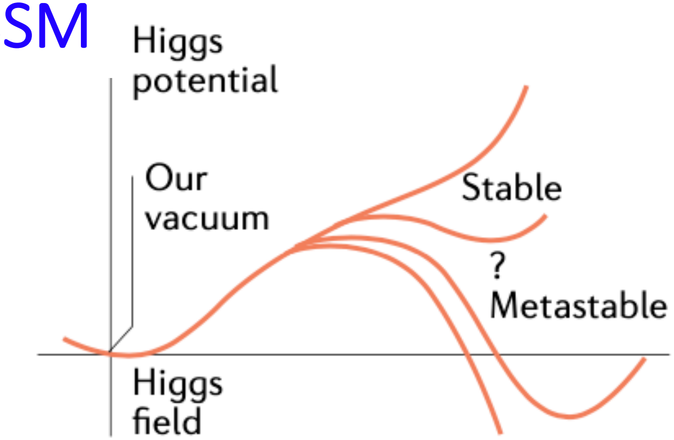
The nature of Higgs potential

- Understand how electroweak symmetry broke in the early universe
- Is mass-generation connected to the matter-antimatter asymmetry, …

SM

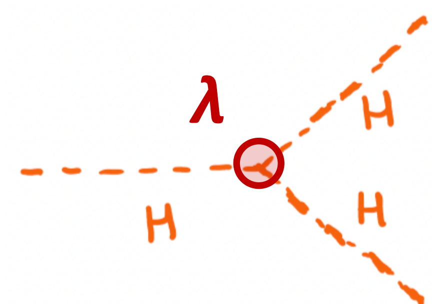


BSM



$$V(h) = \boxed{\frac{1}{2}M_H^2 H^2} + \boxed{\frac{1}{3!}\sqrt{3\lambda_H}M_H H^3 + \frac{1}{4!}\lambda_H H^4}$$

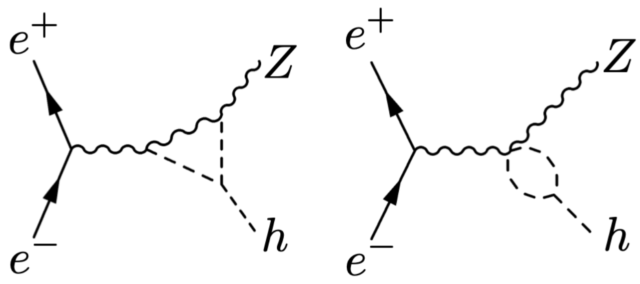
Higgs mass — Shape of potential



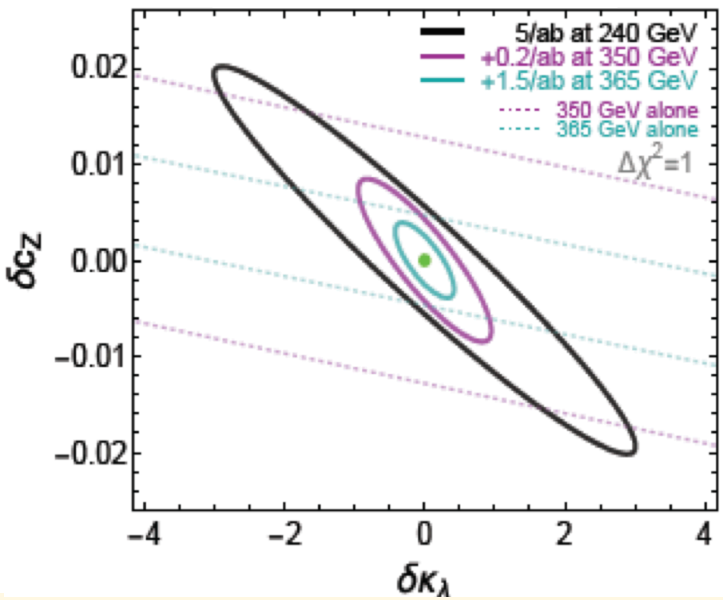
Higgs-self coupling at FCC

- FCC-ee: via loops

Ref



19% (**12%**) precision for 2 (4) IPs
[other couplings at SM-values]



Global fit: ~20% and 4 IPs
NB: **Importance** of different CM energies

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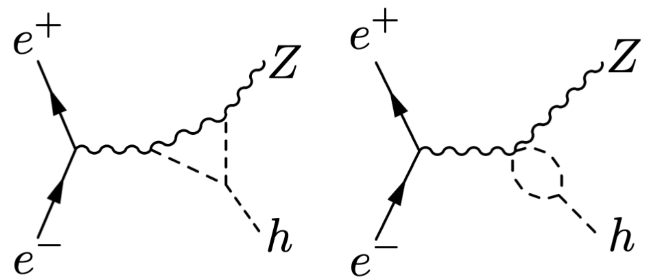

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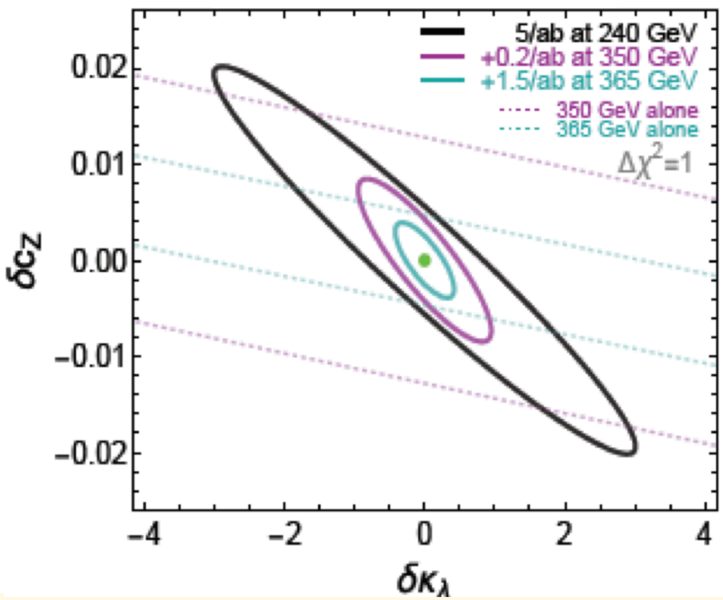

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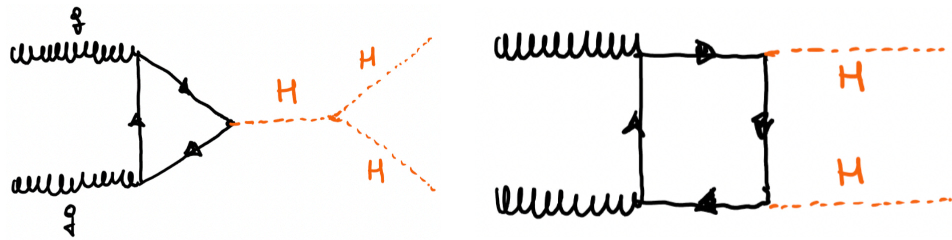
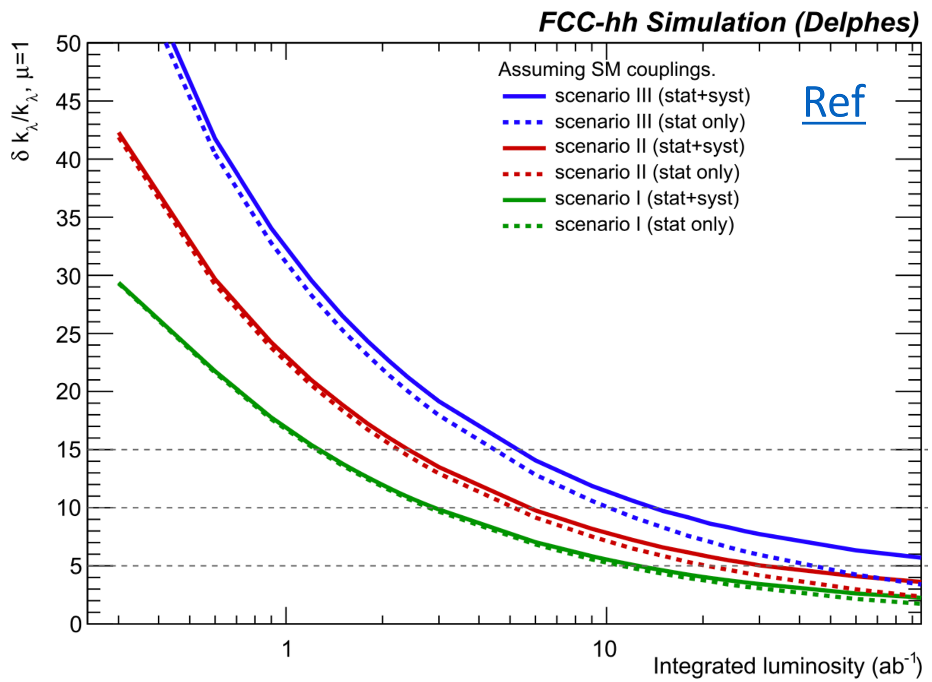
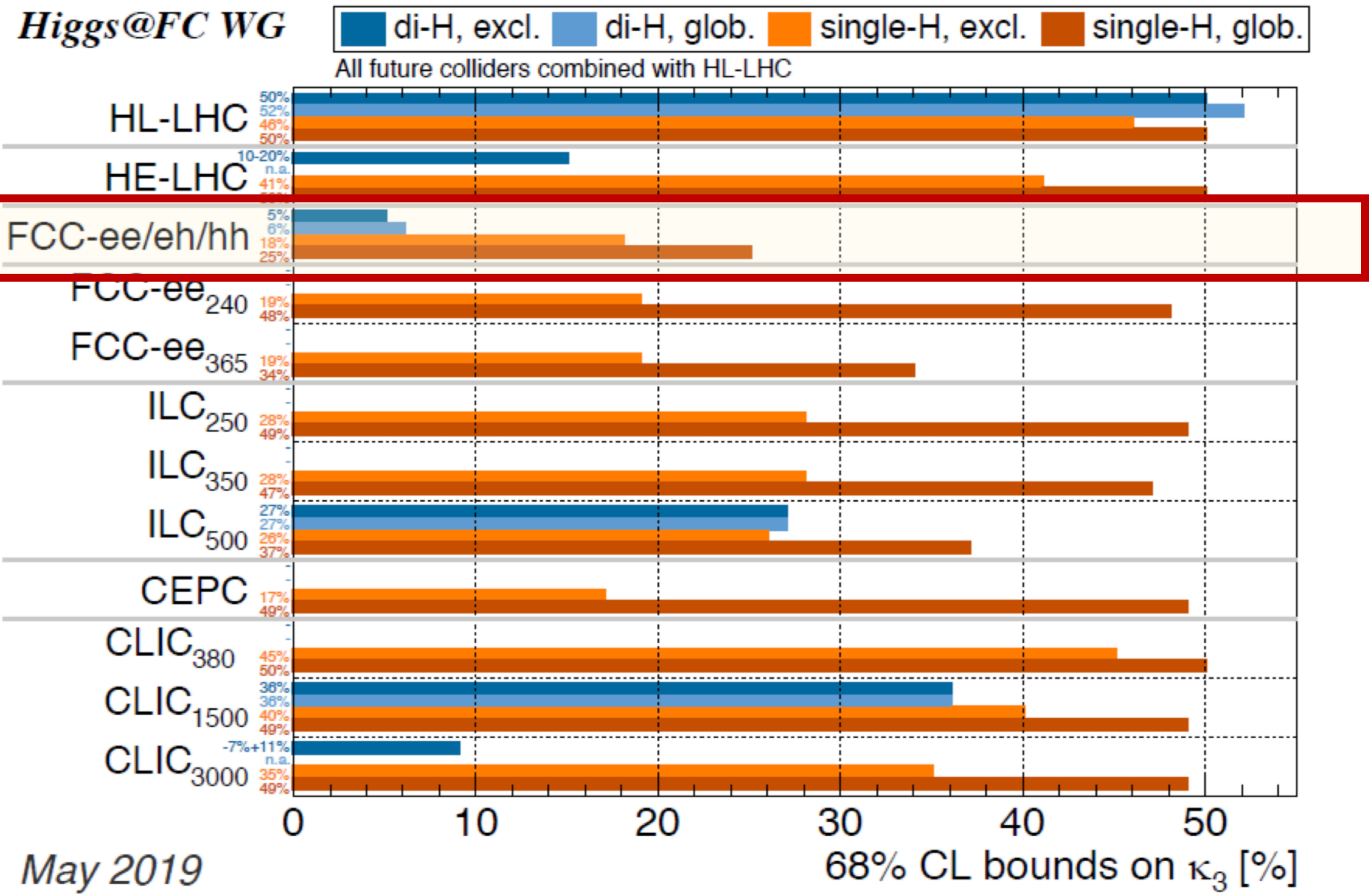
- FCC-hh: "THE HH machine"





- 5% at the end of FCC-hh program
- Reach CLIC sensitivity in O(2) years
- En route to HHH → HHVV [backup]

Higgs-self coupling: Grand summary

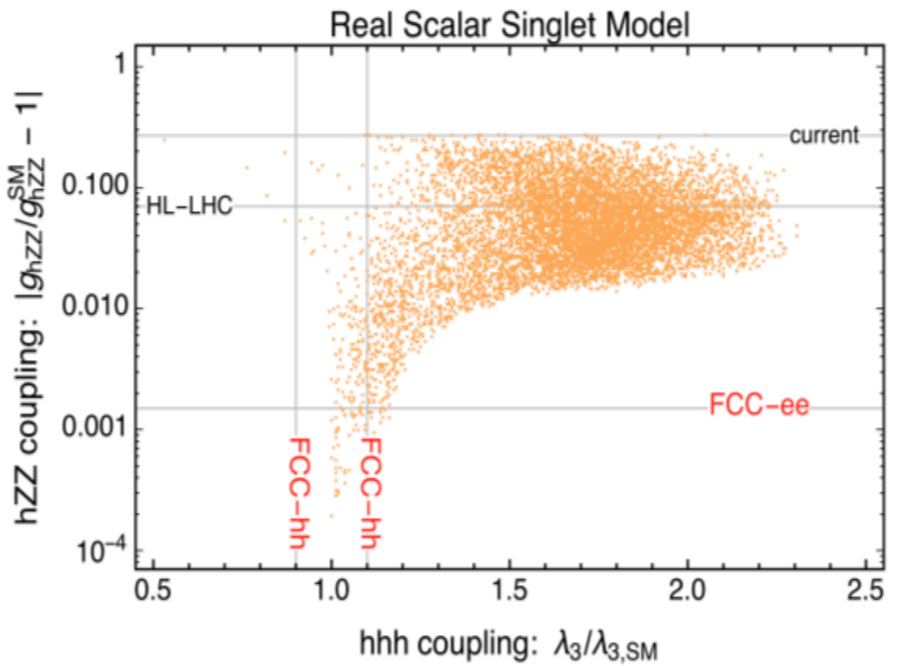


Matter-antimatter asymmetry

- Possible explanation: "Violent" transition to the broken symmetry
  - 1st order phase transition
  - Requires sources of CP-violation

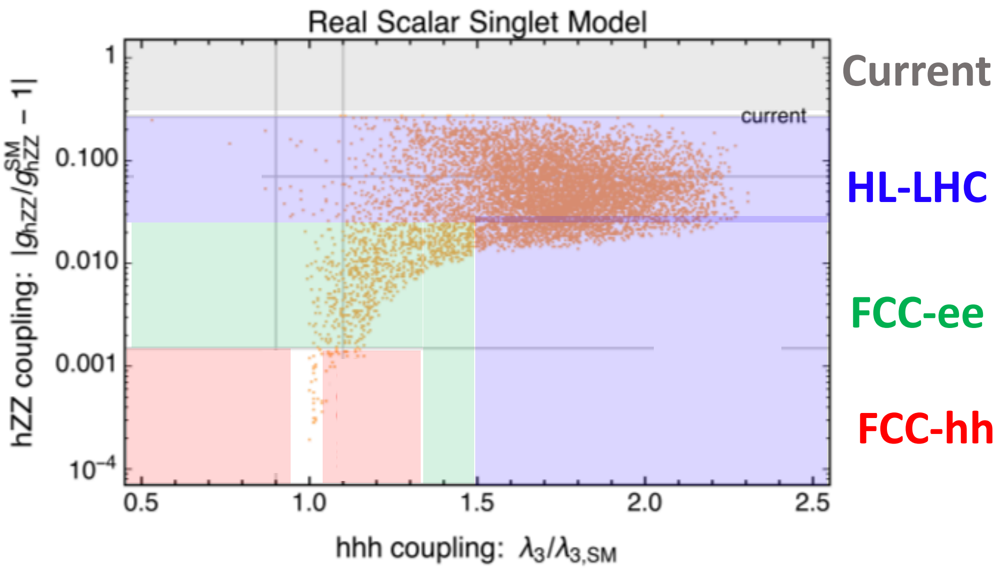
- Cannot be accommodated by SM
  - needs new particle(s) with O(TeV) mass

- Simplest extension to SM: additional singlet scalar
  - Two Higgs-like scalars:
    - h1 (m=125 GeV) and h2
  - Modification of (~few %) in Higgs self-coupling & Z-H coupling
  - Direct production of scalar pairs
    - Resonant Di-Higgs production



Matter-antimatter asymmetry (II)

Deviation from SM Higgs couplings



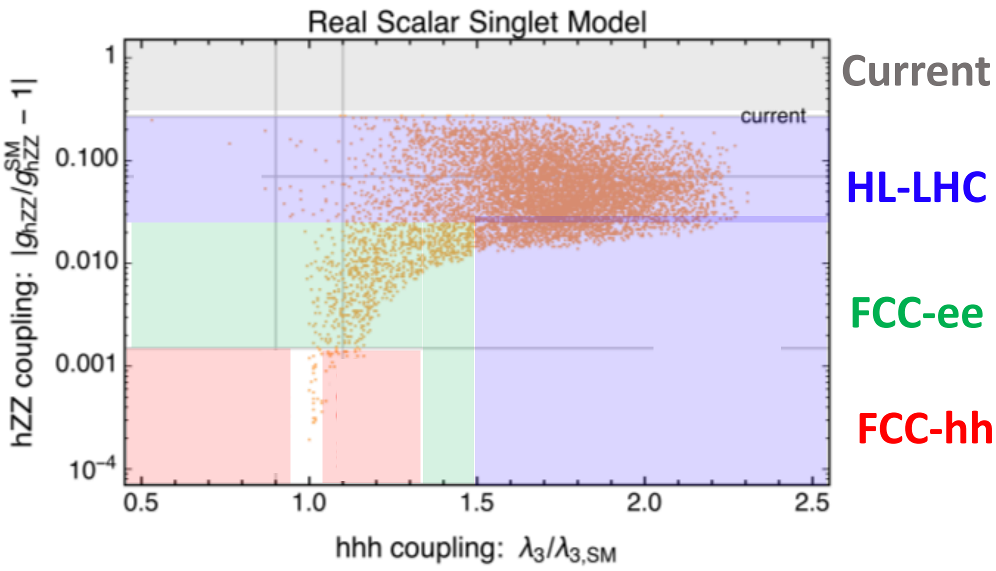
- **Modification on Higgs self-coupling**
  FCC-hh: Direct probe
  FCC-ee: Indirect (global fit on single-H)
- **Modification n Higgs-Z coupling**
  FCC-ee @ 0.1% level, FCC-hh sensitive

FCC-ee + FCC-hh synergy:

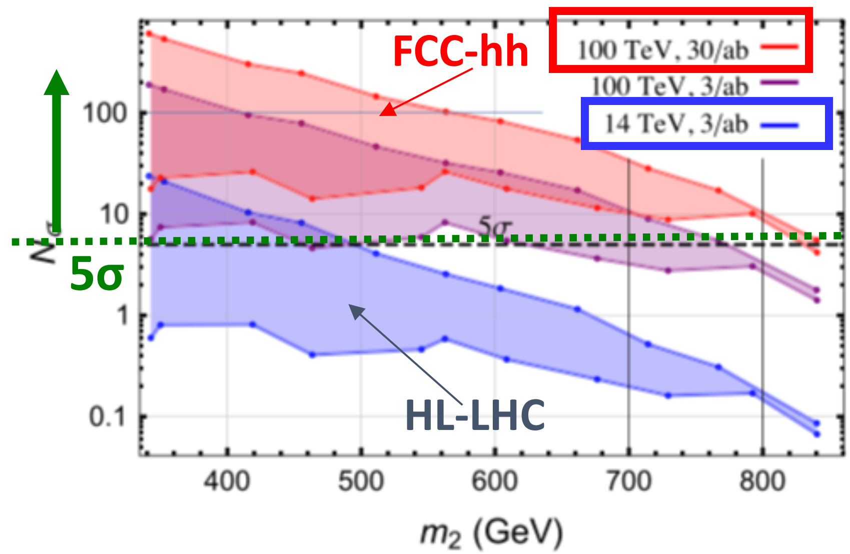
- cover almost the entire parameter space

Matter-antimatter asymmetry (II)

Deviation from SM Higgs couplings



Discovery potential in resonant Di-Higgs searches



- **Modification on Higgs self-coupling**
  FCC-hh: Direct probe
  FCC-ee: Indirect (global fit on single-H)
- **Modification n Higgs-Z coupling**
  FCC-ee @ 0.1% level, FCC-hh sensitive

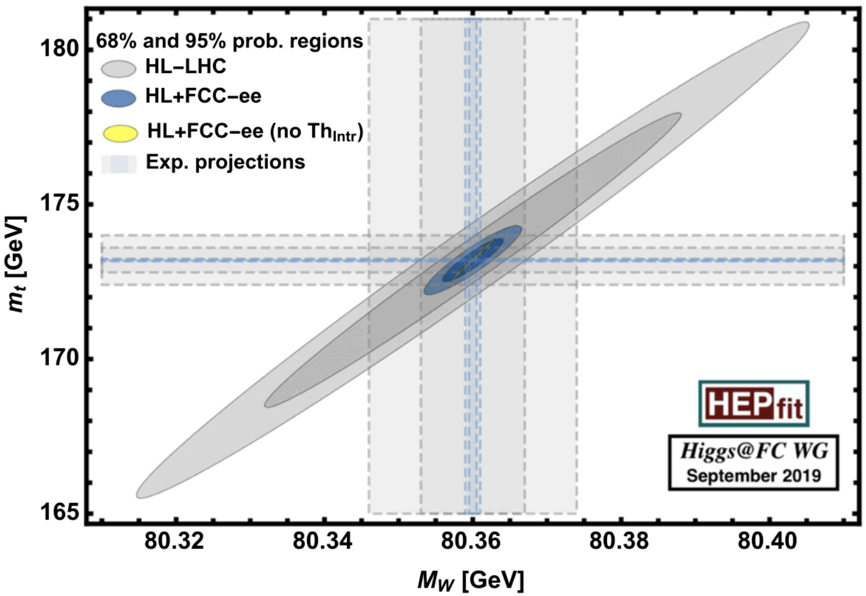
- **FCC-hh discovery potential** over the entire viable parameter space
- Very limited discovery potential @HL-LHC
- **FCC-hh:** powerful to other models w/ non-resonant production of scalars

FCC-ee + FCC-hh synergy:
- cover almost the entire parameter space
- Provide definite answers to fundamental questions

Beyond Higgs physics

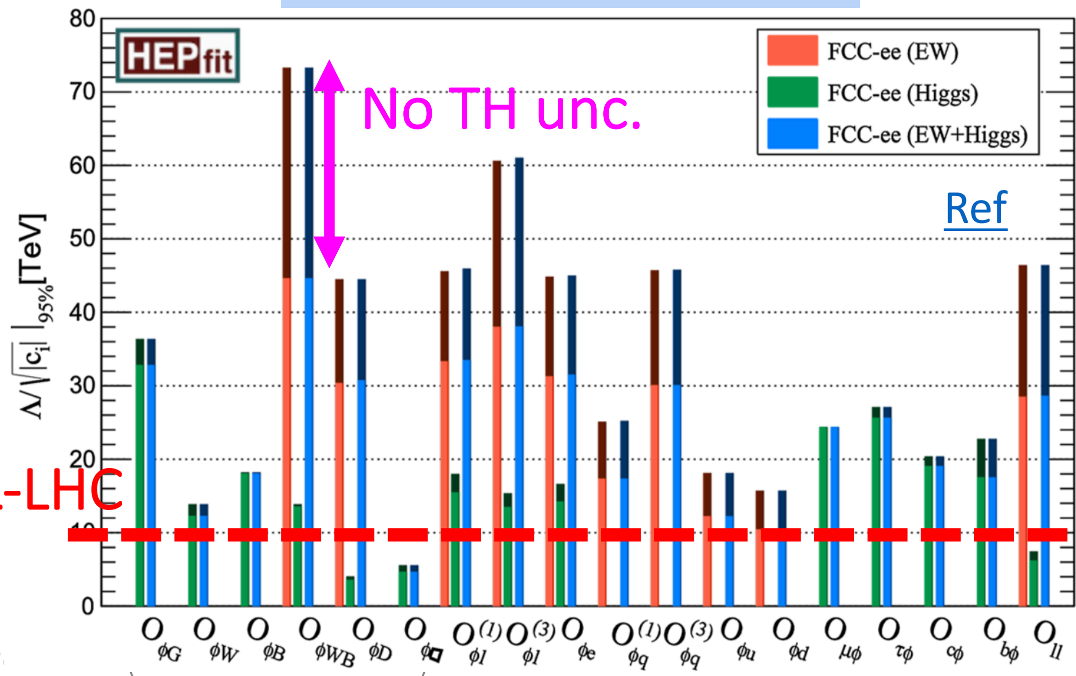
(Highlights)

FCC-ee: precision (Higgs+EW)



- **FCC-ee:** Precise measurement of EWK parameters e.g. m_Z~100 keV, Γ_Z~25 keV, m_W~500 keV, …

EFT interpretation



→ **Complementarity** b/w EW and Higgs programs

→ **Key:** control stat & syst unc

→ **Lot's of work** ahead to exploit **FCCee true potential**

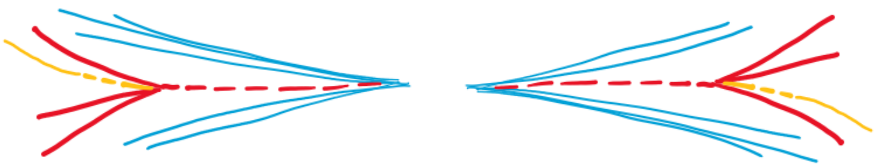
→ **FCCee reach**: Λ ~50-70 TeV

Pave the way for FCC-hh

FCCee: Flavor physics

- $5x10^{12}$ Z bosons @ Zpole: Stress test for flavor sector of SM

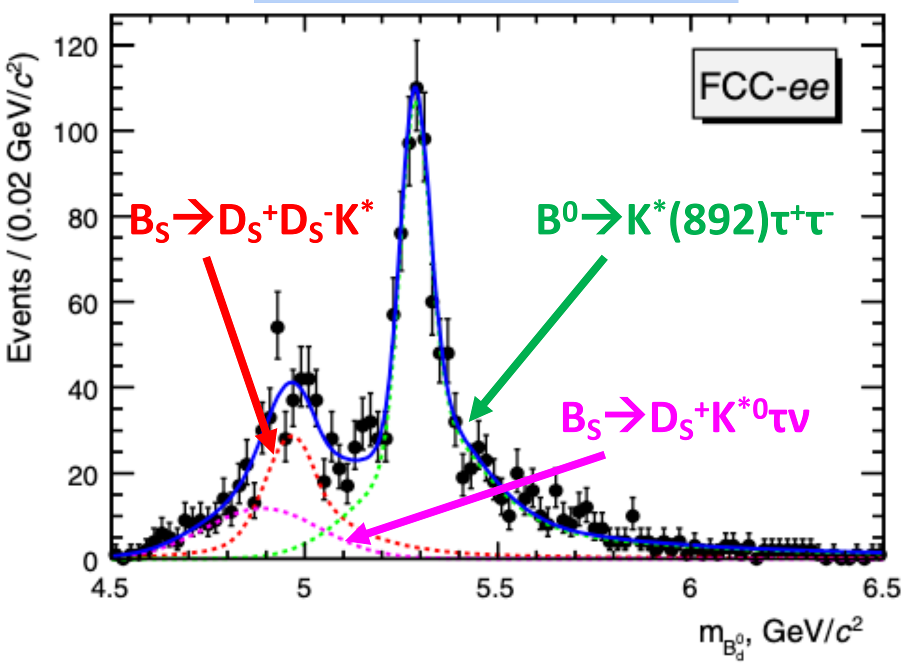
Tag → Search



Few examples

Decay mode	Belle II	LHCb	FCC-ee
$B^0 \rightarrow K^*(892)e^+e^-$	2000	20000	200000
$B^0 \rightarrow K^*(892)\tau^+\tau^-$	10	-	1000
$BR(B_S(B^0) \rightarrow \mu^+\mu^-)$	-	4.4 (9.4)%	4 (12)%

b→s transitions



Decay	Current bound	FCC-ee sensitivity
Z -> eμ	0.75 x -6	10^{-8}
Z -> μτ	12 x 10^{-6}	10^{-9}
Z -> eτ	9.8 x 10^{-6}	10^{-9}

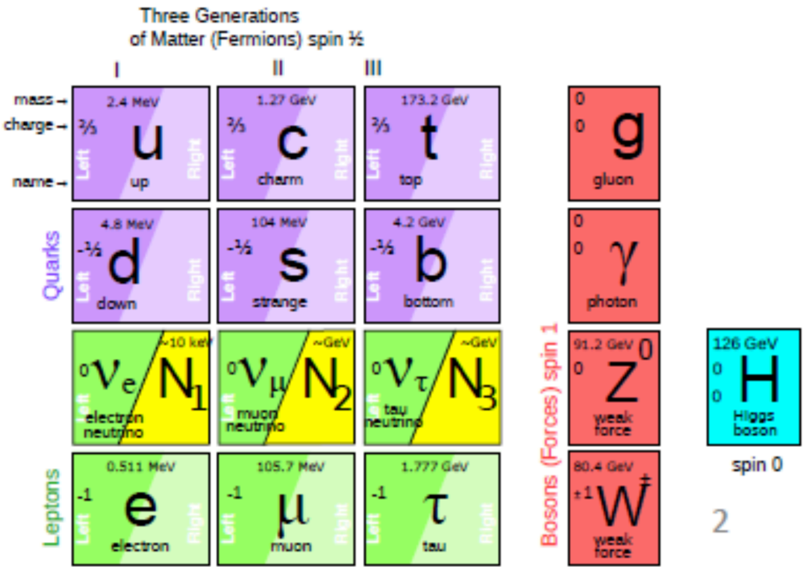
- O(10-100) more stats at FCC-ee
- Possibility for angular analysis
- Many of these measurements **challenging/impossible @pp (ie LHC)**
- **Key:** detector, reconstruction

Direct search for BSM

(Very) weakly interacting particles

- FCCee@Zpole → unprecedented stats → explore unchartered territory
  - Axion-like particles, dark-photons, heavy neutral leptons,…

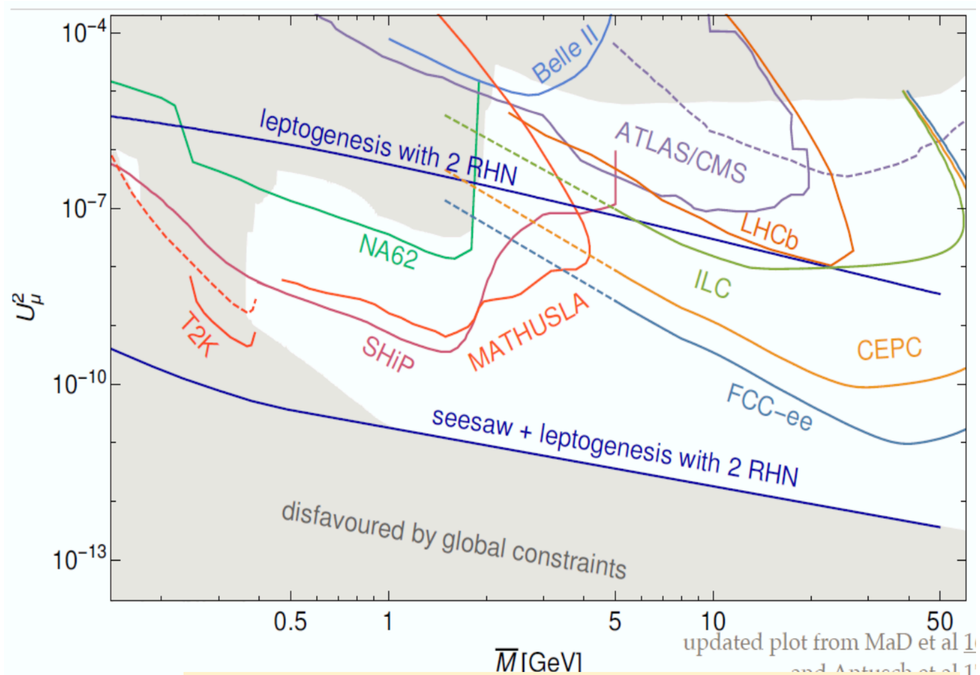
e.g. Heavy Neutral Leptons (*N*)



Could provide answers to several big questions in "one-shot"

$$e^+e^- \rightarrow \nu N$$
$$\hookrightarrow N \rightarrow e^- W^{*+}$$

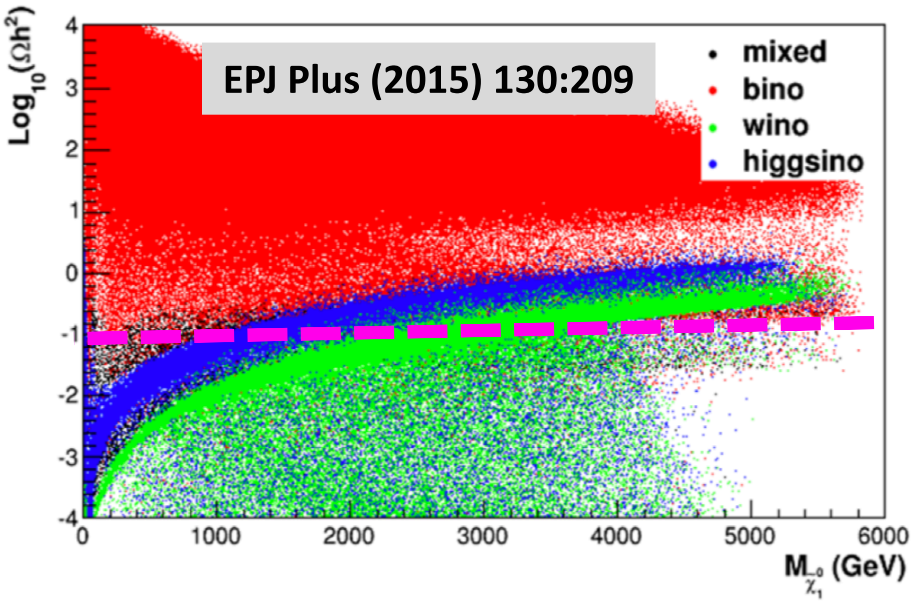
Signature: displaced particles + MisE

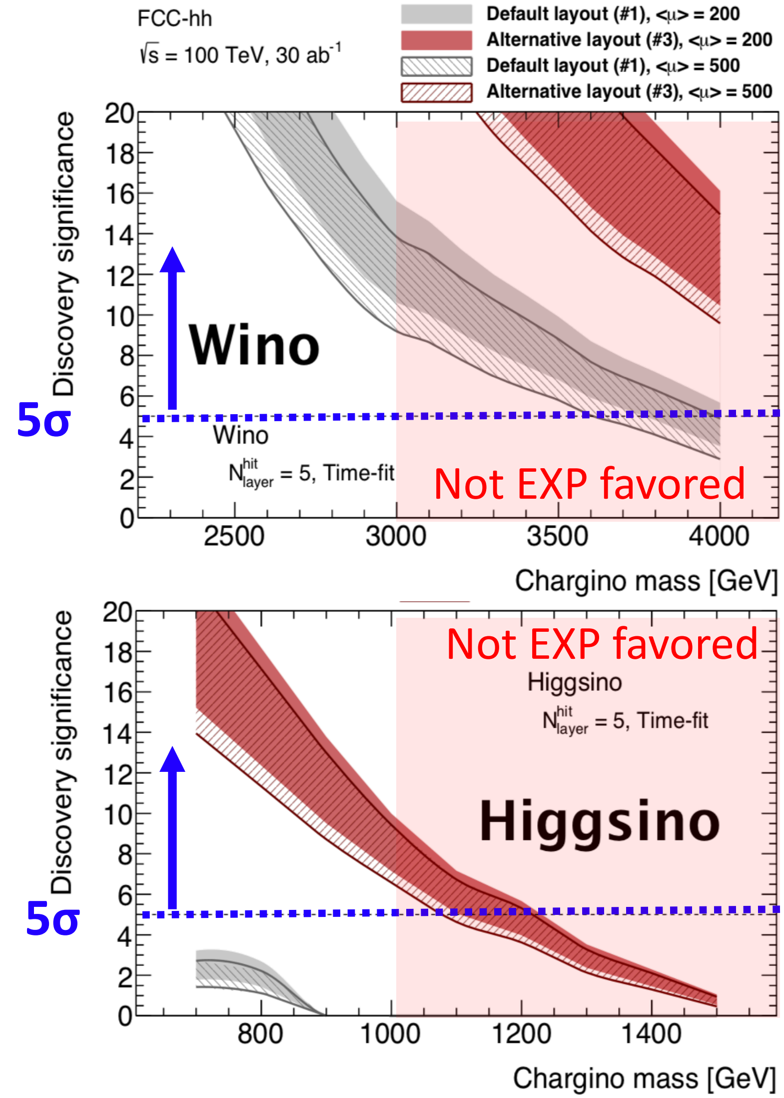


Huge improvement compared to existing and foreseen experiments

FCC-hh: WIMP Dark matter

- Neutralino: excellent dark matter candidate





- Pure Wino or Higgsino favoured
  - compressed spectra: soft, displaced vertices

→ Most TH & EXP motivated scenarios for thermal DM can be **discovered** at FCC-hh

→ But: we need to modify the "ref FCC detector" i.e. **introduce** a <u>5-layer pixel detector</u>

→ And, exploit **timing detector**

FCC-hh: New particles/resonances

- Exotic resonances/particles/forces
  - Multi-TeV objects: “stress-test” for detector design/performance and object reconstruction techniques
- FCC-ee: set the scale of NP from precision measurements
- FCC-hh: “classical” bump hunt, “typical” SUSY searches …

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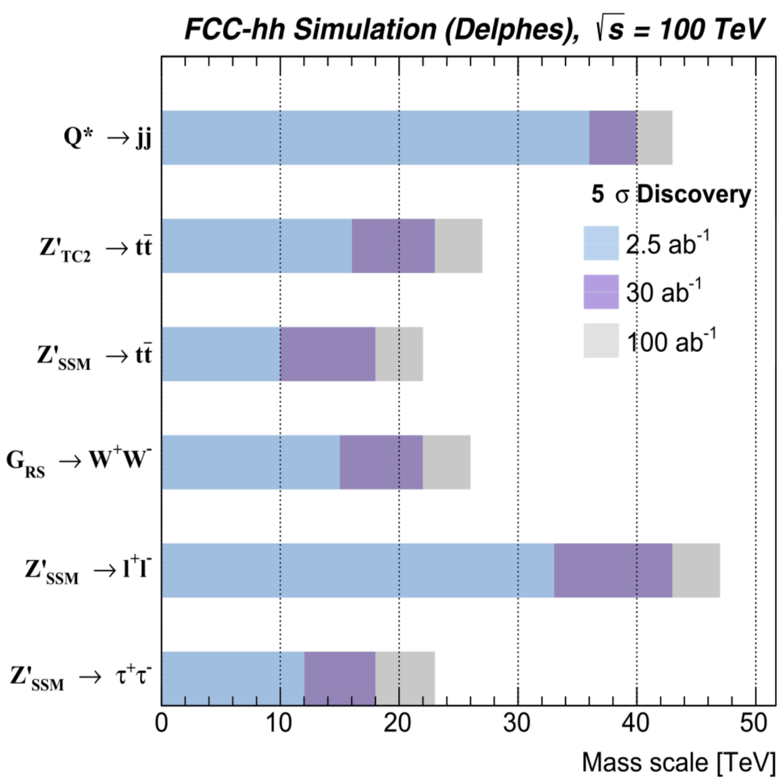

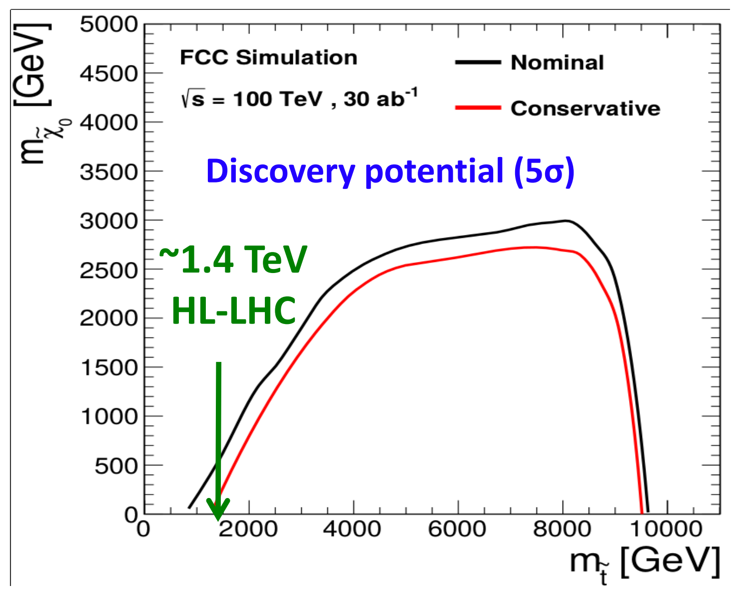

Discover scalars up to O(10) TeV
→favored by several theories

Summary and outlook

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- Unique situation: no clear direction of where to look for New Physics
  - but we have very strong reasons to believe it exists

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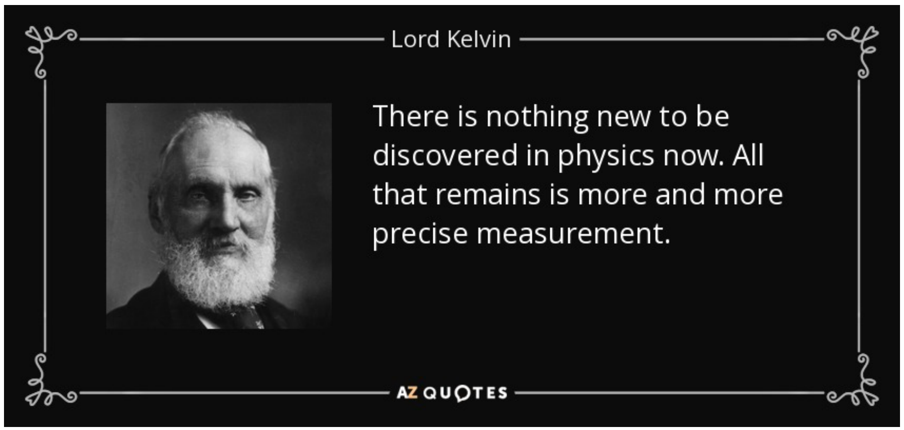

.. and we all know what followed after this statement

Summary and outlook

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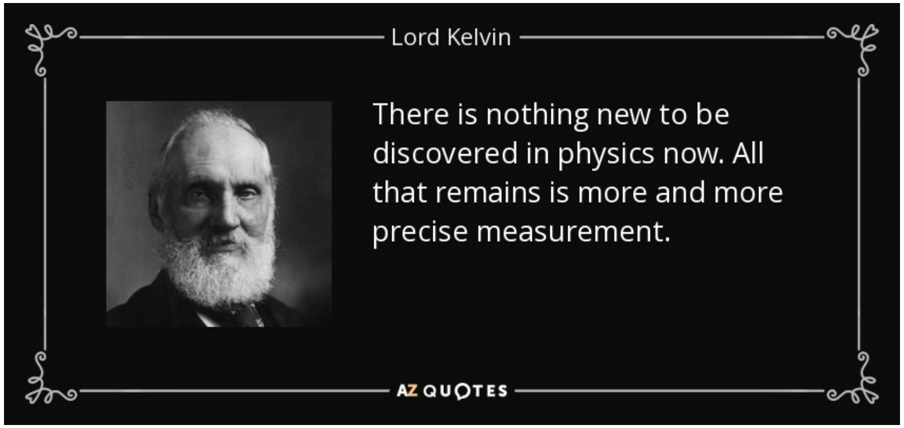

.. and we all know what followed after this statement

- Next experiment should:
  - Improved sensitivity and precision
  - Higher collision energies
  - Versatile

Summary and outlook

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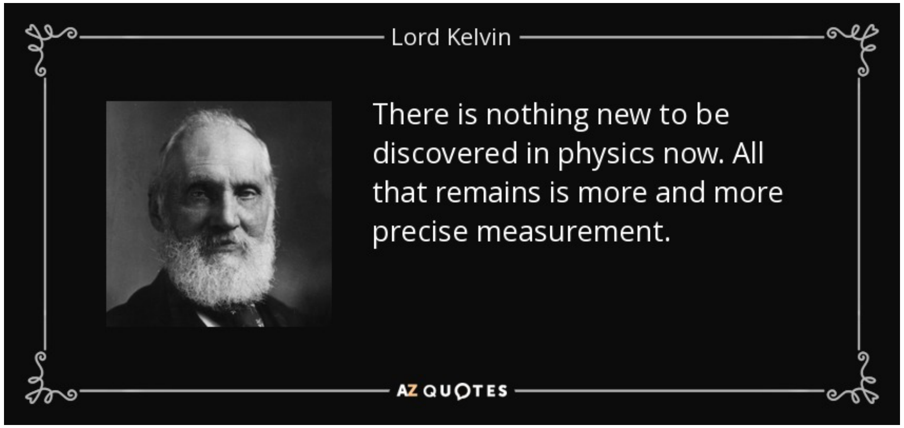


.. and we all know what followed after this statement

- Next experiment should:
  - Improved sensitivity and precision
  - Higher collision energies
  - Versatile

→ FCC (ee,eh,hh)

Summary and outlook

- FCC: Powerful, Broad, Outstanding physics program
  - Starting with FCC-ee → then ultimate goal: FCC-hh
    - During FCC-ee: develop >16T magnets
  - An ambitious [yet realistic] program: pushing frontiers on all fronts
    - knowledge, technology, civil engineering, …

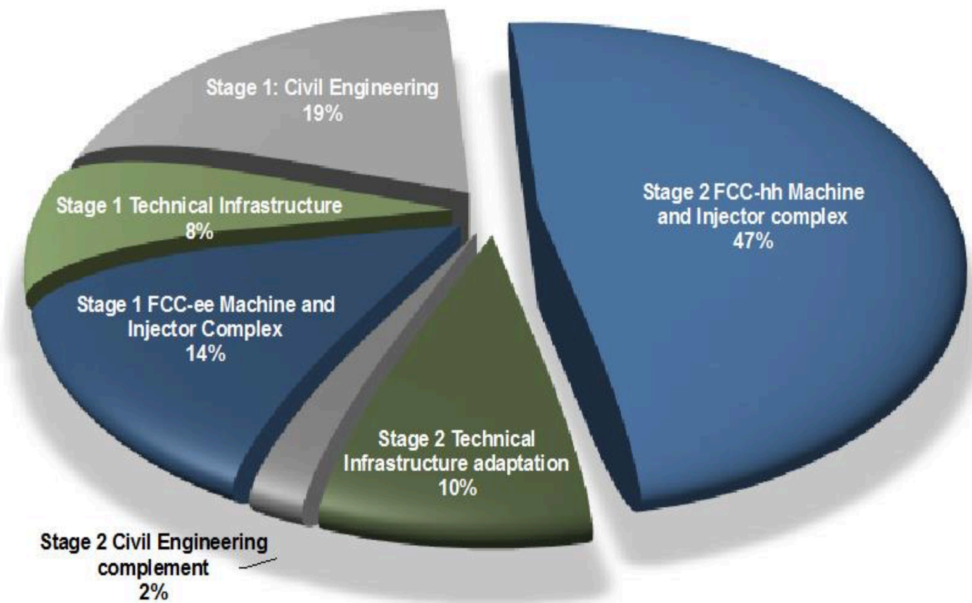
- Current focus: Feasibility studies → to make it a reality
  - **Goal:** decision at next ESG (2027) → operation at the end of HL-LHC
  - Join the effort → Shape the future of HEP
    - Lot's of room for important and innovative contributions

Additional material

FCC-ee/hh

- Timeline: FCCee [immediately after HL-LHC]:15 ys → FCC-hh: 25ys
  - total of 40 yrs or operation ; > 50 Years including preparation
- Cost:

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



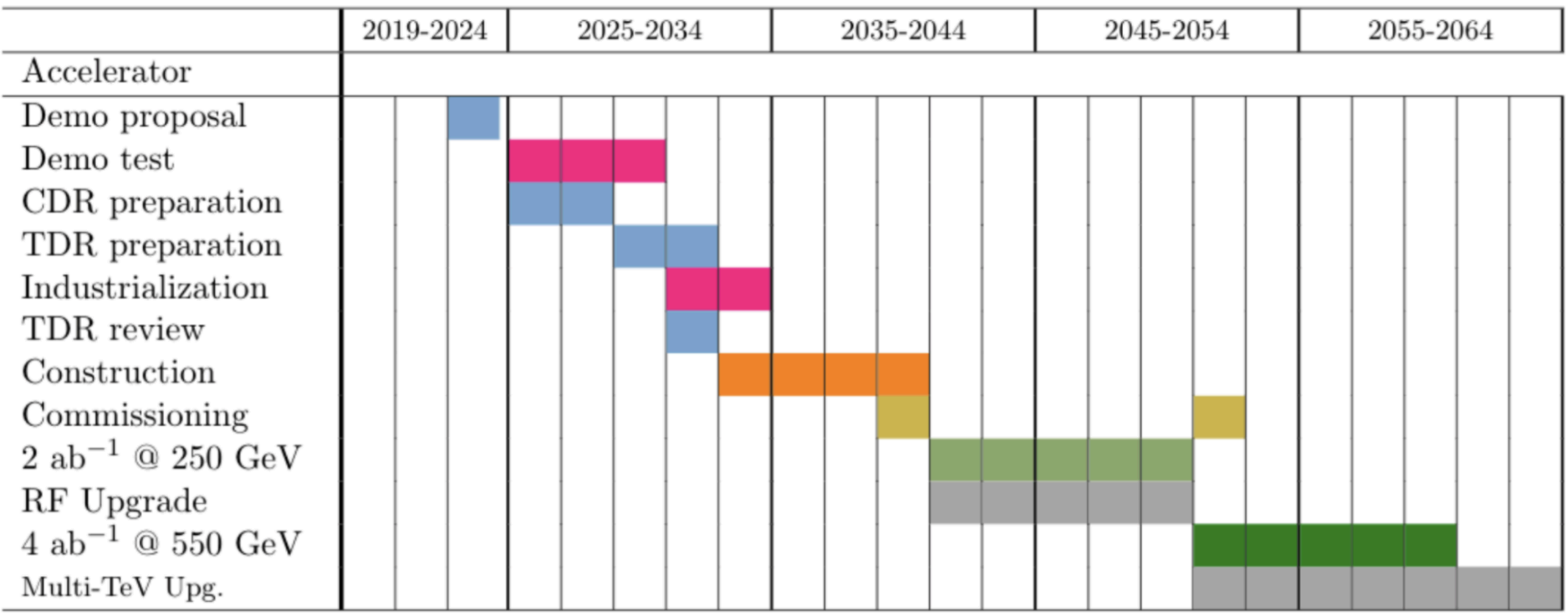
  - FCC-hh alone: CHF: 25B

CLIC

- Timeline:
  - Construction 2026 → beams 2036 → for 25-30 years
- Cost: CHF 6-8B (380 GeV) + CHF 5-6B (for 1.5 TeV)

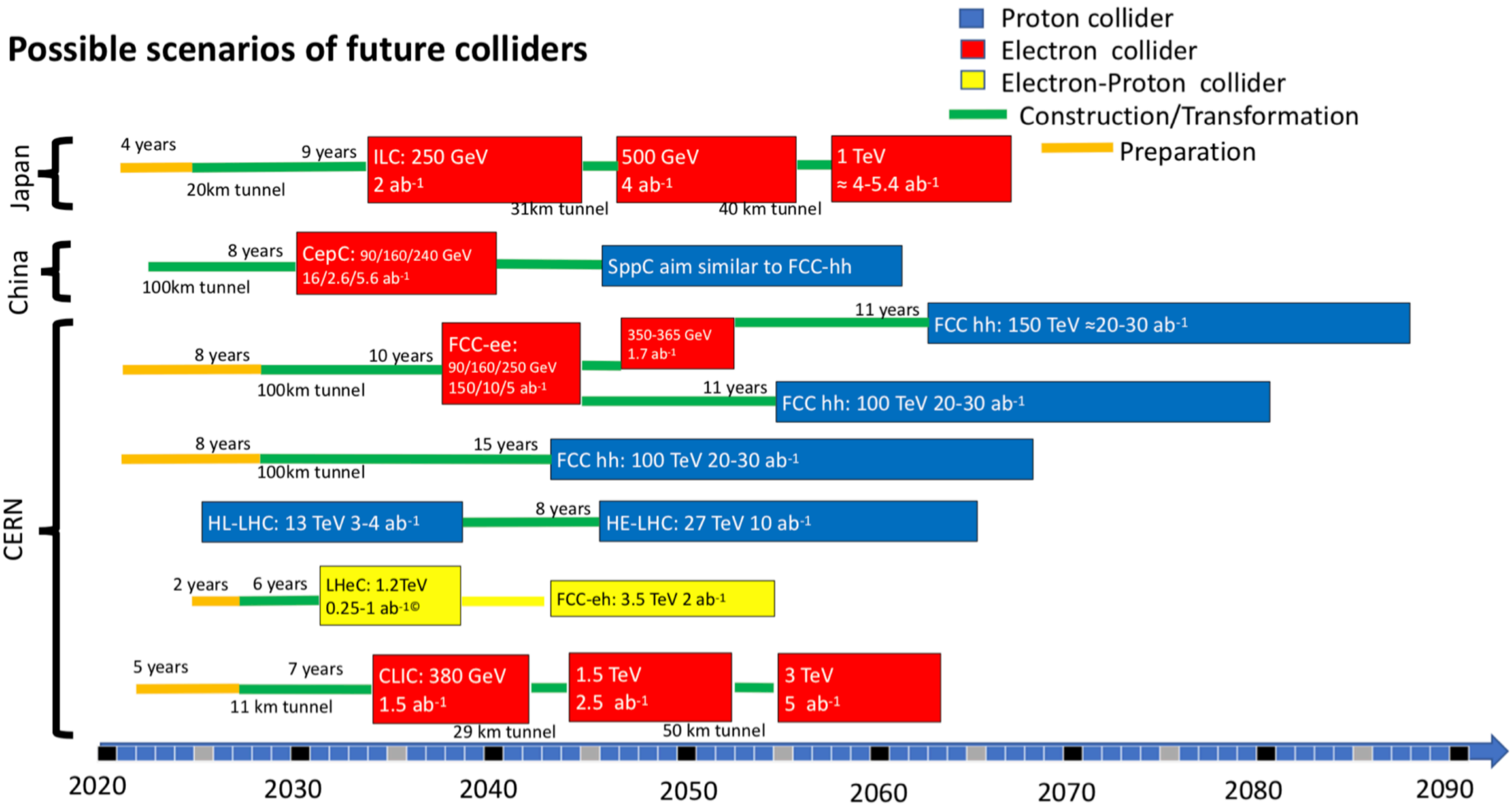
C3

- Sensitivity and detectors similar to ILC
- Cost: $100M



Landscape of future colliders

Possible scenarios of future colliders



Interpretation of results

- *kappa*(κ)-framework:
  - Simplest parametrization which can probe deviations from the SM by BSM ph

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

    - Does not require any BSM computations
    - Fits for 10 κ-parameters: κ_W, κ_Z, κ_c, κ_b, κ_t, κ_τ, κ_μ, κ_γ, κ_g, $\kappa_{Z\gamma}$
  - but:
    - Higgs couplings preserve same helicity structure
    - also blind to polarization/ angular-dependent observables

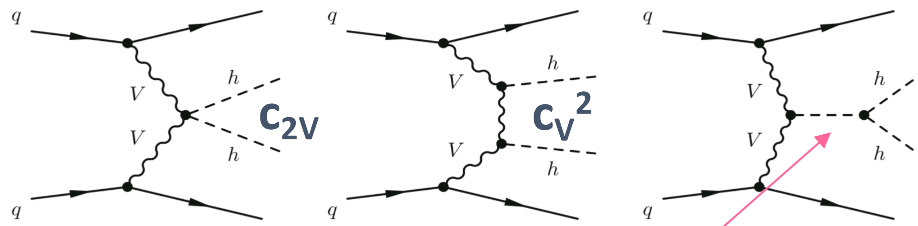
- Effective Field Theory [EFT] description:
  - Extension of the κ-framework: probe helicity structure and polarization

$$\mathscr{L}_{\mathrm{Eff}} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^3}\mathscr{L}_7 + \frac{1}{\Lambda^4}\mathscr{L}_8 + \cdots , \qquad \mathscr{L}_d = \sum_i c_i^{(d)} \mathscr{O}_i^{(d)}$$

En route to HH → VBF HH

- Measure VVHH coupling:

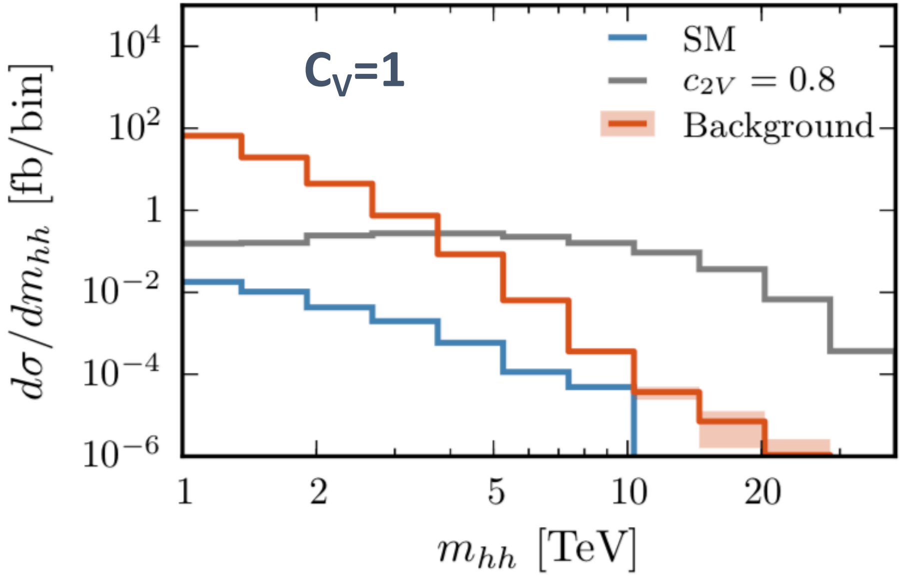
$$A(V_L\, V_L \to HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}),$$



SM: vanishes
BSM: can be significantly modified
grows with E

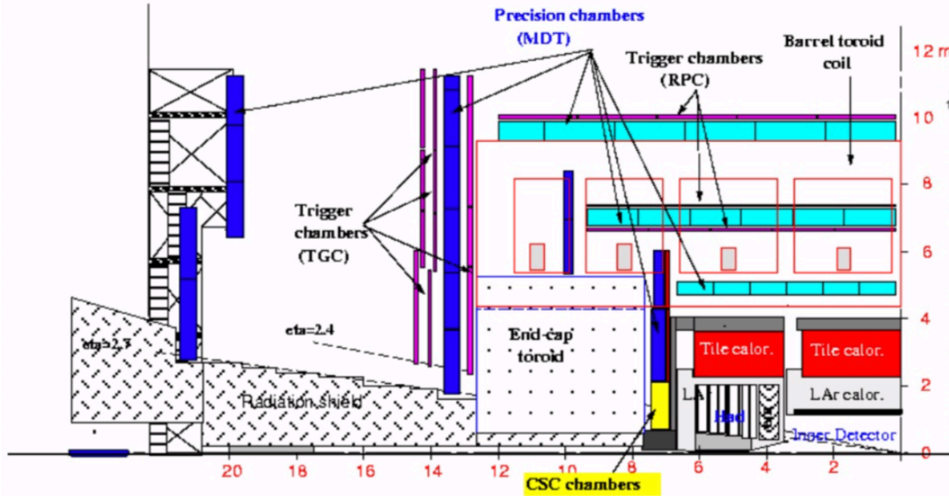
SM: negligible at large m_{HH}
highly off-shell

- Strategy: HH→4b (large BR)
  - Large p_T(H); suppress many BKGs
  - Further suppress BKG using jet-substructure
  - Fit m_{HH} spectrum

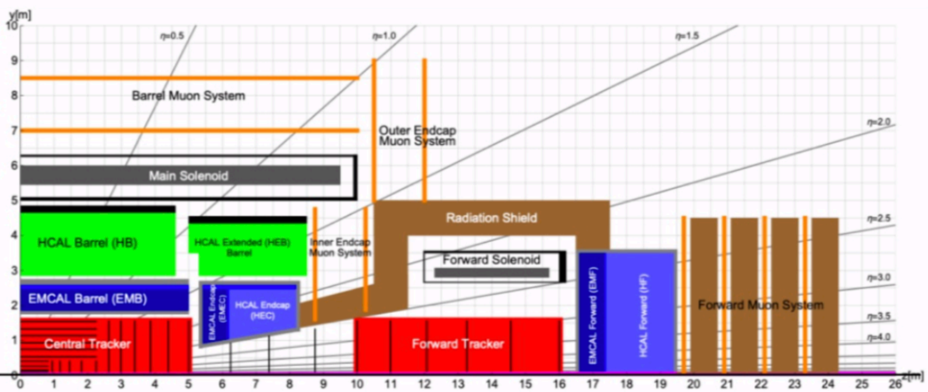


- Input from FCC-ee: C_V (κ_V)~O(0.1%) pr
  - $\delta(C_{2V})$ better than 1% at FCC-hh

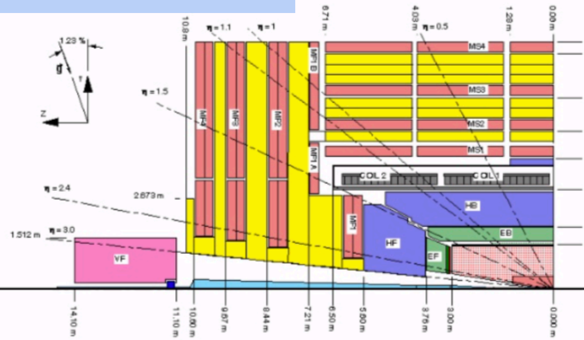
ATLAS

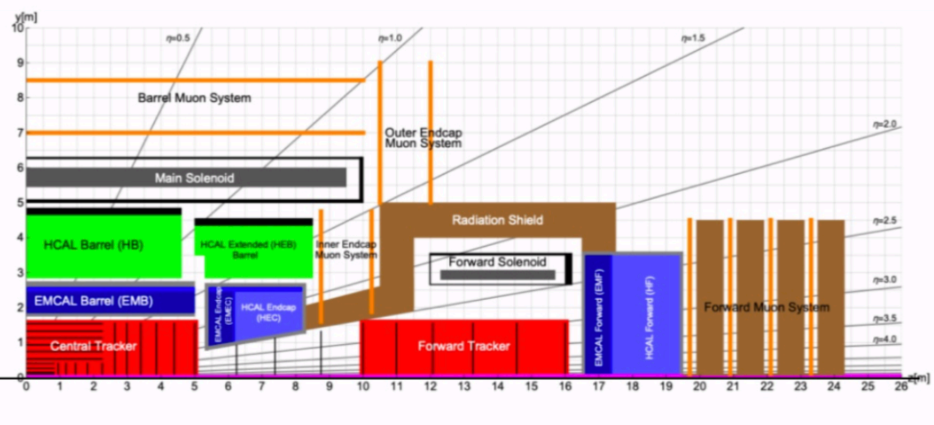


FCC-hh

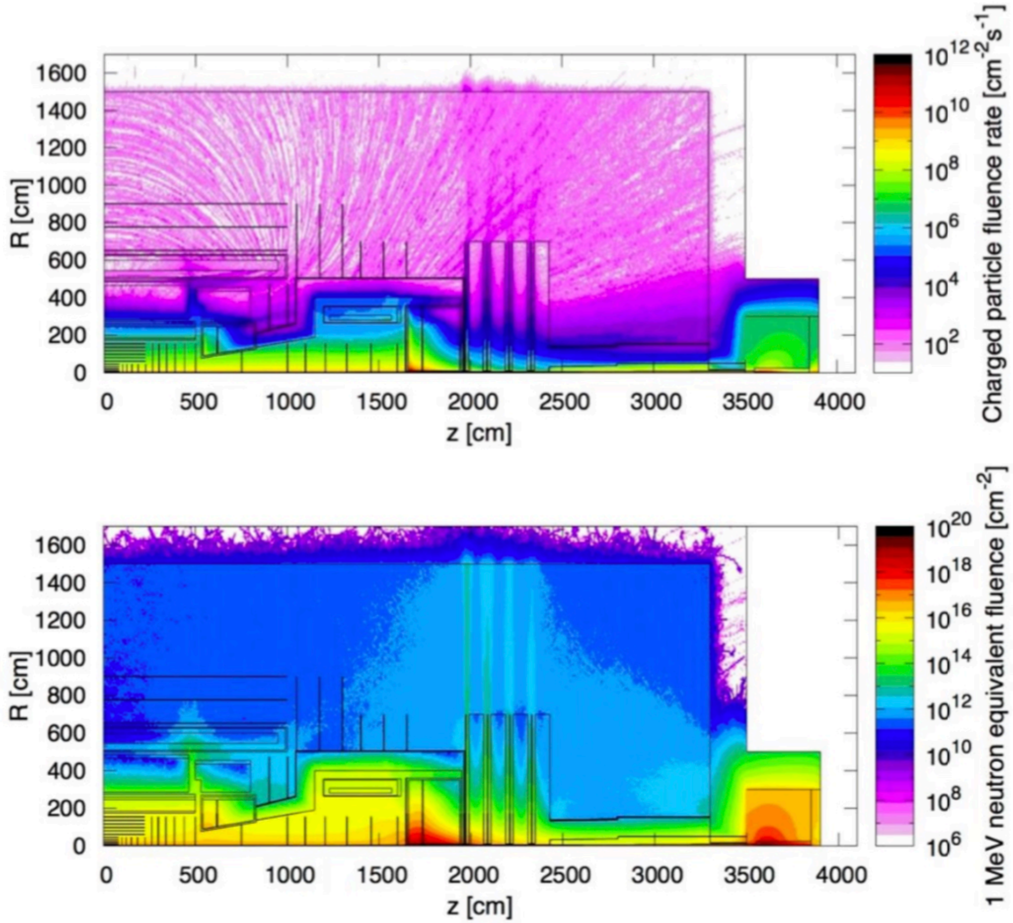


CMS



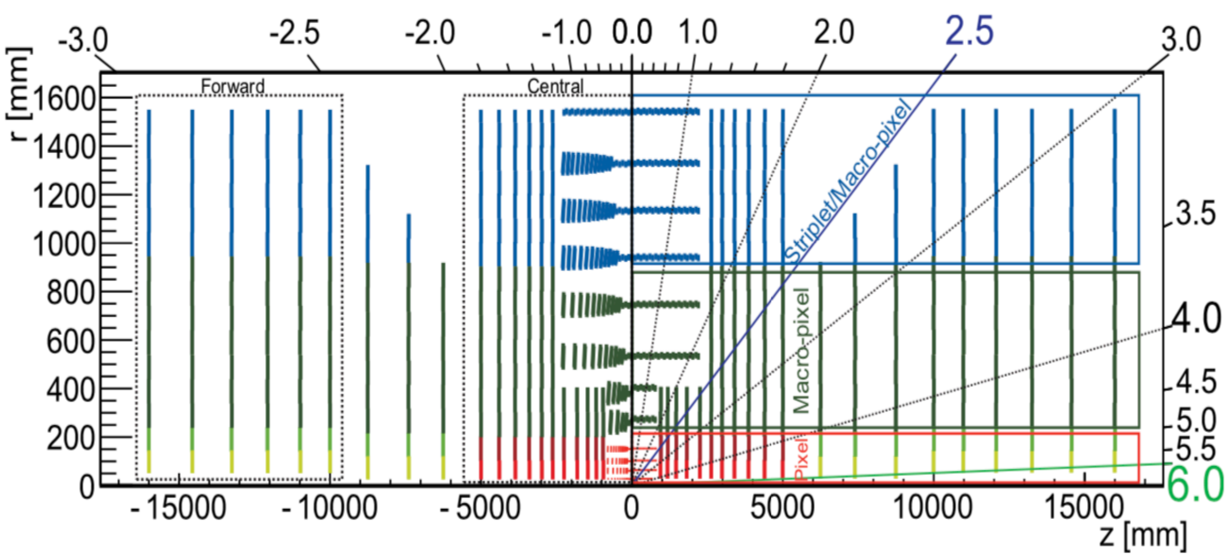


Radiation studies

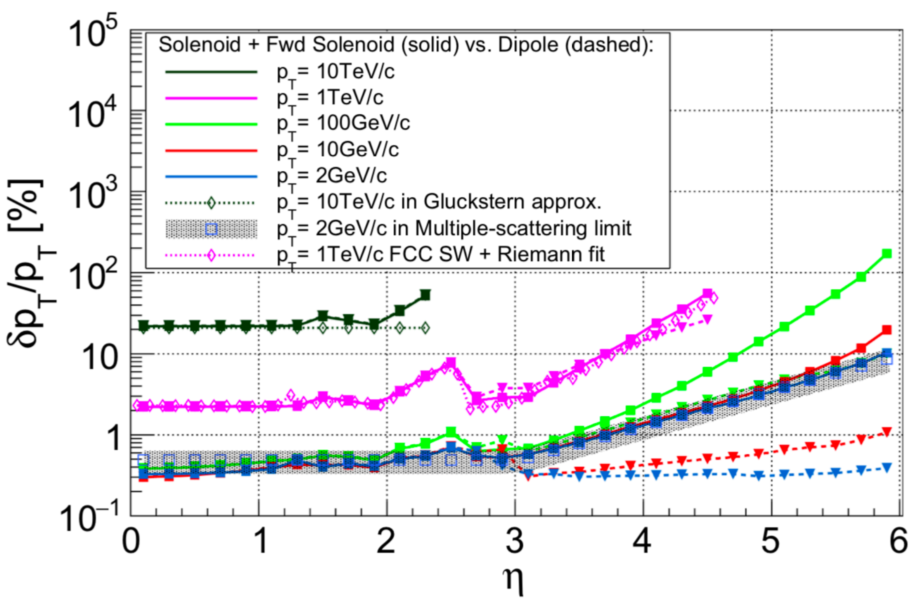


The FCC-hh detector: TRK

Titled geometry | **Flat geometry**



- → **Titled geometry:** ~50% less material, better performance 390 m² Silicon/ 250 m² CMS
- → Material budget less than CMS/ATLAS
- → **16x10⁹ readout chan.** 3 (8)x more than CMS (ATLAS)



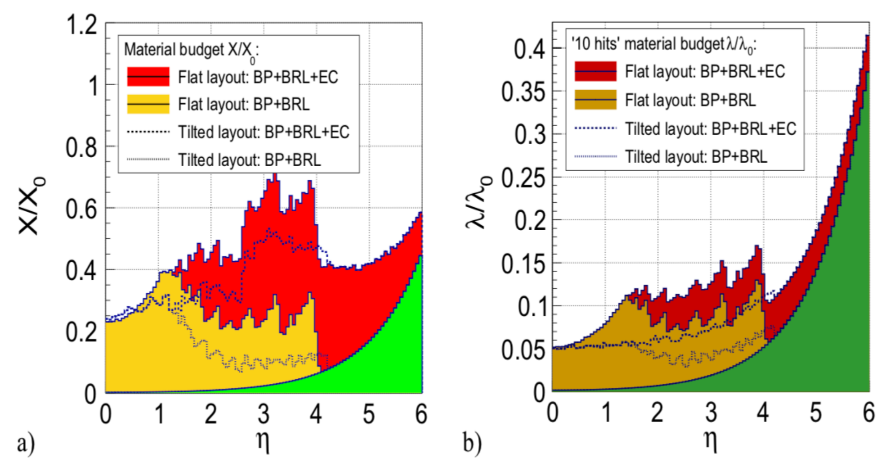
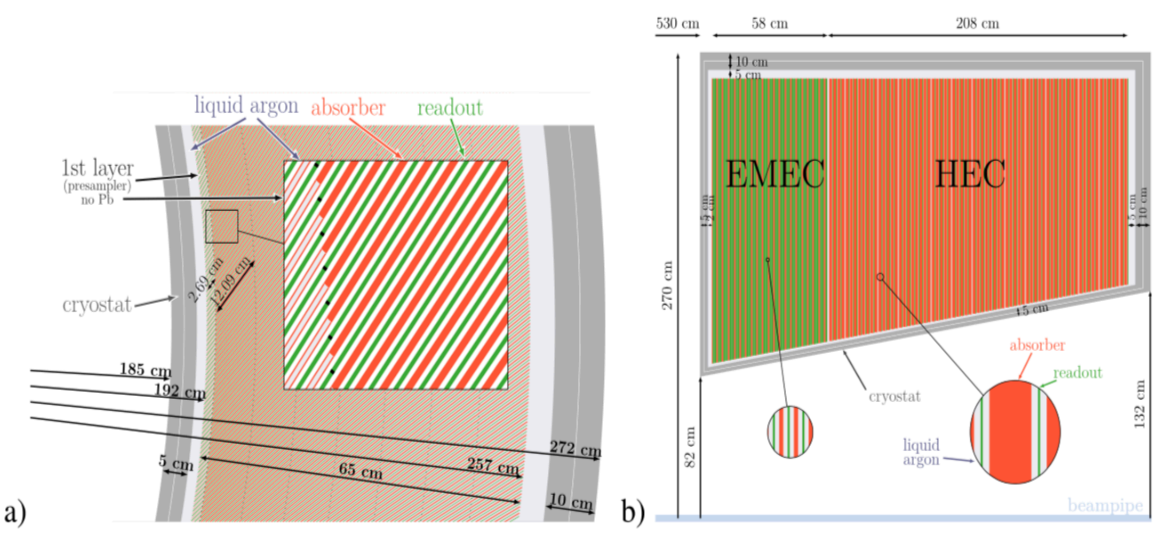
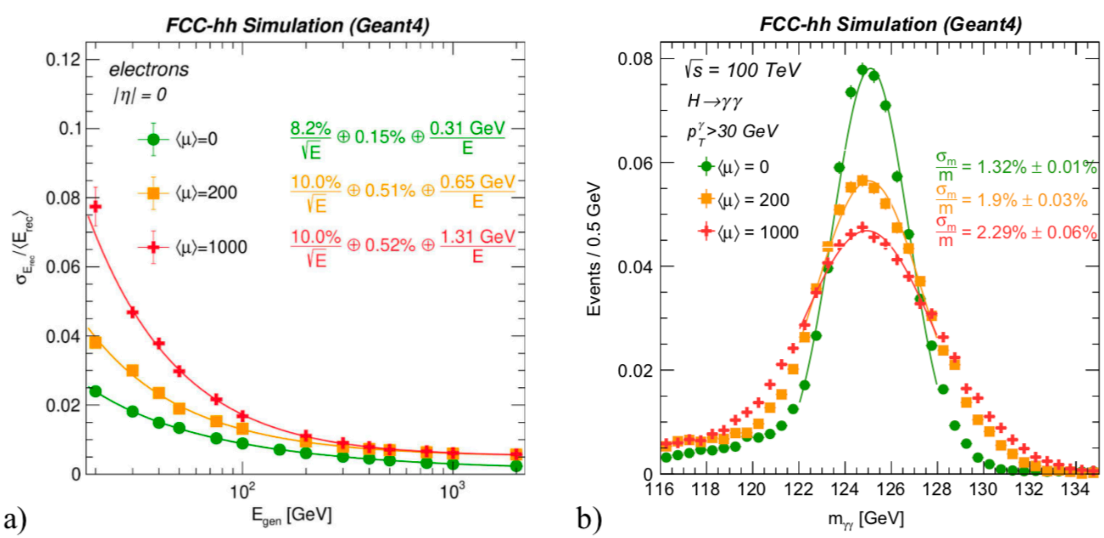


Fig. 7.14. (a) Material budget in units of radiation length for the flat and tilted tracker geometries. (b) Material budget in units of nuclear interaction length for the flat and tilted tracker geometries, assuming a limit of 10 hits on the track.

The FCC-hh detector: ECAL

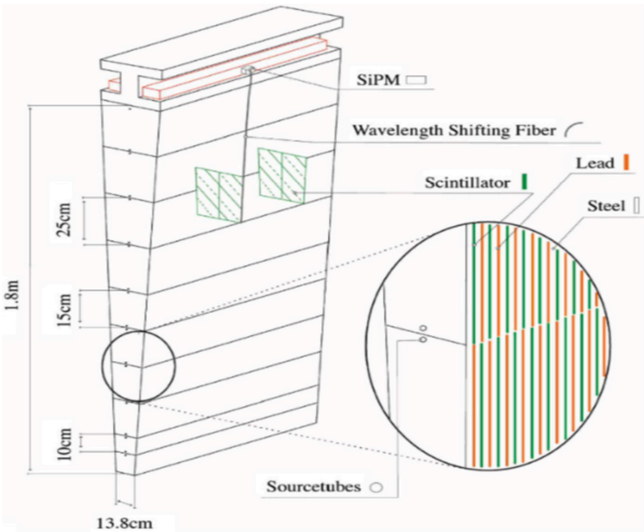


- → **LAr/Pb (Lar/Cu):** Barrel (Fwd) rad hard & stability alternative ala CMS-HGCal [Si/Pb(W)]
- → **ΔηxΔϕ~0.01x0.01:** ~4x more granular than ATLAS/CMS
- → **Long. segmentation:** 8 layers

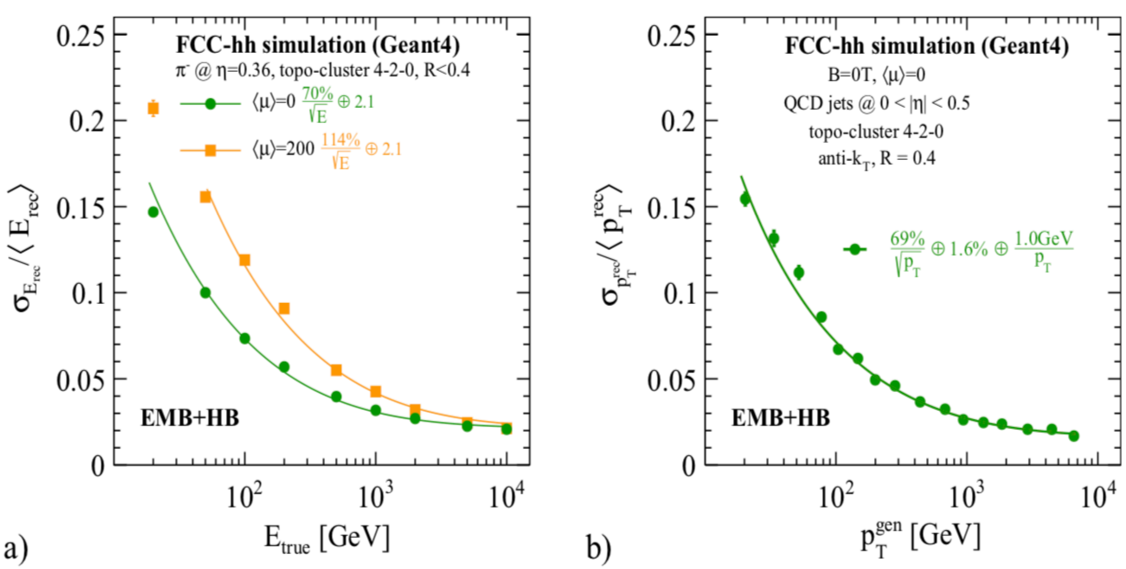


- → comparable mass resolution with CMS in the case of low PU
- → ~2x degradation in $m_{\gamma\gamma}$ resolution for PU=1000
  However: no TRK info exploited

The FCC-hh detector: HCAL



- → **Organic scintillating tiles & steel with wavelength shifting fibers (WLS)**: Similar technology to ATLAS
- → **ΔηxΔϕ~0.025x0.025:** ~4x more granular than ATLAS/CMS
- → **Long. segmentation:** 8 or 10 layers



- → comparable mass resolution with CMS in the case of low PU
- → Effect of PU significant: Needs more sophisticated algorithms and TRK information

The FCC-hh detector: Calo summary

Table 7.3. Calorimeter system for the reference detector.

	η_{min}	η_{max}	a	c	$\Delta\eta$	$\Delta\phi$	Fluence	Dose	Material	Mix	Seg.
Unit			$\%\sqrt{\text{GeV}}$	%			cm^{-2}	MGy			
EMB	0	1.5	10	0.7	0.01	0.009	5×10^{15}	0.2	LAr/Pb/PCB	1/0.47/0.28	8
EMEC	1.5	2.5	10	0.7	0.01	0.009	3×10^{16}	4	LAr/Pb/PCB	1/0.75/0.6	6
EMF	2.5	4	10	0.7	0.025	0.025			LAr/Cu/PCB	1/50/6	6
	4	6	30	1	0.025	0.025	5×10^{18}	5000	LAr/Cu/PCB	1/50/6	6
HB	0	1.26	50	3	0.025	0.025	3×10^{14}	0.006	Sci/Pb/Fe	1/1.3/3.3	10
HEB	0.94	1.81	50	3	0.025	0.025	3×10^{14}	0.008	Sci/Pb/Fe	1/1.3/3.3	8
HEC	1.5	2.5	60	3	0.025	0.025	2×10^{16}	1	LAr/Cu/PCB	1/5/0.3	6
HF	2.5	4	60	3	0.05	0.05	5×10^{18}	1000	LAr/Cu/PCB	1/200/6	6
	4	6	100	10	0.05	0.05	5×10^{18}	1000	LAr/Cu/PCB	1/200/6	6

Notes. Acceptance, performance goals (single electron for ECAL and single pion for ECAL+HCAL), granularity, radiation levels for $\mathcal{L}_{\text{int}} = 30\,\text{ab}^{-1}$ and technologies chosen.

The FCC-hh detector: Muons

- MDTs technologies ala ATLAS

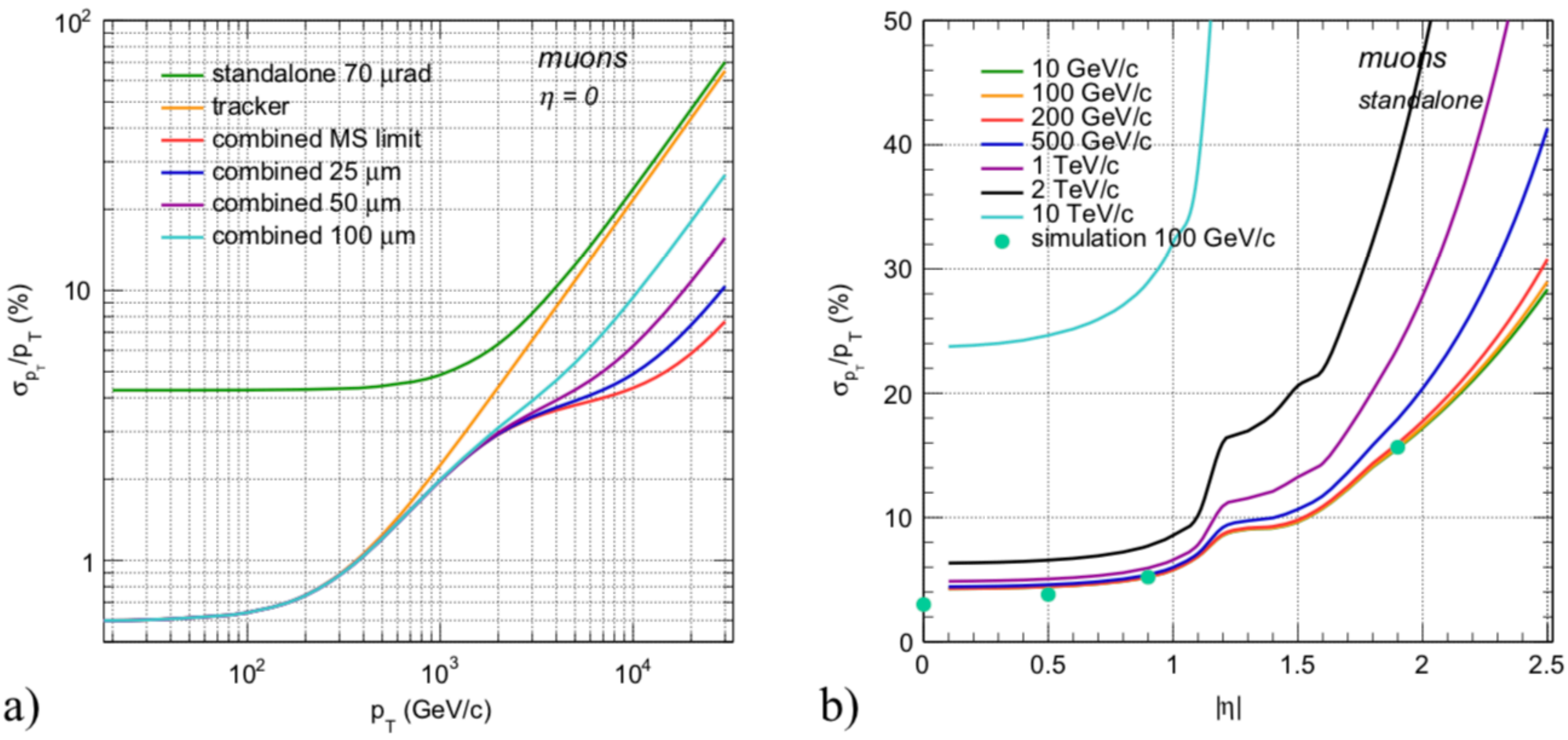
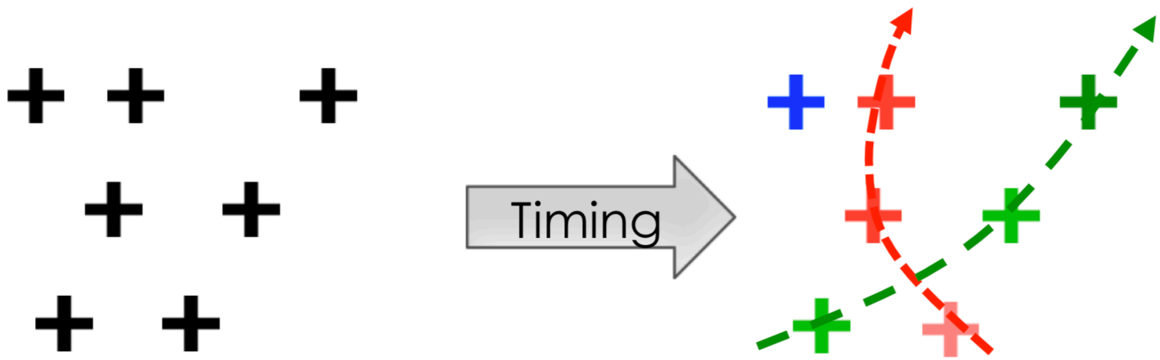


Fig. 7.21. (a) Muon momentum resolution at $\eta = 0$. (b) Muon stand-alone momentum resolution as a function η for different muon momenta.

Timing layers



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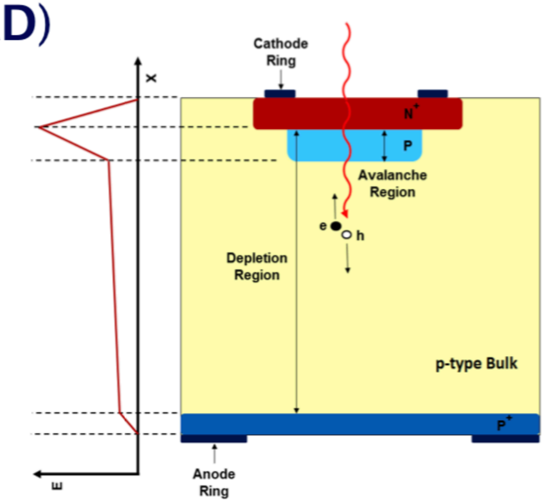
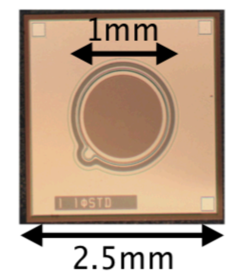
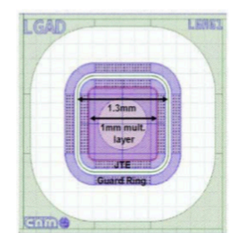
ATLAS HGTD







Low–Gain Avalanche Detector (LGAD)

- $\lesssim$ 30 ps time resolution feasible
- ongoing study for radiation hardness

Assumed in this study that 30~50 ps time resolution can be achieved for the inner-pixel tracker at FCC