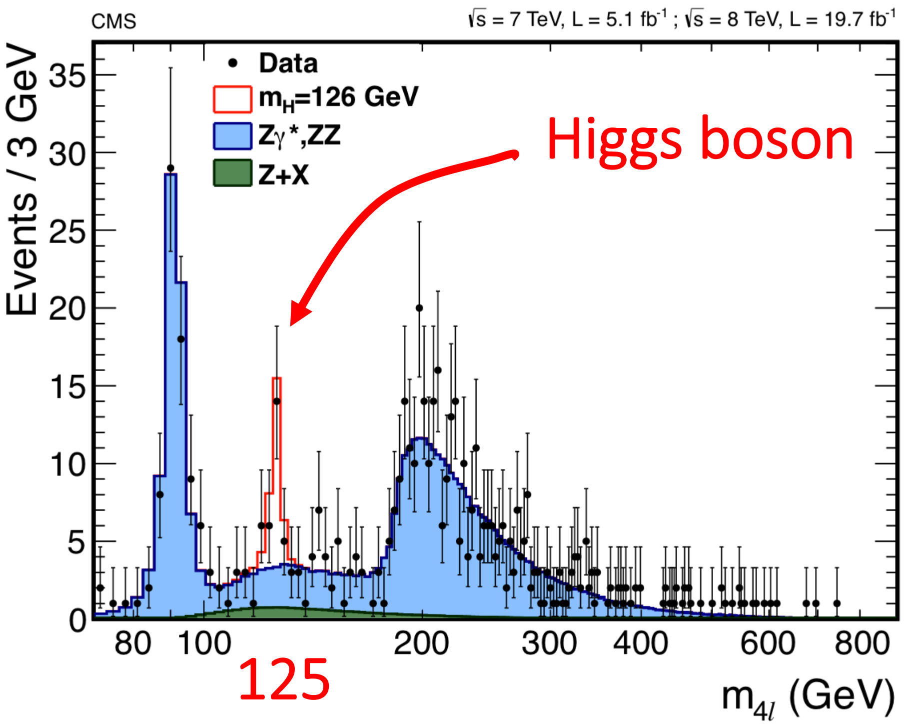
# Higgs Physics with future accelerators

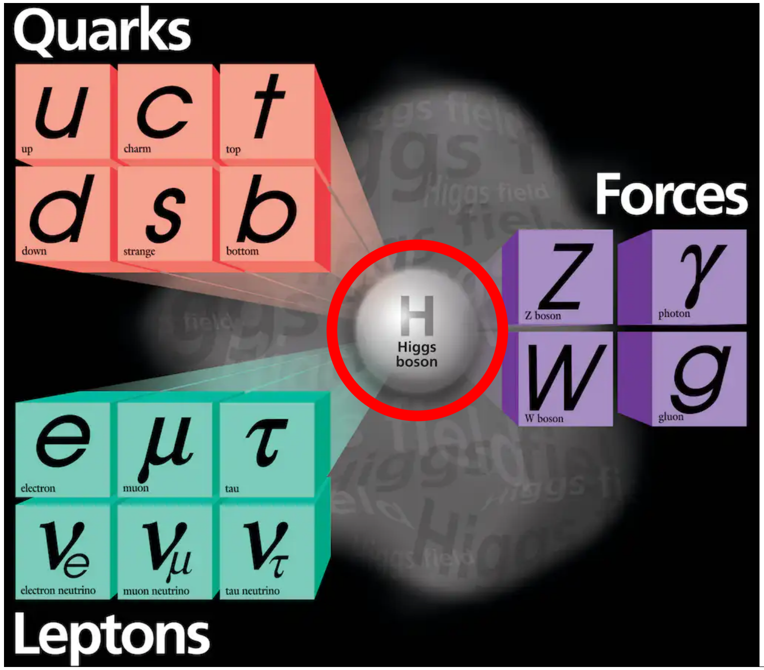
Loukas Gouskos (CERN)

Workshop on Future Accelerators, Corfu (2023)

# The triumph of Standard Model (SM)

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




- SM particle content is complete
- Higgs boson: Plays a very central role; interacts with all particles
- It is the only fundamental scalar particle that we have seen

# Is that all?

- The big open questions.. that beg for Beyond SM (BSM) physics
  - Experiment-driven
    - Dark matter
    - Dark energy
    - Matter antimatter asymmetry, ….
  - Theory-driven
    - Hierarchy problem and naturalness
    - Number of generations
    - Origin of fermion families, …

More in T. You's talk

- 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, Flavour physics, …

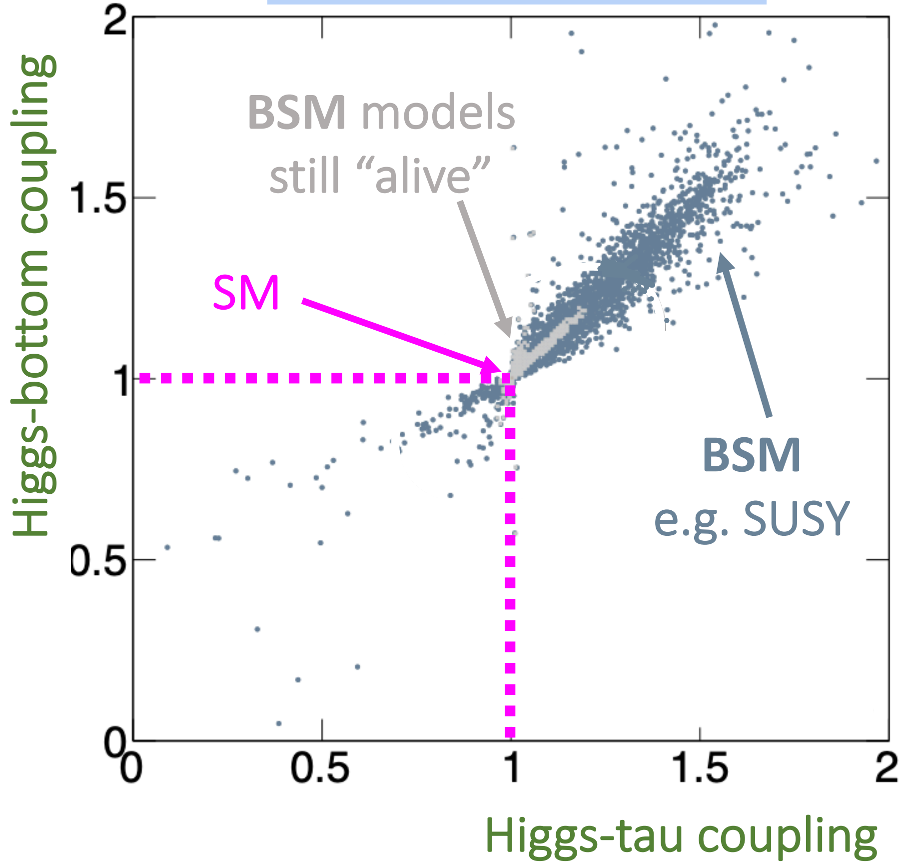
Complementary approaches

- This talk: Higgs Physics at future accelerators [EXP-view]
  - TH-view: H. Baer's talk

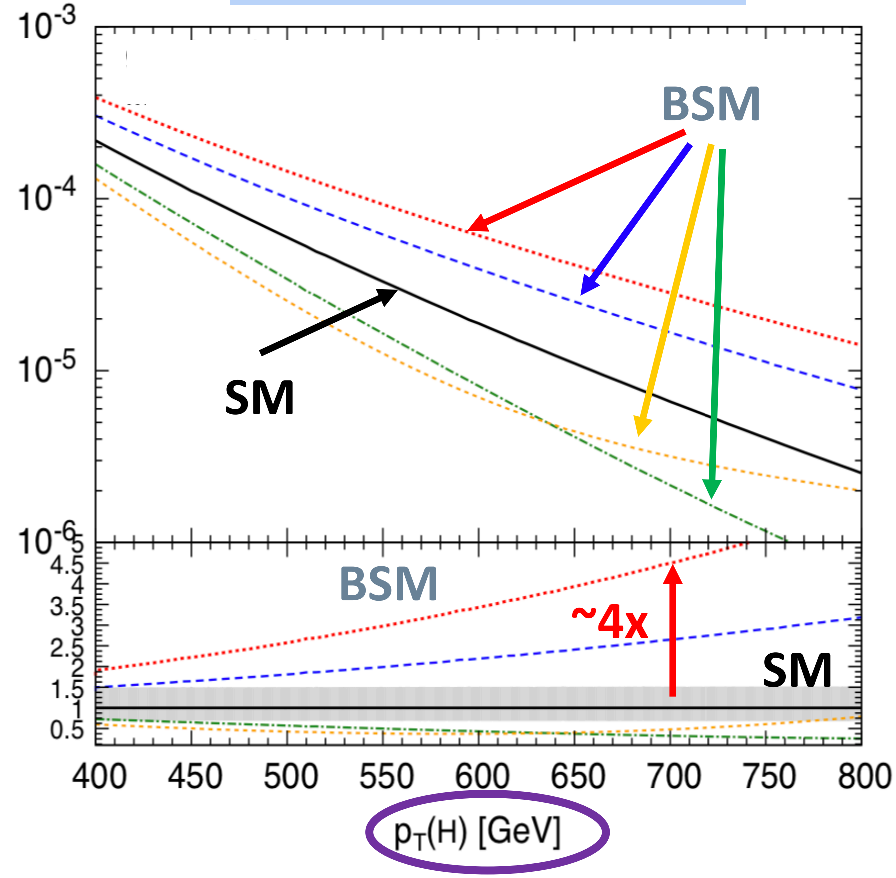
# Higgs as an exploration tool

- BSM can modify the properties of the Higgs particle

## Higgs couplings




## Higgs kinematics




The discovery of the Higgs boson
opens a whole new chapter of exploration

# Interpretation of results

- *Signal strength (μ)* := cross-section x BR
  - [probably] not most sensitive test after observation of specific process

- *Coupling modifiers (κ):*
  - Simplest framework to probe deviations from SM
  - express "$\mu$" to "$\kappa$":
  - no need of BSM calculations [but simplifications]

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

- *Effective Field Theory* description:
  - Extension of $\kappa$–framework
    - probe helicity structure and polarization
  - sensitive to higher-order effects [via operators]

$$\mathscr{L}_d = \sum_i c_i^{(d)} \mathscr{O}_i^{(d)}$$

Interpret results → look for deviations

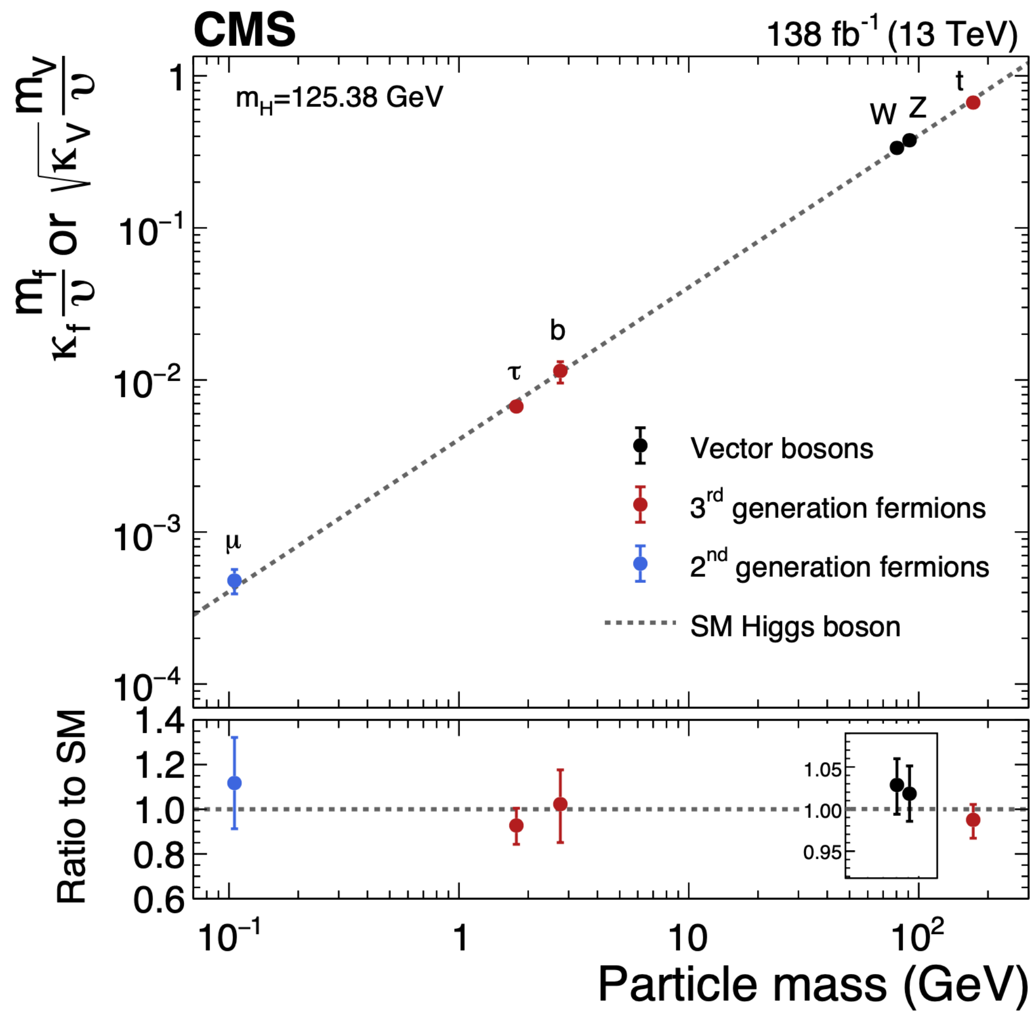
# Physics landscape after 10y of LHC

*Details: J. Wang's talk

- Higgs Physics
  - Already established:
    - Inclusive rates
    - Couplings to **bosons**
    - Couplings to 3rd-Gen fermions
  - Current focus:
    - Couplings to 2nd-Gen fermions

**Everything look very SM**

- Also: Direct searches
  - No new particles up ~few TeV




**Unique situation:**

Current results do not concretely point to any BSM scenario/mass scale

# The landscape at the end of HL-LHC

## Which precision?

- BSM effect on couplings:

$$\frac{v^2}{\Lambda^2} \sim \frac{6\%}{\Lambda^2(\mathrm{TeV})}$$

  - e.g. Λ=1 (5)TeV→~6 (0.1)%

## Impact of BSM O(1TeV):

| Model | $b\bar{b}$ | $c\bar{c}$ | $gg$ | $WW$ | $\tau\tau$ | $ZZ$ | $\gamma\gamma$ | $\mu\mu$ |
|---|---|---|---|---|---|---|---|---|
| MSSM [40] | +4.8 | -0.8 | - 0.8 | -0.2 | +0.4 | -0.5 | +0.1 | +0.3 |
| Type II 2HD [42] | +10.1 | -0.2 | -0.2 | 0.0 | +9.8 | 0.0 | +0.1 | +9.8 |
| Type X 2HD [42] | -0.2 | -0.2 | -0.2 | 0.0 | +7.8 | 0.0 | 0.0 | +7.8 |
| Type Y 2HD [42] | +10.1 | -0.2 | -0.2 | 0.0 | -0.2 | 0.0 | 0.1 | -0.2 |
| Composite Higgs [44] | -6.4 | -6.4 | -6.4 | -2.1 | -6.4 | -2.1 | -2.1 | -6.4 |
| Little Higgs w. T-parity [45] | 0.0 | 0.0 | -6.1 | -2.5 | 0.0 | -2.5 | -1.5 | 0.0 |
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Ref

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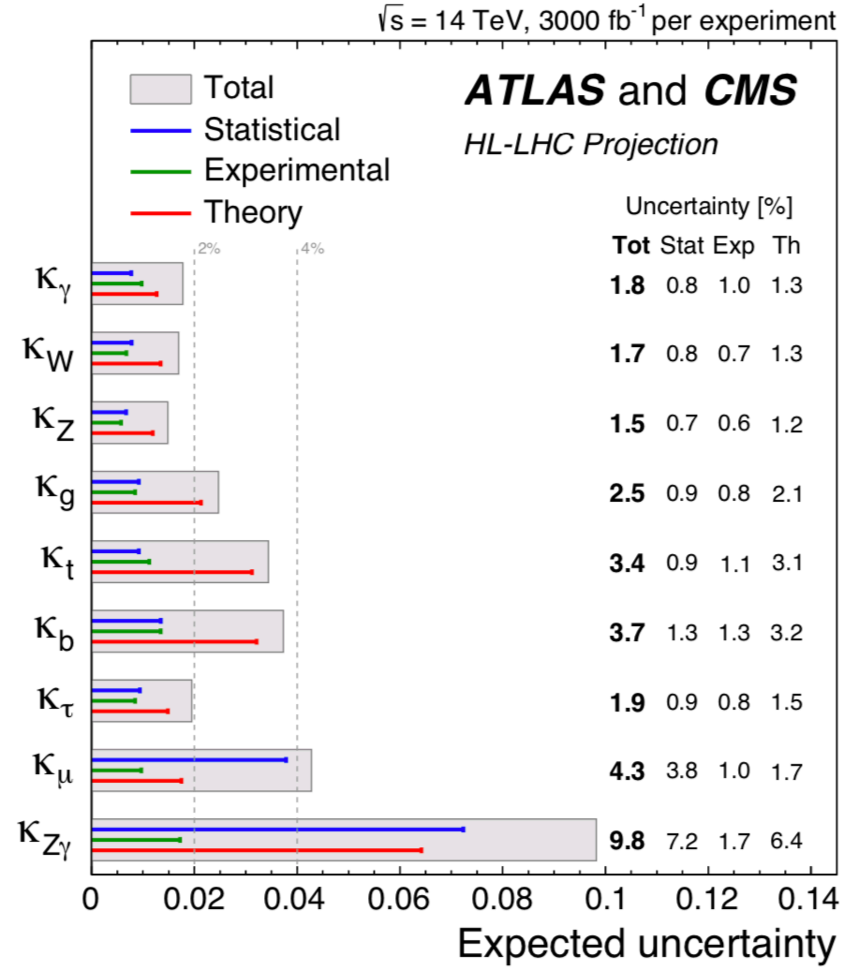
## HL-LHC




**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

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New colliders are necessary to explore the multi-TeV regime

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

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

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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."

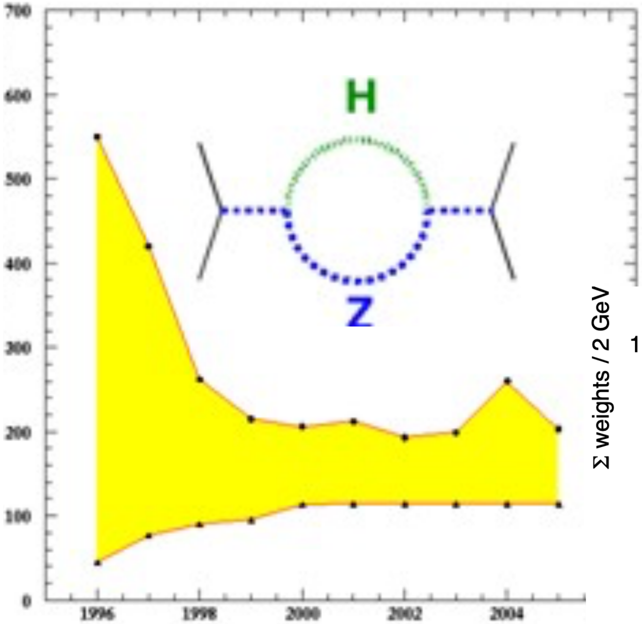
… Similar recommendations from the US-side

- Exploit full potential of (HL-)LHC
- Exhaustively study the Higgs → lepton collider
- O(10) reach in mass scale → hadron collider

# Building on success stories: the "Higgs"

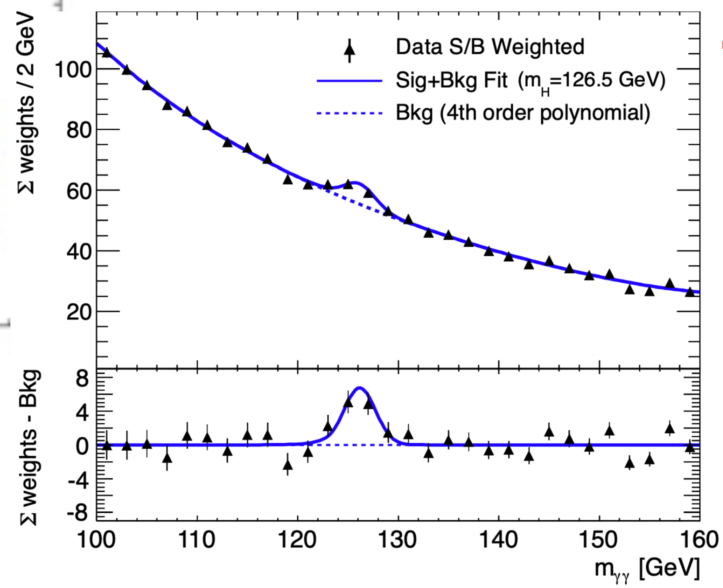
LEP: prediction

Predicted Higgs mass

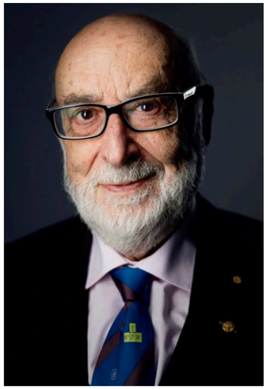



Year

LHC: discovery




Nobel Prize (2013)



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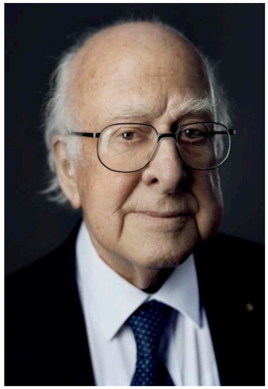
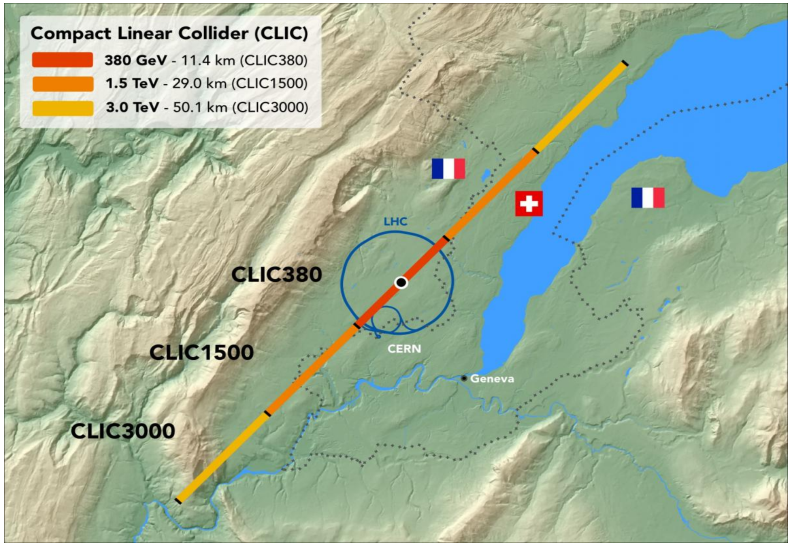
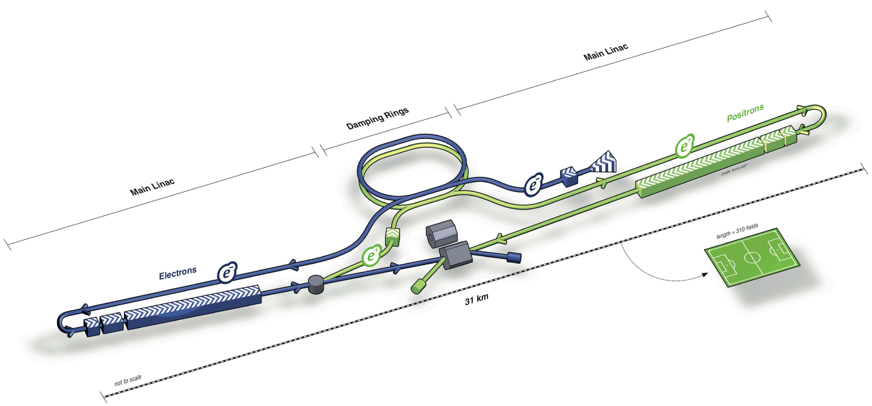


Higgs

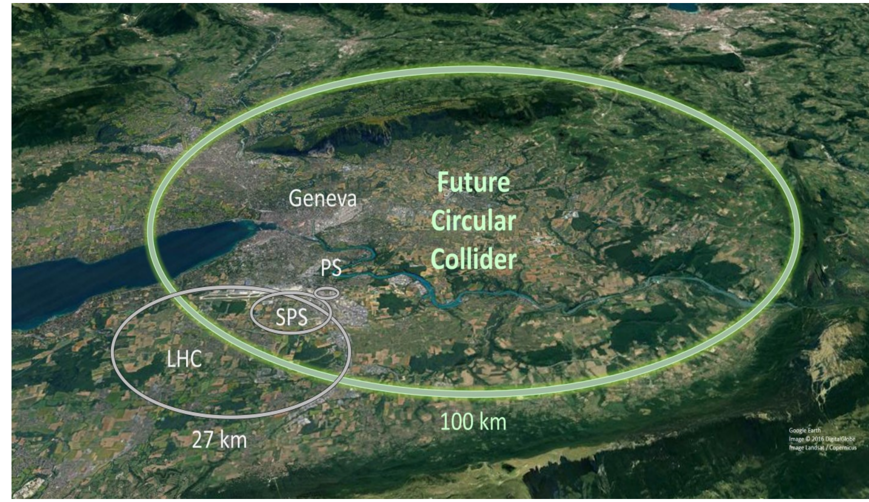
# Possible future accelerators

## Linear ($e^+e^-$) colliders




## Circular ($e^+e^-$/hh) colliders

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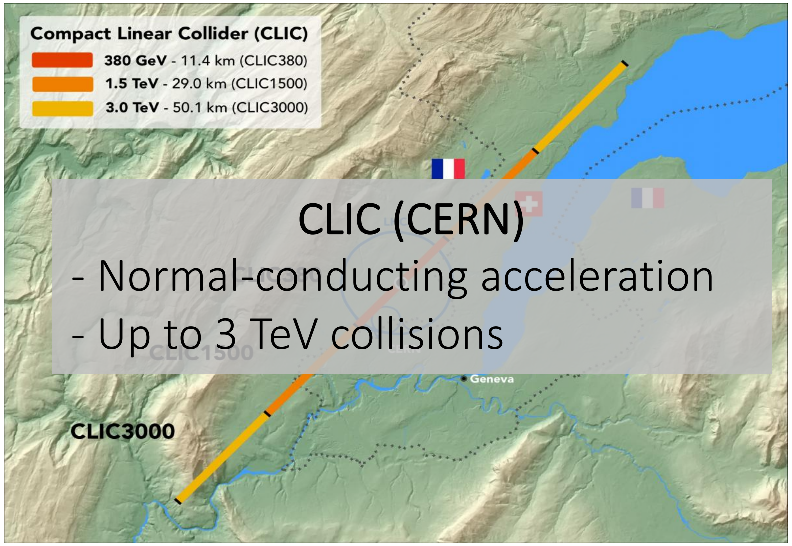
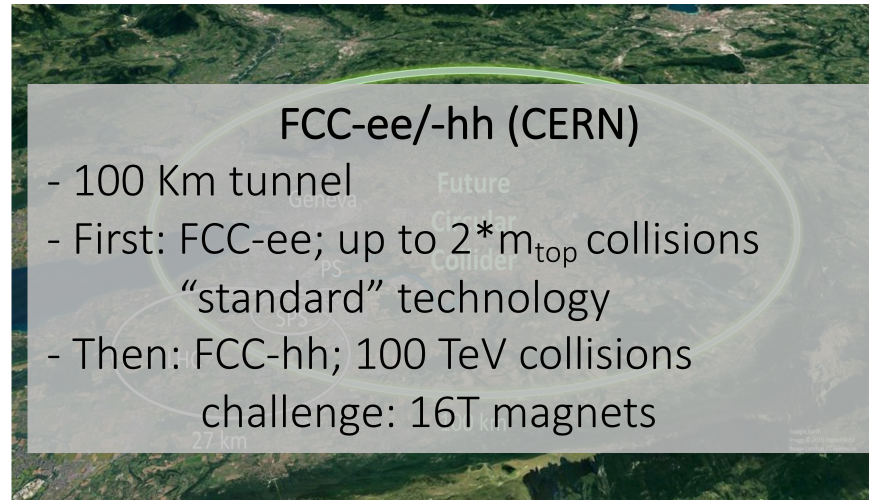



**CLIC (CERN)**
- Normal-conducting acceleration
- Up to 3 TeV collisions


**ILC (Japan)**
- Super-conducting acceleration
- 250 – 500 [1000?] GeV collisions

+ other recent proposals

## Circular ($e^+e^-$/hh) colliders

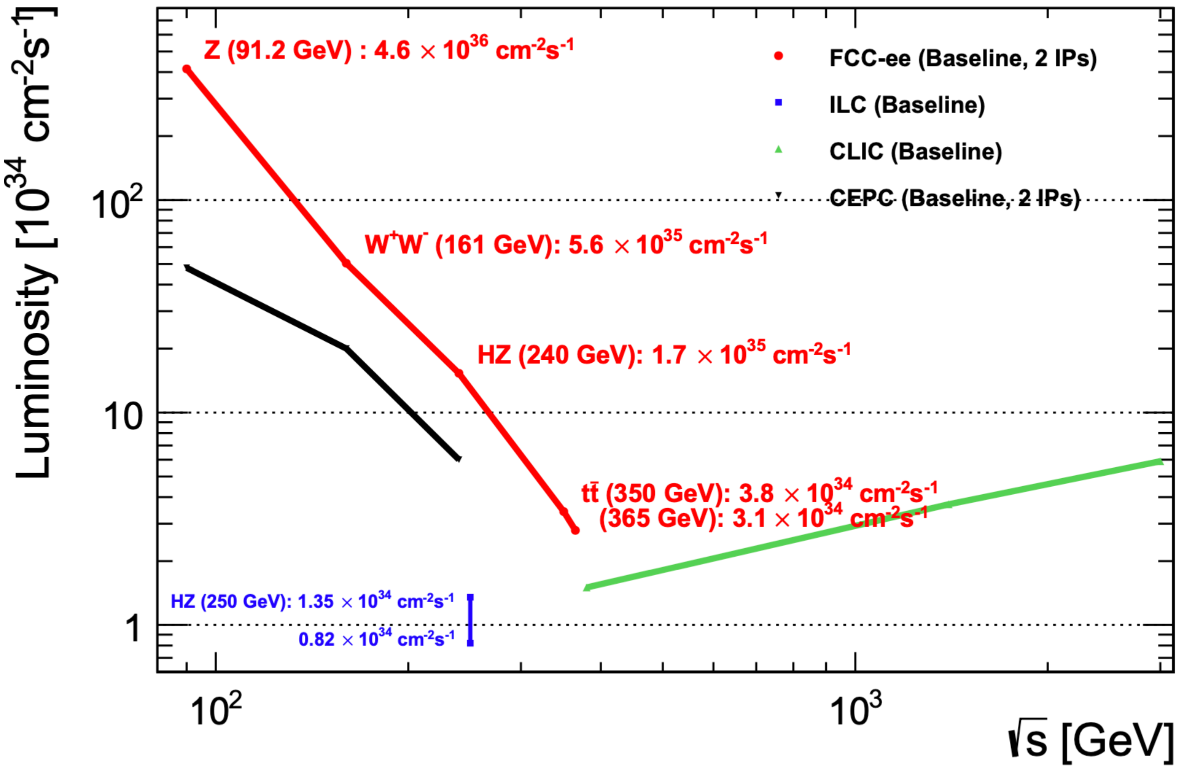


**FCC-ee/-hh (CERN)**
- 100 Km tunnel
- First: FCC-ee; up to $2*m_{top}$ collisions
  "standard" technology
- Then: FCC-hh; 100 TeV collisions
  challenge: 16T magnets


**CEPC/SppC (China)**
- 100 Km tunnel
- Essentially an FCC-ee/ FCC-hh
- More conservative luminosity scenarios

# In a nutshell

- e+e-: Different strategies
  - different luminosity and $E_{CM}$ scenarios
  - FCC-ee/CEPC:
    - Study Z, W, H and top with unprecedented precision
      - e.g. $10^{12}$ Z, 1M H
  - CLIC/ILC:
    - Rich Higgs program
    - Direct access to HH

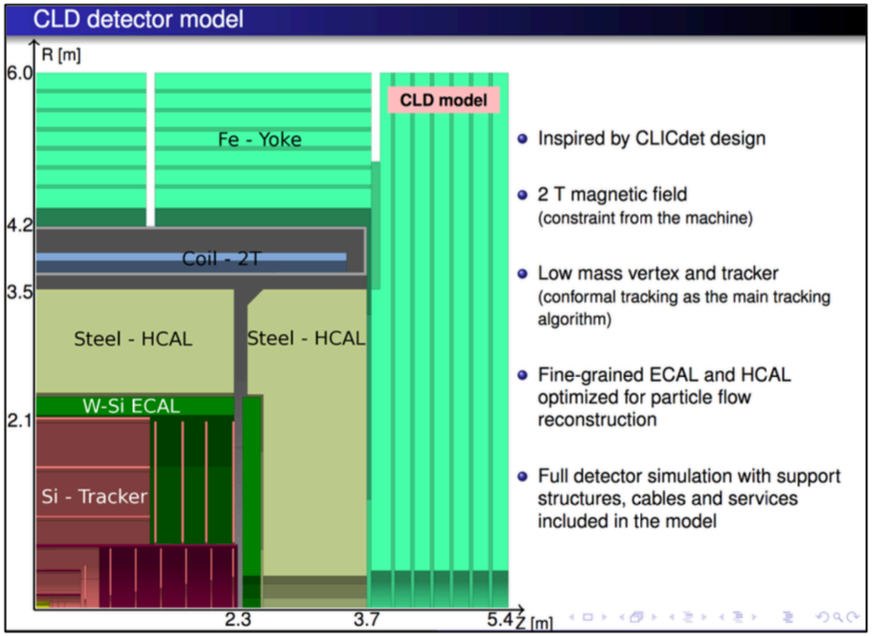



- Ultimate goal: O(100 TeV) pp collider
  - FCC-hh/SppC: use same tunnel constructed for FCC-ee/CepC

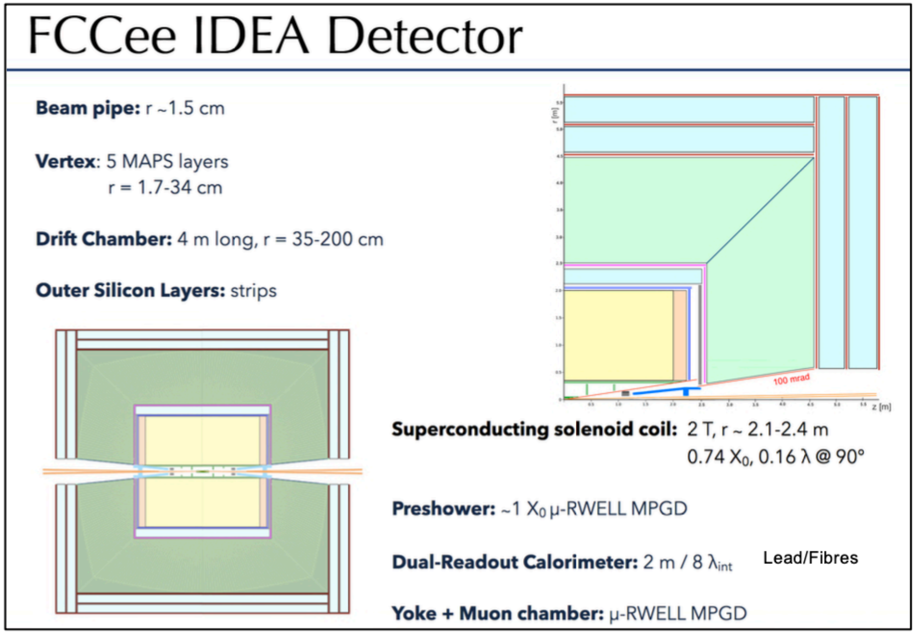
# Detector concepts: $e^+e^-$

- Physics driven design
  - excellent tracking (little material), hadronic resolution, timing info

CLD concept

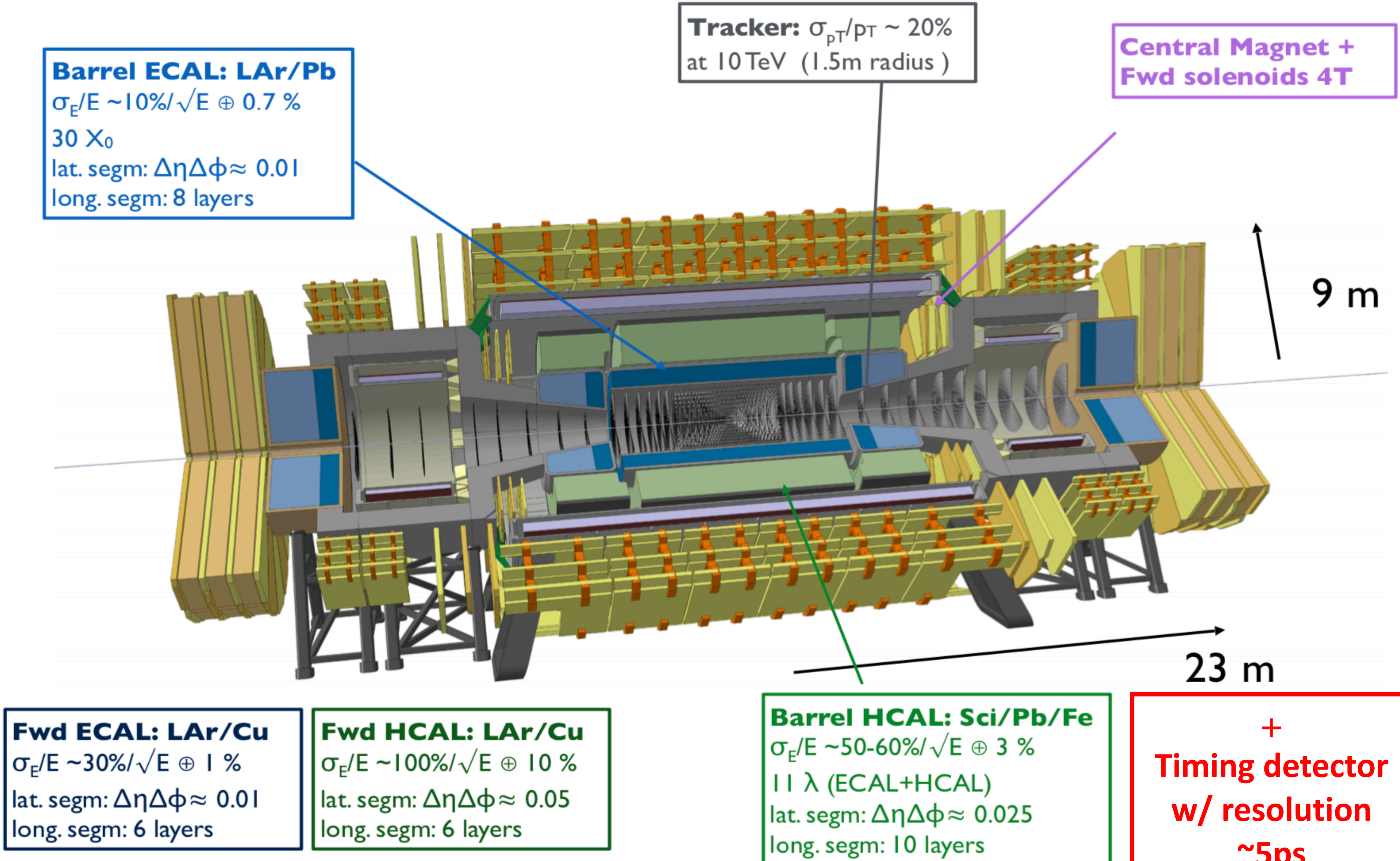



IDEA concept




Complementary approaches with lot's of important and innovative work
Details on concepts/challenges: J. List talk, M. Dams talk, G. Casse talk

# Detector concept: pp@100 TeV



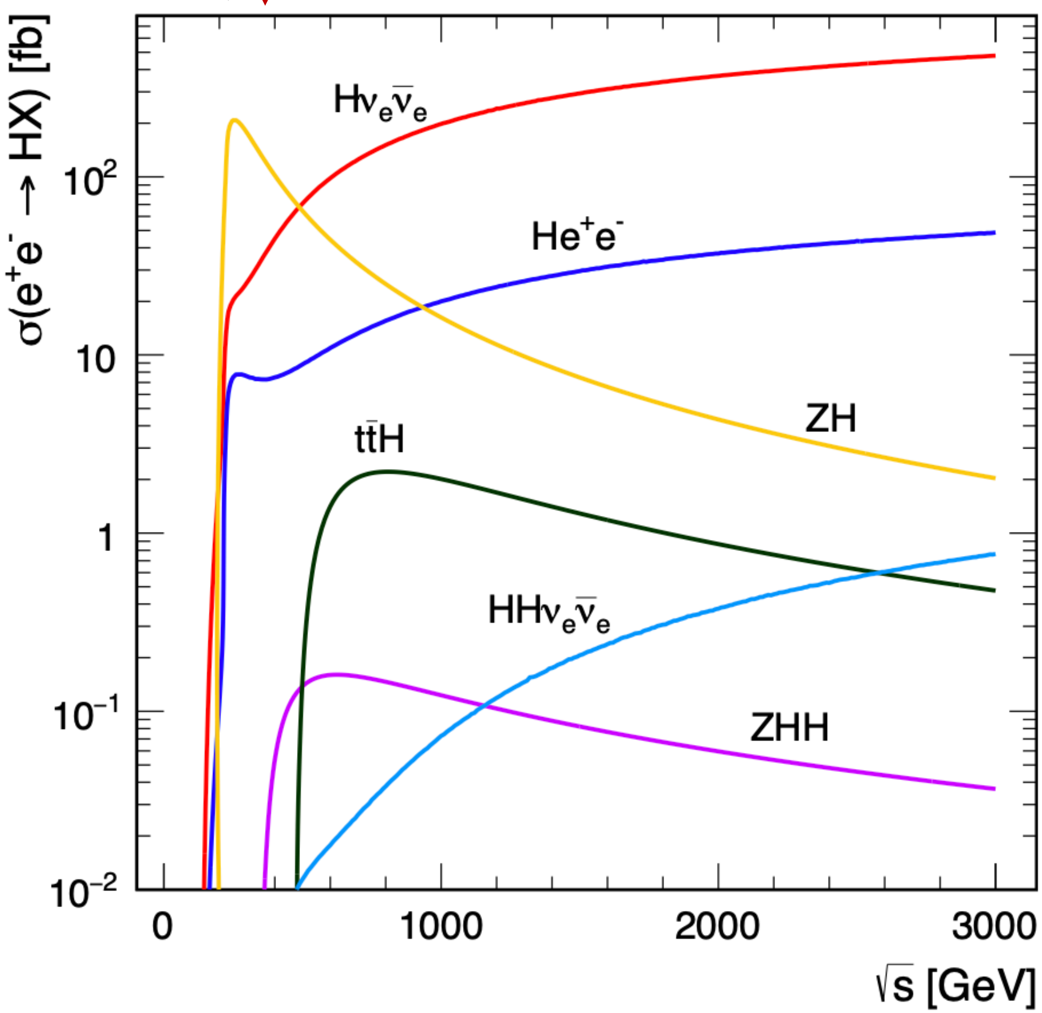

**+ Timing detector w/ resolution ~5ps**

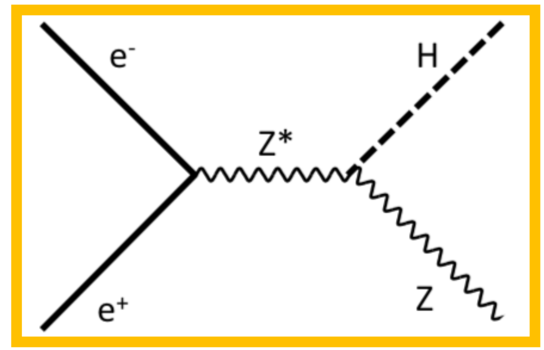
# Higgs as an exploration tool

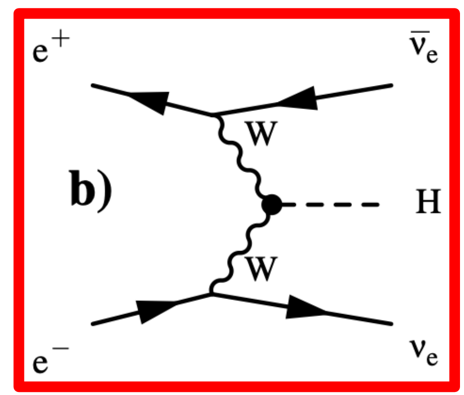
# Higgs production at $e^+e^-$

FCC/CepC/ILC:
$E_{CM}$@240 GeV

CLIC/ILC:
$E_{CM}$>350 GeV



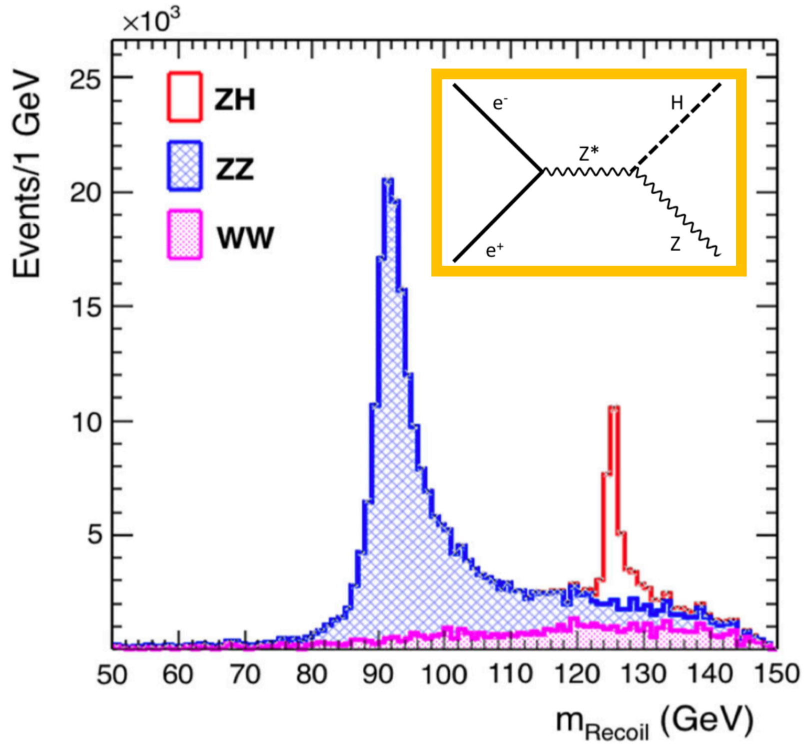



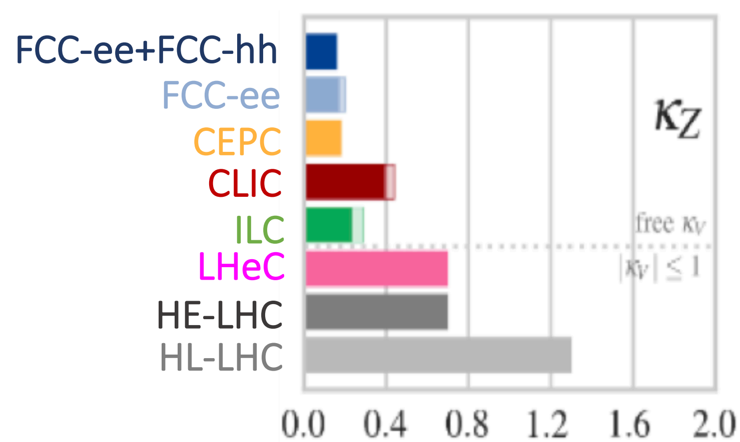
# Model-independent measurements

- ZH production in $e^+e^-$
  - Unbiased tagging of Higgs boson
    - via Z→LL, $m_{recoil}$, $E_{beam}$ constraints

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




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

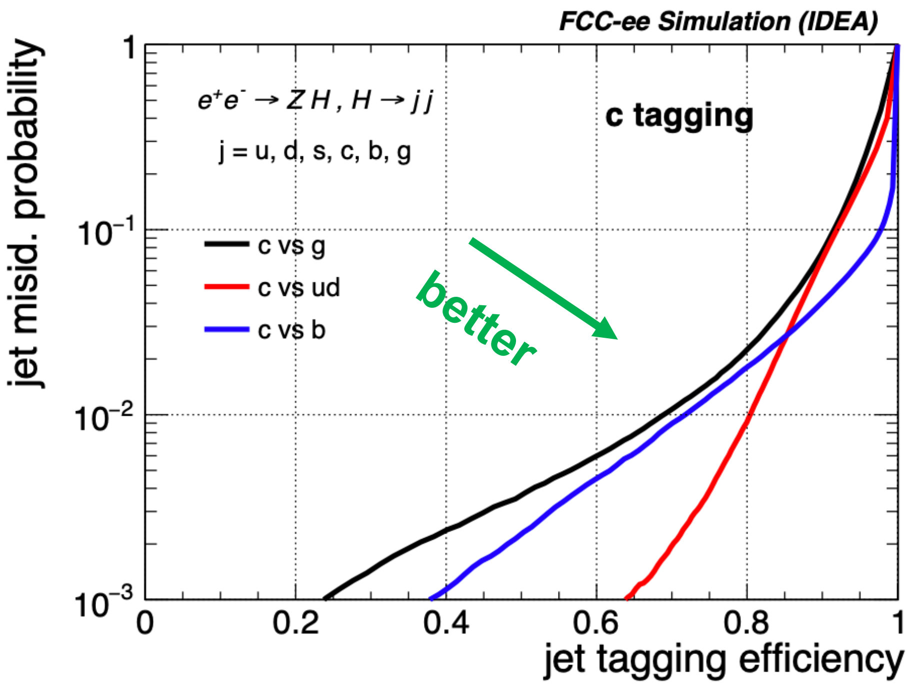



- Unique in $e^+e^-$ machines in ZH
- "standard candle" for other Higgs measurements (incl. FCC-hh)

# More on Higgs couplings

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

**Novel Deep Learning** based algorithms under development




NB: example from FCC-ee
Tools/techniques relevant for all $e^+e^-$ options

# More on Higgs couplings (II)

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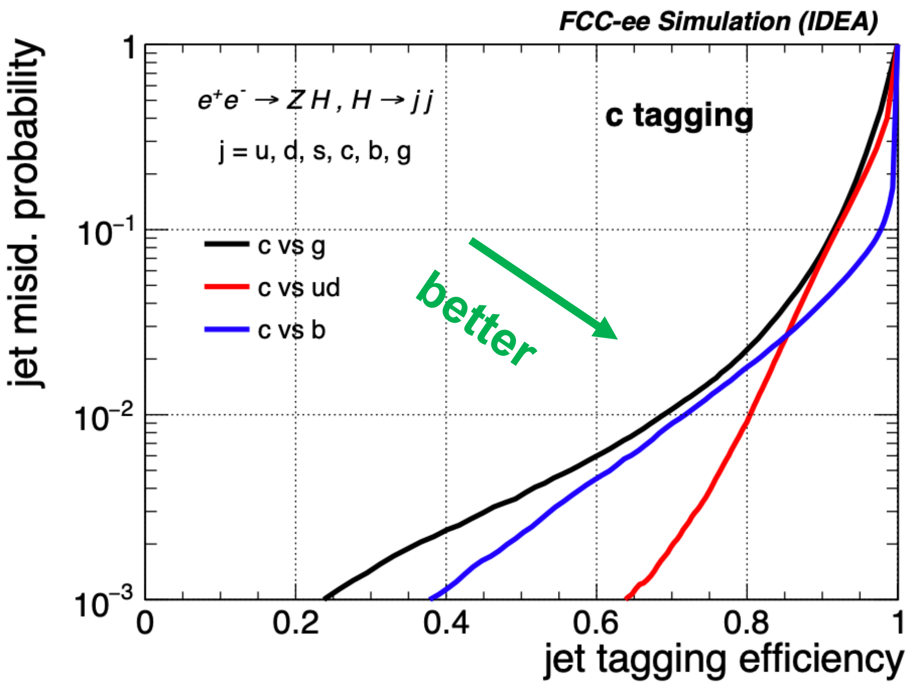


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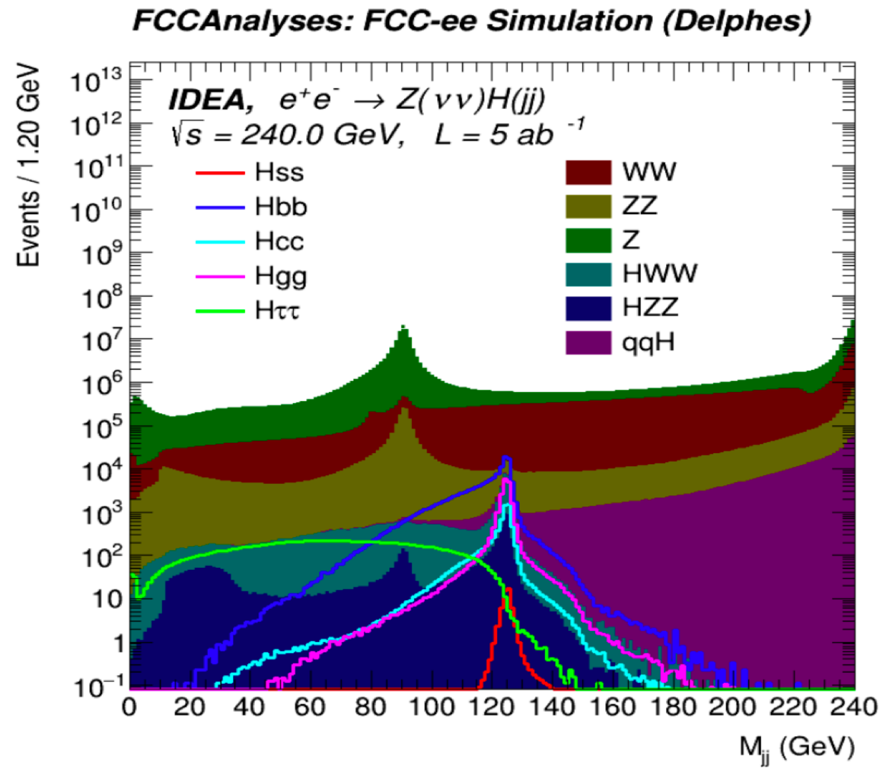
Signal extraction:
2D fit: $m_{rec}$ vs. $m_H$

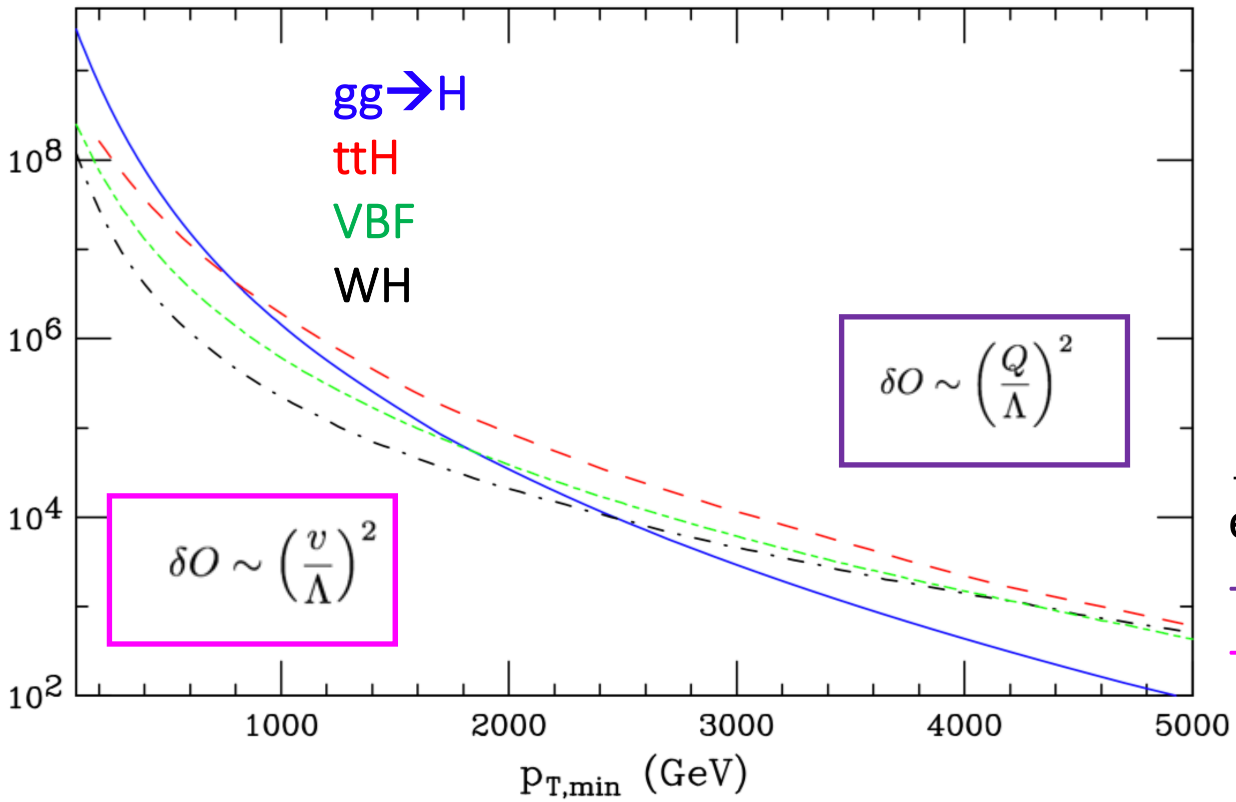



| Z(→νν)H(→qq) | bb | cc | ss | gg |
|---|---|---|---|---|
| δκ/κ (%) | 0.2 | 1.4 | 50 | 0.6 |

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

# Higgs couplings @ 100 TeV

- Higher collision energies [FCC-hh/SppC]:
  - Larger luminosity
    - Precise measurement of rare decays (e.g. μμ, Zγ)
    - sensitivity to forbidden channels (e.g. τμ)
  - Larger kinematic range /probe multi-TeV regime




- Typically improved S/B
- Heavy new particles running in the loops i.e. indirect probe of BSM

<u>precision vs. sensitivity</u>

e.g. Λ~10 TeV:

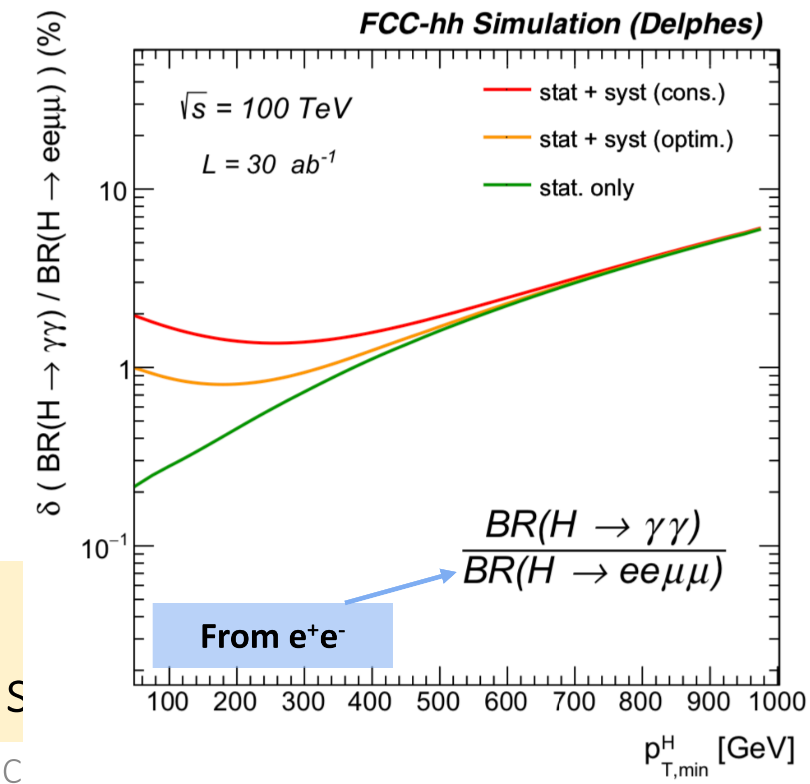
- δ~5% at $p_T$(H)> 2TeV
- δ<0.1% at low $p_T$(H)

# Higgs couplings @ 100 TeV

- General strategy:
  - e+e-: H-Z coupling at ~0.1%
  - pp@100TeV: 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

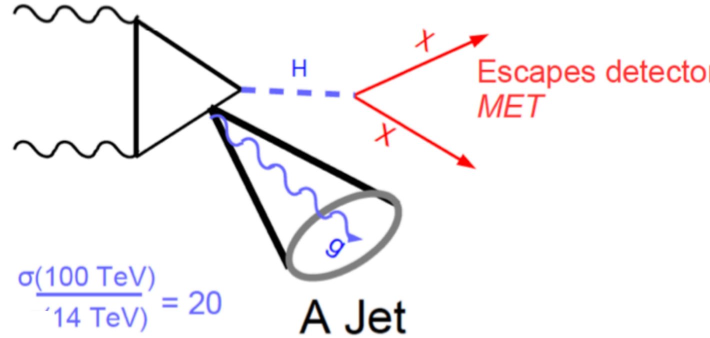
| Experiment | $\kappa_\gamma$ [%] | $\kappa_\mu$ [%] |
|---|---|---|
| HL-LHC | 1.5 | 4.5 |
| ILC/CLIC/FCC-ee | 1.0 | 3.5 |
| FCC-ee+FCC-hh | 0.2 | 0.5 |

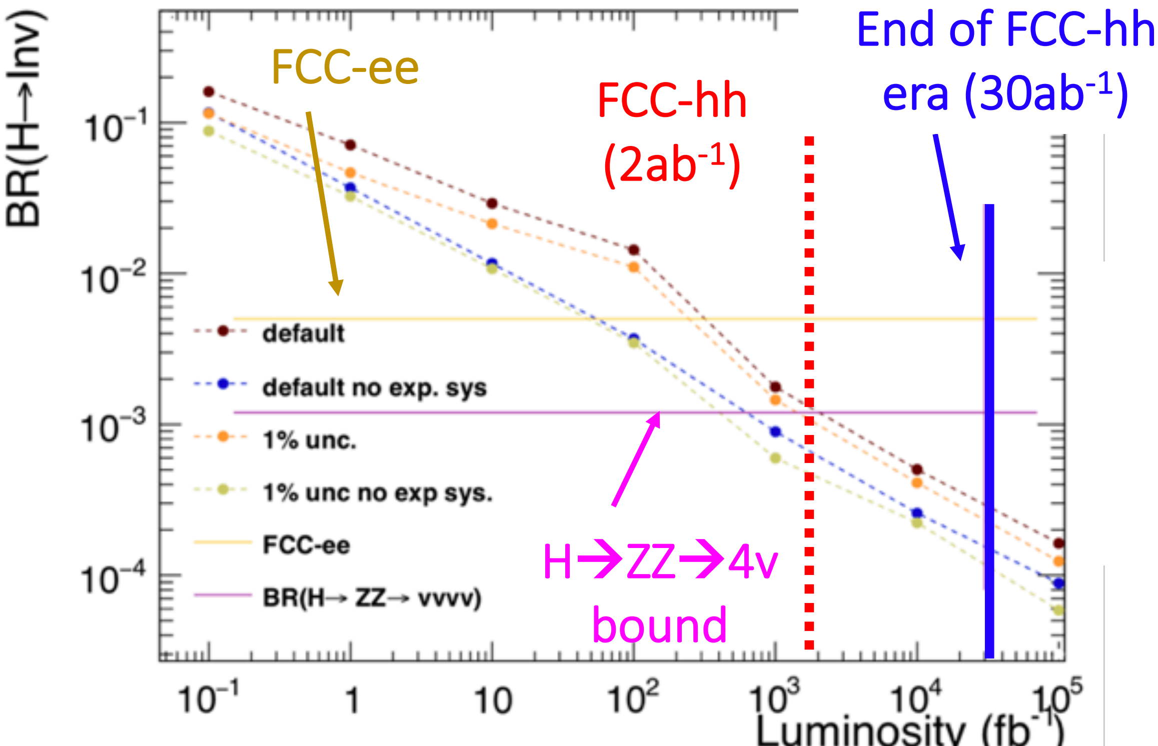



**Synergy** and **complementarity**
b/w **e$^+$e$^-$** and **pp@100TeV** programs

# Higgs→invisible

- Portal to Dark Matter (DM)
  - DM only via Higgs decays (?)



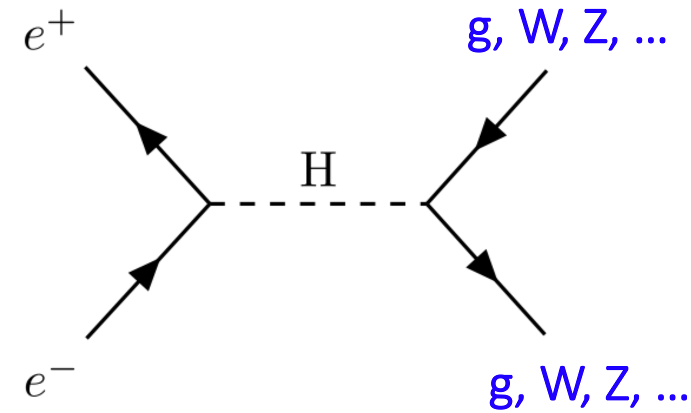




Key: control EXP and TH uncertainties

- $e^+e^-$: O(10) improvement wrt HL-LHC, but cannot reach nu-bound…
- **pp@100TeV:** Reach neutrino bound within only 2yrs!

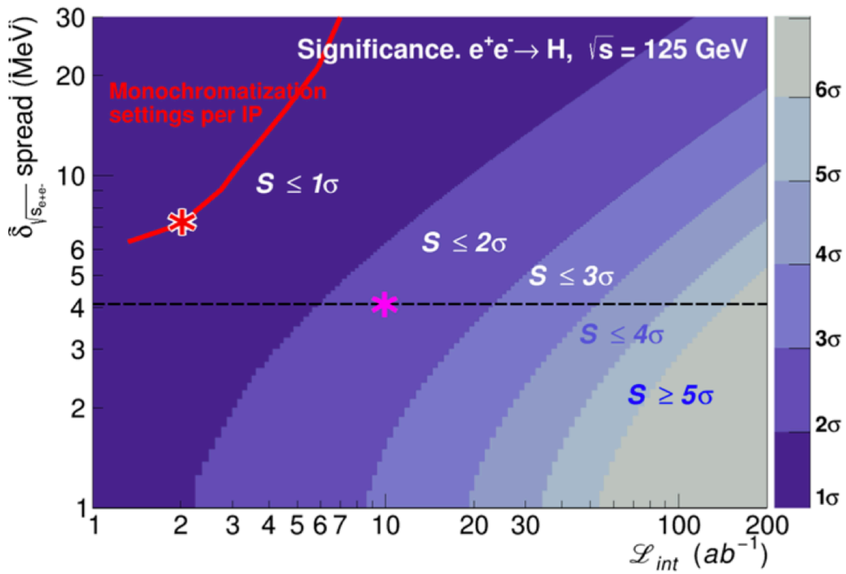
# Unique at FCC-ee: H→ee

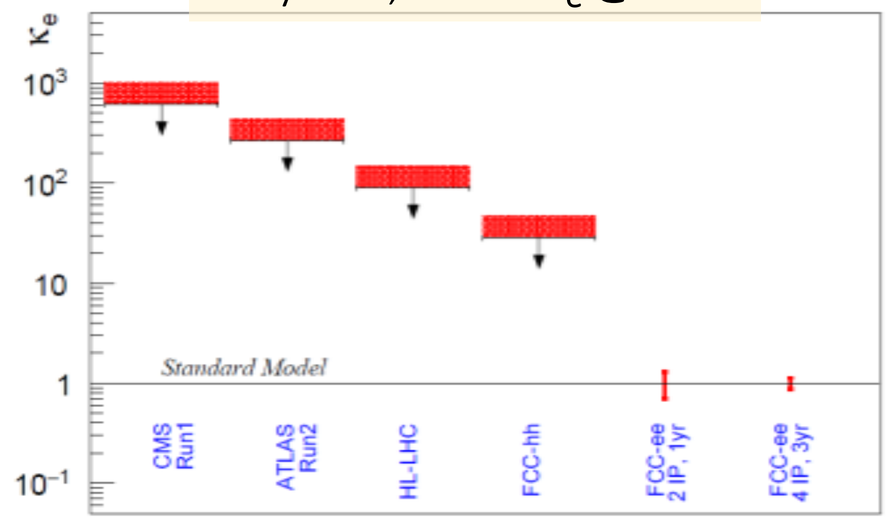
- Extremely challenging: BR(H→ee) ~$10^{-9}$
- FCC-ee: Resonant Higgs production
  - tiny signal (1.64 fb) vs. huge BKGs
  - but: huge luminosity at FCC-ee
    - 20 $ab^{-1}$/year/IP → 30K Higgs



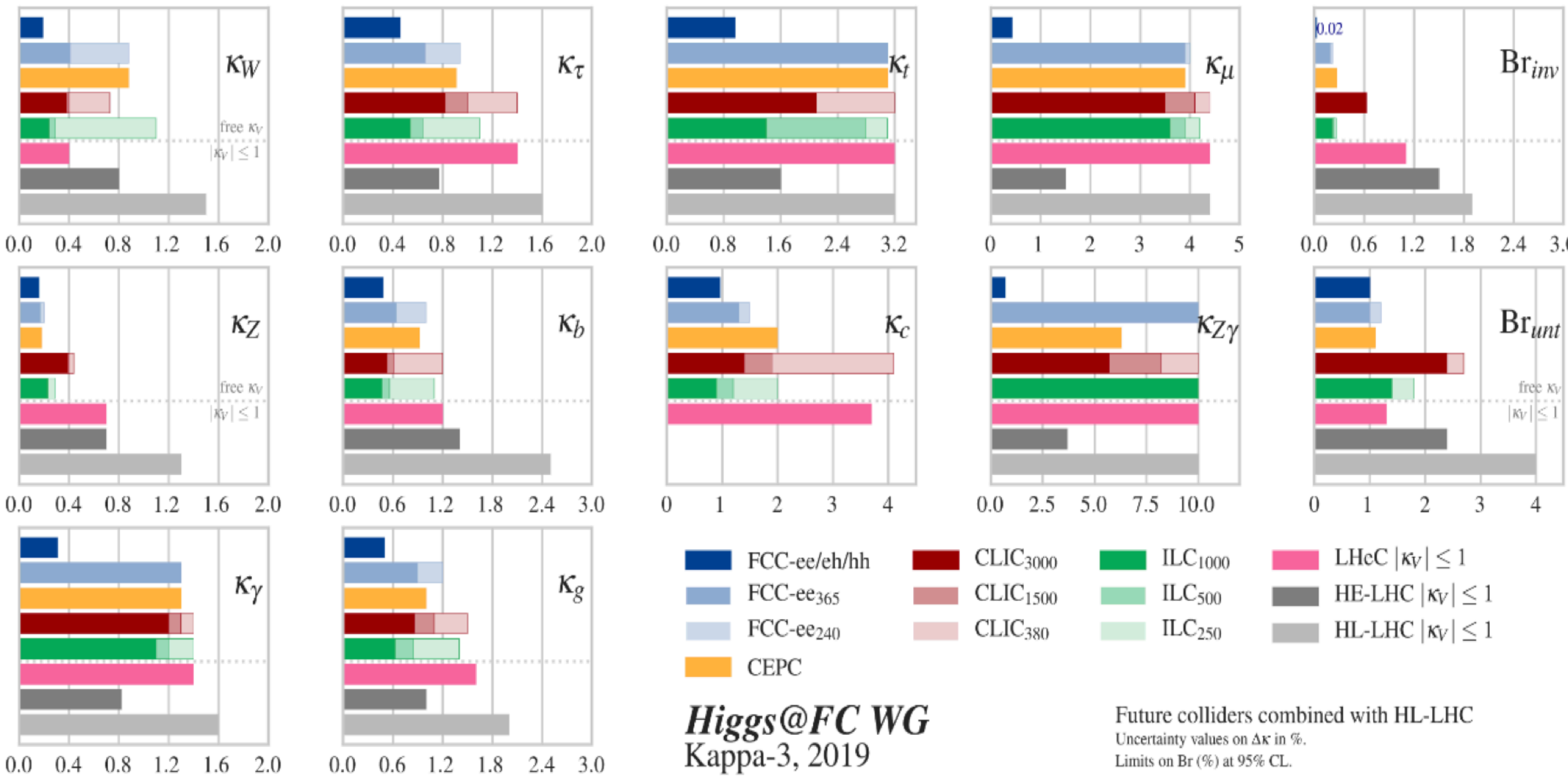

- Key points:
  - Beam spread (~MeV) → monochromatization
  - Precise $m_H$ → from ZH run

- 1 year, 2 IPS: **2σ**
- 3 years, 4 IPS: **$\kappa_e$ @15%**



# Single-Higgs: Grand summary

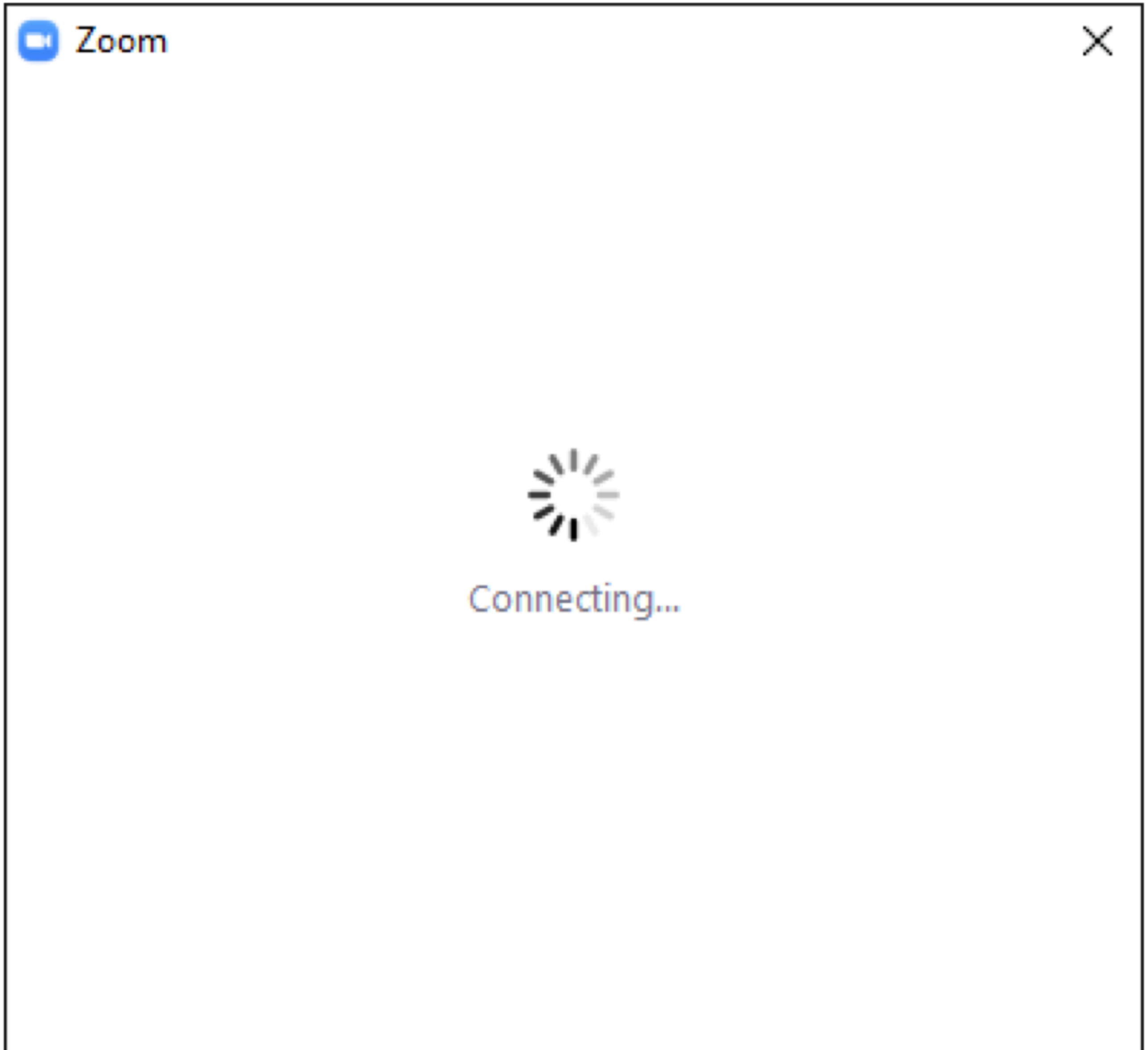



- O(10) improvement compared to HL-LHC
- $e^+e^-$: Higgs-Z/W and H→inv at $10^{-3}$
- $e^+e^-$ + pp@100 TeV: all coupling better than 1%

Teaser:

Higgs-neutrino couplings

A. Blondel's talk

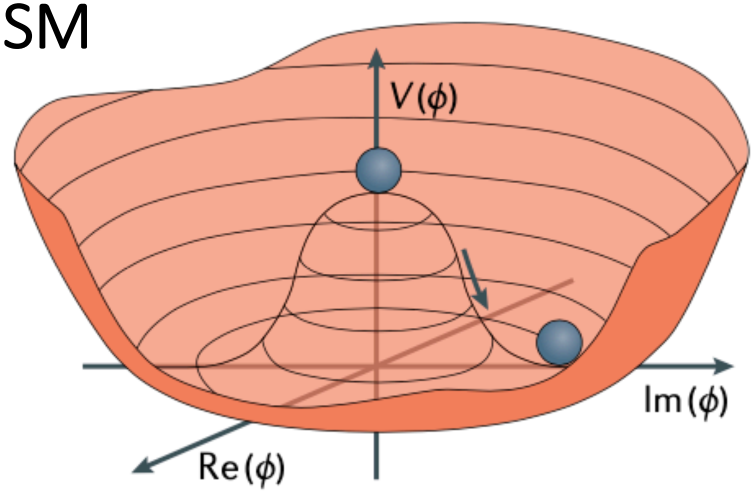

Zoom
Connecting...

# Higgs-self coupling

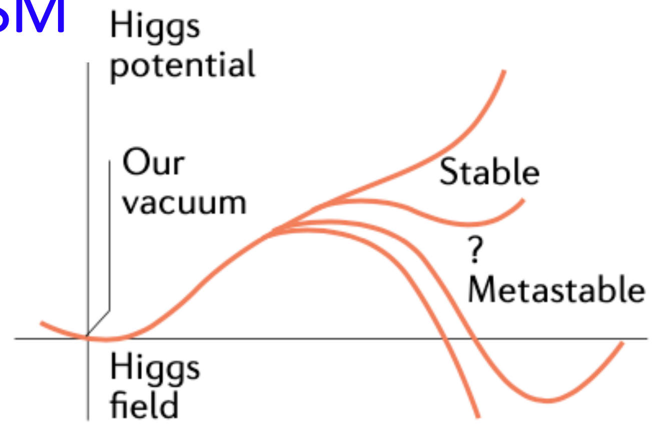
# The nature of Higgs potential

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

SM

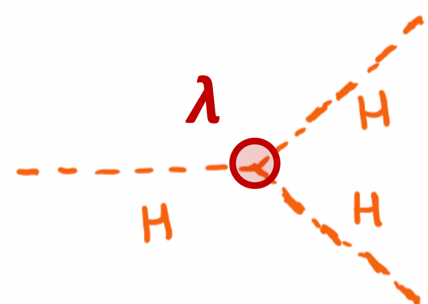



BSM



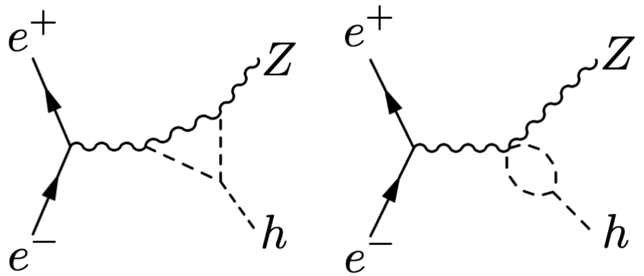

$$V(h) = \frac{1}{2}M_H^2 H^2 + \frac{1}{3!}\sqrt{3\lambda_H} M_H H^3 + \frac{1}{4!}\lambda_H H^4$$

Higgs mass — Shape of potential

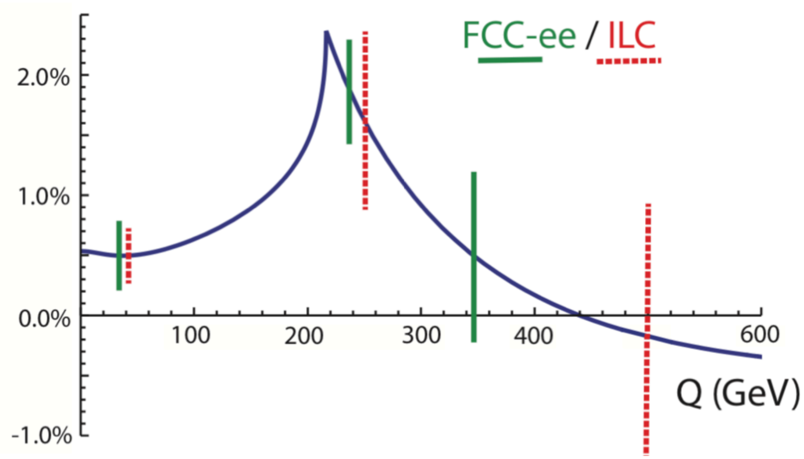


# Higgs-self coupling at $e^+e^-$

- FCC-ee/CepC: via loops Ref

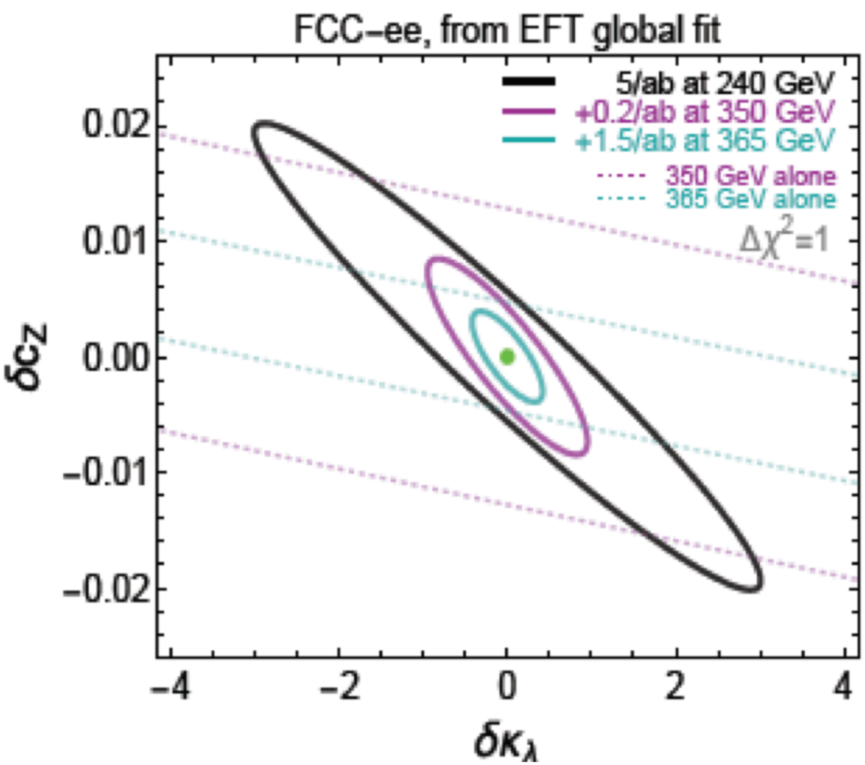



Relative enhancement of ZH production



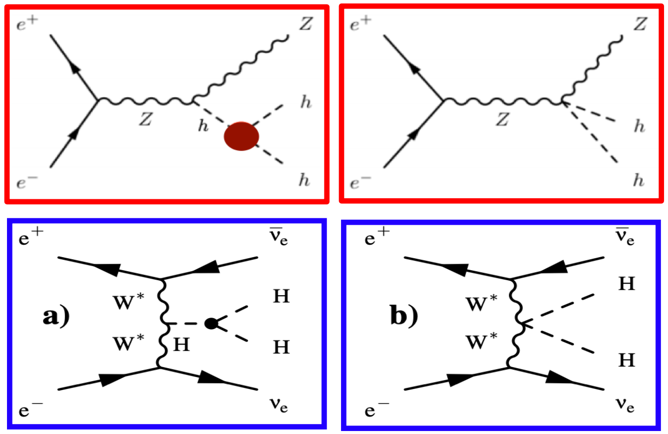

- Needs several collision energies

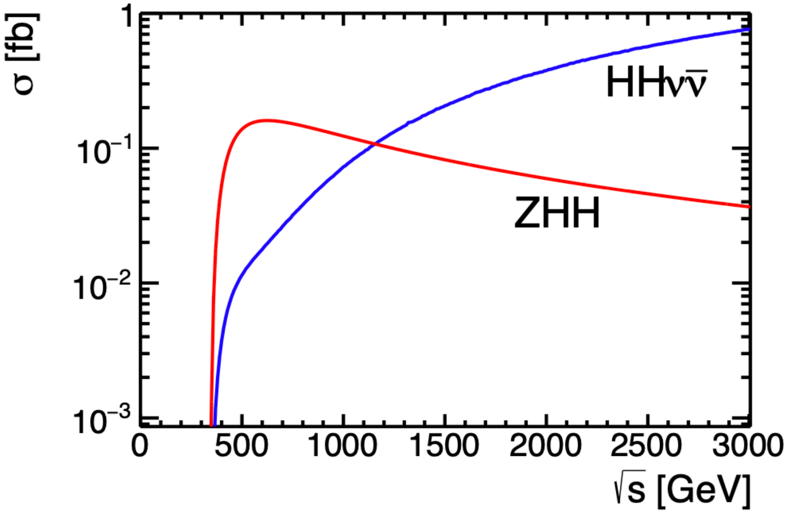
O(10-20%) precision on self-coupling [other couplings at SM-values]



# Higgs-self coupling at $e^+e^-$

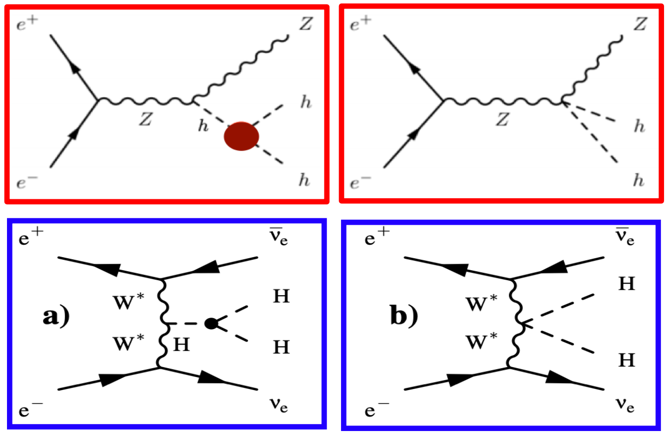
- Direct access [$E_{CM}$>500GeV]: ILC/CLIC

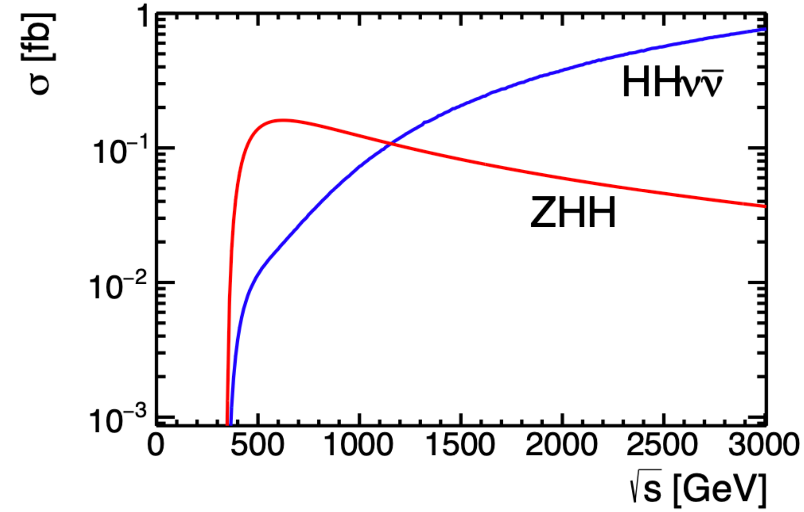


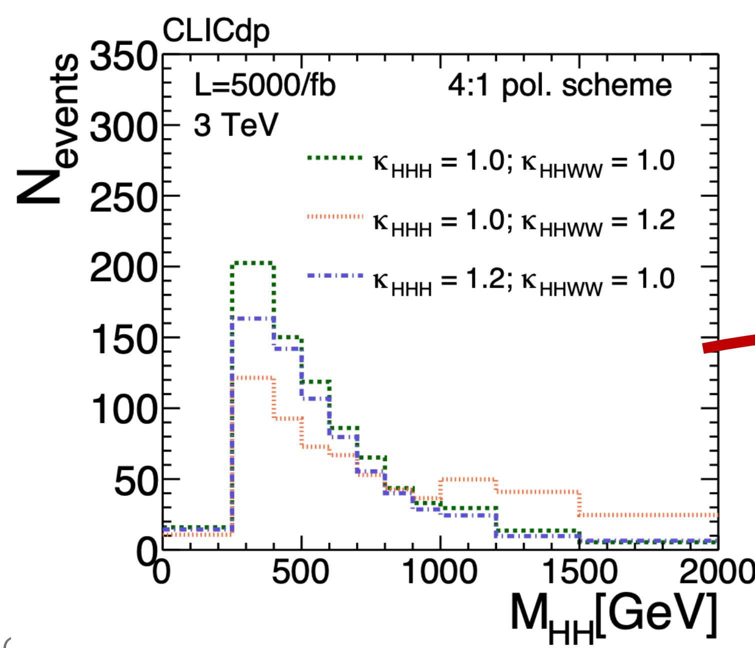
# Higgs-self coupling at $e^+e^-$

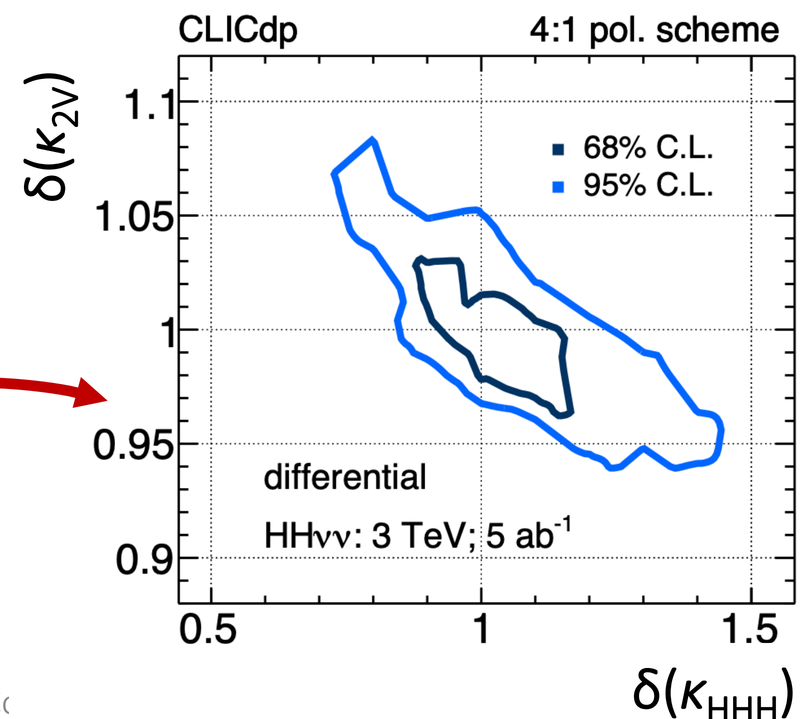
- Direct access [$E_{CM}$>500GeV]: ILC/CLIC



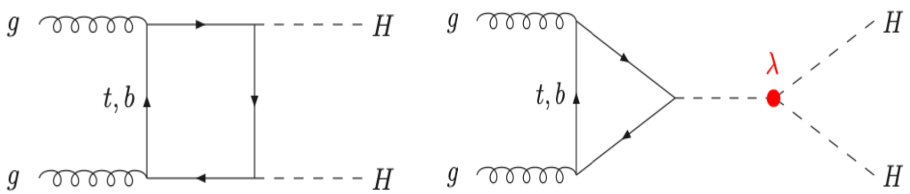

- Use $m_{HH}$ to disentangle HHH/HHVV

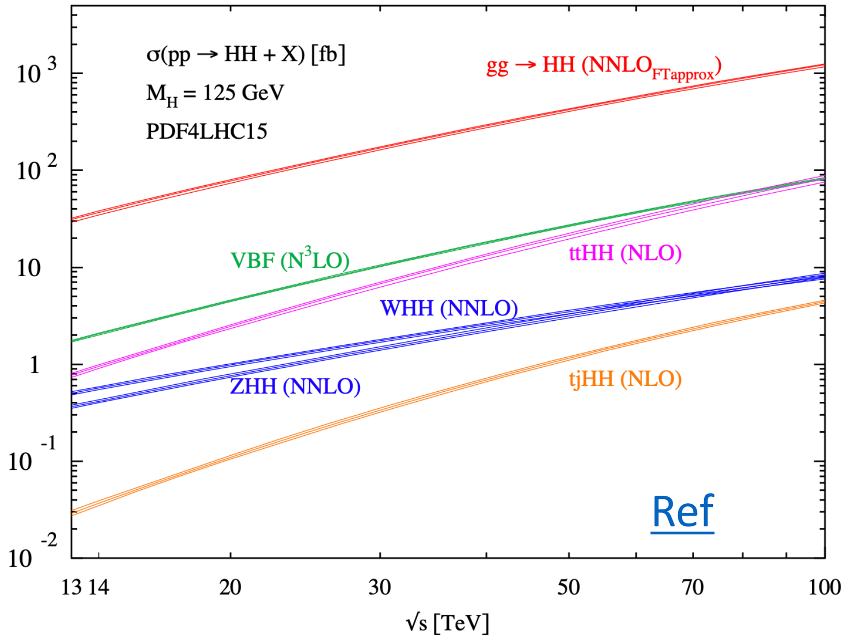


# pp@100 TeV: The "HH machine"

- Main production modes:




- O(50x) higher than (HL-) LHC
- O(1000x) higher than $e^+e^-$ @1.5 TeV [but harsher conditions]

# pp@100 TeV: The "HH machine"

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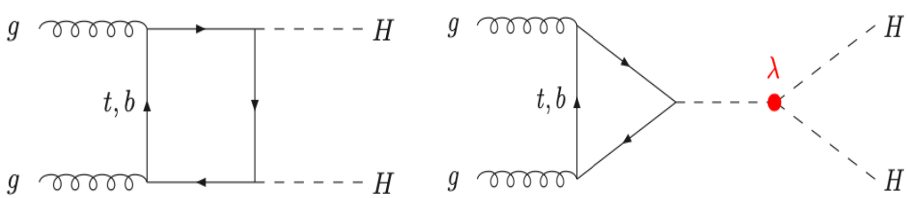
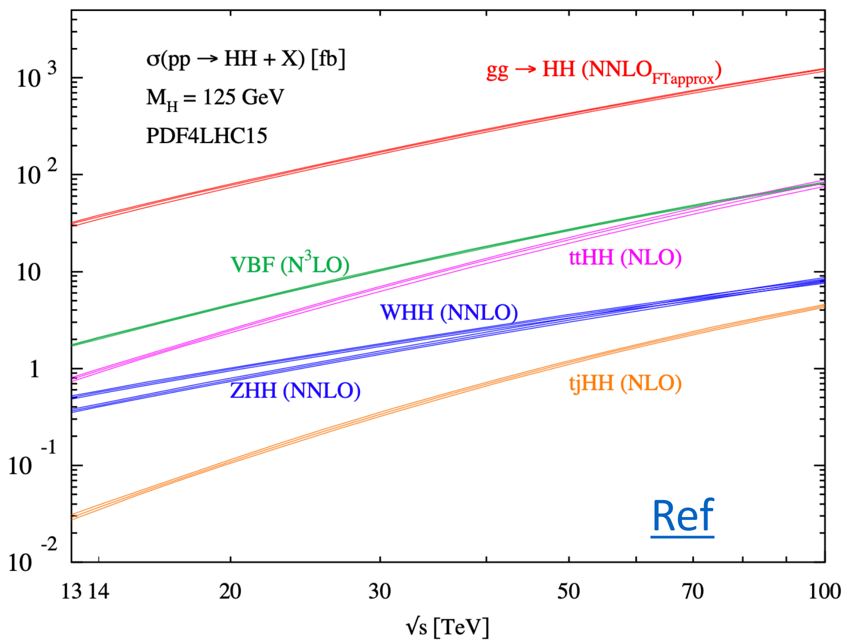
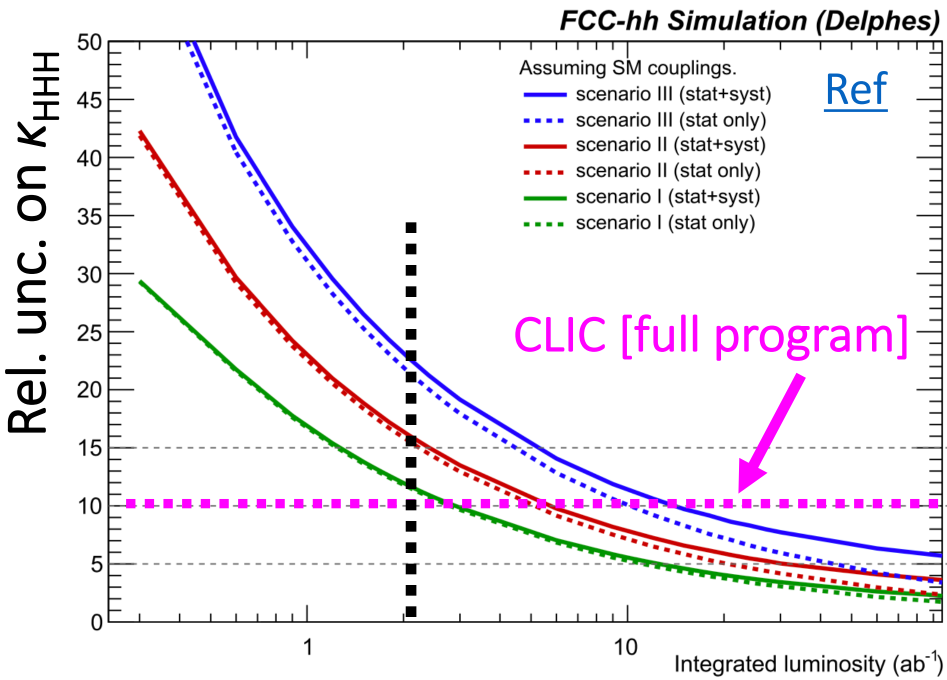


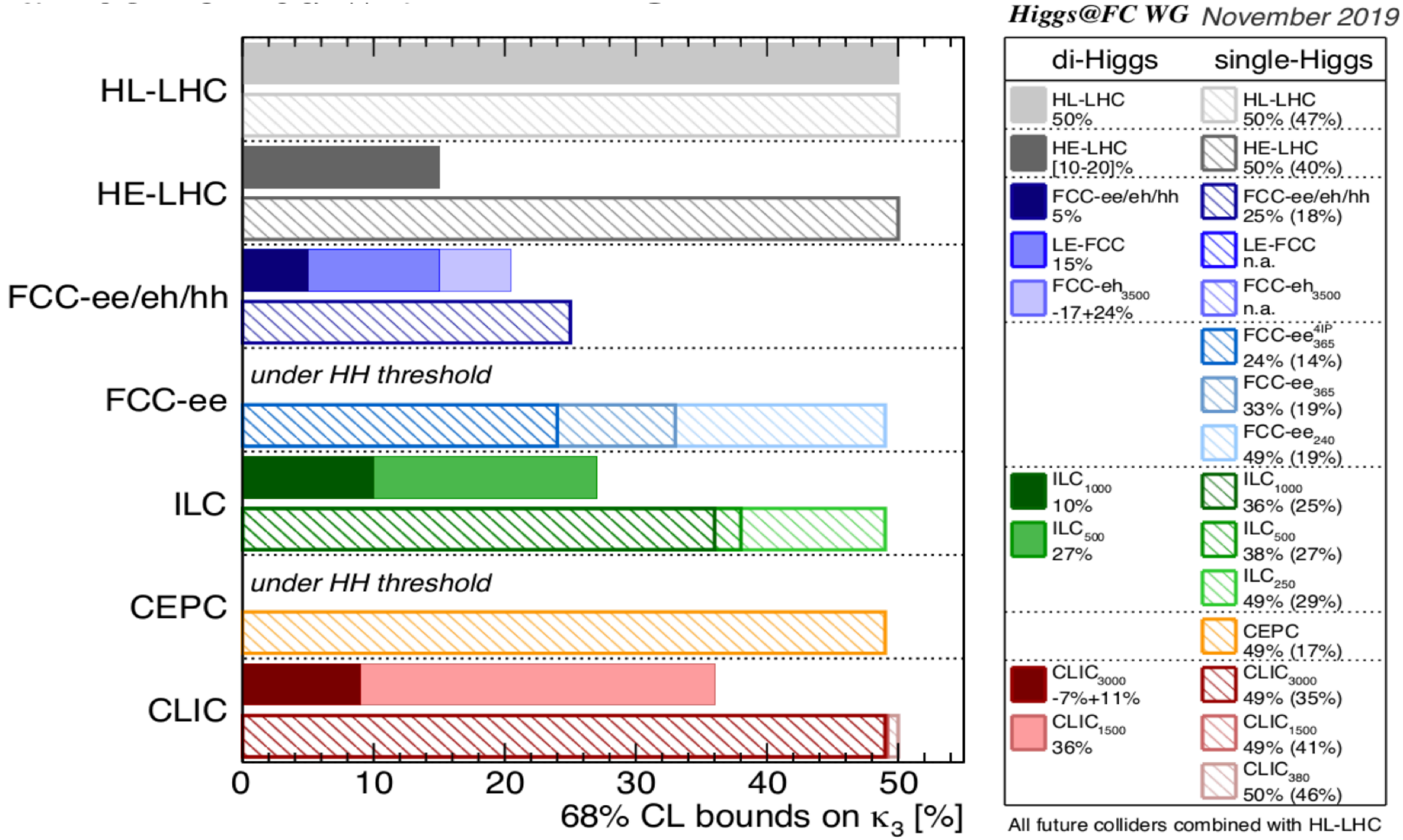

- Driving channel: bbγγ
  - bbττ, bbbb channels also analyzed




- O(50x) higher than (HL-) LHC
- O(1000x) higher than $e^+e^-$ @1.5 TeV [but harsher conditions]

- 5% at the end of FCC-hh program
- Reach CLIC sensitivity in O(2yrs)

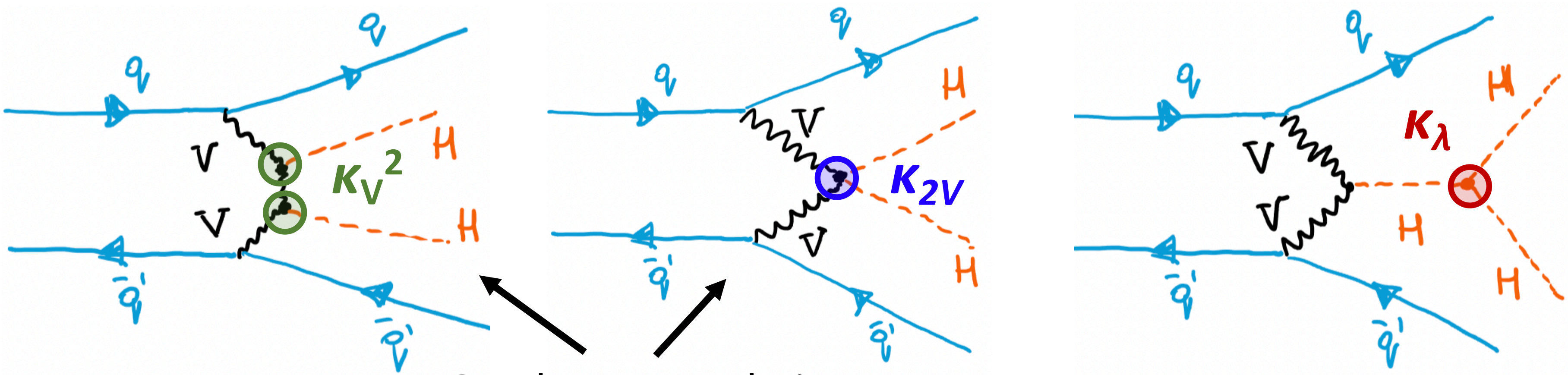
# Higgs-self coupling: Grand summary



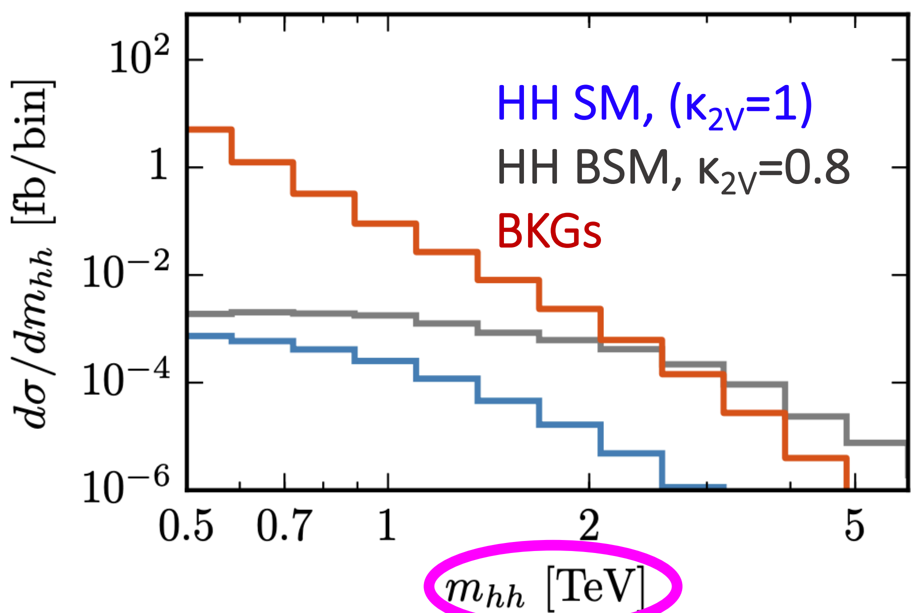

- **HL-LHC:** Confirm the existence of Higgs-self coupling @ 95% CL [if exists]
- **FCC-ee:** achieve <20% uncertainty via single-H measurements
- **CLIC/ILC:** observe HH interaction [5σ →20% uncertainty]
- **FCC Full program:** 5% unc. [start probing quantum corrections on H potential]

# En route to Higgs self coupling

- Very rare: but direct sensitivity to VVHH ($\kappa_{2V}$) coupling




**SM:** large cancelation

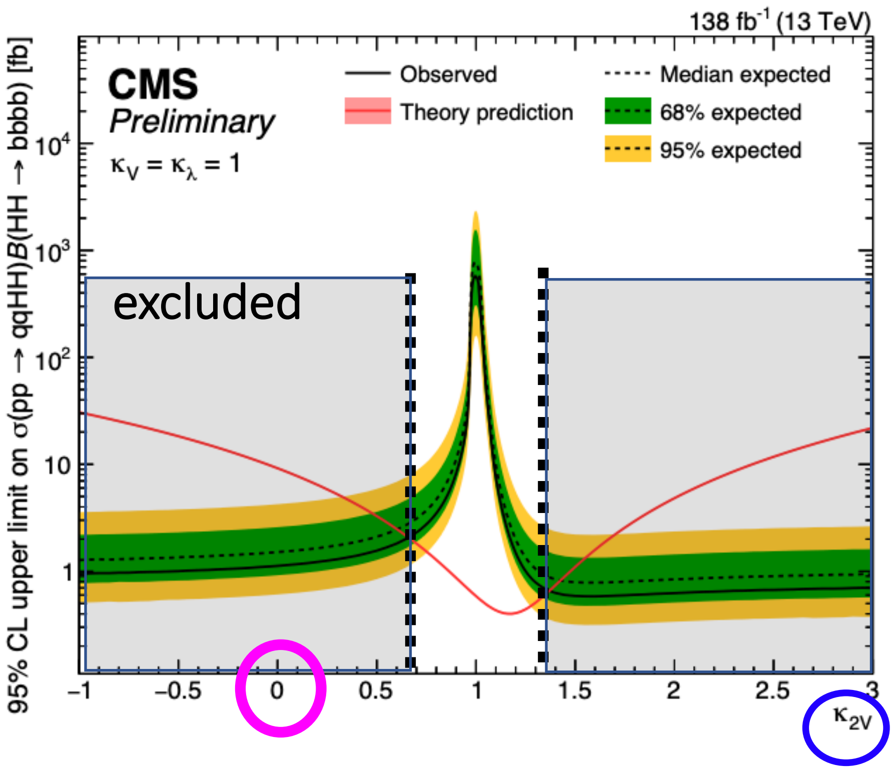



Powerful probe of BSM

- BSM: striking effect on $m_{HH}$
- **Signature:** high $p_T$ Higgs bosons

# En route to Higgs self coupling (II)

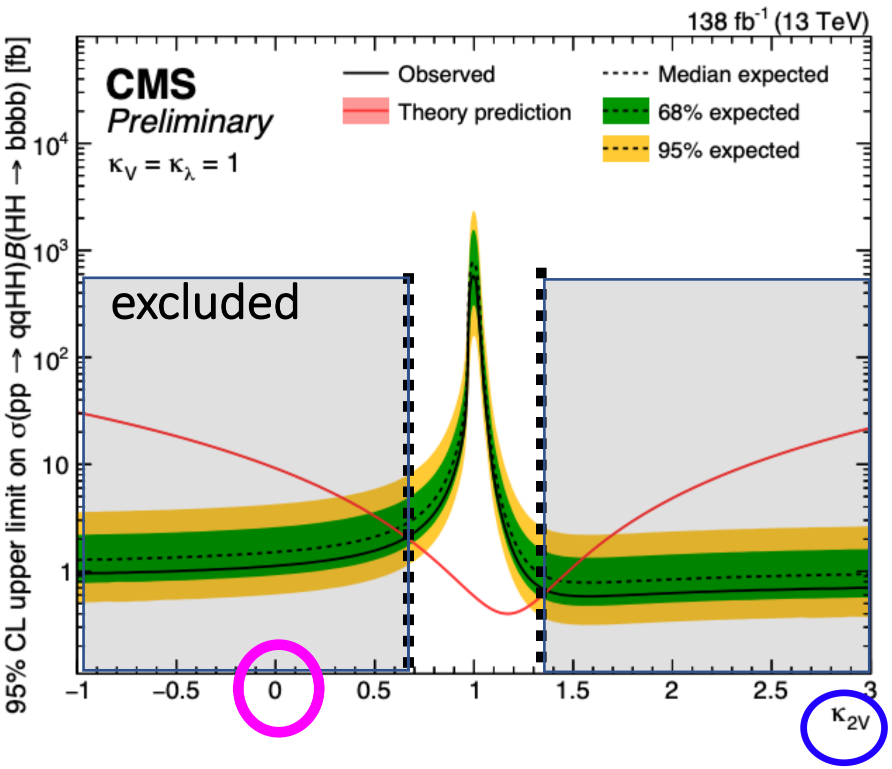
LHC Run 2




$\kappa_{2V}$=0 excluded by > 6σ
→ 1st confirmation of HH-VV coupling

# En route to Higgs self coupling (III)

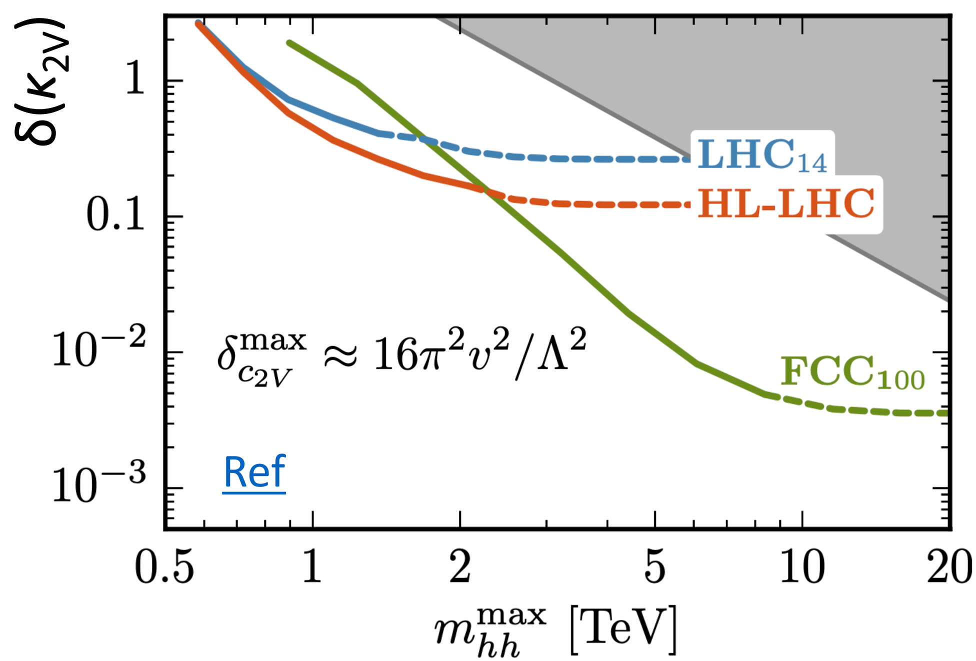
**LHC Run 2**




$\kappa_{2V}$=0 excluded by > 6σ
→ 1st confirmation of HH-VV coupling

**FCC full program**

- Strategy: HH→4b (large BR)
  - Large $p_T(H)$; jet-substructure
  - Fit $m_{HH}$ spectrum



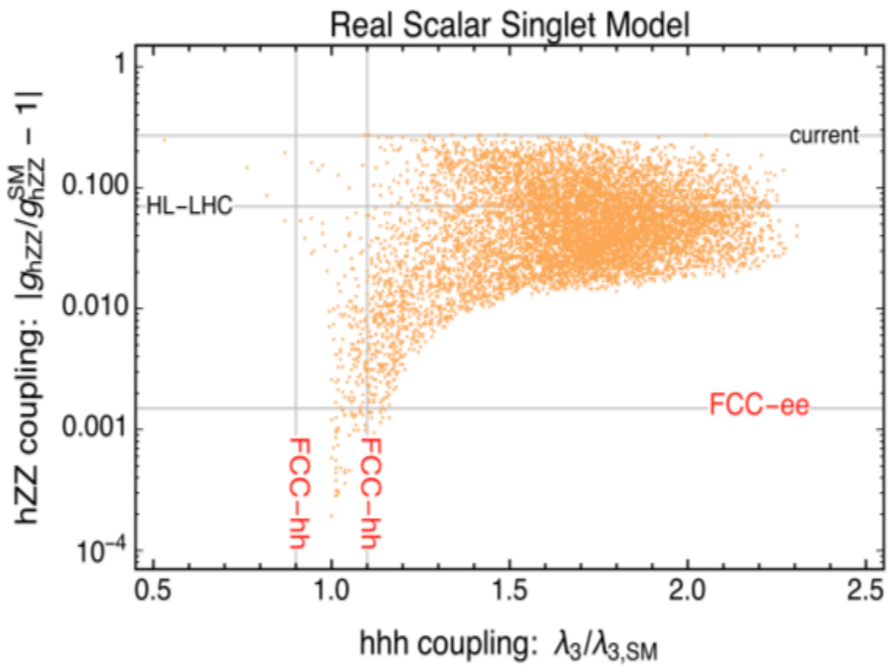

- Input from $e^+e^-$ : $\kappa_V$~0.1%]
- Then: pp@100TeV $\delta(\kappa_{2V})$ < 1%

# Matter-antimatter asymmetry

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

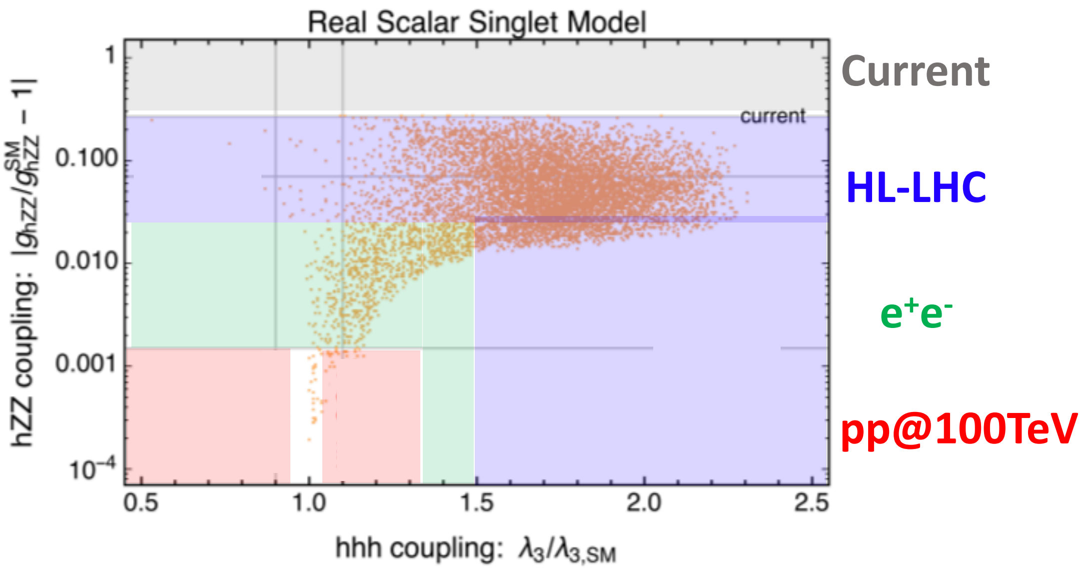
- Cannot be accommodated by SM
  - needs new particle(s) with O(TeV) mass

- 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 n Higgs-Z coupling
  $e^+e^-$ @ 0.1% level
- Modification on Higgs self-coupling
  pp@100TeV: Direct probe
  $e^+e^-$: Indirect (global fit on single-H)

**Synergy between $e^+e^-$ and pp colliders:**

- cover almost the entire parameter space

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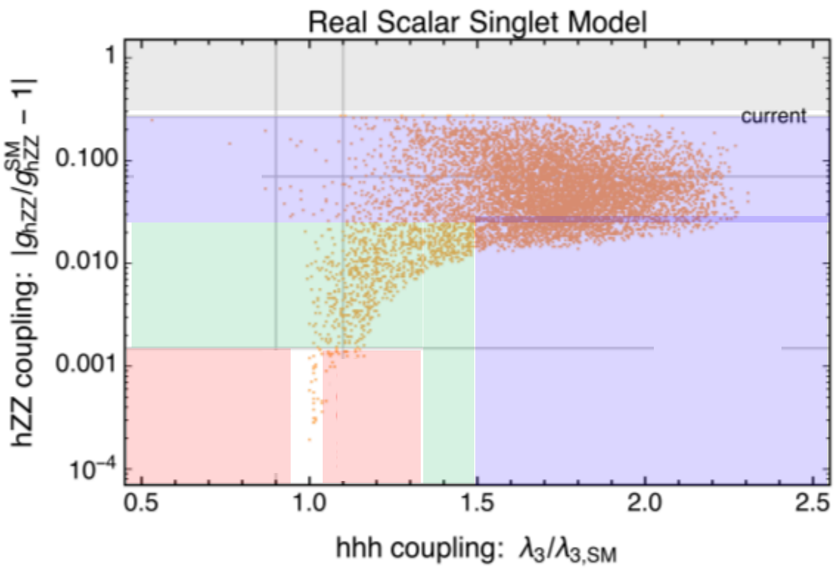
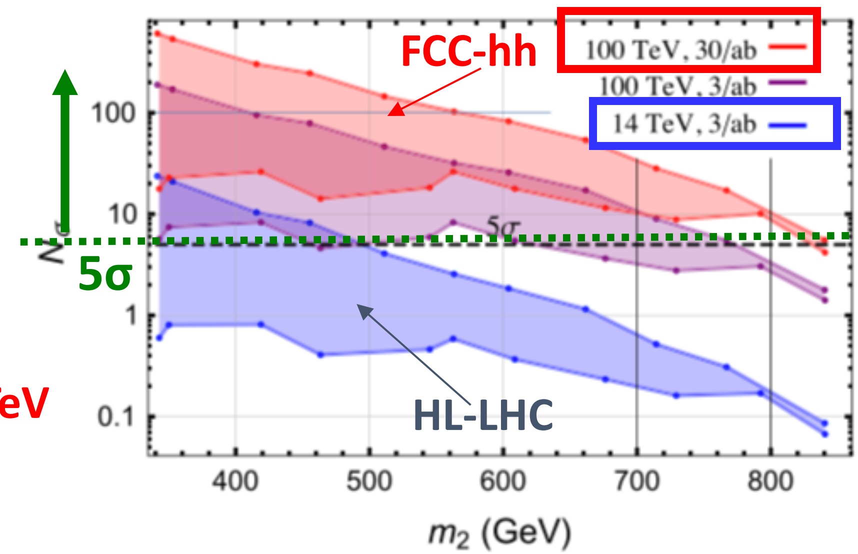
Deviation from SM Higgs couplings




Discovery potential in resonant Di-Higgs searches




- **Modification n Higgs-Z coupling**
  $e^+e^-$ @ 0.1% level
- **Modification on Higgs self-coupling**
  pp@100TeV: Direct probe
  $e^+e^-$: Indirect (global fit on single-H)

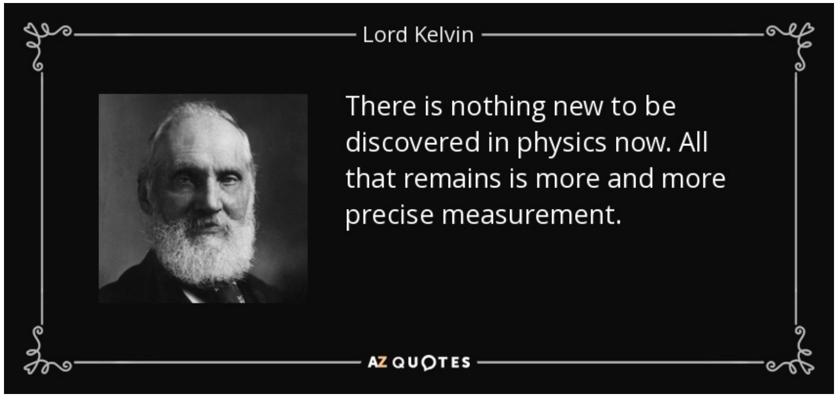
- **pp@100TeV discovery potential** over the entire viable parameter space
- Very limited discovery potential @HL-LHC
- **Obviously:** powerful to other models w/ non-resonant production of scalars

**Synergy between $e^+e^-$ and pp colliders:**
- cover almost the entire parameter space
- Provide definite answers to fundamental questions

# Summary and outlook

# Summary and outlook

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




.. and we all know what followed after this statement

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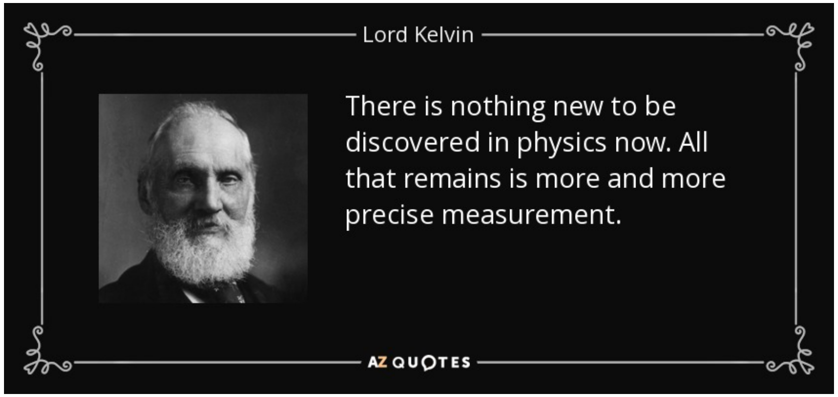


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- We need new accelerators… Which one?
  - Improved precision: H- couplings O(1%) or better → $e^+e^-$
  - Higher collision energies: Higgs self-coupling O(few %) → pp@O(100 TeV)
  - **But also:** complementarity, cost, completion time, …

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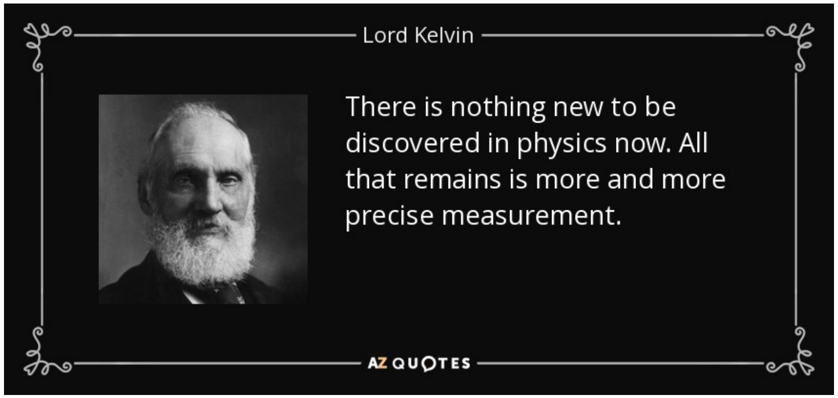


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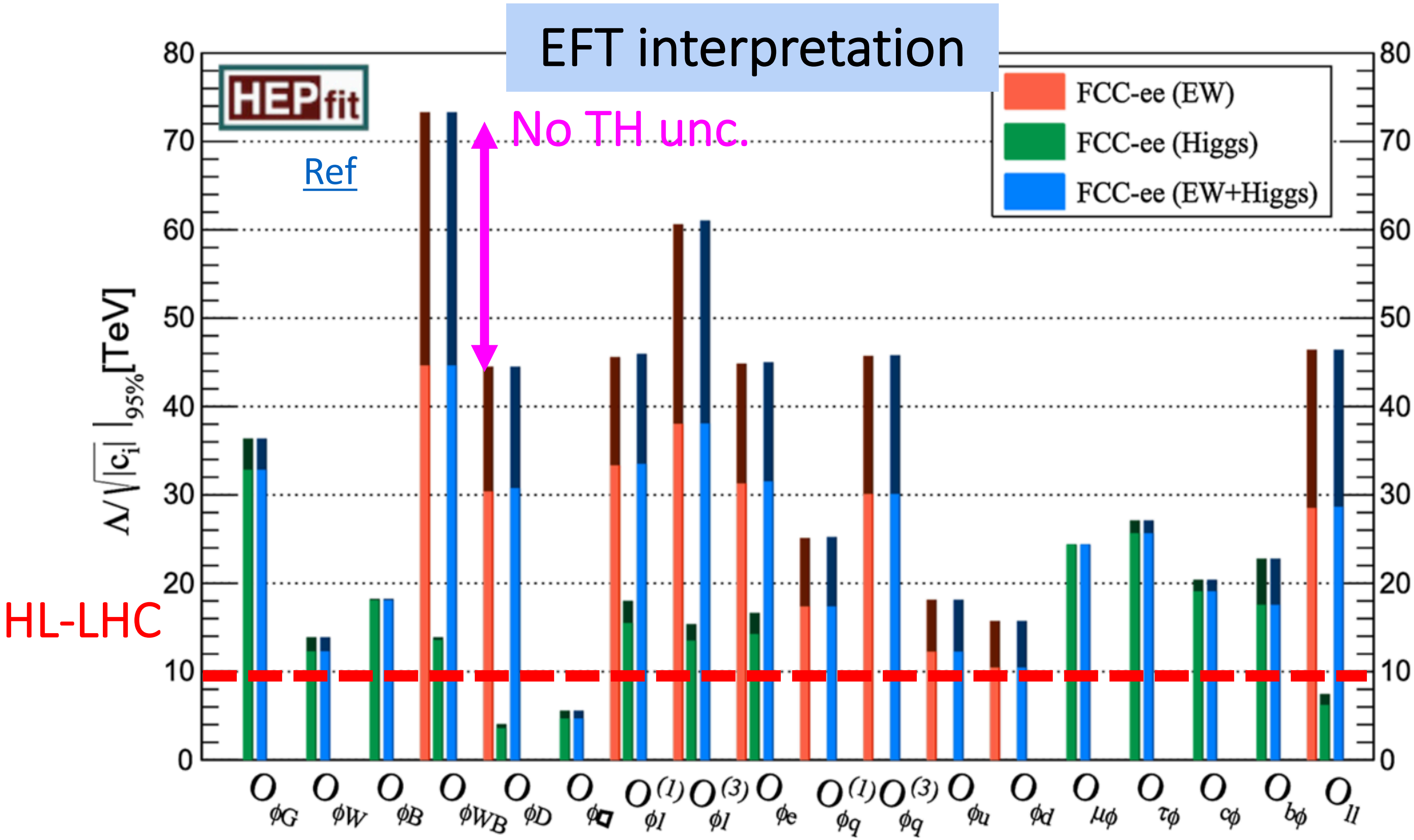
- We need new accelerators… Which one?
  - Improved precision: H- couplings O(1%) or better → $e^+e^-$
  - Higher collision energies: Higgs self-coupling O(few %) → pp@O(100 TeV)
  - **But also:** complementarity, cost, completion time, …
- Focus: Feasibility studies → to make it a reality
  - **Ideally:** 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

# Low $E_{CM}$ $e^+e^-$: Pave the way to 100 TeV

- e.g.: FCC-ee: Precise measurement of Higgs [and EWK] parameters

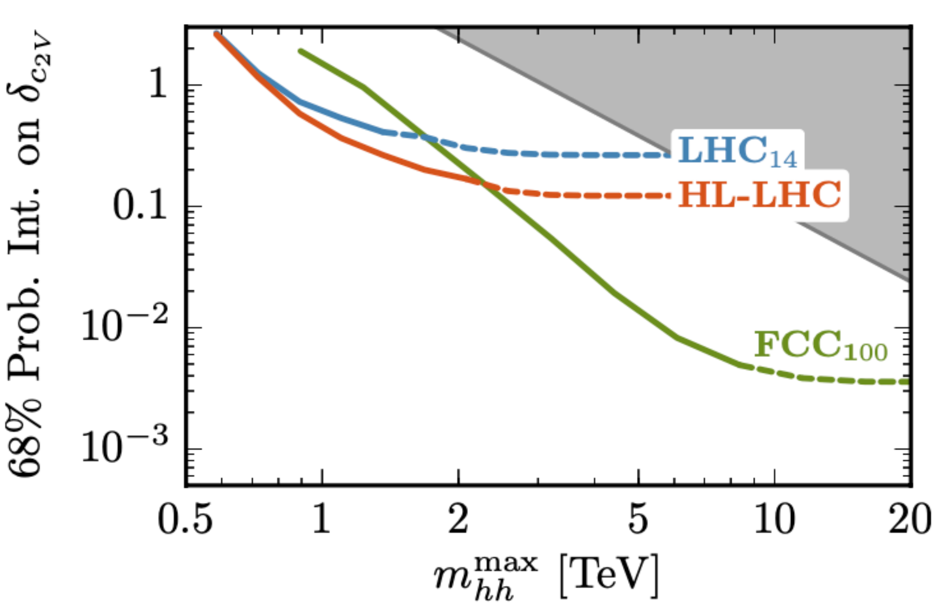



→ **Complementarity** b/w EW and Higgs programs

→ **$e^+e^-$ reach**: Λ ~50-70 TeV [key: control TH and syst uncertainties]

# En route to Higgs self coupling

$$\delta_{c_{2V}}^{\max} \approx 16\pi^2 v^2/\Lambda^2$$



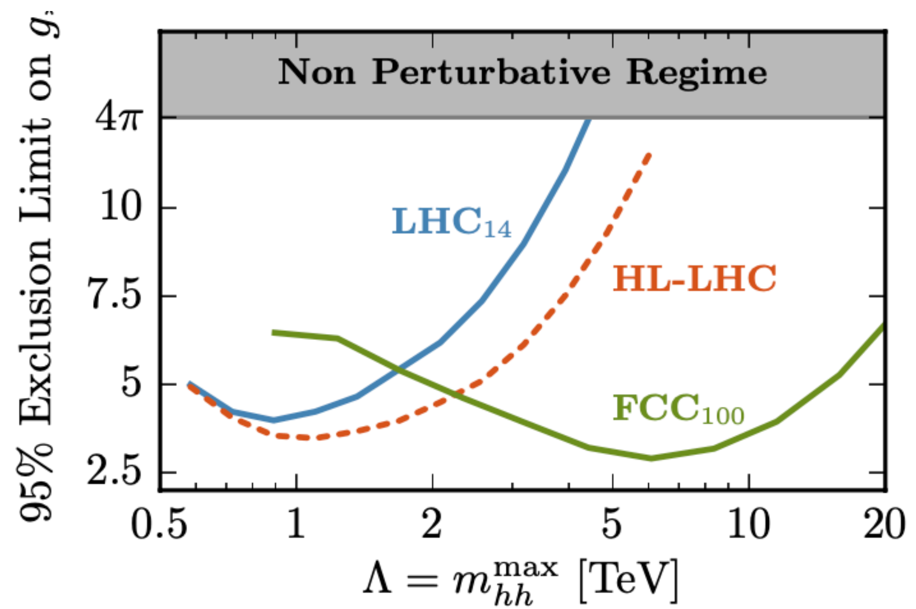



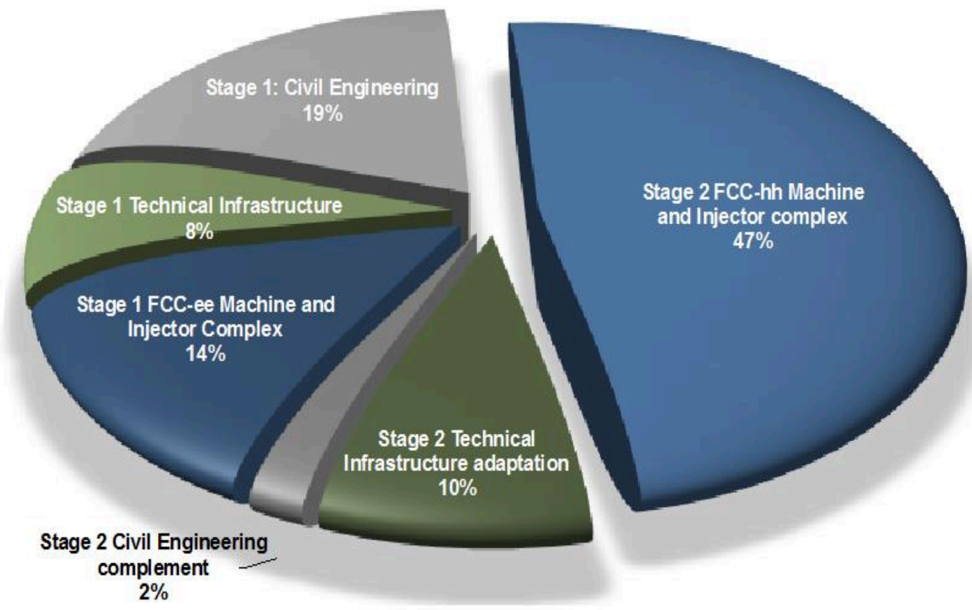

**Table 3** Summary of the sources of systematic uncertainties in the 3 scenarios. The last column indicates the processes that are affected by the corresponding source of uncertainty. For each given object (b-jet, $\tau$-jet, $\gamma$, lepton), the quoted uncertainty on reconstruction and identification efficiency is applied as many times as the object appears in the final-state

| Uncertainty source | Scenario I (%) | Scenario II (%) | Scenario III (%) | Processes |
|---|---|---|---|---|
| b-jet ID eff. /b-jet | 0.5 | 1 | 2 | Single H, HH, ZZ |
| $\tau$-jet ID eff. /$\tau$ | 1 | 2.5 | 5 | Single H, HH, ZZ |
| $\gamma$ ID eff./$\gamma$ | 0.5 | 1 | 2 | Single H, HH |
| $\ell = e$-$\mu$ ID efficiency | 0.5 | 1 | 2 | Single H, HH, ZZ |
| Luminosity | 0.5 | 1 | 2 | Single H, HH, ZZ |
| Theoretical cross section | 0.5 | 1 | 1.5 | Single H, HH, ZZ |

# 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** |



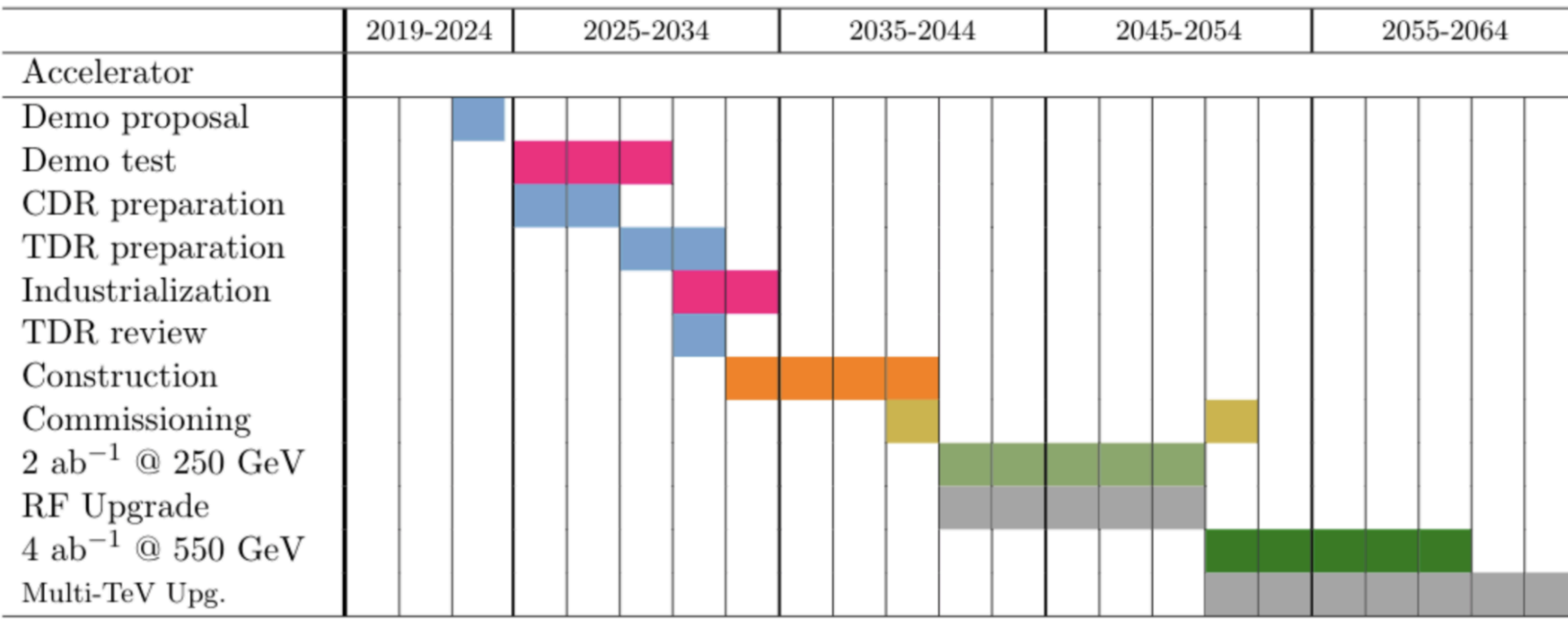

  - FCC-hh alone: CHF: 25B

# CLIC

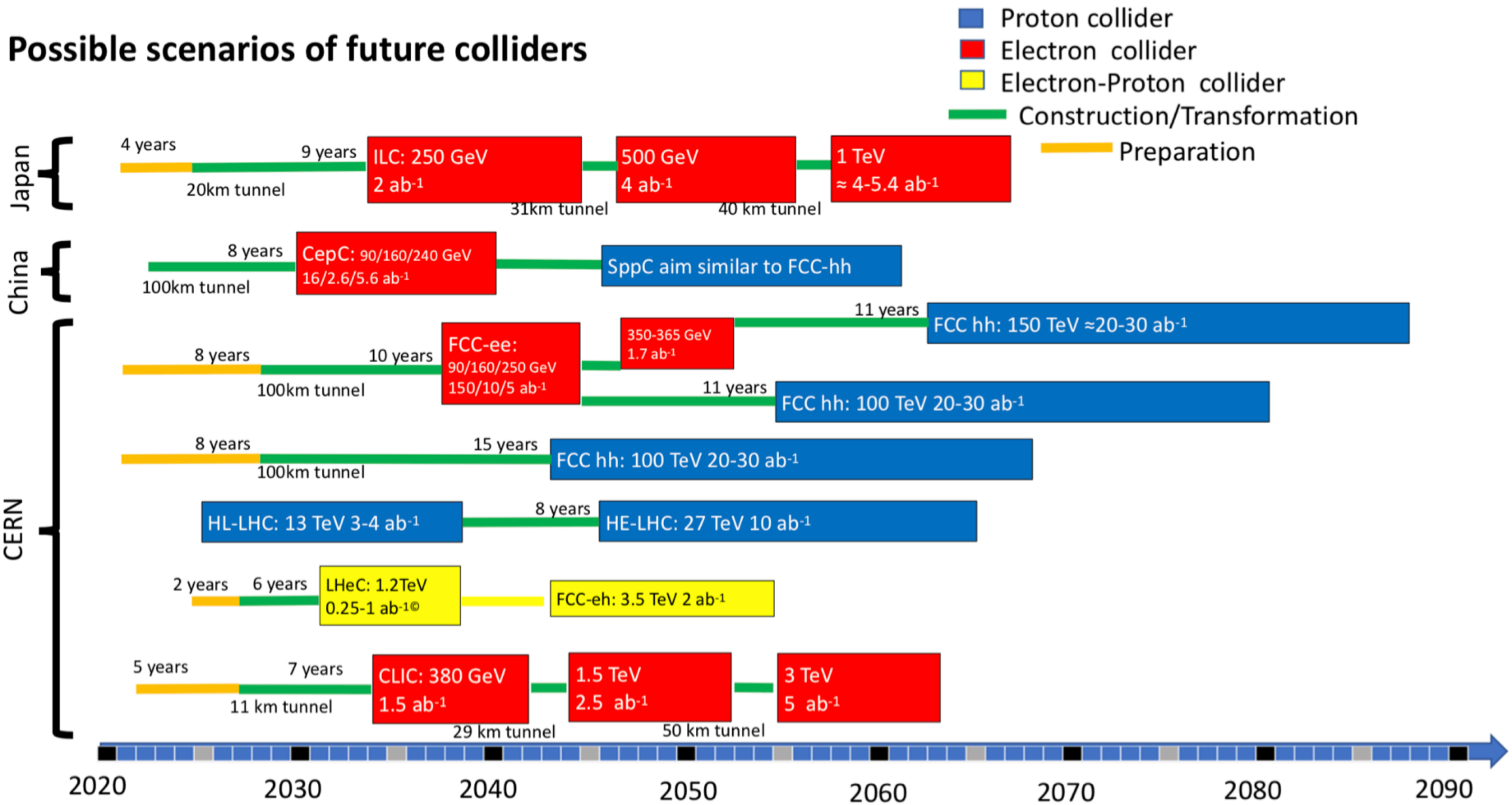
- Timeline:
  - Construction 2026 → beams 2036 → for 25-30 years
- Cost: CHF 6-8B (380 GeV) + CHF 5-6B (for 1.5 TeV)

# C3

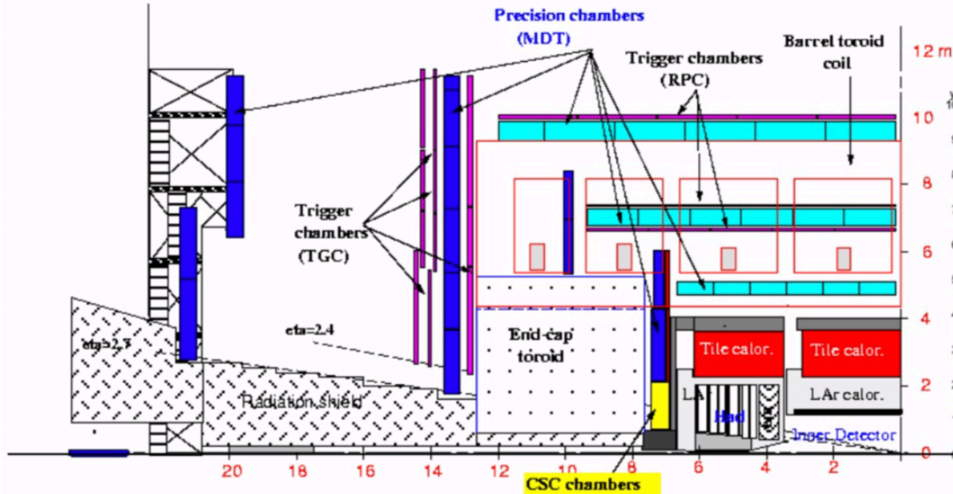
- Sensitivity and detectors similar to ILC
- Cost: $100M



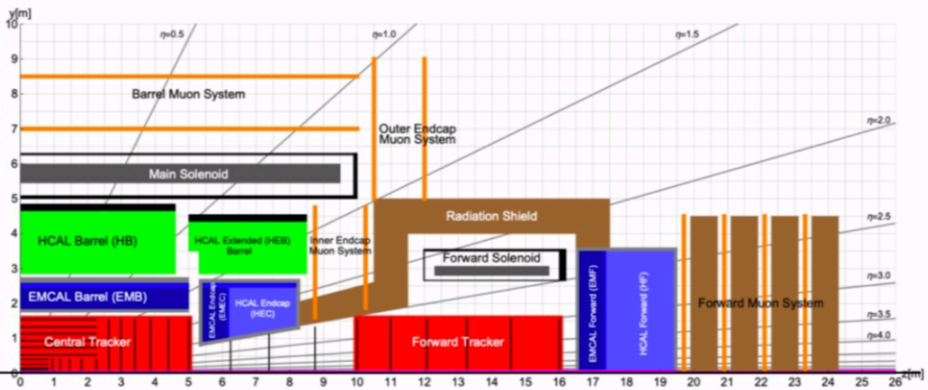
# Landscape of future colliders



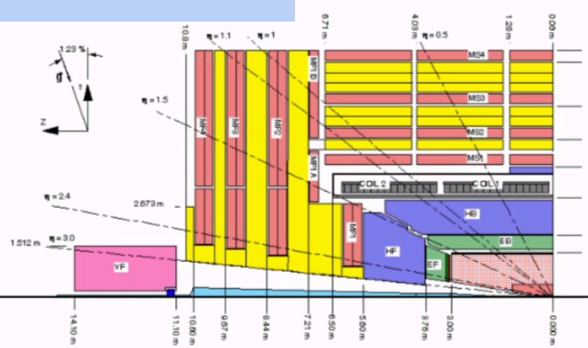
# ATLAS

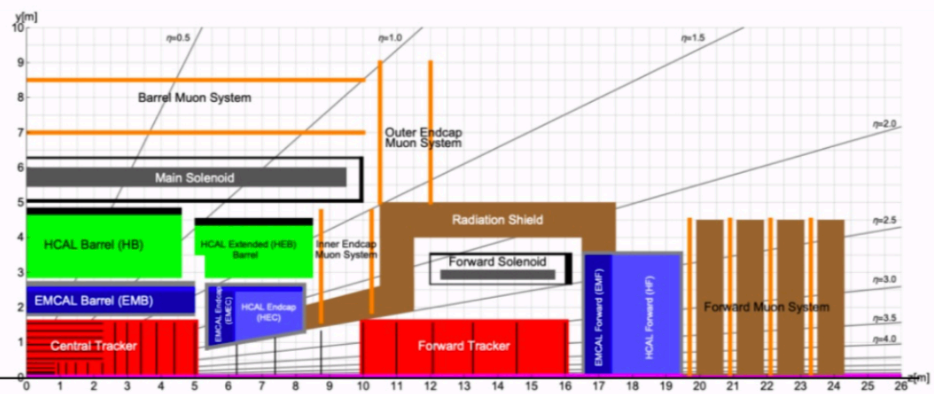



# FCC-hh

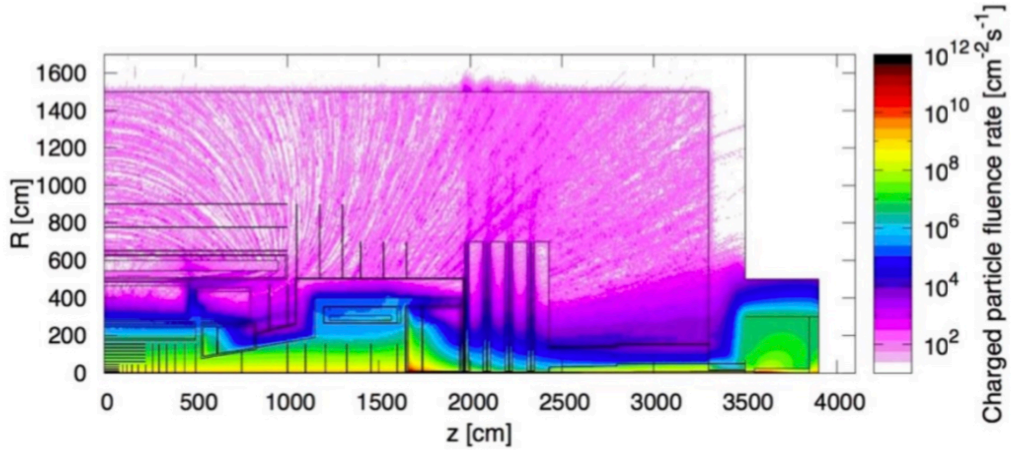


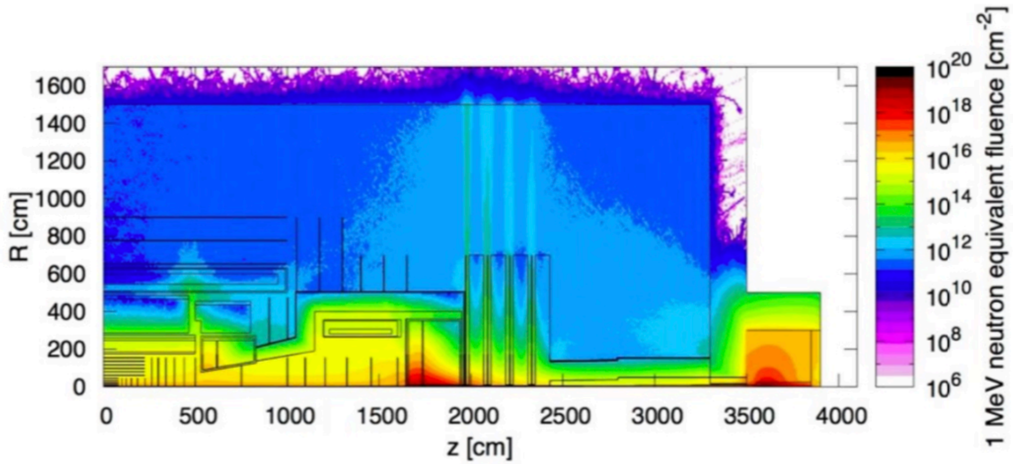

# CMS



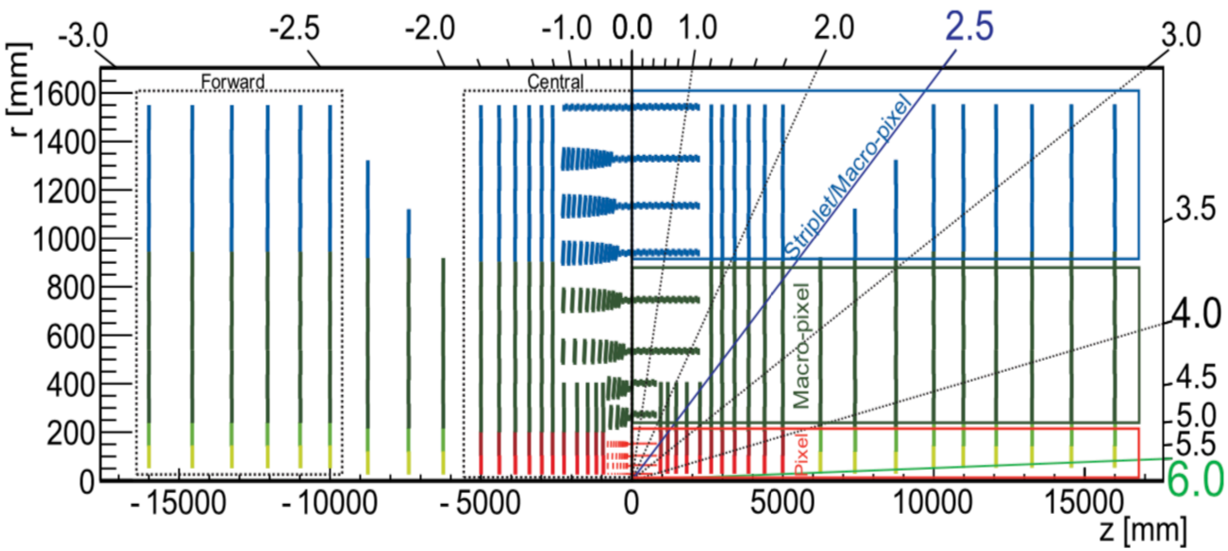
# Radiation studies



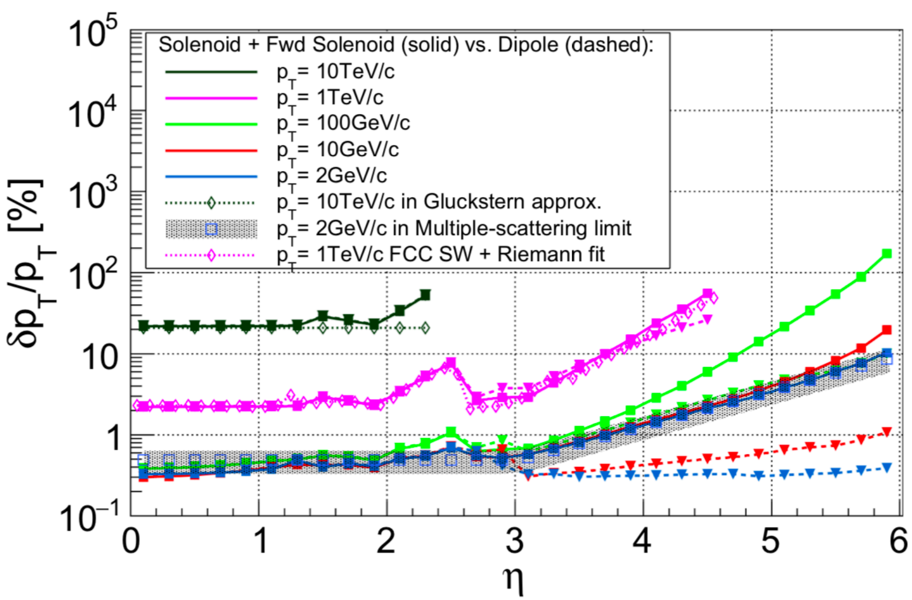



# The FCC-hh detector: TRK

**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)



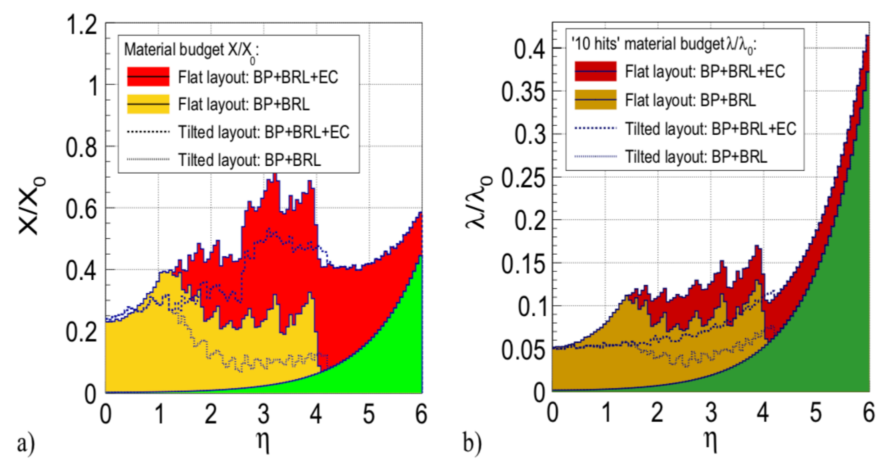
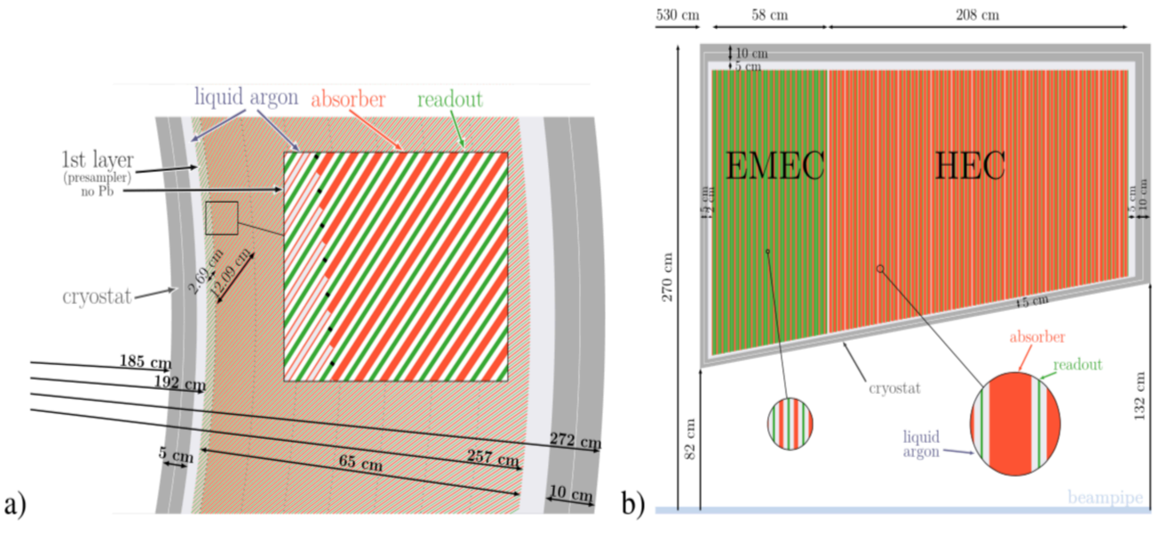
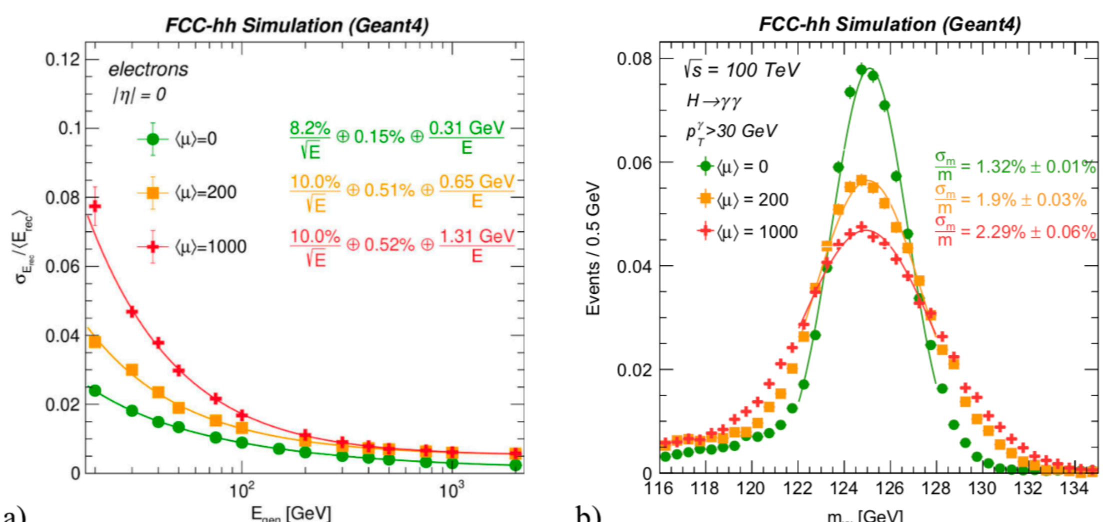




**Fig. 7.14.** (a) Material budget in units of radiation length for the flat and tilted tracker geometries. (b) Material budget in units of nuclear interaction length for the flat and tilted tracker geometries, assuming a limit of 10 hits on the track.

# The FCC-hh detector: ECAL

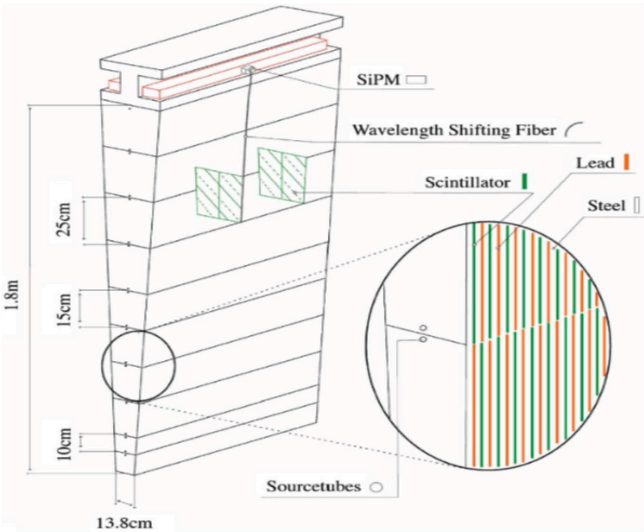



- → **LAr/Pb (Lar/Cu):** Barrel (Fwd)
  rad hard & stability
  alternative ala CMS-HGCal
  [Si/Pb(W)]
- → **ΔηxΔϕ~0.01x0.01:** ~4x more granular than ATLAS/CMS
- → **Long. segmentation:** 8 layers

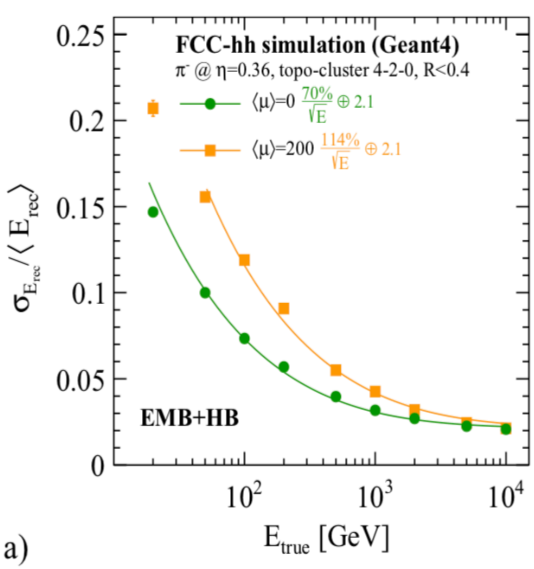


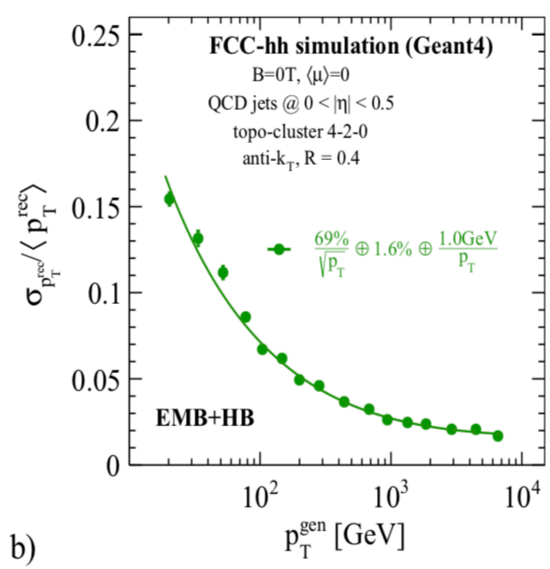

- → comparable mass resolution with CMS in the case of low PU
- → ~2x degradation in $m_{\gamma\gamma}$ resolution for PU=1000
  **However:** no TRK info exploited

# 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.

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

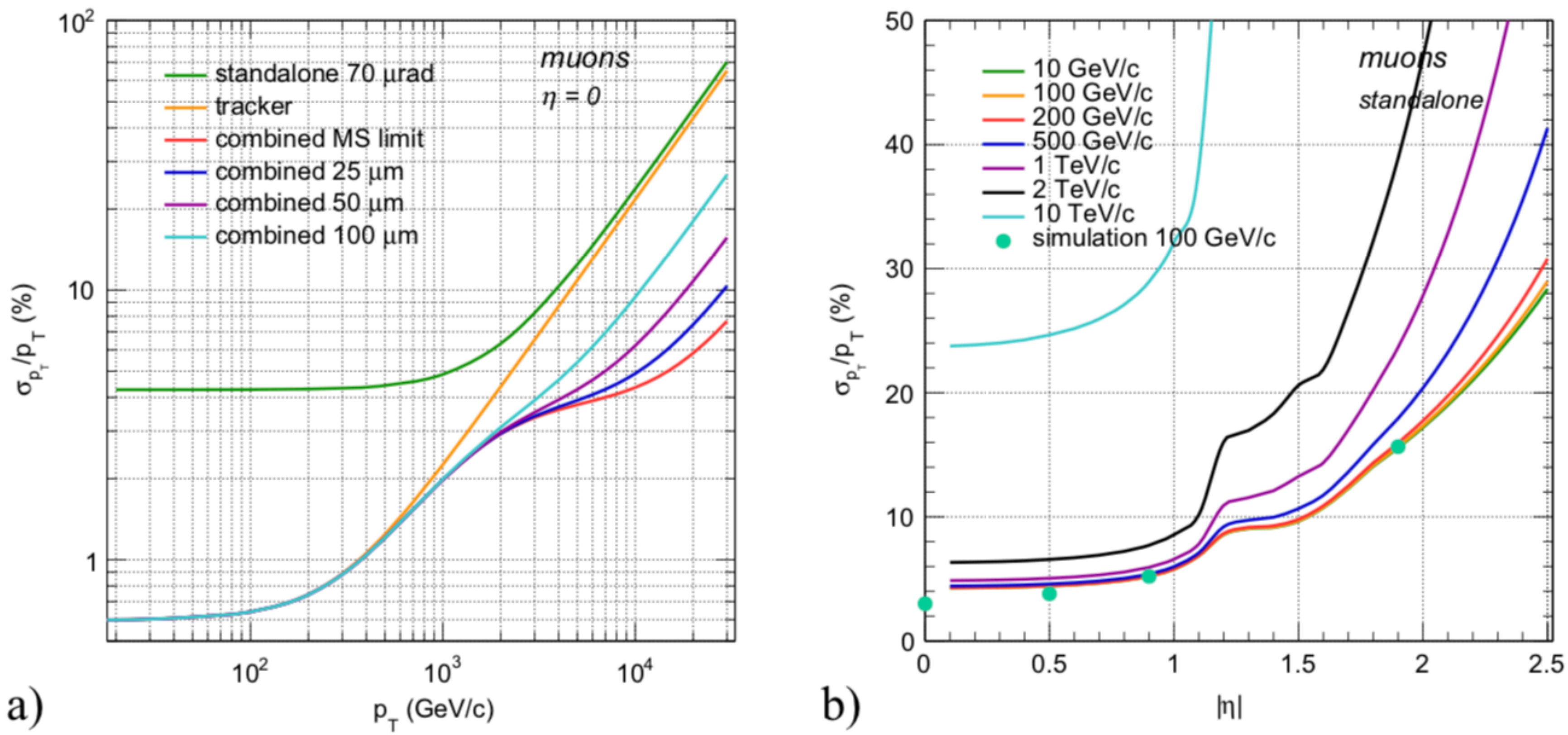
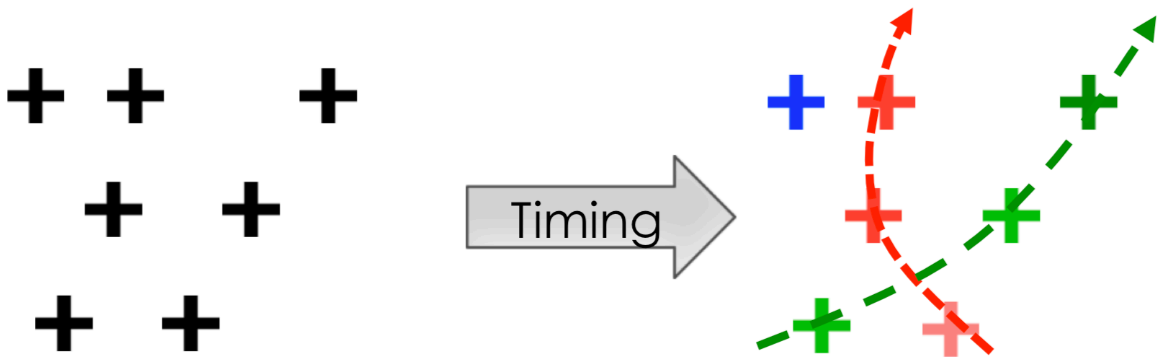



**Fig. 7.21.** (a) Muon momentum resolution at $\eta = 0$. (b) Muon stand-alone momentum resolution as a function $\eta$ for different muon momenta.

# Timing layers



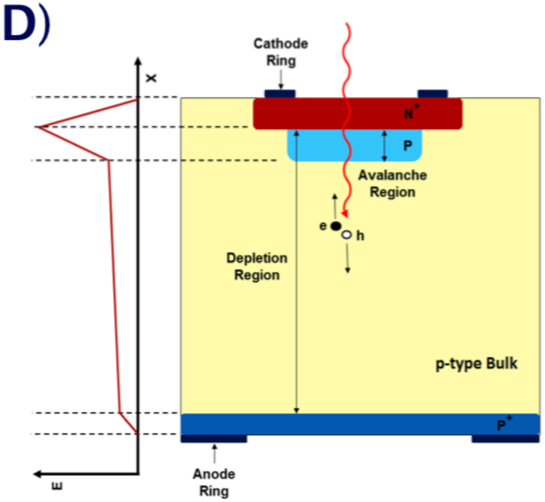

ref: 1901.10389

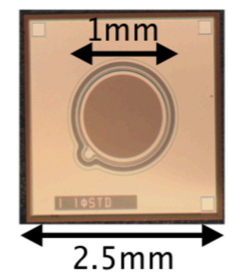
Low–Gain Avalanche Detector (LGAD)

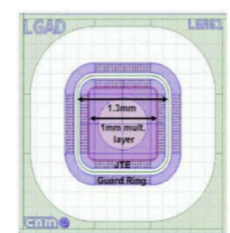
- ≲ 30 ps time resolution feasible
- ongoing study for radiation hardness

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

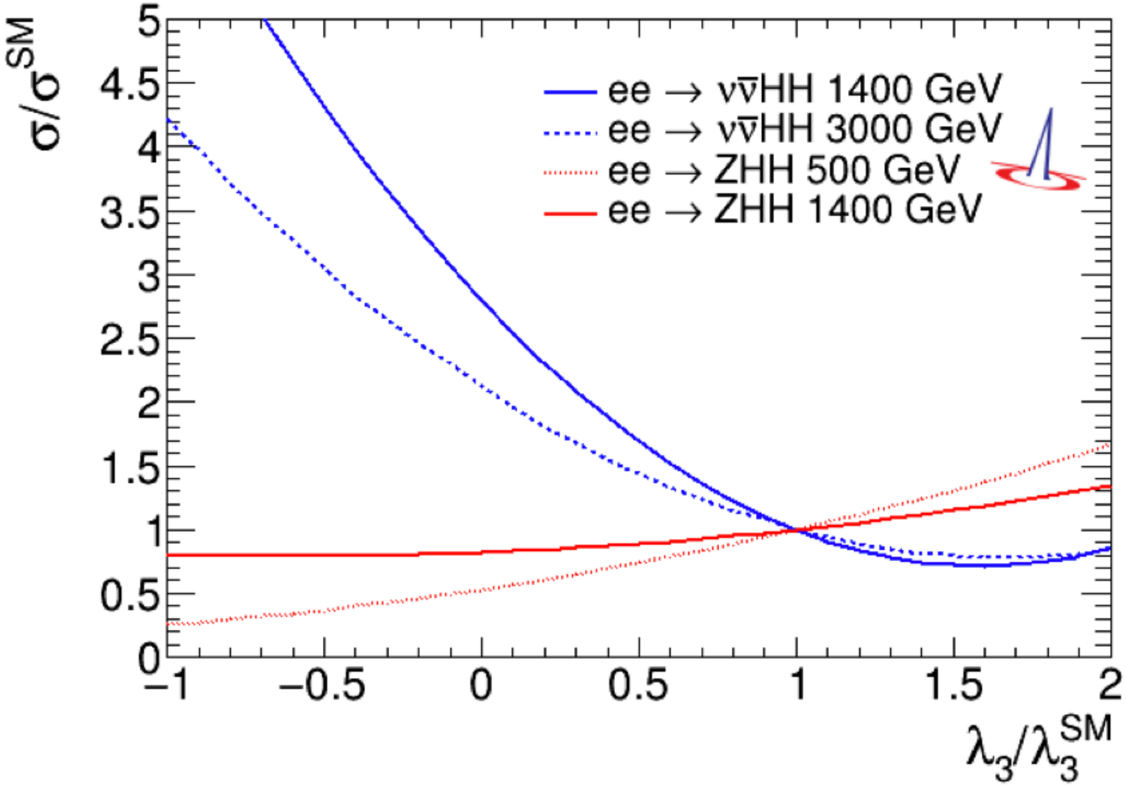
ATLAS HGTD



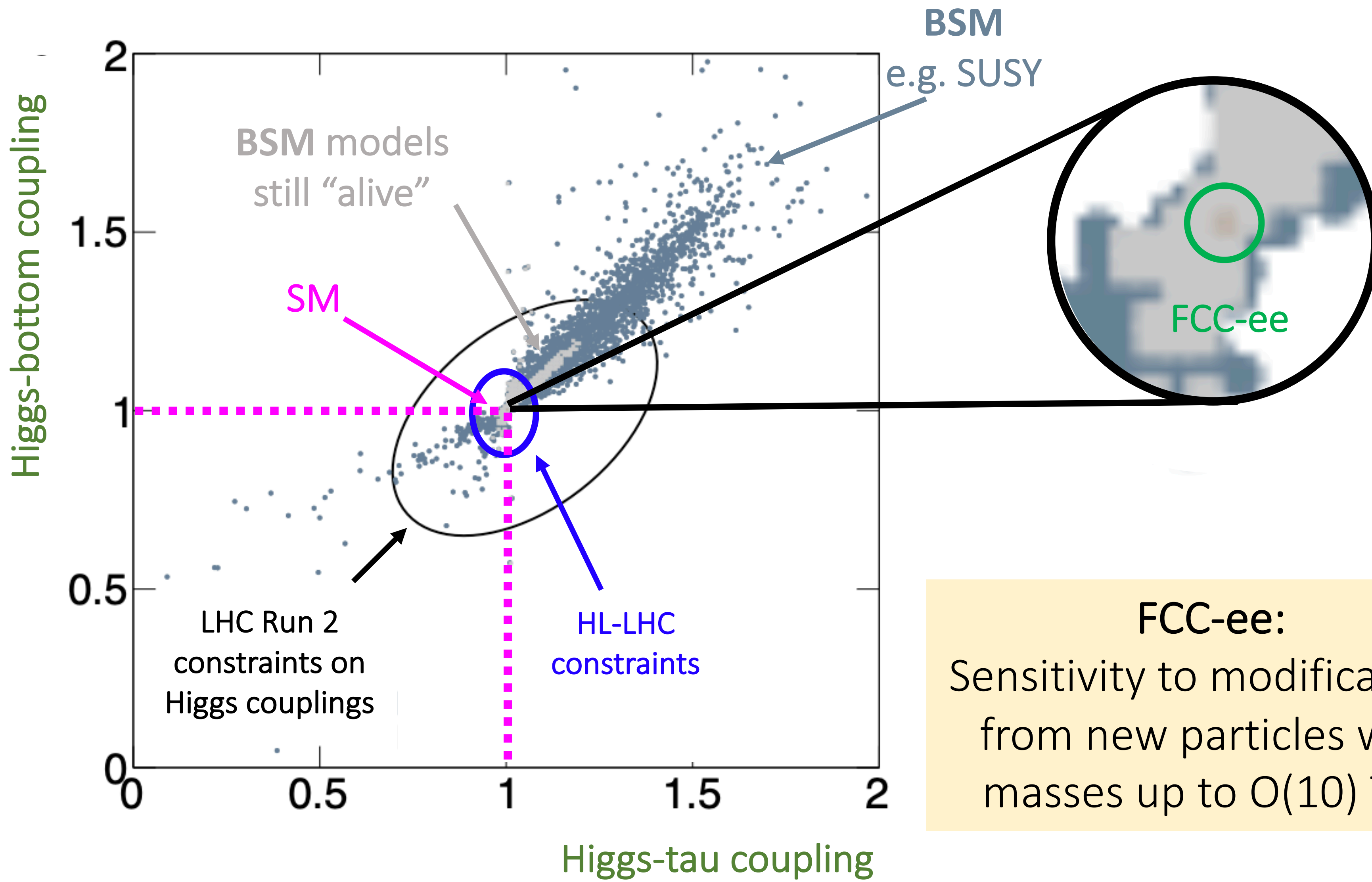



# Higgs-self coupling at $e^+e^-$




**Critical for HH measurement**
- multiple ECM
- production modes
- $m_{HH}$ [next slide]

# Precision → Sensitivity to New Physics




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