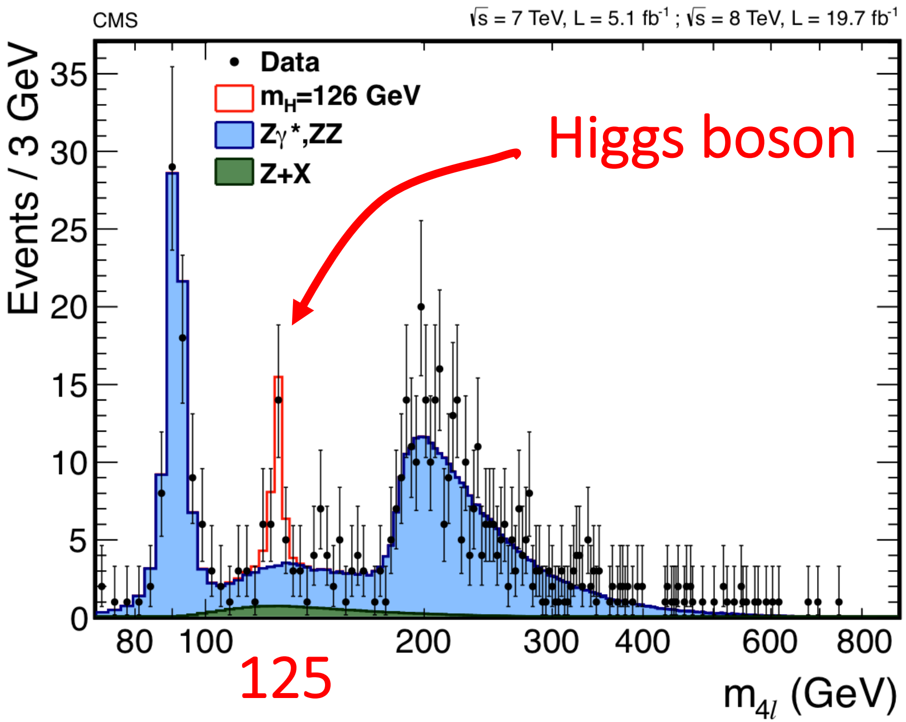
The Physics at Future e^+e^- colliders

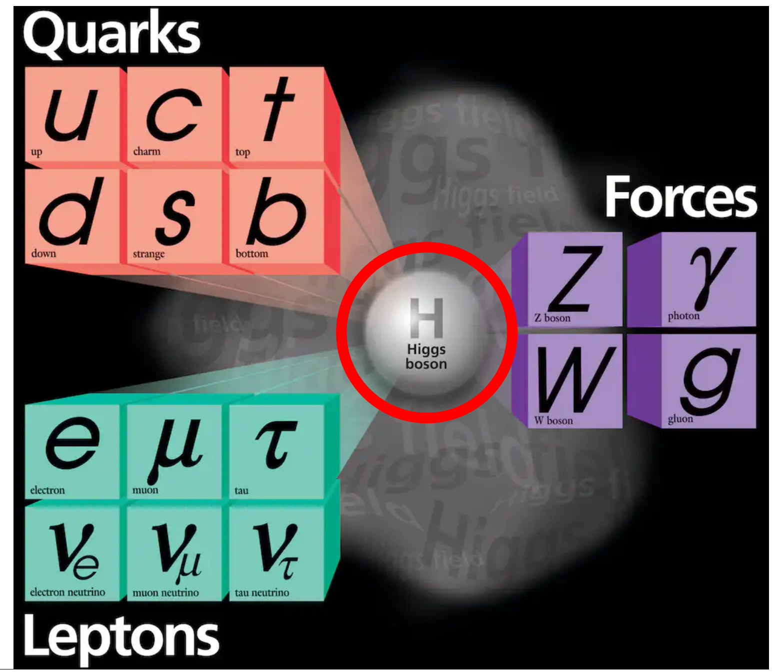
Loukas Gouskos (Brown)

Fermilab-CERN Hadron Collider Physics Summer School (2024)

The triumph of Standard Model (SM)

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





SM particle content is complete

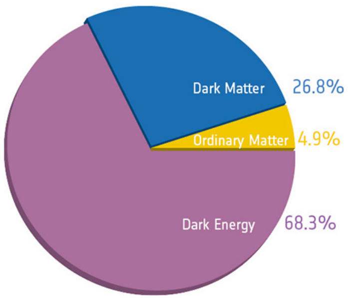
- Higgs boson: Plays a very central role; interacts with all particles

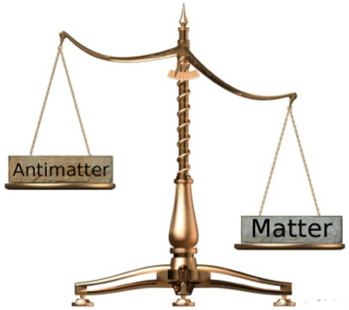
Is that all ?

Is that all ?

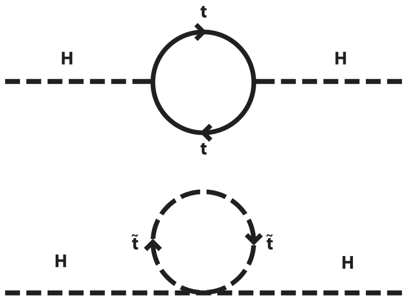
- Nope… The big open questions in Particle Physics

◆ Experiment – driven
- Dark Matter
- Dark energy
- Matter-Antimatter asymmetry
- …





◆ Theory – driven
- Hierarchy problem & naturalness
- Number of generations
- Origin of fermion families
- …



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All beg for New Physics..

- How/Where to search for? At which scale/precision?

Searching for New Physics (@colliders)

- Two complementary approaches
  - **Direct searches** for new particles/interactions
  - **Sensitive tests of the SM** and look for deviations

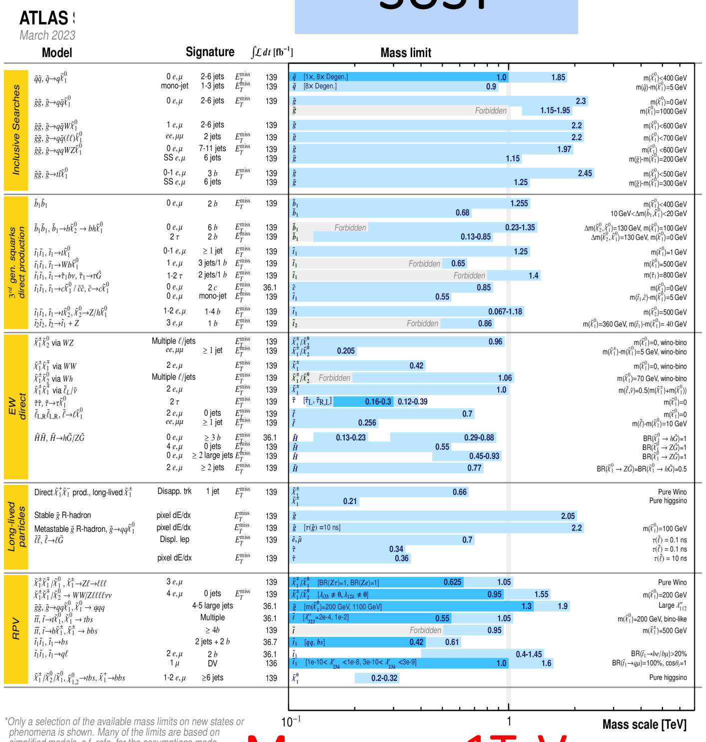
Outline

- Introduction
  - The physics landscape after LHC Run 2 and at HL-LHC
- Shaping the future
  - Particle colliders
  - The need for an electron-positron collider
  - Proposed e^+e^- colliders (executive summary)
- The Physics in e^+e^- colliders
  - The Higgs sector
  - EWK precision measurements
  - Direct searches and potential discoveries
- Outlook and summary

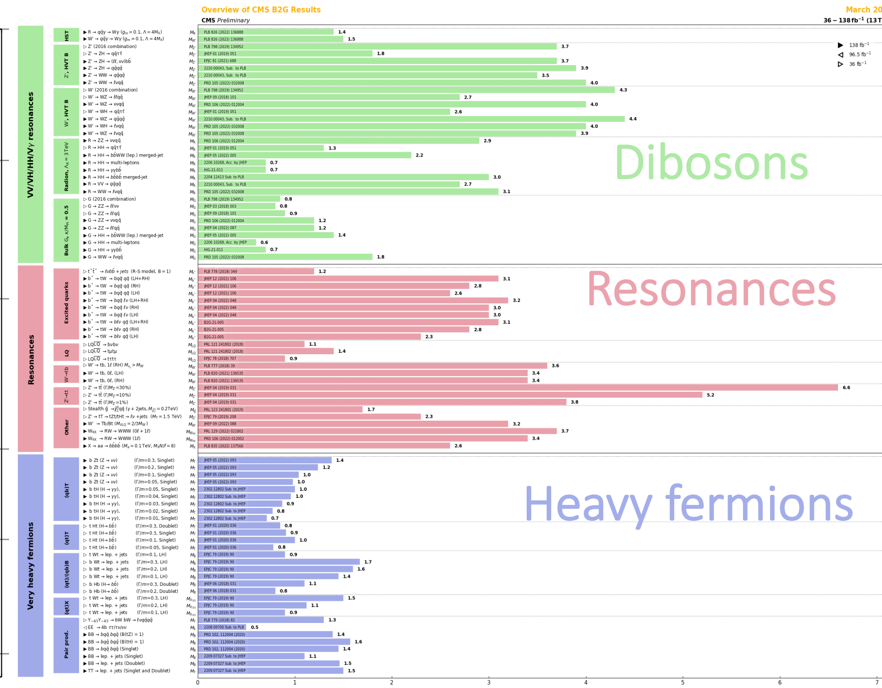
Physics landscape today: Direct searches

- Plethora of Beyond SM (BSM) searches

SUSY



Heavy resonances

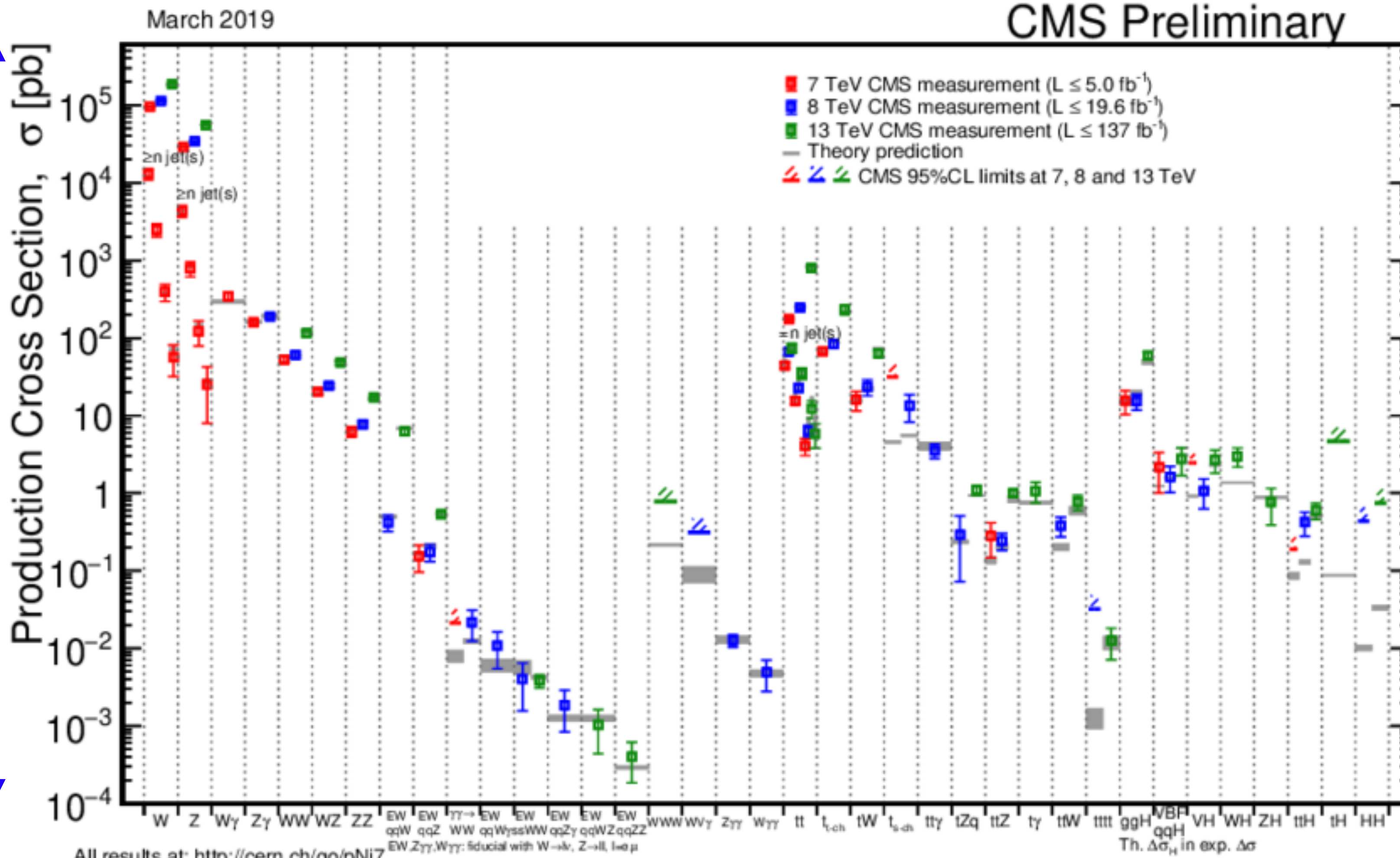


Mass: 1TeV 1TeV 5TeV

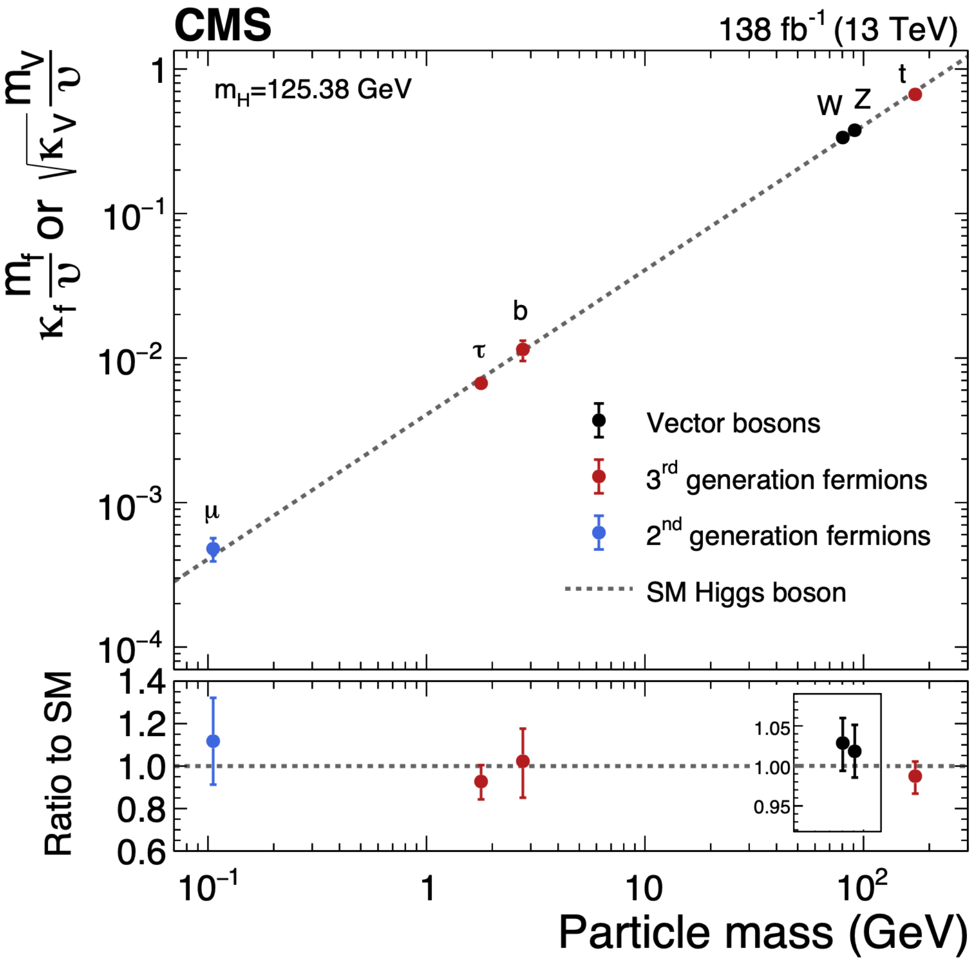
- ◆ and many many more channels/topologies/signatures
- Nothing came up yet

Physics landscape today: The SM

13 orders of magnitude



Physics landscape today: The Higgs



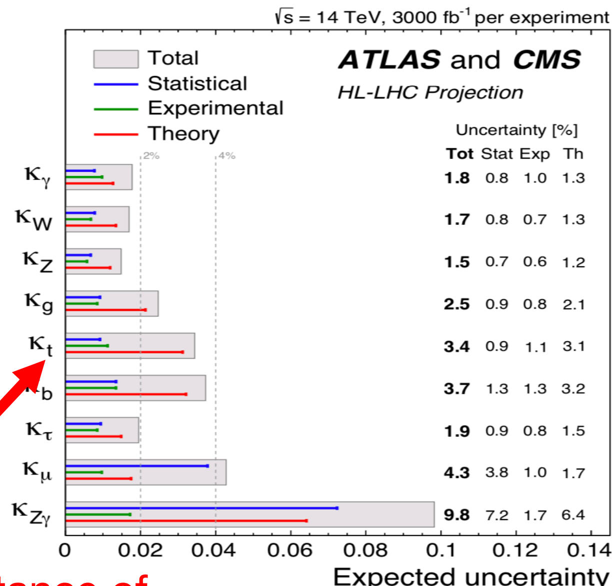
- Established interactions:
  - **Gauge bosons** [Run 1]
  - **3rd-Gen** charged fermions
- Evidence for **2nd-Gen** charged leptons
- + CP, differential measurements, STXS, EFT,..

Whole new chapter of exploration
- modification of Higgs properties
  → sign of BSM

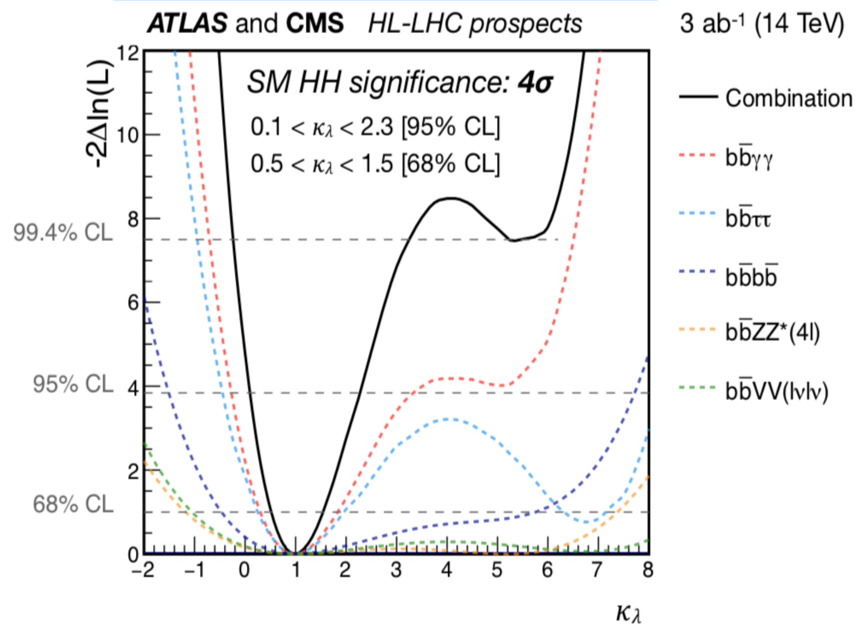
Physics landscape after HL-LHC

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

Higgs couplings



Higgs-self coupling



NB: Importance of TH uncertainties

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

HL-LHC: <u>Cannot guarantee</u> definite answers to any of the <u>big open Qs</u>

Shaping the future

Shaping the future

- Where is New Physics:
  - **Within (HL-) LHC reach:** In difficult corners and/or small σ
  - **Beyond (HL-) LHC reach:** very massive new particles

New colliders necessary to explore the multi-TeV regime

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- 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

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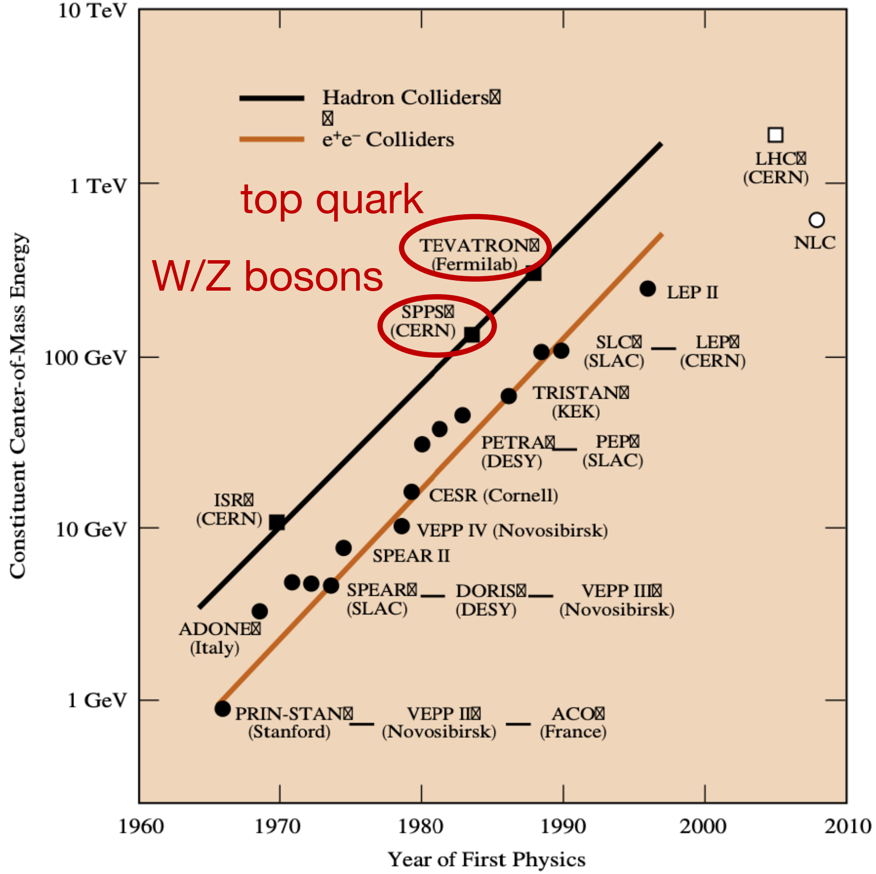
No "guaranteed discoveries" rather than "guaranteed deliverables"

Building on success stories

- Two complementary approaches
  - Hadron colliders (pp, ppbar)
    - Higher mass scales/rates
      → **Discovery** of new particles
  - Lepton colliders (e^+e^-)
    - Higher precision
      → prediction @higher scales

W. Panofsky [link]



Further reading:
The evolution of particle accelerators [link]

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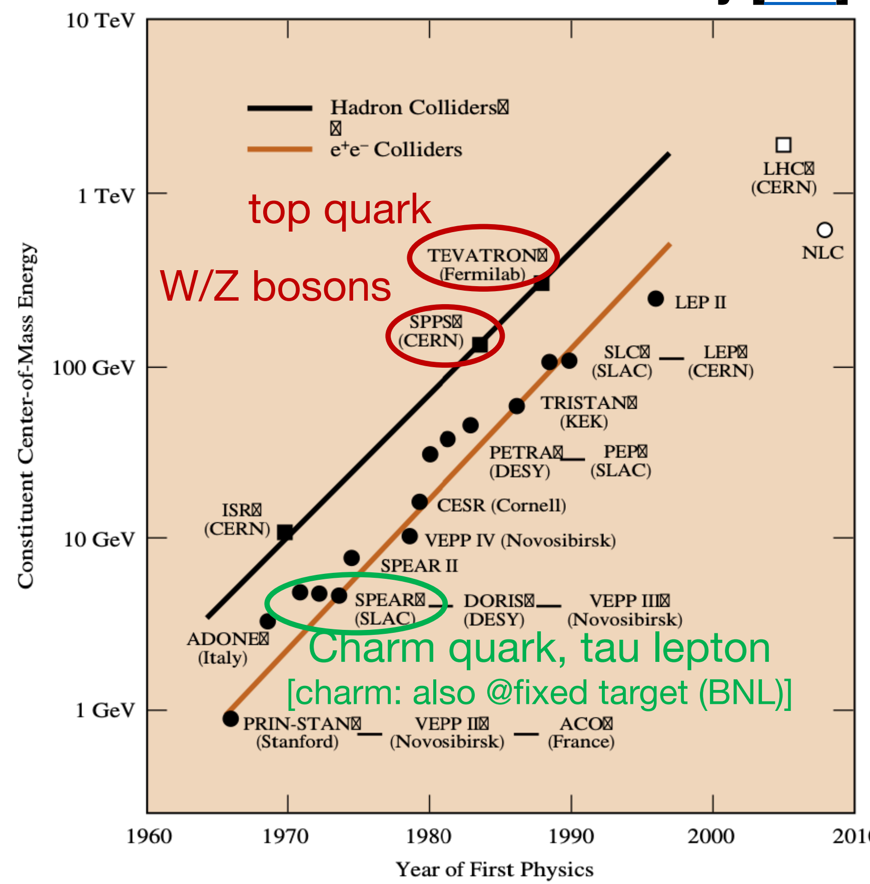
    - but .. also discoveries ;-)

W. Panofsky [link]



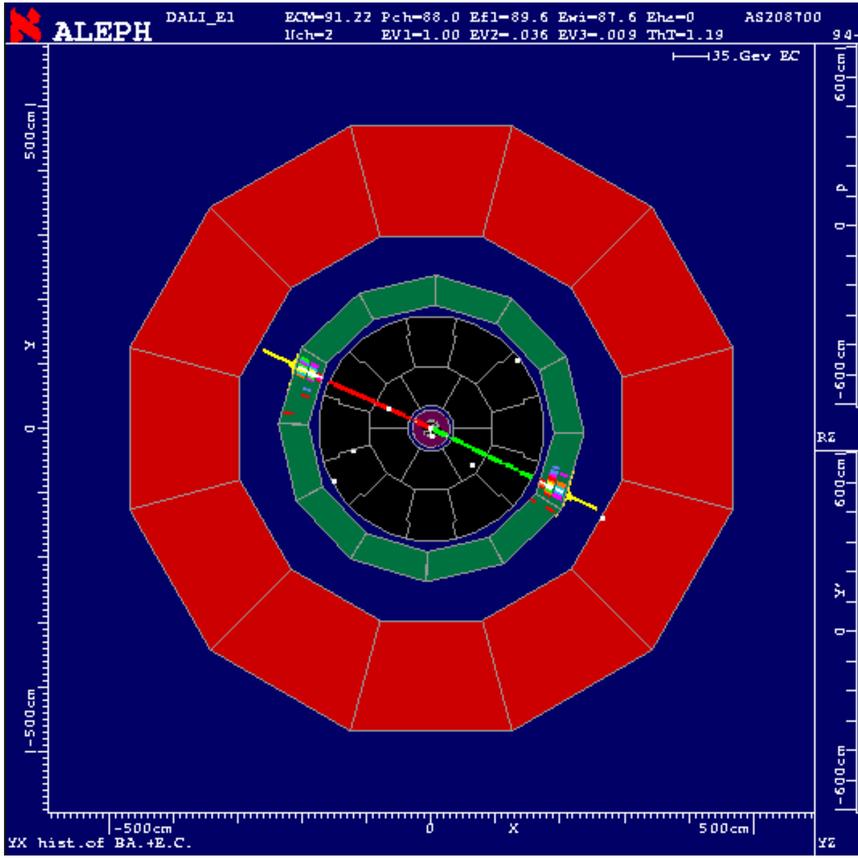
Further reading:
The evolution of particle accelerators [link]

An e^+e^- event

- e^+/e^-: elementary particles
  - No internal structure
  - No underlying event

- $Z \rightarrow e^+e^-$ event
  - Extremely clean environment
    - An e^+e^- & nothing else
  - Energy and momentum known
  - Use E-p conservation to improve the measurement of the physics objects

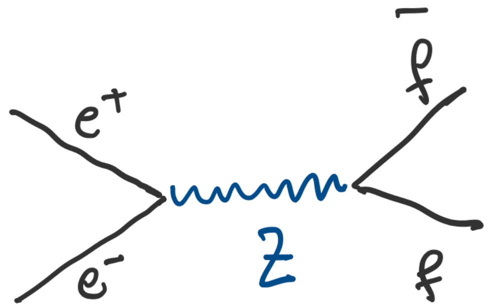
Example from ALEPH (LEP/CERN)



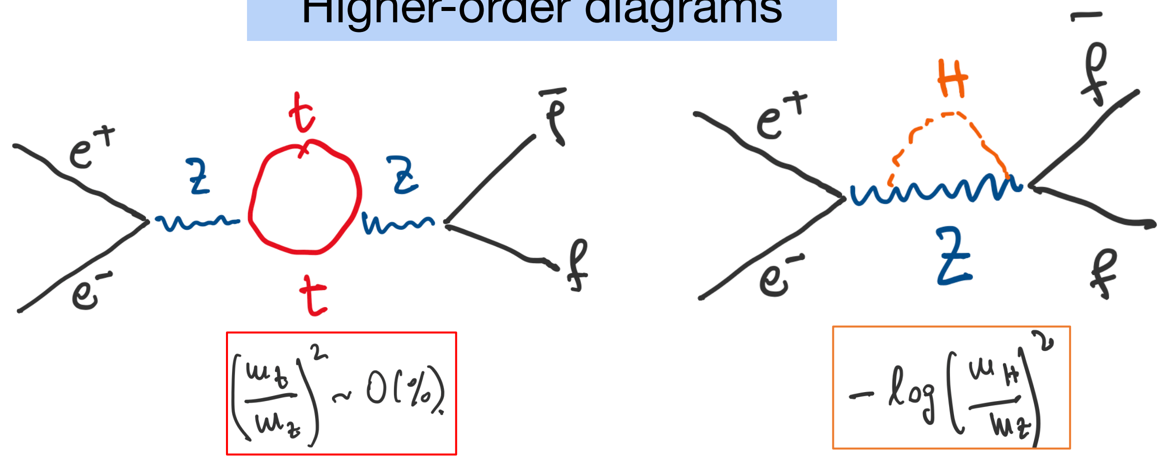
Importance of precision

- The SM is a quantum field theory
  - Tree-level diagrams: Not sufficient to describe nature
  - Need to account of quantum effects in higher order calculations

Leading order (Tree-level)



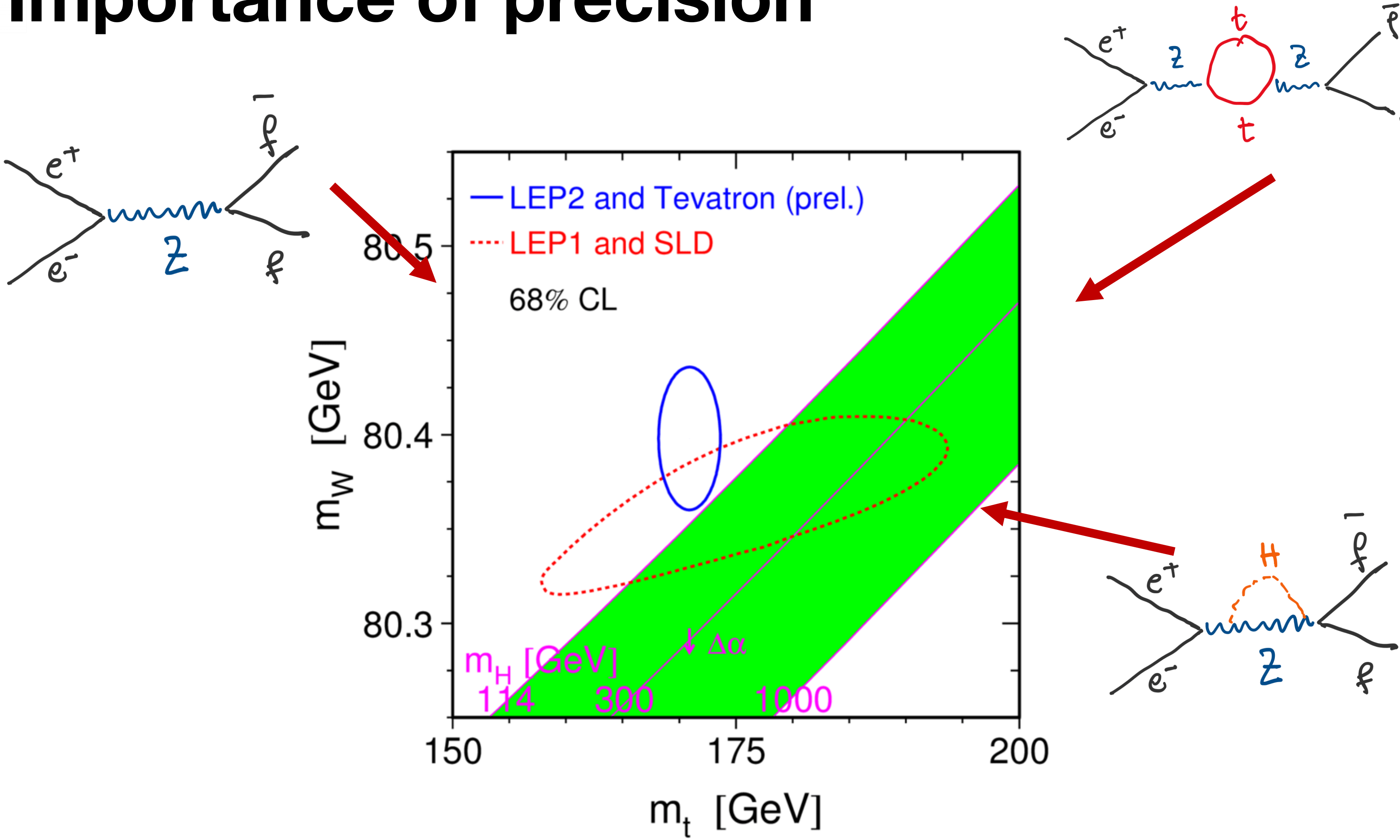
Higher-order diagrams



- Putting pieces together:
  - $\Gamma_Z \rightarrow \Gamma_Z \times (1+cor)$; cor ~ (cor(t), cor(H))
  - Similarly for W, etc…

BSM (if exists) will/could contribute as well

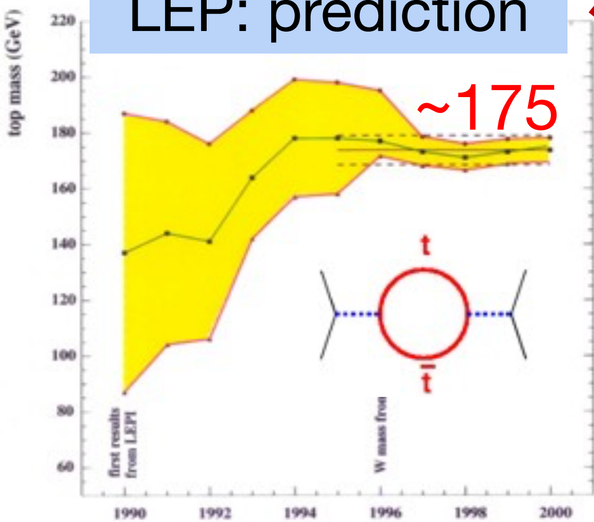
Importance of precision



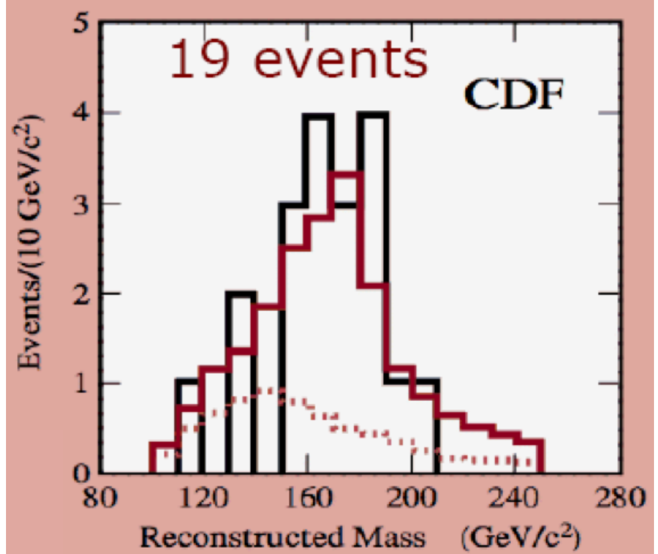
Indirect measurement of $\mathbf{m_W}$ and $\mathbf{m_{top}}$ (from **Z boson** properties)

Building on success stories: The “top”

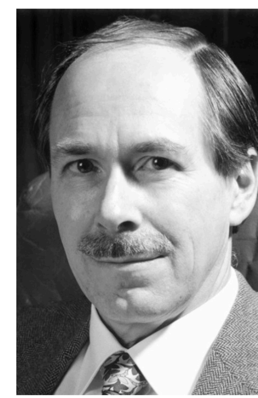
LEP: prediction



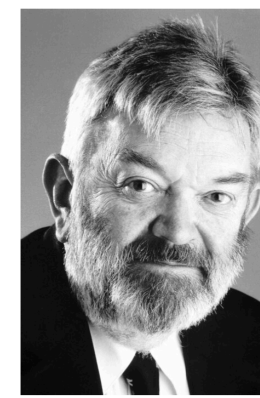
Tevatron: discovery



Nobel Prize (1999)



‘t Hooft

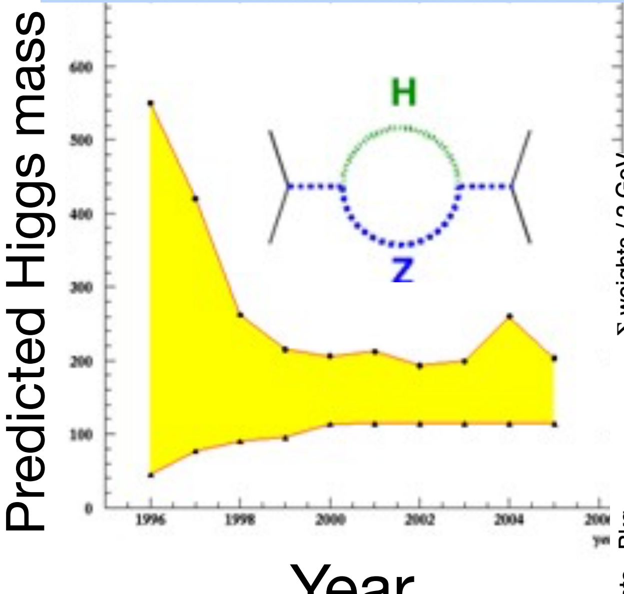


Veltman

“for elucidating the quantum structure of electroweak interactions in physics” [ref]

Building on success stories: The “Higgs”

LEP(e^+e^-): prediction

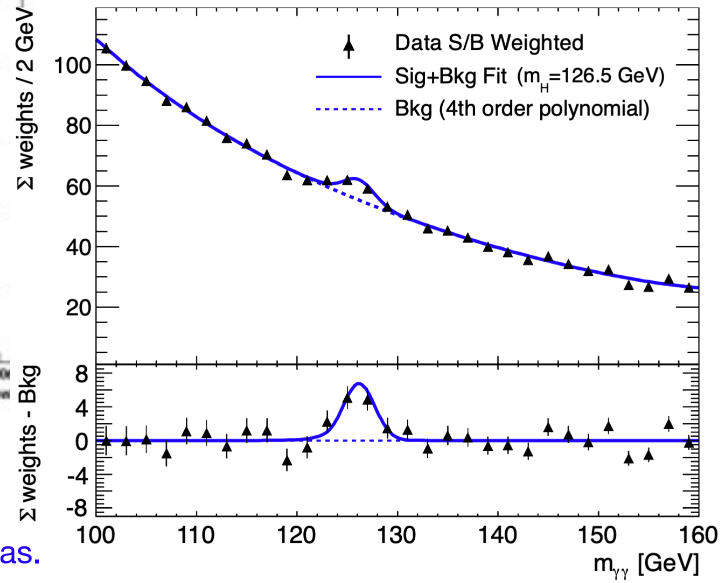


direct search

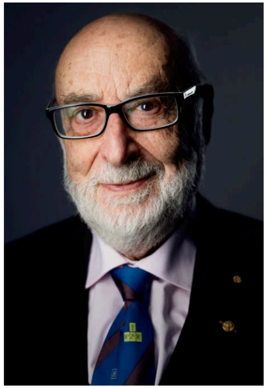
114 < m_H < 152 GeV

precision meas.

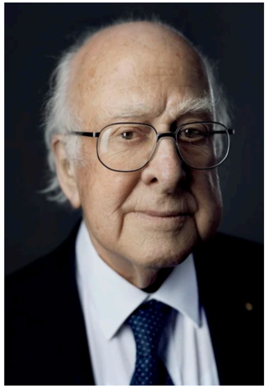
LHC (pp): discovery



Nobel Prize (2013)



Englert



Higgs

“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider” [ref]

The road ahead

- Similar recommendations in both sides of the Atlantic

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."

e^+e^- collider

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

Z, W, top factory

Luminosity

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."

The road ahead

- Similar recommendations in both sides of the Atlantic

US P5 update (2015):

The hadronic HL-LHC and e^+e^- ILC are highly complementary discovery accelerators. If new particles are observed directly at the LHC/HL-LHC, the pattern of deviations in the combined measurements of Higgs boson couplings at both the HL-LHC and ILC adds essential knowledge in determining the underlying structure of the new physics. If no new physics is found directly at the LHC/HL-LHC, the precision of the ILC measurements for the Higgs couplings can indirectly uncover new physics present at mass scales beyond that kinematically accessible at the LHC/HL-LHC.

US P5 update (2023):

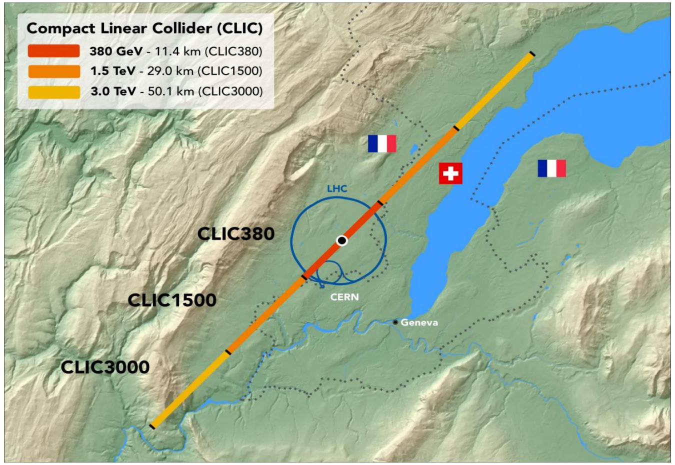
A Higgs factory is the next step toward fully revealing the secrets of the Higgs boson within the quantum realm. We advocate substantial US participation in the design and construction of accelerators and detectors for an offshore facility, and we advocate investment of effort to support development of the Future Circular Collider-electron (e^-) positron (e^+) (FCC-ee) and the International Linear Collider (ILC), along with a parallel and increasingly intensive program of R&D pursuing revolutionary accelerator and detector technologies.

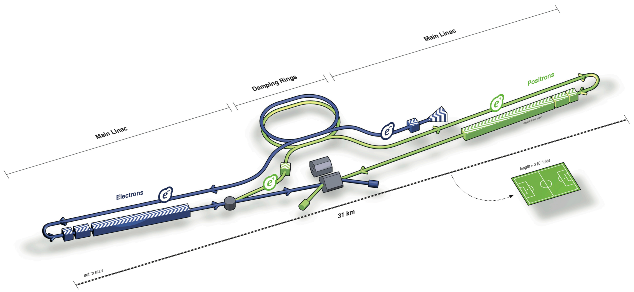
The road ahead

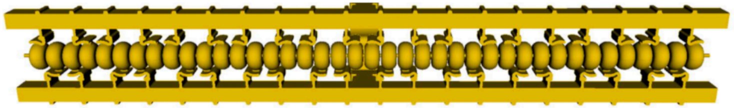
- Clear recommendation:
  - The next particle collider should be an e^+e^-
- The open question: Circular or linear?
  - Need to decide based on physics/sustainability/risk..
- Disclaimer:
  - I will mainly focus on the physics potential of an e^+e^- machine
    - Discuss pros/cons of each approach when necessary
  - I have a preference
    - But I’ll do my best to be as unbiased as possible

Proposed e^+e^- colliders

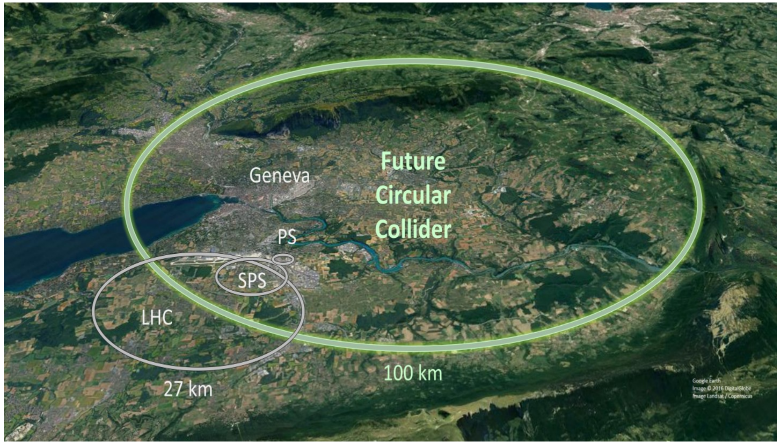
Linear (e^+e^-) colliders





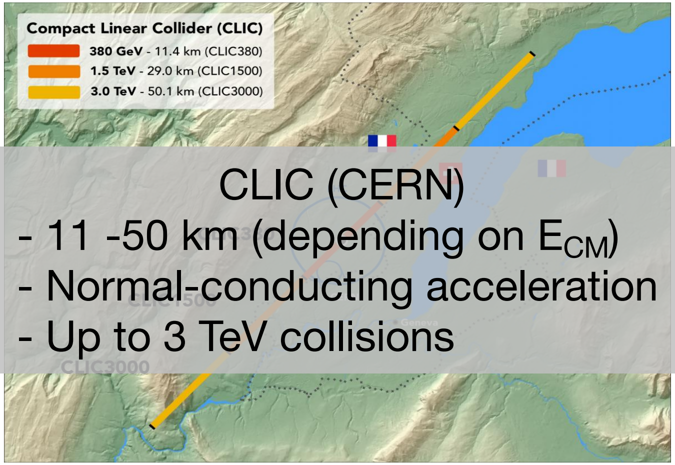


Circular (e^+e^-/hh) colliders

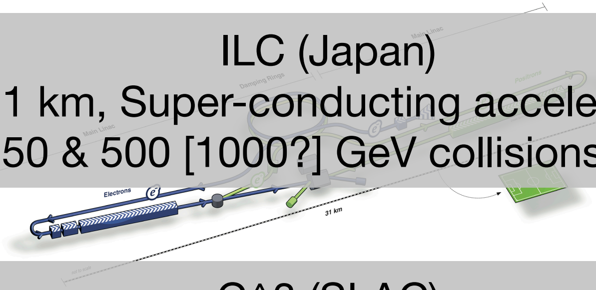


Proposed e^+e^- colliders (add details)

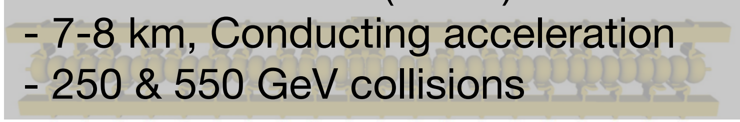
Linear (e^+e^-) colliders



CLIC (CERN)
- 11 -50 km (depending on E_{CM})
- Normal-conducting acceleration
- Up to 3 TeV collisions

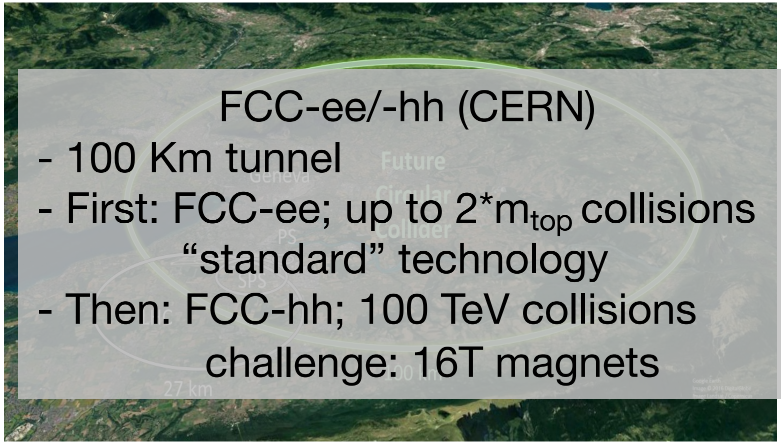


ILC (Japan)
- 31 km, Super-conducting acceleration
- 250 & 500 [1000?] GeV collisions

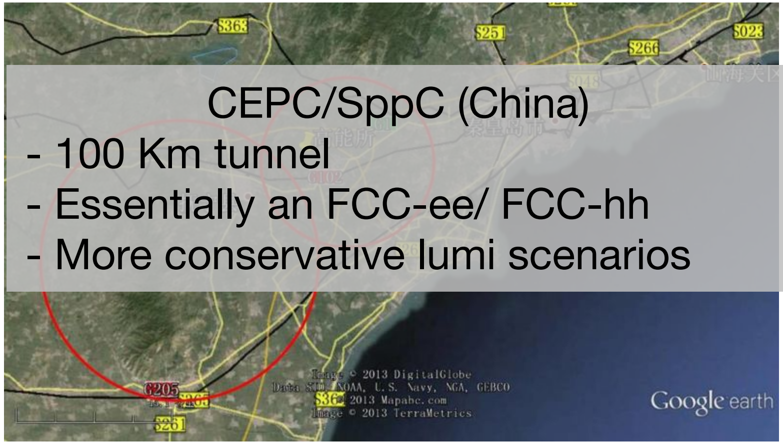


C^3 (SLAC)
- 7-8 km, Conducting acceleration
- 250 & 550 GeV collisions

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 lumi scenarios

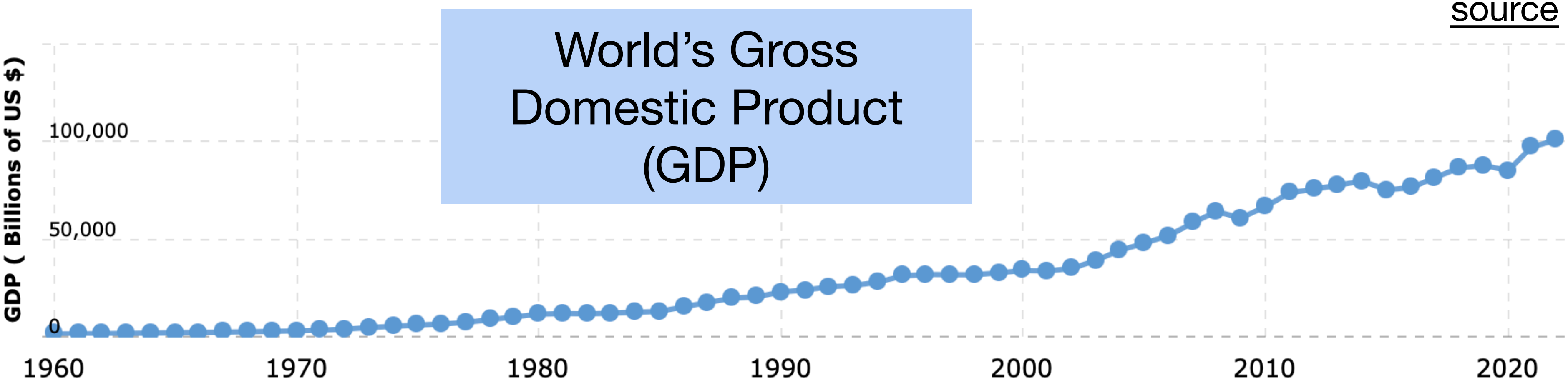
Cost

- All around the O(10-20) billion CHF/USD/EUR…

Cost

- All around the O(10-20) billion CHF/USD/EUR…

source



Cost

- All around the O(10-20) billion CHF/USD/EUR…

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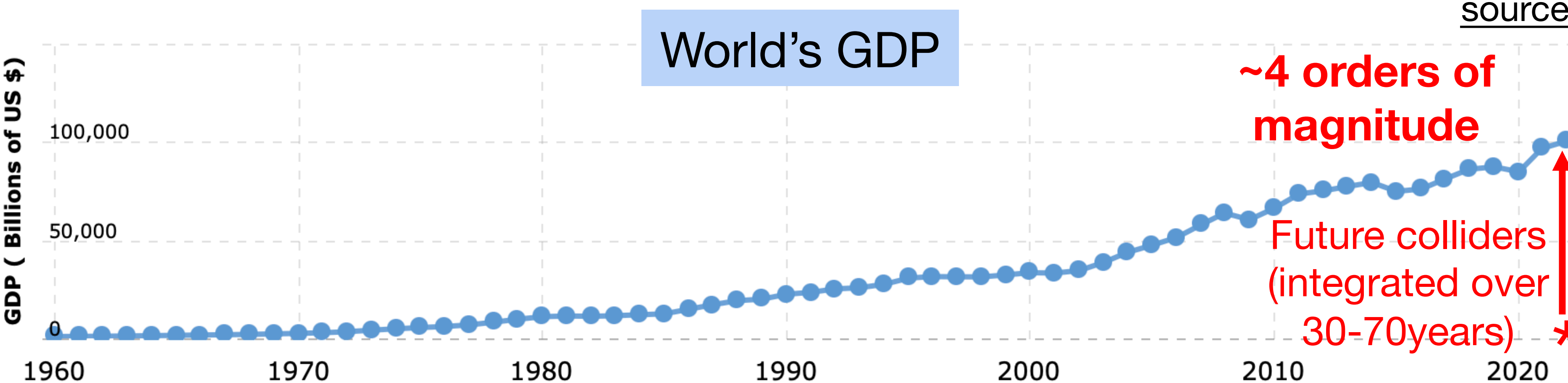

Cost

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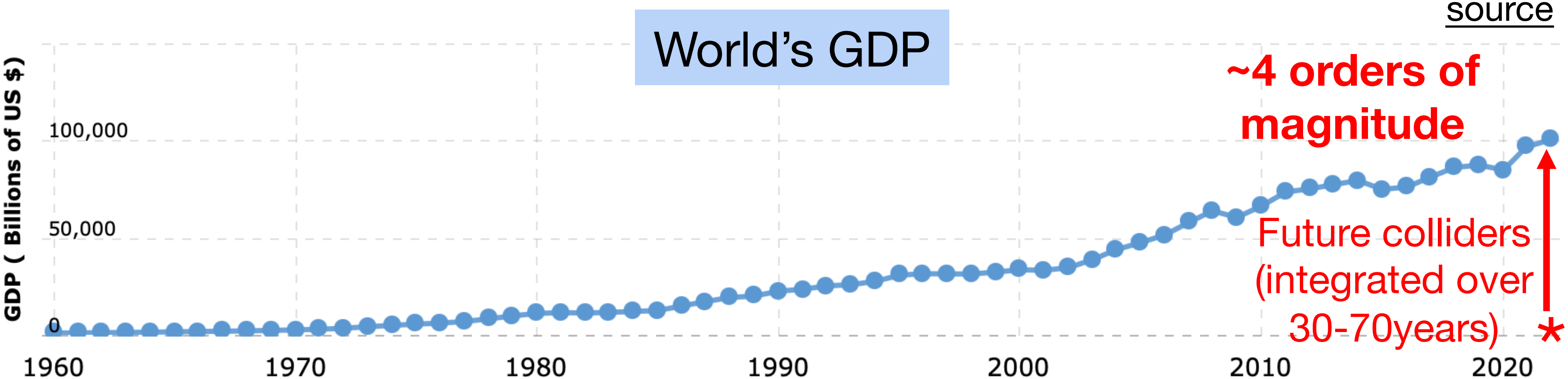

- In other words:
  - Full FCC (ee/pp) cost: $20B
  - Cup of coffee: $5
  - US polulation: ~330M

Cost equivalent/US person:
1 cup of coffee/month

…Let's put the cost on the side and focus on the physics

Circular vs. Linear: Some history

- Pre-LHC: New physics is "just around the corner" (i.e., ~TeV)
  - Discover SUSY even before the Higgs

- Efforts for building the next e^+e^- linear collider (i.e., ICL) started early 00s
  - > 20 years of experience
  - Technical design report (TDR) published 2013 (link)
    - Roughly when thoughts for a circular e^+e^- collider started

- The discovery of a Higgs boson @125 GeV sparked interest for Circular e^+e^- collider (FCC/CEPC)
  - Also: No signs of new physics @TeV scale
    - Motivation for high E_{CM} e+e- not very strong

In a nutshell

- e^+e^-: Different strategies
  - Different luminosity
  - Different E_{CM} scenarios
- FCC-ee/CEPC:
  - Study Z, W, H and top with unprecedented precision
- CLIC/ILC/C^3:
  - Higgs program (of course)
  - Direct access to HH

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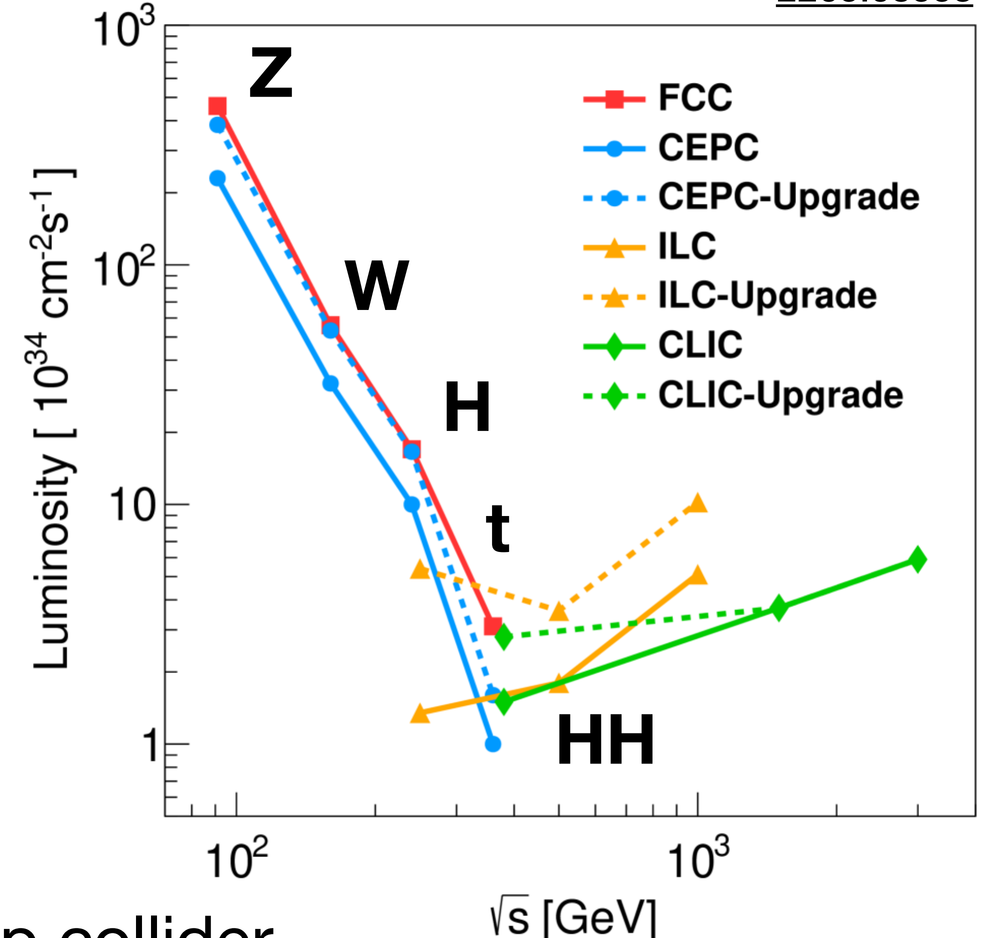


- Ultimate goal: O(100 TeV) pp collider
  - FCC-hh/SppC: use same tunnel constructed for FCC-ee/CepC

Circular vs. Linear →Lumi vs. E_{CM}

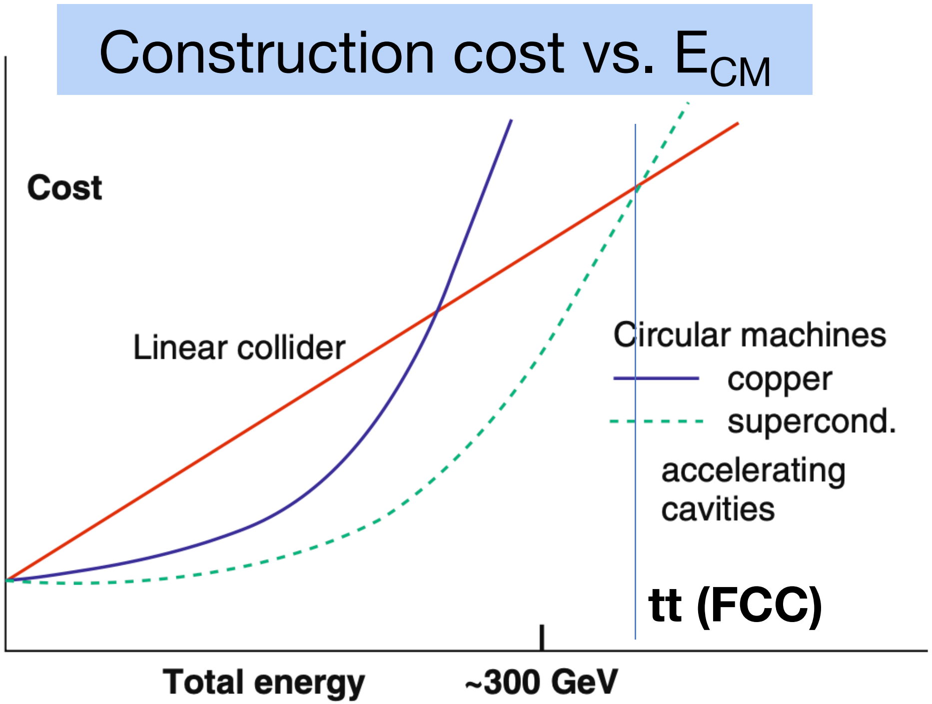
- Circular (FCC):
  - 4 Experiments (Cross-check, dedicated technology, Lumi, ..)
  - **Z-pole**: 150 ab^{-1} (5×10^{12} Z) → 100K Z/sec; LEP: 10^6 Z events
  - **WW**: 12 ab^{-1} → 10K W/sec
  - **ZH**: 5 ab^{-1} →1.5K Higgs/day
  - **top**: 0.2-1.5 ab^{-1} →1.5K top/day
- Linear (ILC); assuming: 500/fb @500 GeV, 200/fb @350 GeV, 500/fb @250 GeV
  - One experiment (maybe 2)
  - Direct access to Higgs-pair production
  - **Z's**: 3×10^9 , **W's:** 2×10^6
  - **Higgs:** 1.4×10^5 **WW**: 12 ab^{-1}
  - **top:** 10^5

HW: Why lower Luminosity in linear colliders?

Both will achieve >100x the stats of LEP

Circular Colliders: Why not higher E_{CM}

Circular Colliders: Why not higher E_{CM}



plot from:
"LEP: The Lord of the Collider Rings at CERN", H. Shopper [CERN Library]

- Why?
  - Circular machines emit synchrotron radiation:

$$E_{\text{rad}} \sim (E/m)^4/R$$

  - FCC-ee: ~7GeV/turn
- Must compensate: RF accelerated cavities
  - Cost ~E^4

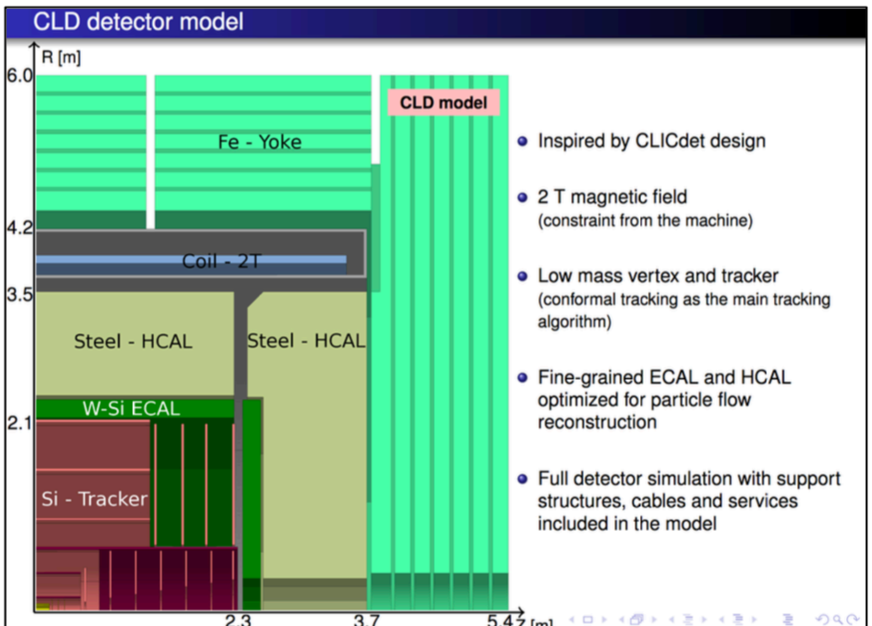
Only viable option for e^+e^- collider with E_{CM}>~400 GeV is a linear collider

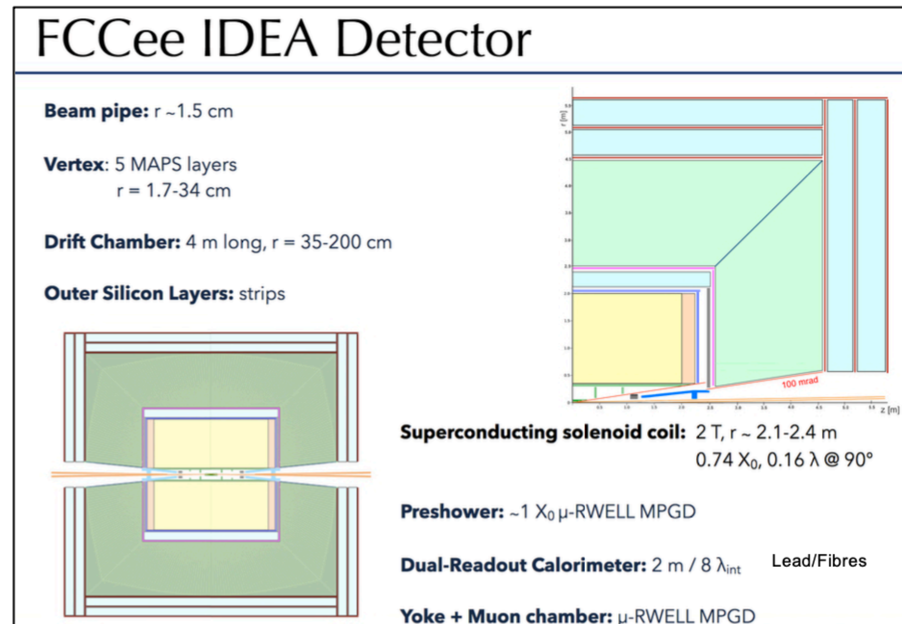
Detectors

- Heavily based on technologies developed at (HL-)LHC
  - but better… (excellent tracking, hadronic resolution, timing..)

CLD concept

IDEA concept





Complementary approaches with lot's of important and innovative work; more concepts under investigation..

The Higgs sector

The Higgs sector

N. A. Hamed (FCC Week 2019)

Higgs is Really New Physics!

* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum
* MUST LOOK AT IT CLOSELY!

The Higgs as an exploration tool

BSM O(1TeV): Impact on H-couplings

1708.08912

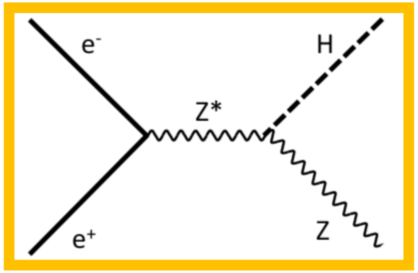
Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
Composite Higgs [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
Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

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

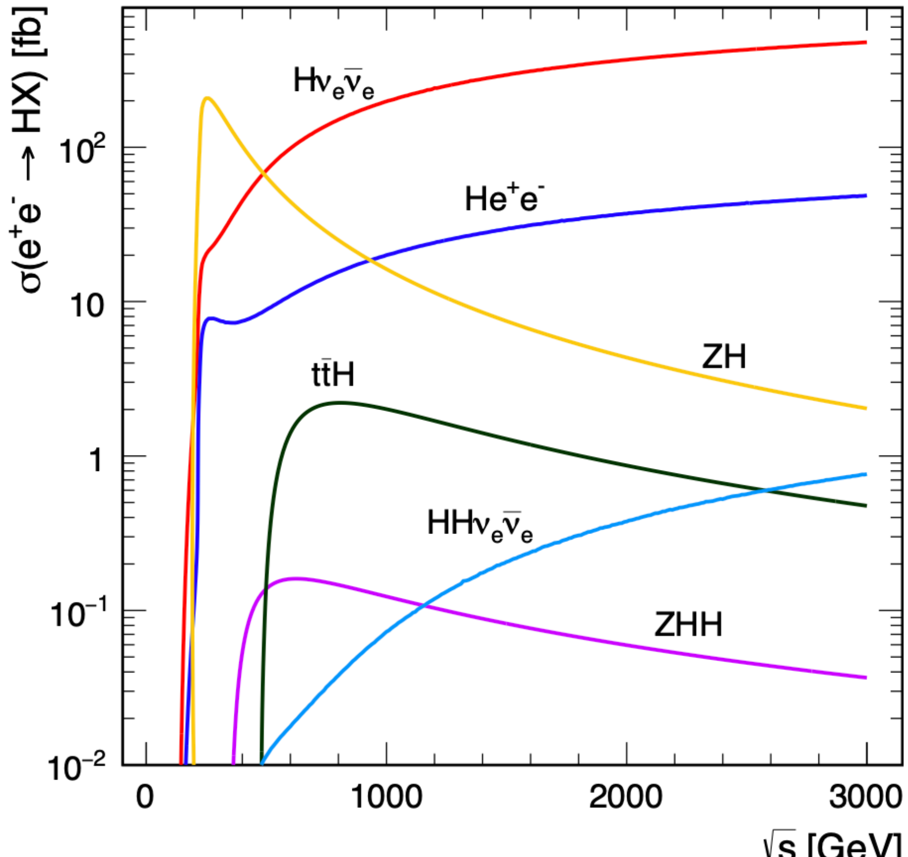
e.g. Λ=1 (5)TeV→~5 (0.1)%

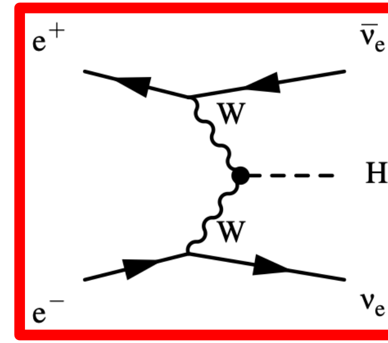
- Future e^+e^- colliders: O(0.1)% precision
- In as many as possible decay modes

Higgs production @e^+e^-



E_{CM} ~(240 GeV):
ZH production dominates



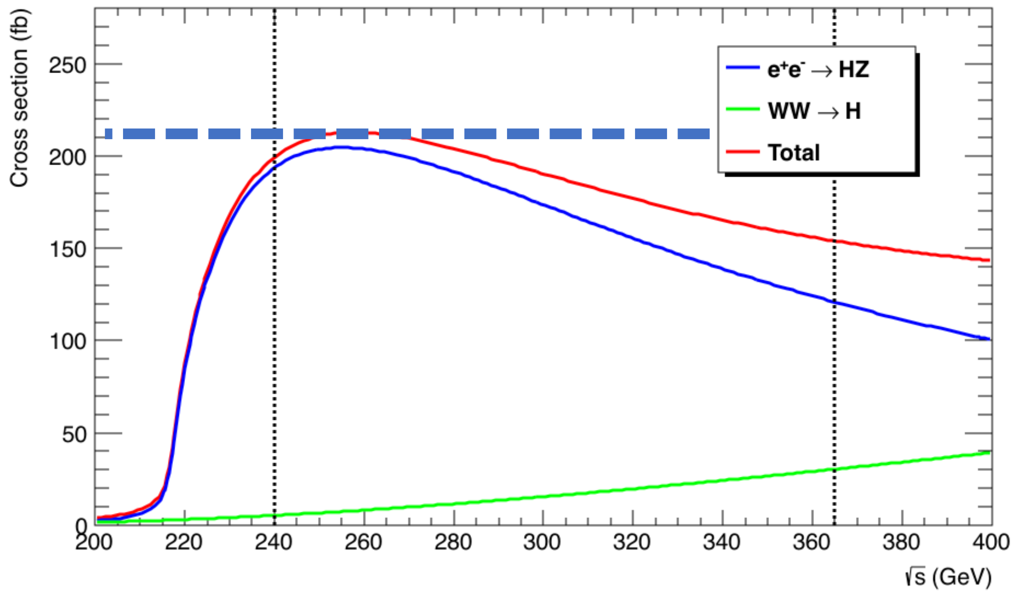


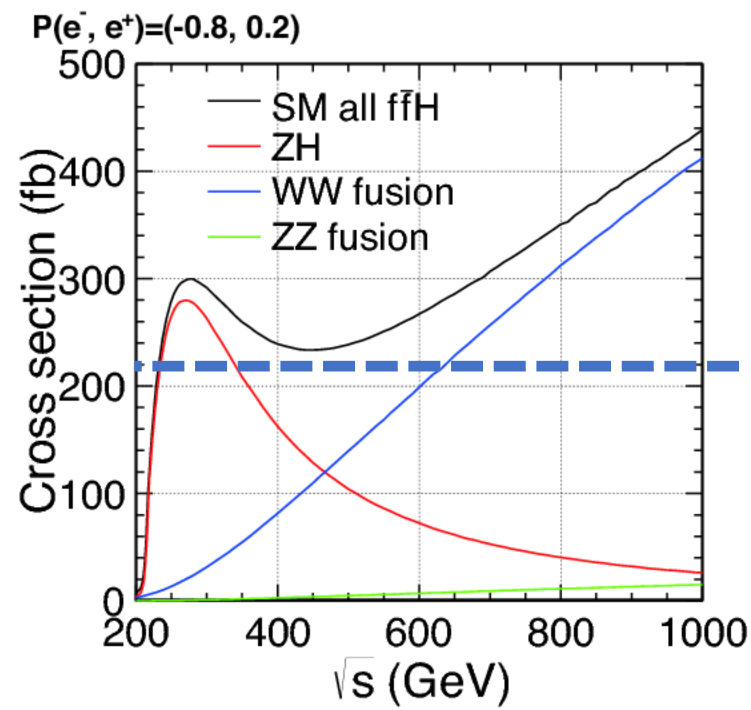
E_{CM}>500 GeV:
Hνν is dominant

E_{CM}>500 GeV:
Opens direct access to HH

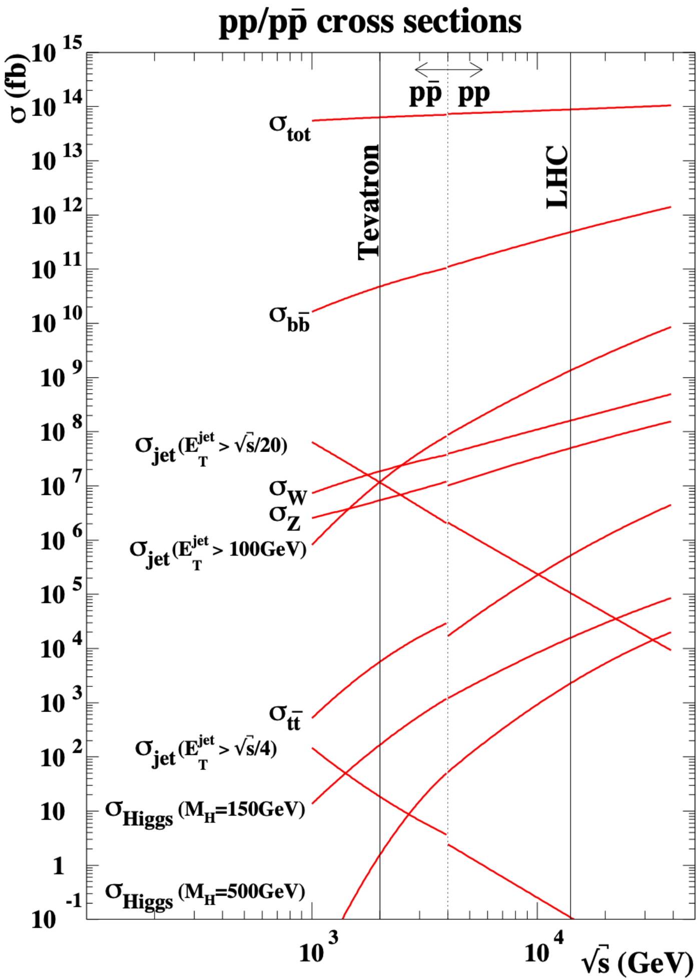
Intermezzo: σ_{Higgs} Circular vs. linear

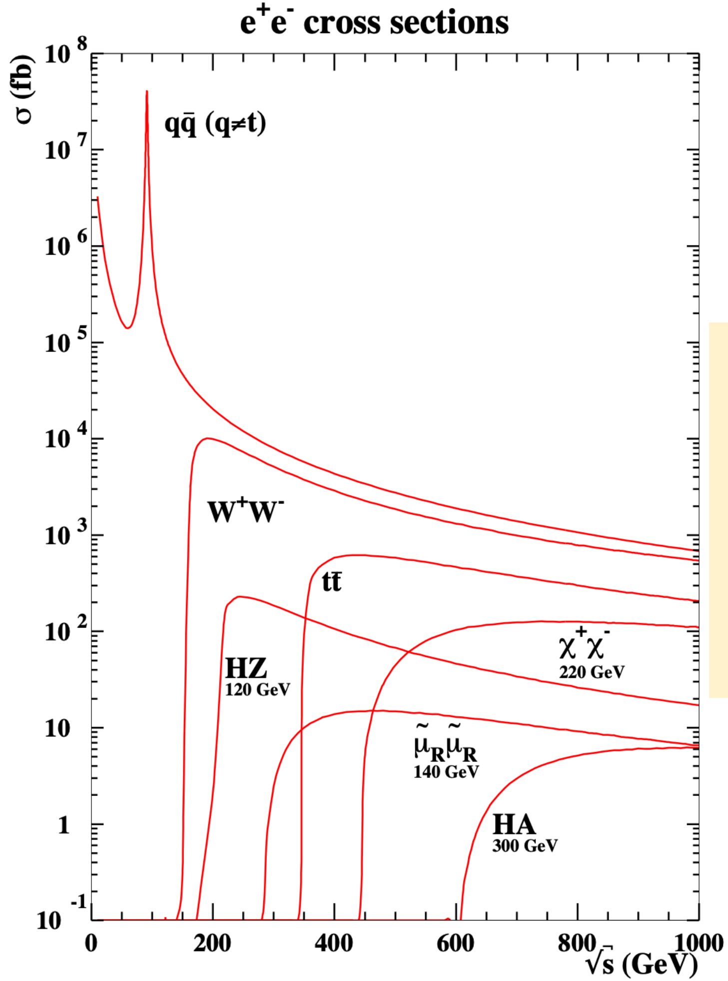
- HW: Why Higgs production cross-section larger in linear colliders (for same E_{CM})?
  - Tip: bean polarization





e^+e^-: Ideal to study the Higgs





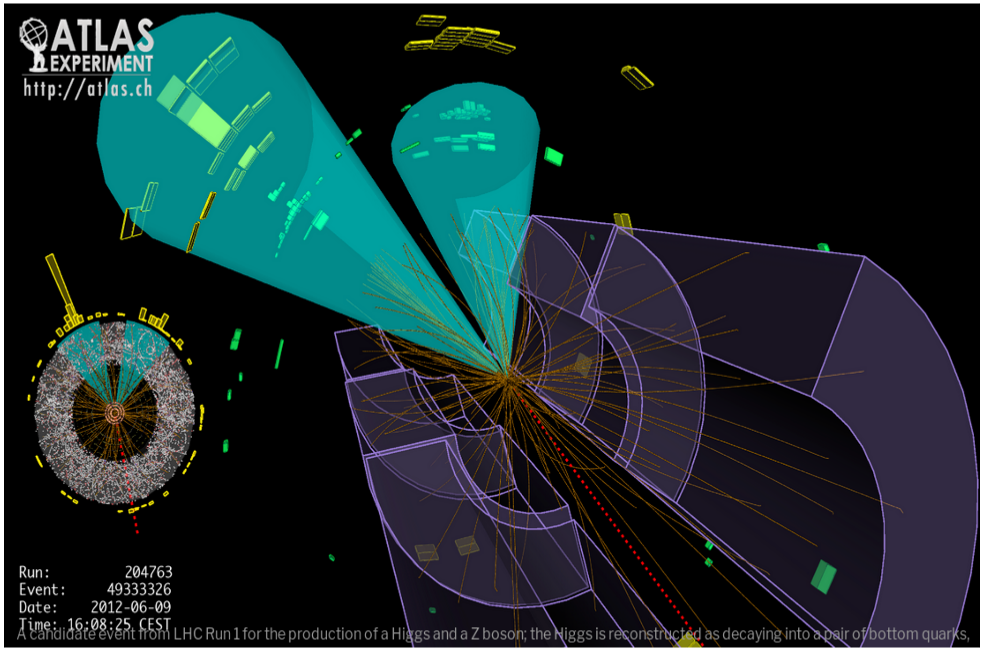
Phys. Rep. 426 (2006)

e^+e^- colliders:
Much (much) smaller BKGs than in hadron colliders

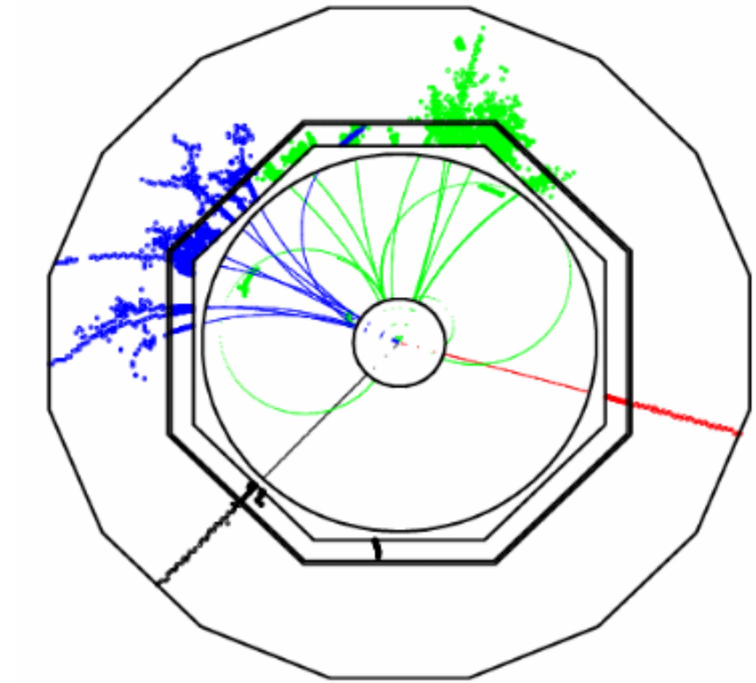
NB: old plots (before Higgs discovery)

e^+e^-: Ideal to study the Higgs

LHC: Z(->νν)H(->bb)



e^+e^-: Z(->μμ)H(->bb)

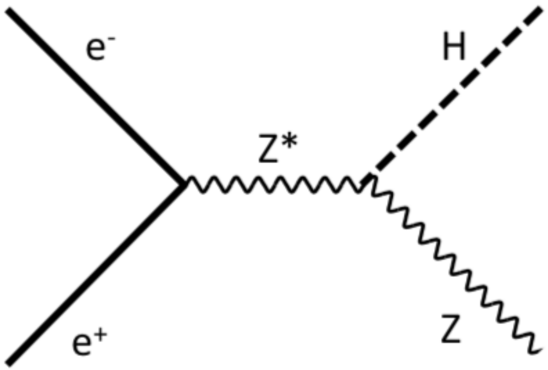


e^+e^- colliders:

- Much cleaner environment
- Record all events (trigger-less readout)
- Essentially every event is signal/interesting

The recoil mass (m_{rec}) method

$e^+e^- \rightarrow ZH$ production



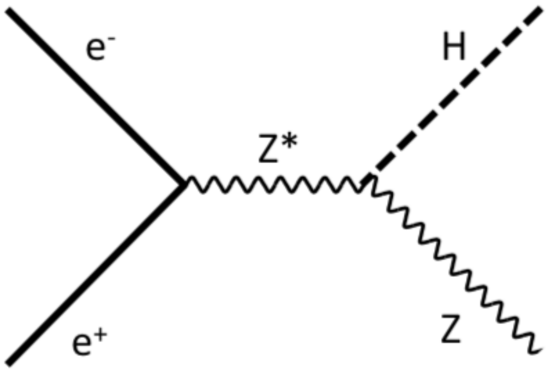
- Tag the Z-boson
- Calculate recoil mass (m_{rec})
  - E/p conservation;
    we know E_{CM} ;-)

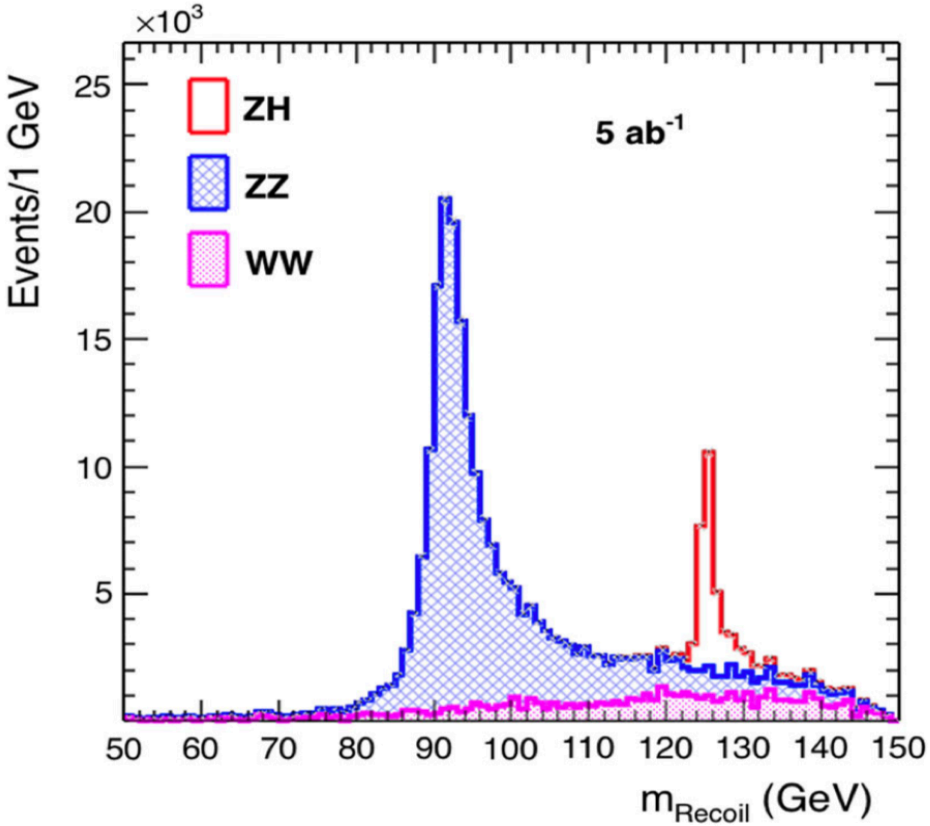
$$m^2_{\mathrm{Recoil}} = s + m^2_{\mathrm{Z}} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

HW: derive this equation

The recoil mass (m_{rec}) method

$e^+e^- \rightarrow ZH$ production





- Tag the Z-boson
- Calculate recoil mass (m_{rec})
  - E/p conservation; we know E_{CM} ;-)

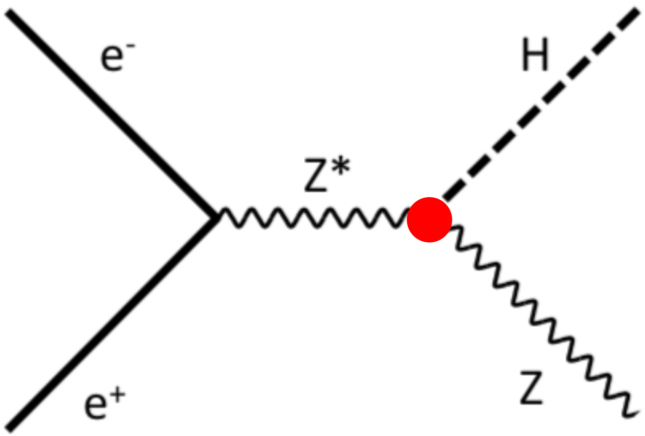
$$m^2_{\text{Recoil}} = s + m^2_Z - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

HW: derive this equation

Unbiased Higgs boson tagging
Unique at e+e- colliders

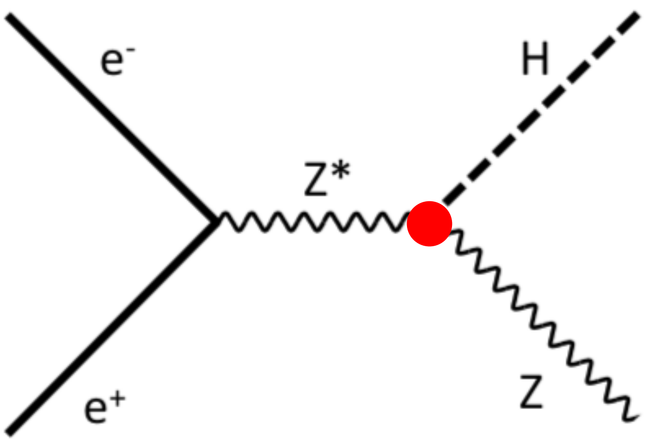
HW: Can be used for BSM particles?

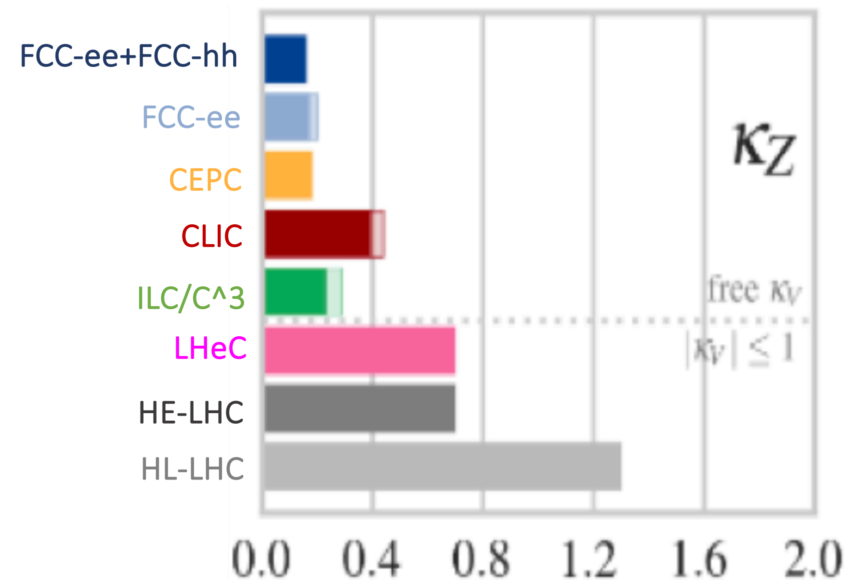
Model independent measurements



- First: measure **ZH** production
  - Rate $\sim g_{HZZ}^2$
    - FCC-ee: O(2M) Higgs bosons: $\delta(g_{HZZ})/g_{HZZ} \sim 0.1\%$

Model independent measurements

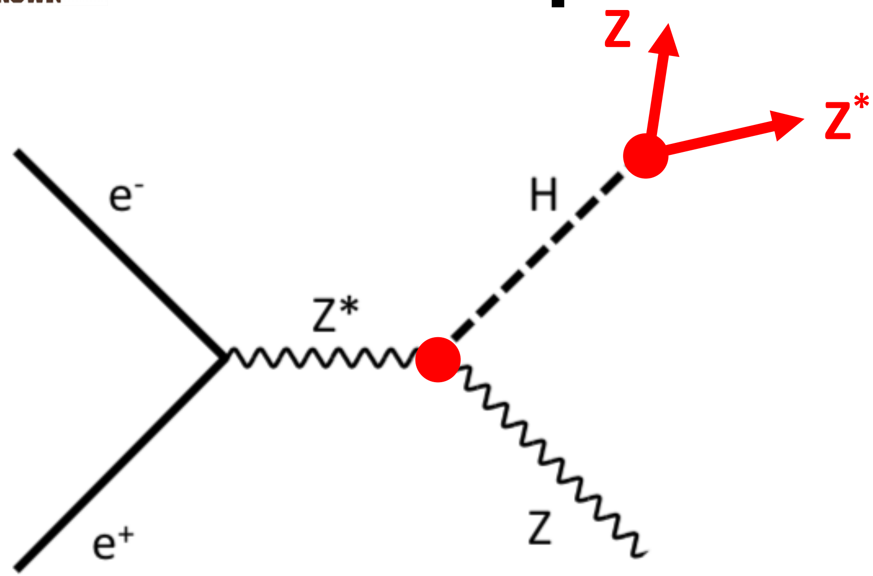


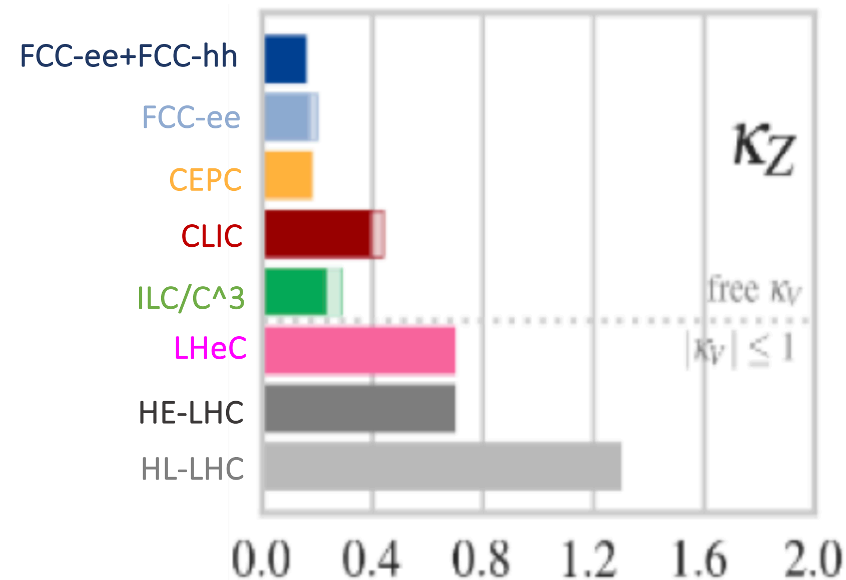


- First: measure **ZH** production
  - Rate ~g_{HZZ}^2
    - FCC-ee: O(2M) Higgs bosons: $\delta(g_{HZZ})/g_{HZZ}$~0.1%

- O(10) improvement wrt HL-LHC
- "Standard candle" for other Higgs measurements (incl. FCC-hh)

Model independent measurements



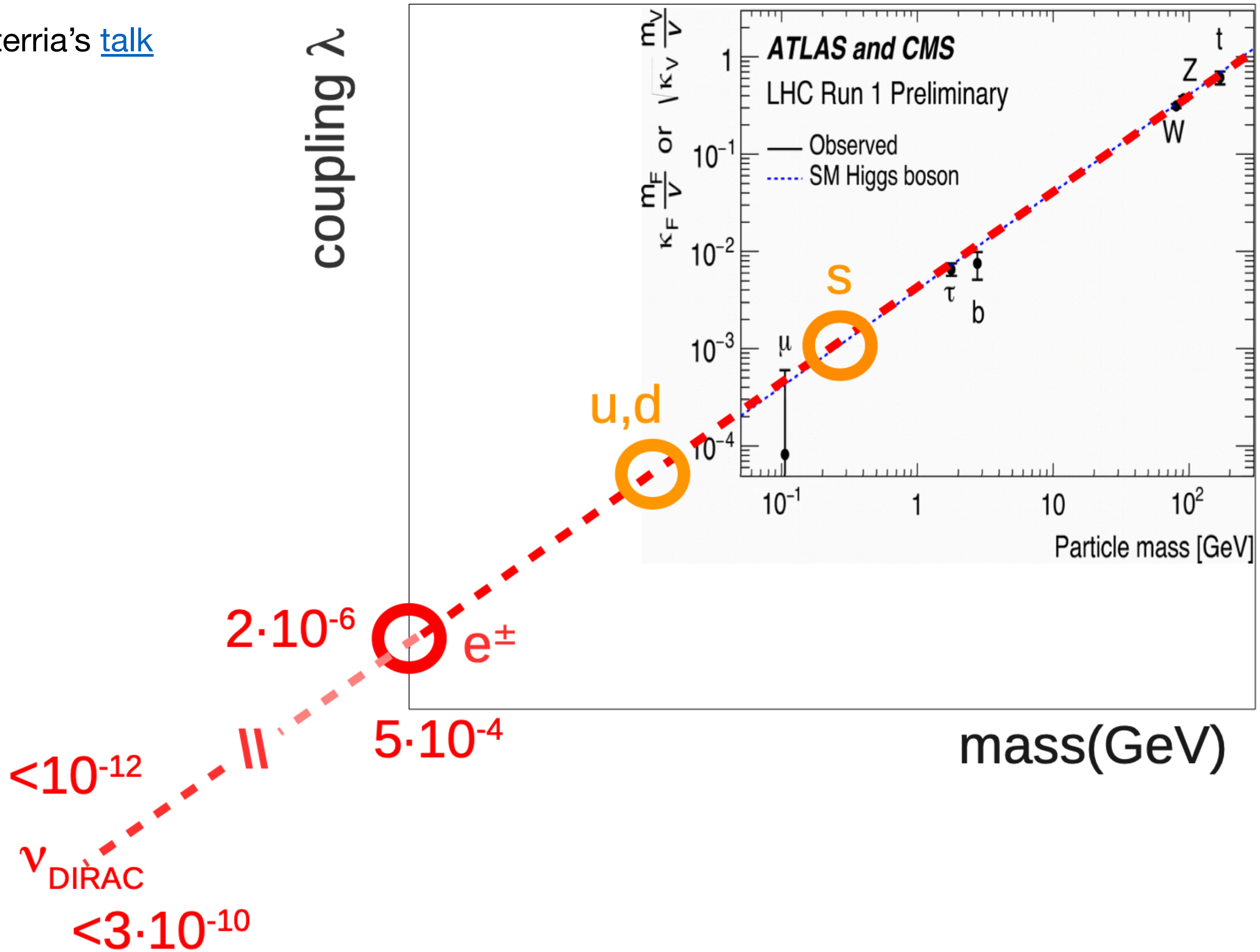


- First: measure **ZH** production
  - Rate ~g_{HZZ}^2
    - FCC-ee: O(2M) Higgs bosons: $\delta(g_{HZZ})/g_{HZZ}$~0.1%
- Then: The width via **ZH**(→**ZZ**)
  - rate ~$g_{HZZ}^4/\Gamma(H)$ → $\delta(\Gamma(H))/\Gamma(H)$~1%

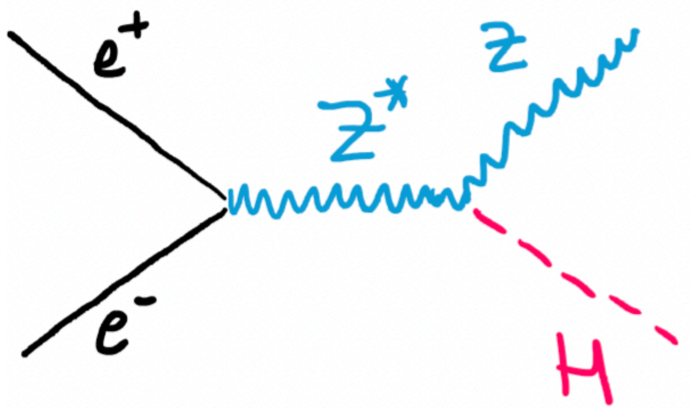
- O(10) improvement wrt HL-LHC
- "Standard candle" for other Higgs measurements (incl. FCC-hh)

Next: Additional Higgs couplings

From D. d'Enterria's talk



Single-Higgs measurements



Z boson reconstruction:
- explore several decay modes
- recoil mass

Higgs boson reconstruction:
- as many as possible decay modes

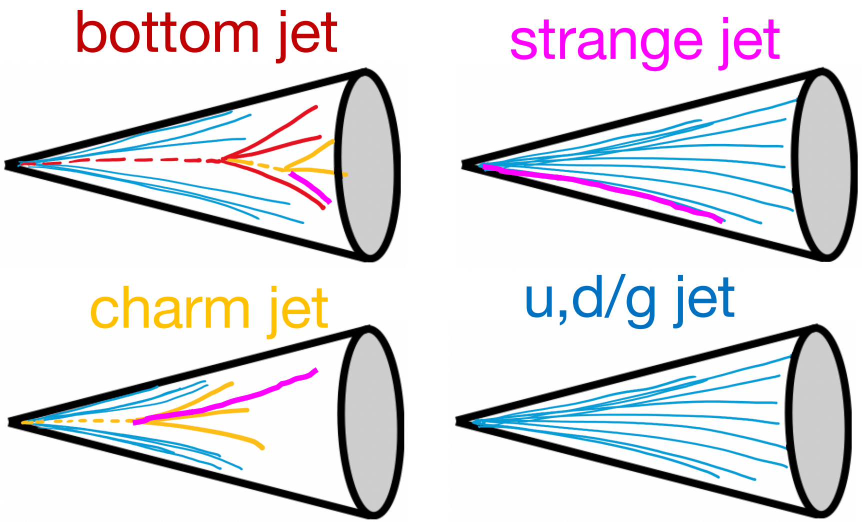
→bb, cc, gg, **ss (!!)**, ..

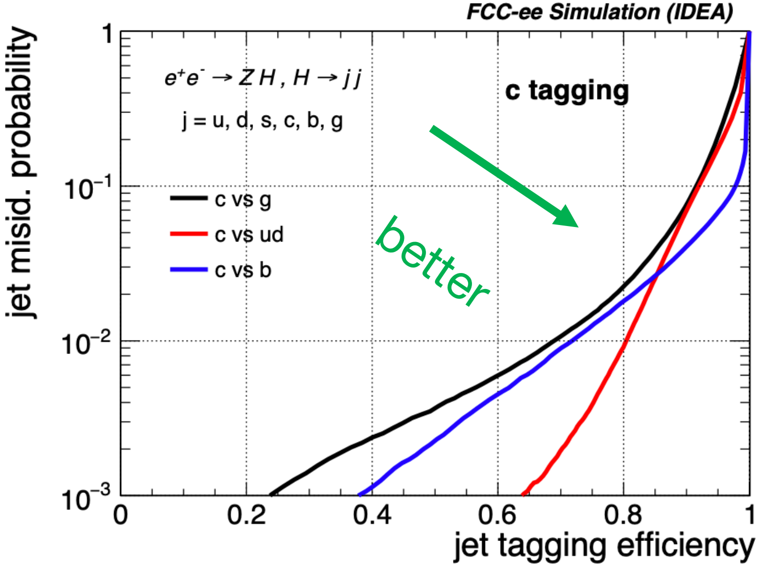
BR(H→hadrons) ~ 80%
BR(Z→hadrons) ~ 70%
Optimal reconstruction and
ID (“tagging”) of hadronic final states essential

Jet identification: The rise of AI/ML

- Started at the LHC (in much more challenging environment)
  - Key player for future lepton colliders

Novel Deep Learning based algorithms under development



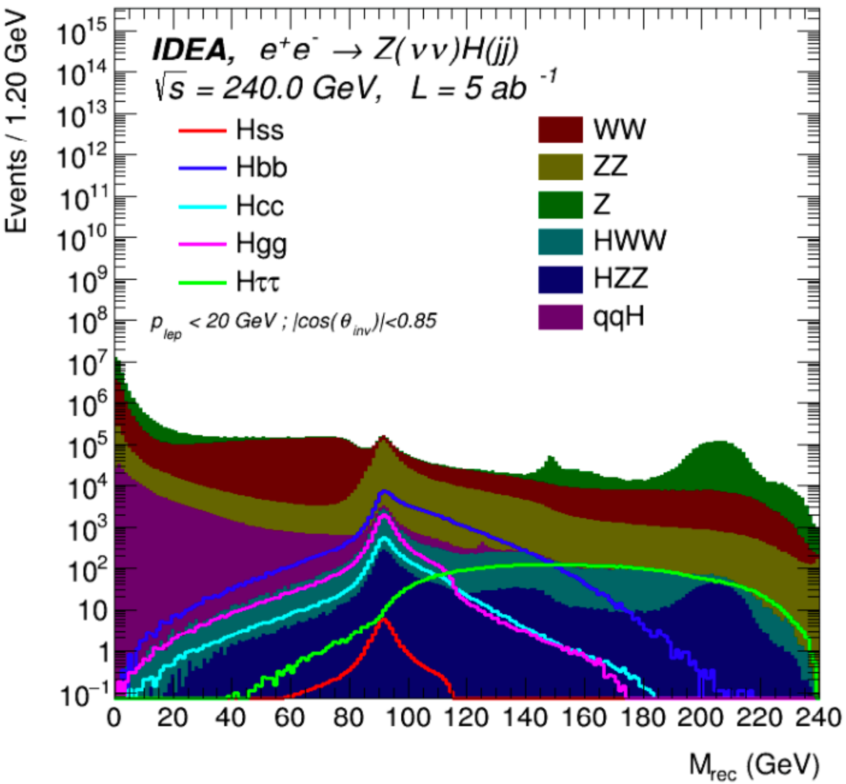


NB: example from FCC-ee; many other tools (e.g., 2202.03285, 2203.07535,2310.03440)

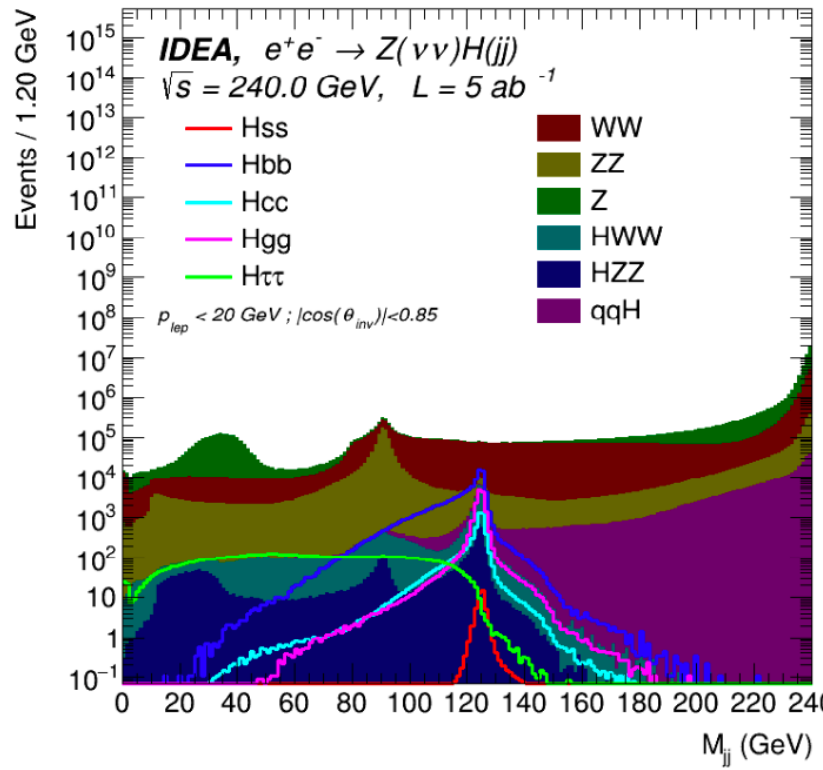
Higgs couplings to "visible" particles

- "LHC style" analyses: Bump hunt in 2D

m_{rec}

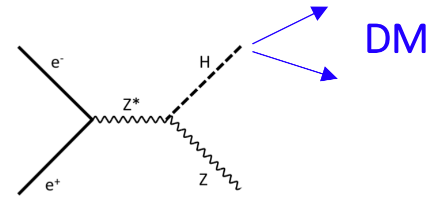


m_{jj}



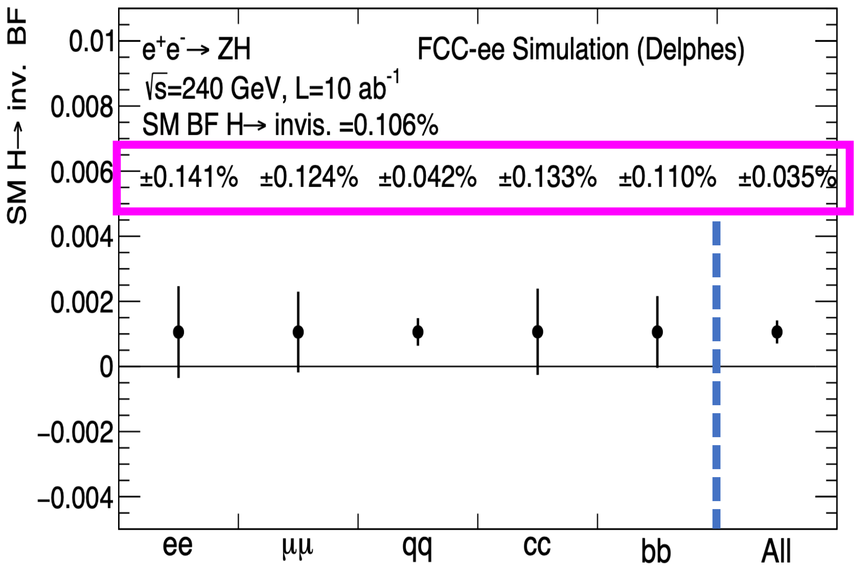
Higgs to invisible

- Portal to Dark Matter (DM)
  - SM: BR(H→ZZ*→4ν) ~0.1%



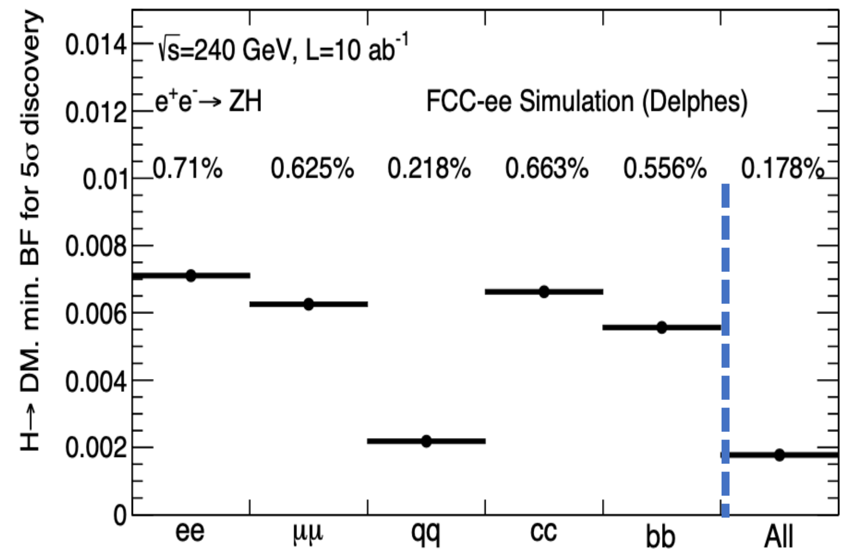
Goal: Reach neutrino floor

SM H→inv reach



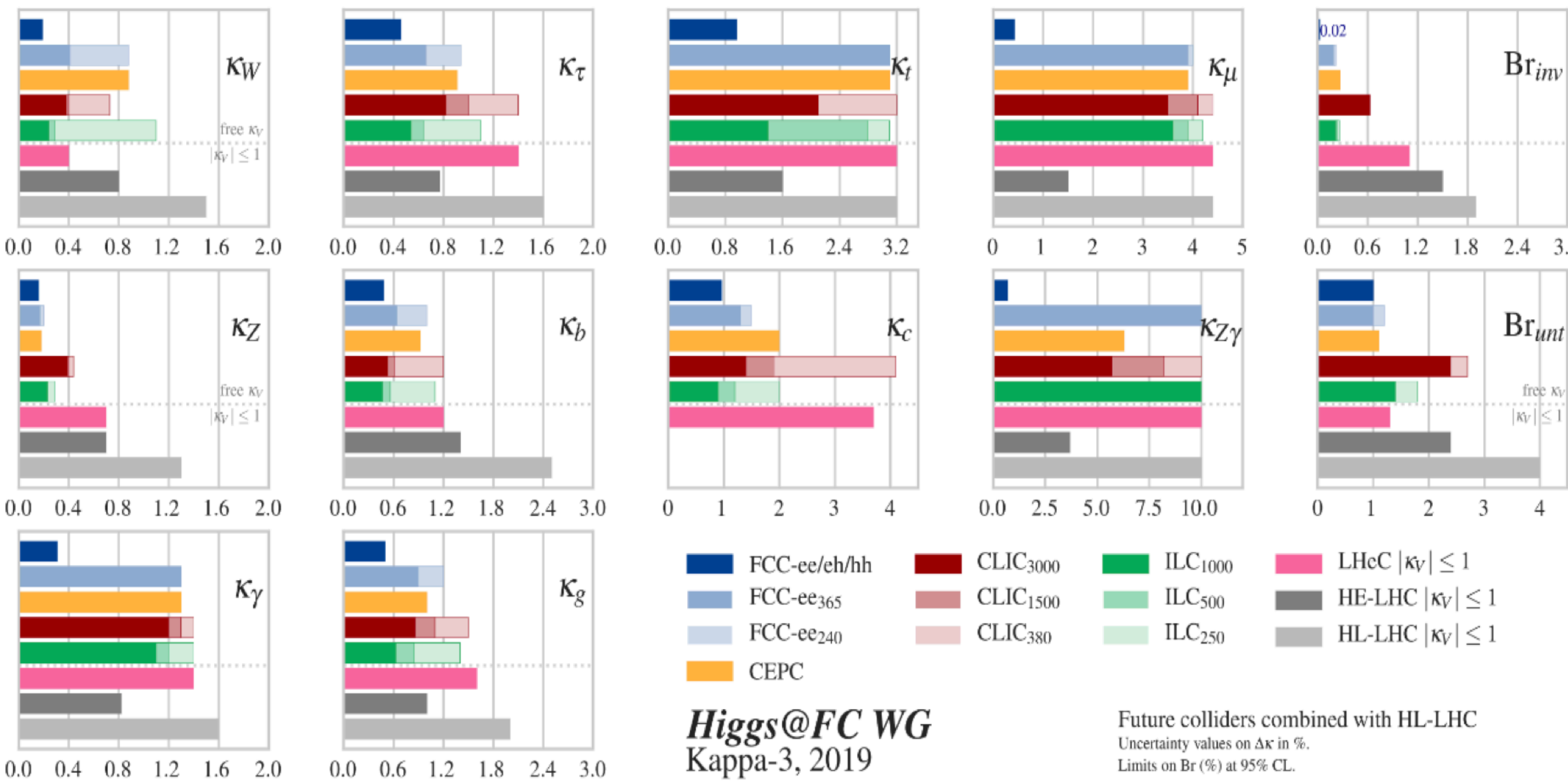
Impossible at the HL-LHC

5σ discovery potential



Single-Higgs: Grand Summary

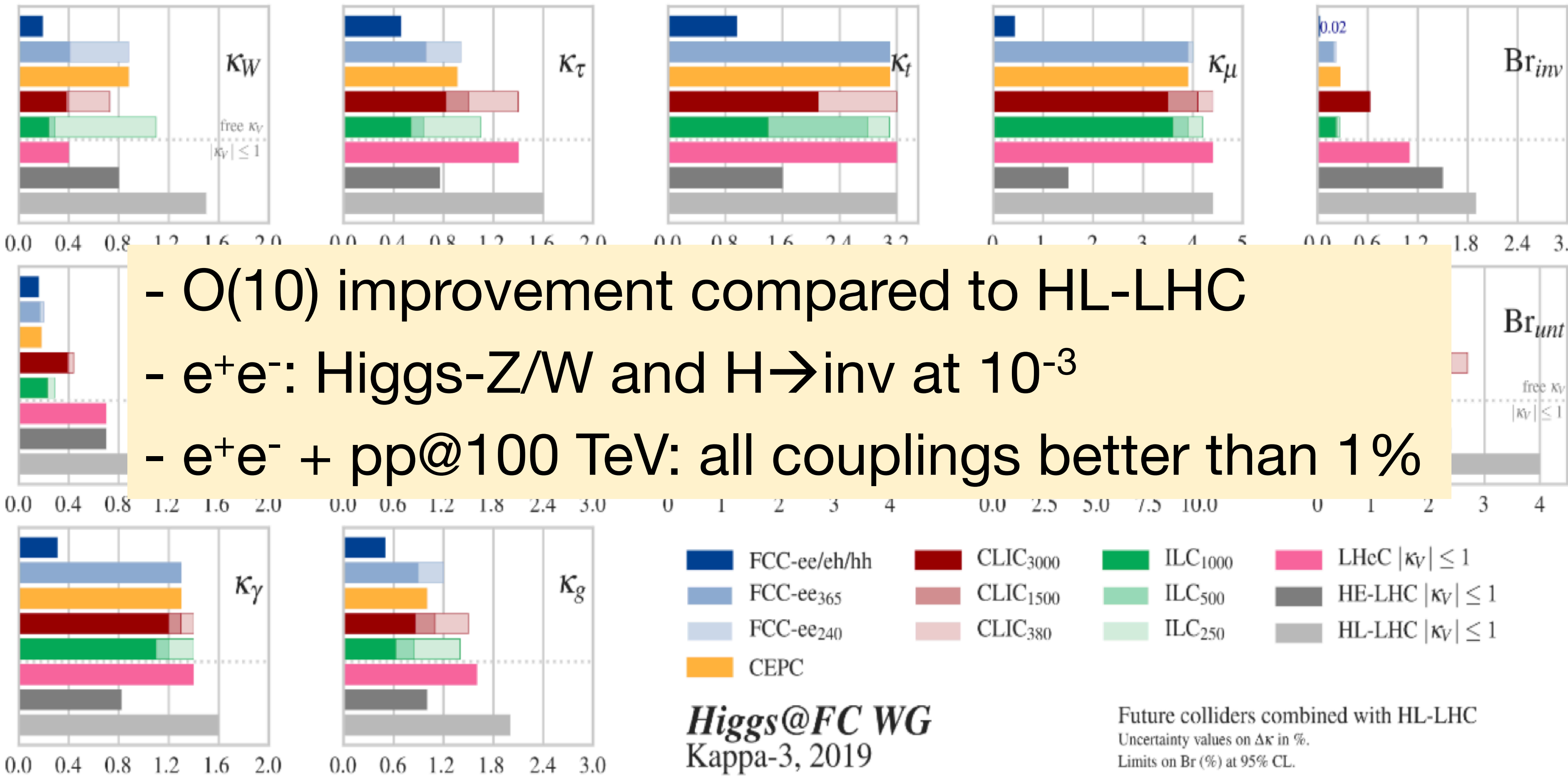
1905.03764



Single-Higgs: Grand Summary

1905.03764

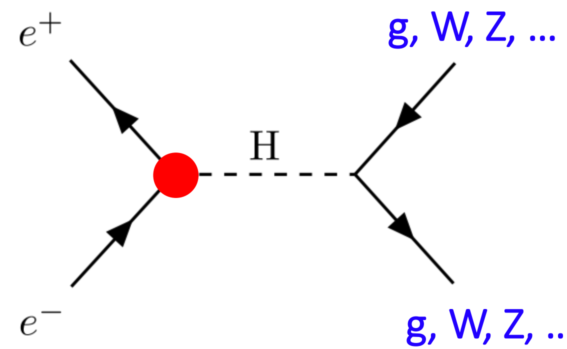
- O(10) improvement compared to HL-LHC
- e^+e^-: Higgs-Z/W and H→inv at 10^{-3}
- e^+e^- + pp@100 TeV: all couplings better than 1%



Unique at Circular Colliders: H→ee

2203.06520
2107.02686

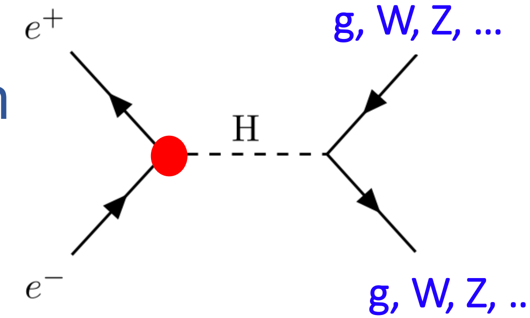
- FCC-ee/CEPC: Resonant Higgs production
  - Tiny signal BR(H→ee) ~10^{-9} vs. huge BKGs
    - Impossible using the standard approach [i.e., target H→ee decays]
- Instead:
  - Resonant Higgs production
  - Probe **Higgs-e coupling** at production
- Thanks to large luminosity at FCC-ee
  - 20 ab^{-1}/year/IP → ~10K Higgs
  - There is potential ..

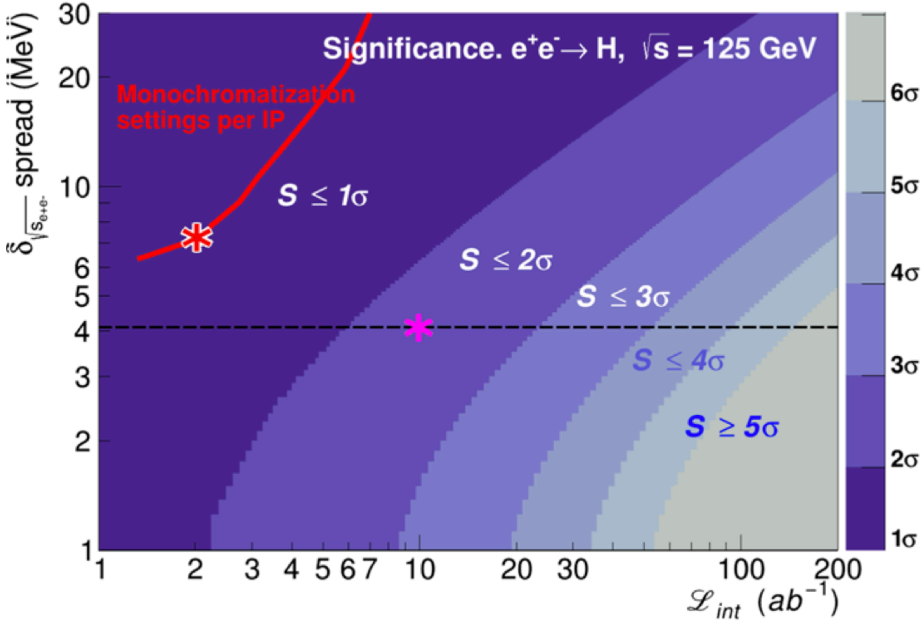


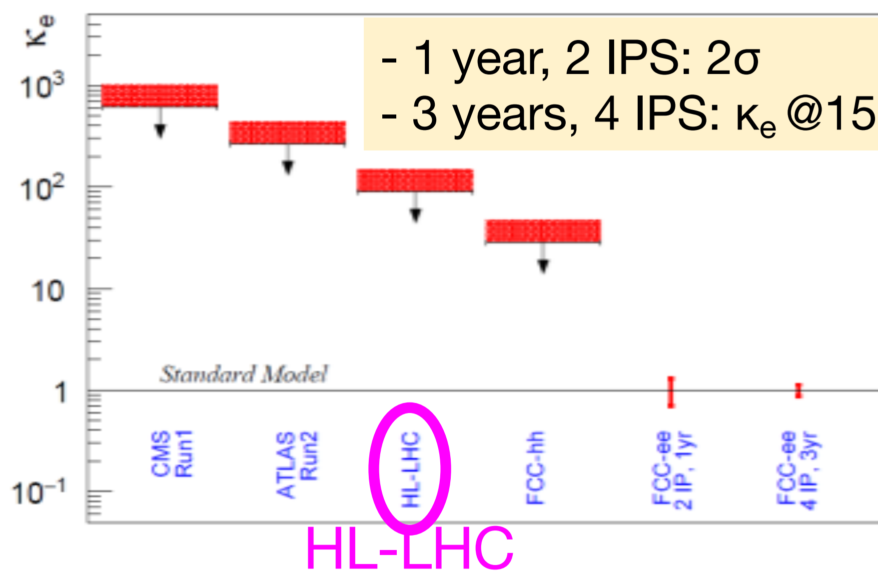
Unique at Circular Colliders: H→ee

2203.06520
2107.02686

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

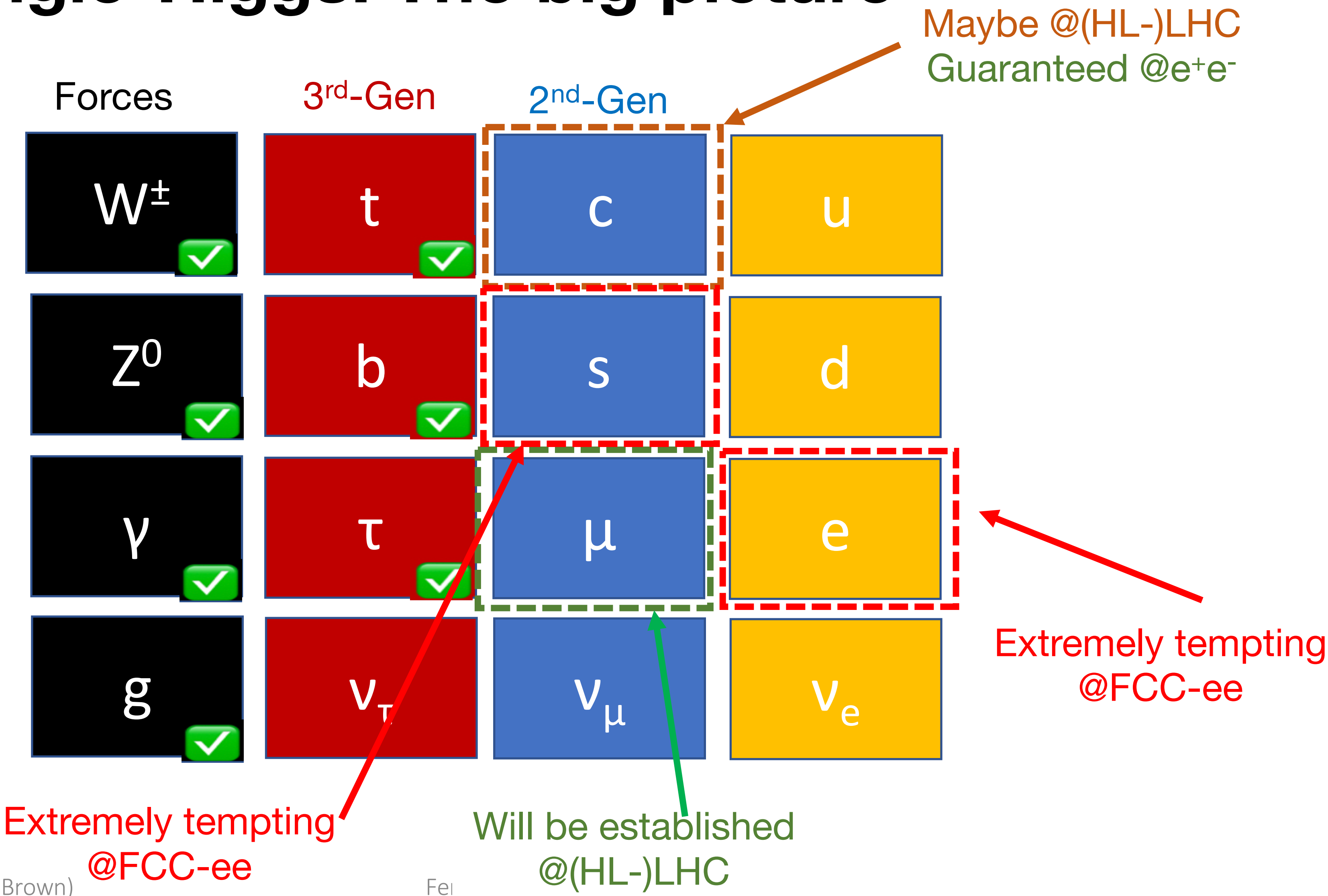




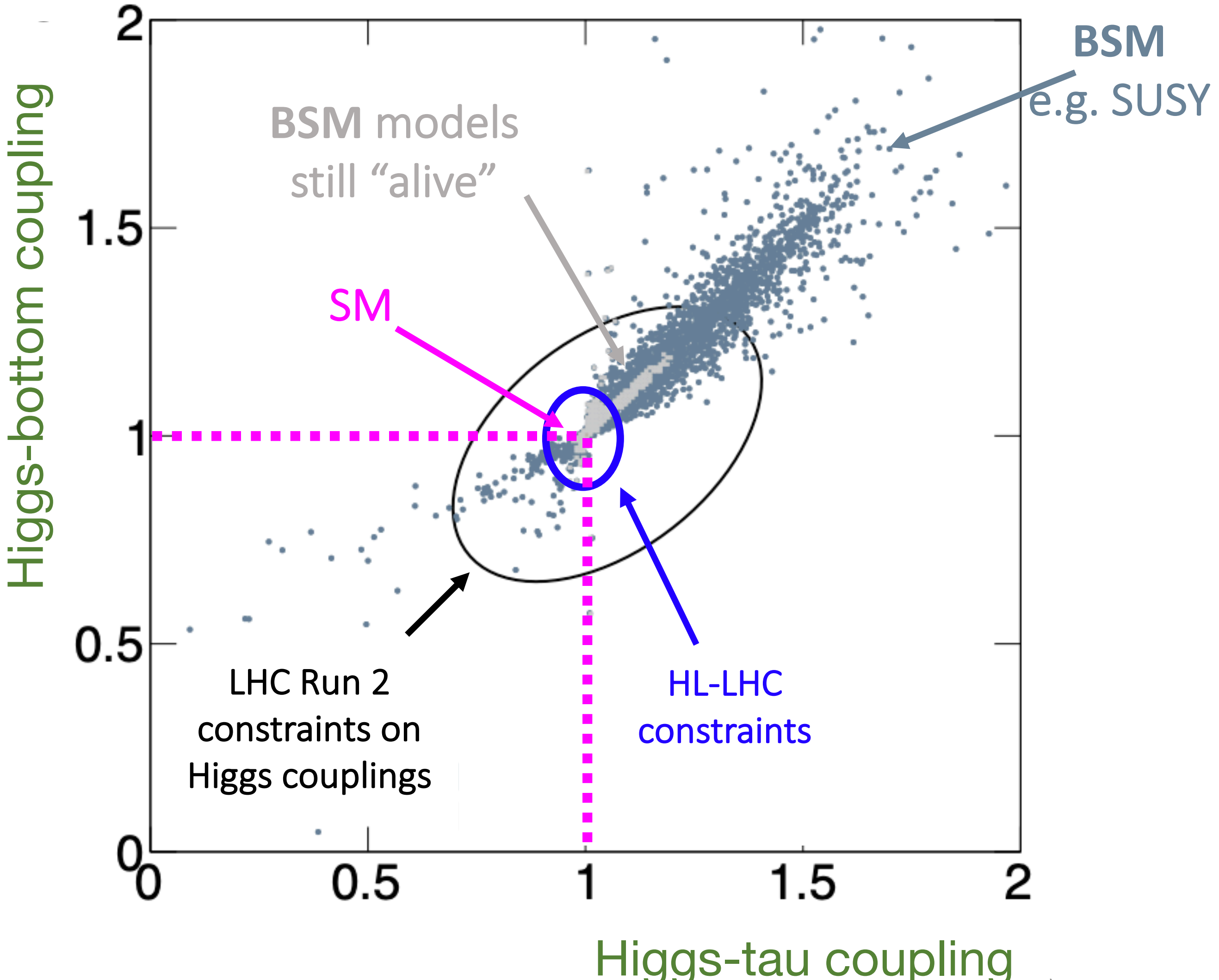


- 1 year, 2 IPS: 2σ
- 3 years, 4 IPS: κ_e @15%

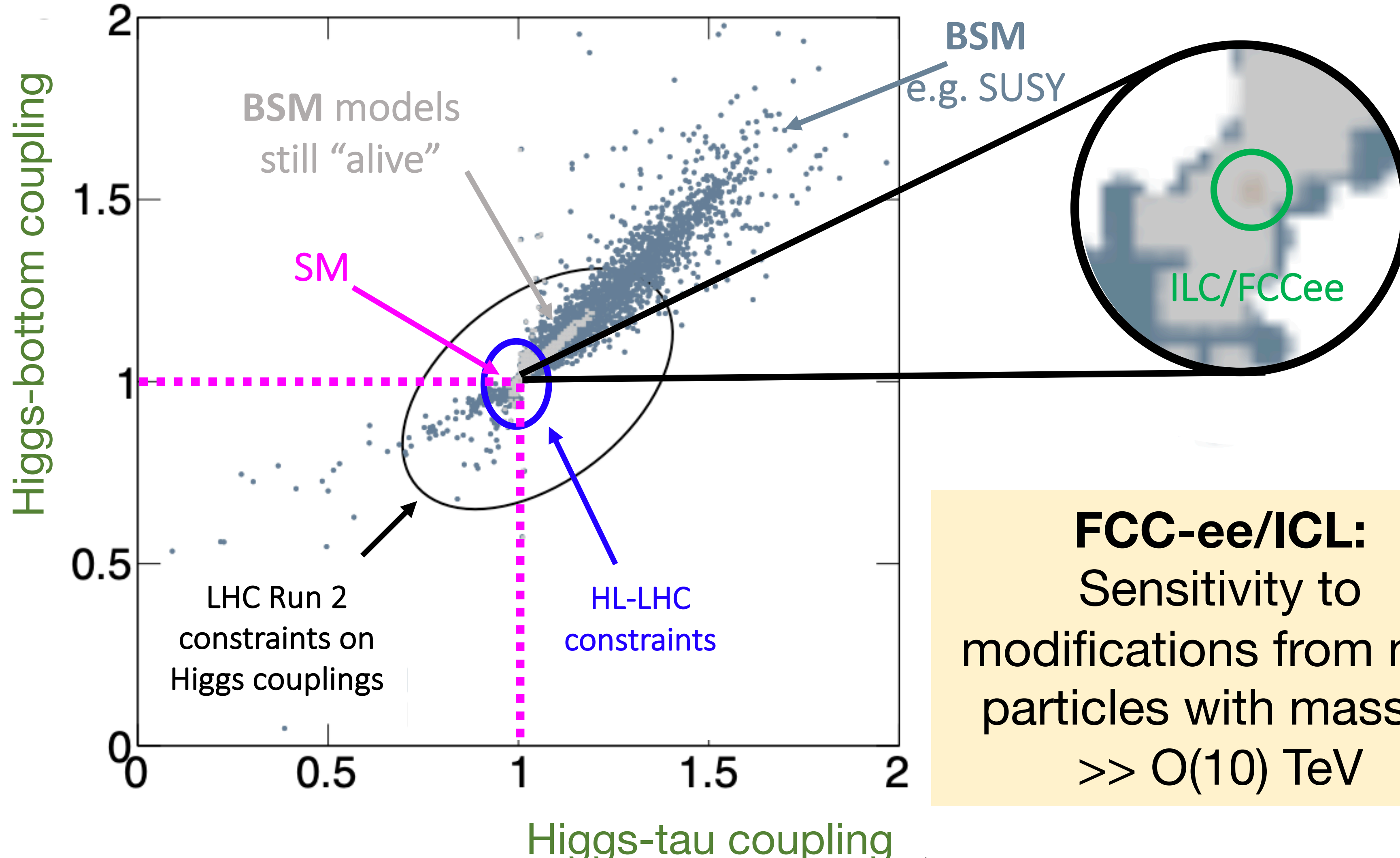
Single-Higgs: The big picture



Precision → Sensitivity to New Physics



Precision → Sensitivity to New Physics

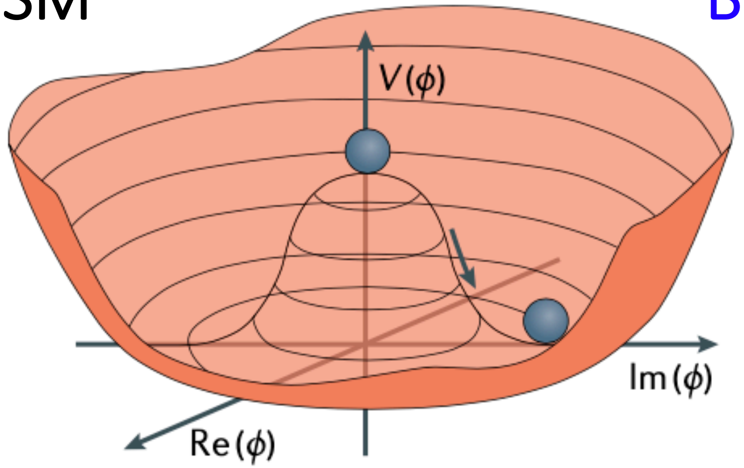


FCC-ee/ICL:
Sensitivity to modifications from new particles with masses >> O(10) TeV

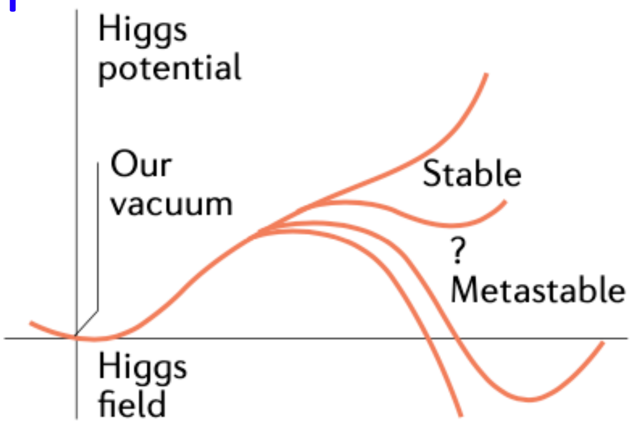
The nature of the Higgs potential

- Major milestone towards fully exploring the Higgs properties
  - Understand how EWK symmetry broke in the early universe
    - Is mass generation connected to the matter-antimatter asymmetry

SM



BSM



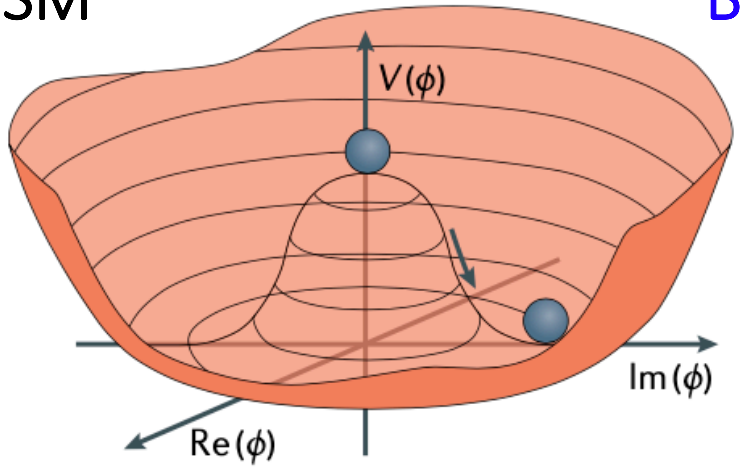
$$V(h) = \boxed{\frac{1}{2}M_H^2 H^2} \cdots$$

Higgs mass

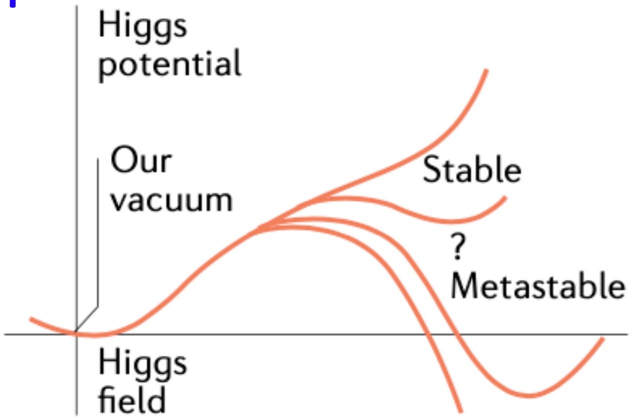
The nature of the Higgs potential

- Major milestone towards fully exploring the Higgs properties
  - Understand how EWK symmetry broke in the early universe
    - Is mass generation connected to the matter-antimatter asymmetry

SM

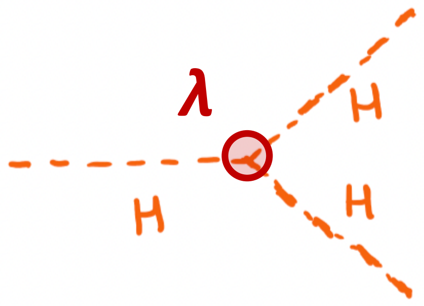


BSM



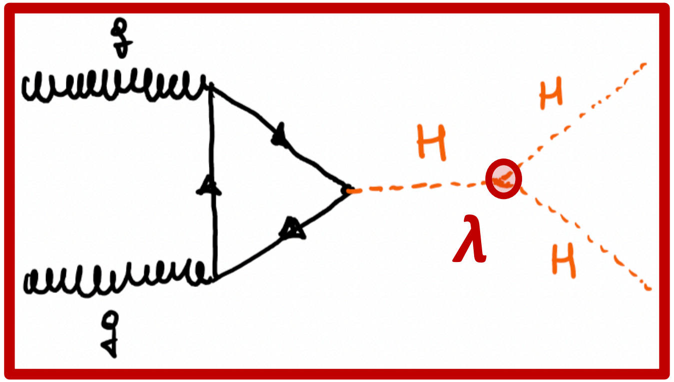
$$V(h) = \frac{1}{2}M_H^2 H^2 + \frac{1}{3!}\sqrt{3\lambda_H} M_H H^3 + \frac{1}{4!}\lambda_H H^4$$

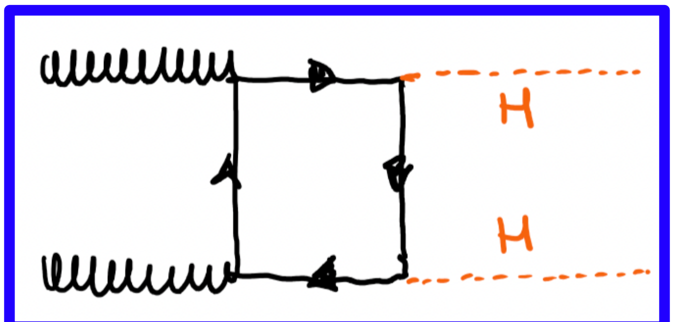
Higgs mass — Shape of potential



Higgs self coupling (λ): (HL-)LHC

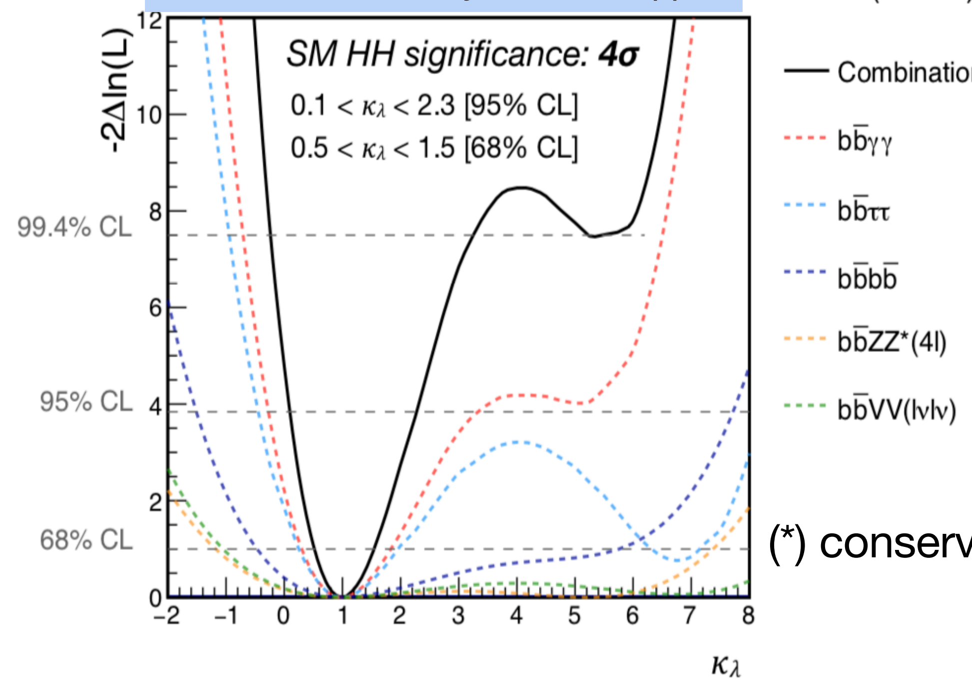
Dominant production: ggF





- Extremely rare (σ ~31fb)
  - 1/1000 of single-H; ~4K HH LHC Run 2

HL-LHC Projections (*)



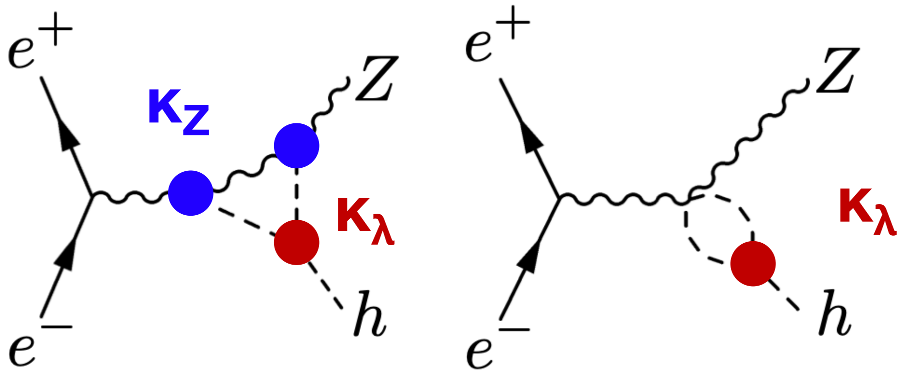
(*) conservative

Which precision?
- BSM @("few" TeV): ~25-50%
- Loop diagrams: ~10%
- Quantum corrections: ~1%

Higgs self coupling (λ): e^+e^-

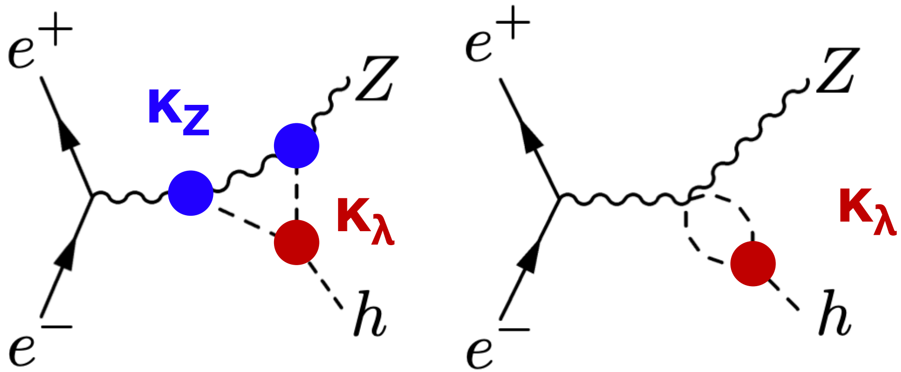
(a) Via loops (FCC-ee/CepC)

2107.02686

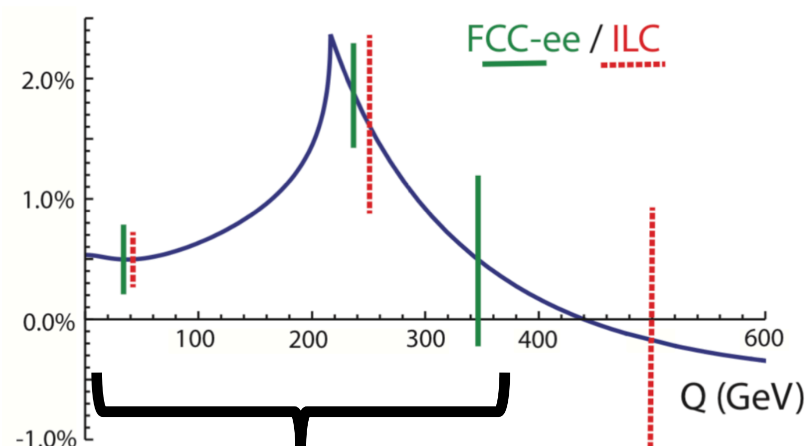


(a) Via loops (FCC-ee/CepC)

2107.02686



Relative enhancement of ZH production

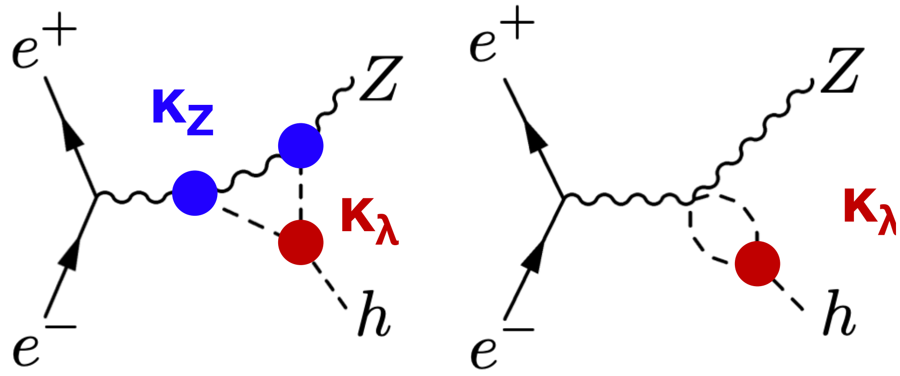


Indirect access

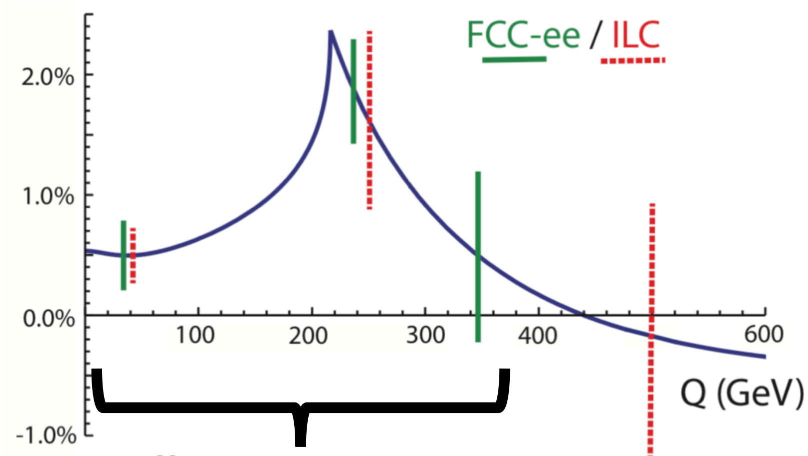
Direct access

(a) Via loops (FCC-ee/CepC)

2107.02686



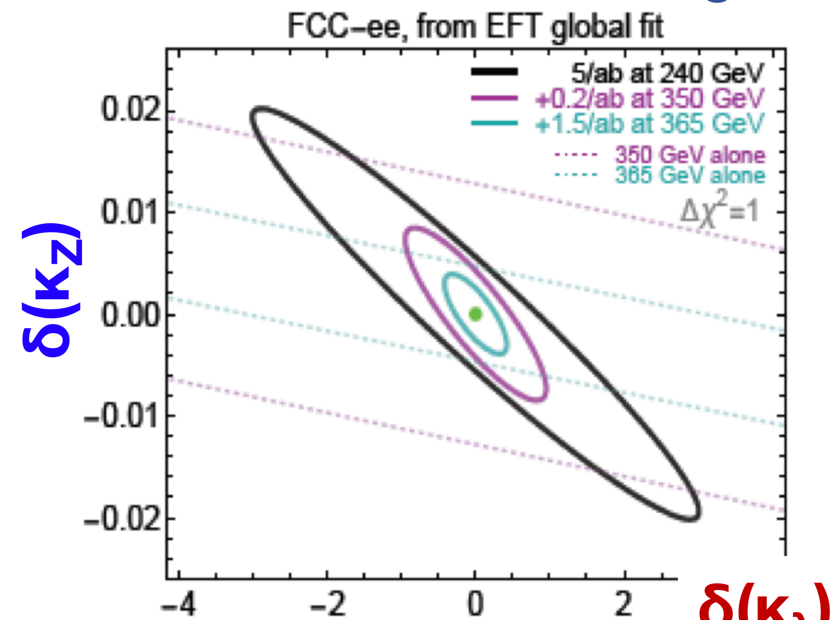
Relative enhancement of ZH production



Indirect access

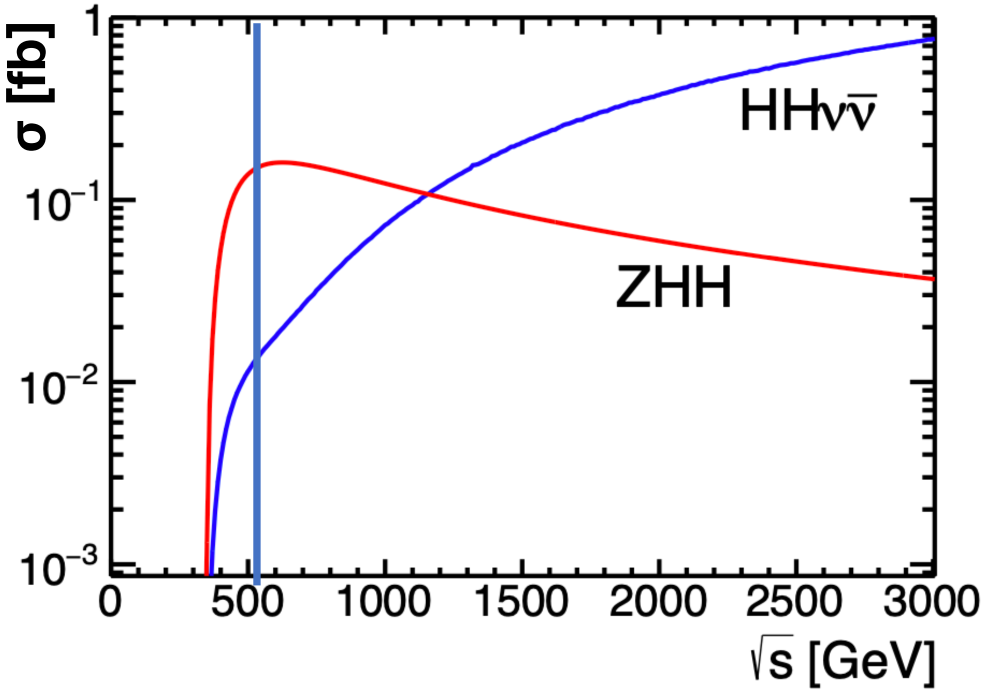
Direct access

- Key points:
  - Precise κ_Z measurement
  - Different collision energies

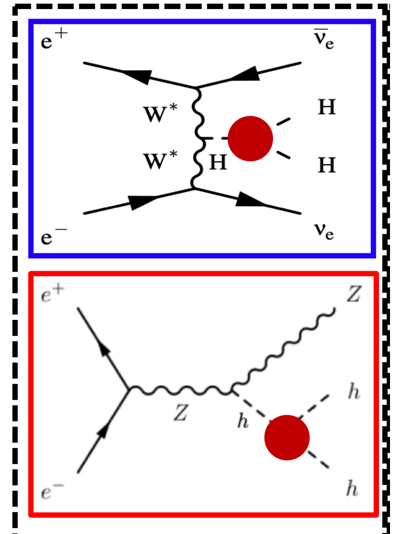


O(10-20%) precision on λ
[other couplings at SM-values]
model-dependence

(b) Direct access (ILC/C^3/CLIC)

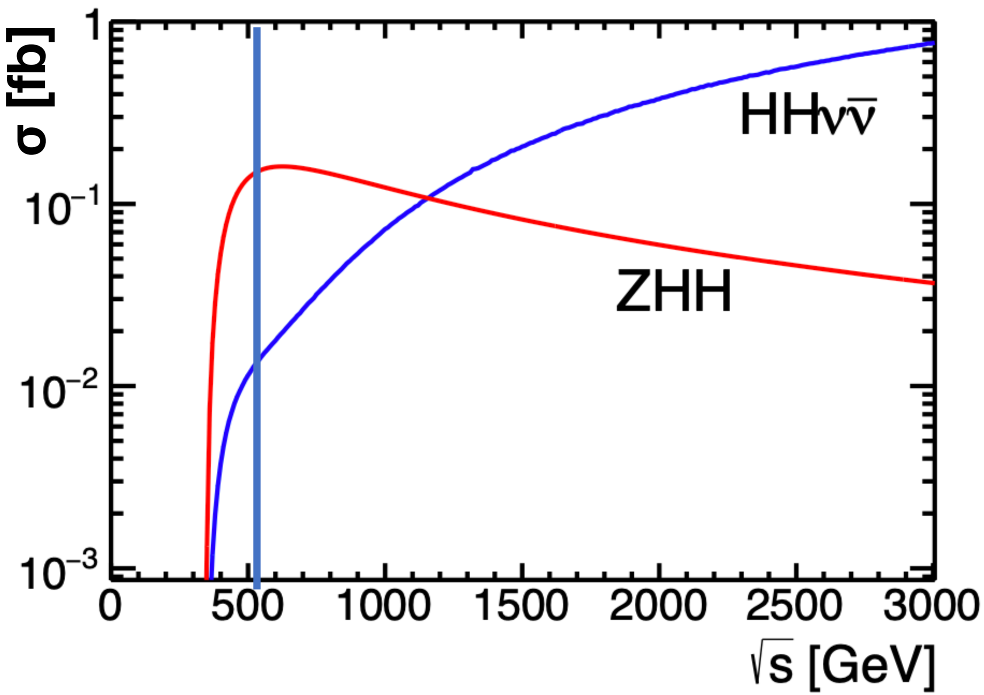


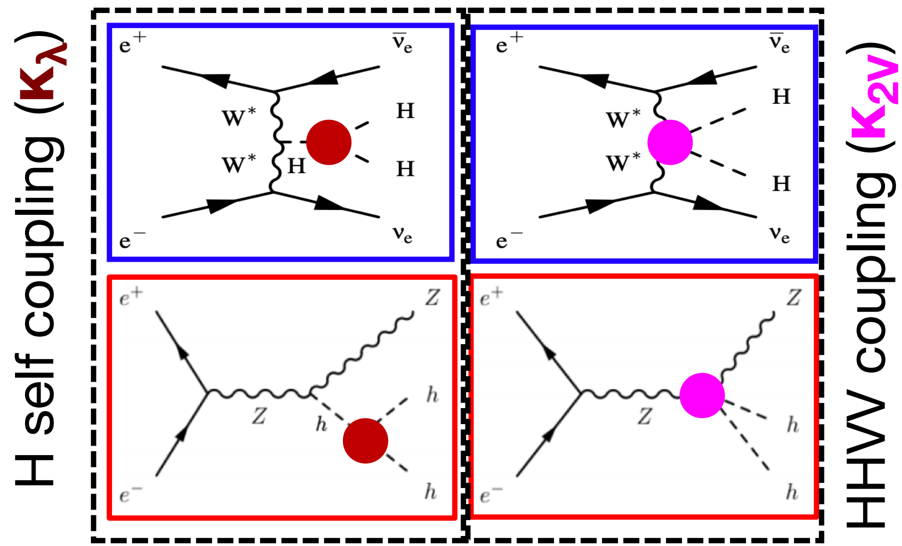
H self coupling (κ_λ)



- 30x smaller rate compared to hadron colliders
  - but much much smaller BKGs

(b) Direct access (ILC/C^3/CLIC)



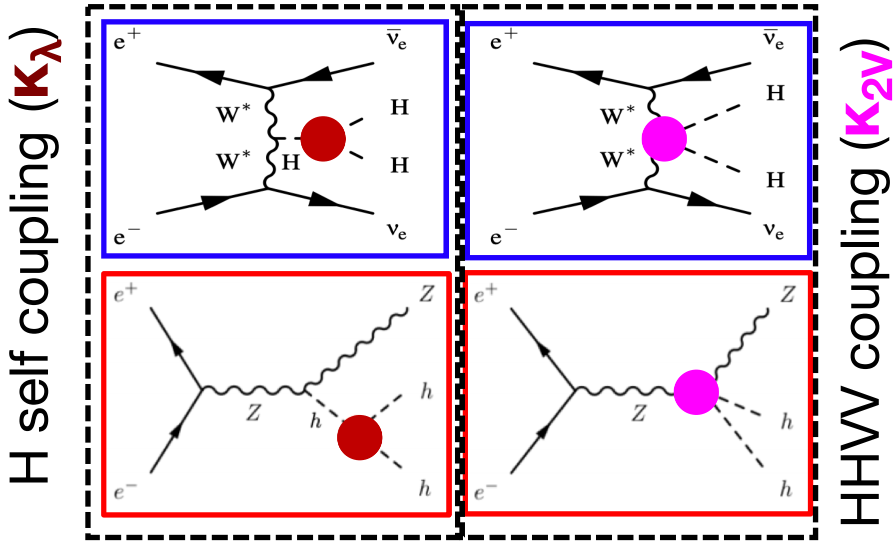


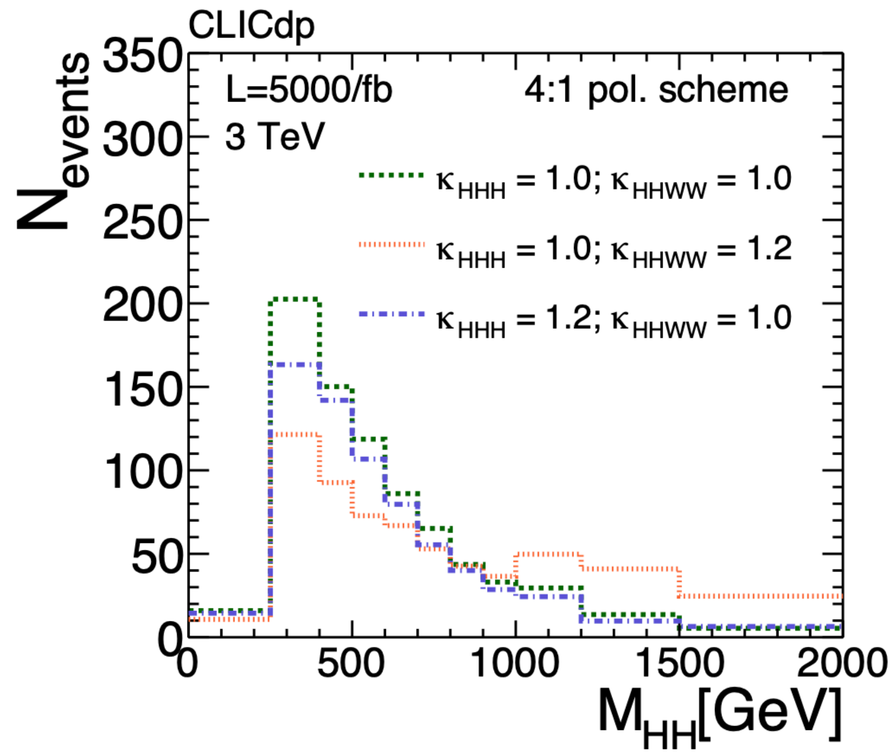
- 30x smaller rate compared to hadron colliders
  - but much much smaller BKGs

Need to disentangle κ_λ and κ_{2V}

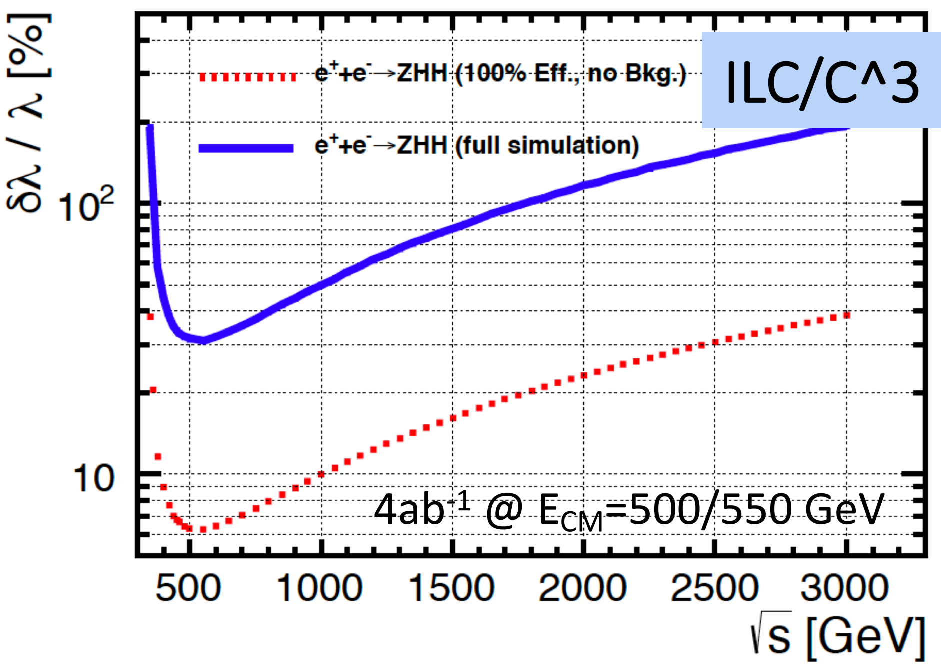
(b) Direct access (ILC/C^3/CLIC)

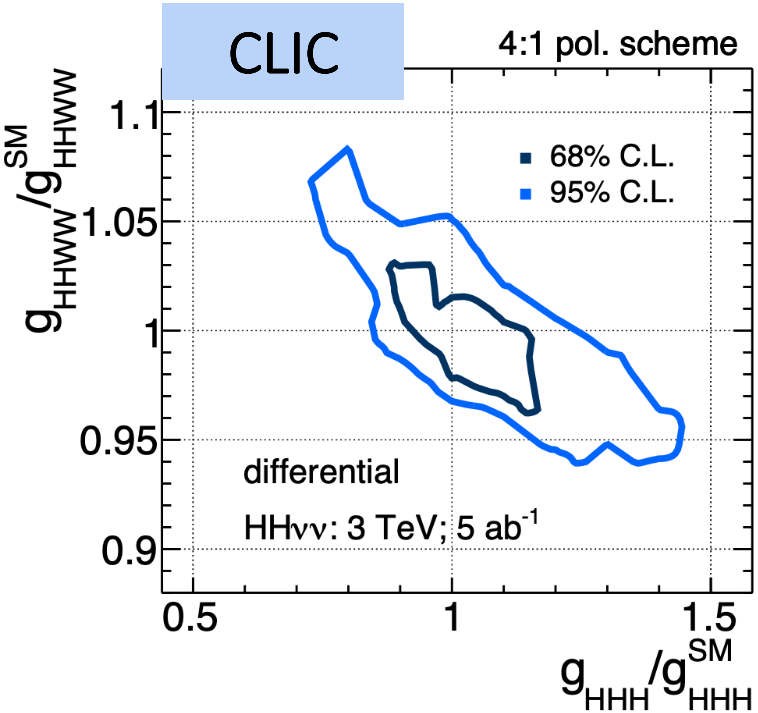
Use m_{HH} to disentangle κ_λ-κ_{2V}





- **Higgs** → 4b, bbWW; **Z** → leptonic+hadronic decays





- **ZHH:** ILC/C^3: $\delta(\kappa_\lambda)$~20-30%; CLIC: ZHH observation ~6σ
- **HHνν:** >3σ evidence @CLIC E_{CM}=1.4 TeV

Requires smart ideas to reach the statistical limit (red) → you ?

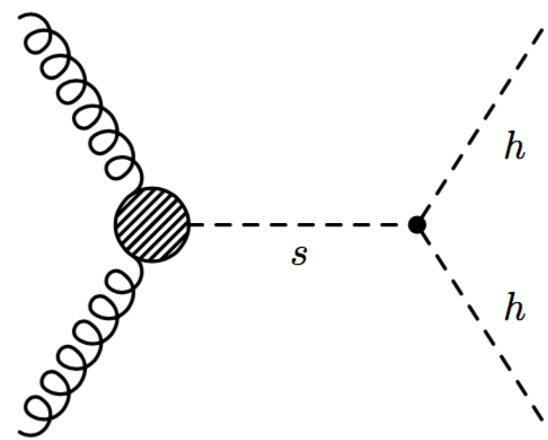
Higgs-self coupling: Grant Summary

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	—	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	—	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	—	33%
FCC-ee (4 IPs) [55]	24%	—	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

- 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]

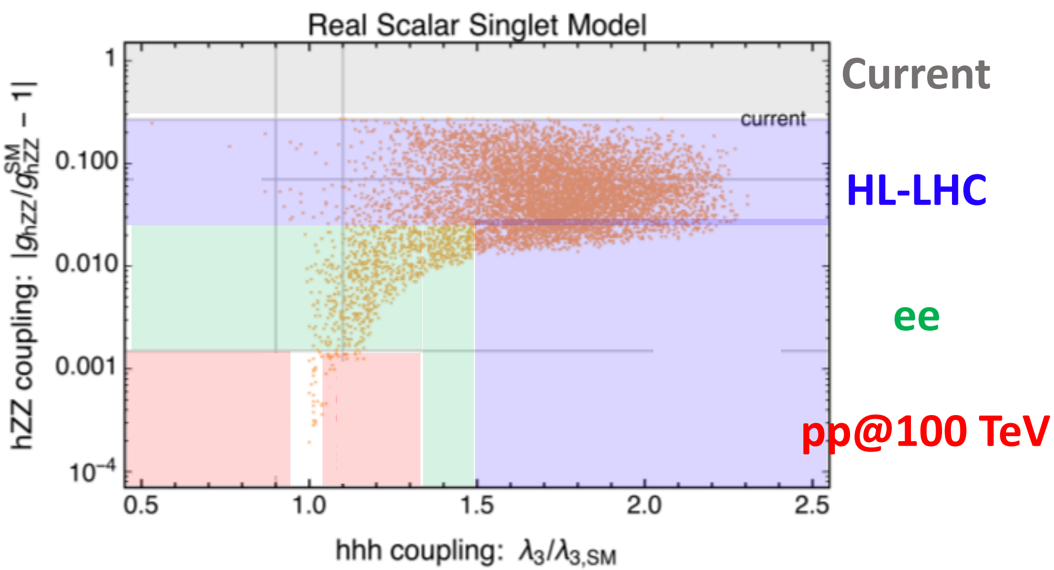
Complementarity b/w e^+e^- & pp

- Example: Matter –antimatter asymmetry
  - Possible explanation: "Violent" transition to 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 (S)
  - Two Higgs-like scalars:
    - h1 (m=125 GeV) and h2
  - ~few %) in κ_λ and κ_Z
  - Direct production of scalar pairs
    - Resonant Di-Higgs production



Complementarity b/w e^+e^- & pp

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

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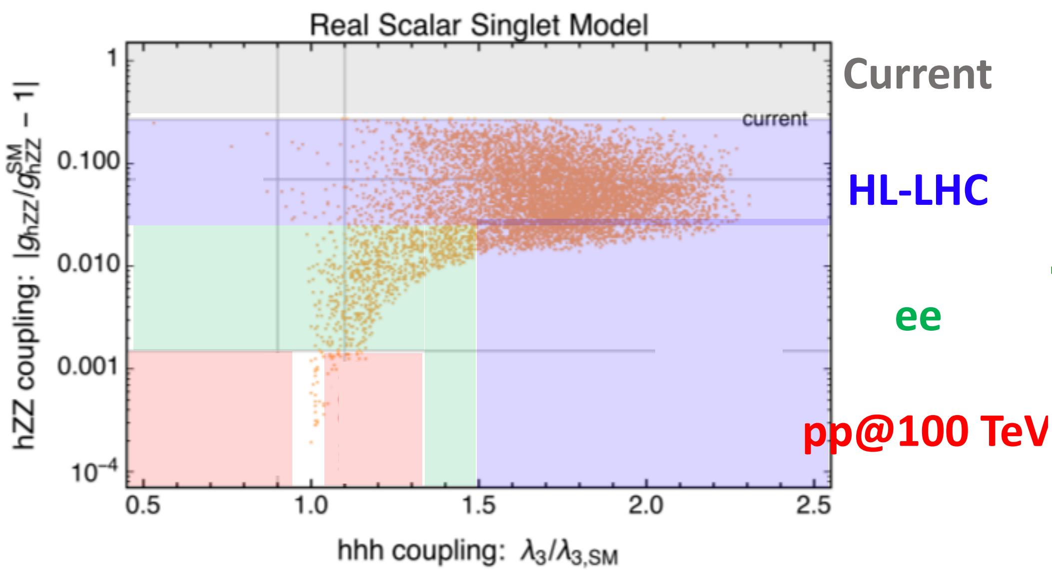
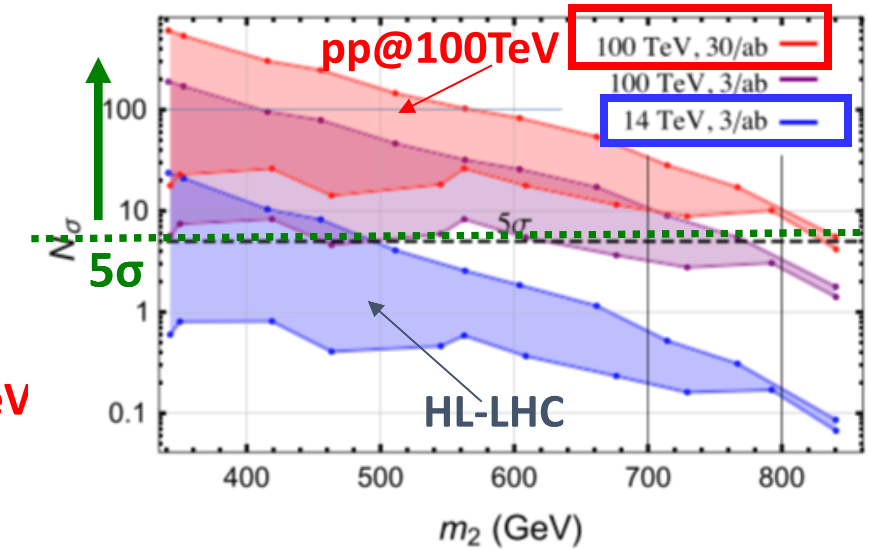


Discovery potential in resonant Di-Higgs searches



- Modification on Higgs self-coupling
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- Modification n Higgs-Z coupling
  FCC-ee @ 0.1% level, FCC-hh sensitive

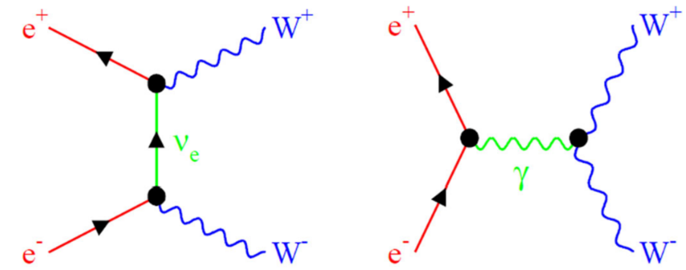
- FCC-hh discovery potential over the entire viable parameter space
- Very limited discovery potential @HL-LHC
- FCC-hh: powerful to other models w/ non-resonant production of scalars

Provide definite answers to fundamental questions

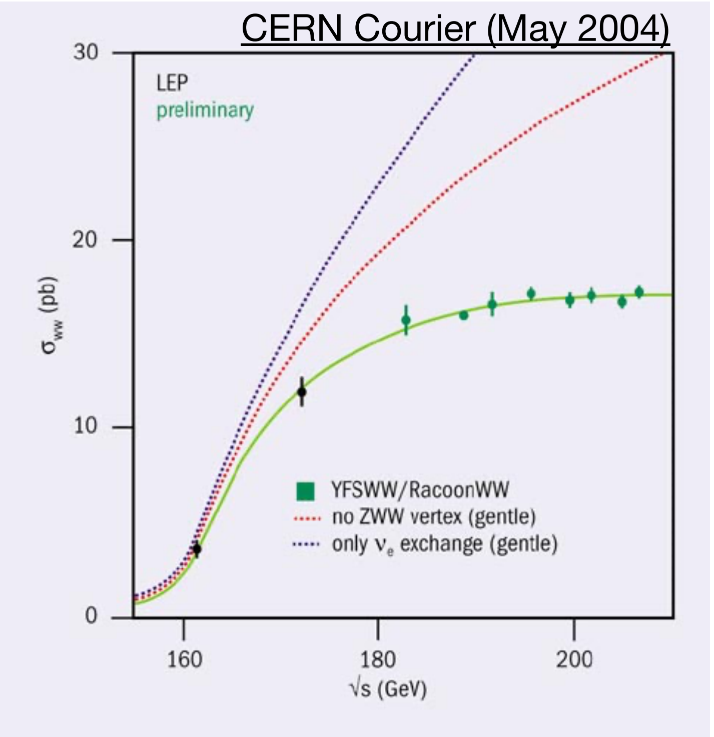
Beyond a Higgs factory

Precision EWK measurements: The m_W

- A W-boson factory @E_{CM}~160 GeV
  - FCC 10^8 (ILC 10^6) WW events
  - 10^4 (10^2) > LEP



- Measure m_W
  - Use the "lineshape" technique
    - developed at LEP [details]



- In a nutshell
  - WW cross-section depends: m_W, Γ_W
  - Generate TH curves for different m_W, Γ_W vs. E_{CM}
  - Fit observed data and choose the m_W, Γ_W that gives best agreement

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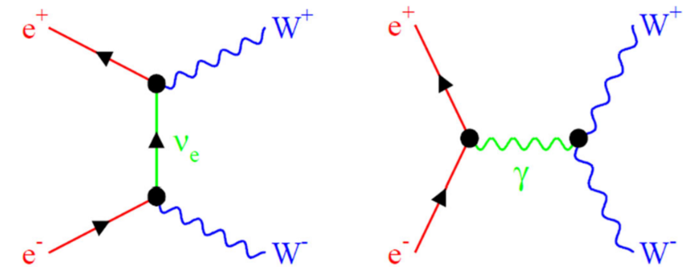

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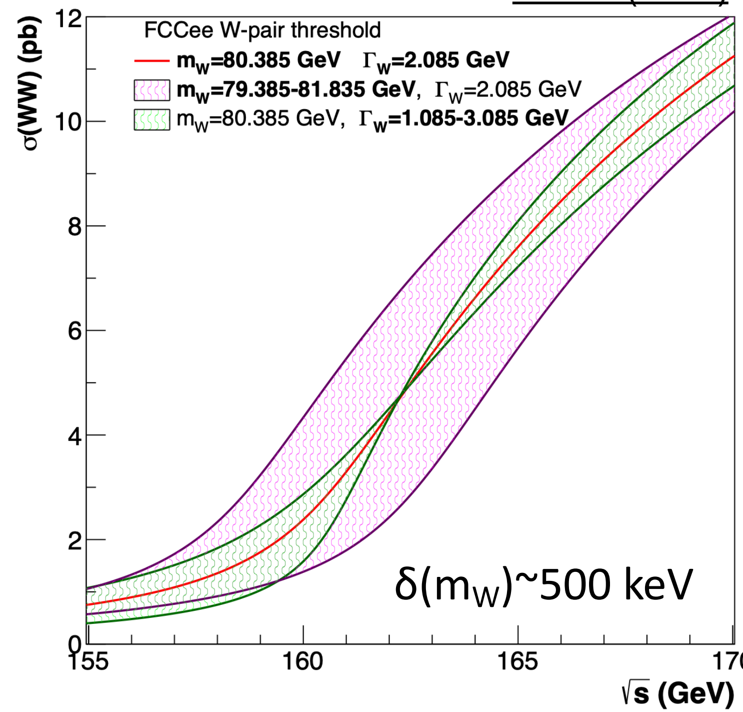

Precision → Scale of New Physics

- Several precision measurements in future e+e- colliders
  - Measure EWK parameters with keV (!!) precision
    - m_Z~100 keV, Γ_Z~25 keV, m_W~500 keV, … [numbers for FCC-ee]

- Use these measurements to probe New physics at higher scales
  - EFT: model-independent parametrization of BSM effects
  - Add higher-Dim operators → capture low energy effects

Strength of those new interactions

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

Capture effects of new interactions

Scale of New Physics

EFT interpretation

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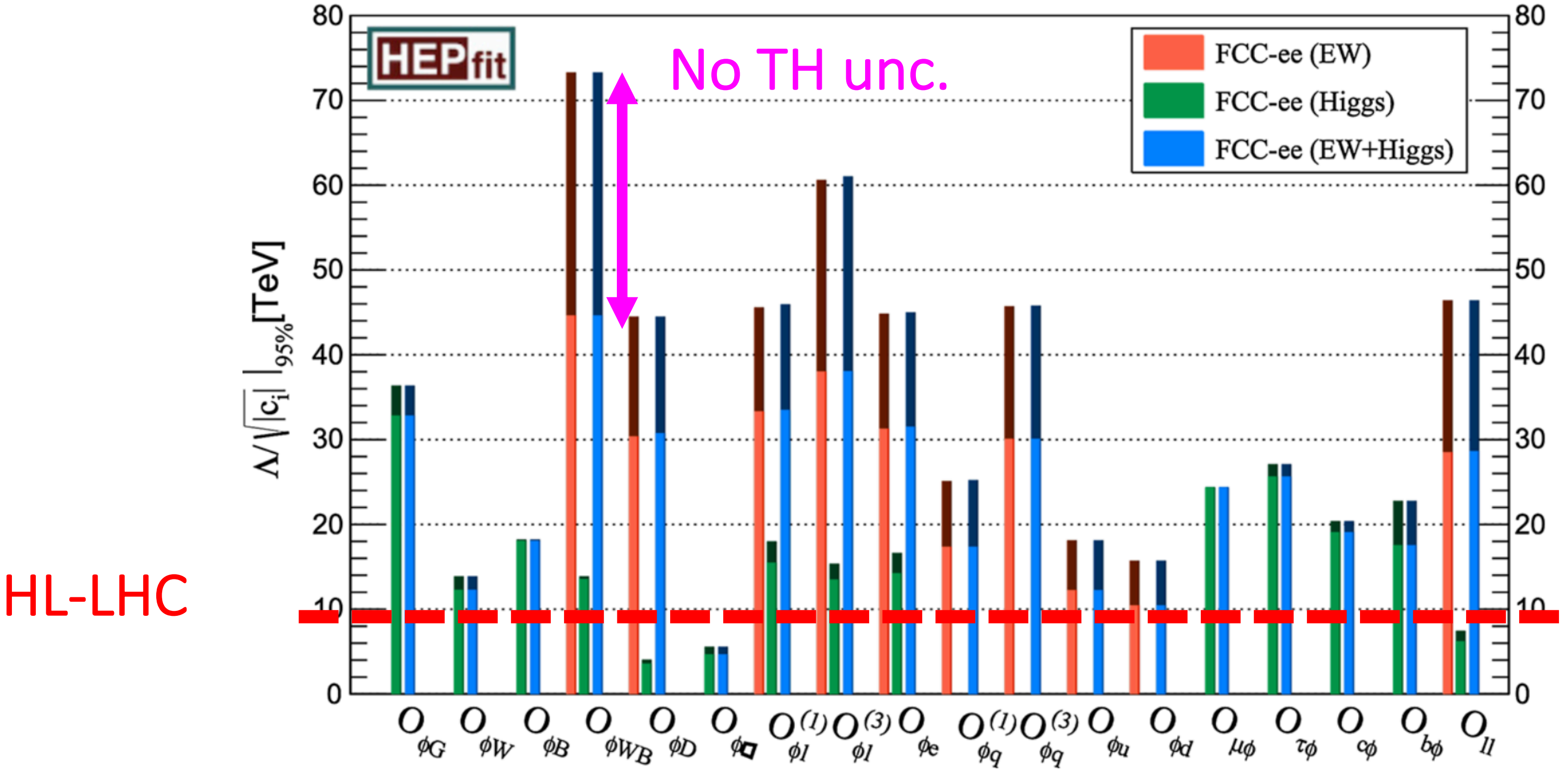
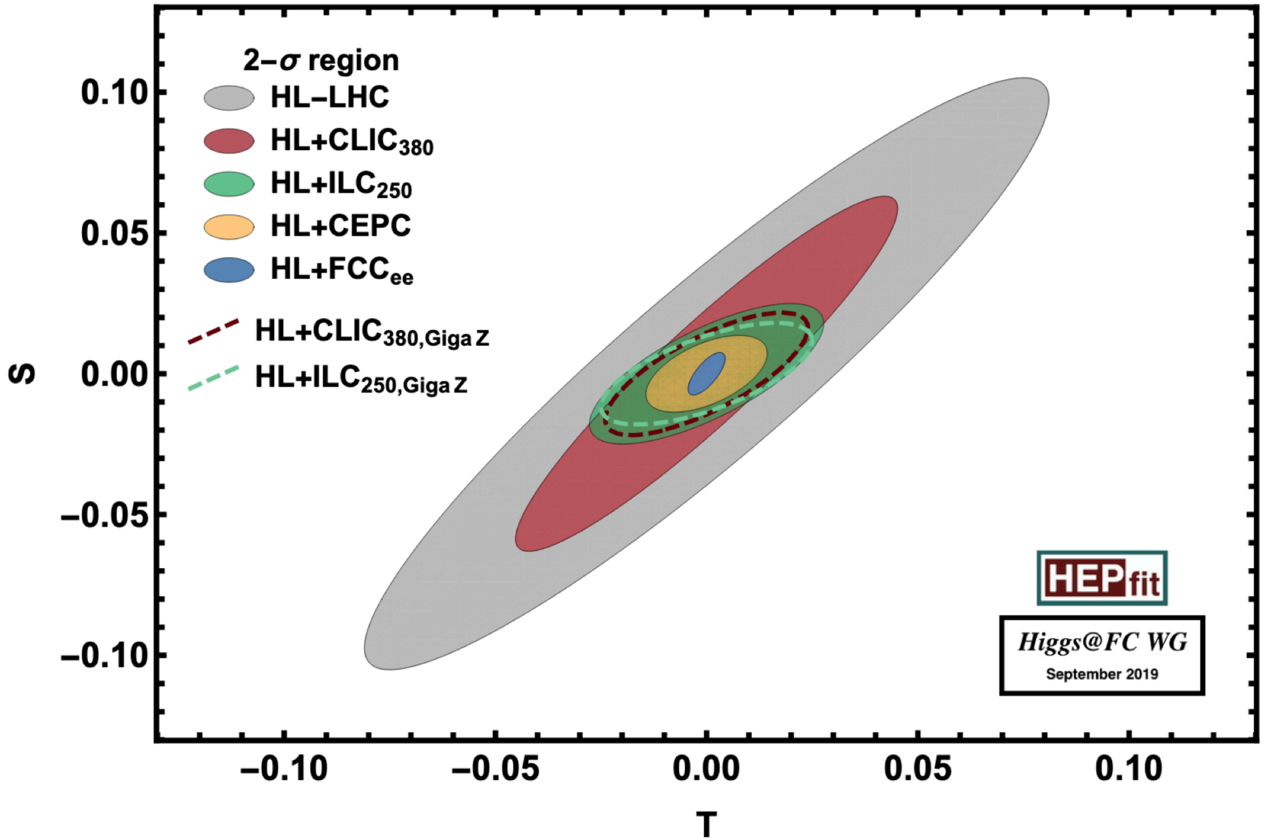


- Complementarity b/w EW and Higgs programs
- Key: control stat & syst unc
- FCCee: Λ ~100 TeV (LEP ~ 10TeV) → Pave the way for FCC-hh
- Lot's of work ahead to exploit true potential

Precision: ILC/CLIC/FCC

2203.06520

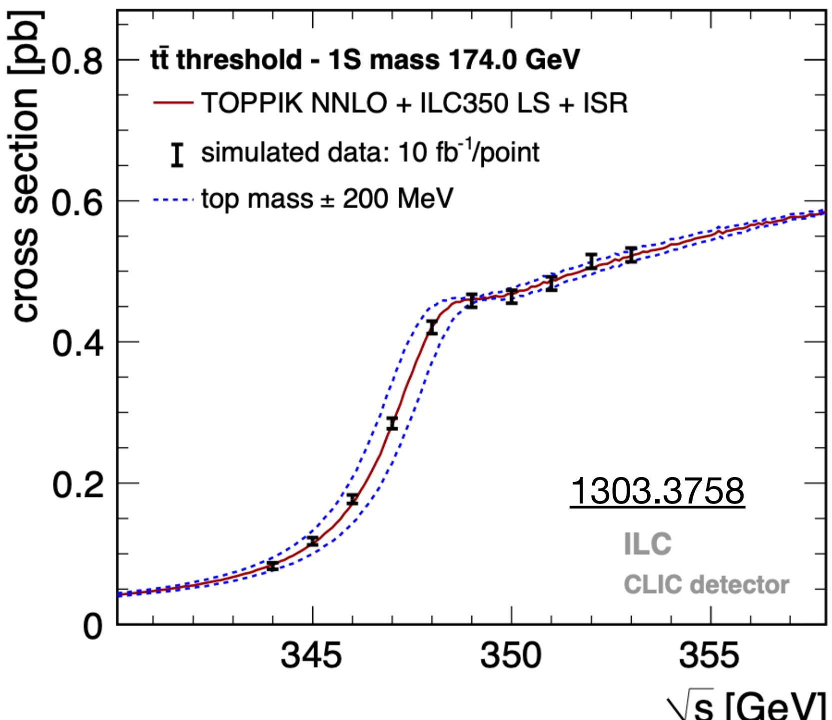


Take home:
- Future e+e-: Major improvement wrt HL-LHC
- Importance of Z-pole (FCC vs. ILC/CLIC)
- Importance of Luminosity (Z, Higgs)

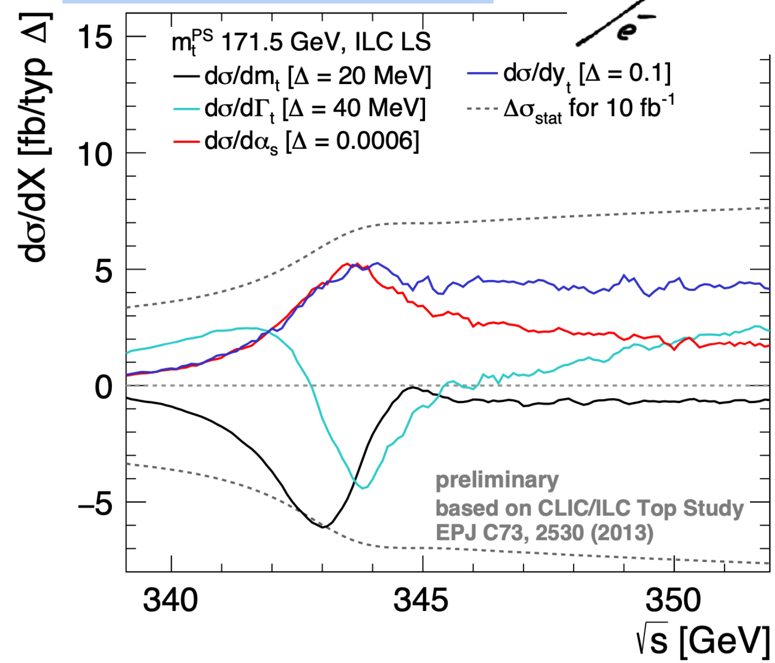
Precision: The top sector

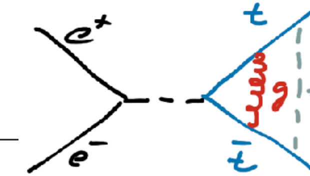
- Top factory: FCC 1M tt events (ILC: 100K- baseline)

Top mass measurement



Higgs-top Yukawa coupling



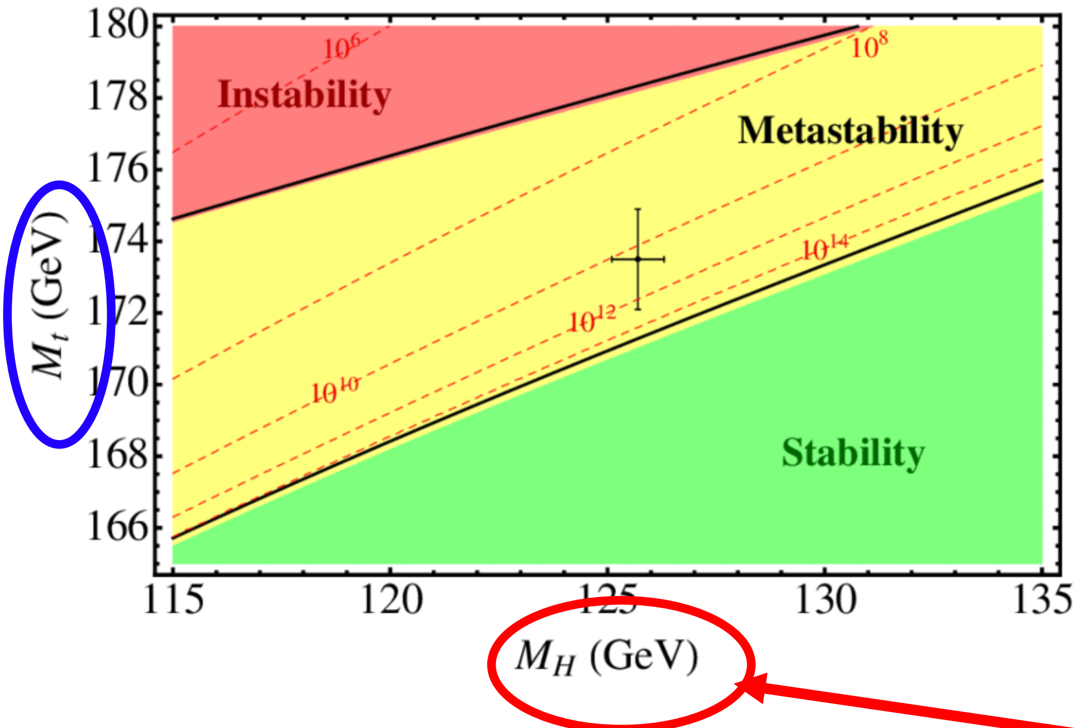


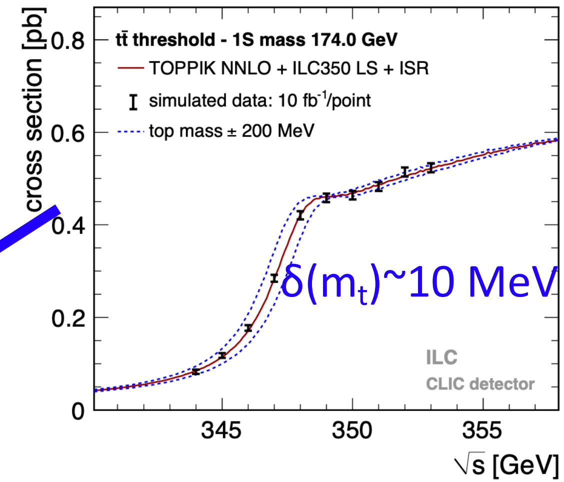
- **HL-LHC:** $\delta(m_t)$~O(100) MeV
- **FCC/ILC:** $\delta(m_t)$~O(10) MeV

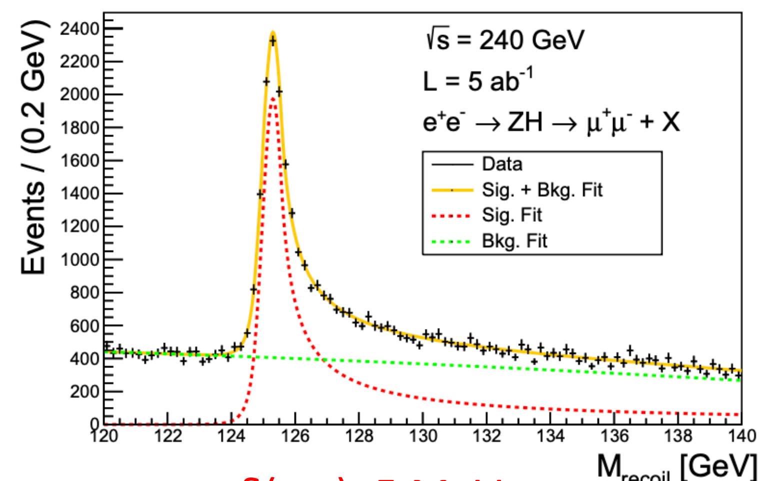
- **FCC/ILC:** $\delta(y_t)$~O(few) % in a model independent way

Precision → Fate of the universe

1512.01222



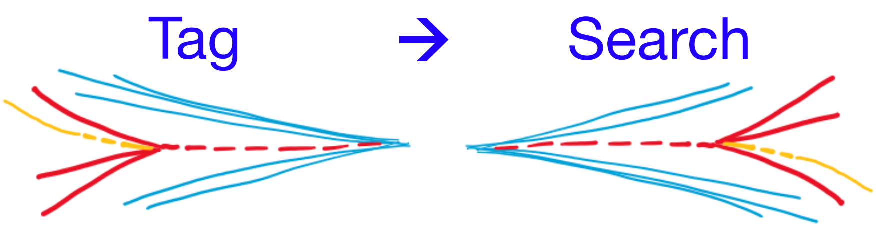




$\delta(m_H)$~5 MeV

The flavor sector

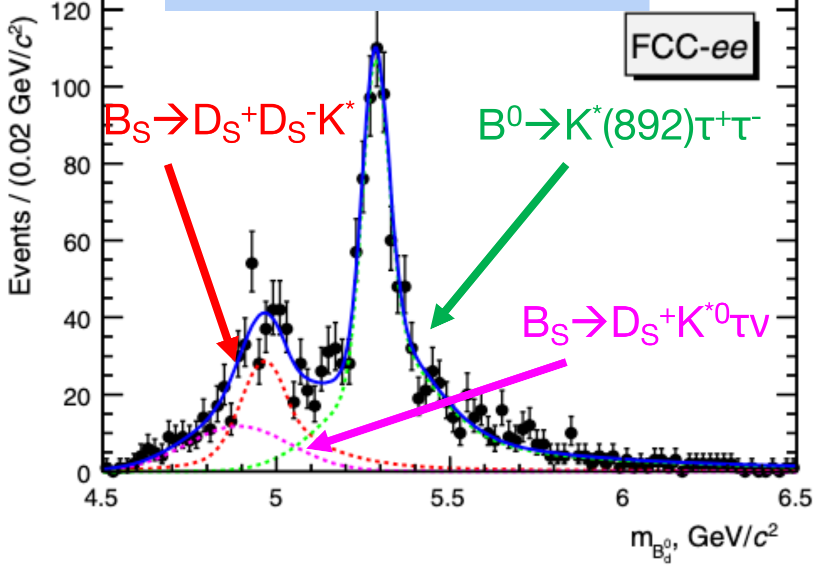
- Circular colliders: The “Tera-Z”: 5×10^{12} Z bosons (LEP 10^6)
  - Stress test for flavor sector of SM



Few examples

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

b→s transitions



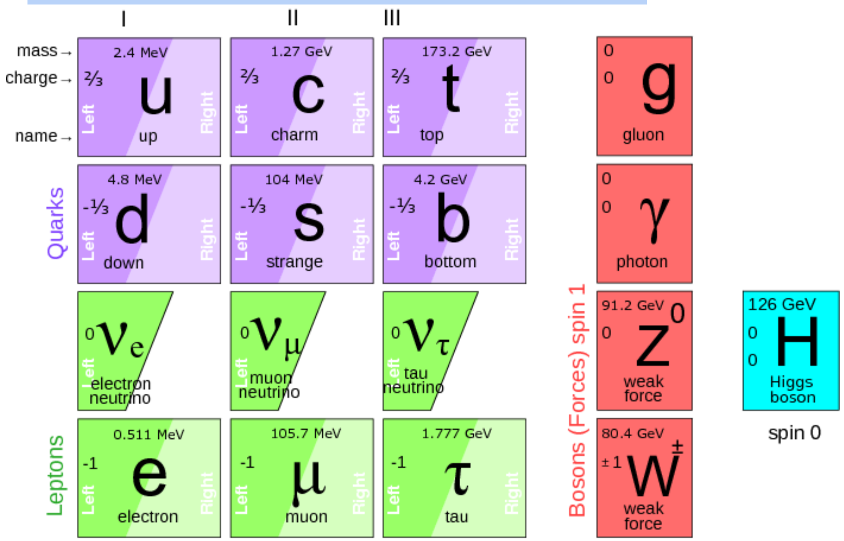
Decay	Current bound	FCC-ee sensitivity
Z -> eμ	$0.75 \times ^{-6}$	10^{-8}
Z -> μτ	12×10^{-6}	10^{-9}
Z -> eτ	9.8×10^{-6}	10^{-9}

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

Direct searches @Z-pole

- Unprecedented stats → explore unchartered territory
  - Axion-like particles, dark-photons, heavy neutral leptons,…

The SM is complete



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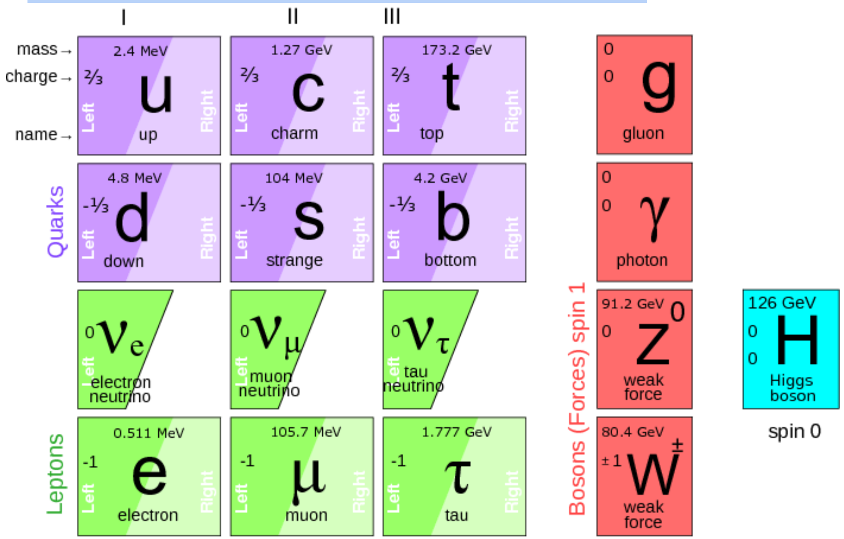
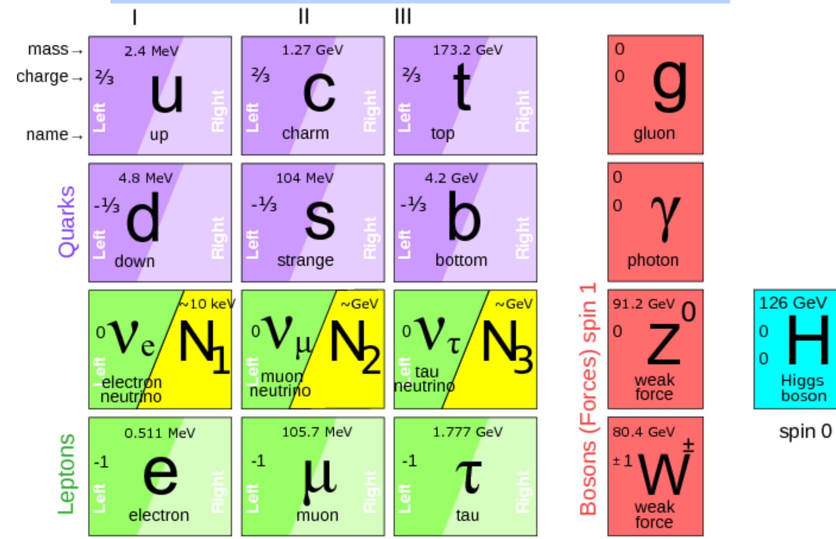


… or maybe not ?



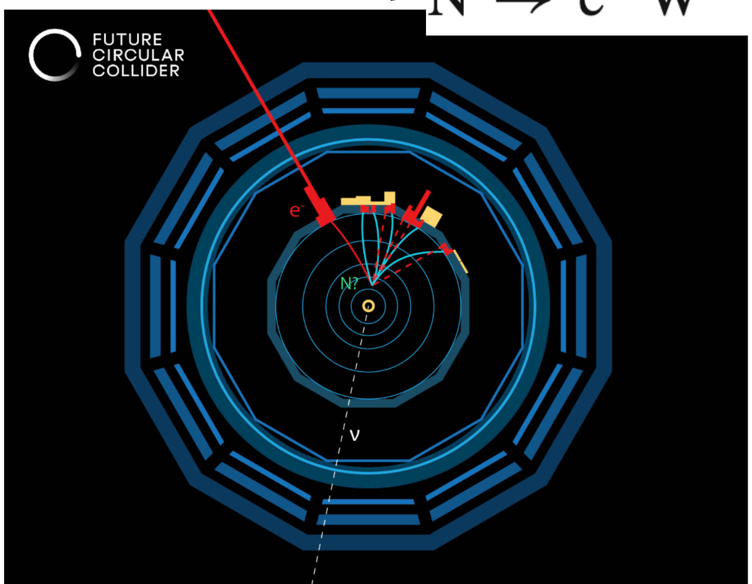
- We have not observed Right Handed Neutrinos (N)
- If exist: extremely challenging to find (veeery small couplings)
- but: Can explain many pressing questions (Baryon asymmetry, DM, ..)

Direct searches @Z-pole

- Signature:
  - Slight reduction (enhancement) of $\Gamma_Z^{(inv)}$ ($\Gamma_H^{(inv)}$) → **precision**
  - Exotic signatures → **direct search**

Displaced particles + Missing Energy

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



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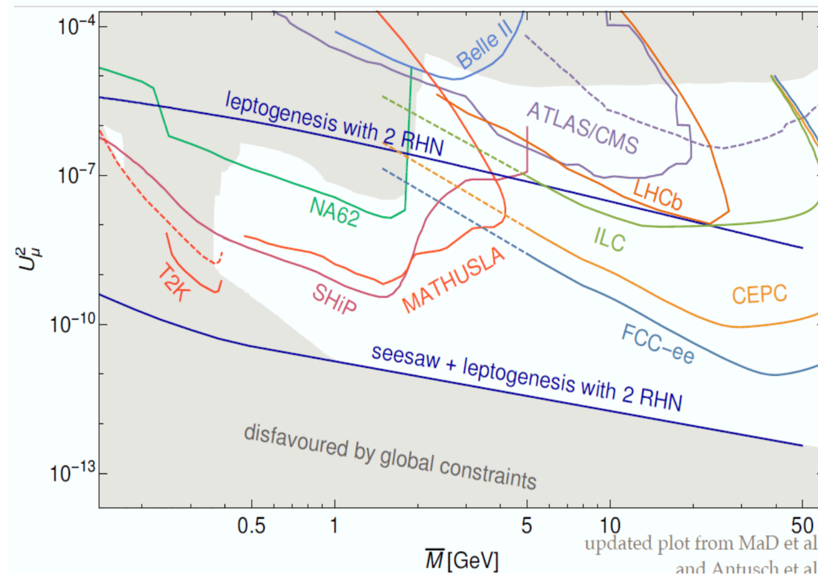
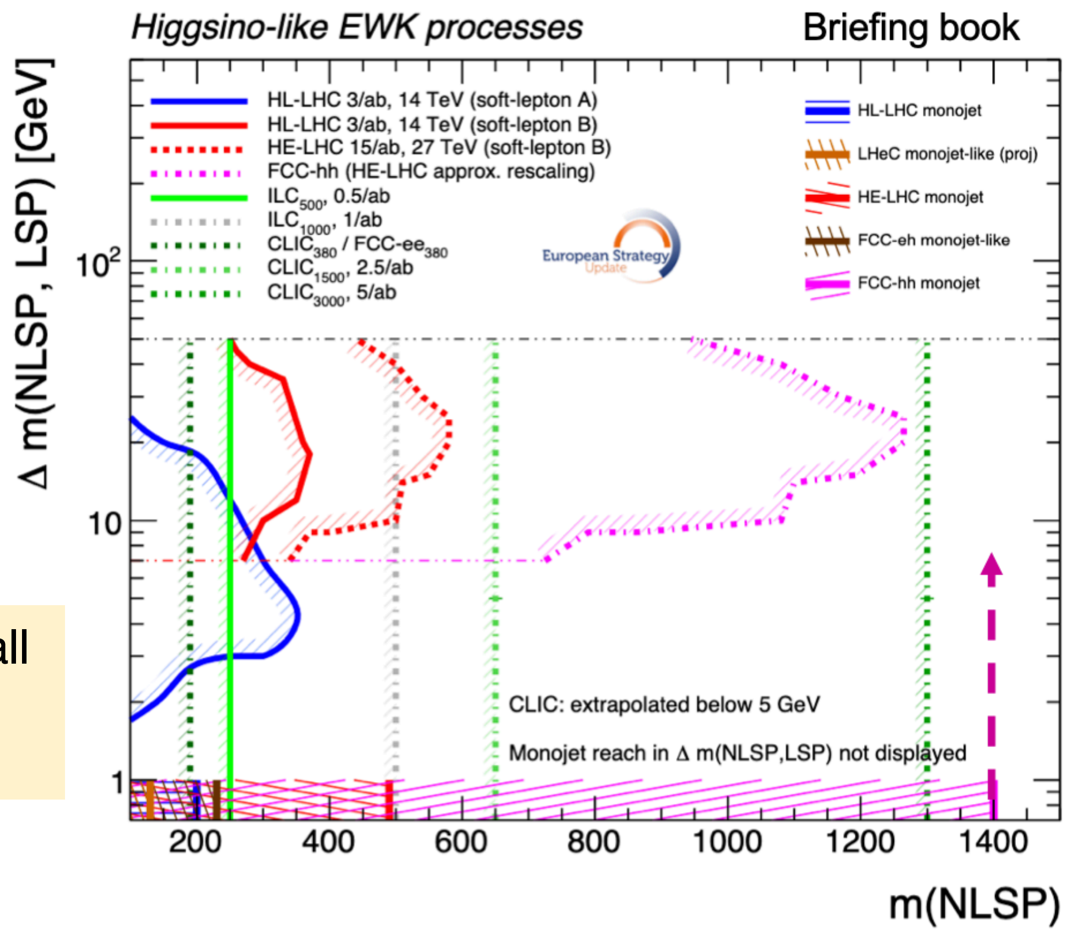


Huge improvement compared to existing and foreseen experiments

Direct searches @TeV

- EWK production of BSM
  - Around the TeV range
  - Can escape (HL-)LHC
    - even pp@100 TeV
- Direct production at e^+e^- if $m_{BSM}<E_{CM}/2$

- Effect on EWK/Higgs properties small (i.e., circular e+e- not ideal)
- "Bread-&-butter" for linear colliders



Summary and Outlook

- Unique situation: no clear direction of where New Physics is
  - but we have very strong reasons to believe it exists
- We need a new colliders… Which one?
  - e^+e^-: provide precision O(10) times better than HL-LHC
    - particularly for challenging decay modes (e.g., charm, strange..)
  - e+e- program extends well beyond Higgs physics
    - Z-pole, ttbar, axions, LLPs, right-handed neutrinos,…
- Far from "over-subscribed"
  - Lot's of room of innovation and out-of-the-box thinking in several areas
    - Detector design, event reconstruction, physics analyses, …

Summary and Outlook (II)

- My advice: Take part in **shaping the future** of particle physics
    - Join the effort
        - build and then operate the next generation of e^+e^- colliders
        - Contribute to some of the most fundamental questions in physics.
    - Innovate and Lead:
        - Development and operation of these colliders require innovative approaches and cutting-edge technology.
- ..and not forget:

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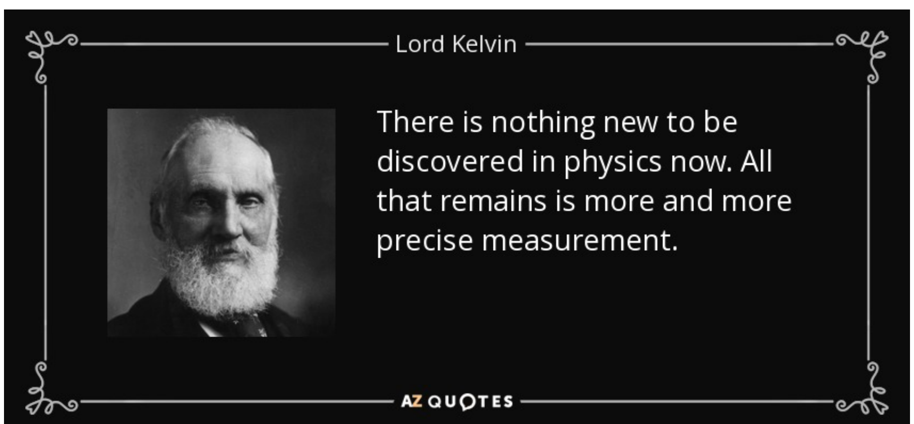

.. and we all know what followed after this statement