Physics analyses review for future Higgs factories

Loukas Gouskos (Brown University)

LCHP 2024 @Boston

Introduction

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

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

1708.08912

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

e.g. Λ=1 (5)TeV→~5 (0.1)%

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- HL-LHC:
  - Direct searches: O(5) TeV
  - H-couplings:
    - Bosons/ 3rd-Gen fermions @ few %
    - 2nd Gen fermions: maybe evidence of H→cc
    - Self-coupling~50%
- Future e^+e^- collider:
  - Measure H-couplings at O(0.1)% level

Details in S. Dawnson's talk

Introduction

Today: Focus on Higgs physics [just a subset]

- e^+e^-: physics program extends well beyond Higgs

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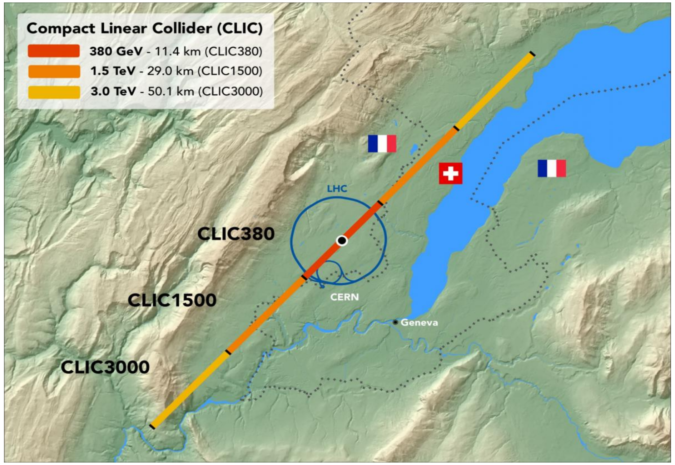
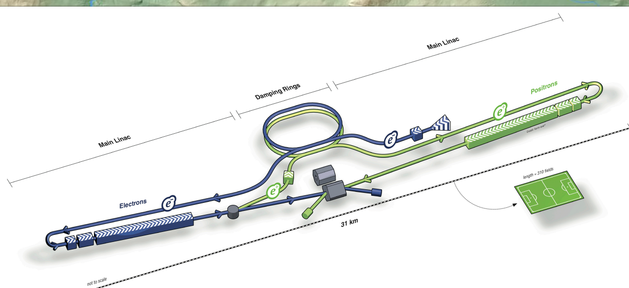
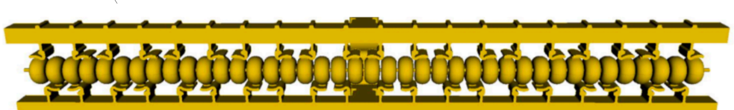
Details in S. Dawnson's talk

Proposed future accelerators

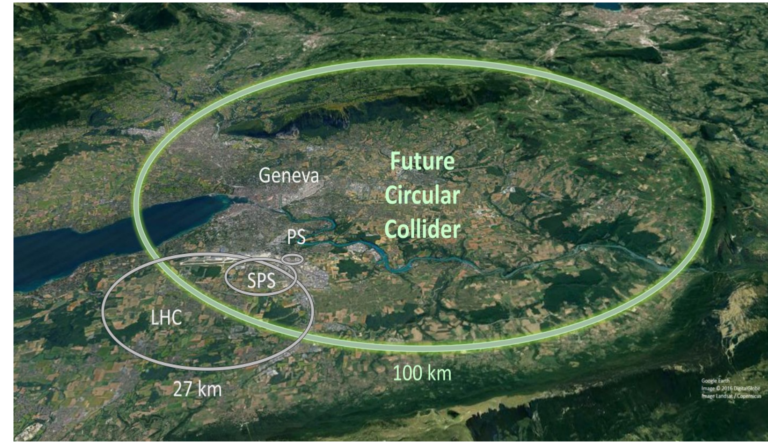
Linear (e^+e^-) colliders







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



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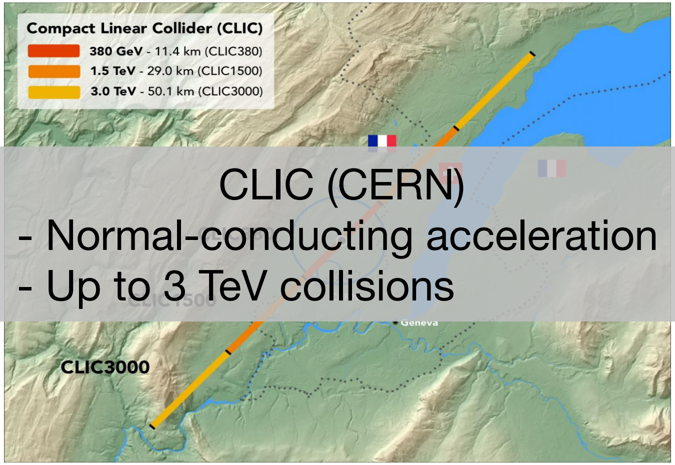
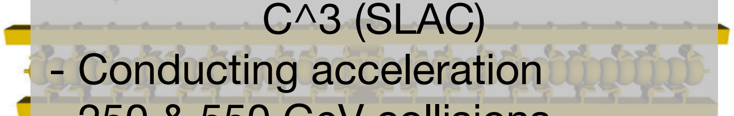


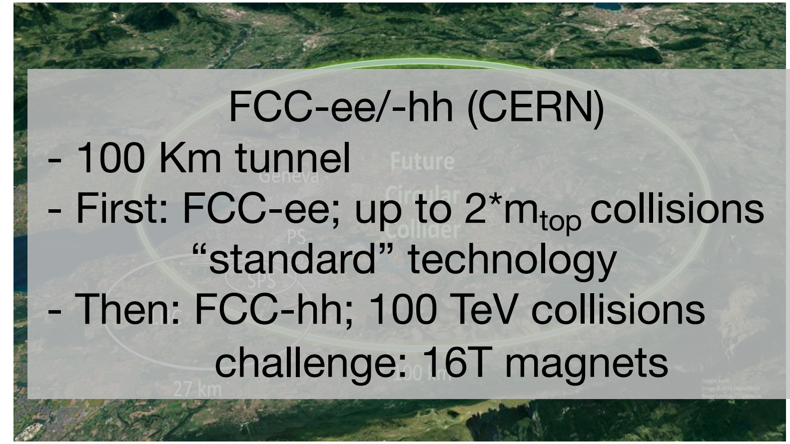
CLIC (CERN)
- Normal-conducting acceleration
- Up to 3 TeV collisions

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

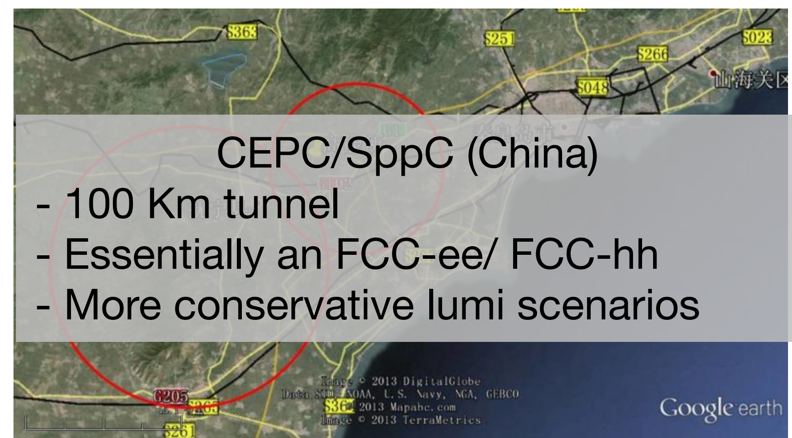


C^3 (SLAC)
- Conducting acceleration
- 250 & 550 GeV collisions

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

Details in E. Nanni's talk

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, O(1M) H-bosons
- CLIC/ILC/C^3:
  - 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

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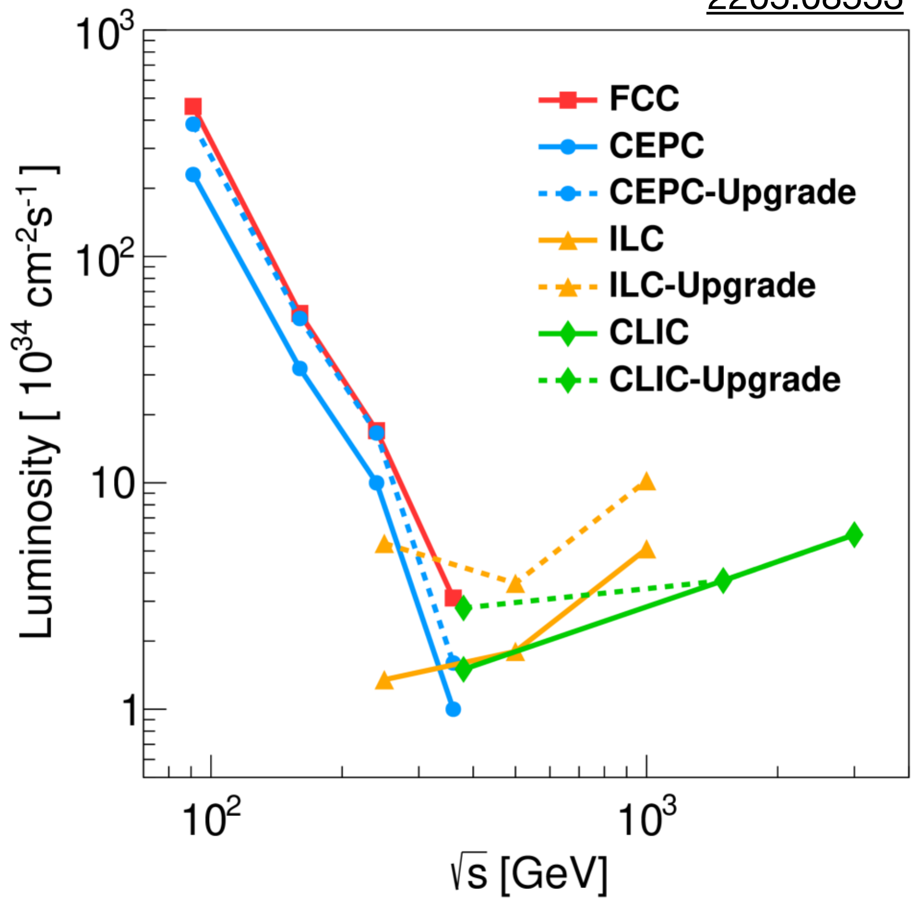
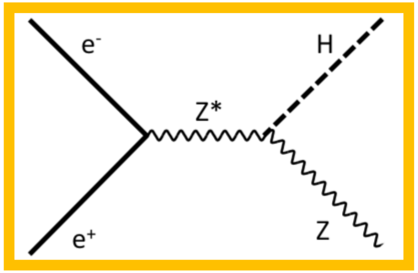
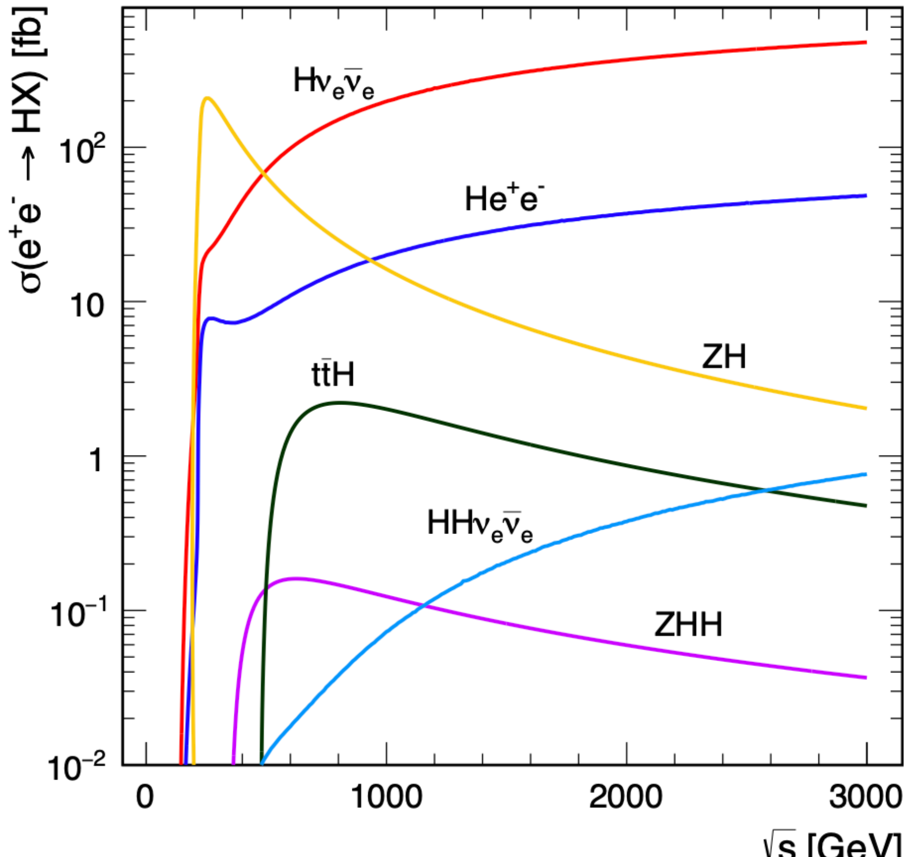


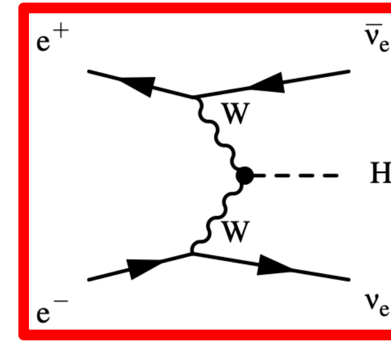
Higgs as an exploration tool

Higgs production at 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

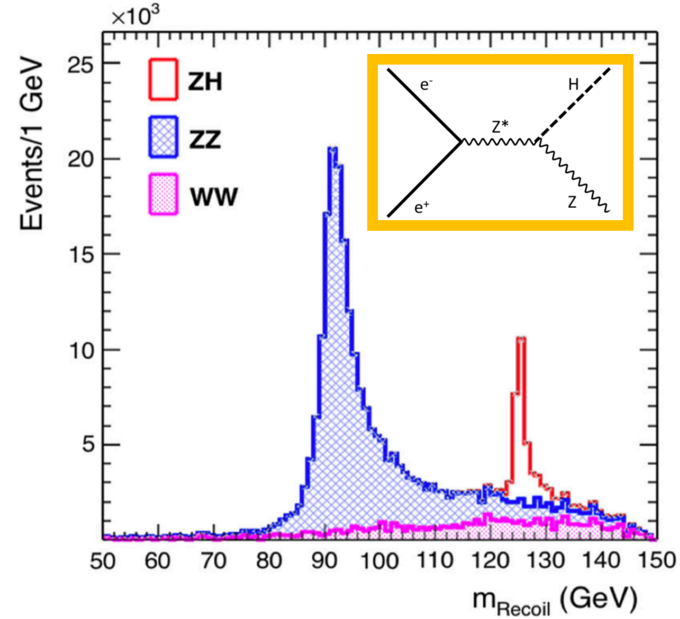
Model-independent measurements

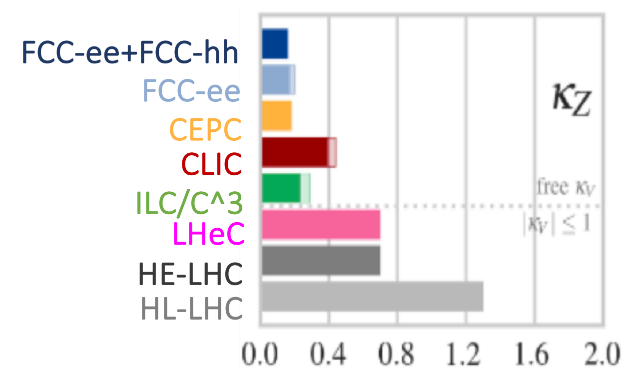
- ZH production in e^+e^-
  - Unbiased tagging of Higgs boson
    - via $Z \to LL$, m_{recoil}, E_{beam} constraints

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

- Strategy:
  - First: measure ZH production
    - rate $\sim\kappa_Z^2 \to \delta(\kappa_Z)/\kappa_Z \sim 0.1\%$
  - Then: measure ZH($\to$ZZ)
    - rate $\sim\kappa_Z^4/\Gamma(H) \to \delta(\Gamma(H))/\Gamma(H) \sim 1\%$

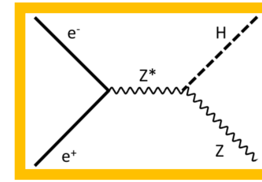
- Unique in e^+e^- machines @ZH
- "standard candle" for other Higgs measurements (incl. pp@100TeV)





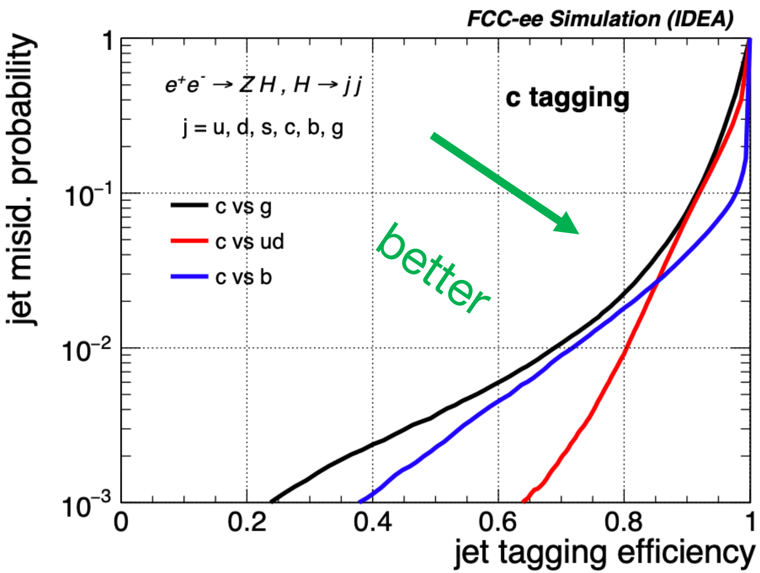
O(10) improvement wrt HL-LHC

More on Higgs couplings



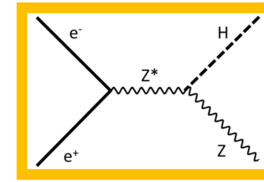
- Next step: Study as many as possible Higgs decays
  - key: identification of decay flavor

Novel Deep Learning based algorithms under development



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

More on Higgs couplings



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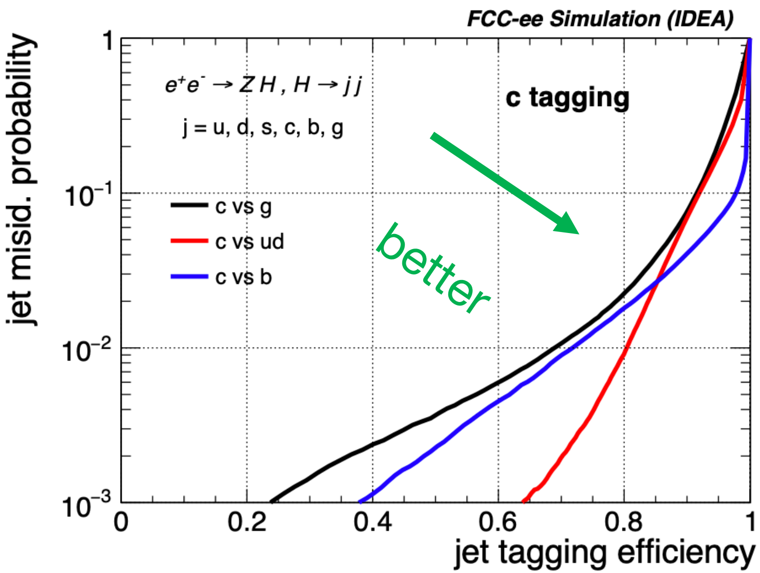

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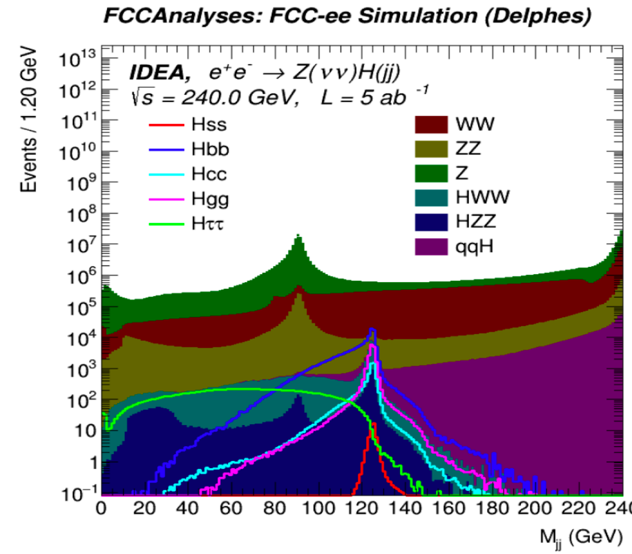
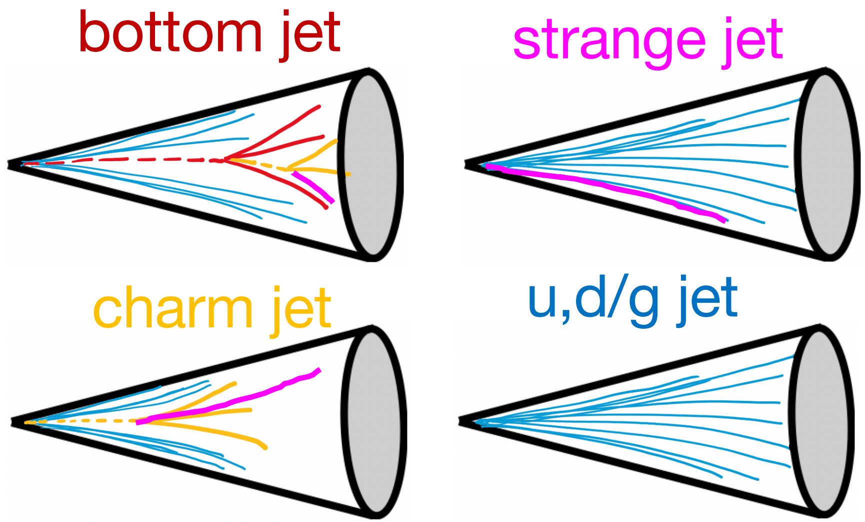
Signal extraction: 2D fit: m_{rec} vs. m_H



Final state	Z(ll)H(jj) [%]	Z(vv)H(jj) [%]	Z(jj)H(jj) [%]	Comb. [%]
$H \to bb$	0.81	0.36	0.3	0.22
$H \to cc$	4.93	2.6	3.5	1.92
$H \to gg$	2.73	1.1	2.4	0.94
$H \to ss$	?	?	?	?

Towards H→ss

- Tiny BR~10^{-4}: e.g., O(100) expected at FCC-ee (@ZH)



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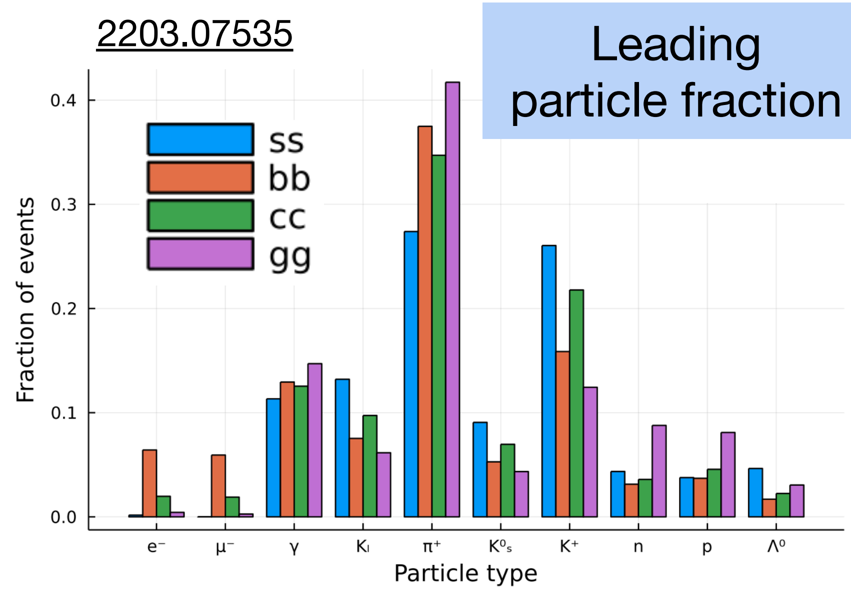
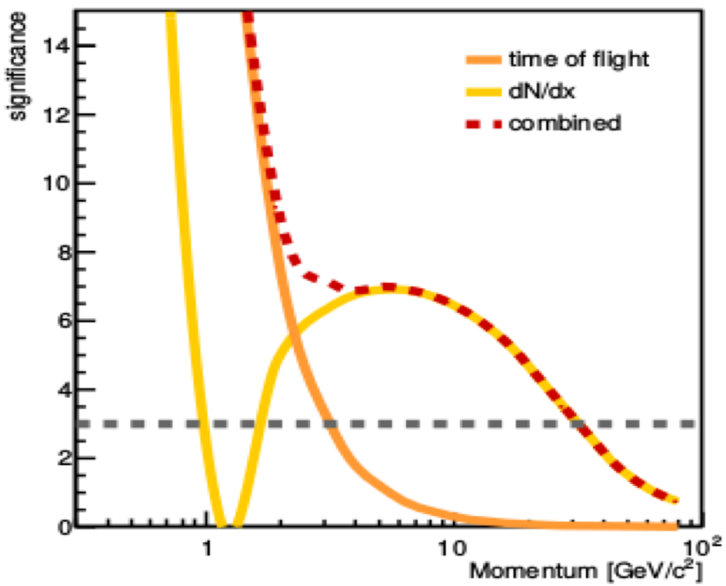


- Key points:
  - Enhanced **Kaon** fraction; Strange tagging critical
  - Need powerful identification up to O(30-40) GeV

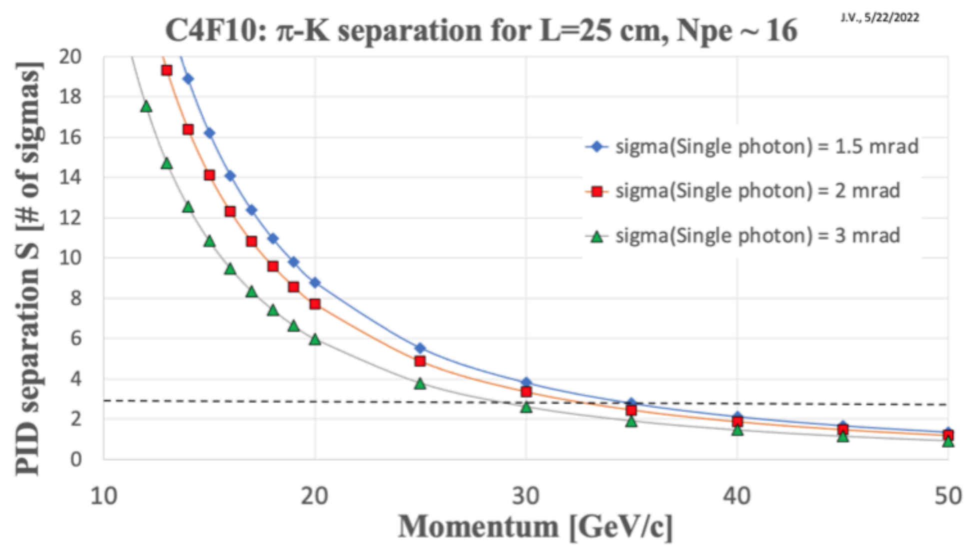
Towards H→ss

- Big effort to design optimal PID detectors and algorithms to exploit their full potential [e.g., ECFA H→ss team, Wiki]

dN/dx+TOF



RICH



Achieve 3σ π/K separation for up to ~30 GeV momenta

Details in D. Bortoletto's talk

Towards H→ss

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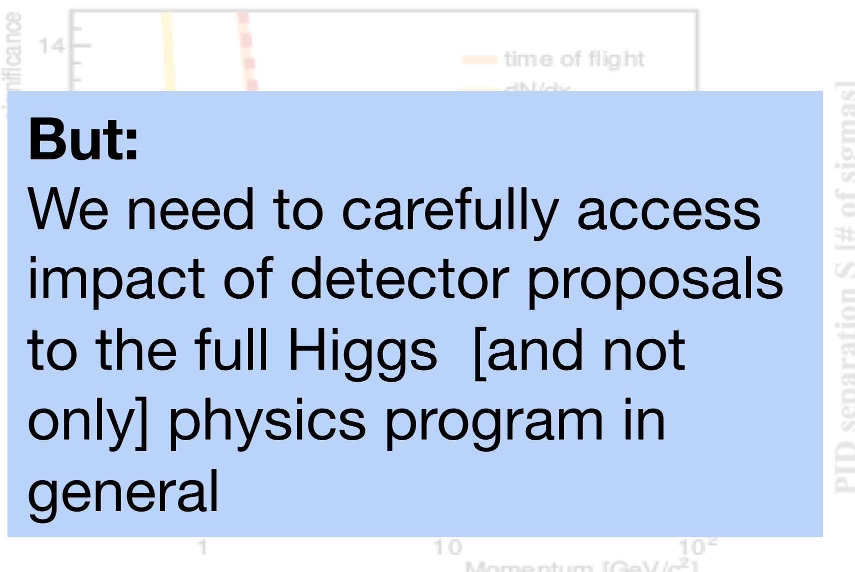
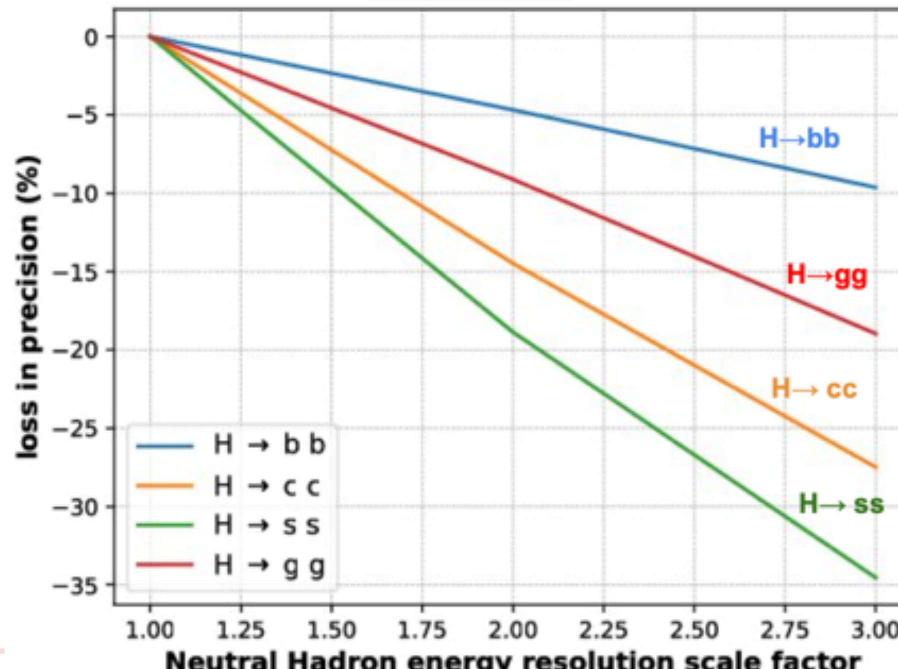


But:
We need to carefully access impact of detector proposals to the full Higgs [and not only] physics program in general

RICH



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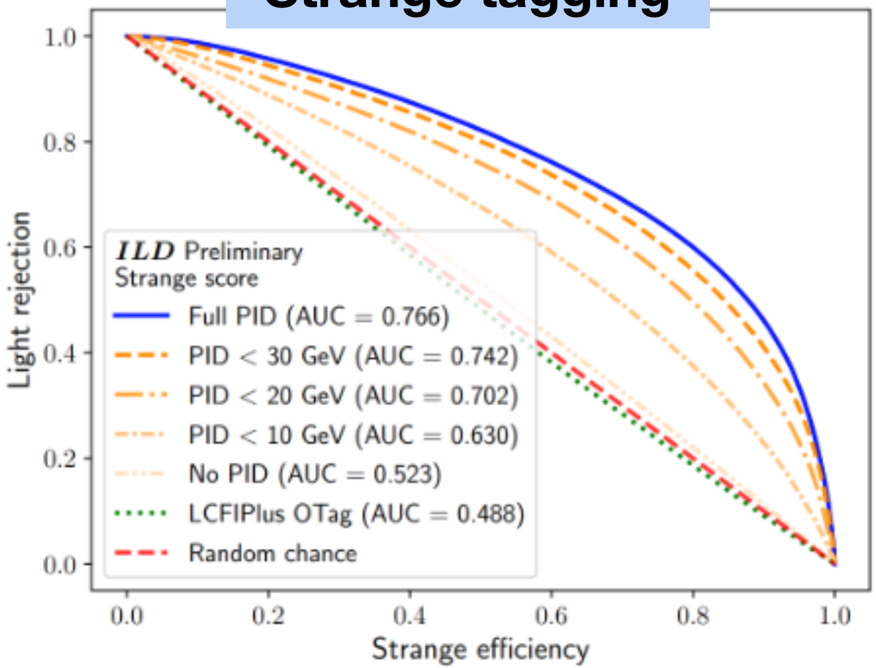
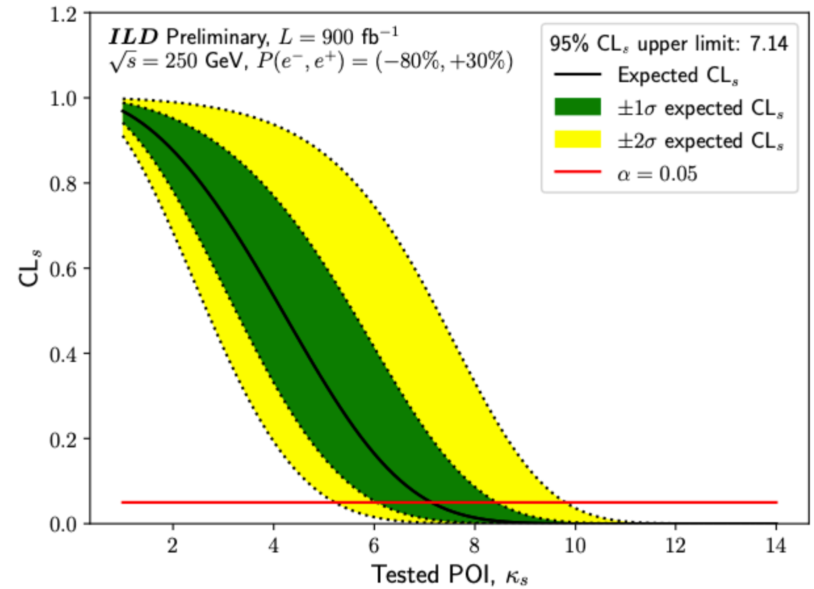
Towards H→ss

Strange tagging



UL on H-S coupling



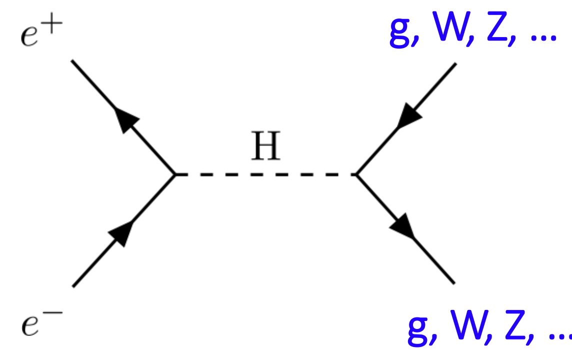
- Strong dependence on detector design, jet tagging, Lumi ..
  - Most sensitive results currently ~2σ (CEPC/FCC-ee)

Opportunity to **fully establish second generation** charged fermions!
→ Impossible at the HL-LHC/hadron colliders

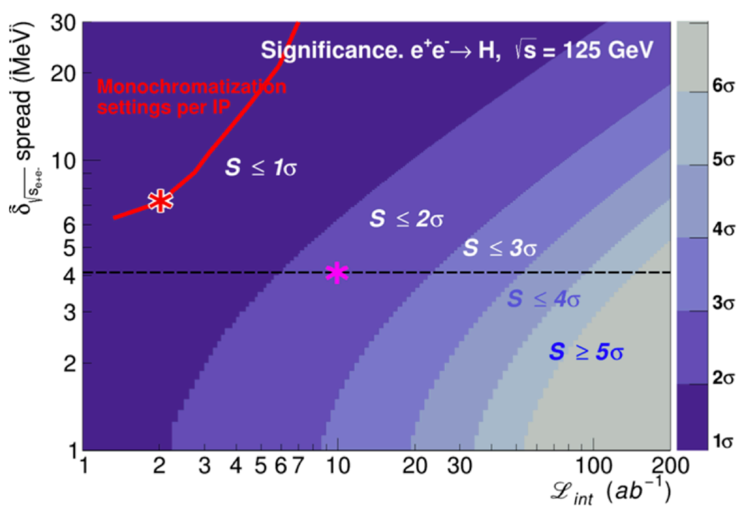
Unique at Circular Colliders: H→ee

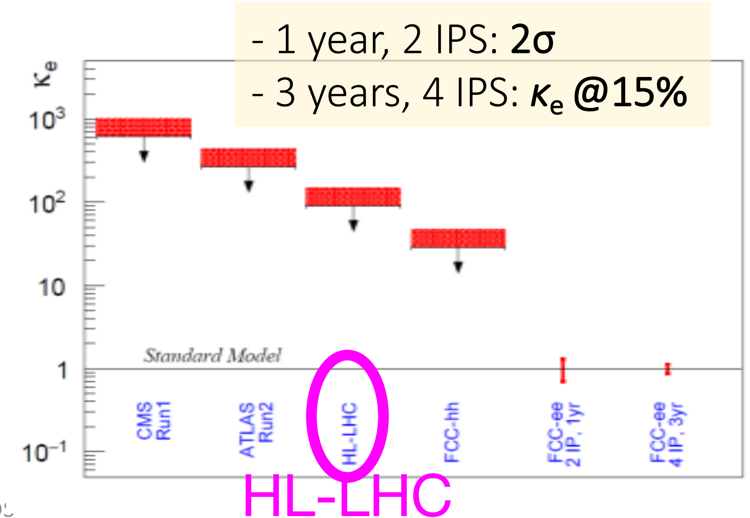
2107.02686

- FCC-ee/CEPC: Resonant Higgs production
  - Tiny signal BR(H→ee) ~10^{-9} vs. huge BKGs
  - but: large luminosity at FCC-ee
    - 20 ab^{-1}/year/IP → ~10K Higgs



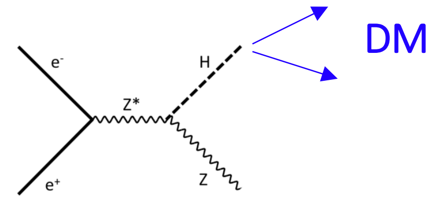
- Key points:
  - Beam spread (~MeV) → monochromatization
  - Precise m_H → from ZH run





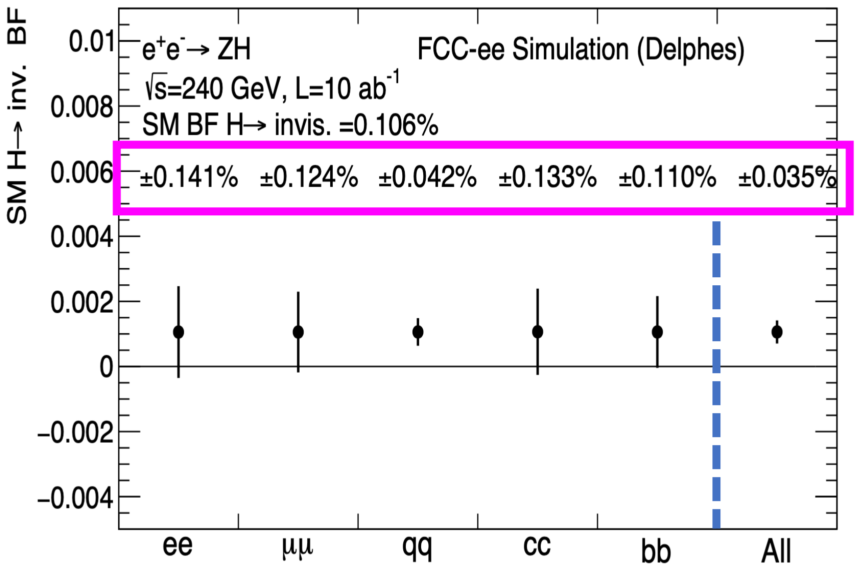
Higgs to invisible

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



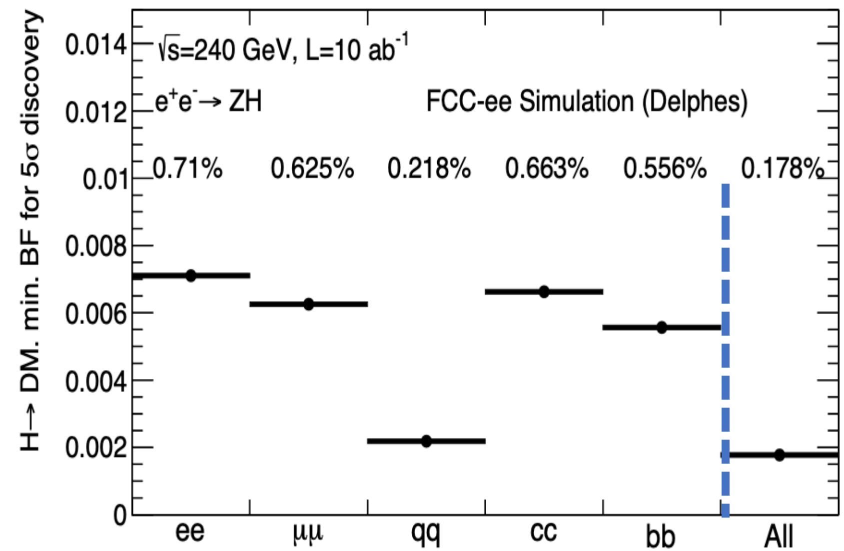
Goal: Reach neutrino floor

SM H→inv reach



Impossible at the HL-LHC

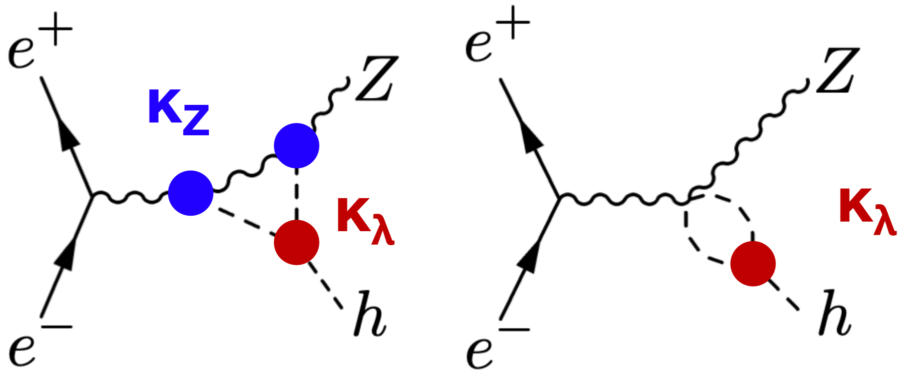
5σ discovery potential



NB: 5% poorer σ_E/E(Had)
→ **<u>80% increase</u>** in δ(H→inv)
Keep in mind for detector design/choice

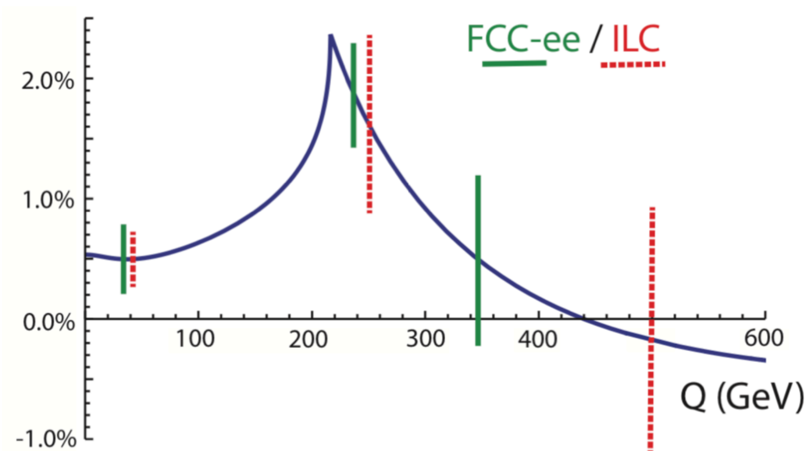
Higgs self coupling (λ) @ e^+e^-

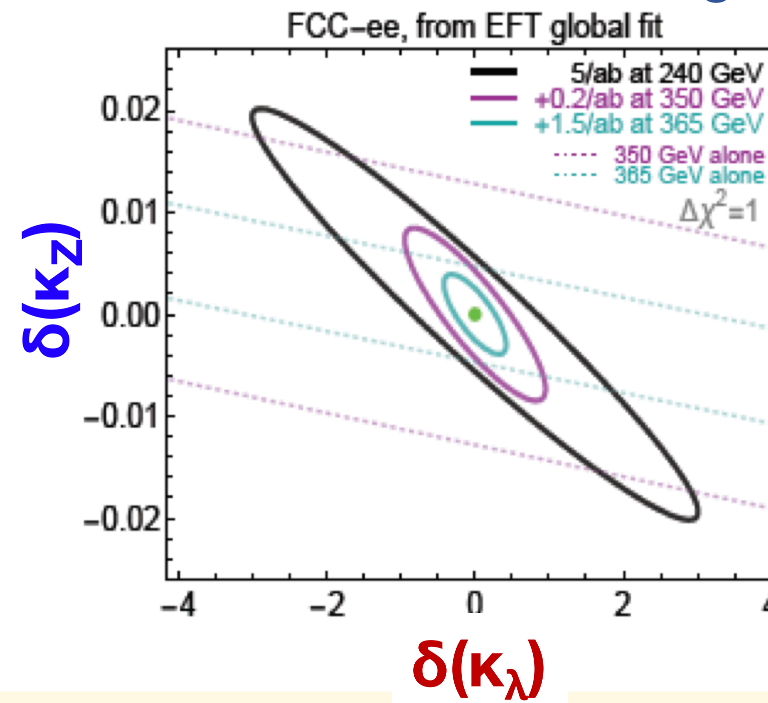
(a) Via loops (FCC-ee/CepC)



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

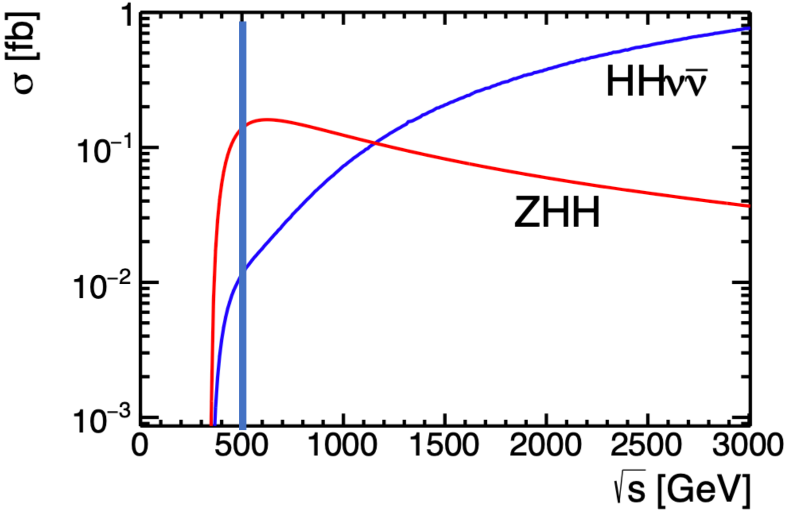
Relative enhancement of ZH production



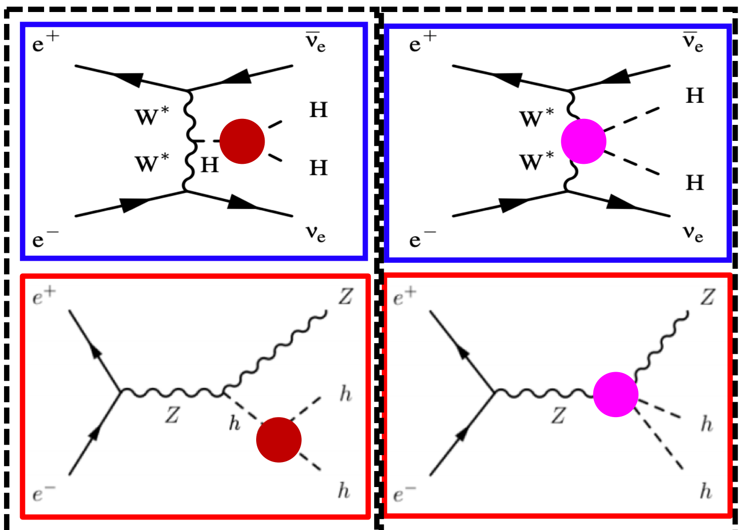


O(10-20%) precision on λ
[other couplings at SM-values]

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



H self coupling (κ_λ)



HHVV coupling (κ_{2V})

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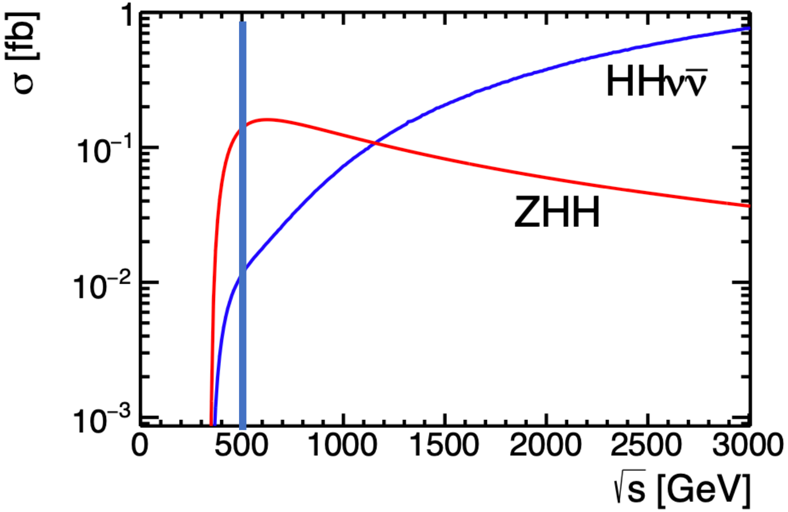
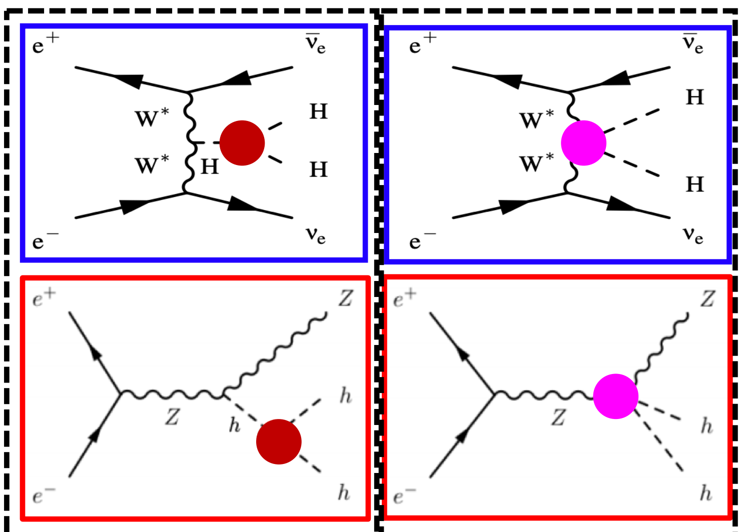
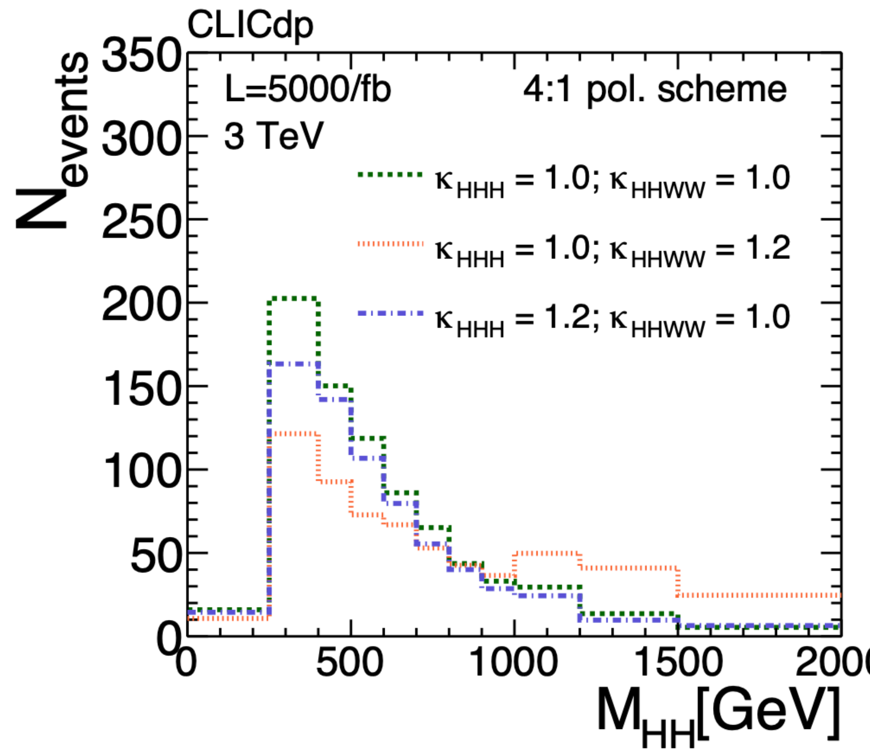


H self coupling (κ_λ)



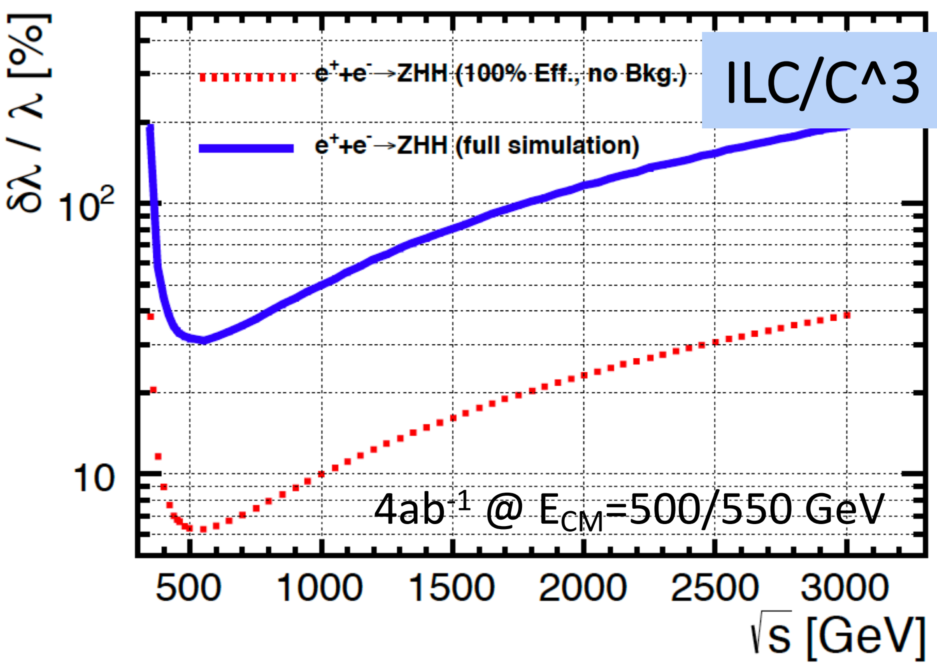
HHVV coupling (κ_{2V})

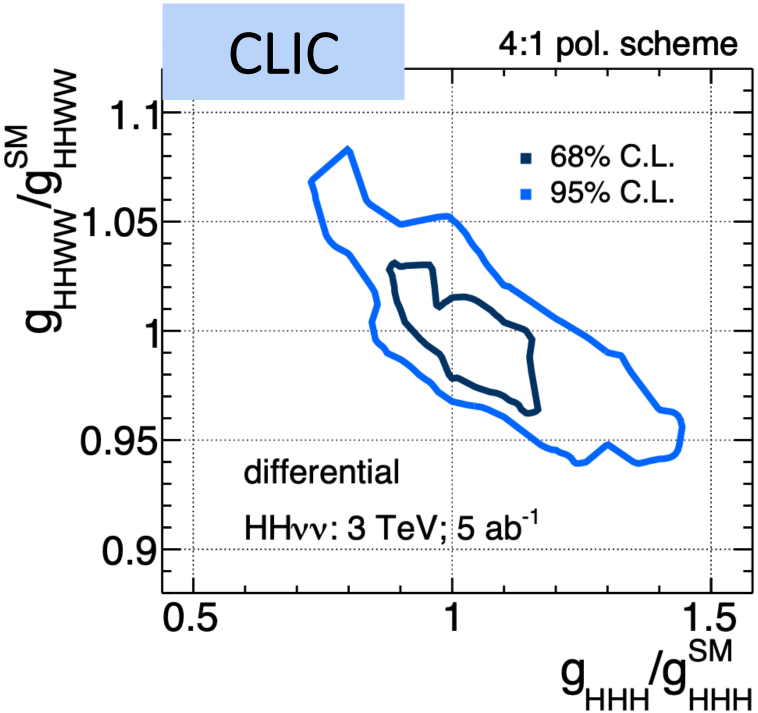
Use m_{HH} to disentangle κ_λ-κ_{2V}



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

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



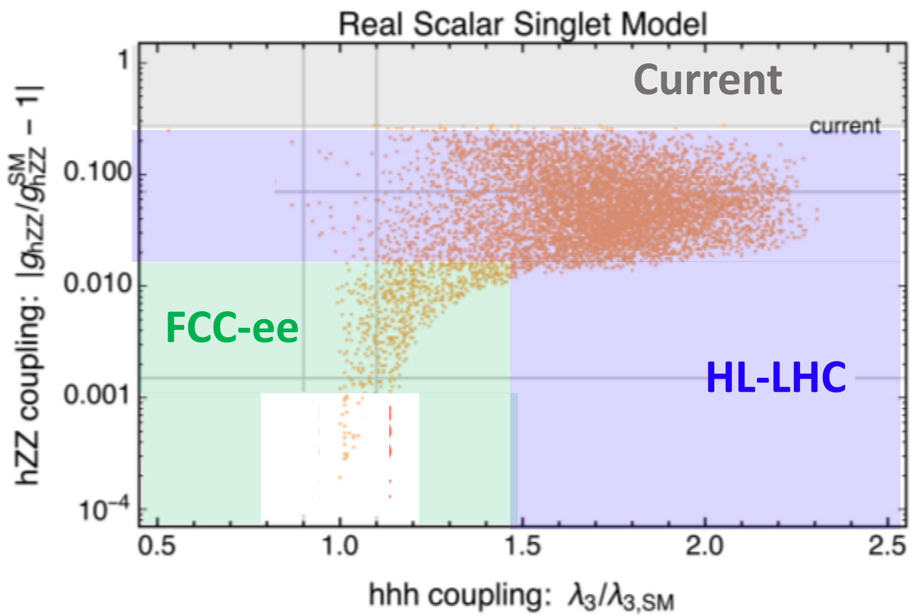


- **ZHH:** ILC/C^3: $\delta(\kappa_\lambda)$~20-30%; CLIC: ZHH observation ~6σ
- **HHνν:** >3σ evidence @CLIC E_{CM}=1.4 TeV

Higgs-self coupling summary

2209.07510

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%



e^+e^- vs. HL-LHC

- O(10) improved precision on **κ_Z**
- Up to 2-3x improvement on **κ_λ**

e^+e^-: Potential to probe several baryogenesis models

Summary

- Unique situation: no clear direction of where to look for New Physics
  - 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, …