Model independent Higgs boson couplings determination at FCC-ee

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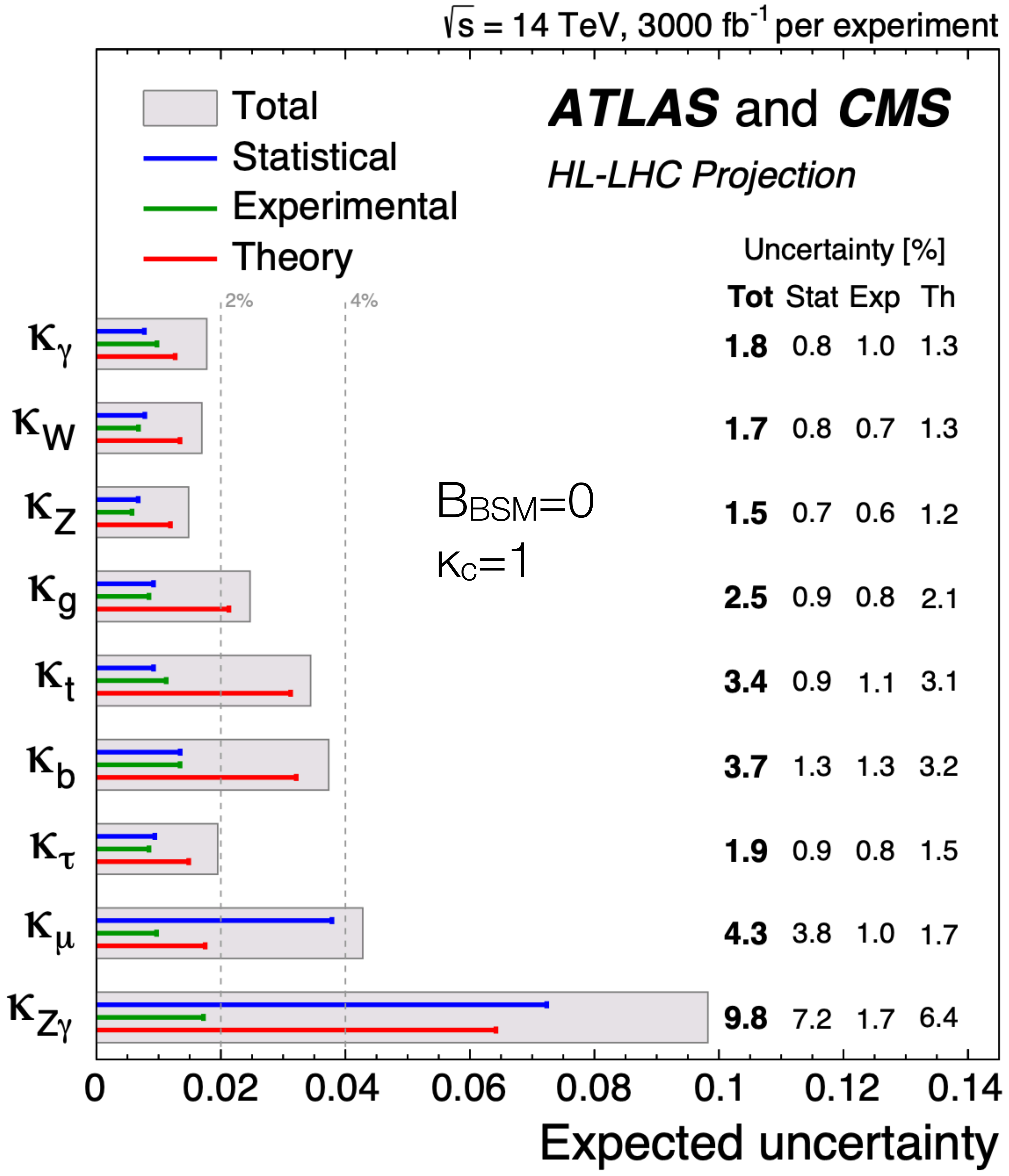
Higgs boson couplings at the HL-LHC

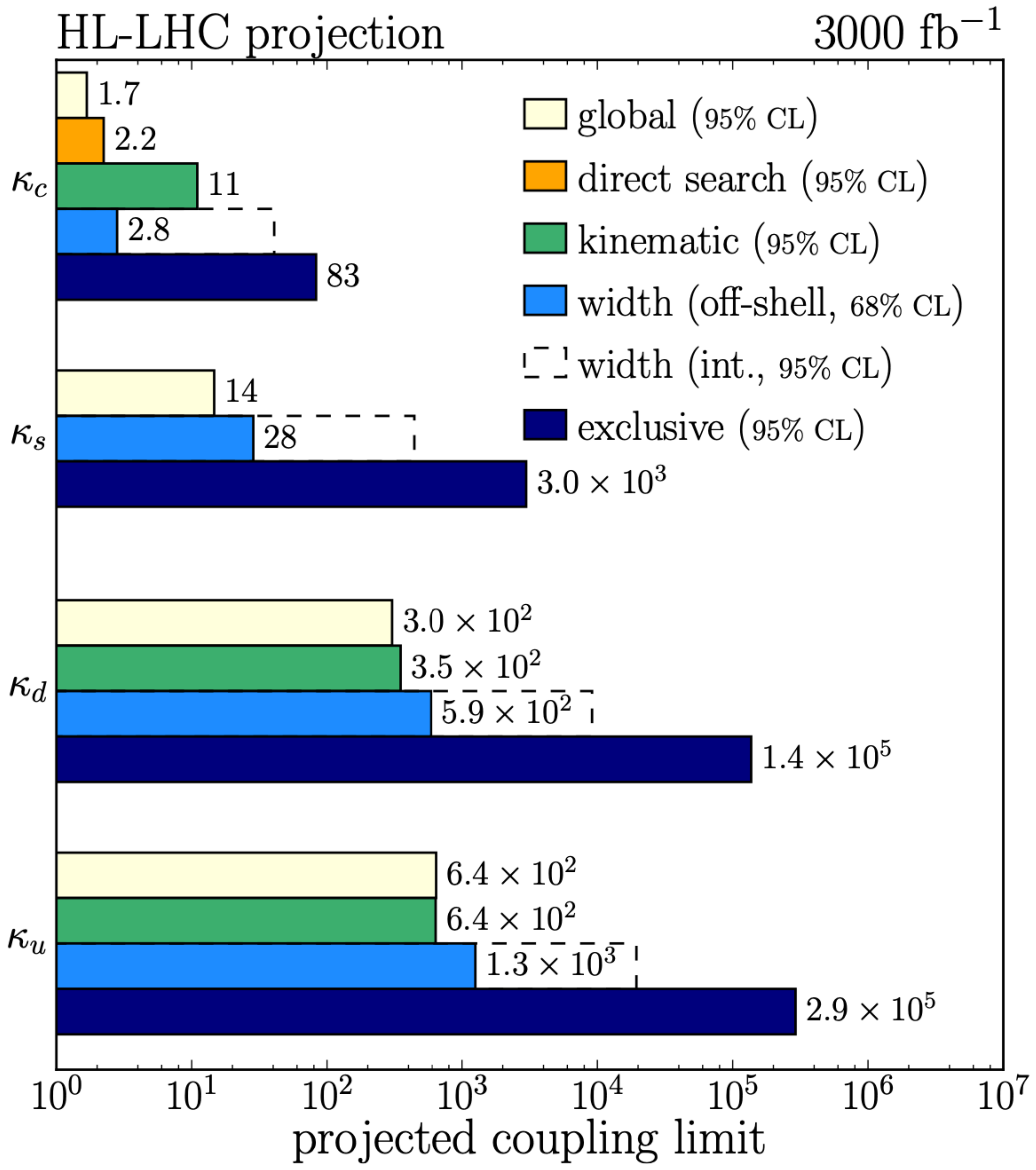
κ framework:

$$\mu_i^f \equiv \frac{\sigma \cdot BR}{\sigma_{SM} \cdot BR_{SM}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{SM}$$

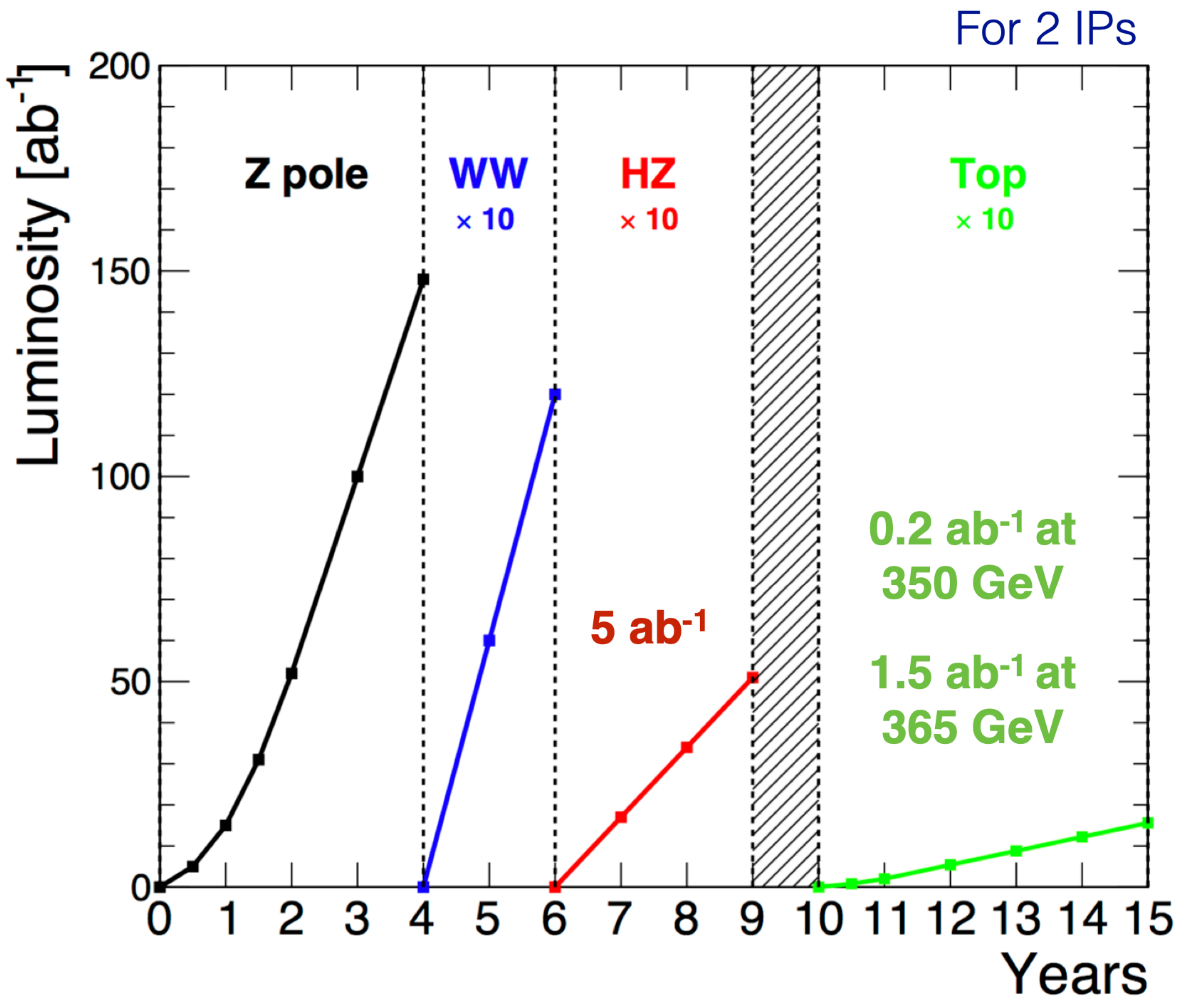
$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - BR_{BSM}} \qquad \kappa_H^2 \equiv \sum_j \frac{\kappa_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

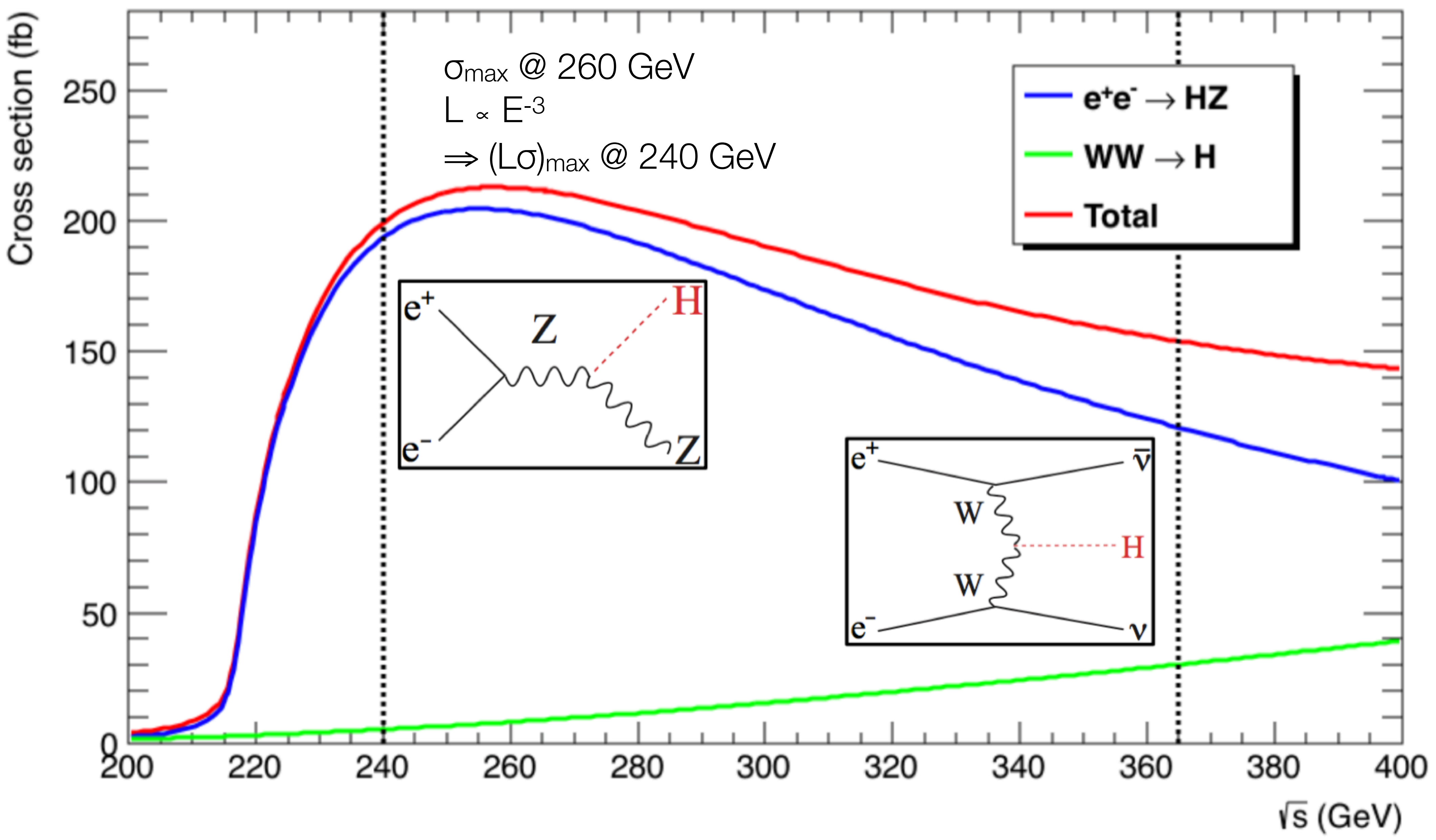




- **Typical precision: 1.5-4%** (**mainly** couplings to **gauge bosons, 3rd generation fermions, muons**), **limited by systematic uncertainties**
- **Model dependence**: results depend on **assumptions** (e.g. on BSM decays)
- **To improve our understanding of the Higgs sector further, and search for O(%) deviations induced by BSM physics at the multi-TeV scale, we need to go (sub-)percent level and model-independent measurements**

Higgs boson production at the FCC-ee



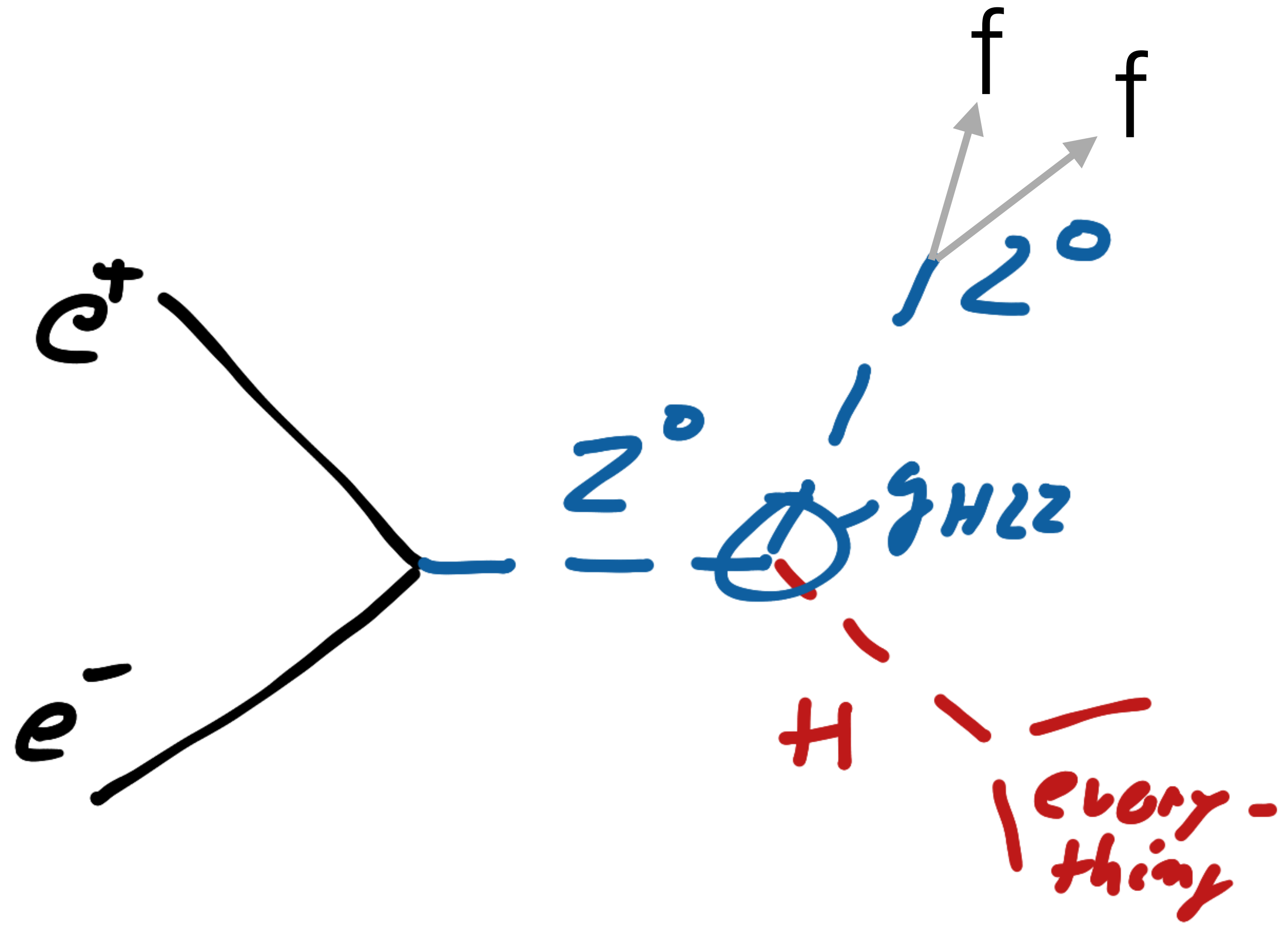


	5/ab @ 240 GeV	0.2/ab @ 350 GeV 1.5/ab @ 365 GeV
# Higgs from HZ	1,000,000	200,000
# Higgs from VBF	25,000	50,000

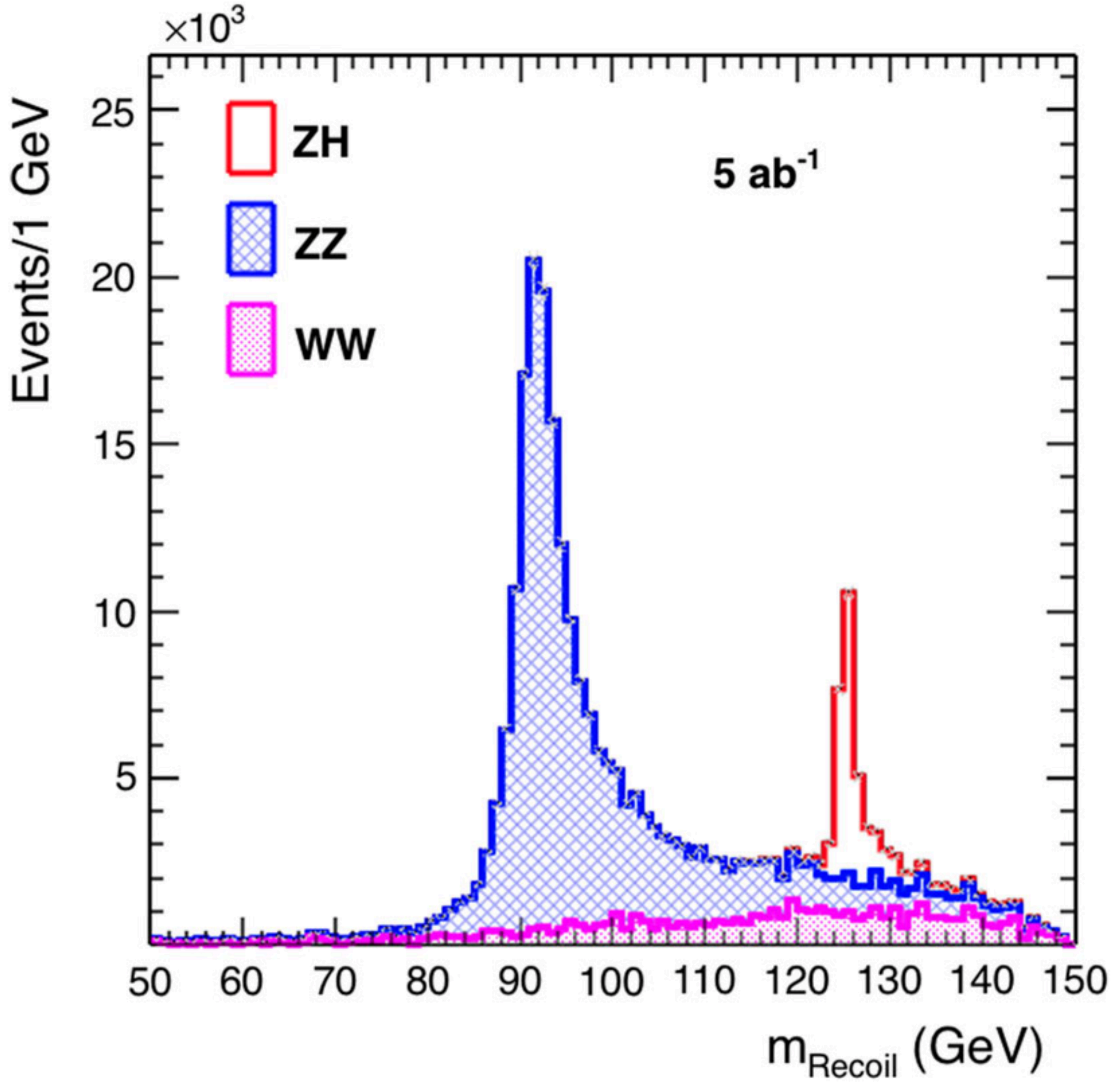
- “**Clean**” (good S/B, no pileup) **and abundant** Higgs boson production
  - **S ~ 10^6**
    - Small wrt pp colliders due to small xsection (but large acceptance!); large wrt linear ee colliders due to larger luminosity
  - **S/B (before selection) ~ 1/100-1000**
    - Much larger than pp colliders (S/B as low as 10^{-7} for hadronic signatures such as gg→H→bb)

Model independence: the ZH Higgs-strahlung process

- Measuring the Higgs couplings **without strong assumptions on how it decays** (but assume same kind of interactions as in the SM..) can be done by "**tagging**" Higgs boson production without observing its decay, detecting only the accompanying Z boson ⇒ **recoil mass**



$$(E_H + E_{ff}, \vec{p}_H + \vec{p}_{ff}) = \left(\sqrt{s}, \vec{0}\right) \Rightarrow m^2_{recoil} = \left(\sqrt{s} - E_{ff}\right)^2 - p^2_{ff}$$
$$= s + m_Z^2 - 2E_{ff}\sqrt{s} \approx m_H^2$$



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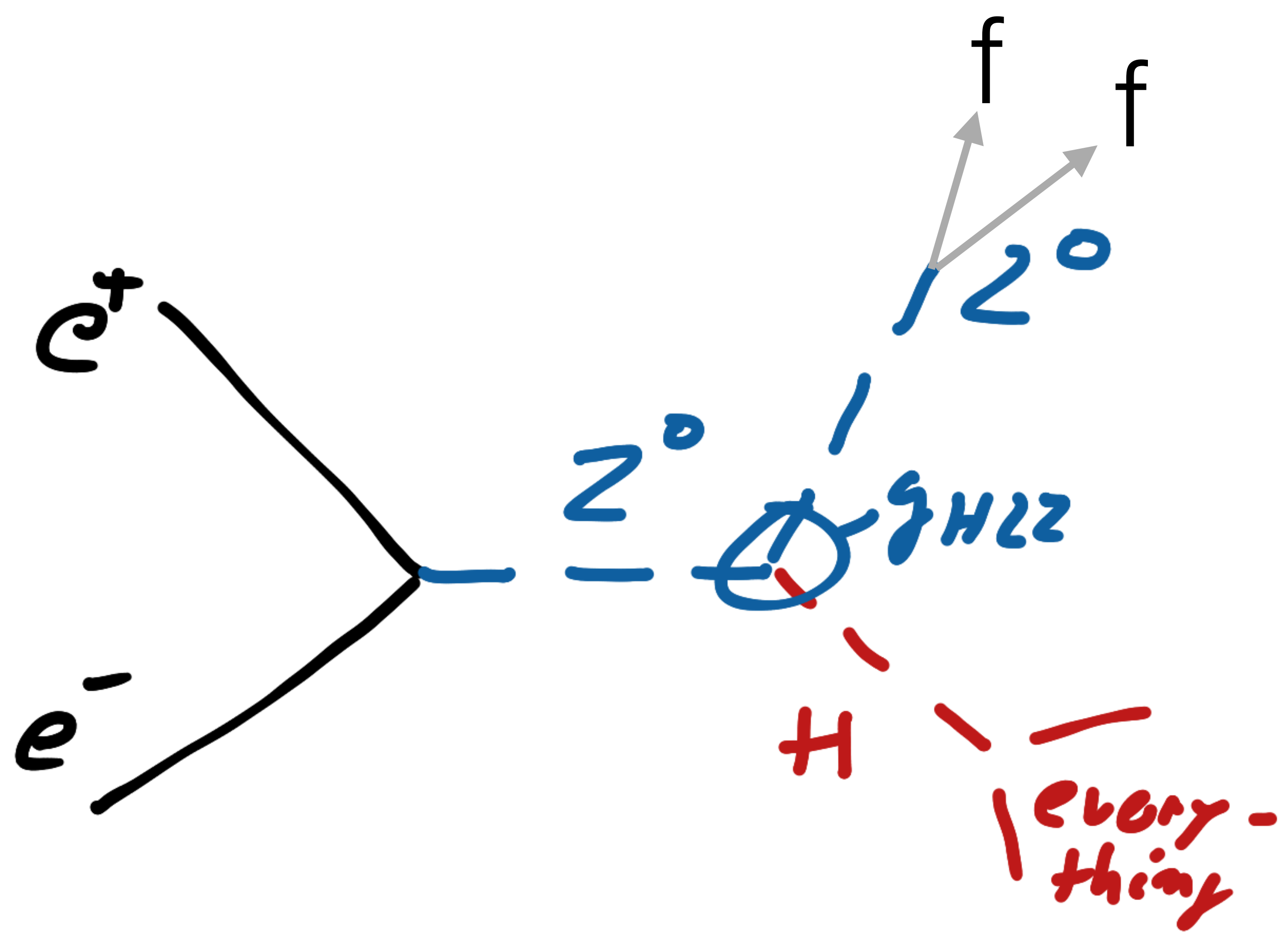

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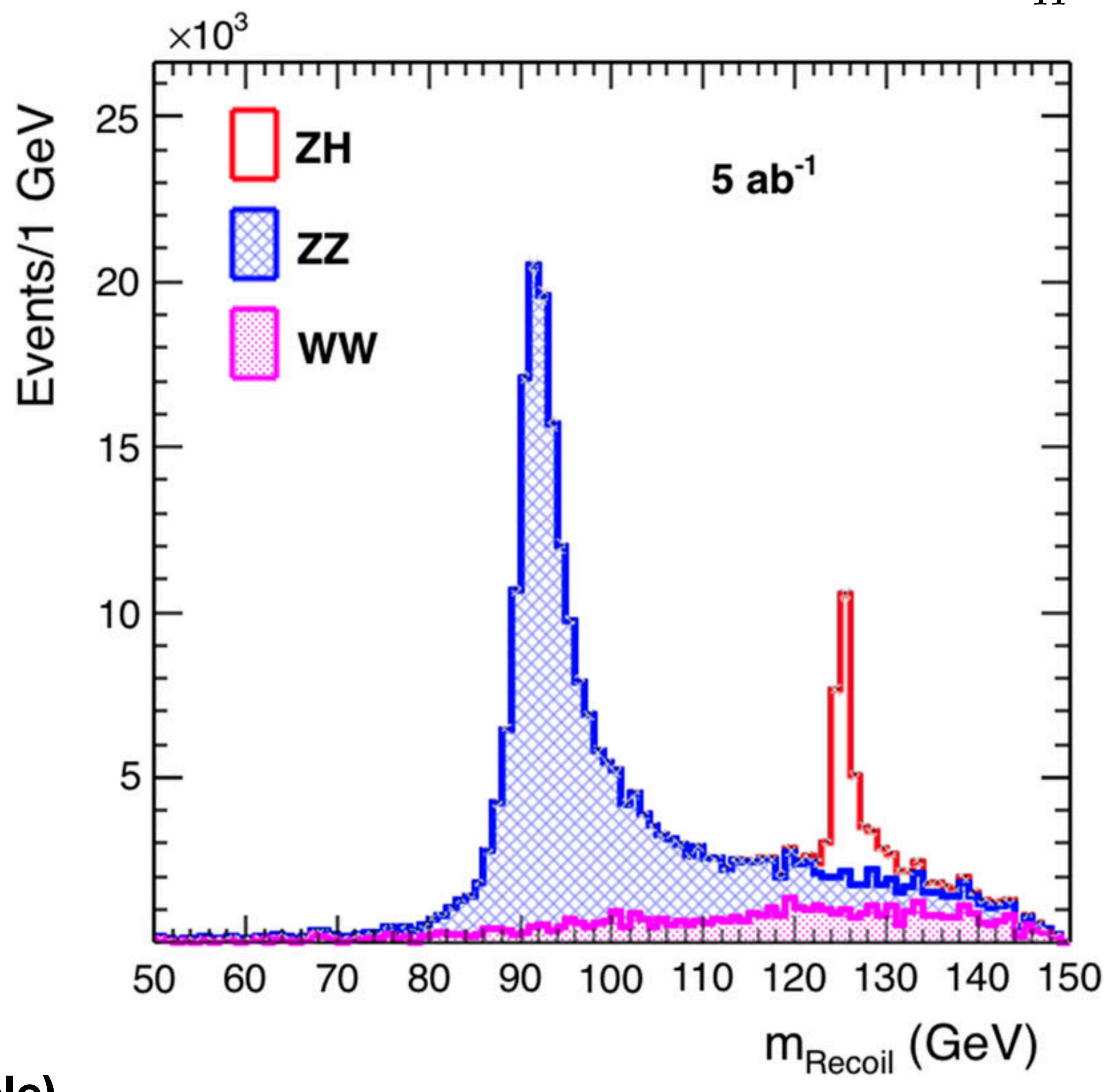


- **Without looking at the Higgs decay:**

$$\sigma(ee \to ZH) \Rightarrow g^2_{HZZ}$$

- **Reconstructing H→ZZ:**

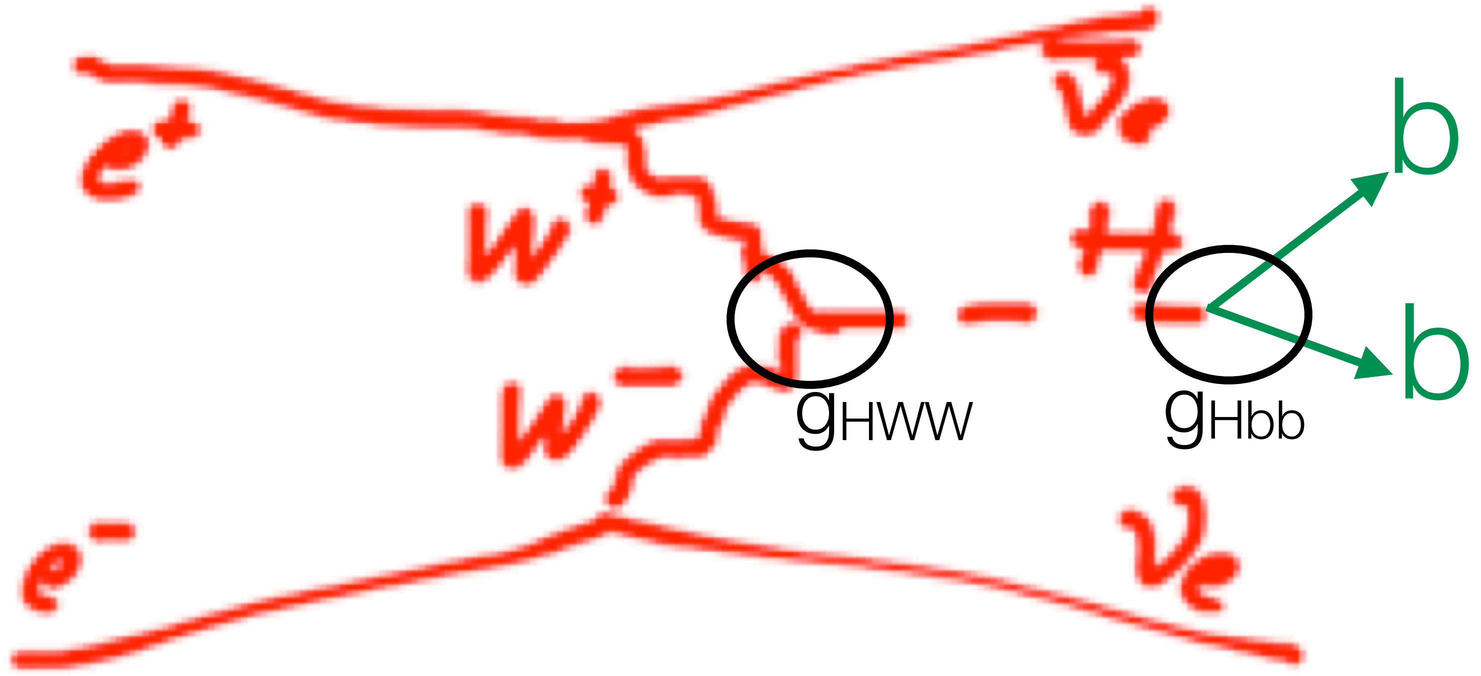
$$\sigma(ee \to ZH)BR(H \to ZZ) \propto \frac{g^4_{HZZ}}{\Gamma} \Rightarrow \Gamma$$

- **Reconstructing other Higgs Boson decays H→XX:**

$$\sigma(ee \to ZH)BR(H \to XX) \propto \frac{g^2_{HZZ} g^2_{HXX}}{\Gamma} \Rightarrow g^2_{HXX}$$

- **Looking at "invisible" Higgs decays (large missing energy) ⇒ BR(H→invisible)**

Improving the precision with the VBF process



- In combination with measurements @240 GeV, any σ(vvH)BR(H→XX) measurement @365 GeV leads to a
  - a new determination of g_{HWW}:

$$\frac{\sigma(ee \to \nu\nu H)BR(H \to XX)}{\sigma(ee \to ZH)BR(H \to XX)} \propto \frac{g^2_{HWW}}{g^2_{HZZ}}$$

  - a new determination of g_{HXX}:

$$\frac{\sigma(ee \to \nu\nu H)BR(H \to XX)}{\sigma(ee \to ZH)BR(H \to WW)} \propto \frac{g^2_{HXX}}{g^2_{HZZ}}$$

  - a new determination of the total width:

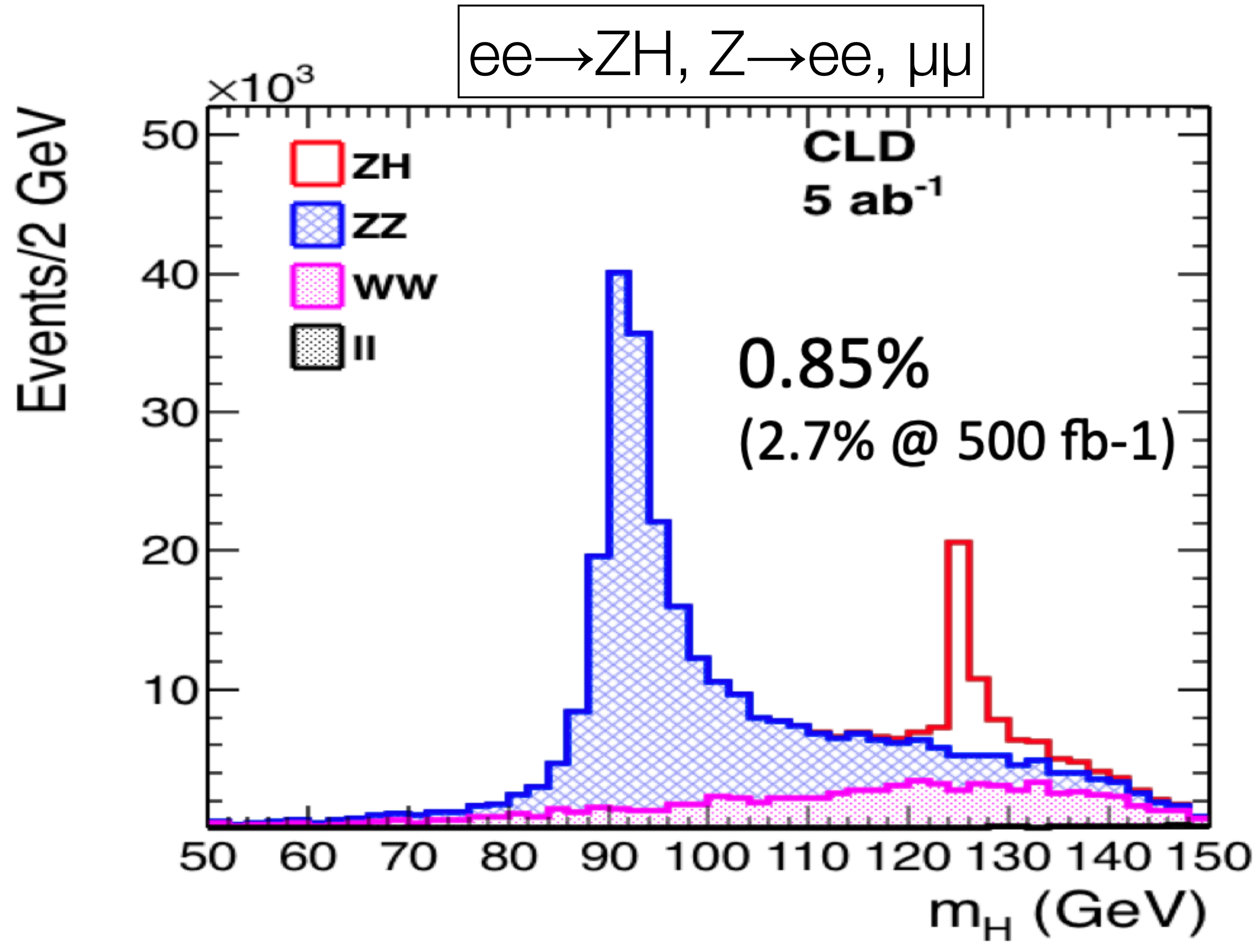
$$\sigma(ee \to \nu\nu H)BR(H \to XX) \propto \frac{g^2_{HWW} g^2_{HXX}}{\Gamma}$$

Analysis strategy

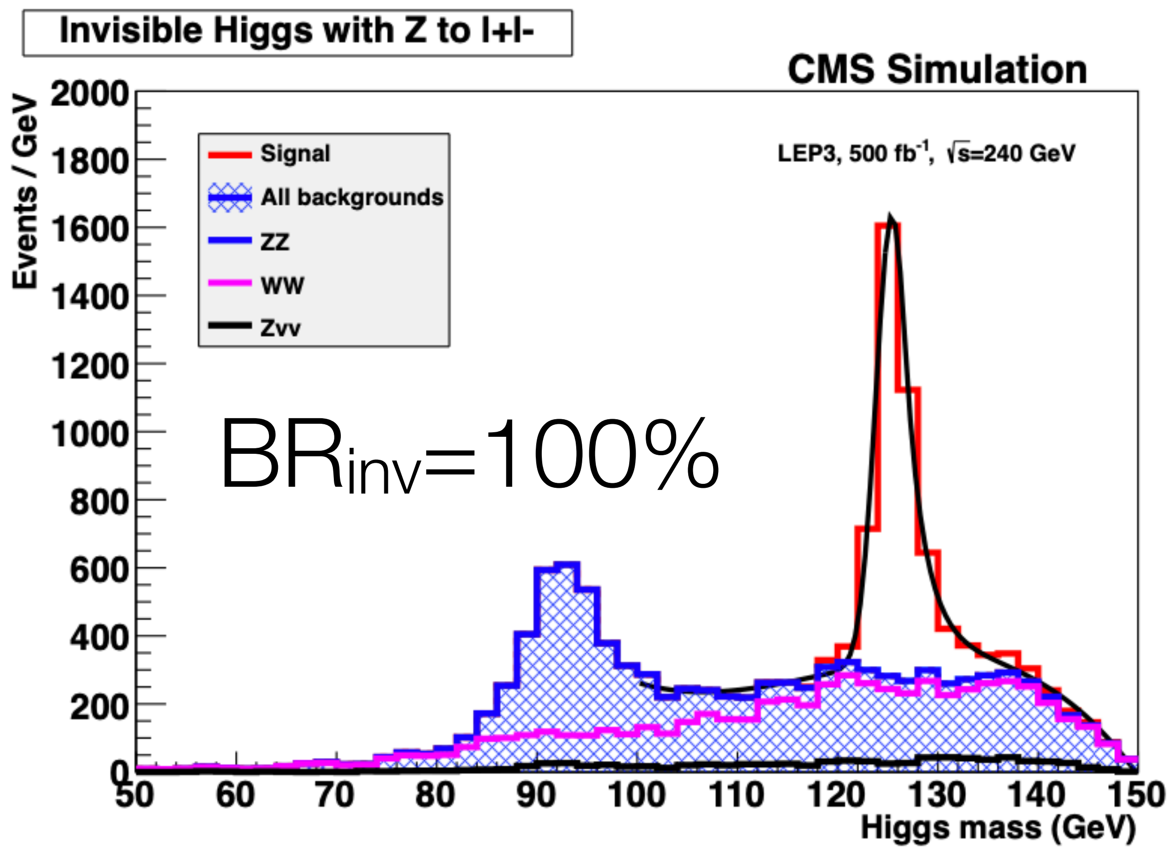
- **Analysis strategy first outlined in public document with studies for LEP3 (ee in LEP/LHC tunnel)** **[LEP3 note]**
  - Detector performance in initial studies were estimated **using CMS detector simulation**
  - Multivariate analysis assumed to reduce bkg by x2 wrt simple selection, ~15-20% improvement in sensitivity
- **Projections updated with a fast simulation of the performance foreseen for an optimised detector design (CLD)** **[slides]**
  - all-silicon tracker for reconstruction of charged particle and interaction vertices
  - High-granularity calorimeter for particle-flow reconstruction together with the silicon tracker
  - Muon system outside of the magnet coil
  - **⇒ ~10–40% improvement in sensitivity wrt CMS**
- **Numbers in CDR are based on ILC/CLIC expected sensitivities, scaled to account for the larger integrated luminosity of FCCee**
  - 2 IPs, 5/ab (2.5/ab/IP) @240 GeV, 1.5/ab @365 GeV
- **Similar analyses also performed and detailed in CEPC CDR, leading to similar expected performance**
- **In the following slides, I will show a few examples of cases that were studied in some detail, before giving the overall picture of the sensitivity to the different couplings**

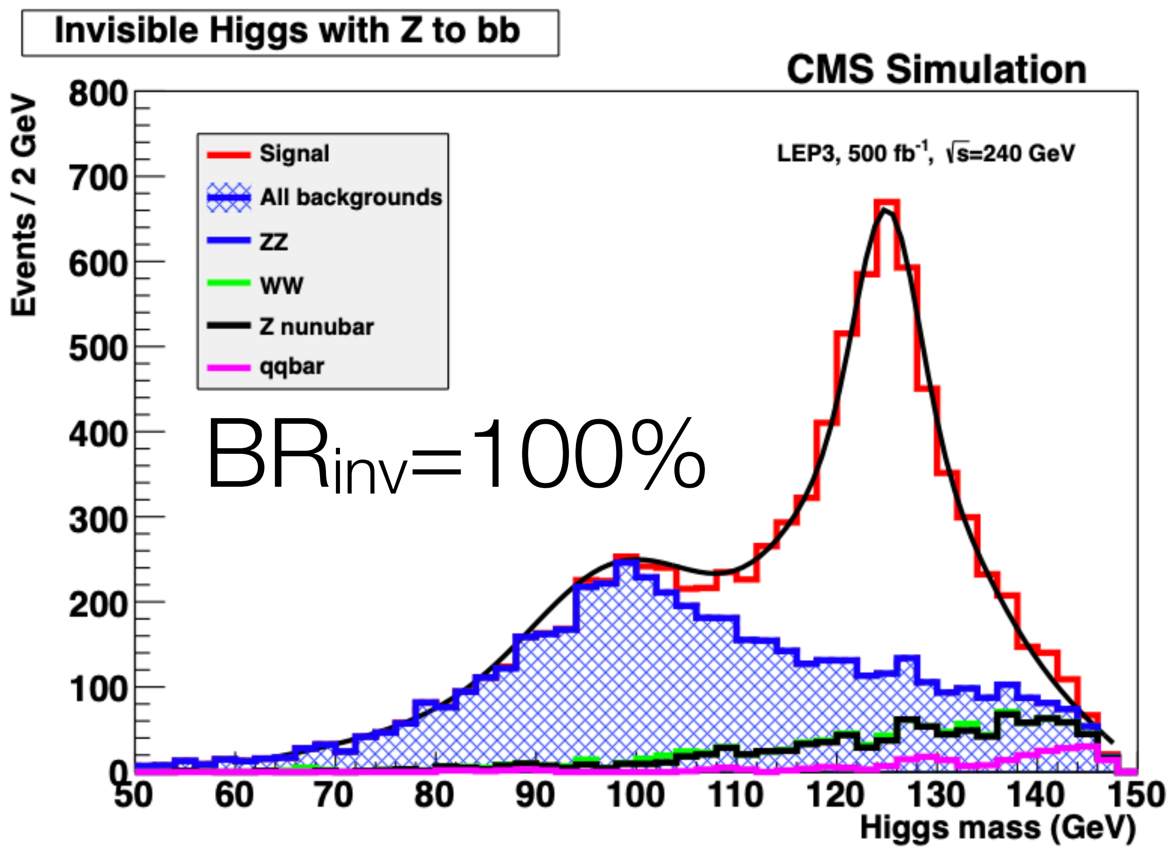
Measurement of σ(HZ) and of σ(HZ)*BR(H→invisible)

- **Total ZH cross section:**
  - Opposite-charge, same-flavour lepton pair (e, μ)
  - m_{ll}~m_Z (after FSR correction)
  - Kinematic cuts to reject bkg from ee→ll(γ) (p_T^{ll}, p_L^{ll}, lepton acoplanarity) and ee→ZZ (lepton acollinearity)
  - Perform S+B fit to m_{recoil} distribution
    - **0.5% uncertainty on event rate at FCCee**



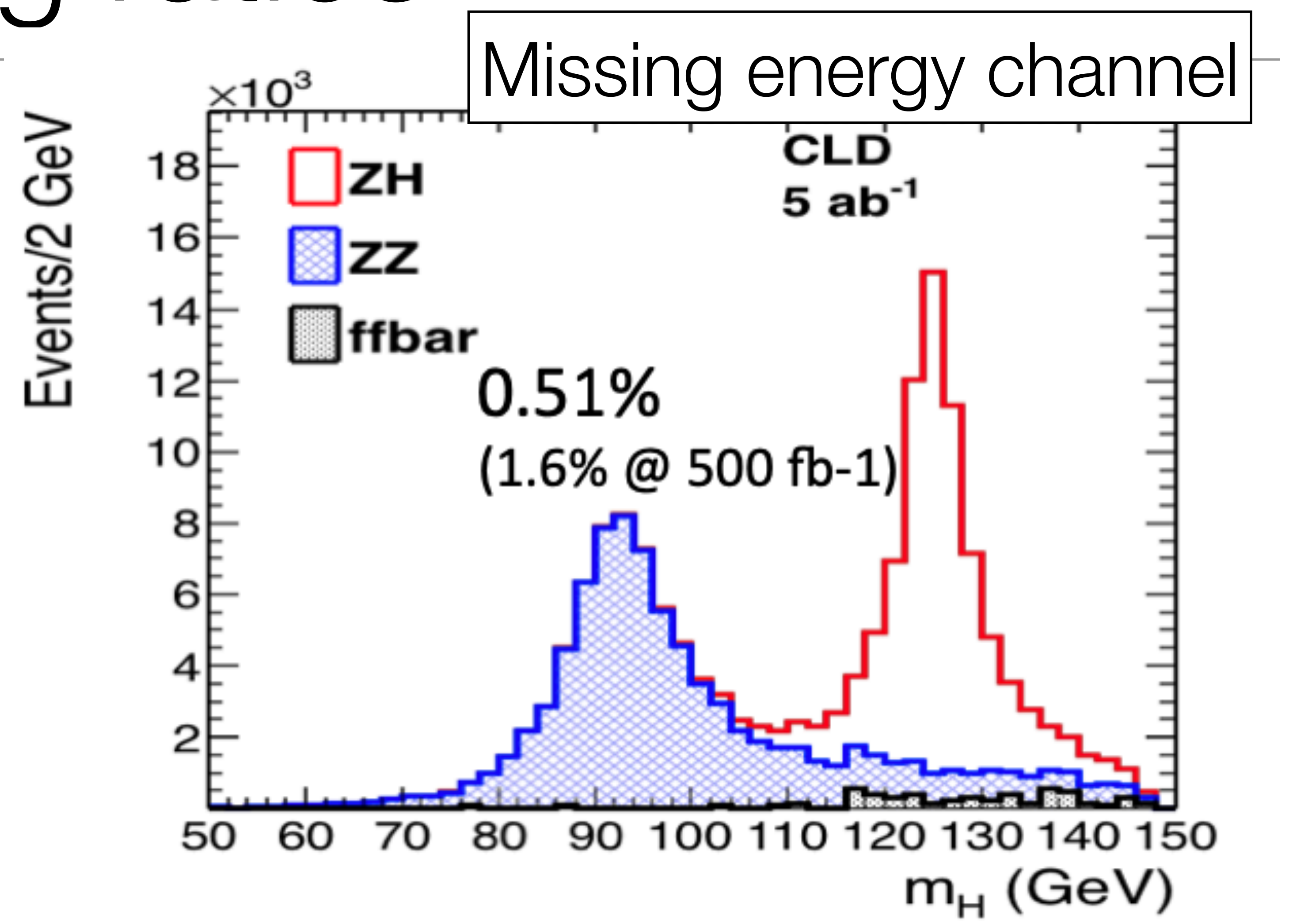
- **Invisible branching ratio: ZH, Z→ll/bb, H→invisible**
  - Z→ll as before
  - Z→bb: require >=2 jets, recluster original jets until 2-jets are obtained. Require at least 1 b-tagged jet, m_{jj}~m_Z, and same jet kinematic cuts as in the Z→ll case
  - Veto any extra particles
  - Perform S+B fit to m_{recoil} distribution
    - **BR<0.3% at 95% C.L. at FCCee**

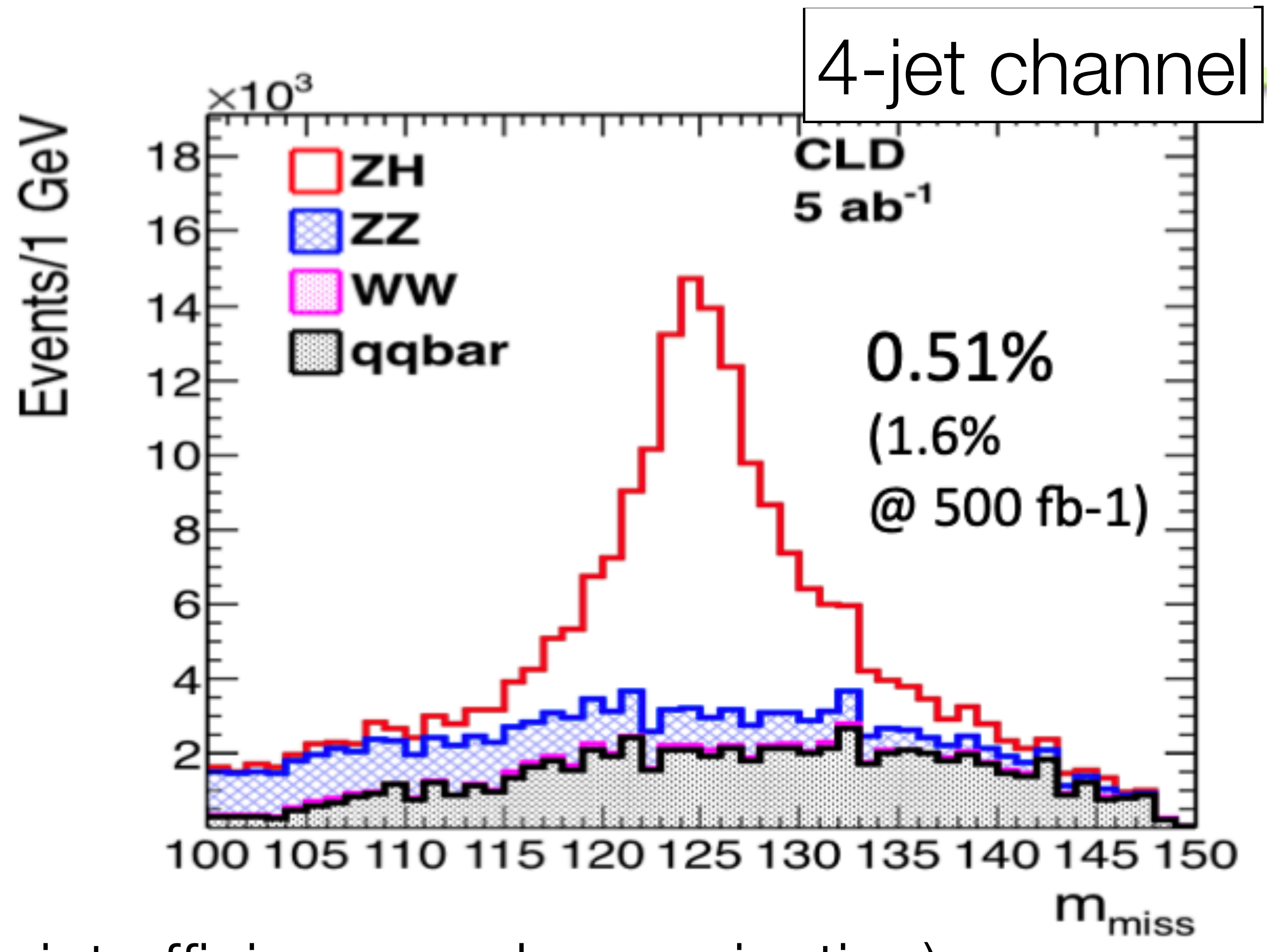




Measurement of hadronic Higgs boson branching ratios

- **H→bb**
  - **3 channels: 2l (Z→ll), high E_T^{miss} (Z→νν), 4j (Z→qq)**
    - **2l**: same selection as for σ(HZ) + at least one b-tagged jets in recoil.
    - **High E_T^{miss}**: similar selection as for BR(H→inv) measurement, require m_{miss}~m_Z. Rescale jet energies such that m_{miss}=m_Z
    - **4j**: at least 4-jets, reclustered into 4 iteratively recombining the jet pair with the smallest invariant mass, and recalibrated (no change in direction) from E,p conservation
      - Reject jets without hadrons or <5 particles (reject Z→leptons)
      - Reject events with large missing energy: visible mass > 180 GeV. (reject Z→νν)
      - Veto events in which m_{j1j2}, m_{j3j4} ~ m_W or m_{j1j2}, m_{j3j4} ~ m_Z (suppress WW, ZZ)
      - Keep events with m_{j1j2} ~ m_H, m_{j3j4} ~ m_Z. j1 and j2 must be b-tagged
    - Fit recoil or dijet mass distribution
  - **0.3% uncertainty on event rate from combination of the 3 channels at FCCee**





- **H→cc, gg**
  - Similar selection as H→bb, **use other working points of b-tagging algorithms** (different b-jet efficiency and c, g rejection) **or dedicated c, g tagging** to obtain **system of equations relating measured Higgs yields to BR(H→bb), BR(H→cc), BR(H→gg)**
  - **2.2% uncertainty on cc, 1.9% on gg event rate at FCCee (sensitivity very dependent on vertex detector design, should be confirmed with dedicated full-simulation study and implementation of real flavour-tagging algorithm)**

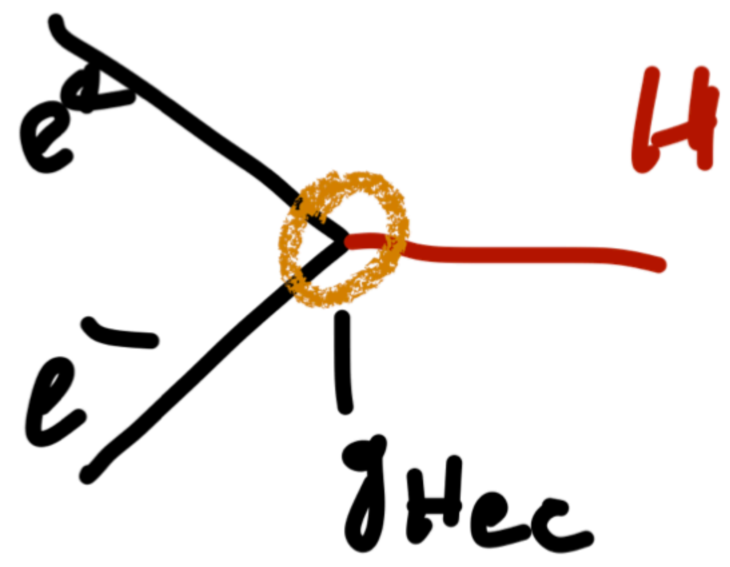
Expected coupling uncertainties (κ framework)

Collider	HL-LHC	FCC-ee		
Luminosity (ab^{-1})	3	5 @ 240 GeV	+ 1.5 @ 365 GeV	+ HL-LHC
Years	25	3	+ 4	–
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	3.1
BR_{EXO} (%)	SM	< 1.2	**< 1.0**	< 1.0

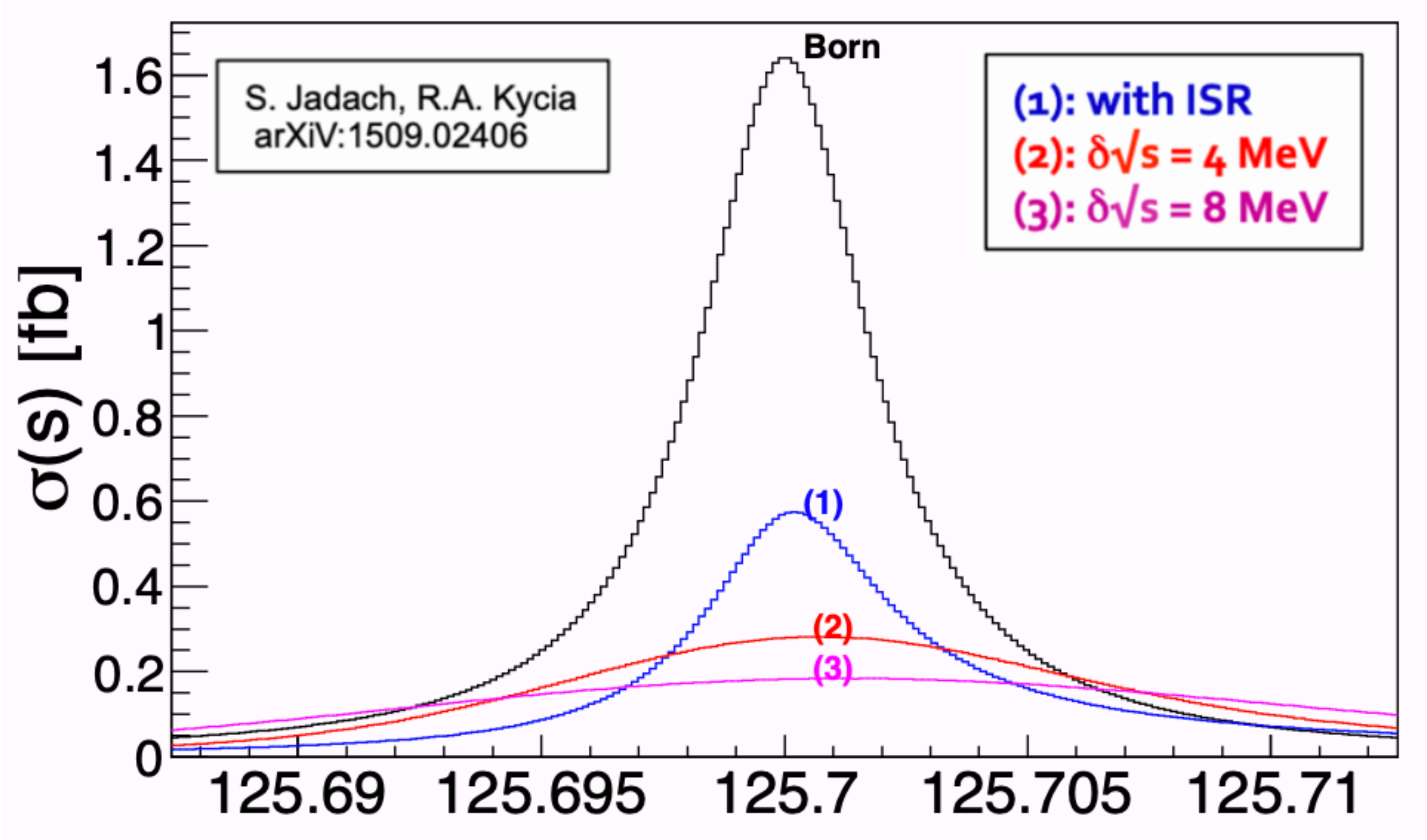
FCC CDR volume 1: Physics opportunities https://doi.org/10.1140/epjc/s10052-019-6904-3

- For **FCC-ee$_{240}$**, global fit to recoil cross section and σ*BR leads to **absolute** couplings measurements with:
  - **0.2% uncertainty** in coupling to **Z** (**>10x better** than HL-LHC)
  - **<2% uncertainty** in couplings to **W, τ, g, b, c** (1.3, 1.4, 1.5, 2.8, **O(30)** x **better** than HL-LHC)
  - **poor constraints** on couplings to **μ and Zγ** (rare processes, low yield) and **none** on coupling to **top** (ttH not accessible)
- **FCC-ee$_{365}$**: more stat as well as WW→H production ⇒ **smaller uncertainties (up to x3), <% for W, g, b, τ** (**2.5-6x better** than HL-LHC)
  - κ_W improvement directly related to g_{WW} measurement in WBF
  - κ_g, κ_τ, κ_b improvement driven by larger stat as well as reduced uncertainty on Γ-Γ_W.
  - Improvement for couplings inducing rare decays (small contribution to Γ), κ_μ, κ_γ, goes down like $\sqrt{(\sigma L)}$ (benefiting only from larger stat)
- **Combination with HL-LHC** leads to **1.3% uncertainty on κ_γ** and **3-4% on κ_μ, κ_t.** (**10-40% better** than HL-LHC, **no hypothesis on Γ**)

Measuring first generation Higgs couplings?



- 1st generation couplings very small ⇒ **BR(H→ee/dd/uu) too small to be measured ~O(10^{-9})**
  - **Can only measure κ_e through study of s-channel Higgs production in ee collisions**
- **$\sigma_{ee\to H}$=1.64 fb, Γ_H=4.2 MeV** ⇒ **need very high luminosity+very small E spread** at $\sqrt{s}=m_H$
- At FCC-ee@125 GeV, **L=2e36 cm^{-2}s^{-1} ⇒ 20 ab^{-1}/yr ⇒ ~30k H/yr** if no E spread and ISR
  - **ISR + 4.2 MeV energy spread** ⇒ ~80% reduction (290 ab, **~6k H/yr**)



- **Feasibility study w/ Pythia8:** generate ee→H→X and ee→VV, γγ, gg, qq (q=t,b,c,l) (slides)
  - **10 final states chosen based on S and S/B: bb, gg, ττ, WW, ZZ, γγ**
  - Selection based on kinematic quantities characterising single particles, pairs, or global event
  - Simplified assumptions on efficiencies and fake rates for b/c/l/τ tagging algorithms (and e↔γ)
  - **Most significant channel: H→WW*→lνjj**

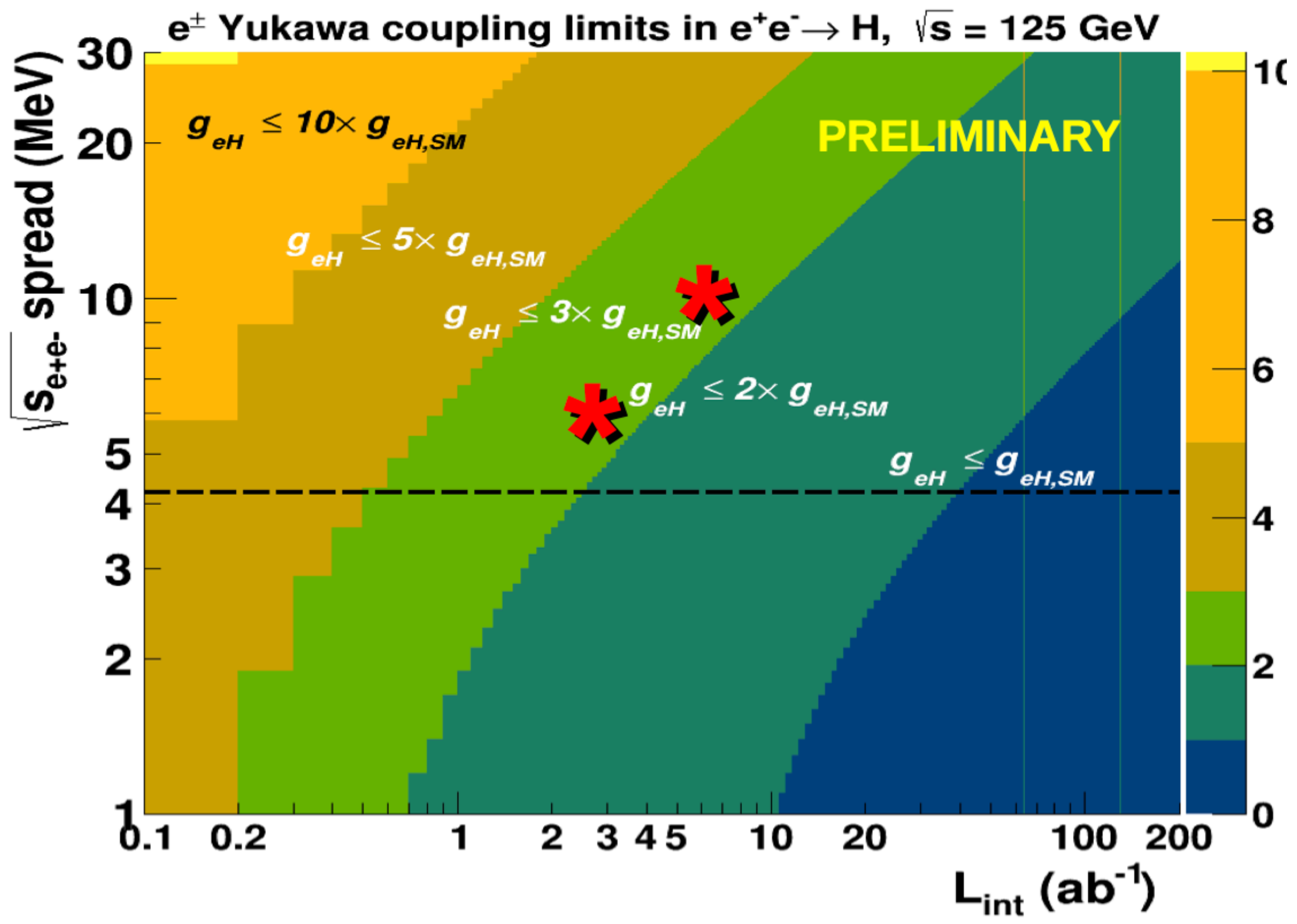
$E_{j1,j2}$ < 52,45 GeV ← Kills $e^+e^-\to q\bar{q}$
$m_{w(l\nu)}$ > 12 GeV/c² ← Kills $e^+e^-\to q\bar{q}$
E_{lepton} > 10 GeV ← Kills $e^+e^-\to q\bar{q}$
ME > 20 GeV ← Kills $e^+e^-\to q\bar{q}$
m_{ME} < 3 GeV/c² ← Kills $e^+e^-\to\tau\tau$
BDT MVA ← Kills $e^+e^-\to$WW* continuum
(exploits opposite W± polarizations in H decay)

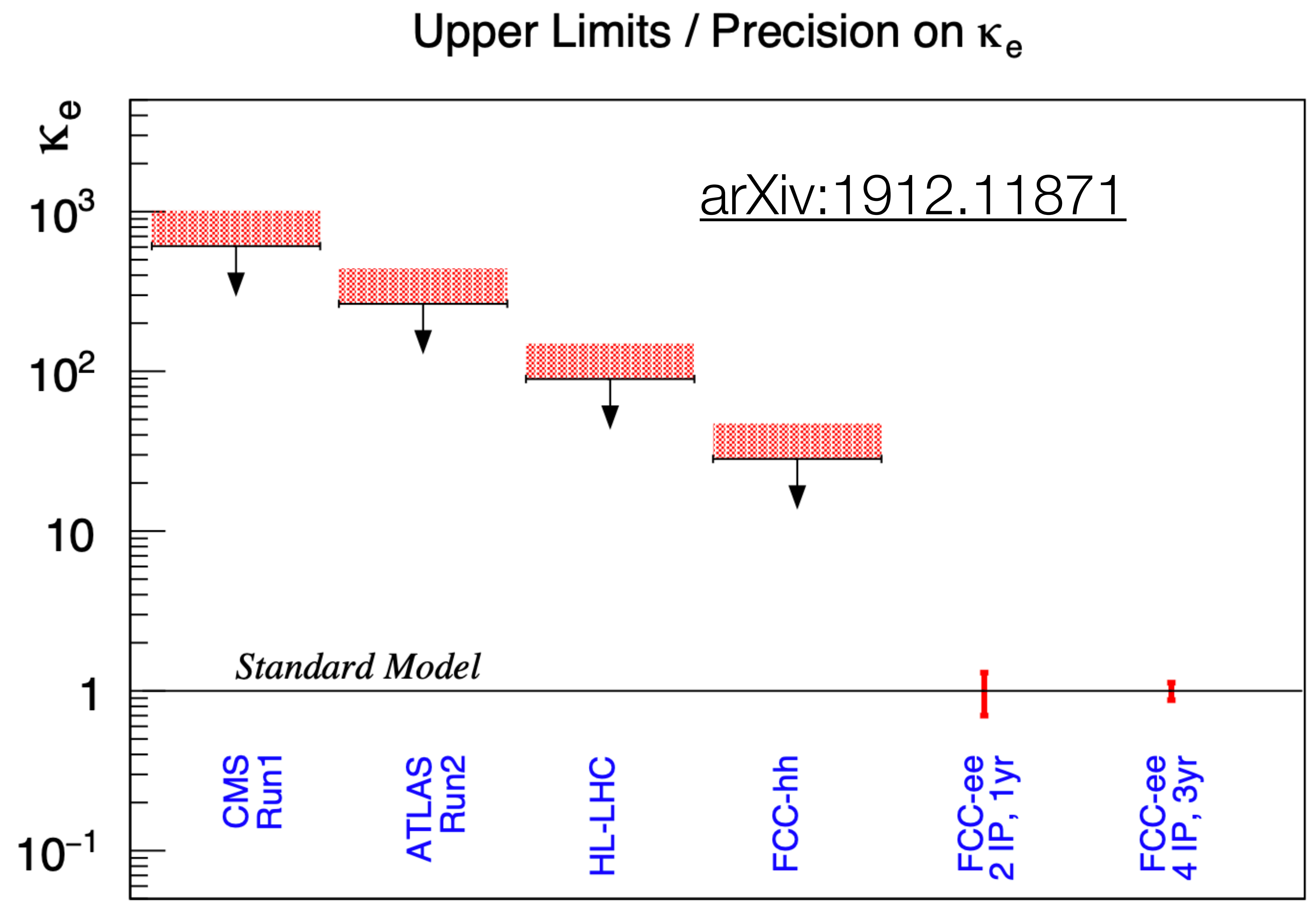
$q\bar{q}$:	σ = 22 pb	⇒	σ(after) = 4 ab
τ τ:	σ = 1 pb	⇒	σ(after) = 2.6 ab
WW*:	σ = 16.3 fb	⇒	σ(after) = 2.7 fb
H(WW*):	σ = 23 ab	⇒	σ(after) = 8 ab

For L_{int}=10 ab^{-1}
S/√B =80/√27000 ≈ 0.5
Significance ≈ 0.5

Measuring first generation Higgs couplings?

- Combining all channels together:





- **Current monochromatisation options** (*): energy spread = 6 or 10 MeV, L_{int}=3/ab or 7/ab per experiment*year
  - **κ_e < 2.2 @95% CL (1 experiment, 1 year)**
  - **Could exclude κ_e =0 @2.5σ w/ 2 experiments after 1 yr (κ_e =1±0.4)**
  - **Could reach >3σ on κ_e w/ 2 experiments running 3 yrs at Higgs pole (κ_e =1±0.23)**
  - **Constraints on κ_e are x100 (x30) better than at HL-LHC (FCC-hh)**

➡ **Few years at $\sqrt{s}=m_H$ are not in baseline FCC-ee run plan but would be a very interesting add-on!**

Conclusion

- Clean and abundant production of Higgs boson at FCC-ee, in well-known initial state, with accompanying tagging Z boson, and small backgrounds, will lead to **model-independent determination, with (sub-)% level uncertainty, of absolute Higgs boson couplings**
- Additional running at $\sqrt{s}$=125 GeV could lead to **a measurement of the coupling to the 1st generation** (κ_e), setting constraints that are **order of magnitudes better than those achievable at hadron machines and can reach sensitivity to SM**
- **More work is needed in the future on detector optimisation, full simulation and analysis optimisation efforts to further improve the sensitivity and consolidate the results**
- *Haven't talked about self-coupling as well as EFT interpretation ⇒ in next talk by Roberto*

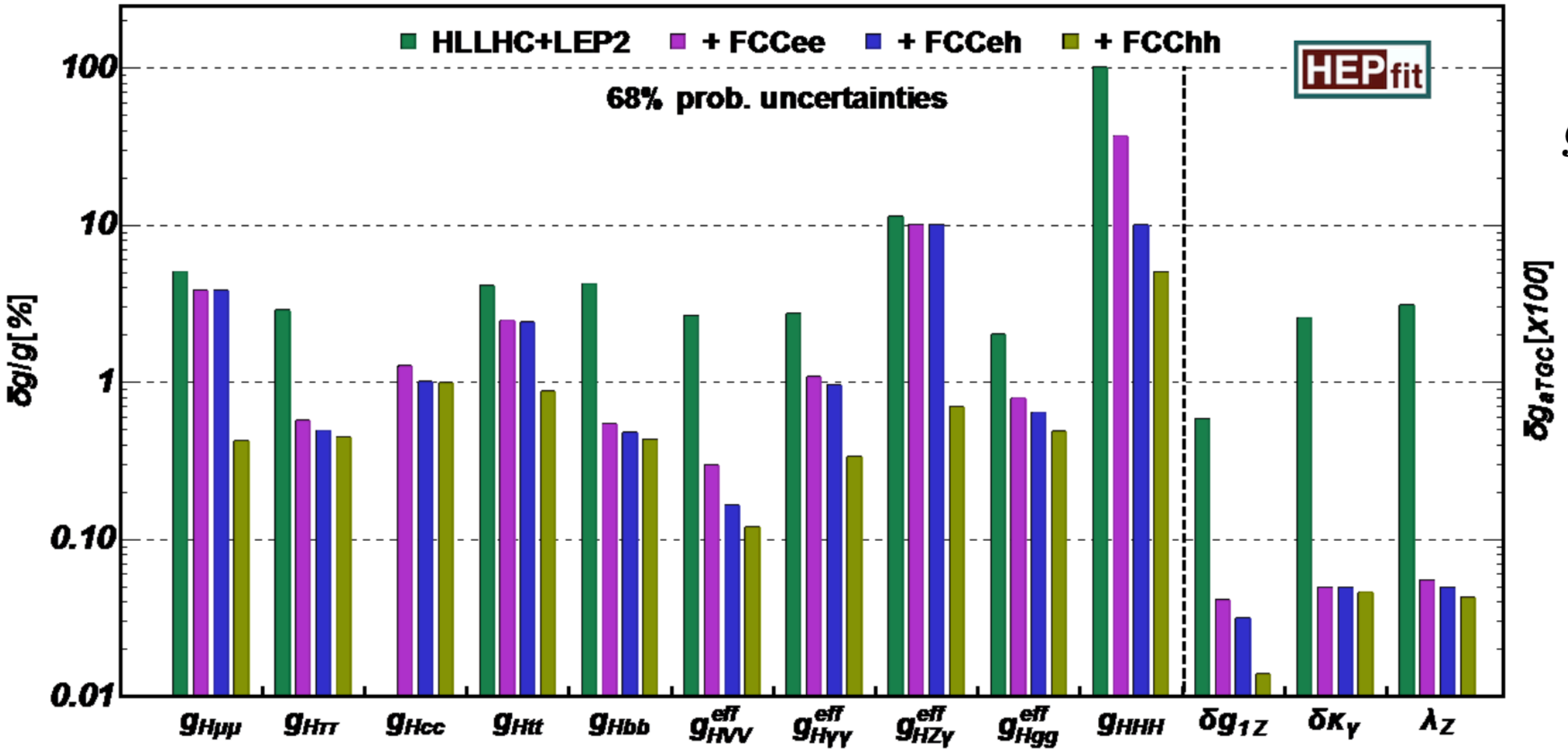
Backup

FCCee - uncertainties on the event rates

Table 4.1 Relative statistical uncertainty on the measurements of event rates, providing $\sigma_{HZ} \times BR(H \to XX)$ and $\sigma_{\nu\bar{\nu}H} \times BR(H \to XX)$, as expected from the FCC-ee data. This is obtained from a fast simulation of the CLD detector and consolidated with extrapolations from full simulations of similar linear-collider detectors (SiD and CLIC). All numbers indicate 68% C.L. intervals, except for the 95% C.L. sensitivity in the last line. The accuracies expected with 5 ab^{-1} at 240 GeV are given in the middle columns, and those expected with 1.5 ab^{-1} at $\sqrt{s} = 365$ GeV are displayed in the last columns

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	± 0.5		± 0.9	
$H \to b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
$H \to c\bar{c}$	± 2.2		± 6.5	± 10
$H \to gg$	± 1.9		± 3.5	± 4.5
$H \to W^+W^-$	± 1.2		± 2.6	± 3.0
$H \to ZZ$	± 4.4		± 12	± 10
$H \to \tau\tau$	± 0.9		± 1.8	± 8
$H \to \gamma\gamma$	± 9.0		± 18	± 22
$H \to \mu^+\mu^-$	± 19		± 40	
$H \to$ invis.	< 0.3		< 0.6	

Global EFT fit



g_{Hff} : modified Yukawa coupling

$$(g^{\text{eff}}_{HXX})^2 \equiv \Gamma_{H\to X}/\Gamma^{\text{SM}}_{H\to X}$$

Figure S.1: One-σ precision reach at the FCC on the effective single Higgs couplings, Higgs self-coupling, and anomalous triple gauge couplings in the EFT framework. Absolute precision in the EW

Compared with LHC and LEP, FCC-ee/eh will improve the measurements of EFT parameters by roughly one order of magnitude. A combination with the LHC measurements provides a marginal improvement for most of the parameters. For $g^{\text{eff}}_{H\gamma\gamma}$, $g^{\text{eff}}_{HZ\gamma}$ and $g_{H\mu\mu}$, the improvements are more significant, as the small rates and clean signals make the LHC reaches comparable to that of lepton colliders. Other couplings, e.g. g^{eff}_{HVV} and g_{Hbb}, are also indirectly improved in the combination. It should be noted that the measurements of the H → gg branching fraction only constrain a linear combination of g^{eff}_{Hgg} and g_{Htt}. These two couplings are thus only constrained independently by lepton colliders when $\bar{t}tH$ production is measured. Therefore, combination with LHC measurements is required for the FCC-ee to constrain these couplings independently. The resulting bound on g_{Htt} is then even substantially better than that set by the LHC alone.

FCC-ee Higgs Couplings

➡Unique measurements at highest precision

Collider	HL-LHC	ILC$_{250}$	CLIC$_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+ 1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	8	3	+4	–	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.30	0.60	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.3	**0.61**	0.56	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	1.6	**1.01**	0.90	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.4	**0.74**	0.67	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	10.1	**9.0**	3.8	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	4.8	**3.9**	1.3	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	3.1	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	$< \mathbf{1.0}$	< 1.0	n.a.

➡Uncertainties not limited by experimental or theoretical uncertainties. Statistics sets the floor.

➡Indirect sensitivity to Higgs self-coupling

Coupling sensitivities (k framework) including FCC-hh

- With respect to FCC-ee, FCC-hh has high-enough energy to **produce ttH** (and thus the **coupling to the top**) as well as much larger cross sections, which are particularly beneficial for measuring the couplings that induce **rare decays** (**couplings to photons, to Z+photon, and to muons**) or set more stringent limits on the **invisible BR**

kappa-0	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.3	0.43	0.14
κ_Z [%]	0.20	0.17	0.12
κ_g [%]	1.7	1.0	0.49
κ_γ [%]	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	81⋆	75⋆	0.69
κ_c [%]	1.8	1.3	0.95
κ_t [%]	—	—	1.0
κ_b [%]	1.3	0.67	0.43
κ_μ [%]	10	8.9	0.41
κ_τ [%]	1.4	0.73	0.44

kappa-2 scenario	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W [%]	1.3	0.44	0.2
κ_Z [%]	0.21	0.18	0.17
κ_g [%]	1.7	1.0	0.52
κ_γ [%]	4.8	3.9	0.32
$\kappa_{Z\gamma}$ [%]	71.∗	66.∗	0.71
κ_c [%]	1.8	1.3	0.96
κ_t [%]	-	-	1.0
κ_b [%]	1.3	0.69	0.48
κ_μ [%]	10.	8.9	0.43
κ_τ [%]	1.4	0.74	0.49
BR_{inv} (<%, 95% CL)	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.2	1.1	1.0

kappa-3 scenario	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W [%]	0.88	0.41	0.19
κ_Z[%]	0.20	0.17	0.16
κ_g[%]	1.2	0.9	0.5
κ_γ [%]	1.3	1.3	0.31
$\kappa_{Z\gamma}$ [%]	10.∗	10.∗	0.7
κ_c [%]	1.5	1.3	0.96
κ_t [%]	3.1	3.1	0.96
κ_b [%]	1.	0.64	0.48
κ_μ [%]	4.	3.9	0.43
κ_τ [%]	0.94	0.66	0.46
BR_{inv} (<%, 95% CL)	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.2	1.	1.

Peak luminosity vs sqrt(s)