XXXIII INTERNATIONAL SEMINAR OF NUCLEAR AND SUBNUCLEAR PHYSICS "FRANCESCO ROMANO" 2022

Physics @Future Colliders - 2

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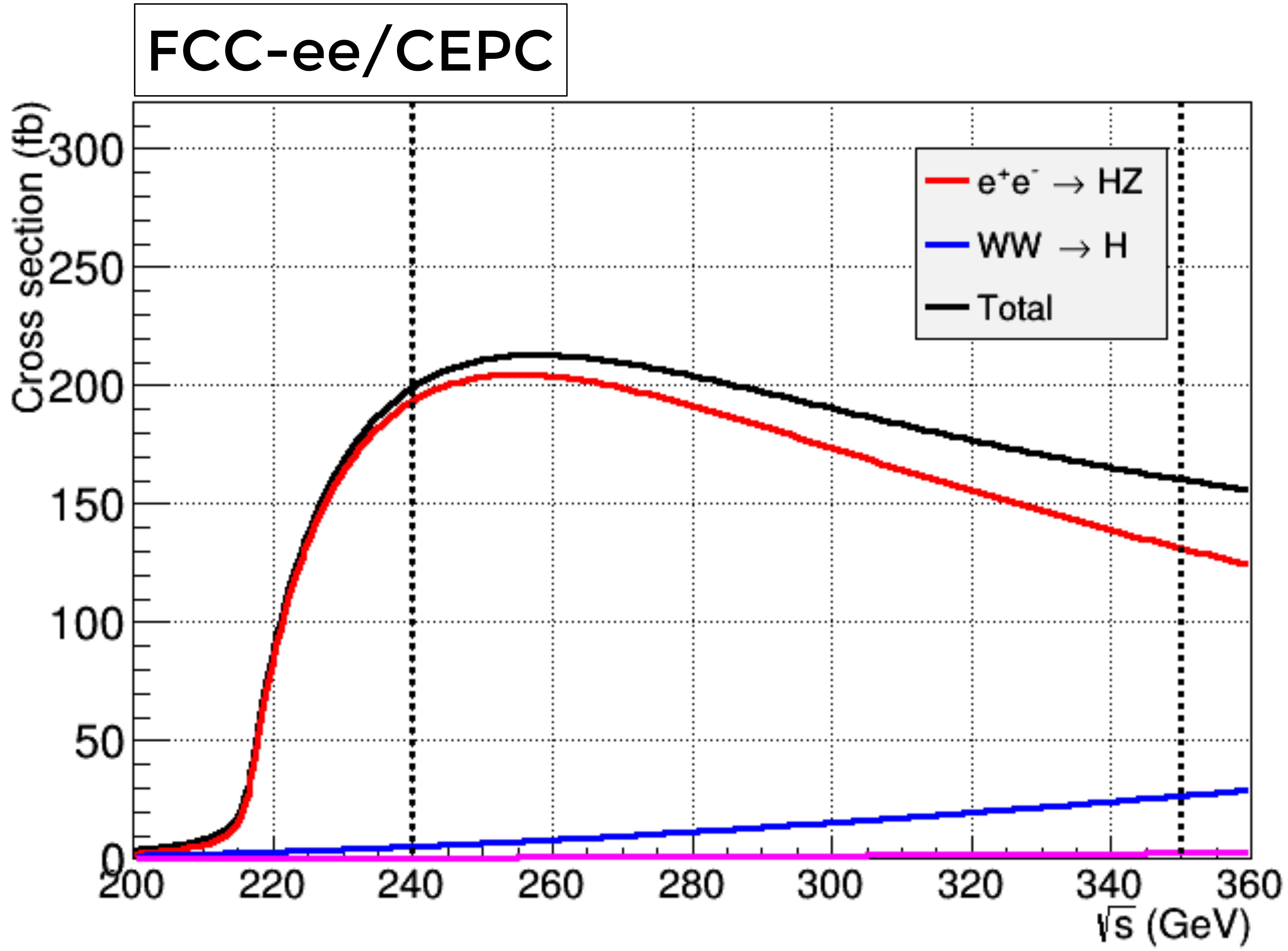
PHYSICS AT e+e- COLLIDERS

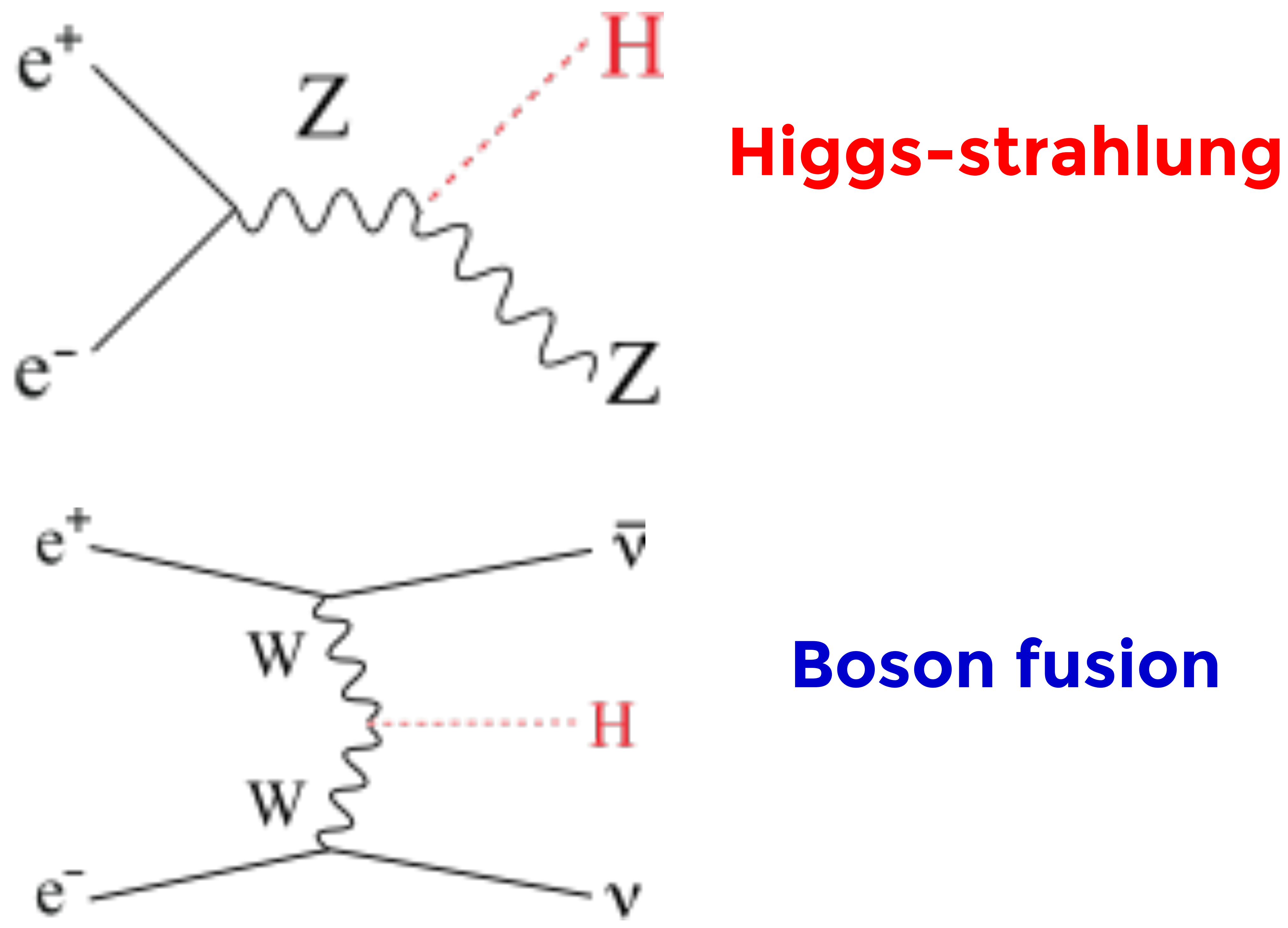
$\sqrt{s}$	Processes	Physics Goals	Observables
91 GeV	• $e^+e^- \to Z$	ultra-precision EW physics **flavour BSM**	$\sin^2\theta_{eff}$ M_Z, Γ_Z, N_ν α, α_S
125 GeV	• $e^+e^- \to H$	*limit on s-channel H production?*	y_e
160 GeV	• $e^+e^- \to W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \to W^+W^-$ • $e^+e^- \to q\bar{q}, \ell\ell\ (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, aTGC N_ν
250 GeV	• $e^+e^- \to ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H κ_V, κ_f, Γ_H
360 GeV	• $e^+e^- \to t\bar{t}$	ultra-precision top mass	M_{top}
>360 GeV	• $e^+e^- \to t\bar{t}$ • $e^+e^- \to ZH$ • $e^+e^- \to H\nu\nu$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \to t\bar{t}H$ • $e^+e^- \to ZHH$ • $e^+e^- \to Z' \to f\bar{f}$ • $e^+e^- \to \chi\chi$ • $e^+e^- \to AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for supersymmetry (SUSY) search for new Higgs bosons	y_{top} λ_{HHH}

Special program

HIGGS PRODUCTION AT LEPTON COLLIDERS

- Dominant production processes for $\sqrt{s} \leq 500$ GeV
  - Higgsstrahlung: e+e- → ZH: $\sigma \sim 1/s$, dominant up to ≈ 450 GeV
  - WW fusion: $e^+e^- \rightarrow H\nu_e\nu_e$: $\sigma \sim \log(s)$, dominant above 450 GeV. Large statistics at high energy

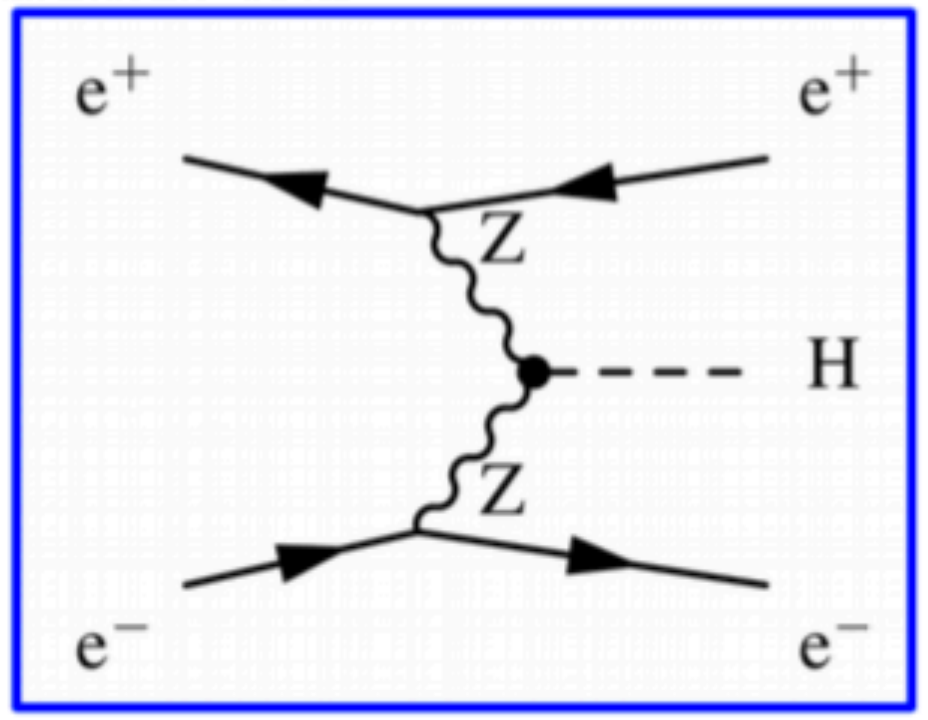




The centre-of-mass energy is chosen so as to maximize the number of ZH events. At FCC-ee, the luminosity steeply increases as the centre-of-mass energy decreases, so that the centre-of-mass energy was fixed to 240 GeV, approximately 15 GeV below the value that maximizes the theoretical ZH cross section

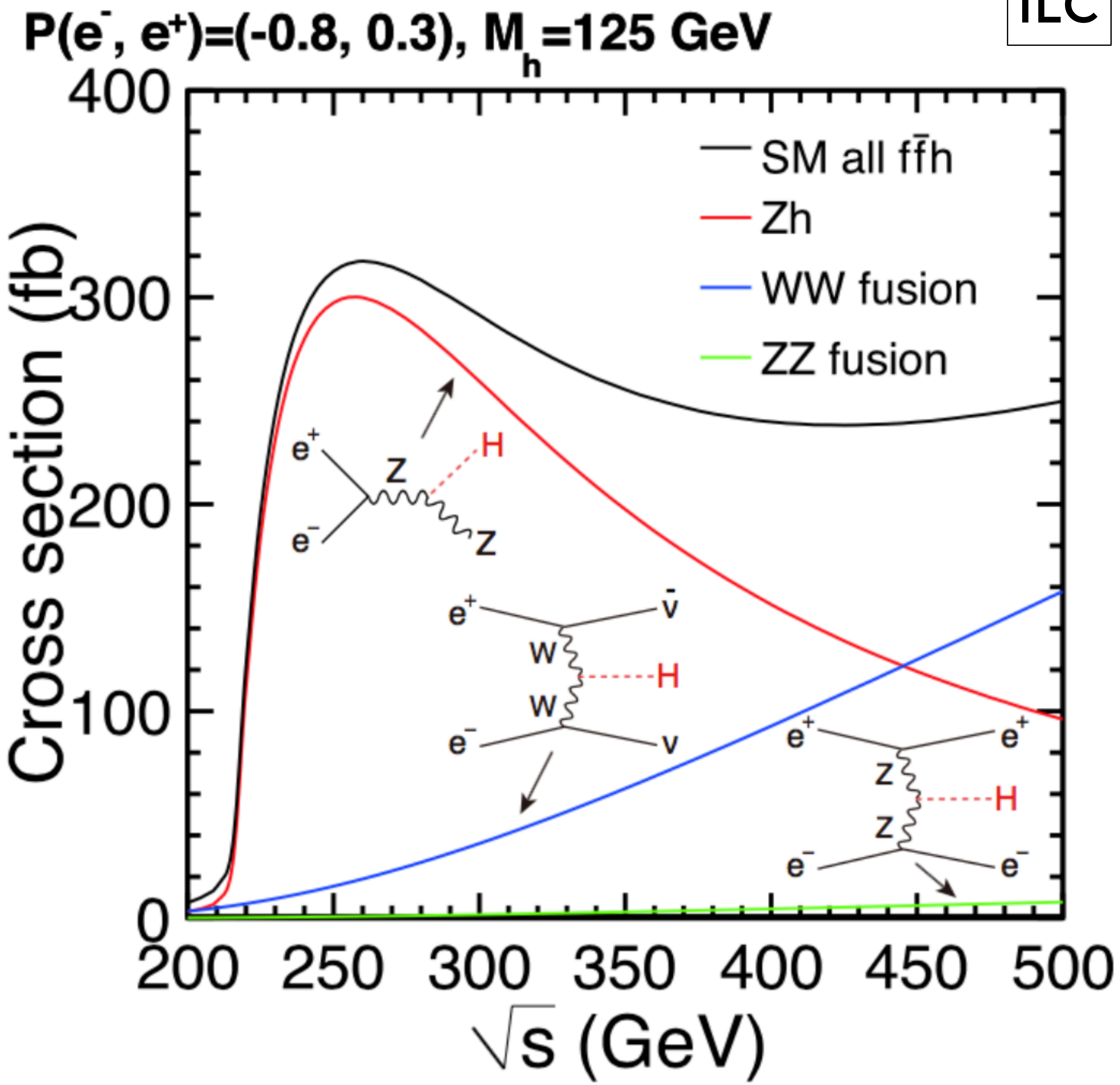
EFFECT OF POLARIZATION ON HIGGS PRODUCTION (ILC)

- Higgs-strahlung cross section multiplied by
  - $1 - P^{-}P^{+} - A_e \times (P^{-} - P^{+})$
- Boson fusion cross section multiplied by $(1-P^{-}) \times (1+P^{+})$

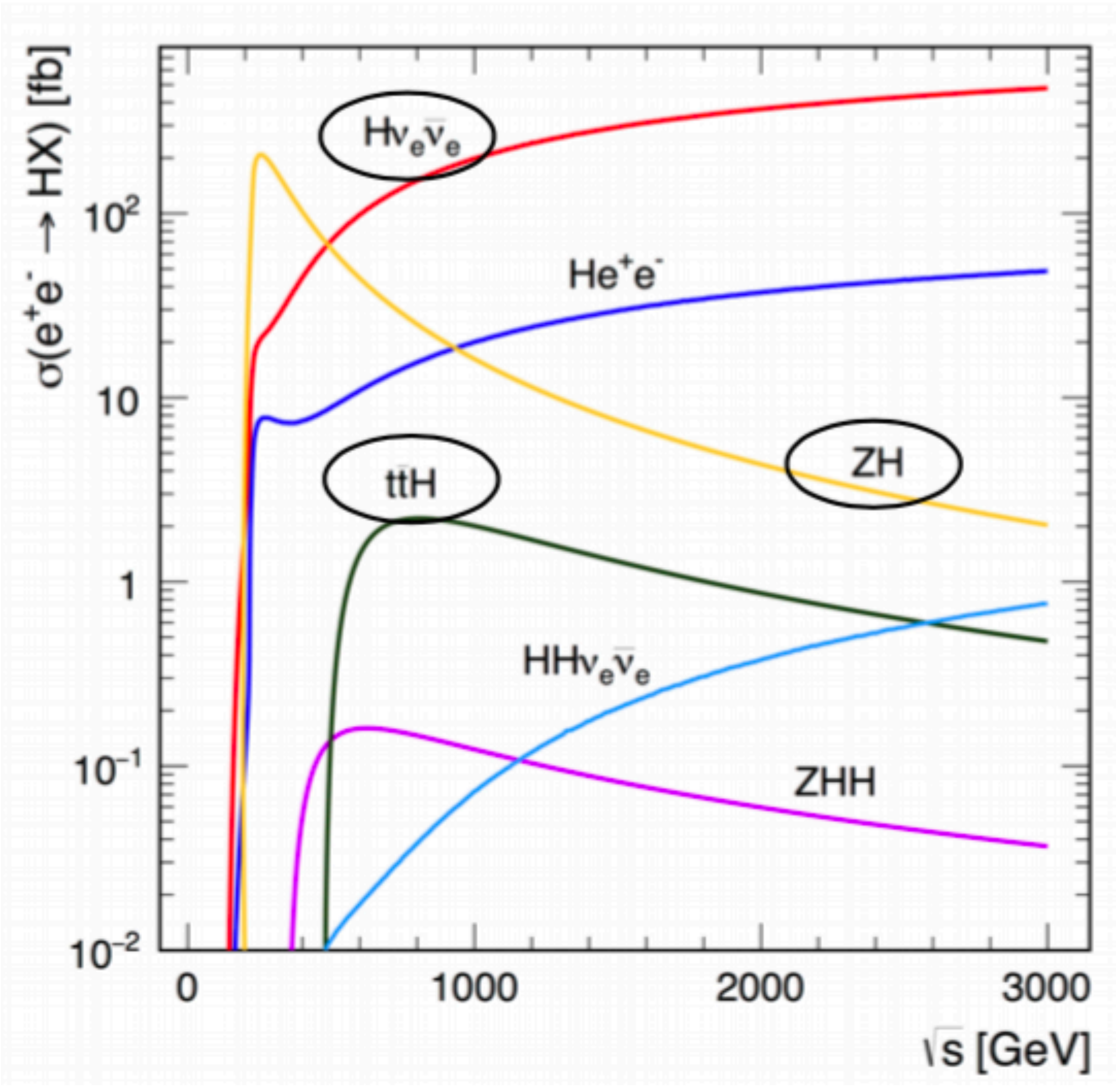


- For CC the gains from polarization are not worth the induced luminosity loss

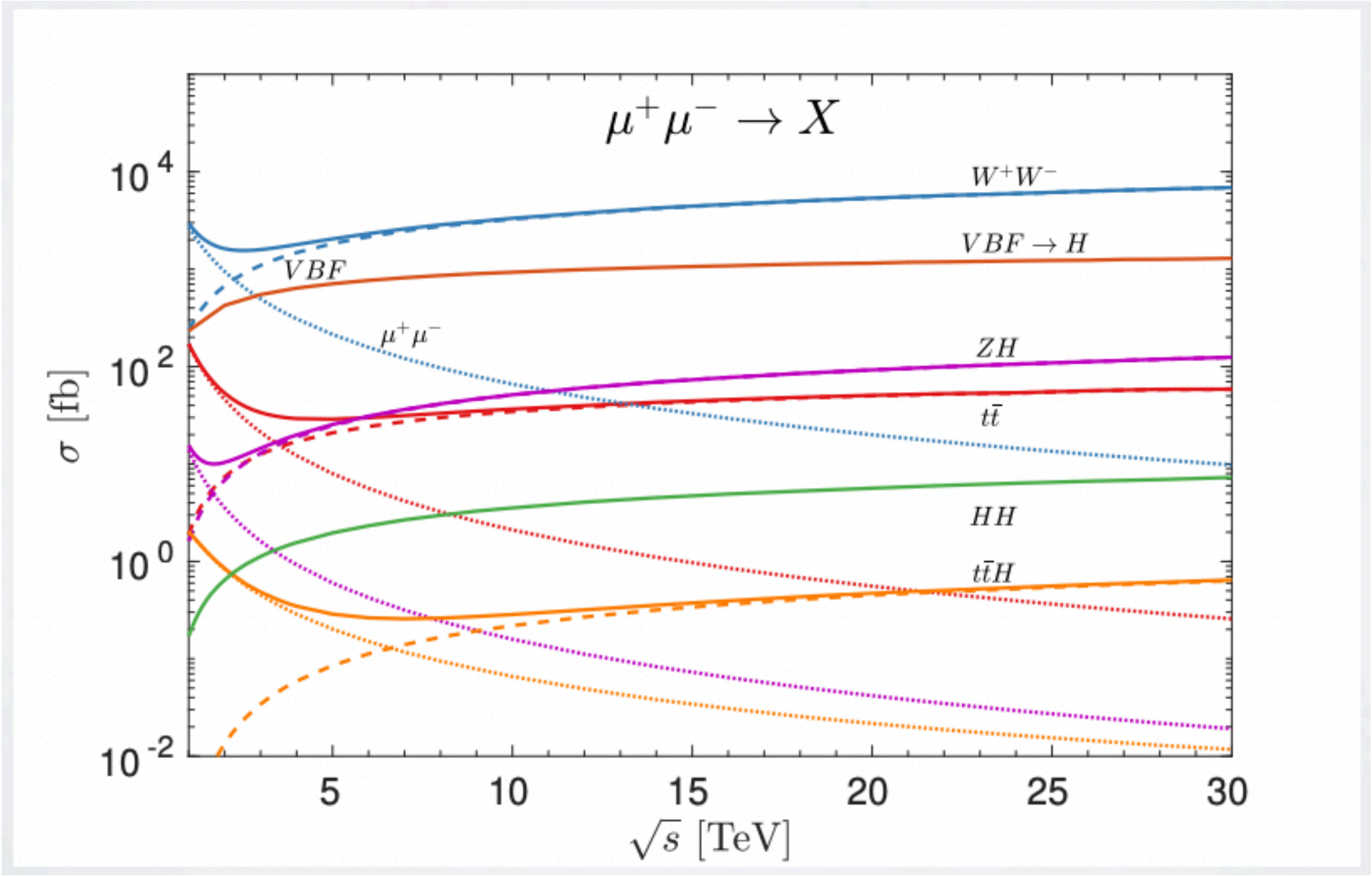
ILC



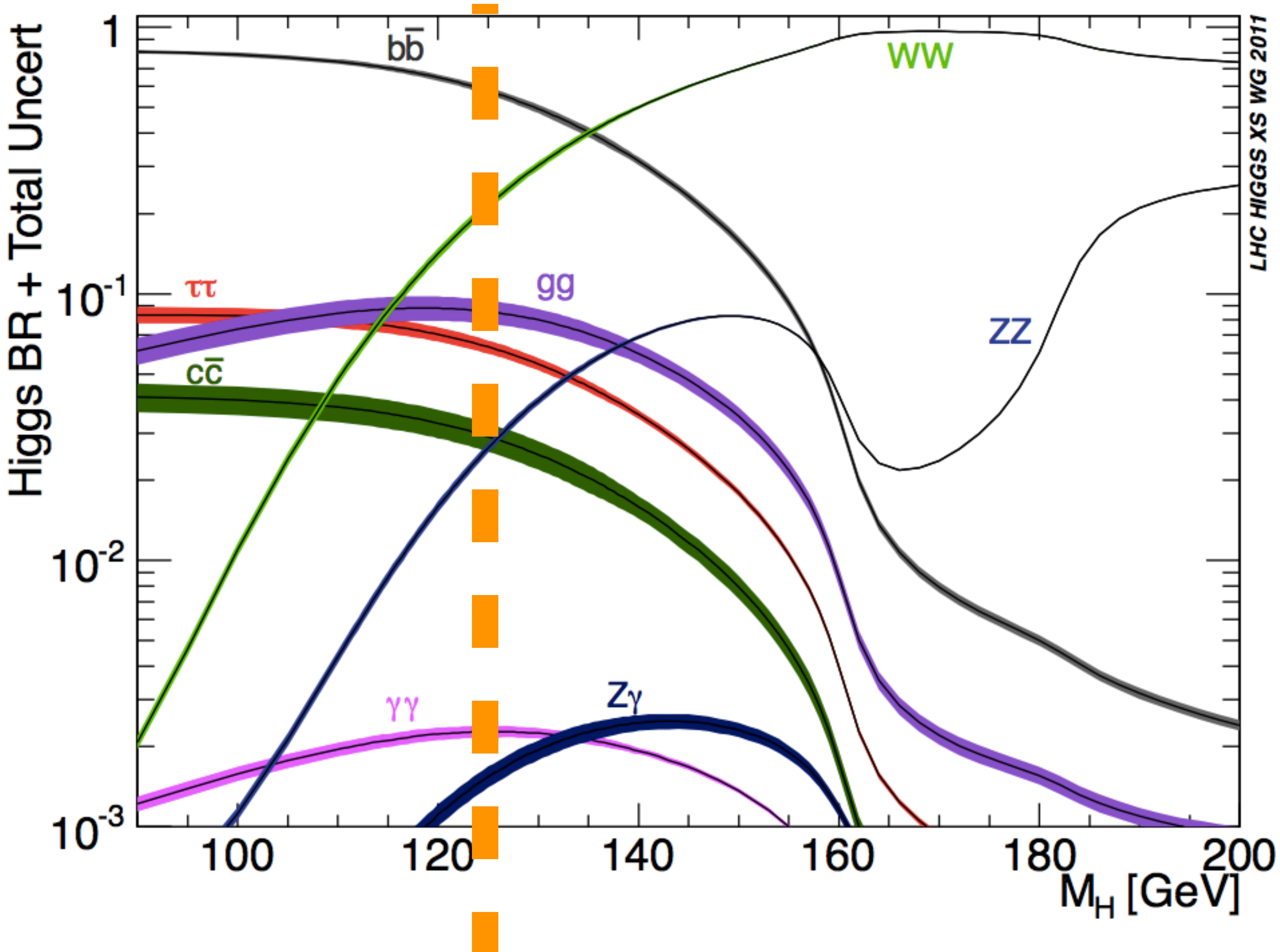
HIGGS PRODUCTION AT HIGHER ENERGIES



- ➤ ttH production: $e^+e^- \to$ ttH
  - ➤ Accessible $\sqrt{s} \geq 500$ GeV, maximum ≈ 800 GeV
  - ➤ Direct extraction of top Yukawa coupling
- ➤ ZHH and HH$\nu_e\nu_e$ production
  - ➤ From $\sqrt{s}$=500 GeV (ZHH) and ≈800 GeV (HH$\nu_e\nu_e$), dual Higgs production
  - ➤ Sensitivity to Higgs self coupling



HIGGS DECAYS



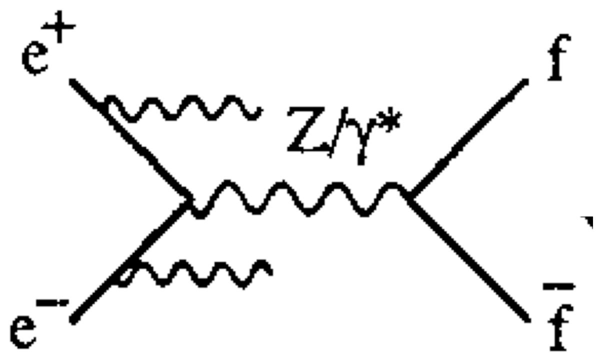
m_H = 125 GeV	
Decay	**BR [%]**
bb	57.7
ττ	6.32
cc	2.91
μμ	0.022
WW	21.5
gg	8.57
ZZ	2.64
γγ	0.23
Zγ	0.15
ΓH [MeV]	4.07

INTERESTING HIGGS PHYSICS GOALS FOR e+e- COLLIDERS VS LHC

- Higgs kinematic parameters: m_H and Γ_H
  - Reduce parametric uncertainties in XS and BR
  - Control the fate of the EW vacuum within the SM
  - Constrain new physics models
- Precise and model-independent access to Higgs couplings
  - <1% level
  - Identification of correlation patterns among deviations
  - Indirect tests of extended Higgs sector/composite nature
- Access to decay modes that are background dominated @LHC
  - Bb/cc/gg
  - Exotic decay modes (portal of Dark Matter)
- Constraints on Higgs flavour violating couplings
  - Smoking gun of BSM physics

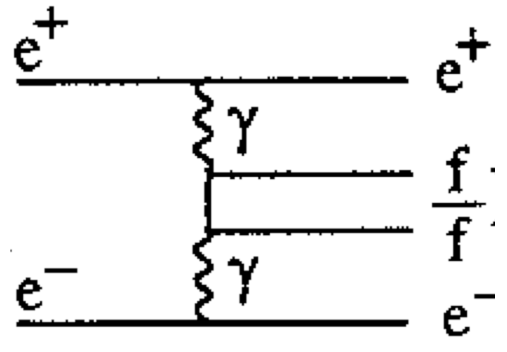
HIGGS PHYSICS BACKGROUNDS

- Physics backgrounds are "small": examples at $\sqrt{s}$=240GeV
  - "Blue" cross sections decrease like 1/s
  - "Green" cross sections increase slowly with s



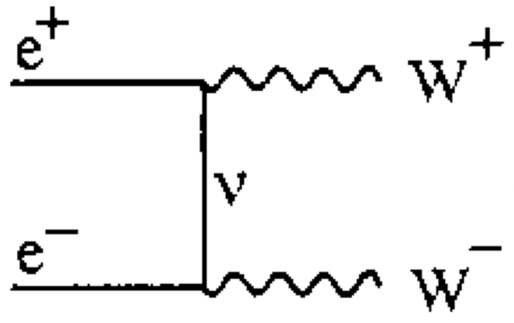
$e^+e^- \rightarrow q\bar{q}, l^+l^-$

60 pb



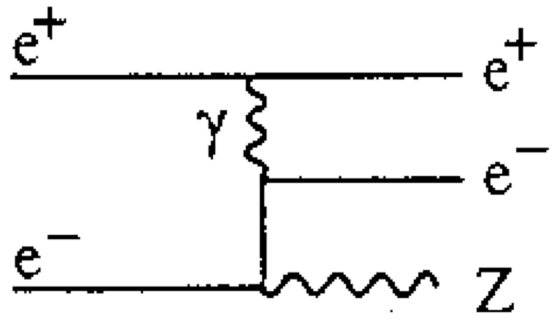
$\gamma\gamma \rightarrow q\bar{q}, \ell^+\ell^-$
m > 30 GeV

30 pb



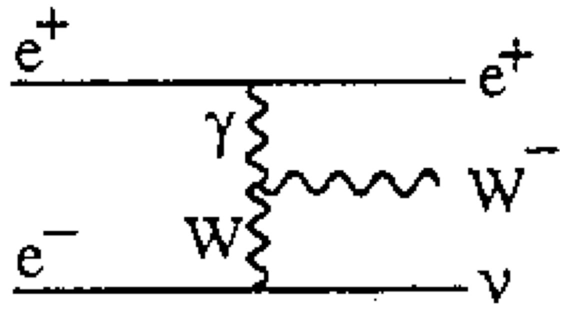
$e^+e^- \rightarrow W^+W^-$

16 pb



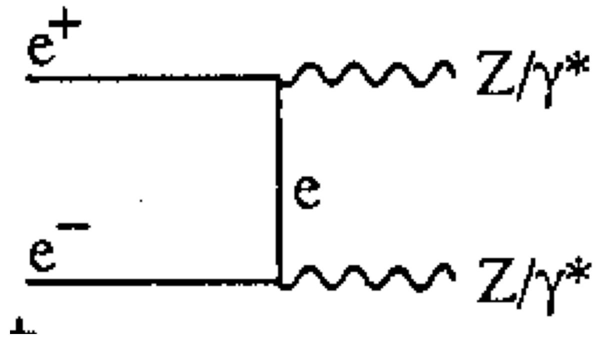
$e^+e^- \rightarrow Ze^+e^-$

3.8 pb



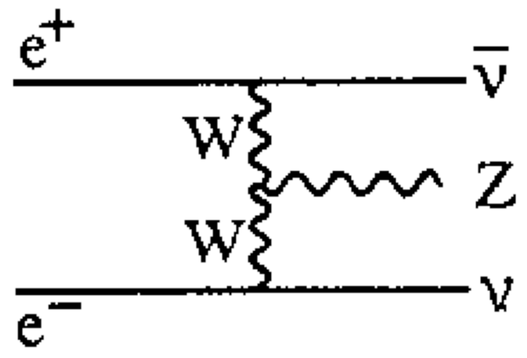
$e^+e^- \rightarrow We\nu$

1.4 pb



$e^+e^- \rightarrow ZZ$

1.3 pb

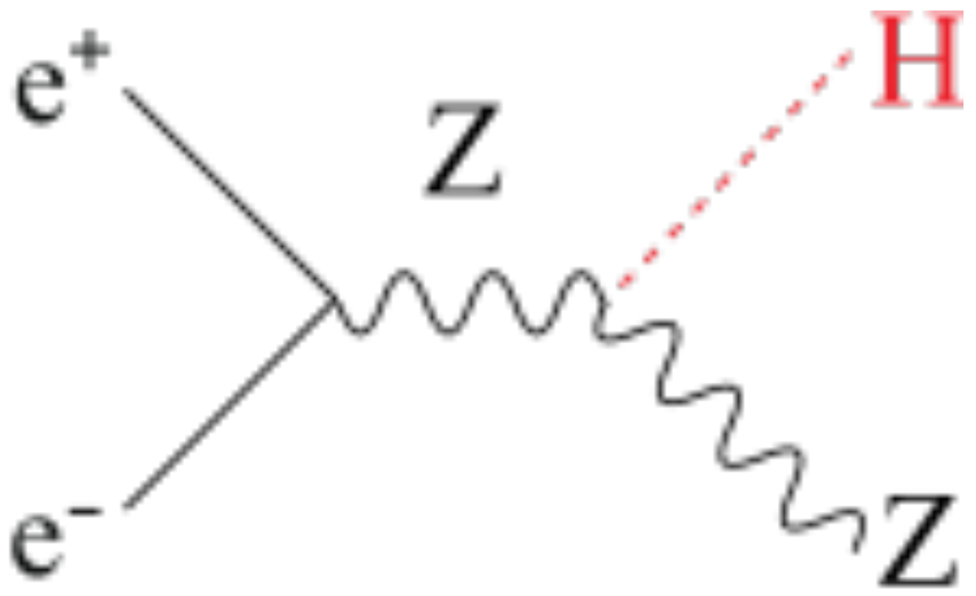


$e^+e^- \rightarrow Z\nu\bar{\nu}$

32 fb

Add $e^+e^- \rightarrow t\bar{t}$
for $\sqrt{s}$ > 345 GeV

0.6 pb

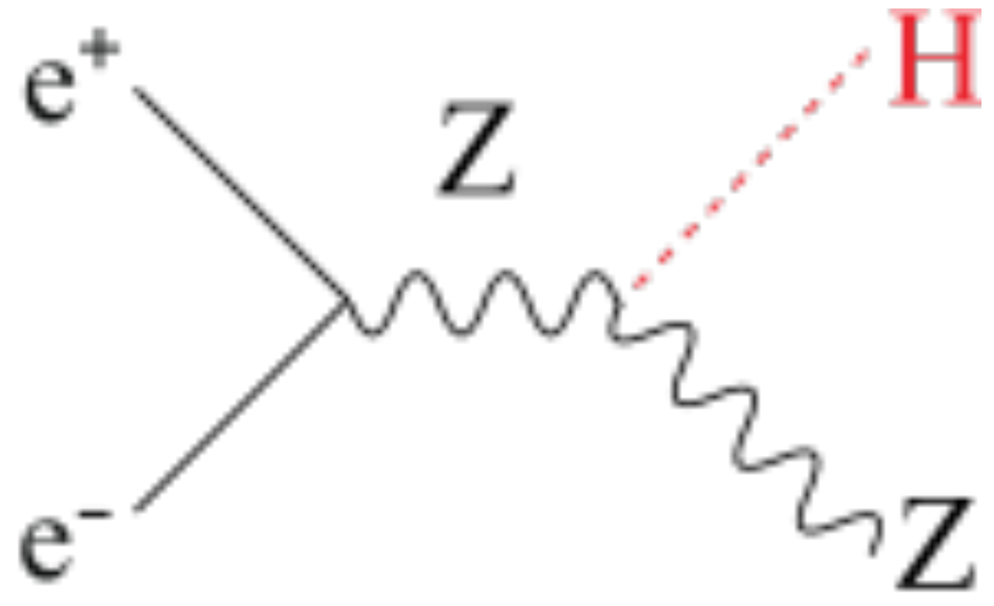


200 fb

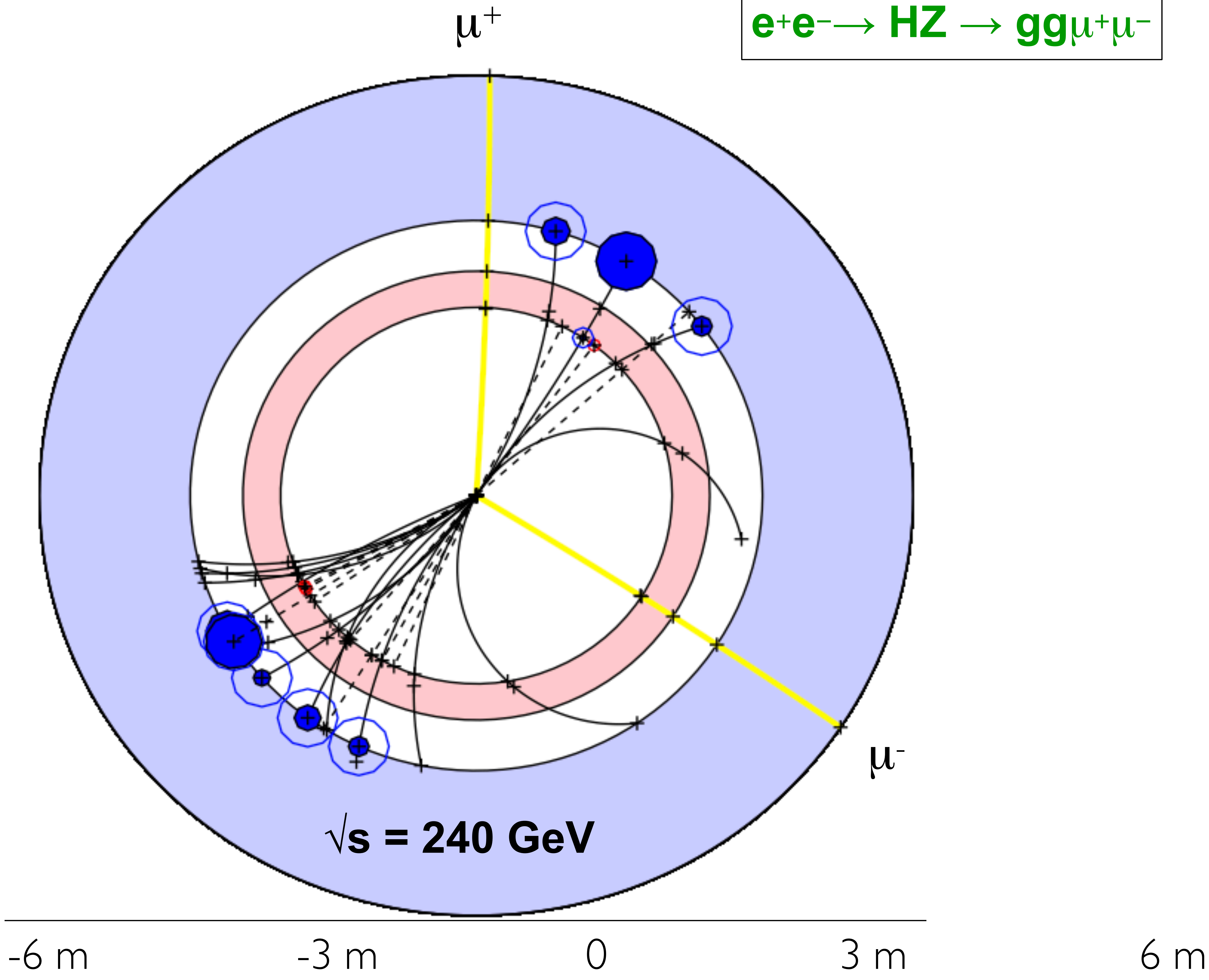
- **Only one to two orders of magnitude smaller**
  - **vs. 11 orders of magnitude in pp collisions**
    - **Trigger is 100% efficient**

HIGGS EVENTS

- Example of a Higgs boson event at a ee collider
  - Tagged with a Z boson
  - Very clean signature



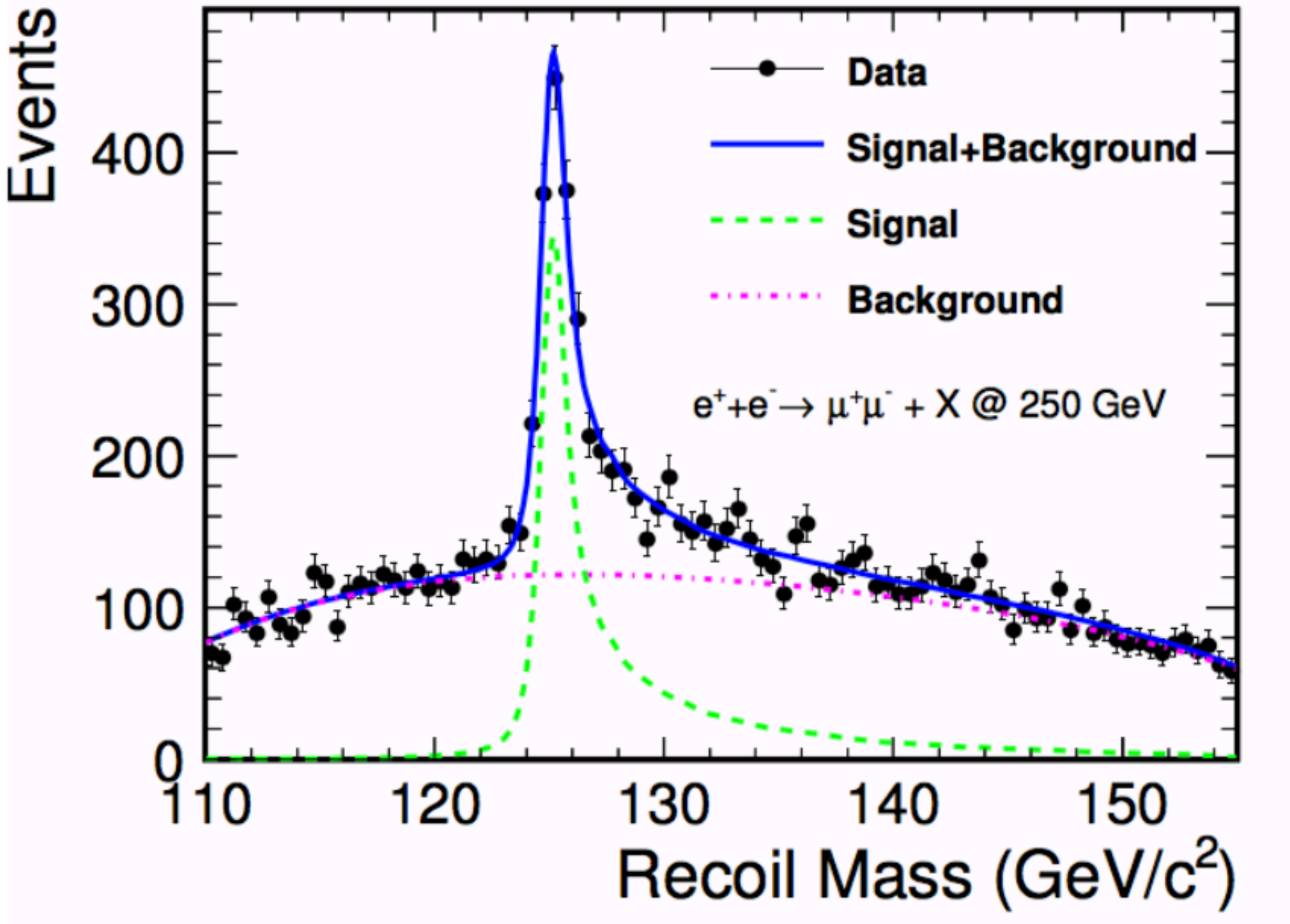
$e^+e^- \rightarrow HZ \rightarrow gg\mu^+\mu^-$



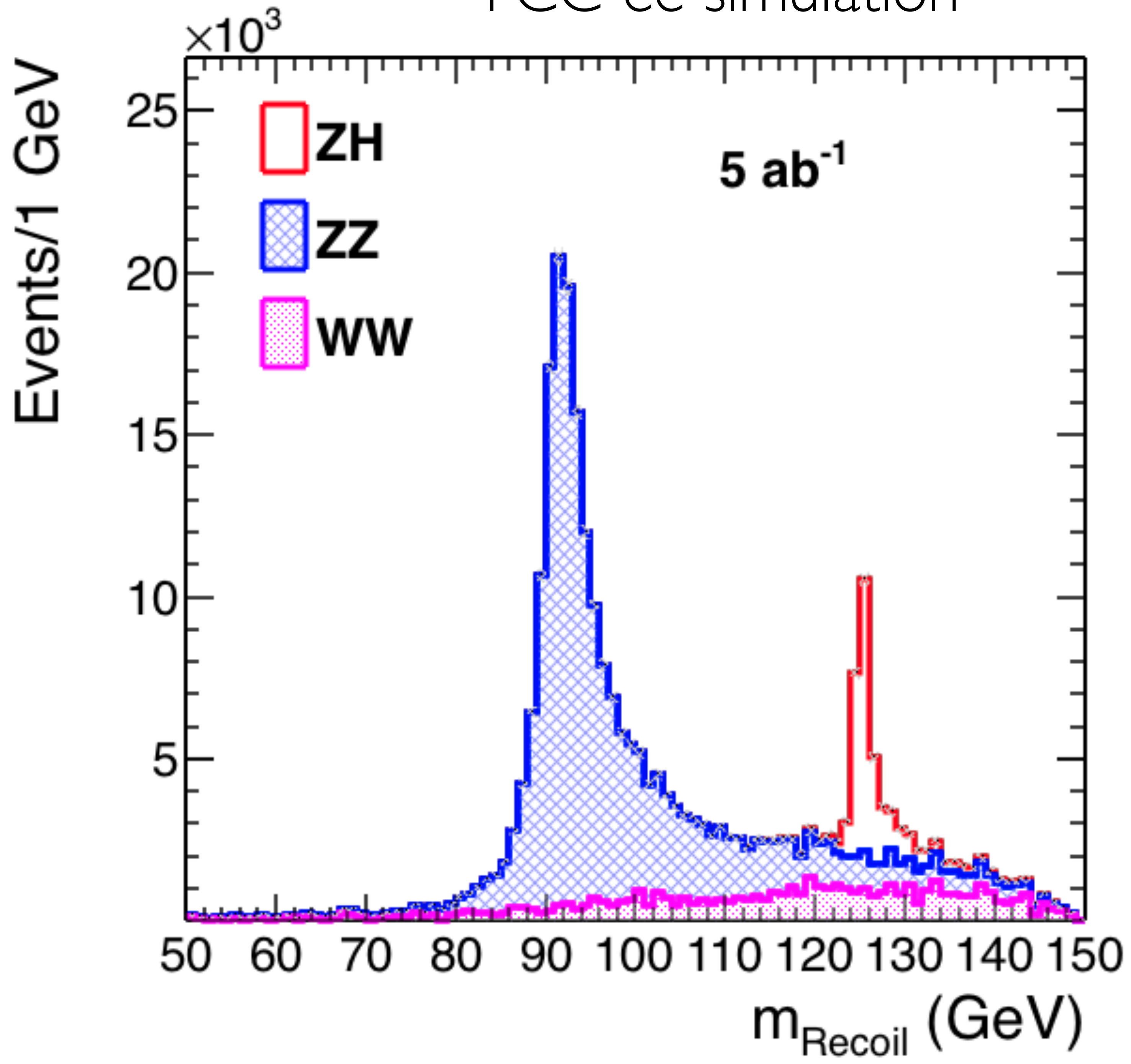
MODEL-INDEPENDENT MEASUREMENT OF σ_{HZ} AND g_{HZZ}

- The Higgs boson in HZ events is tagged by the presence of the $Z \rightarrow e^+e^-, \mu^+\mu^-$
- Select events with a lepton pair, same flavor, opposite sign with mass compatible with m_Z
  - Apply total energy-momentum conservation to determine the "recoil mass"
    $M_{H^2} = s + M_Z^2 - 2\sqrt{s}(p_{\mu^+} + p_{\mu^-})$
  - Plot the recoil mass distribution – resolution proportional to momentum resolution
  - No requirement on the Higgs decays: measure $\sigma_{HZ} \times BR(Z \rightarrow e^+e^-, \mu^+\mu^-)$
- Provides an absolute measurement of g_{HZZ} and sets required detector performance

ILC simulation



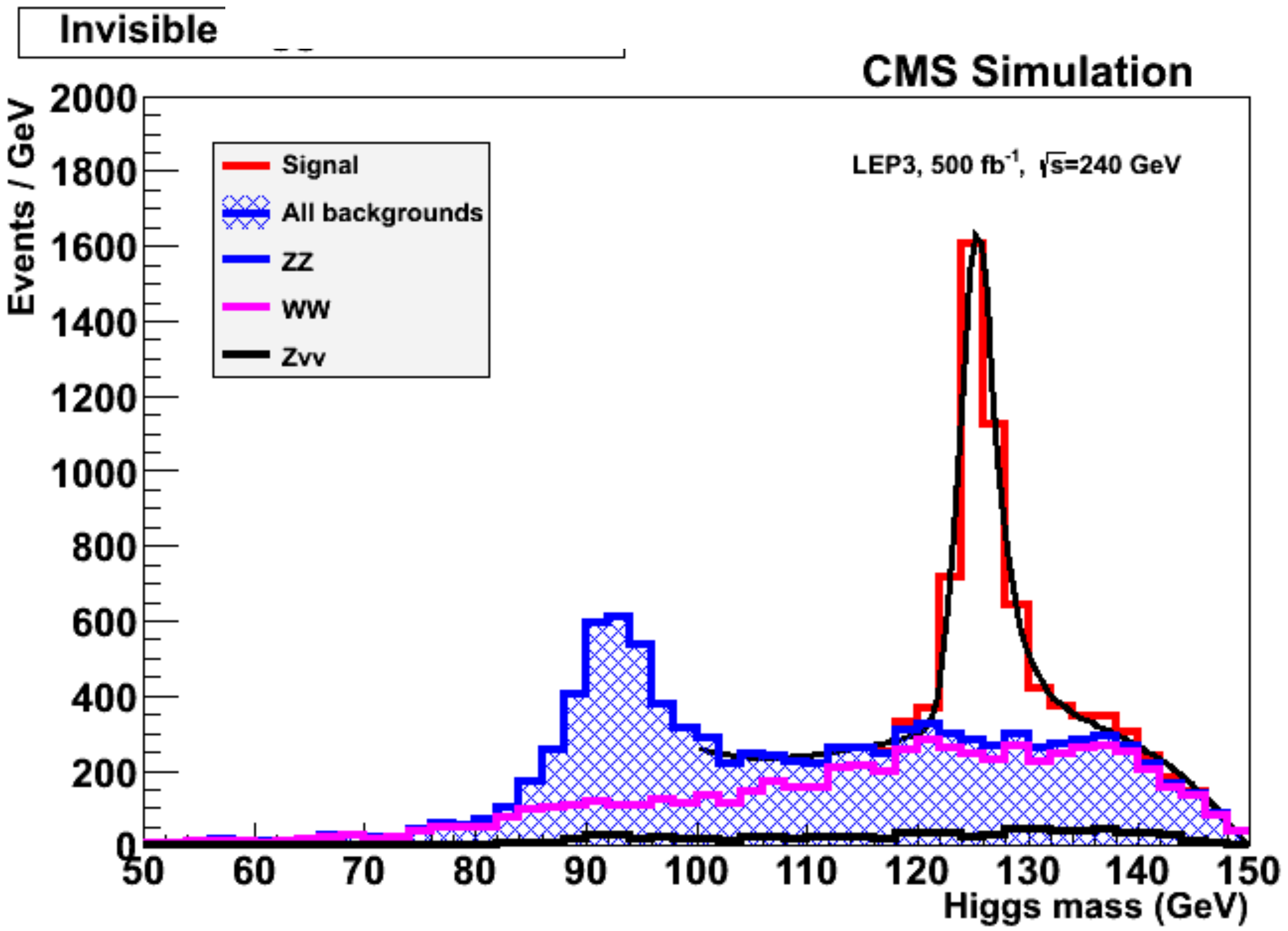
FCC-ee simulation



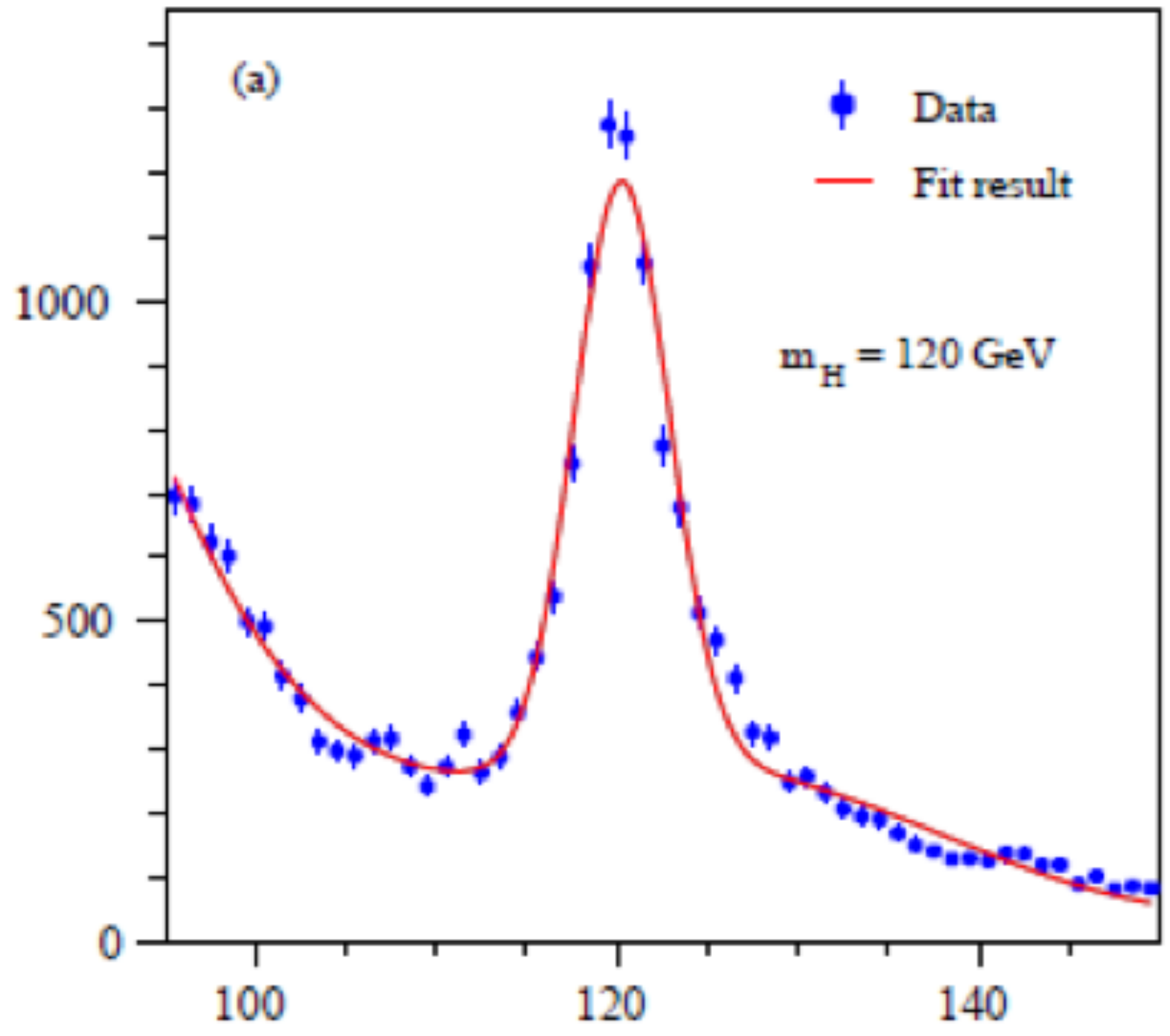
MEASURING THE HIGGS DECAY BR

- Repeat the procedure for all possible final states
  - For all exclusive decays, YY, of the Higgs boson: measure $\sigma_{HZ} \times BR(H \to YY)$
    - Including invisible decays: event containing only the lepton pair with correct (m_{miss}, m_{recoil}), otherwise empty
  - For all decays of the Z (hadrons, taus, neutrinos) to increase statistics [detector requirements]
  - For the WW fusion mode (Hνν final state): measure $\sigma_{WW \to H} \times BR(H \to YY)$

ZH → $\ell^+\ell^-$ + nothing, 0.5



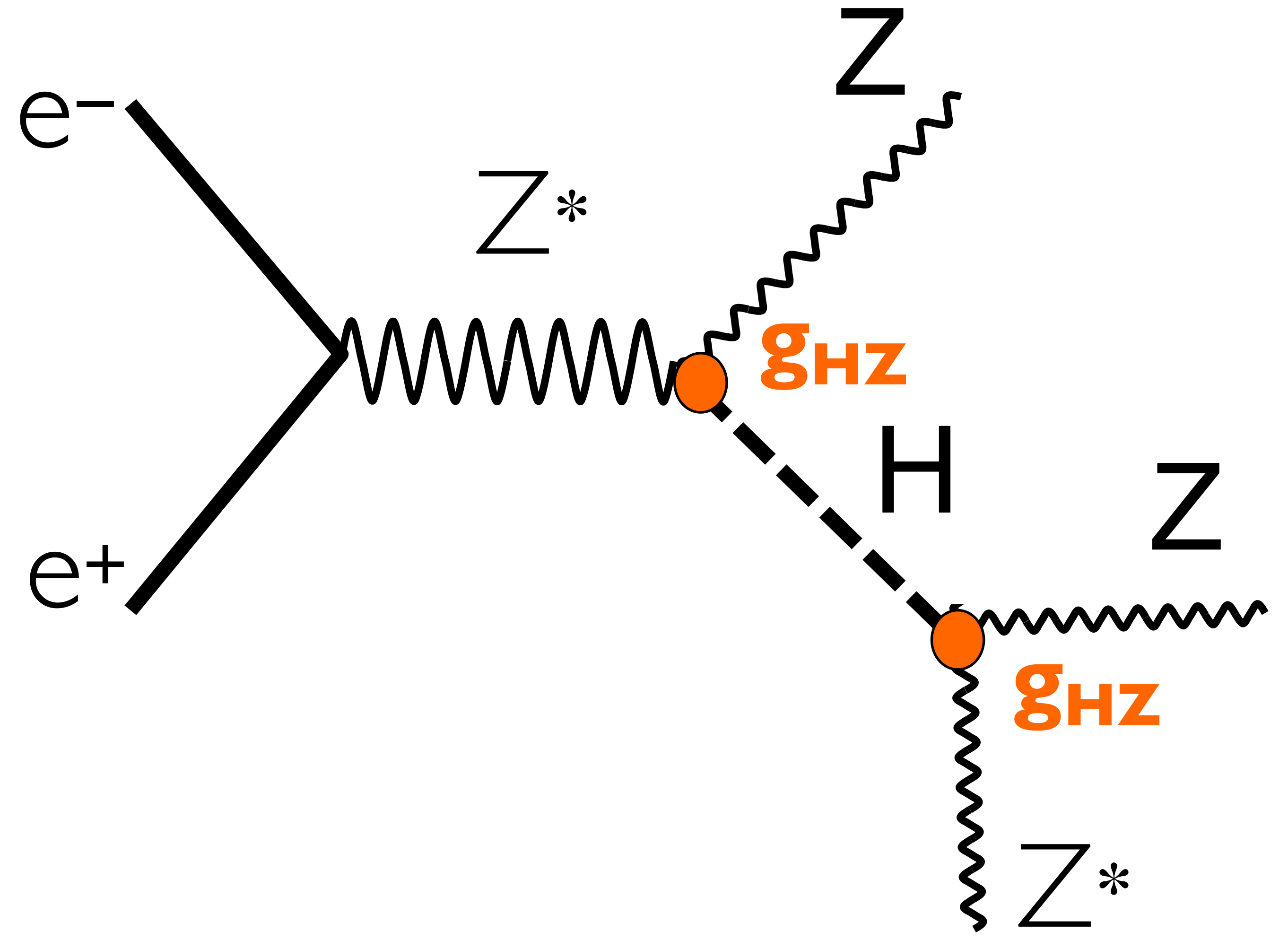
ZH → $q\bar{q}$ $b\bar{b}$, 0.25



HIGGS WIDTH

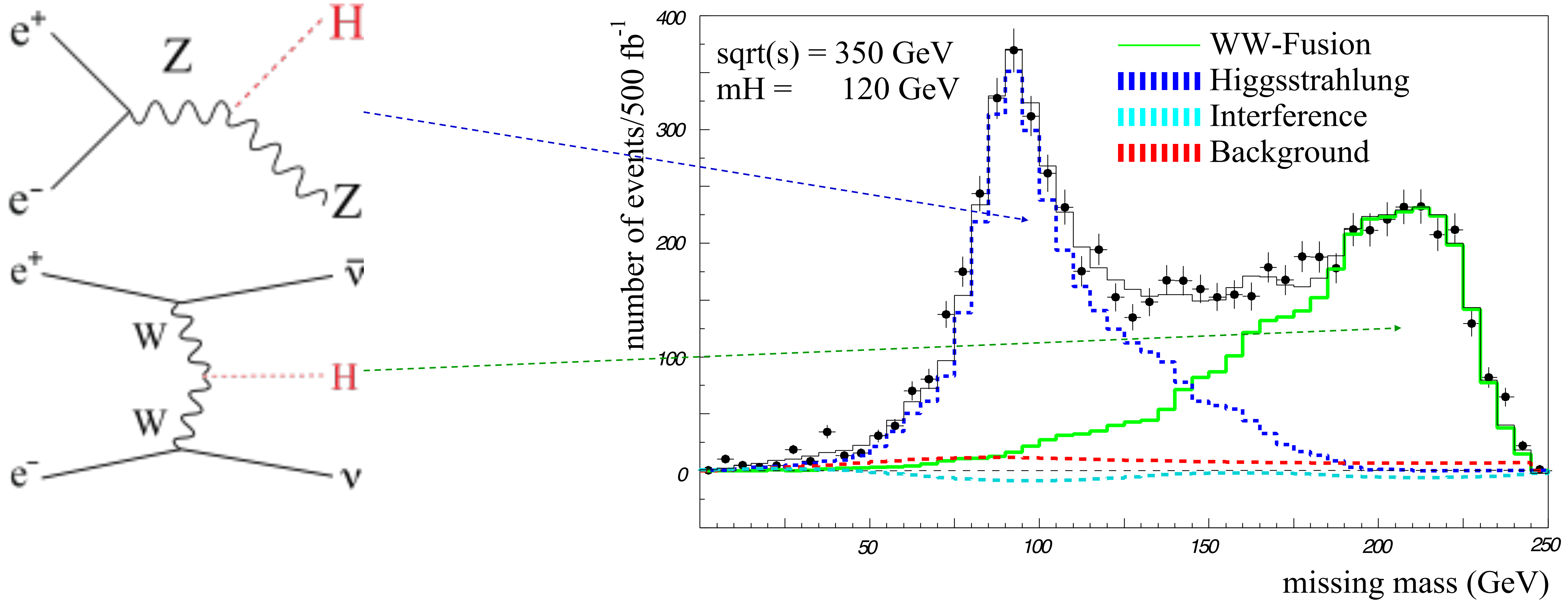
➤ Model independent determination of the total Higgs decay width down to 1.3% with runs at √s=240 and √s=365 GeV

ee →HZ & H → ZZ at √s = 240 GeV



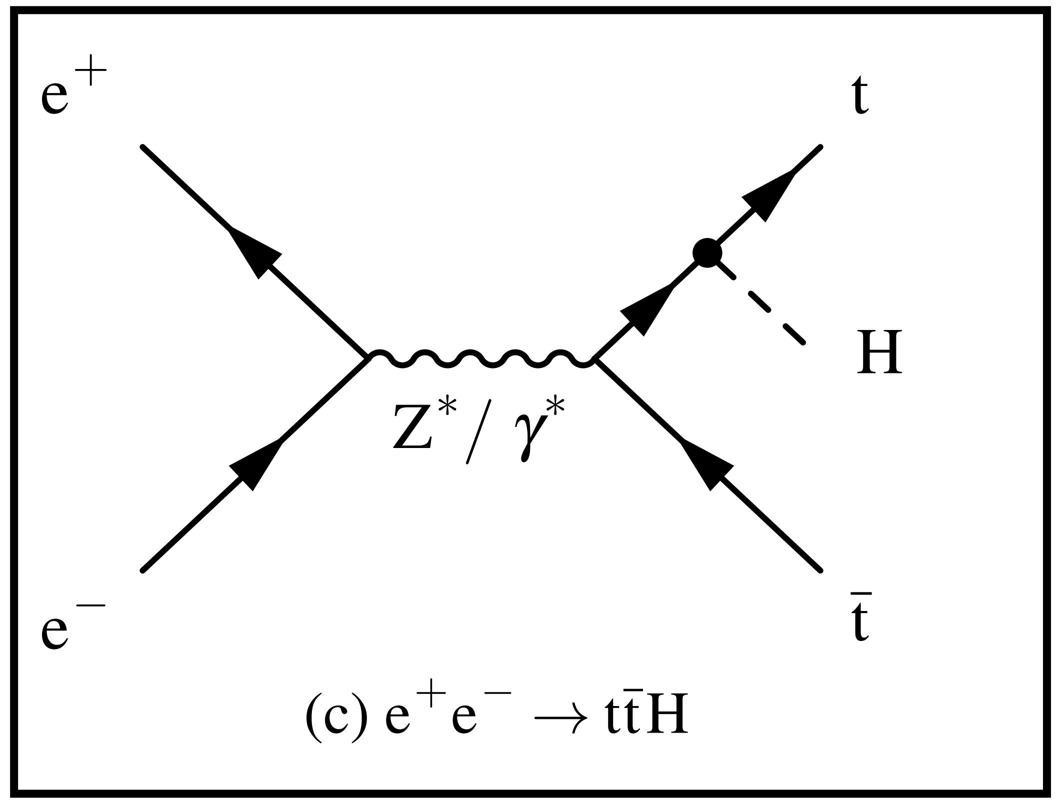
- σ_{HZ} is proportional to g_{HZZ}^2
- $BR(H \to ZZ) = \Gamma(H \to ZZ) / \Gamma_H$ is proportional to g_{HZZ}^2 / Γ_H
  - $\sigma_{HZ} \times BR(H \to ZZ)$ is proportional to g_{HZZ}^4 / Γ_H
- Infer the total width Γ_H

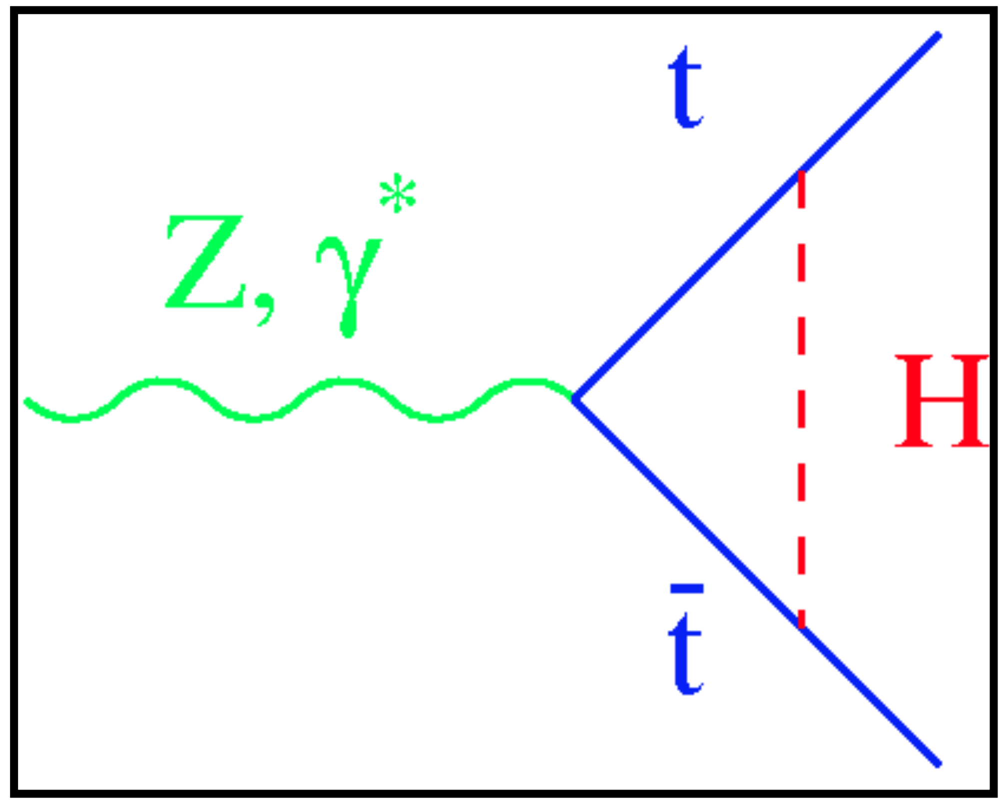
WW → H νν→ bbνν at √s = 365 GeV

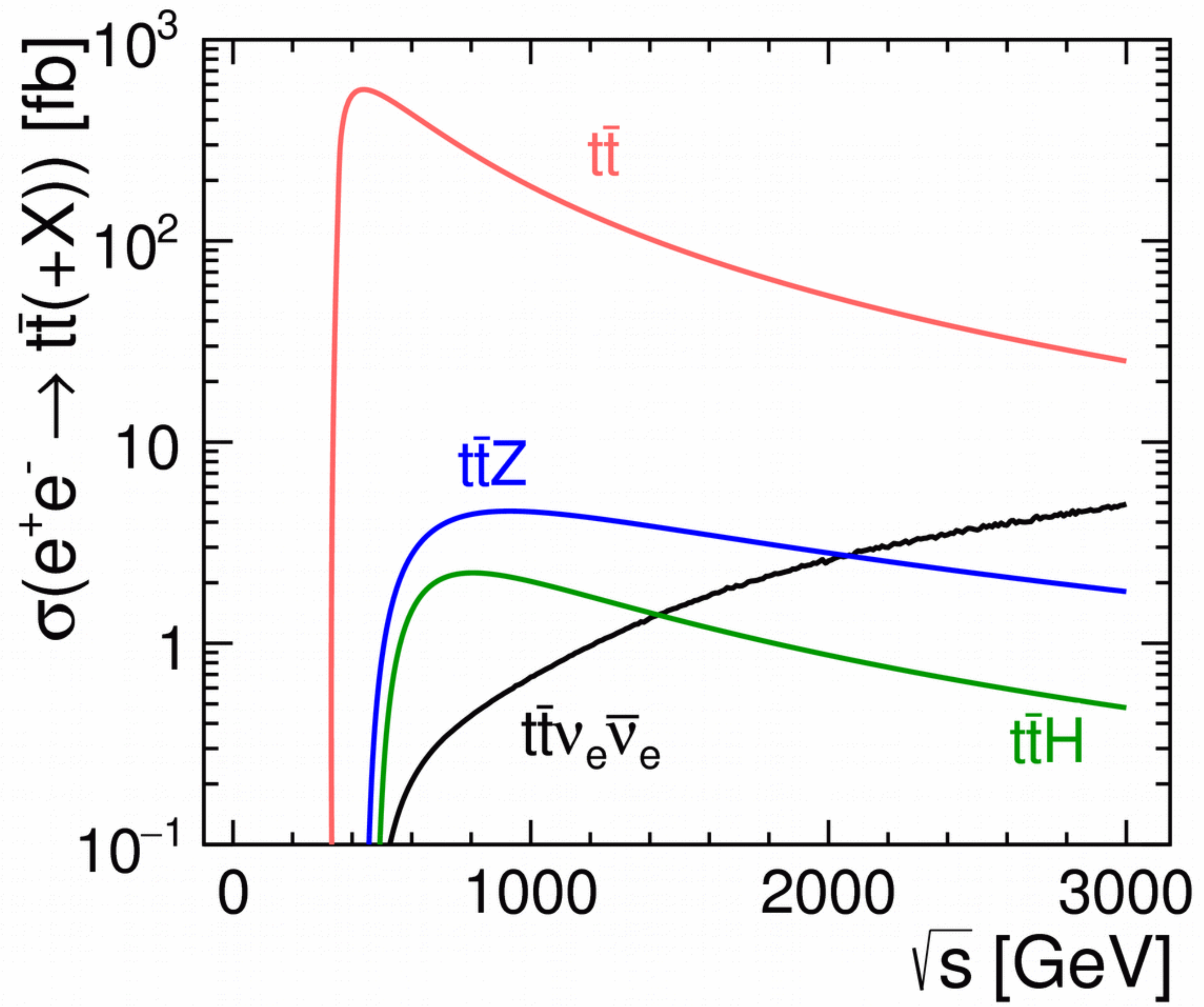


$$\Gamma_H \propto \frac{\sigma_{WW\to H}}{BR(H\to WW)} = \frac{\sigma_{WW\to H\to b\bar{b}}}{BR(H\to WW)\times BR(H\to b\bar{b})}$$

THE TOP YUKAWA COUPLING







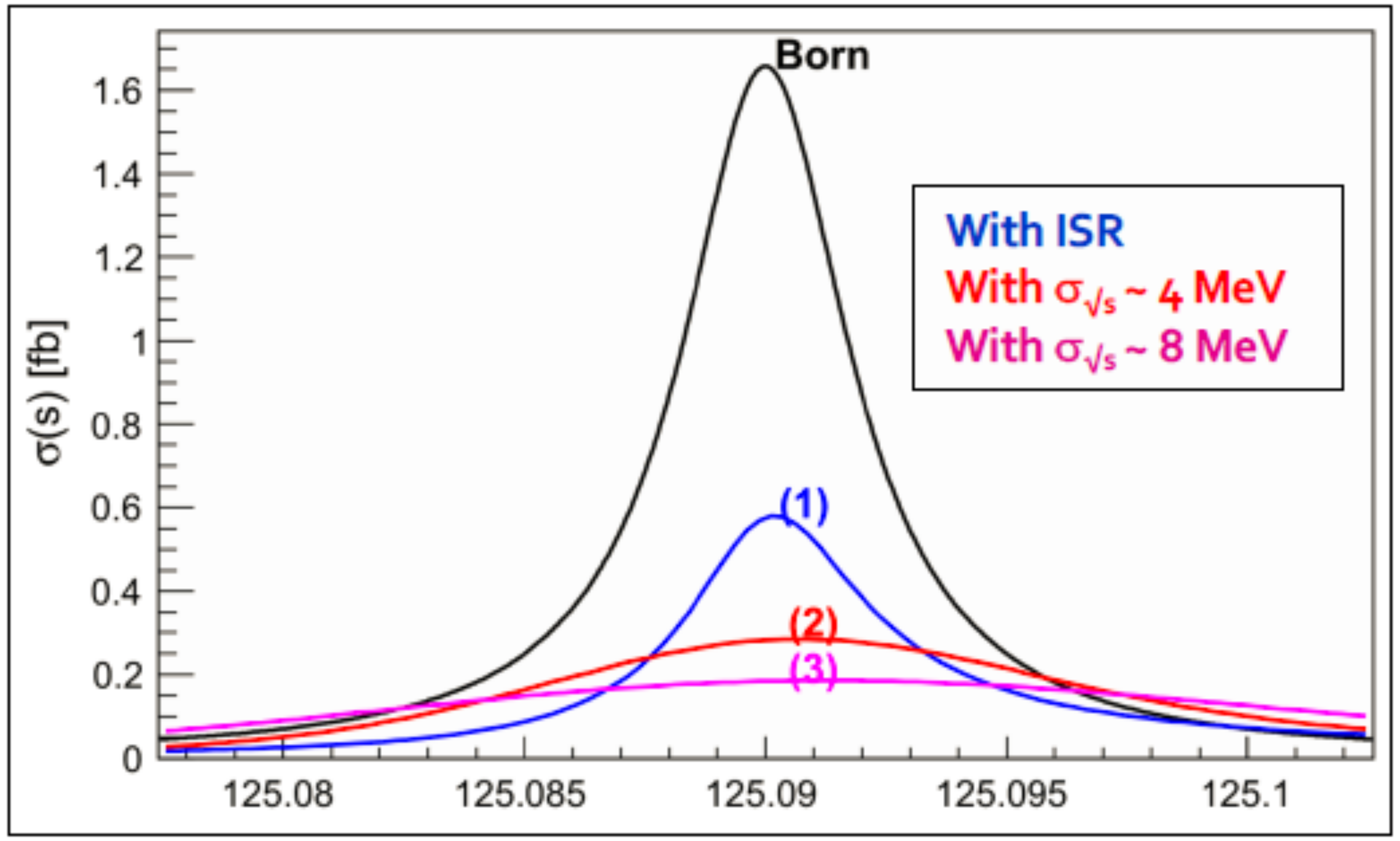
- The coupling between the top and Higgs is an extremely interesting quantity.
  - The HL-LHC is expected to reach a precision of 3.4%.
  - At the FCC-ee the λ_{top} is accessible only indirectly: at threshold the virtual Higgs boson exchange that can give an effect up to 10% on the cross section
  - Combining with HL-LHC, obtain 3.1% (no model dep.)
  - $e^+e^- \rightarrow t\bar{t}H$ production needs at least √s>500 GeV
- Reaching the sub-% will be a job for FCC-hh!

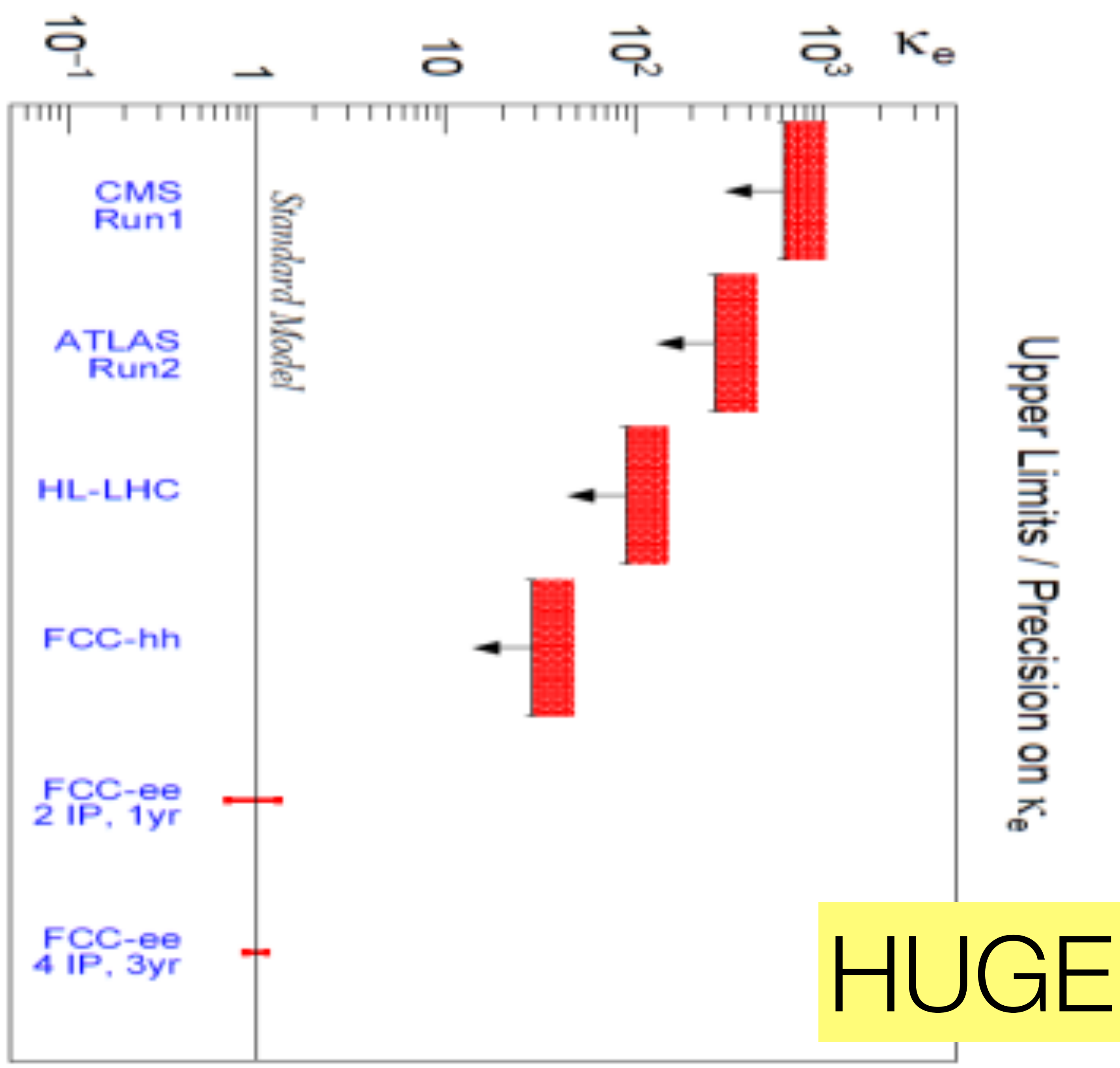
ILC : 3% with 4 ab^{-1} at 550 GeV

ILC : 4% with 1 ab^{-1} at 1 TeV

CLIC : 3.8% with 1.5 ab^{-1} at 1.4 TeV

FIRST GENERATION COUPLING: $e^+e^- \to H$





HUGE CHALLENGE

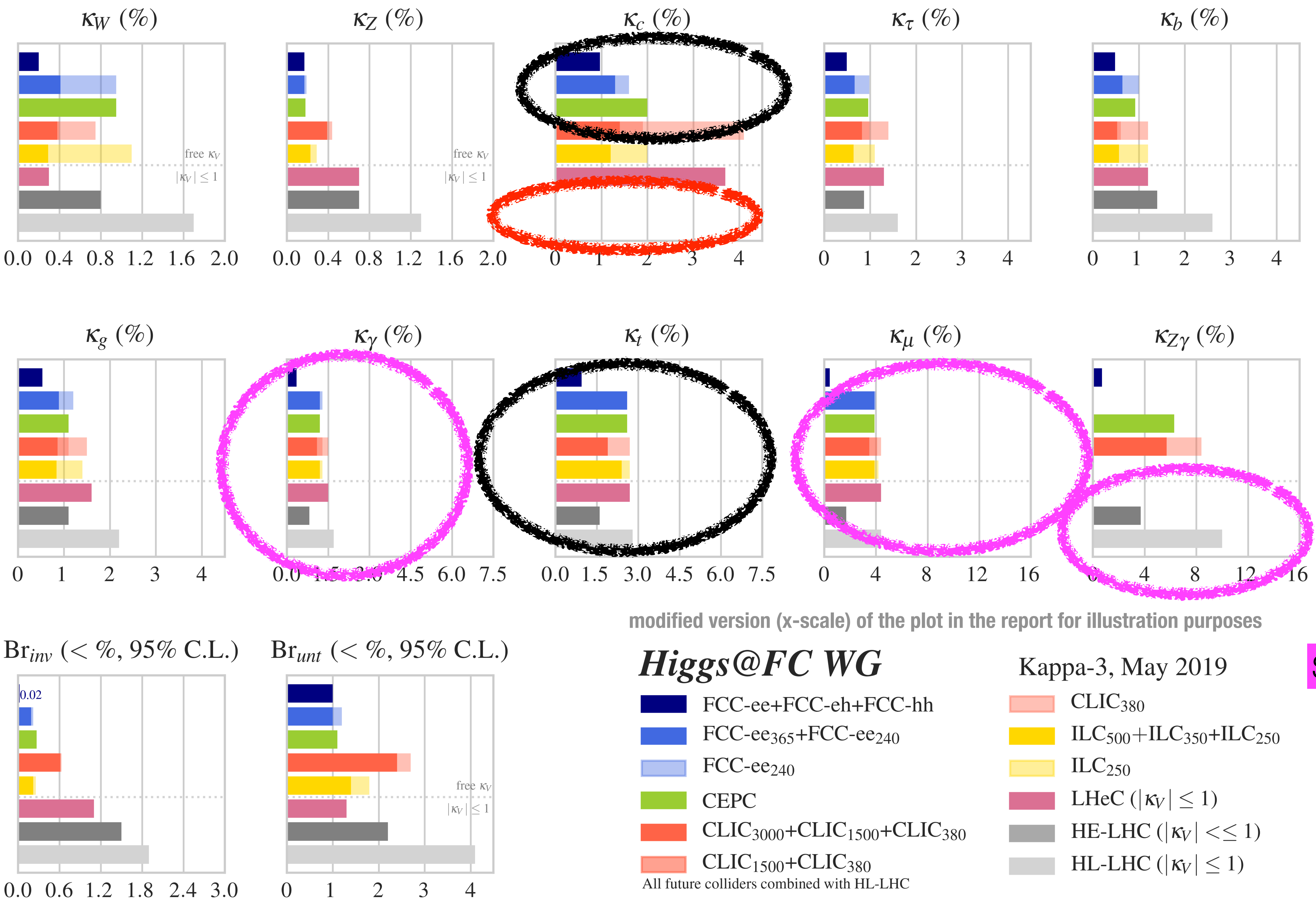
- ➤ e+e- → H @ 125.xxx GeV requires:
  - ➤ Higgs mass to be known to <5 MeV from 240 GeV run (CEPC group almost there)
  - ➤ Huge luminosity
  - ➤ monochromatization (opposite sign dispersion using magnetic lattice) to reduce σ_{ECM}
  - ➤ continuous monitoring and adjustment of ECM to MeV precision (transverse Polarisation)
  - ➤ an extremely sensitive event selection against backgrounds
  - ➤ a generous lab director to spend 3 years doing this and neutrino counting: can reach SM sensitivity in about 5 years

TWO DIFFERENT TYPES OF FITS

- The "kappa" fits
  - Assume the Standard model structure (no new coupling, no new processes)
    - The SM couplings are g_{HXX} allowed to scale by a factor κ_x
  - Nine free parameters : κ_W, κ_Z, κ_t, κ_b, κ_t, κ_g, κ_γ, Γ_{tot}, BR_{EXO}
    - Or more: κ_c, κ_μ, $\kappa_{\gamma Z}$, κ_λ, ...
    - Or less: $\kappa_W = \kappa_Z$, universal κ_f, $\Gamma_{tot} = \Gamma_{SM}$
  - Simple parameterization, transparent interpretation, free from theoretical bias
    - But violates gauge invariance ...

- The "EFT" fits
  - Expand Standard Model in gauge and Lorentz invariant dim. 6 operators (up to 2500!)
    - Only valid for new physics scale much larger than m_H or $\sqrt{s}$
  - Consistent theoretical description, but still involves theoretical assumptions
    - New operators modify Higgs kinematics, add energy dependence
    - Includes correlation with Electroweak Precision Observables
      - ➡ FCC-ee runs at the Z pole, WW and tt thresholds play an important role

RESULTS OF KAPPA3: INCLUDING HL-LHC



modified version (x-scale) of the plot in the report for illustration purposes

Statistically limited @ee

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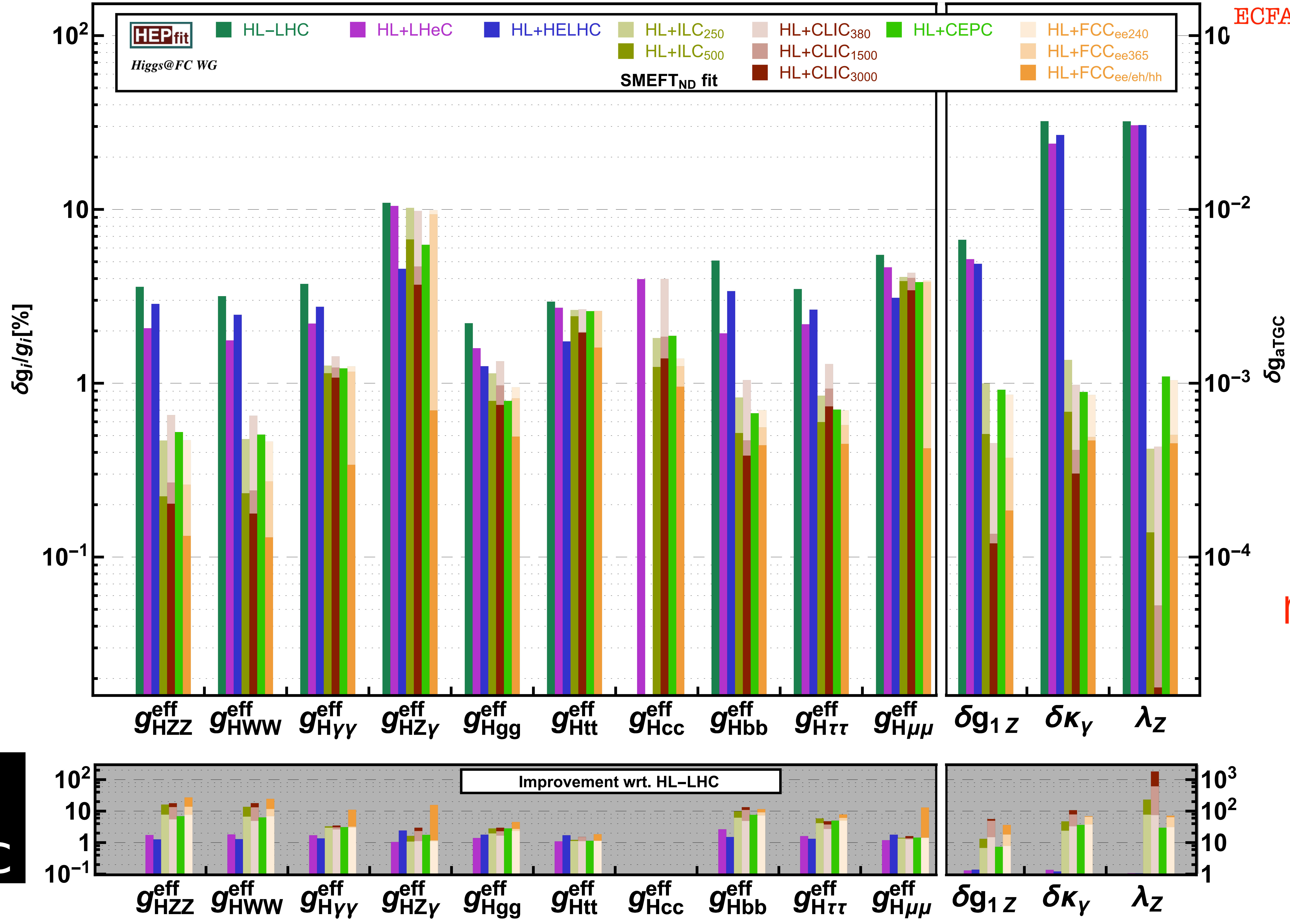
SYNERGIES WITH HADRON COLLIDERS: HL-LHC OR FCC-hh

- The HL-LHC is a Higgs factory: will produce 10^9 Higgs but…
  - $\sigma_{i \to f}^{observed} \propto \sigma_{prod} (g_{Hi})^2 (g_{Hf})^2 / \Gamma_H$
    - σ_{prod} is uncertain and Γ_H is largely unknown
      - Difficult/impossible to extract absolute couplings from the kappa fit
      - Best to do physics with ratios of additional assumptions:
        - Γ_{tot} and g_{Hcc} fixed to their SM values
        - No exotic decays
  - Lepton colliders absolute measurement of g_{HZZ} and Γ_H **solve** the model dependence
    - Rare decay modes allow absolute determination of $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$ in combination with lepton colliders
- **A higher energy hadron collider will profit even more of a lepton collider machine beforehand**

ArXiv ePrint: 1905.03764

GLOBAL EFT FITS: HIGGS EFFECTIVE COUPLINGS

Higgs “effective” couplings: k-modifiers of EFT couplings



ECFA Higgs study group ‘19

more precise

There is life beyond HL-LHC

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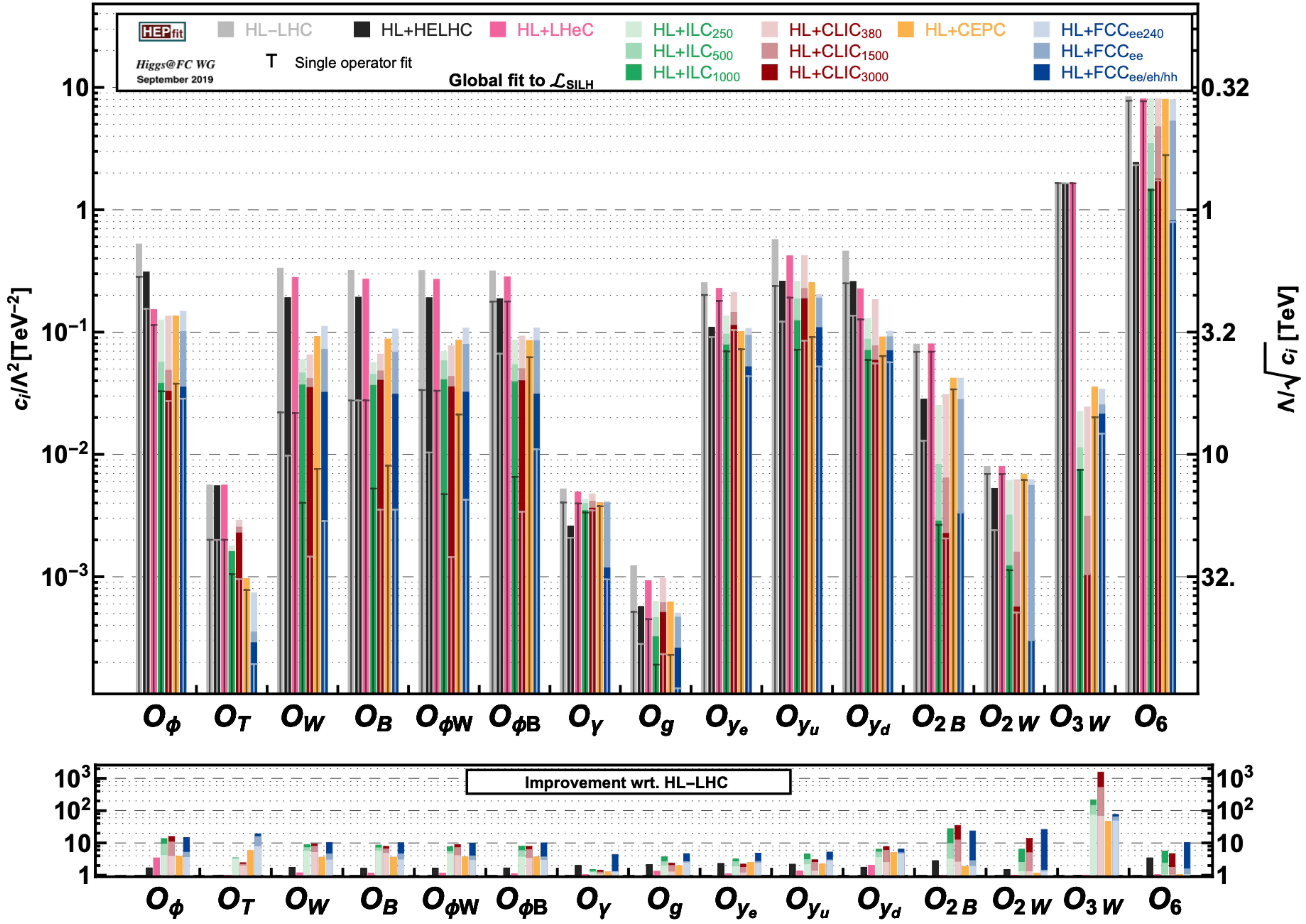
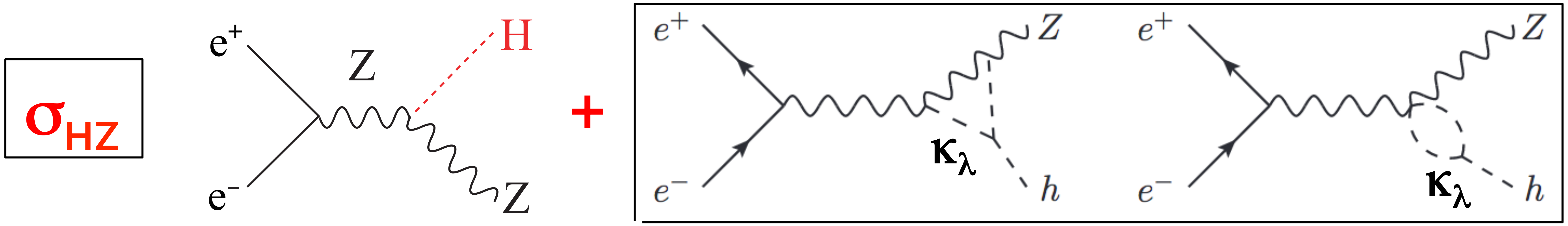
EFT FIT SENSITIVITY



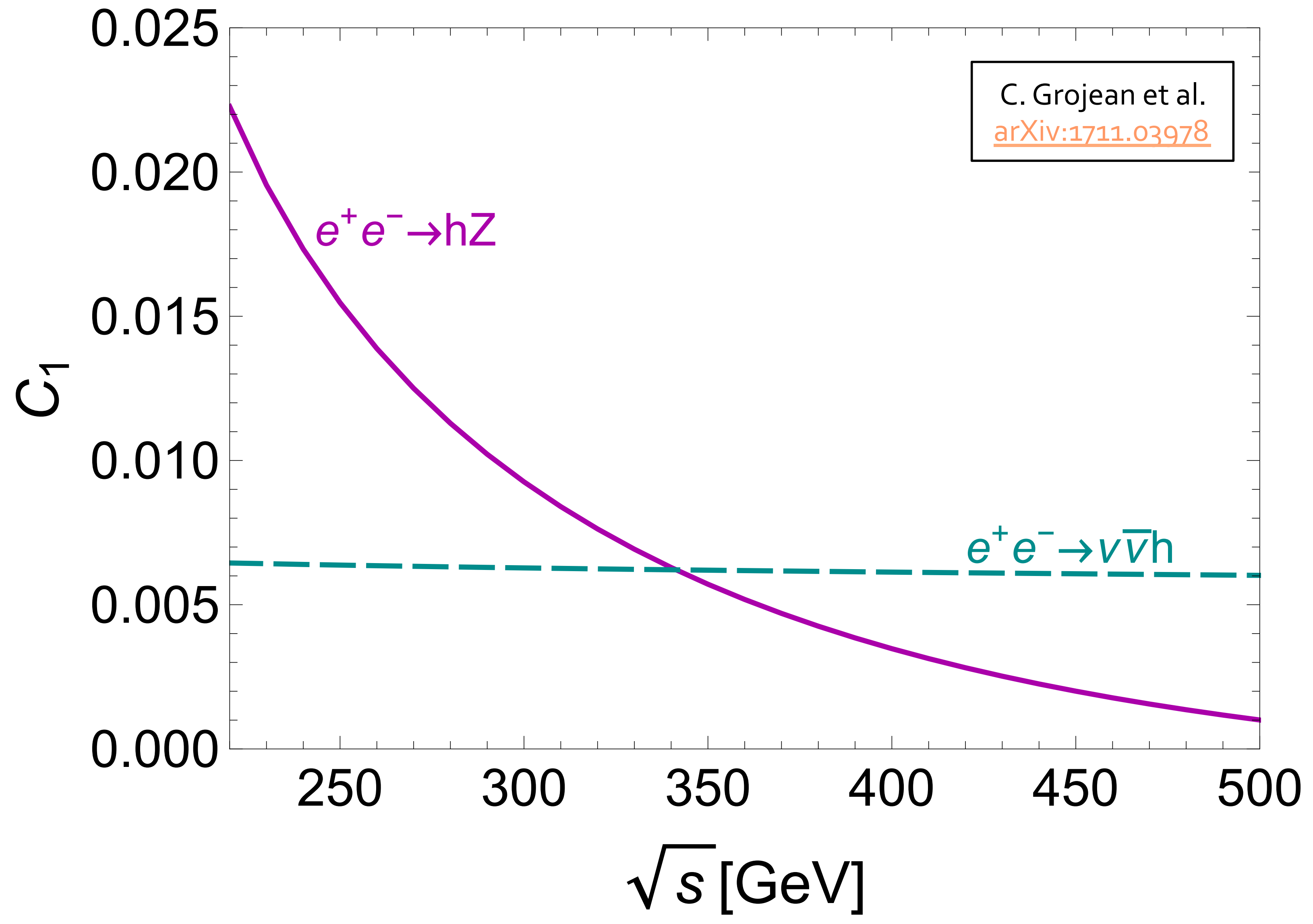
more precision on the EFT operators

HIGGS SELF-COUPLING WITH SINGLE HIGGS

- Higgs self-coupling, λ_3, is a fundamental parameter of the SM whose value should be checked against prediction
- e+e- colliders with $\sqrt{s}$<500 GeV can profit of the significant effect on single Higgs production



M. McCullough
arXiv:1312.3322



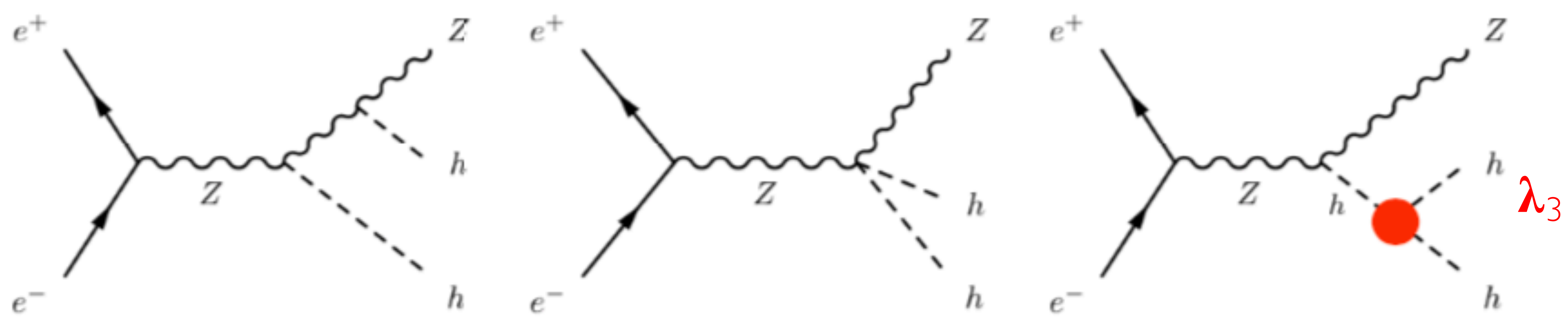
Measurements at different $\sqrt{s}$ also help to lift degeneracy between processes

Precision on k_λ	
FCC-ee	33 %
FCC-ee(4IP)	24 %

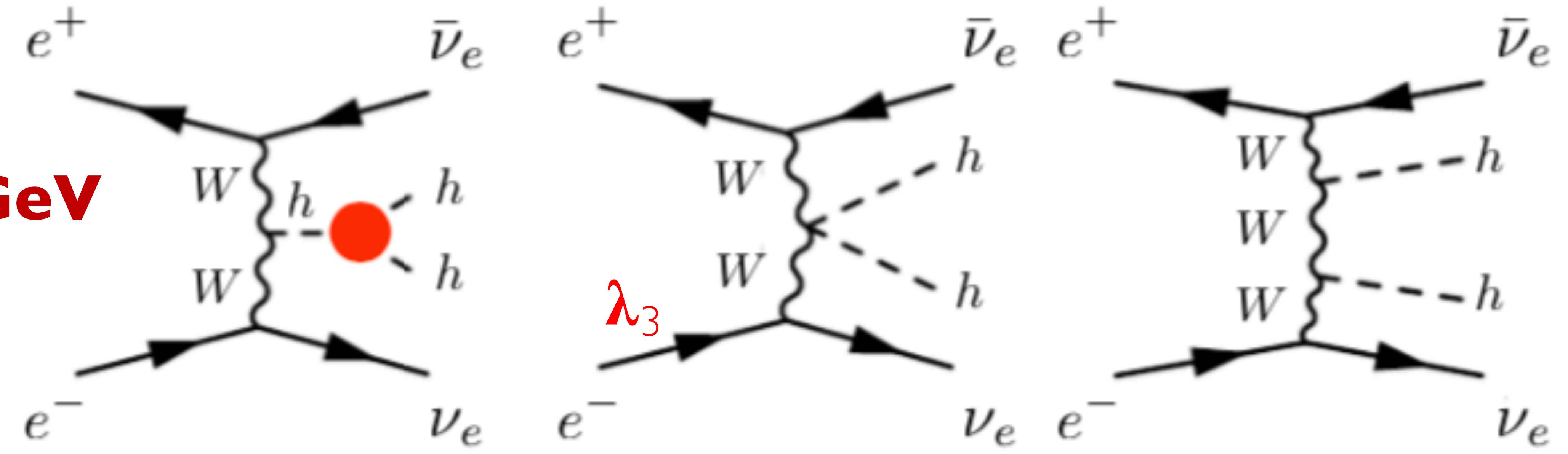
HIGGS SELF-COUPLING WITH DI-HIGGS PRODUCTION

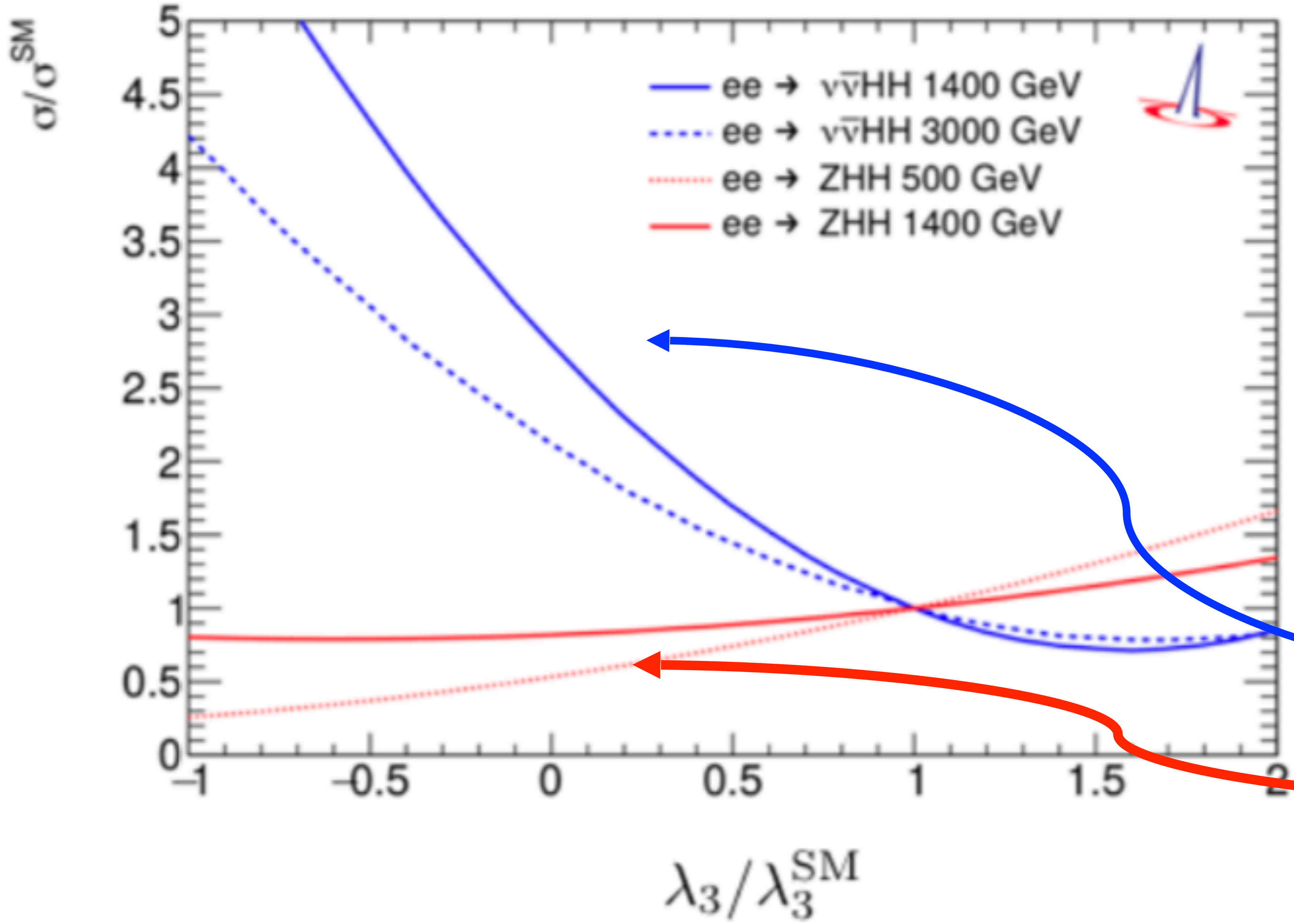
- For $\sqrt{s} \gtrsim 500$ GeV, direct access to di-Higgs production (linear colliders or muon collider)

From 500 GeV



From ≈800 GeV





- In both cases, three interfering diagrams
  - Higgs self coupling, λ_3, extracted from fit to production cross section
    - At 1400 GeV: relatively strong dependence
    - At 500 GeV: weak(er) dependence

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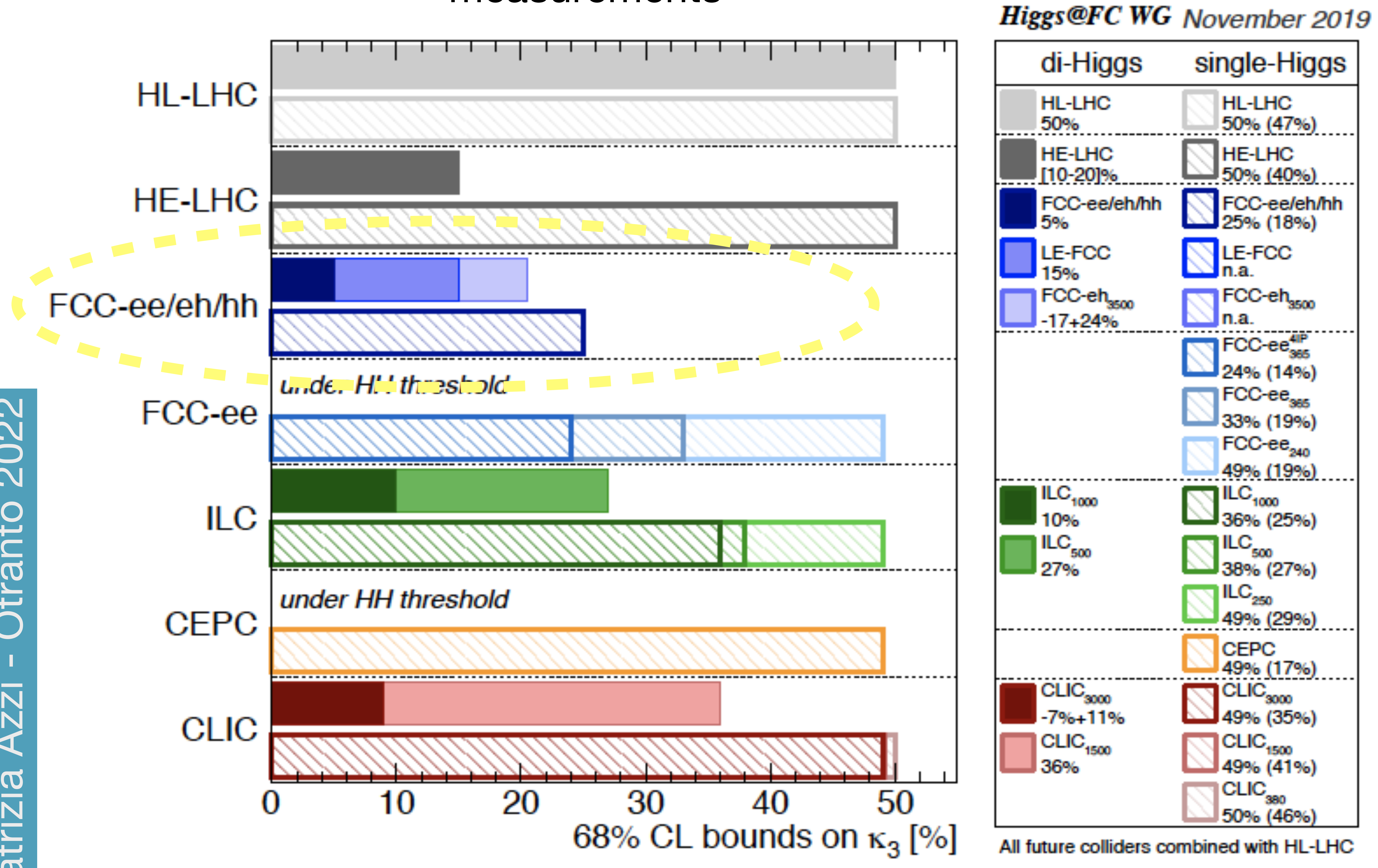
FCC SYNERGIES: TRIPLE HIGGS COUPLING

Projected precision of λ3 measurements



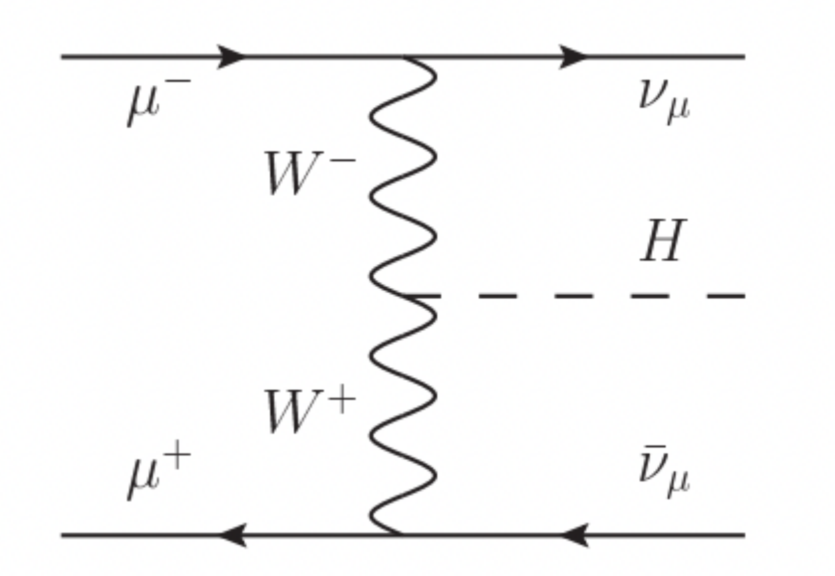
FCC integrated program will measure λ_3 to the 5% level

Muon Collider of 10TeV λ_3 ~3-5%

30TeV λ_3 ~1%

SUMMARY OF HIGGS COUPLINGS AT MUON COLLIDER VS √S

$\sqrt{s}$ (TeV)	3	6	10	14	30	Comparison	
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% (68% C.L.)	**CLIC**
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% (95% C.L.)	**CEPC**
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% , 1% (68% C.L.)	**CLIC/ FCC-hh**
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% (68% C.L.)	**FCC-hh SppC**

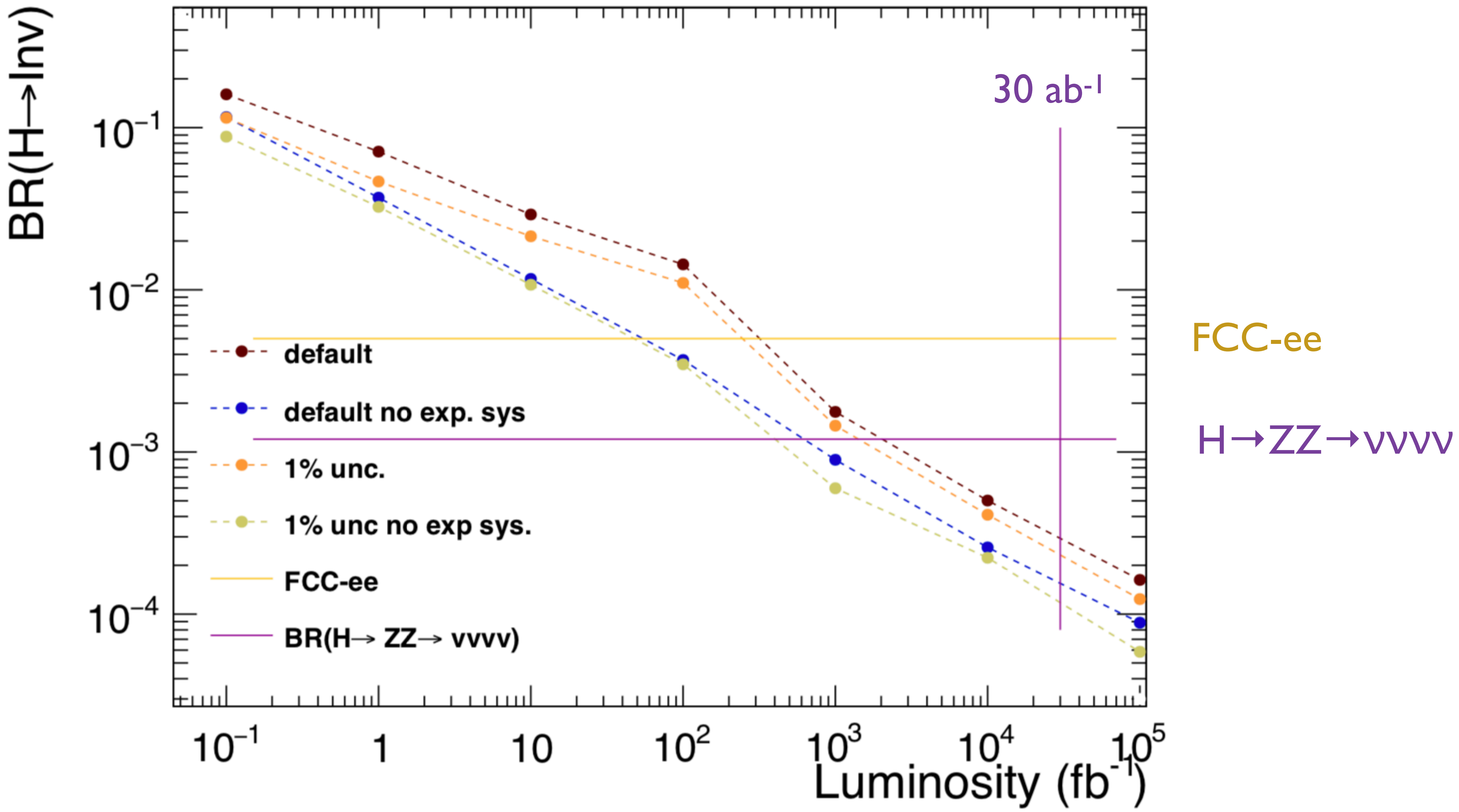


➤ Main production process is the WW fusion

H→INVISIBLE @FCC-hh

- Higgs invisible width can be measured in large missing-E_T signatures
- Derive the BR(H→invisible) from a fit to the missingE_T spectrum
- Constrain background with data driven method using SM W/Z+jets

P. Harris



- $H \rightarrow 4\nu, with\ BR = 1.1 \times 10^{-3}$ can be seen after ~1ab^{-1}

Sensitivity down to 2x10^{-4} with full statistics

Physics with Tera-Z

PHYSICS AT e+e- COLLIDERS

$\sqrt{s}$	Processes	Physics Goals	Observables
91 GeV	• $e^+e^- \to Z$	ultra-precision EW physics **flavour BSM**	$\sin^2\theta_{eff}$ M_Z, Γ_Z, N_ν α, α_S
125 GeV	• $e^+e^- \to H$	*limit on s-channel H production?*	y_e
160 GeV	• $e^+e^- \to W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \to W^+W^-$ • $e^+e^- \to qq, \ell\ell\ (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, aTGC N_ν
250 GeV	• $e^+e^- \to ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H κ_V, κ_f, Γ_H
360 GeV	• $e^+e^- \to tt$	ultra-precision top mass	M_{top}
>360 GeV	• $e^+e^- \to tt$ • $e^+e^- \to ZH$ • $e^+e^- \to H\nu\nu$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \to ttH$ • $e^+e^- \to ZHH$ • $e^+e^- \to Z' \to ff$ • $e^+e^- \to XX$ • $e^+e^- \to AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for supersymmetry (SUSY) search for new Higgs bosons	y_{top} λ_{HHH}

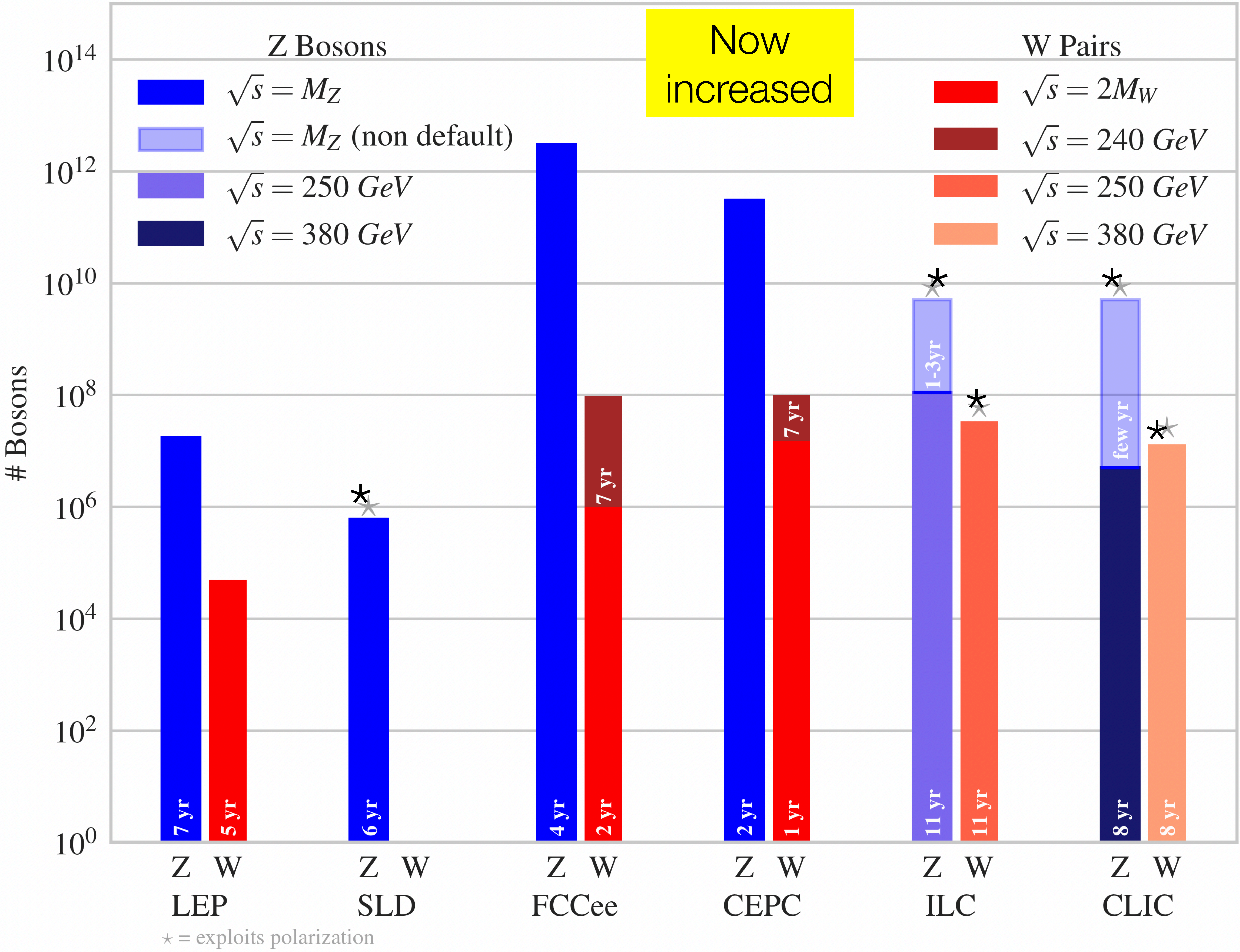
Special program

TERA-Z/GIGA-Z EWK PRECISION PROGRAM

- From data collected in a lineshape energy scan around the Z pole:
  - Z mass: key for jump in precision for EWK fits
  - Z width: jump in sensitivity to EWK radiative correction
  - R_l=hadronic/leptonic width: $\alpha_s(m_Z^2)$, lepton couplings, precise universality test
  - Peak cross section: invisible width, N_ν
  - $A_{FB}(\mu\mu)$: $\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings,
  - Tau polarization: $\sin^2\theta_{eff}$, lepton couplings, $\alpha_{QED}(m_Z^2)$
  - R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$: quark couplings
- **Difference between circular and linear collider is: statistics and control of the beam energy vs polarization capabilities**

NUMBER OF Z AND W EVENTS

- Number of Z bosons and W^+W^- boson pairs at past and future e^+e^- colliders.
    - The numbers are summed over experiments (four for LEP, two for FCC-ee and CEPC and one for the other colliders).
    - For LEP the number of W pairs shown includes all energies $\sqrt{s} \geq 2M_W$.



* = exploits polarization

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SELECTED ELECTROWEAK QUANTITIES (FROM FCC-ee)

Orders of magnitudes of reduction of statistical uncertainties

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
R^Z_ℓ ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R^Z_ℓ above [43]
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R^W_ℓ [45]
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	$172,740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda^{SM}_{top}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

In this context would need from theory full 3-loop calculations for the Z pole and propagator EWK corrections and probably 2-loop for EWK corrections to the WW cross section. Matching these experimental precisions motivates a significant theoretical effort.

EWK VARIABLES TO BE MEASURED: LC VS CC

Partial fermion width:

$$R_f = \frac{N_f}{N_{had}} = \frac{(g_f^L)^2 + (g_f^R)^2}{\sum_{i=1}^{n_q}[(g_i^L)^2 + (g_i^R)^2]}$$

- Sensitive to sum of coupling constants
- Available at linear and circular colliders

Left-right asymmetry:

$$A_{LR} = \frac{1}{|\mathcal{P}_{eff.}|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e = \frac{(g_f^L)^2 - (g_f^R)^2}{(g_i^L)^2 + (g_i^R)^2} \sim 1 - 4\sin^2\theta^\ell_{eff.}$$

- Direct sensitivity to Zee vertex
- Only available at linear colliders due to beam polarisation
- Circular colliders need auxiliary measurement
  - e.g. $P_\tau \sim A_e$

Forward-backward asymmetry:

$$A^f_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \quad \text{for} \quad \mathcal{P}_e = 0.$$

- “Classical” observable to study P-violating effects in ee->ff
- Available at circular and linear colliders
- **Without** beam polarisation interpretatio needs extra inputs t

Like at a Circular collider

Left-right-forward-backward asymmetry:

$$A^f_{FB,LR} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_L + \sigma_l)_R} = -\frac{3}{4}\mathcal{A}_f$$

- Combination of asymmetries above
- Only available linear colliders due to beam polarisation
- Direct and model independent measurement of A_f

https://arxiv.org/pdf/1801.02840.pdf

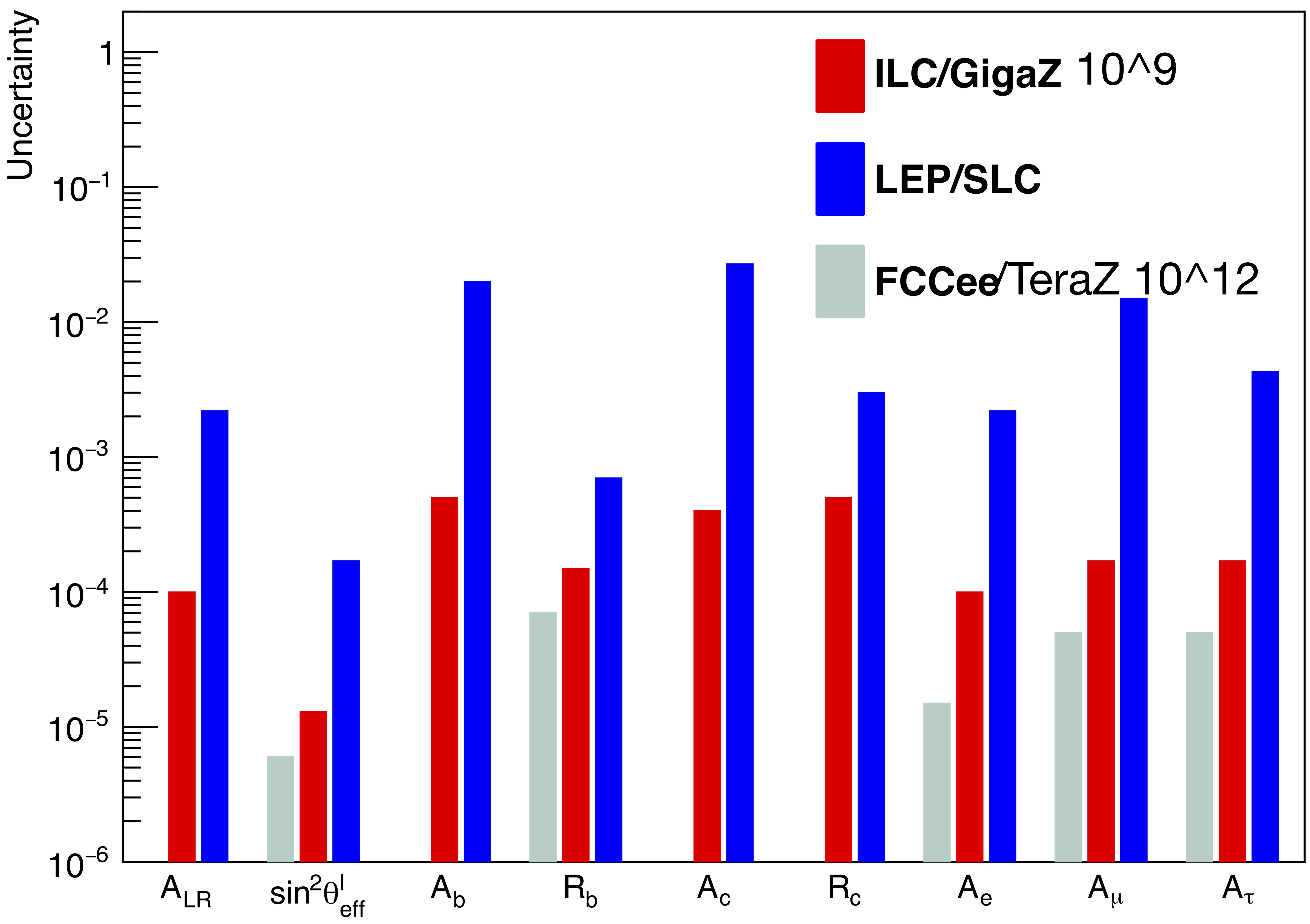
NEUTRAL COUPLINGS AND EWK ANGLE

At linear collider use polarisation to extract Ae

$$A_e = \frac{2g_{V_e}g_{A_e}}{(g_{V_e})^2 + (g_{A_e})^2} = \frac{2g_{V_e}/g_{A_e}}{1 + (g_{V_e}/g_{A_e})^2}$$

- $\sin^2\theta_{eff}$ can be measured at circular colliders with 5x10^-6 (at least) from:
  - **Muon forward-backward asymmetry at pole $A_{FB}^{\mu\mu}(m_Z)$ assuming muon-electron universality**
    - uncertainty driven by knowledge of CM energy (point to point errors)
  - **Tau polarization without assuming lepton universality**
    - Tau polarization measures A_e and A_τ, can input to $A_{FB}^{\mu\mu} = \frac{3}{4}A_eA_\mu$ to measure separately e, μ and τ coupling (with $\Gamma_e, \Gamma_\mu, \Gamma_\tau$)
      - Very large tau statistics and improved knowledge of parameters (BF, decay modeling).
- Asymmetries A_{FB}^{bb}, A_{FB}^{cc} provide input to quark couplings (together with Γ_b, Γ_c)

PRECISION MEASUREMENTS AT Z: A COMPARISON LC VS CC

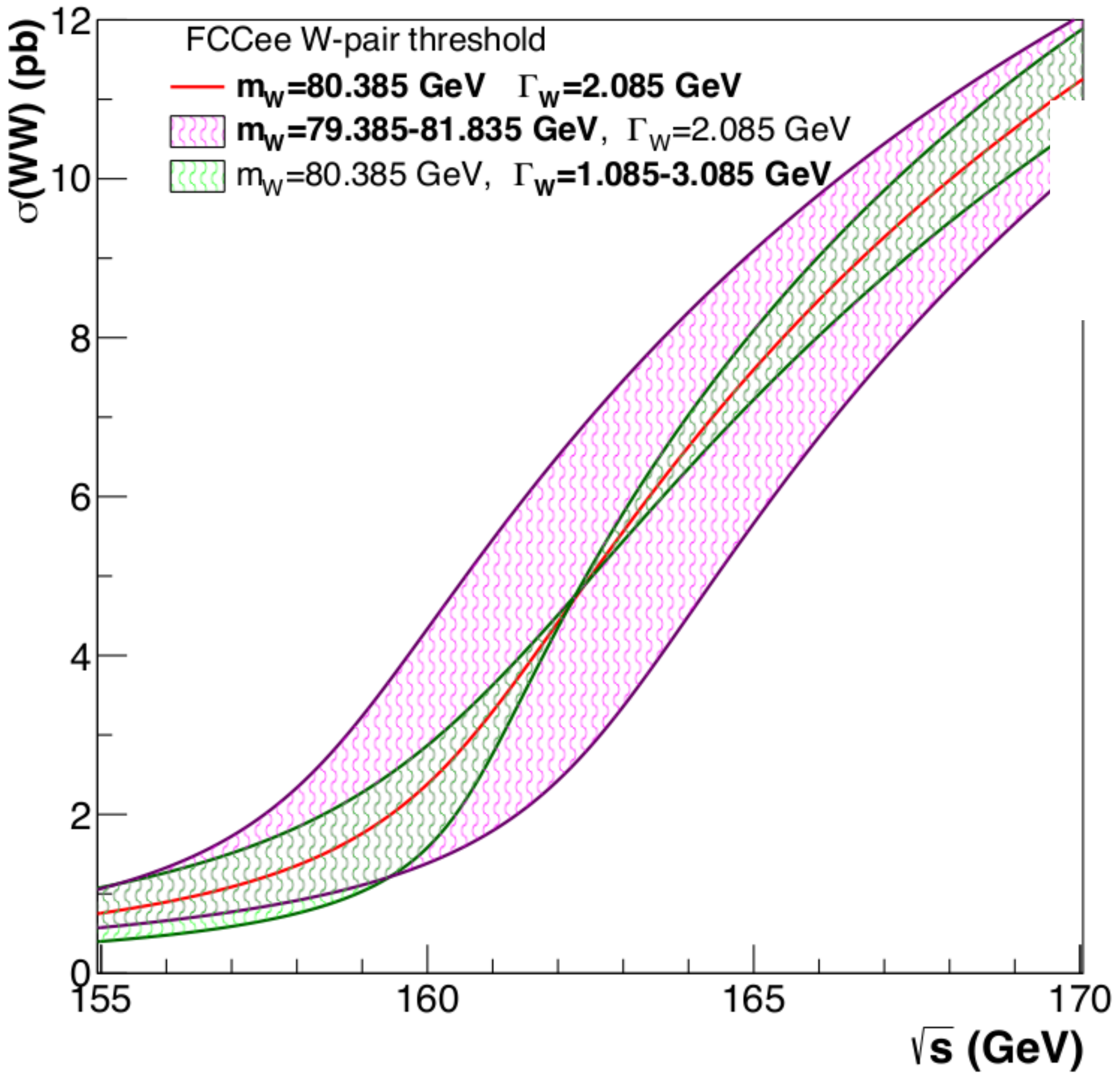


- ILC ten times better than LEP/SLD and competitive with FCC
- Polarisation compensate for ~30 times luminosity
- No assumption on lepton universality at LC
- Excellent measurement of quark asymmetries

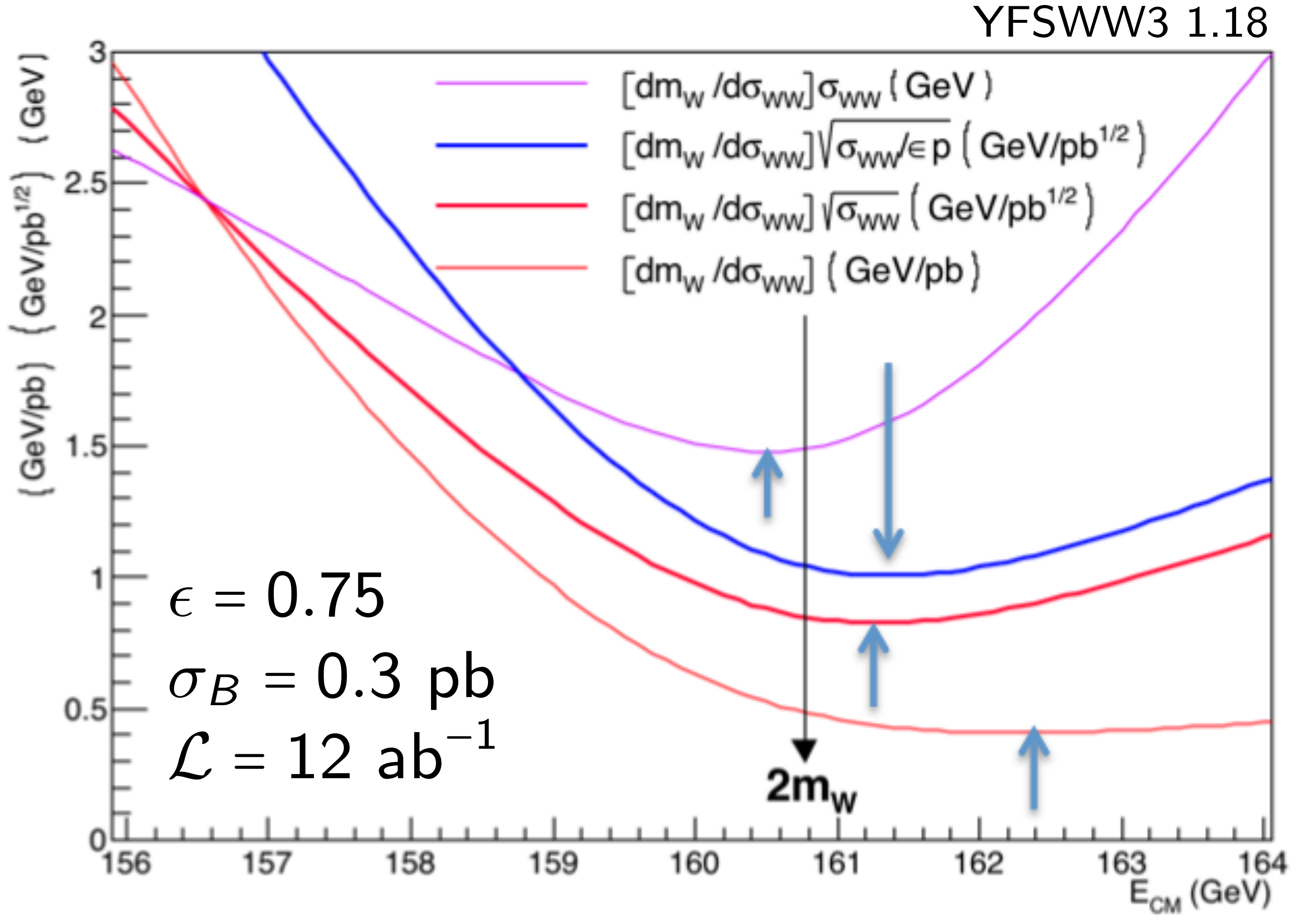
OKU-W (10^8 WW) EWK PRECISION PROGRAM $e^+e^- \to W^+W^-$

- From data collected around and above the WW threshold:
  - W mass: key for jump in precision of EWK fits
  - W width: first precise direct measurement
  - $R_W = \Gamma_{had}/\Gamma_{lep}$ needed for $\alpha_S(m^2_Z)$
  - Γe, $\Gamma \mu$, $\Gamma \tau$: for precise universality test
  - Triple and Quartic Gauge couplings: jump in precision, especially for charged couplings
- Only Circular Colliders consider a run at the WW threshold

W MASS AND WIDTH AT THRESHOLD



$$\Delta M_{W,stat} = \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\mathcal{L}}} \frac{1}{\sqrt{\epsilon p}} \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \frac{\Delta\sigma_B}{\epsilon} \oplus \left(\frac{d\sigma}{dM_W}\right)^{-1} \sigma \left(\frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\right)$$



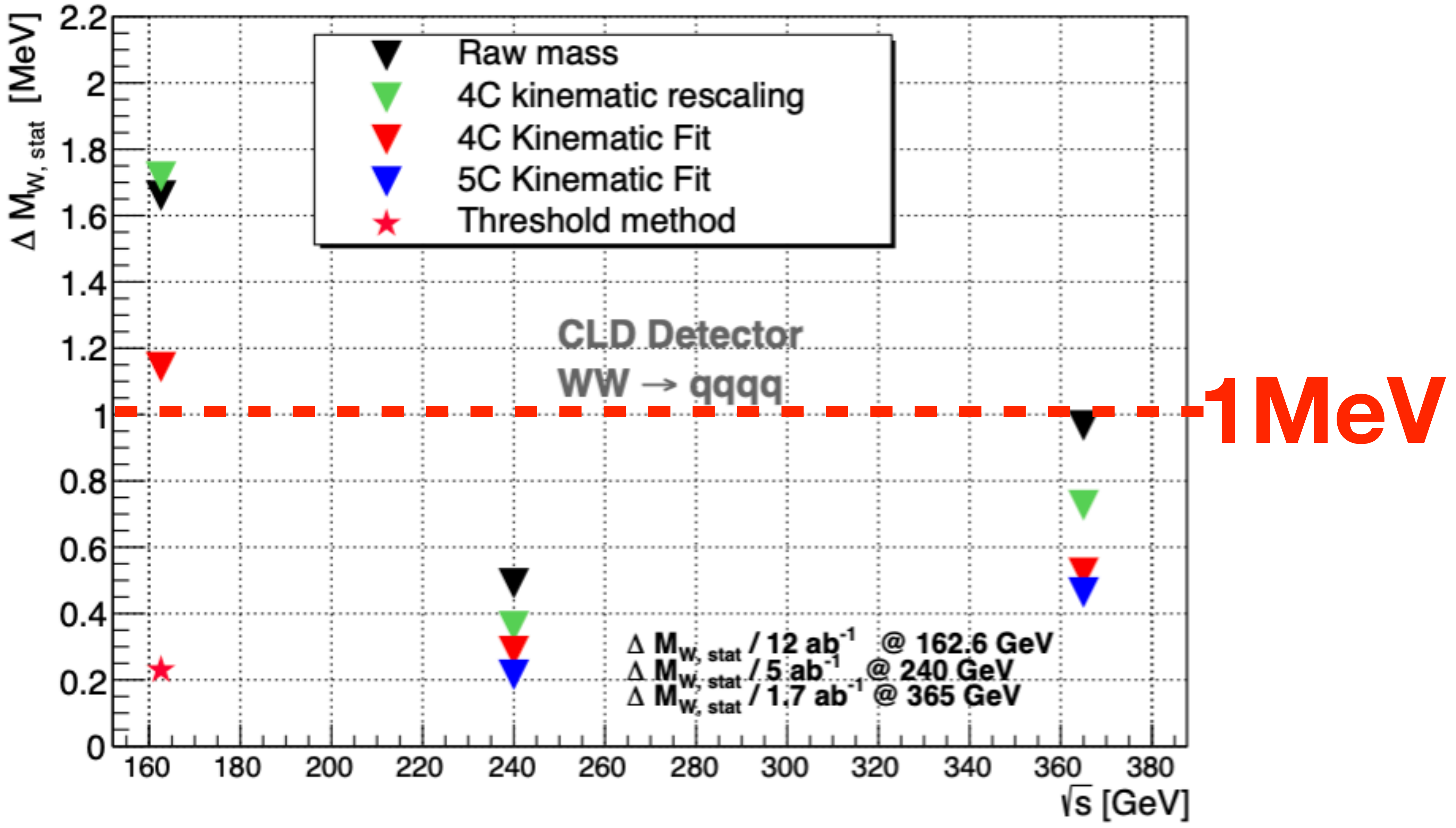
Optimal energy : $E = 161.4$ GeV
$\Delta M_W = 0.23$ MeV

LEP : $\Delta M_W = 210$ MeV
$\mathcal{L} = 10$ pb^{-1}

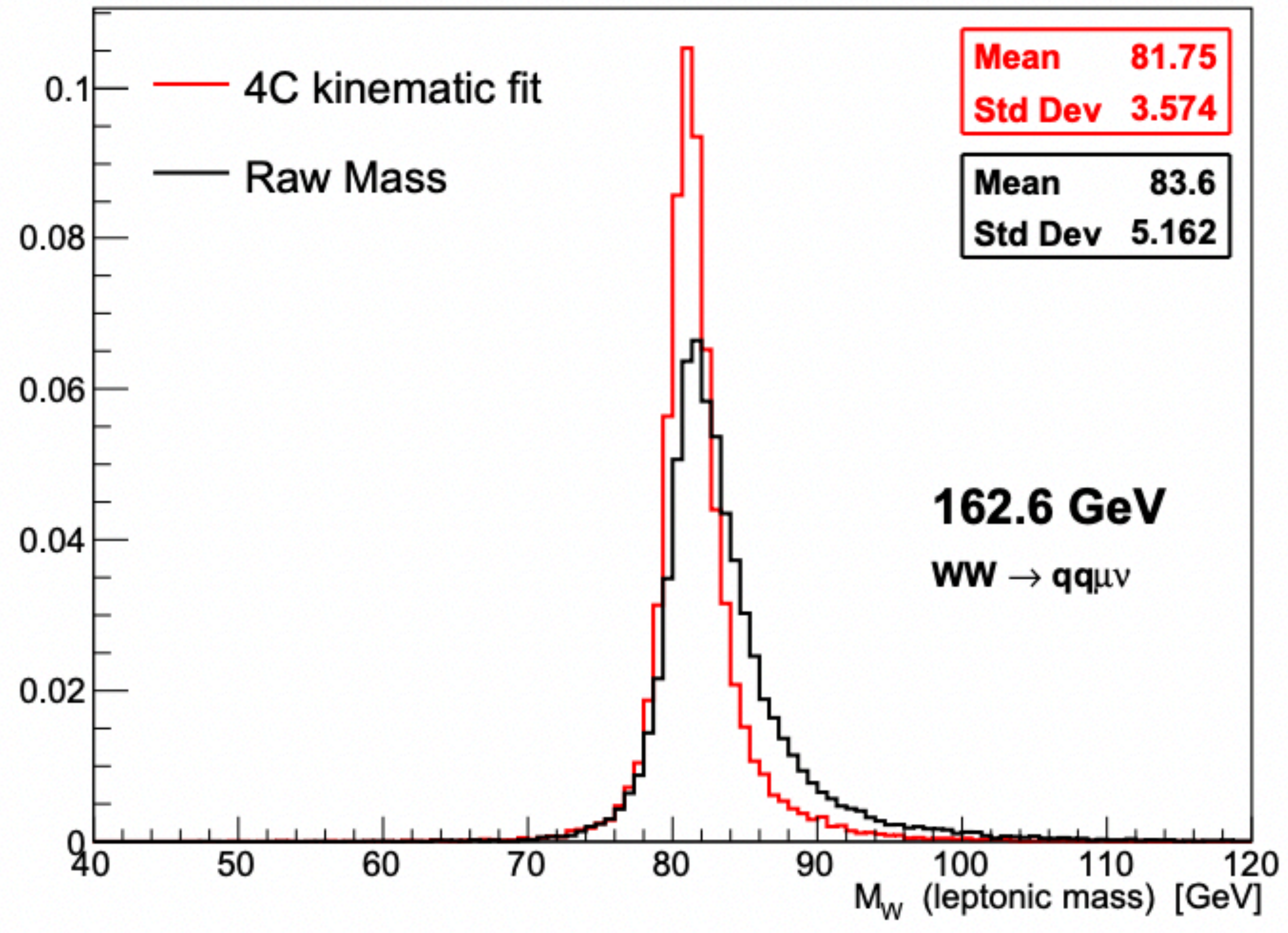
with E_1=**157.1** GeV E_2=**162.3** GeV f=**0.4**
Δm_W=0.62 $\Delta\Gamma_W$=1.5 (MeV)

W MASS DIRECT RECONSTRUCTION

- Precise M(W) from threshold run
- **M(W) direct reconstruction from decay products useful/needed at any √s>threshold**
- Competitive as statistical uncertainty but different challenges to be considered:
  - Event reconstruction, choice of jet algorithms
  - Lepton momentum scale and resolution
  - Kinematical fitting

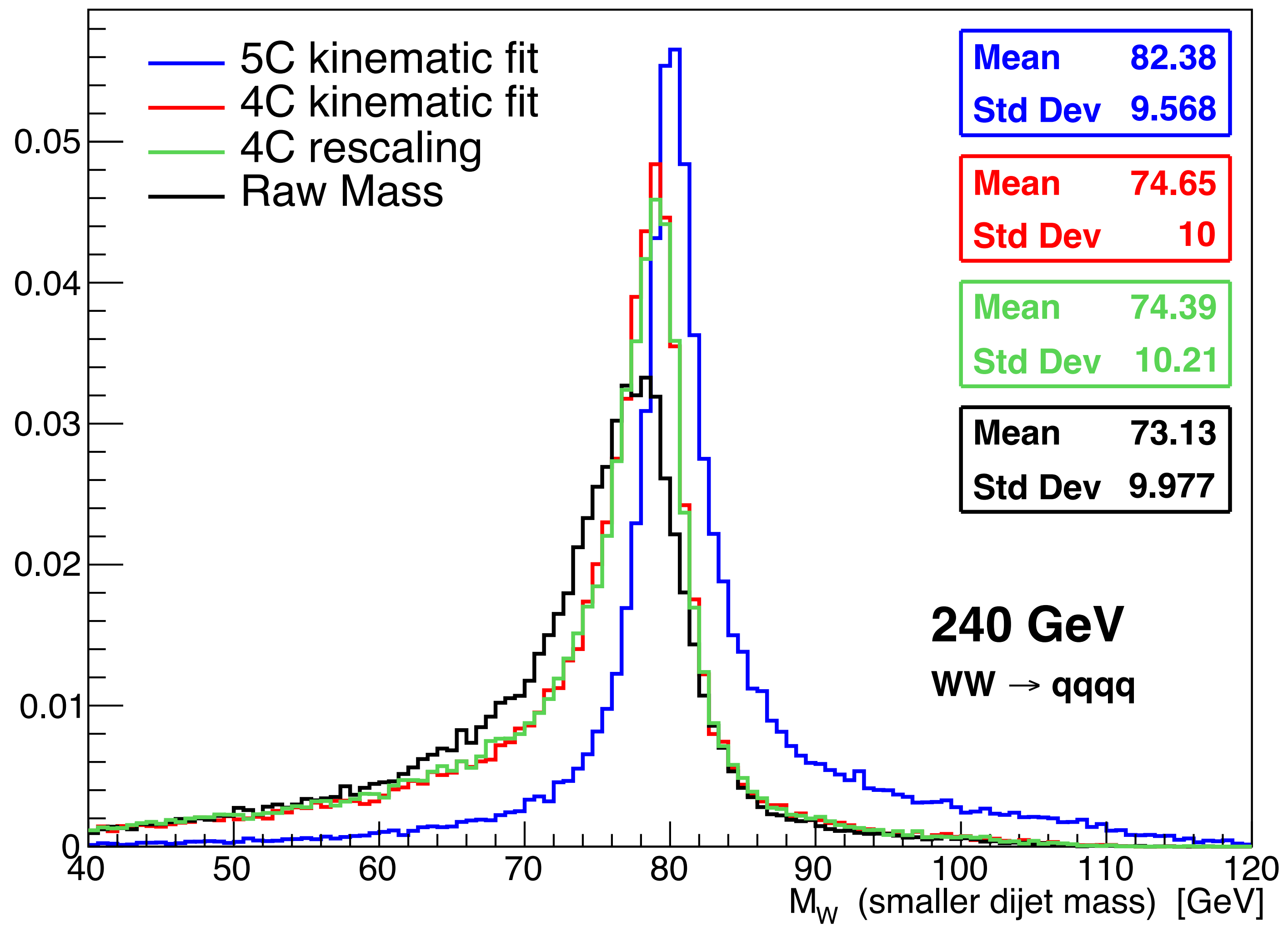


Semi-leptonic channel



M. Beguin

Fully hadronic channel



SMEFT is a "bottom up" effective field theory that describes SM interactions with new physics under certain assumptions

1) Assume that new physics is above some high energy scale
2) Assume that new physics Lorentz and gauge invariance

$\Rightarrow$ Build every possible operator at each order in mass dimension from the existing Standard Model fields

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\forall i, n \geq 5} \frac{C_i \mathcal{O}_i^{(n)}}{\Lambda^{n-4}}$$

Higher (mass) dimension operators suppressed by NP scale

GLOBAL FIT TO EWK COUPLINGS

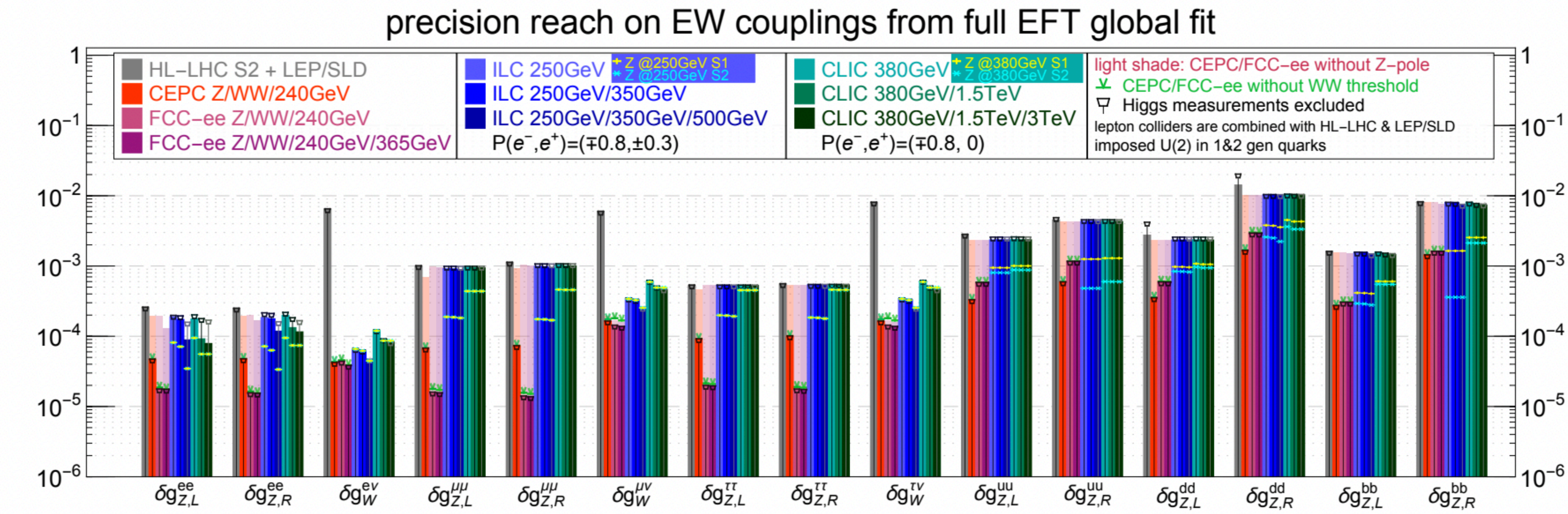
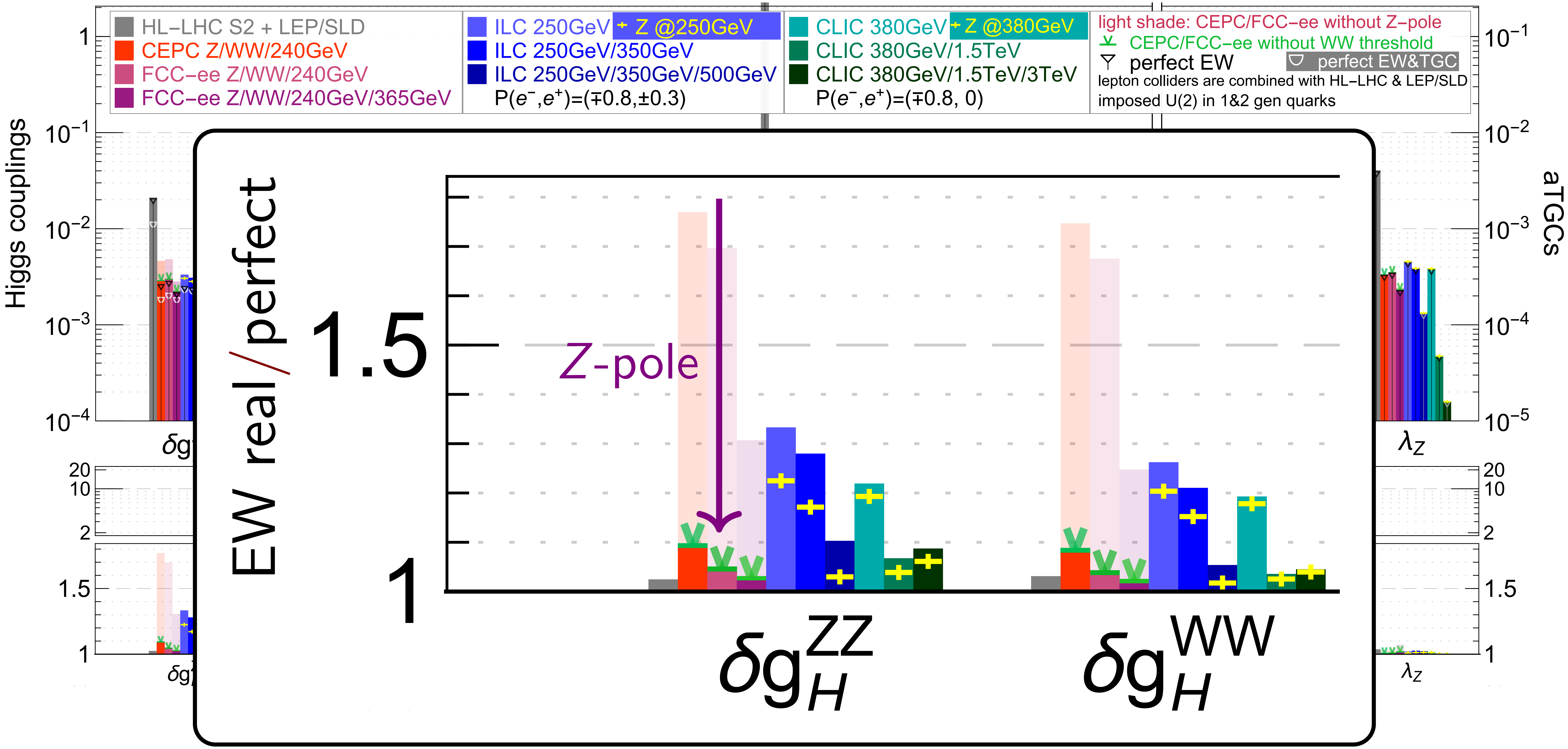


Figure 4: *Global one-sigma reach on electroweak couplings for the same scenarios as in figure 2. Higgs and triple-gauge coupling modifications are marginalized over. Trapezoidal and green marks respectively indicate the prospects obtained with Higgs and WW threshold measurements excluded. The numerical results are reported in table 2.*

https://arxiv.org/pdf/1907.04311.pdf

Impact of Z pole run



15 EW param. also marginalized over / assumed perfectly constrained

- Z-pole run has a big impact

COMBINED FCC-ee SMEFT FIT

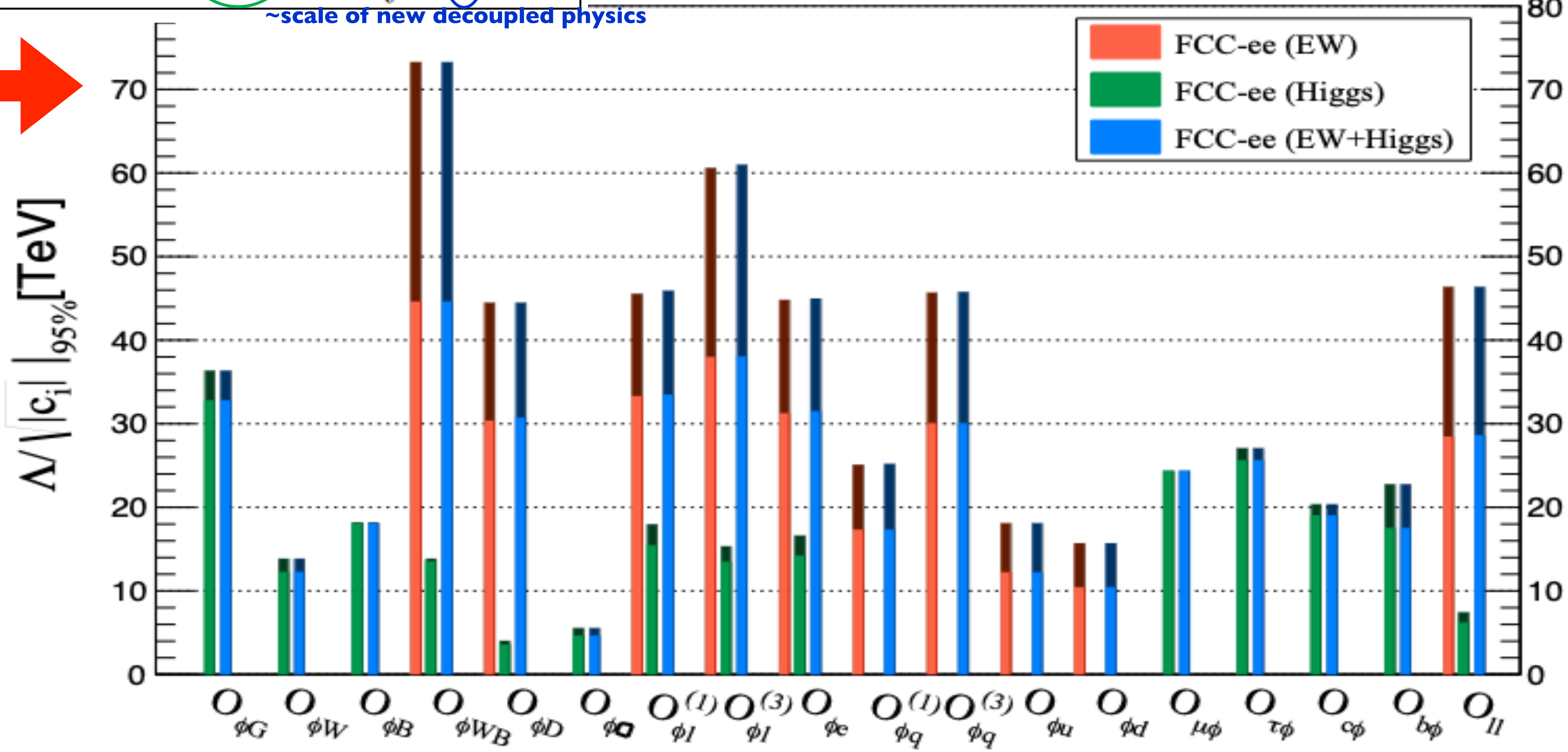
Electroweak + Higgs precison measurements

Standard Model   Dimension-6 operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

~scale of new decoupled physics

Today's limits on new physics scale Λ > 4-10TeV



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THE INTENSITY FRONTIER - FLAVOR PHYSICS

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., b → sττ

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

~15 times Belle's stat

Boost at the Z!

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	$\sim$ 2 000	$\sim$ 10	n/a (5)
LHCb Run I	150	-	$\sim$ 15 (–)
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)
FCC-ee	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)

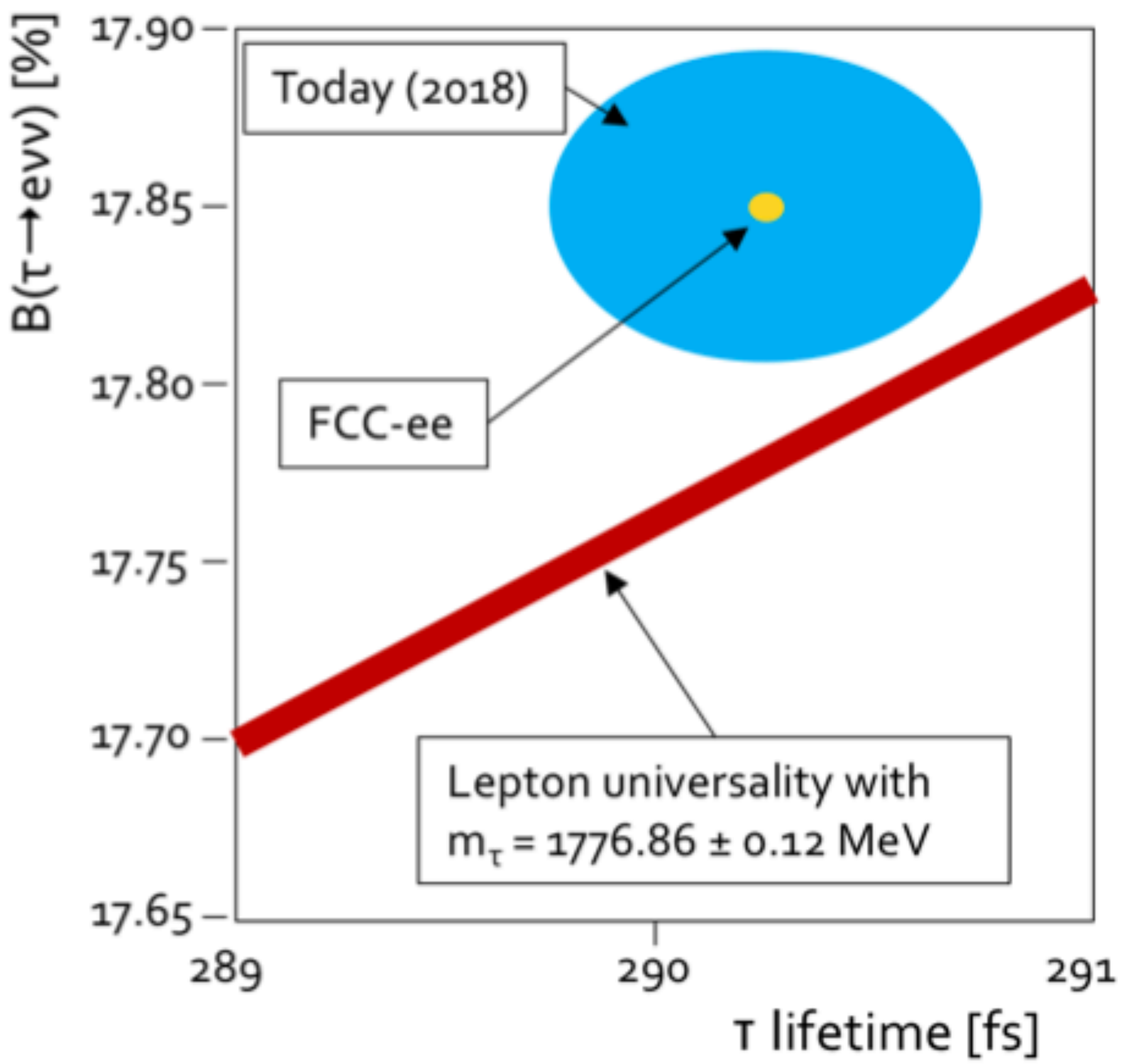
Yelds for flavor anomalies studies:

b→sll yelds and $B^0 \to K^{*0}\tau^+\tau^-$ 👍

Full reconstruction possible

THE INTENSITY FRONTIER - TAU PHYSICS

- ➤ Enormous statistics: 1.7 10^{11} $\tau\tau$ events
- ➤ Clean environment, boost, vertexing
- ➤ Much improved measurement of tau mass, lifetime, BR's will be crucial for:
  - ➤ τ-based EWPOs ($R\tau$, A_{FB}^{pol}, P_τ)
  - ➤ Lepton universality violation tests
  - ➤ PMNS matrix unitarity
  - ➤ Constraints on Light-heavy neutrino mixing

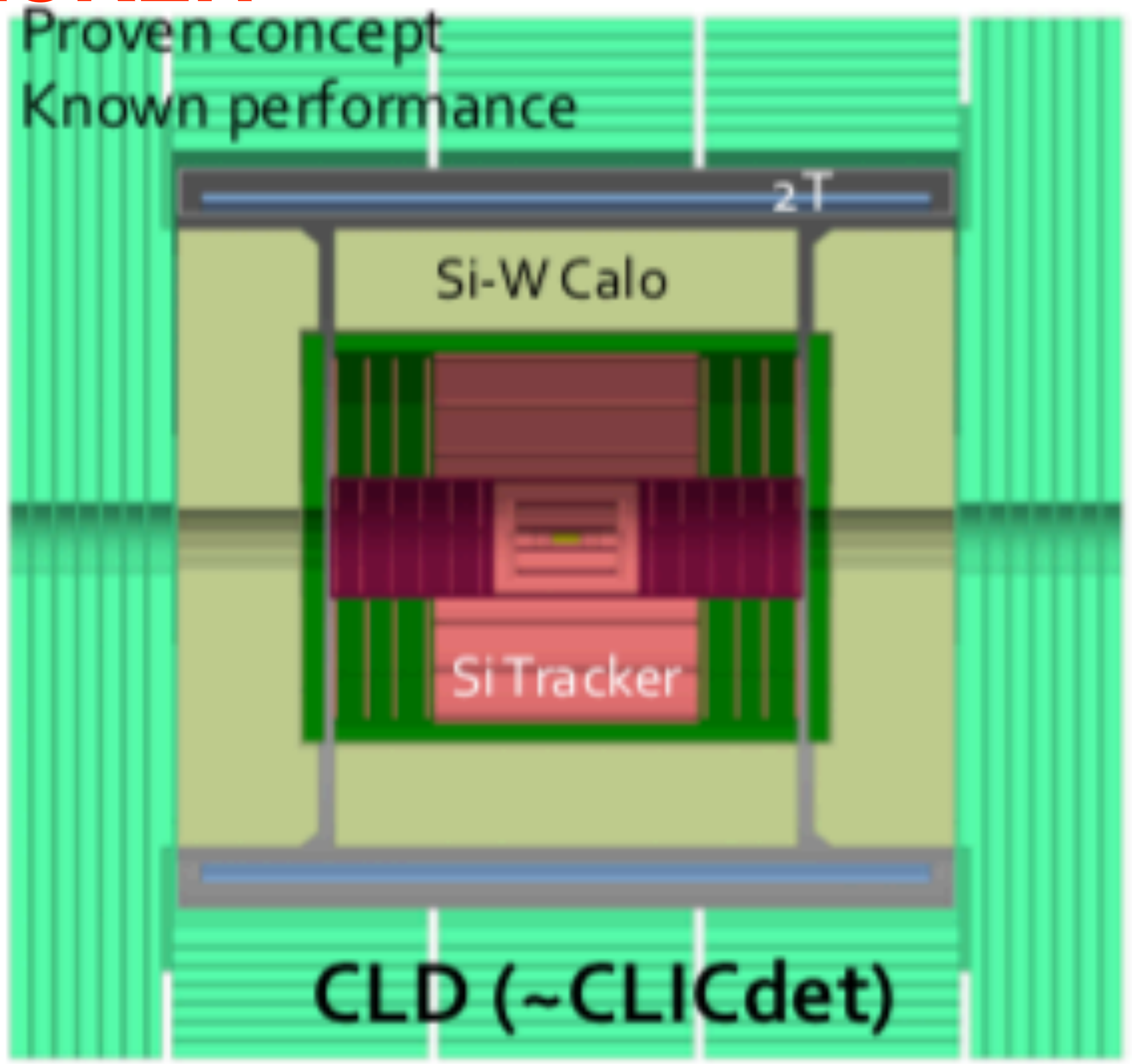


Detector Requirements

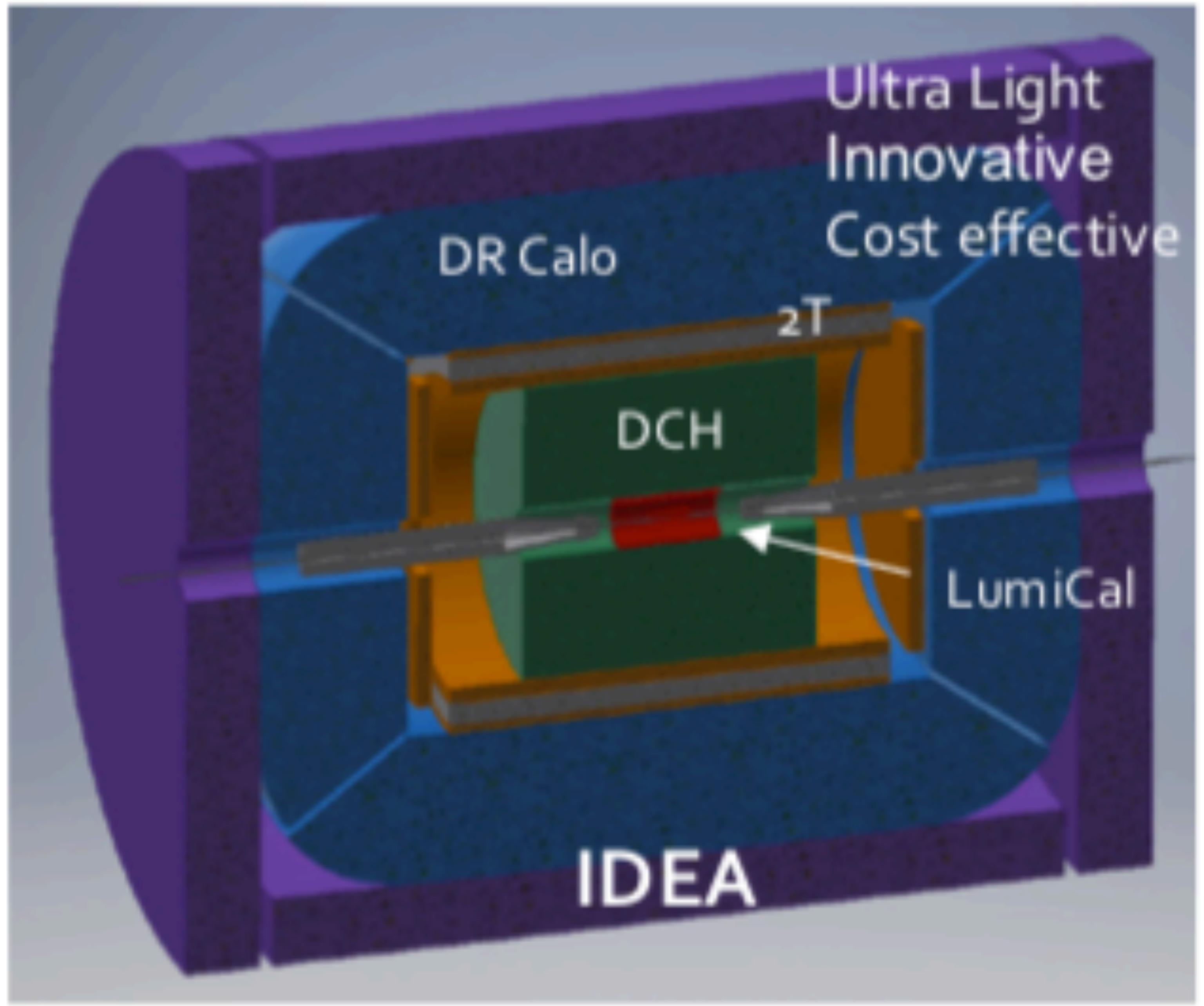
- Momentum resolution for Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions for lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation: BR measurements, EWPOs

A WORD ON THE DETECTORS FOR CC (HERE FCC-ee)

SILICON TRACKER

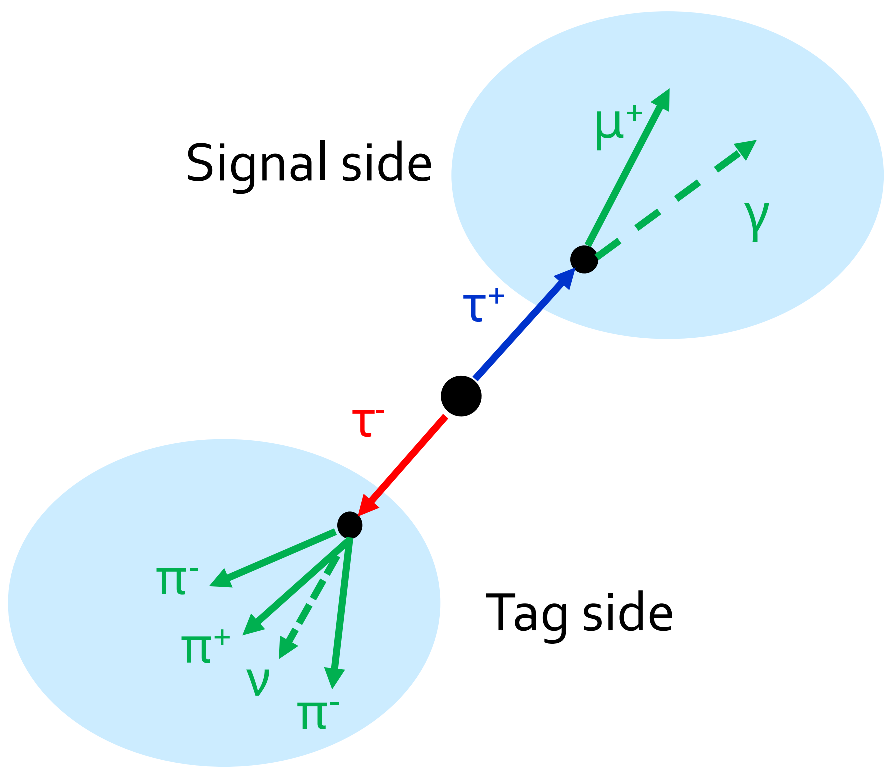


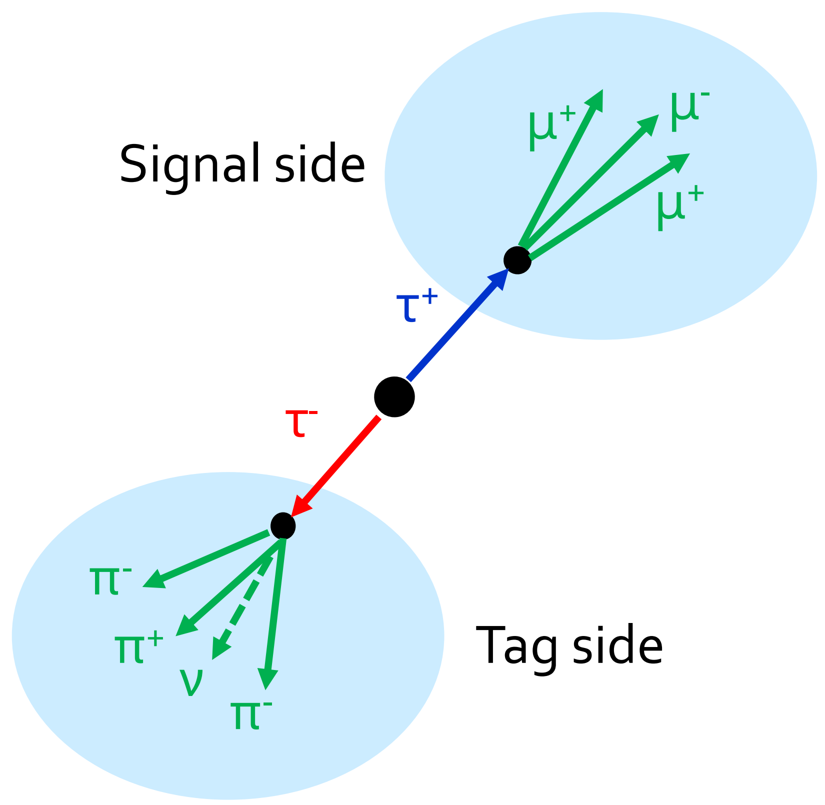
LIGHT DRIFT CHAMBER



- Two main design considered for now (FCC-ee, but CEPC is similar)
- Major point for B physics in a detector: the lightness of the tracker, excellent vertexing and tagging capabilities, particle ID.
- Possibility to develop a detector optimized for B-physics needs (especially if a CC could have four collision points)

TERA-Z TAU STATISTICS AND CLFV DECAYS



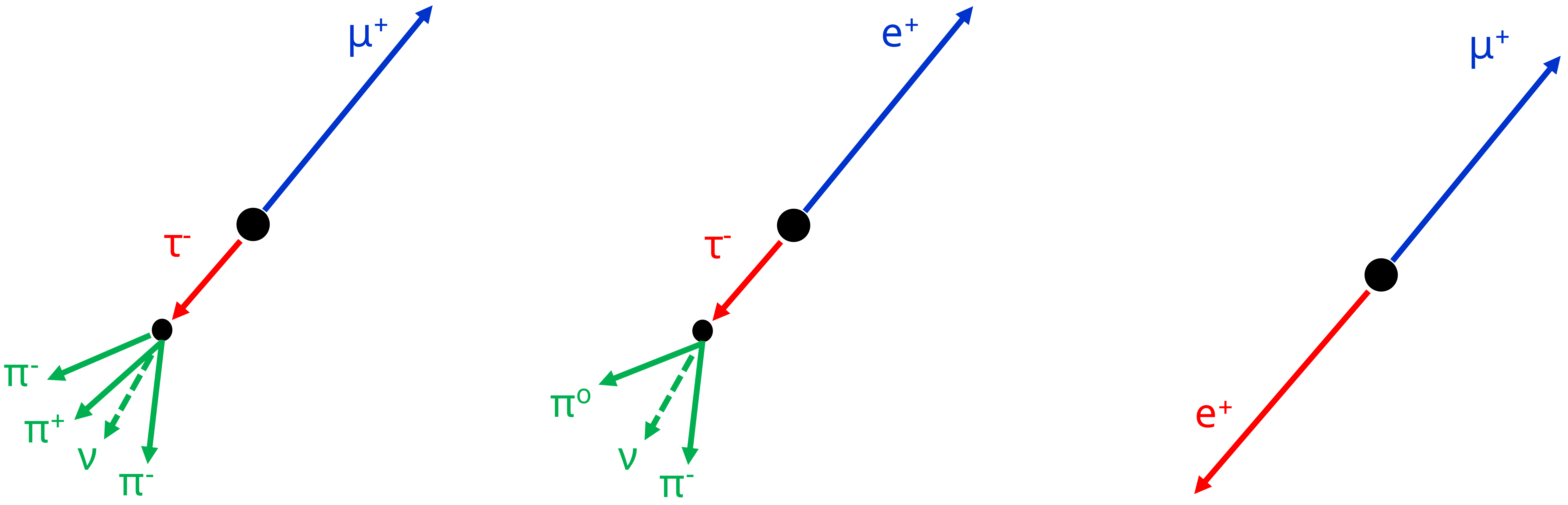


Visible Z decays	3×10^{12}
$Z \rightarrow \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

- Benefits from the huge statistics and boosted topologies.
- Calorimetric performance as ILD.
- Main backgrounds are initial and final state radiative events.

Decay	Current bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2×10^{-8}	10^{-10}

...BUT ALSO LFV Z DECAYS



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- Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m(Z). They could be also DM candidates.
- Signatures explored: photons and long lifetimes (LLP's).
  - Axion-like particles
  - Dark photons
  - Heavy Neutral Leptons

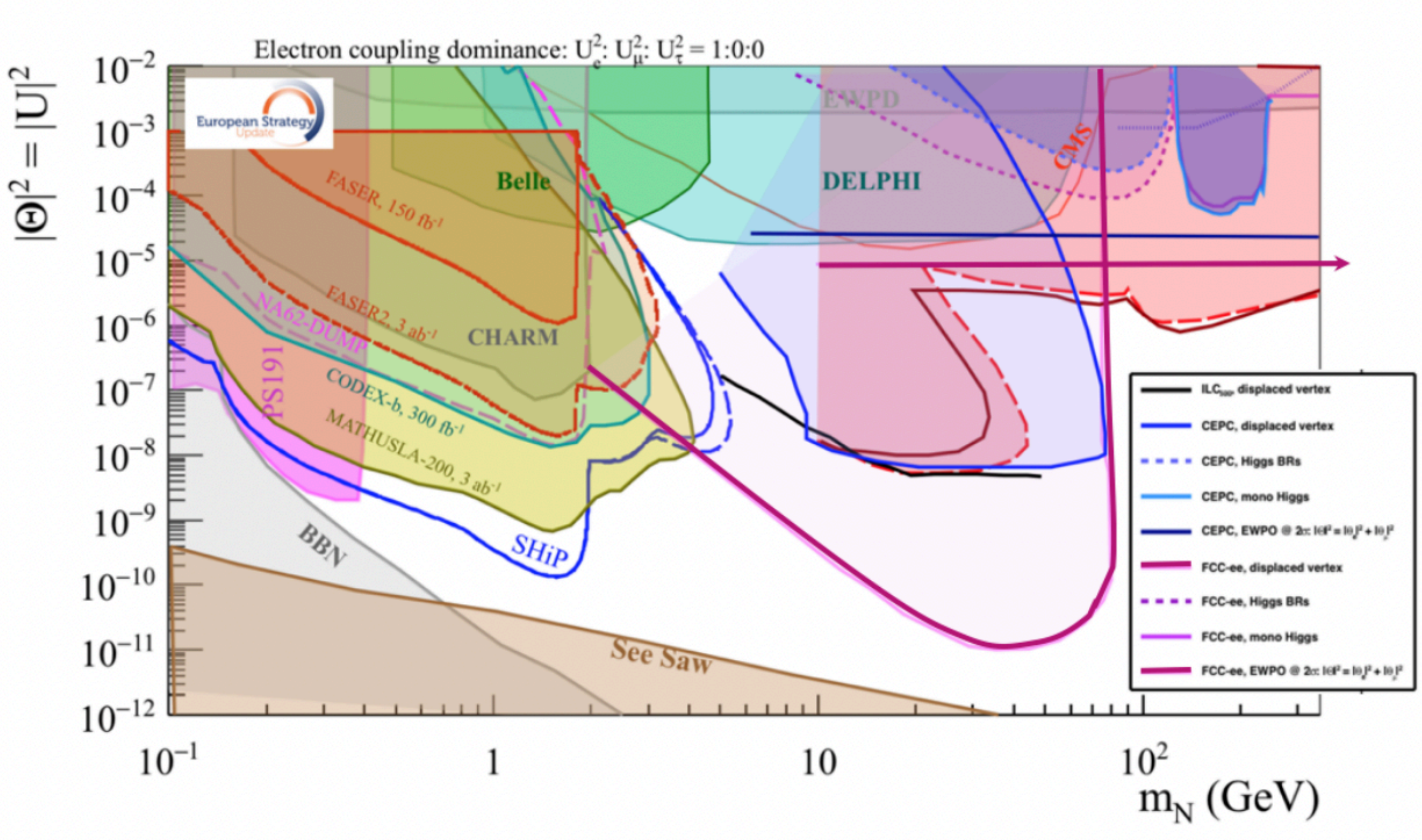
More "extravagant" signatures can be studied in the future profiting of the clean environment

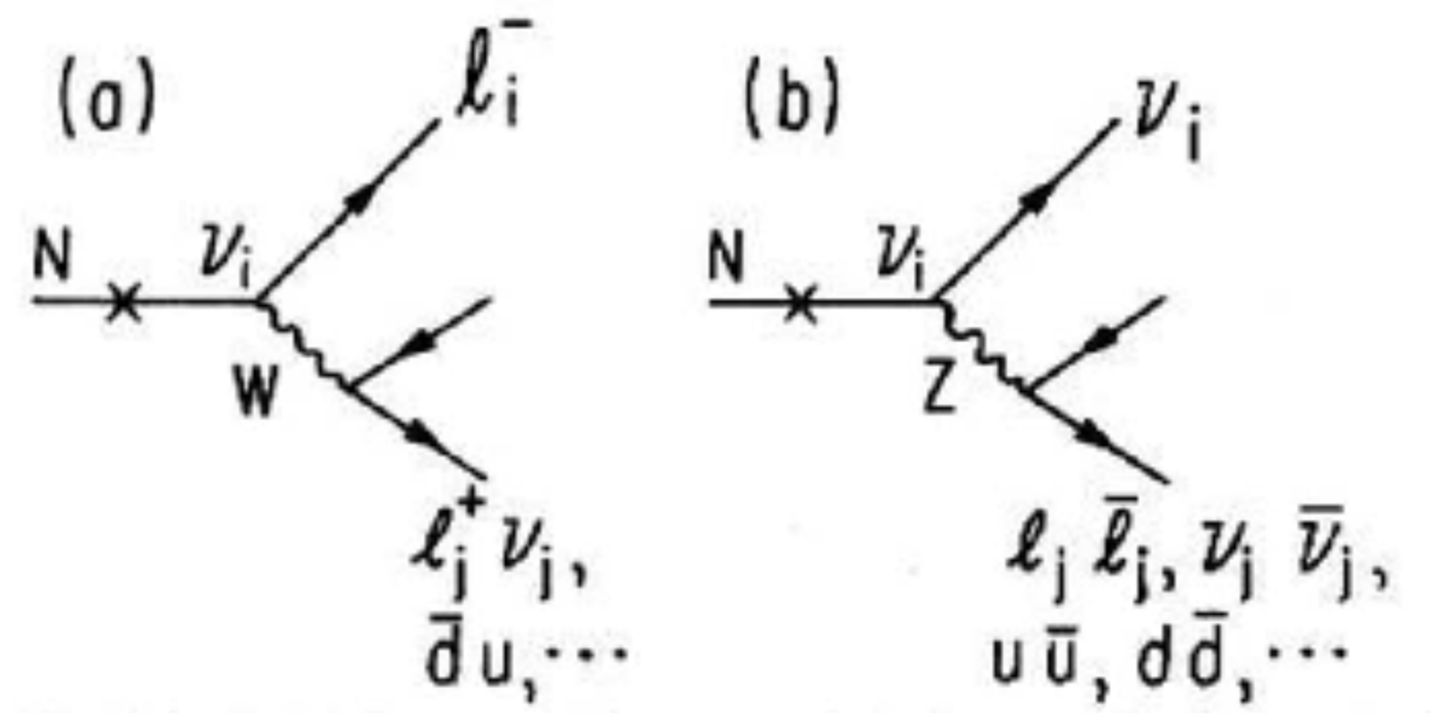
Detector Requirements

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

BSM DIRECT SEARCHES - HEAVY NEUTRAL LEPTONS

- HNL more new studies in progress
- Test minimal type I seesaw hypotesis
- Together with ΔM also tests the compatibility with leptogenesis



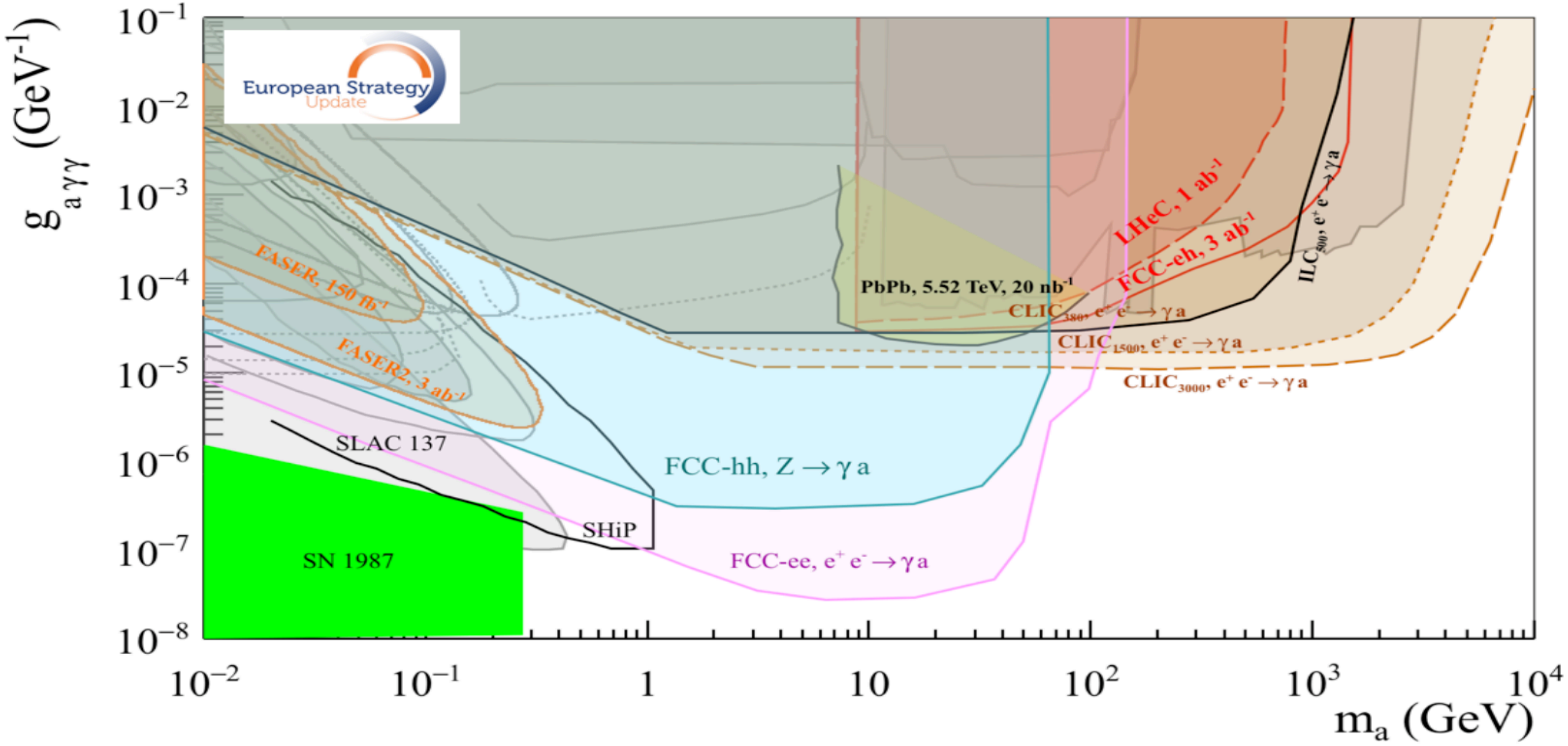


$$L \sim \frac{3\,[cm]}{|U|^2 . (m_N[GeV])^6}$$

L~1m for mN=50GeV and |U|2=10-12

BSM DIRECT SEARCHES - ALPS

- Similar situation for Axion-like-particles: luminosity is key to the game
- Complementarity with high energy lepton collider
- Fertile ground for development of innovative detector ideas!



Backup Material

THE « KAPPA » FRAMEWORK

- Well known and widely used characterisation of Higgs coupling properties in terms of a series of Higgs coupling strength modifier parameters **κ**

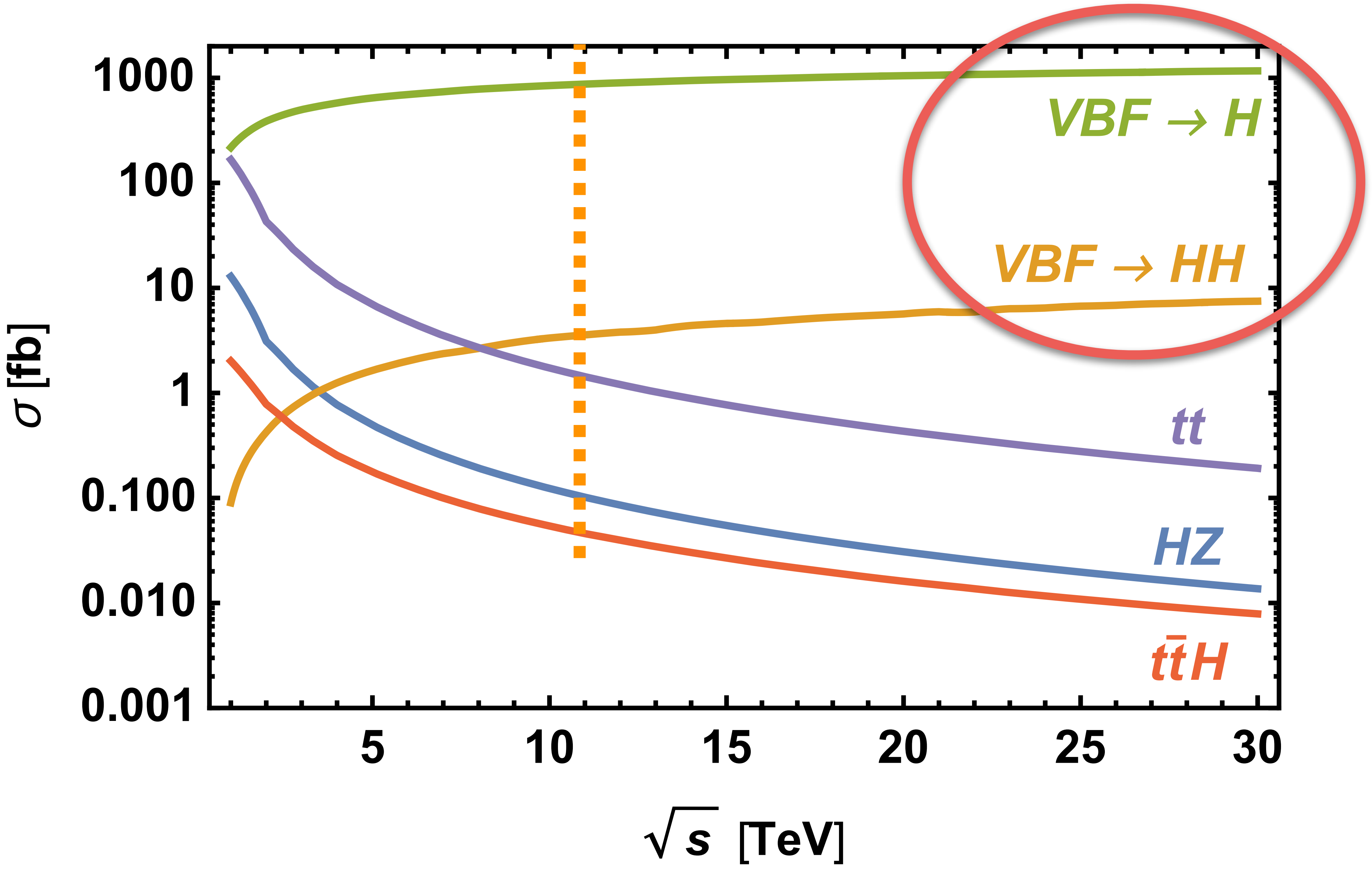
$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

$$\mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2} \qquad \kappa_H^2 \equiv \sum_j \frac{\kappa_j^2 \Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

- **Simplest** parametrisation which can probe the deviation from the SM induced by new physics
  - We fit for κ_W, κ_Z, κ_c, κ_b, κ_t , κ_τ , κ_μ and effective coupling modifiers κ_g, κ_γ and $\kappa_{Z\gamma}$
- Higgs couplings assumed to keep the **same helicity structures** as in the SM
- Directly related to experimental measurements of the Higgs production and decay
- It only compares the experimental measurements to their best SM predictions and does not require any new BSM computations per se

HIGGS SELF-COUPLING @MUON COLLIDER

Huge VBF Higgs: ~ 10^7 Higgses, 30'000 Higgs pairs [at 10 TeV]



Extrapolation to 10TeV muon Collider

10 TeV:
$\delta\lambda_3$= 3%

If **reasonable detector performances.** First detector benchmark.

30 TeV:
$\delta\lambda_3$= 1%

- Huge Higgs production rates:
  - access (very) rare decay modes (eg. 2nd gen,), complementary to FCC-ee
  - push to %-level Higgs self-coupling measurement

- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst. uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (e.g. *decay BRs*) at $Q \sim m_H$

- High energy reach:
  - direct probes of BSM extensions of Higgs sector (e.g. SUSY)
  - Higgs decays of heavy resonances
  - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)

SUMMARY OF DIRECT HIGGS MEASUREMENTS - COMPARISON

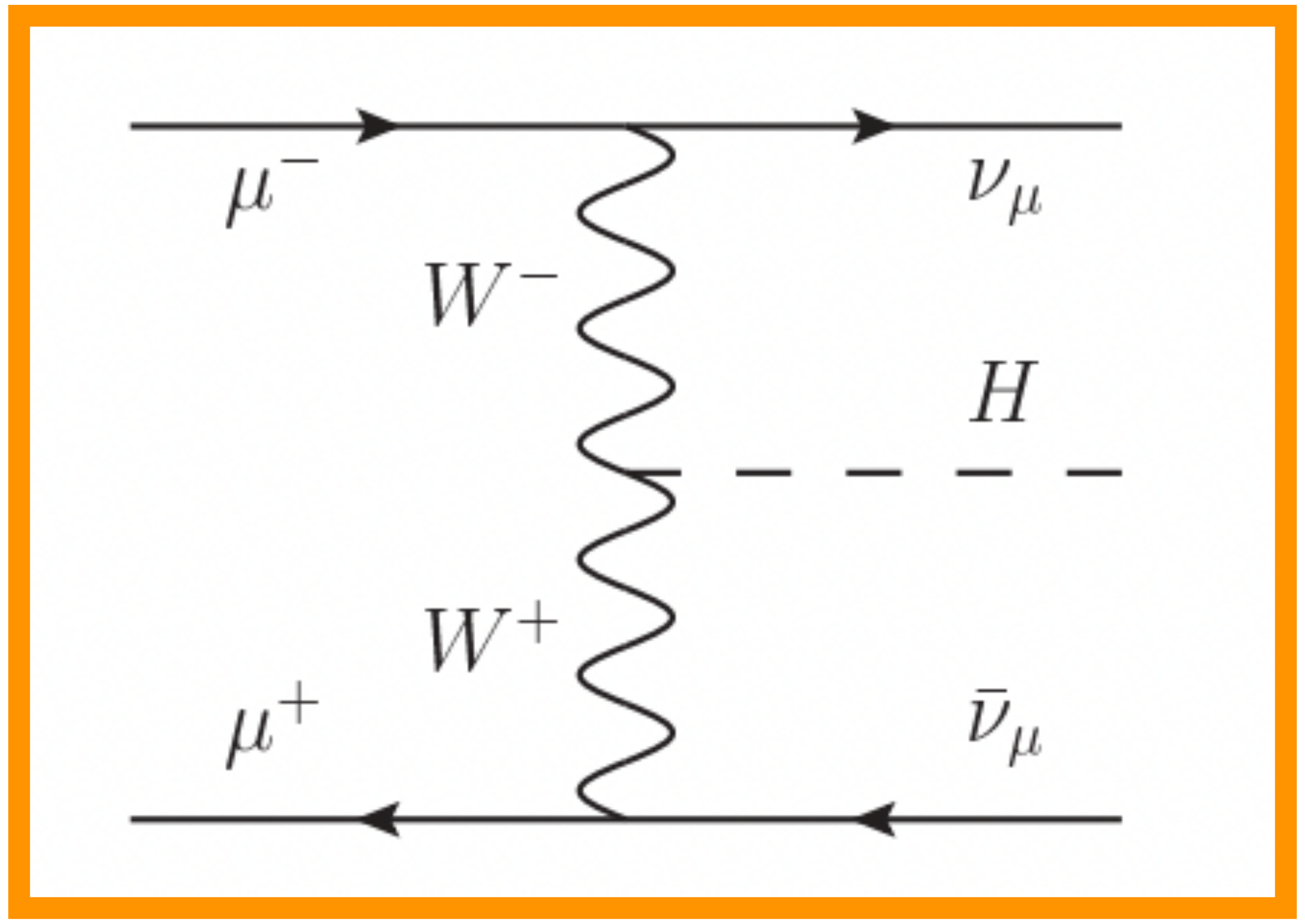
	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65** (*)
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4** (*)
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	**0.95** (**)
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.91** (*)
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**7**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

* From BR ratios wrt B(H→4l) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

HIGGS COUPLINGS AT A 10TEV MUON COLLIDER

- Main production process is the WW fusion



10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
W-fusion	bb	490	7.4	0.17
	cc	24	1.4	1.7
	jj	72	37	0.19
	$\tau^+\tau^-$	53	6.5	0.54
	$WW^*(jj\ell\nu)$	53	21	0.30
	$WW^*(4j)$	86	4.9	0.49
	$ZZ^*(4\ell)$	0.1	6.6	12
	$ZZ^*(jj\ell^+\ell^-)$	2.1	8.9	2.3
	$ZZ^*(4j)$	11	4.6	1.4
	$\gamma\gamma$	1.9	33	1.3
	$Z(jj)\gamma$	0.9	27	2.0
	$\mu^+\mu^-$	0.2	37	0.37
Z-fusion	bb	51	8.1	0.49
	$WW^*(4j)$	8.9	6.2	1.3
W-fusion tth	bb	0.06	12	12

MEASUREMENT OF A_{LR} (LEFT-RIGHT ASYMMETRY) AT SLC

➤ "Just" a counting experiment at the Z pole with a longitudinally polarized e^- beam

$$A_{LR} = \frac{\sigma(-P_e) - \sigma(+P_e)}{\sigma(-P_e) + \sigma(+P_e)} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e P_e \quad \text{with} \quad P_e = \frac{N^+ - N^-}{N^+ + N^-}$$

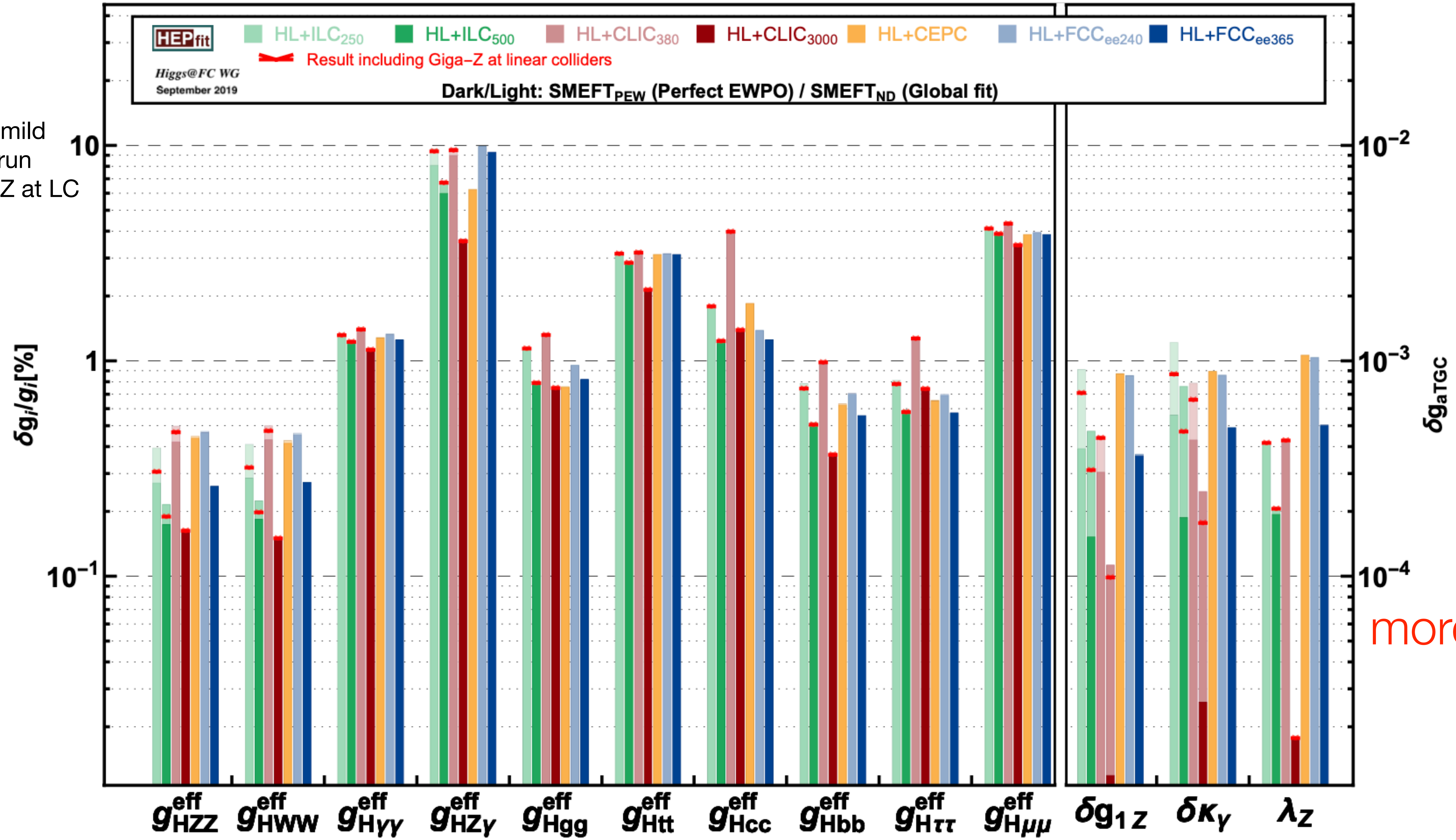
➤ Many advantages

- ➤ $A_{LR} = A_e \sim 14\%$ for a 100% polarized electron beam ($P_e = 1$)
  - ➤ i.e., almost 10 times more sensitive to $\sin^2\theta_W$ than $A_{FB}^{leptons} = \frac{3}{4} A_e A_l \sim 1.5\%$
- ➤ A_{LR} is independent of the final state
  - ➤ Use all Z decays into hadrons, $\tau^+\tau^-$, $\mu^+\mu^-$, e^+e^-
- ➤ A_{LR} is independent of the detector acceptance
  - ➤ Cancels in the ratio: just count the events with neg've and pos've P_e
- ➤ Most theoretical uncertainties cancel in the A_{LR} ratio

A LC achieve the same $\sin^2\theta_W$ precision of a CC with 100 times less statistics

IMPACT OF EWPO ON HIGGS COUPLINGS

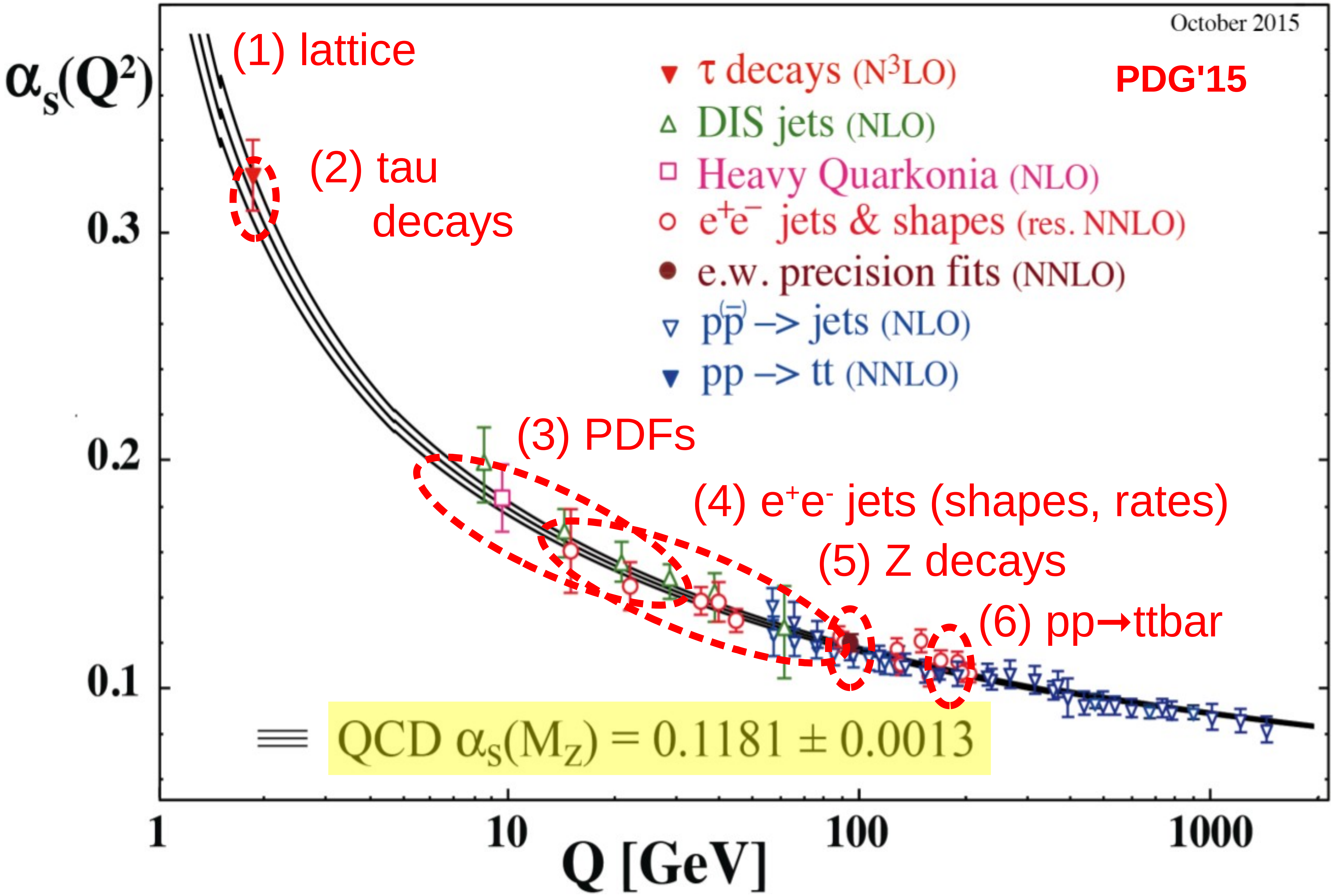
- FCC-ee/CEPC mild difference b/c Z run
- Red-line: Giga-Z at LC



more precise

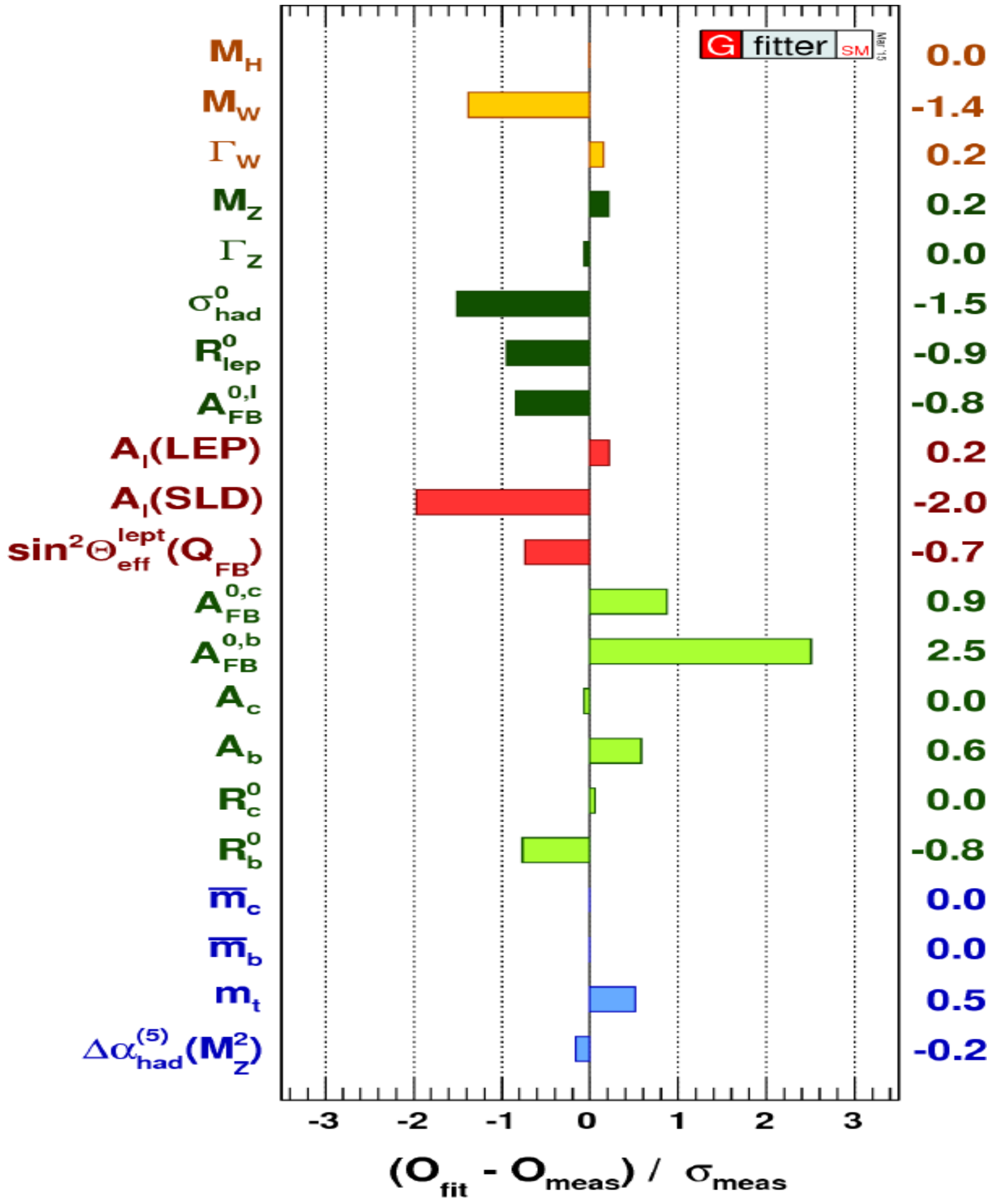
MEASUREMENT OF α_s

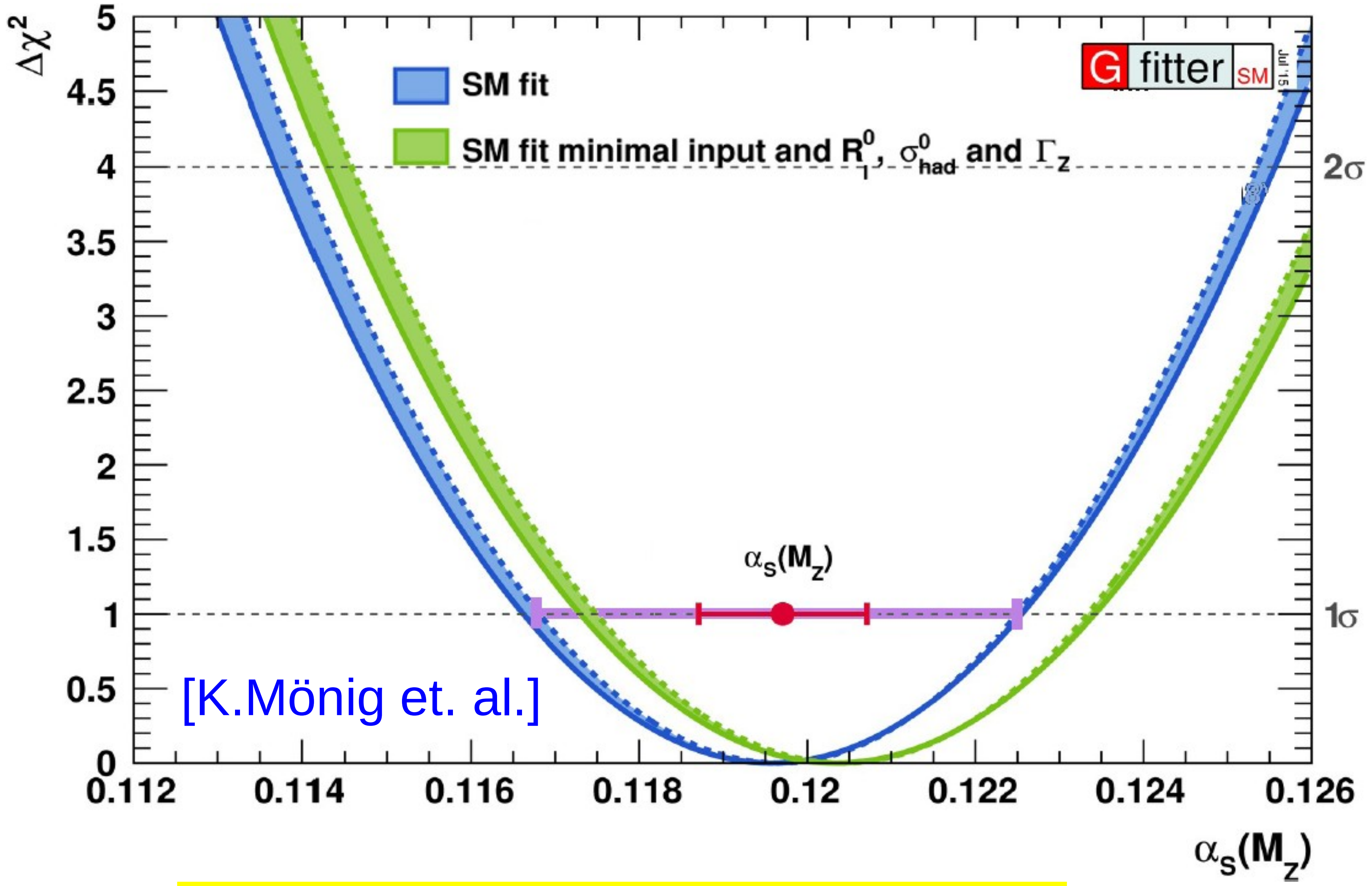
- Determines strength of the strong interaction between quarks & gluons
- Single free parameter in QCD (in the $m_q \rightarrow 0$ limit)
- Determined at a ref. scale ($Q=m_Z$), decreases as $\alpha_s \sim \ln(Q^2/\Lambda^2)^{-1}$, $\Lambda \sim 0.2$ GeV



α_s FROM HADRONIC Z DECAYS

- Computed at N^{3}LO: $R_Z \equiv \dfrac{\Gamma(Z \to h)}{\Gamma(Z \to l)} = R_Z^{EW} N_C \left(1 + \boxed{\sum_{n=1}^{4} c_n \left(\dfrac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5)} + \delta_m + \delta_{np}\right)$
- Experim.: Γ_Z = 2.4952±0.0023 GeV (±0.1%), $R_\ell^0 = \dfrac{\Gamma_{had}}{\Gamma_\ell}$, $\sigma_{had}^0 = \dfrac{12\pi}{m_Z}\dfrac{\Gamma_e \Gamma_{had}}{\Gamma_Z^2}$, $\sigma_\ell^0 = \dfrac{12\pi}{m_Z}\dfrac{\Gamma_\ell^2}{\Gamma_Z^2}$
- After Higgs discovery, α_s can be directly determined from full fit of SM:





$\alpha_s(M_Z) = 0.1196 \pm 0.0030$ (±2.5%)

- Prospects: – Huge Z stats at FCC-ee will lead to: $\delta\alpha_s$ < 0.3%
  – Improved parametric ($\sin^2\theta_{eff}$, m_W, m_t) and TH (N^{4}LO, EW, mixed) uncert.

Patrizia Azzi - Otranto 2022

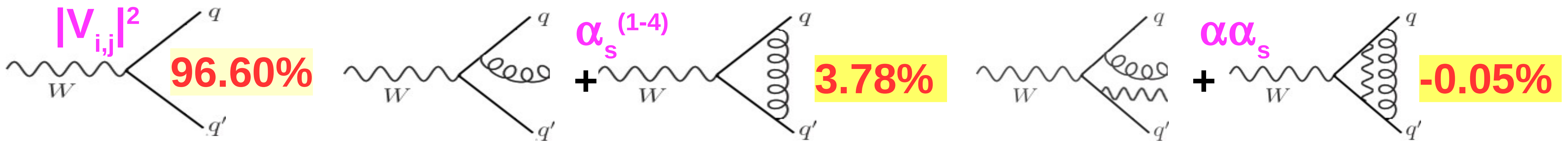
α_s FROM W HADRONIC DECAYS (NOT USED IN PDG YET)

[D.d'E, M.Srebre, arXiv:1603.06501]

- Width (BR) known at N³LO (NNLO). Small sensitivity to α_s (beyond Born)

$$\Gamma_{\rm W,had} = \frac{\sqrt{2}}{4\pi} G_{\rm F} m_{\rm W}^3 \sum_{\rm quarks\ i,j} |V_{\rm i,j}|^2 \left[1 + \sum_{k=1}^{4} \boxed{\left(\frac{\alpha_{\rm s}}{\pi}\right)^k} + \delta_{\rm electroweak}(\alpha) + \delta_{\rm mixed}(\alpha\alpha_{\rm s}) \right]$$

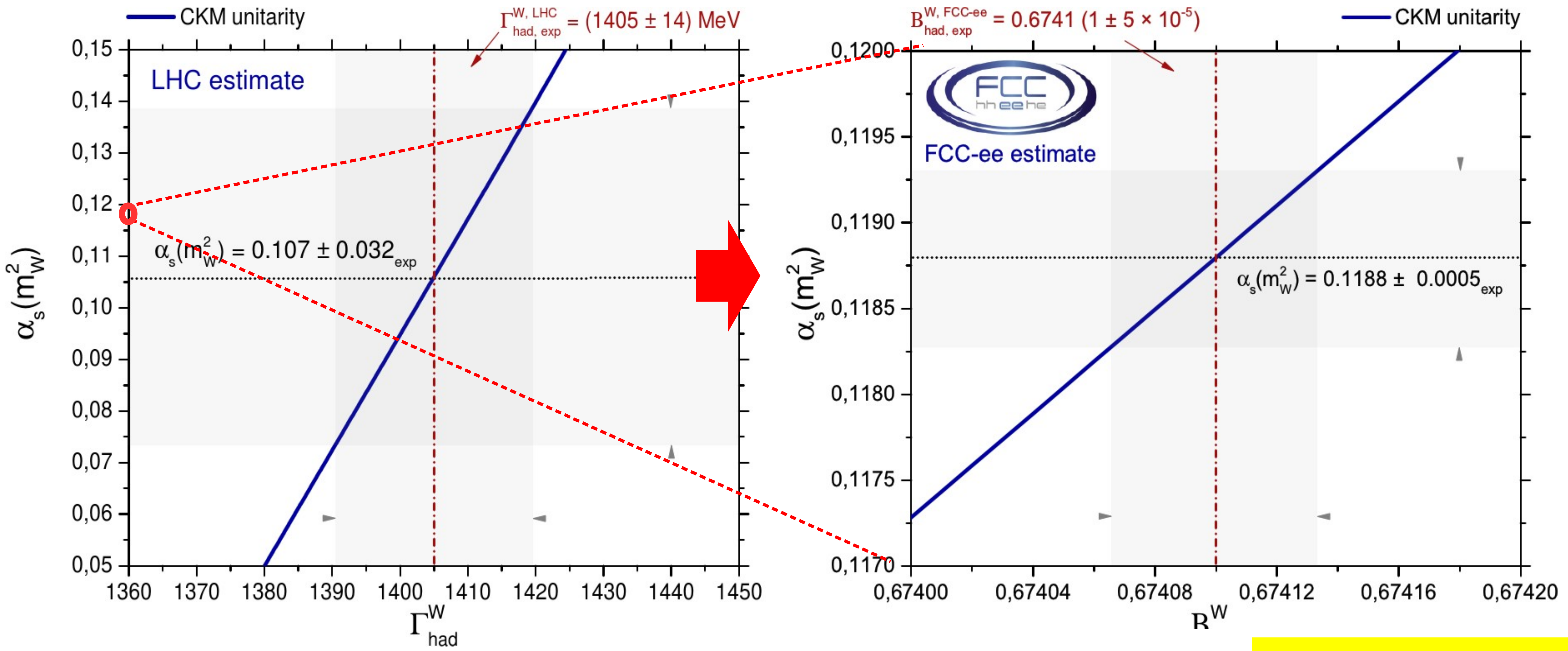
[EWK: -0.35%]



[D.d'E, M.Srebre, arXiv:1603.06501]

- LHC prospects:
  Improved measurement of Γ_W:
  $\delta\alpha_s \sim 10\%$

- FCC-ee prospects:
  Huge ee→WW stats (10^8, $\times 10^3$ LEP):
  $\delta\alpha_s < 0.2\%$

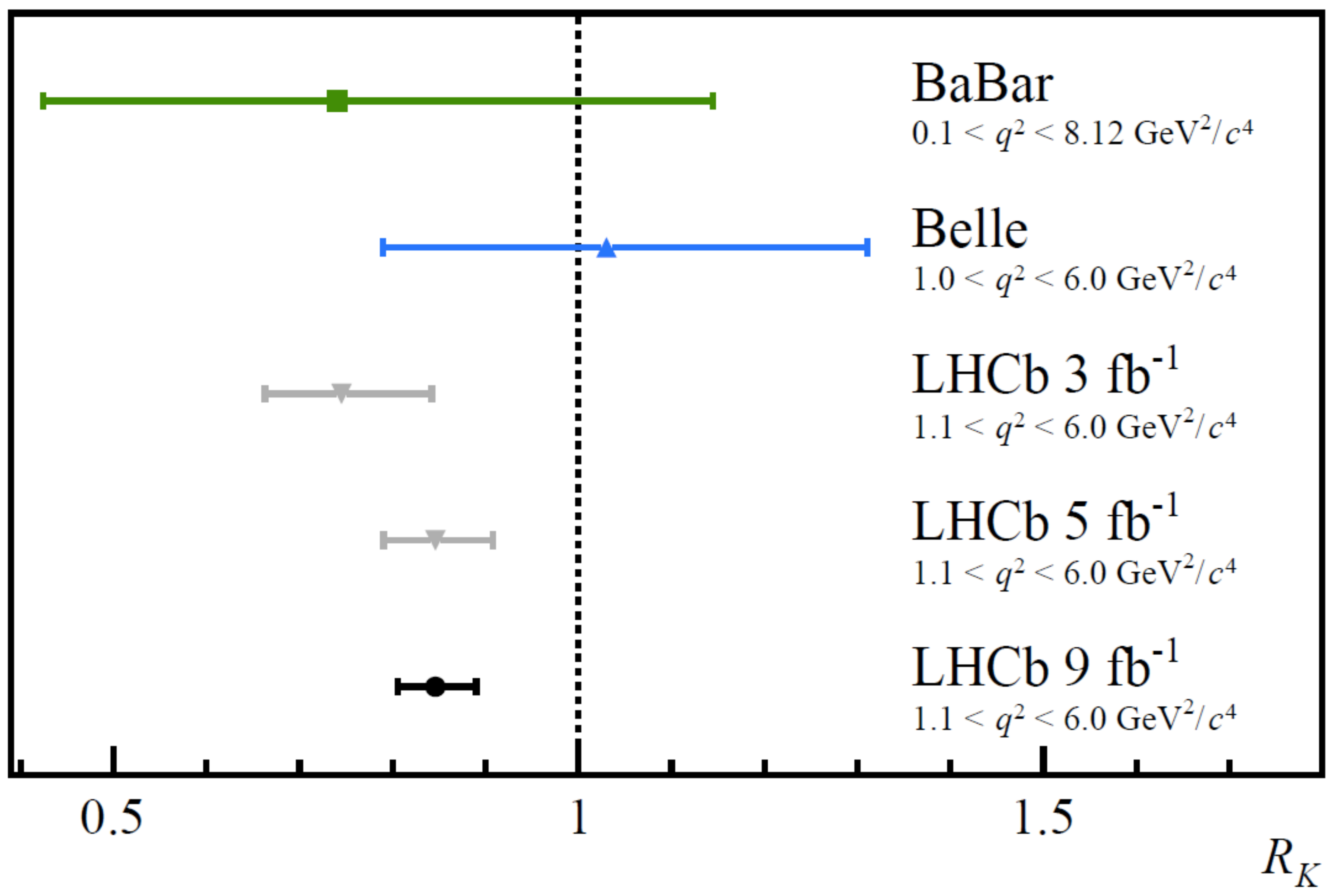


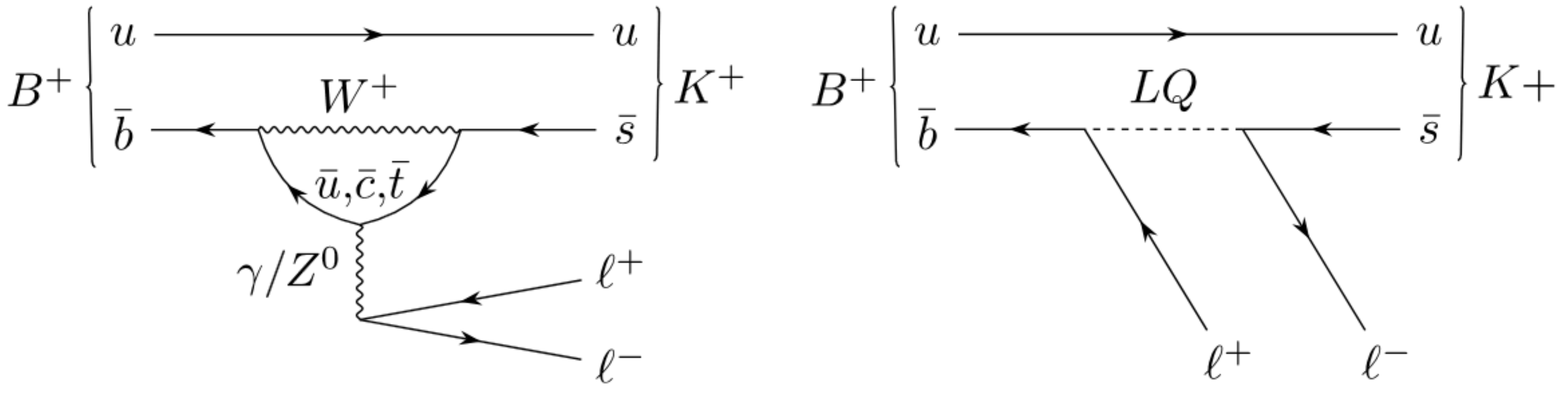
- Combined FCC-ee from W & Z decays: $\alpha_s(M_z) = 0.1190 \pm 0.0002$

$\delta\alpha_s$(exp) < 0.15%. Parametric ($V_{i,j}$, m_W) & TH uncert. to be improved too.

CURRENT TENSIONS IN FLAVOR PHYSICS (2021 UPDATE)

- Current tensions (3.1 σ deviations) of LHCb data with SM predictions (Moriond 2021)
- In particular, lepton flavour universality is challenged in b → s $\ell^+\ell^-$ transitions R_K
  - For example, the rates of B0 (B+) → K*0 (K+) $\ell^+\ell^-$ are different for ℓ = e and ℓ = μ
  - Differences are also observed in the lepton angular distributions
- This effect, if real, could be enhanced for ℓ = τ, in B → K(*) τ+τ−
  - With 10^{12} Z → bb, FCC-ee can solve this issue
  - Decay can be fully reconstructed
  - Full angular analysis possible





$$R_{K^{(*)}} = \Gamma(B \to K^{(*)}\mu^+\mu^-)/\Gamma(B \to K^{(*)}e^+e^-)$$

$$R_{D^{(*)}} = \Gamma(B \to D^{(*)}\tau\bar{\nu})/\Gamma(B \to D^{(*)}l\bar{\nu})$$

$$l = e, \mu$$