Top quark couplings at the FCC

OUTLINE

The FCC-ee : The top-quark electroweak couplings

- The physics programme of the FCC-ee
- Measuring the top electroweak couplings at the FCC-ee
- Sensitivity to new physics

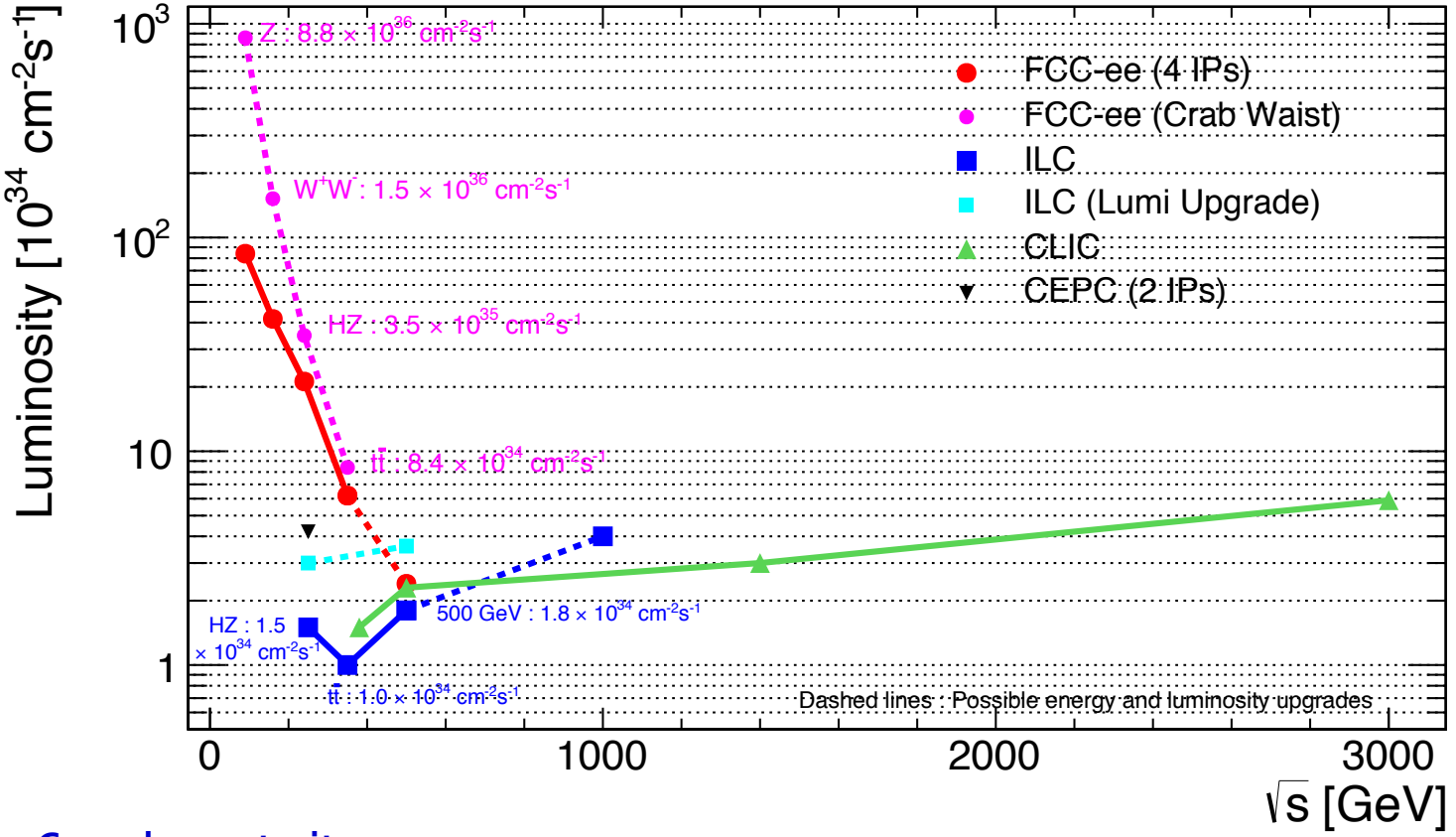
The FCC-hh : The top-quark Yukawa coupling

- Motivation and expected statistical accuracy
- Minimizing the systematic uncertainties with FCC-ee measurements

Conclusion

The physics programme of FCC-ee (1)

- **Performance targets for luminosity**



- **Complementarity**
  - **Ultimate precision measurements with circular colliders (FCC-ee)**
  - **Ultimate e^+e^- energies with linear colliders (CLIC)**

The physics programme of FCC-ee (2)

- **A very rich physics menu !**

See arXiV:1308.6176, "First Look at the Physics Case of TLEP"
FCC-ee physics meetings, https://indico.cern.ch/category/5259/

See also A. Blondel's poster

  - **Core physics programme**
    - **The Z pole scan, $\sqrt{s}$ = 88-95 GeV**
      - **m_Z, Γ_Z to < 100 keV, $\sin^2\theta_W$ to 5×10^{-6}, $\alpha_{QED}(m_Z)$ to 2×10^{-5}, $\alpha_s(m_Z)$ to 2×10^{-4}, …** — M. Dam's talk
      - **Rare decay/process searches and flavour physics with up to 10^{13} Z**
    - **The WW threshold scan, $\sqrt{s}$ = 160-165 GeV**
      - **m_W to 300 keV, $\alpha_s(m_Z)$ to 10^{-4}, …** — M. Dam's talk
    - **The Higgs factory, $\sqrt{s}$ = 240 GeV and above**
      - **Improve HL-LHC precision on Higgs couplings by an order of magnitude** — M. Klute's talk
      - **Measure the Higgs width to better than 1%, and BR_{invis} to 0.1%**
    - **The top threshold scan, $\sqrt{s}$ = 340-350 GeV**
      - **m_{top} to 10-20 MeV** — M. Dam's talk
    - **Set constraints on new physics scale to 100 (10) TeV if weakly (Higgs) coupled**

Well matched to FCC-hh discovery range

      - **Possibly discover very-weakly-coupled new physics through rare processes**
  - **And also …**

This talk

    - **Top electroweak couplings at $\sqrt{s}$ = 365-370 GeV** (as part of the top threshold scan)
    - **The Hee coupling at $\sqrt{s}$ = 125 GeV** — M. Klute's talk
    - **The highest centre-of-mass energy $\sqrt{s}$ = 500 GeV (physics case ?)**

The physics programme of FCC-ee (3)

- **Time needed to achieve this ambitious programme**
  - Number of events expected for each year of running at the FCC-ee

Top couplings ?

√s (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 (tt)	350+ (WW→H)
Lumi (ab^{-1}/yr)	86.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}

  - Number of years needed to complete the core programme $N_Z=10^{(12)13}$

1 year = 10^7 s

# years	(0.3) 2.5	1	3	0.5	3

  - The FCC-ee core programme can be completed in about 8 to 10 years
  - Today, comparisons will be made with the design "H20" scenario for the ILC

R. Poeschl's talk

  - LC = 500 fb^{-1} @ 500 GeV (4y), 200 fb^{-1} @ 350 GeV (1y), 500 fb^{-1} @ 250 GeV (3y)

See arXiV:1506.07830 "ILC Operating Scenarios"

with ±80% / ±30% polarization for e^-/e^+ beams

(*) Optional : 100 fb^{-1} @ 90 GeV (~2y?), 500 fb^{-1} @ 160 GeV (~3y?)

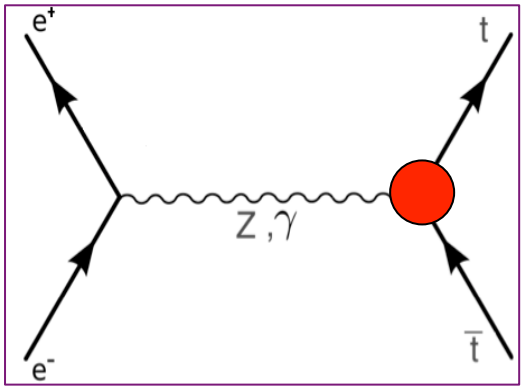
~ 13 years
1 y = 1.6×10^7 s

Events@ILC	3×10^{9} (*)	2×10^{6} (*)	1.4×10^{5}	10^{5}	3.5×10^{4}
ILC @ FCC-ee	< 1 day	< 1 week	1 month	2 months	1 year

  - About one year is needed at the FCC-ee to complete the full ILC precision physics programme

Top Electroweak Couplings at FCC-ee

- **This measurement was originally not part of the FCC-ee core programme**
  - Indeed, the measurement of the top electroweak couplings was claimed — ILC TDR
    - To require $\sqrt{s}$ significantly above the top threshold
    - To require incoming beam polarization
  - This claim was recently revisited for FCC-ee — arXiV:1503.01325 "Top EW Couplings at the FCC-ee"
    - With no incoming beam polarization
    - With a centre-of-mass energy limited to $\sqrt{s} < 500$ GeV



$t\bar{t}$

  - At FCC-ee, the final state top quarks are produced with non-zero polarization (ttZ)
    - The top polarization (and the total rate) depend on the ttZ/γ couplings
    - The top polarization is maximally transferred to the top decay products t → Wb
      - Affect the energy and angular distributions of these decay product

      Similar to τ polarization in $Z \to \tau^+\tau^-$ events at LEP

  - Today, examine the lepton energy and angular distributions from semi-leptonic events

$$e^+e^- \to t\bar{t} \to \ell\nu b\bar{b}q\bar{q}$$ as a function of $\sqrt{s}$

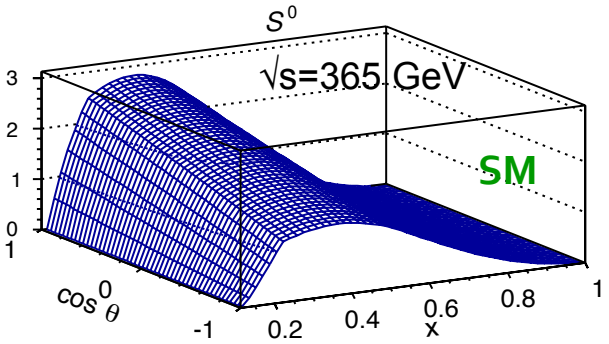
Lepton energy and angular distributions

- **Parameterization of the ttV vertex (V = Z, γ)**

B. Grzadkowski, Z. Hioki, hep-ph/0004223

$$\Gamma^{\mu}_{vt\bar{t}} = \frac{g}{2}\bar{u}(p_t)\left[\gamma^{\mu}\{A_v + \delta A_v - (B_v + \delta B_v)\gamma_5\} + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}(\delta C_v - \delta D_v\gamma_5)\right]v(p_{\bar{t}})$$

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}\cos\theta} =$$



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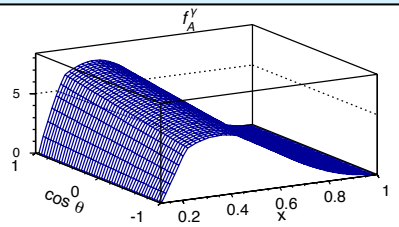
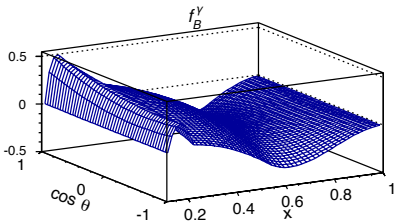
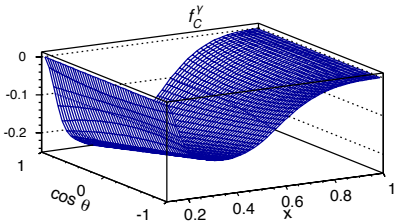
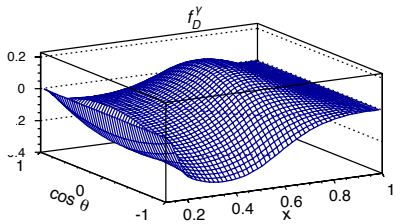
$\delta A_\gamma \times$ 

$\delta B_\gamma \times$ 

$\delta C_\gamma \times$ 

$\delta D_\gamma \times$ 

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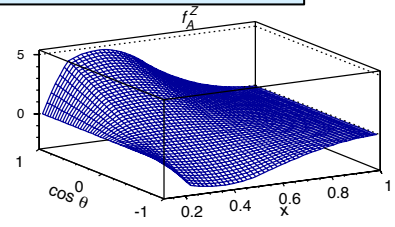
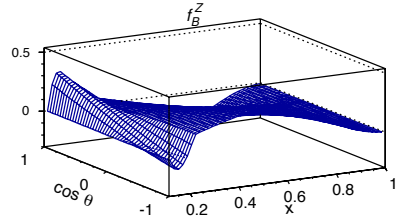
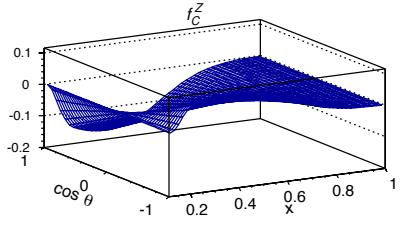
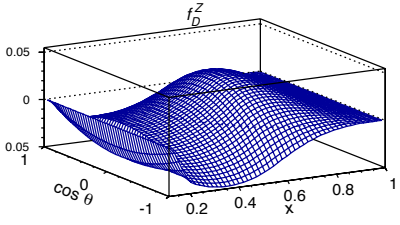
$\delta A_Z \times$ 

$\delta B_Z \times$ 

$\delta C_Z \times$ 

$\delta D_Z \times$ 

$\delta A_V = \delta B_V = \delta C_V = \delta D_V = 0$

$$x_f \equiv \frac{2E_f}{m_t}\sqrt{\frac{1-\beta}{1+\beta}} \qquad \beta\left(\equiv\sqrt{1-4m_t^2/s}\right)$$

Statistical accuracy on anomalous couplings

- **From a likelihood fit to the lepton angular/energy distributions (+ σ_{tot})**
  - FCC-ee benefits from large integrated luminosity : ~2.6 ab^{-1} in 3 years at $\sqrt{s}$ = 365 GeV
    - 1.6 million top pairs in 3 years at FCC-ee
      - ➨ To be compared to 400,000 top pairs with 500 fb^{-1} at $\sqrt{s}$ = 500 GeV
      - ➨ Compensates for the lack of incoming beam polarization
  - Absolute resolutions expected at FCC-ee with leptons only, or with b jets only
    - Under the same hypotheses as in Roman Poeschl's presentation

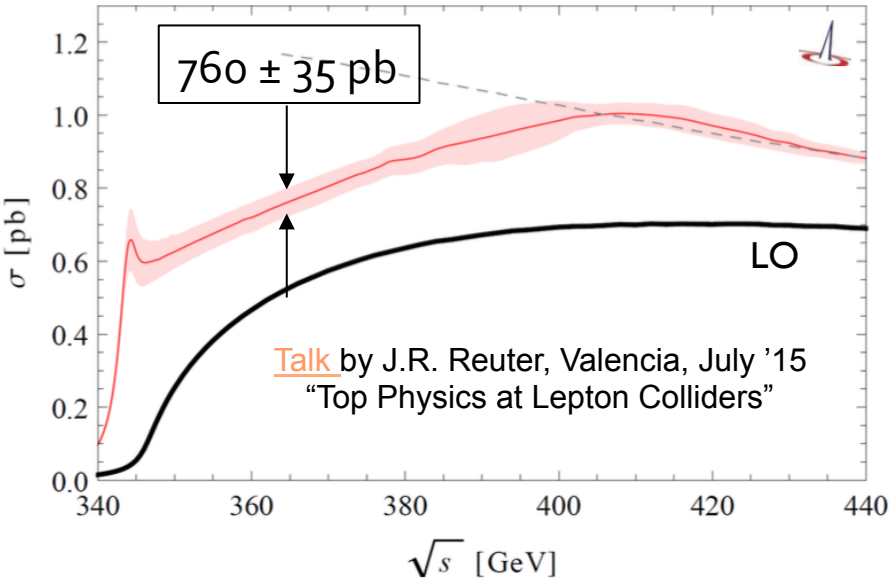
$$gA_{\gamma,Z} = 2e(F_{1V}^{\gamma,Z} + F_{2V}^{\gamma,Z}) \qquad gB_{\gamma,Z} = 2eF_{1A}^{\gamma,Z} \qquad gC_{\gamma,Z} = 2eF_{2V}^{\gamma,Z}$$

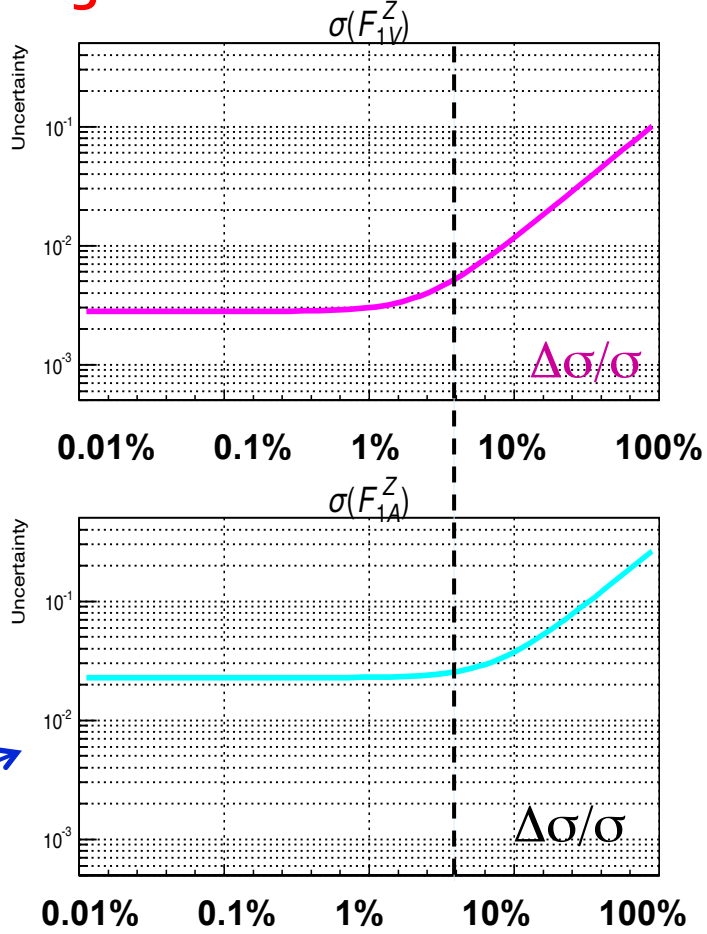
Coupling	$\sigma(F_{1V}^{\gamma})$	$\sigma(F_{1V}^{Z})$	$\sigma(F_{1A}^{\gamma})$	$\sigma(F_{1A}^{Z})$	$\sigma(F_{2V}^{\gamma})$	$\sigma(F_{2V}^{Z})$
Leptons	1.1×10^{-3}	2.8×10^{-3}	1.2×10^{-2}	2.3×10^{-2}	0.8×10^{-3}	2.2×10^{-3}
b jets	1.2×10^{-3}	5.7×10^{-3}	1.5×10^{-2}	1.1×10^{-2}	1.2×10^{-3}	5.7×10^{-3}

  - Very conservative lepton ID efficiencies and angular / momentum resolutions were used
    - A full simulation study is needed to confirm b-jets numbers
      - ➨ In progress as we speak: will allow leptons and b-jets to be combined

Dominant systematic uncertainty : σ_{tot}

- **Top-pair cross section theoretical uncertainty might be sizeable**
  - Especially just above the top threshold
    - $\sqrt{s}$ = 365 GeV is only 20 GeV above threshold
      - ➨ Estimated total uncertainty today: ~ ±4%



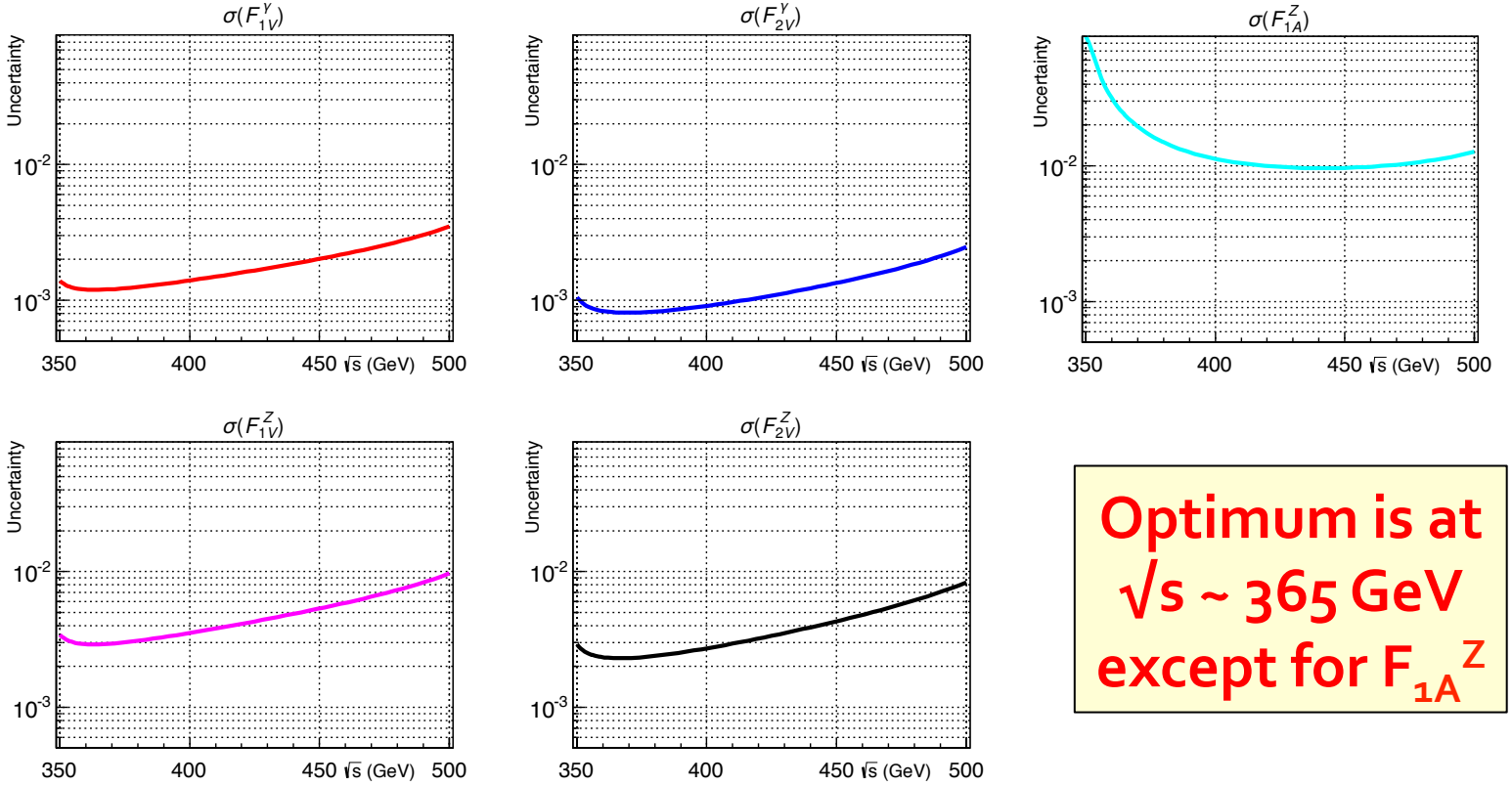


  - Example: Effect on $\sigma(F_{1V}^{Z})$ and $\sigma(F_{1A}^{Z})$

- The theoretical prediction of the top-pair cross section must be controlled to a few %
  - We are almost there today – what will it be when FCC-ee runs at $\sqrt{s}$ = 365 GeV (~2040) ?

What about larger √s ?

- **FCC-ee can in principle reach √s = 500 GeV with three times more RF**
  - **Three years at 365 (500) GeV are worth 2.6 ab^{-1} (500 fb^{-1}) – See slide 2.**
    - **Evolution of the absolute resolutions expected at FCC-ee as a function of √s :**



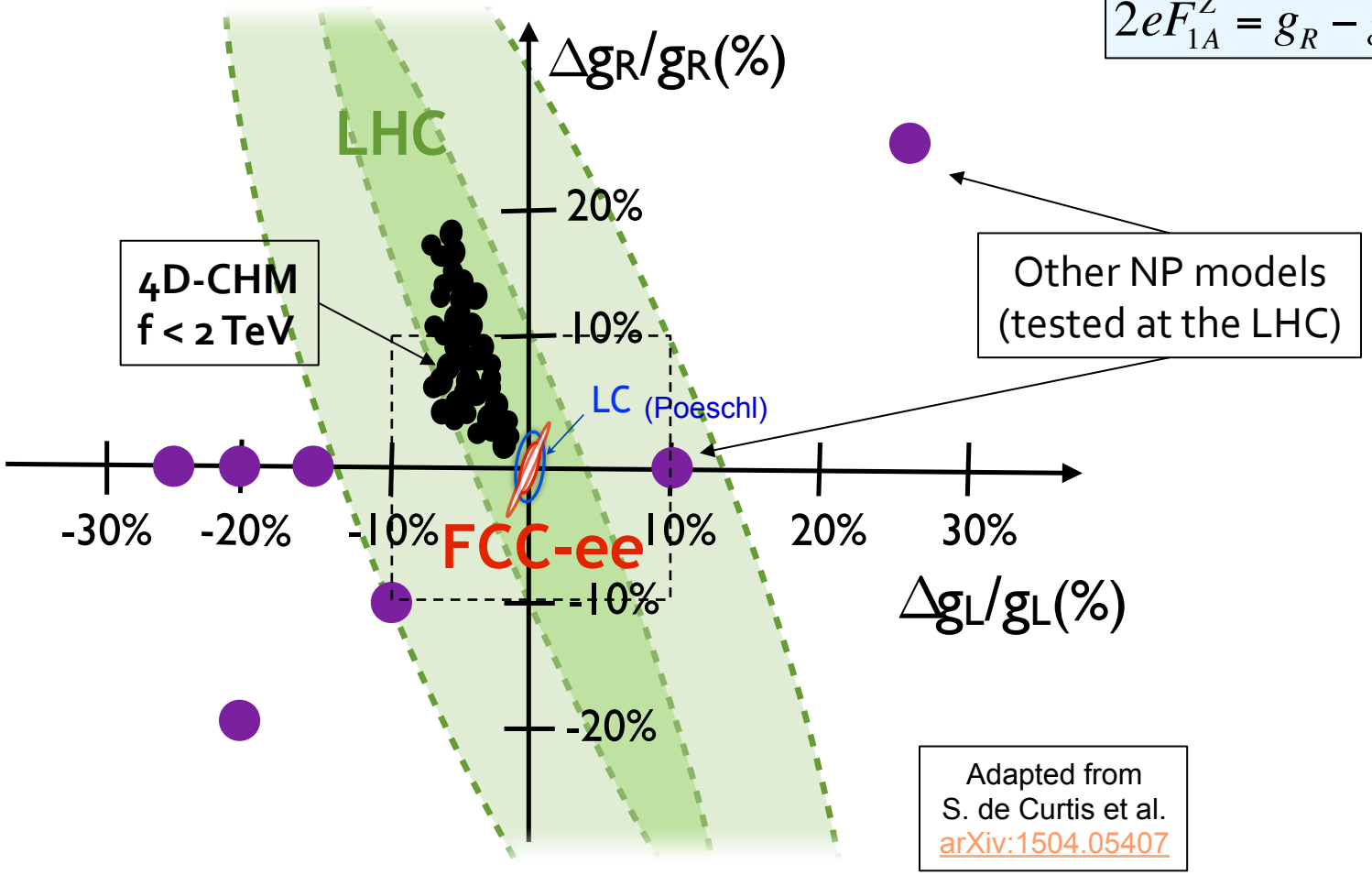
Optimum is at √s ~ 365 GeV except for F_{1A}^{Z}

  - **No physics case (at least from top studies) justifying a larger centre-of-mass energy**

Sensitivity to New Physics (1)

- Example: $t_L t_L Z$ and $t_R t_R Z$ couplings, g_L and g_R
  - Couplings most sensitive to composite Higgs models

$$2eF_{1V}^{Z} = g_R + g_L$$
$$2eF_{1A}^{Z} = g_R - g_L$$



Adapted from
S. de Curtis et al.
arXiv:1504.05407

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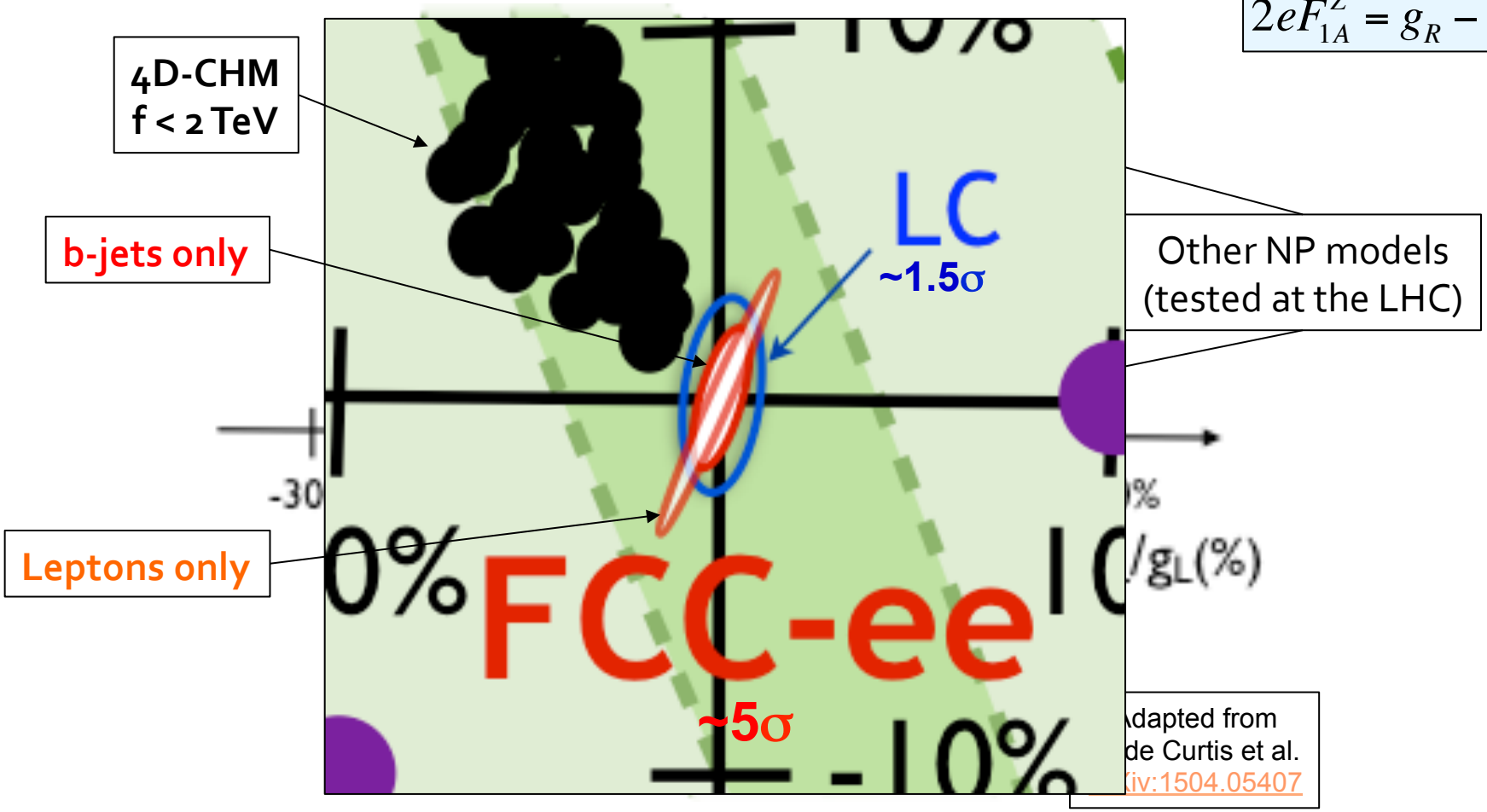
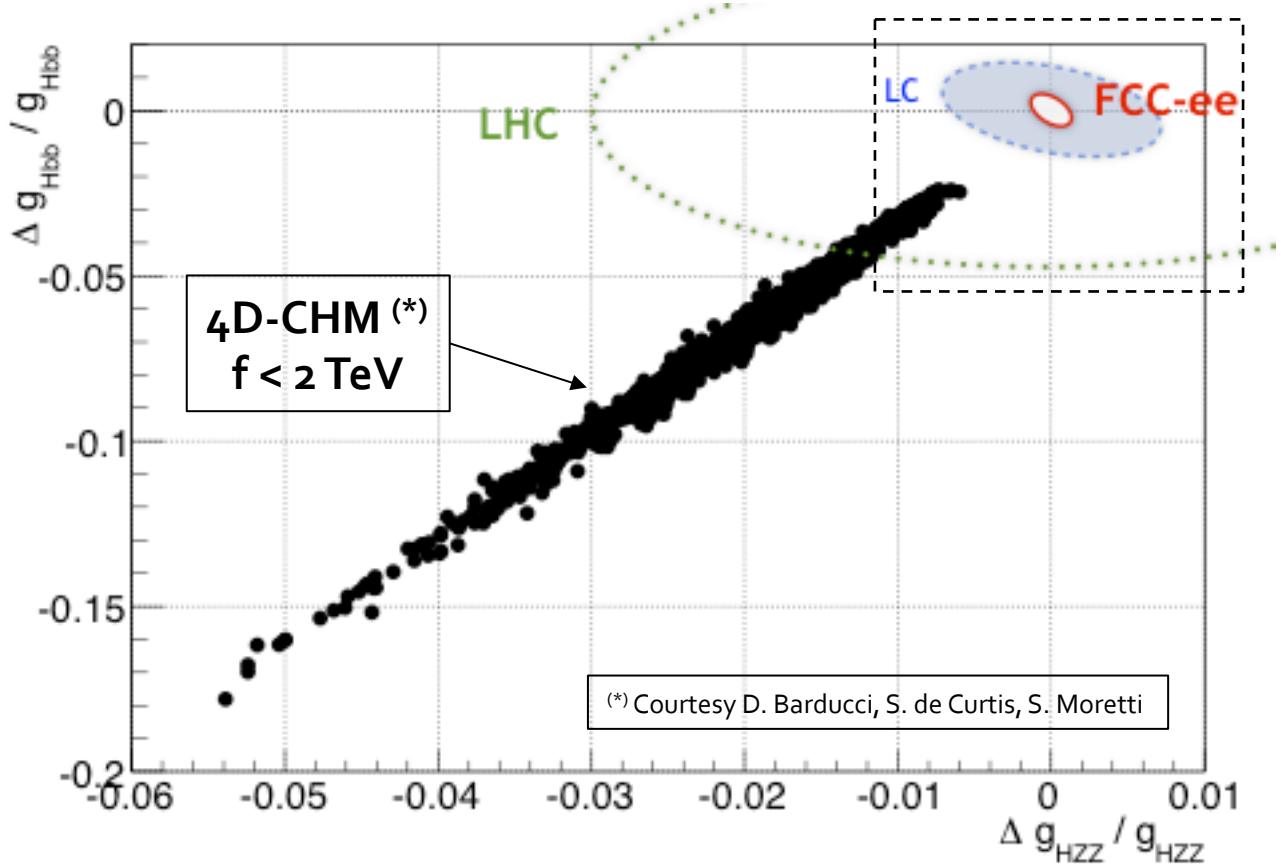


Sensitivity to New Physics (2)

- **Composite Higgs models also affect Higgs couplings**
  - **Example: Effect on g_{HZZ} and g_{Hbb} for the same set of 4D-HCM as in previous slide**



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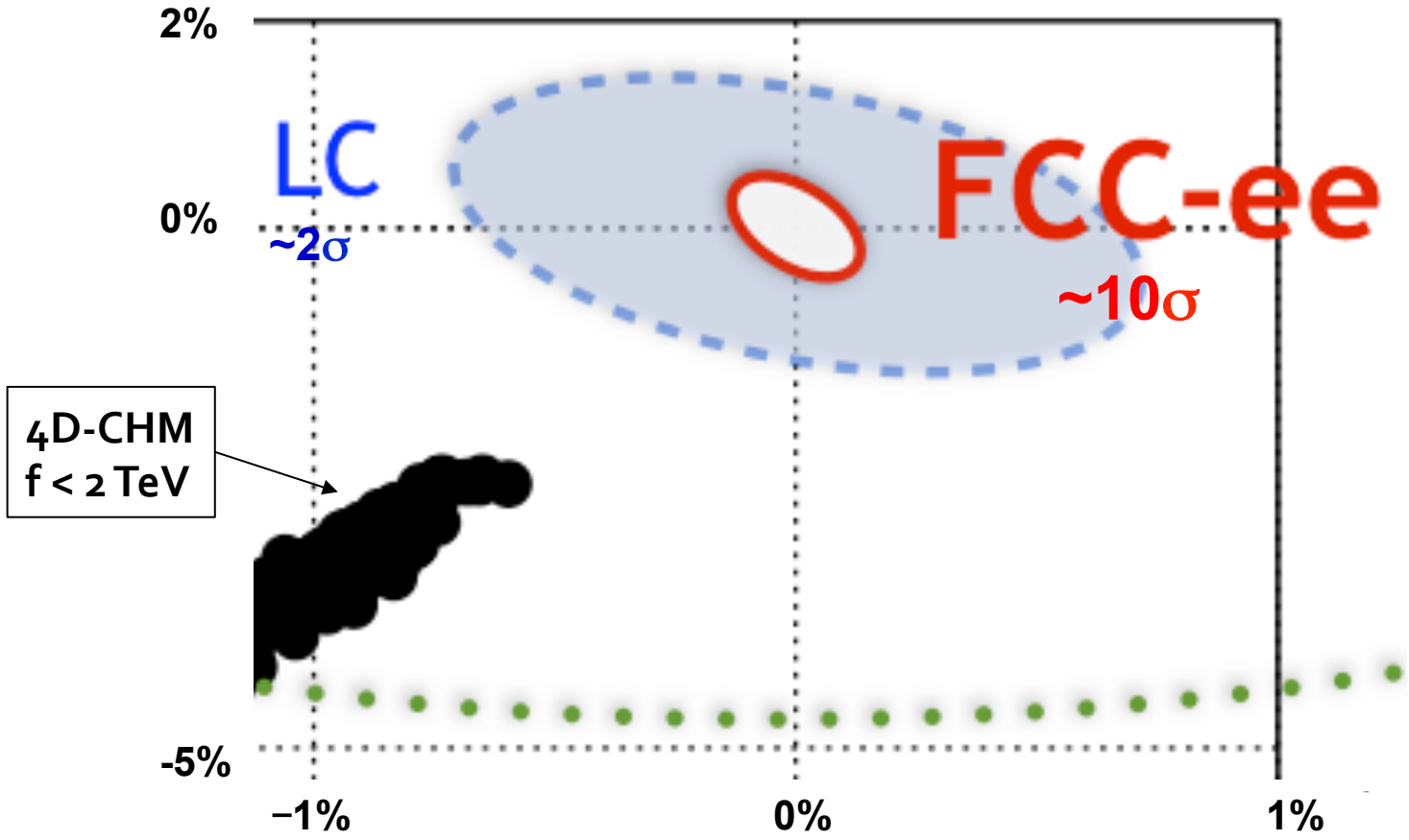
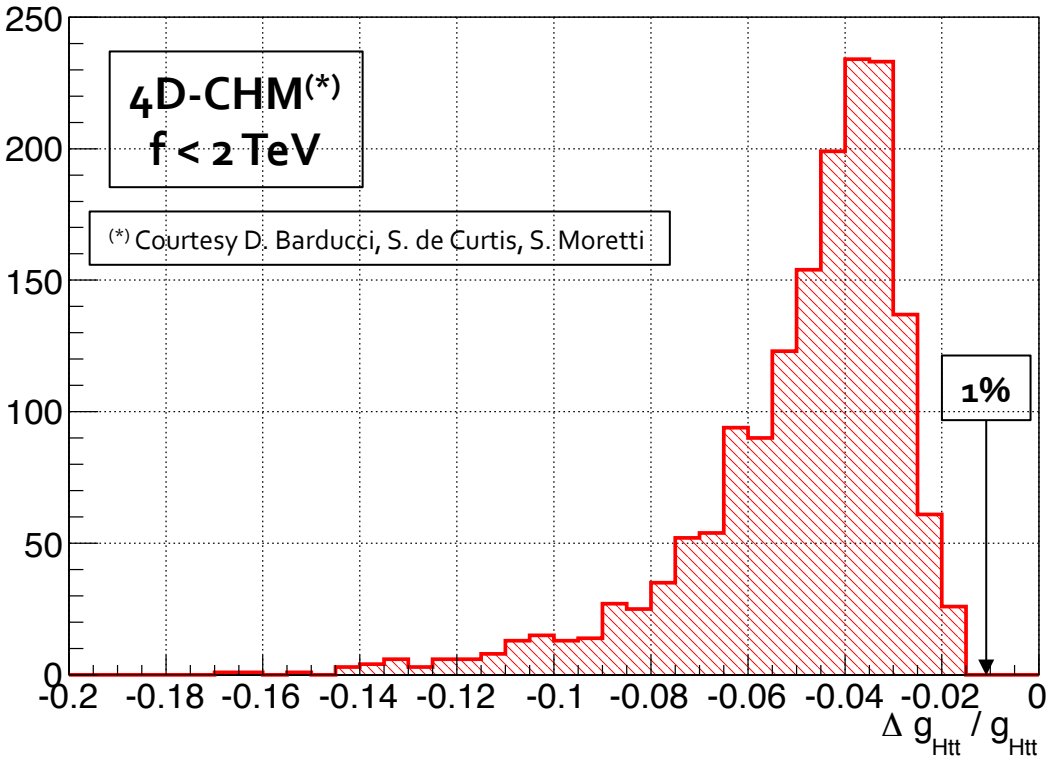
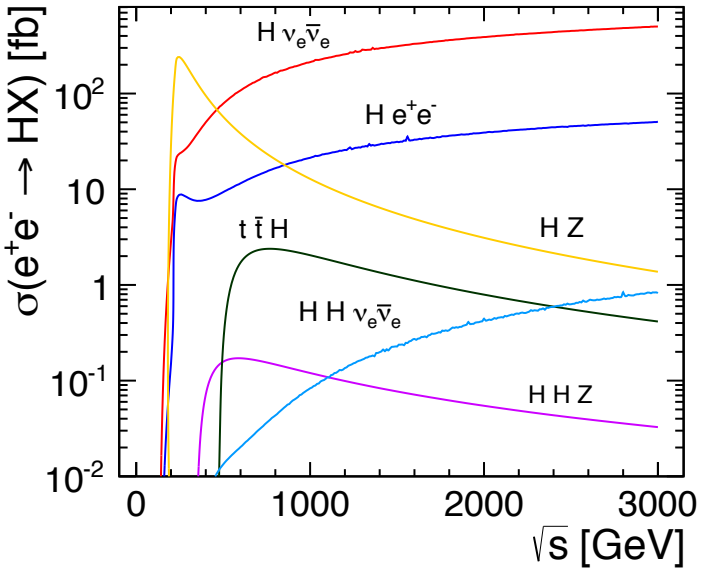


  - Better separation from the standard model than with the ttZ couplings

The top Yukawa coupling (1)

- **New physics is also expected to show up in the ttH coupling**
  - For our set of Higgs composite models, effect of the same size as for Hbb
    - Would need a ttH coupling measurement with a precision much better than 1%
      - ➨ A case for e^+e^- collisions at significantly higher energy ?





The top Yukawa coupling (2)

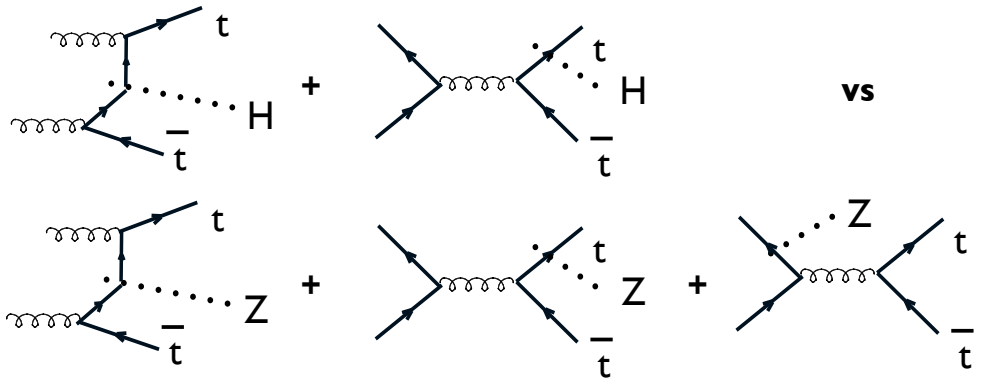
- **Measurement already possible at FCC-ee with the top threshold scan**
  - **But the accuracy on the ttH coupling limited to ~10%**
- **FCC-hh, as ultimate goal for the FCC, is much better suited**

Parameter	LHC	HL-LHC	FCC-hh
√s (TeV)	14		100
Circumference (km)	26.7		100 (80)
Dipole field (T)	8.3		16 (20)
Luminosity (10^{34} $cm^{-2}s^{-1}$)	1	5	5 [→ 30]
Integrated Lumi (ab^{-1})	0.3	3	3 [→ 30]
Bunch spacing (ns)	25		25 {5}
Events / bunch crossing	35	140	170 {34} [→ 1020 {204}]
Total SR Power (MW)	0.007	0.015	5 [→ 30]
σ(gg → ttH)	0.62 pb	0.62 pb	37.8 pb (10^9 events)

  - **Precision at LHC (Run1) ~ 50%**
    - **Statistical precision not an issue for FCC-hh (~0.1%)**

The top Yukawa coupling (3)

- **ttH coupling @ FCC-hh**
  - Measurement of λ_t with $\sigma(ttH) / \sigma(ttZ)$, with H → ZZ, WW, ττ (and bb, γγ)
    - Very similar production mechanism, gg production dominant



$$\frac{\sigma(ttH)}{\sigma(ttZ)} \approx \frac{\lambda_t^2}{\left(F_{1V}^Z\right)^2 + \left(F_{1A}^Z\right)^2}$$

    - Most theory uncertainties cancel: < 1% precision possible on $\sigma(ttH) / \sigma(ttZ)$
      - Denominator given by FCC-ee with a precision of 1.5%
      - Higgs boson BR's given by FCC-ee with a precision of a few 0.1%
  - Summary (together with Higgs self-coupling @ FCC-hh with gg → HH → bbγγ)

Collider	HL-LHC	LC	LC 1-3TeV	FCC-ee+hh
λ_t	4%	14%	2-4%	**<1%**
λ_H	50%	83%	10-15%	**5%**

Summary

- The top electroweak couplings can be precisely(*) measured at the FCC-ee
  - A centre-of-mass energy of 365 GeV is optimal
  - Large integrated luminosity more than compensates the lack of beam polarization
- The top Yukawa coupling can be precisely(*) measured at the FCC-hh
  - In combination with the the Higgs and top EW couplings
    - Precisely(*) measured at the FCC-ee
- Sensitivity to new physics is to be evaluated with a global fit
  - To the measured Z, W, H and top properties at the FCC-ee and FCC-hh
    - Indeed, anomalous top couplings also affect Z and W at quantum level

The combination of FCC-ee and the FCC-hh offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market.

First look at The Physics Case of TLEP
arXiv:1308.6176v2 [hep-ex] 22 Sep 2013

(*) to 1% or better