Higgs measurements at the FCC-hh

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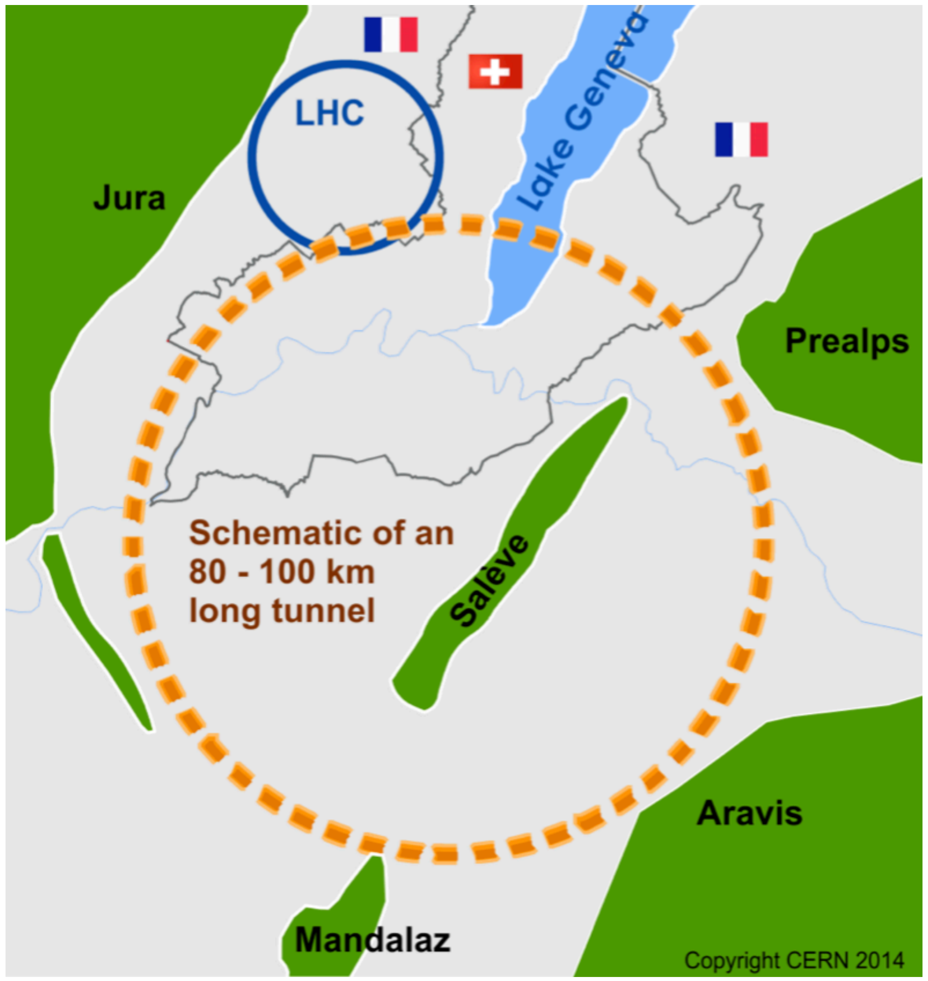
CERN

ICHEP '20

The FCC project



Within the FCC collaboration (CERN as host lab), 5 main accelerator facilities have been studied:

- pp-collider (FCC-hh)
  - defines infrastructure requirements
  - 16 T → 100 TeV in 100 km tunnel
- ee-collider (FCC-ee):
  - as a (potential) first step
- ep collider (FCC-eh)
- HE-LHC :
  - 27 TeV (16T magnets in LHC tunnel)
- Low E FCC-hh
  - 100 km - 6T - 37 TeV

CERN-FCC-PHYS-2019-0001

CDRs and European Strategy documents have been made public in Jan. 2019

https://fcc-cdr.web.cern.ch/

Why measuring Higgs @FCC-hh ?

- 100 TeV provides **unique and complementary measurements** to e+e- colliders:
  - Higgs **self-coupling**
  - **top Yukawa**
  - **Higgs → invisible**
  - **rare decays** (BR(μμ), BR(Zγ), ratios, ..) measurements will be **statistically limited** at FCC-ee

- Assuming, we know production xsec and luminosity, at pp colliders we **measure BR(i) = Γ_i / Γ_H**

Need to improve

	HL-LHC	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM	1.3
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	0.17
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	0.43
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	0.61
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	1.21
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	1.01
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	0.74
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–
$\delta g_{HHH} / g_{HHH}$ (%)	50	40
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%

- By performing measurements of ratios of couplings, (or BRs), FCC-ee allows to "convert" **relative measurements into absolute** via **HZZ**

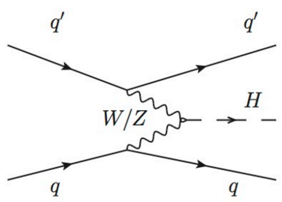
$$BR(H\to XX) / BR(H\to ZZ) \approx g_X^{\,2} / g_Z^{\,2}$$

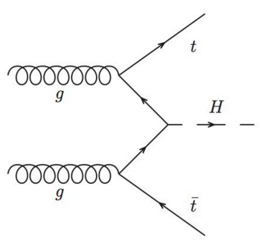
FCC-ee

Why Higgs at FCC-hh?

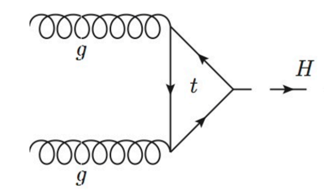
- Large Higgs production rates (x20-60 cross-section wrt to LHC):
  - access (very) rare decay modes (eg. 2nd gen,), complementary to ee colliders
  - push to %-level Higgs self-coupling measurement
- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst. uncertainties (TH and EXP)
  - 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?)

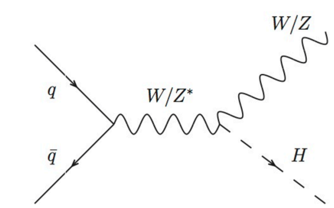
Single Higgs production @FCC-hh





	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N³LO)	49 pb	803 pb	16
VBF (N²LO)	3.8 pb	69 pb	16
VH (N²LO)	2.3 pb	27 pb	11
ttH (N²LO)	0.5 pb	34 pb	55





Expected improvement at FCC-hh:

- **20 billion Higgses** produced at FCC-hh
- **factor 10-50** in cross sections (and Lx10)
- reduction of a **factor 10-20 in statistical** uncertainties

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$
$N_{8} = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$
$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

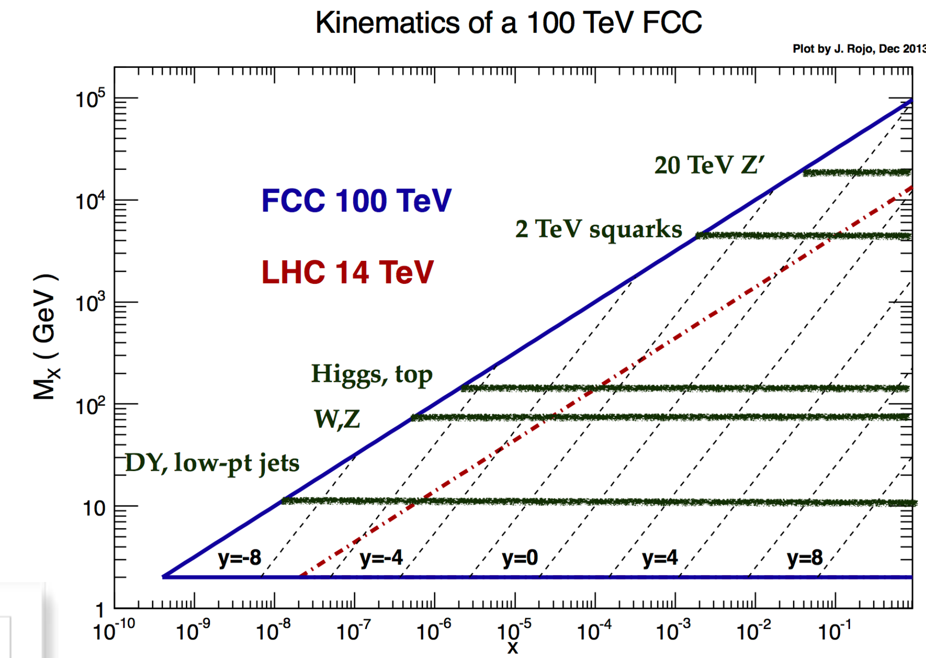
	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

Factor: 1/100 1/10
reduction in stat. unc.

Large statistics will allow:

- for % - **level precision in statistically limited** rare channels (μμ, Zγ)
- in **systematics limited** channel, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

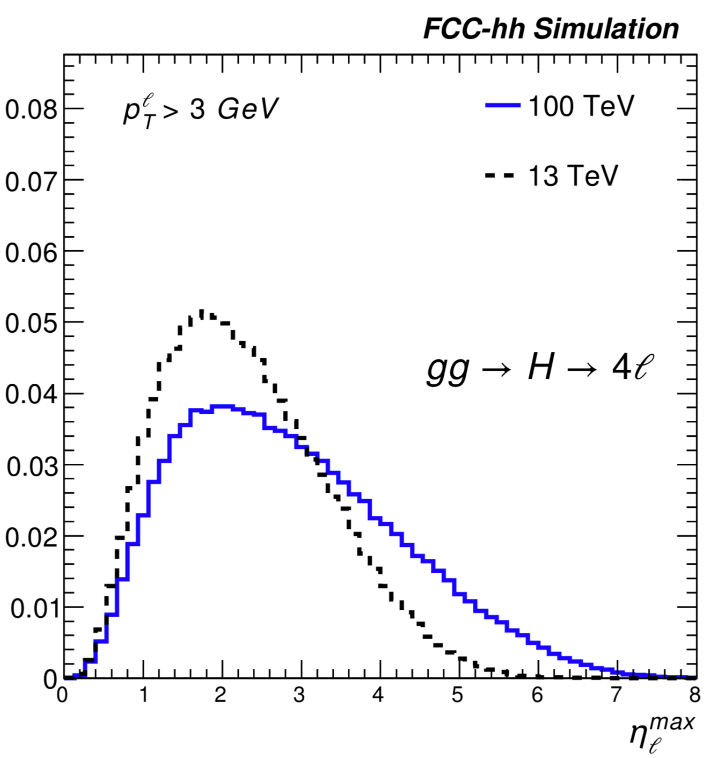
Higgs @threshold

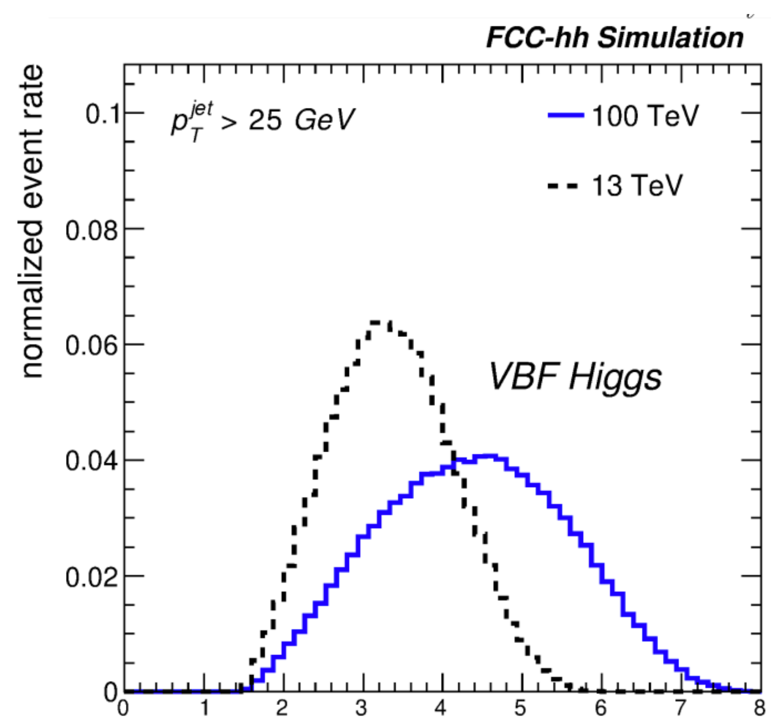


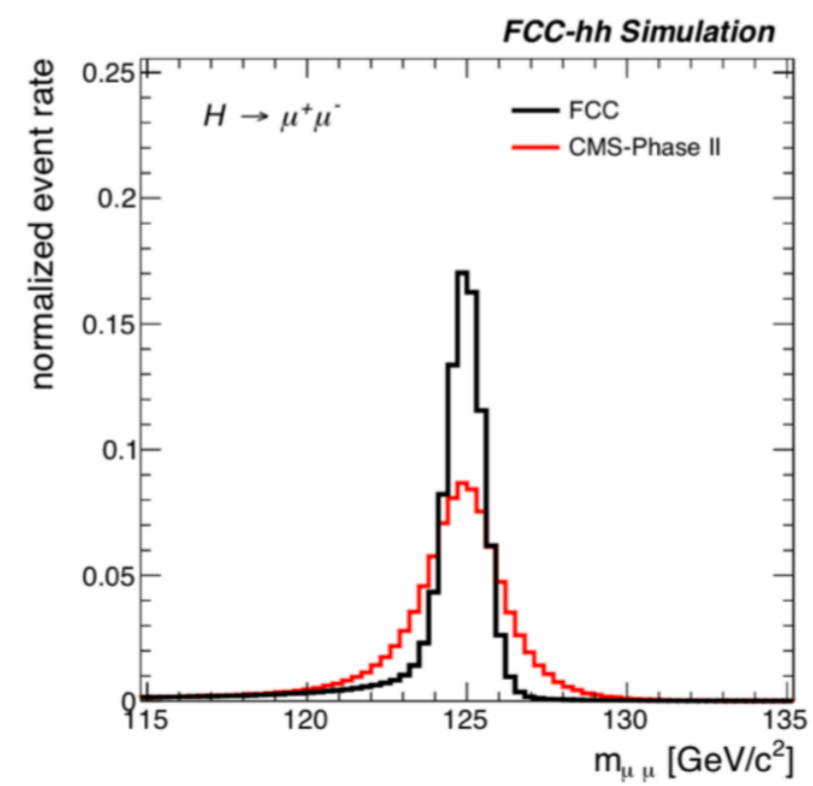
SM Physics produced at threshold is more forward @100TeV

→ in order to maintain sensitivity need **large rapidity** (with tracking) and **low p_T** coverage

- Goals:
  - **Precision spectroscopy** and calorimetry up to |η| < 4
  - Tracking and calorimetry up to |η| < 6

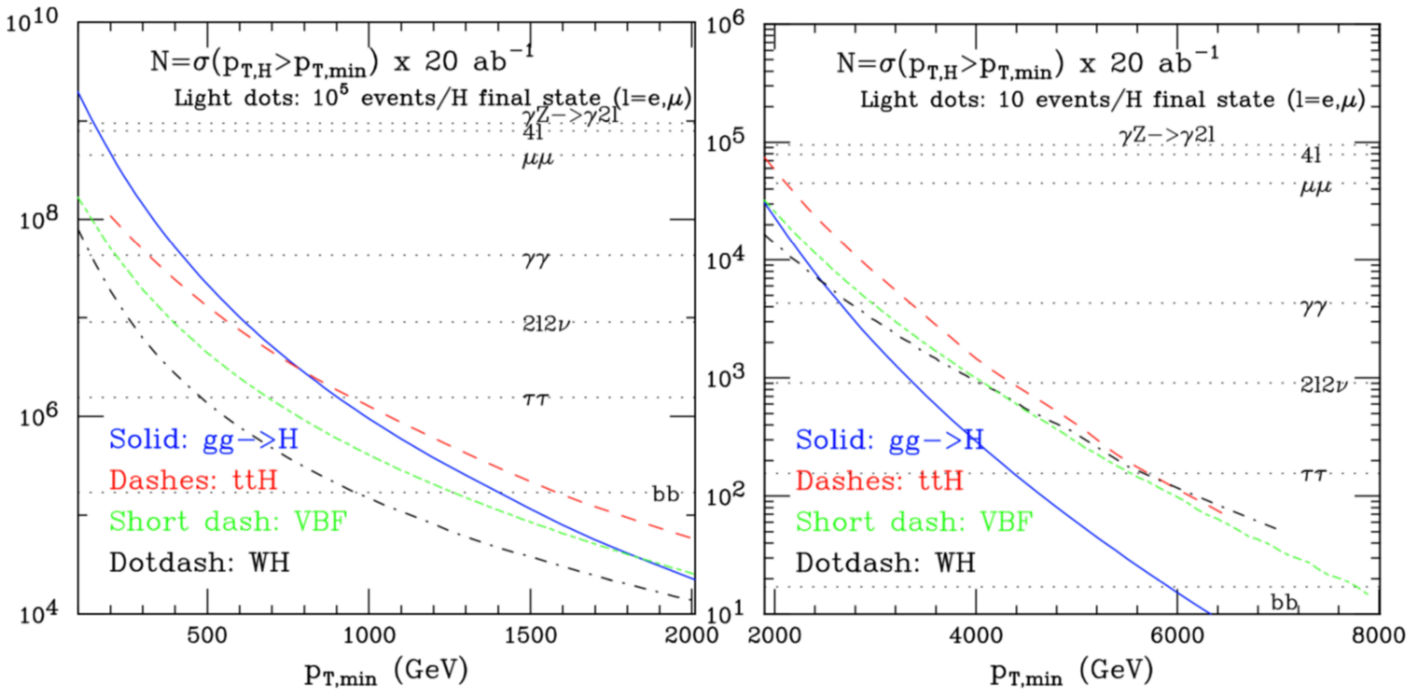




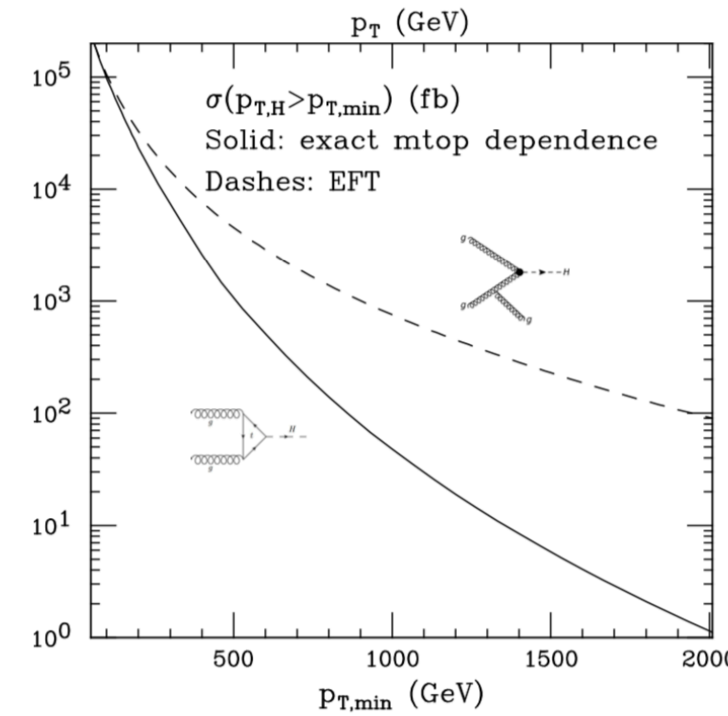


low p_T muons → resolution dominated by MS

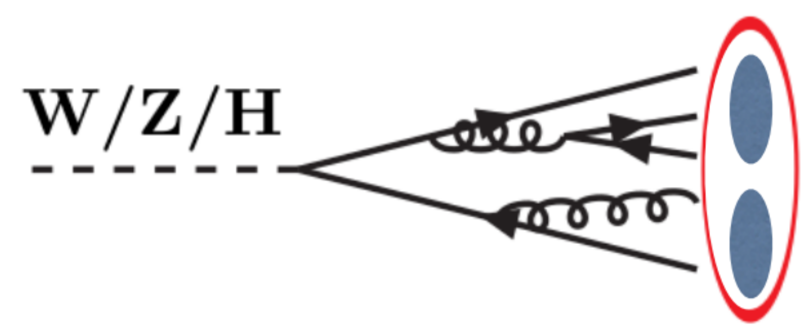
Boosted Higgs at large p_T @100 TeV



N(p_T > $p_{T,\min}$)



- Huge rates at large p_T :
  - **> 10⁶ Higgs** produced with p_T > 1 TeV
  - Higher probability to produce large p_T Higgs from ttH/VBF/VH at large
  - Even rare decay modes can be accessed at large p_T
- Opportunity to measure the Higgs **in a new dynamical regime**
  - Higgs p_T spectrum highly sensitive to new physics.
  - Reduce backgrounds, a smaller systematic uncertainties



$\Delta R = 0.1$

- highly granular sub-detectors:
  - Tracker - pixel:10 μm @ 2cm → $\sigma_{\eta\times\varphi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta\times\varphi} \approx$ 10 mrad
- good energy/p_T resolution at large p_T:
  - σ_p / p = 2% @ 1 TeV

MLM, D. Jamin, C. Helsens, G. Ortona, MS

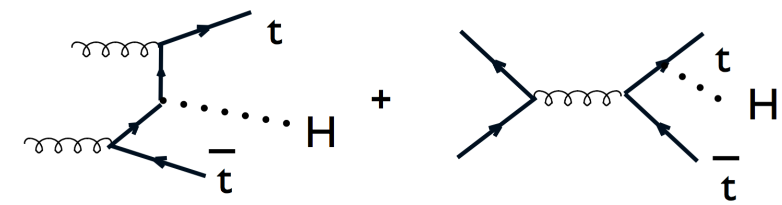
Top Yukawa (production)

- production ratio **σ(ttH)/σ(ttZ)** ≈ $y_t^2\ y_b^2 /\ g_{ttZ}^{\ 2}$
- measure **σ(ttH)/σ(ttZ)** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, scales, pdfs, efficiency) **uncertainties cancel out** in ratio

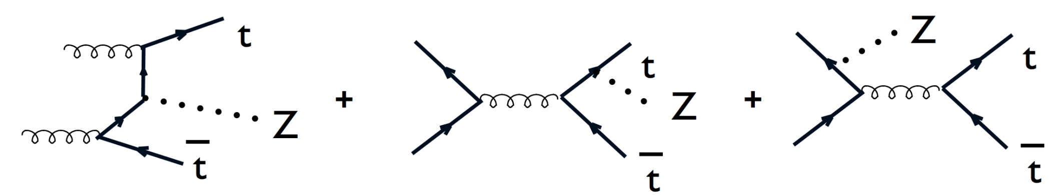
- assuming g_{ttZ} and κ_b known to 1% (from FCC-ee),

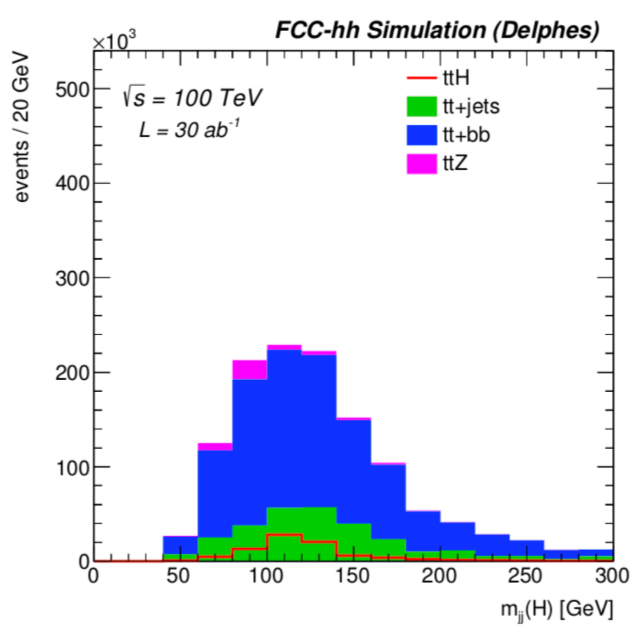
  → measure y_t to 1%

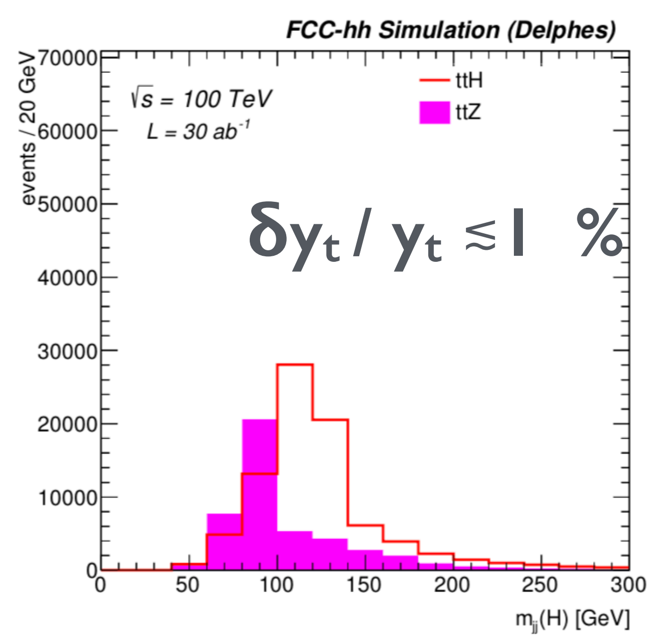
ttH → ttbb



ttZ → ttbb







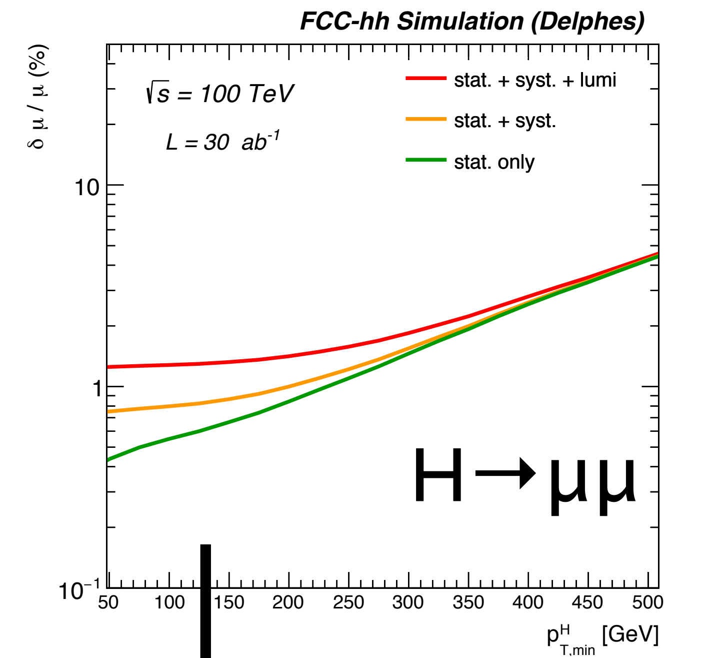
To do:

- Further assess systematics related to ttbb background modelling
- Explore use ttH / ttZ in ttττ decay mode

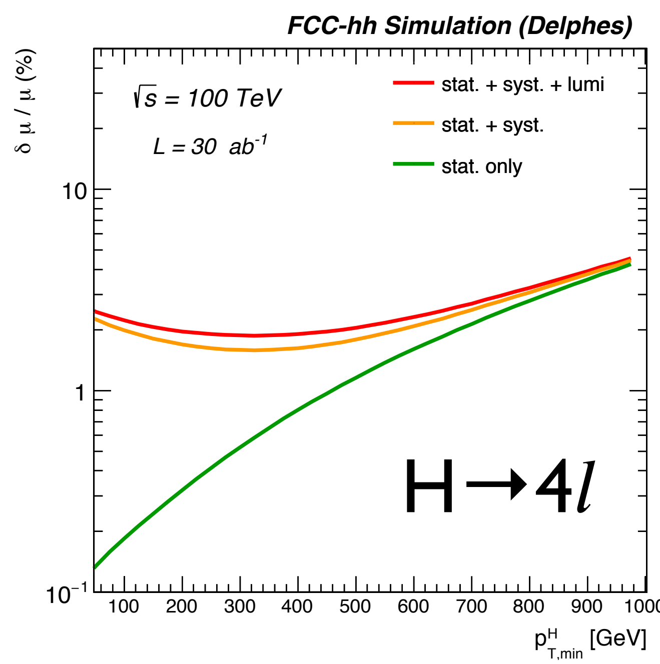
Higgs decays (rare)

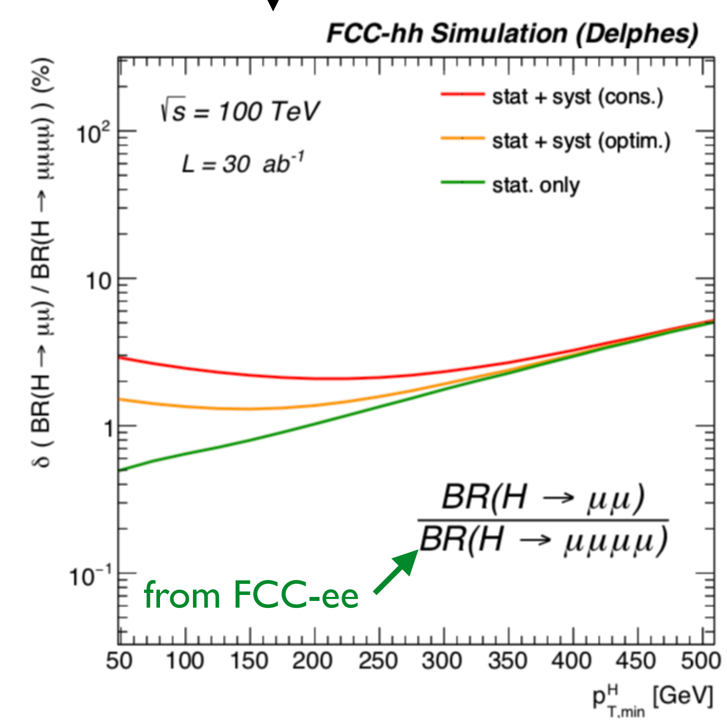
- 1% lumi + theory uncertainty
- p_T dependent object efficiency:
  - $\delta\varepsilon(e/\gamma)$ = 0.5 (1)% at $p_T \rightarrow \infty$
  - $\delta\varepsilon(\mu)$ = 0.25 (0.5)% at $p_T \rightarrow \infty$

- study sensitivity as a function of **minimum p_T(H)** requirement in the **γγ, ZZ(4l), μμ and Z(ll)γ** channels
- **low** p_T(H): **large statistics** and **high syst.** unc.
- **large** p_T(H): **small statistics** and **small syst.** unc.
- **O(1-2%) precision on BR** achievable up to very high p_T (means 0.5-1% on the couplings)



- measure **ratios of BRs** to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)

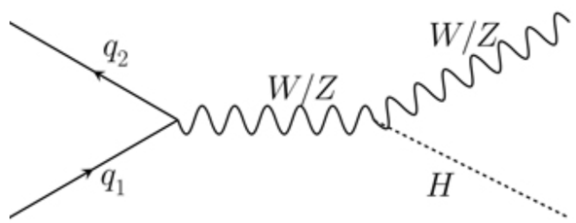


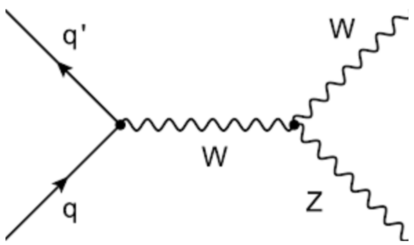


To do:

- Exploit specific signatures of various production modes (categorize)

Higgs decays





$\sigma(WH[\to\gamma\gamma]) / \sigma(WZ[\to e^+e^-])$ → $G_W = g^2_{HWW} \times BR(H \to \gamma\gamma)$

$\sigma(WH[\to\tau\tau]) / \sigma(WZ[\to\tau\tau])$ → $G_\tau = g^2_{HWW} \times BR(H \to \tau\tau)$

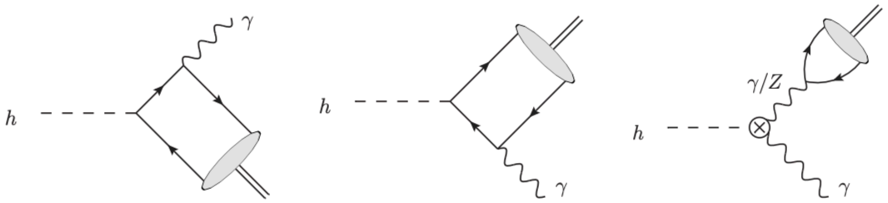
$\sigma(WH[\to bb]) / \sigma(WZ[\to bb])$ → $G_b = g^2_{HWW} \times BR(H \to bb)$

parton level study

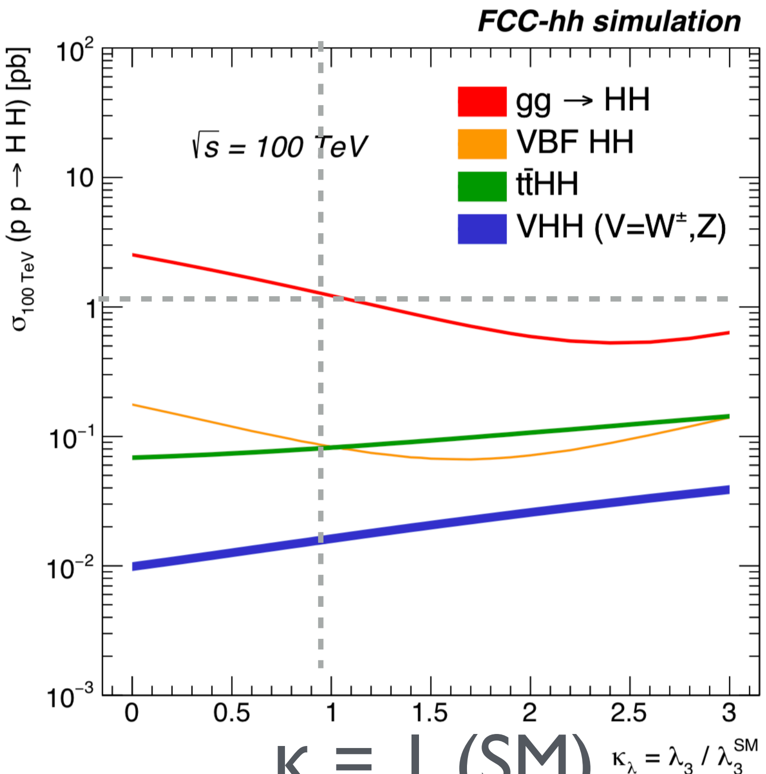
also: $\sigma(Z[\nu\nu]H[\to\gamma\gamma]) / \sigma(Z[\nu\nu]Z[\to e^+e^-])$

$\delta G/G < 1\%$

- Boosted Higgs studies:
  - in hadronic channels (H→bb/cc/WW)
  - exclusive decays H→(J/ψ) ρ / ω / ɣ (resolved/boosted)



Higgs pair production at the FCC-hh

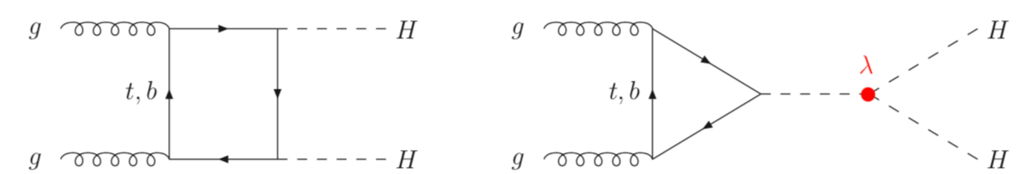


σ ≈ 1 pb

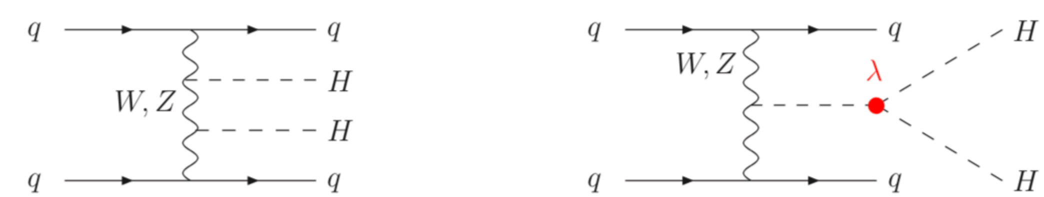
κ = 1 (SM)

≈ 15 %

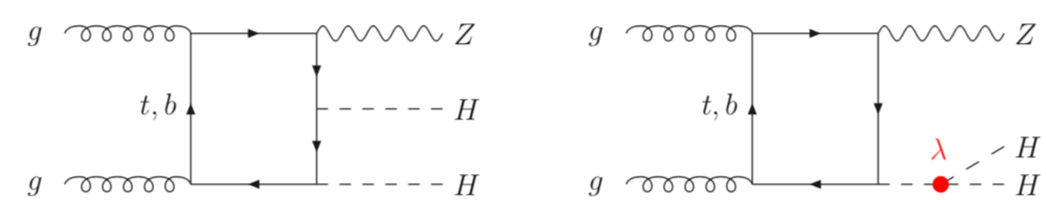
gluon fusion:



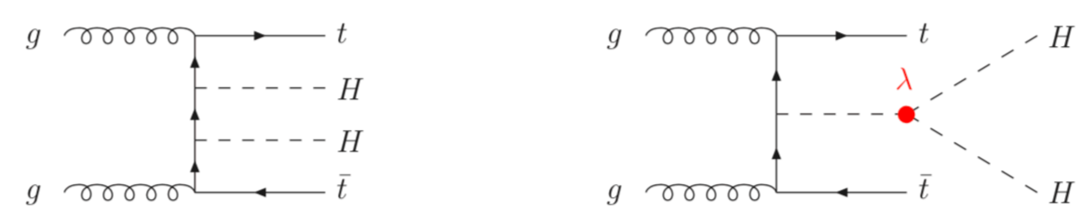
vbf HH:



VHH:



ttHH:



Expected precision:

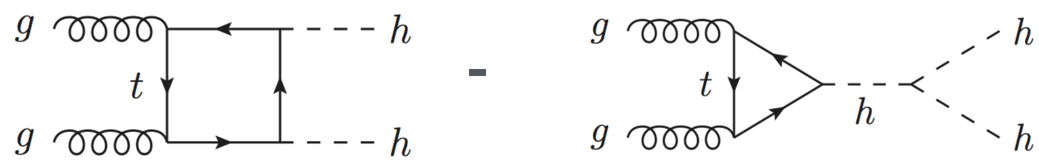
$$\delta_{\kappa_\lambda} = \frac{\delta_\mu}{\left.\frac{d\mu}{d\kappa_\lambda}\right|_{SM}}$$

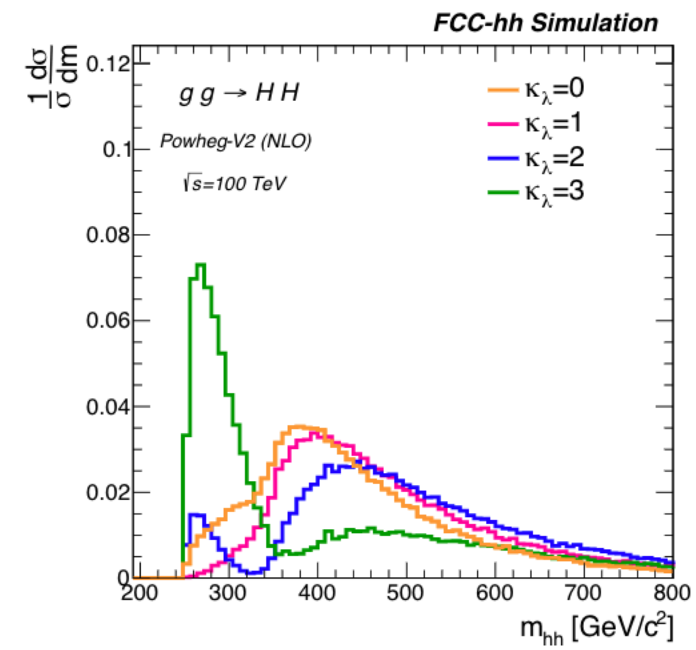
where: $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$

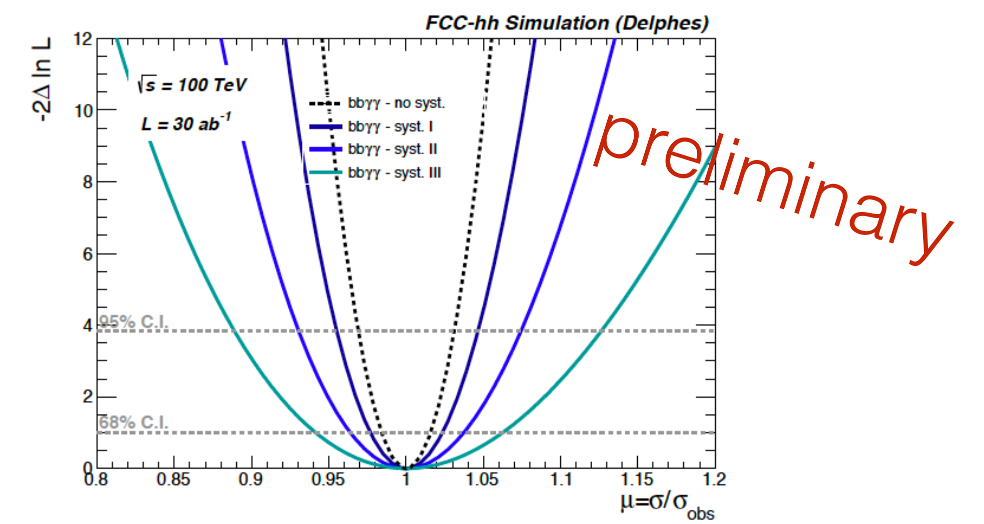
$\mu = \sigma/\sigma_{SM}$

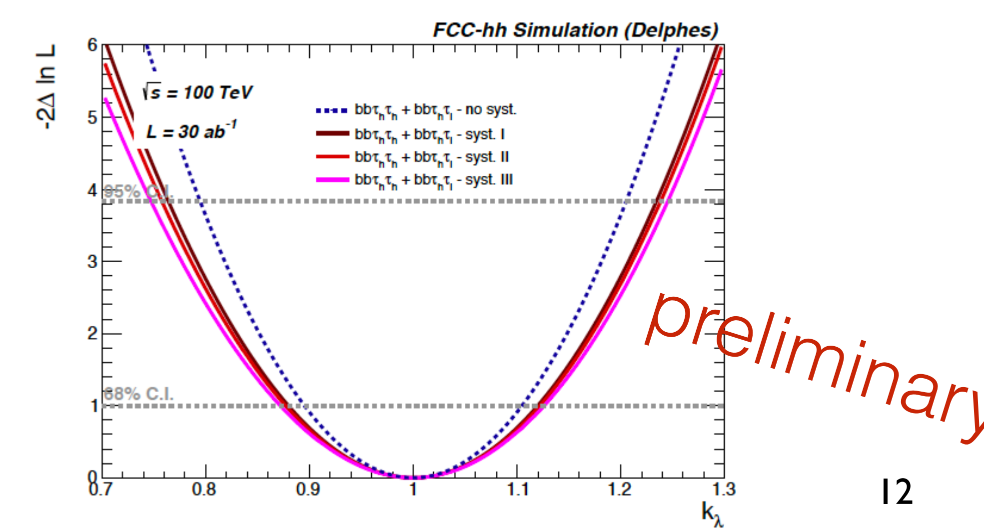
Double Higgs and self-coupling

G. Ortona, MS, MLM
[2004.03505]







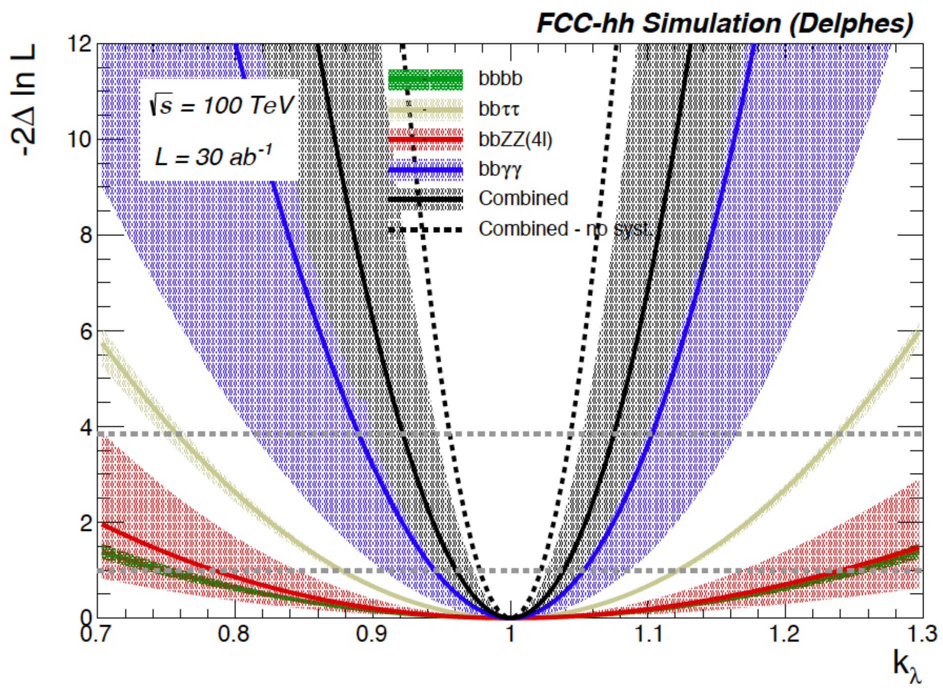


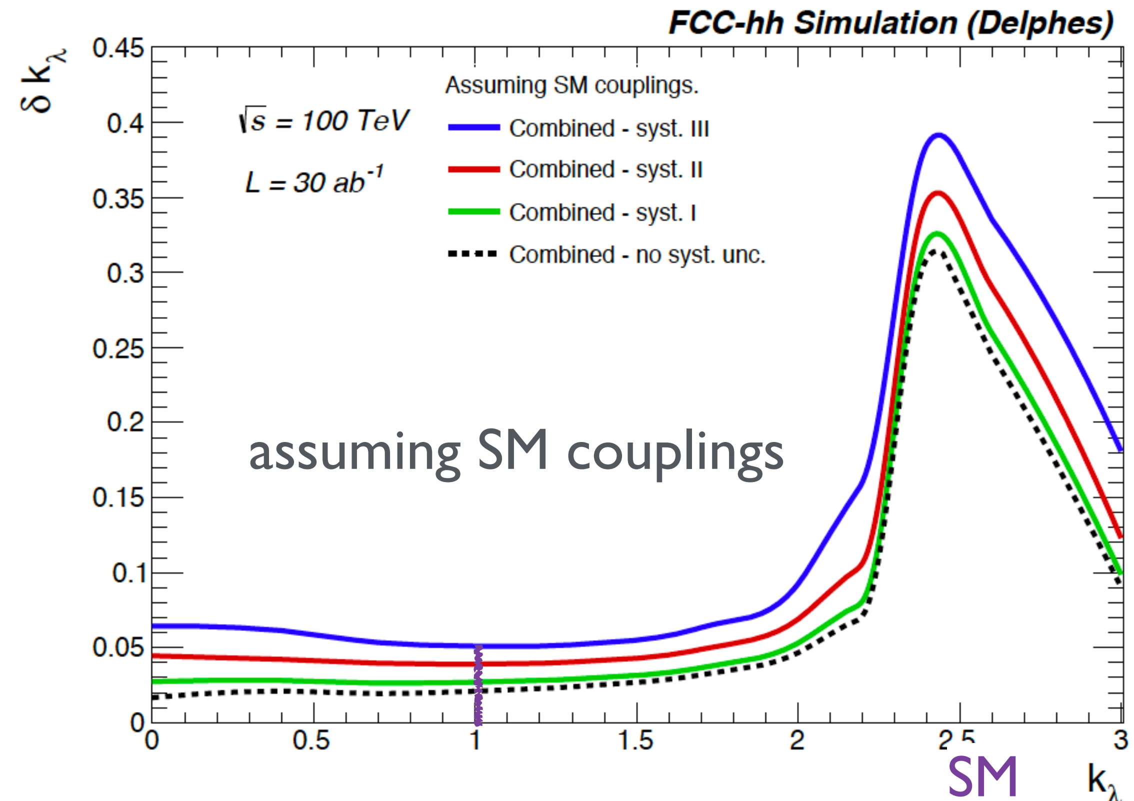
- Very small cross-section due to negative interference with box diagram
- HL-LHC projections : $\delta k_\lambda / k_\lambda \approx 50\%$
- Expect large improvement at FCC-hh:
  - $\sigma(100\,\mathrm{TeV})/\sigma(14\,\mathrm{TeV}) \approx 40$ (and Lx10)
  - x400 in event yields and x20 in precision
- main channels studied (using kin information in BDT):
  - bbγγ ($\delta k_\lambda / k_\lambda \sim$ 3-8%)
  - bbττ ($\delta k_\lambda / k_\lambda \sim$ 12%)
  - bbZZ(4l) ($\delta k_\lambda / k_\lambda \sim$ 15%)
  - bbbb ($\delta k_\lambda / k_\lambda \sim$ 22%)

G. Ortona, MS, MLM
[2004.03505]

Higgs self-coupling (combination)

preliminary





$\delta k_\lambda / k_\lambda$ ~3.0-5.5% assuming SM couplings

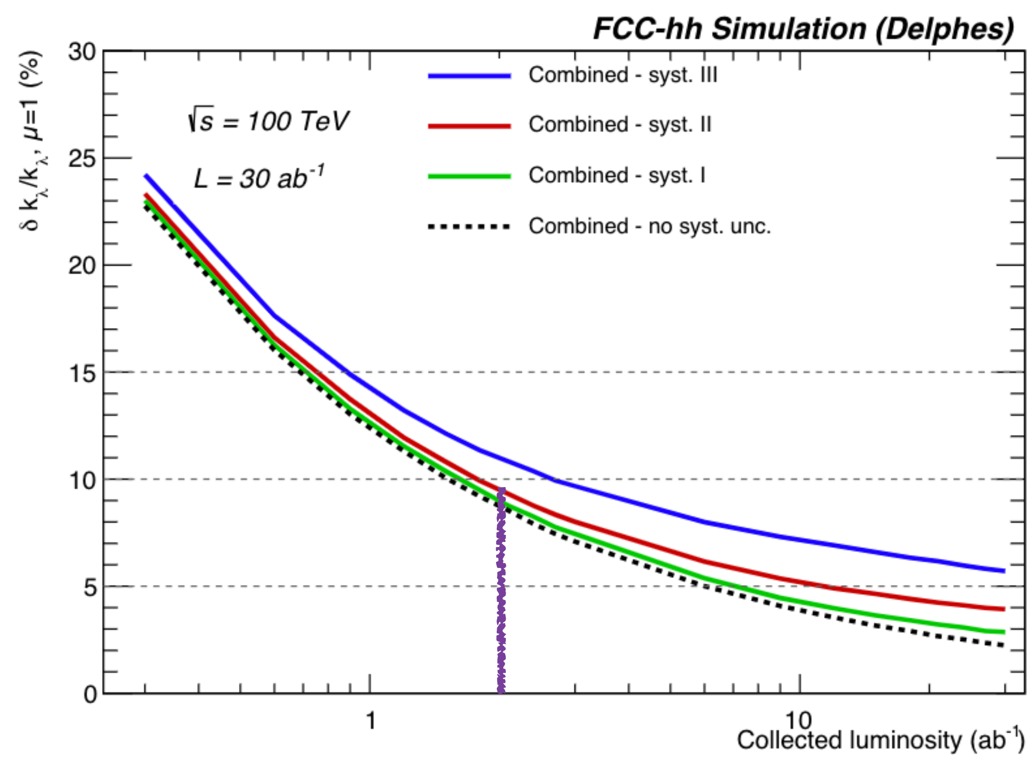


Figure 14. Expected precision on the Higgs self-coupling as a function of the integrated luminosity.

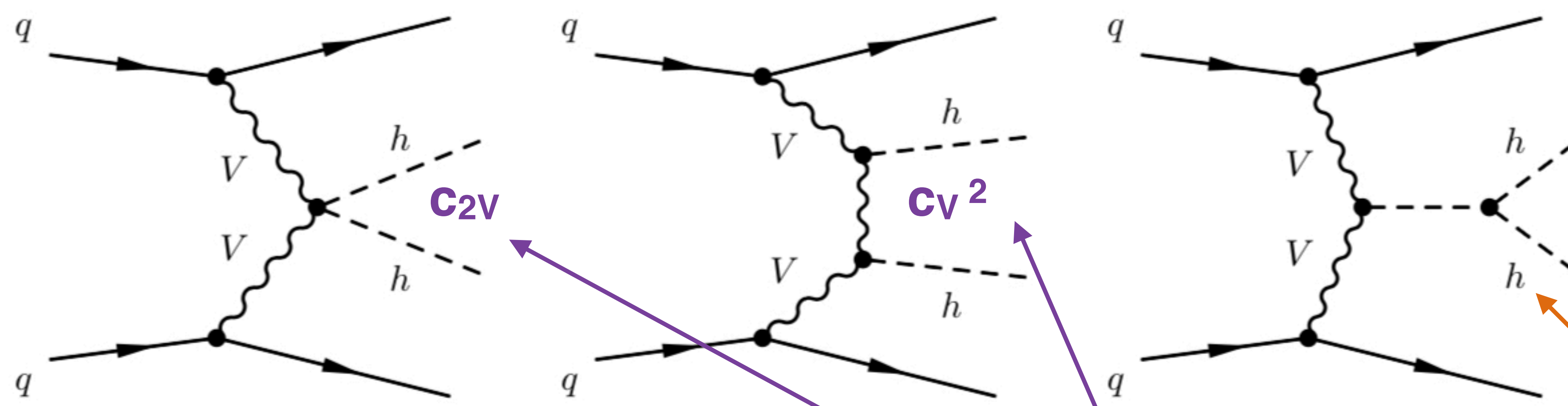
To do: study in the context of a global EFT fit (here κ_λ fit)

Can reach 10% precision with 2 ab $^{-1}$

~ 2 yrs FCC-hh

F. Bishara, R. Contino, J. Rojo

$W_L W_L \to HH$



c_{2V}

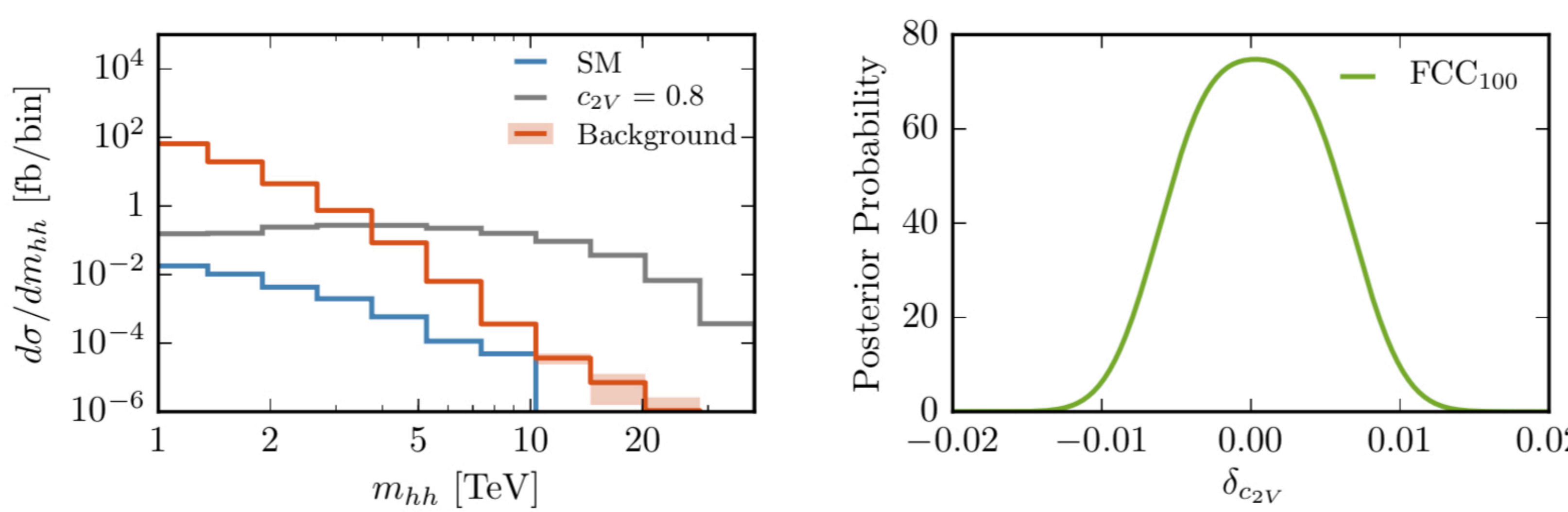
$c_V^{\,2}$

negligible at large m_{HH}

$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}),$$

0 in the SM

high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E



With c_V from FCC-ee, $\delta c_{2V} < 1\%$

Conclusions & outlook

- **Large statistics** (10^{10} **Higgs bosons**) open up a whole new range of possibilities, allowing for precision in new kinematic regimes, and rare decay channels → **complementary to FCC-ee**

- Measuring **ratios of couplings** (or equivalently BRs), allows to cancel systematics (**1% precision on "rare" couplings** within reach after absolute HZZ measurement @ FCCee)

- **Higgs-self coupling** can be measured with $\delta\kappa_\lambda \approx$ **3-5%** precision at FCC-hh (best achievable precision among all future facilites)

- Many more interesting studies to be done, not discussed in this talk:
  - gauge boson pair production at large mass (to study anomalous couplings)
  - differential measurements: Higgs p_T in the multi-TeV, as a probe of BSM physics
  - exclusive decays

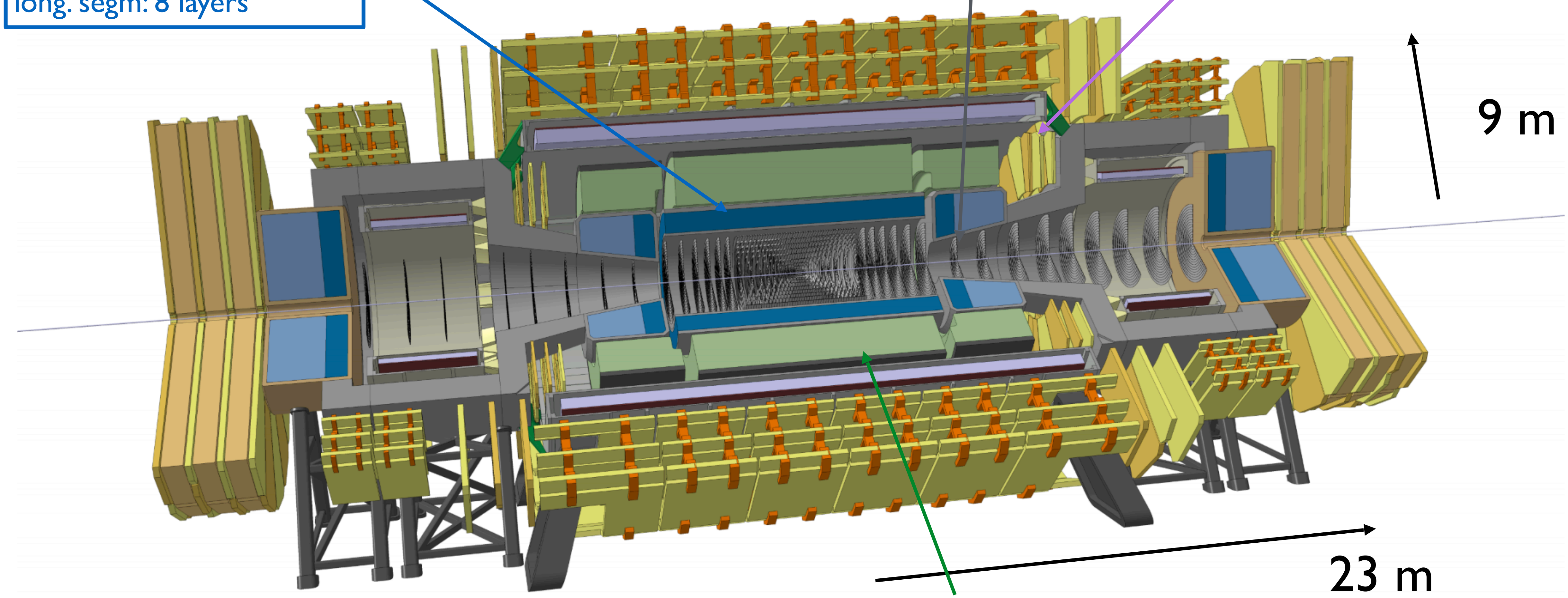
Backup

The FCC-hh detector

Barrel ECAL: LAr/Pb
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\ \%$
$30\ X_0$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers

Tracker: $\sigma_{p_T}/p_T \sim 20\%$
at 10 TeV (1.5m radius)

Central Magnet + Fwd solenoids



Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
$11\ \lambda$ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

Higgs decays: γγ - ZZ - Zγ - μμ

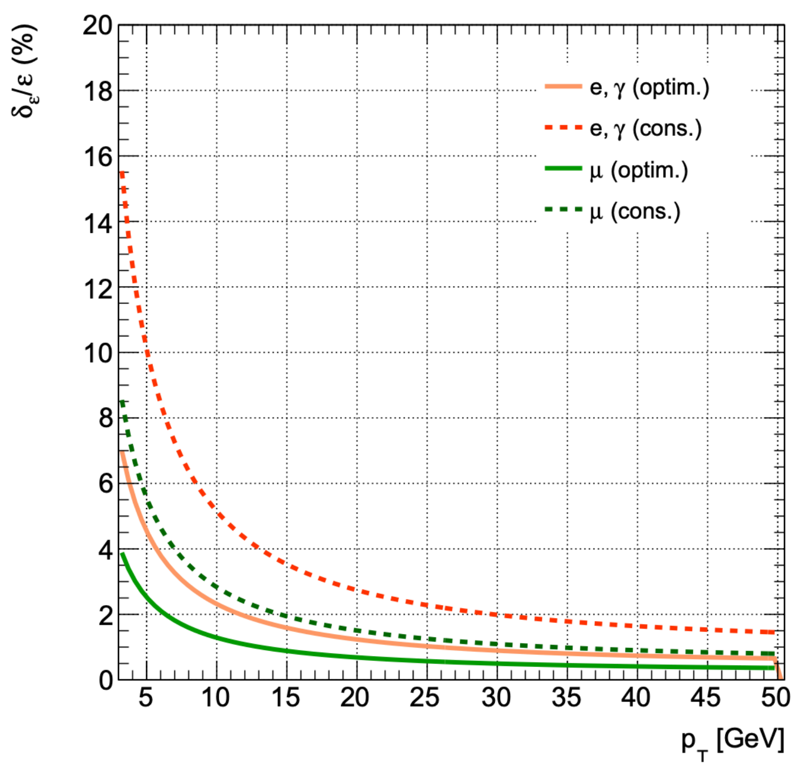
- **1% systematics on (production x luminosity)**, meant as a reference target. Assumes good theoretical progress over the next years, and **reduction of PDF+α_S uncertainties with HL-LHC + FCC-ee**.

- **e/μ/γ efficiency systematics** (shown on the right). In situ calibration, with the immense available statistics in possibly new clean channels ($Z \to \mu\mu\gamma$), will most likely reduce the uncertainties.

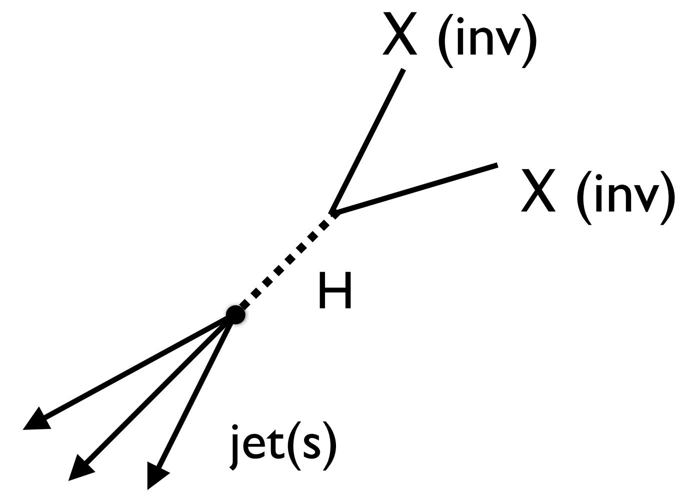
- All final states considered here rely on **reconstruction of m_H** to within few GeV. **Backgrounds** (physics and instrumental) to be **determined with great precision from sidebands** (~infinite statistics)

- **Impact of pile-up**: hard to estimate with today's analyses.
  → **Focus on high-p_T objects** will help to decrease relative impact of pile-up

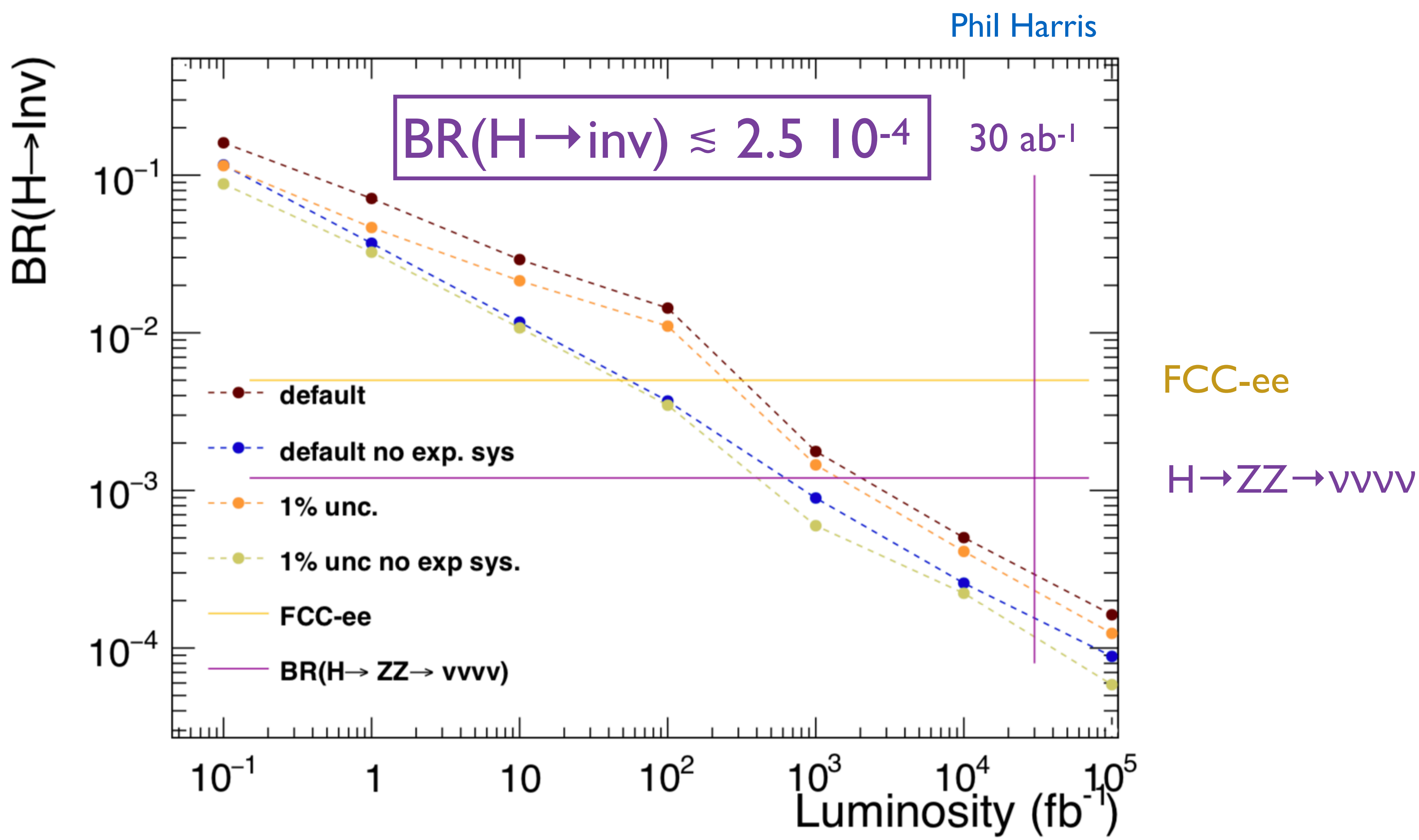
- Following **scenarios** are considered:
  - δ_{stat} → stat. only (I) (signal + bkg)
  - δ_{stat} , δ_{eff} → stat. + syst. (II)
  - δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + syst. + prod (III)



H→invisible

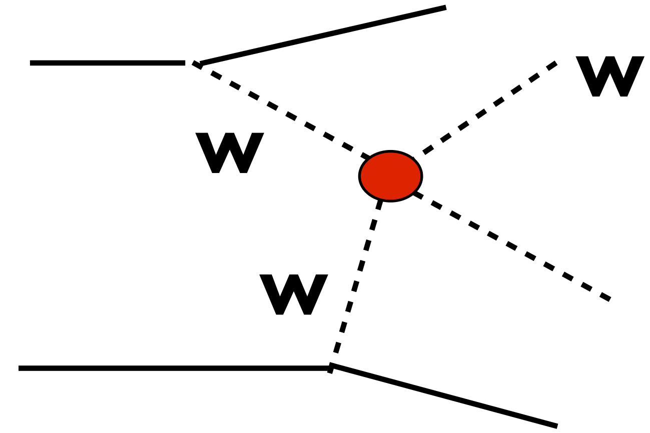


- Measure it from H + X at **large p_T(H)**
- Fit the **E_T^{miss}** spectrum
- Constrain background p_T spectrum from **Z→νν** to the % level using NNLO QCD/EW to relate to measured Z, W and γ spectra (low stat)
- Estimate Z→νν from Z→ee/μμ control regions (high stat).



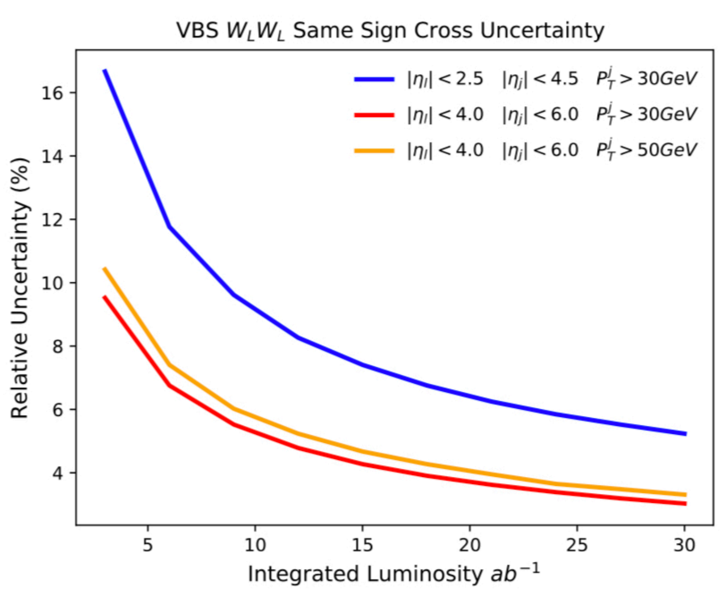
Vector Boson Scattering

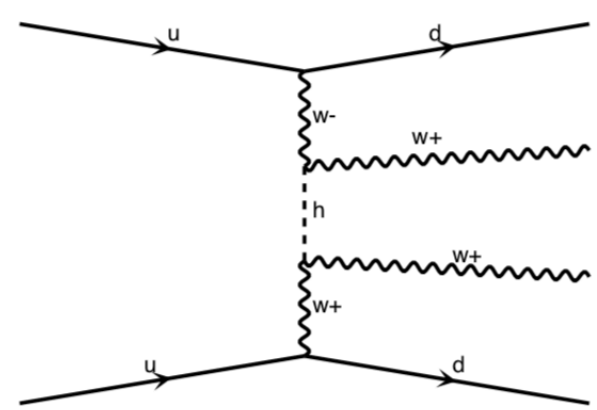
A. Sznajder, MS



large m_{WW}

- Sets constraints on **detector acceptance** (fwd jets at $\eta \approx 4$)
- Study **$W^{+/-}$-$W^{+/-}$ (same-sign)** channel
- **Large WZ** background at FCC-hh
- **3-4% precision on $W_L W_L$ scattering** xsec. achievable with full dataset (only 3σ HL-LHC)
- Indirect measurement of HWW coupling possible, **$\delta\kappa_W / \kappa_W \approx 2\%$**





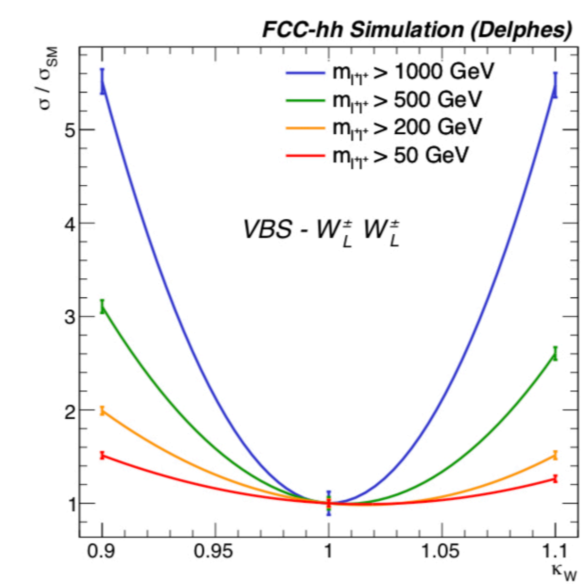


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process.

$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

Detector and systematic uncertainty assumptions

- FCC-hh baseline detector performance studied in full simulation:
  - parameterised in DELPHES:
    - pile-up is not directly simulated (would result in overly pessimistic performance)
    - assumes necessary measures (hardware, software) will be taken to **recover pile-up performance**
    - assumes 100% trigger efficiencies, but object efficiencies parameterised in Delphes.

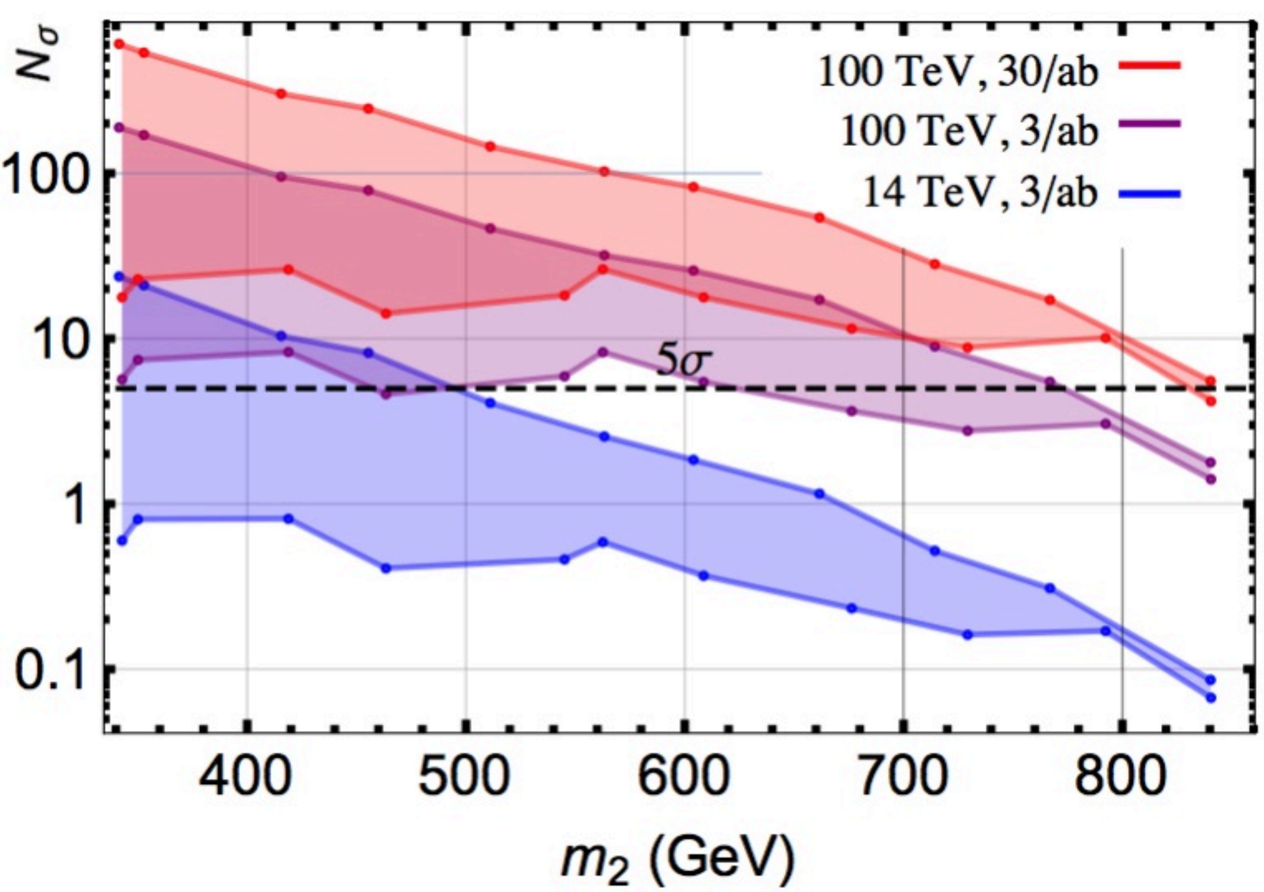
	scenario (I)	scenario (II)	scenario (III)	Process
τ -jet ID	1%	2.5%	5%	HH, tt, H
b-jet ID	0.5%	1%	2%	HH, tt, H
e/μ ID	0.25%	0.5%	1%	HH, ZZ, Z+jets, ttV, ttVV, H
γ ID	0.5%	1%	2%	HH, H, jjjγ, γγjj
Luminosity	0.5%	1%	2%	All / jjjγ, γγjj, QCD
HH (TH)	0.5%	1%	1.5%	HH
ttbar norm. (TH)	0.5%	1%	1.5%	tt
single H norm. (TH)	0.5%	1%	1.5%	H

Note: assumptions from Phase II YR marked in "red"

Higgs Self-coupling and constraints on models with 1st order EWPT

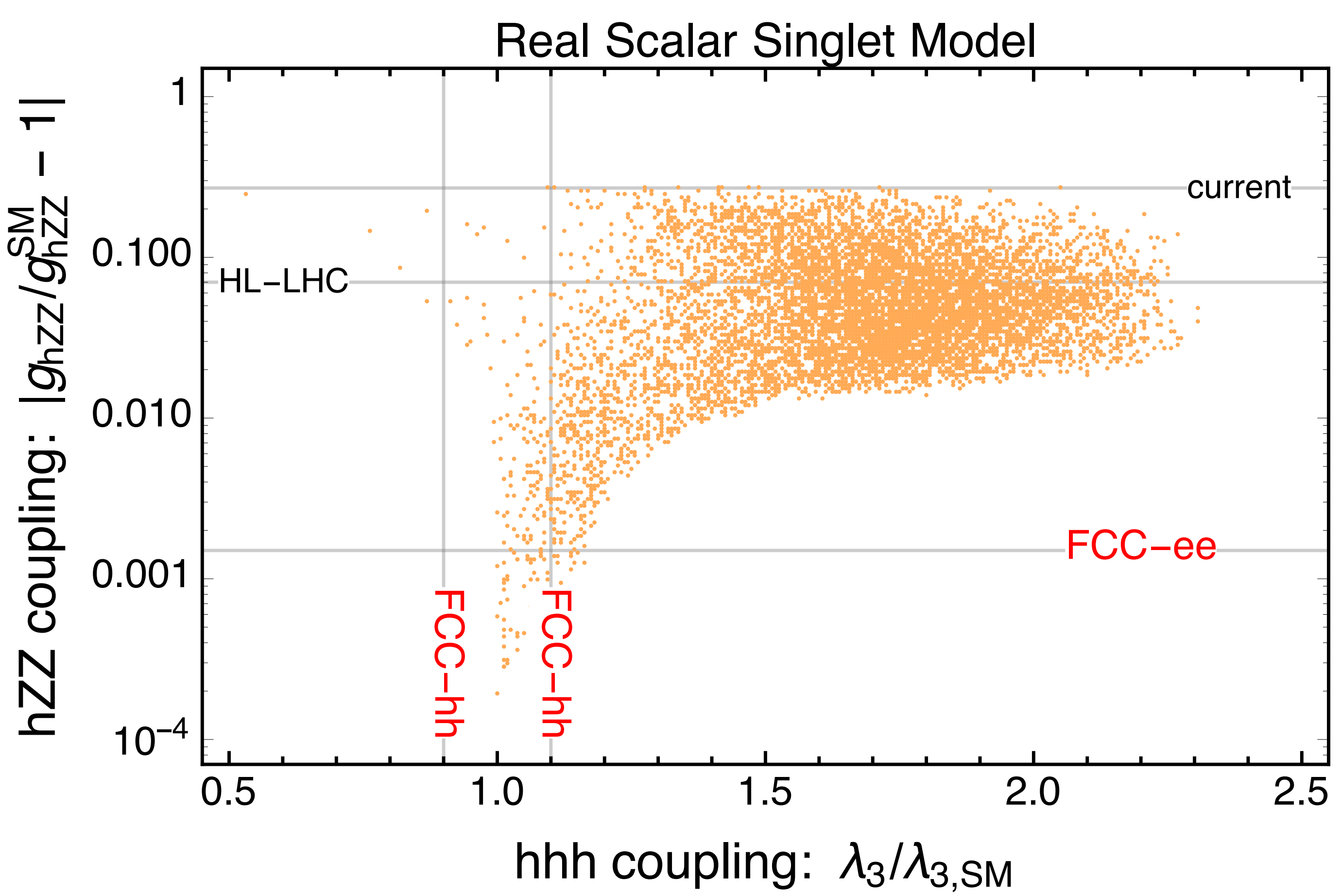
- **Strong 1st order EWPT** (and CP violation) needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.