Higgs @ FCC-hh

Clement Helsens, CERN-EP

Quantum Universe, DESY

Expectation from hadron future collider

Guaranteed deliverables

- Study Higgs and top-quark properties and exploration of EWSB phenomena with unmatchable precision and sensitivity

Exploration potential (New machines are build to make discoveries!)

- Mass reach enhanced by factor √s/14TeV (5-7 at 100TeV)
  - Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC or just above thres.
- Benefit from both direct (large Q^2) and indirect precision probes

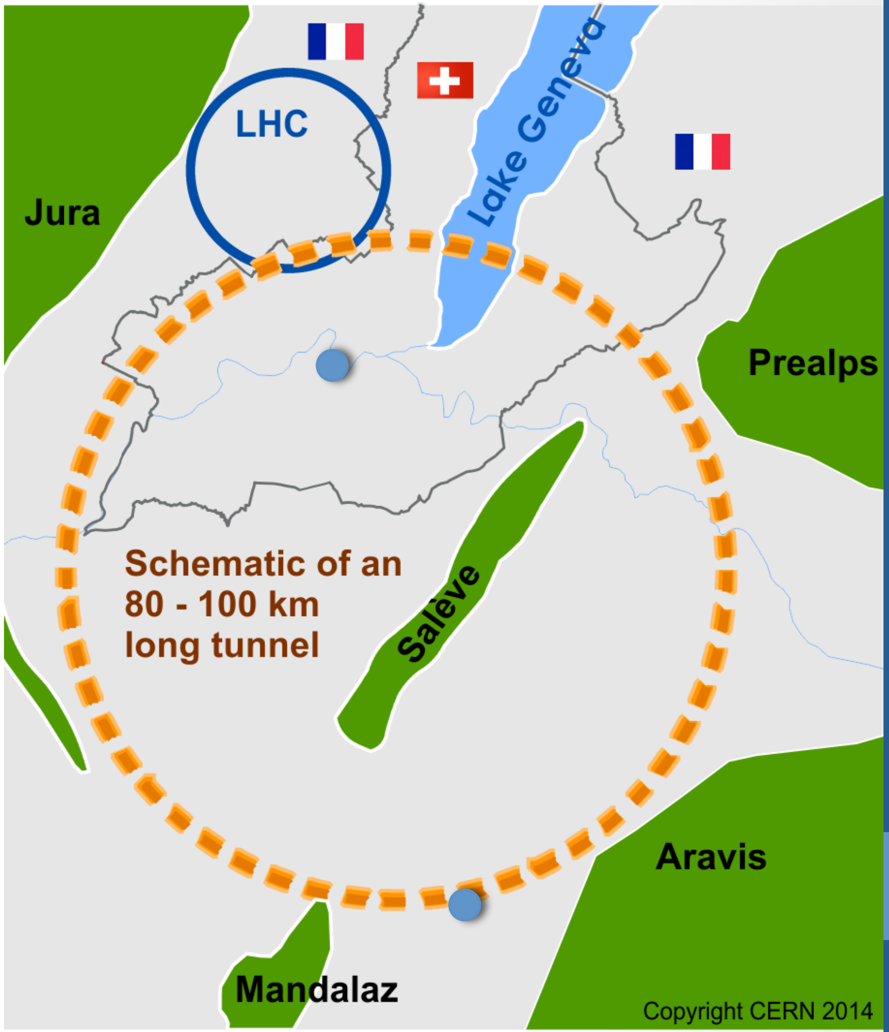
Could provide firm answers to questions like

- Is the SM dynamics all there at the TeV scale?
- Is there a TeV-Scale solution the hierarchy problem?
- Is DM a thermal WIMPS?
- Was the cosmological EW phase transition 1st order? Cross-over?
- Could baryogenesis have taken place during EW phase transition?

The FCC-hh

<u>FCC-hh</u>

- Need a new 100km tunnel
- Need 16 Telsa magnets to reach 100TeV in 100km
  - With more R&D 24 Tesla HTS?
- Baseline Luminosity (10y)
  - 5 10^{34} cm^{-2} s^{-1} (HL-LHC) <μ>200
- Ultimate luminosity (15y)
  - 30 10^{34} cm^{-2} s^{-1} <μ>1000
- 2.4MW sync rad/ring x300 HL-LHC
- Considering 30ab^{-1} for the study

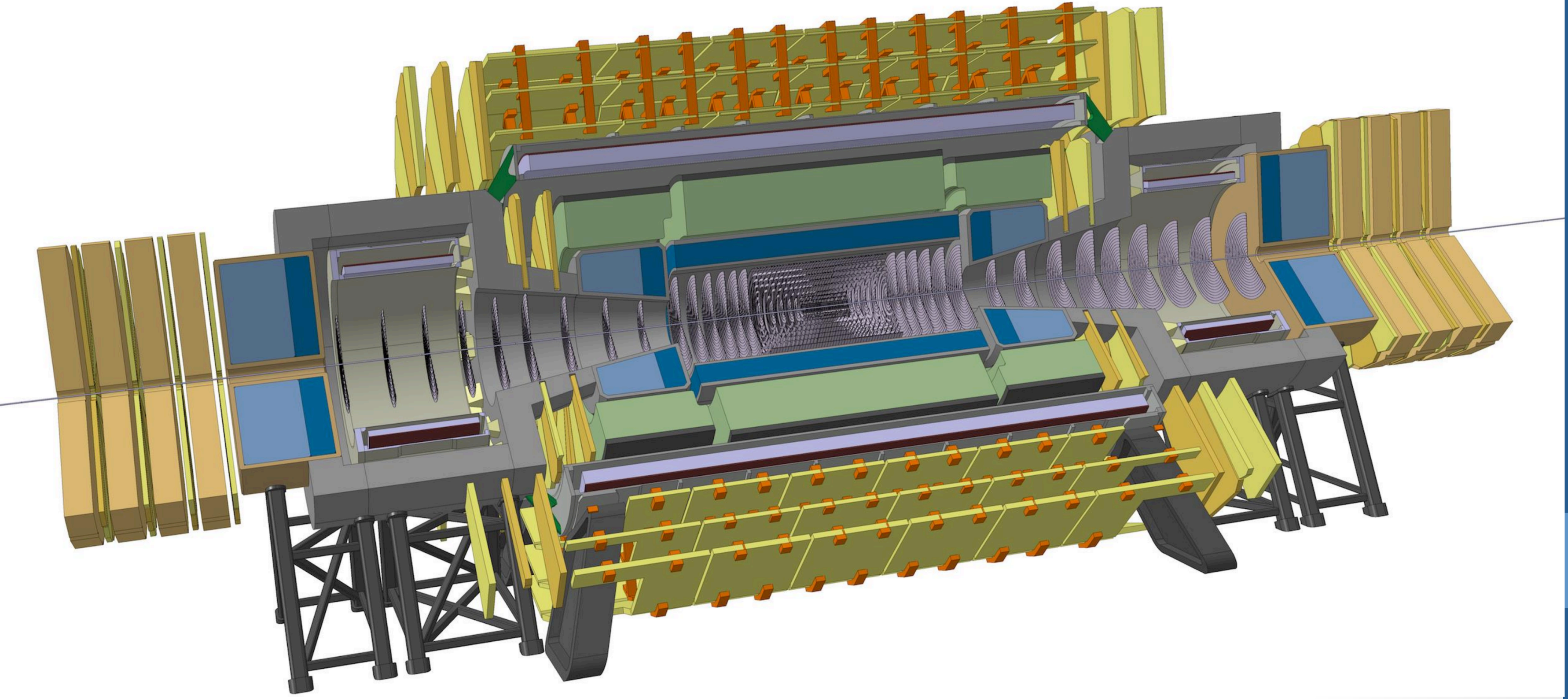


Environment and detector requirements

@100TeV FCC-hh

- From 14 to 100TeV pp cross-section only grows by a factor 2
- 10 times more fluence compared with HL-LHC (x100 wrt to LHC)
  - Need radiation hard detectors
- Increase of radiation level mostly driven by the jump in instantaneous luminosity
- More forward physics -> larger acceptance
  - Precision momentum spectroscopy and energy measurements up to $|\eta|<4$
  - Tracking and calorimetry up to $|\eta|<6$ (at 10cm of beam line at 18m of IP)
- More energetic particles
  - Colored hadronic resonances up to 40TeV -> Full containment of jets up to 20TeV
  - Resonances decaying to boosted objects (top, bosons) -> need very high granularity to resolve such sub-structure

FCC-hh detector

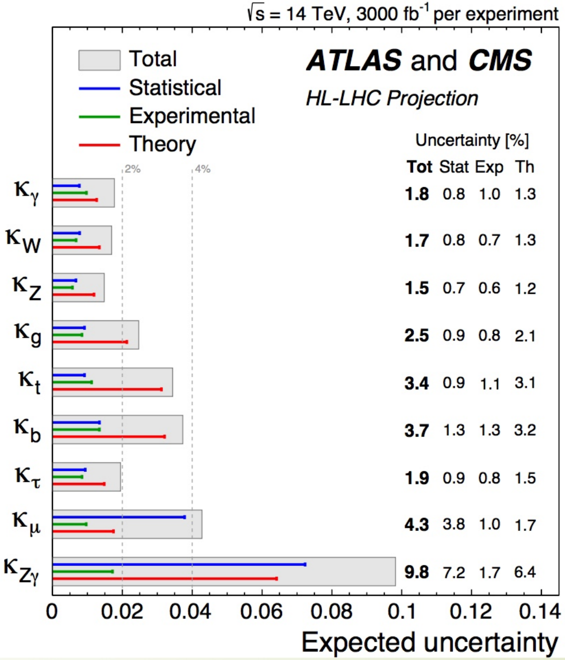


Why measuring Higgs @FCC-hh?

- Higgs precision measurements are part of the guaranteed deliverables

- FCC-hh provides unique and complementary measurements to e^+e^- colliders:
  - Higgs self-couplings
  - Top Yukawa
  - Rare decays (BR(μμ), BR(Zγ), …) measurements will be statistically limited at FCC-ee

HL-LHC



FCC-ee

δm_H (MeV)	6
$\delta\Gamma_H / \Gamma_H$(%)	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	0.68
$\delta g_{HW} / g_{HW}$ (%)	0.47
$\delta g_{H\tau} / g_{H\tau}$(%)	0.80
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	3.8
$\delta g_{H\mu} / g_{H\mu}$ (%)	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	1.0
Br_{invis} (%)$_{95\%CL}$	< 0.25
BR_{EXO} (%)$_{95\%CL}$	< 1.1

SM Higgs event rates @ 100TeV

	ggF	VBF	WH	ZH	ttH	HH
N_{100}	2.4×10^{10}	2.1×10^{9}	4.6×10^{8}	3.3×10^{8}	9.6×10^{8}	3.6×10^{7}
N_{100}/N_{14}	180	170	100	110	530	390

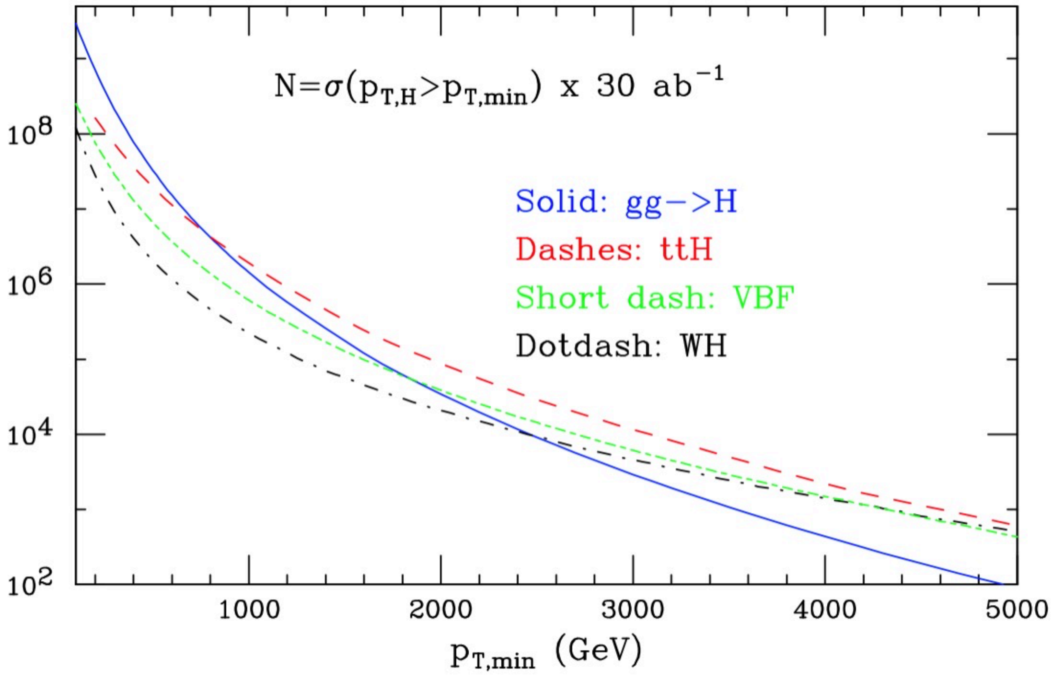
- Huge production rates
  - Access very rare decay modes
  - Push to %-level Higgs self-couplings measurements
- Large dynamic range for H production in p_T^H, m(H+X), .
  - Develop indirect sensitivity to BSM effect at large Q^2
- High energy reach
  - Direct probes of BSM extensions of Higgs sector
    - Susy Higgses
    - Higgs decays of Heavy Resonances

$$N_{100} = \sigma_{100TeV} \times 30\ ab^{-1}$$
$$N_{14} = \sigma_{14TeV} \times 3\ ab^{-1}$$

	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55

Higgs measurements @ FCC-hh

- Large statistics will allow
  - For % - level precision in statistically limited rare channels (μμ, Zɣ)
  - In systematics limited channel, to isolate cleaner samples in regions (e.g. @large Higgs p_T) with :
    - higher S/B
    - smaller impact of systematics

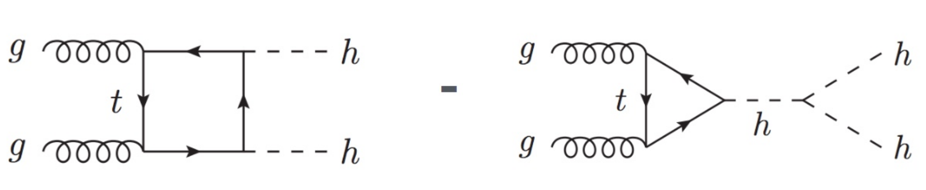


- Hierarchy of changes at large p_T(H):
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

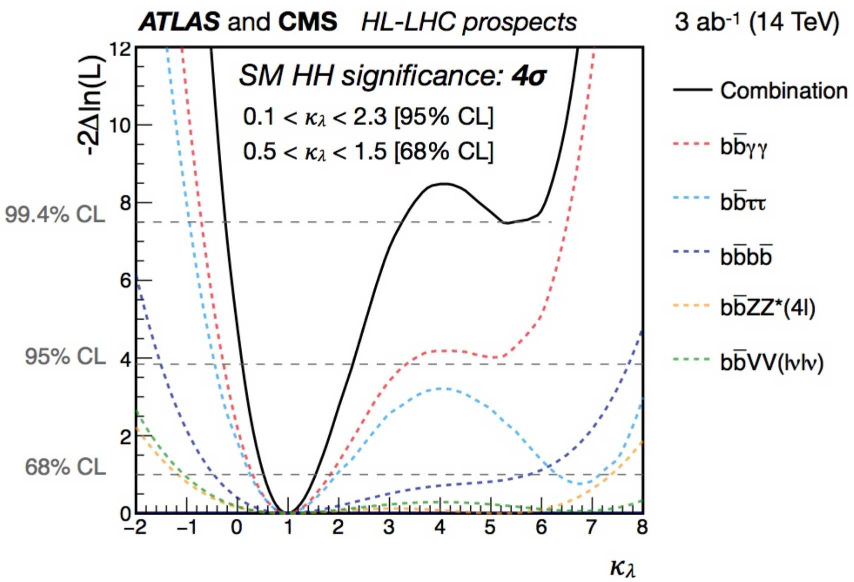
Higgs self-coupling

Higgs self-coupling @ FCC-hh

- Very small cross-section due to negative interference with box diagram



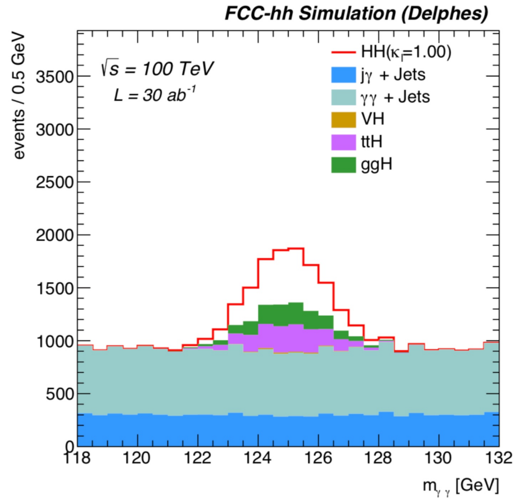
- HL-LHC projections : δ_λ/λ ~ 100%

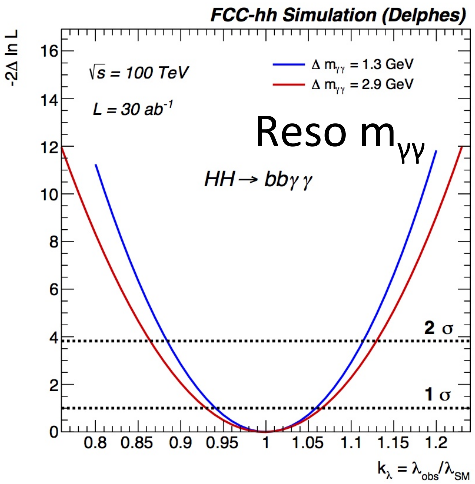


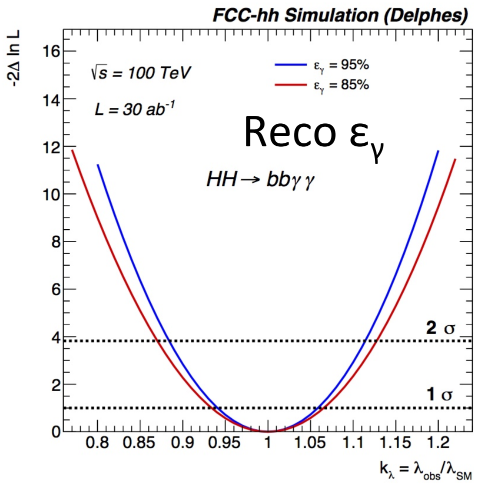
- Expect large improvement at FCC-hh:
  - σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
  - x400 in event yields and x20 in precision
- Mainly 4 channels studied:
  - bbγγ (most sensitive)
  - bbZZ(4l)
  - bbbbj (boosted)
  - bbWW
  - bbττ coming for the FCC week

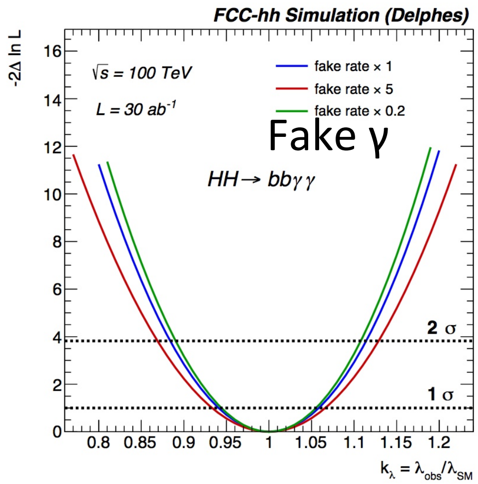
HH →bbγγ

- BR=0.25%, and large QCD backgrounds (jjγγ and γ+jets)
- Main difference w.r.t LHC is the very large ttH background
- Strategy:
  - exploit correlation of means in ($m_{\gamma\gamma}$, m_{hh}) in signal
  - build a parametric model in 2D
  - perform a 2D Likelihood fit on the coupling modifier k_λ
  - $\delta k_\lambda / k_\lambda$ = 5% achievable



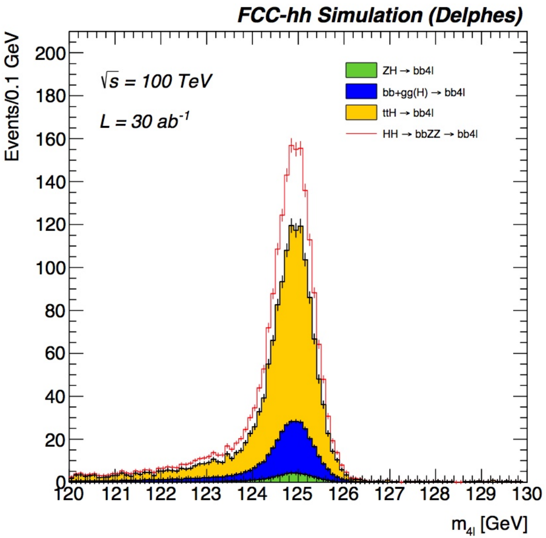


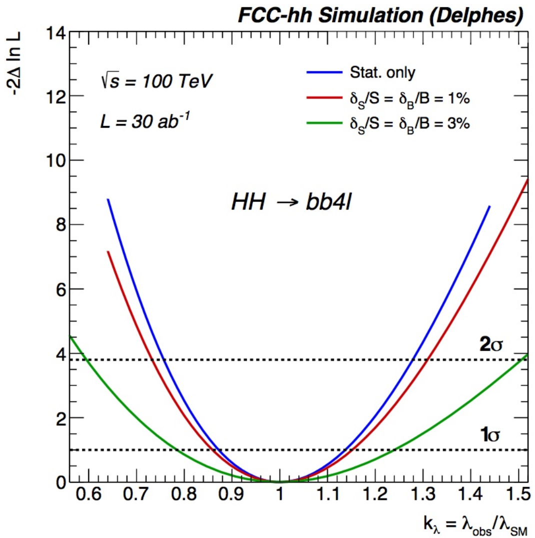


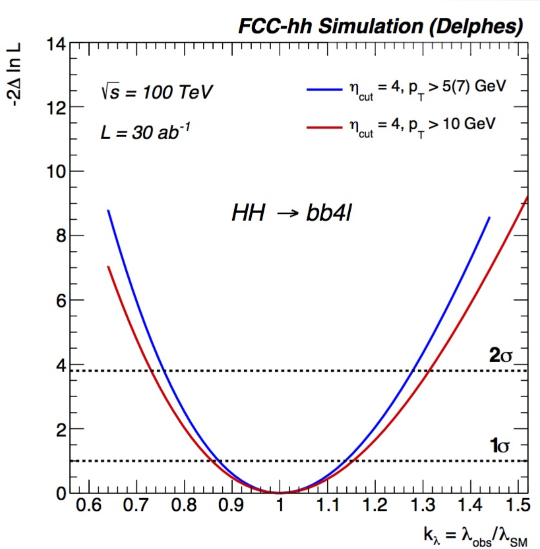


HH →bb4l

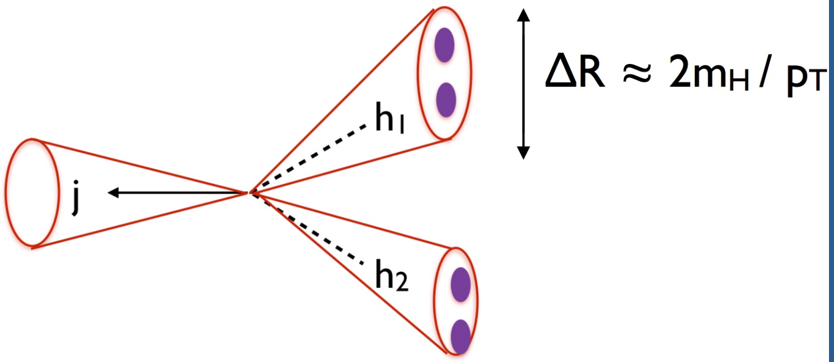
- New channel opening at FCC-hh (cross-section 180ab)
  - Clean channel with mostly reducible backgrounds (single Higgs)
  - Simple cut and count analysis on (4e, 4μ and 2e2μ channels)
  - δk_λ / k_λ = 15-20% depending on systematics assumptions
- Key element for the detector design
  - Powerful reconstruction of low energetic electrons and muons



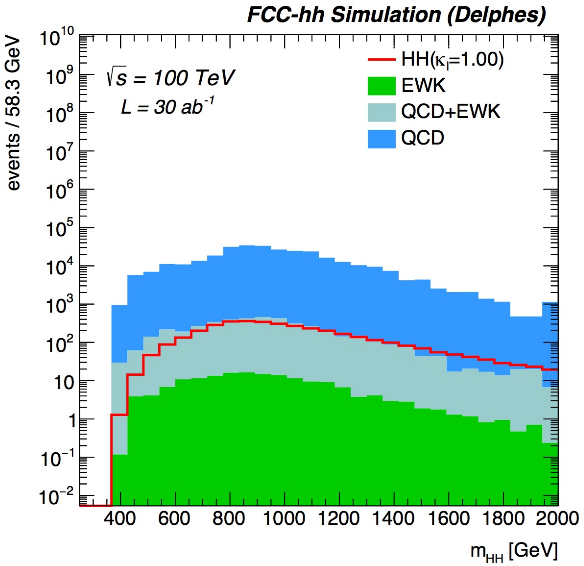


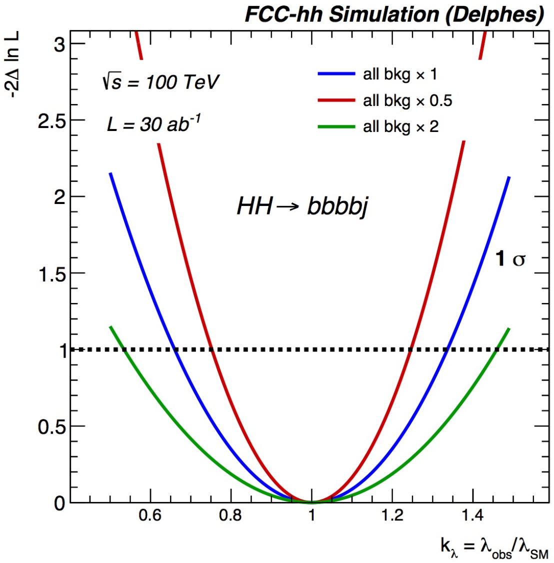


HH →4b+j boosted



- Large rate allow to look for boosted HH recoiling against a jet
  - low m_{HH} drives the sensitivity
- Relies on the identification of two boosted Higgs-jets
- Fit the di-jet mass spectrum dominated by the large QCD background
- $\delta k_\lambda / k_\lambda$ = 20-40% depending on assumed background rate





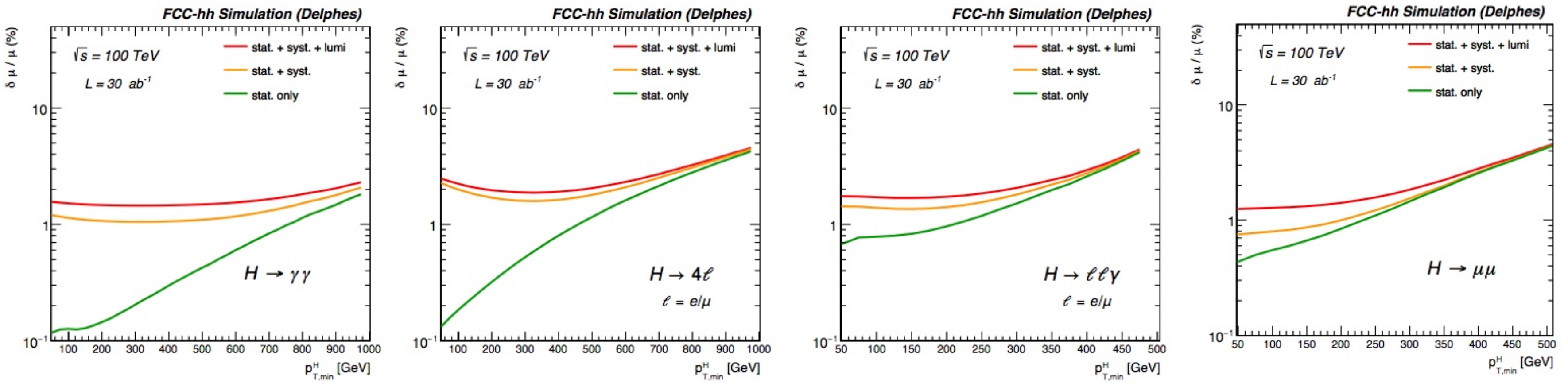
Higgs and EWSB @ FCC-hh

Higgs couplings

Higgs decays

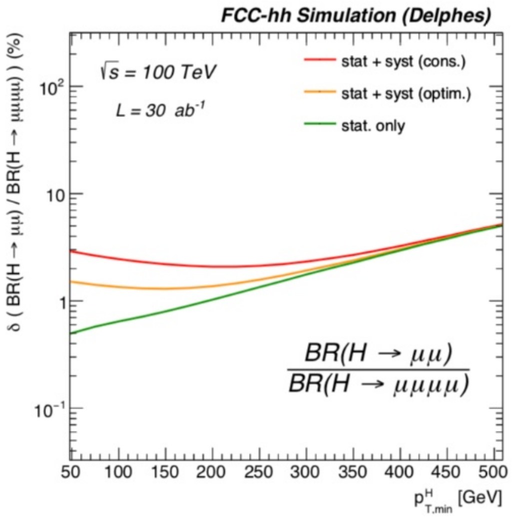
- Study sensitivity as a function of minimum $p_T(H)$ requirement in the γγ, ZZ(4l), μμ, Z(ll)γ channels
- Low $p_T(H)$: small stat. and high syst. unc.
- Large $p_T(H)$: small stat. and high syst. unc.
- O(1-2)% precision on BR achievable up to very high p_T

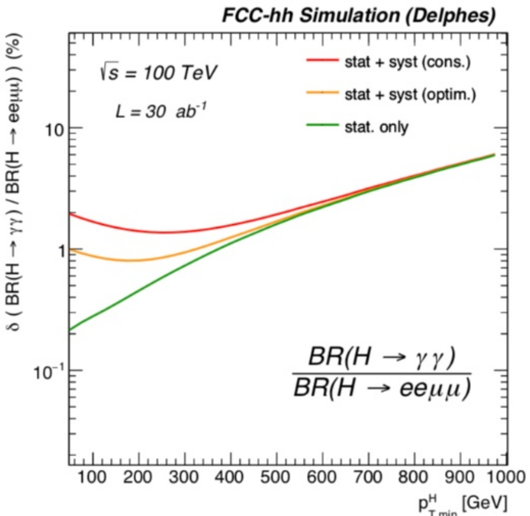
- 1% lumi + theory uncertainty
- p_T dependent object efficiency
  - $\delta\varepsilon(e/\gamma)=0.5(1)\%$ at $p_T \to \infty$
  - $\Delta\varepsilon(\mu)=0.25(0.5)\%$ at $p_T \to \infty$



Ratio of BRs

- Measure ratios of BRs to cancel correlated sources of systematics uncertainties
  - Luminosity
  - Object efficiencies
  - Production cross-section (theory)
- Becomes absolute precision measurement in particular if combined with H->ZZ measurement from e^+e^- (at 0.1%)

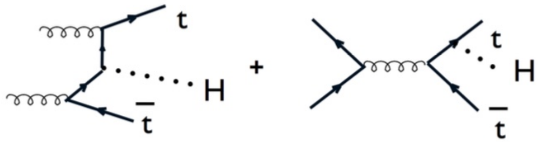




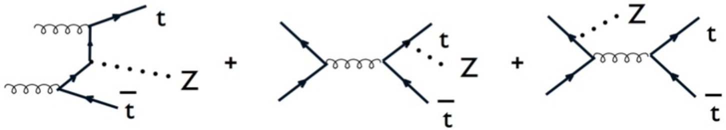
Top Yukawa

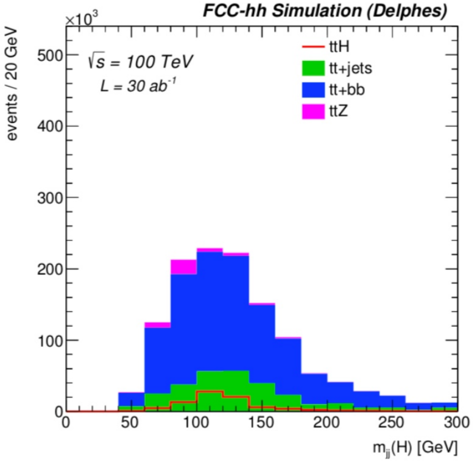
- Production ratio σ(ttH)/σ(ttZ)
- Measure σ(ttH)/σ(ttZ) in H/Z→bb mode in the boosted regime, in the semi-leptonic channel
- Perform simultaneous fit of double Z and H peak
  - lumi, pdfs, efficiency uncertainties cancel out in ratio
- assuming g_{ttZ} and κ_b known to 1% (from FCC-ee) , can measure y_t to 1%

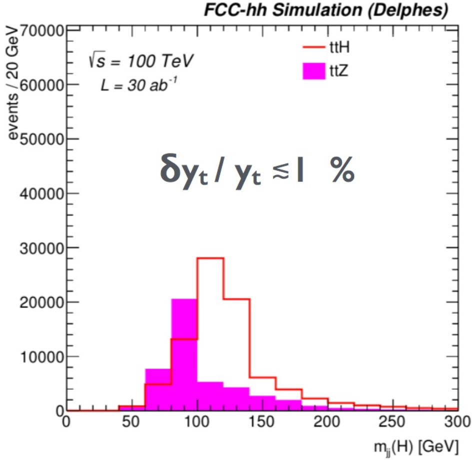
ttH



ttZ





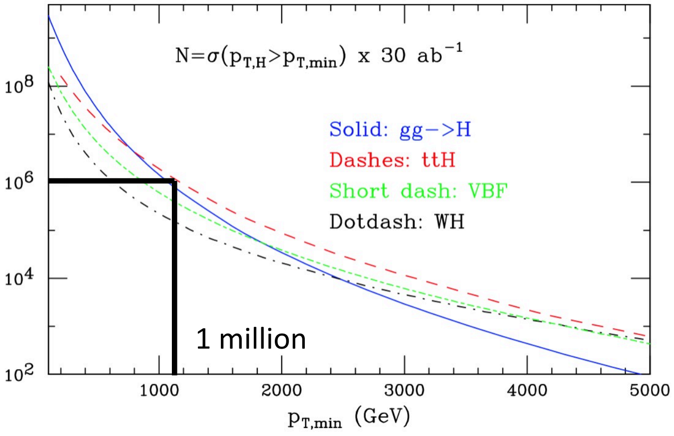


Higgs for BSM

Higgs as a probe for BSM: precision/reach

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$



- For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

- Precision probes large Λ e.g. δO=1% ⇒ Λ ~ 2.5 TeV

- For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

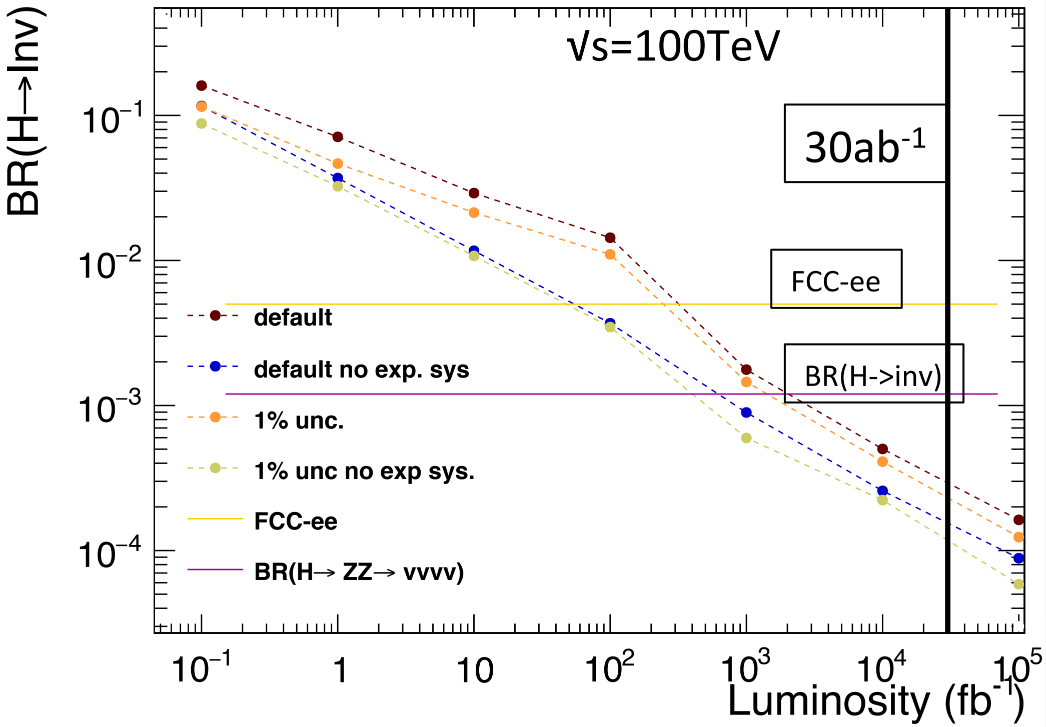
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

- kinematic reach probes large Λ even if precision is "low" e.g. δO=10% at Q=1.5 TeV ⇒ Λ~5 TeV

Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV

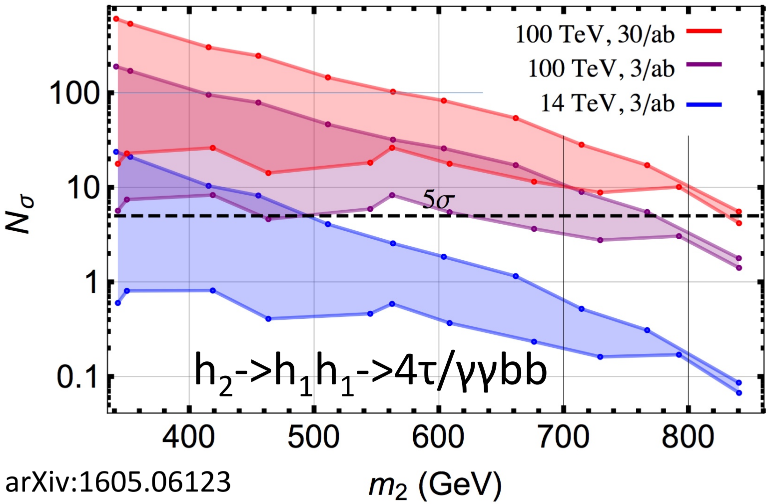
BR(H->inv) in H+X production at large p_T

- Uses missing transverse energy as a probe to higgs p_T
  - S/B increases with MET
- Signal extracted using a simultaneous fit to all control regions
  - Z+jets, W+jets, γ+jets
- Z->νν background constrained to the percent level using NNLO QCD/EW
  - relate to measured Z->ee, W and gamma spectra

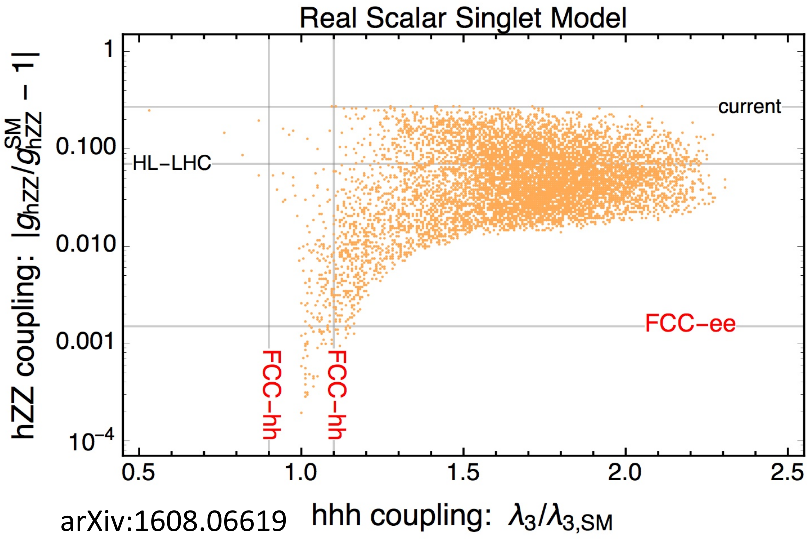


Higgs and EW phase transition

- Strong 1st order EWPT required to induce matter-antimatter asymmetry at EW scale
- Simple model: extension of the SM scalar sector with a single real singlet scalar
  - Contains 2 higgs scalar, h_1 and h_2
  - Interaction of scalar potential can lead to 1st EWPT when SM-like state h_1 has a mass of 125GeV
  - Modifications in Higgs self coupling, shift in Zh_1, direct production of scalar pairs
- Parameter space scan for this simple model extension of the SM



arXiv:1605.06123



arXiv:1608.06619

How can QU contribute

- As an invited speaker, and not necessarily knowing all the implications of this workshop, I am not sure I am the best person who could tell you how you contribute, but I could give some ideas for Higgs @ FCC-hh
- I can also speak with my software coordinator hat

How can QU contribute

- In Grenada it came across several times that we are not using accurate simulations
  - Could lead to large differences between what we can really achieve with a real detector and real data
  - Historical record that simulations made 20 years ahead of time most often give pessimistic results, because analyses are not optimized
  - Some aspects of detector performances have been tested in full simulation to validate the assumption made in parameterized simulation
  - We welcome anybody that would be interested in simulation and reconstruction studies to validate the current results

- Real R&D for radiation hard silicon detectors?

- Possible studies to be done
  - 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
    - VH production at large mass
  - missing HH decay channels (bb$\tau\tau$ (~8%), bbbb, etc ...) and combination

Conclusion and outlook

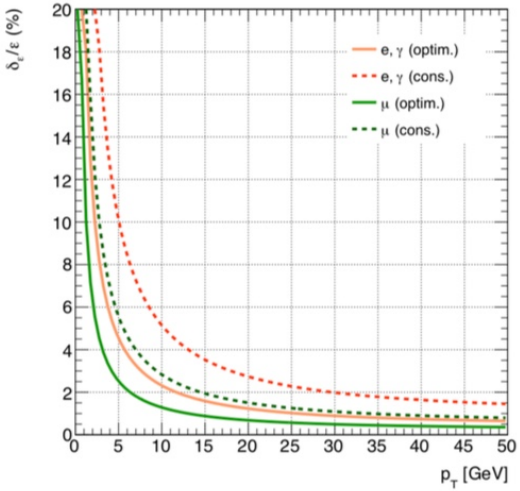
- Higgs-self coupling can be measured with $\delta\kappa_\lambda$(stat) ≈ 5% precision at FCC-hh
  - Best achievable precision among all future facilities
- The FCC-hh machine will produce > 10^{10} Higgs bosons
  - Such large statistics open up a whole new range of possibilities
  - Allowing for precision in new kinematic regimes as well as very strong probe for BSM
- Measuring ratios of couplings (or equivalently BRs)
  - Allows to cancel systematics
  - 1% precision on "rare" couplings within reach after absolute HZZ measurement in e^+e^-
- Extremely rich Higgs program at the FCC, that goes much beyond what was presented
  - light yukawa, Higgs off-shell width measurement, Higgs differentials still to be studied ...

Additional material

Systematics assumptions on Higgs couplings

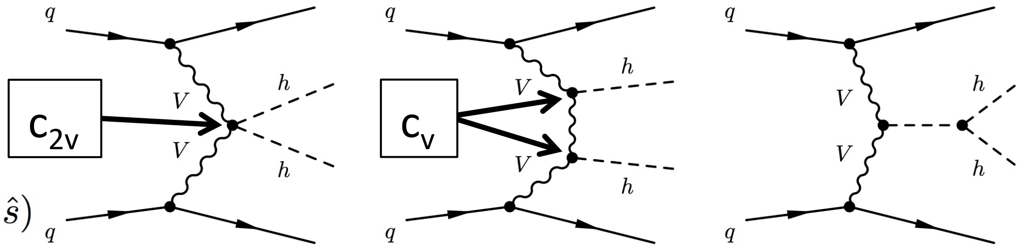
- **1% systematics on (production x luminosity)**, meant as a reference target. Assumes good theoretical progress over the next years, and **reduction of PDF+αS uncertainties with HL-LHC + FCC-ee**.
- **e/μ/γ efficiency systematics** shown on the right. Conservative ~ today. In situ calibration, with the immense available statistics in possibly new clean channels (Z→μμγ), will most likely reduce the uncertainties.
- All final states considered here rely on reconstruction of mH 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-pT objects** will help to decrease relative impact of pile-up
- Assume **(un-)correlated uncertainties** for **(different) same** final
- state objects
- Following **scenarios** are considered:
- δstat → stat. only (I) (signal + bkg)
- δstat , δeff → stat. + eff. unc. (II)
- δstat , δeff , δprod = 1% → stat. + eff. unc. + prod (III)

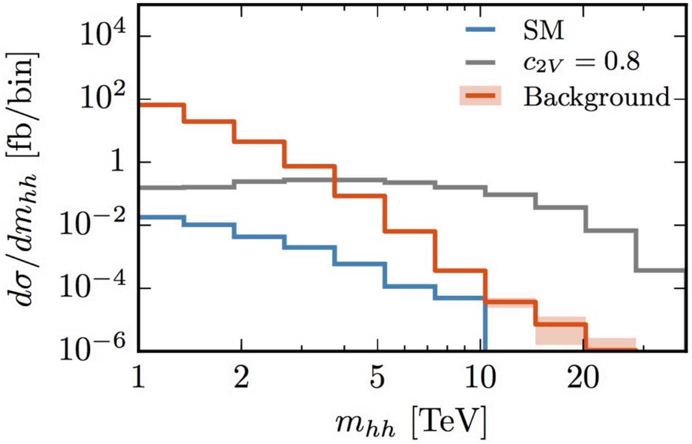


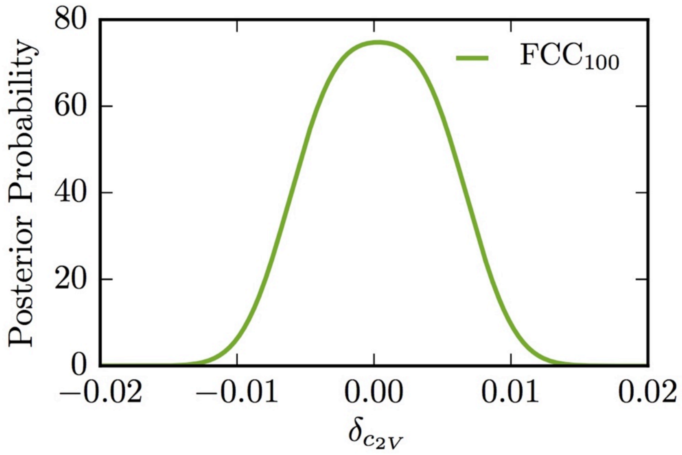
Di-higgs in VBS

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



In the SM, $c_{2v}=c_v^2$

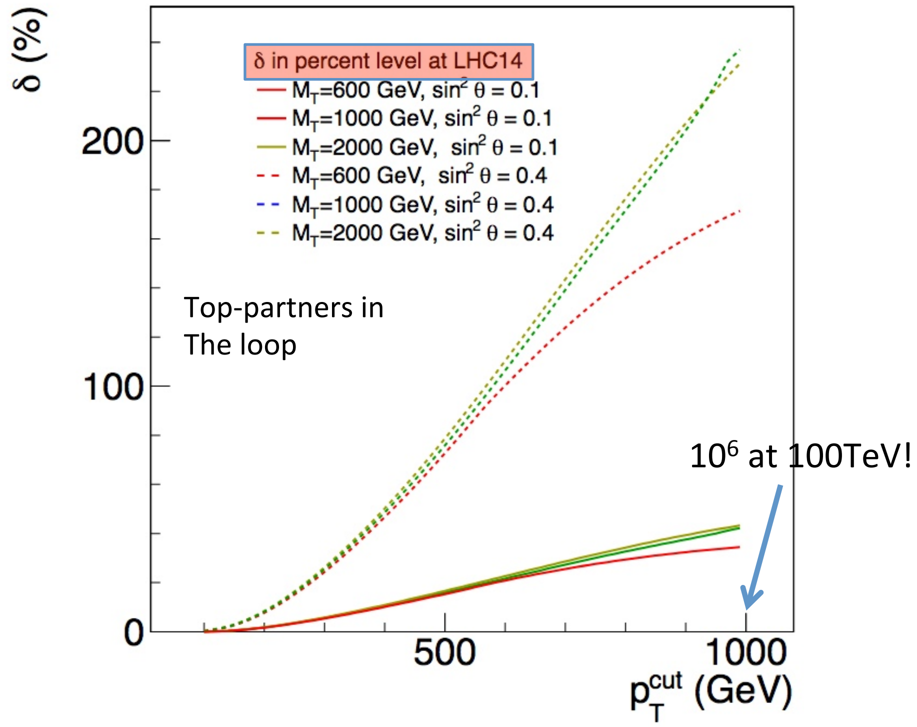




arXiv:1611.03860

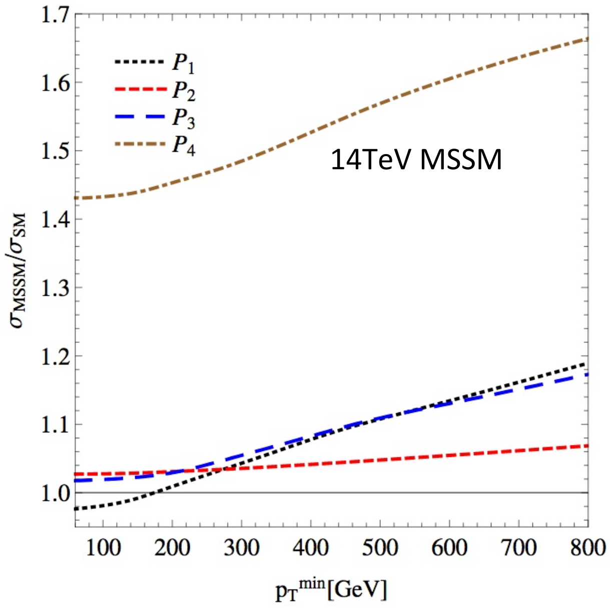
- Considering the 4b boosted final state
- c_v measured at per mille a FCC-ee

Deviations in the Higgs p_T spectrum



arXiv:1308.4771

Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18

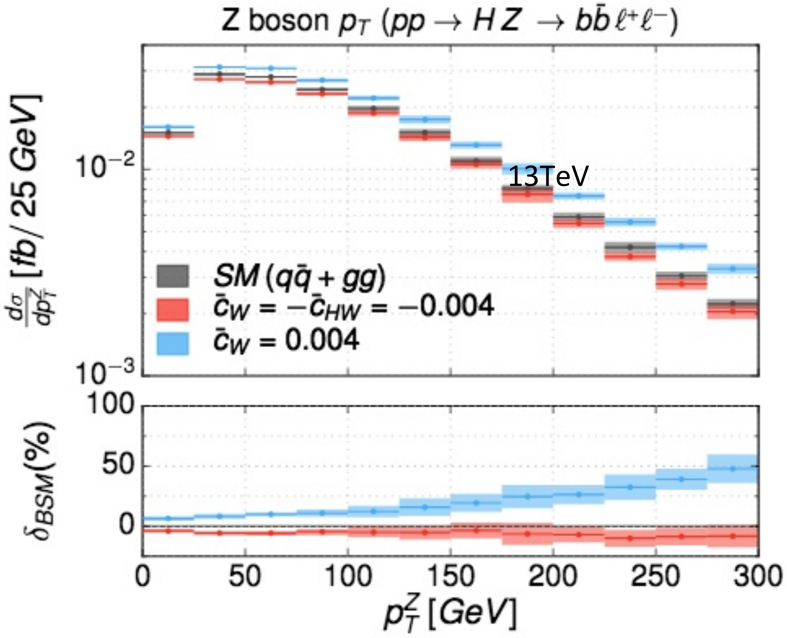


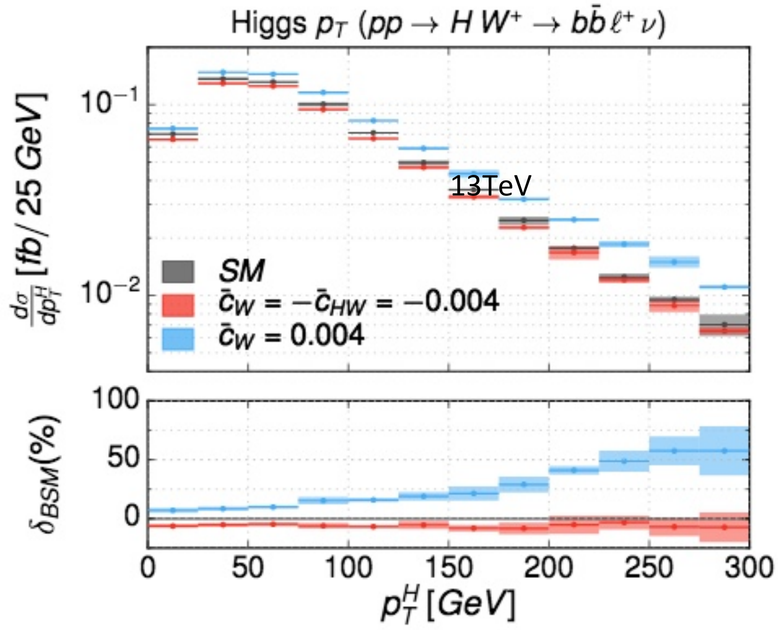
arXiv:1312.3317

VH production at large m(VH)

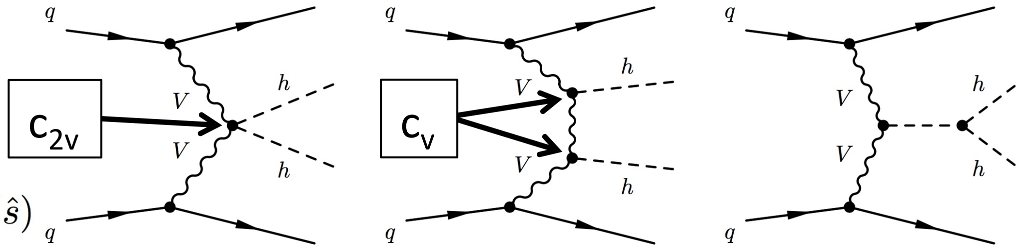
arXiv:1512.02572

- Considering anomalous couplings to gauge boson
- Treated here in the context of an effective field theory (EFT)



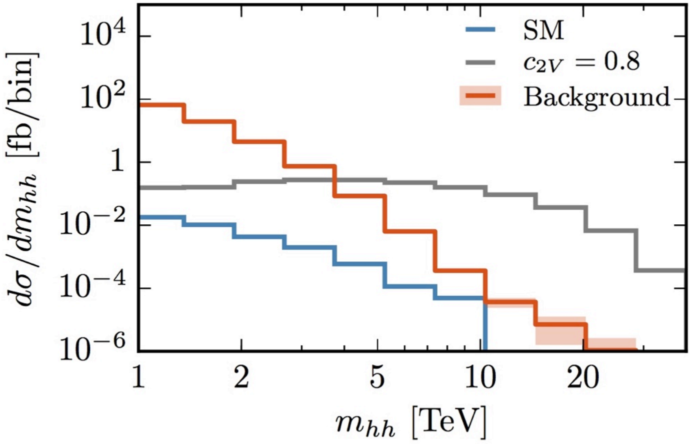


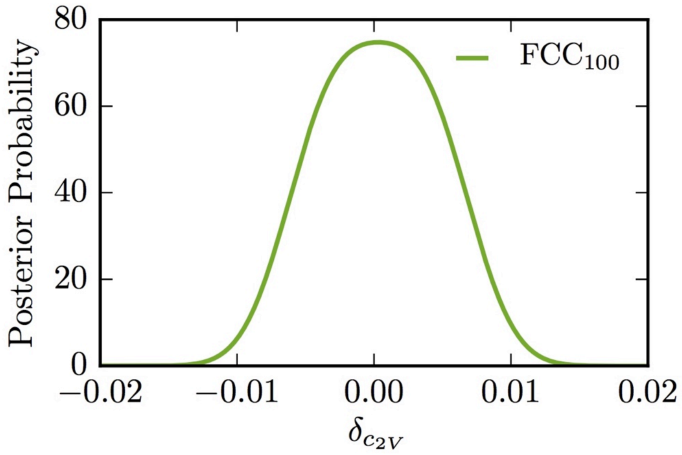
Di-higgs in VBF



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

In the SM, $c_{2V}=c_V^2$





arXiv:1611.03860

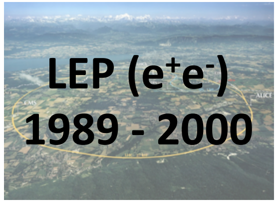
- Considering the 4b boosted final state
- c_V measured at per mille a FCC-ee

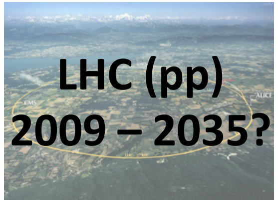
A 100km circular collider as "natural" next the step

Tevatron 2TeV → x 7 → **LHC 14TeV** → x 7 → **FCC-hh 100TeV**

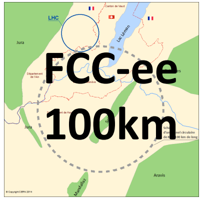
M. Aleksa pECFA

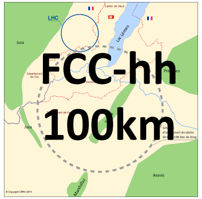
27km tunnel

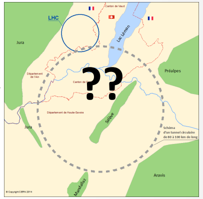




The next step: 100km tunnel







The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology

Both FCC-ee and FCC-hh have outstanding physics cases

We are ready to move to the next step, as soon as possible