Higgs and EWSB @ FCC-hh

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On behalf of the FCC-hh physics group

Higgs Couplings 2018, Tokyo

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 $\sqrt{s}$/14TeV (5-7 at 100TeV)
  - Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC
- Benefit from both direct (large Q^2) and indirect precision probes

Could provide firm answers to questions like

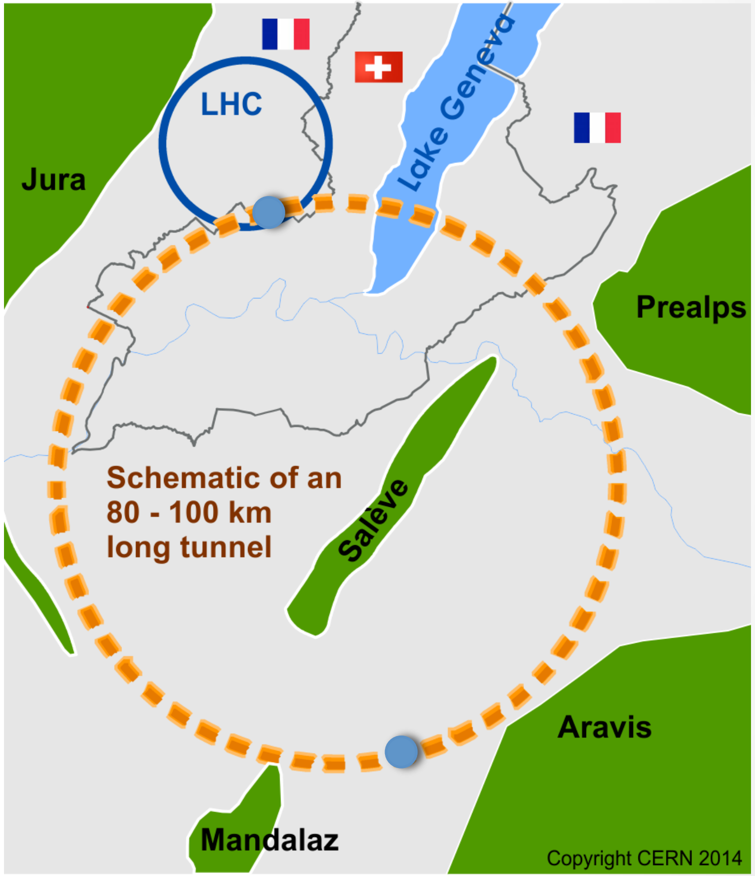
- Is the SM dynamics all there at the TeV scale?
- Is there a TeV-Scale solution the hierarchy problem?
- Is DM a thermal WIMPS?
- Was the cosmological EW phase transition 1st order? Cross-over?
- Could baryogenesis have taken place during EW phase transition?

M.L. Mangano

The FCC-hh

FCC-hh

- Need a new 100km tunnel
- Need 16 Telsa magnet to reach 100TeV in 100km
- 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

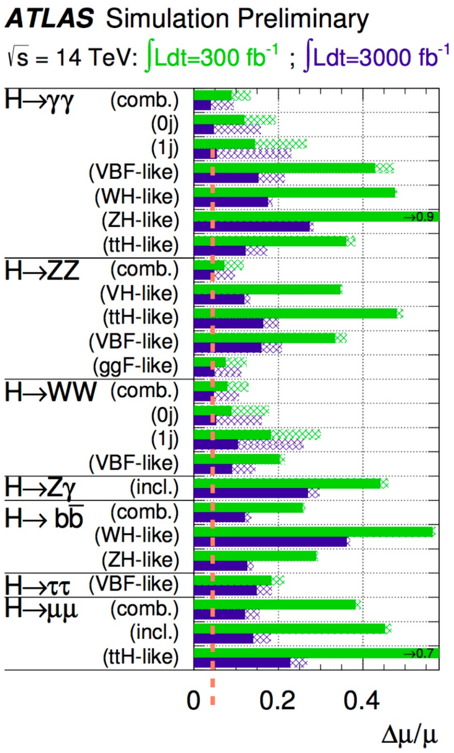
@100TeV FCC-hh

- pp cross-section from 14 to 100TeV only grows by a factor 2
- 10 times more fluence compared with HL-LHC (x100 wrt to LHC)
  - Need radiation hard detectors
- The radiation level increase 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

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), ratios, …) measurements will be statistically limited at FCC-ee

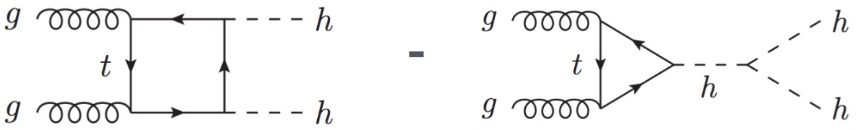
HL-LHC



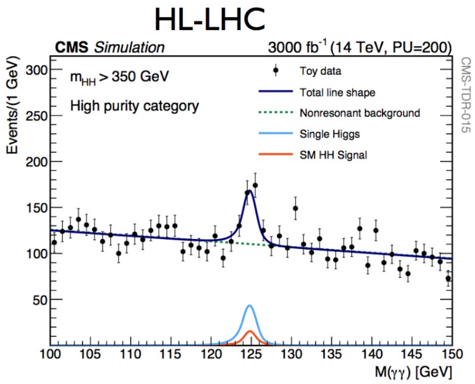
FCC-ee

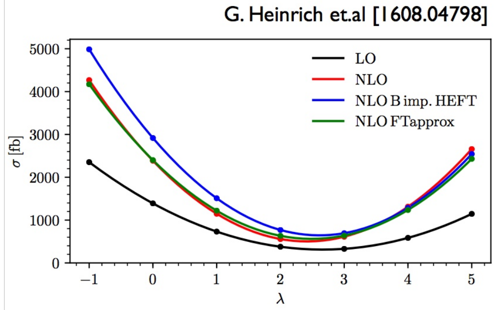
δm_H (MeV)	6
$\delta\Gamma_H / \Gamma_H$(%)	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	0.68
$\delta g_{HW} / g_{HW}$ (%)	0.47
$\delta g_{H\tau} / g_{H\tau}$(%)	0.80
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	3.8
$\delta g_{H\mu} / g_{H\mu}$ (%)	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	1.2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

Higgs self-coupling @ FCC-hh



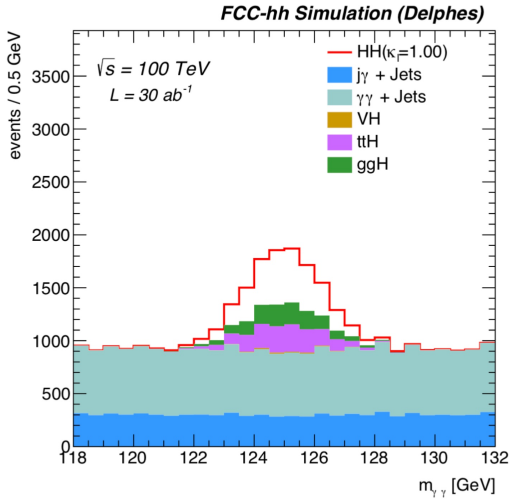
- Very small cross-section due to negative interference with box diagram
- HL-LHC projections : $\delta\lambda/\lambda$ = 100%
- Expect large improvement at FCC-hh:
  - σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
  - x400 in event yields and x20 in precision
- Mainly 4 channels studied:
  - bbγγ (most sensitive)
  - bbZZ(4l)
  - bbbbj (boosted)
  - bbWW

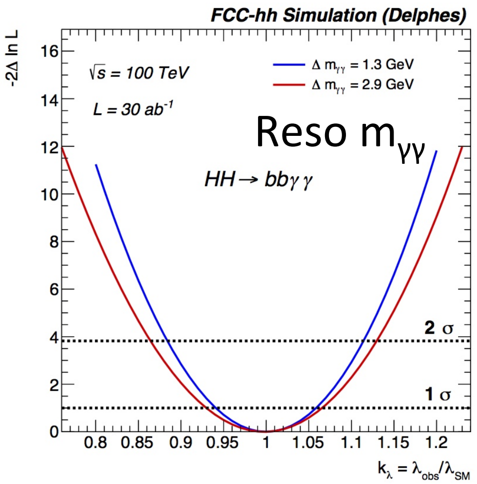


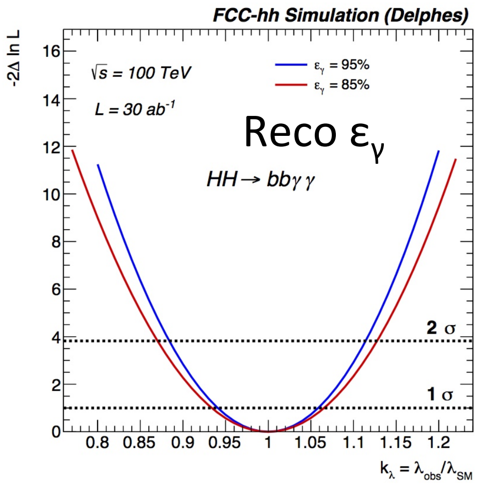


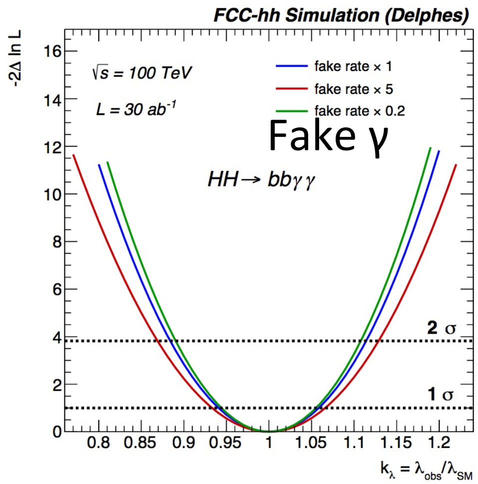
HH →bbγγ

- 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



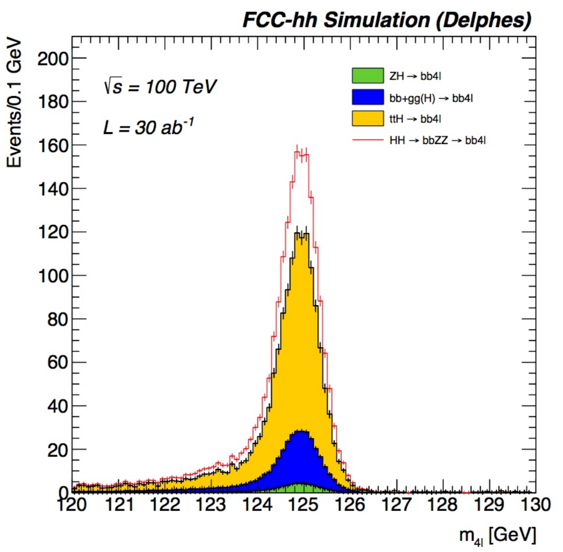


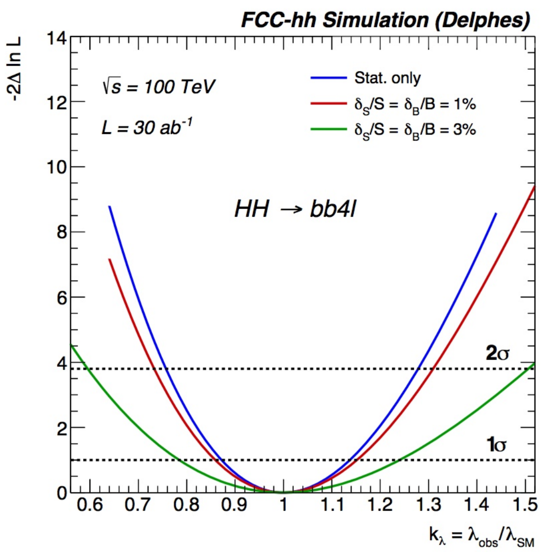


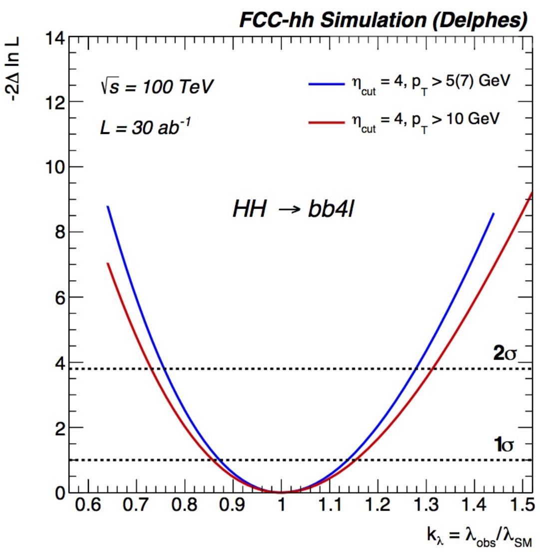


HH →bb4l

- **New channel** opening at (cross-section 180ab) FCC-hh !!
- 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 are powerful reconstruction of low energetic electrons and muons

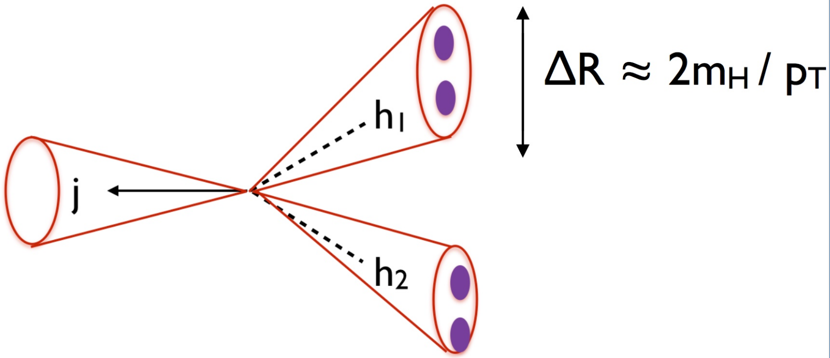


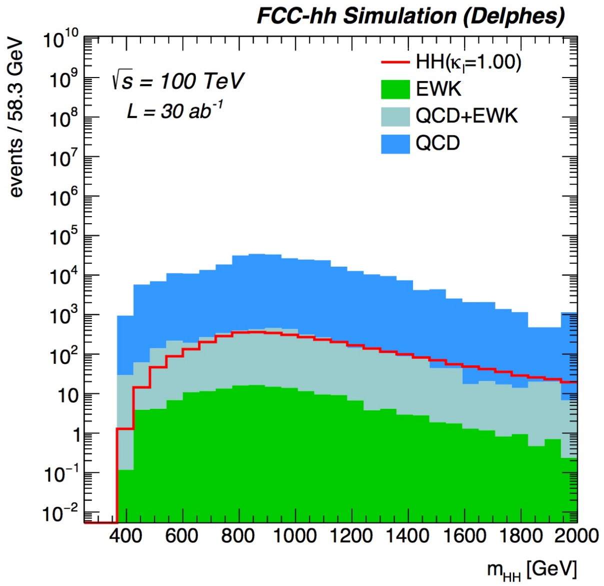


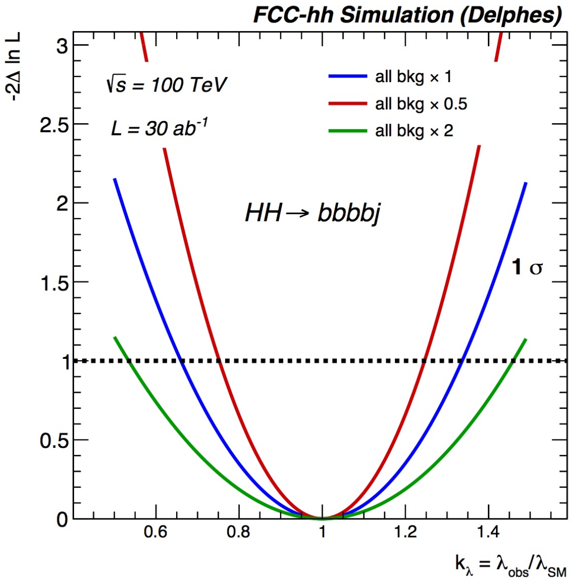


HH →4b+j boosted

- 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

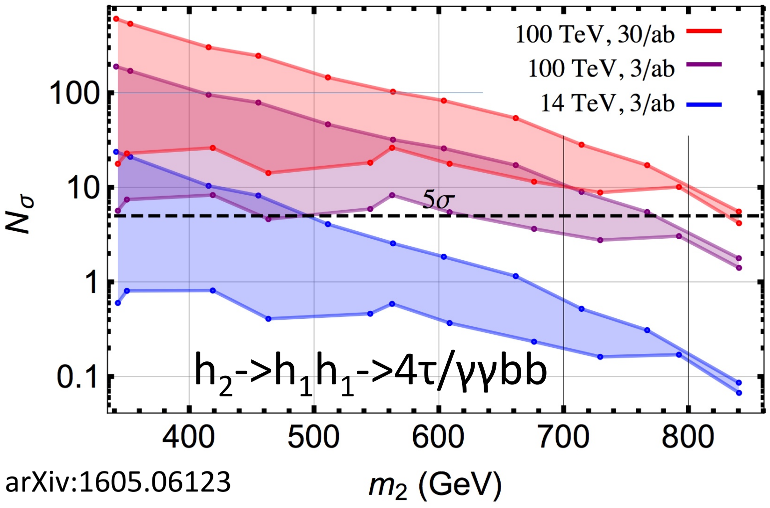




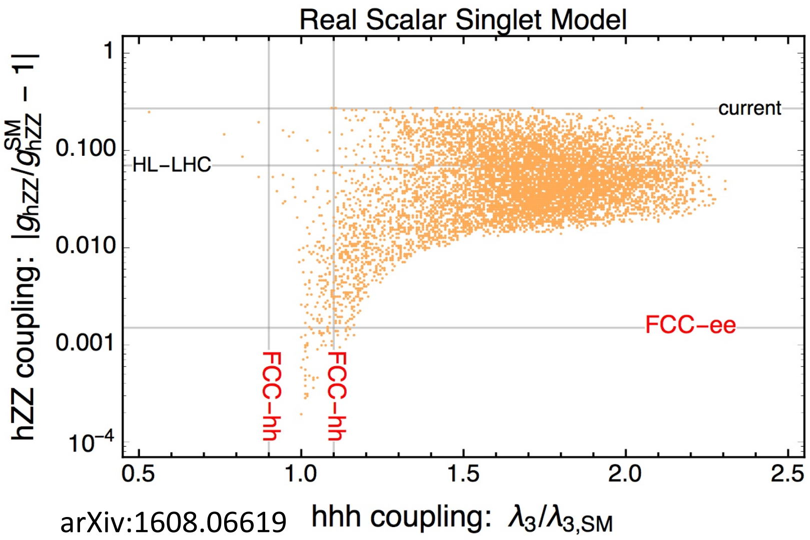


Higgs and EW phase transition

- 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

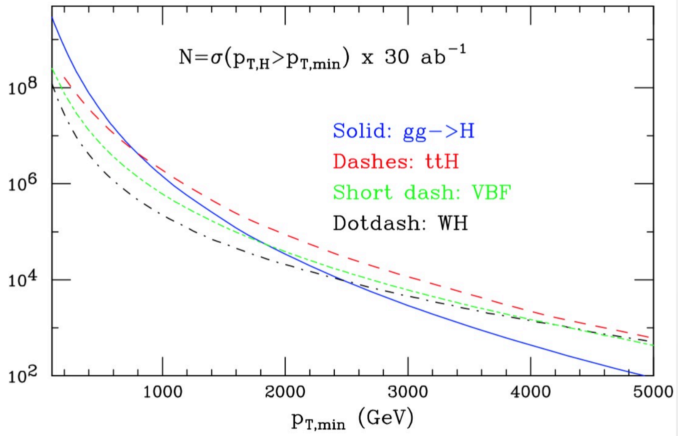


arXiv:1608.06619

Higgs measurements @ FCC-hh

- Expected improvements @ FCC-hh:
  - 2 10^{10} Higgses produced
  - Factor 10-50 in cross sections (and Lx10)
  - Reduction of a factor 10-20 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 impact of systematics

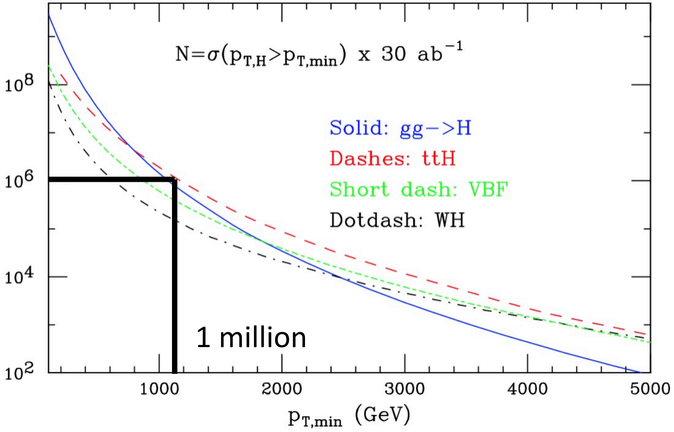
	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55



Higgs 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

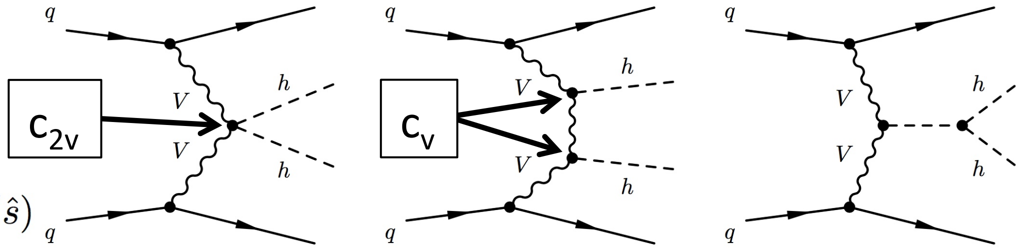
- For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

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

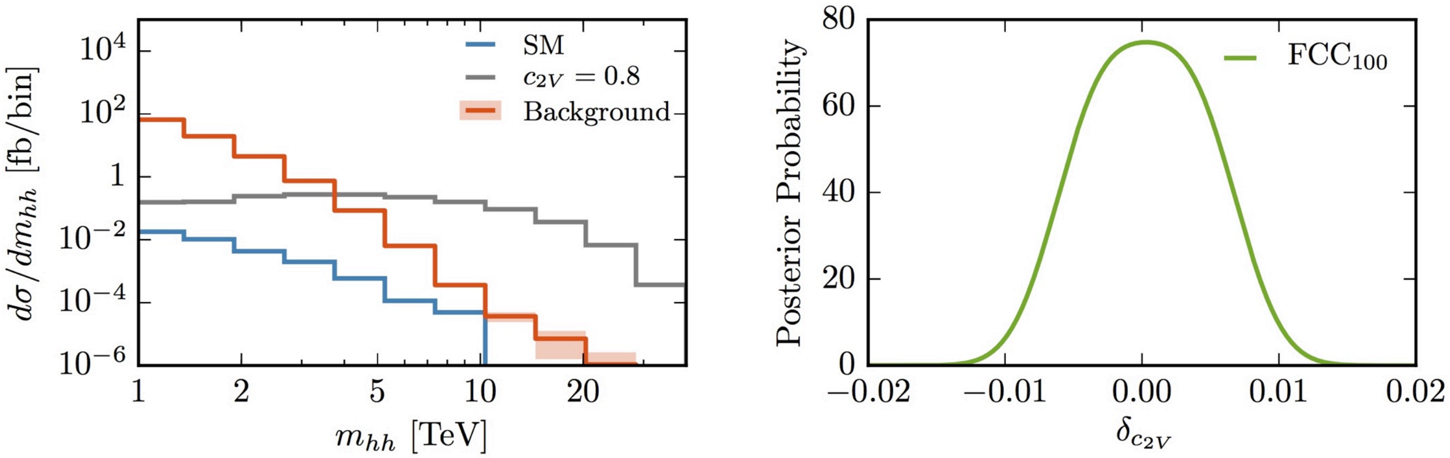
- kinematic reach probes large Λ even if precision is "low" e.g. δO=10% at Q=1.5 TeV ⇒ Λ~5 TeV

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

Di-higgs in VBS



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



arXiv:1611.03860

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

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 (light yukawa, Higgs off-shell width measurement, Higgs differentials) still to be studied ...
- FCC CDRs for sign-up https://indico.cern.ch/event/750953/
- Soon printed and published

HEP Landscape

G.F.Giudice, ICFA, Nov. 2017

- Particle accelerators are built to answer some of the most fundamental questions about the natural world
- Physics priorities are likely to shift swiftly, as we advance in our exploration, both experimentally and theoretically
- There are many unknowns ahead of us that may reshuffle the cards (e.g. any discoveries of HL-LHC)

→ We need a broad and bold program capable of adapting to the swift changes in the physics landscape that are likely to happen

→ 100TeV hadron collider – In times of uncertainty, bold exploration is the way to go

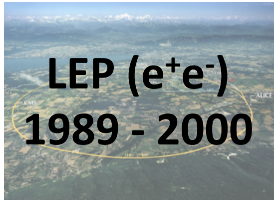
Complementarity and synergy with high-luminosity lepton machine, FCC-ee

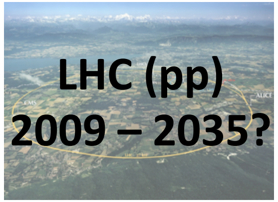
A 100km circular collider as “natural” next the step

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

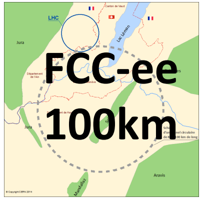
M. Aleksa pECFA

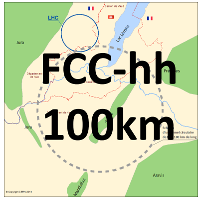
27km tunnel

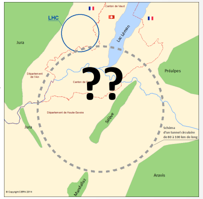




The next step: 100km tunnel







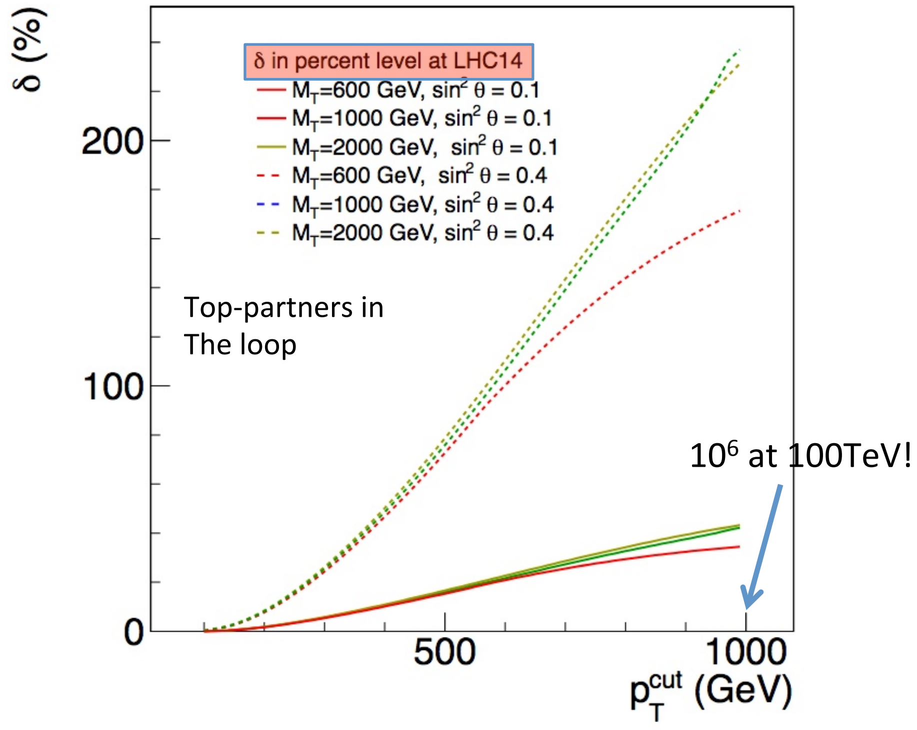
The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology

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

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

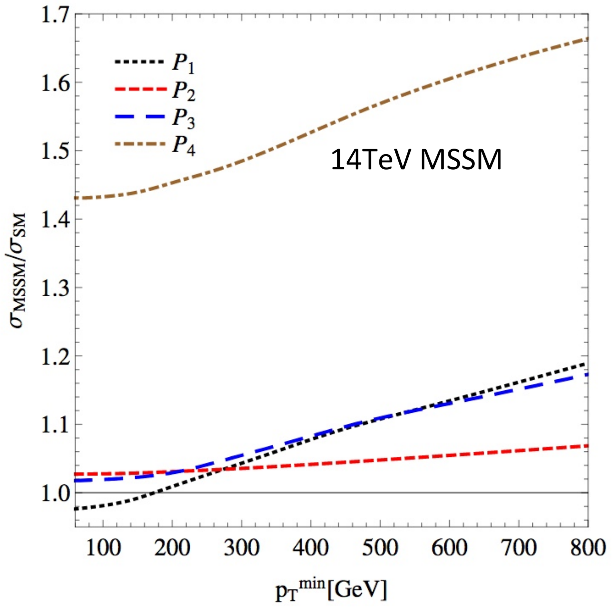
Additional material

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

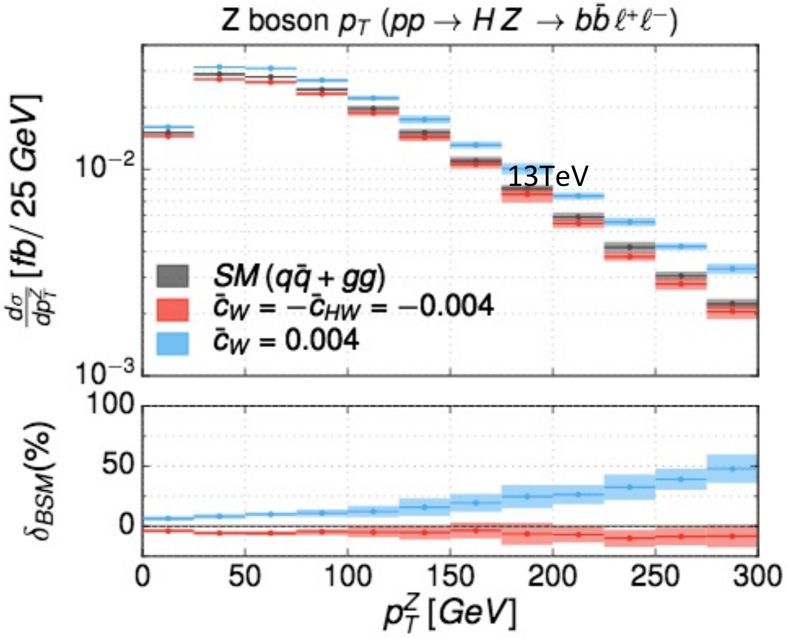


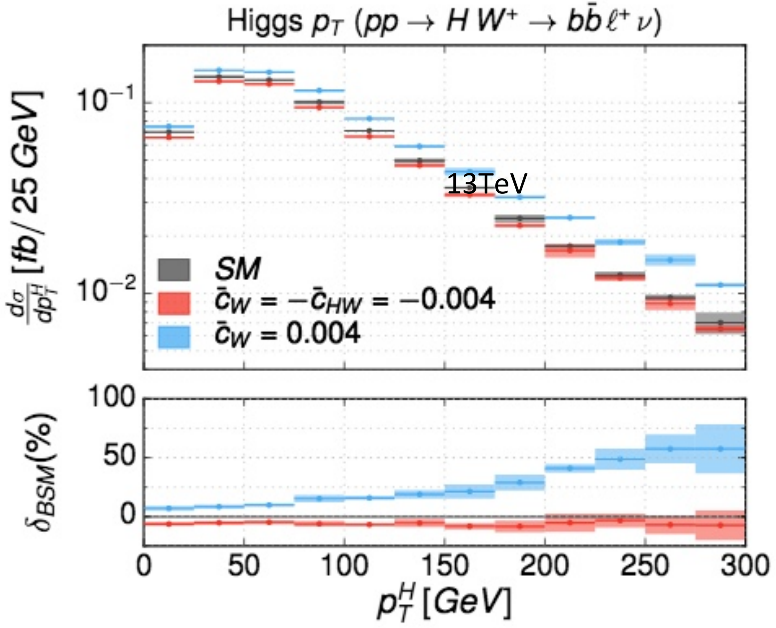
arXiv:1312.3317

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

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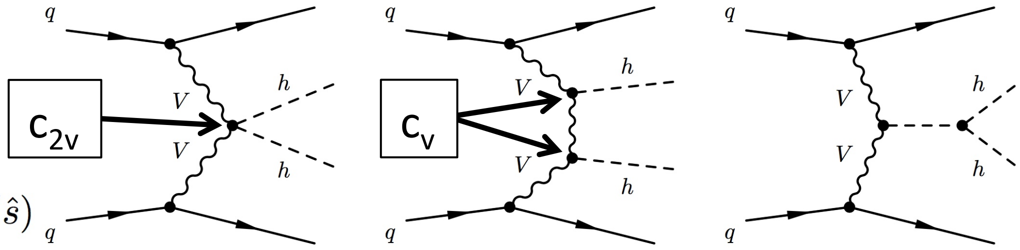
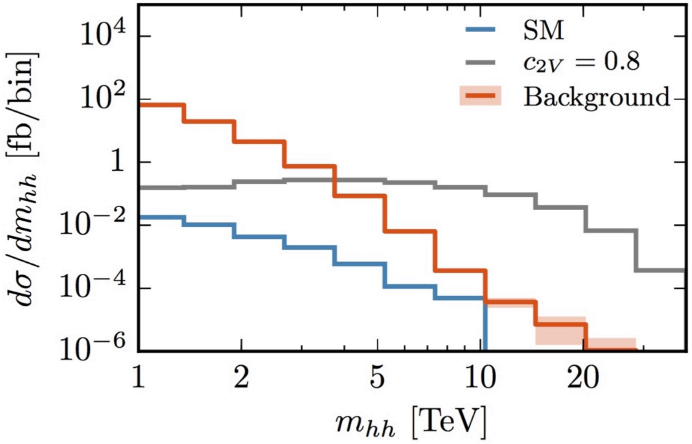
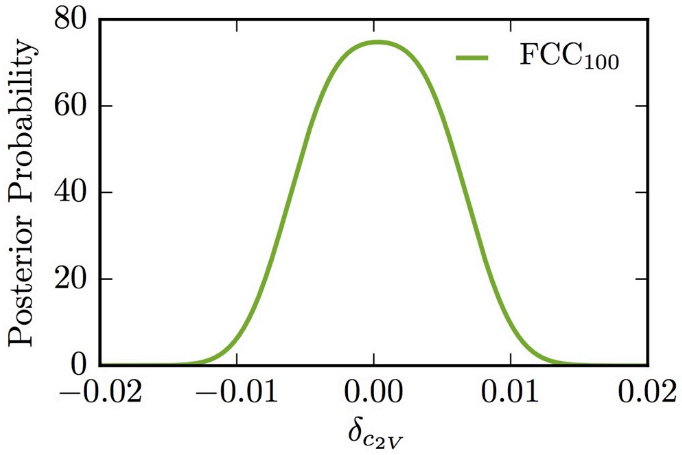


In the SM, $c_{2v}=c_v^2$





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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 to relate to measured Z->ee, W and gamma spectra