Snowmass 2021 — Energy Frontier
*WG-01 meeting: **Higgs distributions and CPV***
24 June 2020

FCC-hh Higgs studies

Michelangelo L. Mangano
michelangelo.mangano@cern.ch
Theoretical Physics Department
CERN

For an **overview** of Higgs studies and **links** to existing documents, see

C.Helsens, M.Mangano, M.Selvaggi,
A framework and goals for FCC-hh physics studies at Snowmass 2021,
http://cds.cern.ch/record/2717892

In particular, see:
- Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies, Contino et al, https://arxiv.org/abs/1606.09408
- Higgs measurements at FCC-hh, L.Borgonovi et al, https://cds.cern.ch/record/2642471

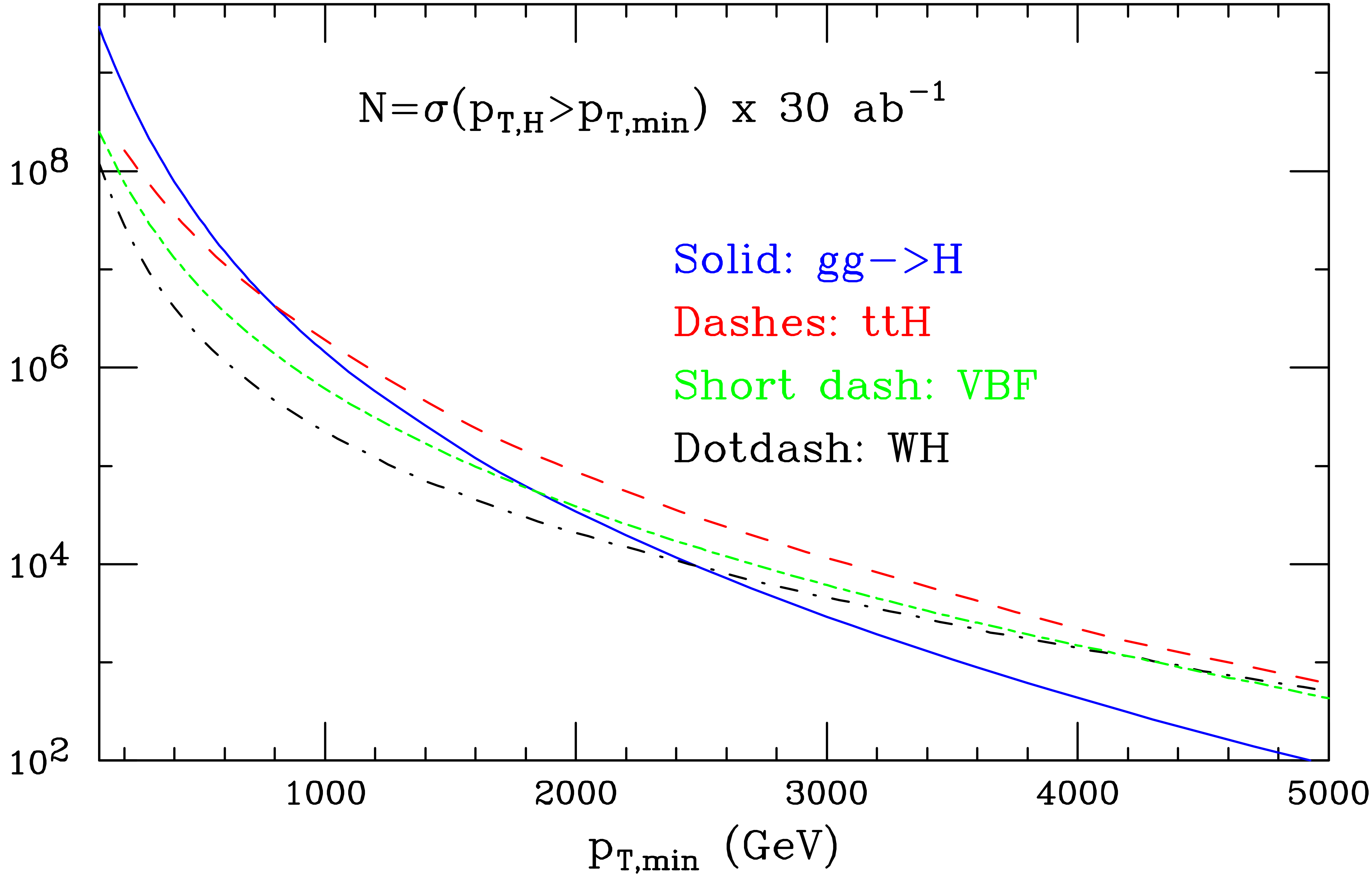
SM Higgs: event rates at 100 TeV

	$gg \to H$	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	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

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

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

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

Three kinematic regimes

- Inclusive production, $p_T > 0$:
  - largest overall rates
  - most challenging experimentally:
    - triggers, backgrounds, pile-up ⇒ low efficiency, large systematics

  ➡ det simulations challenging, likely unreliable ⇒ regime not studied so far

- $p_T \gtrsim 100$ GeV :
  - stat uncertainty ~few × 10^{-3} for $H\to 4l, \gamma\gamma, \ldots$
  - improved S/B, realistic trigger thresholds, reduced pile-up effects ?

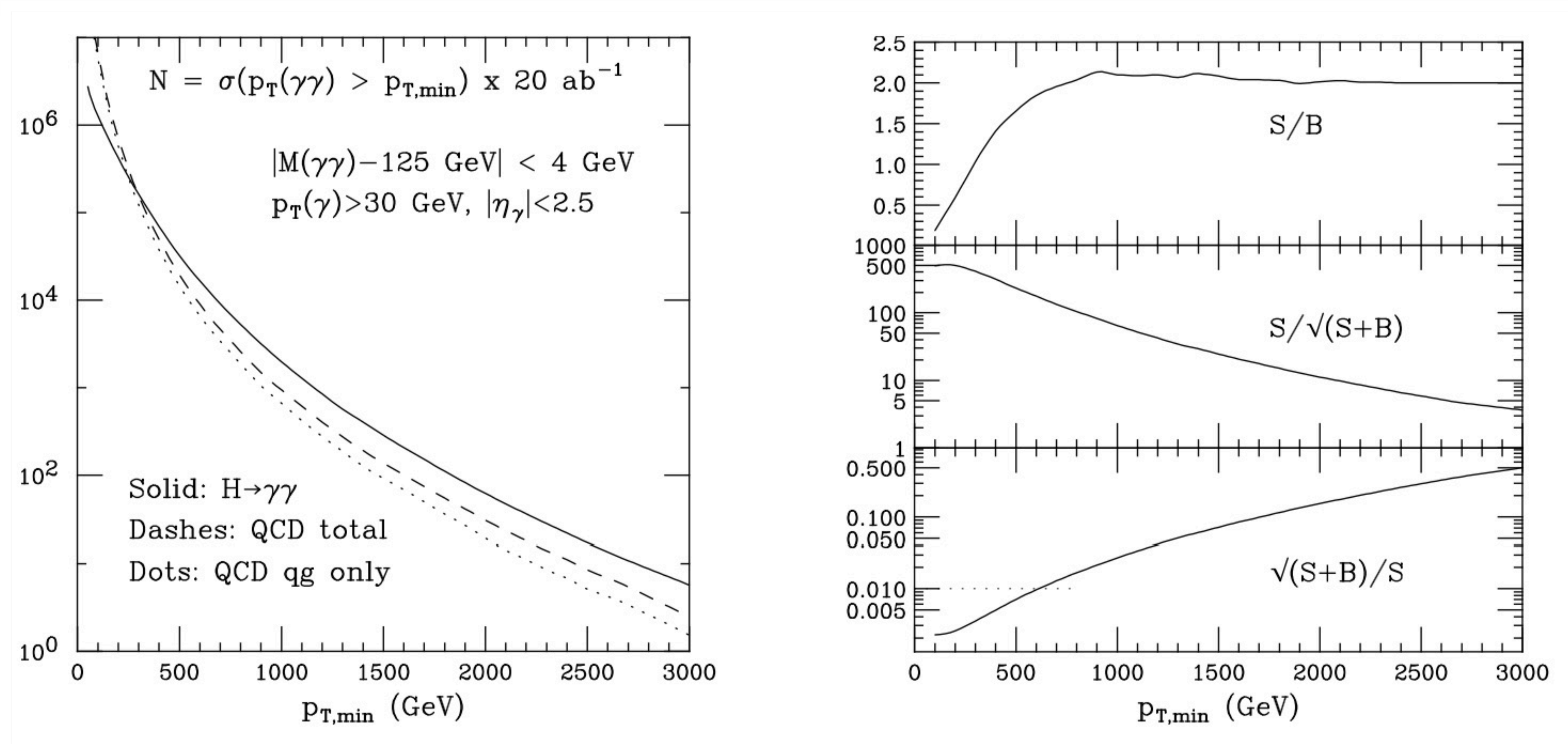
  ➡ current det sim and HL-LHC extrapolations more robust

  ➡ focus of FCC CDR Higgs studies so far

  ➡ sweet-spot for precision measurements at the sub-% level

- $p_T \gtrsim$ TeV :
  - stat uncertainty O(10%) up to 1.5 TeV (3 TeV) for $H\to 4l, \gamma\gamma$ ($H\to bb$)
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q\sim m_H$

gg→H→γγ at large p_T



- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

Delphes-based projections

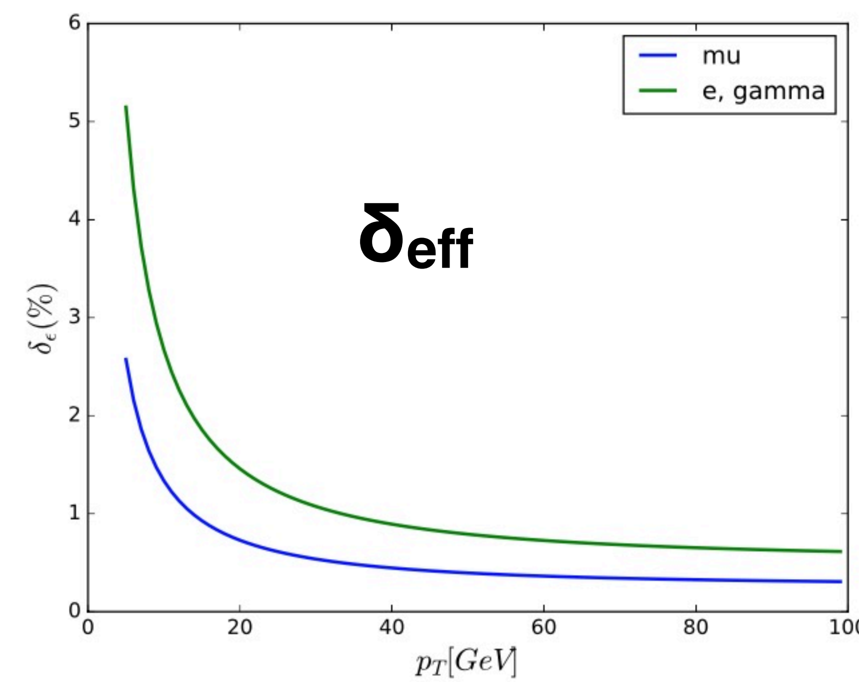
For detailed links, see http://cds.cern.ch/record/2717892

All **signal and background samples** have been generated via the following chain (using the FCCSW): http://fcc-physics-events.web.cern.ch/fcc-physics-events/LHEevents.php

- **MG5aMC@NLO + Pythia8**
  - LO (MLM) matched samples (up to 1/2/3 jets) and global K-factor applied to account for $N^{2/3}LO$ corrections
  - full list of signal prod. modes simulated (ggH with finite m_{top})
- **Delphes-3.4.2** with baseline FCC-hh detector

Consider the following categories of uncertainties:

- δ_{stat} = statistical
- δ_{prod} = production + luminosity systematics
- $\delta_{eff}^{(i)}$ (pT) = object reconstruction (trigger+isolation+identification) systematics
- δ_B = 0, background (assume to have ∞ statistics from control regions)



Assume (un-)correlated uncertainties for (different) same final state objects

Following scenarios are considered:

- δ_{stat} → stat. only (I)
- δ_{stat} , δ_{eff} → stat. + eff. unc. (II)
- δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + eff. unc. + prod (III)

could be seen as syst in the normalization of production*lumi wrt standard candles such as pp→Z→ee

Remarks

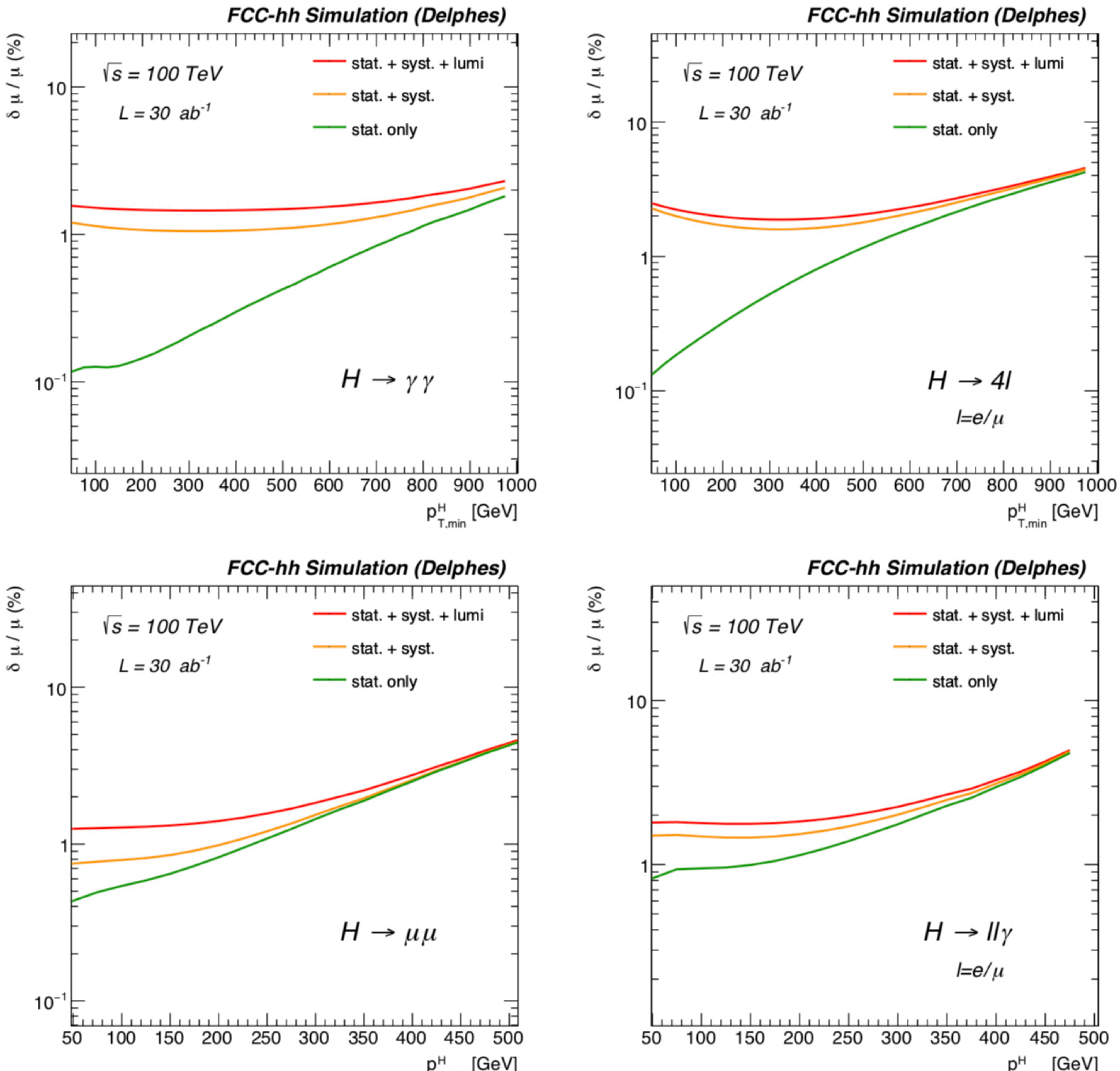
- 1% systematics on (production x luminosity) is meant as a reference target.
  - Reasonably justified by foreseen theoretical progress over the next few decades. Few % is already achievable **today** for channels such as VH or VBF:

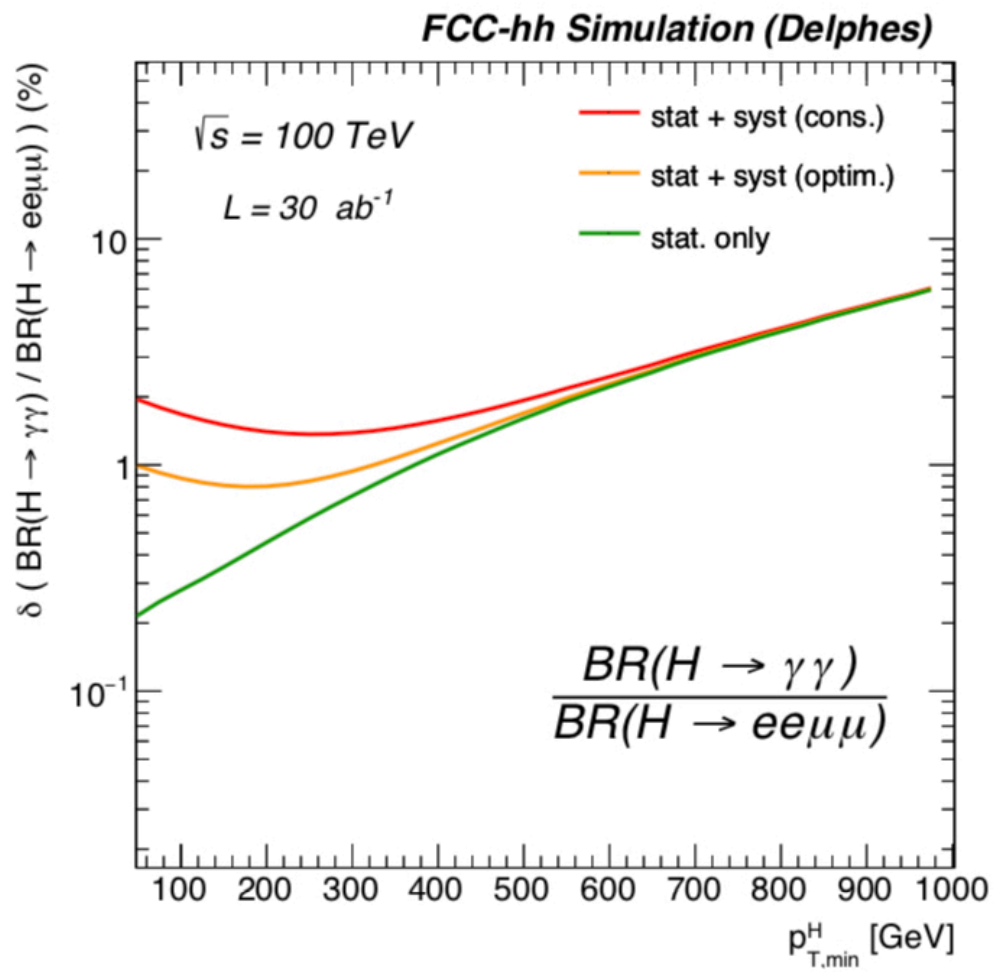
14 TeV	σ[fb]	Δ_{scale} (%)	$\Delta_{PDF+\alpha S}$ (%)
pp -› lν H	66.6	$^{+0.52}_{-0.64}$	±1.9
pp -› l+ l− H	33.1	$^{+3.6}_{-2.9}$	±1.9
VBF	4260	$^{+0.45}_{-0.34}$	±2.1

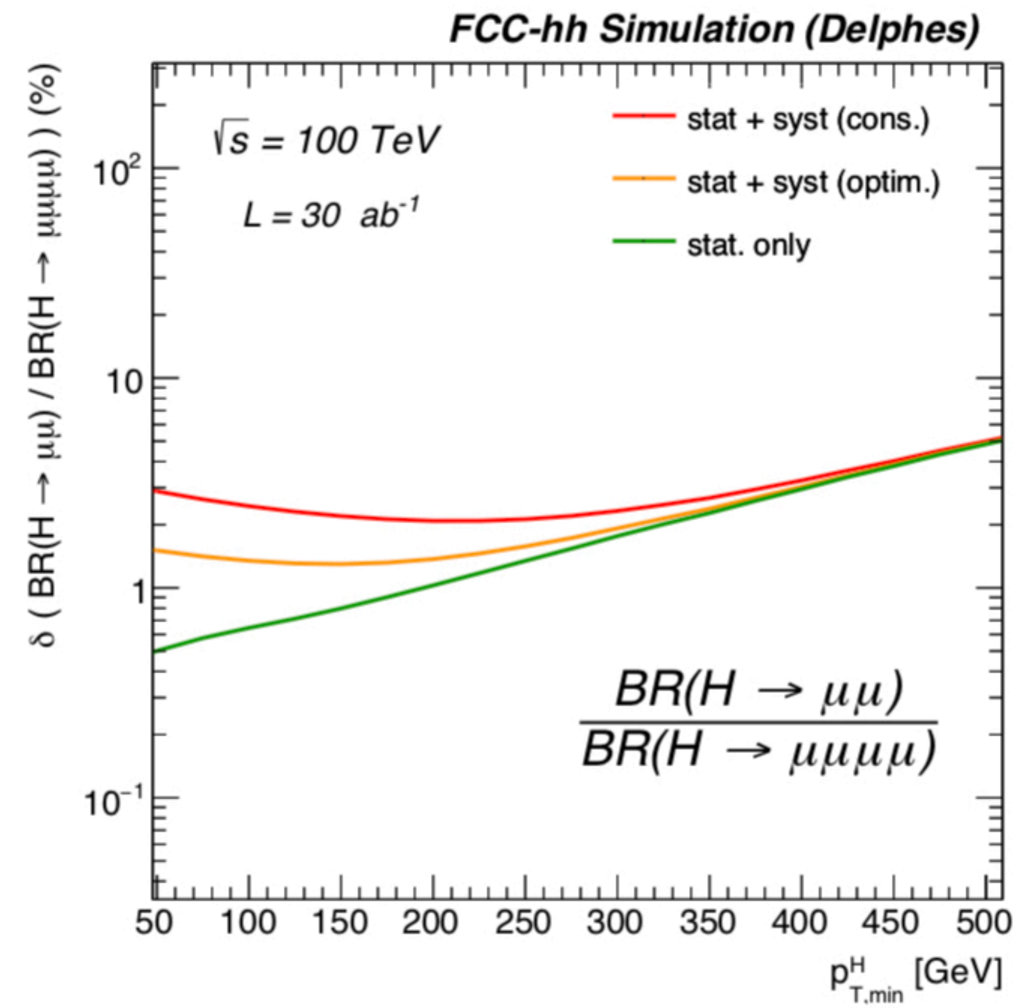
Dominated by gg->ZH systematics

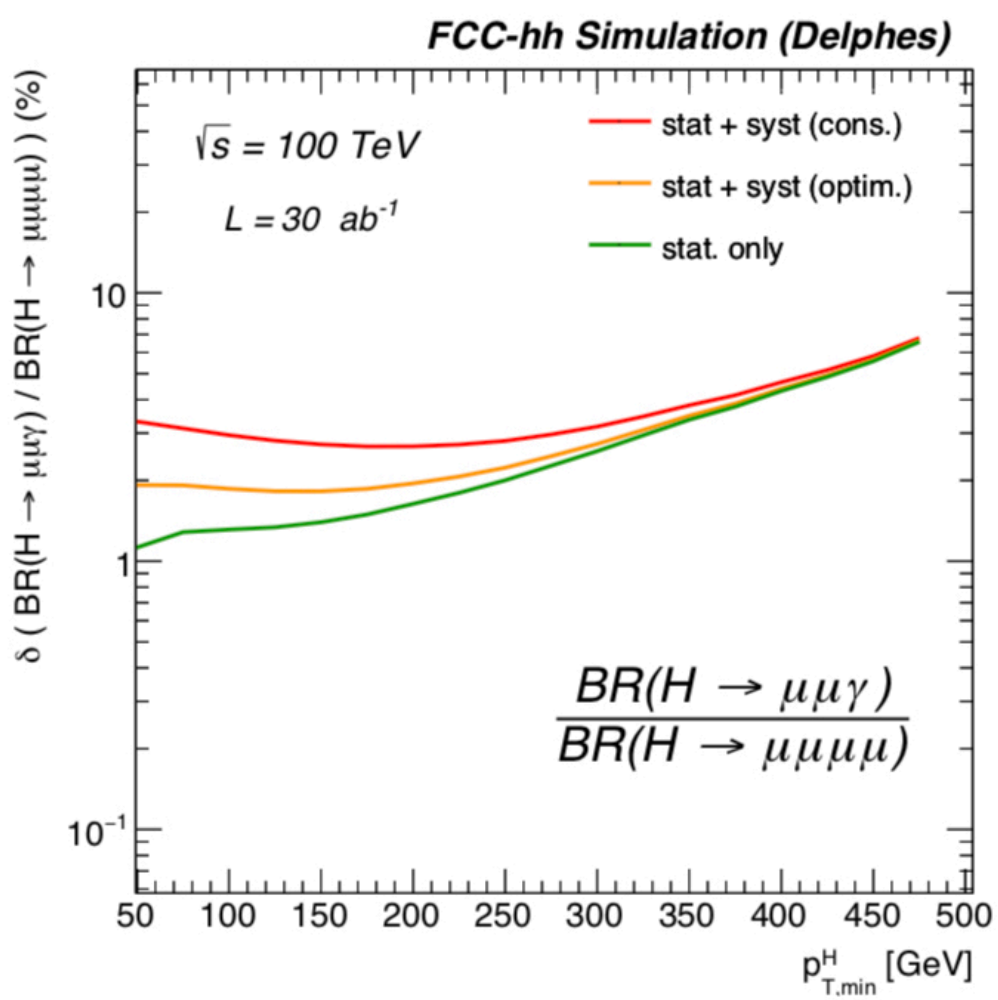
(VH and VBF statistics at FCC by itself will allow for sub-% statistical precision in the relevant decay channels)

  - This systematics drops out when considering ratios of BRs, which after the FCC-ee are anyway the most interesting observables
- e/μ/γ efficiency systematics based on **today's** performance. In situ calibration, with the immense available statistics, will most likely reduce the uncertainties
- Final states used for precision measurements rely on reconstruction of mH to within few GeV. All bg's (physics and instrumental) to be determined with great precision from sidebands
- Impact of pile-up: hard to estimate with today's analyses. Expect that focus on high-pT objects will mitigate the issue


FCC-hh Simulation (Delphes)
√s = 100 TeV
L = 30 ab⁻¹
stat. + syst. + lumi
stat. + syst.
stat. only
H → γγ
H → 4l
l=e/μ
H → μμ
H → llγ
l=e/μ
δ μ / μ (%)
p^H_T,min [GeV]







Normalize to BR(4l) from ee => sub-% precision for absolute couplings

Possible work: explore in more depth data-based techniques, to validate and then reduce the systematics in these ratio measurements, possibly moving to lower pt's and higher stat

Importance of standalone precise “ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

$BR(H\to\gamma\gamma)/BR(H\to ZZ^*)$

loop-level tree-level

$BR(H\to\mu\mu)/BR(H\to ZZ^*)$

2nd gen’n Yukawa gauge coupling

$BR(H\to\gamma\gamma)/BR(H\to Z\gamma)$

different EW charges in the loops of the two procs

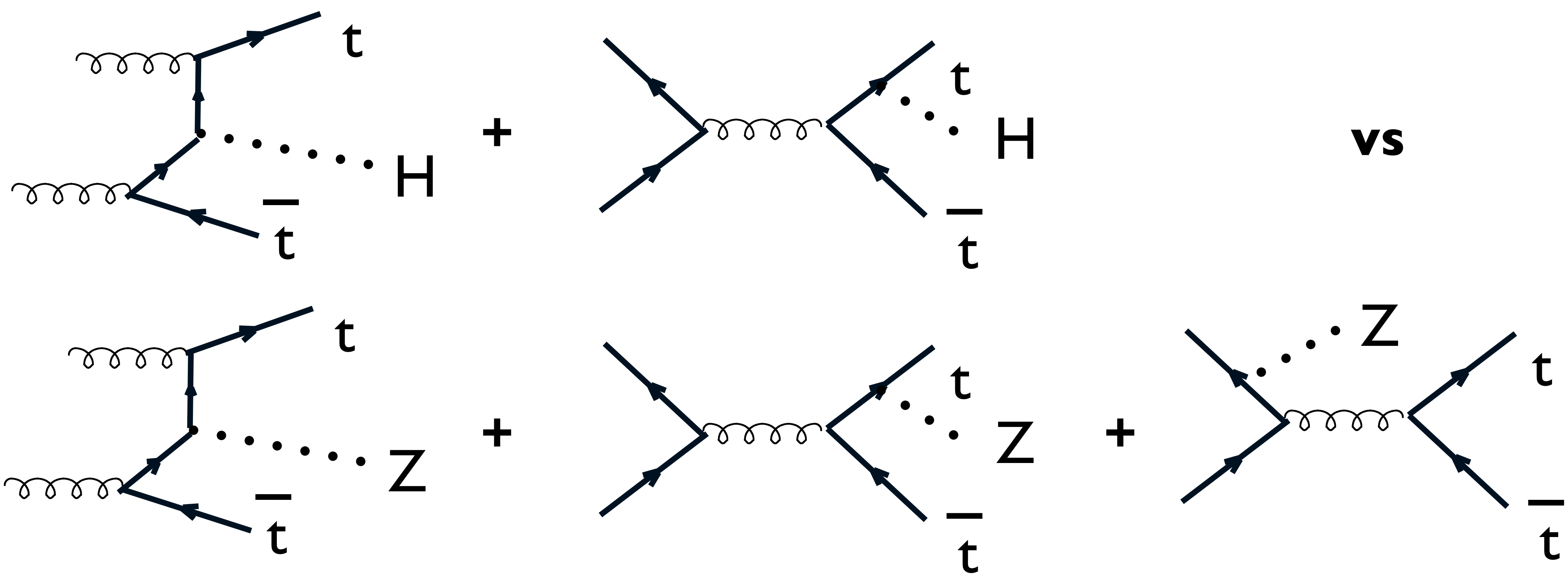
$BR(H\to inv)/BR(H\to\gamma\gamma)$

tree-level neutral loop-level charged

Possible work: study impact of precise ratio measurements in the context of specific BSM models, set targets. Any special opportunities?

Top Yukawa coupling from σ(ttH)/σ(ttZ)

arXiv:1507.08169



To the extent that the qqbar → tt Z/H contributions are subdominant:

- **Identical production dynamics:**

  o correlated QCD corrections, correlated scale dependence
  o correlated α_s systematics

- **$m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:**

  o correlated PDF systematics
  o correlated m_{top} systematics

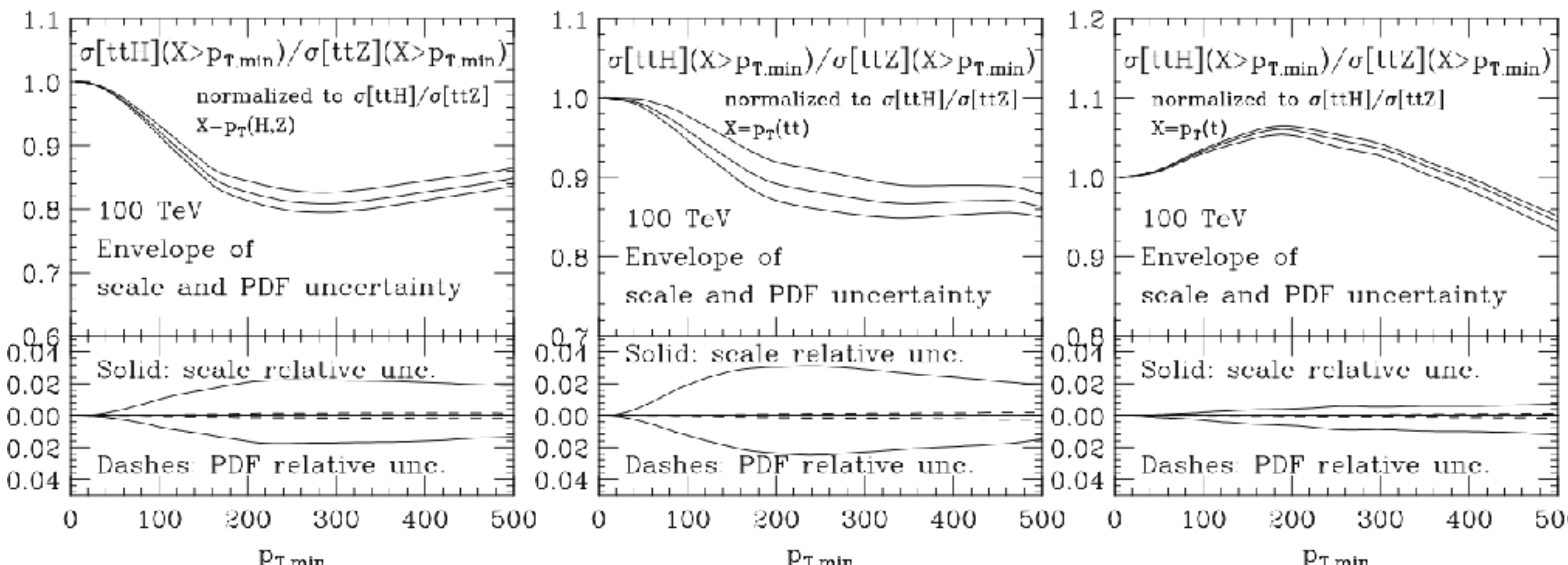
For a given y_{top}, we expect σ(ttH)/σ(ttZ) to be predicted with great precision

Cross section ratio stability

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

scale PDF

Production kinematics ratio stability



Analysis in arXiv:1507.08169 used boosted H/Z→bb decays (large stat, reduced combinatoric bg, correlated b-tagging efficiencies, …)
Reloaded with FCC-hh det sim in https://cds.cern.ch/record/2642471

- ttjj and ttbb bgs "measured" with data at mjj>200 with negligible δ_{stat} . Syst to be assessed for shape modeling under mH peak systematics
- ttZ kinematics validated with Z→leptons
- N(ttH)/N(ttZ) = 1.64 ± 0.01 (stat.) after perfect bg subtraction

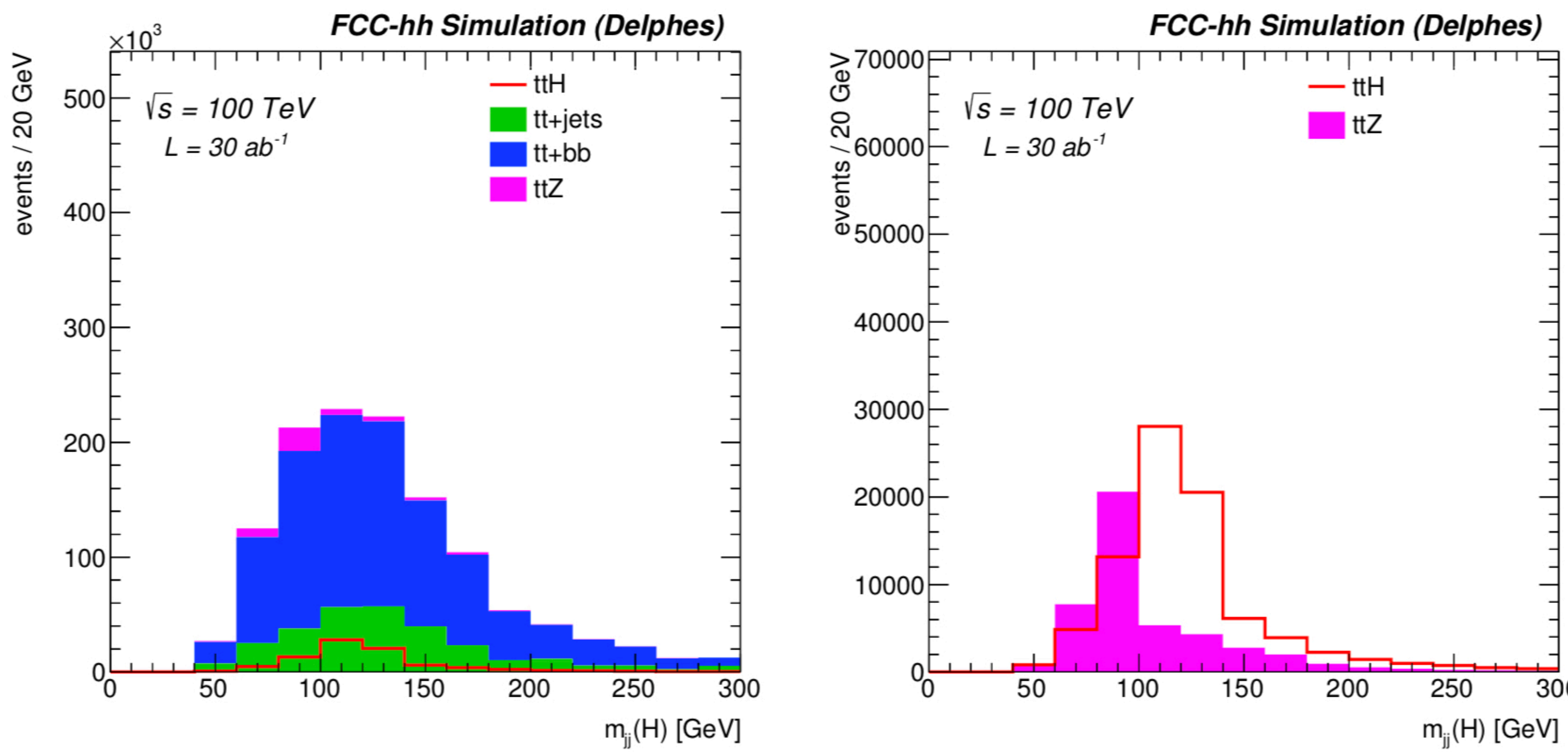


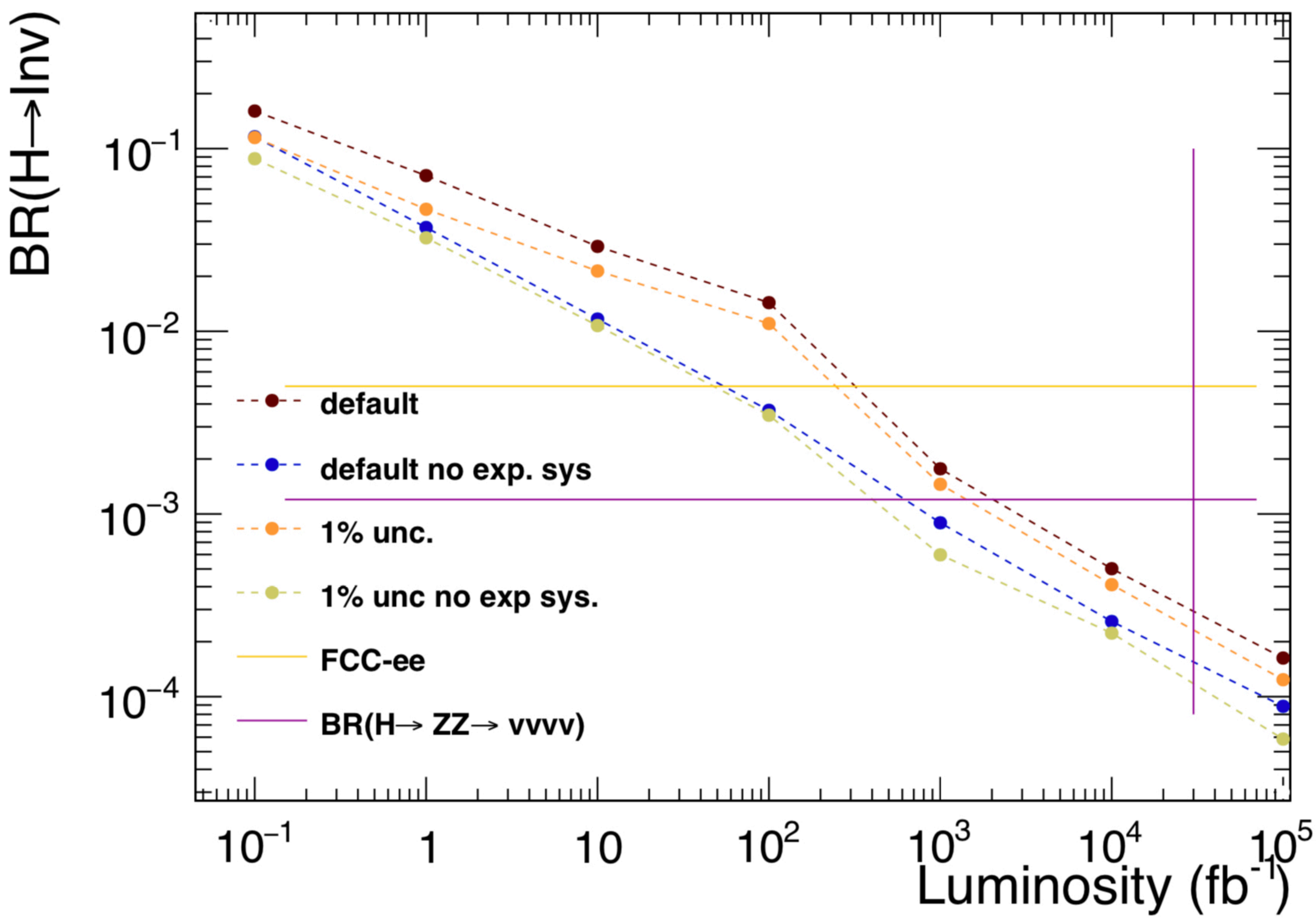
Figure 7: Invariant mass the di-jet pair forming the Higgs candidate including all backgrounds (left) and after (perfect) background subtraction as input for measuring the ttH/ttZ fraction (right).

Remarks

- This measurement requires knowledge of ttZ EW coupling to % level => FCC-ee
- **Further work to be done:**
  - consolidate determination of bg shapes and impact on overall fit of ttH and ttZ components ($H/Z \to bb$)
  - explore different final states…
  - Eg ttH($\to\gamma\gamma$) / ttZ($\to$ee): doesn't require large boost, much reduced bgs, correlated E scales and ID eff (e vs γ), …

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

Constrain bg pt spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z→ee, W and γ spectra



SM sensitivity with 1ab^{-1}, can reach few x 10^{-4} with 30ab^{-1}

Table 4.4: Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling λ. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(HH) \times B(H \to \gamma\gamma) B(H \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = B(H \to \mu\mu\gamma)/B(H \to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

Further work to do on decay-properties measurements:

- Apply to FCC-hh the various techniques proposed for the measurement of the total H width at the LHC: what is the precision reach?
- Consider decays to other large-BR channels, bb, WW, ττ:
  - unlikely to improve FCC-ee measurements, but …
  - … can use to extend use of H as a tool (eg to reach larger p_T^H regions)
- Probes of Hcc: H→cc in boosted jets, exclusive H→J/ψ γ decays, …
- Couplings to lighter quarks (exclusive decays)
- Rare/forbidden decays (eμ, μτ, eτ, …, multibodies, …)

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

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

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. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

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

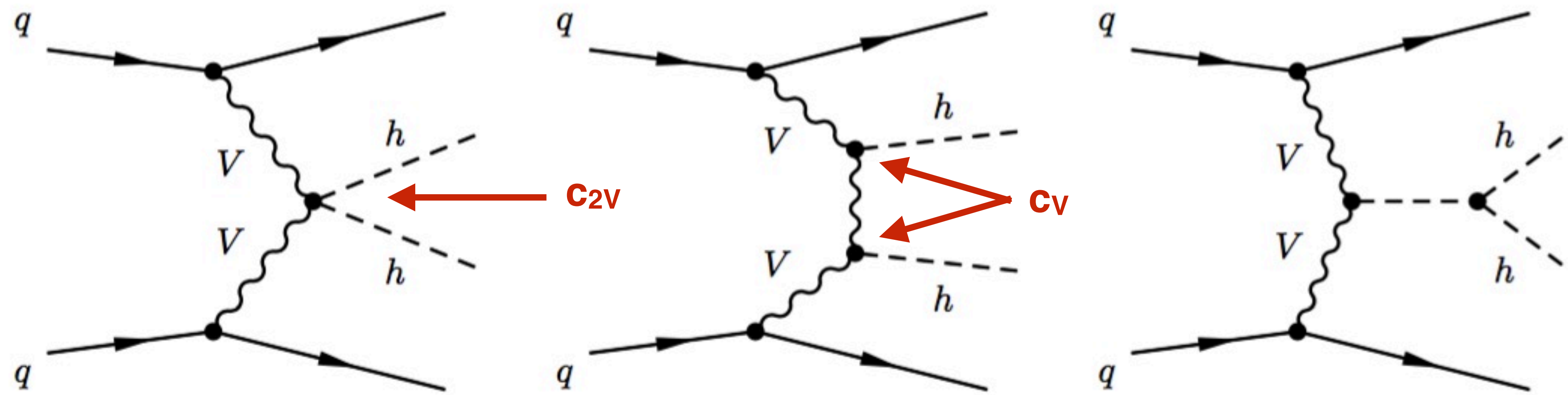
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes

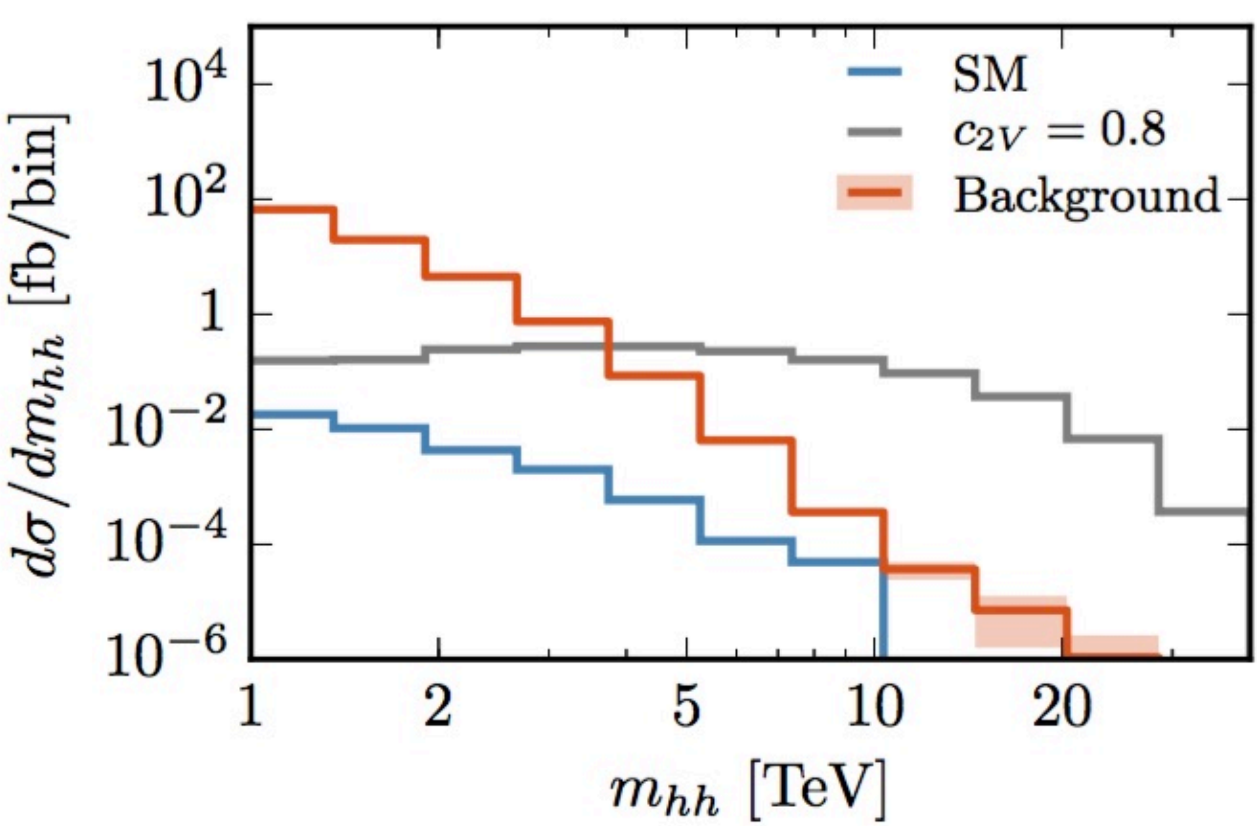
large Λ even if precision is low

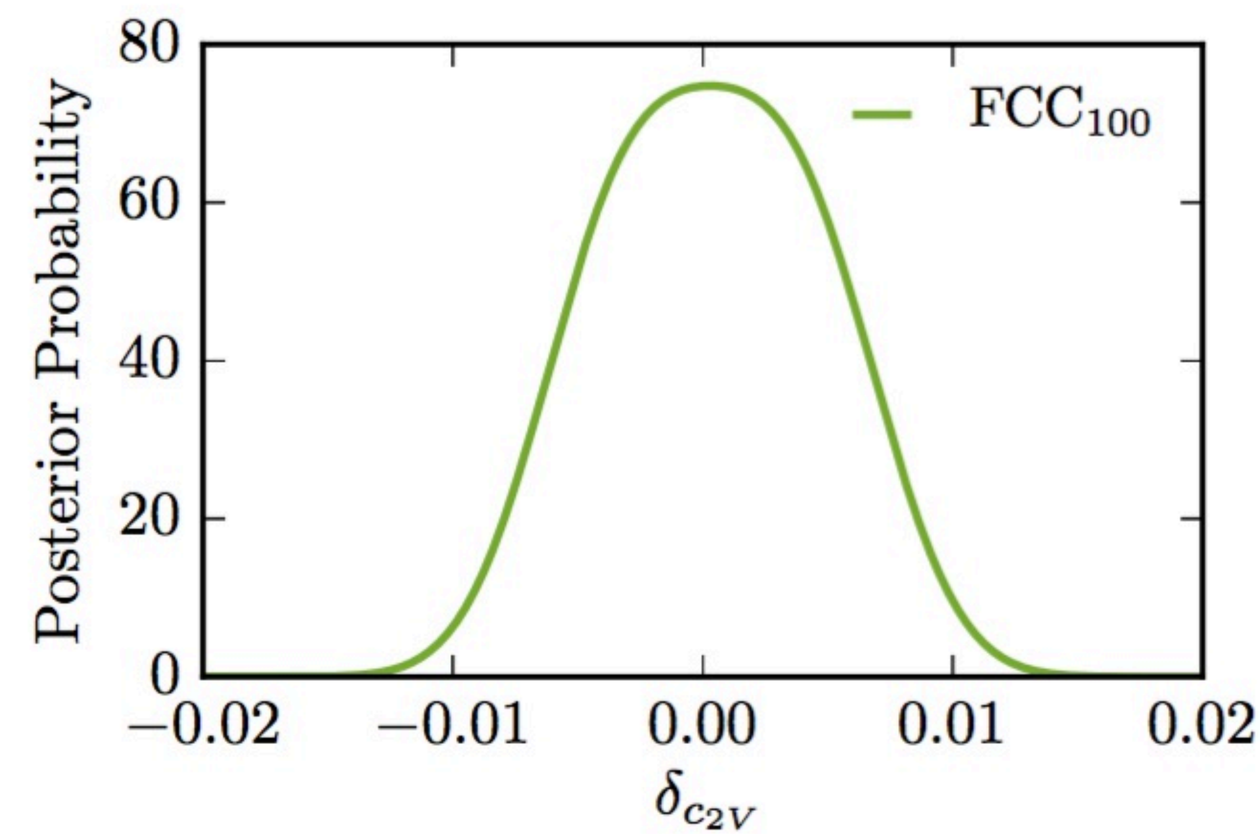
e.g. $\delta O = 15\%$ at Q=1 TeV ⇒ $\Lambda \sim 2.5$ TeV

Example: high mass VV → HH

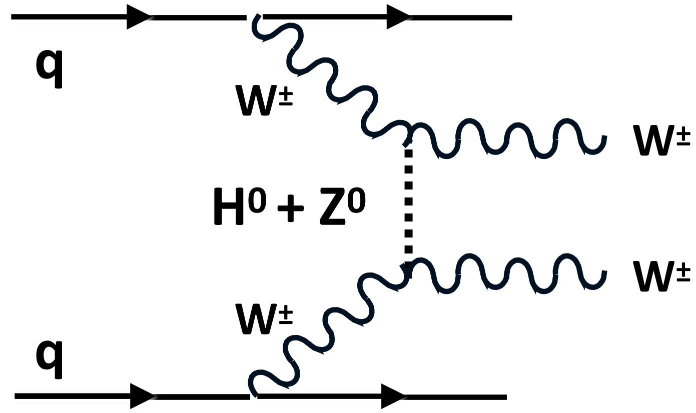


$$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) \cdot$$ **where** $$\begin{cases} c_V = g_{HVV}/g_{HVV}^{SM} \\ c_{2V} = g_{HHVV}/g_{HHVV}^{SM} \end{cases} \Rightarrow \left(c_{2V} - c_V^2\right)_{SM} = 0$$

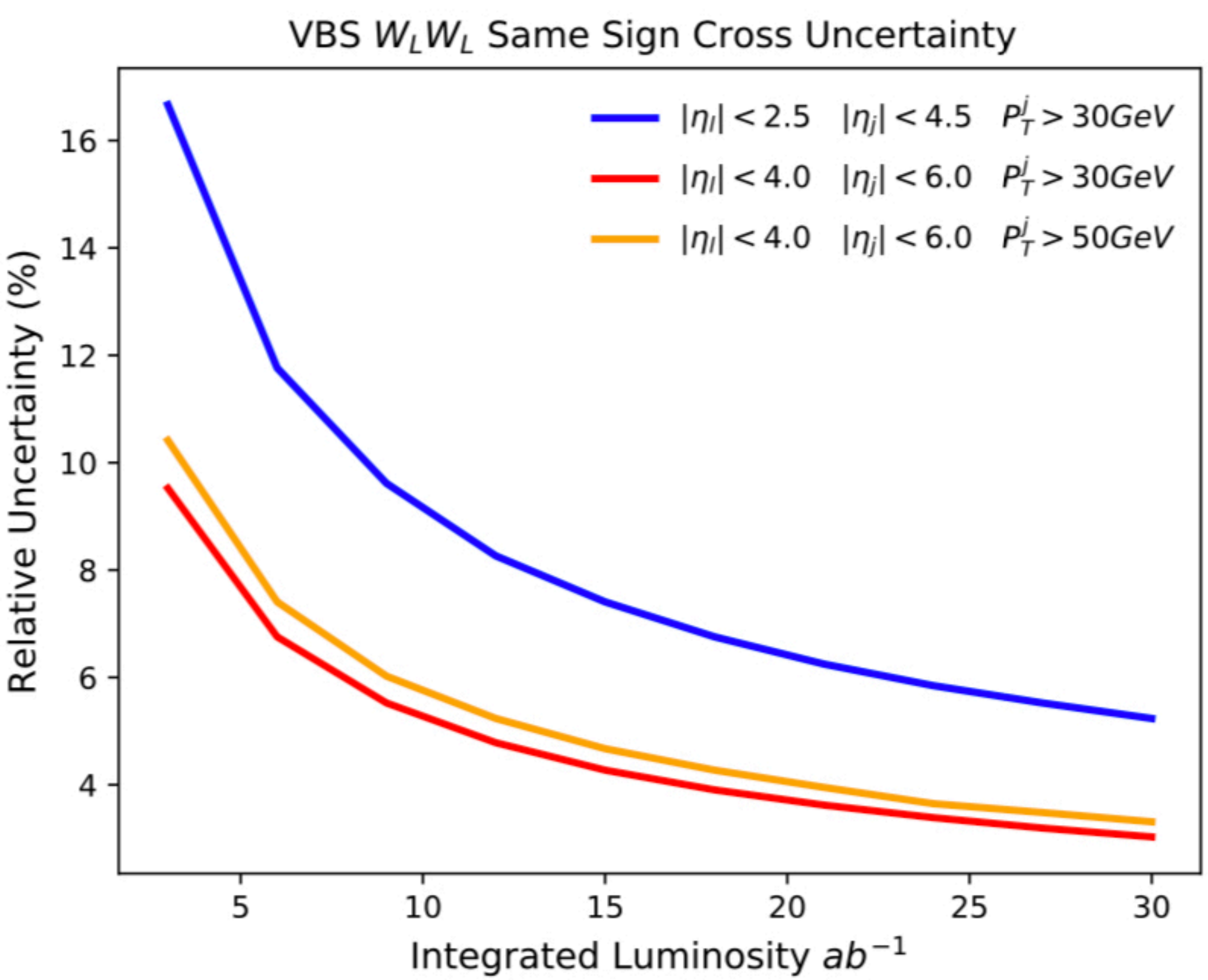




$W_L W_L$ scattering



large m_{WW}



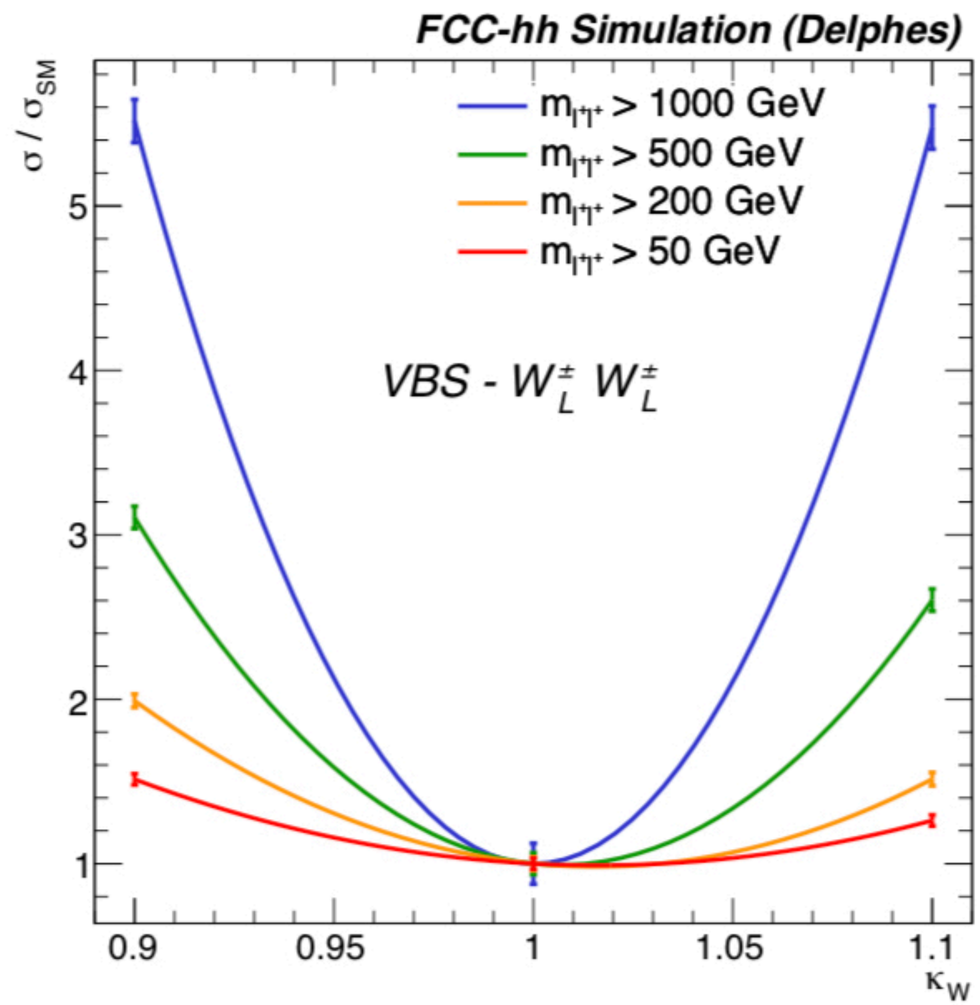


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process.

$m_{l^+l^+}$ 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]

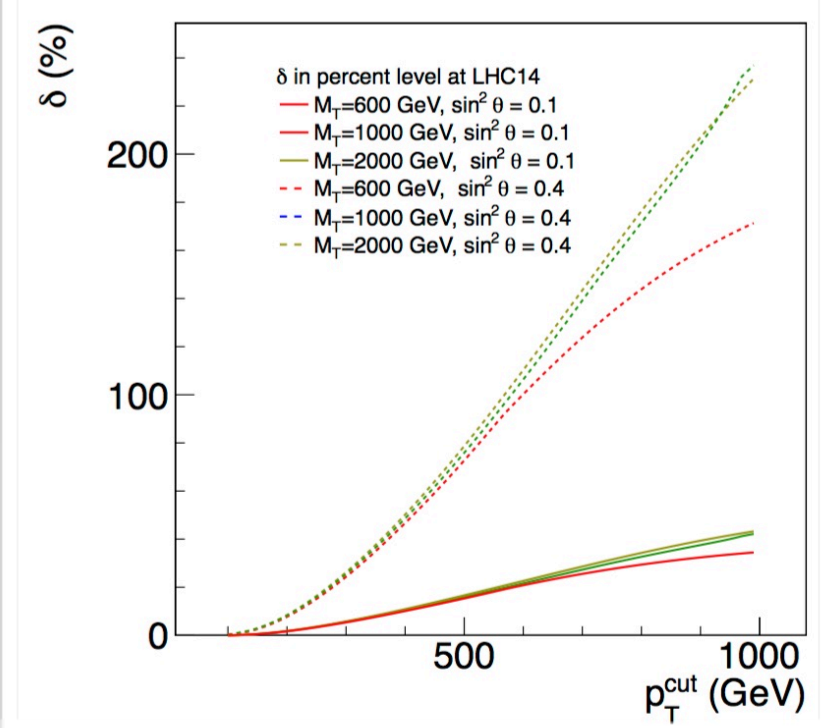
$$\kappa_W = \frac{g_{HWW}}{g_{HWW}^{SM}}$$

to do's

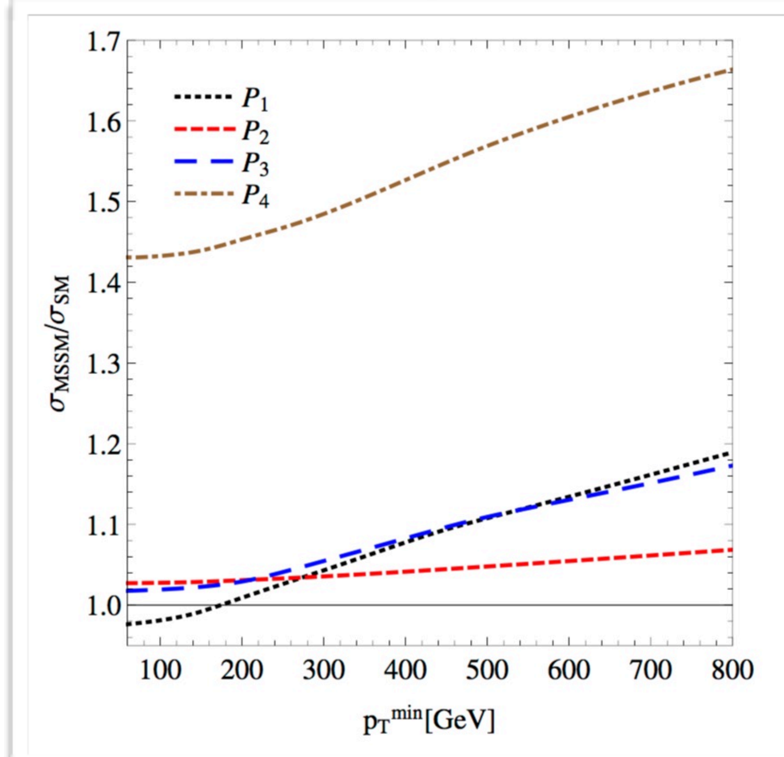
=> Re-iterate at 100 TeV the many studies done for LHC about BSM constraints from high-pT Higgs production. Eg

gg→Hg

Banfi Martin Sanz, arXiv:1308.4771



top partners T in the loop

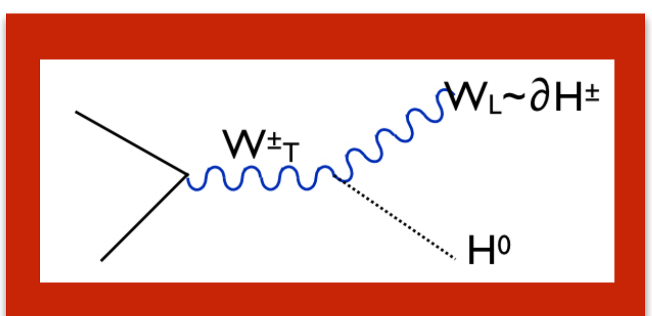


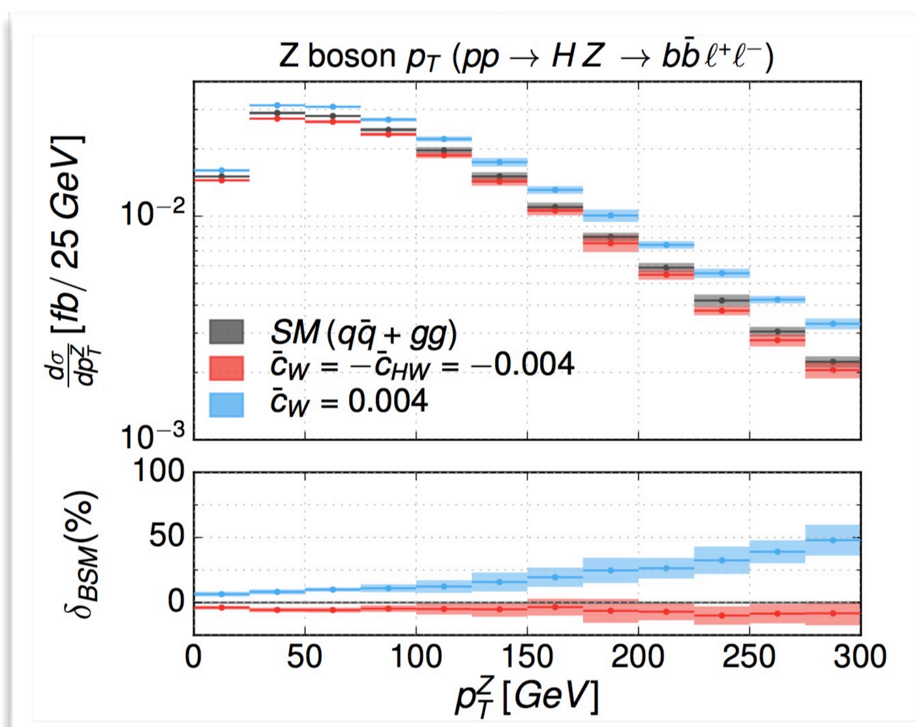
Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18

top squarks in the loop

Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

(See also Azatov and Paul arXiv:1309.5273v3)





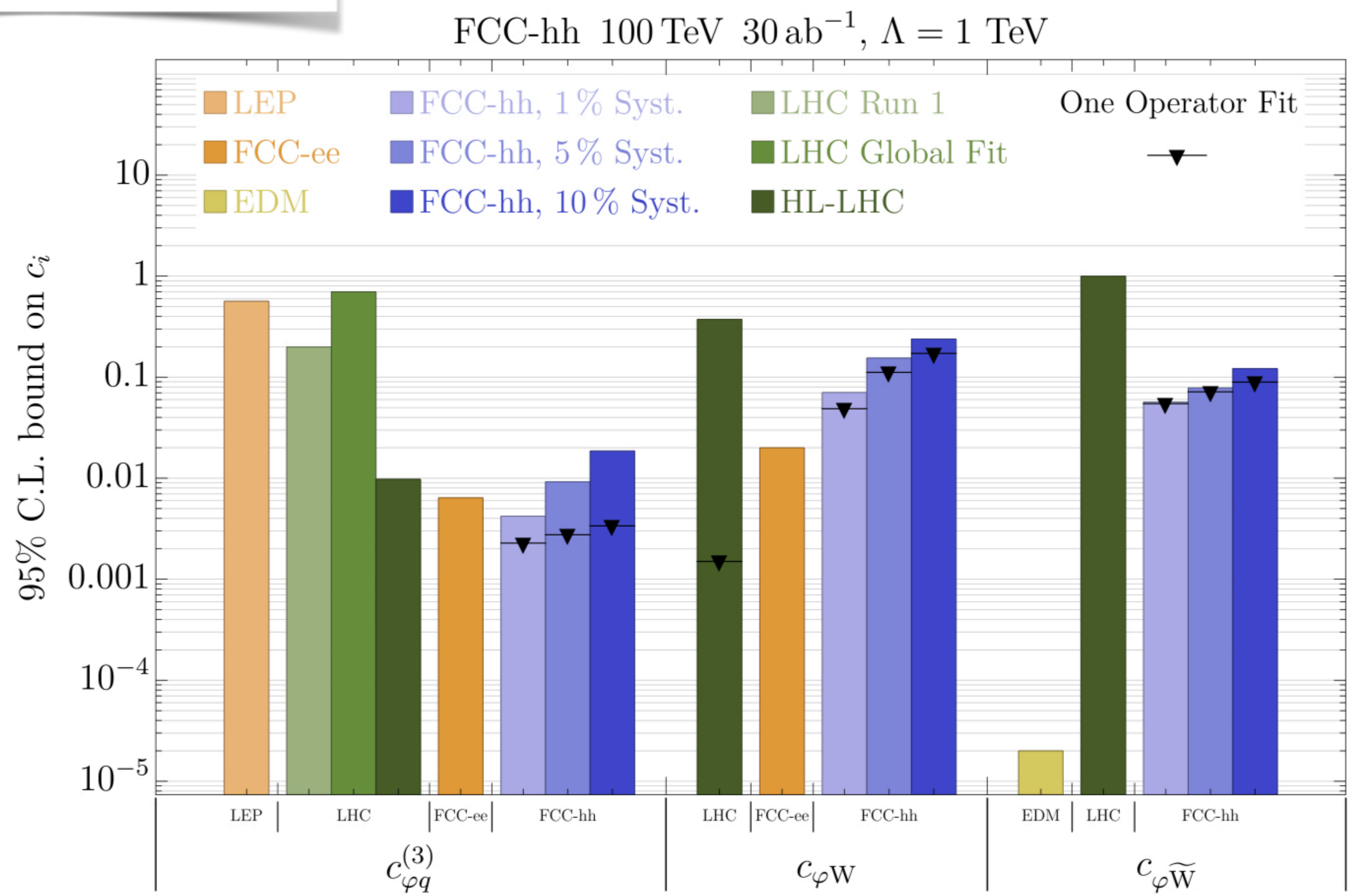
Mimasu, Sanz, Williams, arXiv:1512.02572v

See also Bieköotter, Knochel, Krämer, Liu, Riva, arXiv:1406.7320

Example of recent studies*

$$\mathcal{O}_{\varphi q}^{(3)} = \left(\overline{Q}_L \sigma^a \gamma^\mu Q_L\right)\left(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)$$
$$\mathcal{O}_{\varphi \mathrm{W}} = H^\dagger H\, W^{a,\mu\nu} W^a_{\mu\nu}\,,$$
$$\mathcal{O}_{\varphi \widetilde{\mathrm{W}}} = H^\dagger H\, W^{a,\mu\nu} \widetilde{\mathrm{W}}^a_{\mu\nu}\,.$$

WH(→γγ) at large pT, Bishara et al, arxiv:2004.06122



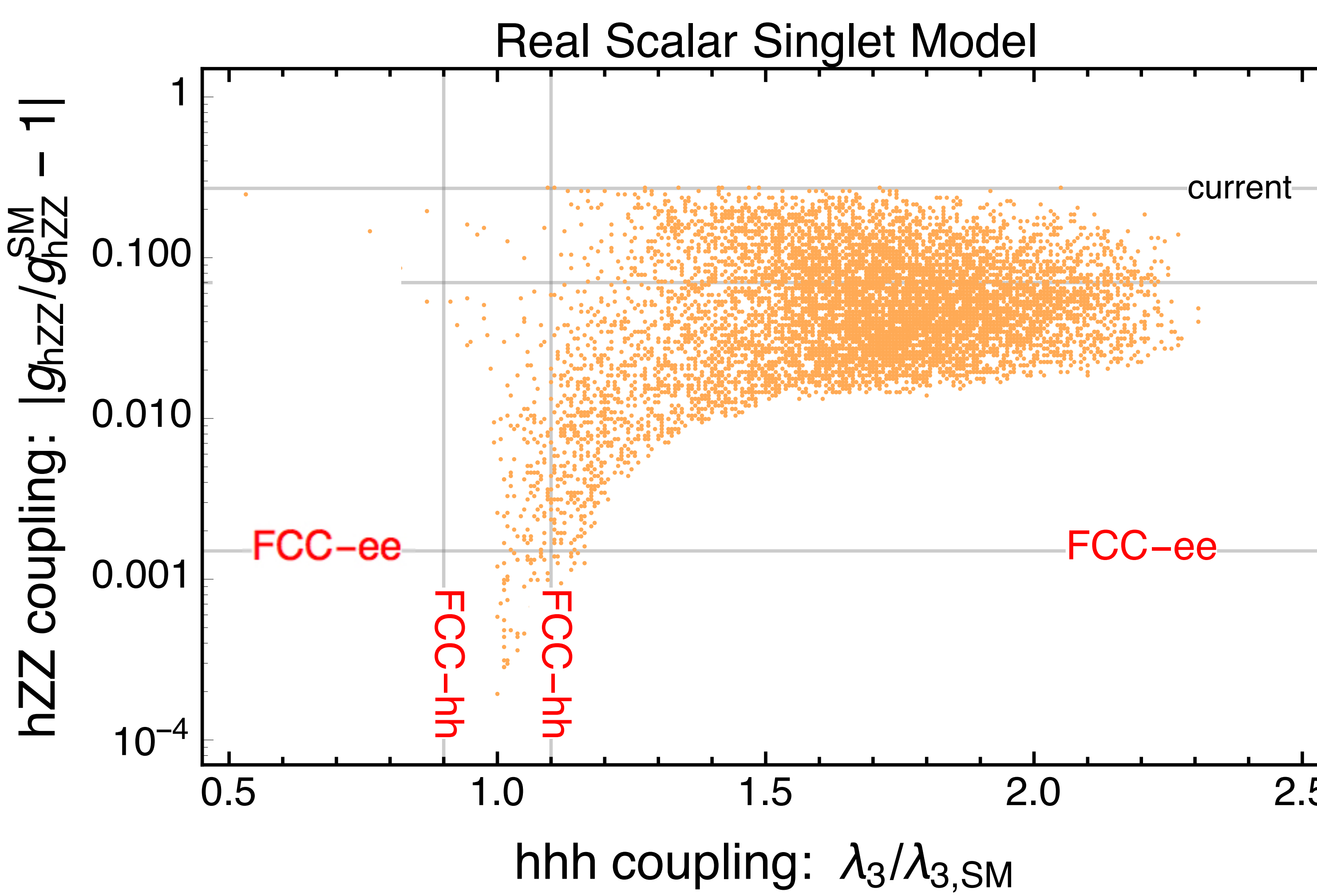
* see also recent results and "work in progress" reported at
3rd FCC Physics & Experiments workshop , Jan 2020 (agenda)

more to do's

- Assess current TH systematics at large p_T for various production channels
  - for LHC, see K.Becker et al, https://arxiv.org/abs/2005.07762
- Study separation of different Higgs production modes, and define analysis strategies, at large p_T
- **Quantify complementarity and synergy** among precision measurements from FCC-ee (H and EW properties) and Higgs/EW measurements (including high-Q2) at 100 TeV. In particular, consider concrete BSM scenarios, play the "inverse problem" game using all available inputs…

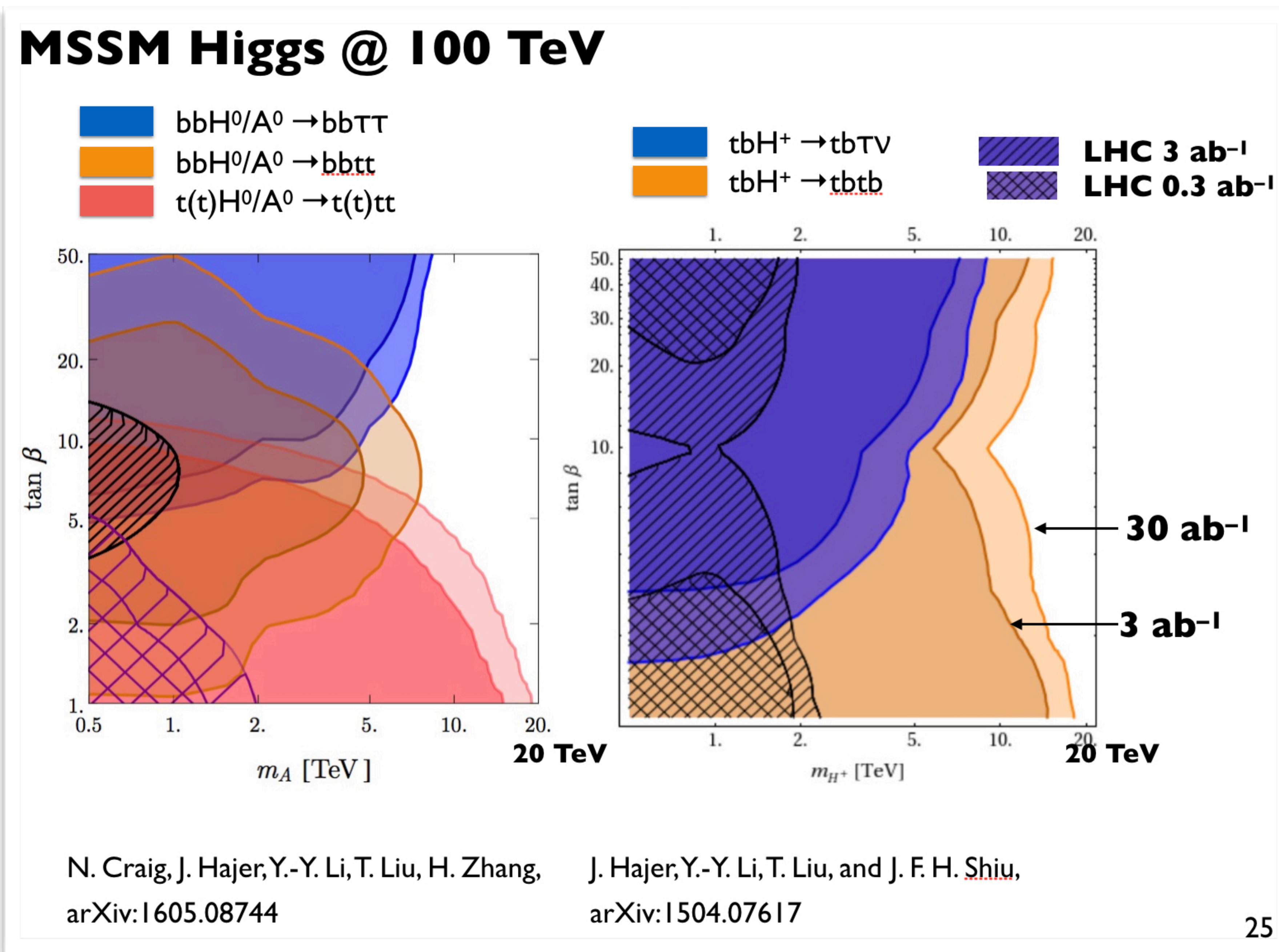
Eg Constraints on models with 1st order phase transition

$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$



more to do's

- Continue study of BSM Higgs scenarios, direct production, CPV, etc



Higgs self-coupling

- Latest studies (https://arxiv.org/abs/2004.03505 , https://arxiv.org/abs/2003.12281):
    - uncertainty below 5% for SM measurement, syst dominated, relies on % knowledge of top Yukawa
- Large literature on Higgs probes of the nature of the EW phase transition, and impact of self-coupling measurement
- ***TO DO:*** *more systematic studies needed to explore sensitivity to BSM deviations. Eg*
    - *m_{HH} shape fits in presence of multiple EFT ops (see eg https://arxiv.org/abs/1502.00539, https://arxiv.org/abs/1908.08923)*
    - *global EFT fits including single-H and EW observables*