Higgs physics at FCC-hh

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most of the results for FCC-hh from:
M. Mangano (ed.), "Physics at the FCC-hh, a 100 TeV pp collider", CERN YR 2017-003-M
(in particular chapter 2: "Higgs and EWSB studies", 1606.09408 [hep-ph])

Why Higgs at 100 TeV pp?

1. **FCC-hh** is an **energy frontier** experiment
   - direct searches for extended Higgs sectors
   - study of high-energy tails of kinematic distributions

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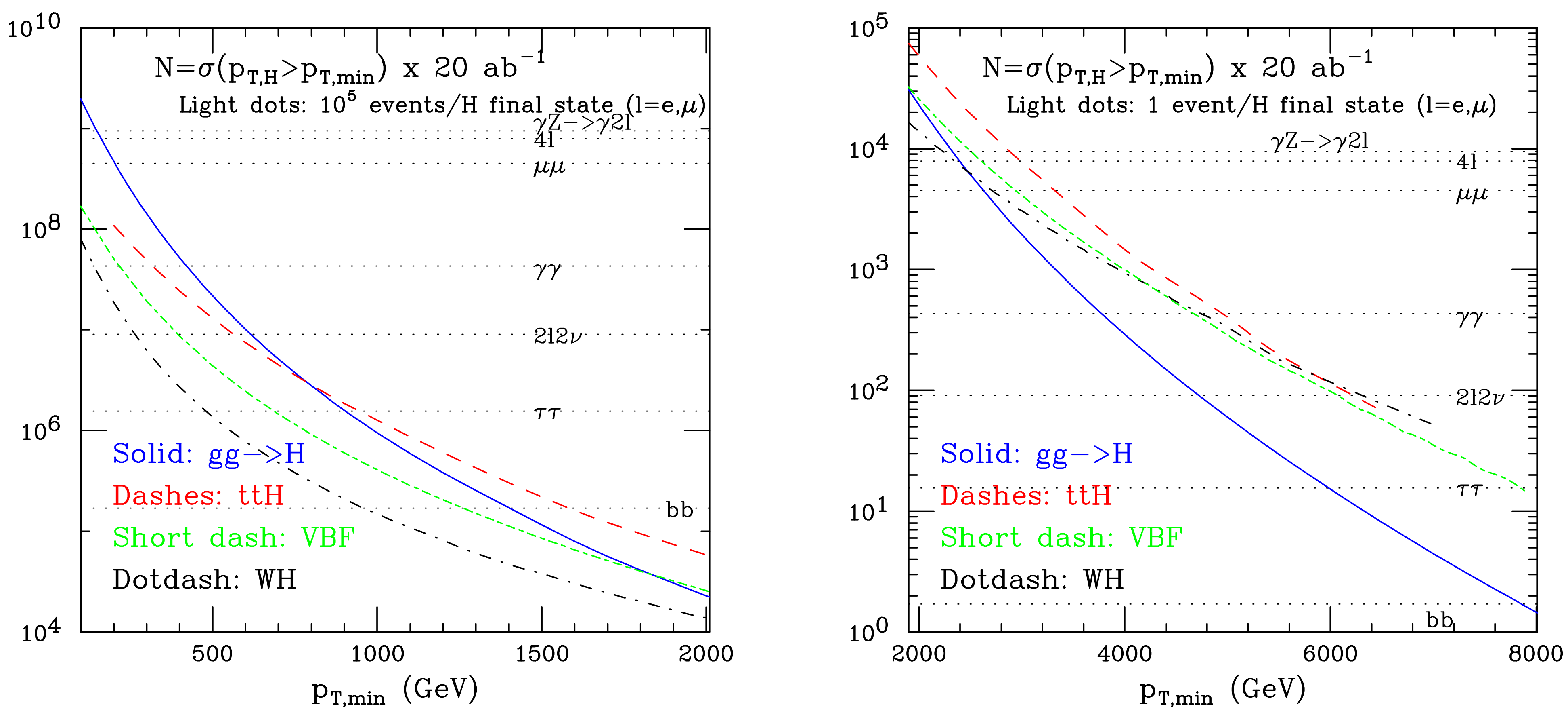
integrated Higgs transverse momentum rates



- many single Higgs channels with 1% stat. uncertainty at $p_{T,H}$ > 1 TeV
- possible to probe $p_{T,H}$ > 3 - 4 TeV

Why Higgs at 100 TeV pp?

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2. **FCC-hh** is an **intensity frontier** experiment
   - precision studies of Higgs couplings
   - access to rare processes

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number of events in single Higgs channels

	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

benchmark with **L = 20 ab^{-1}**

- huge number of Higgs bosons produced ($\sim 10^{10}$)
- rare channels get large boost wrt LHC (eg. ttH rate enhanced by ~400)

Why Higgs at 100 TeV pp?

Huge statistics has **several advantages**

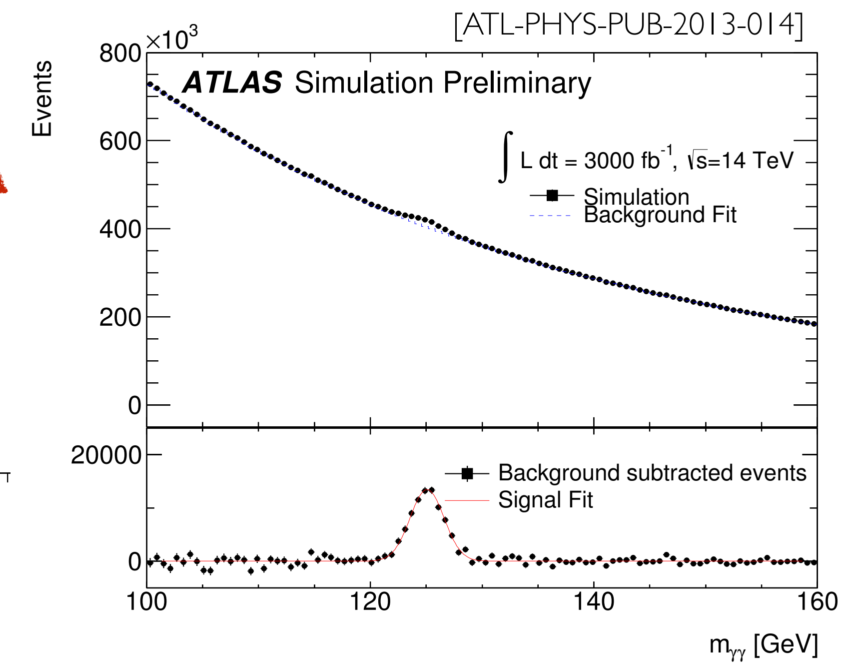
- can afford harder kinematical cuts
  - → **better control** on backgrounds and systematics
- explore new kinematic regimes (eg. high-energy tails):
  - → **more sensitive** to new physics
  - → **new tests** of SM and BSM

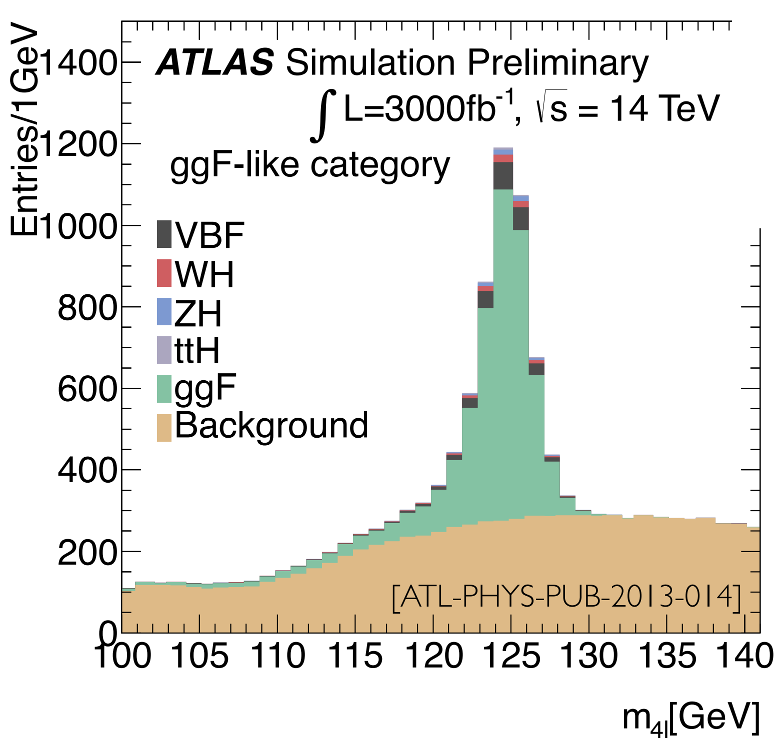
Single Higgs processes

Higgs couplings at HL-LHC

Higgs searches at **LHC** have several **limitations**

- limited **S/B** (even in clean channels)
  - $gg \to H \to \gamma\gamma$ → S/B ~ *few %*
  - $gg \to H \to ZZ^* \to 4\ell$ → S/B ~ 1





Higgs couplings at HL-LHC

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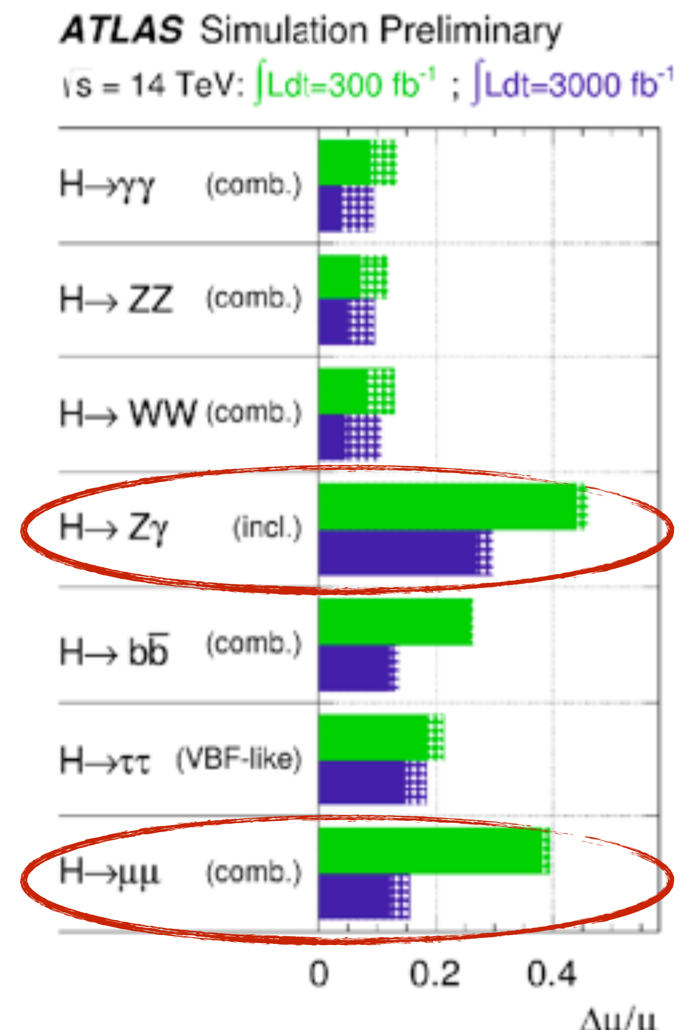
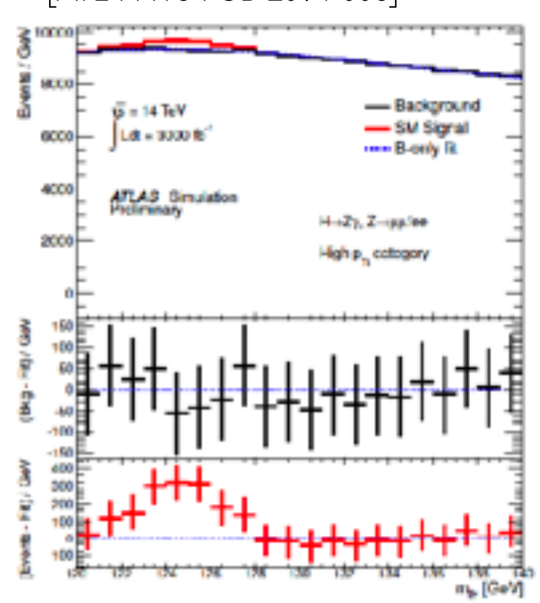
  - $gg \to H \to ZZ^* \to 4\ell$ ⟶ S/B ~ 1
- limited **statistics** (error on measurement dominated by stat.)
  - $gg \to H \to \mu\mu$ ⟶ ~ **10 %** precision
  - $gg \to H \to Z\gamma \to \ell\ell\gamma$ ⟶ ~ **25 %** precision



[ATL-PHYS-PUB-2014-006]



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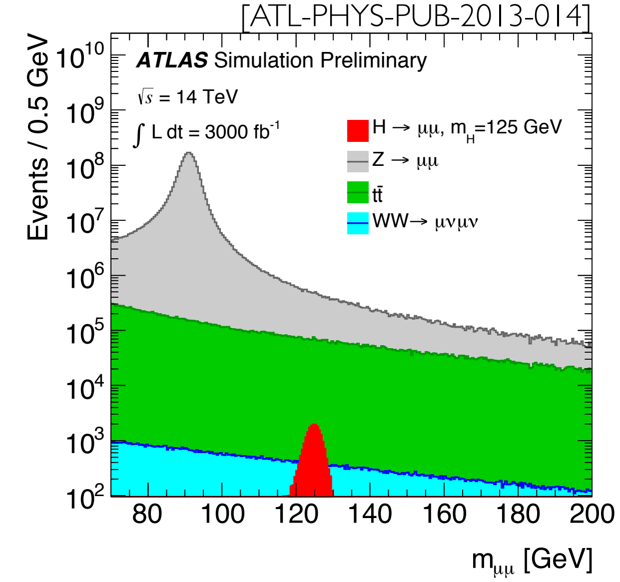
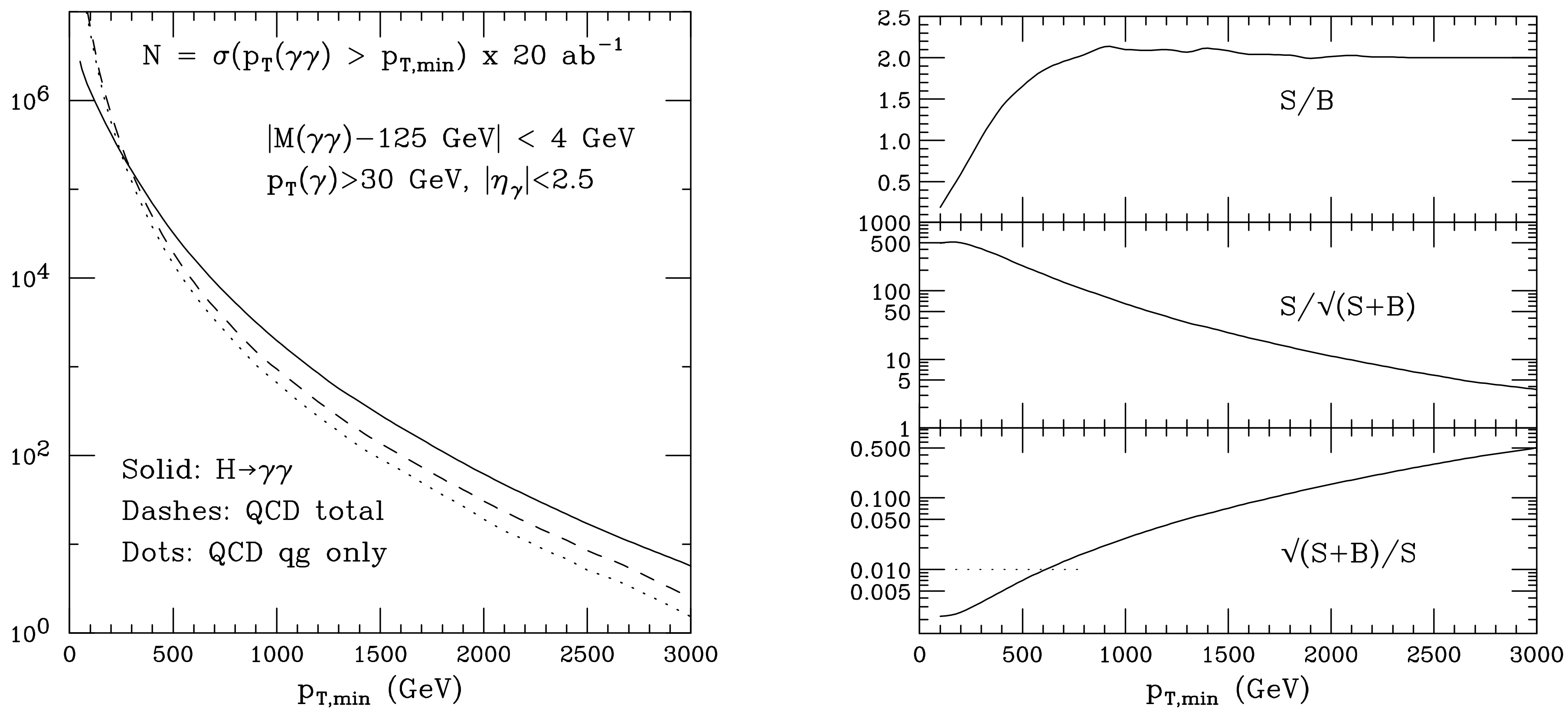


Coupling to photons at FCC-hh

The $gg \to H \to \gamma\gamma$ channel

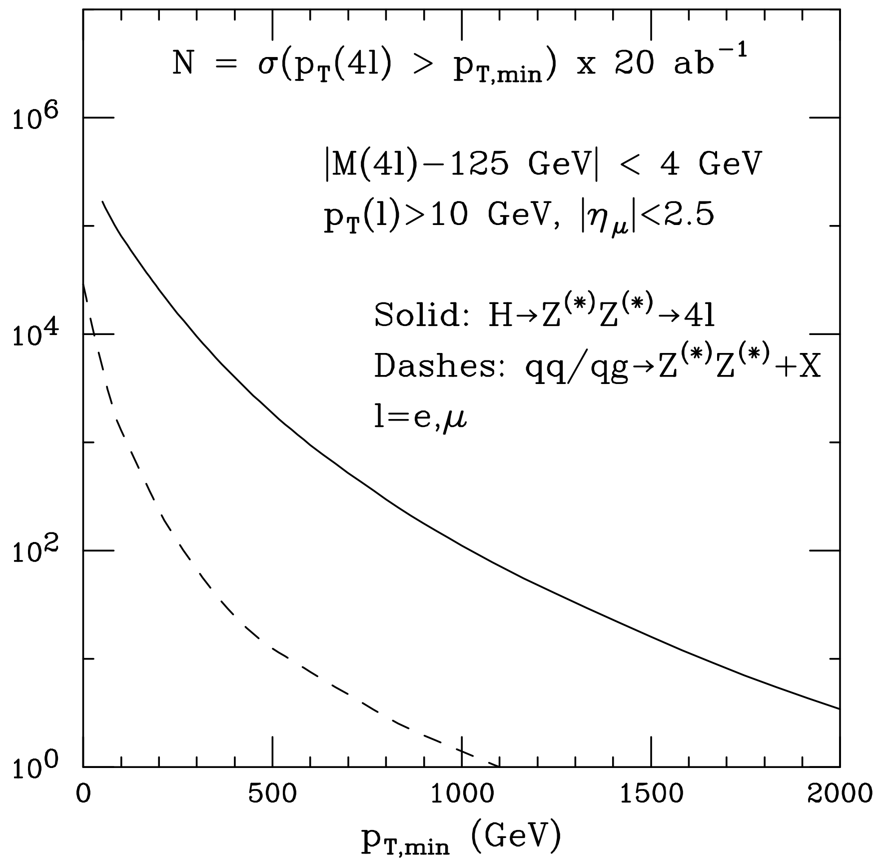


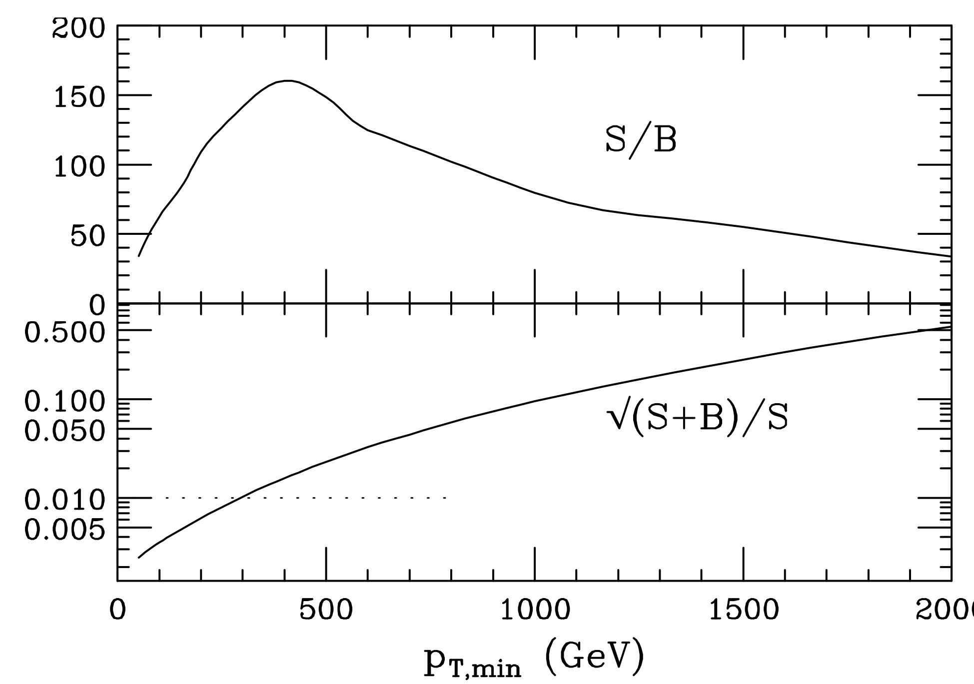
- Higgs channel dominates over bkg at large p_T
- large S/B at high $p_{T,H}$ (S/B ~ 1 for $p_{T,H}$ > 300 GeV)
- accurate probe of Higgs p_T spectrum
- better than 1% stat. error for $p_{T,H}$ < 600 GeV

$p_{T,H}$(GeV)	$\delta_{\rm stat}$
100	0.2%
400	0.5%
600	1%
1600	10%

Coupling to Z bosons at FCC-hh

The $gg \to H \to ZZ^* \to 4\ell$ channel



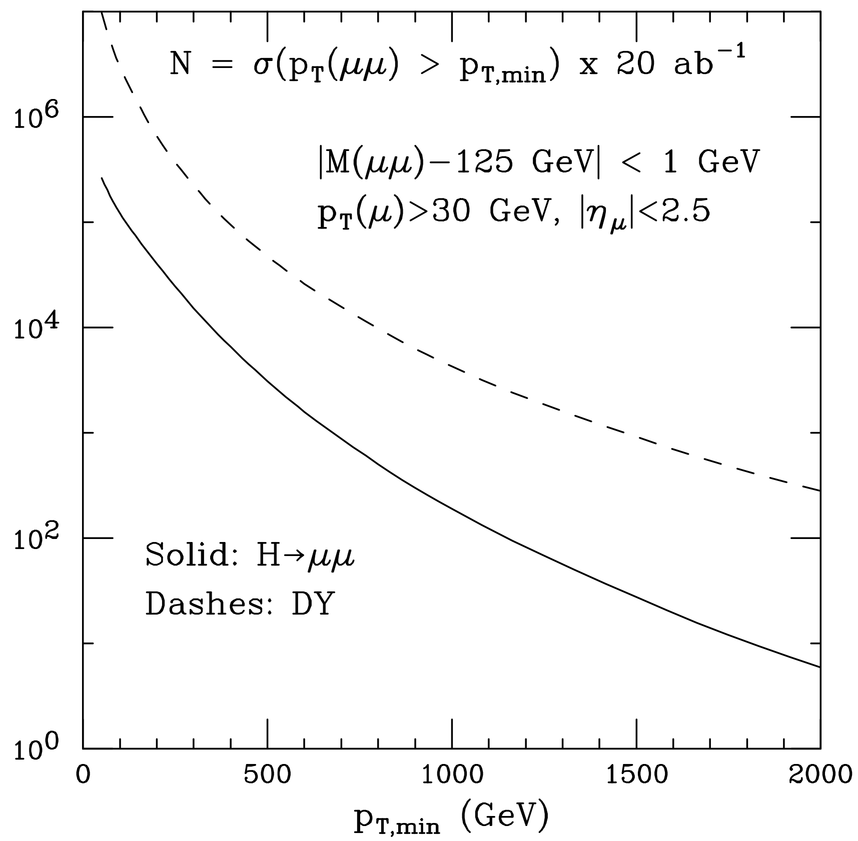


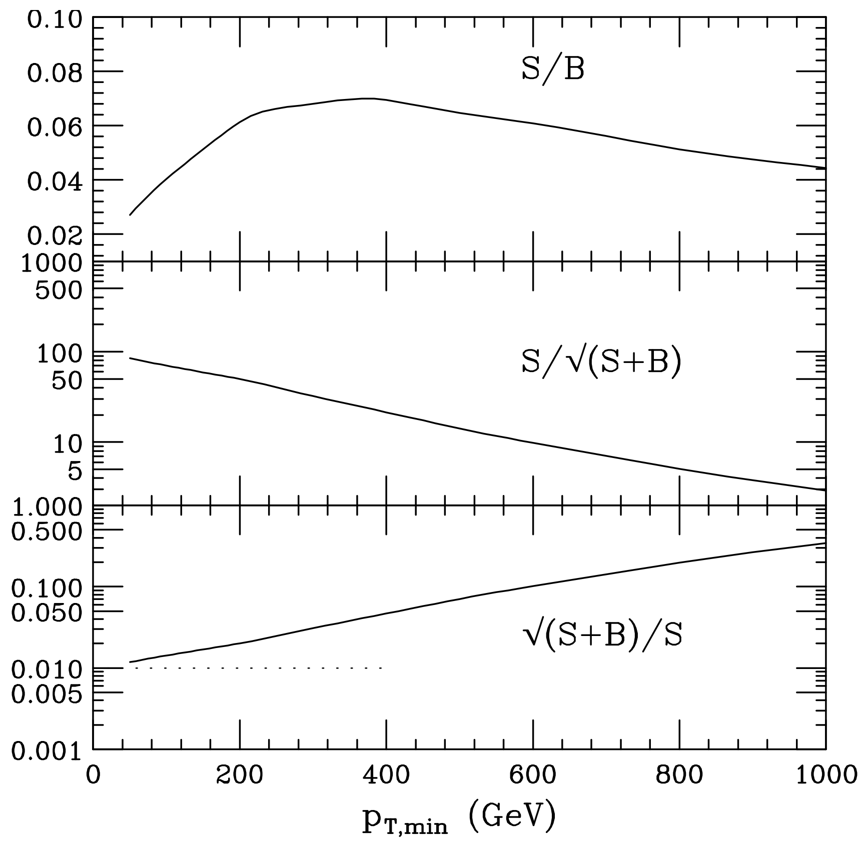
- very low bkg for $p_{T,H}$ > 100 GeV
- better than 1% stat. error for $p_{T,H}$ < 300 GeV

$p_{T,H}$(GeV)	$\delta_{\rm stat}$
100	0.3%
300	1%
1000	10%

Coupling to muons at FCC-hh

The $gg \to H \to \mu\mu$ channel



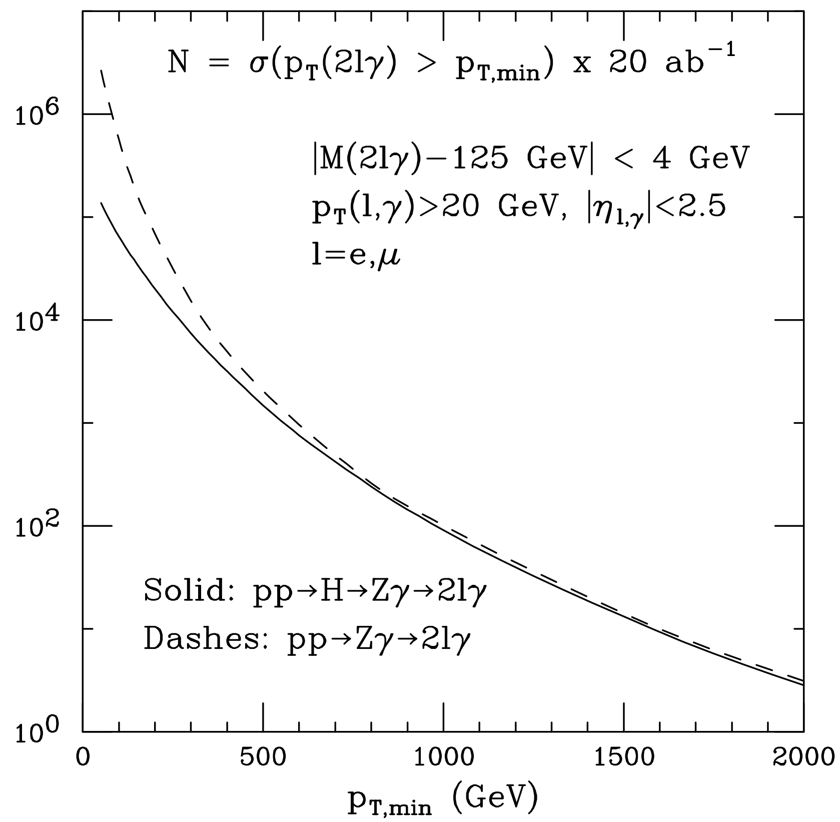


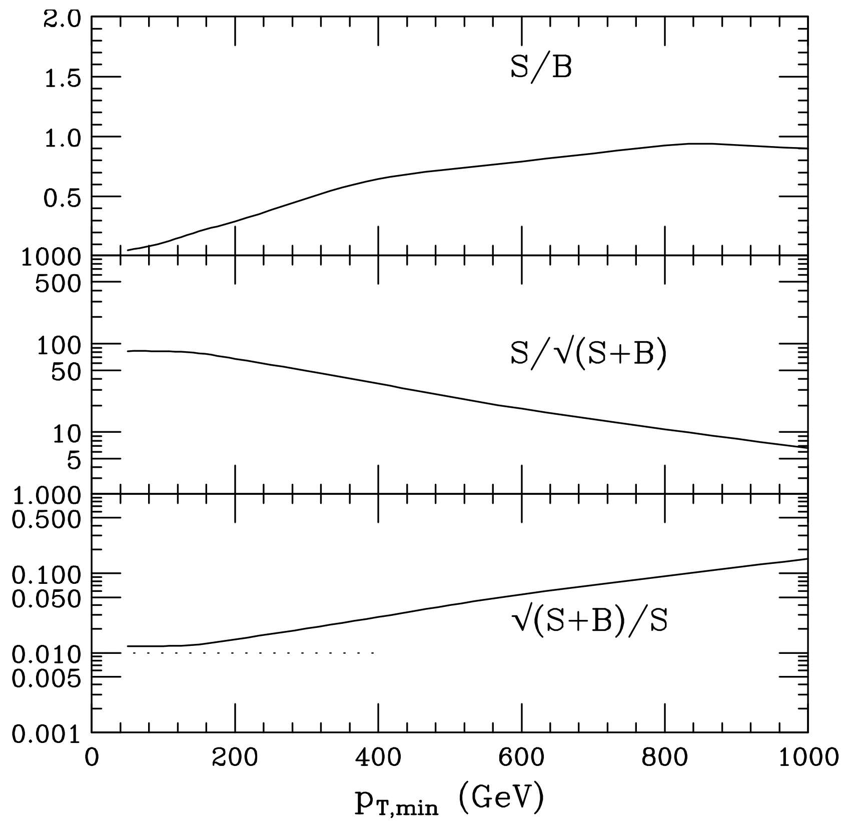
- good statistical error (~1%) for $p_{T,H}$ > 100 GeV
- could be used to improve muon Yukawa
  (using ratio $\mathrm{BR}(H \to \mu\mu)/\mathrm{BR}(H \to \gamma\gamma)$ could help with syst.)

$p_{T,H}$(GeV)	$\delta_{\rm stat}$
100	1%
500	10%

Coupling to Zγ at FCC-hh

The $gg \to H \to Z\gamma \to \ell\ell\gamma$ channel





- huge improvement in stat. error (~1%) wrt LHC
- good signal S/B ~ 1
- can allow for precision test of HZγ
  (BSM deviations possible, eg. composite Higgs)

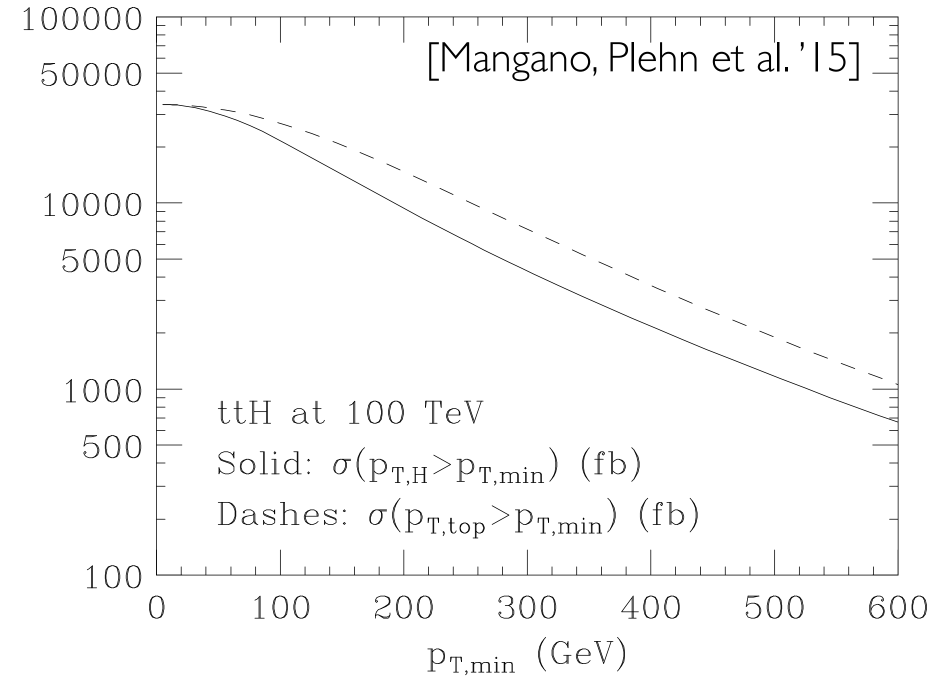
$p_{T,H}$ (GeV)	$\delta_{\rm stat}$
100	1%
900	10%

Top Yukawa at FCC-hh

Large rates in **ttH production** allow to access several final states

$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

events w/ L = 20 ab^{-1} with $tt \to \ell\nu + jets$



- $H \to \gamma\gamma$ channel could lead to ~1% precision
- $H \to 2\ell 2\nu$ also promising
- additional interesting channel $H \to b\bar{b}$ [Mangano, Plehn et al.'15]
  - huge number of events
  - could use ratio $t\bar{t}H/t\bar{t}Z$ to reduce syst. uncertainties

✦ Determination of **top Yukawa** at **~1%** could be achievable at FCC-hh much better than LHC reach (~10%)!

Rare Higgs decays at FCC-hh

Exclusive Higgs decays can probe light quark Yukawa's

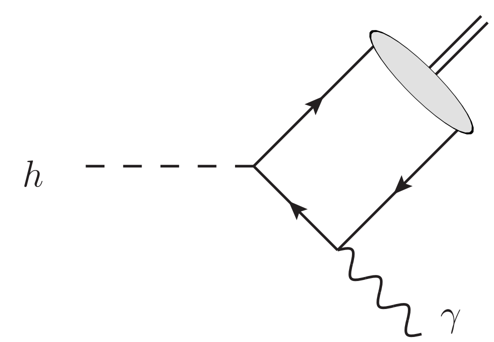
[Bodwin et al. '13; Kagan et al. '15]

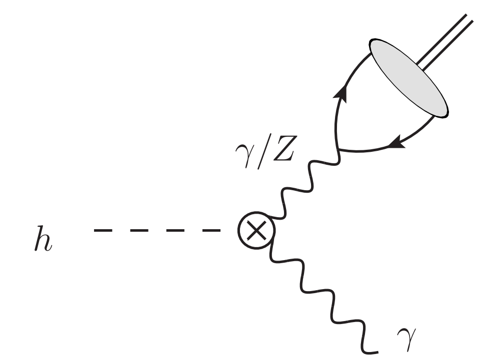
- SM rates $\mathrm{BR}(H \to V\gamma) \sim 10^{-6}$

$H \to J/\psi\,\gamma$ → y_c

$H \to \phi\,\gamma$ → y_s

$H \to \rho\,\gamma$ → $y_{u,d}$





- Estimate of **LHC** limits on $H \to J/\psi\,\gamma$:

LHC (14 TeV 300 fb^{-1}) $\lesssim 150 \times 10^{-6}$

HL-LHC (14 TeV 3 ab^{-1}) $\lesssim 45 \times 10^{-6}$

far from SM value

statistically limited:
~3 events at HL-LHC

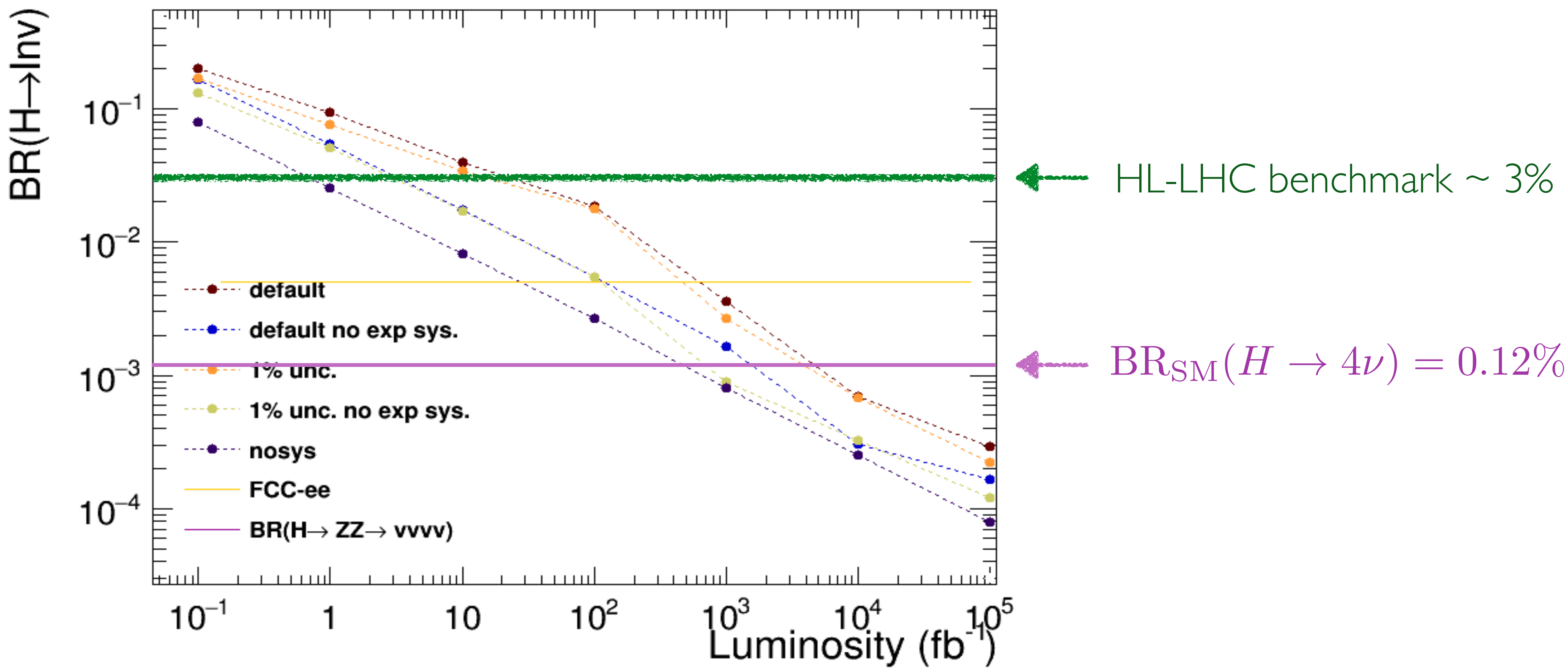
✦ **FCC-hh** gives a O(100) enhancement in rate

→ possible to **reach SM value!**

Invisible Higgs BR at FCC-hh

Large statistics and better control of systematics can allow for a good determination of **Higgs invisible BR** at FCC-hh

[see talk by P. Harris at FCC workshop and Physics WG meeting]



- most sensitive channels at FCC-hh: monojet and ttH
- reach **sensitivity to SM** H → invisible for with ~ *few* ab^{-1}
- with ~ 20 ab^{-1} can test $BR(H \to \text{invisible}) \sim \textit{few}\ 10^{-4}$

Multiple Higgs production

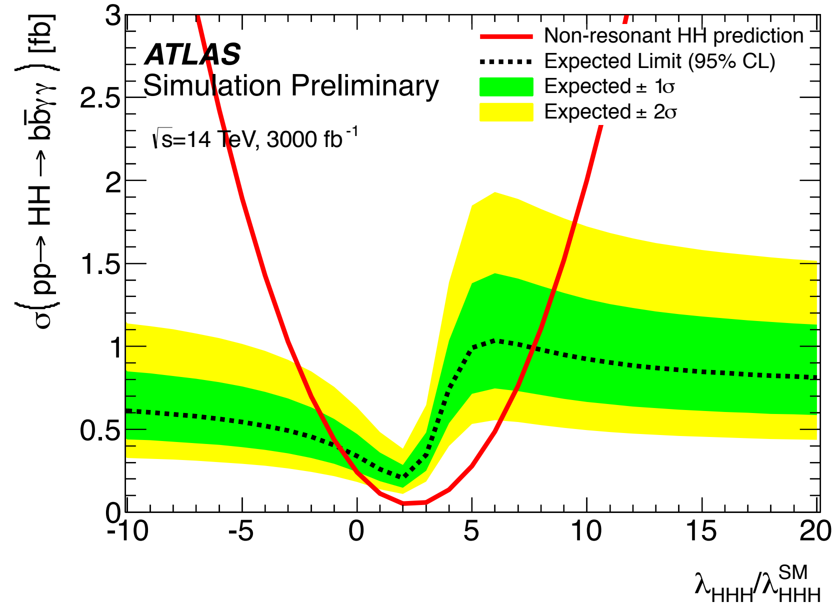
non-linear Higgs couplings

Testing the Higgs self couplings

Testing the **shape of the Higgs potential** is very difficult at the LHC

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

- ✦ small sensitivity to trilinear coupling (mainly accessible through Higgs pair production)
  - only O(1) determination possible at HL-LHC
- ✦ (almost) no sensitivity to quartic coupling

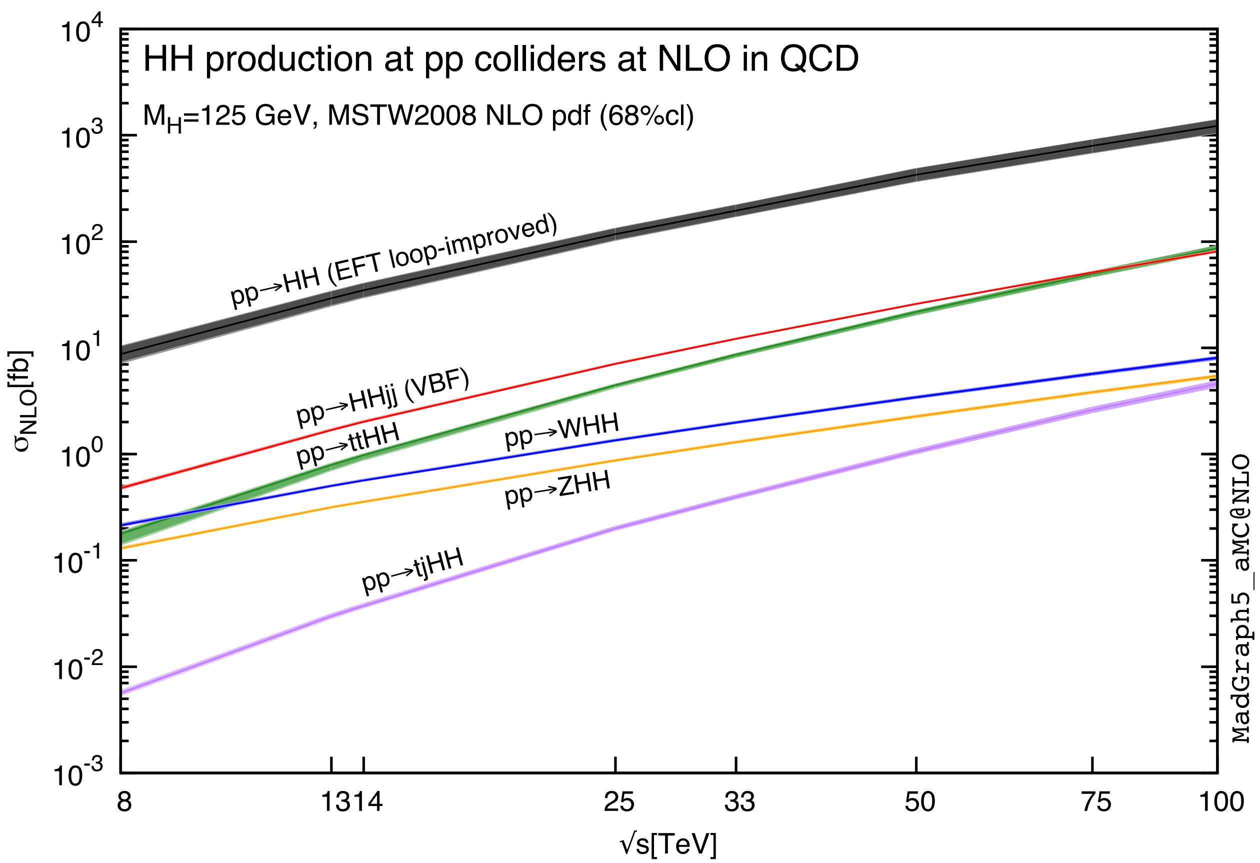


Higgs self-coupling **important for BSM**:

- **sizable deviations** in many BSM models (eg. composite Higgs, Higgs portal)
- controls **EW phase transition** (consequences for baryogenesys/cosmology)

Multiple Higgs production

Multiple Higgs production rates **hugely enhanced!**



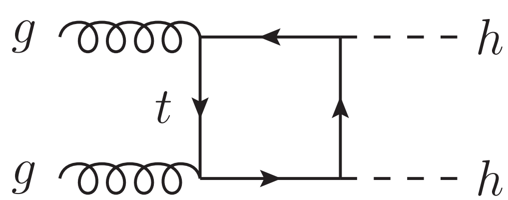
process	σ_{FCC-hh}	$\sigma_{\mathrm{FCC-hh}}/\sigma_{\mathrm{LHC14}}$
HH (ggf)	1749 fb	39
$HHjj$ (VBF)	80.3 fb	41
HHZ	8.23 fb	20
HHW^+	4.70 fb	17
HHW^-	3.30 fb	17
$HHt\bar{t}$	82.1 fb	87
$HHtj$	4.44 fb	122
HHH	4.82 fb	54

- **double Higgs** production in gluon fusion becomes precision channel
- **triple Higgs** production channel becomes visible

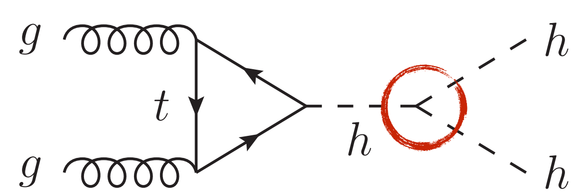
Trilinear Higgs coupling at FCC-hh

Leading production via **gluon fusion**

- sensitive to h^3 interaction

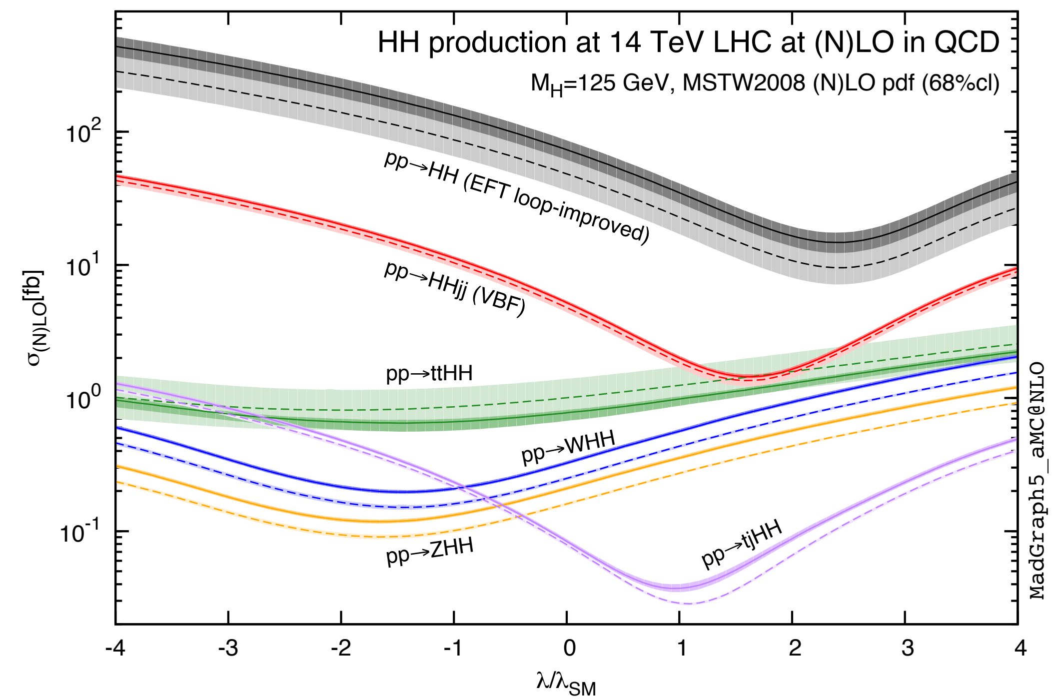


$\sim const.$



$\sim \lambda_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$

main sensitivity at threshold



✦ clean channel $gg \to HH \to b\bar{b}\gamma\gamma$

[Contino, Englert, GP, Papaefstathiou, Ren, Selvaggi, Son Spannowsky, Yao in FCC report]

	# signal events in $b\bar{b}\gamma\gamma$
LHC 14TeV 300 fb^{-1}	36
LHC 14TeV 3 ab^{-1}	360
FCC 100TeV 30 ab^{-1}	138000

entering ~% precision

	events ($L = 30\text{ab}^{-1}$)
$h(b\bar{b})(\gamma\gamma)$ SM	12060
$bbj\gamma$	14000
$jj\gamma\gamma$	4910
$t\bar{t}h(\gamma\gamma)$	4880
$b\bar{b}\gamma\gamma$	2950
$b\bar{b}h(\gamma\gamma)$	227
$bj\gamma\gamma$	155
total bkg	27122

w/ stat. error only:

$S/B \simeq 0.45$

$\sqrt{S+B}/S \simeq 0.016$

Trilinear Higgs coupling at FCC-hh

$\Delta\lambda_3(\%)$	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%	5.8%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%	6.1%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%	6.4%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%	6.8%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%	7.3%

theory error: uncertainty on signal rate

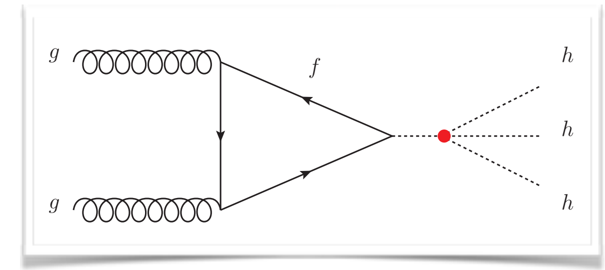
$$\Delta_S = \frac{\Delta\sigma(pp \to hh)}{\sigma(pp \to hh)}$$

overall rescaling of bkg rate $n_B \to r_B \times n_B$

- precision likely to be limited by systematics
  (theory syst. dominant for $\Delta_S \gtrsim 2.5\%$, leading to $\Delta\lambda_3 \simeq 2\,\Delta_S$)
- ultimate FCC-hh reach in the 3 - 6 % range
- HE-LHC (~30 TeV) could reach ~30 % precision with ~10 ab^{-1}

Higgs quartic coupling at FCC-hh

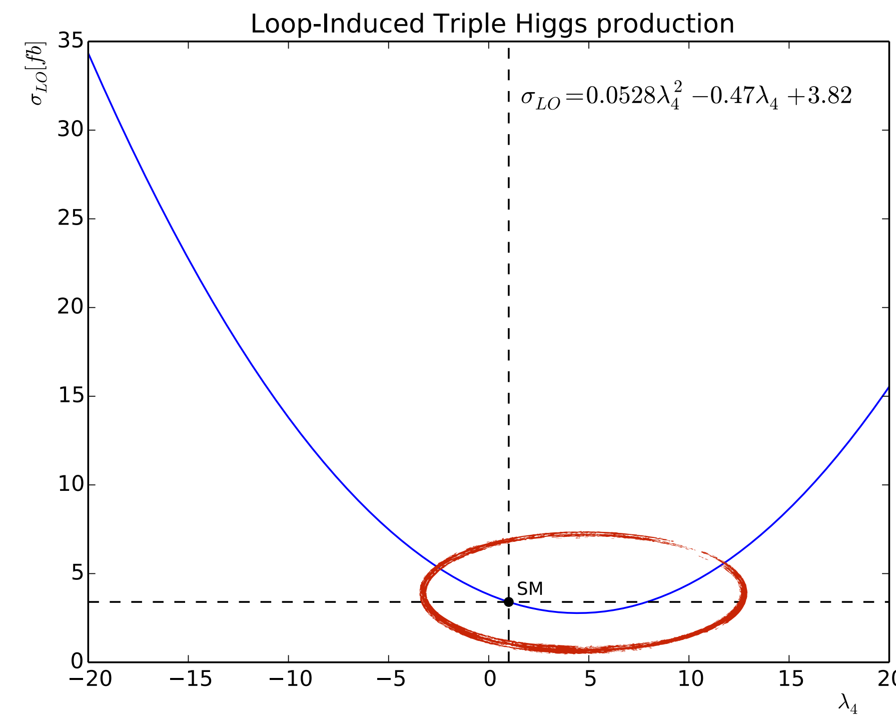
Higgs **quartic self coupling** much more **challenging!**



- clean channel $HHH \to (b\bar{b})(b\bar{b})(\gamma\gamma)$ bur very small production rate

$$N^{\rm ev}_{30{\rm ab}^{-1}} \sim 10$$

after cuts



- small dependence on λ_4 close to SM

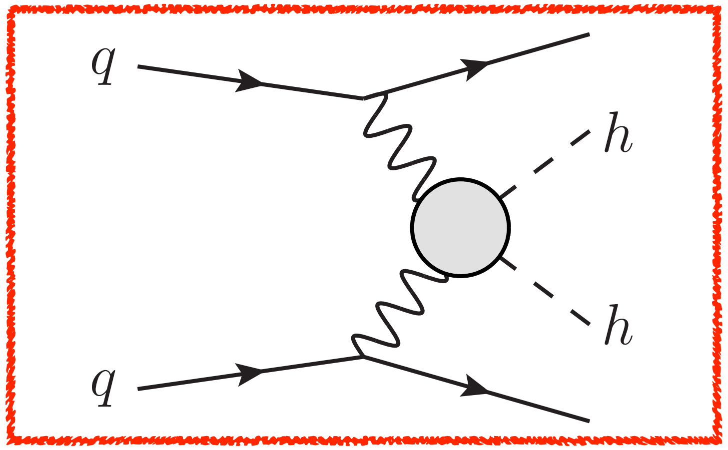
‣ SM signal can be probed with O(100%) precision

‣ order-of-magnitude test of Higgs quartic coupling $\lambda_4 \in [-4, +16]$

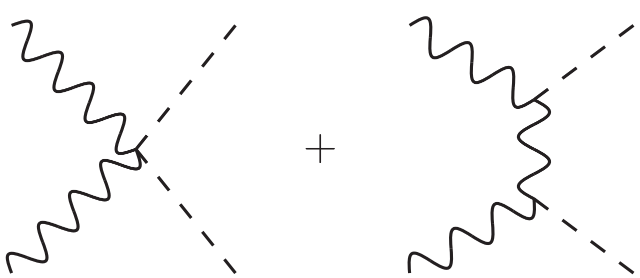
Double Higgs from VBF

VBF can test perturbative unitarization and strength of Higgs dynamics

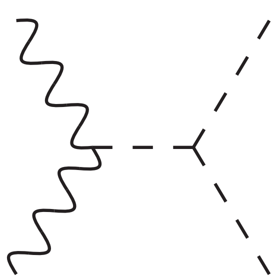
$$\mathcal{L} \supset \left(m_W^2 W_\mu^2 + \frac{m_Z^2}{2} Z_\mu^2 \right) \left(1 + 2c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2} \right)$$



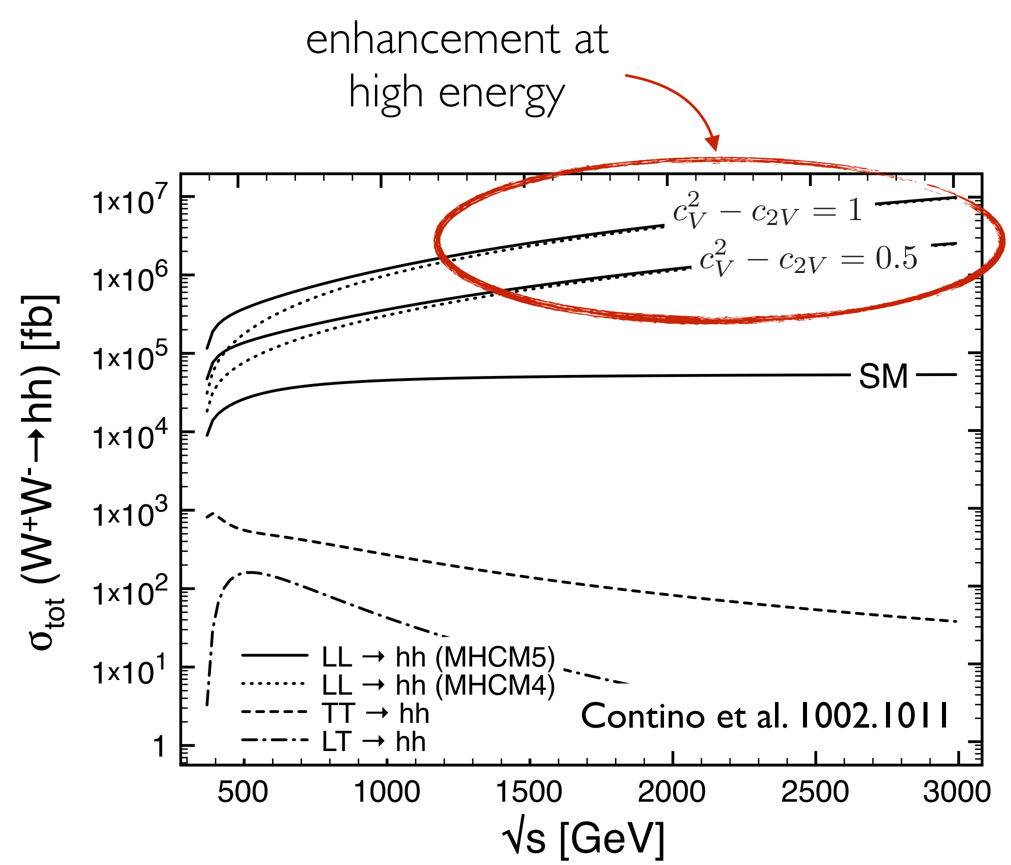
- ✦ Cross section grows at high m_{hh} if SM couplings are modified (in the SM $c_V = c_{2V} = 1$)



$$\sim \frac{\hat{s}}{v^2}(c_V^2 - c_{2V})$$



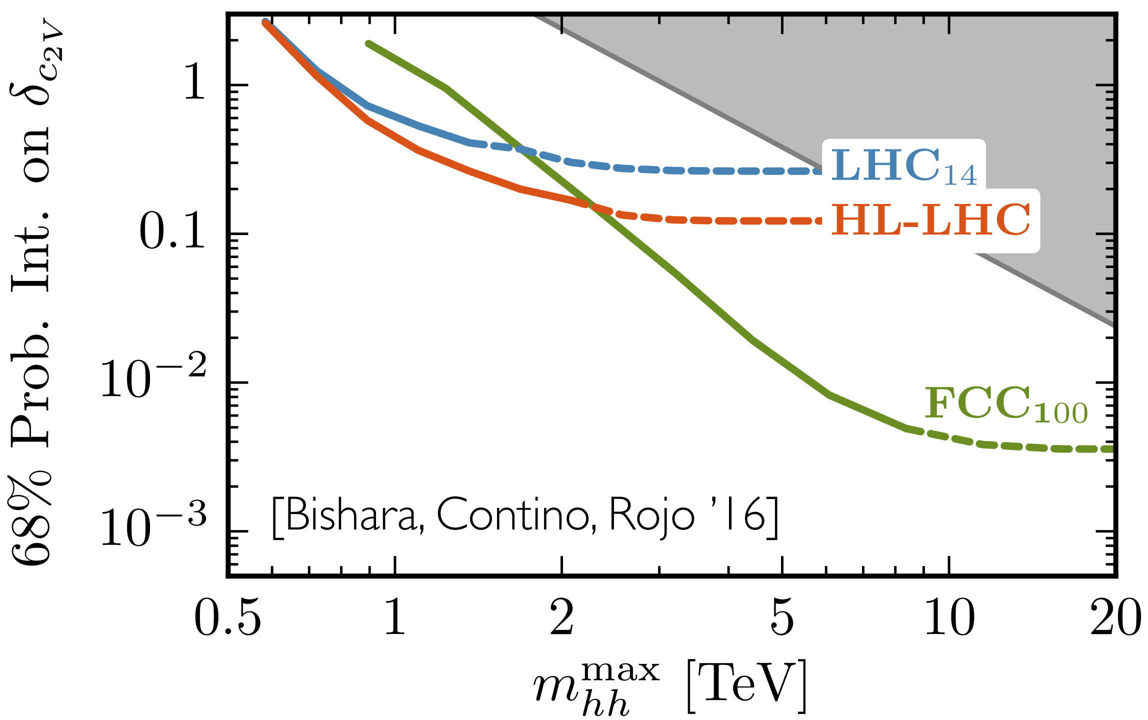
$$\sim \frac{m_h^2}{v^3}\lambda_3 c_V$$



Double Higgs from VBF

- limited reach at HL-LHC (very small statistics)
- huge improvement at **FCC-hh: probe ~1% deviations**

	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\text{bkg}}$	$3 \times \sigma_{\text{bkg}}$
LHC$_{14}$	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC$_{100}$	$[0, 0.01]$	$[-0.01, 0.01]$



- strong implications for explicit scenarios

eg. SO(5)/SO(4) composite Higgs models: $c_{2V} = 1 - 2\xi = 1 - 2v^2/f^2$

$$|\delta c_{2V}| \lesssim 1\% \longrightarrow f \gtrsim 3.5 \text{ TeV}$$

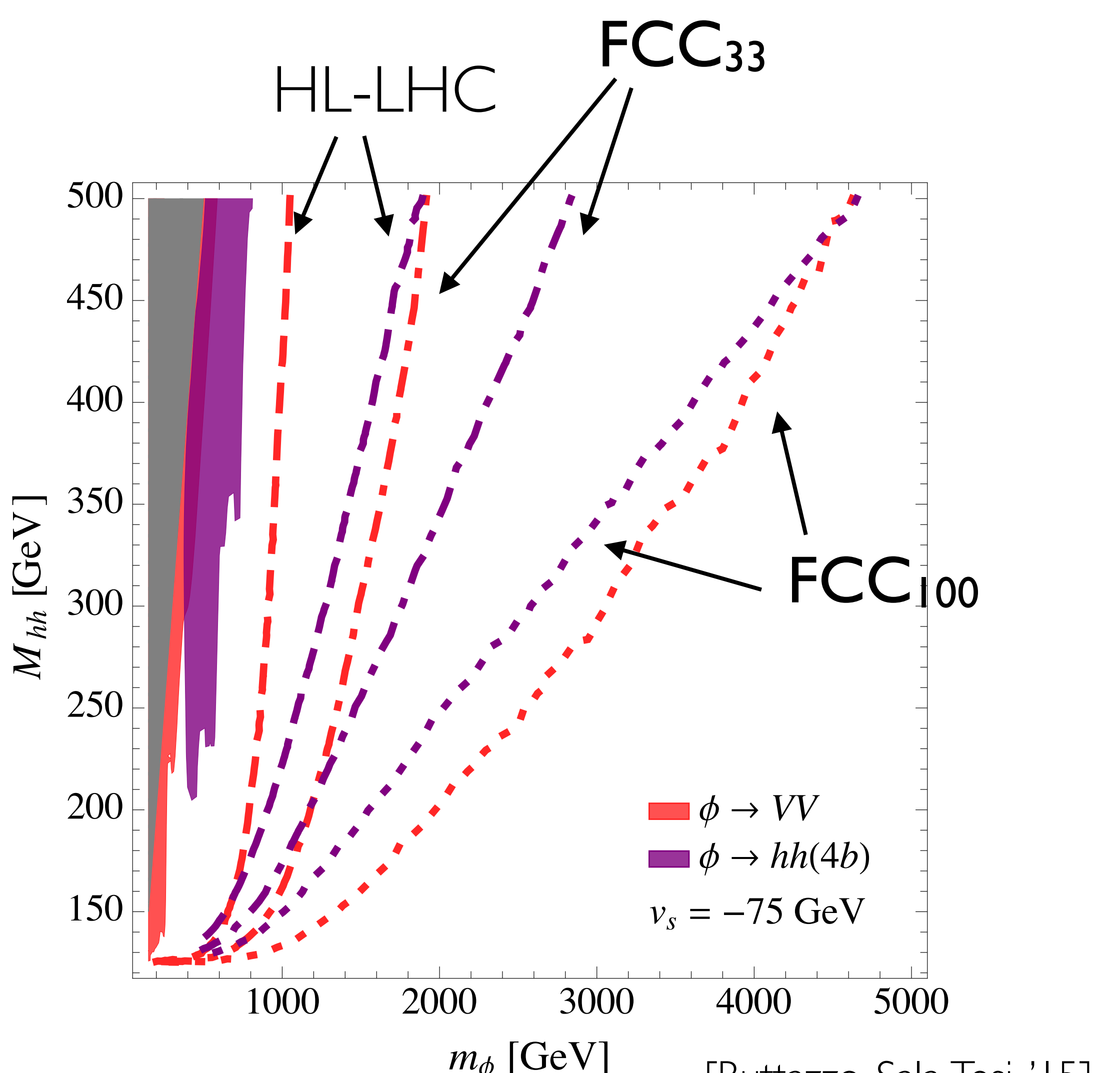
Extended Higgs sectors

Additional scalar singlet

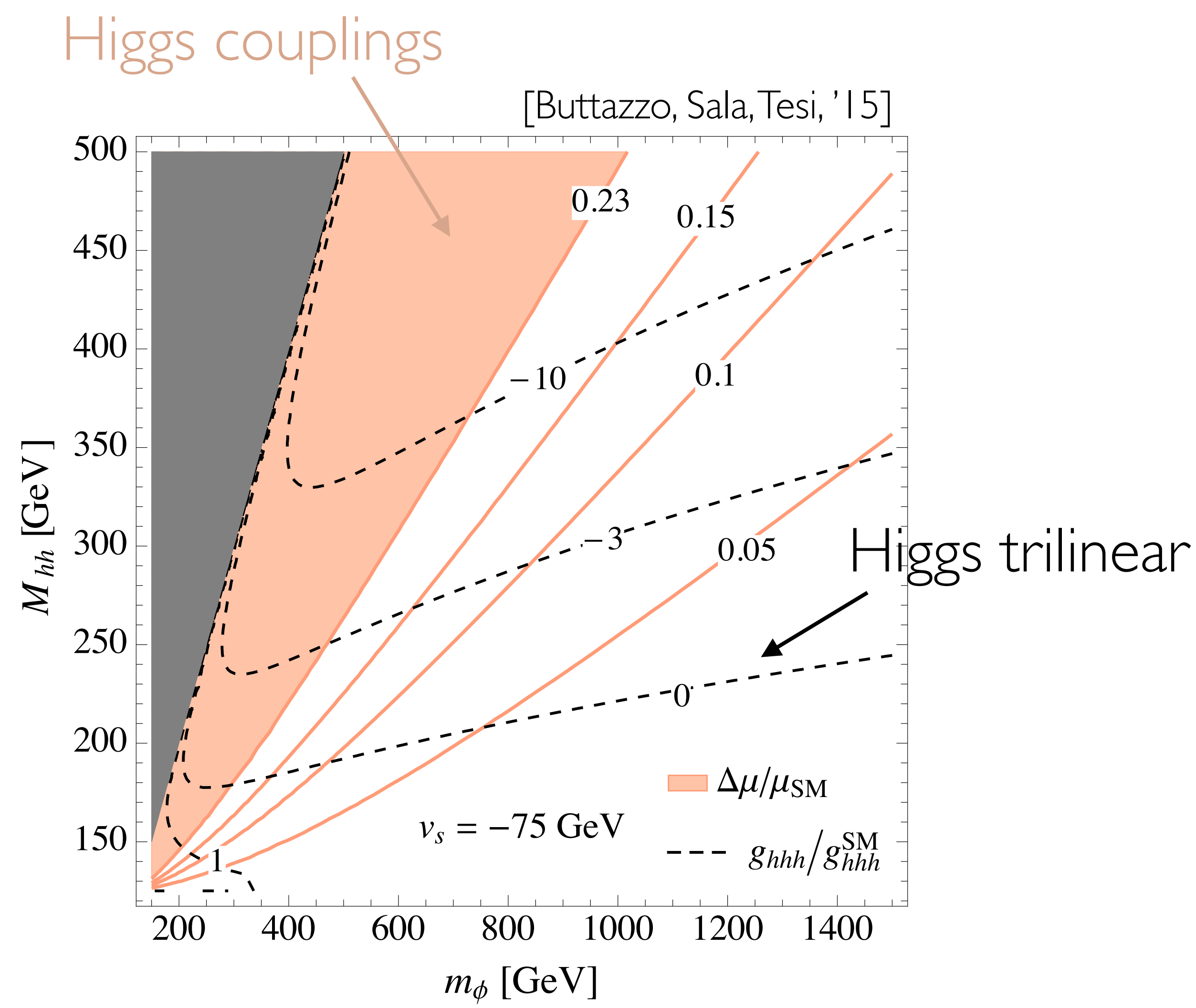
Extensions of the Higgs sector are quite common in BSM scenarios

eg. additional **singlet** ϕ often present (eg. NMSSM, Twin Higgs, …)

results taken from Buttazzo, Sala, Tesi, 1505.05488
see also references therein



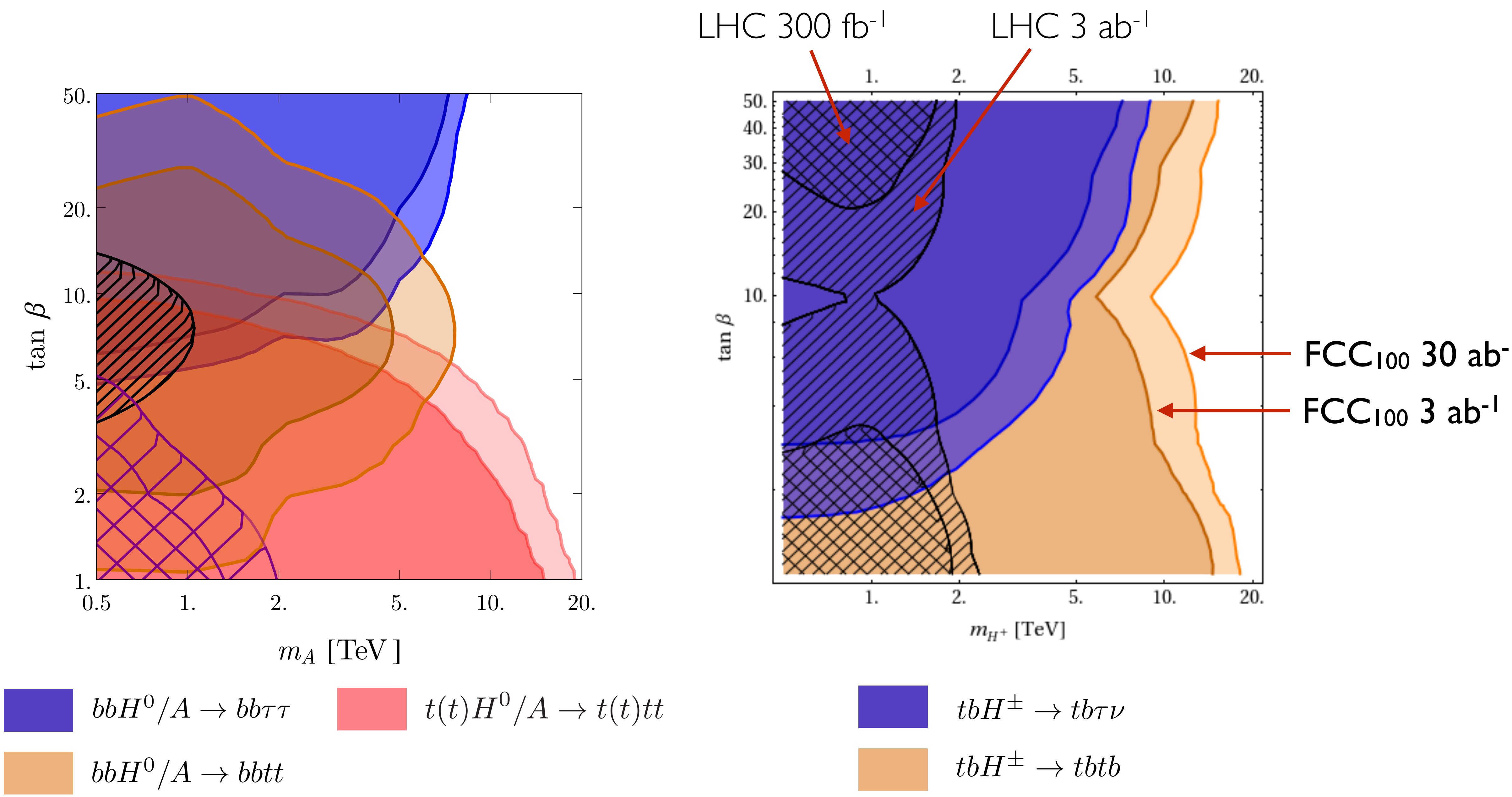
[Buttazzo, Sala, Tesi, '15]



- **complementarity** of direct searches and Higgs coupling measurements

MSSM Higgs sector

Classical scenario: **direct searches** for MSSM Higgs sector can access ~10 TeV states

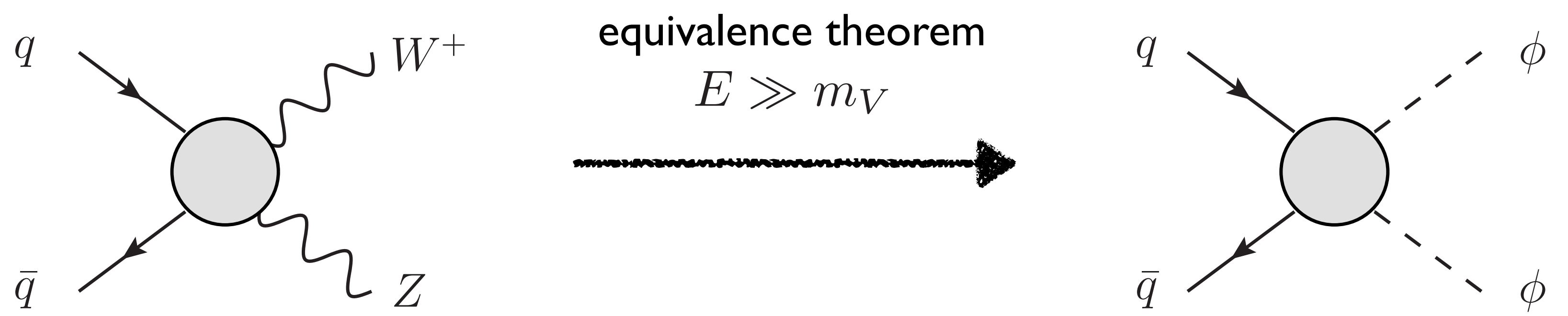


Precision EW measurements

Precision EW measurements

Effective **Higgs couplings** can also be tested through **EW precision measurements** at high energy

- high-energy longitudinally polarized gauge fields can be "traded" for **Higgs/Goldstones**



→ probing di-boson production at high-energy is a way to test **Higgs dynamics!**

Precision EW measurements

- ✦ deviations from SM typically **grow with energy**

$$\frac{\mathcal{A}_{\rm SM+BSM}}{\mathcal{A}_{\rm SM}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

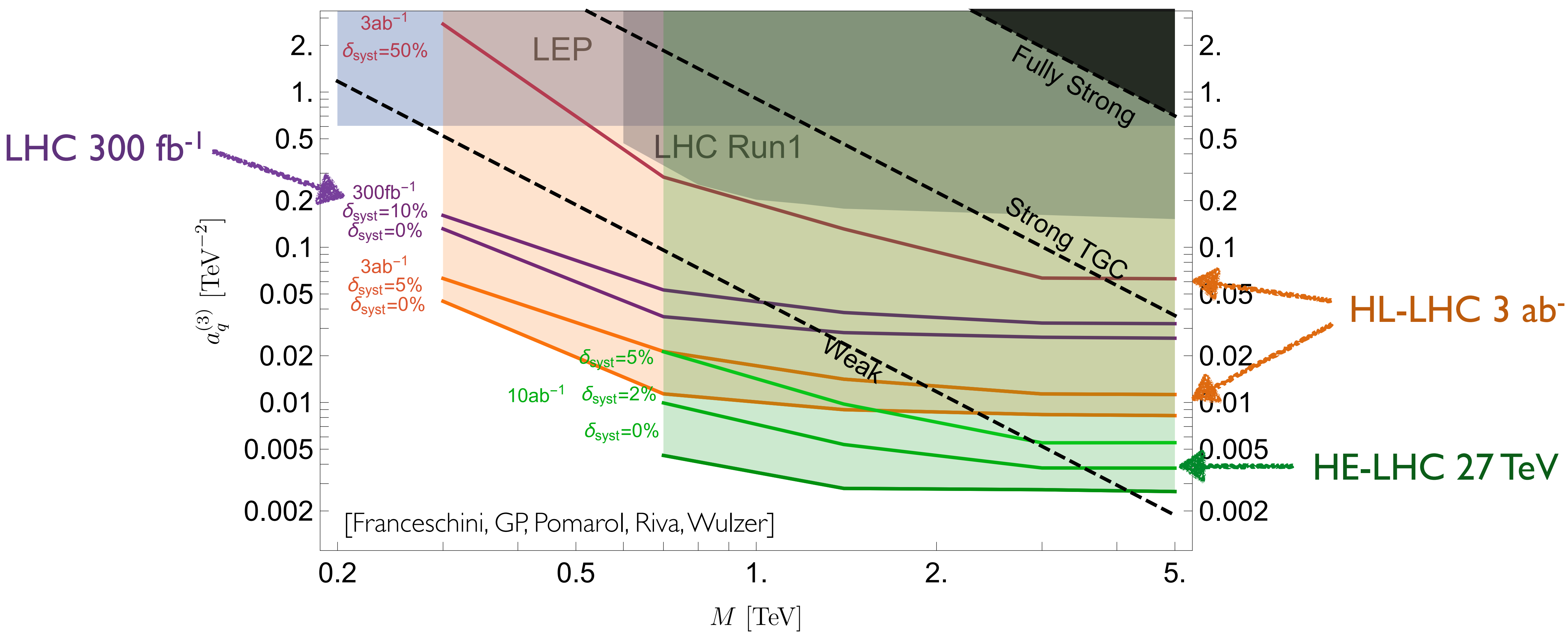
- ✦ LHC could match LEP sensitivity by going at **high energy**

$$0.1\ \%\quad \text{at}\quad 100\ \text{GeV} \quad \longrightarrow \quad 10\ \%\quad \text{at}\quad 1\ \text{TeV}$$

- enhancement can **compensate limited accuracy** at hadron machines

Analysis of WZ fully leptonic

eg.: dim.-6 **Higgs contact interaction** $\frac{a_q^{(3)}}{(1\,\mathrm{TeV})^2}(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{q}_L\sigma^a\gamma^\mu q_L)$



- stronger bounds by exploiting the high-energy enhancement
- already LHC can **improve LEP bound**, even better at future machines
- **other channels** might give complementary information: WH, ZH, WW.

Conclusions

Conclusions

FCC-hh has huge potential to explore new physics territories and improve our knowledge of the Higgs

- Exploiting the **energy frontier**
  - probe extended Higgs sectors (2HDM, additional singlets, …)
  - access high-energy tails of distributions (enhanced new-physics effects)
    - test Higgs interactions in di-boson processes (HH in VBF, WZ, …)

- Exploiting the **intensity frontier**
  - precision studies of Higgs couplings
    - $H \to \mu\mu$ and $H \to Z\gamma$ enter precision era
    - large improvement in top Yukawa (~1%)
  - access to rare processes
    - test light quark Yukawa's (eg. charm)
    - test SM Higgs invisible BR
    - test Higgs potential: trilinear coupling 3 -5 %; quadrilinear [-4, +16]