Higgs self-coupling @100 TeV

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also based on:
[1606.09408], [1802.01607]

FCC week 2018 - 11/04/2018 - Amsterdam

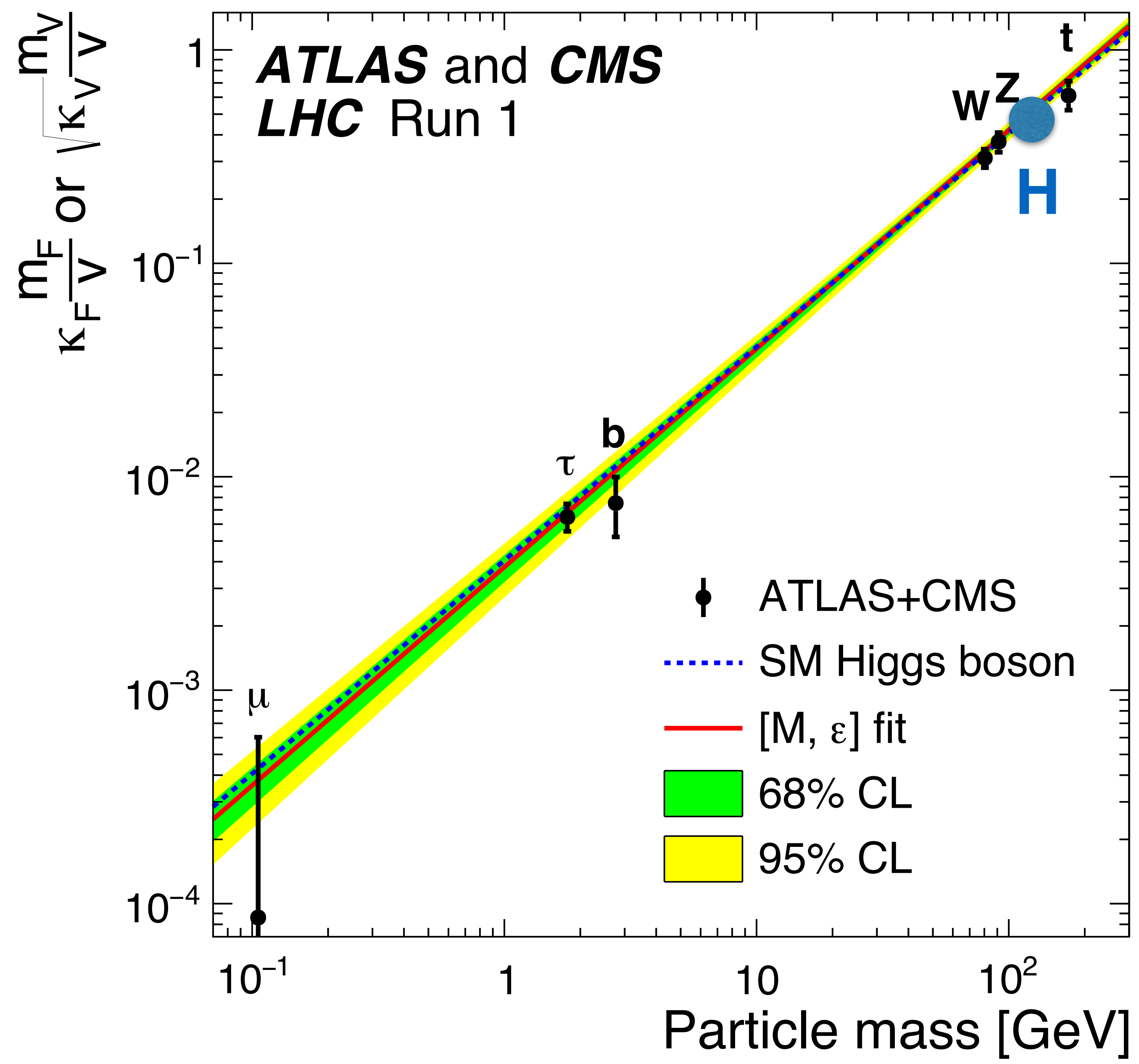
Why measure HH?

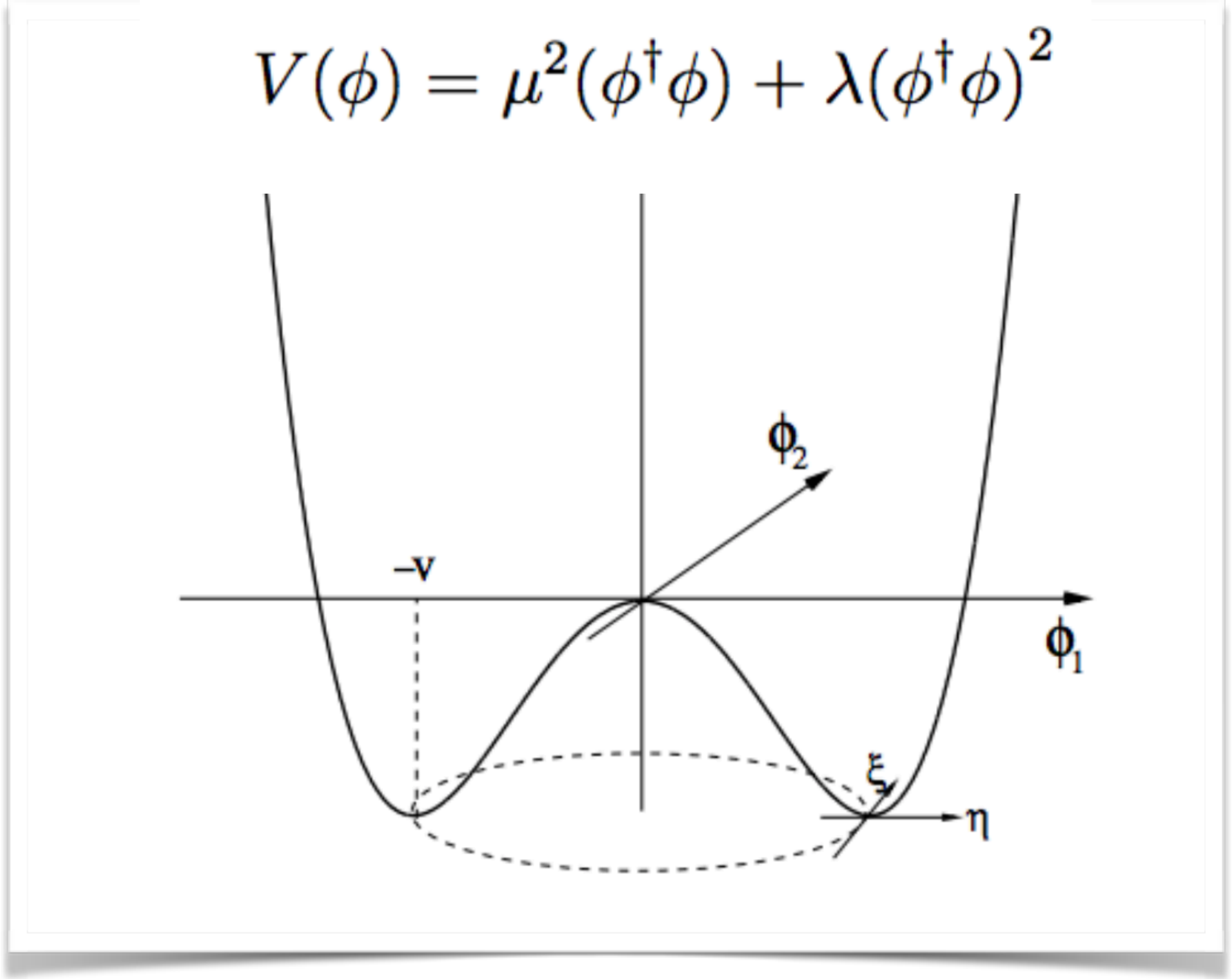
- Measurement of HH gives access to the magnitude of the **Higgs self-interaction**:

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

- Higgs trilinear coupling constant **λ** only depends on the Higgs field VEV and Higgs mass. Purely determined by EWSB (in the SM).

- Shape of the **Higgs potential** is determined by the self coupling value (EWPT)

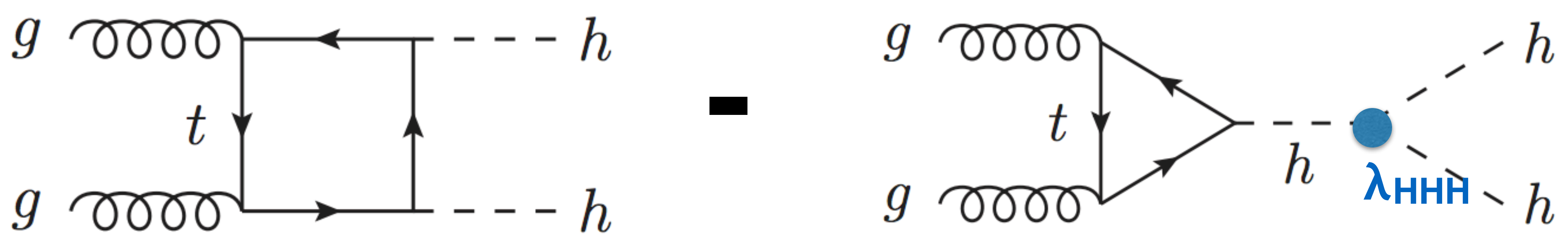




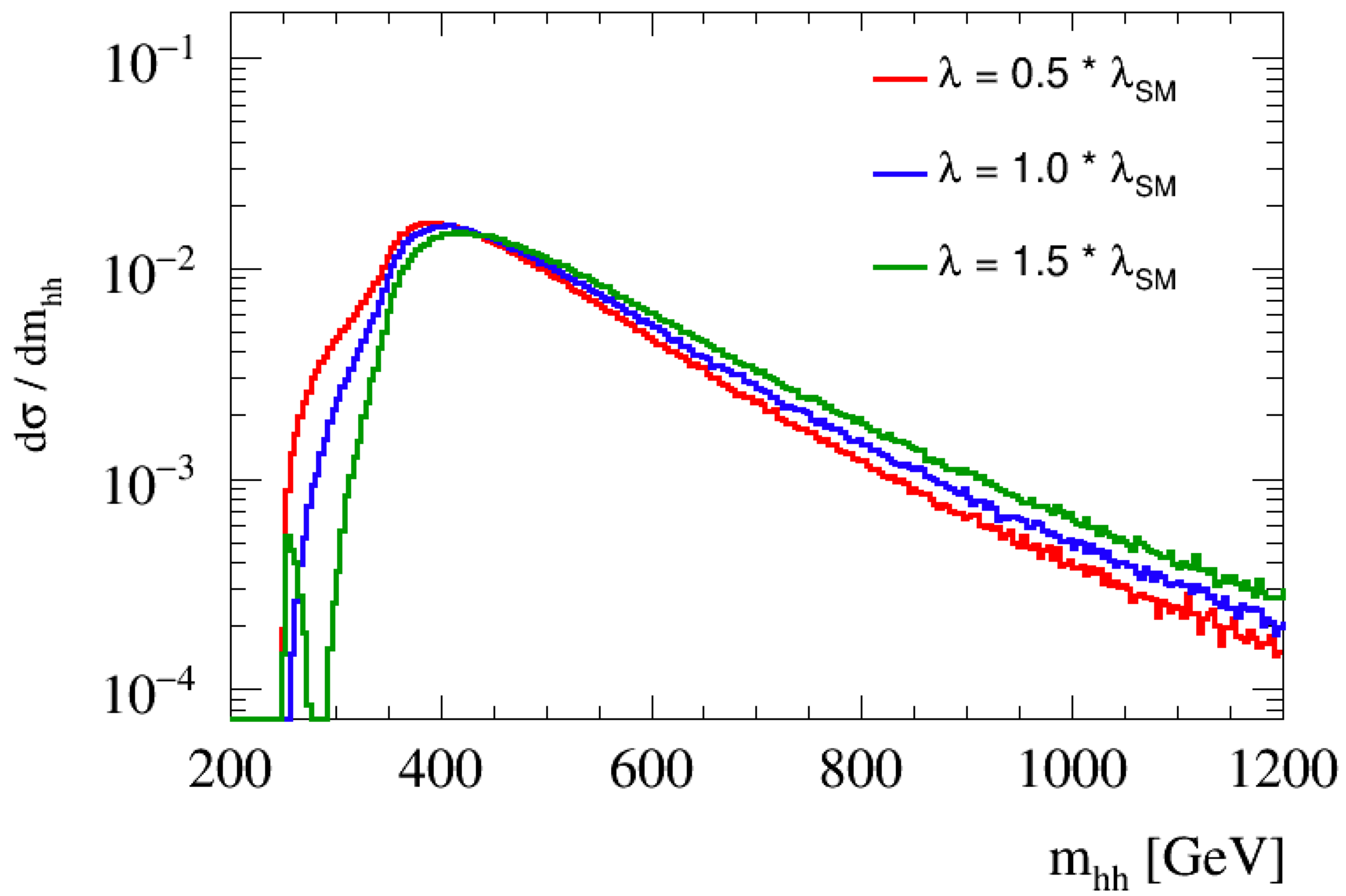
HH@ FCC-hh: production

σ(100 TeV) / σ(14 TeV) ≈ 40

gluon fusion:



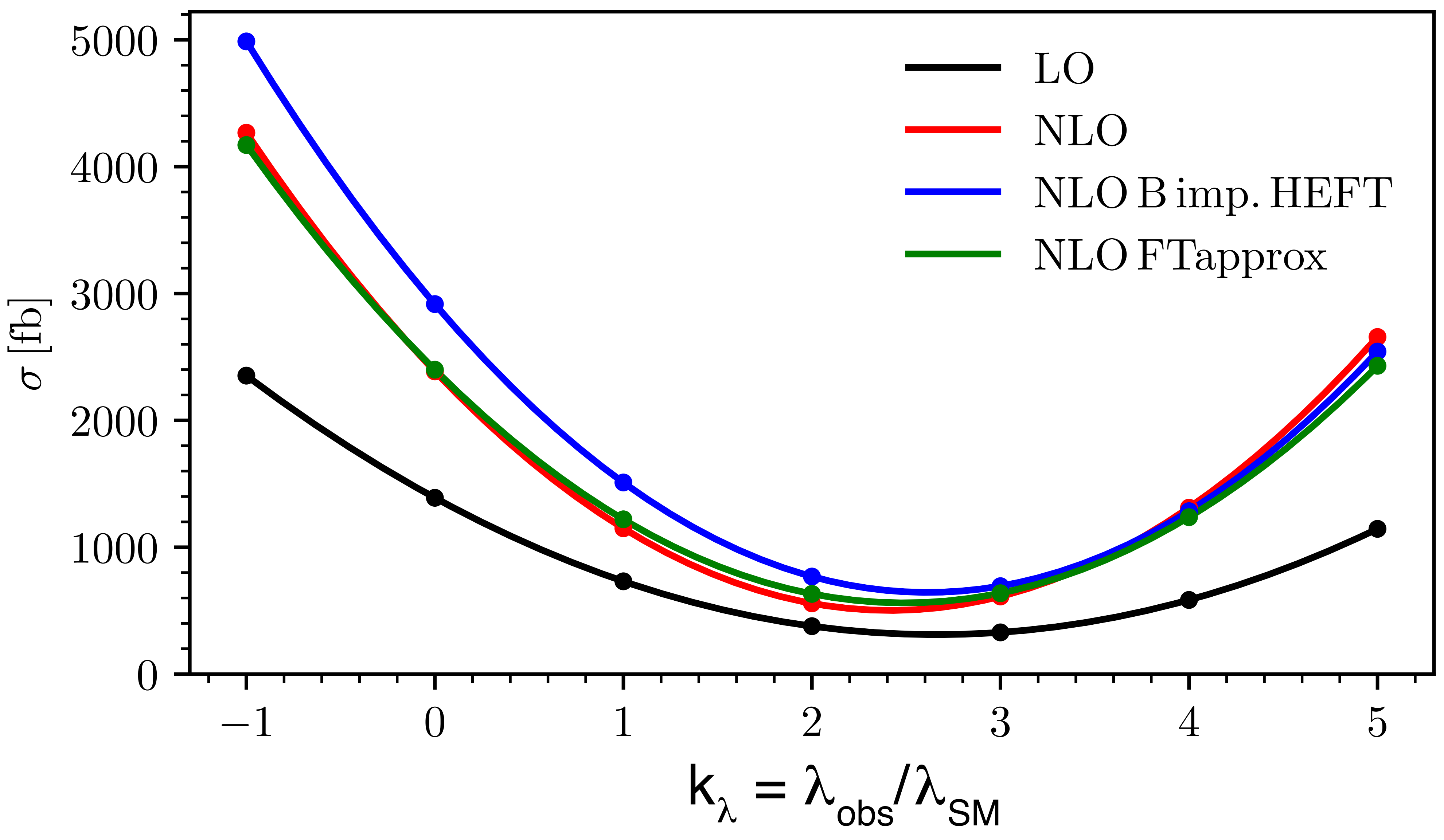
- **negative interference** between **box** and **triangle**
- **high m_{hh} region suppressed** by off-shell propagator in triangle (and dominated by box)

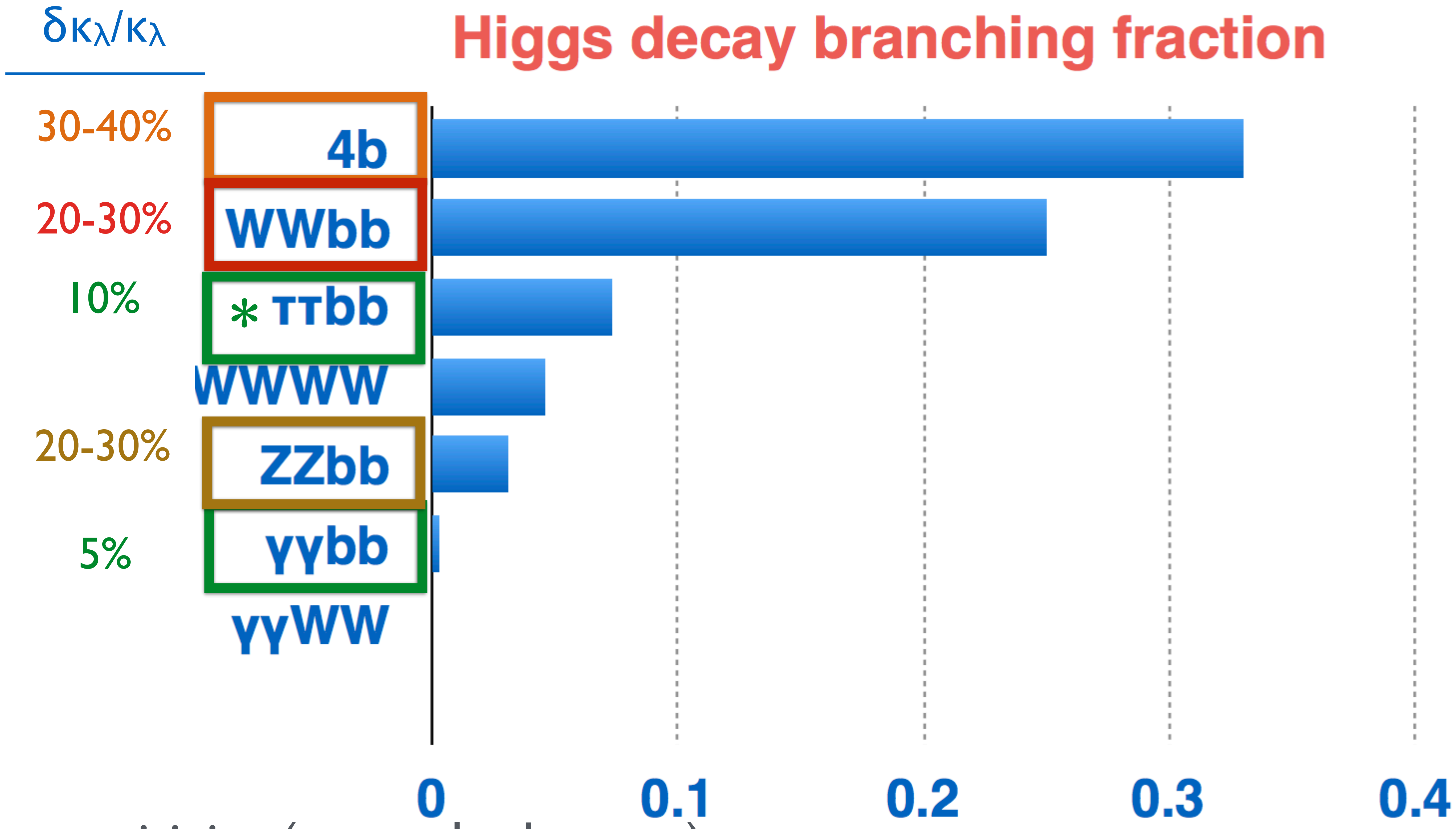


→ **sensitivity** to the self-coupling is determined by **low m_{hh} region**

HH@ FCC-hh: production and decay

G. Heinrich et.al [1608.04798]





- Higher order in QCD helps λ-dependent K-factor sensitivity (not only the rate)
  → included here (bbɣɣ, bbZZ)!

- Total rate still taken to be given by NNLL+NNLO in EFT (although known to be overshooting by 20%), but missing the following (should compensate?):
  - higher orders other channel (N^nLO, n>2)
  - VBF-HH/ttHH

bbɣɣ

Selection

Acceptance cuts

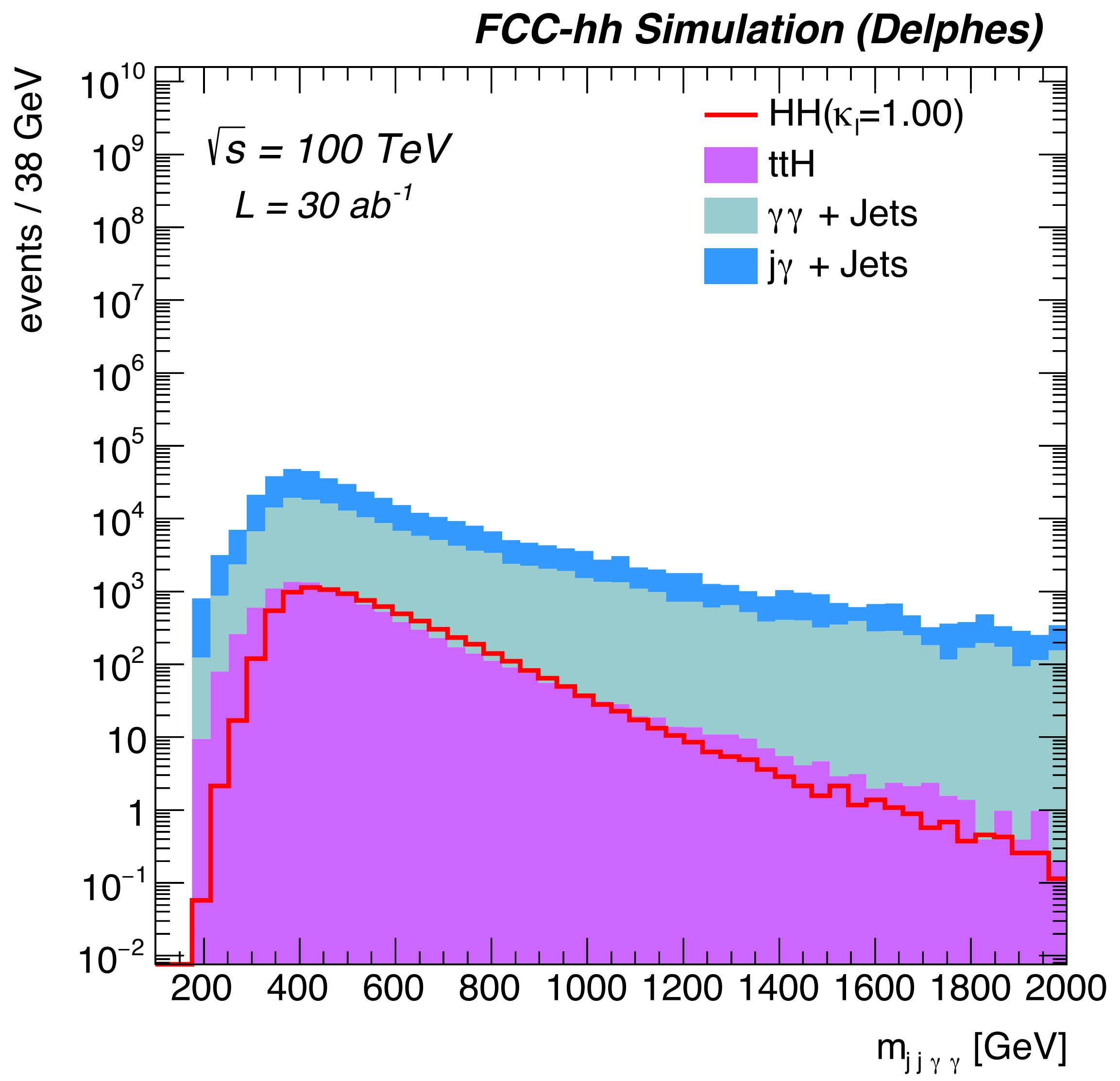
γ isolation $R = 0.4$
$(p_T(had)/p_T(\gamma) < 0.15)$
jets: anti-k_T, parameter $R = 0.4$

$|\eta_{b,\gamma,j}| < 6$

$p_T(b), p_T(\gamma), p_T(j) > 35$ GeV

$m_{bb} \in [60, 200]$ GeV

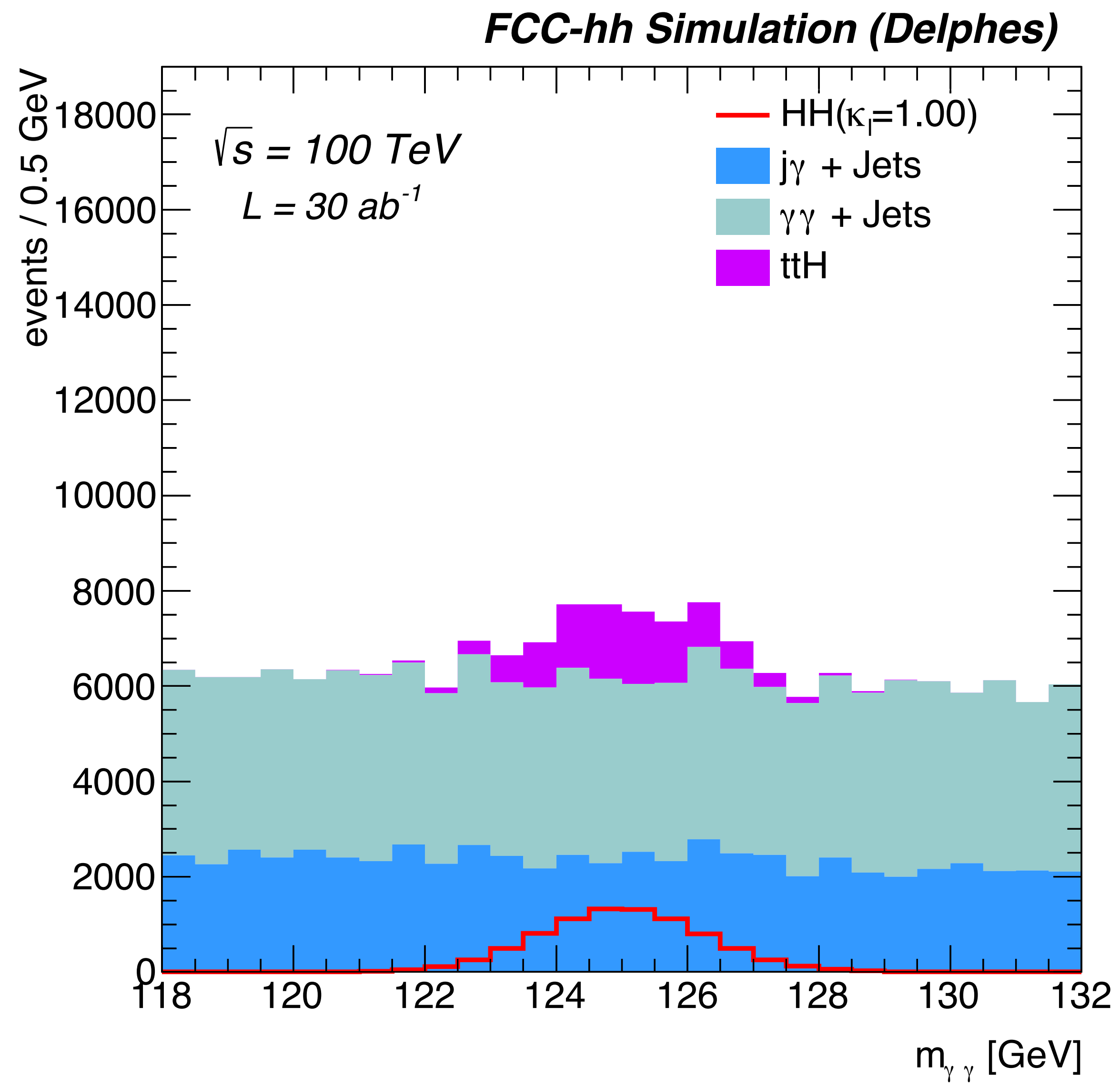
$m_{\gamma\gamma} \in [100, 150]$ GeV



Backgrounds

- ttH
- jjγγ
- jjjγ (fake photons, fake b's)

$$p_{j\to\gamma} = \alpha \exp(-p_{T,j}/\beta)$$



Final selection

γ isolation $R = 0.4$
$(p_T(had)/p_T(\gamma) < 0.15)$
jets: anti-k_T, parameter $R = 0.4$

$|\eta_{b,\gamma}| < 4.5$

$p_T(b_1), p_T(\gamma_1) > 60$ GeV

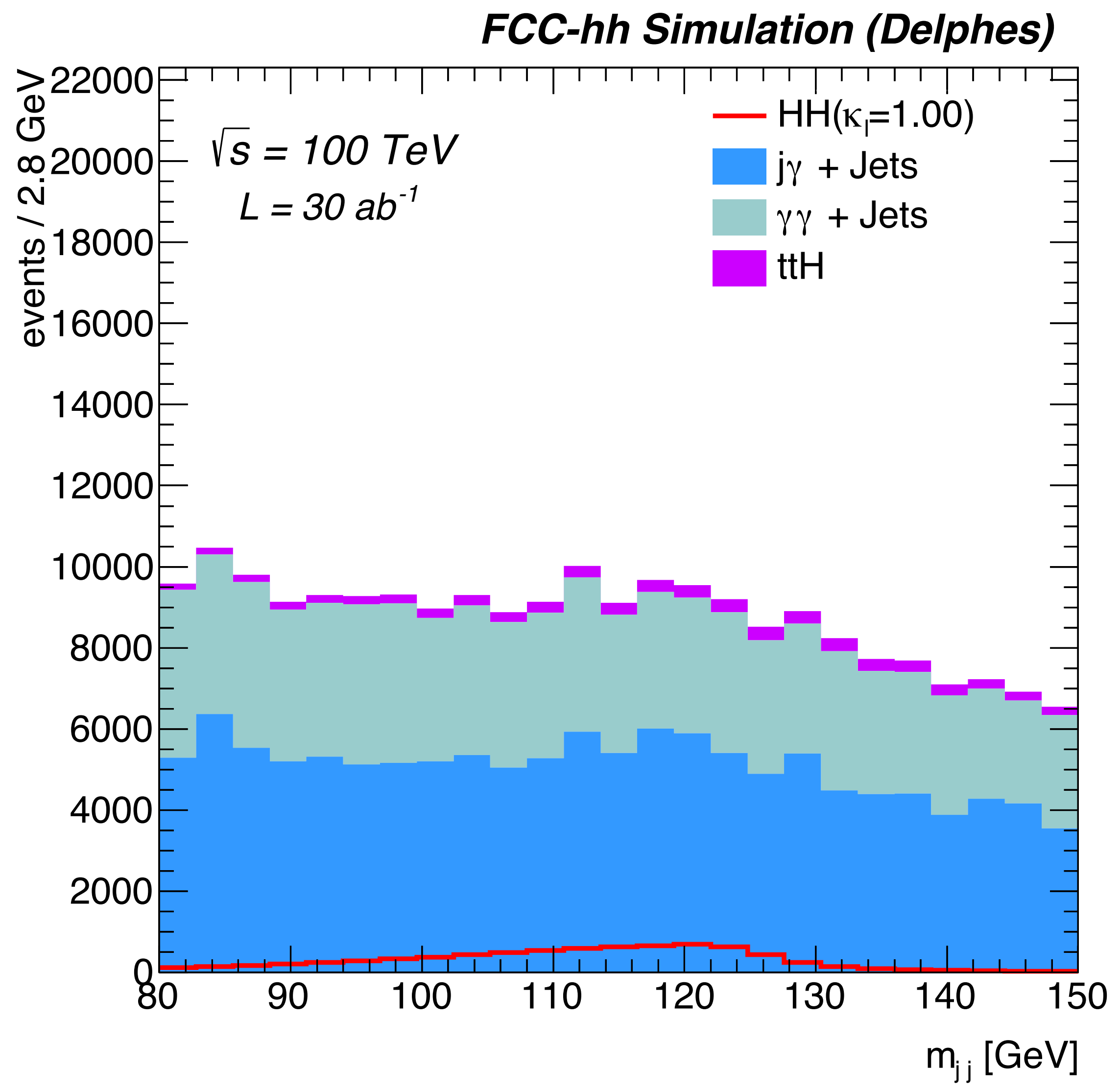
$p_T(b_2), p_T(\gamma_2) > 35$ GeV

$m_{bb} \in [100, 150]$ GeV

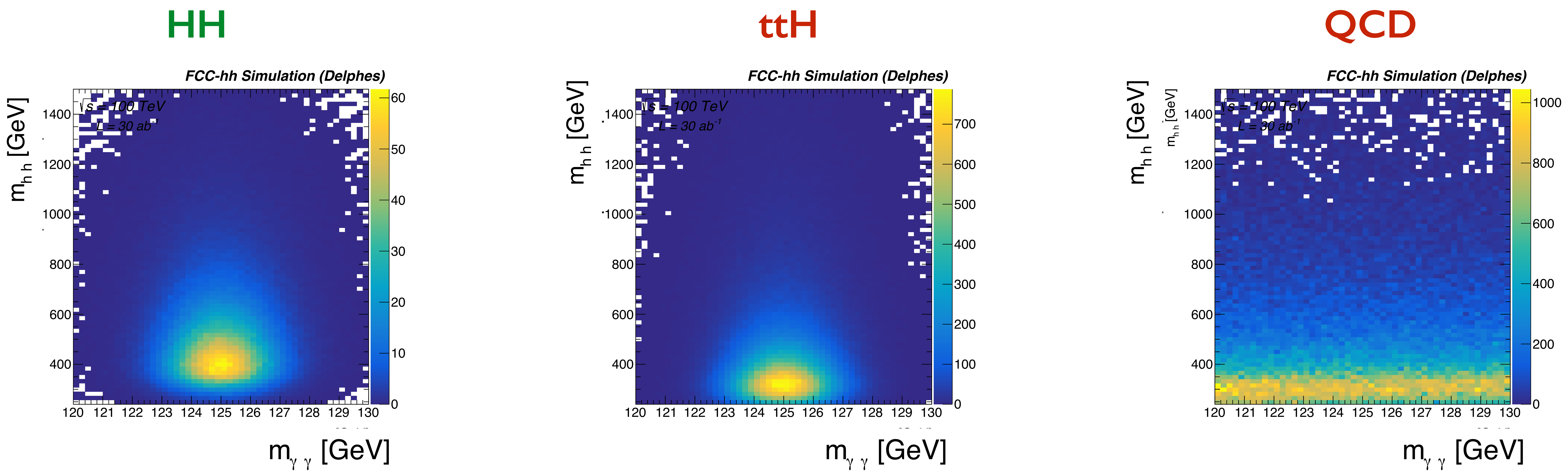
$p_T(bb), p_T(\gamma\gamma) > 100$ GeV

$\Delta R(bb), \Delta R(\gamma\gamma) < 2.5, 3.0$

no isolated leptons with $p_T > 25$ GeV



2D shapes



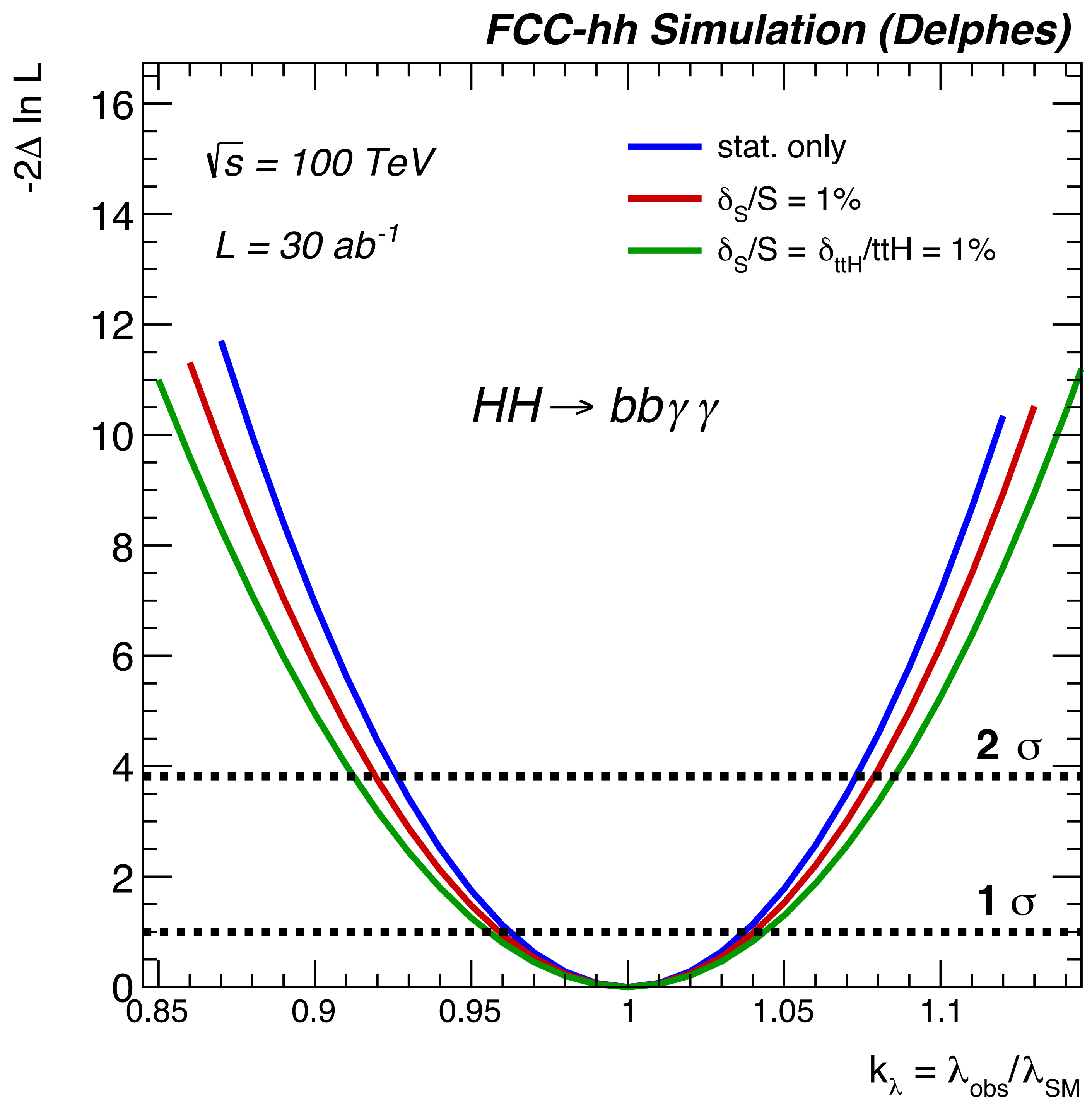
- exploit correlations of means in the signal, ex: **$m_{\gamma\gamma}$ vs m_{hh}**
- build **parametric model** in 2D → **$m_{\gamma\gamma}$** : gauss, **m_{hh}**: landau+exp
- perform **2D Likelihood fit** on the **signal strength** and **coupling modifier:**

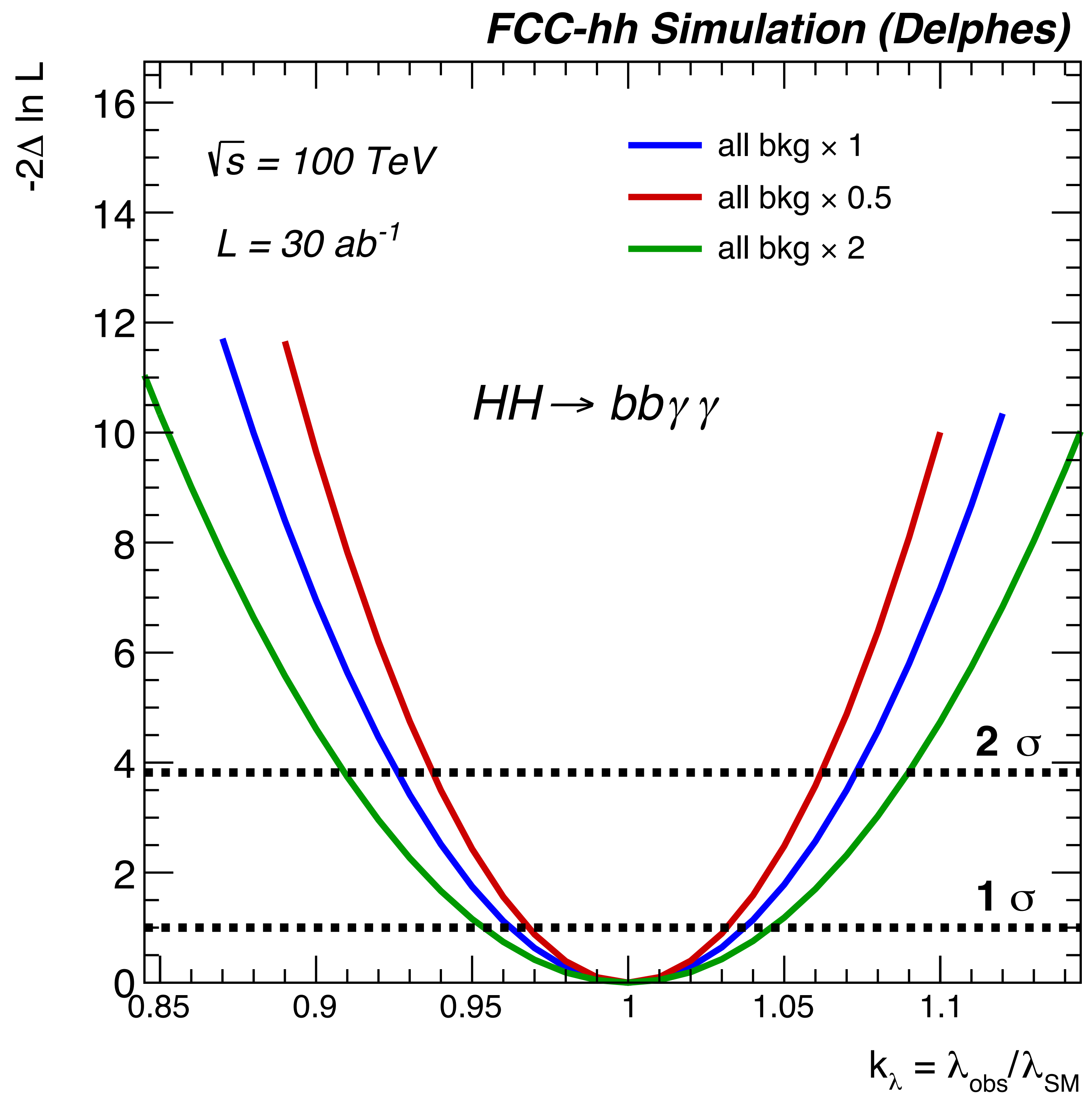
$$\mu = \sigma_{obs}/\sigma_{SM}$$

$$\kappa_\lambda = \lambda_{obs}/\lambda_{SM}$$

Precision on the self-coupling

assuming QCD can be measured from sidebands





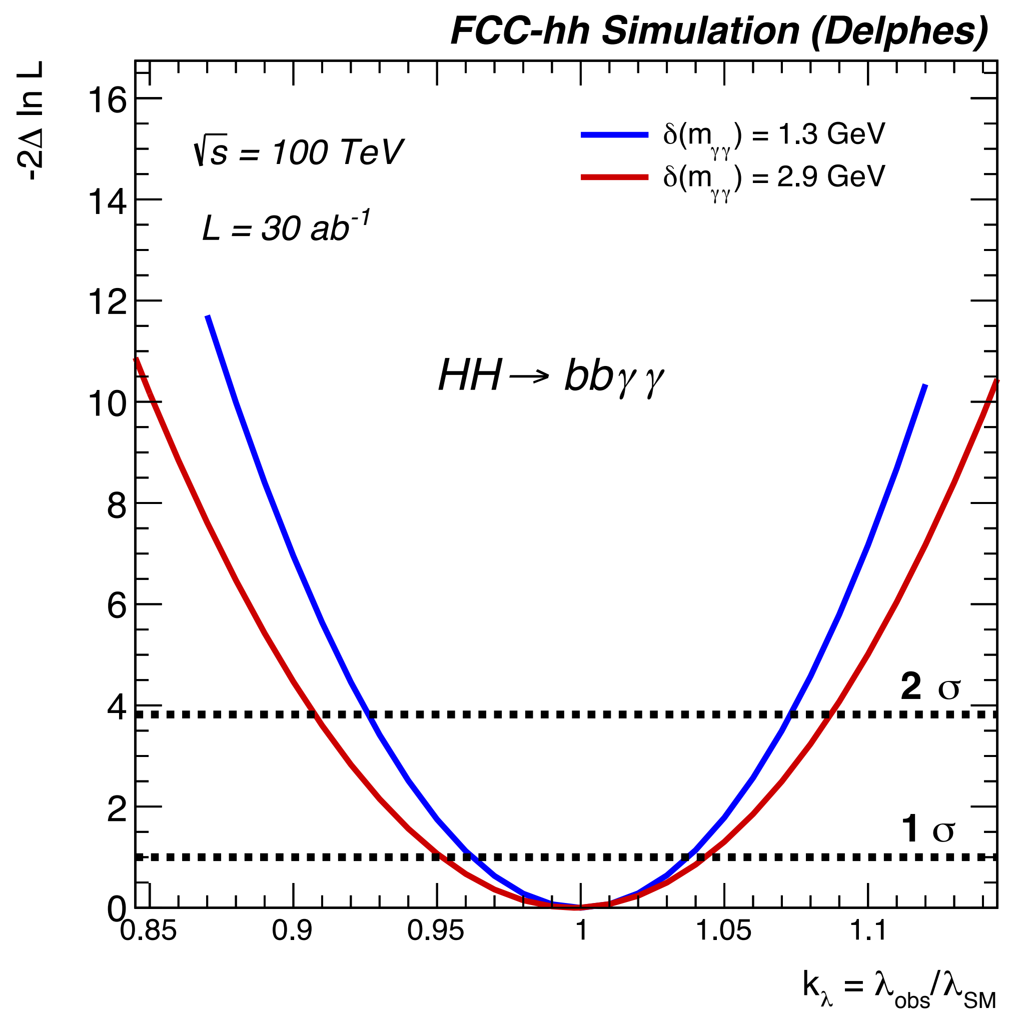
nominal background yields:

$\delta\kappa_\lambda$(stat) ≈ 3.5 %
$\delta\kappa_\lambda$(stat + syst) ≈ 4.5 %
δr(stat) ≈ 2.5 %
δr(stat + syst) ≈ 3 %

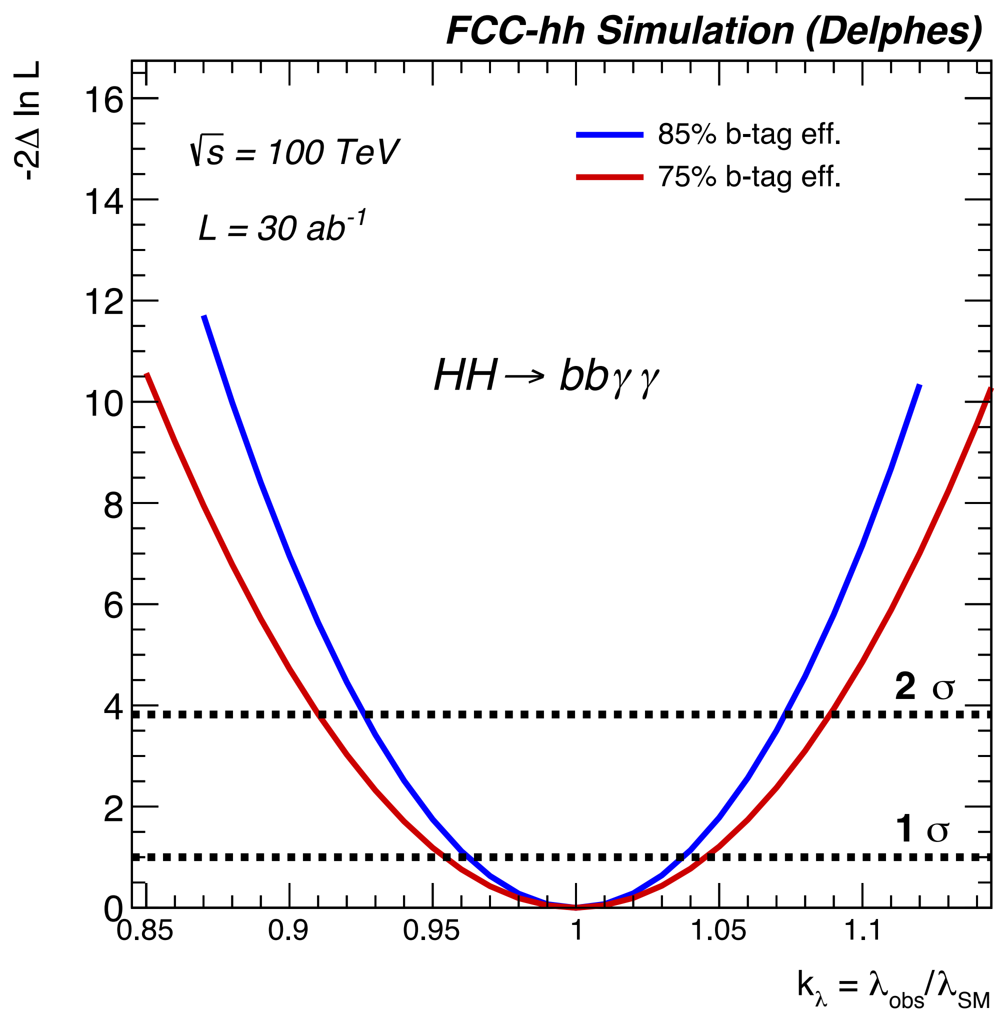
varying (0.5x-2x) background yields:

$\delta\kappa_\lambda$(stat) ≈ 3 - 5 %
δr(stat) ≈ 2 - 3%

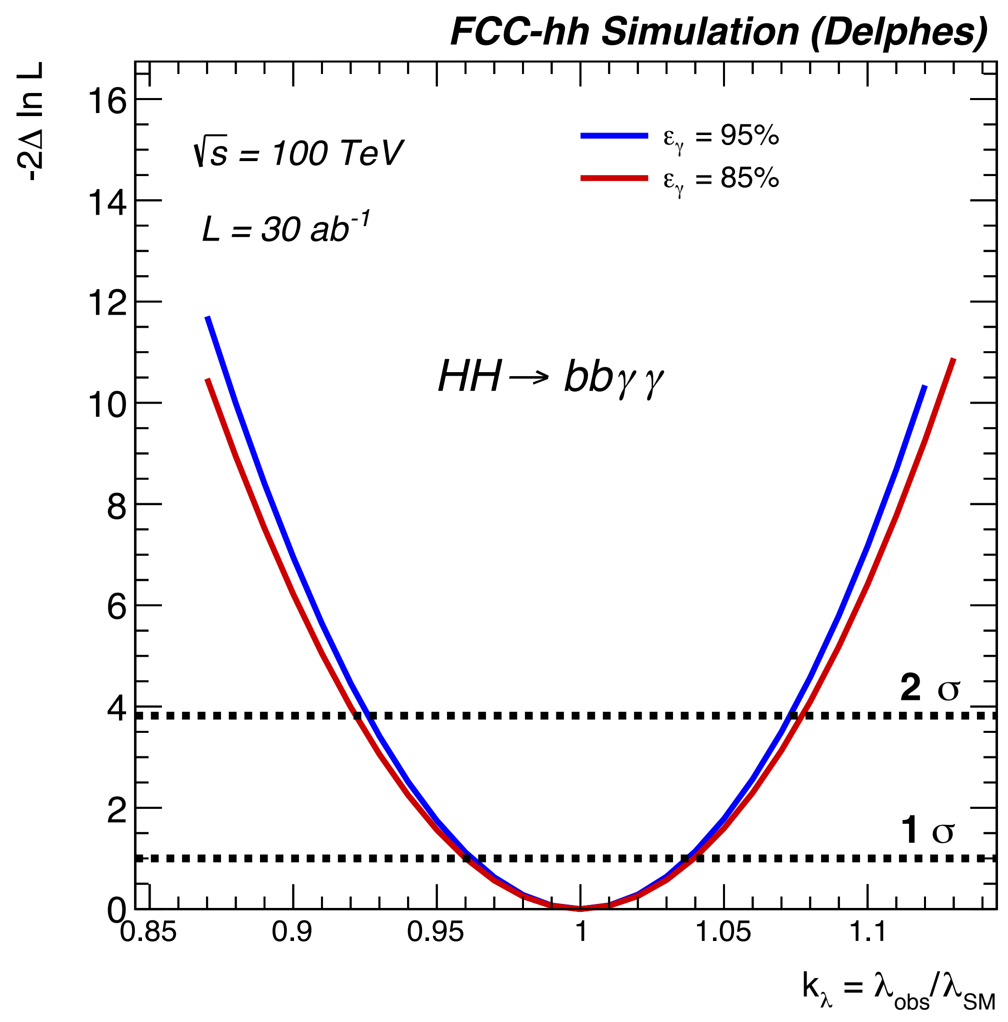
Varying detector specifications



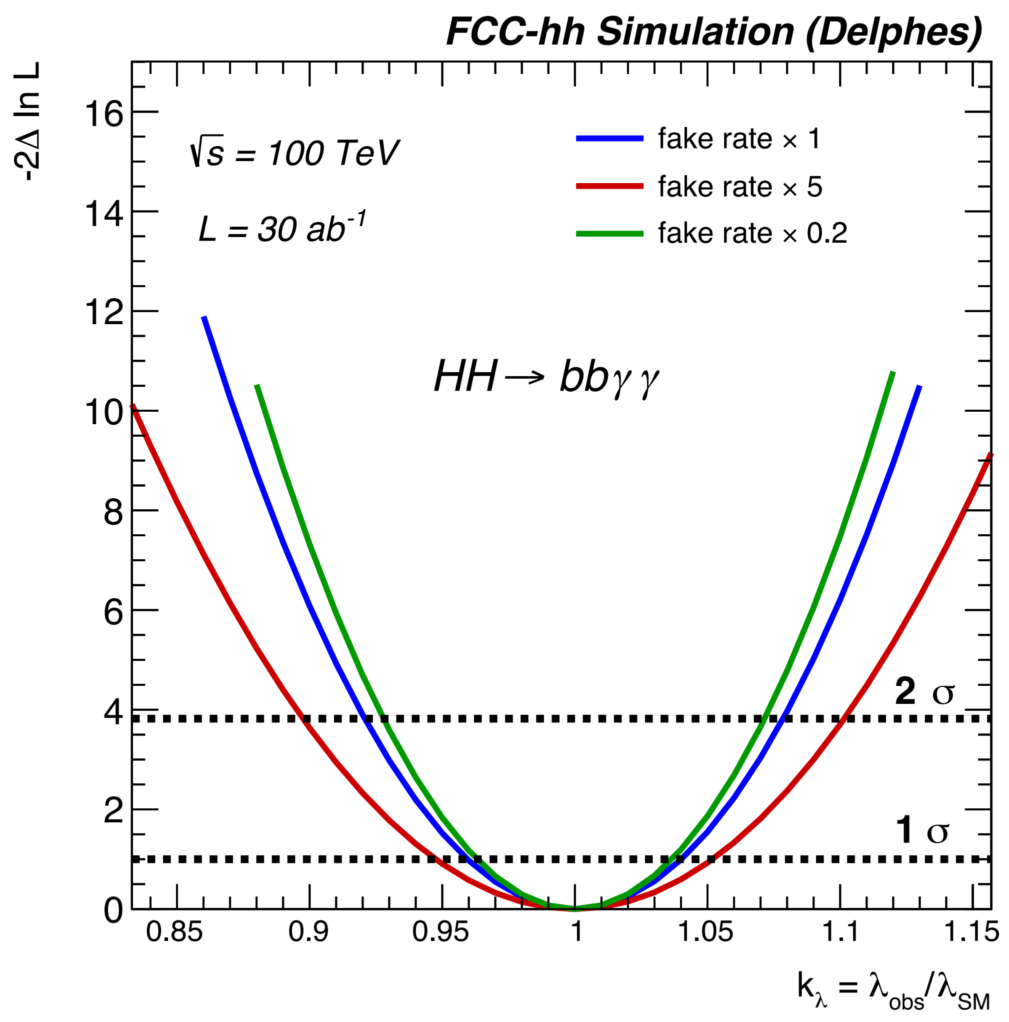
m(ɣɣ) resolution



B-tag efficiency



Photon efficiency

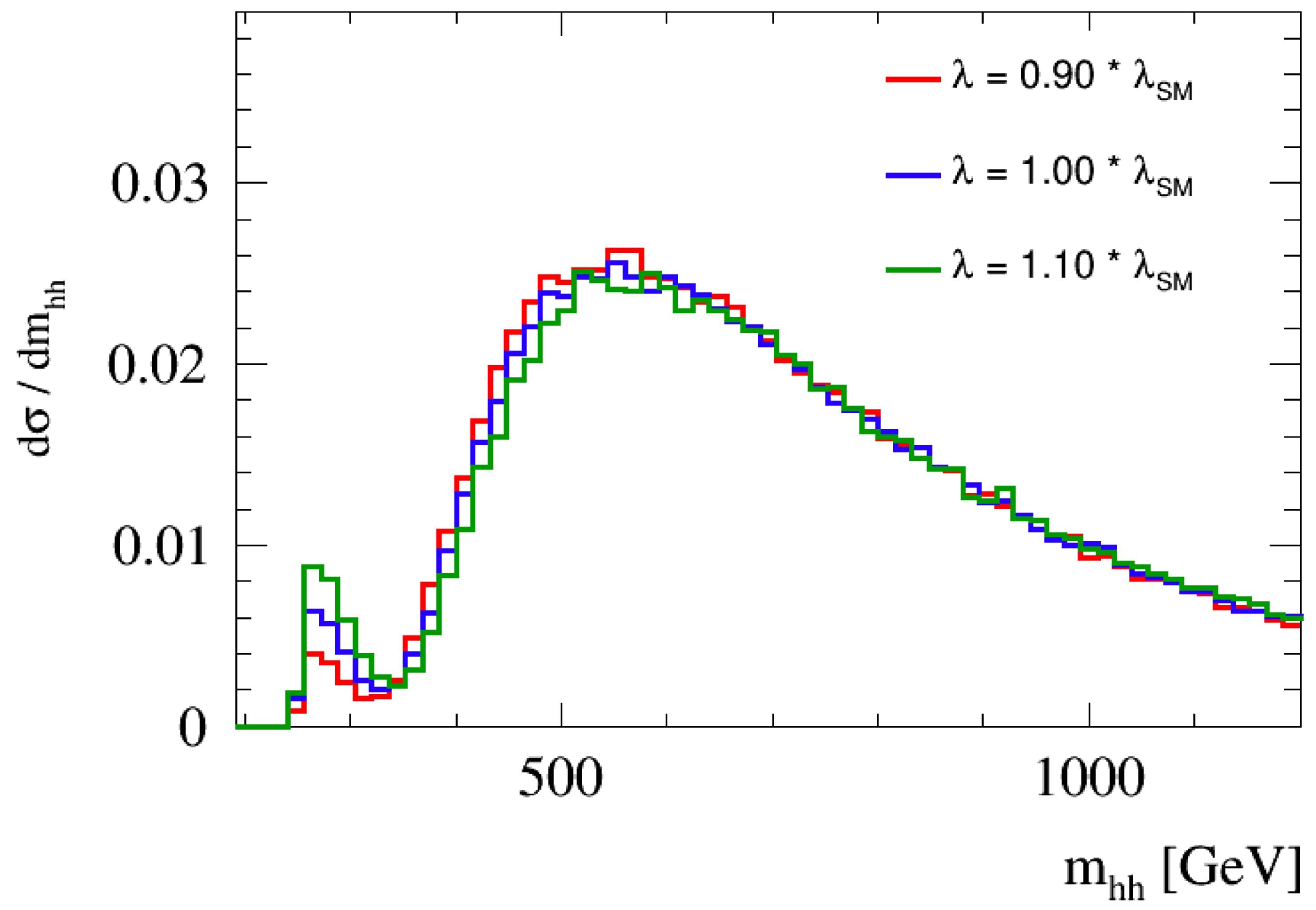


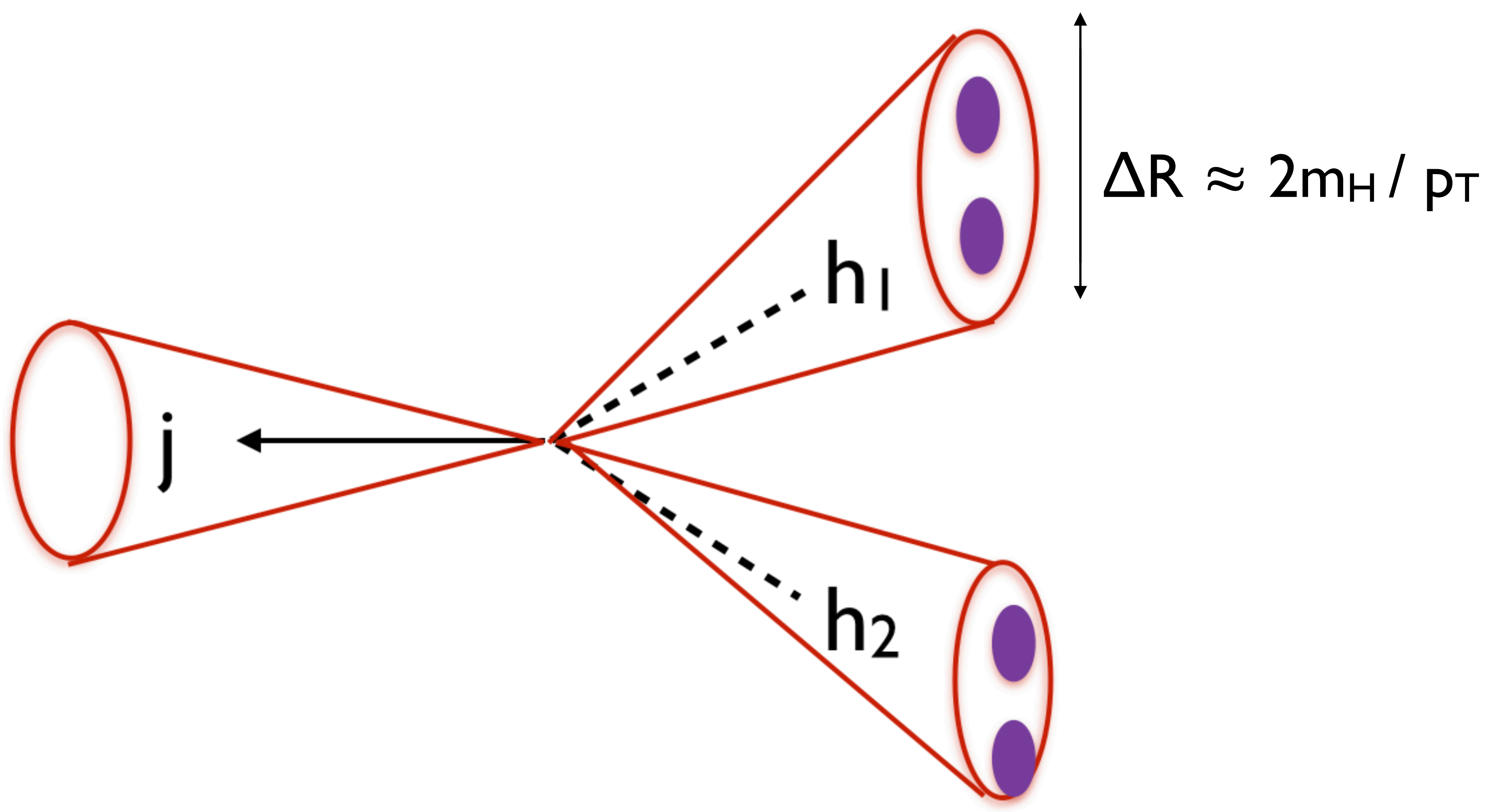
Photon fake-rate

- Model tunable to include various effects/conditions on the objects
- Even with non-ideal configurations, **5% precision** on kλ seems to be within reach

4b - boosted

Approach

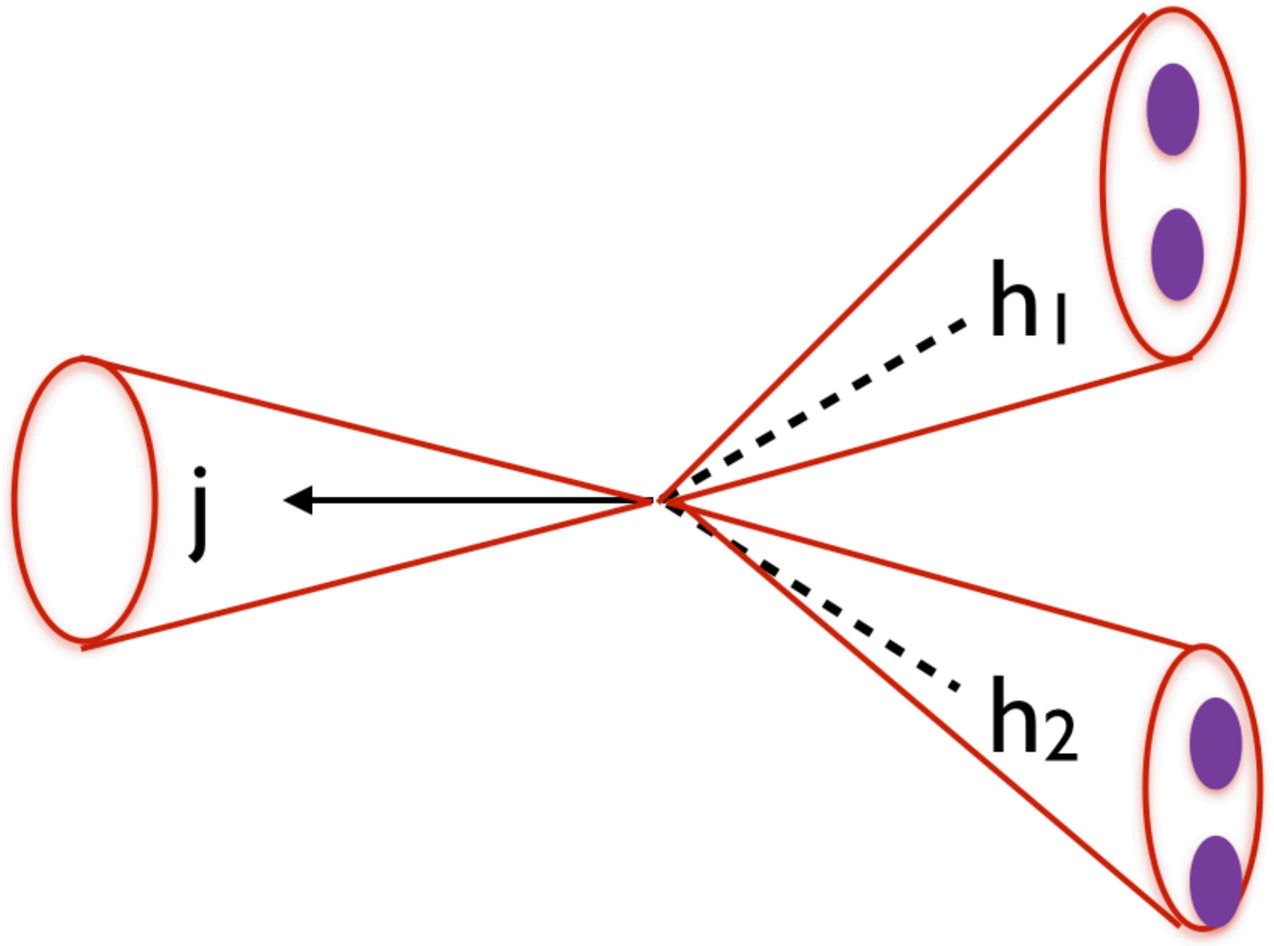




- σ(pp→hhj, 100 TeV) ≈ 100 * σ(pp→hhj, 14 TeV) , with p_T(j) > 100 GeV
- Exploit **large branching ratio** BR(H→bb)^2 ≈ 0.3
- Requiring a **boosted HH system recoiling against jet(s)**, contains the invariant mass to small values → maintain sensitivity to the self-coupling
- In practice **low mass region** (m_{HH} ≈ 200 GeV) is **unresolvable**:

$$m_{HH} \gtrsim p_T * 2R_{jet} \quad \text{and} \quad R_{jet} \approx 2m_H/p_T \quad \Rightarrow \quad m_{HH} \gtrsim 3\text{-}4\ m_H$$

Signal and backgrounds



Backgrounds

- QCD: (double gluon to b-bar splitting recoiling against jet)
  - p p → 4b + j (or simply p p → j g g)

σ^{4b+j} (pT(j) > 500 GeV) ~ 57 pb (10^9 @ $30ab^{-1}$)

- ttbar, ZH …

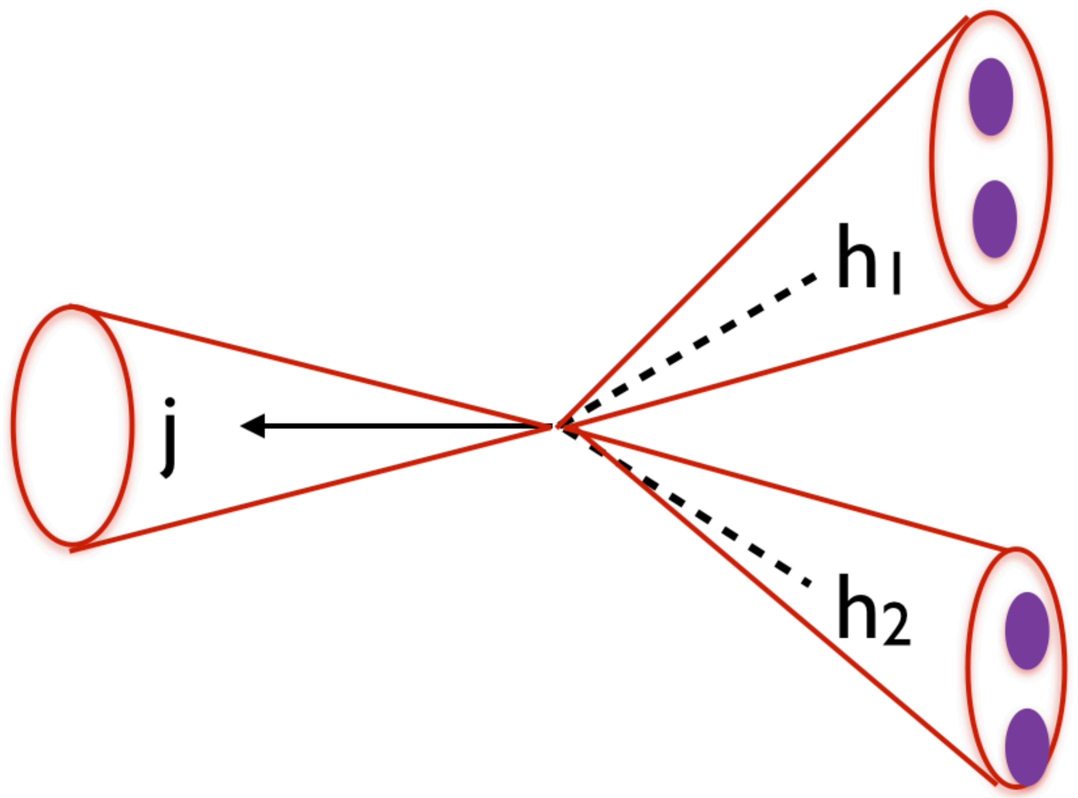
Signal

- p p → h h + j

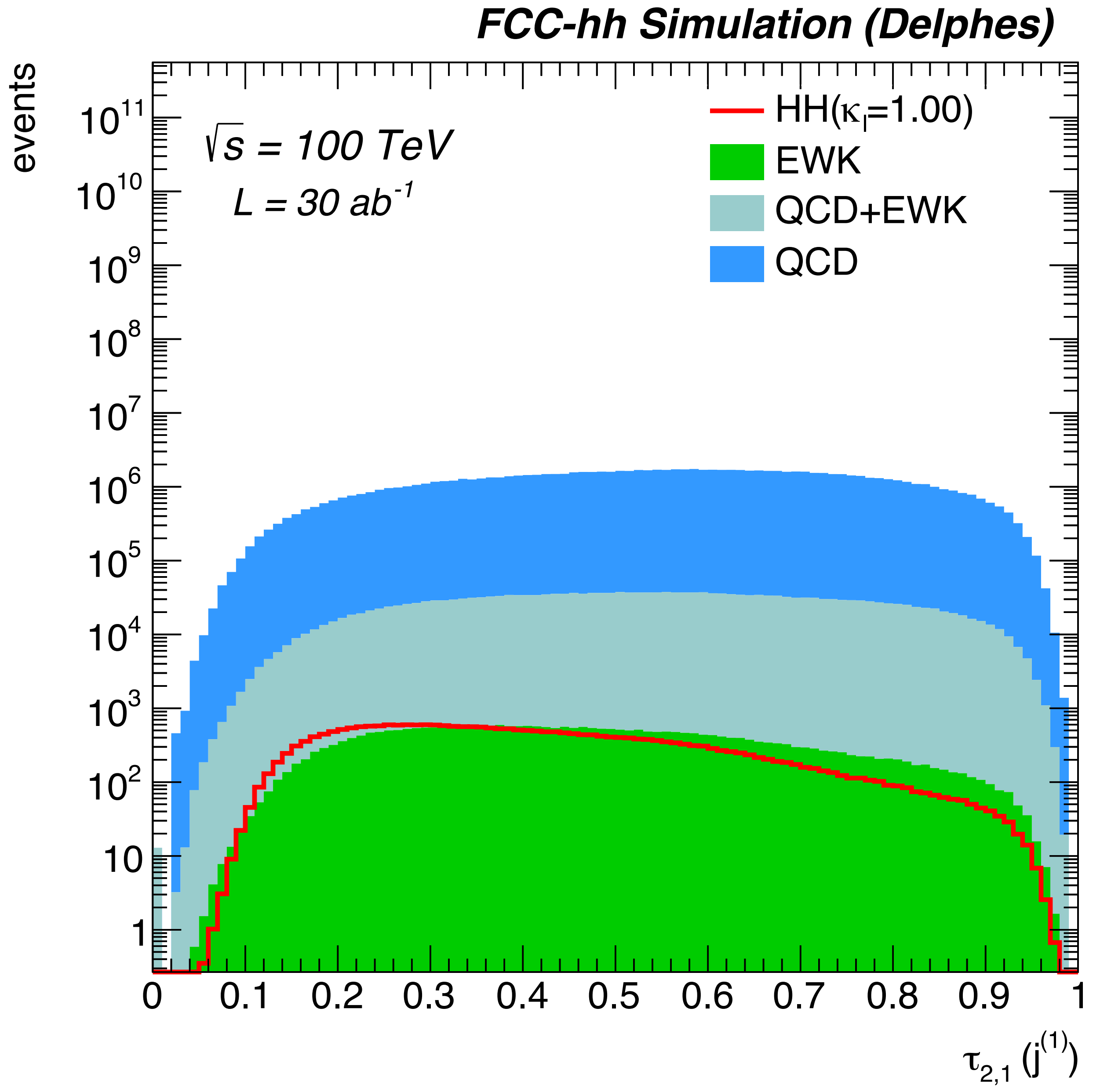
σ^{hh+j} (pT(j) > 500 GeV) ~ 4 fb (10^5 @ $30ab^{-1}$)

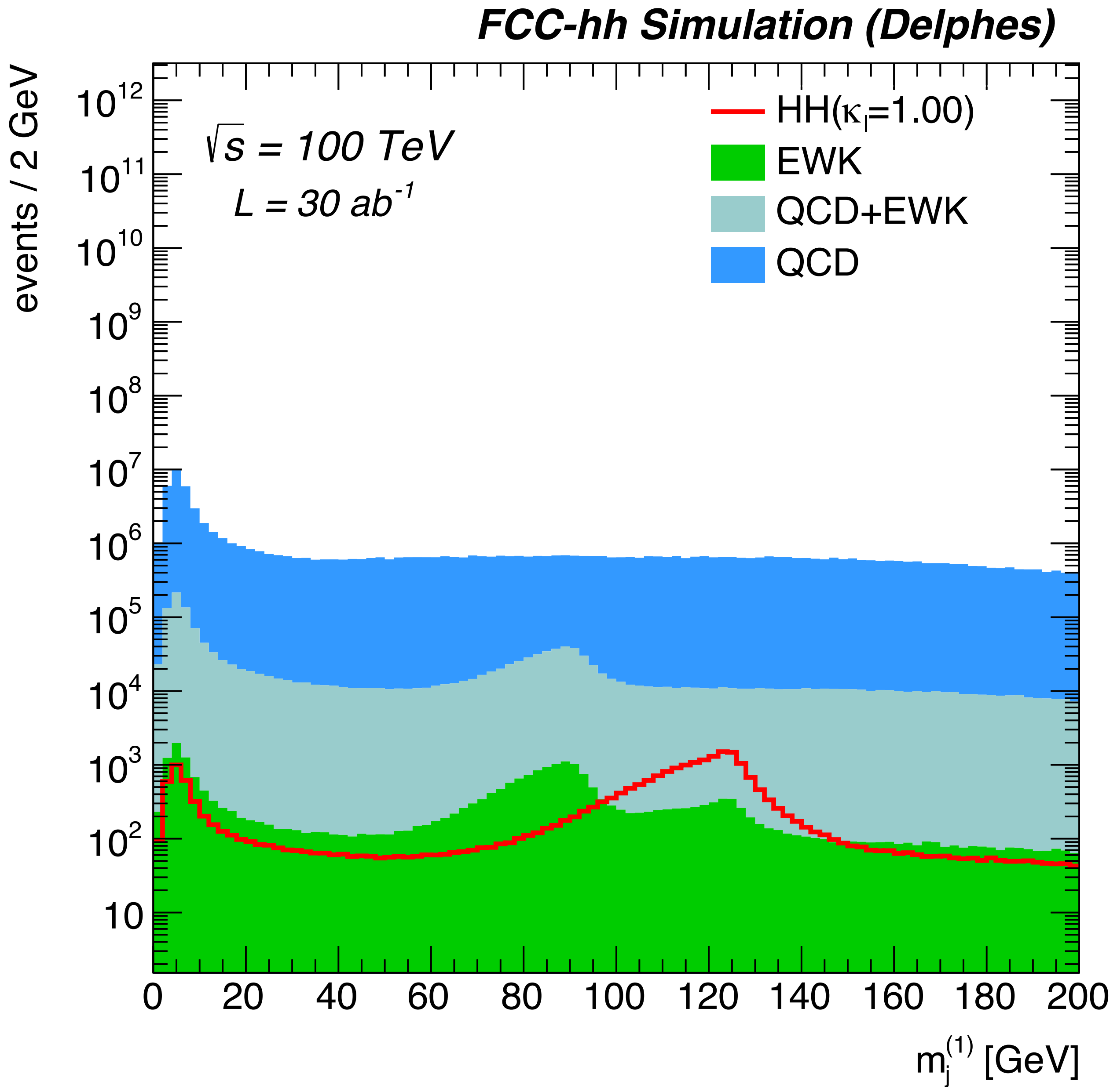
If aim for % level precision, need S,B ≳ 10^4 after cuts:
, i.e. a **factor of 10^5 in background rejection** → very hard !!
→ explore lower p_T(hh) range as well ….

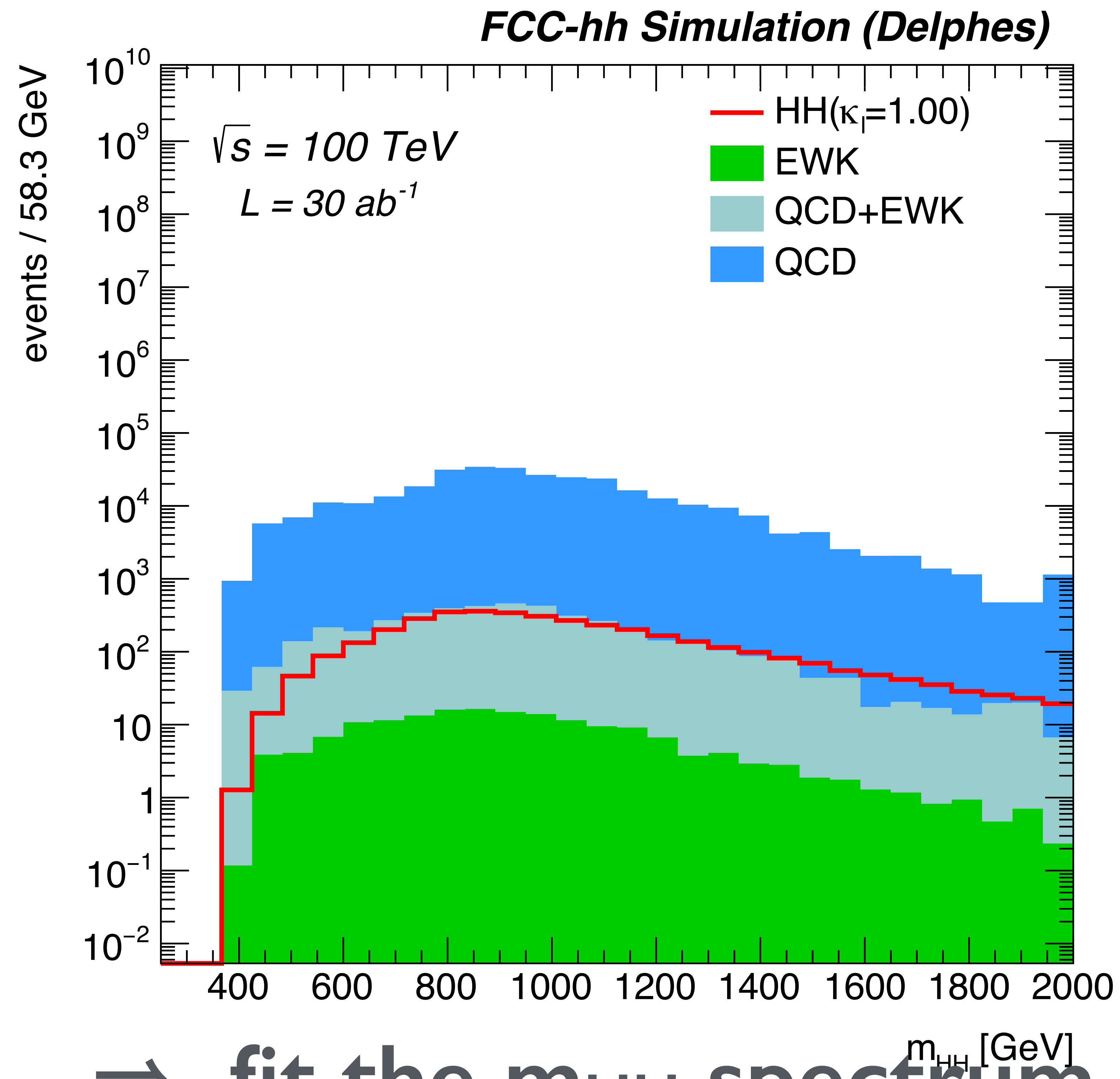
Selection strategy



- Boost the di-Higgs system:
  - $p_T(h_1 h_2) > 250$ GeV
- Preselection: Require $\gtrsim$ 2 b-tagged fatjets R = 0.8
  - $p_T(h_1) > 400$ GeV and $|\eta_1| < 3.0$
  - $p_T(h_2) > 300$ GeV and $|\eta_2| < 3.0$
- Higgs tagging:
  - $100 < m_{SD}(h_1) < 135$ and $\tau_{2,1}$[1] $(h_1) < 0.4$
  - $100 < m_{SD}(h_2) < 135$ and $\tau_{2,1}$ $(h_2) < 0.4$





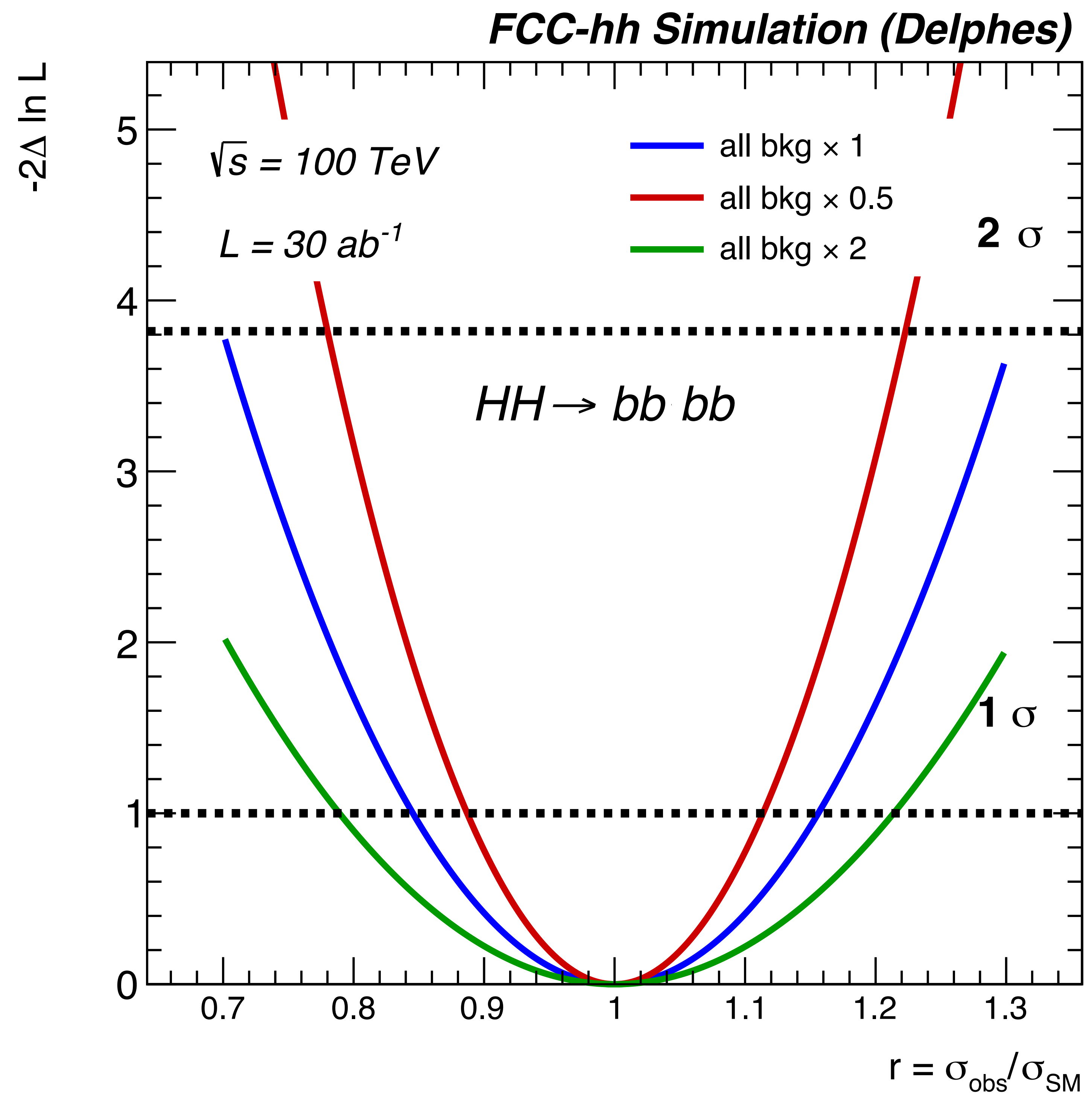


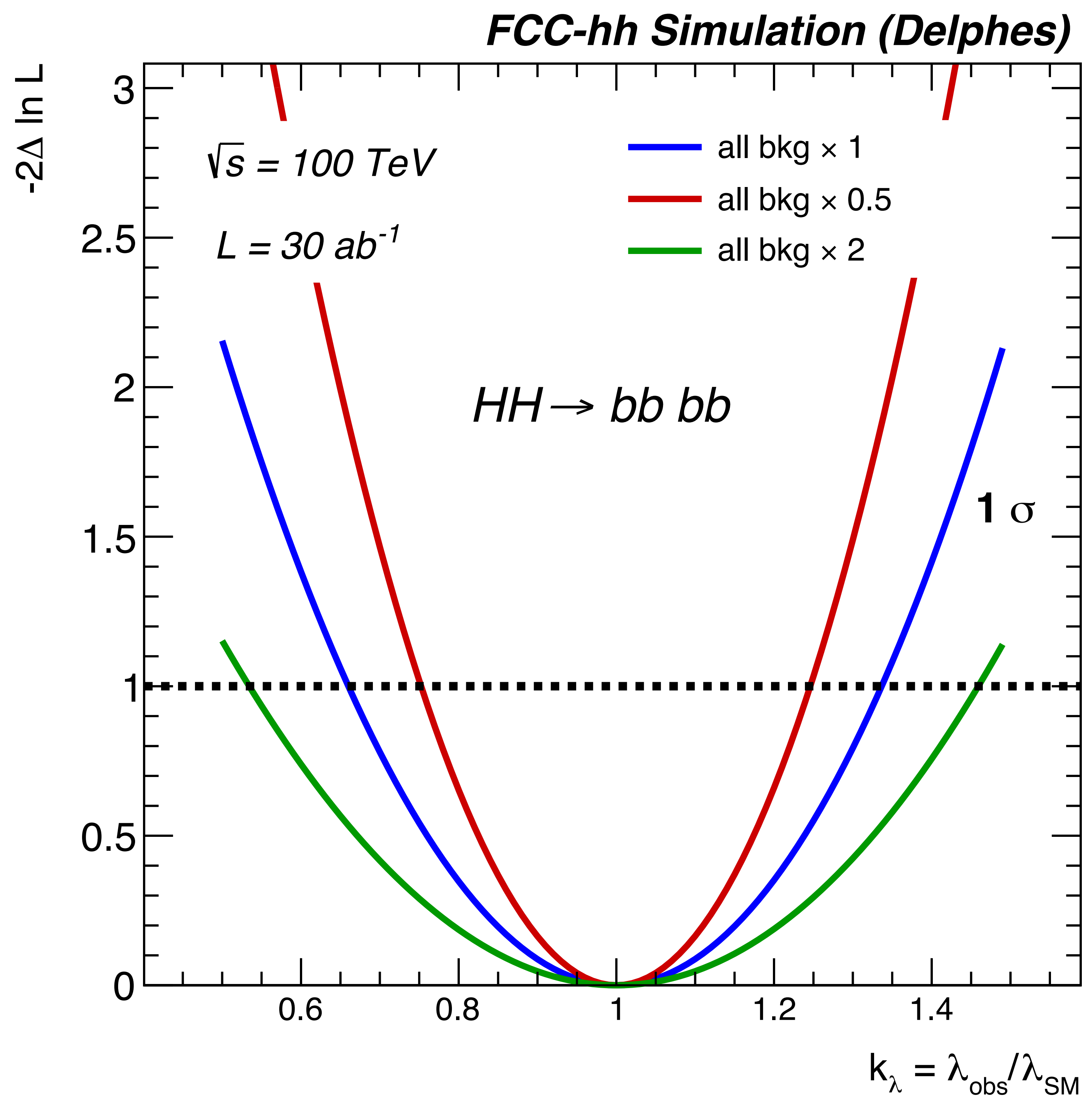
⇒ fit the m_{HH} spectrum

[1] Jesse Thaler, Ken Van Tilburg, JHEP 1103 (2011) 015

Expected sensitivity

varying (0.5x-2x) background yields:





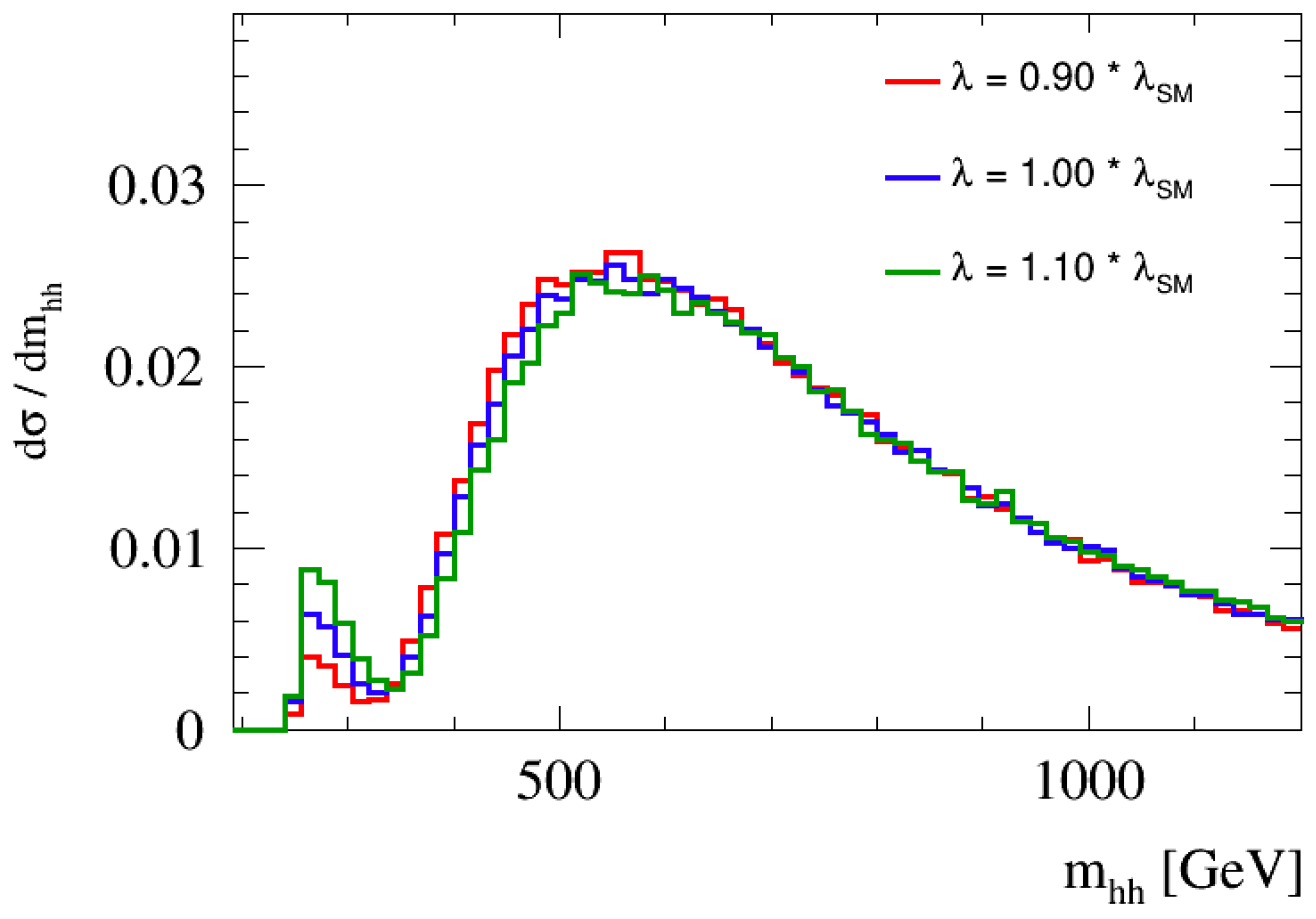
$\delta\mu$(stat) ≈ 10 - 20 %

$\delta\kappa_\lambda$(stat) ≈ 20 - 40 %

$bb\tau\tau$ -boosted

[1802.01607]

Approach



Backgrounds:

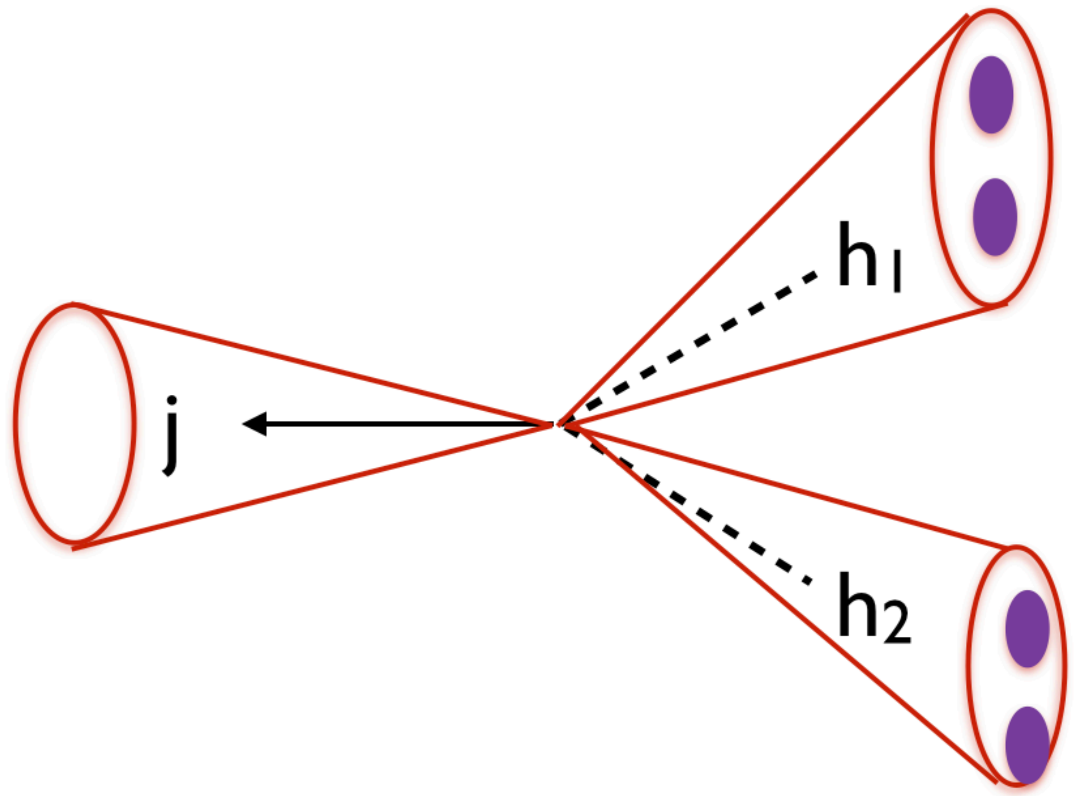
- tt+jets
- Z bb + jets (EWK + QCD)
- ZZ/ZH (EWK)
- W+jets (neglected)

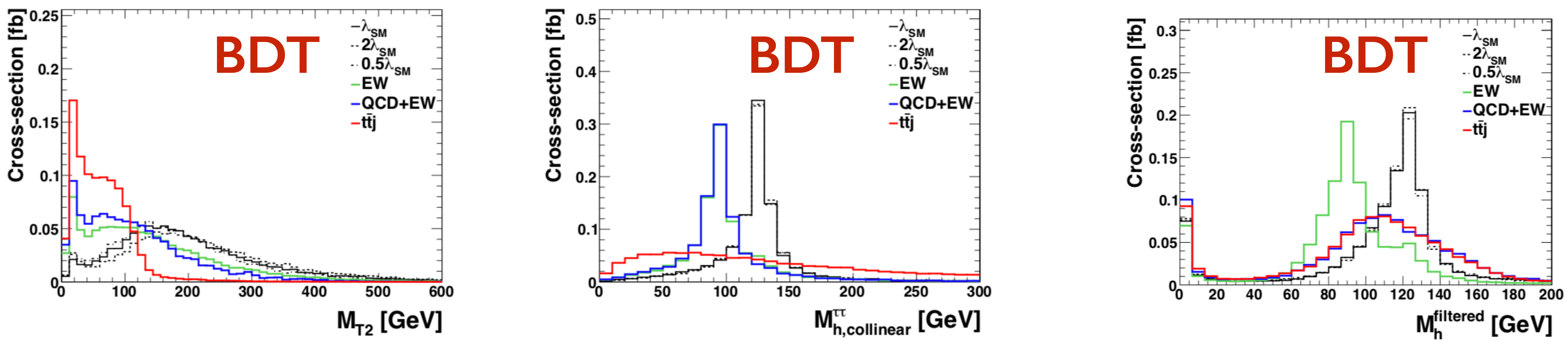
- $\sigma(pp \to hhj$, 100 TeV$) \approx 100 * \sigma(pp \to hhj$, 14 TeV$)$, with $p_T(j) > 100$ GeV
- Exploit **large branching ratio** $2*BR(H \to bb)*BR(H \to \tau\tau) \approx 7\%$
- Requiring a **boosted HH system recoiling against jet(s)**, contains the invariant mass to small values → maintain sensitivity to the self-coupling
- Final states: both $\tau_{lep}\tau_{had}$ and $\tau_{lep}\tau_{lep}$ considered, but $\tau_{lep}\tau_{had}$ by far the best…
- Resolved analysis and $\tau_{had}\tau_{had}$ final state were not considered, but they are by far the most sensitive ones at LHC-PhaseII and in HL-LHC simulations

Caveat: no detector simulation!

Analysis strategy

- 1 Higgs tagged jet, with double-b tag , p_T > 150 GeV
- τ_{had} tagged
- lepton pT > 20 GeV
- BDT based analysis





	signal	QCD+EW	EW	$t\bar{t}j$	tot. background	S/B	$S/\sqrt{B}$, 30/ab
$\kappa_\lambda = 0.5$	0.169					0.176	29.81
$\kappa_\lambda = 1$	0.141	0.52	0.07	0.37	0.96	0.147	24.97
$\kappa_\lambda = 2$	0.105					0.109	18.49

$$0.76 < \kappa_\lambda < 1.28 \quad 3/\text{ab},$$
$$0.92 < \kappa_\lambda < 1.08 \quad 30/\text{ab}$$

→ **$\delta\kappa_\lambda$(stat) ≈ 8 %**

S. Braibant
L. Borgonovi
E. Fontanesi
N. De Filippis
A. Taliercio

bb4l

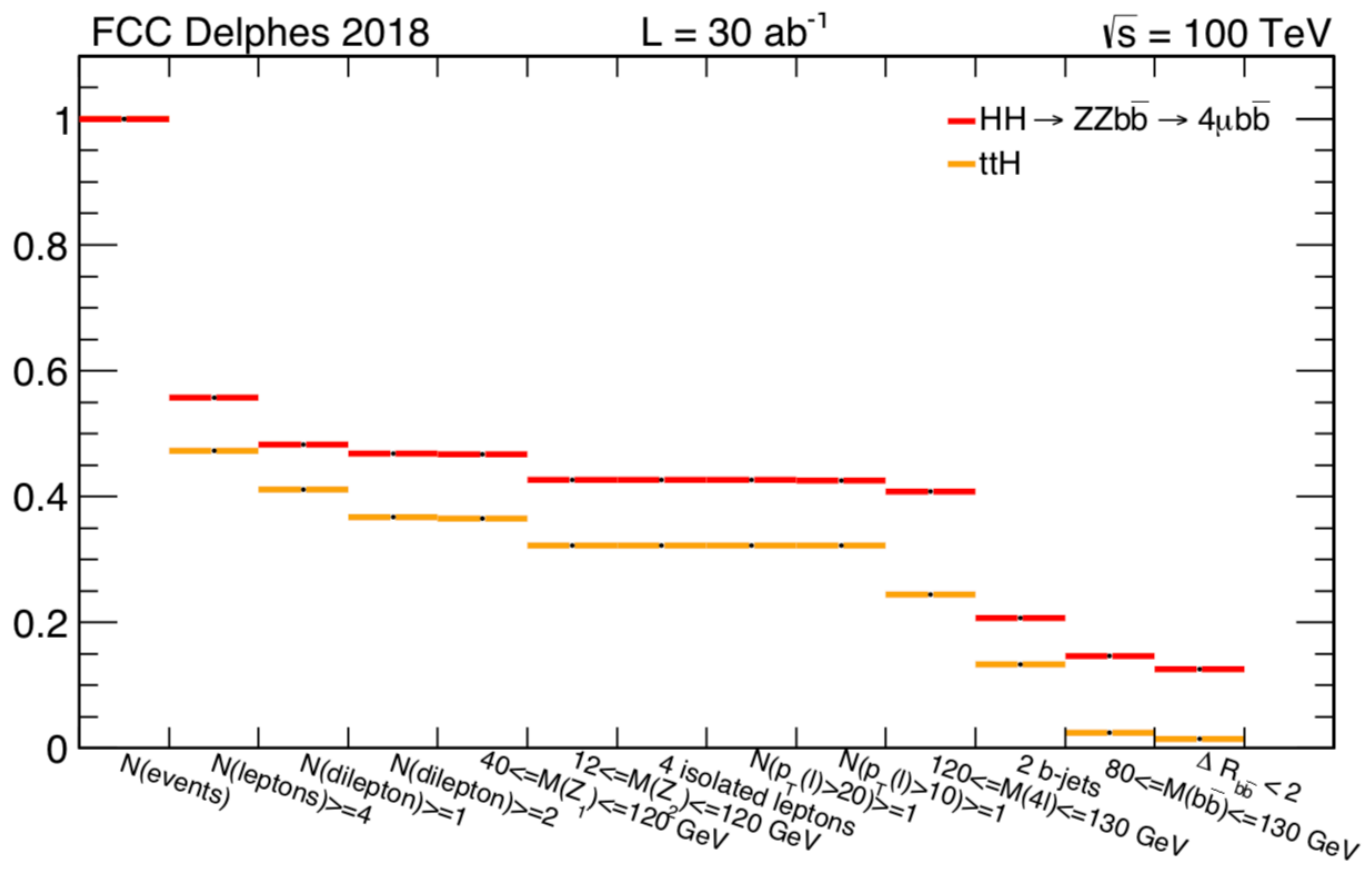
Analysis strategy

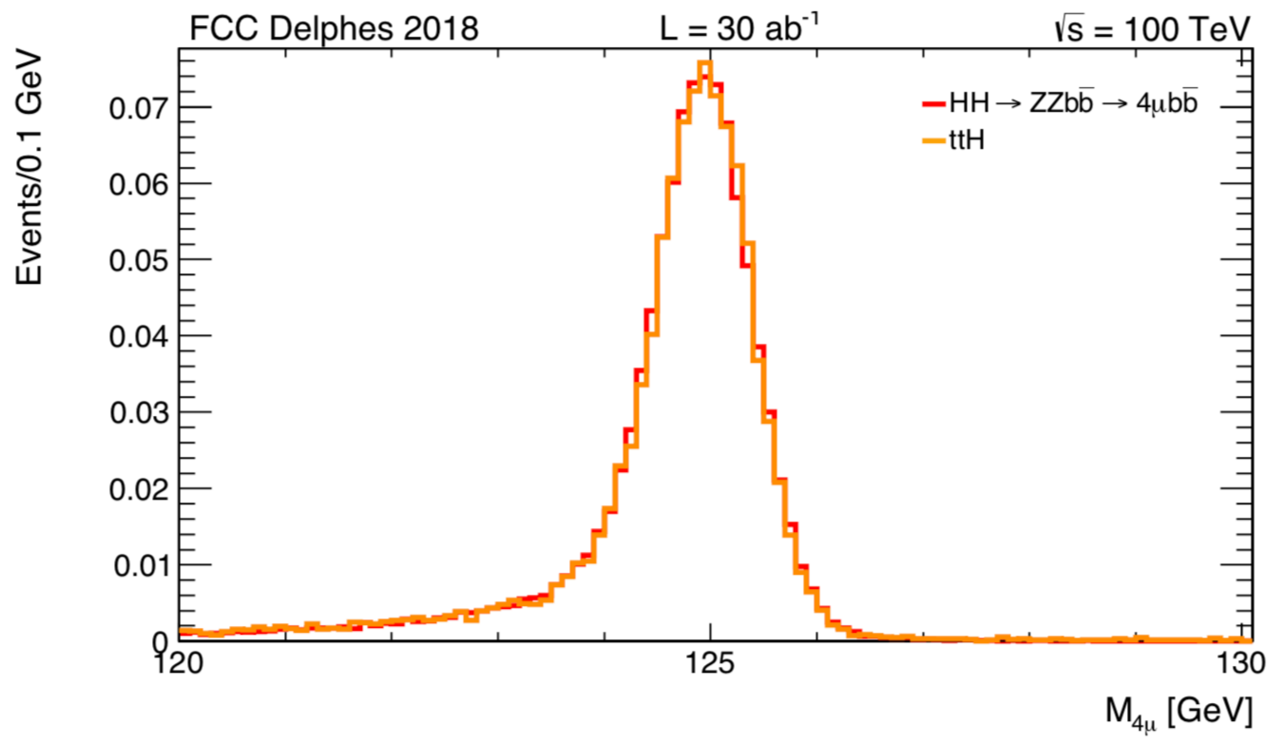
- H→4 leptons + 2b's (for now only muons)

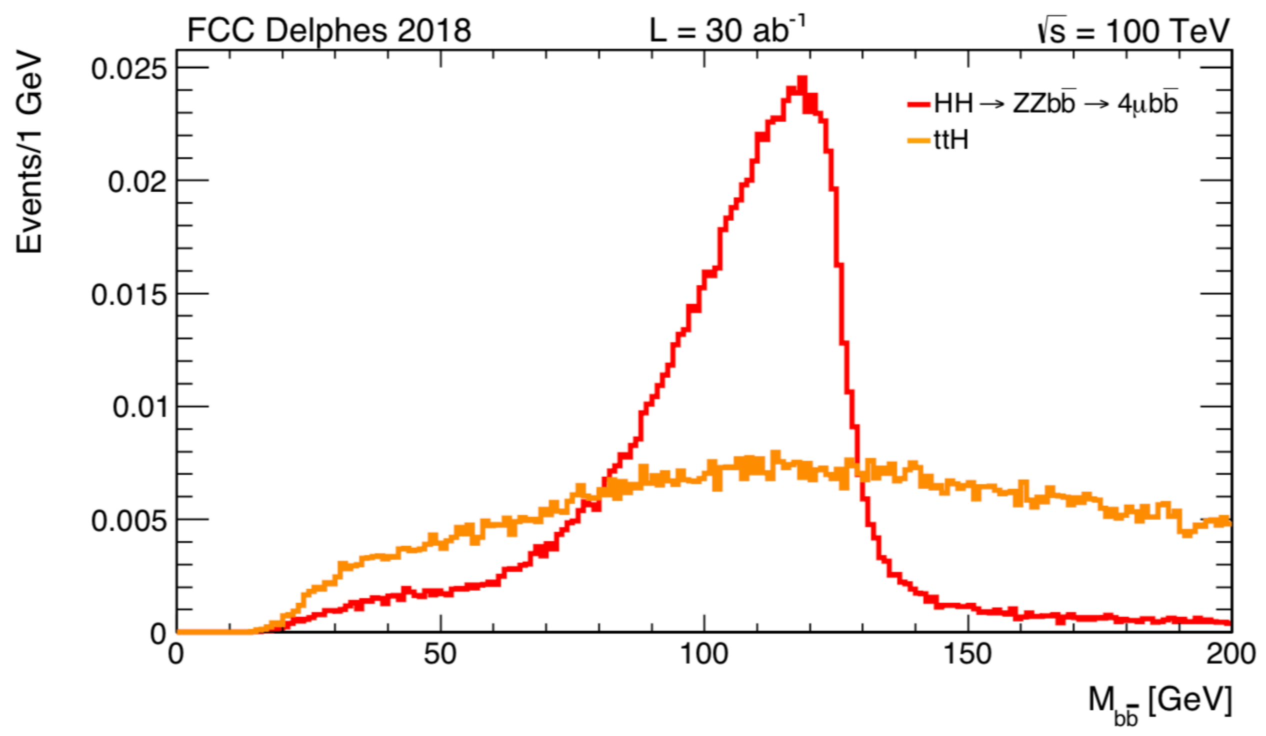
Backgrounds:
- ttH , H → 4 leptons
- 4l + jets (ZZ*, Z*Z*, ZZ) continuum (neglected for now)
- p p → H b b →4l bb

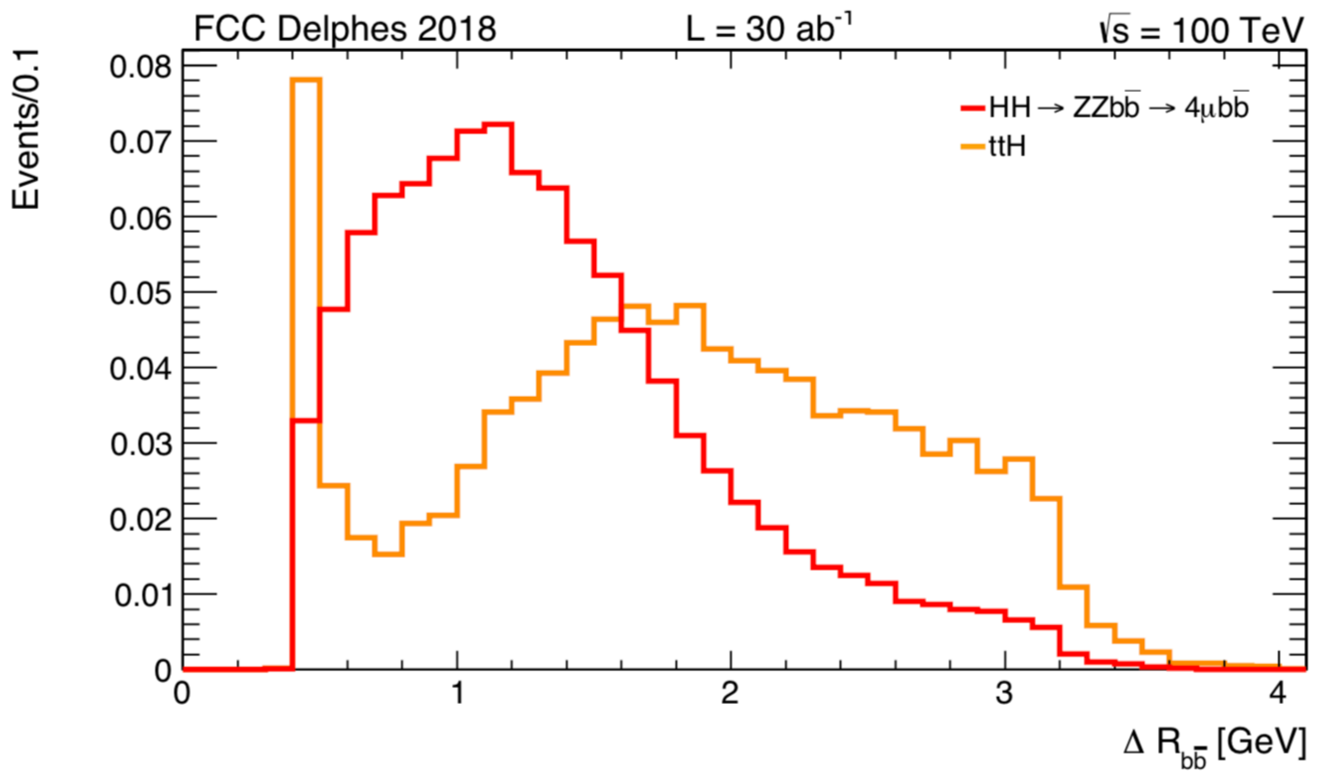
Method:
- reconstruct Higgs peak
- $120<M_{4\mu}<130$; $80<M_{bb}<130$
- additional handle for ttH → ΔR(b,b)

Cut Flow

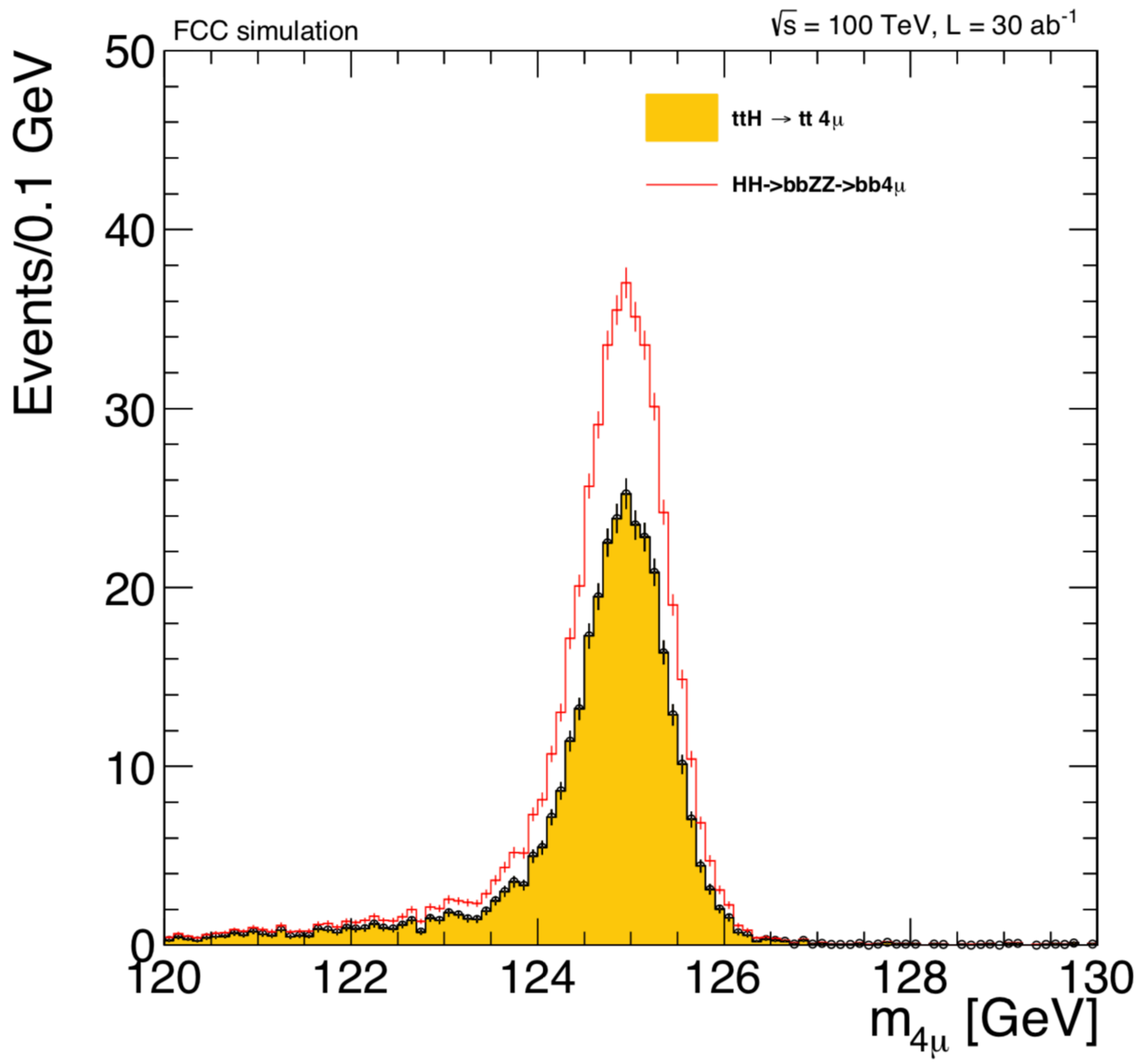


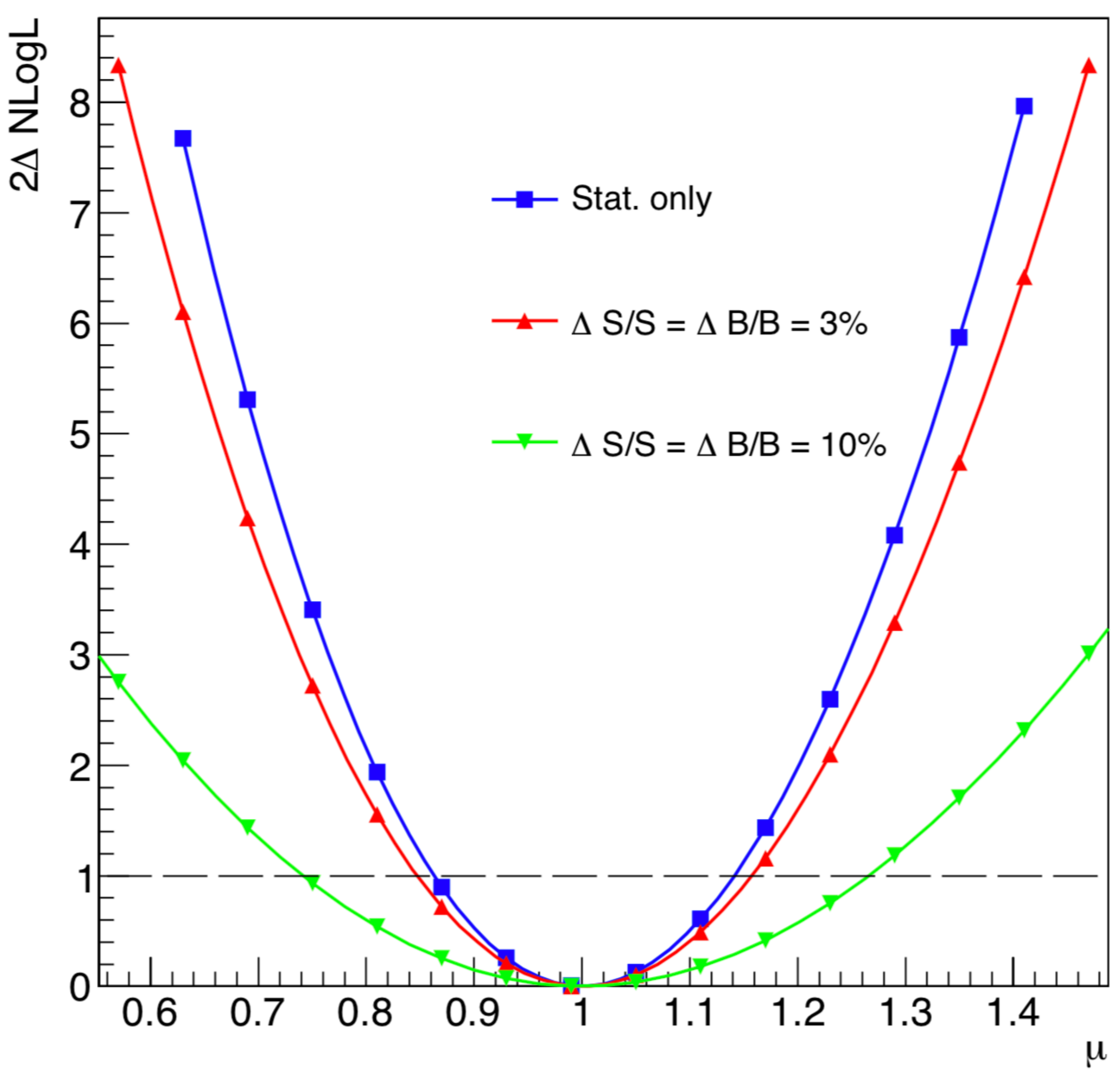






Precision on the signal strength





$\delta r(\text{stat}) \approx$ 10-15% → $\delta\kappa_\lambda(\text{stat}) \approx$ 20 - 30 %

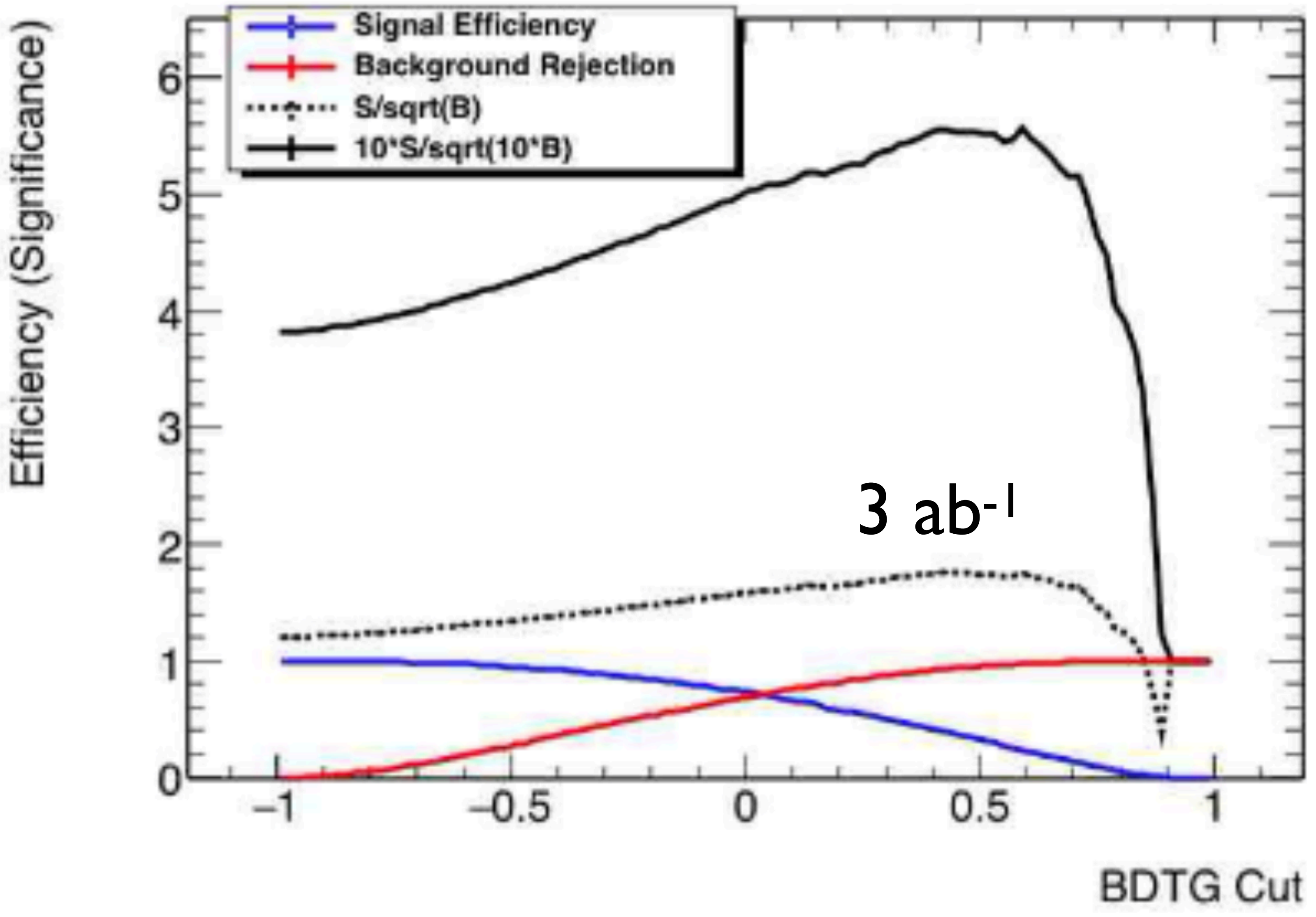
bbWW→bblνqq

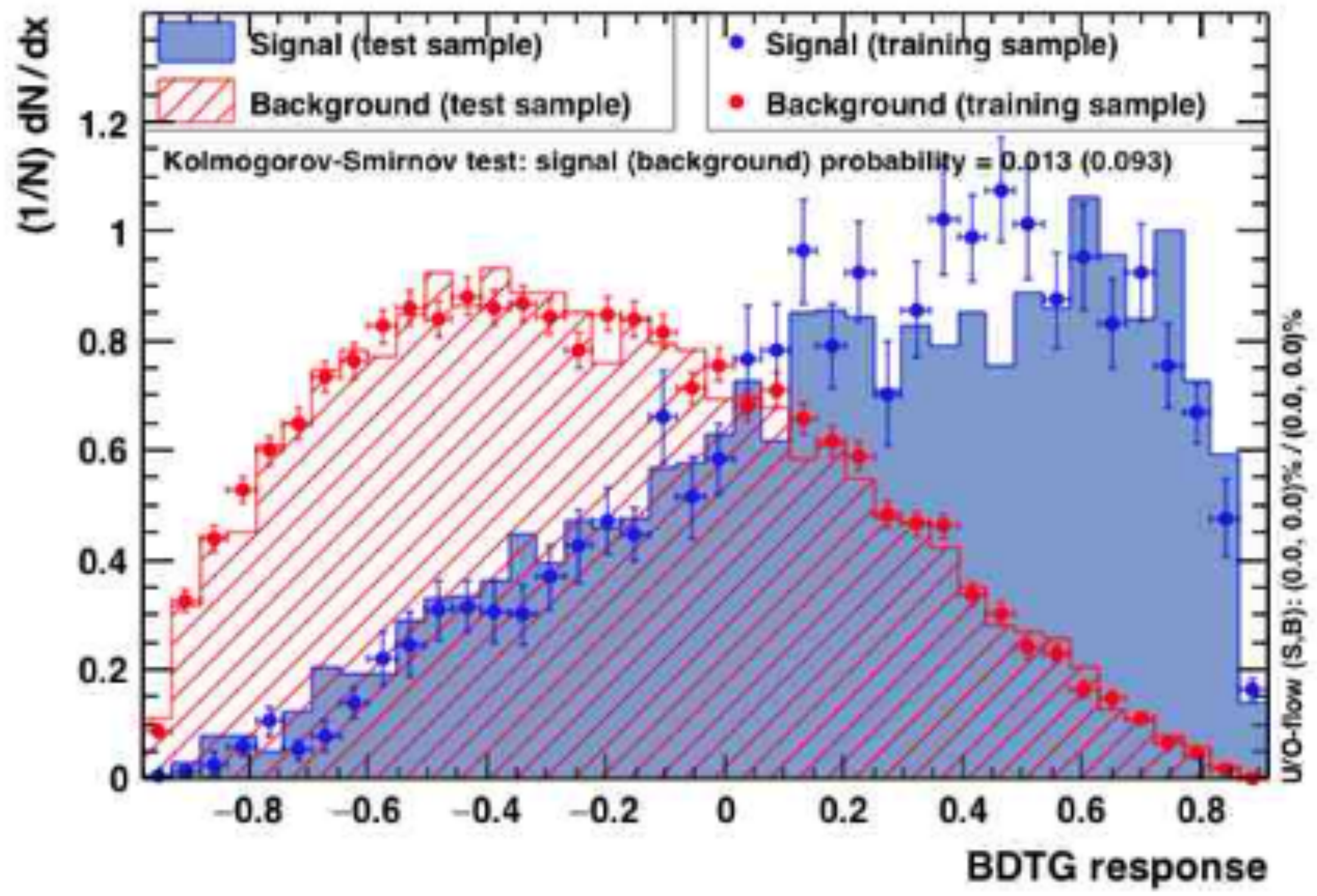
B. Di Micco
M. Testa
M.Verducci

- 80 < mbb < 150 GeV
- p_T(WW) > 150 GeV

Backgrounds:

- bbWW
- V+jets





$\delta r(\text{stat}) \approx$ 20% → $\delta\kappa_\lambda(\text{stat}) \approx$ 40%

Conclusions & outlook

- **HH→bbγγ** analysis has been performed with more recent detector description and new MC samples
  - small differences have been observed but overall comparable performance on sensitivity **$\delta\kappa_\lambda$(stat) ≈ 3.5 %**

- **HH recoil** displays lower performance due to huge QCD background

  - bbbbj: sensitivity **$\delta\kappa_\lambda$(stat) ≈ 20-30%**
  - bbττj: sensitivity found **$\delta\kappa_\lambda$(stat) ≈ 10%** (using only $\tau_{lep}\tau_{had}$)

- **HH → 4lbb** (preliminary)
  - looks very promising with **$\delta\kappa_\lambda$(stat) ≈ 20-30%**

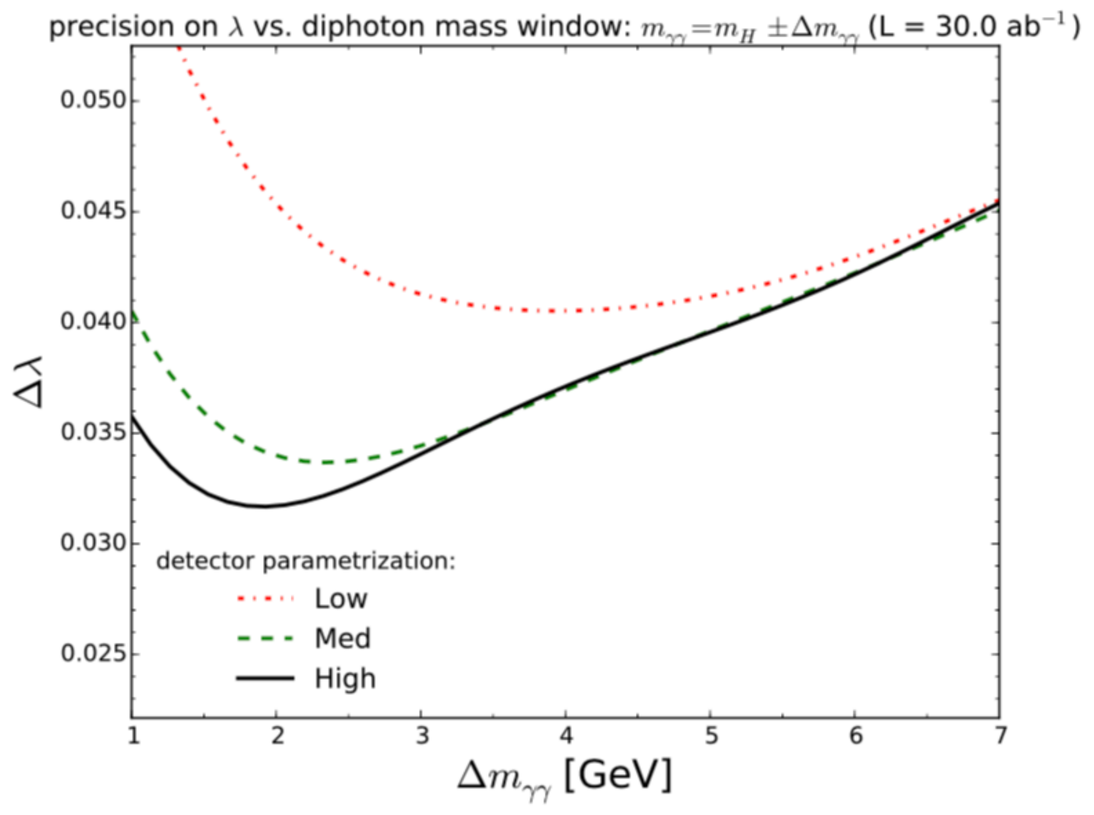
- **HH→ bbWW**→ lvbbjj
  - **$\delta\kappa_\lambda$(stat) ≈ 40%**

BACKUP

Baseline

[R. Contino, C. Englert, G. Panico, A. Papaefstathiou, J. Ren, MS, M. Son, M. Spannowsky, W. Yao]

- Detailed analysis performed in 2016 (summarised in the Yellow Report [1606.09408])
  - **cut-based analysis**
  - reported sensitivity on **λ** after 30 ab-1 at 100 TeV
  - studied impact of **detector performance**, systematics, background normalisation



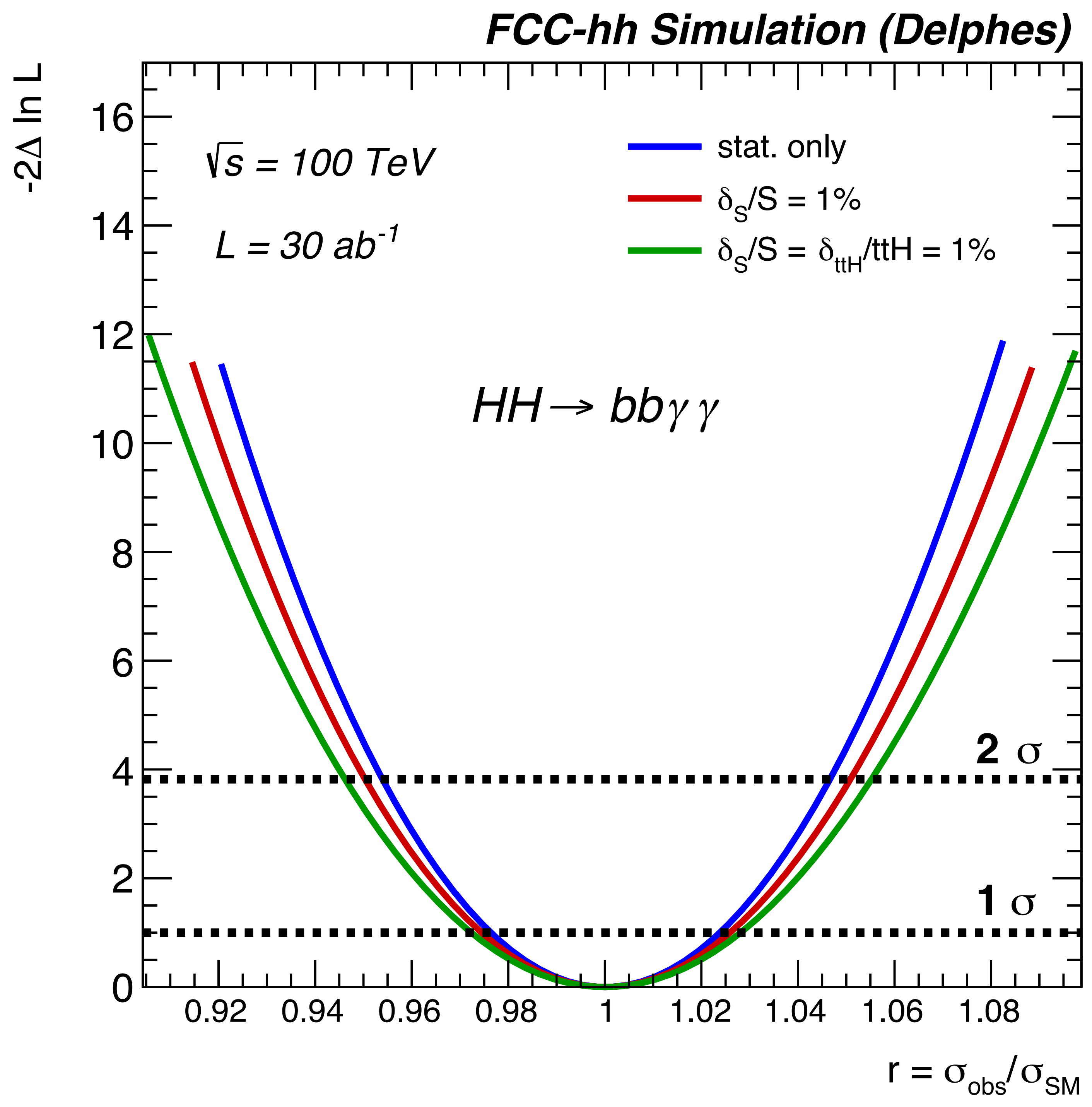
	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%	5.8%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%	6.1%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%	6.4%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%	6.8%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%	7.3%

UPDATES:

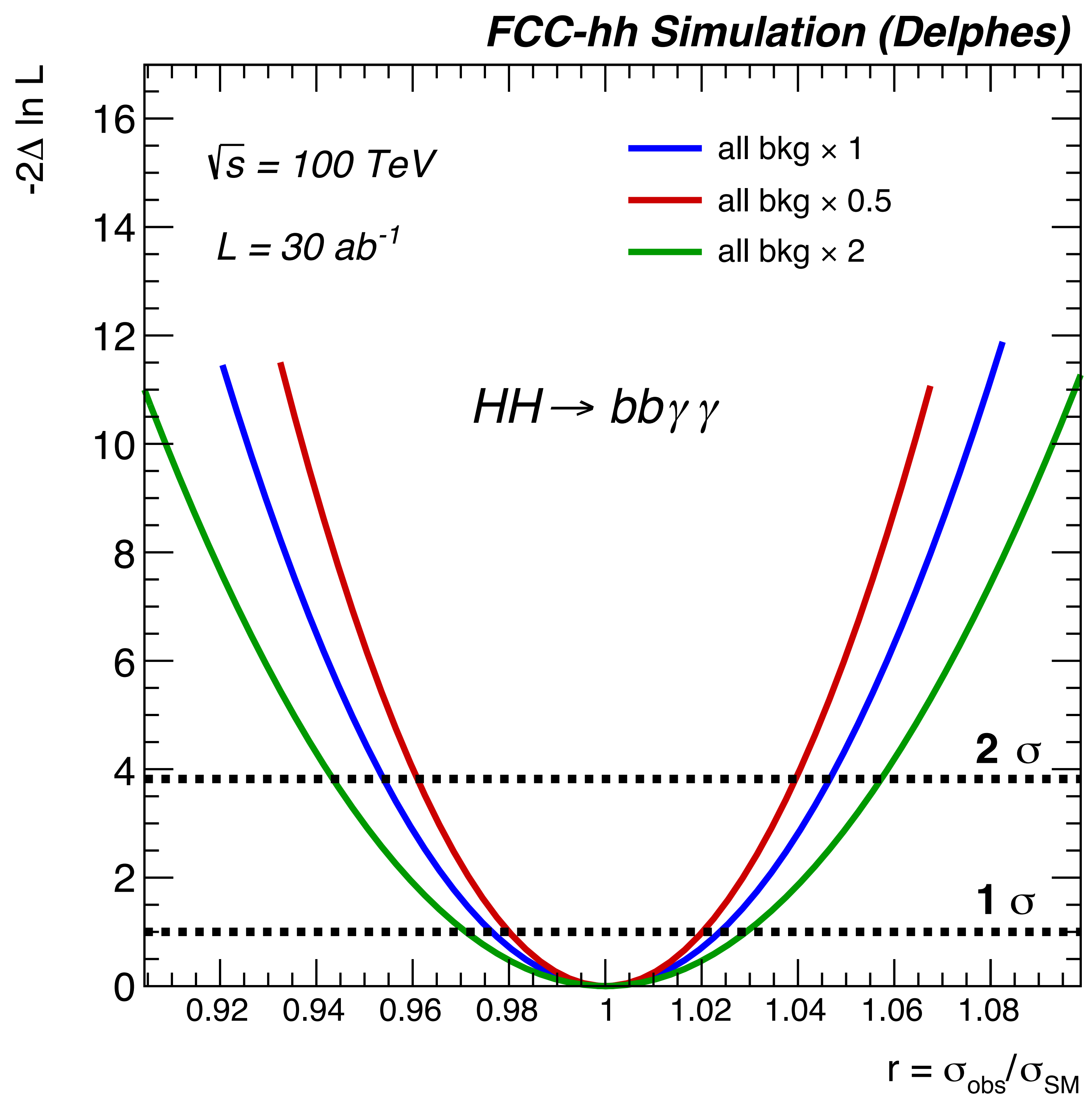
- up-to-date **parton shower/underlying event modelling** (Pythia8 vs Pythia6)
- more recent FCC-hh **detector** description (4T vs 6T, smaller detector size)
- QCD background generation using **5f scheme** (jjjɣ, jjɣɣ)
- Up-to-date **k-factors** for backgrounds (ttH) and signal (**λ-dependent**)

Precision on the signal strength

assuming QCD can be measured from sidebands



nominal background yields:

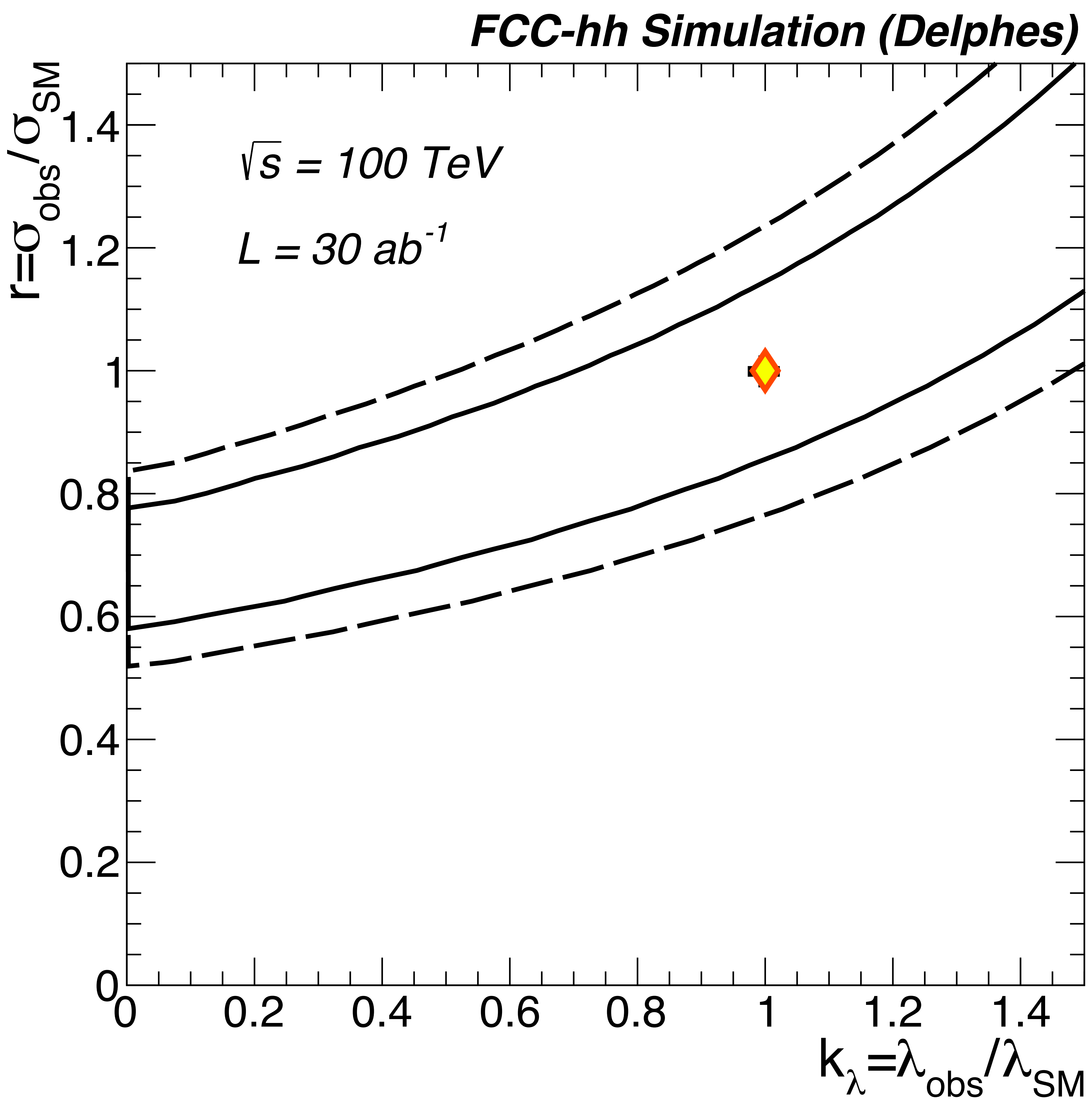


varying (0.5x-2x) background yields:

$\delta r(\text{stat}) \approx 2.5$ %
$\delta r(\text{stat + syst}) \approx 3$ %

$\delta r(\text{stat}) \approx 2 - 3\%$

2D scan

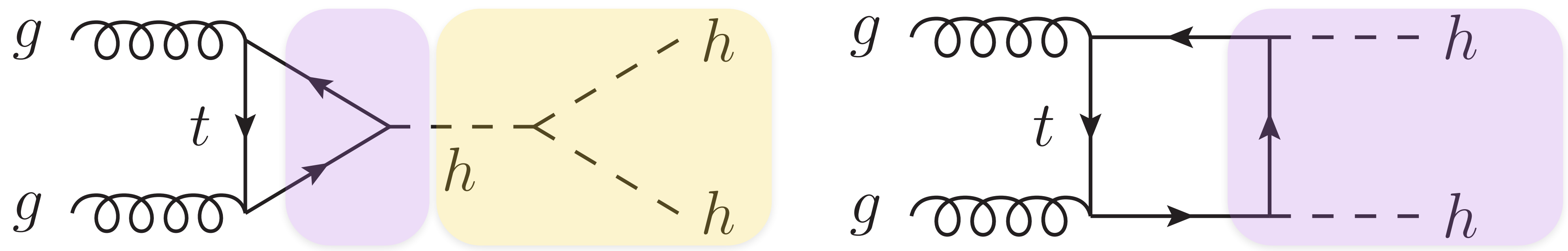


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
$r=\sigma_{obs}/\sigma_{SM}$
$k_\lambda=\lambda_{obs}/\lambda_{SM}$
0
0.2
0.4
0.6
0.8
1
1.2
1.4

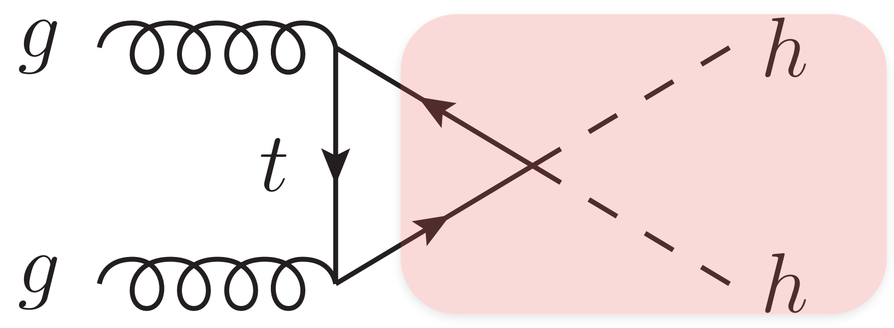
The relevant lagrangian terms of gg→HH production in D=6 EFT

$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3 + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)G^a_{\mu\nu}G_a^{\mu\nu}$$
$$- \left[\frac{m_t}{v}\left(1 - \frac{c_H}{2} + c_t\right)\bar{t}_L t_R h + \text{h.c.}\right] - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2} - \frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \text{h.c.}\right]$$

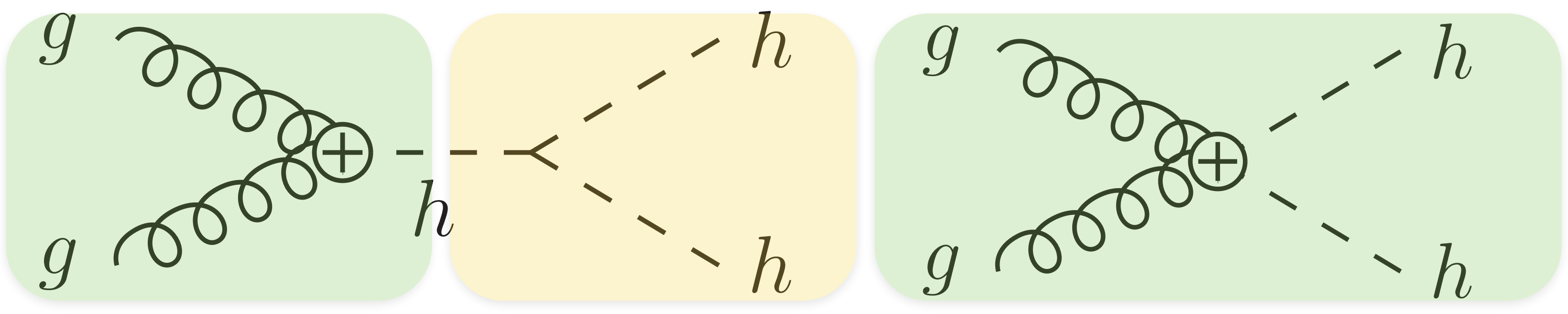
arXiv:1410.3471



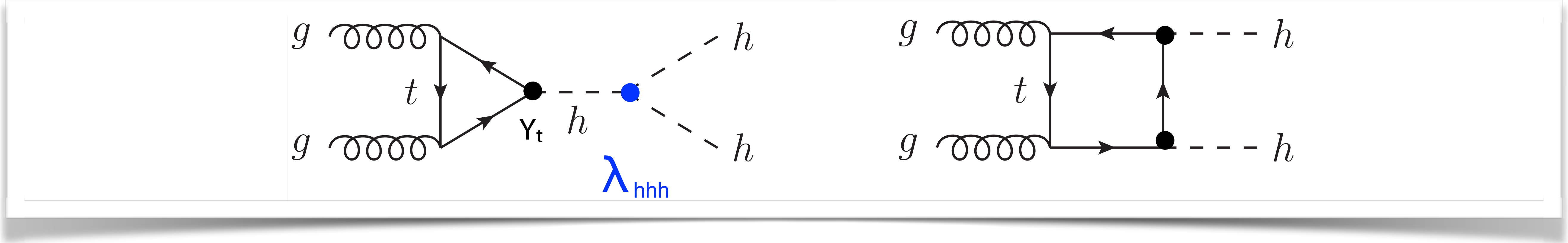
SM diagrams



ttHH non-linear interaction



Higgs-gluon contact interactions

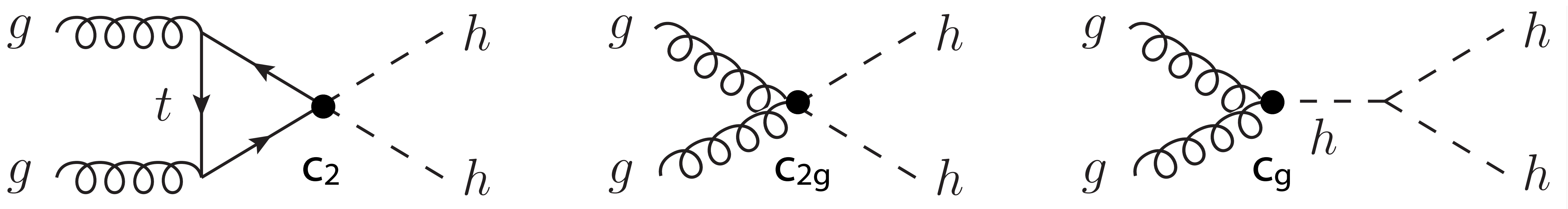


$\sigma^{SM}_{hh}(13\text{TeV}) = 33.45\text{fb}^{+4.3\%}_{-6.0\%}$(scale unc.) ±3.1%(PDF+$\alpha_S$ unc)[1]

The non-resonant double Higgs production allows to directly probe the Higgs trilinear coupling (λ_{hhh}). Even if in Run2 we do not have full sensitivity to "measure" SM λ_{hhh}

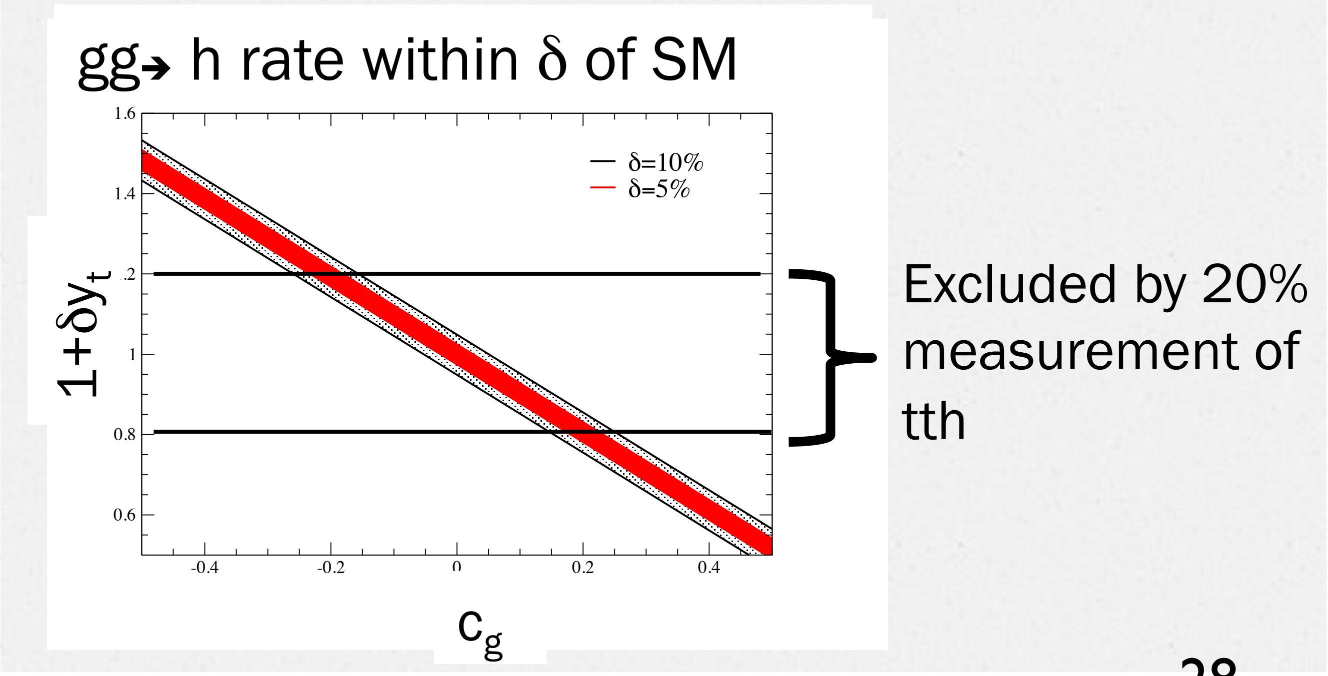
→ The BSM physics can be modelled in EFT adding dim-6 operators[2] to the SM Lagrangian, and the physics can be described with 5 parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

- Non SM top Yukawa and λ_{hhh} couplings
- New diagrams and couplings in the game



To be noted :

in a linear EFT $c_g = c_{2g}$ and $c_2 = -(3m_t/2v)y_t$



[1] LHCHXSWG Yellow Report 4
[2] *Phys. Rev.* **D91** (2015), no. 11, 115008