Measuring Higgs self-coupling at the FCC

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also based on:
[1606.09408], [1802.01607], [1809.10041]

FCC week 2019 - 27/06/2019 - Bruxelles

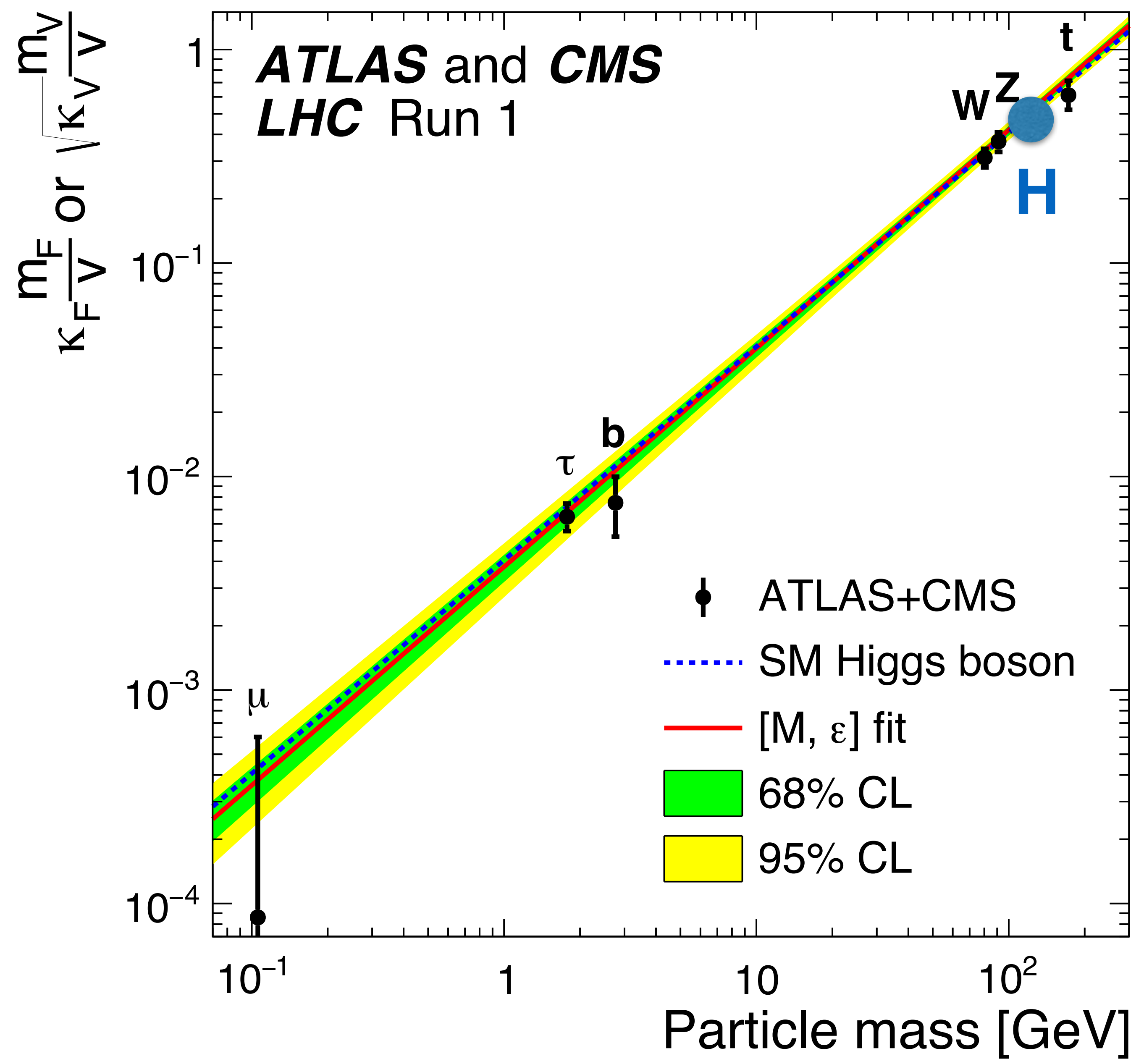
Why measure HH?

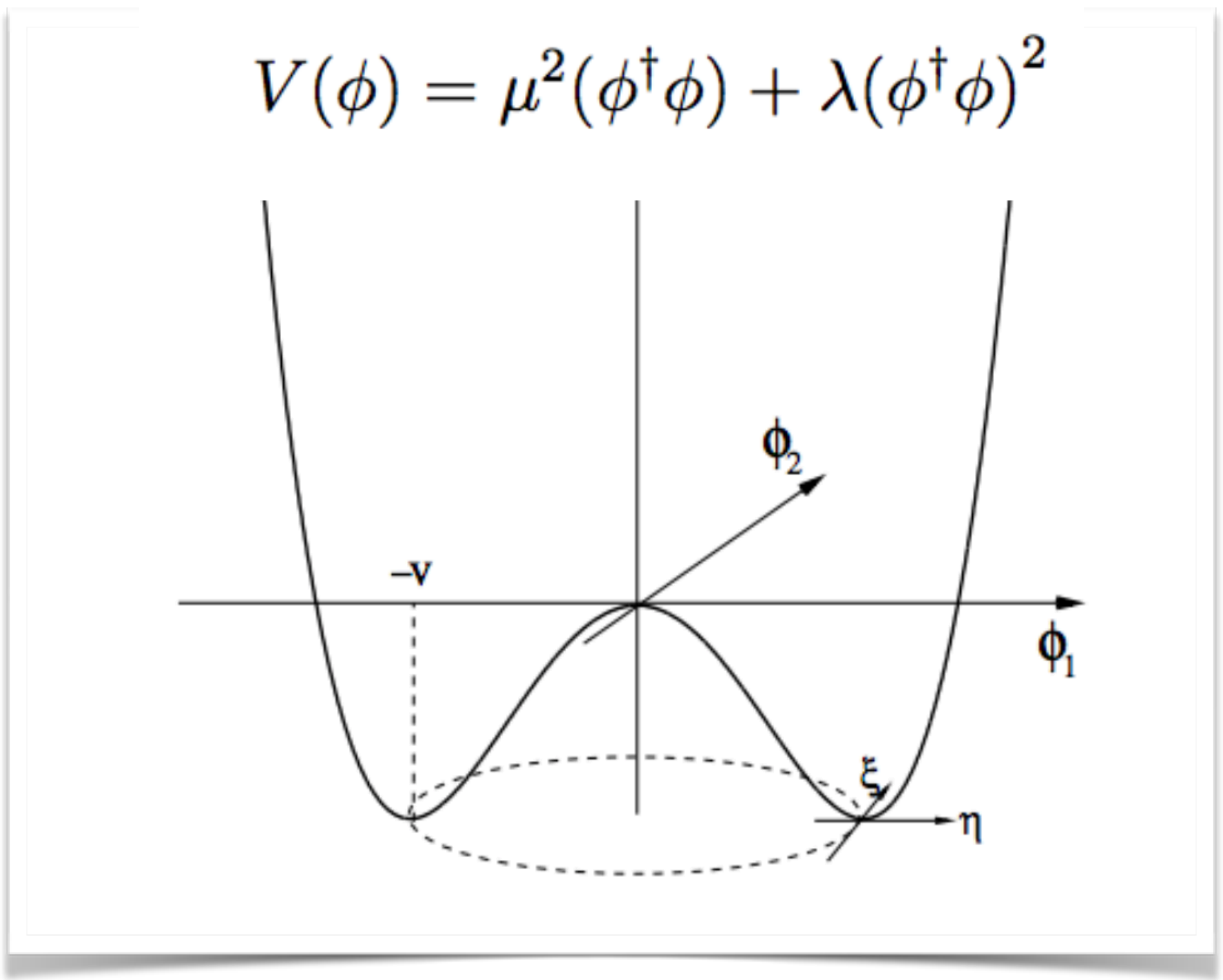
- Measurement of HH gives access to the magnitude of the **Higgs self-interaction**:

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

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

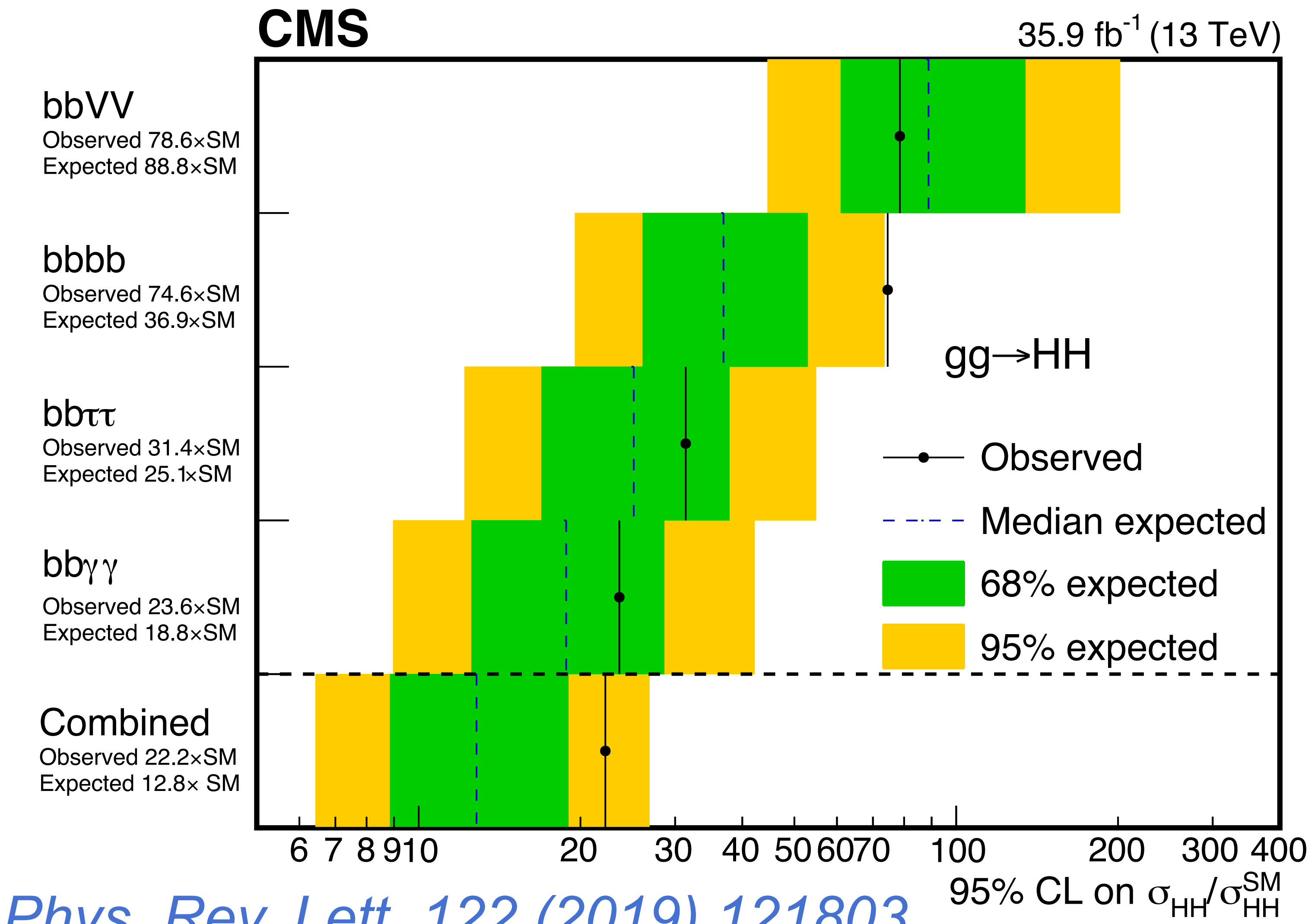
- Shape of the **Higgs potential** is determined by the self coupling value (EWPT)





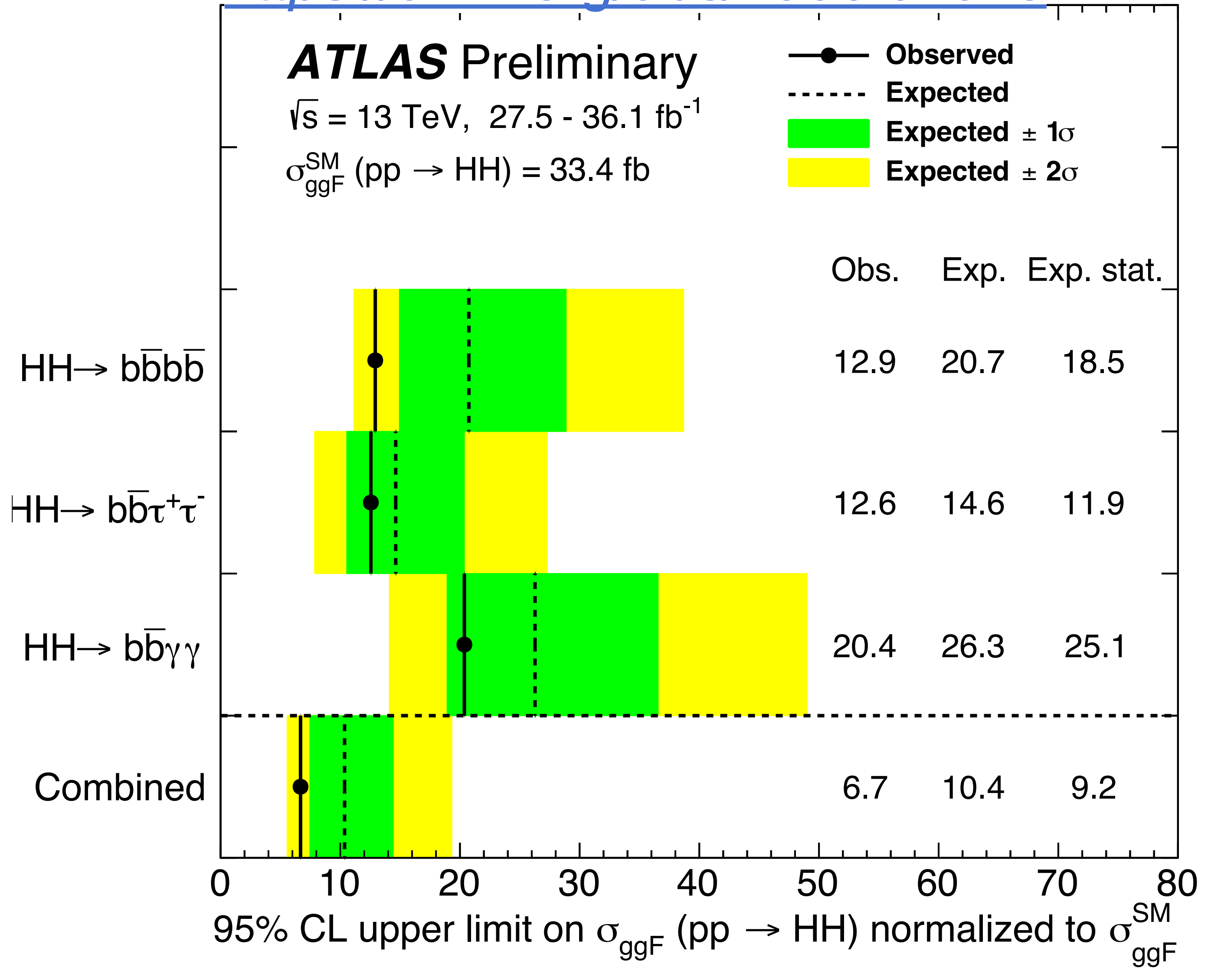
Prospects for HH measurements

1) LHC
   - O(10)-O(3)
   - Could detect large anomalous coupling

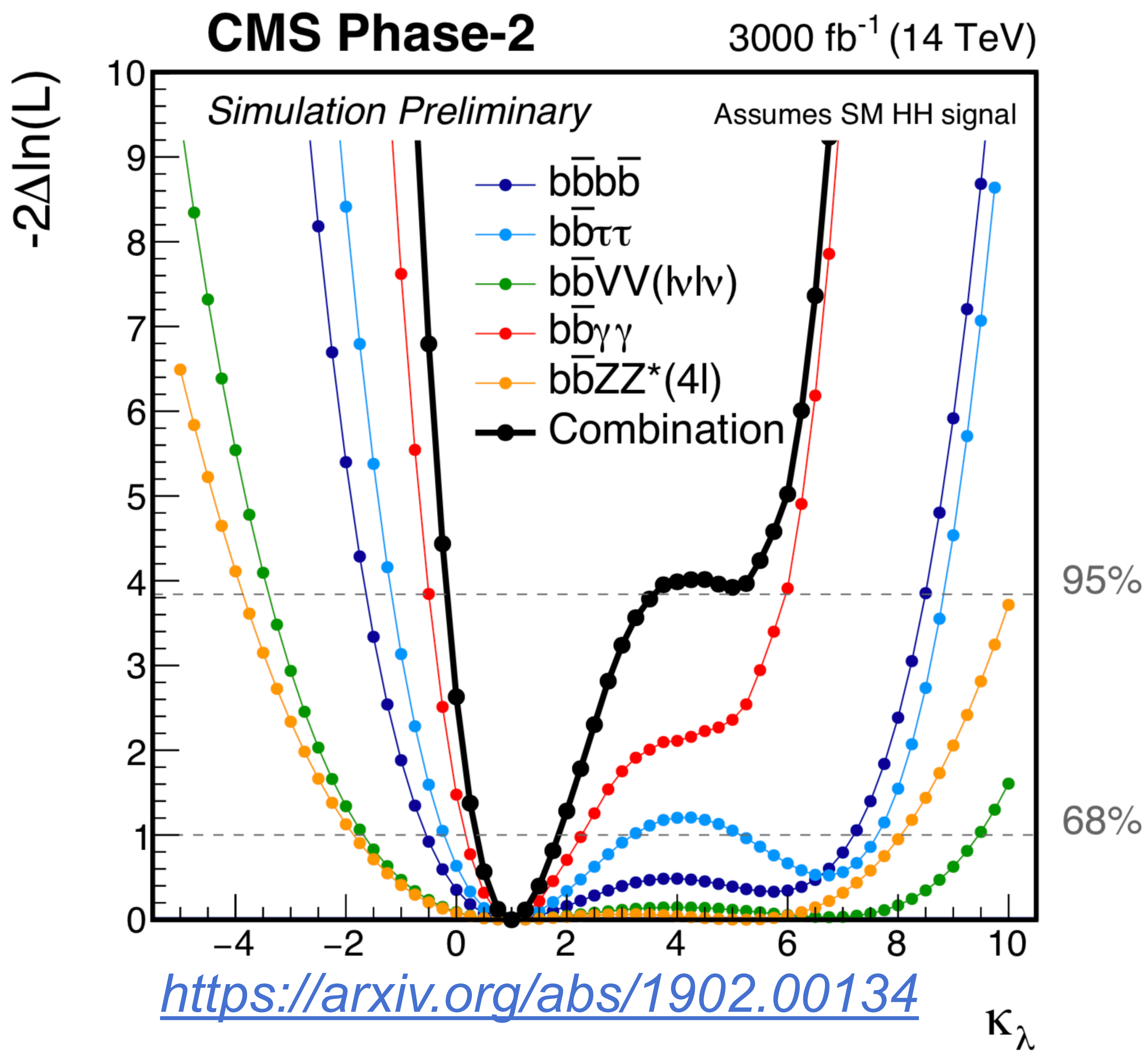


Phys. Rev. Lett. 122 (2019) 121803

https://arxiv.org/abs/1906.02025



2) HL-LHC
   - O(1)
   - Potential for evidence (3σ precision)



https://arxiv.org/abs/1902.00134

3) FCC-ee : single H couplings + indirect measurement
   - Potential for observation (5σ precision)

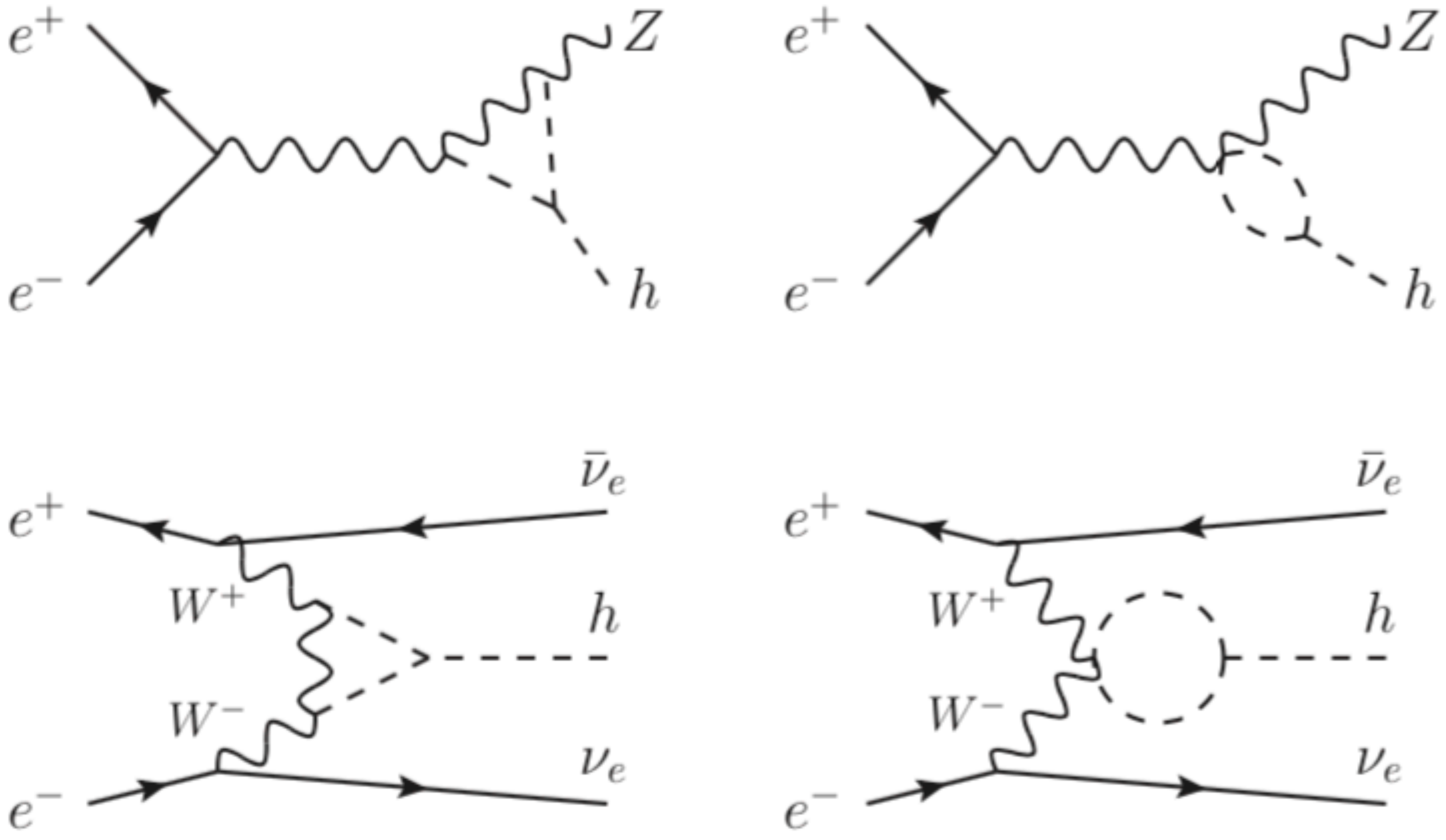
4) FCC-hh : precision measurement

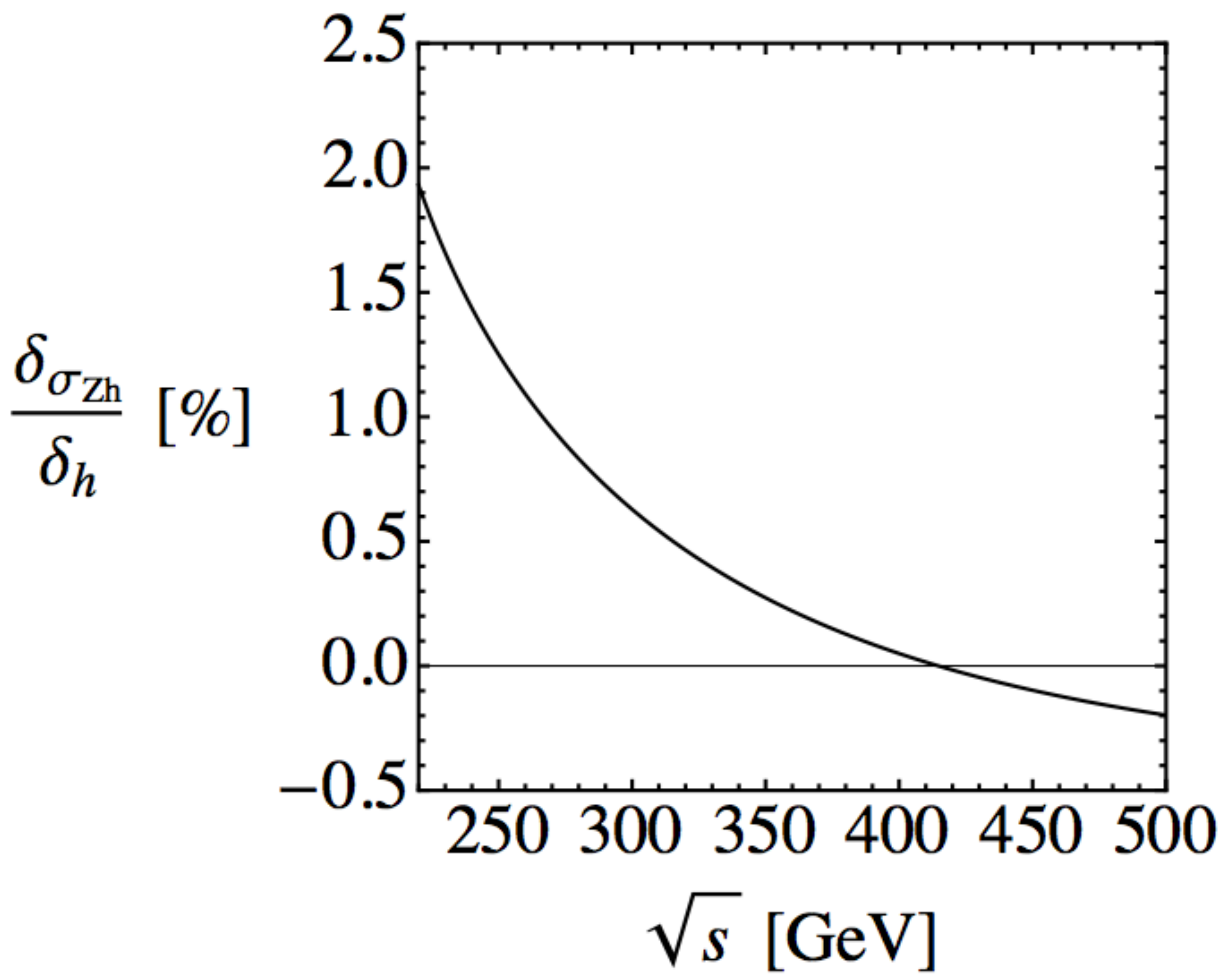
Measuring the Higgs self-coupling at FCC-ee

NEW

- High precision measurement of Higgs BR
- Large Luminosity, high precision on single Higgs couplings
  - Possible to determine Higgs self coupling via indirect measurement
- A 100% modification of the Higgs self-coupling changes the HZ cross section by 2% at 240 GeV and 0.5% at 365 GeV

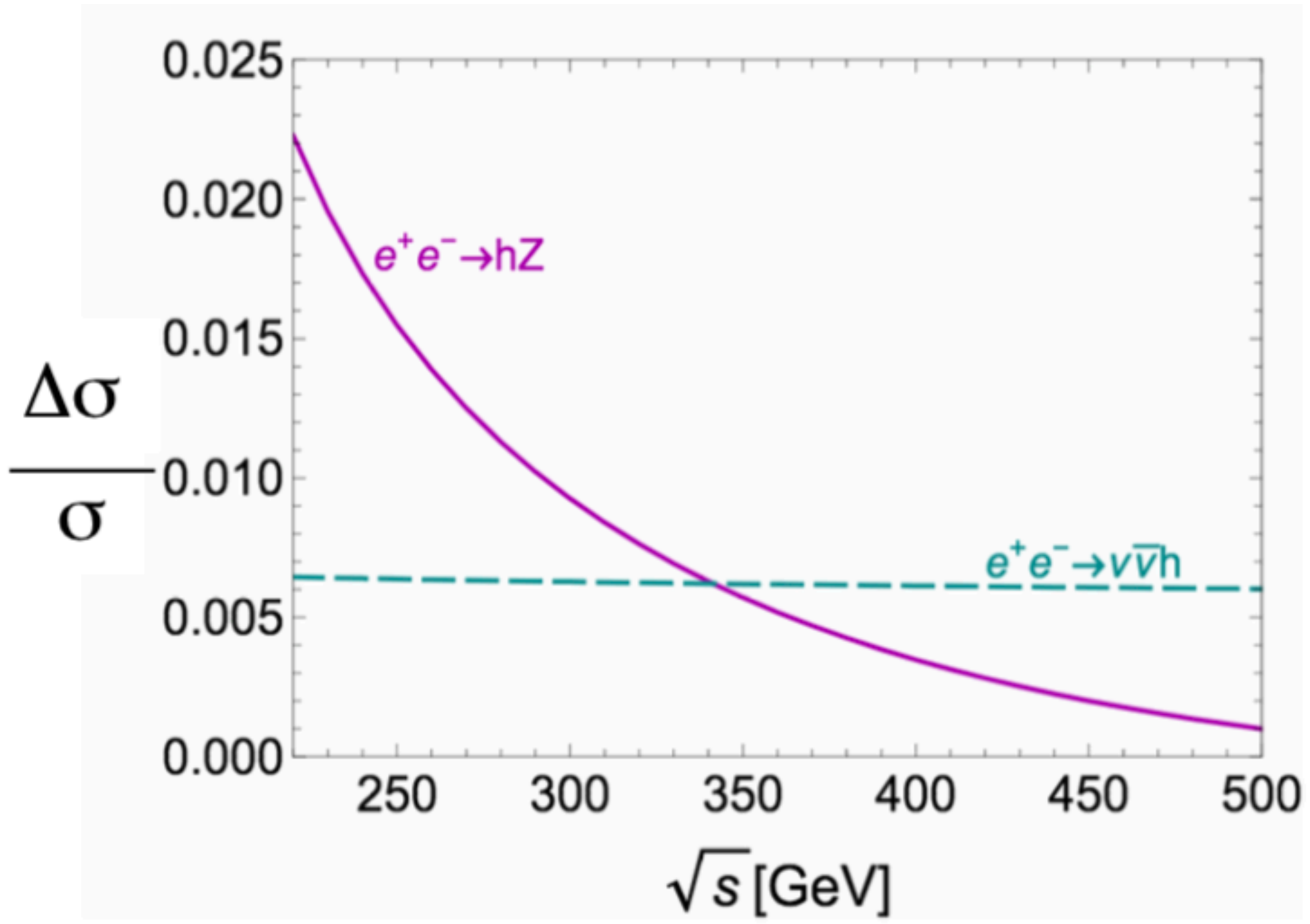
McCullough [1312.3322]
DeVita et al.[1711.033978]





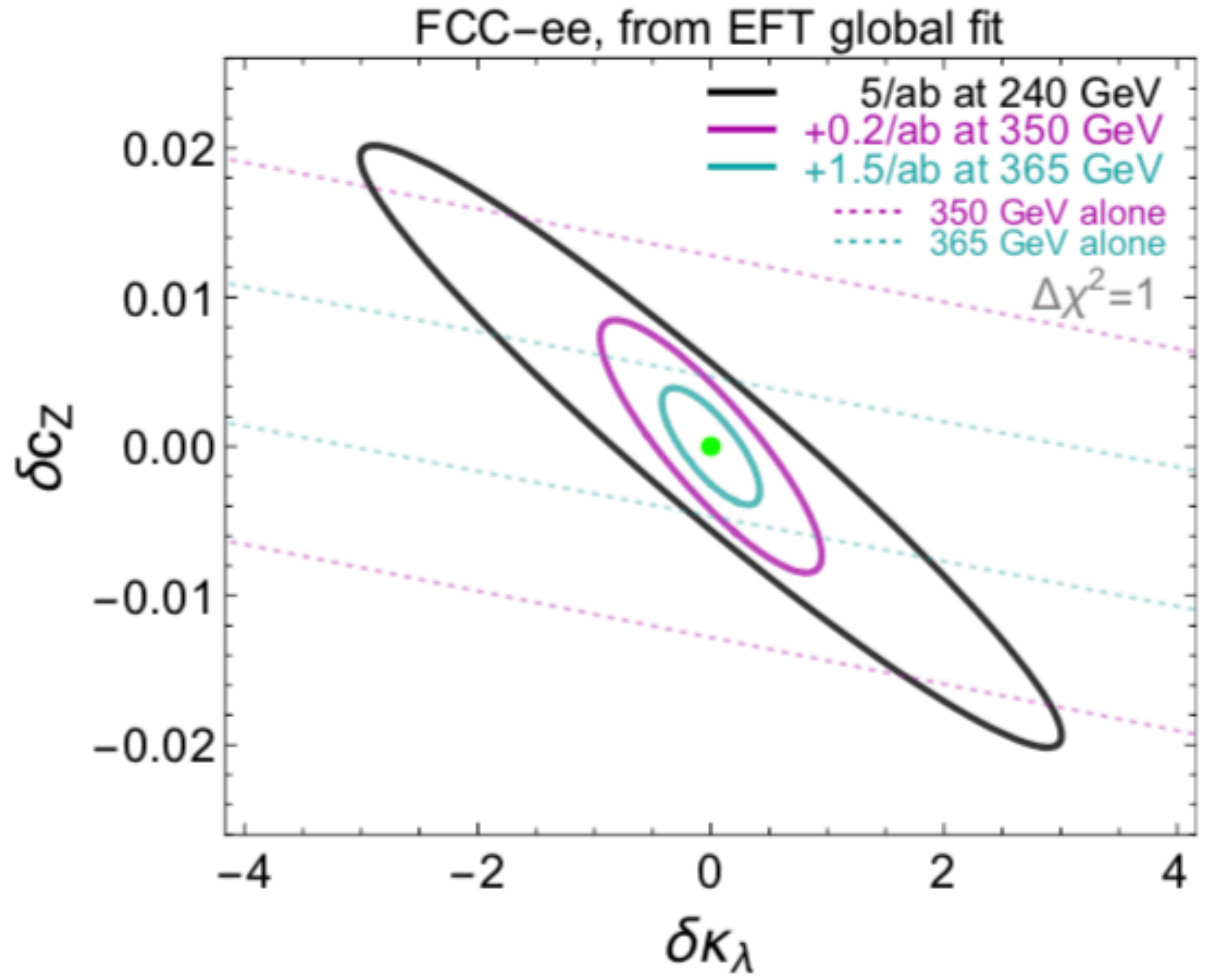
Blondel and Janot [1809.10041]

Higgs trilinear coupling at FCC-ee



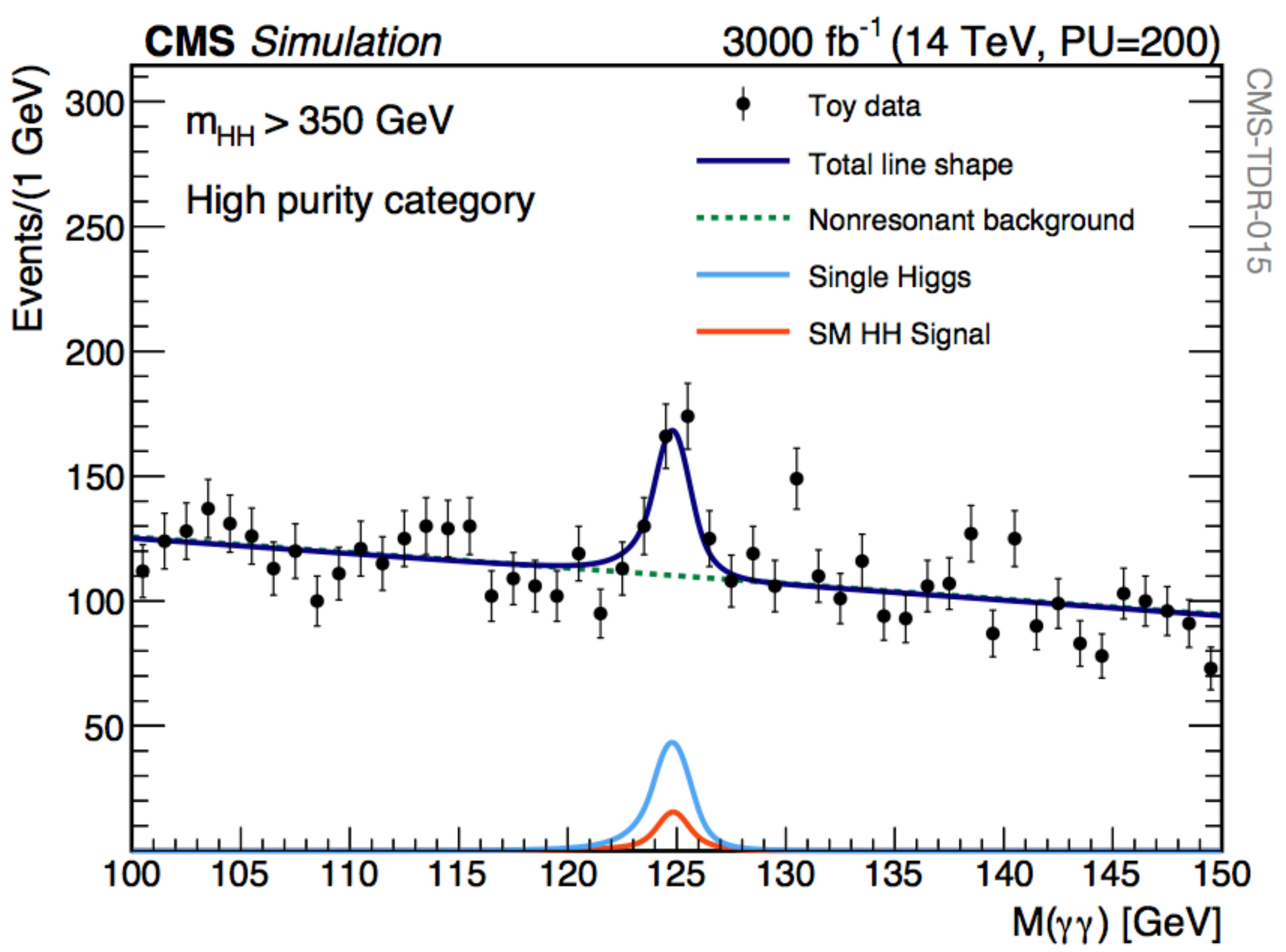
- If all other **SM coupling fixed** (in particular HHVV, HVV coupling):
  - $\delta\kappa_\lambda \approx 12$ % (2 IPs - baseline FCC-ee)
  - $\delta\kappa_\lambda \approx 9$ % (4 IPs)
- Single Higgs cross section at loop level depends on HVV and HHVV:
- At least two energy points lift the degeneracy

- With baseline design, **2 IPs**, 15 years at sqrt(s)=90+160+240+350+365 GeV
  - $\delta\kappa_\lambda \approx 42$ % **(34% combined with HL-LHC)**
    - To be compared with 30 years of $ILC_{250+500}$
- With **4IPs** and 15 years of running:
  - $\delta\kappa_\lambda \approx 25$ % **(21% combined with HL-LHC)**
    - To be compared with 15 years of $CLIC_{380+1500}$
    - 5σ sensitivity by 2050

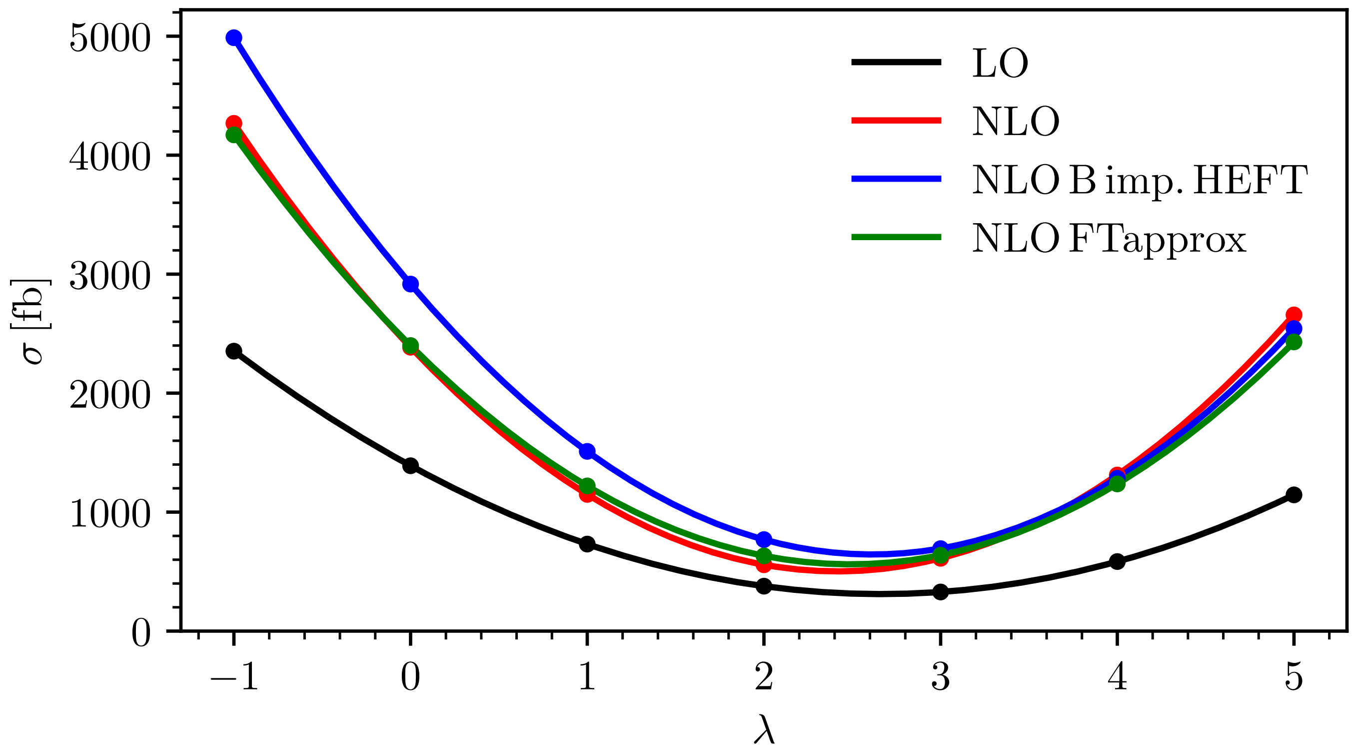


Higgs self-coupling at FCC-hh

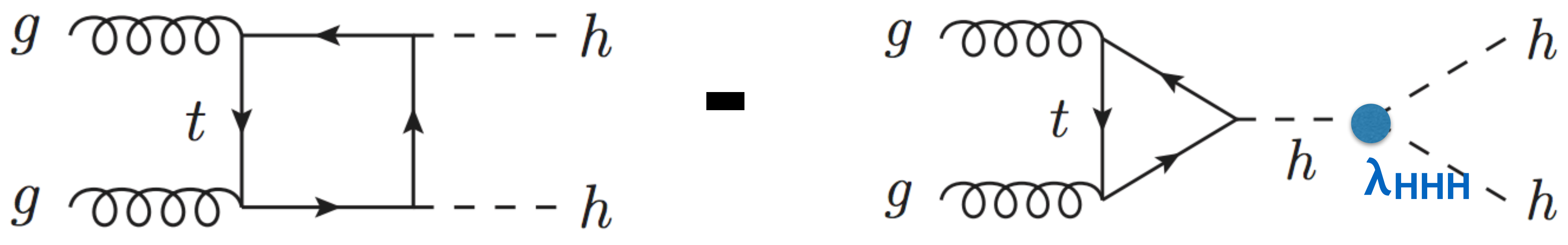
HL-LHC



G. Heinrich et.al [1608.04798]



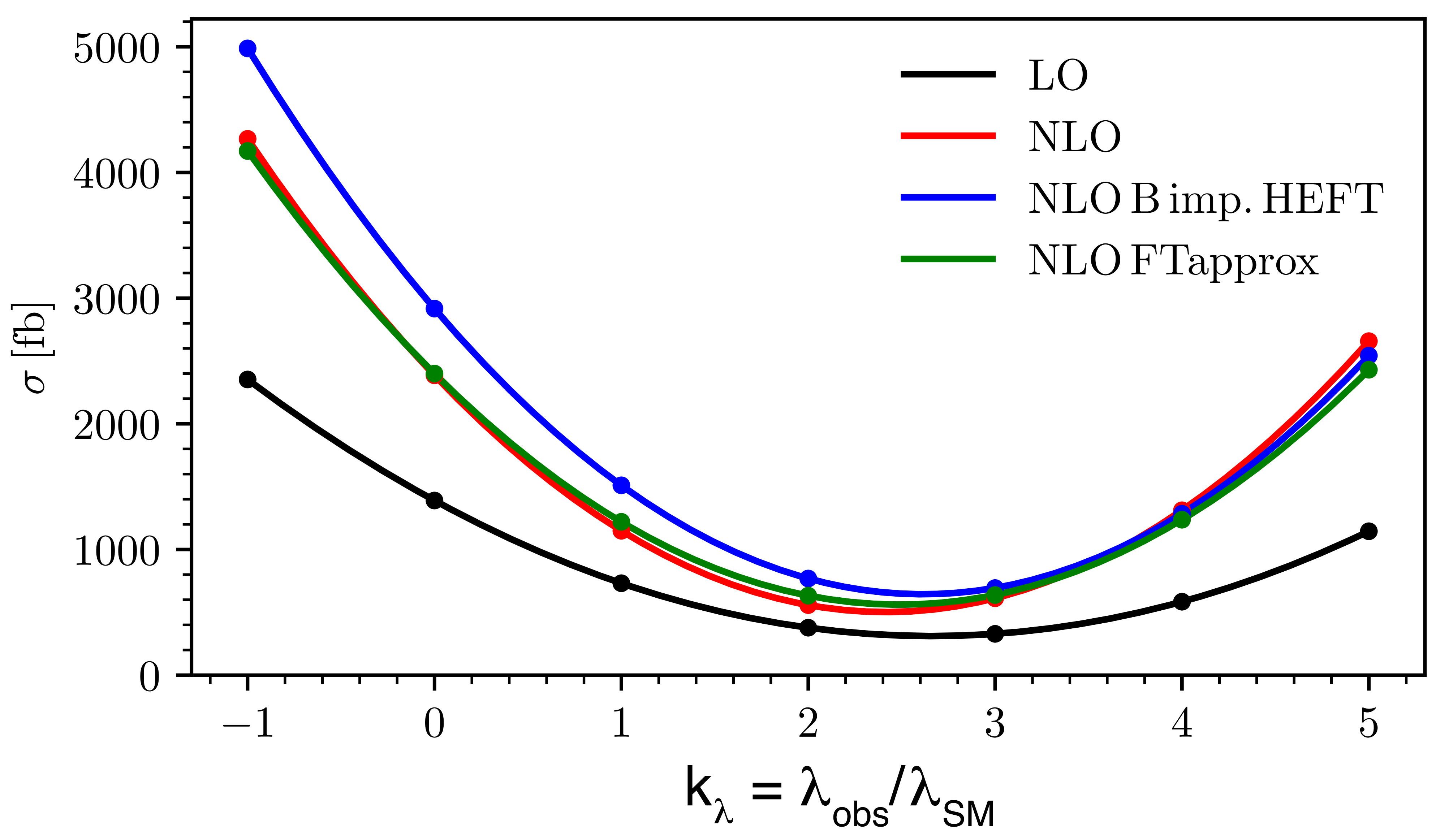
gluon fusion:

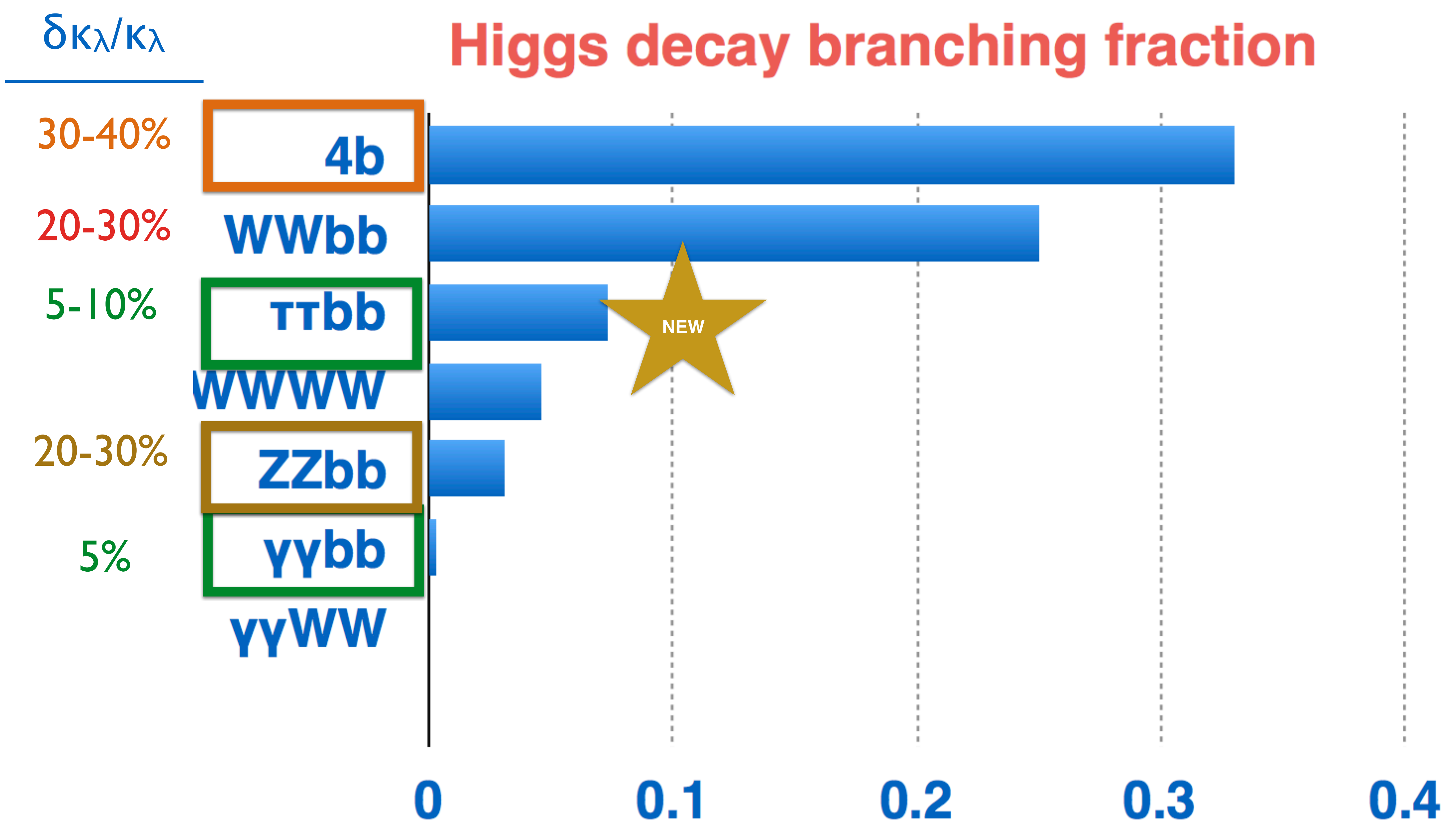


- Very small cross-section due to **negative interference** with box diagram
- HL-LHC projections : $\delta k_\lambda / k_\lambda \approx$ 50-100%
- Expect large improvement at FCC-hh:
  - σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
  - x400 in event yields and x20 in precision
- main channels studied:
  - bbɣɣ (golden channel)
  - bbZZ(4l)
  - bbbbj
  - NEW bbττ

HH@ FCC-hh: production at 100 TeV and decay

G. Heinrich et.al [1608.04798]

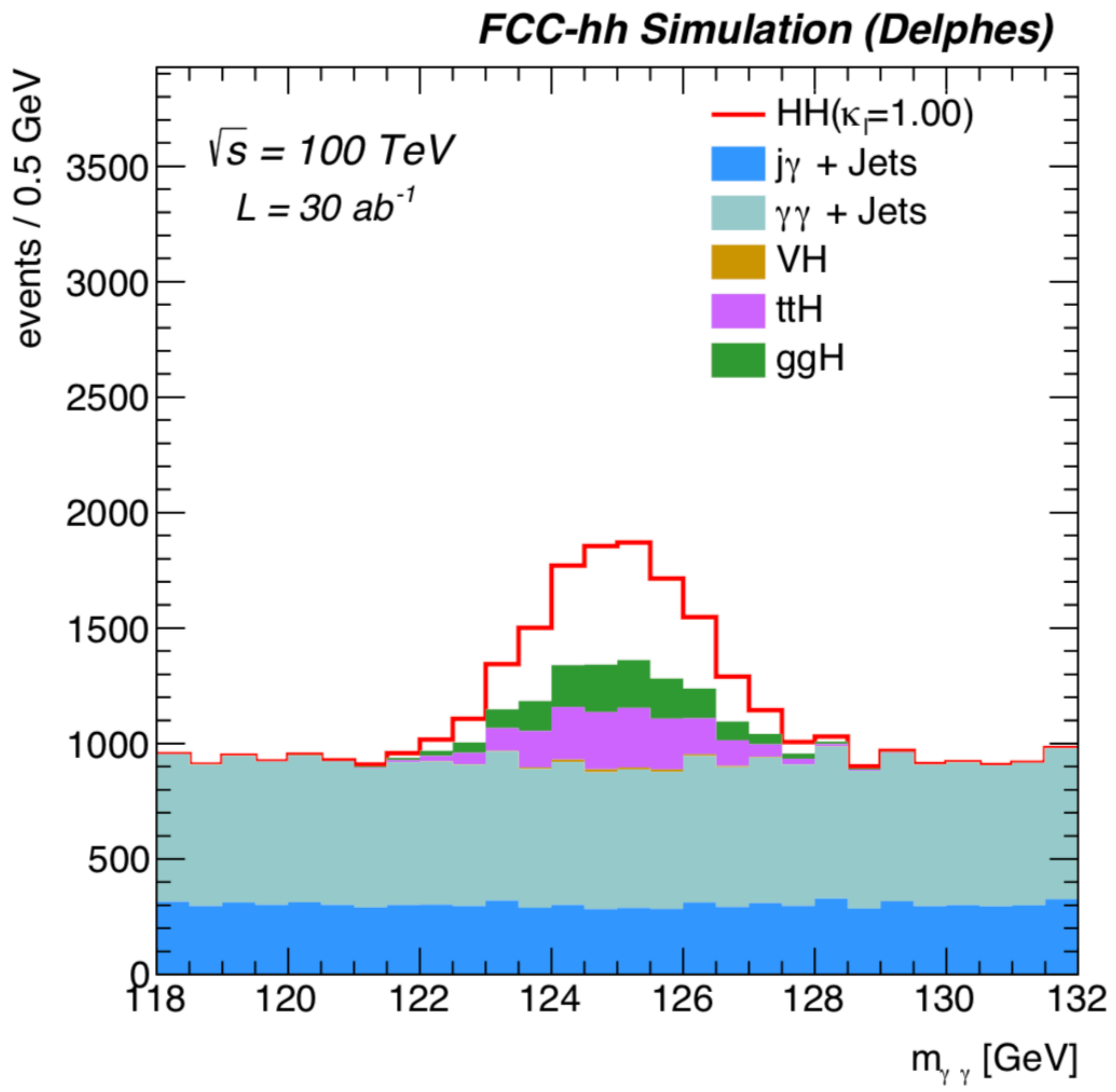


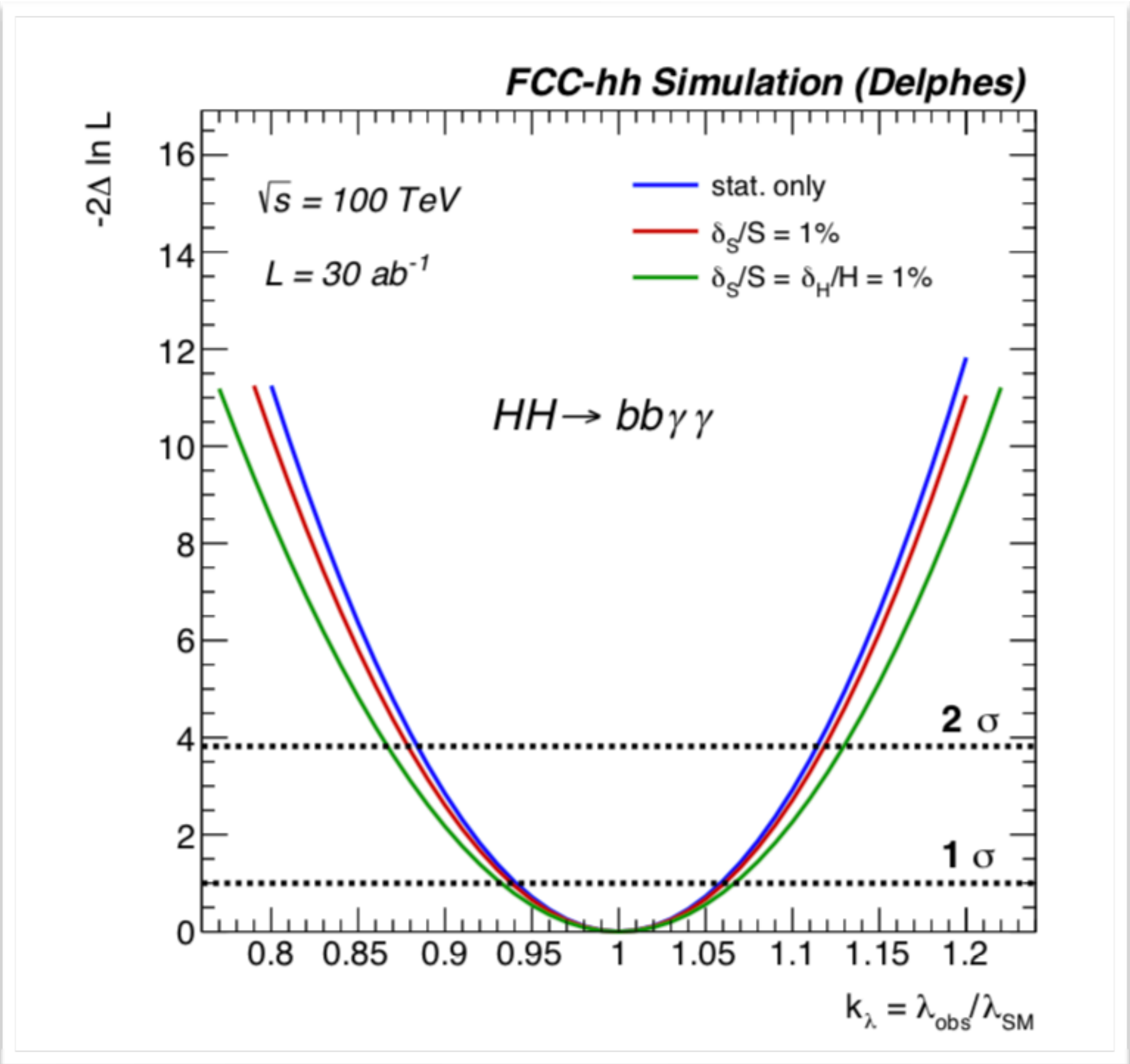


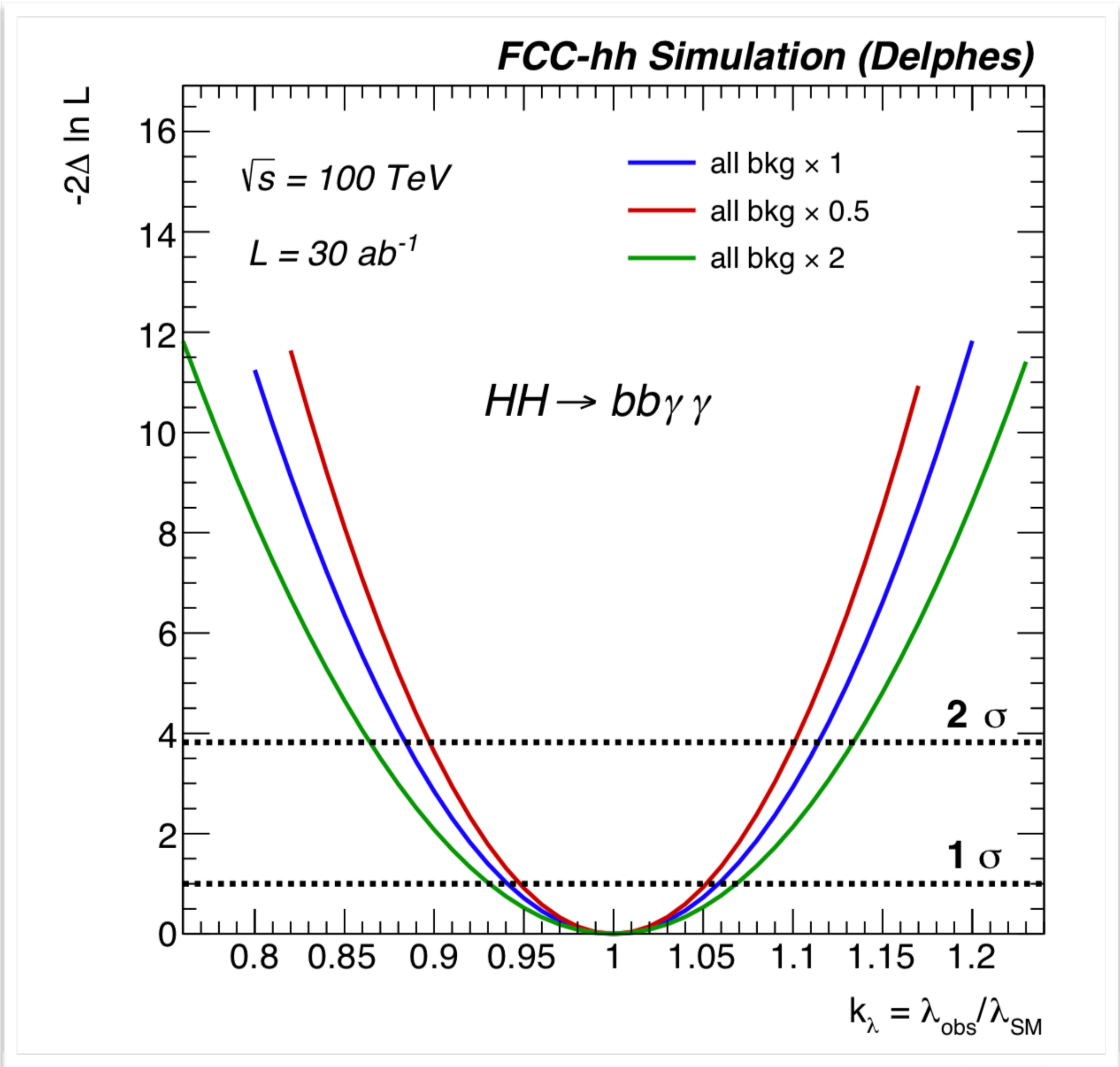
- Higher order in QCD helps λ-dependent K-factor sensitivity (not only the rate)
  → included here (bbγγ, bbZZ)!

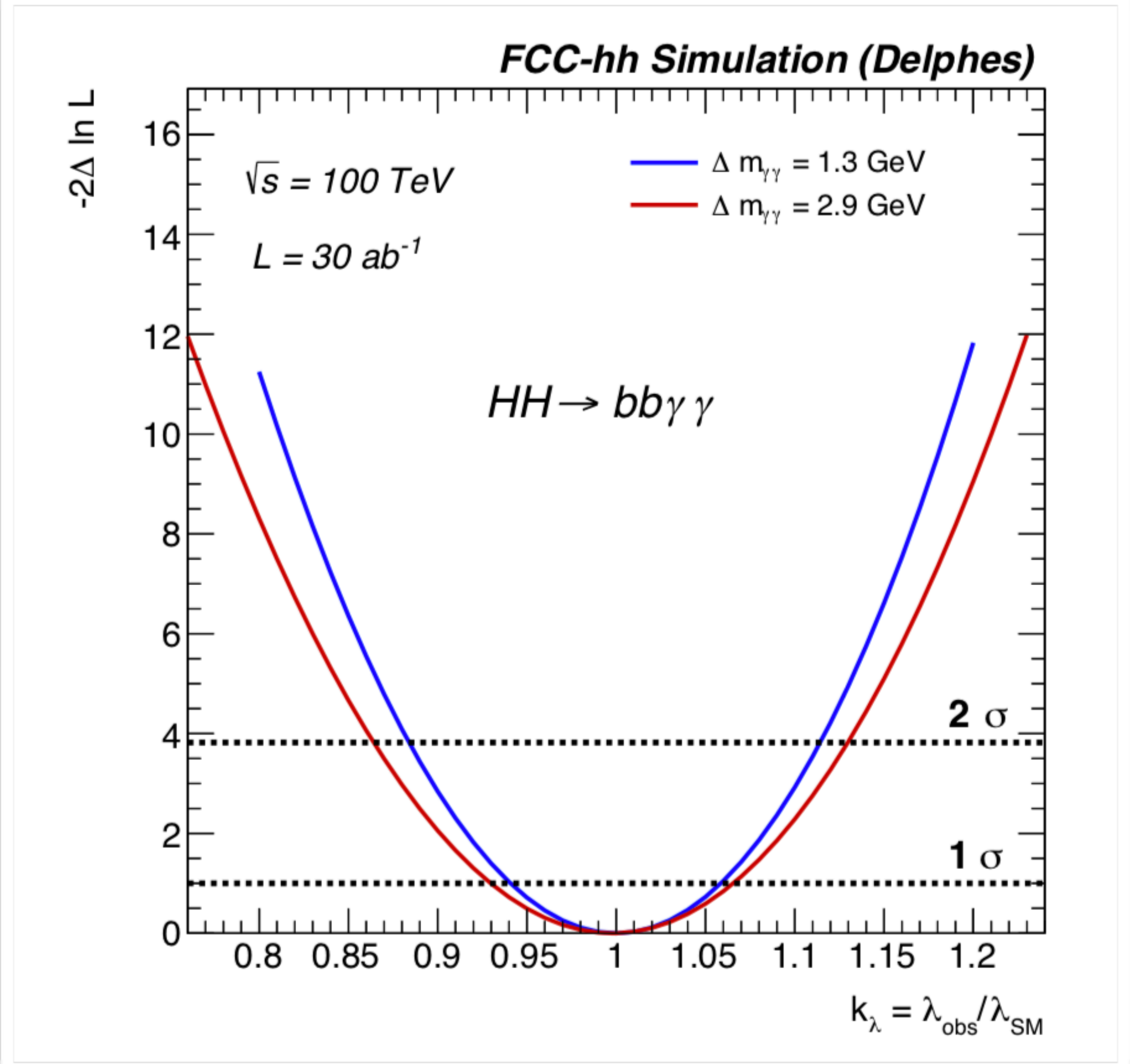
HH →bbɣɣ

- **Large QCD** backgrounds (jjɣɣ and ɣ+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
  - **$\delta k_\lambda / k_\lambda$ = 5-7% (stat - stat+syst.)** in this channel alone



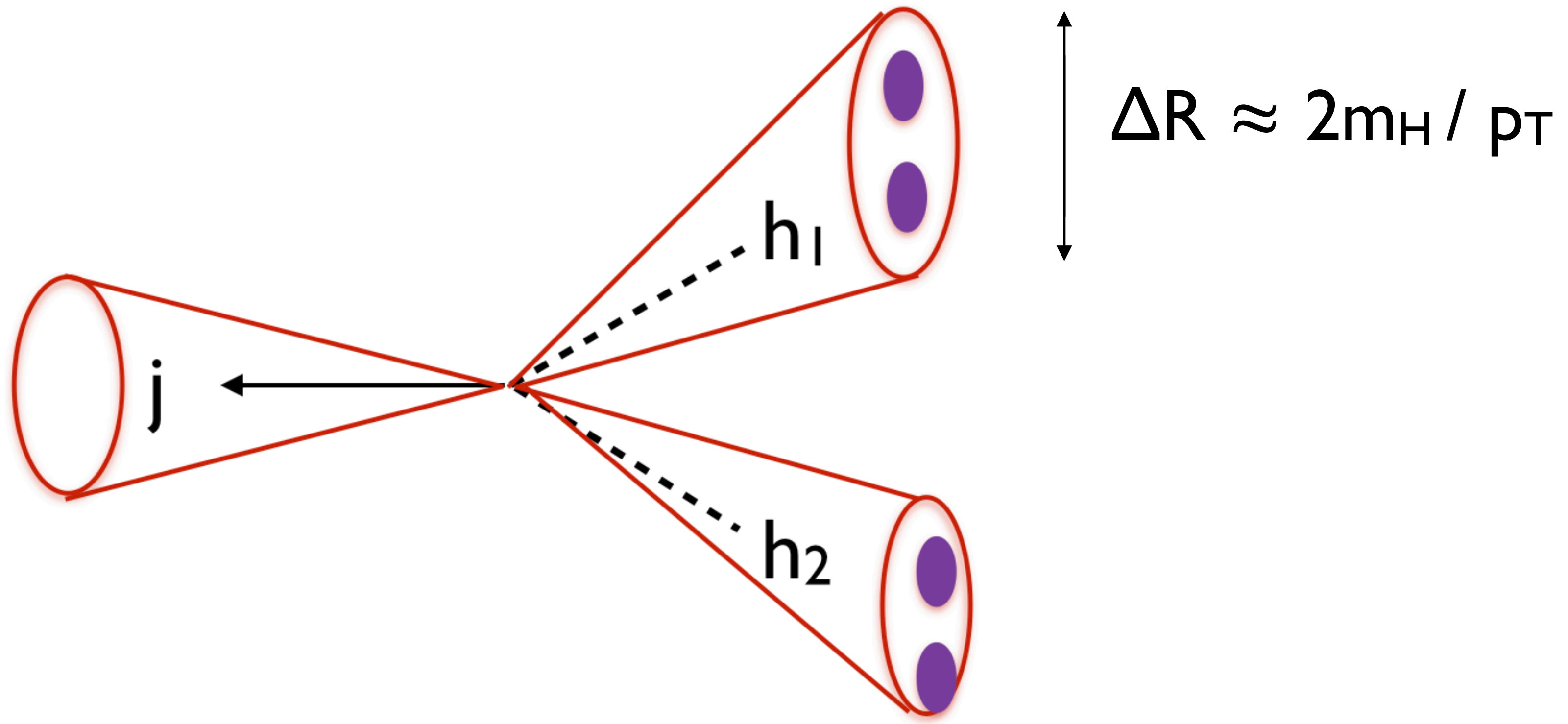


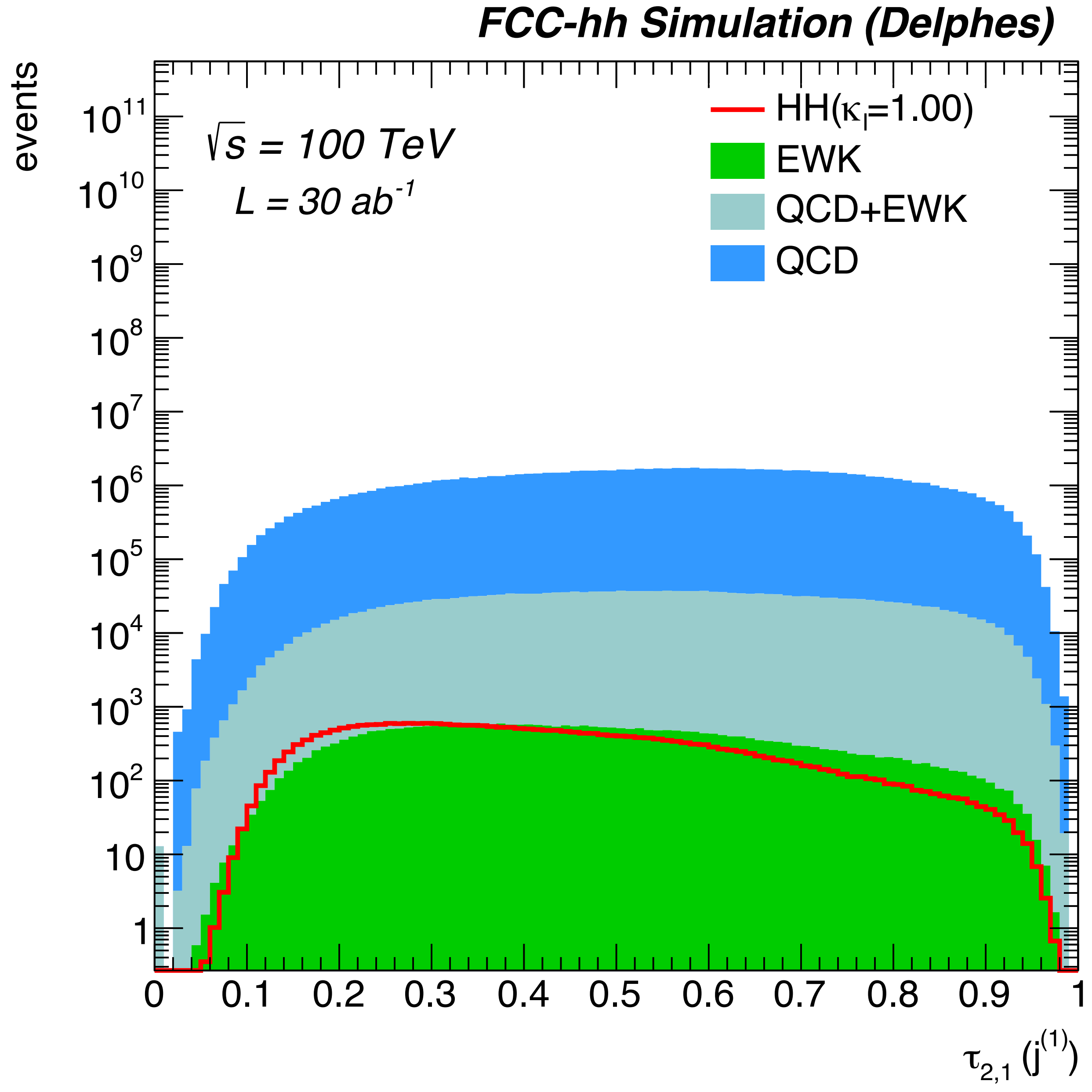


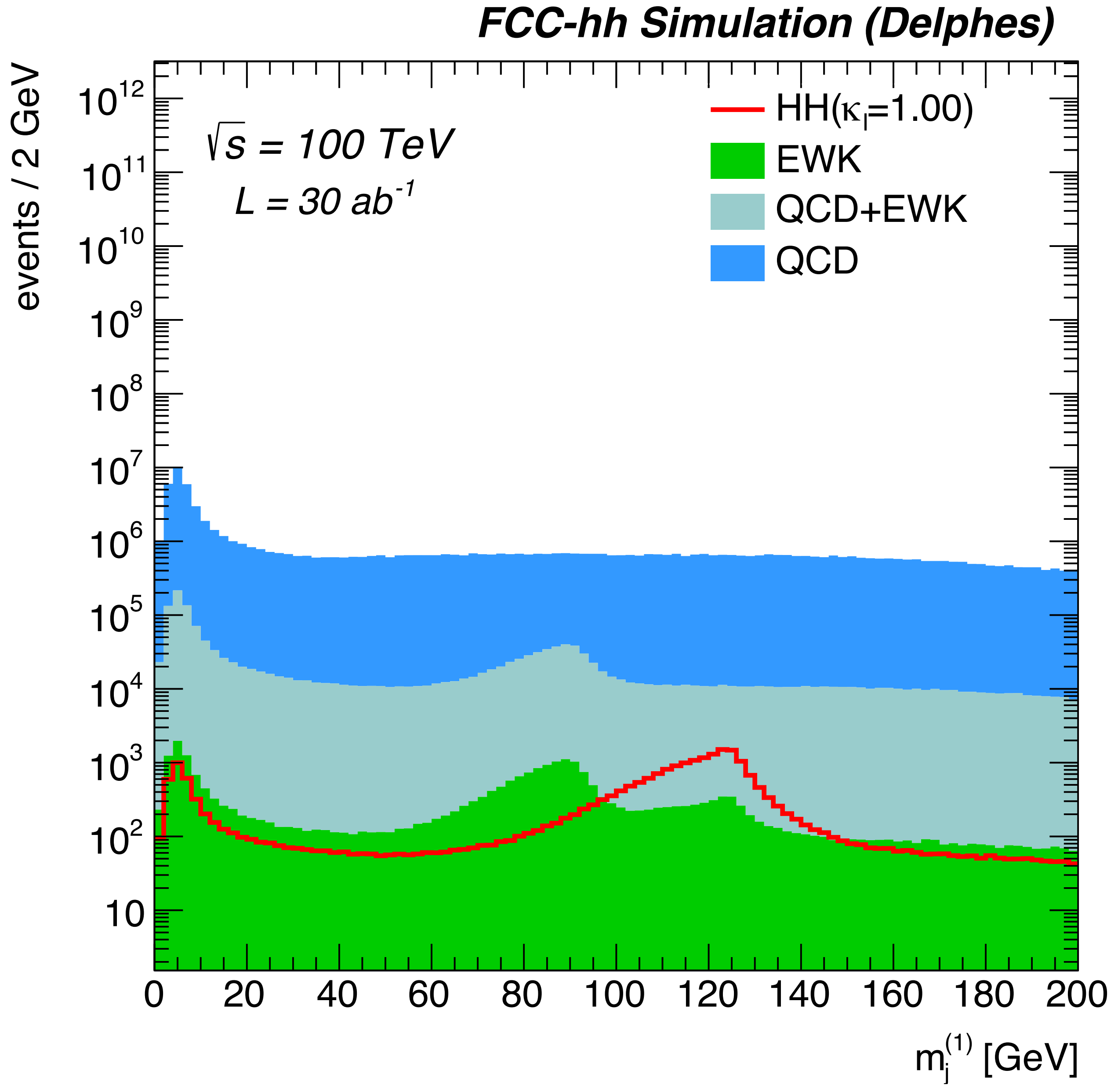


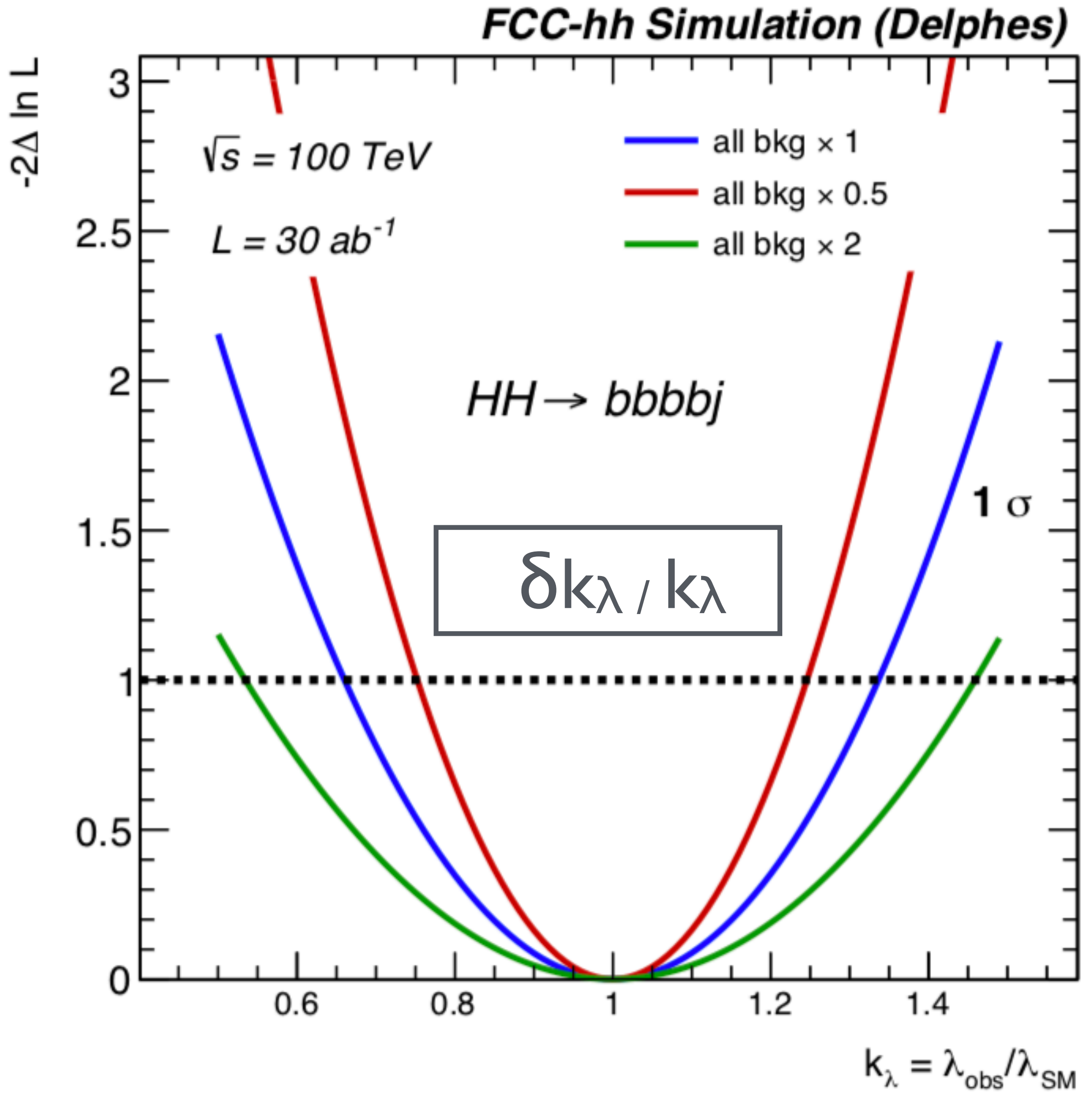
HH →4b+j boosted

- Large rates allow to look for **boosted HH** recoiling against a jet (**low m_{HH}** drives the sensitivity)
- relies on identification **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



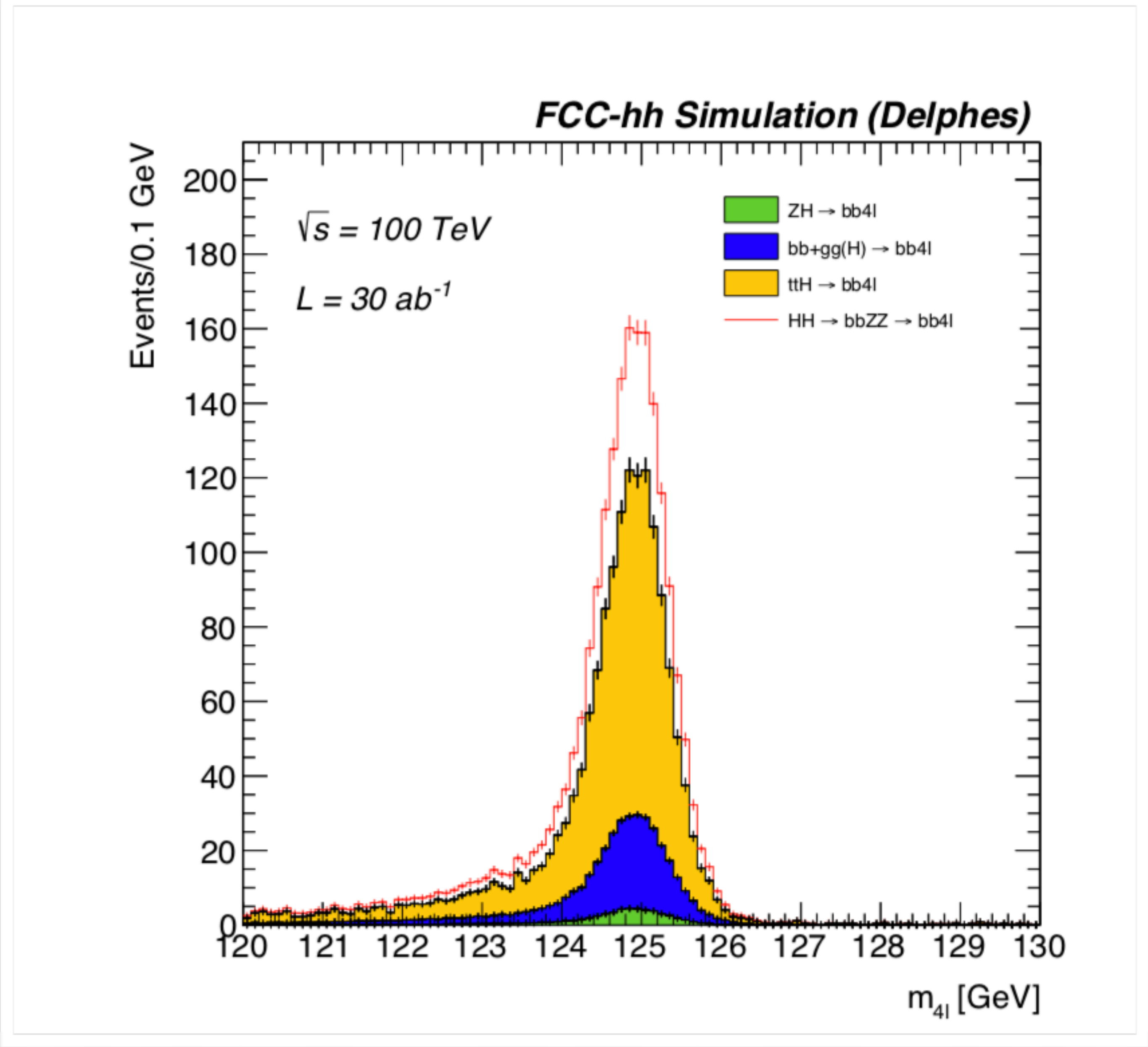






HH →bb4l

[Borgonovi, Braibant, De Filippis, Fontanesi, GO, MS]



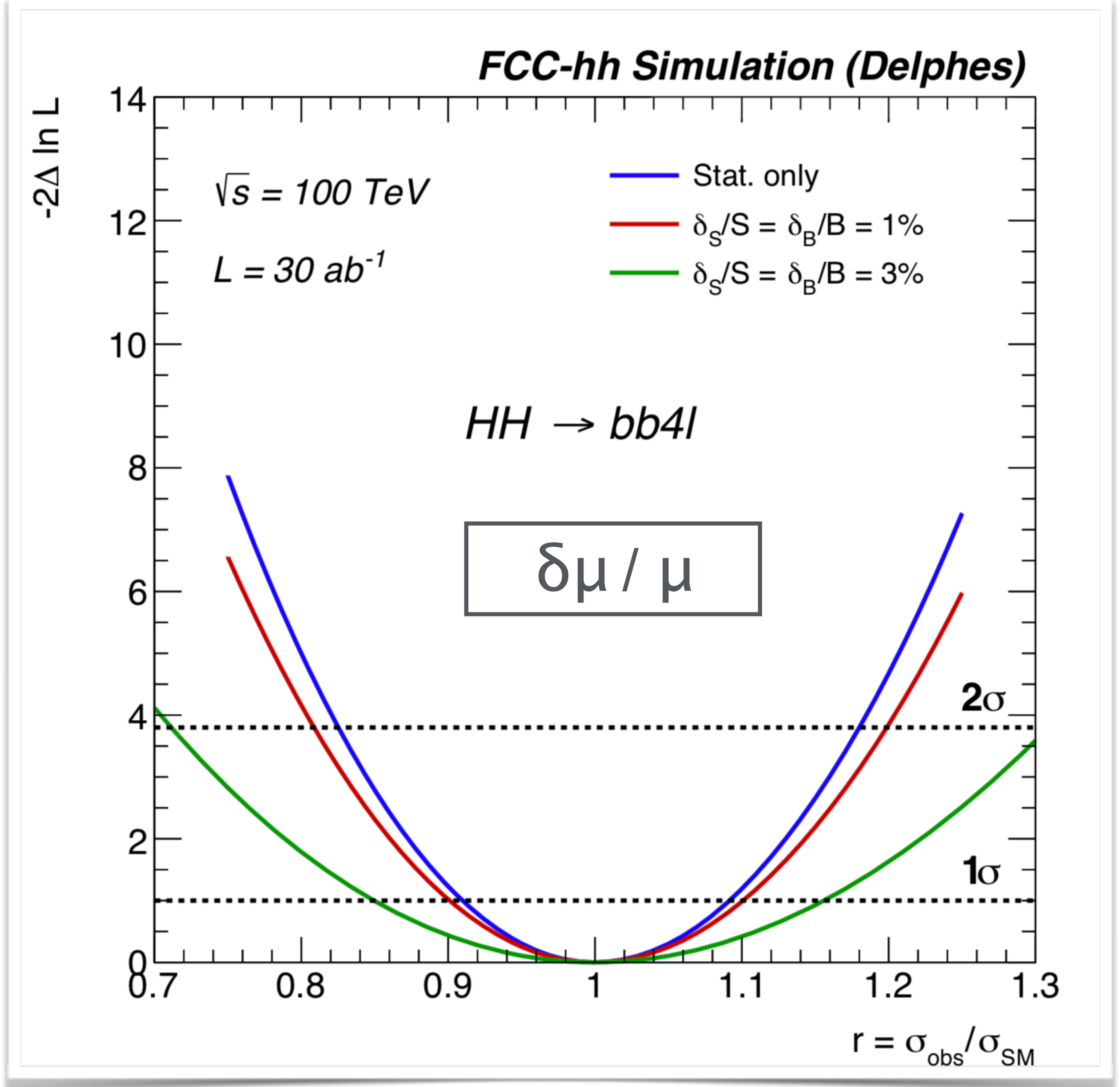
- **New channel** opening at FCC-hh !!
- clean channel with mostly reducible backgrounds (**single Higgs**)
- Simple cut and count analysis on (4e, 4μ and 2e2μ channels)

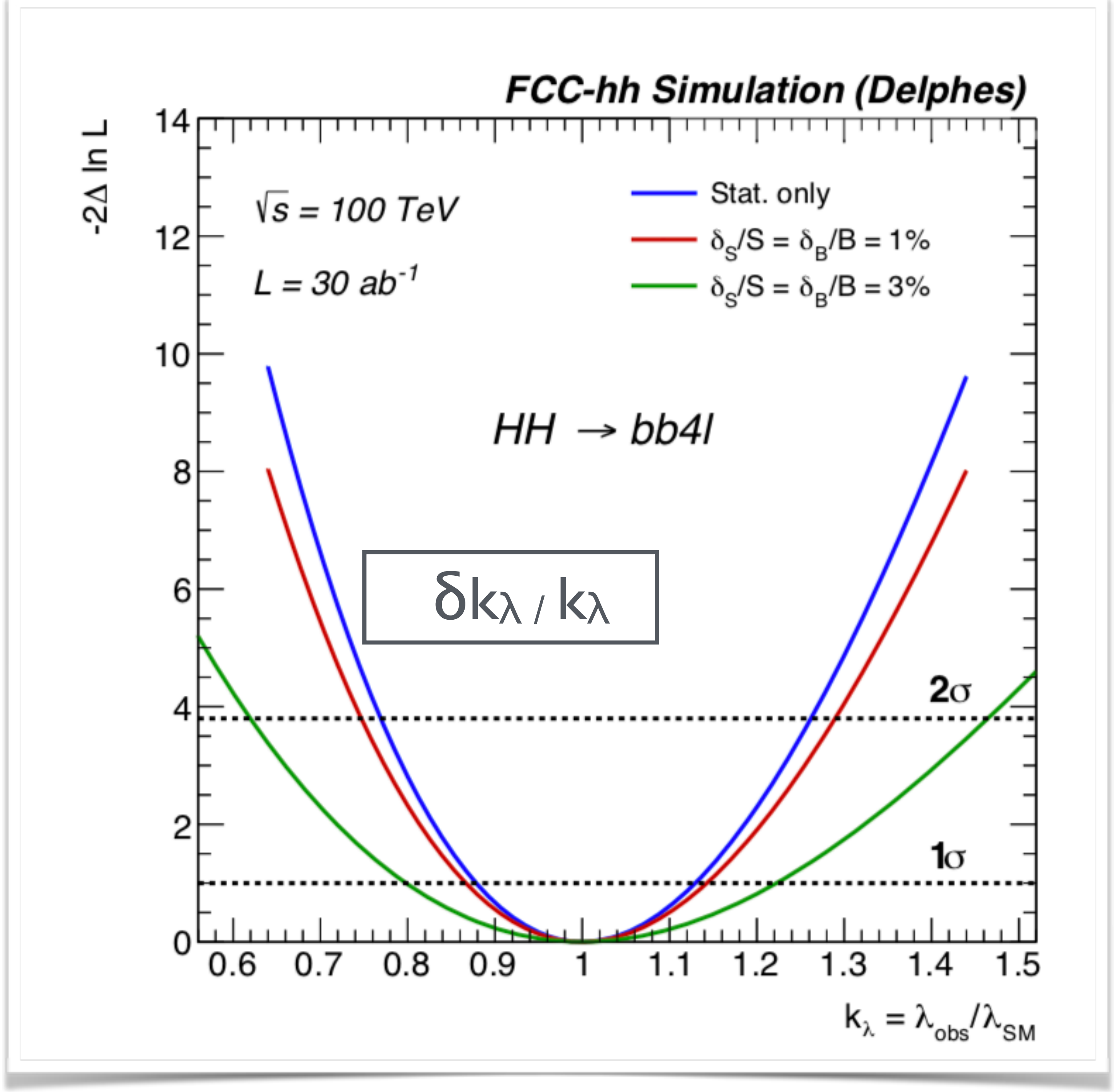
Backgrounds:

- ttH , H → 4 leptons
- 4l + jets (ZZ*, Z*Z*, ZZ) continuum
- p p → H b b →4l bb

$\delta k_\lambda / k_\lambda$ = 15-20%

depending on systematics assumptions





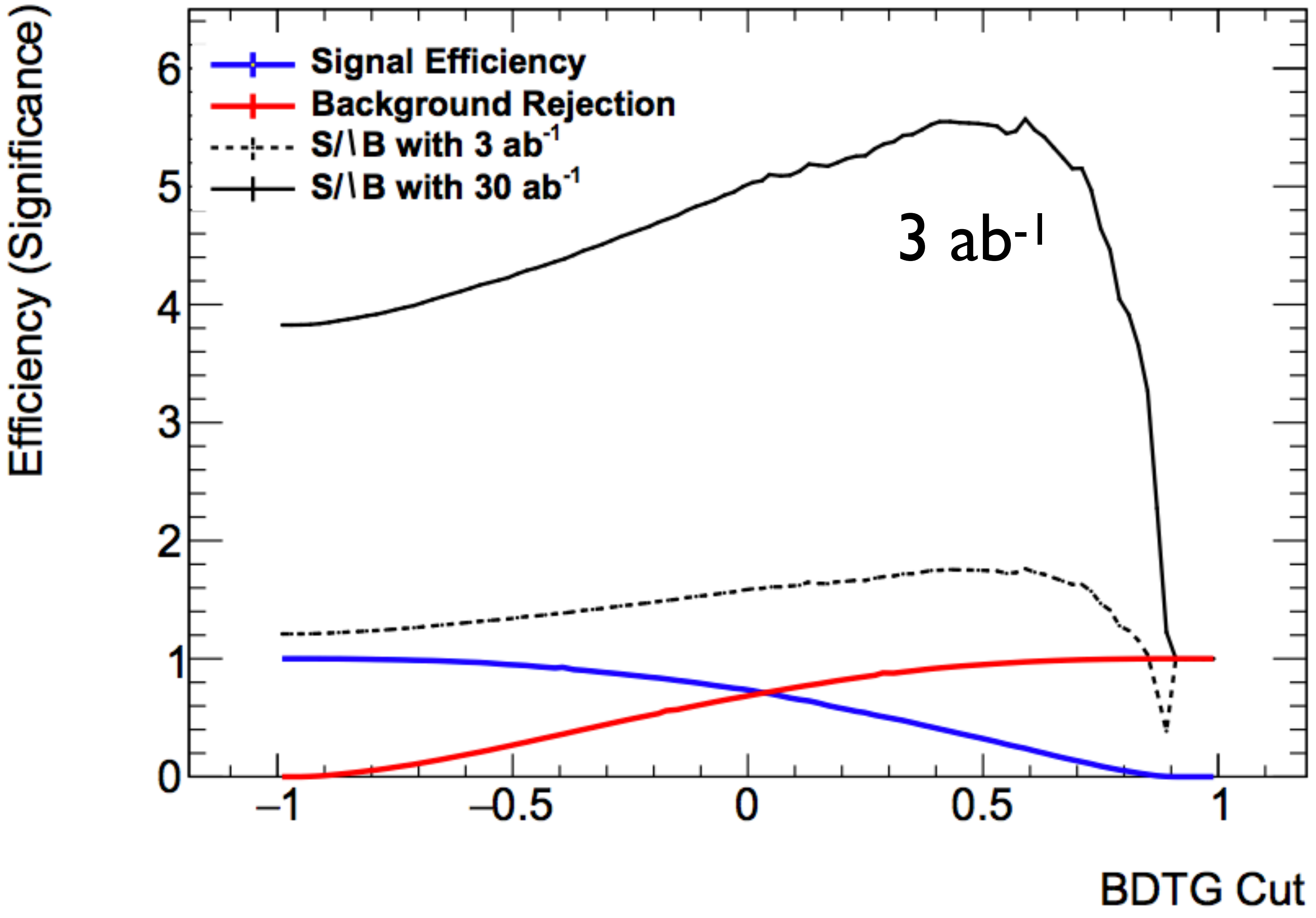
bbWW → bblvqq

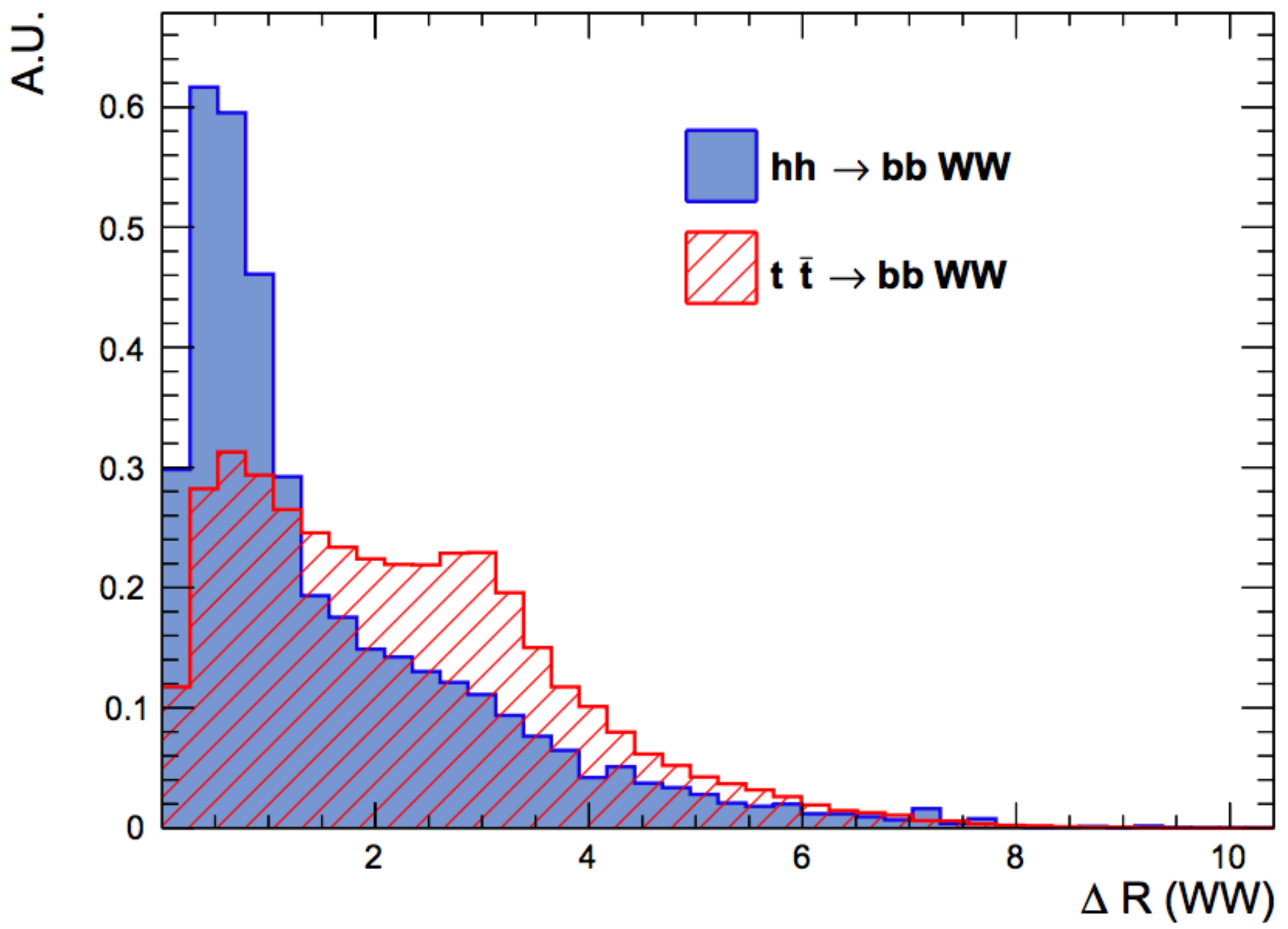
Method:

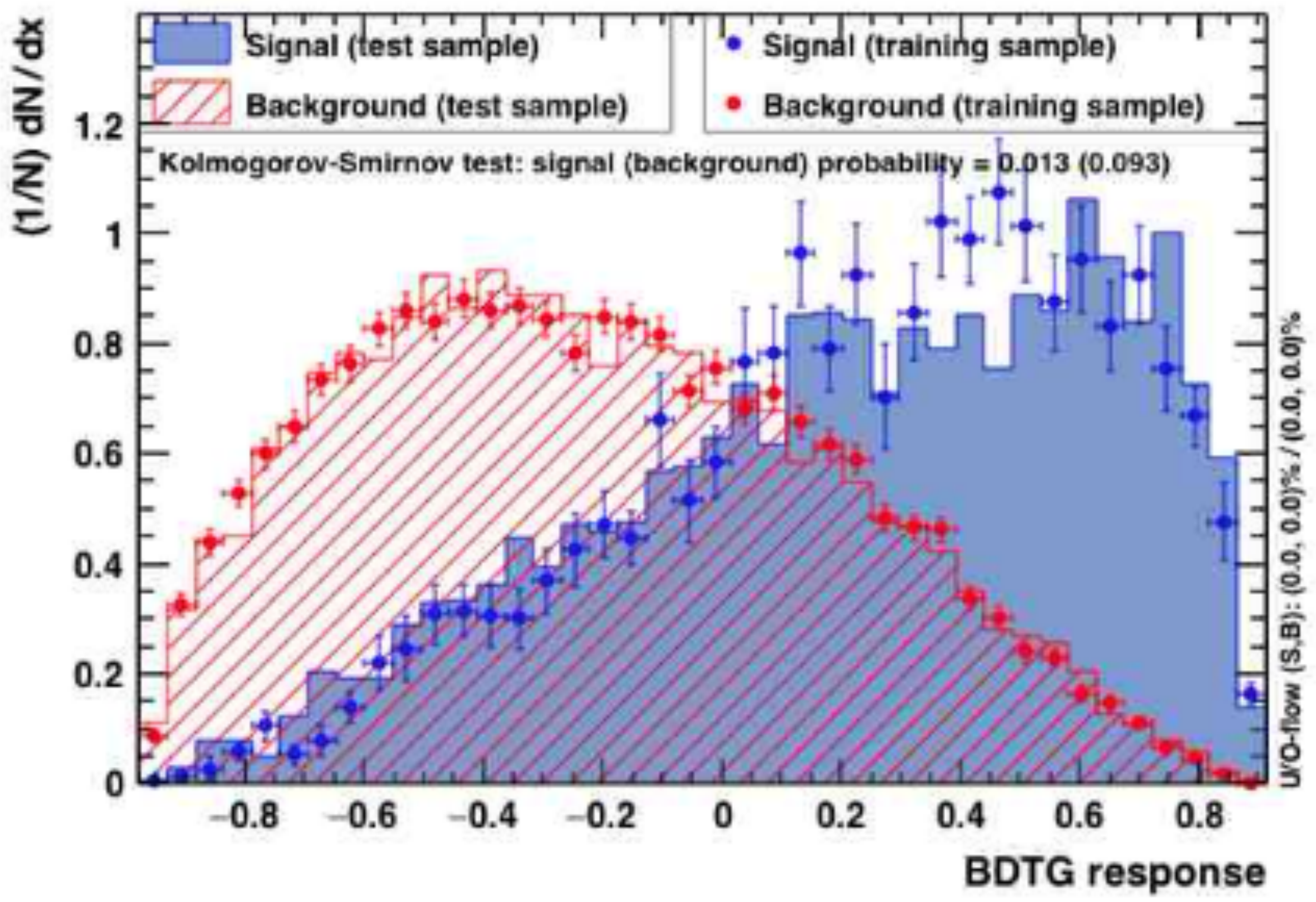
- 80 < mbb < 150 GeV
- p_T(WW) > 150 GeV
- BDT

Backgrounds:

- ttbar → bbWW
- V+jets







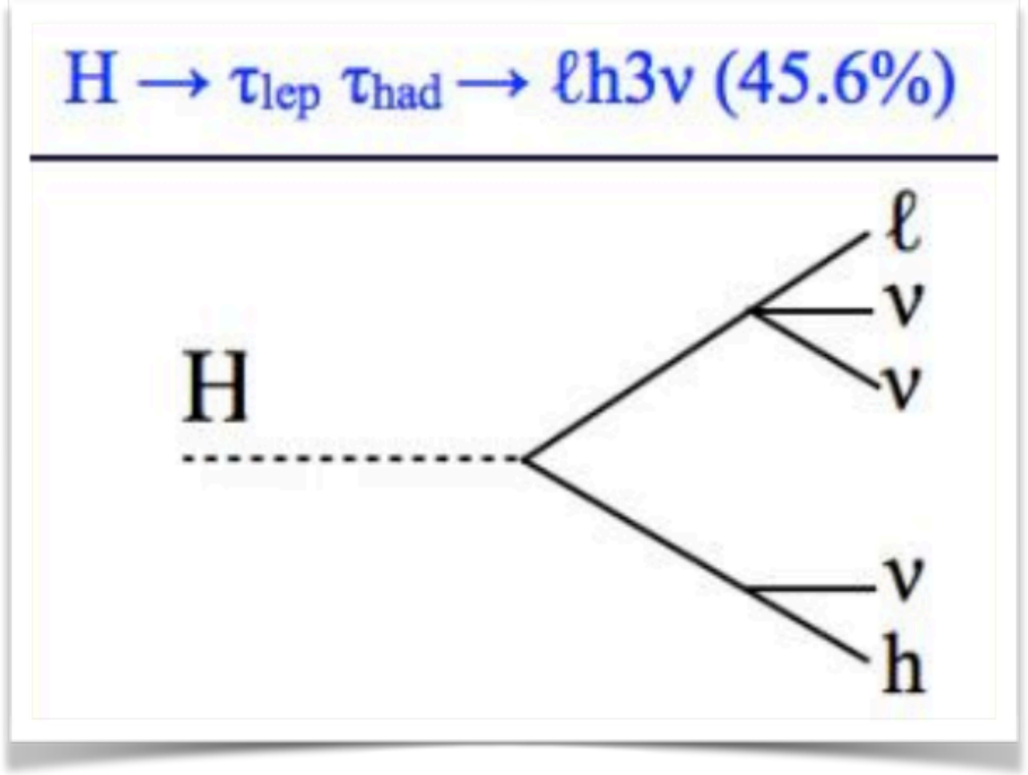
$\delta r(\text{stat}) \approx 20\%$ → $\delta\kappa_\lambda(\text{stat}) \approx 40\%$

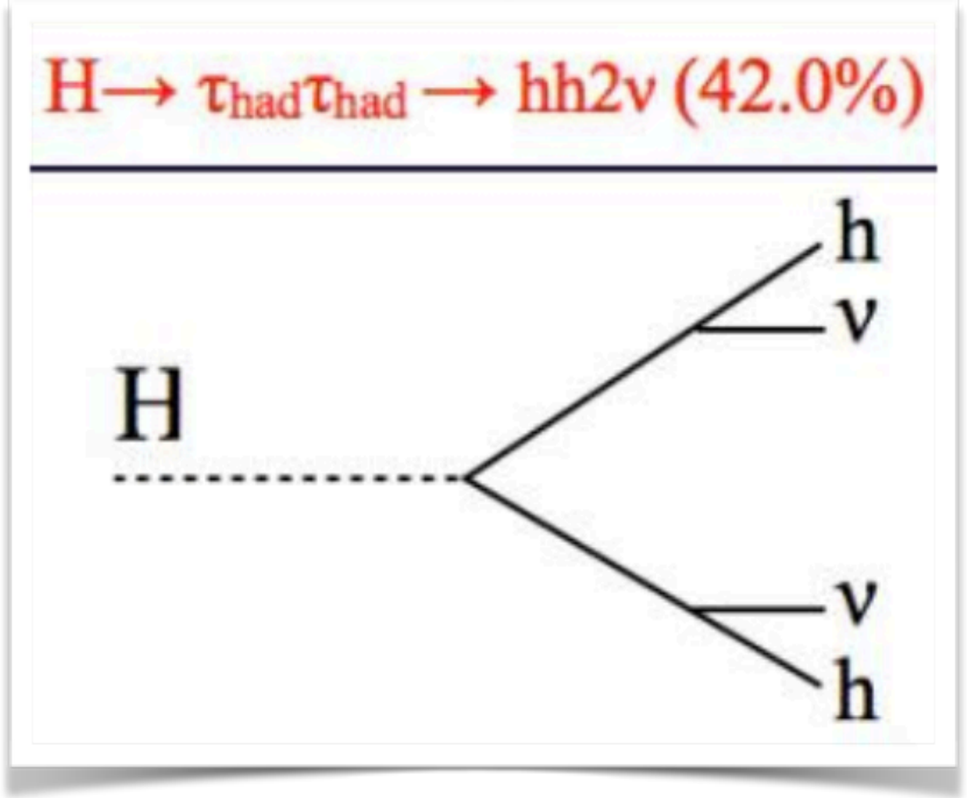
NEW

$bb\tau\tau$

PRELIMINARY !!!

The bbττ channel





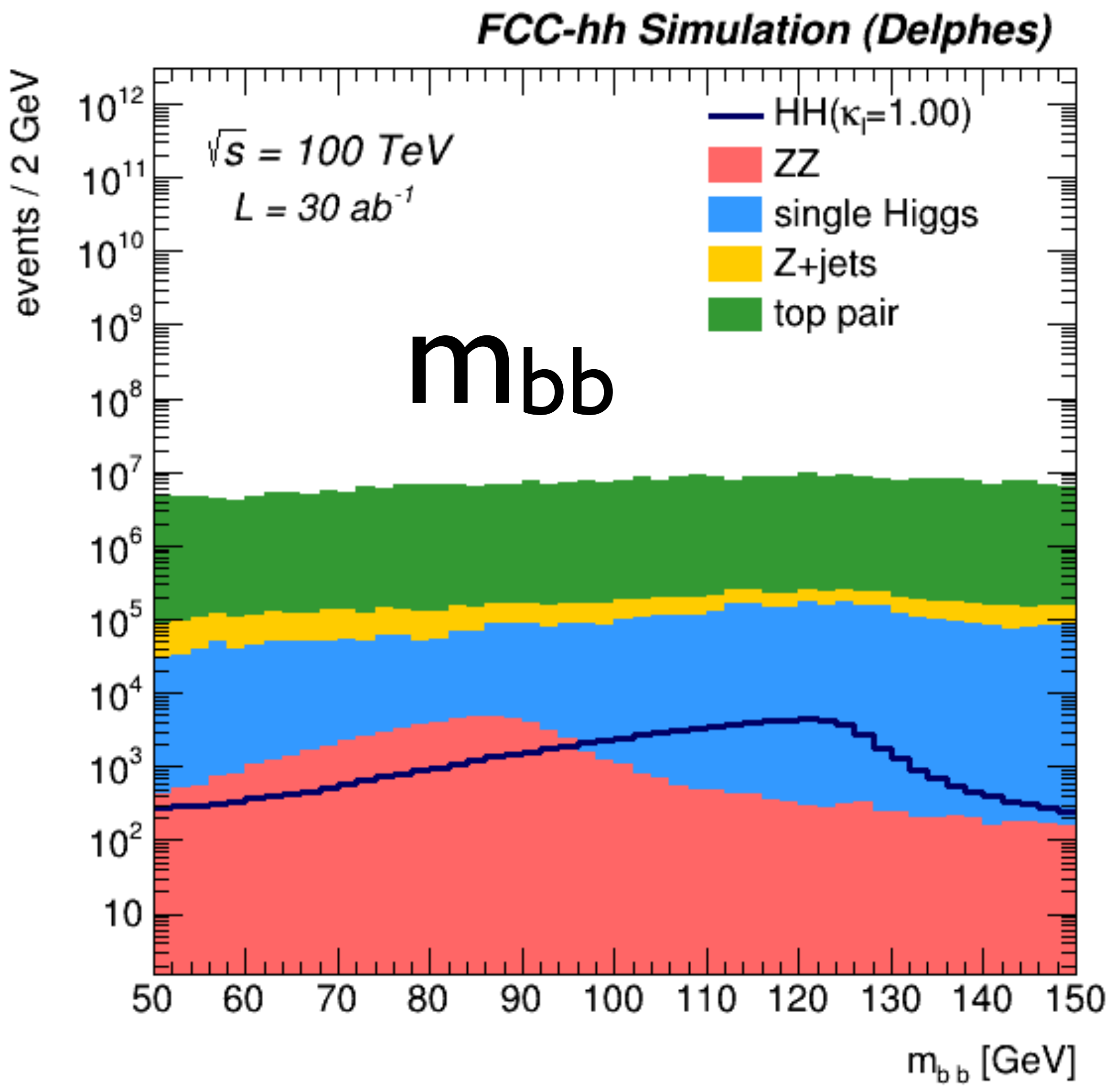
<u>Detector assumptions:</u>

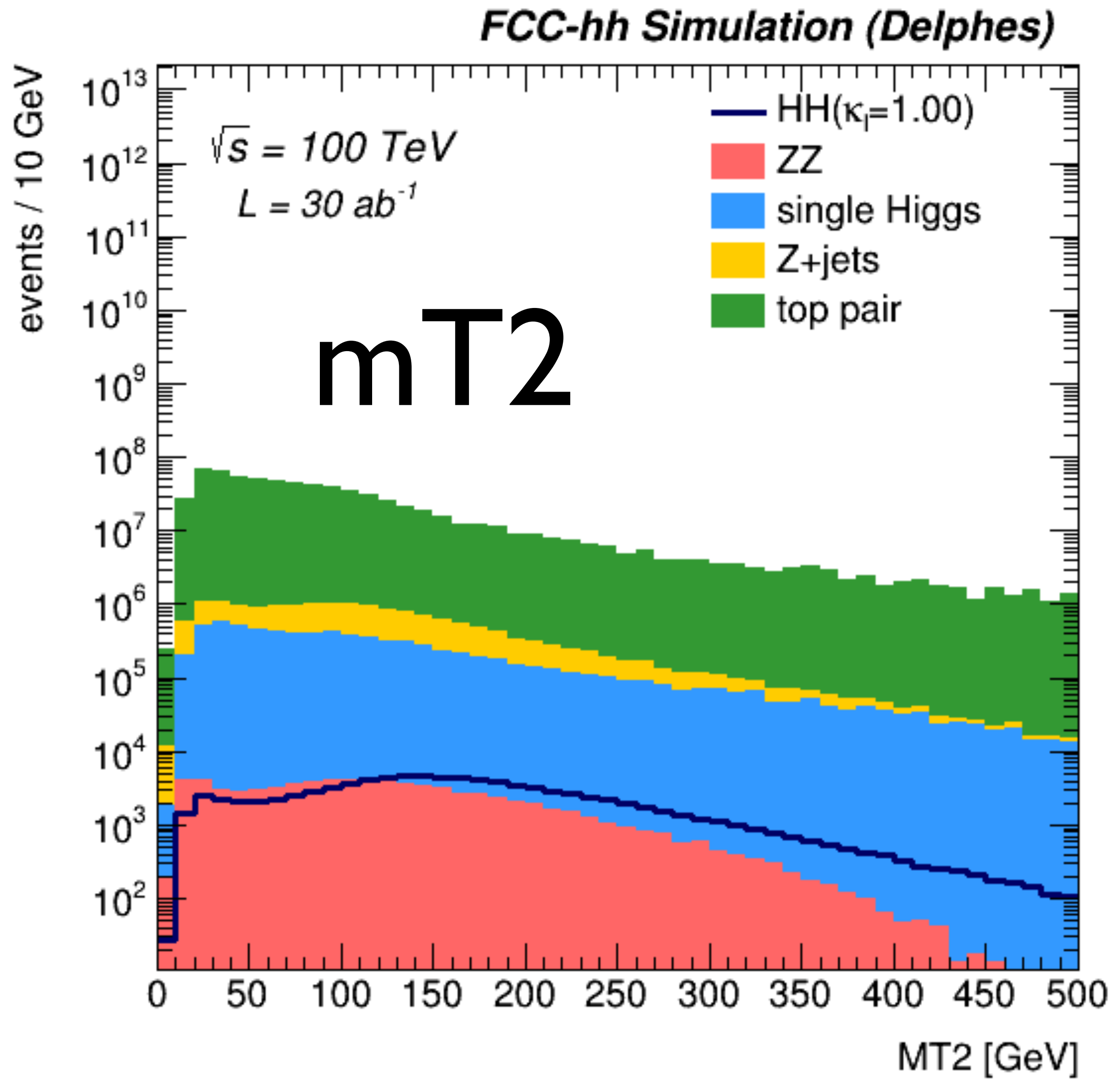
- No Pile-up
- **Nominal** FCC-hh detector resolutions:
    - b-tagging : ε_b = 85%, $\varepsilon_{j \to b}$ = 1% (~ HL-LHC)
    - τ-tagging : ε_τ = 80%, $\varepsilon_{j \to \tau}$ = 1%. (~ HL-LHC)

- Exploit **large branching ratio** 2*BR(H→bb)*BR(H→ττ) ≈ 7.3%
- Final states: both $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ considered:
- <u>Backgrounds:</u>
    - **Top pair**
    - **single Higgs (VH, ttH, ggH)**
    - Z + bb →ττ + bb
- $\tau_{lep}\tau_{had}$ has larger B contamination
    - ttbar with τ_{had} + e/mu (in addition to $\tau_{lep}\tau_{had}$)

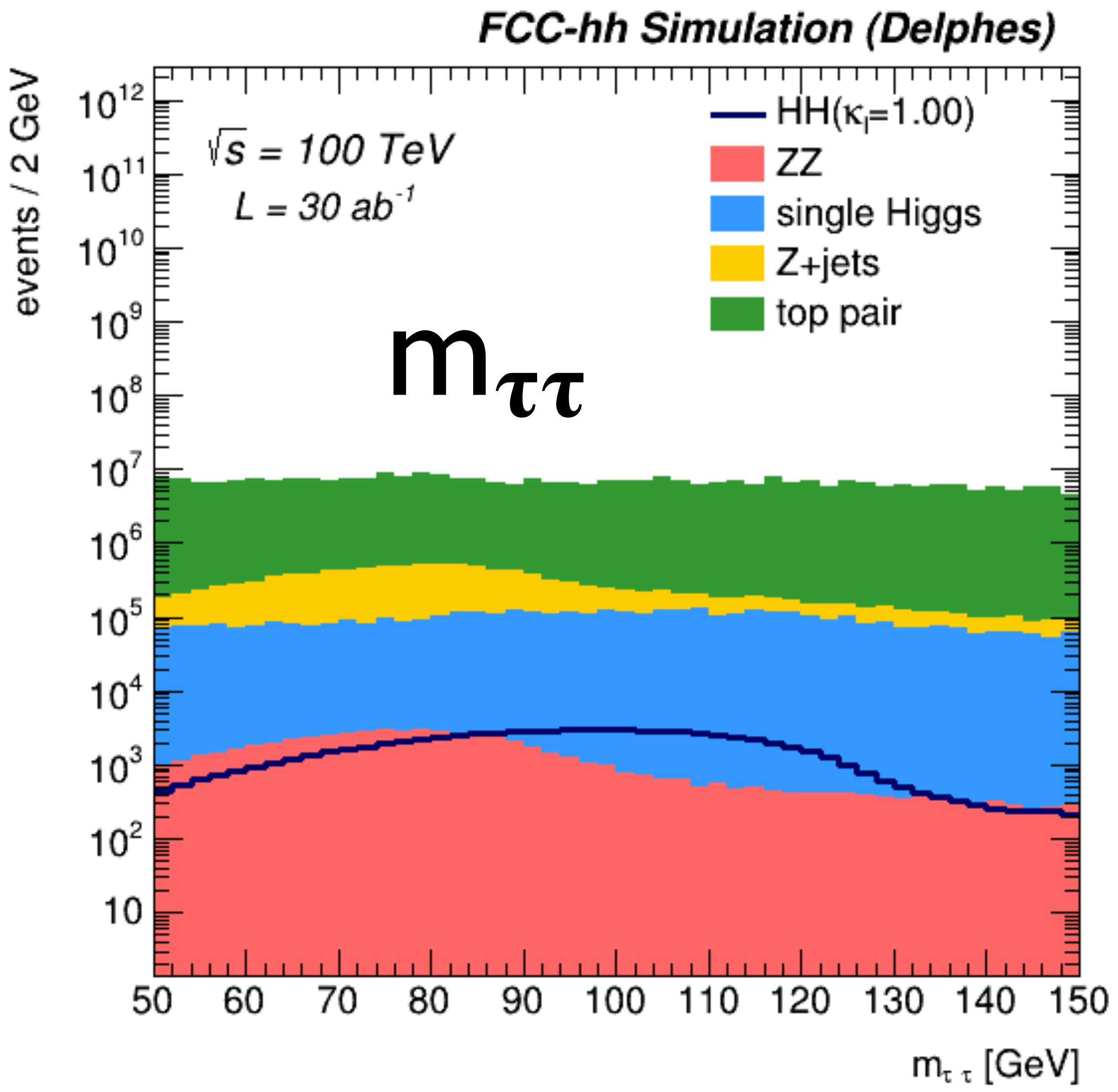
Preselection $\tau_{had}\tau_{had}$

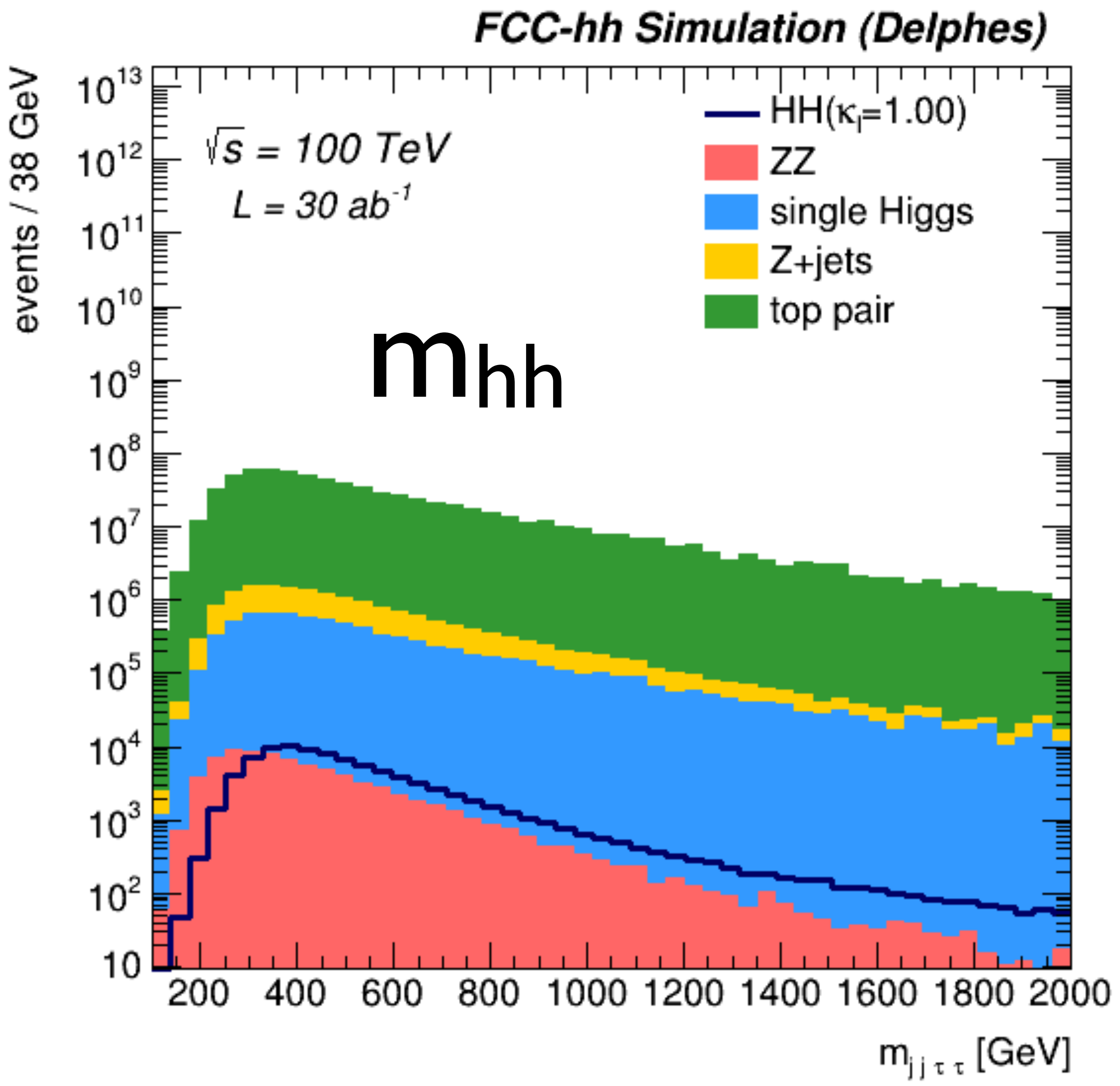
- Simple preselection:
  - **At least two τ-tagged jets** with:
    - $p_T(\tau_{had}) > 45$ GeV, $|\eta(\tau_{had})| < 3.0$
  - **At least two b-tagged jets** with:
    - $p_T(b) > 30$ GeV, $|\eta(b)| < 3.0$
  - **Lepton-veto** ($p_T(l) > 25$ GeV, $|\eta(l)| < 3.0$)





DISCRIMINATING VARIABLES

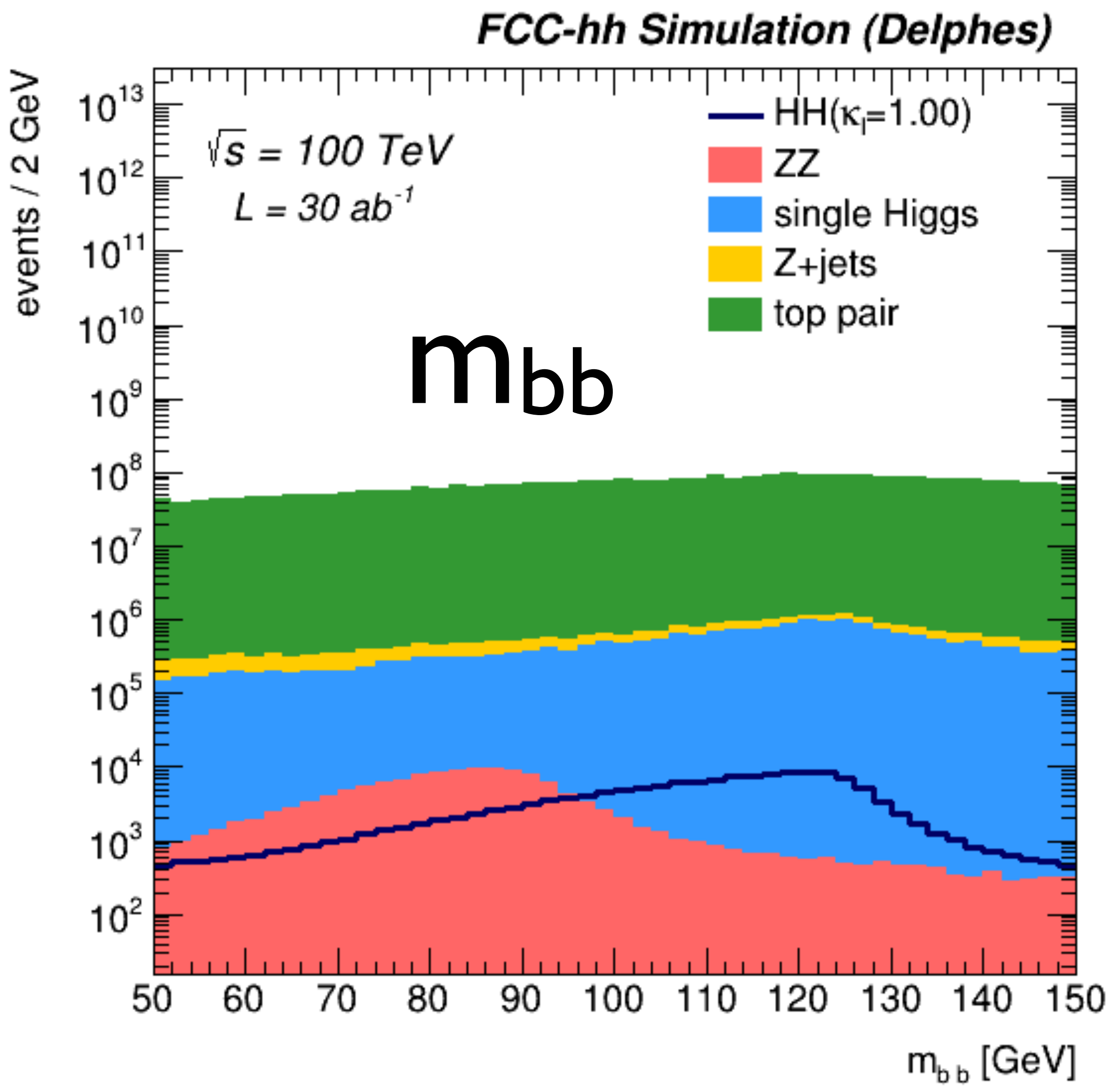


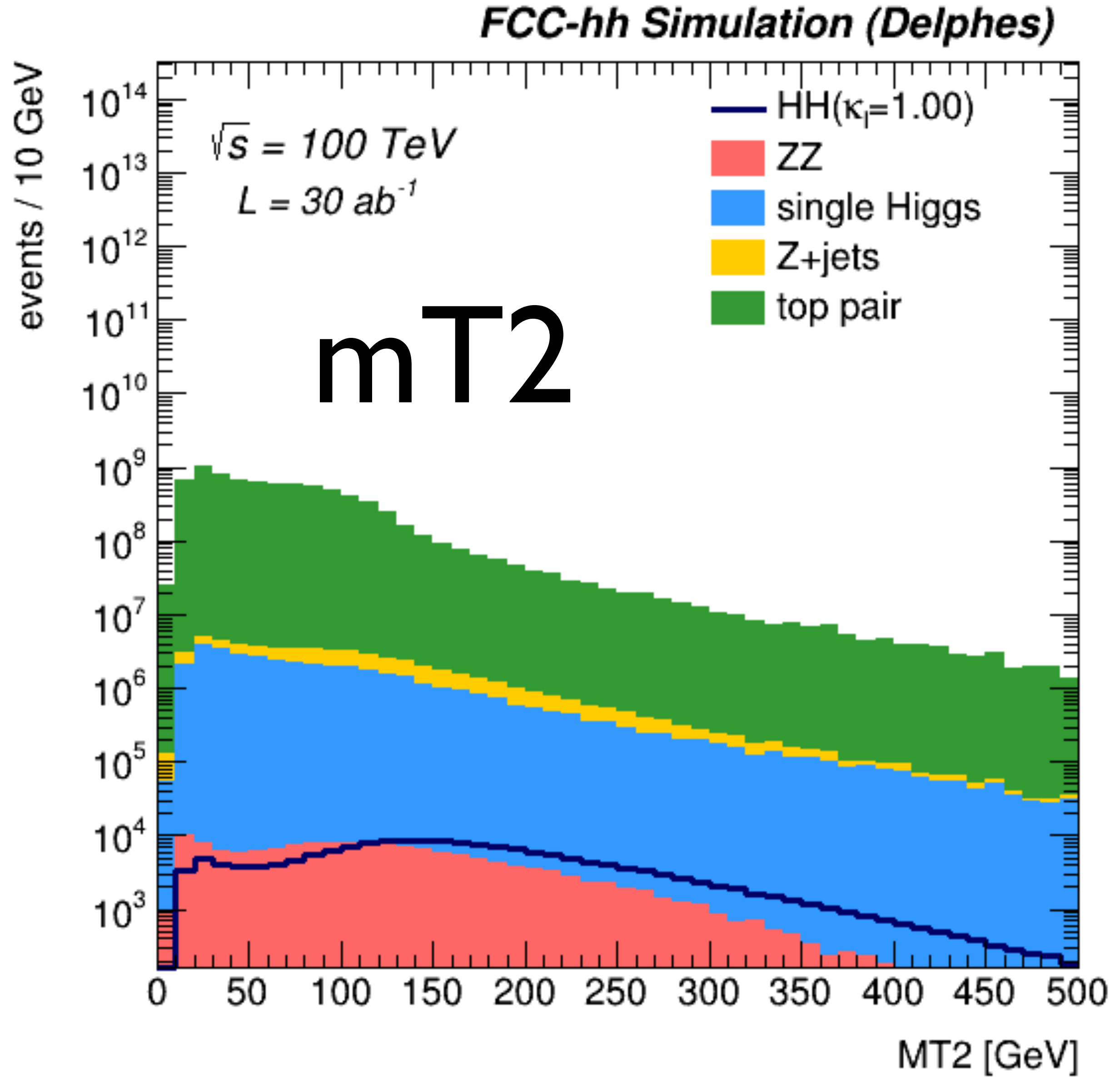


Preselection $\tau_{had}\tau_{lep}$

- Simple preselection:
  - **One hadronic τ-tagged jet** with:
    - $p_T(\tau_{had}) > 45$ GeV, $|\eta(\tau_{had})| < 3.0$
  - **At least two b-tagged jets** with:
    - $p_T(b) > 30$ GeV, $|\eta(b)| < 3.0$
  - **Exactly one lepton**
    - ($p_T(l) > 25$ GeV, $|\eta(l)| < 3.0$)

smaller S/B





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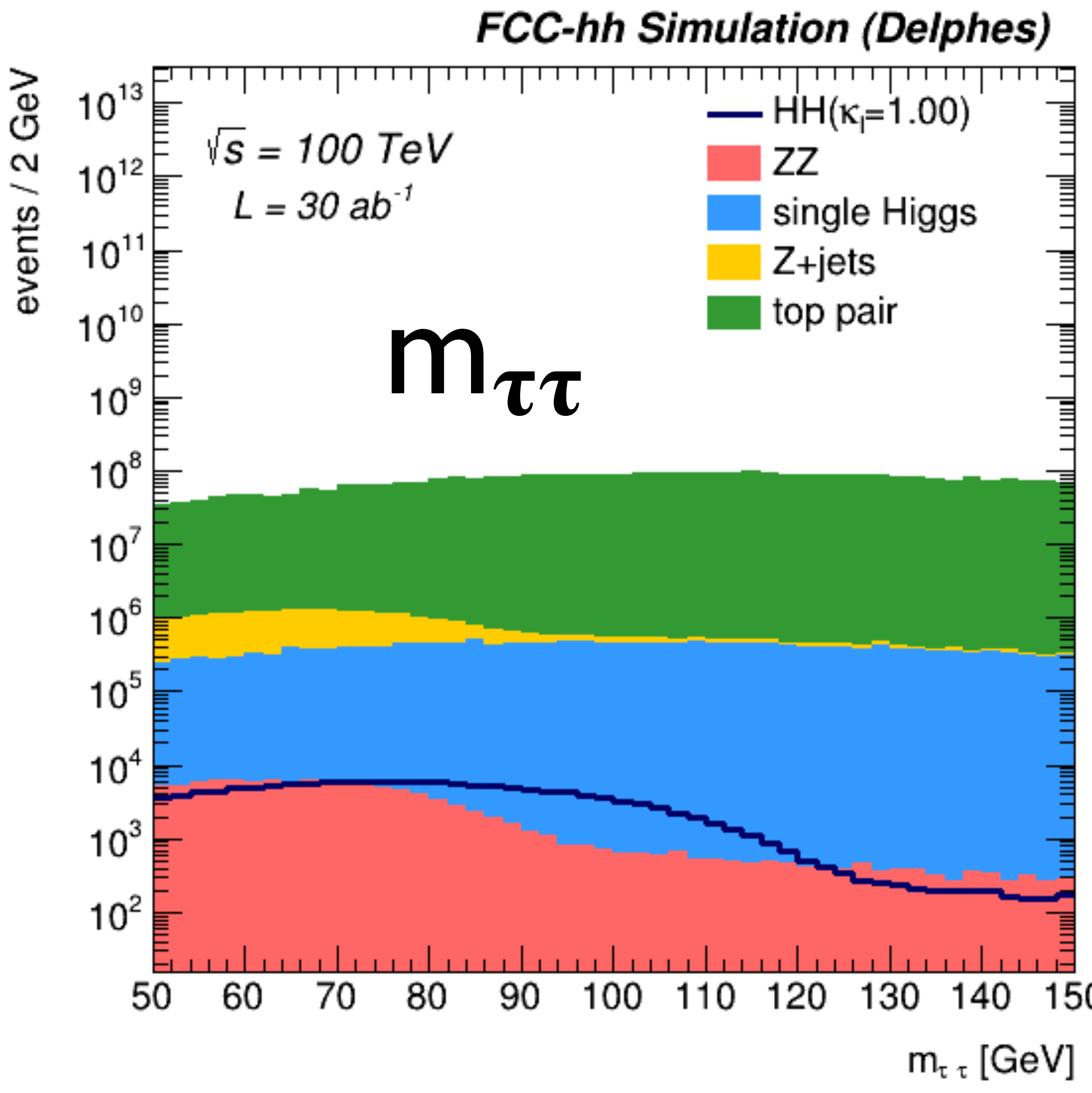
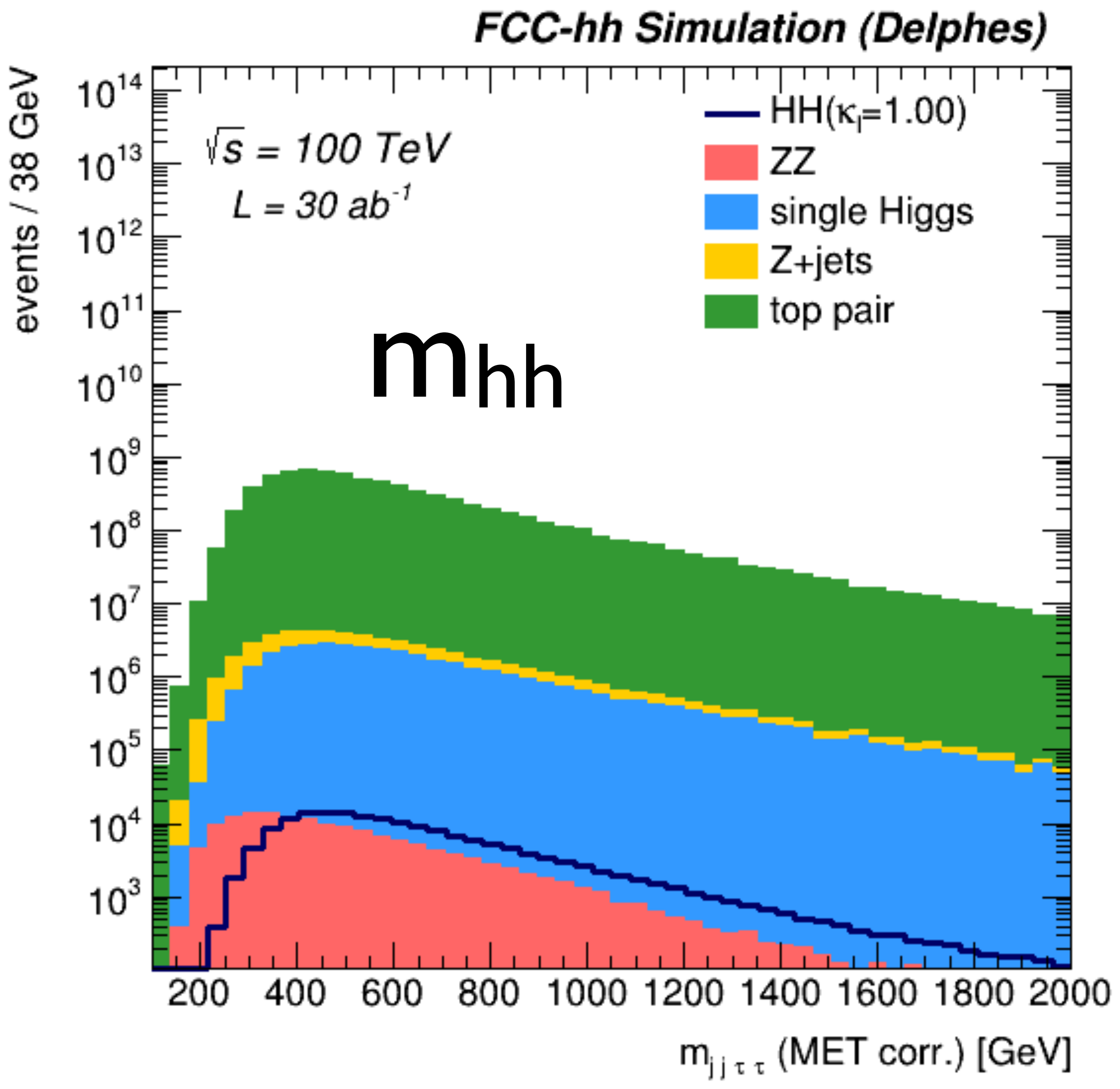


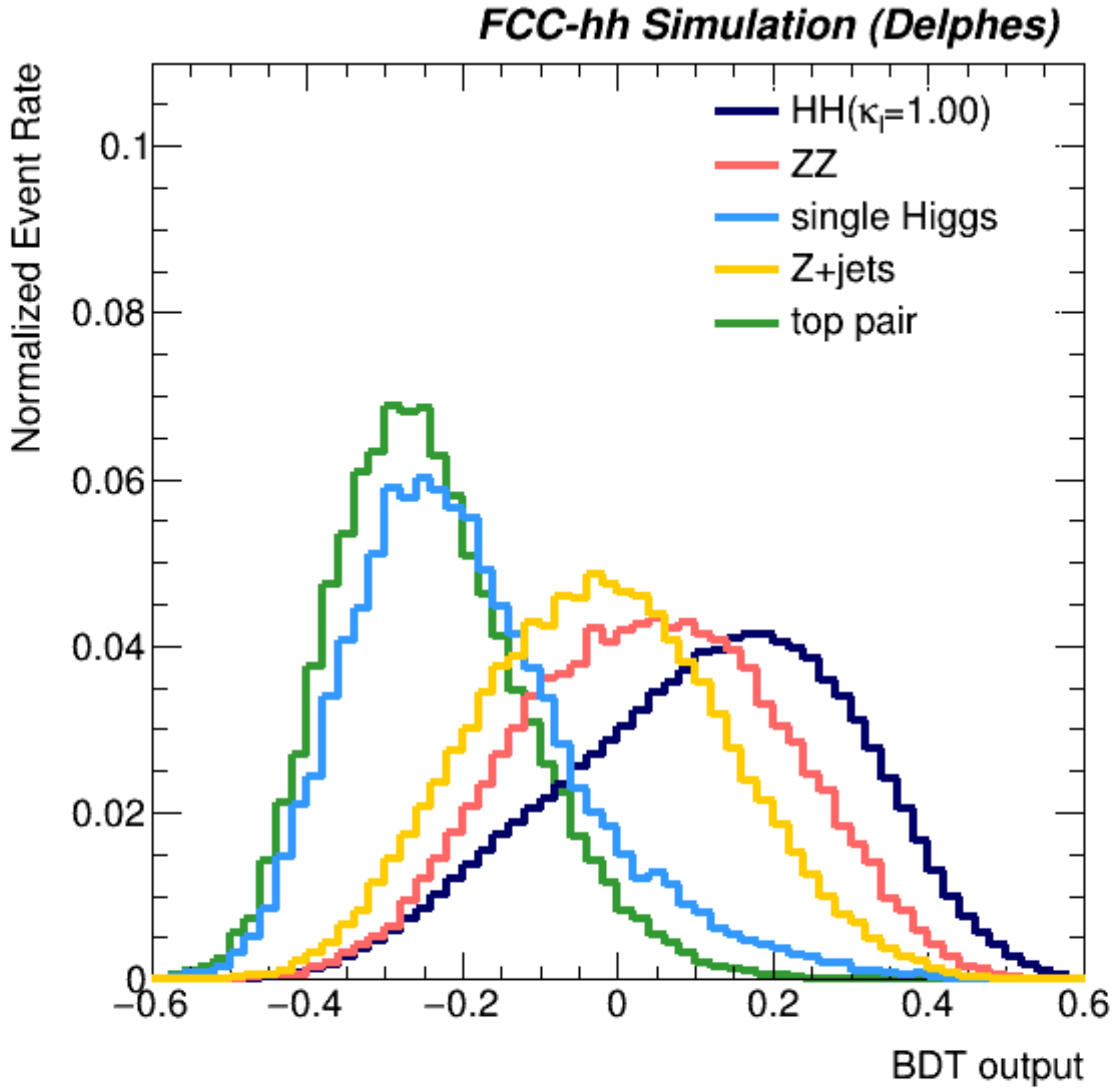


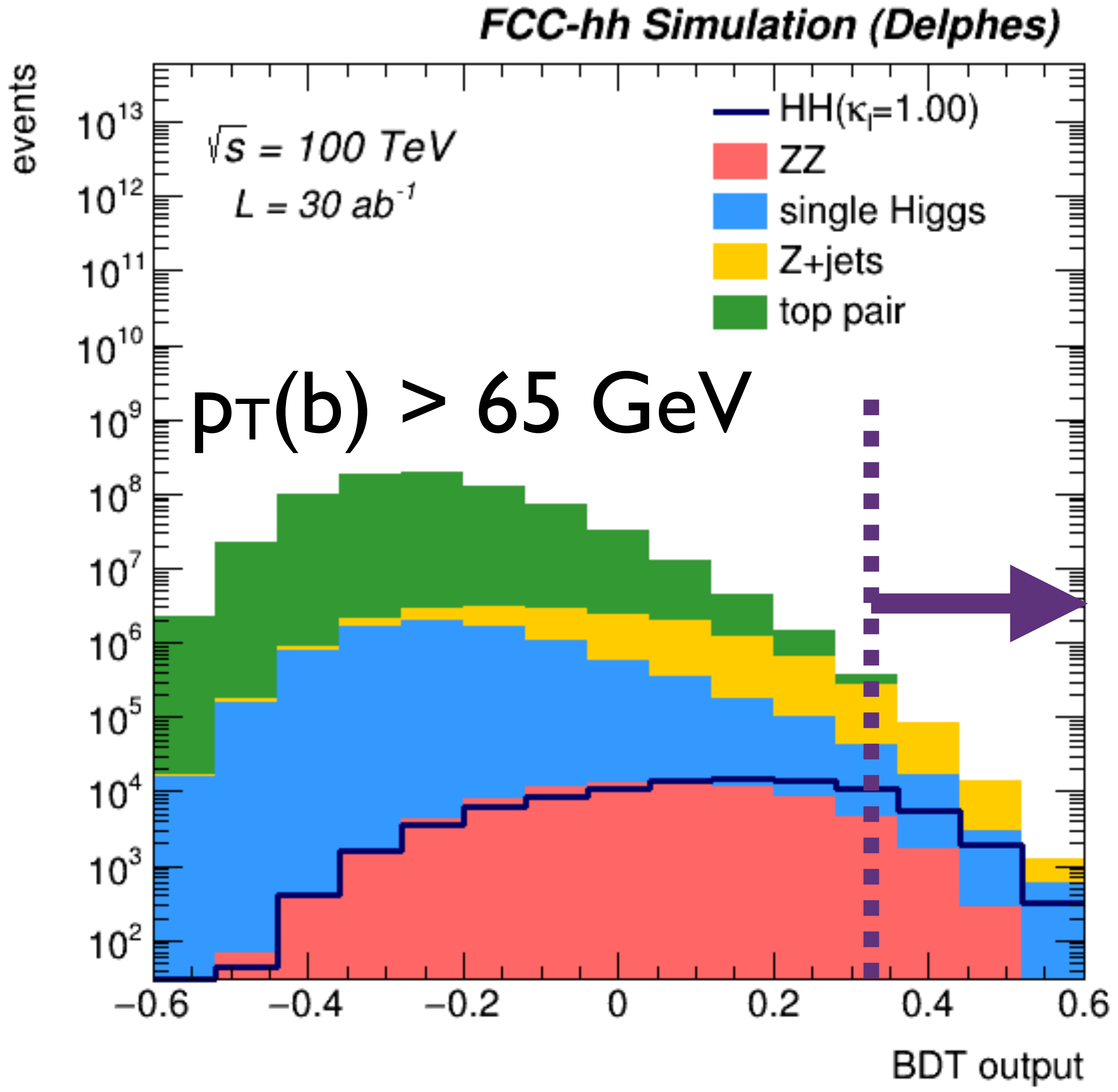
BDT training - $\tau_{had}\tau_{had}$

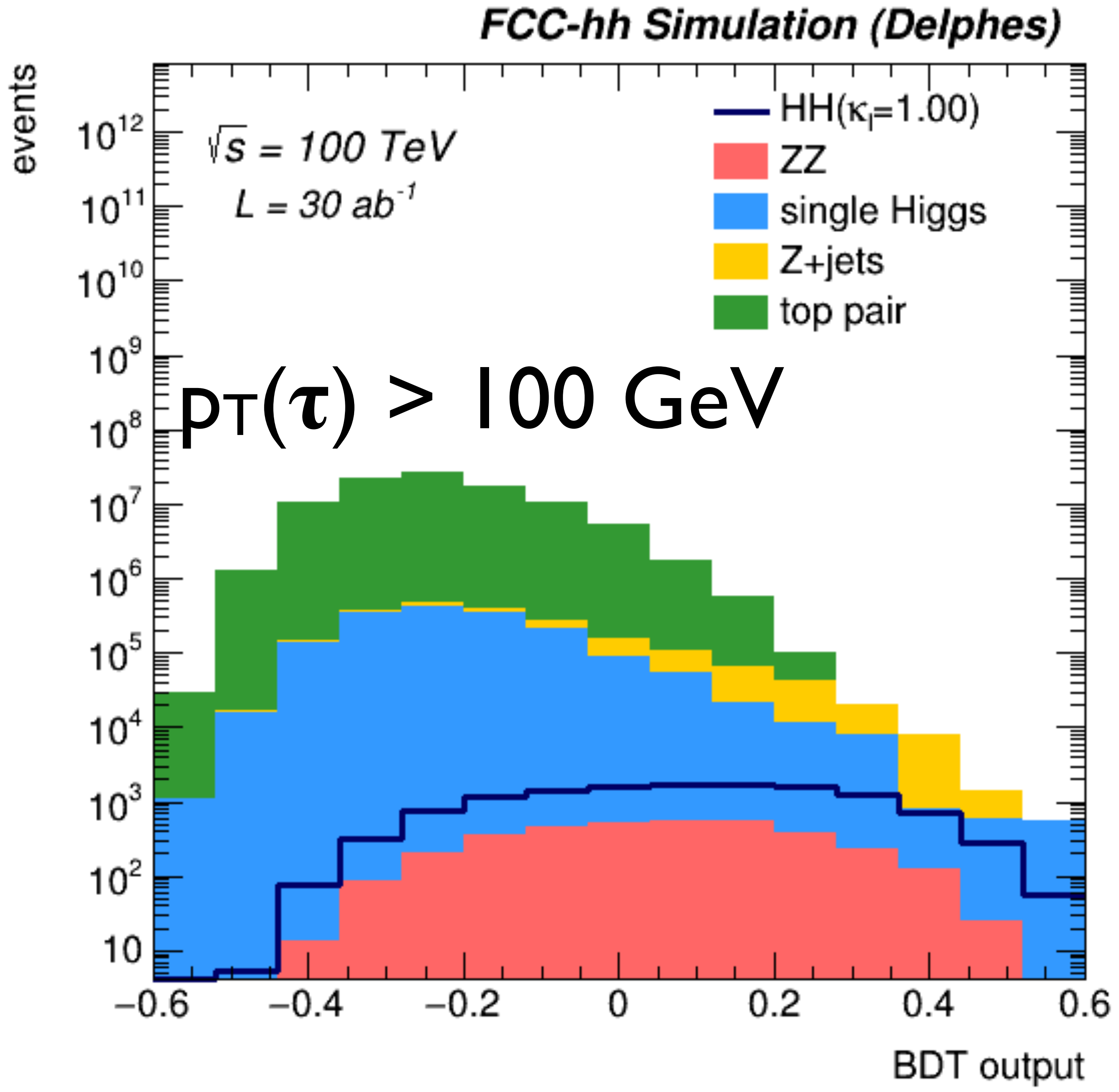
- **BDT** training input:
  - 4-vectors of τ_1, τ_2, b_1, b_2
  - 4-vectors of $H_{\tau\tau}$, H_{bb}, HH
  - E_T miss
  - MT2, $m_T(\tau_1)$, $m_T(\tau_2)$, H_T

TRAINED vs. ttbar

- Final Selection:
  - $100 < m_{bb} < 130$ GeV
  - $80 < m_{\tau\tau} < 130$ GeV
  - **BDT > 0.34**





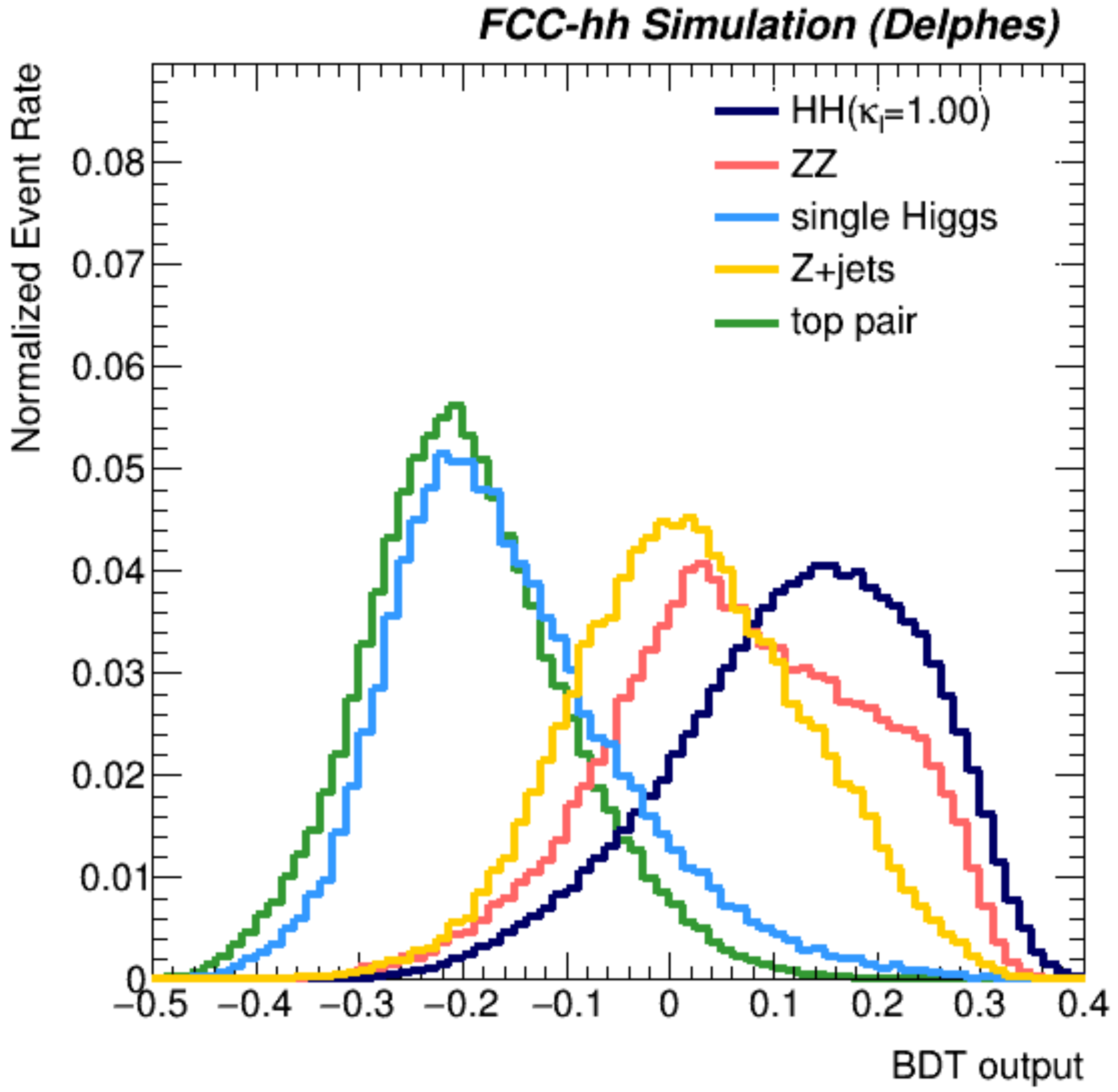


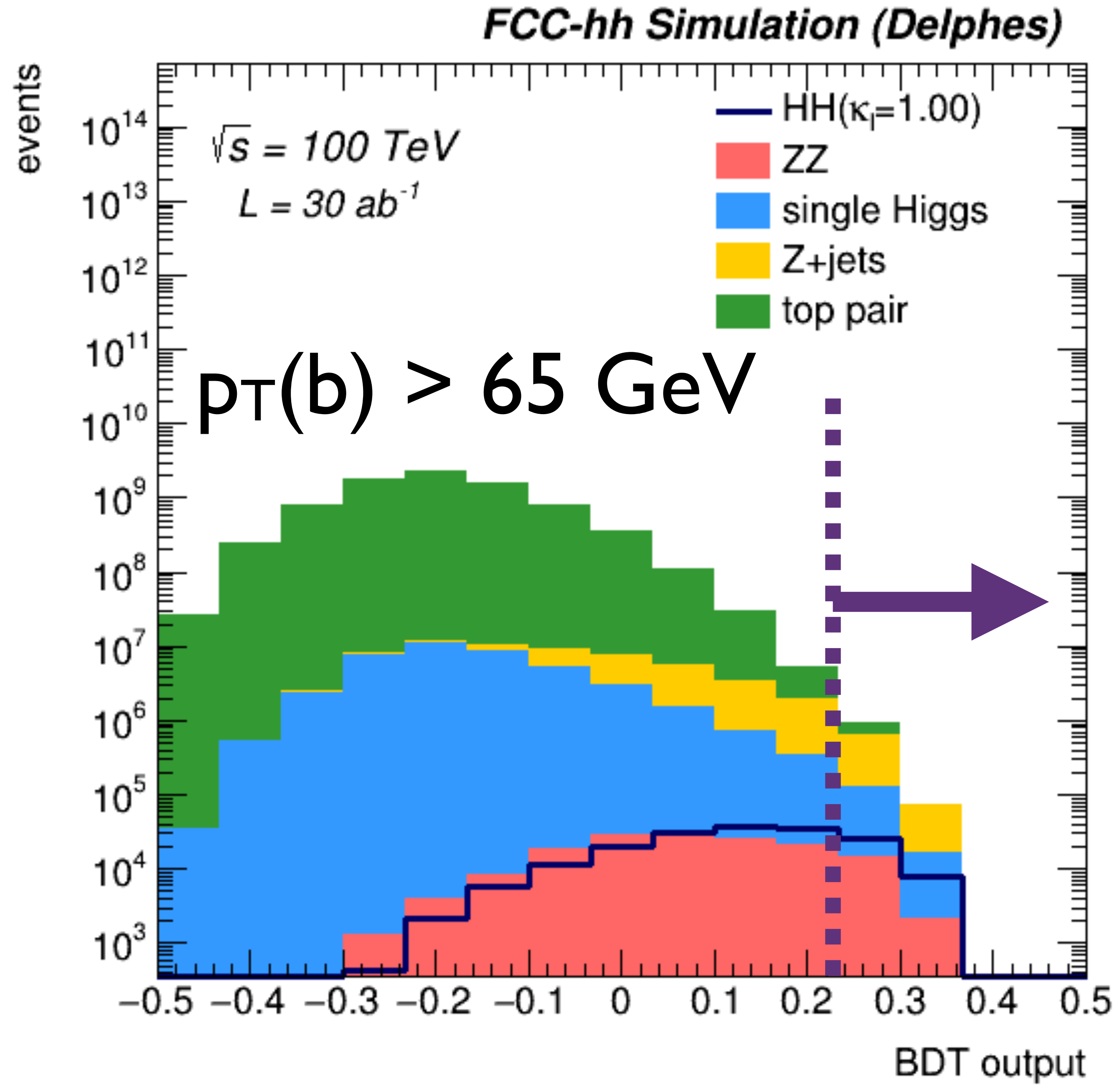
BDT training - $\tau_{had}\tau_{lep}$

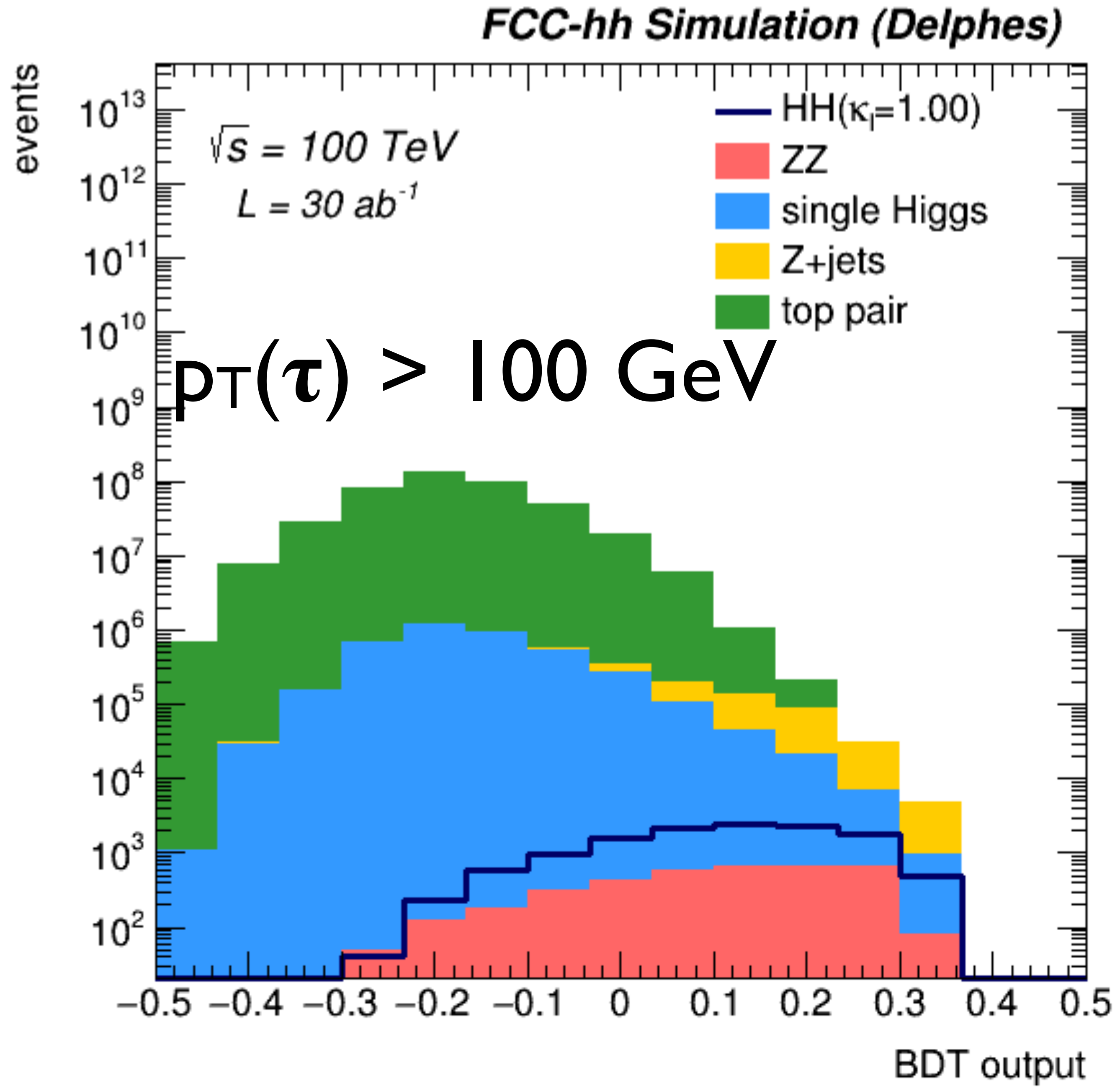
- **BDT** training input:
  - 4-vectors of τ_1, τ_2, b_1, b_2
  - 4-vectors of $H_{\tau\tau}$, H_{bb}, HH
  - E_T miss
  - MT2, $m_T(\tau_1)$, $m_T(\tau_2)$, H_T

TRAINED vs. Top pair

- Final Selection:
  - $100 < m_{bb} < 130$ GeV
  - $80 < m_{\tau\tau}$ (MET corr.) < 130 GeV
  - **BDT > 0.26**





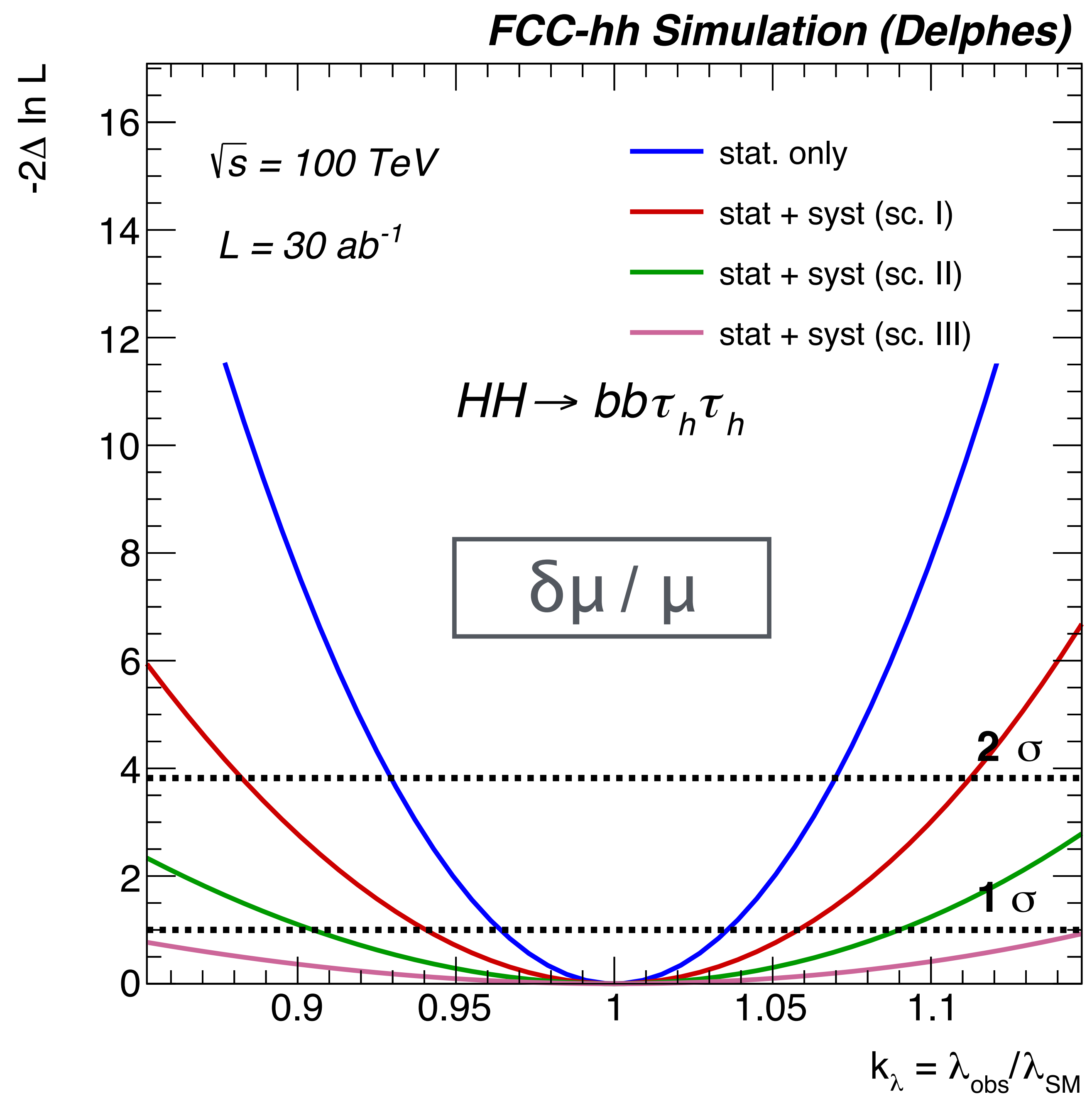


Systematics assumptions

	Very aggressive (I)	Aggressive (II)	Conservative (III)
Tau ID	1 %	2,5 %	5 %
b-jet ID	0,25 %	0,5 %	1 %
ele ID	0,25 %	0,5 %	1 %
mu ID	0,1 %	0,25 %	0,5 %
ttbar norm.	1 %	1 %	1 %
single H norm.	1 %	1 %	1 %
Luminosity	1 %	1 %	1 %

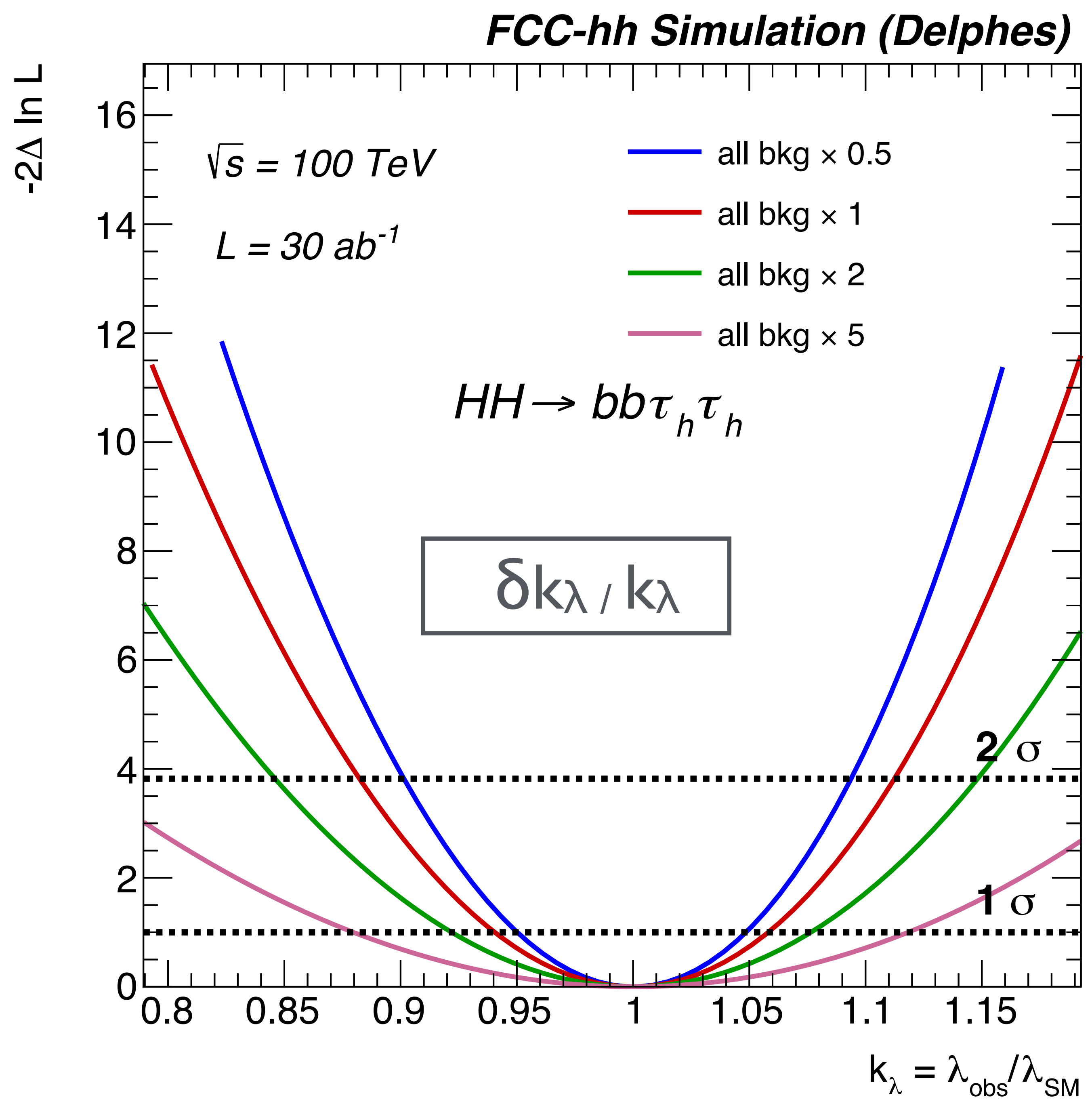
Expected sensitivity: $bb\tau_{had}\tau_{had}$

always assuming SC.III



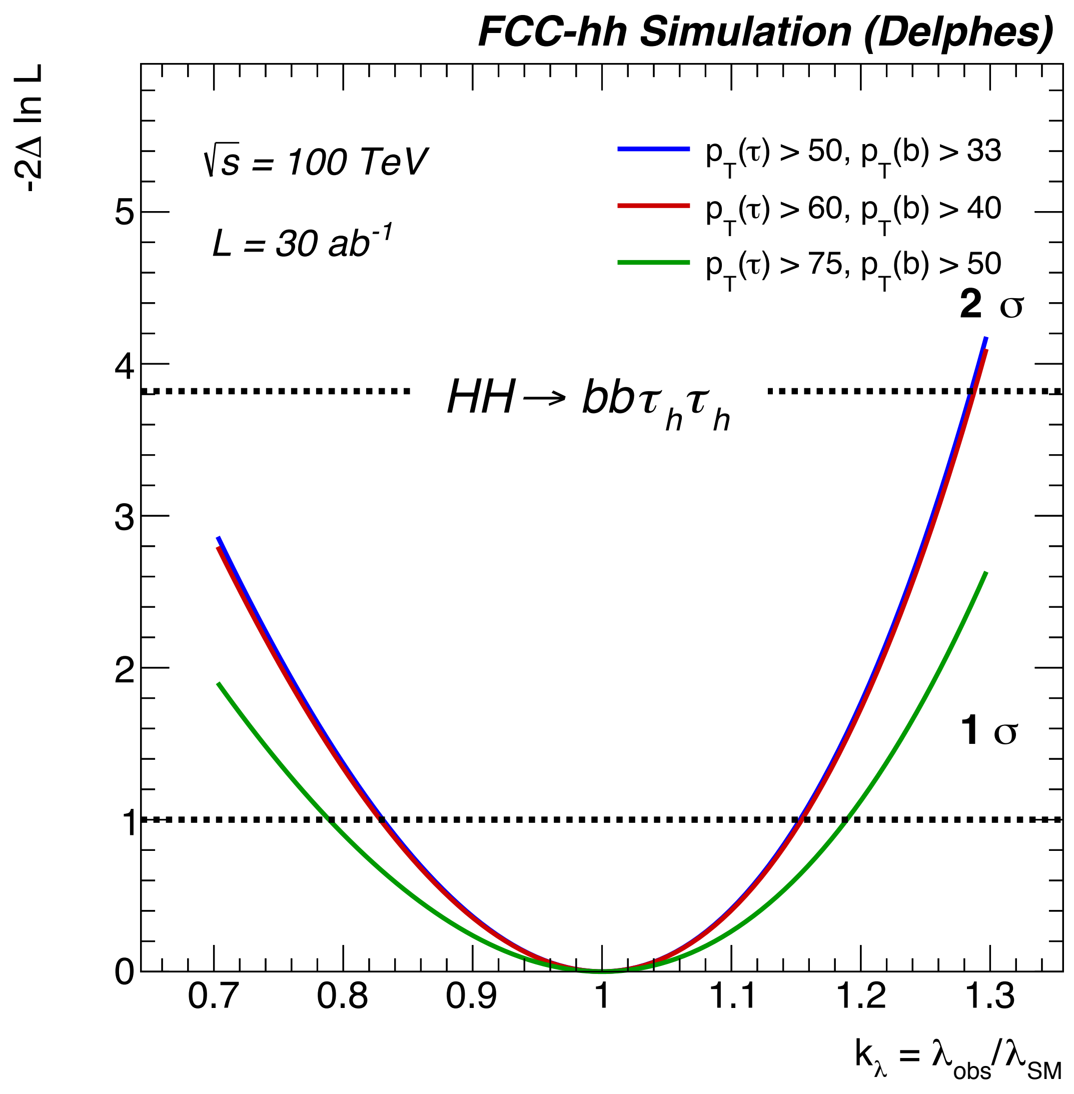
varying uncertainties:

δκλ(stat) ≈ 3 %
δκλ(stat + syst) ≈ 5-10%

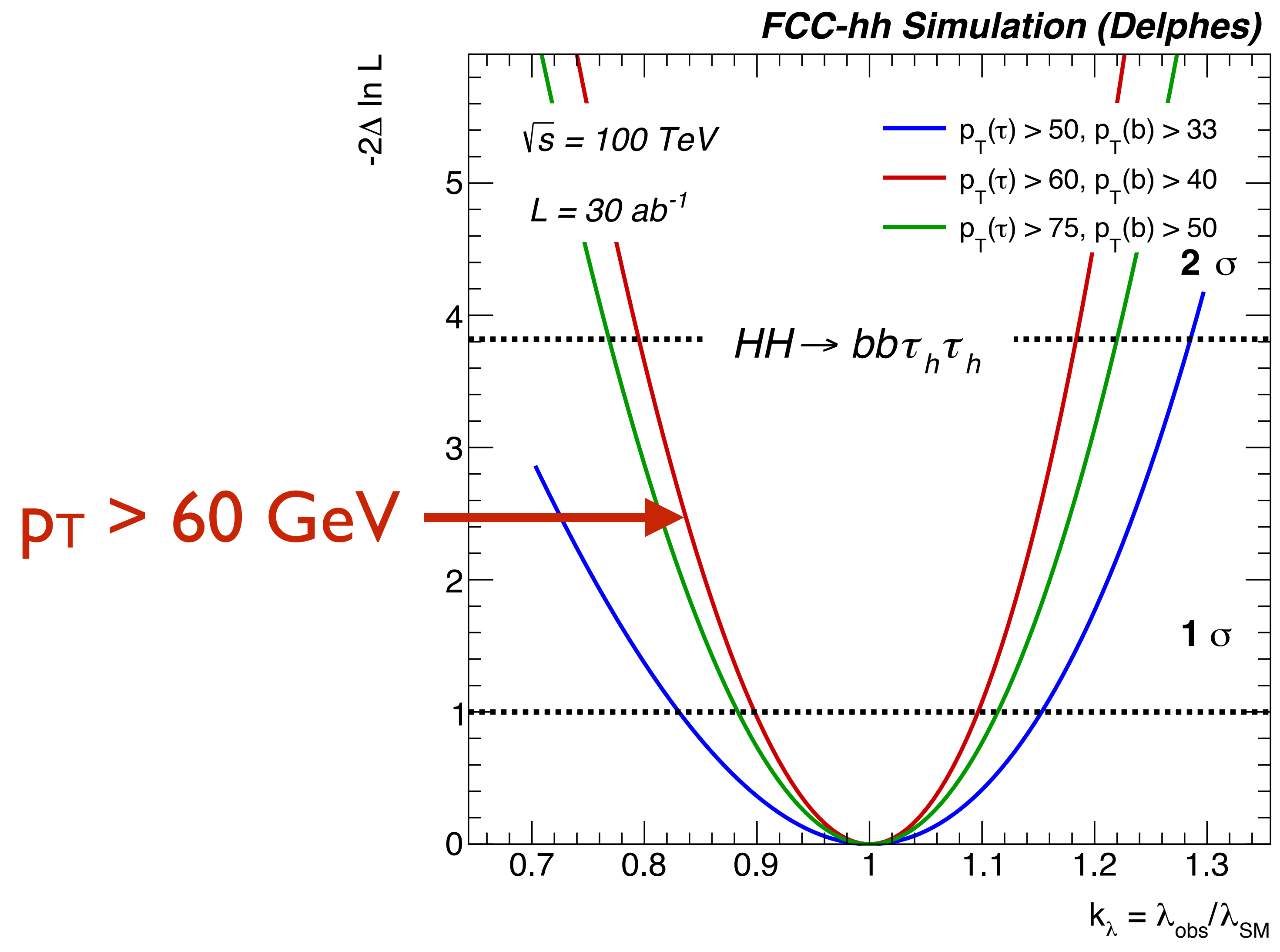


varying (0.5x-5x) background yields:

δκλ ≈ 5-15 %

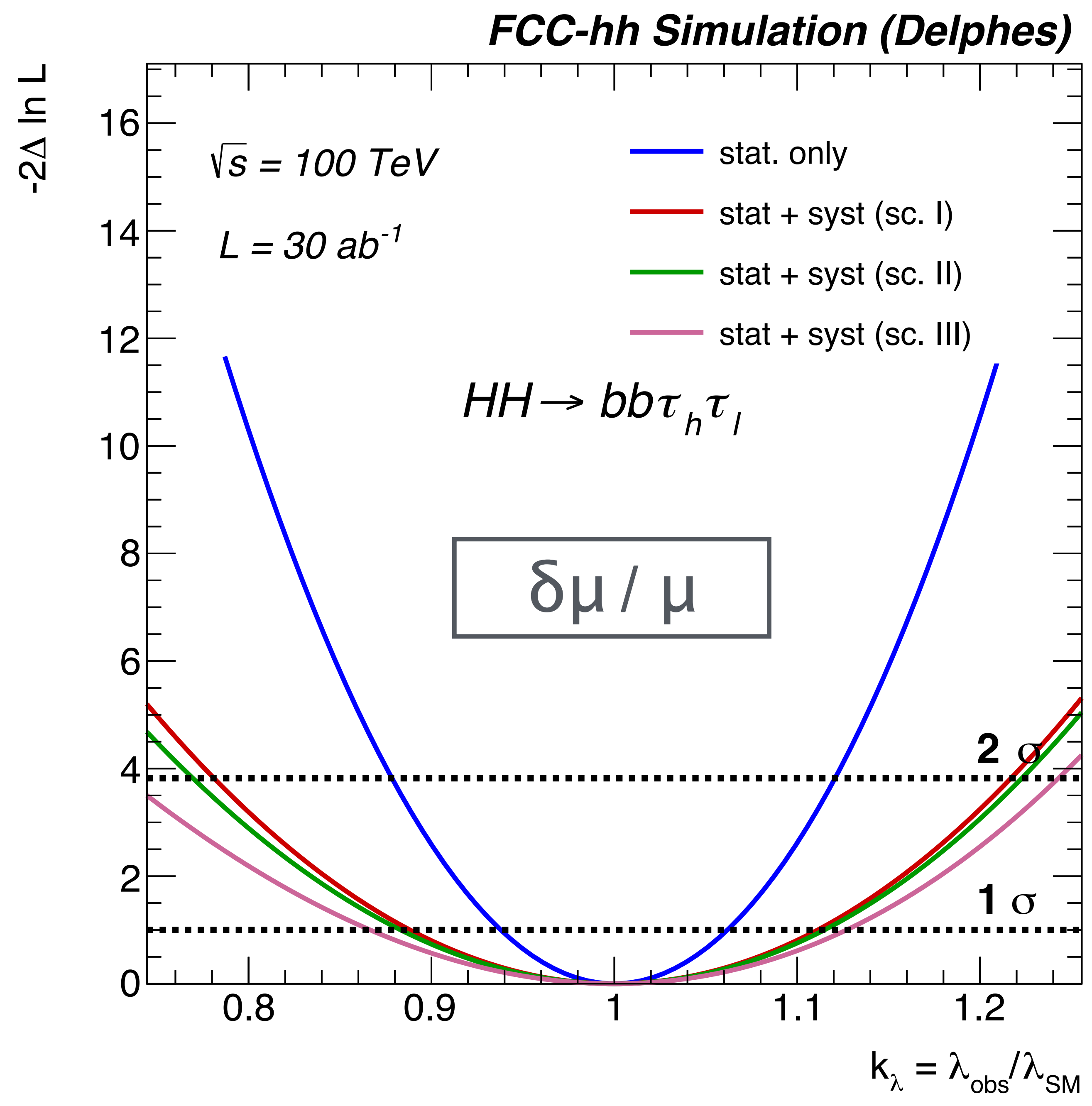


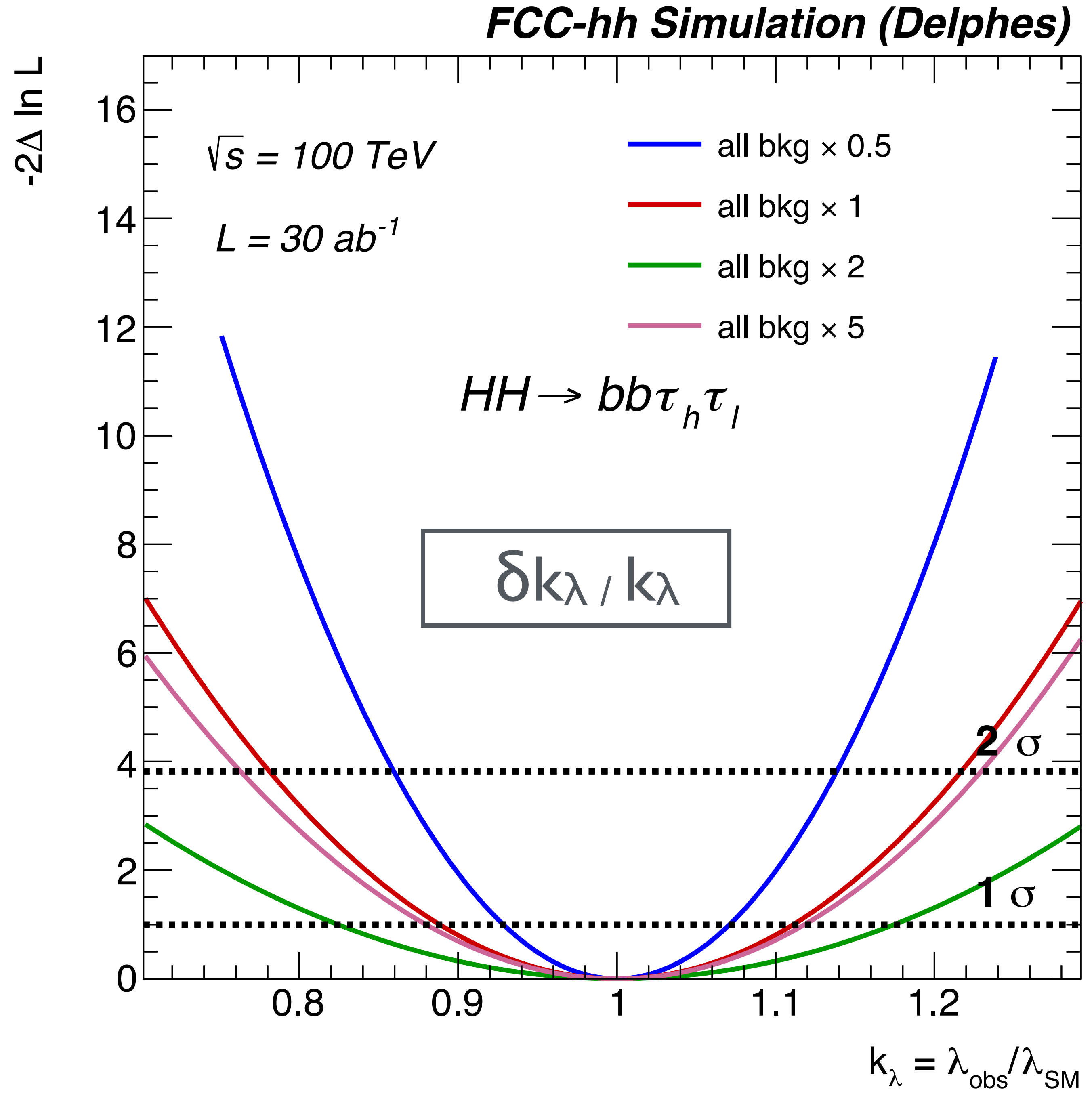
assuming SC.III → SC. I

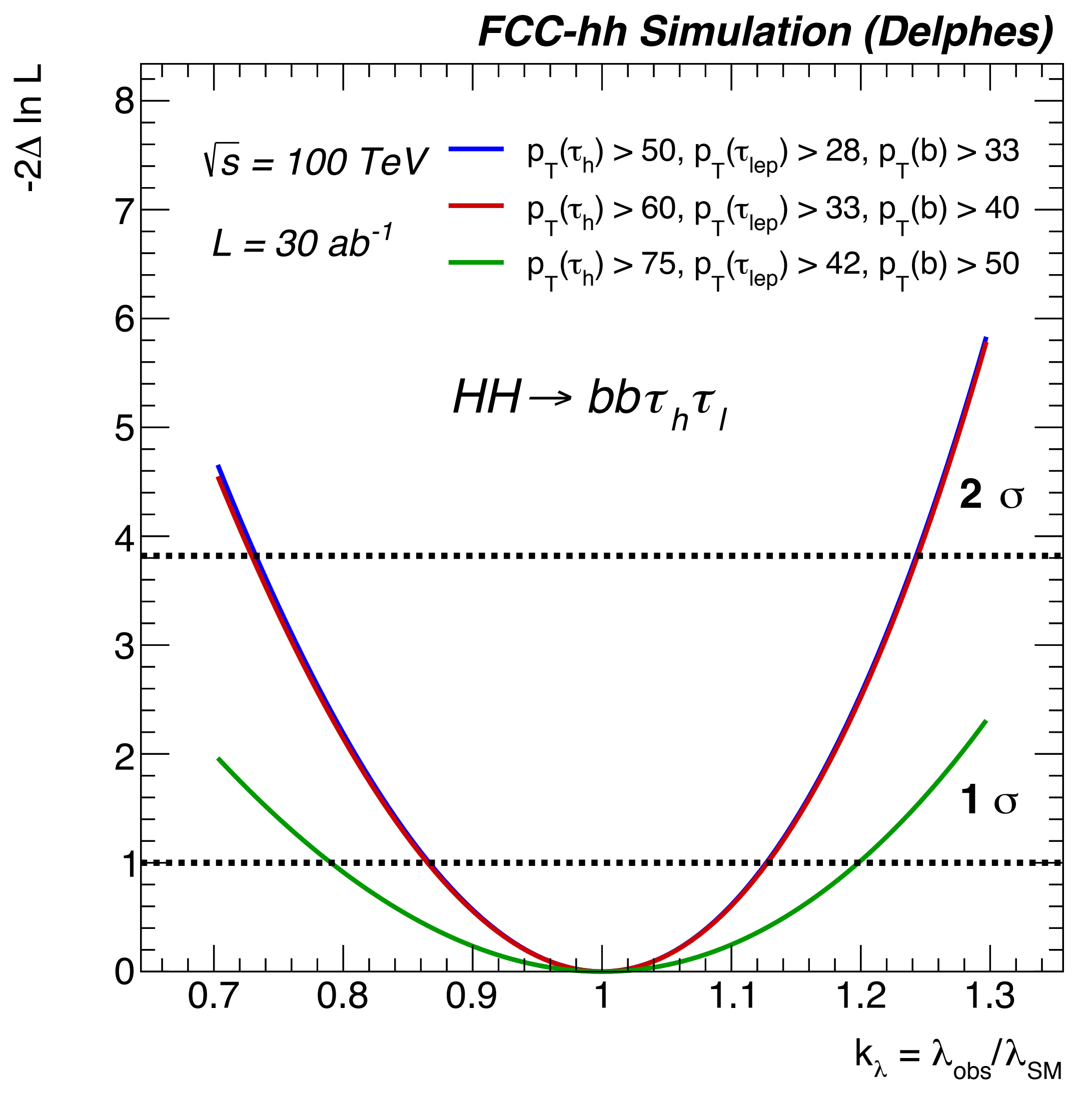


Expected sensitivity: bb$\tau_{had}\tau_{lep}$

always assuming SC.III







varying uncertainties:

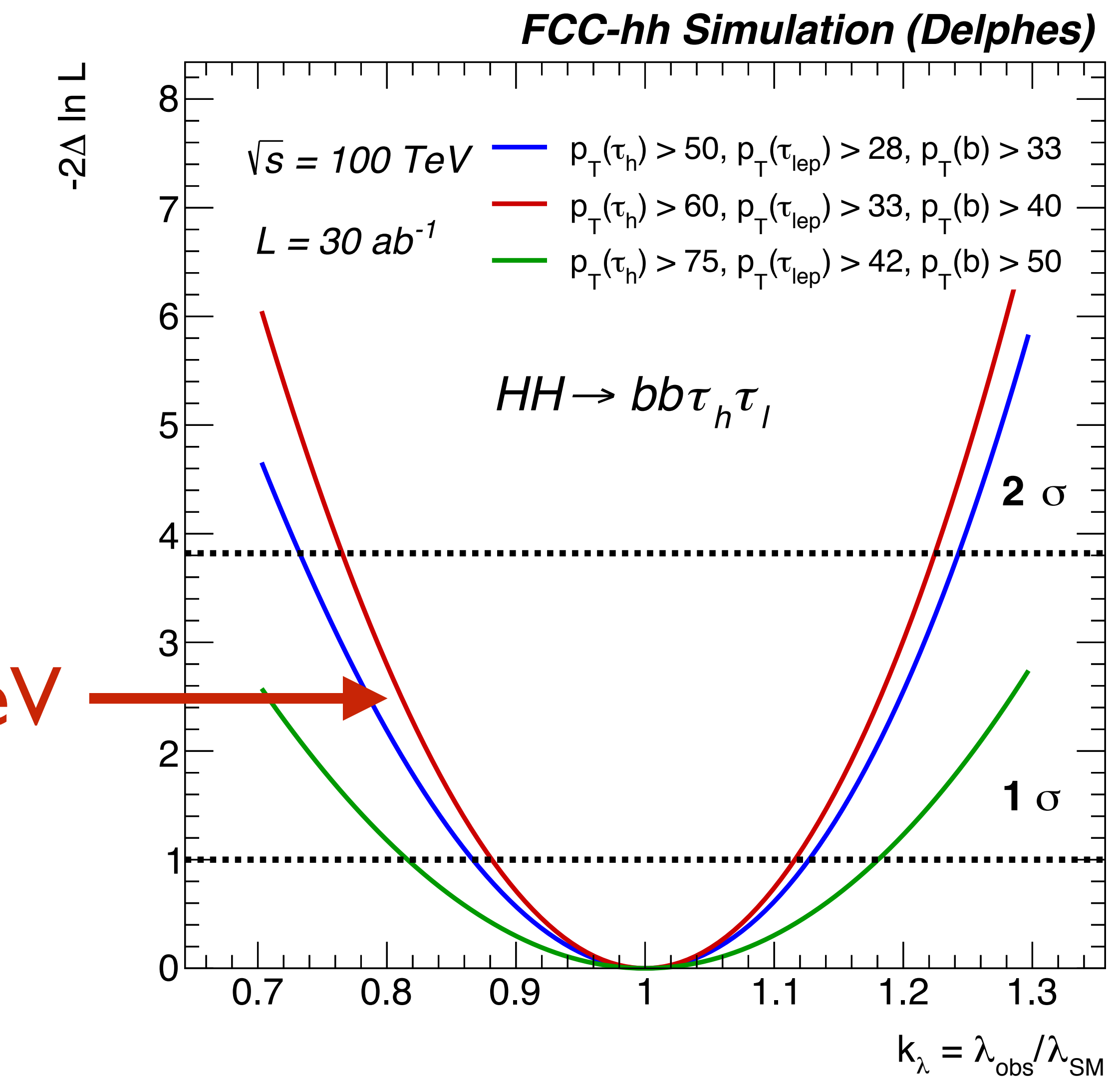
$\delta\kappa_\lambda(\text{stat}) \approx 6\ \%$
$\delta\kappa_\lambda(\text{stat + syst}) \approx 10\text{-}12\%$

varying (0.5x-5x) background yields:

$\delta\kappa_\lambda \approx 6\text{-}16\ \%$

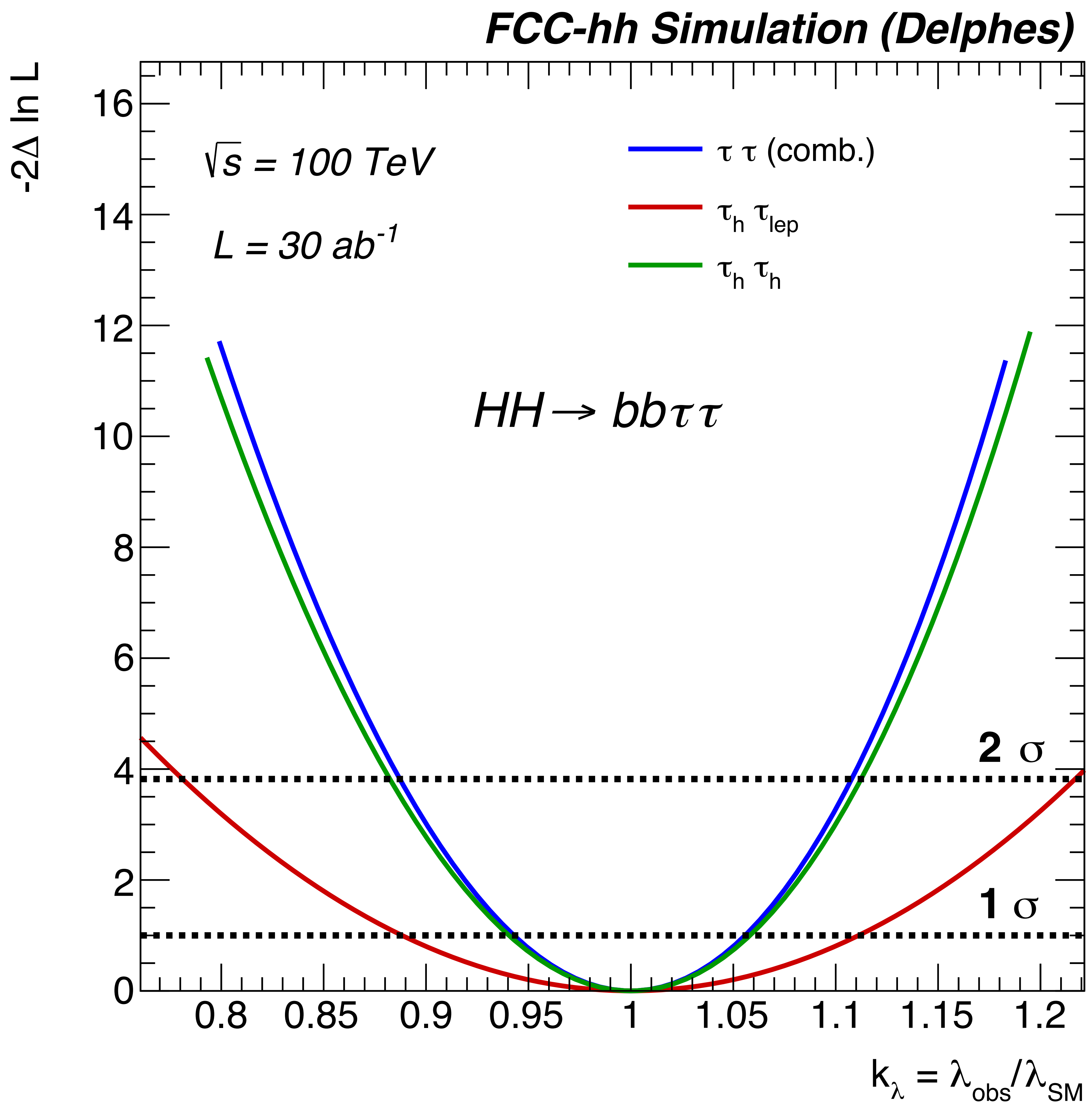
assuming SC.III → SC. I

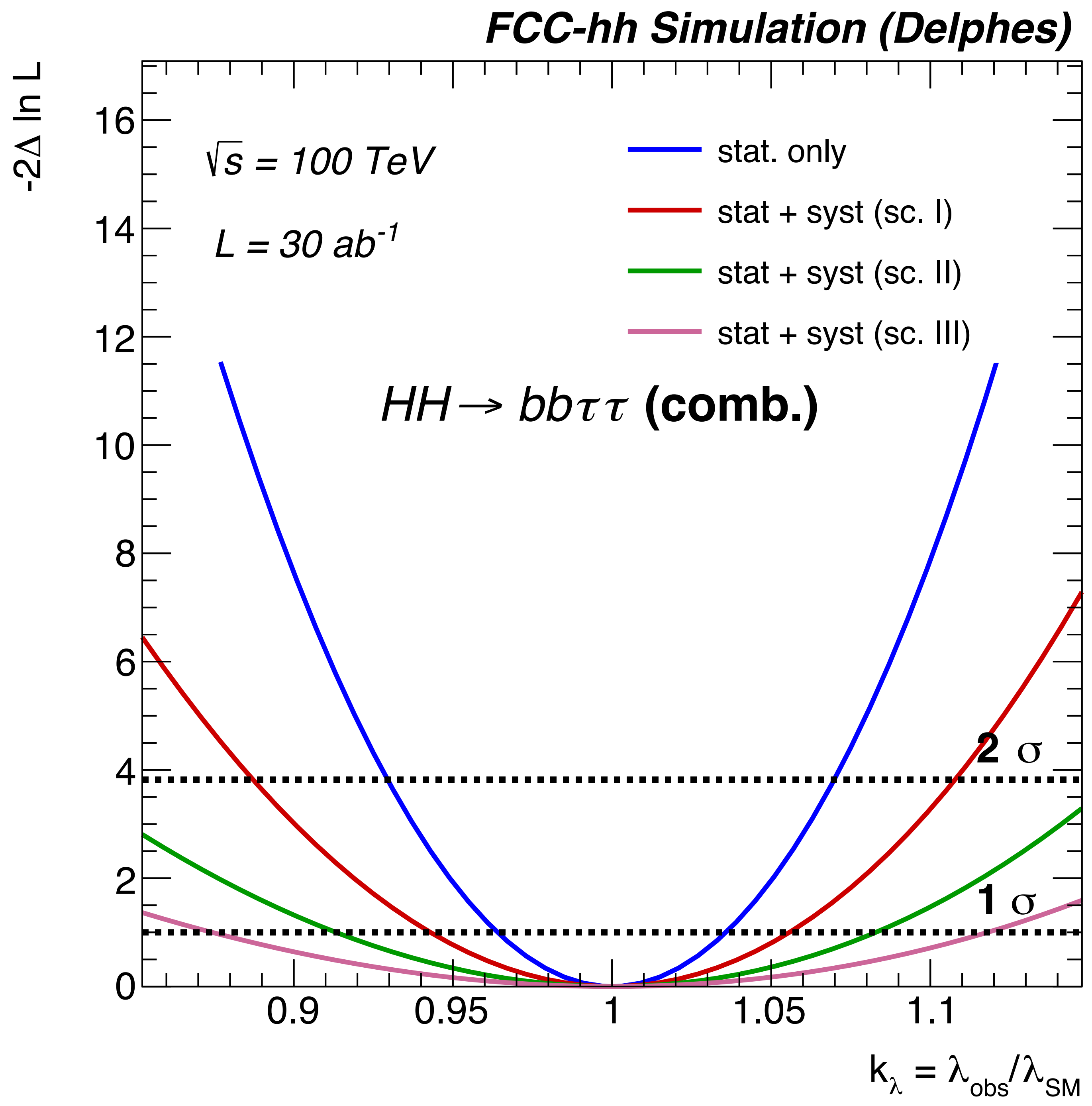
$p_T > 60$ GeV



Combination bb$\tau\tau$

Fully hadronic versus semi-leptonic

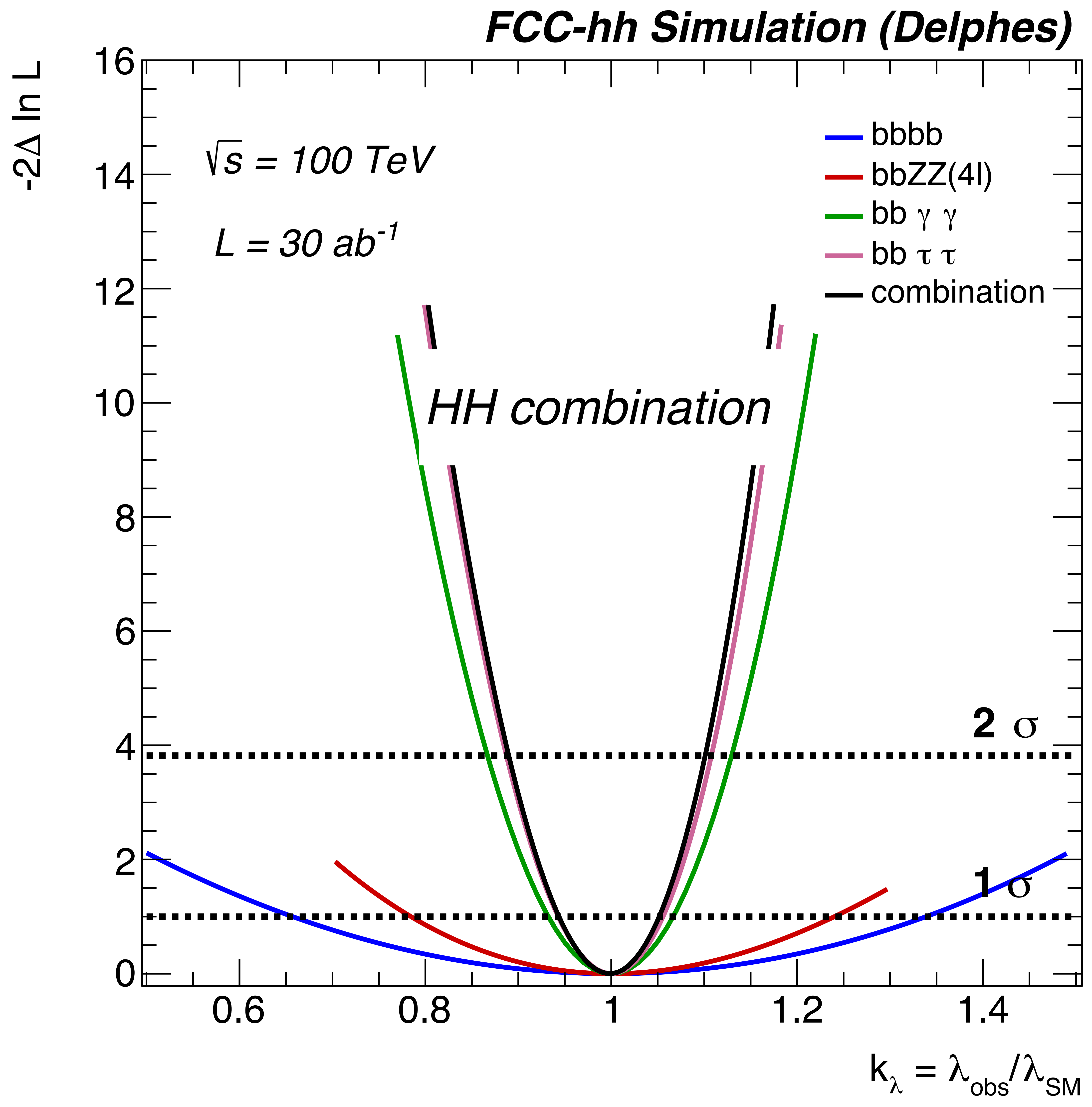




varying uncertainties:

$\delta\kappa_\lambda$(stat) ≈ 4 %
$\delta\kappa_\lambda$(stat + syst) ≈ 5-12 %

Combination of all channels



Most aggressive systematic scenario for bbττ

Conclusions & outlook

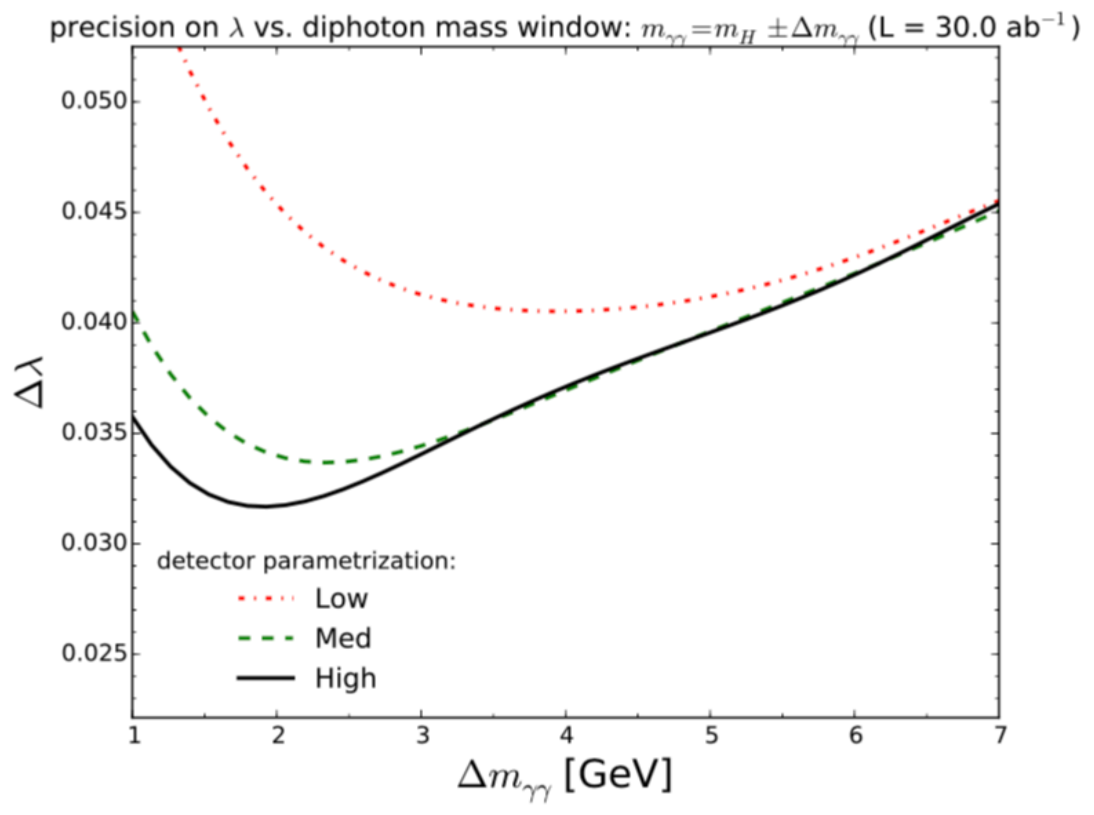
- FCC-ee can measure in single Higgs production:
  - $\delta\kappa_\lambda$(stat) ≈ 35% (21%) with 2 IPs (4IPs)
- FCC-hh can reach $\delta\kappa_\lambda$(stat) ≈ 5% using double Higgs production, via:
  - $bb\gamma\gamma$: $\delta\kappa_\lambda$ ≈ **5-7%**
  - $bb\tau\tau$: $\delta\kappa_\lambda$ ≈ **5-10%** (using $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$)
  - bb4l: $\delta\kappa_\lambda$ ≈ **10-20%**
  - bbbb: $\delta\kappa_\lambda$ ≈ **20-30%**
  - bbWW: $\delta\kappa_\lambda$ ≈ **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%

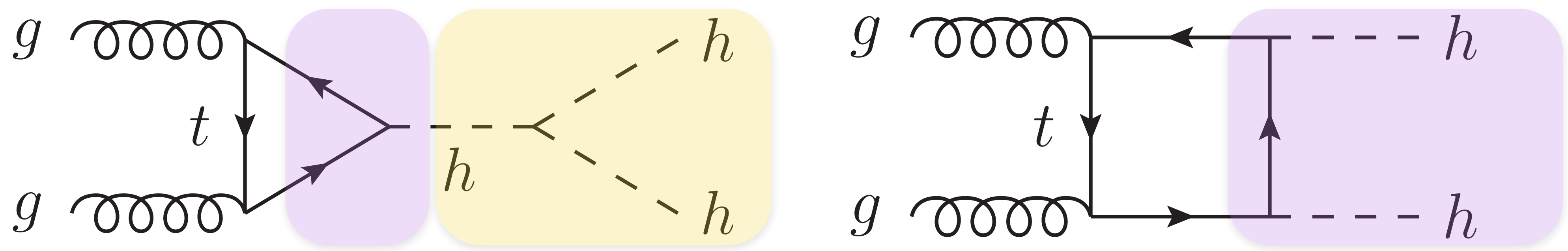
UPDATES:

- 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**)

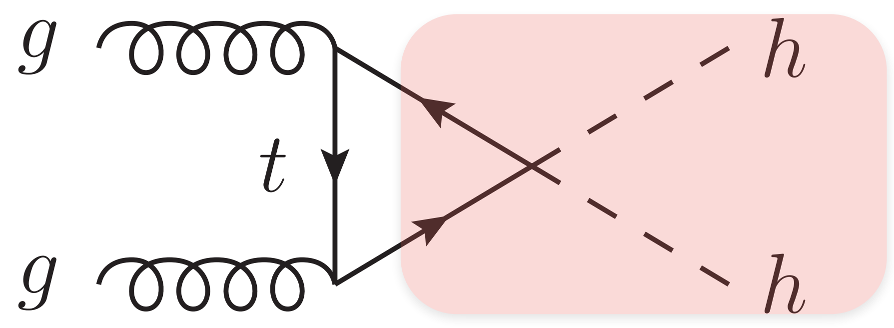
The relevant lagrangian terms of gg→HH production in D=6 EFT

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

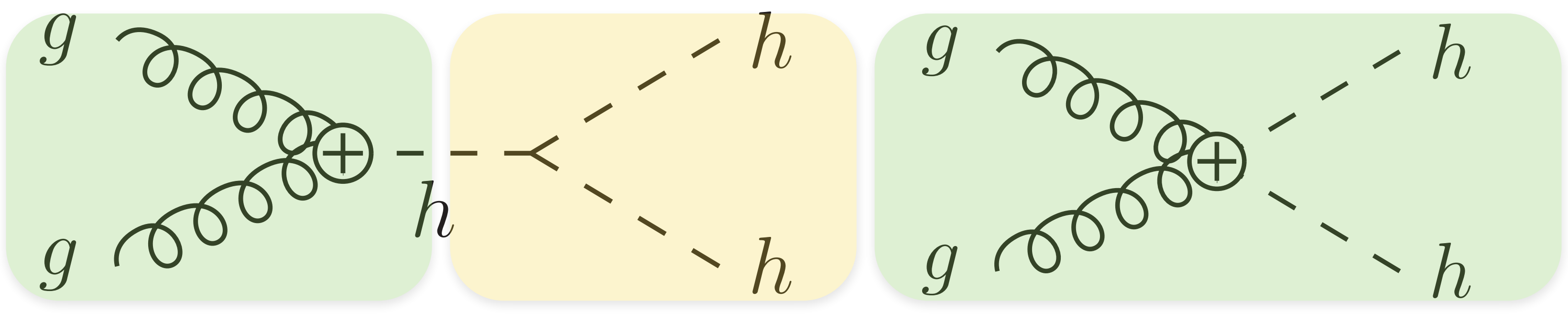
arXiv:1410.3471



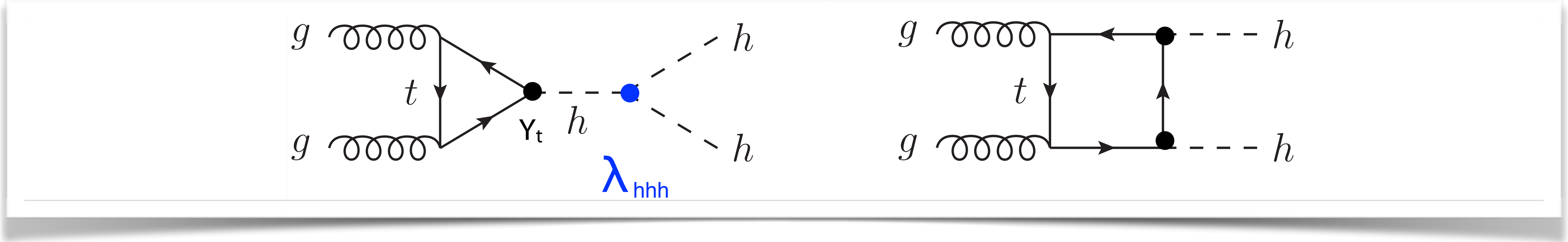
SM diagrams



ttHH non-linear interaction



Higgs-gluon contact interactions

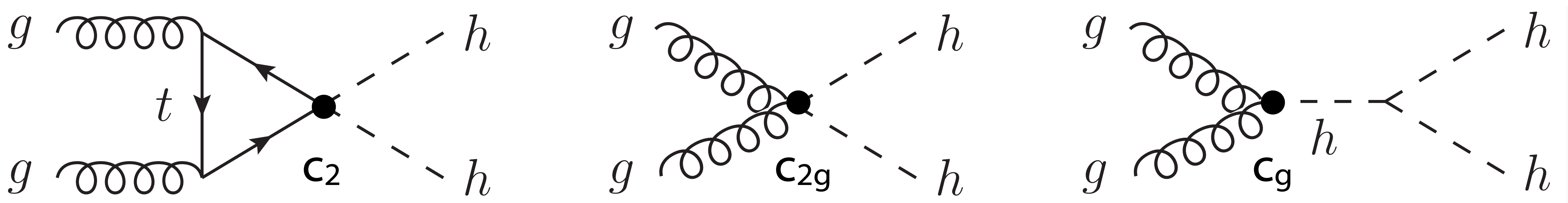


$\sigma^{SM}_{hh}(13TeV) = 33.45fb^{+4.3\%}_{-6.0\%}$(scale unc.) ±3.1%(PDF+$\alpha_S$ unc)[1]

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}

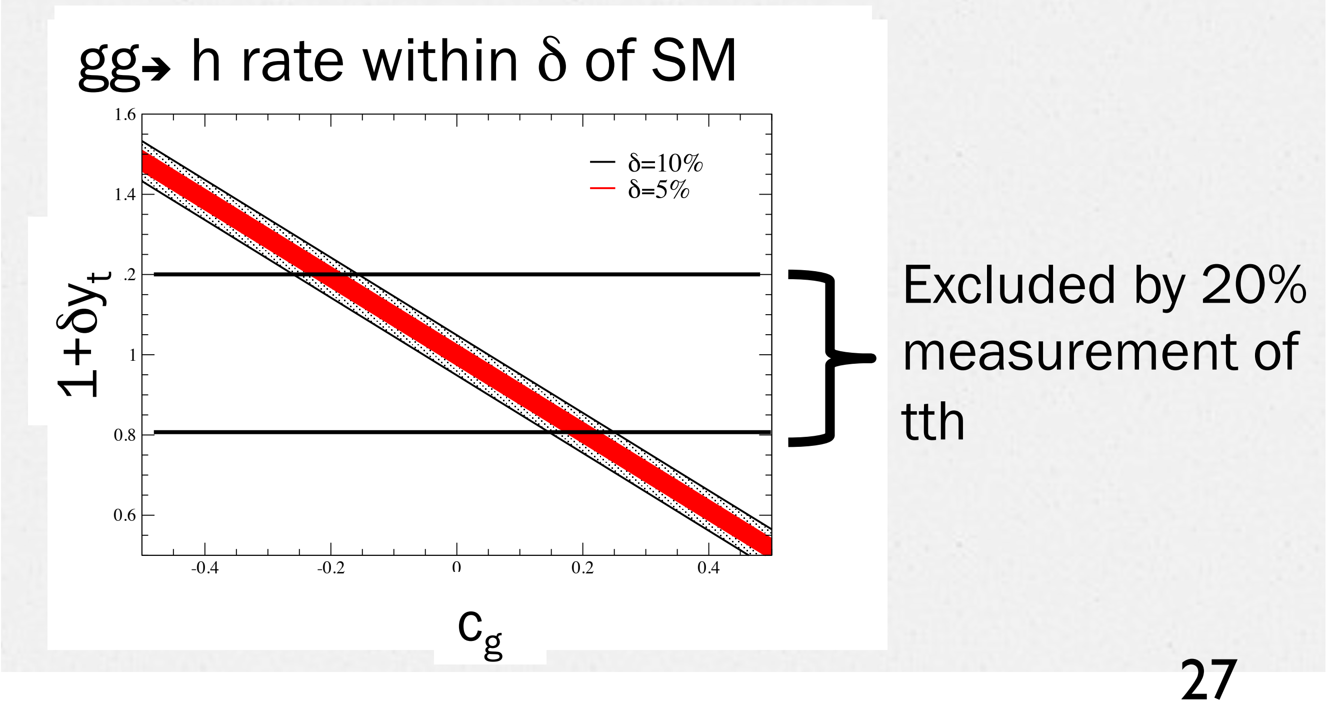
→ The BSM physics can be modelled in EFT adding dim-6 operators[2] to the SM Lagrangian, and the physics can be described with 5 parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

- 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