HH at colliders

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Snowmass21 EF02

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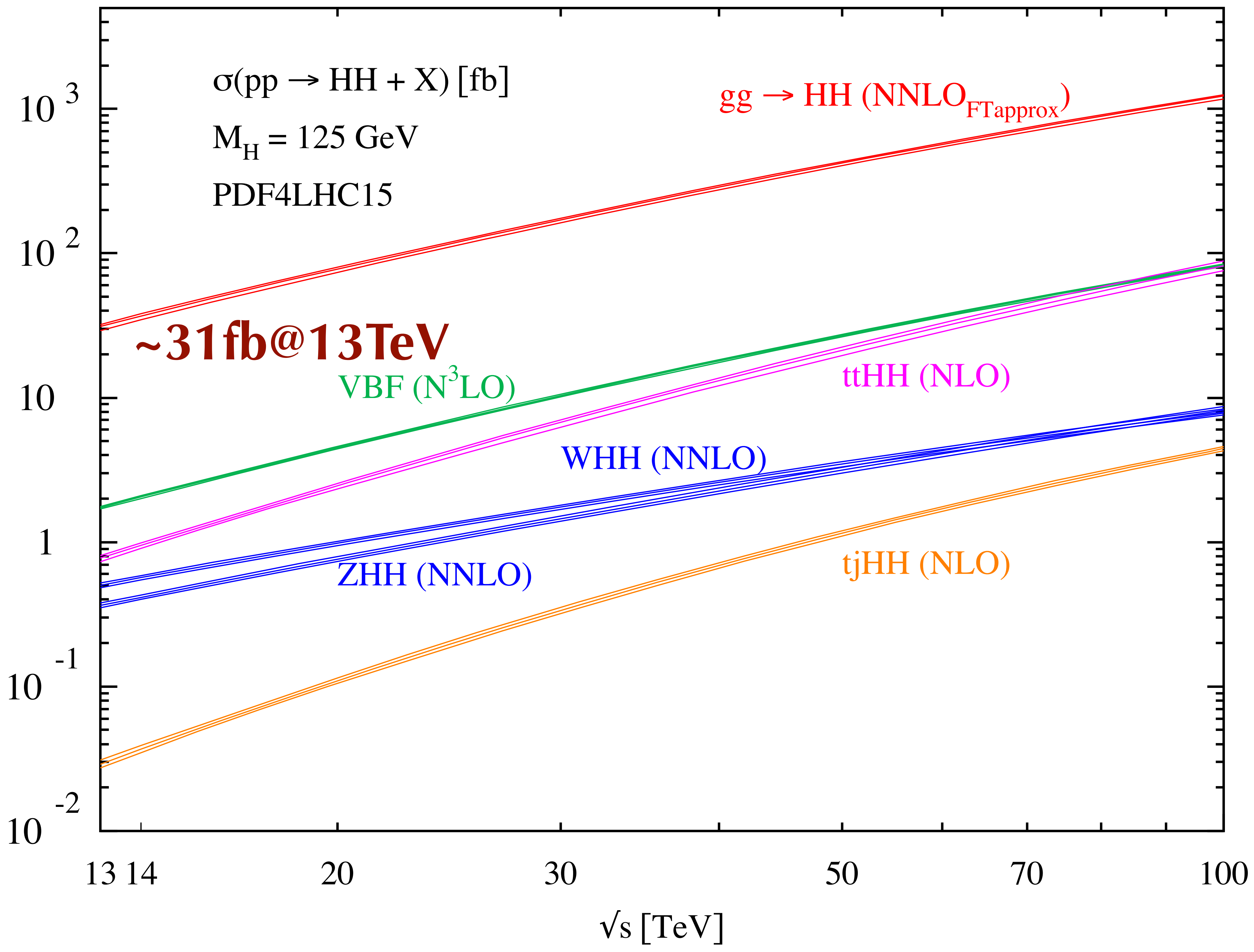
Caveat : we already have discussed the interplay/complementarity between single H and HH searches to probe the Higgs boson self-coupling (see EF01 meetings) at e+e- and pp machines.

Today I'm going to focus on HH and what a unique signature is to probe new physics.

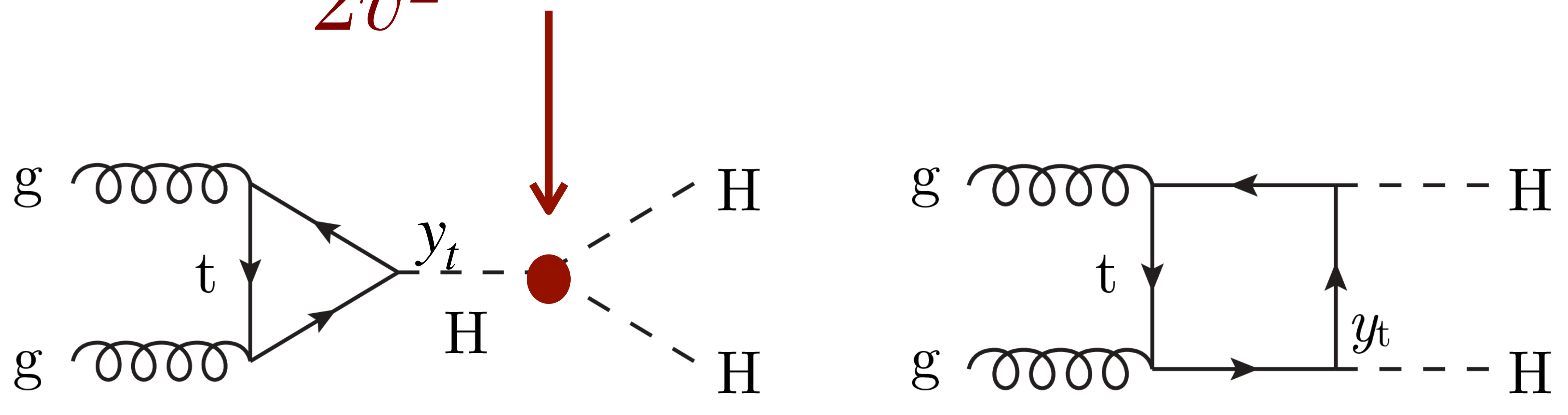
HH at pp colliders

arXiv:1910.00012



~31fb@13TeV

$$\lambda = \frac{m_{\mathrm{H}}^2}{2v^2} = 0.13$$



HH production allows to probe the self-coupling: $\Delta\sigma/\sigma \sim \Delta\lambda/\lambda$ **if** $\lambda \sim \lambda_{SM}$

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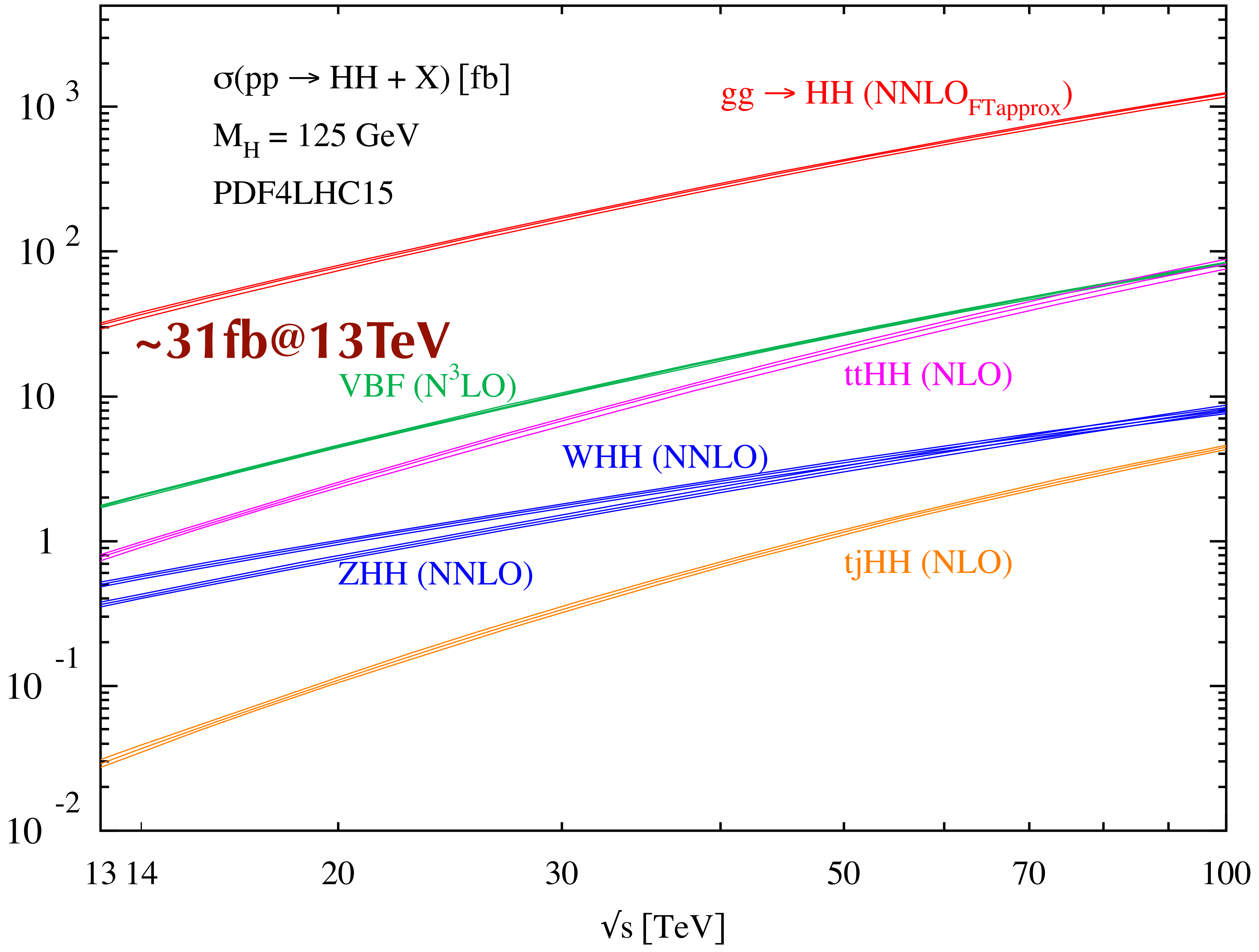

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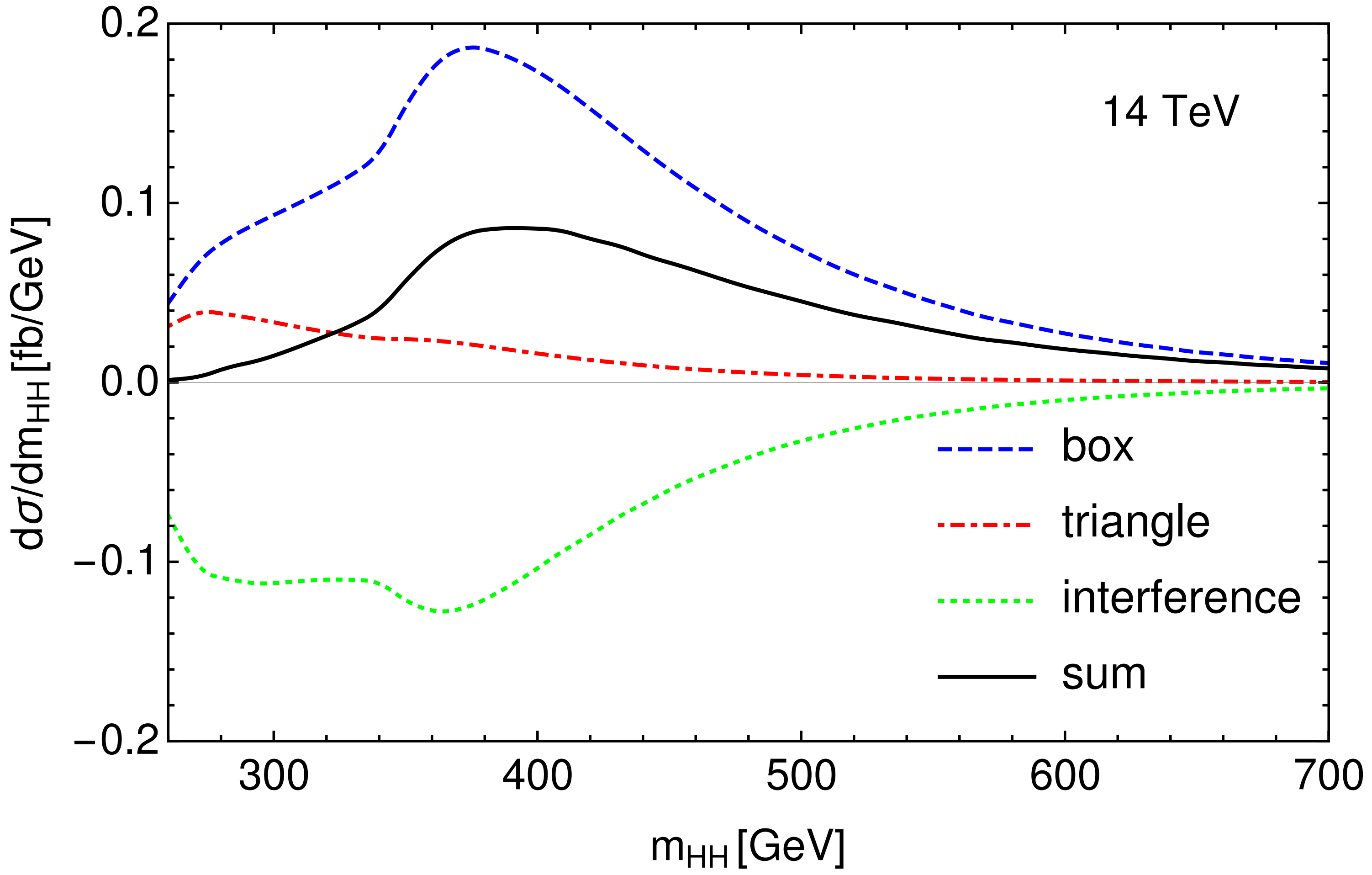

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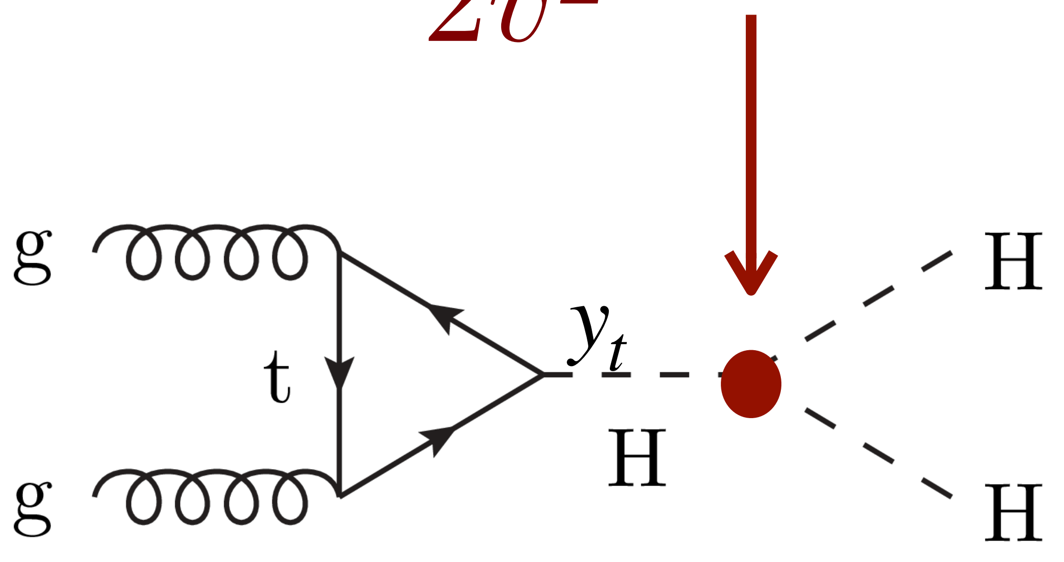

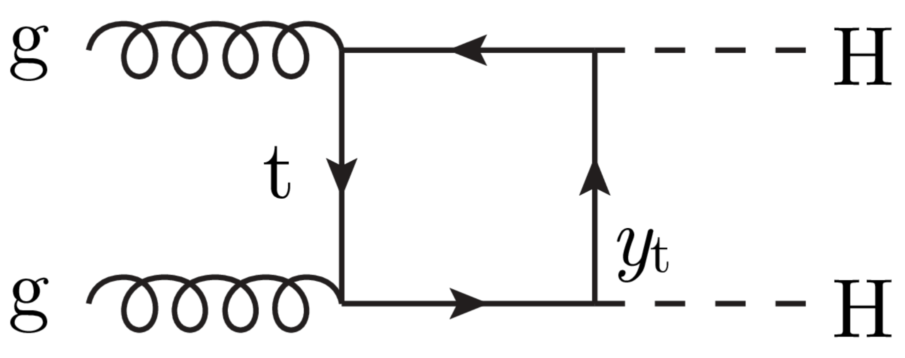

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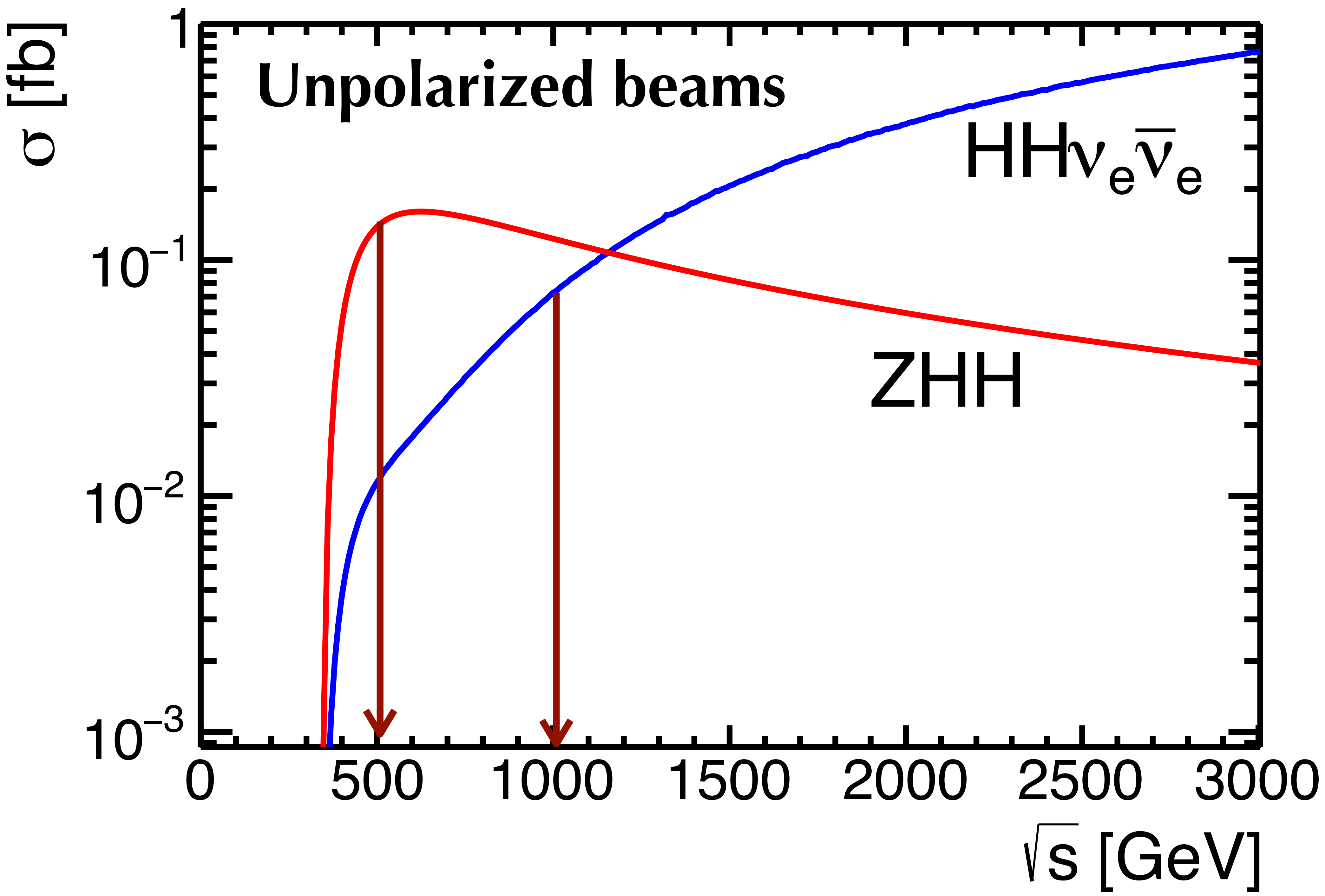
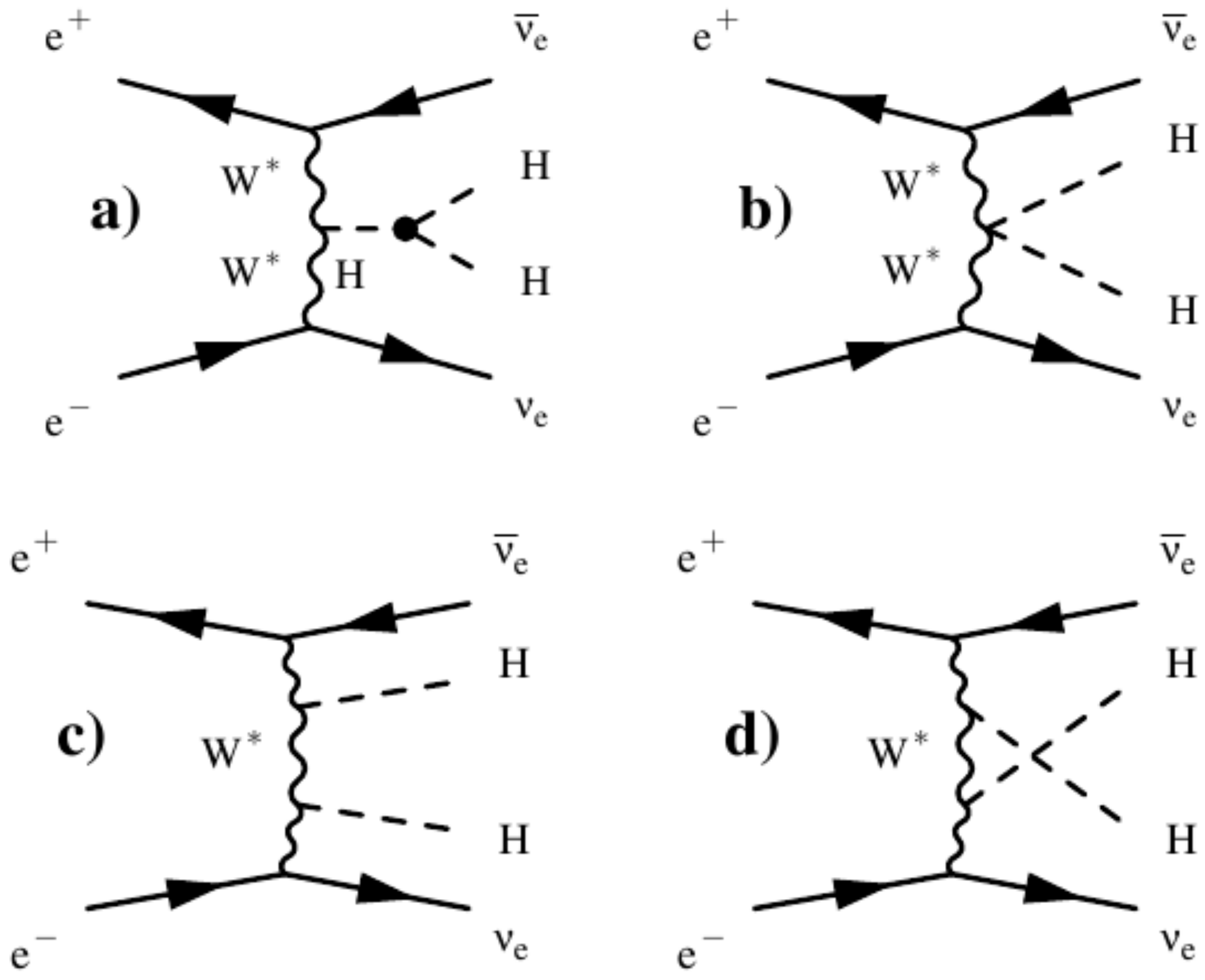
HH at future e+e- linear colliders

arXiv:1910.00012





- The intrinsic precision (1% level) on single Higgs production processes is one of the main advantages of e^+e^- beams
- **HHvv** requires $e^-_L e^+_R$, the use of polarized beams could increase the cross-section by a factor ~2
- For both **ZHH** and **HHvv** processes there are diagrams involving the self-coupling in constructive/deconstructive interference with diagrams that do not contain this coupling.
  - No matter what is the sign of the deviation of the Higgs self-coupling from its SM value, one process is always enhanced

Which precision on λ is needed?

arXiv:1910.00012

Bronze 100%

Silver 25–50%

Gold 5–10%

Platinum 1%

Sensitivity to models with the largest new physics effects, in which new particles of few hundred GeV mass appear in tree diagrams or as s-channel resonances

Sensitivity to mixing of the Higgs boson with a heavy scalar with a mass of order 1 TeV (i.e. electroweak baryogengesis)

Sensitivity to a broad class of loop diagram effects that might be created by any new particle with strong coupling to the H

Sensitivity to typical quantum corrections to the Higgs self-coupling generated by loop diagrams

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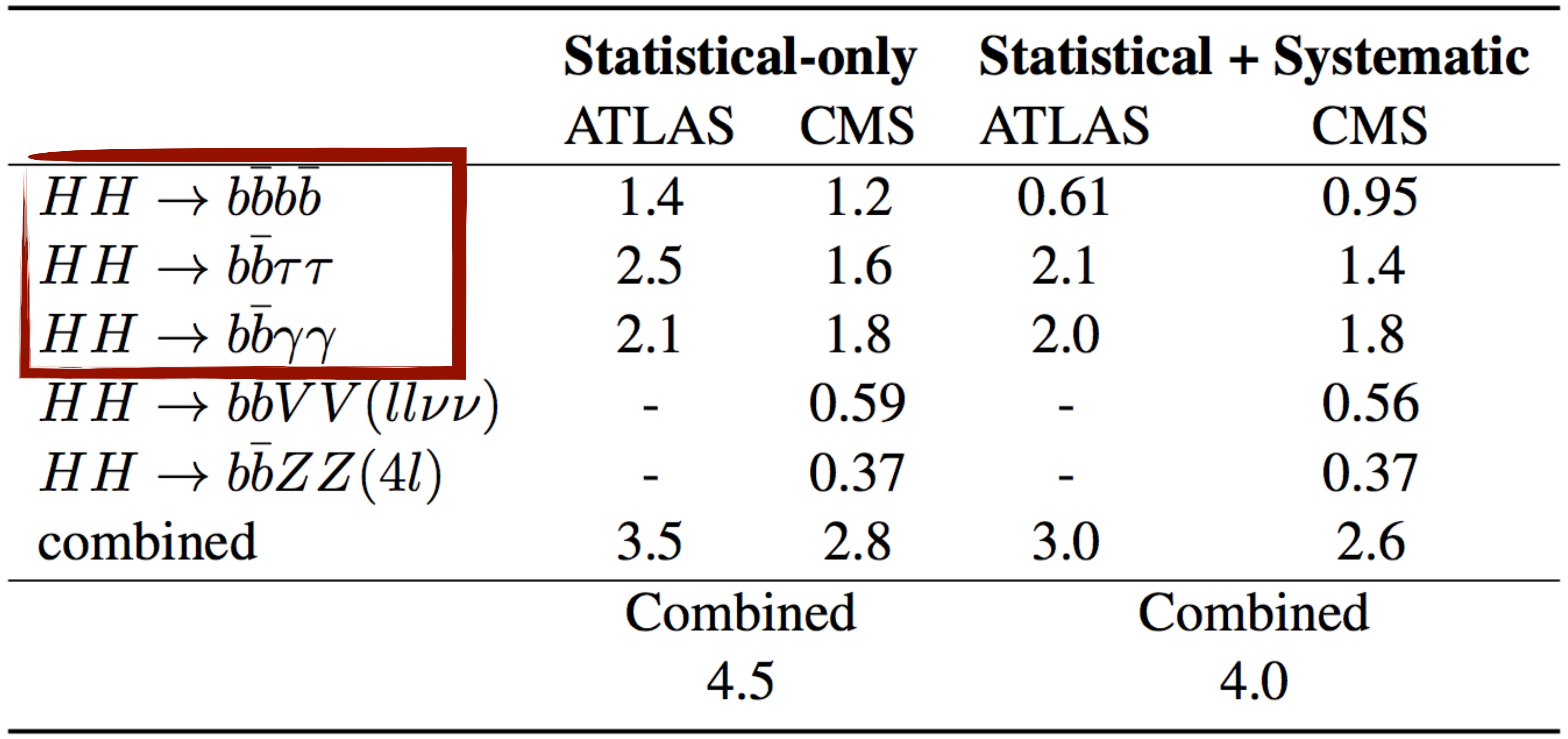
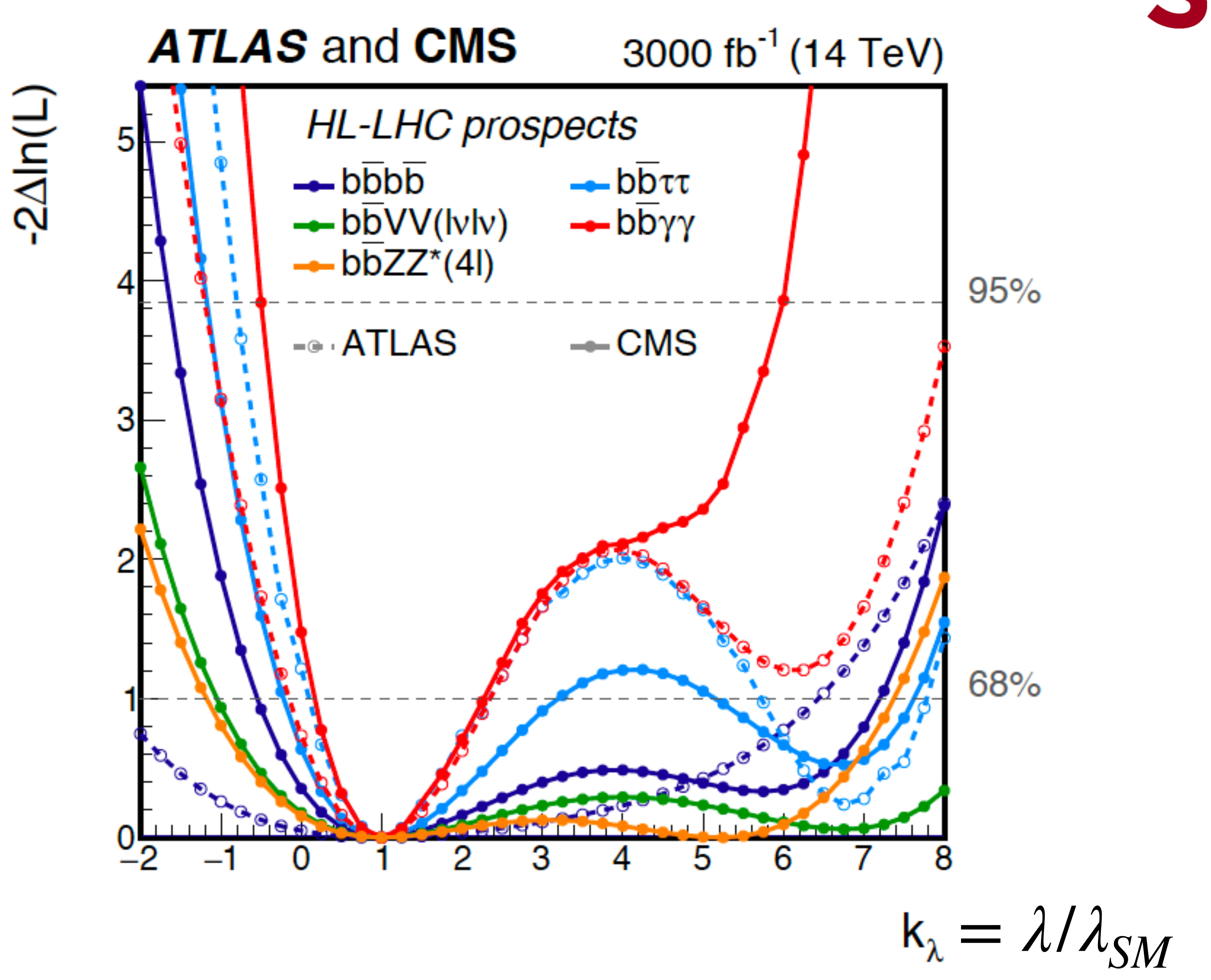
Interplay between precisions inference and direct searches for new particles

Most recent projections for HL-LHC

ArXiv:1902.00134

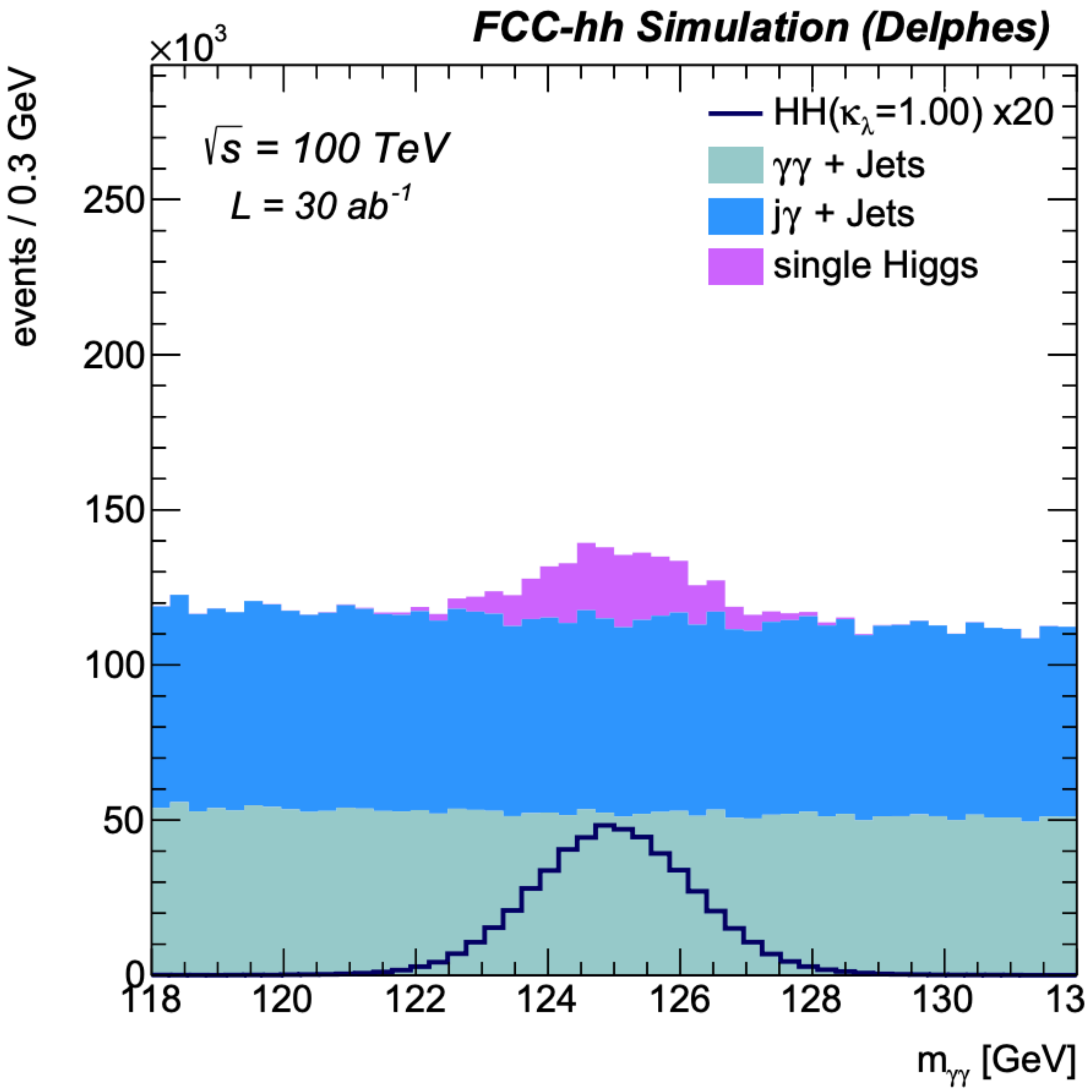


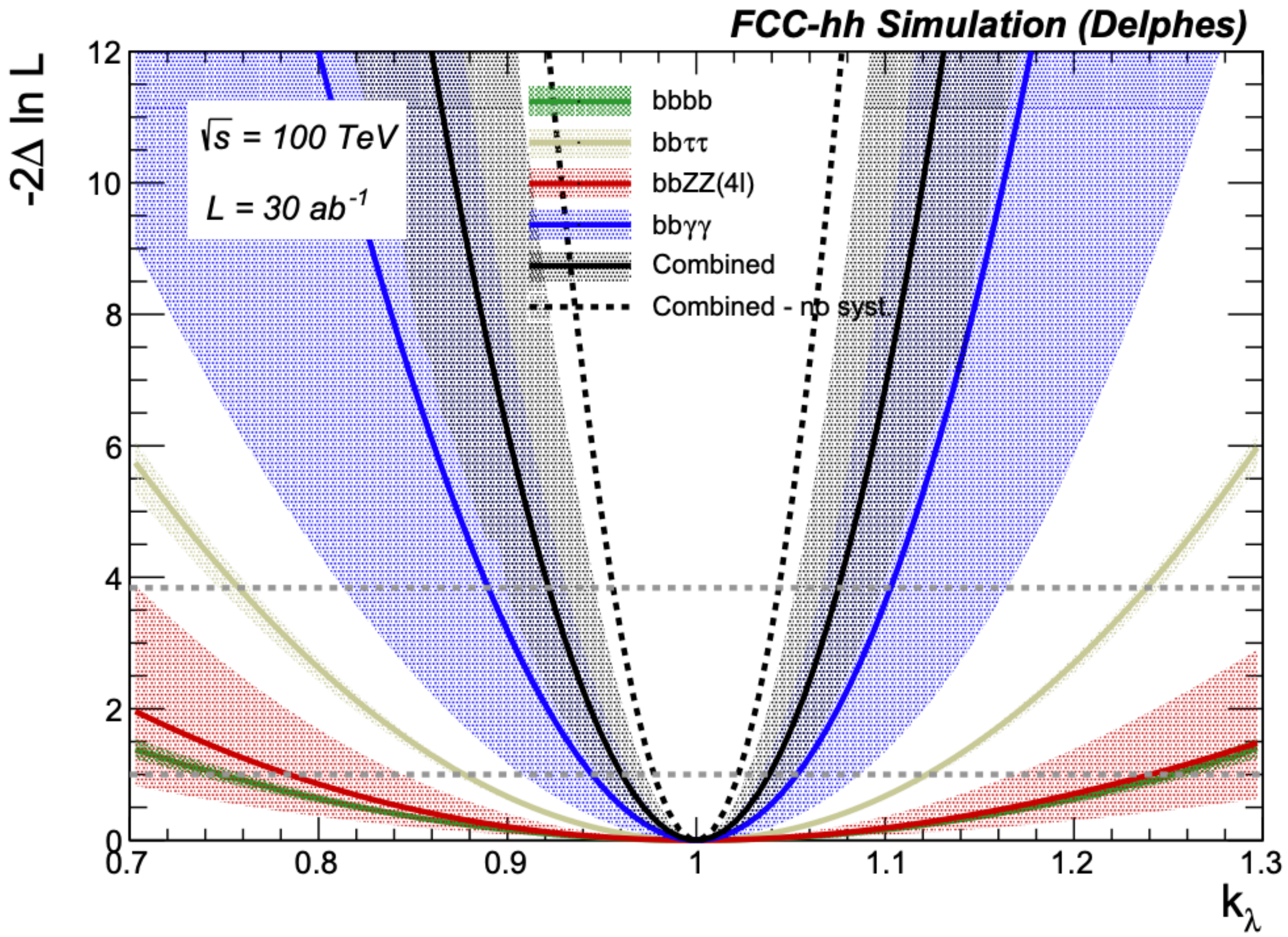
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



- A combined significance to the **SM HH process of 4σ** can be achieved with all systematic uncertainties
  - This corresponds to **~50% (silver)** precision on the Higgs self-coupling (largely driven by the HH)
- Estimates of the sensitivity to HH at HL-LHC are based on:
  - dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200
  - extrapolations from **early** Run-2 analyses
- **More sophisticated (= sensitive) results on their way**
  - ***It would be great to take into account for Snowmass21 the actual sensitivity of HL-LHC***

HH at future pp colliders



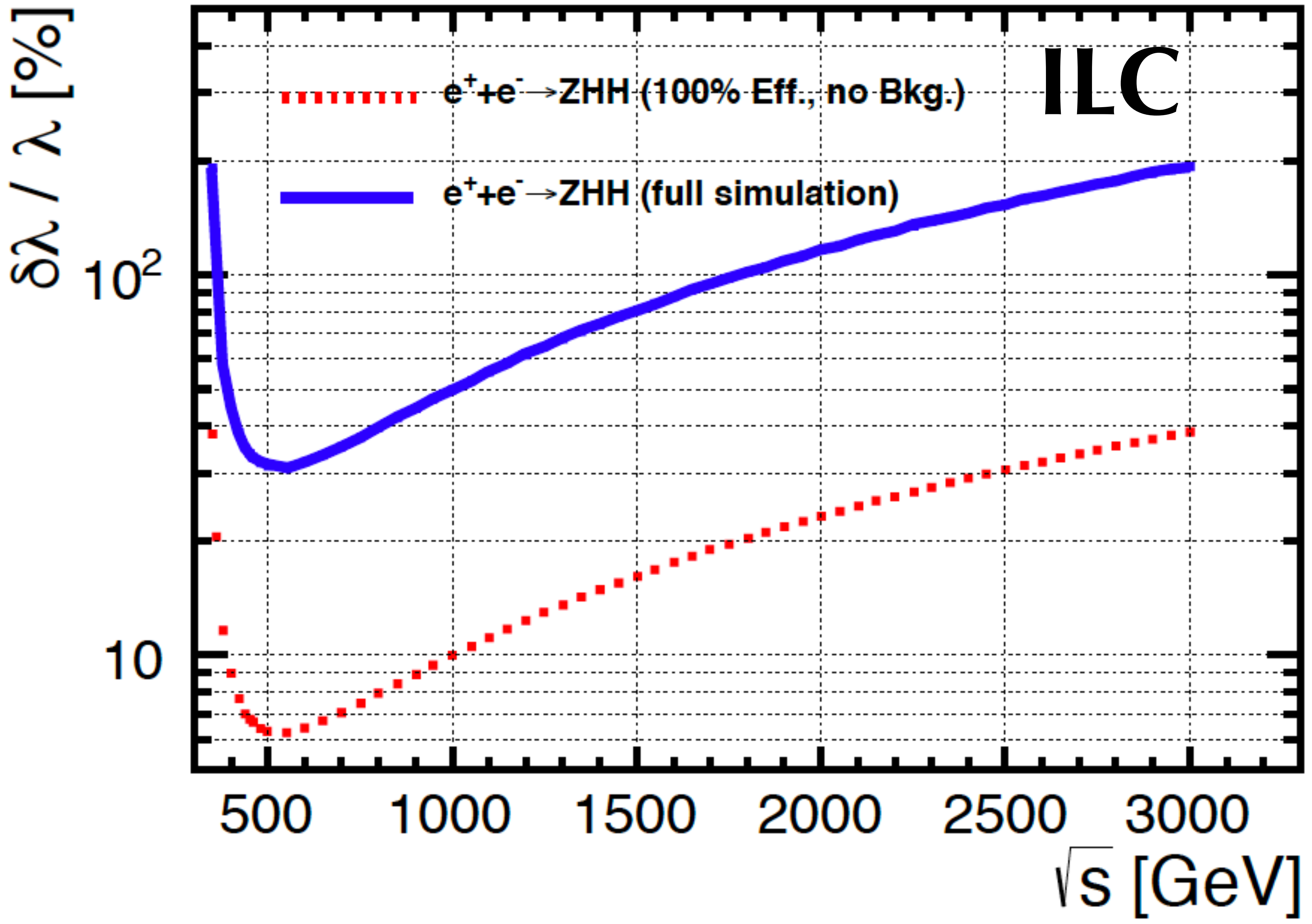


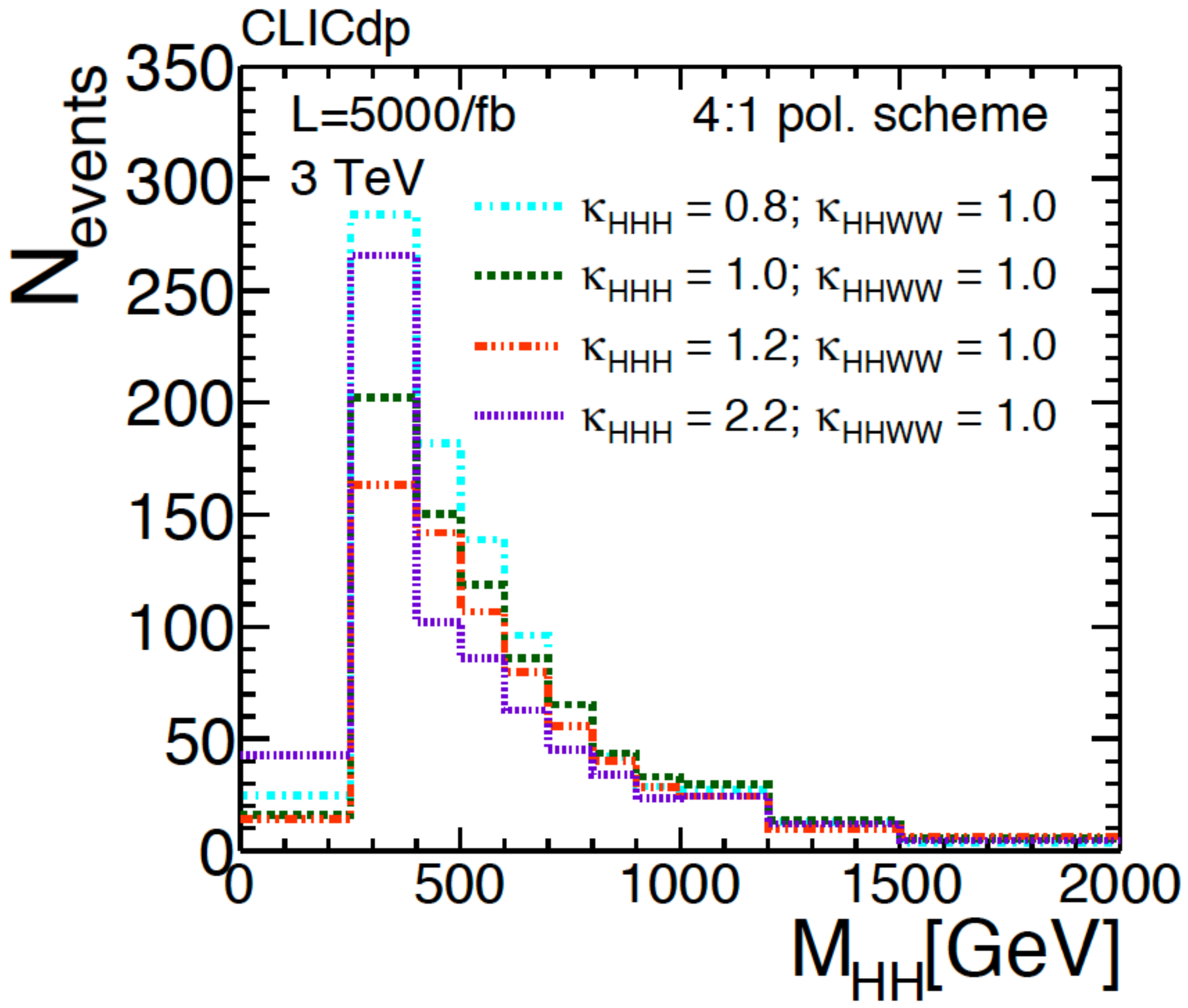
- The **FCC-hh** with 30/ab at **100 TeV** and assuming similar performance to the HL-LHC detectors
  - 2.9-5.5% (gold) depending on the systematic assumptions

		$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}ZZ^*$ (4ℓ)	$b\bar{b}WW^*$ (2j$\ell\nu$)	$b\bar{b}b\bar{b}$ +jet
$\kappa_\lambda = \lambda/\lambda_{SM}$	$\delta\kappa_\lambda$	3.5-8.5%	12%	14%	40%	25%

Studying HH at e^+e^-

arXiv:1910.00012





- Both the $b\bar{b}b\bar{b}$ and $b\bar{b}WW$ final states are considered with Z to leptons/neutrino/quarks
- For **ILC analyses** with an expected luminosity of 4/ab at 500 GeV, the combination of the various channels yield a precision of 16.8% on the HH total cross section which corresponds to an uncertainty of 27% on κ_λ coupling.
- For **CLIC studies** at 1.4 TeV, evidence for ννHH production is found with a significance of 3.6σ, and the ZHH process can be observed at this stage with a significance of 5.9σ
  - The ambiguity in the interpretation of the total cross-section results is resolved by measuring the HH invariant mass distribution in the ννHH process.

HH & self-couplings, a 'short' summary

arXiv:1910.00012
arXiv:1905.03764

The goal for **future machines** beyond the HL-LHC should be to be able to reach at least **gold quality (5-10%)** precision for the Higgs boson self-coupling

- **Future circular lepton** machines (CEPC/FCC-ee@240GeV) will benefit from very large datasets at the Higgs, WW (and top pair) thresholds.
  - The Higgs self-interaction can be probed only **through single-H**
- **Lepton Linear machines**, ILC250 and CLIC380, can probe the Higgs self-coupling through the single-H, and reach levels of **50% precision**
  - They can probe the self-coupling **through HH**
  - It will be important to have data at two different CM energies to reach the silver level of precision.
- **Future circular hadronic machines**, FCC-hh (100 TeV), allow for both higher luminosities and high energies compared to the HL-LHC
  - The sensitivity to the self-coupling is largely driven by the **HH searches**

	collider	single-H	HH	combined
●	HL-LHC	100-200%	50%	50%
	CEPC$_{240}$	49%	–	49%
	ILC$_{250}$	49%	–	49%
●	ILC$_{500}$	38%	27%	22%
●	ILC$_{1000}$	36%	10%	10%
	CLIC$_{380}$	50%	–	50%
	CLIC$_{1500}$	49%	36%	29%
●	CLIC$_{3000}$	49%	9%	9%
	FCC-ee	33%	–	33%
●	FCC-ee (4 IPs)	24%	–	24%
	HE-LHC	-	15%	15%
●	FCC-hh	-	5%	5%

These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

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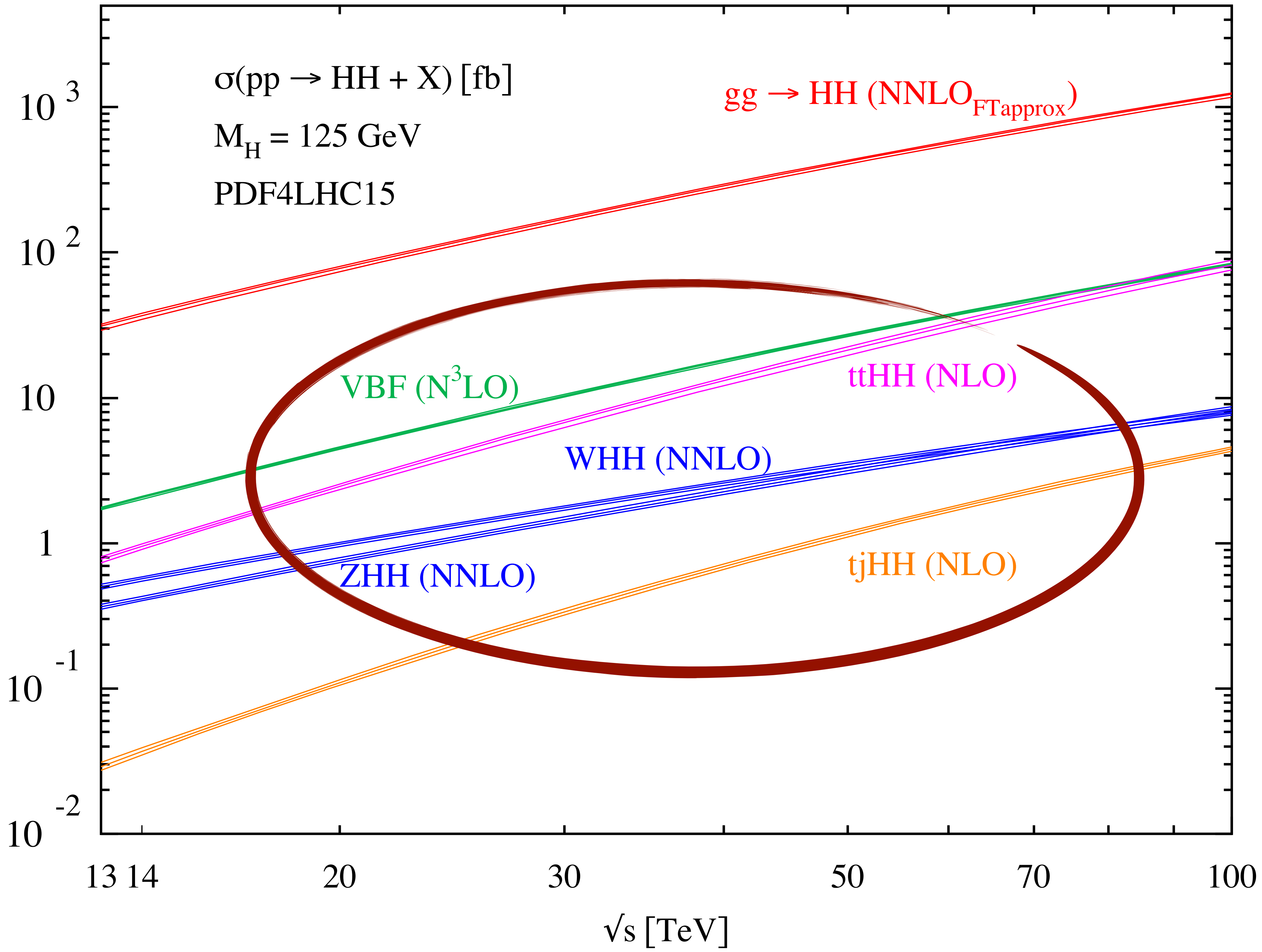
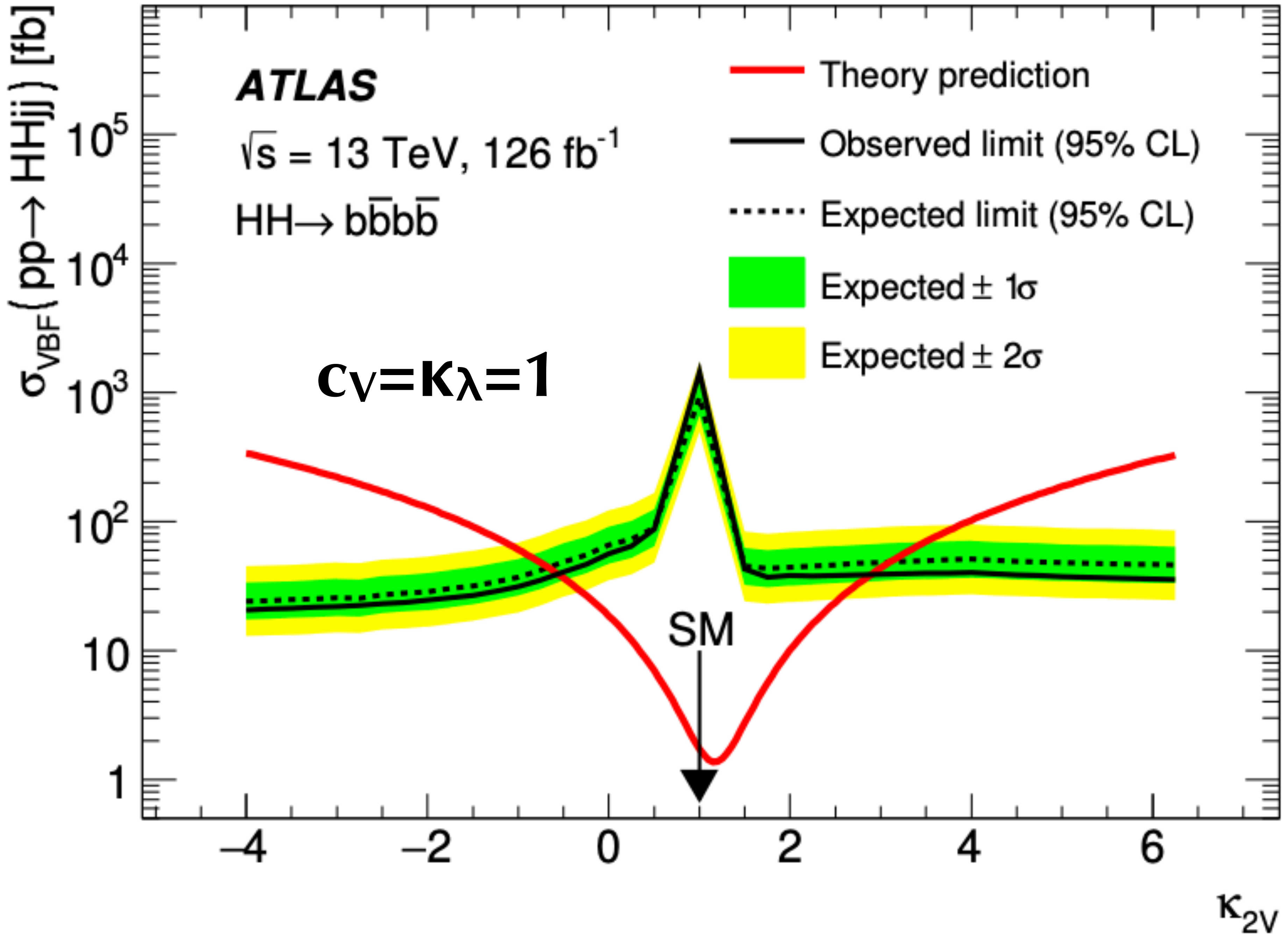
* arXiv:2004.03505 2.9-5.5% depending on the systematic assumptions



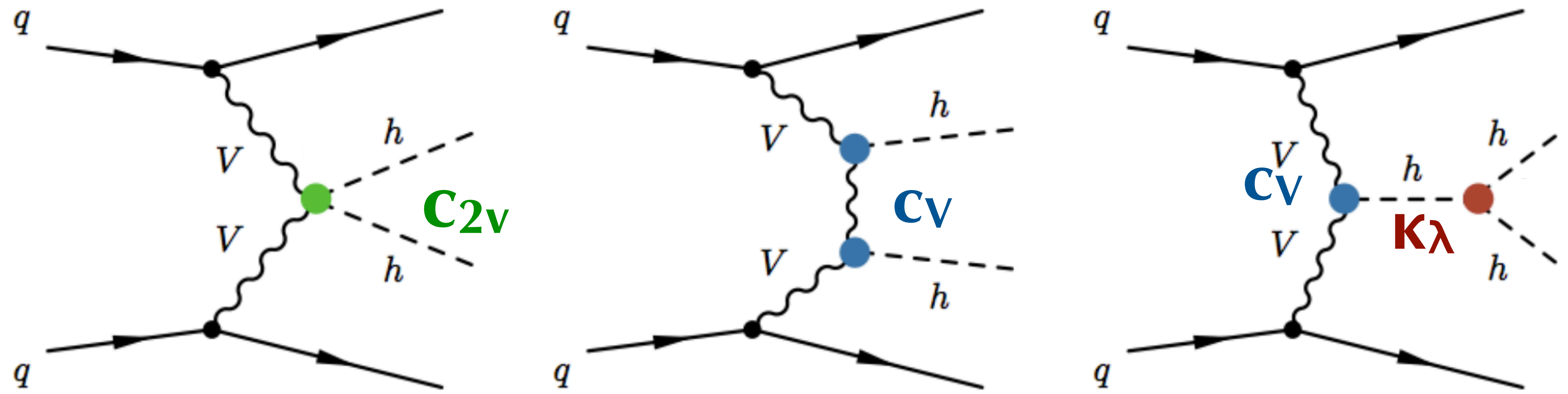
What about the other HH mechanisms ?
>> not really explored for the ESG

VBF HH @LHC

arXiv:2001.05178, submitted to JHEP



- two high p_T forward jets provide a very specific topology
- allow to probe **c_{2V}** (**VVHH**), **c_V** and **κ_λ**



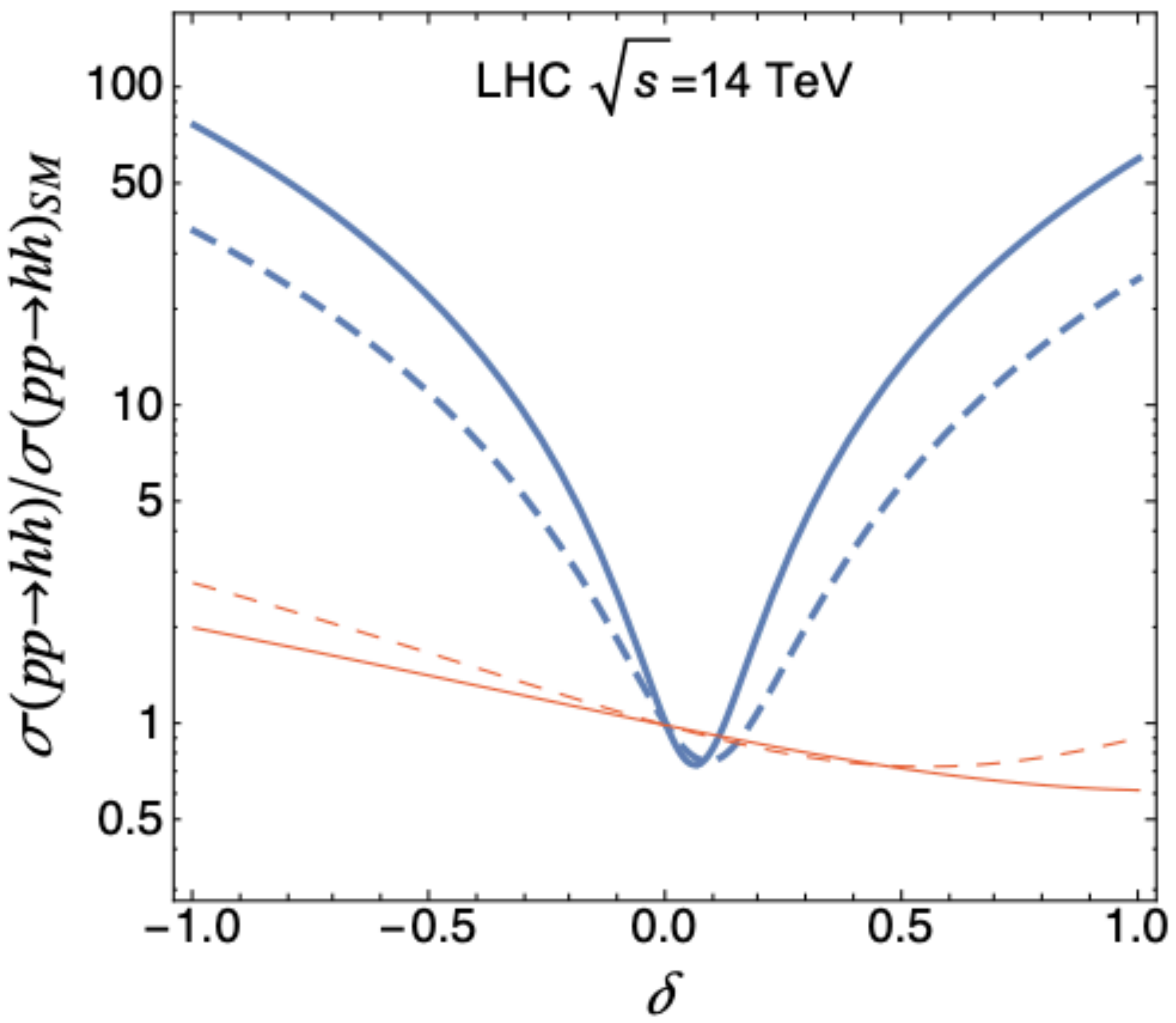
- First search from ATLAS in the $b\bar{b}b\bar{b}$ final state in Run2
  - It probes large deviations of c_V and c_{2V} from their SM predictions, which result in a **harder m_{HH} spectrum and higher momentum for the b-jet** from the Higgs boson decay.
- VBF production mode will benefit at the HL-LHC **from the extended tracker acceptance and the improved ability to identify forward jets** from the hard-scattering

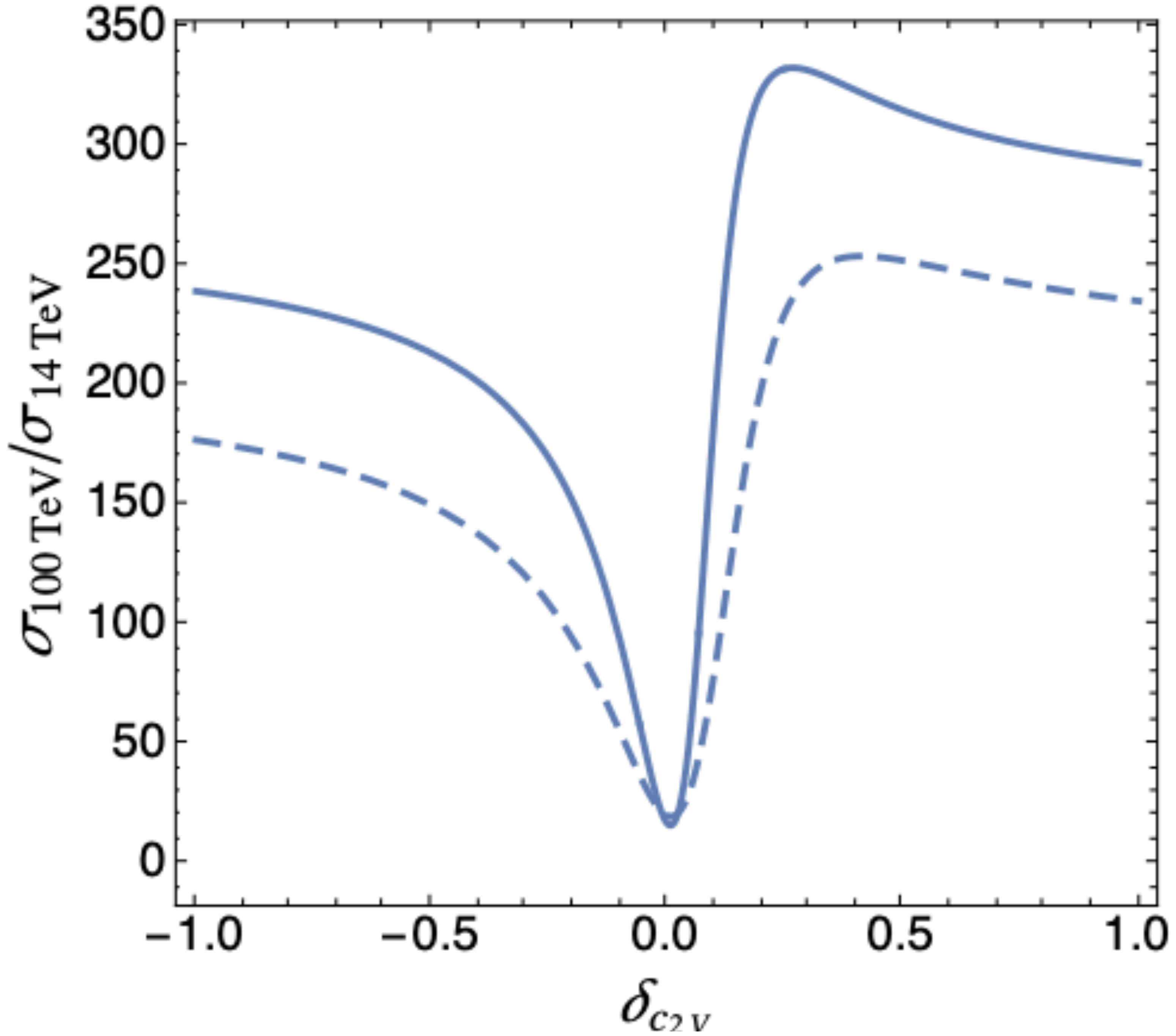
—> **it would be great to understand the potential of HL-LHC to probe the HHVV vertex**

Perspective on c_{2V} at FCC-hh

arXiv:1611.03860

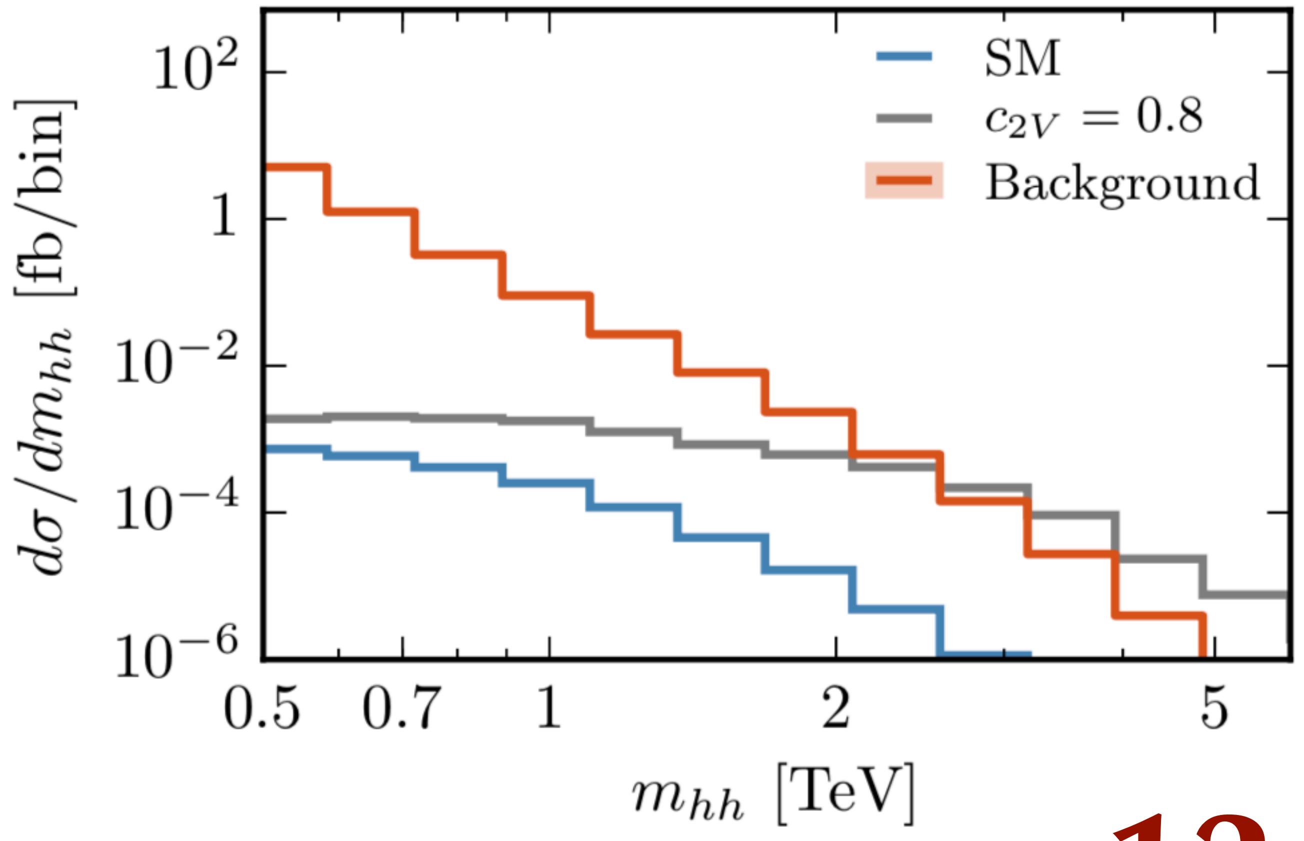
- c_V will be measured with a few per-mille precision at e+e-
- the cubic Higgs self-coupling contribution is suppressed at the multi-TeV mass values
- the constraints on δc_{2V} at **FCC-hh is expected to be better than ±1%**
    - a large improvement compared to the precision that can be obtained at the HL-LHC.





$$A(V_LV_L \to HH) \sim \frac{\hat{s}}{v^2}(\delta_c) + \mathcal{O}(m_W^2/\hat{s})$$

$$\delta_c = c_{2V} - c_V^2$$



ttHH

arXiv:1409.8074
arXiv:1904.07886

- While in a linearized realization the ttH and the ttHH vertices (c_t and c_{tt} in SMEFT) are correlated
  - one may probe these couplings independently by exploiting the ttHH channel
  - Important input in an agnostic global fit for non-linear EFT parameters along with the parameters affecting the tth, ggh and gghh vertices
- The ttHH cross section increases by a factor of ~ 75 upon going from the 14 TeV to the 100 TeV pp machine

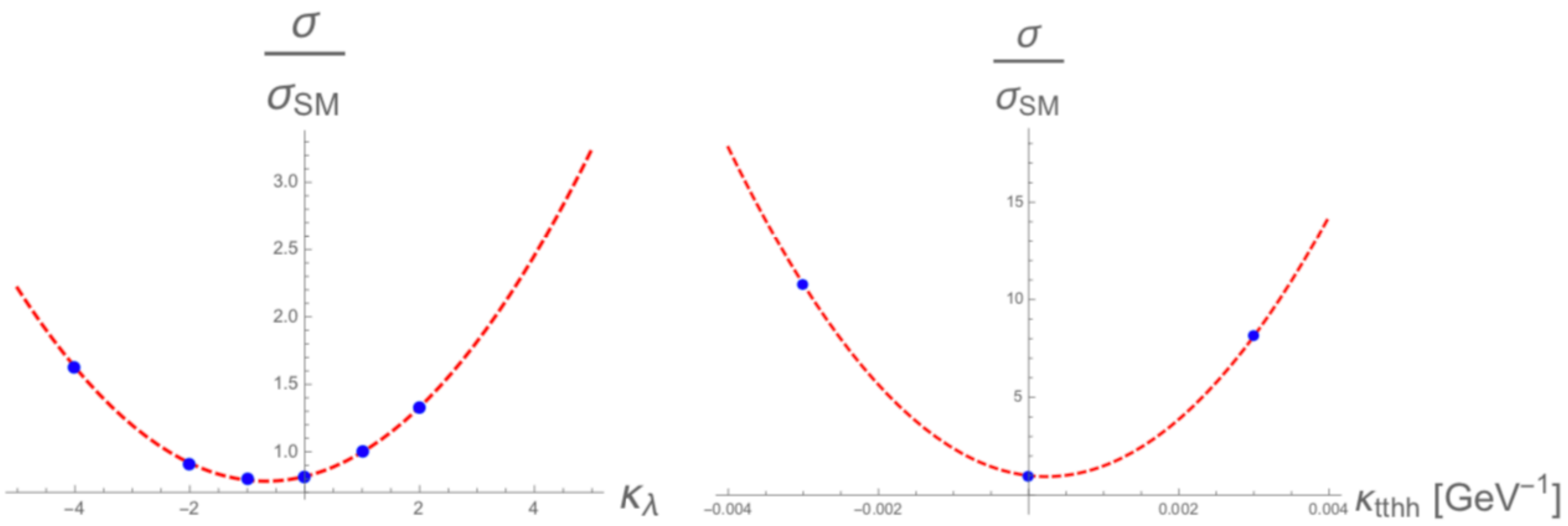


Figure 10.15: σ/σ_{SM} as a function of κ_λ (left) and $\kappa_{t\bar{t}HH}$ [GeV^{-1}] (right), where $\kappa_{t\bar{t}HH} = -m_t c_{tt}/v^2$.

Higher energies are needed to probe ttHH vertex directly

Beyond HH, quartic coupling

arXiv:1606.09408
arXiv:1508.06524

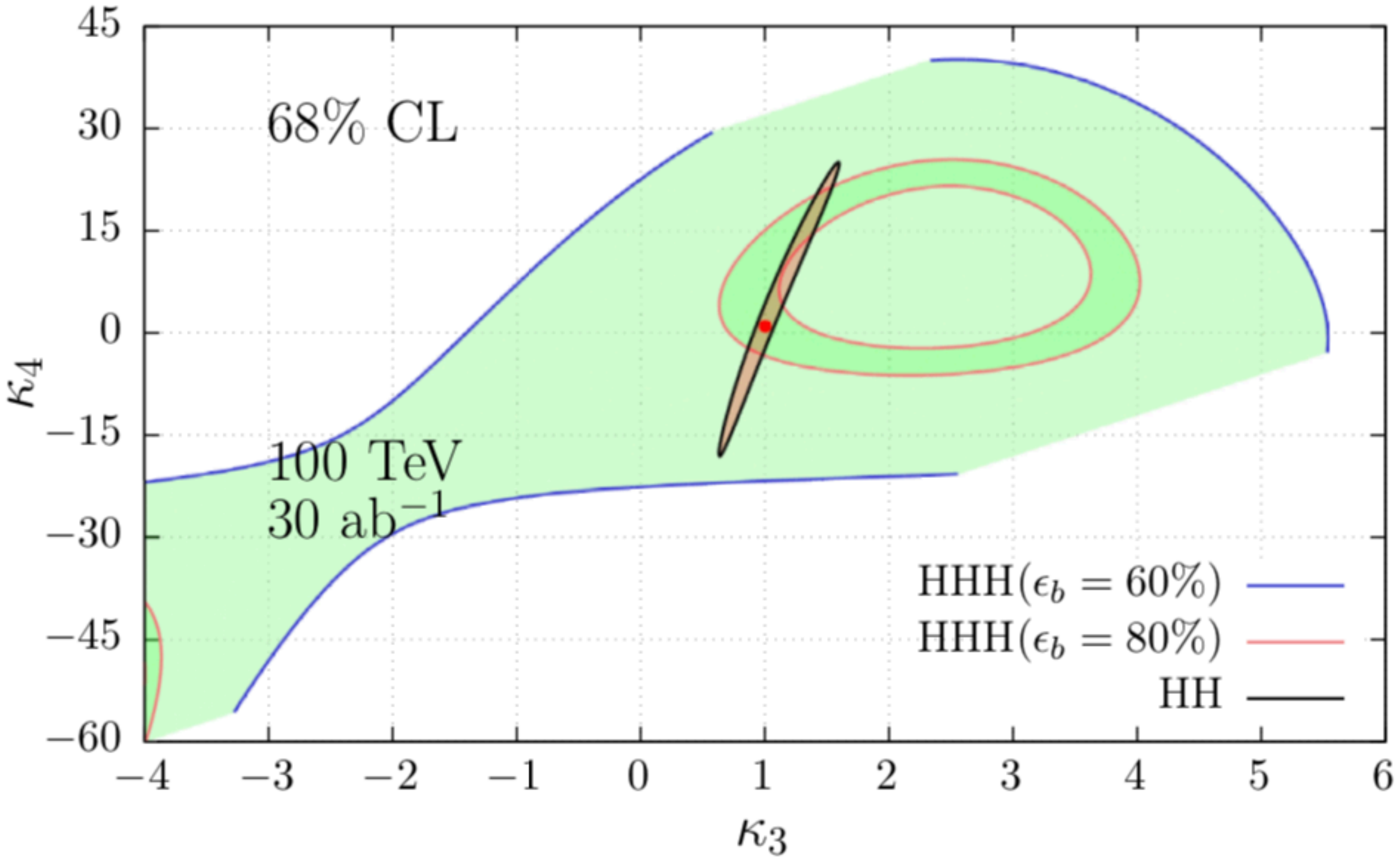
- An estimate for FCC-hh is based on the bbbbγγ signature, assuming an optimistic (80%) and a conservative (60%) scenarios on the b-tagging efficiency.
  - $\kappa_4 \in [-2.3, 4.3]$ at 68%CL (10.2)

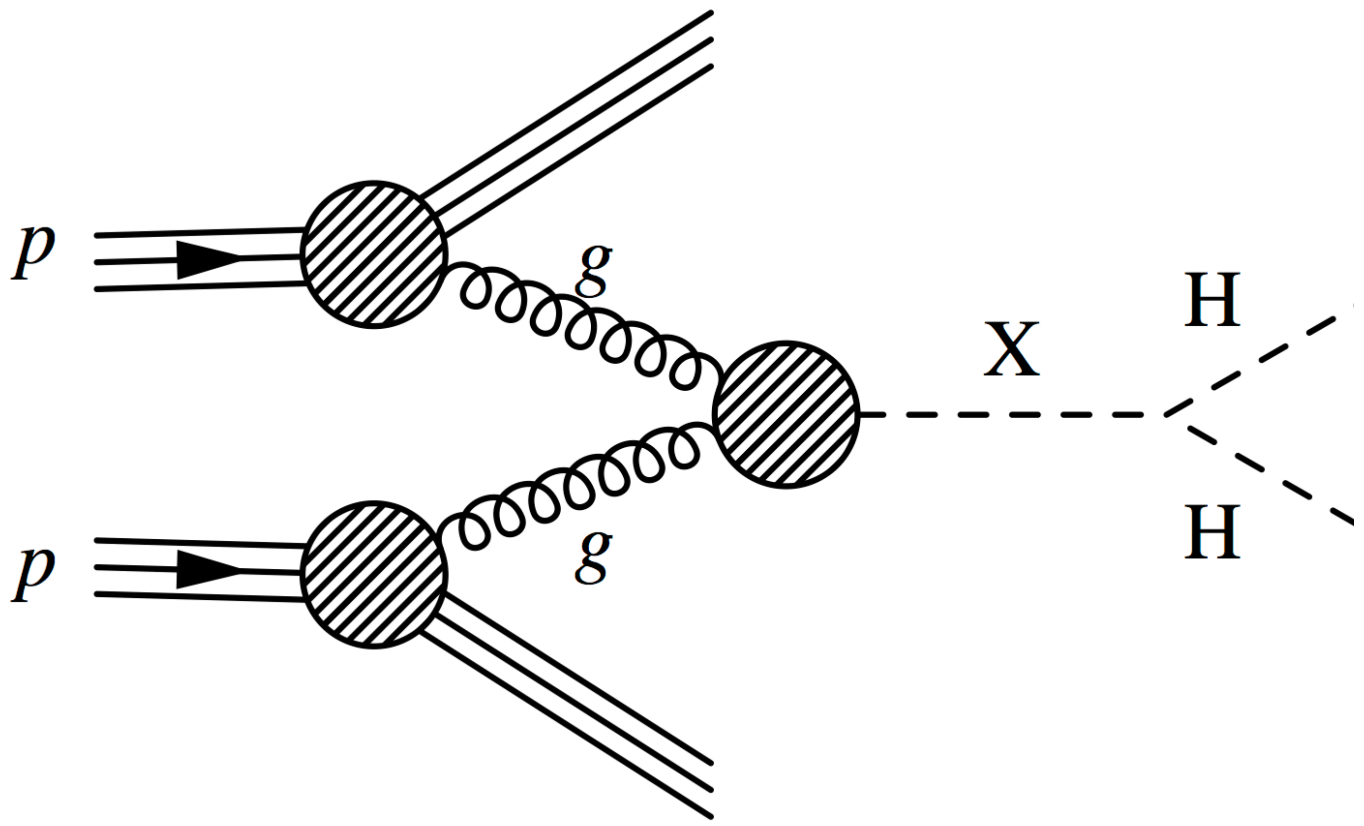
- At future e+e− colliders the SM rate for triple Higgs production can be accessed only at the very high energies.
  - the cross-section strongly depends on κ_4, and so it is possible to obtain significant constraints.
  - The constraints that can obtained at CLIC at 3 TeV via W boson fusion HHH production are similar to those that would be obtained at a FCC-hh 100 TeV

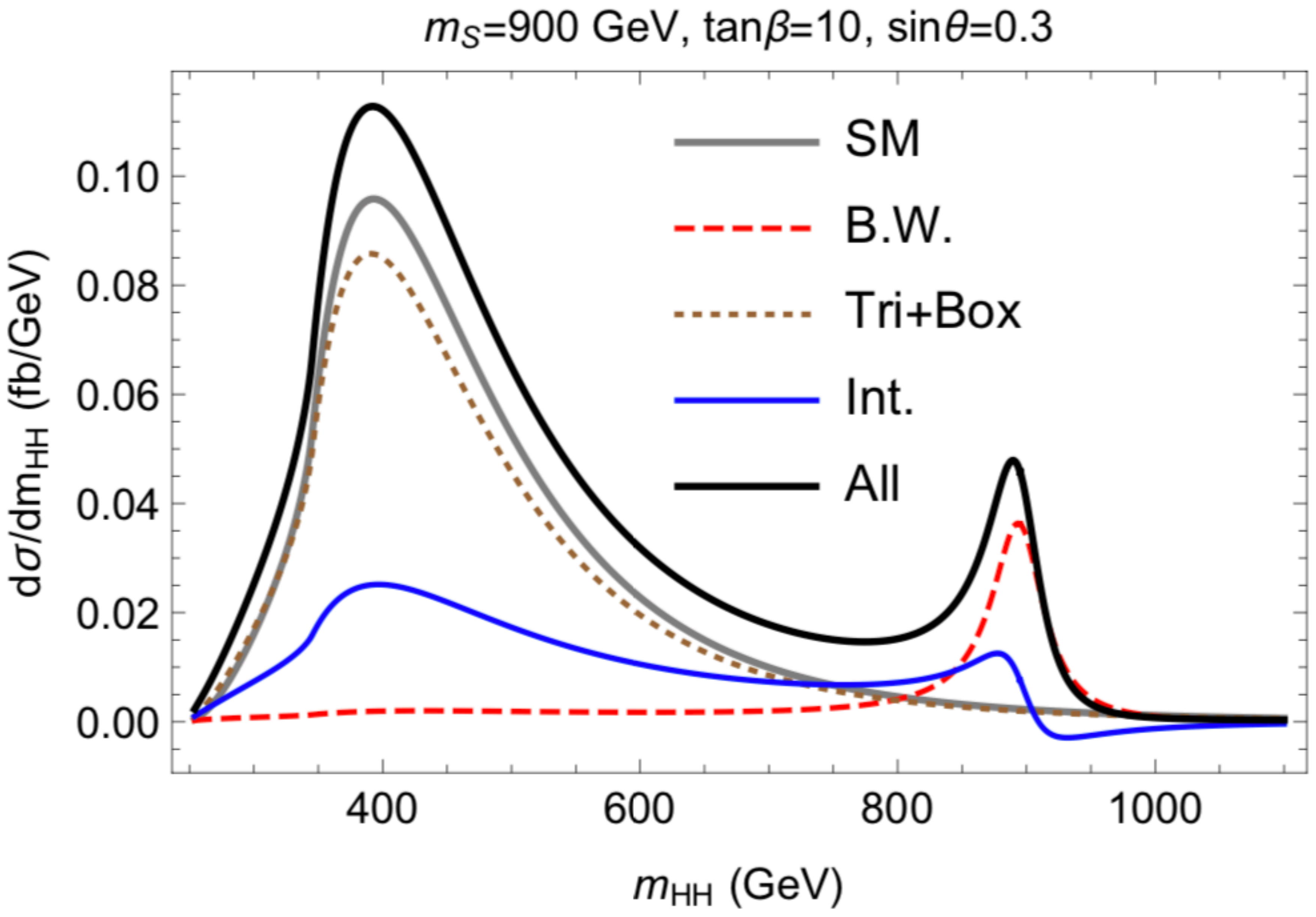
$$\Delta\mathscr{L} = -\frac{\bar{c}_6}{v^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3 - \frac{\bar{c}_8}{v^4}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^4$$

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{SM}} = 1 + c_6$$

$$\kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{SM}} = 1 + 6c_6 + c_8\,.$$



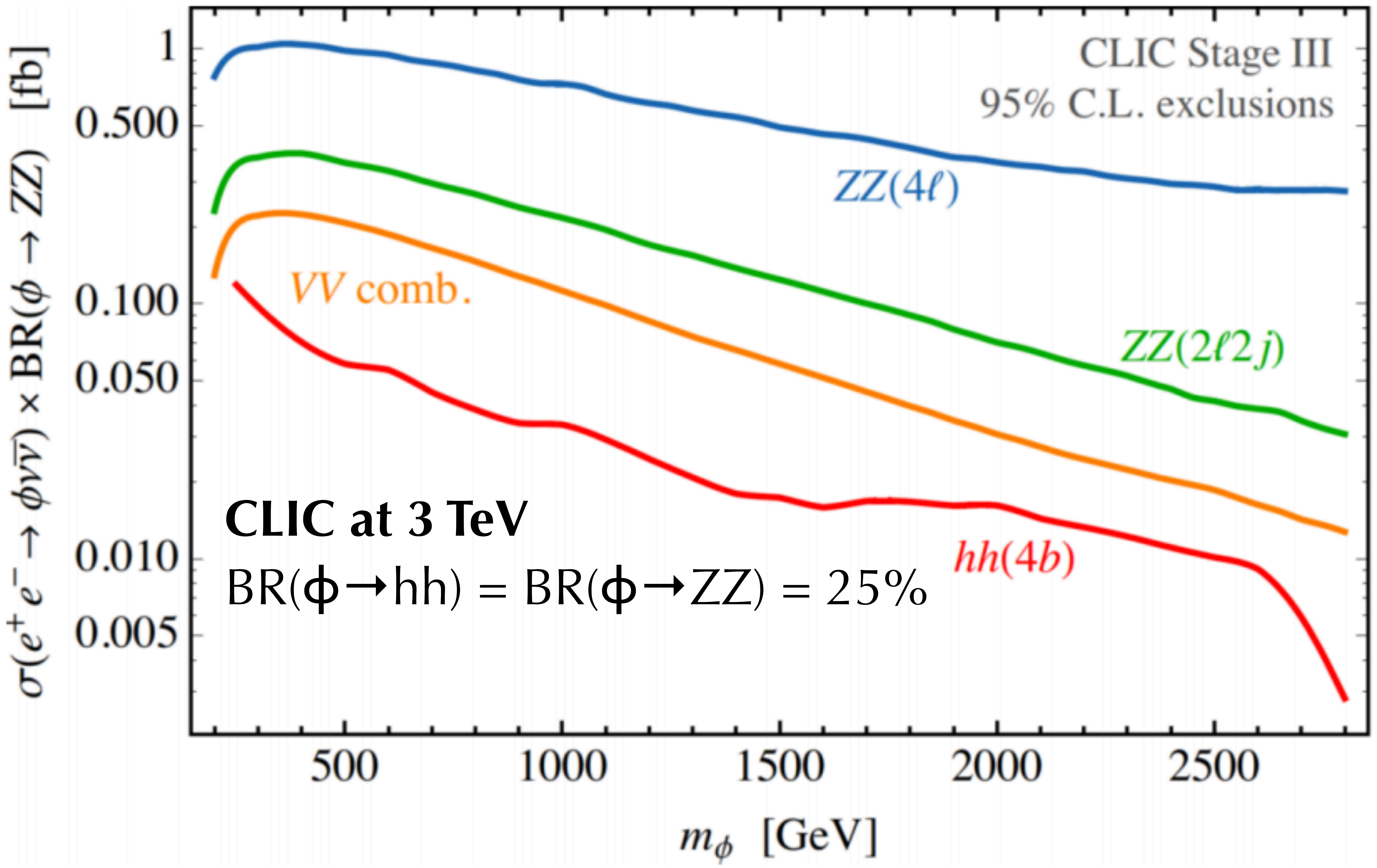


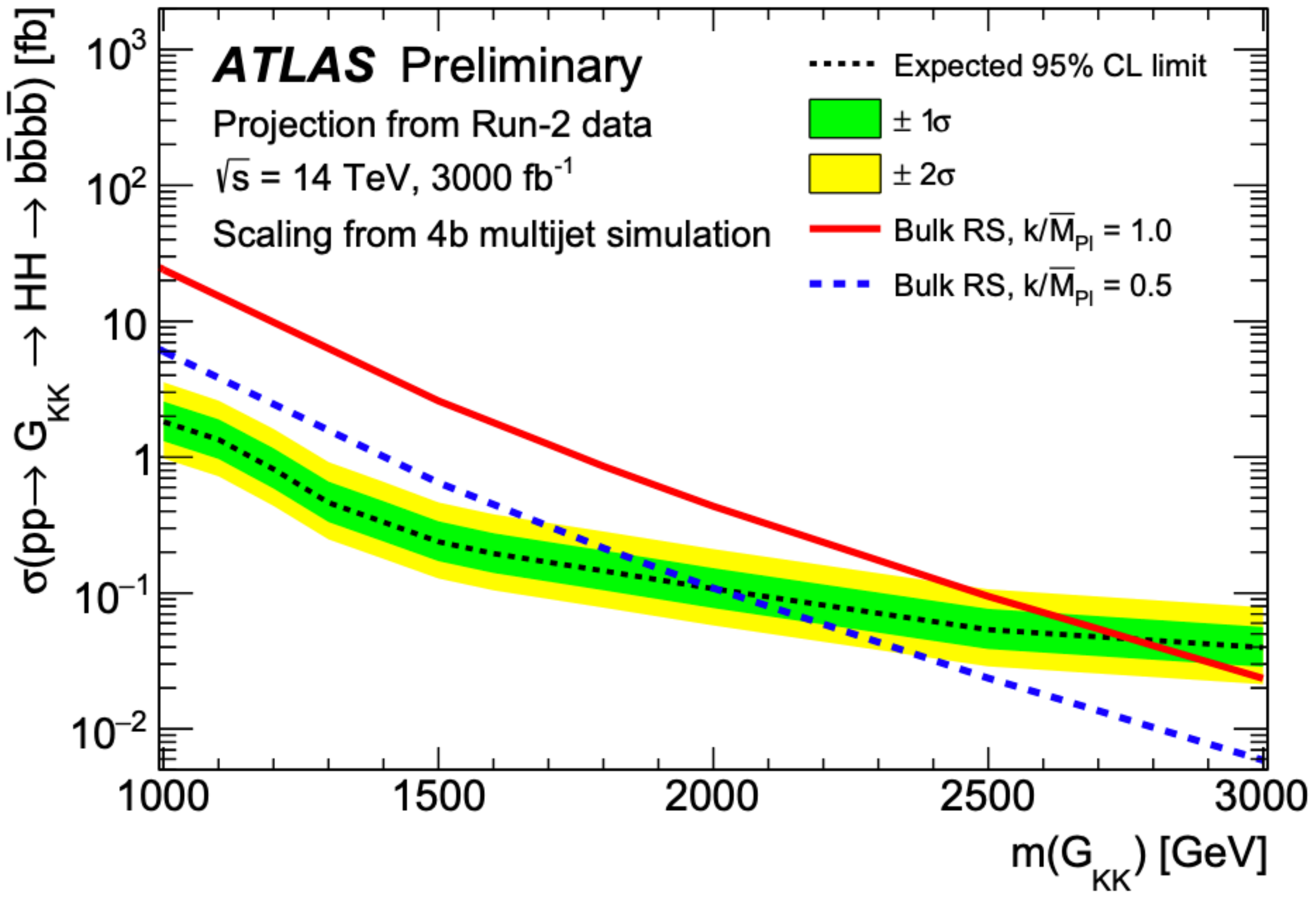


- While one of the major objectives is certainly the determination of the trilinear Higgs self-coupling, many BSM models have new particles
  - One of the most spectacular signatures is **resonant HH production**
  - Care must be taken to incorporate interference effects to correctly interpret results
- Many models predict additional scalar particles that can also be produced in pairs or in association with the observed Higgs boson:
  - expanding di-Higgs production to di-scalar production

New particles decaying to HH

JHEP 11,144 (2018)
ATL-PHYS-PUB-2018-028

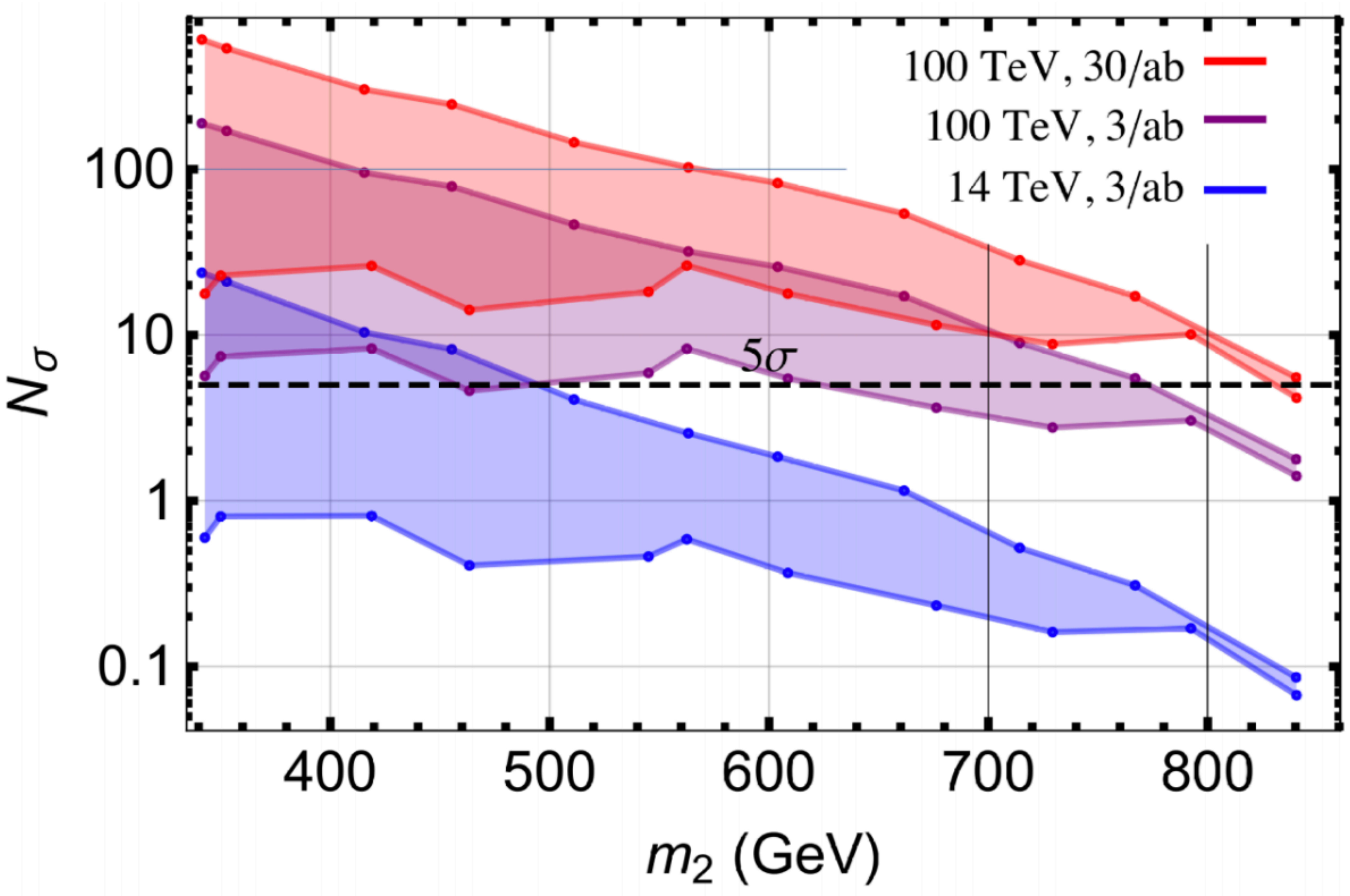




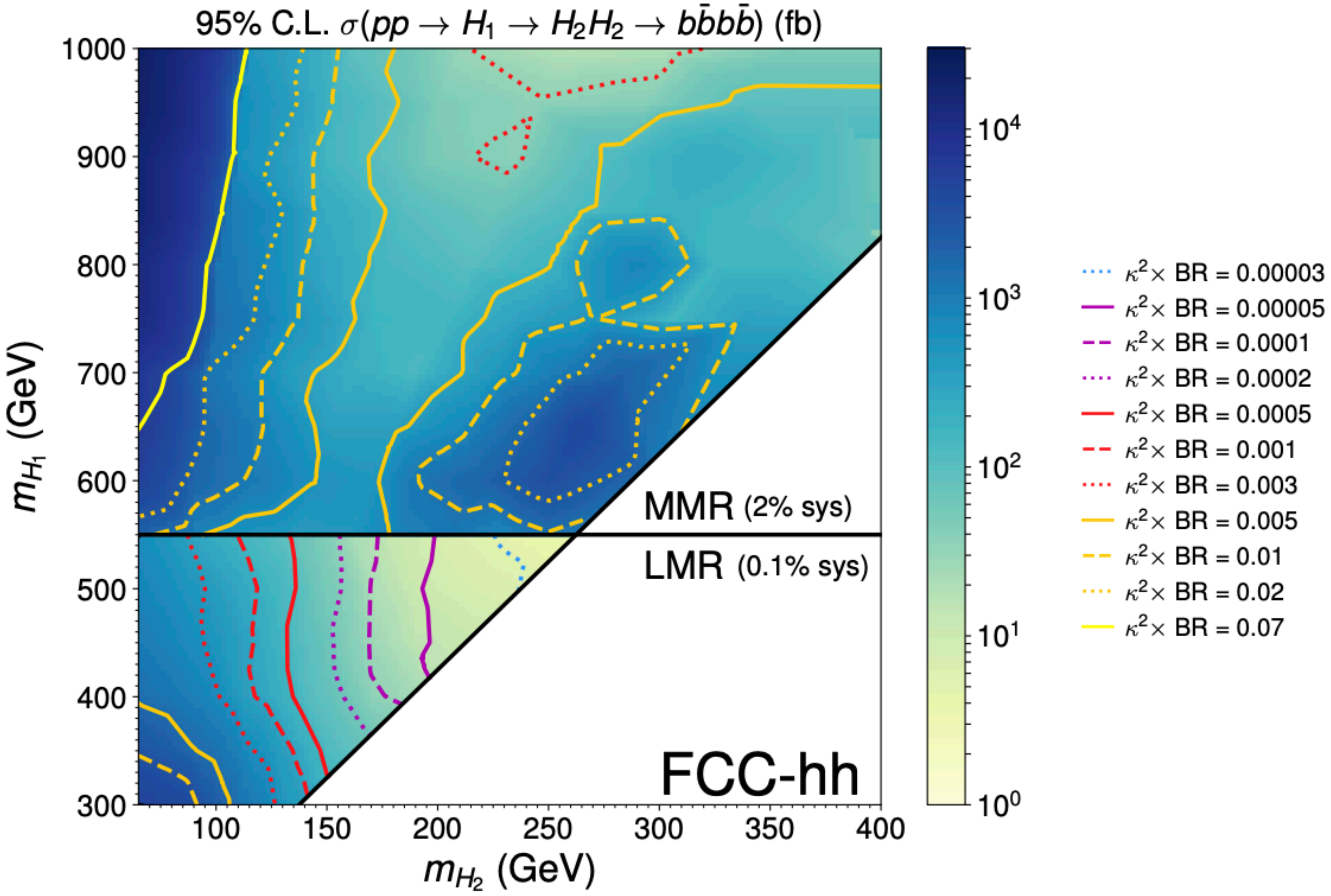
- For CLIC: hh → bbbb more sensitive than ZZ or WW (all limited by statistics, backgrounds are lowest)
- The HL-LHC study is limited to the resonance mass range between 1.0 and 3.0 TeV due to the extrapolation procedure
  - Higher mass range should be within the reach of HL-LHC
  - Lower mass will require either dedicated trigger or investigating other final states (such as bbγγ)

Generic di-scalar production: H_1 to H_2H_2

Phys. Rev. D 94, 035022 (2016)
JHEP 02 (2020) 002



4τ and bbγγ final states (generator level)



4b final state (extrapolated from Run 2 CMS results)
Note that requires good trigger performance for multi-jet final states

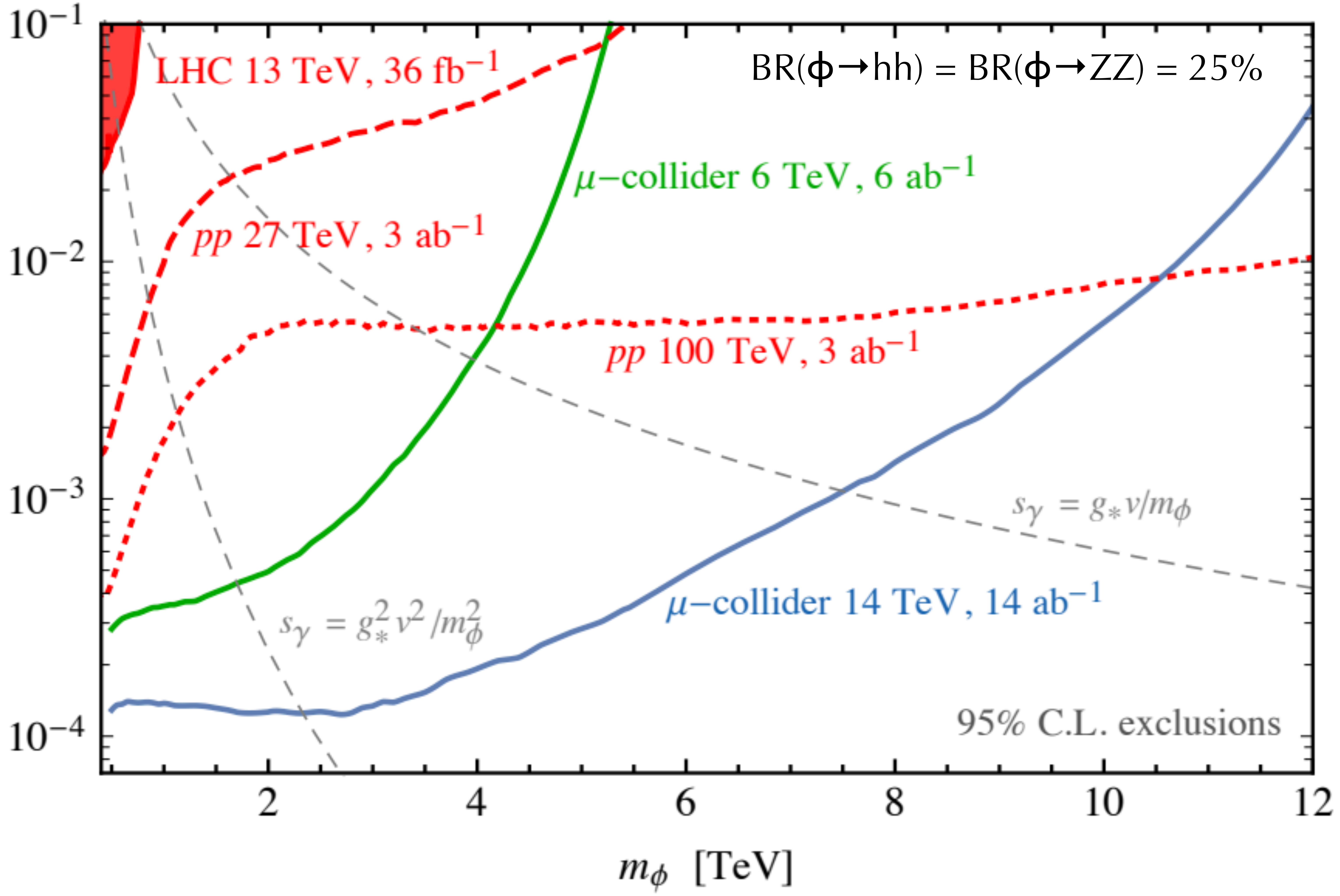
Summary & Conclusions

- Several studies are available to understand the potential of future colliders to probe the Higgs boson self-coupling
  - The goal for **future machines** beyond the HL-LHC should be to be able to reach at least **gold quality (5-10%)** precision for the Higgs boson self-coupling
  - HL-LHC potential to probe direct HH production has to be better understood with more sophisticated Run 2 analyses
- Clear **complementarity between lepton and hadronic machines**:
  - Single vs HH production
  - Direct access to additional production mechanisms to fully study the Higgs boson potential (VVHH, ttHH)
- We need to better connect the **precision goals for the measurement of HH production** at future colliders, and the implications of each level for the discovery new physics scenarios.
  - Exploring HH production and more generally di-scalar production will set some benchmark to the collider energy and/or trigger performance
    - Any information missing from existing publications?

spares

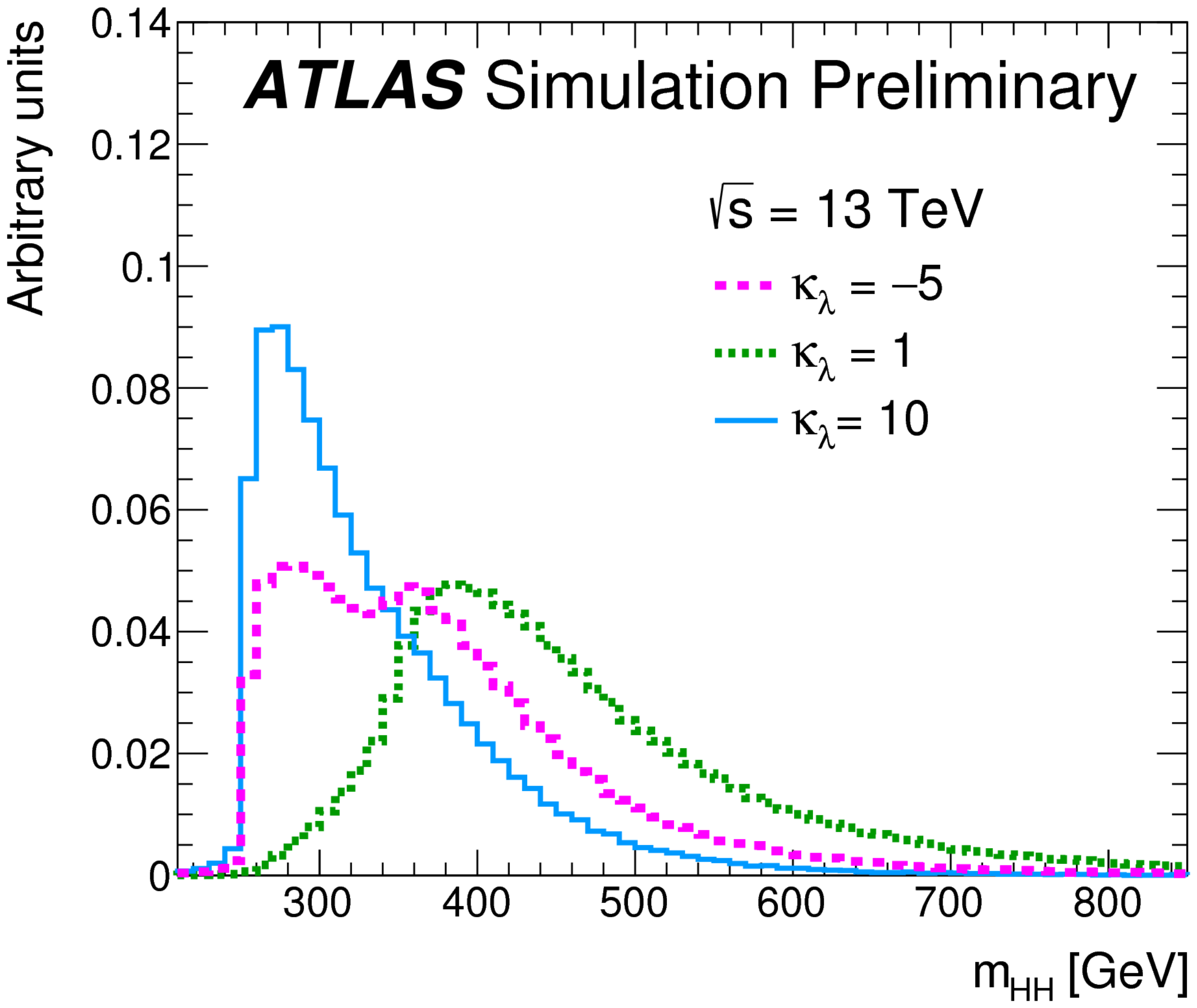
Complementarity between e+/e- and pp

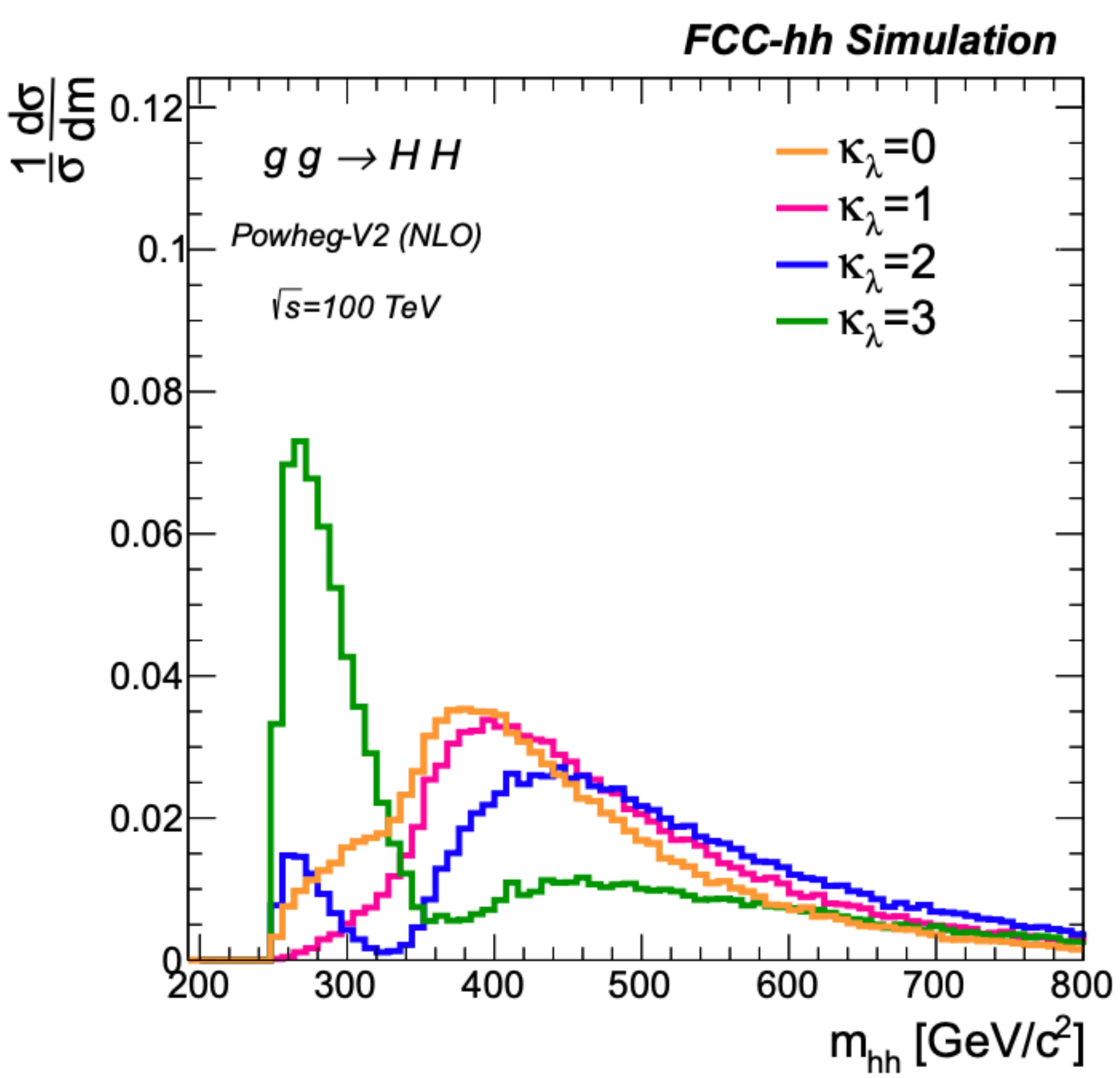
JHEP 11,144 (2018)

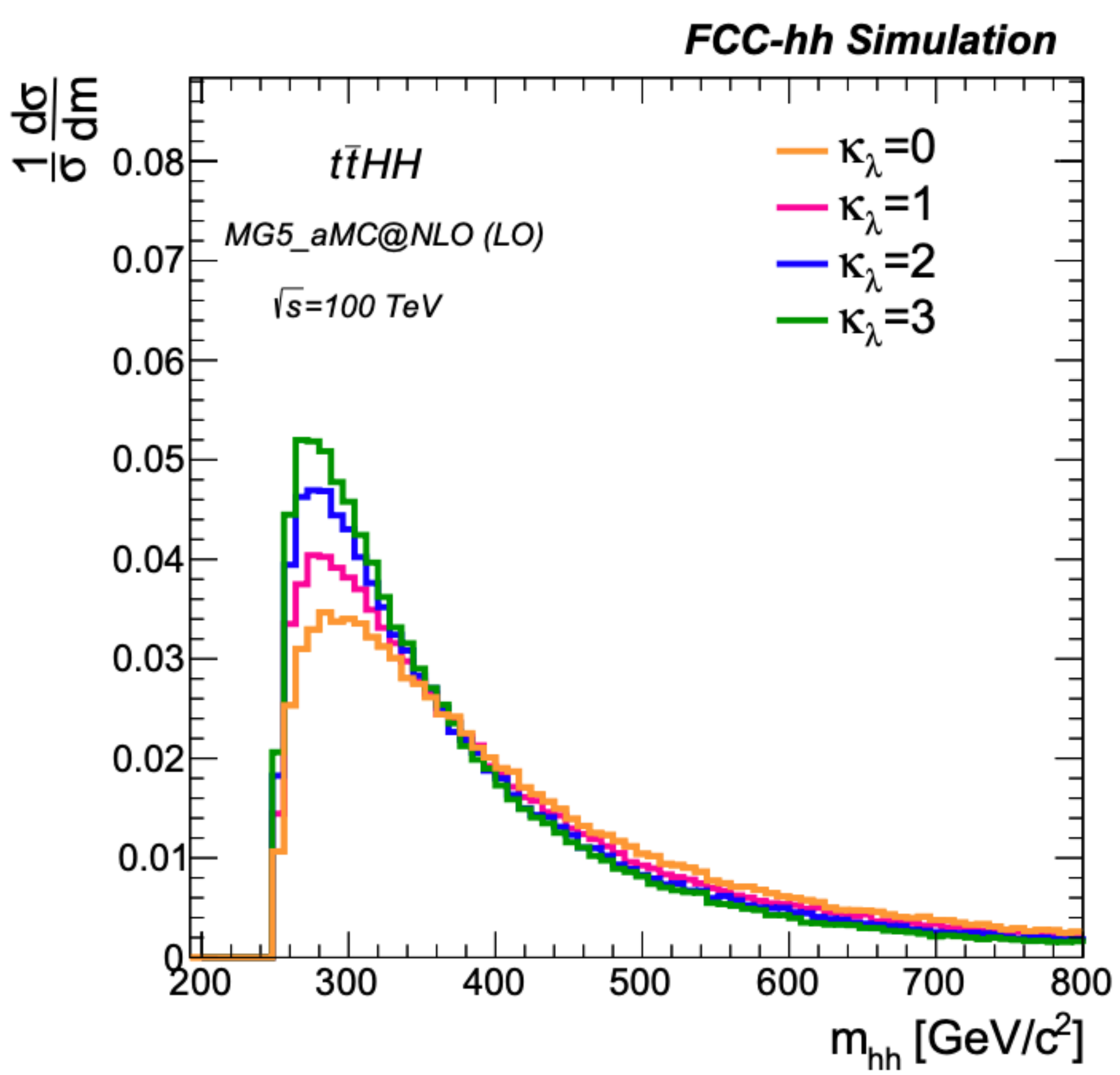


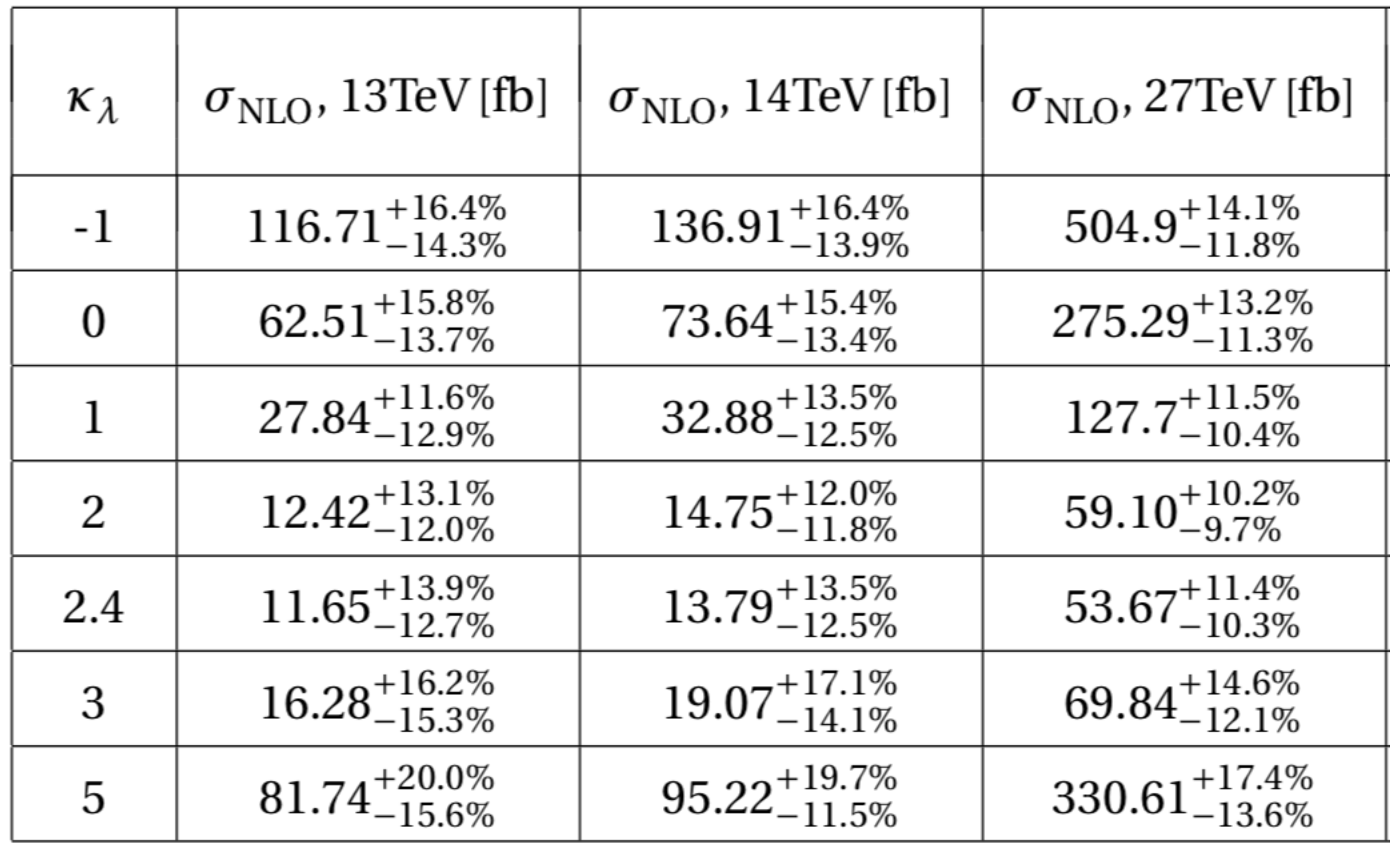
- High energy lepton colliders in the very high energy regime could become very powerful discovery machines
  - competitive with future hadronic colliders

Constraints on κ_λ







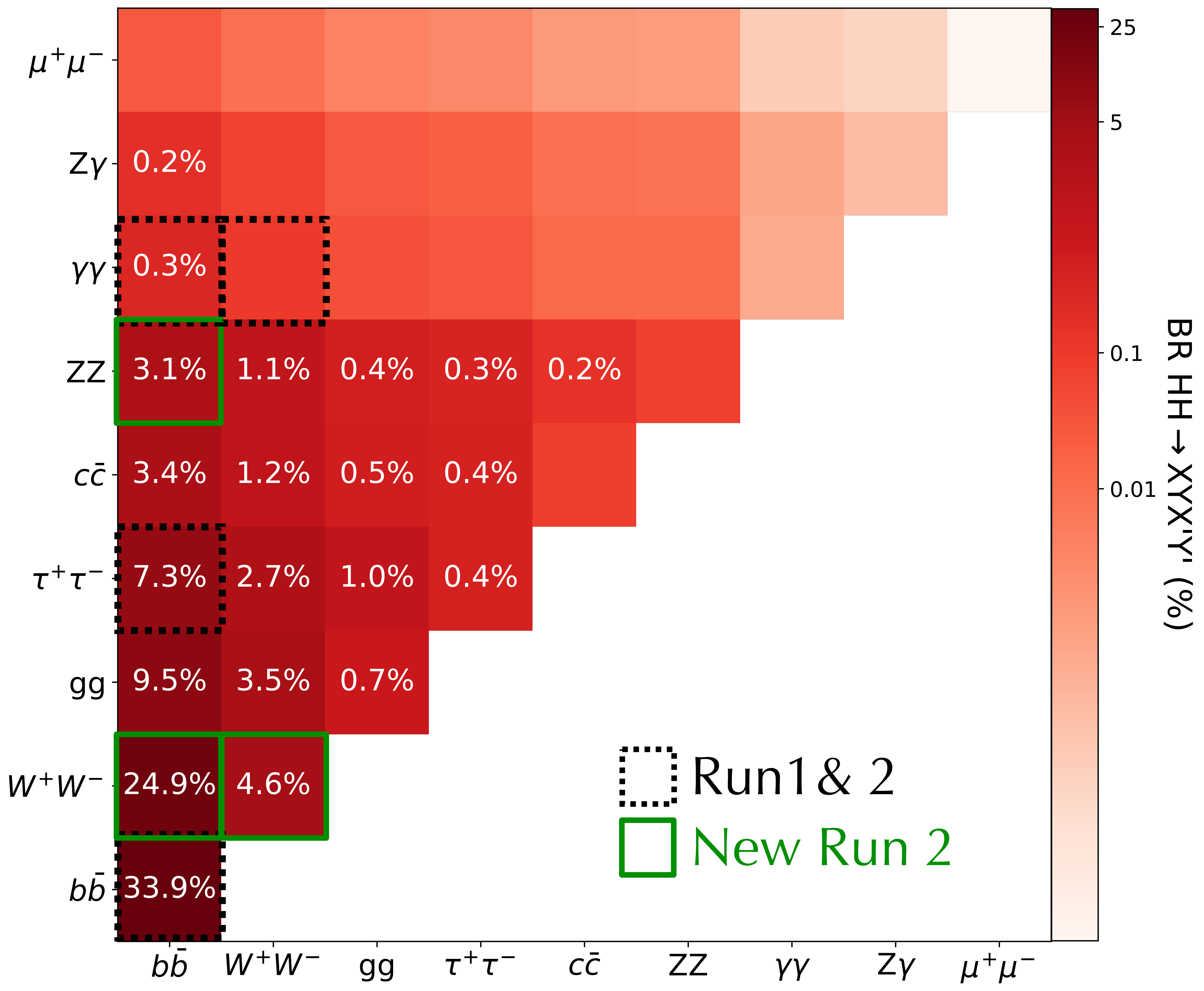


κ_λ	$\sigma_{\rm NLO}$, 13TeV [fb]	$\sigma_{\rm NLO}$, 14TeV [fb]	$\sigma_{\rm NLO}$, 27TeV [fb]
-1	$116.71^{+16.4\%}_{-14.3\%}$	$136.91^{+16.4\%}_{-13.9\%}$	$504.9^{+14.1\%}_{-11.8\%}$
0	$62.51^{+15.8\%}_{-13.7\%}$	$73.64^{+15.4\%}_{-13.4\%}$	$275.29^{+13.2\%}_{-11.3\%}$
1	$27.84^{+11.6\%}_{-12.9\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$
2	$12.42^{+13.1\%}_{-12.0\%}$	$14.75^{+12.0\%}_{-11.8\%}$	$59.10^{+10.2\%}_{-9.7\%}$
2.4	$11.65^{+13.9\%}_{-12.7\%}$	$13.79^{+13.5\%}_{-12.5\%}$	$53.67^{+11.4\%}_{-10.3\%}$
3	$16.28^{+16.2\%}_{-15.3\%}$	$19.07^{+17.1\%}_{-14.1\%}$	$69.84^{+14.6\%}_{-12.1\%}$
5	$81.74^{+20.0\%}_{-15.6\%}$	$95.22^{+19.7\%}_{-11.5\%}$	$330.61^{+17.4\%}_{-13.6\%}$

Besides affecting the cross section, BSM modifications to $\kappa_\lambda = \lambda/\lambda_{SM}$ affect the HH kinematic too (mainly m_{HH} and $p_{T,H}$)

HH, a variety of final states

arXiv:1910.00012



$H(b\bar{b})$ is a key element in the exploration of HH at the LHC

highest BR

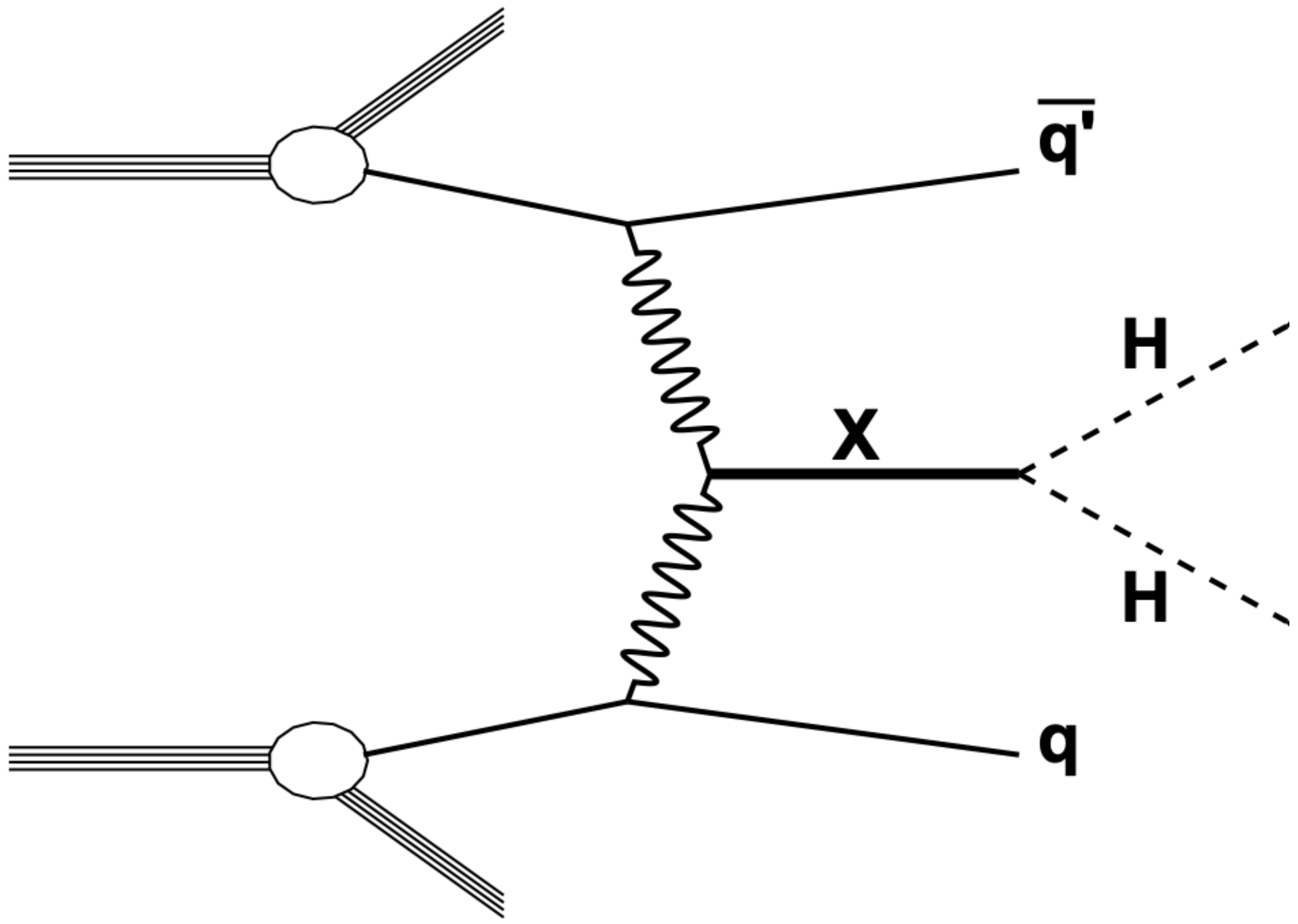
good b-jets identification performance: 70% efficiency at 0.3-1% q/g mistag probability

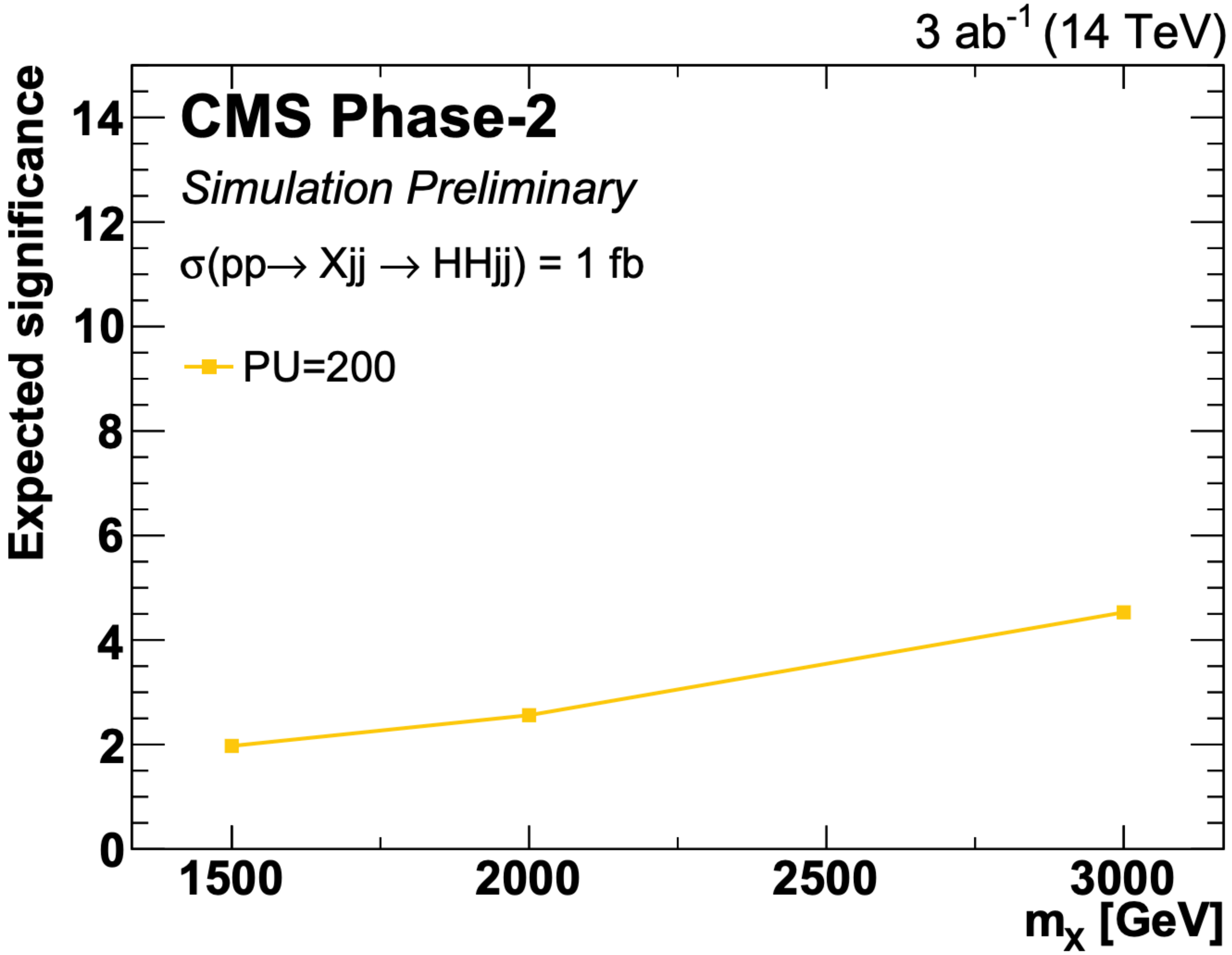
$H(\gamma\gamma)$

clean final state and great trigger and reconstruction efficiency of photons

excellent $m_{\gamma\gamma}$ resolution, ~1%

VBF X to HH





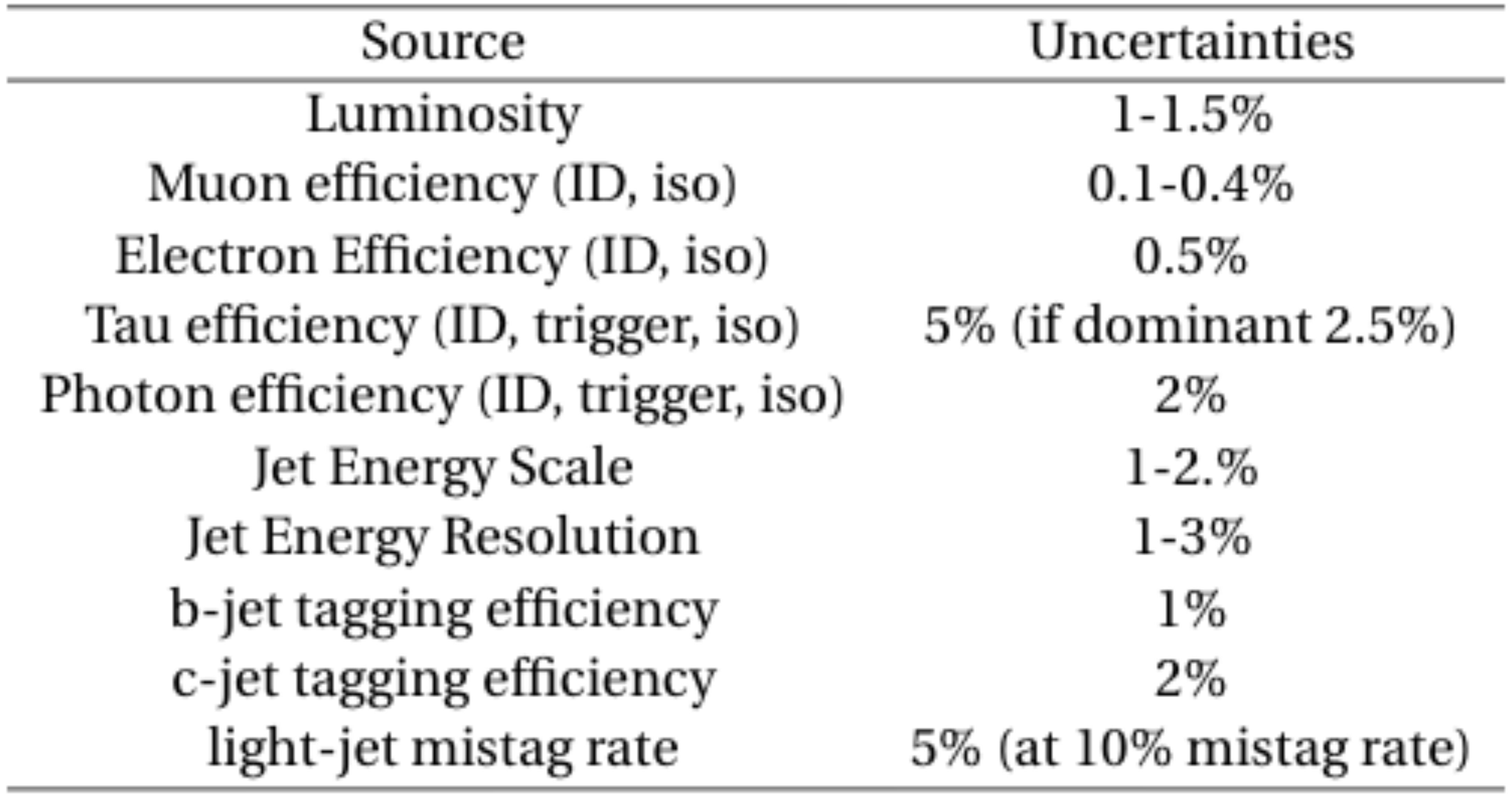
Exploring the bbbb final state

Systematic uncertainties

ArXiv:1902.00134
arXiv:1910.00012

Several assumptions have been made to model the systematic uncertainties

- **Theoretical** uncertainties have been assumed to be reduced by a factor of two with respect to those used in the Run 2 analyses, thanks to the expected developments in both higher-order calculation as well as in the reduction of PDF uncertainties.
- **Experimental** systematic uncertainties are assumed to scale as √L, until a pre-defined lower limit is reached
  - depending on the intrinsic detector limitations, according to detailed simulation studies of the upgraded detector.
  - It is assumed that the degradation due to higher pileup conditions will be compensated by improvements in the reconstruction algorithms



Source	Uncertainties
Luminosity	1-1.5%
Muon efficiency (ID, iso)	0.1-0.4%
Electron Efficiency (ID, iso)	0.5%
Tau efficiency (ID, trigger, iso)	5% (if dominant 2.5%)
Photon efficiency (ID, trigger, iso)	2%
Jet Energy Scale	1-2.%
Jet Energy Resolution	1-3%
b-jet tagging efficiency	1%
c-jet tagging efficiency	2%
light-jet mistag rate	5% (at 10% mistag rate)

Higgs & (SM?)EFT

see also C. Grojean's talk

- **EF01 will be working closely together with EF04 within the SMEFT framework:**
  - Estimate EFT uncertainties (NLO, dim-8 effects, linear vs quadratic…), new physics in backgrounds, theoretical constraints (positivity, analyticity)
  - More combined Higgs and top analysis
    1. effects of top dipoles or 4 fermion ops. with tops
    2. constraints on top EW couplings from their NLO effects in Higgs and diboson processes (particularly relevant for low-energy colliders below ttH threshold)
  - Include differential observables
  - Explore more flavor scenarios (and make connection with flavor data)
- SMEFT is a baseline, how we account for specific assumptions and model-dependency?
  - Complementarity with new physics searches