Higgs boson pair production searches in ATLAS

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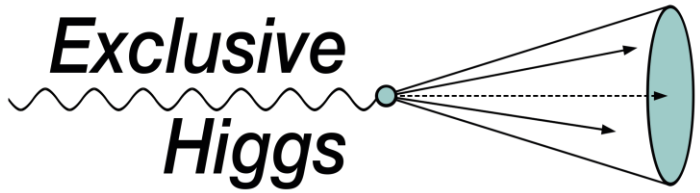
39th Conference on Recent Developments in High Energy Physics and Cosmology

UNIVERSITY OF BIRMINGHAM



This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement no 714893 (ExclusiveHiggs)

16/6/2022

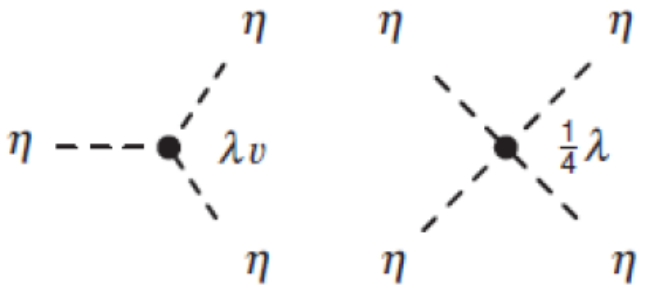
The Higgs potential

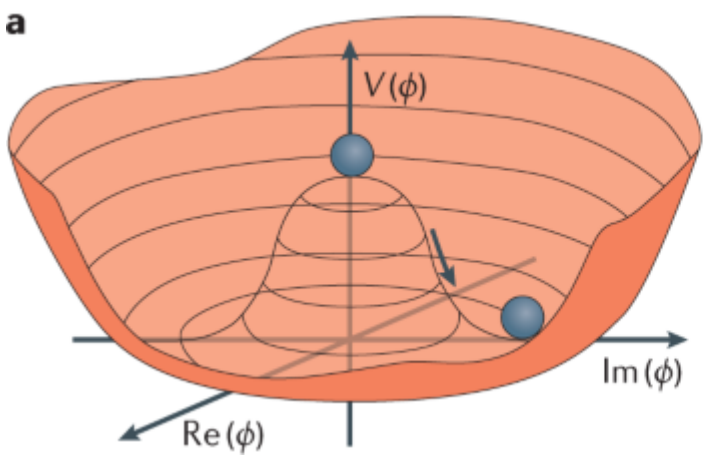
$$V(\phi)=\lambda v(\phi^*\phi)+\lambda(\phi^*\phi)^2$$

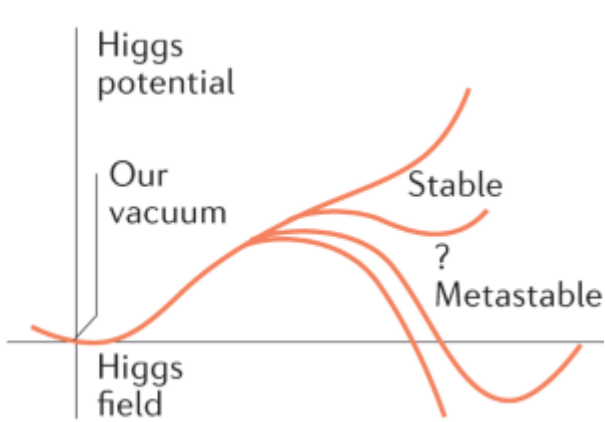
Spontaneous Symmetry Breaking

& Gauge Transformation

$$\frac{1}{2}\lambda v\eta^2+\lambda v\eta^3+\frac{1}{4}\lambda\eta^4$$





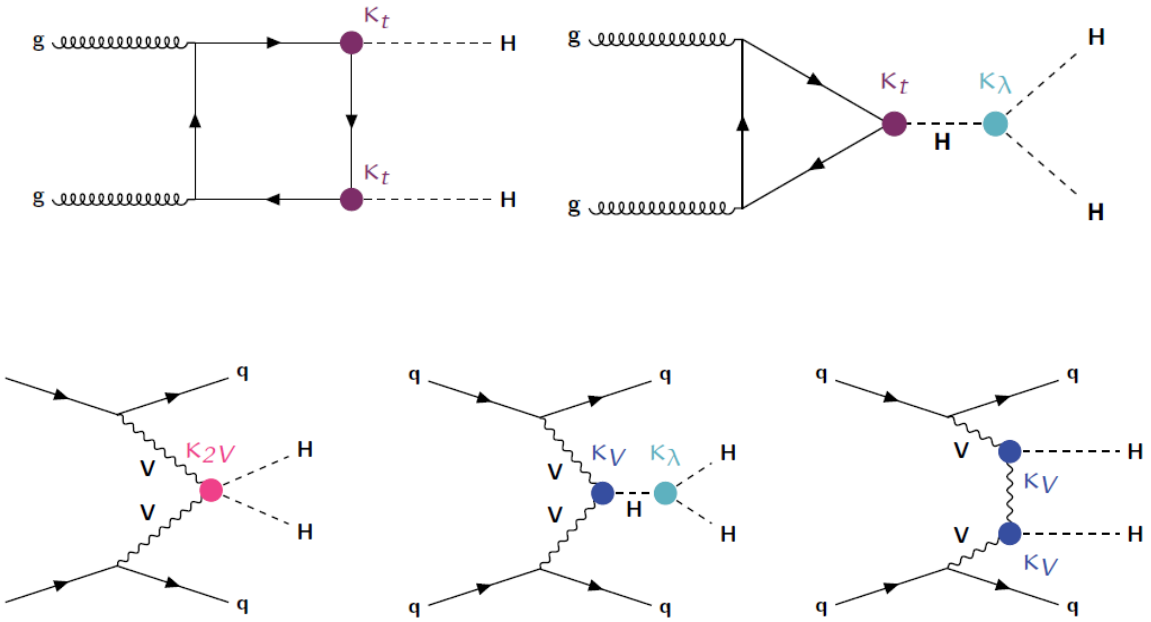


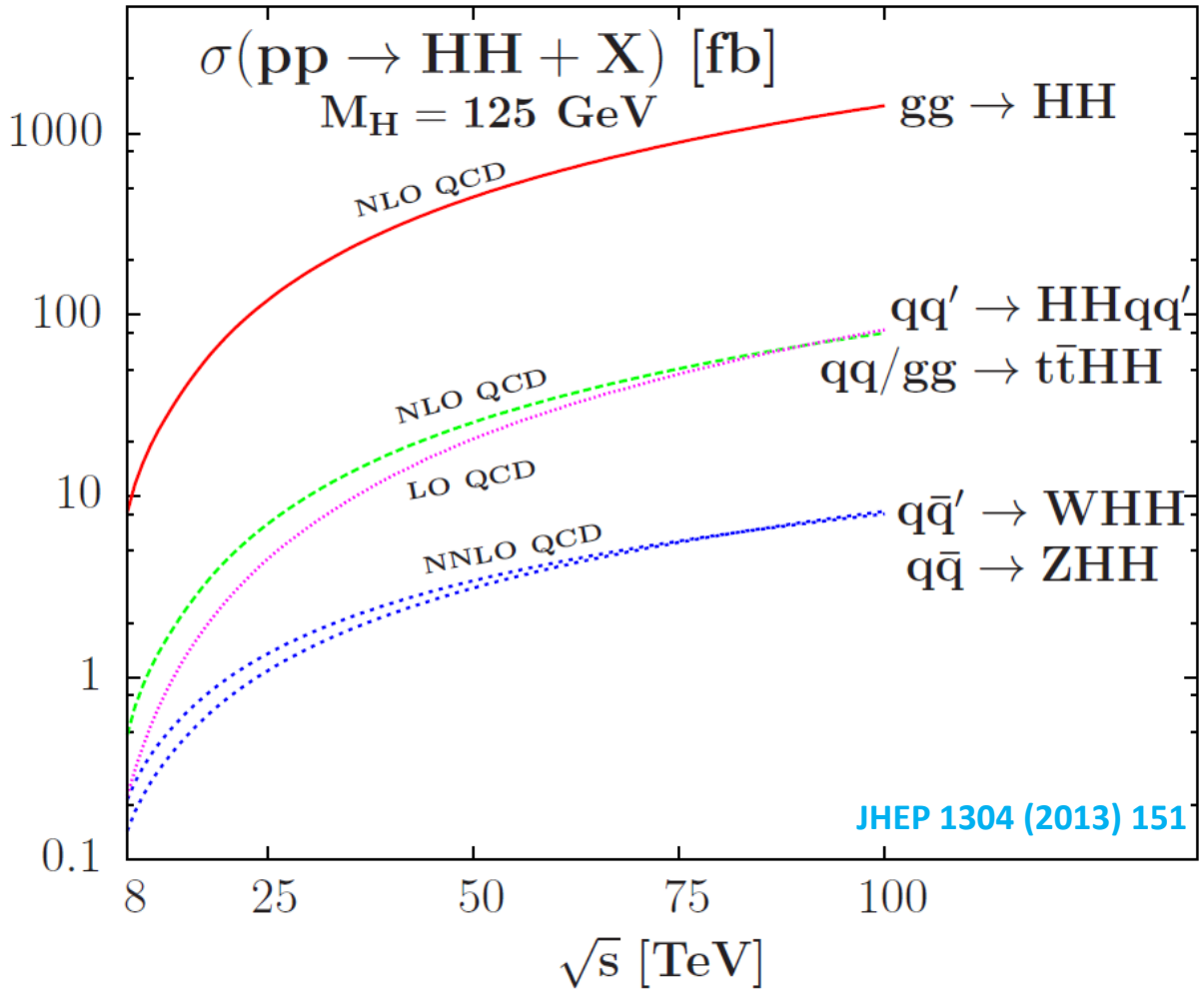
- **Higgs potential**
  - Vacuum expectation value υ & Higgs self coupling λ determine potential shape
  - Metastable universe may decay to "true" min
  - Various cosmological models predict consequences

$$\mathcal{L}=-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}+i\bar{\psi}\gamma^\mu D_\mu\psi+h.c.+\psi_i y_{ij}\psi_j\phi+h.c.+|\gamma^\mu D_\mu\phi|^2-V(\phi)$$

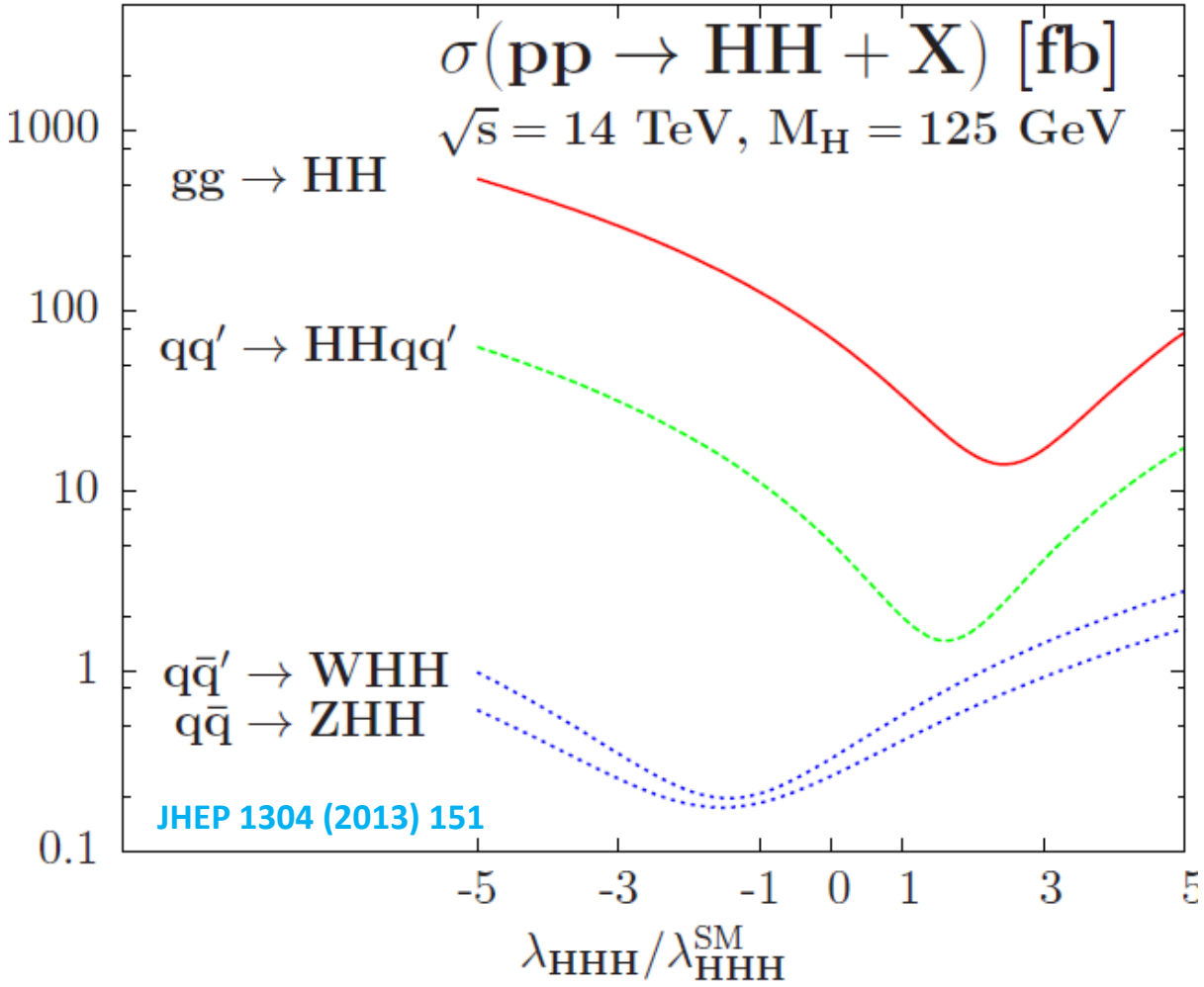
HH production

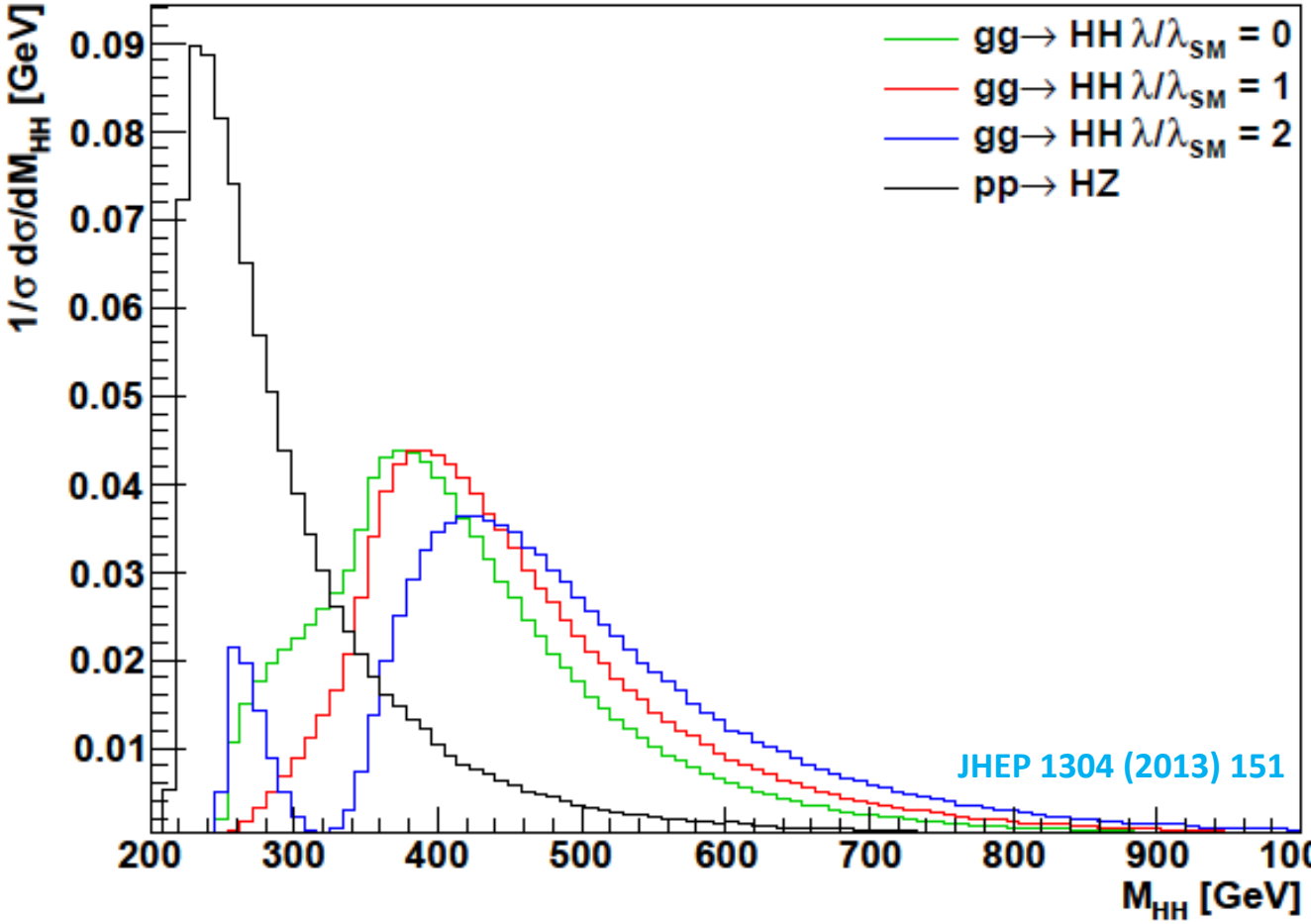
- **Several Di-Higgs production mechanisms**
  - ggF (~31 fb) and VBF (~1.7 fb) at 13 TeV
  - Total HH XS (~33 fb) and single H (~55 pb)

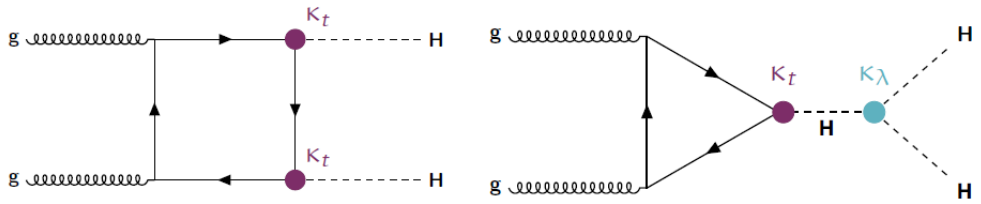




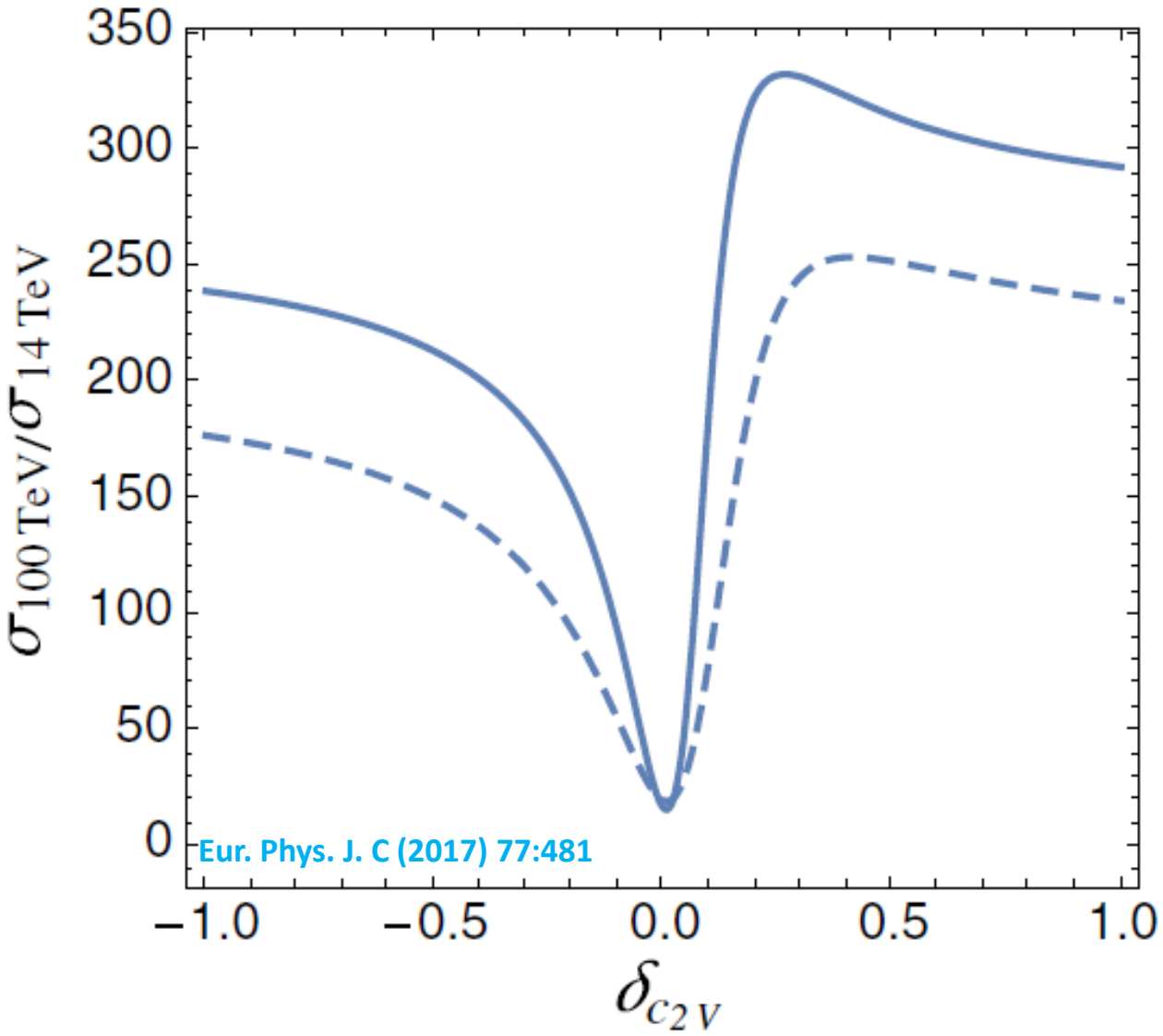
λ_{HHH}

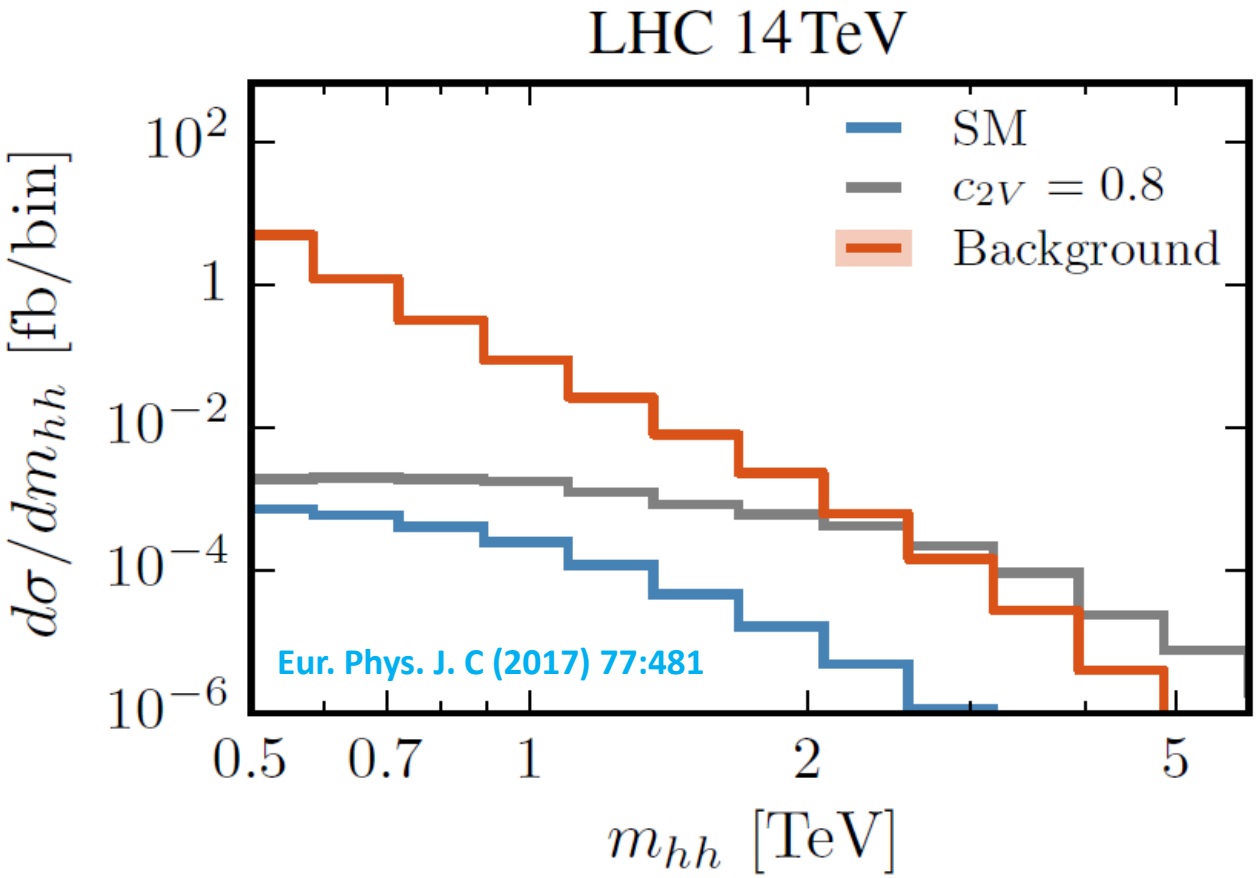

$\sigma(pp \to HH + X)$ [fb]
$\sqrt{s} = 14$ TeV, $M_H = 125$ GeV
$gg \to HH$
$qq' \to HHqq'$
$q\bar{q}' \to WHH$
$q\bar{q} \to ZHH$
JHEP 1304 (2013) 151
1000
100
10
1
0.1
-5
-3
-1
0
1
3
$\lambda_{HHH}/\lambda^{SM}_{HHH}$

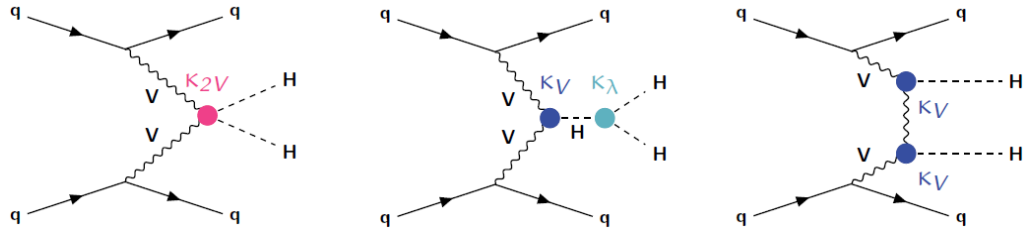

gg→ HH λ/λSM = 0
gg→ HH λ/λSM = 1
gg→ HH λ/λSM = 2
pp→ HZ
1/σ dσ/dMHH [GeV]
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
200
300
400
500
600
700
800
900
MHH [GeV]
JHEP 1304 (2013) 151


g
g
κ_t
κ_t
H
H
g
g
κ_t
κ_λ
H
H
H

C_{2V}

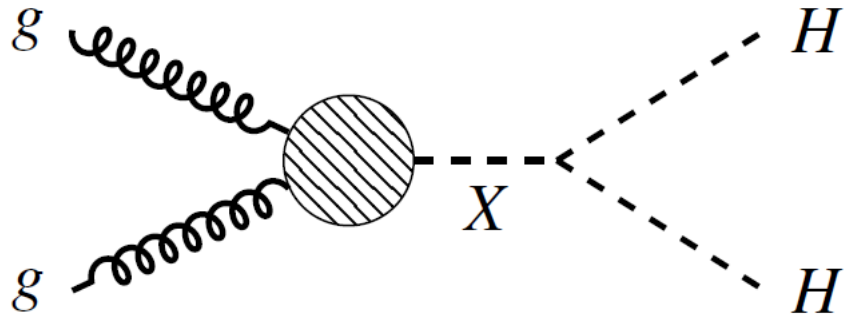

350
300
250
200
150
100
50
0
−1.0
−0.5
0.0
0.5
1.0
$\sigma_{100\,\mathrm{TeV}}/\sigma_{14\,\mathrm{TeV}}$
$\delta_{c_{2V}}$
Eur. Phys. J. C (2017) 77:481


LHC 14 TeV
SM
$c_{2V} = 0.8$
Background
10^2
1
10^{-2}
10^{-4}
10^{-6}
0.5
0.7
1
2
5
$d\sigma/dm_{hh}$ [fb/bin]
m_{hh} [TeV]
Eur. Phys. J. C (2017) 77:481


q
V
H
κ_{2V}
κ_V
κ_λ

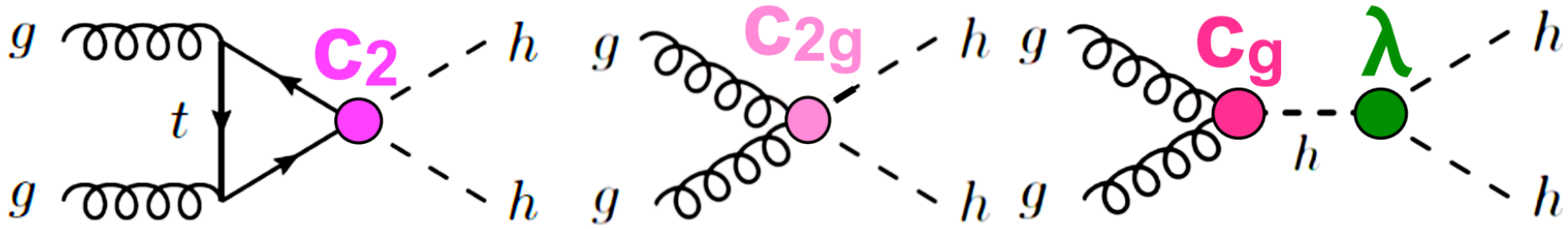
BSM

- **BSM physics can appear via**
  - Any discrepancy in coupling values wrt SM
  - New resonances
  - Anomalous couplings



- **BSM models with high mass resonances decaying to HH**
  - 2HDM
  - Radions
  - hMSSM
  - Warped extra dimensions
  - Composite Higgs

- **New couplings in the EFT framework**



Decay channels

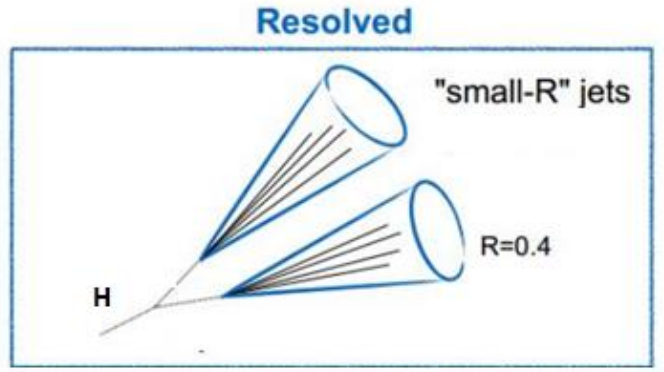
Channel	Lumi (fb^{-1})	Reference
4b	139	Phys. Rev. D 105, 092002 ATLAS-CONF-2022-035 JHEP 07 (2020) 108
2b2τ	139	ATLAS-CONF-2021-030 JHEP 11 (2020) 163
2b2γ	139	arXiv:2112.11876
2blvlv	139	arXiv:1908.0676
2b2W	139	Phys. Lett. B 801 (2020) 135145
comb	139	ATLAS-CONF-2021-052
4W	36	JHEP 05 (2019) 124
2W2γ	36	EPJC 78 (2018) 1007

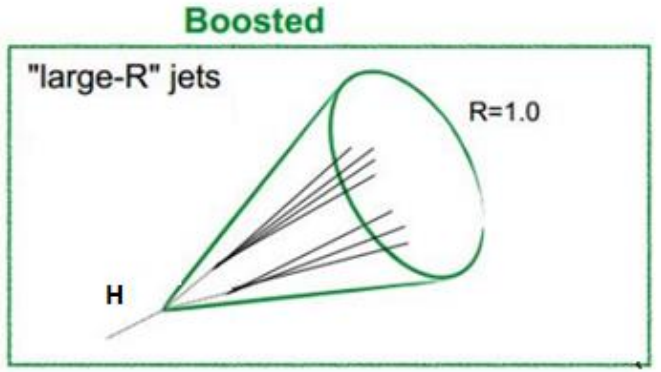
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

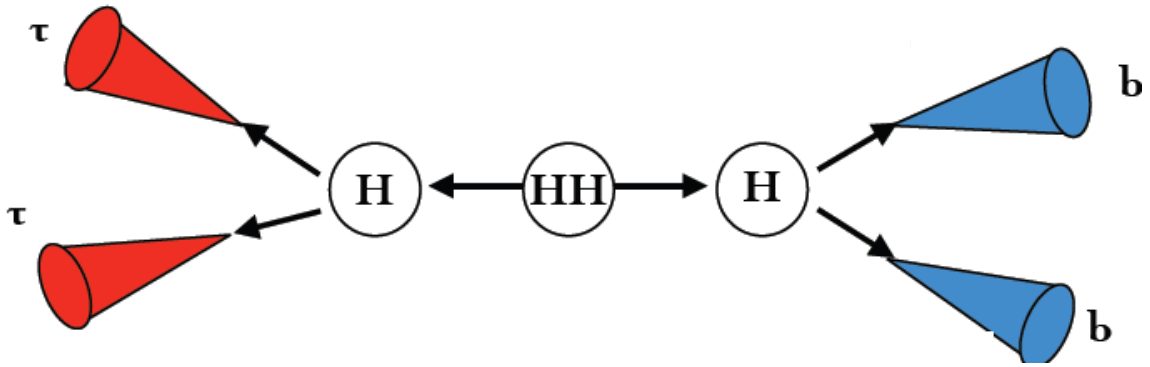
bbττ

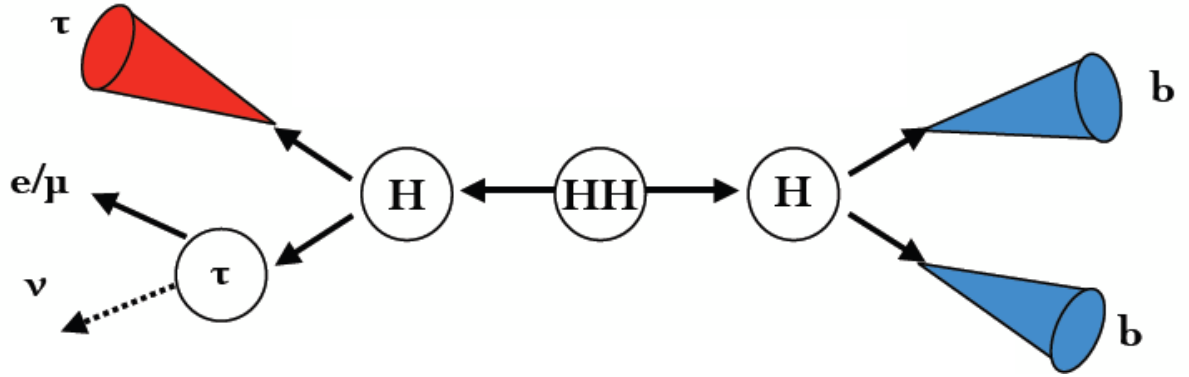
- **bbττ decay channel main features**
  - Considerable branching ratio (7%)
  - Moderate bkg contamination
  - Challenging had τ reco and triggering
  - Neutrinos in τ decays
  - hadhad & lephad channels

- **Di-Higgs according to event topology**
  - Boosted & Resolved
  - Current bbττ is inclusive



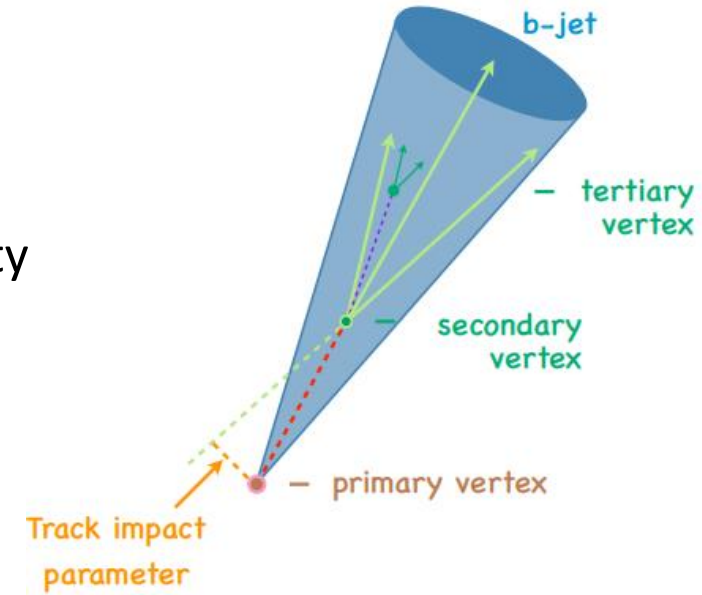






b-tagging

- **b - quark**
  - Long lifetime
  - High mass
  - Large decay multiplicity

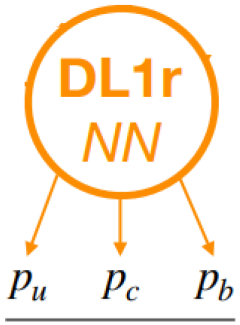


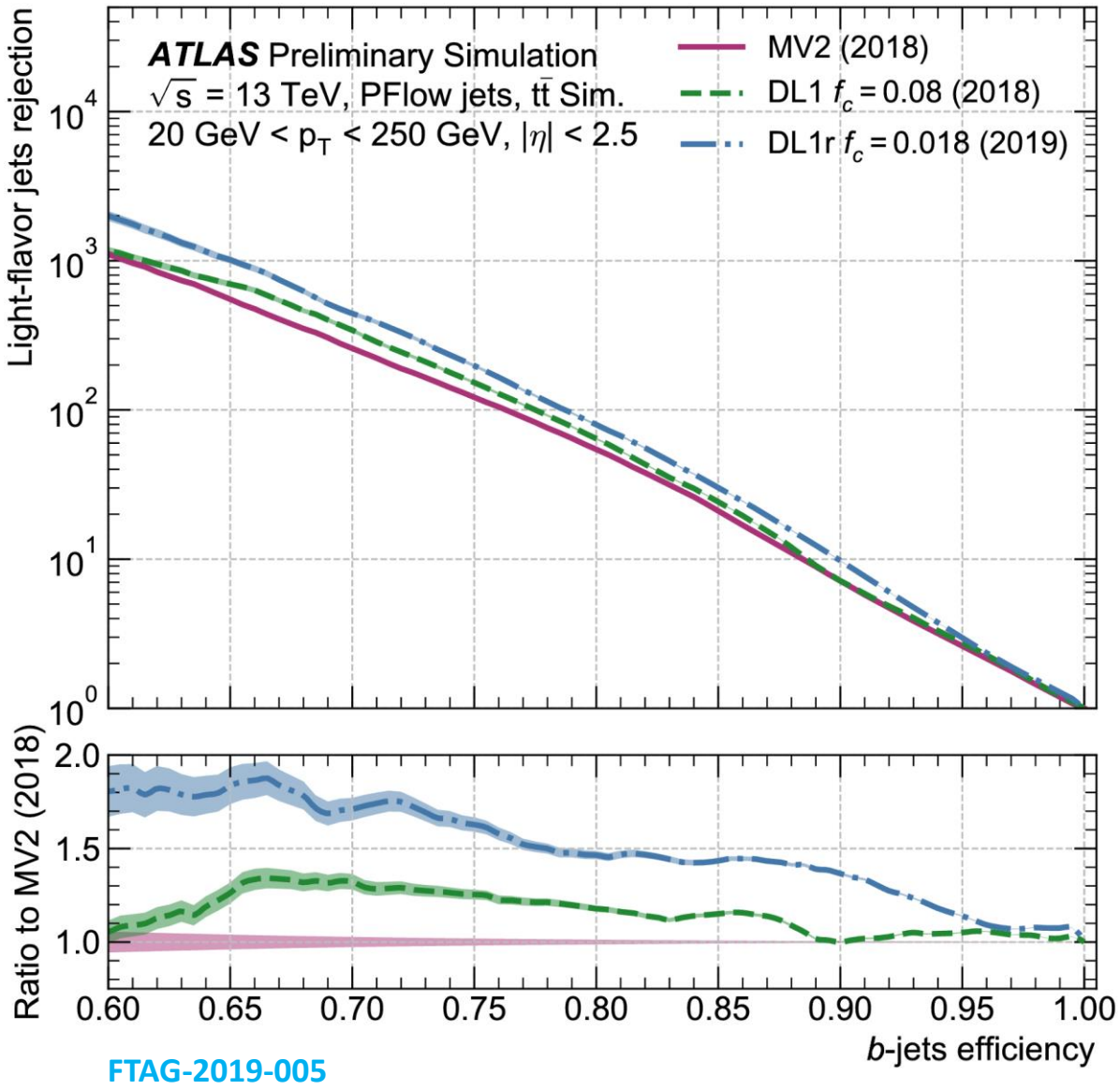
Impact Parameter based (IP2D,IP3D)

NN based on track parameters (RNNIP)

Topological secondary and tertiary vertices (JetFitter)

Inclusive secondary vertex (SV1)

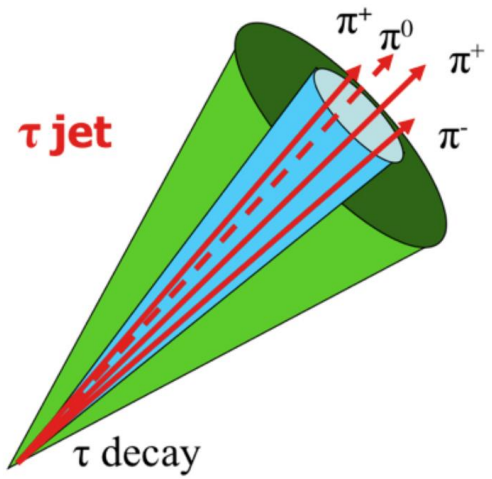


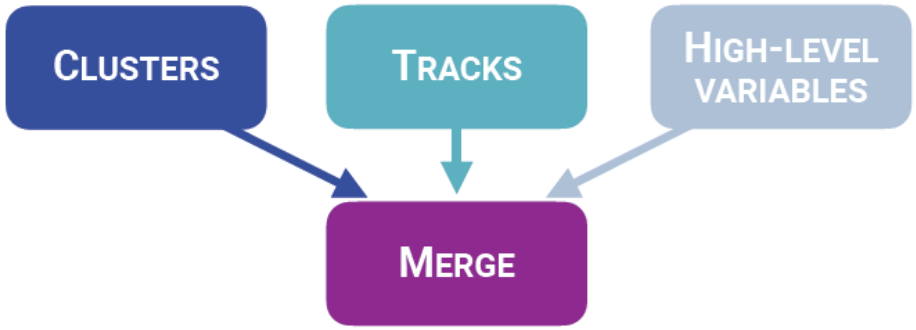


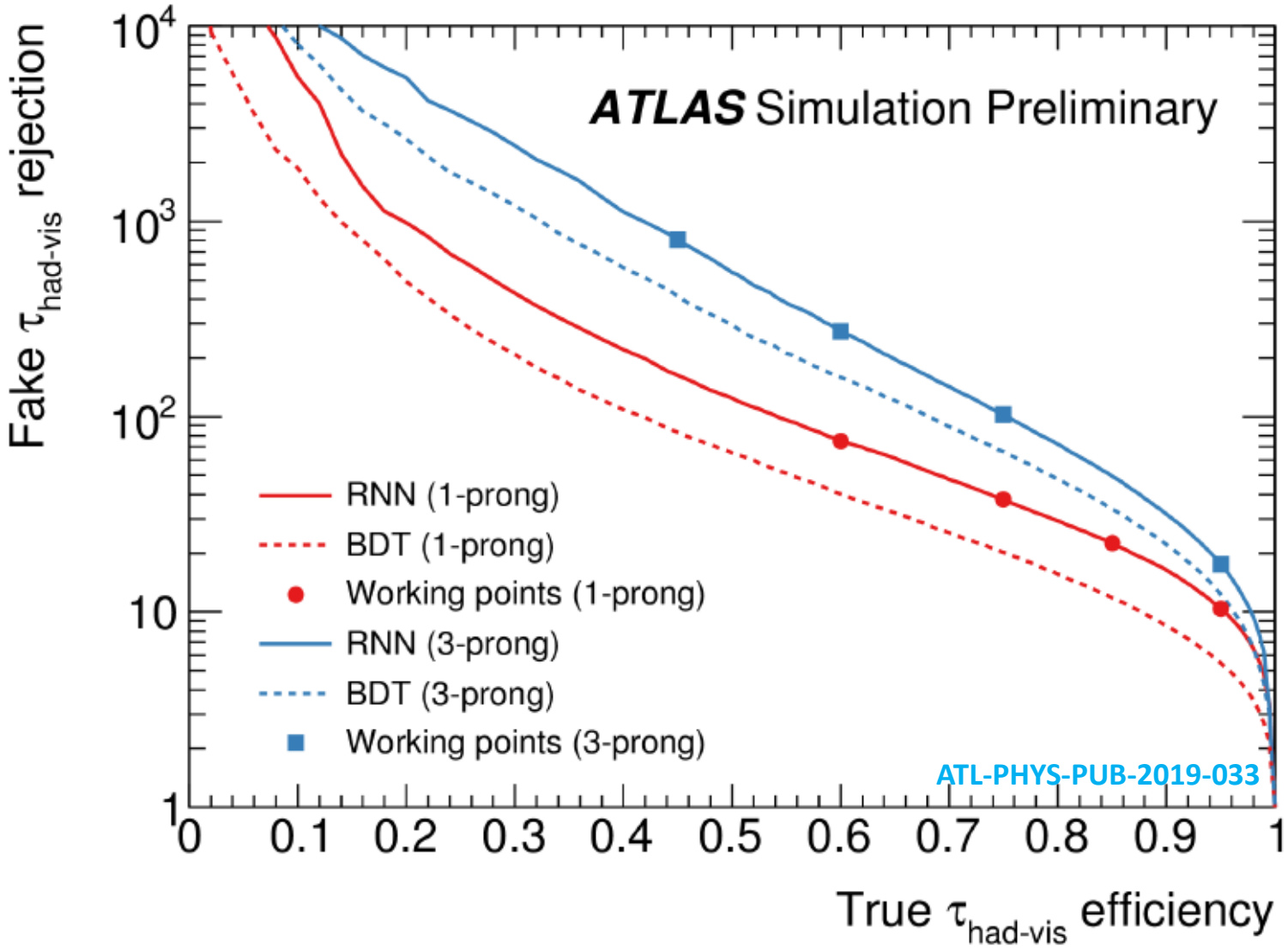
FTAG-2019-005

tau-jets

- **Tau**
  - Very collimated products
  - Low track multiplicity
  - Displaced secondary vertex

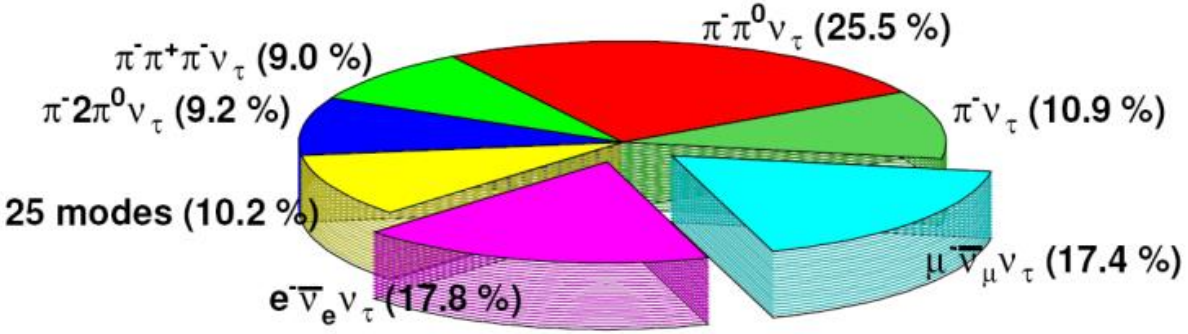


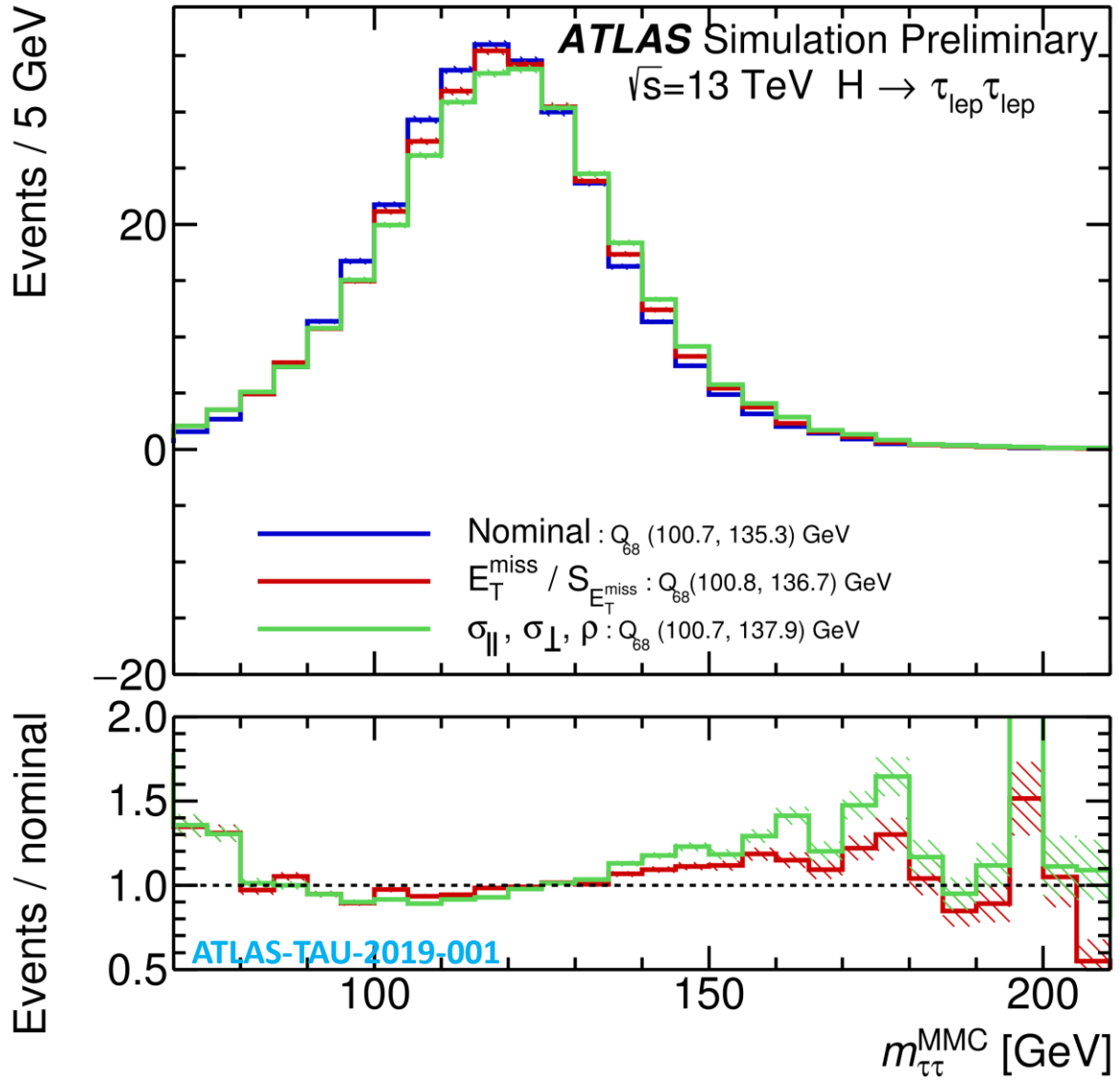




Missing Mass Calculator

- **MMC**
  - Invisible p_x, p_y, p_z for each τ
  - Not all of them calculatable
  - Global event likelihood to provide additional constraints





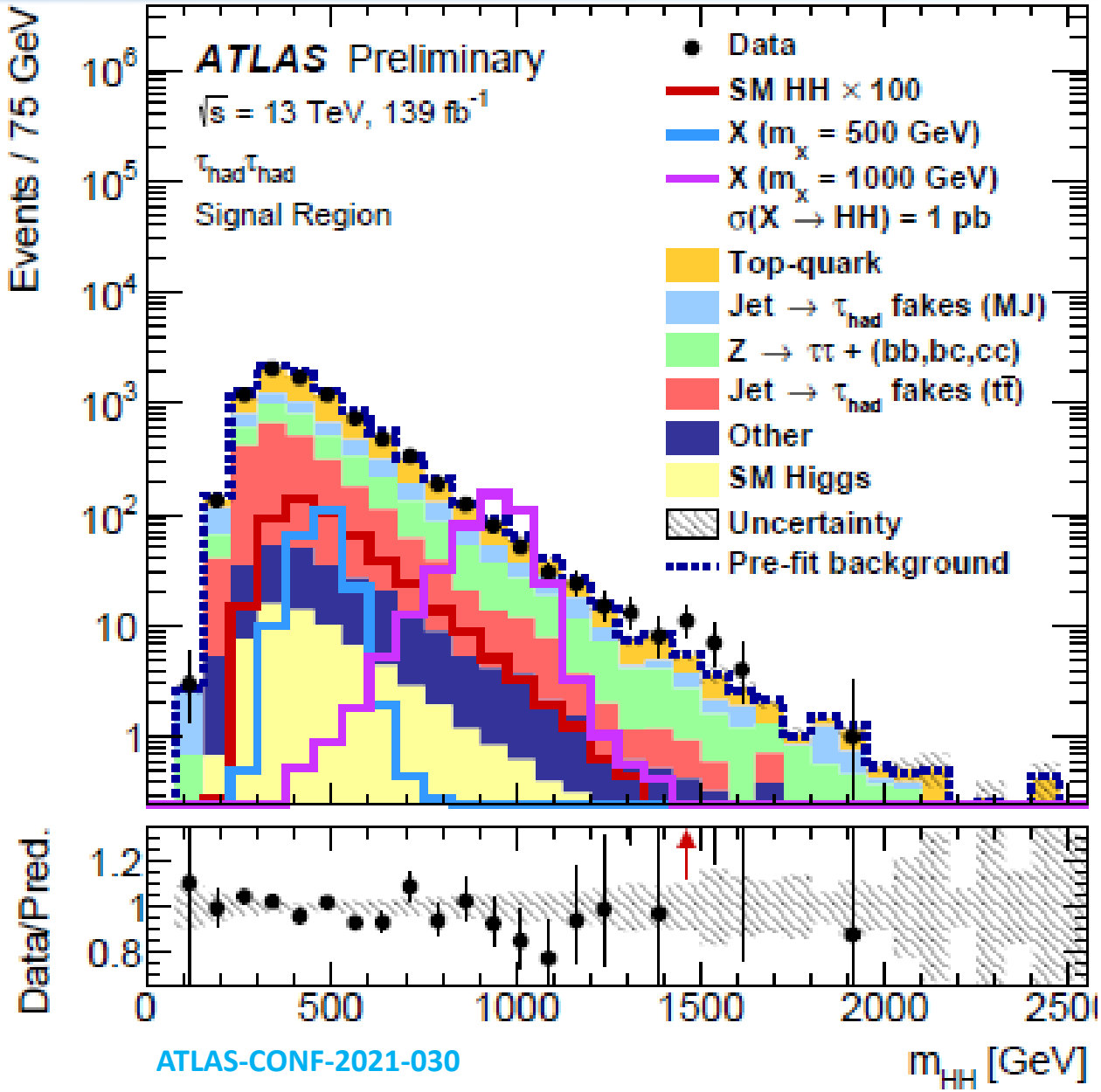
Event Selection

$\tau_{had}\tau_{had}$ category		$\tau_{lep}\tau_{had}$ categories	
single-τ trigger STT	di-τ trigger DTT	single-lepton trigger SLT	lepton-τ trigger LTT
e/μ selection			
No loose e/μ with $p_T > 7$ GeV		Exactly one tight e or medium μ	
		$p_T^e > 25, 27$ GeV	18 GeV $< p_T^e <$ SLT cut
		$p_T^\mu > 21, 27$ GeV	15 GeV $< p_T^\mu <$ SLT cut
		$\lvert\eta^e\rvert < 2.47$, not $1.37 < \lvert\eta^e\rvert < 1.52$	
		$\lvert\eta^\mu\rvert < 2.7$	
$\tau_{had\text{-}vis}$ selection			
Two loose $\tau_{had\text{-}vis}$		One loose $\tau_{had\text{-}vis}$	
$\lvert\eta\rvert < 2.5$		$\lvert\eta\rvert < 2.3$	
$p_T > 100, 140, 180\ (25)$ GeV	$p_T > 40\ (30)$ GeV	$p_T > 20$ GeV	$p_T > 30$ GeV
Jet selection			
≥ 2 jets with $\lvert\eta\rvert < 2.5$			
$p_T > 45\ (20)$ GeV	Trigger dependent	$p_T > 45\ (20)$ GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{MMC} > 60$ GeV			
Opposite-sign electric charges of $e/\mu/\tau_{had\text{-}vis}$ and $\tau_{had\text{-}vis}$			
Exactly two b-tagged jets			
			$m_{bb} < 150$ GeV

Bkgs

- **Several bkg contributions**
  - Top quark : MC shape – Fit norm
  - Z→ττ + heavy flavour: MC shape – Z+HFjets CR norm
  - Multi-jet (fake) Data-driven fake-factor method
  - tt (fake): Data-driven mis-ID efficiency SF to MC
  - Single Higgs : MC
  - Others : MC

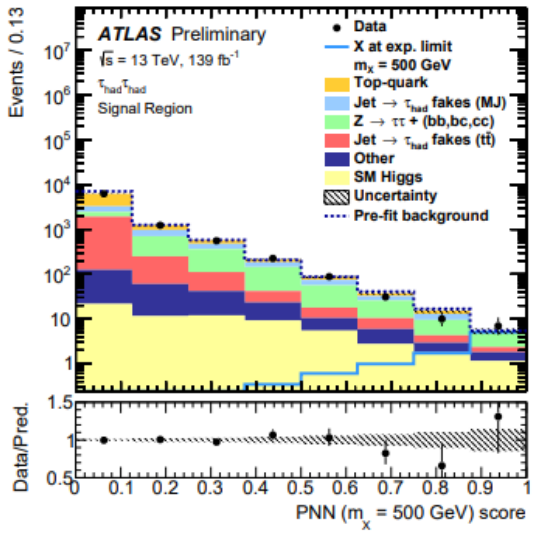
- **Very small signal to bkg ratio for SM HH**
  - lephad SLT → 6 / 100k
  - hephad LTT → 1.5 / 7k
  - hadhad → 5.5 / 10k

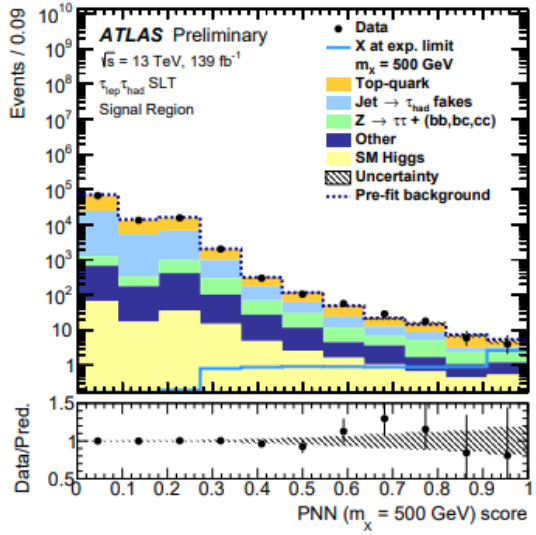


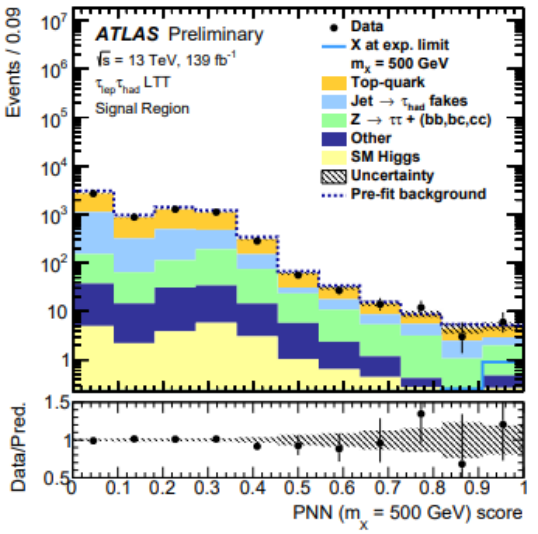
ATLAS-CONF-2021-030

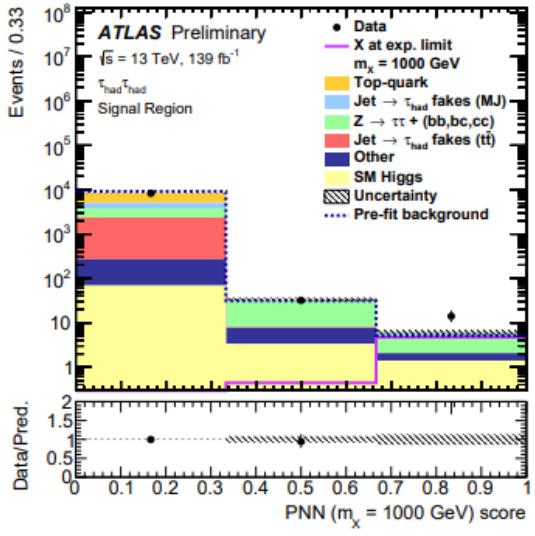
Multivariate analysis

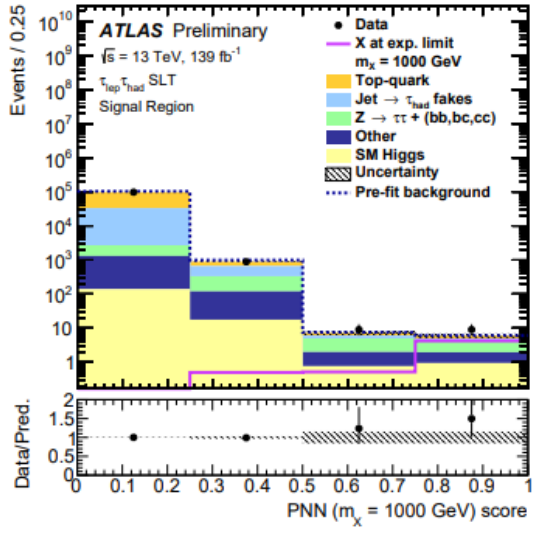
Variable	h-h	l-h SLT	l-h LTT
m_{HH}	√	√	√
$m_{\tau\tau}^{MMC}$	√	√	√
m_{bb}	√	√	√
$\Delta R(\tau,\tau)$	√	√	√
$\Delta R(b,b)$	√	√	
$\Delta p_T(l,\tau)$		√	√
$bjet_2\ p_T$		√	
$m^W{}_T$		√	
E_T^{miss}		√	
p_T^{miss} φ cen/ty		√	
$\Delta\varphi(\tau\tau,bb)$		√	
$\Delta\varphi(l, p_T^{miss})$			√
$\Delta\varphi(l\tau, p_T^{miss})$			√
H_T			√

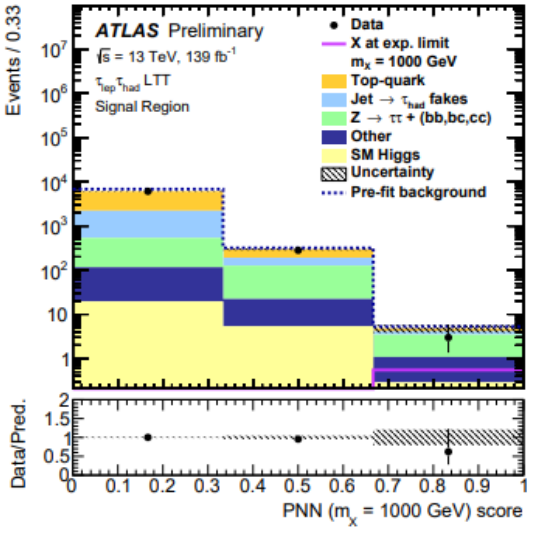










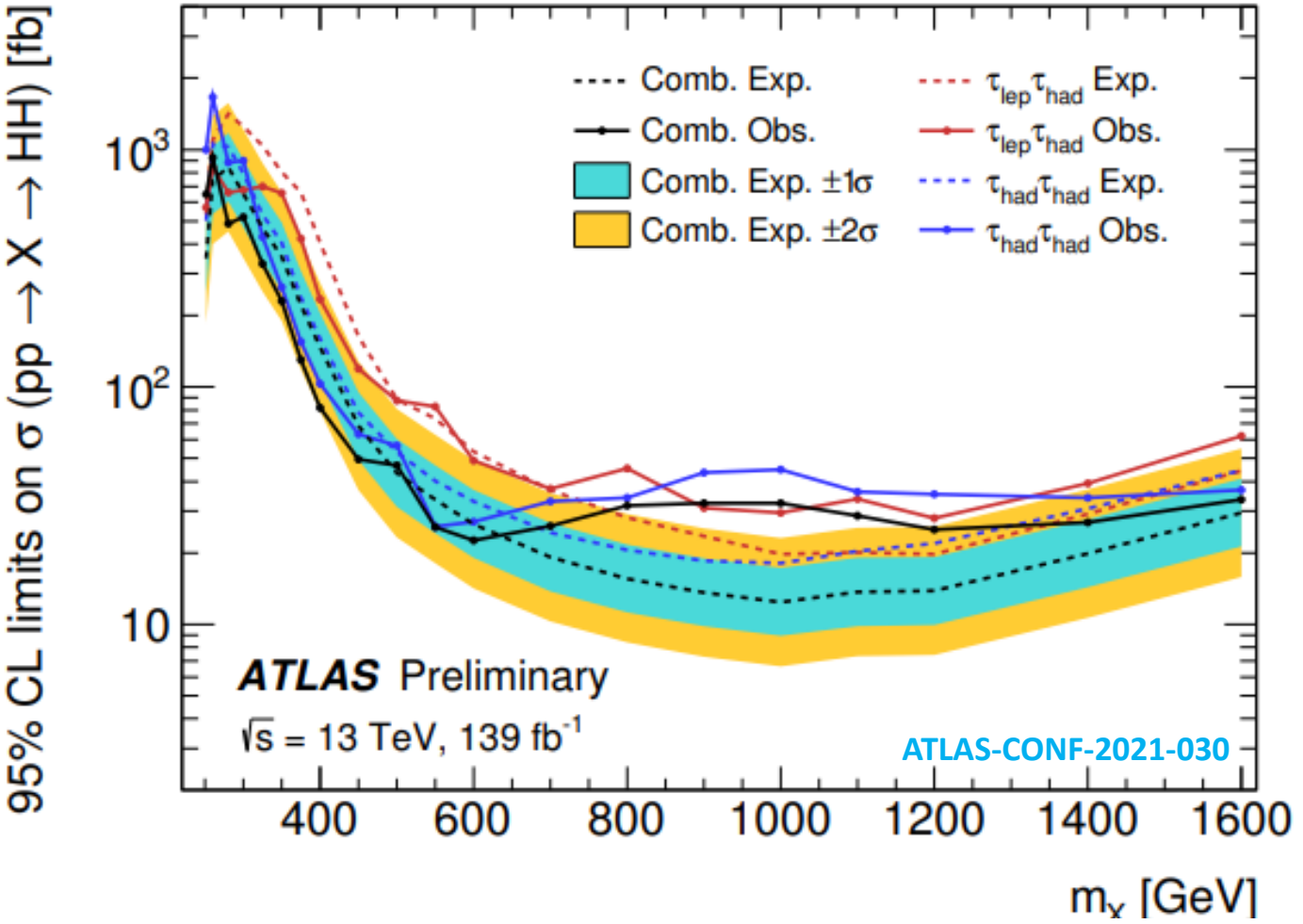


ATLAS-CONF-2021-030

Results

- **Excess around 1 TeV**
  - Local significance = 3.0 σ
  - Global significance = 2.0 σ

- **SM HH limit**
  - 3.87 @ 95% CL
  - New no-resonant analysis in progress



		Observed	−2 σ	−1 σ	Expected	+1 σ	+2 σ
Combined	$\sigma_{ggF+VBF}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.65	2.08	2.79	3.87	5.39	7.22

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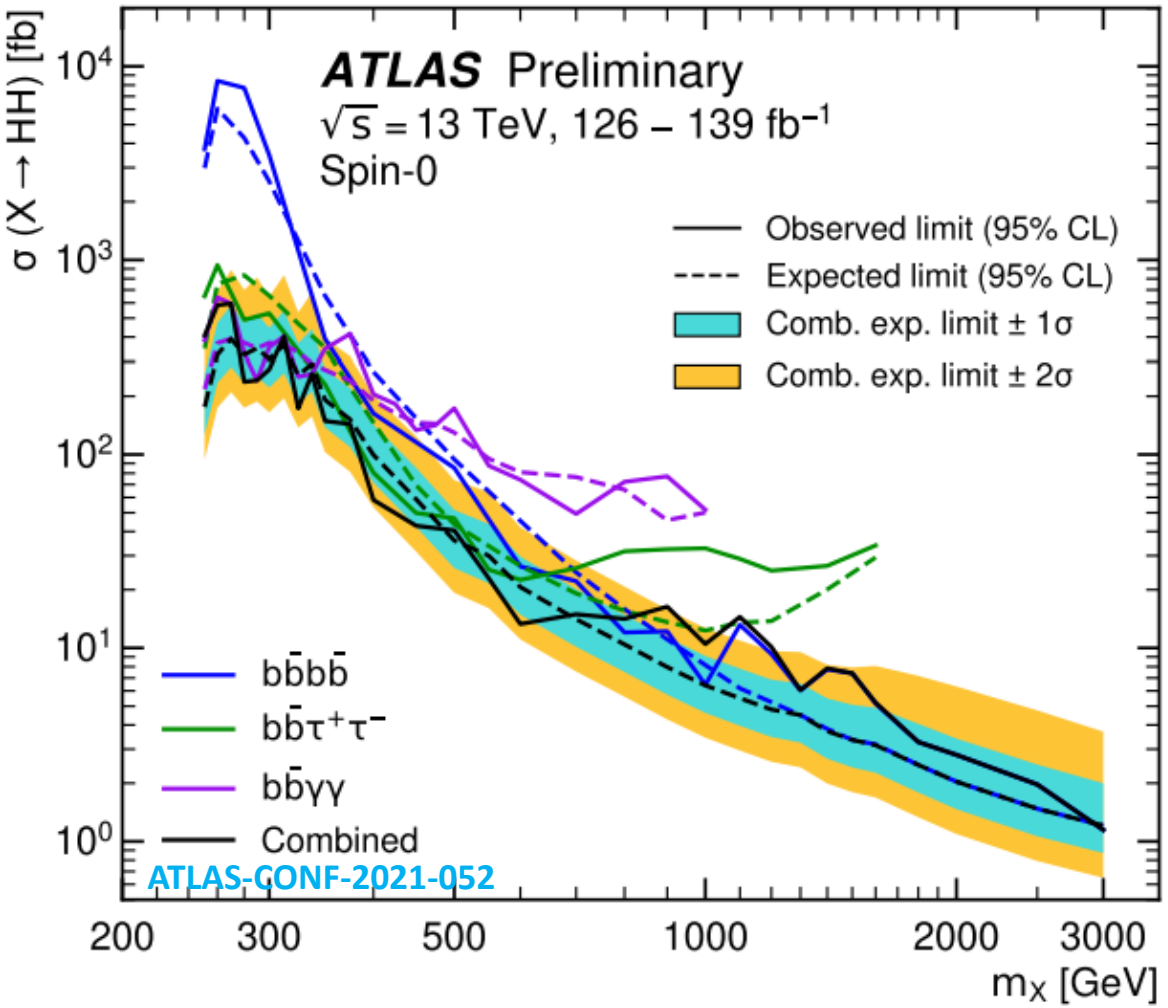
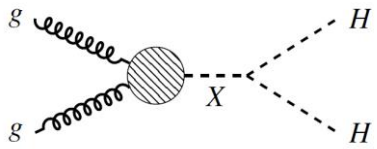
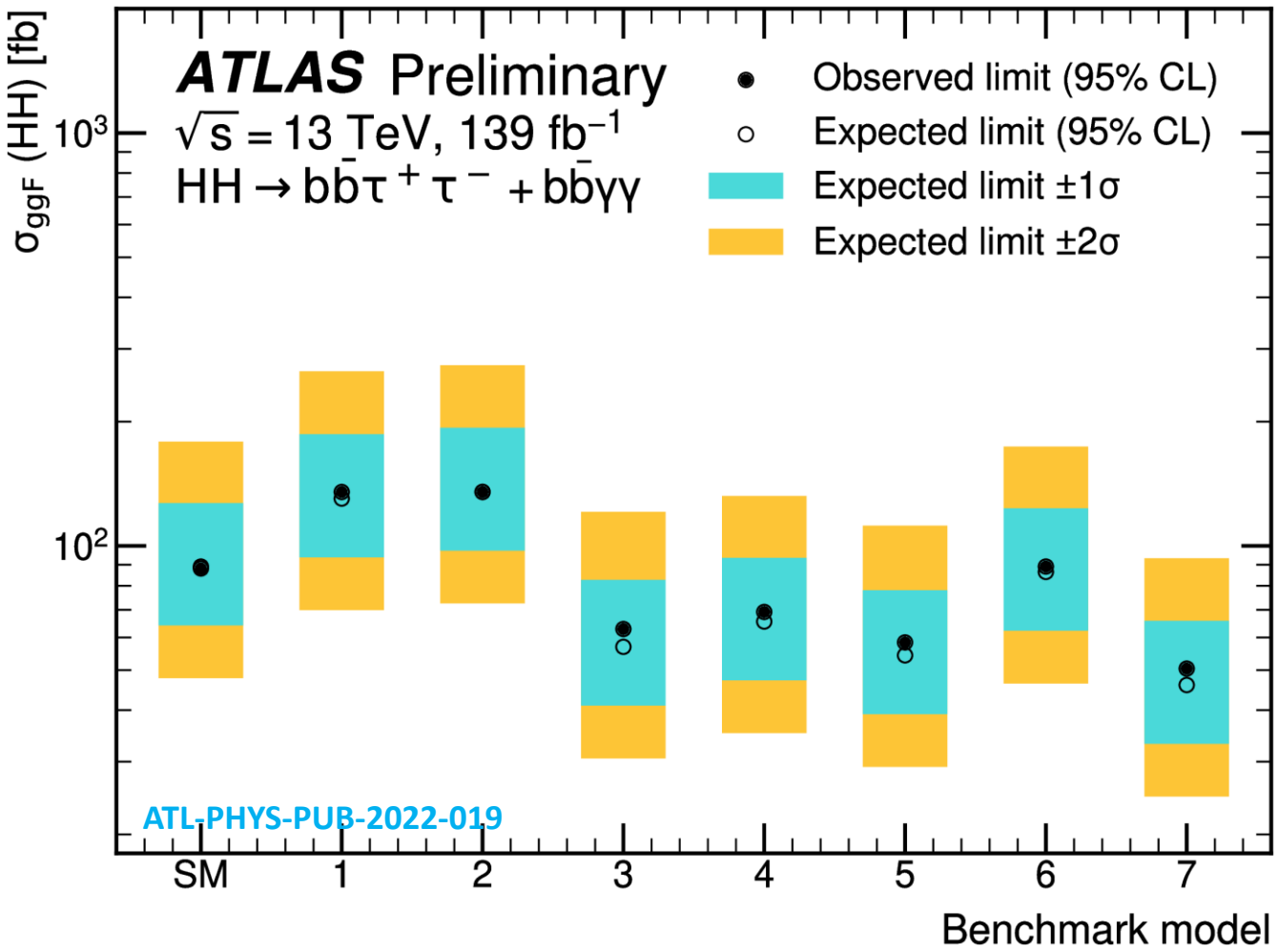
Systematics

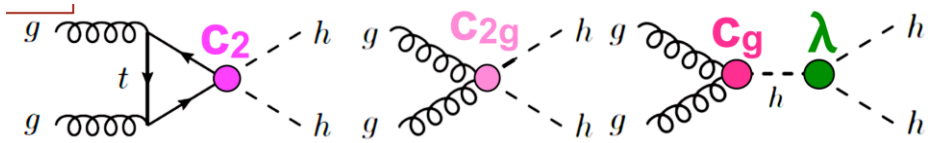
Uncertainty source	Non-resonant HH	Resonant $X \to HH$ 300 GeV	500 GeV	1000 GeV
Data statistical	81%	75%	89%	88%
Systematic	59%	66%	46%	48%
$t\bar{t}$ and Z + HF normalisations	4%	15%	3%	3%
MC statistical	28%	44%	33%	18%
Experimental				
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	7%	28%	5%	3%
b-jet tagging	3%	6%	3%	3%
$\tau_{\text{had-vis}}$	5%	13%	3%	7%
Electrons and muons	2%	3%	2%	1%
Luminosity and pileup	3%	2%	2%	5%
Theoretical and modelling				
Fake-$\tau_{\text{had-vis}}$	9%	22%	8%	7%
Top-quark	24%	17%	15%	8%
$Z(\to \tau\tau)$ + HF	9%	17%	9%	15%
Single Higgs boson	29%	2%	15%	14%
Other backgrounds	3%	2%	5%	3%
Signal	5%	15%	13%	34%

Combined results

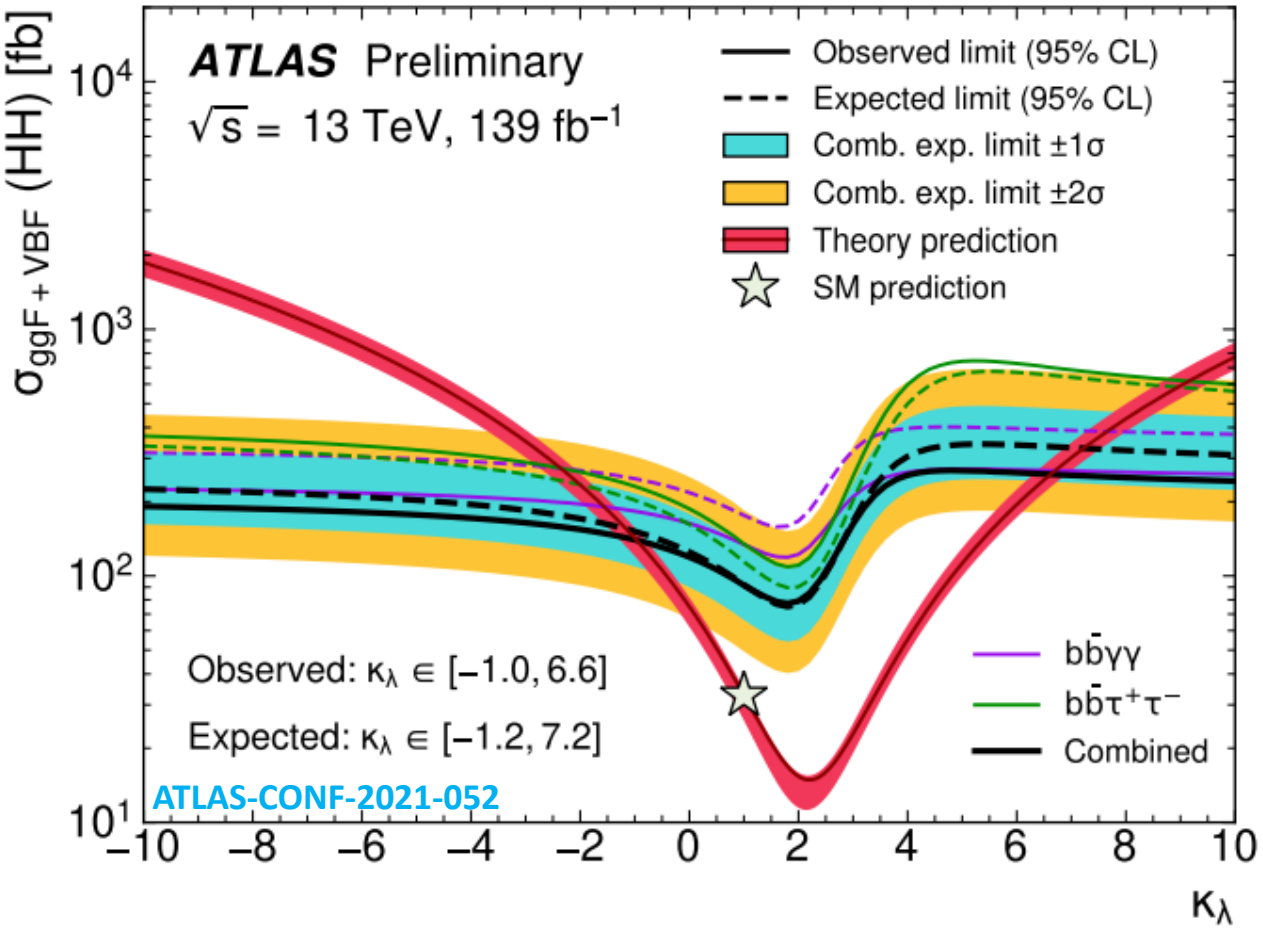


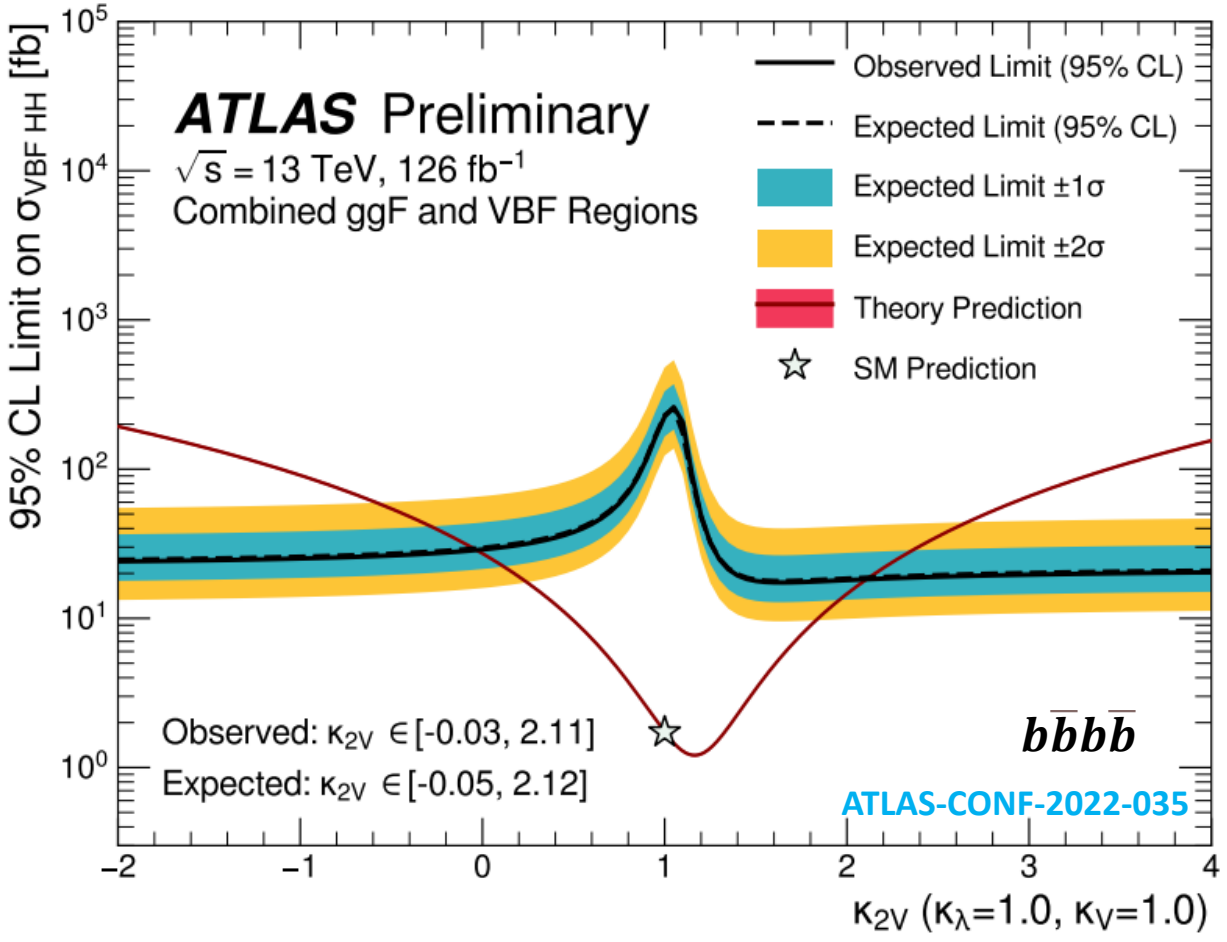


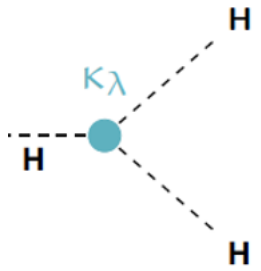


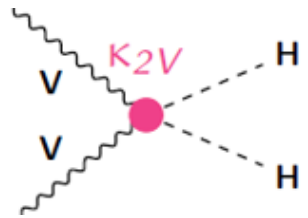


Combined results







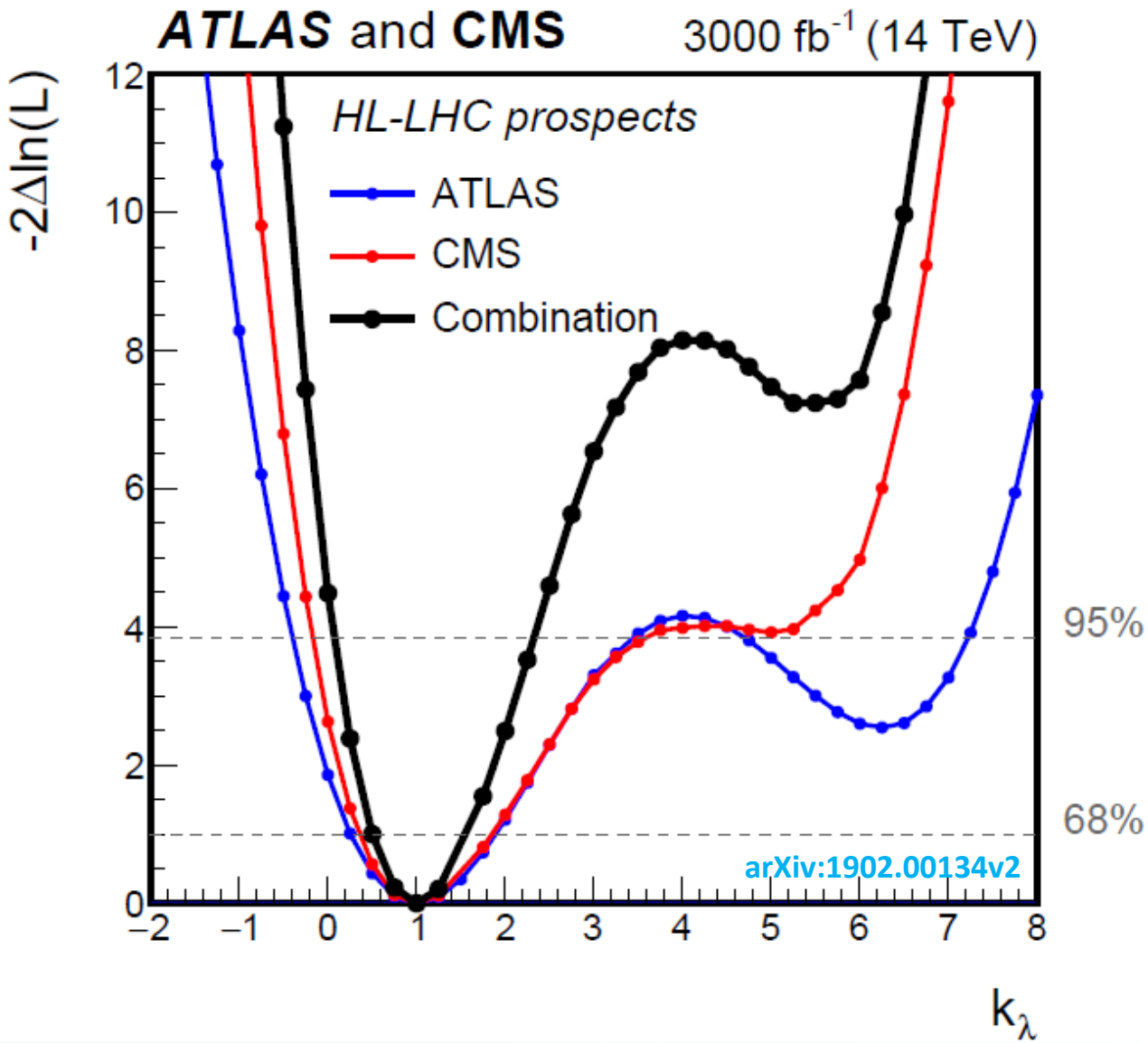


HL-LHC Prospects

- **HL-HLC**
  - 3000 fb^{-1} ATLAS + CMS combination
  - HH observation with 4σ significance
  - $0.1 < \kappa_\lambda < 2.3$ @ 95% CL

	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		Combined	
	4.5		4.0	

arXiv:1902.00134v2



Summary

- **Di-Higgs studies are essential**
  - Uncover Higgs potential shape
  - Measure λ and c_{2v} Higgs couplings
  - Search for BSM resonances
  - Probe BSM effects

- **bbττ one of the most sensitive channels**
  - Resonant analysis recently completed
  - A 3.0(2.0)σ excess found around 1 TeV
  - Non resonant analysis is in progress

- **Future prospects**
  - More channels, production modes, topologies, etc
  - Combination
  - Run 3 & HL-LHC