THE HIGGS SELF-COUPLING

How did the Universe originate and how will it eventually evolve?

Valentina Maria Martina Cairo

CERN

THEORY

Direct measurement of the Higgs self-coupling via HH

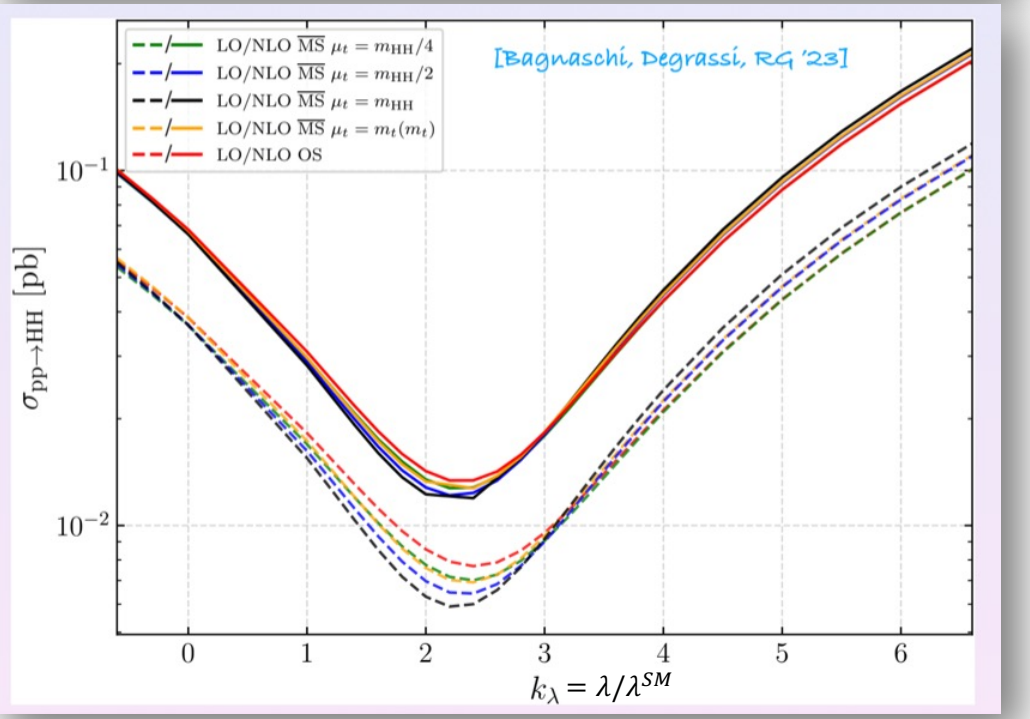
R. Gröber's talk

23.09.24

- Requirement of precise predictions: not so simple, it is a multi-scale problem, still large uncertainties

for Monte Carlo a analytic approach is useful and can be sufficiently precise

New POWHEG implementation

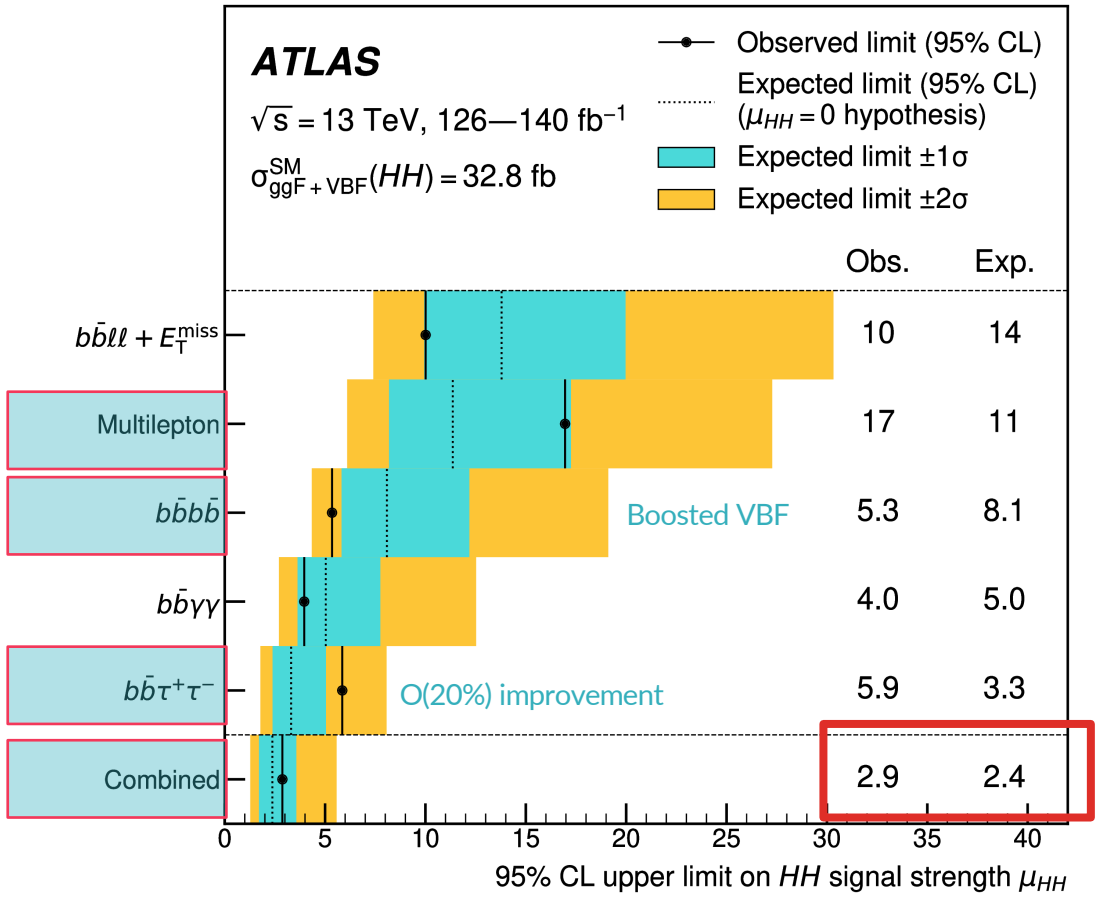


HH CROSS SECTION

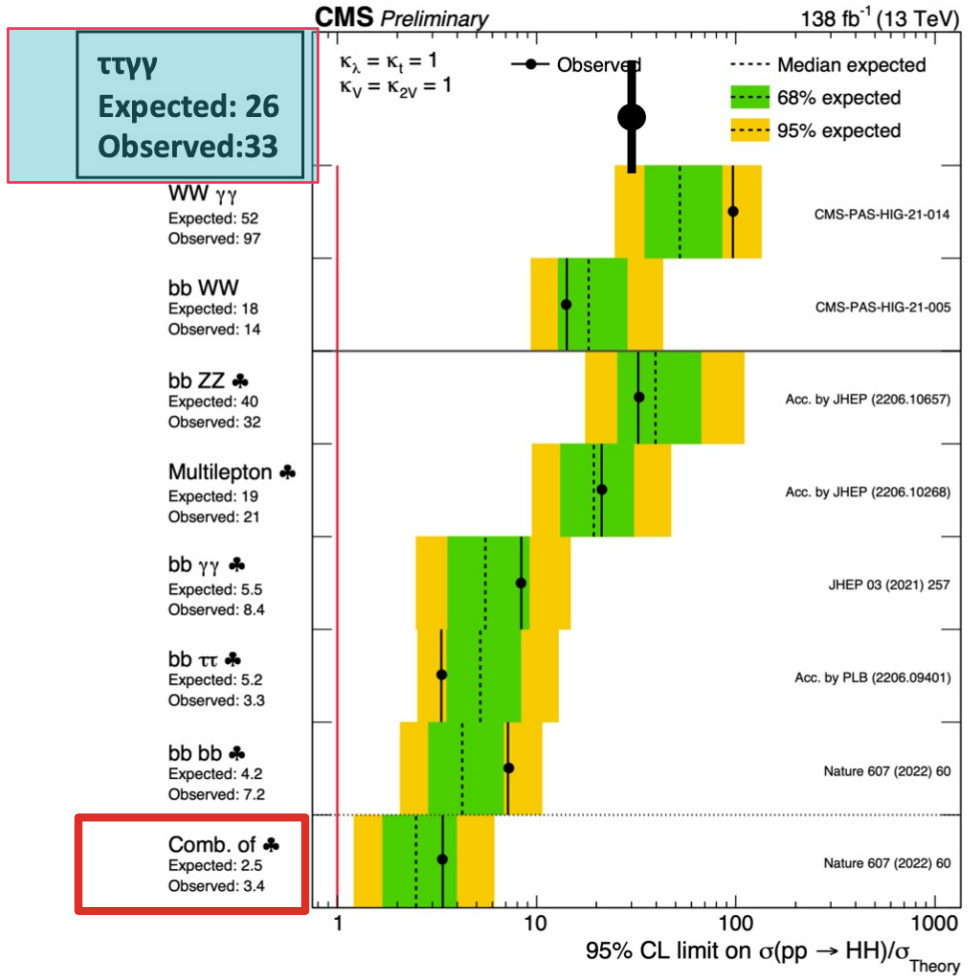
Z. Liang's talk, A. Bethani's talk

Legend:
New from HH2023

23.09.24



Phys. Rev. Lett. 133 (2024) 101801



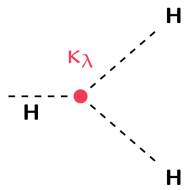
CMSPublic/SummaryResultsHIG

COUPLINGS

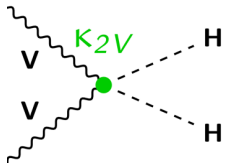
Z. Liang's talk, A. Bethani's talk

Legend:
New from HH2023

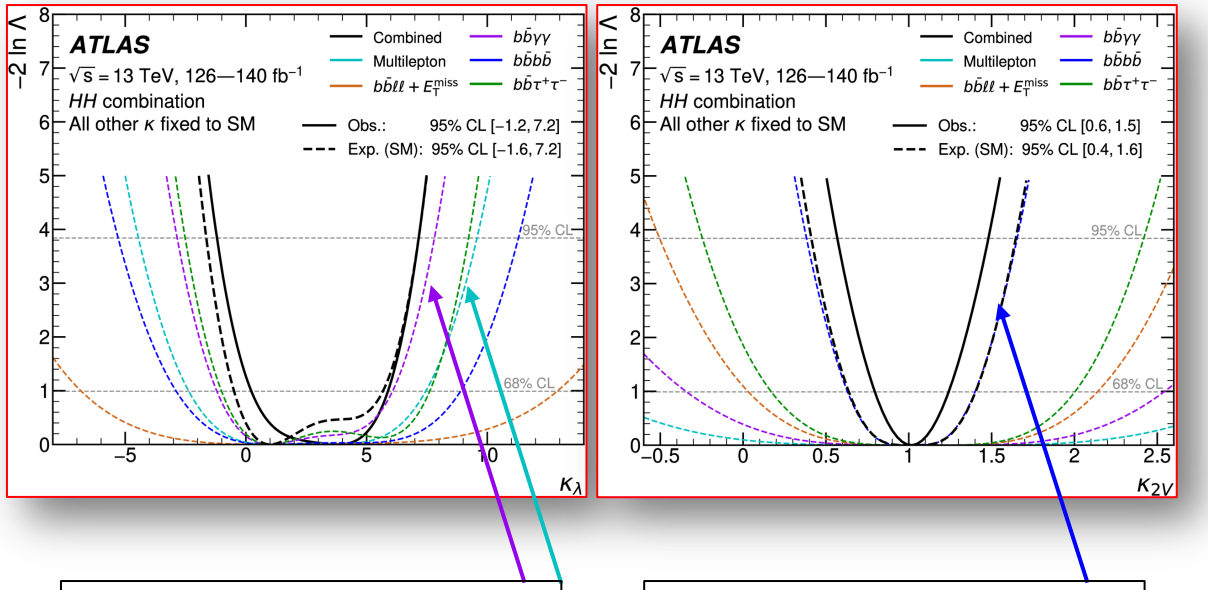
23.09.24



ATLAS
HH
Phys. Rev. Lett. 133 (2024) 101801

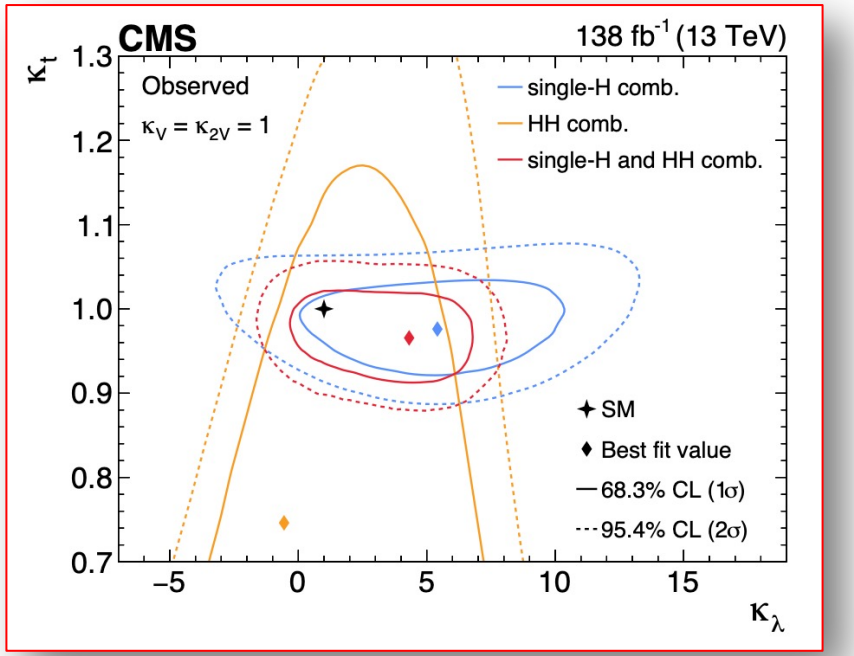


CMS
H+HH
https://arxiv.org/pdf/2407.13554



Photon and lepton triggers powerful at low m_{HH}

Boosted hadronic signatures powerful at high m_{HH}



Latest observed (expected) constraints on k_λ at 95% CL: **ATLAS [-1.2;7.2] (-1.6;7.2), CMS [-1.2;7.5] (-2.0;7.7)**

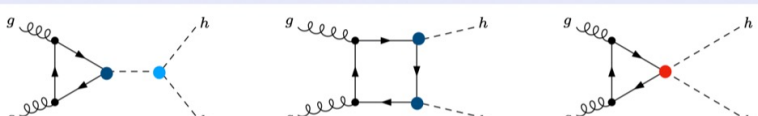
EFFECTIVE FIELD THEORIES

R. Gröber's talk

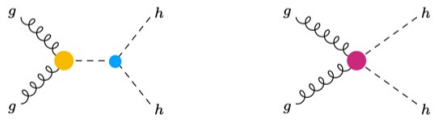
- Higgs pair production can give us lots of information on new physics (beyond just trilinear Higgs self-coupling)
  - can probe SMEFT/HEFT, new resonances, light quark Yukawa couplings

23.09.24

R. Gröber's talk



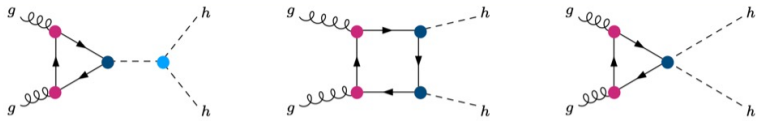
HEFT



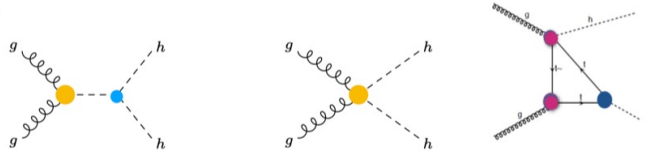
HEFT:

two Higgs couplings only to be probed in HH

$$\mathscr{L} = -m_t \bar{t}t\left(c_t \frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right) + \frac{\alpha_s}{8\pi}\left(c_g \frac{h}{v} + c_{gg}\frac{h^2}{v^2}\right) G^{\mu\nu}G_{\mu\nu} + c_{hhh}\frac{m_h^2}{2v}h^3$$



SMEFT

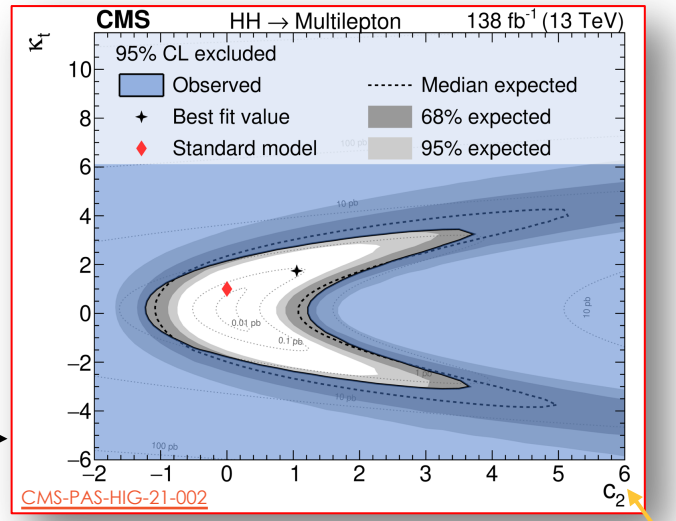


SMEFT:

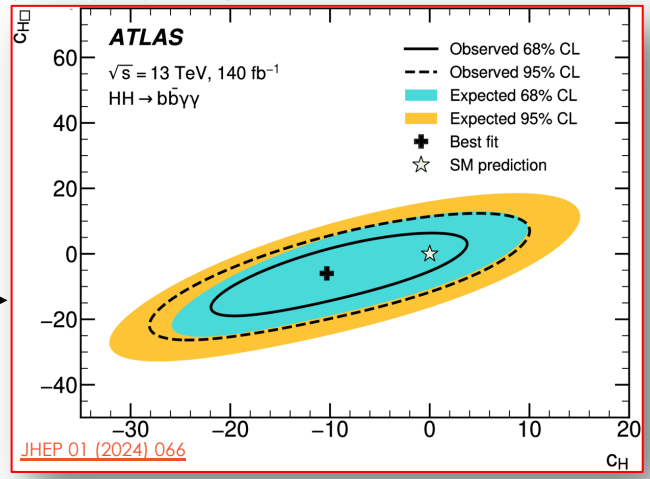
$$\mathscr{L} = C_{H,\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}D_\mu(H^\dagger H)D^\mu(H^\dagger H)^* + C_H|H|^6 + C_{HG}|H|^2 G_{\mu\nu}G^{\mu\nu} + C_{uH}\bar{Q}_L\tilde{H}t_R|H|^2 + h.c. + C_{uG}\bar{Q}_L\sigma_{\mu\nu}T^a\tilde{H}t_R G^a_{\mu\nu} + h.c.$$

Warsaw basis

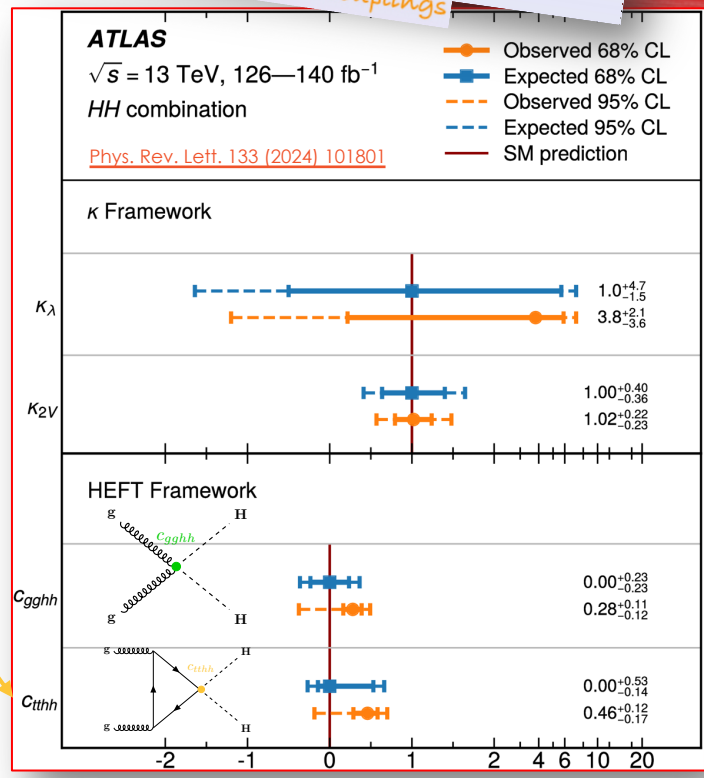
coefficients of $\mathcal{O}(1/\Lambda^2)$



$(H^\dagger H)\Box(H^\dagger H)$

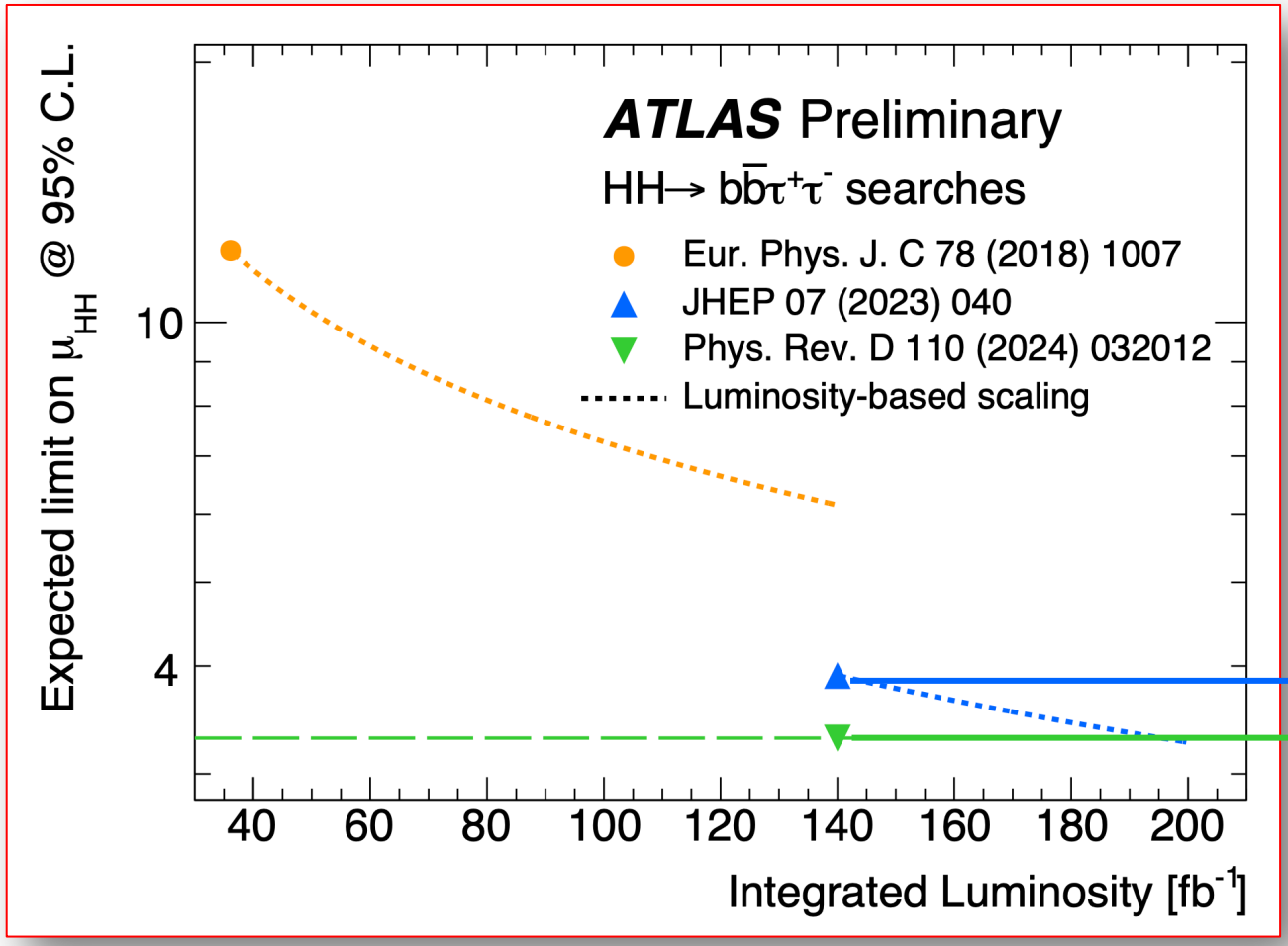


$(H^\dagger H)^3$



WHAT'S NEXT?

Lesson from the past: results exceed expectations!



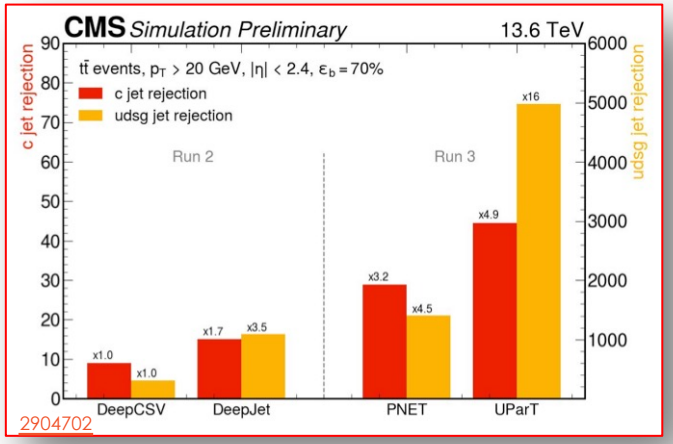
Mostly object reconstruction

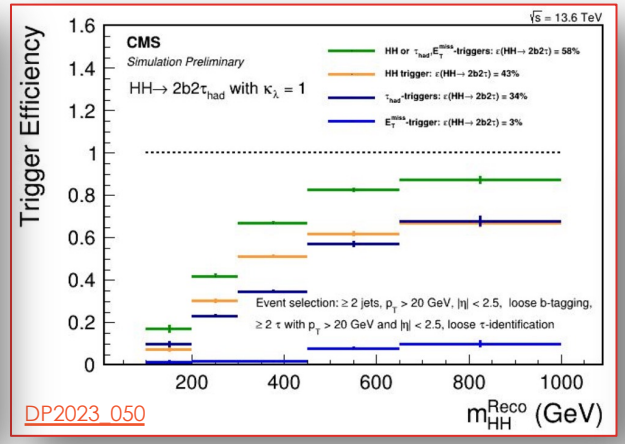
Mostly analysis techniques

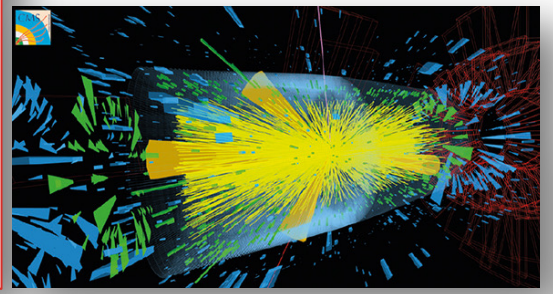
See more in F. Haslbeck's talk and ATL-PHYS-PUB-2024-016

WHAT'S NEXT?

Impressive improvements in flavour tagging (resolved and boosted) & very promising hadronic triggers

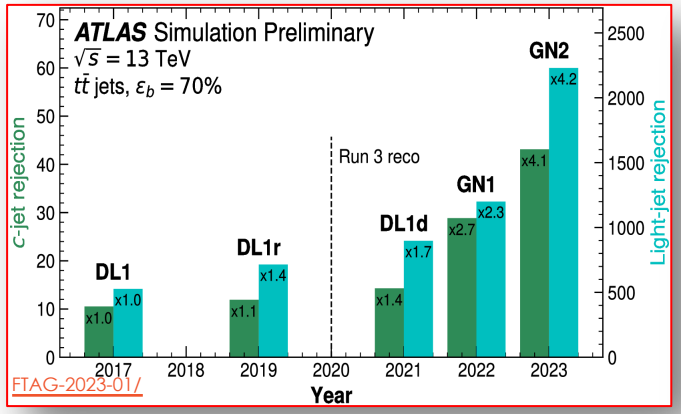


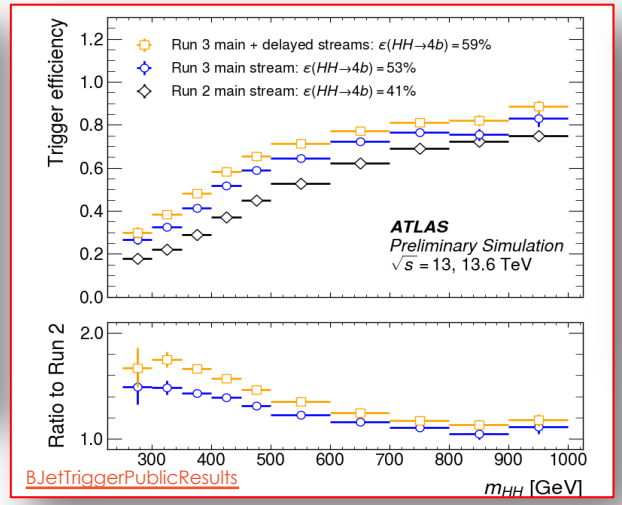


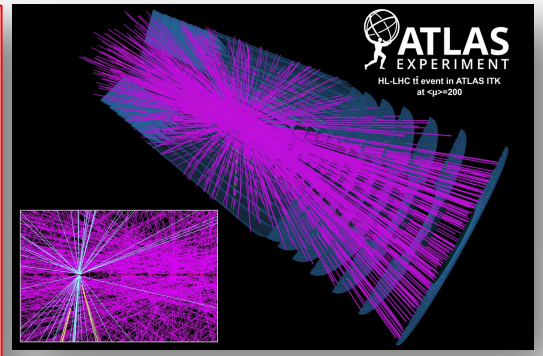


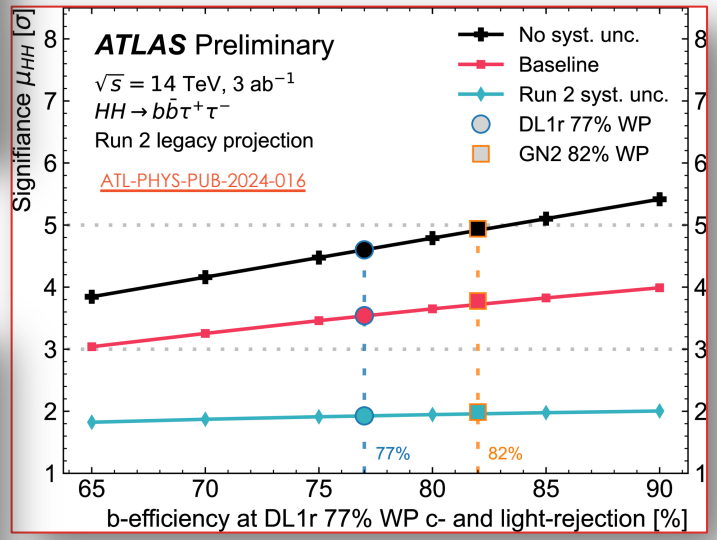
Where will new technologies and new algorithms take us during HL-LHC?

Run 2 **Run 3** **HL-LHC**









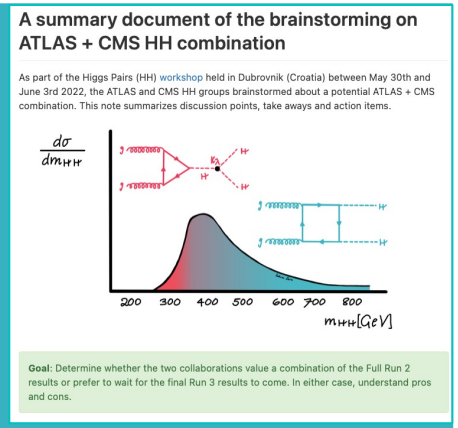
Theory improvements also key, "baseline" assumes th. uncertainties halved!

MORE ON HH COMBINATIONS

Run 2 ATLAS + CMS Combination

2022

Initiated at HiggsPairs



2023

ATLAS & CMS shared workspaces

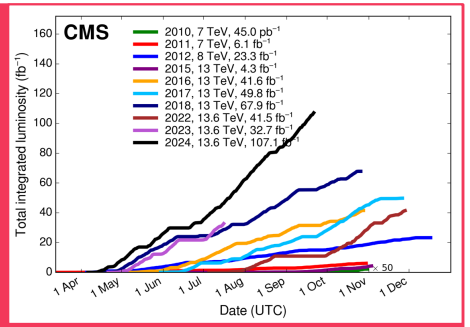
2024

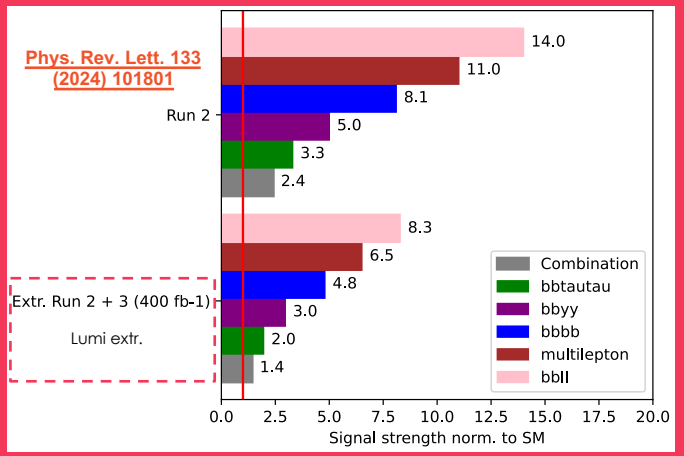
New (and final) Run 2 combination by ATLAS, new workspaces to be shared. CMS?

?

Run 2 + Run 3 reach

Dataset already doubled. Similar sensitivities from ATLAS & CMS!





HL-LHC ATLAS + CMS

Crucial input for the European Strategy Update

European Strategy Update

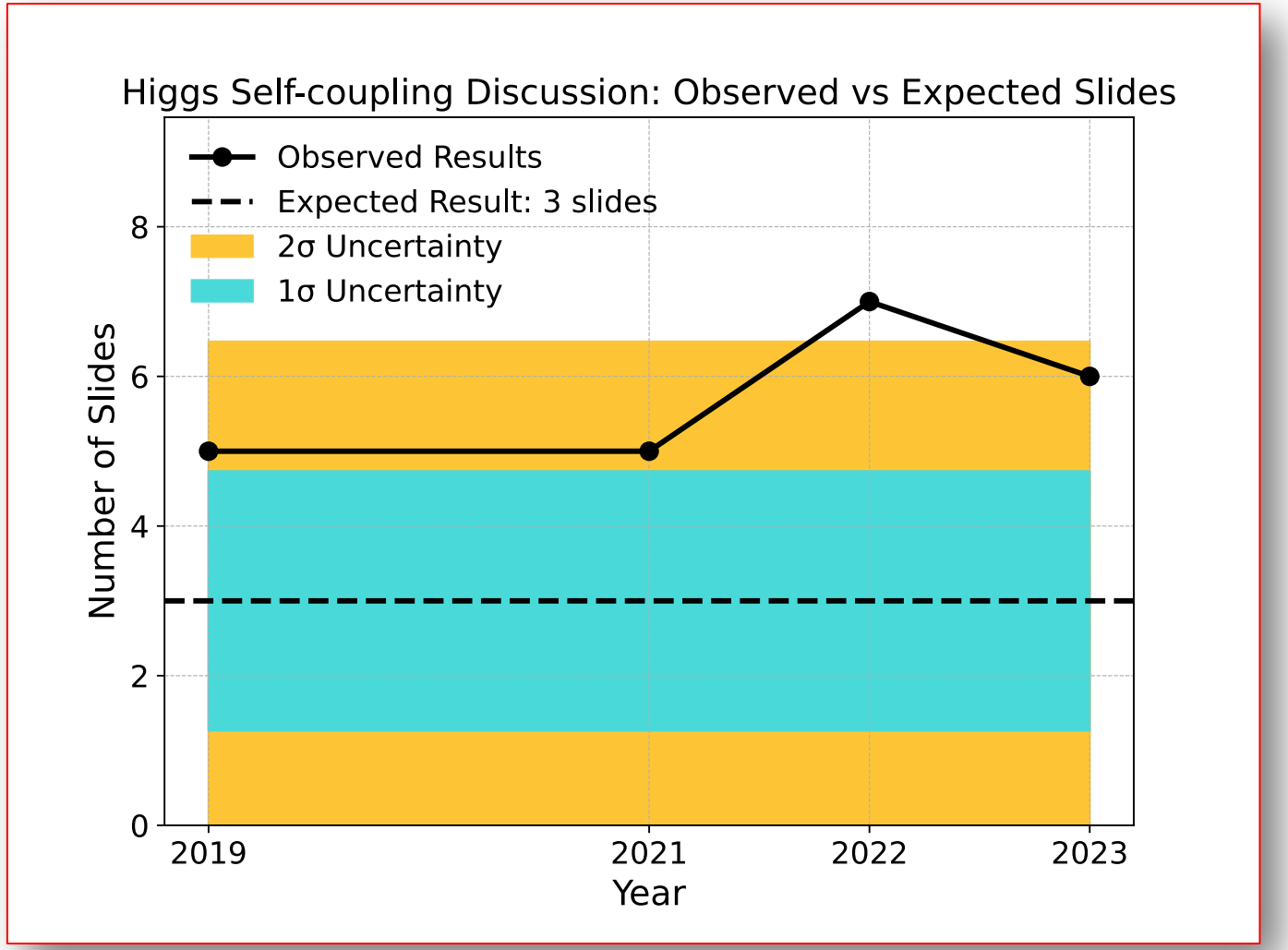
Previous projections (50% precision) *very* outdated

ATLAS+CMS+Theory collaborations to harmonize systematics and enable powerful result interpretation

THANKS FOR YOUR ATTENTION!

LET'S OPEN THE DISCUSSION

"3" TRANSPARENCIES OF COMPARISON



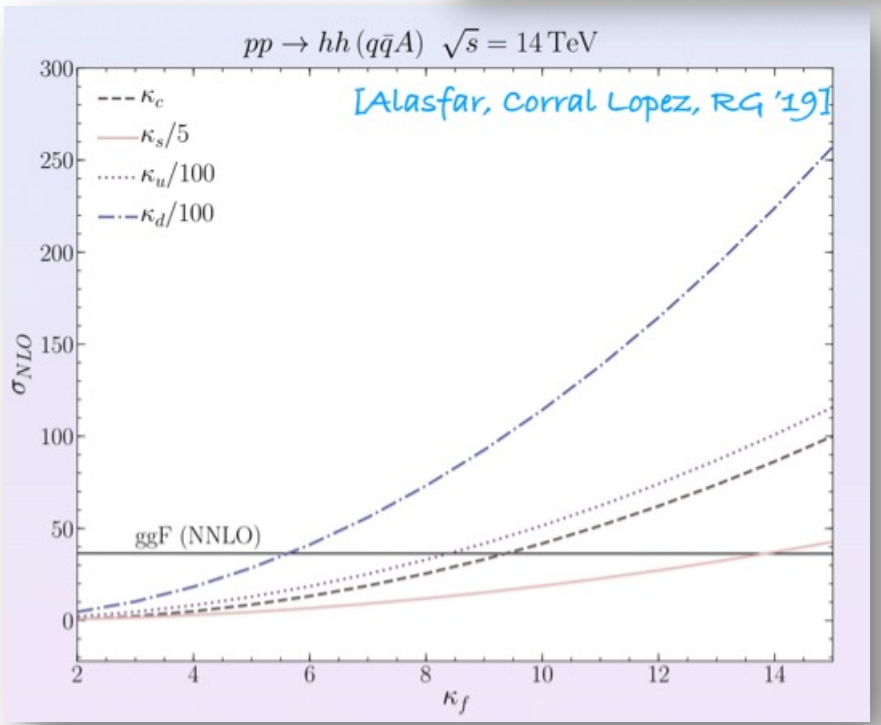
EXTRA SLIDES

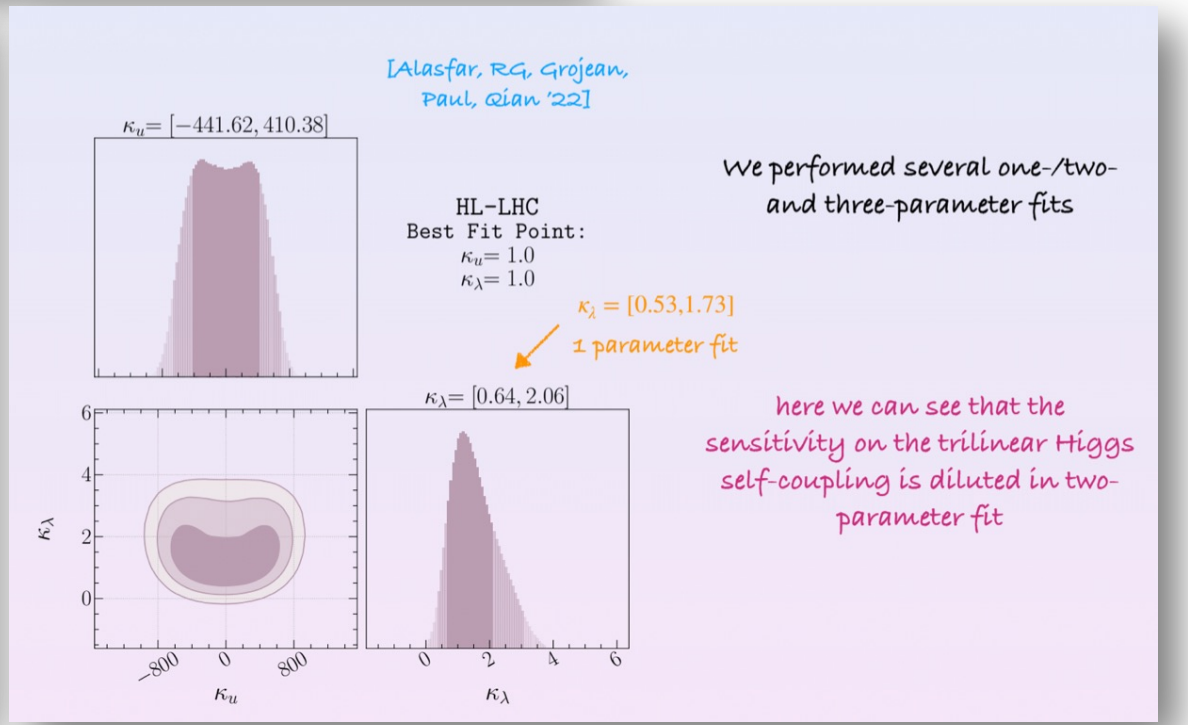
THEORY

- Higgs pair production can give us lots of information on new physics (beyond just trilinear Higgs self-coupling)

R. Gröber's talk

Light quark Yukawa couplings



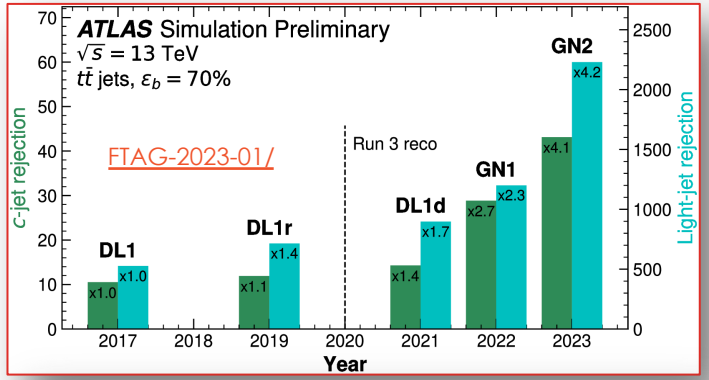


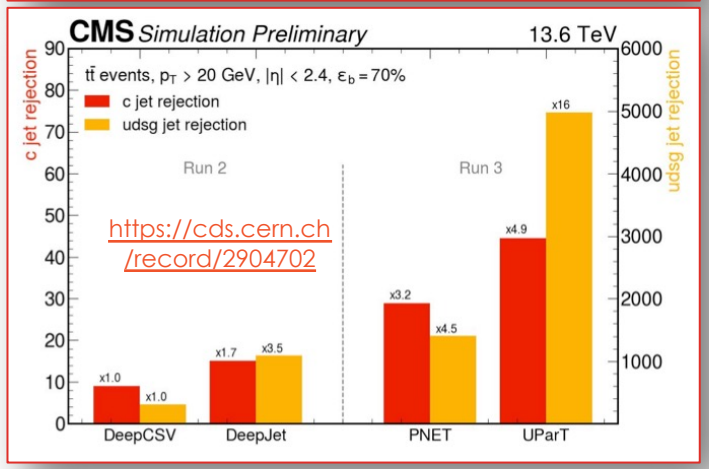
We performed several one-/two- and three-parameter fits

here we can see that the sensitivity on the trilinear Higgs self-coupling is diluted in two-parameter fit

WHAT'S NEXT?

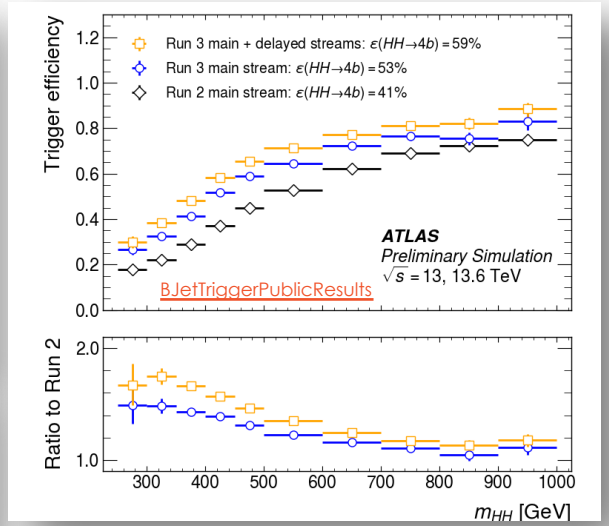
Run 2 to Run 3



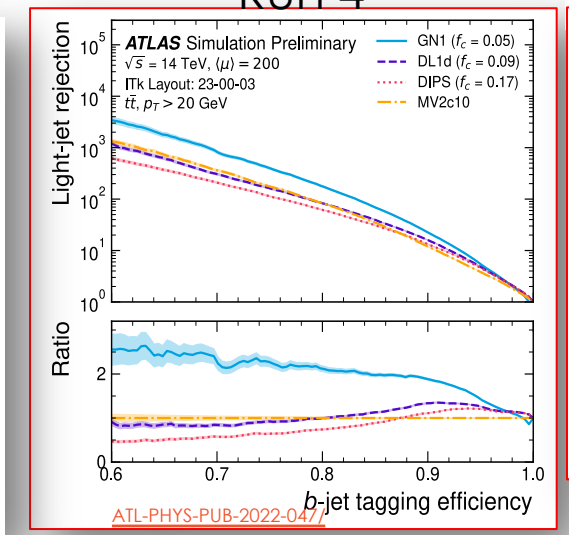


Fake rate improved by ~2 orders of magnitude since the Tevatron! Ref 1, 2

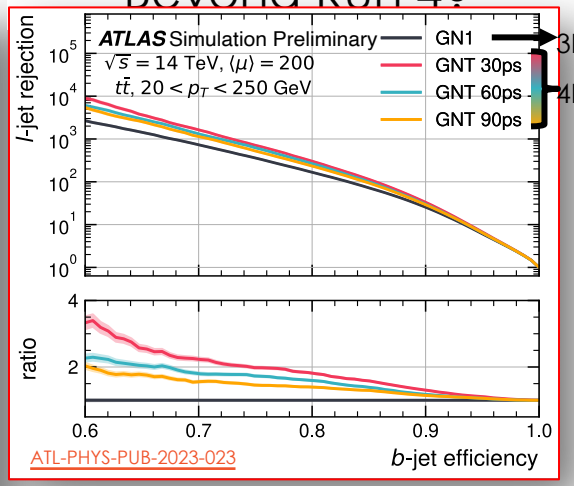
Run 3

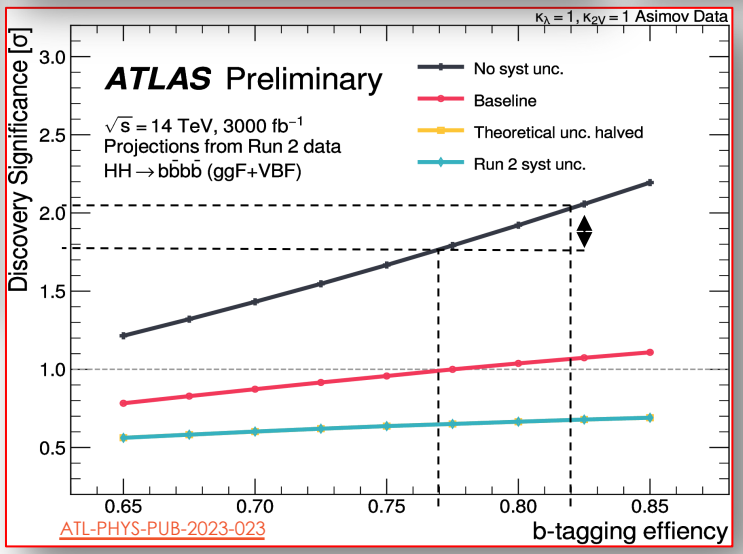


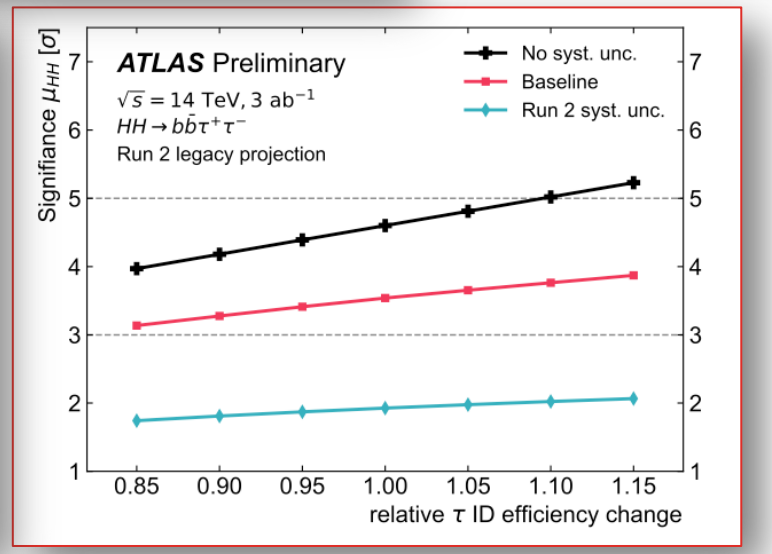
Run 4



Beyond Run 4?

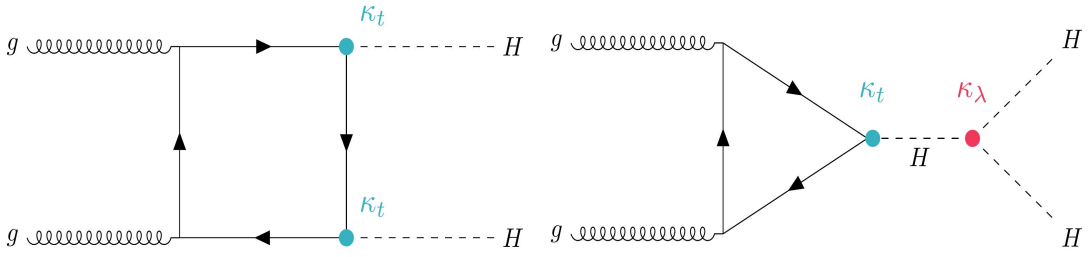


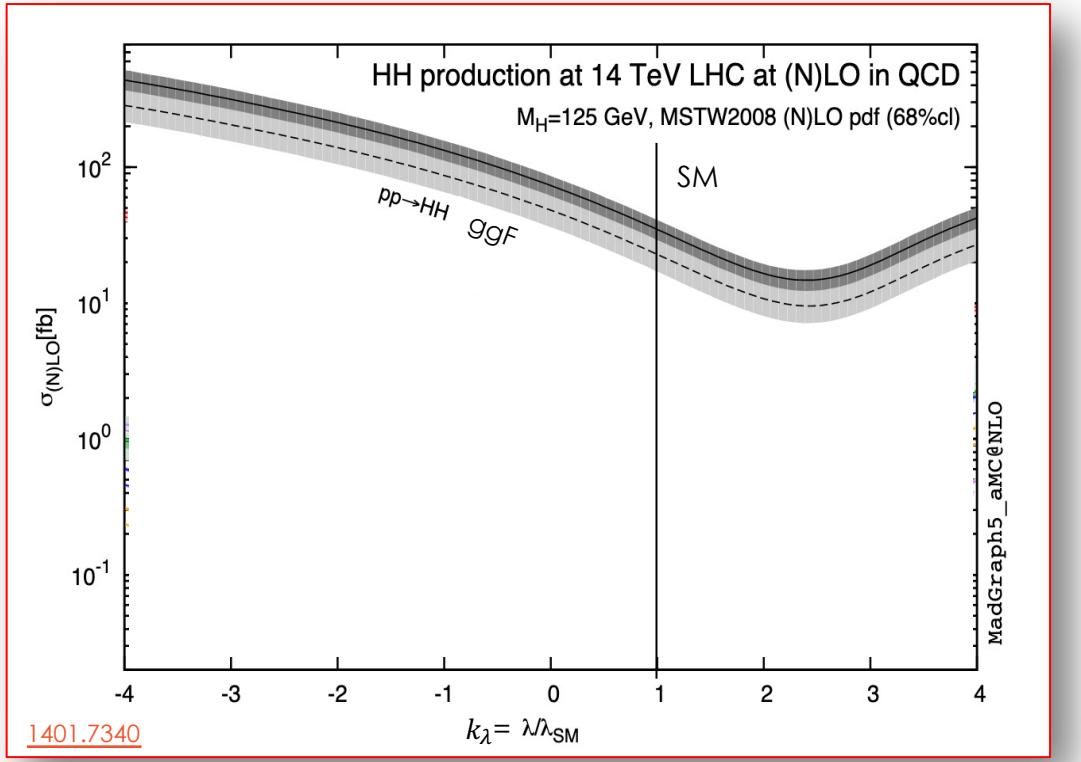




HH PRODUCTION AT THE LHC

Non-resonant σ_{HH}^{ggF} = 31.05 fb at 13 TeV for m_H = 125.00 GeV





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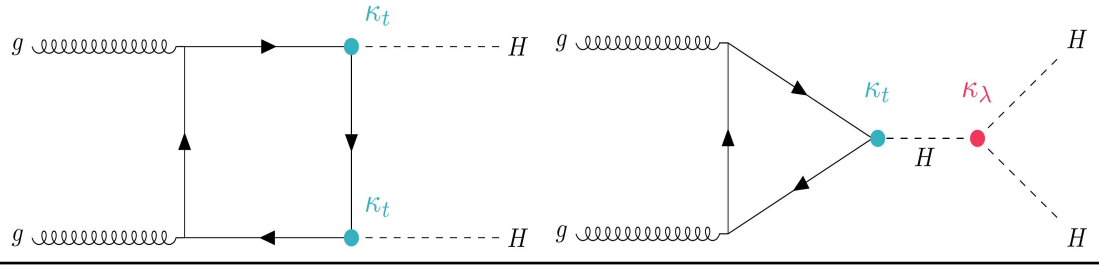
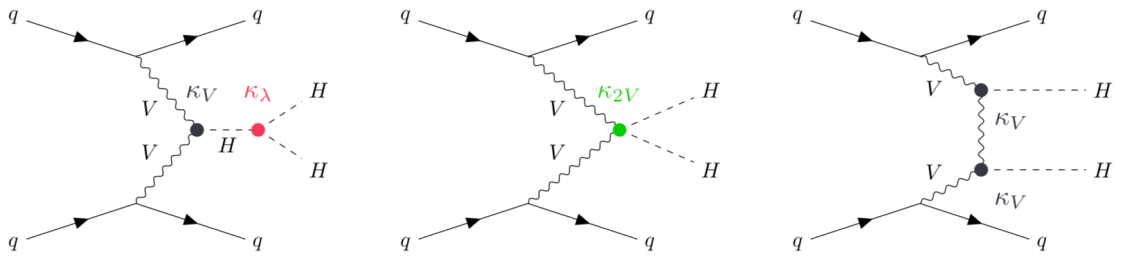
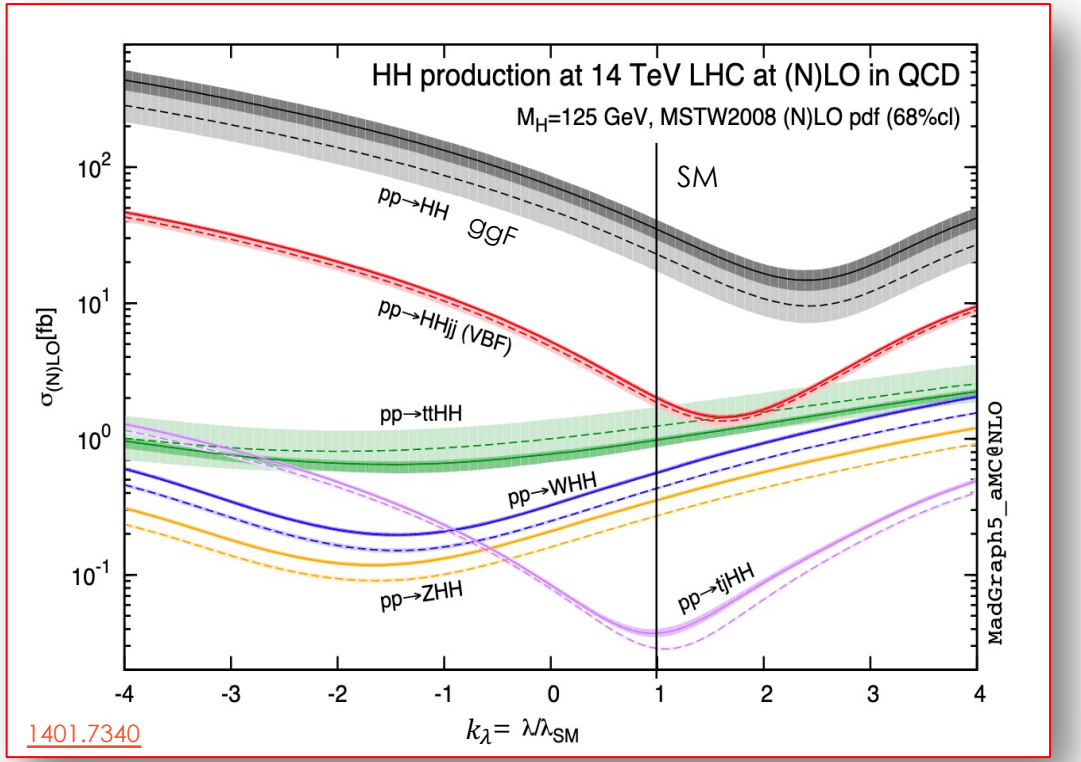
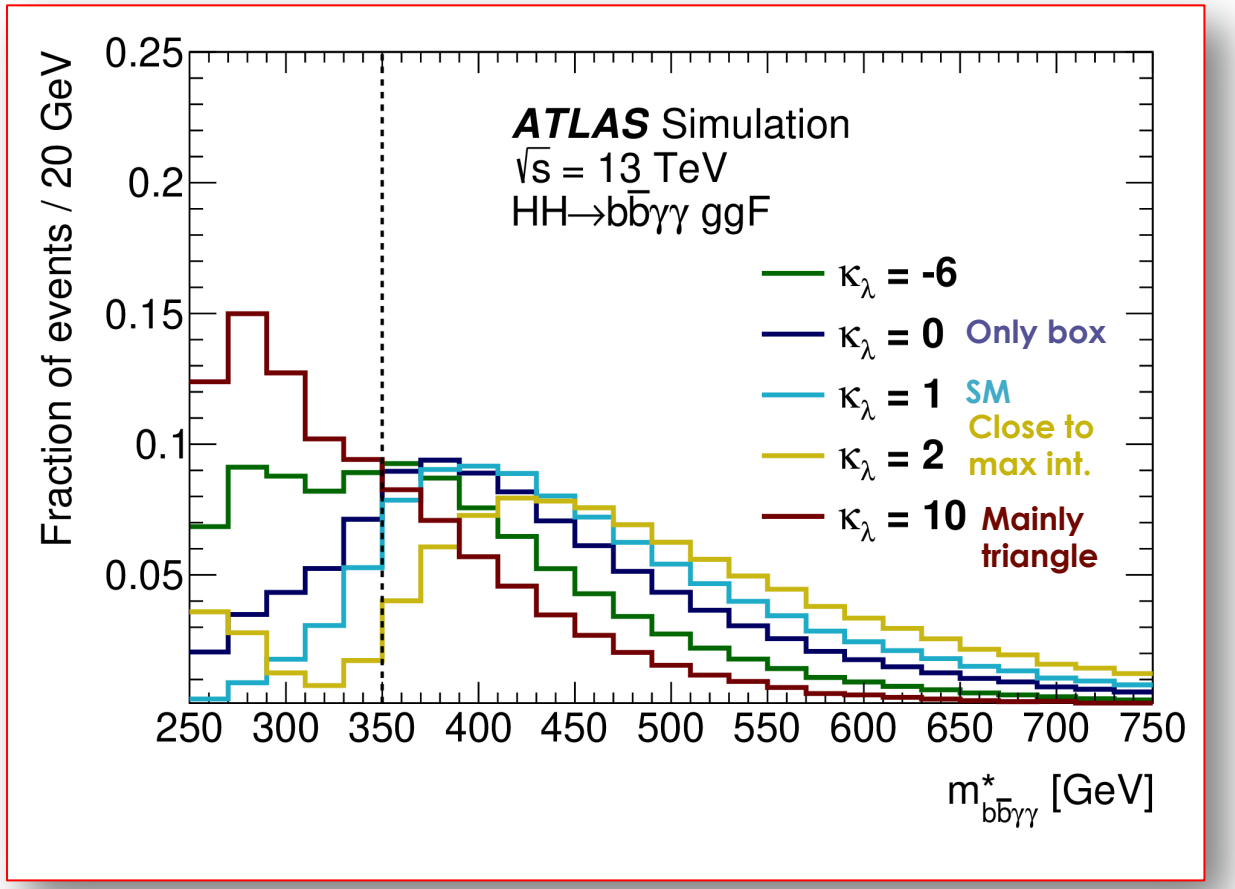


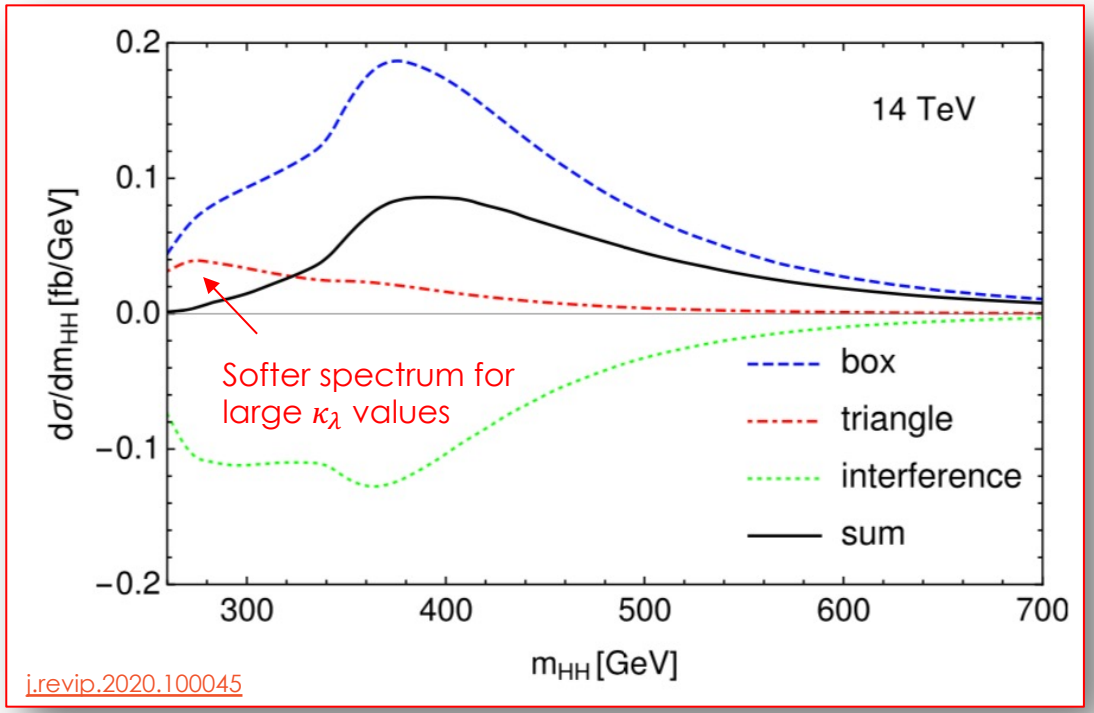
Non-resonant σ_{HH}^{VBF} = 1.73 fb at 13 TeV for m_H = 125.00 GeV



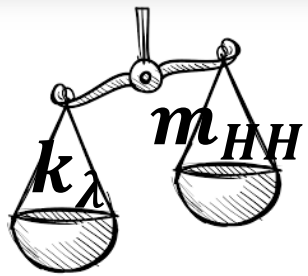


HH PRODUCTION AT THE LHC

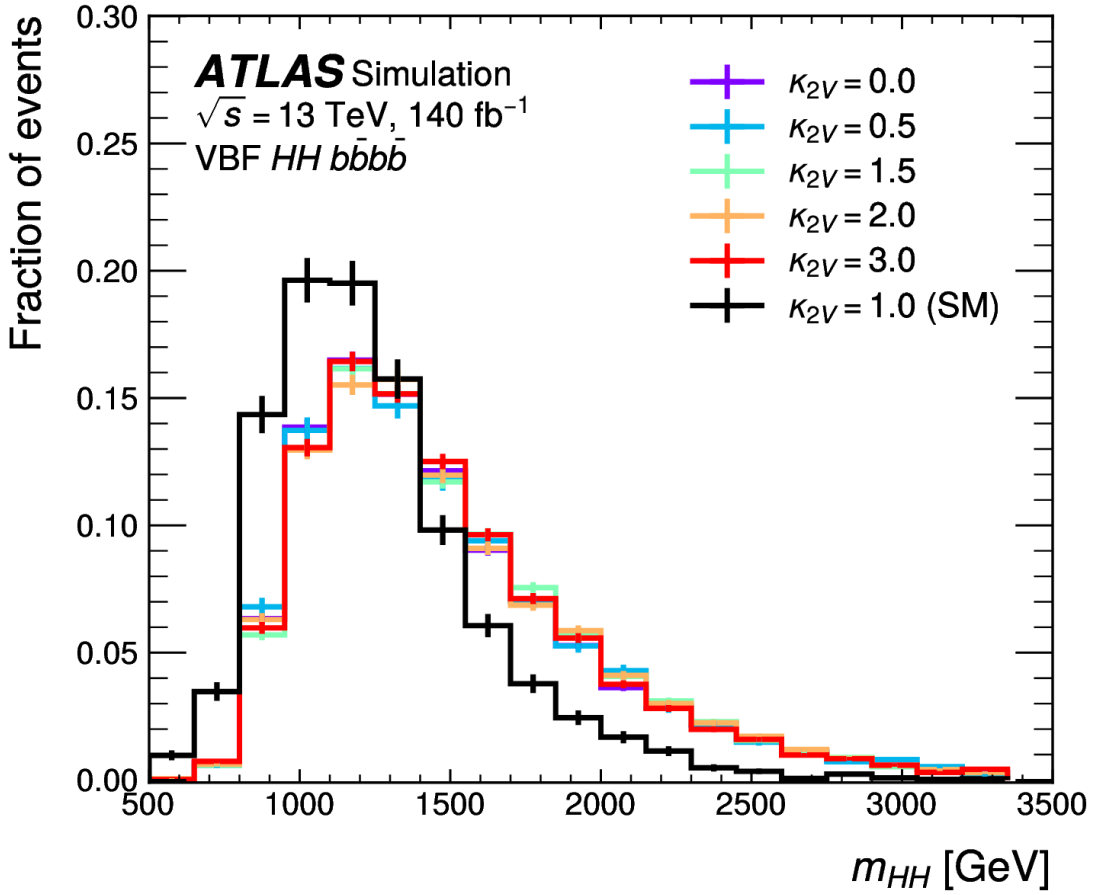




Key experimental handle

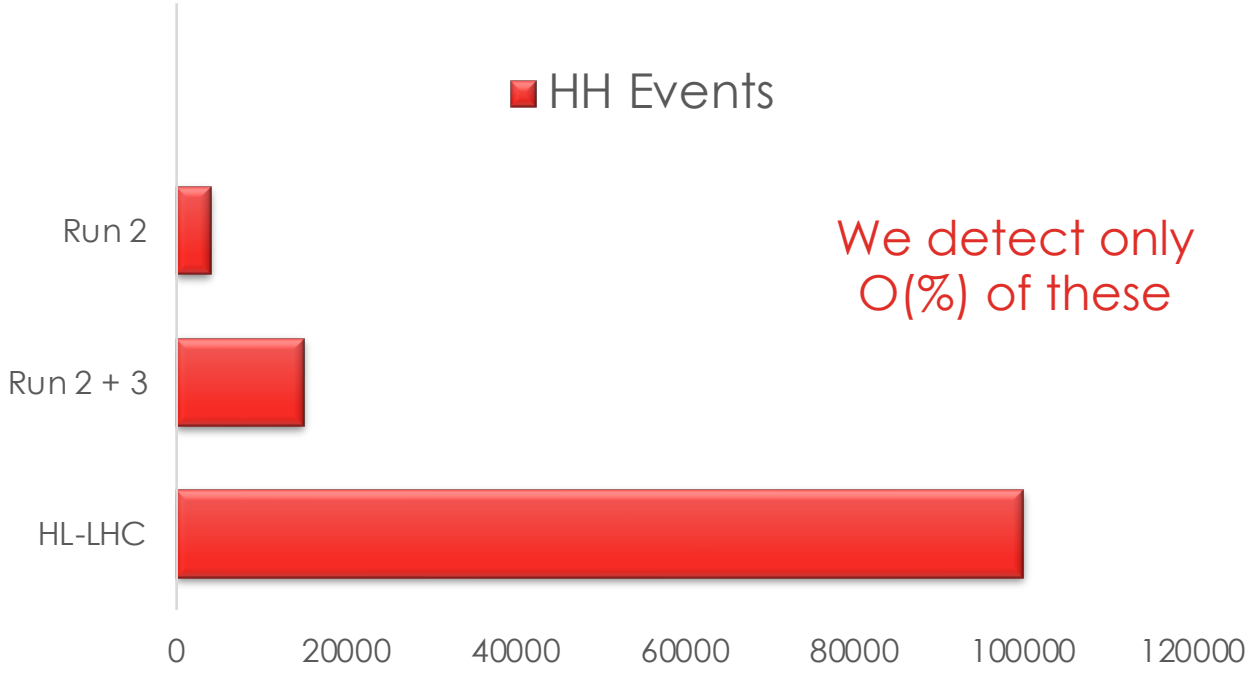


HH PRODUCTION AT THE LHC



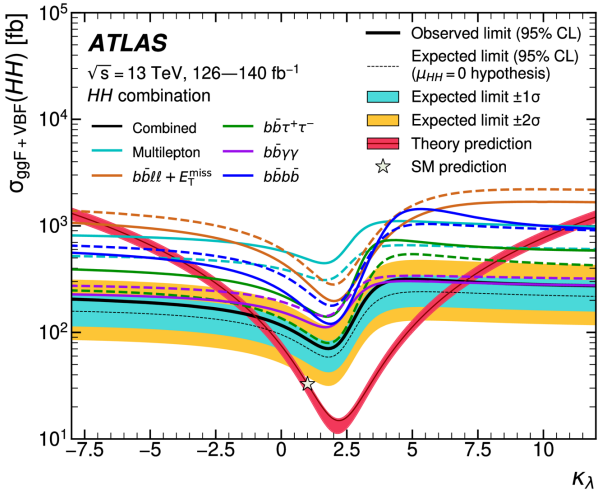
Key experimental handle

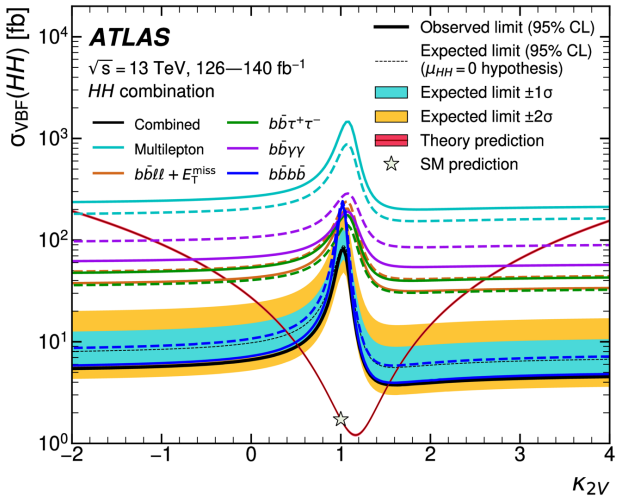
TWICE THE HIGGS, TWICE THE CHALLENGE

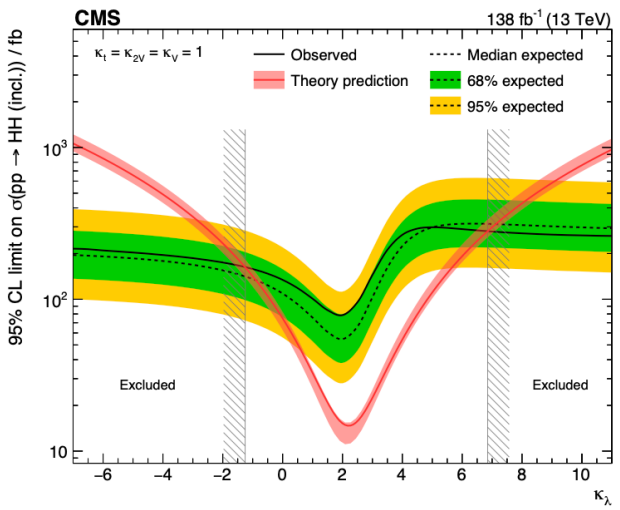


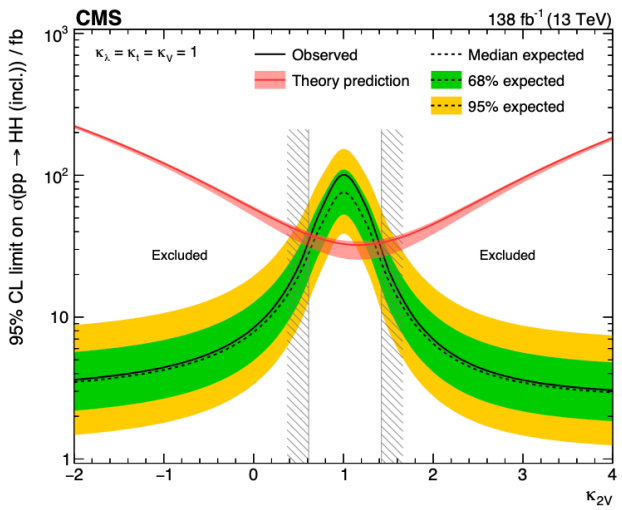
Need to combine multiple signatures of Higgs boson decays to increase sensitivity

COUPLINGS









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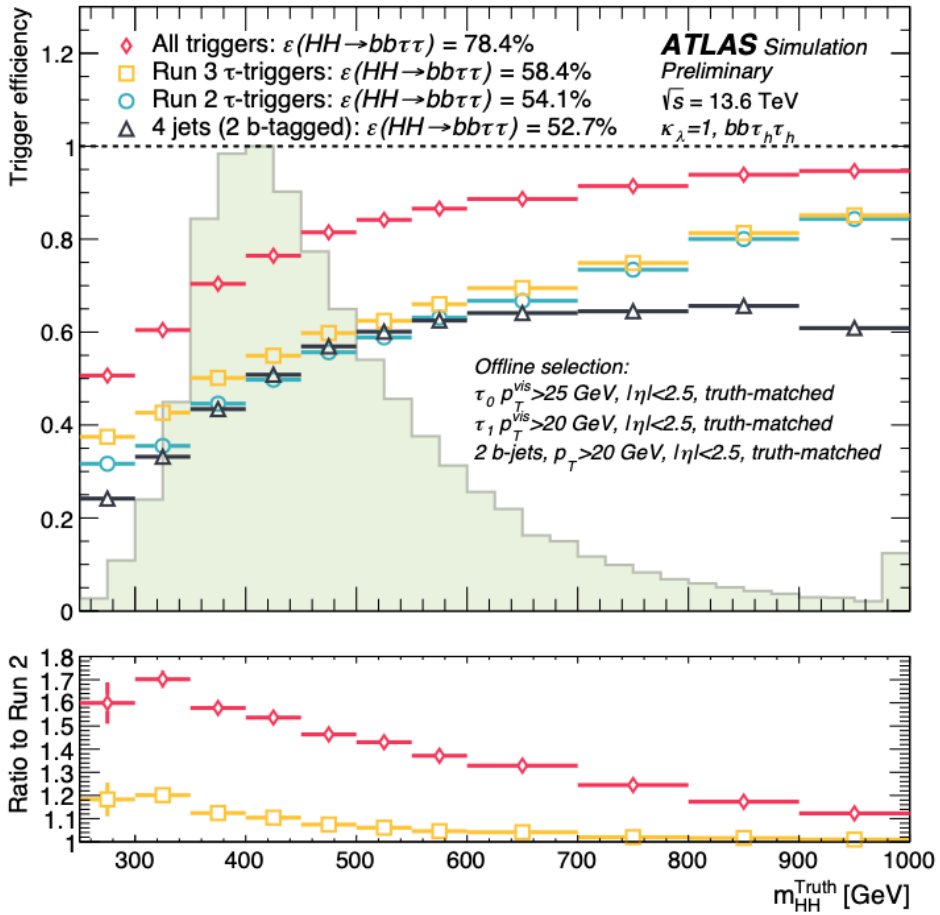
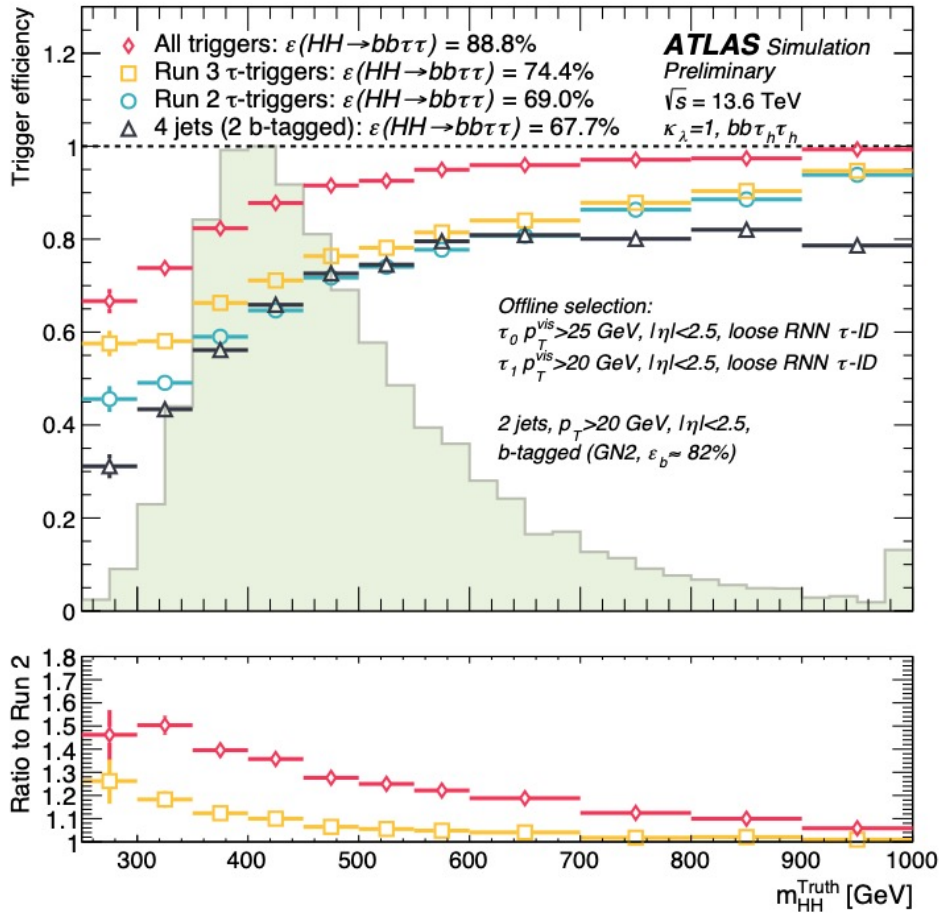
HL-LHC BASELINE

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2024-016/

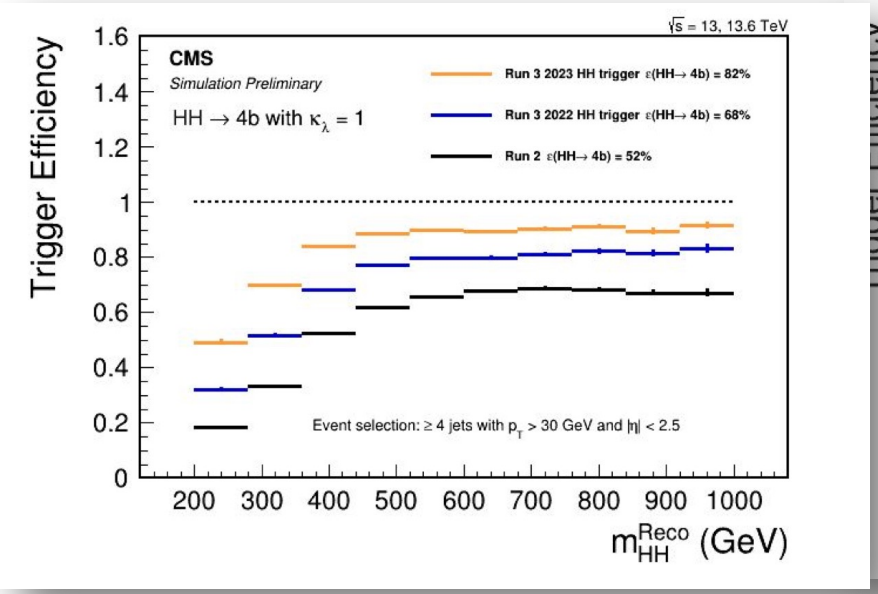
Source	Scale factor
Experimental uncertainties	
Luminosity	1.0
Electrons and muons efficiency	1.0
b-jet b-tagging efficiency	0.5
c-jet b-tagging efficiency	0.5
Light-jet b-tagging efficiency	1.0
τ_{had} efficiency (statistical)	0.0
τ_{had} efficiency (systematic)	1.0
τ_{had} energy scale	1.0
Fake-τ_{had} estimation (statistical)	0.0
Fake-τ_{had} estimation (systematic)	0.5
Jet energy scale and resolution, $E_{\text{T}}^{\text{miss}}$	1.0
Theoretical uncertainties	0.5
MC statistical uncertainties	0.0

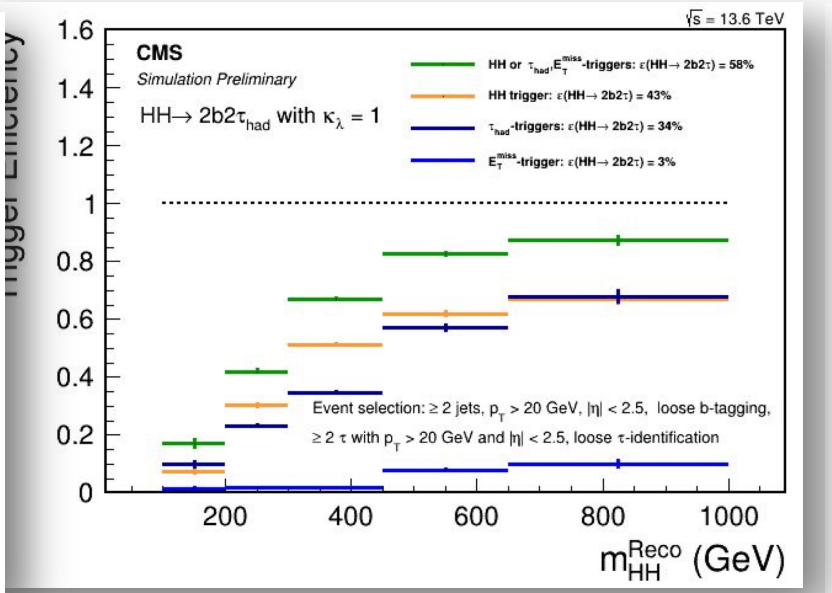
TAU TRIGGERS

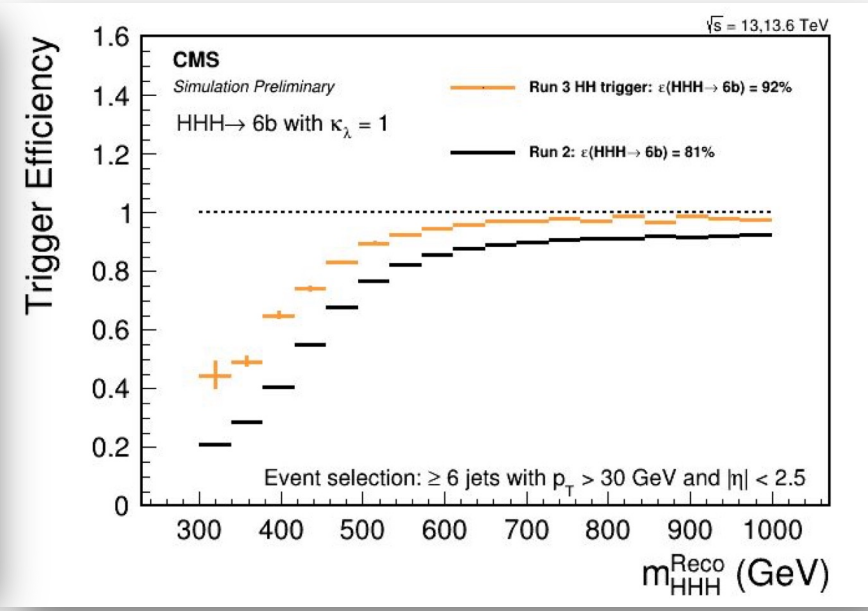




HADRONIC TRIGGERS

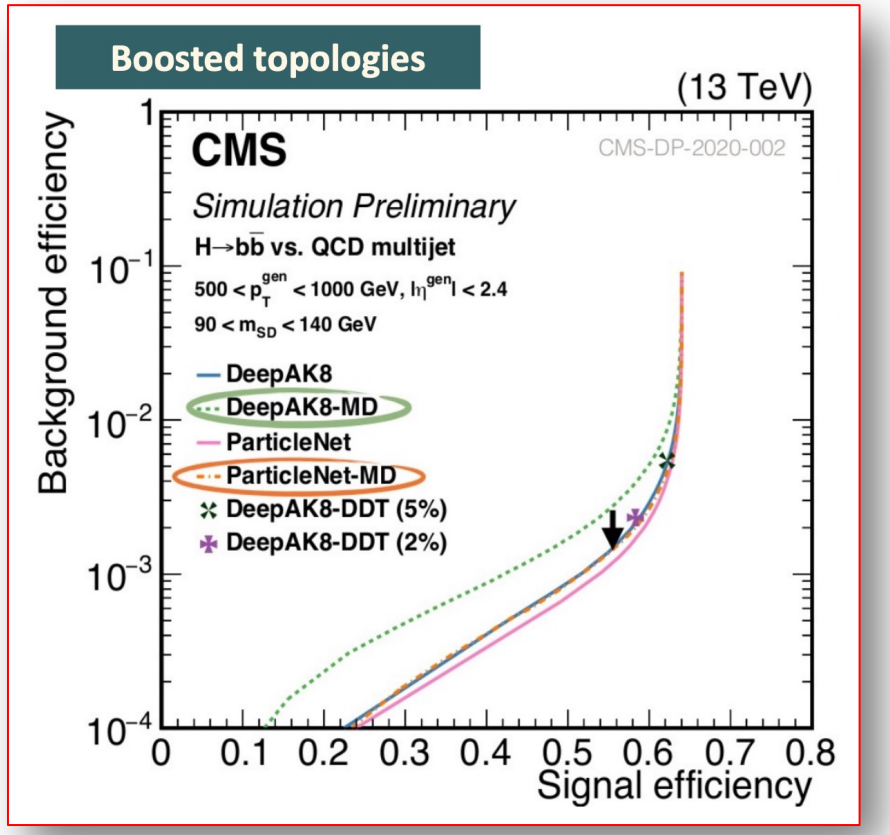




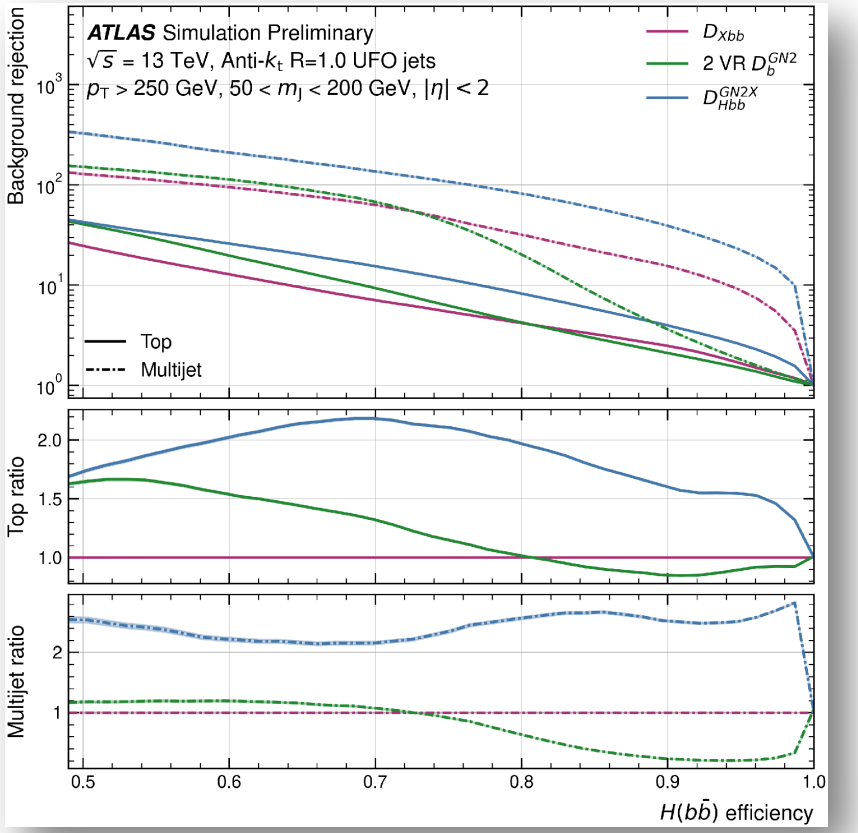


DP2023_050.pdf

BOOSTED OBJECTS

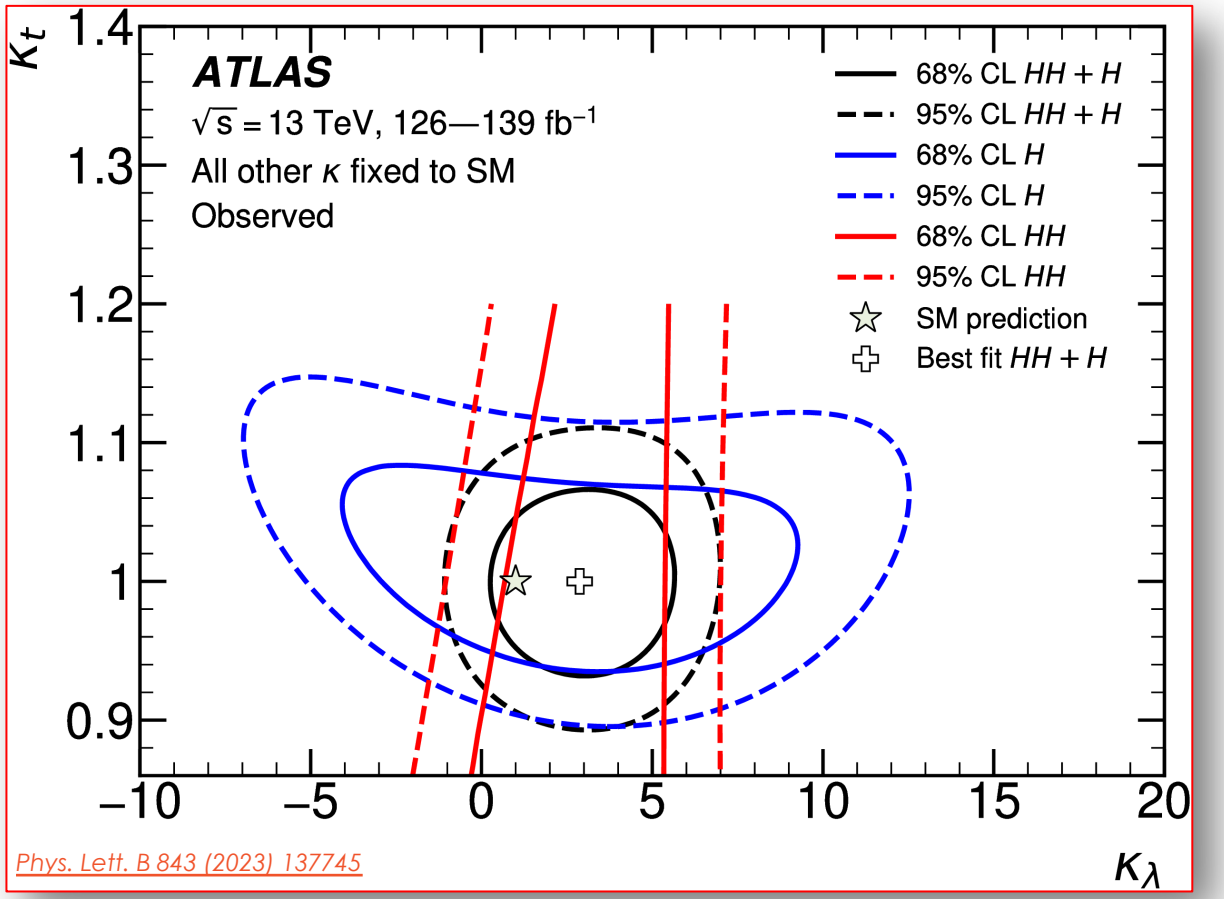


ATL-PHYS-PUB-2023-021/

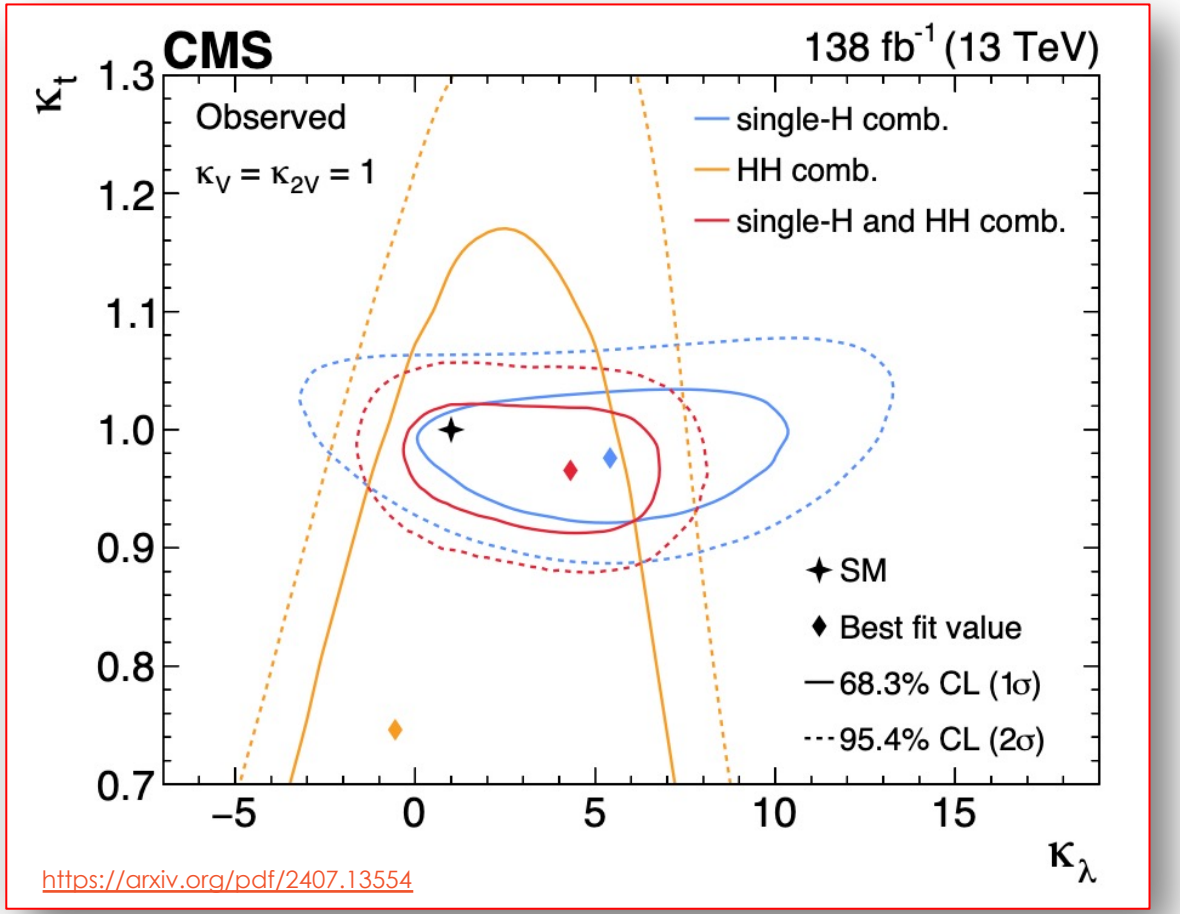


THE POWER OF COMBINATION

$H + HH$



Phys. Lett. B 843 (2023) 137745

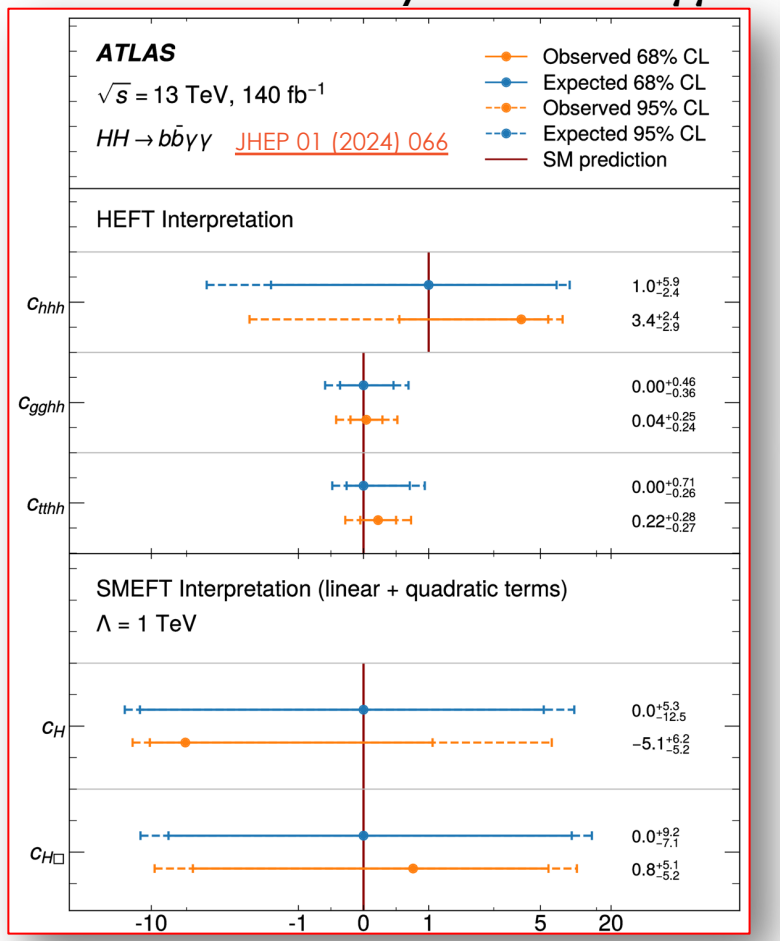


https://arxiv.org/pdf/2407.13554

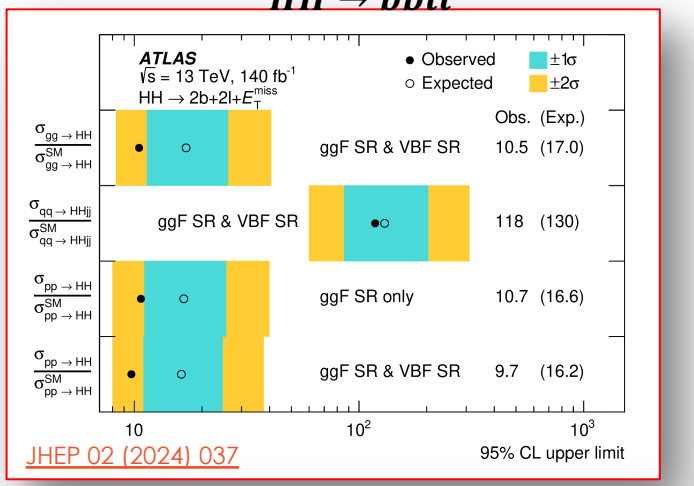
A BROAD AND EXCITING PROGRAMME

Further improvements to leading channels and new areas to characterise the Higgs sector with HH

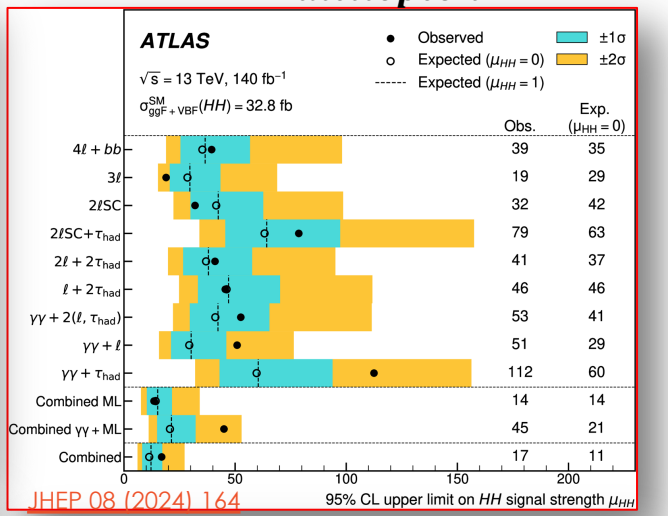
Effective Field Theory with $HH \to bb\gamma\gamma$

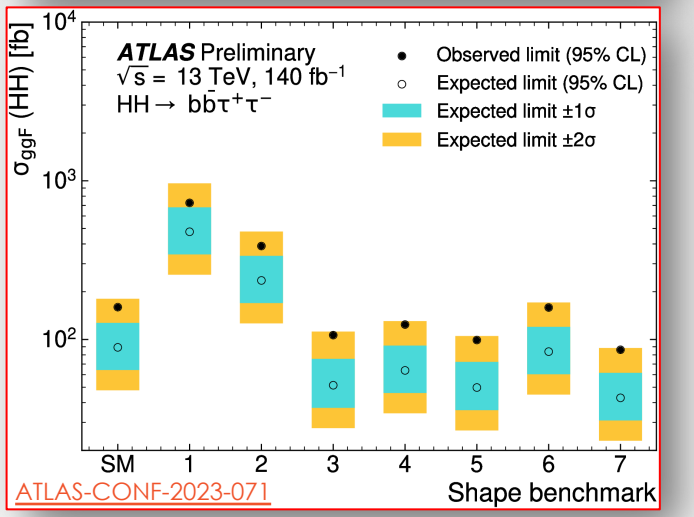


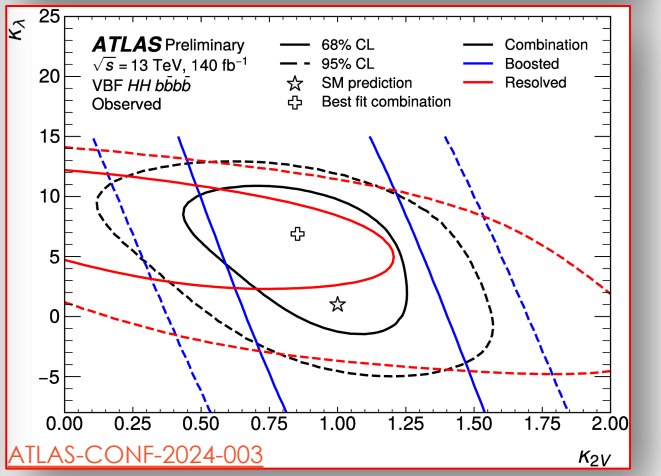
$HH \to bbll$



$HH \to Multilepton$





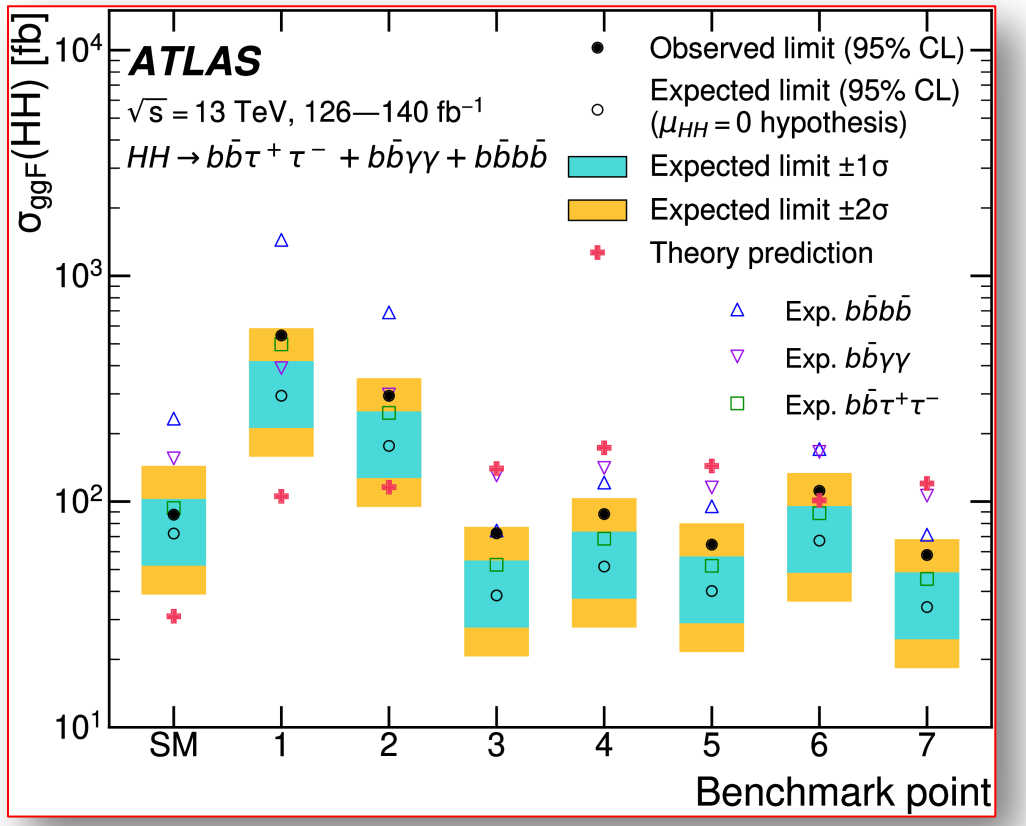


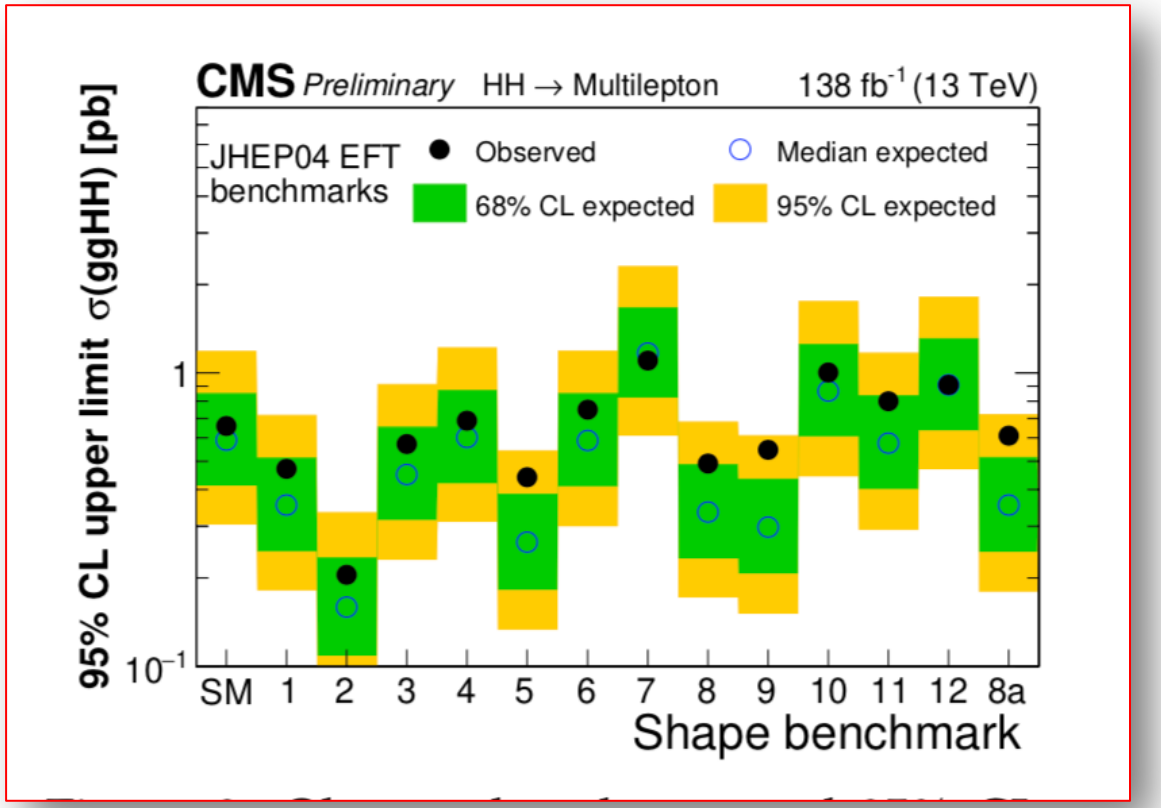
Effective Field Theory with $HH \to bb\tau\tau$

Boosted $HH \to bbbb$

HEFT

To benchmark or not to benchmark? A controversial plot





Phys. Rev. Lett. 133 (2024) 101801

CMS-PAS-HIG-21-002

HEFT

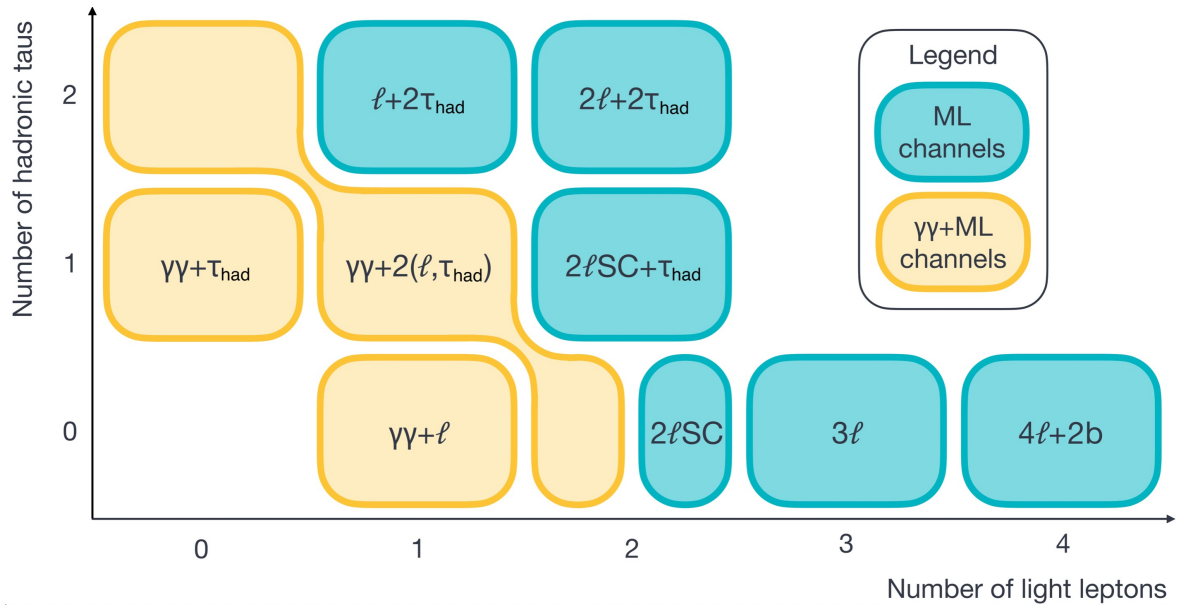
benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6	−0.68	0.90	$-\frac{1}{6}$	$\frac{1}{2}$	0.25
7	−0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$

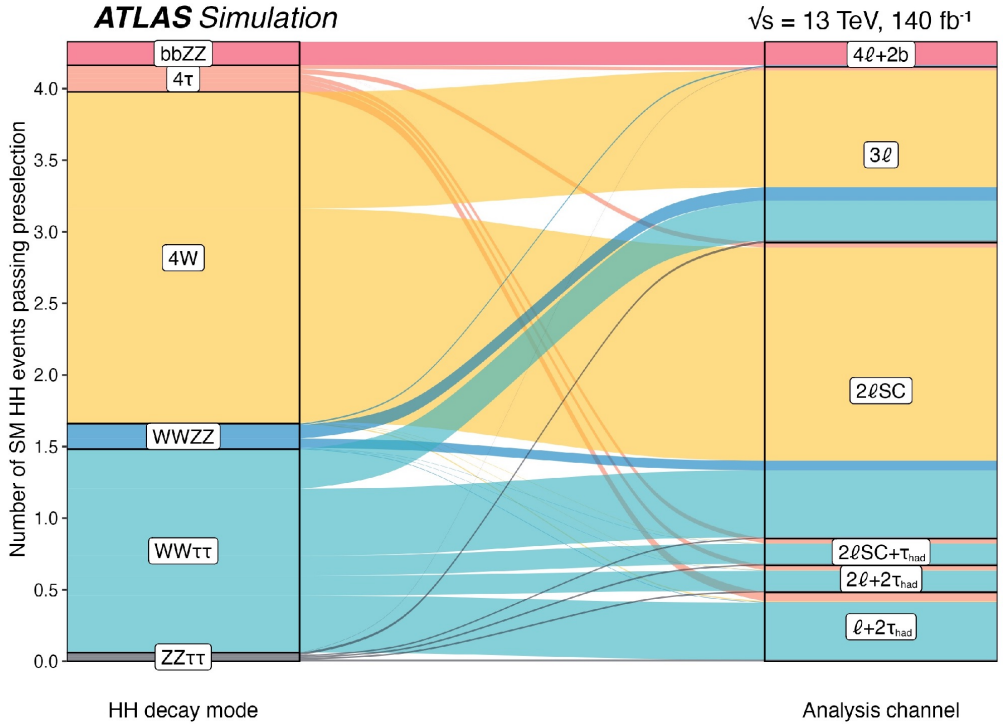
https://arxiv.org/pdf/2304.01968

MULTILEPTONS

- CMS full Run 2 search for $HH -> WWWW, WW\tau\tau, and\ \tau\tau\tau\tau$ https://arxiv.org/abs/2206.10268
- Additional $\gamma\gamma\tau\tau$ search https://inspirehep.net/literature/2784595

- ATLAS ML and yyML combined https://link.springer.com/article/10.1007/JHEP08(2024)164





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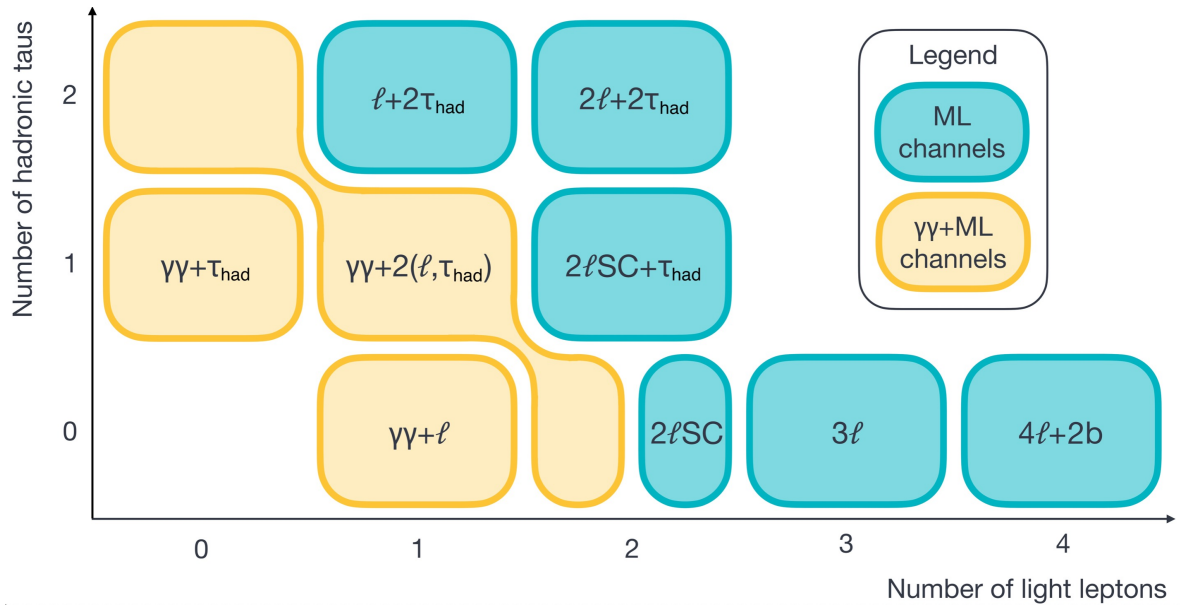

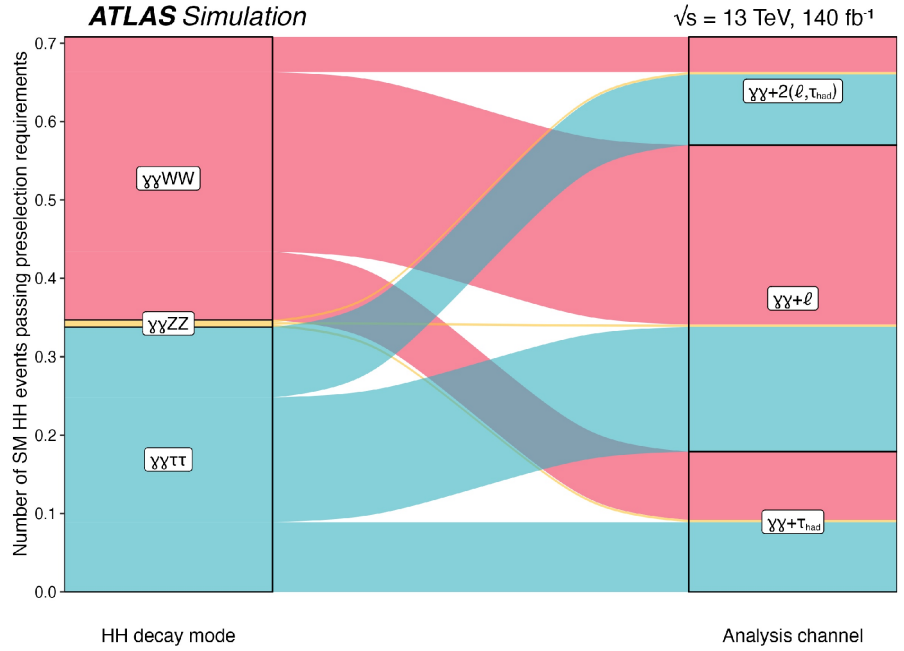

MULTILEPTONS

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- Additional $\gamma\gamma\tau\tau$ search https://inspirehep.net/literature/2784595

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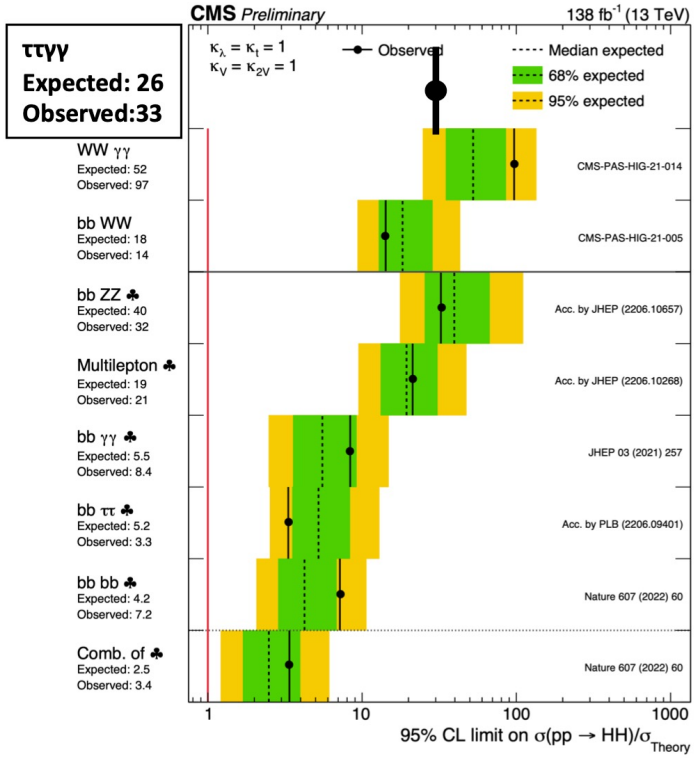
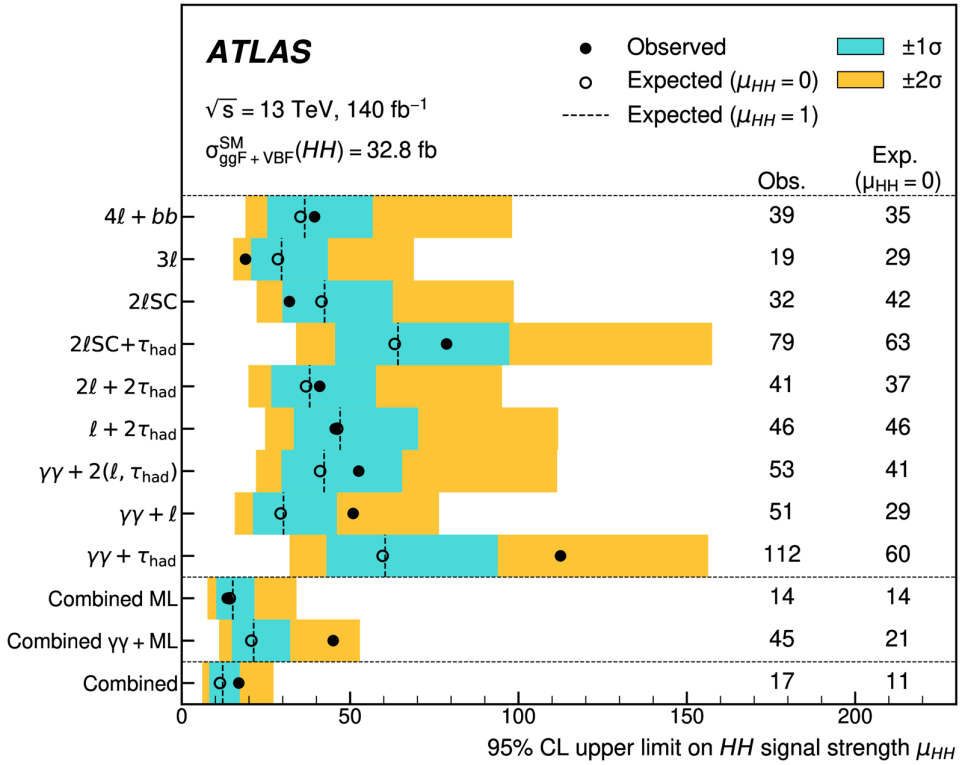
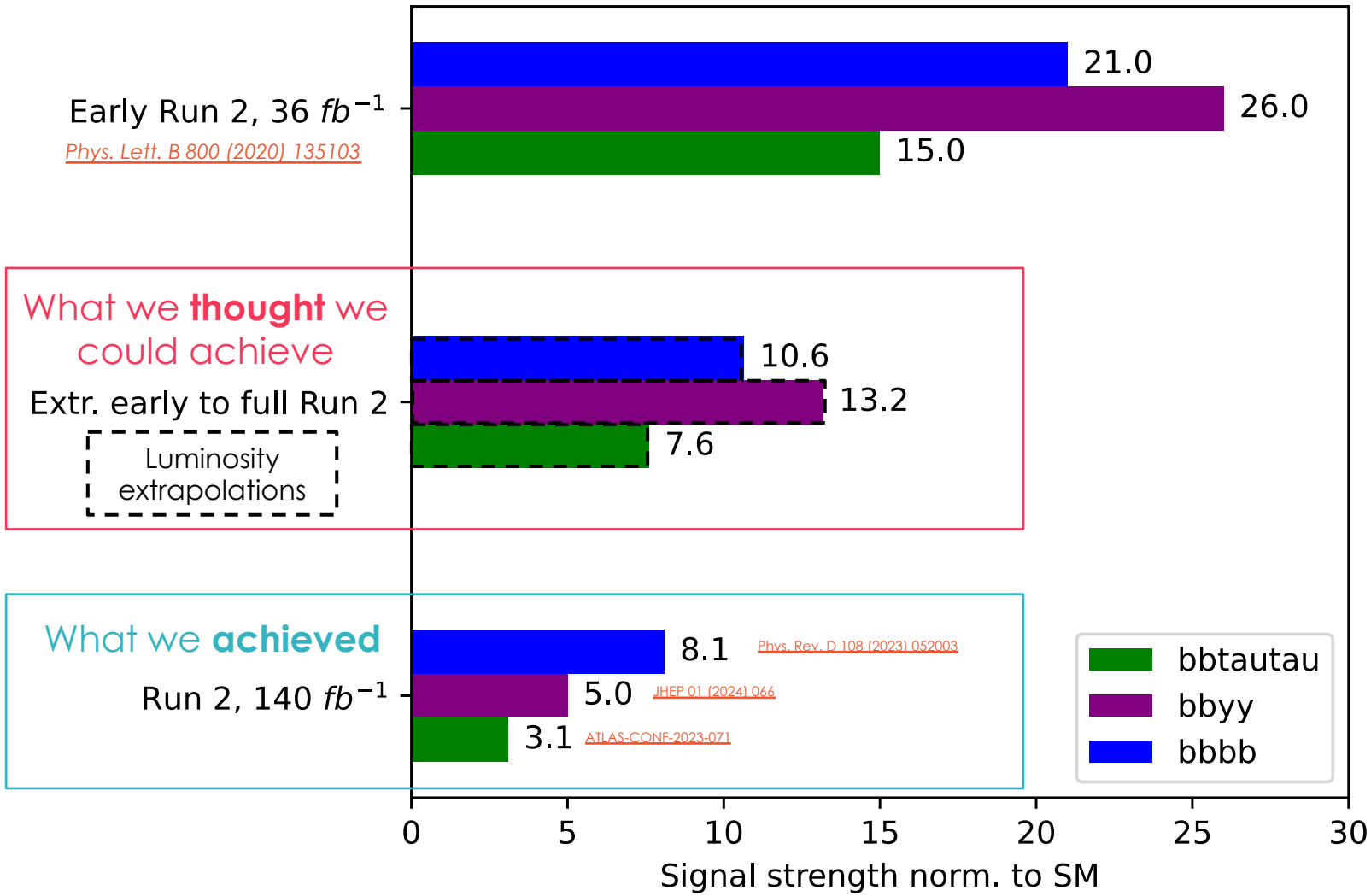


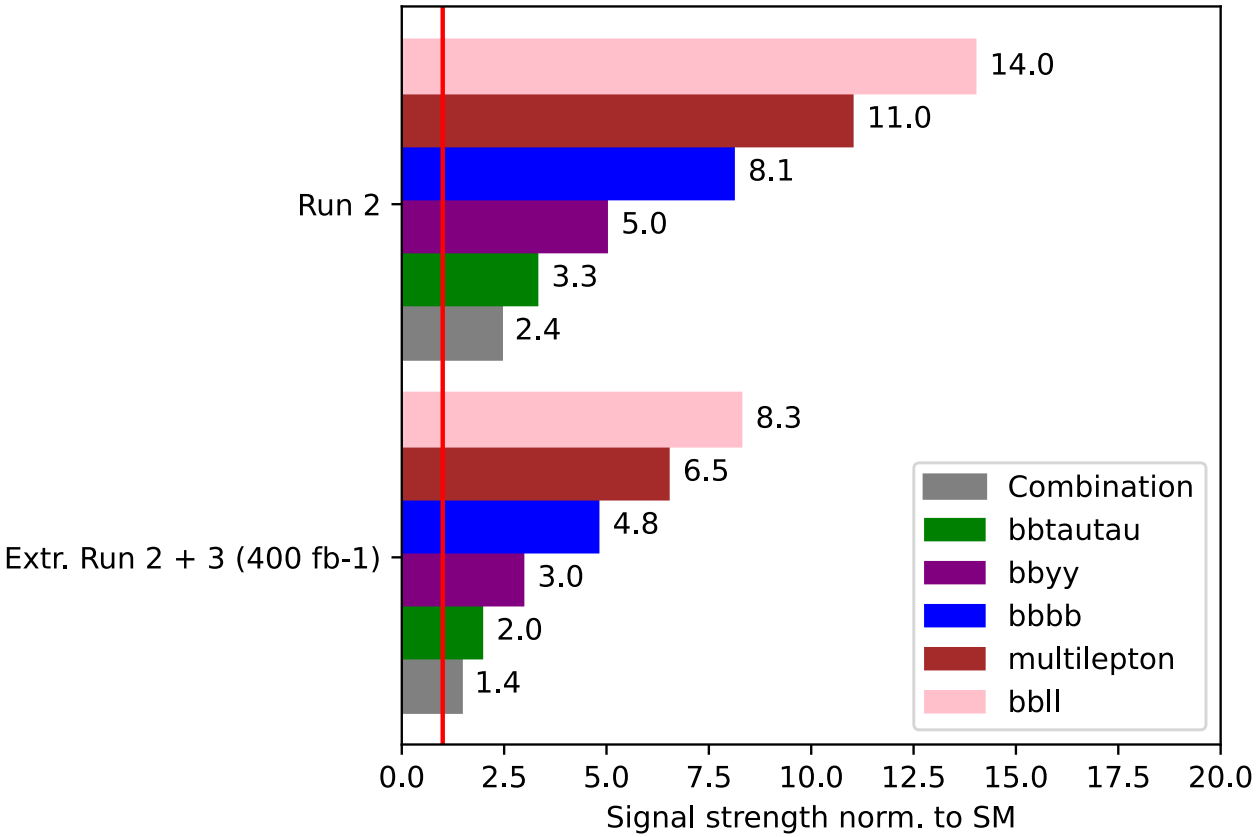


CMSPublic twiki

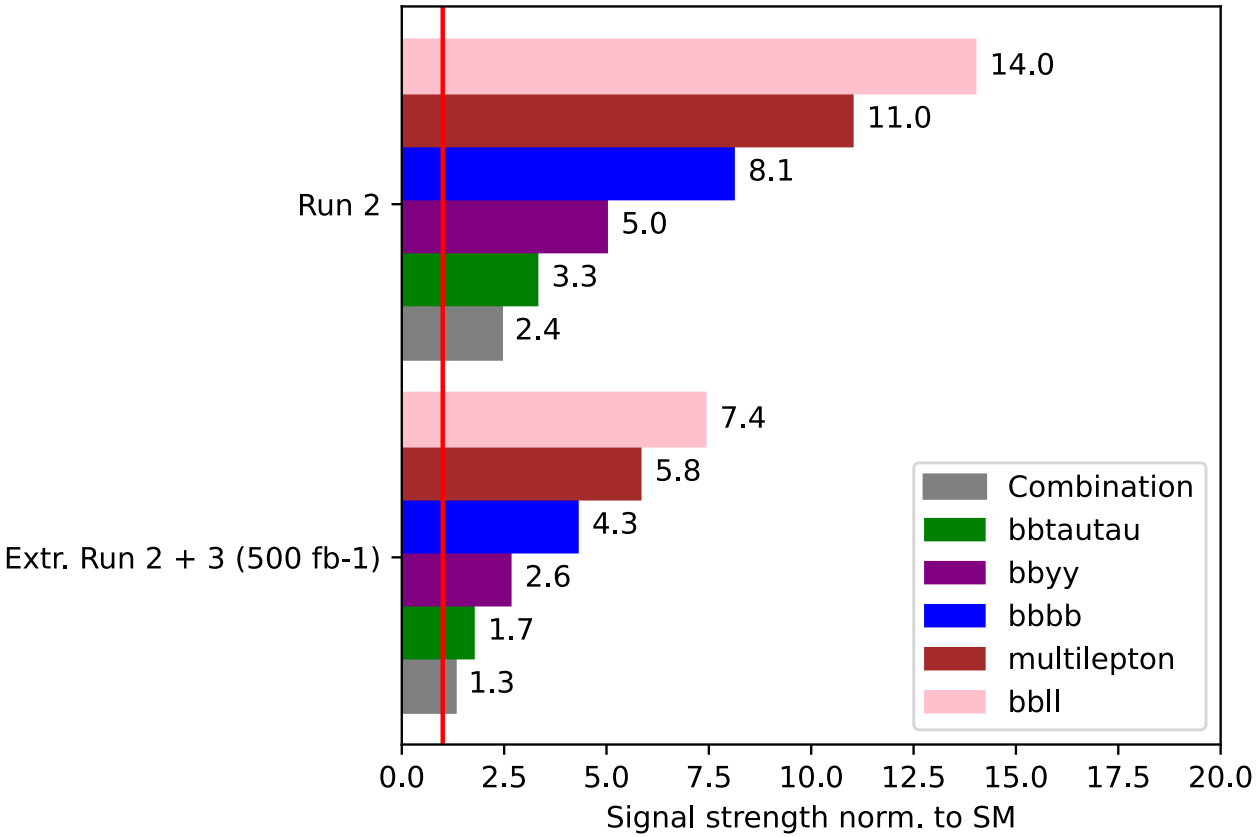
AN IMPRESSIVE SUCCESS



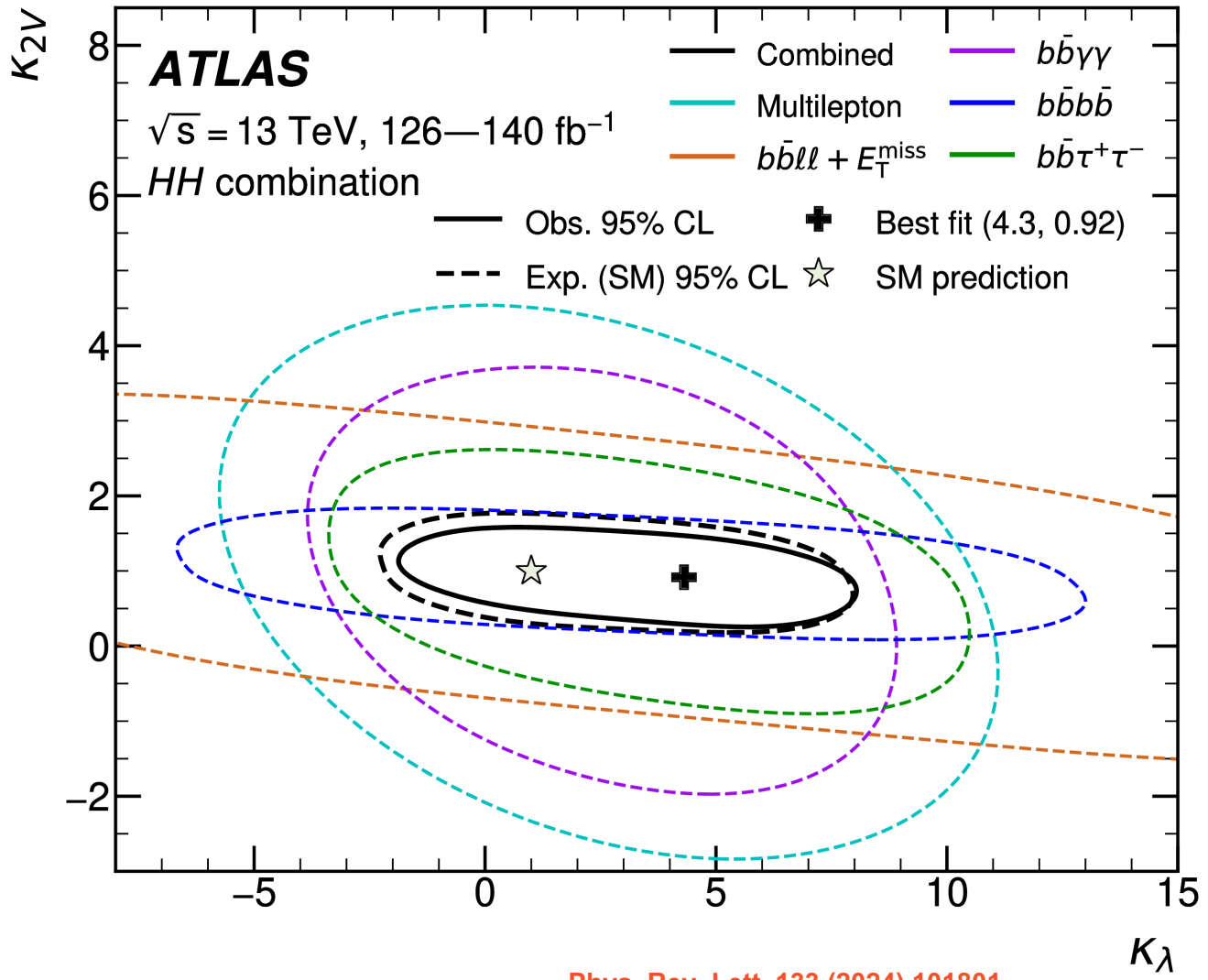
RUN 3 (400 VS 500 FB-1)



RUN 3 (400 VS 500 FB-1)



2D COUPLINGS



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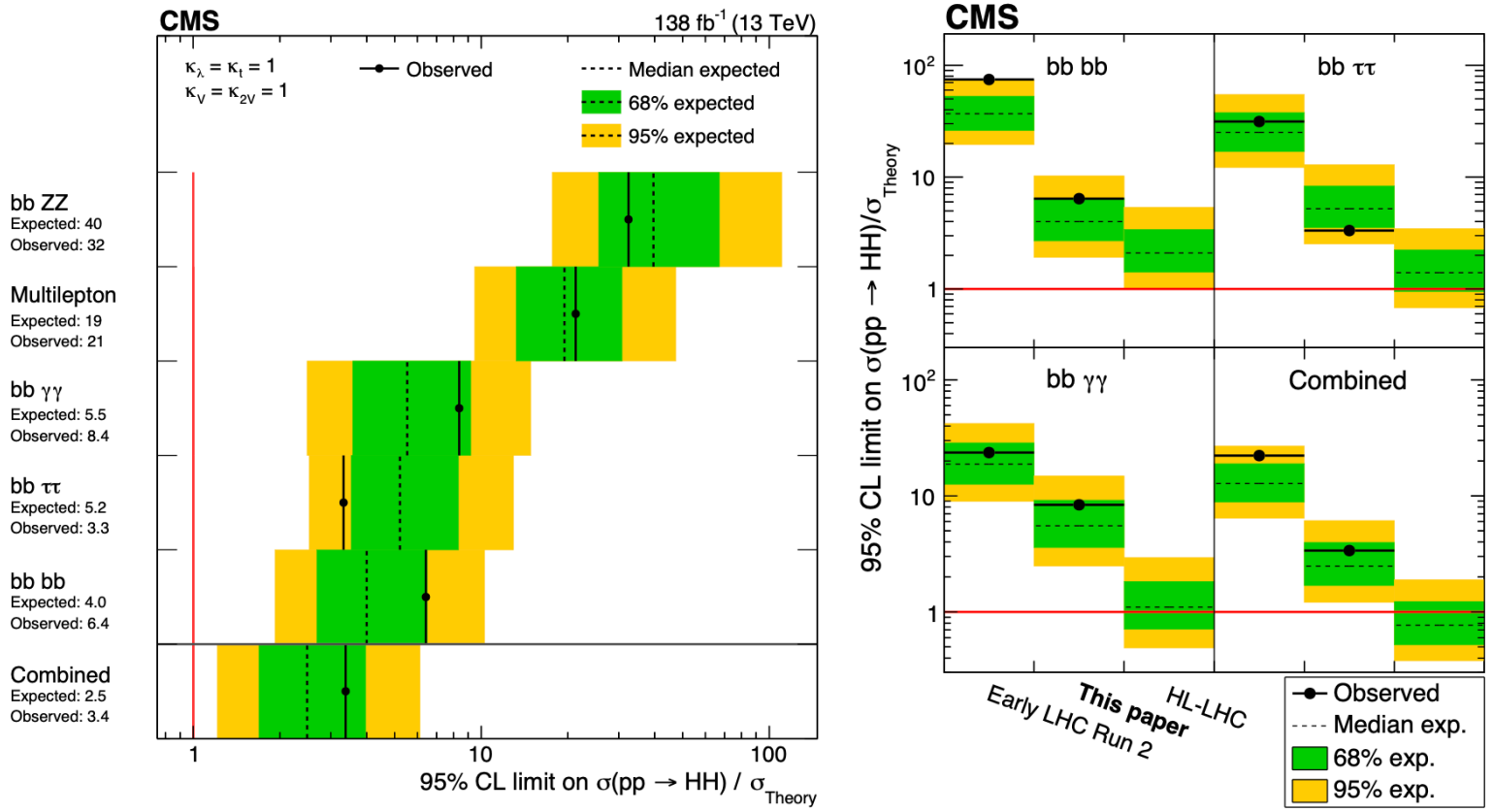
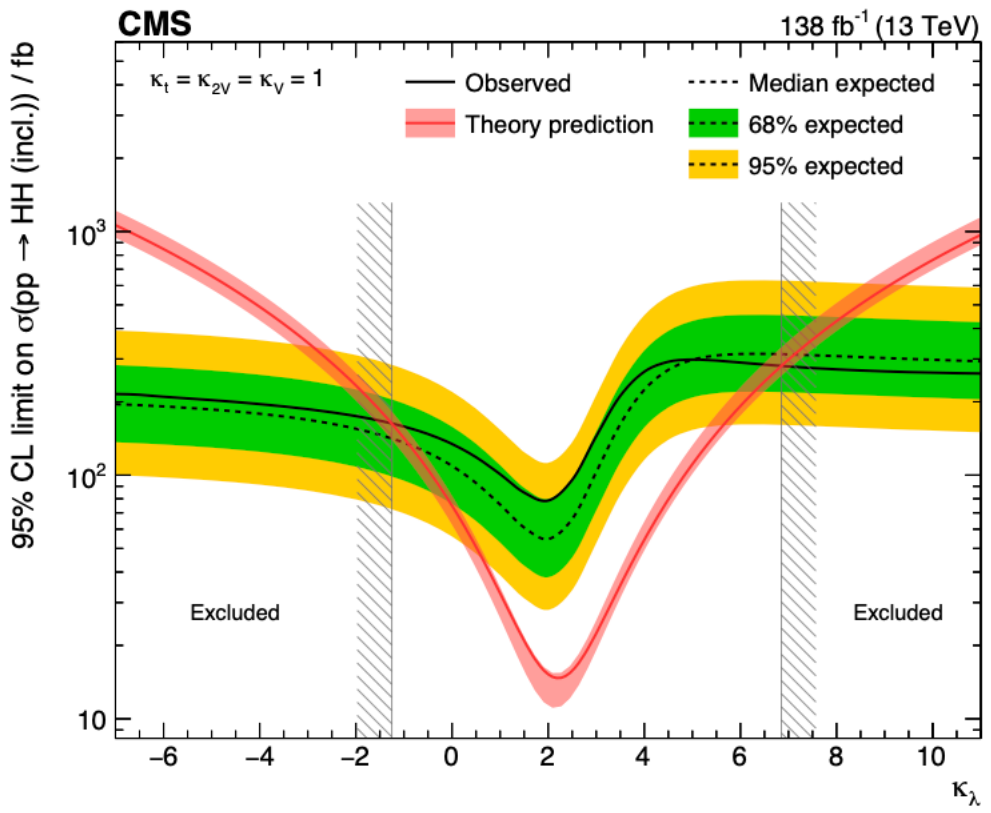
PUTTING EVERYTHING TOGETHER

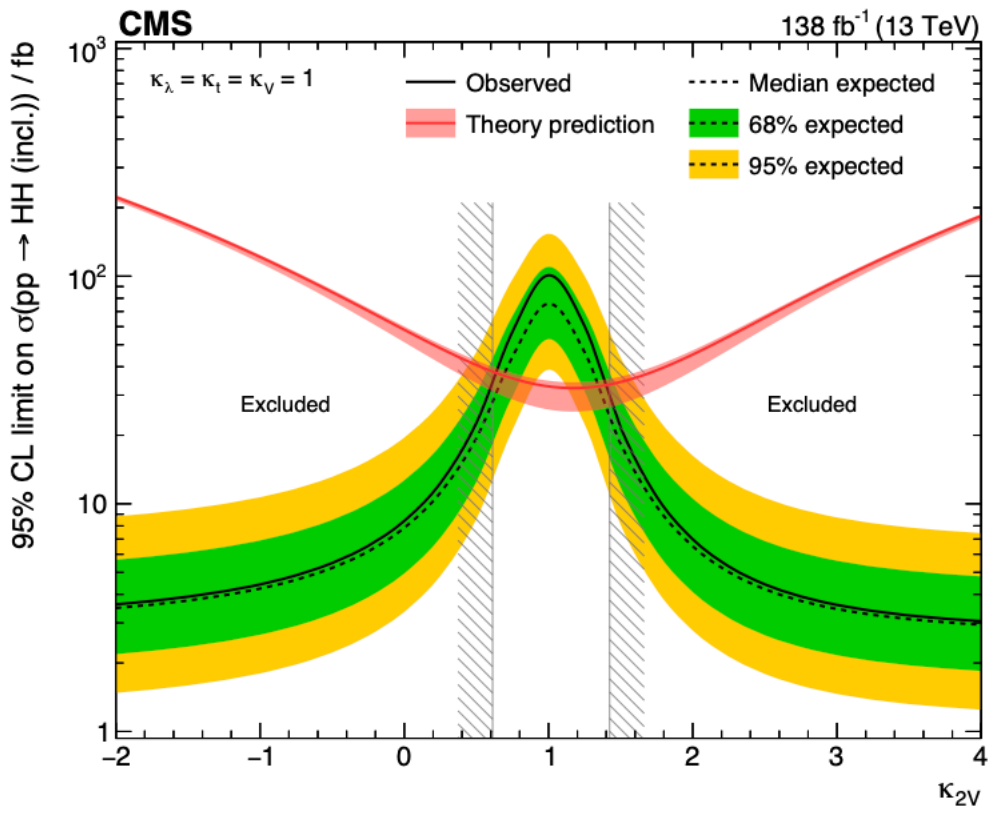
https://arxiv.org/pdf/2207.00043.pdf



PUTTING EVERYTHING TOGETHER

https://arxiv.org/pdf/2207.00043.pdf





VBF HH PRODUCTION VS KL AND K2V

Reviews in Physics 5 (2020) 100045

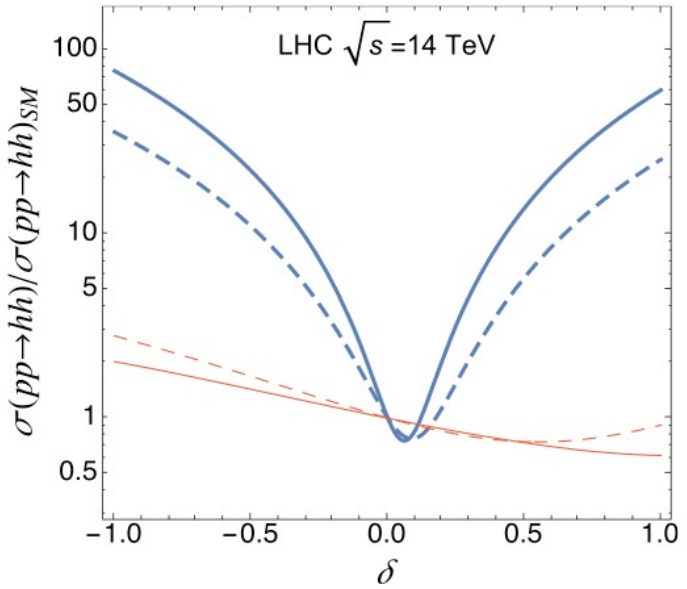
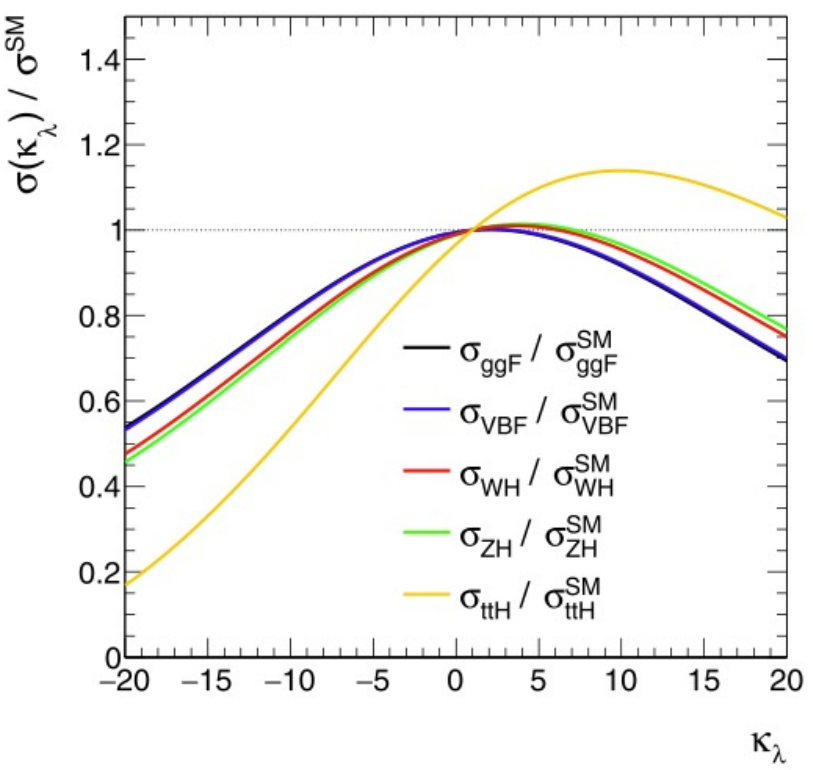
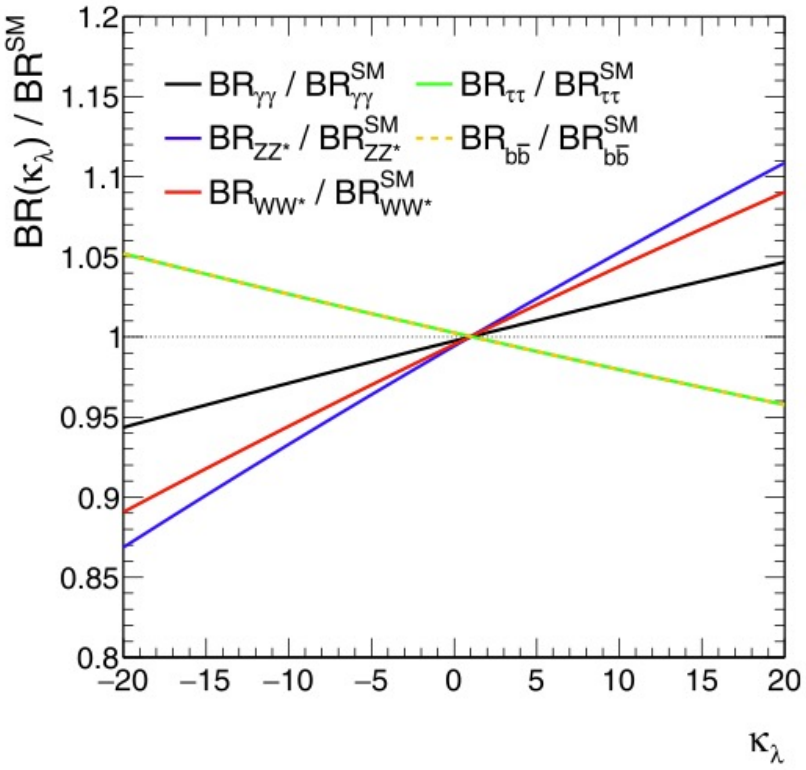


Fig. 82. VBF *HH* production cross section as a function of the coupling deviation from the SM value for the *HHVV* (*HHH*) vertex in blue (red). The solid line is after acceptance cuts, the dashed line is after analysis cuts applied on the rapidity difference and M_{jj} [455]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

SINGLE HIGGS

https://doi.org/10.1016/j.revip.2020.100045

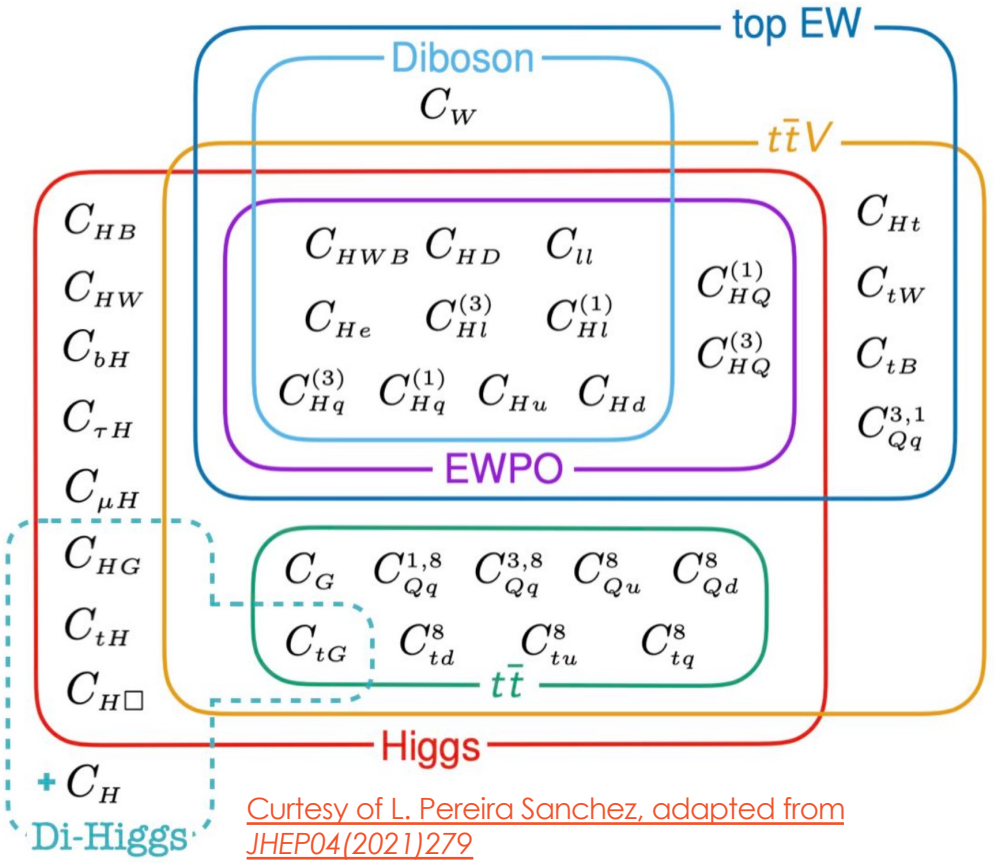




EFFECTIVE FIELD THEORIES AT THE LHC

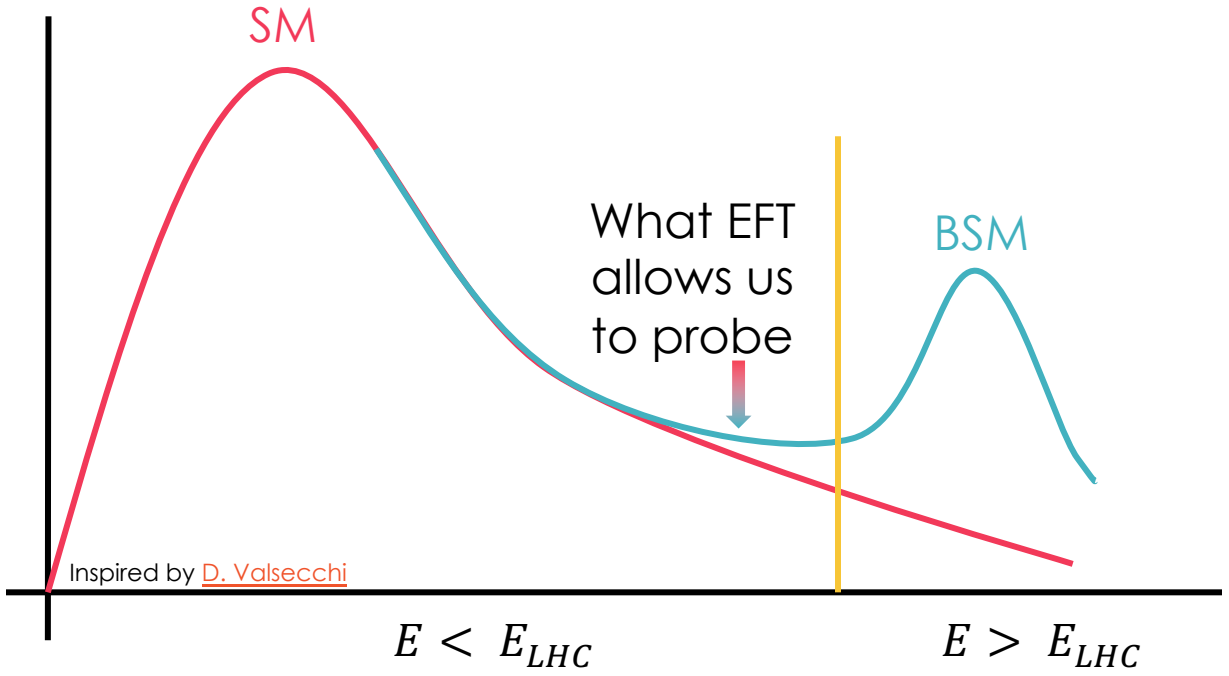
- Searching for **physics Beyond the Standard Model** (BSM) **major goal of particle physics**
- **Higgs, Top and electroweak precision measurements** benefit from a global approach in the framework of **Effective Field Theories (EFT)**
  - Different operators sensitive to different phenomena
- **SMEFT** (**SM EFT,** Higgs fields as doublets) or **HEFT** (**Higgs EFT,** physical Higgs boson)
- SMEFT typically expanded to dim. 6 operators, dim. 8 included to probe certain couplings
- HEFT more general than SMEFT, certain coefficients become independent

SMEFT Wilson coefficients



Curtesy of L. Pereira Sanchez, adapted from *JHEP04(2021)279*

EXPERIMENTAL OBSERVABLES



$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^5 + \mathcal{L}^6 + \mathcal{L}^7 + \mathcal{L}^8 + \cdots ,$$

Odd dim. neglected (l/b number violations)

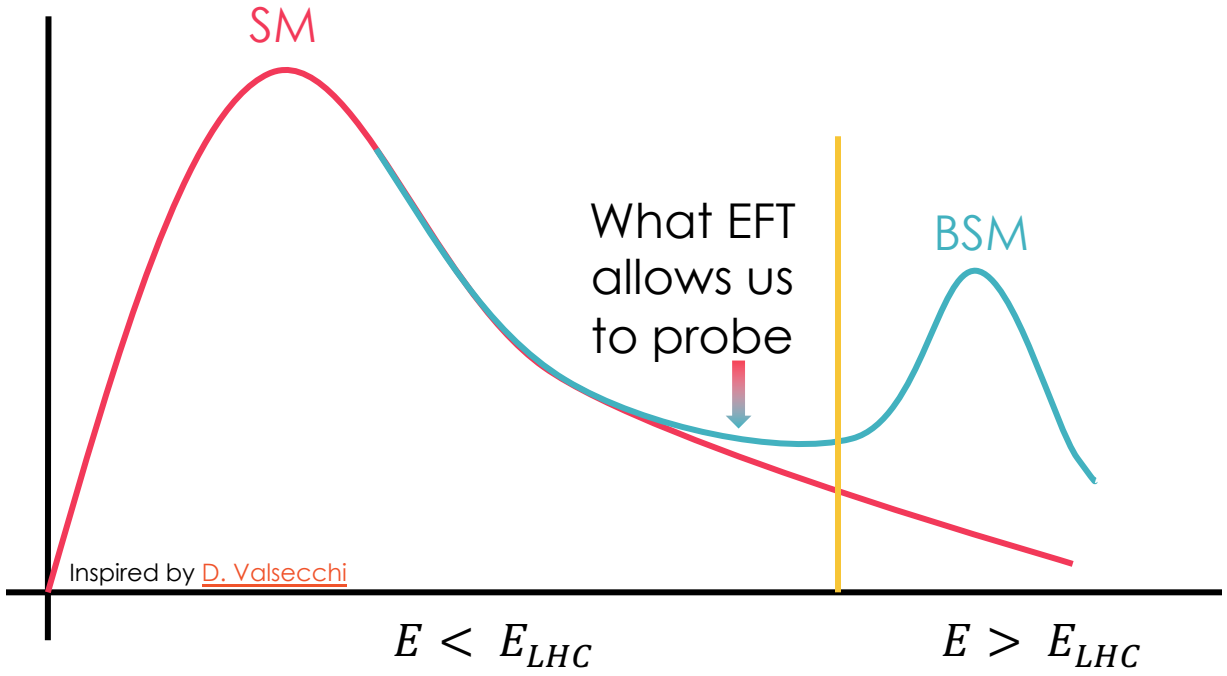
$$\mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4$$

Wilson Coefficient

Scale of BSM physics

Operator
(indicated also with *O*)

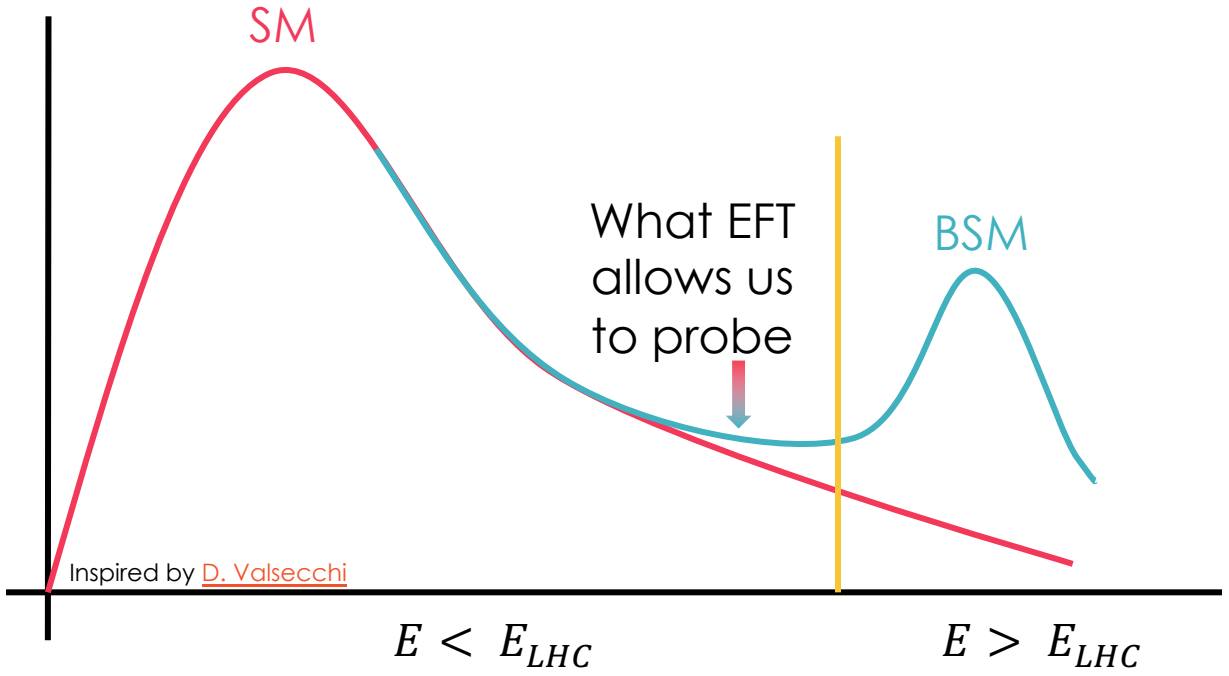
EXPERIMENTAL OBSERVABLES



$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^6 + \mathcal{L}^8 + \cdots \Rightarrow$$

$$\sigma_{SMEFT} = \sigma_{SM} + \underbrace{\sigma_{int,6}}_{\text{linear } (1/\Lambda^2)} + \underbrace{\sigma_{BSM,6} + \sigma_{int,8}}_{\text{quadratic } (1/\Lambda^4)} + \ \ldots$$

EXPERIMENTAL OBSERVABLES



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High energy **tails of kinematic observables** enhance experimental sensitivity to SM deviations

- Lin. vs Lin.+Quad. to probe higher order effects

Differential & **precise** measurements are key

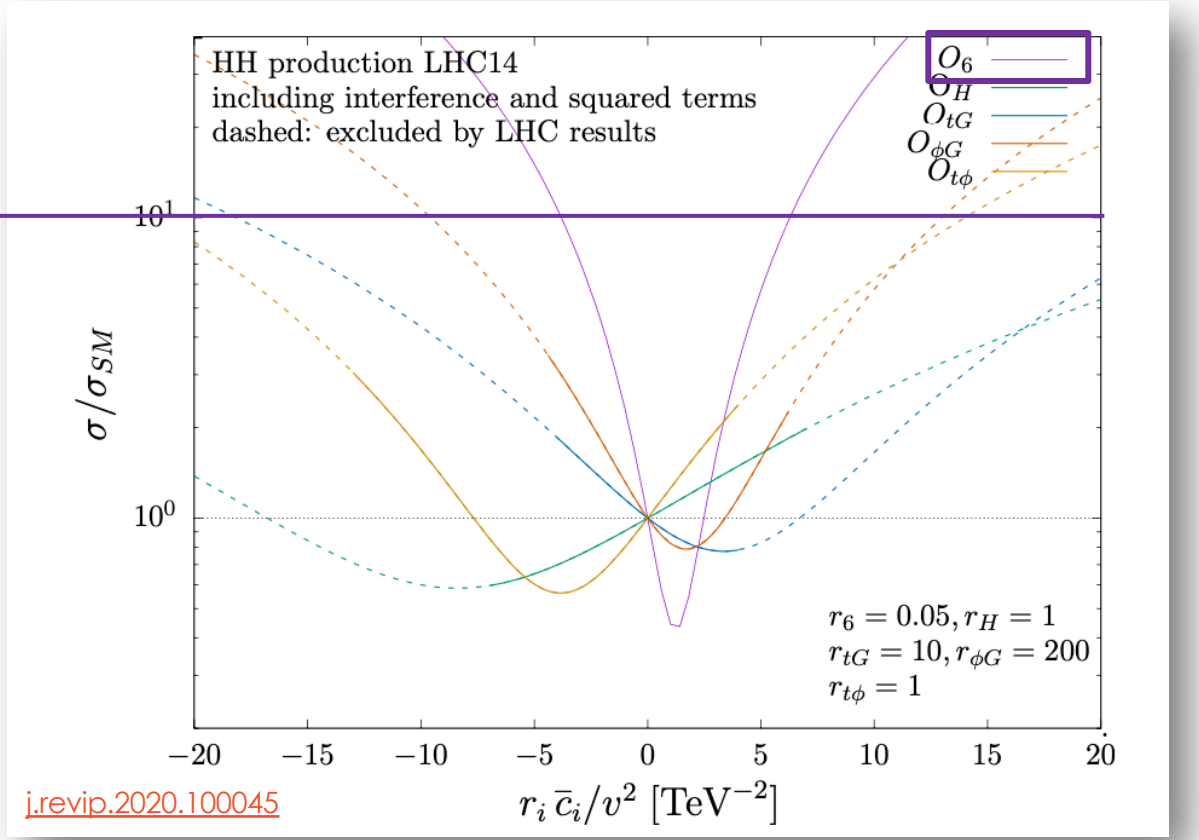
Great complementarity between **SM**, **Top** and **Higgs** sectors to address fundamental physics questions…

WHY HH? AND WHY IN EFT?

Higgs pairs produced by means of various interactions at the LHC, including the **Higgs self-coupling**, λ, giving us *direct* access to its measurement when searching for HH

LHC early Run 2 constraints ≈ 10

No sensitivity to parameters other than O_6 $(\sim k_\lambda)$



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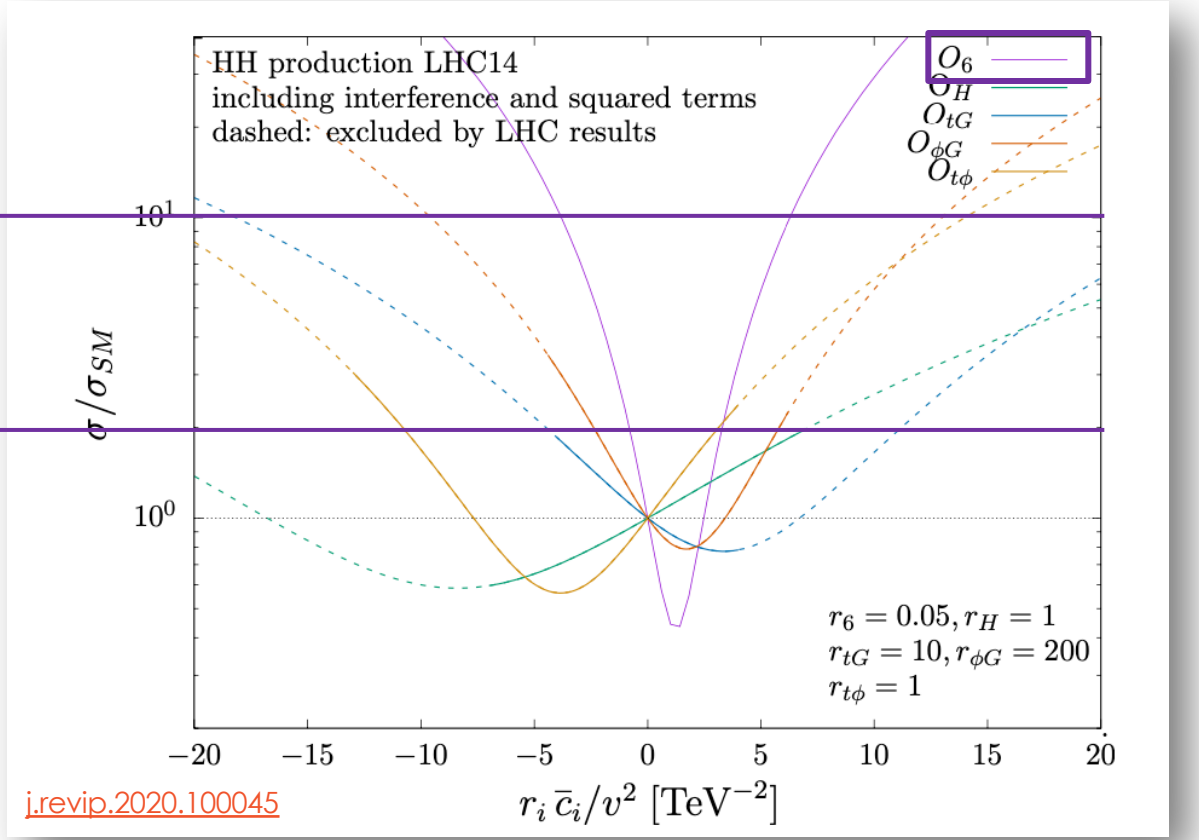
WHY HH? AND WHY IN EFT?

Higgs pairs produced by means of various interactions at the LHC, including the **Higgs self-coupling**, λ, giving us *direct* access to its measurement when searching for HH

LHC early Run 2 constraints ≈ 10

LHC full Run 2 constraints ≈ 3

Relevant to consider general coupling variations



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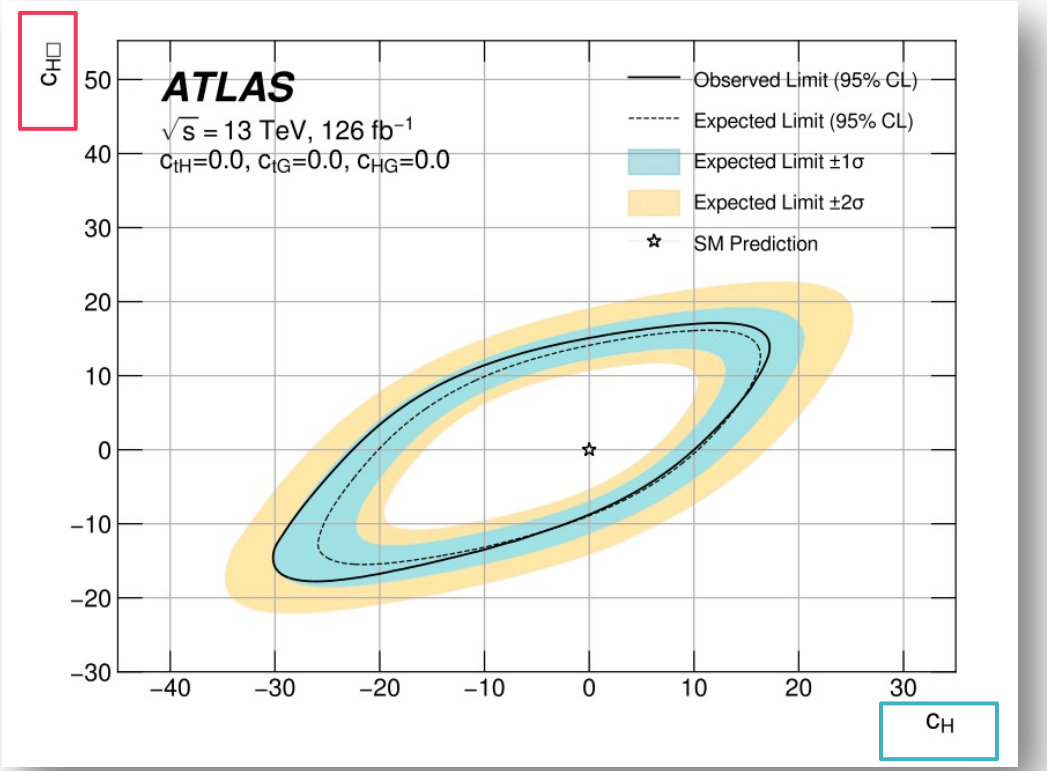
HIGGS PAIRS IN SMEFT [2301.03212]

Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G_A^{\mu\nu}$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$

In Single Higgs, only included in linear combination with other WCs

Probed uniquely by HH

ATLAS $HH \to 4b$



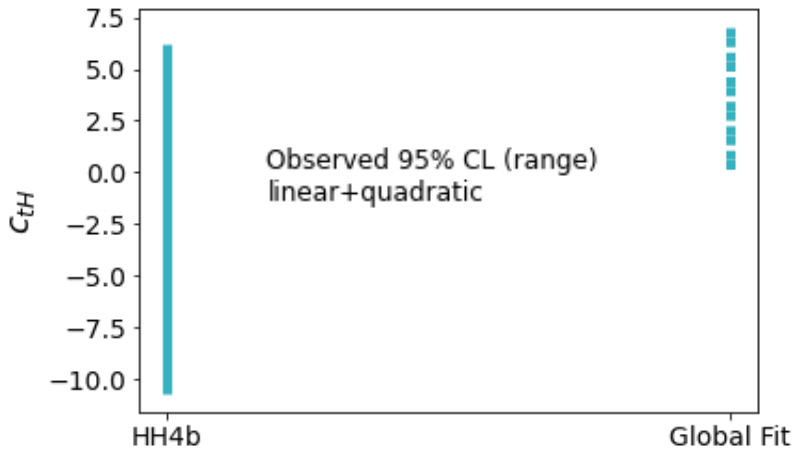
More 2D scans in the extra slides

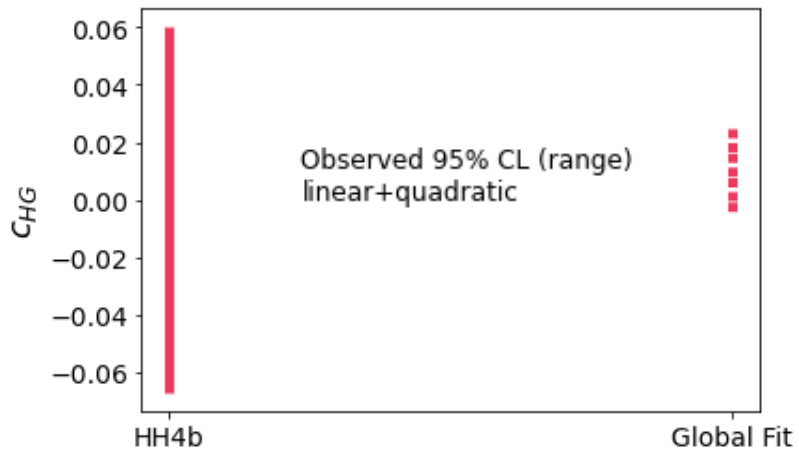
HIGGS PAIRS IN SMEFT [2301.03212]

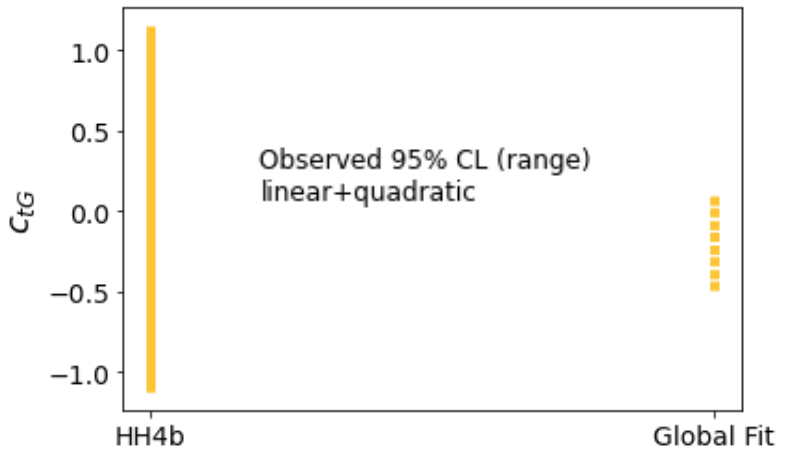
Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G_A^{\mu\nu}$
c_{tG}	$(Q\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$

Limits are ~ comparable with global combination (dominated by single Higgs)

Order-of-magnitude **hand-made** comparison between [2301.03212] *(Global Fit)* and [ATL-PHYS-PUB-2022-037] *(HH4b)*





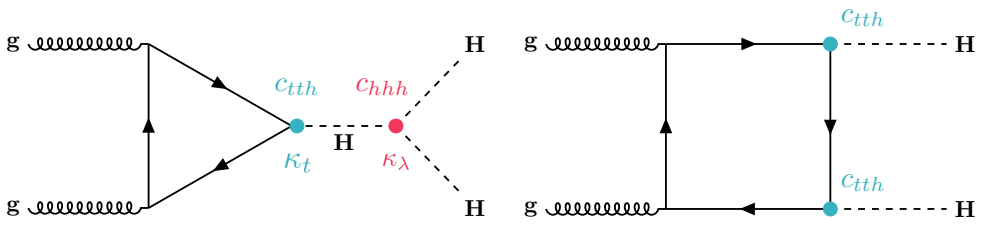


HIGGS PAIRS IN HEFT

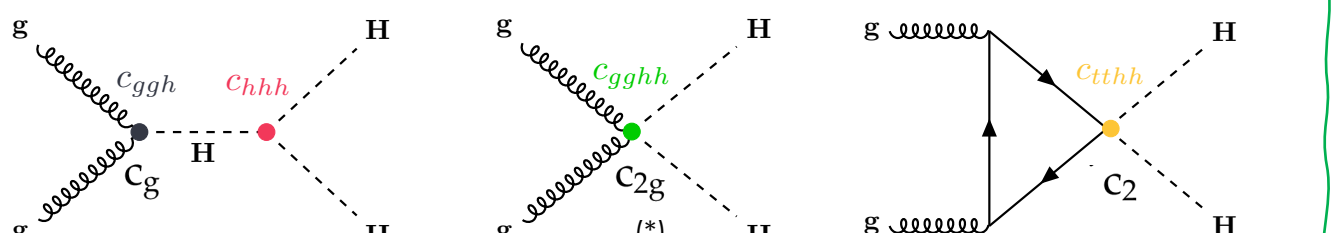
2301.03212, ATL-PHYS-PUB-2022-019, JHEP 03 (2021) 257

In **HEFT**, anomalous **single-Higgs couplings ≠ *HH* couplings** ($c_{ggHH} \neq c_{ggH}, c_{ttHH} \neq c_{ttH}$)

Standard Model



Beyond Standard Model



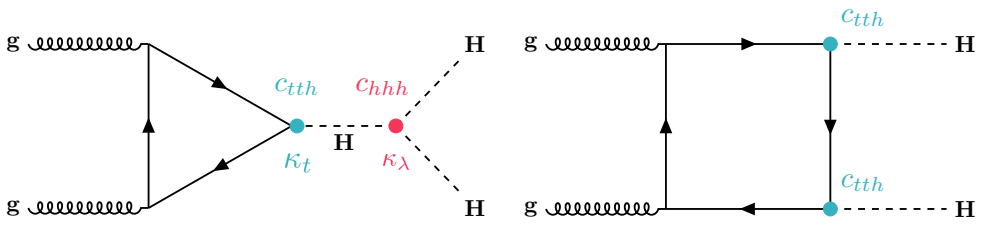
(*) In black the CMS WCs convention, in colors the ATLAS one

HIGGS PAIRS IN HEFT

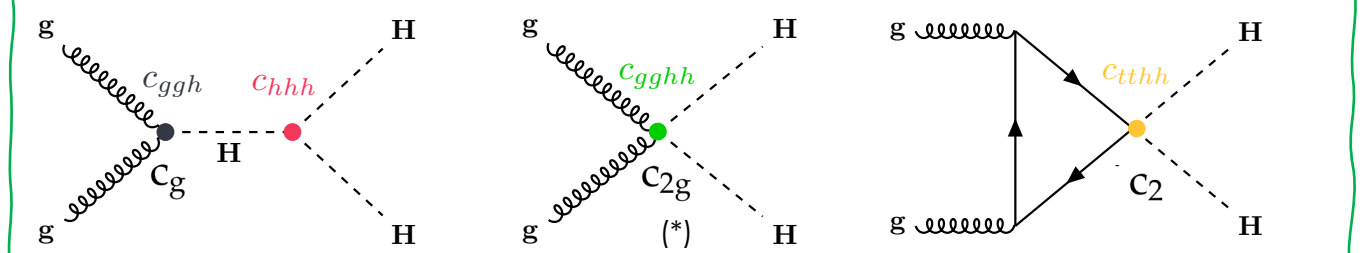
2301.03212, ATL-PHYS-PUB-2022-019, JHEP 03 (2021) 257

In **HEFT**, anomalous **single-Higgs couplings ≠ *HH* couplings** ($c_{ggHH} \neq c_{ggH}, c_{ttHH} \neq c_{ttH}$)

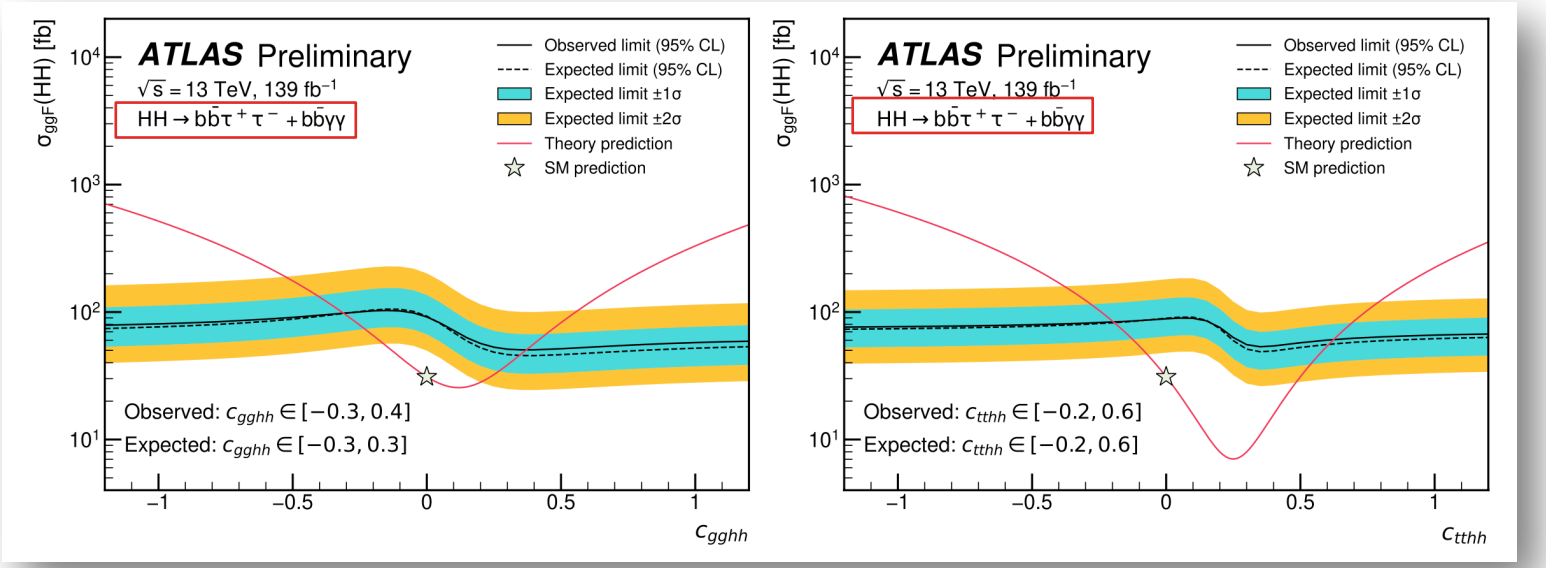
Standard Model



Beyond Standard Model



HEFT results for ATLAS $HH \to \gamma\gamma bb$ + $HH \to bb\tau\tau$ ($\sigma/\sigma_{SM} < 0(3)$), ATLAS $HH \to 4b$ and CMS $HH \to \gamma\gamma bb$

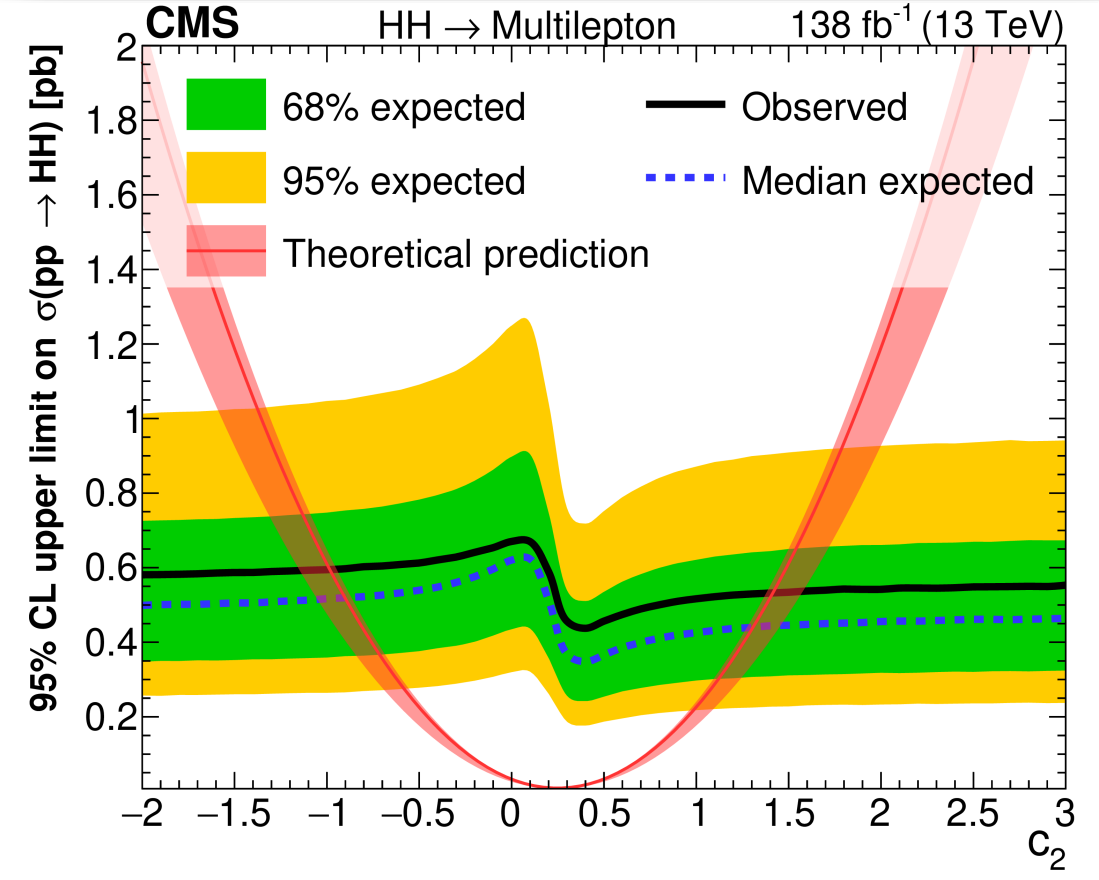


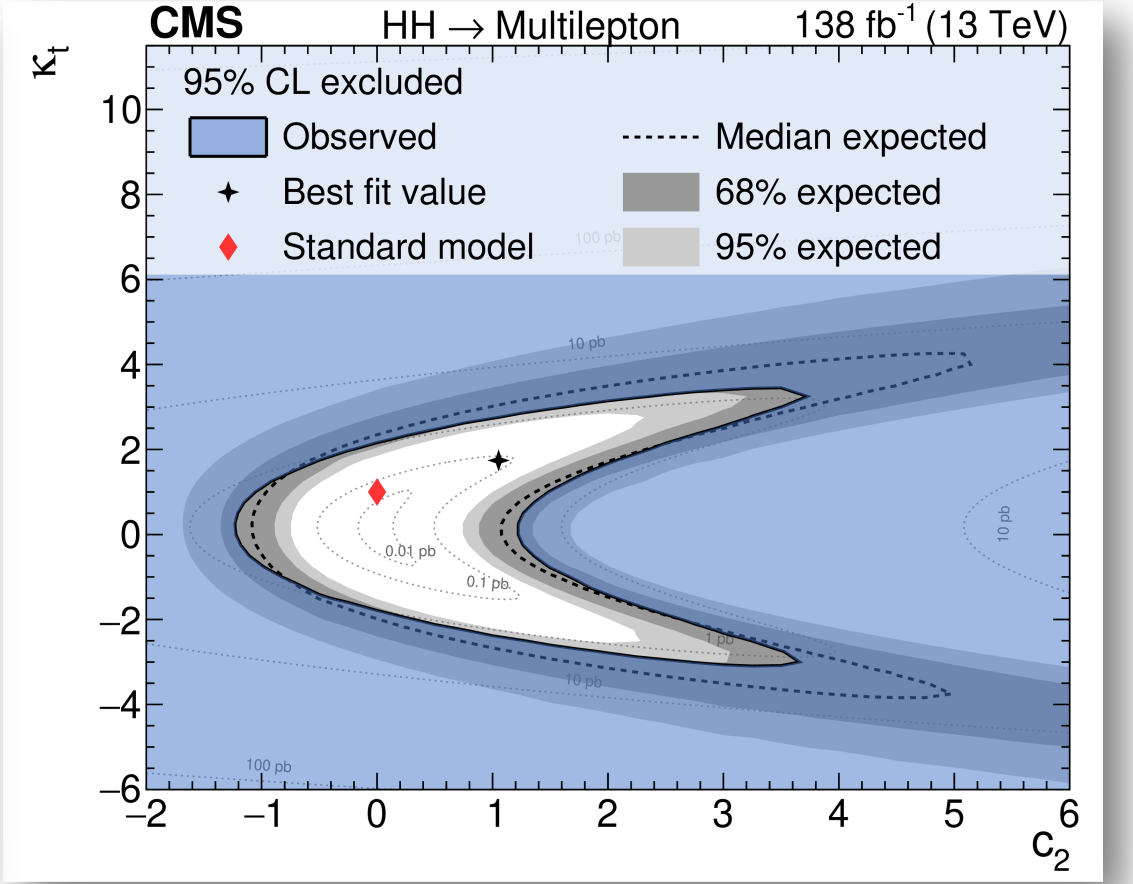
See extra slides for constraints on "*benchmarks*", i.e. xs limits on recommended combinations of WCs values

(*) In black the CMS WCs convention, in colors the ATLAS one

HIGGS PAIRS IN HEFT [2206.10268]

- CMS full Run 2 search for $HH -> WWWW, WW\tau\tau, and\ \tau\tau\tau\tau$
- Require multi-leptons (e, μ, τ_{had}) in the final state
- $\sigma/\sigma_{SM} < 0(20)$

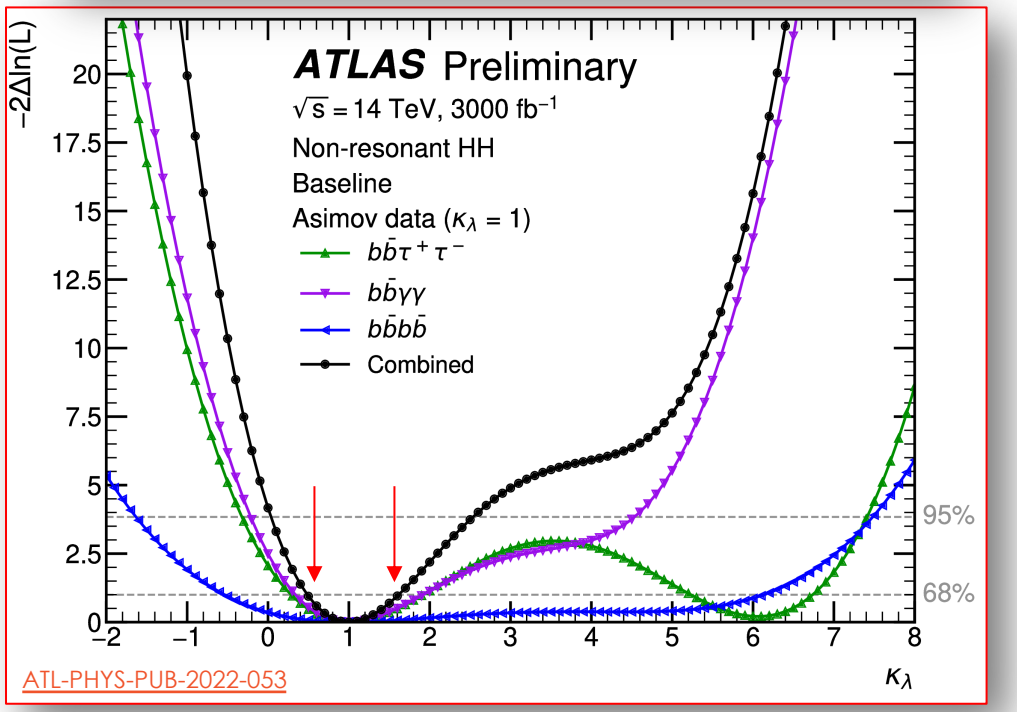




HOW DOES HH LOOK IN HL-LHC?

Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination
No syst. unc.	2.3	4.0	1.8	4.9
Baseline	2.2	2.8	0.99	3.4

was 3.3!



ATLAS alone comparable to previous expectation from ATLAS + CMS

$0.5 \lesssim k_\lambda \lesssim 1.6$ at 1σ

FUTURE COLLIDERS

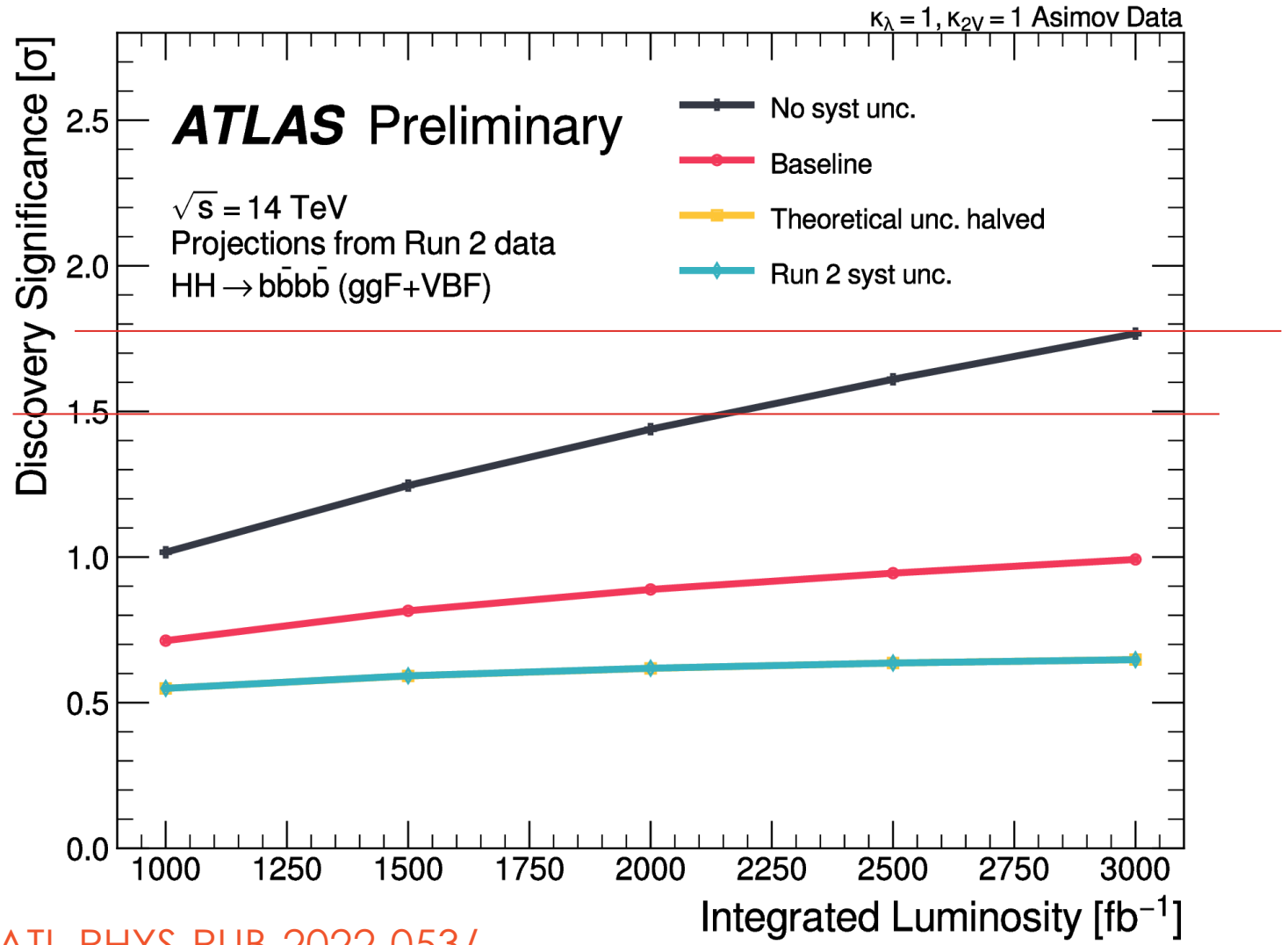
arXiv:1907.02078v2

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2} (H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

	a	b	c_1	c_2	c_3	d_3	d_4
relevant couplings	hVV	$hhVV$	$h\bar{t}t$	$hh\bar{t}t$	$hhh\bar{t}t$	hhh	$hhhh$
SM	1	1	1	0	0	1	1
SMEFT (with O_6)	1	1	1	0	0	$1 + c_6 \frac{v^2}{\Lambda^2}$	$1 + c_6 \frac{6v^2}{\Lambda^2}$
MCH_{5+5}	$1 - \frac{\xi}{2}$	$1 - 2\xi$	$1 - \frac{3}{2}\xi$	-2ξ	$-\frac{2}{3}\xi$	$1 - \frac{3}{2}\xi$	$1 - \frac{25}{3}\xi$
CTH_{8+1}	$1 - \frac{\xi}{2}$	$1 - 2\xi$	$1 - \frac{1}{2}\xi$	$-\frac{1}{2}\xi$	$-\frac{1}{6}\xi$	$1 - \frac{3}{2}\xi$	$1 - \frac{25}{3}\xi$
CW Higgs (doublet)	1	1	1	0	0	$\frac{5}{3}(1.75)$	$\frac{11}{3}(4.43)$
CW Higgs (singlets)	1	1	1	0	0	$\frac{5}{3}(1.91)$	$\frac{11}{3}(4.10)$
Tadpole-induced Higgs	$\simeq 1$	$\simeq 1$	$\simeq 1$	0	0	$\simeq 0$	$\simeq 0$

Table 1: Higgs couplings, defined in Eqs. (2.1) and (2.3), for the SM and various NP scenarios. For the Coleman-Weinberg (CW) Higgs scenario, we also present in the parenthesis the Higgs self-couplings up to the two-loop order, predicted in the two of the simplest conformal extensions of the scalar sector: SM Higgs doublet with another doublet [14], and SM Higgs doublet with two additional singlets [15].

HOW DOES HH LOOK IN HL-LHC?



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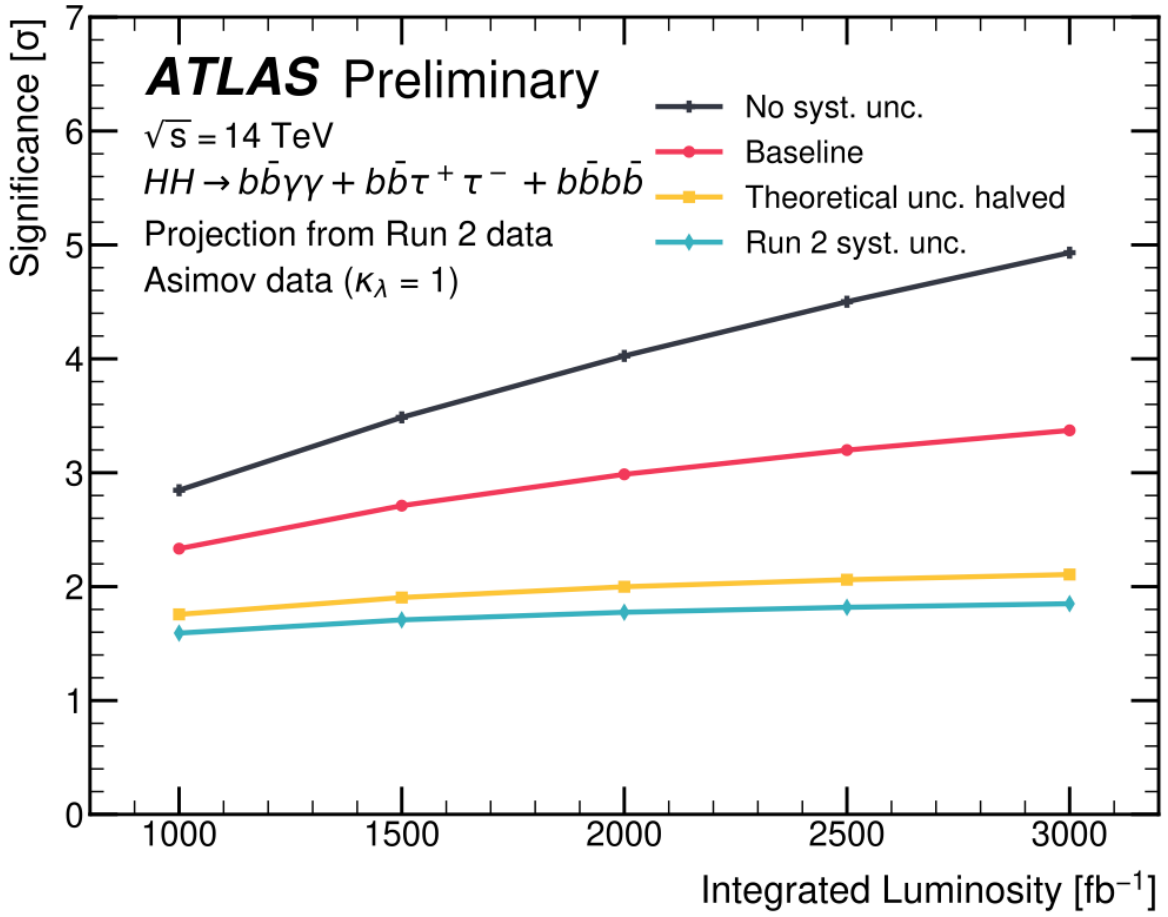
HOW DOES HH LOOK IN HL-LHC?



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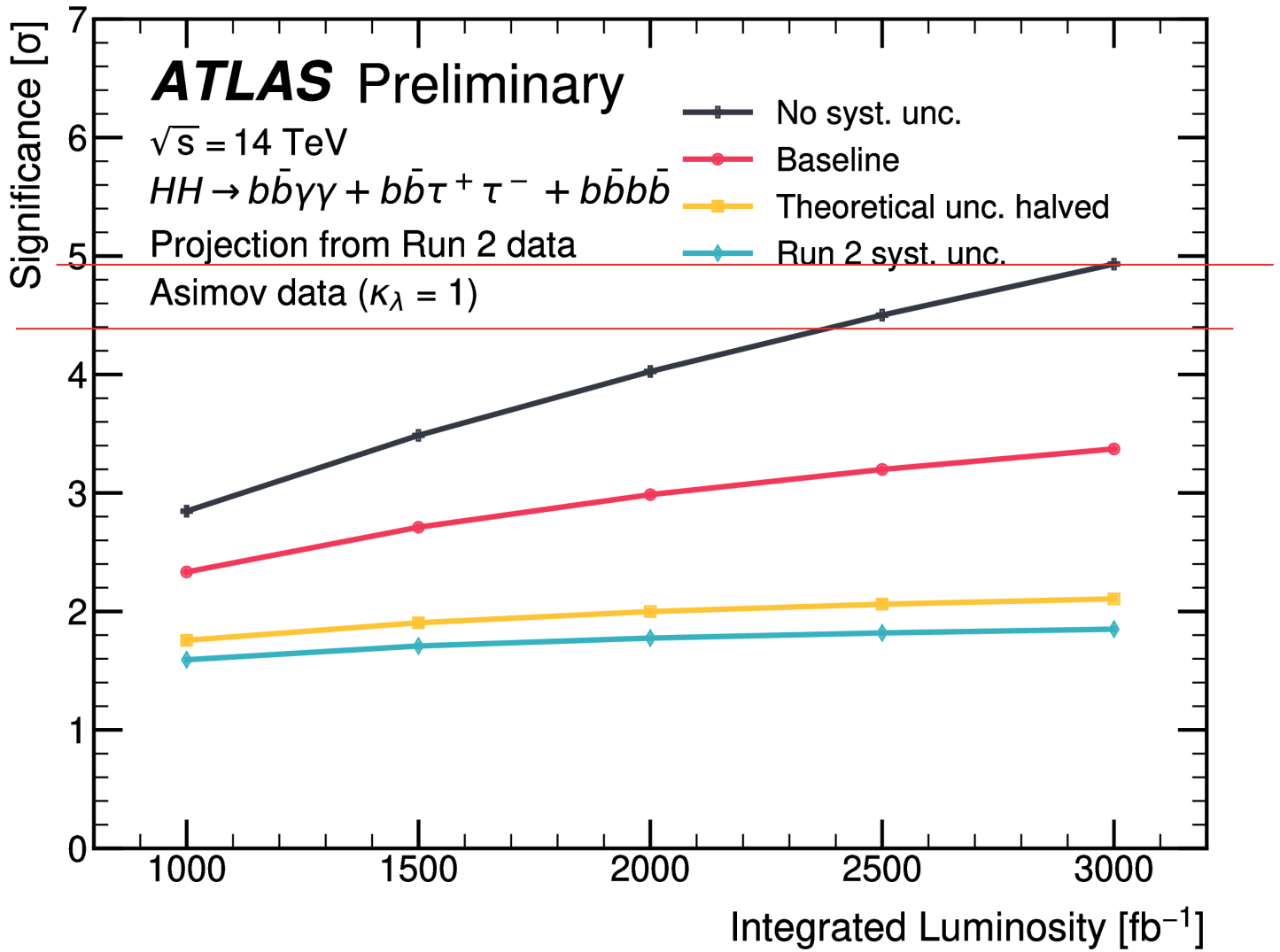
HOW DOES HH LOOK IN HL-LHC?



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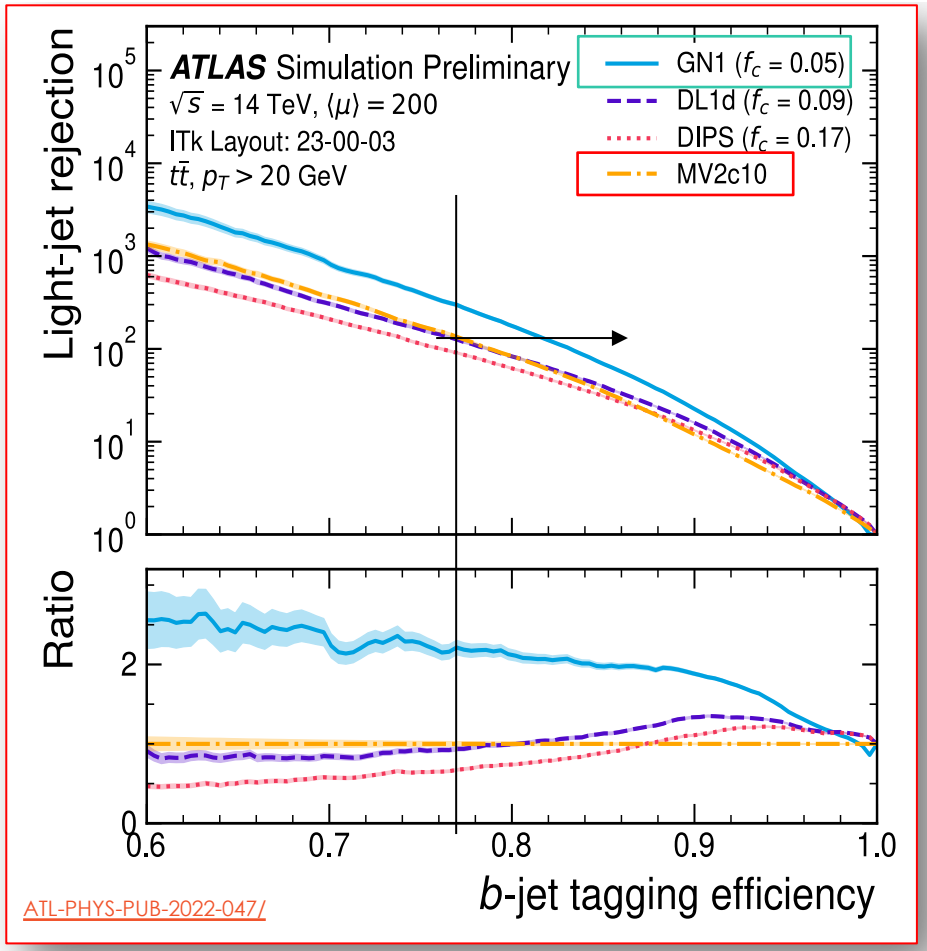
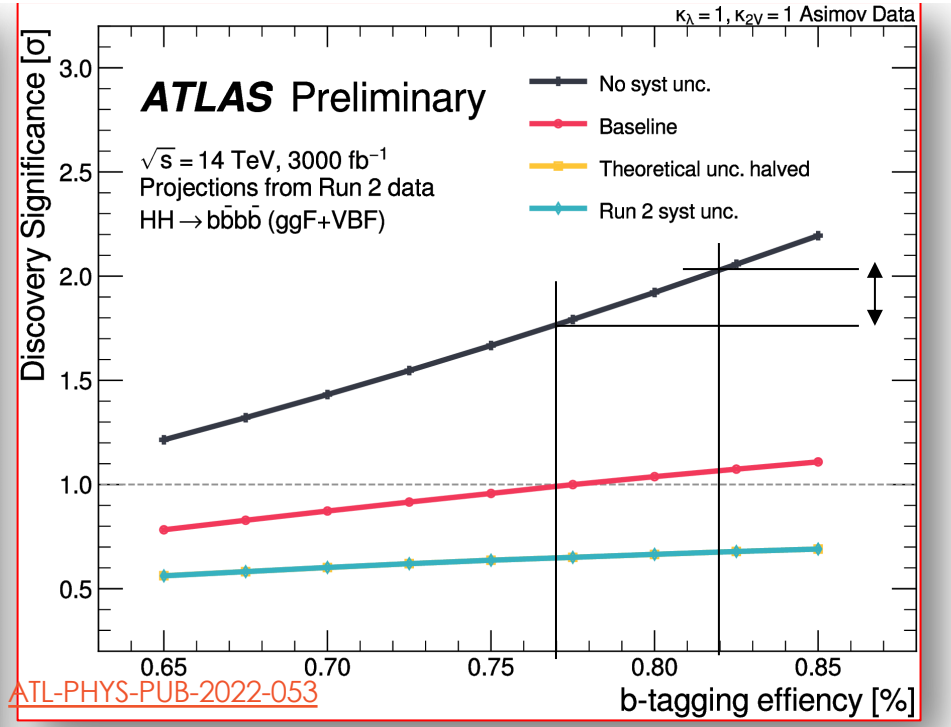
HOW DOES HH LOOK IN HL-LHC?

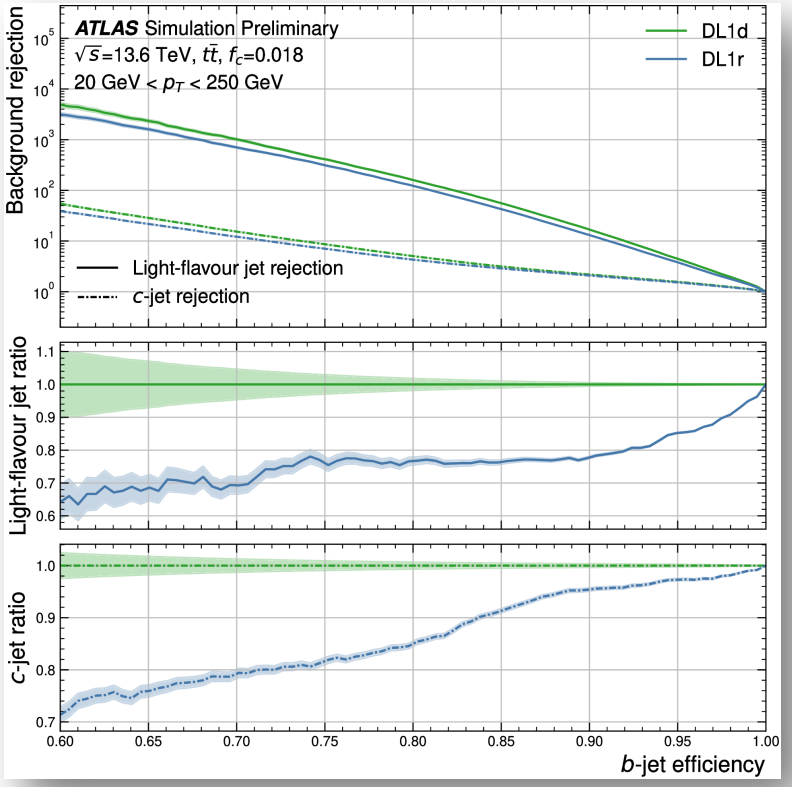
Modern flavor tagging algorithms based on **Graph Neural Networks** fully exploit the potential of the ITk → large sensitivity gains for HH!





+ 5% efficiency for the same mistag rate → + 0.3 σ sensitivity gain for $HH \rightarrow b\bar{b}b\bar{b}$

RUN 3 b-TAGGING



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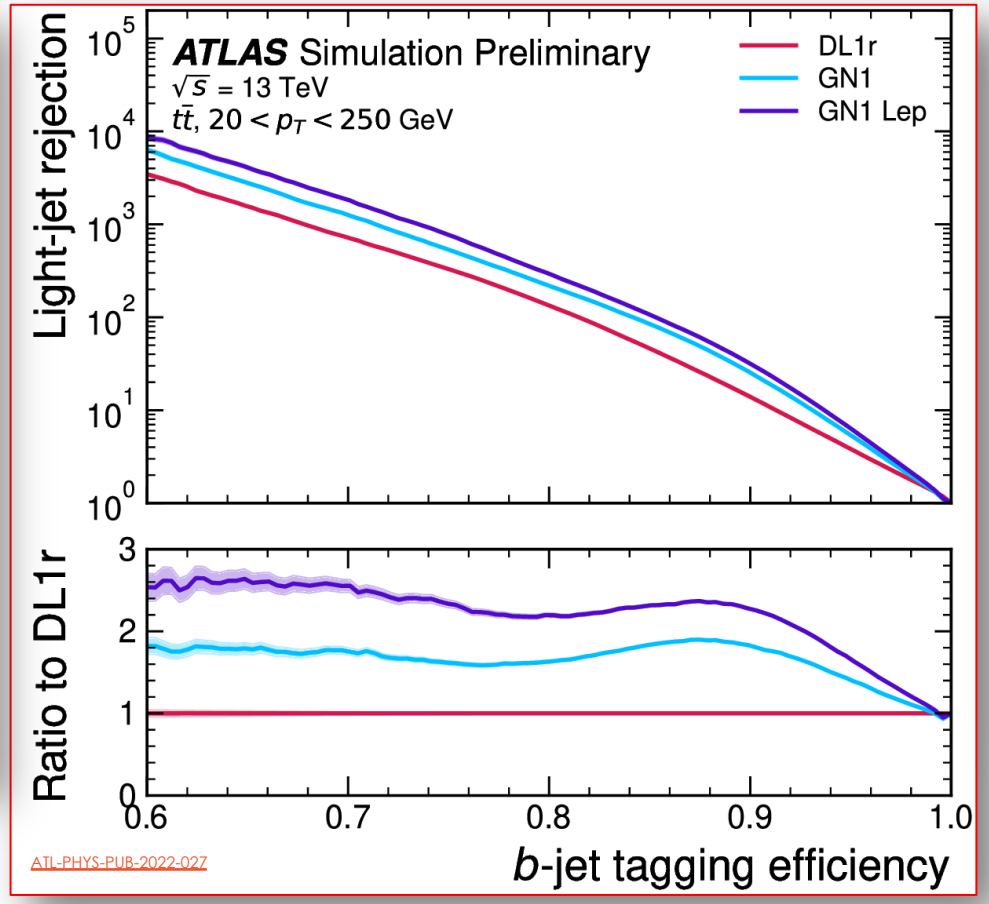

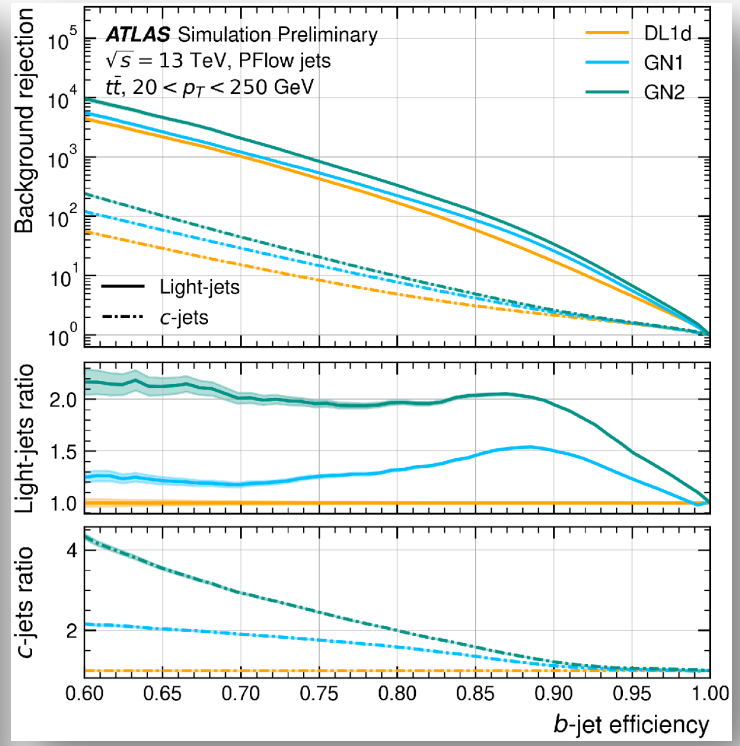

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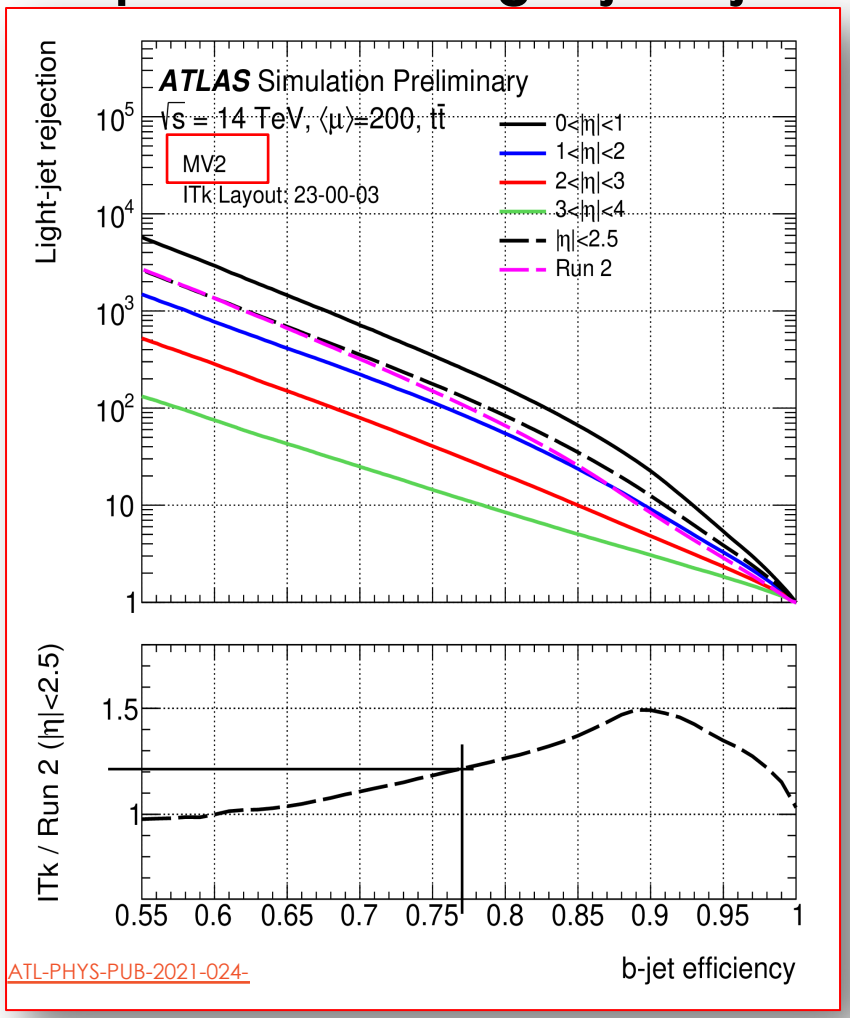
ITK BTAGGING

Moder taggers based on **Graph Neural Networks** further exploit the potential of the ITk: **up to x2 improvement in light-jet rejection**!



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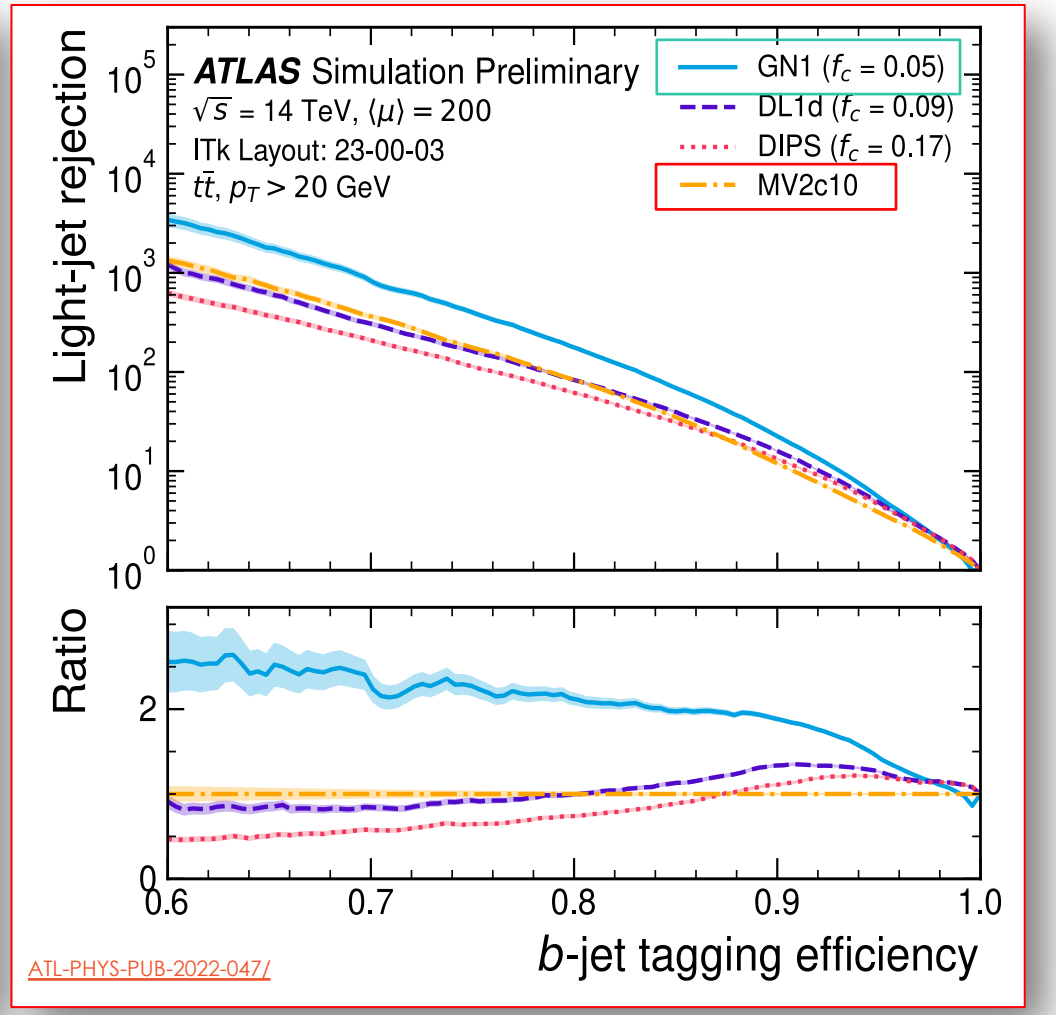

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