Recent

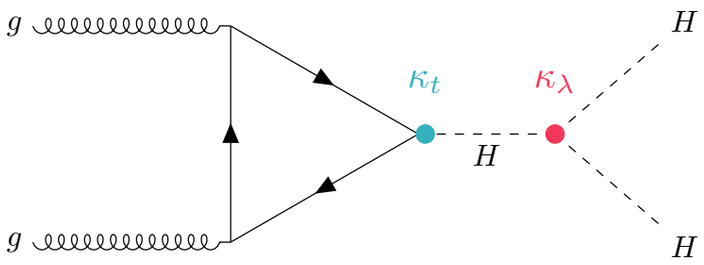
"Multiple-Higgs searches at ATLAS and CMS"

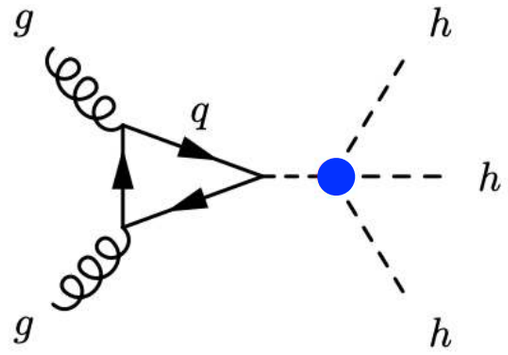
Valerio Dao *(Stony Brook University)*
o.b.o. ATLAS and CMS collaborations

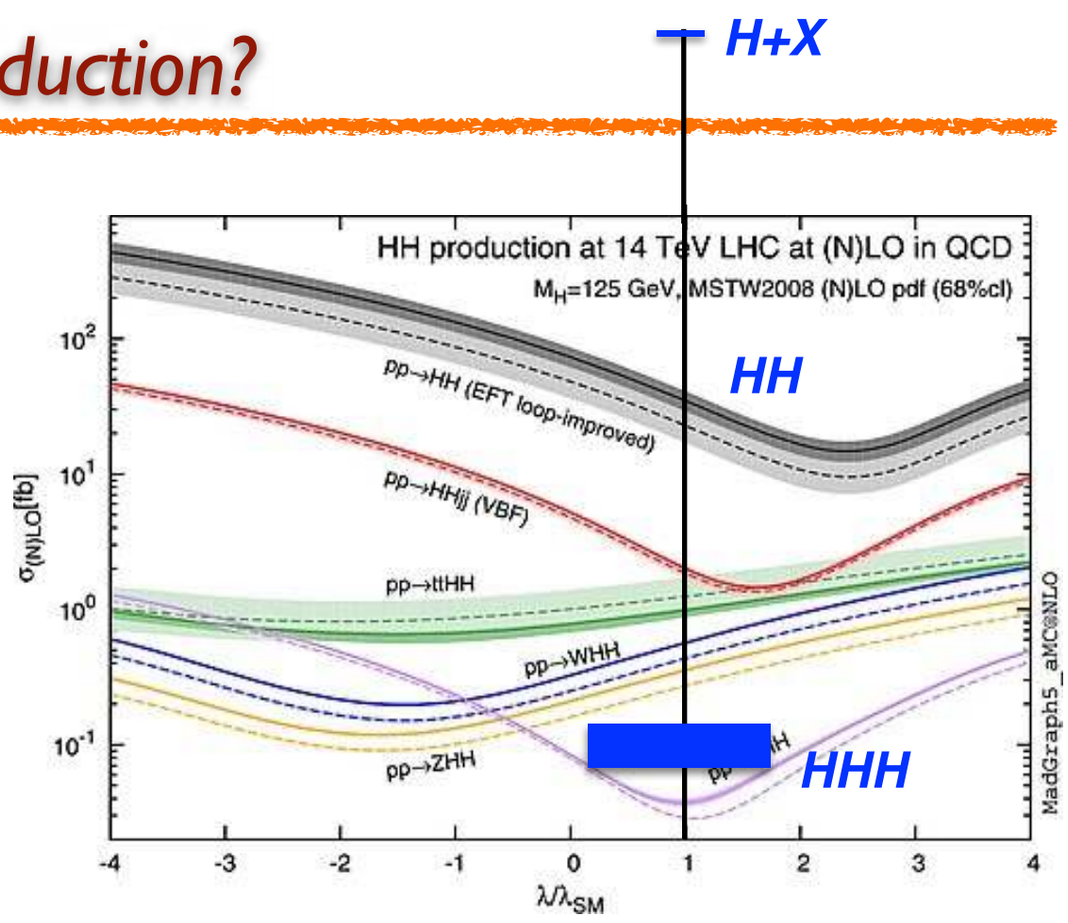
Moriond EWK '26

Why multi-Higgs production?

- ***Di-Higgs (HH) and triple Higgs (HHH)*** *production are rare / extremely rare processes predicted by the SM*







- ***Key predictions to consolidate our understanding of the EWK symmetry breaking and look for BSM effects***

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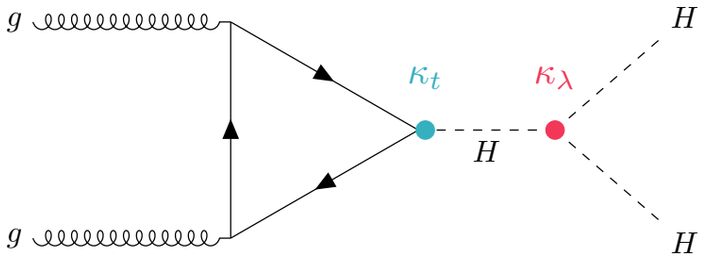
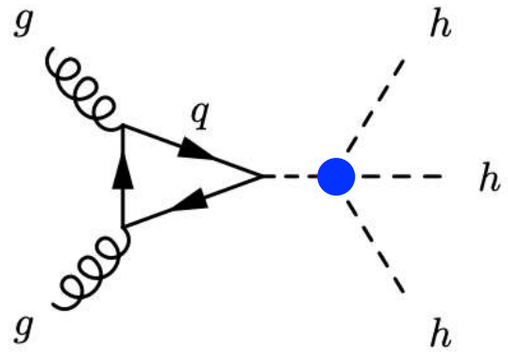
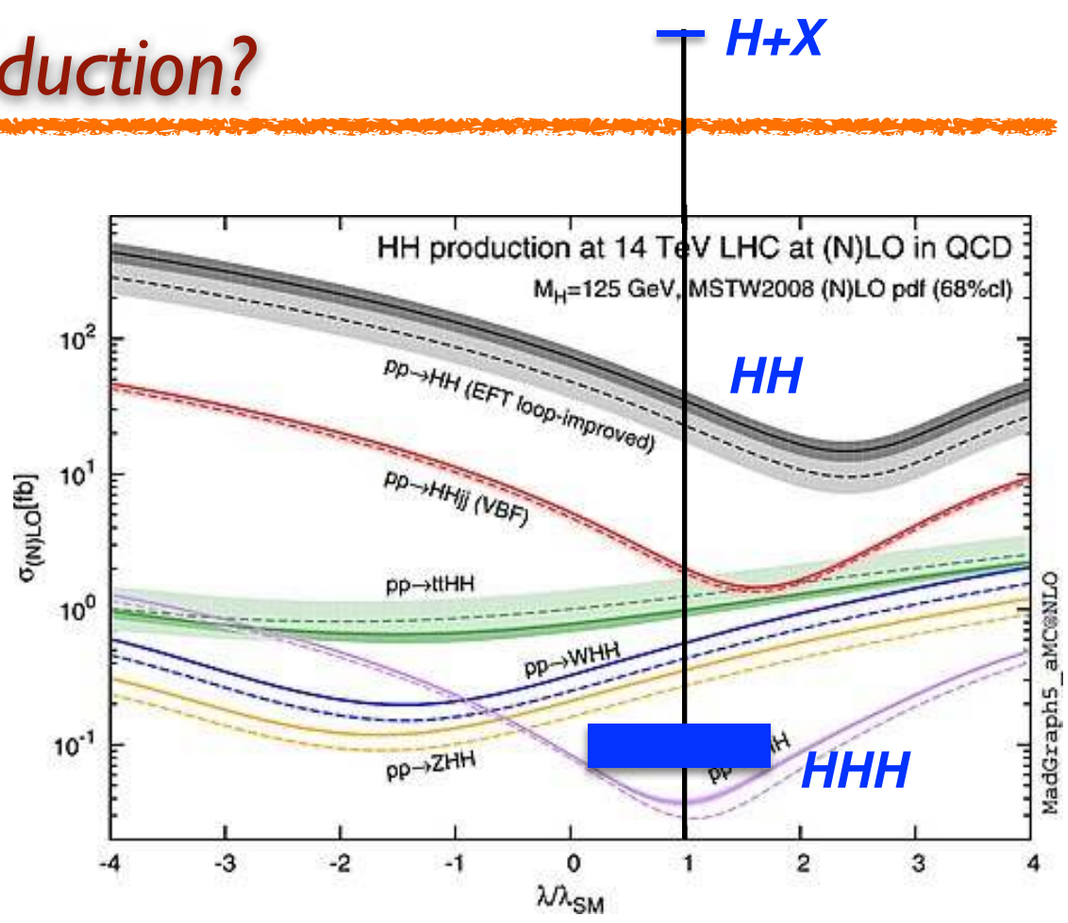




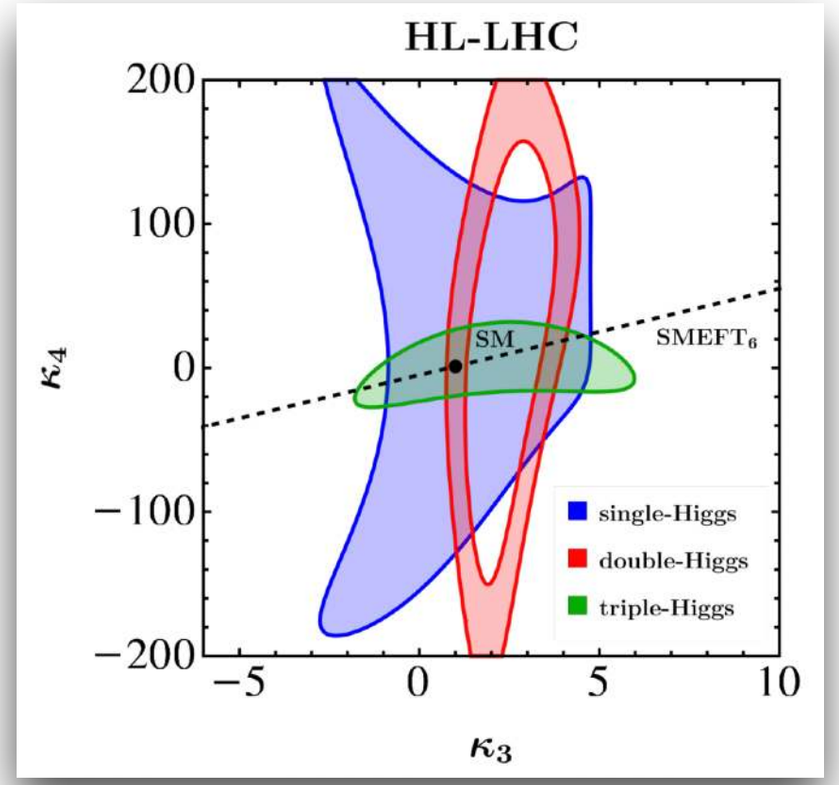


- ***Key predictions to consolidate our understanding of the EWK symmetry breaking and look for BSM effects***

- ***Direct sensitivity to Higgs boson self couplings:*** <u>understanding the shape of the Higgs potential:</u>

$$V(H) = \frac{1}{2}m_H^2 H^2 + \nu\lambda_3 H^3 + \frac{1}{4}\lambda_4 H^4$$

$$\kappa_3 = \frac{\lambda_3}{\lambda_{\mathrm{SM}}} \qquad \kappa_4 = \frac{\lambda_4}{\lambda_{\mathrm{SM}}}$$



arXiv:2505.20463

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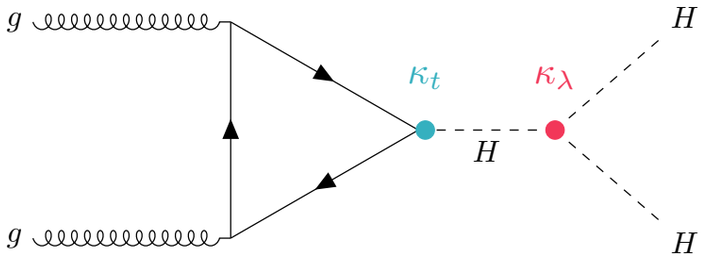
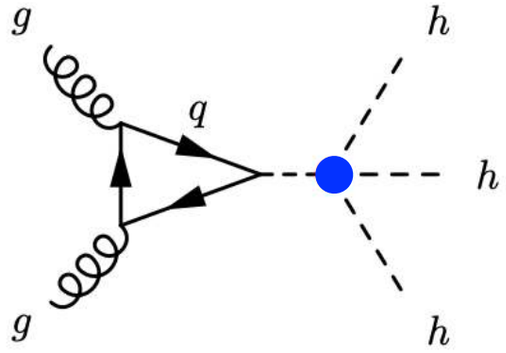
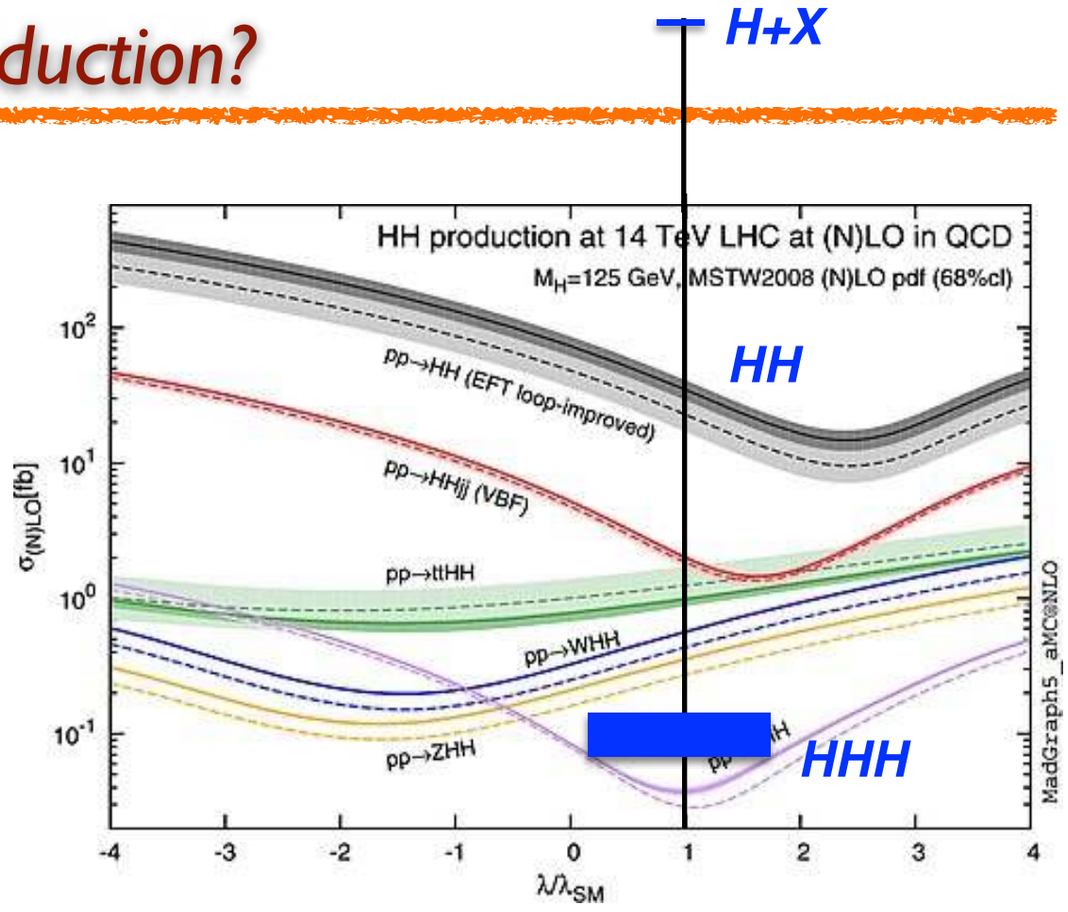
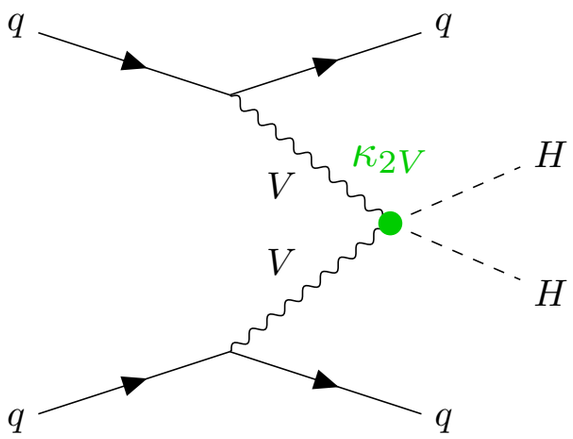
- ***Di-Higgs (HH) and triple Higgs (HHH)*** *production are rare / extremely rare processes prediction by the SM*

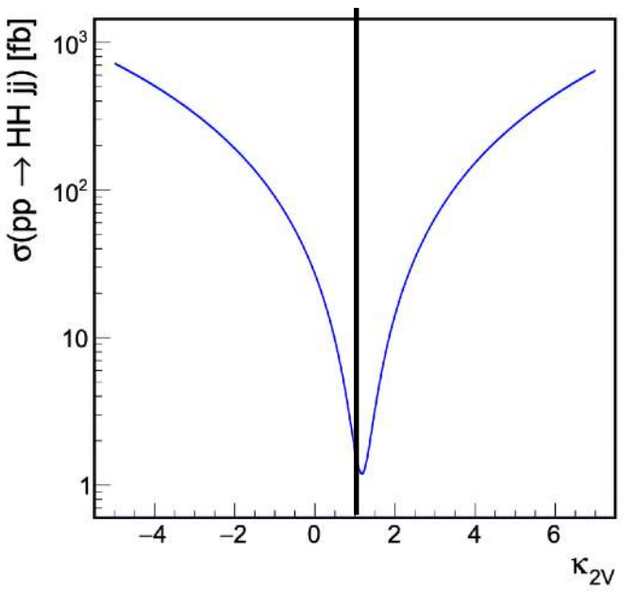




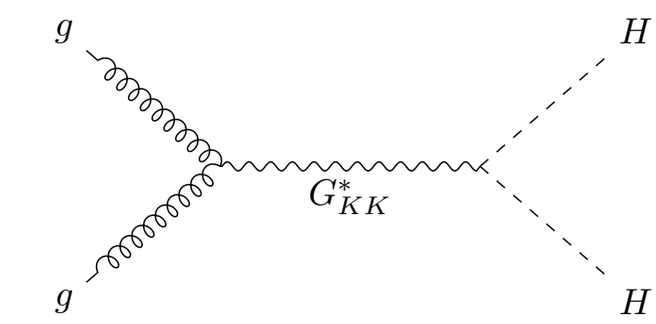


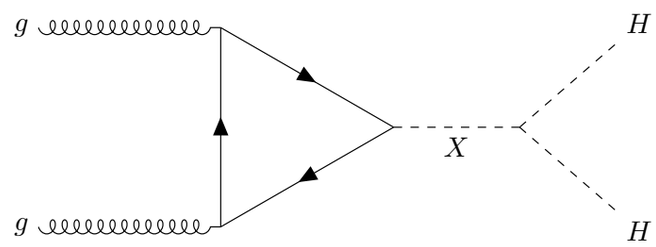
- ***Key predictions to consolidate our understanding of the EWK symmetry breaking and look for BSM effects***





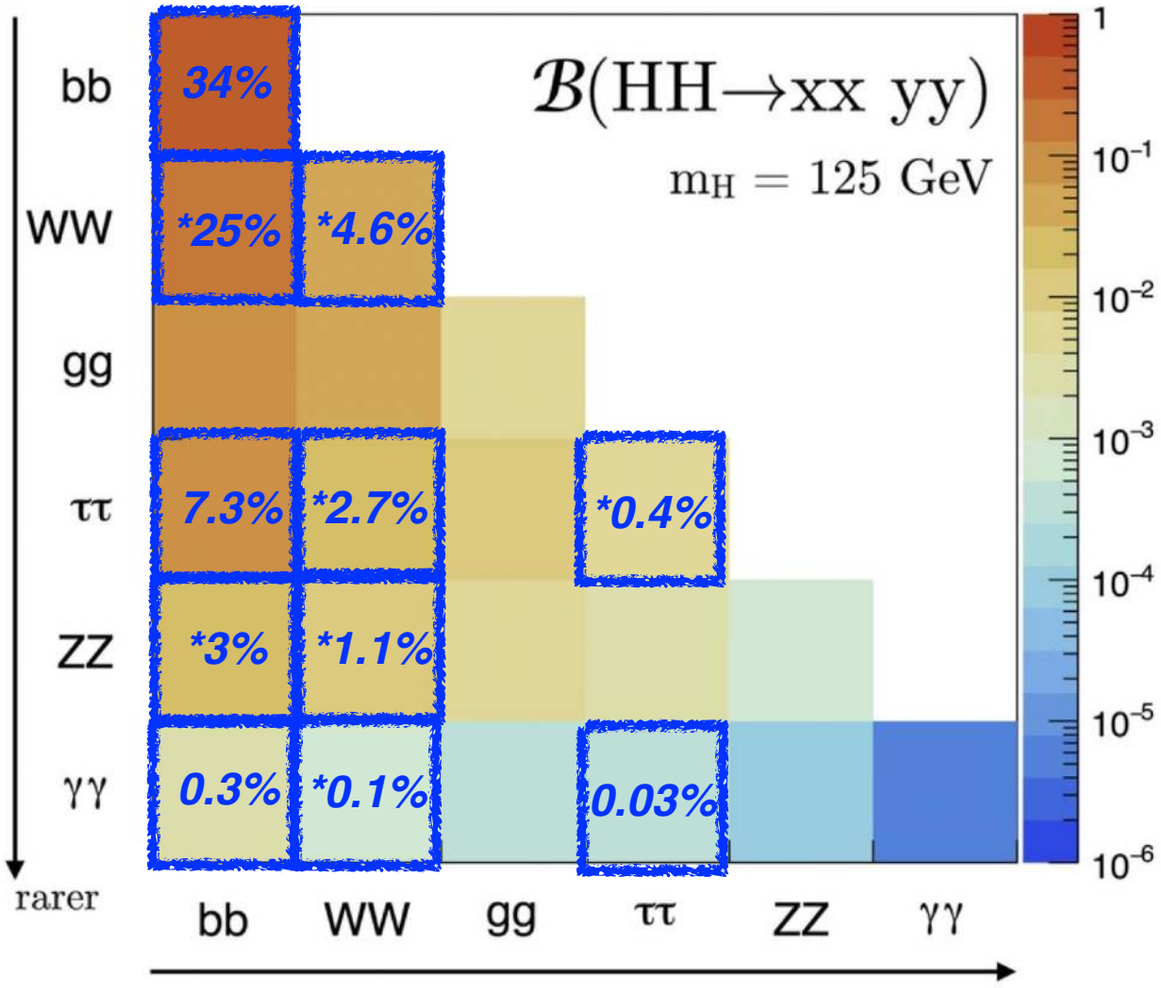
- ***Strong sensitivity to anomalous couplings***





- ***Searches for new resonances***

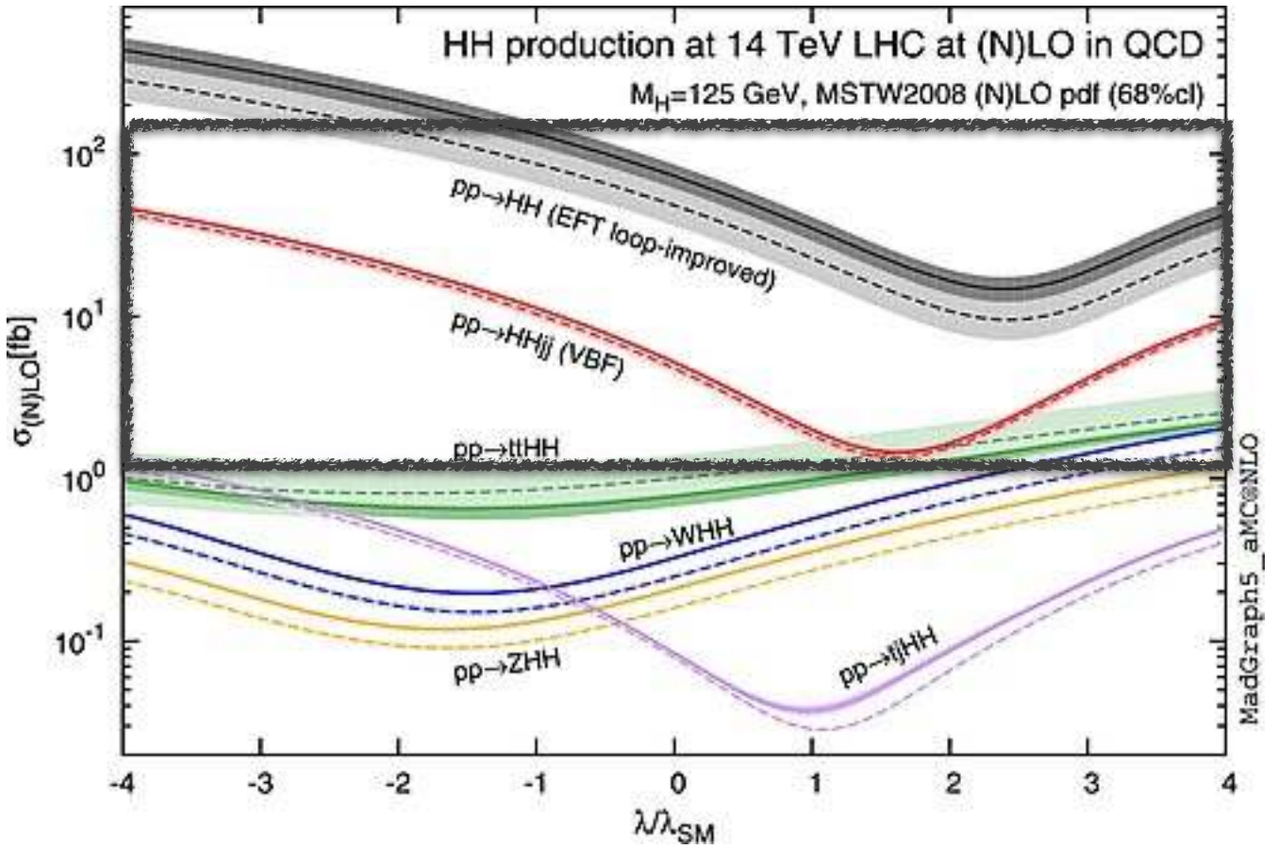
HH: a Rich phenomenology



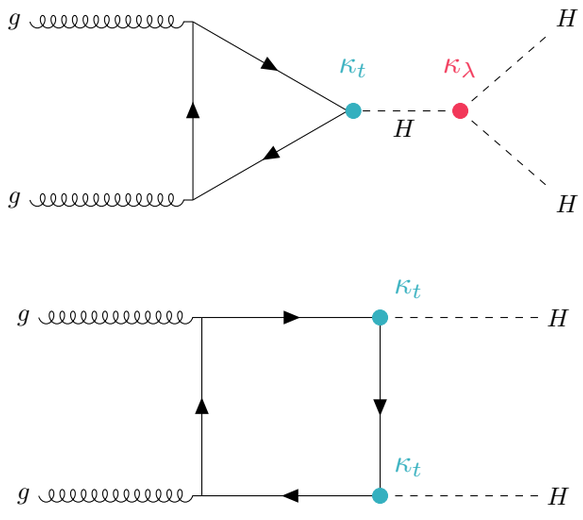
- ***Both experiments have a broad physics program to cover many decay modes:***
  - only 22% of HH decays are completely uncovered
  - VV channels mainly exploited through electron / muon decay channels
  - require excellent performance from all physics objects

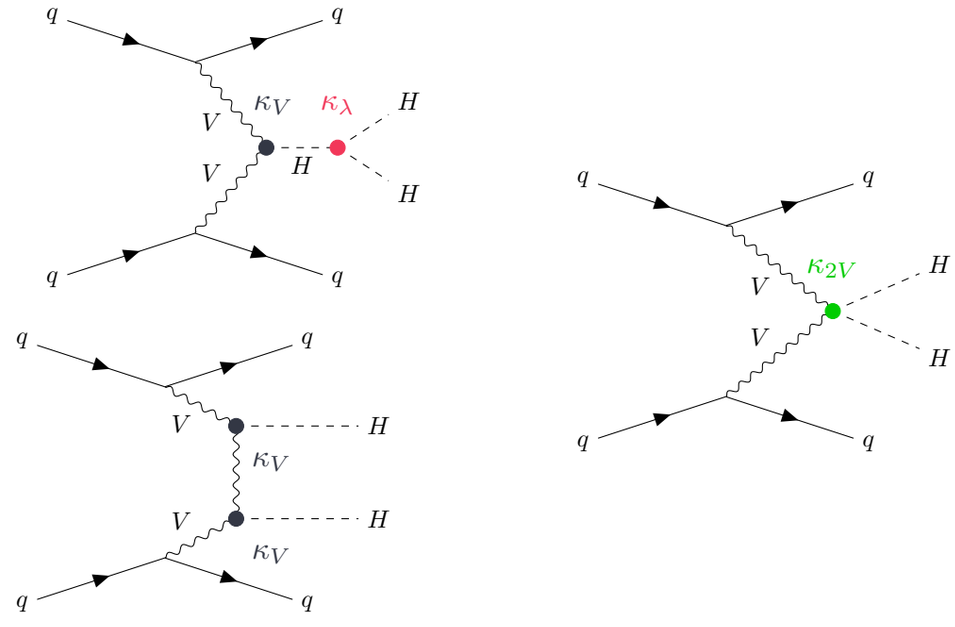
- ***A large variety of analysis strategies:***
  - very complex analyses with multiple SR targeting multiple production modes simultaneously
  - usually relying on (H)Higgs decay products to collect events

* only partly exploited



'Inclusive' / 'main' (ggF+VBF) HH searches

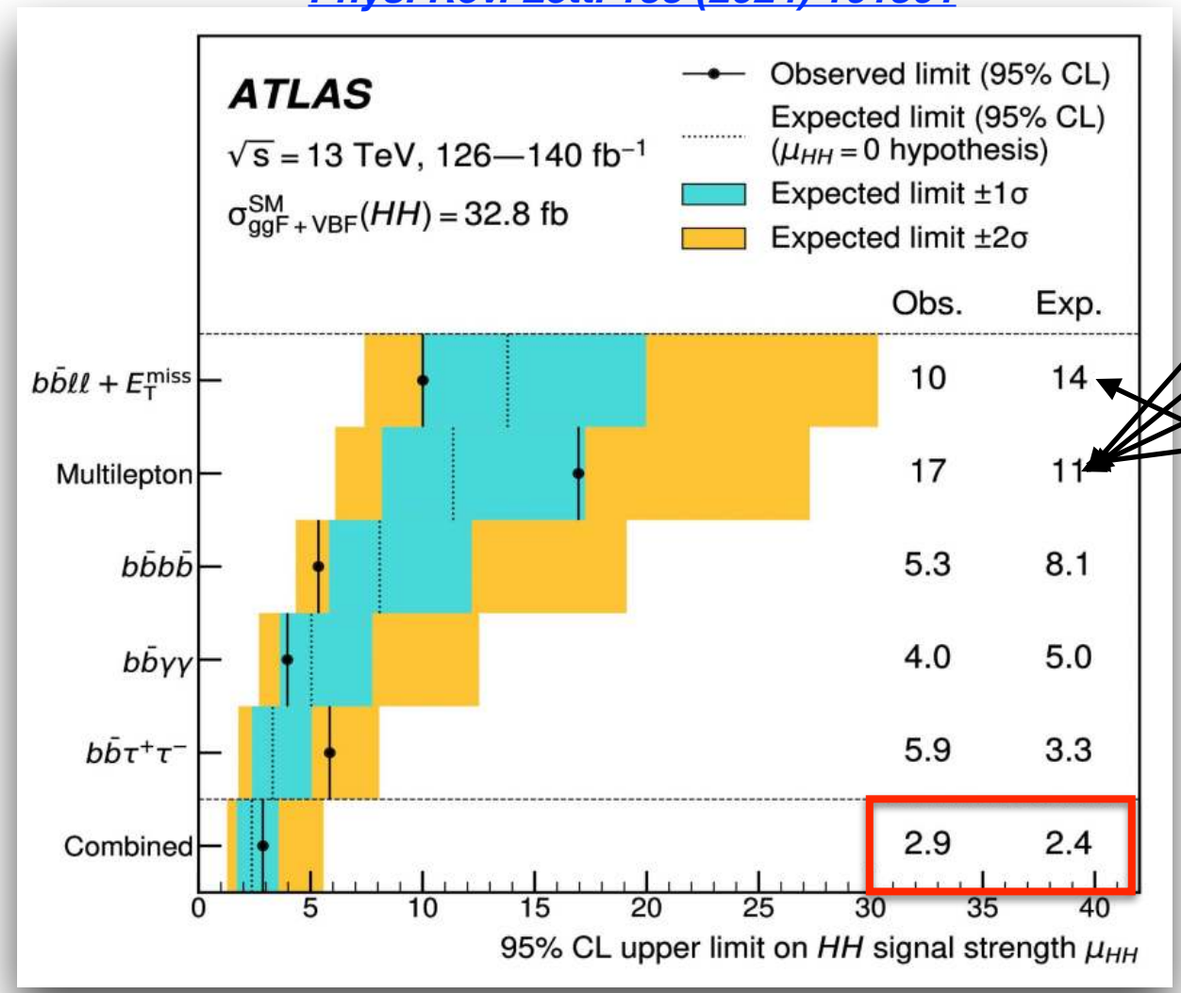




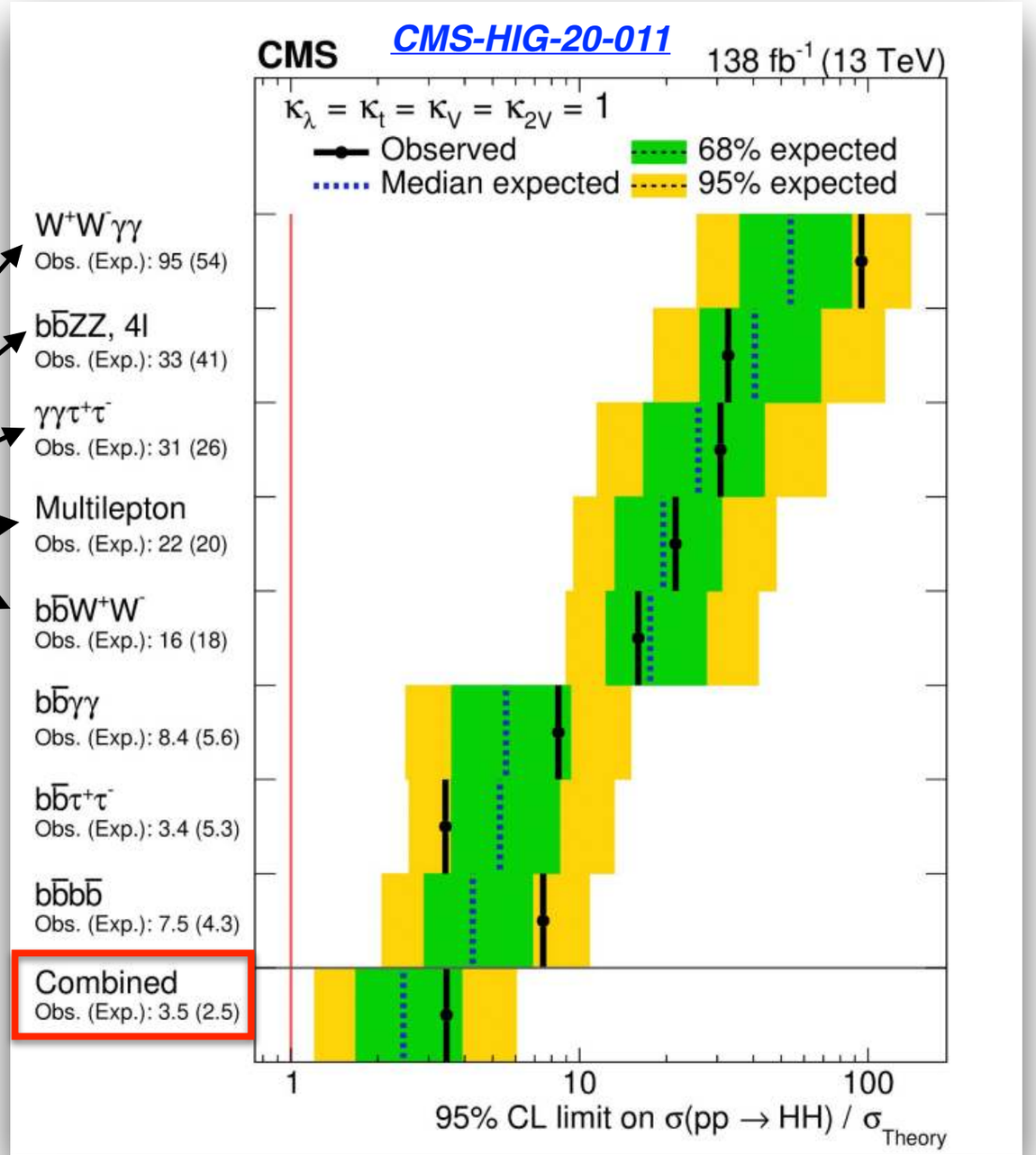
HH: Run2 snapshot

- ***3 main channels:*** bbtt, bbyy, bbbb

Phys. Rev. Lett. 133 (2024) 101801



CMS-HIG-20-011

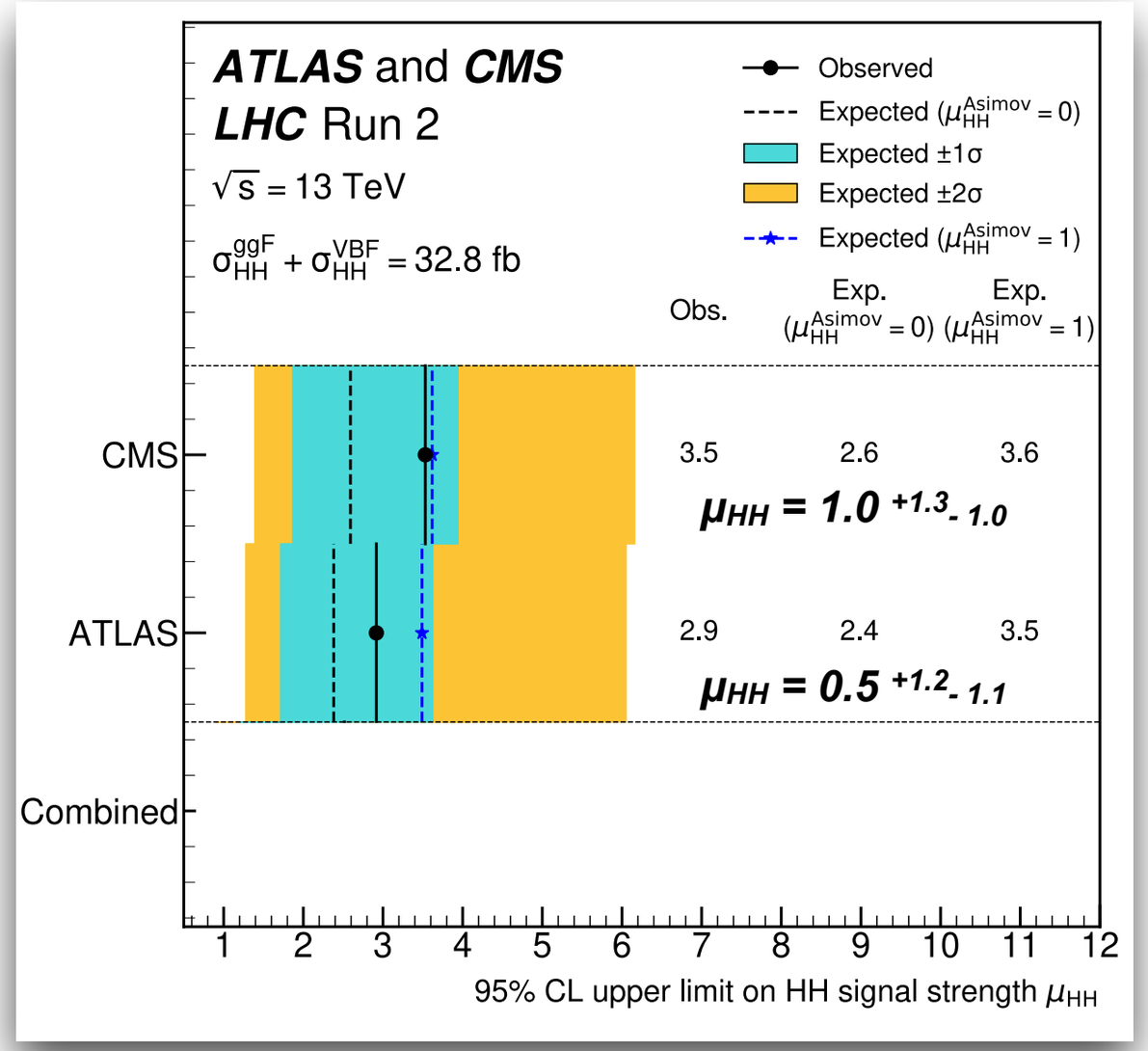


- ***Much more than a single number:***
  - Upper limit on inclusive SM production, upper limit on VBF production, constraints on k_λ and k_{2v}
  - *hierarchy among analyses (and experiments) changes with the figure of merit*
- ***> factor 3 jump in sensitivity with respect to 2016 results with 1/4 of the stat.***

ATLAS-CMS Run 2 HH combination

- ***Statistical combination of Run 2 results:***
  - harmonising signal predictions among experiments [Powheg as main MC]
  - understanding correlated uncertainty sources: *HH XS* (leading contribution), Higgs Br, single H background XS, ggH+HF
  - reproducing results with each-others frameworks

CERN-EP-2026-011 ***(submitted to PRL)***



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- ***Assuming SM HH prediction:***
  - **best limit on HH XS**: 30% improvement over single experiment results
  - significance: ***1.1** (1.3) **σ obs.** (exp.)* *
  - still statistically limited

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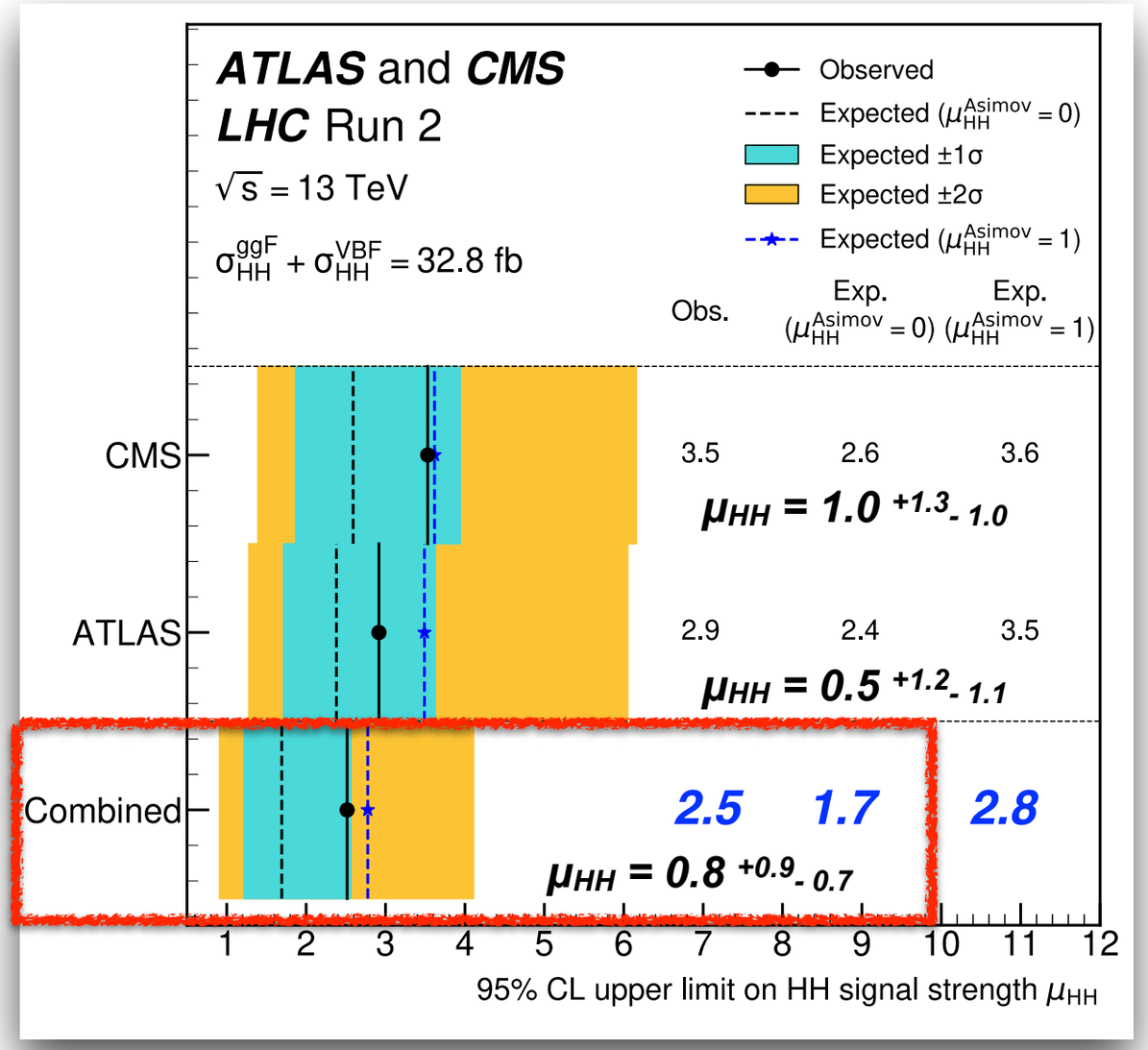

* w.r.t. B-only predictions

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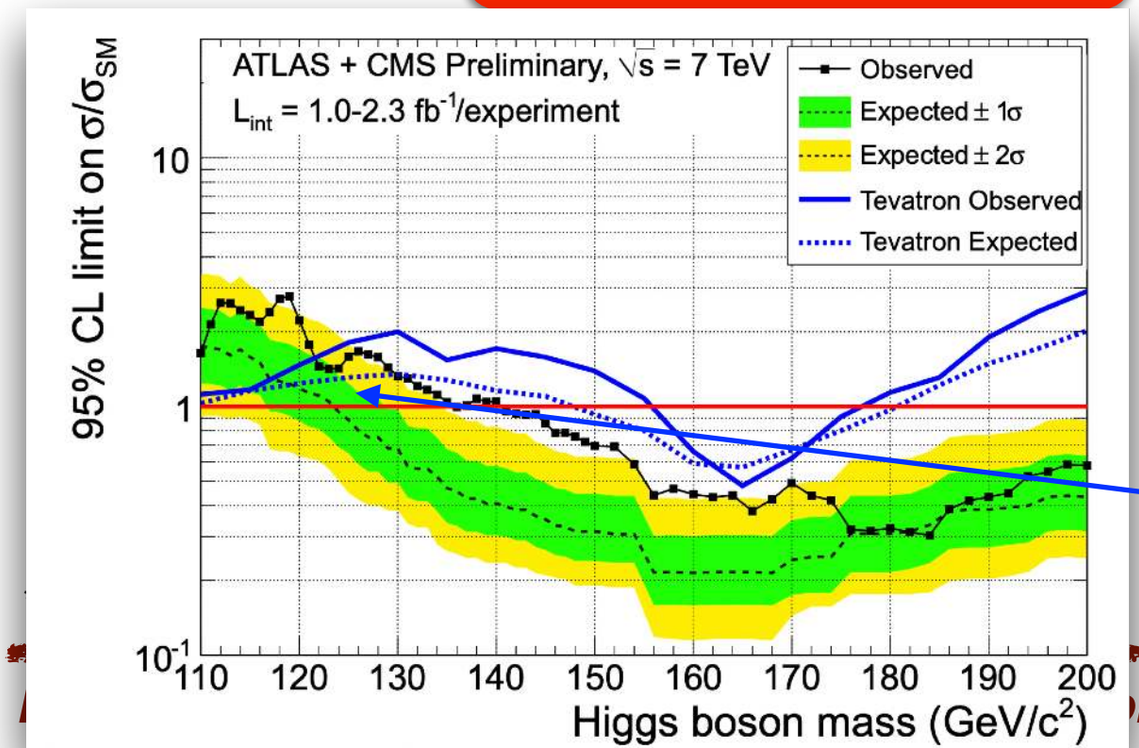
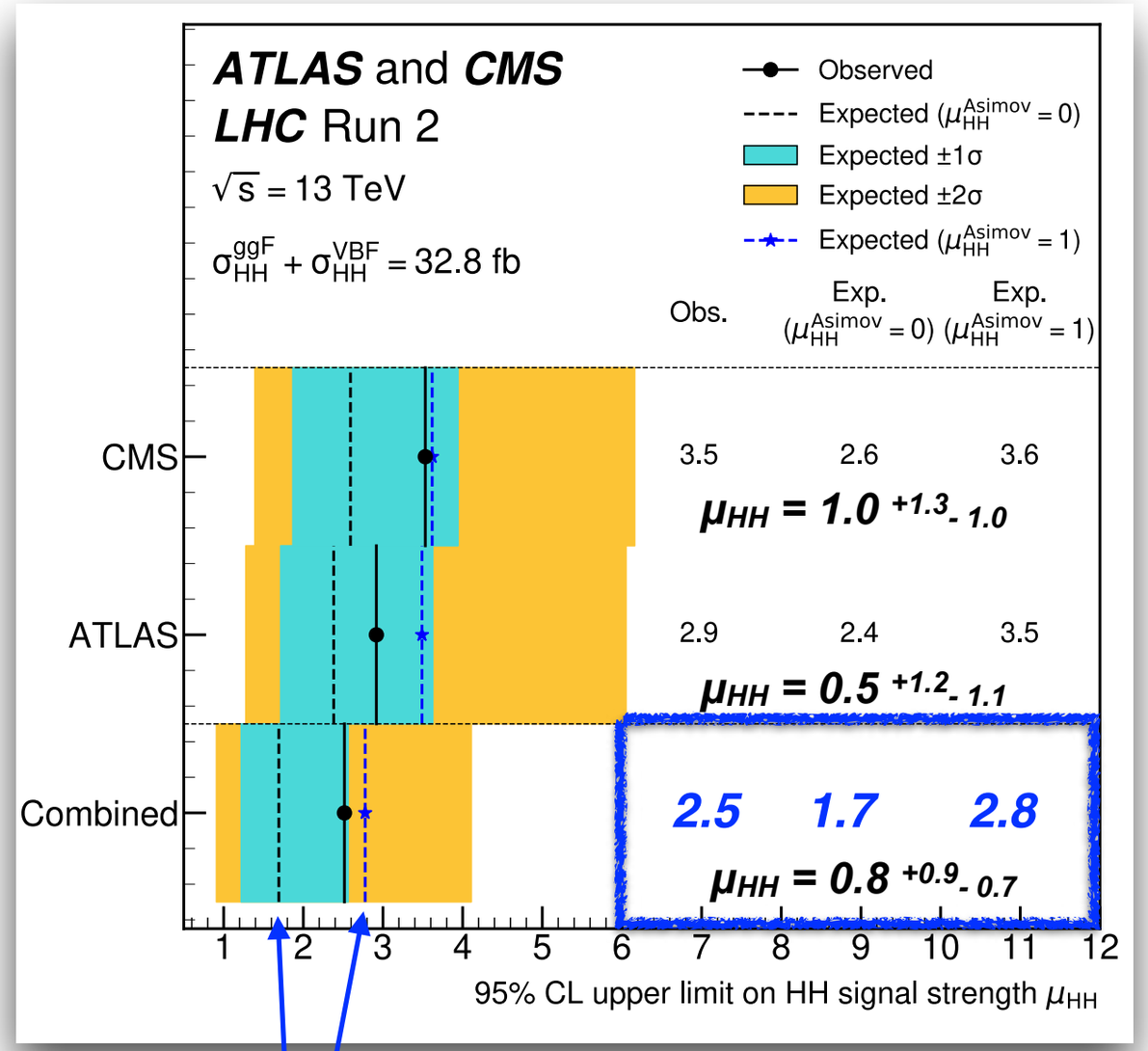


CERN-EP-2026-011 (submitted to PRL)

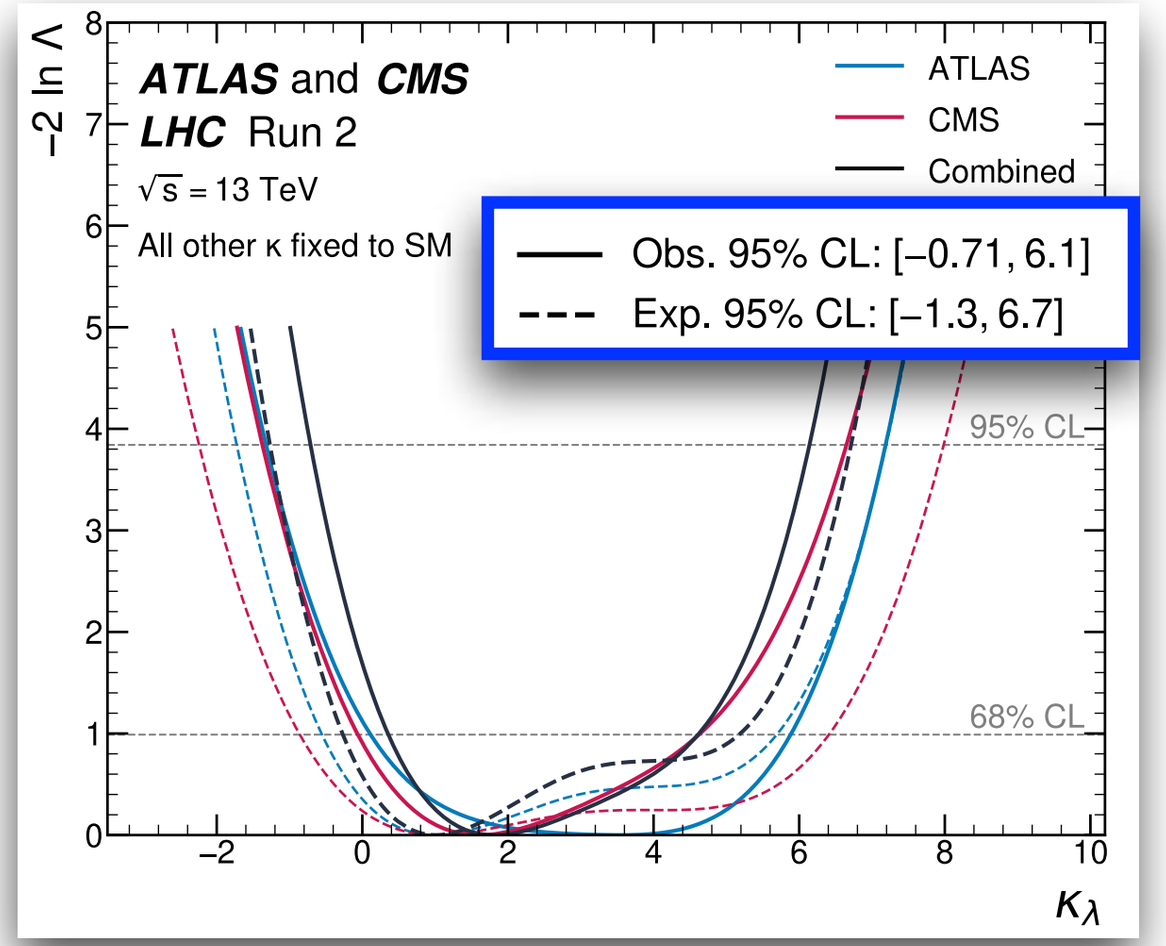


- ***For single Higgs production expected and observed limits started diverging 14.5 years ago***

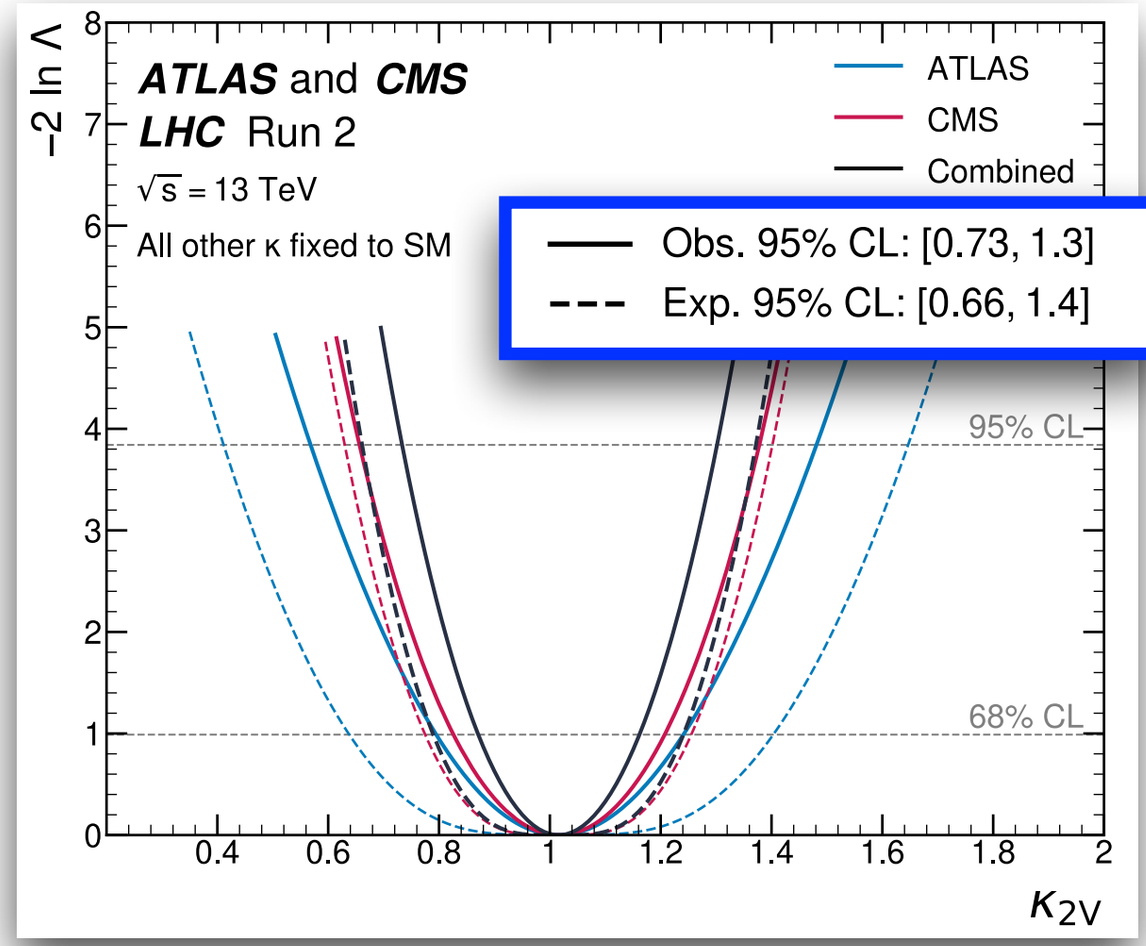
Anomalous couplings

CERN-EP-2026-011 (submitted to PRL)

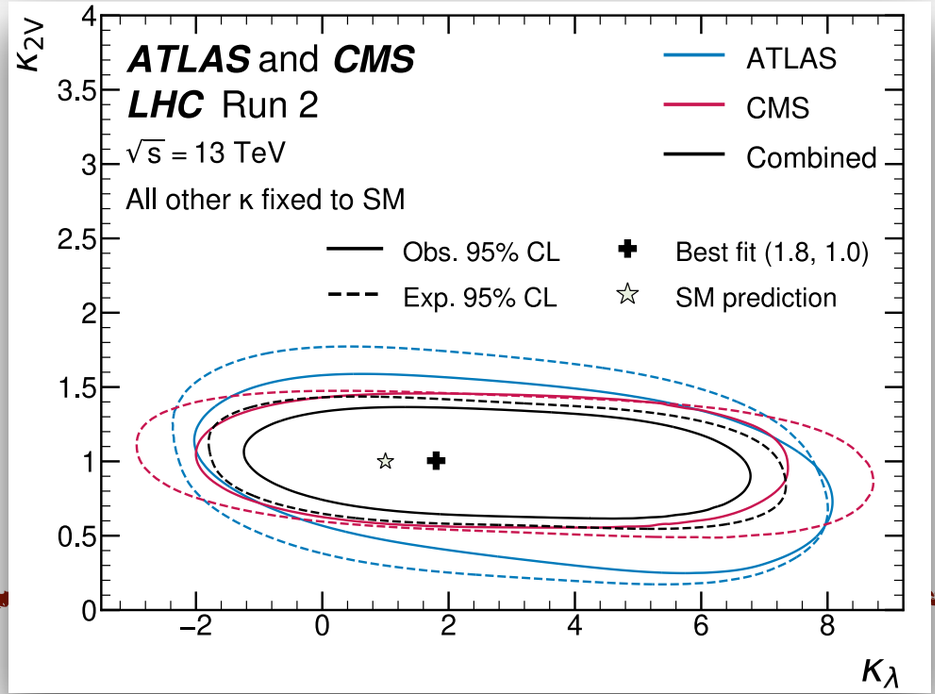
driven by bbyy and bbtt



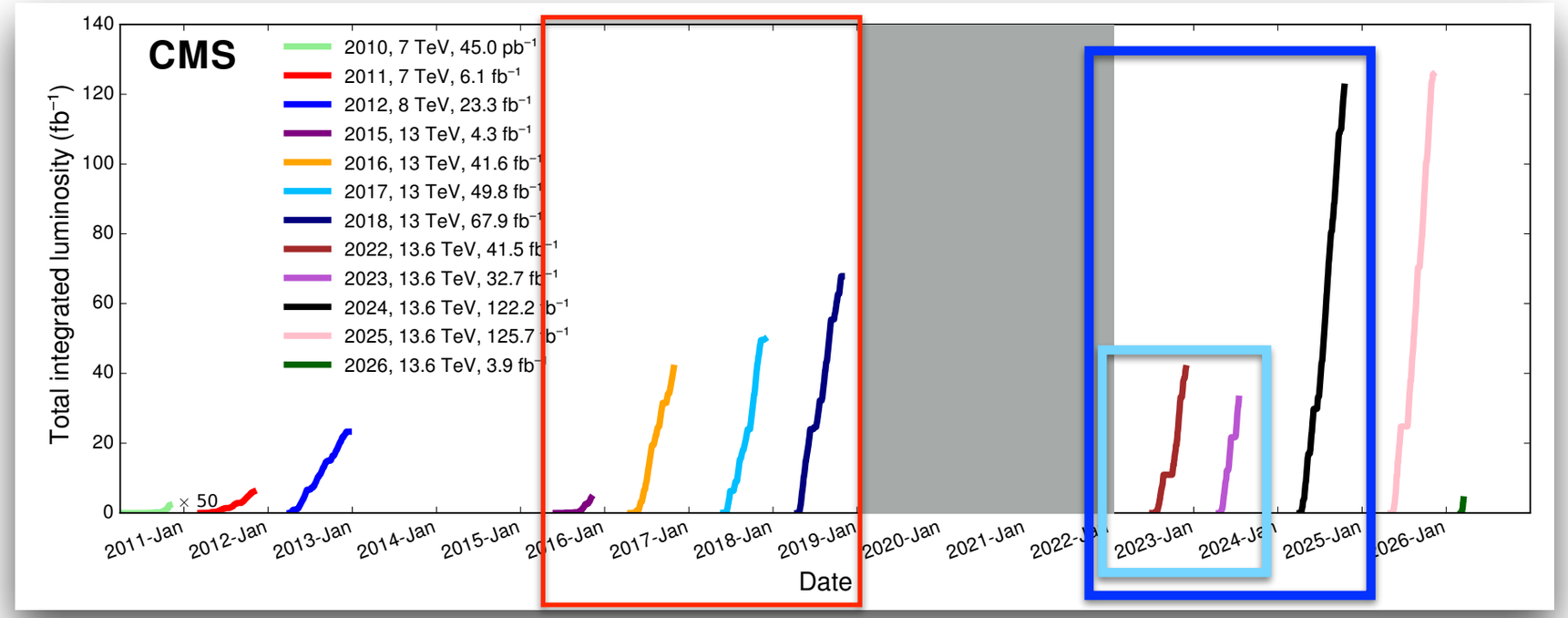
driven by (boosted) bbbb



- ***Very little correlation between k_λ and k_{2v}***
  thanks to dedicated optimisation for gluon fusion and VBF production

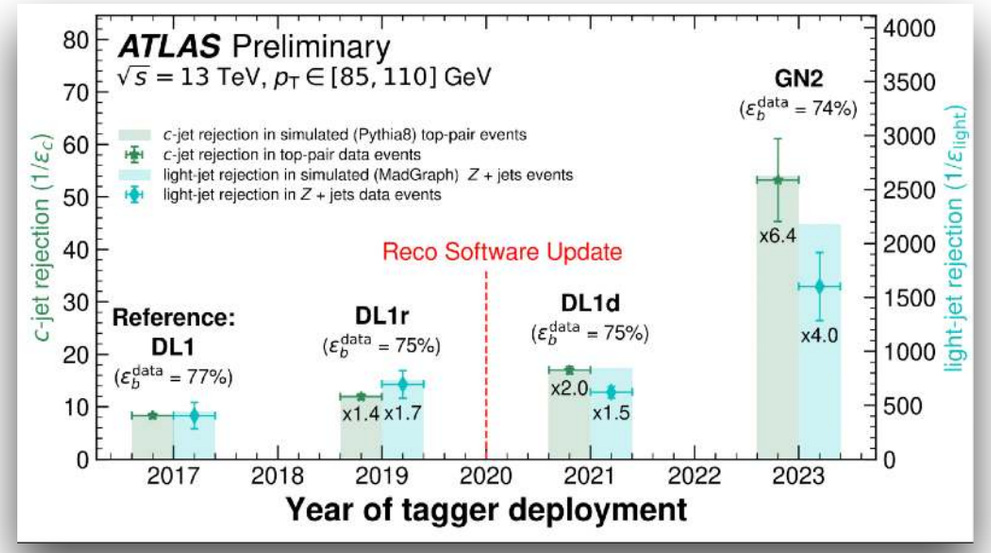


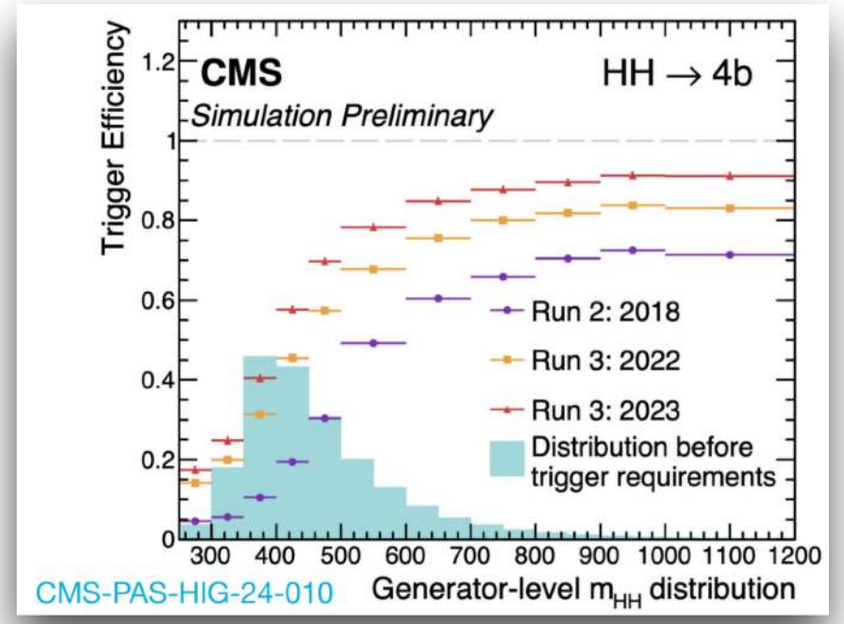
Run 3 analyses are already here



- ***Challenges and opportunities:***
- *opportunities*: new data, upgraded detectors, **more powerful AI-powered algorithms, new triggers**
- *challenges*: harsher conditions, understanding detector performance, aging detectors, bookkeeping

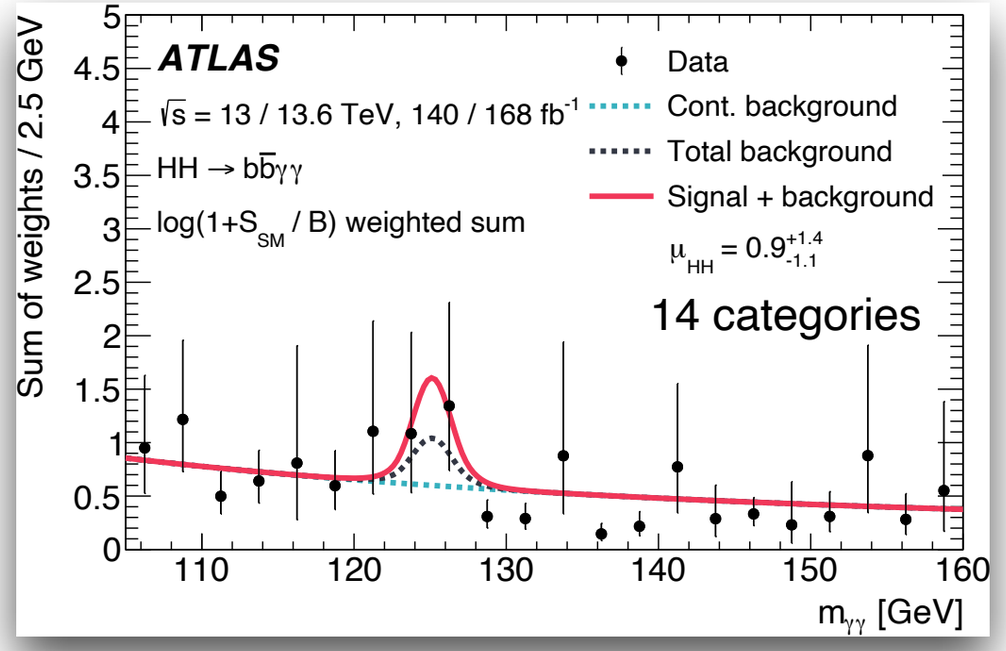
[Nature Comm. 17 (2026) 541]



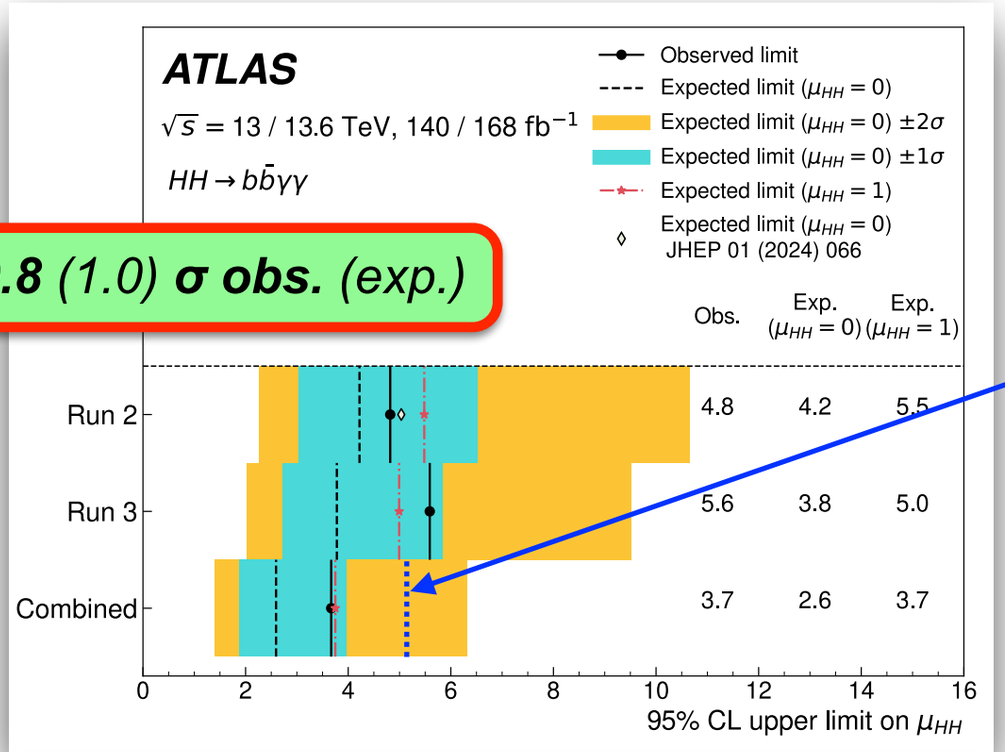


bbyy: ATLAS

- Coherent (re) analysis of Run 2 and of 2022+23+24 data **(first ATLAS analysis with 2024 data)*:***
  - loose b-tag WP thanks to new algorithm: +20%
  - kinematic fit to improve b-jet resolution: +5%
  - correlating bkgd shape between Run 2 and Run 3: +10%
  - x2 more data: +40%

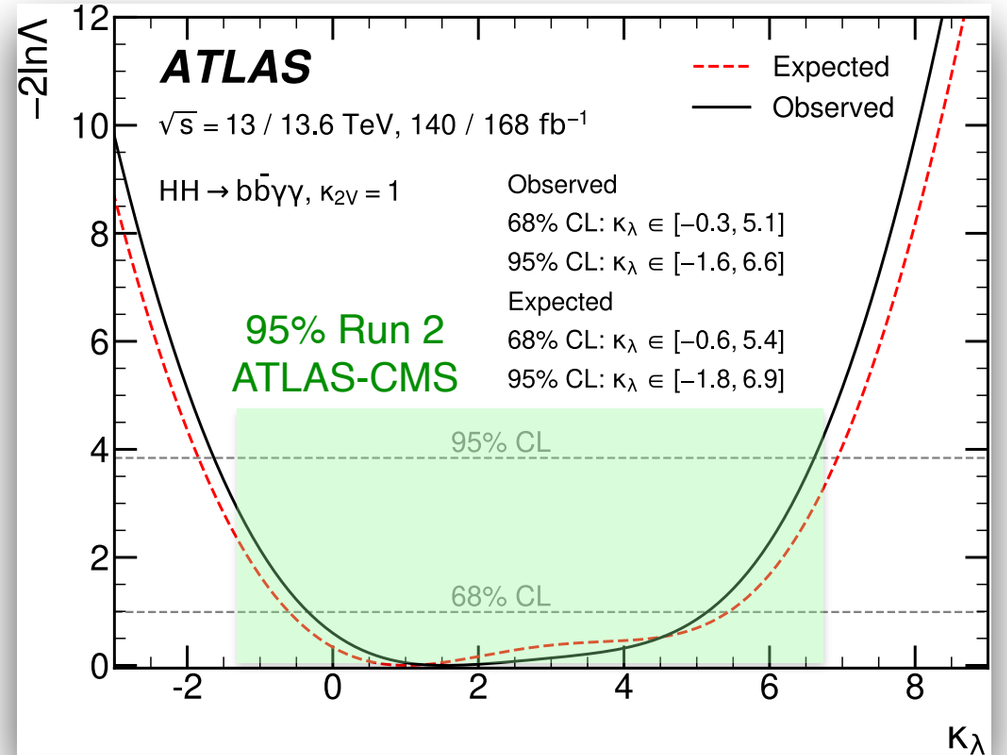


- ***Factor 2 improvement over previous Run 2 result,*** and still stat. limited



***0.8** (1.0) **σ obs.** (exp.)*

prev Run 2 result



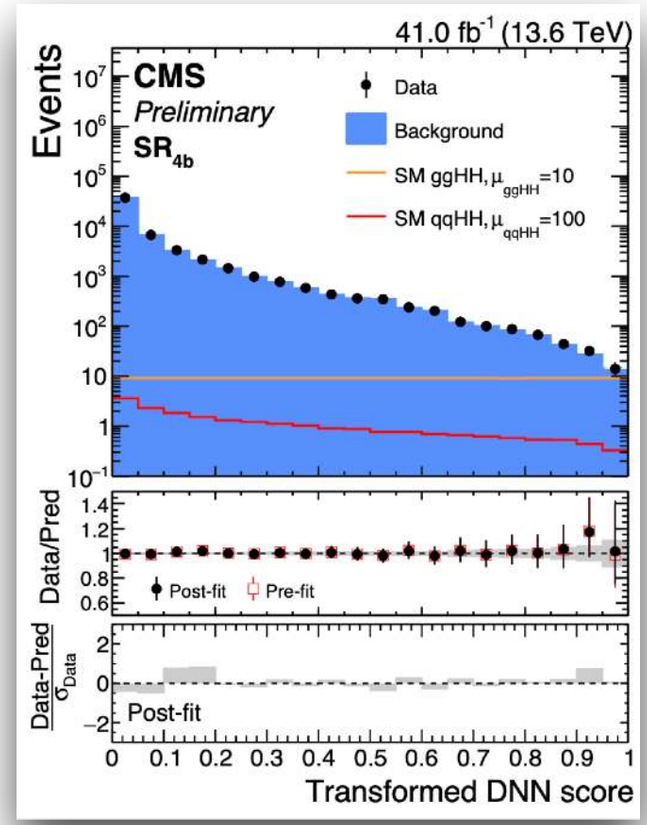
***Also used for complete EFT interpretation** (backup)*

bbbb: CMS

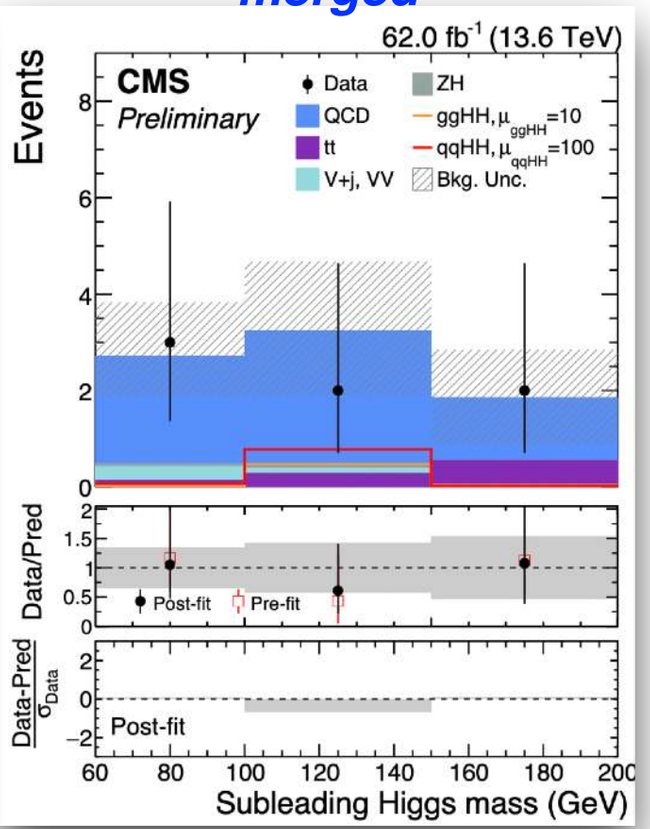
HH->4b:

- greatly profiting from new Run 3 triggers using advanced b-tagging algorithms
- both ggF and VBF enriched regions
- *resolved analysis*:
  - extracting background shape from 2b->4b CRs
  - final DNN for signal discrimination
- *merged analysis*: (p_T>300,250 GeV)
  - background predictions extrapolated across sublead. H (H2) tag score
  - final discriminat: DNN (ggF SR), m_{H2} (VBFCR)

resolved

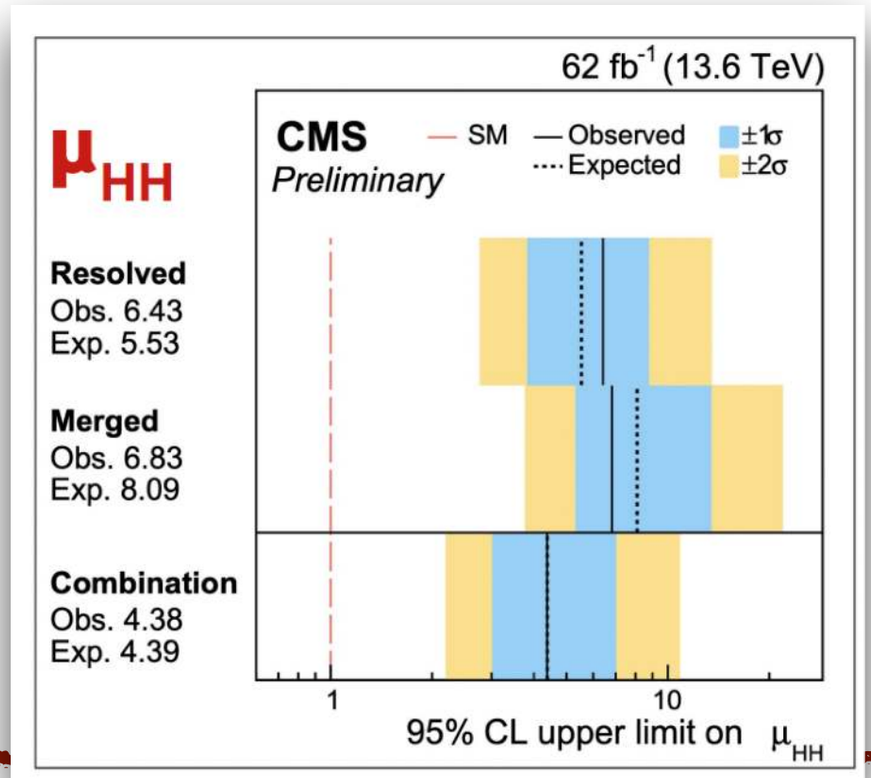


merged



Run3 results ('22-'23):

- **Performance very similar to full Run 2 result with half the dataset**
- $-3.3 < k_\lambda < 9.7$ @ 95% C.L. — driven by resolved
- $0.63 < k_{2V} < 1.43$ @ 95% C.L. — driven by merged
- alternative approaches giving compatible results

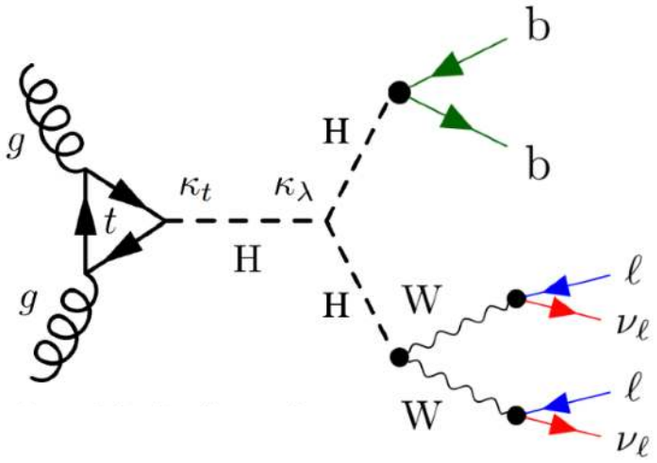


See E. Koenig' YSF talk today for more

bbll: CMS

[CMS-HIG-25-018](#)

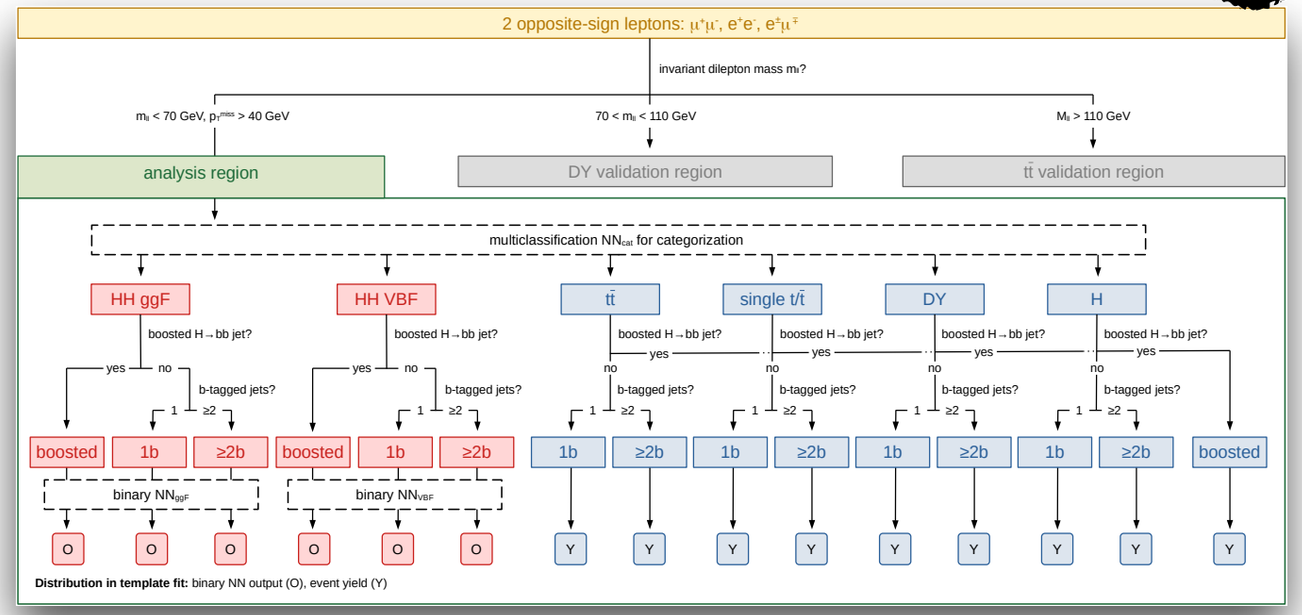
NEW

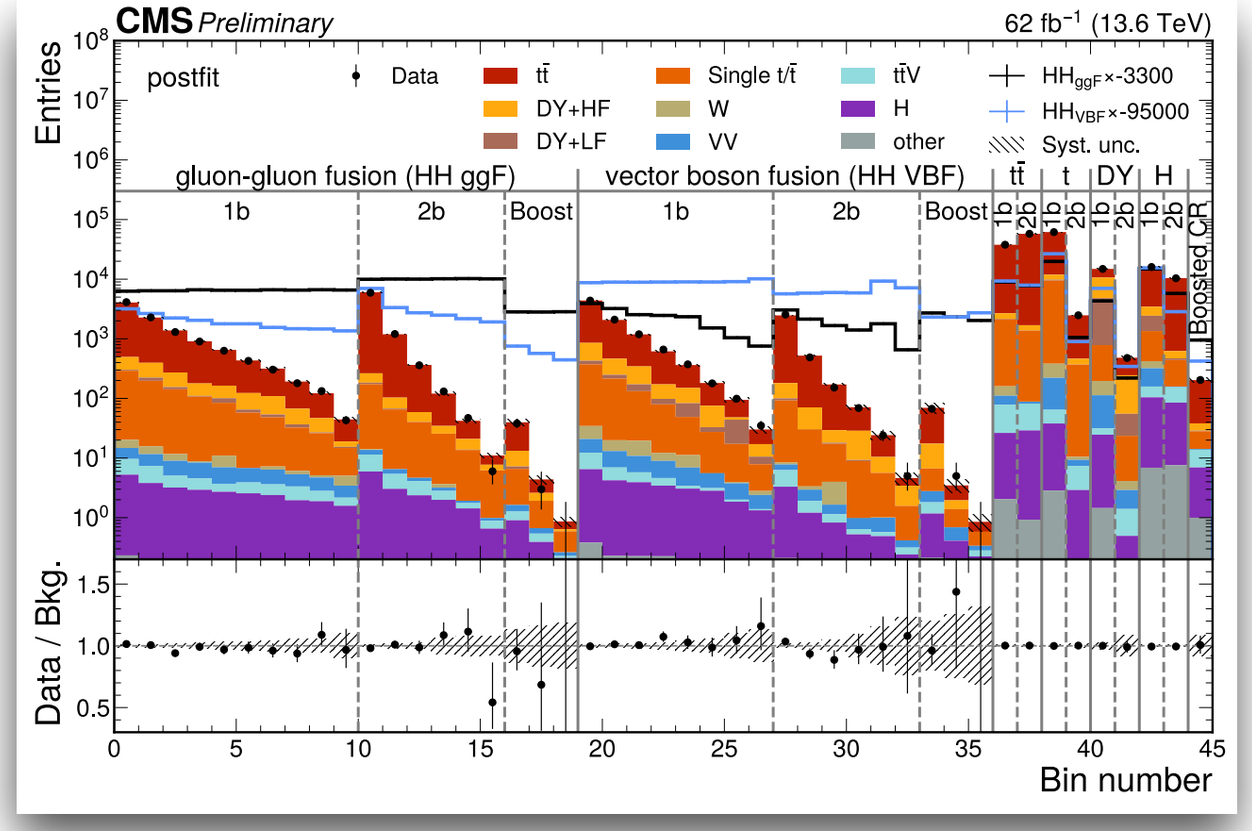


- ***HH->bbll:***
  - dominated by bbWW decays
  - NN-based categorisation and final discriminant
  - considering both ggF and VBF and boosted / resolved SRs

- ***Run 3 ('22-'23) analysis:***
  - **μ_{HH}< 13 (19) x SM at 95% CL** [ATLAS expected full Run 2 result **μ_{HH}< 14 x SM**]
  - $-9.7 < k_\lambda < 15.8$ @ 95% C.L.
  - $-0.3 < k_{2V} < 2.3$ @ 95% C.L.
  - stat. limited

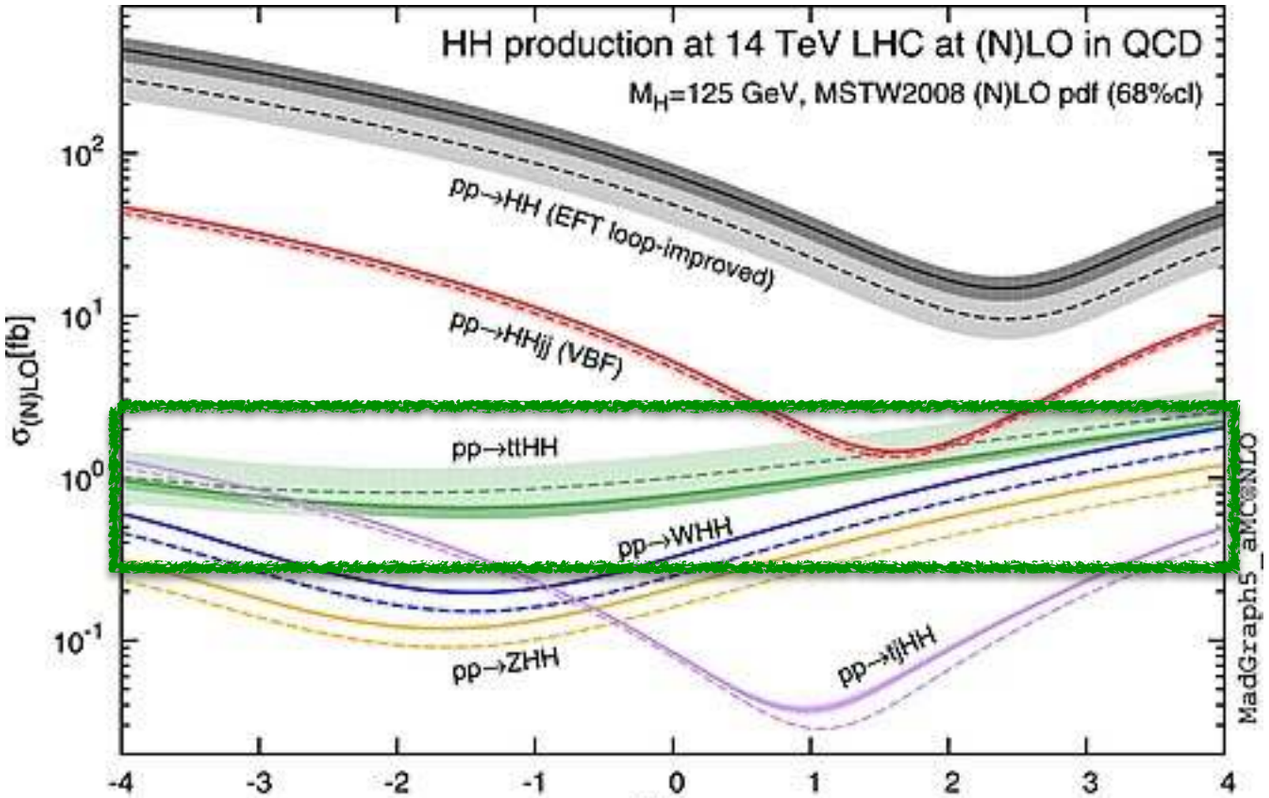
2nd best CMS analysis on k_{2v}

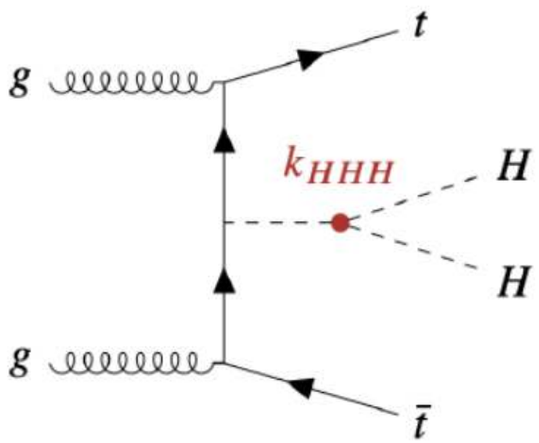


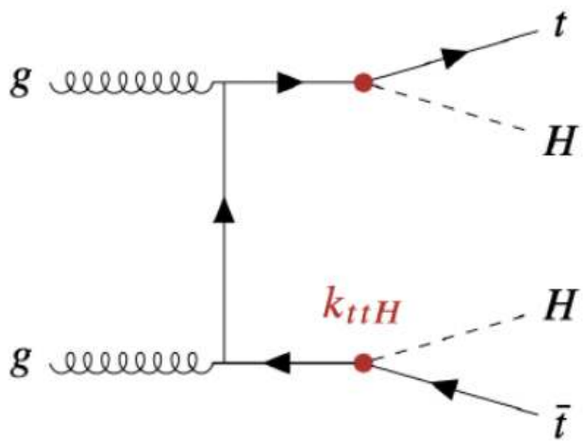


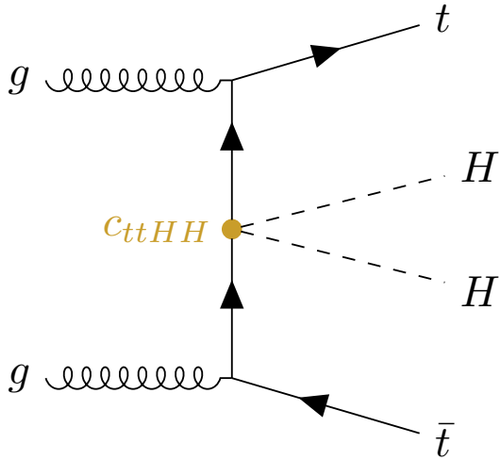
Other production modes:

ttHH









- ***VHH searches also performed:*** **Eur. Phys. J. C 83 (2023) 519 , JHEP 10 (2024) 061**

NEW

ttHH: ATLAS

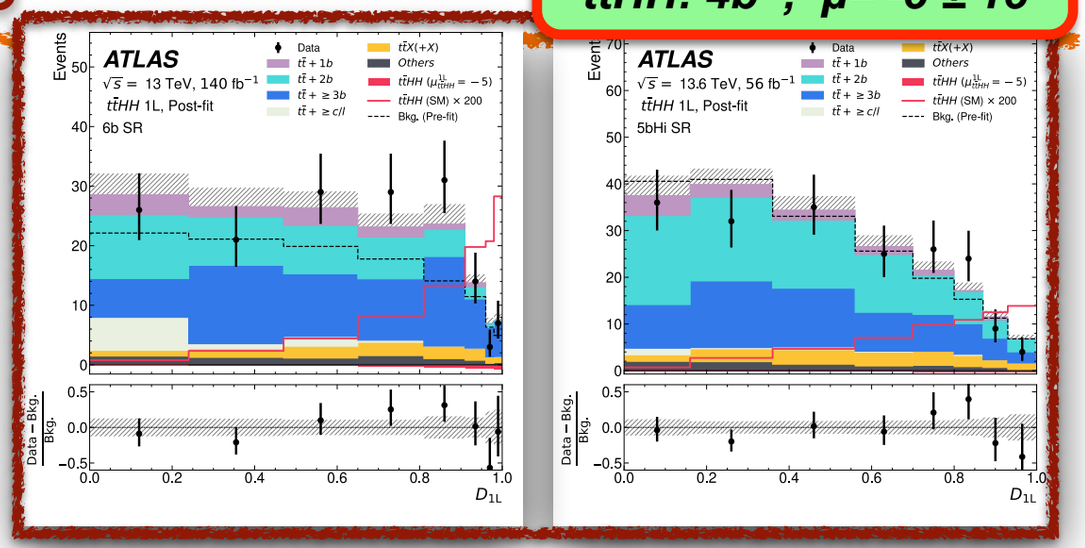
arXiv:2603.13113

- ***Search with Run 2 + Partial Run 3*** (’22 - ‘ 23)

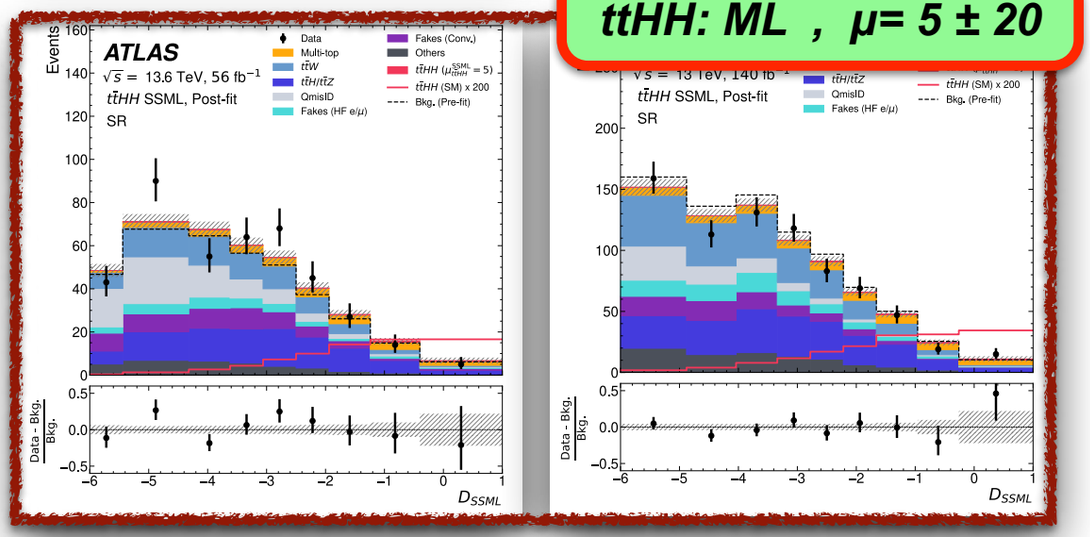
- ***Exploit several HH and ttbar decay channels:***
  - *bbbb:* 1 electron/muon from ttbar decay
    - 5 and 6 b-jets SRs
    - main bkgd.: *ttbar+HF*
  - *SSML*: mainly HH->bbWW
    - 2l SS / 3L selection: >=6 (5) jets , >=2 b-jets
    - main bkgd.: *ttW, ttH*
  - *bbyy*: >=3 b-jets selection, 3 SR defined by multiple BDTs against yy+bb, ttH, tt+yy, H+HH

- ***Strong synergies with other flagship analyses:*** *HH*, *ttH*, *4-tops*

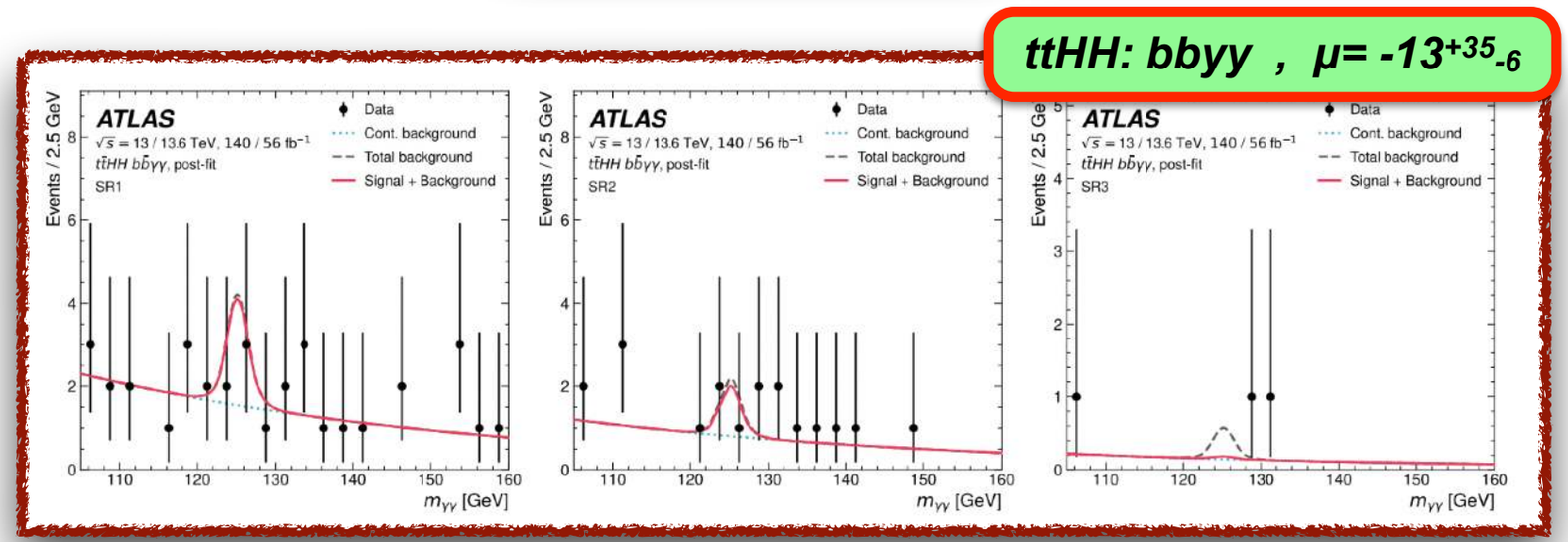
ttHH: 4b , μ= -5 ± 15



ttHH: ML , μ= 5 ± 20



ttHH: bbyy , μ= -13^{+35}_{-6}



NEW

ttHH: ATLAS

arXiv:2603.13113

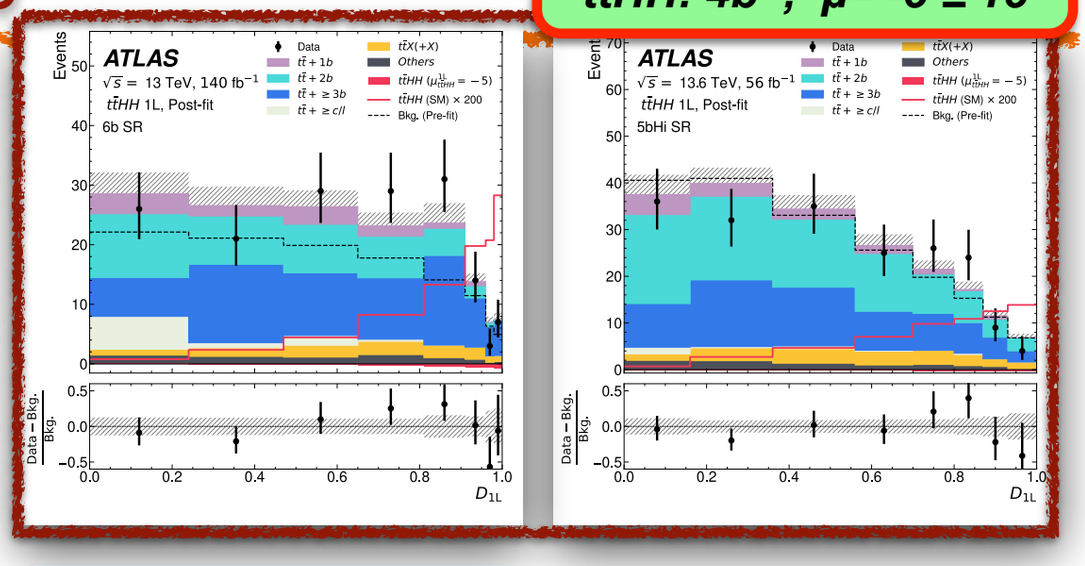
- ***Search with Run 2 + Partial Run 3*** [22-23]

- ***Exploit several HH and ttbar decay channels:***
  - *bbbb:* 1 electron/muon from ttbar decay
    - 5 and 6 b-jets SRs
    - main bkgd.: *ttbar+HF*
  - *SSML*: mainly HH->bbWW
    - 2l SS / 3L selection: >=6 (5) jets , >=2 b-jets
    - main bkgd.: *ttW, ttH*
  - *bbyy*: >=3 b-jets selection, 3 SR defined by multiple BDTs against yy+bb, ttH, tt+yy, H+HH

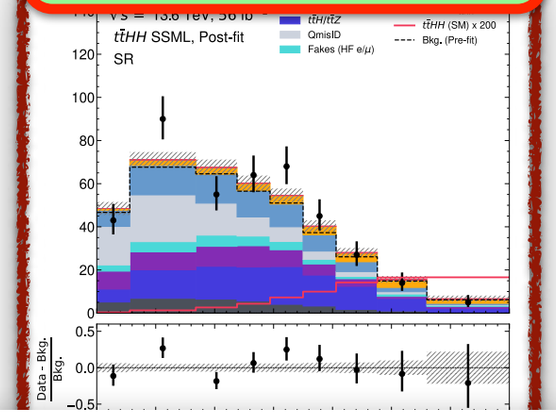
- ***Strong synergies with other flagship analyses:*** *HH, ttH, 4-tops*

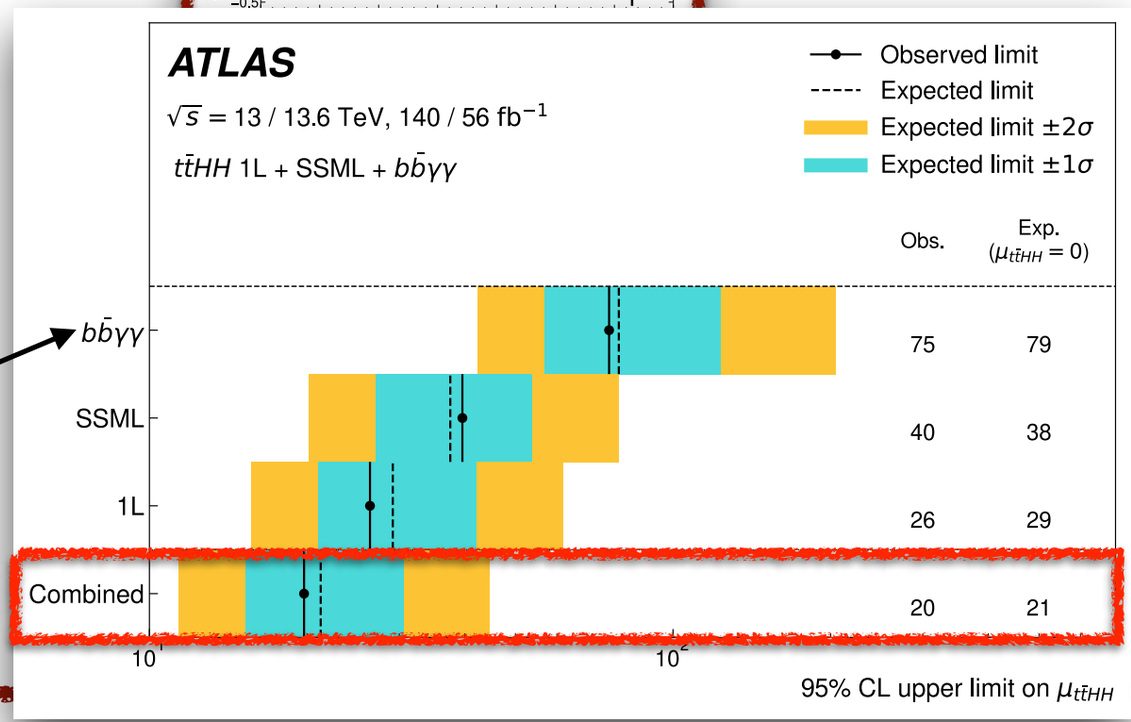
- ***No significant excess over bkgd-only predictions:***
  - ***μ_{HH} < 20 x SM at 95% C.L.***
  - CMS result [CMS-PAS-HIG-23-004]: μ_{HH} < 120 (86) x SM 95% UL only using the bbyy decay alone

ttHH: 4b , μ= -5 ± 15

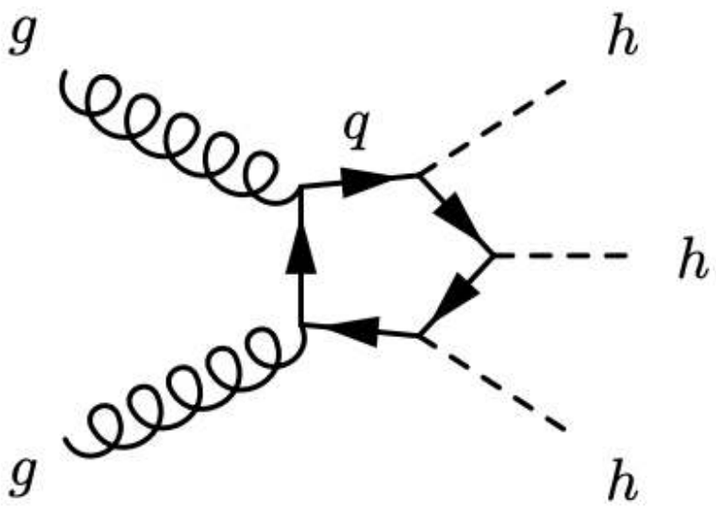


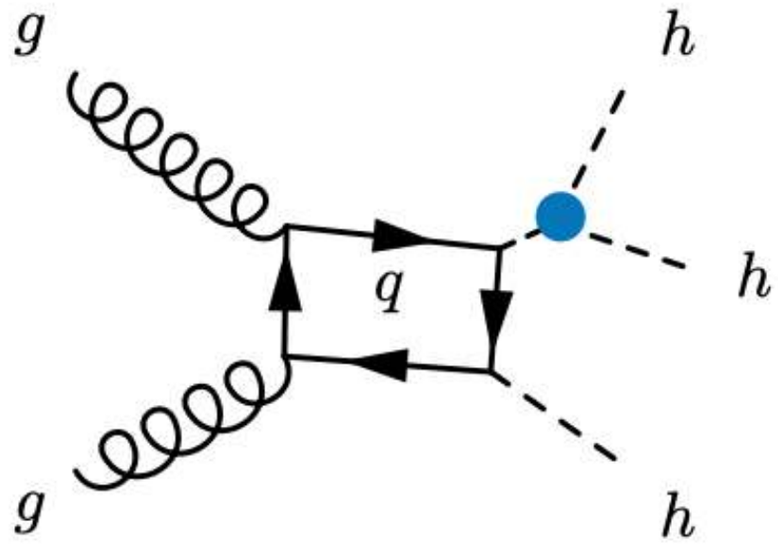
ttHH: ML , μ= 5 ± 20



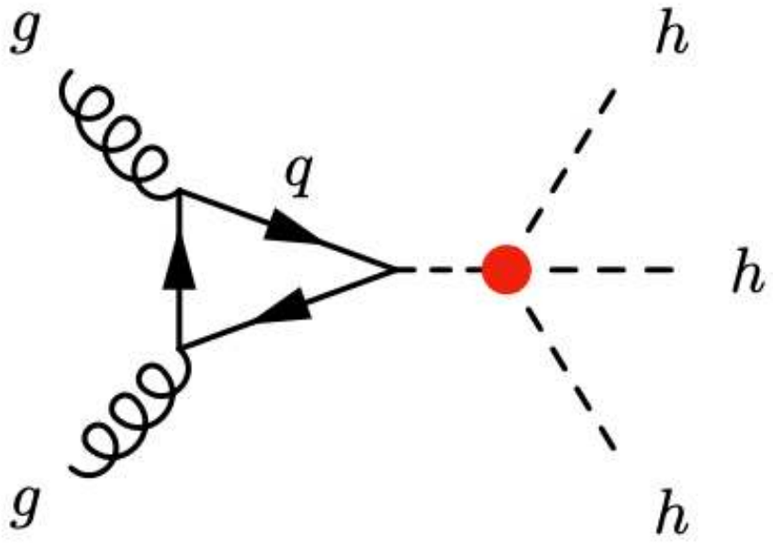


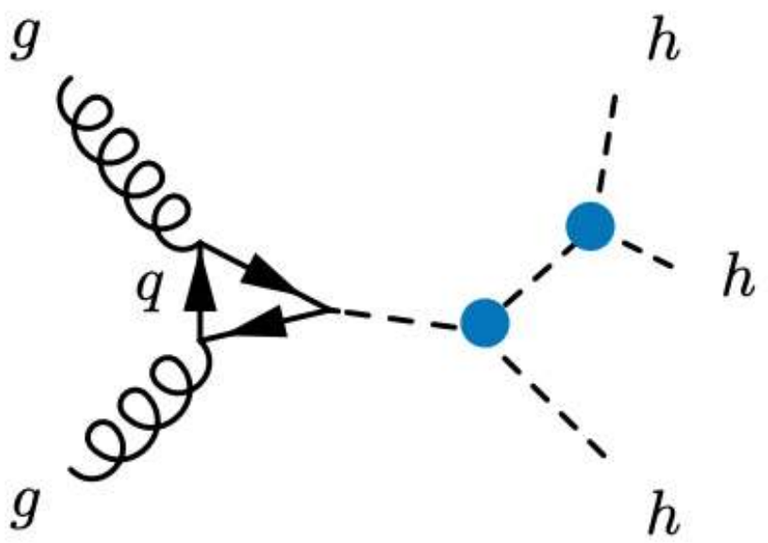
See A. Auriol' YSF talk today for EFT extraction





HHH

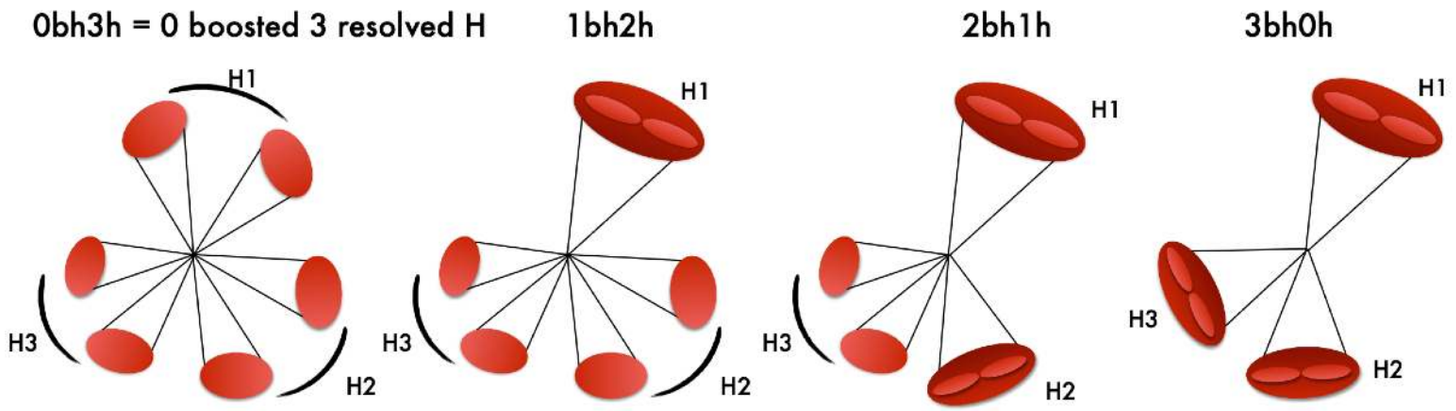




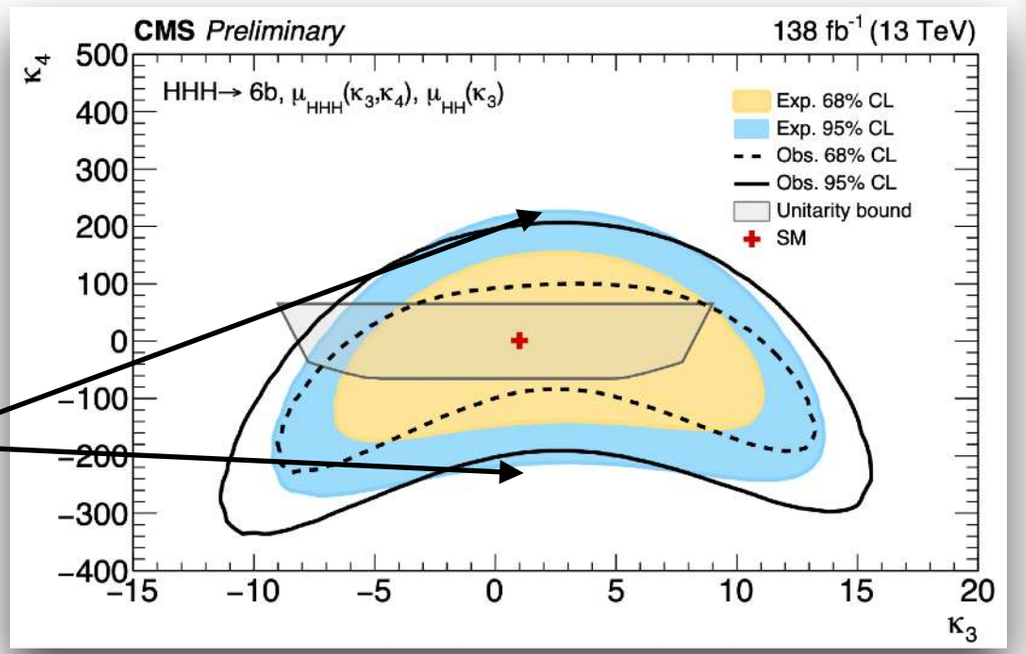
CMS: HHH->6b

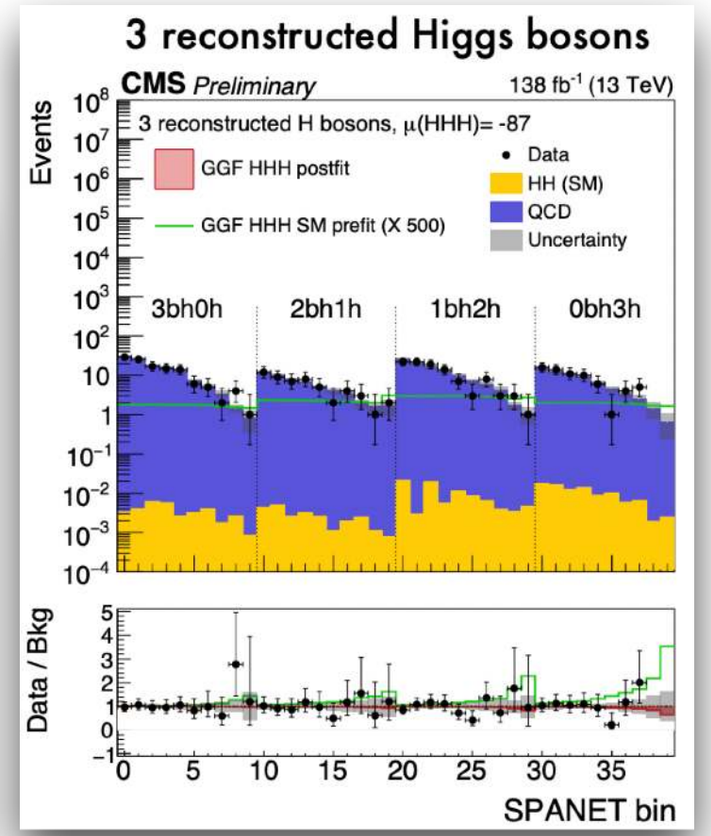
[CMS-HIG-24-012]

- ***CMS analysis:***
  - ***every event counts***
  - categorising events using both boosted and resolved Higgs
  - also considering events when only 2 Higgs can be reconstructed (+25% eff.)
  - final classifier: SpaNET



- ***CMS Run 2 result:***
  - ***7 SRs***
  - ***μ_{HHH} < 570 (590) x SM*** *@ 95% CL*
  - **$-190 < k_4 < 190$ (exp.)**





- ***ATLAS Run 2 result*** *[Phys. Rev. D 111 (2025) 032006]* (1 SR): ***μ < 760 (750) x SM*** *@ 95% CL*

- ***First HHH->4b2y from CMS [CMS-PAS-HIG-2024-015]:*** ***μ_{HHH} < 3400*** *(2100) x SM @ 95% CL*

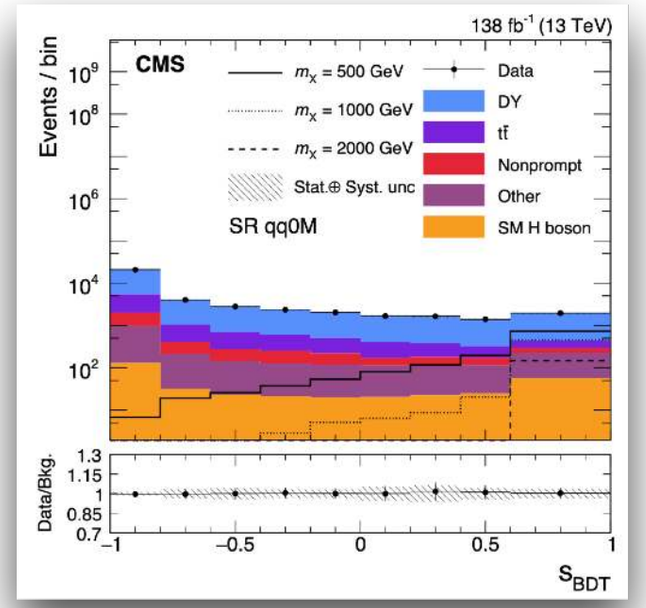
NEW

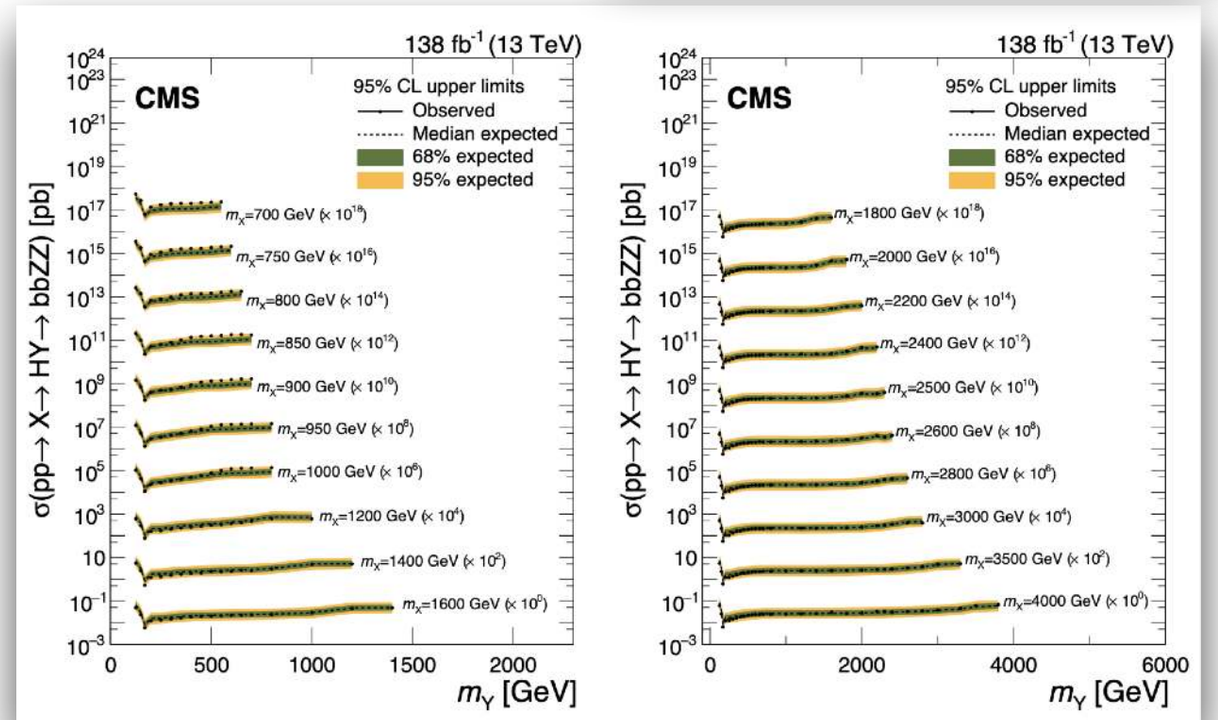
Resonances

See also A. Agapitos' talk for more final states

CMS: X->H(bb)Y(ZZ) [CERN-EP-2026-020]

- Considering llqq and llvv Y decays
- resolved selection and merged H->bb and Z->qq selection
- final discriminant: “mass average” BDT (resolved), mX mass (merged)



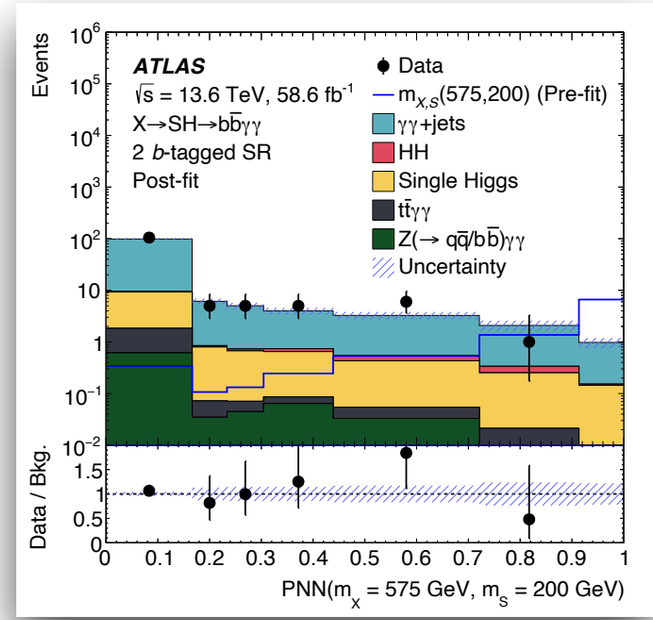


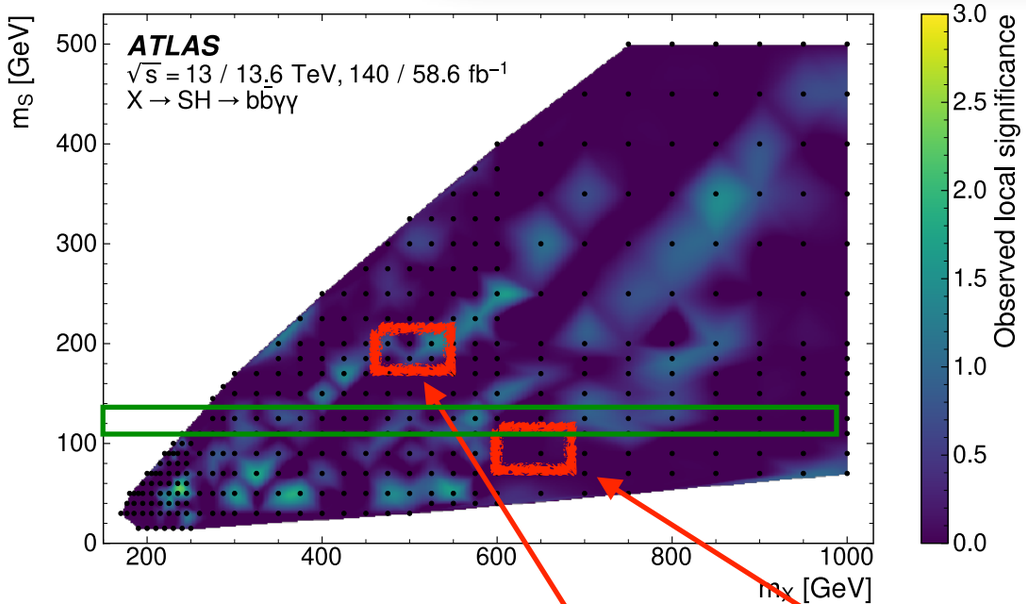
- *Also including limit on X->HH*

ATLAS: Y->S(bb)H(yy) [CERN-EP-2025-204]

Run 2 + Partial Run3 (22-23) analysis

- 1 and 2 b-jets selection to improve acceptance
- resolves and merged bb selection to cover low m_s values
- PNN for signal extraction





- *Previous excesses from ATLAS and CMS not confirmed*

Summary and conclusions

- ***Broad and very active program by ATLAS and CMS collaborations on HH searches:*** *discovery can't come from one channel*

- ***Major milestones already hit with approx 5% of the LHC program data:***
  - covering the majority of HH decays and production modes down to sub fb processes
  - increased level of sophistication and precision (following lessons / conventions from single H)
  - *ATLAS+CMS full Run 2 combination: passing the 1-sigma bar*

- ***Bright future ahead*** *(HL-LHC projections)**:***
  - Solid observation of HH (if SM) in reach by the end of HL-LHC
  - <50% precision on k_λ active for any possible anomalous value
  - a lot of room for improvements but also a lot of challenges to get there

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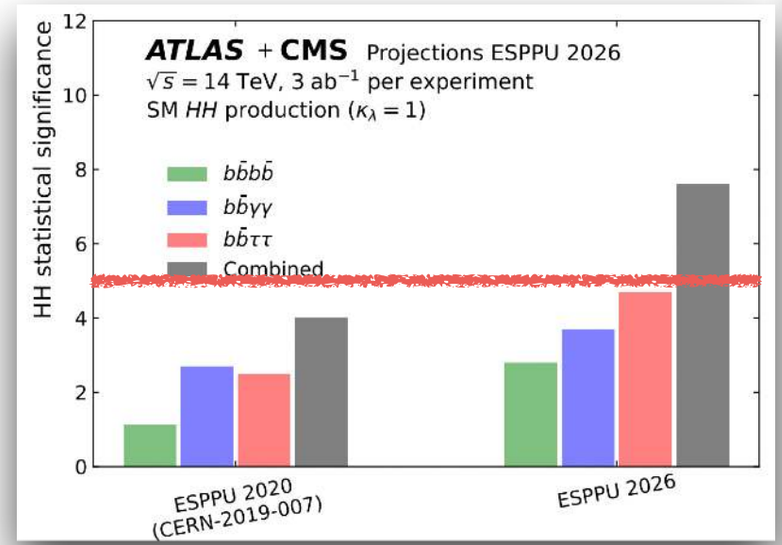
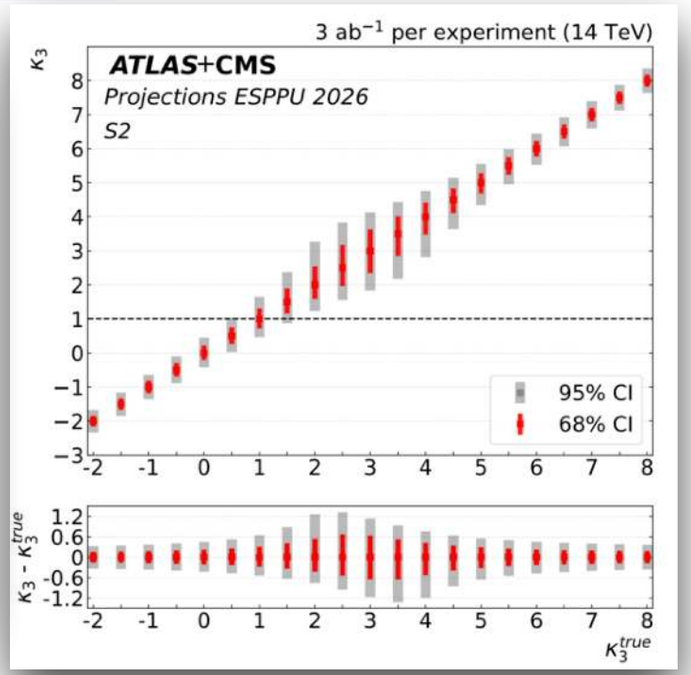




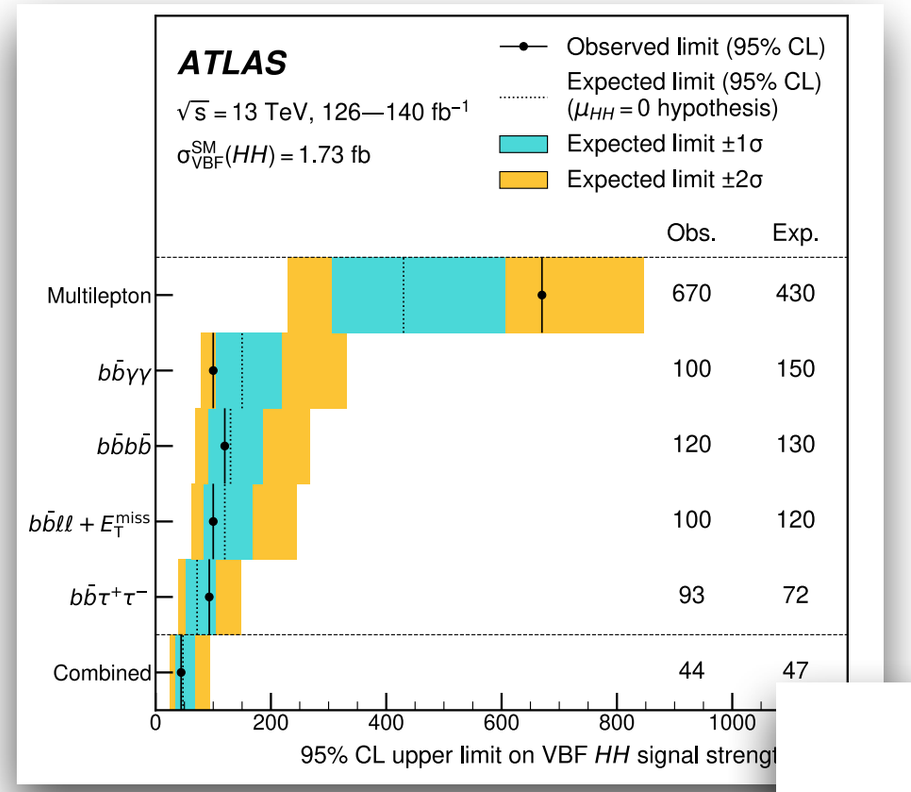
Early Run 3 analyses are showing impressive gains exceeding these projections:

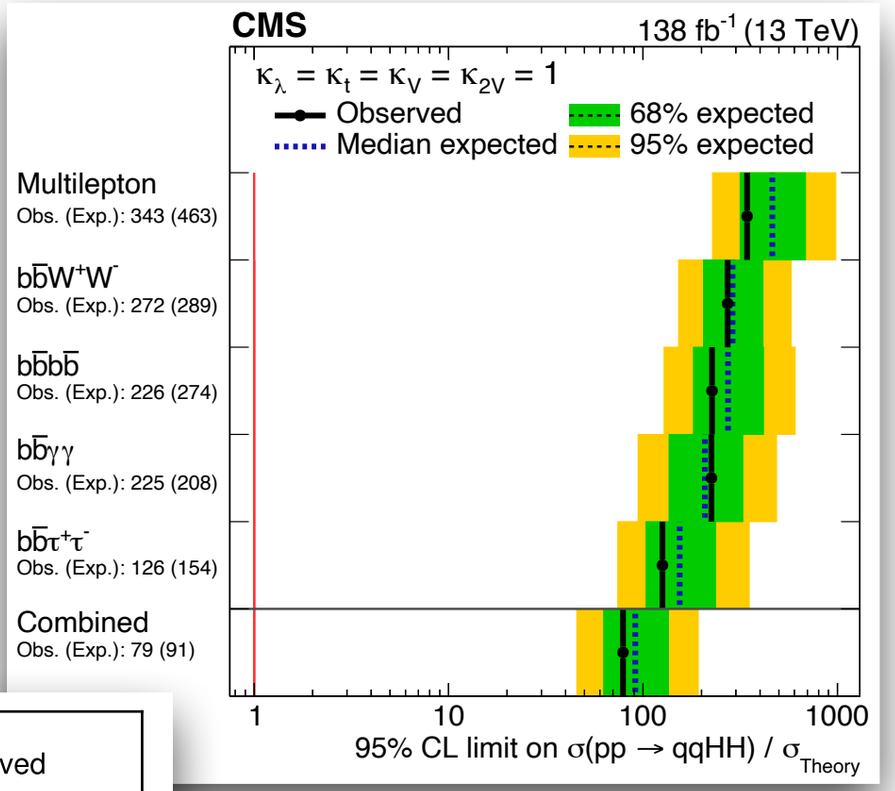
Stay tuned for more upcoming results

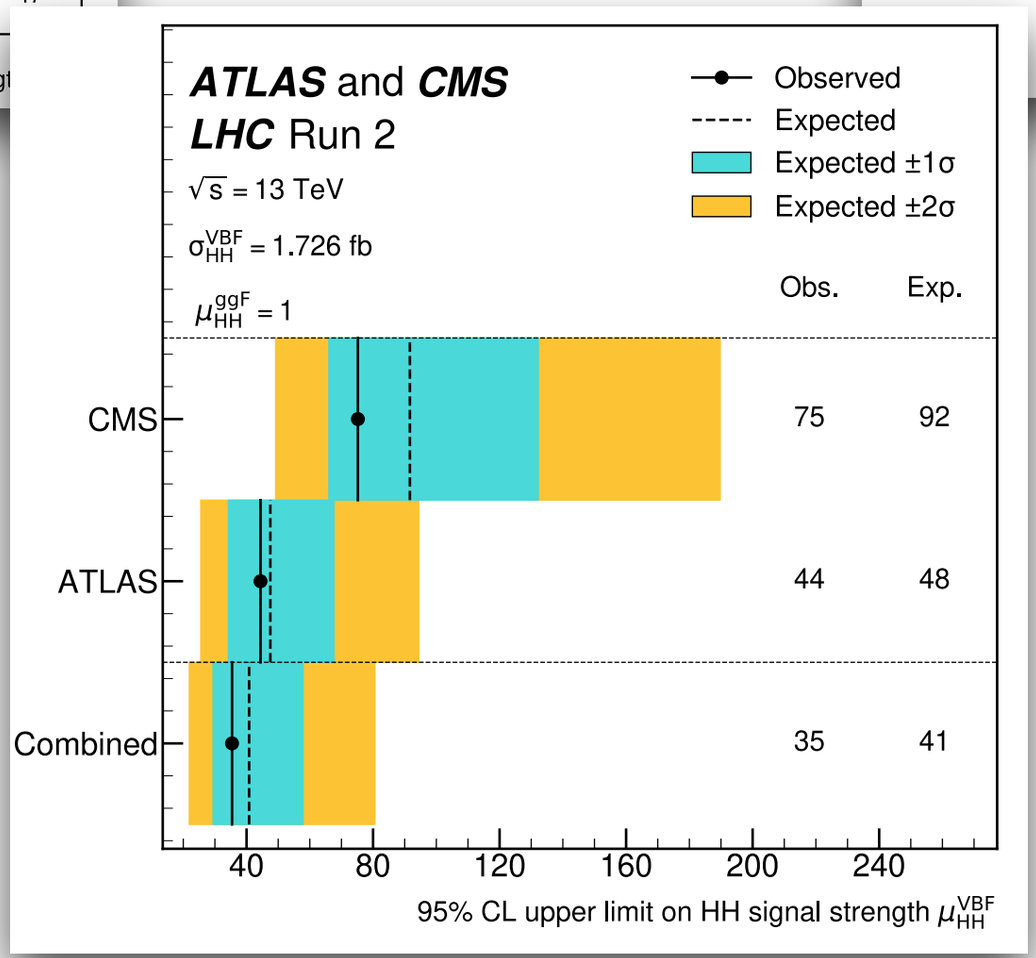
BackUp

$$\hat{\mu}_{\mathrm{HH}}^{\mathrm{exp}} = 1.0^{+0.9}_{-0.8} = 1.0^{+0.7}_{-0.6}(\mathrm{stat.})^{+0.5}_{-0.3}(\mathrm{theory})^{+0.3}_{-0.3}(\mathrm{exp.})$$

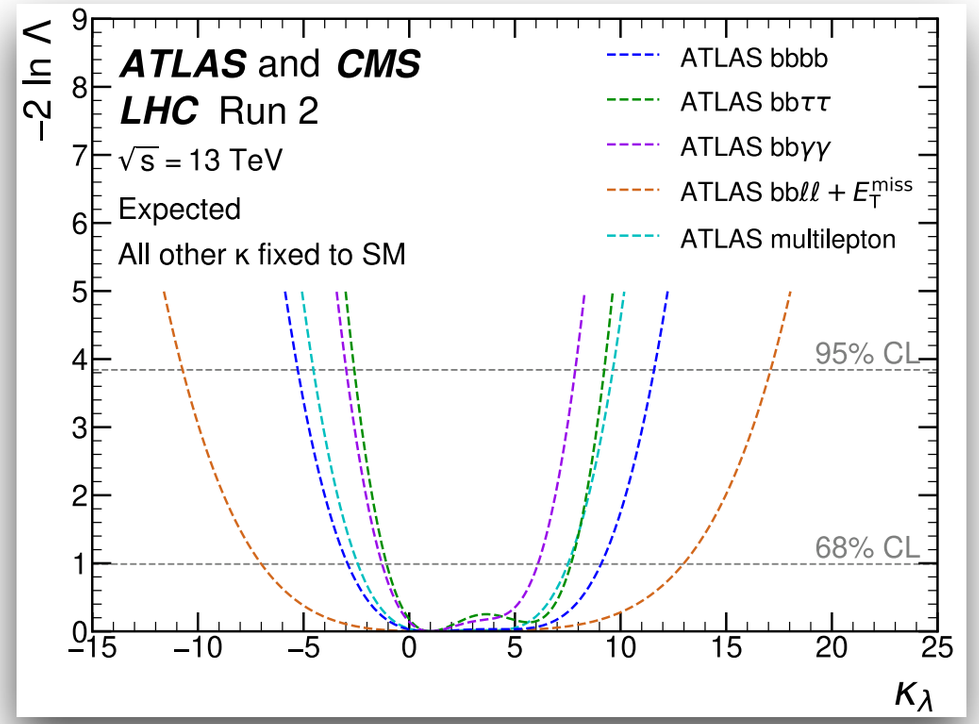
HH searches: ATLAS VS CMS

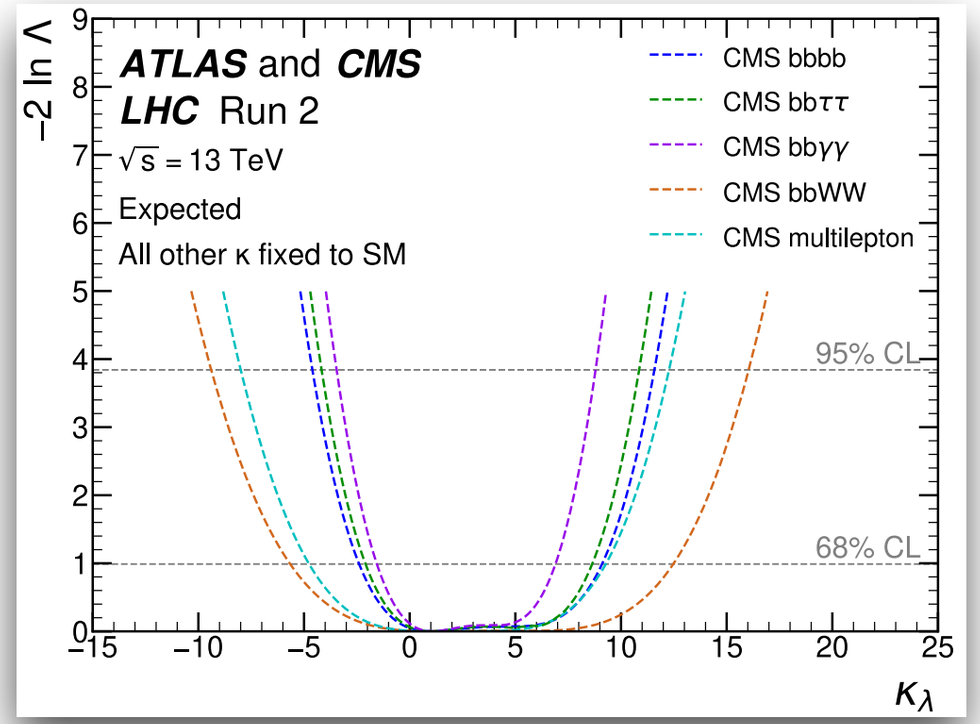


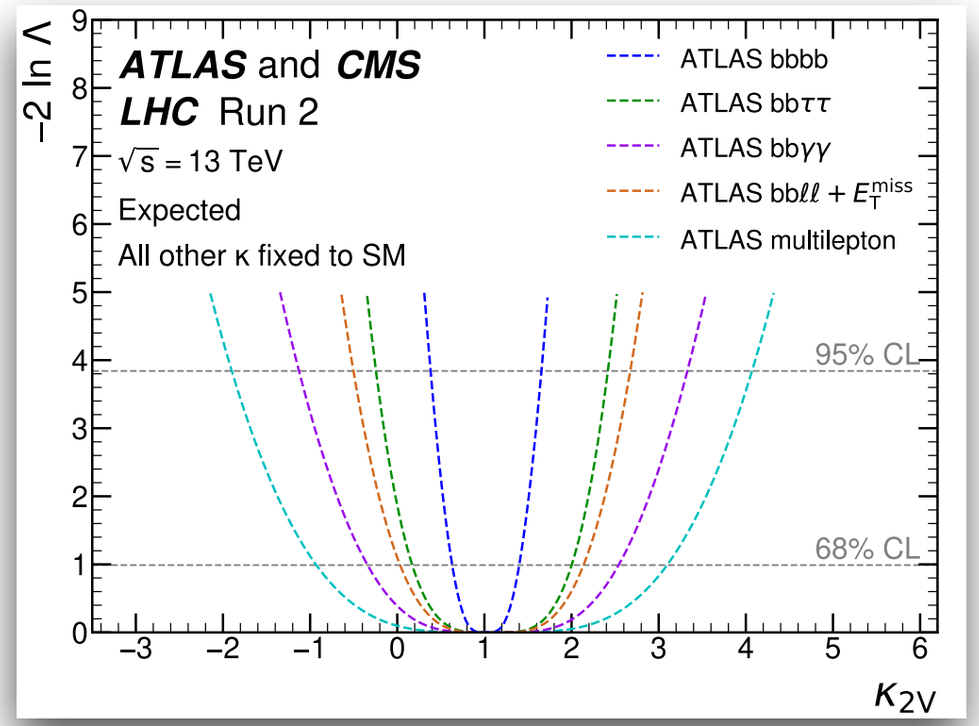


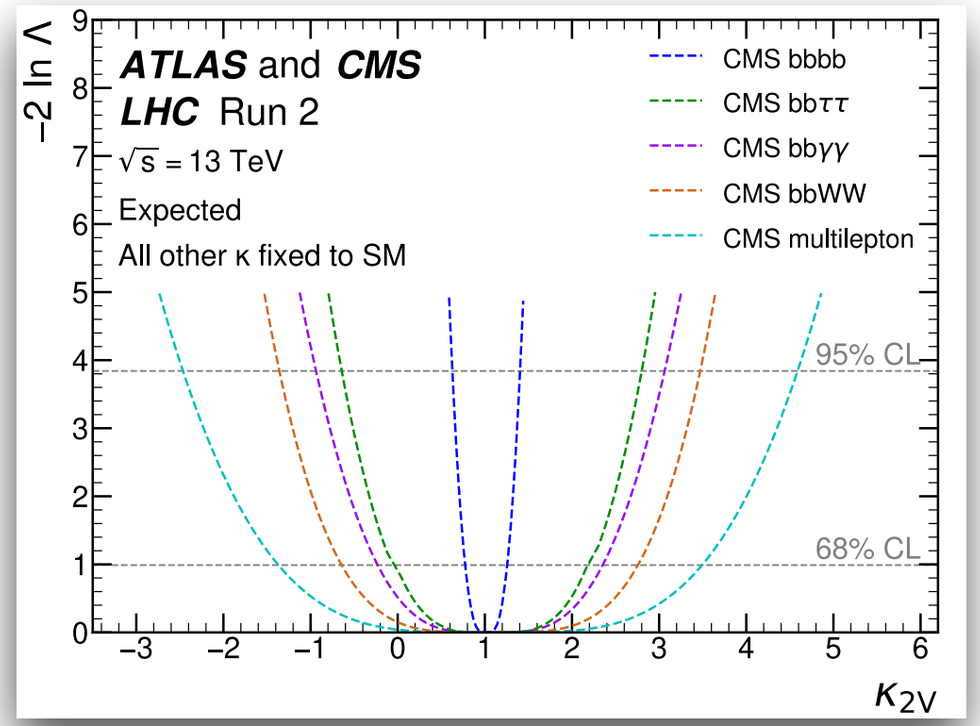


HH searches: ATLAS VS CMS

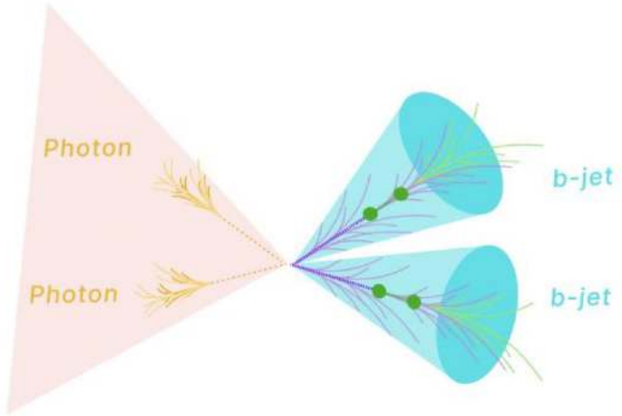


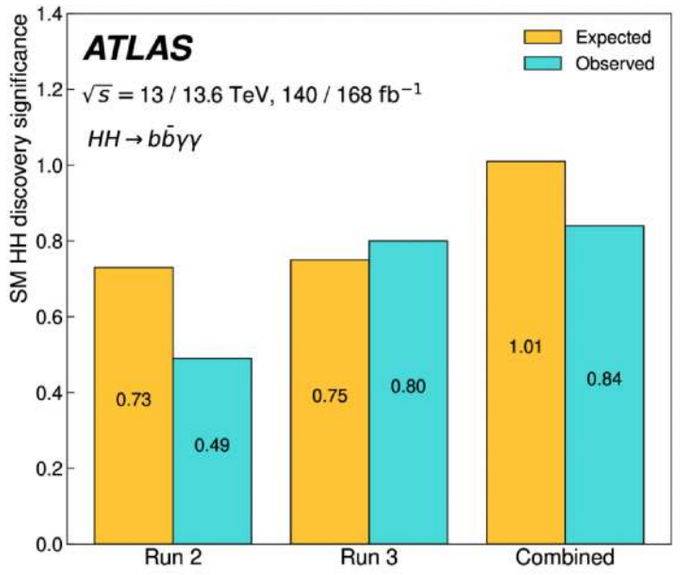




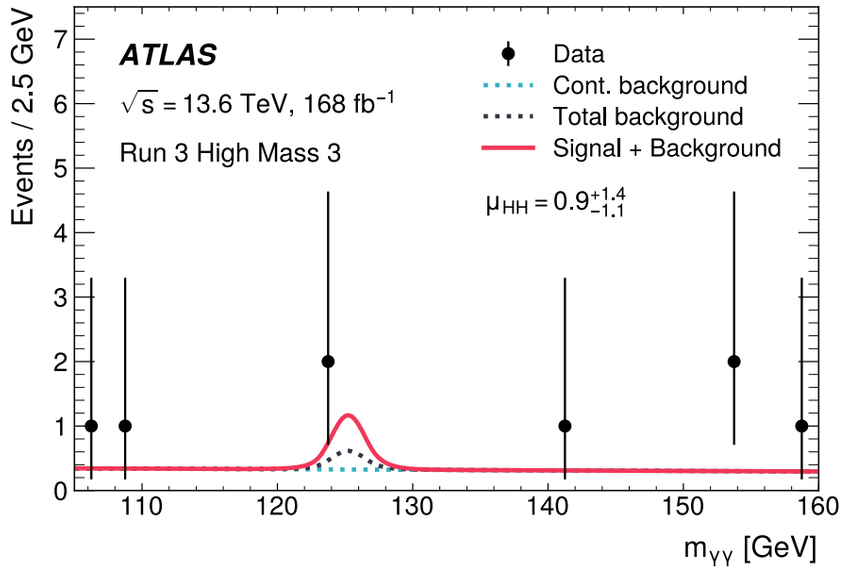


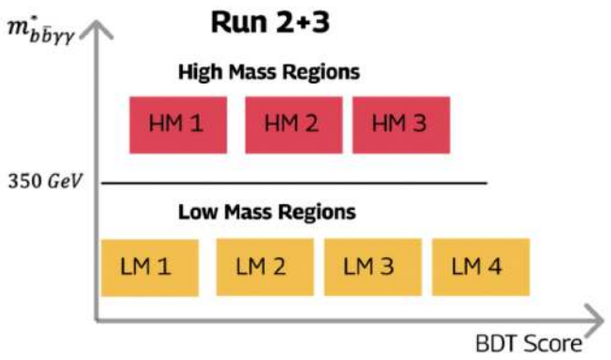
ATLAS: bbyy

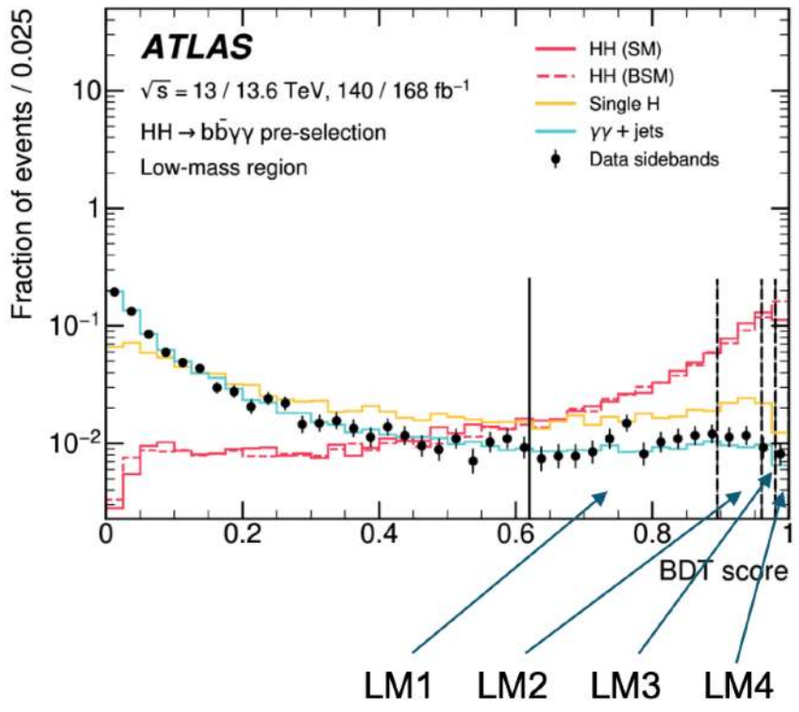


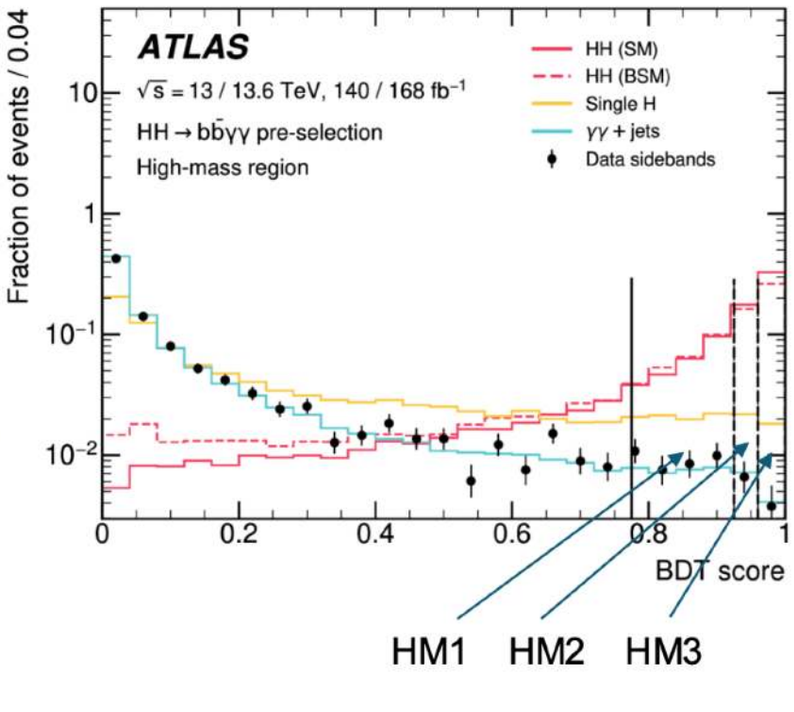


most sensitive SR









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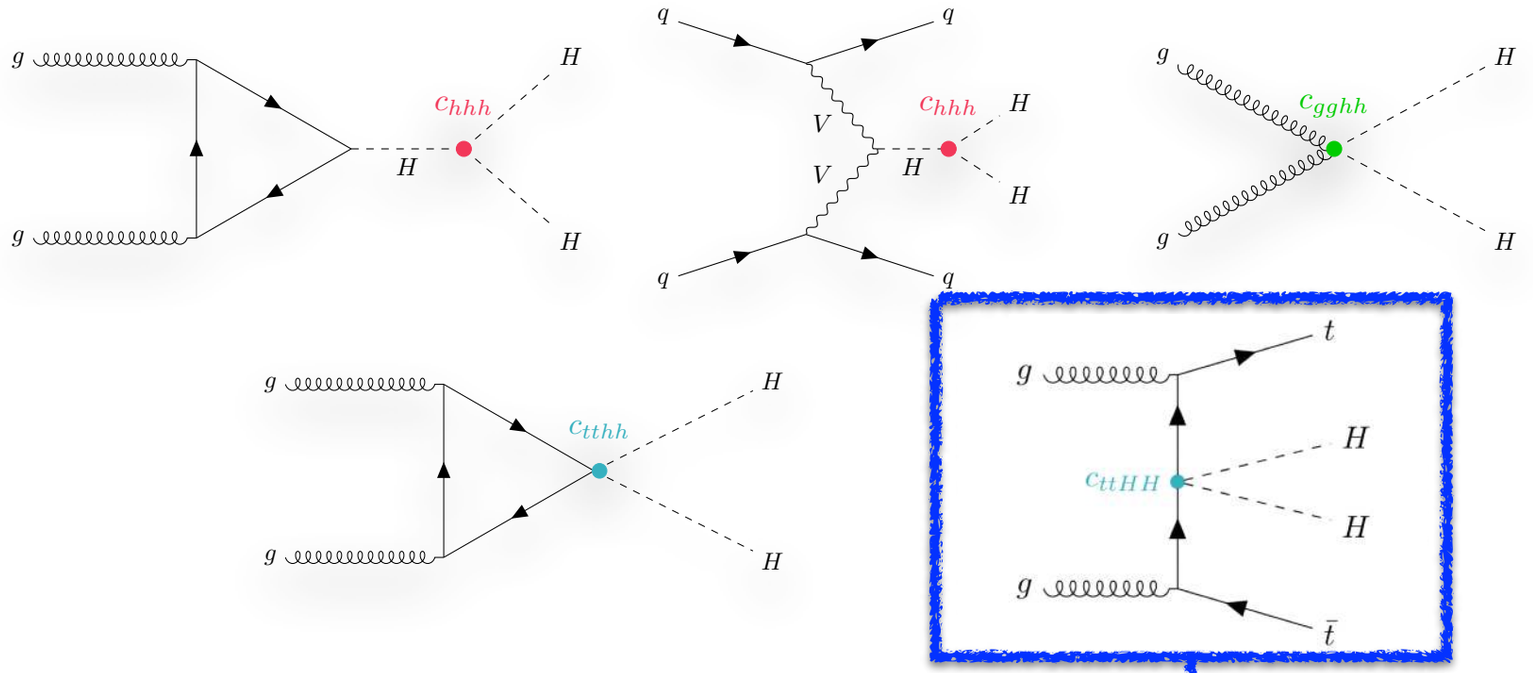
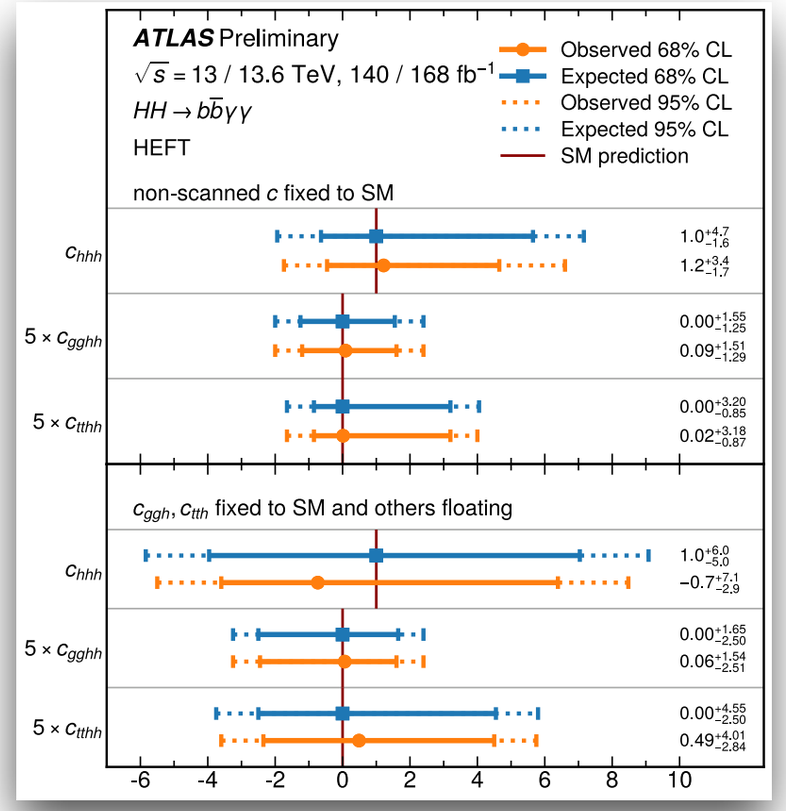
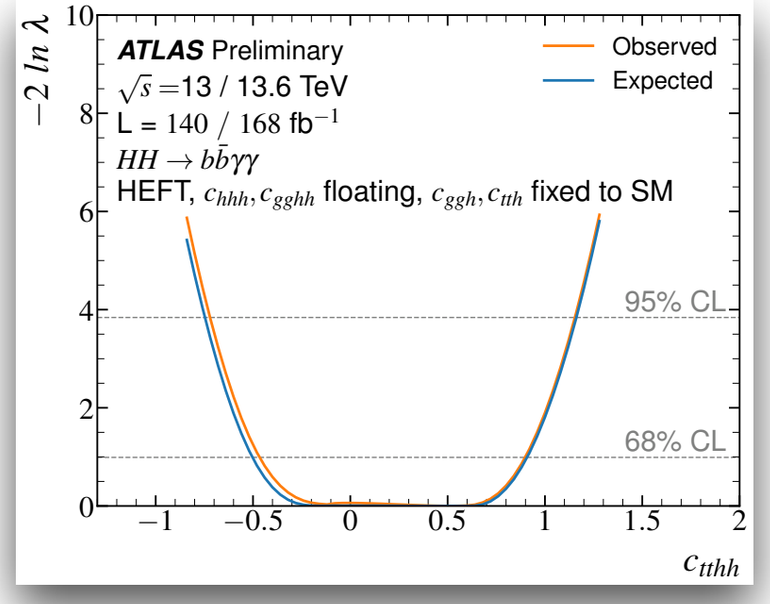
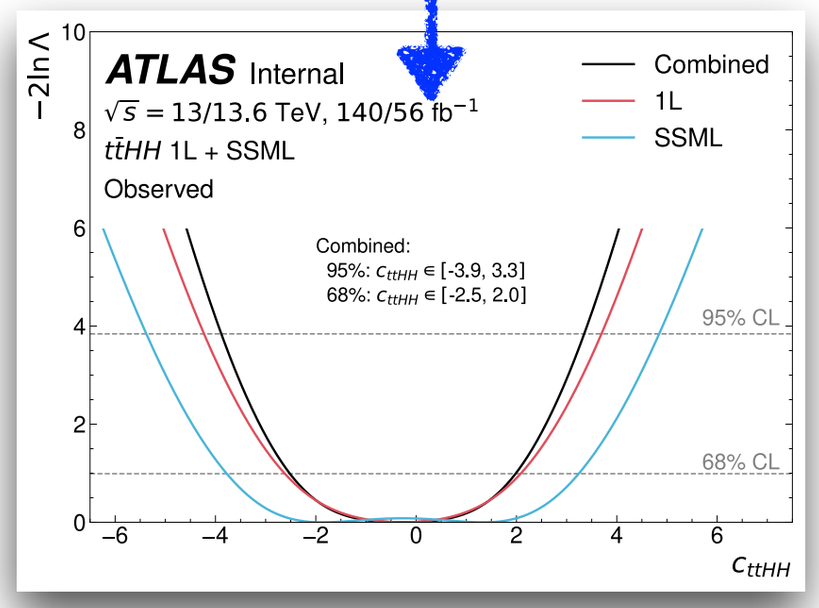
- ***HEFT interpretation of ATLAS bbyy analysis:***
  - *focusing on operators where HH brings unique sensitivity*
  - both individual and simultaneous 3-operators fit



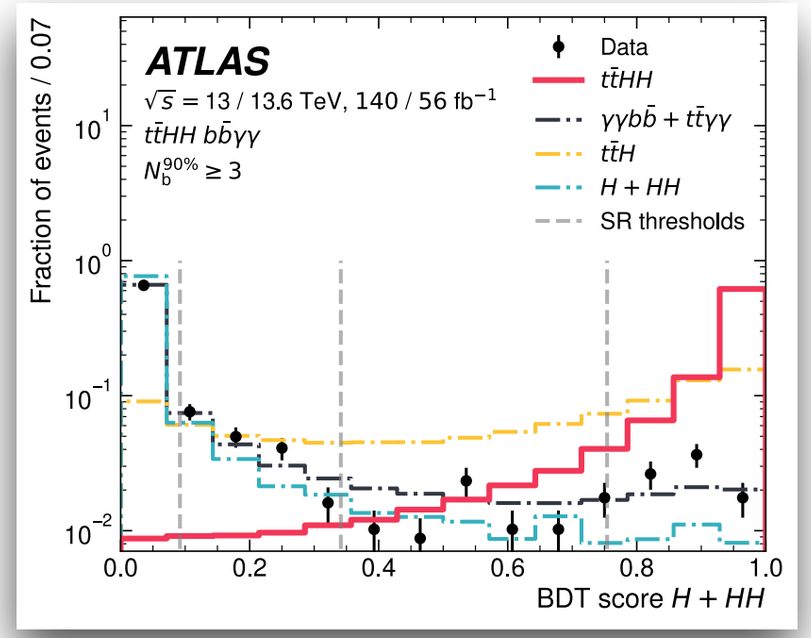


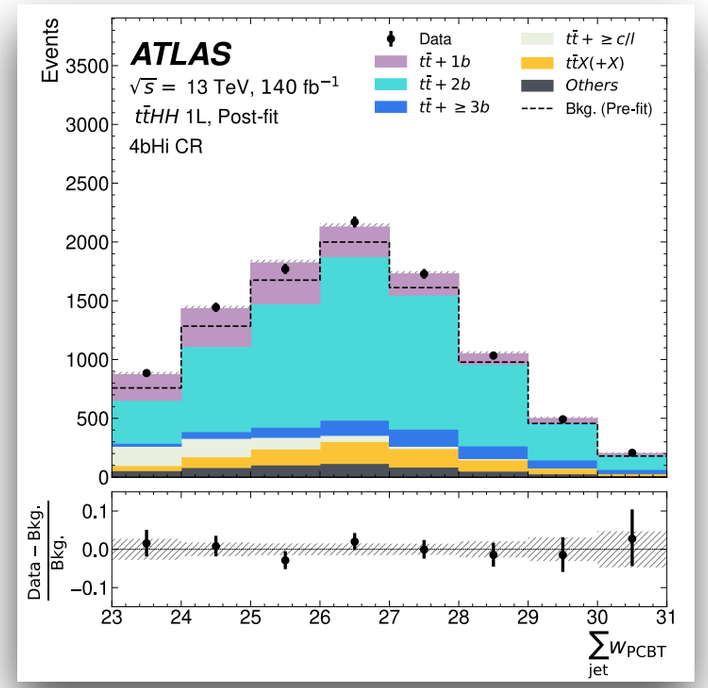


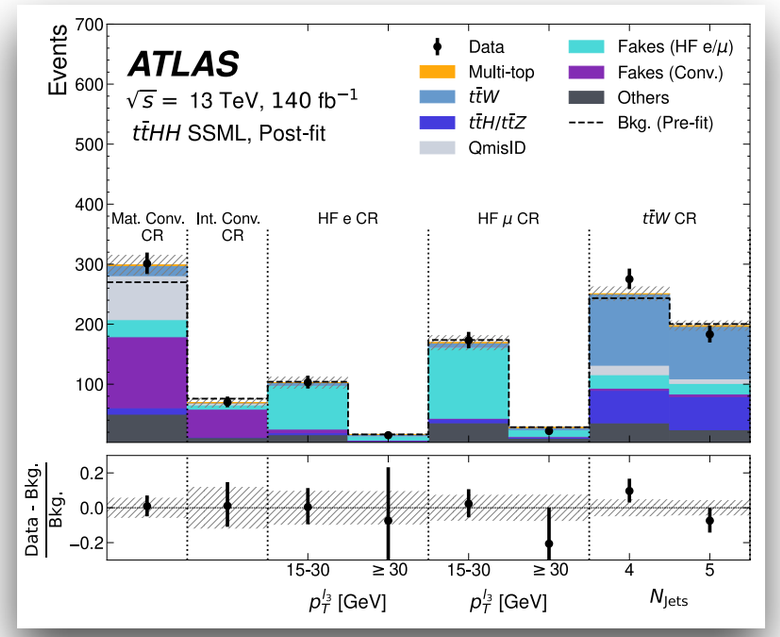


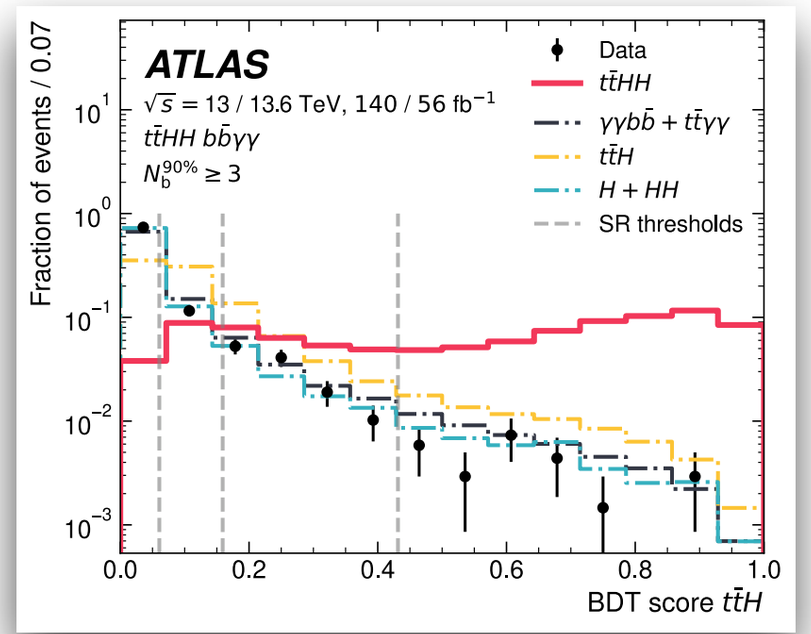
- ***Also interpreted with SMEFT framework*** including effects on backgrounds

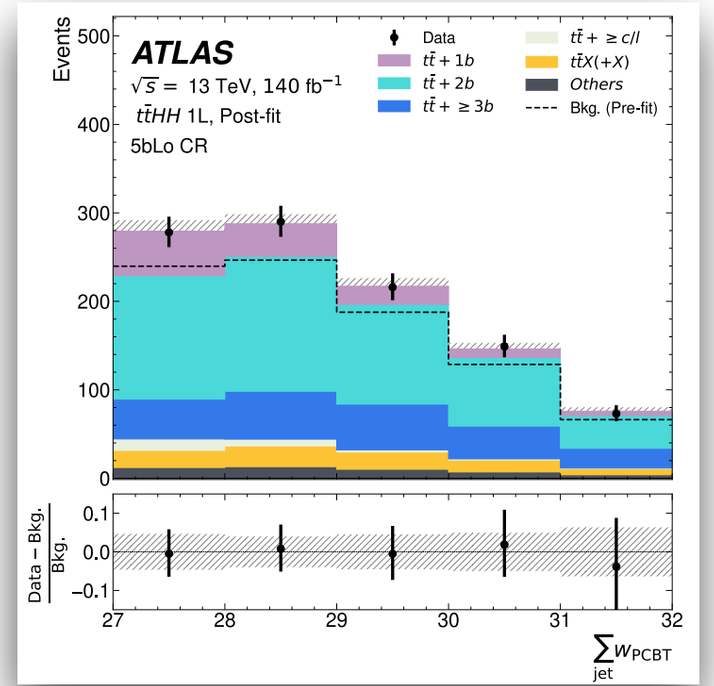
ttHH

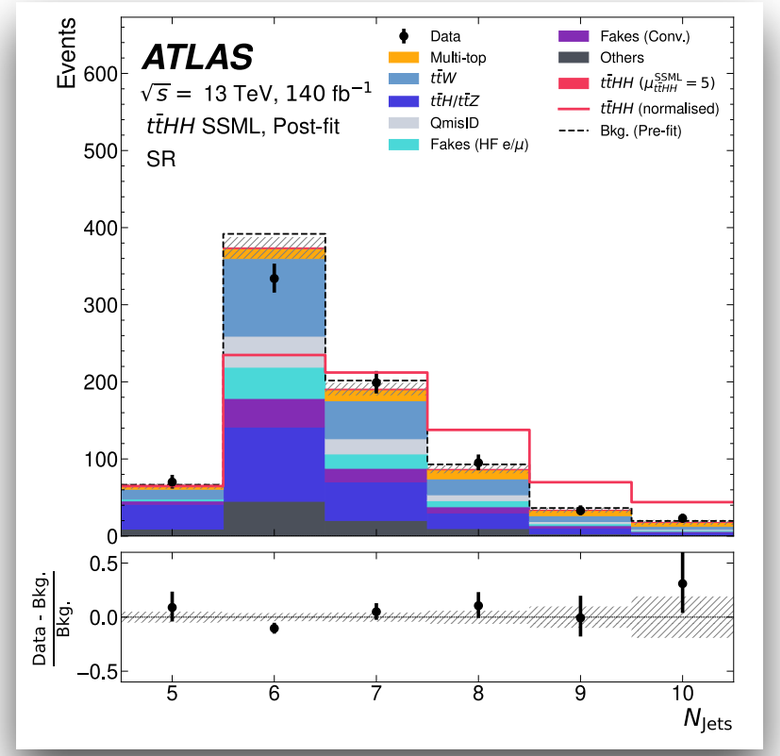

ATLAS
$\sqrt{s}$ = 13 / 13.6 TeV, 140 / 56 fb^{-1}
$t\bar{t}HH\ b\bar{b}\gamma\gamma$
$N_b^{90\%} \geq 3$
Data
$t\bar{t}HH$
$\gamma\gamma b\bar{b} + t\bar{t}\gamma\gamma$
$t\bar{t}H$
$H + HH$
SR thresholds
Fraction of events / 0.07
BDT score $H + HH$

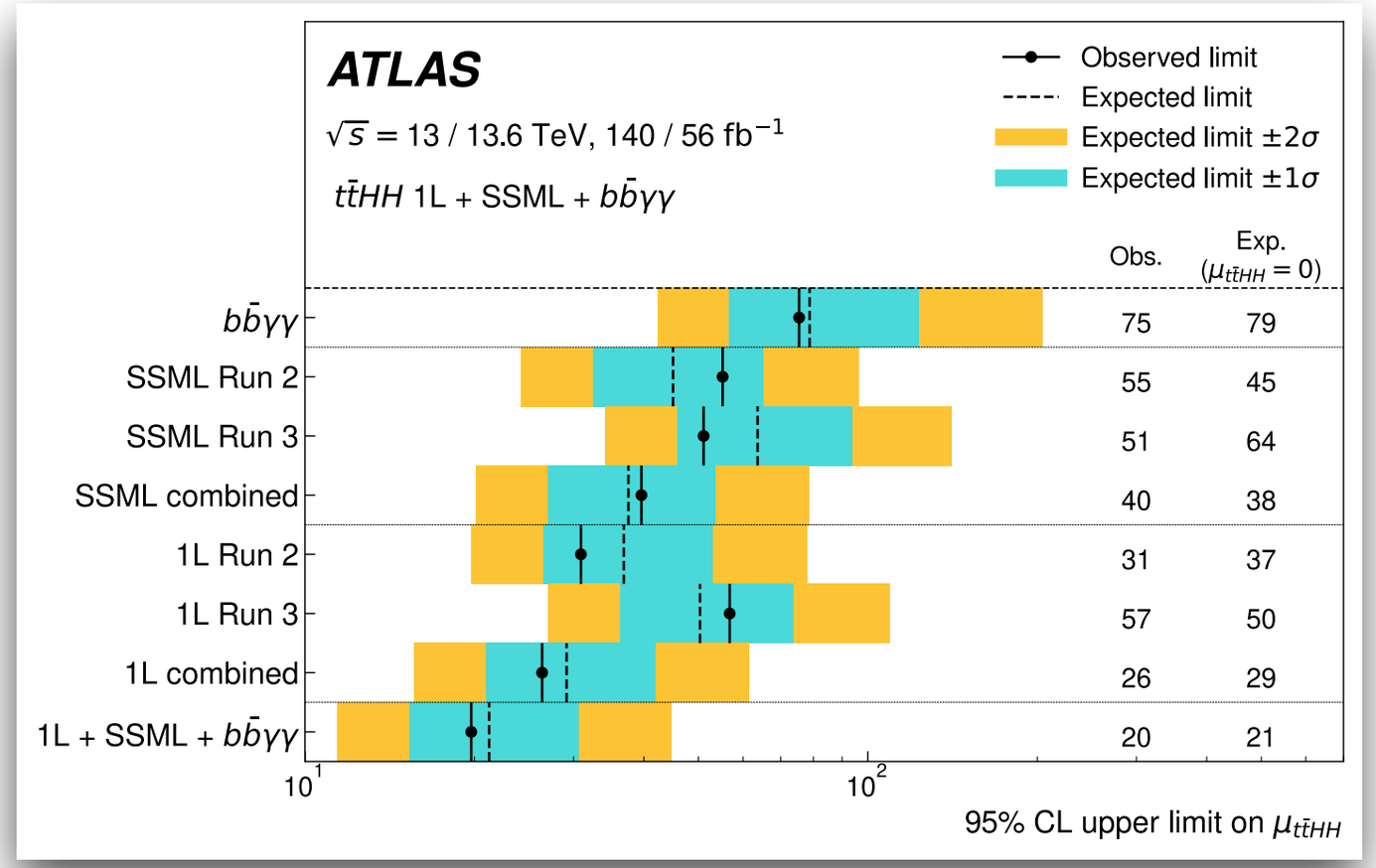

ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
$t\bar{t}HH$ 1L, Post-fit
4bHi CR
Data
$t\bar{t}+1b$
$t\bar{t}+2b$
$t\bar{t}+\geq 3b$
$t\bar{t}+\geq c/l$
$t\bar{t}X(+X)$
Others
Bkg. (Pre-fit)
Events
Data − Bkg. / Bkg.
$\sum_{jet} w_{PCBT}$


ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
$t\bar{t}HH$ SSML, Post-fit
Data
Multi-top
$t\bar{t}W$
$t\bar{t}H/t\bar{t}Z$
QmisID
Fakes (HF e/μ)
Fakes (Conv.)
Others
Bkg. (Pre-fit)
Mat. Conv. CR
Int. Conv. CR
HF e CR
HF μ CR
$t\bar{t}W$ CR
Events
Data - Bkg. / Bkg.
$p_T^{l_3}$ [GeV]
N_{jets}


ATLAS
$\sqrt{s}$ = 13 / 13.6 TeV, 140 / 56 fb^{-1}
$t\bar{t}HH\ b\bar{b}\gamma\gamma$
$N_b^{90\%} \geq 3$
Data
$t\bar{t}HH$
$\gamma\gamma b\bar{b} + t\bar{t}\gamma\gamma$
$t\bar{t}H$
$H + HH$
SR thresholds
Fraction of events / 0.07
BDT score $t\bar{t}H$


ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
$t\bar{t}HH$ 1L, Post-fit
5bLo CR
Data
$t\bar{t}+1b$
$t\bar{t}+2b$
$t\bar{t}+\geq 3b$
$t\bar{t}+\geq c/l$
$t\bar{t}X(+X)$
Others
Bkg. (Pre-fit)
Events
Data − Bkg. / Bkg.
$\sum_{jet} w_{PCBT}$


ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
$t\bar{t}HH$ SSML, Post-fit
SR
Data
Multi-top
$t\bar{t}W$
$t\bar{t}H/t\bar{t}Z$
QmisID
Fakes (HF e/μ)
Fakes (Conv.)
Others
$t\bar{t}HH$ ($\mu_{t\bar{t}HH}^{SSML} = 5$)
$t\bar{t}HH$ (normalised)
Bkg. (Pre-fit)
Events
Data - Bkg. / Bkg.
N_{Jets}


ATLAS
$\sqrt{s}$ = 13 / 13.6 TeV, 140 / 56 fb^{-1}
$t\bar{t}HH$ 1L + SSML + $b\bar{b}\gamma\gamma$
Observed limit
Expected limit
Expected limit ±2σ
Expected limit ±1σ
Obs.
Exp. ($\mu_{t\bar{t}HH}$ = 0)
$b\bar{b}\gamma\gamma$ 75 79
SSML Run 2 55 45
SSML Run 3 51 64
SSML combined 40 38
1L Run 2 31 37
1L Run 3 57 50
1L combined 26 29
1L + SSML + $b\bar{b}\gamma\gamma$ 20 21
10^1
10^2
95% CL upper limit on $\mu_{t\bar{t}HH}$

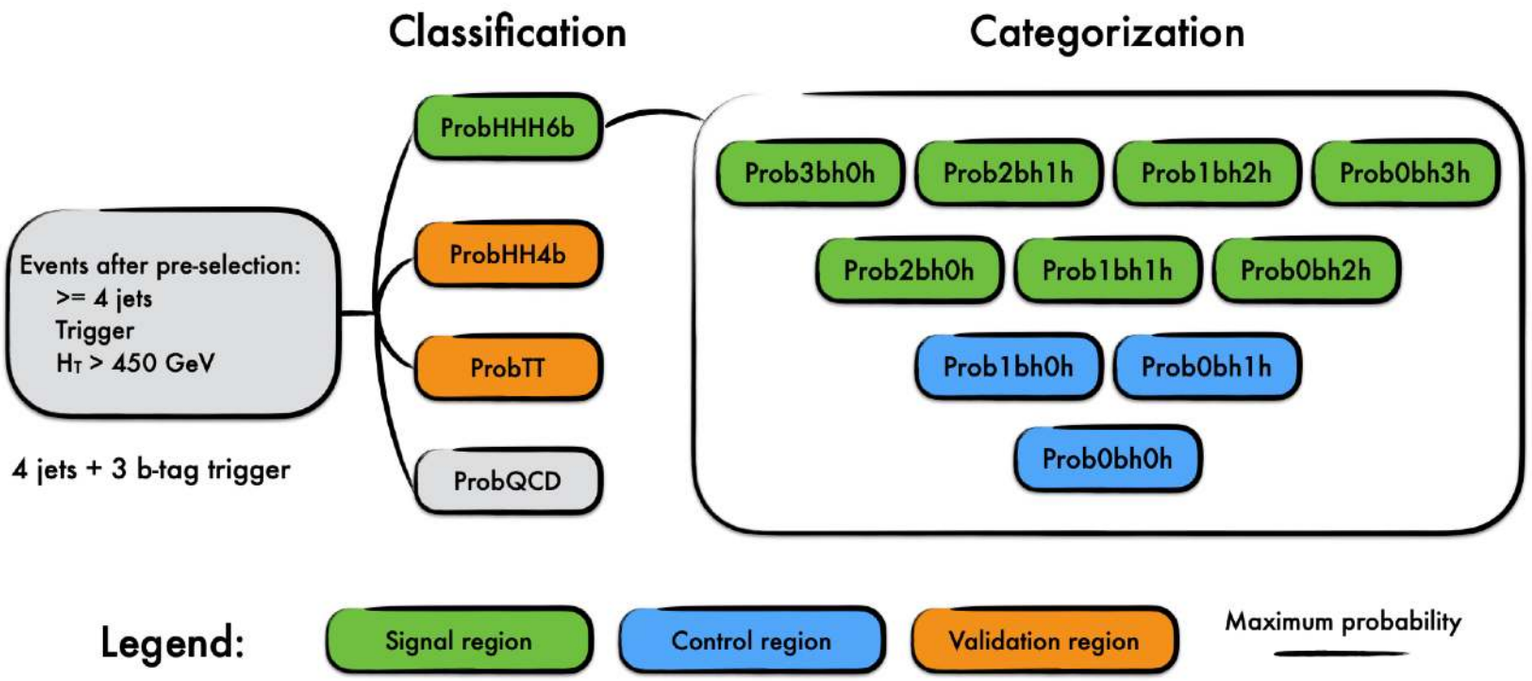
Non-resonant $HHH \rightarrow 6b$

Number of reconstructible Higgs in **2 AK4**

Reconstructible Higgs in **AK8**

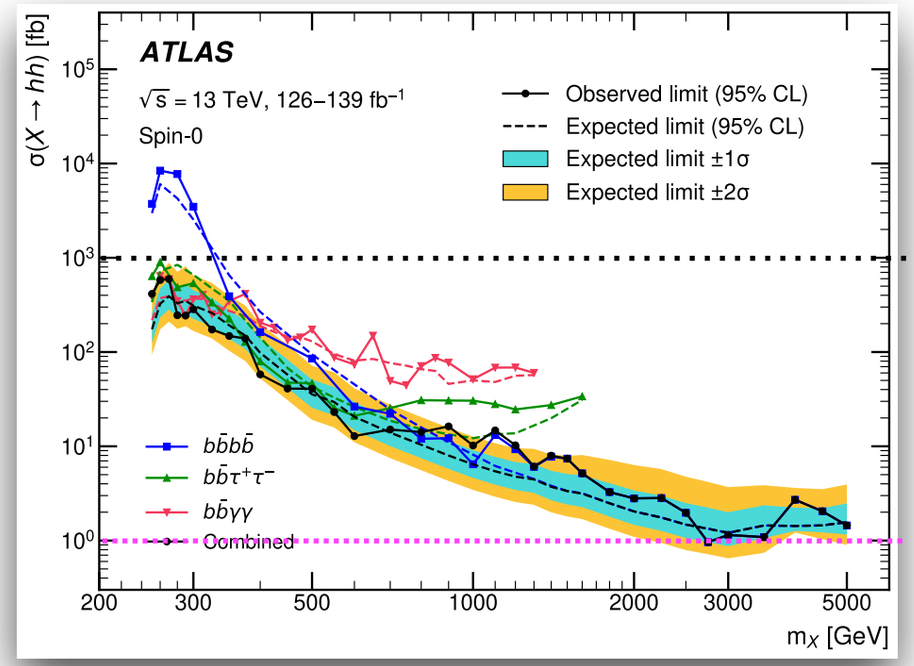
	0h	1h	2h	3h
3bh	1.7%			
2bh	12.5%	5.9%		
1bh	8.6%	**17.5%**	**7.9%**	
0bh	1.3%	11.1%	**22.0%**	**11.1%**

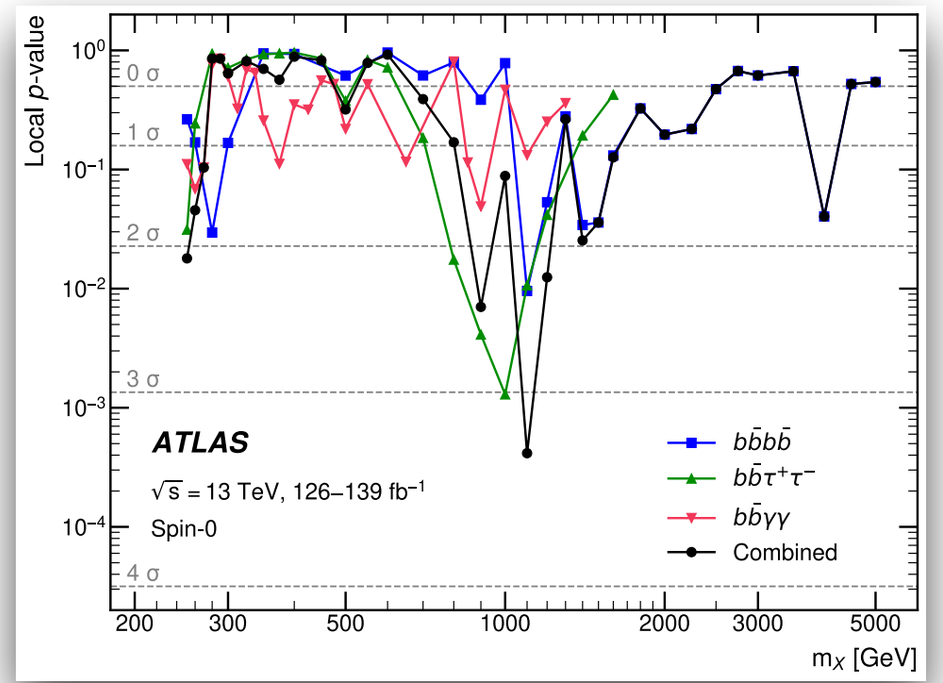
0Higgs 1.3% | 1Higgs 19.7% | 2Higgs 52% | 3Higgs 27%



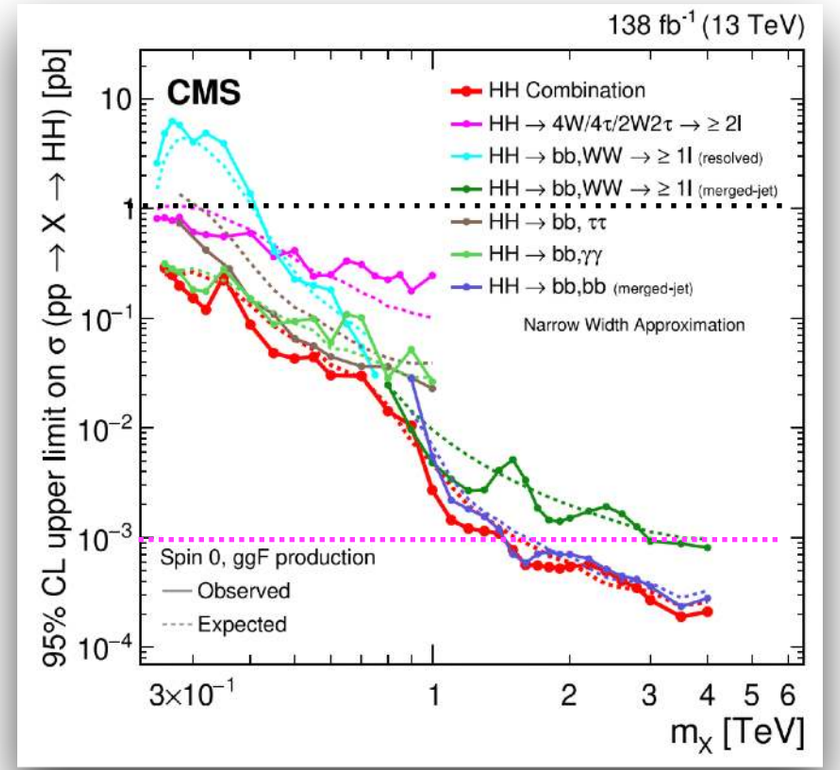
HH resonant

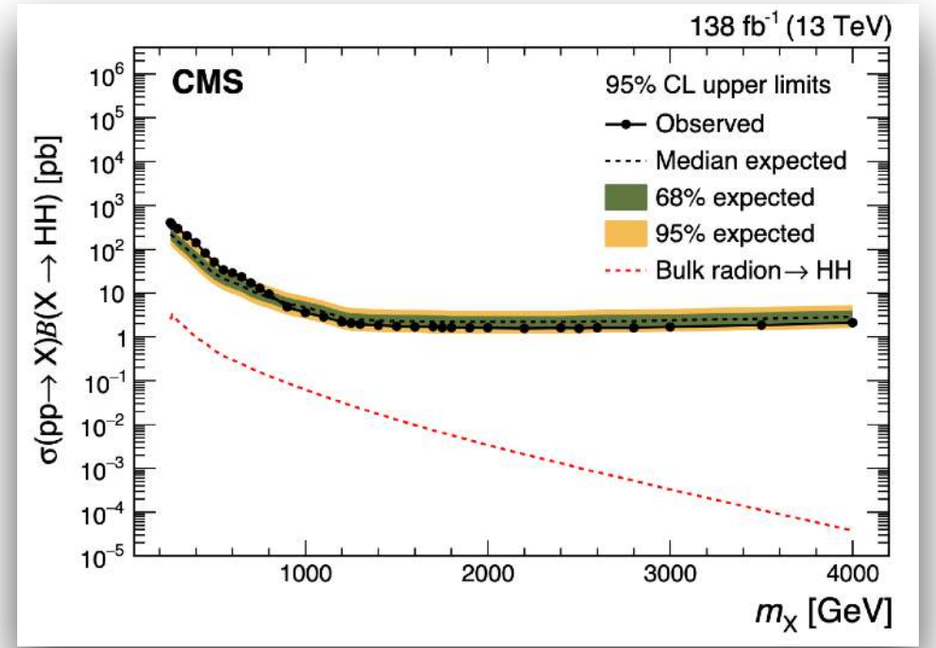
[Phys. Rev. Lett. 132 (2024) 231801]



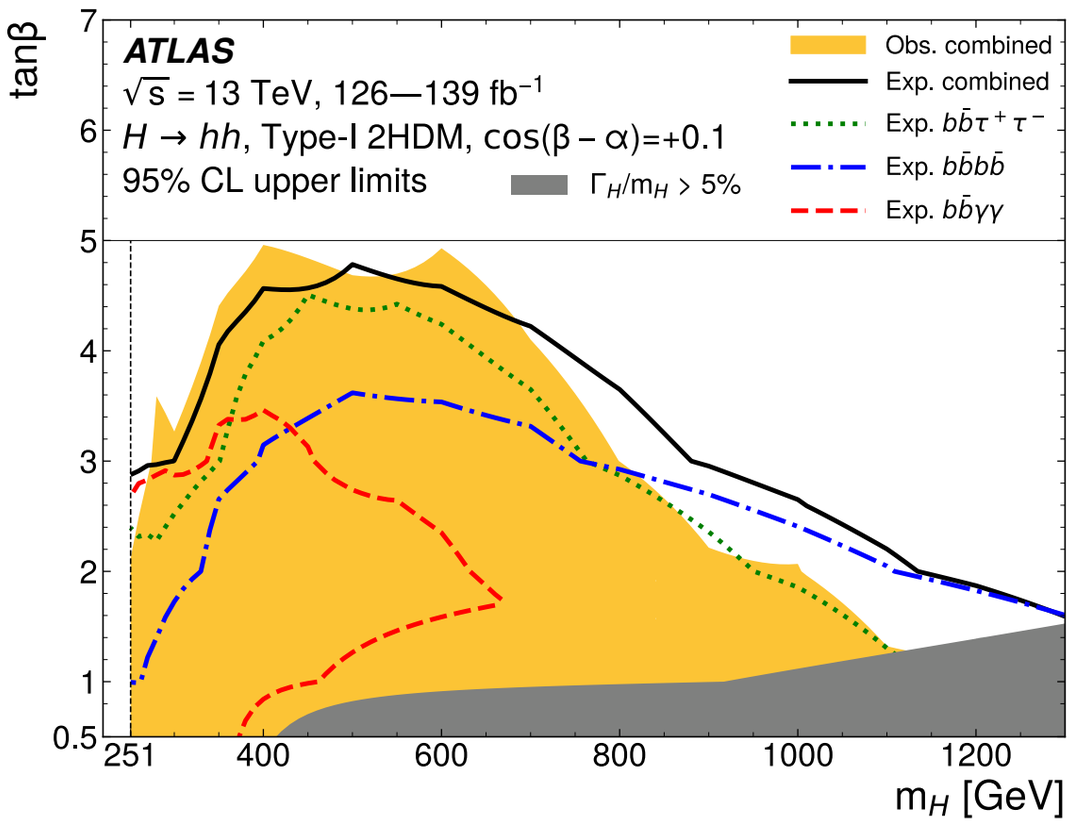


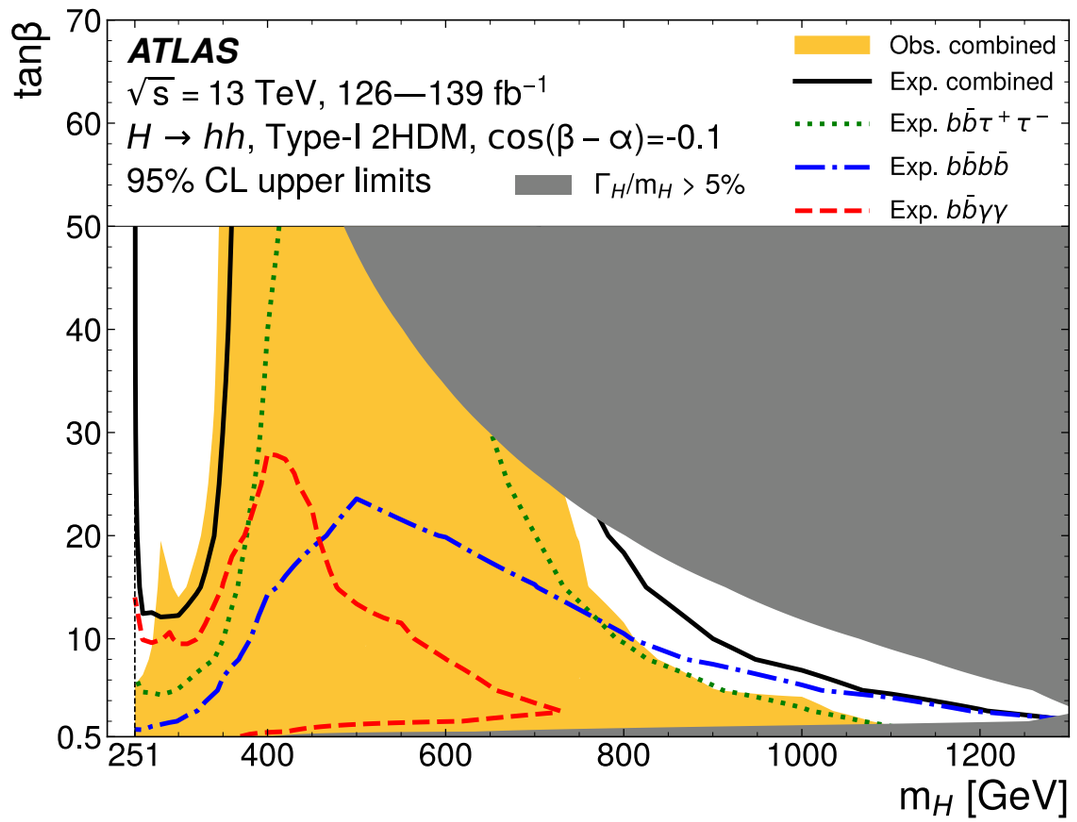
[Physics Reports Volume 1115, 17 Ap. 2025, 368-447]





HH resonant: interpretation



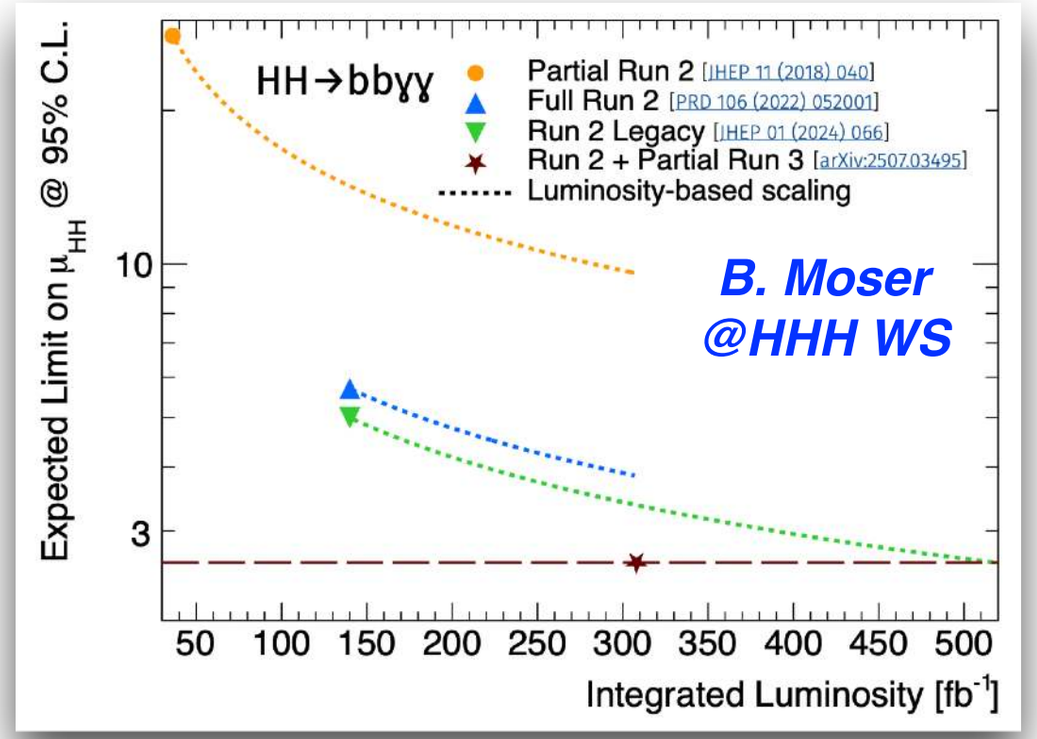


Realistic approach

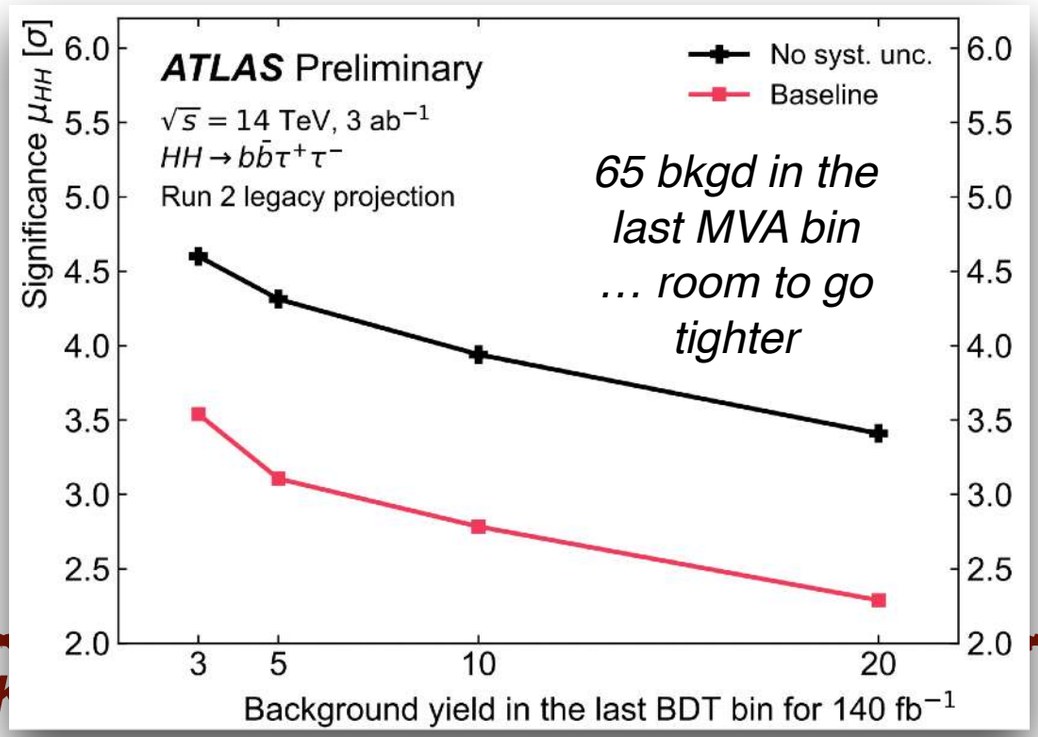
- Hard to make concrete projections
  - New challenges at the HL-LHC (pileup, trigger, detector performance)
  - New opportunities! (we've already seen huge improvements due to object and event reconstruction, novel analysis techniques, etc.)
- n.b. Despite my optimism, we won't get this "for free" - requires work in detector upgrades, trigger, …

Reasons for optimism

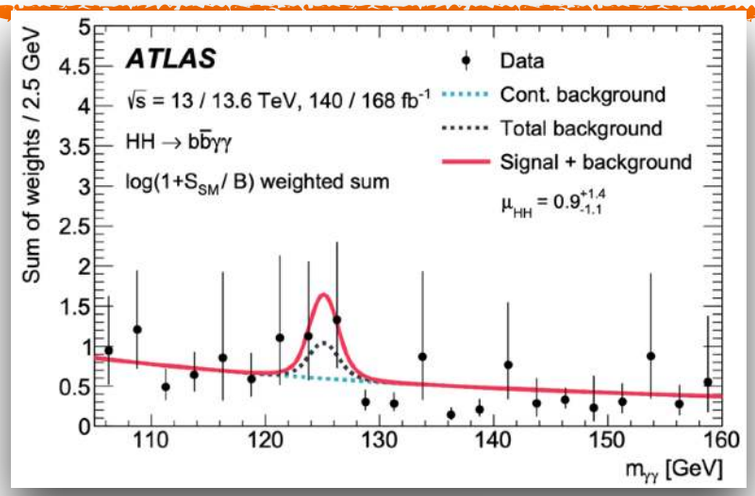
John: "we typically outperform predictions"



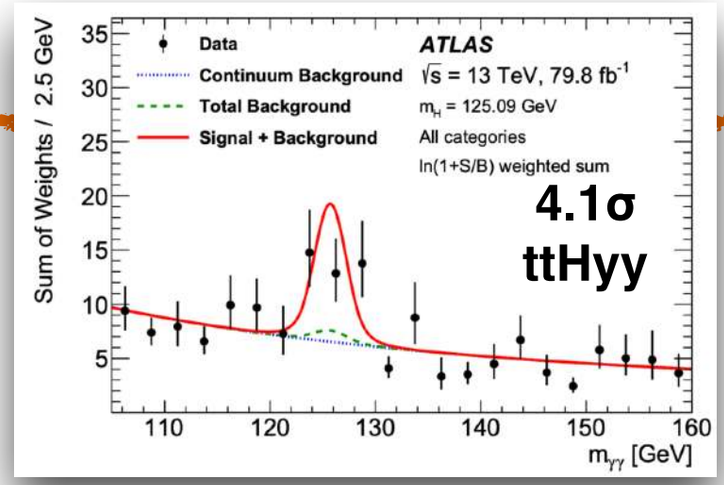
Extrapolation don't change analysis strategy
[not even binning]

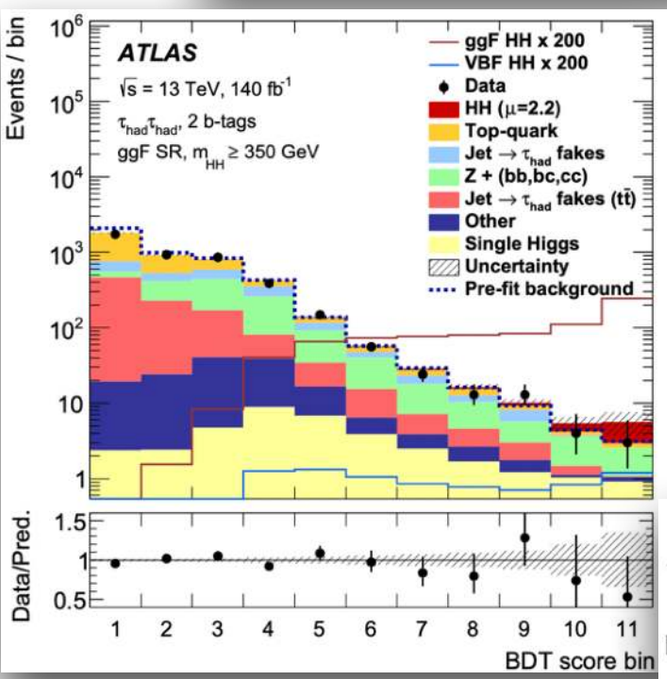


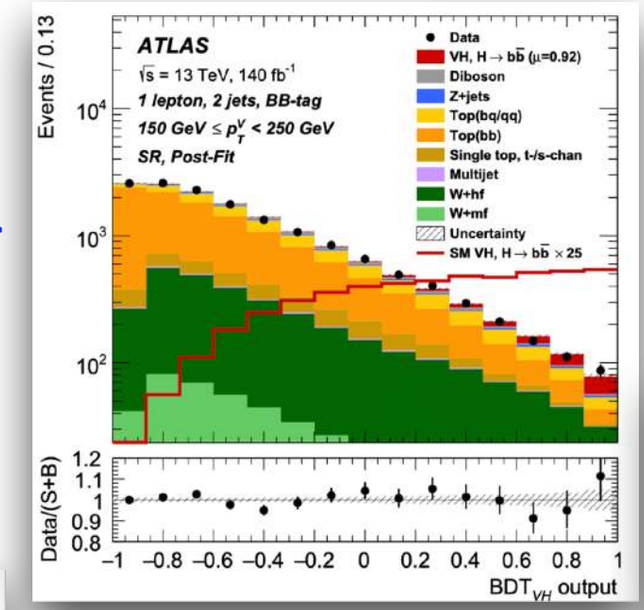
Are we ready to measure?



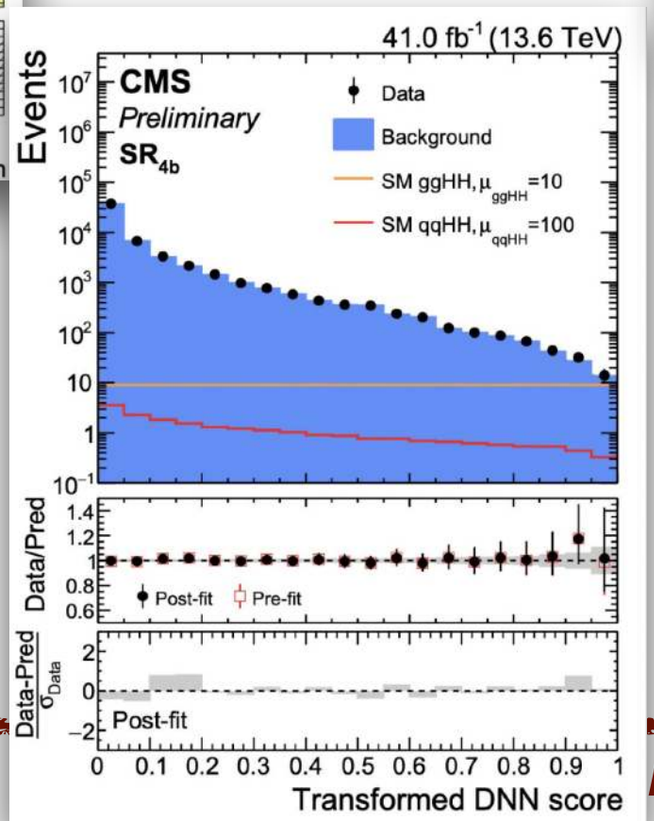
successful analysis with similar strategy



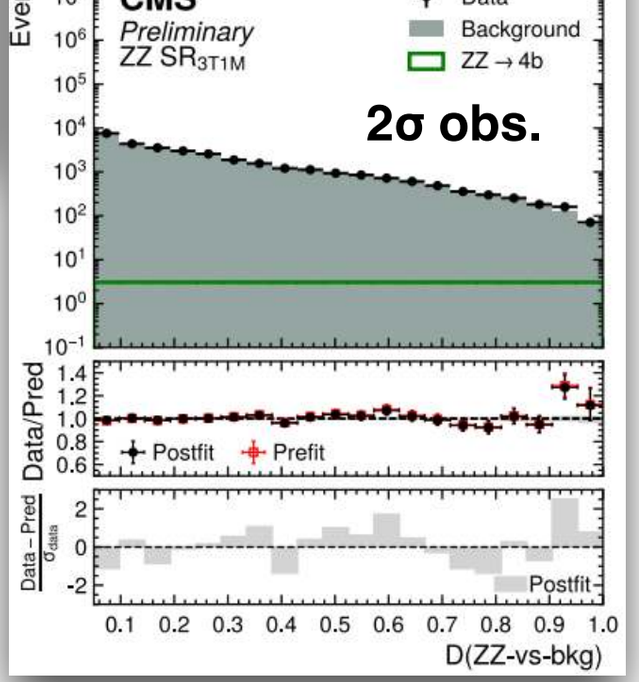




2.4σ
WHbb



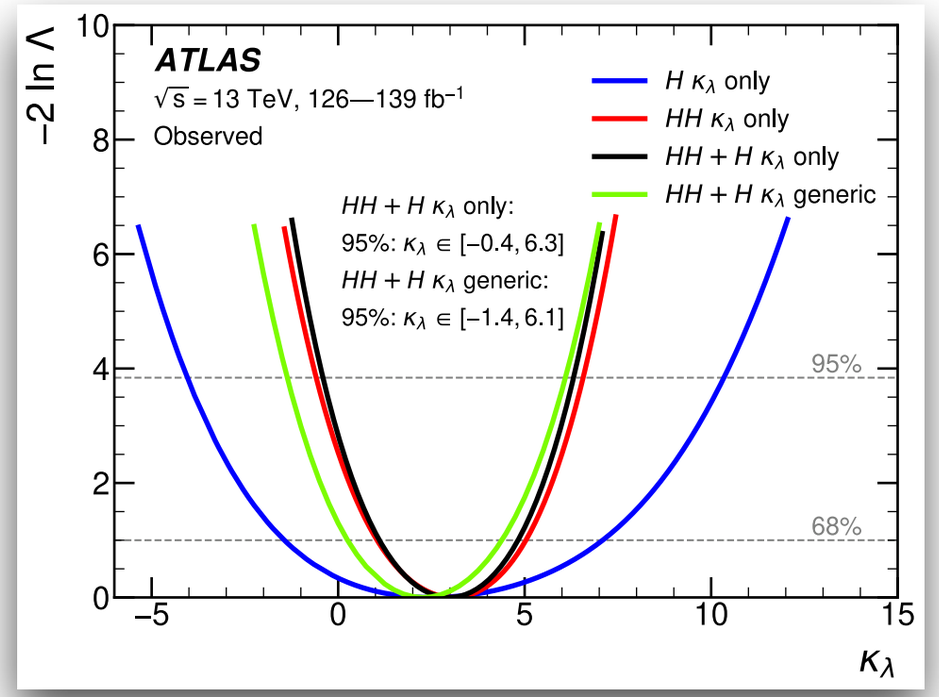
ZZ4b = (3.7 +/- 2)

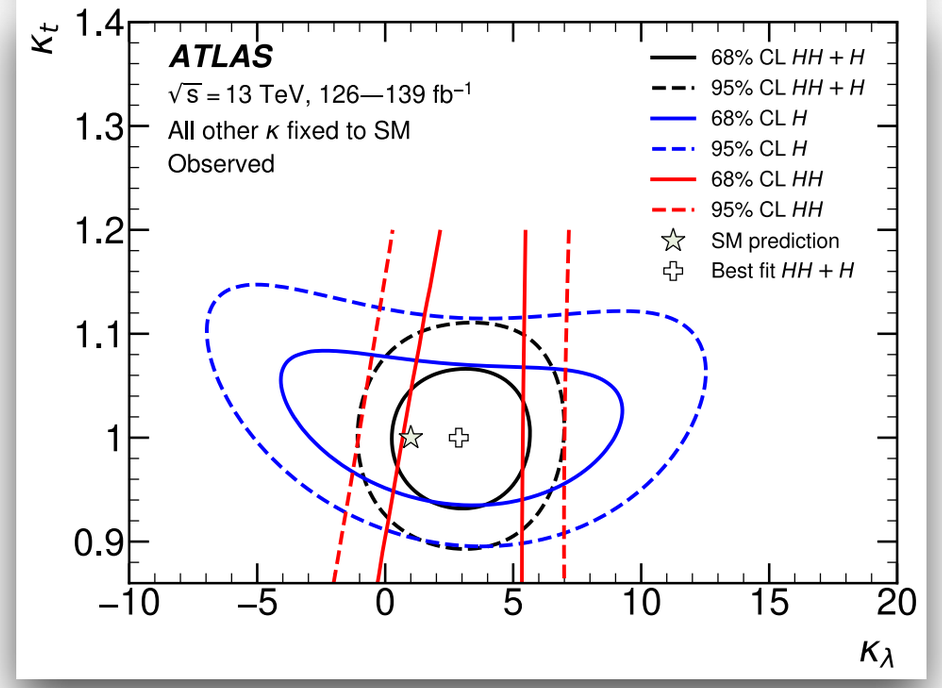


Huge value in measuring standard candles with same techniques (ttZ, ZZ, ZH)

kappa_L from single Higgs

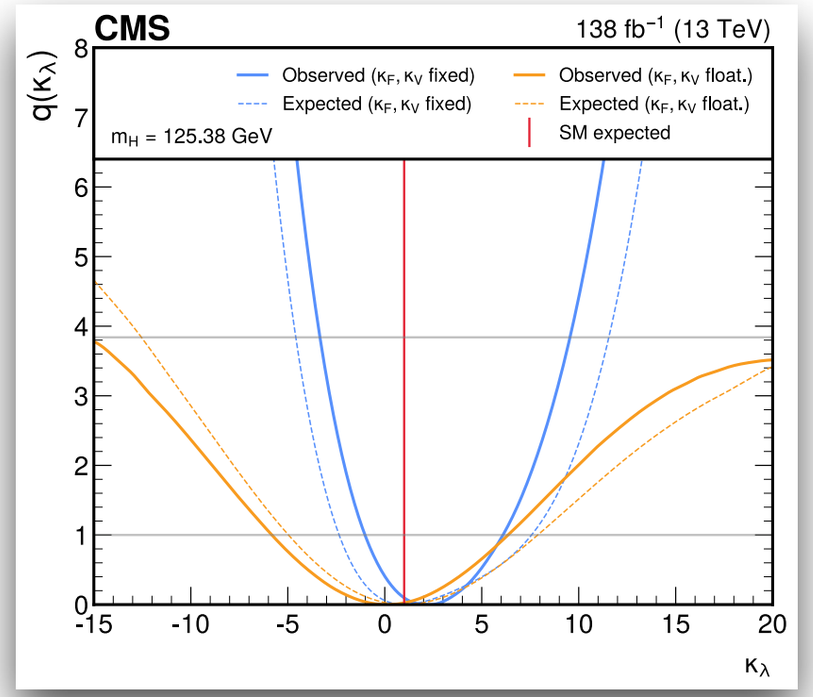
[Phys. Lett. B 843 (2023) 137745]

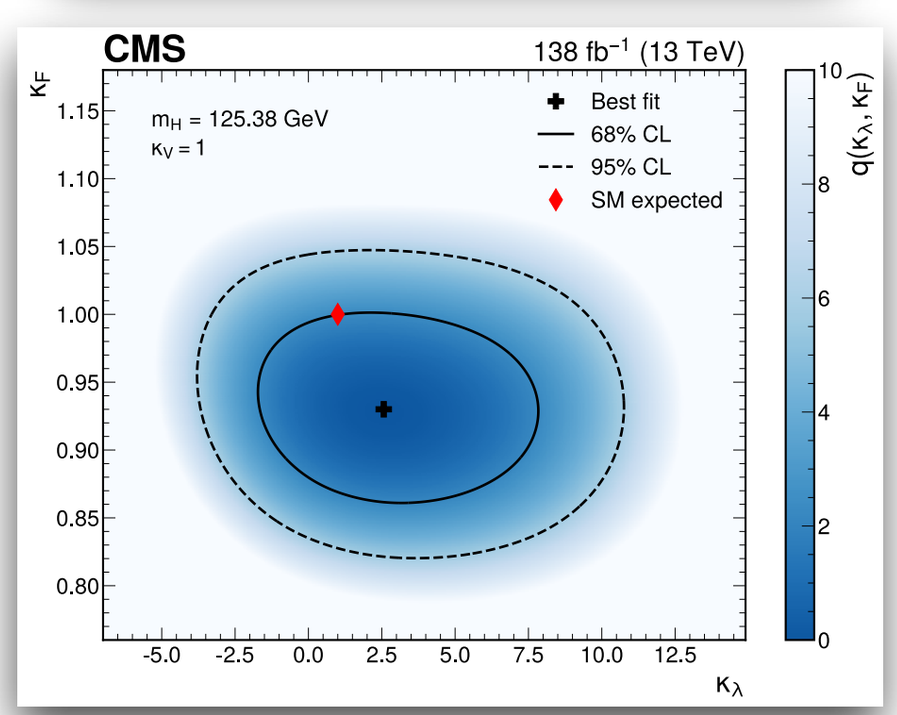




Caveat: not the latest HH and single H combinations from ATLAS

[CMS-HIG-21-018]





Caveat: SingleHiggs only results