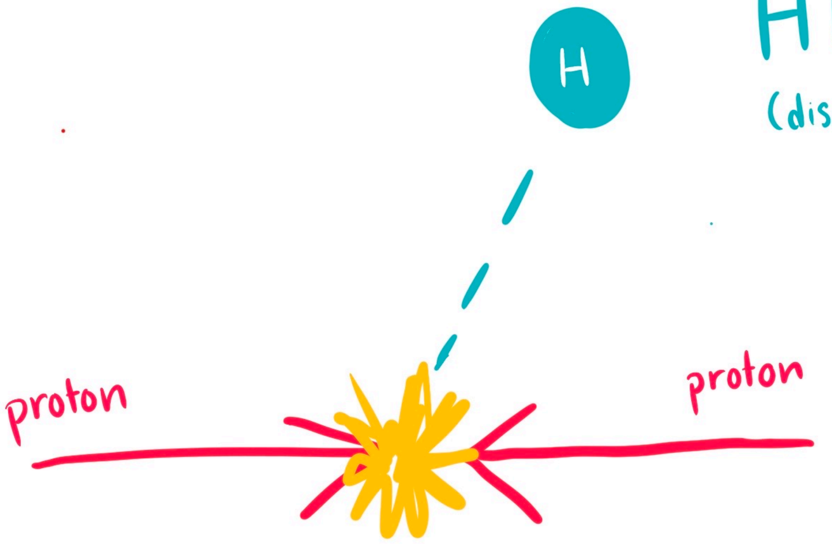
HH @ ATLAS
Latest Results

Jannicke Pearkes

SLAC FPD Seminar

31.05.2022

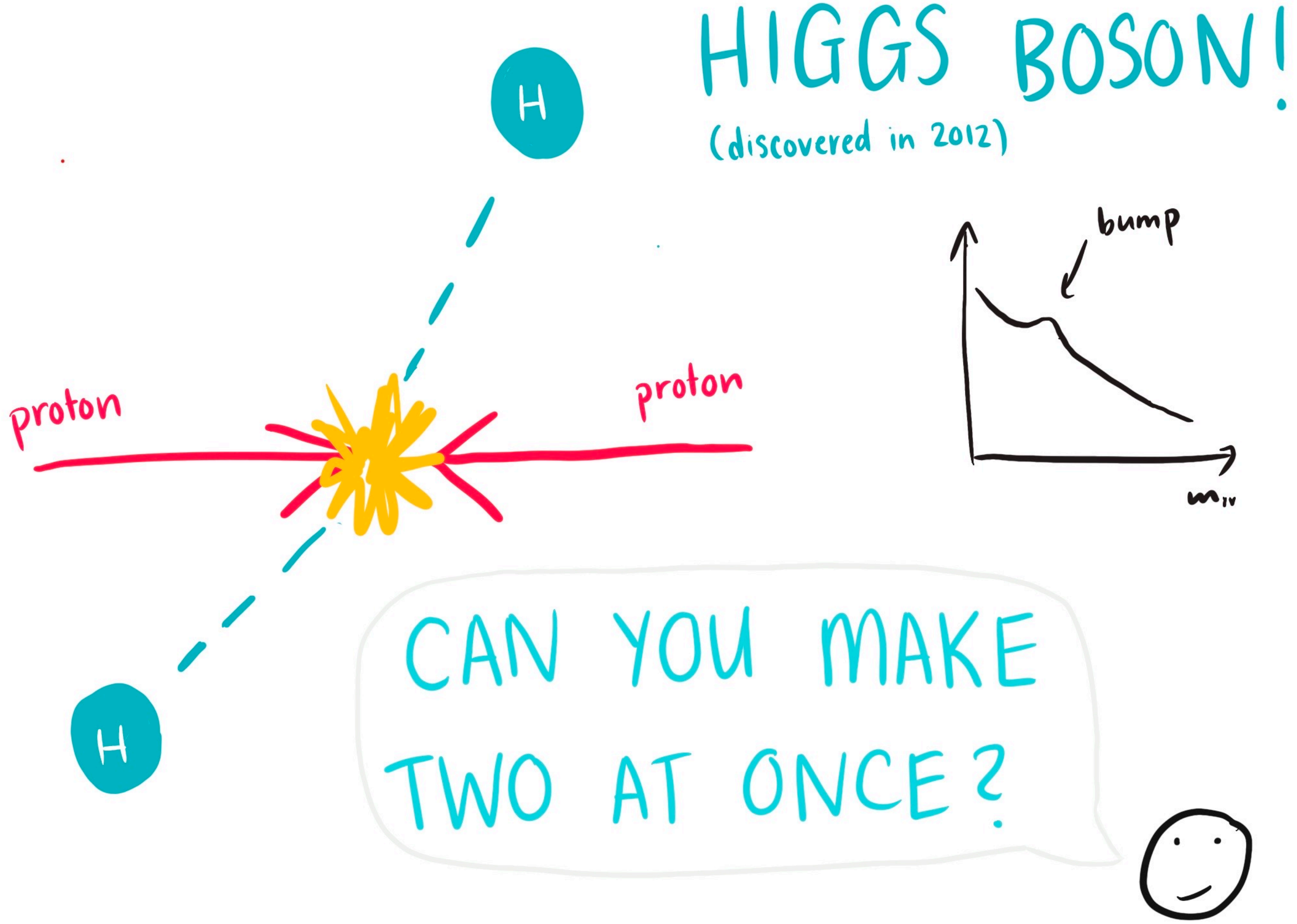
What is HH?



HIGGS BOSON!

(discovered in 2012)

What is HH?


HIGGS BOSON!
(discovered in 2012)
bump
$m_{\gamma\gamma}$
H
H
proton
proton
CAN YOU MAKE TWO AT ONCE?

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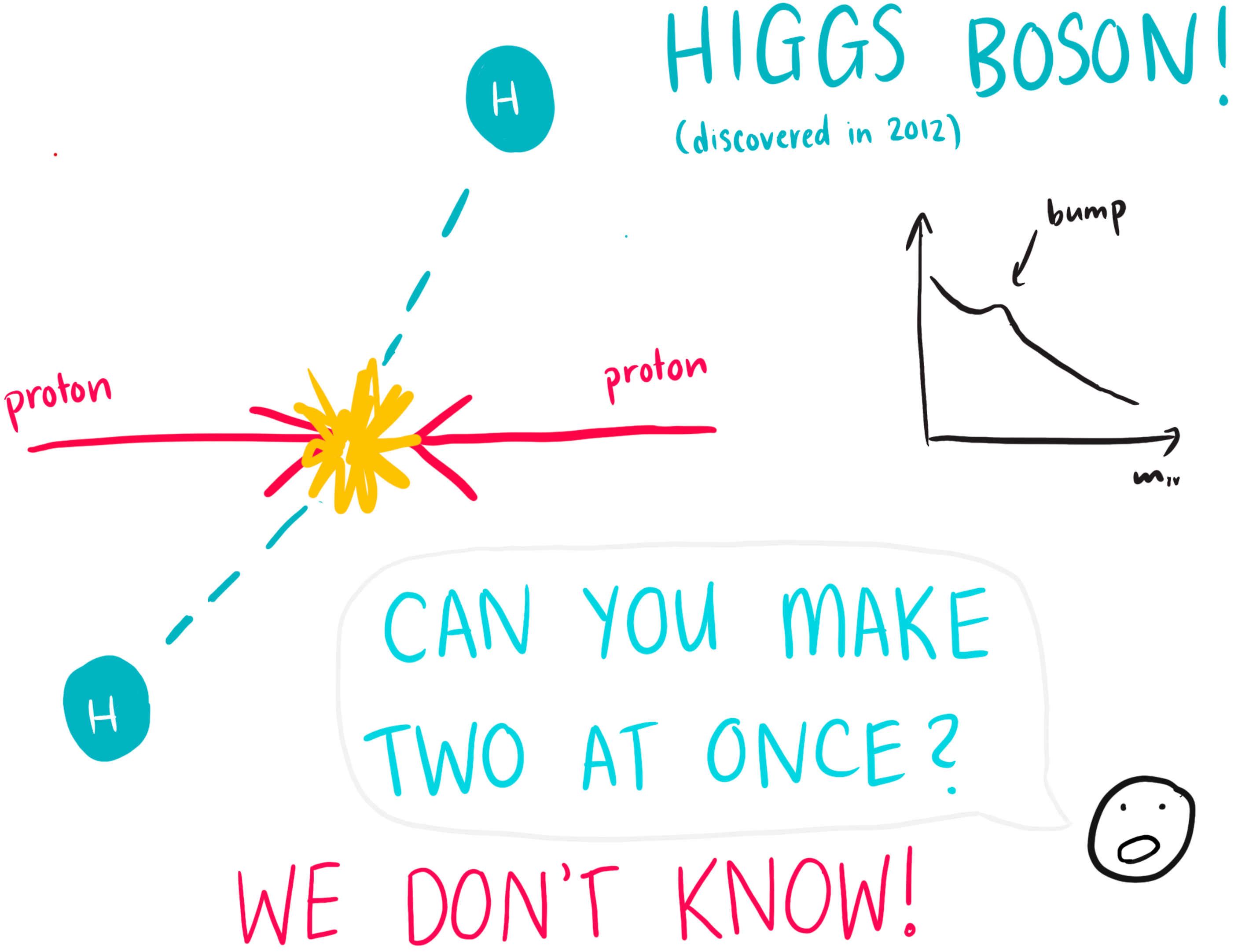
HIGGS BOSON!
(discovered in 2012)
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proton
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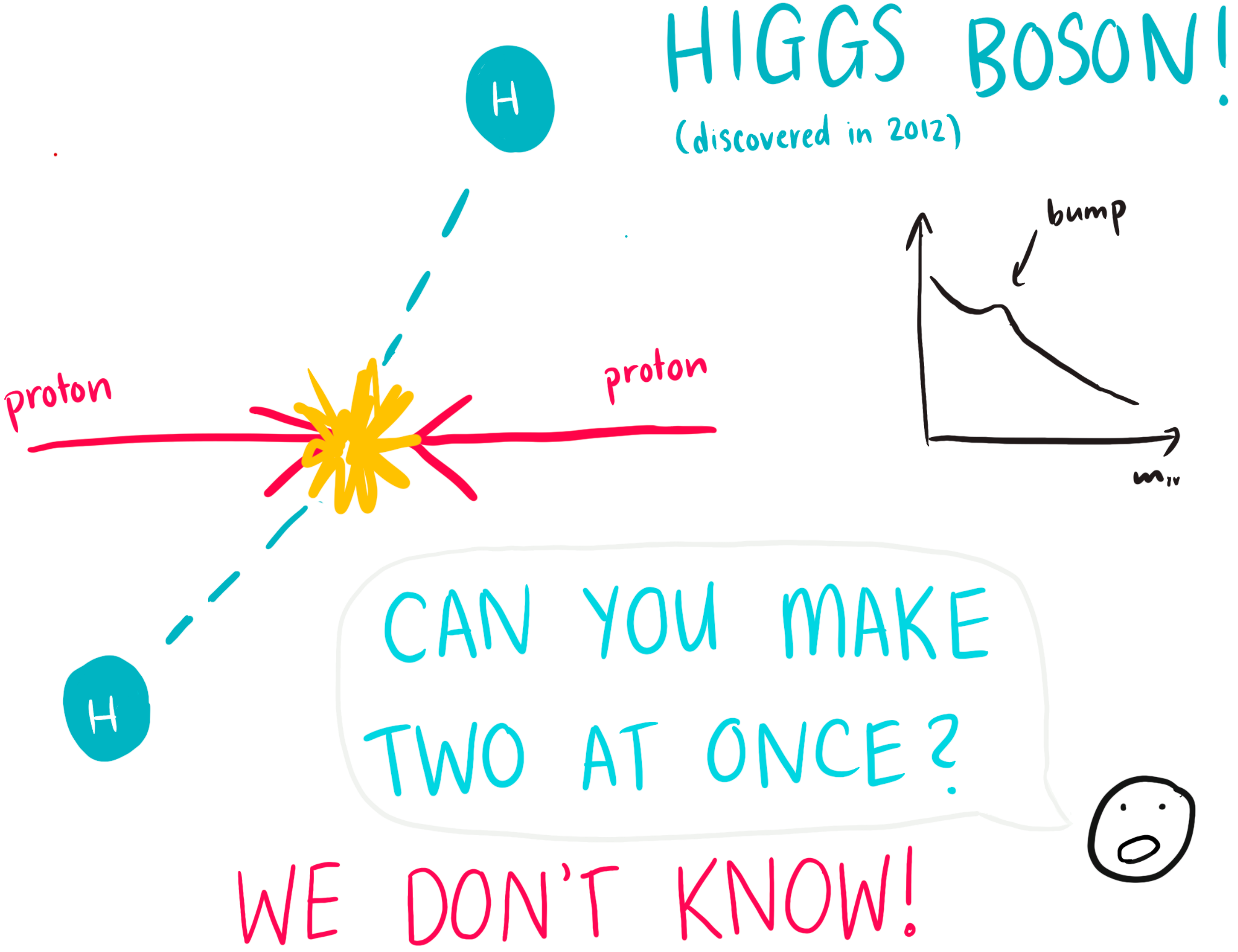
H
CAN YOU MAKE TWO AT ONCE?
WE DON'T KNOW!

What is HH?

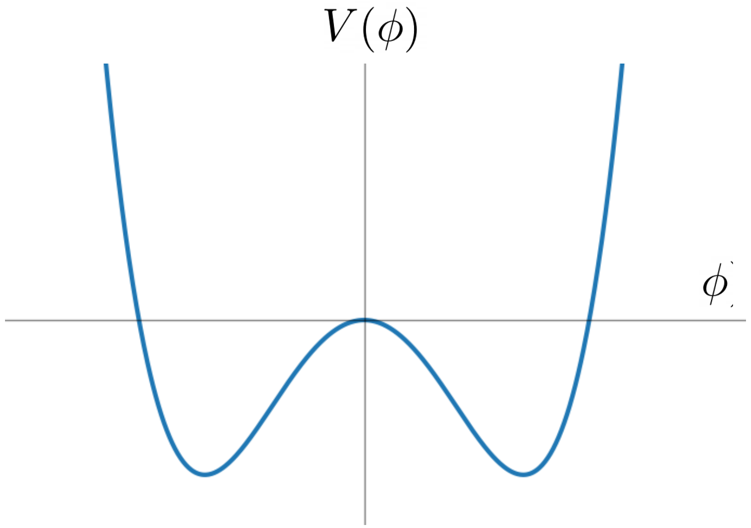


Today:
- Why?
- How?
- When?

The Higgs Potential

The Standard Model Higgs Potential is:

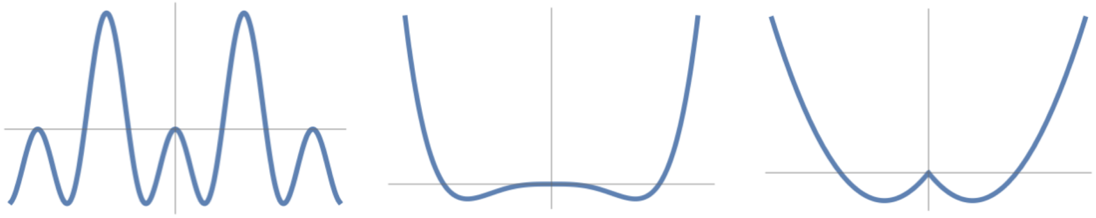
$$V(\phi) = -\underset{\substack{\uparrow \\ \text{mass term}}}{\mu^2}\phi^2 + \underset{\substack{\uparrow \\ \text{self-coupling term}}}{\lambda}\phi^4$$



In the SM the shape of the potential is well constrained by the Higgs boson mass and vacuum expectation value.

$$\lambda = \frac{m_h^2}{2\nu^2} = 0.129$$

New physics could alter the shape of the potential.



Phys. Rev. D 101, 075023 (2020)

Connection with the Early Universe

Exact nature of electro-weak phase transition is unknown.

- If first order, could be the source of baryogenesis and show up as O(1)modifications to the Higgs self-coupling.
  (Noble, Perelstein, arXiv:0711.3018)

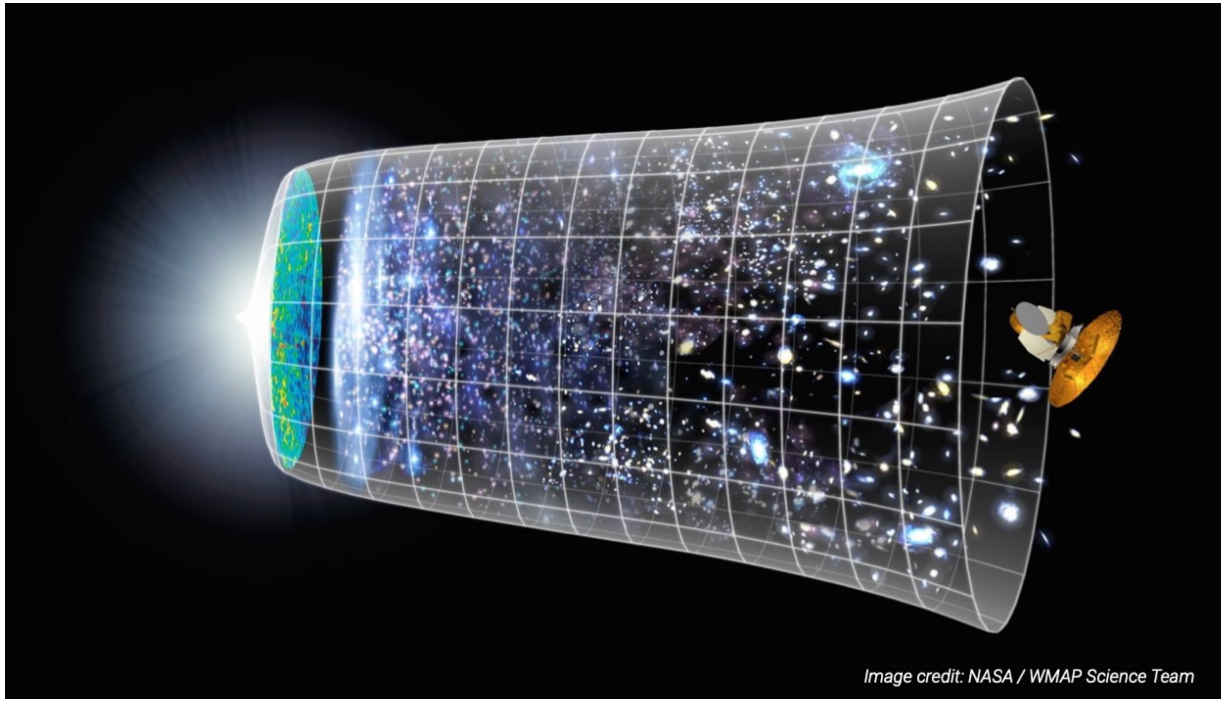
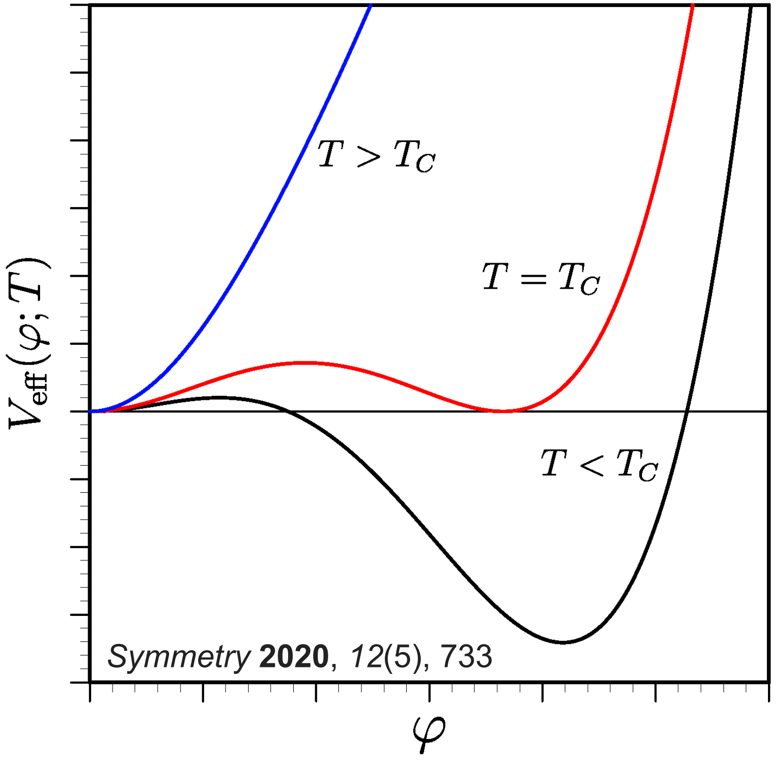
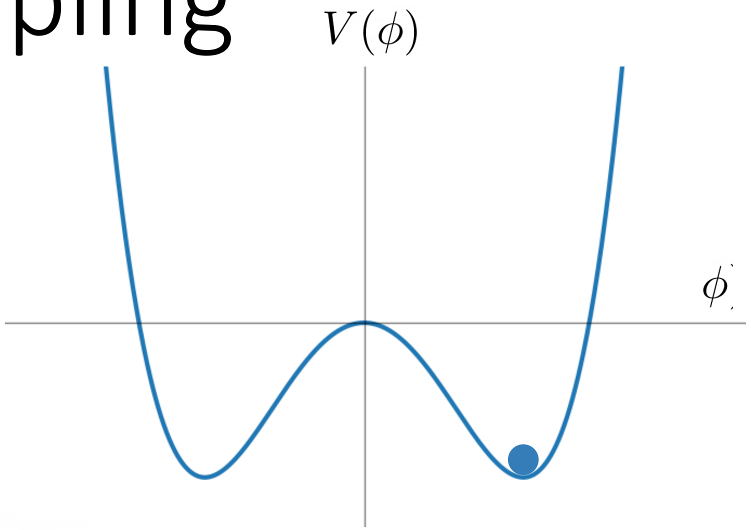


Image credit: NASA / WMAP Science Team



Symmetry **2020**, *12*(5), 733

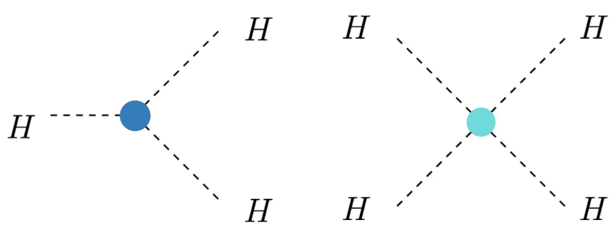
Testing the Higgs self-coupling



$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

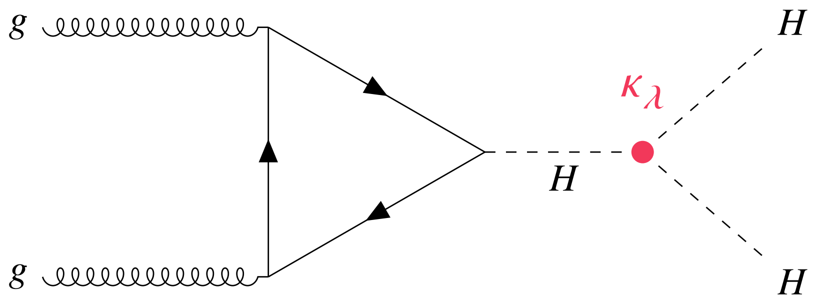
Perturb by h about minimum ν

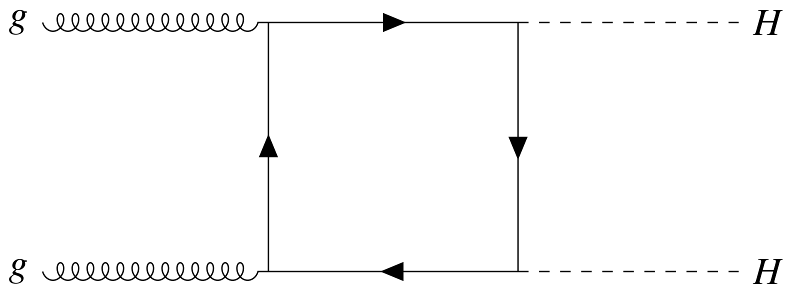
$$V(\nu + h) = -\mu^2(\nu + h)^2 + \lambda(\nu + h)^4$$
$$= V_0 + \frac{1}{2}{m_h}^2h^2 + \lambda v h^3 + \lambda h^4 + \ldots$$

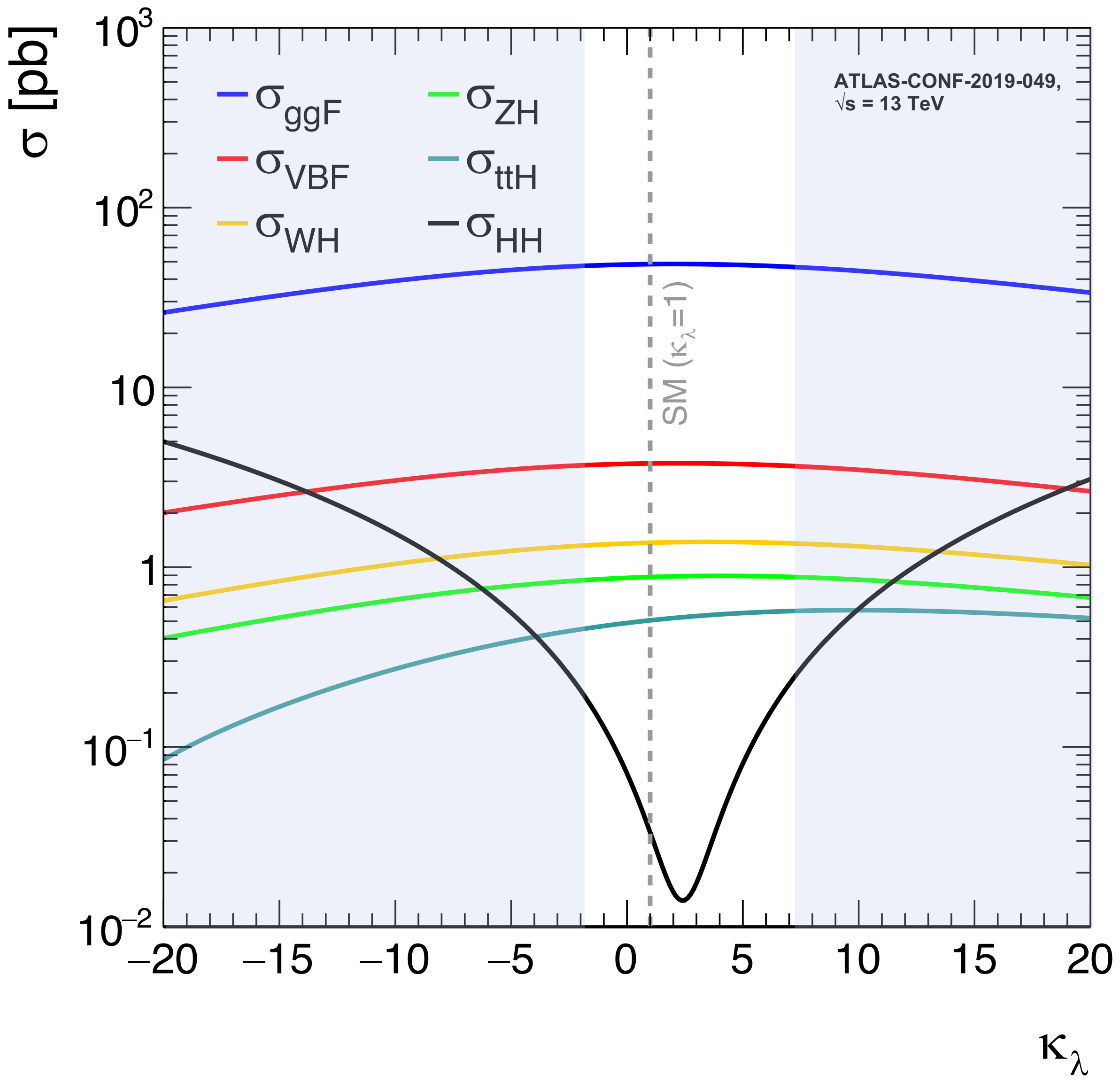


Measuring κ_λ

Direct measurement (HH):







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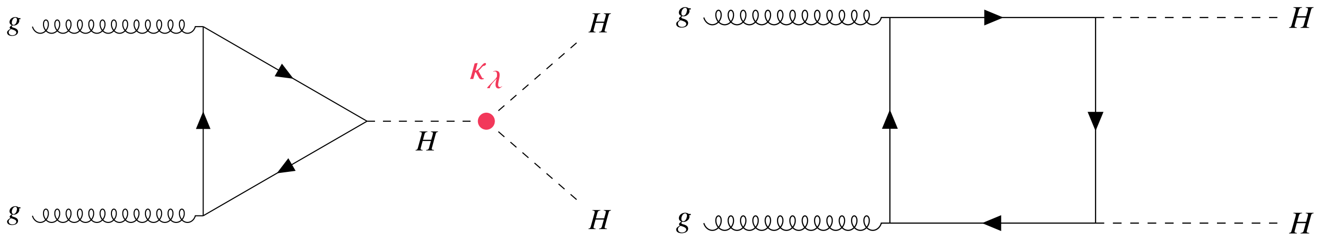
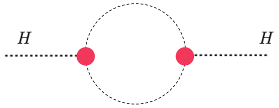
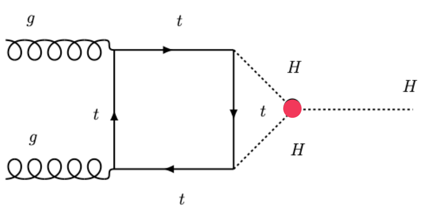
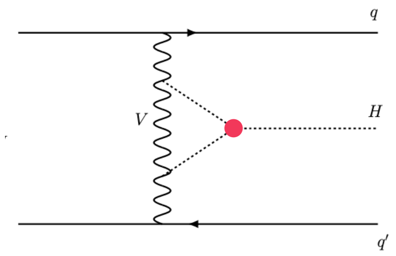
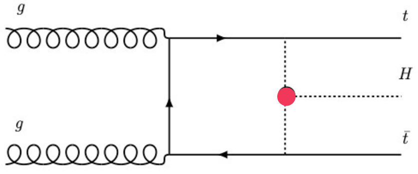


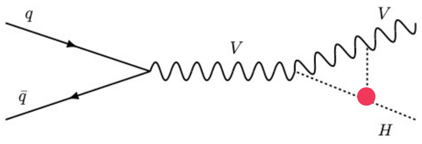
Indirect measurement (single H):

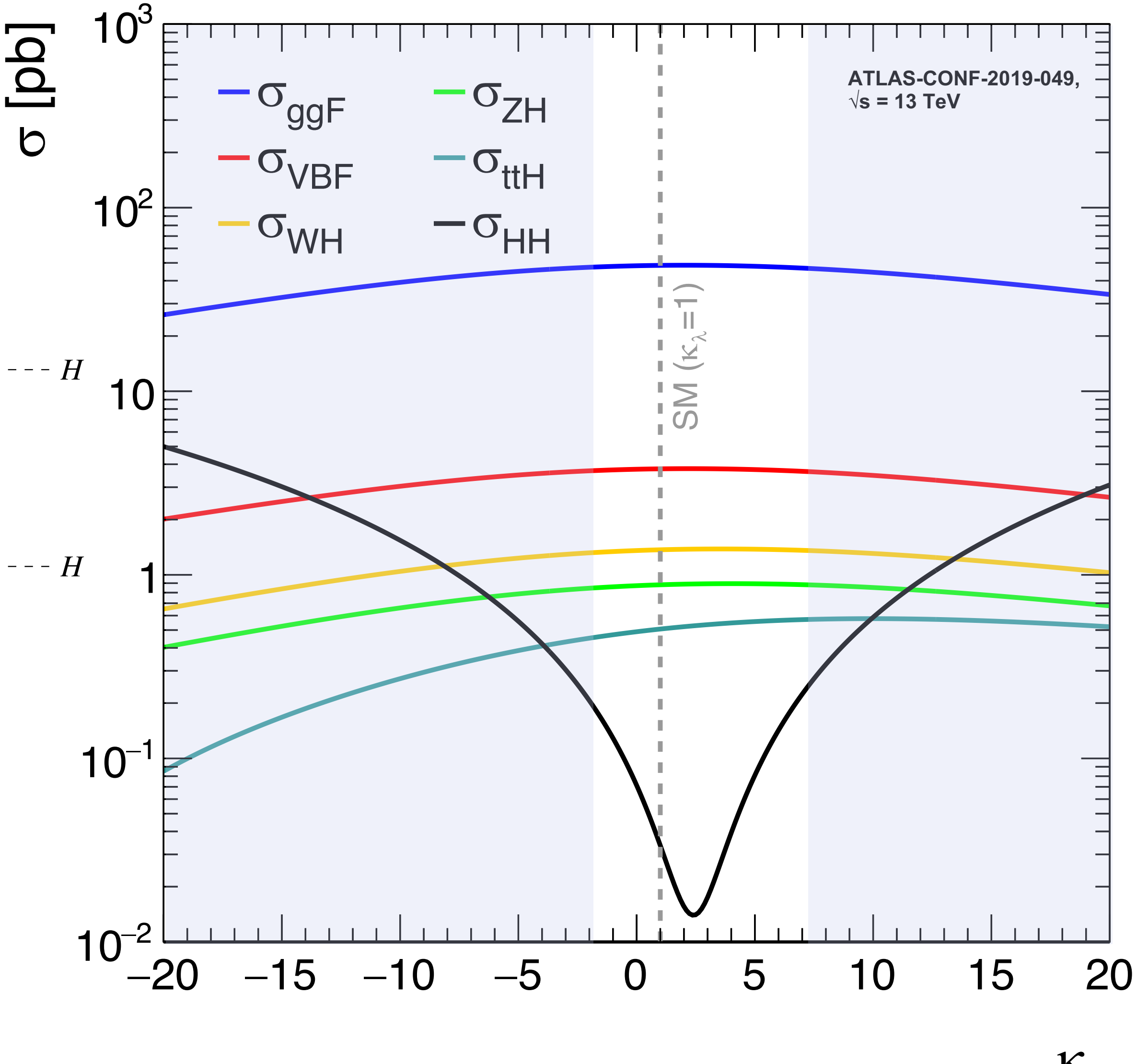












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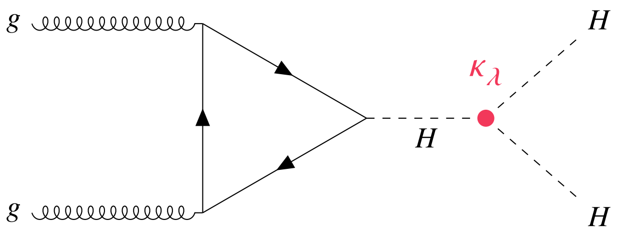

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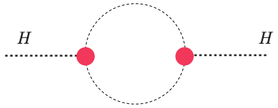
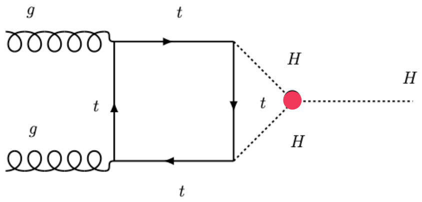
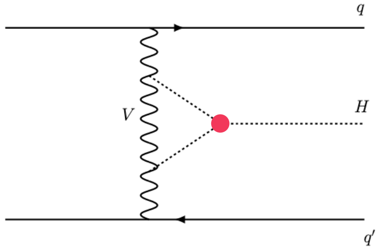
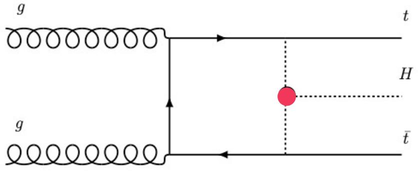
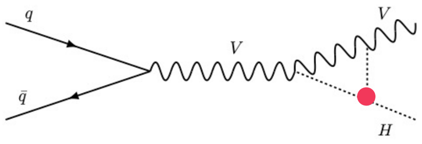
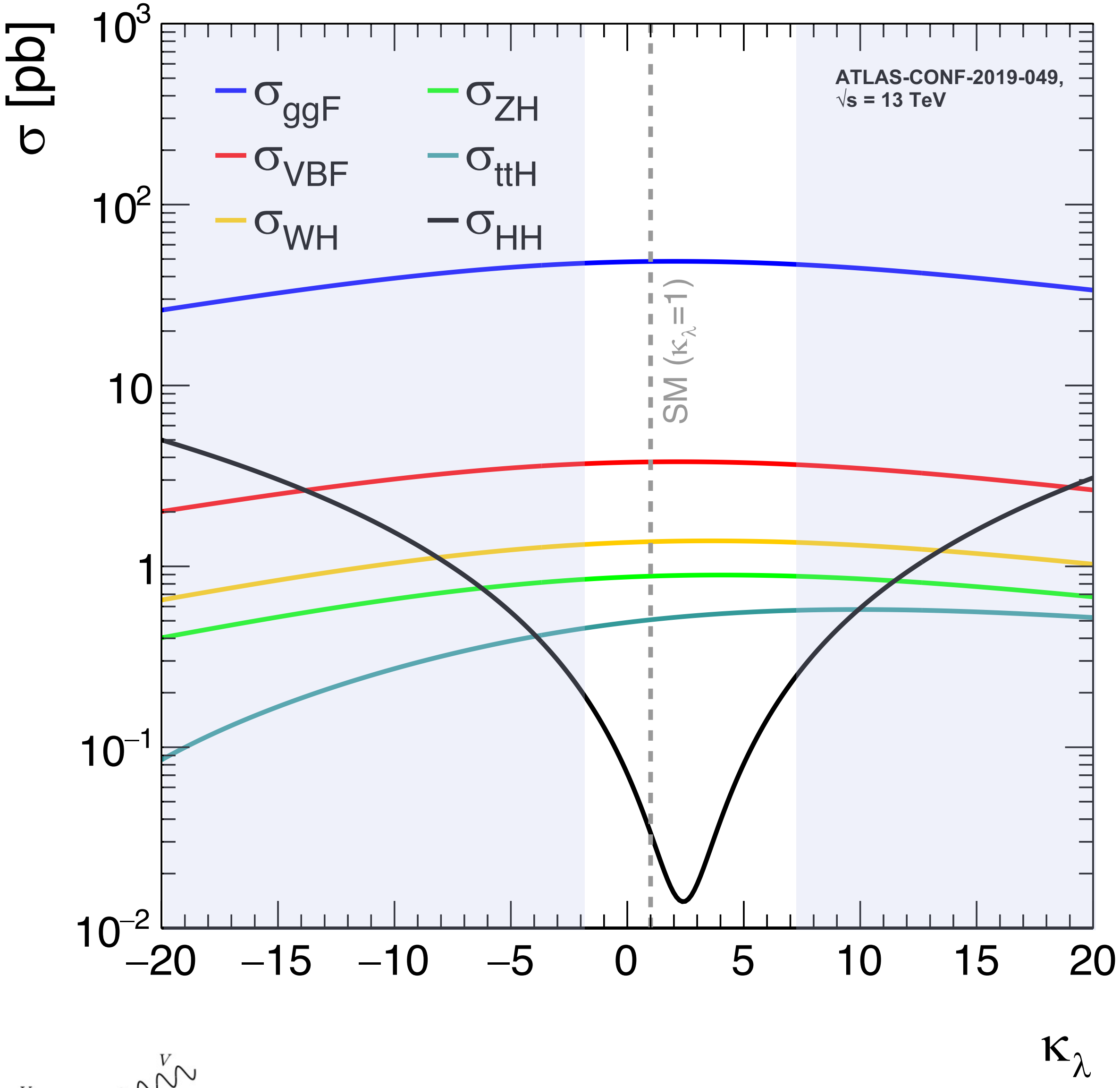






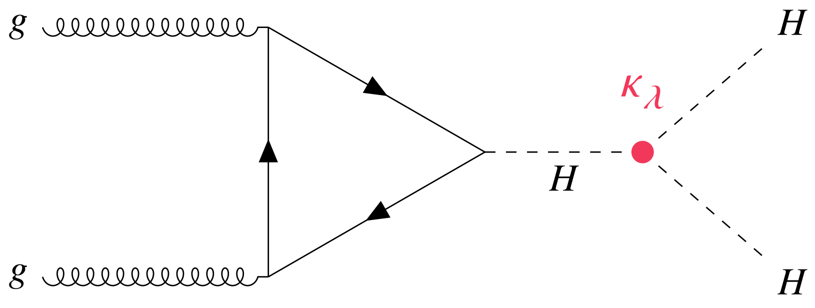


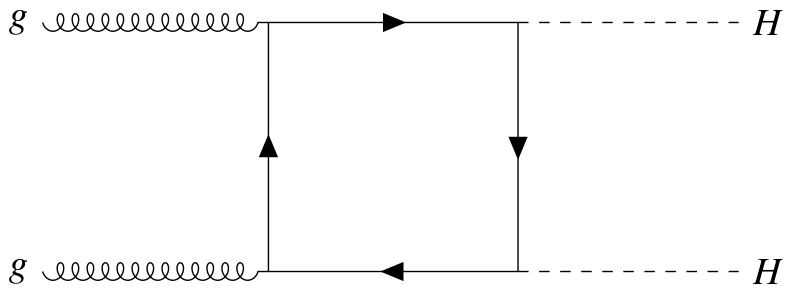


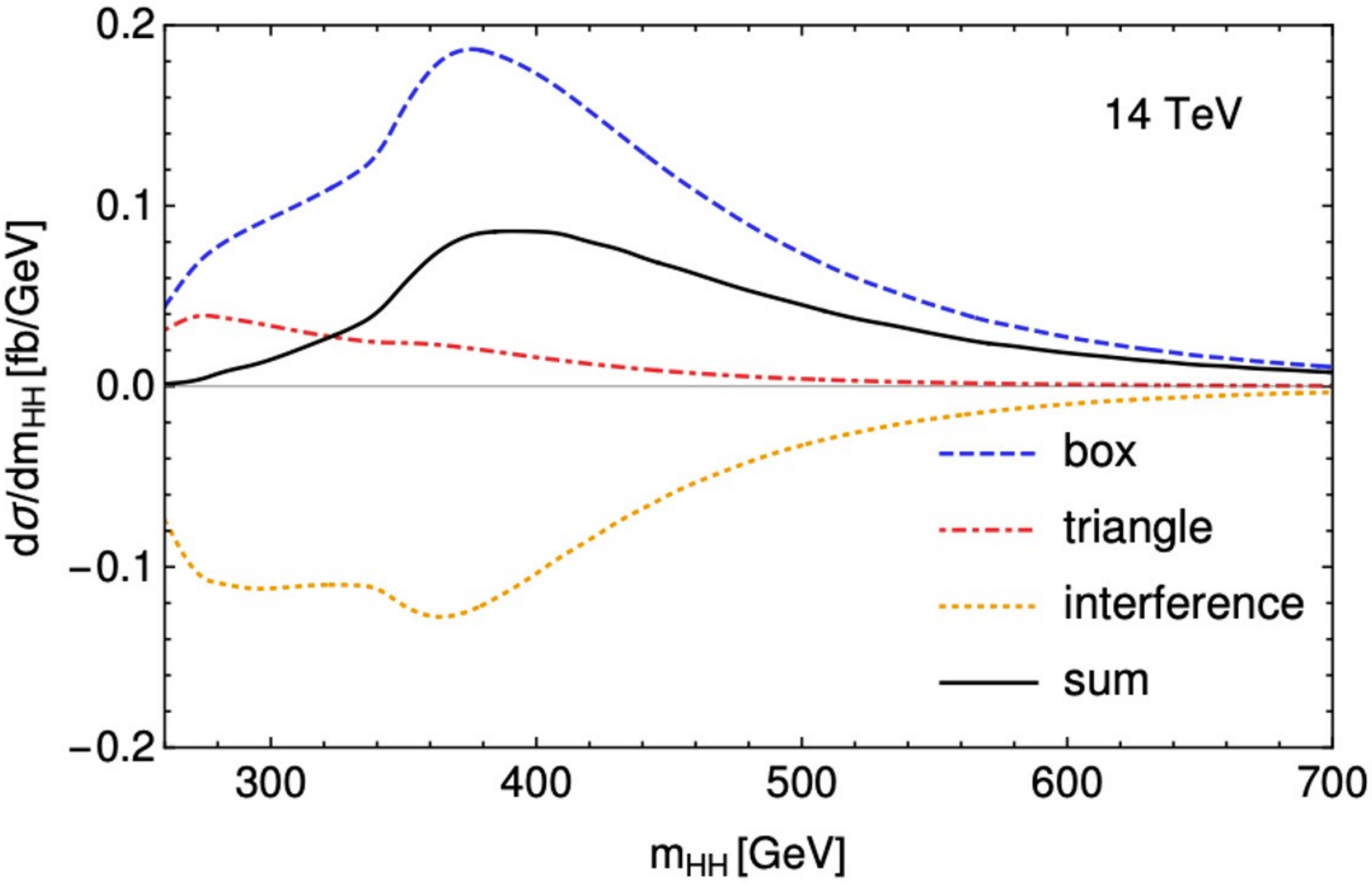


In Run 2 we expect ~4000 HH events compared to 8 million single Higgs events!

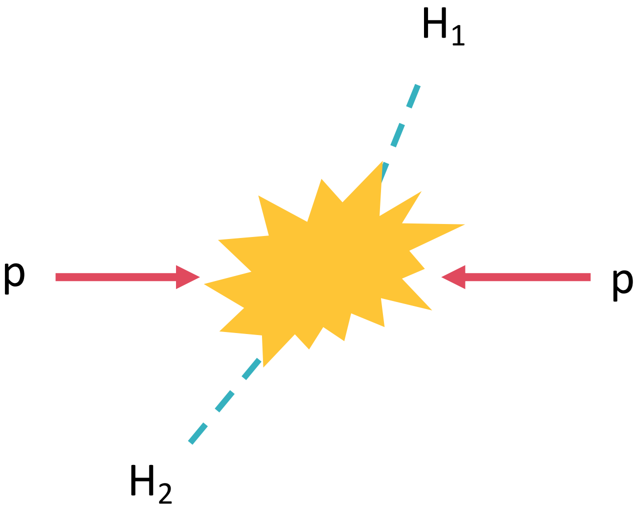
Interference Between Box and Triangle Diagrams

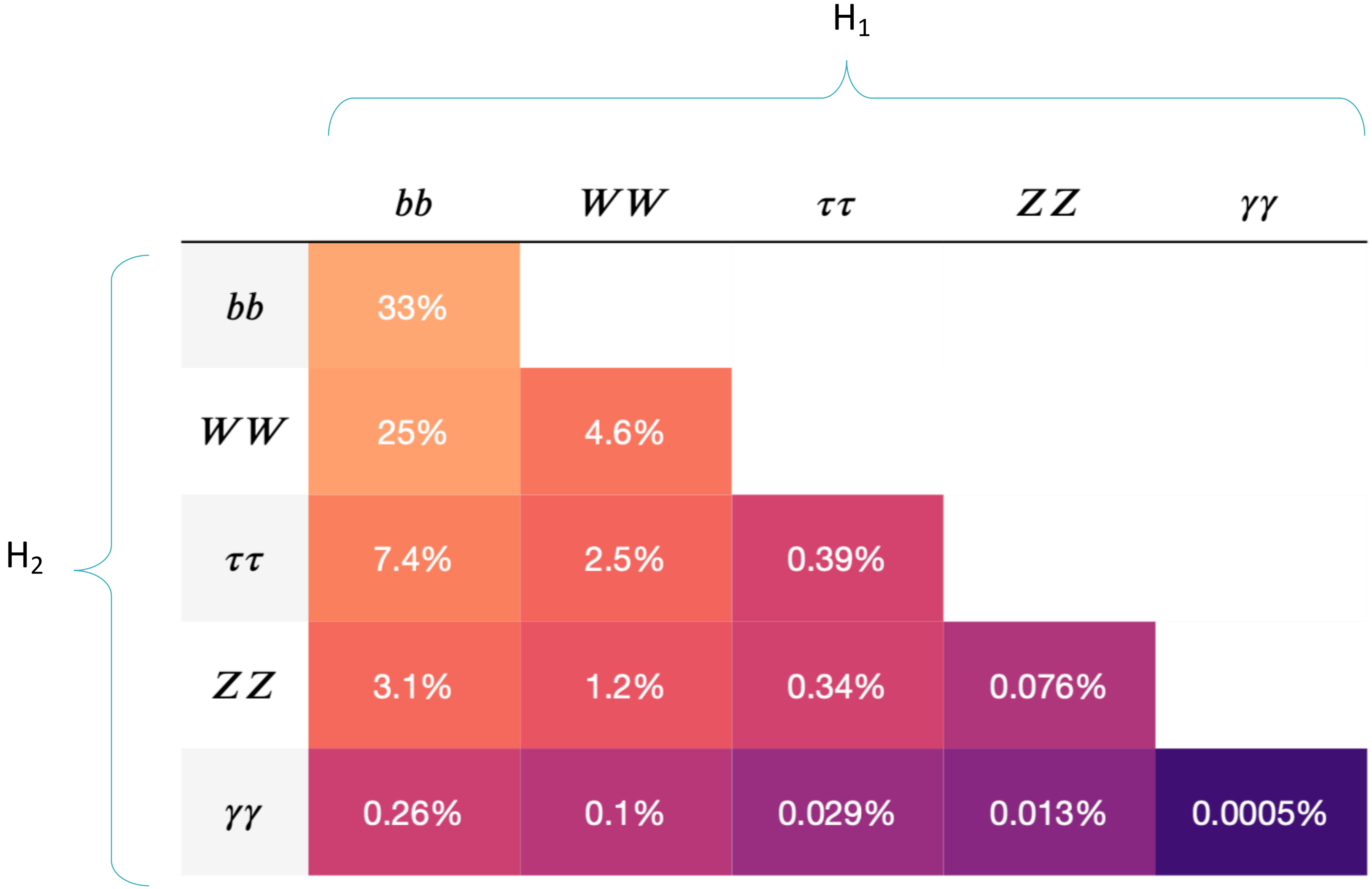






HH Decay Channels





	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%	0.1%	0.029%	0.013%	0.0005%

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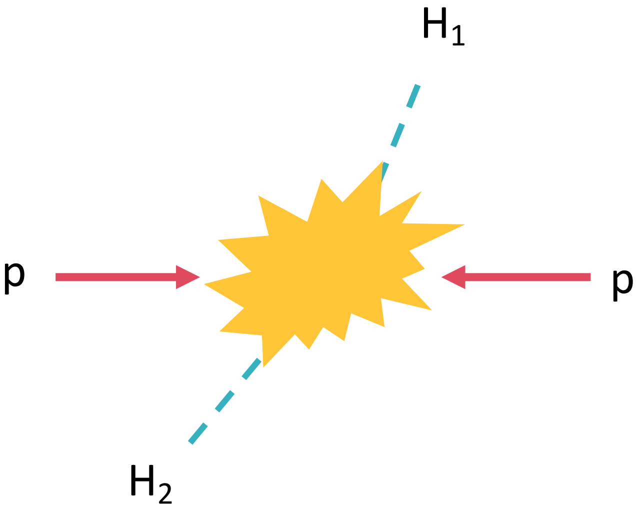

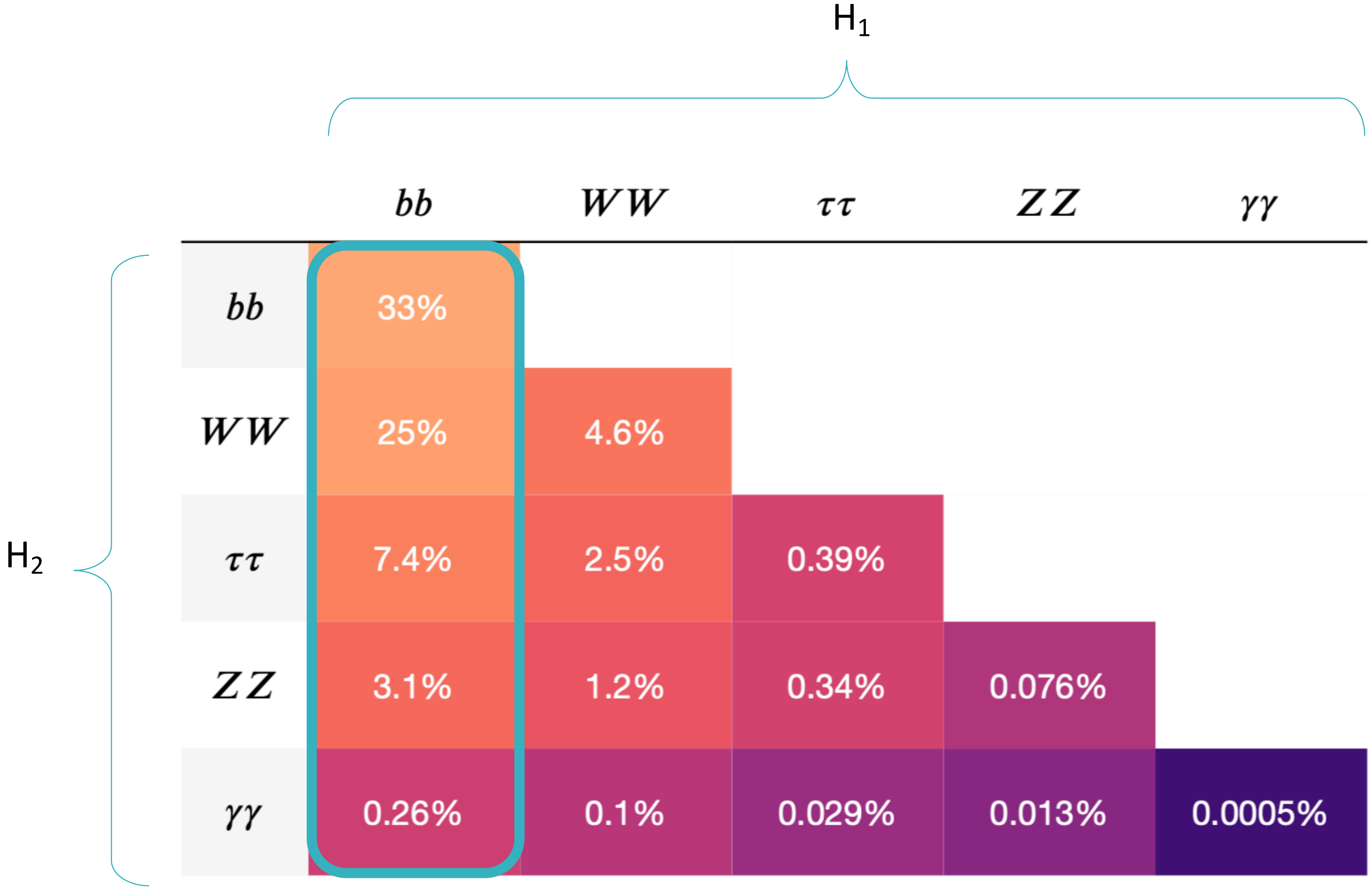

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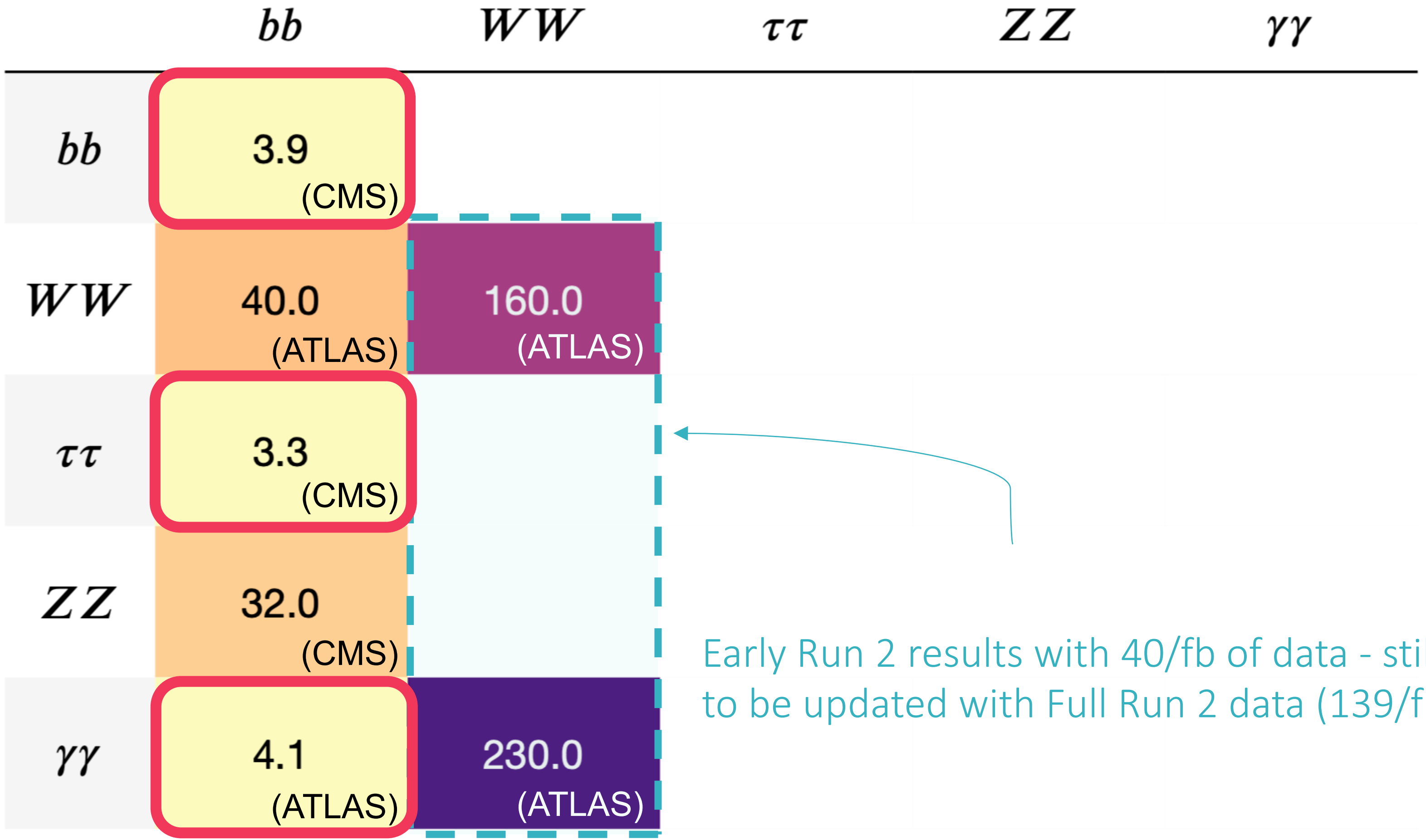
Leading Standard Model HH Limits

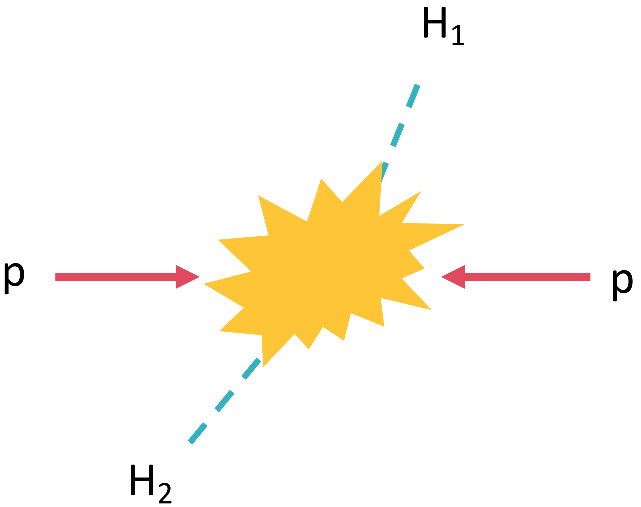
The three most competitive channels, bbbb, bbττ & bb$\gamma\gamma$ have wildly varying branching ratios, but are complementary to each other.

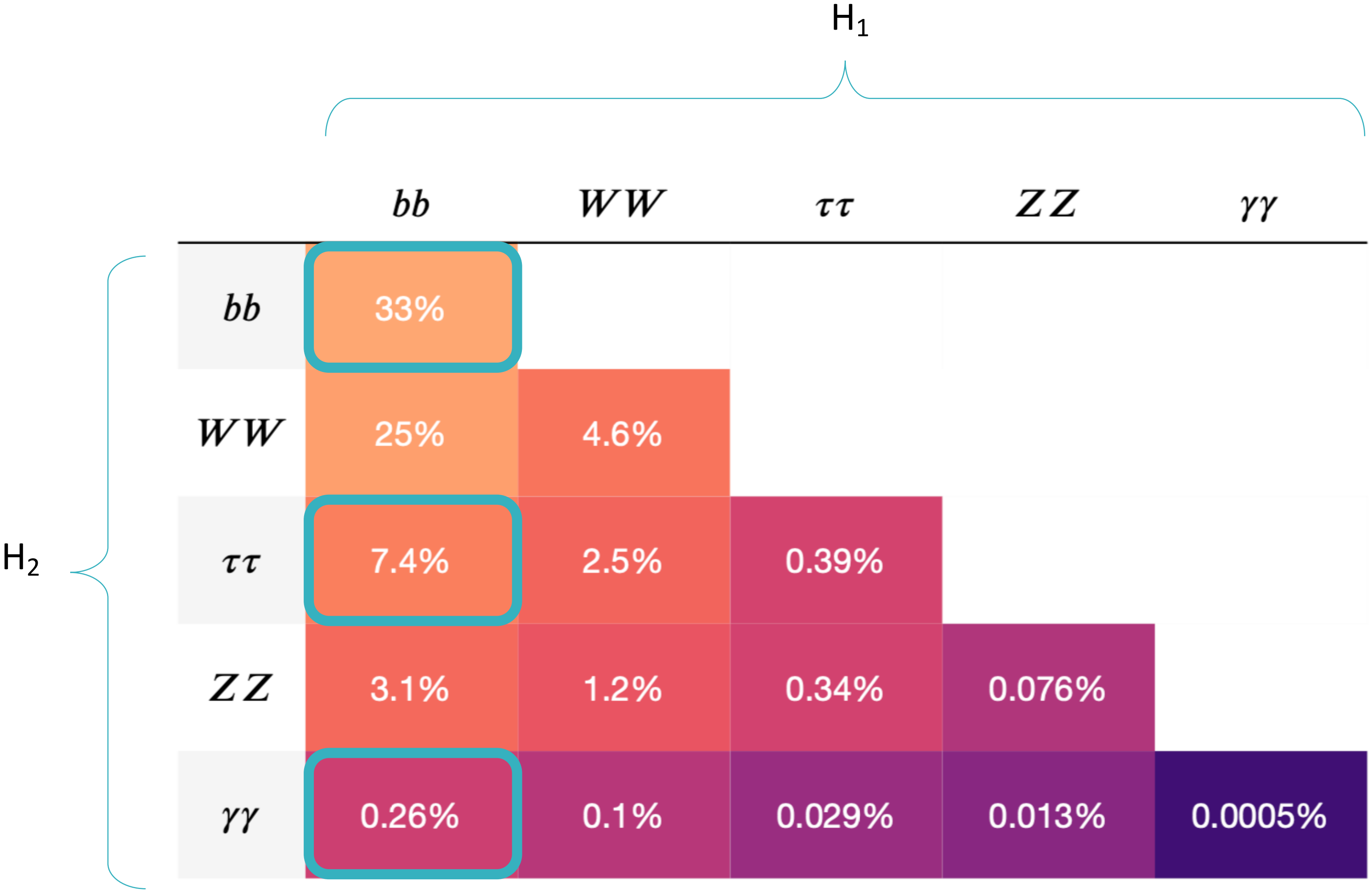


	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	3.9 (CMS)				
WW	40.0 (ATLAS)	160.0 (ATLAS)			
$\tau\tau$	3.3 (CMS)				
ZZ	32.0 (CMS)				
$\gamma\gamma$	4.1 (ATLAS)	230.0 (ATLAS)			

Early Run 2 results with 40/fb of data - still to be updated with Full Run 2 data (139/fb)

HH Decay Channels





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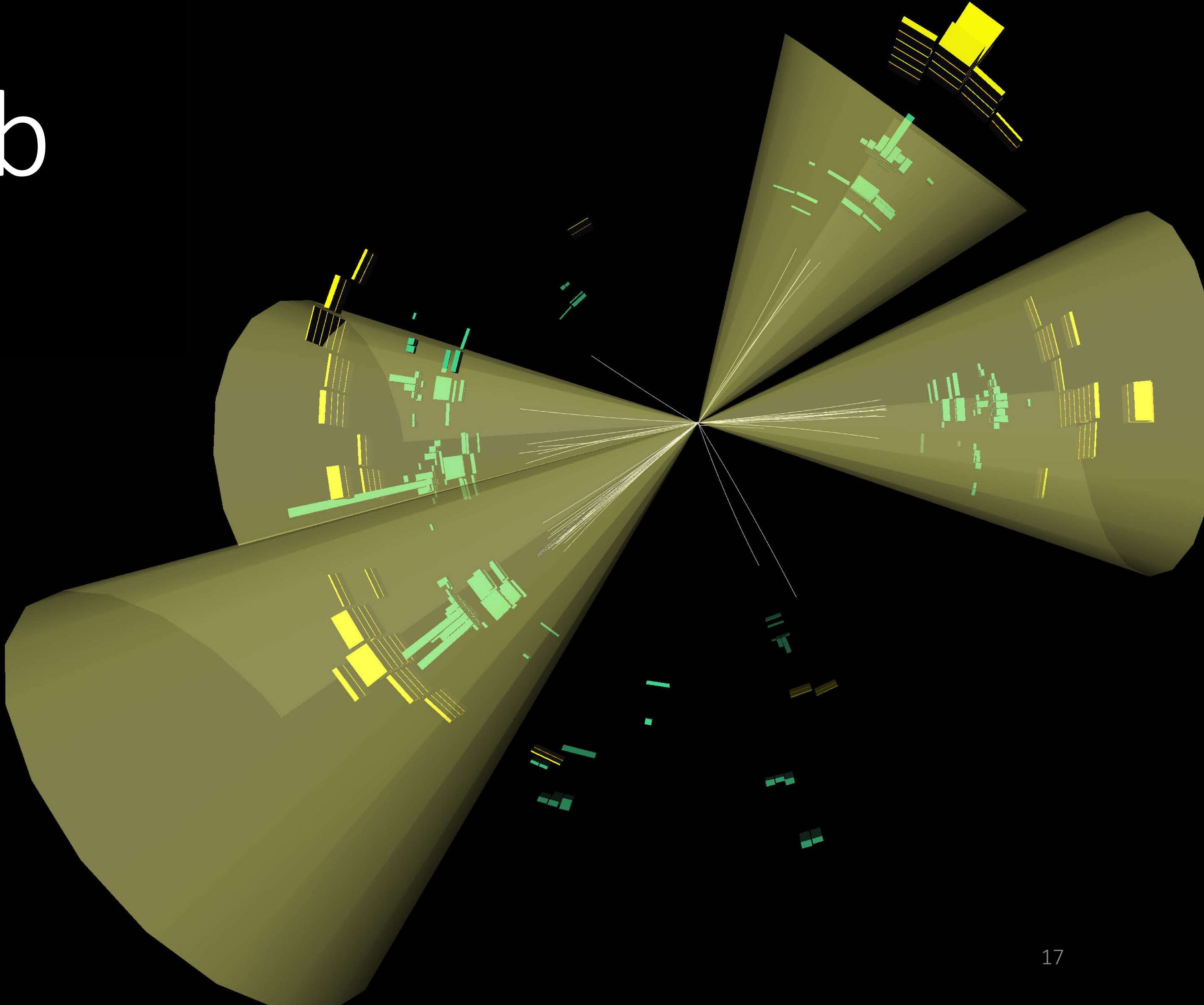
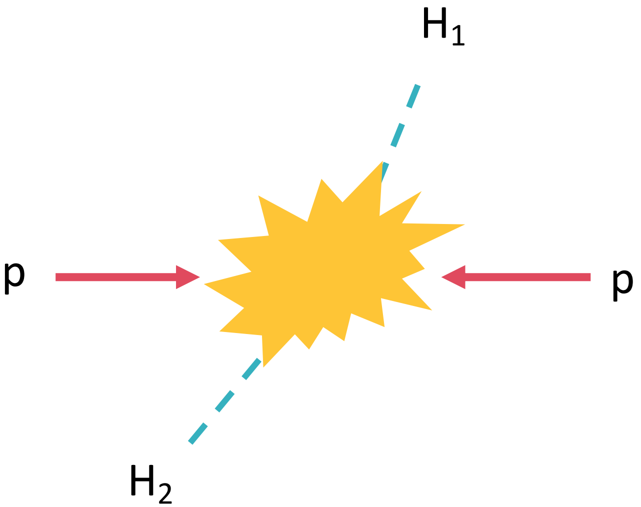
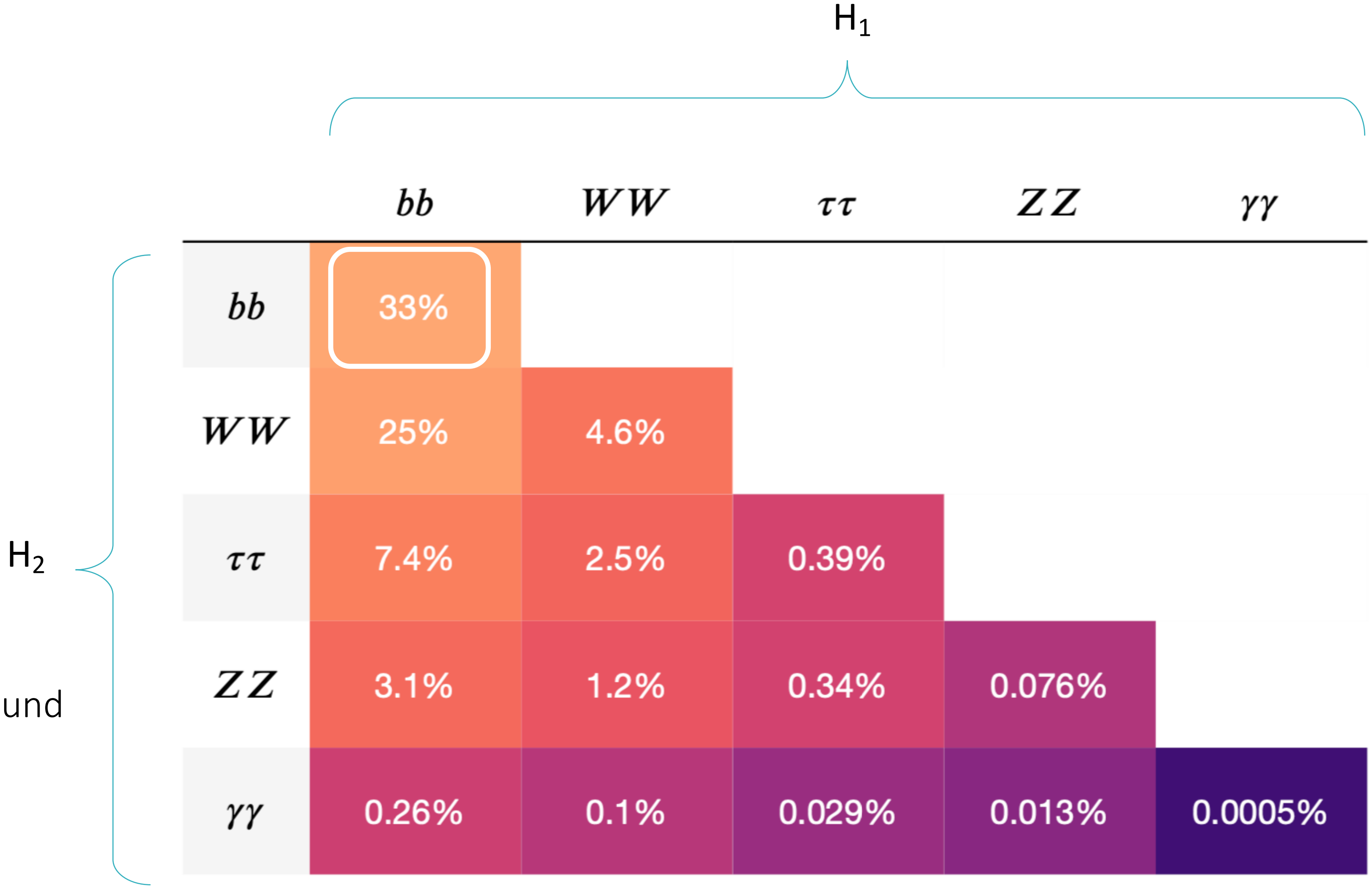
HH→bbbb



HH 4b



- Large branching ratio
- Challenging QCD multi-jet background



H_1

H_2

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
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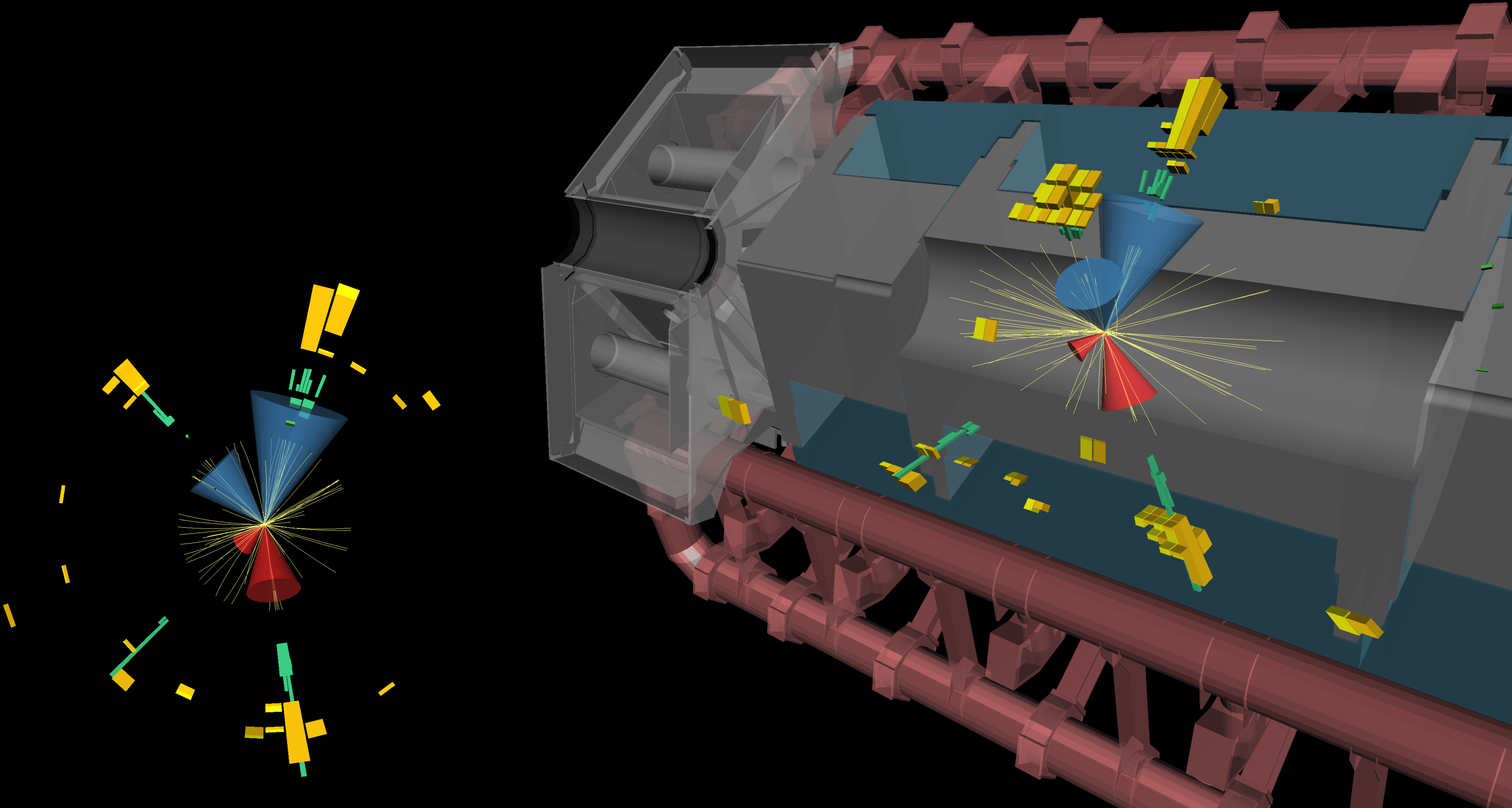
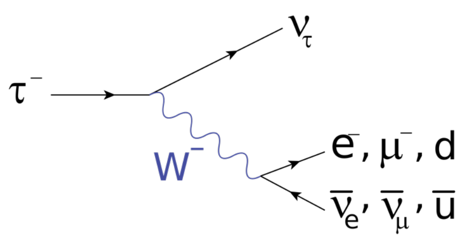
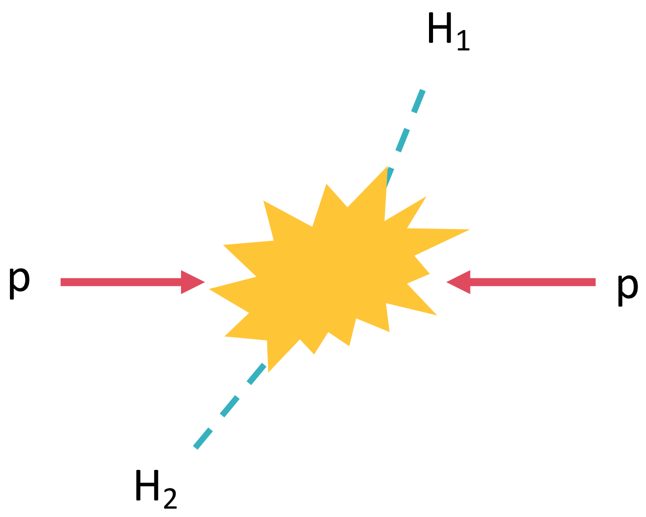
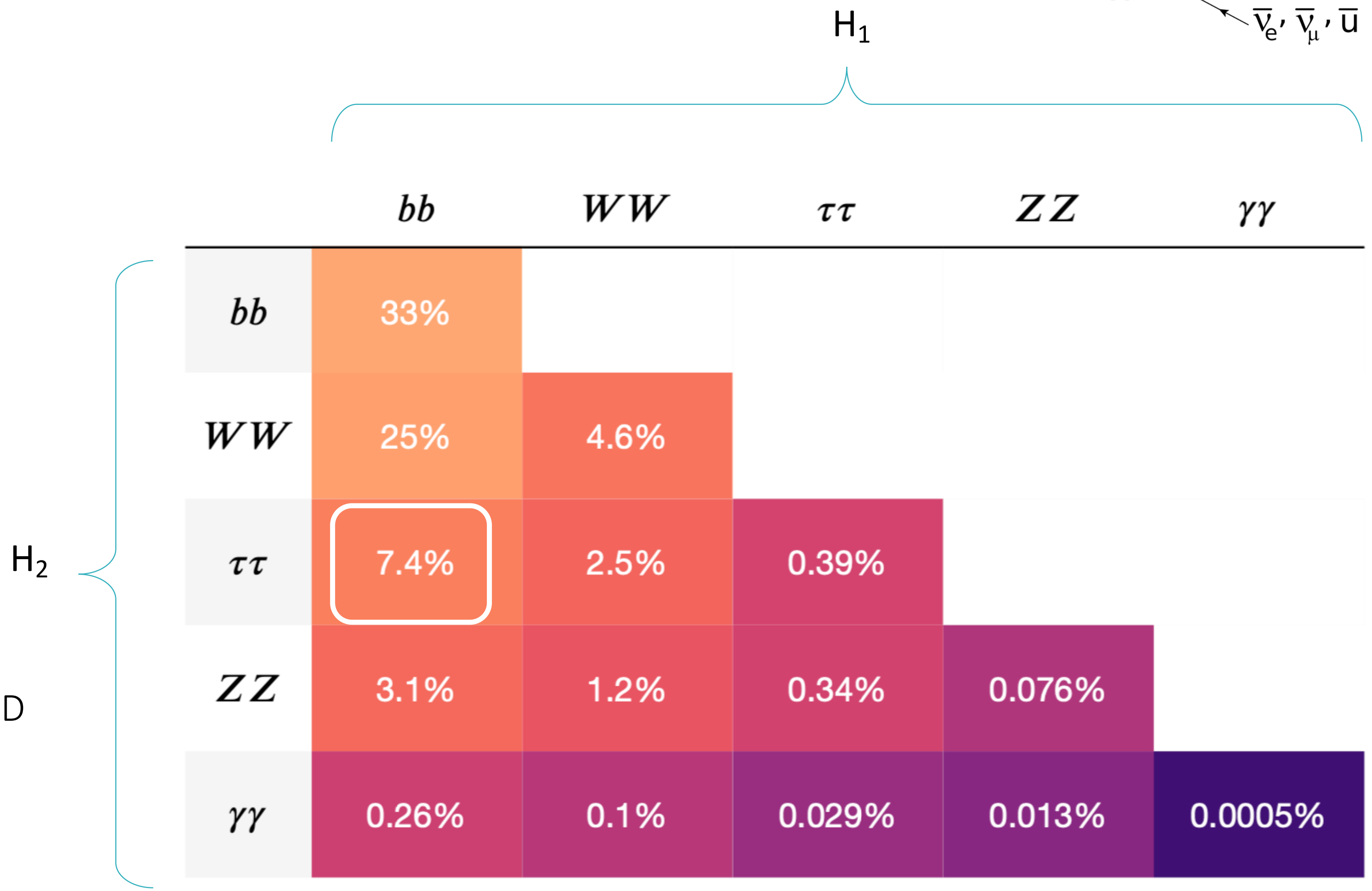
HH→bbττ



HH Decay Channels







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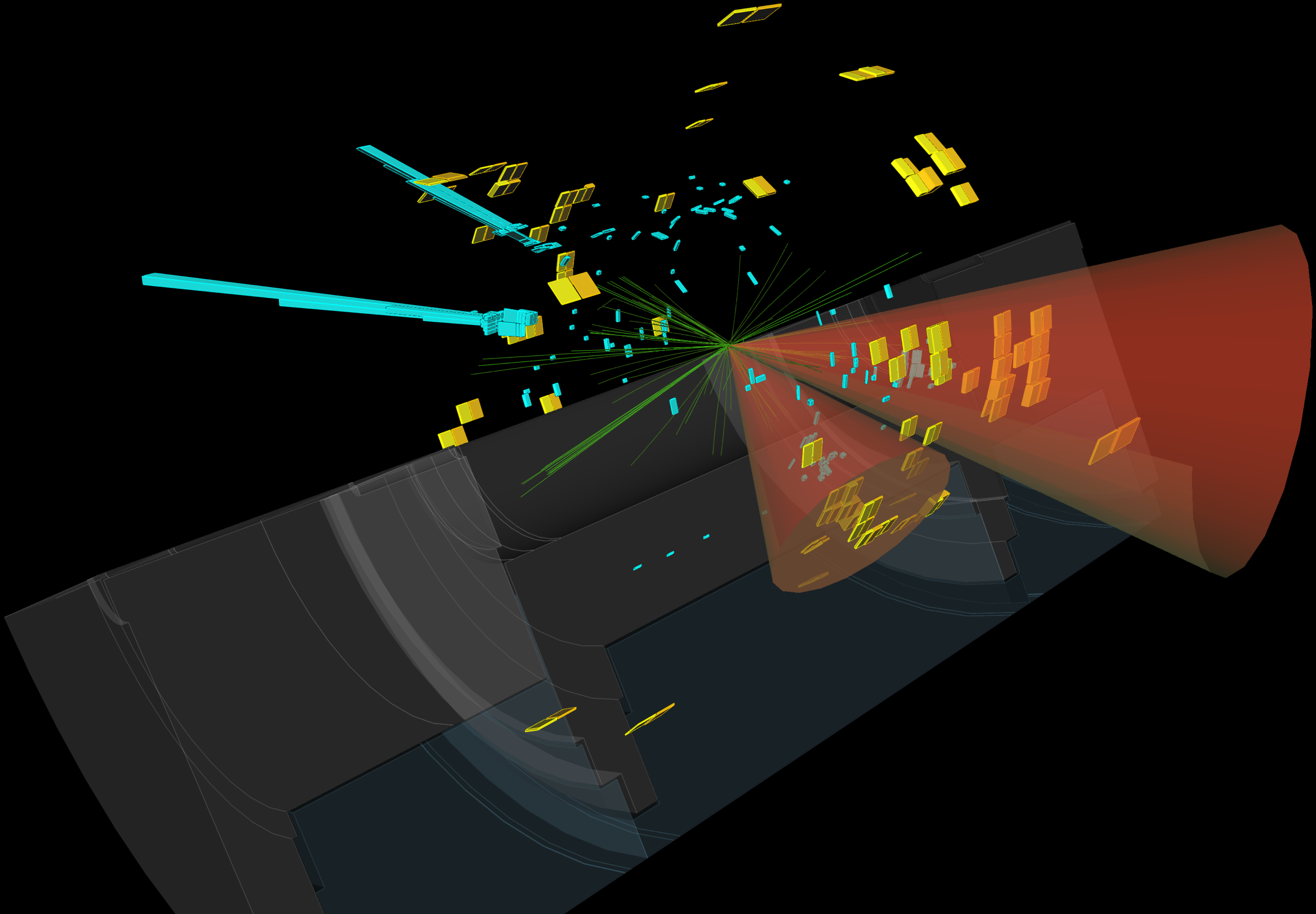
- Medium branching ratio
- Taus effective against rejecting QCD multi-jet background
- Challenging electro-weak and top backgrounds



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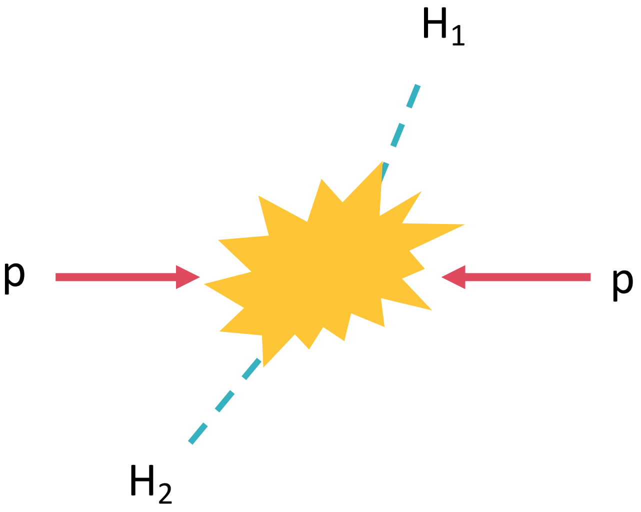

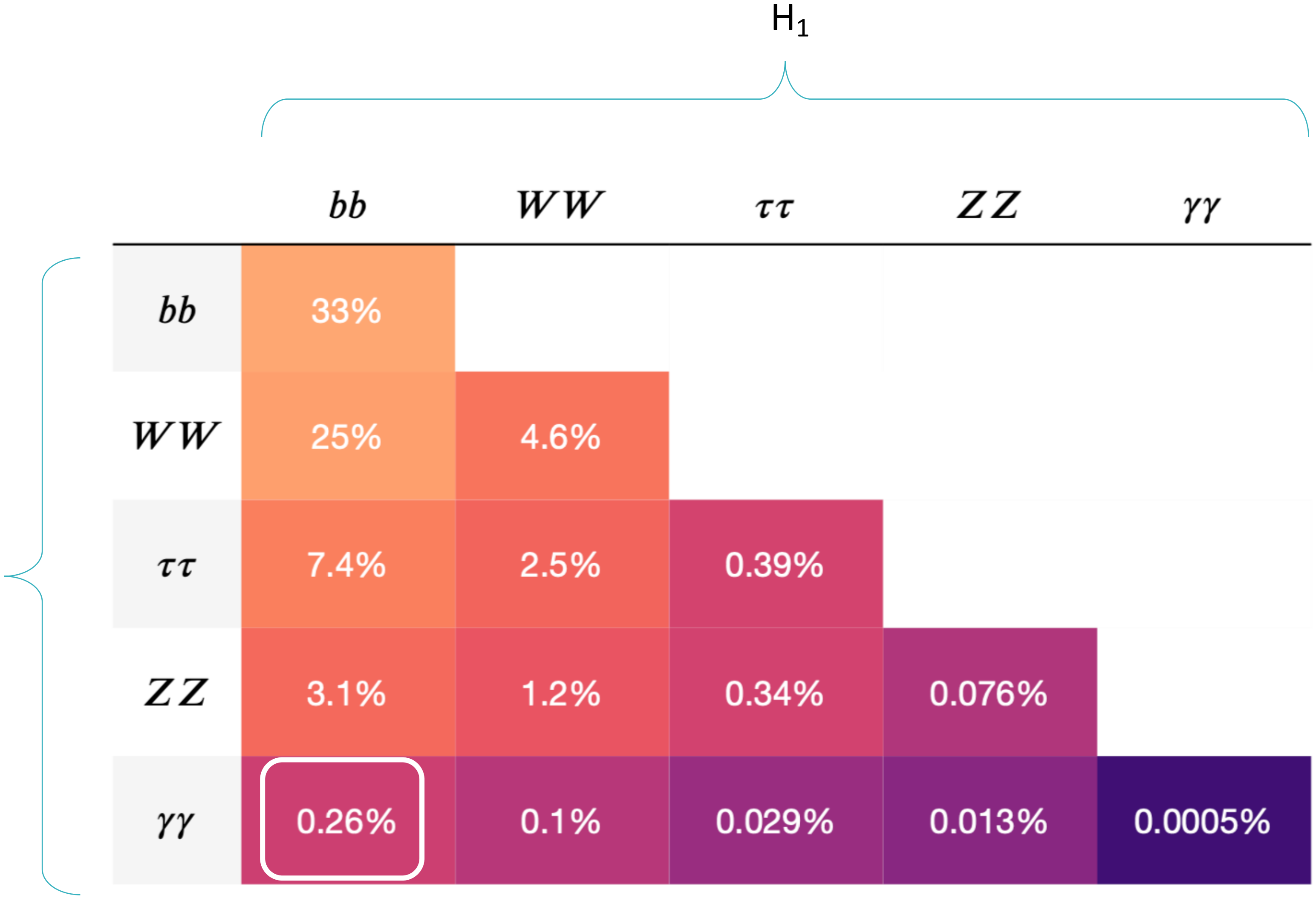

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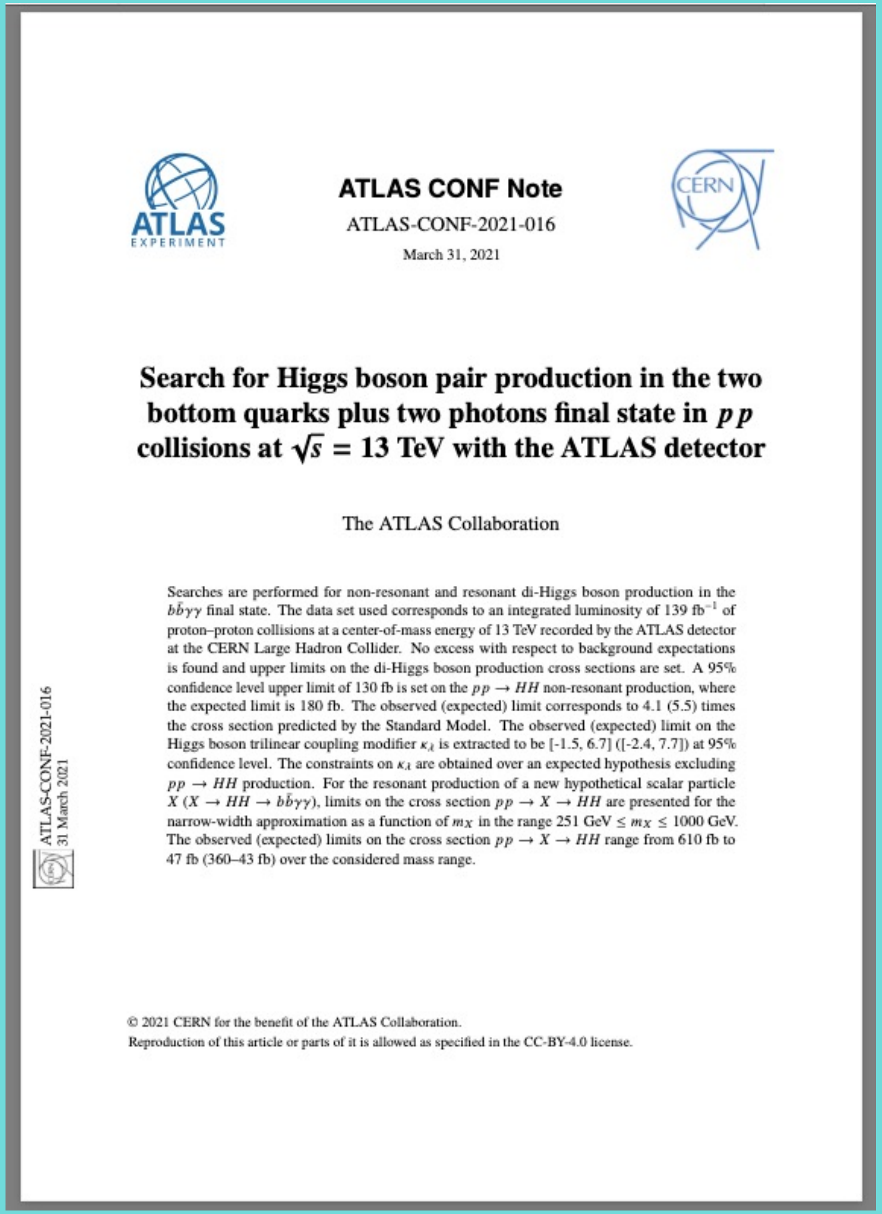
- Tiny branching ratio
- Excellent di-photon mass resolution
- Di-photon system provides excellent background rejection
- ~10 events in all of Run 2 😱

HH to bb$\gamma\gamma$ Search



ATLAS CONF Note
ATLAS-CONF-2021-016
March 31, 2021

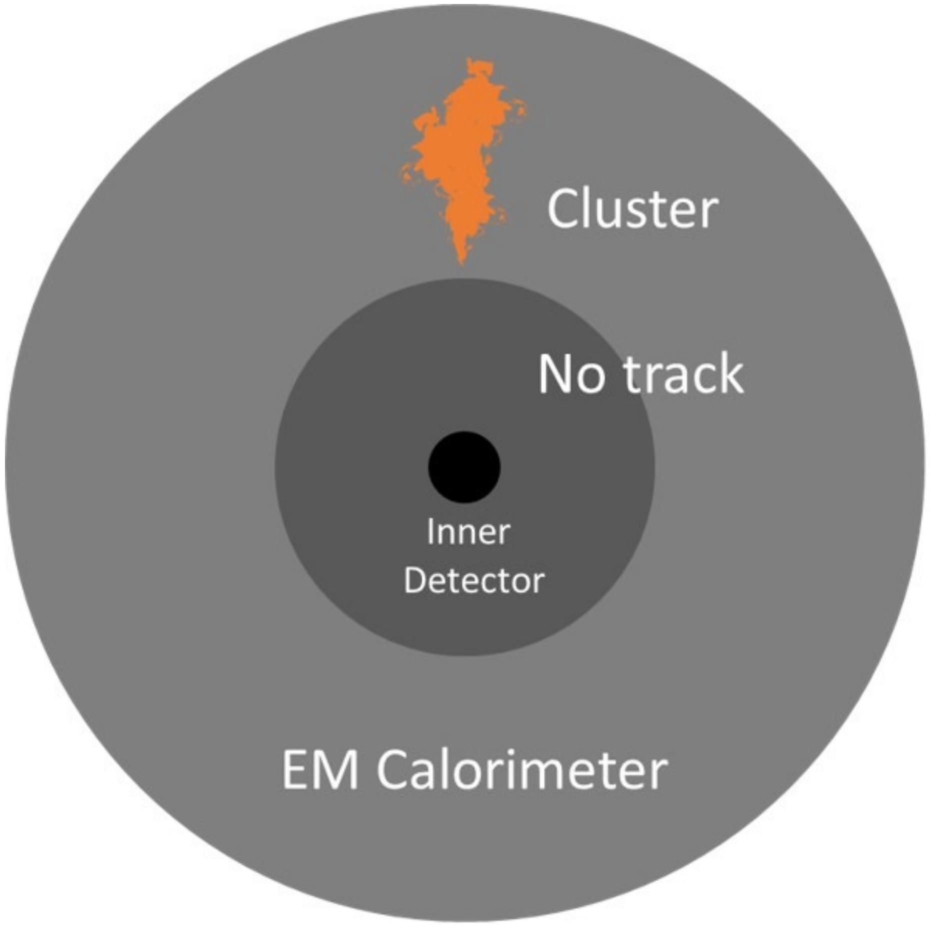
ATLAS-CONF-2021-016
31 March 2021

Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

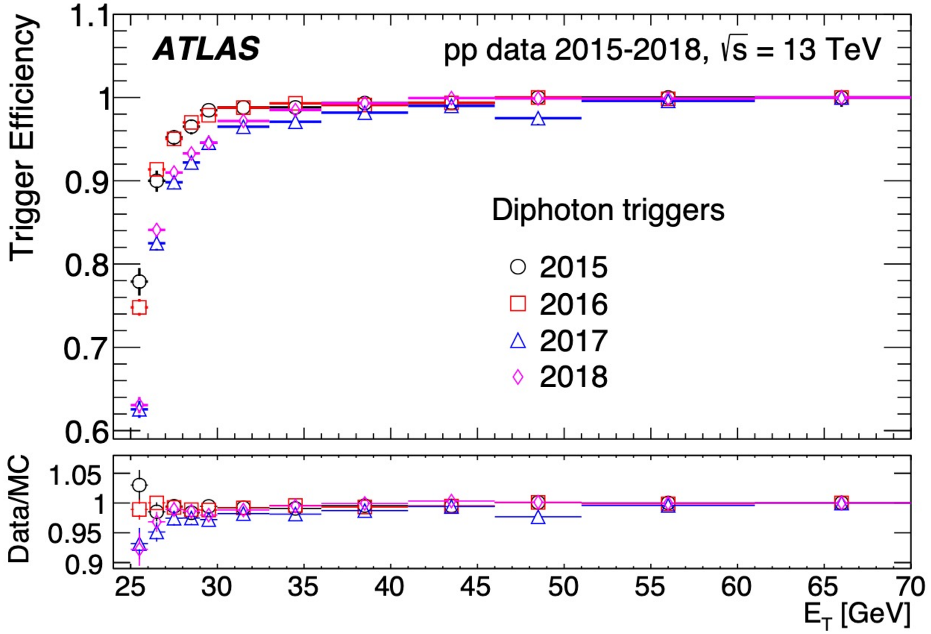
The ATLAS Collaboration

Searches are performed for non-resonant and resonant di-Higgs boson production in the $b\bar{b}\gamma\gamma$ final state. The data set used corresponds to an integrated luminosity of 139 fb^{-1} of proton–proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider. No excess with respect to background expectations is found and upper limits on the di-Higgs boson production cross sections are set. A 95% confidence level upper limit of 130 fb is set on the $pp \rightarrow HH$ non-resonant production, where the expected limit is 180 fb. The observed (expected) limit corresponds to 4.1 (5.5) times the cross section predicted by the Standard Model. The observed (expected) limit on the Higgs boson trilinear coupling modifier κ_λ is extracted to be [-1.5, 6.7] ([-2.4, 7.7]) at 95% confidence level. The constraints on κ_λ are obtained over an expected hypothesis excluding $pp \rightarrow HH$ production. For the resonant production of a new hypothetical scalar particle X ($X \rightarrow HH \rightarrow b\bar{b}\gamma\gamma$), limits on the cross section $pp \rightarrow X \rightarrow HH$ are presented for the narrow-width approximation as a function of m_X in the range 251 GeV $\leq m_X \leq$ 1000 GeV. The observed (expected) limits on the cross section $pp \rightarrow X \rightarrow HH$ range from 610 fb to 47 fb (360–43 fb) over the considered mass range.

What makes bb$\gamma\gamma$ special? Photons!



Trigger on two photons at 35 GeV and 25 GeV



For comparison: HH to 4b requires 2 b-jets at 35 GeV *and* either 2 other jets with 35 GeV or 1 b-jet with > 100 GeV

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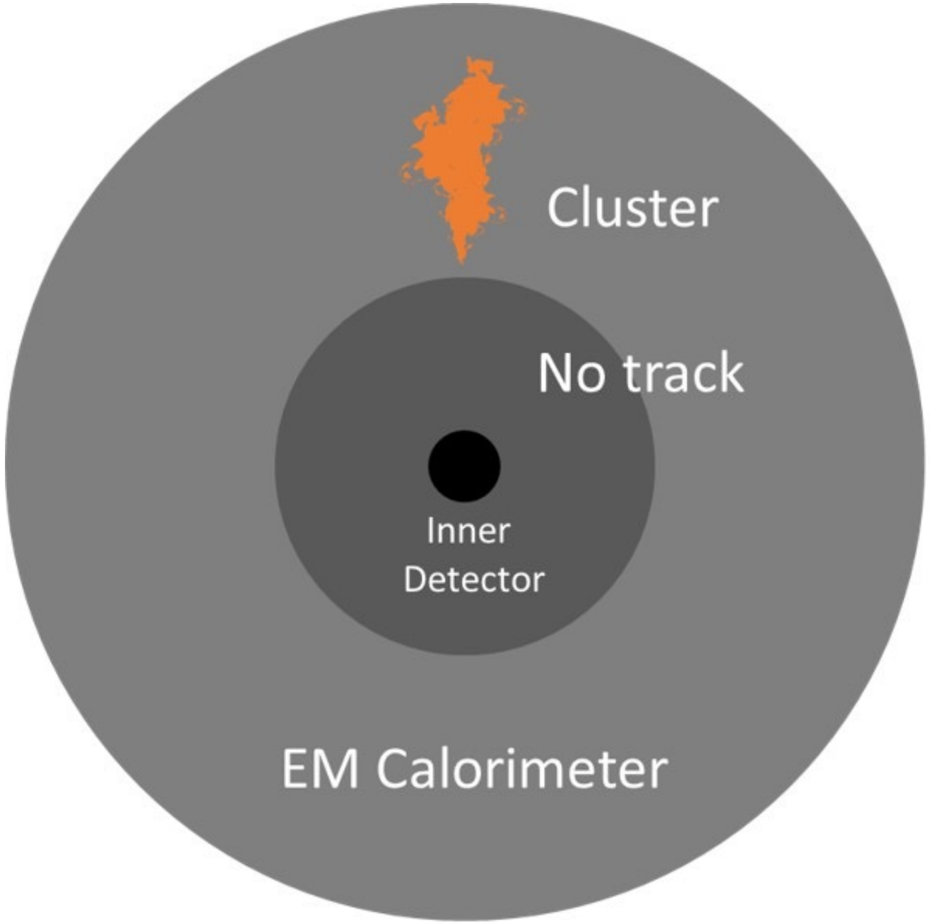

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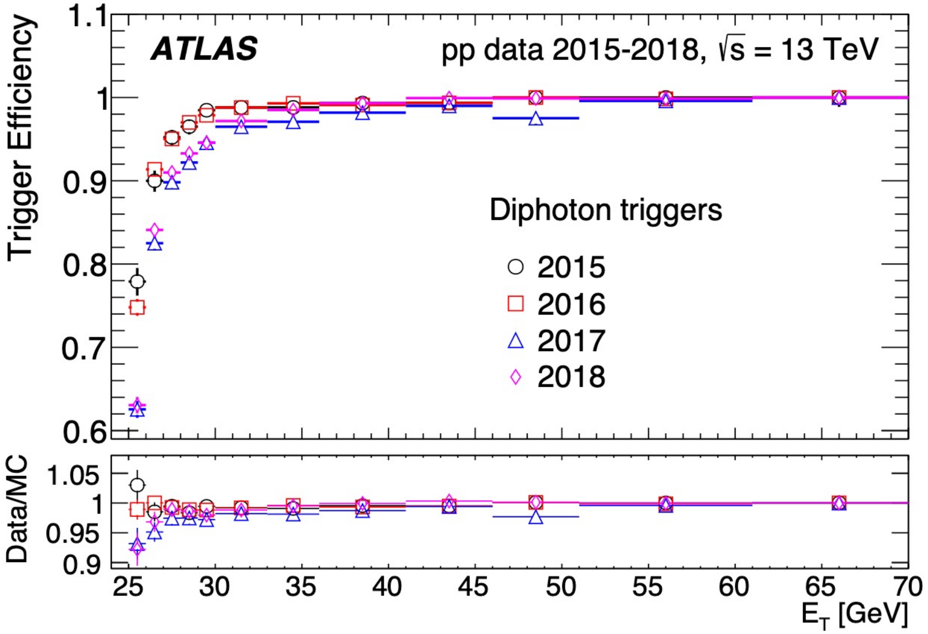
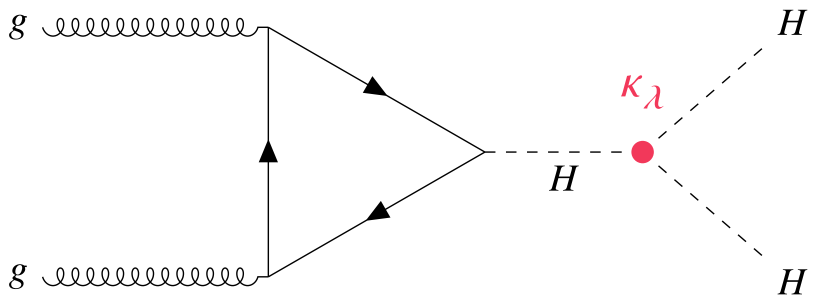
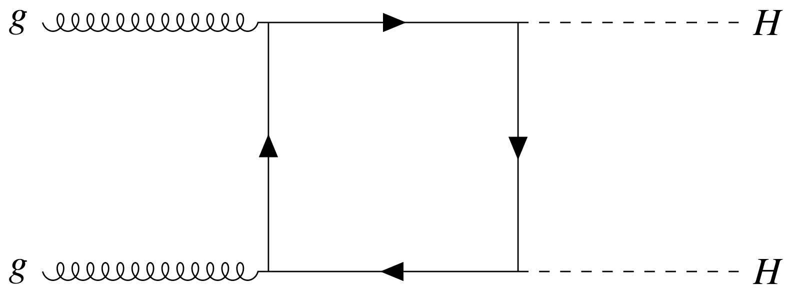


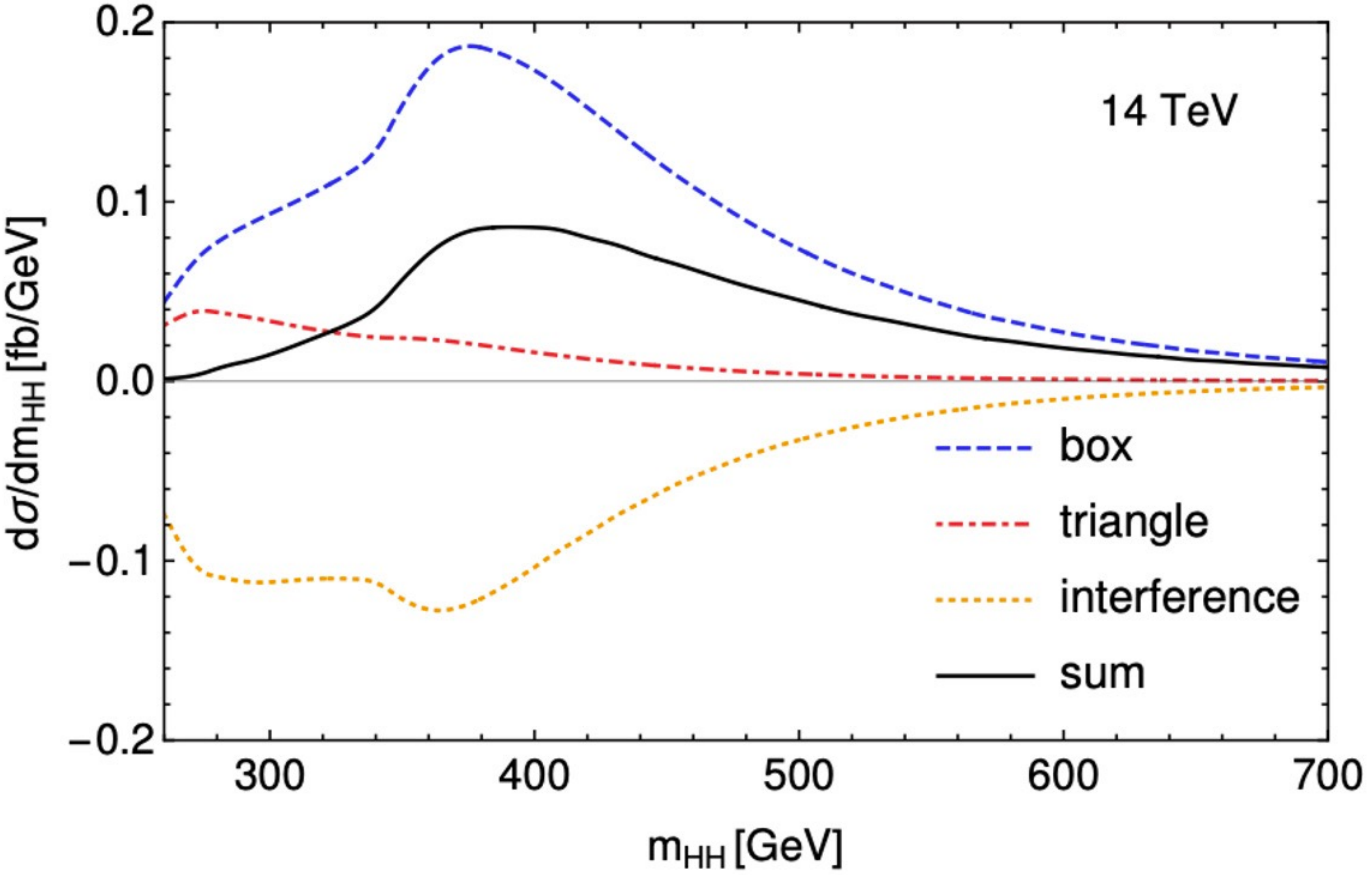
For comparison: HH to 4b requires 2 b-jets at 35 GeV *and* either 2 other jets with 35 GeV or 1 b-jet with > 100 GeV

This is important because it means that we can trigger on events with low HH invariant masses

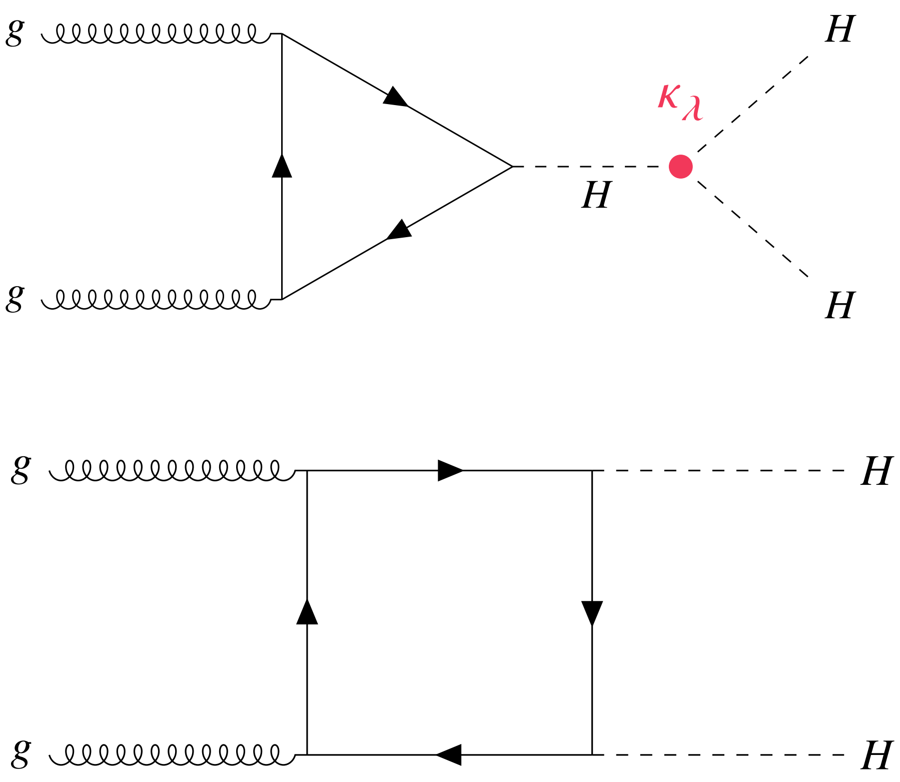
Interference Between Box and Triangle Diagrams

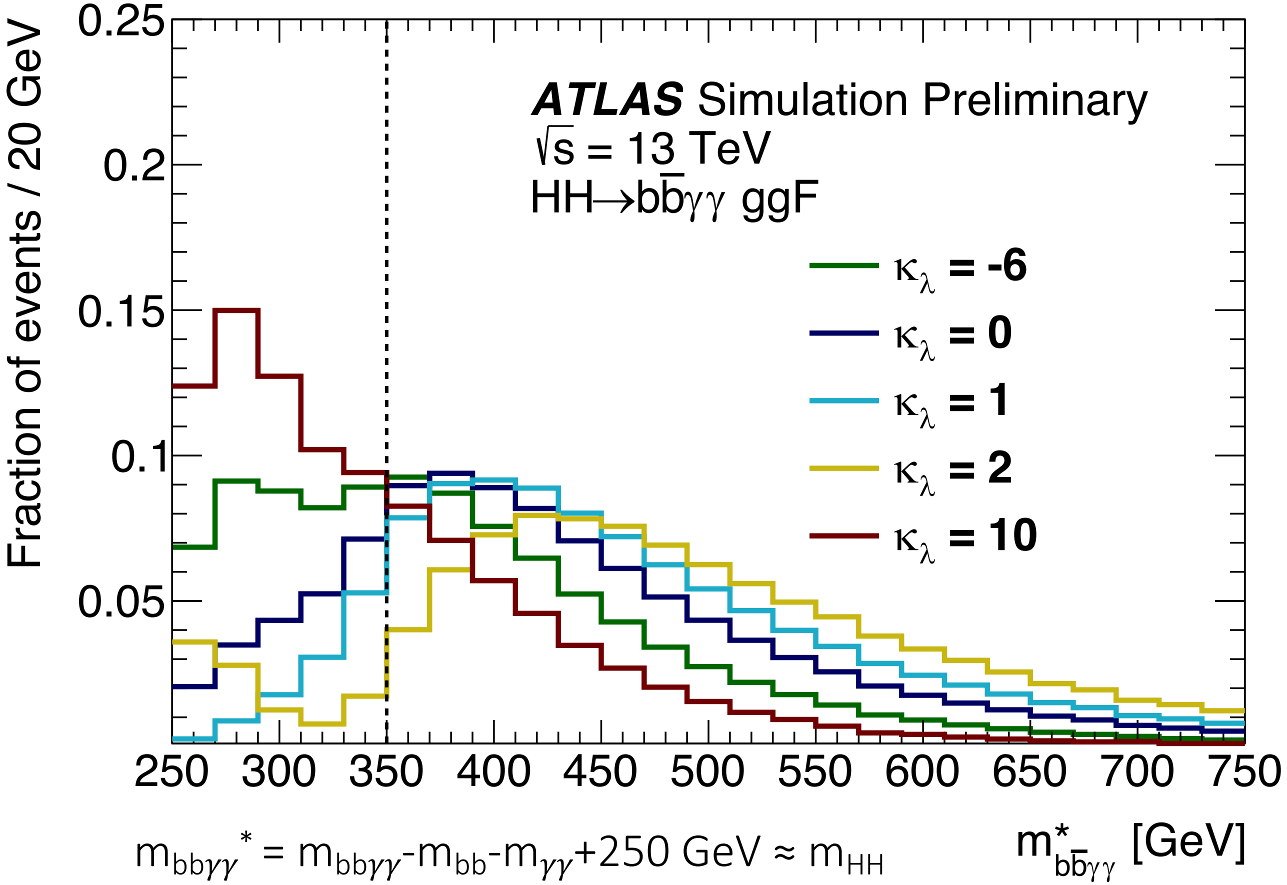






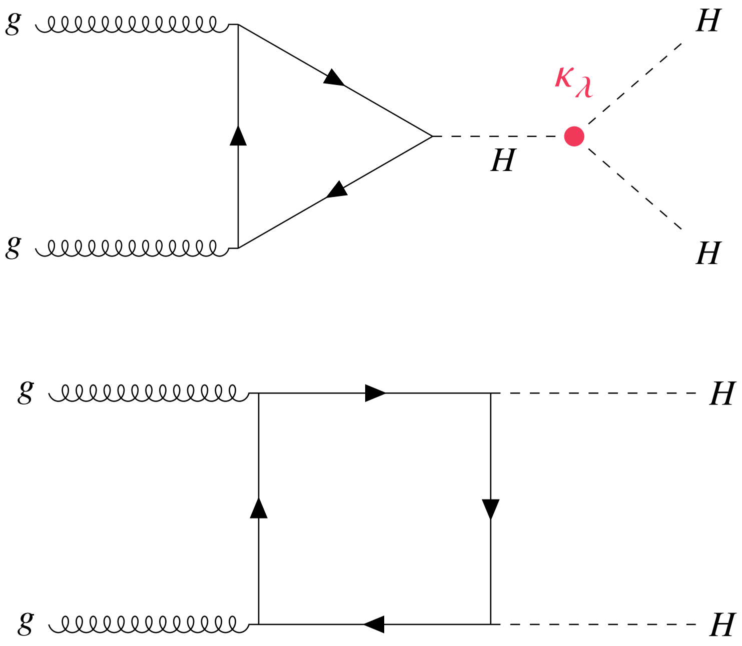
Why HH to bb$\gamma\gamma$?

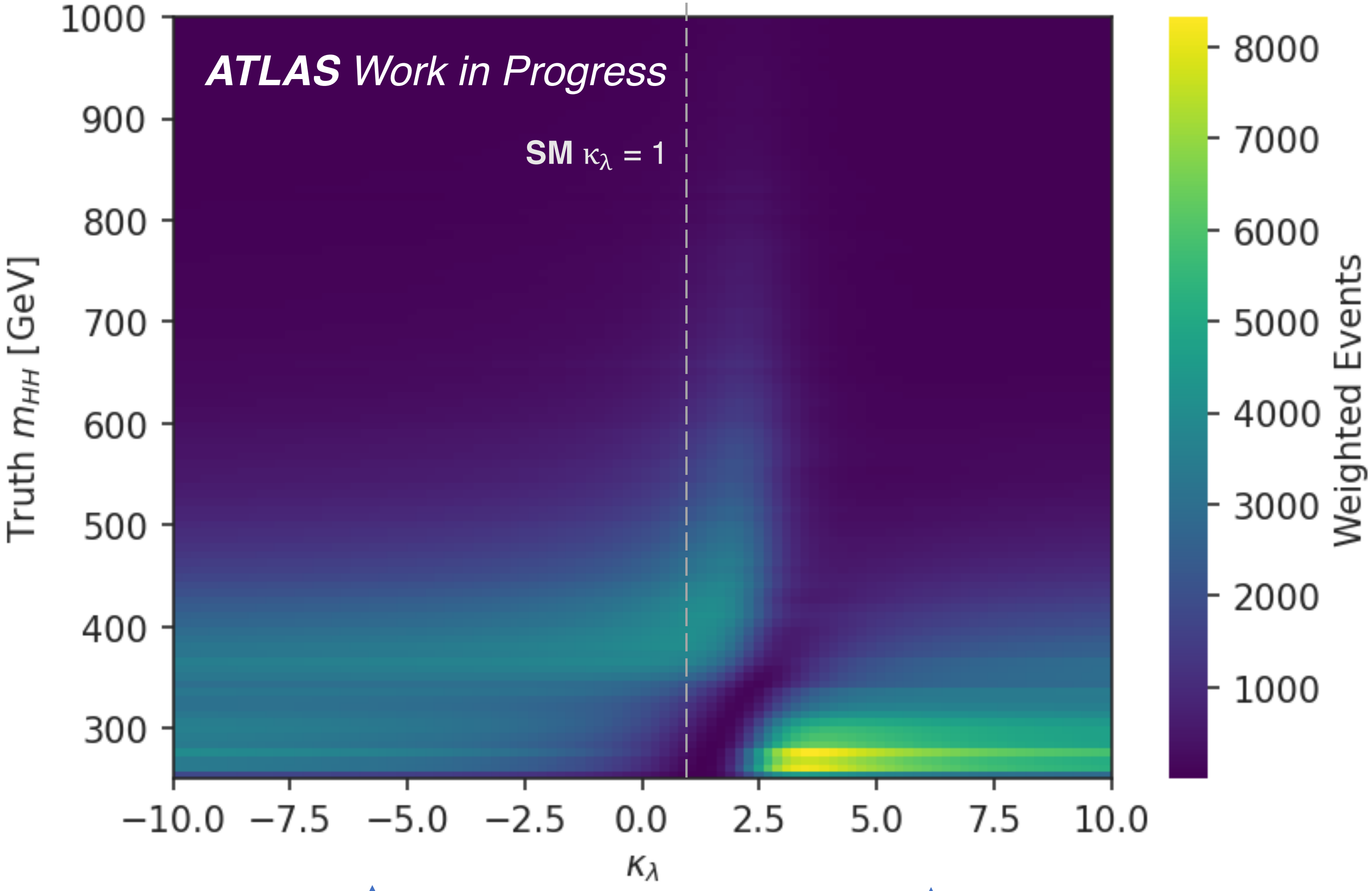




$m_{bb\gamma\gamma}{}^* = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250 \text{ GeV} \approx m_{HH}$

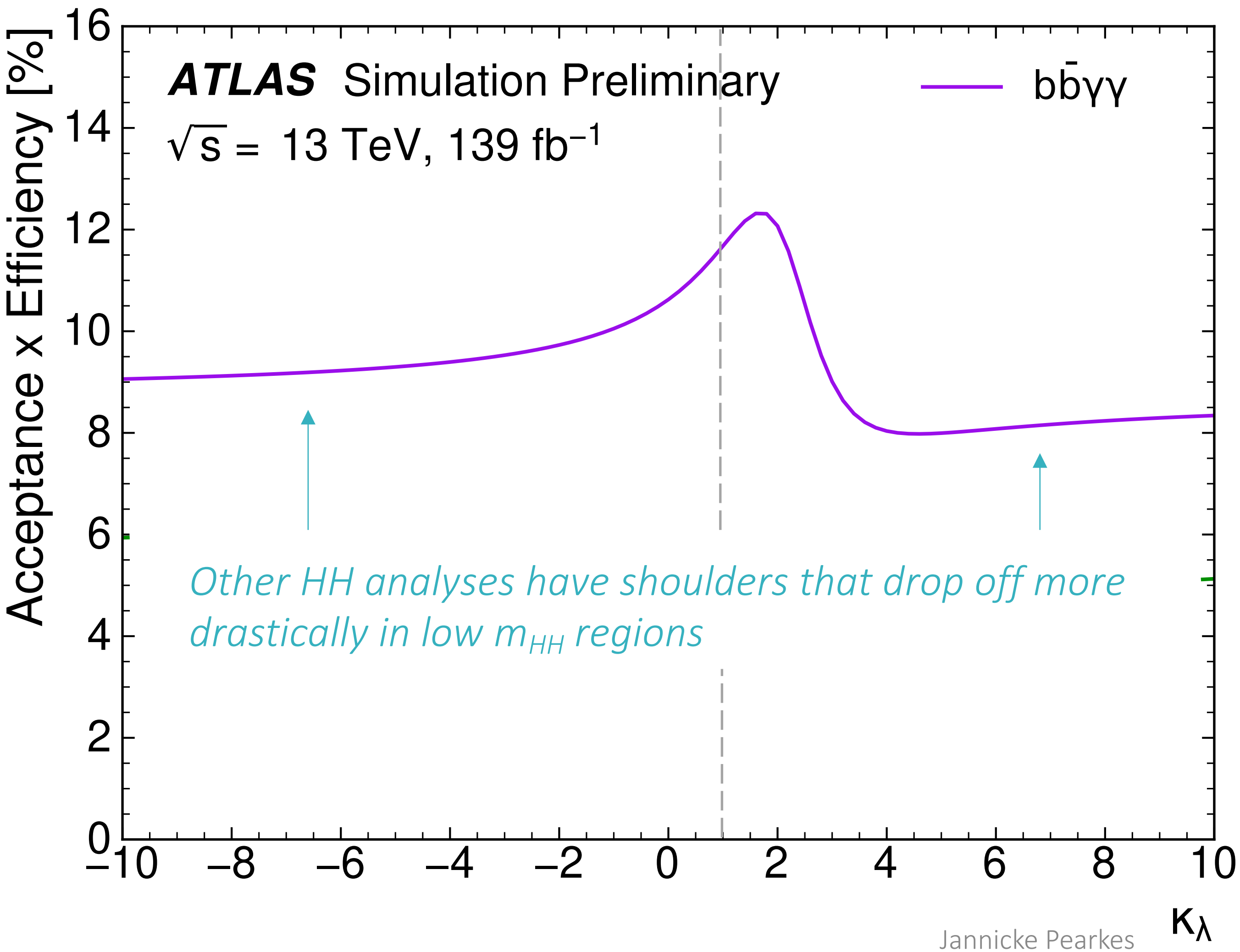
Why HH to bb$\gamma\gamma$?



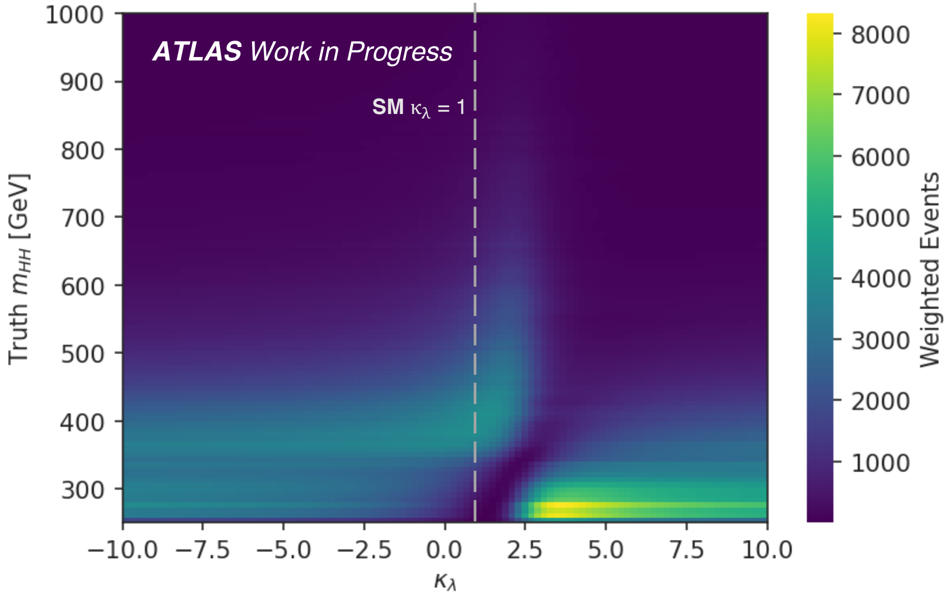


Non-SM values of κ_λ shift HH invariant mass distribution downwards.

Acceptance x Efficiency as a function of k_λ

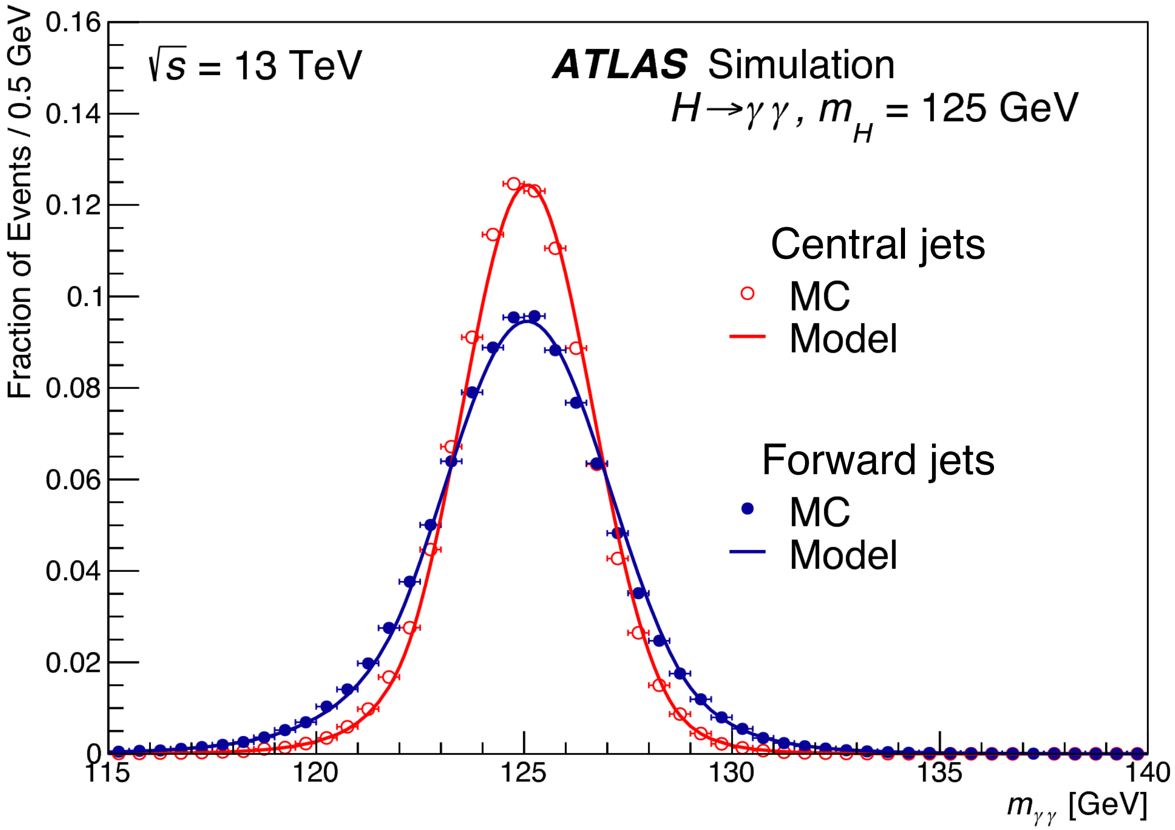


Other HH analyses have shoulders that drop off more drastically in low m_{HH} regions



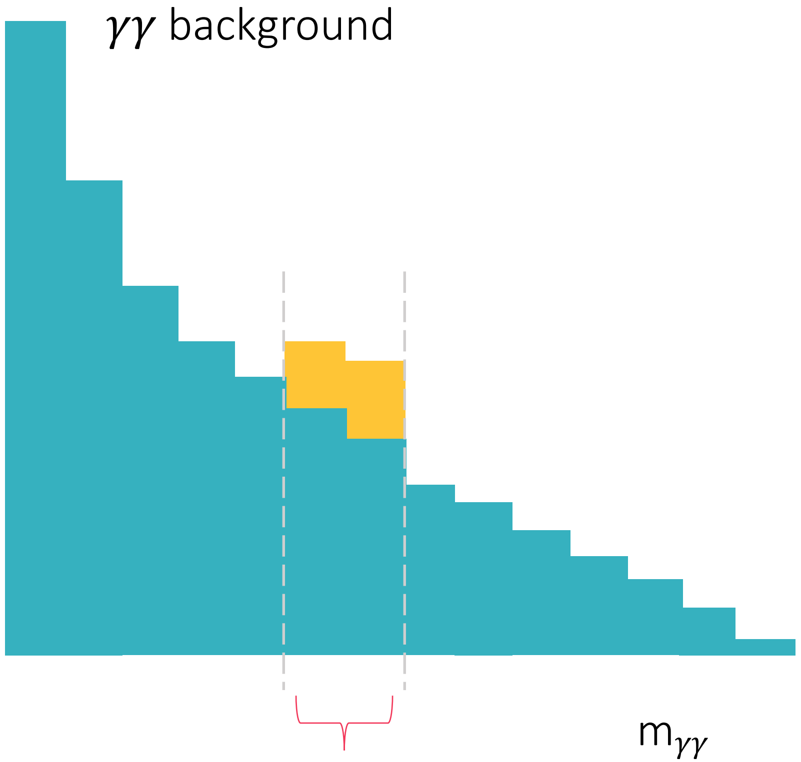
Photon Mass Resolution

JINST 14 (2019) P12006

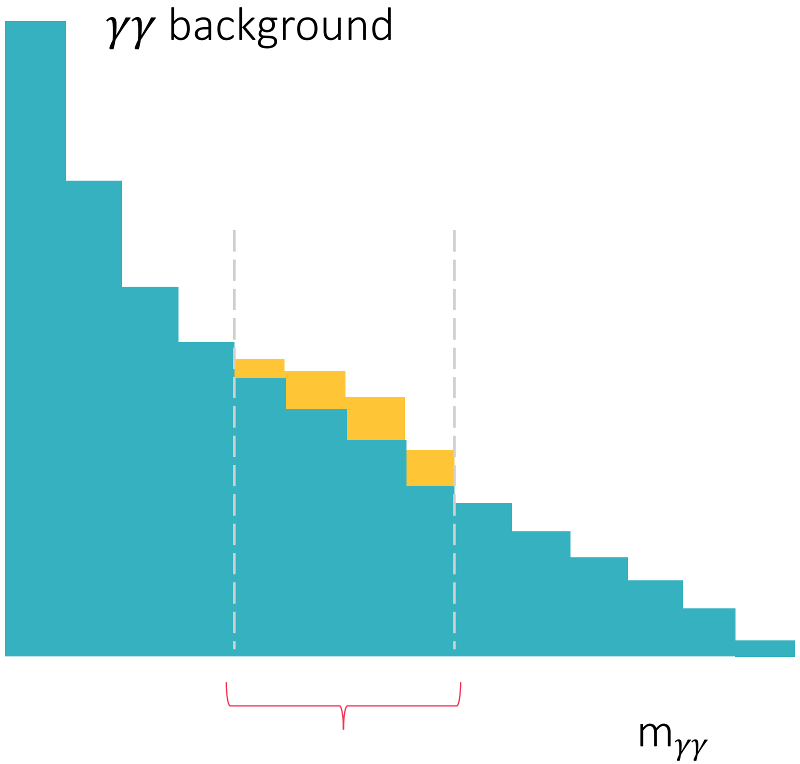


Excellent photon energy resolution <1% leads to very narrow peak in $m_{\gamma\gamma}$: σ ~1.5 GeV

Photon Mass Resolution

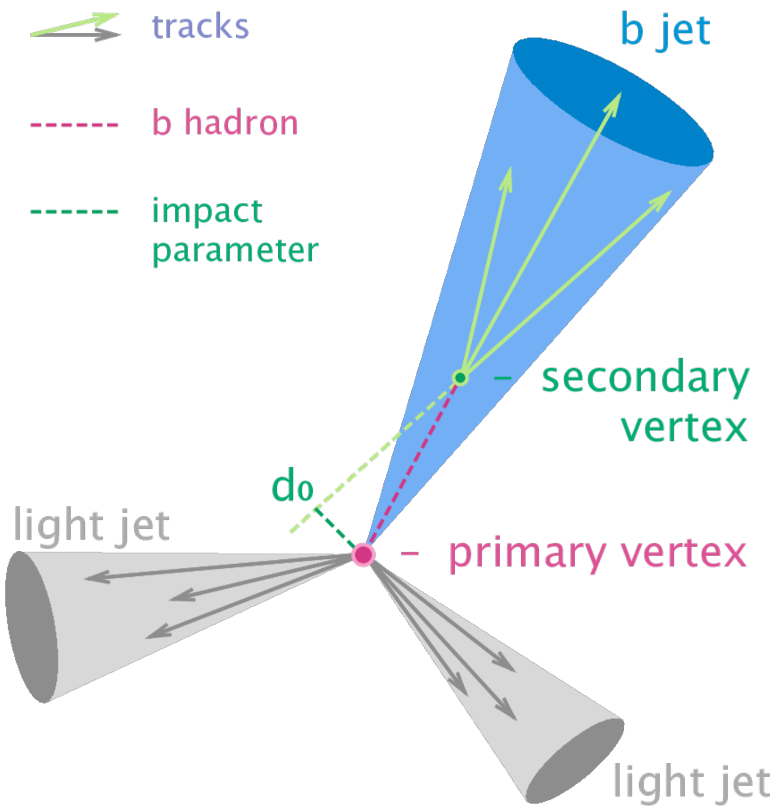


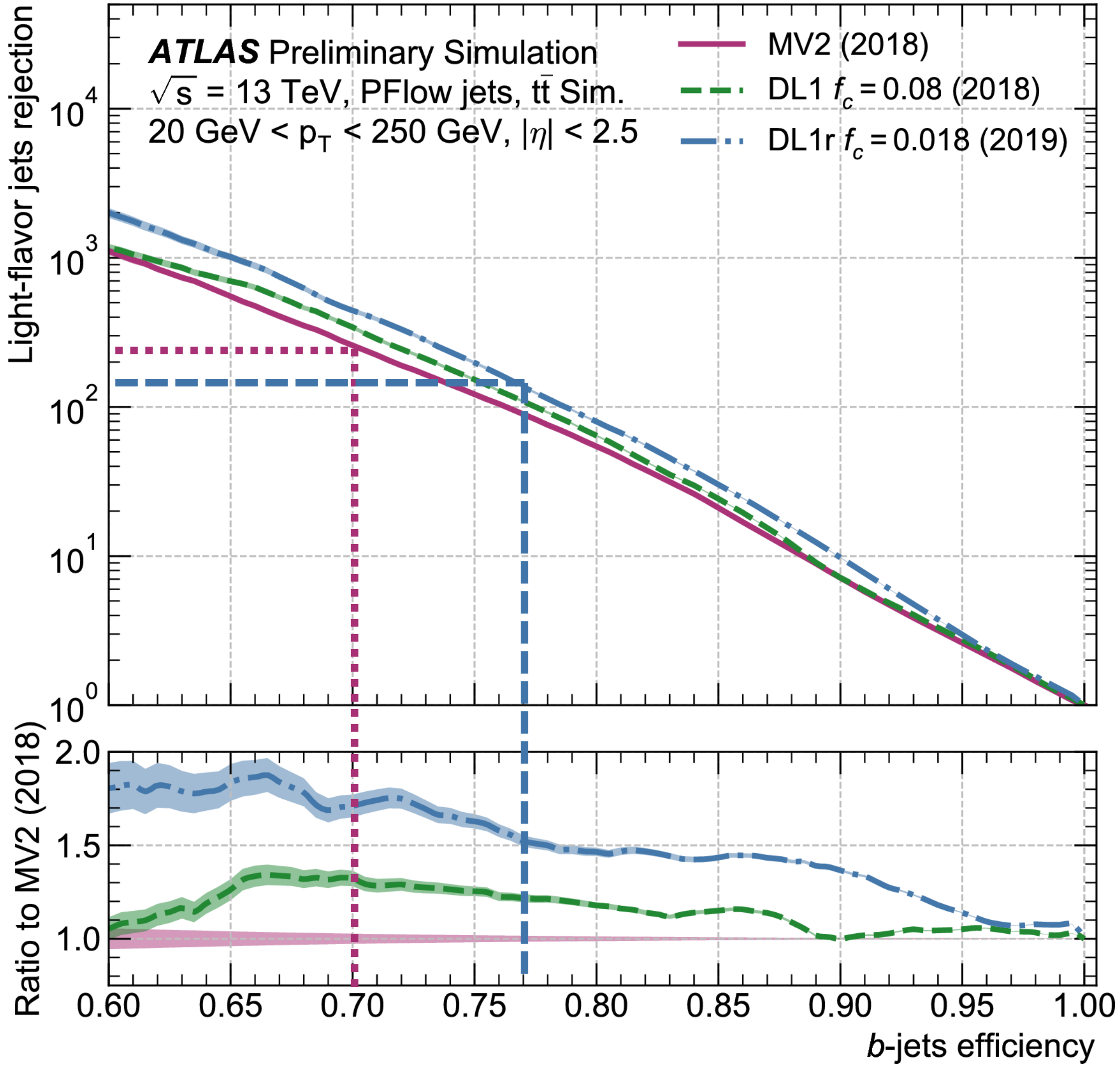
Better mass resolution,
better signal over background



Worse mass resolution, need to have broader signal region to accept same amount of signal

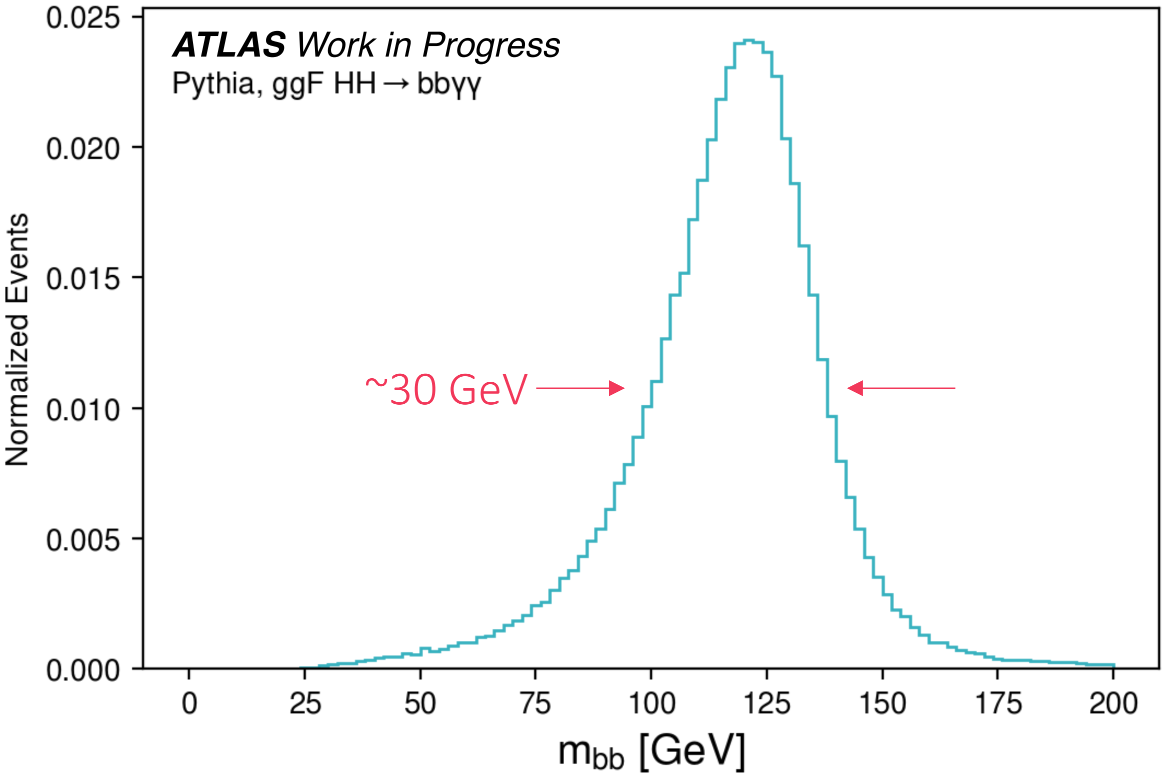
b-jets

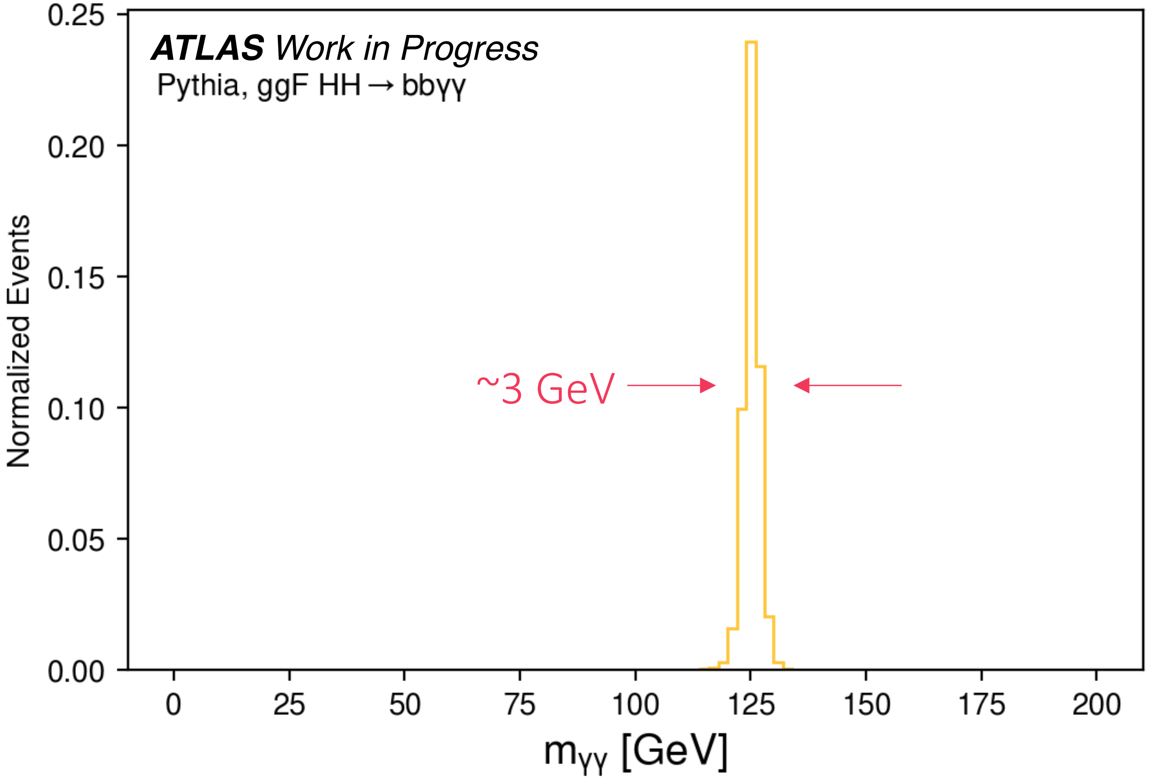




All HH analyses moved from 70% to 77% b-jet working points between Early Run 2 and Full 2 Run.
Analyses with 2 b-jets improved signal acceptance by 10%

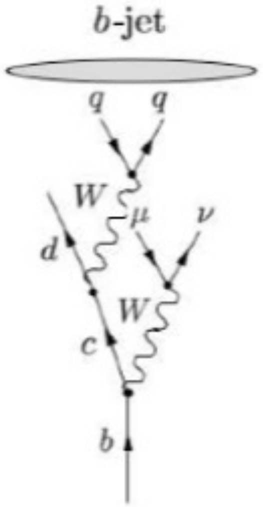
Mass resolution comparison

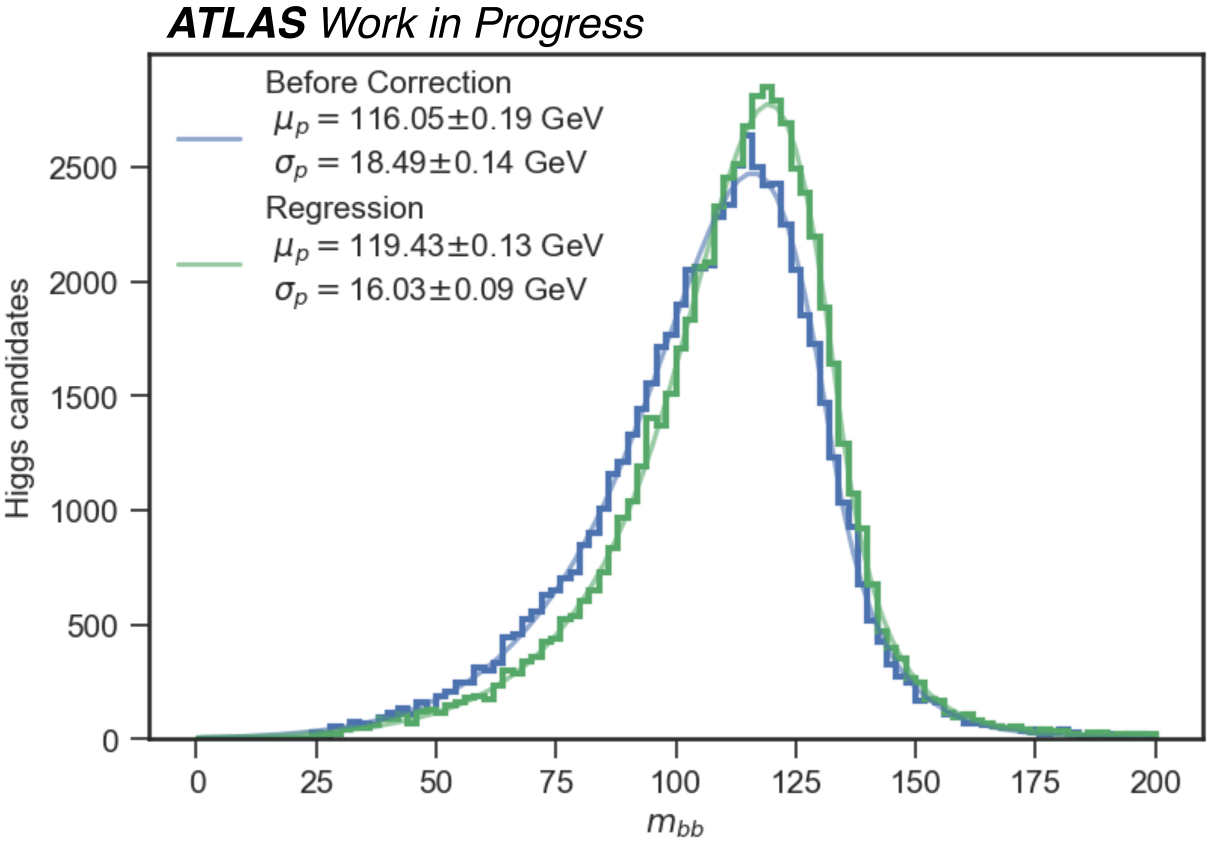




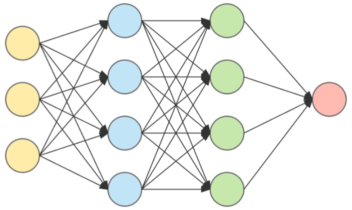
B-jet Regression

B-jets have higher fraction of neutrinos & leptons in b-jets due to semi-leptonic B hadron decays (~30%)





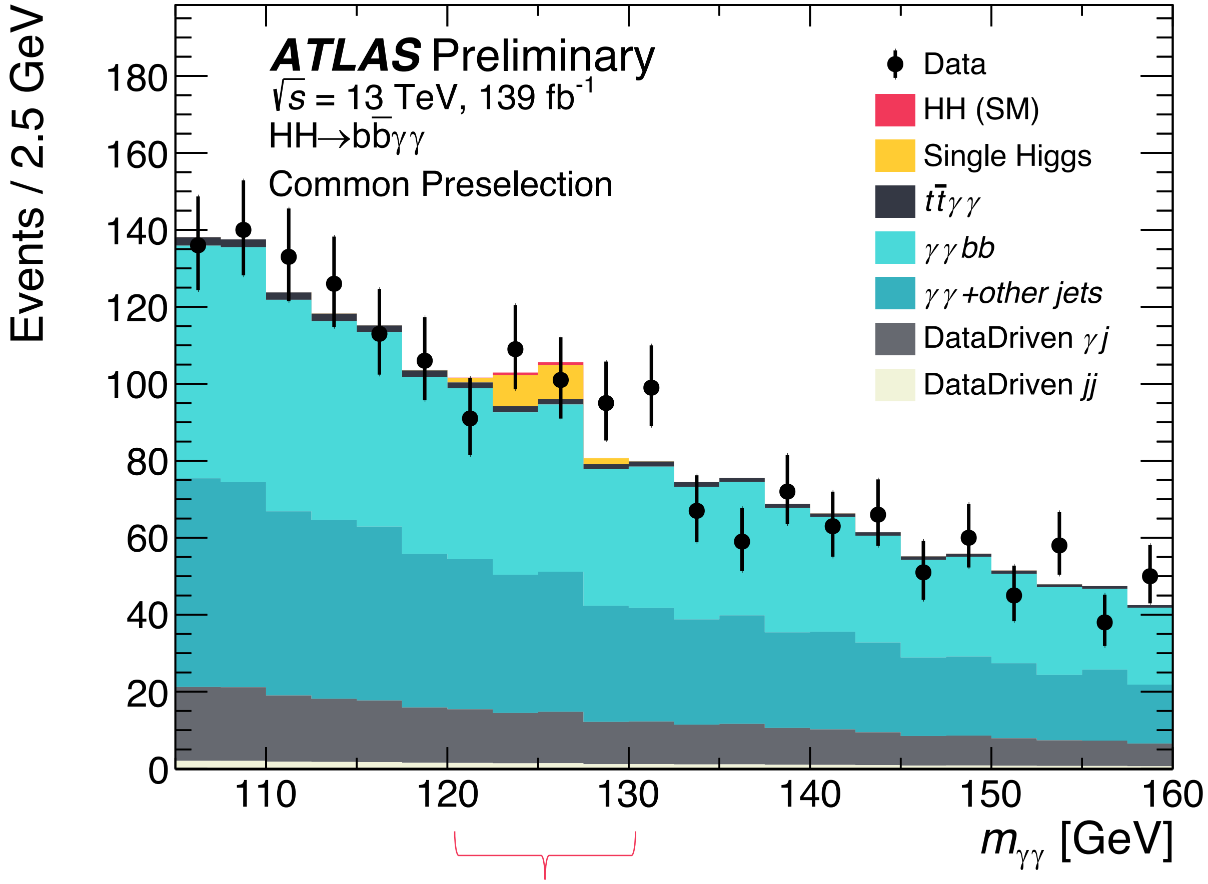
Developed addition calibration to correct b-jet p_T on a jet-by-jet basis with a neural network.



**Ended up using a simpler correction with similar performance in final analysis*

Selection Strategy

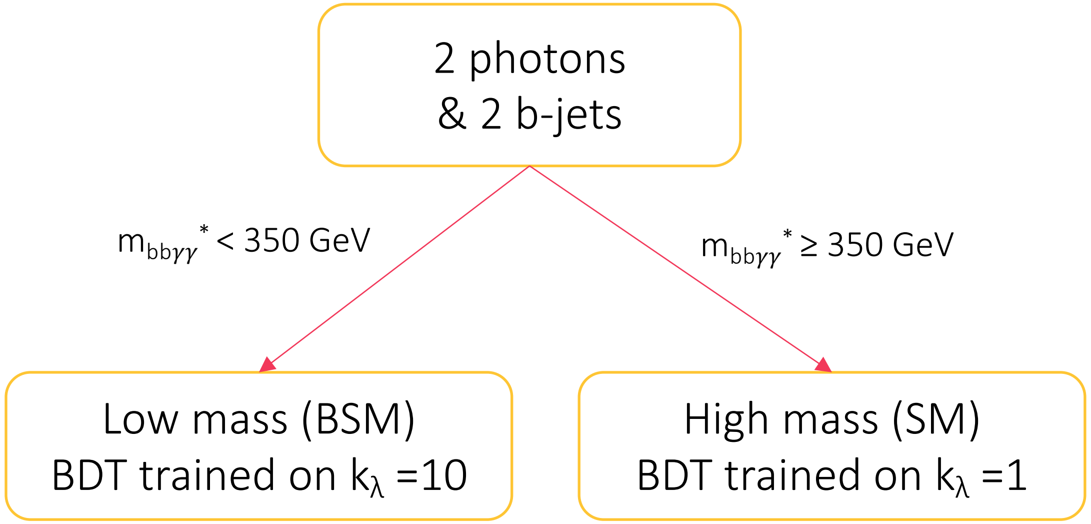
2 photons
& 2 b-jets



Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

s/b in signal region after pre-selection is ~0.1%

Selection Strategy



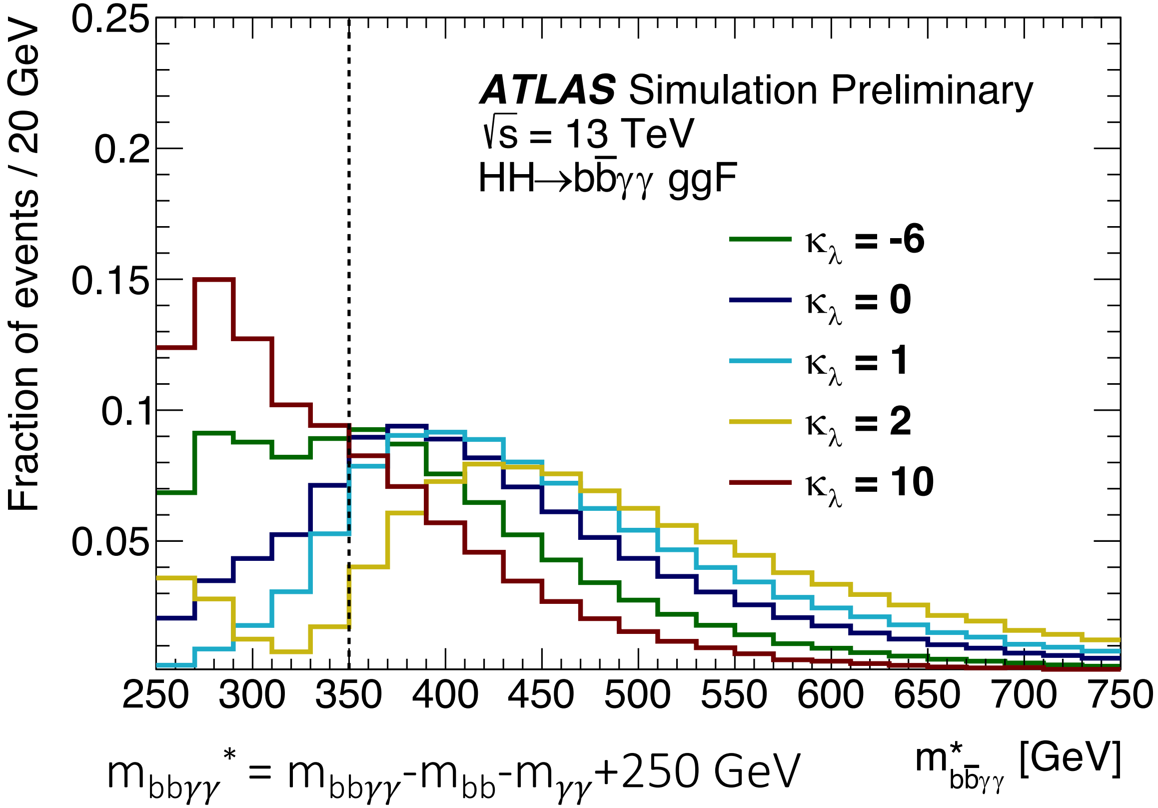
2 photons
& 2 b-jets

$m_{bb\gamma\gamma}^* < 350$ GeV

$m_{bb\gamma\gamma}^* \geq 350$ GeV

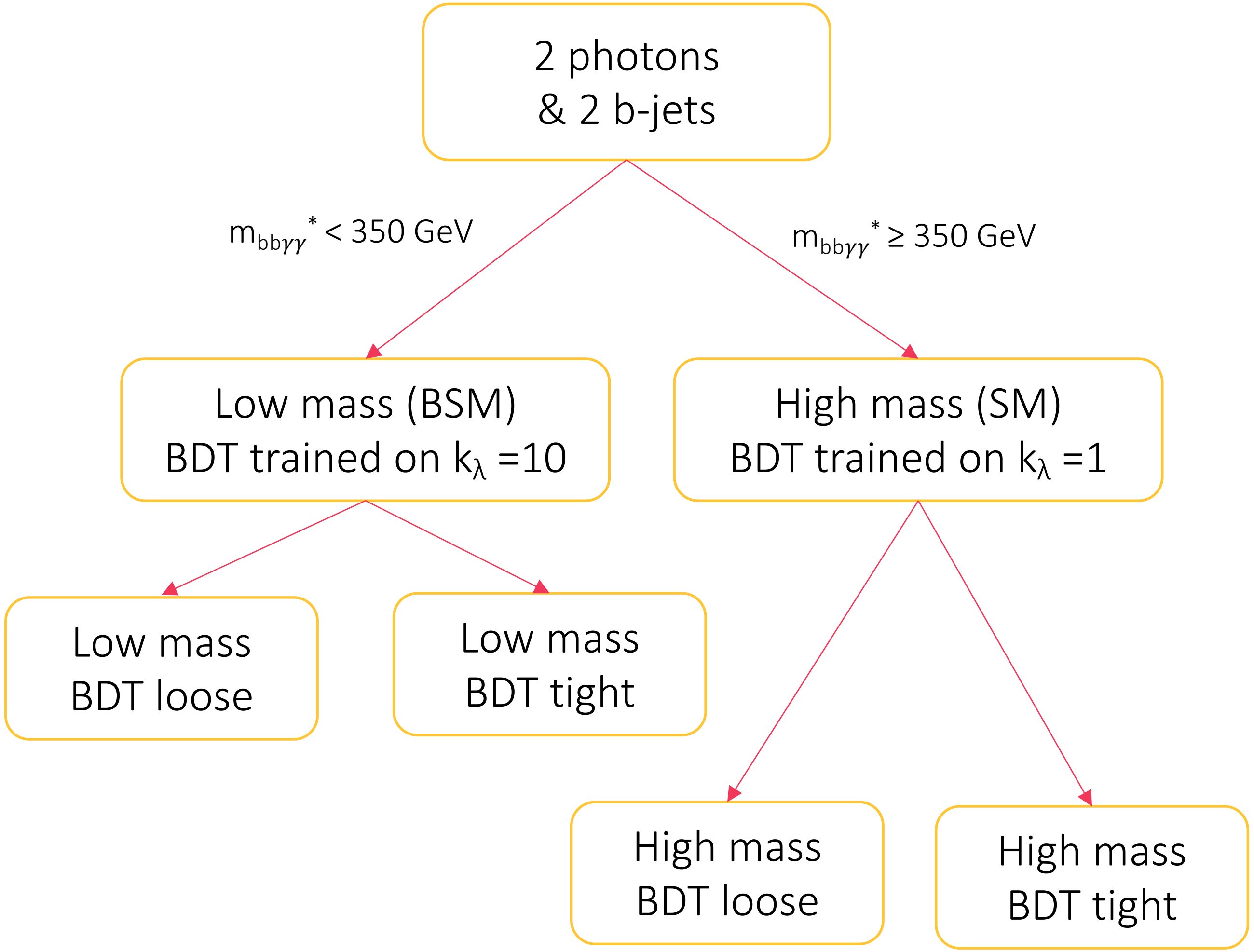
Low mass (BSM)
BDT trained on $k_\lambda = 10$

High mass (SM)
BDT trained on $k_\lambda = 1$



$m_{bb\gamma\gamma}^* = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV

Selection Strategy



2 photons
& 2 b-jets

$m_{bb\gamma\gamma}^* < 350$ GeV

$m_{bb\gamma\gamma}^* \geq 350$ GeV

Low mass (BSM)
BDT trained on $k_\lambda = 10$

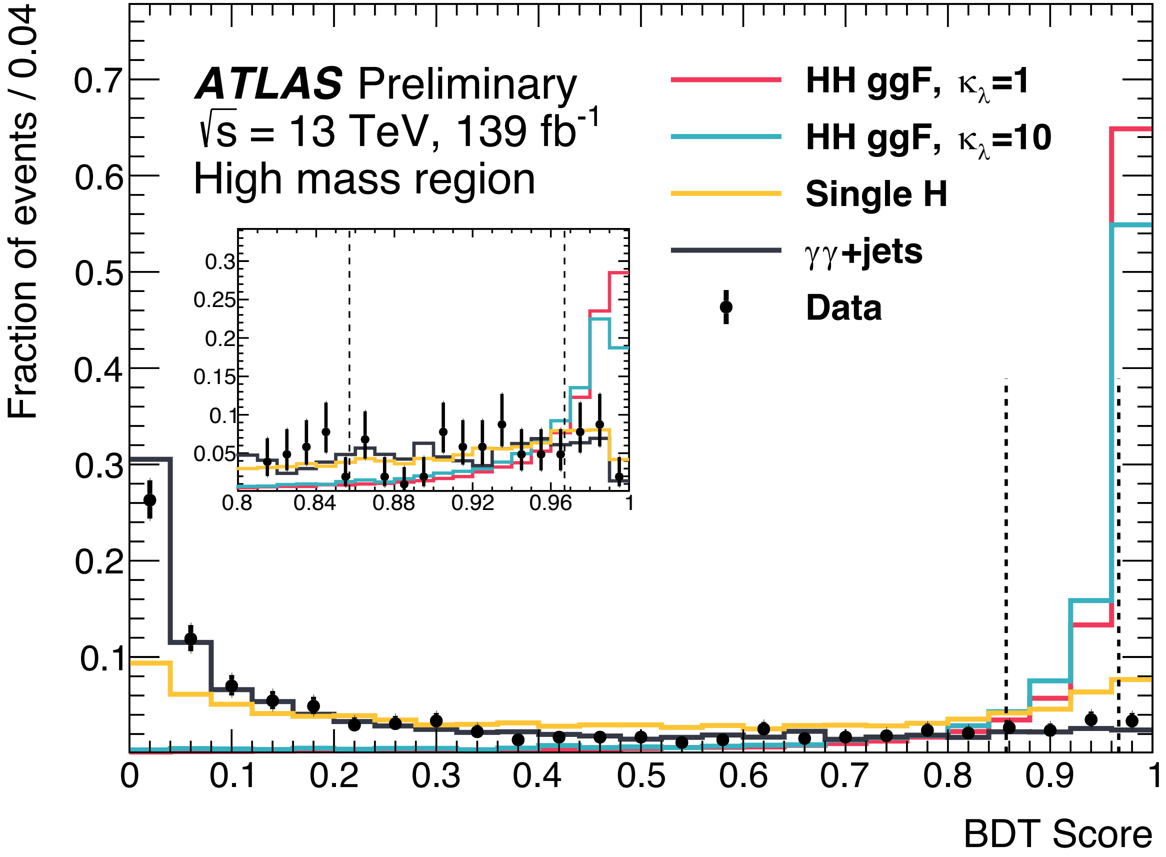
High mass (SM)
BDT trained on $k_\lambda = 1$

Low mass
BDT loose

Low mass
BDT tight

High mass
BDT loose

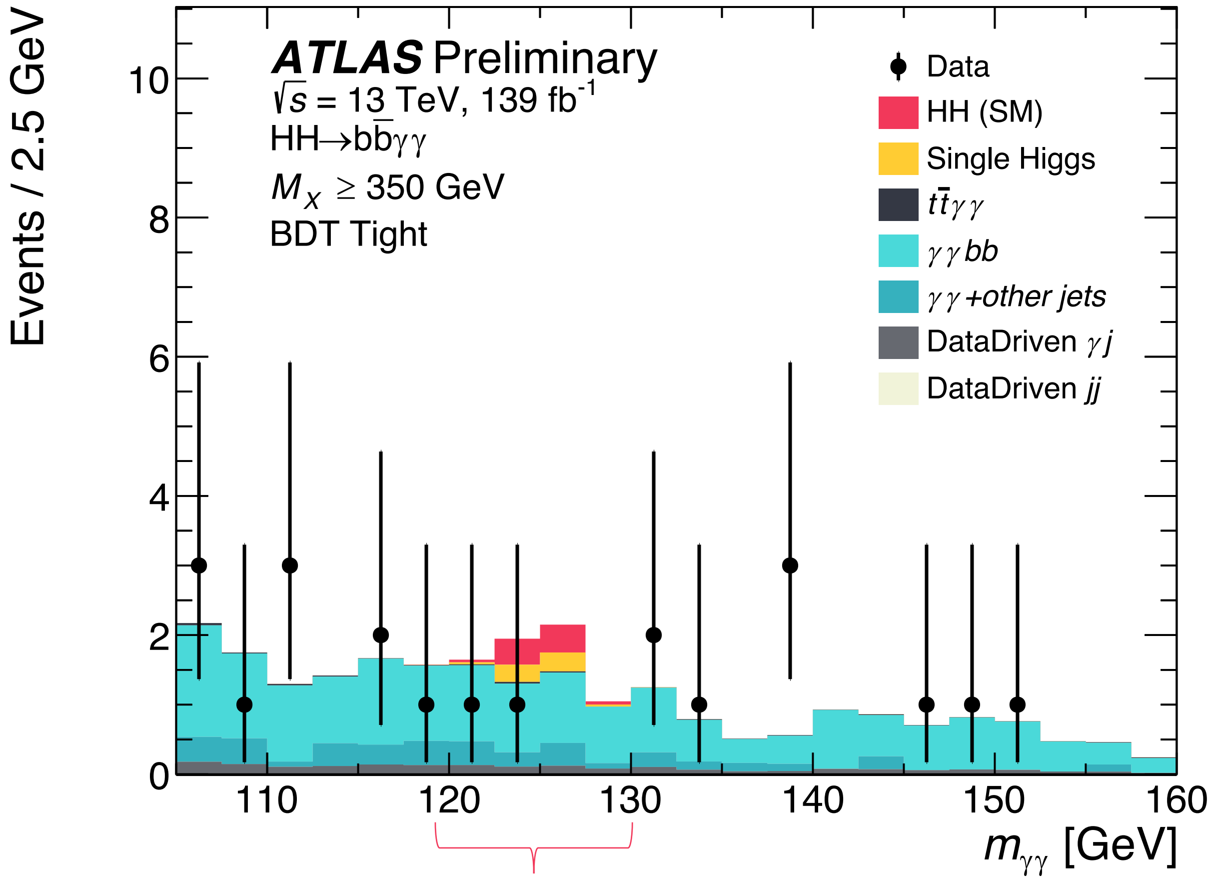
High mass
BDT tight



<u>4 BDT Categories</u>

Cuts on BDT scores optimized to maximize Asimov significance.

Post Selection Data/Predictions



Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

s/b in signal region after high mass BDT tight selection is 14%

Signal Extraction

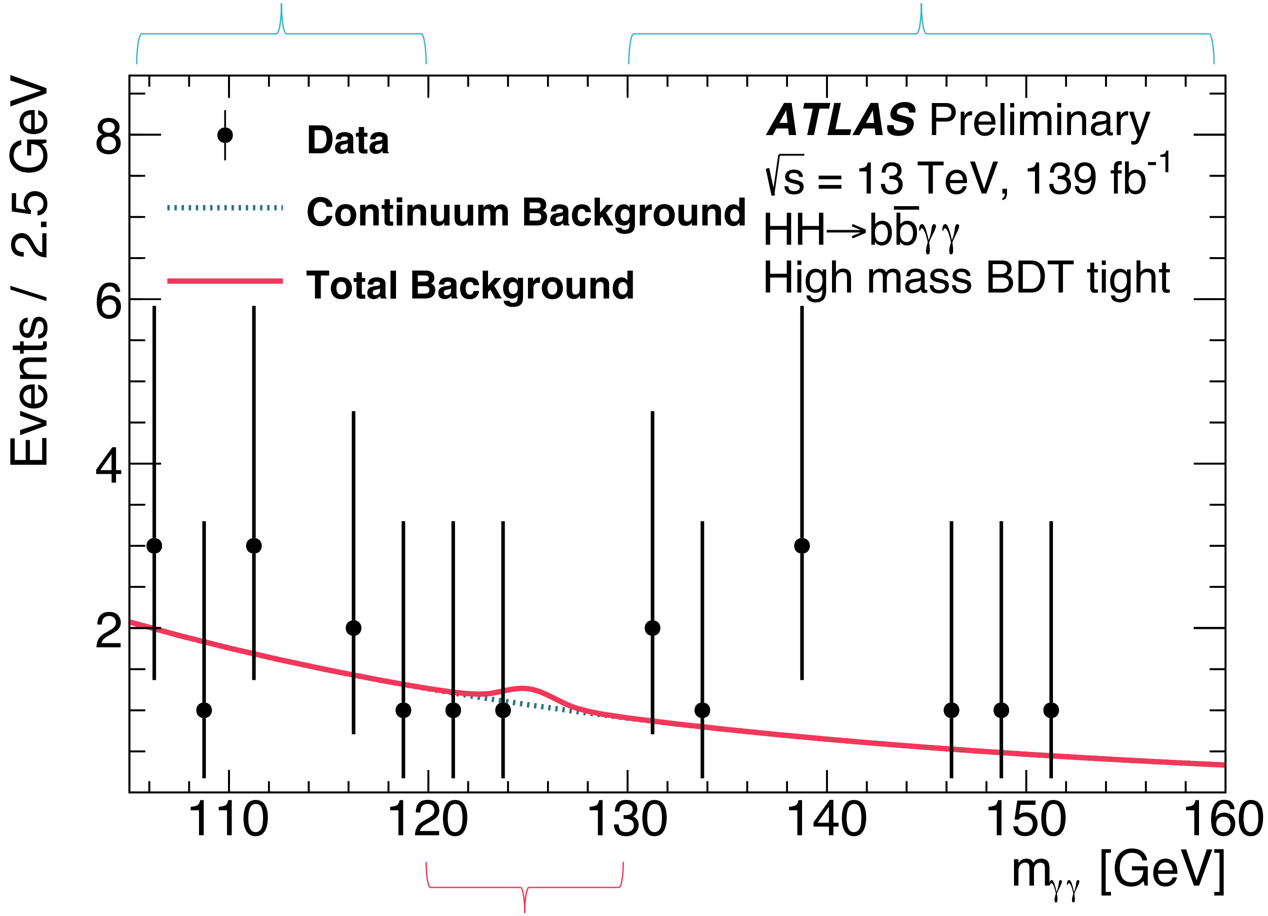
Signal model: Double-Sided Crystal Ball
Normalization and shape for HH signal and single Higgs background models determined from fits to Monte Carlo simulation.

Background model: Exponential function
Shape chosen by fitting Monte Carlo simulation. Normalized to the data sidebands.

HH signal strength determined through maximum likelihood fit on $m_{\gamma\gamma}$ across all four BDT categories

Sideband

Sideband



Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

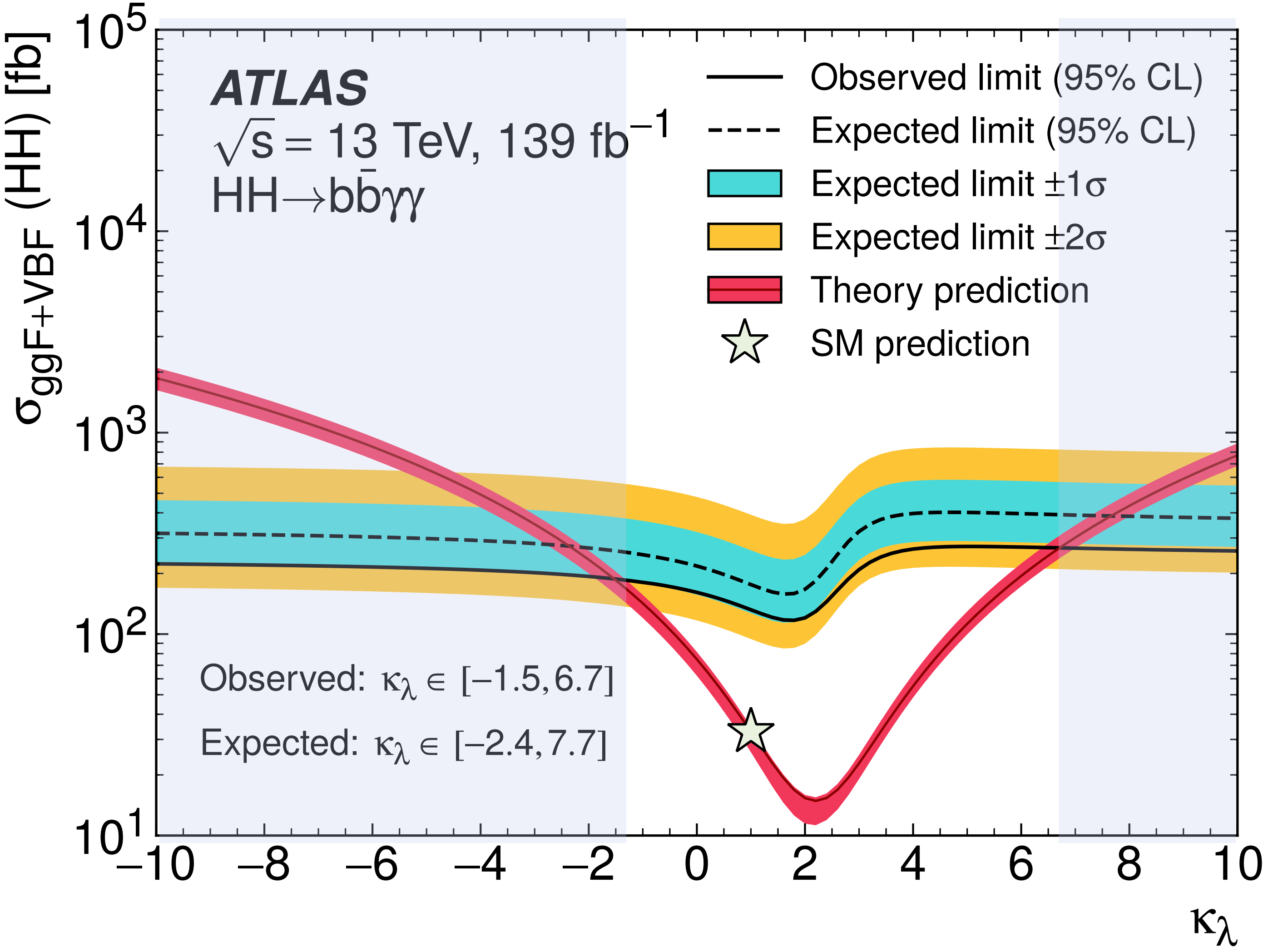
Results

No excess was observed, upper limits on the SM cross-section are set using the CLs method.

Observed 95% CL limit on SM signal strength is 4.1xSM (5.5xSM expected)

Observed (expected) limits on k_λ :
$-1.5 < k_\lambda < 6.7$, $(-2.4 < k_\lambda < 6.7)$

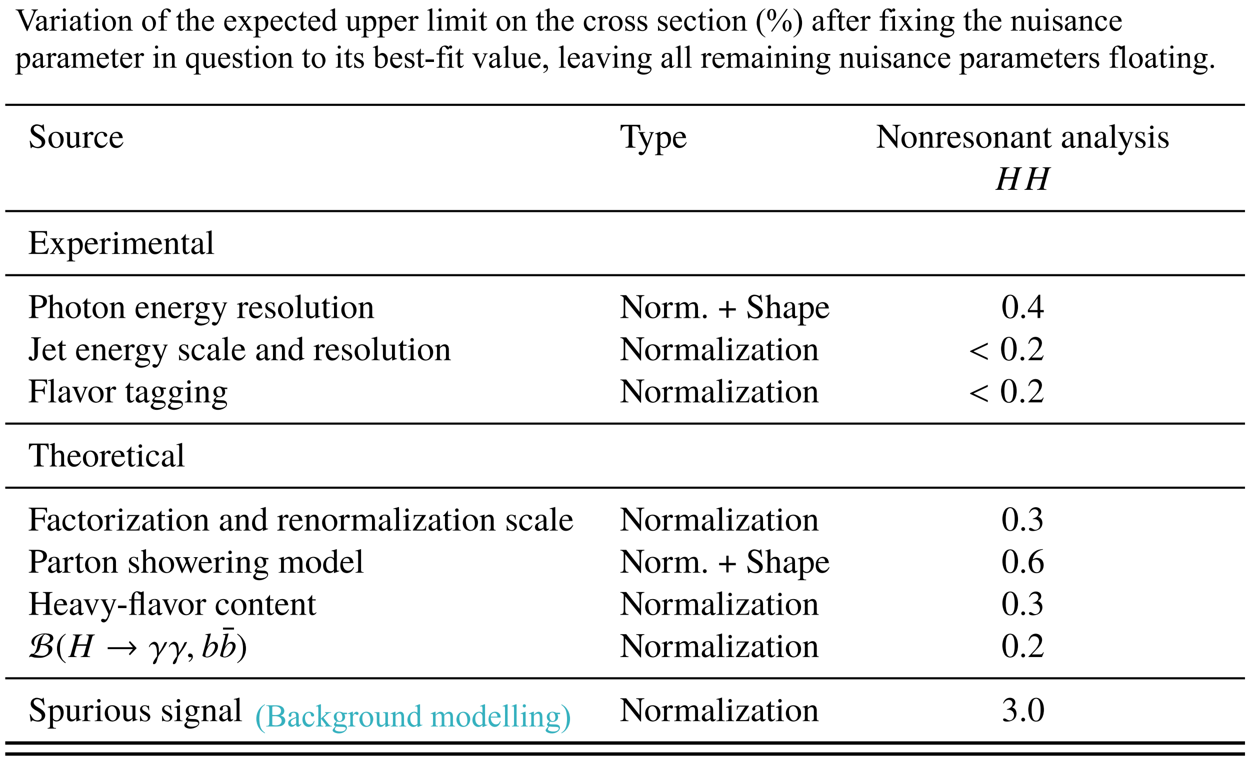
Previous Run 2 limits with 36.1 fb^{-1} : 20xSM, $-8.2 < k_\lambda < 13.2$. New limits greatly improved by updated selection strategies.



Systematic Uncertainties

Extremely statistically limited analysis: Expected signal strength is 1 +- 2.23 (stats) +- 0.8 (systematic)

Systematics with biggest impact:



Variation of the expected upper limit on the cross section (%) after fixing the nuisance parameter in question to its best-fit value, leaving all remaining nuisance parameters floating.

Source	Type	Nonresonant analysis HH
Experimental		
Photon energy resolution	Norm. + Shape	0.4
Jet energy scale and resolution	Normalization	< 0.2
Flavor tagging	Normalization	< 0.2
Theoretical		
Factorization and renormalization scale	Normalization	0.3
Parton showering model	Norm. + Shape	0.6
Heavy-flavor content	Normalization	0.3
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	0.2
Spurious signal (Background modelling)	Normalization	3.0

impact on upper limit is < 1% for most uncertainties

largest impact

Comparison with CMS https://arxiv.org/abs/2011.12373

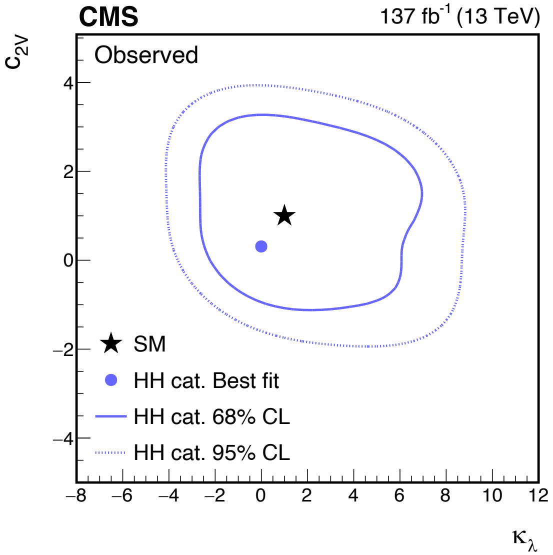
	Observed SM limit	Expected SM limit
ATLAS	4.1	5.5
CMS	7.7	5.2

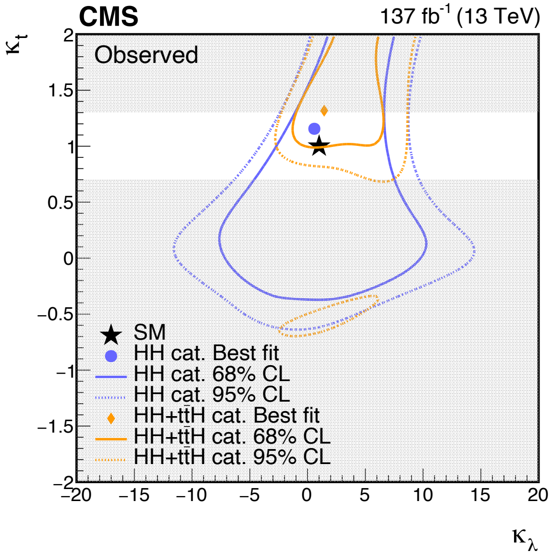
	Observed k_λ limit	Expected k_λ limit
ATLAS	$-1.5 < k_\lambda < 6.7$	$-2.4 < k_\lambda < 6.7$
CMS	$-3.3 < k_\lambda < 8.5$	$-2.5 < k_\lambda < 8.2$

ATLAS and CMS limits are competitive with each other despite different detectors and analysis strategies.

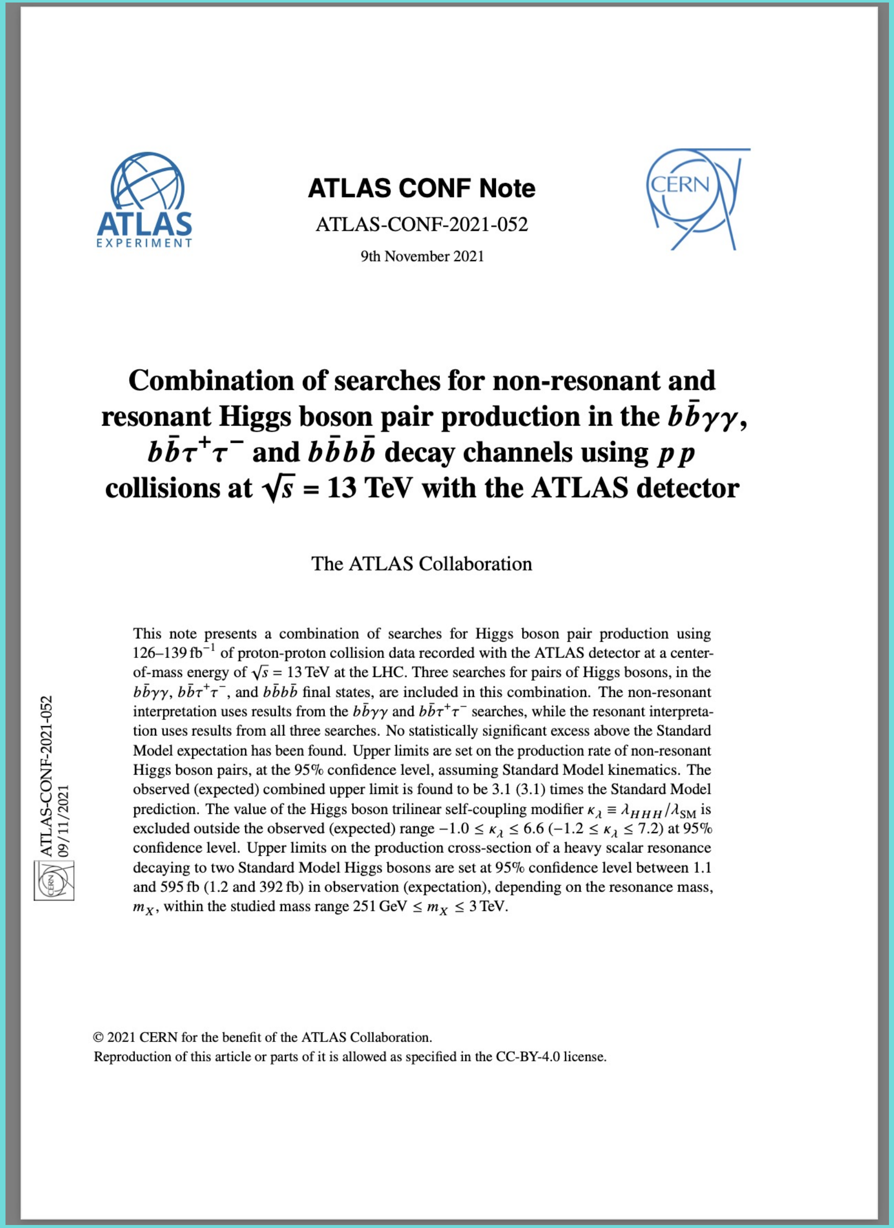
CMS has put a lot of effort into scans profiling k_λ, k_t and k_{2V}

In the future, as HH sensitivity rises, will move towards more generic interpretations of results i.e. through effective field theories.





HH Combination



ATLAS CONF Note
ATLAS-CONF-2021-052
9th November 2021

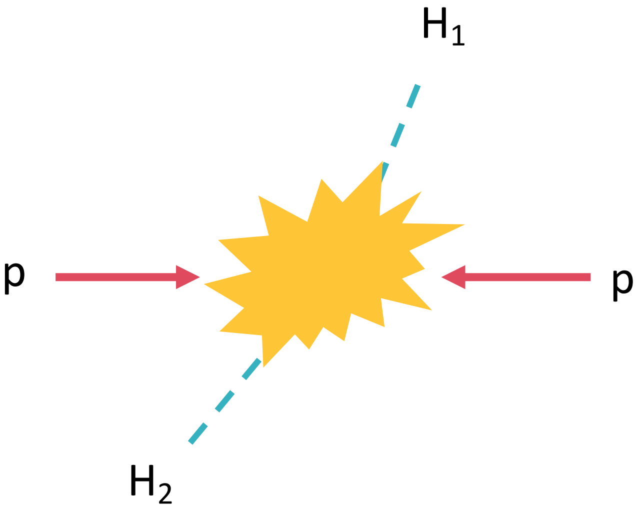
Combination of searches for non-resonant and resonant Higgs boson pair production in the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}b\bar{b}$ decay channels using pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

ATLAS-CONF-2021-052
09/11/2021

This note presents a combination of searches for Higgs boson pair production using 126–139 fb^{-1} of proton-proton collision data recorded with the ATLAS detector at a center-of-mass energy of $\sqrt{s} = 13$ TeV at the LHC. Three searches for pairs of Higgs bosons, in the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}b\bar{b}$ final states, are included in this combination. The non-resonant interpretation uses results from the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ searches, while the resonant interpretation uses results from all three searches. No statistically significant excess above the Standard Model expectation has been found. Upper limits are set on the production rate of non-resonant Higgs boson pairs, at the 95% confidence level, assuming Standard Model kinematics. The observed (expected) combined upper limit is found to be 3.1 (3.1) times the Standard Model prediction. The value of the Higgs boson trilinear self-coupling modifier $\kappa_\lambda \equiv \lambda_{HHH}/\lambda_{\text{SM}}$ is excluded outside the observed (expected) range $-1.0 \leq \kappa_\lambda \leq 6.6$ ($-1.2 \leq \kappa_\lambda \leq 7.2$) at 95% confidence level. Upper limits on the production cross-section of a heavy scalar resonance decaying to two Standard Model Higgs bosons are set at 95% confidence level between 1.1 and 595 fb (1.2 and 392 fb) in observation (expectation), depending on the resonance mass, m_X, within the studied mass range 251 GeV $\leq m_X \leq$ 3 TeV.

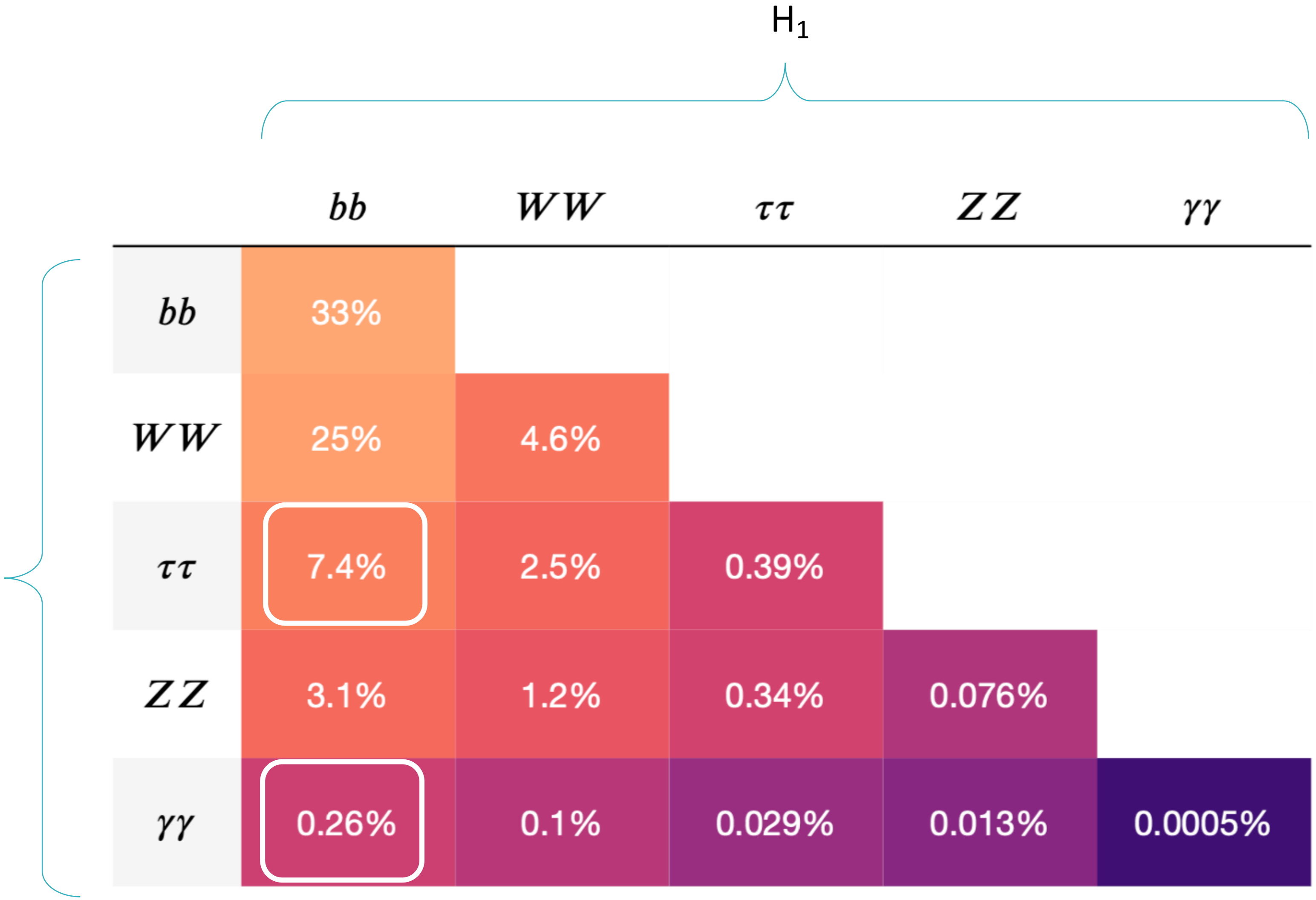
HH Decay Channels



bbττ - ATLAS-CONF-2021-030
https://cds.cern.ch/record/2777236

bb$\gamma\gamma$ - CERN-EP-2021-180
https://arxiv.org/abs/2112.11876

Combination - ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865

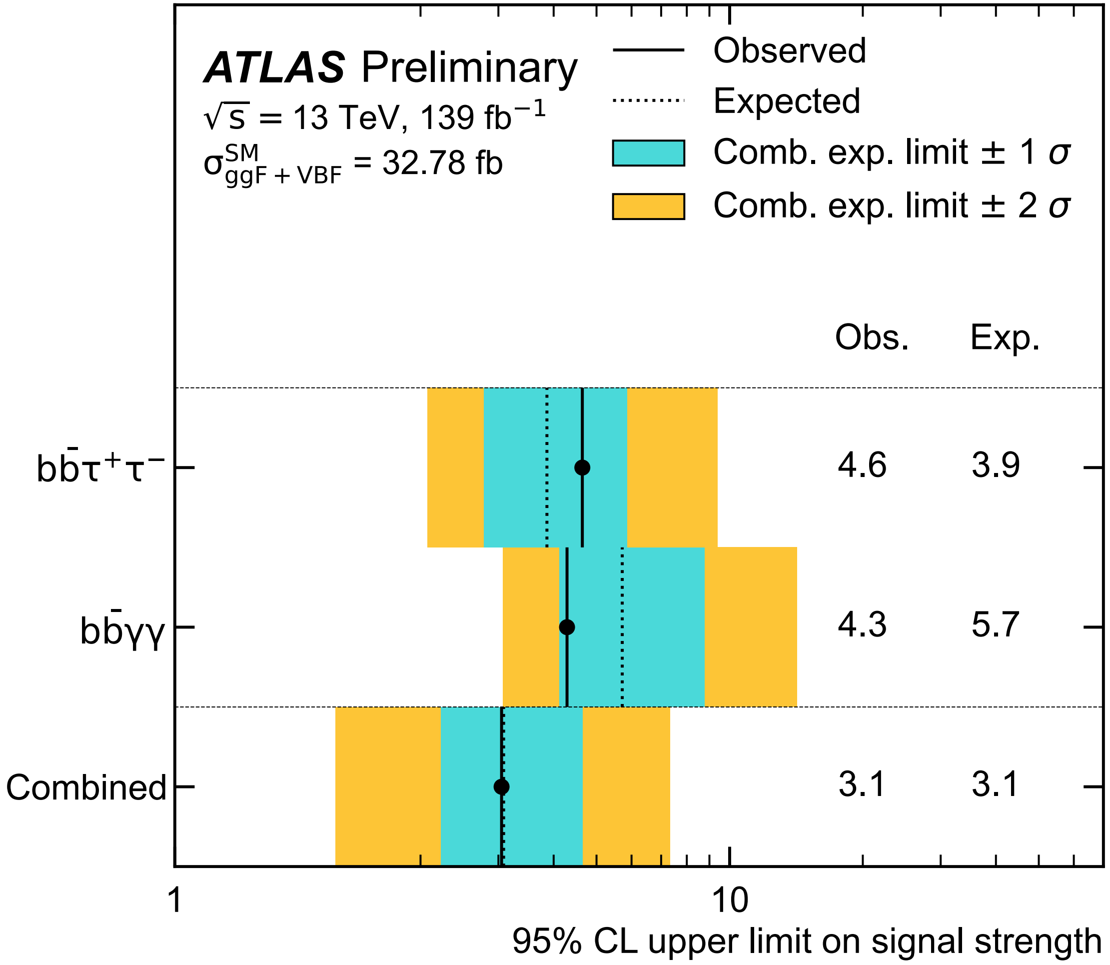


	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%	0.1%	0.029%	0.013%	0.0005%

More channels to come with more public results

Latest Limits on HH Signal Strength

Interpretation: As no HH signal is observed, can place the following limits at 95% confidence level

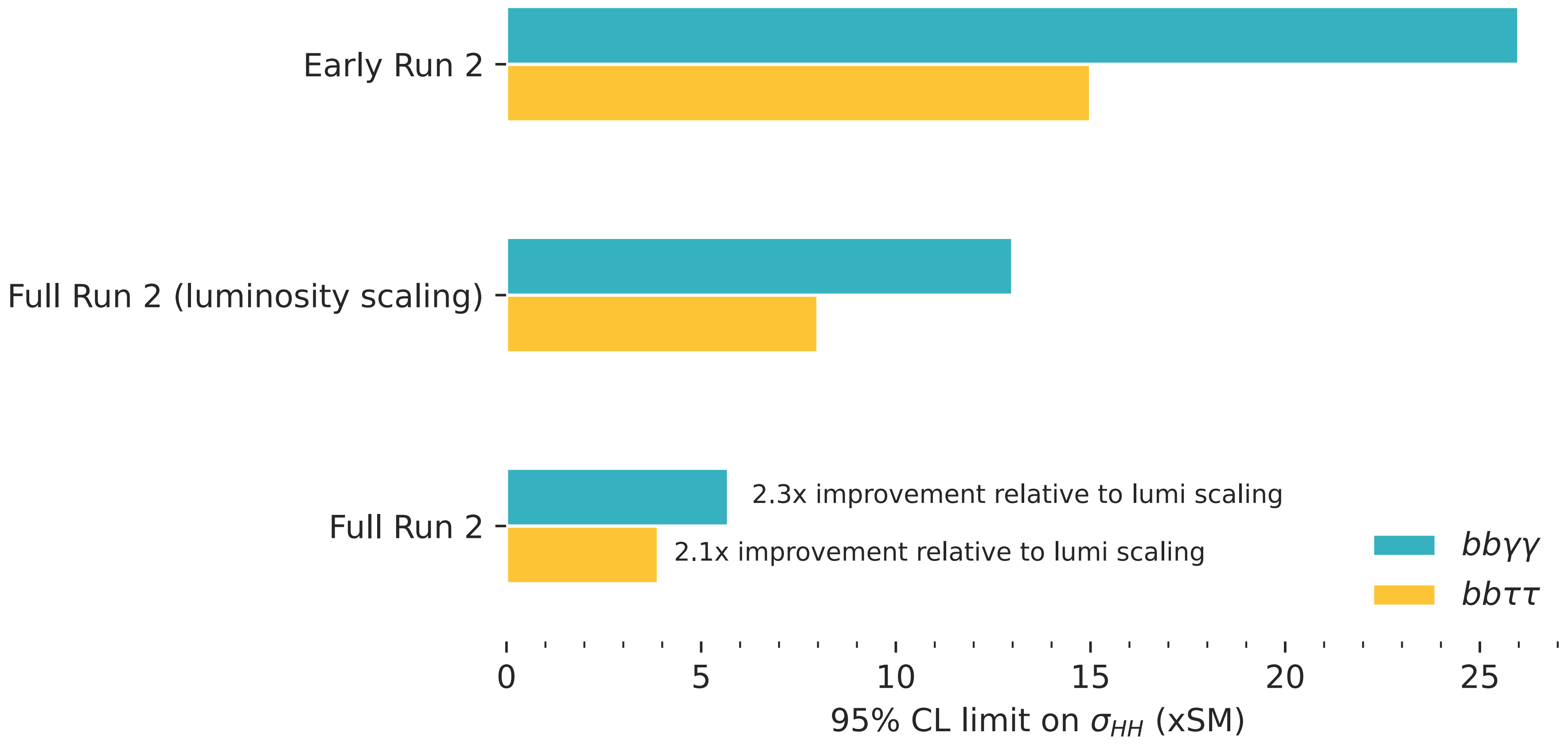


World-leading limit!

ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865

Improvements Relative to Early Run 2

Data from VMM Cairo: https://indico.cern.ch/event/1079757/



$bb\gamma\gamma$:
improved analysis strategy, categorization in m_{HH} with two BDTs targeting SM-like and BSM-like HH signals

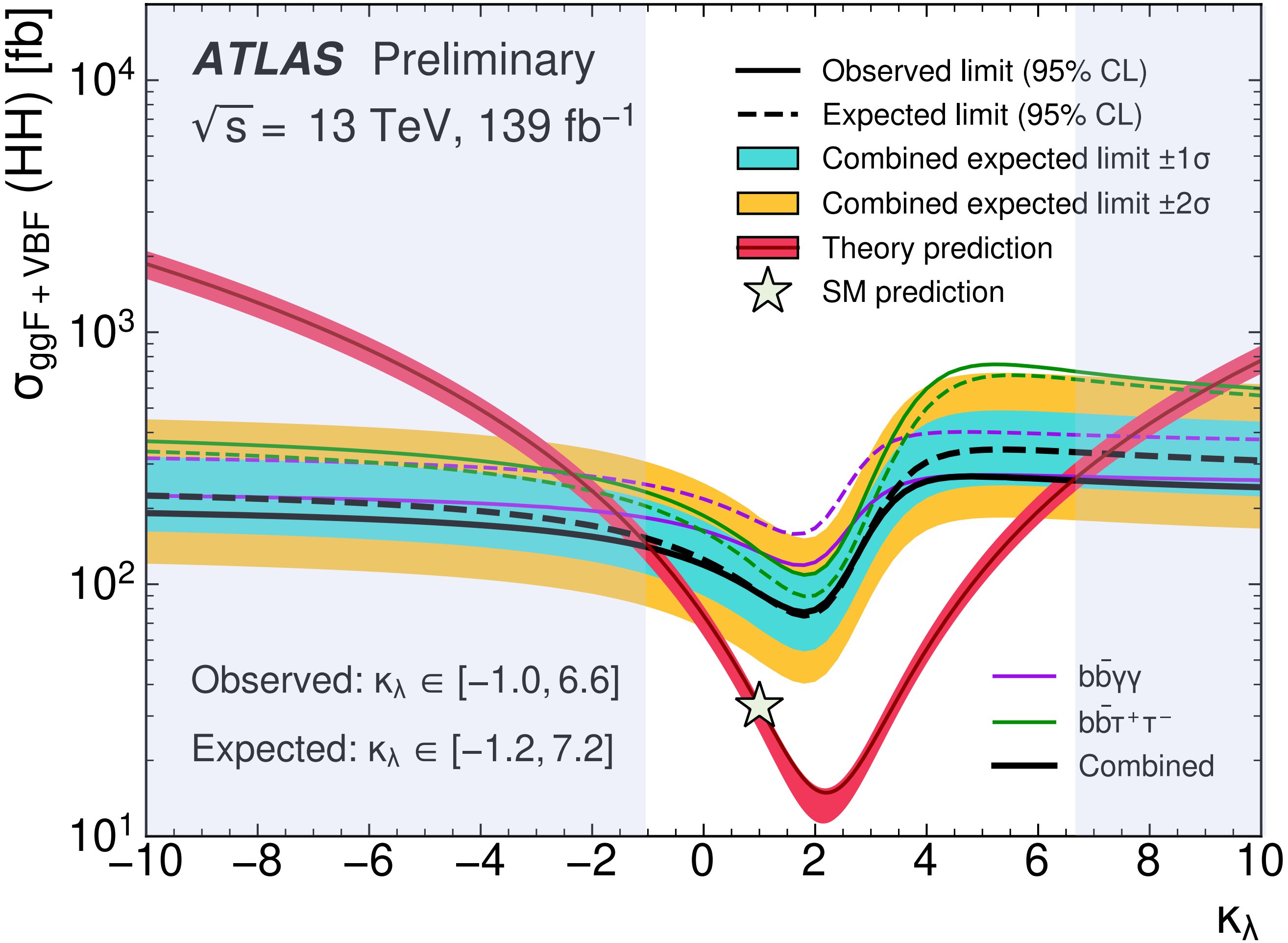
$bb\tau\tau$:
- improved τ-id (25-38%) efficiency
- 10% b-jet id efficiency

Both channels include VBF HH production in signal now too (1.73 fb vs 31.05 fb for ggF).

Further ingenuity may continue to improve these limits in the future.

Latest Constraints on the Higgs Boson Self-Coupling

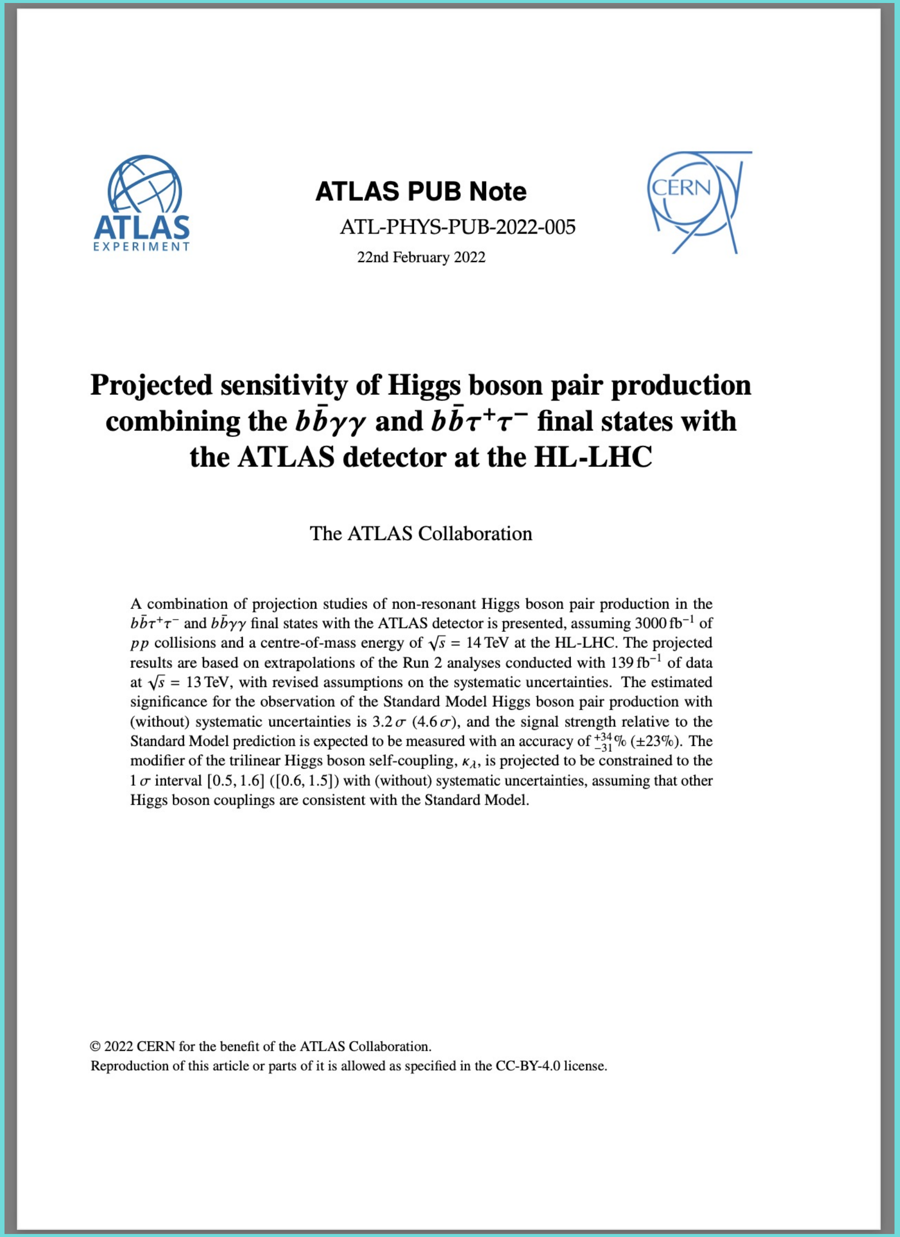
Interpretation: As no HH signal is observed, can place the following constraints at 95% confidence level



World-leading limit!

ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865

HL-LHC Prospects



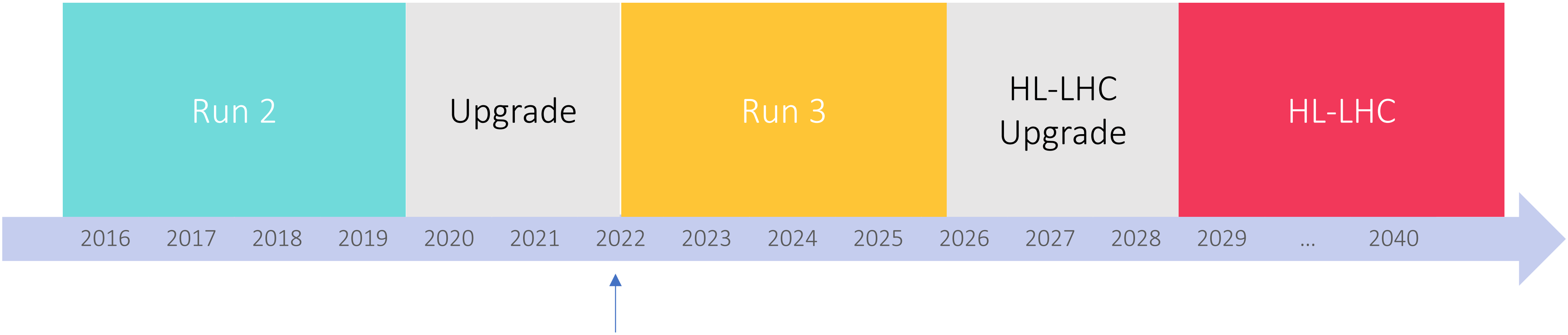
ATLAS PUB Note
ATL-PHYS-PUB-2022-005
22nd February 2022

Projected sensitivity of Higgs boson pair production combining the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states with the ATLAS detector at the HL-LHC

The ATLAS Collaboration

A combination of projection studies of non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ final states with the ATLAS detector is presented, assuming 3000 fb^{-1} of pp collisions and a centre-of-mass energy of $\sqrt{s}$ = 14 TeV at the HL-LHC. The projected results are based on extrapolations of the Run 2 analyses conducted with 139 fb^{-1} of data at $\sqrt{s}$ = 13 TeV, with revised assumptions on the systematic uncertainties. The estimated significance for the observation of the Standard Model Higgs boson pair production with (without) systematic uncertainties is $3.2\,\sigma$ ($4.6\,\sigma$), and the signal strength relative to the Standard Model prediction is expected to be measured with an accuracy of $^{+34}_{-31}$% (±23%). The modifier of the trilinear Higgs boson self-coupling, κ_λ, is projected to be constrained to the $1\,\sigma$ interval [0.5, 1.6] ([0.6, 1.5]) with (without) systematic uncertainties, assuming that other Higgs boson couplings are consistent with the Standard Model.

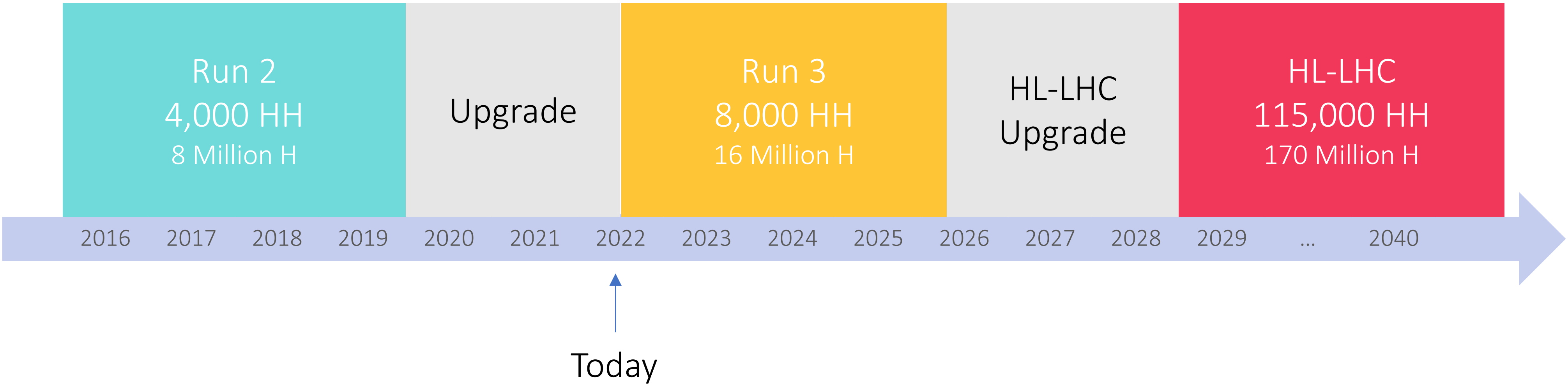
HL-LHC Timeline



Today

Instantaneous luminosity will increase 5x
Expect to collect ~20x more data!

HL-LHC Timeline



Run 2
4,000 HH
8 Million H

Upgrade

Run 3
8,000 HH
16 Million H

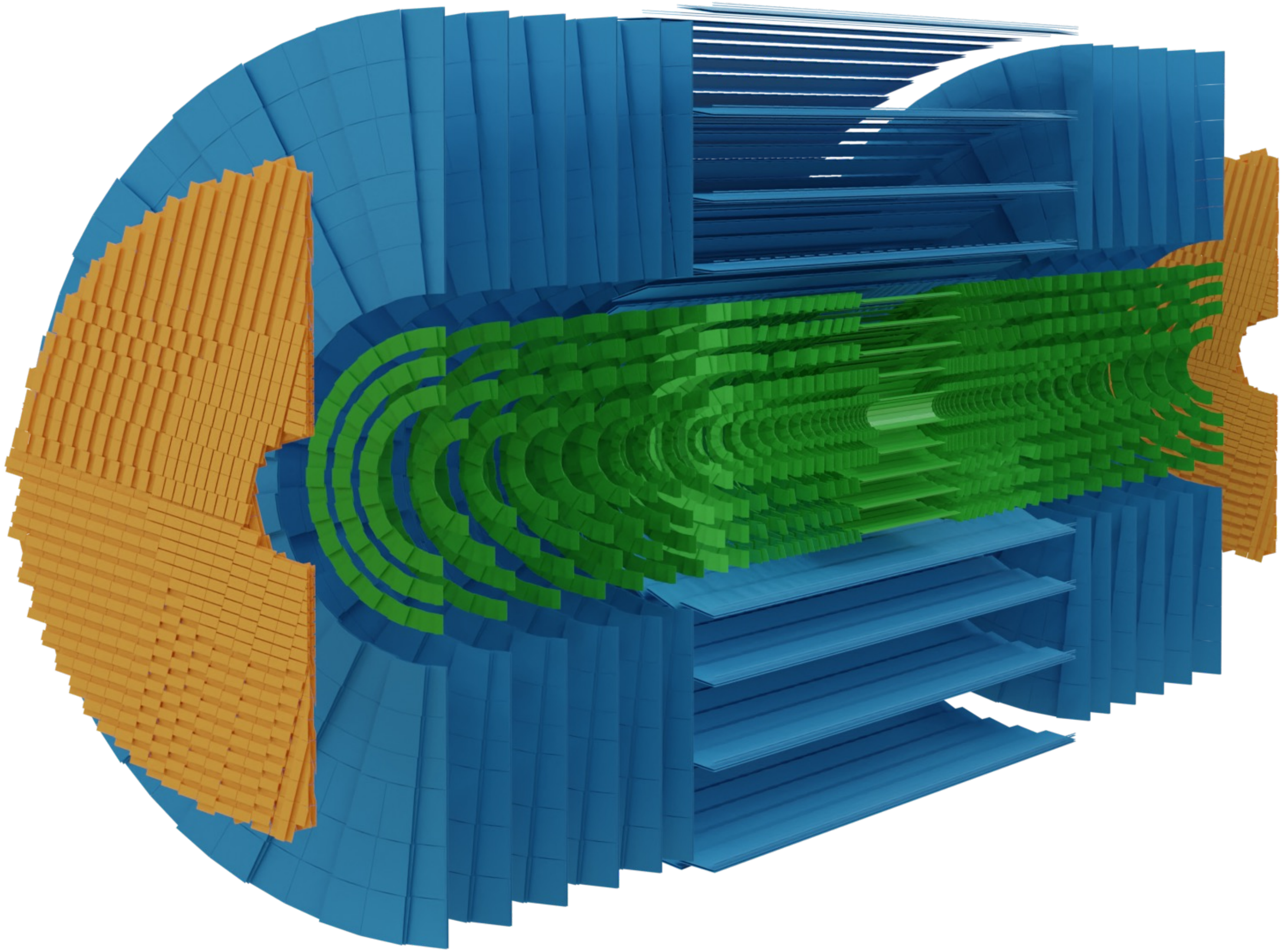
HL-LHC
Upgrade

HL-LHC
115,000 HH
170 Million H

2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 … 2040

Today

ATLAS Upgrades



HL-LHC will increase pile-up from 40 to 200. Upgrades required to handle the massive amount of pile-up at HL-LHC without degrading performance.

Key upgrades:

- Brand new all silicon tracking detector - two innermost layers being constructed at SLAC!
- New high-granularity timing detector
- Upgraded electronics for various subsystems, trigger and data acquisition.

ITk & HGTD visualized with ACTS: https://arxiv.org/abs/2106.13593

HL-LHC Extrapolation Procedure

Extrapolating from Run 2 results obtained with 139fb^{-1} of data at 13 TeV

Luminosity scaled to $3000\ \text{fb}^{-1}$ 21x more data than Run 2!

Cross-sections scaled to adjust from 13 to 14 TeV

Assumes no improvement on object performance, triggering or analysis strategy.

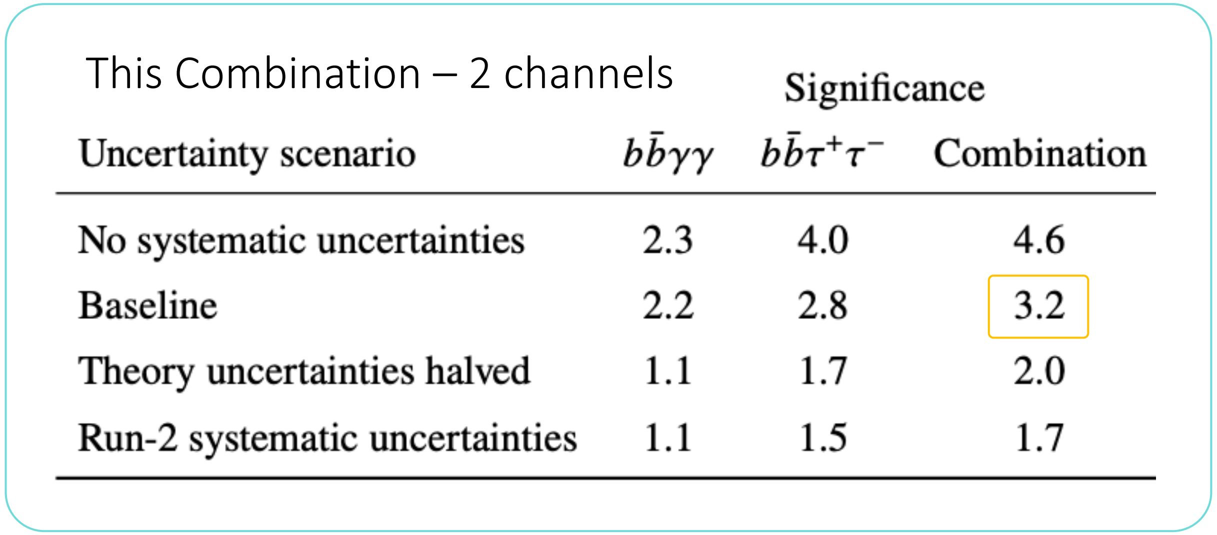
For baseline, uncertainties scaled as follows:

Statistical Uncertainties	$\propto 1/\sqrt{L}$
Experimental Uncertainties	$\propto 1/\sqrt{L}$ Until floor reached
Theoretical Uncertainties	x 0.5

Also interpret with no systematics, Run 2 systematics, and Run 2 systematics with theory uncertainties halved.

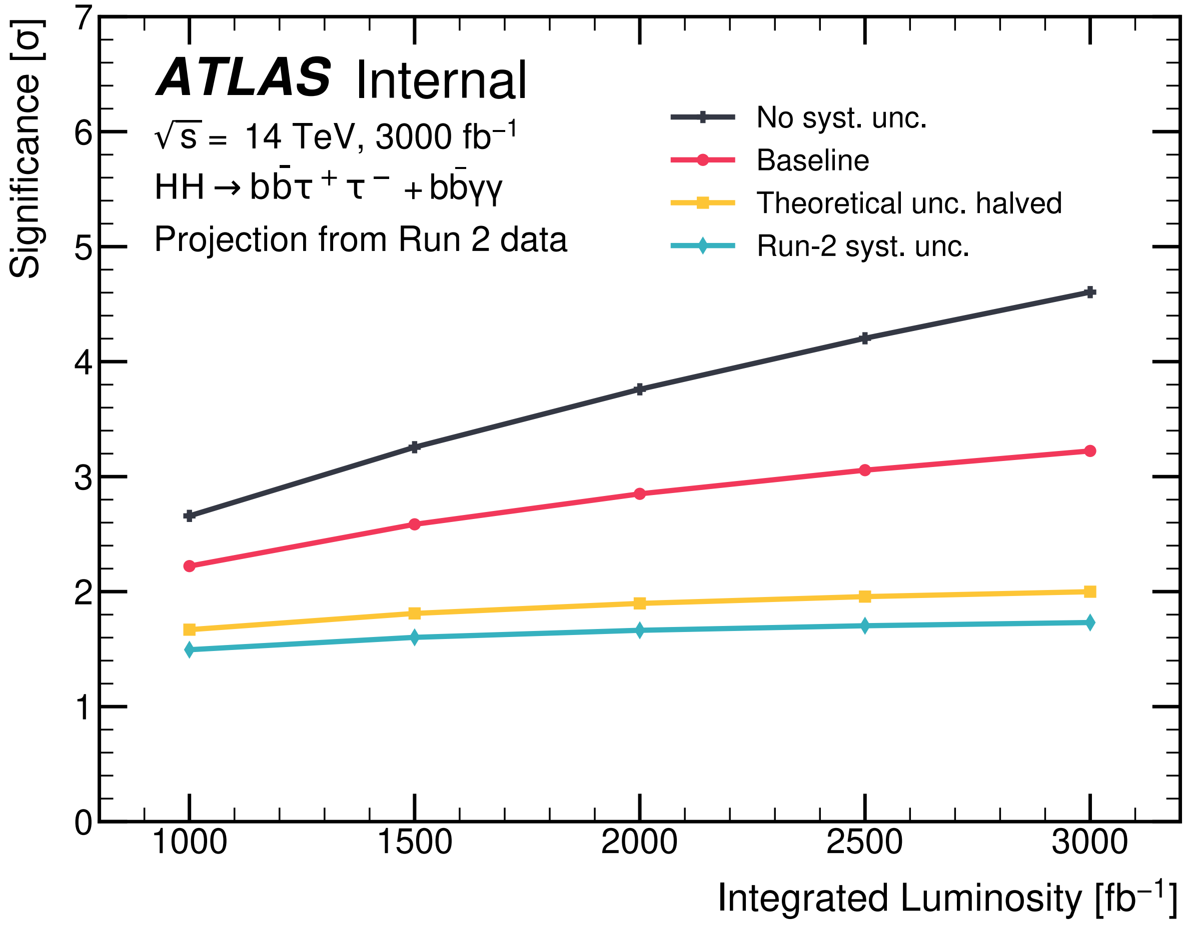
HH Significance

ATLAS-CONF-2021-052



This Combination – 2 channels

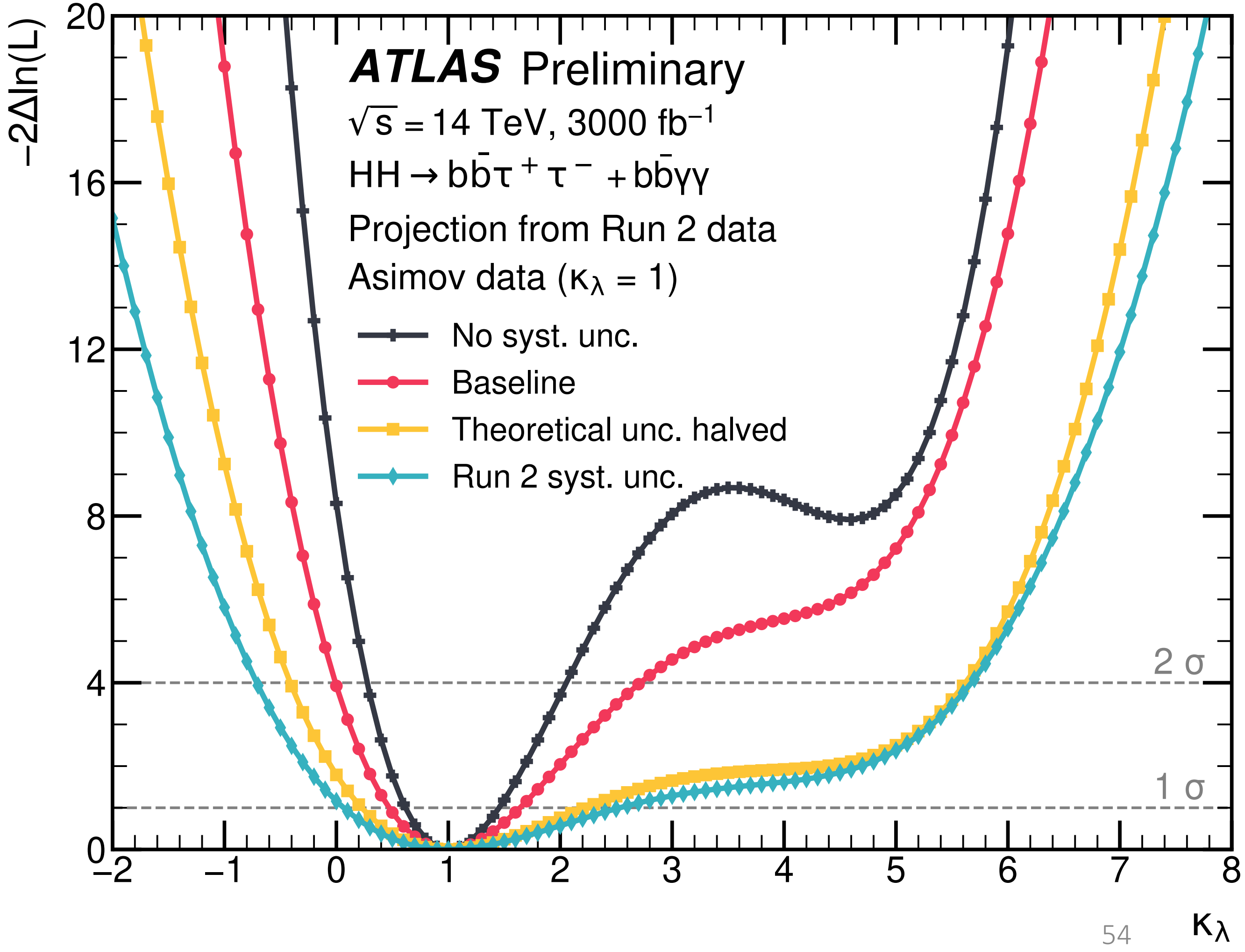
Uncertainty scenario	Significance		
	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination
No systematic uncertainties	2.3	4.0	4.6
Baseline	2.2	2.8	3.2
Theory uncertainties halved	1.1	1.7	2.0
Run-2 systematic uncertainties	1.1	1.5	1.7



HH Likelihood Scan ATLAS-CONF-2021-052

Negative log of the likelihood ratio comparing different k_λ hypotheses to an Asimov dataset constructed with $k_\lambda = 1$

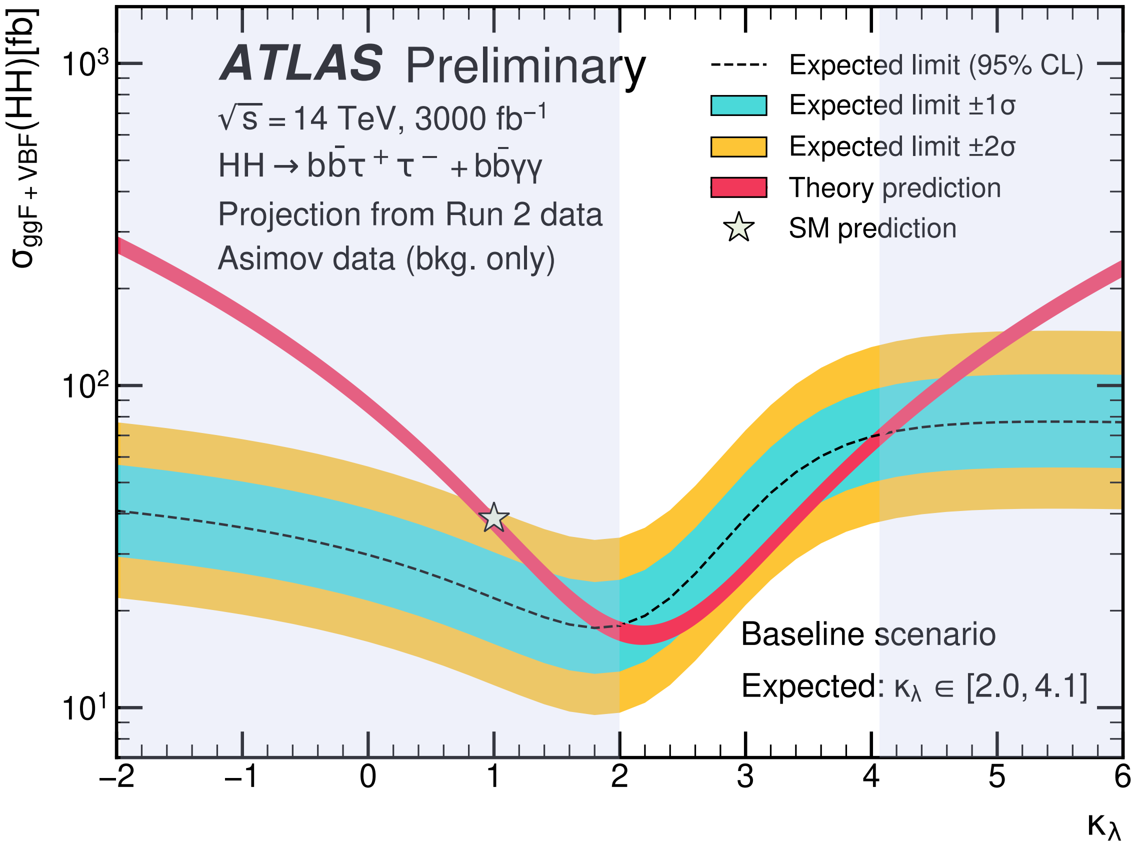
Uncertainty scenario	Likelihood scan 1σ CI	Likelihood scan 2σ CI
No systematic uncertainties	$[0.6, 1.5]$	$[0.3, 2.1]$
Baseline	$[0.5, 1.6]$	$[0.0, 2.7]$
Theory uncertainties halved	$[0.2, 2.2]$	$[-0.4, 5.6]$
Run-2 systematic uncertainties	$[0.1, 2.5]$	$[-0.7, 5.7]$



Projected Constraints on Higgs Boson Self-Coupling

Interpretation: If no HH signal is observed, can place the following constraints at 95% confidence level

ATL-PHYS-PUB-2022-005 http://cdsweb.cern.ch/record/2802127



If we see no evidence of SM HH production, k_λ=1 expected to be excluded!

Summary

Three main channels used to search for HH. Each channel starting to approach SM sensitivity.

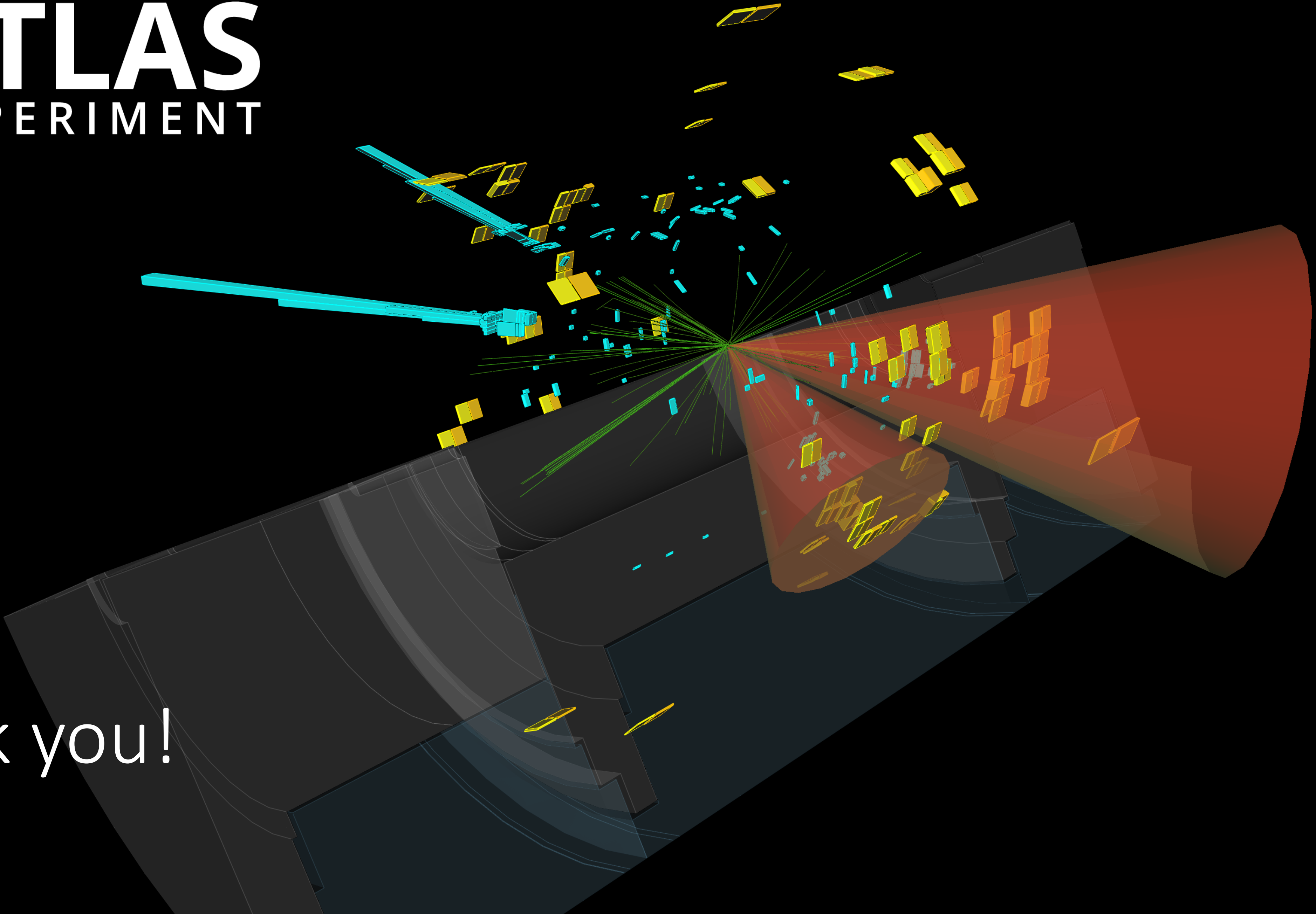
HH $bb\gamma\gamma$: Observed limit on SM signal strength: **4.1xSM**, observed limits on $k_{\lambda,}$ $-1.5 < k_\lambda < 6.7$

HH combination:
$bb\tau\tau$ + $bb\gamma\gamma$ - Observed limit on SM signal strength: **3.1xSM**, observed limits on k_λ $-1.0 \leq k_\lambda \leq 6.6$

HH at HL-LHC
Baseline combined expected SM significance @ HL-LHC of **3.2σ** with just $bb\tau\tau$ and $bb\gamma\gamma$ channels.
Will likely be able to constrain k_λ to within **50%** uncertainty.

Next steps:
More channels, combination with single Higgs analyses, EFT interpretations and more data will improve current and projected results.

Future:
In addition to HL-LHC, future e+e- Higgs factory colliders will allow us to further study the Higgs boson self-coupling with precision.



Thank you!

References

2018 HL-LHC Prospects Combination http://cdsweb.cern.ch/record/2652727

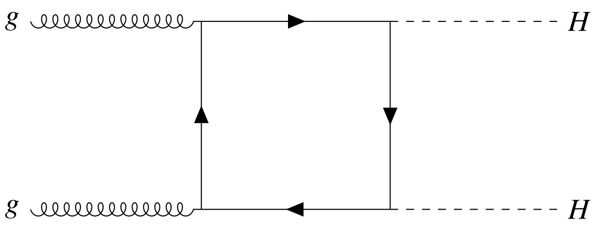
2021 HL-LHC Prospects bbττ https://cds.cern.ch/record/2798448
2022 HL-LHC Prospects bb$\gamma\gamma$ http://cdsweb.cern.ch/record/2799146
2022 HL-LHC Prospects Combination http://cdsweb.cern.ch/record/2802127

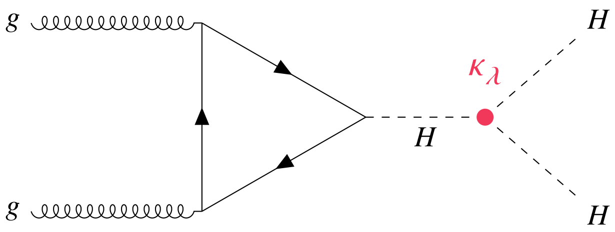
2021 Full Run 2 bbττ https://cds.cern.ch/record/2777236
2021 Full Run 2 bb$\gamma\gamma$ https://arxiv.org/abs/2112.11876
2021 Full Run 2 HH Combination https://cds.cern.ch/record/2786865
2022 Full Run 2 HH HEFT Interpretations
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-021/

HH Production Channels

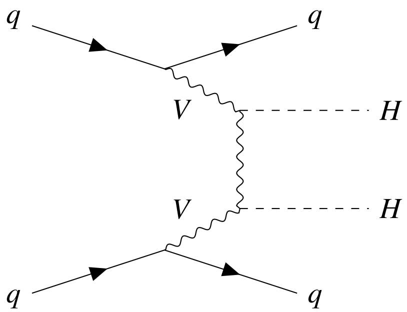
Non-Resonant

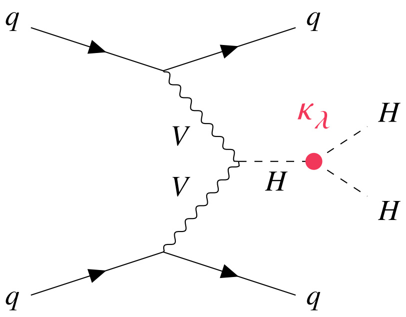
ggF: σ_{SM} = 31.05 fb

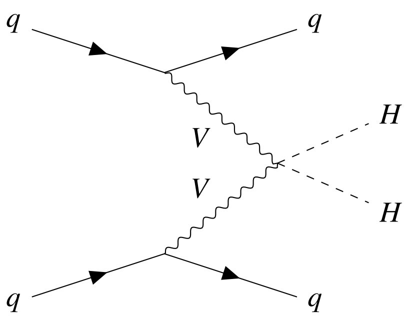




VBF: σ_{SM} = 1.73 fb







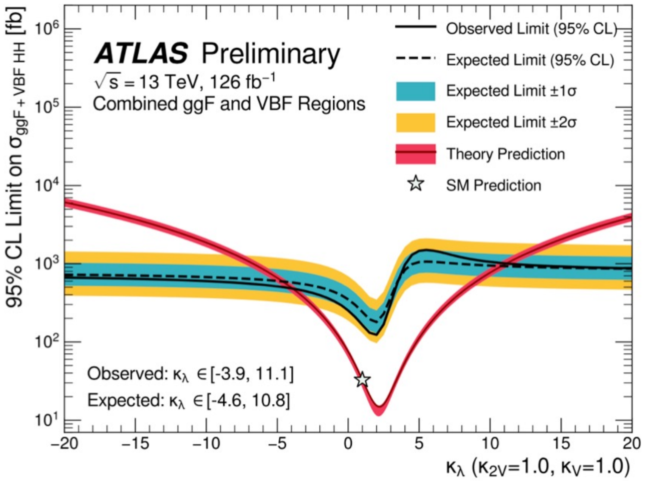
HH→$b\bar{b}b\bar{b}$ non-resonant results

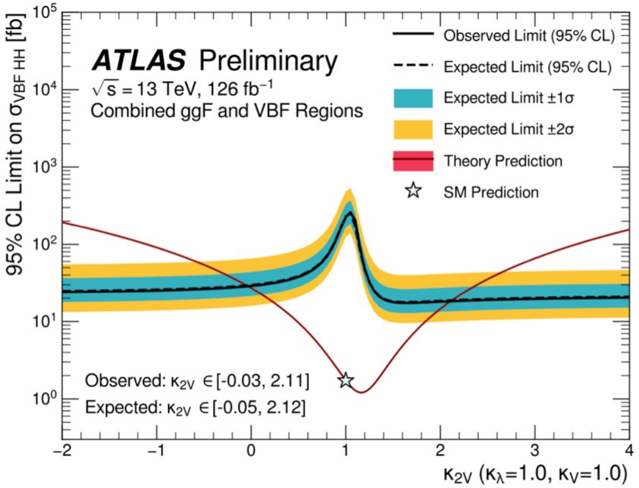
More in Non-resonant HH Tue 9:00

Slides from Rui Zhang: https://indico.cern.ch/event/1001391/

	Observed Limit	**-2σ**	**-1σ**	**Expected Limit**	**$+1\sigma$**	**$+2\sigma$**
$\sigma_{\text{ggF}}/\sigma_{\text{ggF}}^{\text{SM}}$	5.5	4.4	5.9	8.2	12.4	19.6
$\sigma_{\text{VBF}}/\sigma_{\text{VBF}}^{\text{SM}}$	130.5	71.6	96.1	133.4	192.9	279.3
$\sigma_{\text{ggF+VBF}}/\sigma_{\text{ggF+VBF}}^{\text{SM}}$	5.4	4.3	5.8	8.1	12.2	19.1

- 2.5x improvement wrt previous ggF result (11.1(20.7) x SM)
- 4.1x improvement wrt previous VBF results (840(550) x SM)





k$_\lambda$ Parameterization

ggF

$$\frac{d\sigma(\kappa_\lambda)}{dm_{HH}} = |A(\kappa_\lambda)|^2 = |\kappa_\lambda M_\triangle(m_{HH}) + M_\Box(m_{HH})|^2$$

$$\frac{d\sigma(\kappa_\lambda)}{dm_{HH}} = \kappa_\lambda^2 a_1(m_{HH}) + \kappa_\lambda a_2(m_{HH}) + a_3(m_{HH})$$

VBF

$$\sigma(\kappa_{2V}, \kappa_\lambda, \kappa_V) = |A|^2 = |\kappa_V \kappa_\lambda M_s + \kappa_V^2 M_t + \kappa_{2V} M_x|^2$$

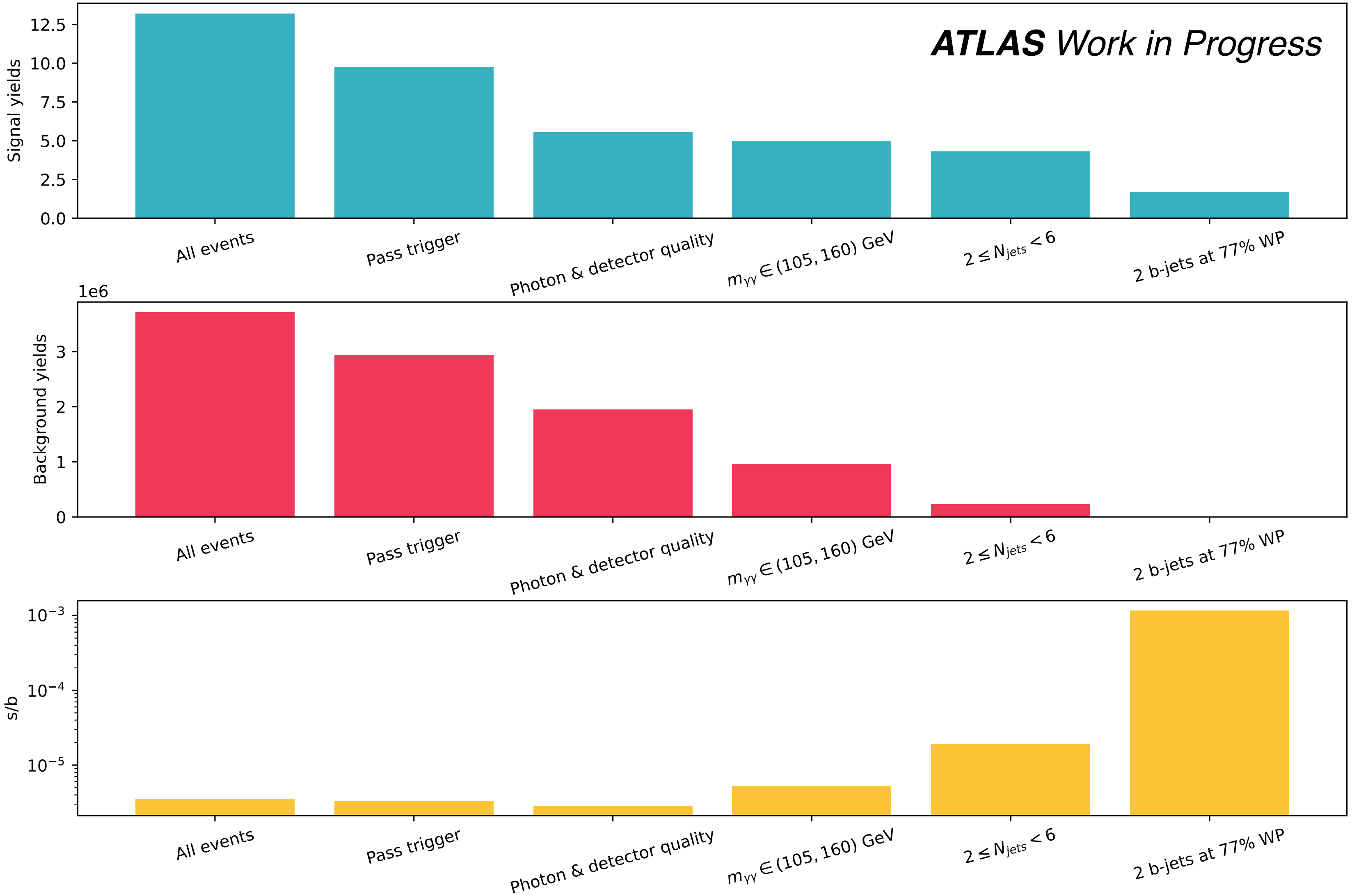
$$\sigma = \kappa_V^2 \kappa_\lambda^2 a_1 + \kappa_V^4 a_2 + \kappa_{2V}^2 a_3 + \kappa_V^3 \kappa_\lambda a_4 + \kappa_V \kappa_\lambda \kappa_{2V} a_5 + \kappa_V^2 \kappa_{2V} a_6$$

$$\sigma = \kappa_\lambda^2 a_1 + \kappa_\lambda a_2 + a_3$$

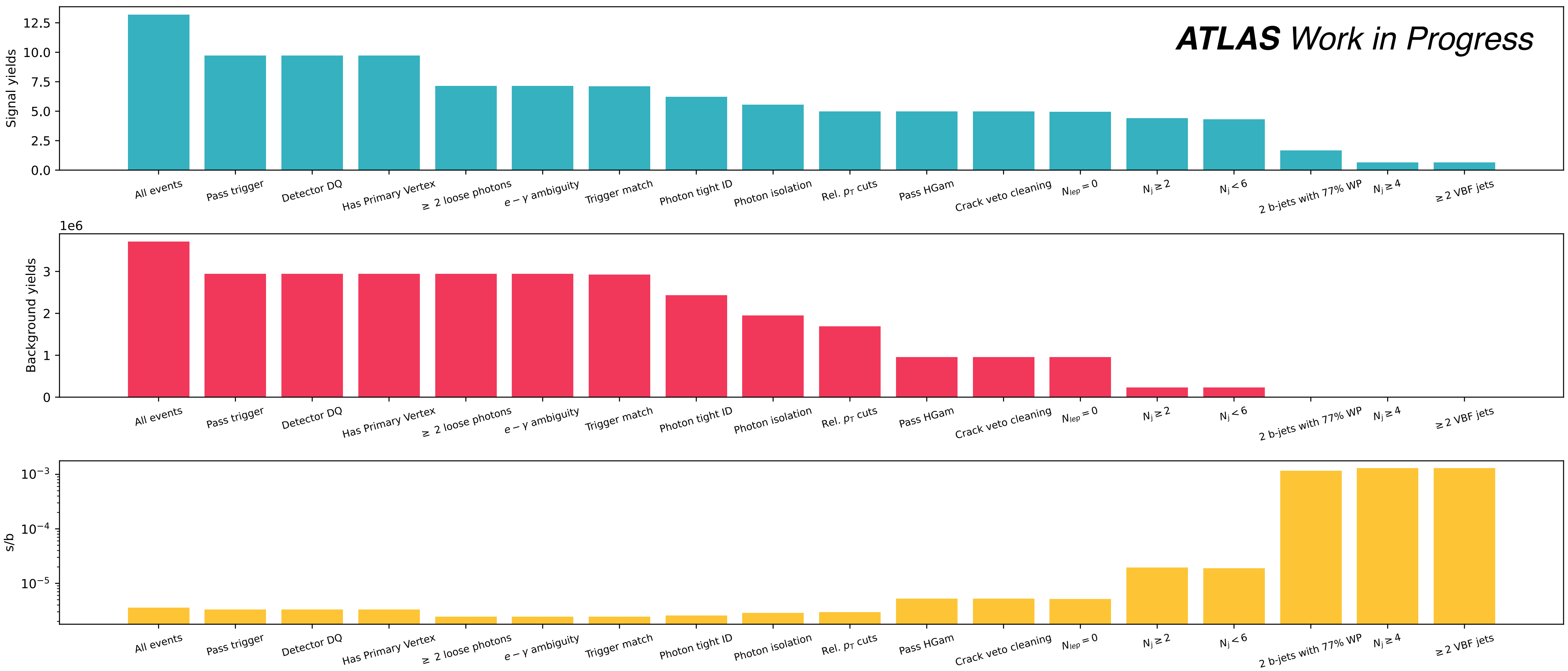
<- If kv and k2v are SM

$$\begin{aligned}\sigma(\kappa_{2V}, \kappa_\lambda, \kappa_V) = \\ \left(\frac{\kappa_\lambda^2}{9} - \frac{4\kappa_\lambda}{3} + \frac{20}{9}\right) \times \sigma(1,1,1) \\ + \left(-\frac{\kappa_\lambda^2}{8} + \frac{11\kappa_\lambda}{8} - \frac{5}{4}\right) \times \sigma(1,2,1) \\ + \left(\frac{\kappa_\lambda^2}{72} - \frac{\kappa_\lambda}{24} + \frac{1}{36}\right) \times \sigma(1,10,1)\end{aligned}$$

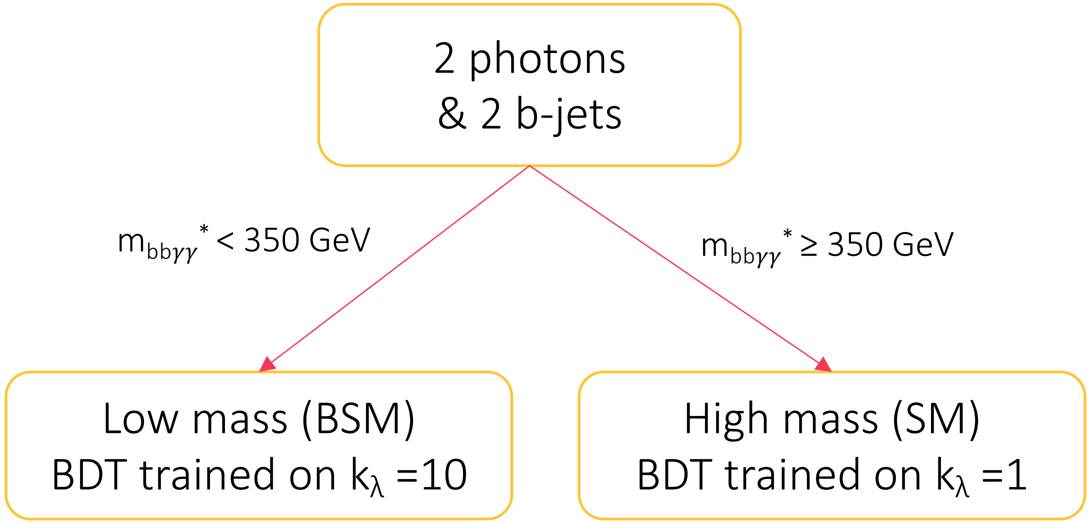
Pre-Selection Cutflow (simplified)



Detailed bbyy Cutflow



bb$\gamma\gamma$ Selection Strategy



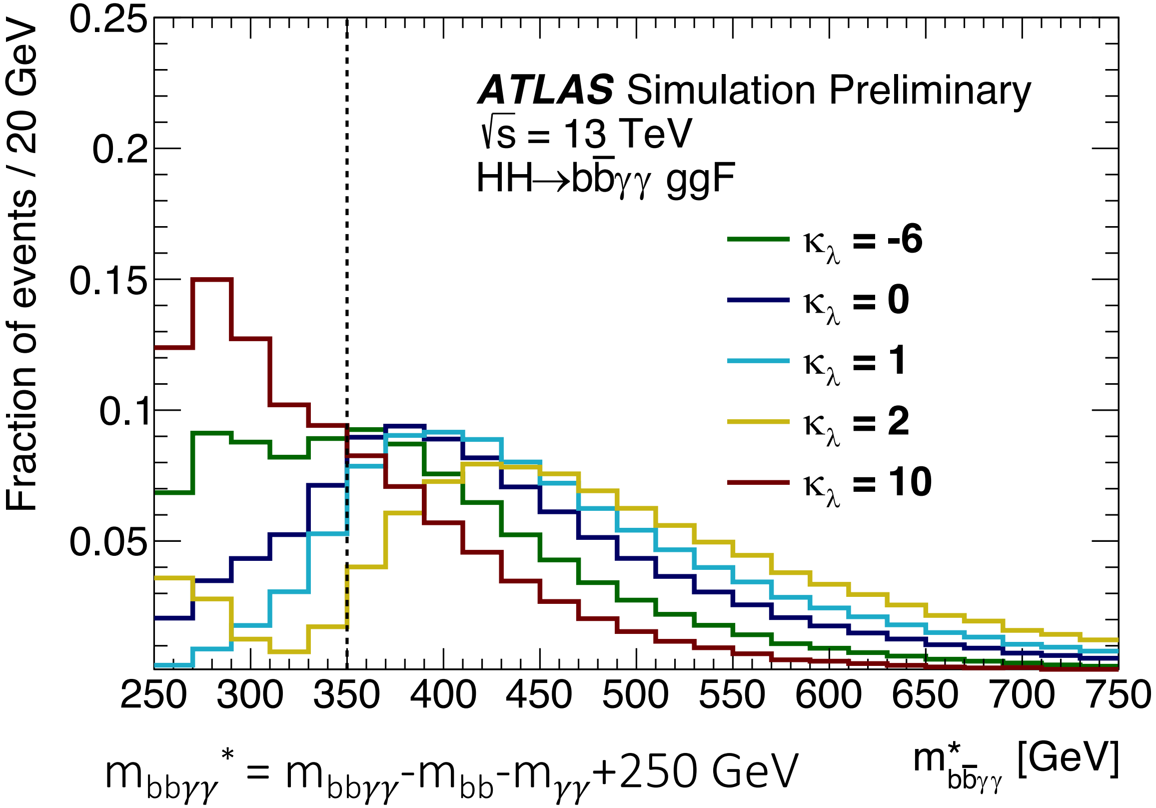
2 photons
& 2 b-jets

$m_{bb\gamma\gamma}{}^{*} < 350$ GeV

$m_{bb\gamma\gamma}{}^{*} \geq 350$ GeV

Low mass (BSM)
BDT trained on k_λ =10

High mass (SM)
BDT trained on k_λ =1

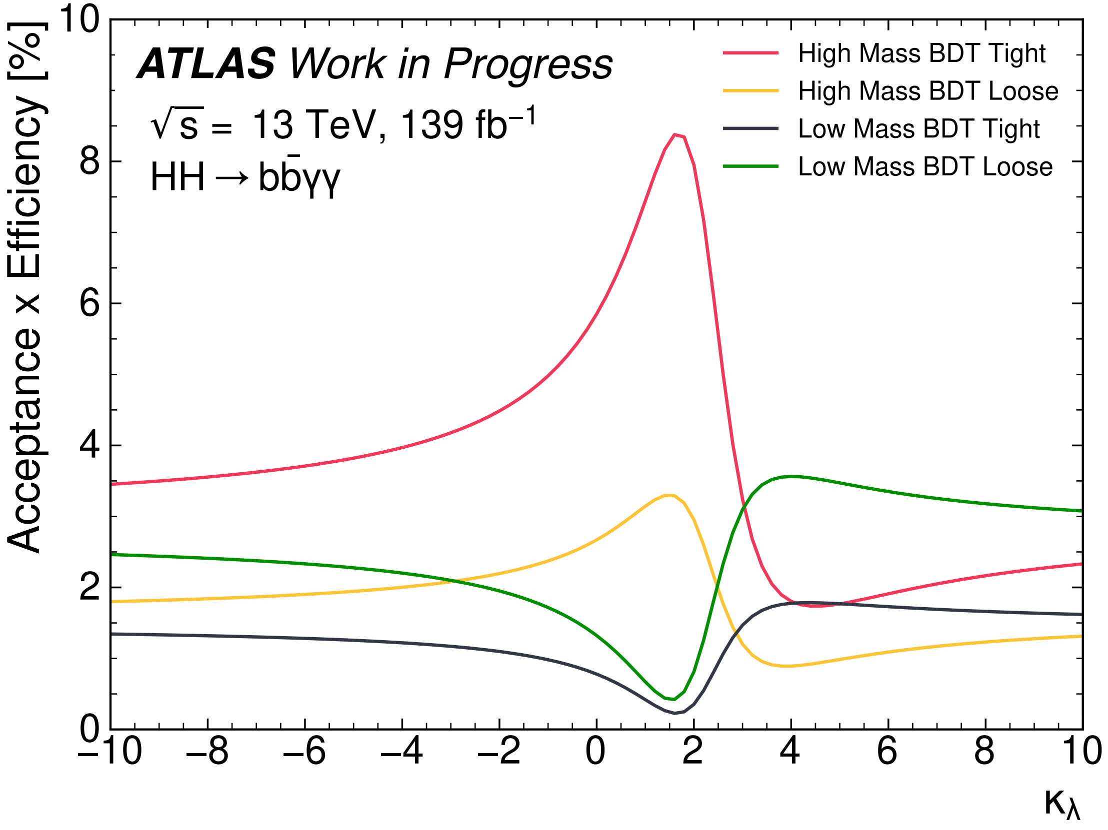


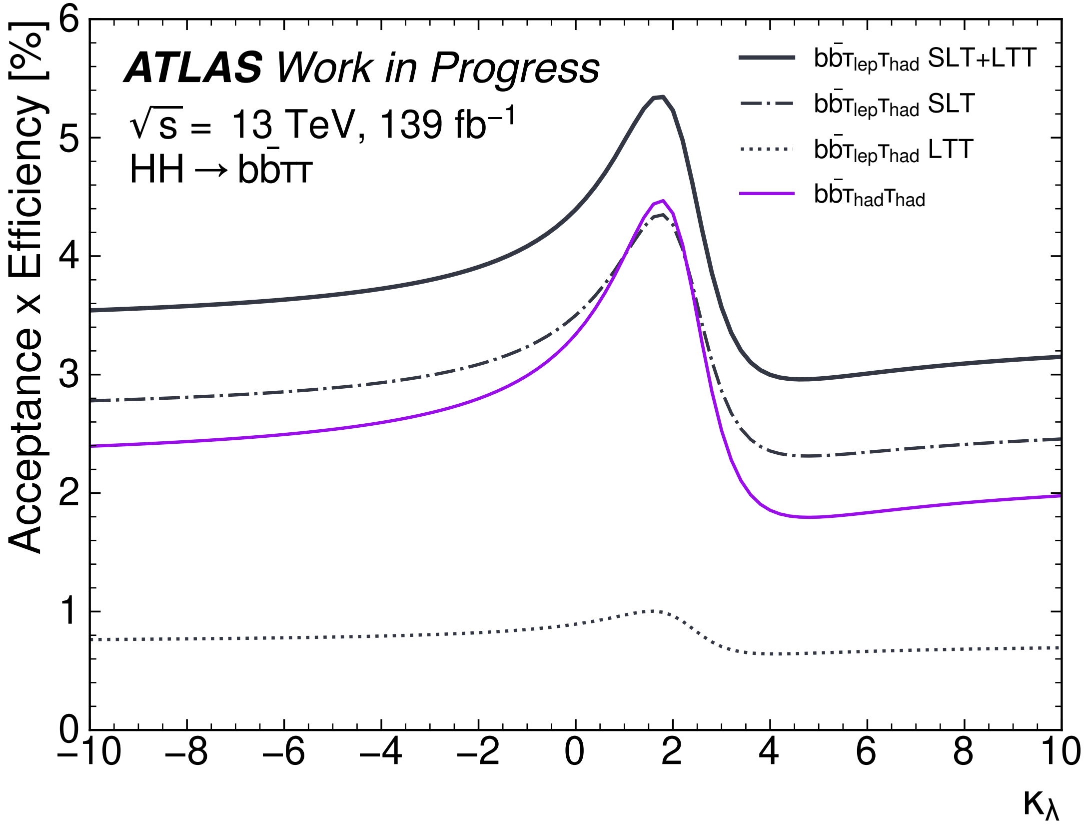
$m_{bb\gamma\gamma}{}^{*} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV

Split signal regions by $m_{bb\gamma\gamma}{}^{*}$ for sensitivity to SM and BSM HH.

Train two BDTs to target each signal region.

Acceptance x Efficiency as a function of k_λ

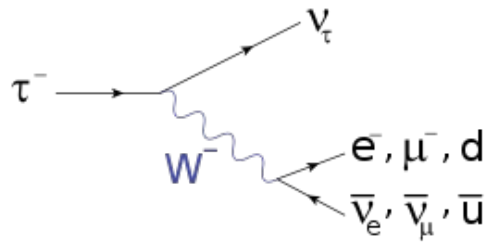


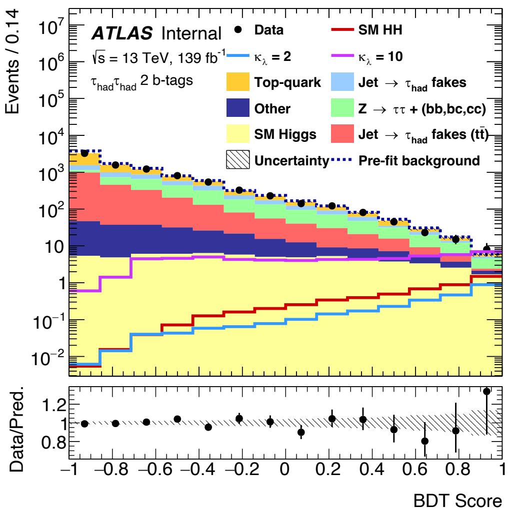


Analysis Overviews

bbττ: https://cds.cern.ch/record/2777236

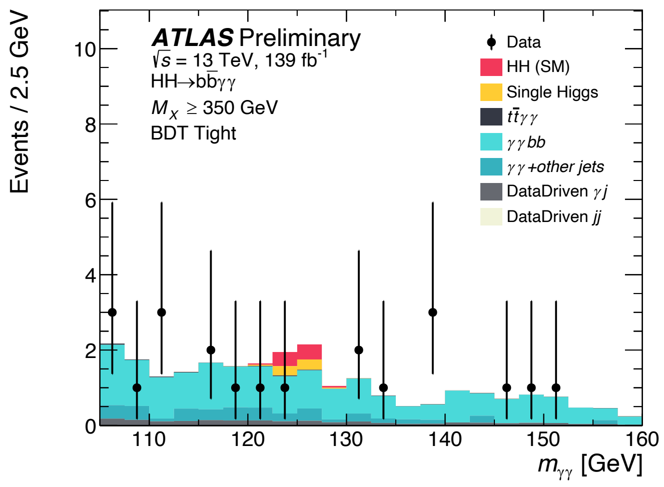
- Lep-had and had-had channels
- Lep-had includes single-lepton (SLT) and lepton+tau (LTT) triggers
- NN used in lep-had channels
- BDT used for had-had channel
- Final fit on MVA output distributions in 3 signal regions and m_{ll} in Z+HF control region



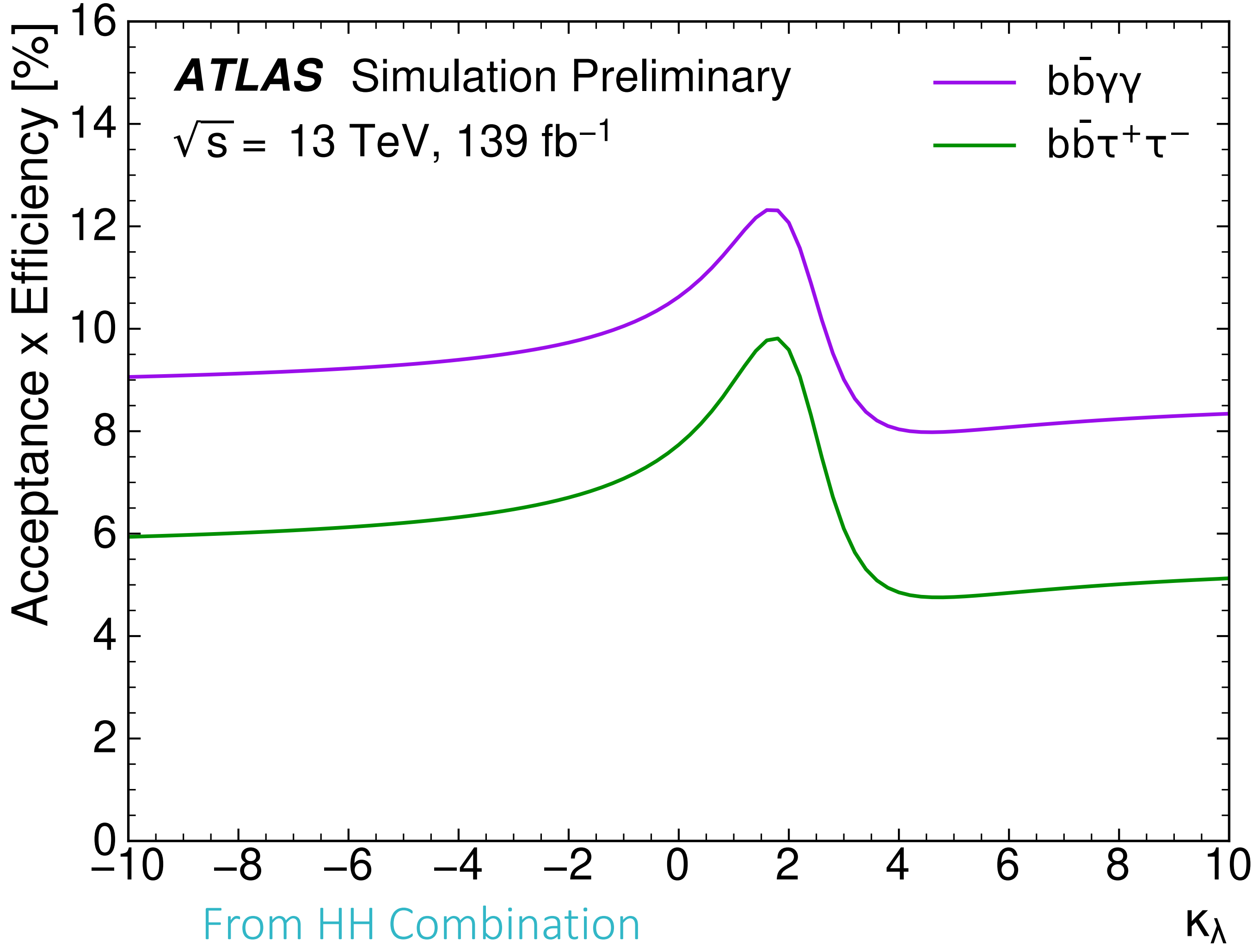


bb$\gamma\gamma$: https://arxiv.org/abs/2112.11876

- Small branching ratio, but clean diphoton signature for triggering
- Excellent $m_{\gamma\gamma}$ resolution (~1.5 GeV)
- BDTs with for high mass and low mass categories
- $m_{\gamma\gamma}$ peak fit with double-sided crystal ball
- Continuum $\gamma\gamma$+jets background fit with exponential
- Un-binned maximum likelihood fit in $m_{\gamma\gamma}$

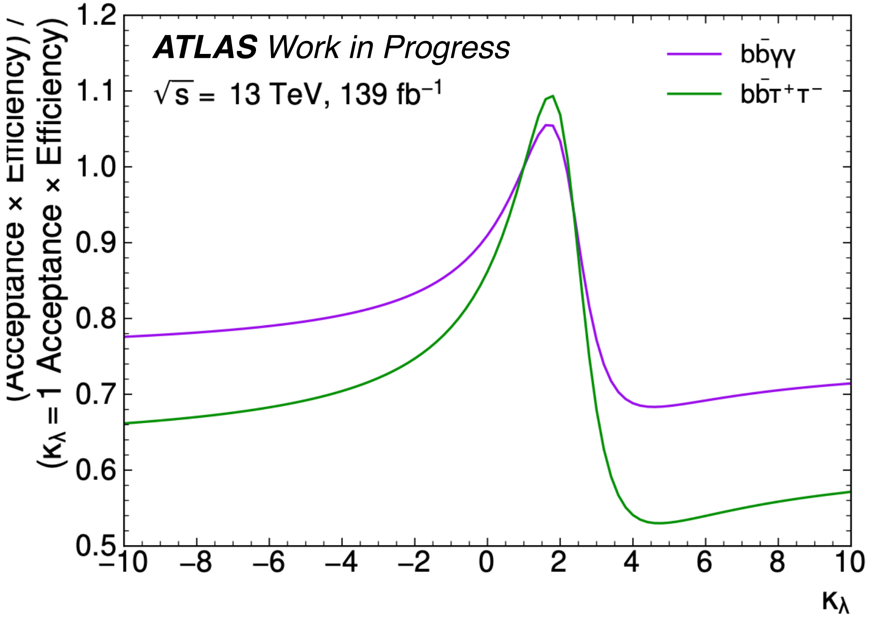


Acceptance x Efficiency as a function of k_λ



From HH Combination

$$\text{Acceptance x Efficiency} = \frac{\text{Yield}}{\sigma * \text{BR} * 139\,\text{fb}^{-1}}$$



Theory Uncertainties

- Missing higher-order effects of QCD corrections beyond N^3LO (δ(scale)).
- Missing higher-order effects of electroweak and mixed QCD-electroweak corrections at and beyond $\mathcal{O}(\alpha_S\alpha)$ (δ(EW)).
- Effects due to finite quark masses neglected in QCD corrections beyond NLO (δ(t,b,c) and $\delta(1/m_t)$

- Mismatch in the perturbative order of the parton distribution functions (PDF) evaluated at NNLO and the perturbative QCD cross sections evaluated at N^3LO (δ(PDF-TH)).

https://cds.cern.ch/record/2703572/files/94-87-PB.pdf

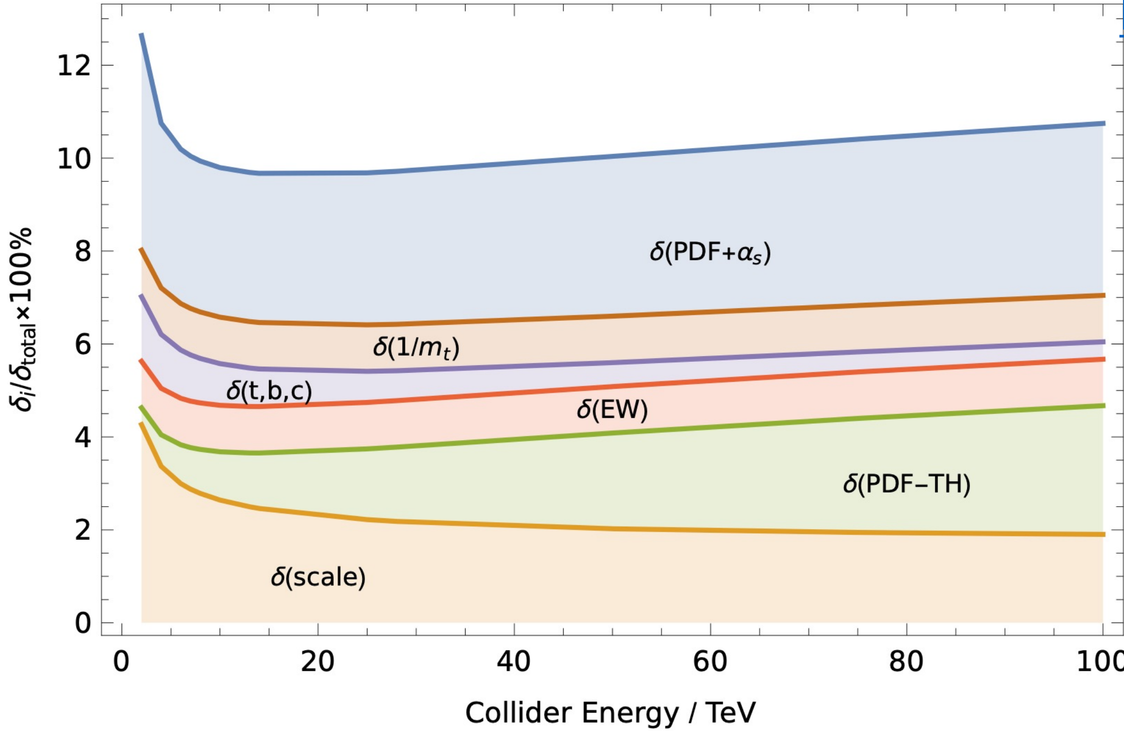
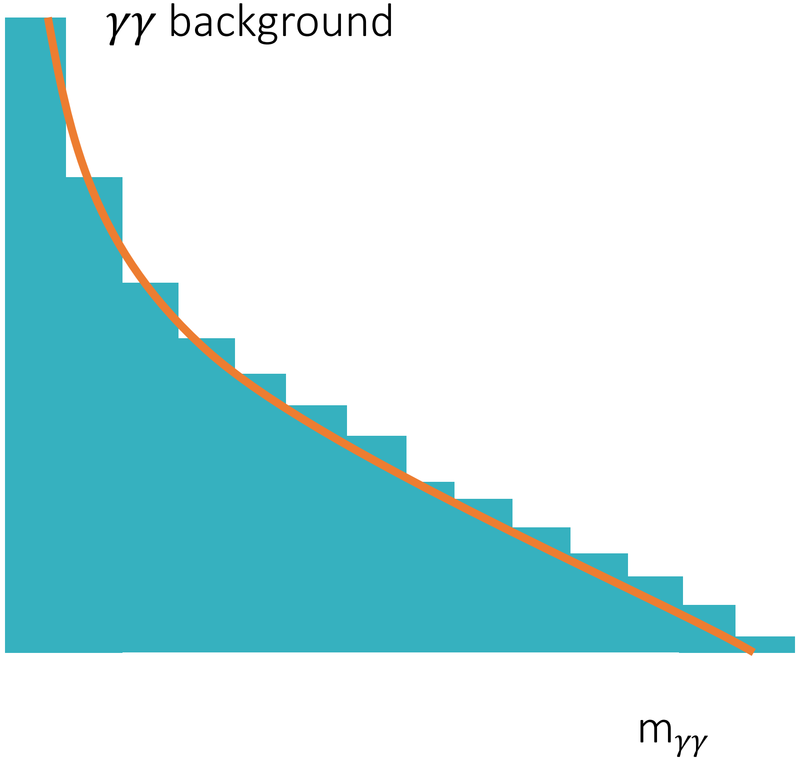


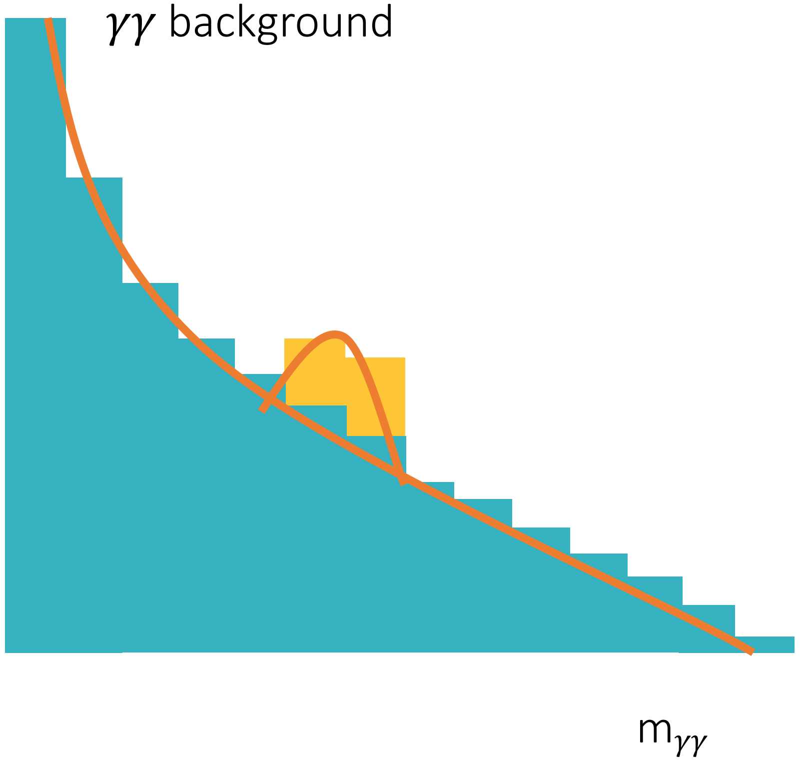
Fig. 1: The figure shows the linear sum of the different sources of relative uncertainties as a function of the collider energy. Each coloured band represents the size of one particular source of uncertainty as described in the text. The component $\delta(\text{PDF}+\alpha_S)$ corresponds to the uncertainties due to our imprecise knowledge of the strong coupling constant and of parton distribution functions combined in quadrature.

Spurious Signal Studies



Fit background with an exponential function

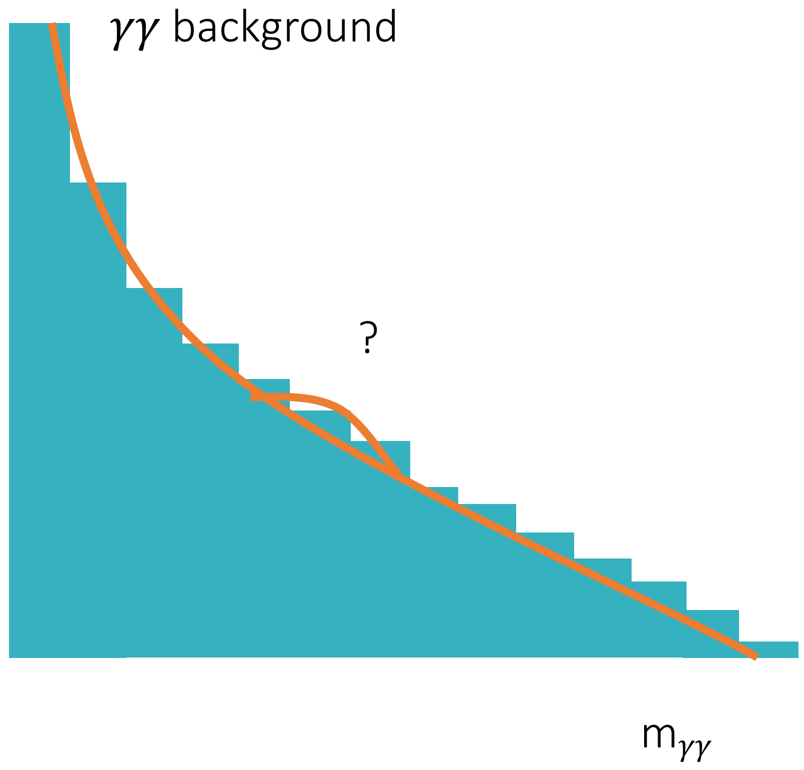
Spurious Signal Studies



Fit background with an exponential function

Fit signal with a double-sided crystal ball function

Spurious Signal Studies



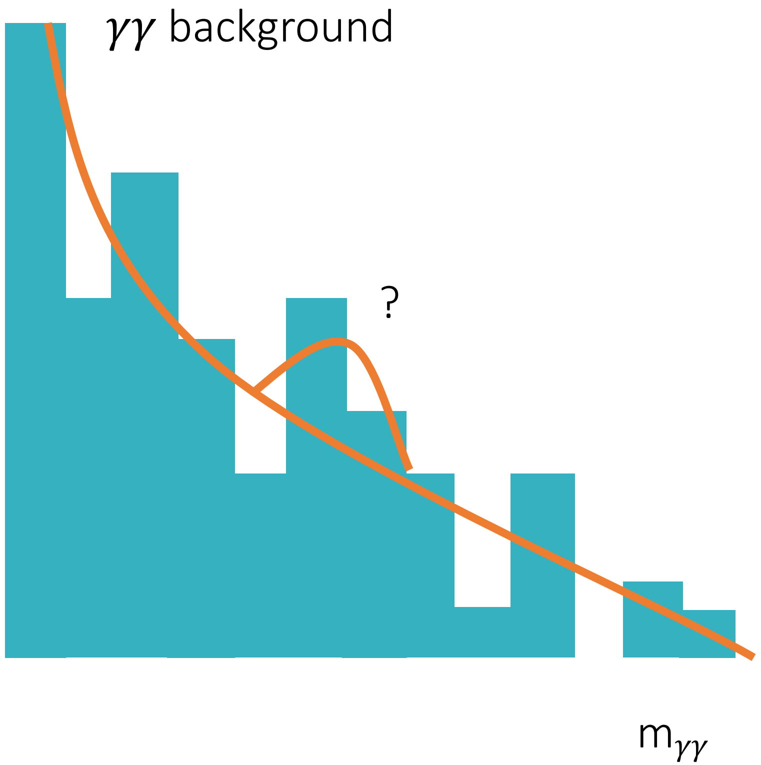
Fit background with an exponential function

Fit signal with a double-sided crystal ball function

Could we fit a signal even if it doesn’t exist?

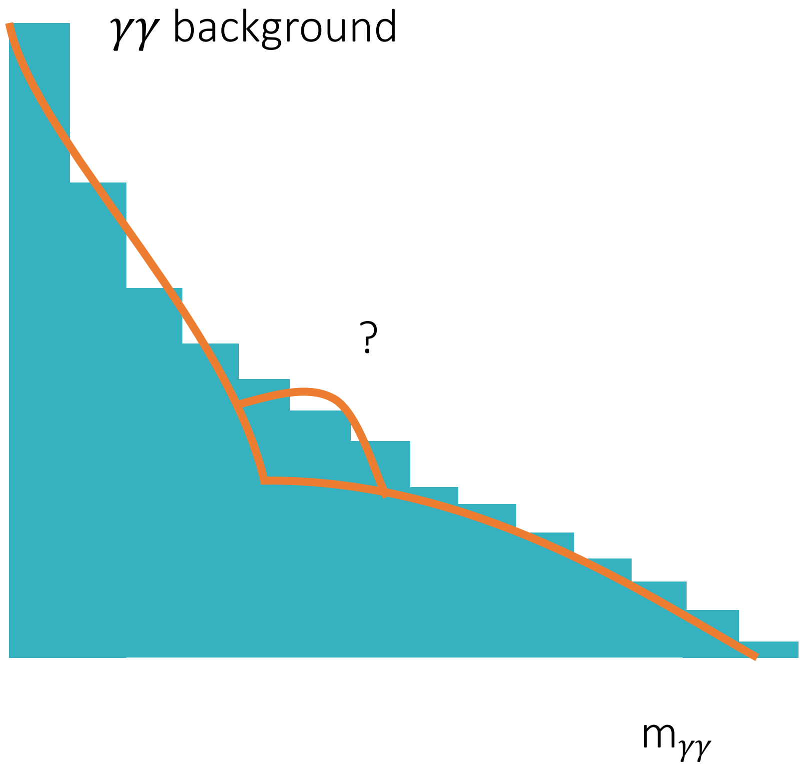
Spurious signal uncertainty tries to characterize this by adding an uncertainty proportional to the size of the fitted spurious signal.

Spurious Signal Studies



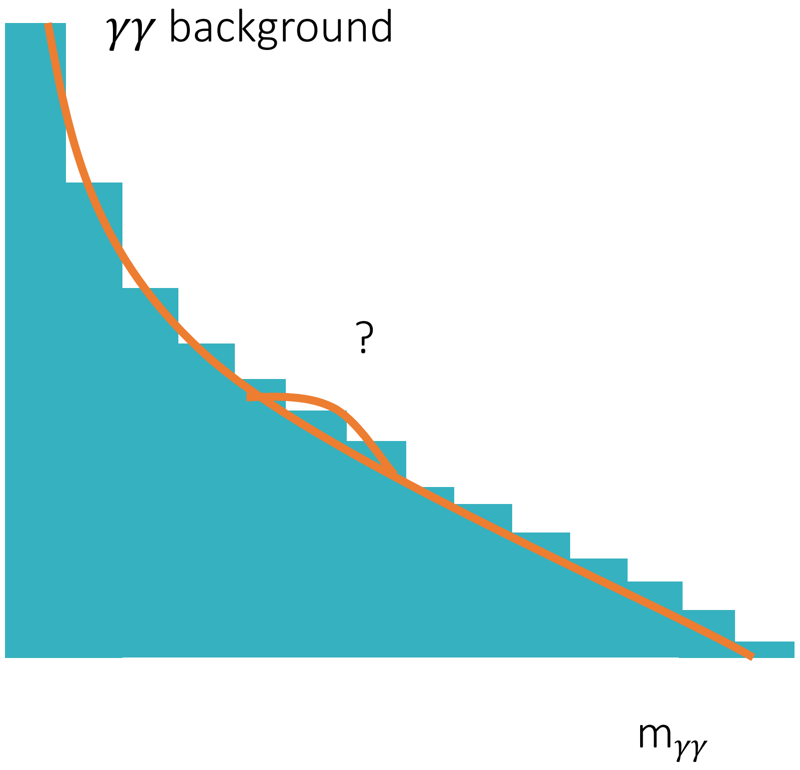
Low MC statistics can lead us to a bigger spurious signal

Spurious Signal Studies



A poor background modelling function could also lead to more spurious signal.

Spurious Signal Studies



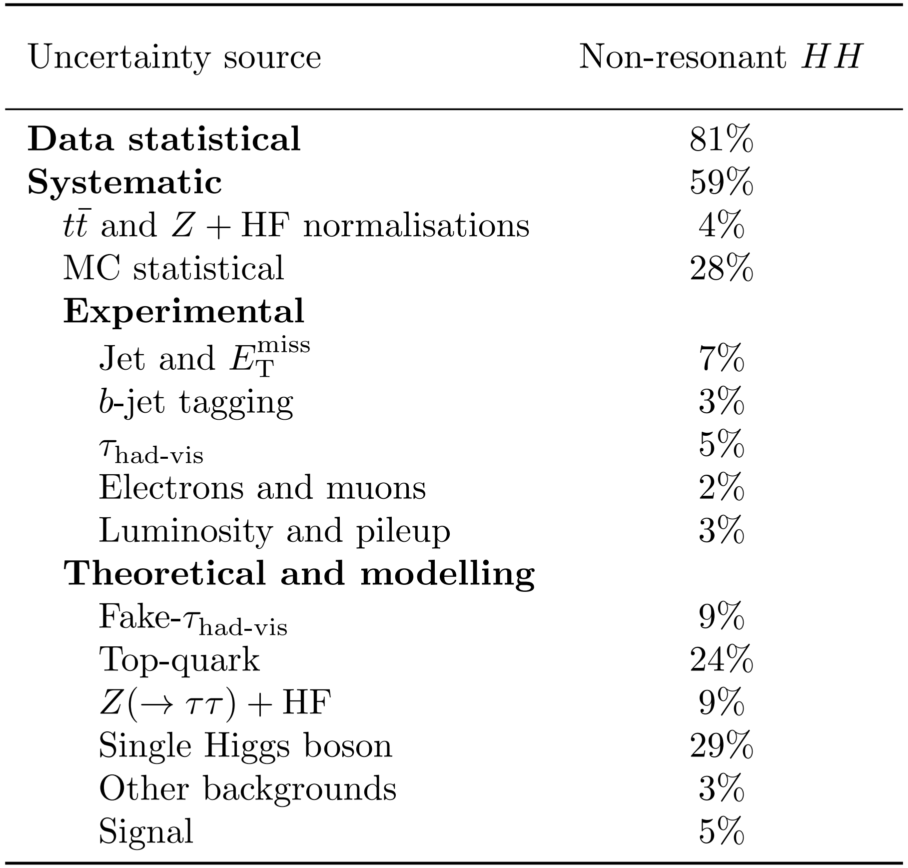
A poor background modelling function could also lead to more spurious signal.

In the future expect more MC statistics, and better modelling e.g. with Gaussian processes to reduce the impact of the spurious signal uncertainty.

… okay, so what were the results?!

Dominant Uncertainties bbττ - Full Run 2

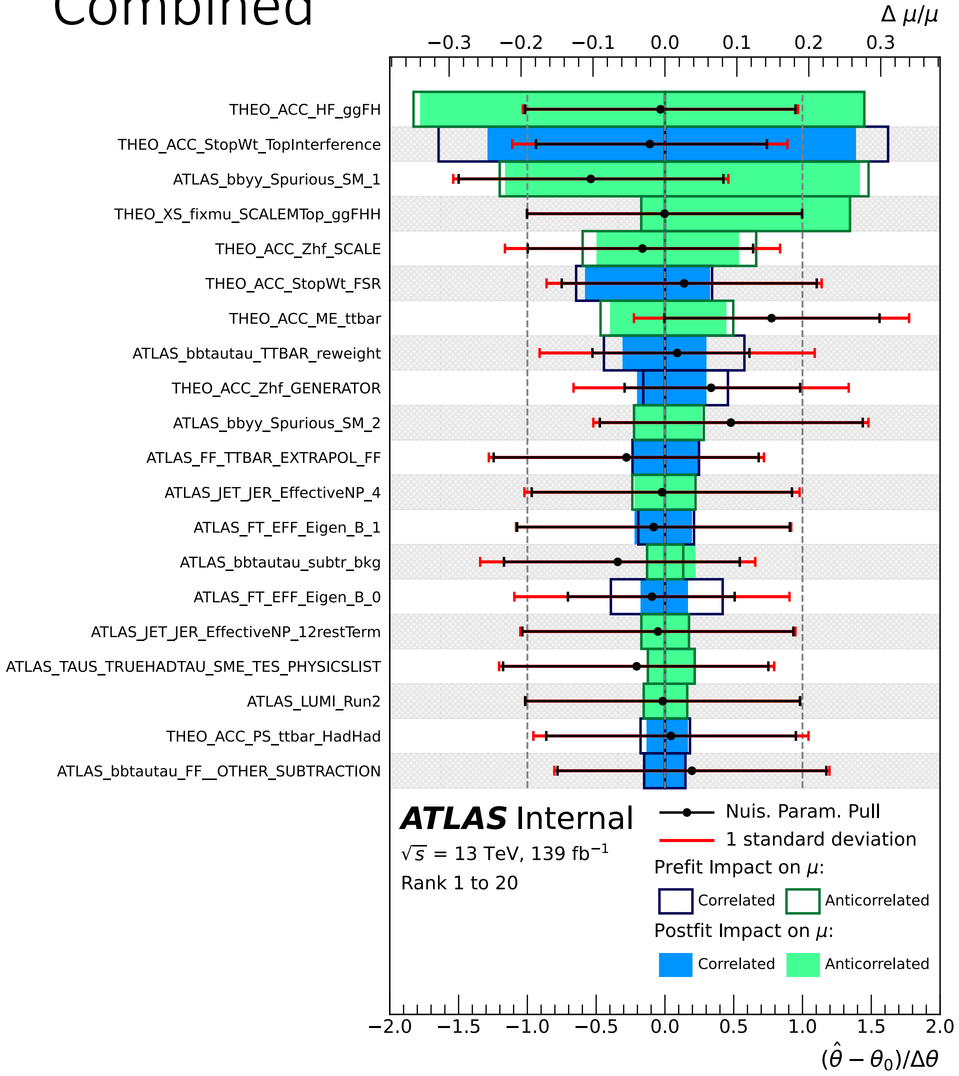
Relative contributions to the uncertainty in the extracted signal cross-sections, as determined in the likelihood fit to data.



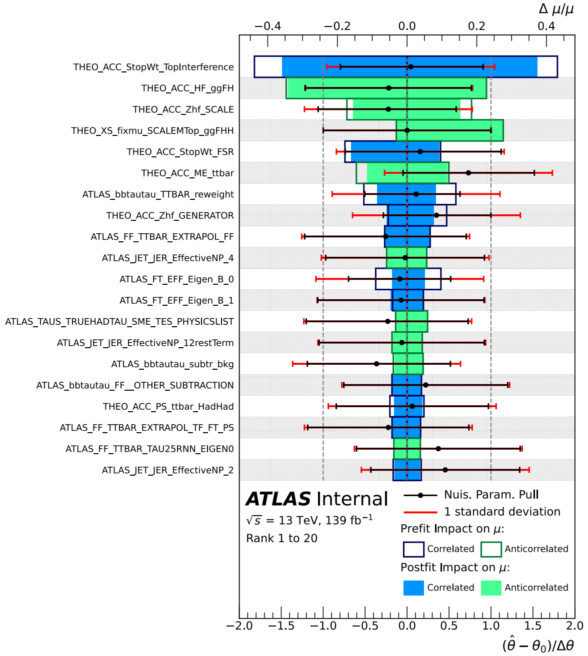
Uncertainty source	Non-resonant HH
Data statistical	81%
Systematic	59%
$t\bar{t}$ and $Z+\mathrm{HF}$ normalisations	4%
MC statistical	28%
Experimental	
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	7%
b-jet tagging	3%
$\tau_{\text{had-vis}}$	5%
Electrons and muons	2%
Luminosity and pileup	3%
Theoretical and modelling	
Fake-$\tau_{\text{had-vis}}$	9%
Top-quark	24%
$Z(\to\tau\tau)+\mathrm{HF}$	9%
Single Higgs boson	29%
Other backgrounds	3%
Signal	5%

NP Rankings – Non-Resonant

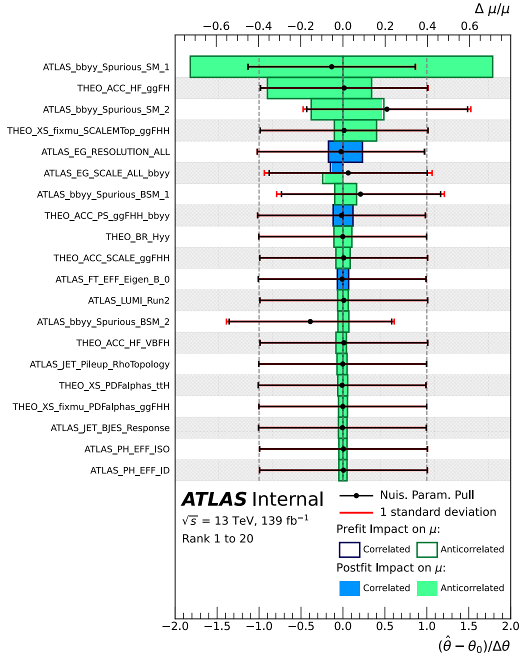
Combined



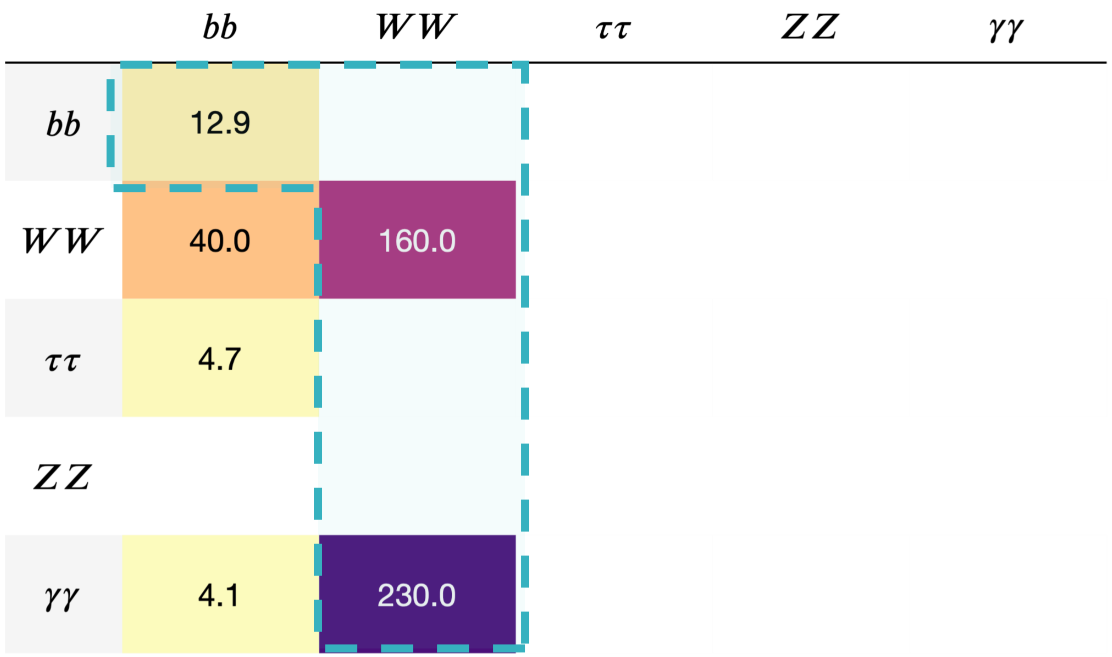
bbττ



bb$\gamma\gamma$



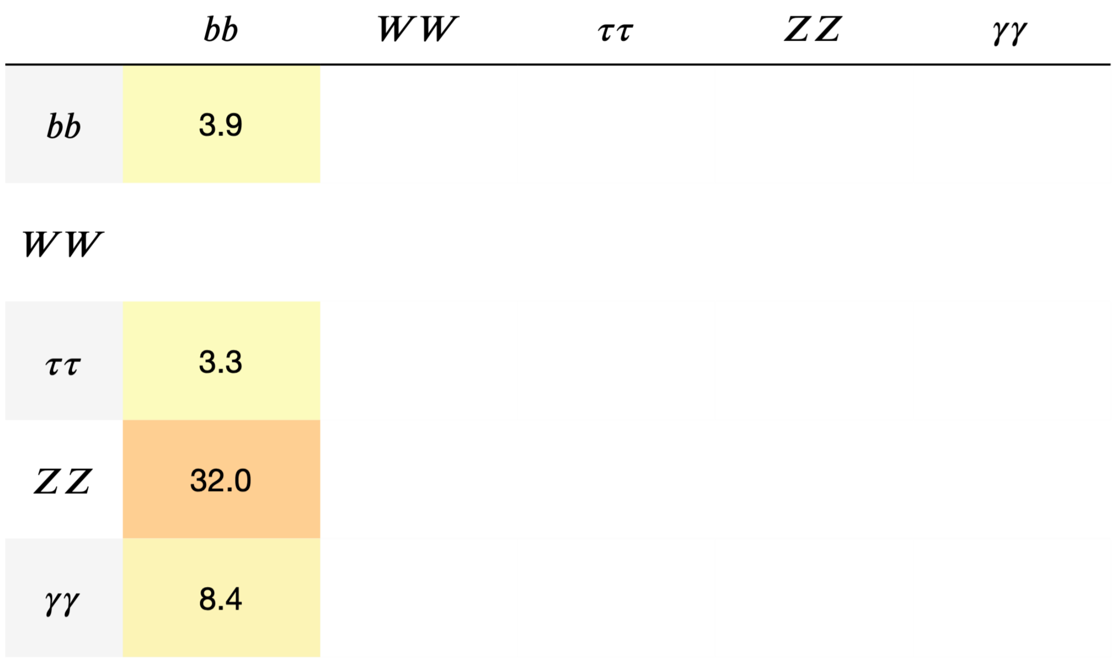
Observed SM Upper Limits



ATLAS

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	12.9				
WW	40.0	160.0			
$\tau\tau$	4.7				
ZZ					
$\gamma\gamma$	4.1	230.0			

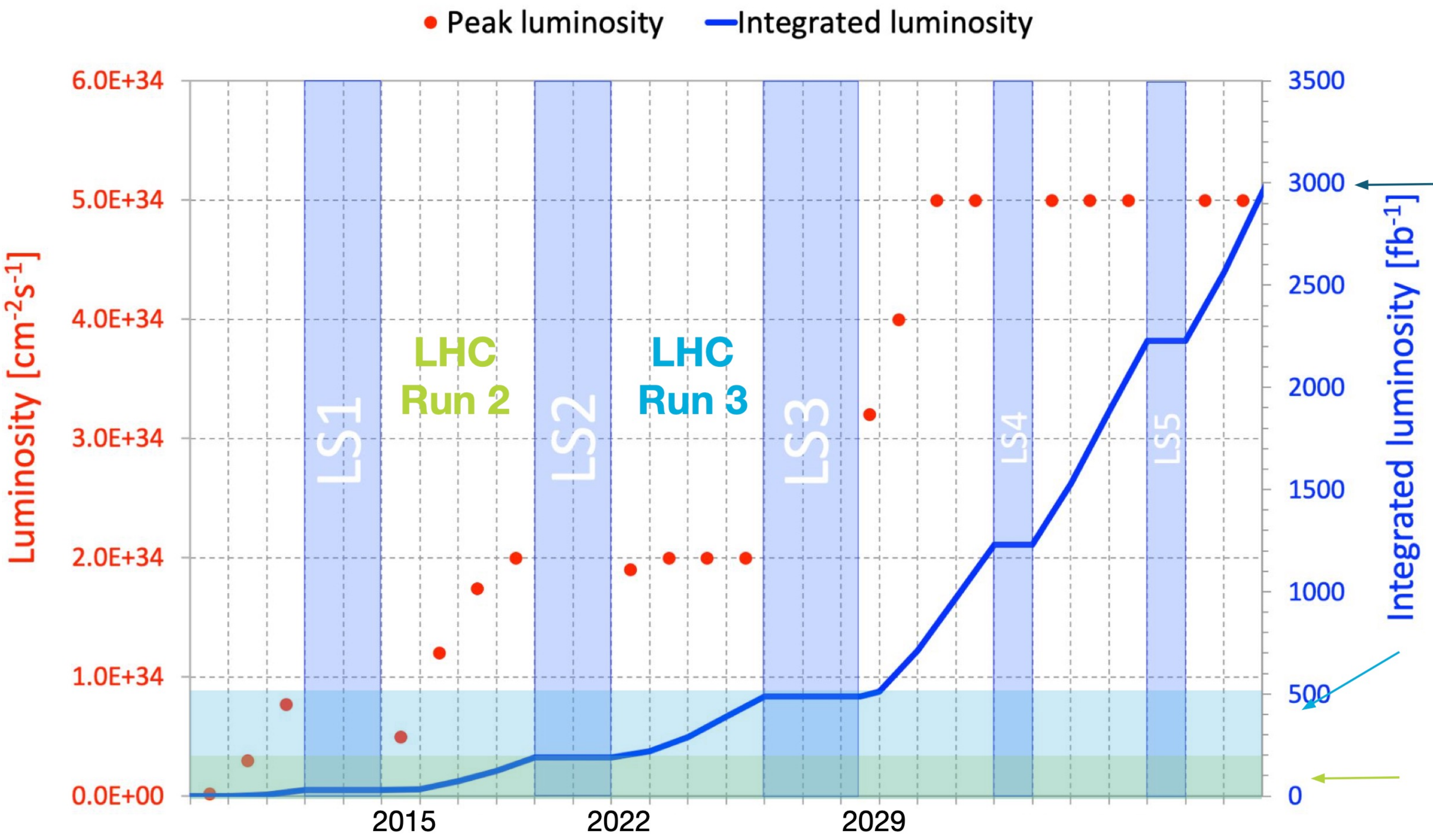
Still to be updated with Full Run 2 data



CMS

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	3.9				
WW					
$\tau\tau$	3.3				
ZZ	32.0				
$\gamma\gamma$	8.4				

HL-LHC



Full HL-LHC dataset

LHC Run 3: 10% of total dataset collected

LHC Run 2: 5% of total dataset collected

Slide from Elizabeth Brost

Extrapolation Procedure

1. Luminosity scaling to 3000 fb^{-1}
2. Cross-sections scaled to adjust to 14 TeV

Process	Scale factor
Signals	
ggF HH	1.18
VBF HH	1.19
Backgrounds	
ggF H	1.13
VBF H	1.13
WH	1.10
ZH	1.12
$t\bar{t}H$	1.21
Others	1.18

Recommendations from Higgs HL-LHC WG

Increased gluon-luminosity

3. Systematic uncertainties updated (next page)

HL-LHC Extrapolation Procedure

ATL-PHYS-PUB-2022-005
http://cdsweb.cern.ch/record/2802127

Systematic uncertainties updated to provide envelope for interpreting the results:

1. No systematic uncertainties
2. Baseline - Experimental uncertainties scaled, and theory uncertainties halved
3. Theory uncertainties halved – but with Run 2 experimental systematic uncertainties
4. Run 2 systematic uncertainties

optimistic
↓
conservative

Systematic Uncertainty Extrapolation

Source	**Scale factor**	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$
Experimental Uncertainties			
Luminosity	0.6	*	*
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*	
Photon energy scale and resolution	1.0	*	
Jet energy scale and resolution, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.0	*	*
b-jet tagging efficiency	0.5	*	*
c-jet tagging efficiency	0.5	*	*
Light-jet tagging efficiency	1.0	*	*
τ_{had} efficiency (statistical)	0.0		*
τ_{had} efficiency (systematic)	1.0		*
τ_{had} energy scale	1.0		*
Fake-$\tau_{\mathrm{had\text{-}vis}}$ estimation	1.0		*
Value of m_H	0.08	*	
κ_λ reweighting	0.0	*	*
Spurious signal	0.0	*	
Theoretical Uncertainties	0.5	*	*

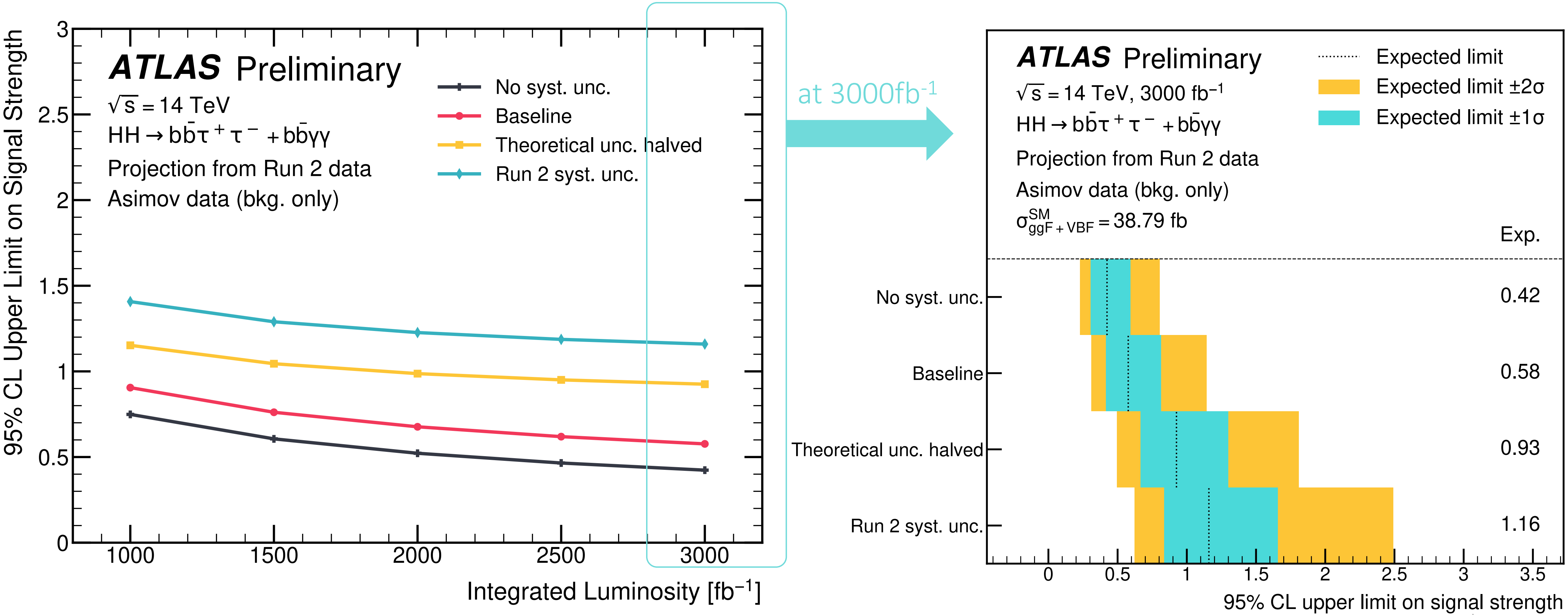
Detector performance expected to remain similar, but uncertainties on heavy jet tagging expected to decrease slightly with ITk and continued algorithm developments.

MC related uncertainties

Theory uncertainties halved

Upper Limits on SM Signal Strength

Interpretation: If no HH signal is observed, can place the following limits at 95% confidence level



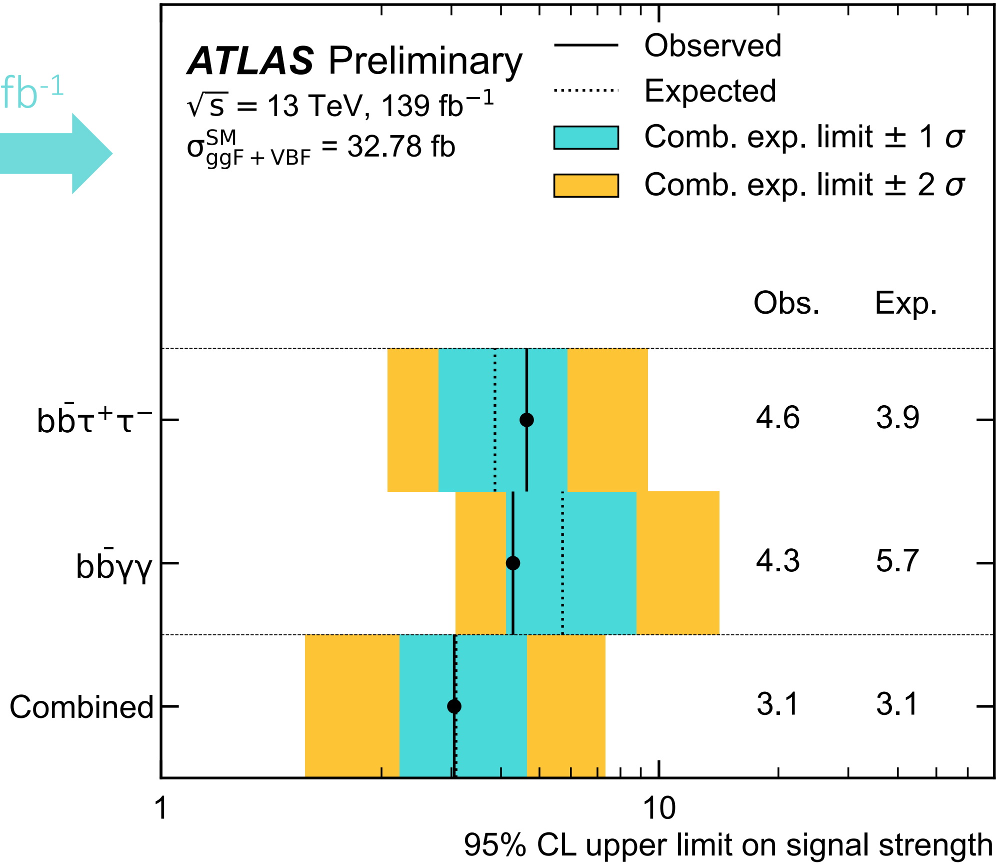
For comparison, Full Run 2 bbττ, and bb$\gamma\gamma$ combination is at 3.1x SM

Projected Limits on HH Signal Strength

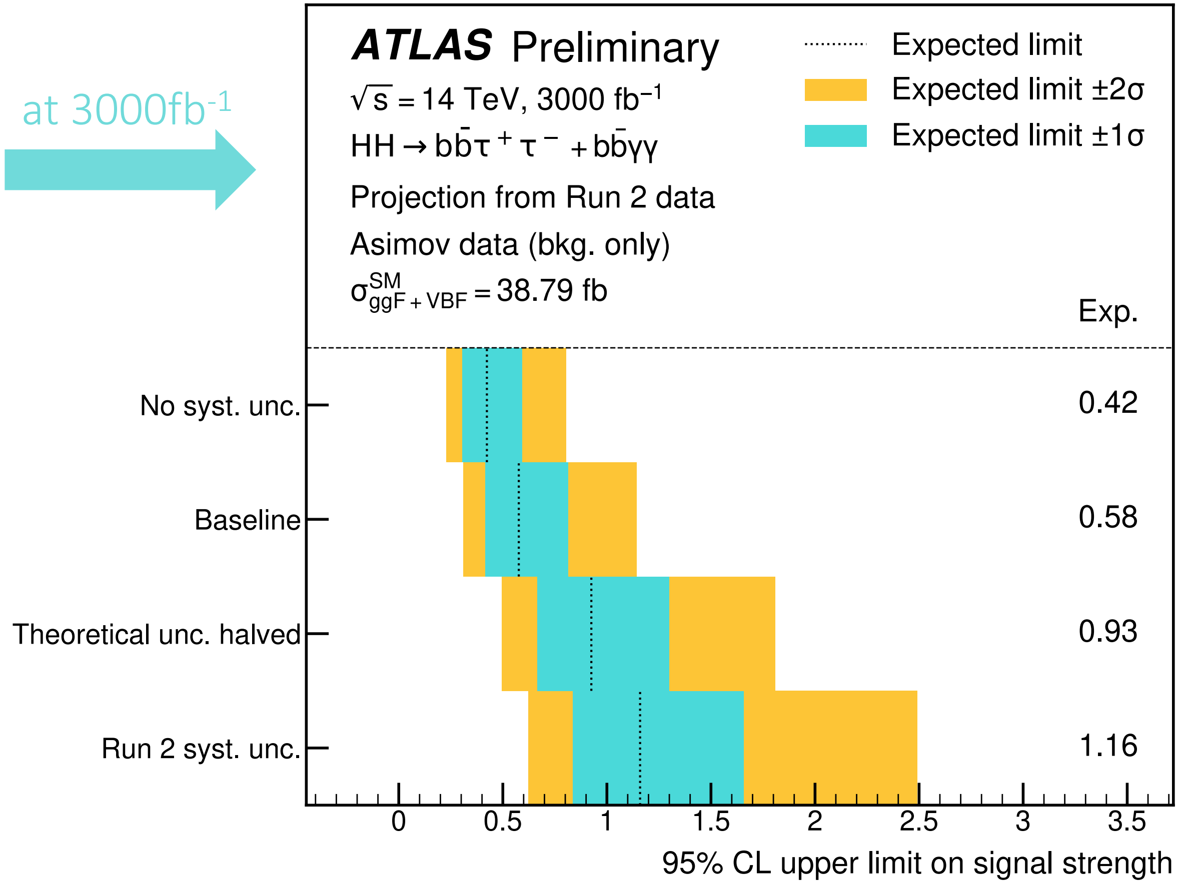
Interpretation: If no HH signal is observed, can place the following limits at 95% confidence level

ATL-PHYS-PUB-2022-005 http://cdsweb.cern.ch/record/2802127

at 139fb^{-1}

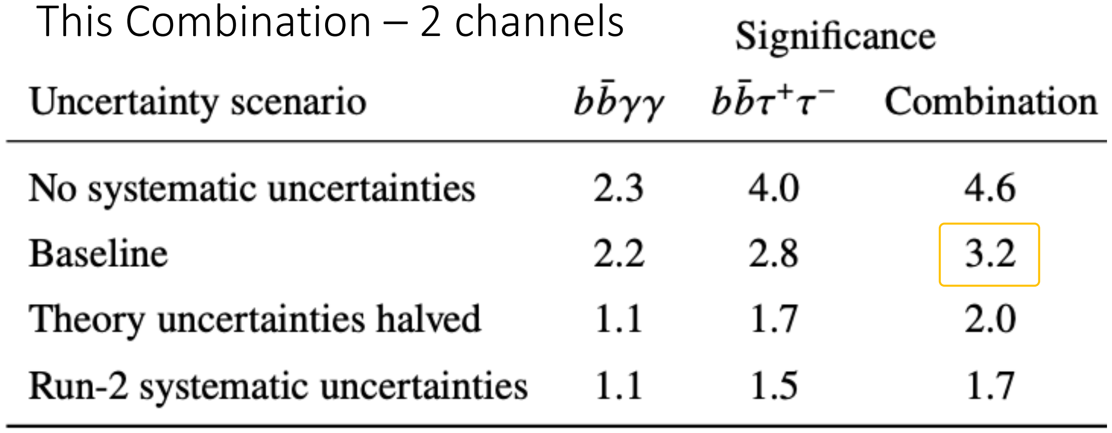


at 3000fb^{-1}



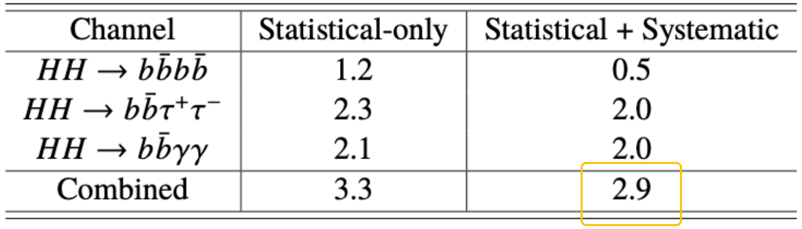
Significance - Combination

This Combination – 2 channels

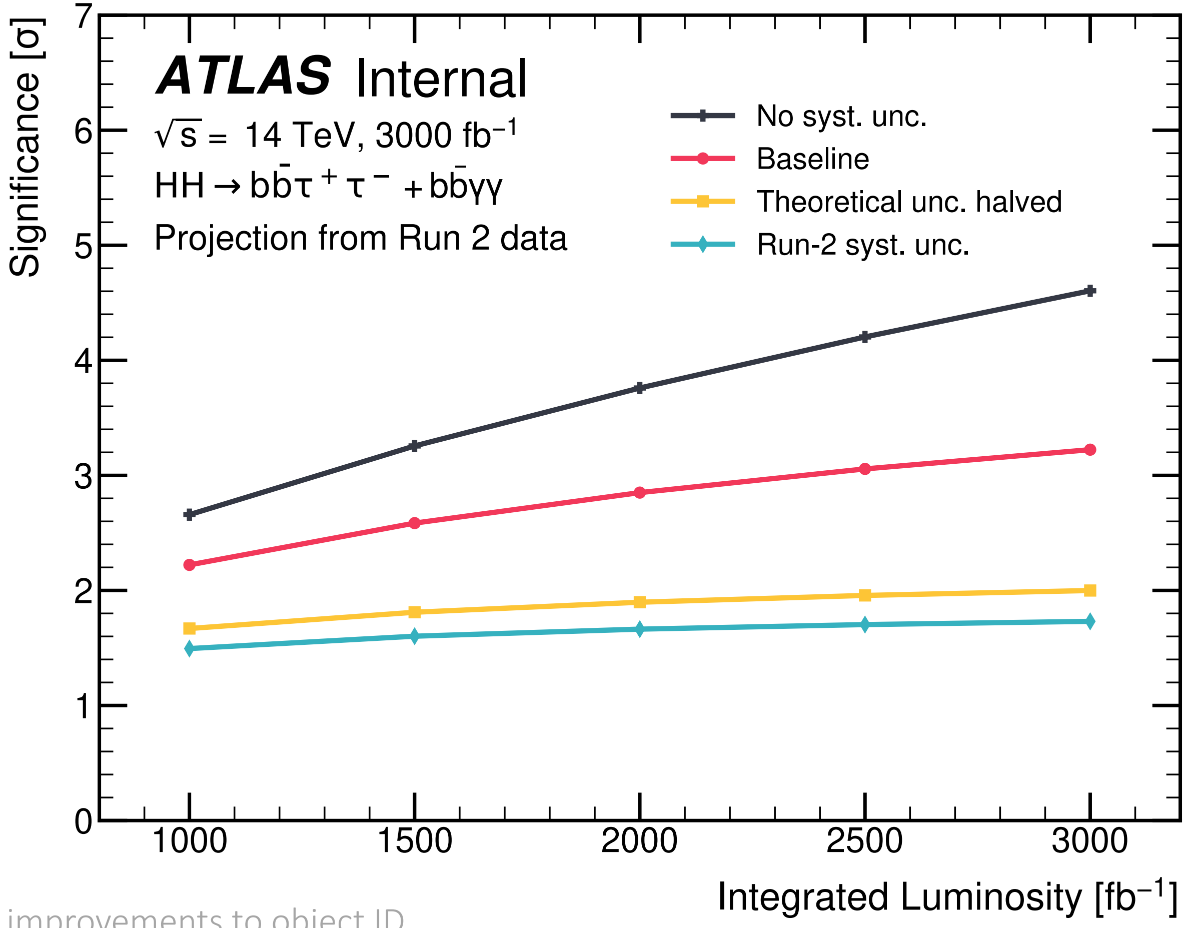


	Significance		
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination
No systematic uncertainties	2.3	4.0	4.6
Baseline	2.2	2.8	3.2
Theory uncertainties halved	1.1	1.7	2.0
Run-2 systematic uncertainties	1.1	1.5	1.7

2018 Projections Combination – 3 channels
(ATL-PHYS-PUB-2020-005)

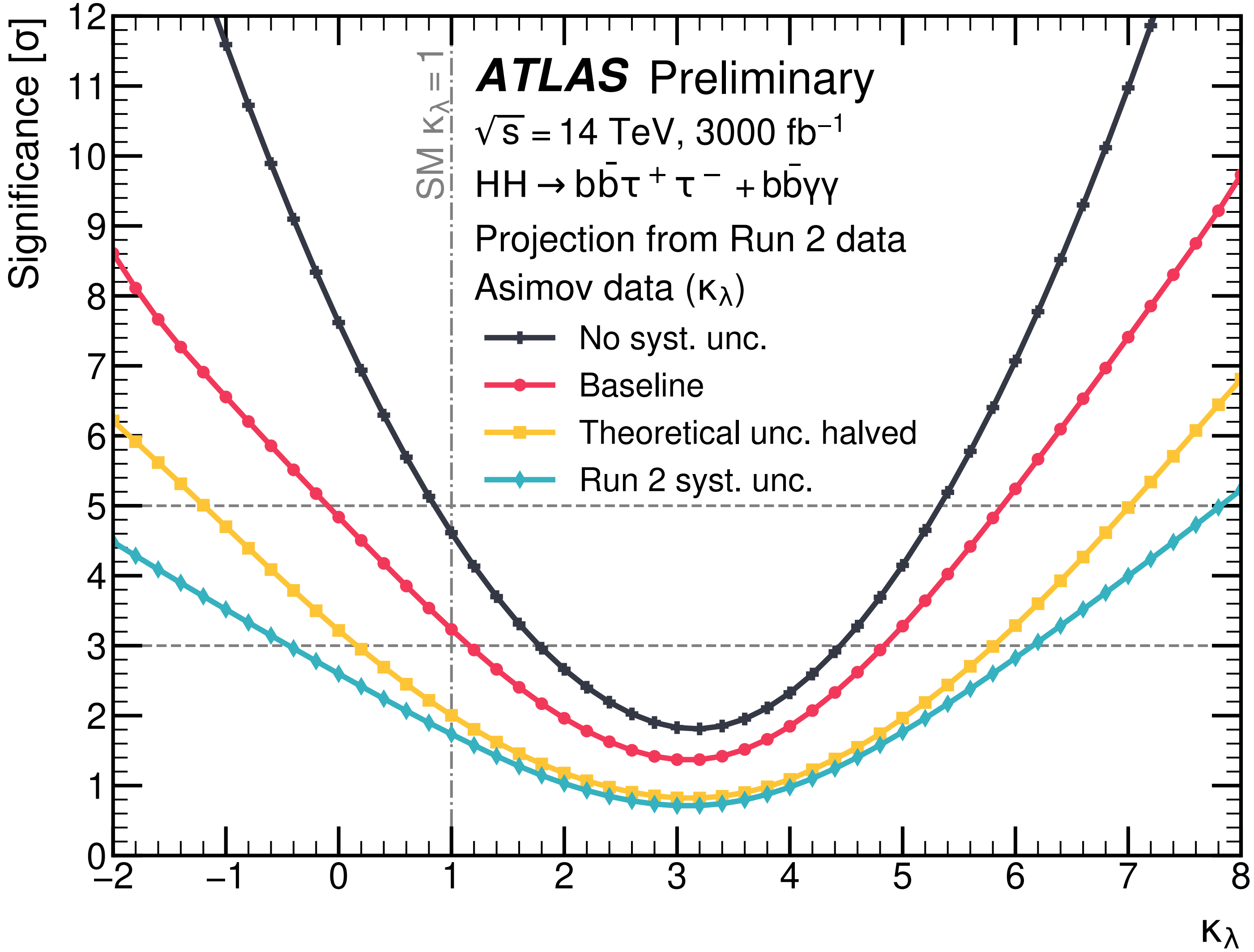


Channel	Statistical-only	Statistical + Systematic
$HH \rightarrow b\bar{b}b\bar{b}$	1.2	0.5
$HH \rightarrow b\bar{b}\tau^+\tau^-$	2.3	2.0
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.3	2.9



bbττ: gains mainly from improvements to object ID
bb$\gamma\gamma$: previous results from truth MC

Significance as a function of k_λ - Combined

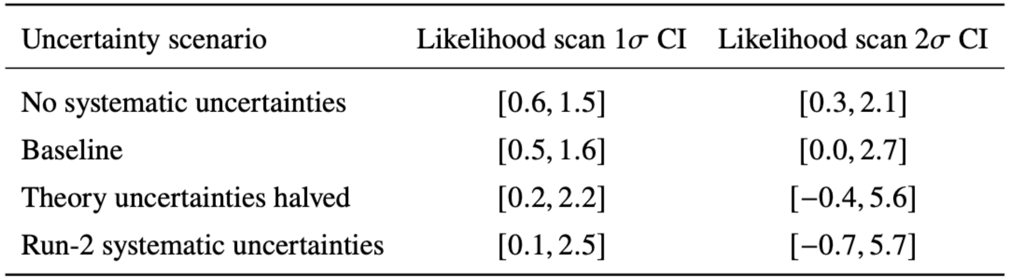


Interpretation:

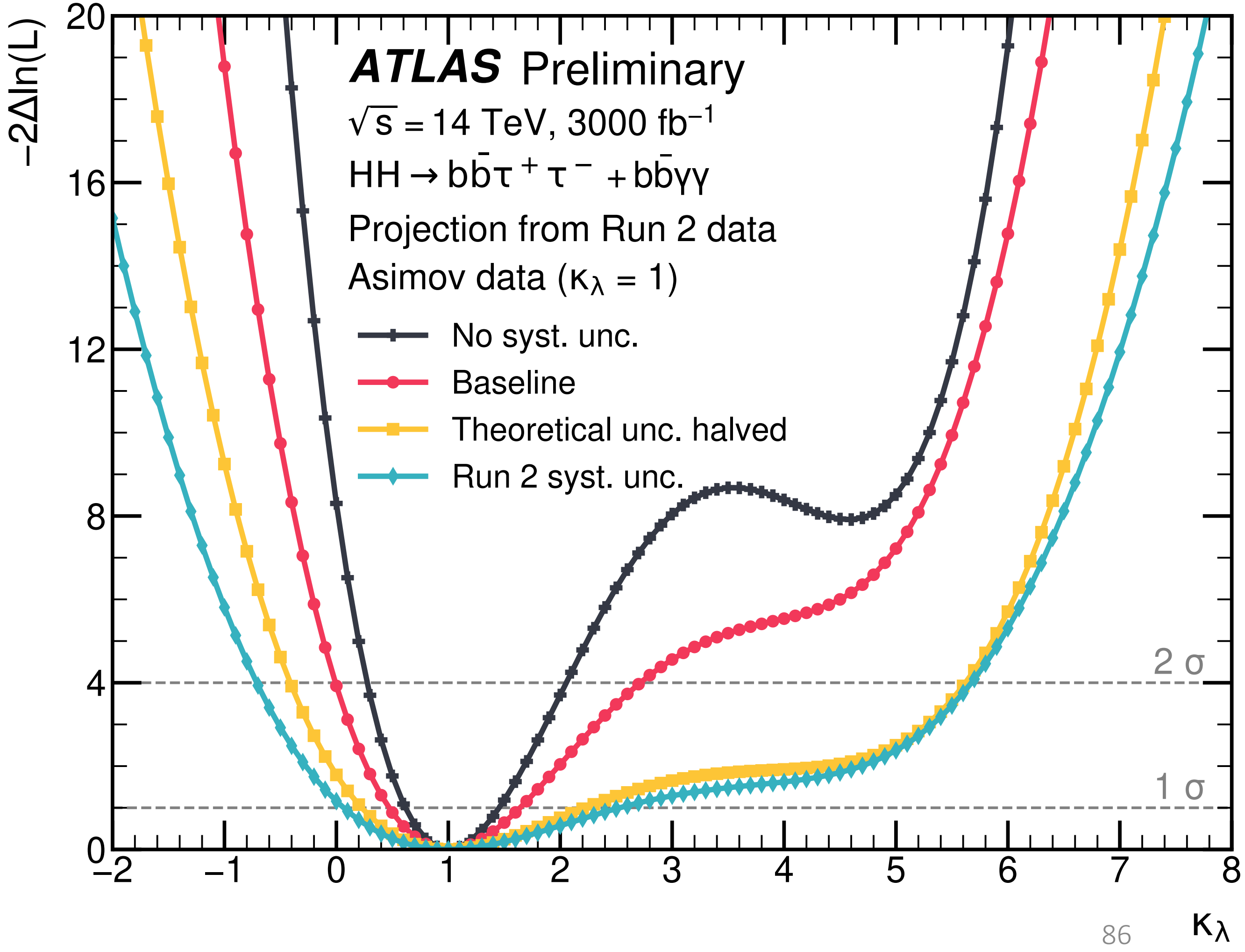
If HH signal present at these k_λ values, expect to measure the signal with the shown significance.

Likelihood Scan - Combined

Negative log of the likelihood ratio comparing different k_λ hypotheses to an Asimov dataset constructed with $k_\lambda = 1$

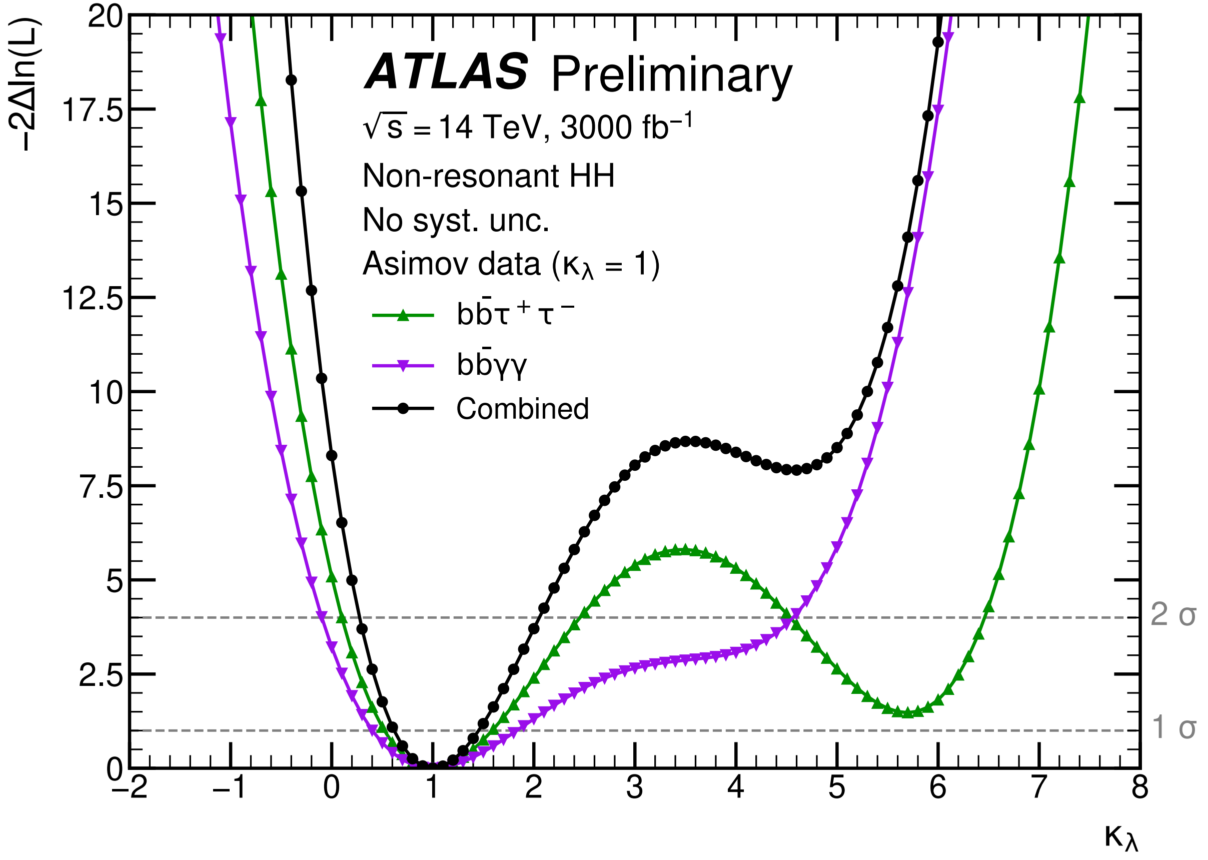


Uncertainty scenario	Likelihood scan 1σ CI	Likelihood scan 2σ CI
No systematic uncertainties	$[0.6, 1.5]$	$[0.3, 2.1]$
Baseline	$[0.5, 1.6]$	$[0.0, 2.7]$
Theory uncertainties halved	$[0.2, 2.2]$	$[-0.4, 5.6]$
Run-2 systematic uncertainties	$[0.1, 2.5]$	$[-0.7, 5.7]$

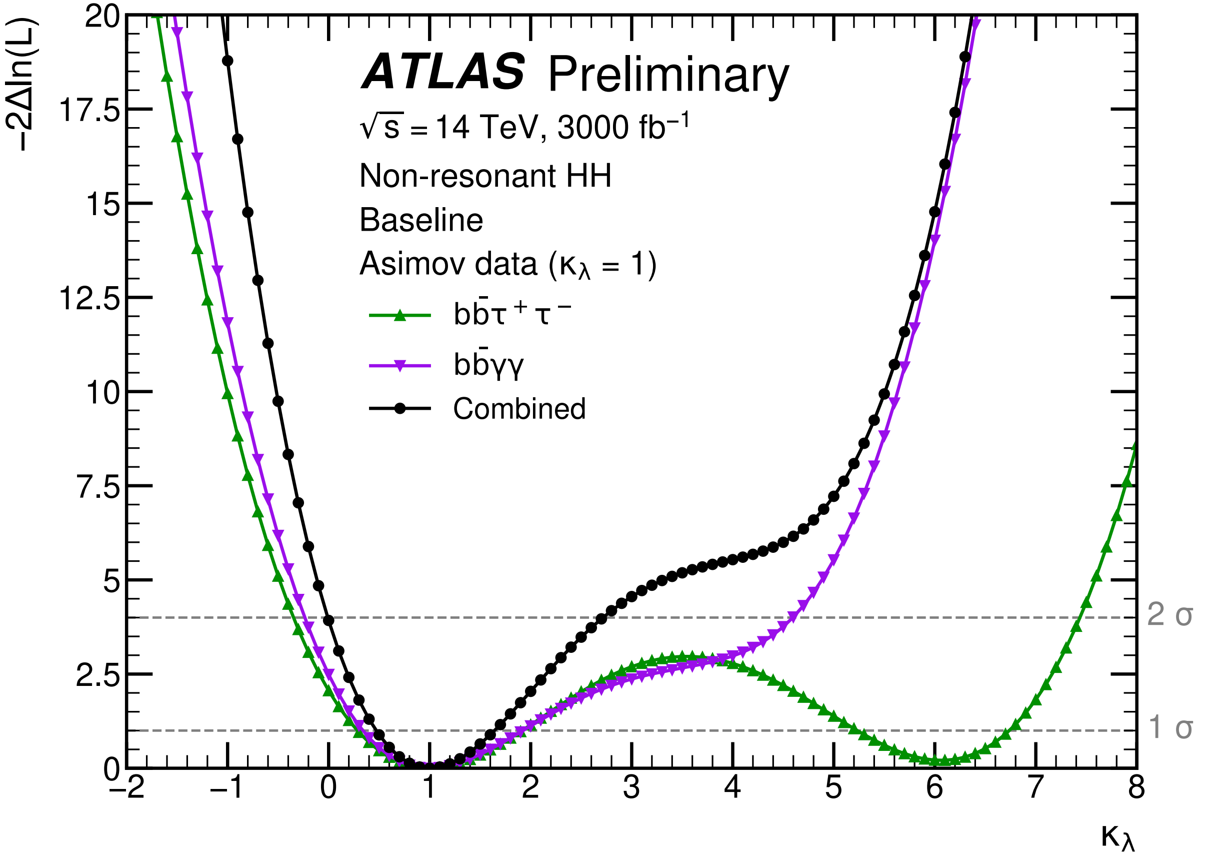


Likelihood Scan – Different Scenarios

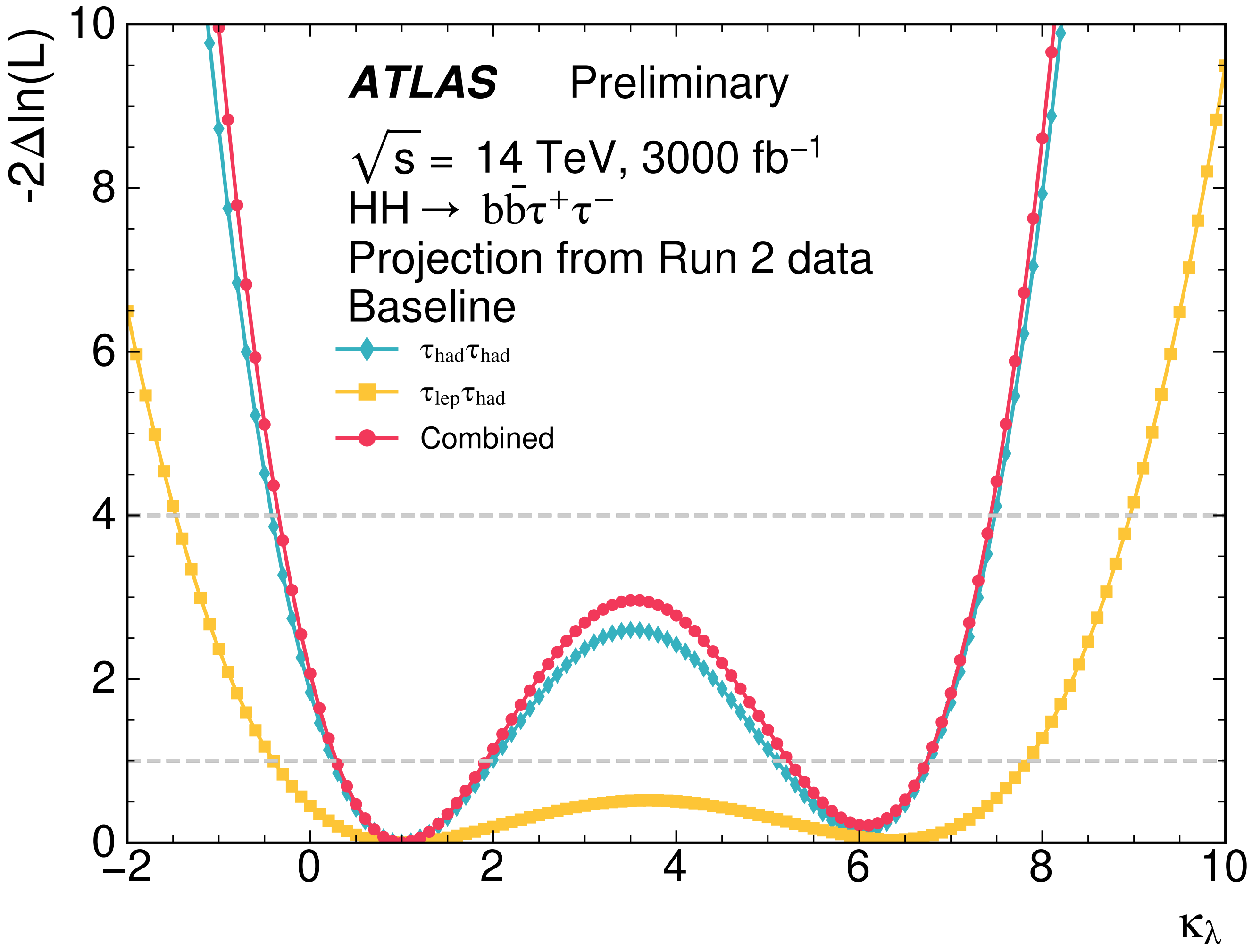
No Systematics



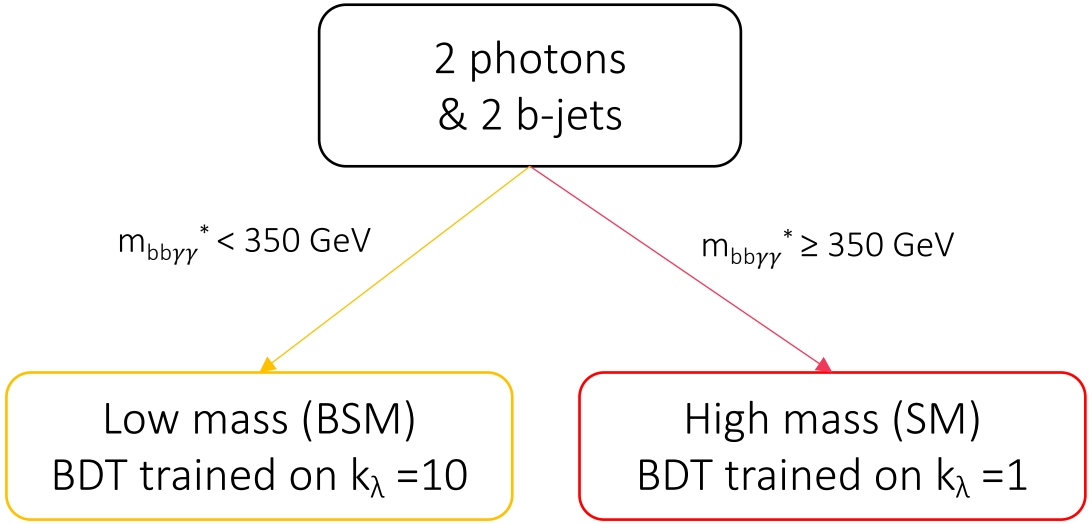
Baseline



Effect of Different Channels - bbττ



Effect of Different Analysis Categories - bb$\gamma\gamma$



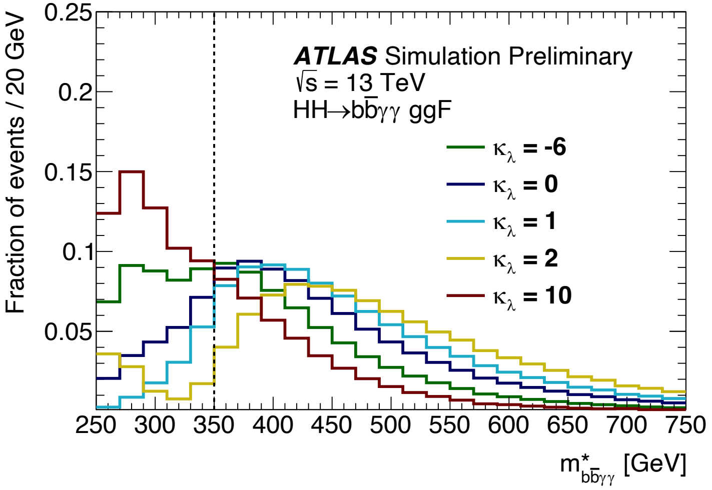
2 photons
& 2 b-jets

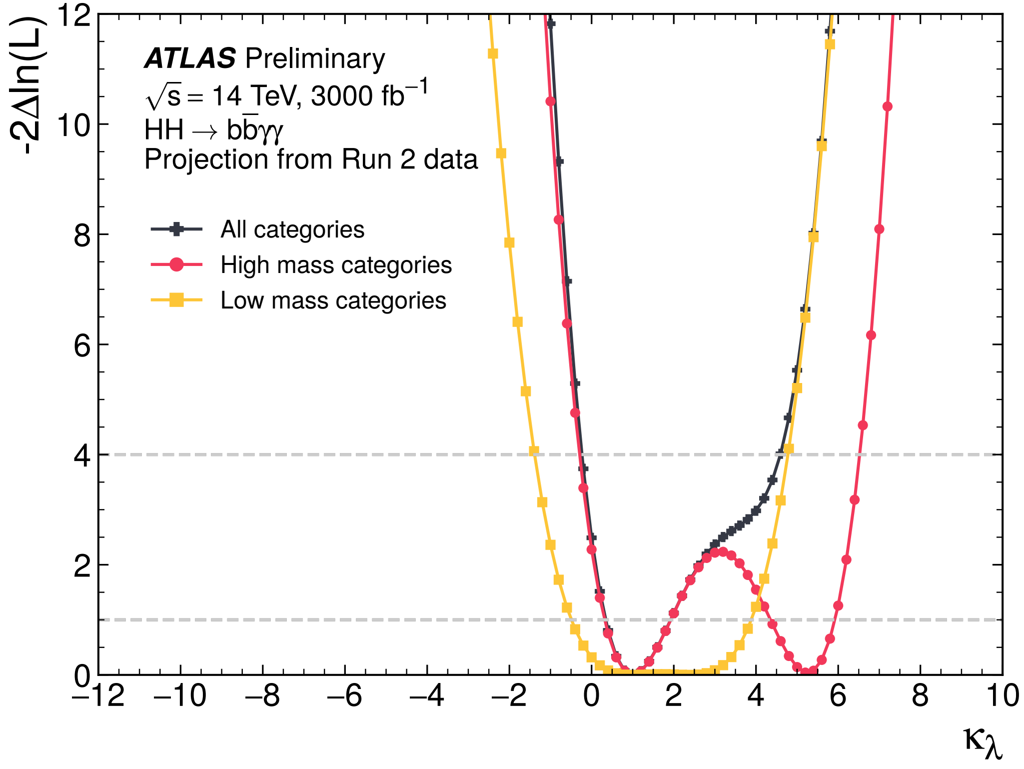
$m_{bb\gamma\gamma}{}^{*} < 350$ GeV

$m_{bb\gamma\gamma}{}^{*} \geq 350$ GeV

Low mass (BSM)
BDT trained on $k_\lambda = 10$

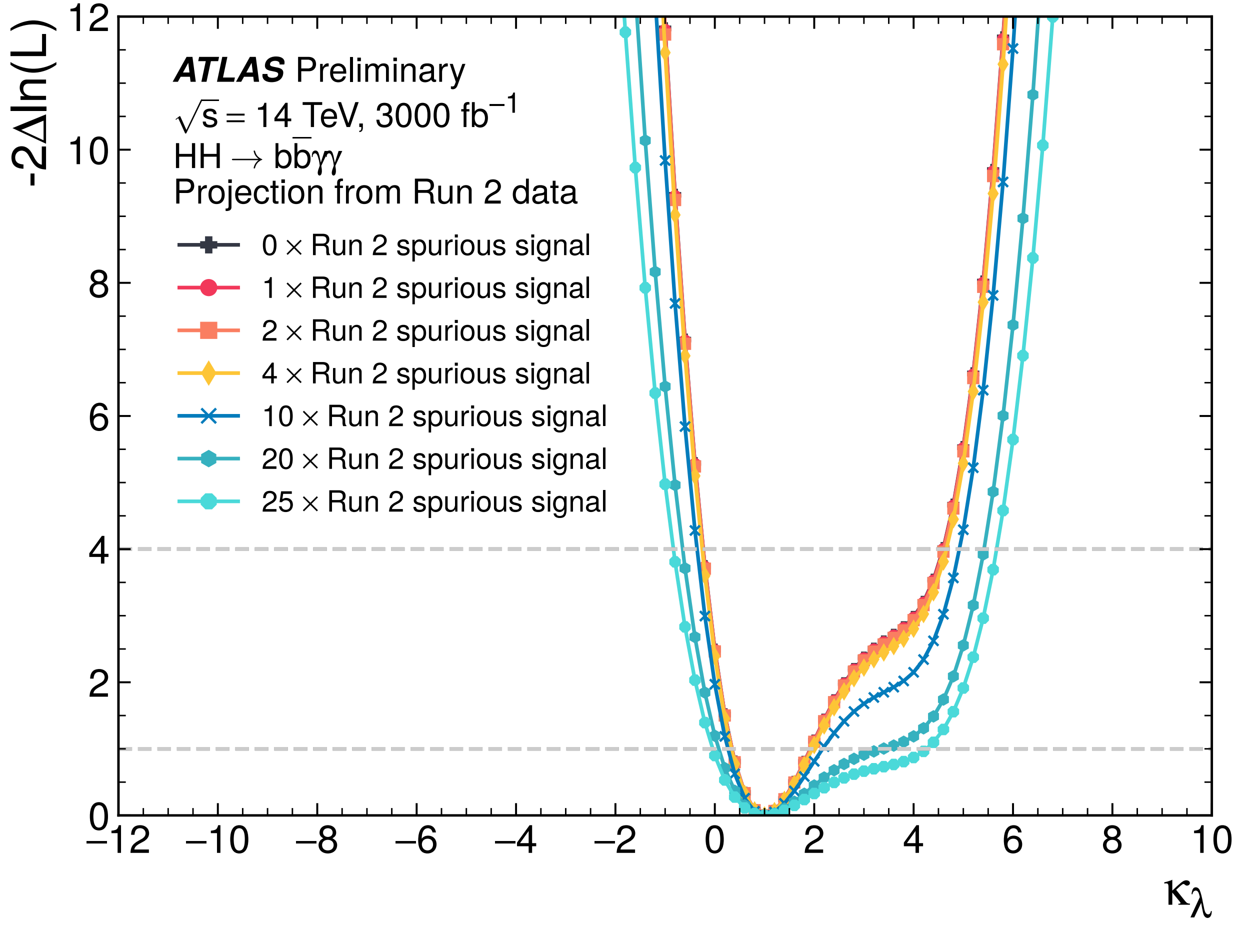
High mass (SM)
BDT trained on $k_\lambda = 1$





$$m_{bb\gamma\gamma}{}^{*} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250 \text{ GeV}$$

Spurious Signal Studies - $bb\gamma\gamma$

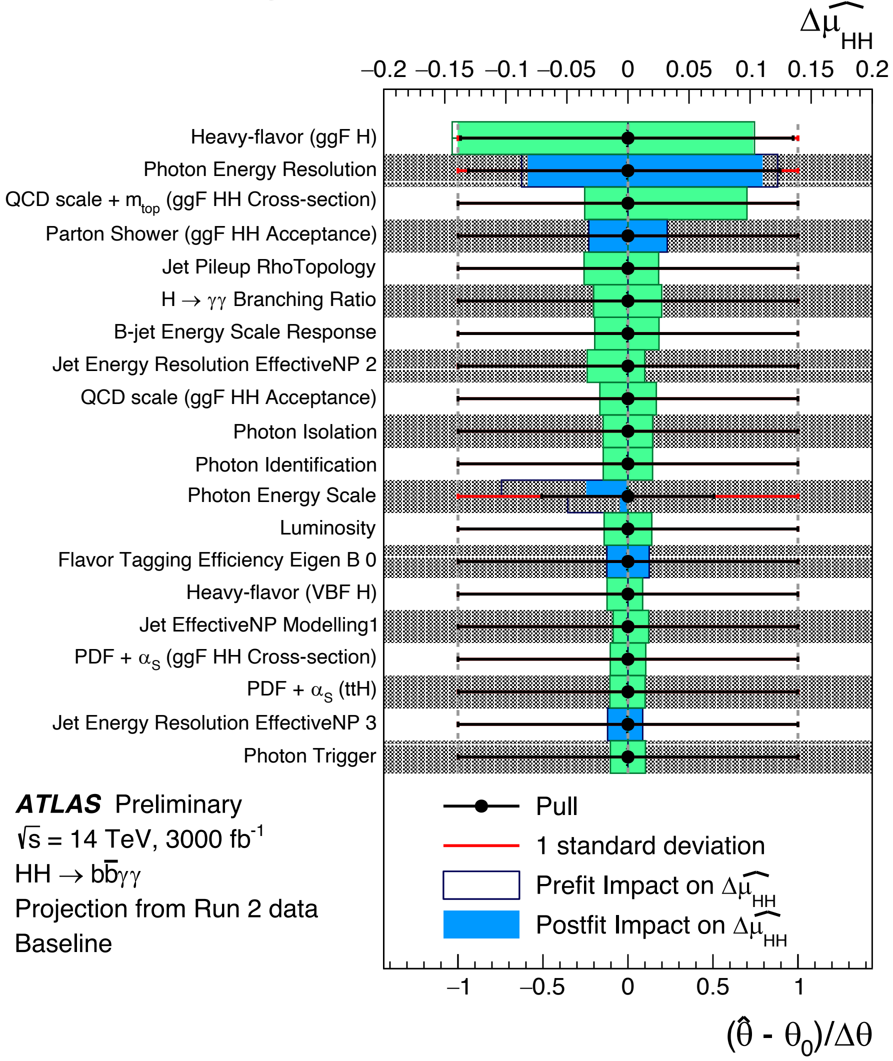


Spurious signal scaling	Effect on Baseline combined significance
0x	0
4x	<1%
25x	<10%

Dominant Systematics @ HL-LHC

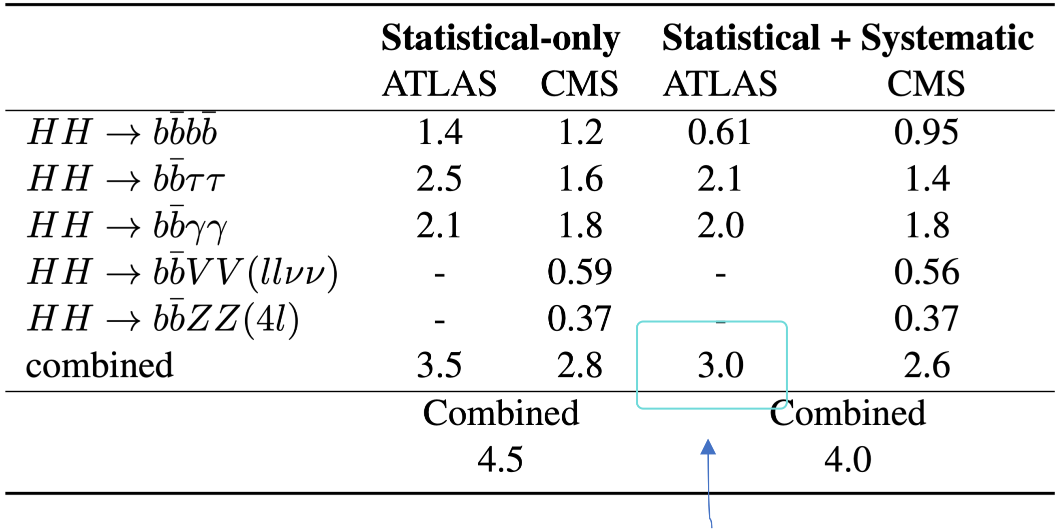
Theory uncertainties:
- ggF H (in association with b, or c)
- Wt tt interference (bbττ)
- ggF HH cross-section

Experimental uncertainties
- MC statistical uncertainties (bbττ)
- Spurious signal, background modelling (bb$\gamma\gamma$)
- Photon energy resolution



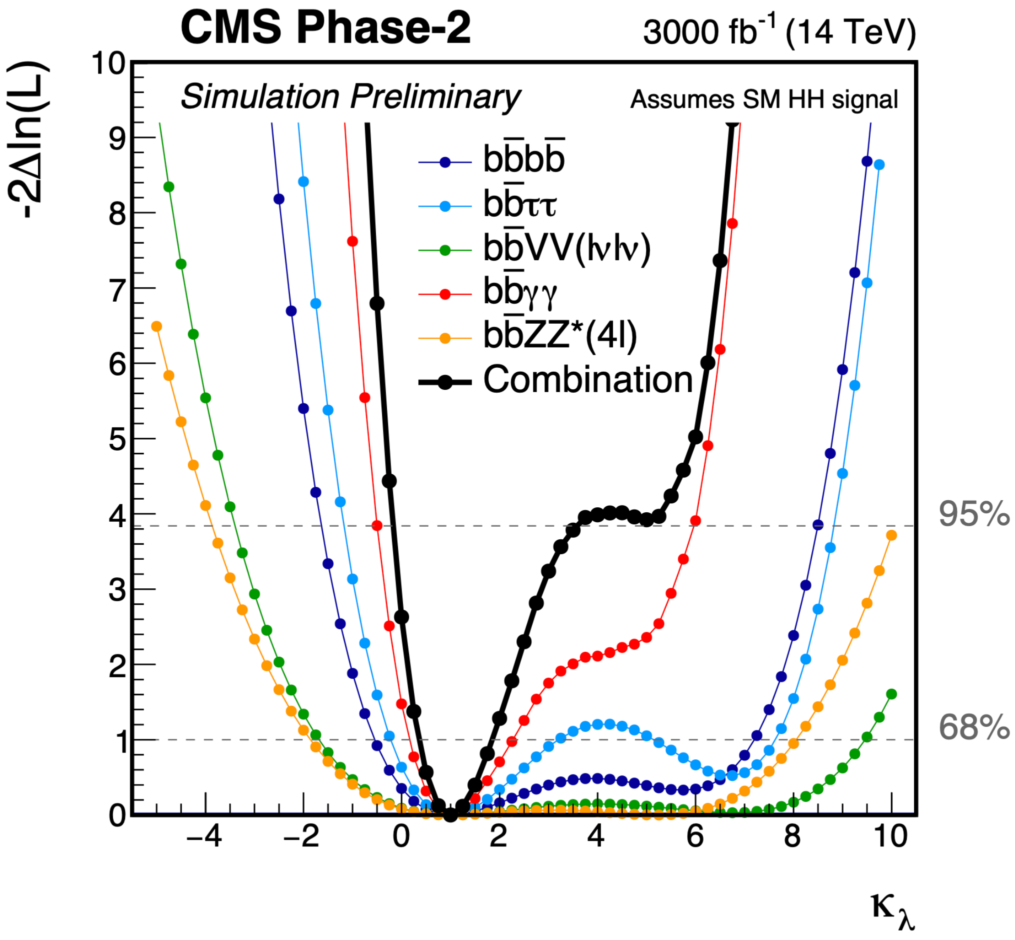
HL-LHC CMS+ATLAS Combination

From Yellow Report: https://arxiv.org/abs/1902.00134



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

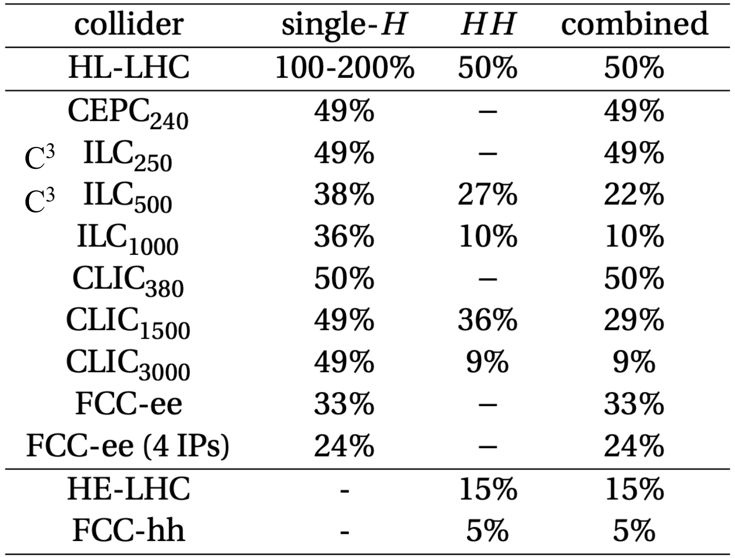
Our latest result improves on this significance with just two channels!



Future Colliders

Future:

In addition to HL-LHC, future e+e- Higgs factory colliders will allow us to further study the Higgs boson self-coupling with precision.

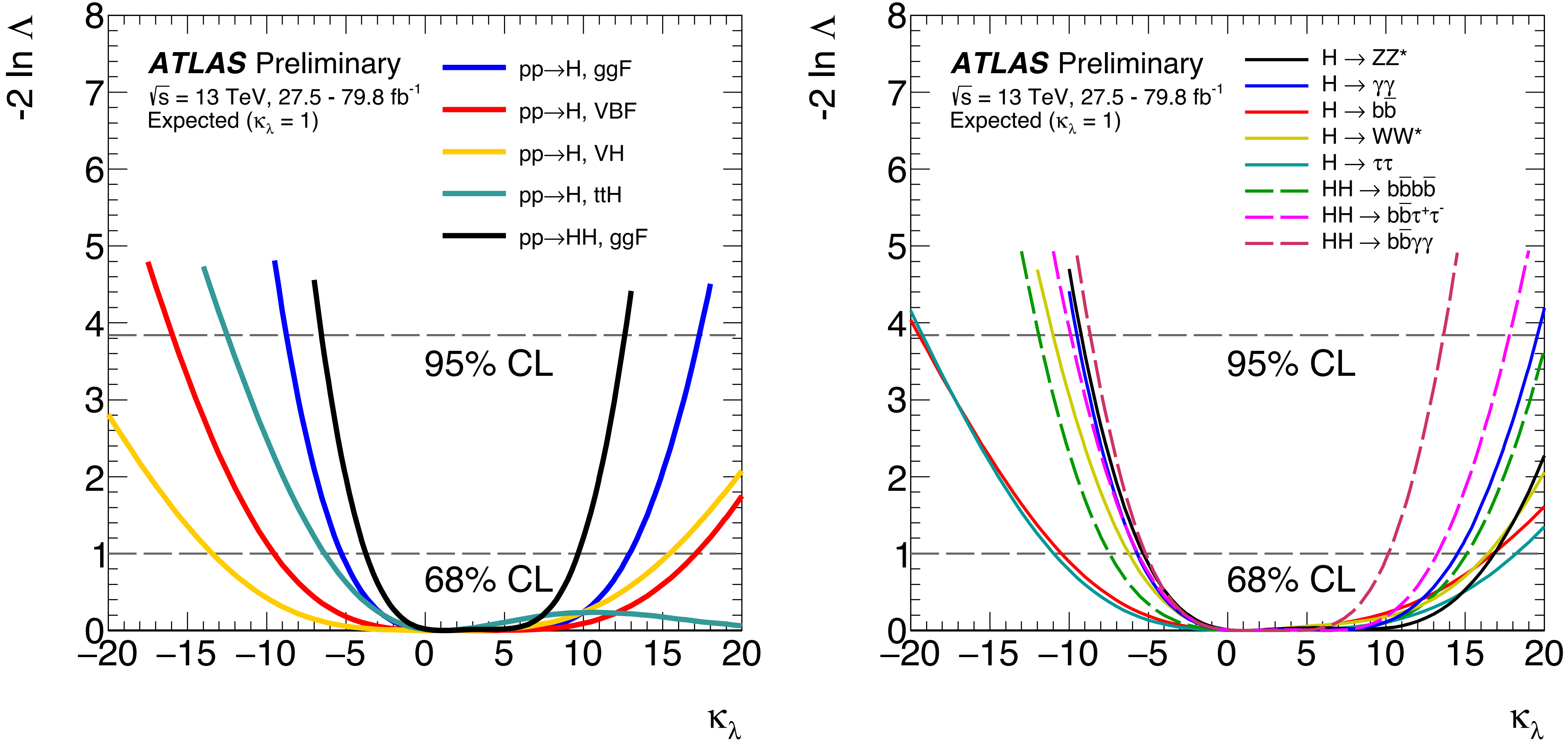


collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
CEPC$_{240}$	49%	–	49%
C^3 ILC$_{250}$	49%	–	49%
C^3 ILC$_{500}$	38%	27%	22%
ILC$_{1000}$	36%	10%	10%
CLIC$_{380}$	50%	–	50%
CLIC$_{1500}$	49%	36%	29%
CLIC$_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

Expected precision on k_λ at future colliders
https://arxiv.org/abs/1910.00012

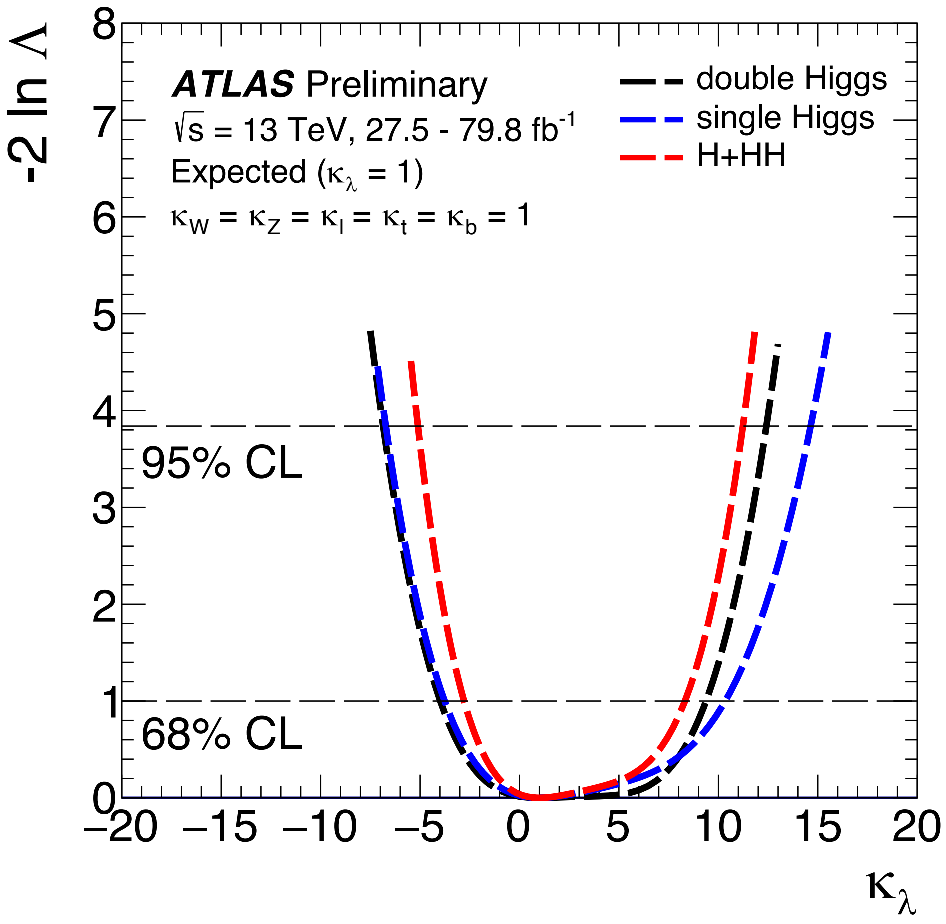
Single Higgs + HH κ_λ

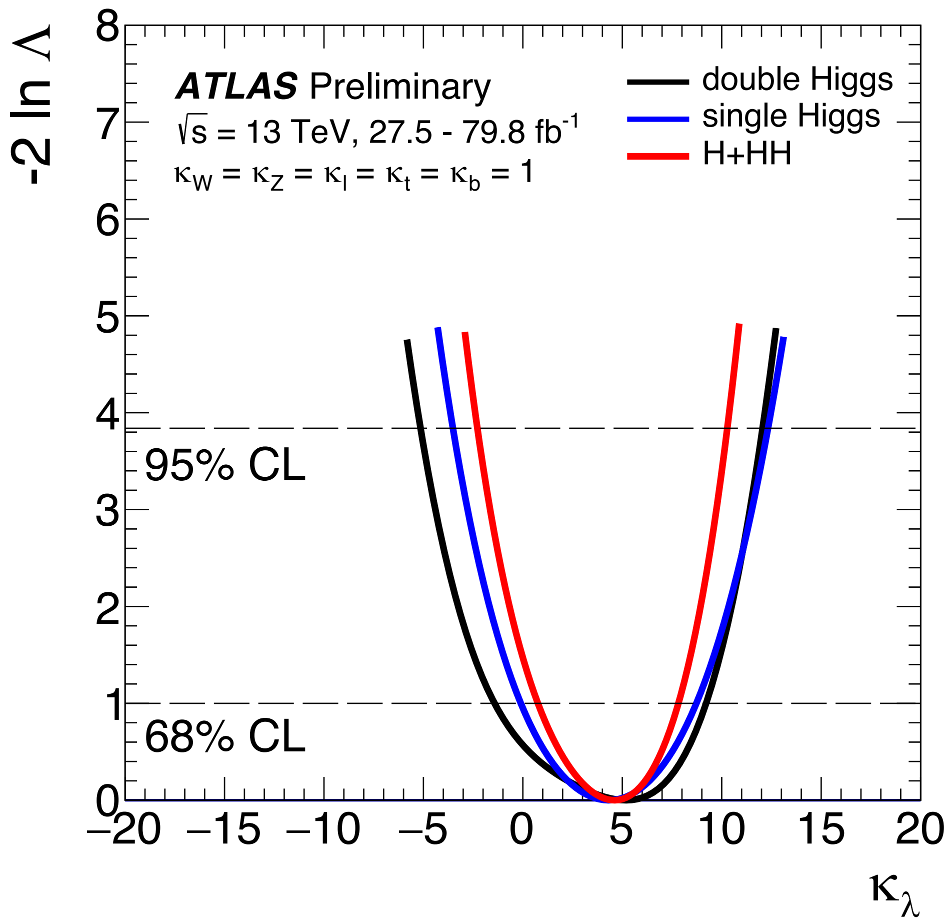
ATLAS-CONF-2019-049



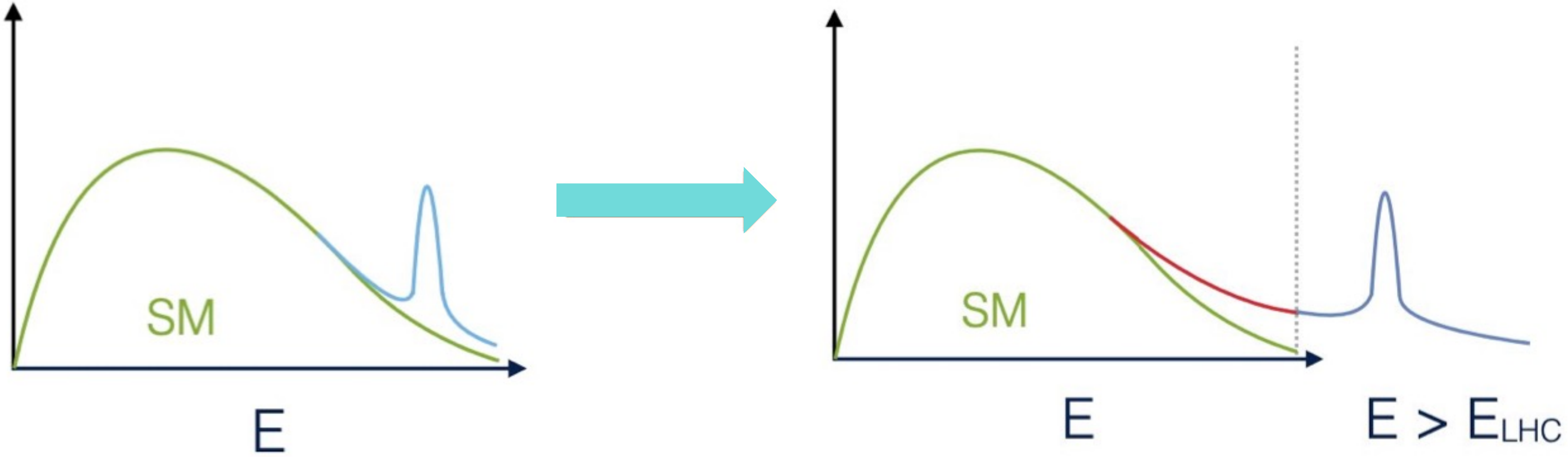
Single Higgs + HH κ_λ

ATLAS-CONF-2019-049





Effective Field Theory Interpretations

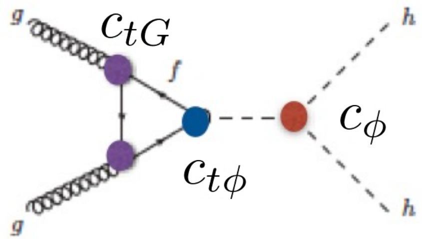


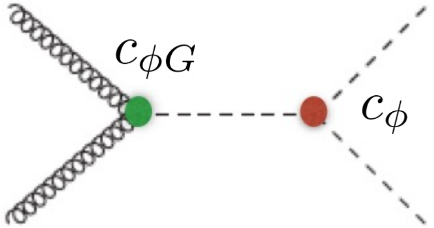
Measurements in low-stats, high p_T tails will also be most accessible at HL-LHC.

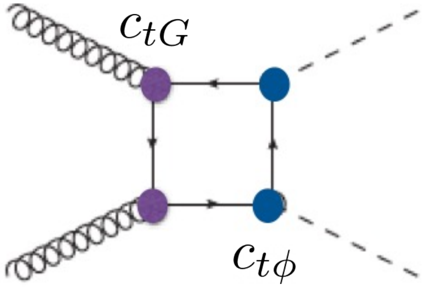
Differential measurements and their interpretations will maximize sensitivity to new physics.

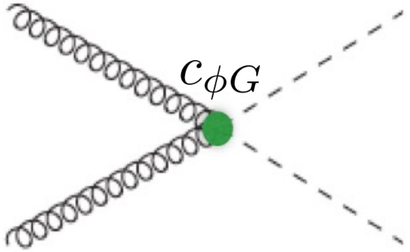
Standard Model Effective Field Theory

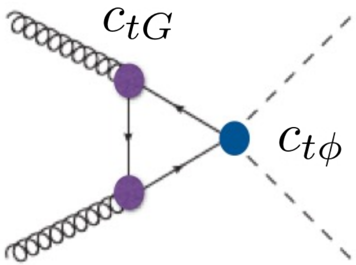
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_k c_k^{(6)} Q_k^{(6)}$$

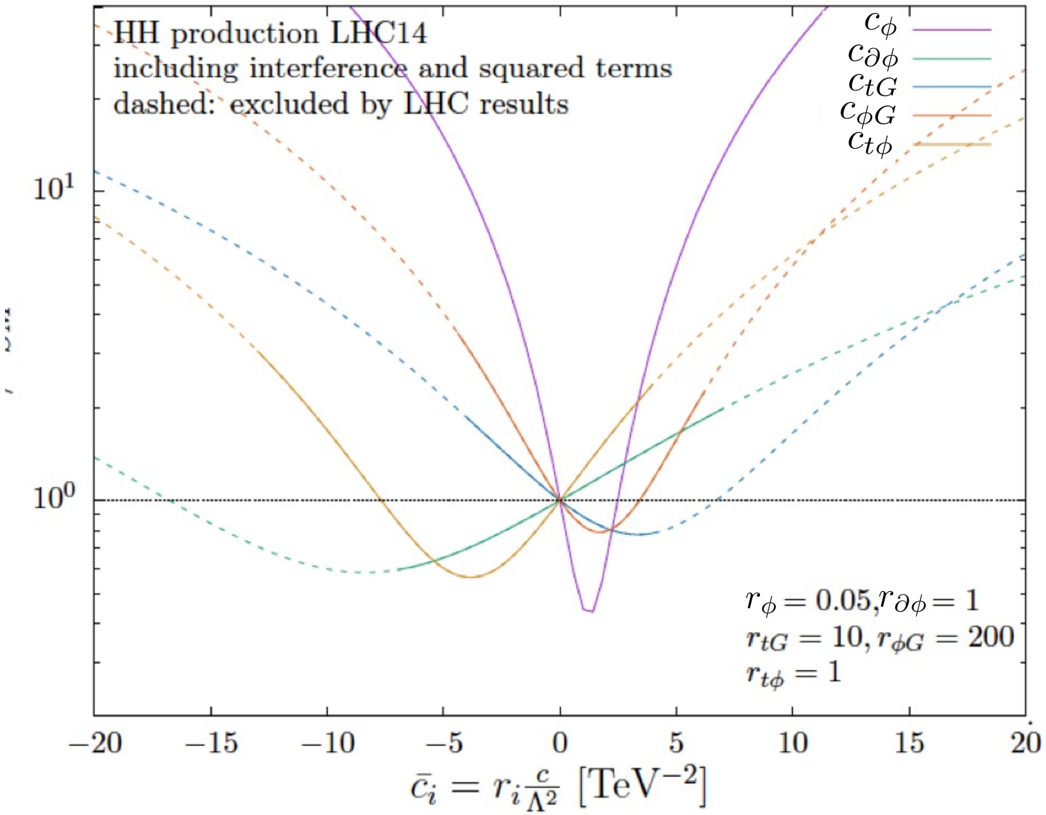








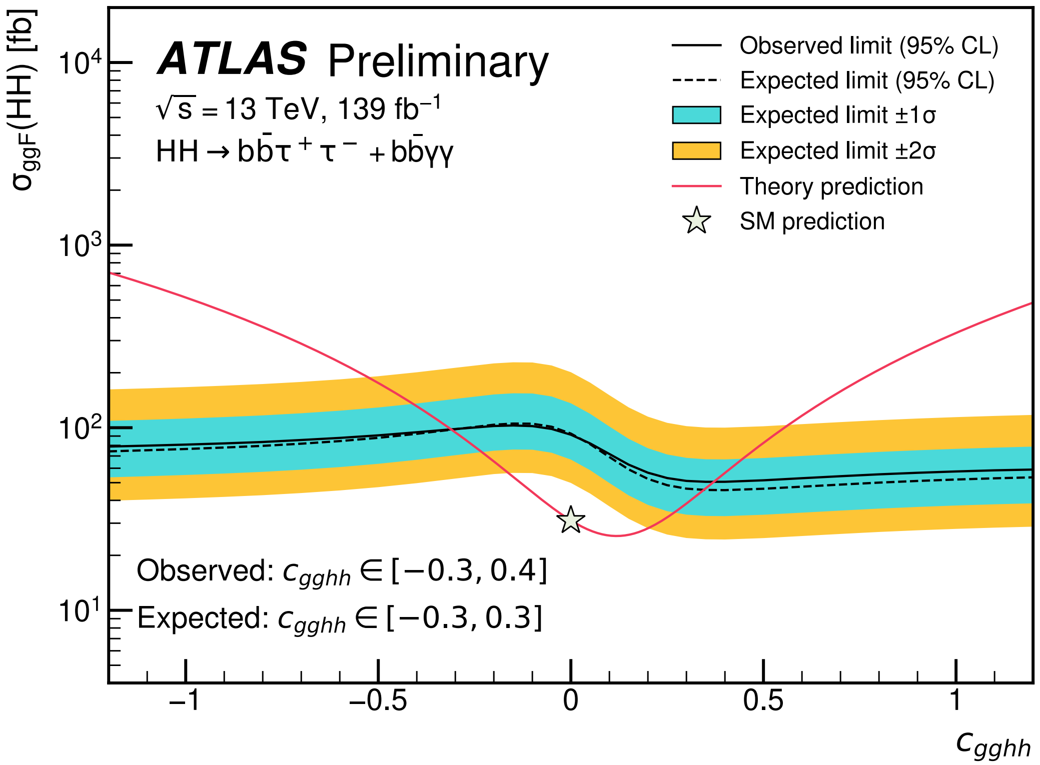


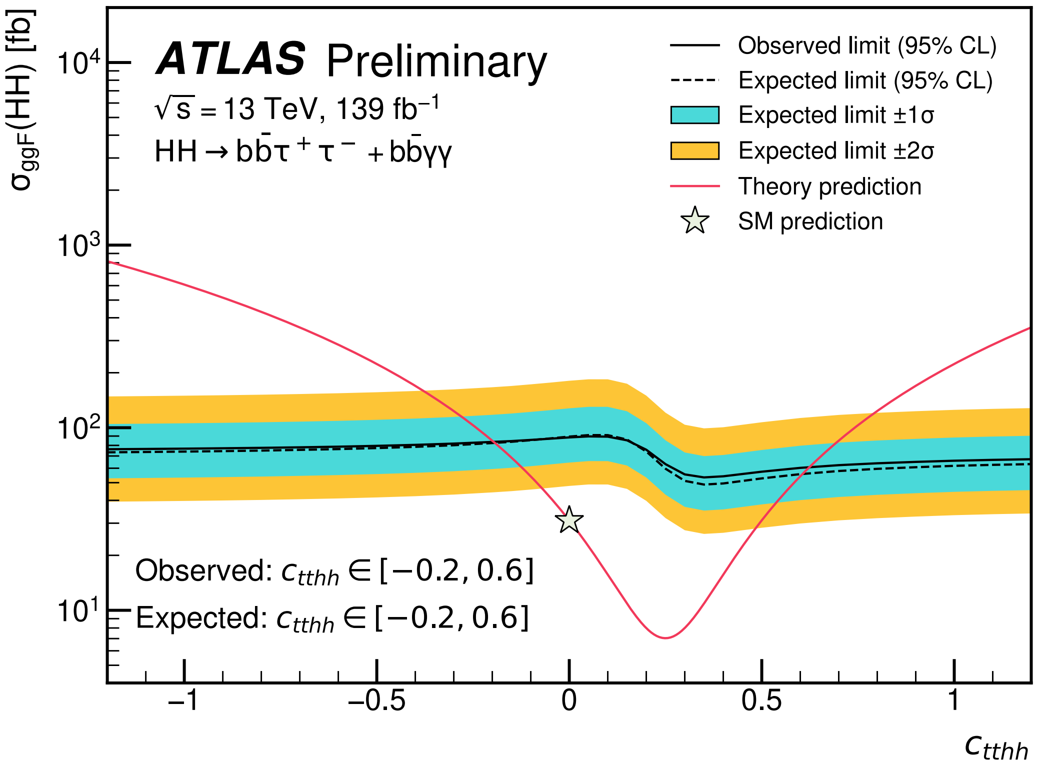


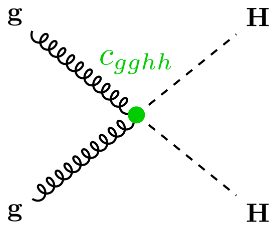
$c_{\partial\phi}$ Universal rescaling

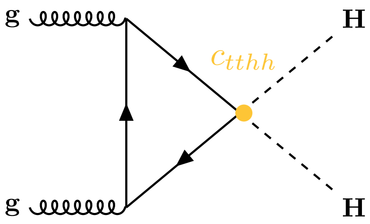
HEFT Interpretations

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-021/

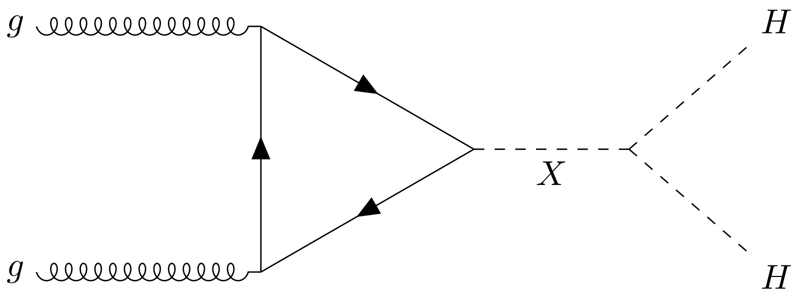


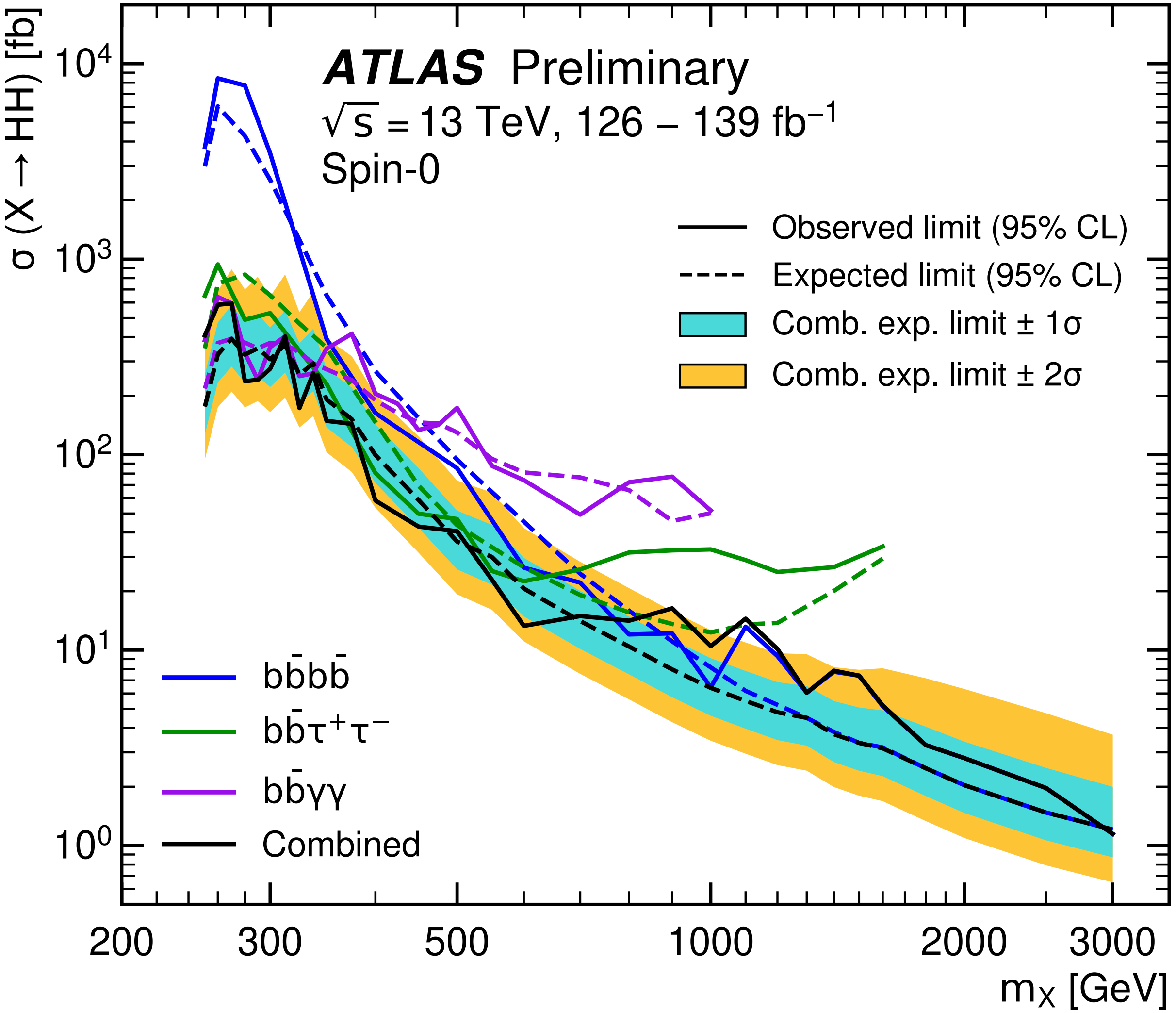




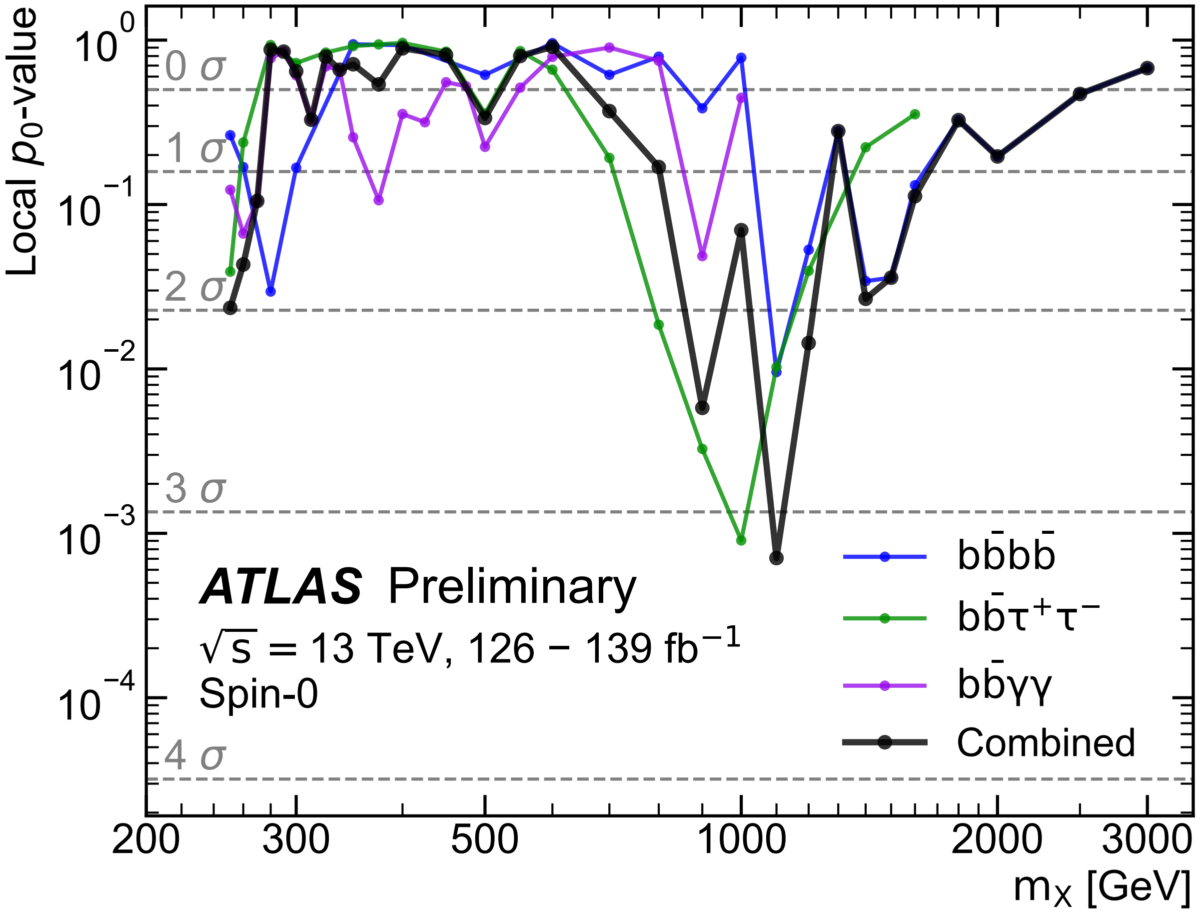


Resonant Run 2 Combined Results





Resonant Run 2 Combination - Largest Excess



Largest excess in m_X in ~1100 GeV region

At m_X = 1100 GeV:
Local significance = 3.2 σ
Global significance = 2.1 σ

Combination - ATLAS-CONF-2021-052
https://cds.cern.ch/record/2786865