Higgs Pair Production Searches at the LHC and HL-LHC

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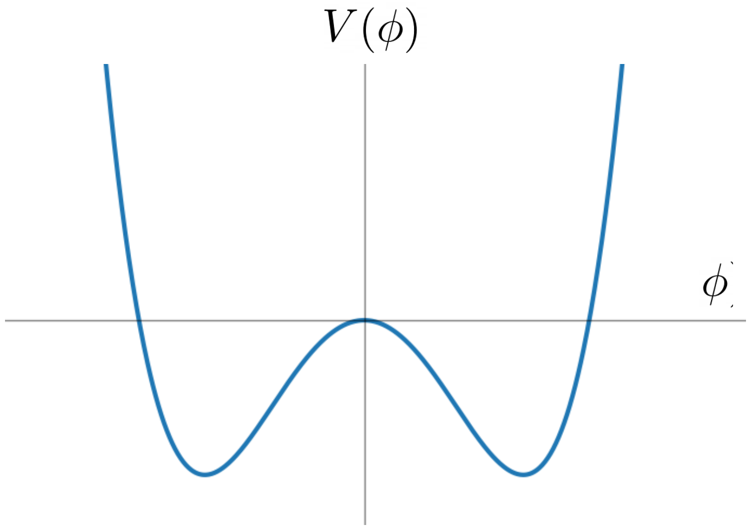
The Higgs Potential

The Standard Model Higgs Potential is:

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

mass term

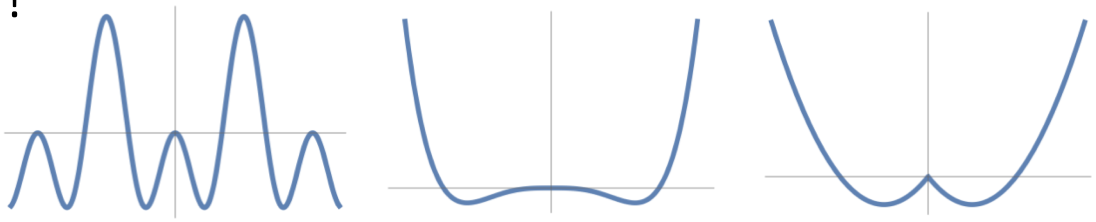
self-coupling term



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

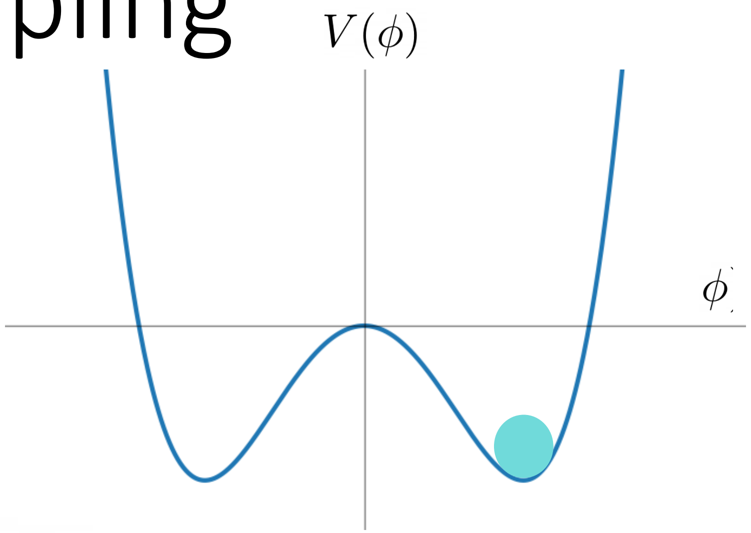
But we haven't thoroughly tested the shape!

New physics could alter the shape of the potential.



Phys. Rev. D 101, 075023 (2020)

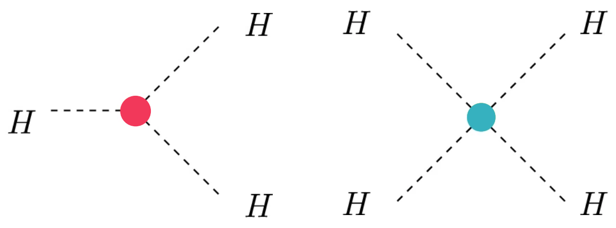
Testing the Higgs self-coupling



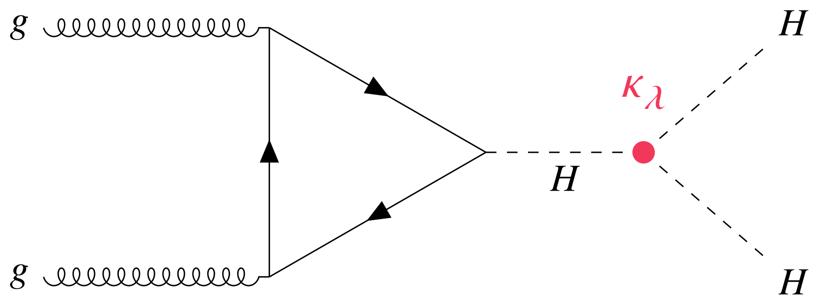
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

Perturb by h about minimum ν

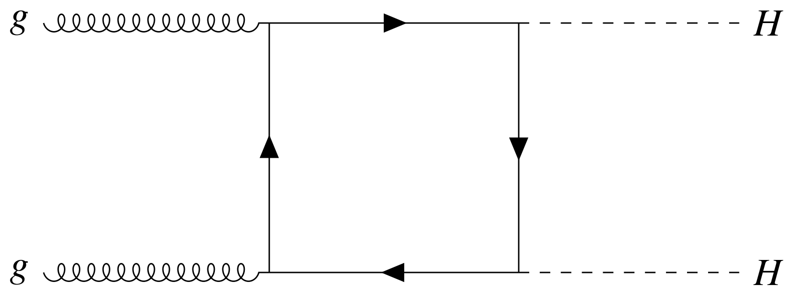
$$V(\nu + h) = -\mu^2(\nu + h)^2 + \lambda(\nu + h)^4$$
$$= V_0 + \frac{1}{2}{m_h}^2h^2 + \lambda v h^3 + \lambda h^4 + \ldots$$



HH Production at the LHC

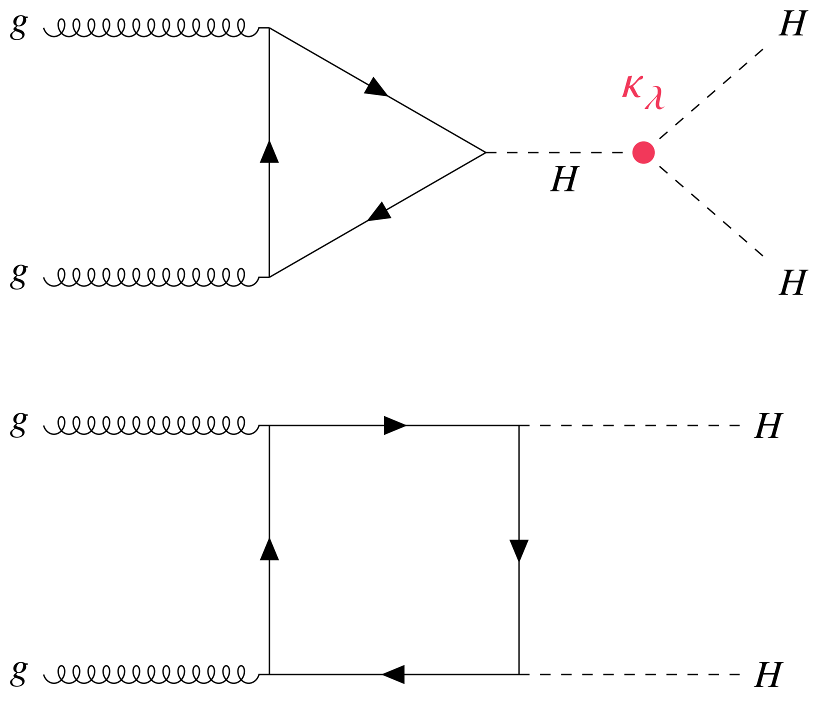


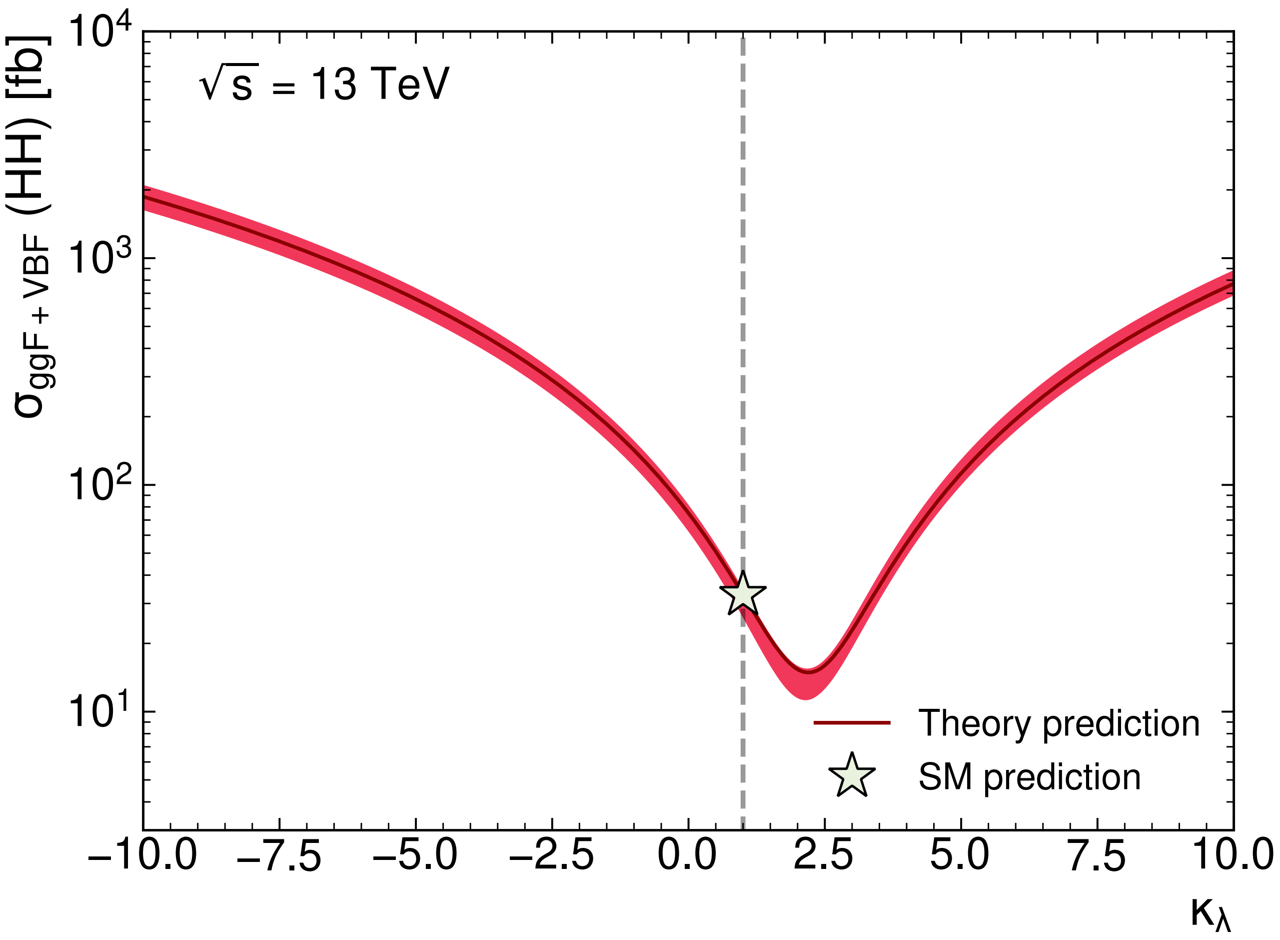
Triangle diagram $\kappa_\lambda = \dfrac{\lambda}{\lambda_{\mathrm{SM}}}$



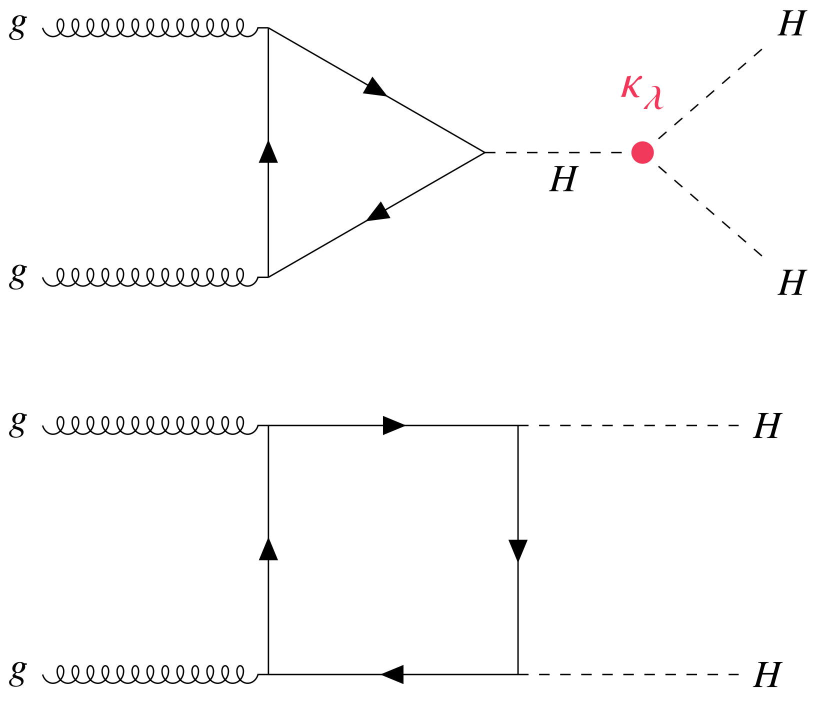
Box diagram

HH Production at the LHC

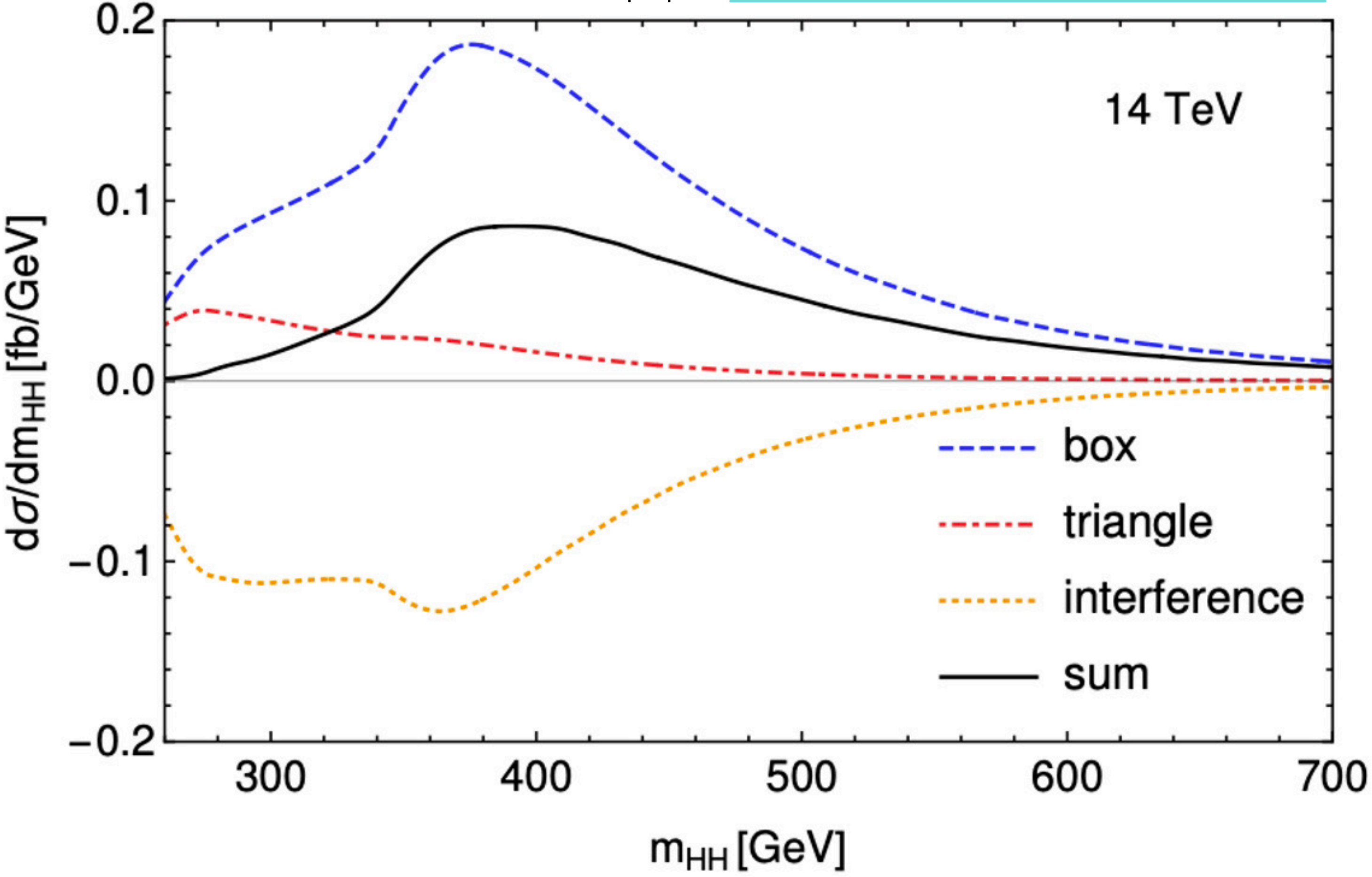




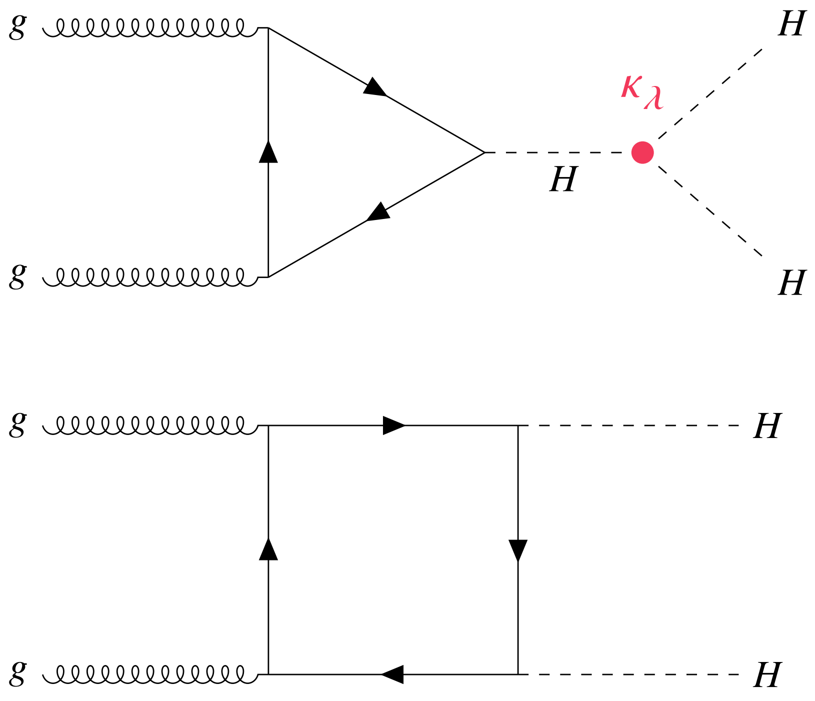
Interference Between Box and Triangle Diagrams

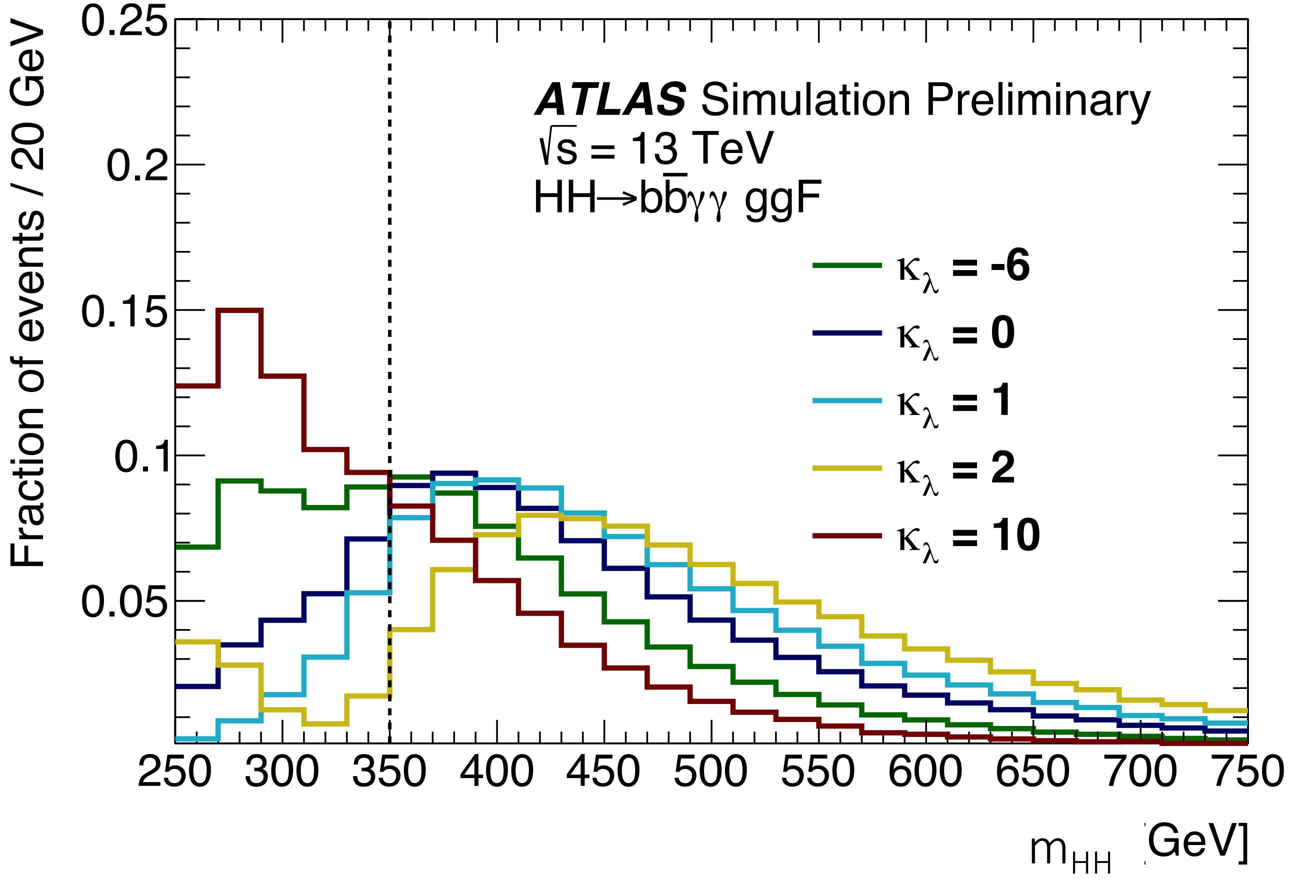


HH Whitepaper https://arxiv.org/pdf/1910.00012.pdf

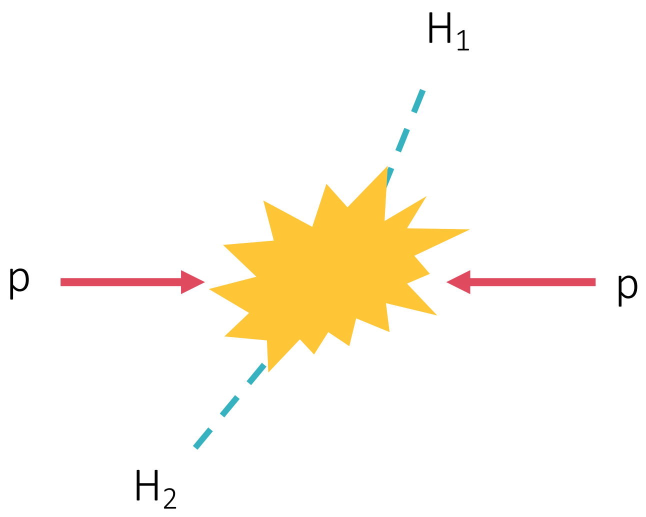


Higgs self-coupling and m_{HH}





HH Branching Ratios

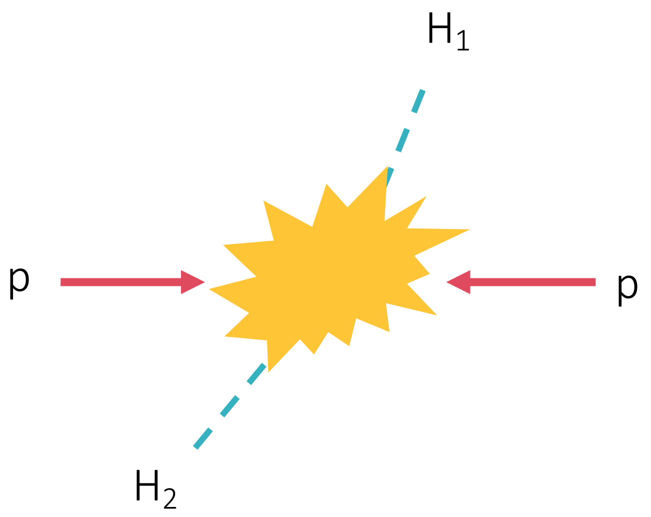


H_1

H_2

	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%

HH Decay Channels



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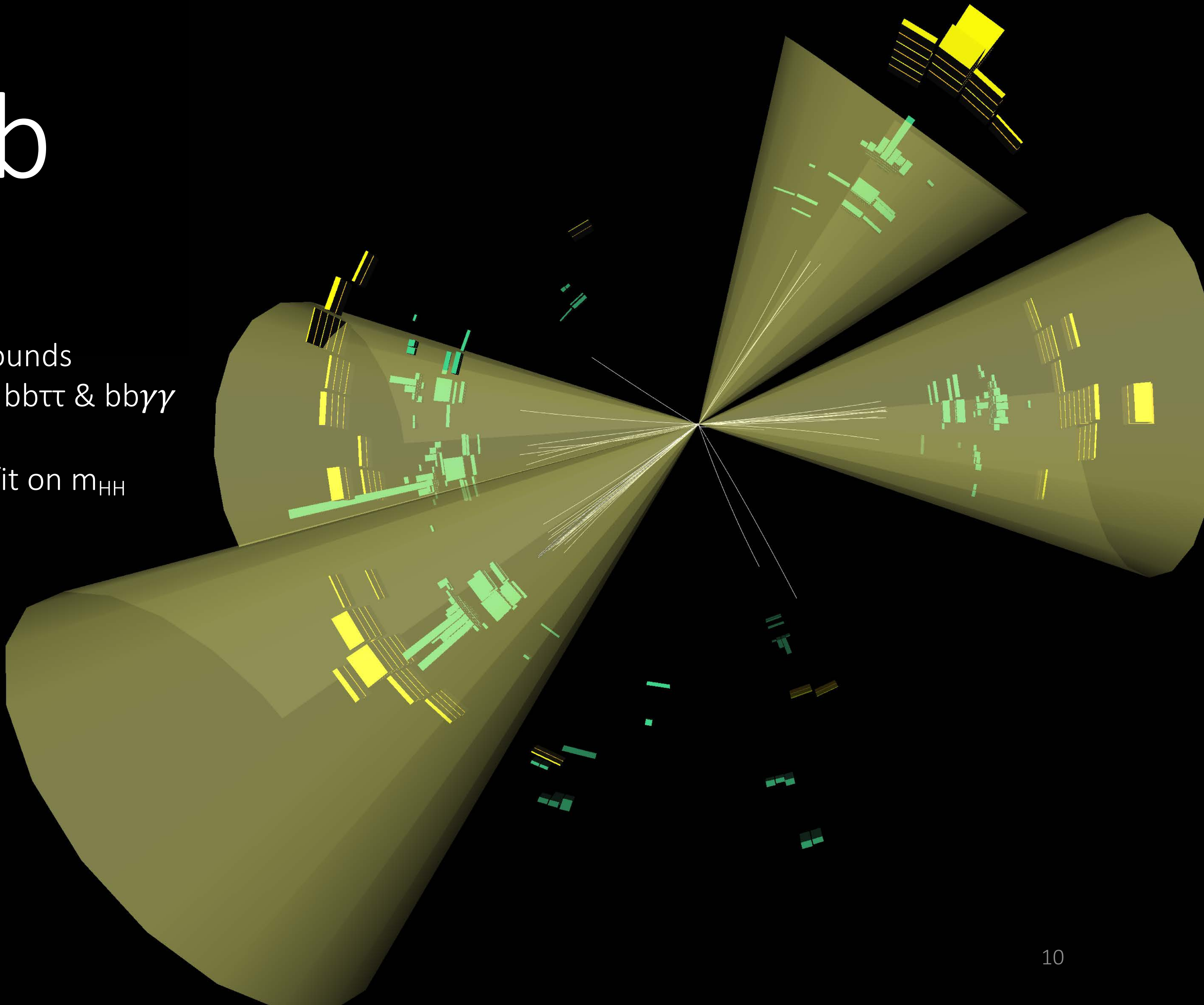
$\gamma\gamma$	0.26%	0.1%	0.029%	0.013%	0.0005%

HH→bbbb

Branching Ratio: 33%

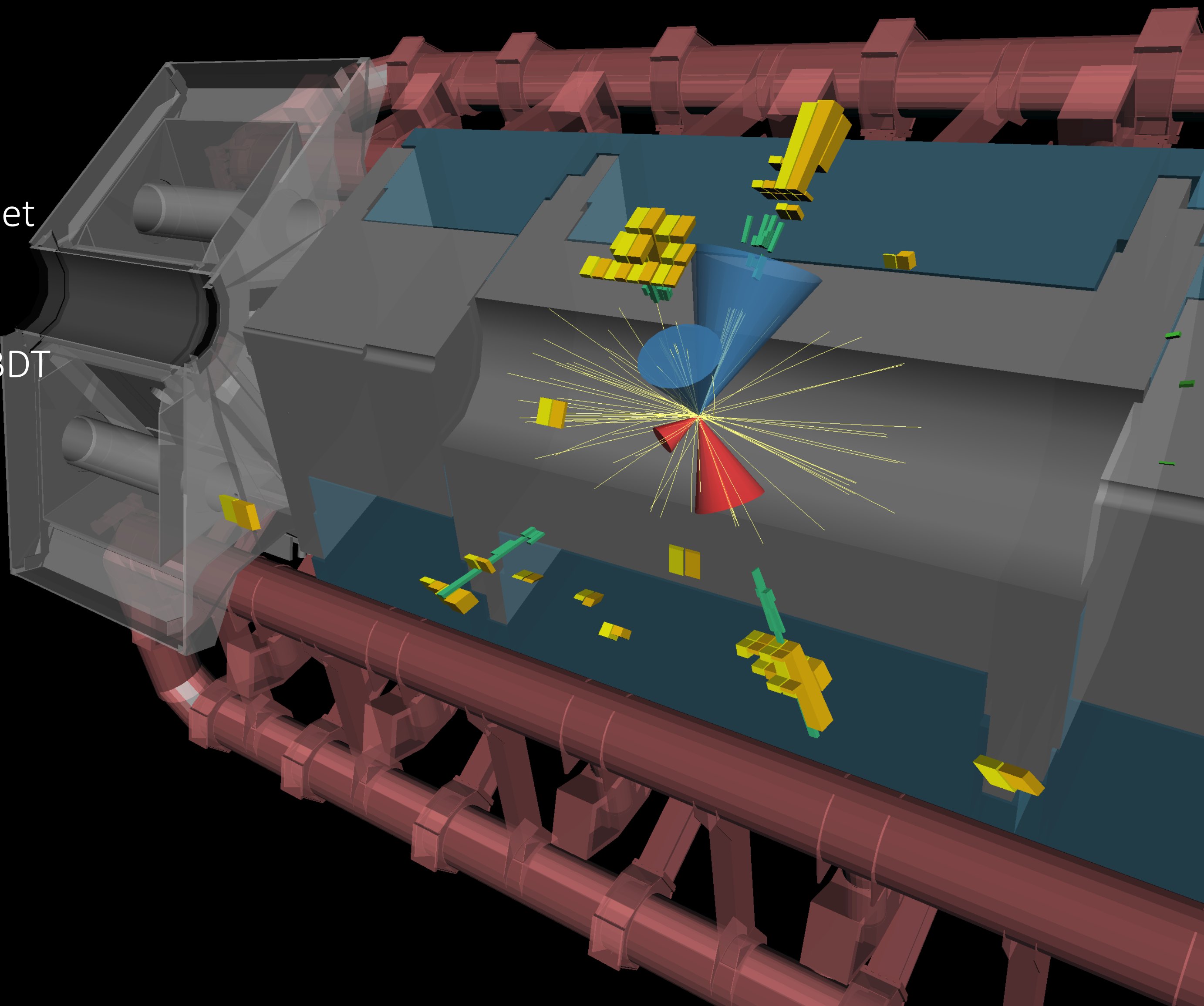
- Challenging QCD multi-jet backgrounds
- High trigger thresholds relative to bb$\tau\tau$ & bb$\gamma\gamma$
    - min: (4x 35 GeV)
- Signal extraction through binned fit on m_{HH}



HH→bbττ

Branching Ratio: 7.4%

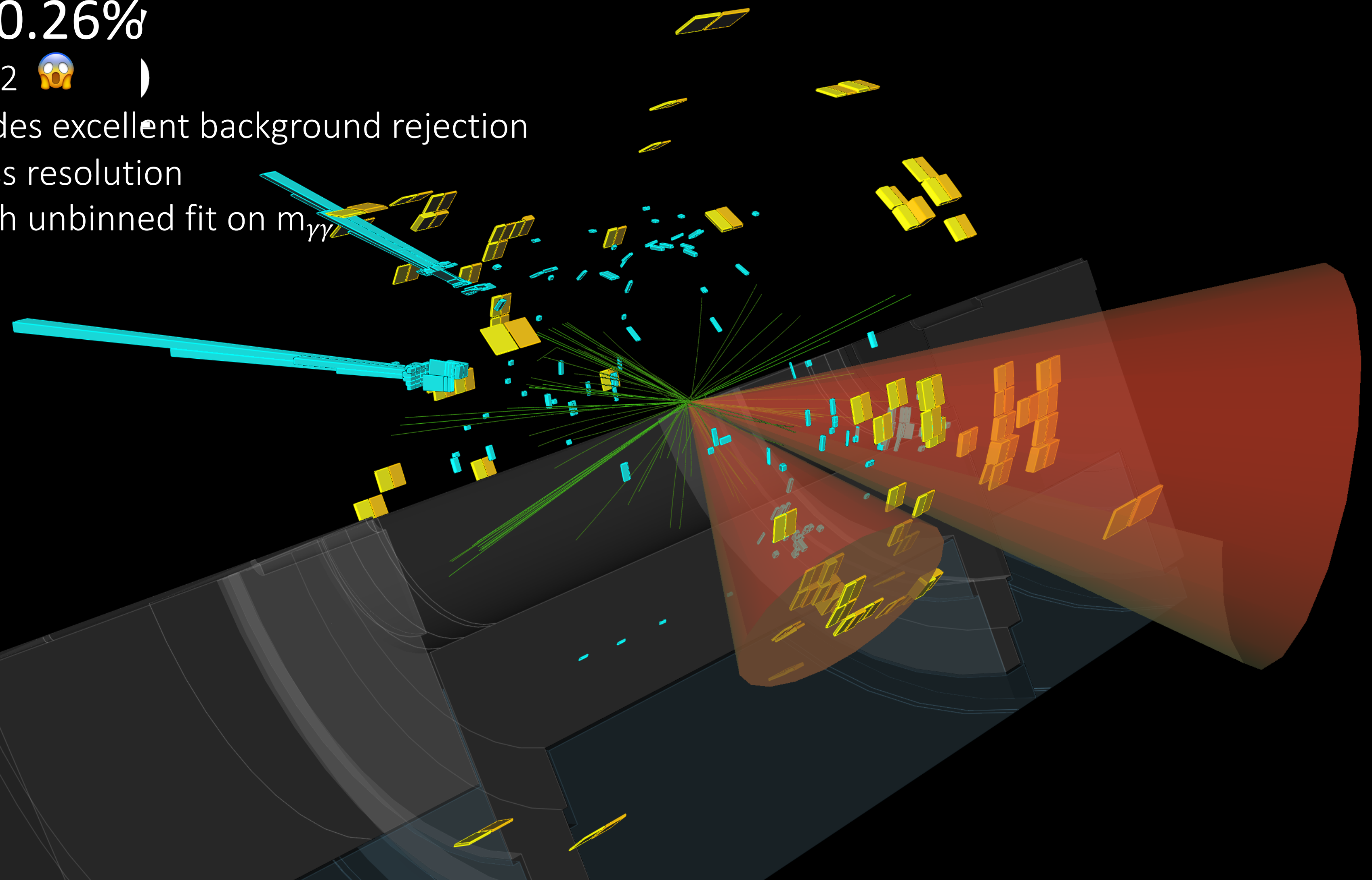
- Tau leptons effective against rejecting QCD multi-jet background
- Challenging electro-weak and top backgrounds
- Signal extraction through binned fit on DNN and BDT outputs



HH→bb$\gamma\gamma$

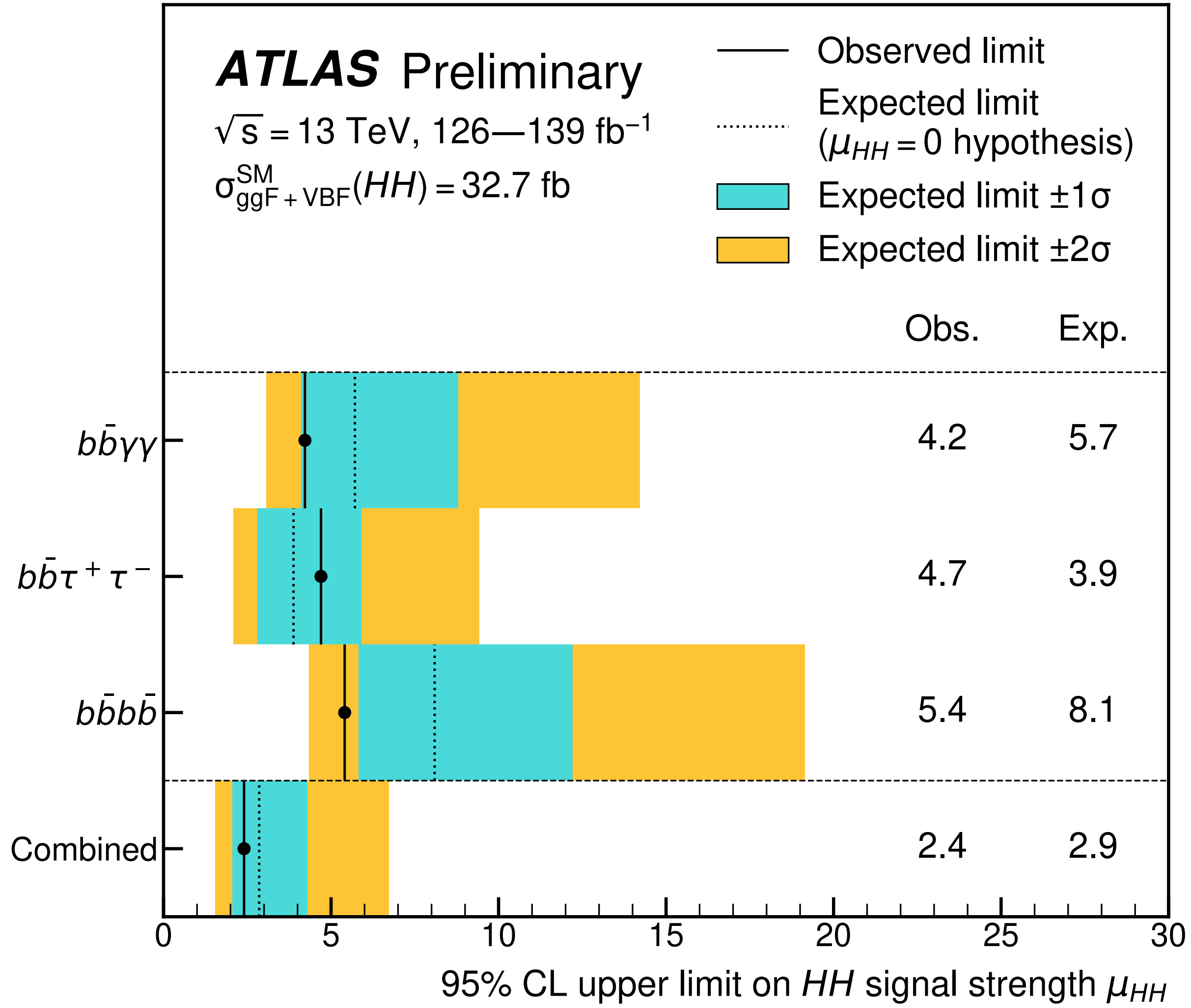
Branching Ratio: 0.26%

- ~10 events in all of Run 2 😱
- Di-photon system provides excellent background rejection
- Excellent di-photon mass resolution
- Signal extraction through unbinned fit on $m_{\gamma\gamma}$



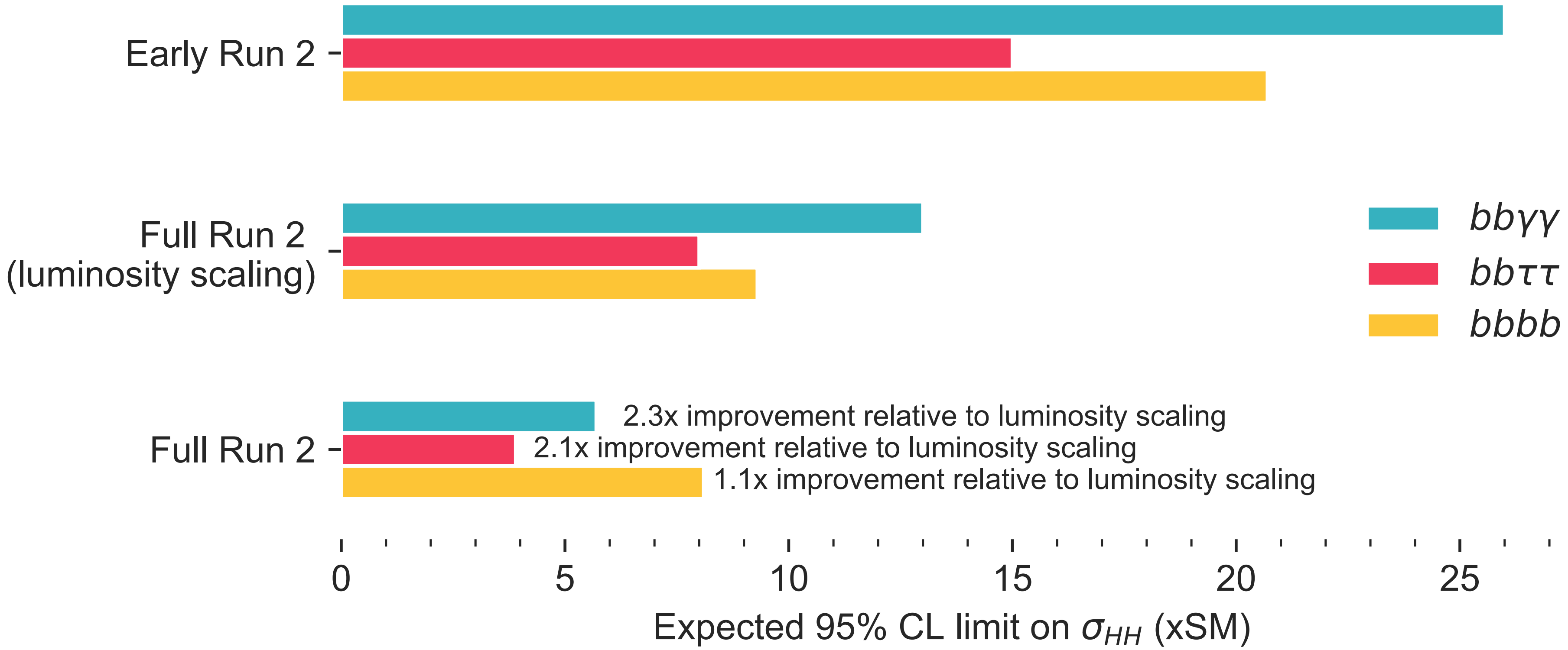
Latest Limits on HH Signal Strength

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



ATLAS-CONF-2022-050
https://cds.cern.ch/record/2816332

Improvements Since Early Run 2

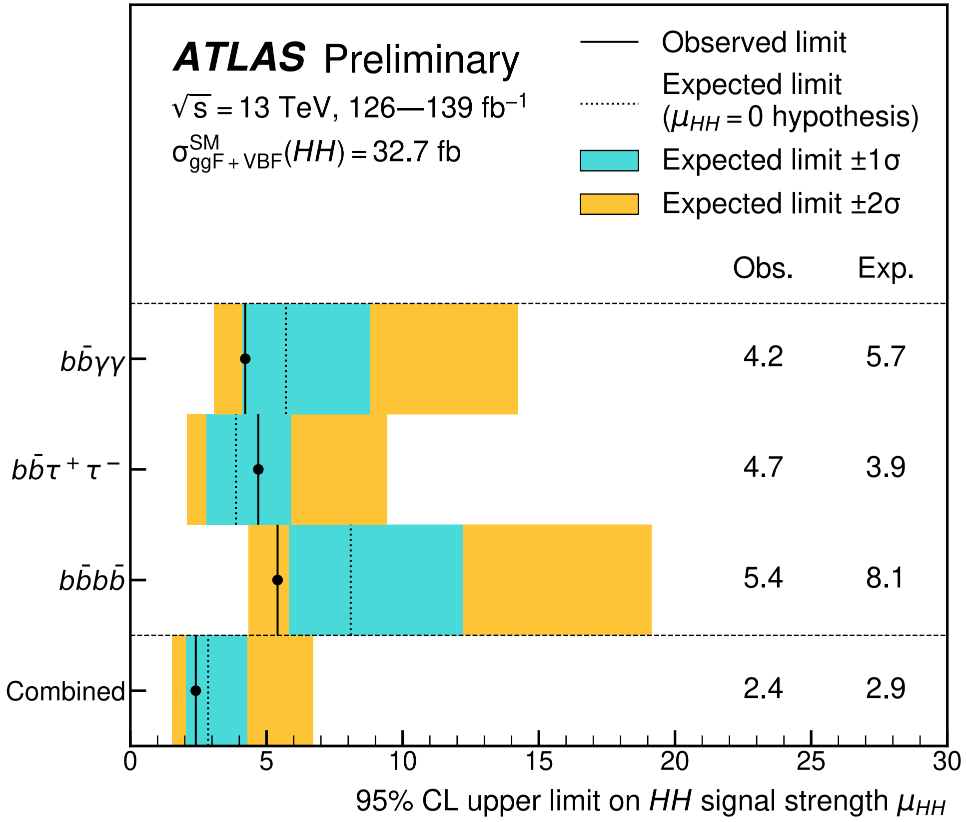


Some key improvements between Early (27-36/fb) and Full Run 2 (126-139/fb) coming from:

- improved analysis strategies (large adoption of multivariate methods)
- improved b-tagging (switched from 70%→77% WP)
- improved tau lepton identification

Latest Limits on HH Signal Strength

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



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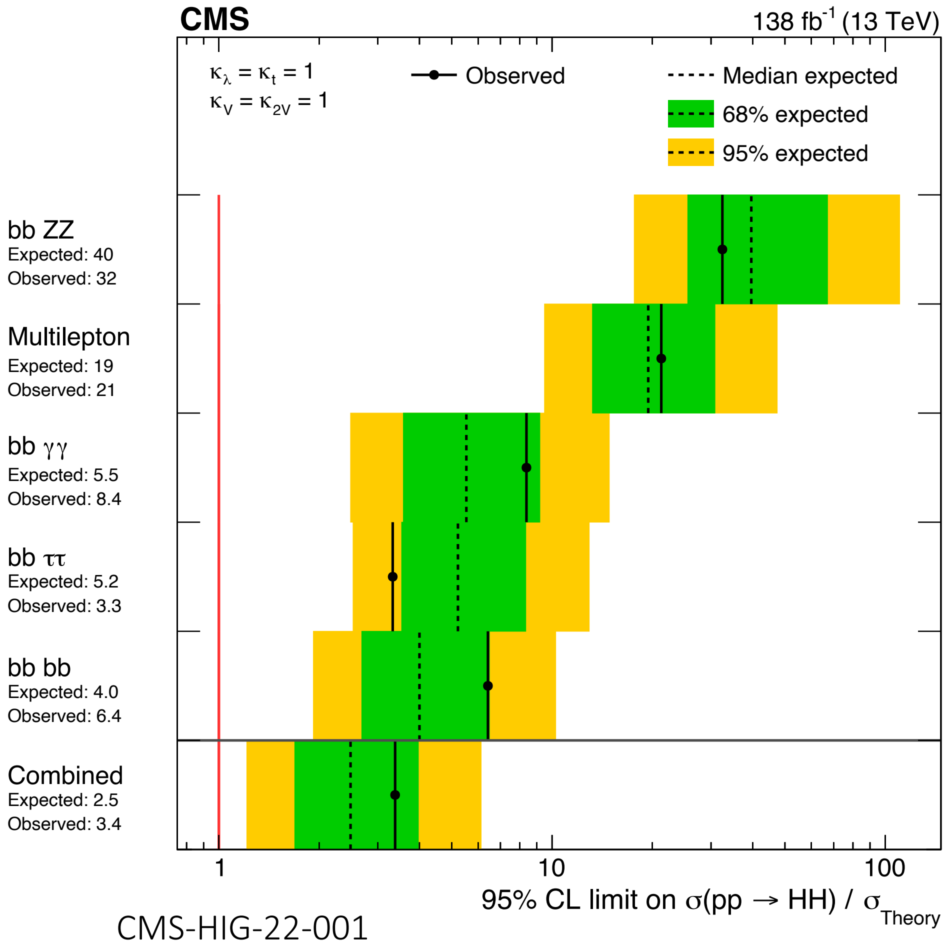
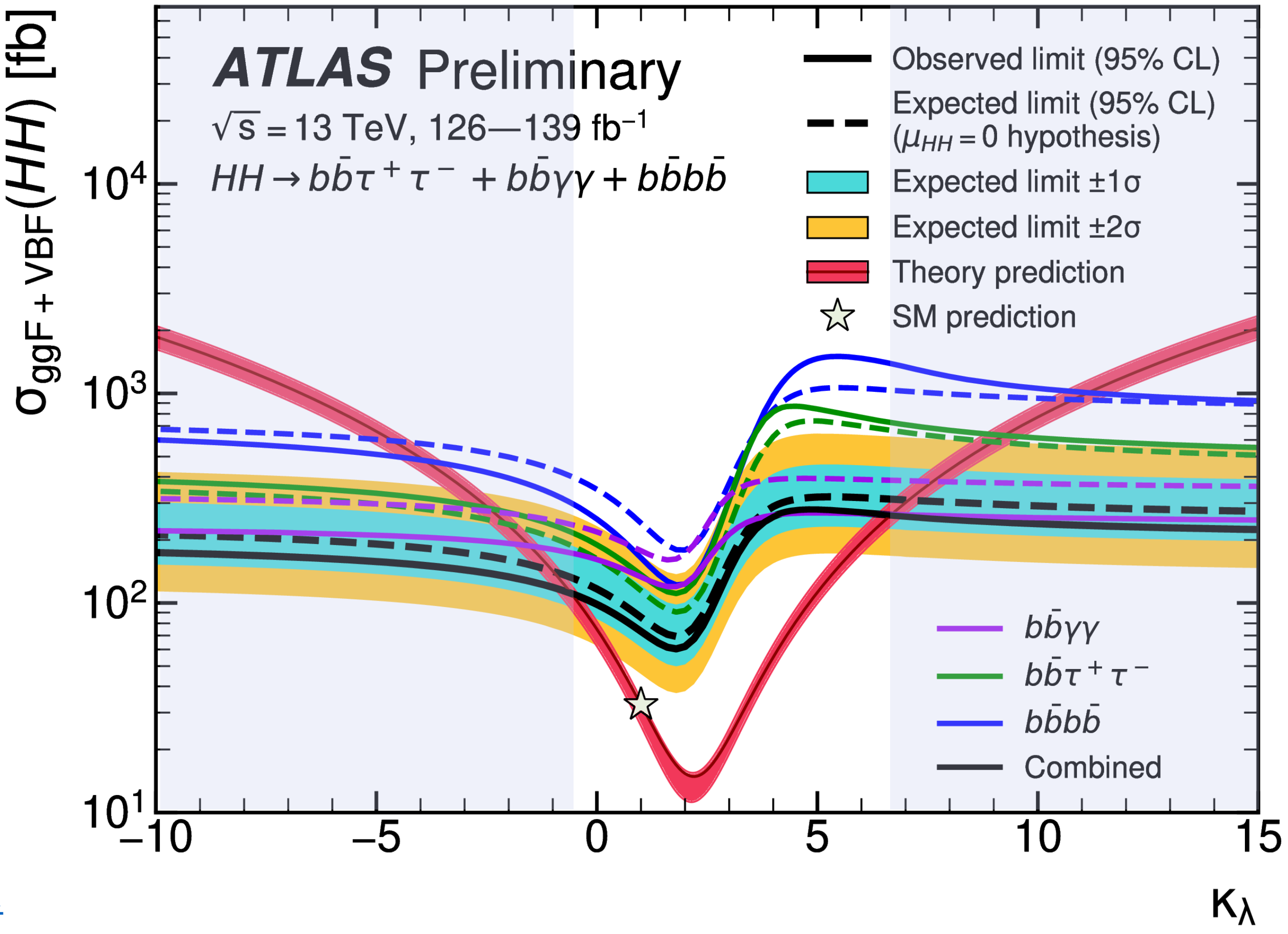


CMS-HIG-22-001
https://cds.cern.ch/record/2814513/

Latest Constraints on the Higgs Boson Self-Coupling

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

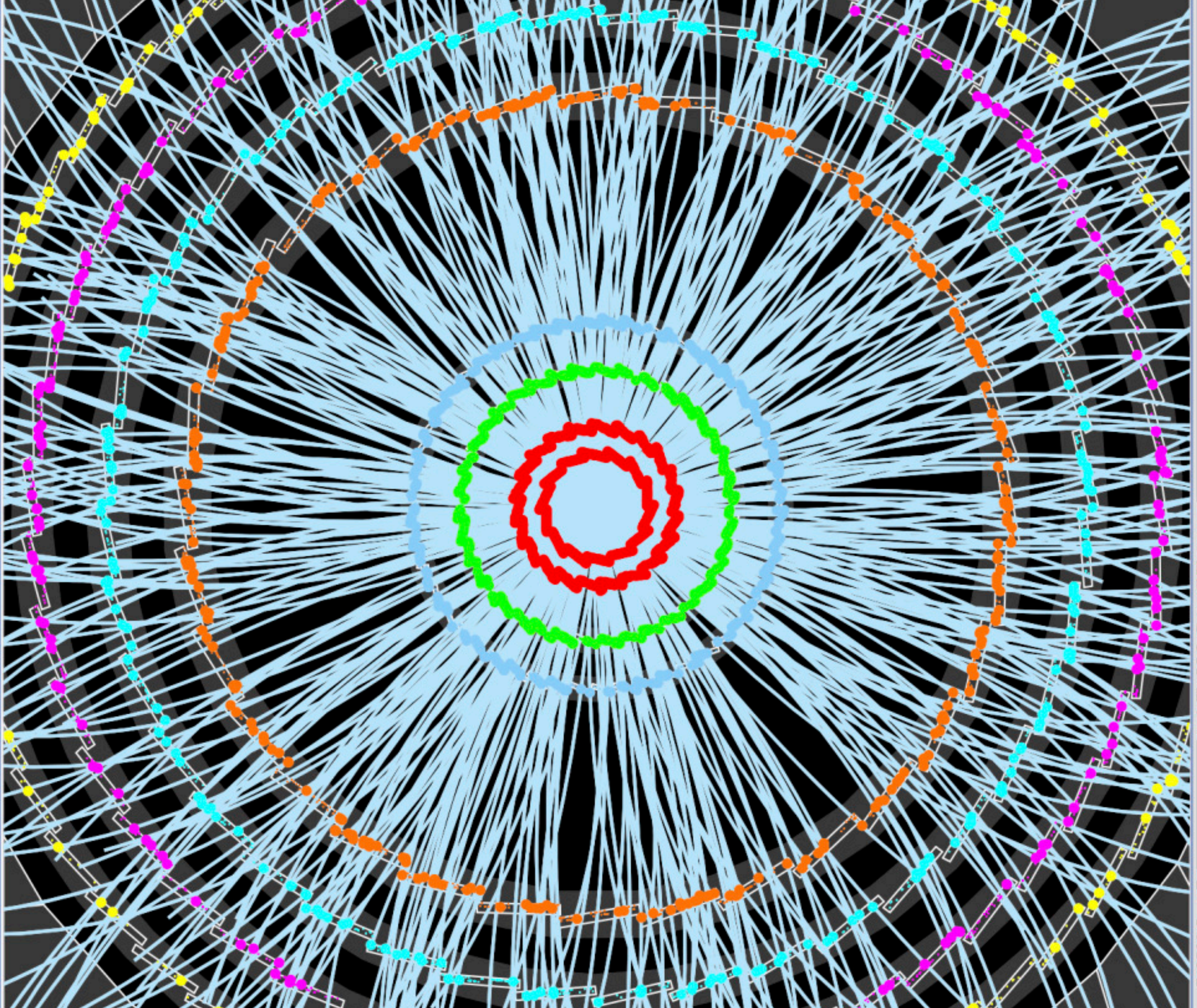


Observed $k_\lambda \in$ [-0.6, 6.6]
Expected $k_\lambda \in$ [-1.0, 7.1]

ATLAS-CONF-2022-050
https://cds.cern.ch/record/2816332

HL-LHC Timeline

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

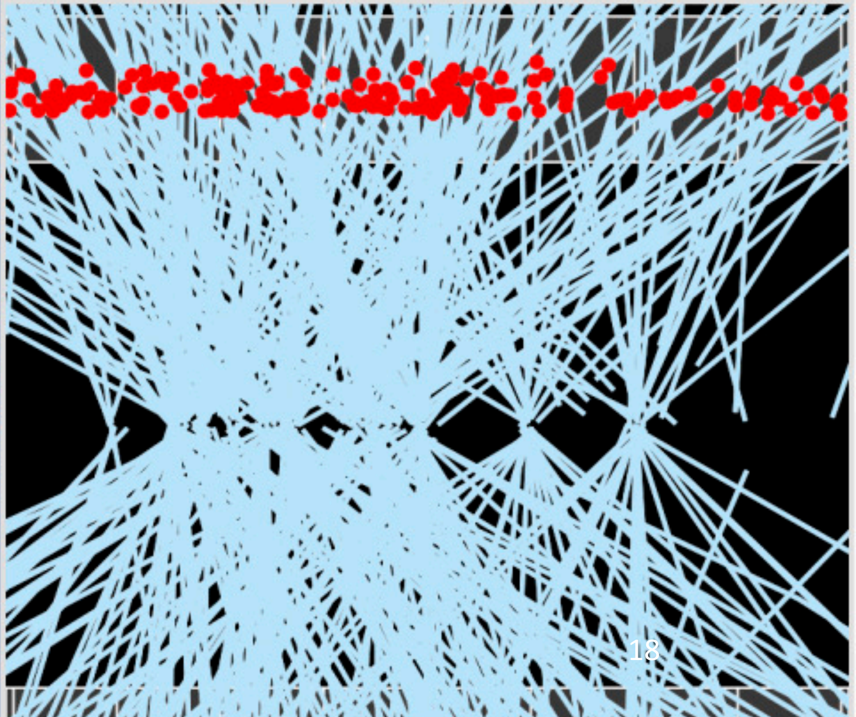


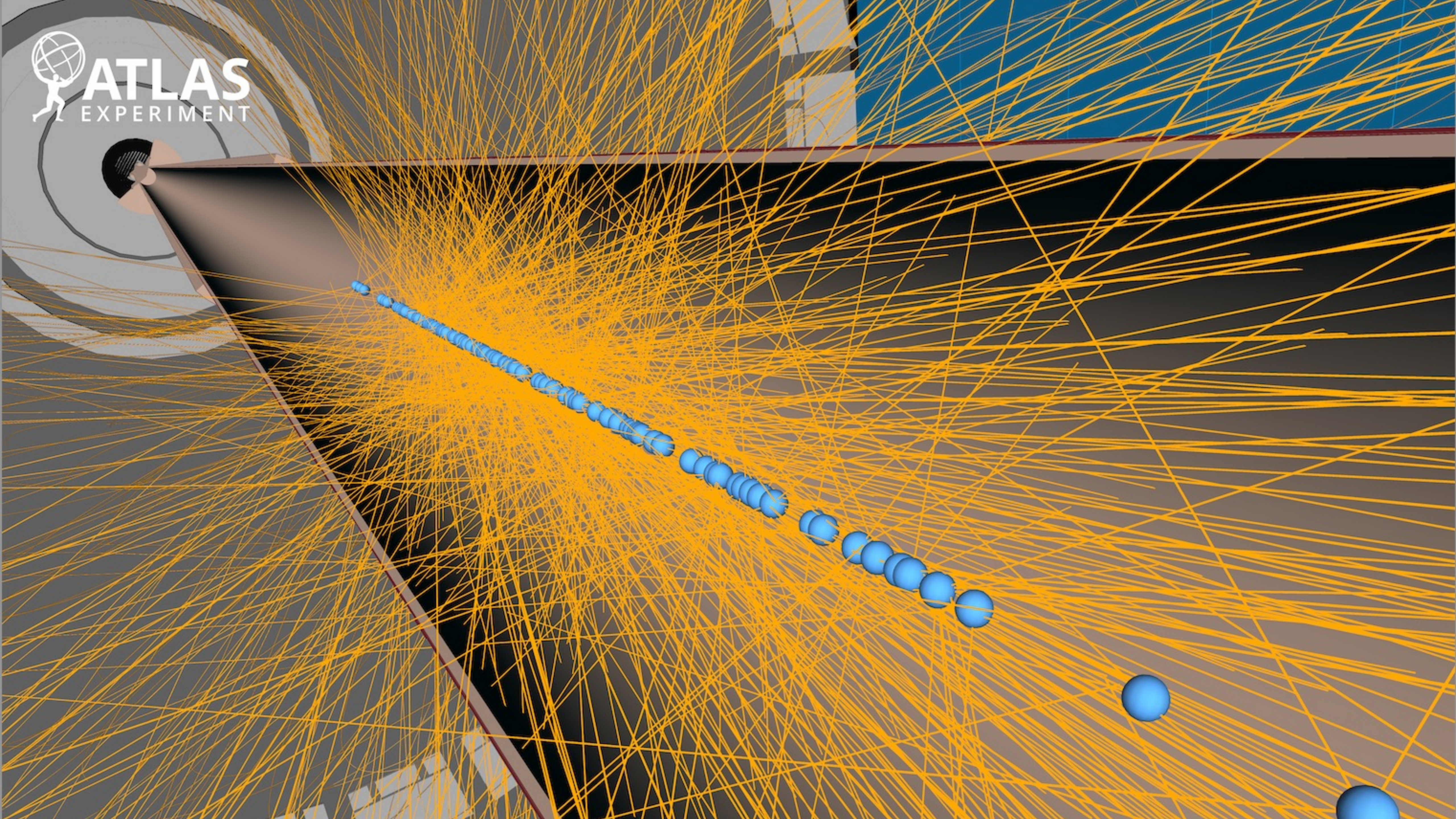
ATLAS EXPERIMENT

Run Number: 266904, Event Number: 25884805

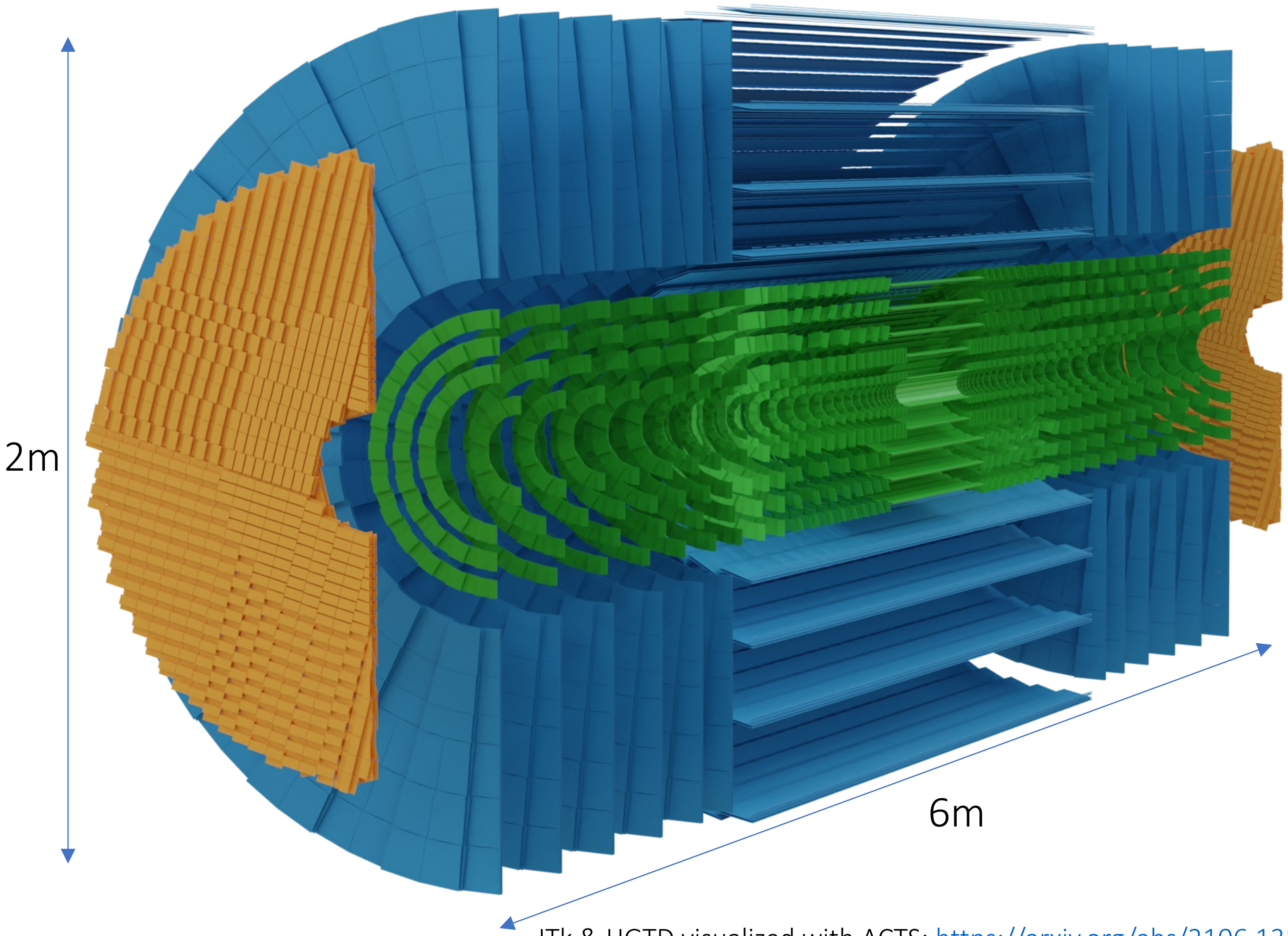
Date: 2015-06-03 13:41:54 CEST

NPV = 17, <μ>=13




ATLAS
EXPERIMENT

The ATLAS Inner Tracker Upgrade



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

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.

Brand new all silicon tracking detector

Extrapolation Procedure

1. Luminosity scaling to 3000 fb^{-1} (21x more data than Run 2)
2. Cross-sections increased to adjust from 13 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 slide)

HL-LHC Extrapolation Procedure

Assume 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

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

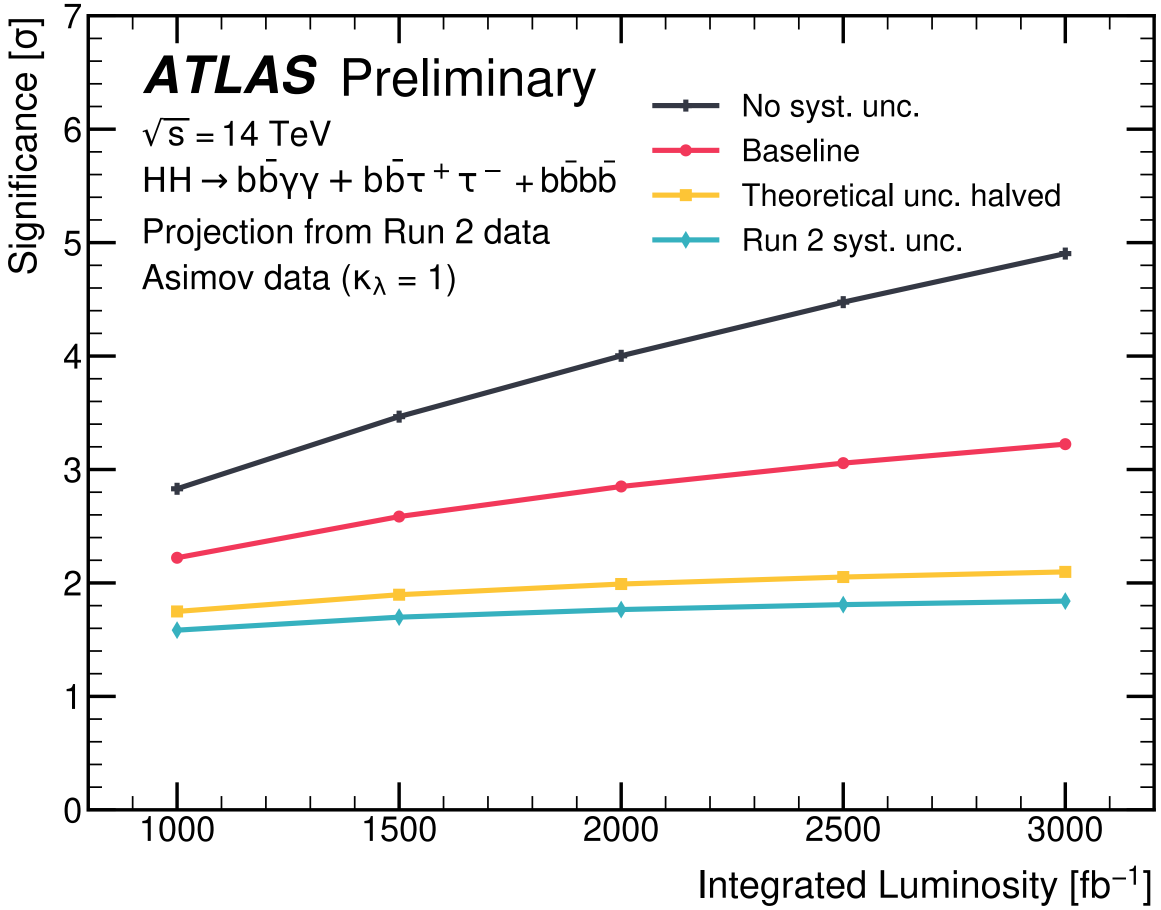
optimistic

conservative

Projected HH Significance

Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination
	Significance $[\sigma]$			
No syst. unc.	2.3	4.0	1.7	4.9
Baseline	2.2	2.8	0.95	$\boxed{3.2}$
Theoretical unc. halved	1.1	1.7	0.62	2.1
Run 2 syst. unc.	1.1	1.5	0.62	1.8

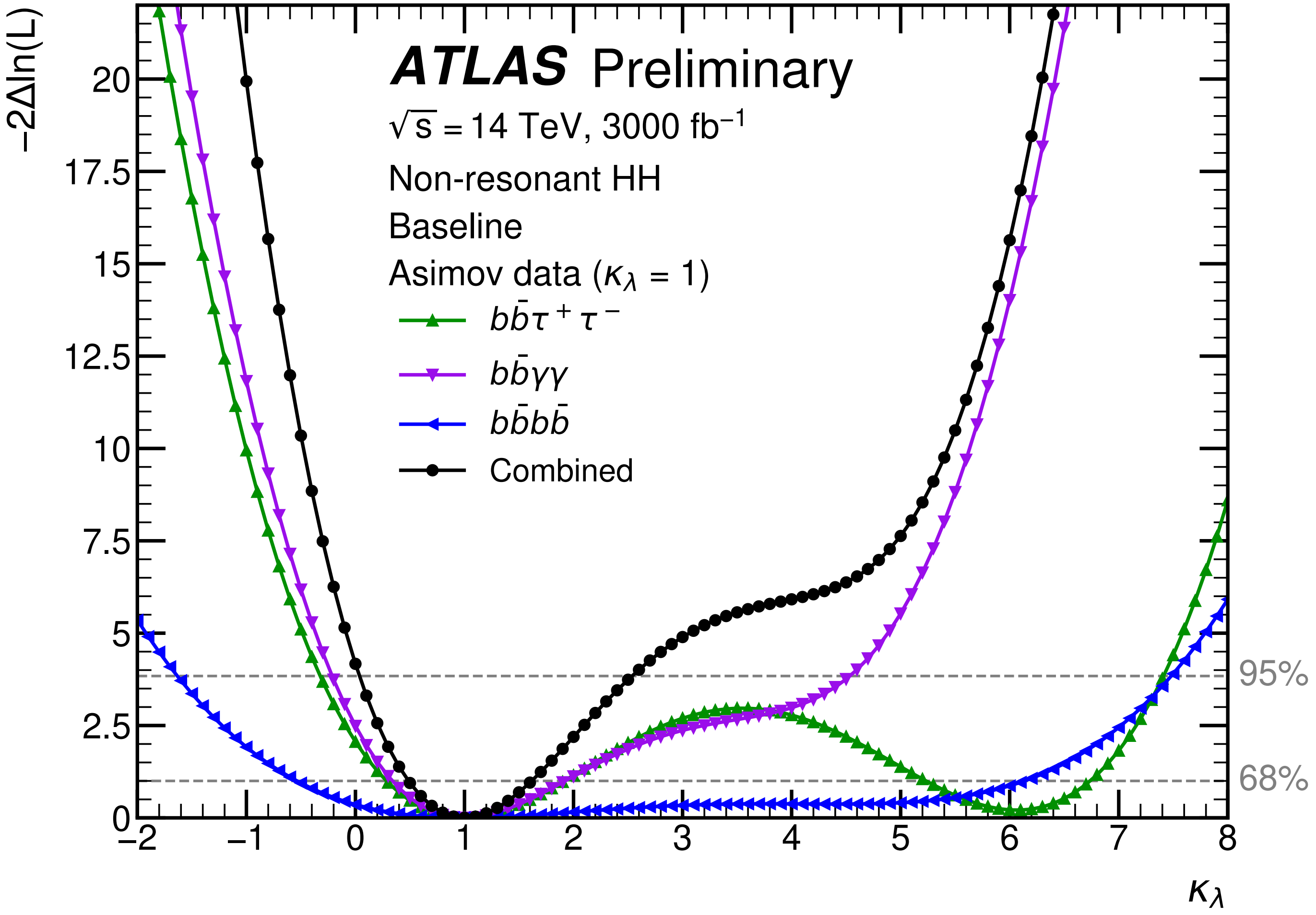
ATLAS-CONF-2021-052



HH Likelihood Scan ATLAS-CONF-2021-052

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

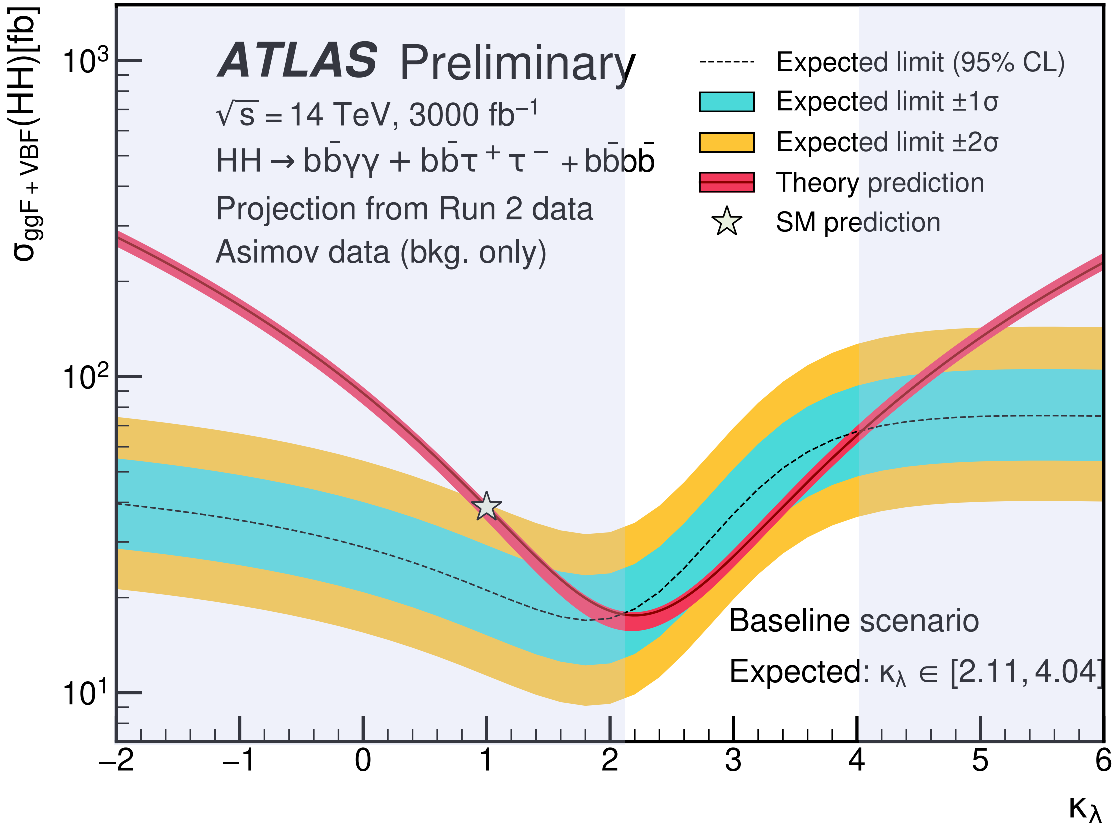
Uncertainty scenario	Likelihood scan $1\,\sigma$ CI	Likelihood scan $2\,\sigma$ CI
No syst. unc.	$[0.7, 1.4]$	$[0.3, 2.0]$
Baseline	$\boxed{[0.5, 1.6]}$	$[0.0, 2.6]$
Theoretical unc. halved	$[0.3, 2.2]$	$[-0.4, 5.6]$
Run 2 syst. unc.	$[0.1, 2.4]$	$[-0.7, 5.6]$



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!

HL-LHC CMS+ATLAS Combination

From Yellow Report (2019): 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	$\boxed{3.0}$	2.6
	Combined 4.5		Combined 4.0	

*Our latest projections adjust this significance to 3.2σ

Comparison of k_λ measurements at future colliders

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

Constraints from HL-LHC likely to be strongest for many years to come.

High energy e+e-, muon or pp colliders required for <10% uncertainty

From Snowmass EF01 Report: https://snowmass21.org/_media/energy/snowmass2021_higgs_report_final.pdf

Summary

Three main channels used to search for HH on ATLAS, each channel starting to approach SM sensitivity.

HH combination:
bbb+ bbττ + bb$\gamma\gamma$ –
Observed limit on SM signal strength: **2.4xSM**, observed limits on k_λ $-0.6 \leq k_\lambda \leq 6.6$

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

HH searches will be interesting for many years to come!

Thank you!

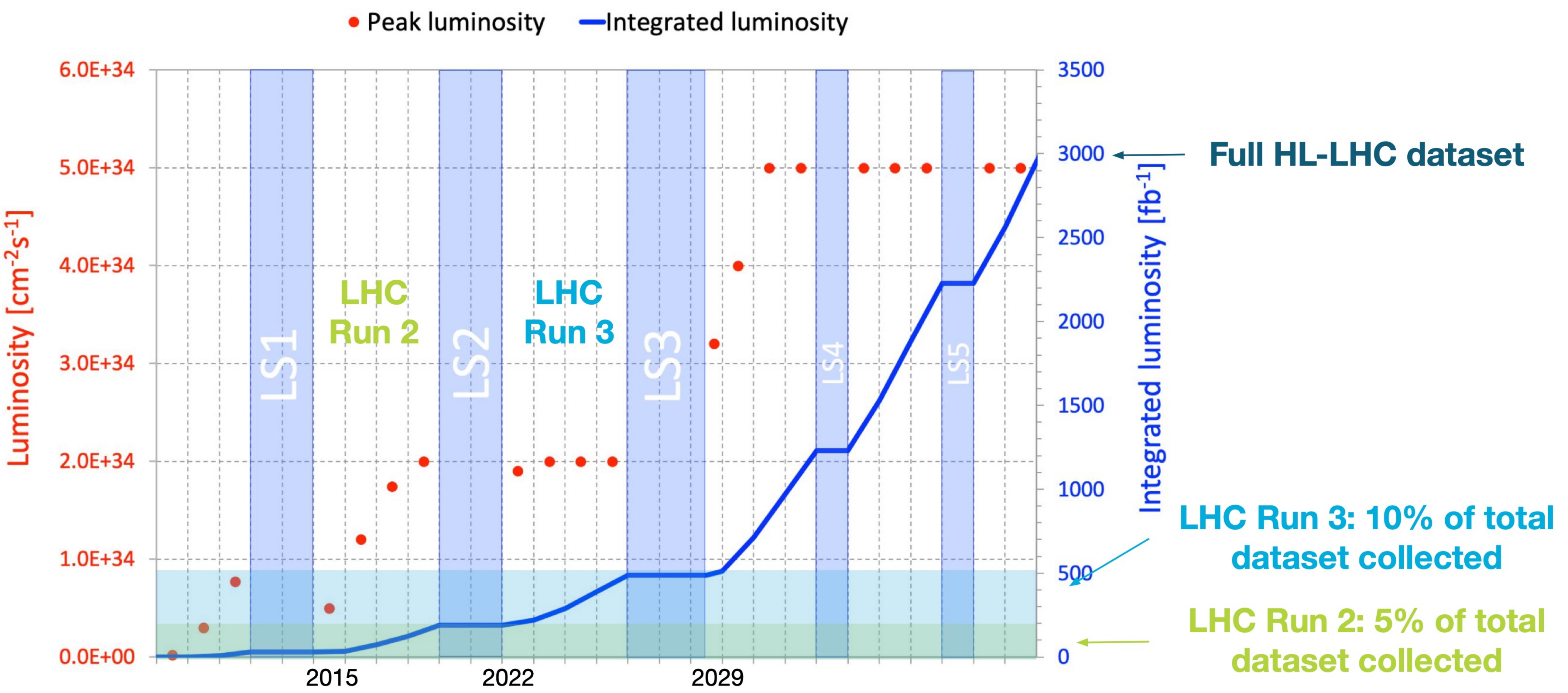
References

2022 HL-LHC Prospects Combination http://cdsweb.cern.ch/record/2802127
2021 HL-LHC Prospects bbττ https://cds.cern.ch/record/2798448
2022 HL-LHC Prospects bb$\gamma\gamma$ http://cdsweb.cern.ch/record/2799146
2018 HL-LHC Prospects Combination http://cdsweb.cern.ch/record/2652727

2021 Full Run 2 bbττ https://cds.cern.ch/record/2777236
2021 Full Run 2 bb$\gamma\gamma$ https://arxiv.org/abs/2112.11876
2022 Full Run 2 bbbb https://cds.cern.ch/record/2811390

2021 Full Run 2 HH Combination (bb$\gamma\gamma$+ bbττ) https://cds.cern.ch/record/2786865
2022 Full Run 2 HH+H Combination (bbbb+bb$\gamma\gamma$+ bbττ) https://cds.cern.ch/record/2816332
2022 Full Run 2 HH HEFT Interpretations
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-021/

HL-LHC

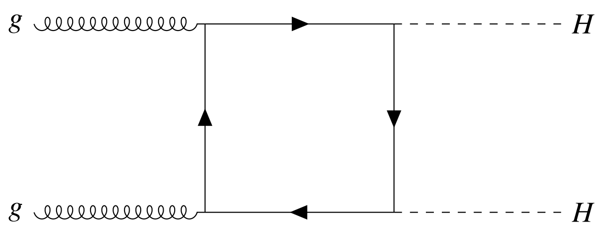


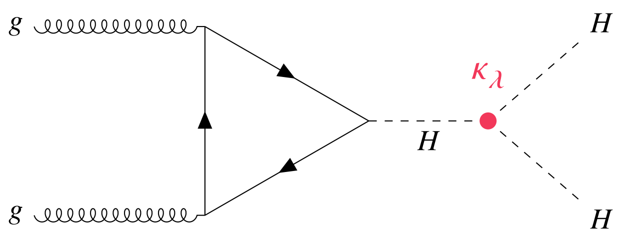
Slide from Elizabeth Brost

HH Production Channels

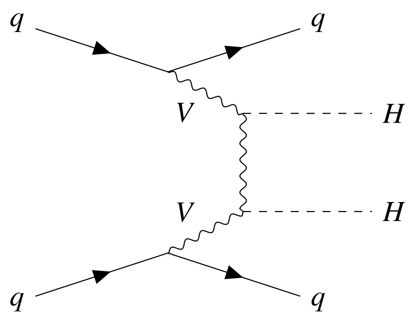
Non-Resonant

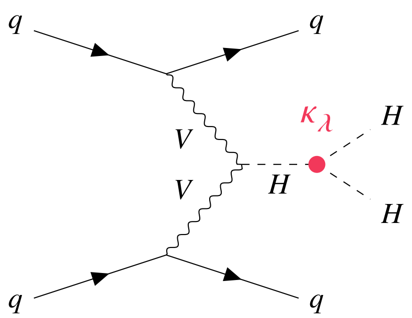
ggF: σ_{SM} = 31.05 fb

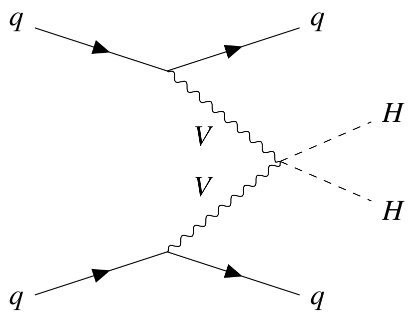




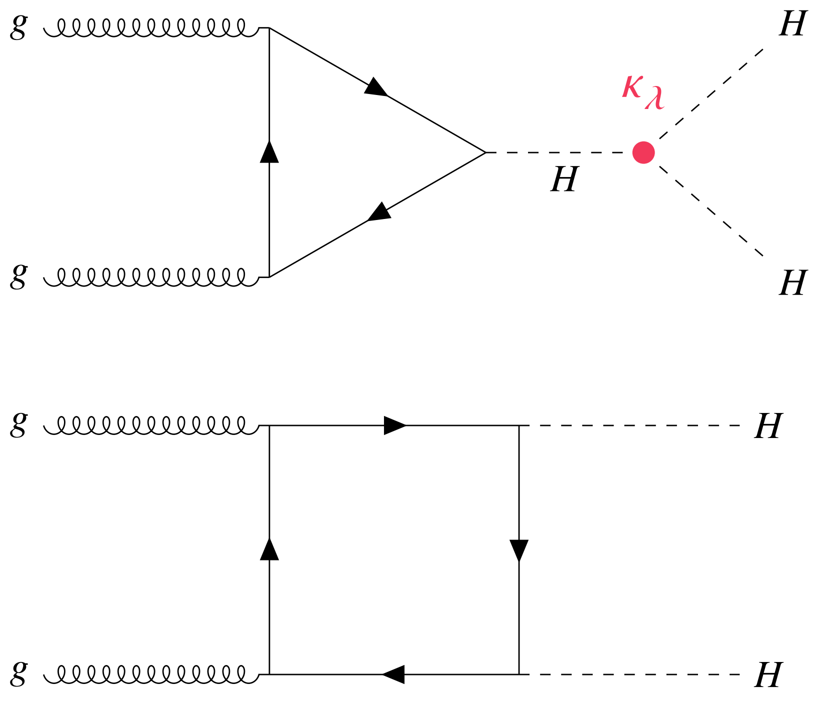
VBF: σ_{SM} = 1.73 fb

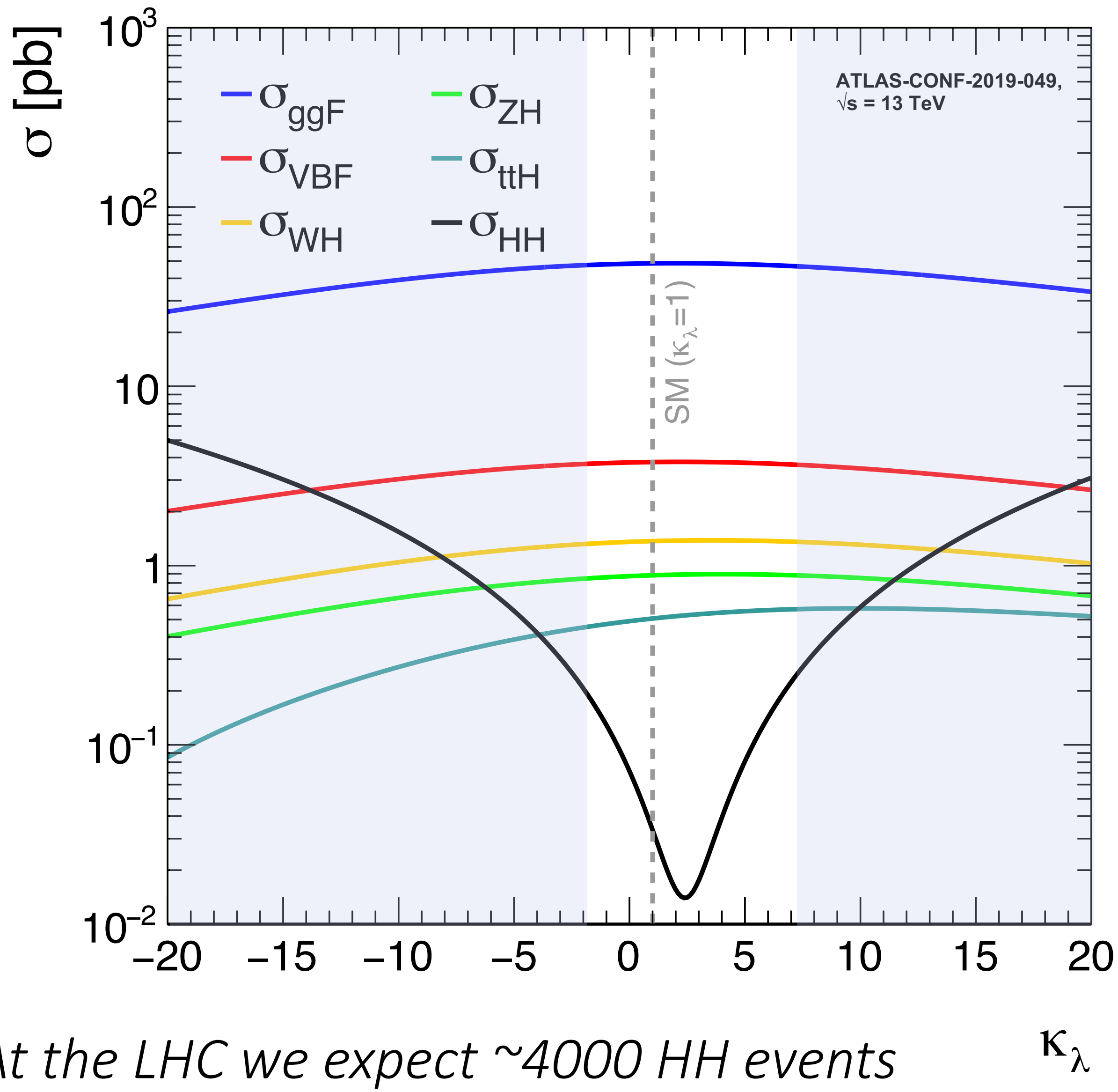






HH Production

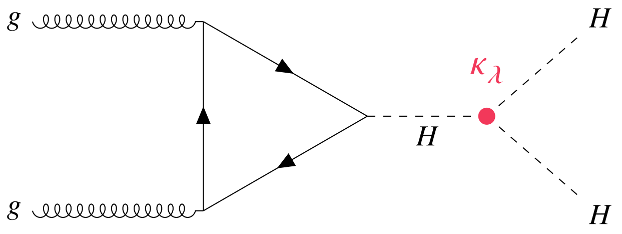


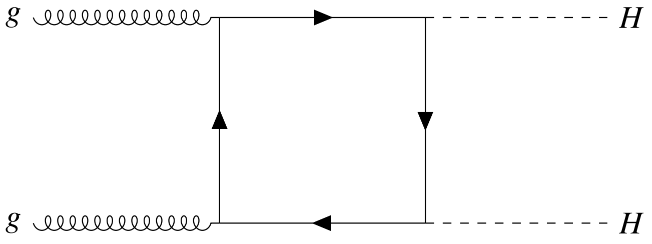


At the LHC we expect ~4000 HH events compared to 8 million single Higgs events!

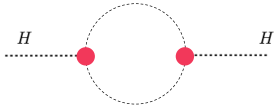
Measuring κ_λ

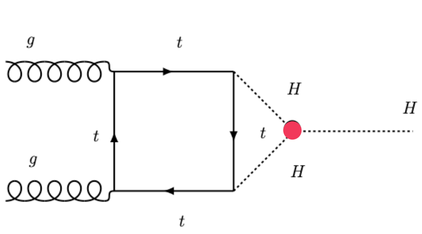
Direct measurement (HH):

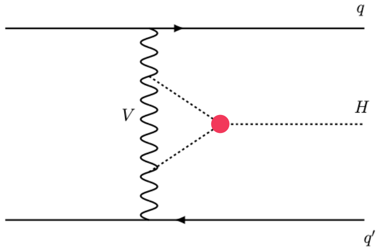


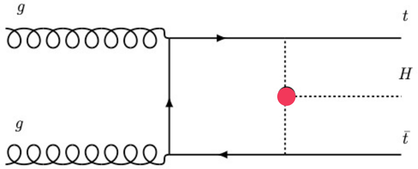


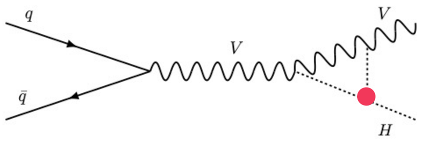
Indirect measurement (single H):

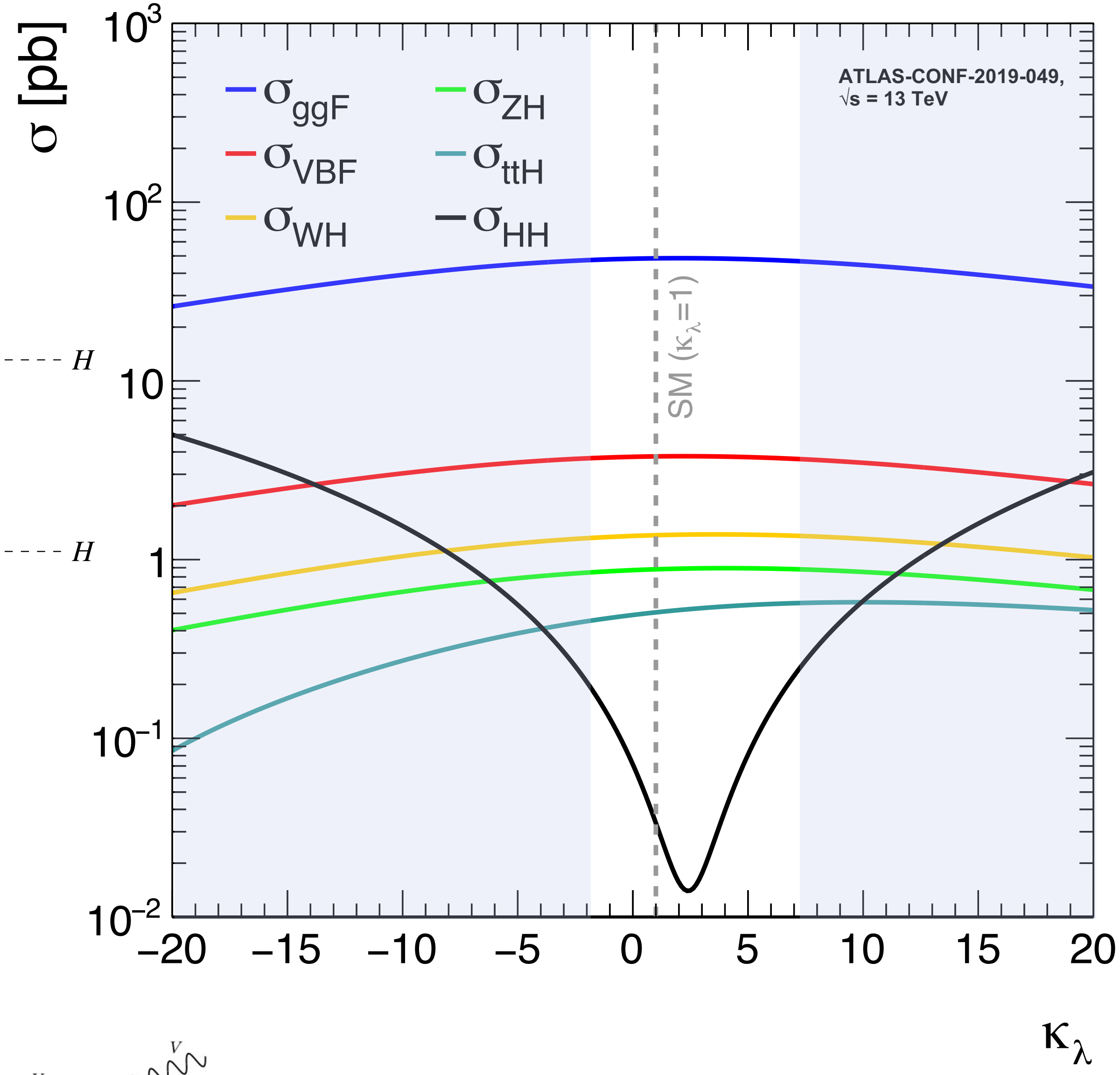








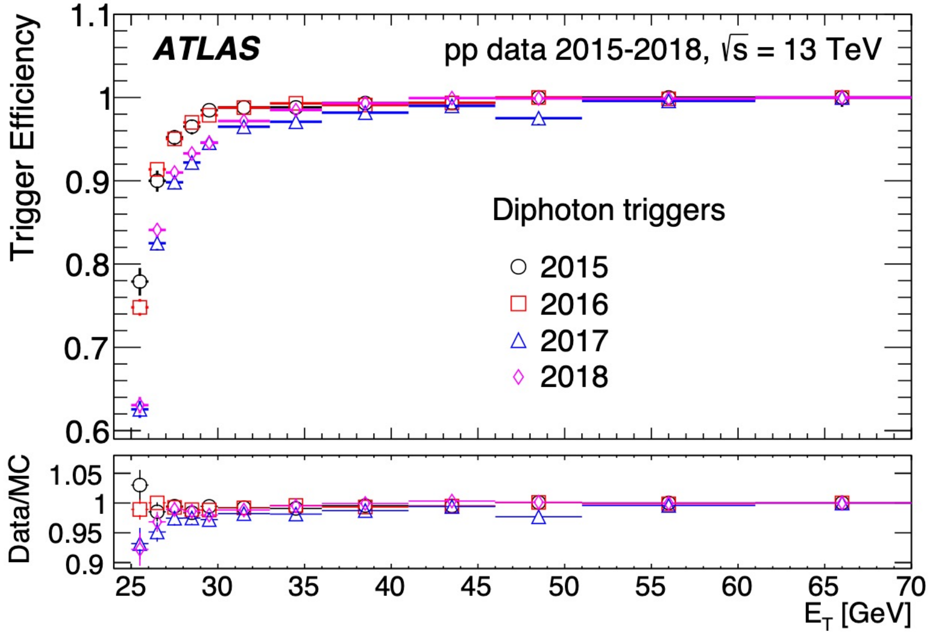




In Run 2 we expect ~4000 HH events compared to 8 million single Higgs events!

Photons in ATLAS

Trigger on two photons at 35 GeV and 25 GeV

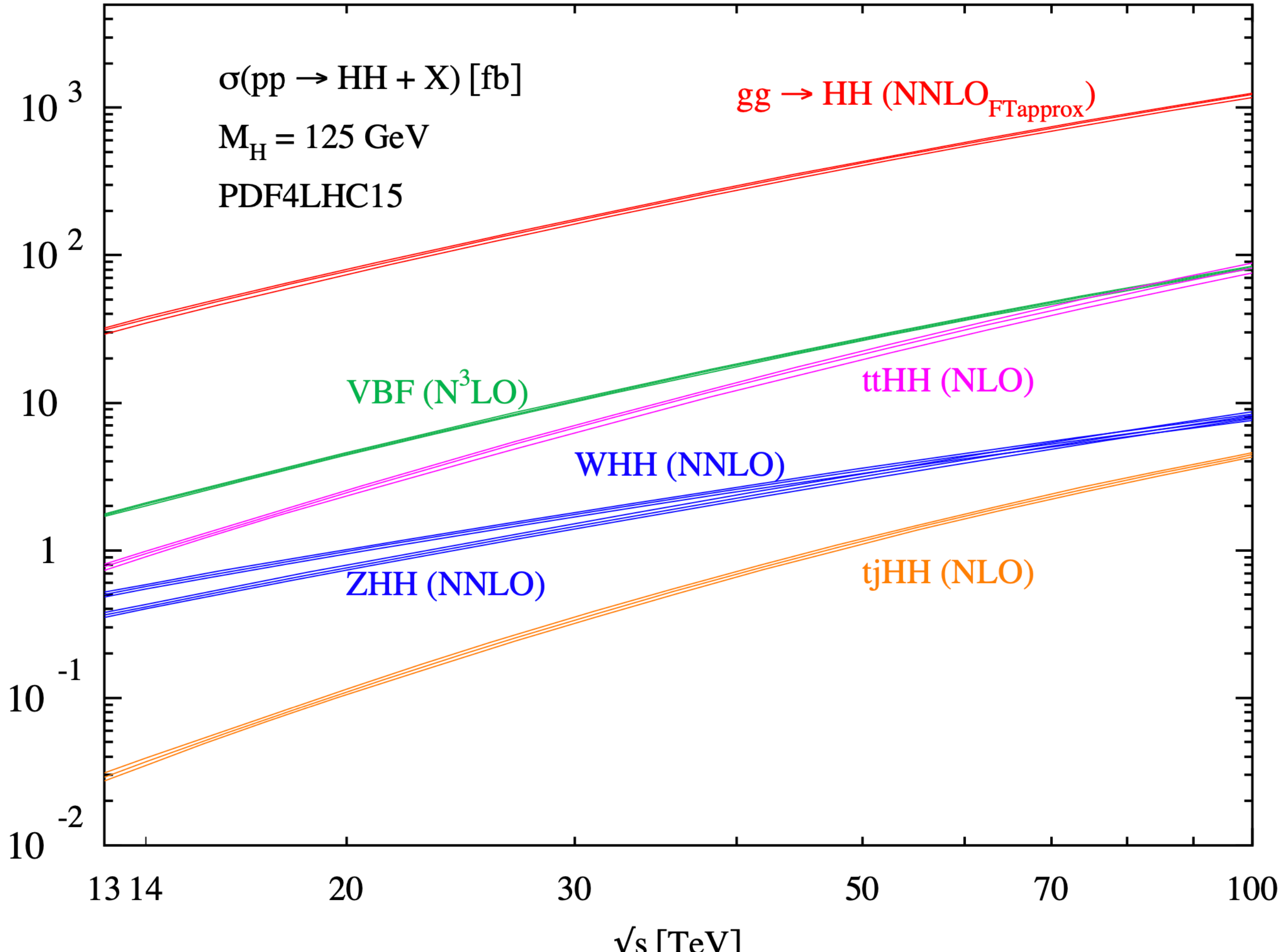


This is important because it means that we can trigger on events with low HH invariant masses

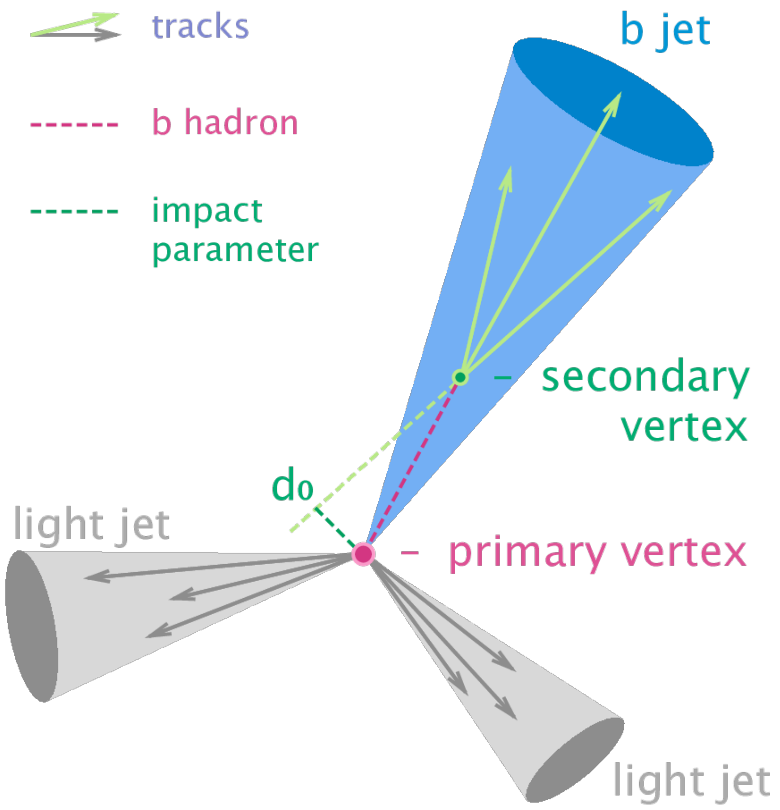
For comparison: HH to 4b requires 2 b-jets at 35 GeV *and* either 2 other jets with 35 GeV or 1 b-jet with > 100 GeV

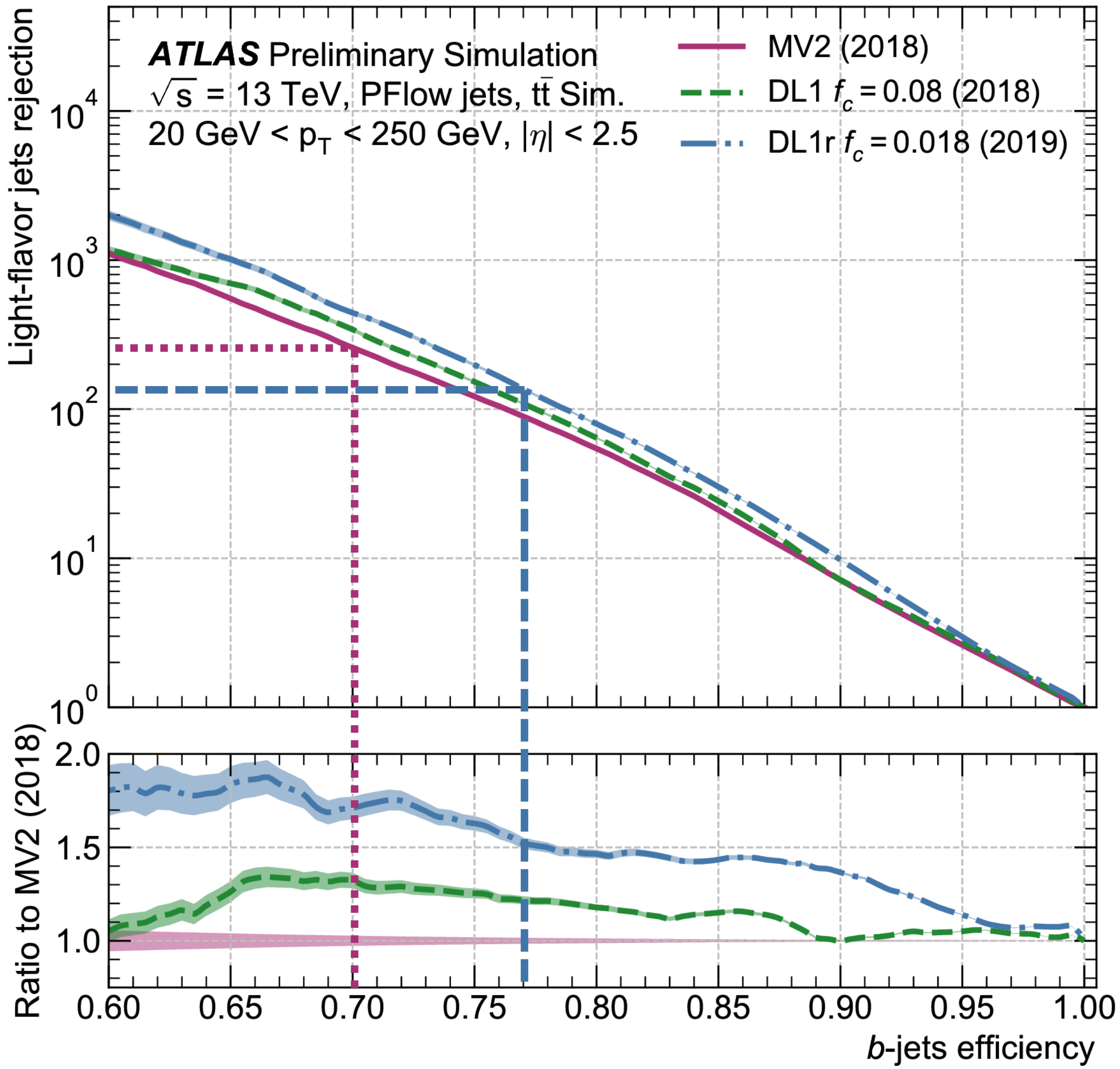
HH Production at Hadron Colliders

HH Whitepaper https://arxiv.org/pdf/1910.00012.pdf



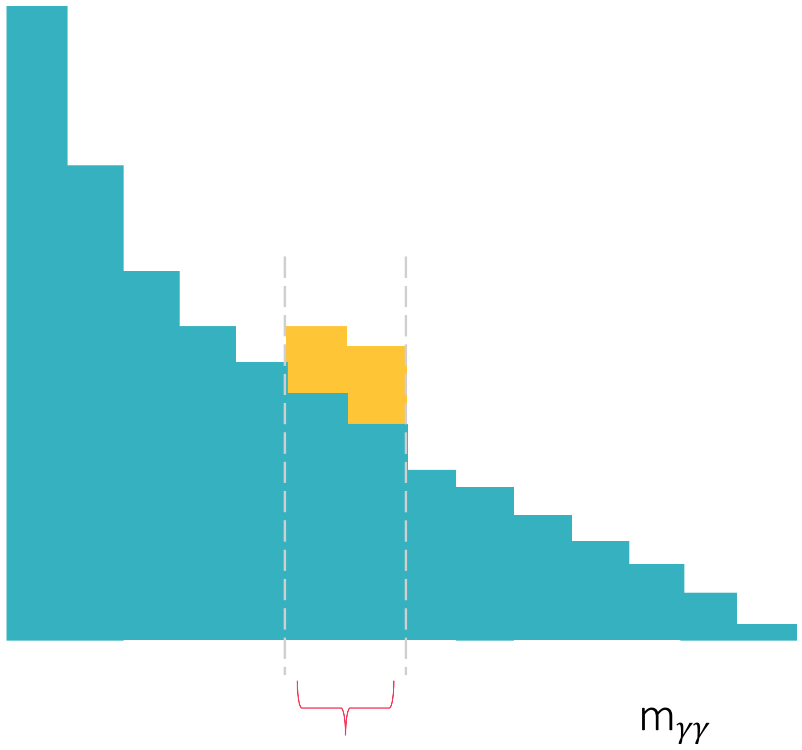
b-jets



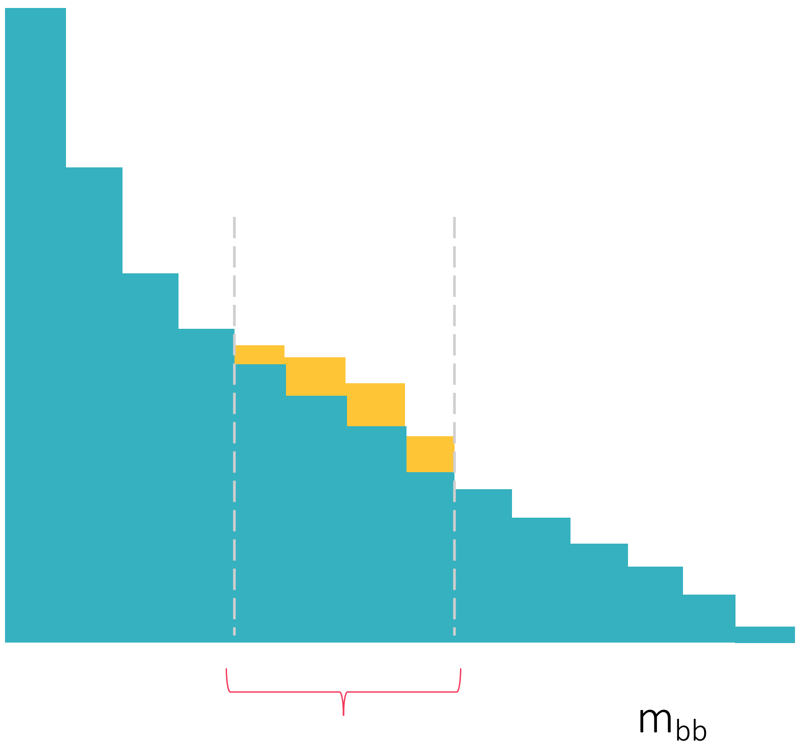


All HH analyses moved from 70% to 77% b-jet working points between Early Run 2 and Full 2 Run.

Importance of Mass Resolution



Better mass resolution,
better signal over background



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

Selection Strategy

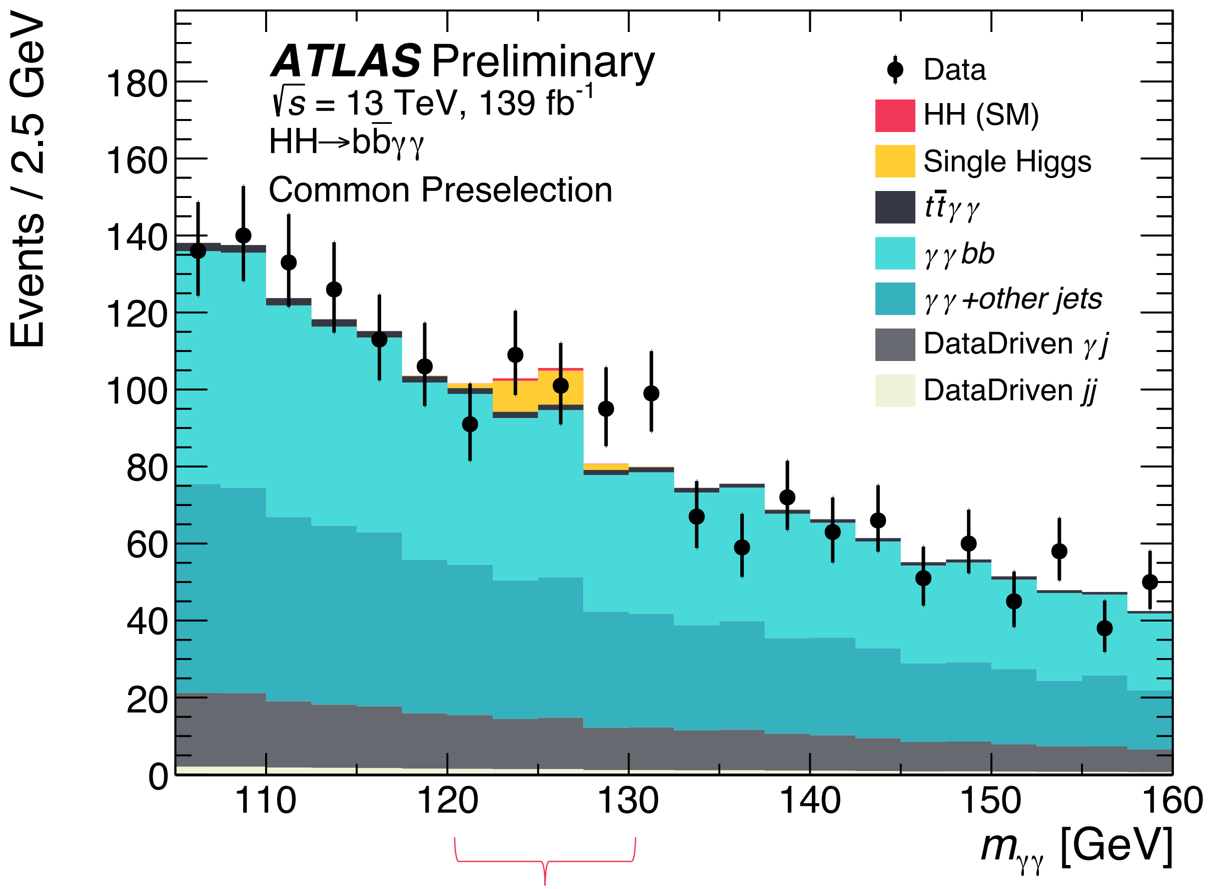
Require events with two photons & two b-jets

Signal:

- HH(bb$\gamma\gamma$)

Main backgrounds:

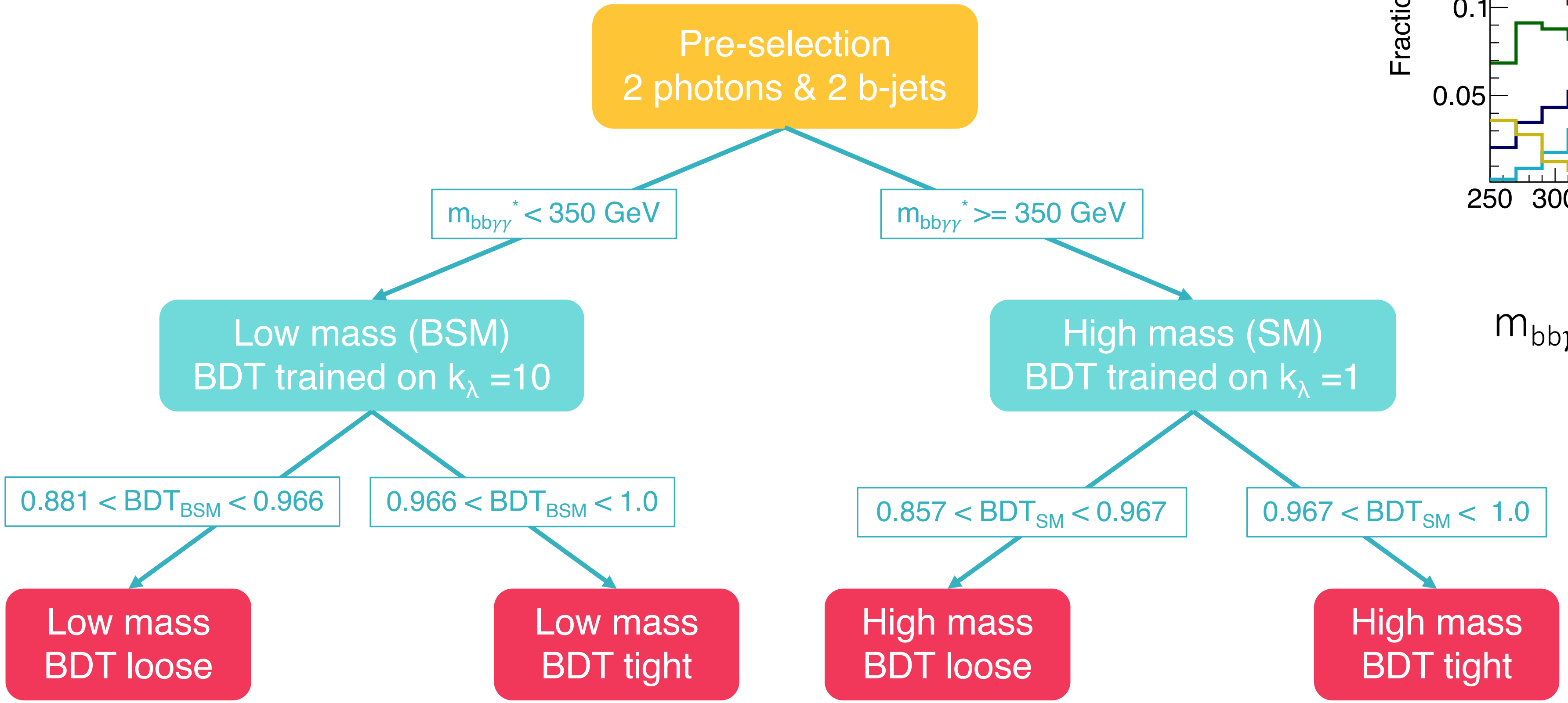
- Single Higgs (ggF H, ttH, ZH, & others)
- Diphoton
- γj+jj (data-driven)

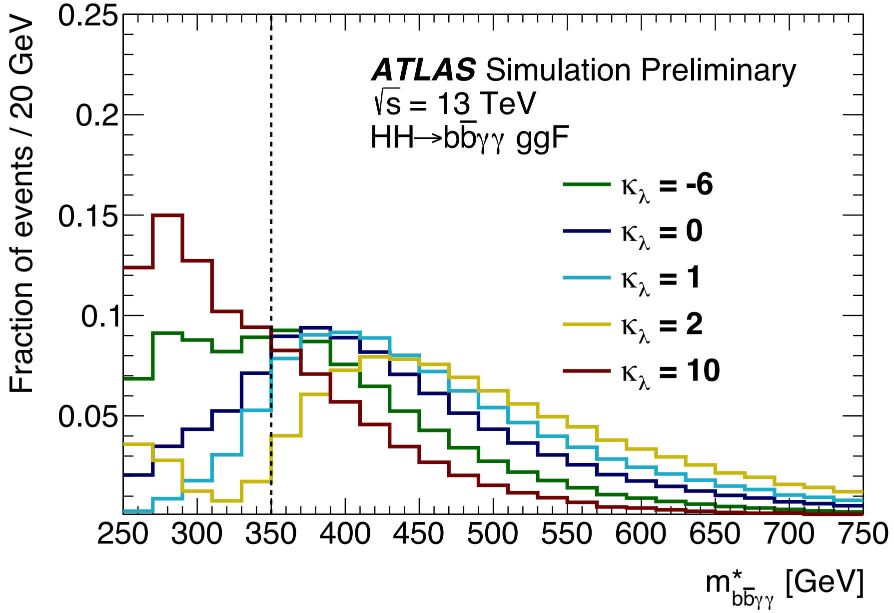


Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

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

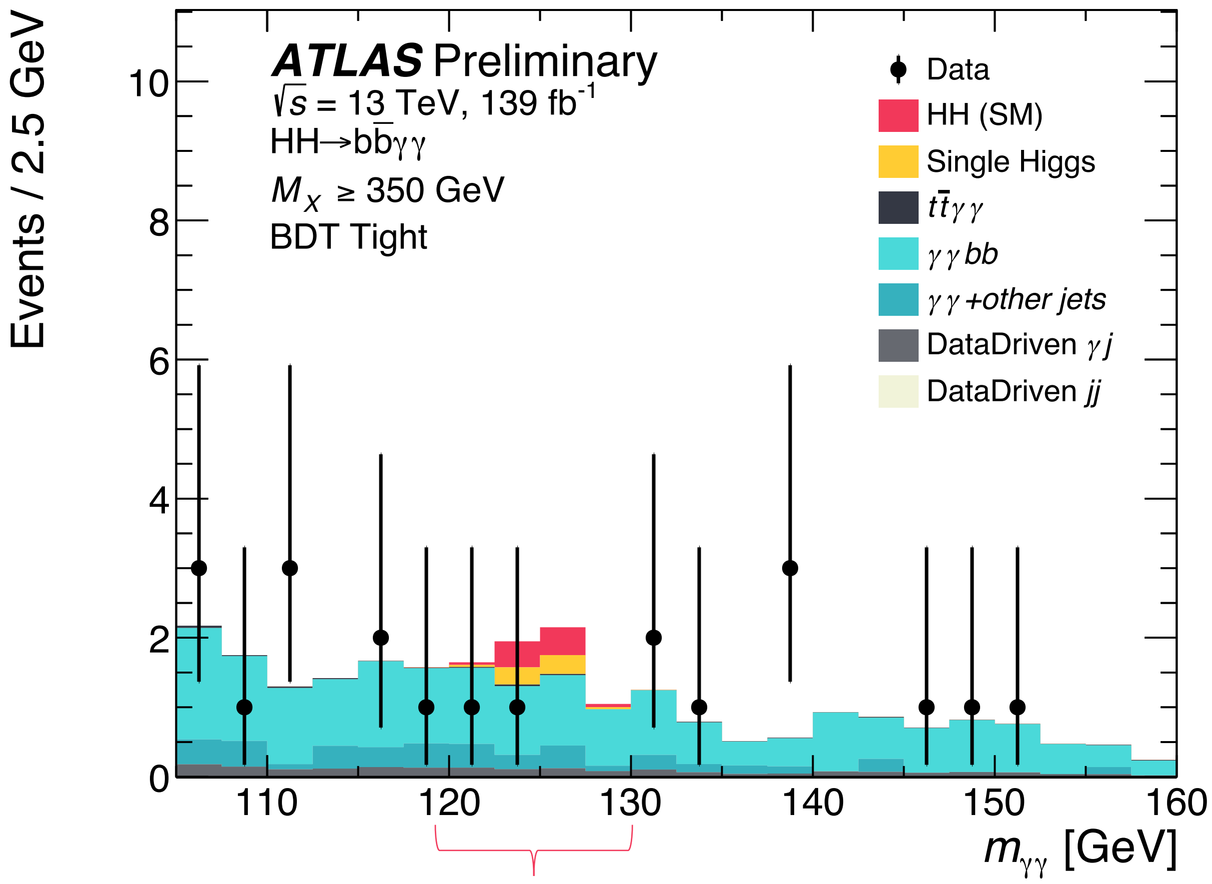
Selection Strategy





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

Post Selection Data/Predictions

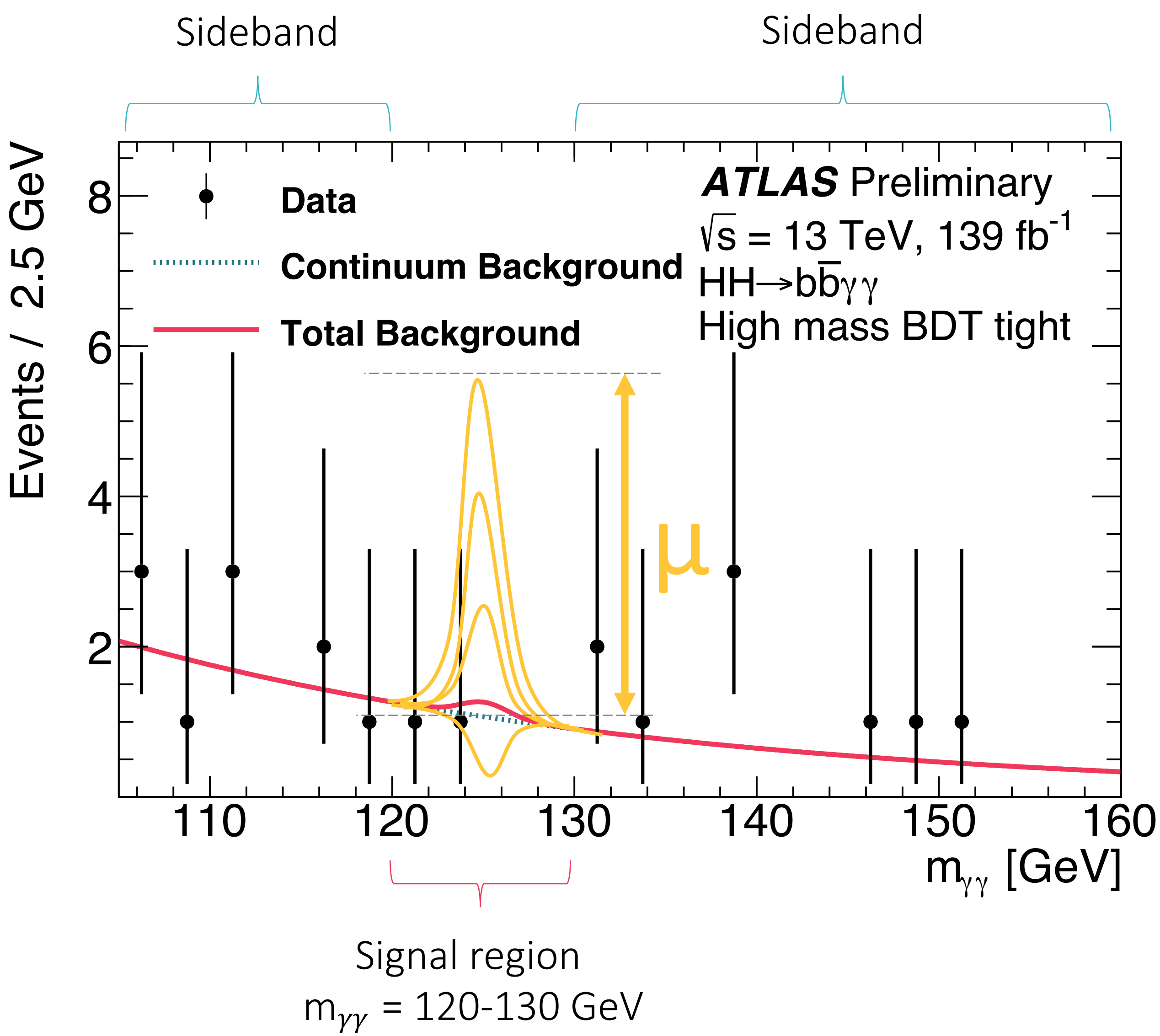


Signal region
$m_{\gamma\gamma}$ = 120-130 GeV

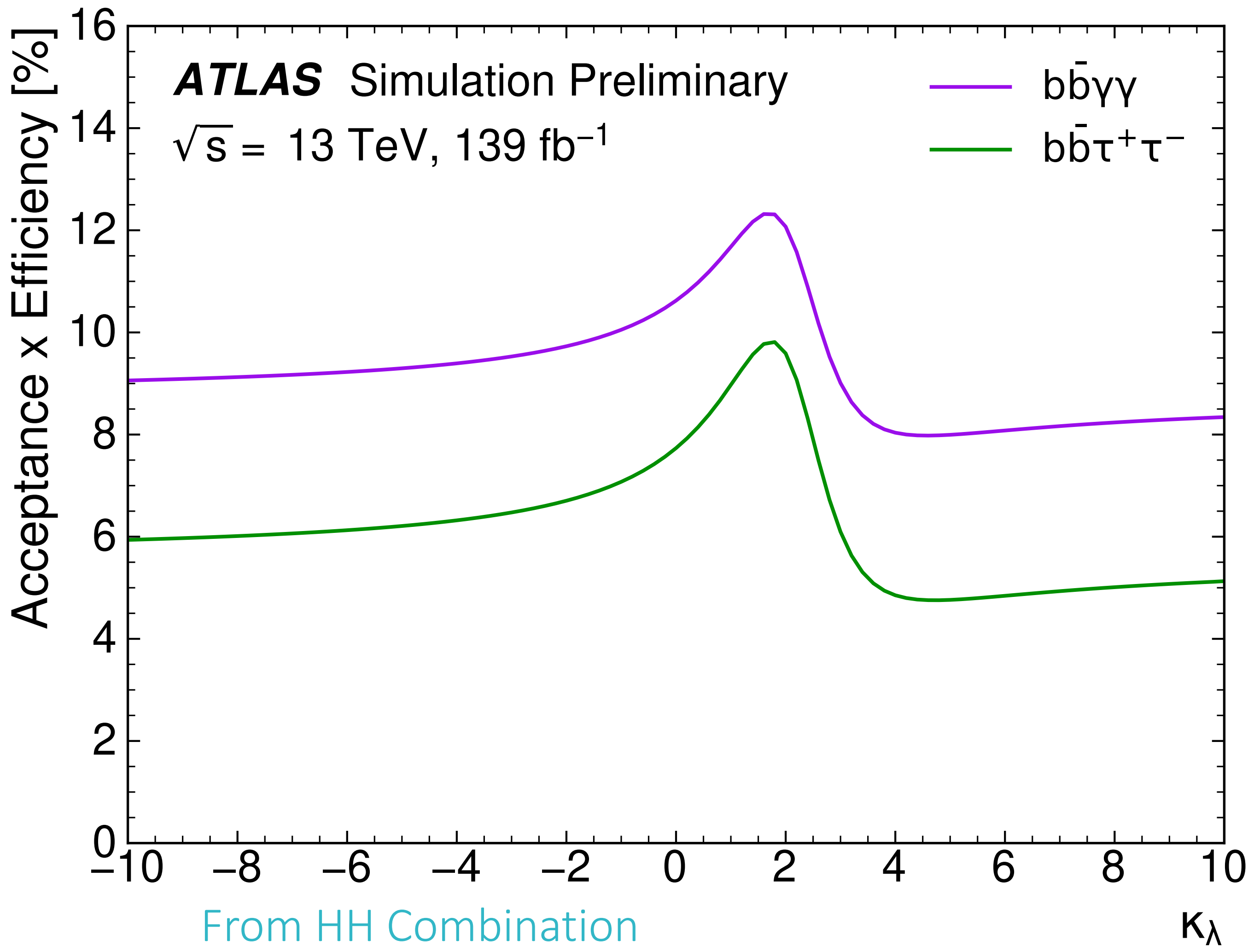
s/b in signal region after high mass BDT tight selection is 14%

Signal Extraction

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



Acceptance x Efficiency as a function of k_λ



From HH Combination

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

Dominant Systematic Uncertainties bbyy

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

Dominant Systematic Uncertainties bbττ

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%
$Z(\rightarrow \tau\tau)+\mathrm{HF}$	9%
Single Higgs boson	29%
Other backgrounds	3%
Signal	5%

Summary of Latest ATLAS & CMS HH Results

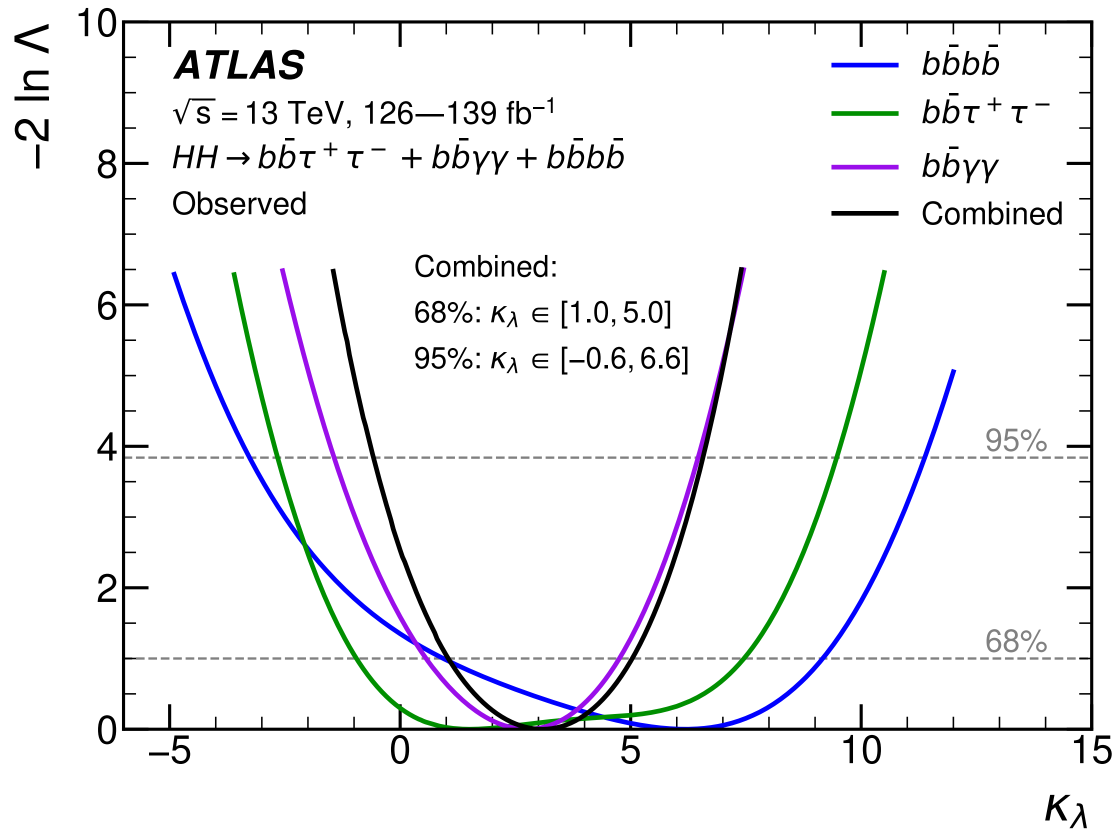
Search channel	Collaboration	Luminosity (fb^{-1})	95% CL Upper Limit expected	95% CL Upper Limit observed
$b\bar{b}b\bar{b}$	ATLAS [33]	126	5.4	8.1
	CMS [34]	138	4.0	6.4
$b\bar{b}\gamma\gamma$	ATLAS [35]	139	4.2	5.7
	CMS [36]	137	5.5	8.4
$b\bar{b}\tau^+\tau^-$	ATLAS [37]	139	4.7	3.9
	CMS [38]	138	5.2	3.3
$b\bar{b}VV^*$	ATLAS [39]	36.1	40	29
	CMS [40]	137	40	32
$WW^*\gamma\gamma$	ATLAS [41]	36.1	230	160
	CMS	–	–	
WW^*WW^*	ATLAS [42]	36.1	160	120
	CMS [43]	138	19	21
comb	ATLAS [44]	126-139	2.5	3.4
	CMS [17]	138	2.4	2.9

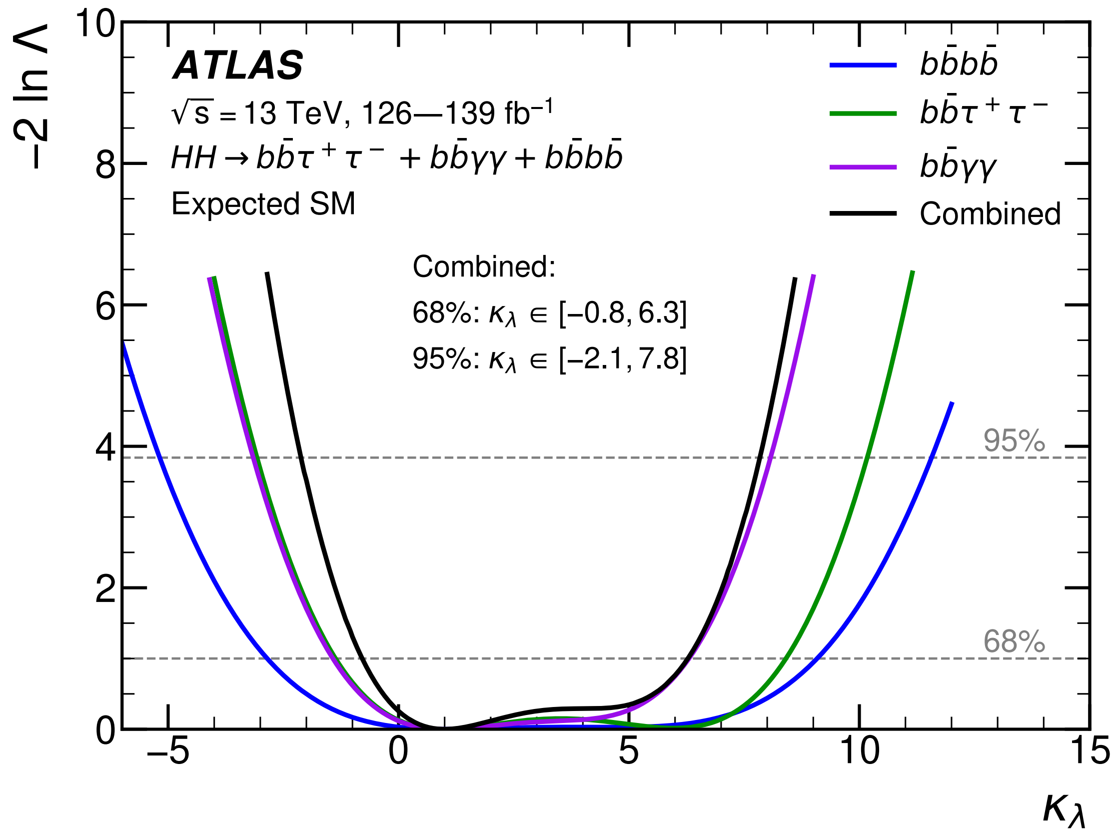
From Snowmass EF01 Report: https://snowmass21.org/_media/energy/snowmass2021_higgs_report_final.pdf

HH Combined Likelihood Scan

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

ATLAS-CONF-2022-050

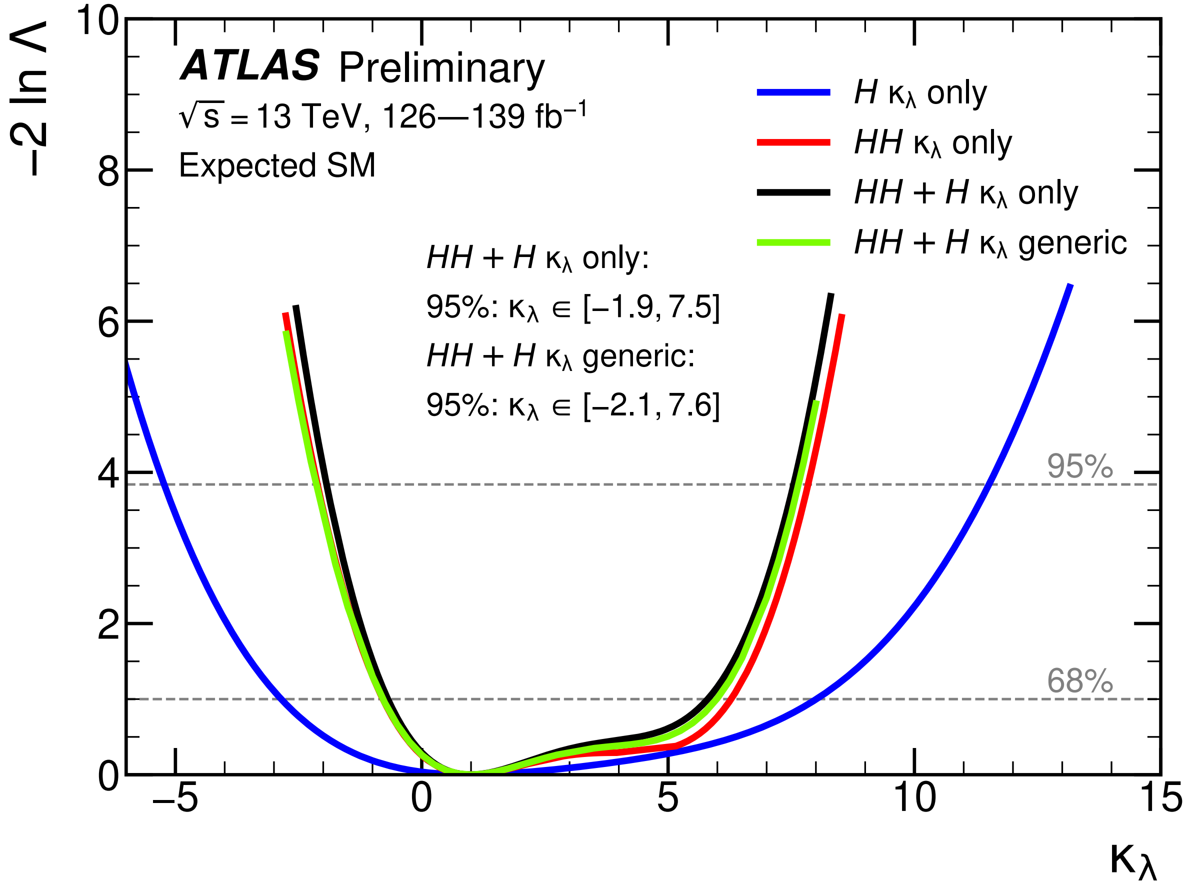


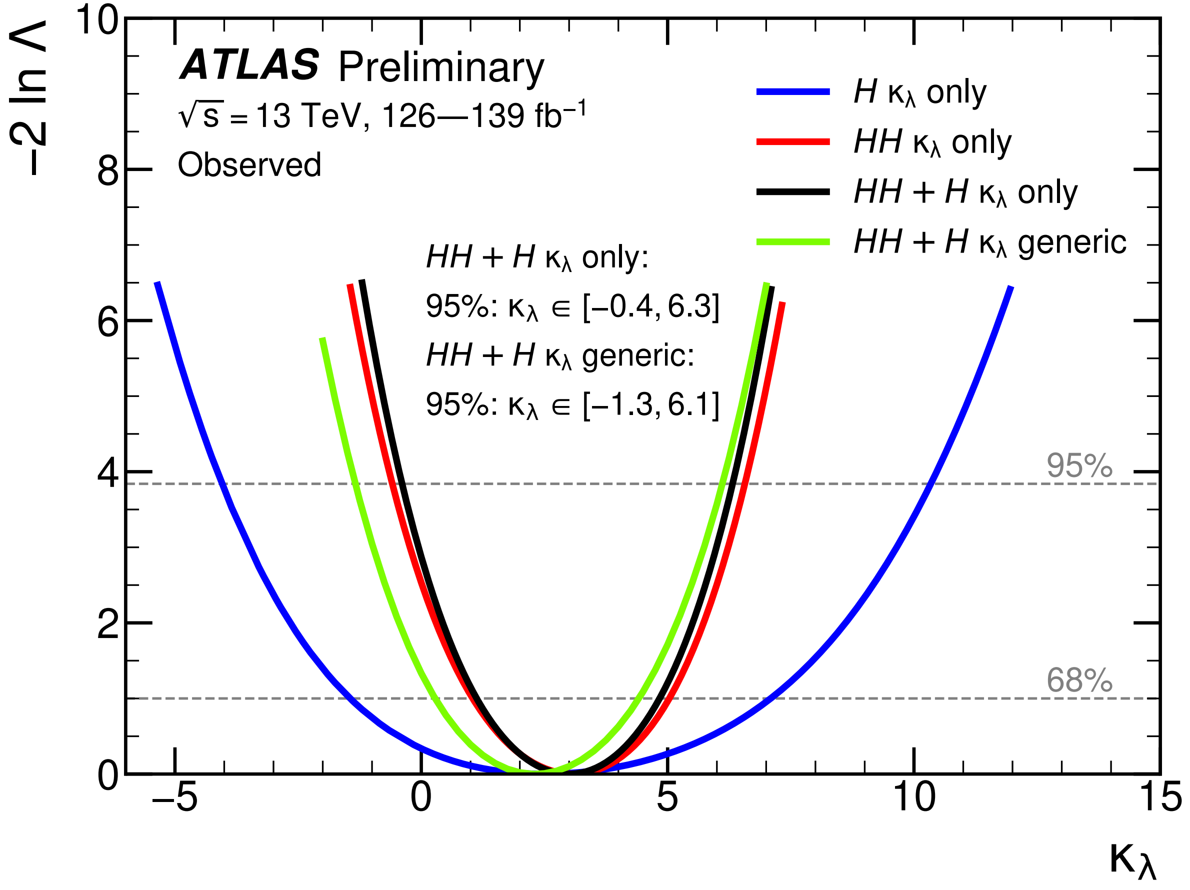


Single Higgs + HH κ_λ

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

ATLAS-CONF-2022-050

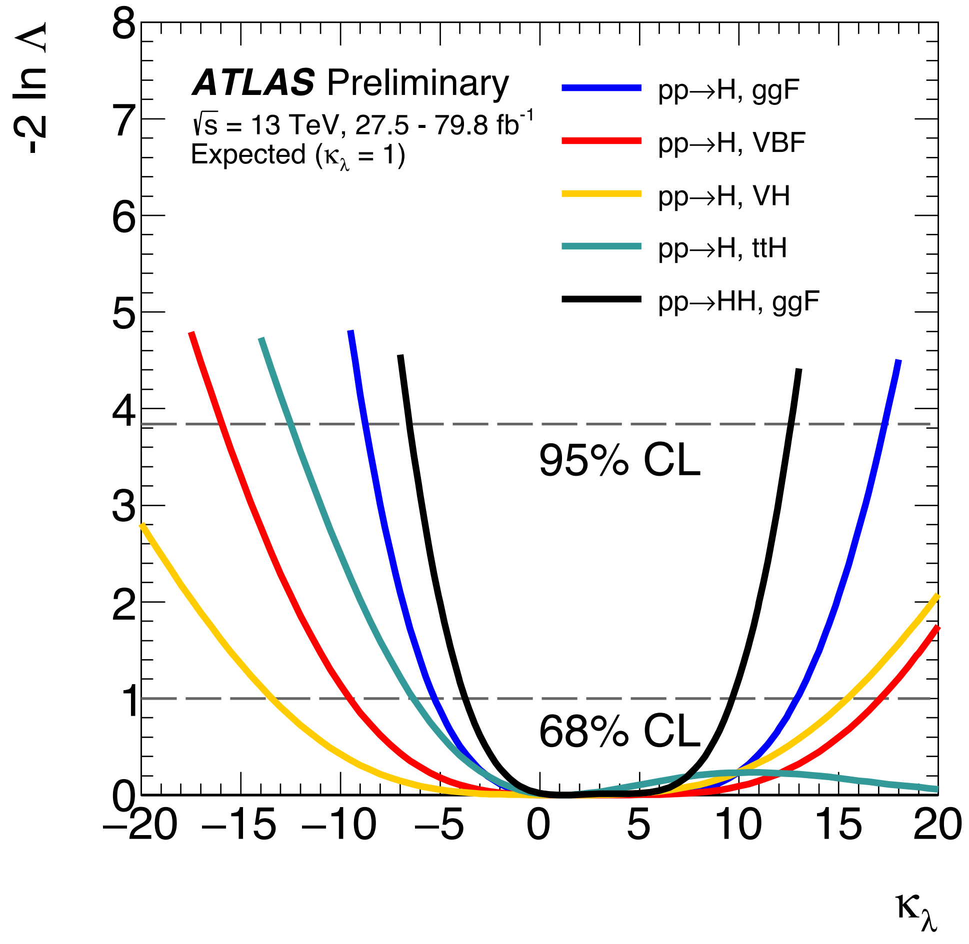


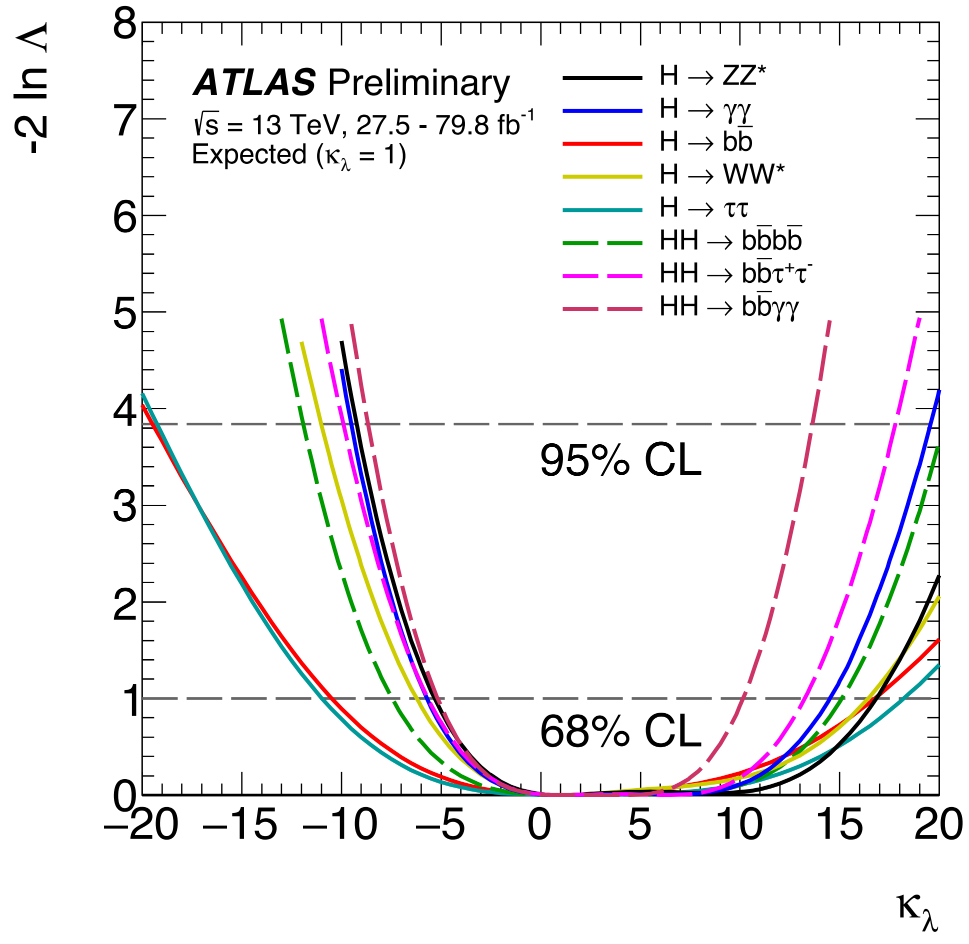


Single Higgs + HH κ_λ

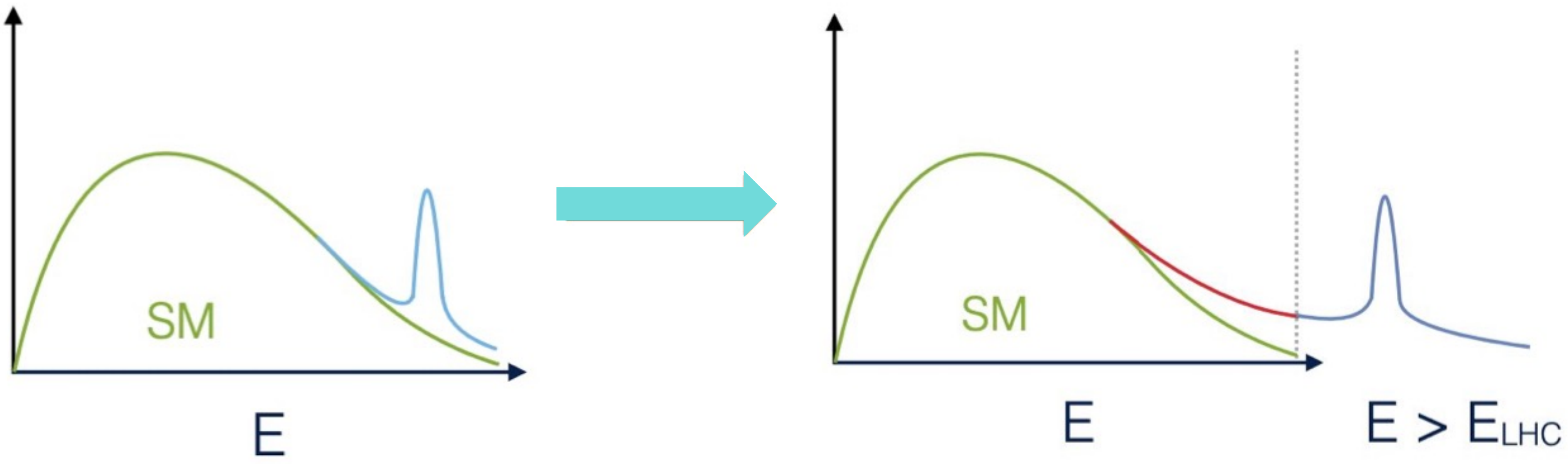
Negative log of the likelihood ratio comparing different k_λ hypotheses to an Asimov dataset constructed with $k_\lambda = 1$

ATLAS-CONF-2019-049





Effective Field Theory Interpretations

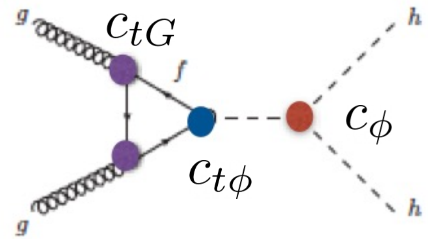


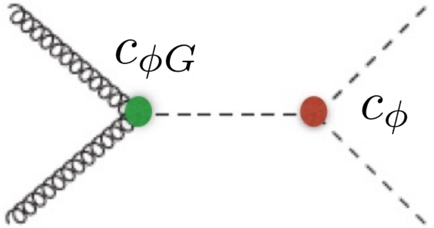
Measurements in low-stats, high p_T tails will also be most accessible at HL-LHC.

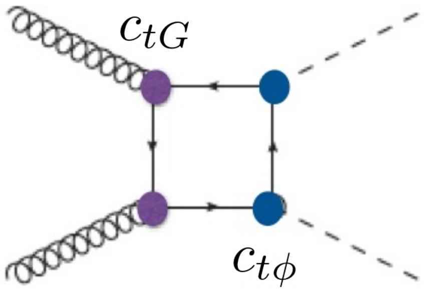
Differential measurements and their interpretations will maximize sensitivity to new physics.

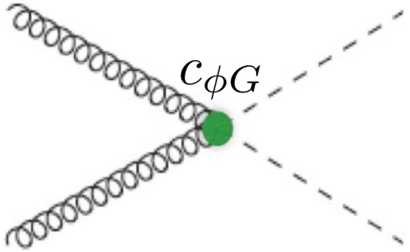
Standard Model Effective Field Theory

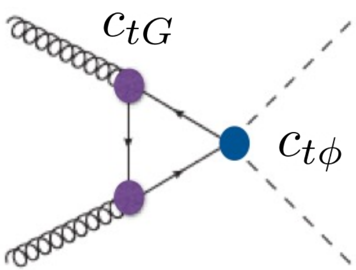
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_k c_k^{(6)} Q_k^{(6)}$$

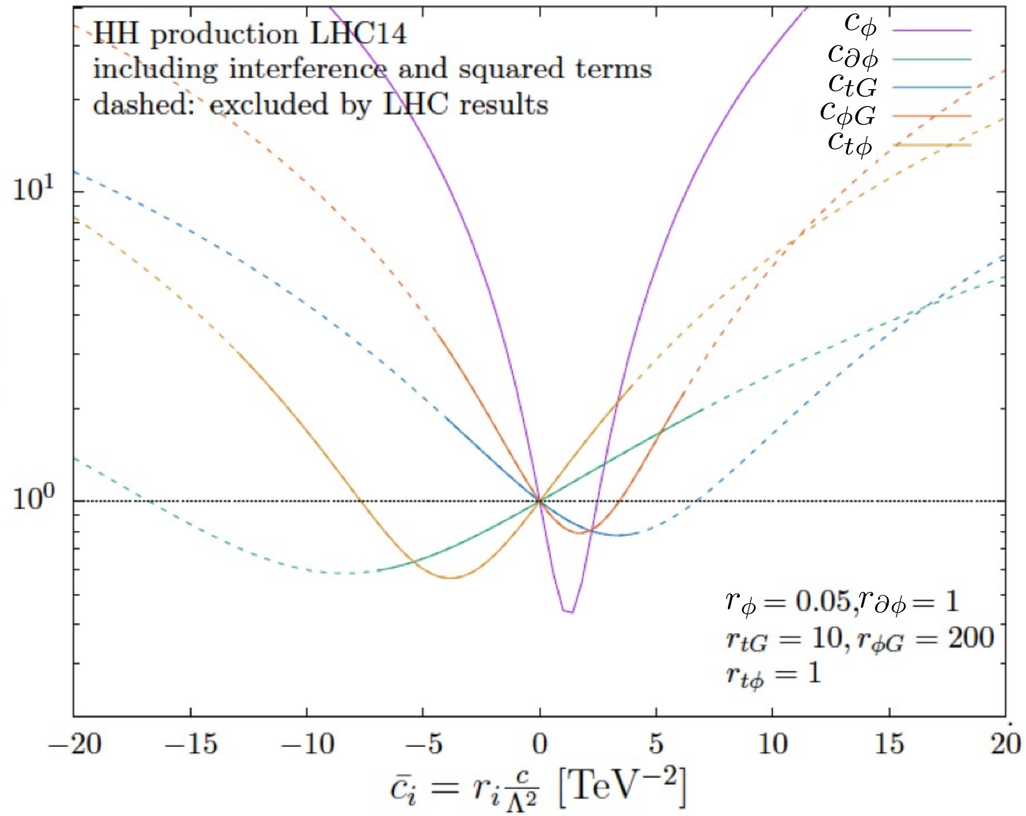












$c_{\partial\phi}$ Universal rescaling

Systematic Uncertainty Extrapolation

Source	Scale factor	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$
Experimental Uncertainties				
Luminosity	0.6	*	*	
b-jet tagging efficiency	0.5	*	*	*
c-jet tagging efficiency	0.5	*	*	*
Light-jet tagging efficiency	1.0	*	*	*
Jet energy scale and resolution, E_T^{miss}	1.0	*	*	*
κ_λ reweighting	0.0	*	*	*
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*		
Photon energy scale and resolution	1.0	*		
Spurious signal	0.0	*		
Value of m_H	0.08	*		
τ_{had} efficiency (statistical)	0.0		*	
τ_{had} efficiency (systematic)	1.0		*	
τ_{had} energy scale	1.0		*	
Fake-τ_{had} estimation	1.0		*	
MC statistical uncertainties	0.0		*	
Background bootstrap uncertainty$\times$0.5			*	
Background shape uncertainty	1.0			*
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.

Simulation related uncertainties

Theory uncertainties halved

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

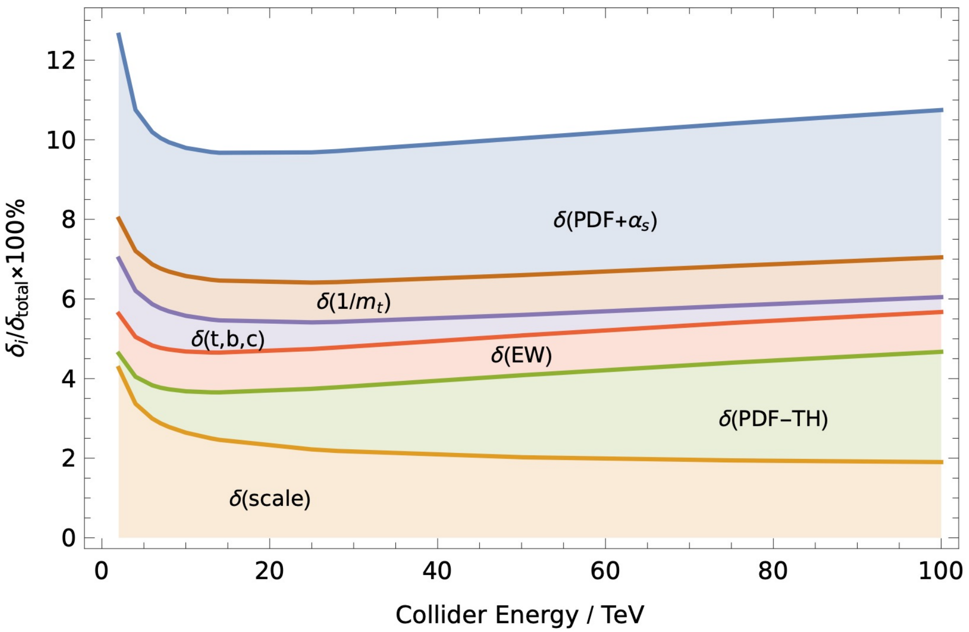


Fig. 1: The figure shows the linear sum of the different sources of relative uncertainties as a function of the collider energy. Each coloured band represents the size of one particular source of uncertainty as described in the text. The component $\delta(\text{PDF}+\alpha_S)$ corresponds to the uncertainties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

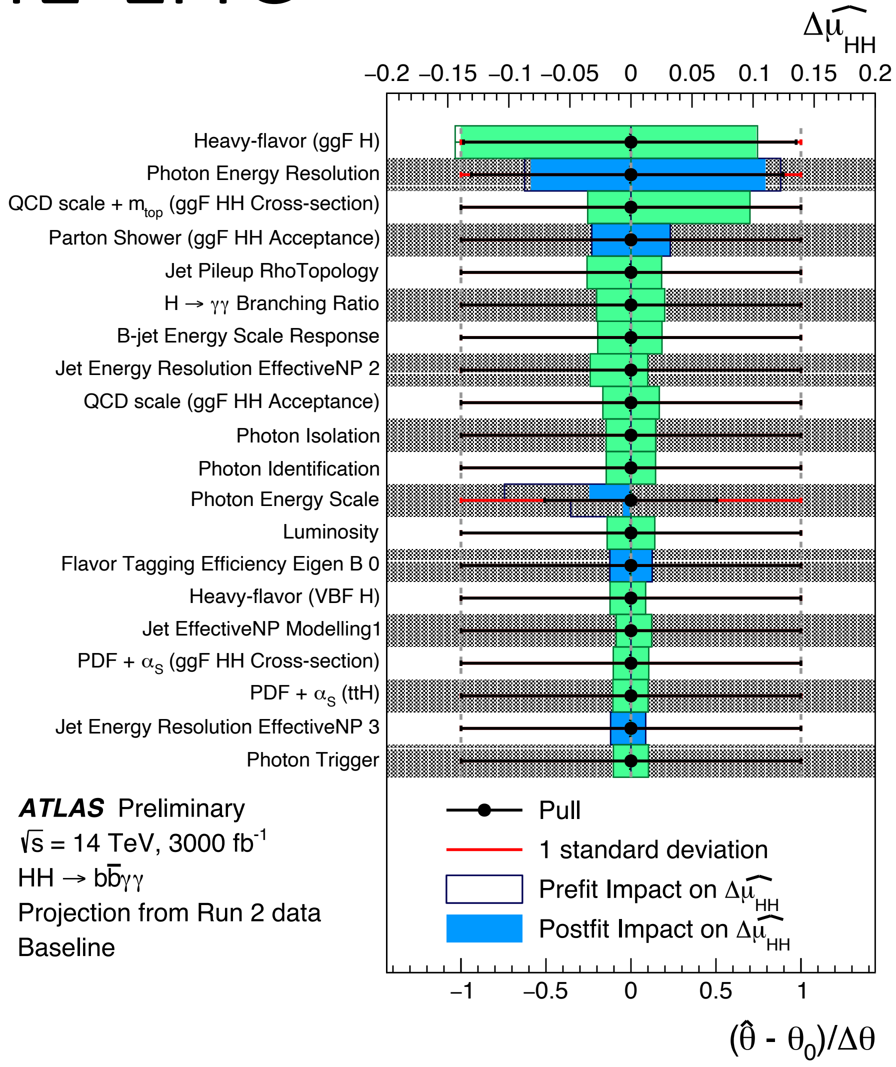
– Missing higher-order effects of QCD corrections beyond N^{3}LO (δ(scale)).
– Missing higher-order effects of electroweak and mixed QCD-electroweak corrections at and beyond $\mathcal{O}(\alpha_S\alpha)$ (δ(EW)).
– Effects due to finite quark masses neglected in QCD corrections beyond NLO (δ(t,b,c)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

Dominant Systematics @ HL-LHC

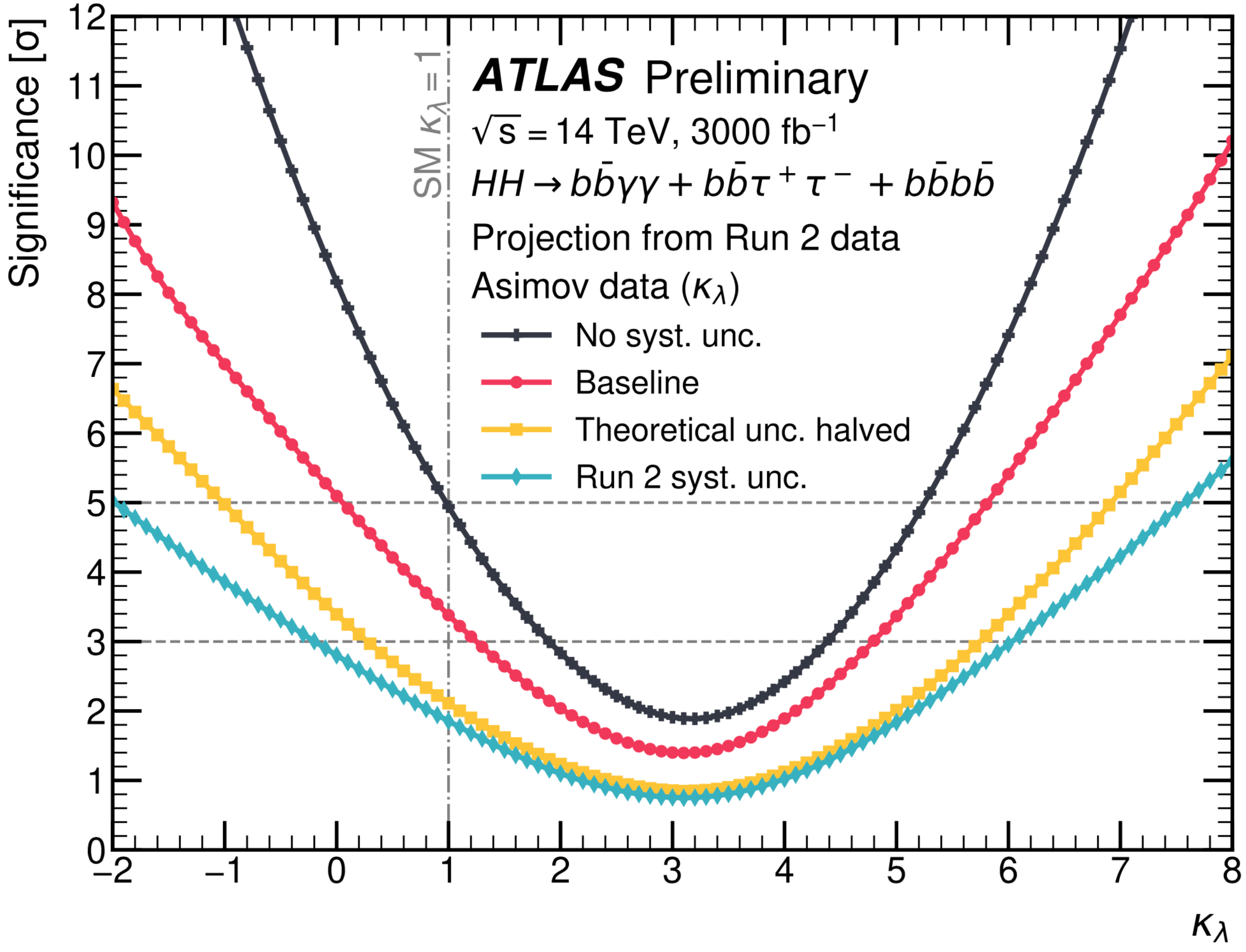
Theory uncertainties:
- ggF H (in association with b, or c)
- Wt tt interference (bbττ)
- ggF HH cross-section

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



2022 HL-LHC Prospects bb$\gamma\gamma$
http://cdsweb.cern.ch/record/2799146

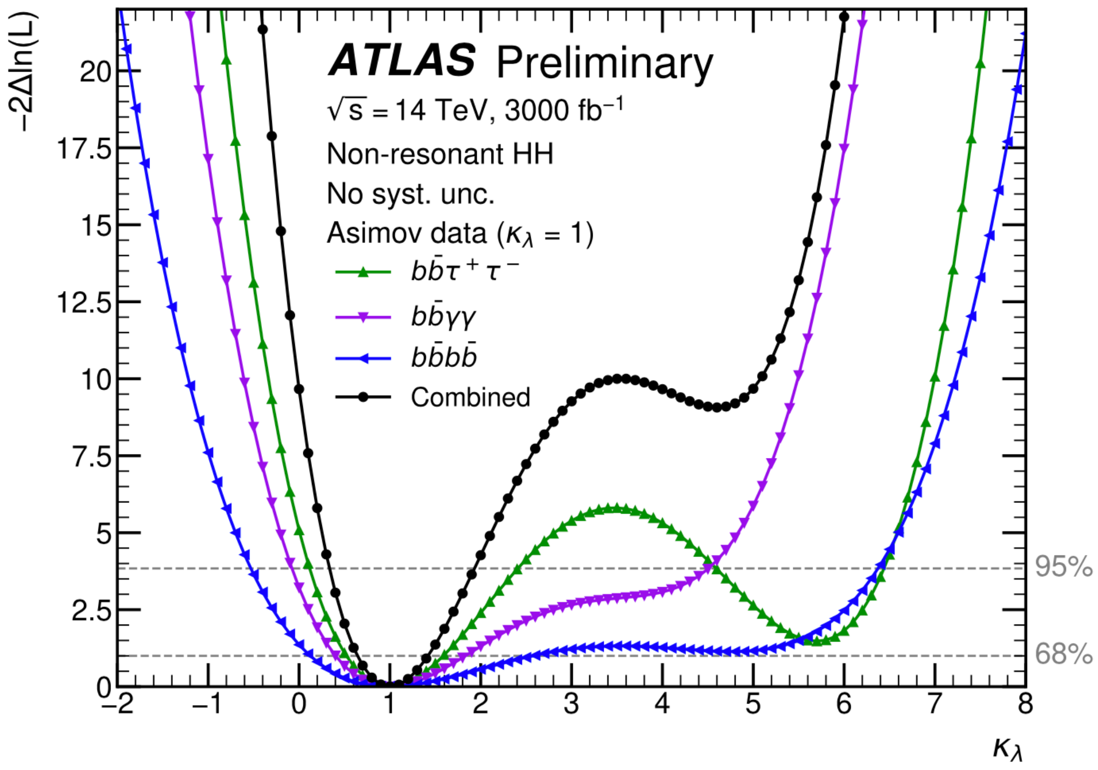
Significance as a function of k_λ - Combined



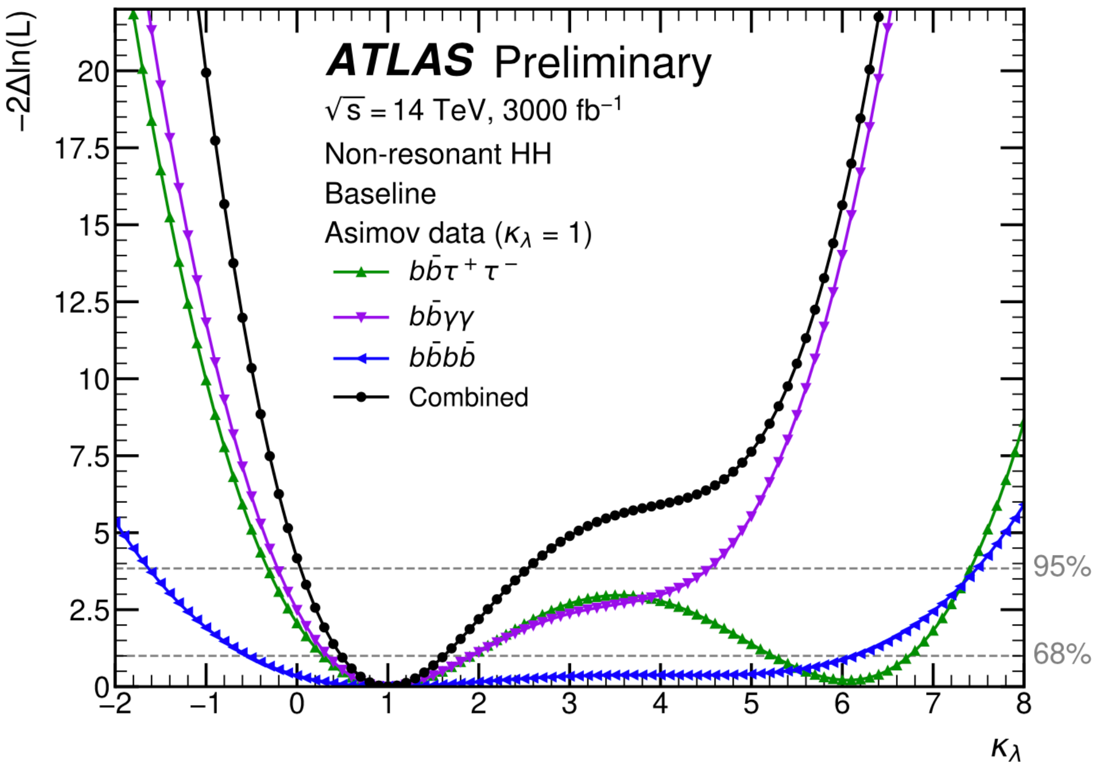
Interpretation:
If HH signal present at these k_λ values, expect to measure the signal with the shown significance.

Likelihood Scan – Different Scenarios

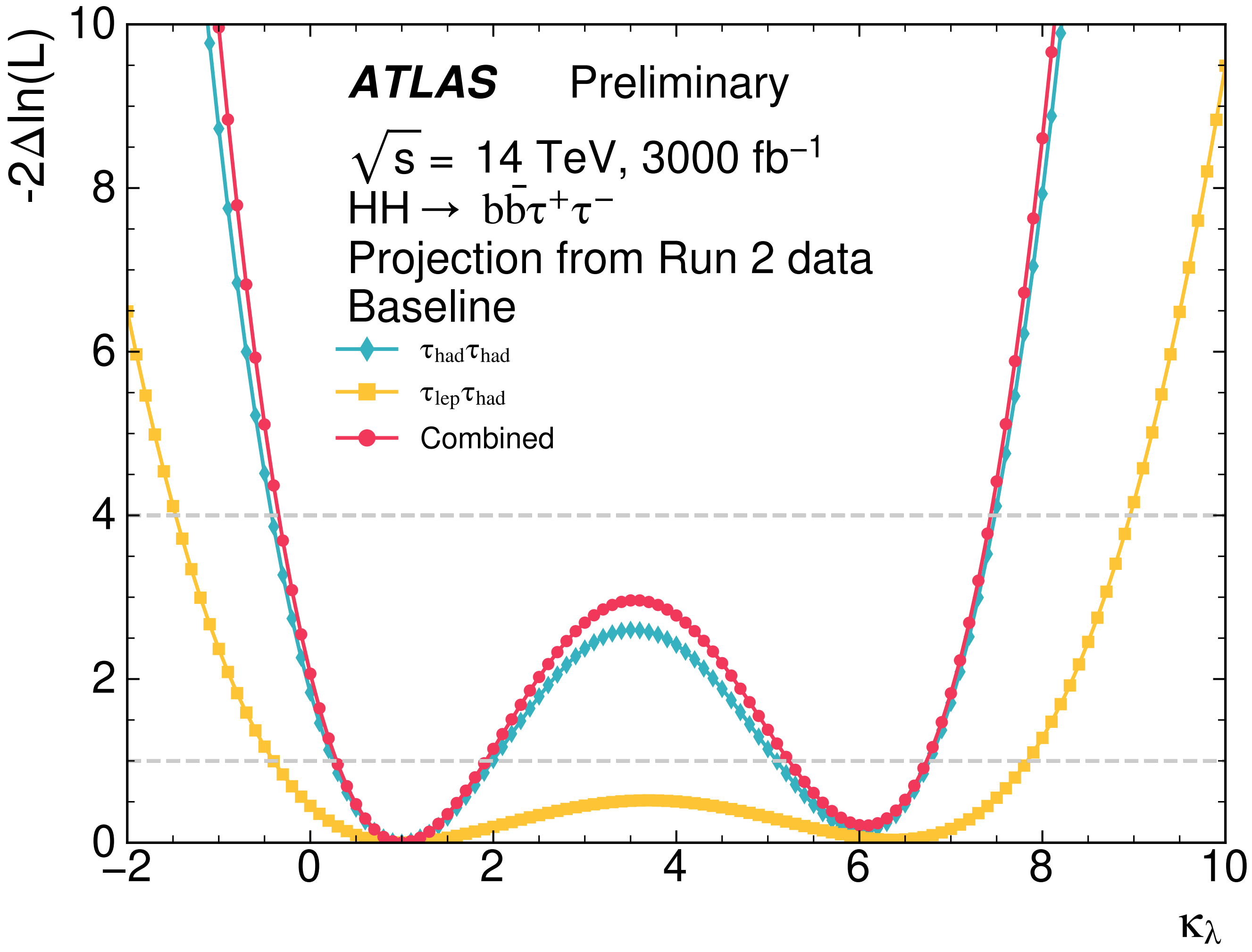
No Systematics



Baseline



Effect of Different Channels - bbττ



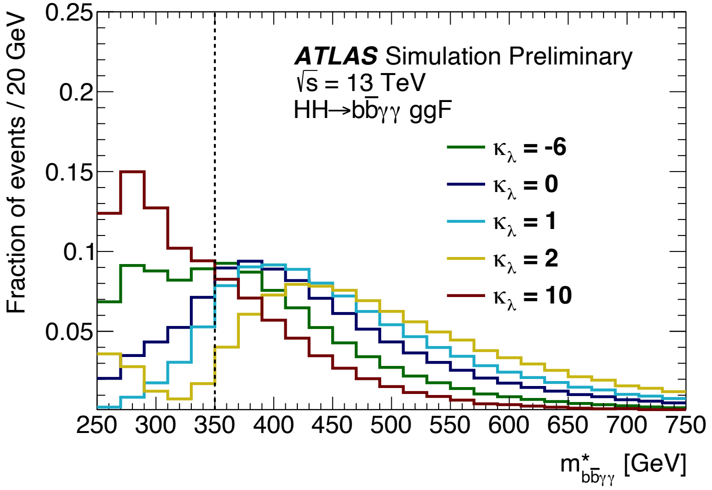
2021 HL-LHC Prospects bbττ
https://cds.cern.ch/record/2798448

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

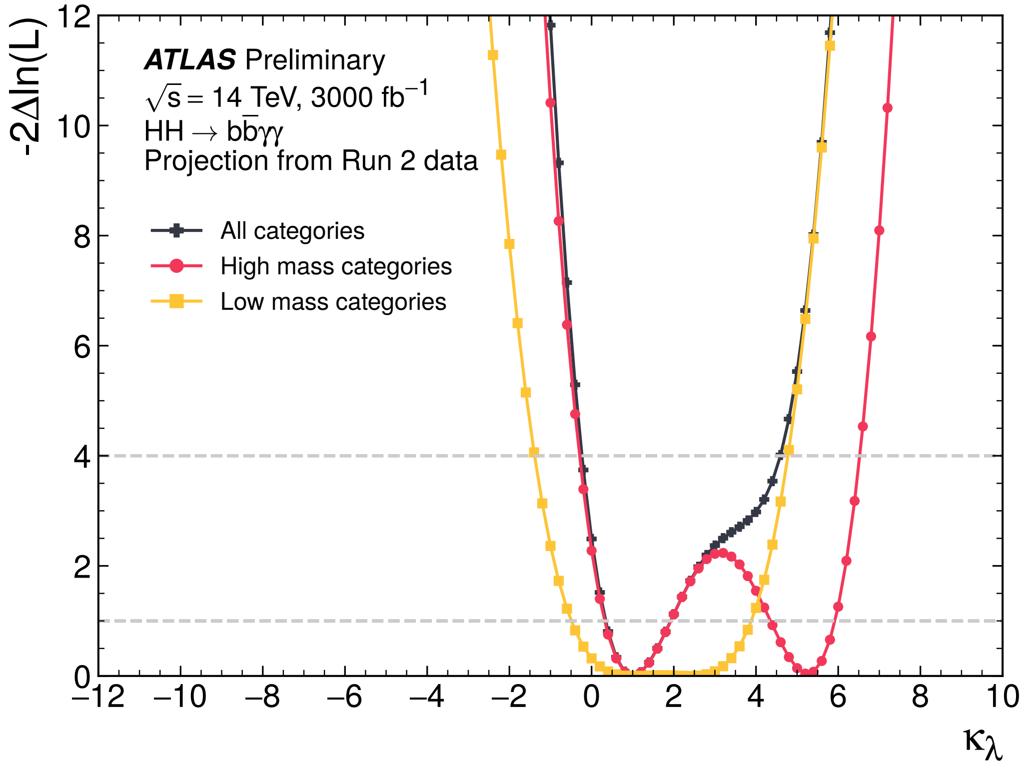
2 photons
& 2 b-jets

$m_{bb\gamma\gamma}{}^* < 350$ GeV → Low mass (BSM)
BDT trained on $k_\lambda = 10$

$m_{bb\gamma\gamma}{}^* \geq 350$ GeV → High mass (SM)
BDT trained on $k_\lambda = 1$

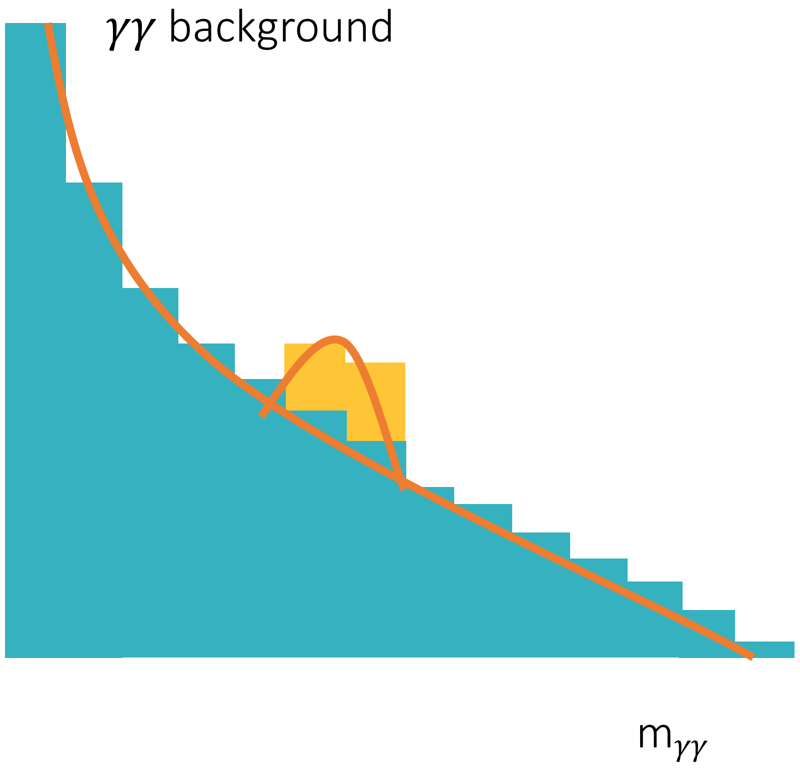


$$m_{bb\gamma\gamma}{}^* = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250 \text{ GeV}$$



2022 HL-LHC Prospects $bb\gamma\gamma$
http://cdsweb.cern.ch/record/2799146

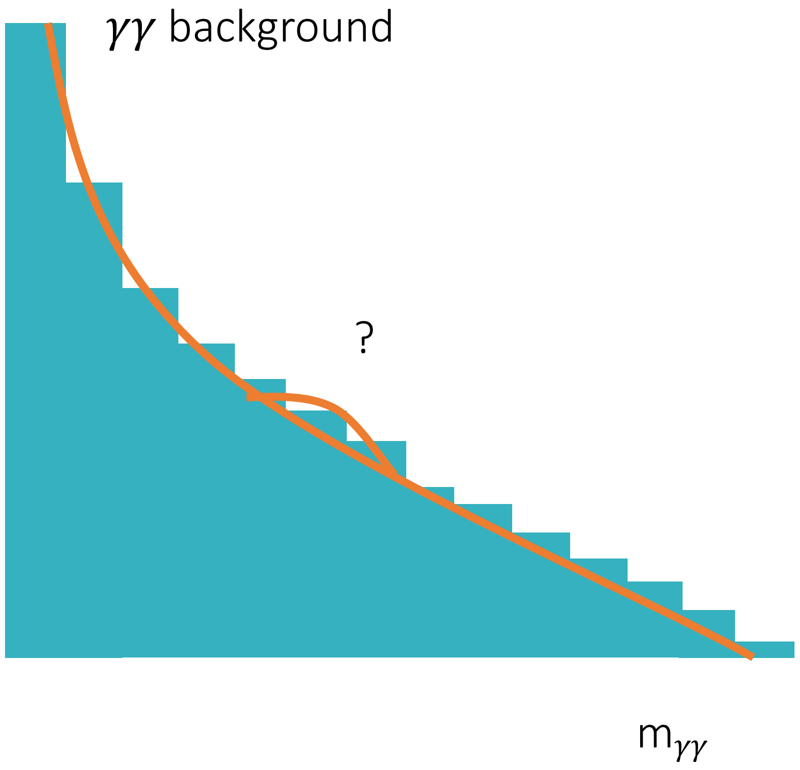
Spurious Signal Studies



Fit background with an exponential function

Fit signal with a double-sided crystal ball function

Spurious Signal Studies



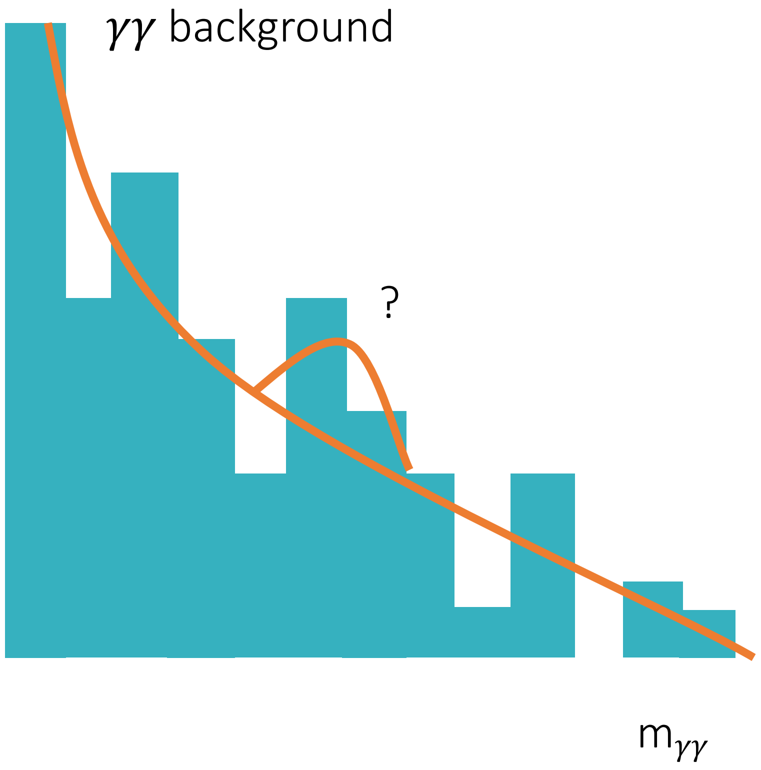
Fit background with an exponential function

Fit signal with a double-sided crystal ball function

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

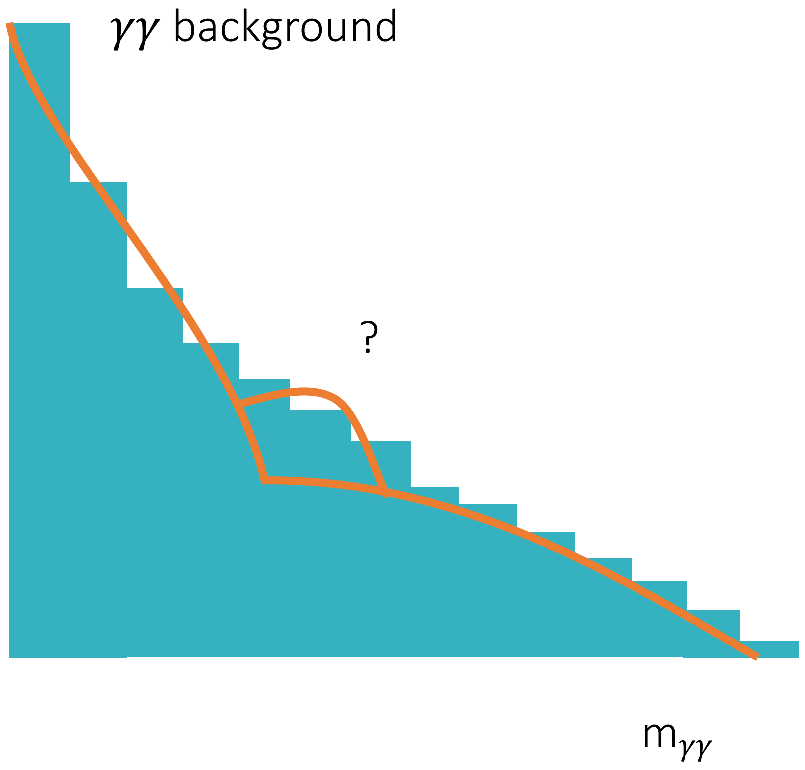
Spurious signal uncertainty tries to characterize this by adding an uncertainty proportional to the size of the fitted spurious signal.

Spurious Signal Studies



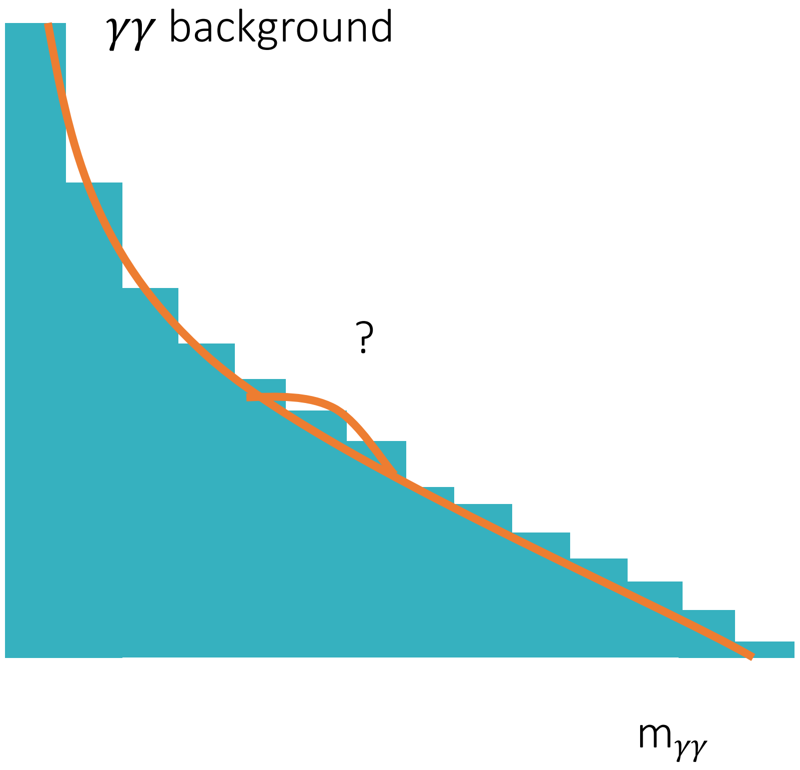
Low MC statistics can lead us to a bigger spurious signal

Spurious Signal Studies



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

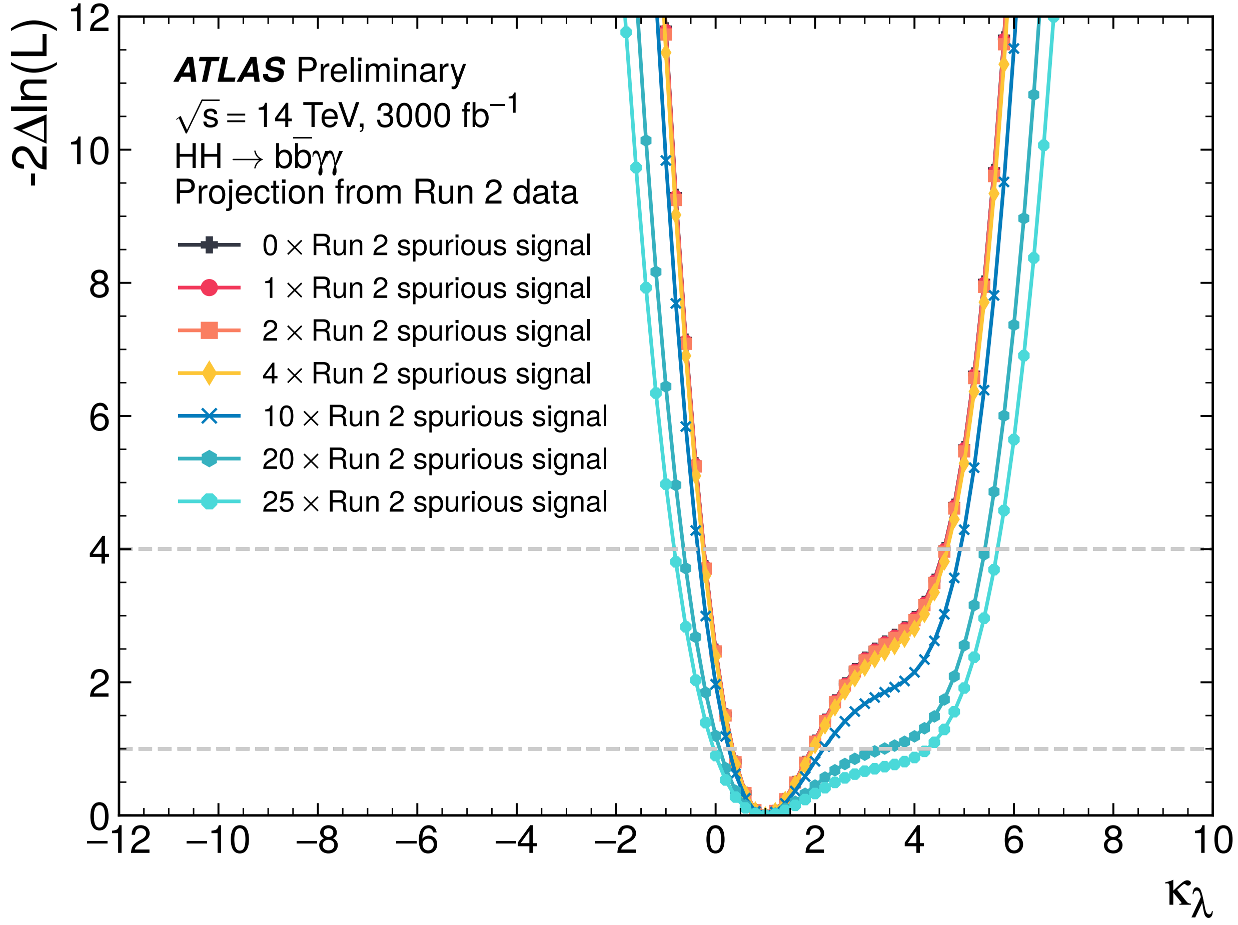
Spurious Signal Studies



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.

Spurious Signal Studies - $bb\gamma\gamma$



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

2022 HL-LHC Prospects $bb\gamma\gamma$
http://cdsweb.cern.ch/record/2799146