

# Higgs Physics at

XIX Mexican Workshop on Particles & Fields

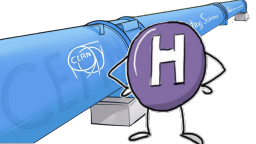
Arely CORTES GONZALEZ



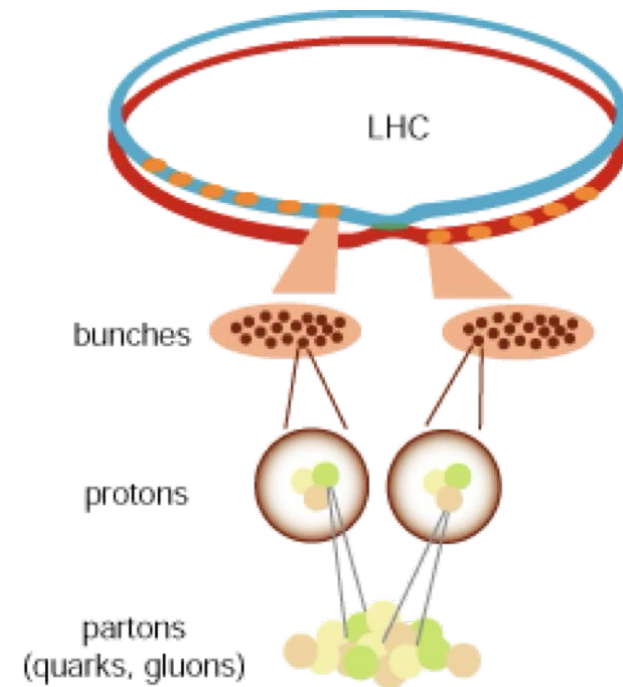
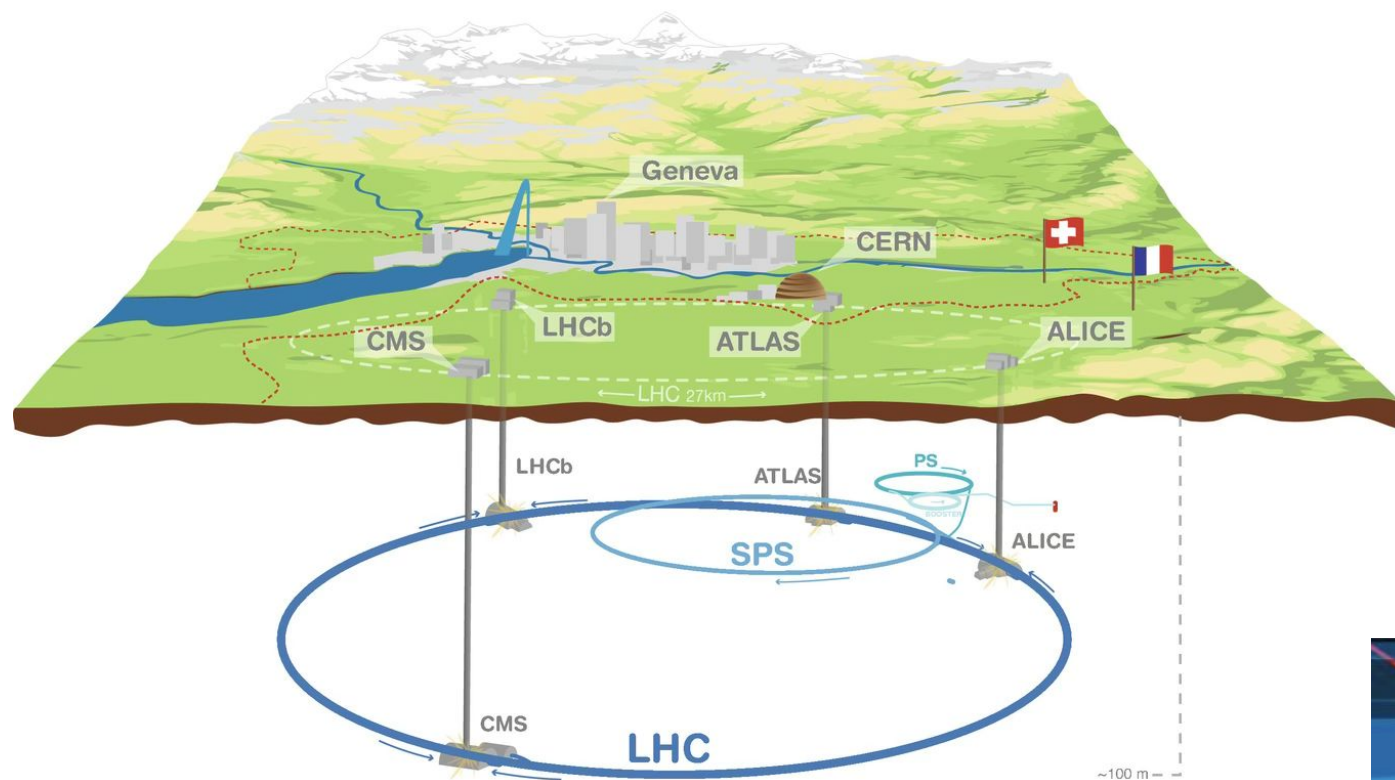
ICEPP



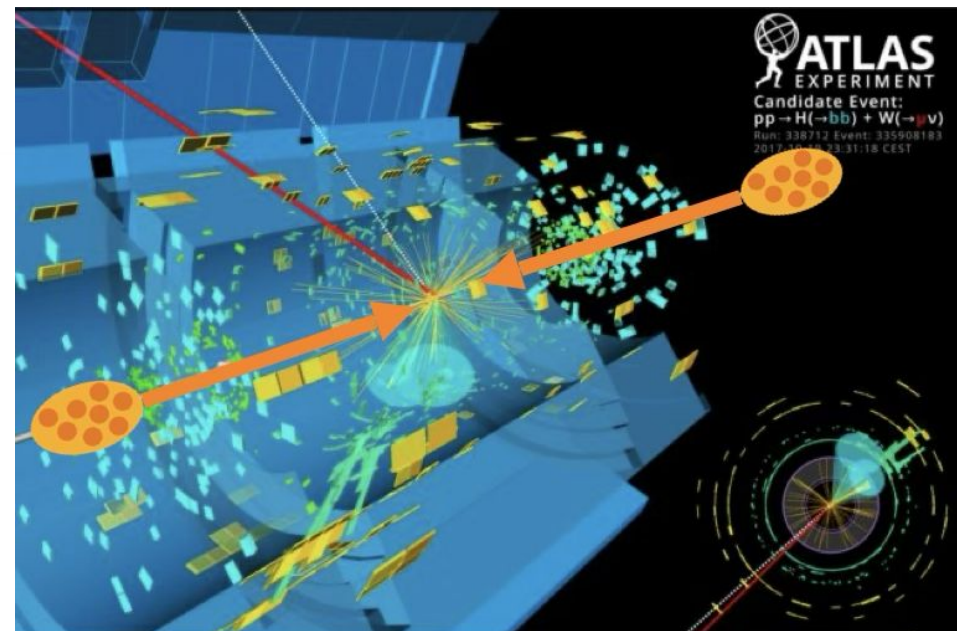
UTokyo

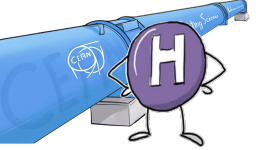


# LHC



- proton-proton collider at CERN.
- 27 km of circumference.
- Several experiments:
  - ATLAS & CMS: general purpose detectors.
  - ALICE (studying heavy ion collisions),
  - LHCb (flavour physics).
- Collisions energy: 7 TeV  $\rightarrow$  13.6 TeV





# ATLAS

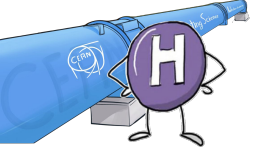
Solenoid and toroidal magnets

Charged particles tracking at the inner detector

Electromagnetic and hadronic Calorimeters provide energy measurements

Muon spectrometer

Trigger: hardware based Level 1 (100 kHz) and software based High-level (1-3 kHz)



# Higgs boson in the SM

## Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.2 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon	
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson	
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson	

**QUARKS** (left side of the quark section)

**LEPTONS** (left side of the lepton section)

**SCALAR BOSONS** (right side of the Higgs box)

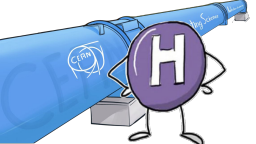
**GAUGE BOSONS VECTOR BOSONS** (right side of the photon, Z, and W boxes)

The Higgs boson in the Standard Model:

- Elementary particle
- Strength of interaction with other particles are relative to their mass.
- Interacts with itself.
- SM does not predict mass.
  - At the start of the LHC the Higgs mass was the only missing SM parameter to predict production and decay rates.
- Unique in the SM!
  - Scalar (spin 0).
  - It makes the SM complete (i.e. explains mass of particles)

Discovered by the ATLAS and CMS Collaborations in 2012 (see [10<sup>th</sup> year anniversary Scientific Symposium](#)).

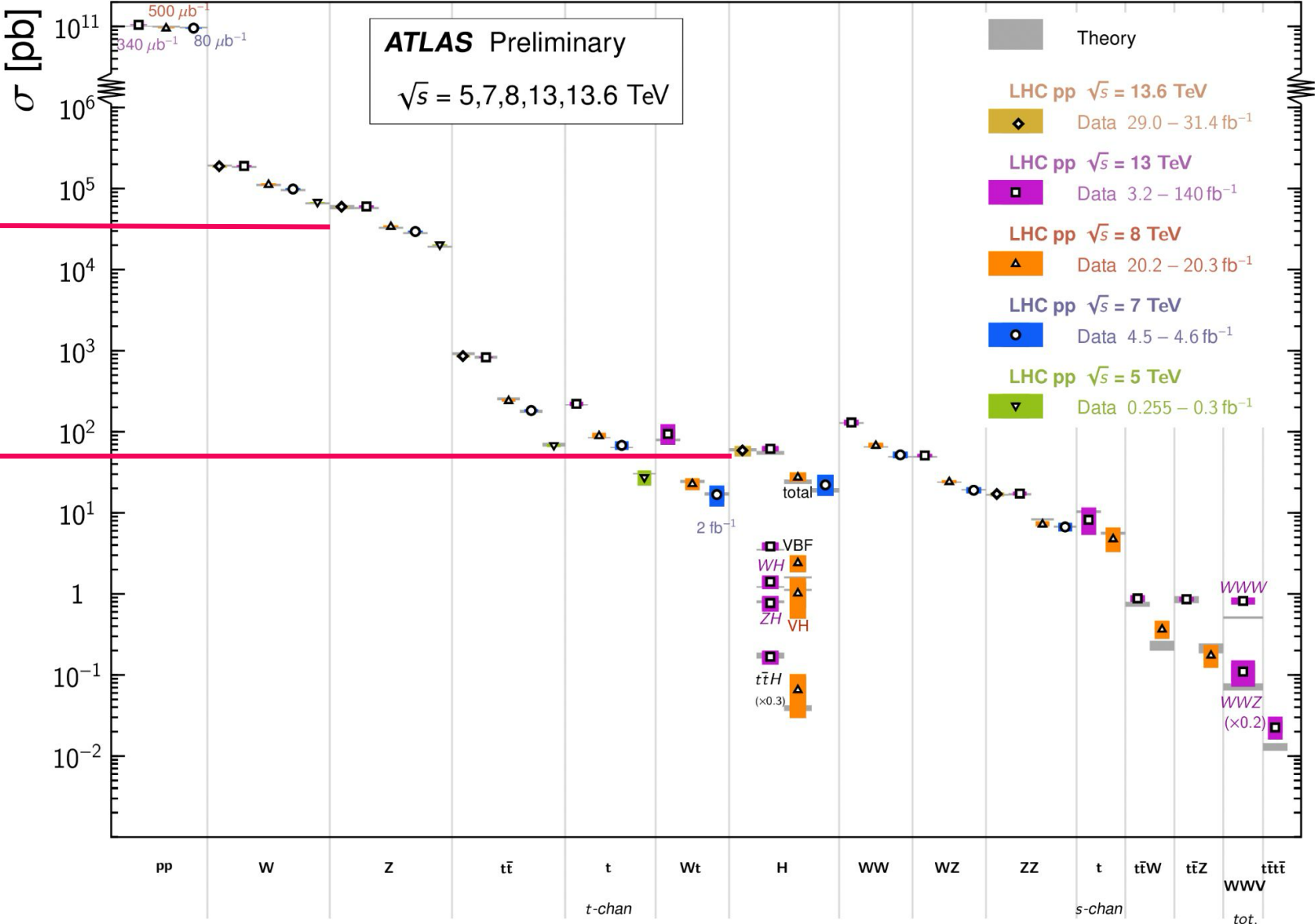


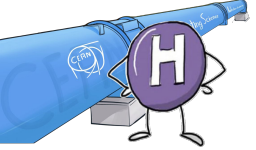


# Standard Model processes

### Standard Model Total Production Cross Section Measurements

Status: June 2024

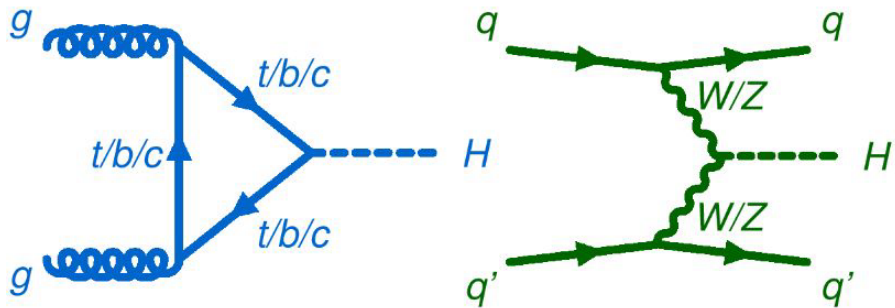




# Higgs boson at the LHC

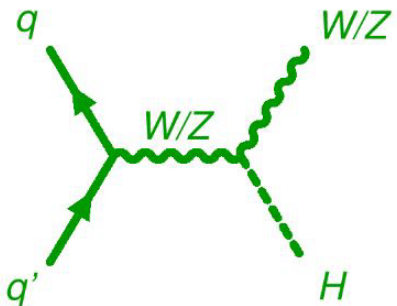
[Handbook of LHC Higgs Cross Sections](#)

Main production mechanisms in pp collisions.

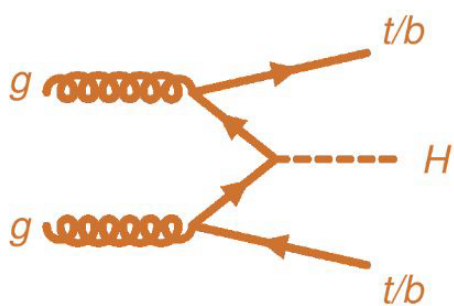


ggF ~88%  
gluon-gluon fusion

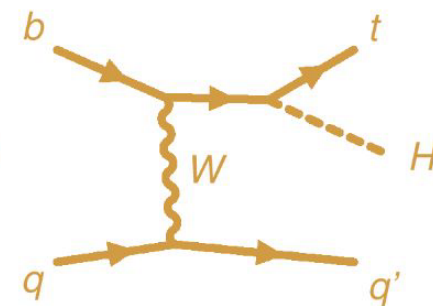
VBF ~7%  
vector-boson fusion



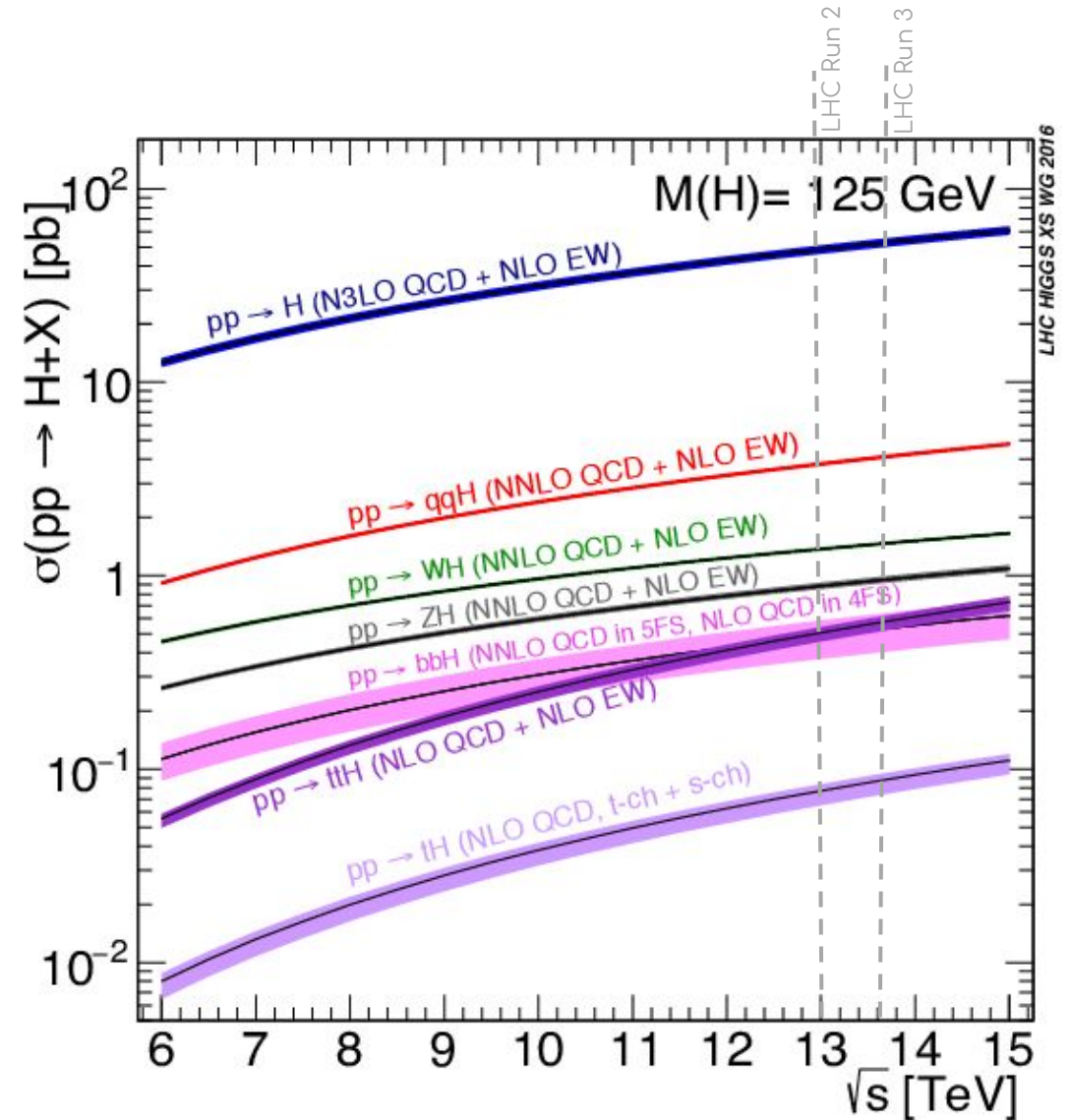
VH ~4%  
vector boson  
associated production

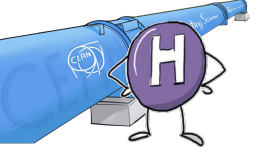


ttH ~1%  
tt associated  
production



tH  
top quark associated  
production

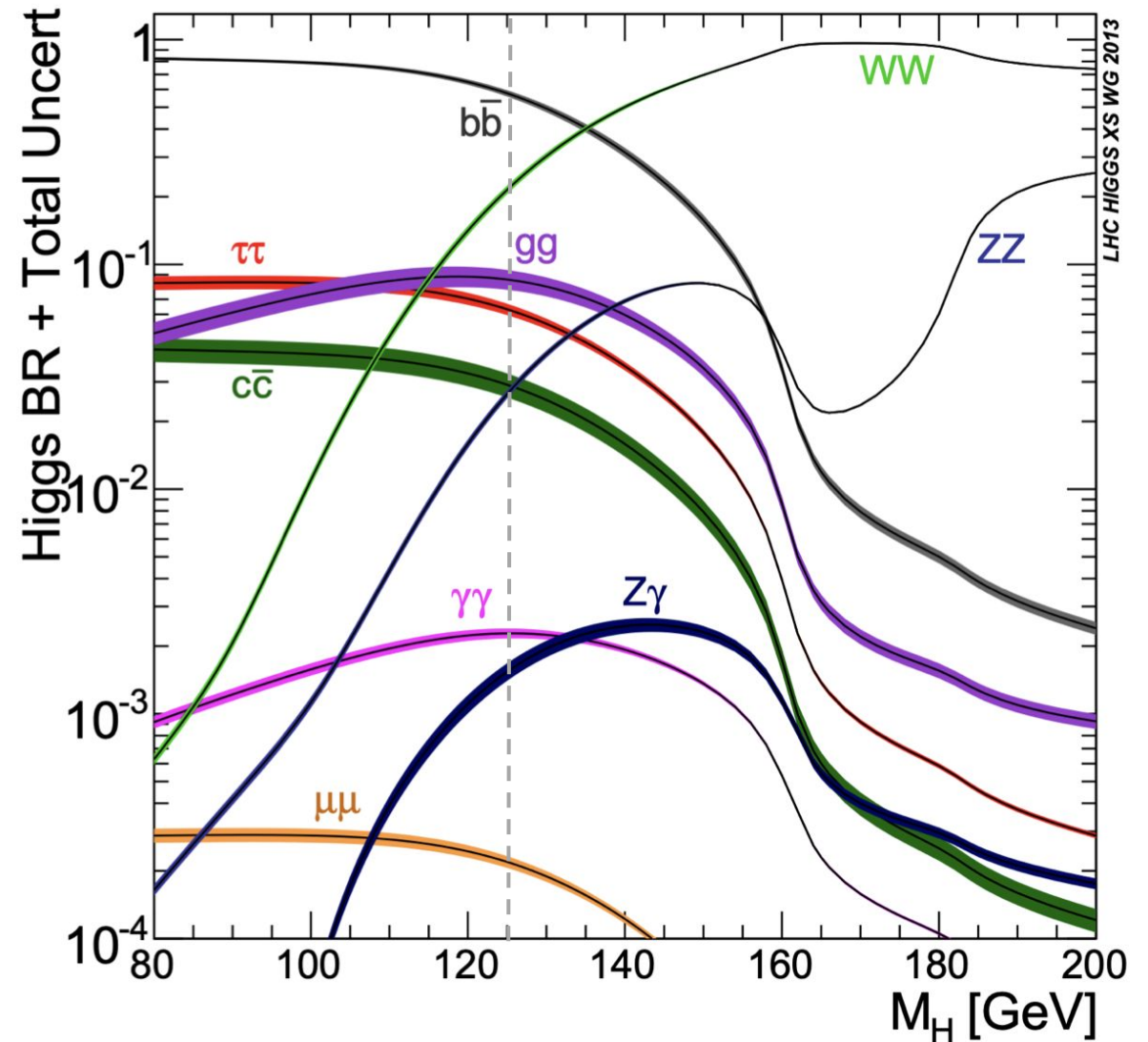
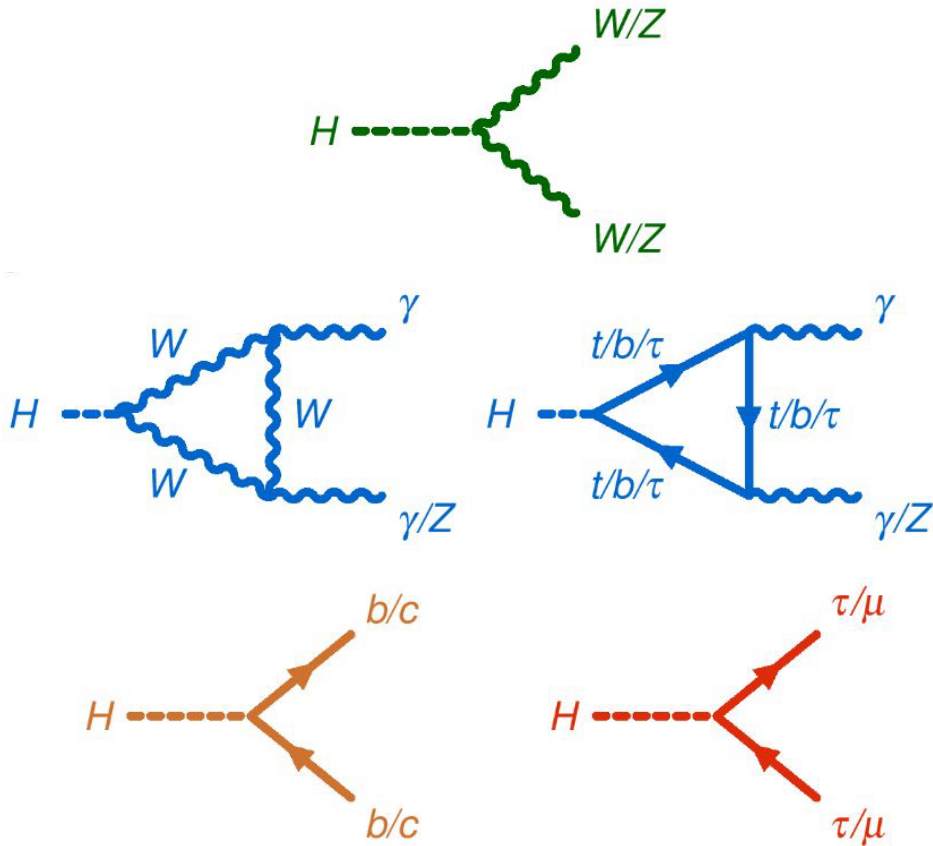




# Higgs boson at the LHC

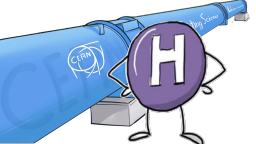
Main decay mechanisms: branching ratios dependant on the Higgs mass.

[Handbook of LHC Higgs Cross Sections](#)



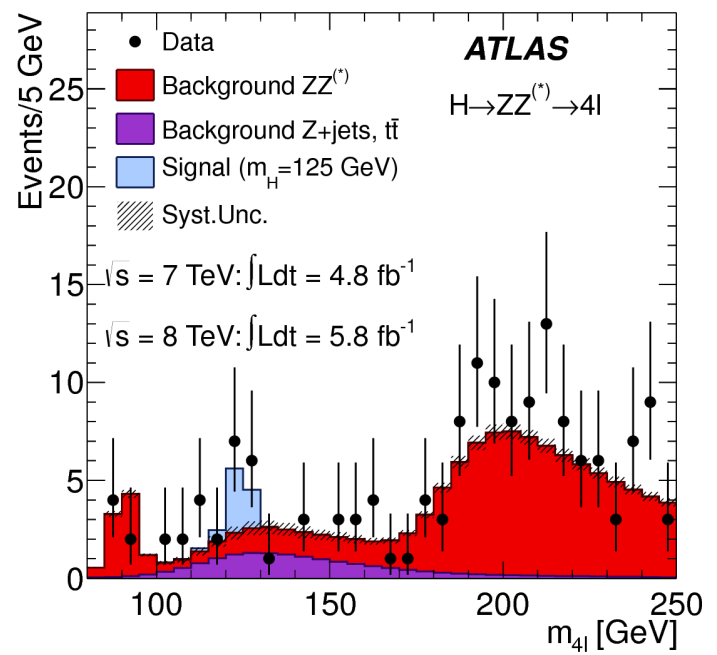
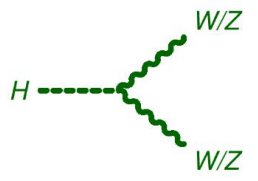
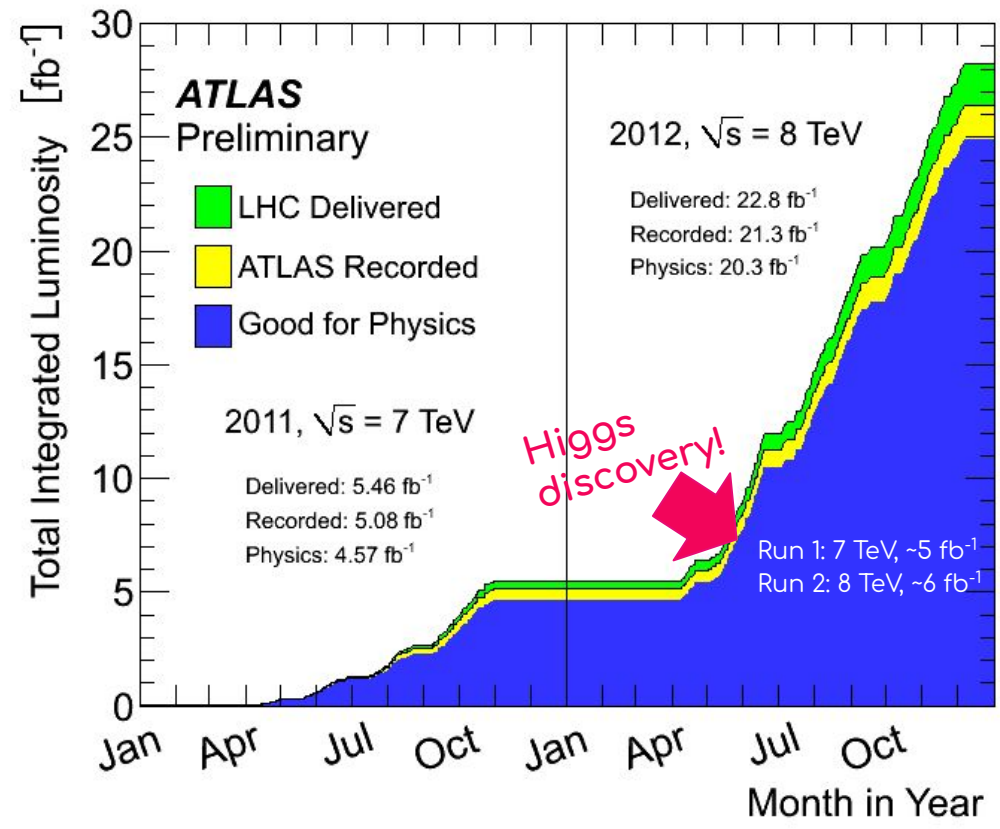
How do we choose which **channels** to search for?

- High branching ratio.
- Clean signature (good detector resolution).

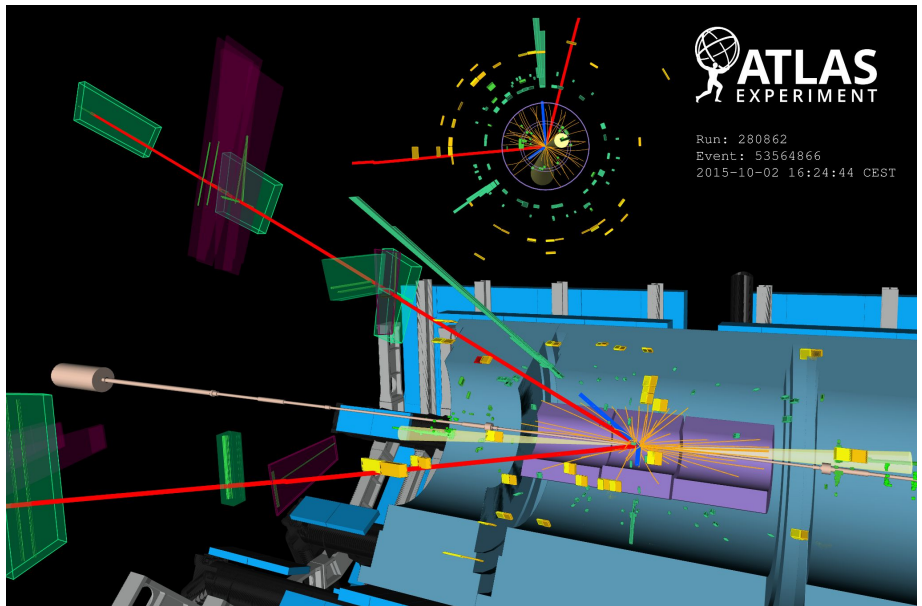


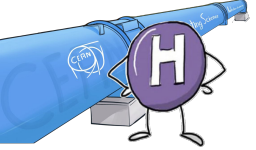
# We found a Higgs!

[ATLAS discovery paper](#)

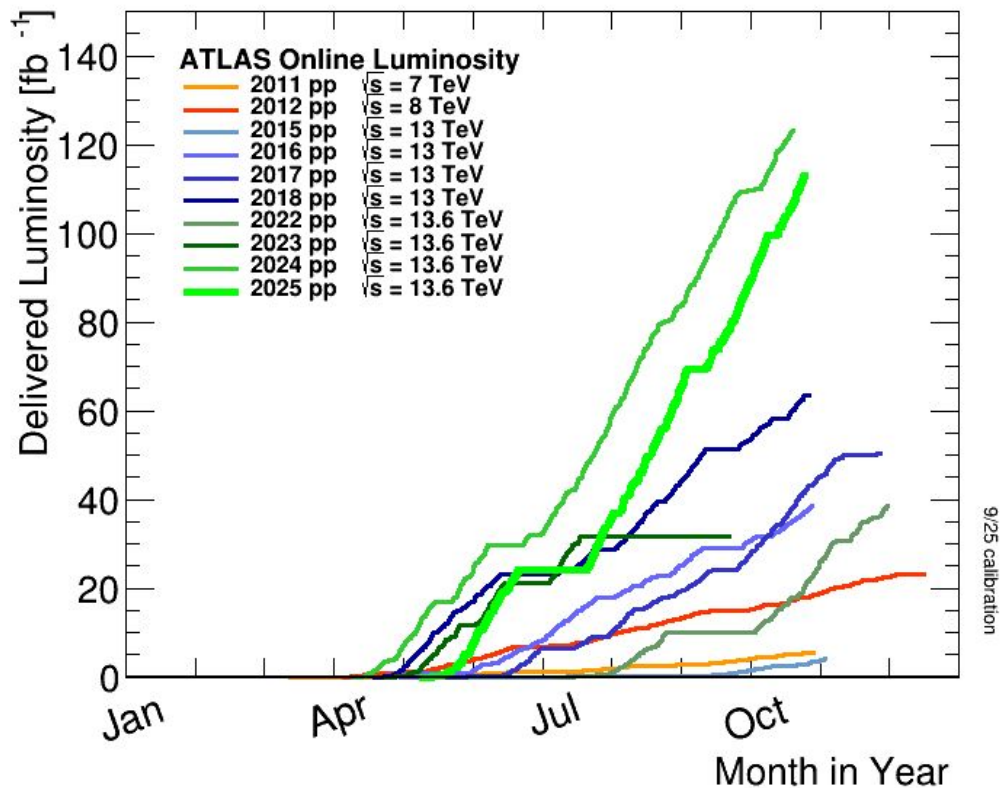


- A large search program in all decays channels from the start of the LHC Run 1.
- Main channels leading to the discovery:
  - $H \rightarrow ZZ^* \rightarrow 4\ell$ ,  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ .



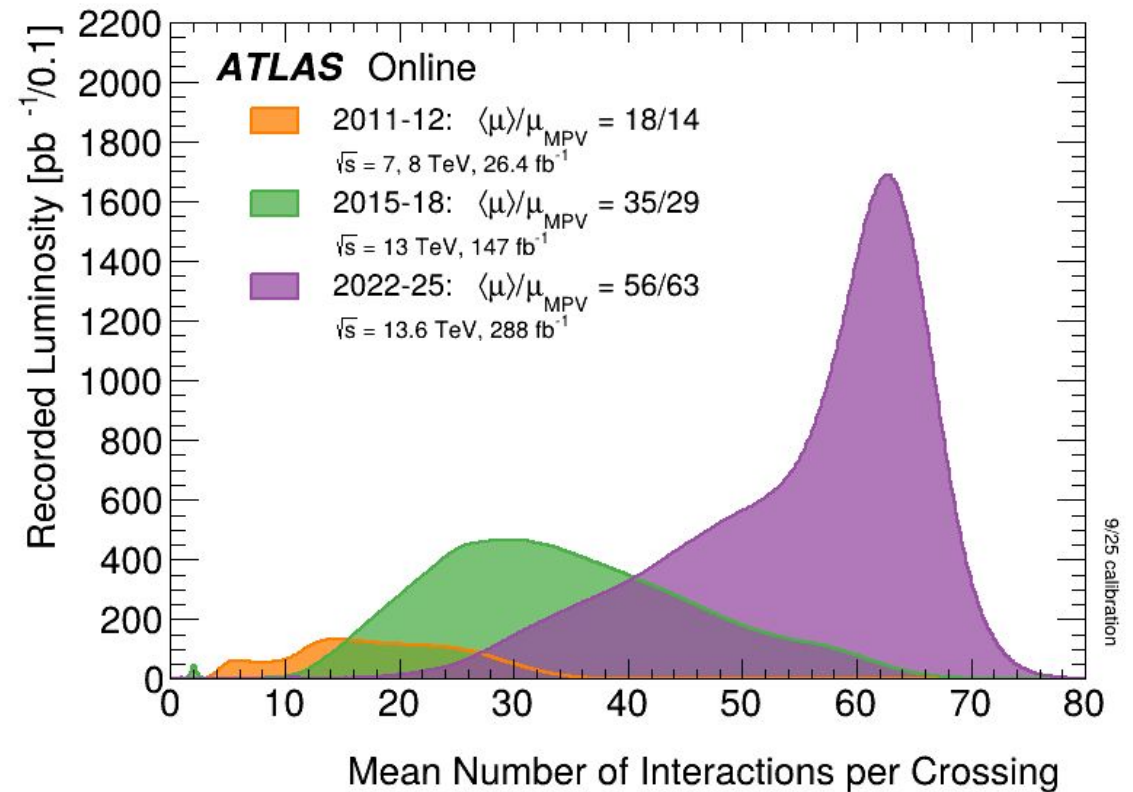


# The LHC dataset now



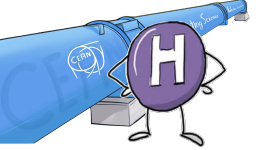
## Luminosity collected by ATLAS

- Run 1: 5 fb<sup>-1</sup> at 7 TeV & 20 fb<sup>-1</sup> at 8 TeV
- Run 2: 140 fb<sup>-1</sup> at 13 TeV
- Run 3: ~300 fb<sup>-1</sup> at 13.6 TeV
  - ending in 2026.



## Pileup conditions are much more challenging!

- Efficiency and resolution of objects reconstruction requires more work.



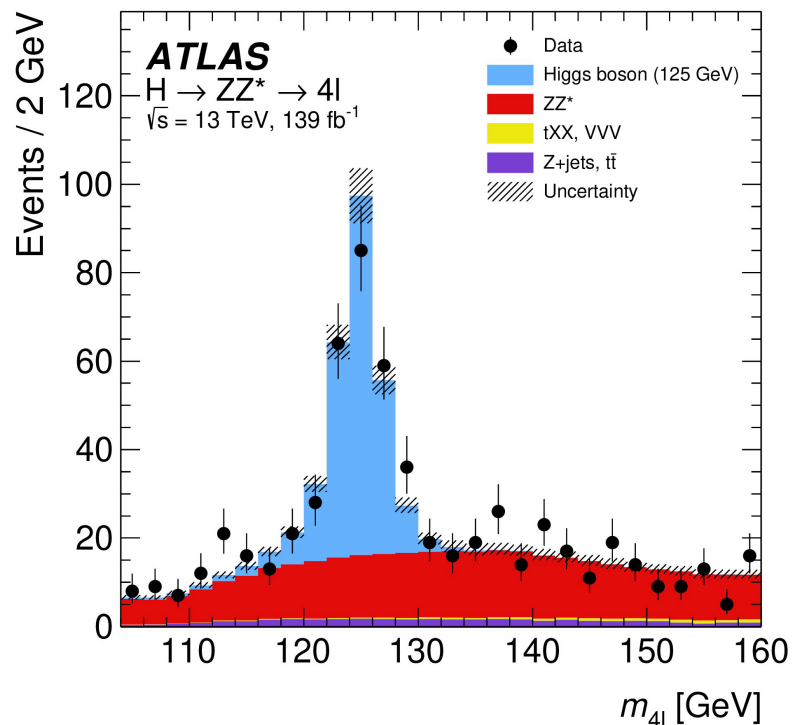
# Characterising the Higgs boson

## Mass measurement



$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$
$$V = V_0 + \frac{1}{2}m_H^2 h^2 + \frac{m_H^2}{2v^2}vh^3 + \dots$$

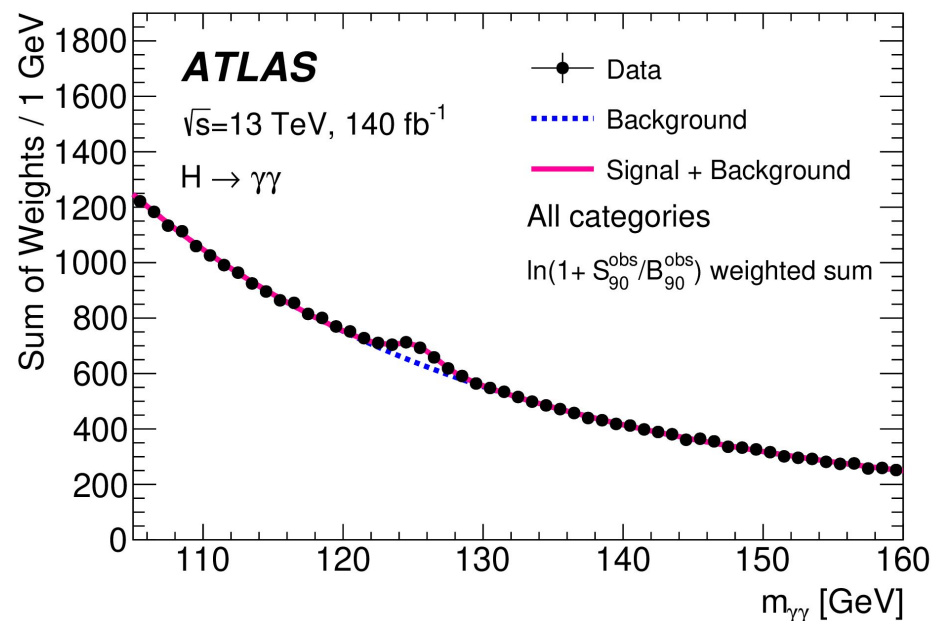
[Phys. Lett. B 843 \(2023\) 137880](#)

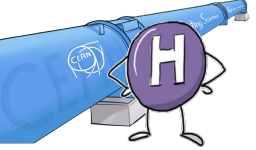


The mass is the only free parameter in the Higgs mechanism.

- Crucial input to predict Higgs production cross sections and decay rates
- Measurement in decay channels with good resolution:
  - $H \rightarrow ZZ^* \rightarrow 4\ell$  and  $H \rightarrow \gamma\gamma$  (fully reconstructable final states)
  - Relies on precise momentum calibration of muons, electrons and photons.

[Phys. Lett. B 847 \(2023\) 138315](#)

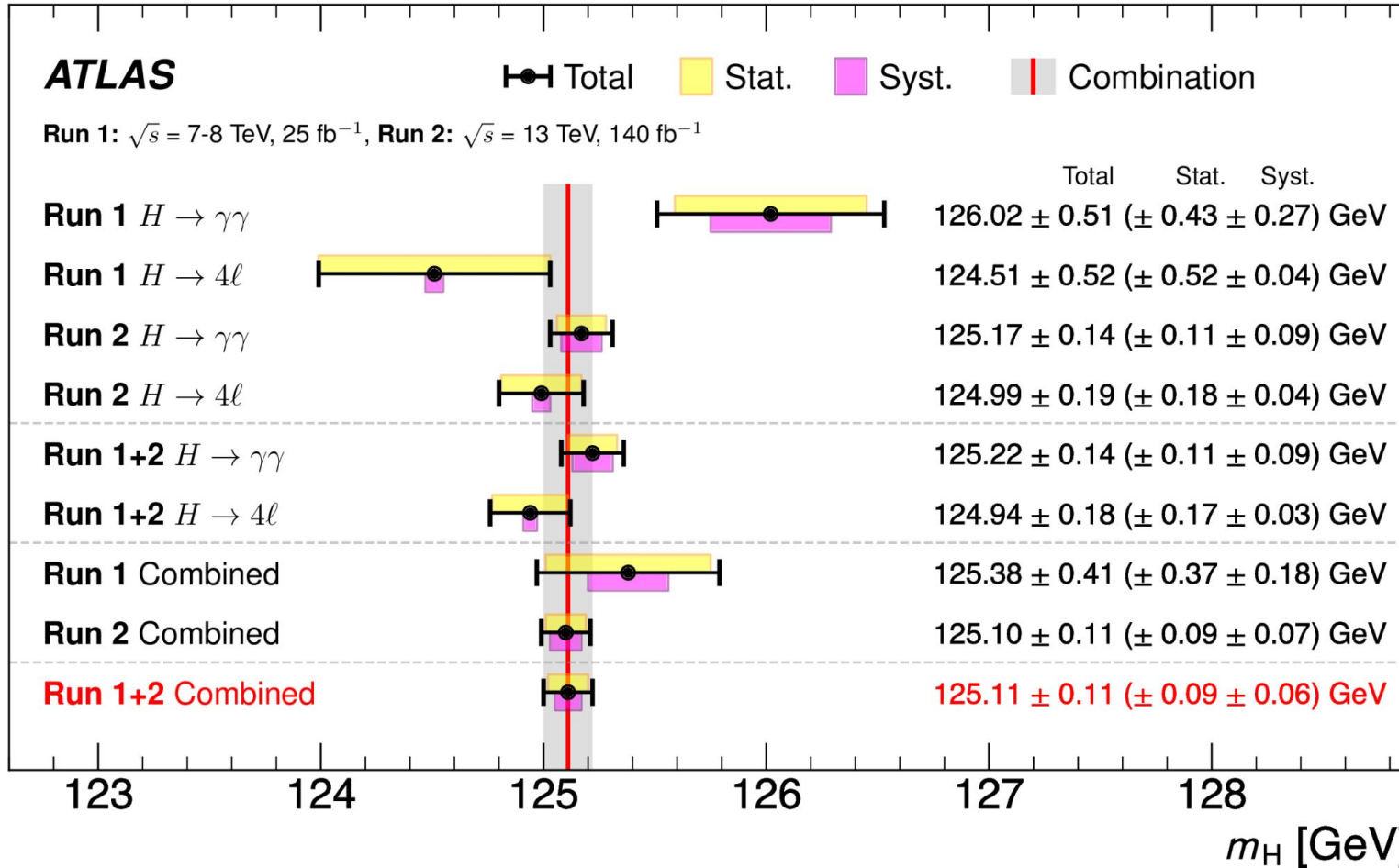




# Characterising the new boson

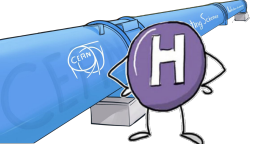
## Mass measurement

[Phys. Rev. Lett. 131 \(2023\) 251802](https://arxiv.org/abs/2207.16261)



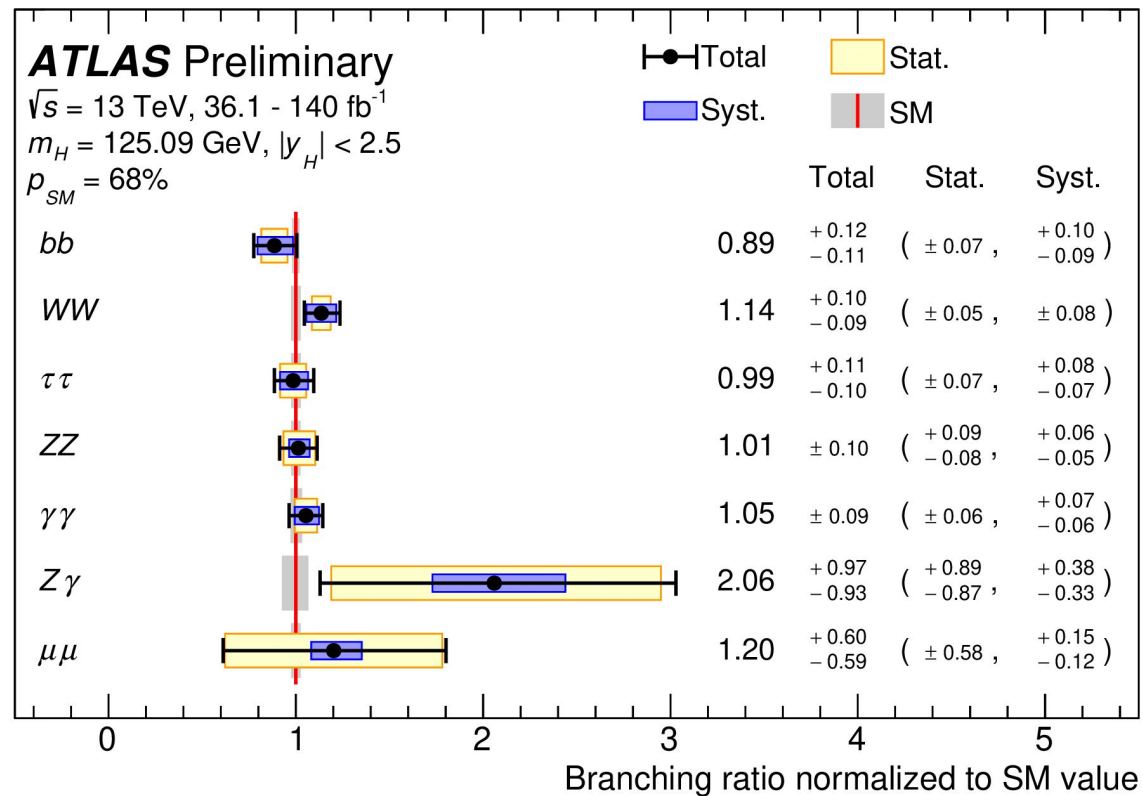
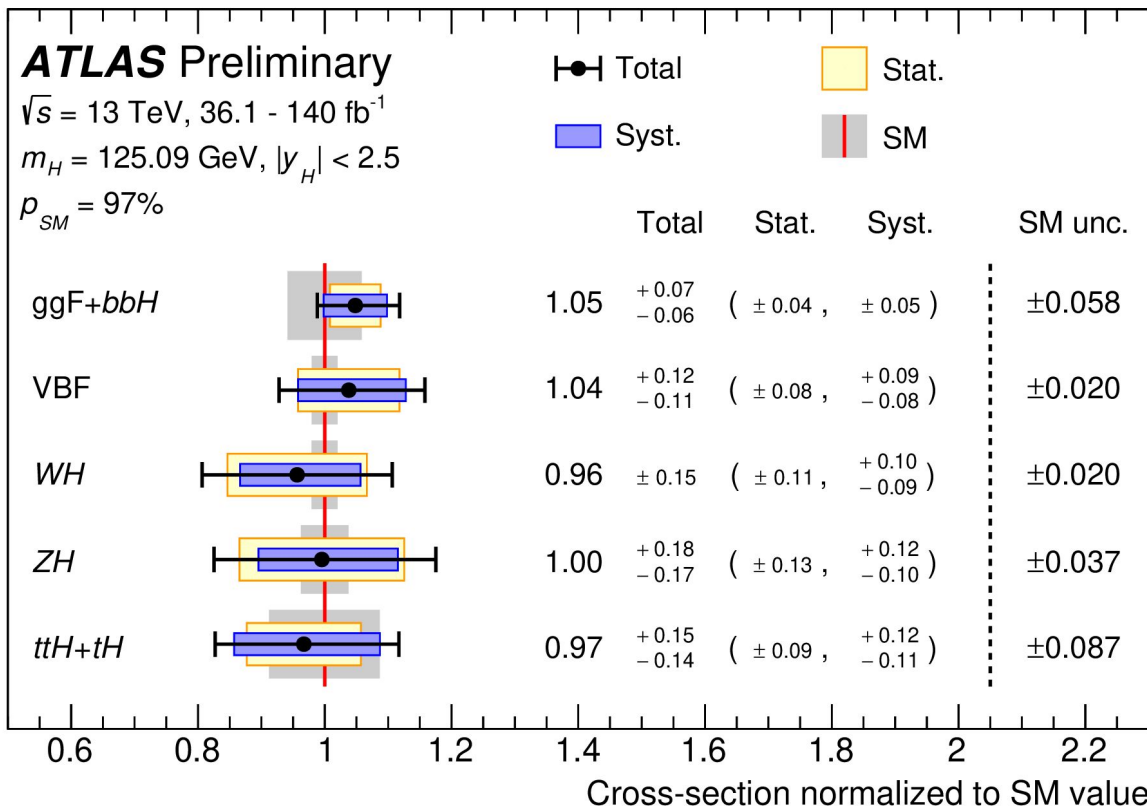
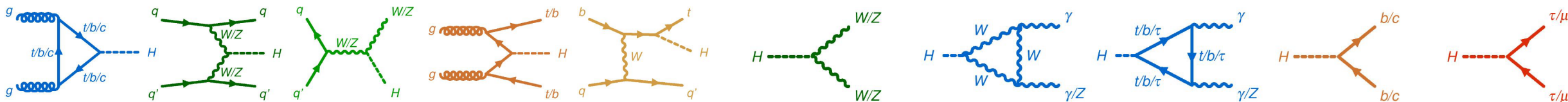
- First precision measurement at the LHC!
  - **Current precision at 0.09%!**
- Compare to Run 1, Run 2 combined measurement ( $H \rightarrow ZZ^* \rightarrow 4\ell$  and  $H \rightarrow \gamma\gamma$ ) is equally limited by statistical and systematic uncertainties.
- Precise calibration of energy/momentum scale of leptons and photons.

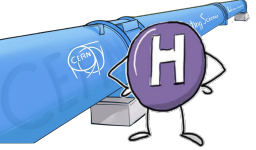
Source	Systematic uncertainty on $m_H$ [MeV]
$e/\gamma$ $E_T$ -independent $Z \rightarrow ee$ calibration	44
$e/\gamma$ $E_T$ -dependent electron energy scale	28
$H \rightarrow \gamma\gamma$ interference bias	17
$e/\gamma$ photon lateral shower shape	16
$e/\gamma$ photon conversion reconstruction	15
$e/\gamma$ energy resolution	11
$H \rightarrow \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7



# Higgs Couplings

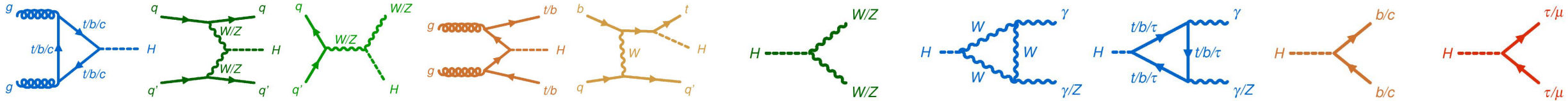
After more than 10 years: five main production channels and main decay channels have been observed and are being used for measurements.





# Higgs Couplings

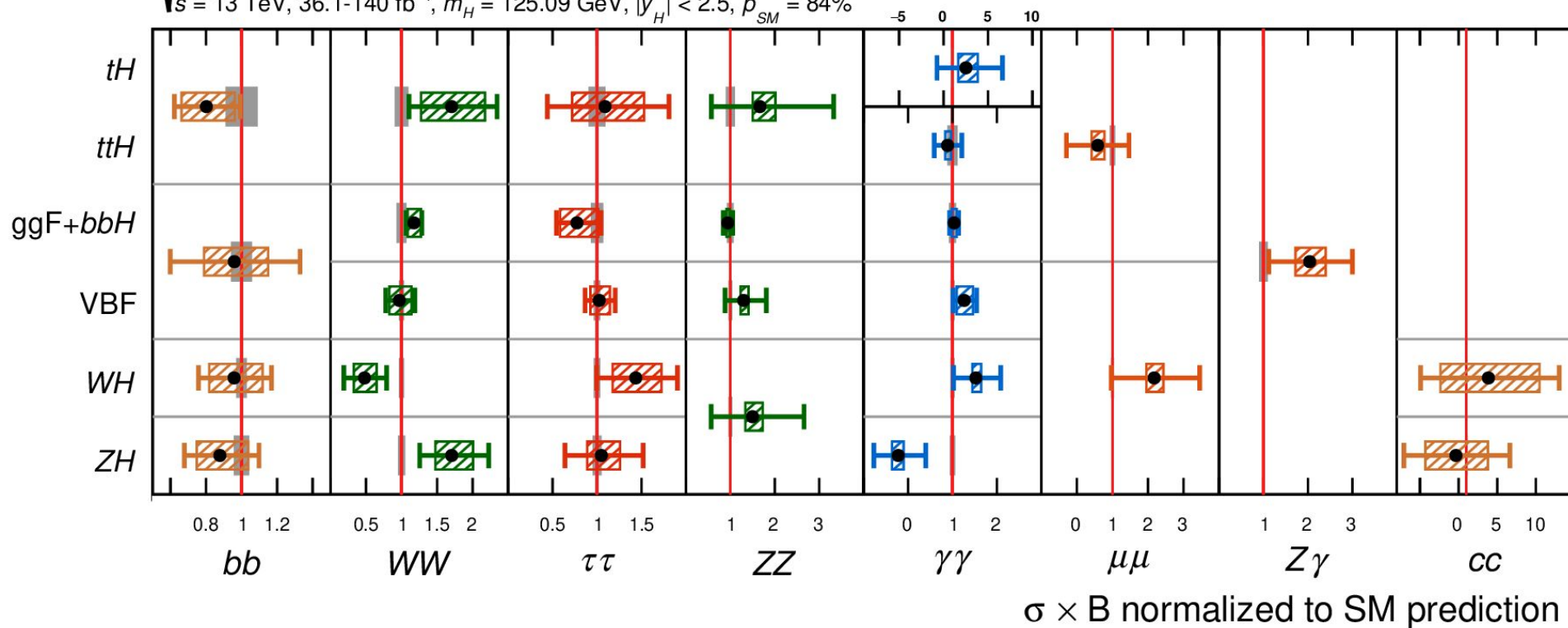
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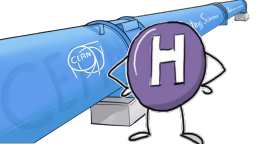


**ATLAS Preliminary**

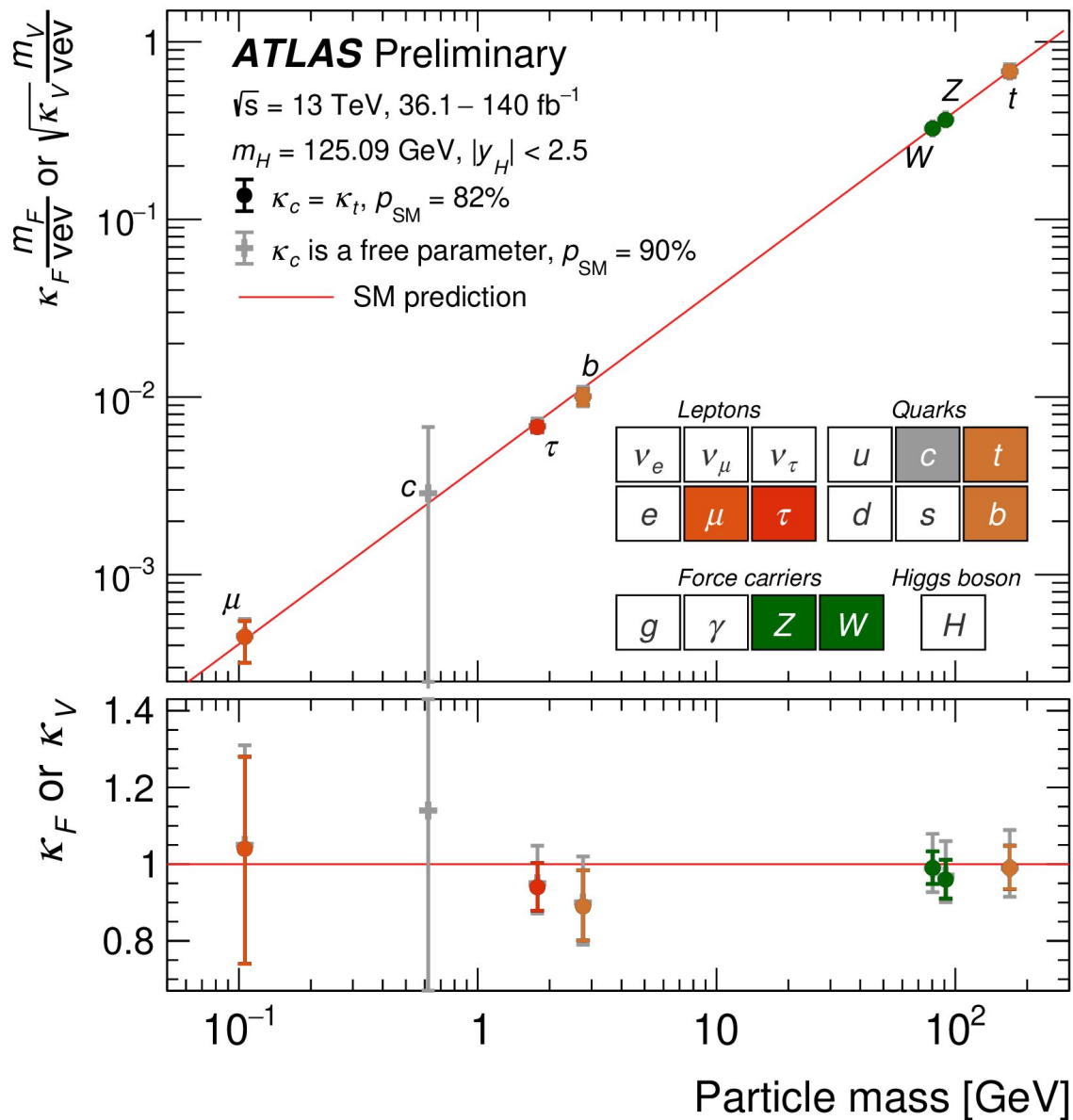
$\sqrt{s} = 13 \text{ TeV}$ ,  $36.1\text{-}140 \text{ fb}^{-1}$ ,  $m_H = 125.09 \text{ GeV}$ ,  $|y_H| < 2.5$ ,  $p_{SM} = 84\%$

● Data (Total Unc.)    ▨ Syst. Unc.    ■ SM prediction

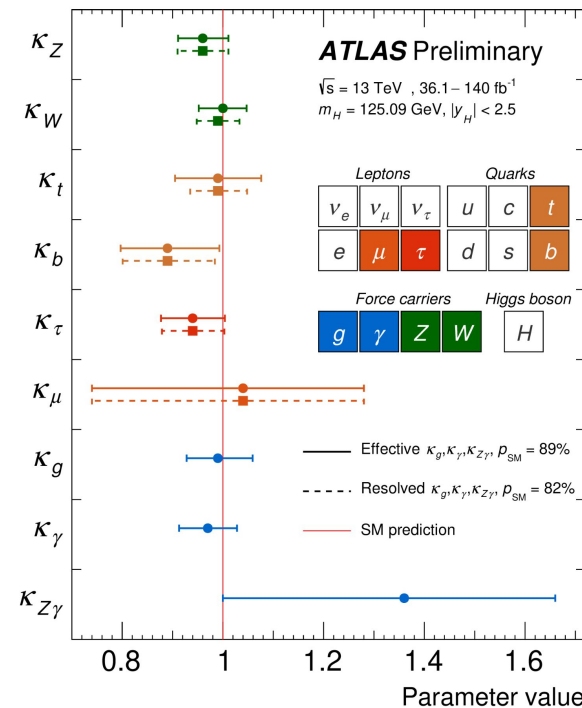
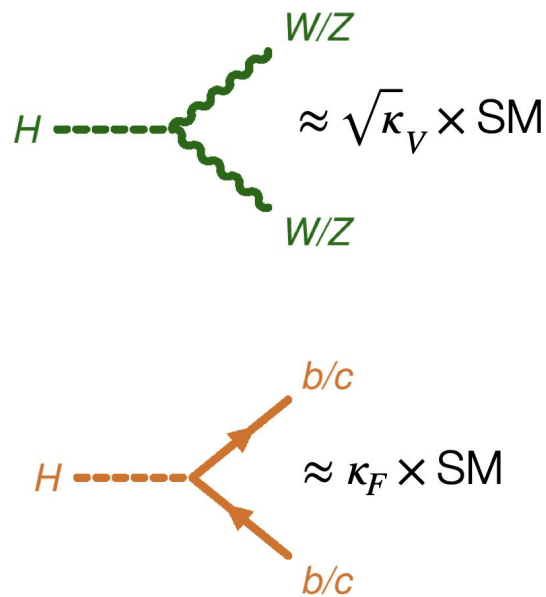


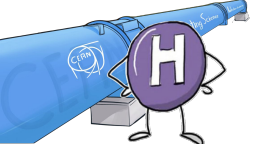


# Higgs Couplings

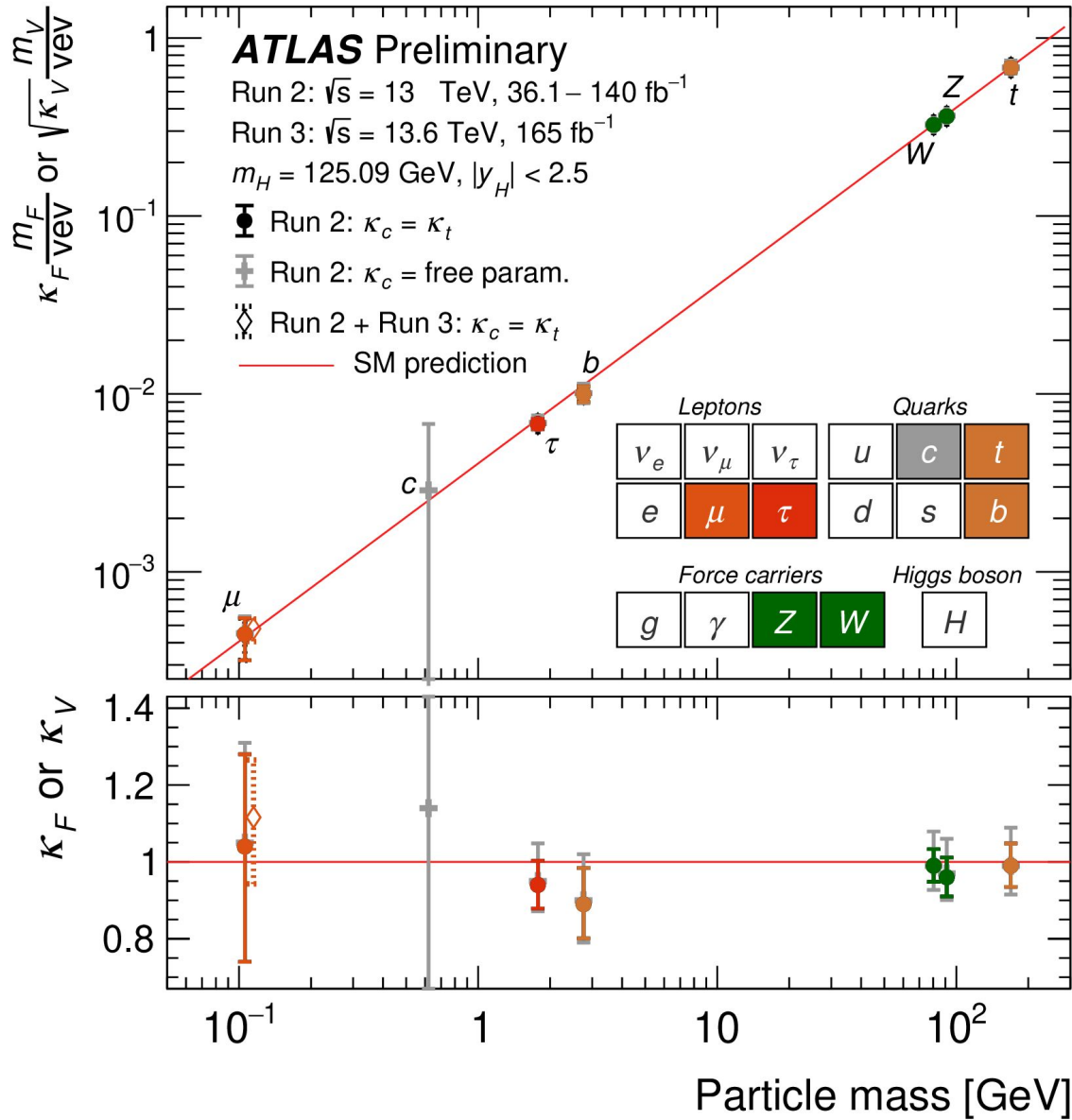


Relationship between mass and coupling as predicted by SM within current uncertainties.

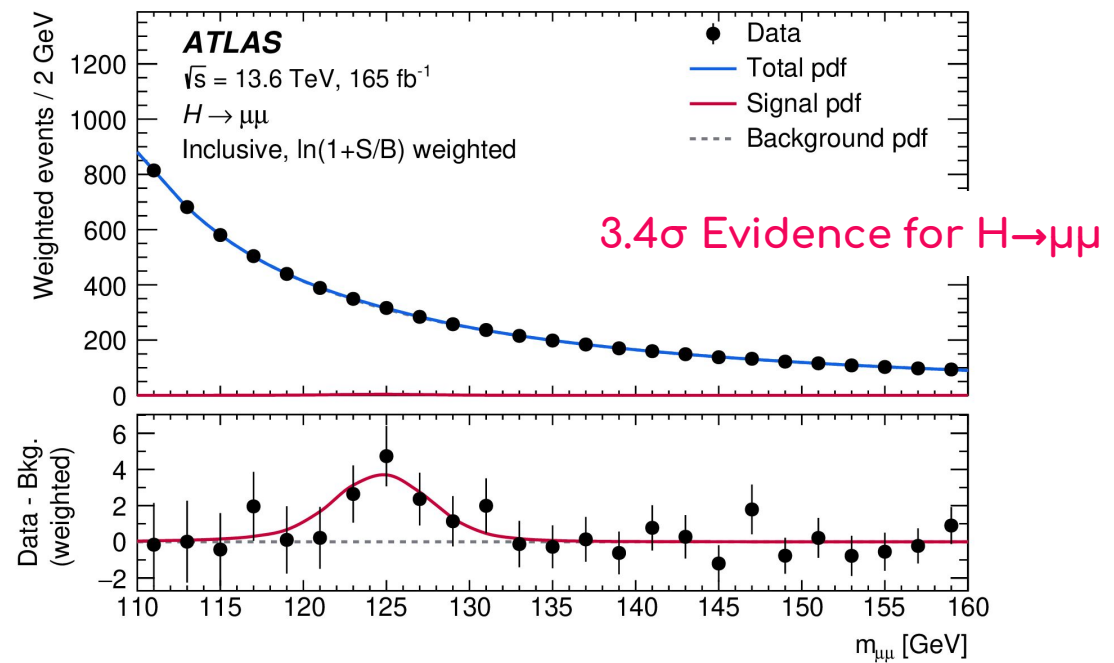




# Higgs Couplings

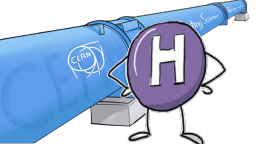


With **Run 3 data** we can improve our measurements in more challenging signatures!



**ATLAS**  
 $H \rightarrow \mu\mu$

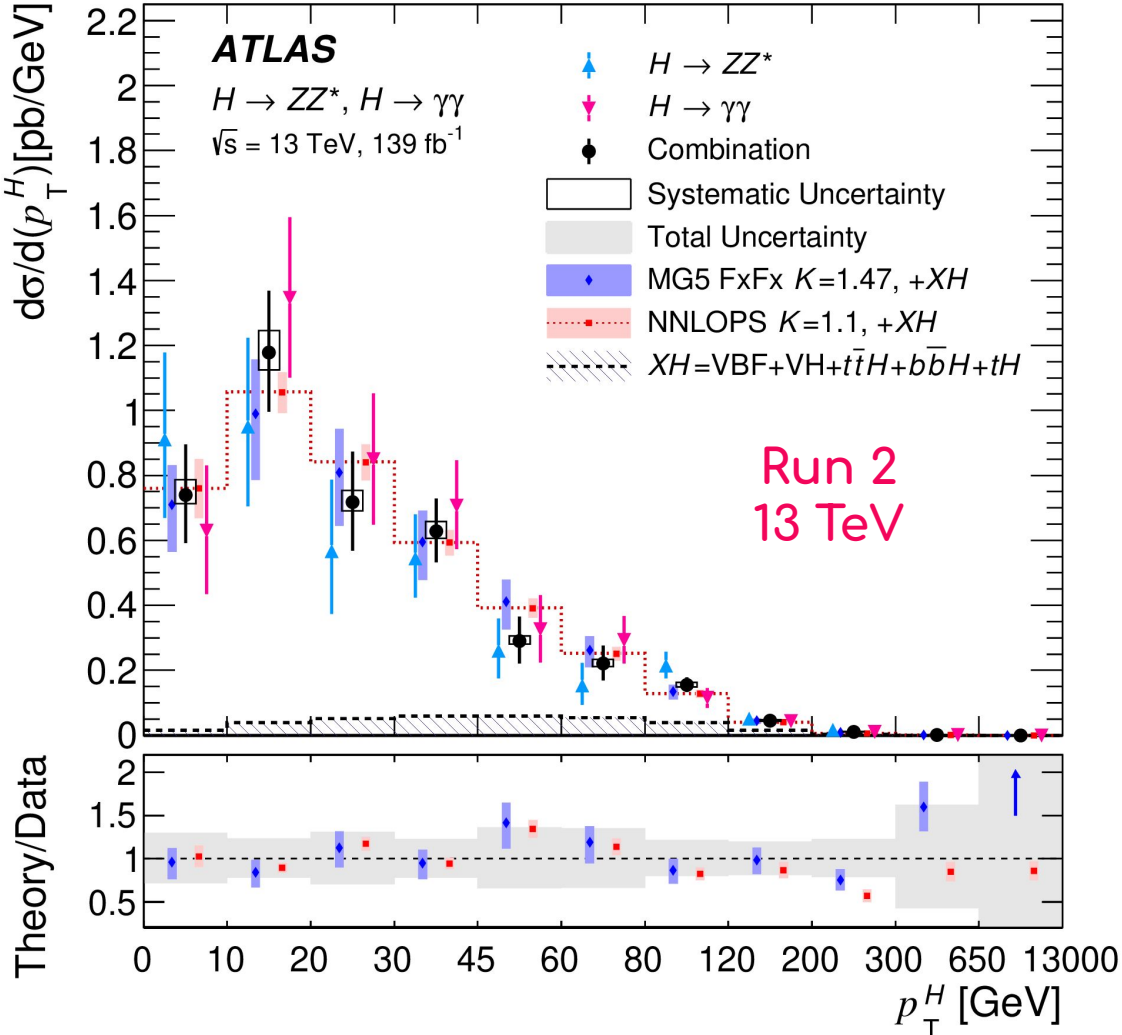
	Run 2: $\sqrt{s} = 13$ TeV, 140 fb <sup>-1</sup>	Run 3: $\sqrt{s} = 13.6$ TeV, 165 fb <sup>-1</sup>
	Total	Total
	Stat.	Stat.
	Syst.	Syst.
	SM	SM
Combined Run 2	$1.2 \pm 0.6$ ( $\pm 0.6$ , $+0.2$ )	
Combined Run 3		$1.6 \pm 0.6$ ( $+0.6$ , $-0.5$ , $\pm 0.2$ )
<b>Combined Run 2 + Run 3</b>	<b><math>1.4 \pm 0.4</math> (<math>\pm 0.4</math>, <math>\pm 0.1</math>)</b>	



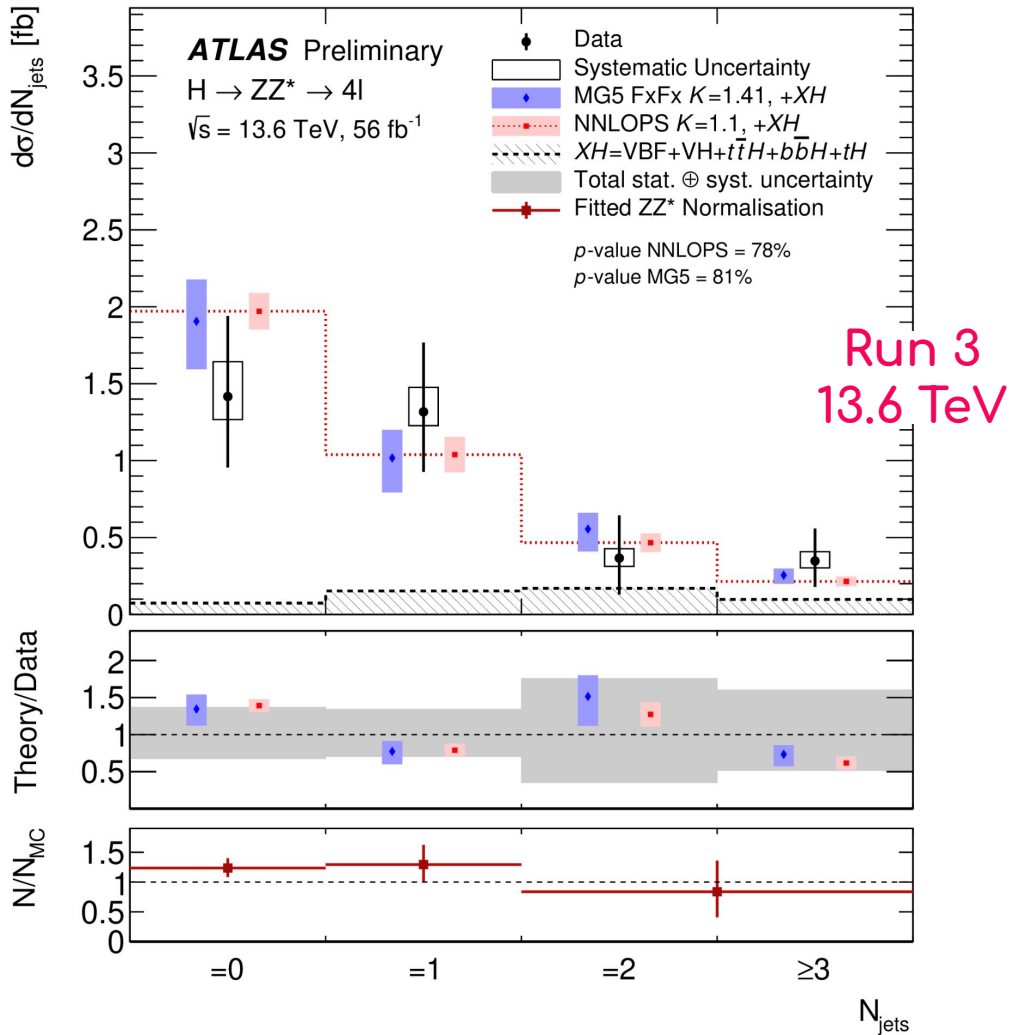
# We can go beyond...

- We can also study kinematic distributions in Higgs production (beyond the measurements of total rates).
- Physics beyond the Standard Model may be enhanced in the tails of these distributions.

[JHEP 05 \(2023\) 028](#)



[ATLAS-CONF-2025-002](#)



# Trilinear Higgs Coupling

Standard Model  
Higgs potential

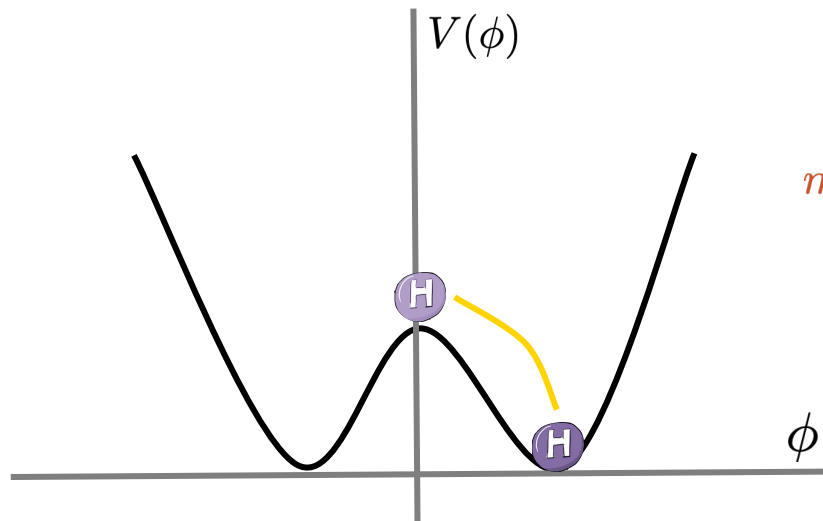
$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4$$

Our universe lives in the  
minimum:

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 - \frac{\lambda}{v^4}$$

mass

$$V = V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \dots$$



minimum of the  
potential

$$m_H = \sqrt{2\lambda v} \approx 125 \text{ GeV}$$

$$\lambda_{\text{SM}} \approx 0.13$$

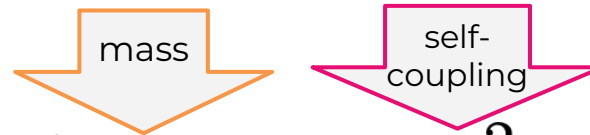
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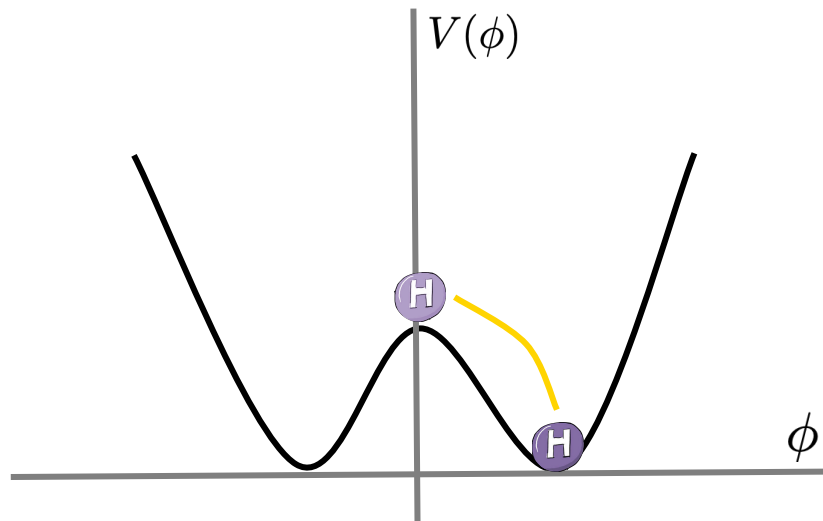
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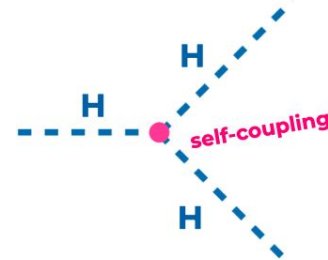
$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 - \frac{\lambda}{v^4}$$



$$V = V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \dots$$



we can probe this via  
the HH production



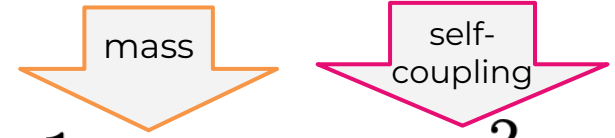
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Standard Model  
Higgs potential

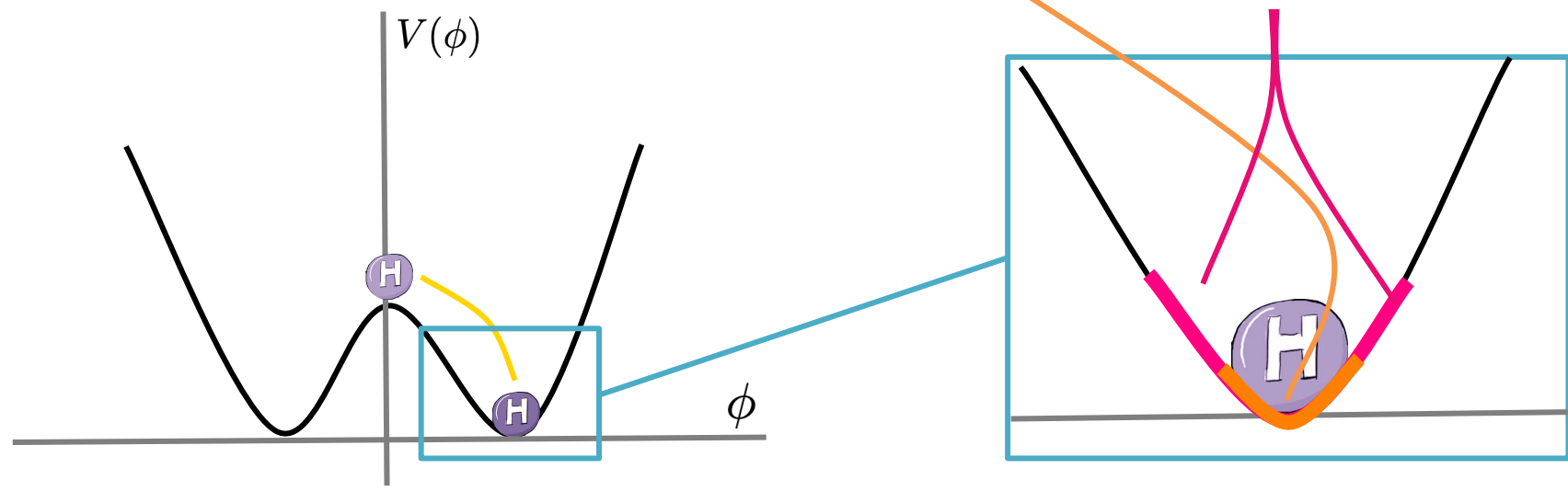
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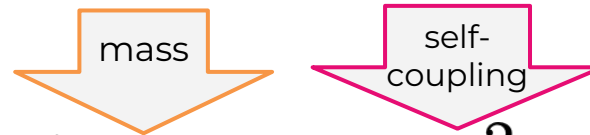
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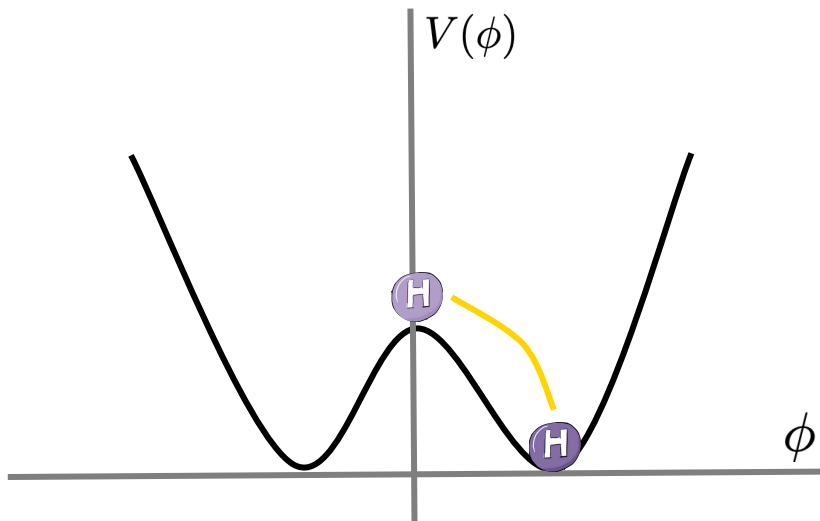
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$$V = V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \dots$$



In the Standard  
Model:

$$\lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2}$$

$$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$$

Non-resonant HH production searches probe the shape of the Higgs potential by measuring the Higgs self coupling:  $\kappa_\lambda$ .

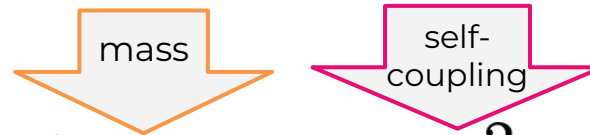
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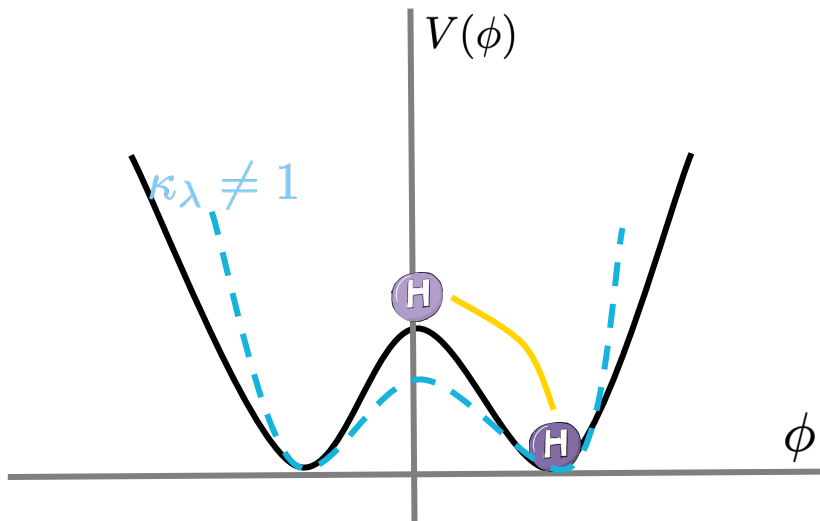
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In the Standard  
Model:

$$\lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2}$$

$$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$$

Non-resonant HH production searches probe the shape of  
the Higgs potential by measuring the Higgs self coupling:  $\kappa_\lambda$ .

$\kappa_\lambda \neq 1$  could indicate beyond Standard Model physics.

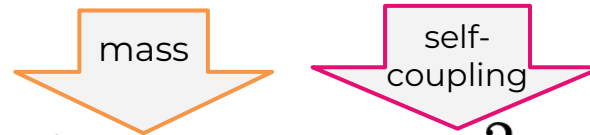
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Standard Model  
Higgs potential

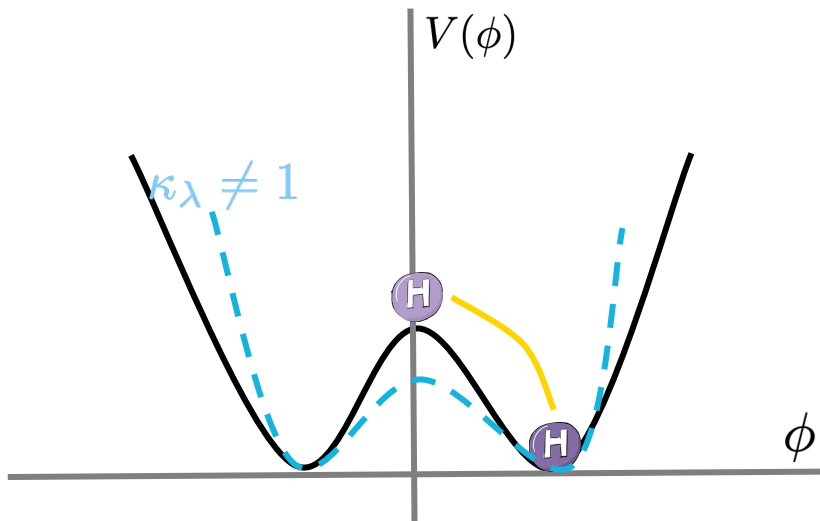
$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4$$

Our universe lives in the  
minimum:

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 - \frac{\lambda}{v^4}$$

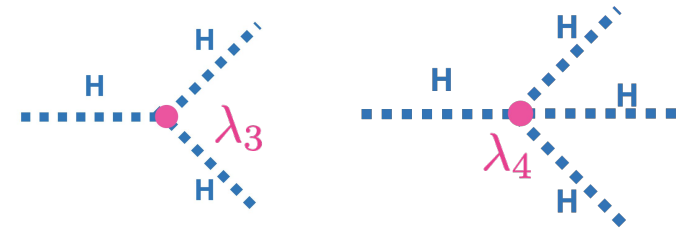


$$V = V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \dots$$



Moreover, in the SM:

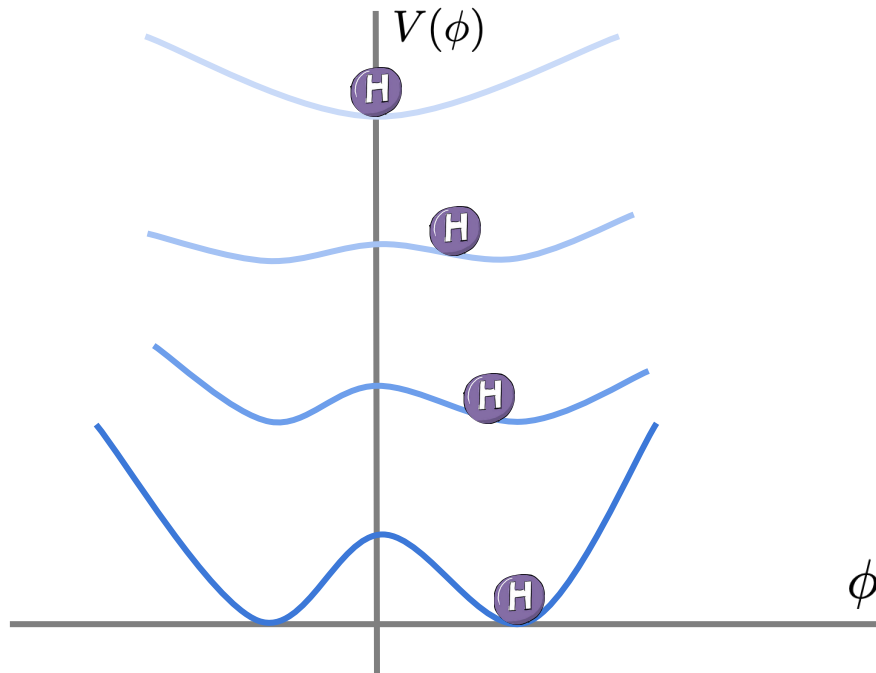
$$\lambda_3 = \lambda_4$$



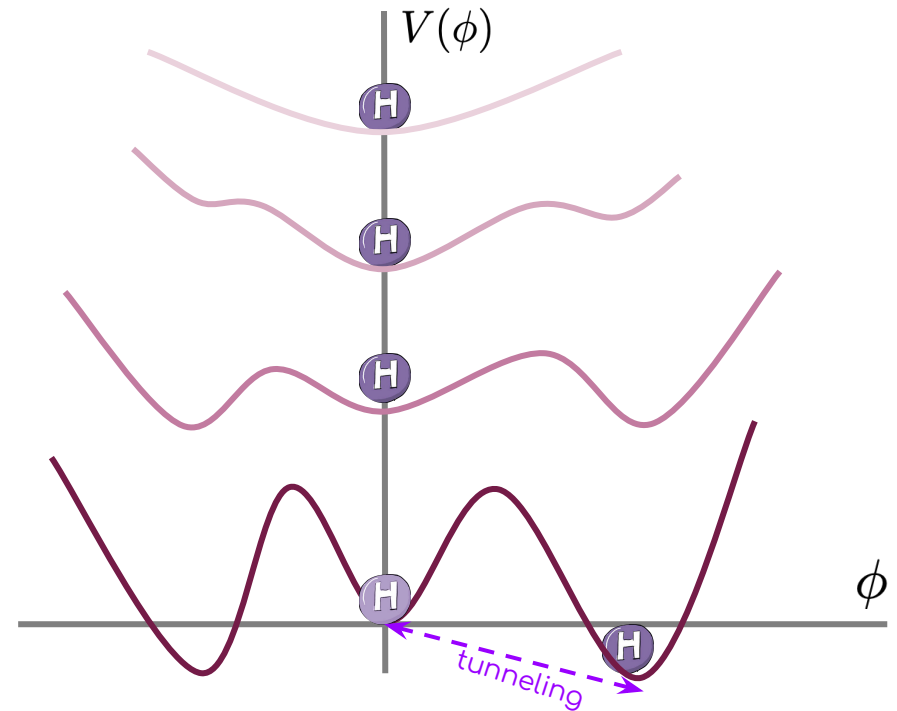
We can use HHH searches to independently constrain  $\lambda_4$

# Electroweak phase transition

Measurements of the Higgs self-coupling can give insight about our universe!



SM: 2<sup>nd</sup> order phase transition. Continuous cross-over from one phase to the other.



BSM: 1<sup>st</sup> order phase transition.

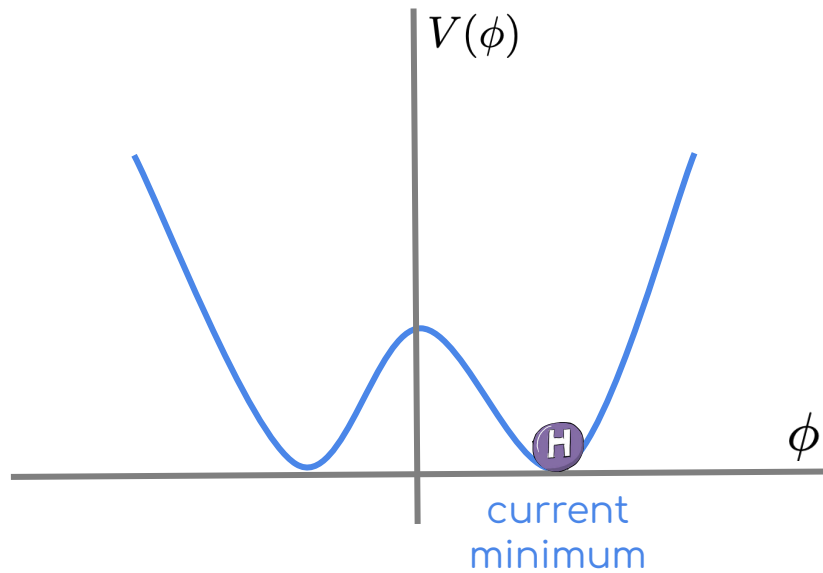
Baryogenesis requires a first order electroweak phase transition, which would lead to a modification to the Higgs potential ...

# Stability of the Universe

Measurements of the Higgs self-coupling can give insight about our universe!

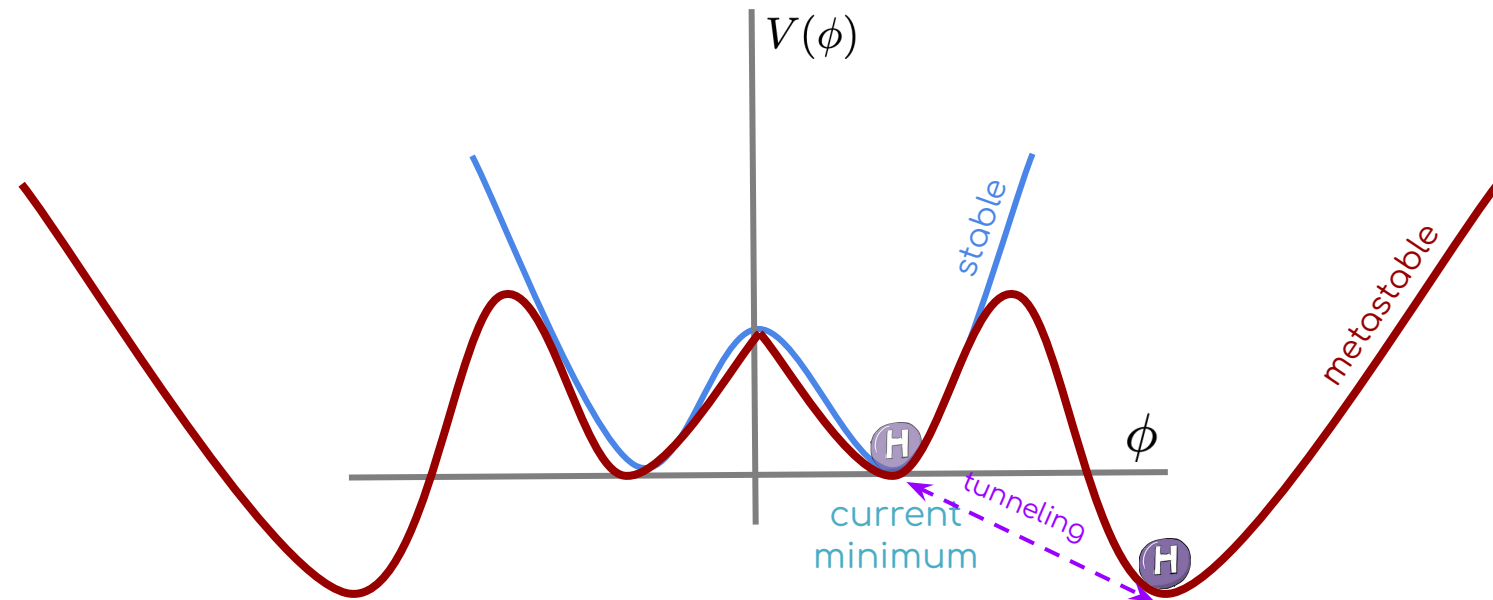
## Stable universe

- Current minimum is the absolute minimum.
- Higgs fields will remain like this forever.



## Metastable universe

- Current minimum is a *false* vacuum.
- Lifetime is larger than the age of the universe, but eventually it will decay to the new minimum...

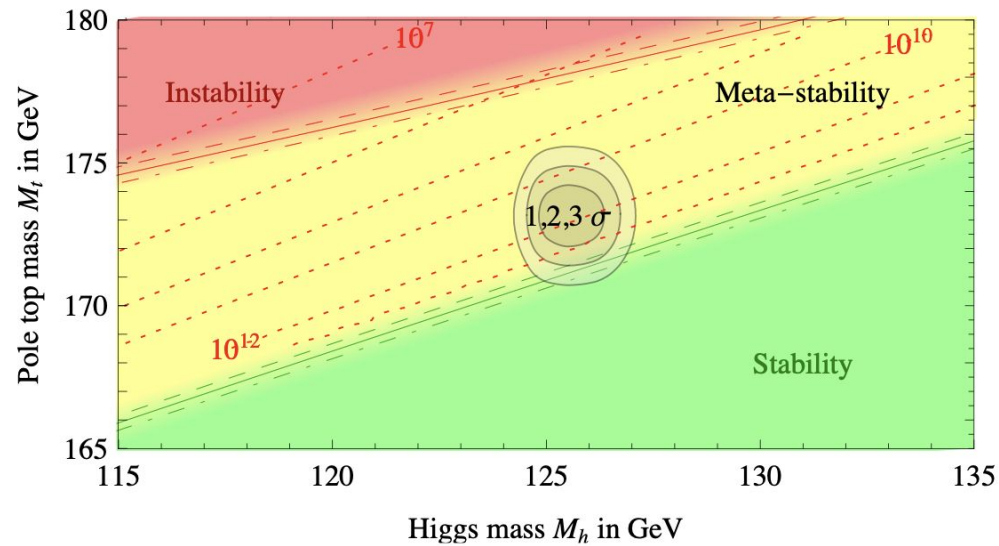


# Stability of the Universe

Measurements of the Higgs self-coupling can give insight about our universe!

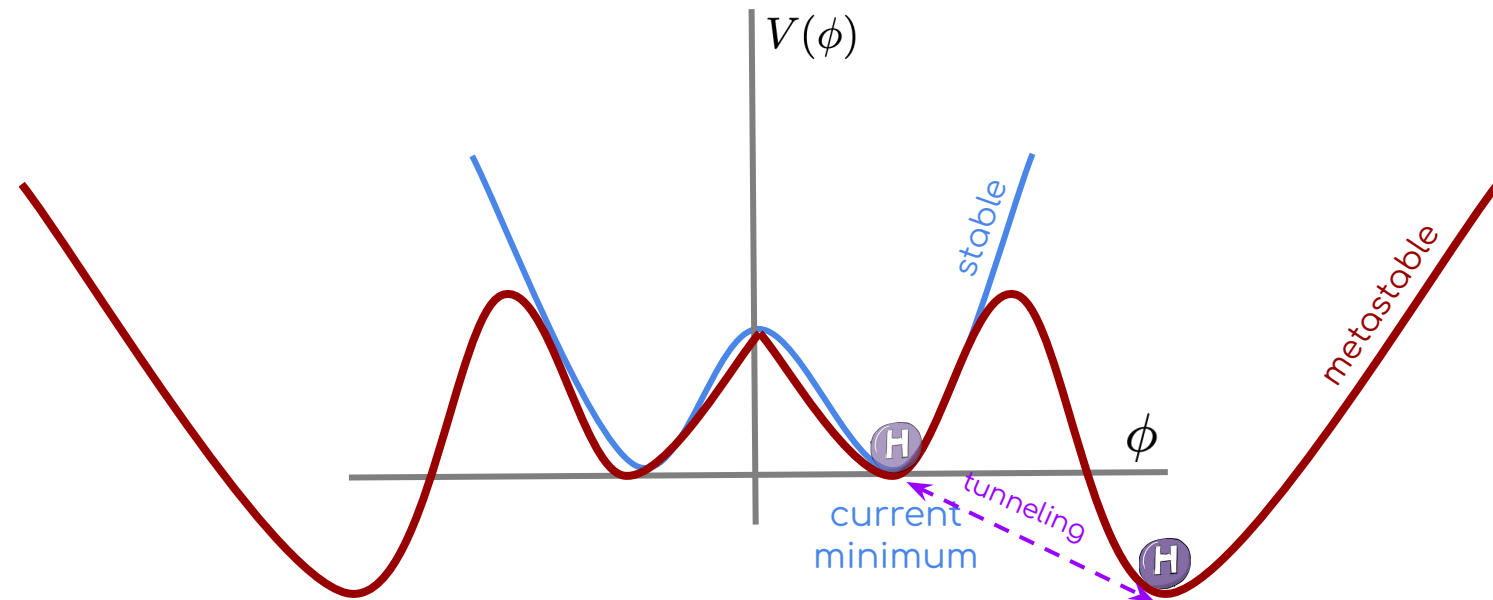
Precision on top mass is also fundamental to answer the question on the **metastability** of the universe.

[arXiv:1205.6497](https://arxiv.org/abs/1205.6497)



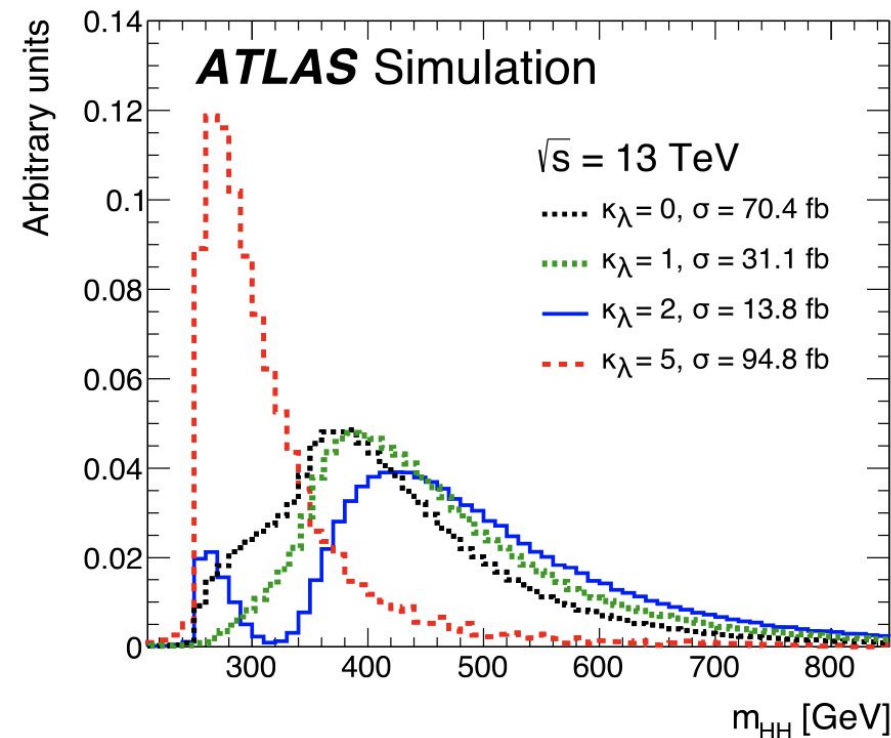
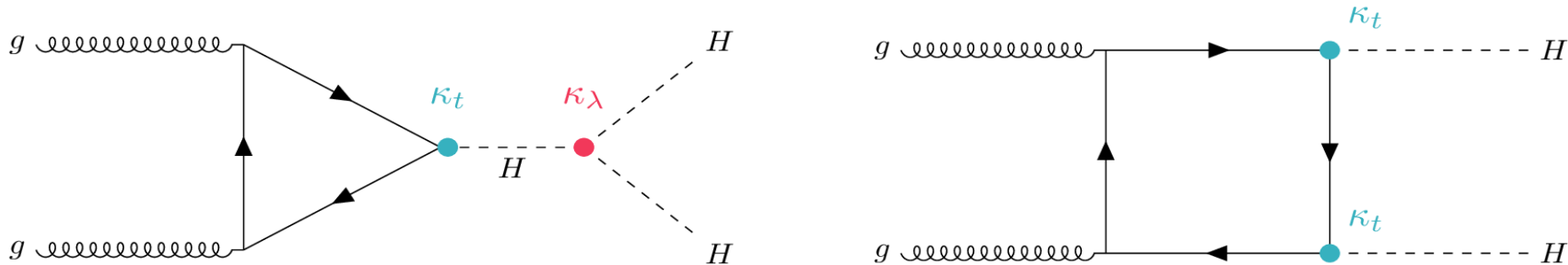
## Metastable universe

- Current minimum is a *false* vacuum.
- Lifetime is larger than the age of the universe, but eventually it will decay to the new minimum...



# HH production

Search for non-resonant di-Higgs production allows us to probe the shape of the Higgs potential by measuring the trilinear self-coupling  $\kappa_\lambda$  of the Higgs boson.



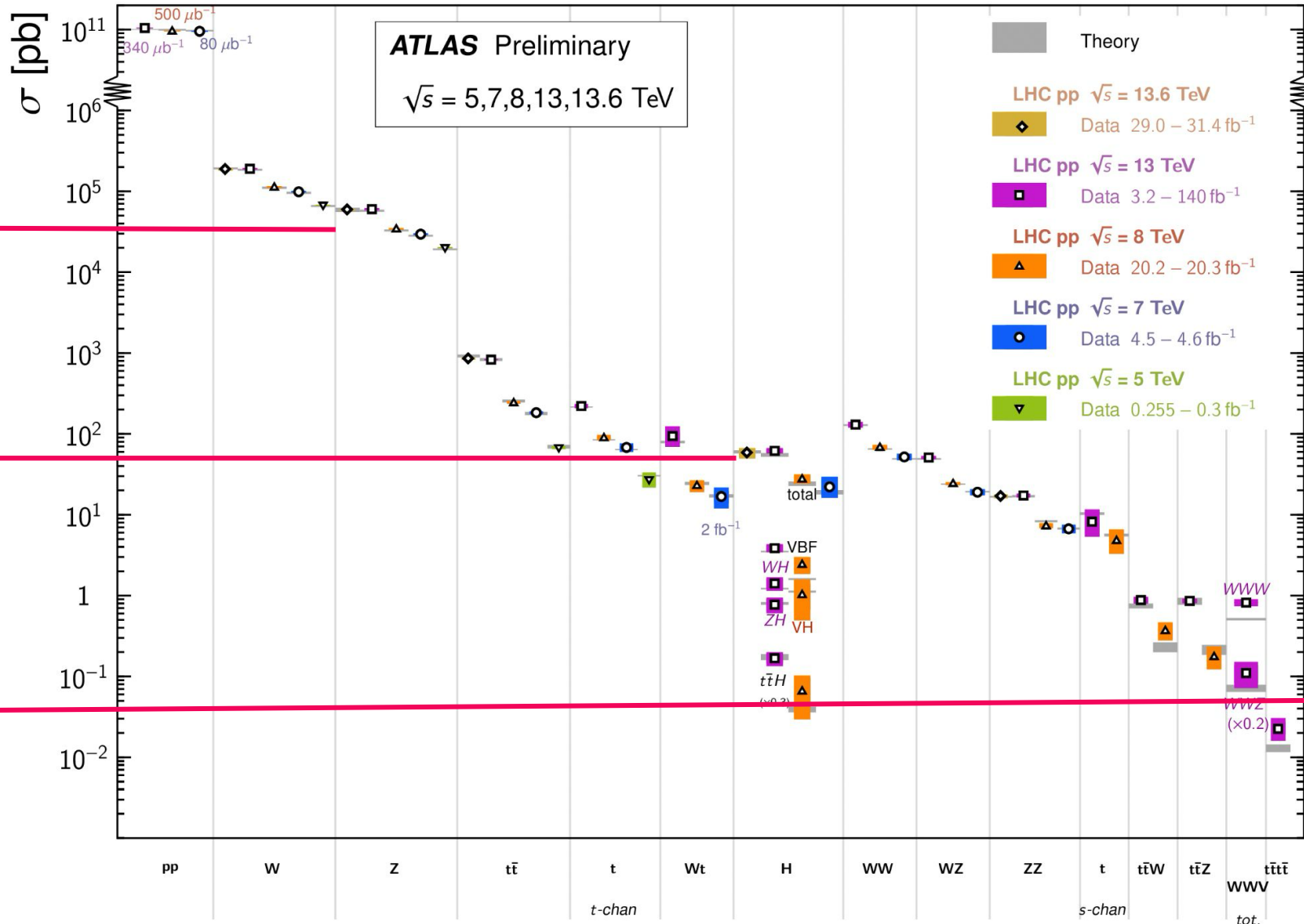
There is destructive interference between the box and triangle diagrams, thus the cross section is suppressed ( $\sim 10^3$  times smaller than single Higgs x-section). Deviations from SM can increase this cross section.

- $m_{HH}$  distribution depends on  $\kappa_\lambda$ .
- For values of  $\kappa_\lambda \neq 1$ , x-section can be enhanced.
- For large values of  $\kappa_\lambda$  the triangle diagram dominates.

# Standard Model processes

Standard Model Total Production Cross Section Measurements

Status: June 2024



# Search channels

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

- Channels with large decay fractions may lead to challenging signatures.
- Exploring a mixture of different higgs decay channels to increase the sensitivity.
- Different analysis strategies developed.

Combination  
is key in this search!

# Search channels

	bb	WW	$\tau\tau$	ZZ	$\Upsilon\Upsilon$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\Upsilon\Upsilon$	0.26%	0.10%	0.028%	0.012%	0.0005%

- **[bbbb]** Largest decay fraction, exploit data driven techniques to estimate dominant multijet background.

*Resolved* [Phys. Rev. D 108 \(2023\) 052003](#)

*Boosted VBF* [Submitted to Phys. Lett. B](#)

*VHH* [Eur. Phys. J. C 83 \(2023\) 519](#)

- **[bb $\tau\tau$ ]** Medium decay fraction, good signal selection purity.

[JHEP 07 \(2023\) 040](#)

[Phys. Rev. D 110 \(2024\) 032012](#)

- **[bb $\Upsilon\Upsilon$ ]** Lower decay fraction, but excellent  $m_{\Upsilon\Upsilon}$  mass resolution.

[Phys. Rev. D 106 \(2022\) 052001](#)

[JHEP 01 \(2024\) 066](#)

# Search channels

	bb	WW	$\tau\tau$	ZZ	YY
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
YY	0.26%	0.10%	0.028%	0.012%	0.0005%

- [**bb $\ell\ell$  + MET**] Targeting multiple decay fractions, with one Higgs not decaying into bb (bbWW/bb $\tau\tau$ /bbZZ).

[JHEP 02 \(2024\) 037](#)

- [(**yy**) multi-lepton] Covering multiple decay modes, where both Higgs don't decay into bb (and bbZZ(4 $\ell$ )).

[Submitted to JHEP](#)

**Combination!**

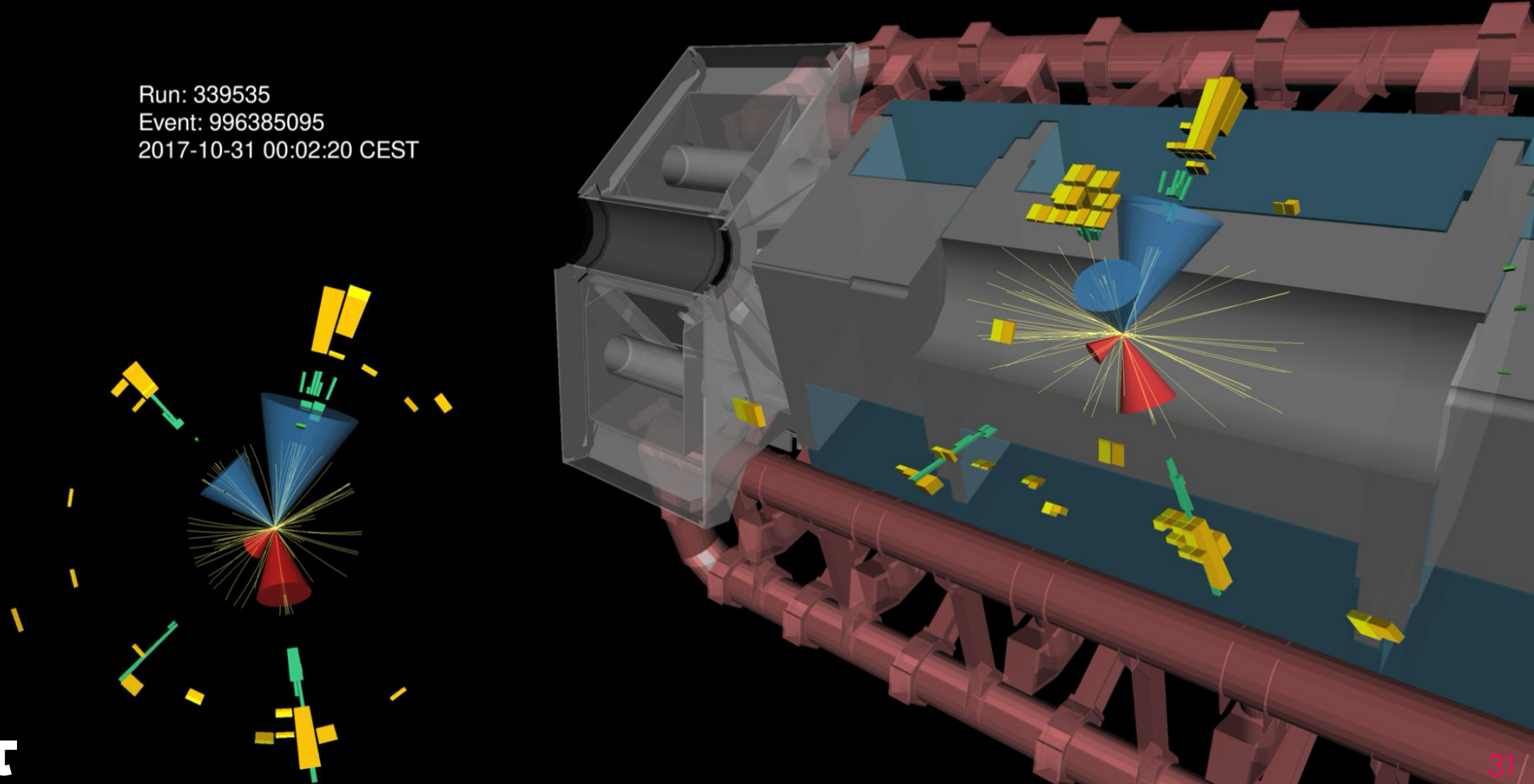


[Phys. Rev. Lett. 133 \(2024\) 101801](#)



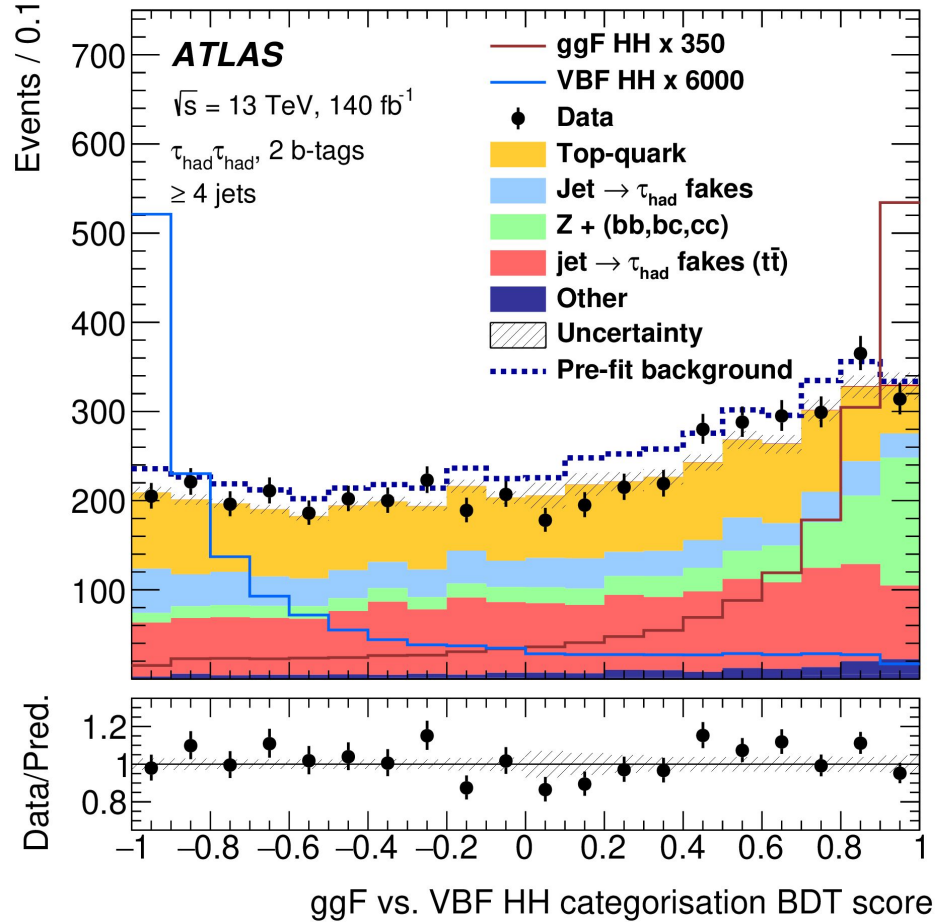
[PAS-HIG-20-011](#)

Run: 339535  
Event: 996385095  
2017-10-31 00:02:20 CEST



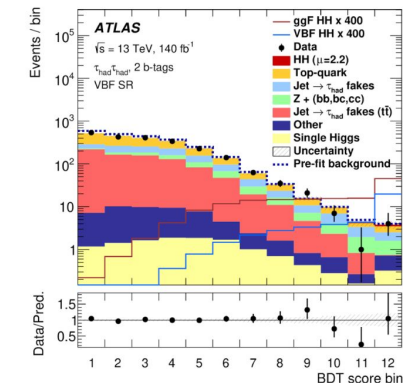
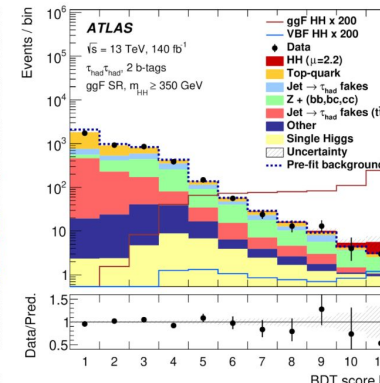
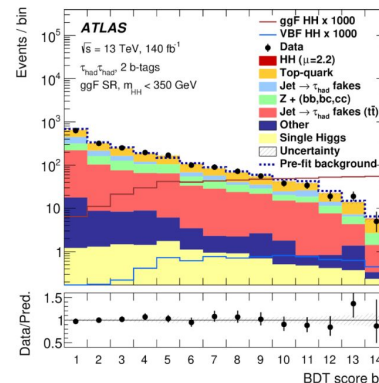
# HH $\rightarrow$ bb $\tau\tau$

Select 2 b-tagged PFlow jets and 2 OS taus ( $\tau_{had}\tau_{had}$  and  $\tau_{lep}\tau_{had}$ ).



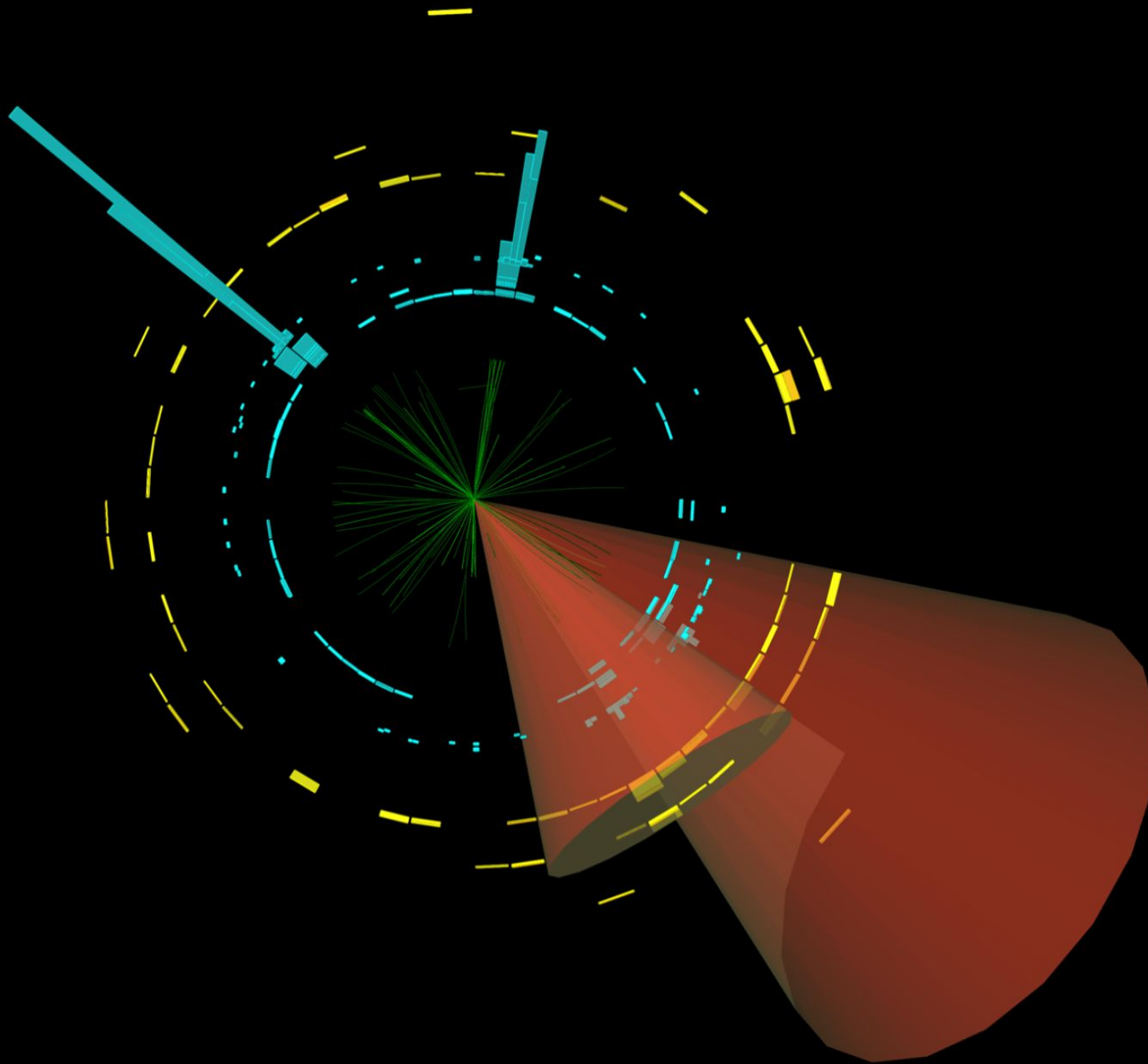
## main challenges

- MC modelling and statistics.
- Tau-fakes estimation.
- Categorisation is key:
  - Trigger selection for different decay channels:
    - $H \rightarrow \tau_{lep}\tau_{had}$ : single-lepton (SLT) or lepton+tau (SLT+DLT) triggers,
    - $H \rightarrow \tau_{had}\tau_{had}$ : combination of single-tau (STT) and di-tau triggers.
  - VBF and ggF signal separation:
    - In each channel a BDT is trained to separate VBF and ggF
  - Signal-Background discrimination: train a BDT per category.
    - ggF: define two low and high  $m_{HH}$  categories.
    - VBF: single category.



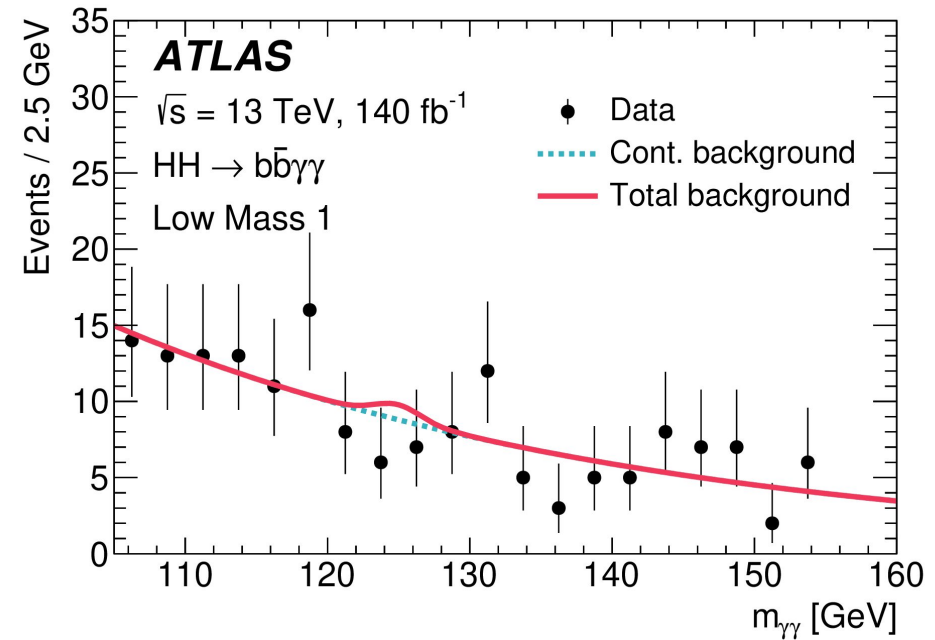
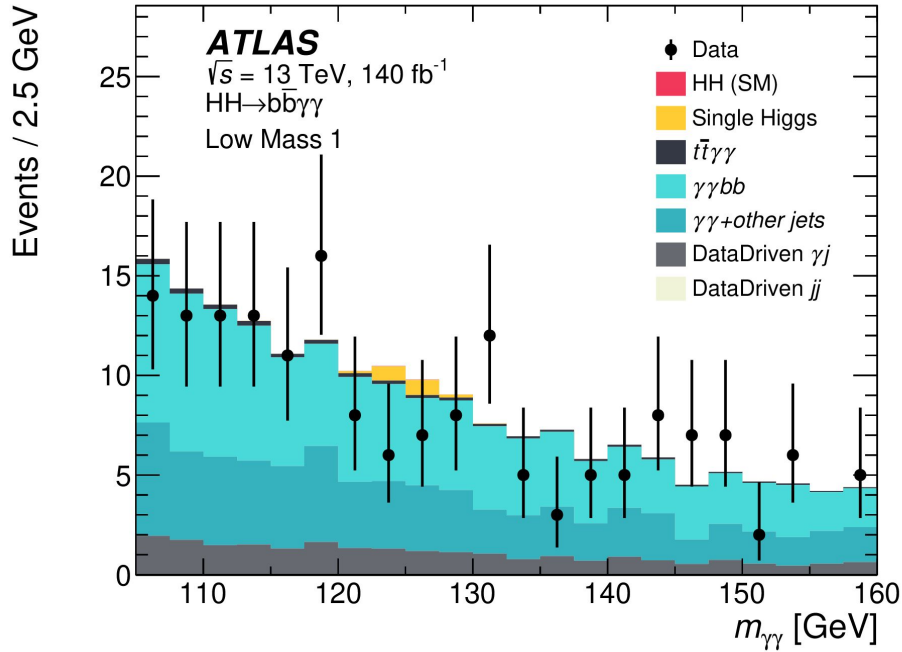


Run: 329964  
Event: 796155578  
2017-07-17 23:58:15 CEST



# HH $\rightarrow$ bb $\gamma\gamma$

Select 2 b-tagged PFlow jets and 2 high  $p_T$  photons.



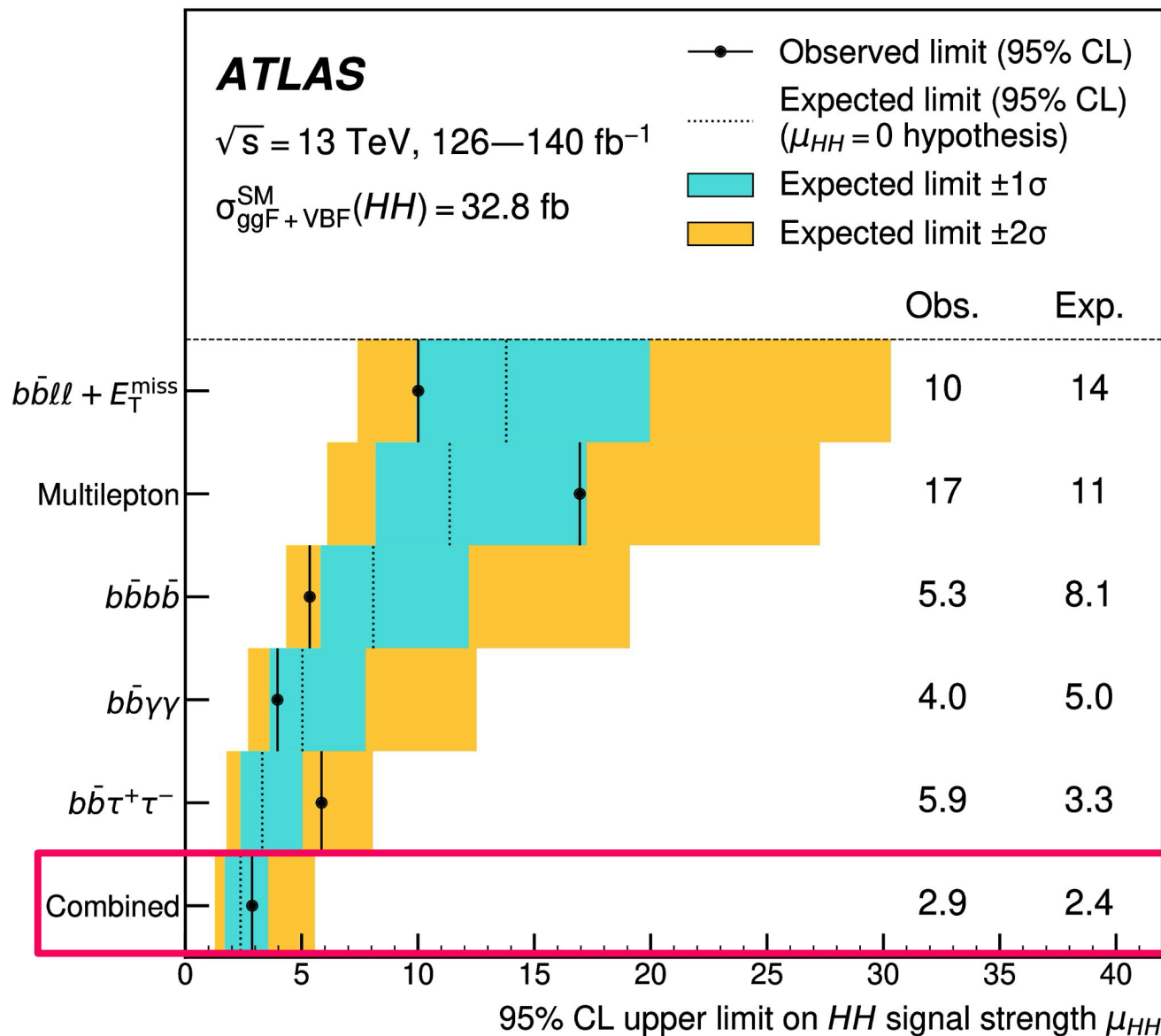
## main challenges

- Analysis limited by statistics.
- Large impact of single Higgs production normalisation.
- Events categorised into high and low  $m_{bb\gamma\gamma}^*$  regions (low mass regions retain sensitivity for large  $\kappa_\lambda$ ).
- For each mass category BDTs are trained (and further categories are defined based on BDT score).
- Model signal and background  $m_{\gamma\gamma}$  shapes with analytic functions. Final background prediction comes from  $m_{\gamma\gamma}$  fit.

# ATLAS Combination

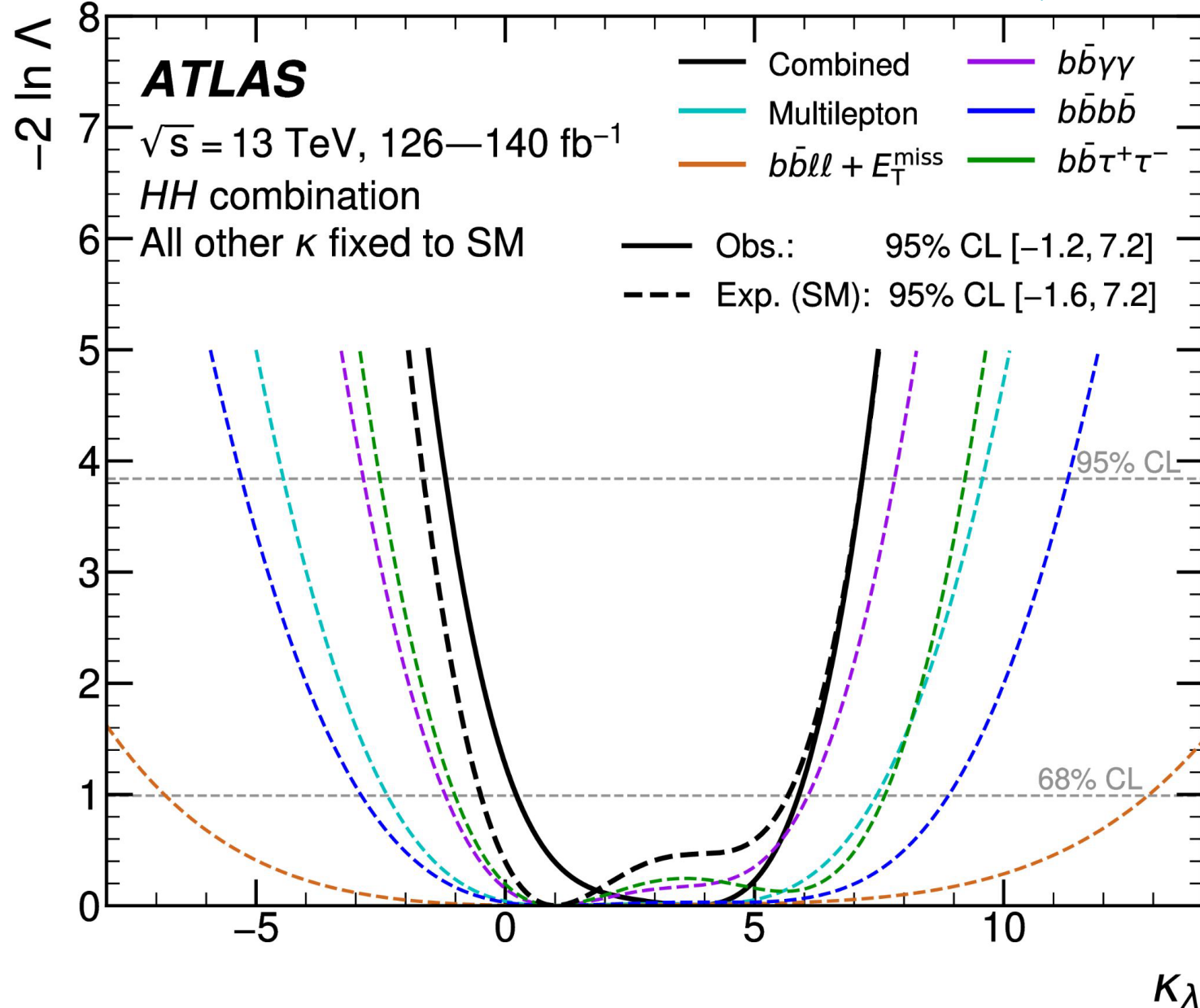
[Phys. Rev. Lett. 133 \(2024\) 101801](#)

- **ATLAS** combination for searches of Higgs boson pair production!
- 
- Best expected sensitivity to date on HH cross section:
  - $\mu_{HH} < 2.9$  (2.4 exp.)
  - $\mu_{HH} < 2.9$  (44.3) for ggF (VBF) production
  - $\sigma_{HH} < 85.8$  (71.1 exp) fb
- HH theory cross section uncertainty becomes relevant for the sensitivity.



# ATLAS Combination

[Phys. Rev. Lett. 133 \(2024\) 101801](#)



Most stringent expected constraints to the Higgs boson self-coupling  
 $-1.2 < \kappa_\lambda < 7.2$  ( $-1.6 < \kappa_\lambda < 7.2$  exp) 95% CL

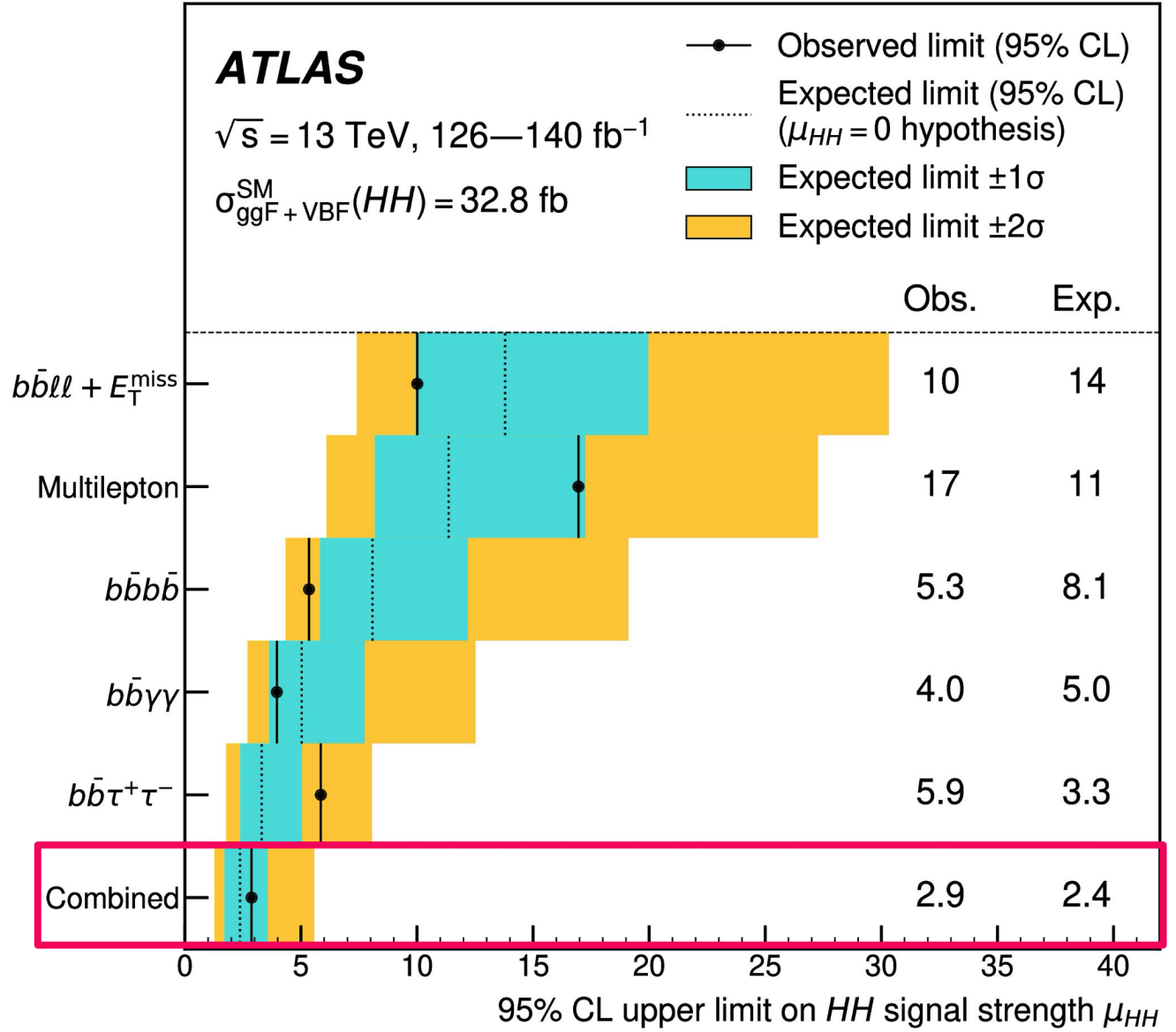
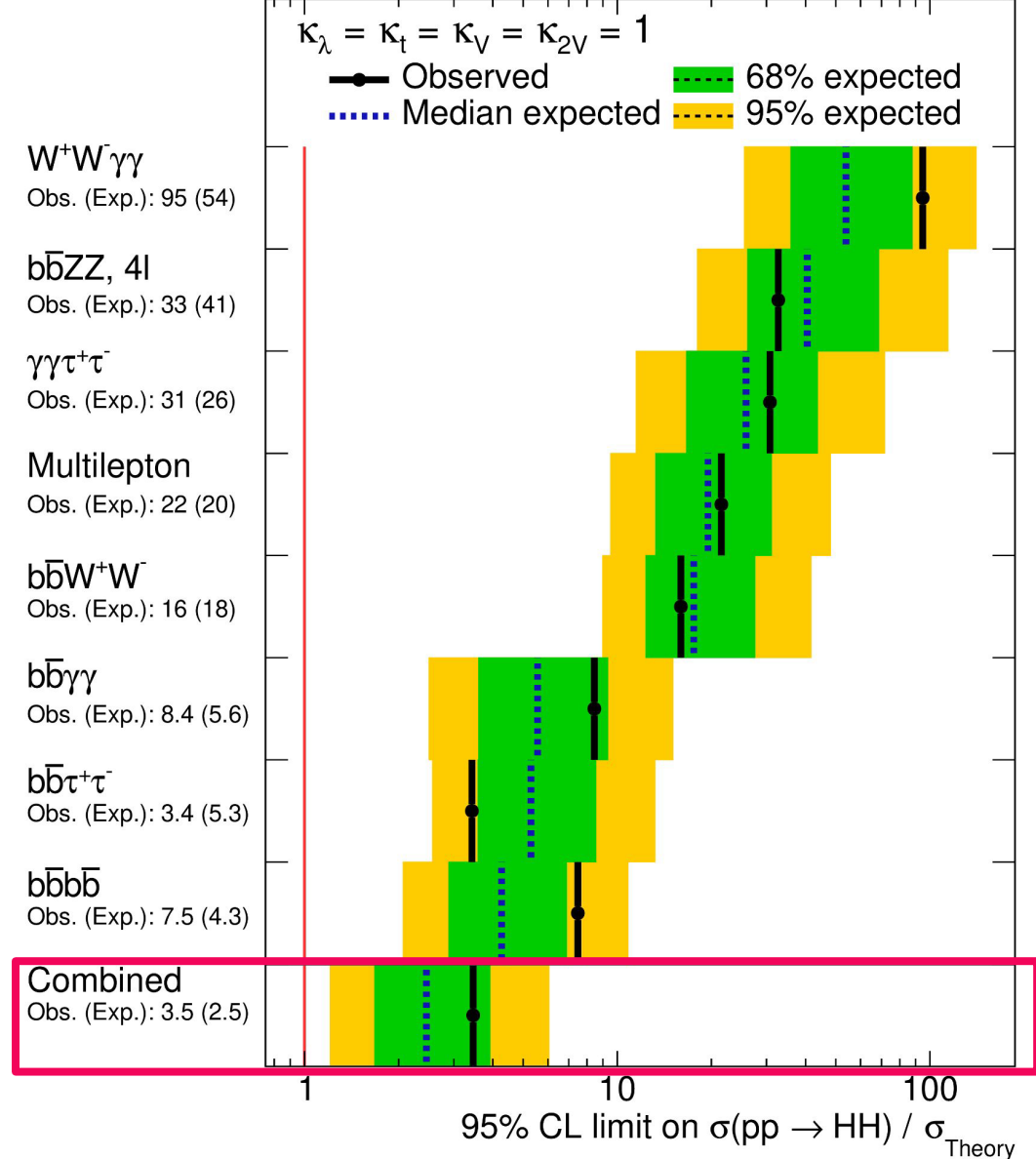
# ATLAS & CMS

PAS-HIG-20-011

**CMS Preliminary**

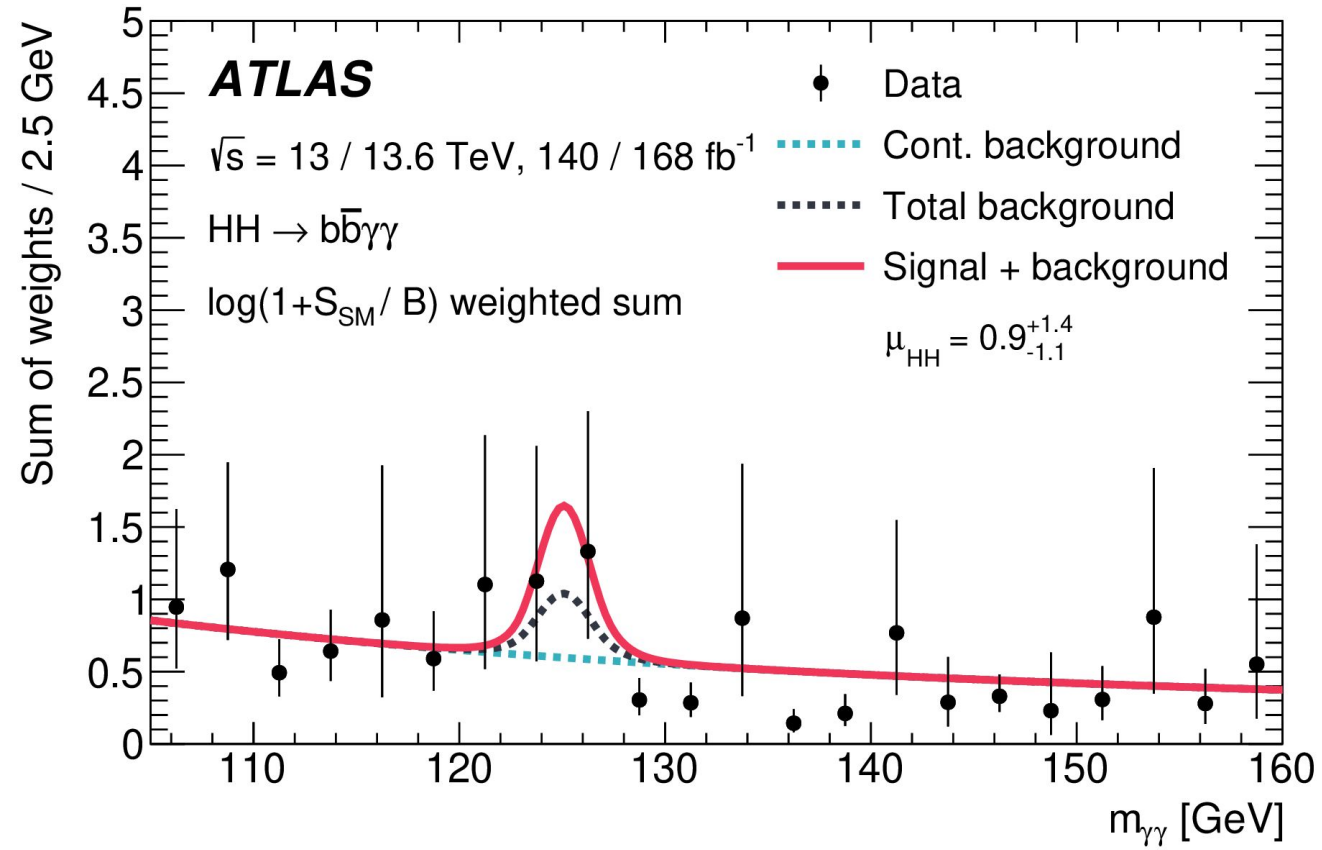
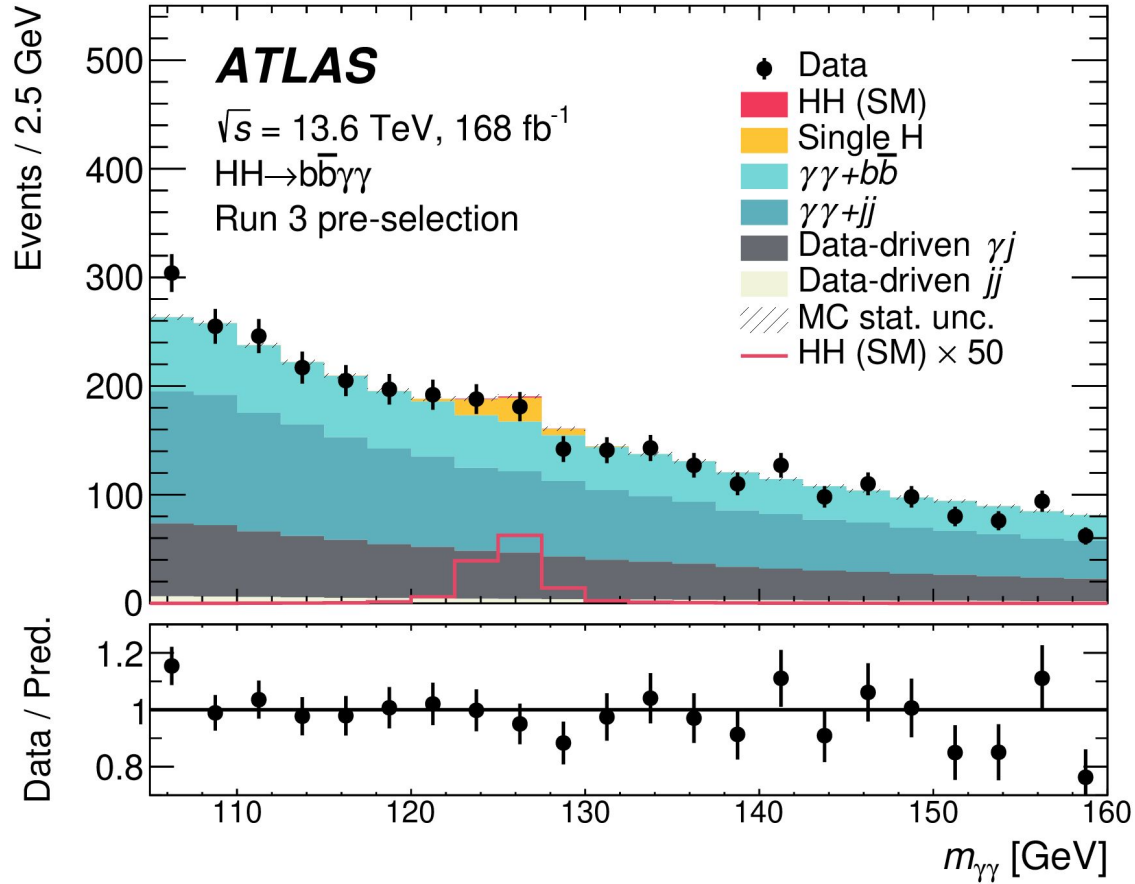
138 fb<sup>-1</sup> (13 TeV)

[Phys. Rev. Lett. 133 \(2024\) 101801](#)



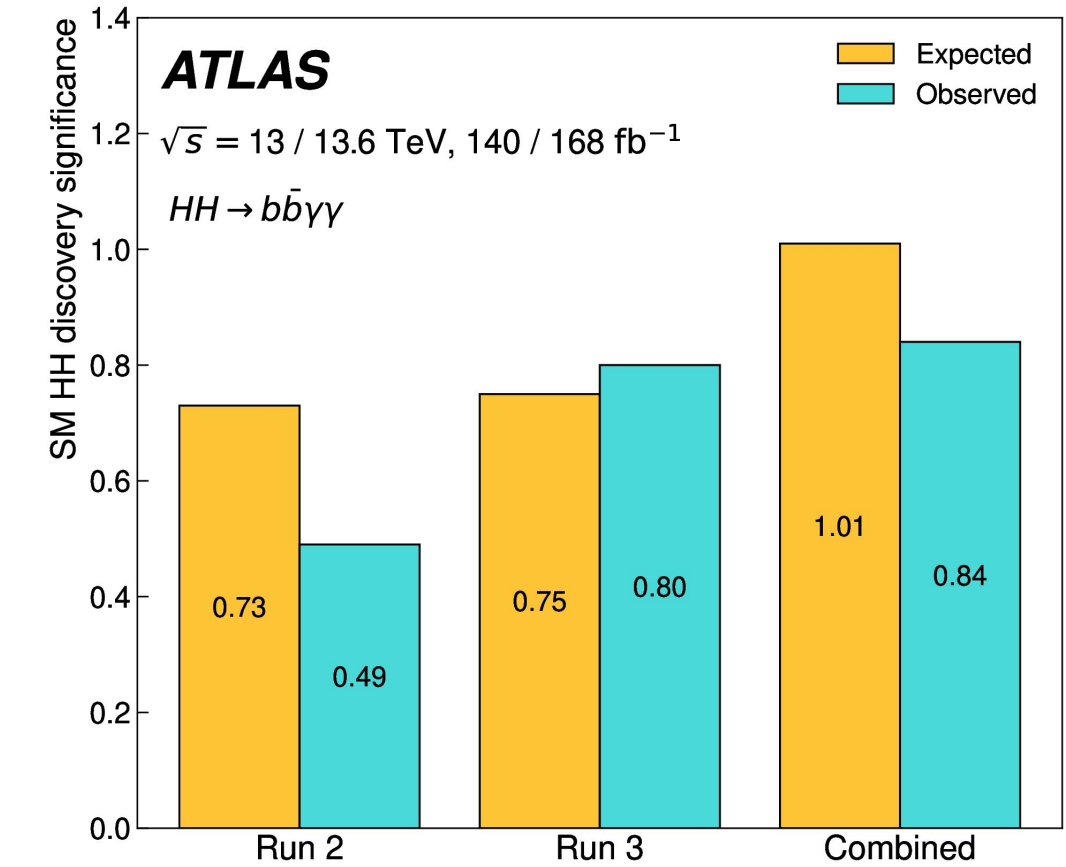
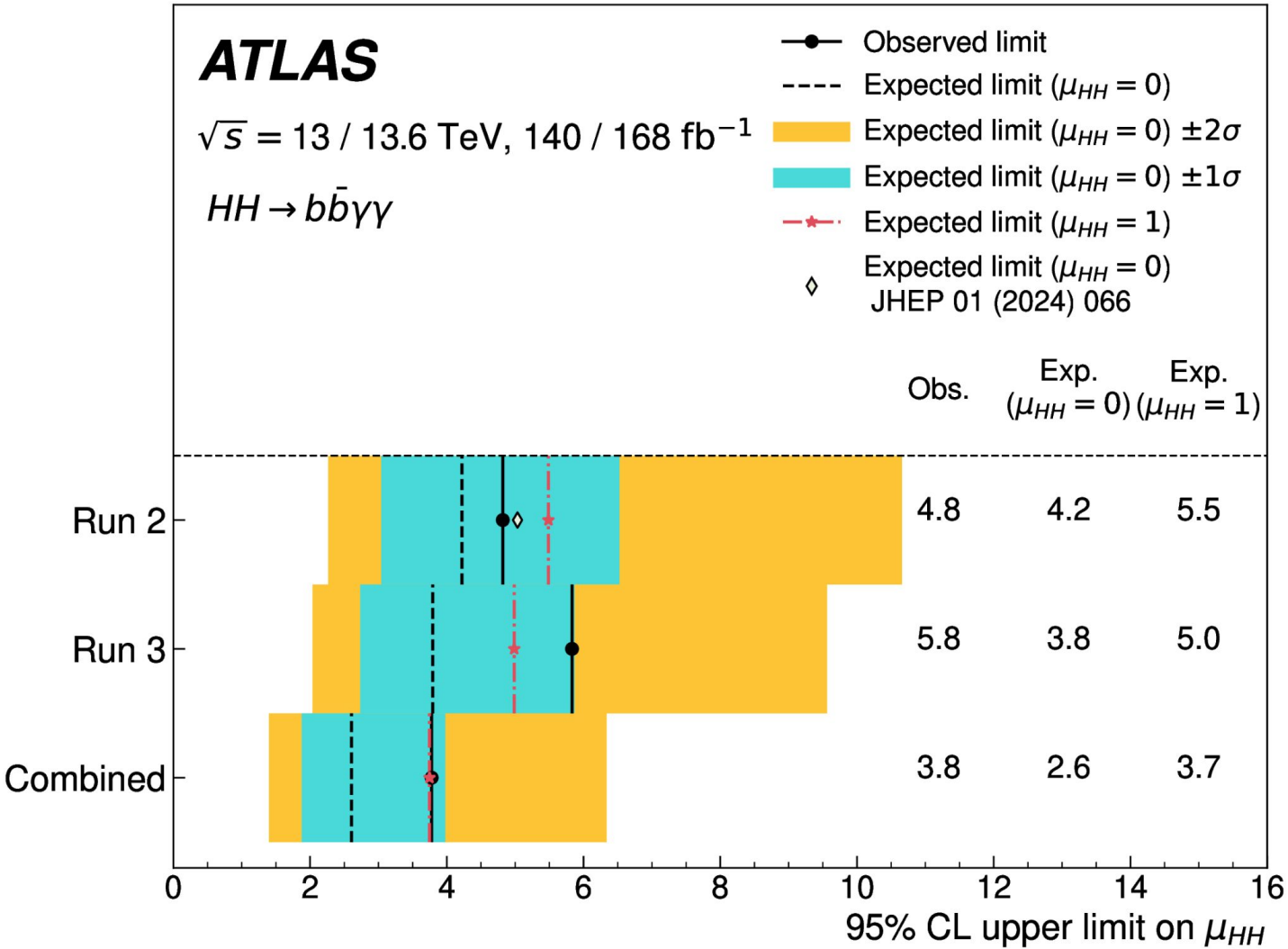
# HH $\rightarrow$ $b\bar{b}\gamma\gamma$

[arXiv:2507.03495](https://arxiv.org/abs/2507.03495)



# HH → bb̄γγ

[arXiv:2507.03495](https://arxiv.org/abs/2507.03495)



5 $\sigma$  (3 $\sigma$ ) for observation (evidence) of the HH production!

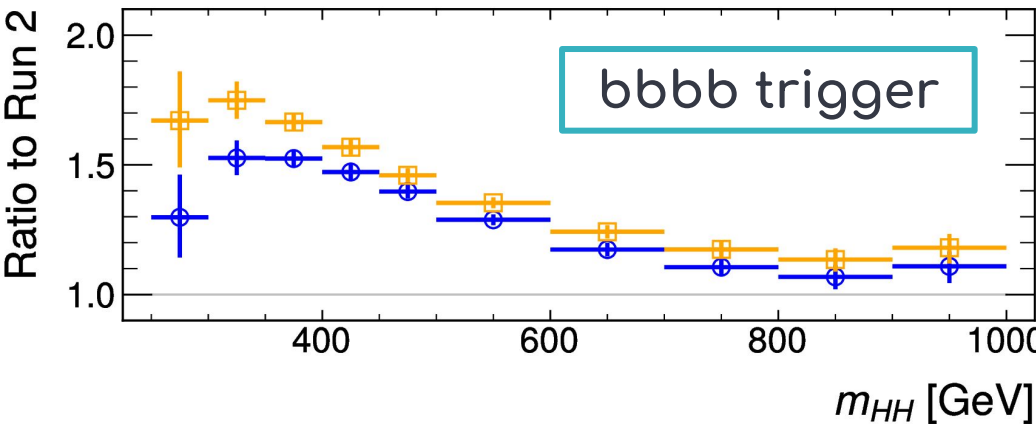
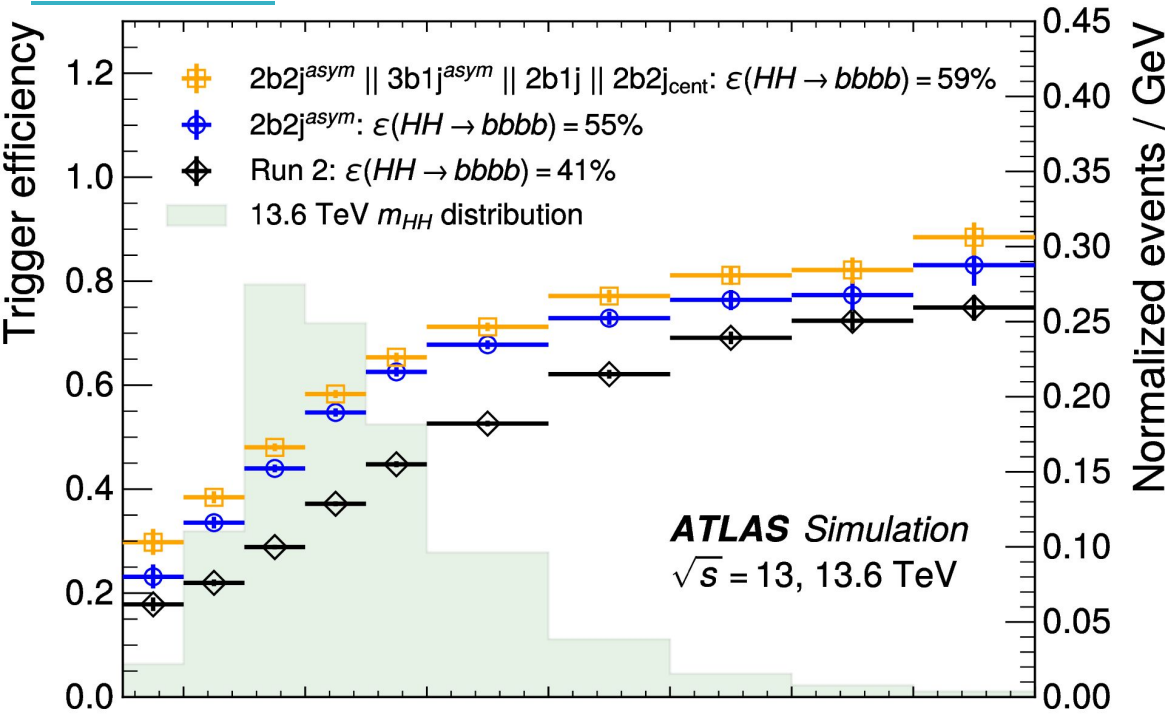
# Towards LHC Run 3 and HL-LHC

# LHC Run 3

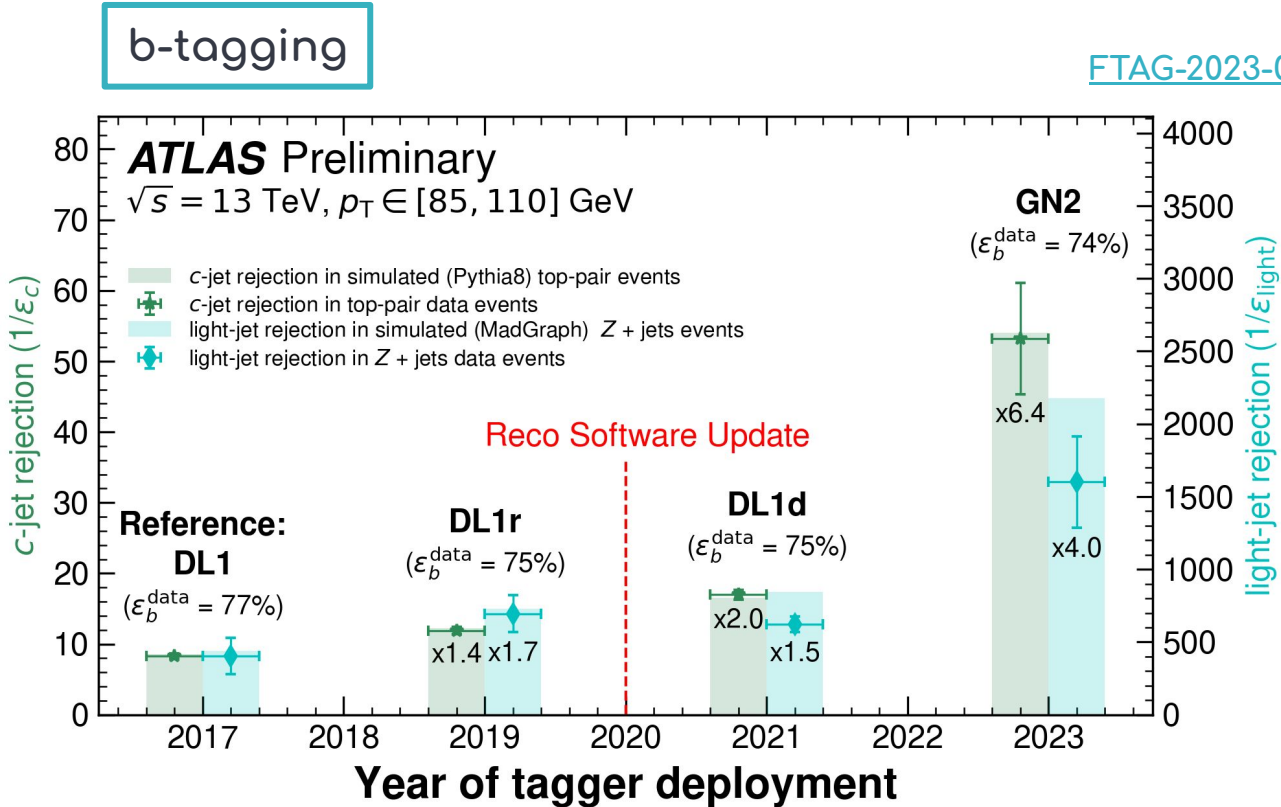


More data, better **triggers**, better **taggers**, better performance!

TRIG-2022-02

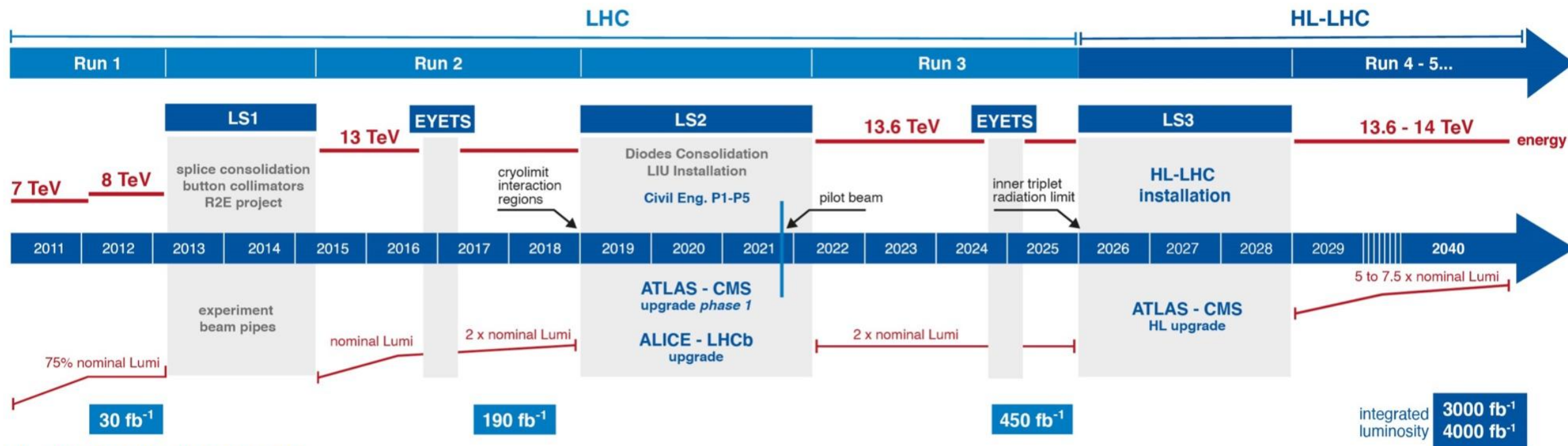


FTAG-2023-07

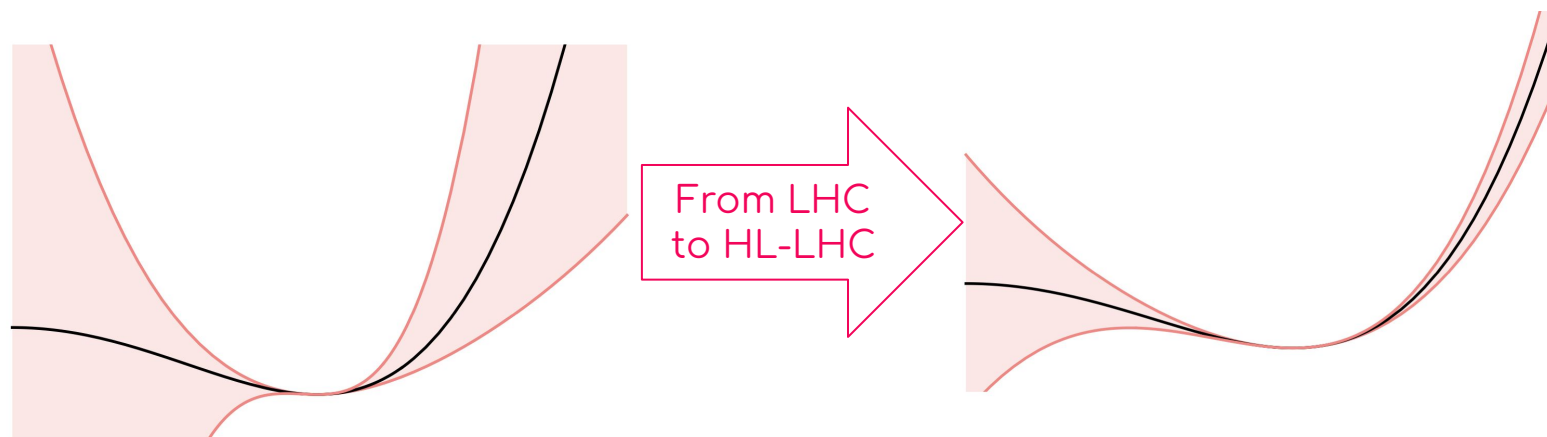


Significant improvements using state-of-the-art machine learning architectures on identification techniques.

# LHC / HL-LHC Plan



What will be our sensitivity to observe Di-Higgs production with the HL-LHC dataset (i.e. to what precision will be measure  $\kappa_\lambda$ ?)

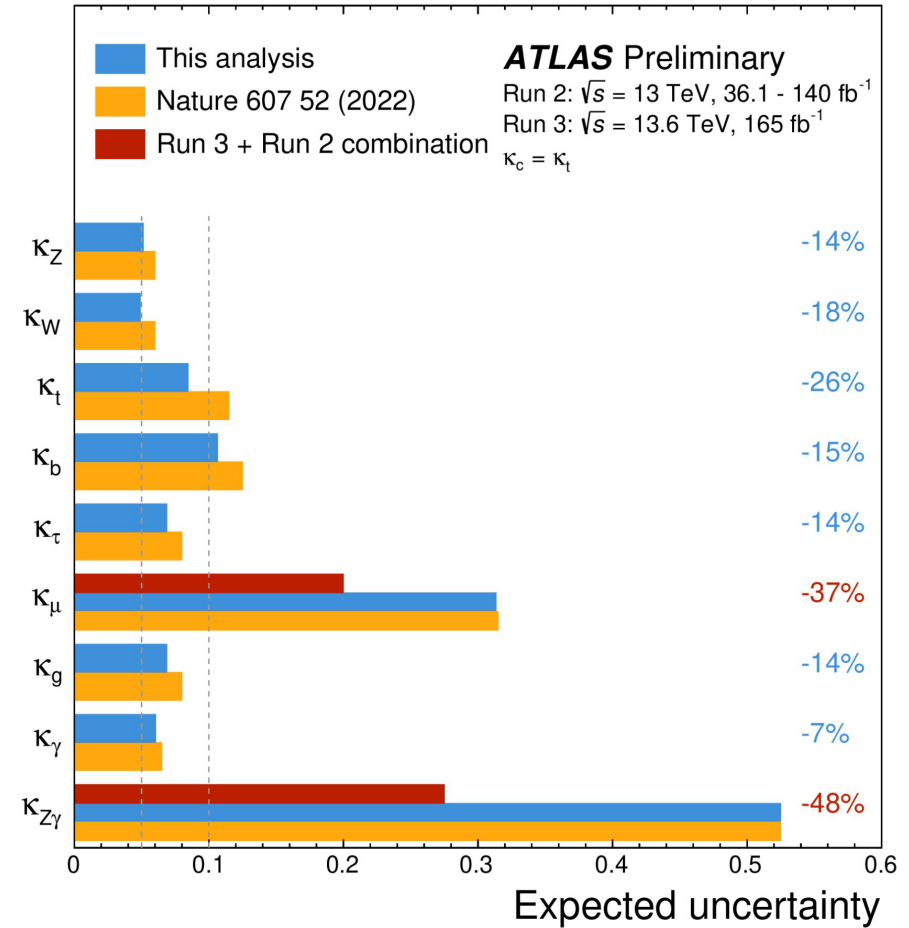
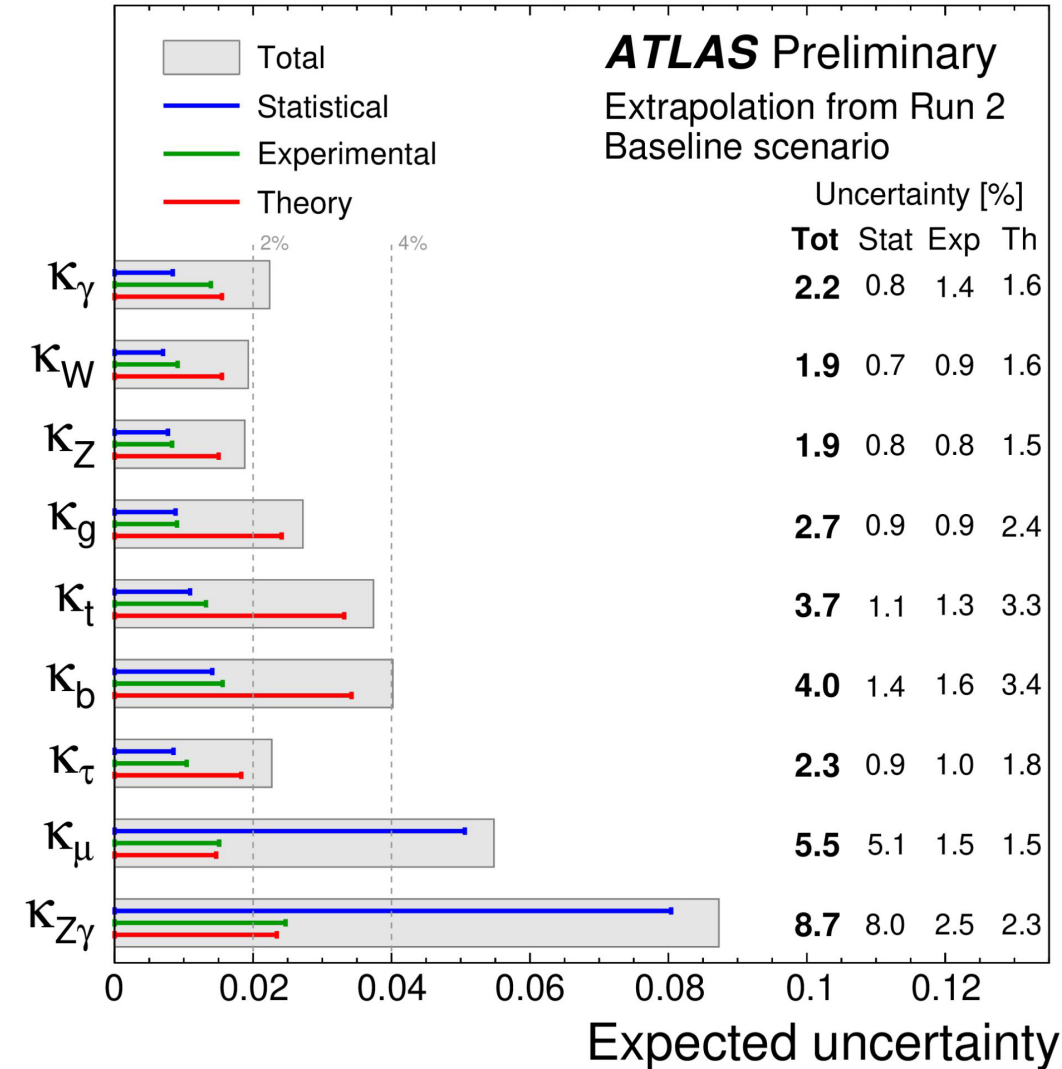


# ATLAS Higgs measurements at HL-LHC

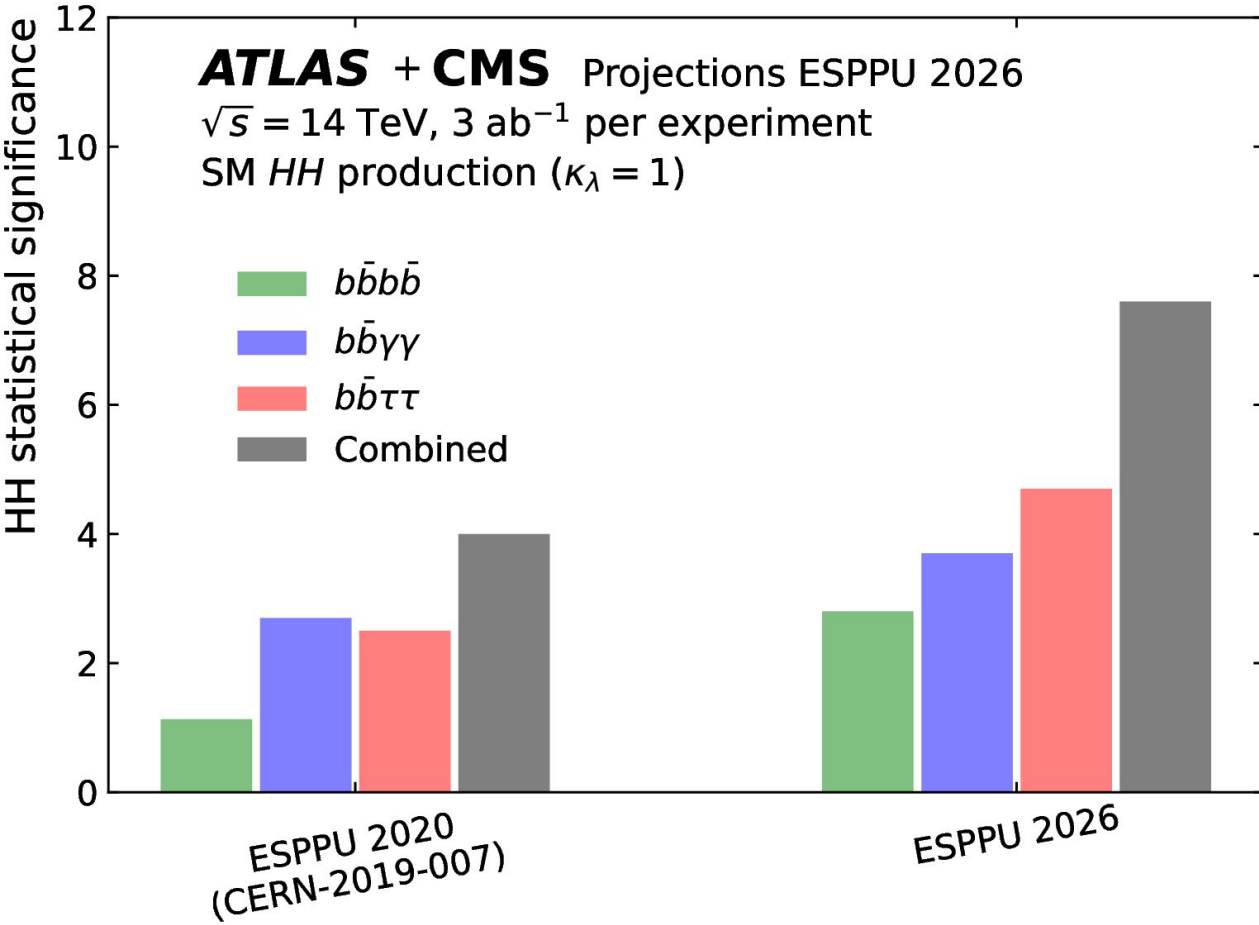
We will soon be dominated by theoretical uncertainties!

$\sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1}$

Statistically limited channels will profit immediately from Run 3 results.



# ATLAS + CMS HH at HL-LHC



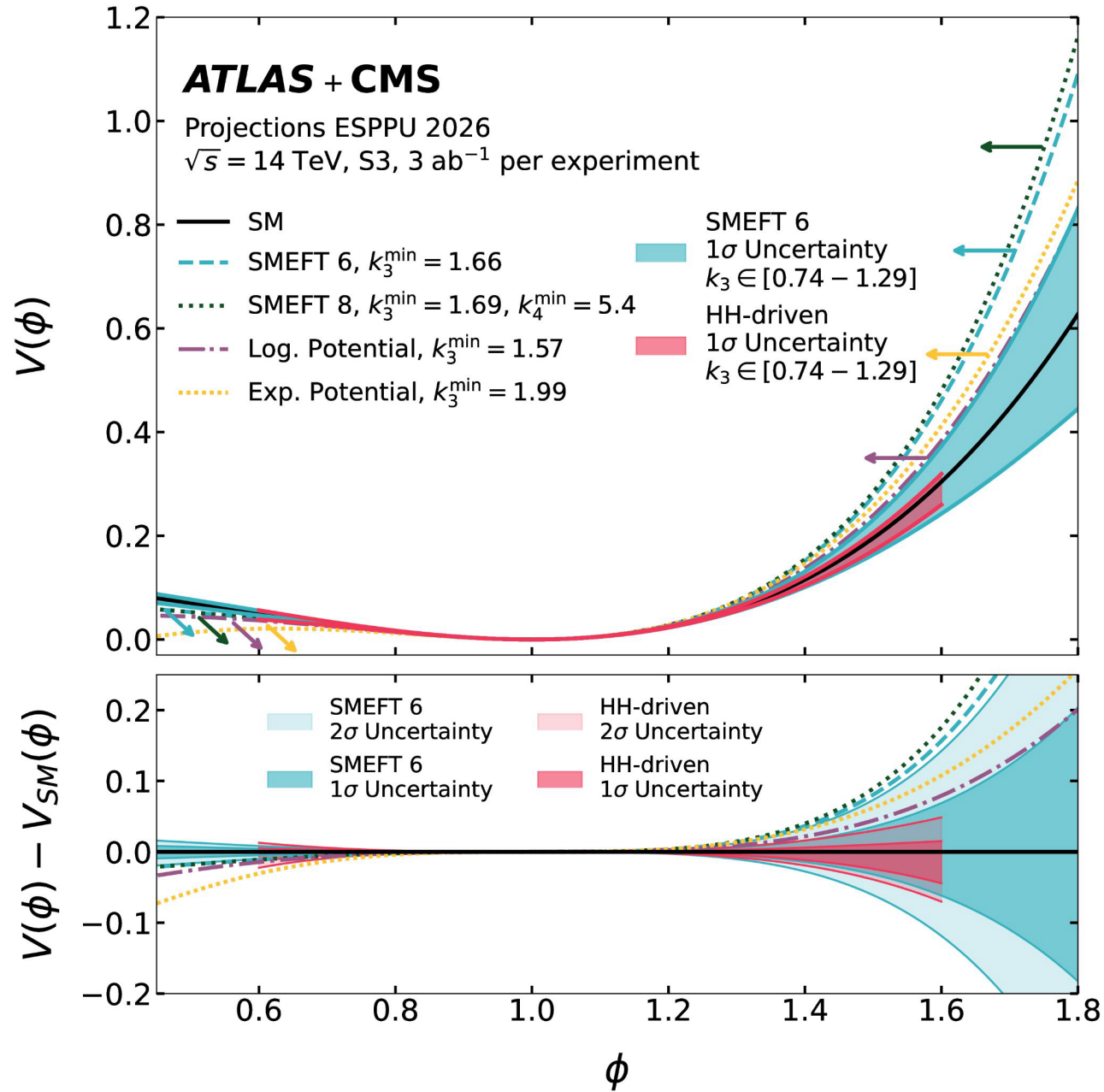
	$3 \text{ ab}^{-1}$ (S2)		$3 \text{ ab}^{-1}$ (S3)	
	ATLAS	CMS	ATLAS	CMS
<i>HH</i> statistical significance				
$bb\tau^+\tau^-$	3.5 <sup>†</sup>	2.4	<b>3.8<sup>†</sup></b>	<b>2.7</b>
$bb\gamma\gamma$	2.4 <sup>†</sup>	2.4 <sup>†</sup>	<b>2.6<sup>†</sup></b>	<b>2.6<sup>†</sup></b>
$bbb$ resolved	1.0	1.2 <sup>†</sup>	<b>1.0</b>	<b>1.3<sup>†</sup></b>
$bbb$ boosted	–	2.2 <sup>†</sup>	–	<b>2.2<sup>†</sup></b>
Multilepton	1.0 <sup>†</sup>	–	<b>1.0<sup>†</sup></b>	–
$bb\ell^+\ell^-$	0.5 <sup>†</sup>	–	<b>0.5<sup>†</sup></b>	–
Combination	4.3	4.2	<b>4.5</b>	<b>4.5</b>
<b>ATLAS+CMS</b>	<b>7.2</b>		<b>7.6</b>	

	$\kappa_3$ 68% confidence interval	
ATLAS+CMS uncertainty	–27% / +31%	–26% / +29%

- A  $>5\sigma$  observation will be possible already with  $2000 \text{ fb}^{-1}$  combining both experiments in the baseline scenario (S2).
  - $3000 \text{ fb}^{-1}$  may allow a single-experiment observation.
- Including 5% improvement in the b-tagging identification and tau-identification (S3) will increase the precision by 5%.

$\kappa_\lambda$  is expected to be measured as  $1.0^{+0.29}_{-0.26}$ .

# ATLAS + CMS HH at HL-LHC



Measuring the self-coupling can provide discrimination between different scenarios, or different models.  
 See [talk](#) by Patrick Meade.

BSM scenarios where new heavy particles lie beyond a large energy scale cut-off, so cannot be produced at the LHC. The potential is then expressed as a deformation of the SM EWSB potential.  
 Scenarios considered are in the context of SMEFT (dim 6 and 8) and modifications of the low-energy SM Higgs potential by small term (logarithmic or exponential).

These scenarios predict a strong first-order phase transition in the early universe for  $\kappa_\lambda > \kappa_{\text{min}}$ .

# Final remarks

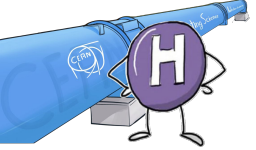
- We have a very broad and rich Higgs physics program in ATLAS!
  - Very important precision measurements are being updated with the larger dataset of LHC Run 3.
  - Rare decays and production processes are now becoming accessible:  $H \rightarrow \mu\mu$ ,  $H \rightarrow Z\gamma$ , etc.
- Of particular interest for our community is the di-Higgs production.
  - Multiple searches are performed simultaneously: ultimate goal for the **HH** physics program is the **combination** of all searches!
- For both single Higgs precision measurements and di-Higgs searches, there are many areas to improve on (in addition to adding more data)"
  - We can explore different signatures (e.g. boosted topologies).
  - New triggers, object reconstruction and identification (e.g. improved taggers),
  - novel analysis techniques (including broader use of machine learning).
- Great prospective for Higgs measurements and Di-Higgs searches at the LHC and HL-LHC.
  - Important to reach this milestone HH discovery in these hadron accelerators.

¡Gracias!

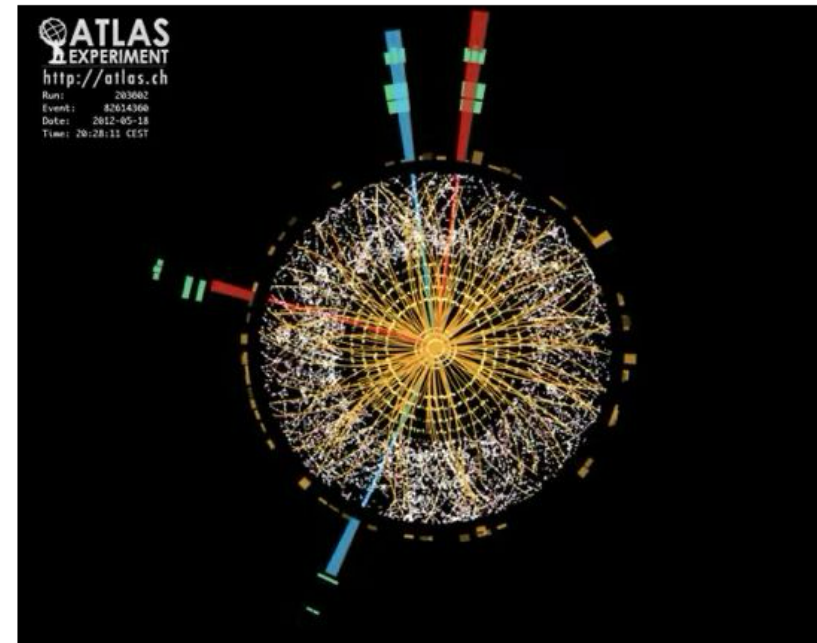
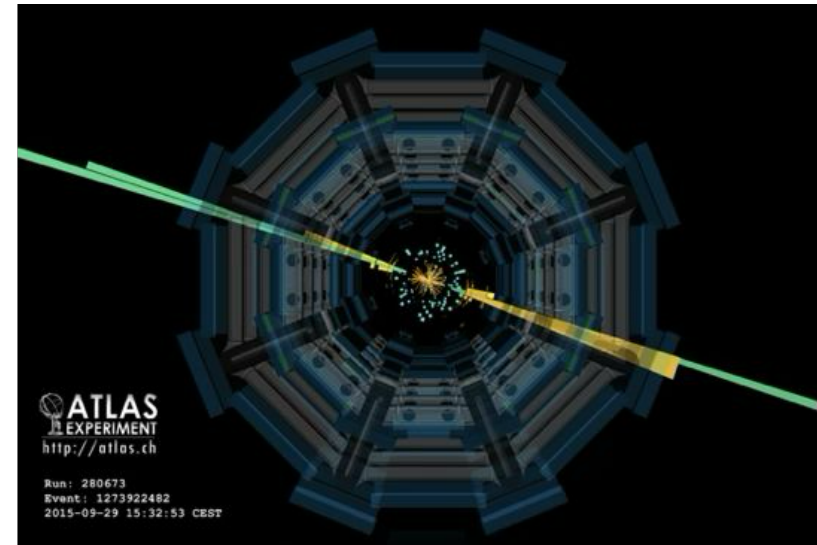
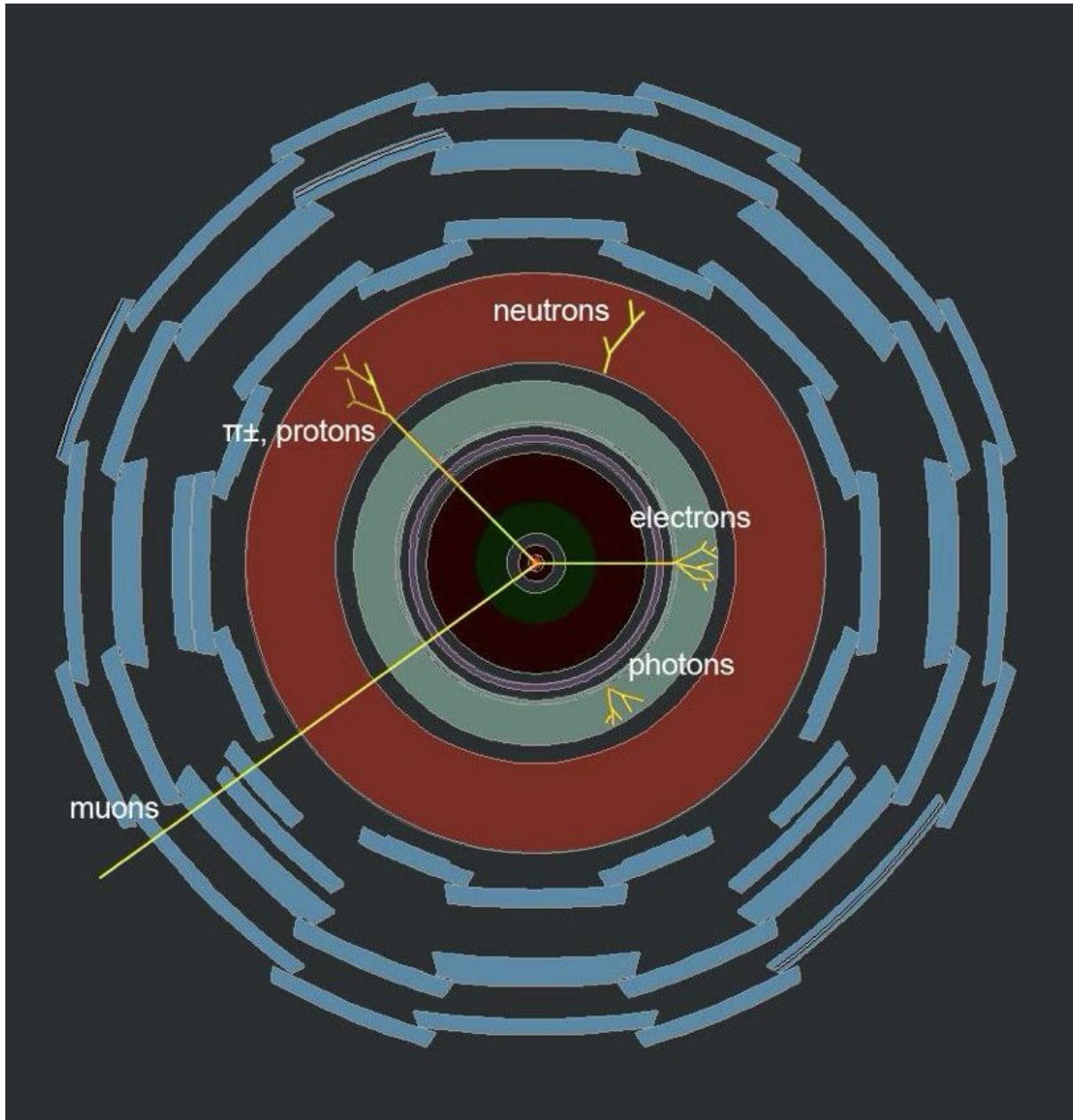


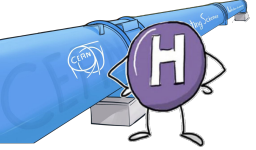
# Other resources

- [ATLAS Lectures](#)
  - Great resource for different topics of the work we do in ATLAS.
  - [Chronicles of the Higgs boson](#) by Haider Abidi.
  - [Seeing double \(Higgs bosons\)](#) by Katharine Leney.
  - [Probing new physics with the Higgs boson](#) by Tatjana Lenz.
- Physics reports (collecting latest measurements and searches from ATLAS Run 2):
  - [A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery](#)
  - [Characterising the Higgs boson with ATLAS data from Run 2 of the LHC](#)
  - [ATLAS searches for additional scalars and exotic Higgs boson decays with the LHC Run 2 dataset](#)
- More on HH:
  - LHC seminar: [Revealing the Potential of the Higgs field](#) by Rui Zhang.
  - ATLAS HH workshop invited talk: [Understanding the Higgs potential](#) by Patrick Meade.
- [Highlights of the HL-LHC physics projections by ATLAS and CMS](#)
- [10<sup>th</sup> anniversary of the Higgs boson discovery](#)



# ATLAS





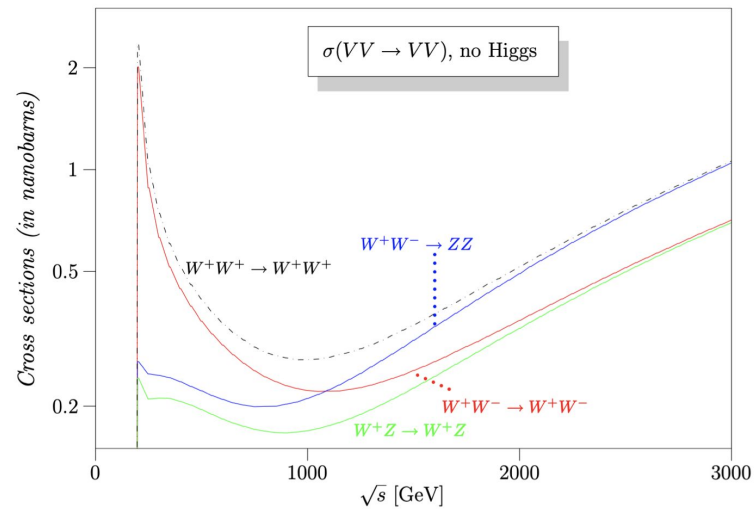
# SM problems

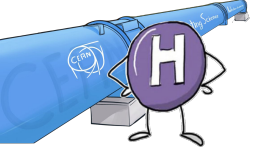
## Problem?

- In SM without Higgs: mass term change under symmetry rotation  $\rightarrow$  SM can't have massive bosons.

## Problem?

- Diboson scattering:  $VV \rightarrow VV$  violates unitarity at  $\sqrt{s} \sim 1$  TeV.





# Higgs Mechanism

Electroweak symmetry breaking (EWSB):

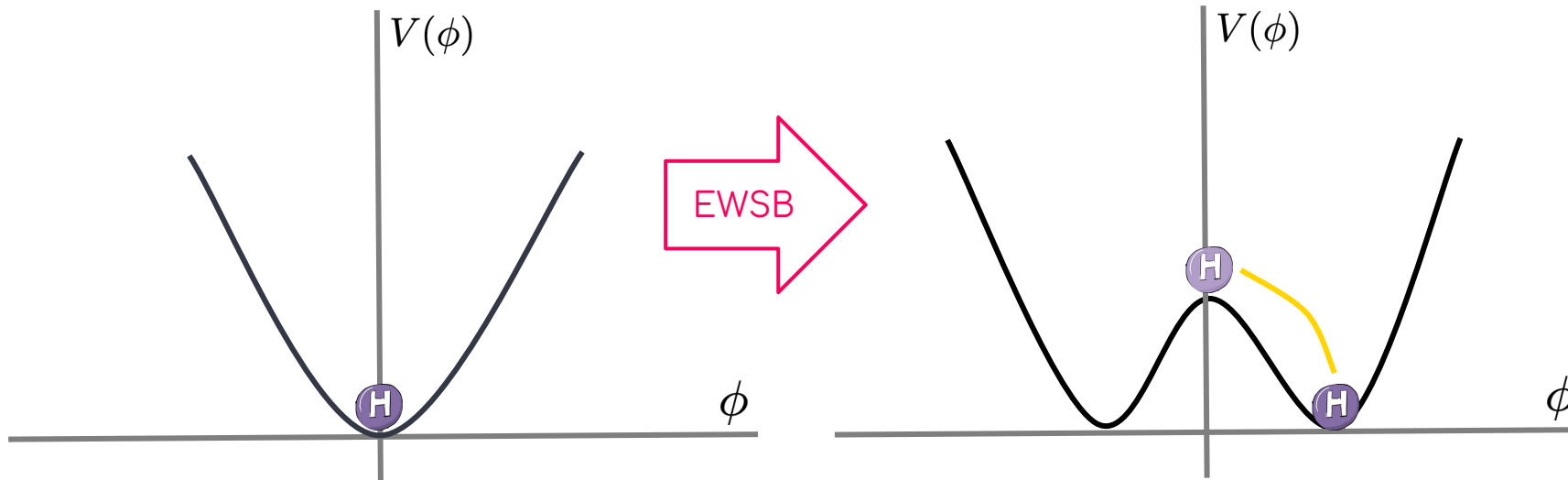
- Higgs mechanism is necessary both for gauge boson and fermion masses!
- Assumption: A scalar field permeates the universe & couples to other particles
  - Non-zero “vacuum expectation value” (VEV)
  - Strength of particle interaction controls the particle mass
  - Higgs boson is an “excitation” of this field.

Standard Model  
Higgs potential

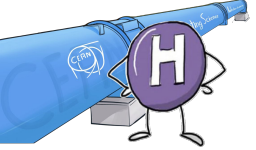
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

Our universe lives in  
the minimum:

$$V = V_0 + \lambda\nu^2 h^2 + \lambda\nu h^3 + \frac{1}{4}\lambda h^4 - \frac{\lambda}{\nu^4}$$



EWSB: Changes the  
potential minima to a  
non zero value.

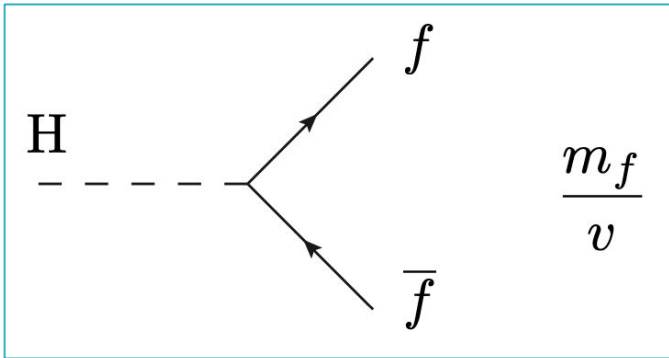


# Higgs Mechanism

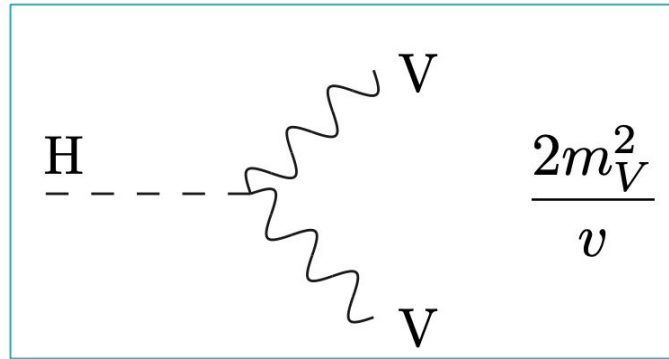
Once we have introduced the Higgs boson to the SM:

- Addition of a fundamental scalar spin-0 boson - *Mass of this particle is a free parameter*
- New Feynman vertices that need to be included in calculations

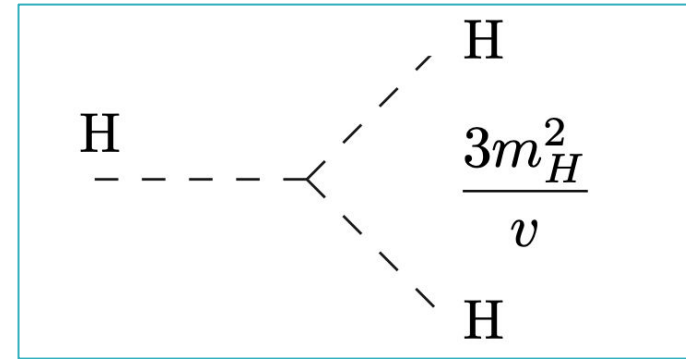
Higgs - fermions coupling



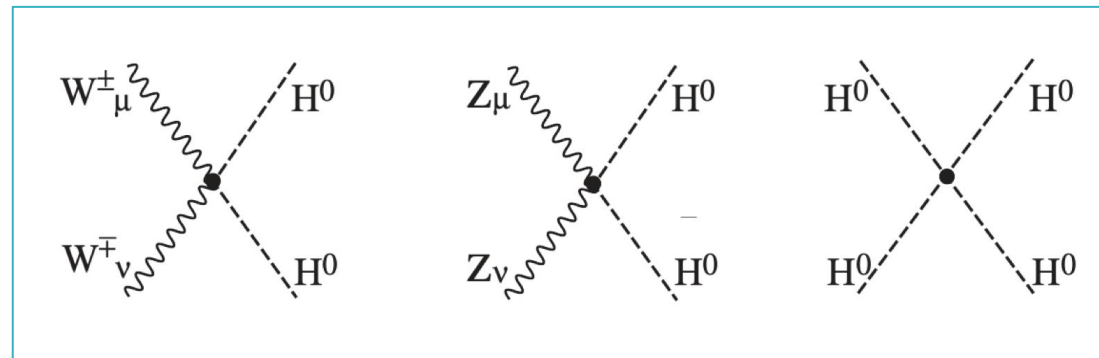
Higgs - vector boson coupling



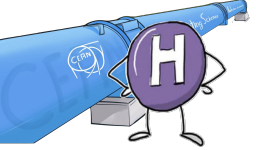
Higgs self-coupling



Multi Higgs and boson coupling



Note that all the couplings of the Higgs boson to Standard Model particles (except itself) were known before the discovery.



# Higgs boson in the SM

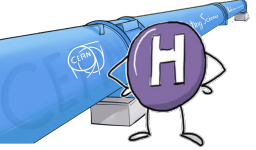
## A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard <sup>\*</sup>) and D.V. Nanopoulos <sup>+</sup>)  
CERN -- Geneva

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm <sup>3),4)</sup> and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

[Nucl. Phys. B 106, 2 \(1976\) 292-340](#)

**DON'T  
PANIC**



# Higgs Solution!

## Problem?

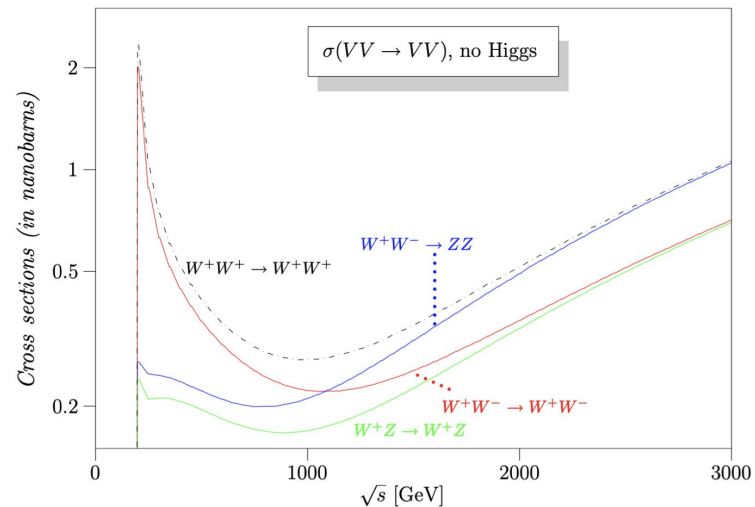
- In SM without Higgs: mass term change under symmetry rotation  $\rightarrow$  SM can't have massive bosons.

## Solution

- SM + Higgs Lagrangian is symmetric under  $SU(2) \times U(1)$

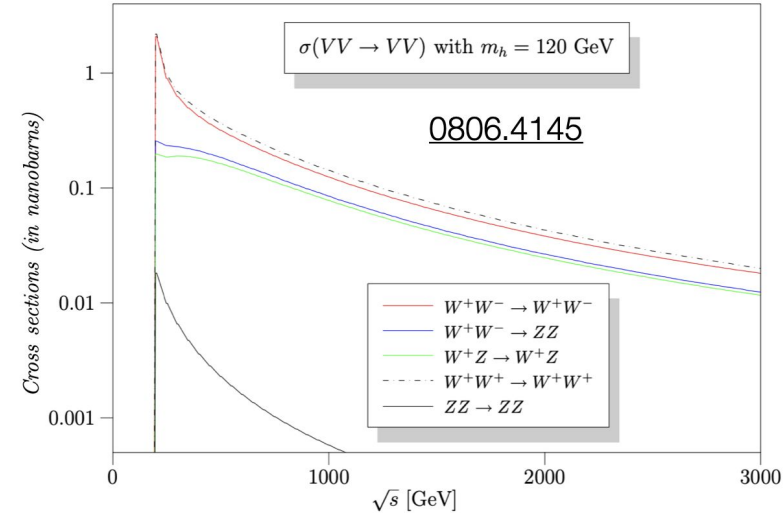
## Problem?

- Diboson scattering:  $VV \rightarrow VV$  violates unitarity at  $\sqrt{s} \sim 1$  TeV.

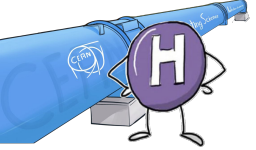


## Solution

- $VV \rightarrow VV$  unitarity violation is canceled by new Feynman diagrams.

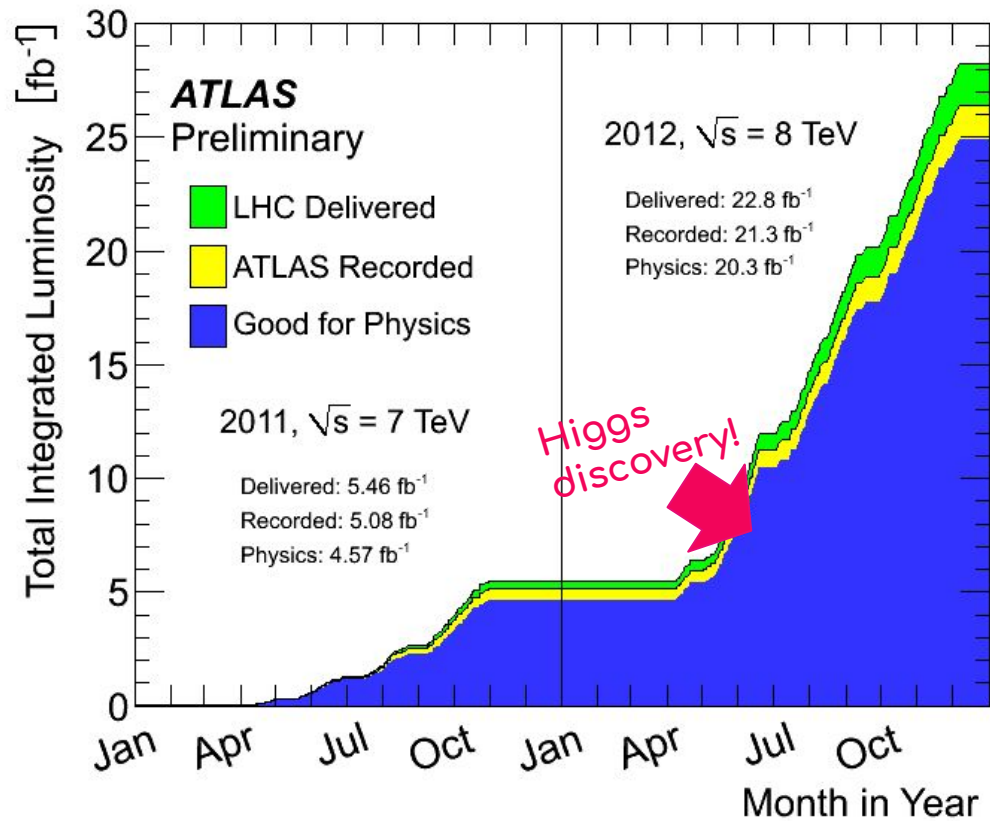


*This imposes an upper limit on the Higgs boson of  $\sim 1$  TeV.*



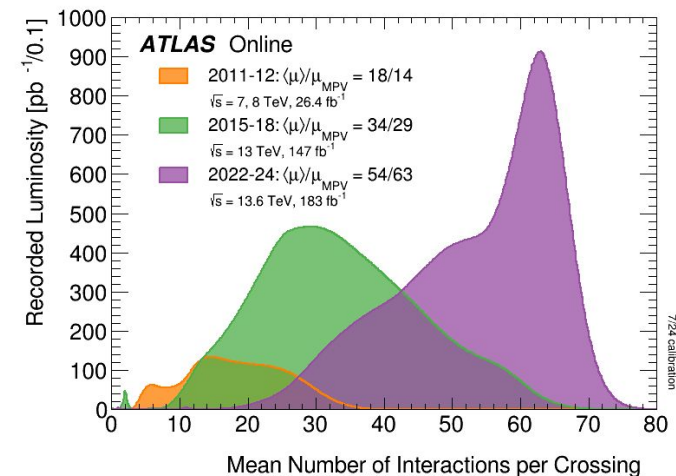
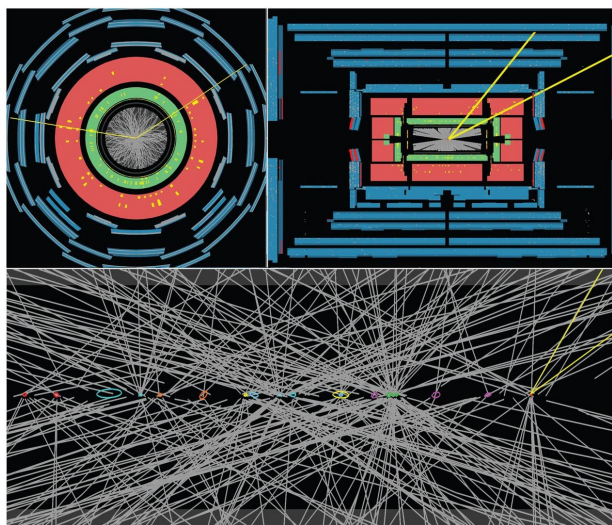
# We found a Higgs!

[ATLAS discovery paper](#)



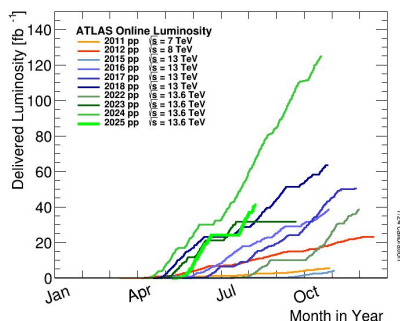
- A large search program in all decays channels from the start of the LHC Run 1.
- Optimise over a wide mass range (we didn't know the mass!)
- The Higgs was discovered with
  - Run 1: 7 TeV, ~5 fb<sup>-1</sup>
  - Run 2: 8 TeV, ~6 fb<sup>-1</sup>
- Main channels leading to the discovery:
  - $H \rightarrow ZZ^* \rightarrow 4\ell$ ,  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ .

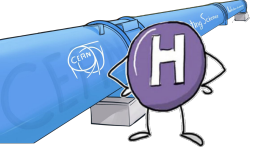
$Z \rightarrow \mu\mu$  event with 20 pileup events from 2008.



Pileup conditions for different years of data taking

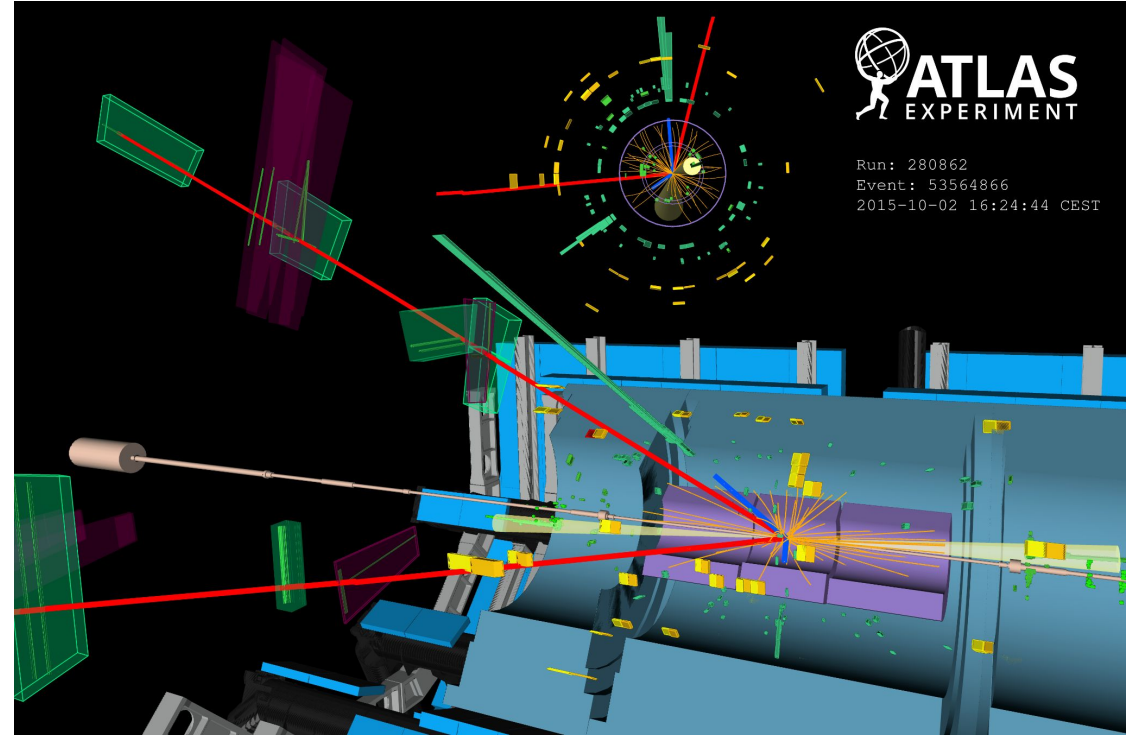
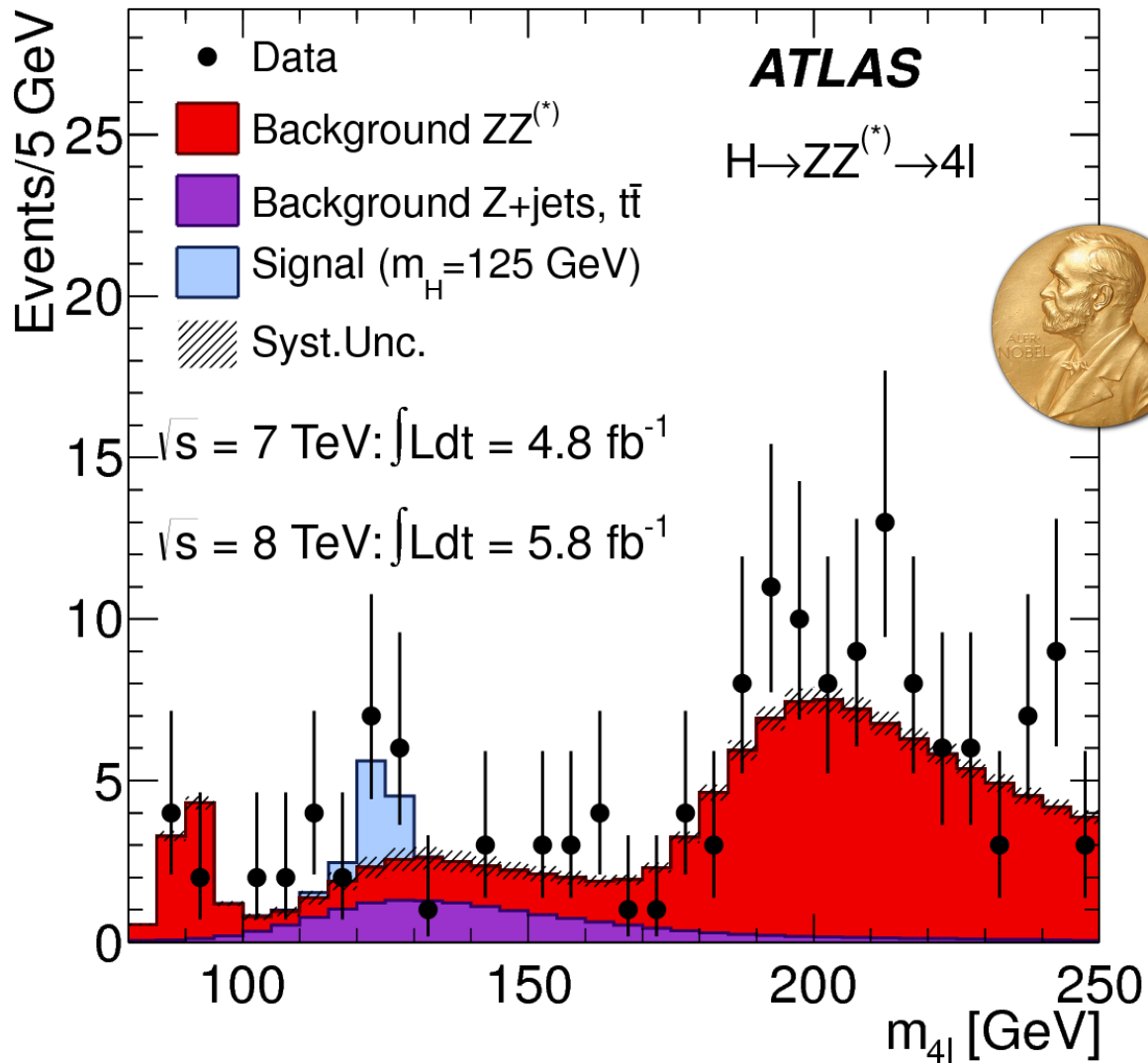
such a small fraction of today's collected data!



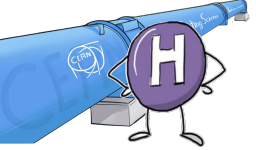


$$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$$

[ATLAS discovery paper](#)

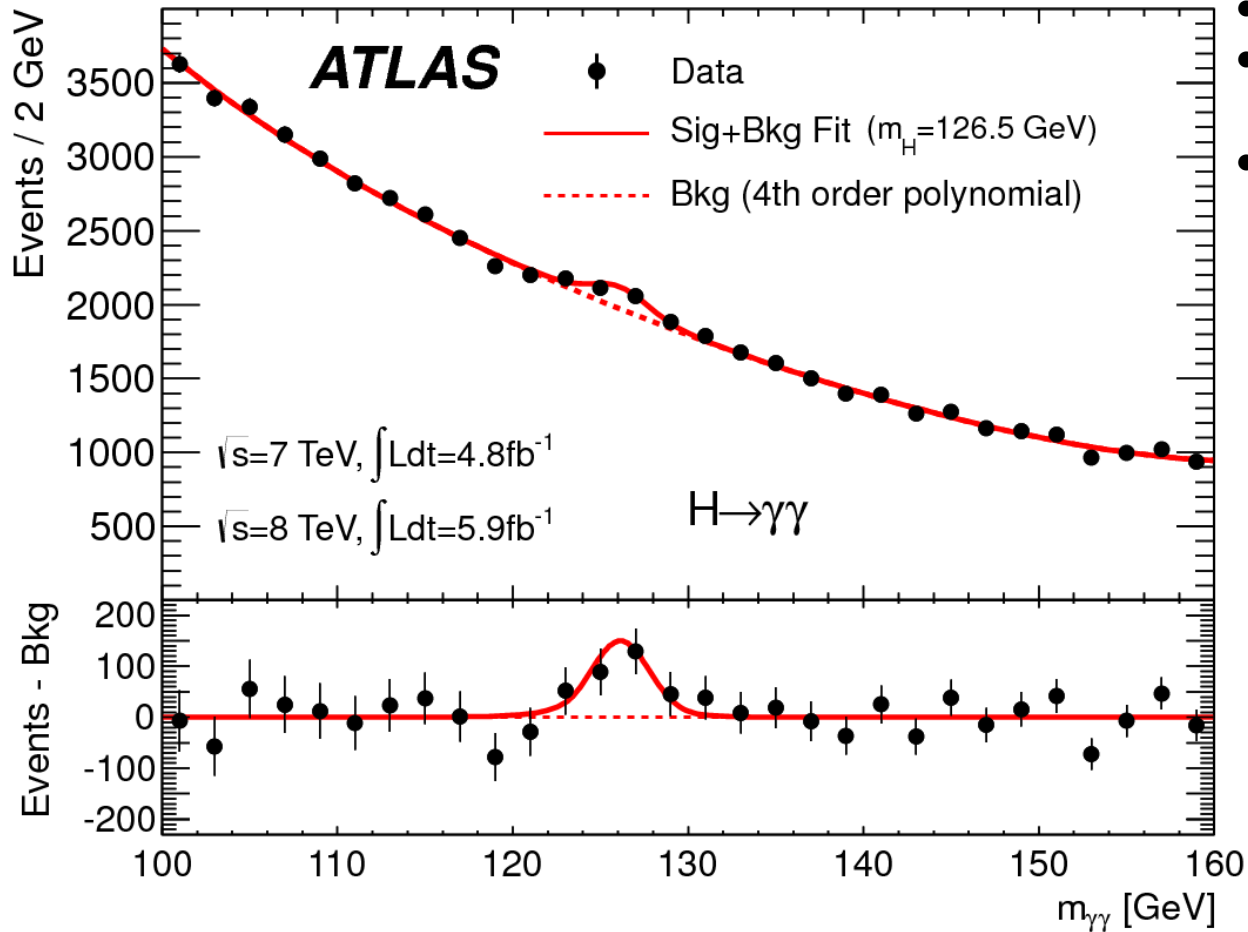


- The “golden channel”.
- Relies on precise energy/momentum calibration of muons and electrons.
- Small backgrounds, mainly from nonresonant  $ZZ^*$ 
  - MC is normalised to the data-driven background estimations.
- Small branching ratio, but excellent mass resolution (1-2%).

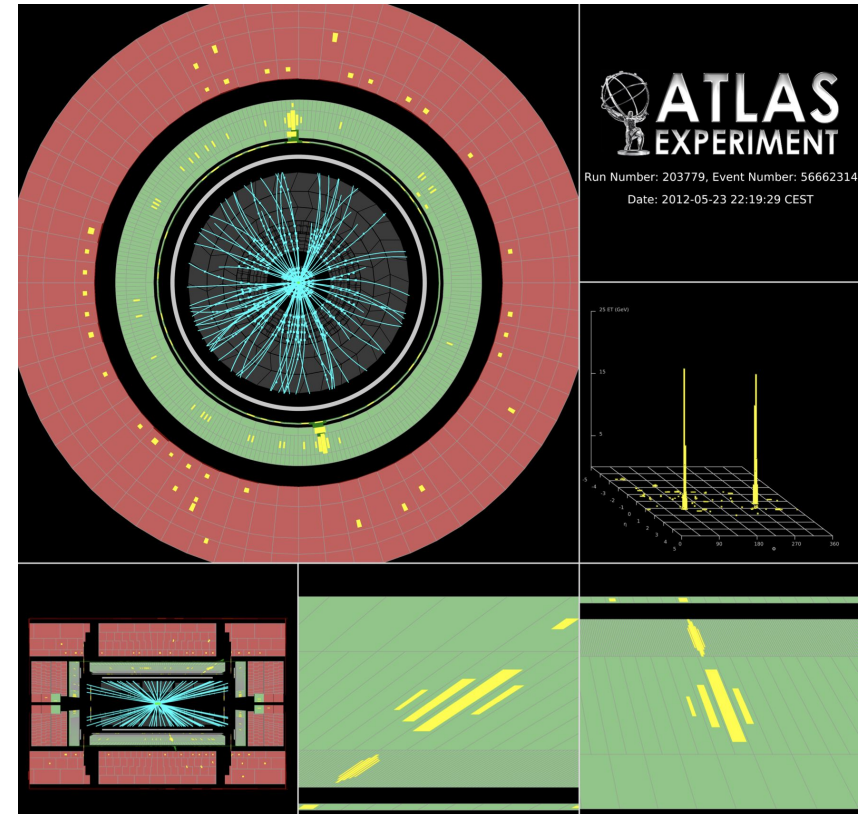


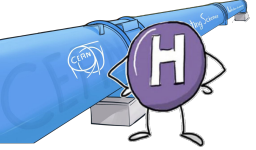
# $H \rightarrow \gamma\gamma$

[ATLAS discovery paper](#)



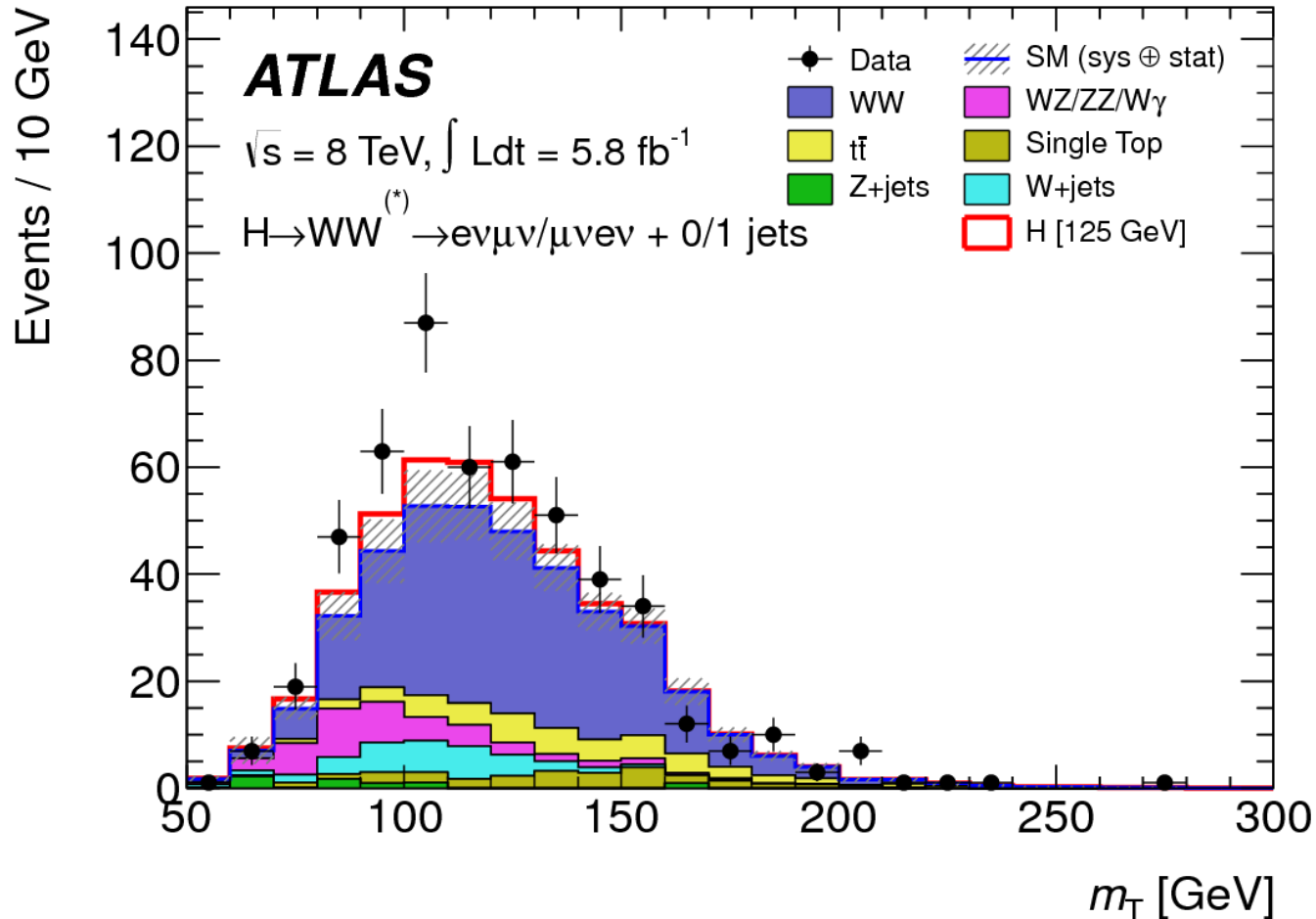
- Relies on precise energy/momentum calibration of photons.
- Large background: continuum  $\gamma\gamma$  background.
  - Use a data-driven prediction.
- Tiny branching ratio  $\sim 0.2\%$  but great  $\gamma\gamma$  mass resolution ( $\sim 1\%$ ).



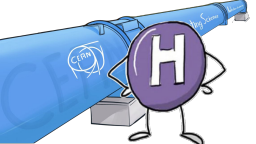


# $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

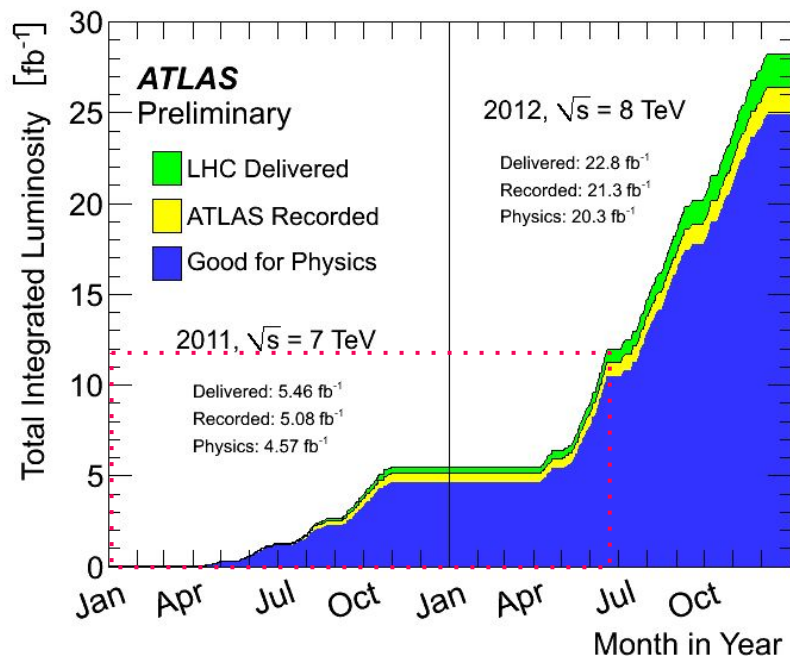
[ATLAS discovery paper](#)



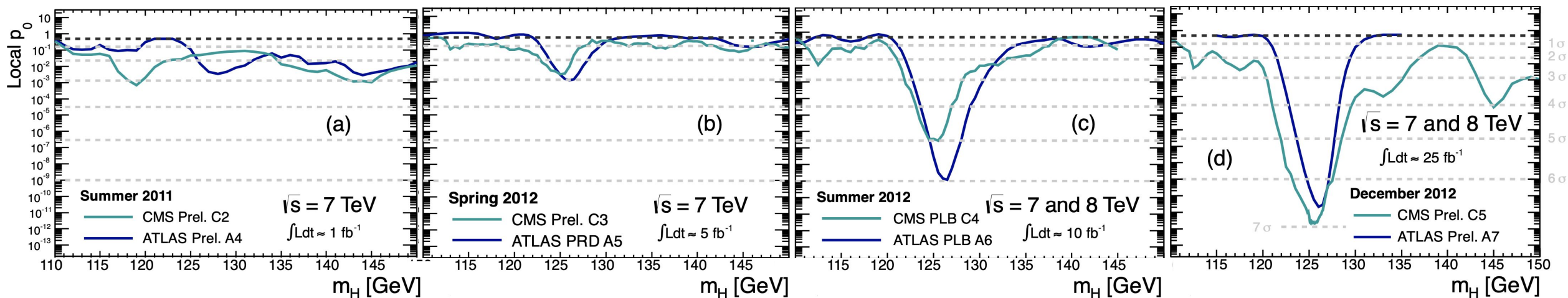
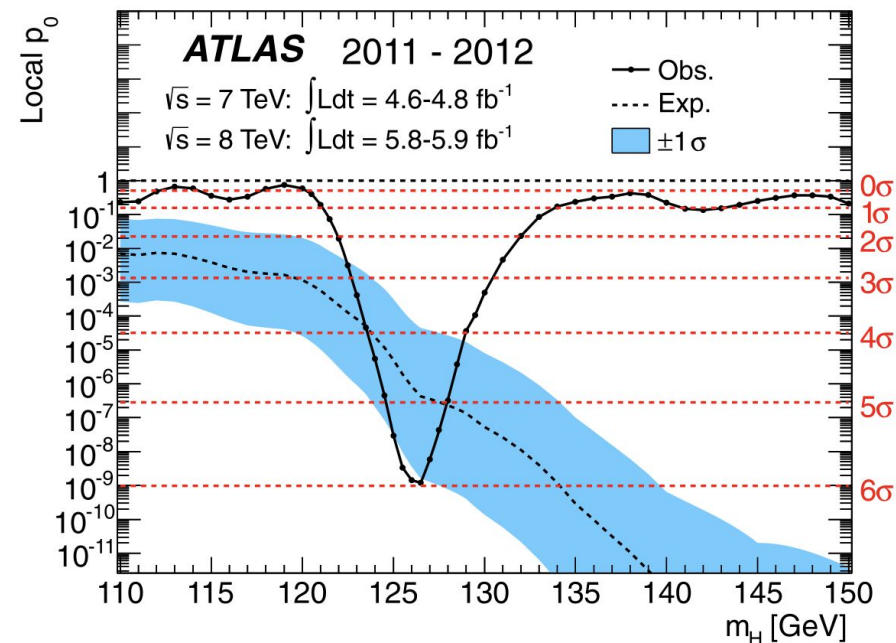
- Relies on precise energy/momentum calibration of leptons.
- Large signal yield (sizeable branching ratio).
- Large background from non-resonant  $WW^*$  and  $t\bar{t}$ 
  - MC normalised to data in control regions.
- Smaller W+jets bkg estimated from data.
- Recontriction/resolution is very challenging due to neutrinos.

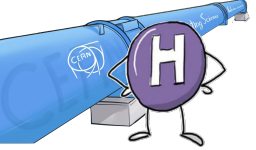


# Patience, the friend of new discoveries



We do expect to see a signal steadily increasing as we increase our datasets!





# Characterising the new boson

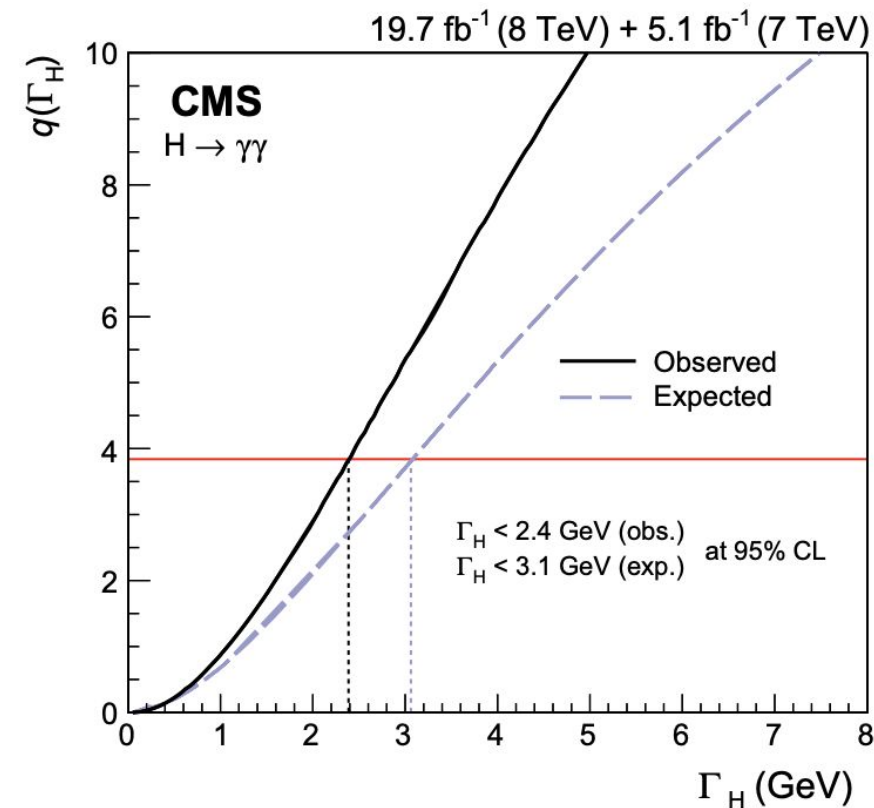
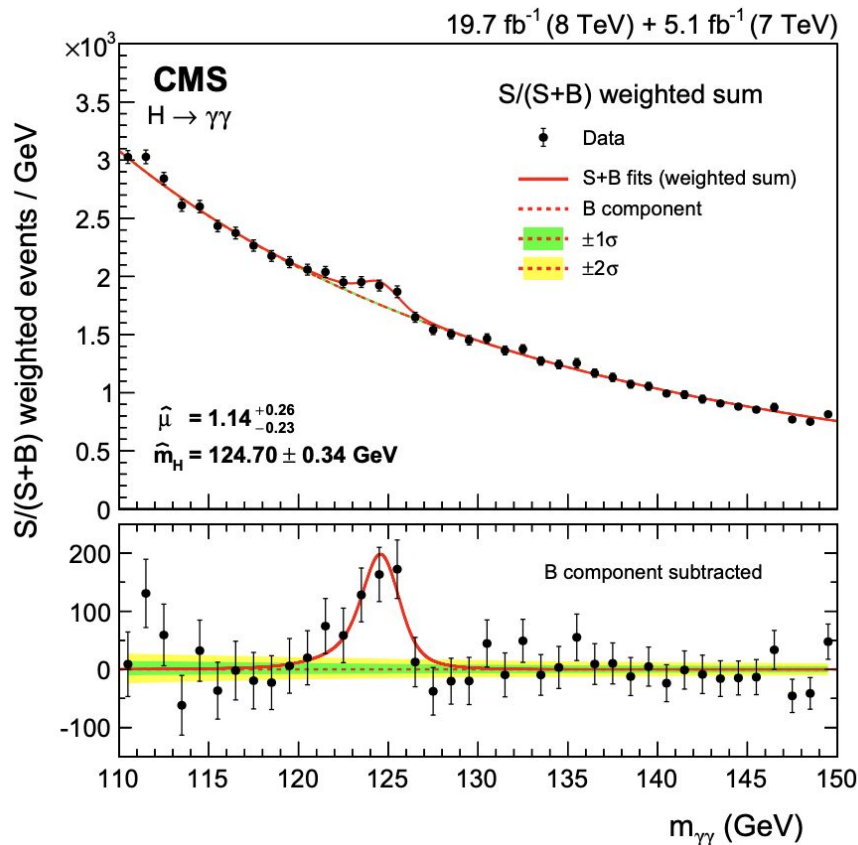
## Width

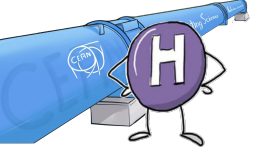
[Phys. Lett. B 805 \(2020\) 135425](#)

- Total Higgs natural width in SM is small → difficult to measure the width directly.

$$\Gamma_H^{\text{SM}} = 4.07 \text{ MeV}$$

- Direct measurement would be dependant on detector resolution.
  - Width too small to be measured experimentally from resonance shape, where the mass peak is reconstructed.



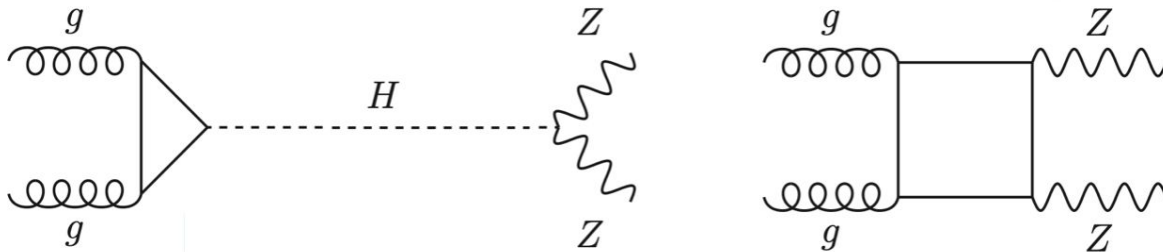


# Characterising the new boson

## Width

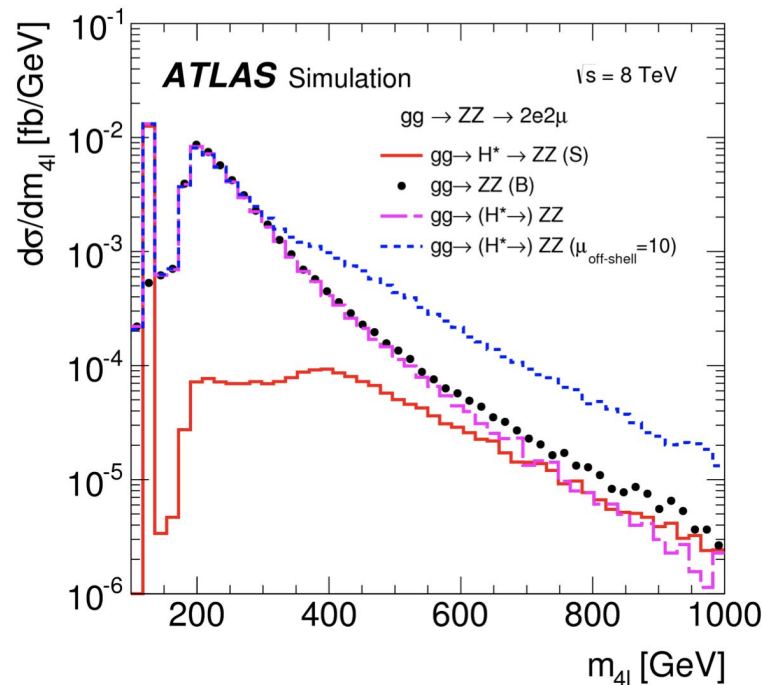
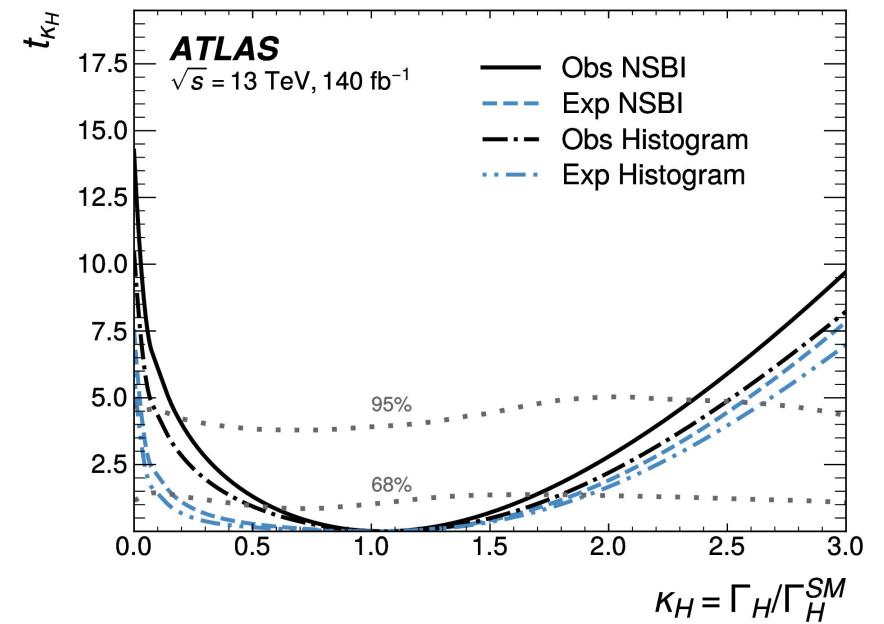
[Rep. Prog. Phys. 88 \(2025\) 057803](#)

- Indirect measurement from off-shell production.
- Higgs boson interferes negatively with the diboson continuum.



Assuming on-shell and off-shell coupling are equal:

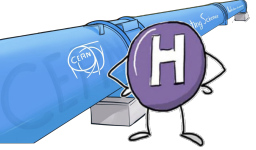
$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$



Measured value of Higgs boson width:

$$4.3^{+2.7}_{-1.9} \quad (4.1^{+3.5}_{-3.4}) \text{ MeV}$$

- $gg \rightarrow H^* \rightarrow ZZ$  signal ( $2e2\mu$ )
- $gg \rightarrow ZZ$  continuum bkg
- $gg \rightarrow (H^* \rightarrow) ZZ$  with SM Higgs coupling
  - signal plus background plus interference.
- $gg \rightarrow (H^* \rightarrow) ZZ$  with  $\mu^{\text{off-shell}}=10$



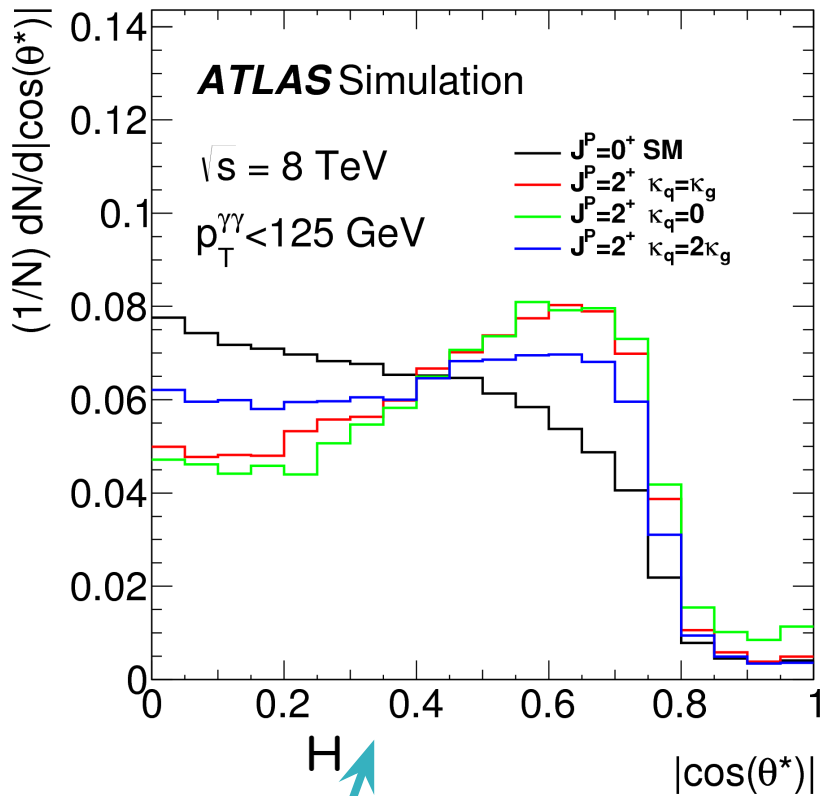
# Characterising the new boson

## Spin

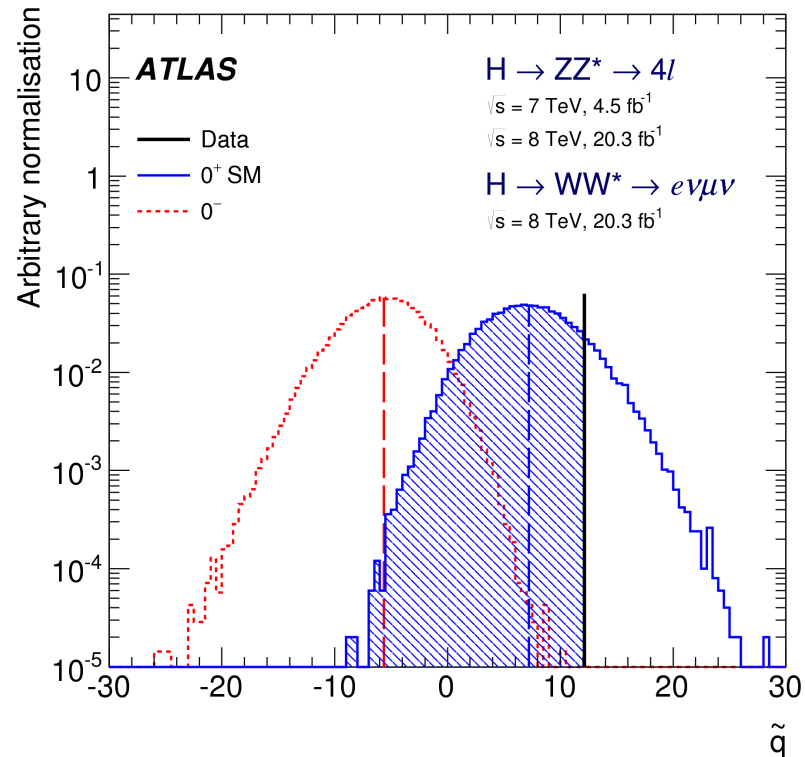
[Eur. Phys. J. C 75 \(2015\) 476](#)

Predicted to be zero in the SM  $\rightarrow$  unique wrt other fundamental particles!

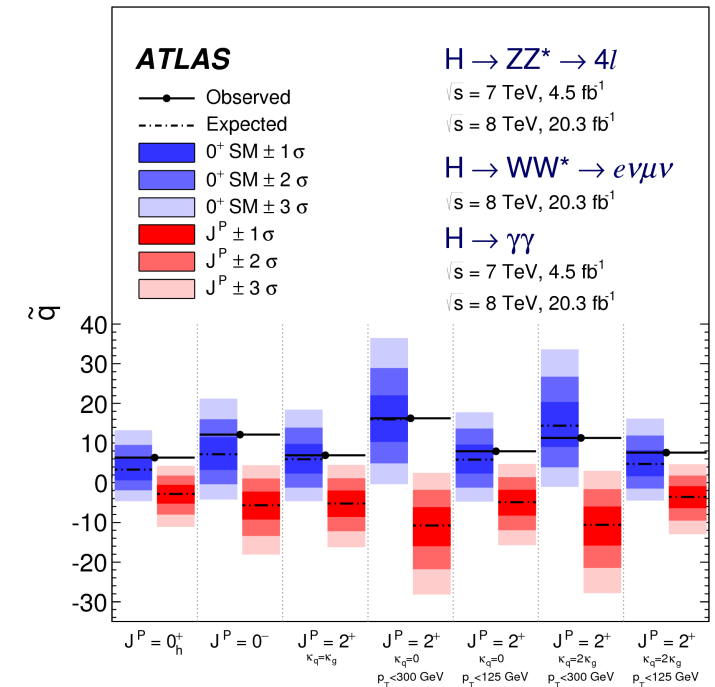
Production and decay angle depend on the spin.



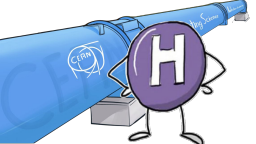
Define a test statistics:  
 $0^+ \text{ vs } 0^-$



Test multiple spin hypotheses.



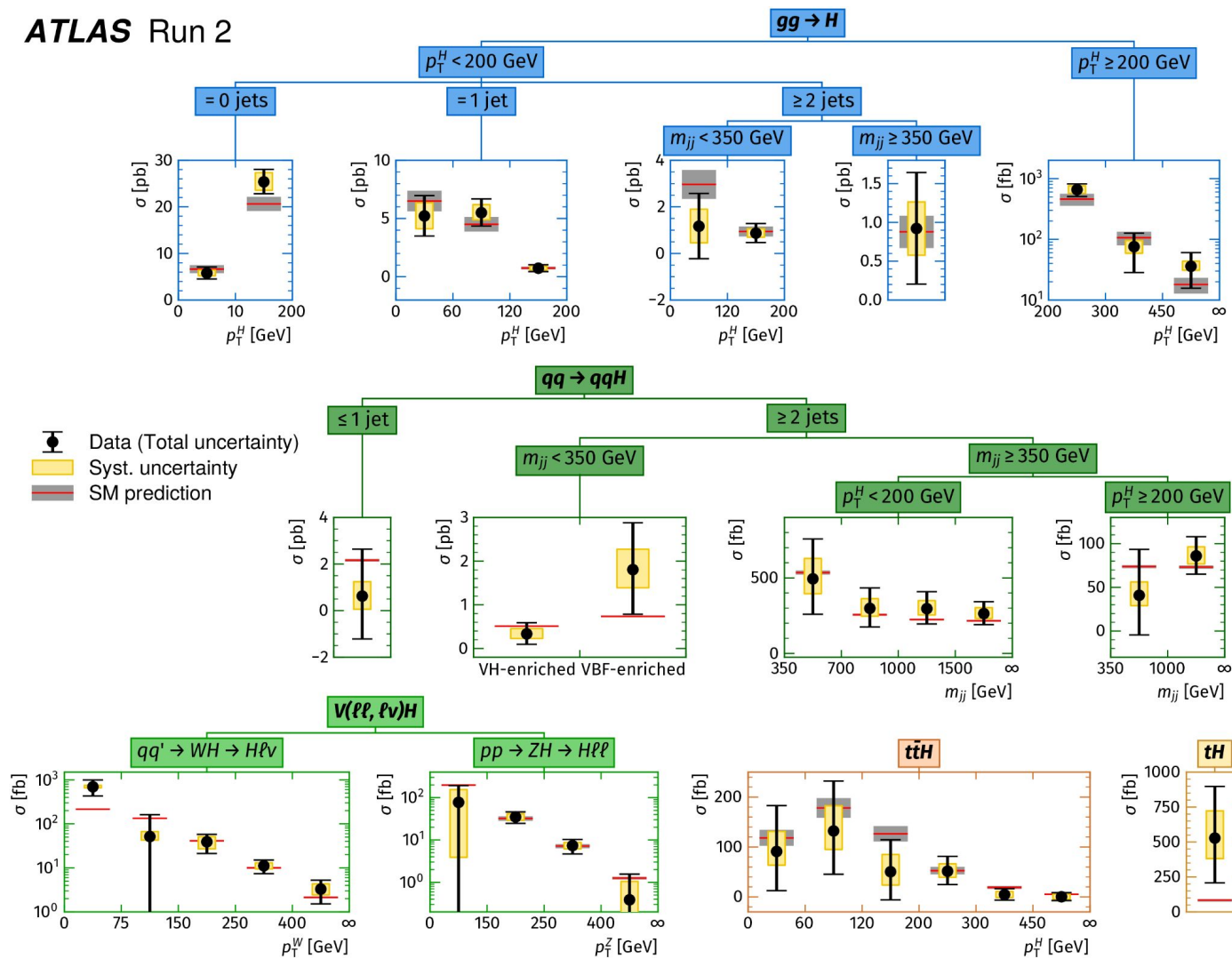
A test statistic  $q^-$  is used to distinguish between the two spin-parity hypotheses is based on a ratio of profiled likelihoods



# We can go beyond... STXS

- STXS model provides a template for *fine grained measurements* from different channel and how to combine them.
- We can study kinematics in all production processes in several kinematic regimes to maximise sensitivity to new physics while limiting model dependence.

ATLAS Run 2



[Nature 607 52 \(2022\)](#)

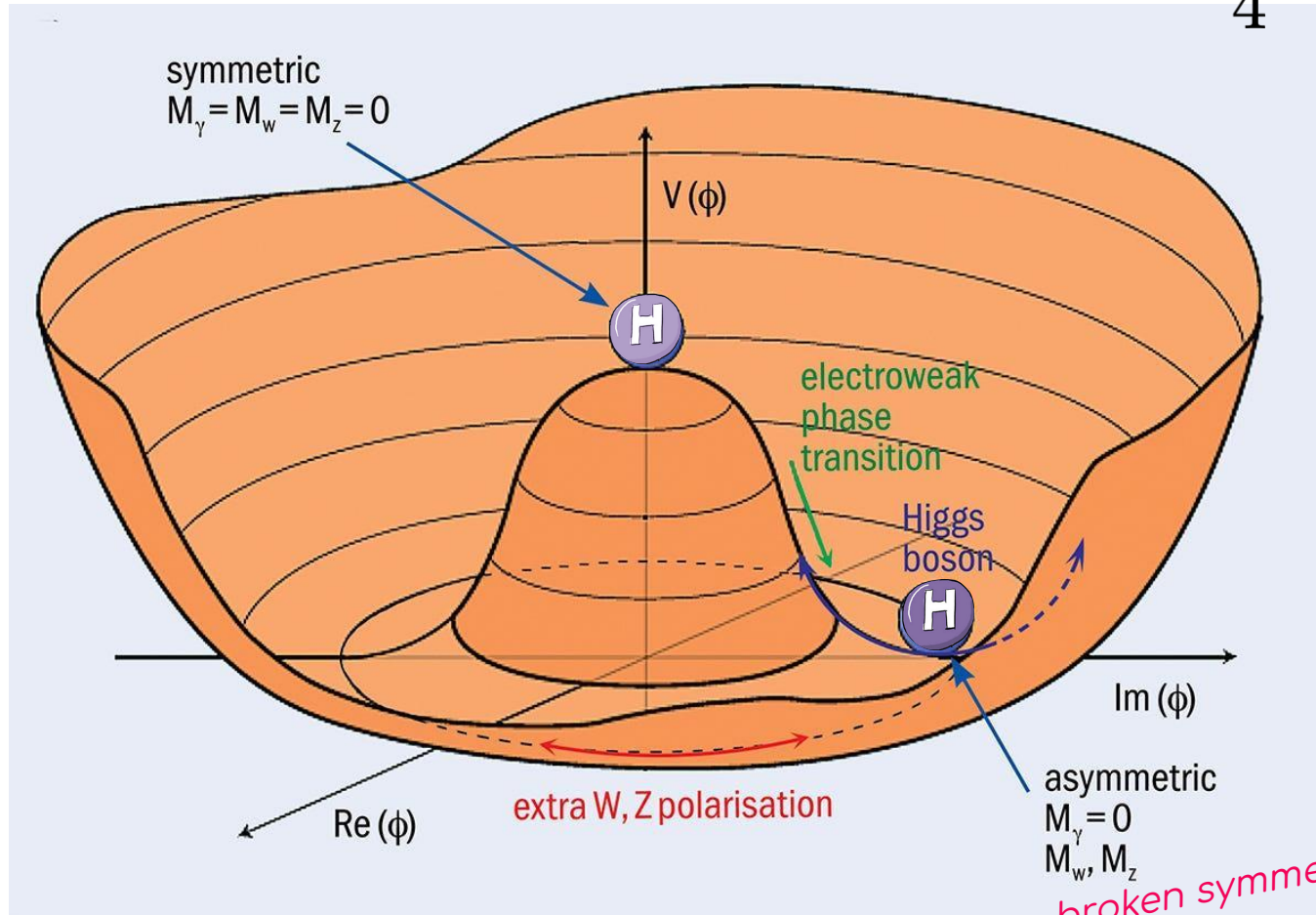
# Trilinear Higgs Coupling

Standard Model  
Higgs potential

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

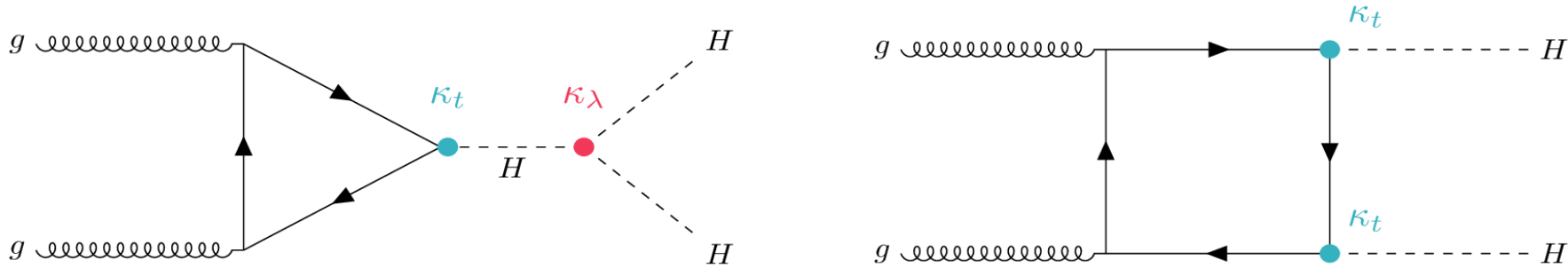
Our universe lives in the  
minimum:

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 - \frac{\lambda}{v^4}$$



# HH production

Search for non-resonant di-Higgs production allows us to probe the shape of the Higgs potential by measuring the trilinear self-coupling  $\kappa_\lambda$  of the Higgs boson.



Higgs potential  
(minimum)

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \dots$$

mass term

trilinear  
coupling

$$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{\text{SM}}$$

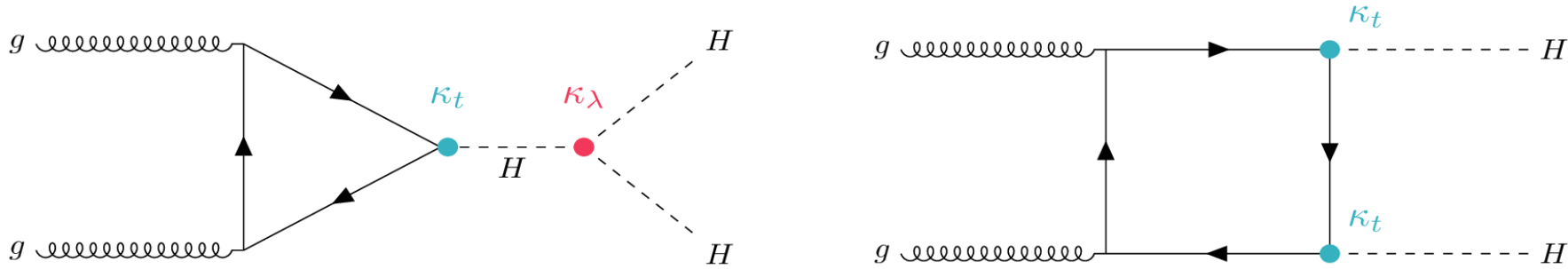
SM predicts  $\kappa_\lambda = 1$

There is however destructive interference between the box and triangle diagrams, thus the **cross section is suppressed** ( $\sim 10^3$  times smaller than single Higgs cross section).

Deviations from SM can increase this cross section.

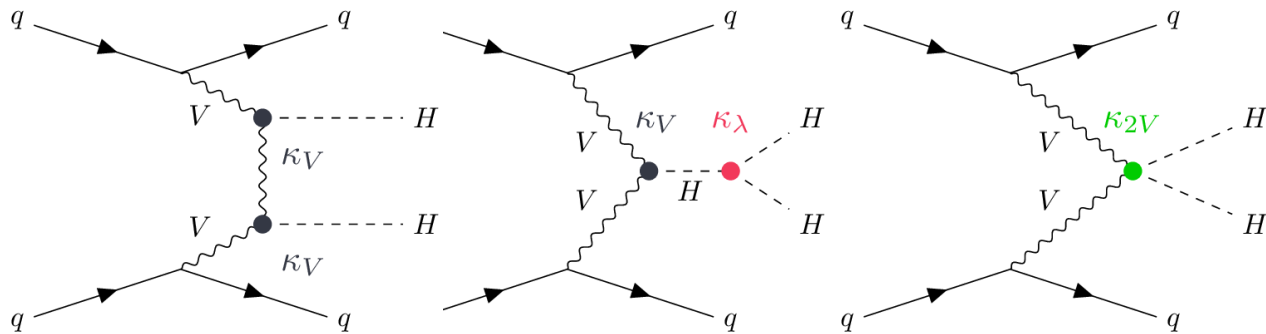
# HH production

Search for non-resonant di-Higgs production allows us to probe the shape of the Higgs potential by measuring the trilinear self-coupling  $\kappa_\lambda$  of the Higgs boson.



Other production mechanisms also allow us to probe different couplings:  $\kappa_{2V}$ ,  $\kappa_V$ .

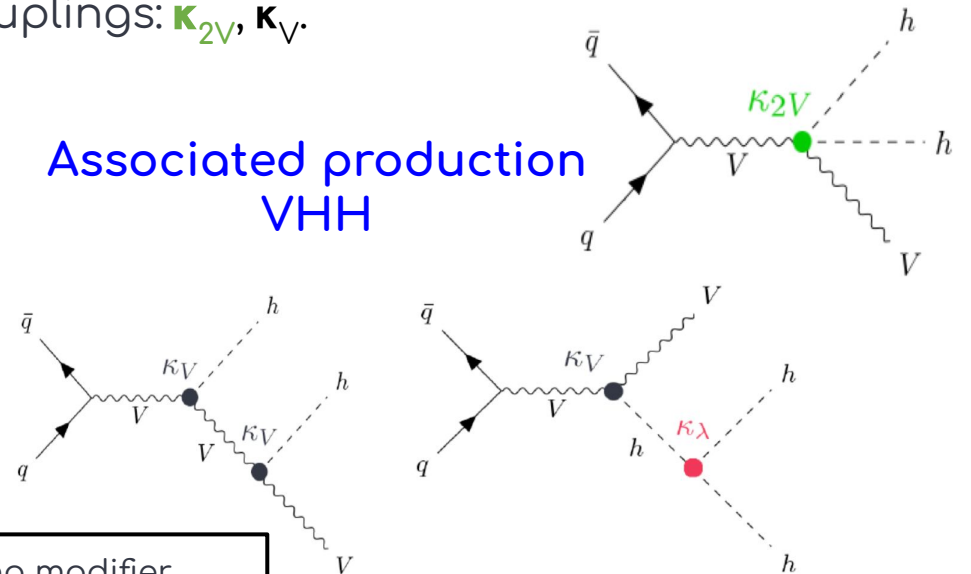
## Vector boson fusion



VVHH coupling modifier  
SM predicts  $\kappa_{2V} = 1$

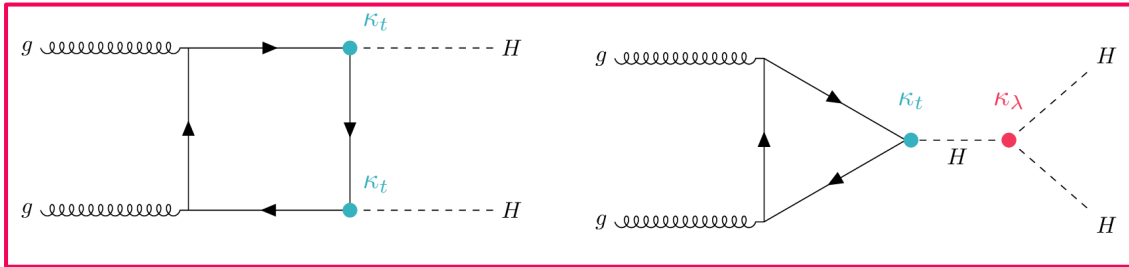
VVH coupling modifier  
SM predicts  $\kappa_V = 1$

## Associated production VHH



# HH production

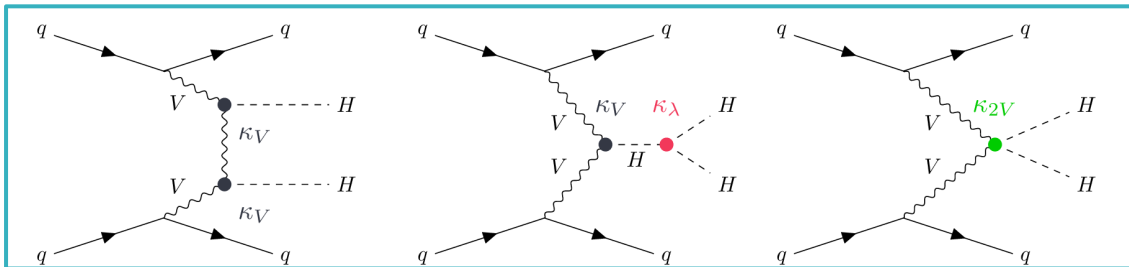
Production cross sections at 13 TeV for  $m_H = 125$  GeV



Gluon fusion (NNLO)

$$\sigma_{\text{ggF}}^{\text{SM}} = 31.05^{+6\%}_{-23\%} (\text{scale} + m_{\text{top}}) \pm 3.0\% (\text{PDF} + \alpha_s) \text{ fb}$$

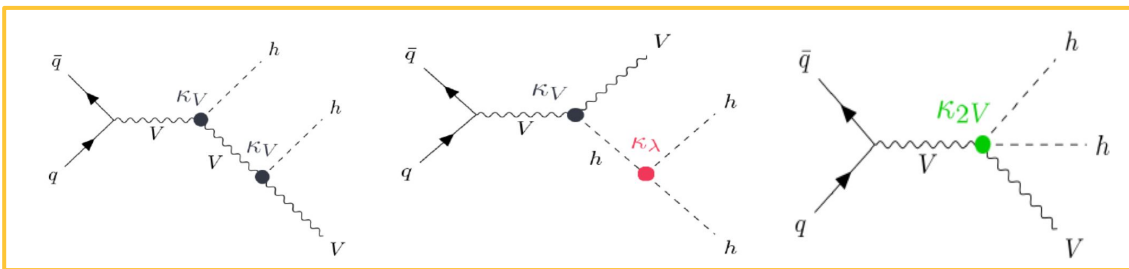
Trilinear self-coupling modifier:  $\mathbf{\kappa}_\lambda$



Vector boson fusion (N<sup>3</sup>LO)

$$\sigma_{\text{VBF}}^{\text{SM}} = 1.73^{+0.03\%}_{-0.04\%} (\text{scale}) \pm 2.1 (\text{PDF} + \alpha_s) \text{ fb}$$

VVHH coupling modifier  $\mathbf{\kappa}_{2V}$



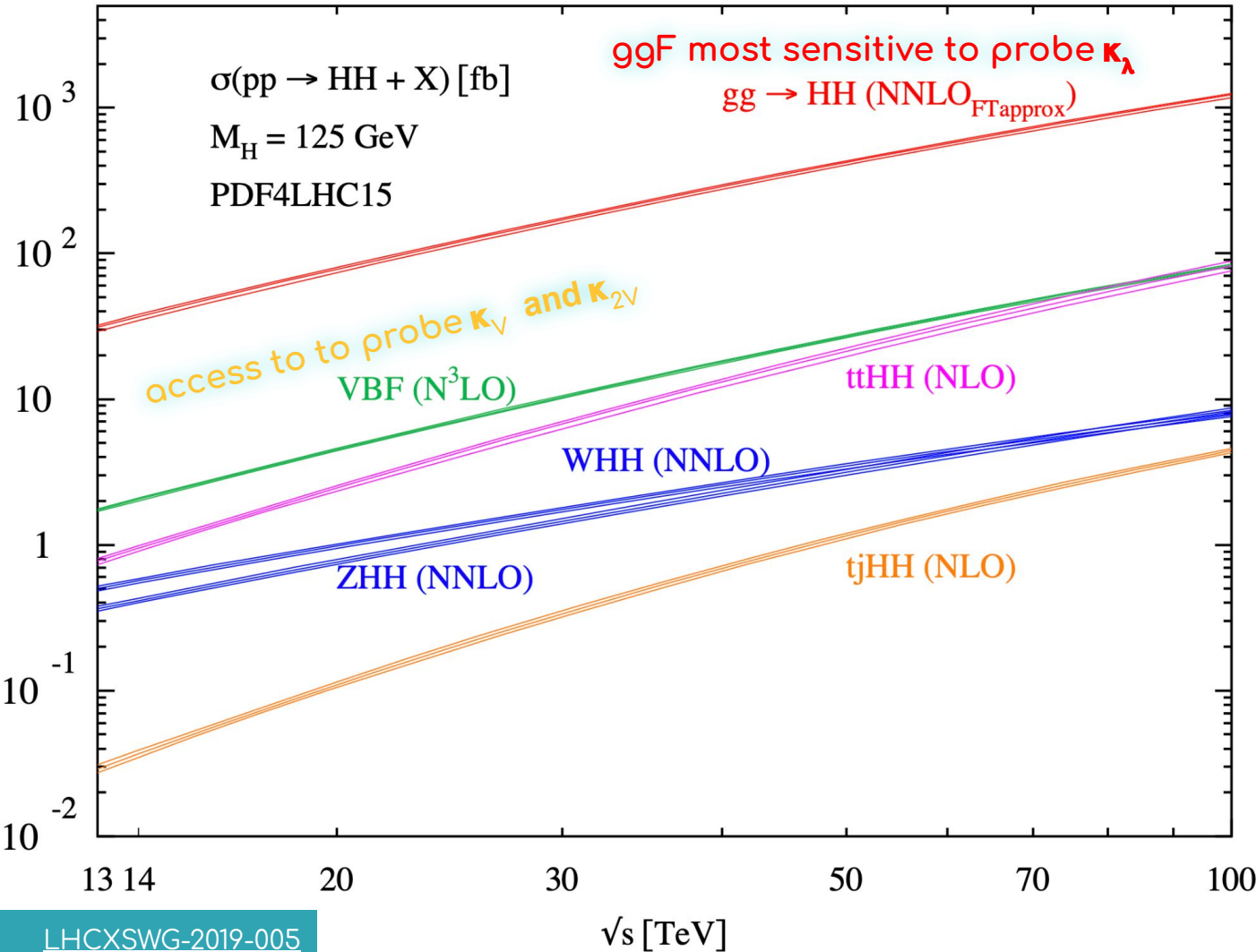
Associated production, VHH (N<sup>2</sup>LO)

e.g.  $\sigma_{\text{ZHH}}^{\text{SM}} = 0.363^{+3.4\%}_{-2.7\%} (\text{scale}) \pm 1.9 (\text{PDF} + \alpha_s) \text{ fb}$

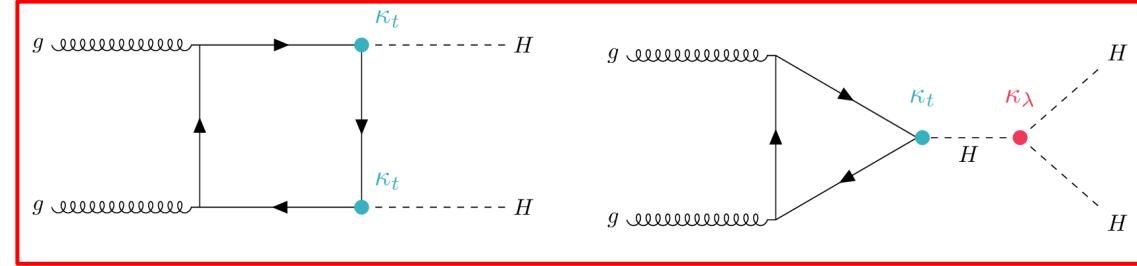
VVH coupling modifier  $\mathbf{\kappa}_V$

SM predicts  $\mathbf{\kappa}_\lambda = 1, \mathbf{\kappa}_{2V} = 1, \mathbf{\kappa}_V = 1$

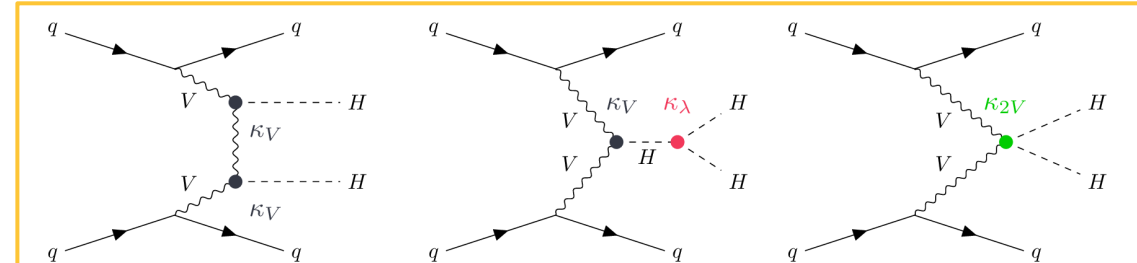
# Higgs boson pair production



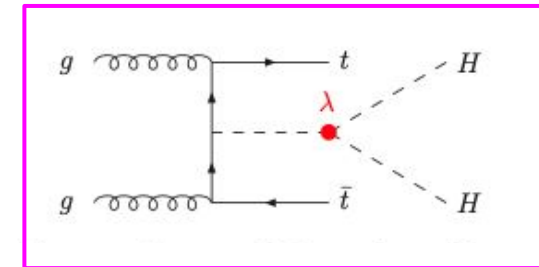
gluon fusion



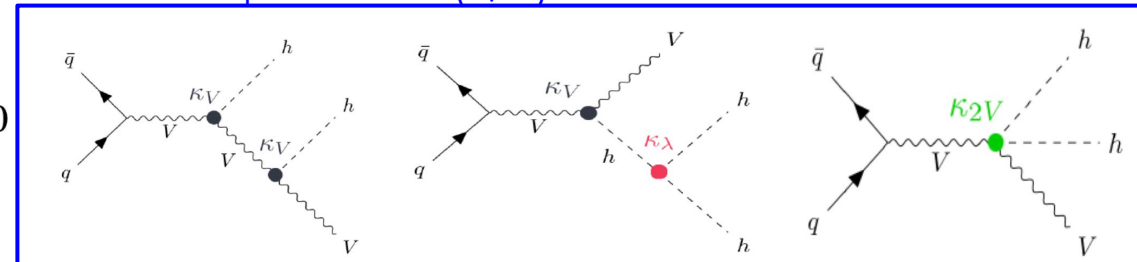
vector boson fusion



associated production (ttbar)



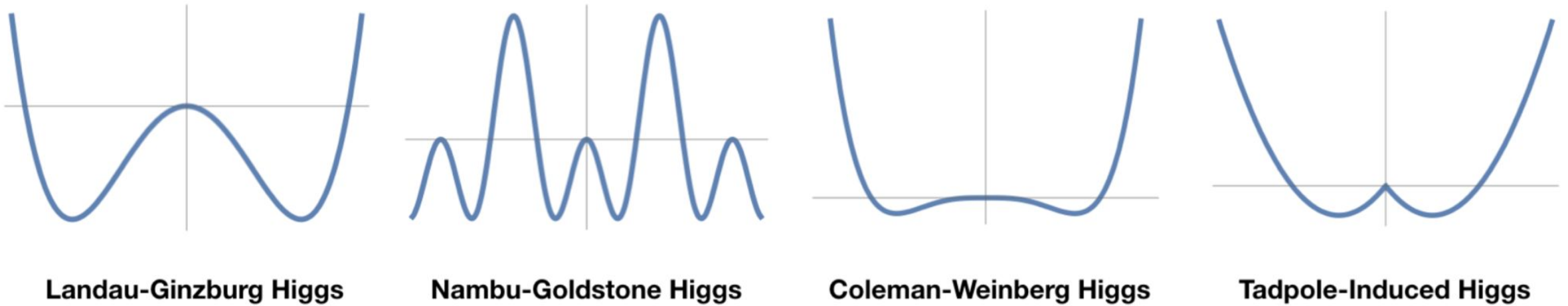
associated production (Z/W)



# Stability of the Universe

Measurements of the Higgs self-coupling can give insight about our universe!

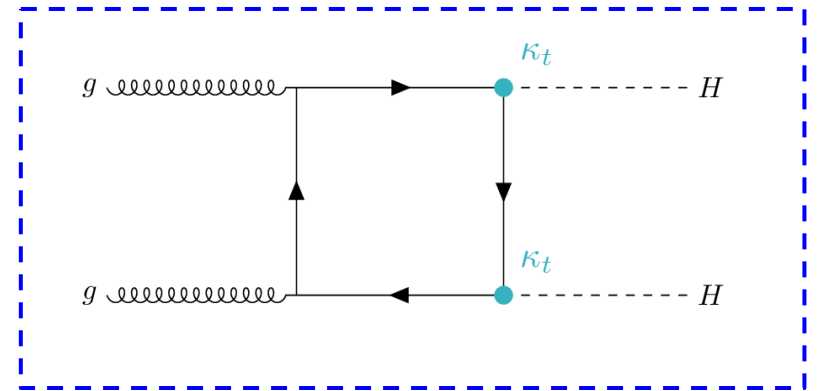
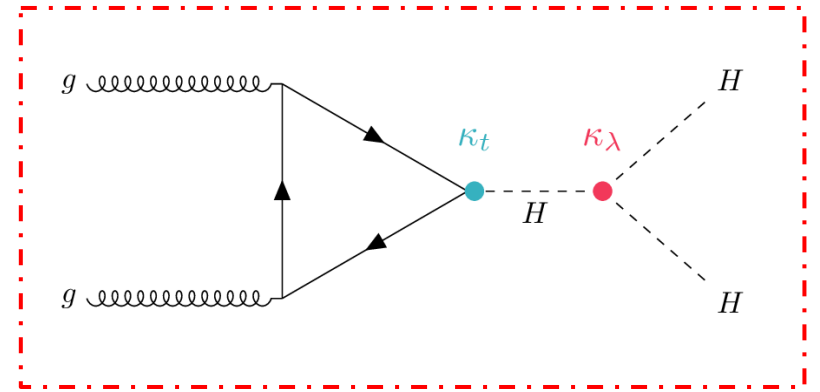
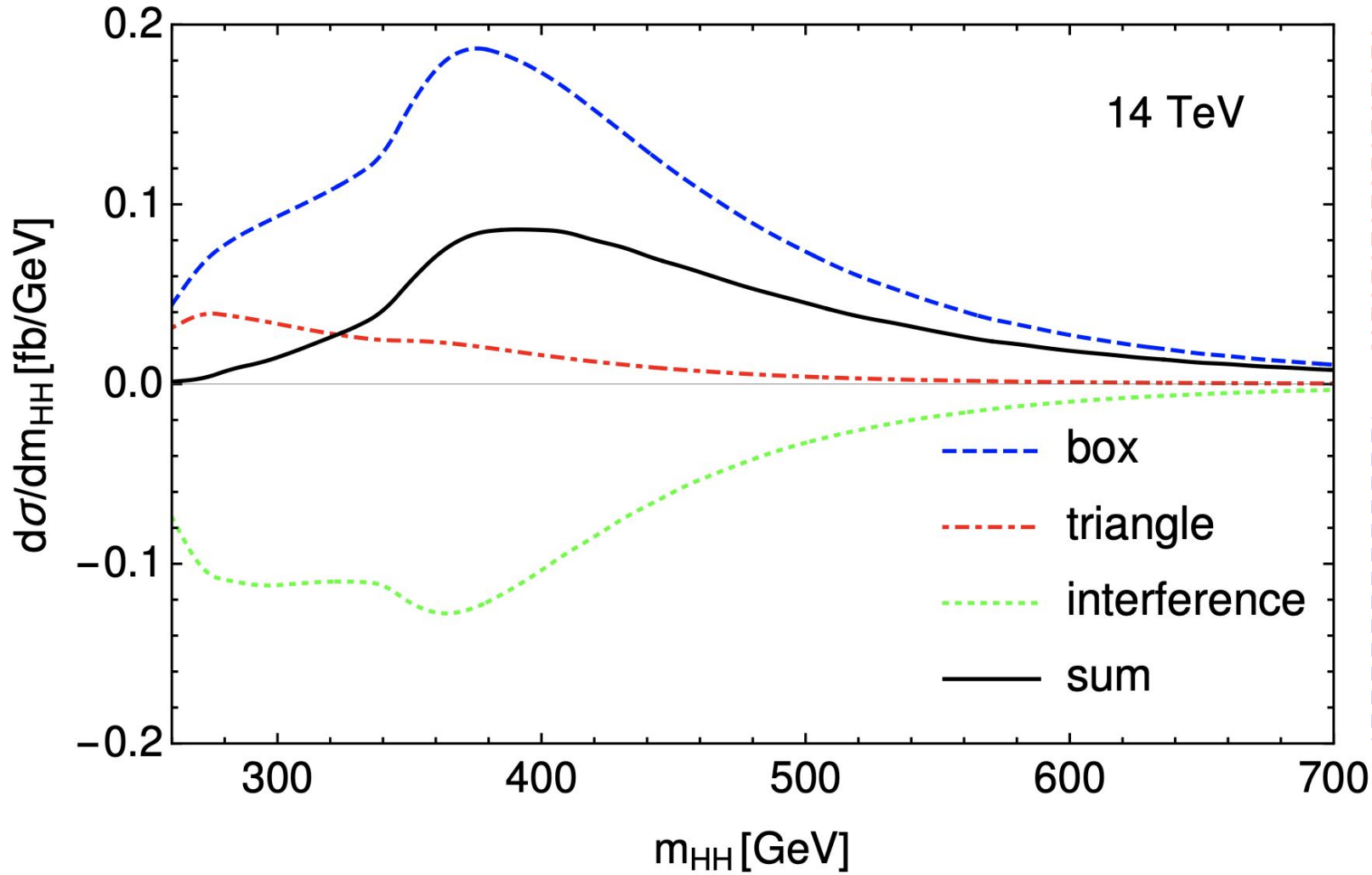
Phys. Rev. D 101, 075023 (2020)



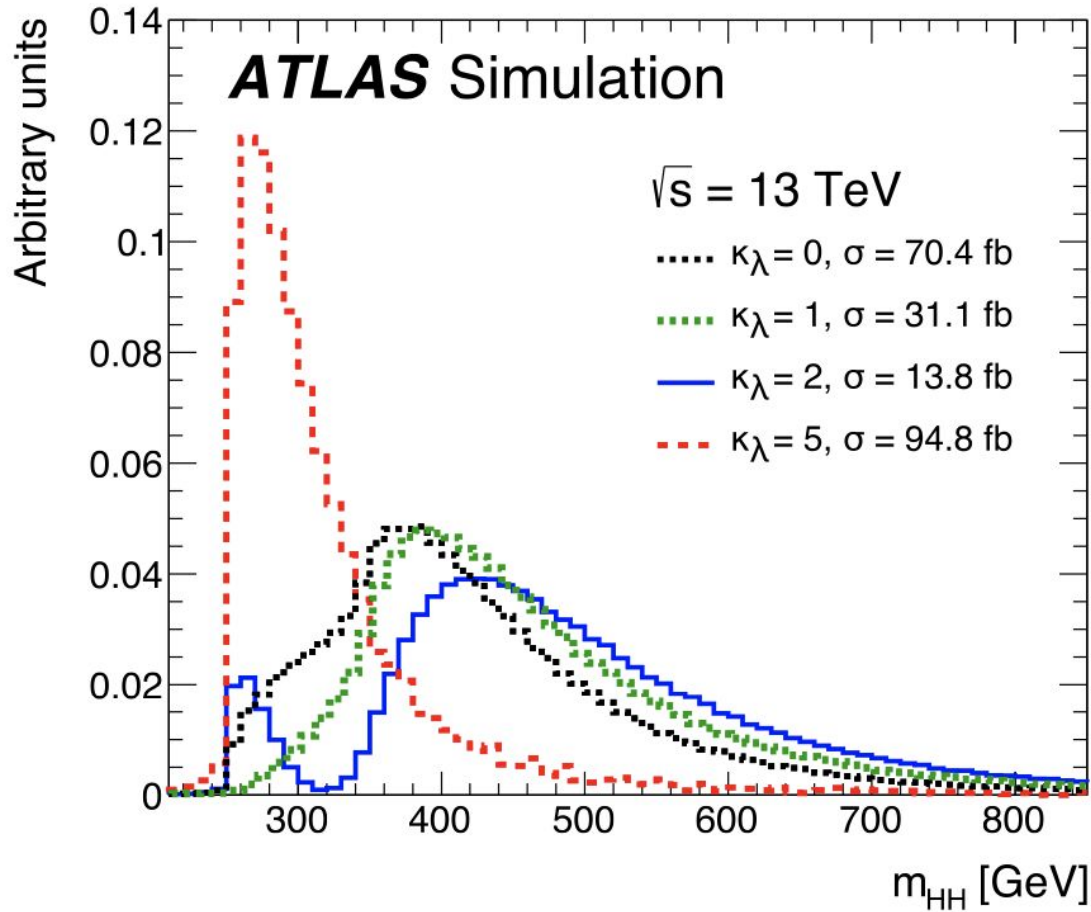
Measuring the self-coupling can provide discrimination between different scenarios, or different models.  
See [talk](#) by Patrick Meade.

But, keep in mind that we will require to measure **triple-Higgs production** to fully describe the shape of the Higgs potential.

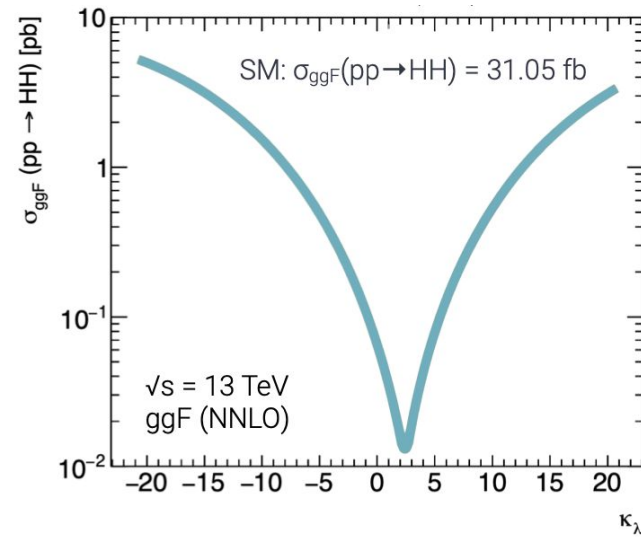
# ggF HH production



# ggF HH production

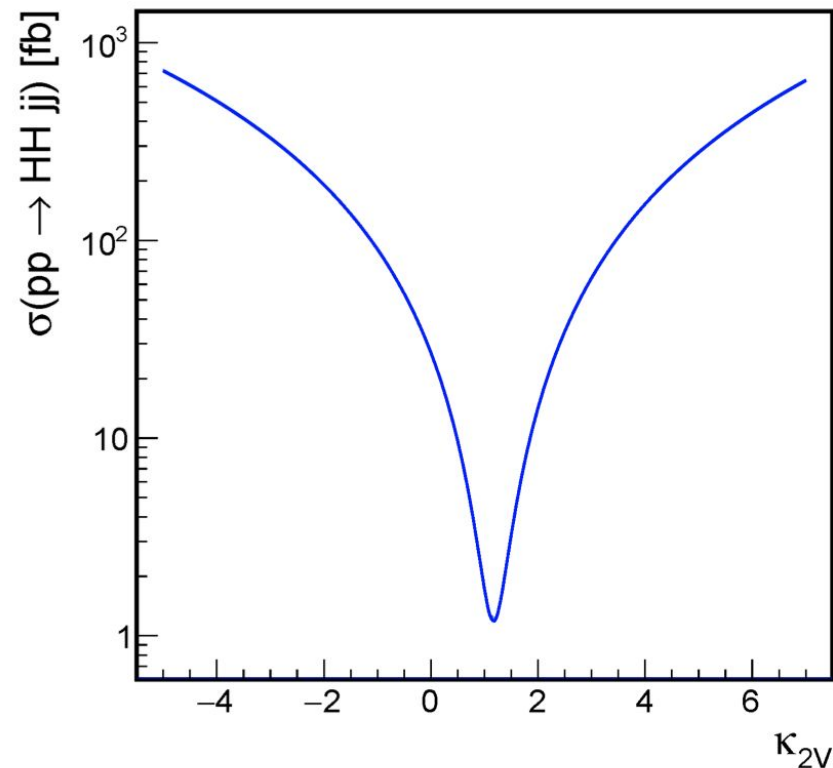
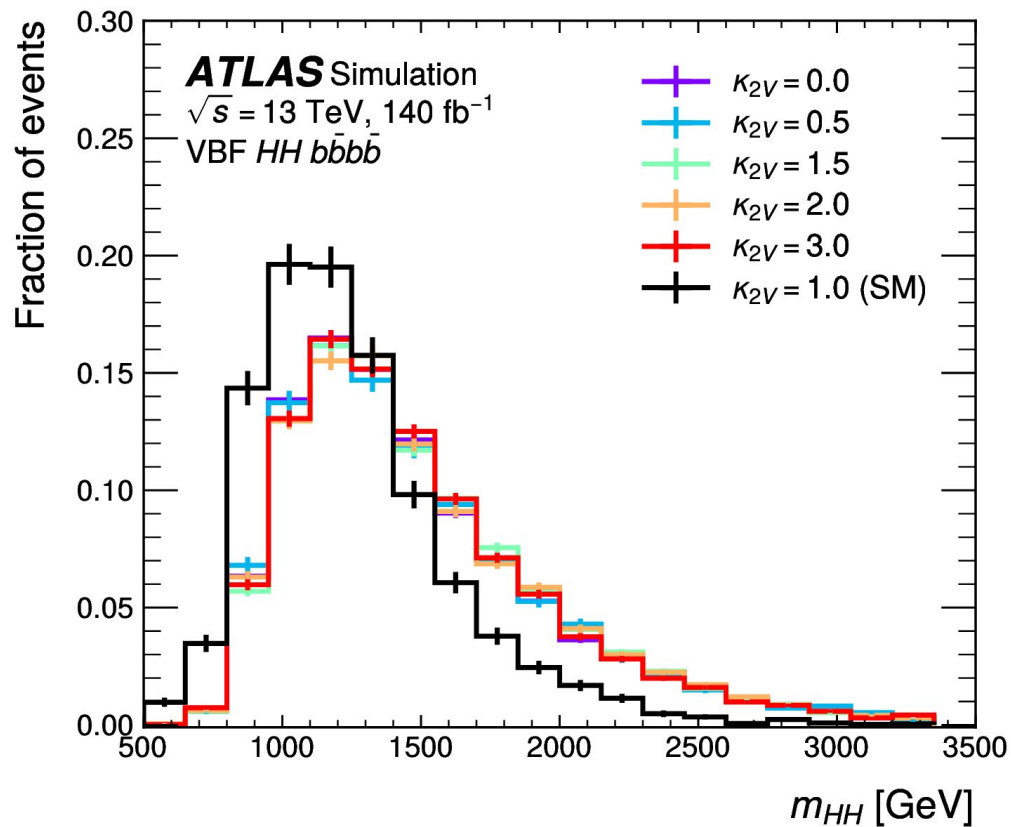


$$\sigma_{\Delta} \propto \lambda^2 y_t^2, \quad \sigma_{\square} \propto y^4, \quad \sigma_{\text{interference}} \propto -\lambda y^3$$



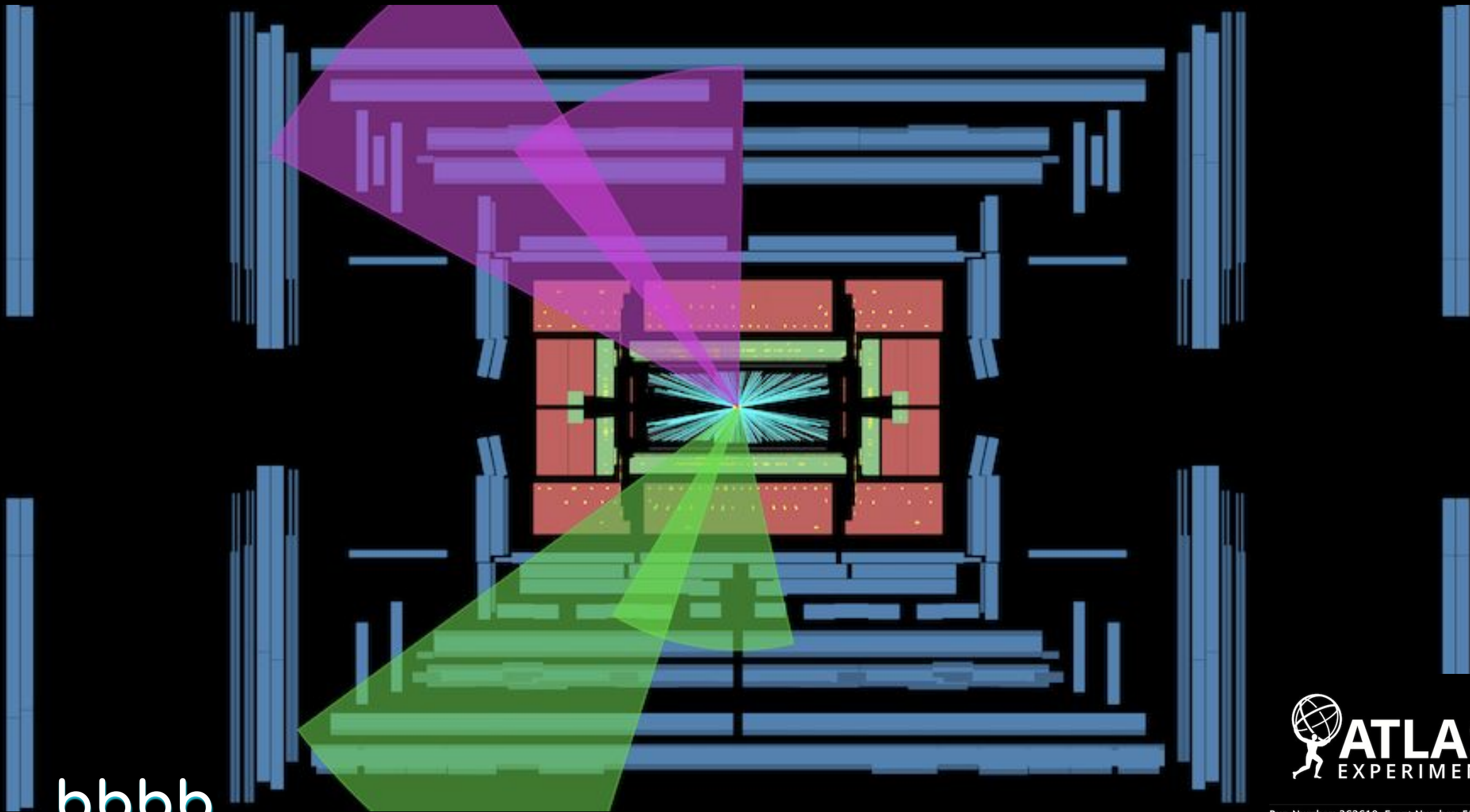
- $m_{HH}$  distribution depends on  $\kappa_\lambda$ .
- For values of  $\kappa_\lambda \neq 1$ , x-section can be enhanced.
- For large values of  $\kappa_\lambda$  the triangle diagram dominates.

# VBF HH production



VBF production:  $\kappa_{2V} \neq 1$  (BSM)

- have larger cross-section,
- the decay production are more energetic.



bbbb

 **ATLAS**  
EXPERIMENT

Run Number: 362619, Event Number: 524614423

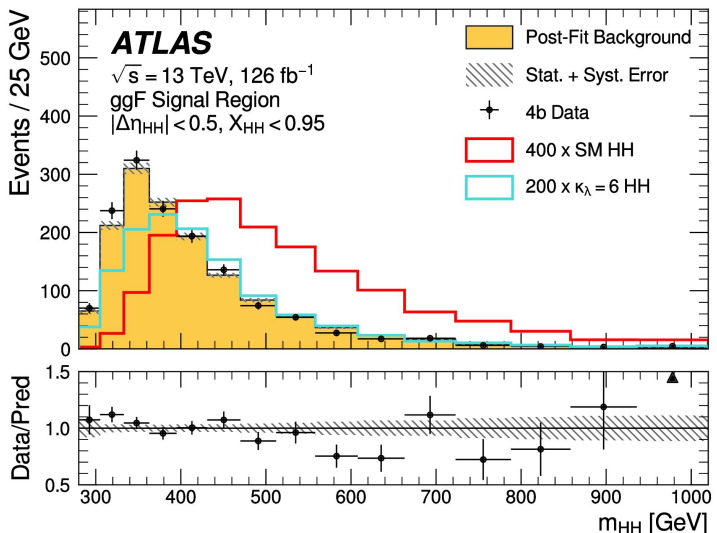
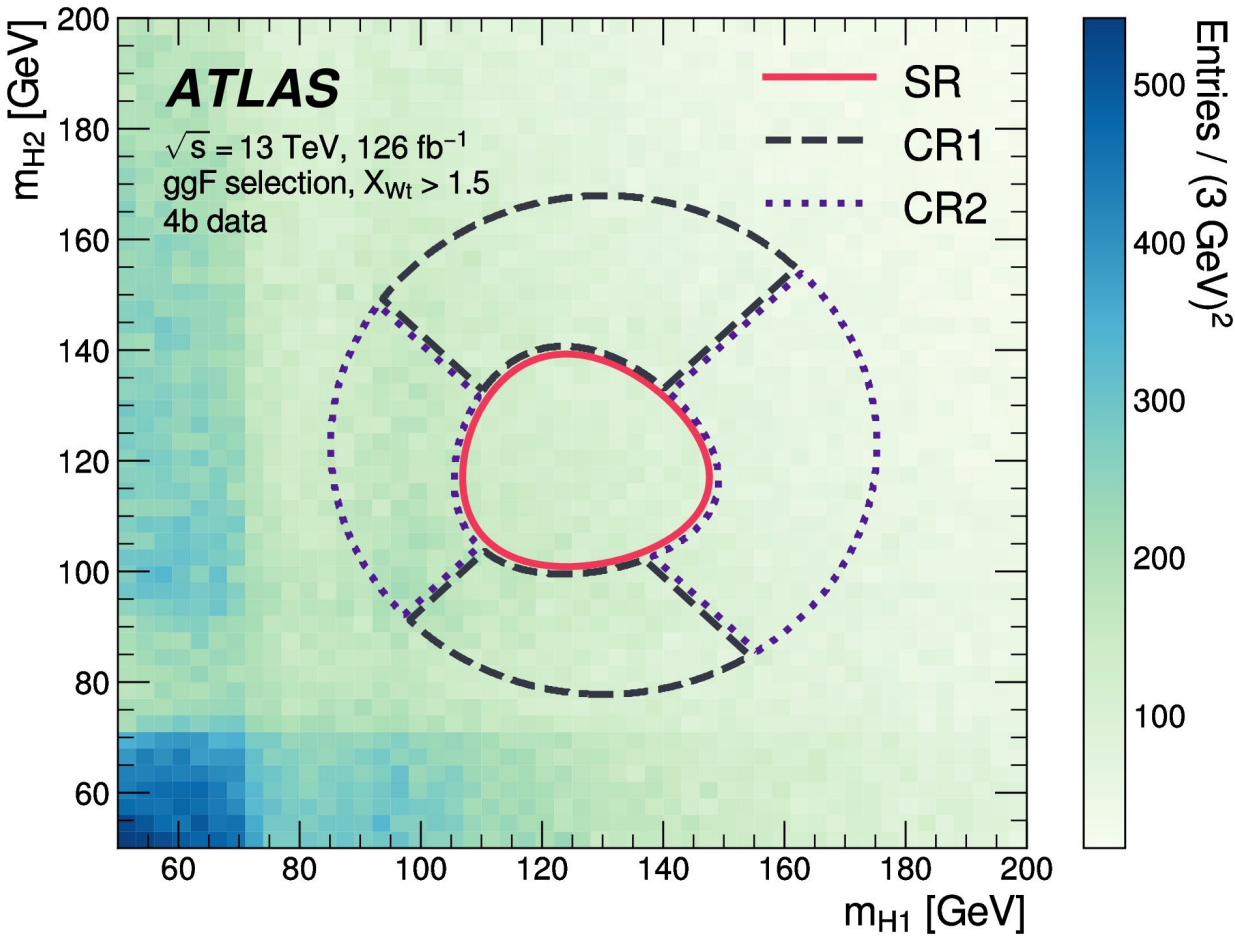
Date: 2018-10-03 17:06:34 CEST

# bbbb

Select 4 b-tagged PFlow jets.  
*VBF selection requires two additional jets.*

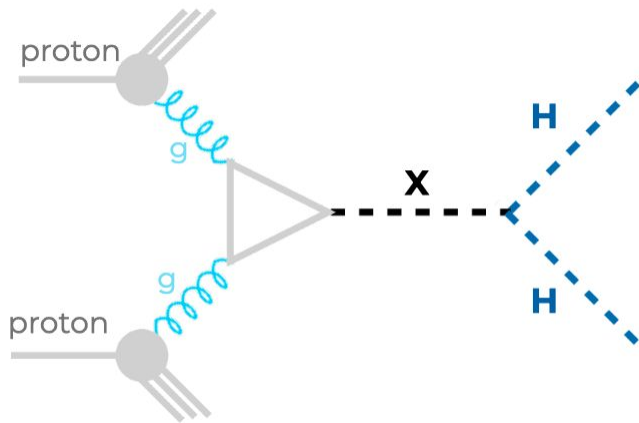
## main challenges

- Background estimation: cannot rely on MC, fully data driven approach.
  - Train a NN to learn 2b-to-4b events kinematic re-weighting.
  - Systematic uncertainties on this method dominant.
- New b-jet triggers for Run 3 to access lower  $m_{HH}$
- Use event categorisation to improve sensitivity.
- Discriminant variable:  $m_{HH}$
- We rely on excellent b-tagging!

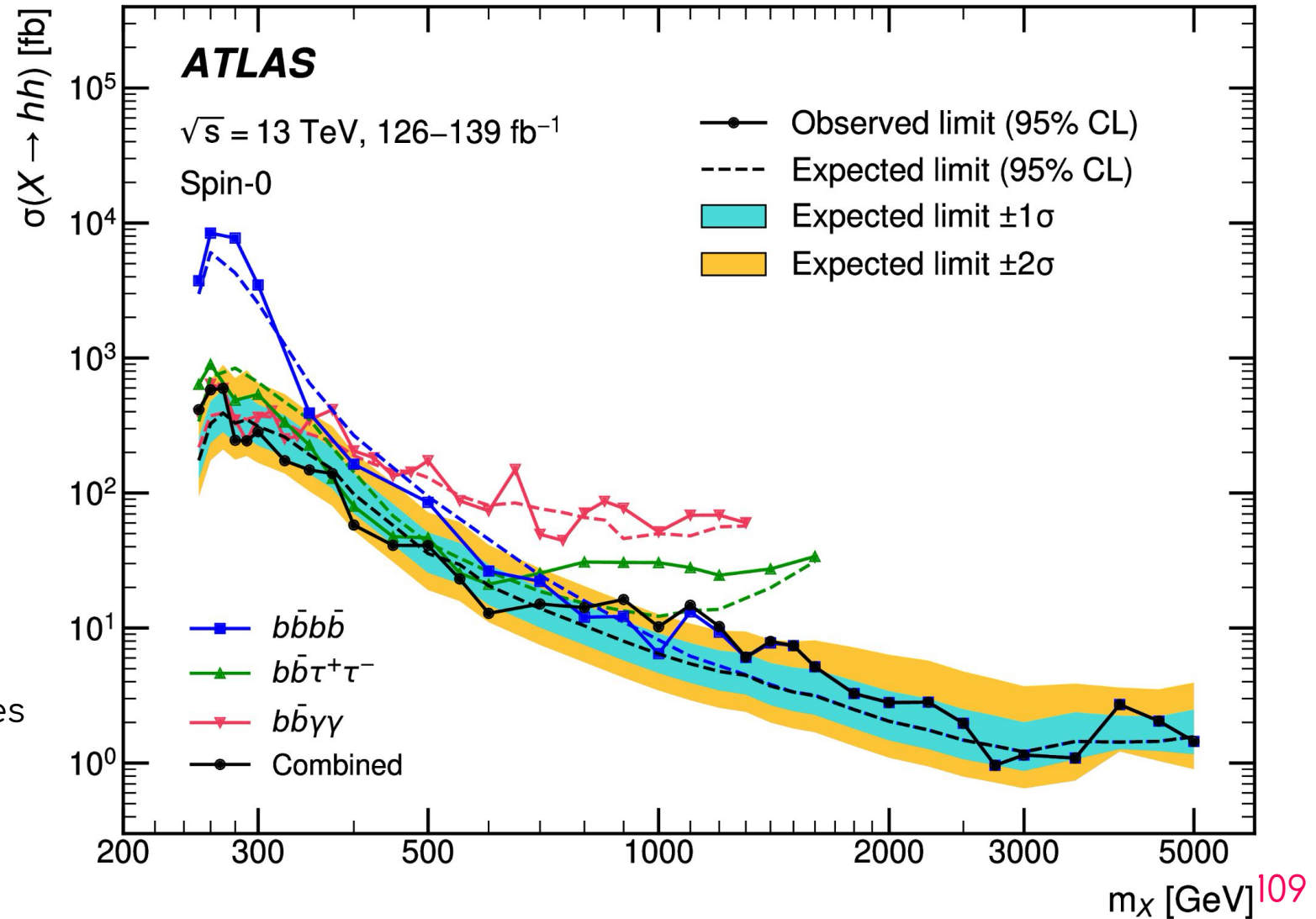


# Resonant $X \rightarrow HH$

$X \rightarrow HH$  is a probe for beyond Standard Model physics.

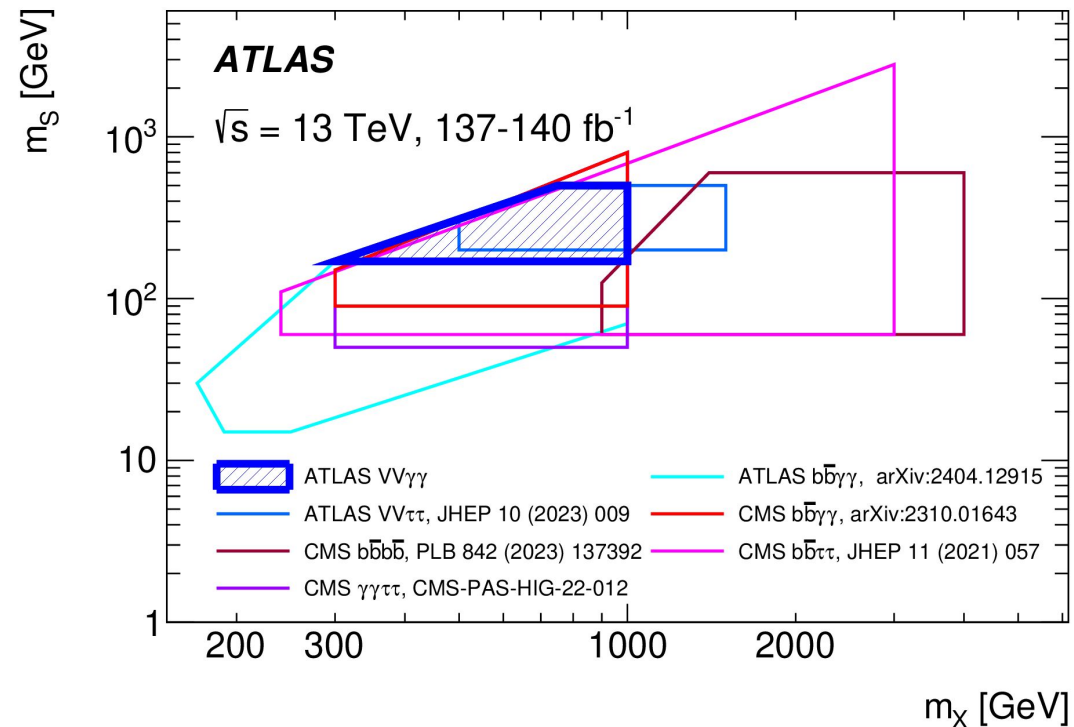


- Non-resonant and resonant analysis have a strong interplay.
- For searches of a new particle  $X \rightarrow HH$ , different kinematic regimes can be explored with complementary topologies and decay modes.



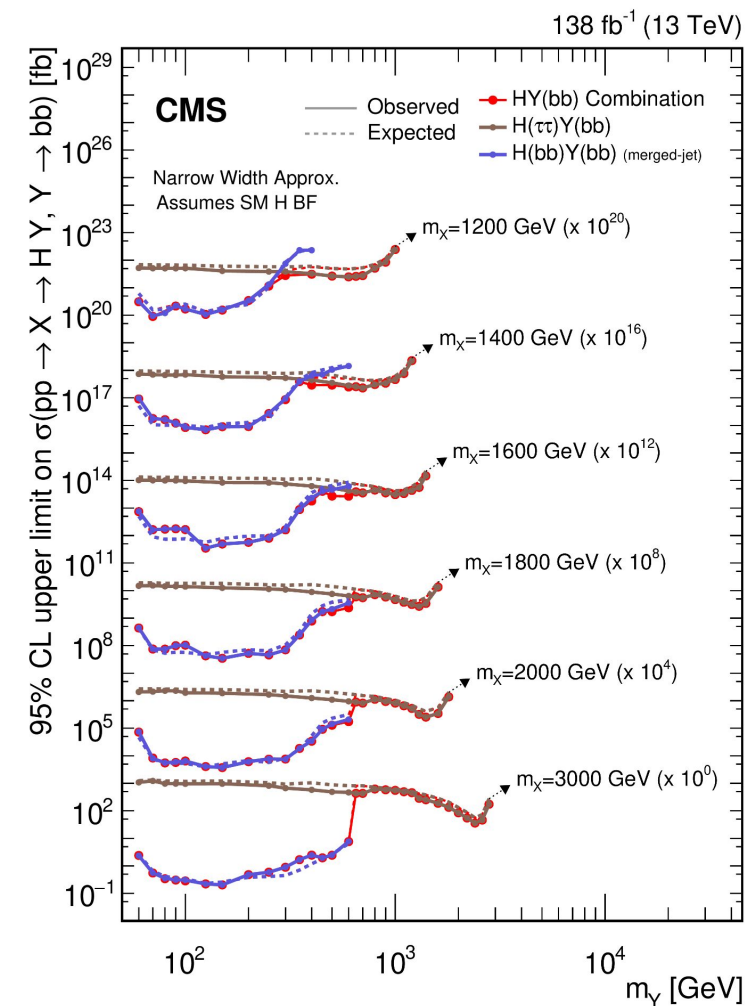
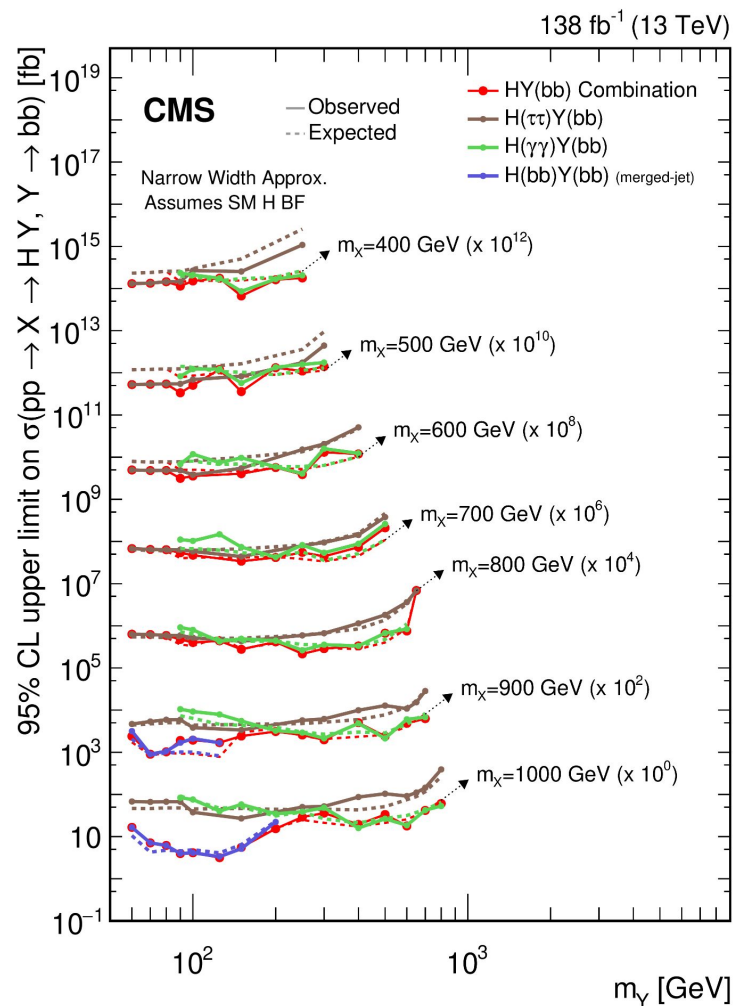
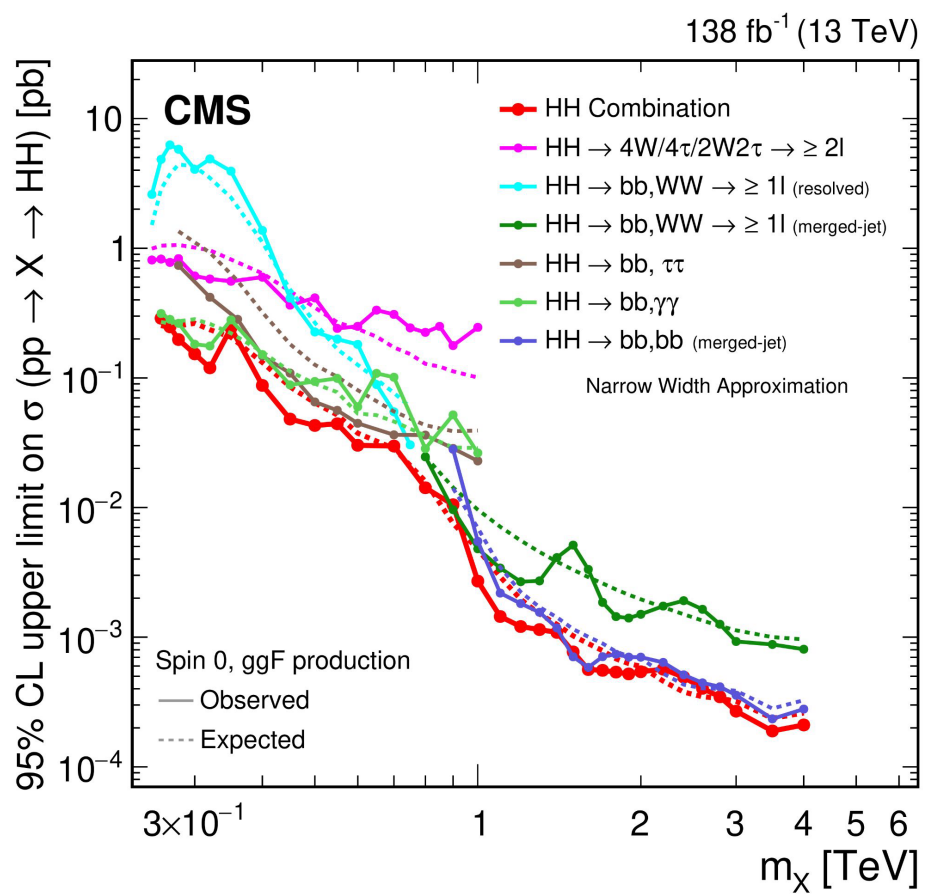
# Resonant $X \rightarrow SH$

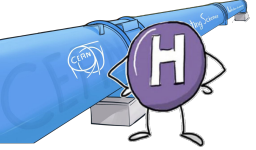
- Two additional scalars motivated by several theoretical models:
  - e.g. N2HDM (extension of 2HDM), TRSM, NMSSM.
- Different signatures can target different  $m_X$  and  $m_S$  regions.
- **Combination** would require a model assumption (or assuming SM Higgs mass-dependent BRs, as [CMS has done](#)).
  
- Published
  - [**bby**] [Submitted to JHEP](#).
  - [**VV**] [JHEP 10 \(2023\) 009](#)
  - [**γγ + VV**] [Submitted to JHE](#)



# Resonant $X \rightarrow SH$

Combination would require a model assumption  
 (or assuming SM Higgs mass-dependent BRs, as [CMS has done](#)).

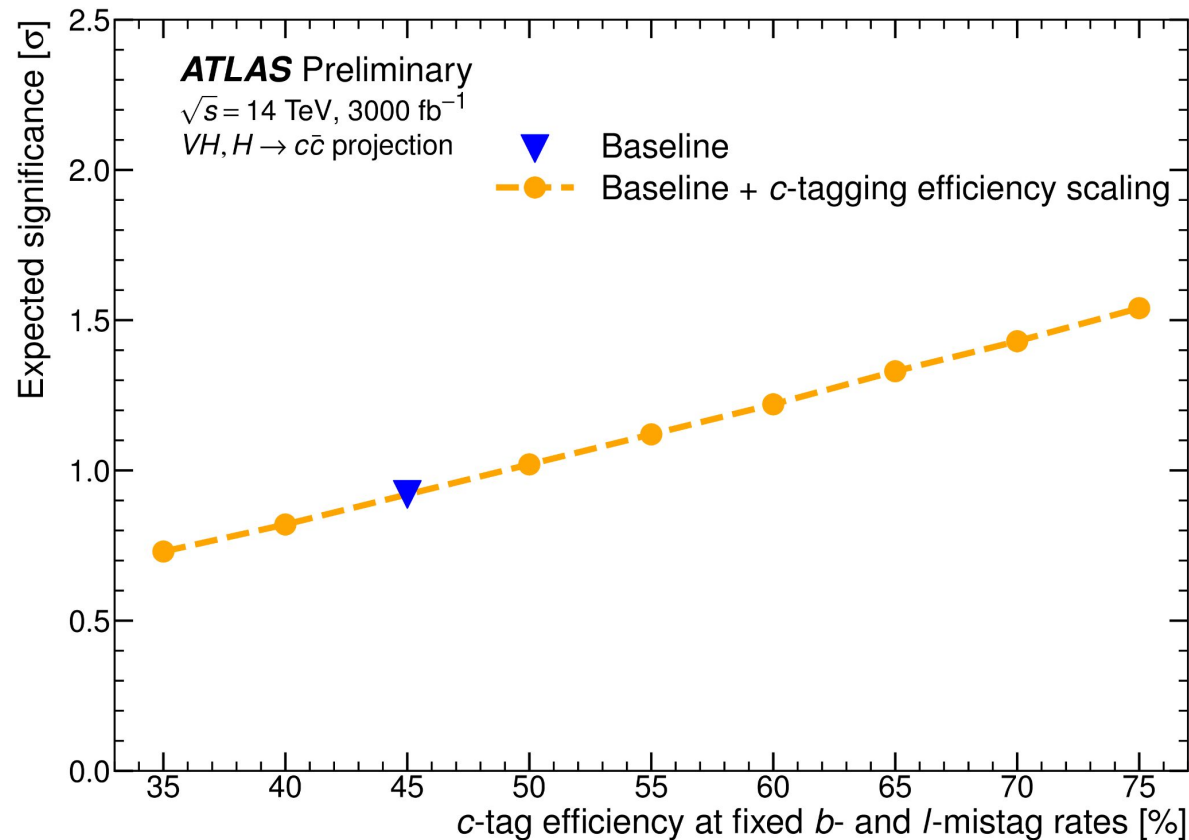
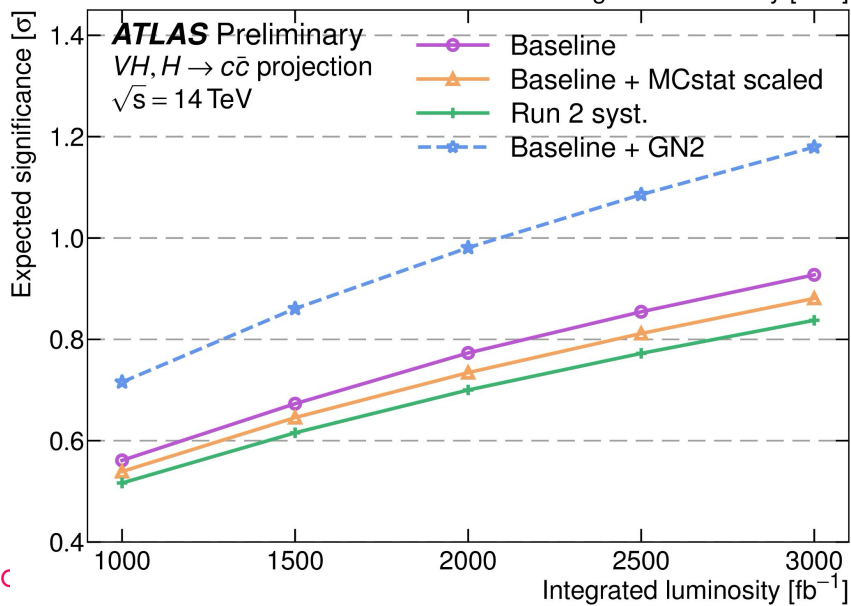
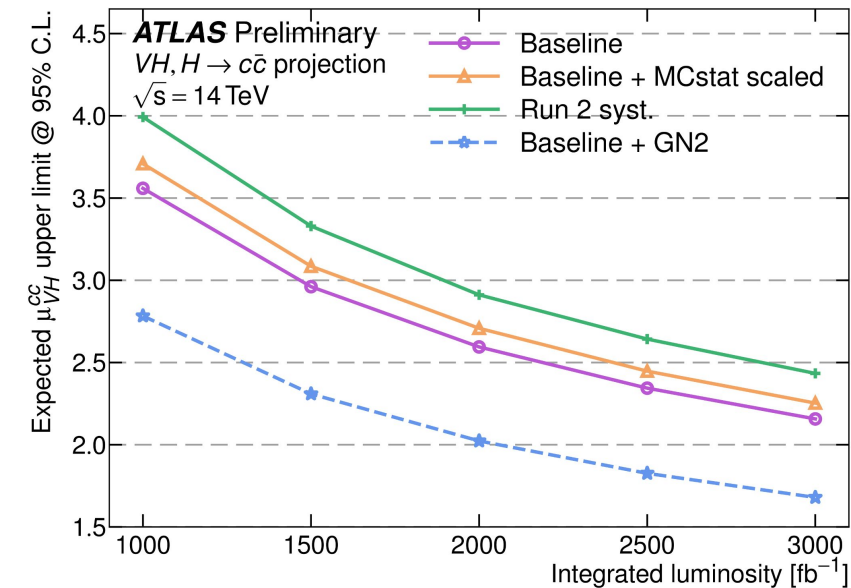




# Higgs measurements at HL-LHC

For the more challenging (or stats limited) channels, important to improve our reconstruction and identification tools

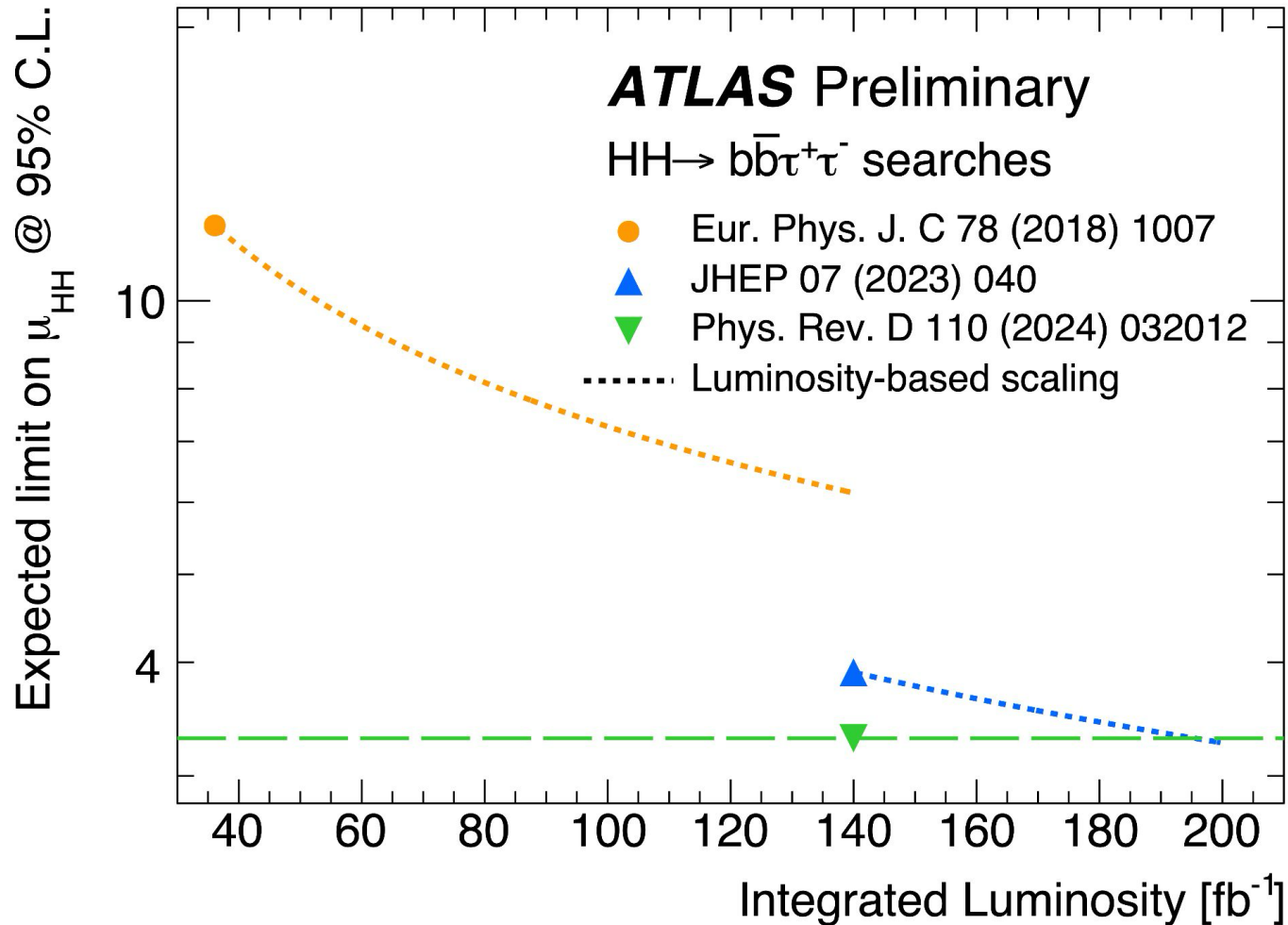
[ATL-PHYS-PUB-2025-012](#)



Better b-jet and c-jet identification would be equivalent to collecting more data!

# HL-LHC: $bb\tau\tau$

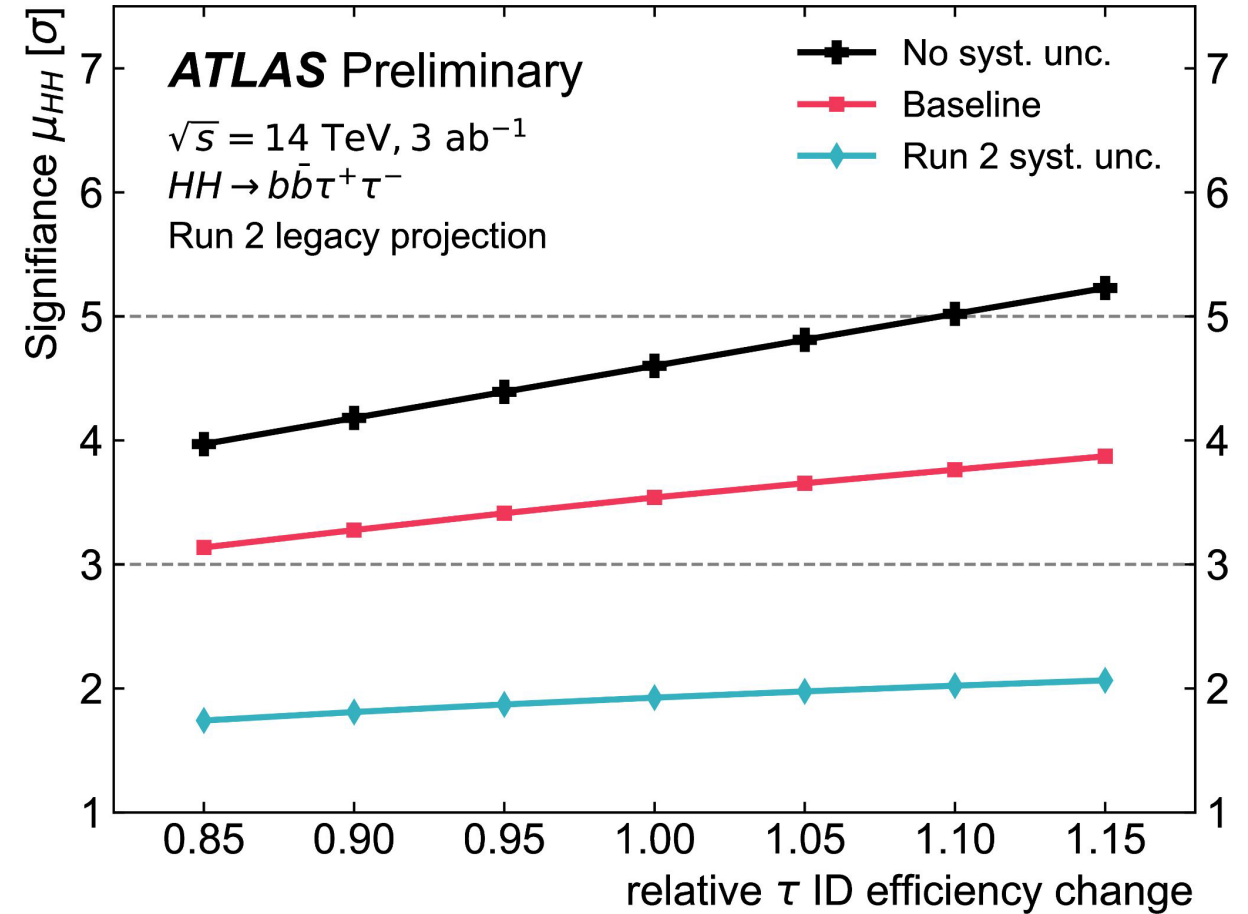
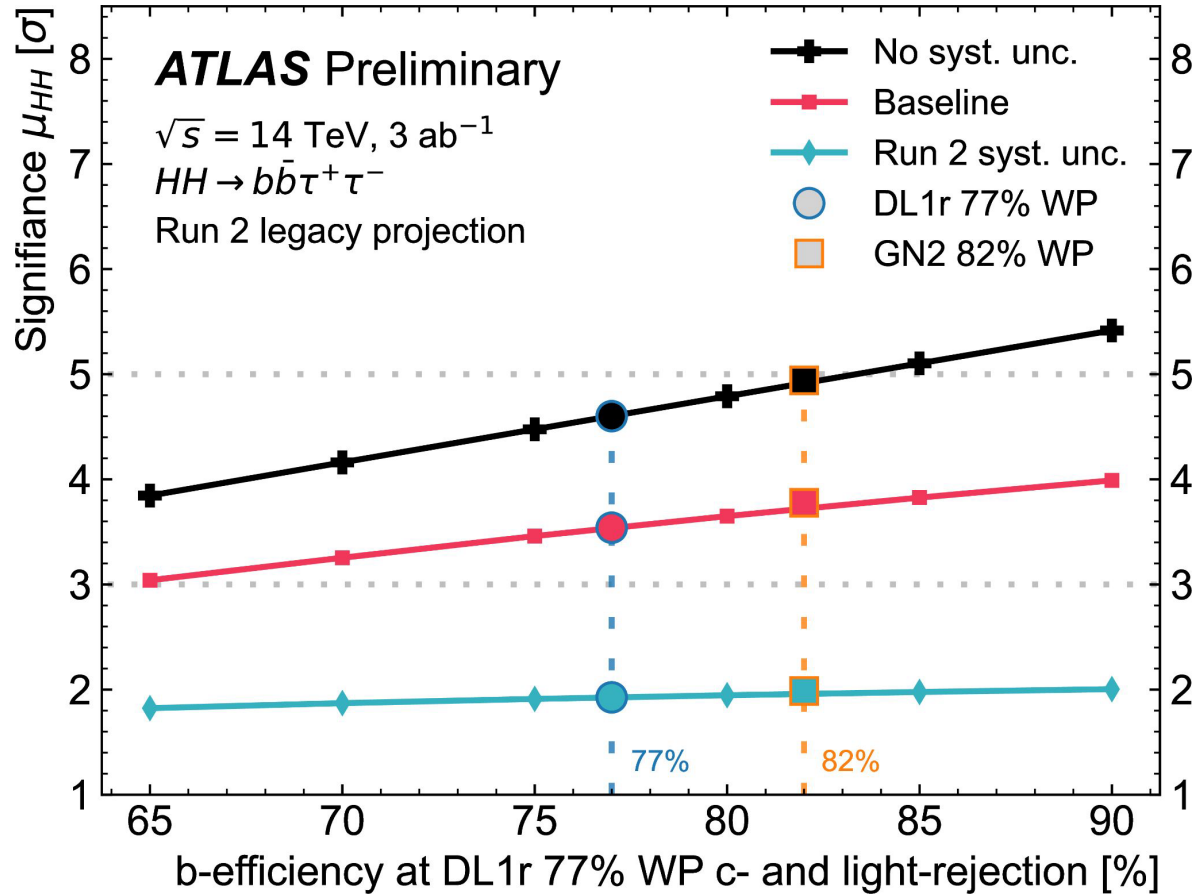
ATL-PHYS-PUB-2024-016



- Difficult to anticipate improvements in reconstruction, identification and overall analysis strategies.
- Important to identify the areas of opportunity in each analysis.
- Latest projections are based in our legacy results from Run 2 (input for the European Strategy Update 2025)
  - [HH combination](#),
  - [\$bb\tau\tau\$](#) ,  [\$bby\gamma\$](#) , [boosted VBF 4b](#),  [\$bb\ell\ell\$ +MET](#), [multi-lepton](#).
- Scenarios explored for the projections:
  - Stat-only (optimistic).
  - Baseline: based on systematic uncertainties from Run 2 analysis (some experimental uncertainties may scale with  $\sqrt{\text{luminosity}}$ , theory uncertainties halved).
  - Run 2 systematic uncertainties (pessimistic).

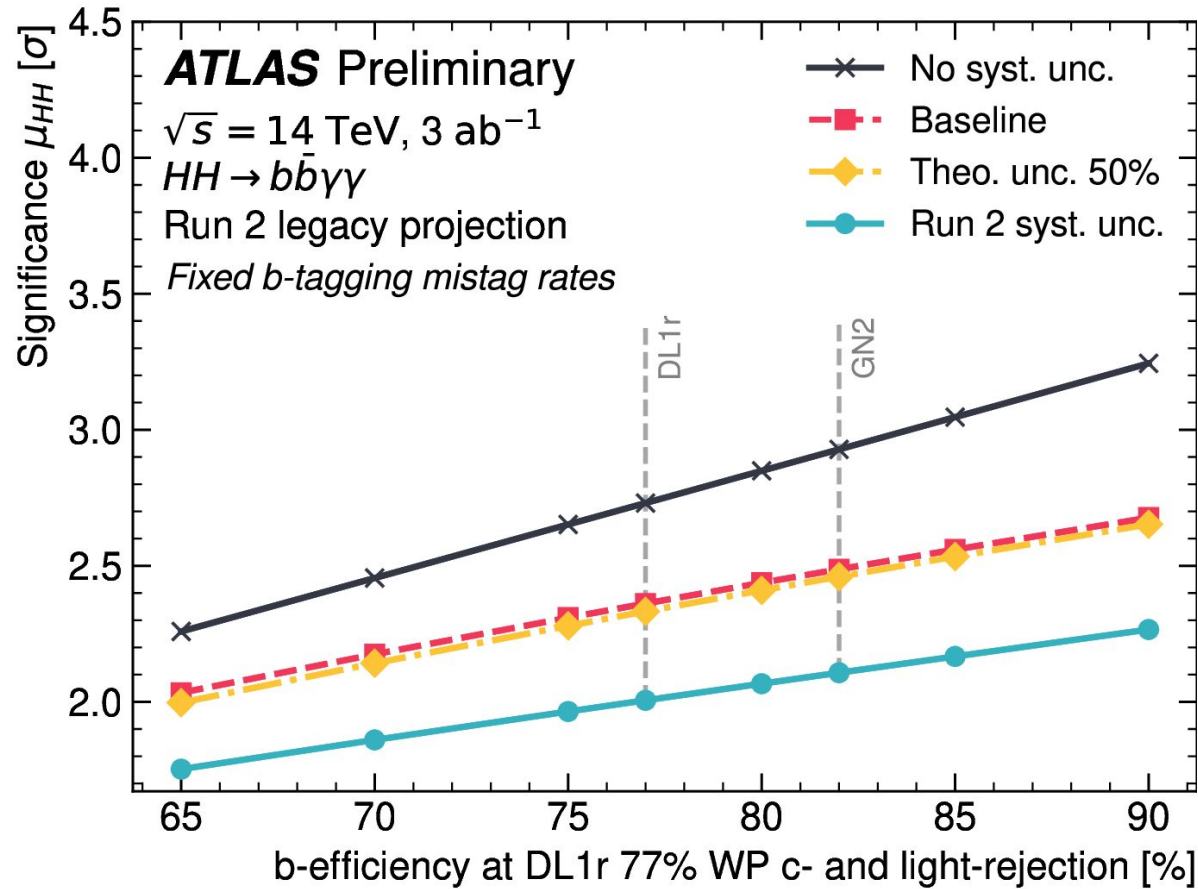
# HL-LHC: $b\bar{b}\tau^+\tau^-$

Improving our b-quark and tau-lepton identification.

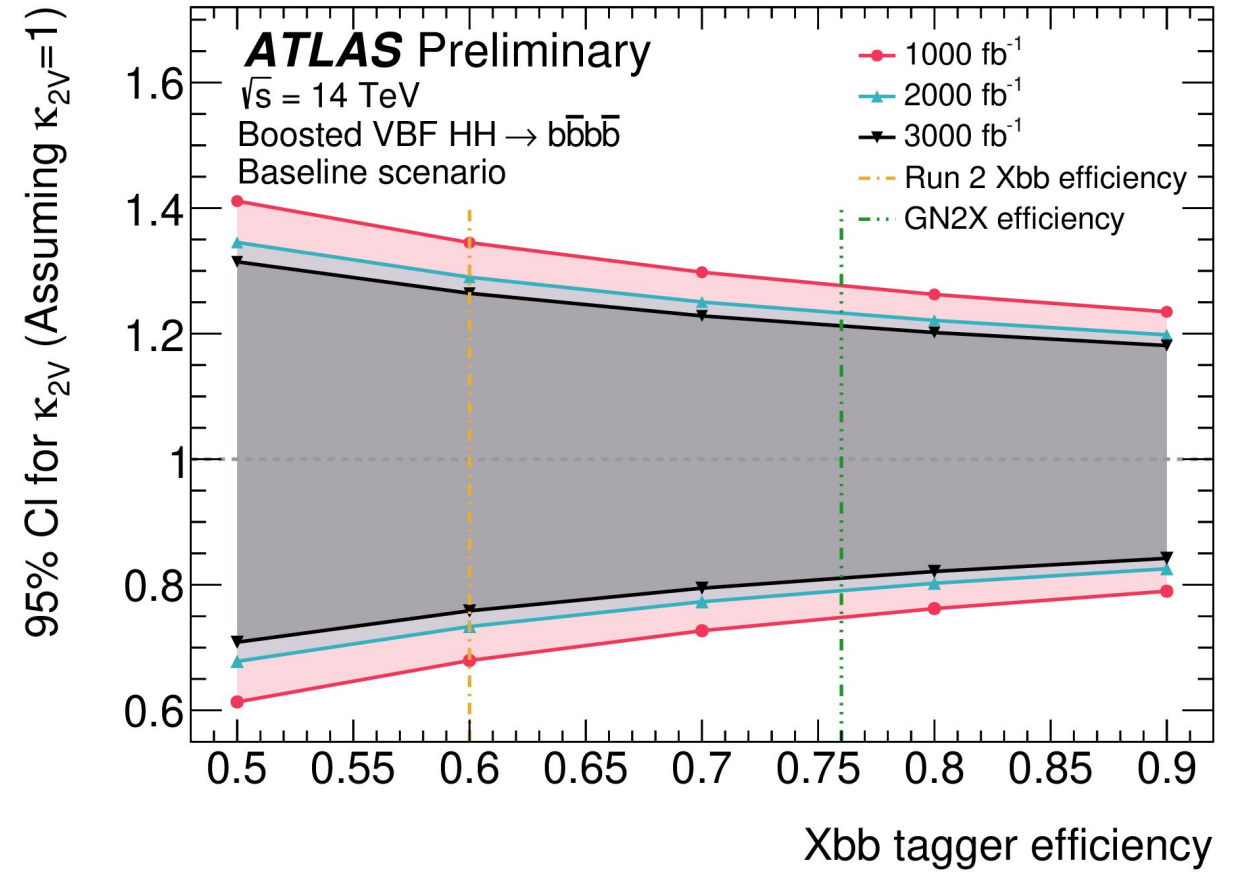


# HL-LHC: $b\bar{b}\gamma\gamma$ & boosted VBF 4b

Improving our b-quark identification.



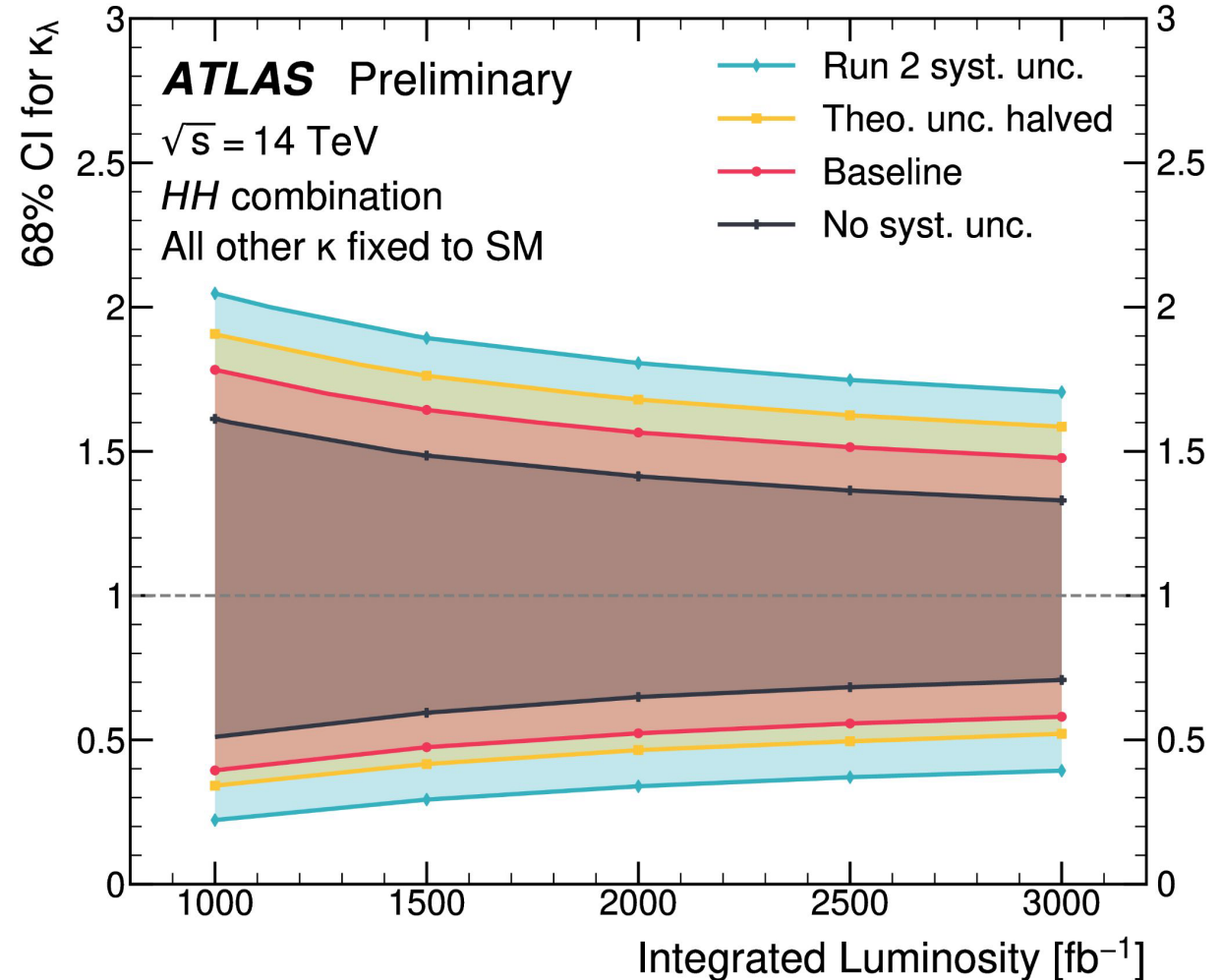
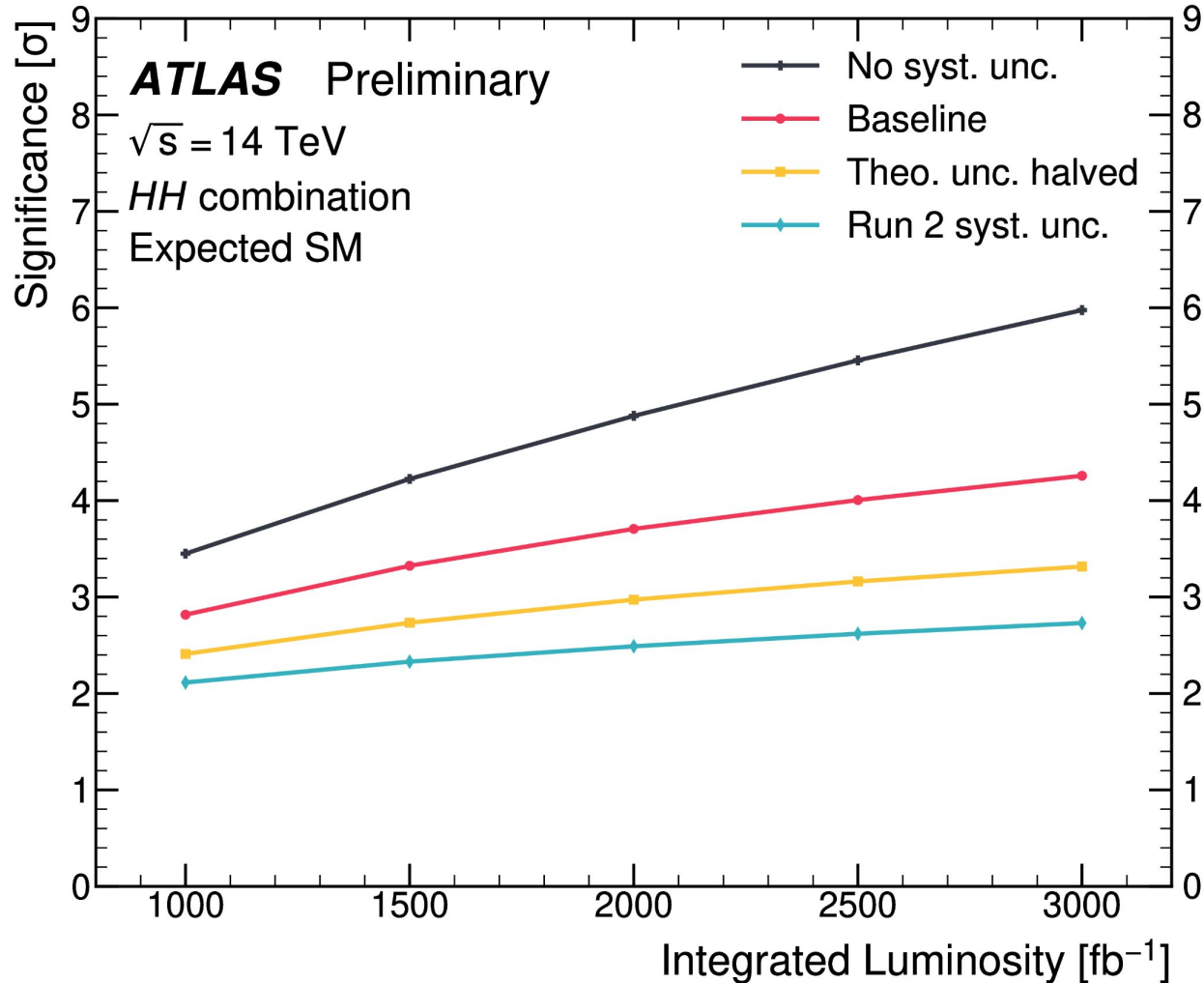
Improving our boosted  $H \rightarrow b\bar{b}$  identification



# HL-LHC discovery potential

For 3000 fb<sup>-1</sup> at 14 TeV the discovery significance for the SM Higgs boson pair production is 4.3σ (5.9σ if systematics are neglected).  $\kappa_\lambda$  is expected to be measured as

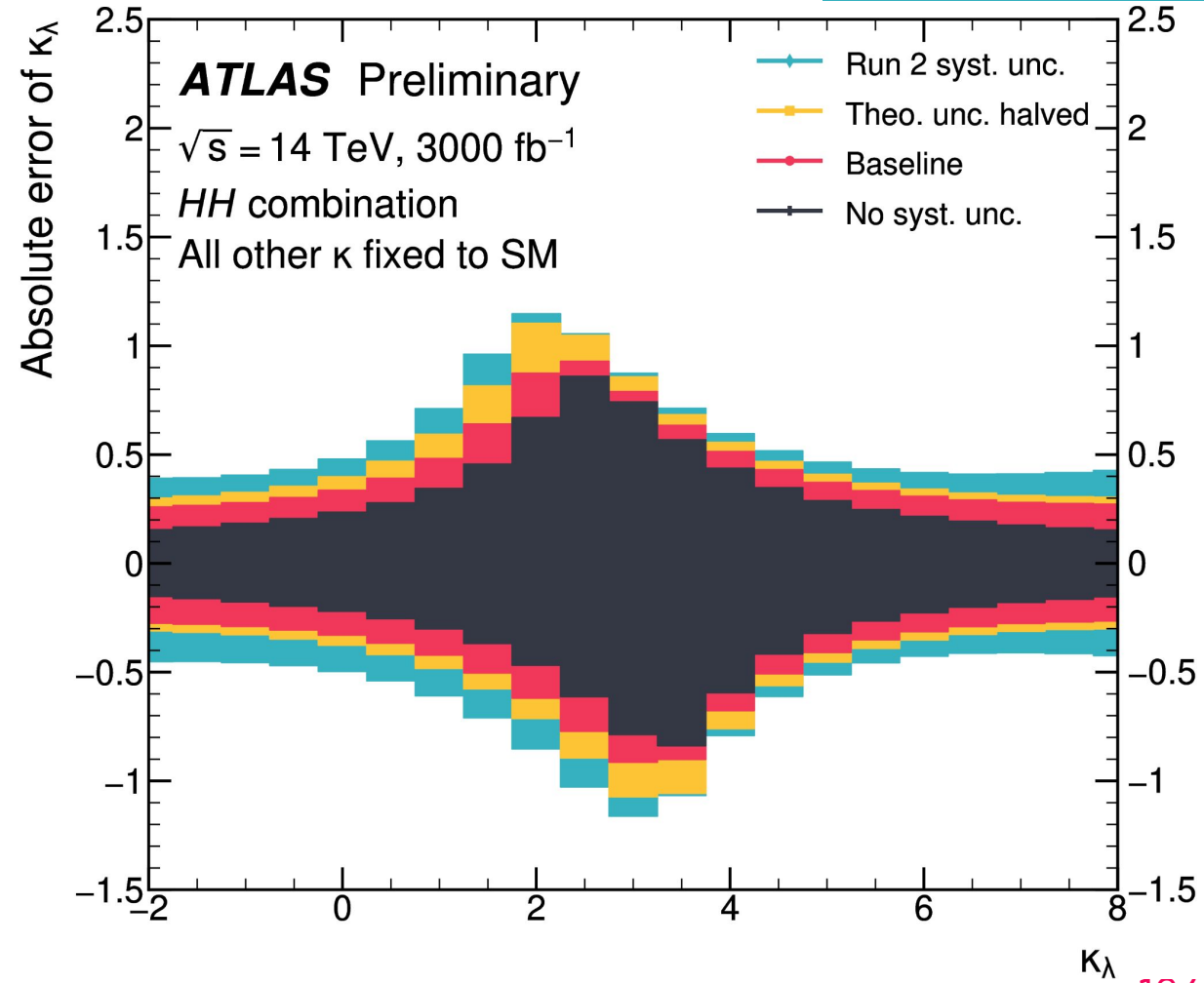
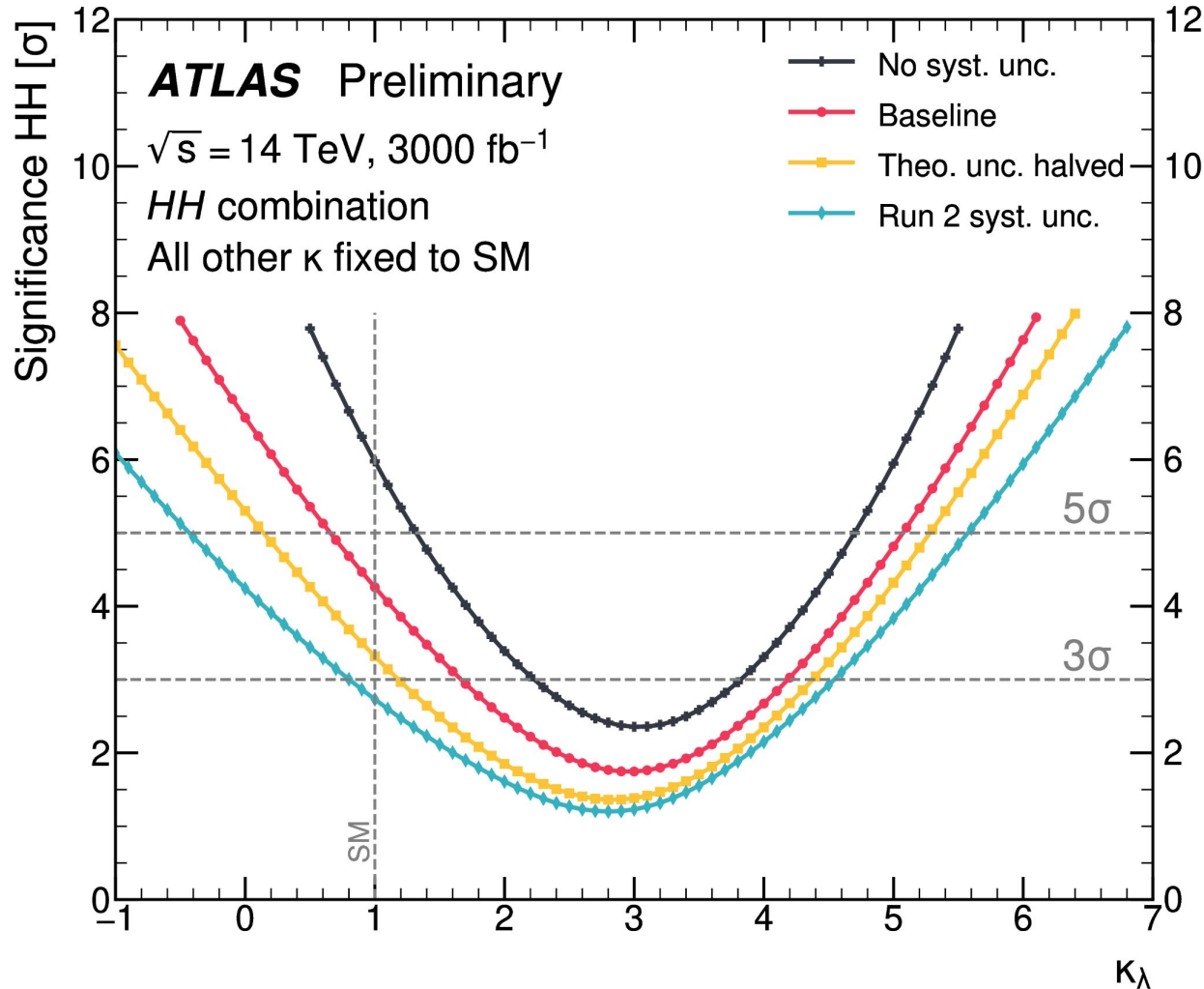
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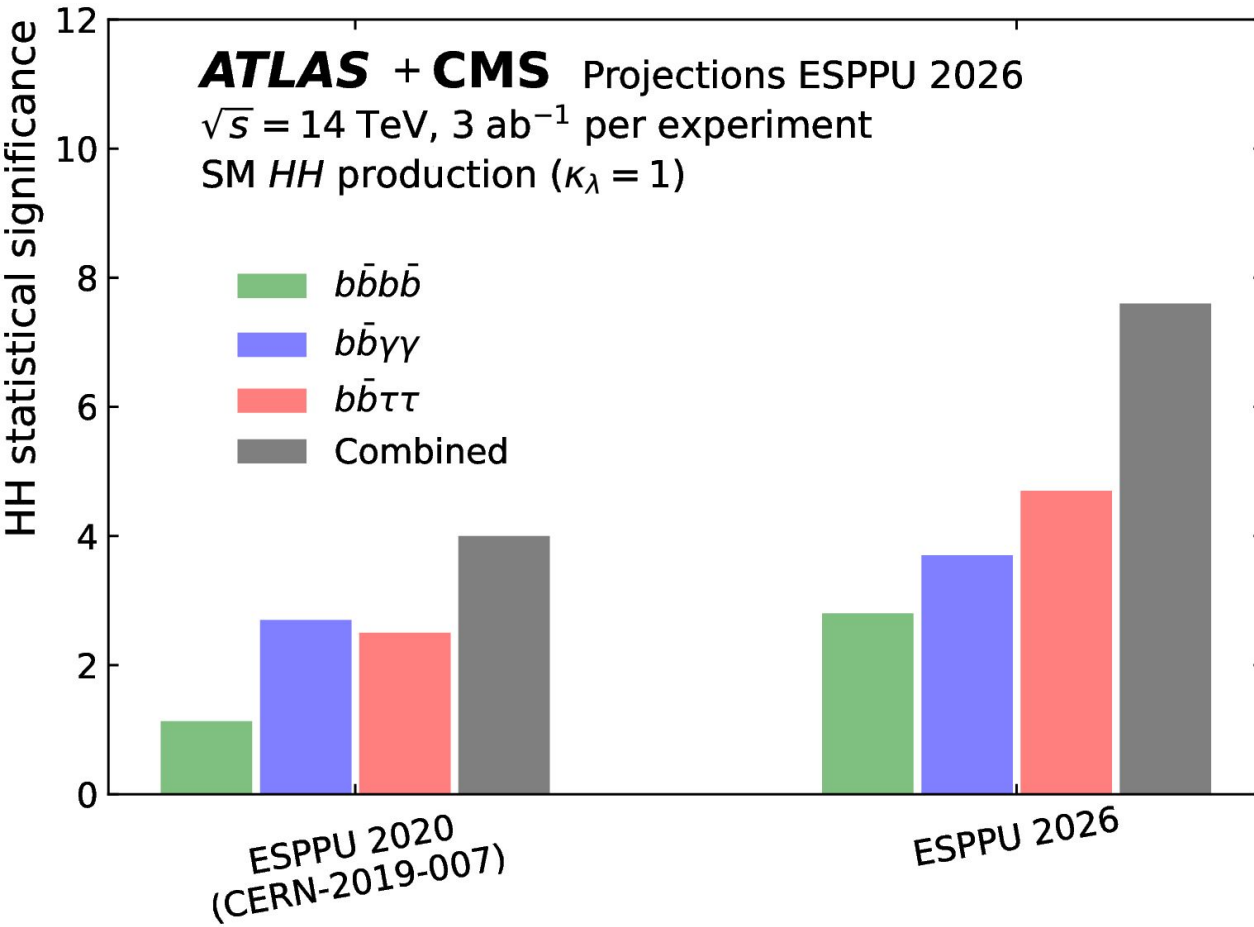
# HL-LHC discovery potential

For 3000 fb<sup>-1</sup> at 14 TeV the discovery significance for the SM Higgs boson pair production is 4.3σ (5.9σ if systematics are neglected).  $\kappa_\lambda$  is expected to be measured as  $1.0^{+0.48}_{-0.42}$ .

ATL-PHYS-PUB-2025-006



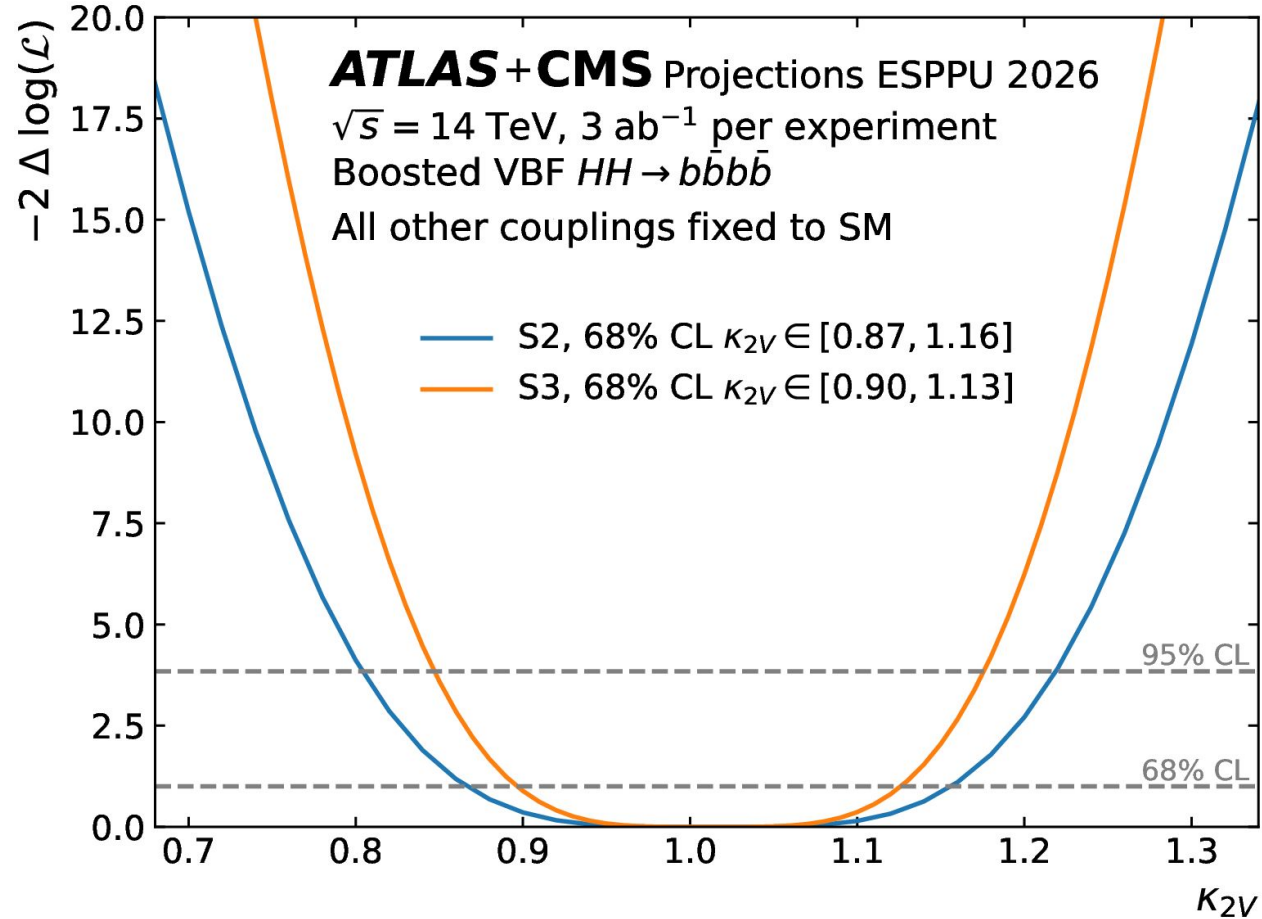
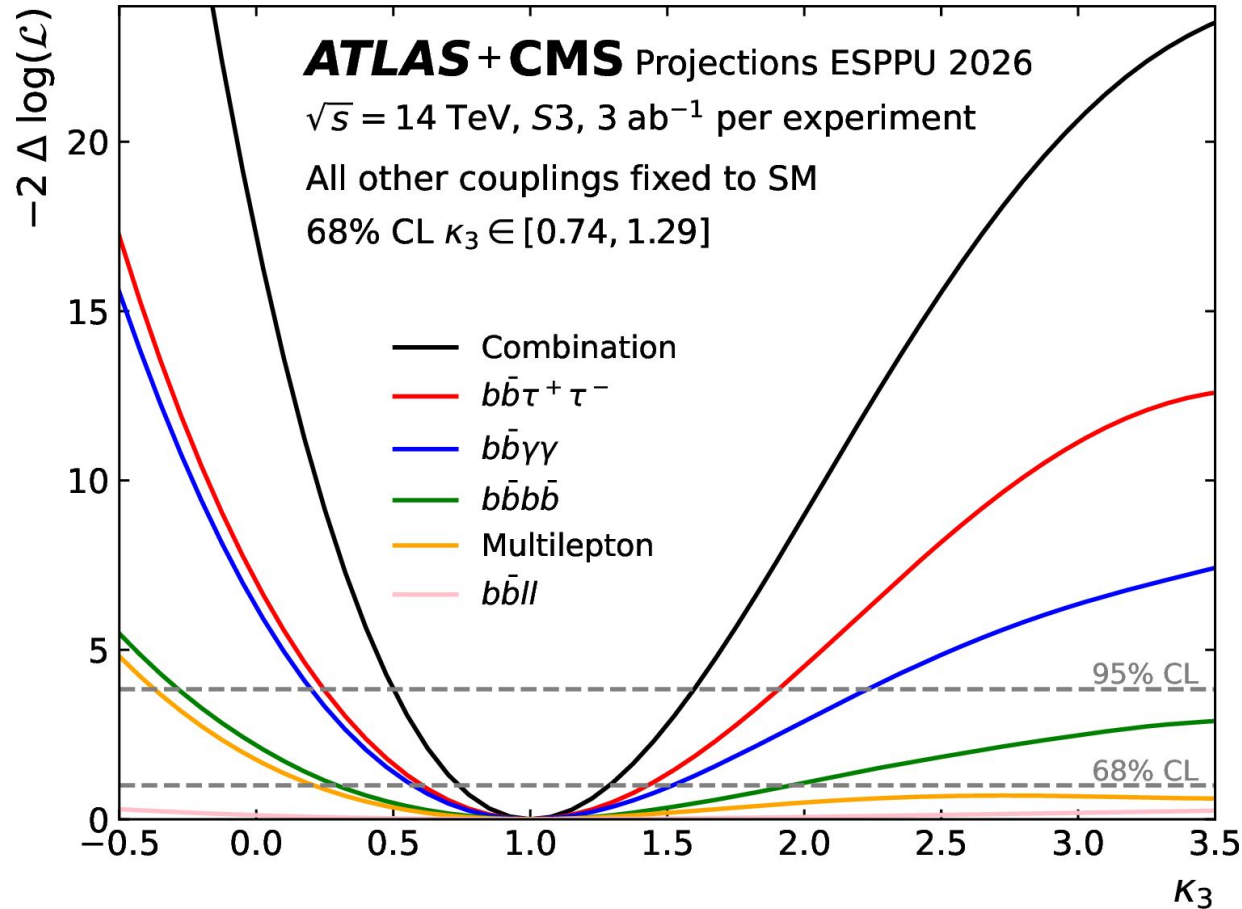
# HL-LHC: ATLAS + CMS



	$3 \text{ ab}^{-1}$ (S2)		$3 \text{ ab}^{-1}$ (S3)	
	ATLAS	CMS	ATLAS	CMS
<i>HH</i> statistical significance				
$b\bar{b}\tau^+\tau^-$	3.5 <sup>†</sup>	2.4	<b>3.8<sup>†</sup></b>	<b>2.7</b>
$b\bar{b}\gamma\gamma$	2.4 <sup>†</sup>	2.4 <sup>†</sup>	<b>2.6<sup>†</sup></b>	<b>2.6<sup>†</sup></b>
$b\bar{b}b\bar{b}$ resolved	1.0	1.2 <sup>†</sup>	<b>1.0</b>	<b>1.3<sup>†</sup></b>
$b\bar{b}b\bar{b}$ boosted	–	2.2 <sup>†</sup>	–	<b>2.2<sup>†</sup></b>
Multilepton	1.0 <sup>†</sup>	–	<b>1.0<sup>†</sup></b>	–
$b\bar{b}l^+l^-$	0.5 <sup>†</sup>	–	<b>0.5<sup>†</sup></b>	–
Combination	4.3	4.2	<b>4.5</b>	<b>4.5</b>
ATLAS+CMS	7.2		<b>7.6</b>	
$\kappa_3$ 68% confidence interval				
ATLAS+CMS uncertainty	–27% / +31%		<b>–26% / +29%</b>	

- A  $>5\sigma$  observation will be possible already with  $2000 \text{ fb}^{-1}$  combining both experiments in the baseline scenario (S2).
  - $3000 \text{ fb}^{-1}$  may allow a single-experiment observation.
- Including 5% improvement in the b-tagging identification and tau-identification (S3) will increase the precision by 5%.

# HL-LHC: ATLAS + CMS

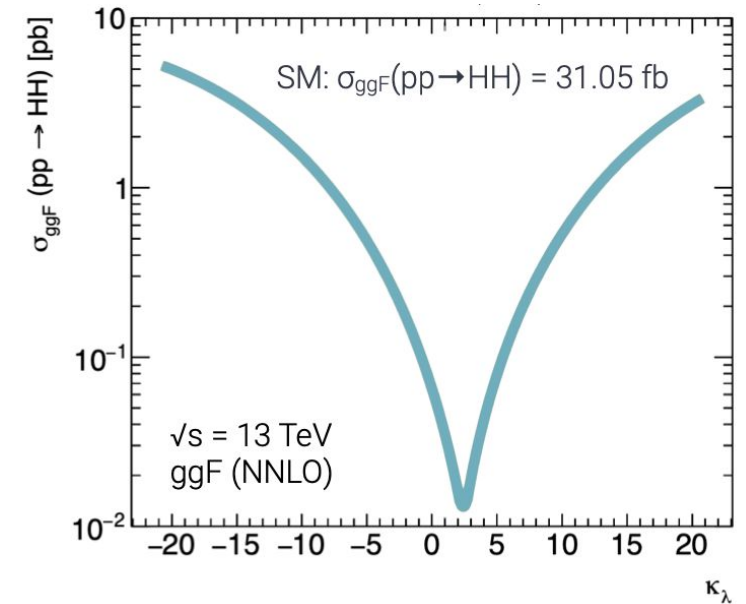
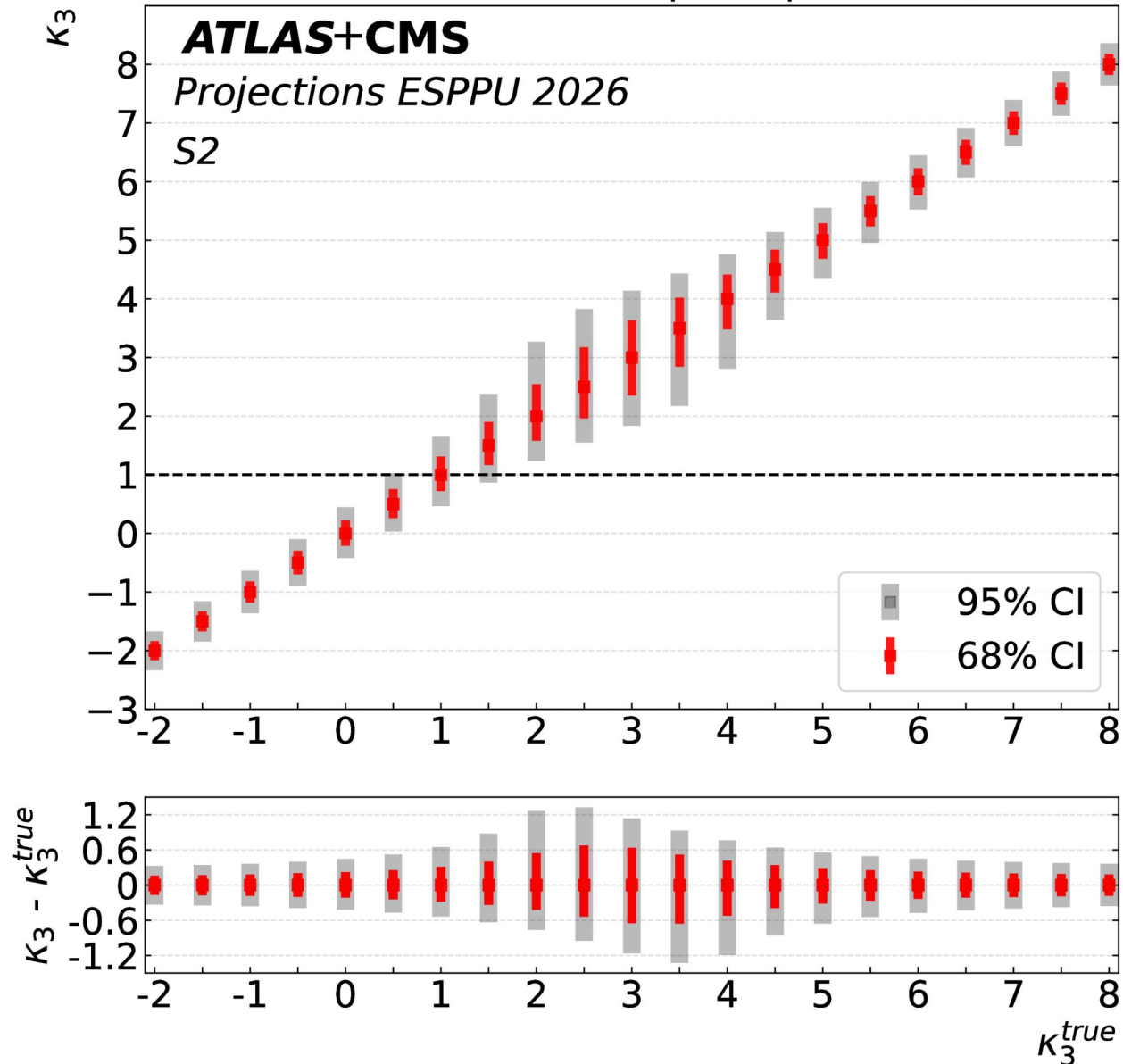


S3: Baseline scenario + additional 5% improvement in b-tagging signal efficiency and tau identification efficiency.  
 (equivalent to the DL1r  $\rightarrow$  GN2 improvement or the expected with GNTau).

$\kappa_\lambda$  is expected to be measured as  $1.0^{+0.29}_{-0.26}$ .

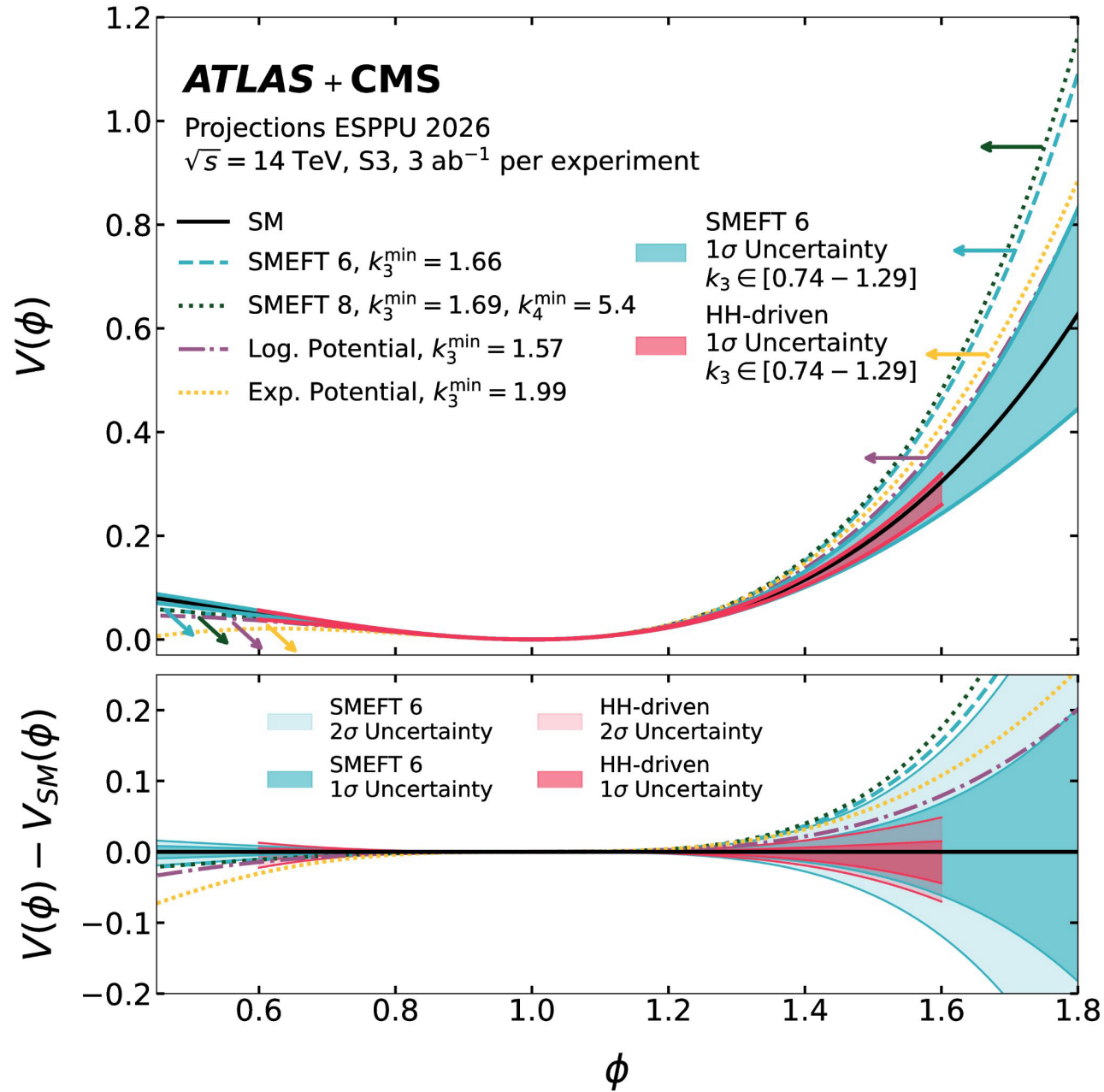
# HL-LHC: ATLAS + CMS

3 ab<sup>-1</sup> per experiment (14 TeV)



S2: baseline scenario  
Our precision depends on the  $\kappa_\lambda$  realised in nature.

# HL-LHC: ATLAS + CMS



Measuring the self-coupling can provide discrimination between different scenarios, or different models.

See [talk](#) by Patrick Meade.

But, keep in mind that we will require to measure **triple-Higgs production** to fully describe the shape of the Higgs potential.

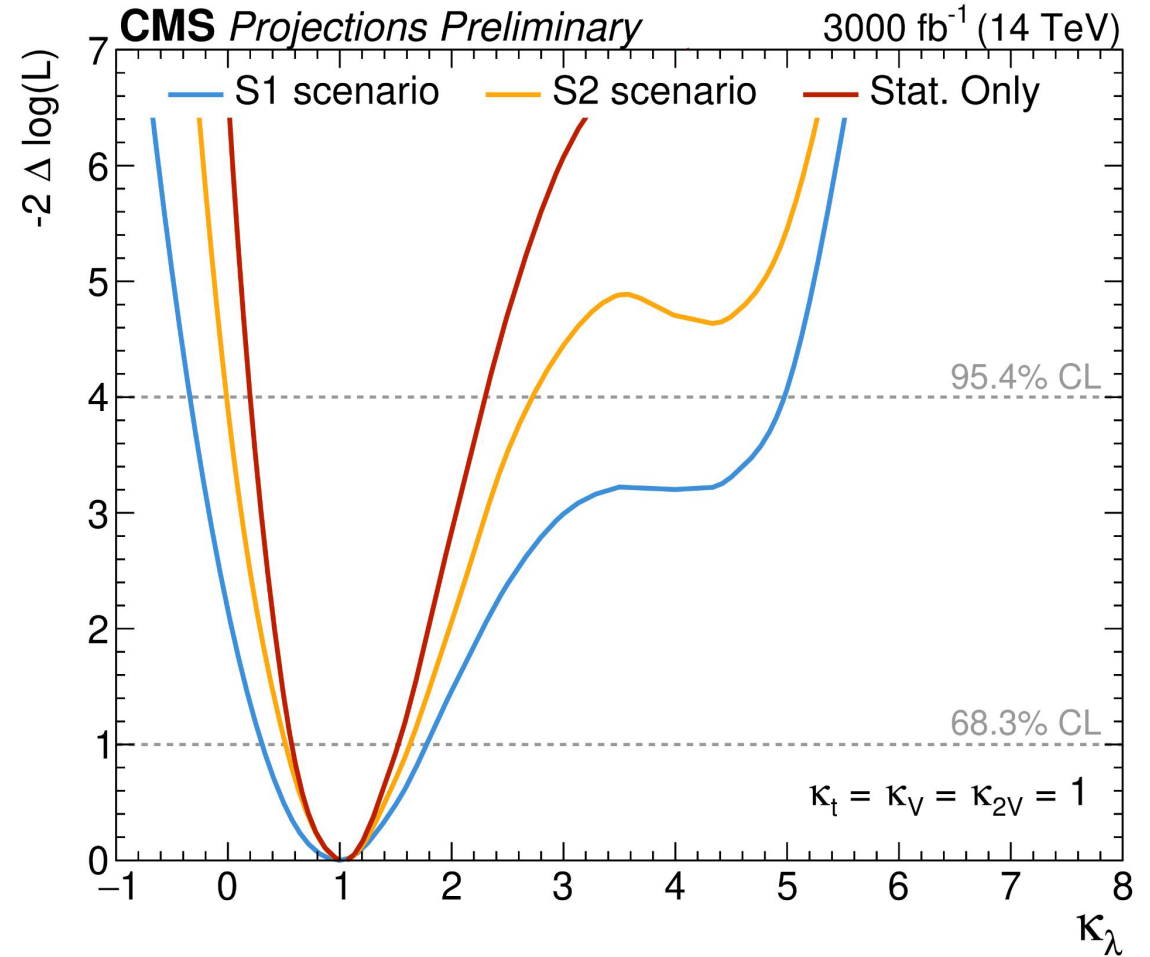
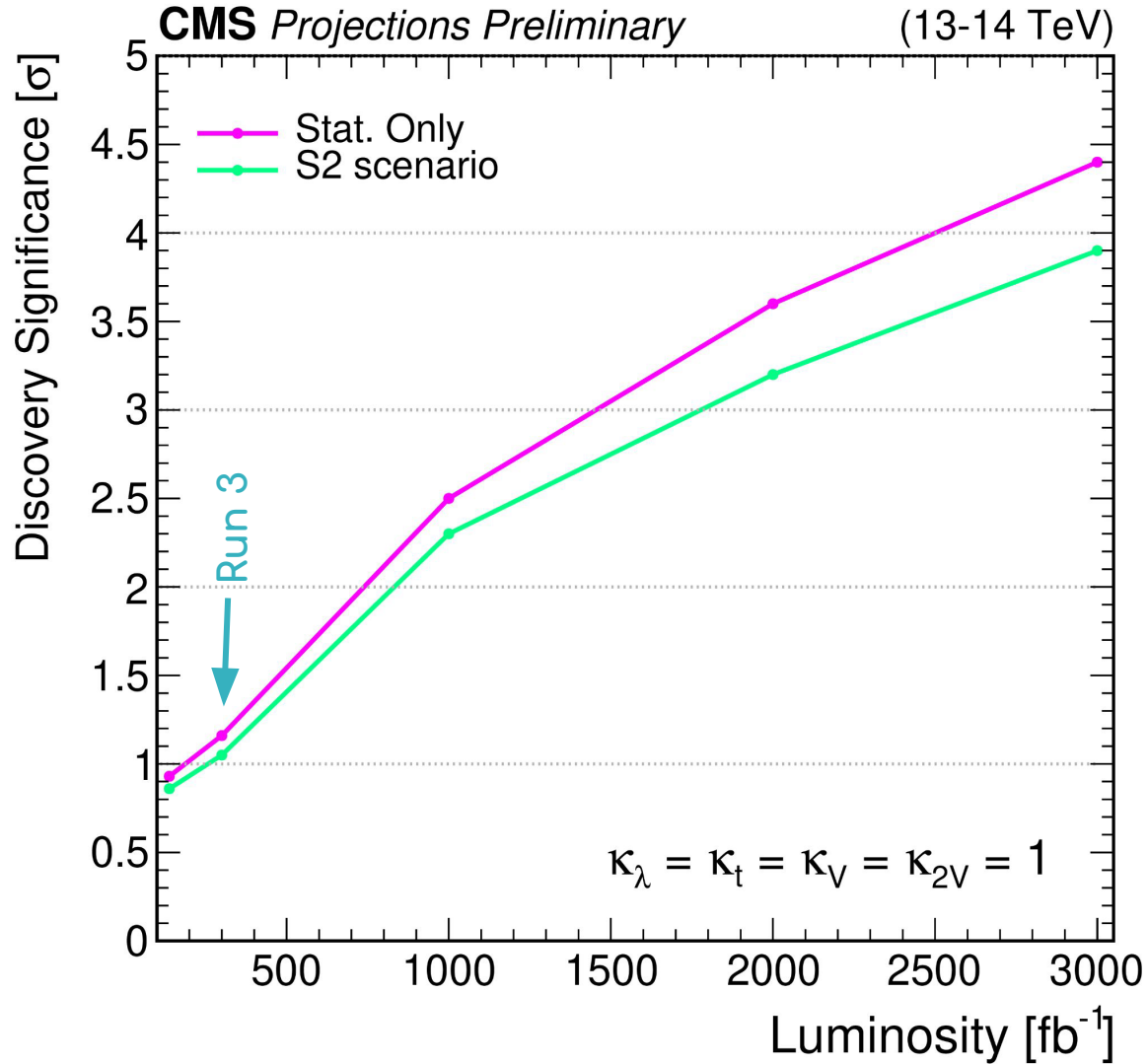
BSM scenarios where new heavy particles lie beyond a large energy scale cut-off, so cannot be produced at the LHC. The potential is then expressed as a deformation of the SM EWSB potential.

Scenarios considered are in the context of SMEFT (dim 6 and 8) and modifications of the low-energy SM Higgs potential by small term (logarithmic or exponential).

These scenarios predict a strong first-order phase transition in the early universe for  $\kappa_\lambda > \kappa_{\text{min}}$ .

# HL-LHC: CMS

Extrapolating their latest combination results.



Discovery significance as a function of  $\kappa_\lambda$

# HHH

