HH at LHC and beyond

Review of latest results and future prospects

16.12.2025

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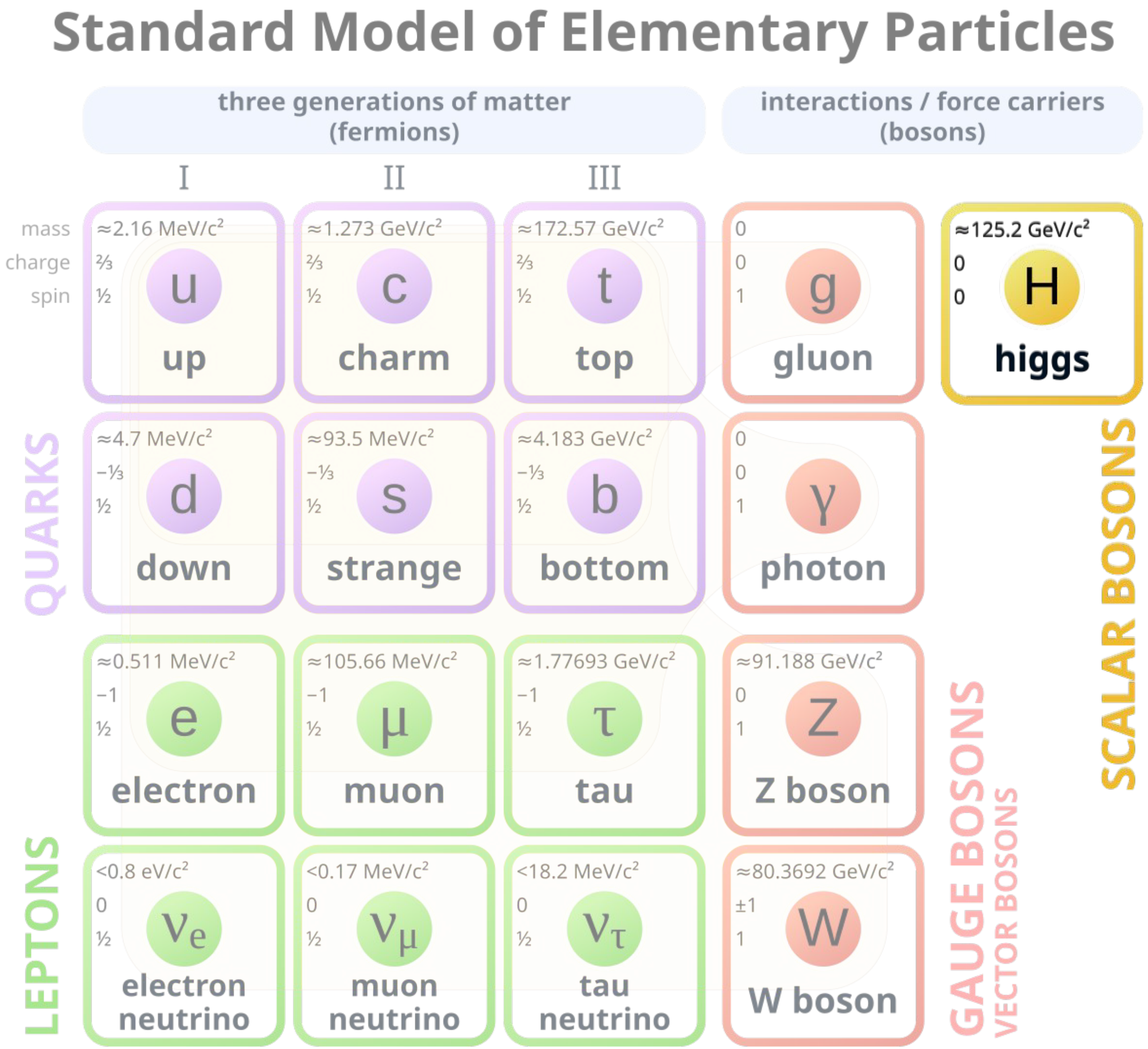
Higgs boson in the SM



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 10th year anniversary Scientific Symposium).

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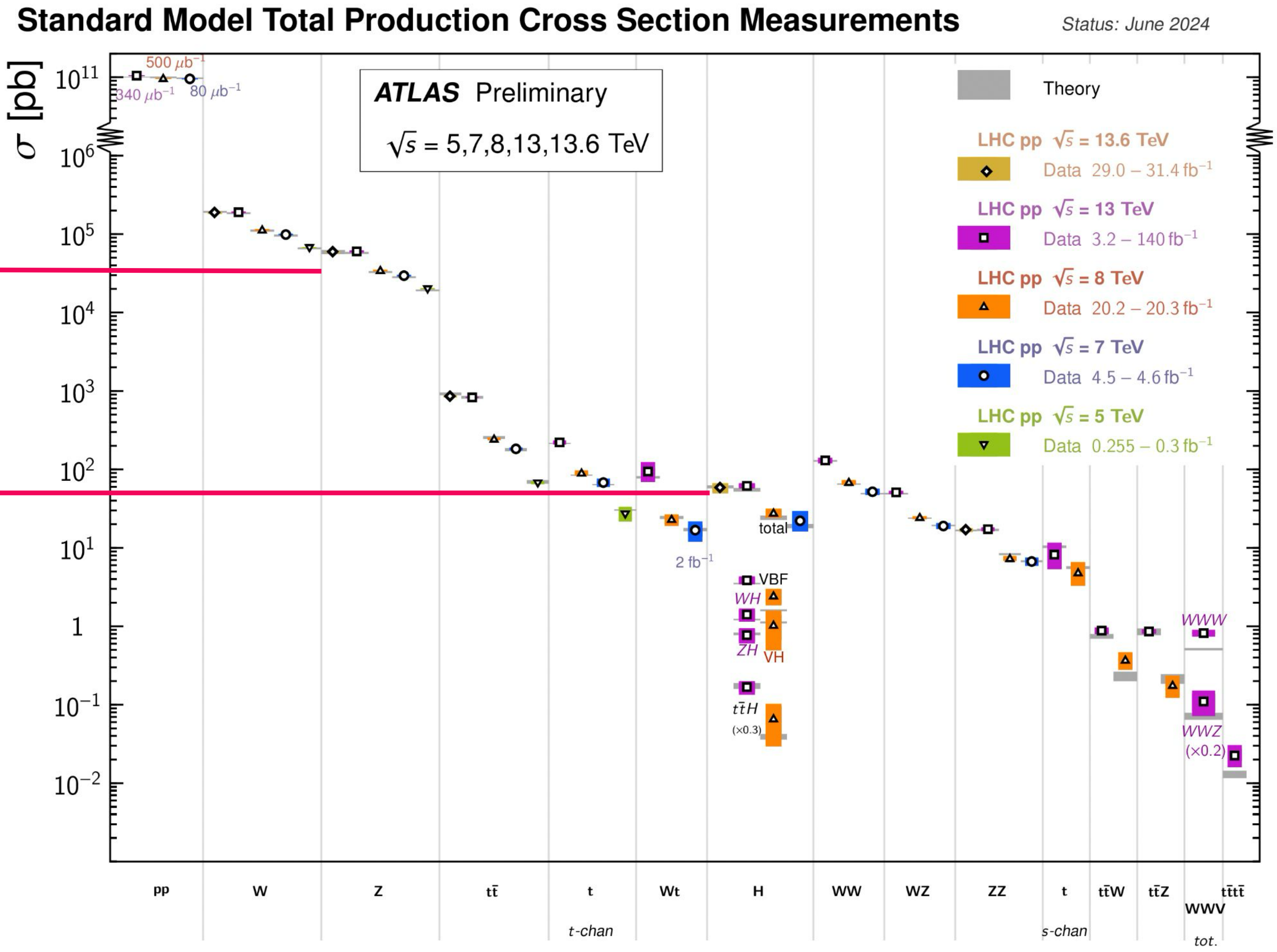
Standard Model processes

[ATLAS Public Results](#)

SM
Z production
x1000

SM
Single Higgs
production



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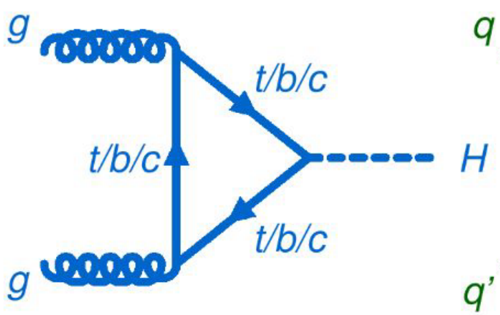
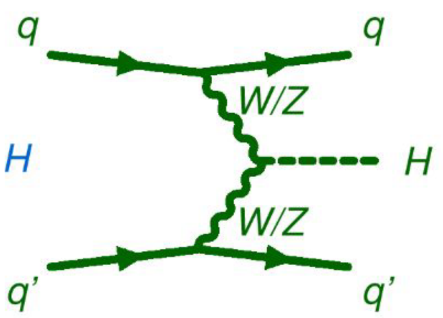
Higgs boson at the LHC

Handbook of LHC Higgs Cross Sections

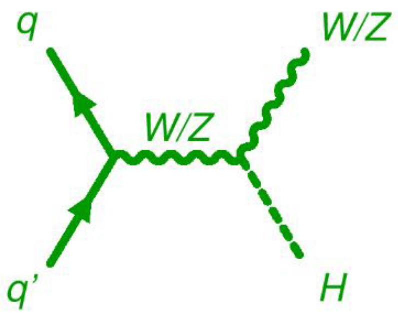
Main production mechanisms in pp collisions.



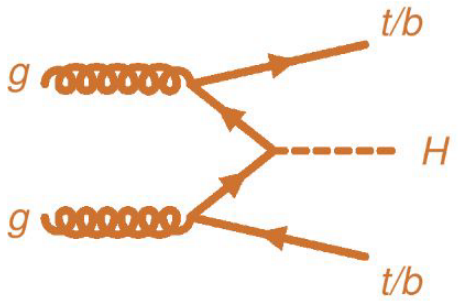
ggF ~88%
gluon-gluon fusion



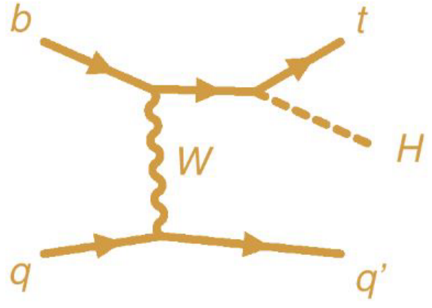
VBF ~7%
vector-boson fusion



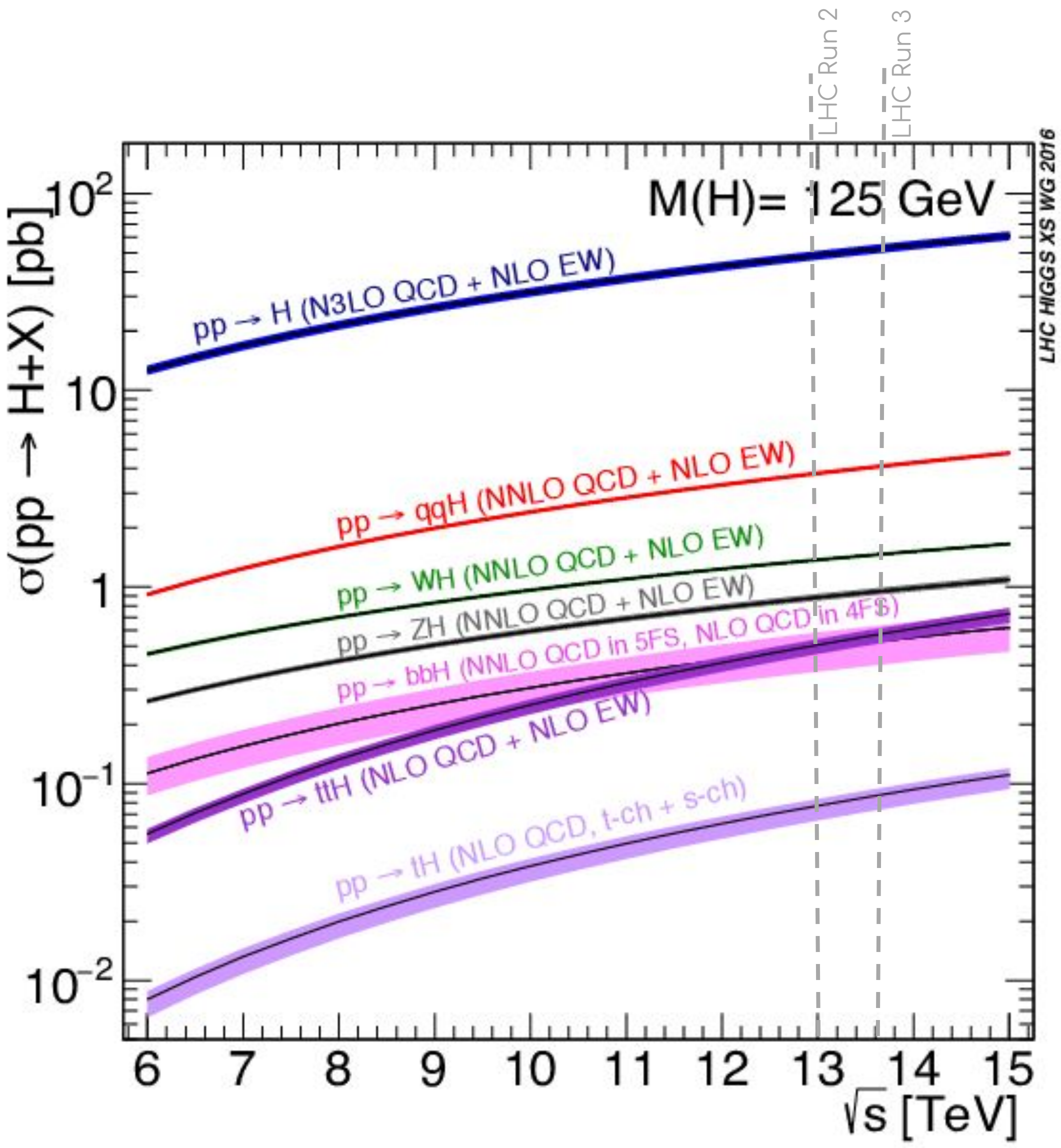
VH ~4%
vector boson associated production



ttH ~1%
tt associated production



tH
top quark associated production



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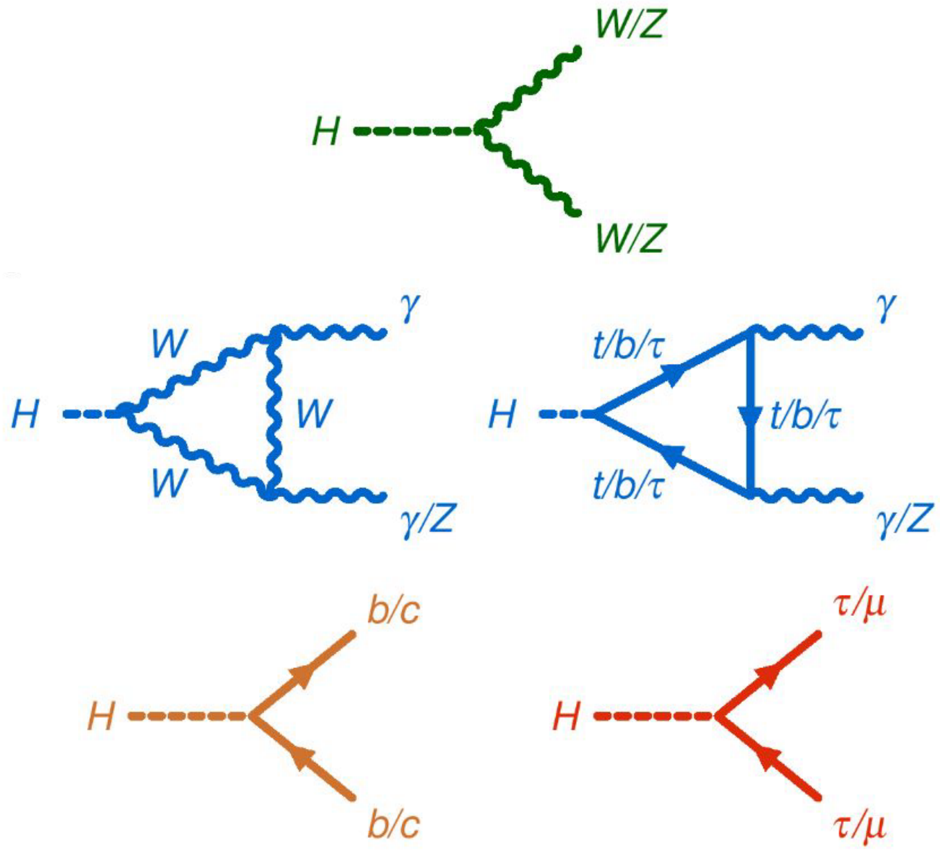
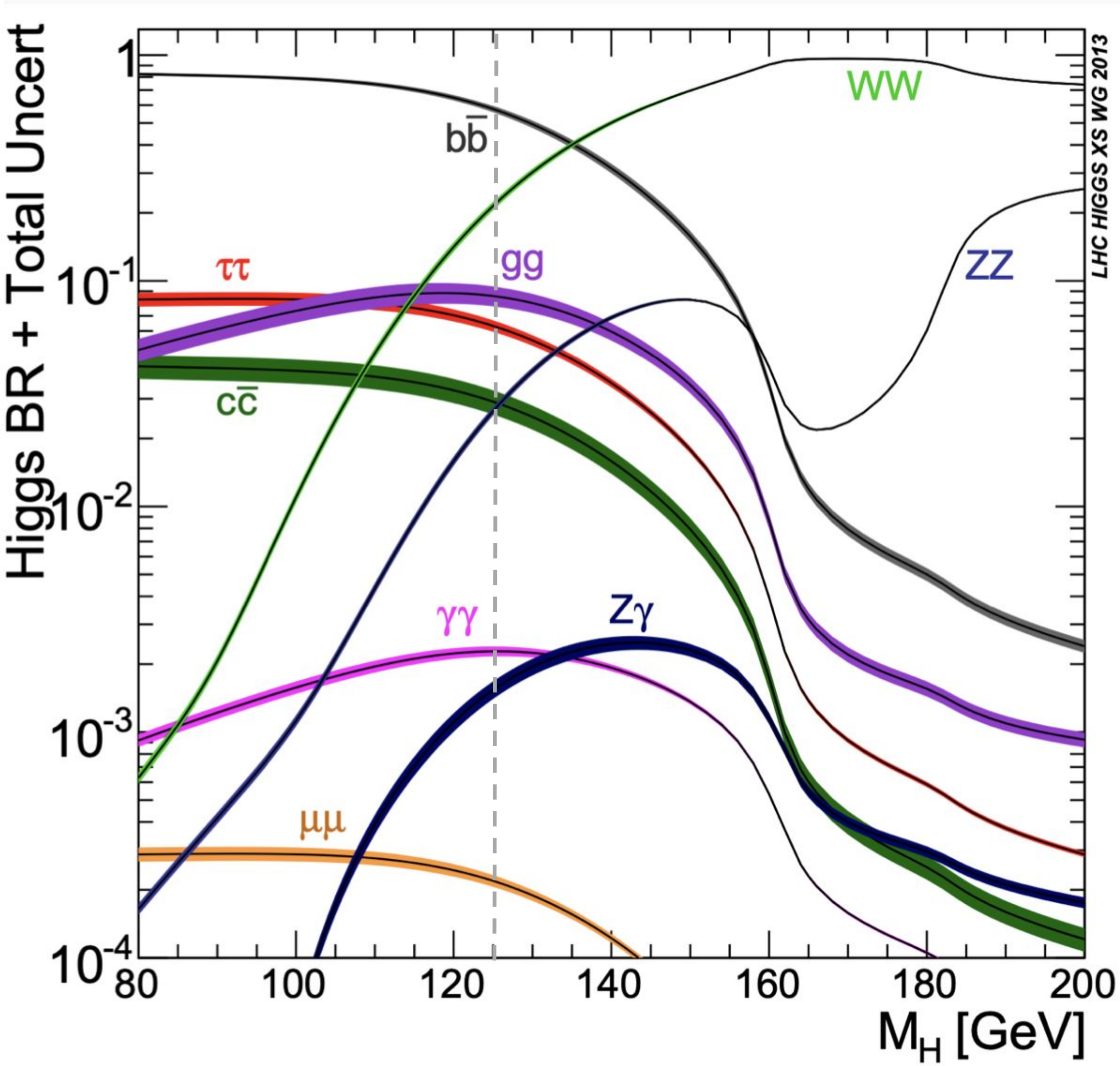
Higgs boson at the LHC

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).

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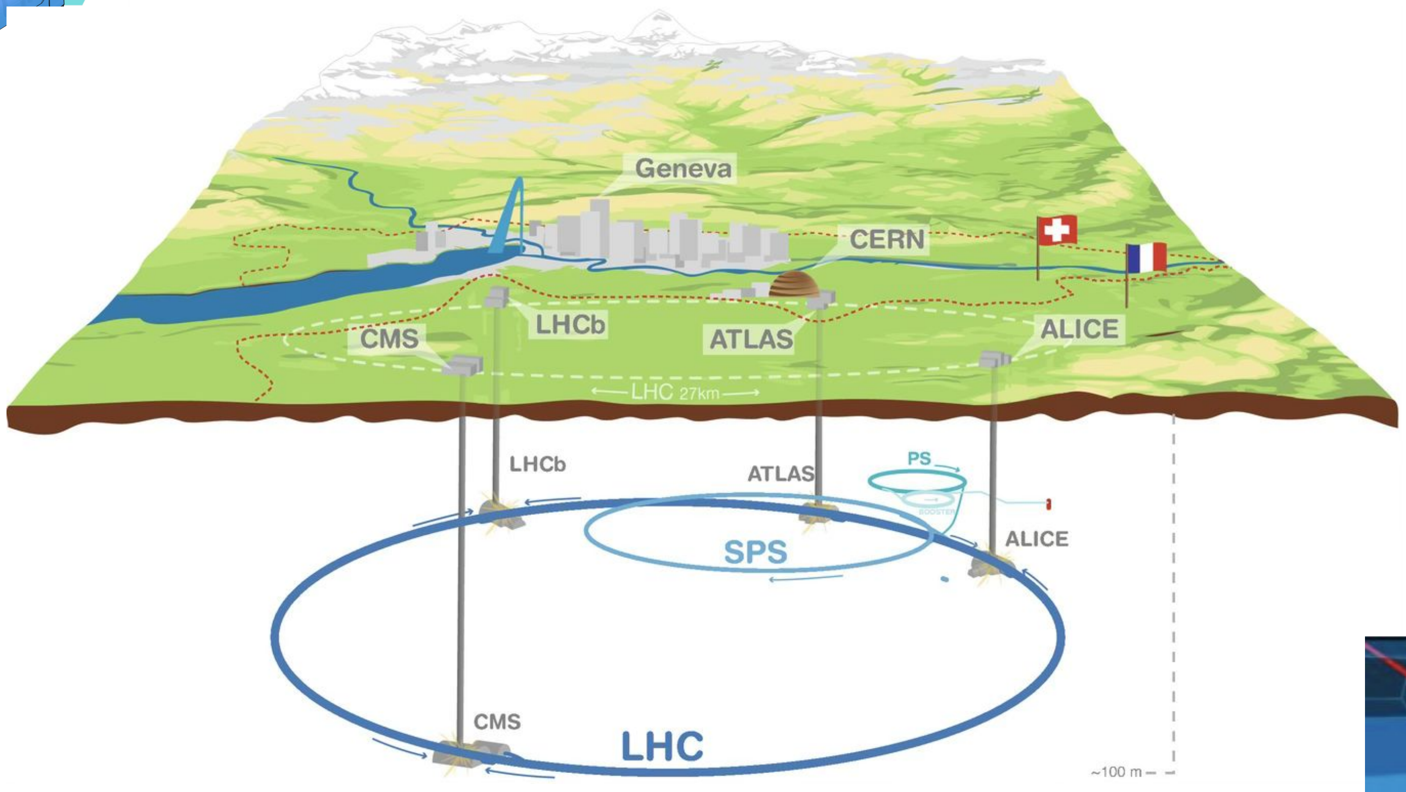
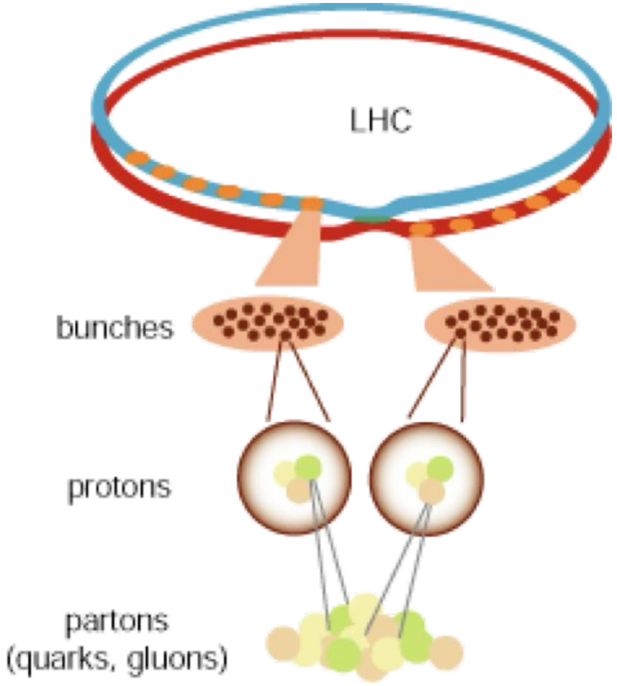
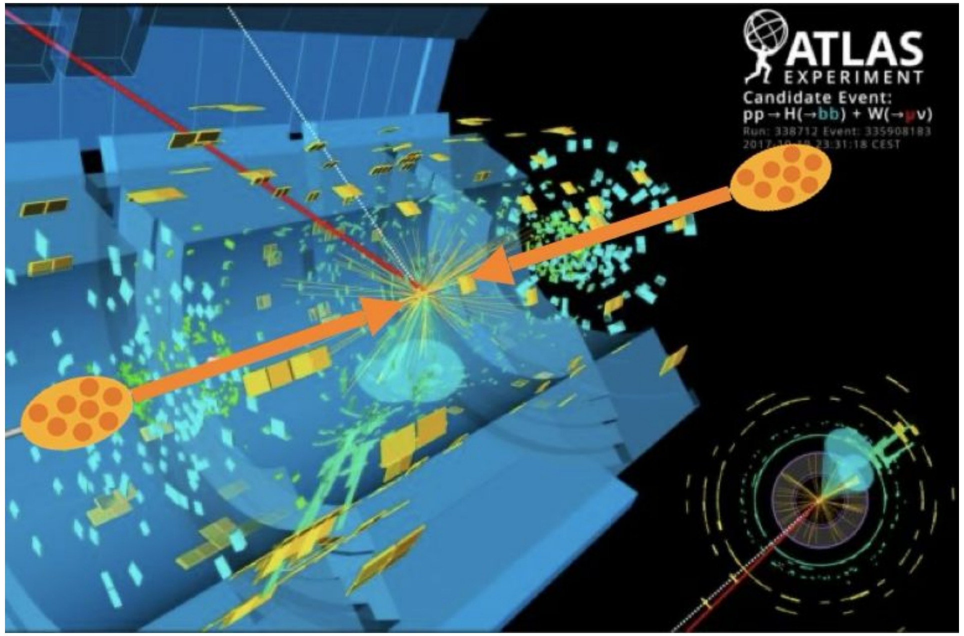
LHC

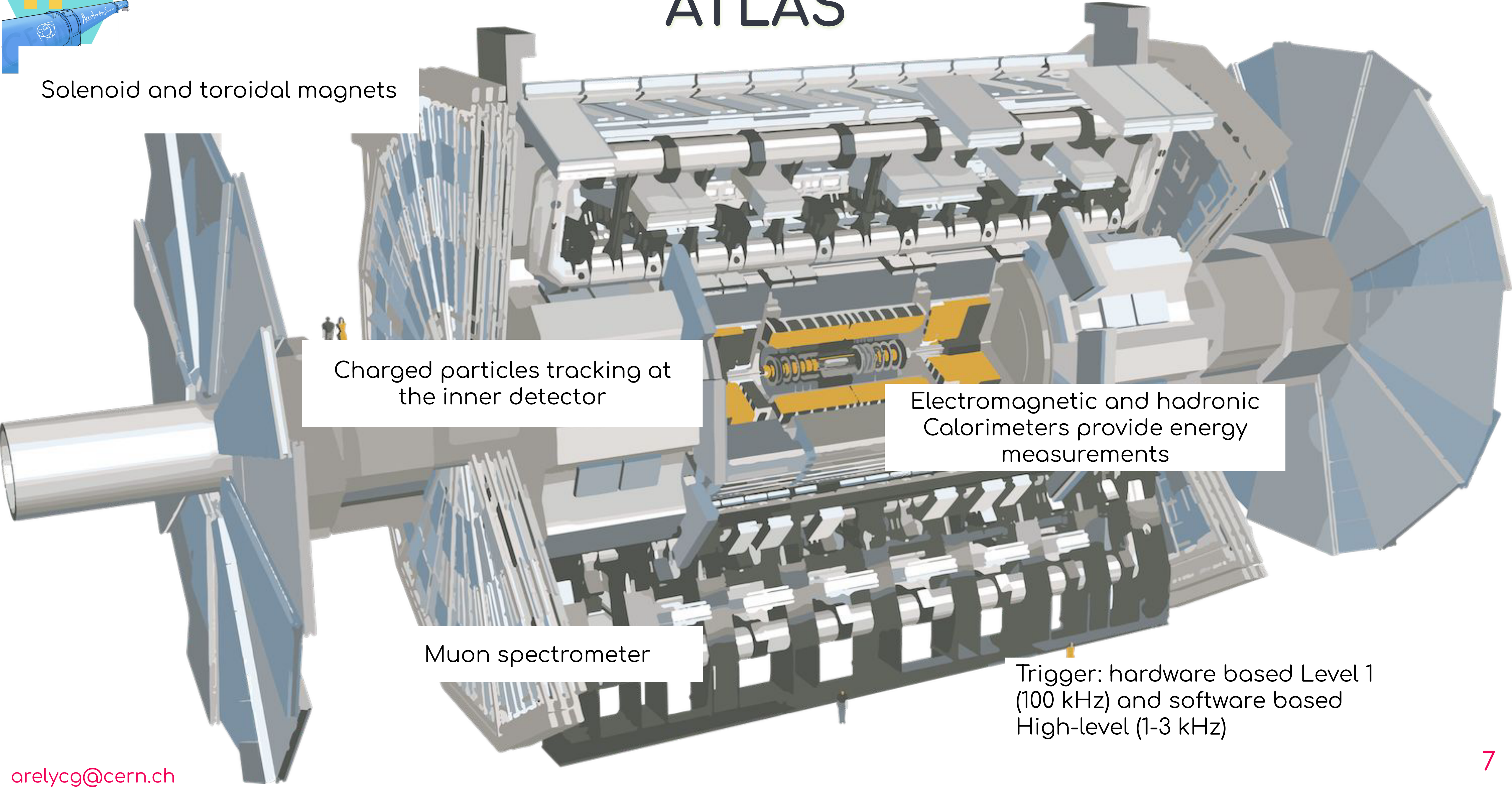






- **proton-proton** collider at CERN.
- 27 km of circumference.
- Several experiments:
  - ATLAS & CMS: **general** purpose detectors.
  - ALICE (studying heavy ion collisions),
  - LHCb (flavour physics).
- Collisions energy: 7 TeV → 13.6 TeV

ATLAS



Solenoid and toroidal magnets

Charged particles tracking at the inner detector

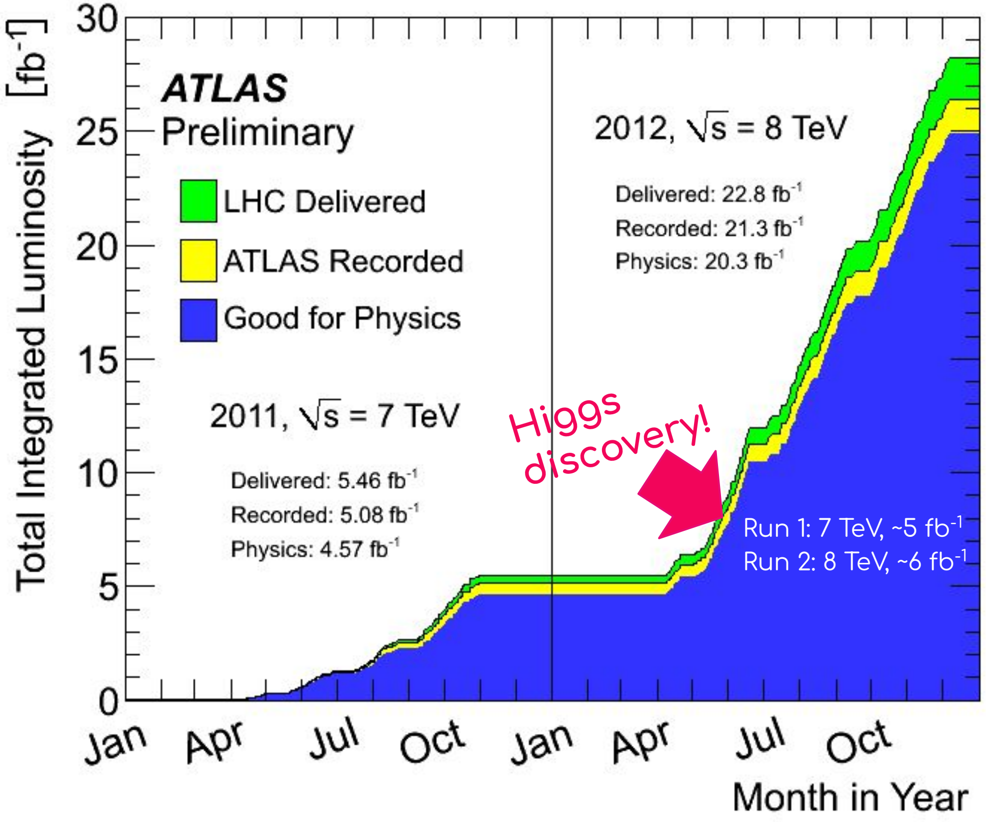
Electromagnetic and hadronic Calorimeters provide energy measurements

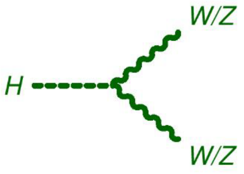
Muon spectrometer

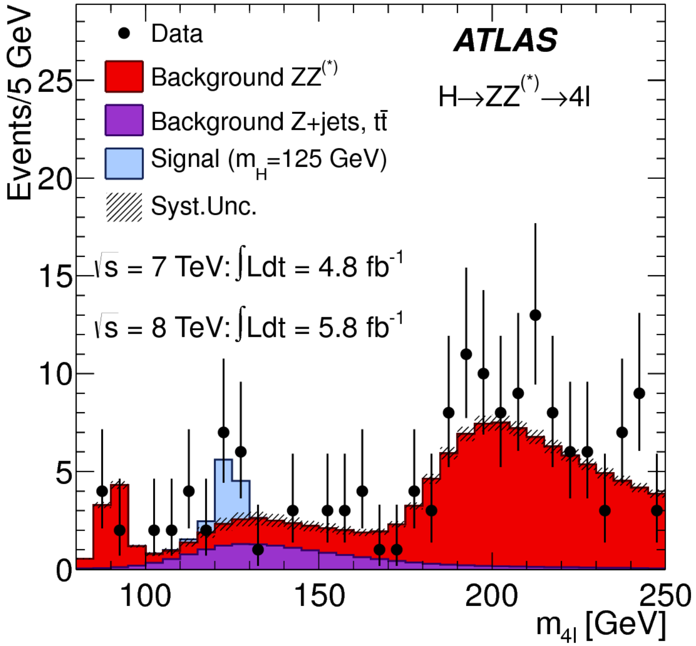
Trigger: hardware based Level 1 (100 kHz) and software based High-level (1-3 kHz)

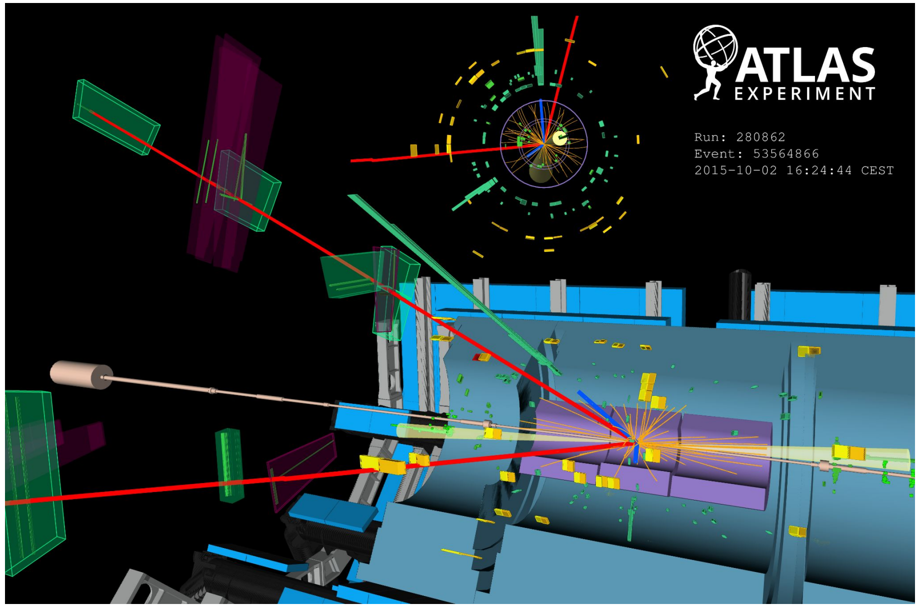
We found a Higgs!

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→ZZ*→4ℓ, H→γγ, H→WW→ℓvℓv.

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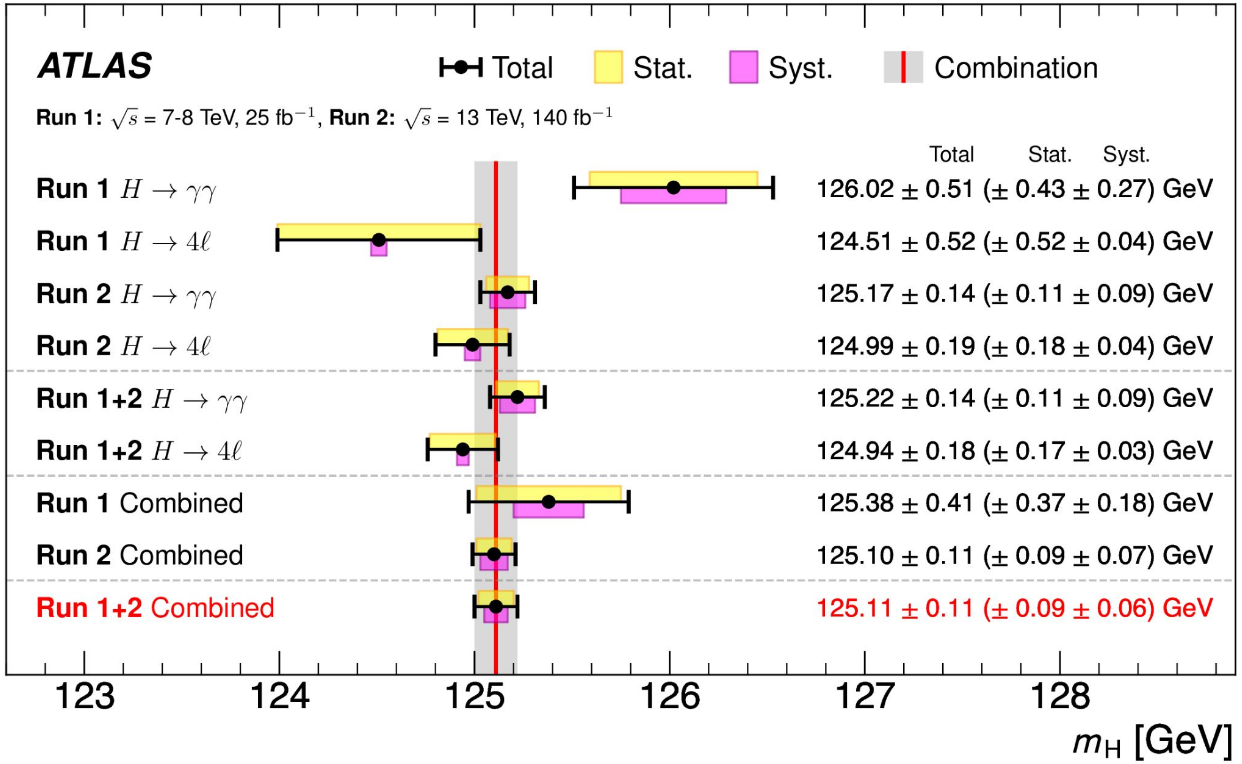
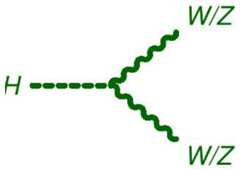
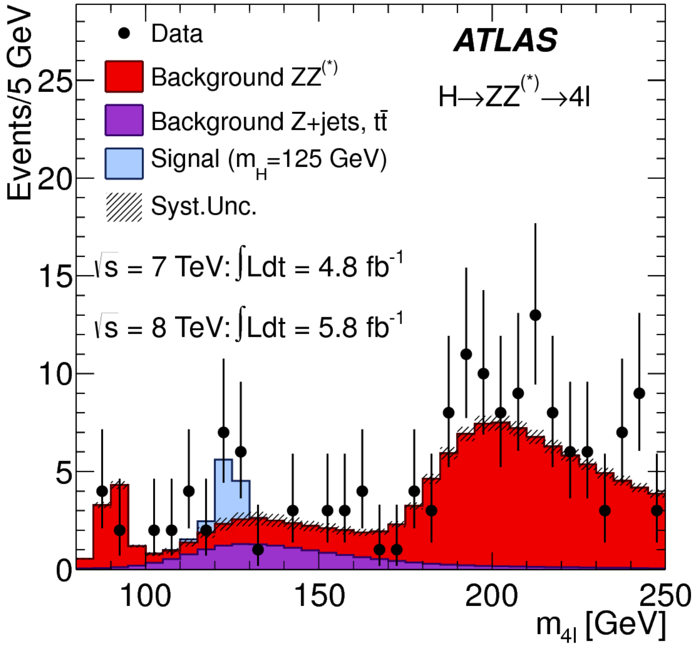
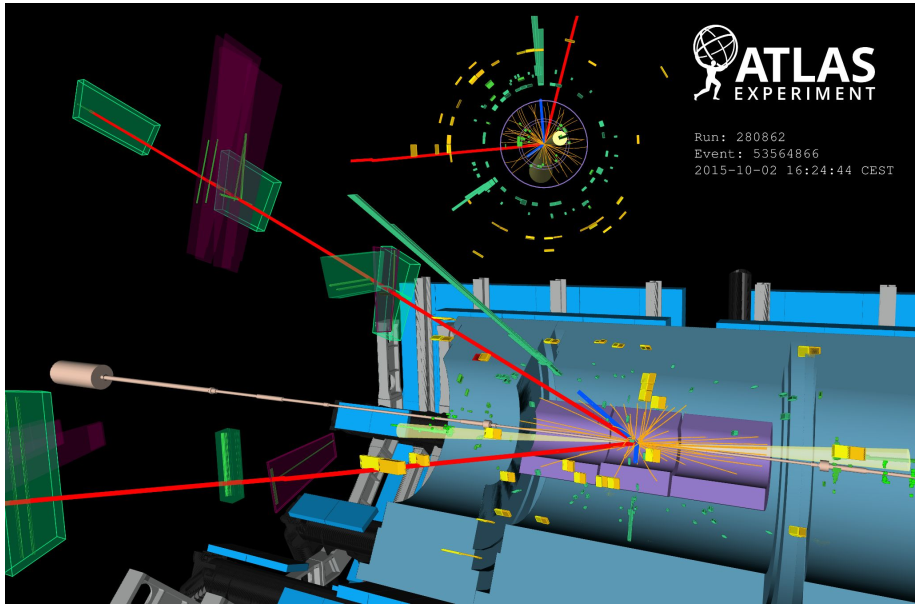
We found a Higgs!









[10th anniversary of the Higgs boson discovery]

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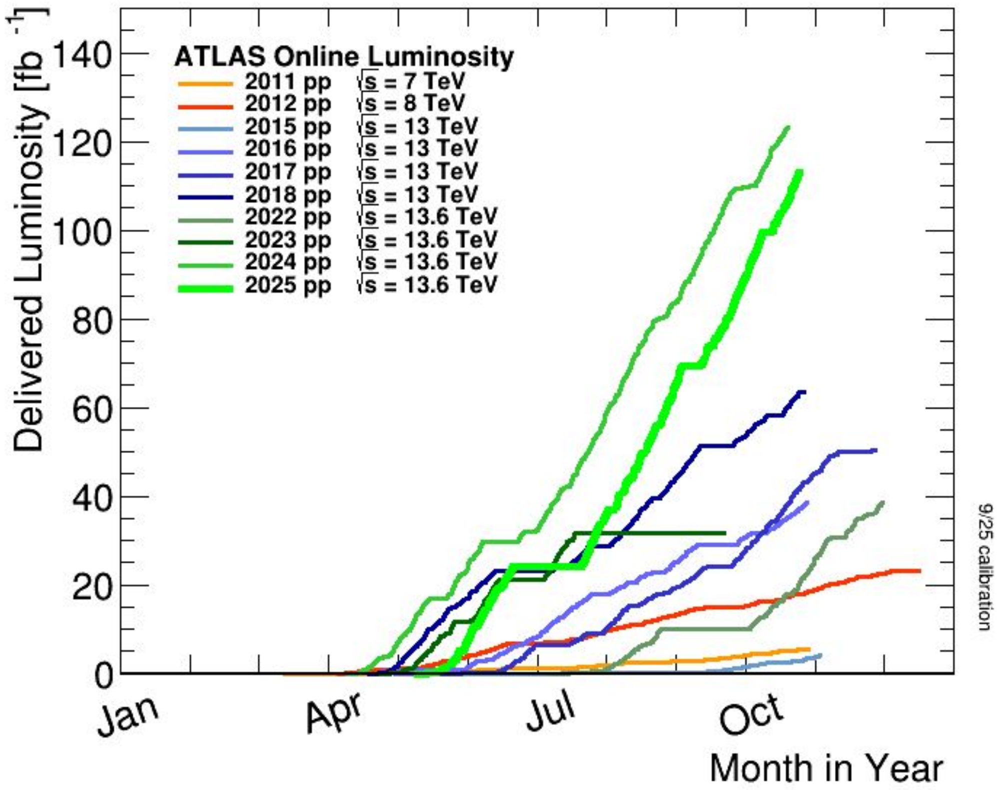
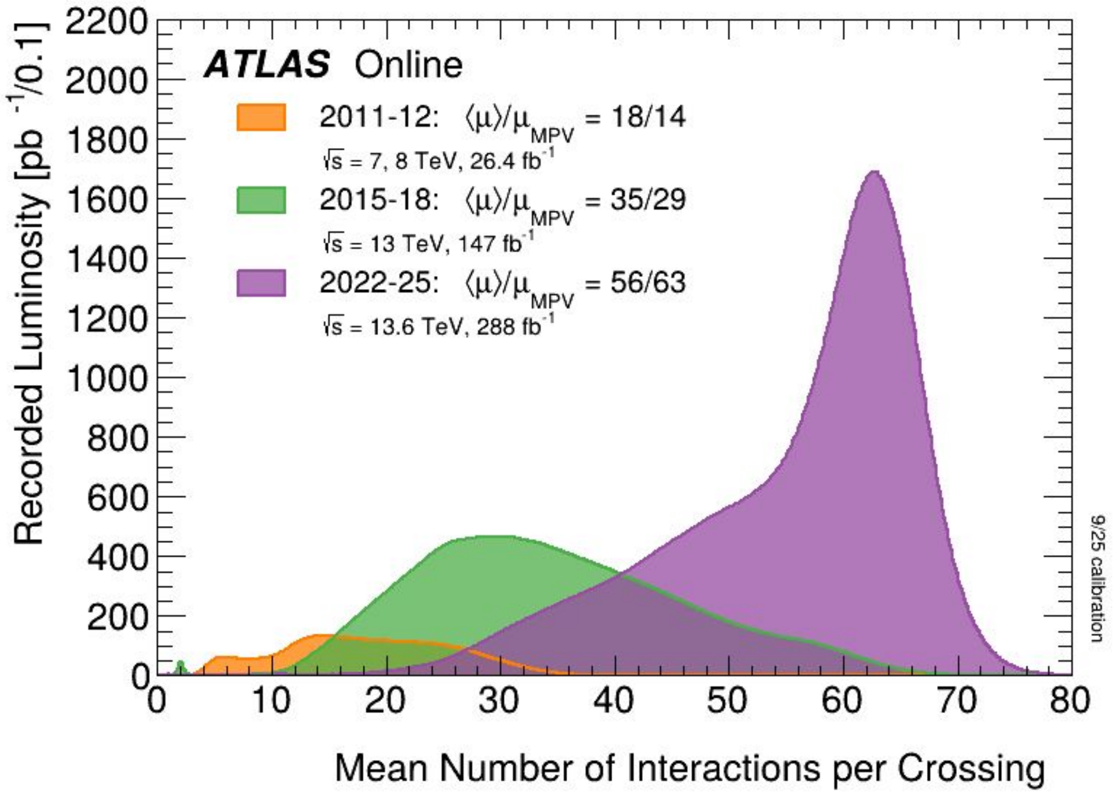
The LHC dataset now





Luminosity collected by ATLAS

- Run 1: 5 fb^{-1} at 7 TeV & 20 fb^{-1} at 8 TeV
- Run 2: 140 fb^{-1} at 13 TeV
- Run 3: ~300 fb^{-1} at 13.6 TeV
  - ending in 2026.

Pileup conditions are much more challenging!

- Efficiency and resolution of objects reconstruction requires more work.

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Trilinear Higgs Coupling

Standard Model Higgs potential

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

Our universe lives in the minimum:

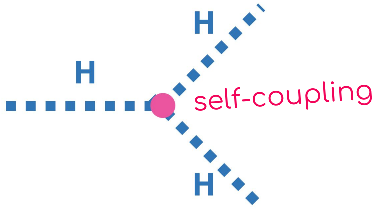
$$V = V_0 + \lambda\nu^2h^2 + \lambda\nu h^3 + \frac{1}{4}\lambda h^4$$

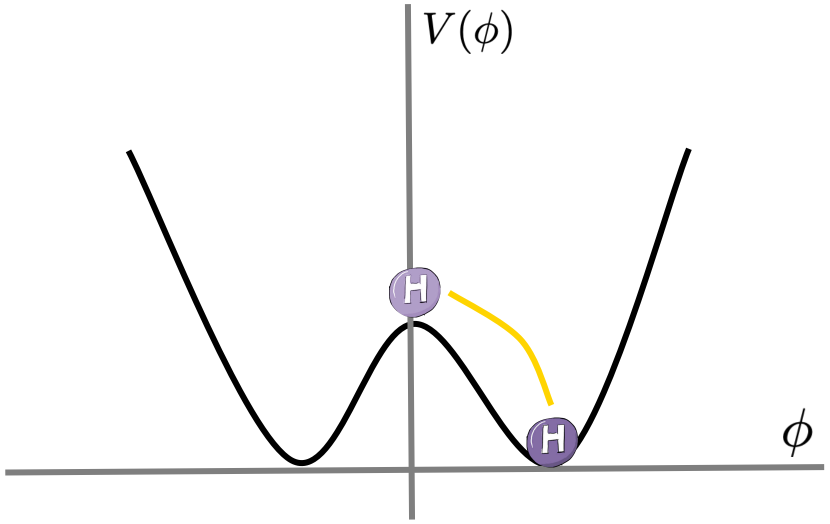
mass

self-coupling

$$\lambda^{\mathrm{SM}} = \frac{m_H^2}{2\nu^2}$$

we can probe this via the **HH production**





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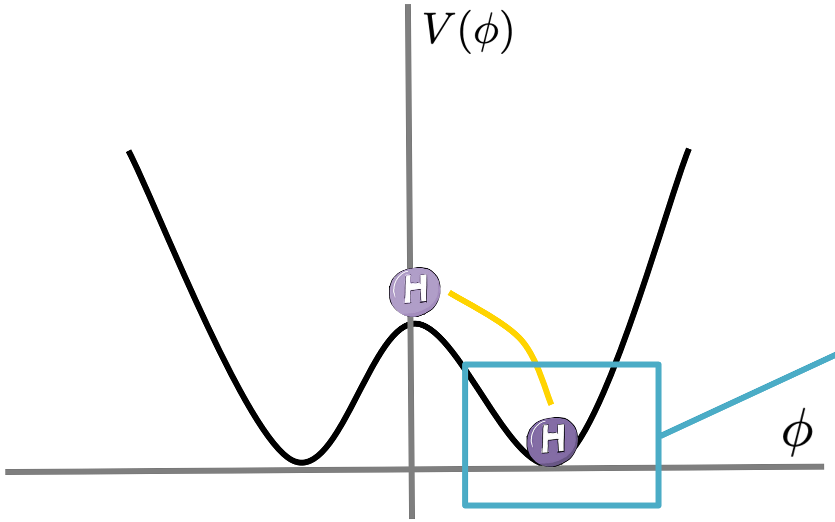
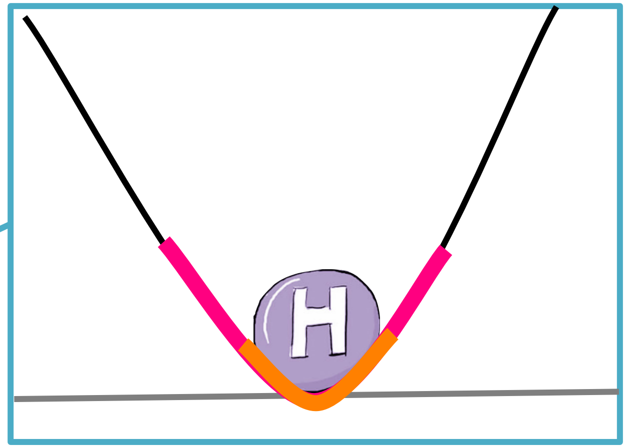
mass → minimum of the potential

self-coupling → shape of the potential





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Trilinear Higgs Coupling

Standard Model Higgs potential

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

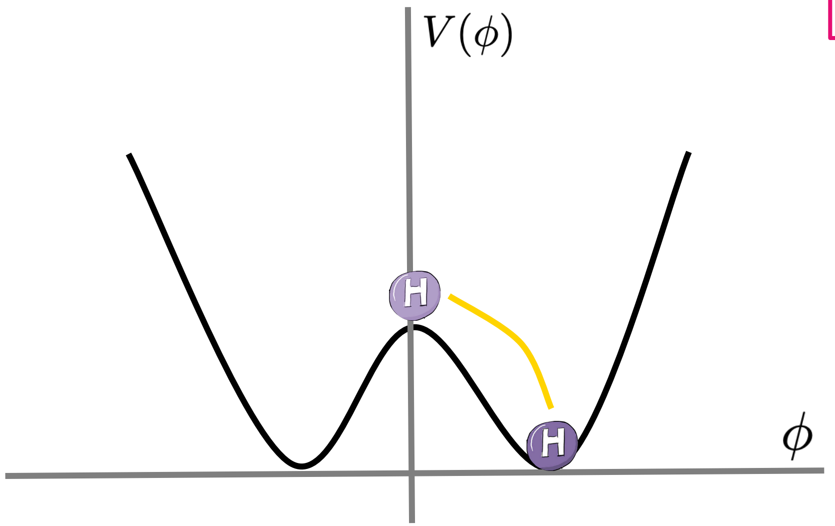
Our universe lives in the minimum:

$$V = V_0 + \frac{1}{2}m_H^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4}\lambda_4 h^4$$

In the Standard Model:

$$\lambda^{\mathrm{SM}} = \frac{m_H^2}{2\nu^2}$$

$$\kappa_\lambda = \lambda/\lambda^{\mathrm{SM}}$$



Non-resonant HH production searches probe the shape of the Higgs potential by measuring the Higgs self coupling: κ_λ.

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Trilinear Higgs Coupling

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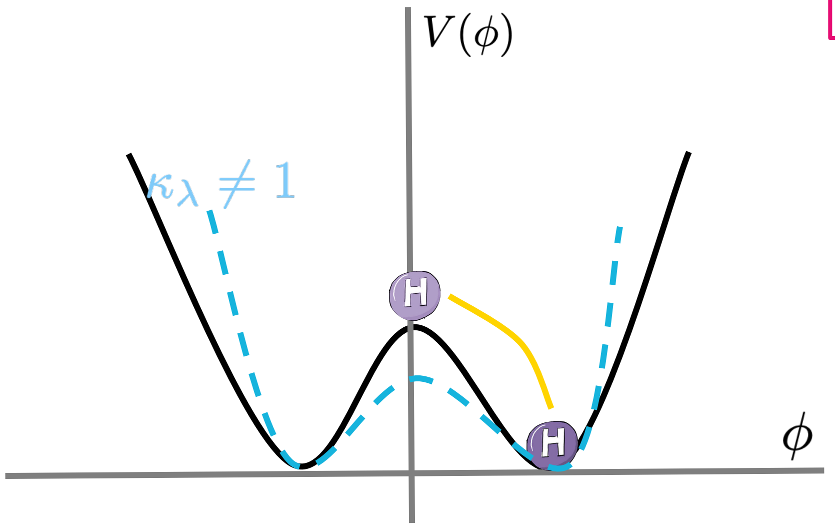

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$\kappa_\lambda \neq 1$ could indicate beyond Standard Model physics.

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Trilinear Higgs Coupling

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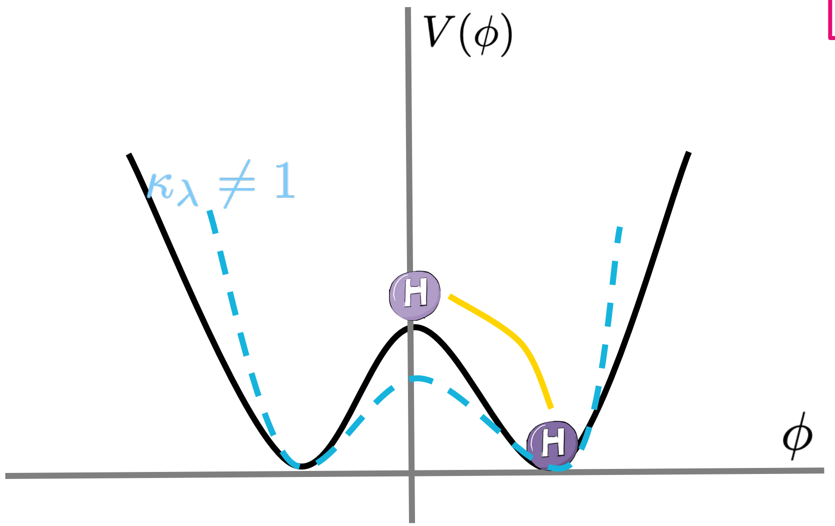
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

Our universe lives in the minimum:
$$V = V_0 + \frac{1}{2}m_H^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4}\lambda_4 h^4$$

In the Standard Model:
$$\lambda^{SM} = \frac{m_H^2}{2\nu^2}$$

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

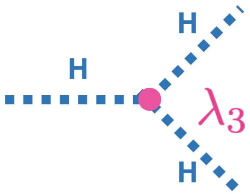


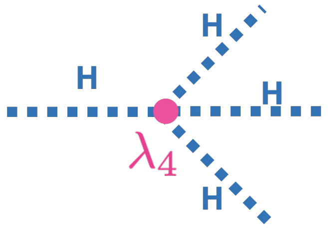
Non-resonant HH production searches probe the shape of the Higgs potential by measuring the Higgs self coupling: κ_λ.

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

Moreover, in the SM:

$$\lambda_3 = \lambda_4$$





We can use HHH searches to independently constrain λ_4

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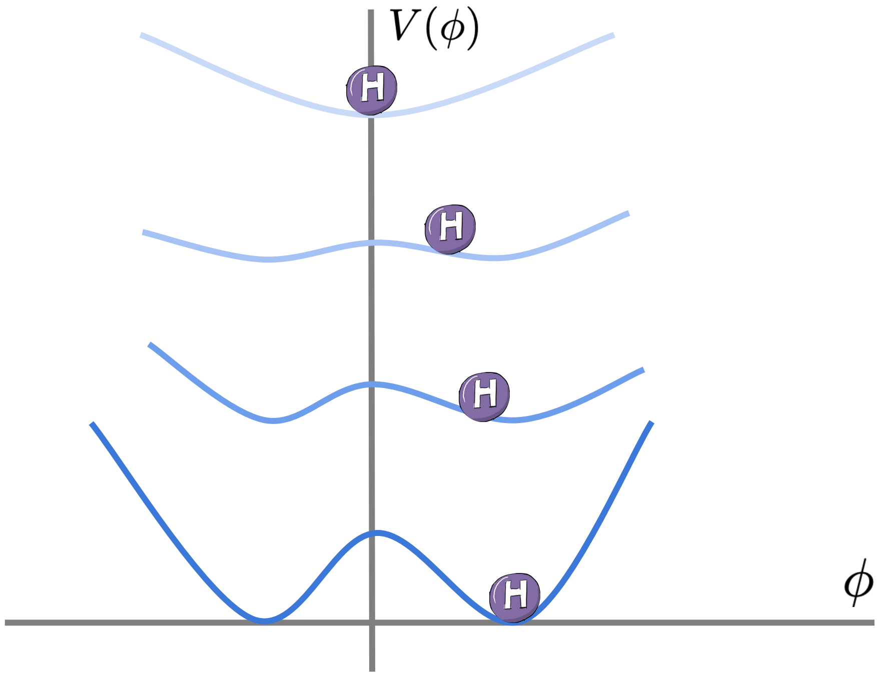
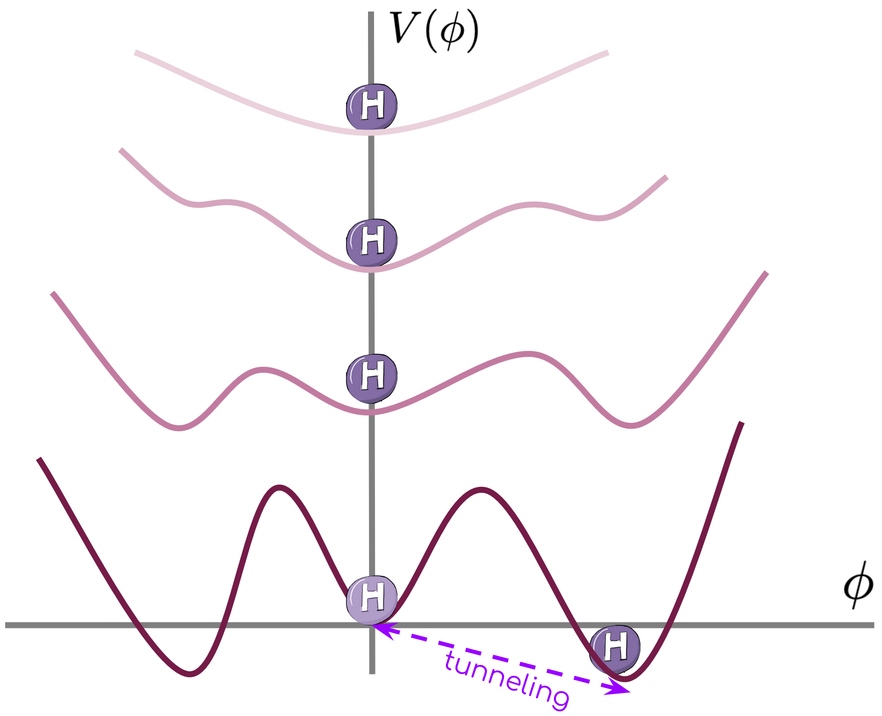
Electroweak phase transition

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



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



BSM: 1st order phase transition.

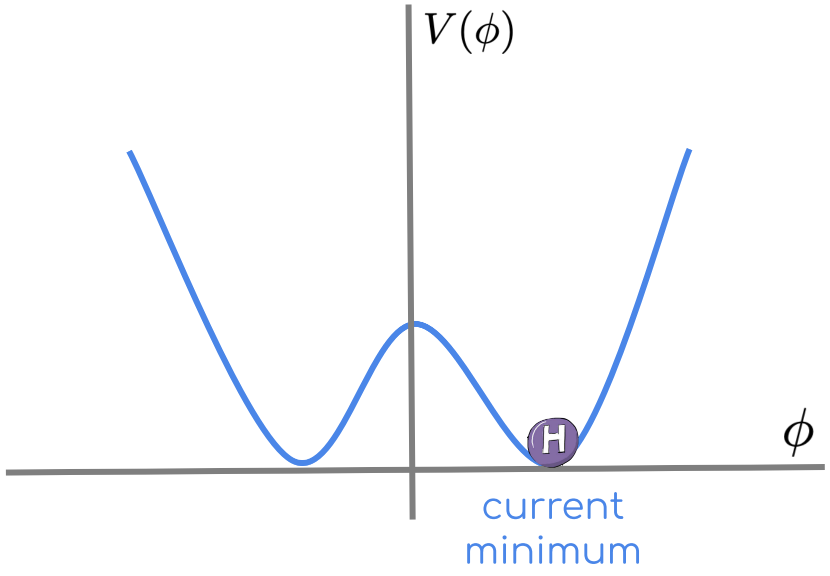
Baryogenesis requires a first order electroweak phase transition, which would lead to a modification to the Higgs potential ...

Stability of the Universe

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

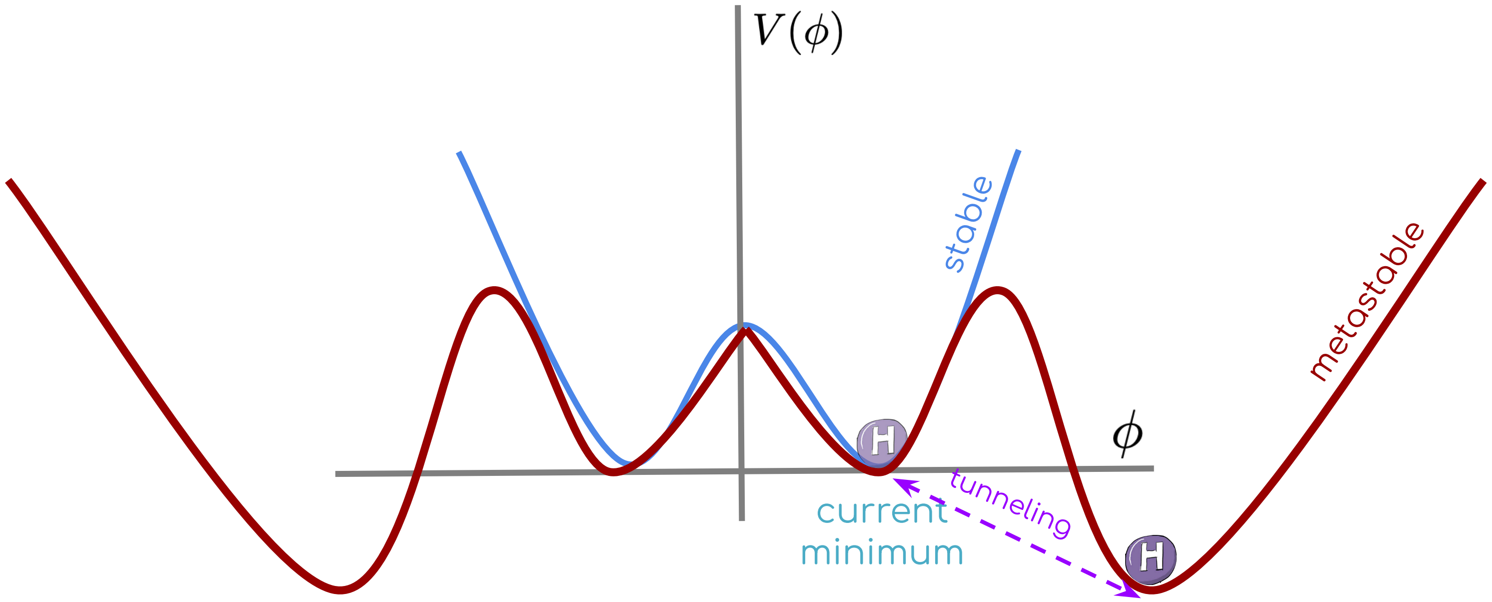
Stable universe

- 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...



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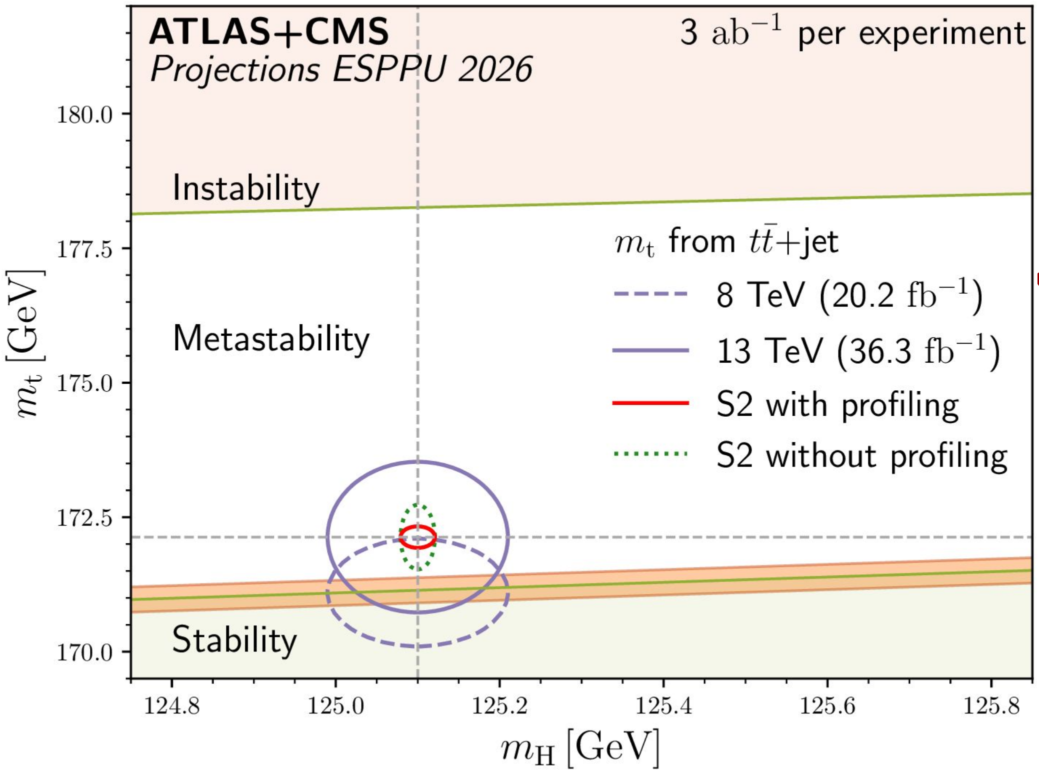
Stability of the Universe

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



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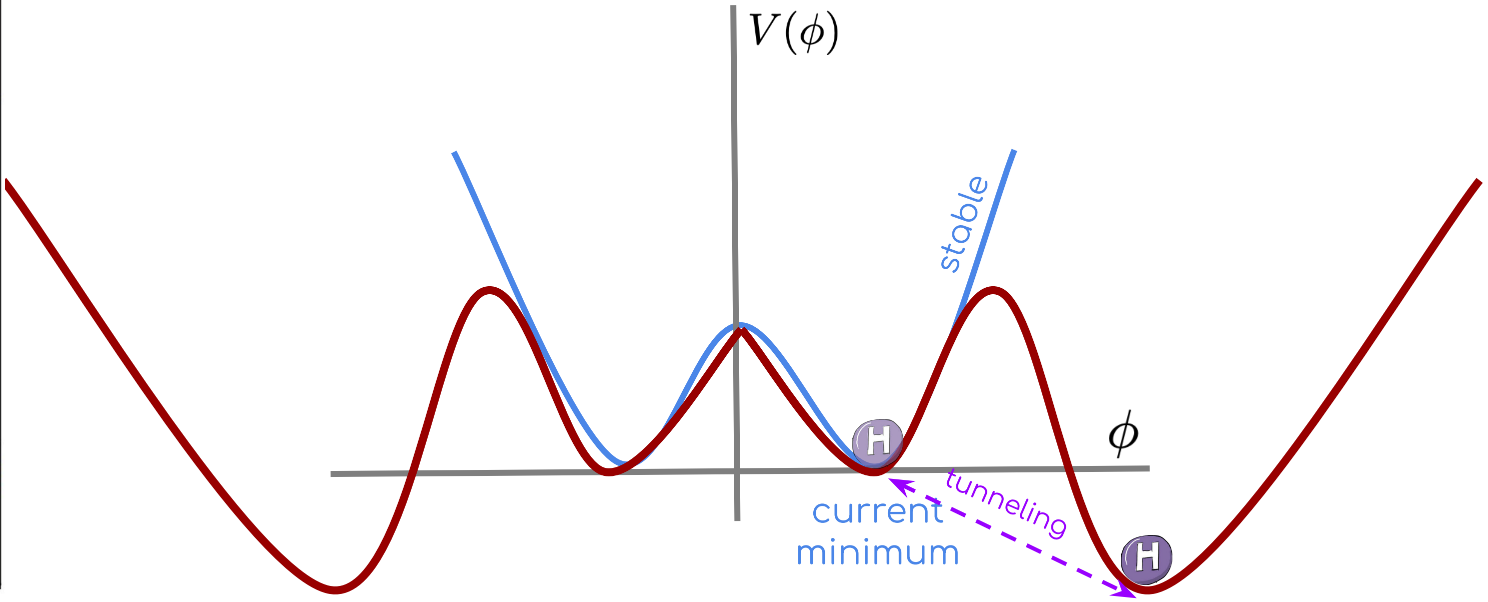
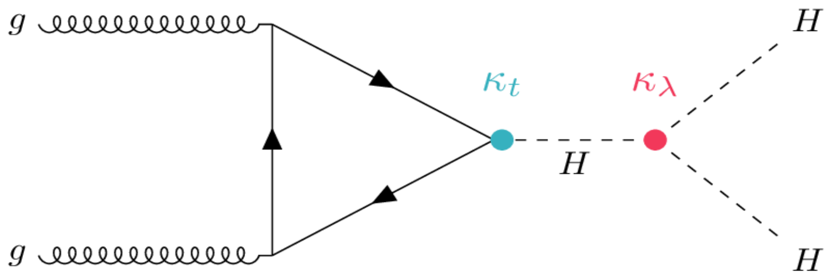
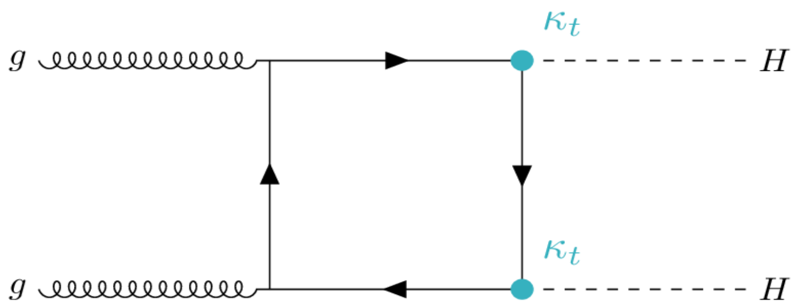


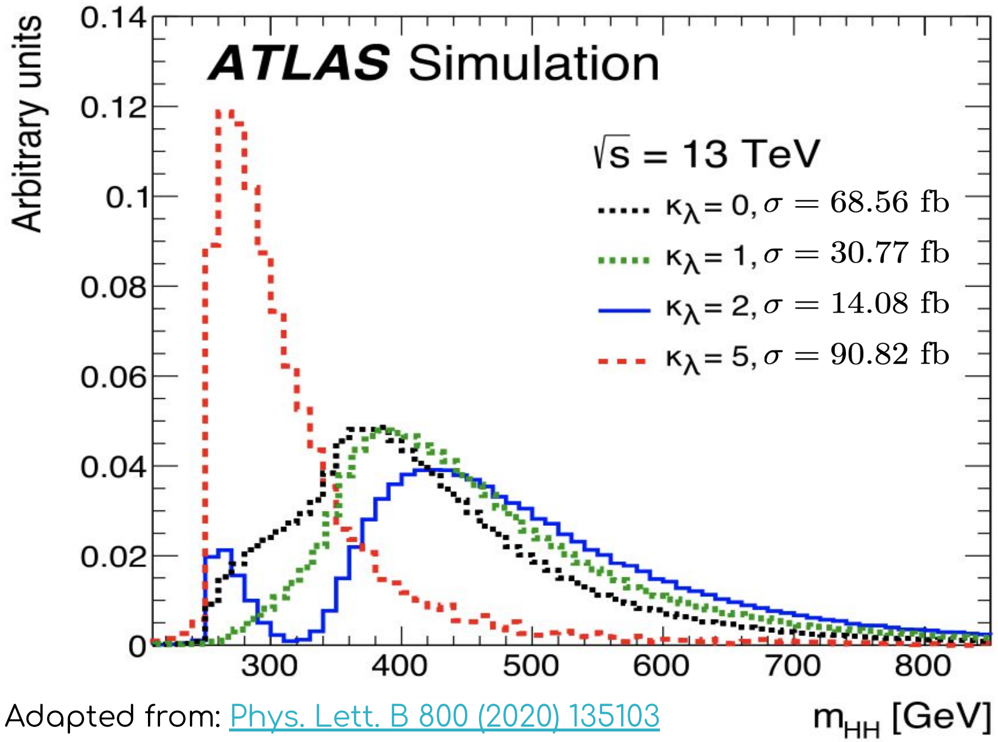
Measuring the self-coupling can provide discrimination between different scenarios, or different models.
But, keep in mind that we will require to measure **triple-Higgs production** to fully describe the shape of the Higgs potential.

HH production

Main production mechanism is via **gluon-gluon fusion**.







Adapted from: Phys. Lett. B 800 (2020) 135103

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

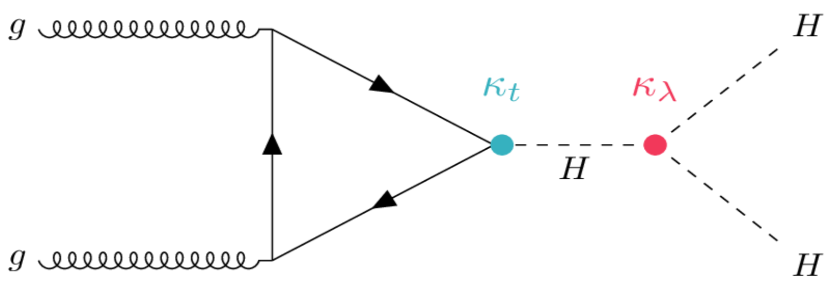
$$\kappa_\lambda = \lambda/\lambda^{\mathrm{SM}}$$

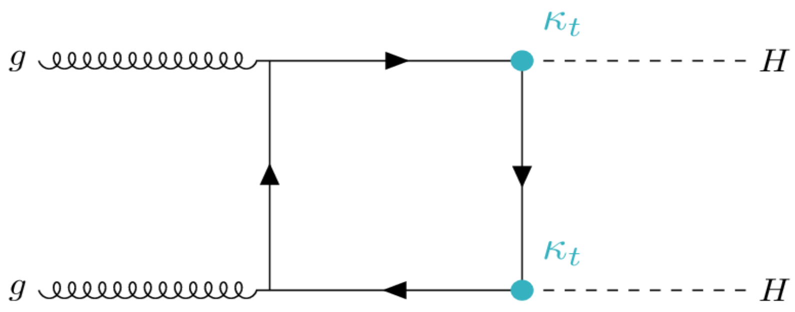
SM predicts $\kappa_\lambda = 1$

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

HH production

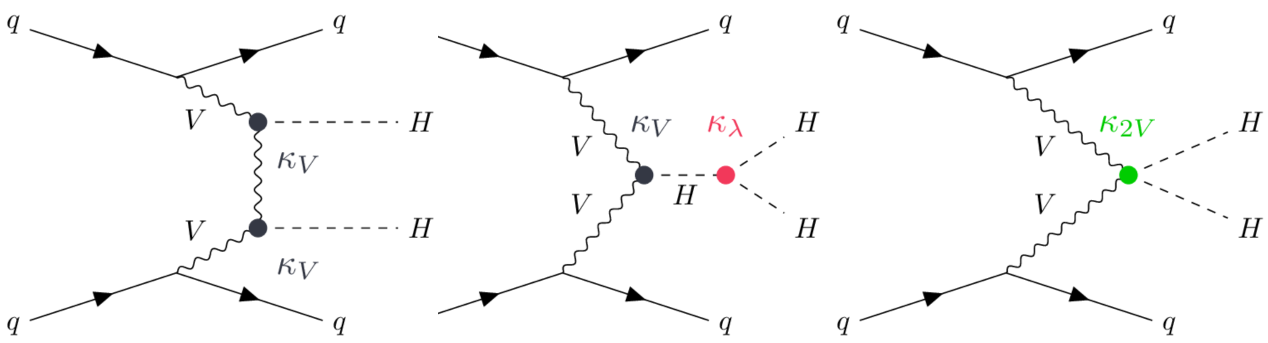
Main production mechanism is via **gluon-gluon fusion**.



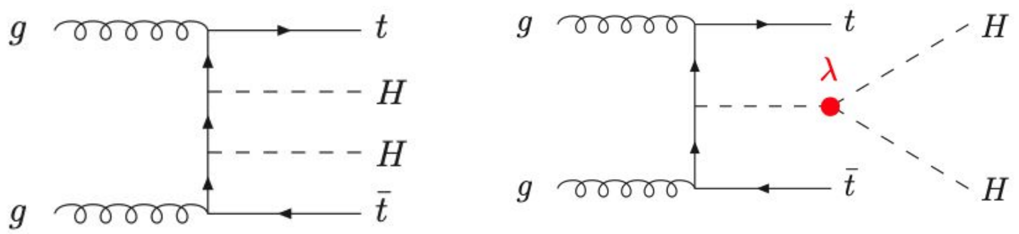


Other production mechanisms also allow us to probe different couplings: κ_{2V}, κ_V.

Vector boson fusion



Associated production ttHH



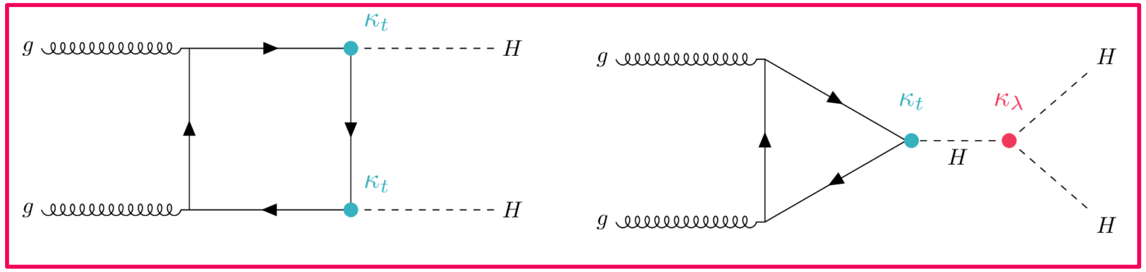
VVHH coupling modifier
SM predicts κ_{2V} = 1

VVH coupling modifier
SM predicts κ_V = 1

HH production

LHCHXSWG-2019-005

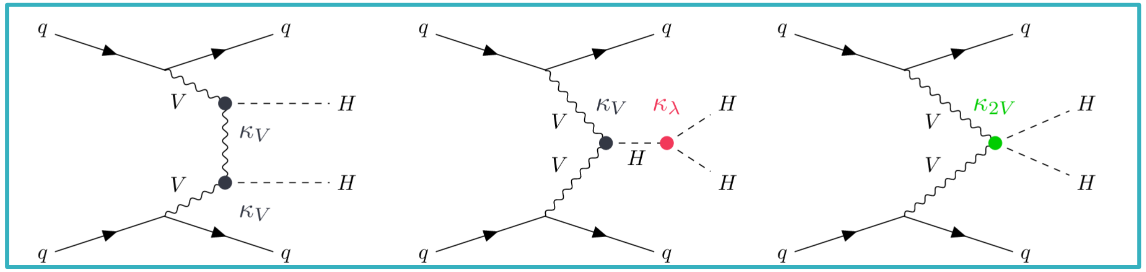
Production cross sections at 13 TeV for m_H = 125 GeV



Gluon fusion (NNLO)

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

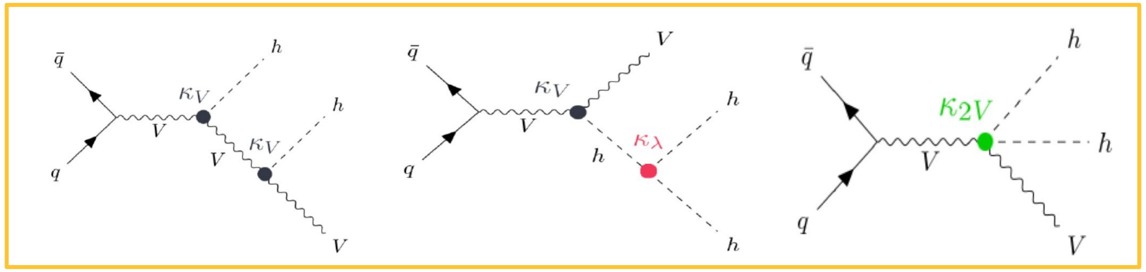
Trilinear self-coupling modifier: κ_λ



Vector boson fusion (N³LO)

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

VVHH coupling modifier κ_{2V}



Associated production, VHH (N²LO)

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

VVH coupling modifier κ_V

SM predicts $\kappa_\lambda = 1$, $\kappa_{2V} = 1$, $\kappa_V = 1$

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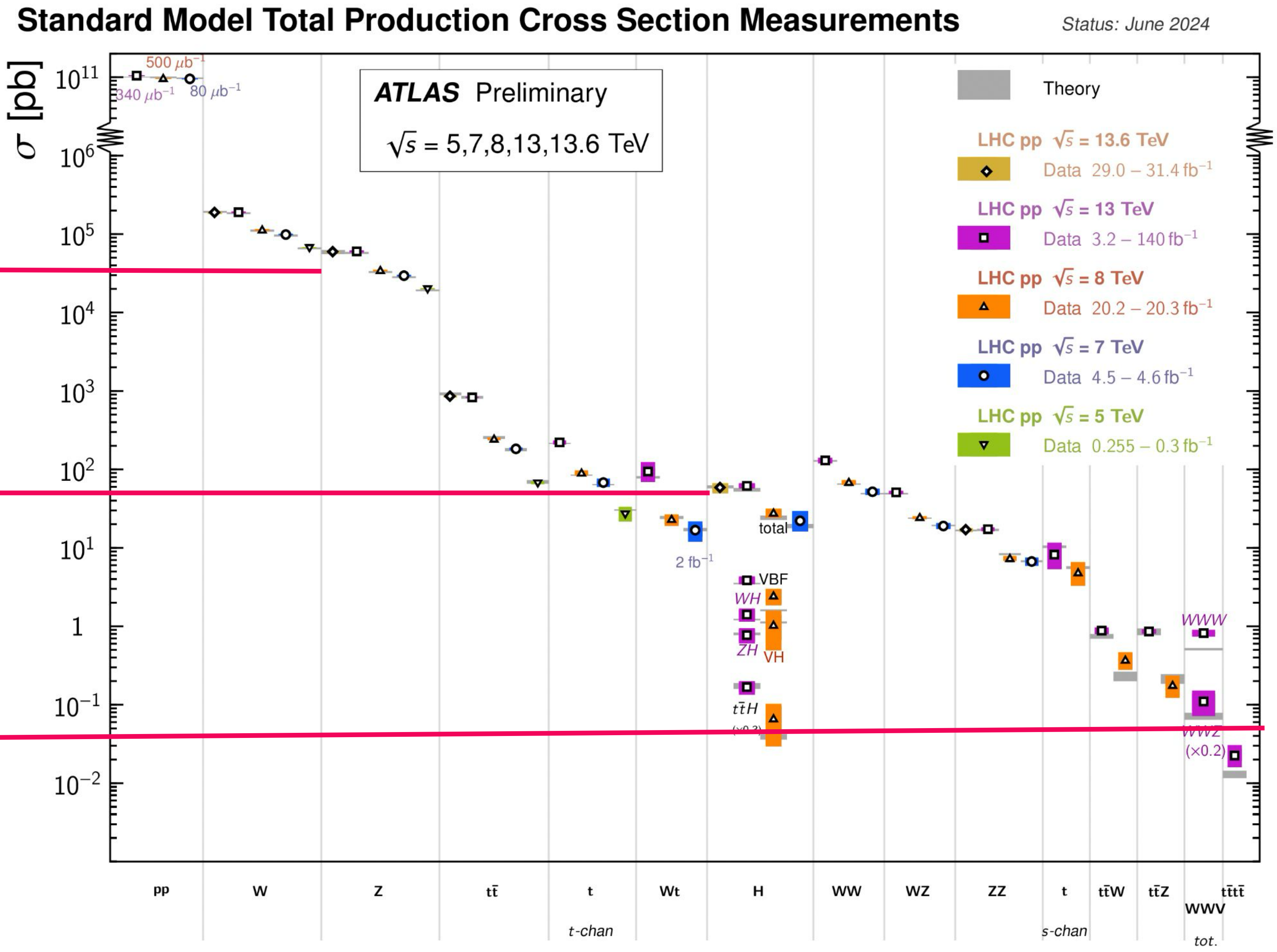
Standard Model processes

[ATLAS Public Results](#)

SM
Z production
x1000

SM
Single Higgs
production
x1000

SM
Di-Higgs
production
33 fb^{-1}



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Search channels

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	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!

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Search channels

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- [bbbb] Largest decay fraction, exploit data driven techniques to estimate dominant multijet background.
- [bbττ] Medium decay fraction, good signal selection purity.
- [bbγγ] Lower decay fraction, but excellent $m_{\gamma\gamma}$ mass resolution.

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Search channels

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

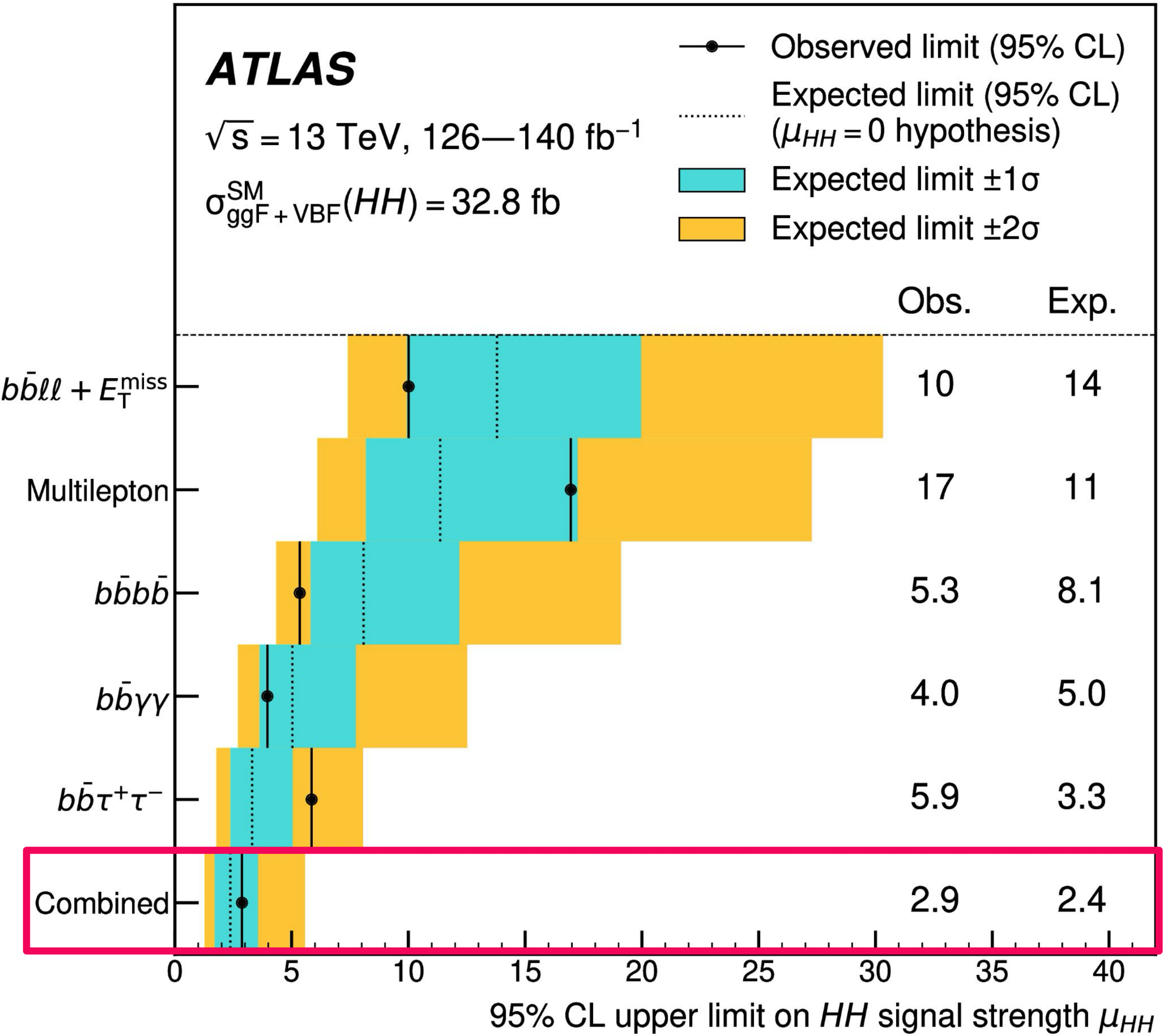
Several other decay channels explored by both Collaborations:

- [bbℓℓ + MET] Targeting multiple decay fractions, with one Higgs not decaying into bb (bbWW/bb**ττ**/bbZZ).
- [(**γγ**) multi-lepton] Covering multiple decay modes, where neither Higgs decay into bb.
- [**γγττ**, WW**γγ**] Very small decay fraction, but signal purity can be large.

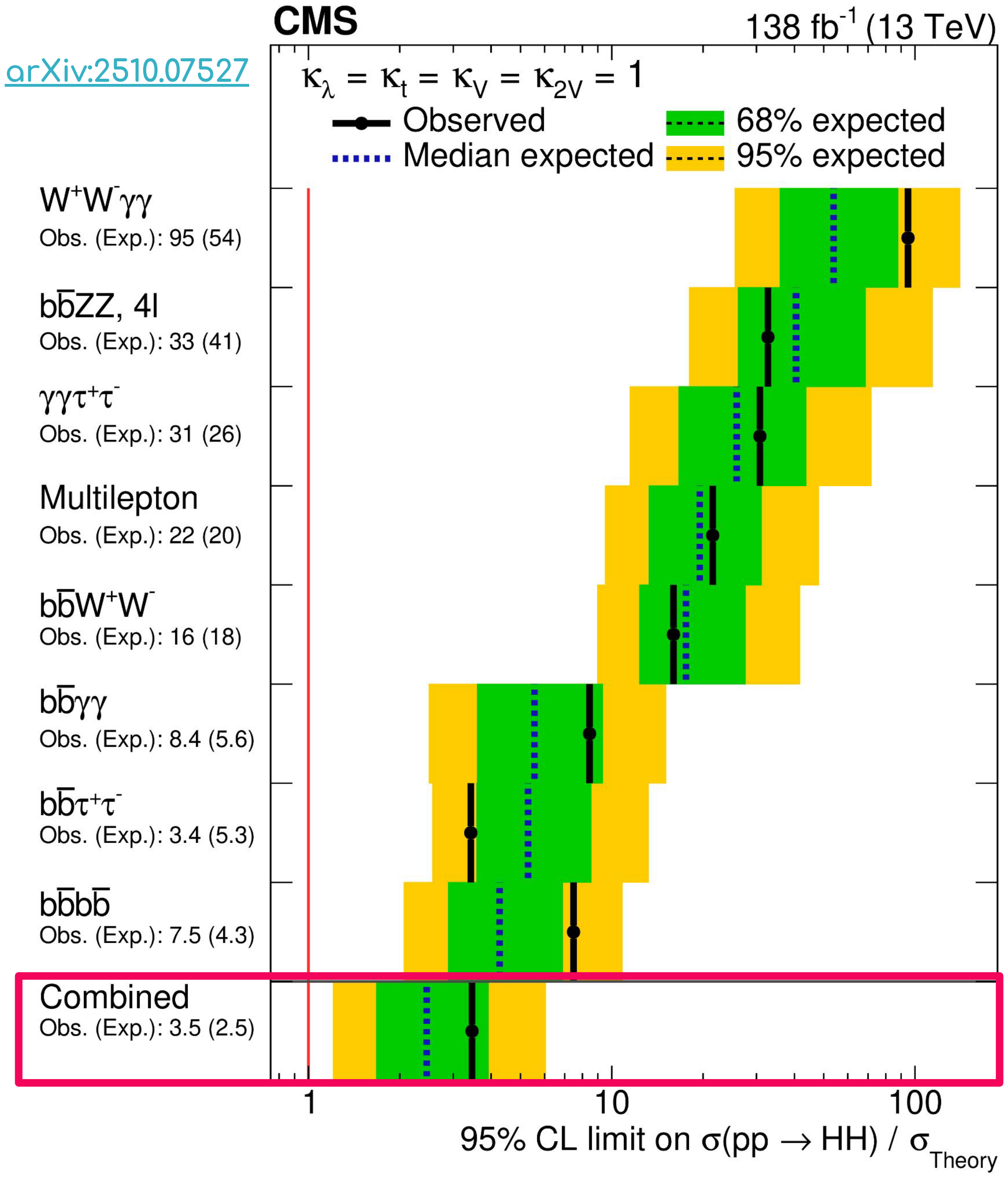
LHC Run 2 Legacy results

LHC Run 2 SM HH limits

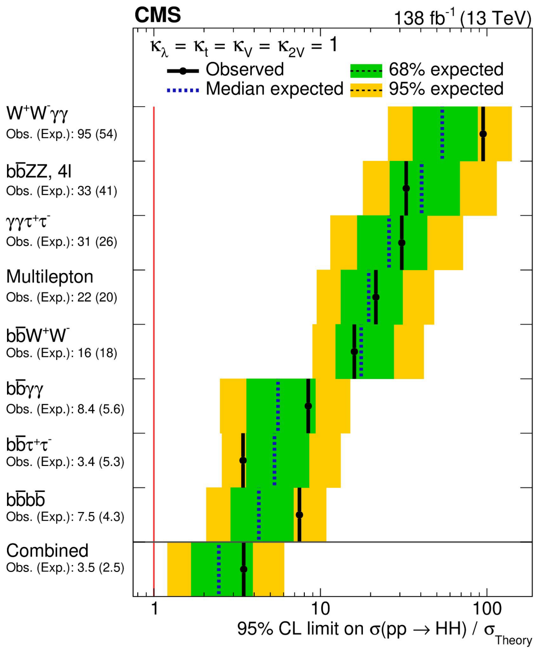
Phys. Rev. Lett. 133 (2024) 101801

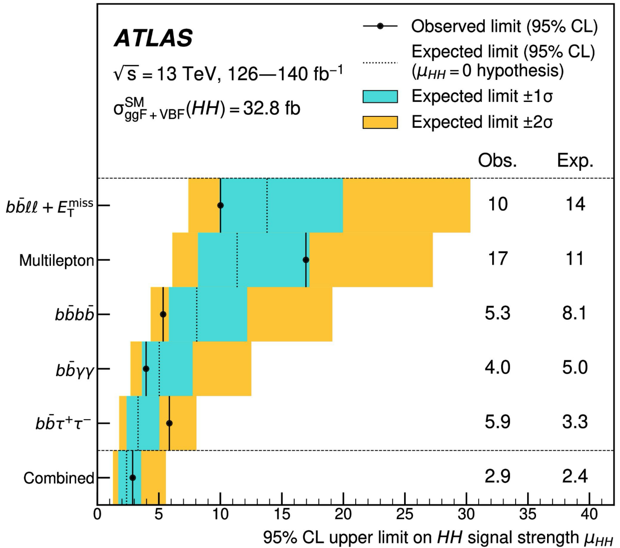


arXiv:2510.07527



LHC Run 2 SM HH limits





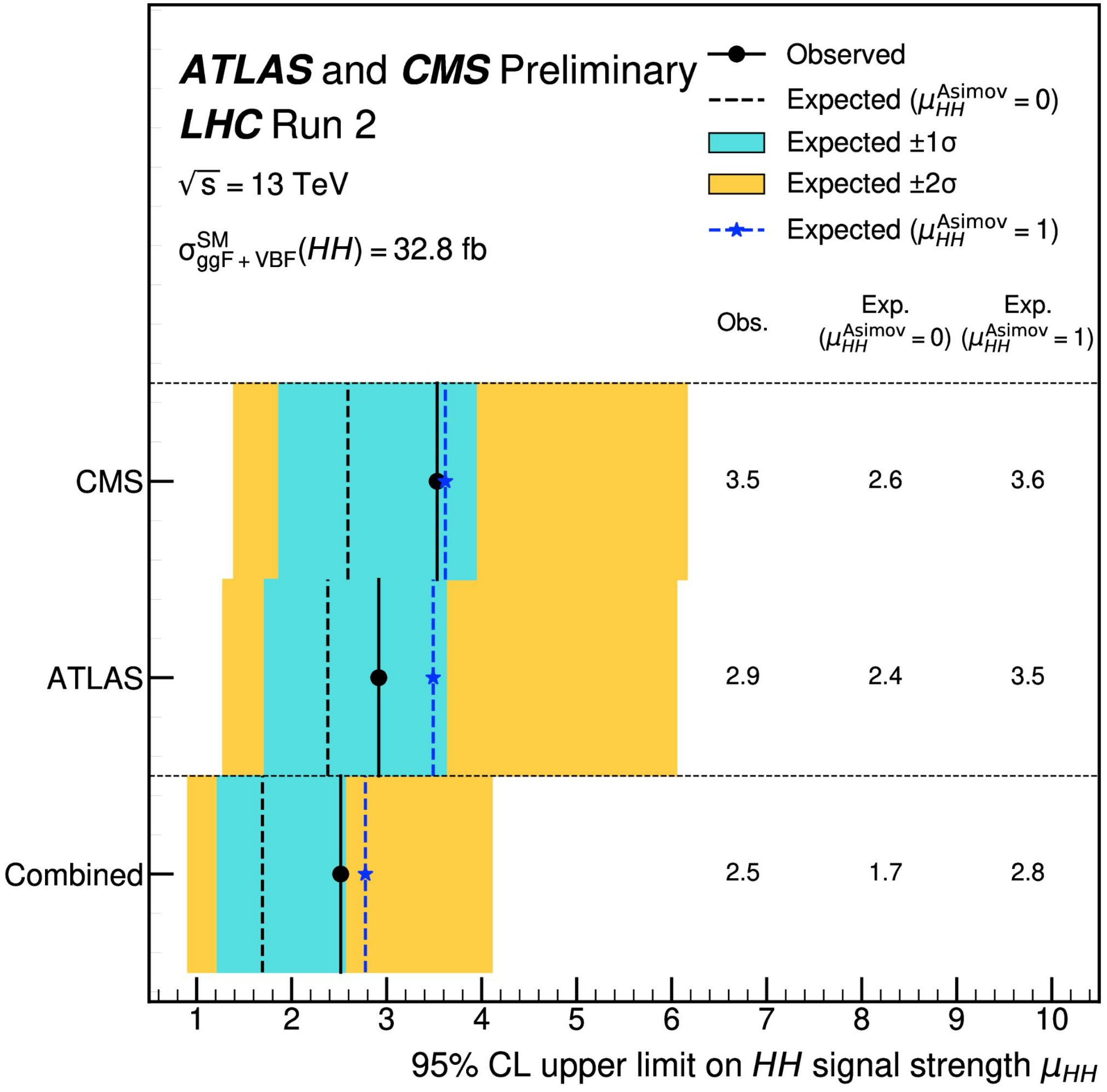
- Competitive results from both ATLAS and CMS.
  - Upper limits on SM HH signal strength:

ATLAS Obs 2.9 (Exp 2.4)	CMS Obs 3.5 (Exp 2.5)

- The sensitivity is dominated by the $bb\tau\tau$, $bb\gamma\gamma$ and bbbb channels.
  - The larger sensitivity of bbbb for CMS comes from the combination of both boosted and resolved ggF analyses.
    resolved expected 7.8; boosted expected 5.1
    ATLAS analyses the boosted topology only for VBF HH production.
  - The larger sensitivity of ATLAS in the $bb\tau\tau$ channel is driven by the tau triggers (in CMS these triggers require tighter selection cuts)
- Additional decay channels add around 5% to the final sensitivity.

ATLAS + CMS combination

ATLAS-CONF-2025-012, CMS-PAS-HIG-25-014



- Legacy **Run 2 limits on SM HH signal strength**
  - **Observed 2.5** (Expected 1.7 for a μ_{HH} = 0 hypothesis)
- The observed (expected) **significance: 1.1σ** (1.3σ).

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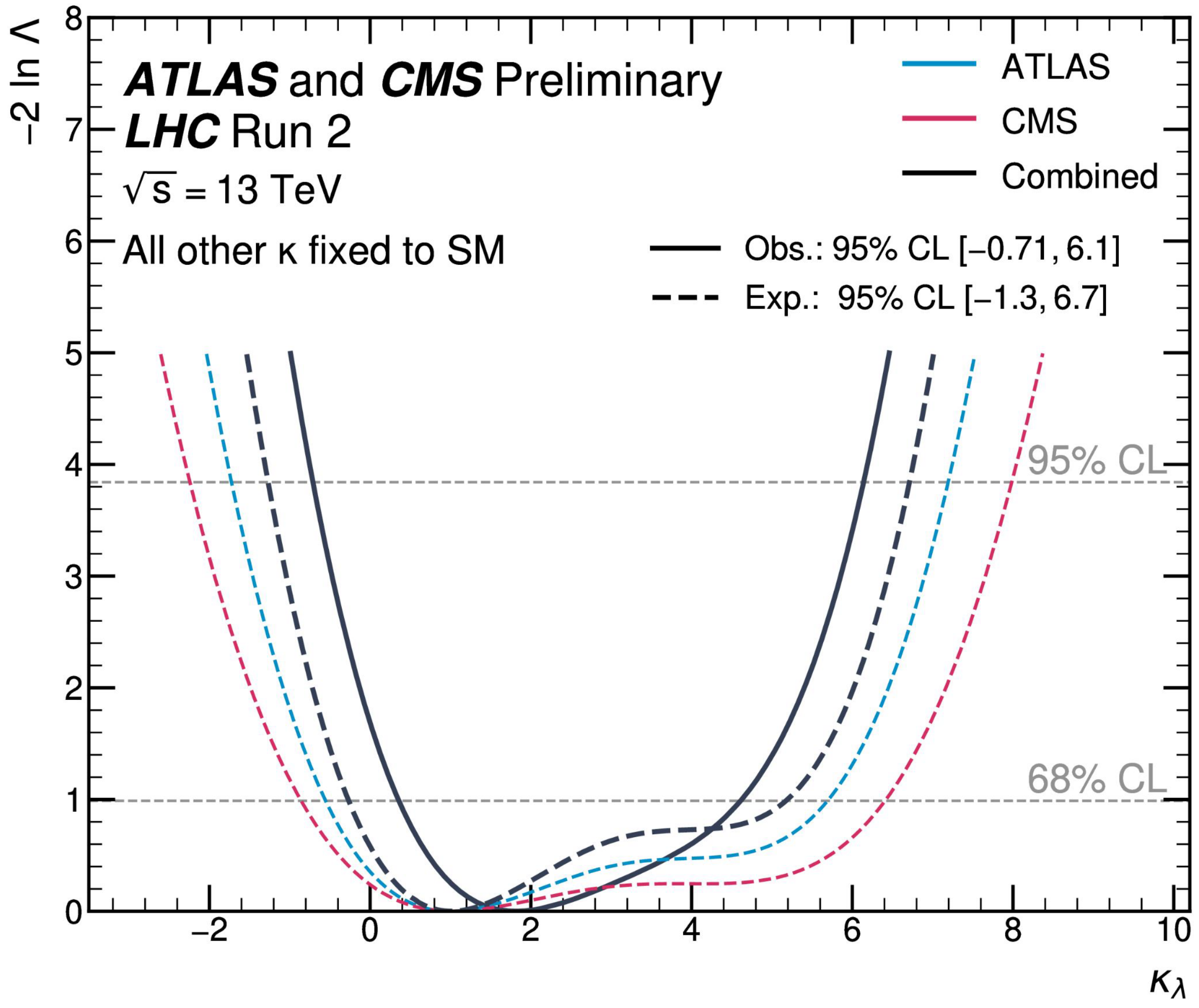
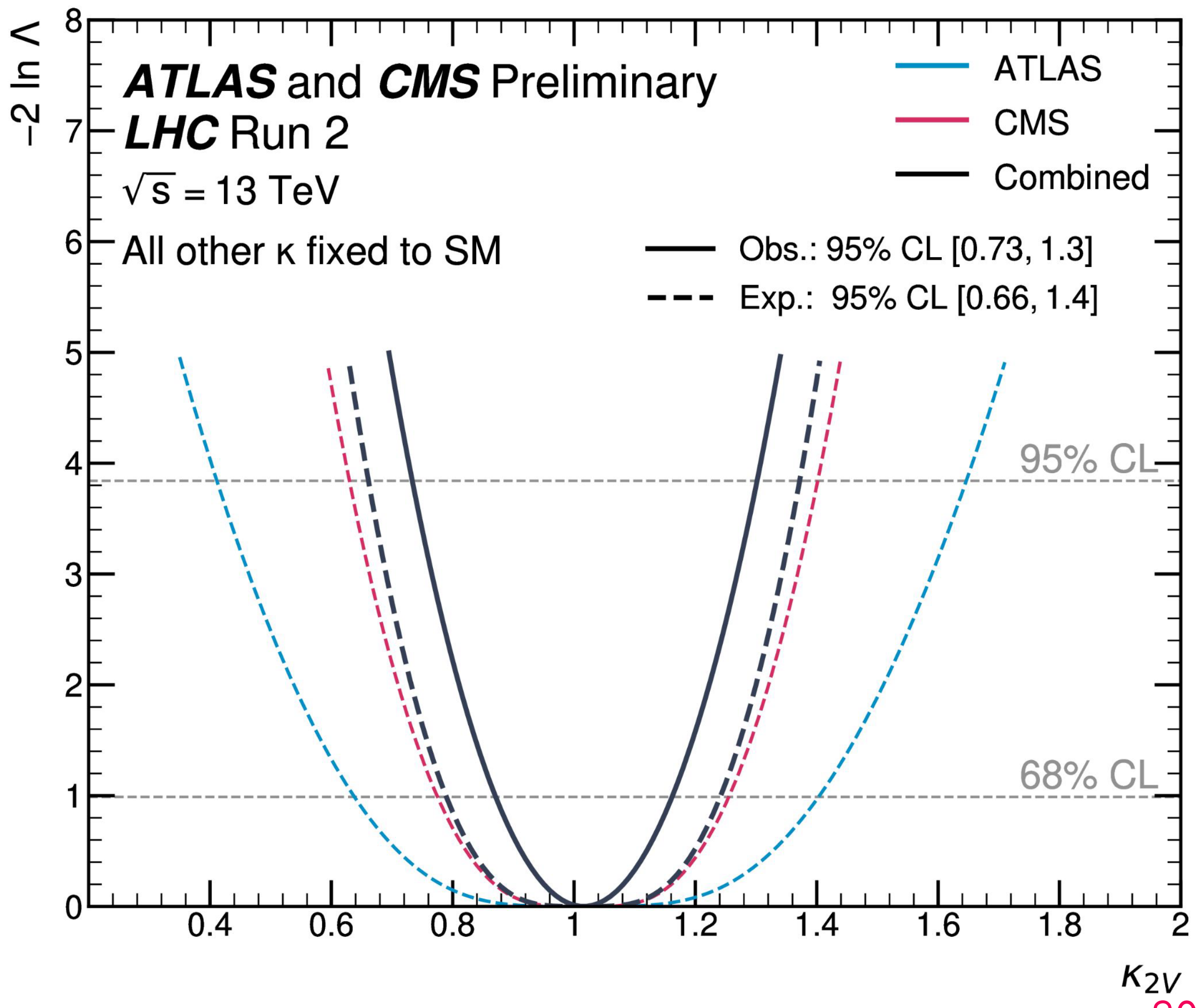
Constraints on κ_λ and κ_{2V}

ATLAS-CONF-2025-012, CMS-PAS-HIG-25-014

Leading sensitivity by $bb\gamma\gamma$ and $bb\tau\tau$ (better access to low m_{HH}).



Dominant channel: boosted VBF bbbb



Main features of these searches

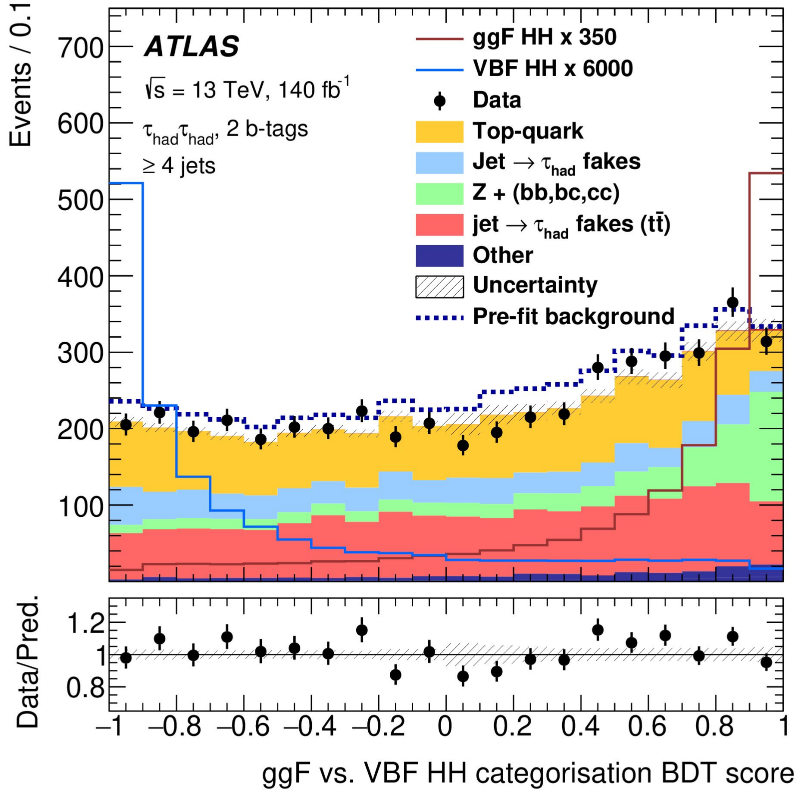
bbττ

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

Phys. Rev. D 110 (2024) 032012

categorisation (based on **triggers**)

$H \to \tau_{had}\tau_{had}$ single-taus (STT) and Di-tau (DTT)	$H \to \tau_{lep}\tau_{had}$ single-lepton (SLT)	$H \to \tau_{lep}\tau_{had}$ lepton+tau triggers (LTT)



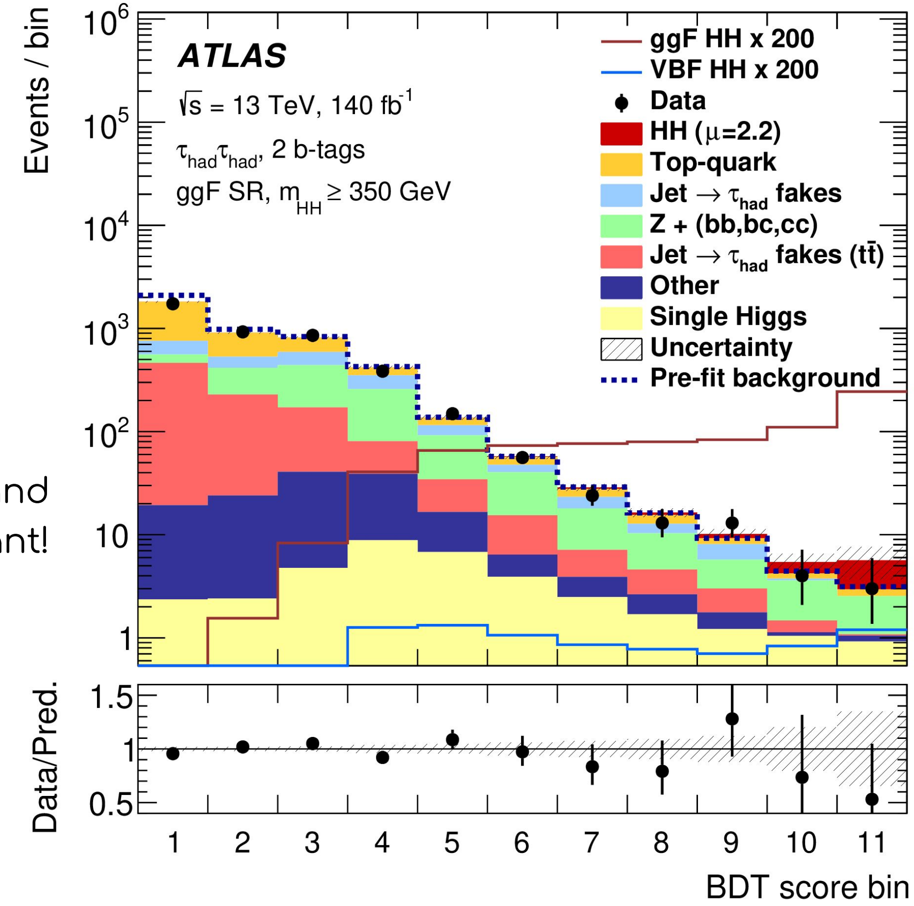
BDT to separate **VBF vs ggF** in each trigger category

Good MC modelling and statistics are important!

Current best expected sensitivity to SM HH by a single channel

ggF categories split into in m_{HH} < 350 GeV and $m_{HH} \geq$ 350 GeV

BDT to separate **signal from bkg** in each category

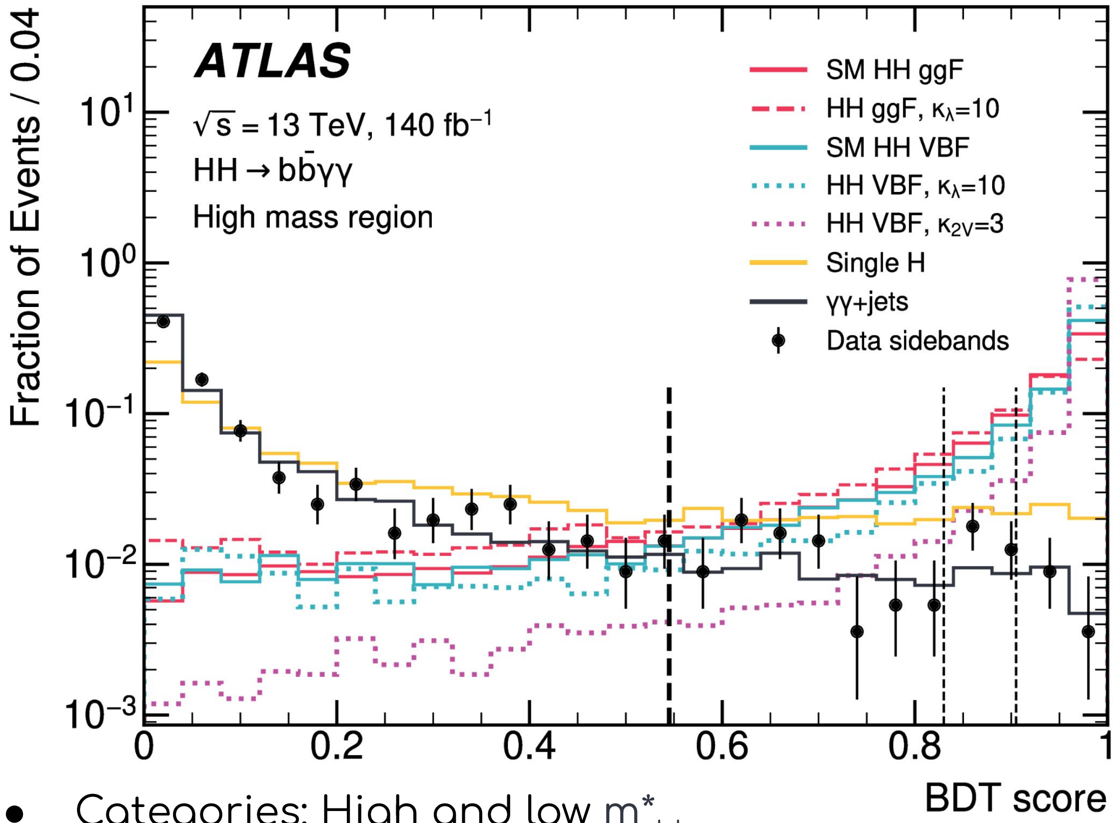


bbγγ

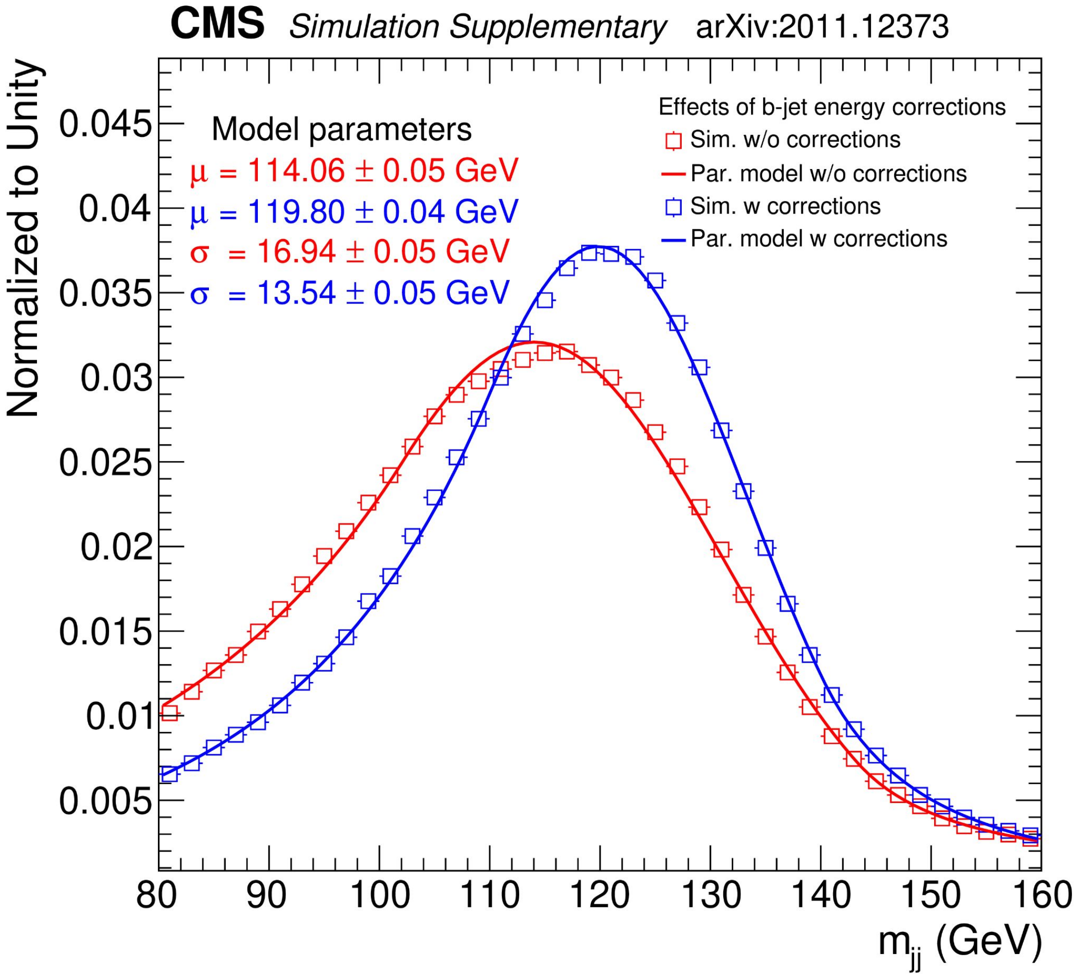
Select **2 b-tagged** jets and **2 high p_T photons**.

JHEP 01 (2024) 066

JHEP 03 (2021) 257



- **b-jet energy corrections** to the H→bb mass reconstruction have a strong impact in sensitivity.



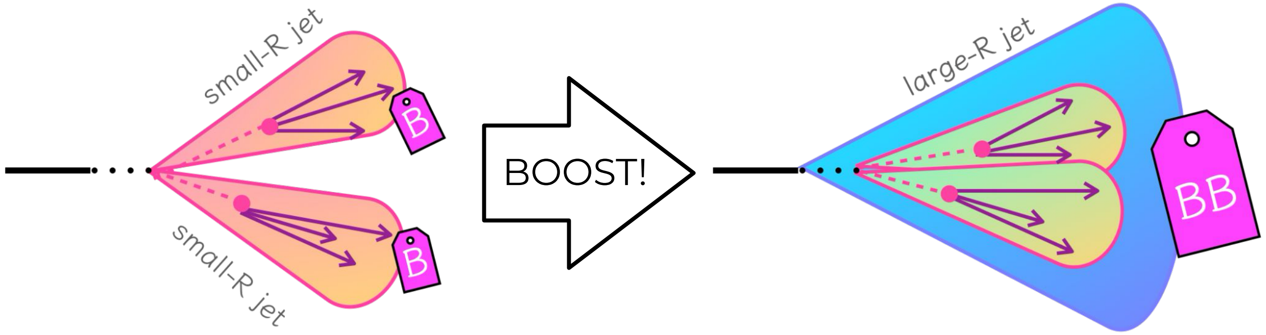
- Categories: High and low $m^*_{bb\gamma\gamma}$

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\ \text{GeV}$$

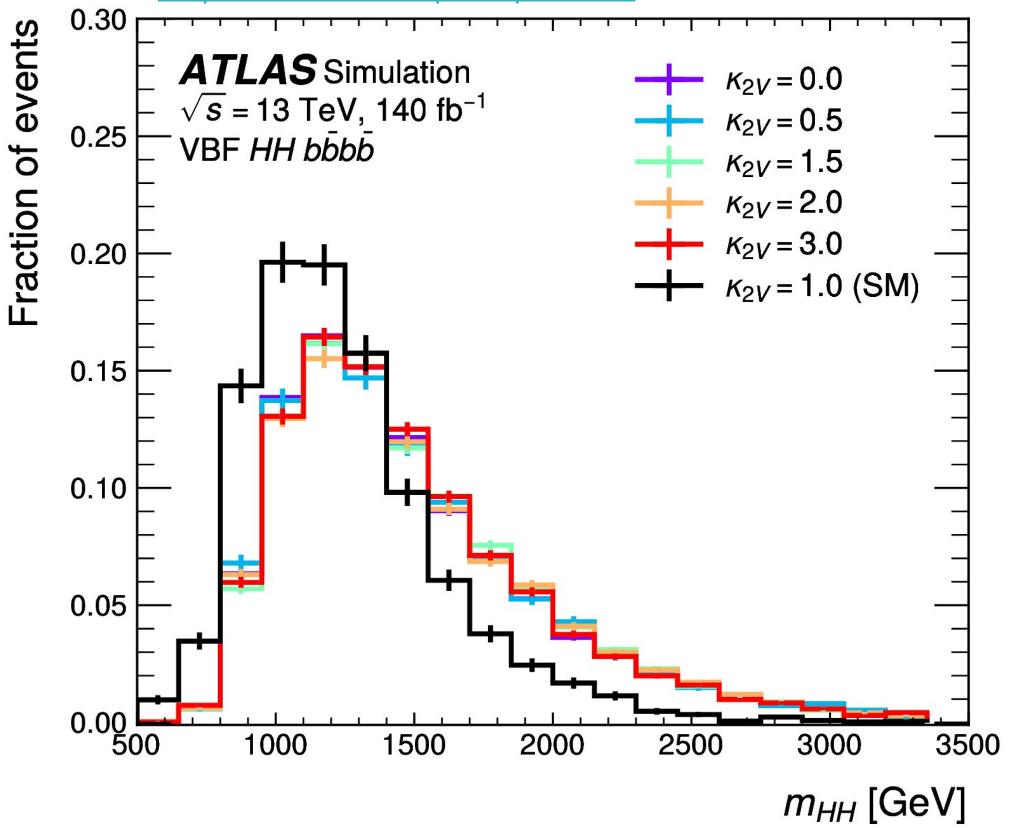
- For each $m^*_{bb\gamma\gamma}$ category BDTs are trained.
  - BDTs scores define further BDT categories.
- Model signal and bkg $m_{\gamma\gamma}$ shapes with analytic functions.

New reconstruction techniques

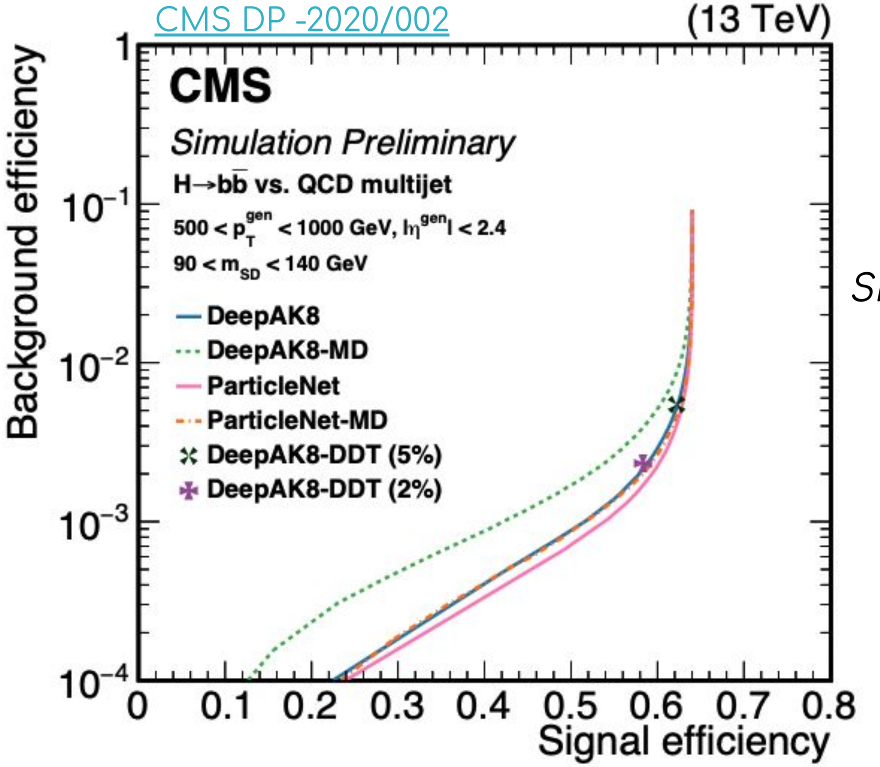
Improve our H→bb signal identification in this boosted regime.



Phys. Lett. B 858 (2024) 139007



CMS DP -2020/002



Significant improvement wrt the previous generation taggers!

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

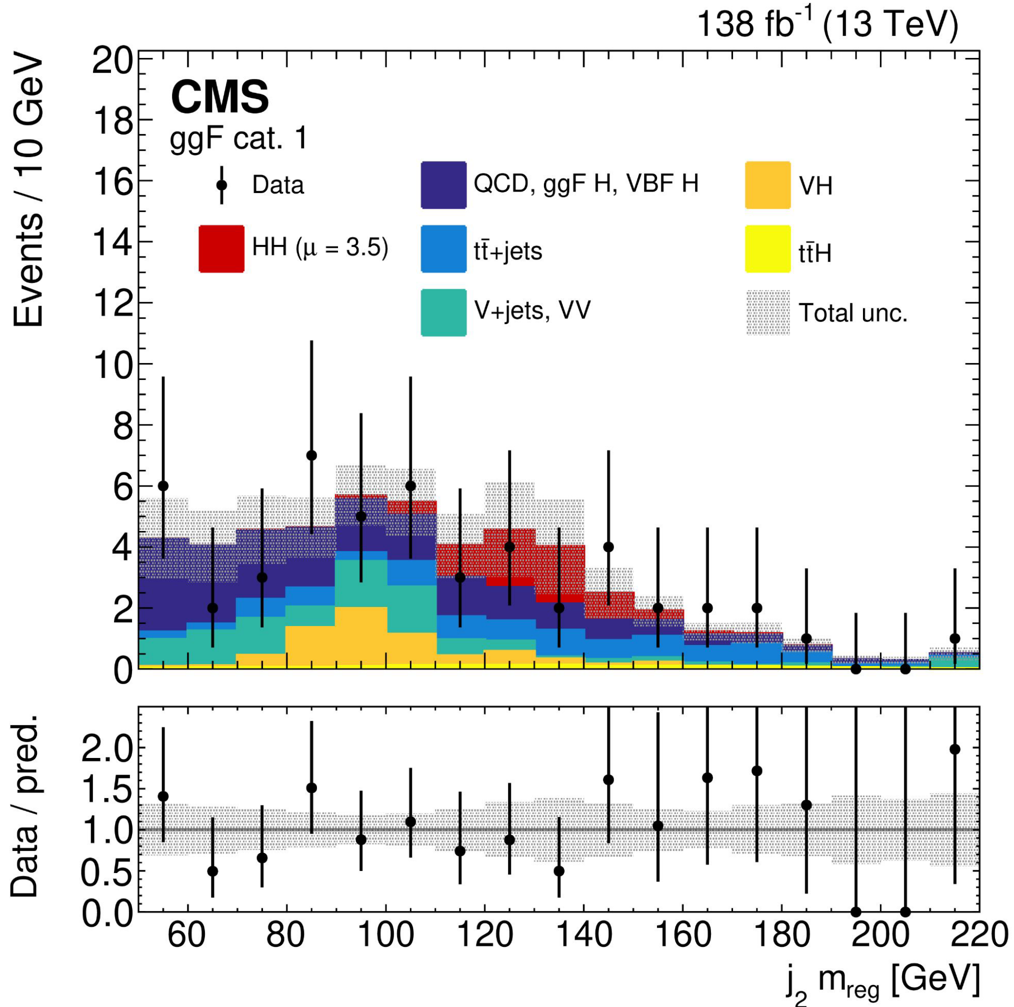
- have larger cross-section,
- the decay production are more energetic; harder m_{HH} spectra, we can exploit boosted signatures.

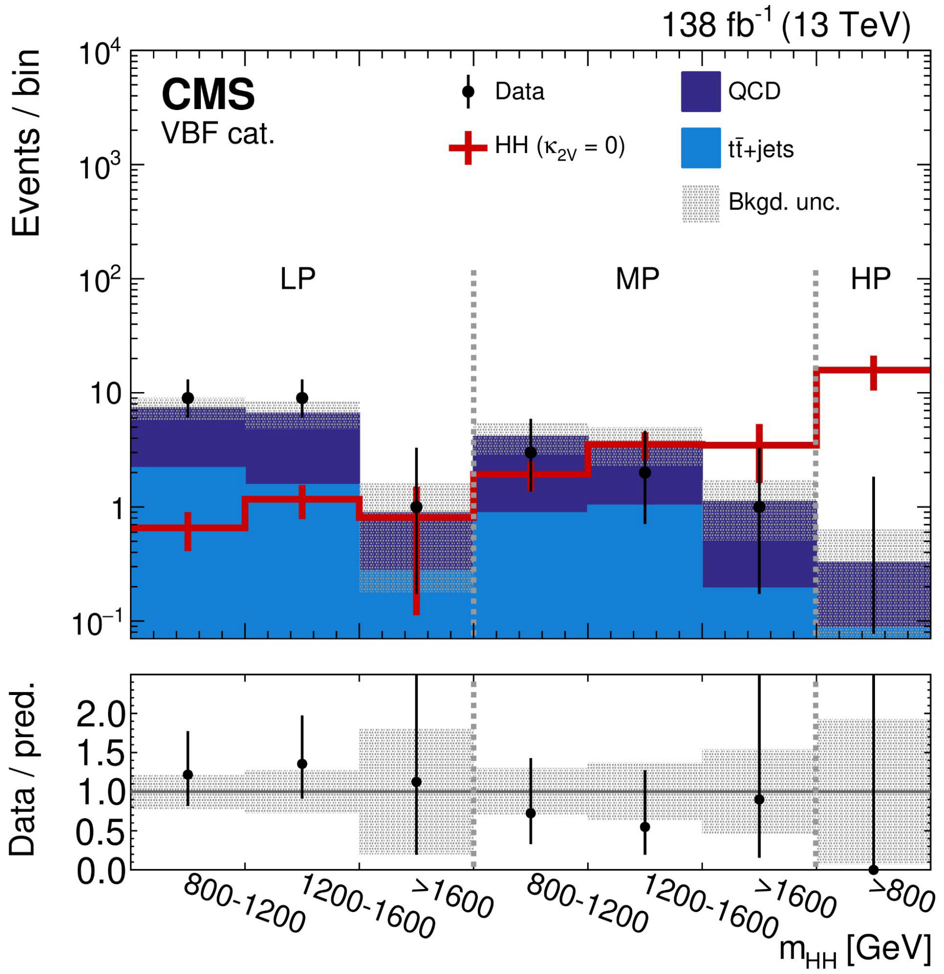
boosted HH→bbbb

Define multiple **ggF and VBF categories**,
to improve sensitivity to both SM and BSM production

Phys. Rev. Lett. 131 (2023) 041803

QCD and ttbar background estimated using **data driven techniques**.





VBF category drives the sensitivity to constrain
κ_{2V}: Obs (exp.) $\kappa_{2V} \in [0.63, 1.41]$ ([-0.66, 1.37])

LHC Run 3

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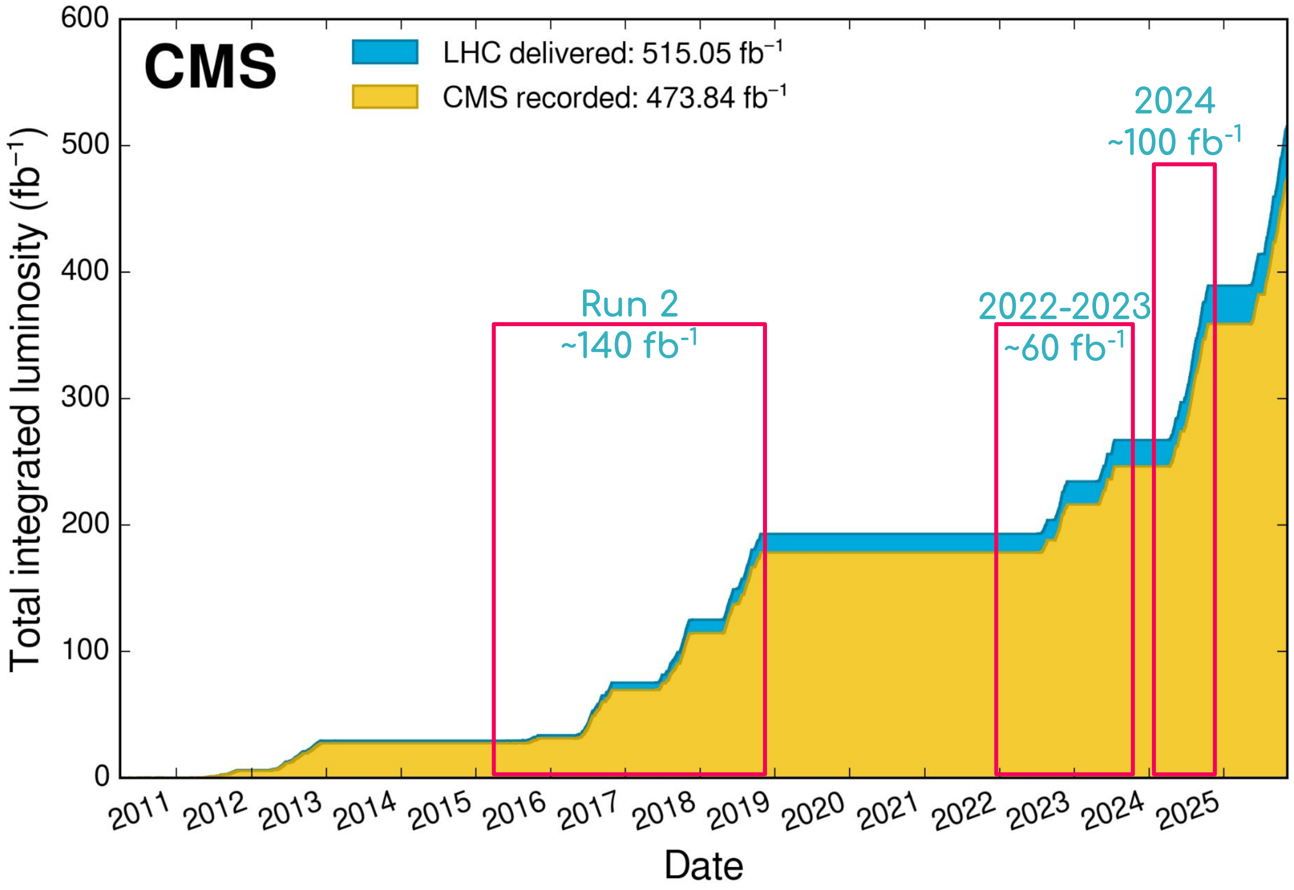
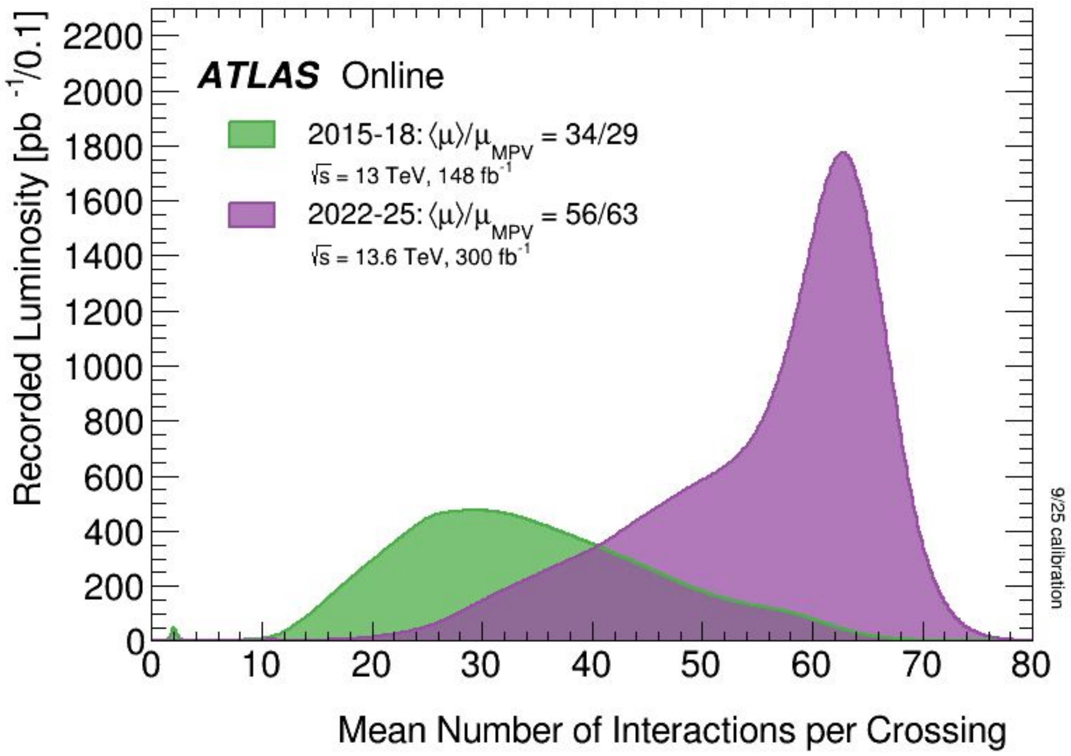
LHC Run 3





Run 3 dataset has surpassed the data collected in Run 2.

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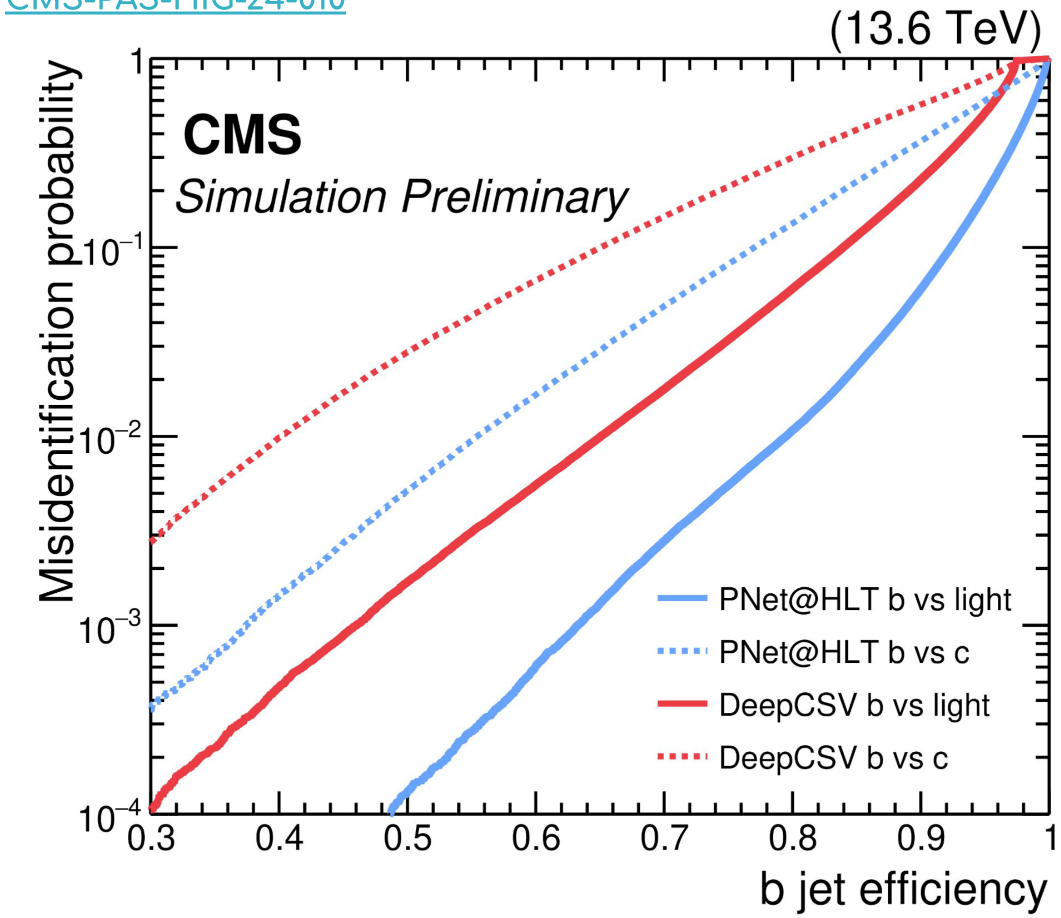
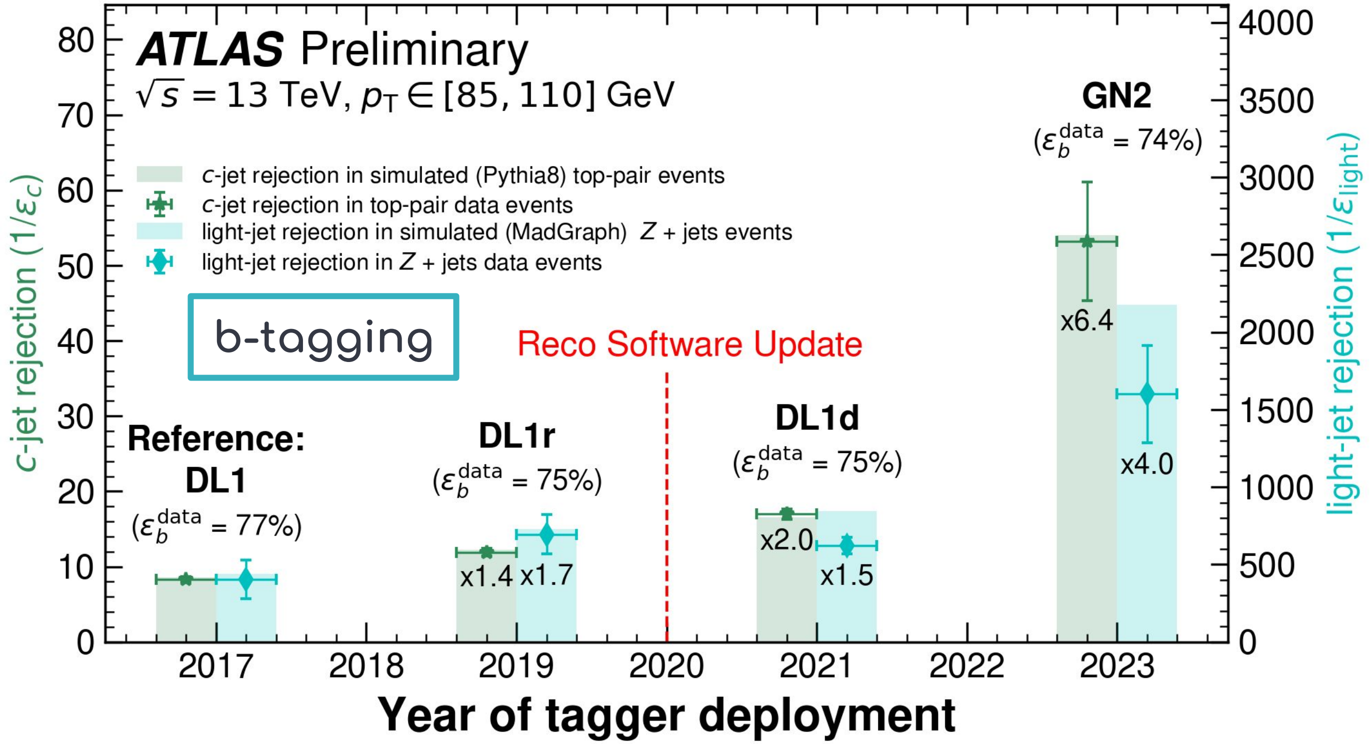
Run 3: Great Expectations

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

CMS-PAS-HIG-24-010



ATLAS-FTAG-2023-07

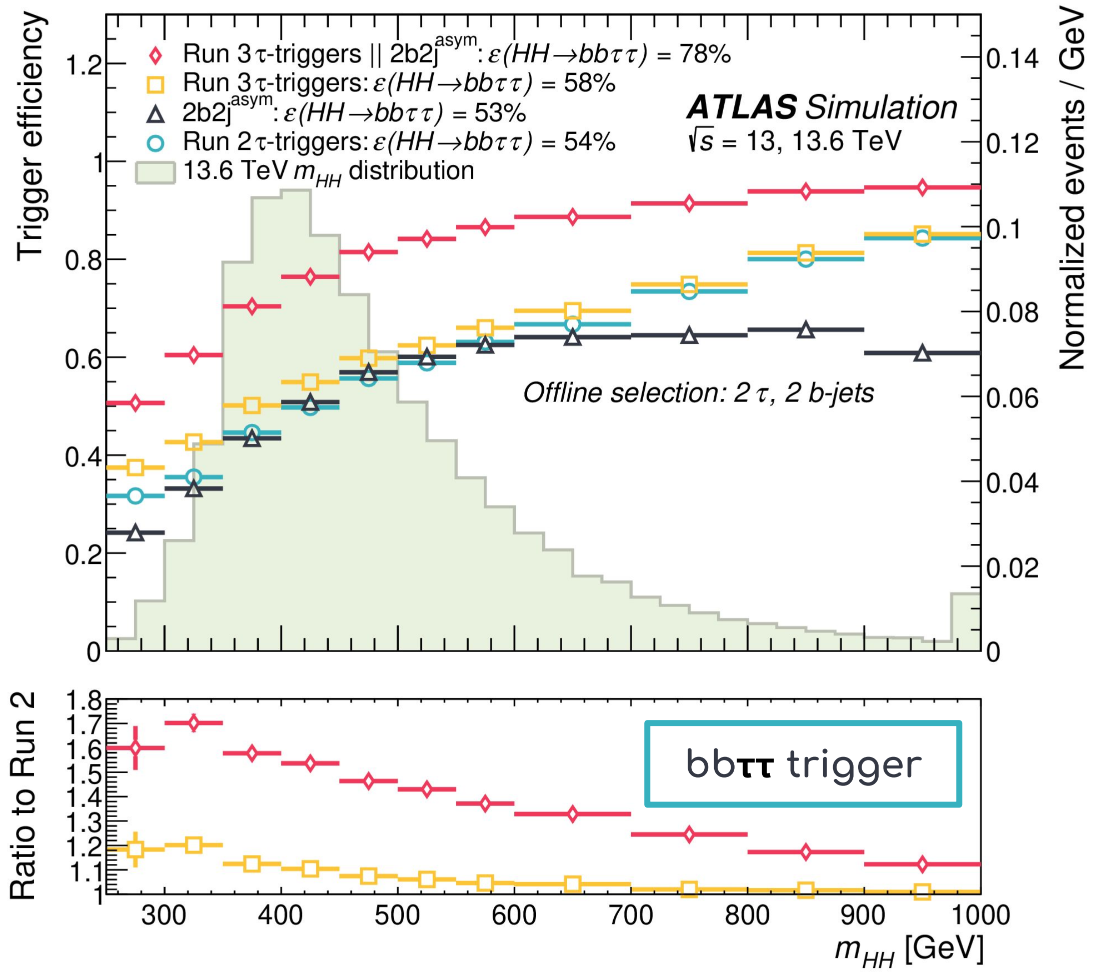


Significant improvements using state-of-the-art machine learning architectures on **identification** techniques.

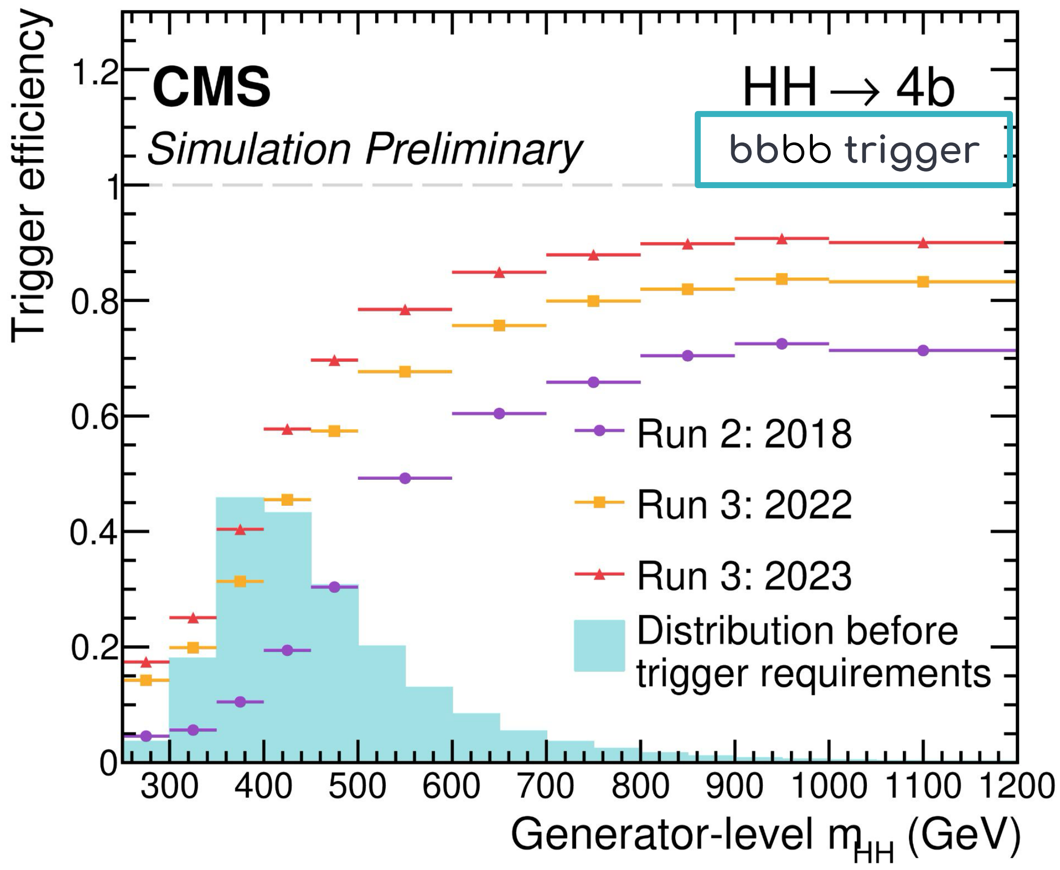
Run 3: Great Expectations

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

TRIG-2022-02



CMS-PAS-HIG-24-010



New triggers for hadronic HH:
Asymmetric ρT thresholds, multi-b / b+τ, delayed stream.

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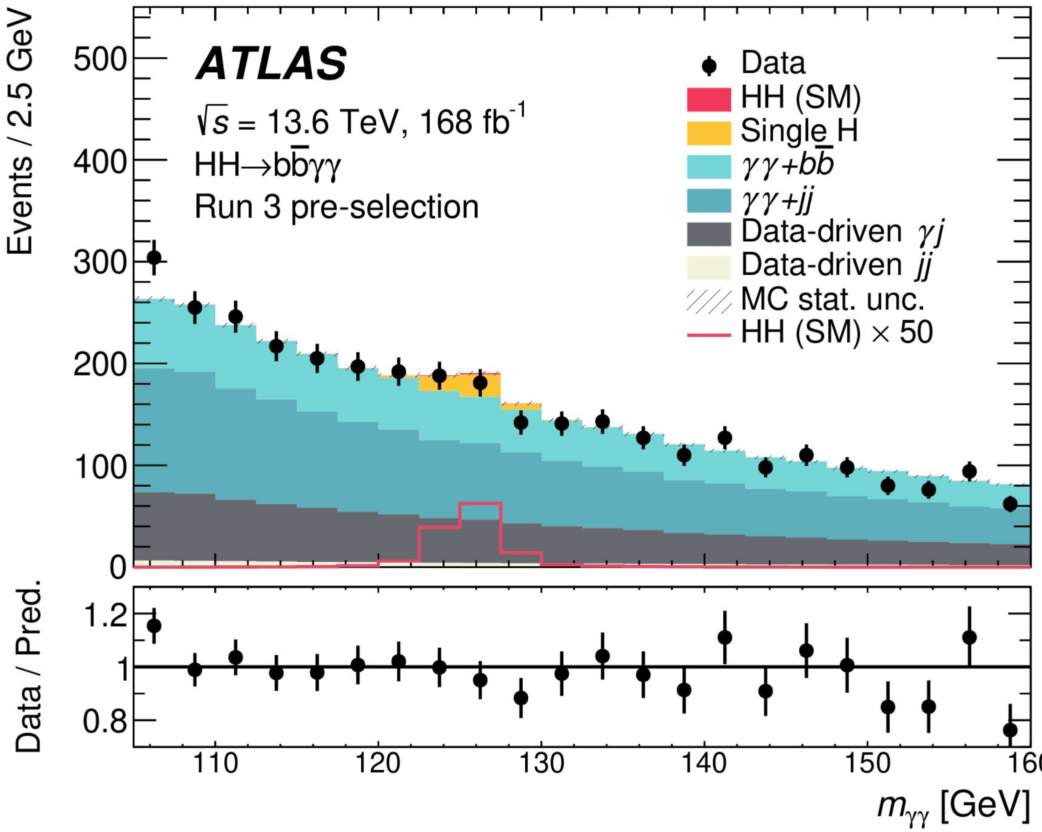
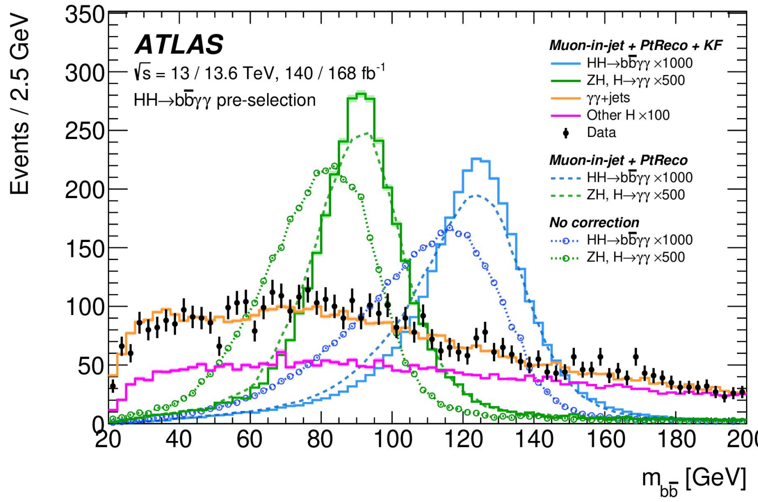
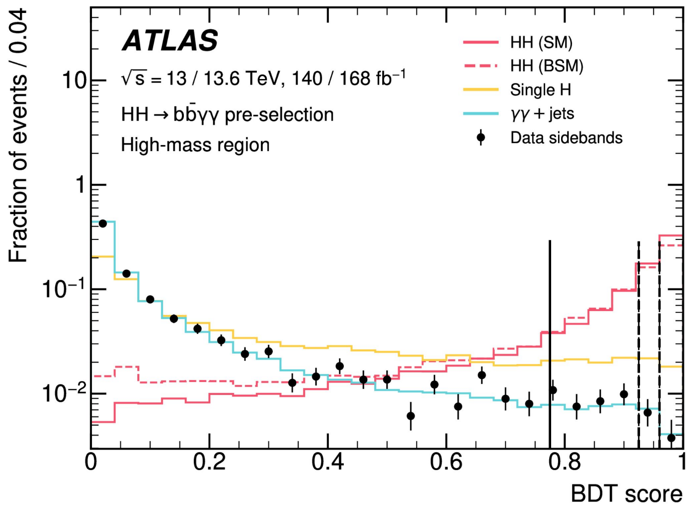
Run 3 results!
including up to 2024 data

ATLAS HH→bbγγ

arXiv:2507.03495





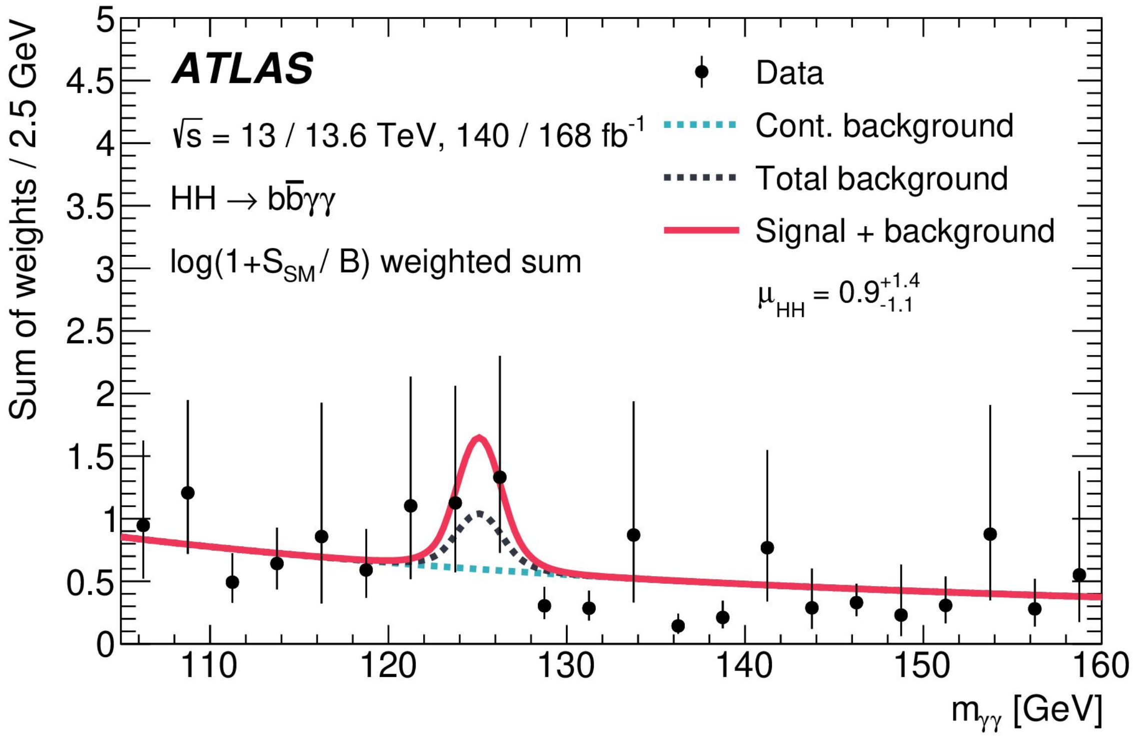


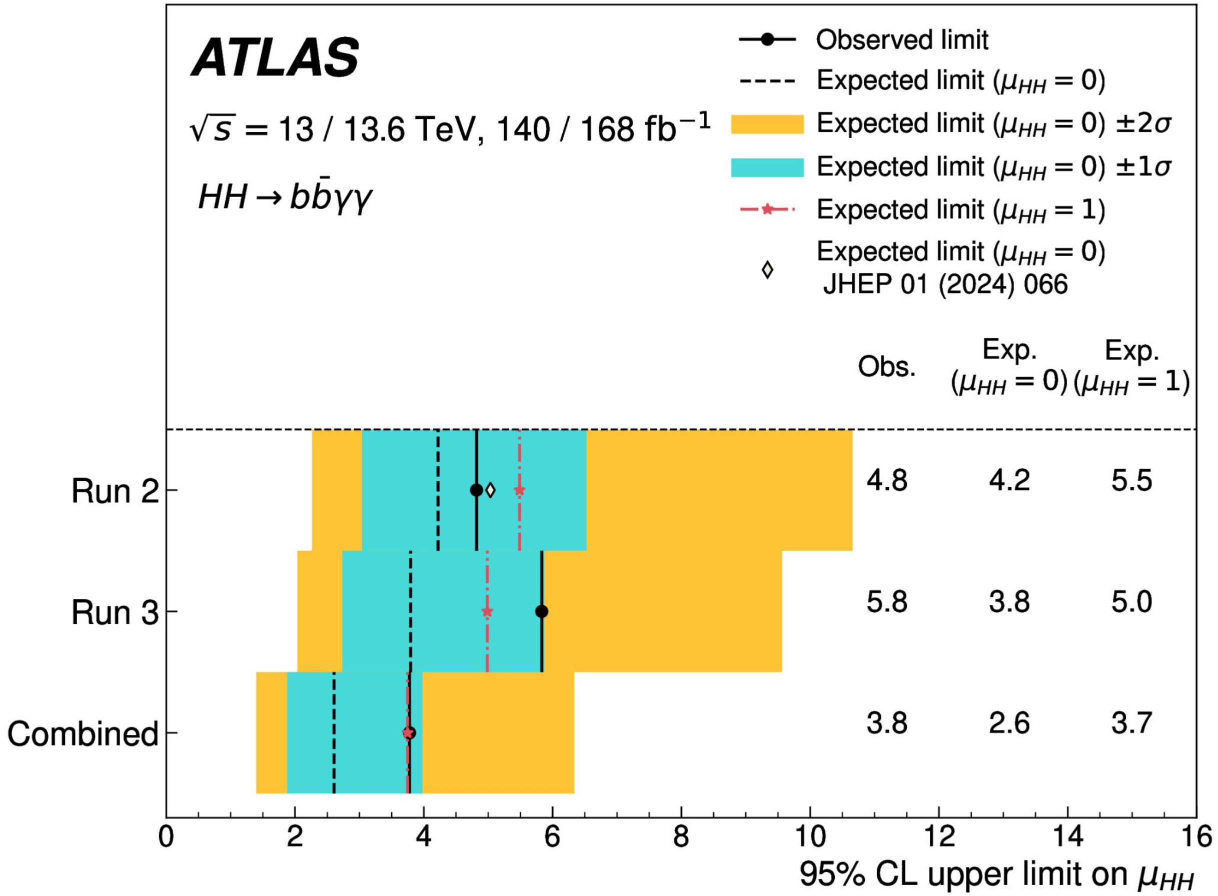
- Kinematic Fit to improve m_{bb} resolution.
- Signal extracted from fit to $m_{\gamma\gamma}$ in 7 BDT categories per LHC Run (defined in Low-mass and high-mass regions).
  - Correlation between Run 2 and Run 3 events in BDT and category optimization
- Non negligible contribution from single H→γγ

ATLAS HH→bbγγ

arXiv:2507.03495

- **Reanalysis of Run 2 data** and new 2022-2024 dataset. Improvements:
  - 50% for additional luminosity.
  - new b-taggers (20%)
  - analysis re-optimisation (10%)
  - kinematic fit to improve σ(m_{bb}) and σ($m_{bb\gamma\gamma}$) (5%





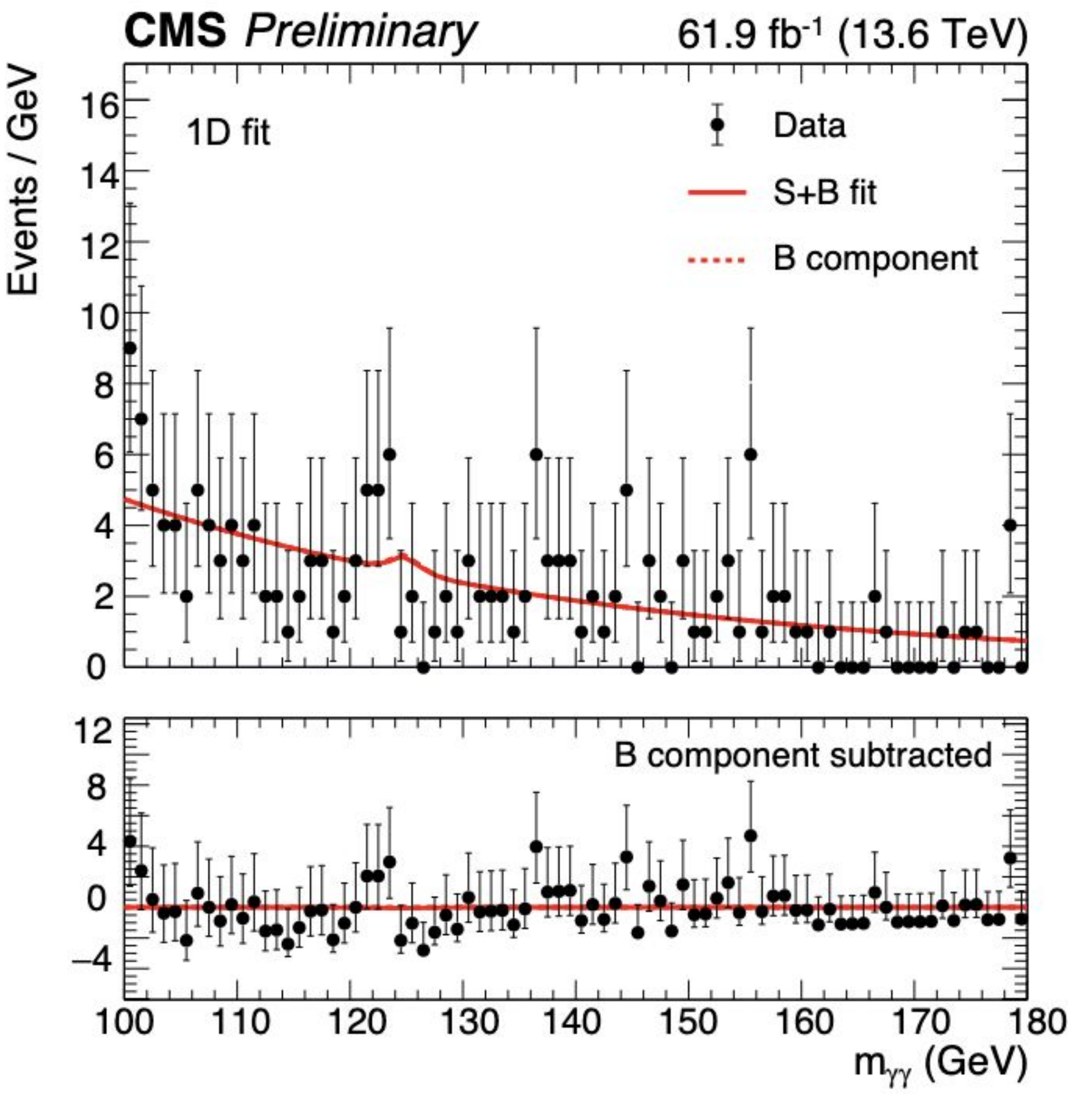
- With +300 fb^{-1}, single analysis is now competitive to the ATLAS Run 2 Legacy
  - μ_{HH} < 3.8 (2.6 exp).
  - Self-coupling: $-1.7 < \kappa_\lambda < 6.6$ ($-1.8 < \kappa_\lambda < 6.9$ exp)
- Combined 0.84σ (1.01σ) discovery significance.

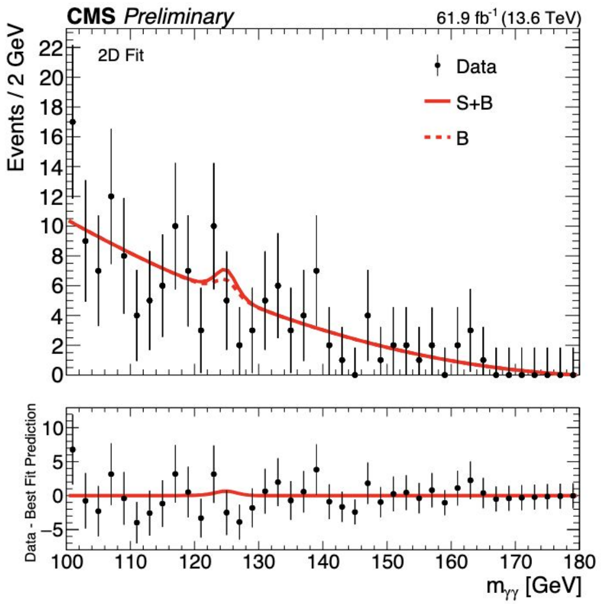
Run 3 results!
including 2022-2023 data

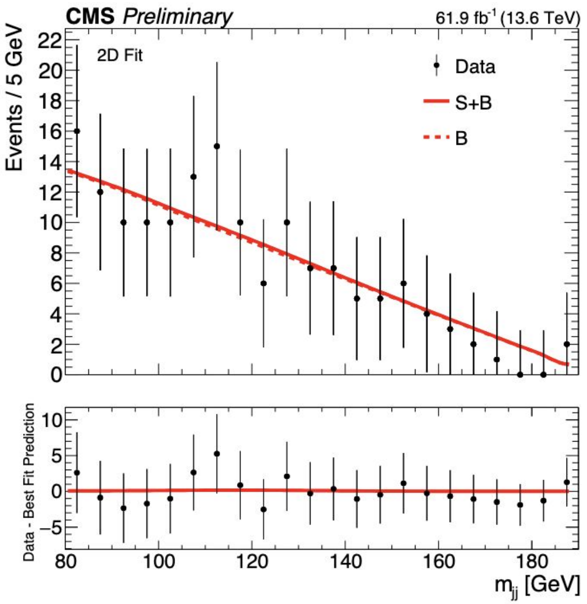
CMS HH→bbγγ

CMS-PAS-HIG-25-007

- Analyses for two categories:
  - Merged (using largeR jets, AK8)
  - Resolved. Done with two alternative approaches using
    - **1D**, $m_{\gamma\gamma}$ fit (m_{jj} as input to BDT)
    - **2D**, Fitting m_{jj}, $m_{\gamma\gamma}$; NN trained (w/o m_{jj}) for signal-bkg discrimination.
- Improve m_{jj} mass resolution:
  - DNN regression and improve flavour tagging (ParticleNet) gives 10-20% improvement.
- Final estimate of non-resonant background from fit to the diphoton mass spectrum.







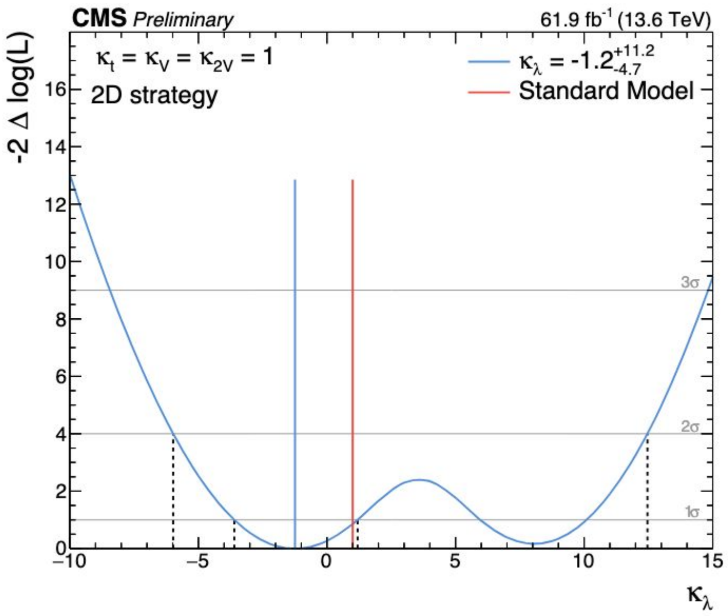
Run 3 results!
including 2022-2023 data

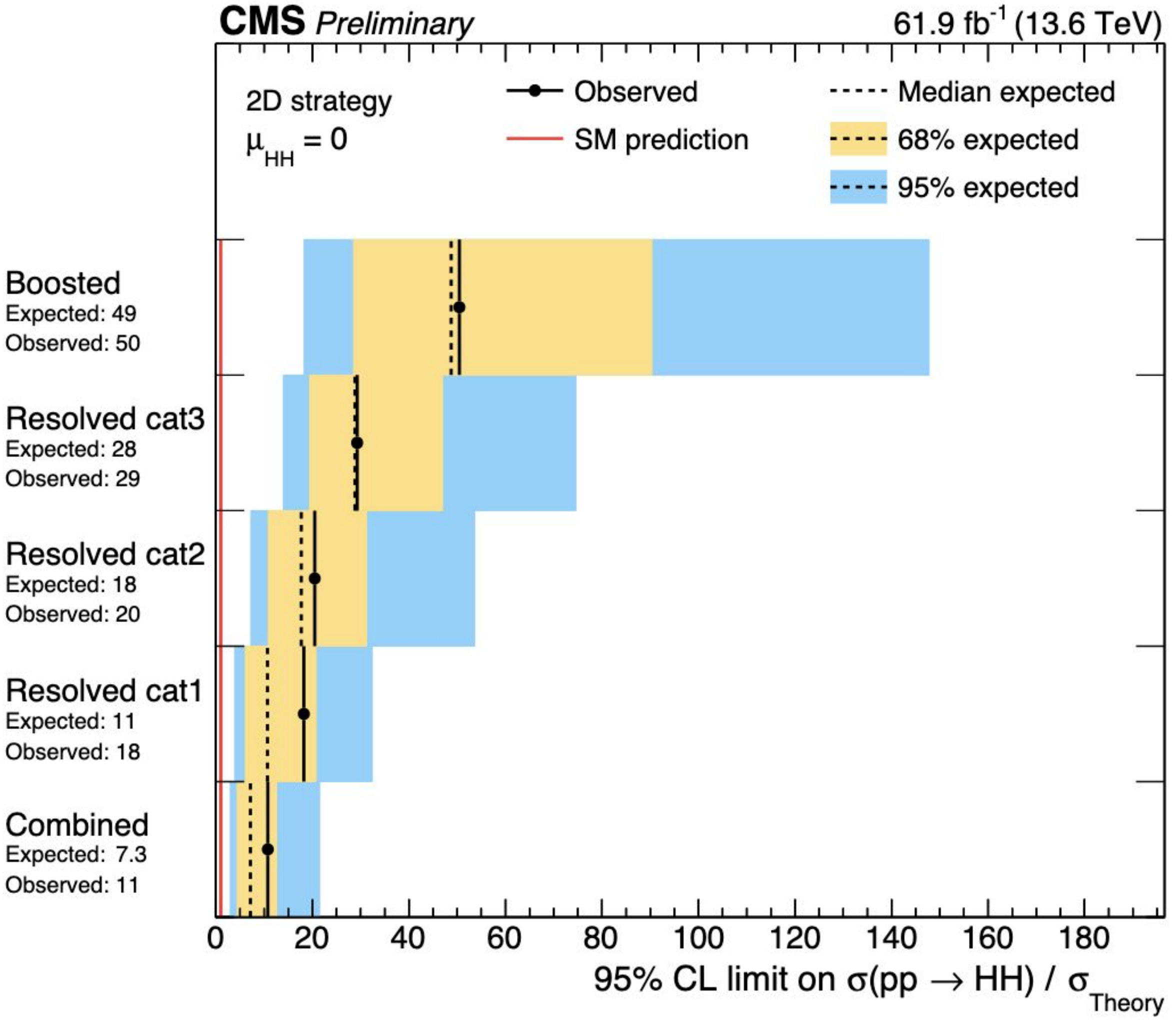
CMS HH→bbγγ

CMS-PAS-HIG-25-007

Resolved topologies

95% CL on $\sigma(pp \to HH)/\sigma_{Th}$	1D	2D
	$\mu_{HH} = 0$	
Exp	8.7	7.3
Obs	7.4	11





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Run 3 results!
including 2022-2023 data

CMS HH→bbbb

CMS-PAS-HIG-24-010

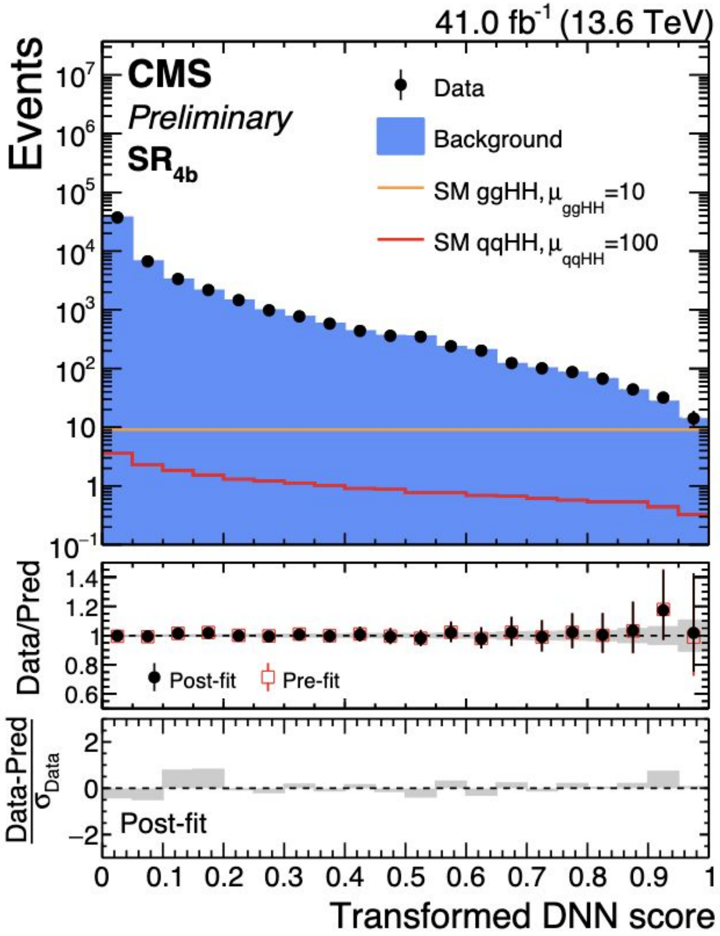
- New results using 22+23 data
  - re-analysis of Run 2 results expected (not yet included in the PAS note).
- Improvement in sensitivity x2
  - new strategy and bkg estimation, parking triggers, PNet tagging at HLT, new taggers…

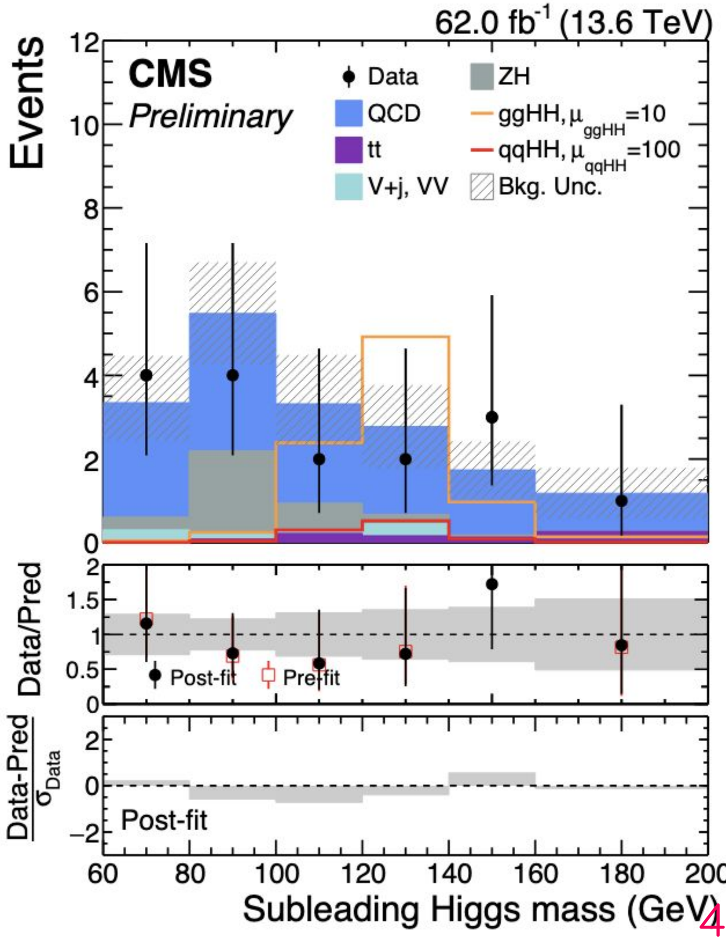
Resolved

- NN used to separate signal from bkg.
- NN trained to learn CR2b → CR4b used to estimate; **background estimate in SR4b from SR2b** (similar to ATLAS Run 2 strategy).
- Additional NN to discriminate ggHH from VBFHH

Boosted:

- New Hbb triggers
- GloParT score to select boosted H→bb candidates.
  - tagger calibration from Z→bb
- QCD multijet extracted from NN reweighing
- DNN used for bkg discrimination.



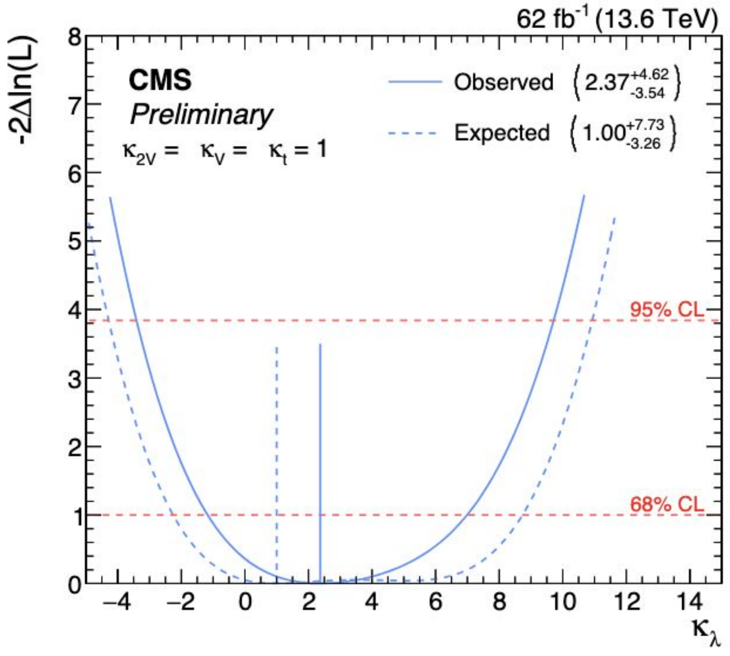


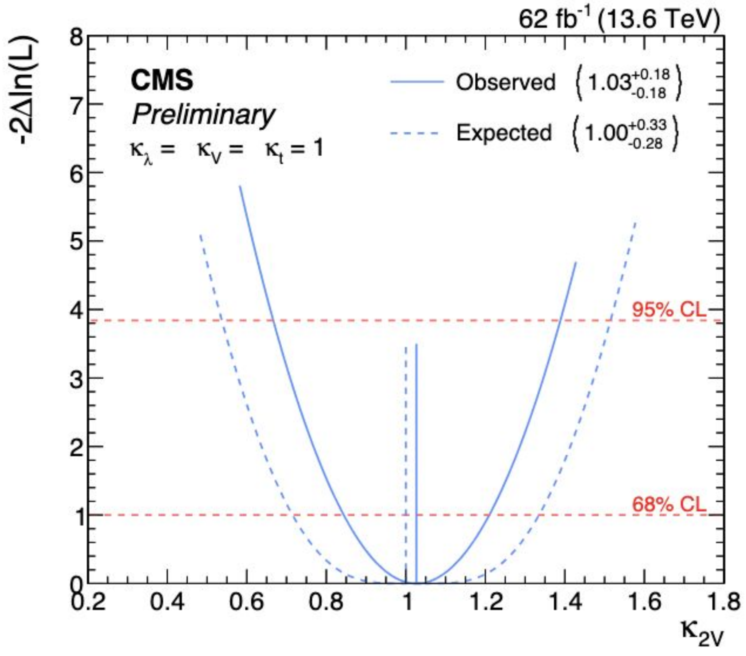
Run 3 results!
including 2022-2023 data

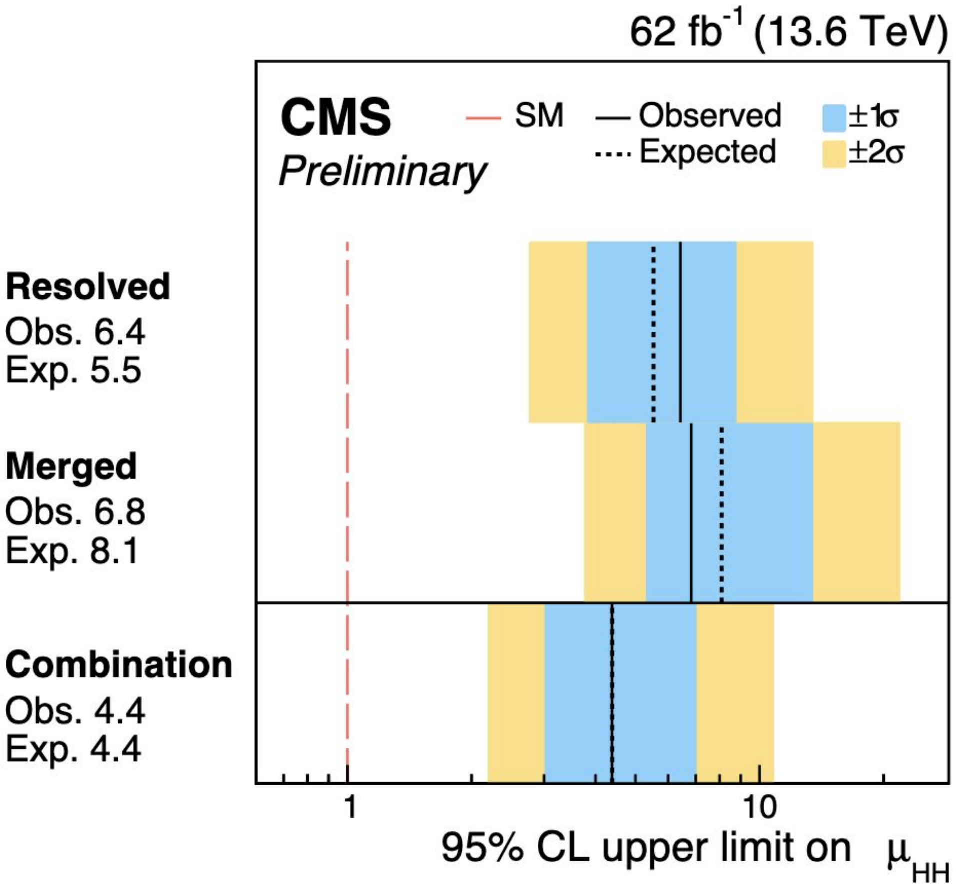
CMS HH→bbbb

CMS-PAS-HIG-24-010

- Limits using 62 fb^{-1} competitive already with the Run 2 results (140 fb^{-1}).
  - **μ_{HH} < 4.4** (4.4 exp).
  - Self-coupling: [−3.3, 9.7] ([−3.4, 10.0])
  - HVV coupling [0.63, 1.43] ([0.54, 1.51])







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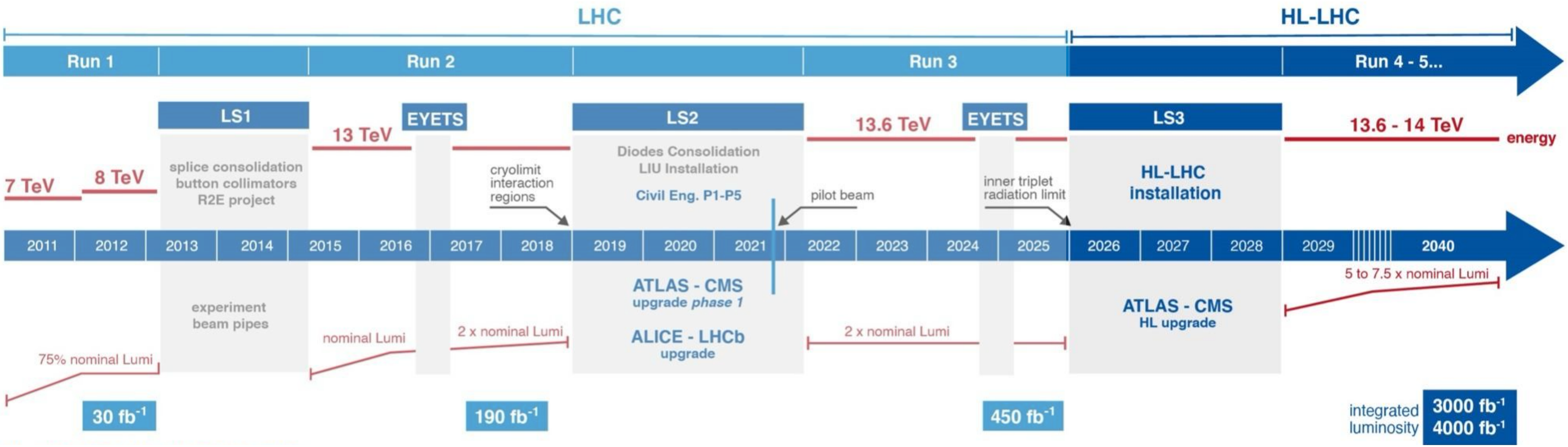
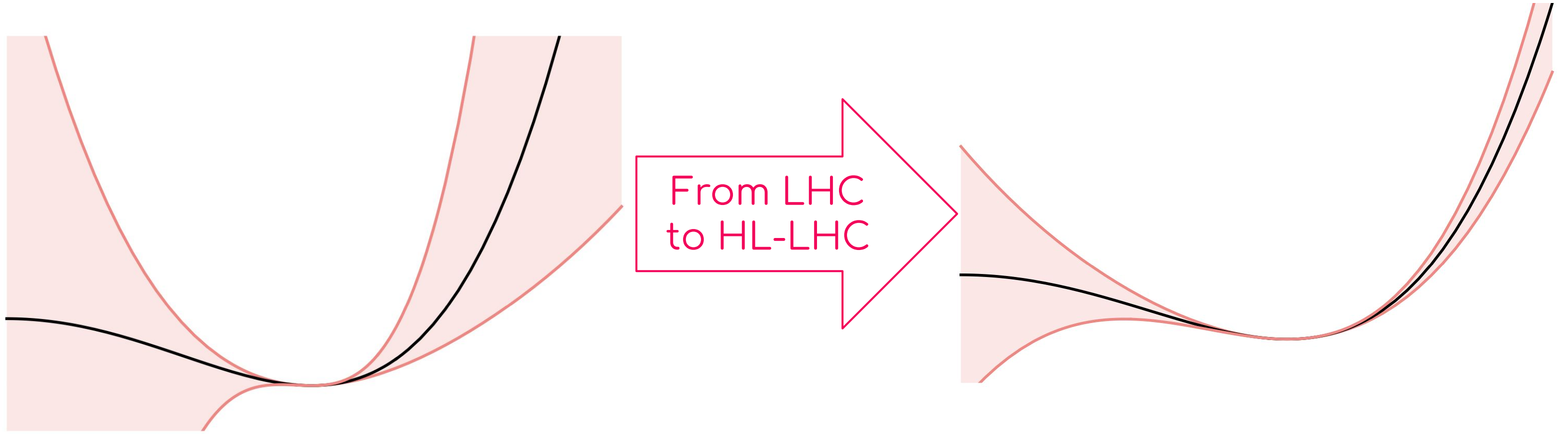
... and beyond!

HL-LHC



What will be our **sensitivity** to observe Di-Higgs production with the HL-LHC dataset?

→ **to what precision will we measure κ_λ?**



H/T N.Craig, R. Petrossian-Byrne

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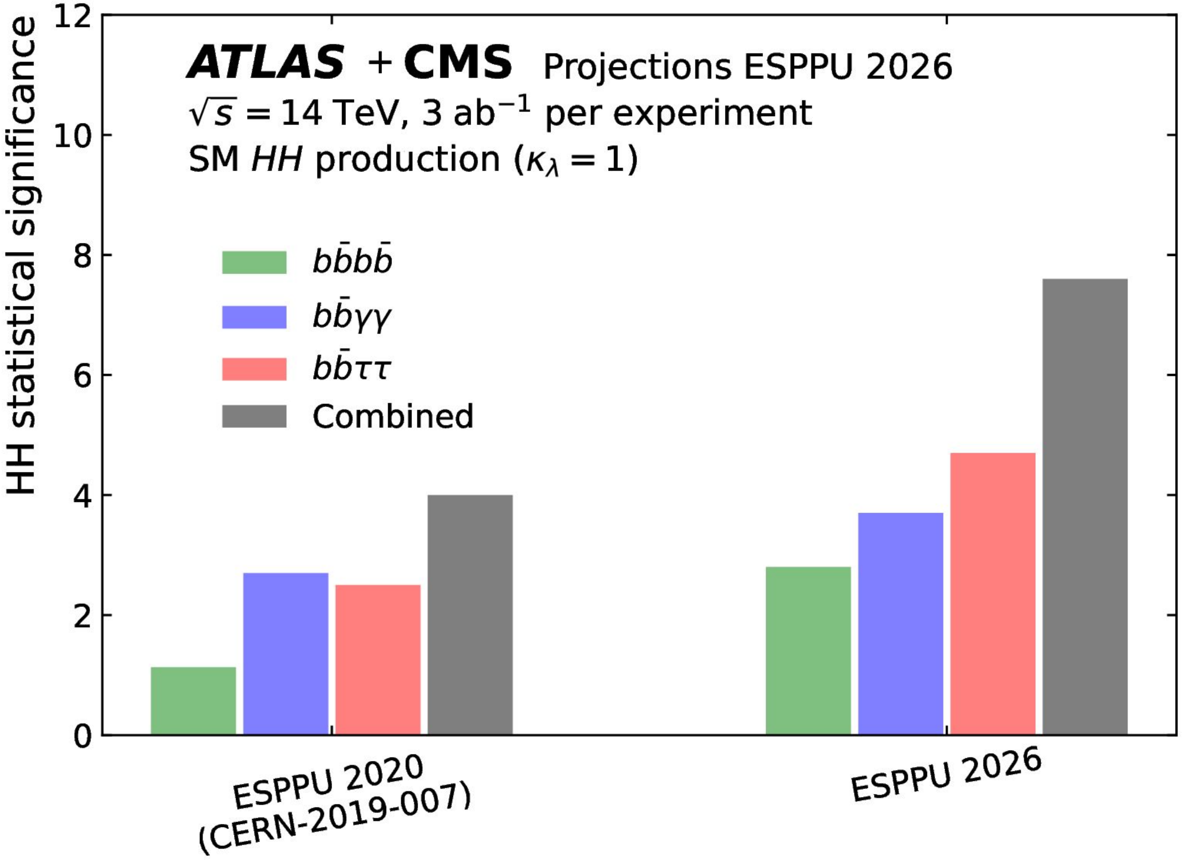
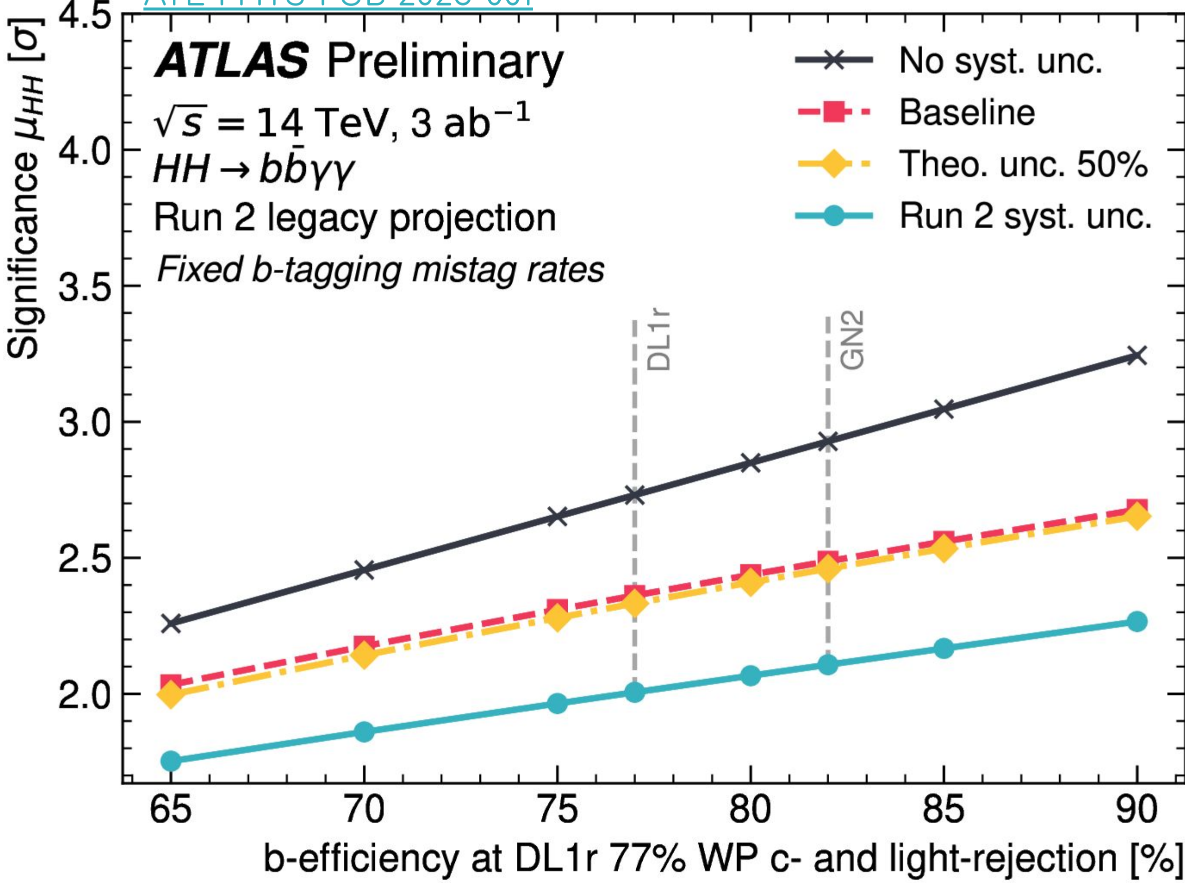
HL-LHC Projections

Difficult to anticipate improvements in **reconstruction**, **identification**, **trigger** and overall analysis **strategies**.
Important to identify the areas of opportunity in each analysis.

arXiv:2504.00672



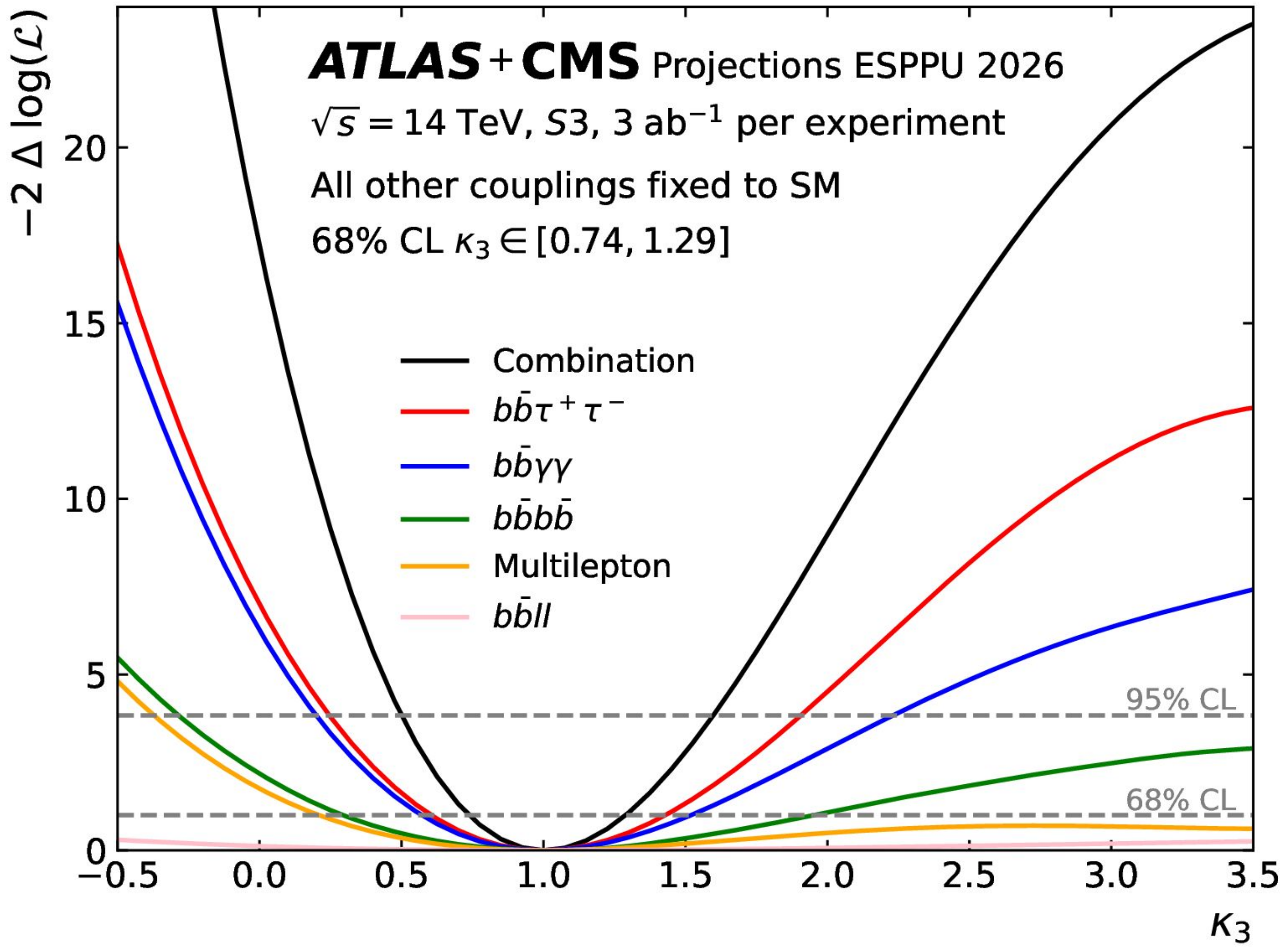
ATL-PHYS-PUB-2025-001



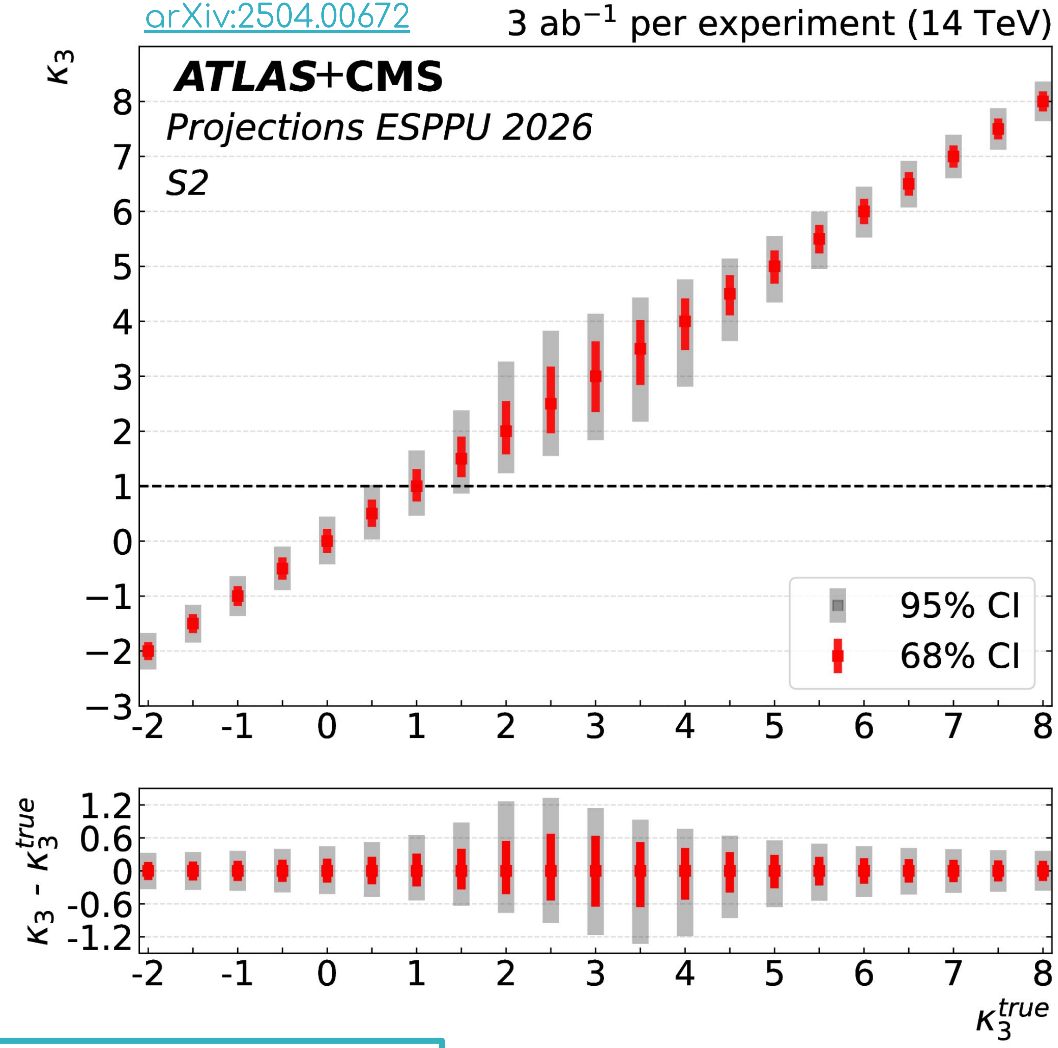
Latest projections are based in our legacy results from Run 2 (input for the European Strategy Update 2025)

- ATLAS: HH combination, bb**ττ**, bbγγ, boosted VBF 4b, bbℓℓ+MET, multi-lepton.
- CMS: HH combination
- ESU-2025

HL-LHC Projections



arXiv:2504.00672



S3 scenario: κ_λ is expected to be measured as $1.0^{+0.29}_{-0.26}$.

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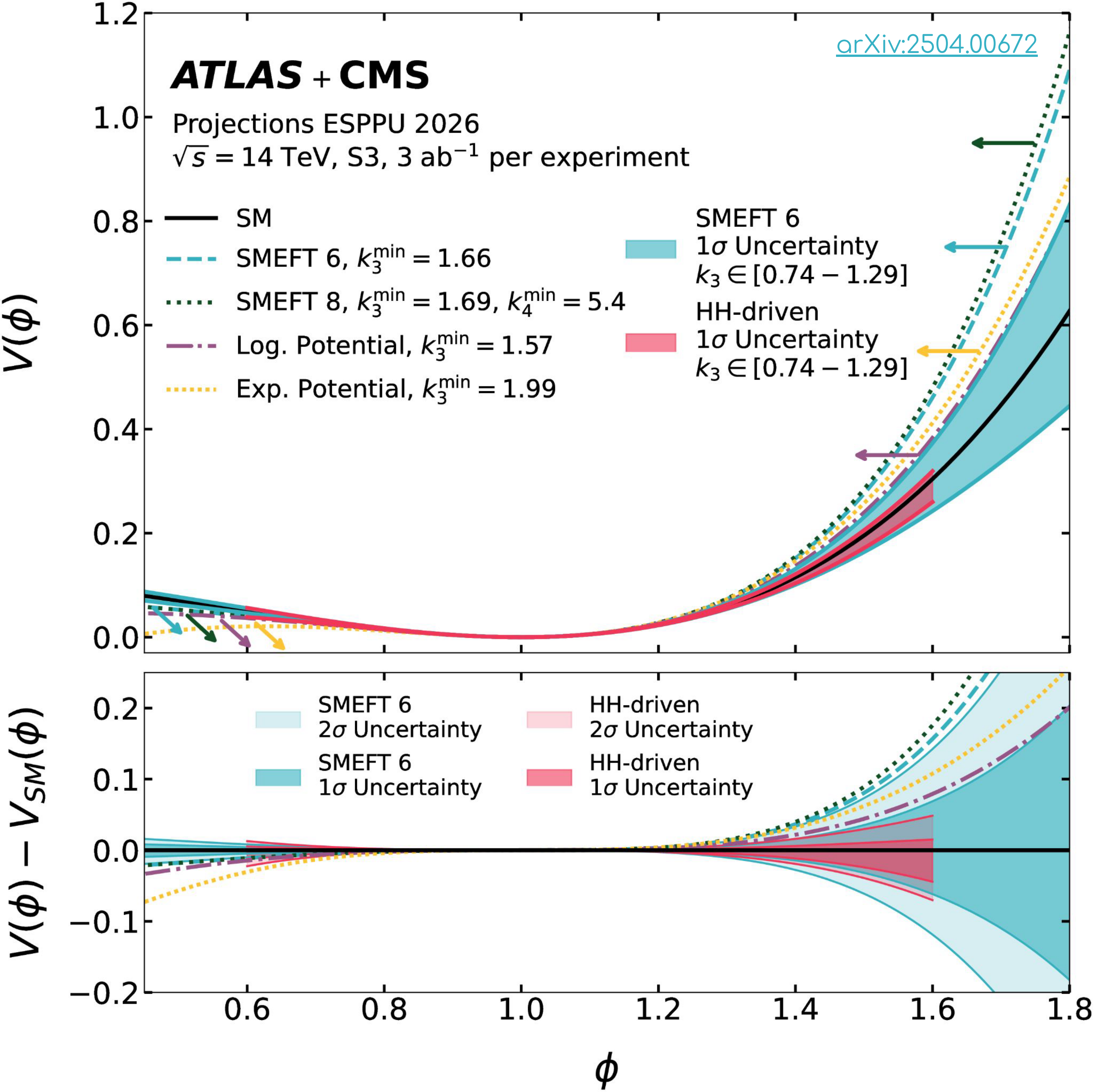

HL-LHC Projections

- Measuring the self-coupling can provide discrimination between different potential scenarios or models.
- BSM potential can be expressed as a deformation of the SM EWSB potential.
- Scenarios considered in the HL-LHC projections 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 $\kappa_\lambda > \kappa_{min}$.

Final remarks

- Ultimate goal for the HH physics program: combination of all searches! We should work on:
  - Improving the sensitivity of the main channels: $bb\tau\tau$, $bb\gamma\gamma$, bbbb.
  - Exploring different signatures: both **boosted** and **resolved** contribute significantly.
  - Other “smaller” channels also have an impact in the final result.

- Not discuss here:
  - **resonant X→HH/SH** searches are also an important branch of this research.
  - Both Collaborations have now published Run 2 searches for **HHH production**, constraining the quartic coupling.
    - ATLAS in the HHH→6b channel for ; HL-LHC projections have been made public for this result.
    - CMS in the HHH→6b and HHH→4b2γ
  - CMS has published a search for **ttHH** (in final states including $H\to\gamma\gamma$)

- Promising outlook for more Run 3 results:
  - New triggers,
  - better object reconstruction and identification,
    - improved large-R jet taggers (for boosted Higgs identification),
  - novel analysis techniques,
  - It is paramount to continue advancing object performance and analysis strategies developments to achieve our goal!

- Great prospective for Di-Higgs searches at the LHC and HL-LHC.
  - Important to reach this milestone discovery in these hadron accelerators.

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ありがとう

Backup slides

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