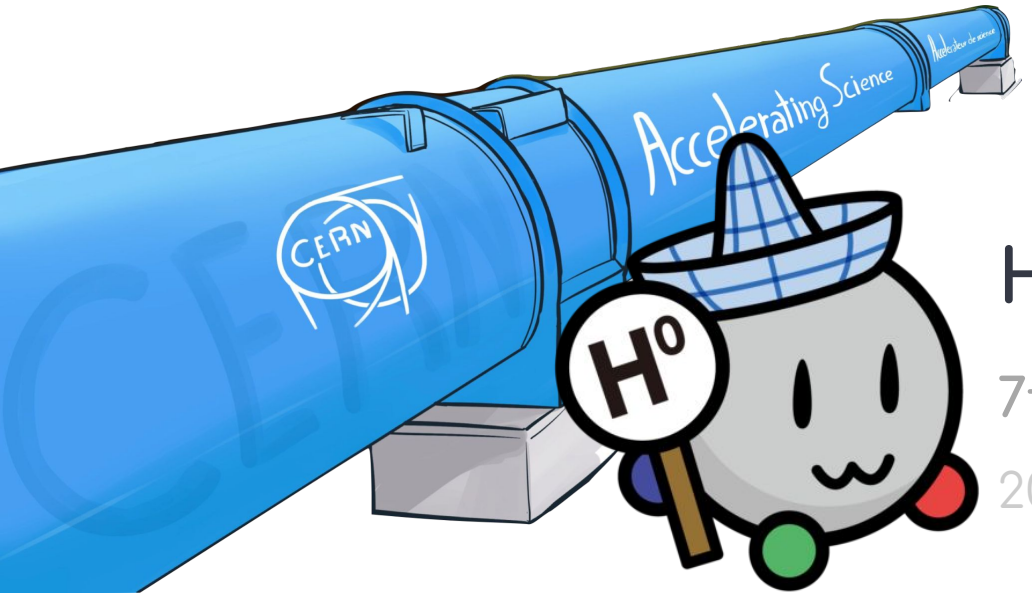


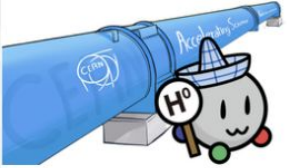
Highlights of Higgs Physics at the LHC

7th KMI International Symposium

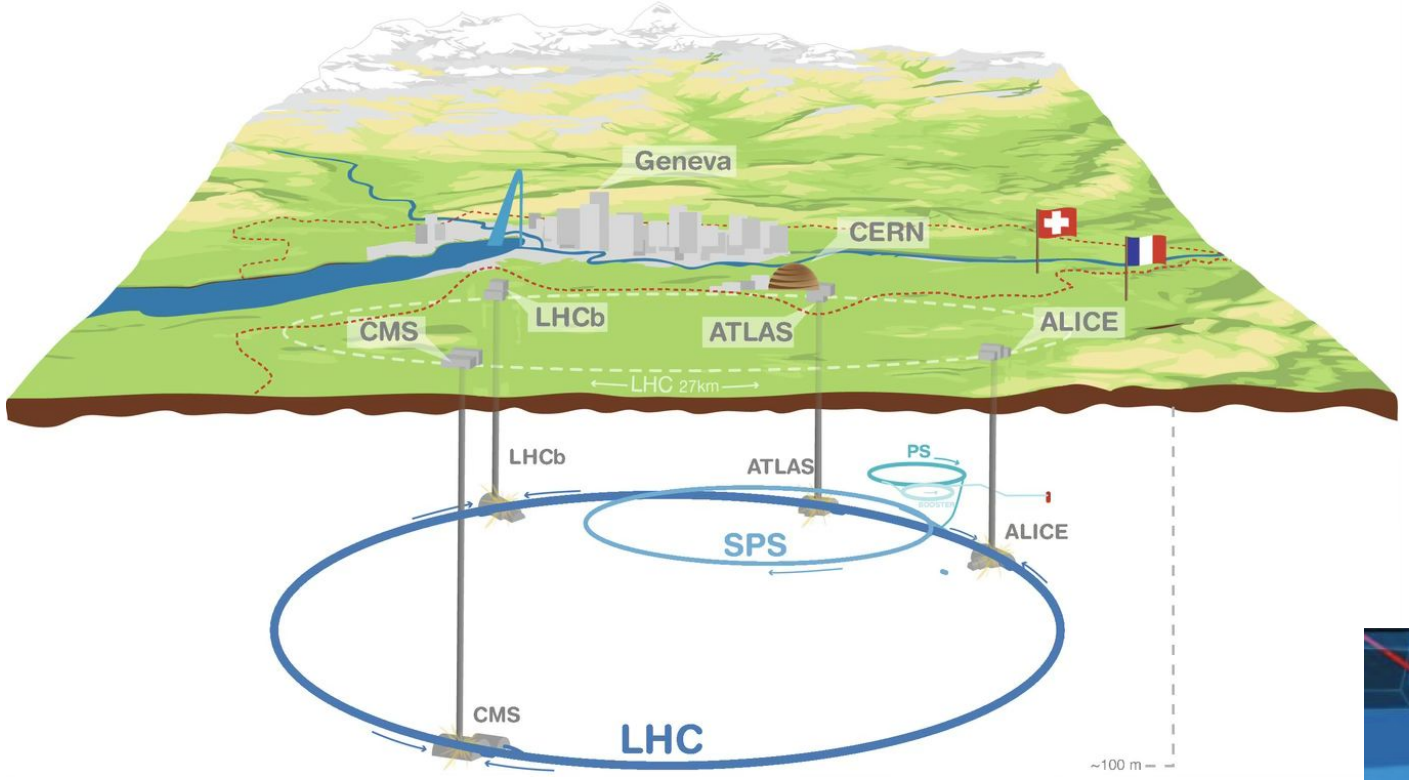
2026.11.09

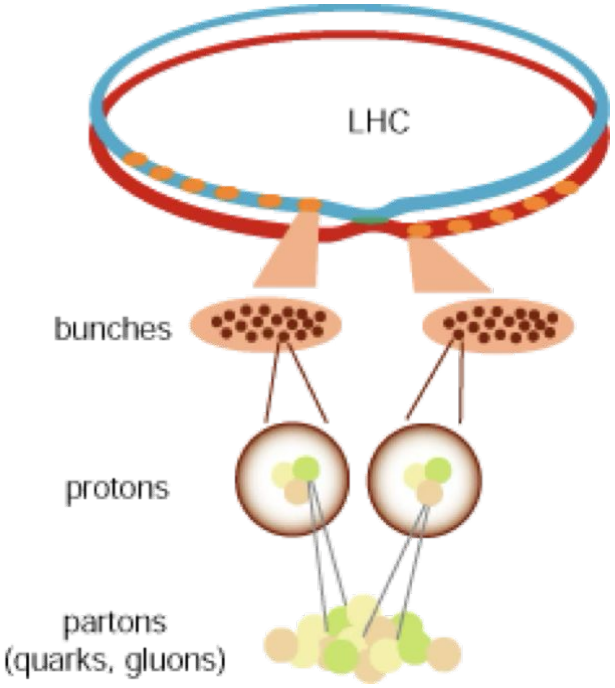
Arely Cortes-Gonzalez

ICEPP UTokyo

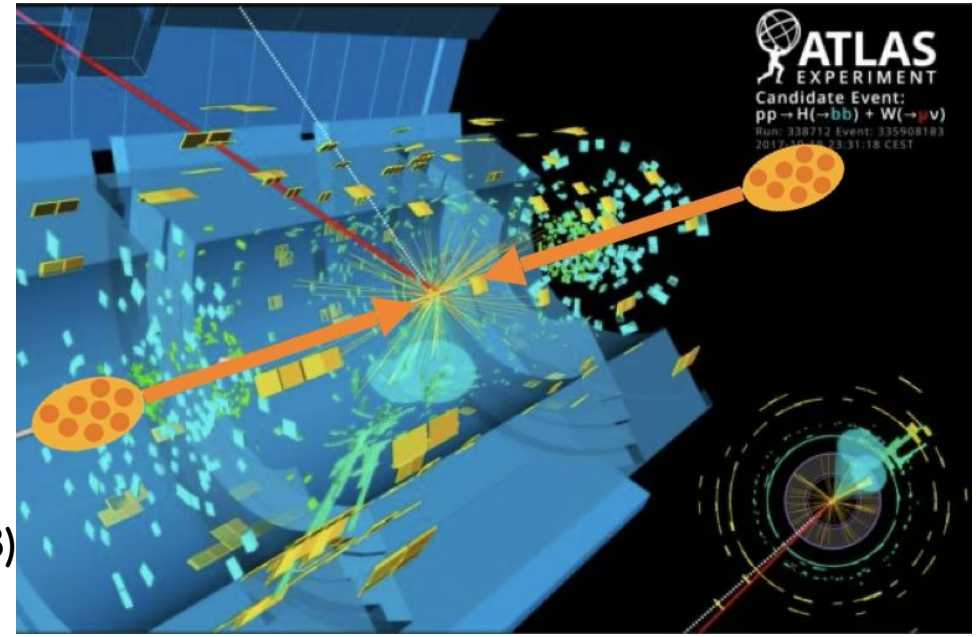


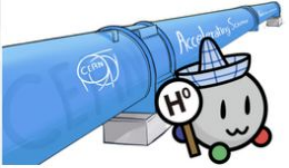
LHC





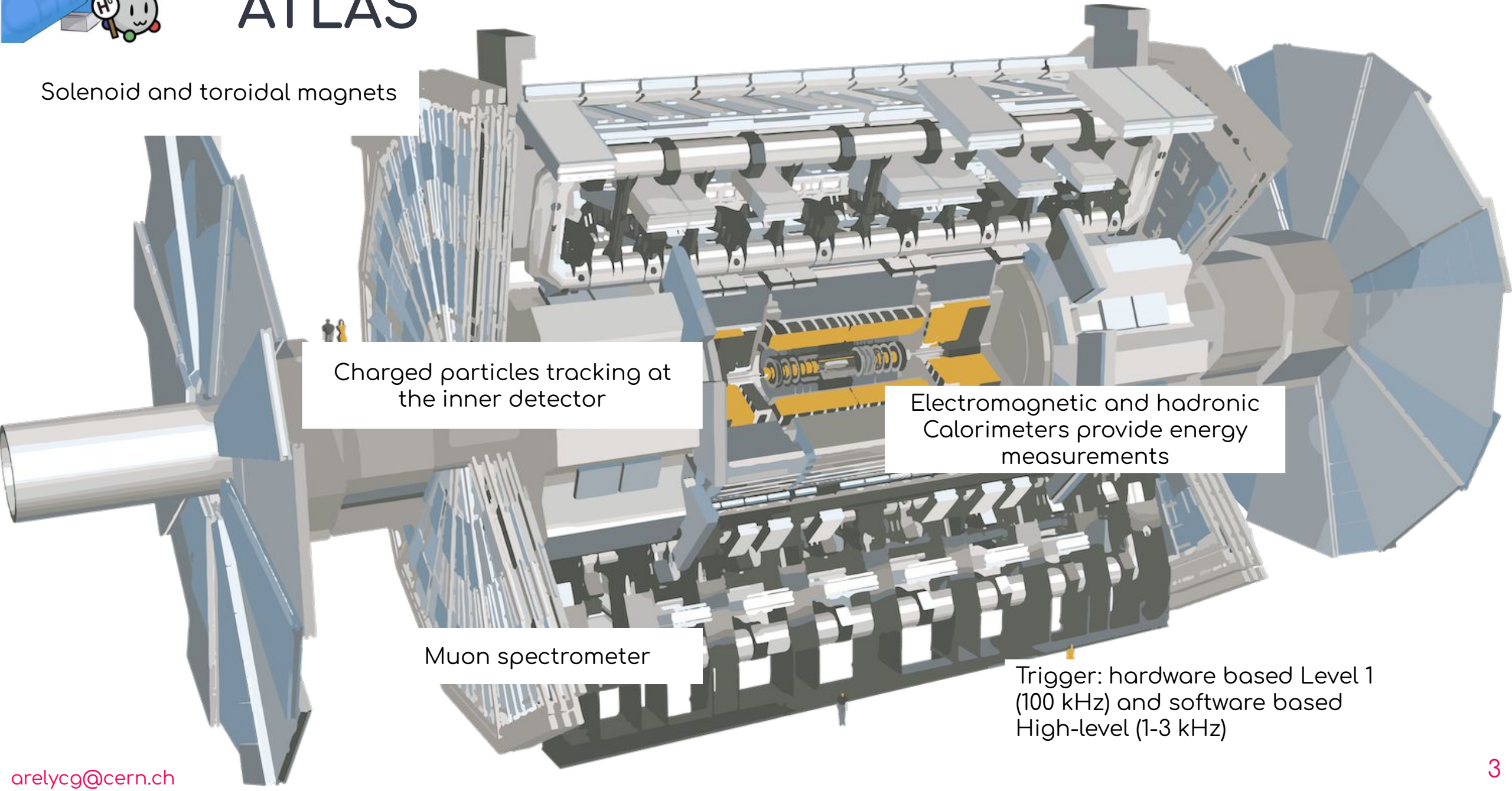
- **proton-proton** collider at
- 27 km of circumference.
- Several experiments:
  - **ATLAS** & **CMS**: general purpose detectors.
  - ALICE (studying heavy ion collisions),
  - LHCb (flavour physics).
- Collisions energy: **7-8 TeV (Run 1), 13 TeV (Run 2)** and **13.6 TeV (Run 3)**





ATLAS

Solenoid and toroidal magnets



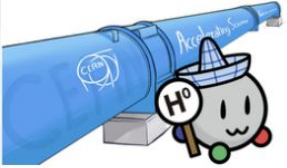
Charged particles tracking at the inner detector

Electromagnetic and hadronic Calorimeters provide energy measurements

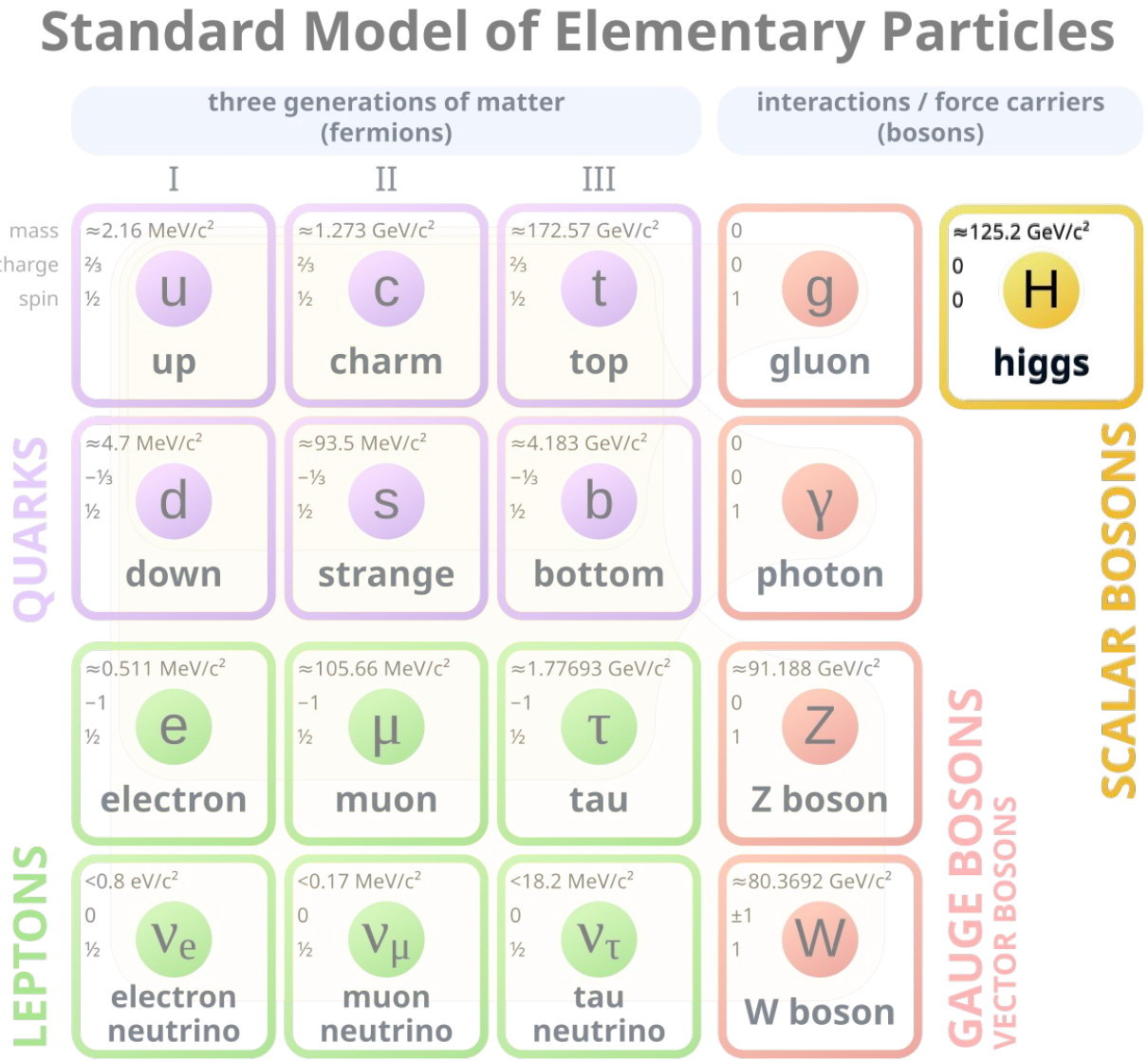
Muon spectrometer

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

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Higgs boson in the Standard Model



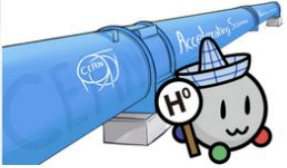
The Higgs boson in the Standard Model:

- 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)

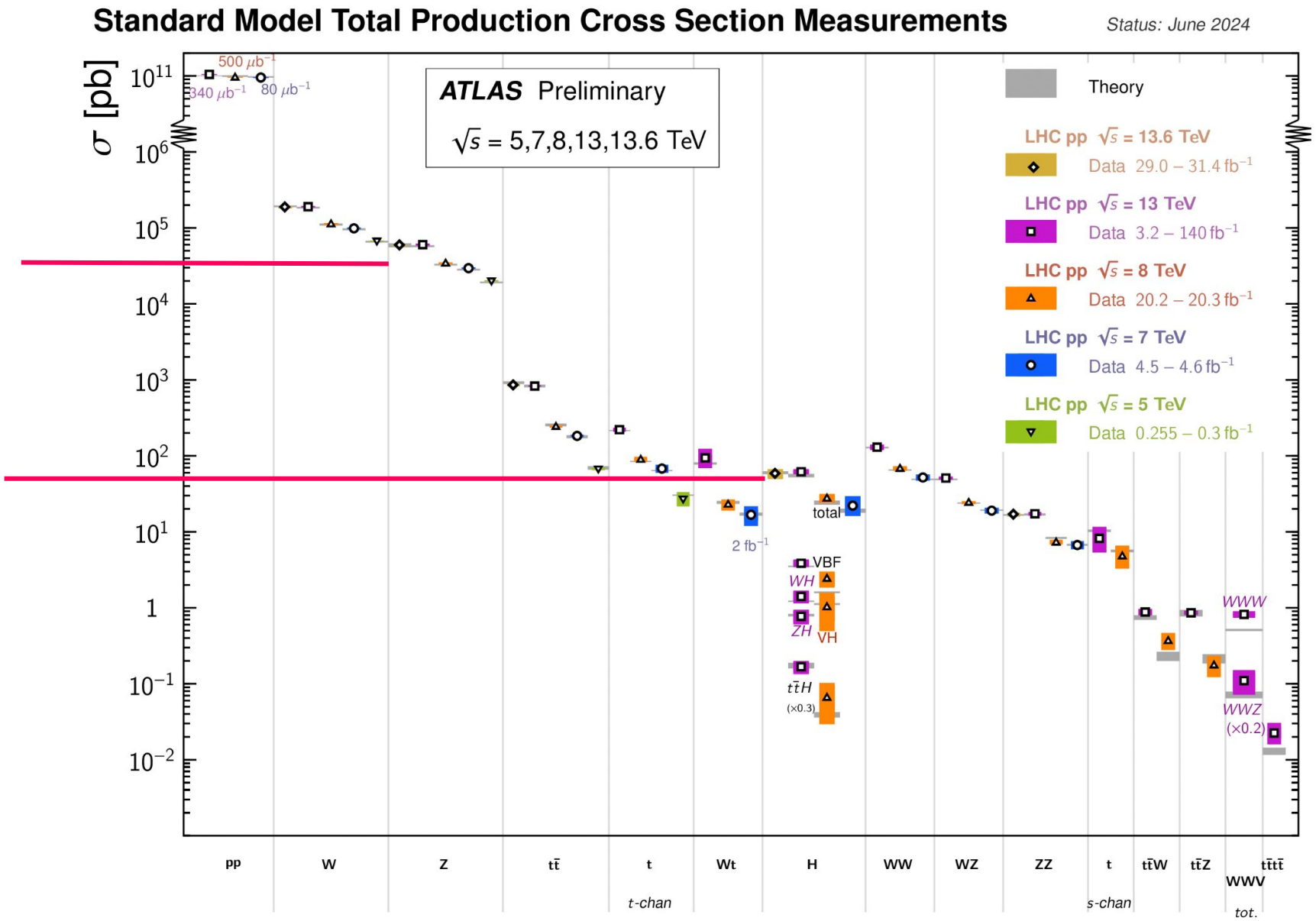
Discovered by the ATLAS and CMS Collaborations in 2012 (see 10th year anniversary Scientific Symposium).



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Higgs boson in the Standard Model



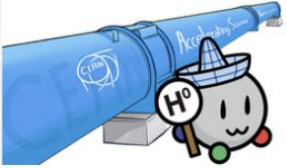
SM
Z production
x1000

SM
Single Higgs
production

ATLAS Public Results

CMS Public Results

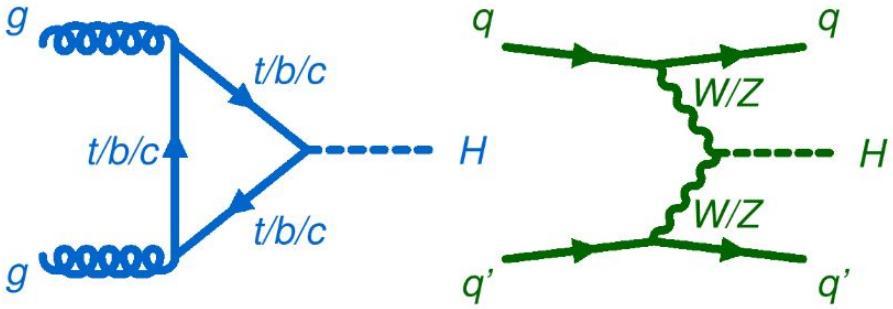
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Higgs boson at the LHC

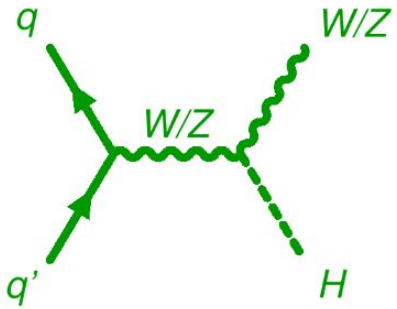
LHCHWG: [Handbook of LHC Higgs Cross Sections]

Main production mechanisms in pp collisions.

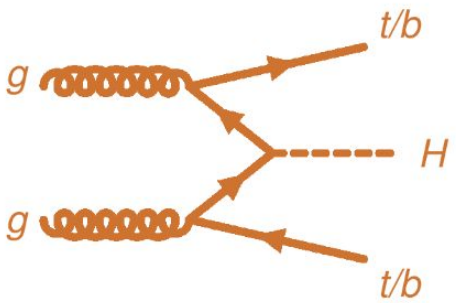


ggF ~88%
gluon-gluon fusion

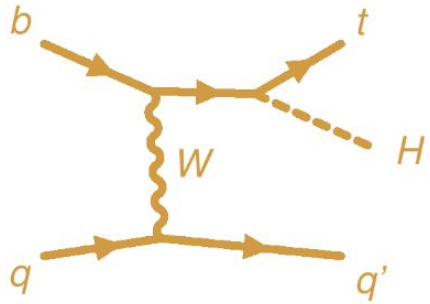
VBF ~7%
vector-boson fusion



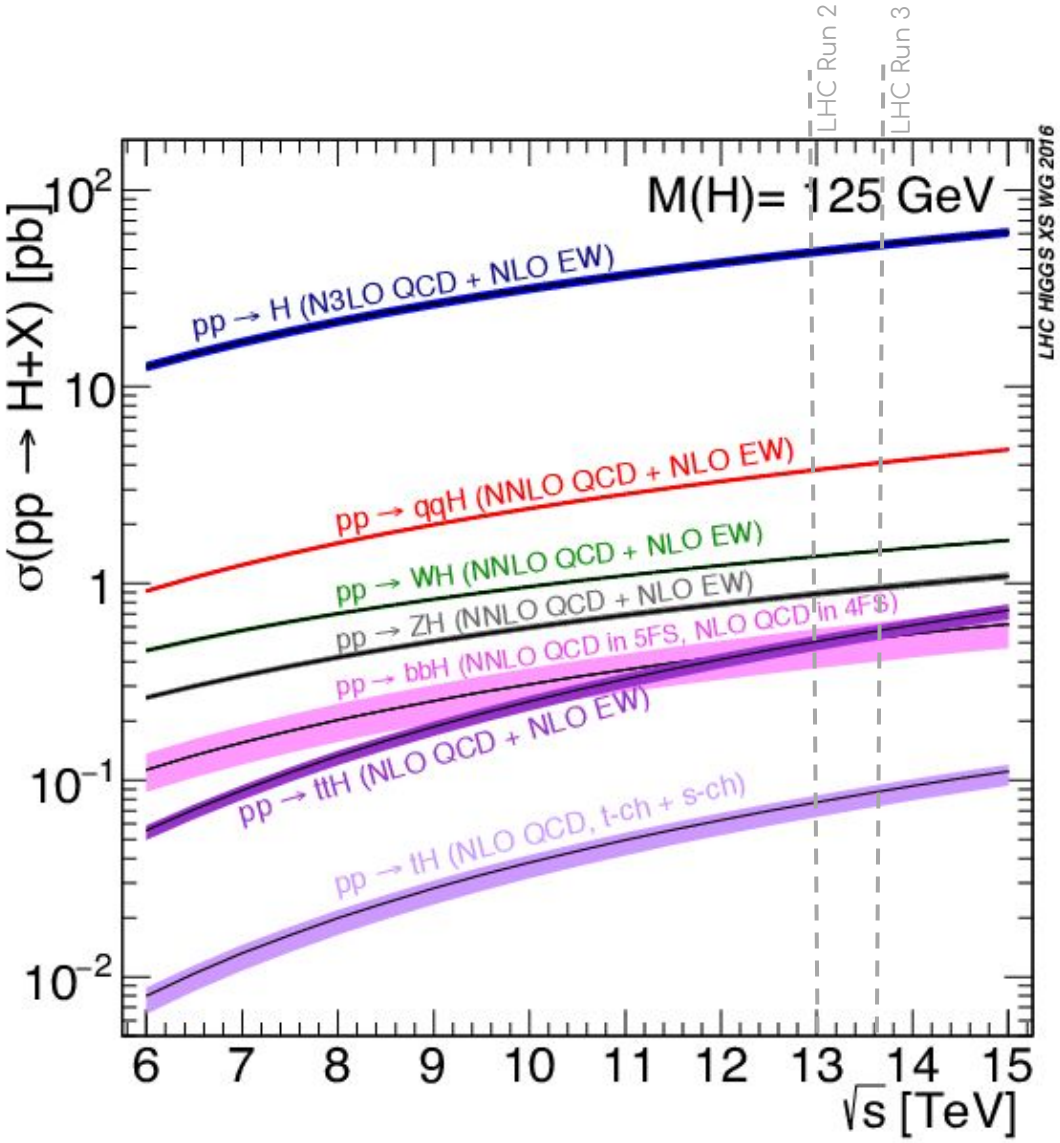
VH ~4%
vector boson associated production

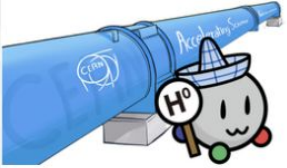


ttH ~1%
tt associated production



tH
top quark associated production

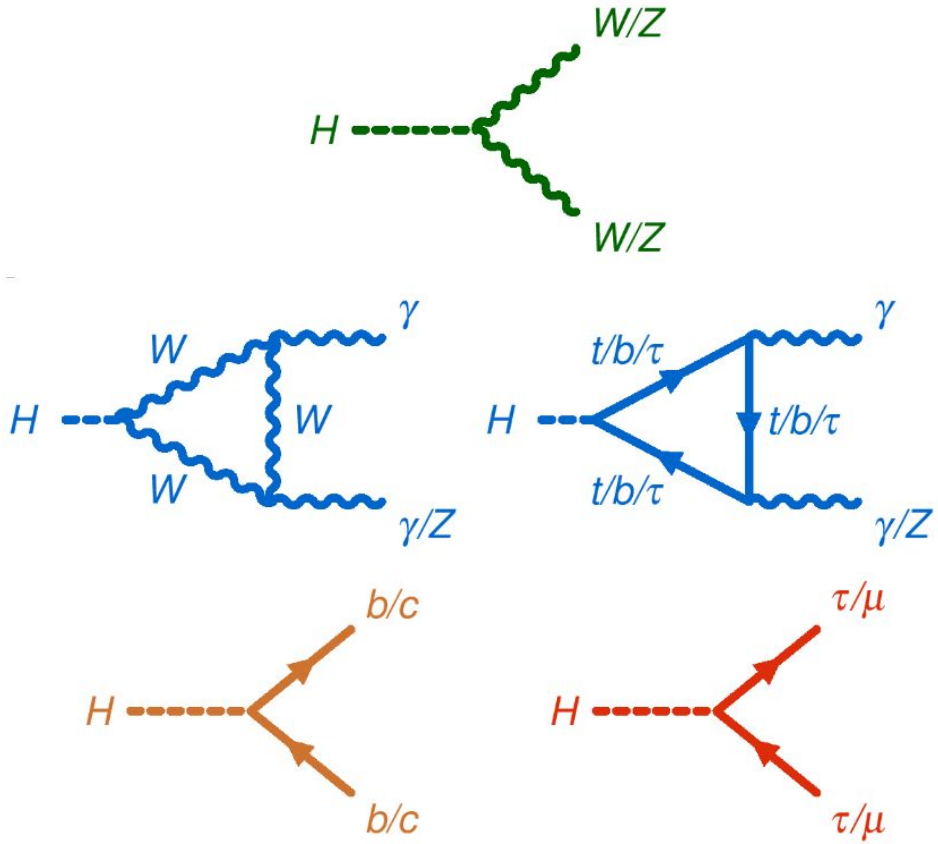


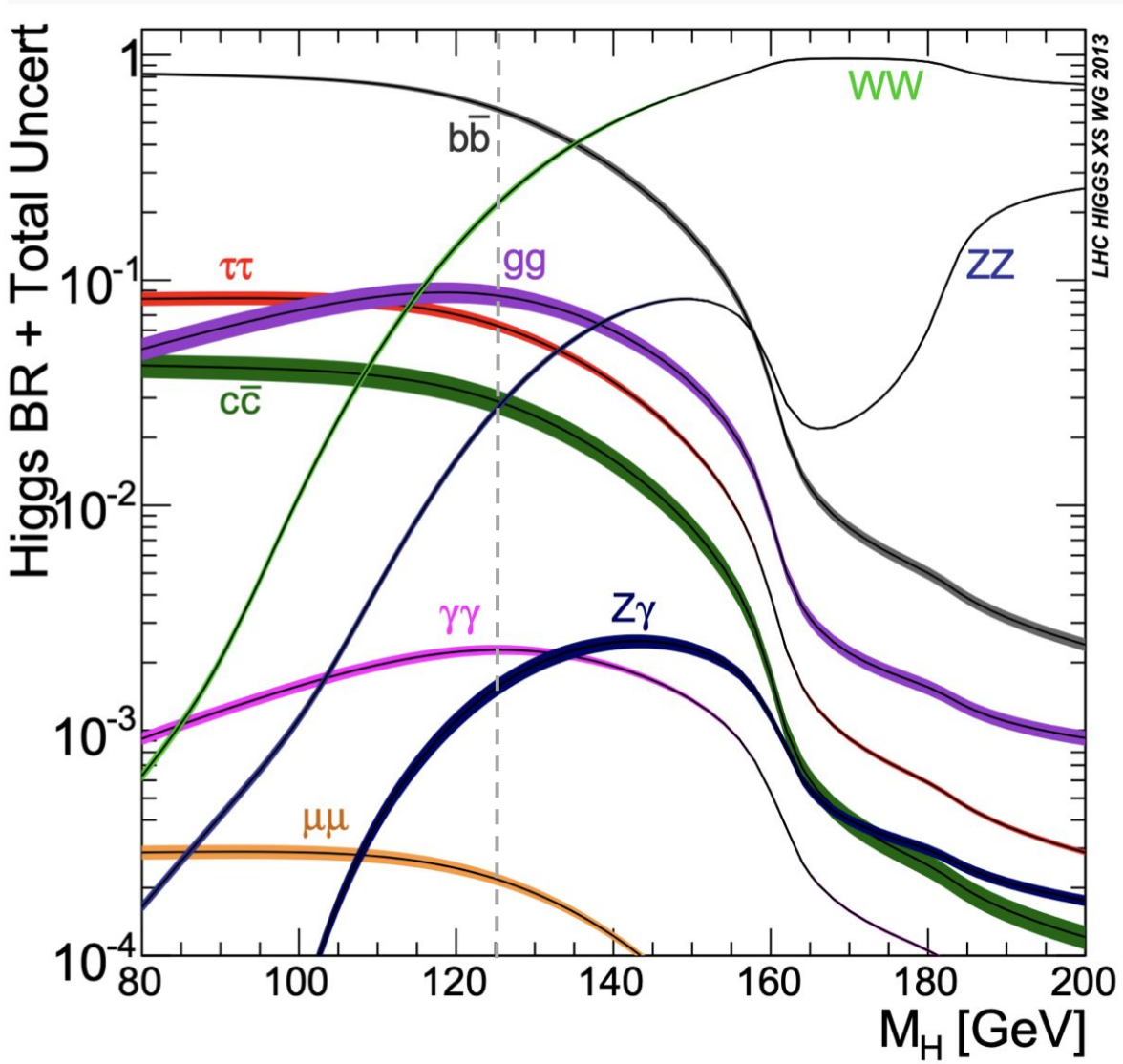


Higgs boson at the LHC

LHCHWG: Handbook of LHC Higgs Cross Sections

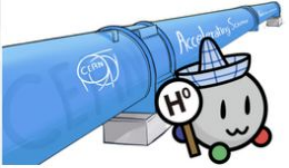
Main decay mechanisms:
branching ratios dependant on the Higgs mass.



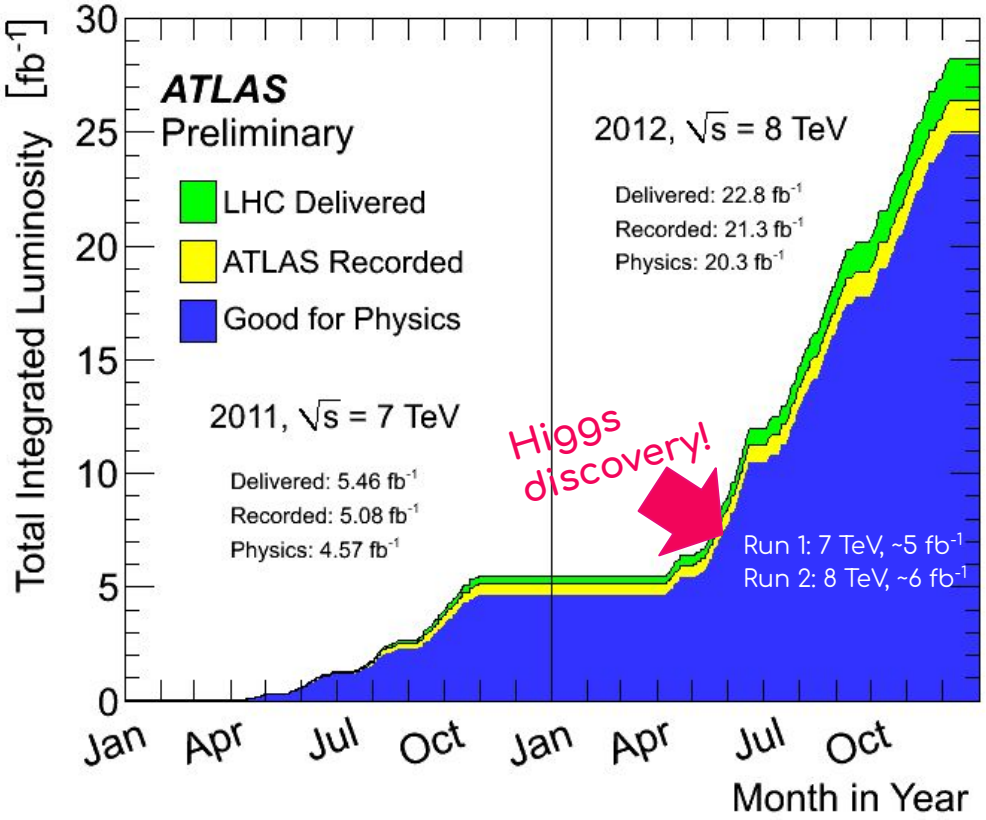


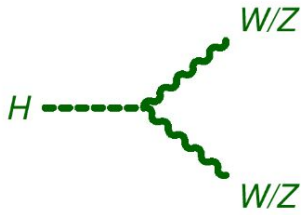
How do we choose which channels to search for?

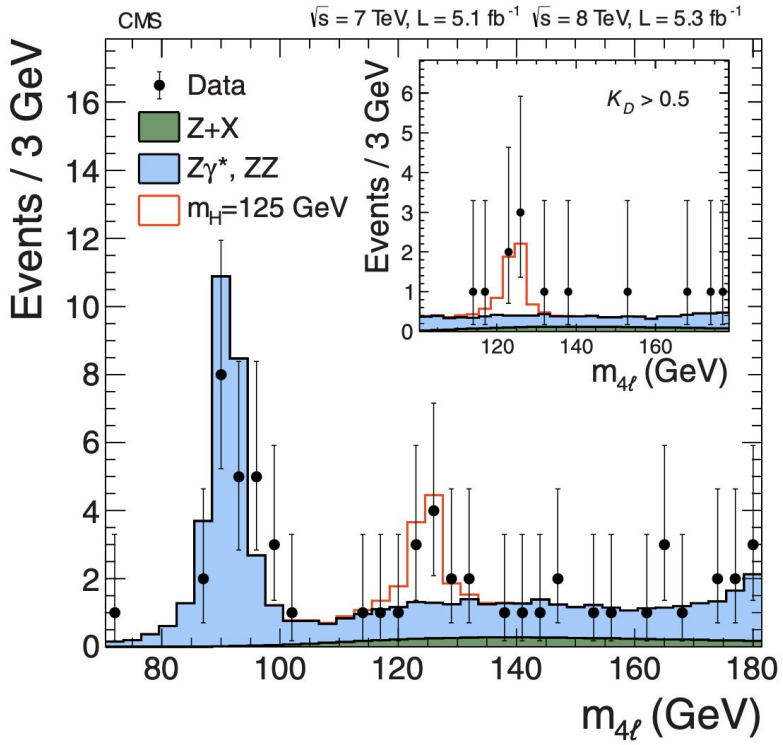
- High branching ratio.
- Clean signature (good detector resolution).

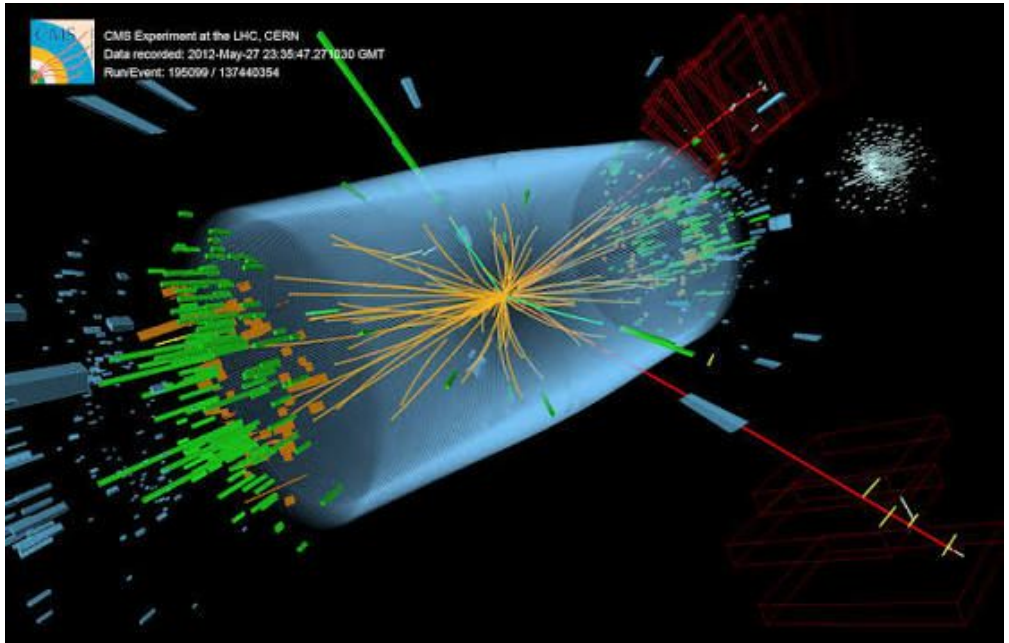


We found a Higgs!





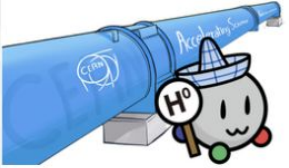




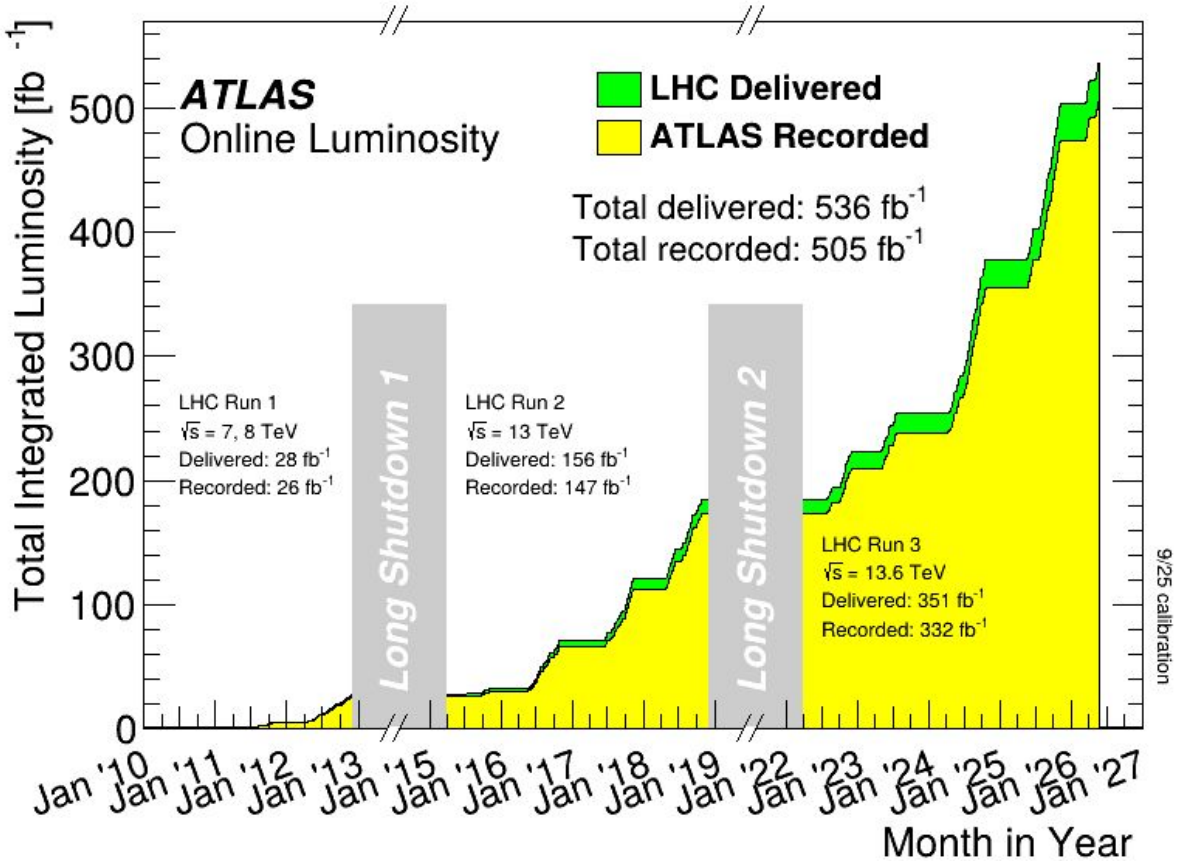
- A large search program in all decays channels from the start of the LHC Run 1.
- Main channels leading to the discovery:
  - H→ZZ*→4ℓ, H→γγ, H→WW→ℓνℓν.

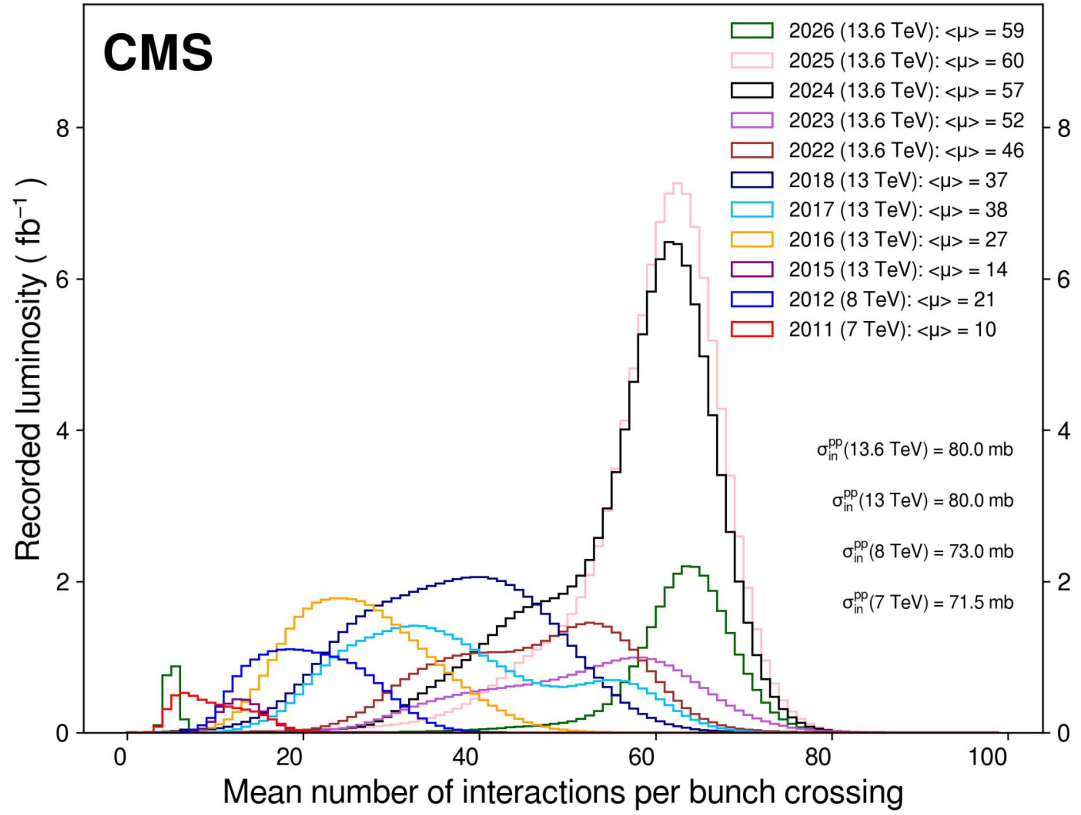
ATLAS / CMS discovery papers

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LHC collision data *now*



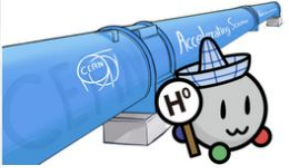


Luminosity collected by ATLAS and CMS

- 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

Pileup conditions are much more challenging!

- Efficiency and resolution of objects reconstruction requires more work.



Characterising the Higgs boson

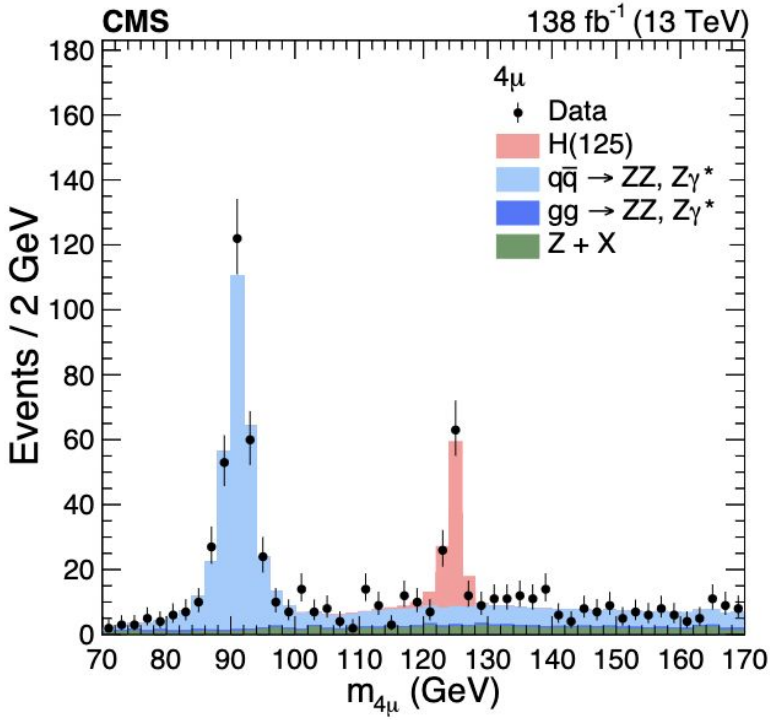
Mass measurement

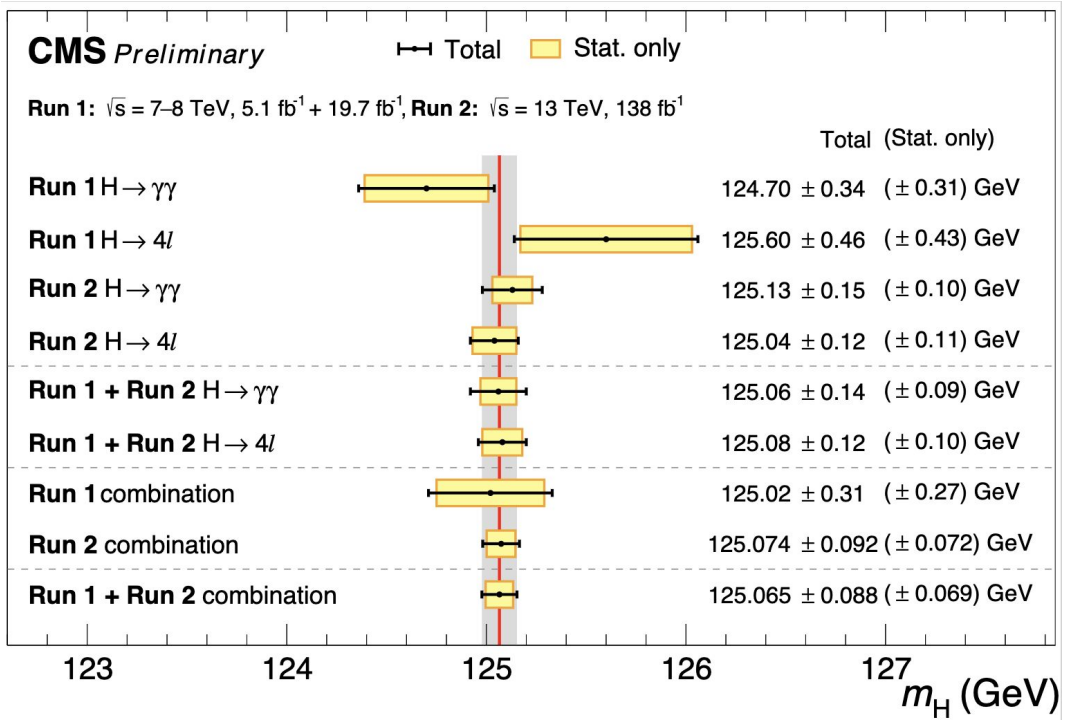
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

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

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→ZZ*→4ℓ and H→γγ (fully reconstructable final states)
  - Relies on precise momentum calibration of muons, electrons and photons.

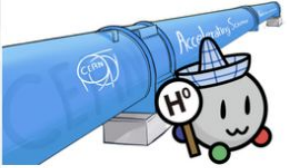




ATLAS: Phys. Rev. Lett. 131 (2023) 251802
CMS: CMS-PAS-HIG-26-010

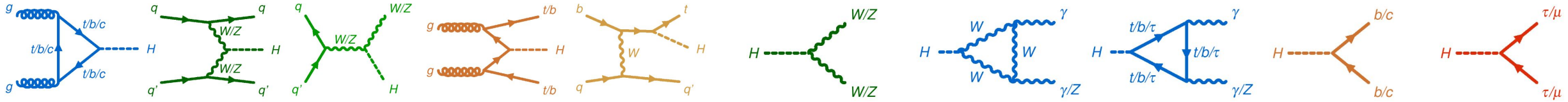
ATLAS measurement: 125.11 ± 0.11 (±0.09 ±0.06) GeV

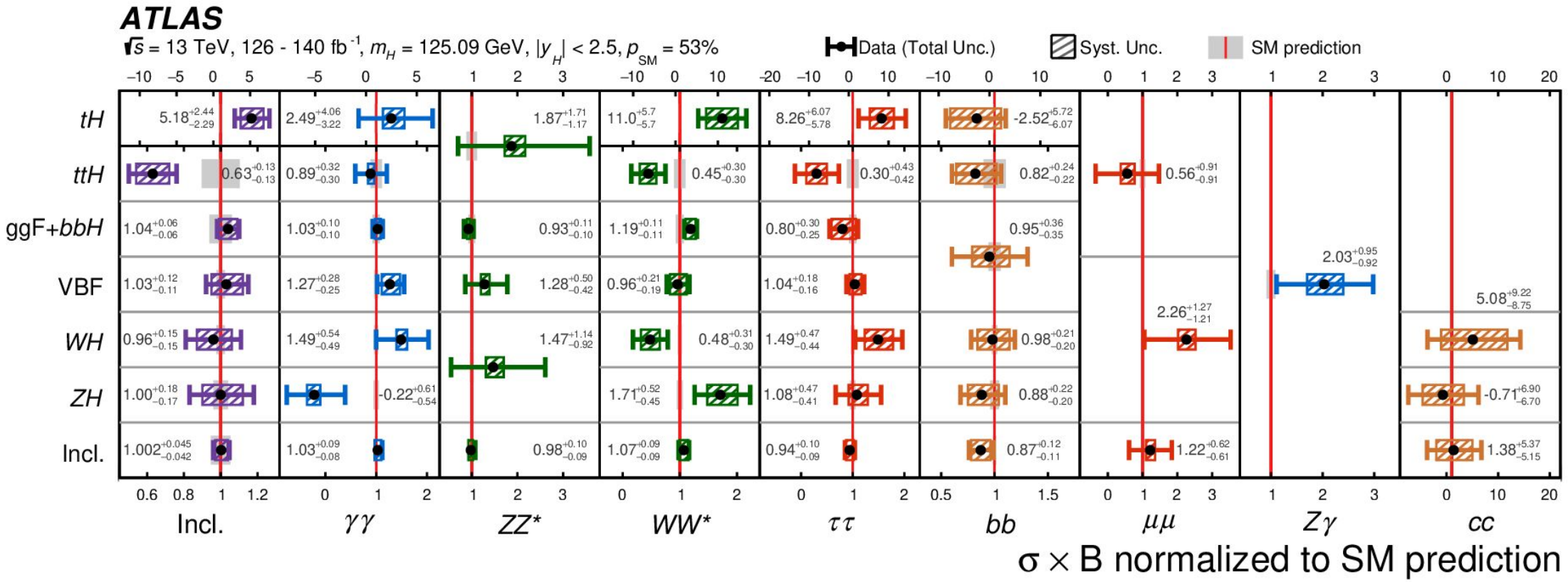
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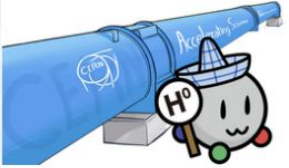
Higgs Couplings

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





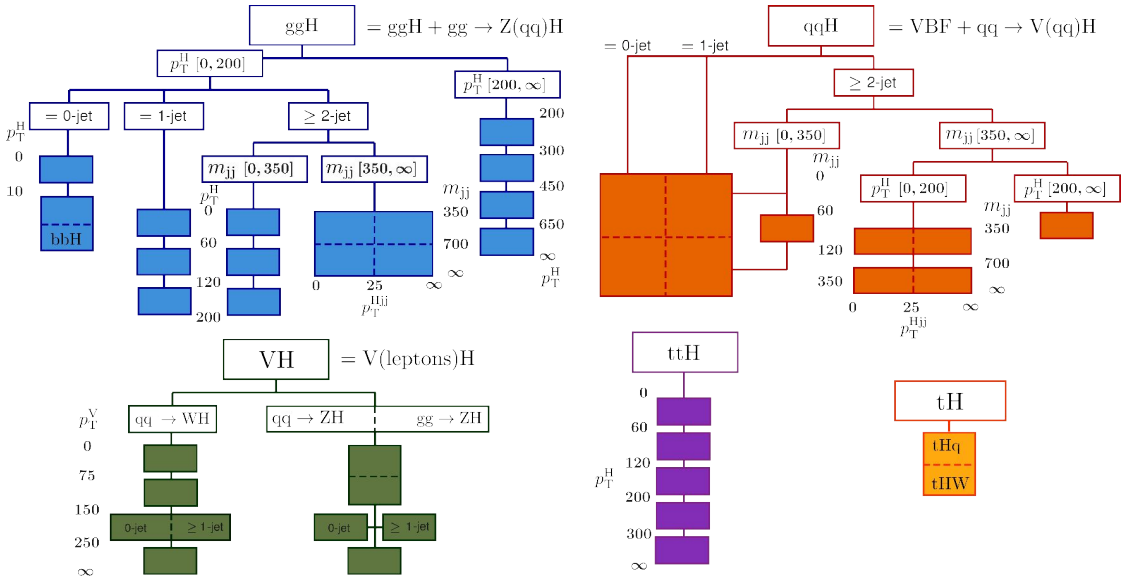
ATLAS and CMS combinations

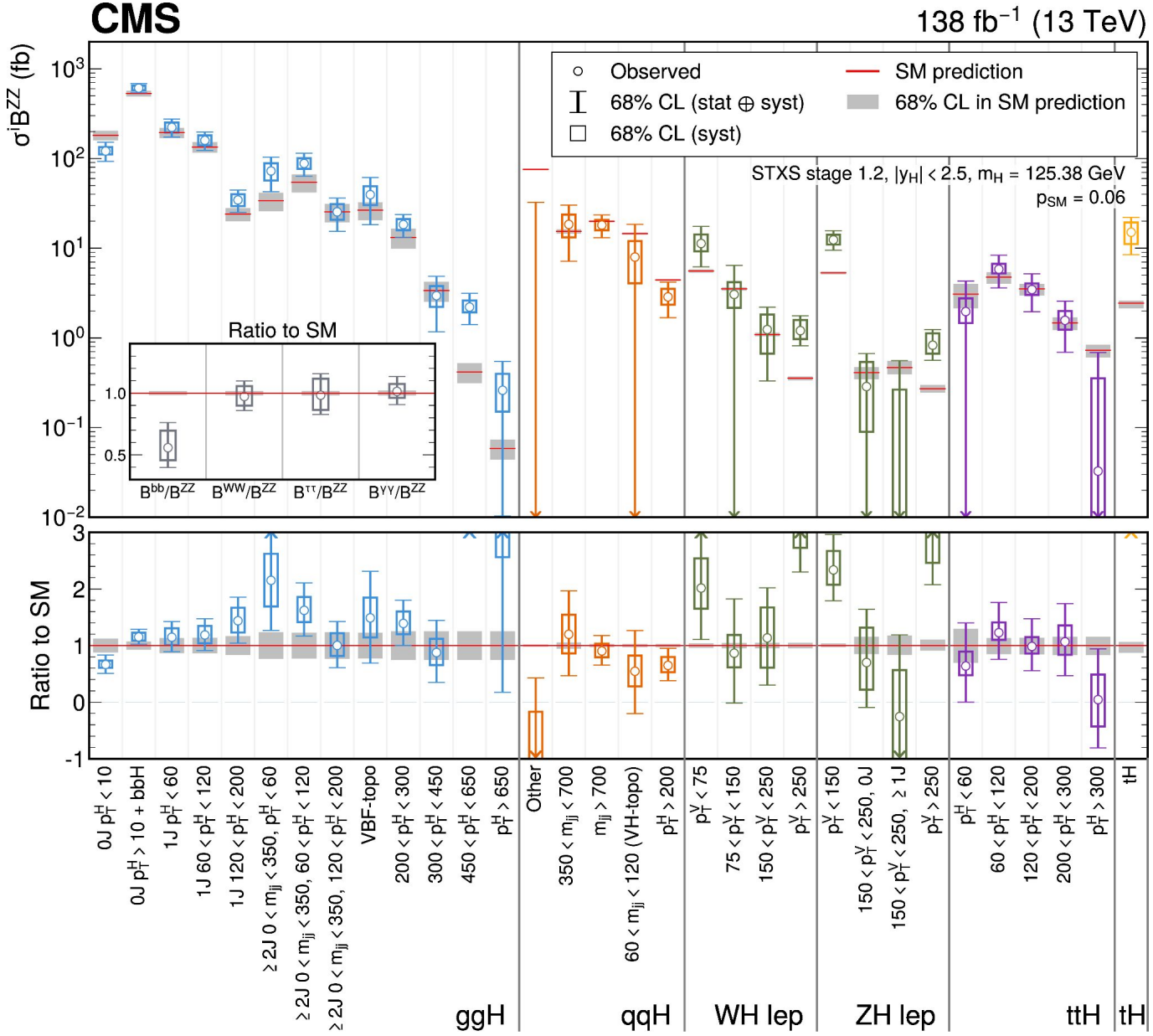


We can go beyond

STXS (simplified template cross section)

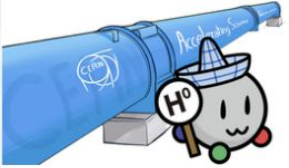
- Signal strengths → cross sections measured in each STXS bin (32 different kinematic regions).
- Important input from the theory community (require SM predictions in this granularity).





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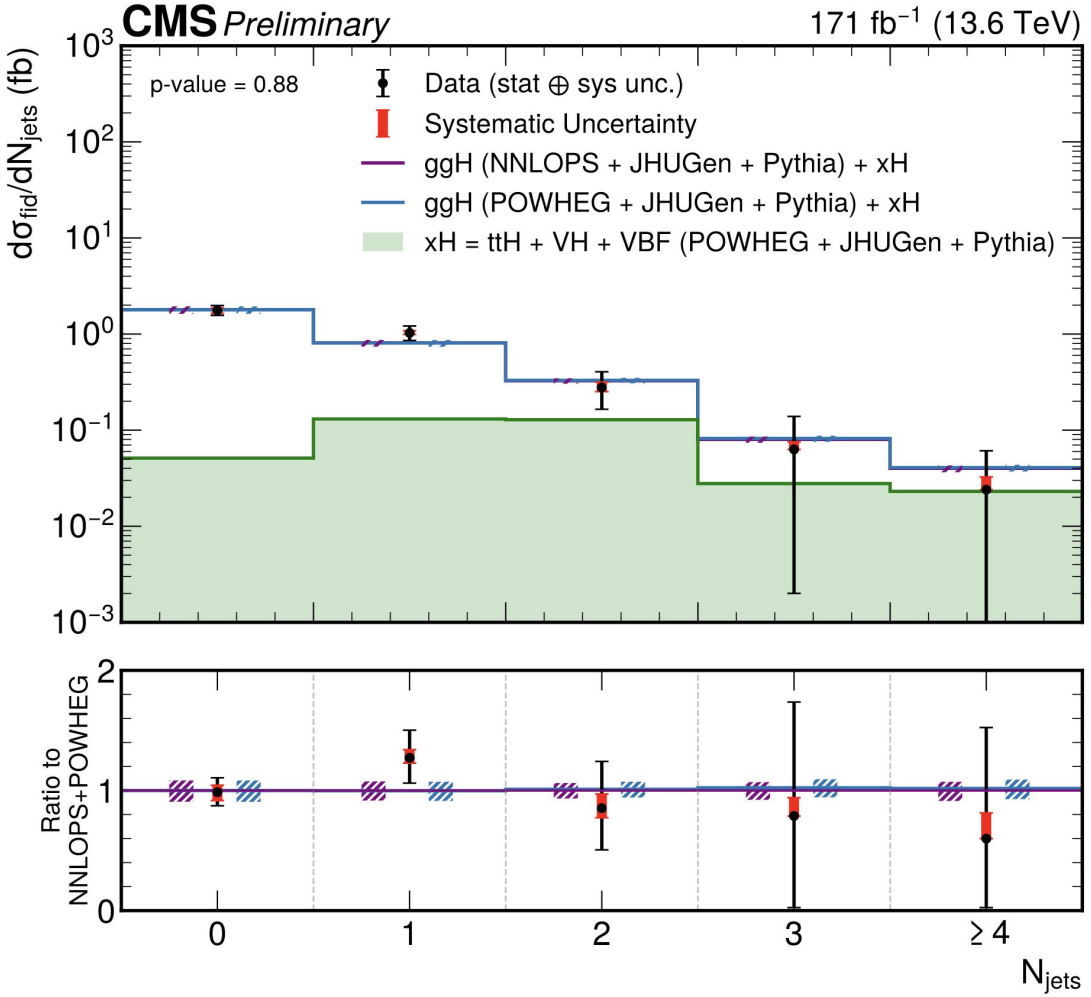
ATLAS and CMS combinations



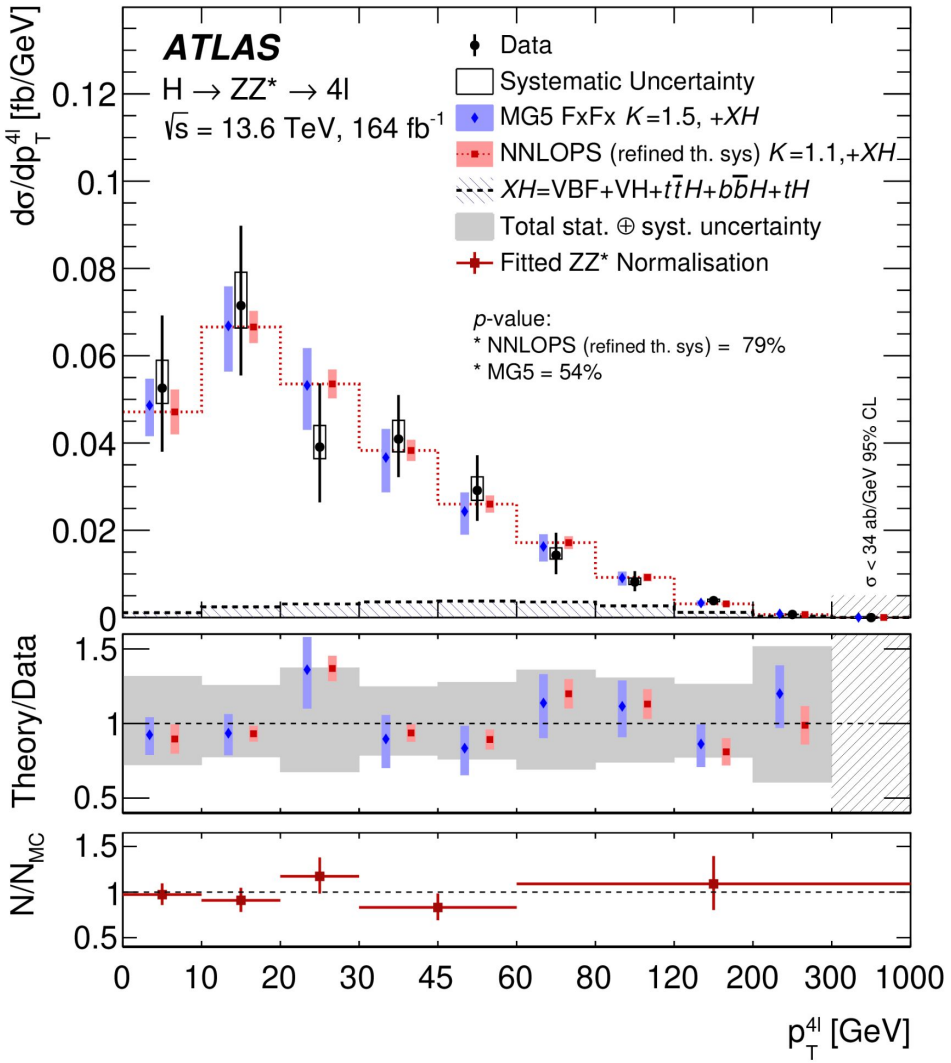
We can go differential

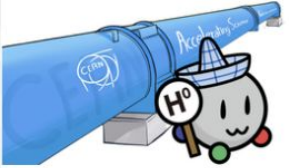
- We can also study **kinematic distributions** in Higgs production (beyond the measurements of total rates).
- Physics beyond the Standard Model may be enhanced in the tails of these distributions.

CMS-PAS-HIG-25-015

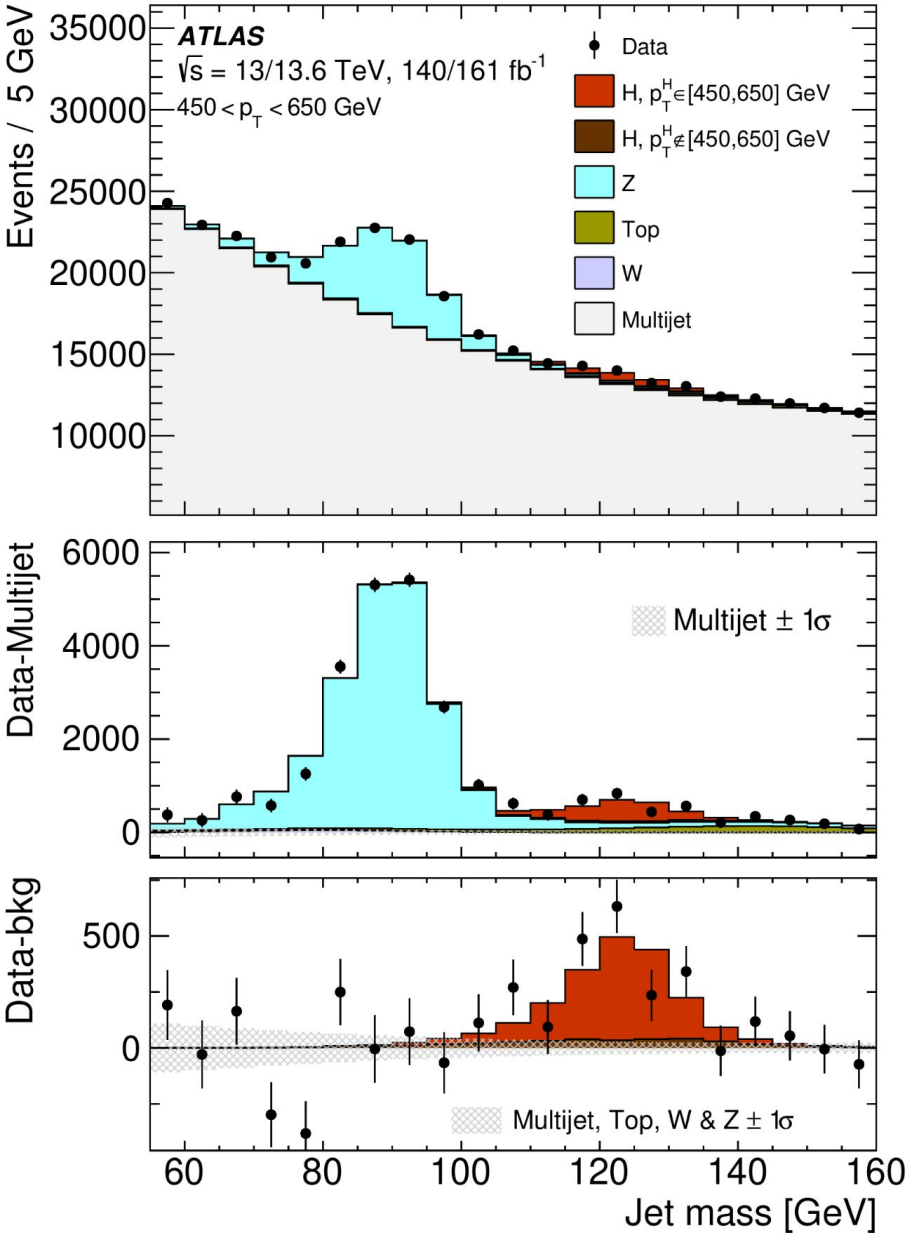


JHEP 08 (2026) 052





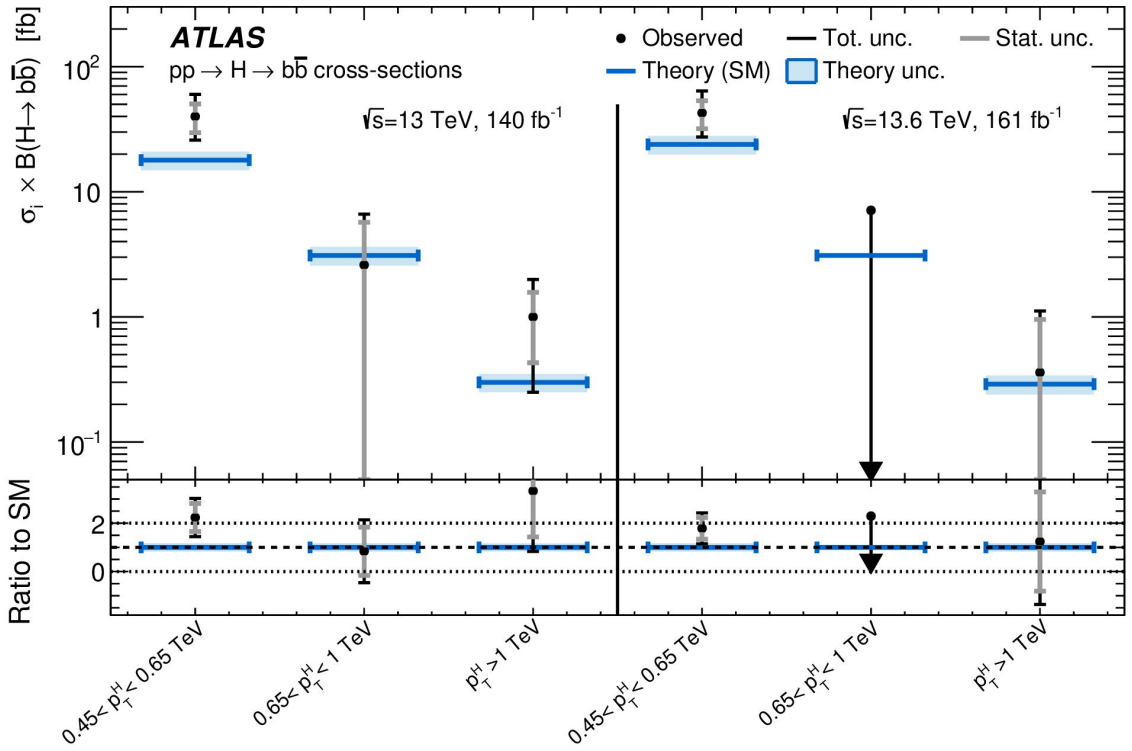
We can go boosted!



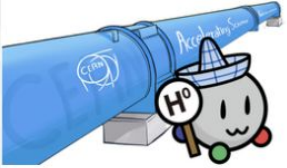
Phys. Rev. Lett. 137 (2026) 071801

High-p_T Higgs production is a great probe for BSM effects

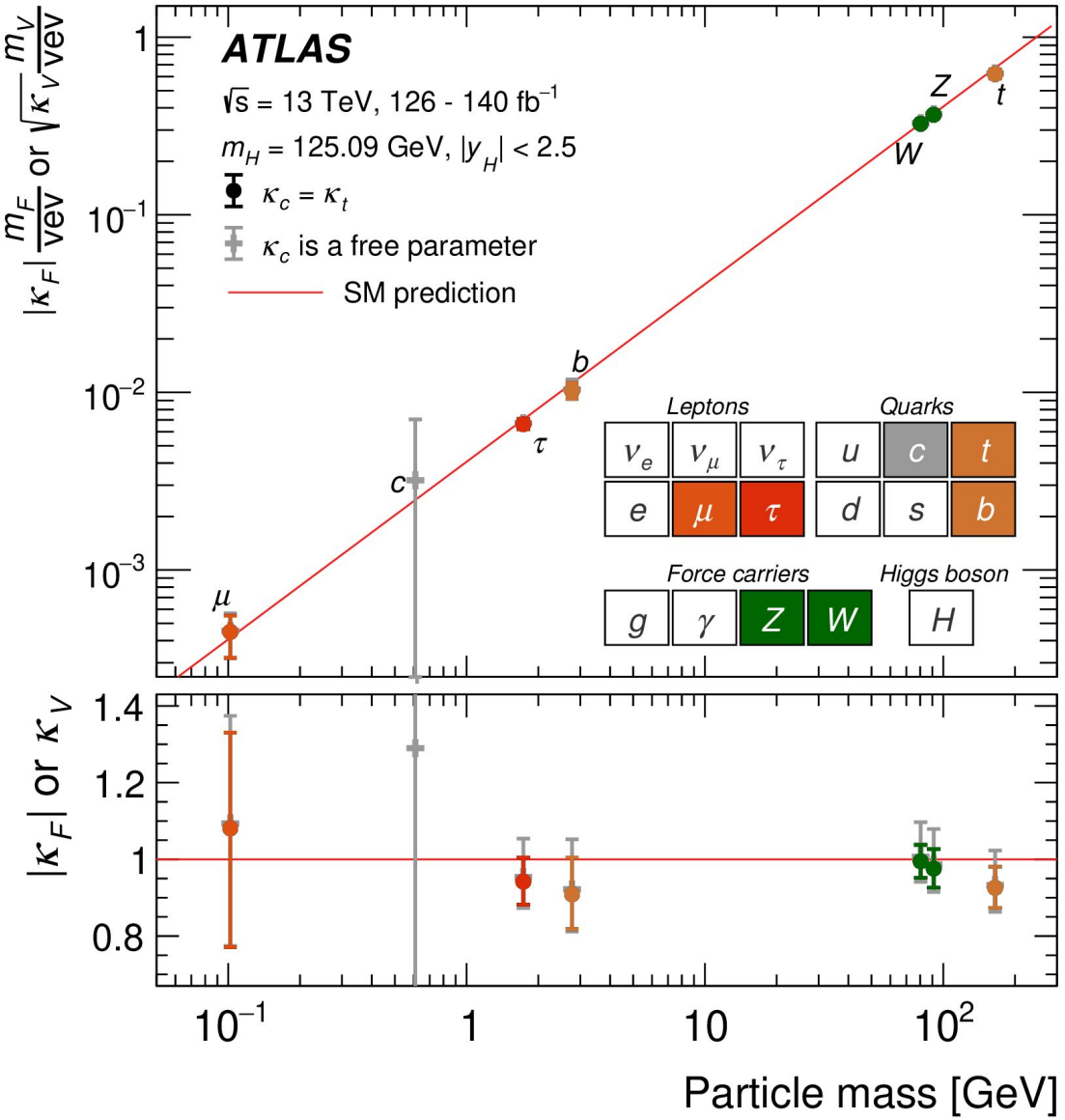
- Evidence for H→bb with $p_T(H) > 450$ GeV at 3.8σ (2.5σ exp.)
- Transformer-based boosted H→bb tagger (GN2X)
  - Improved jet p_T and mass resolution via transformer-based regression model.
  - Z→bb signal used to calibration tagger.



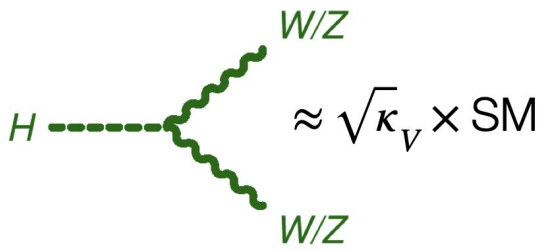
Bonus: search for boosted H→ττ also using advanced ML algorithms to improve identification.

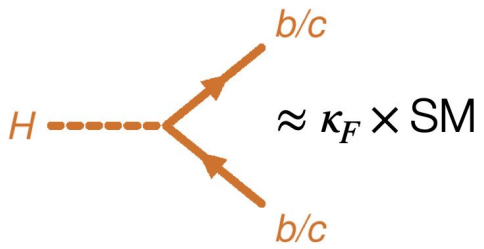


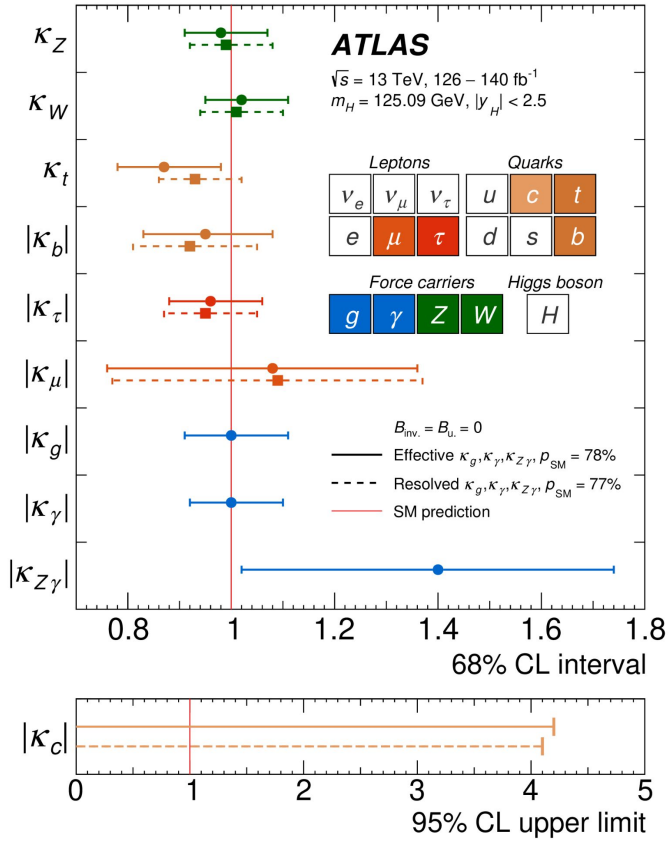
Higgs Couplings

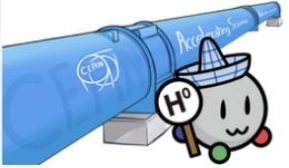


Relationship between mass and coupling as predicted by SM within current uncertainties.



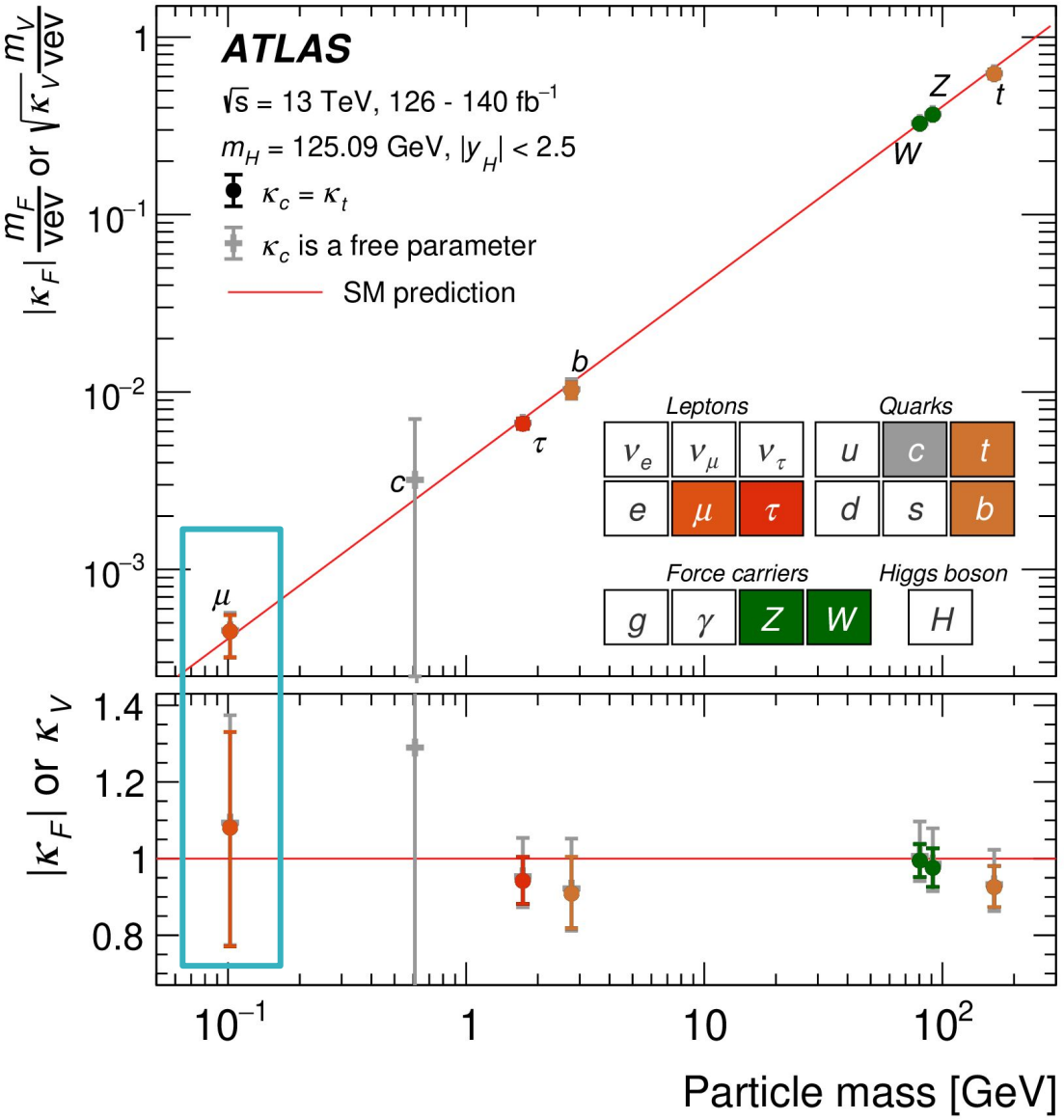




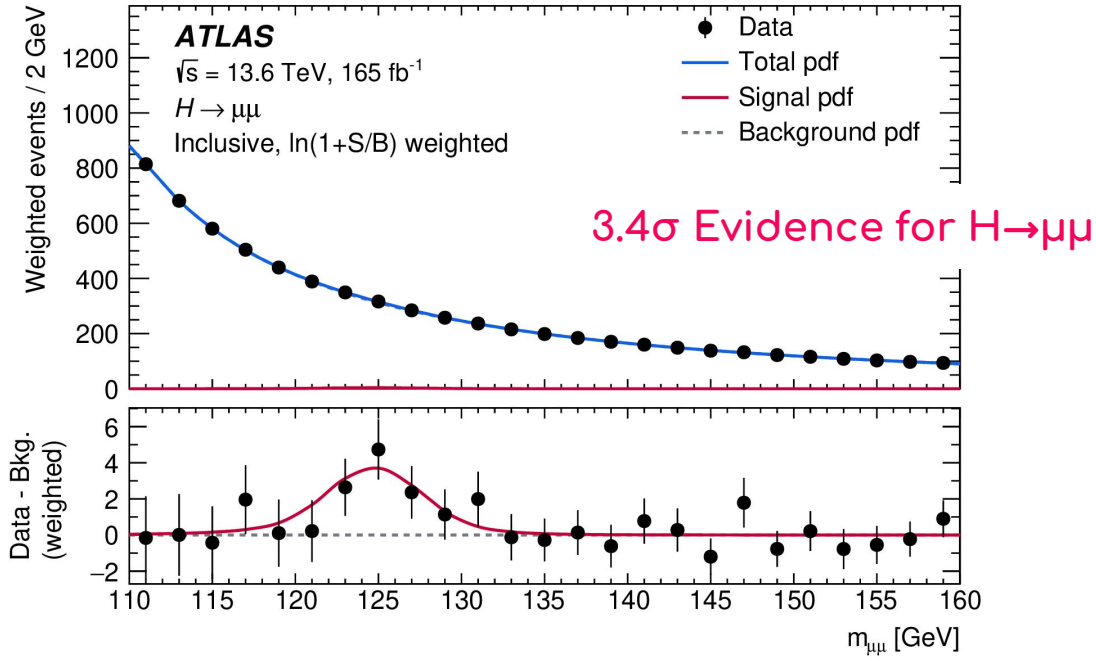


Higgs Couplings

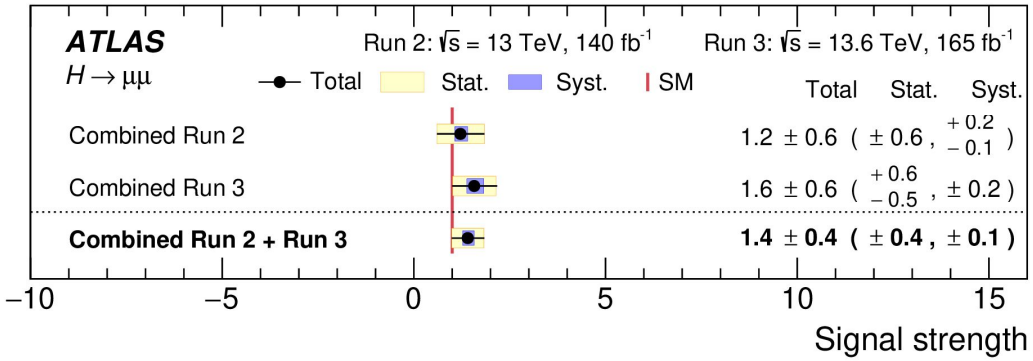
arXiv:2507.03595



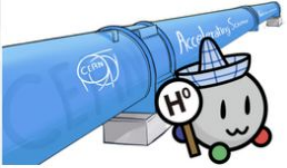
With Run 3 data we can improve our measurements in more challenging signatures!



3.4σ Evidence for H→μμ



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Trilinear Higgs Coupling

Standard Model Higgs potential

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

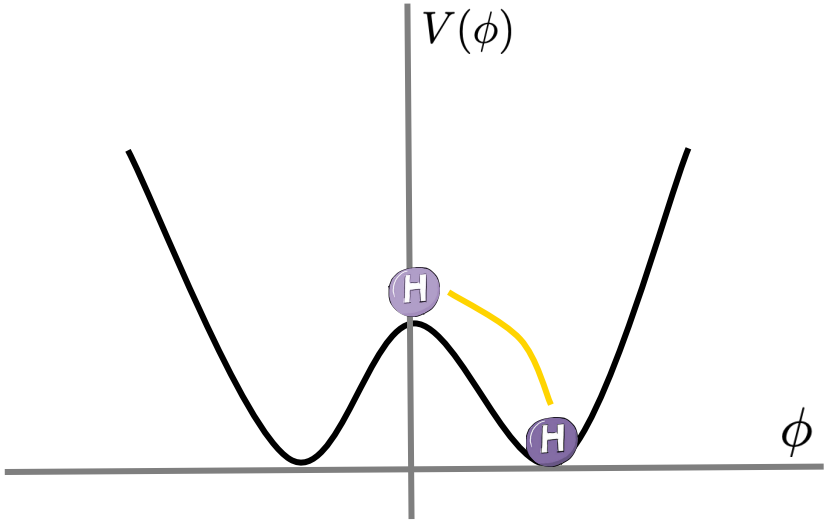
Our universe lives in the minimum:

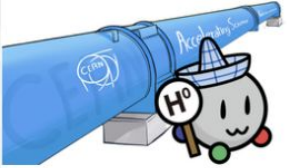
$$V = V_0 + \lambda\nu^2 h^2 + \lambda\nu h^3 + \frac{1}{4}\lambda h^4 - \frac{\lambda}{\nu^4}$$

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





Trilinear Higgs Coupling

Standard Model Higgs potential

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

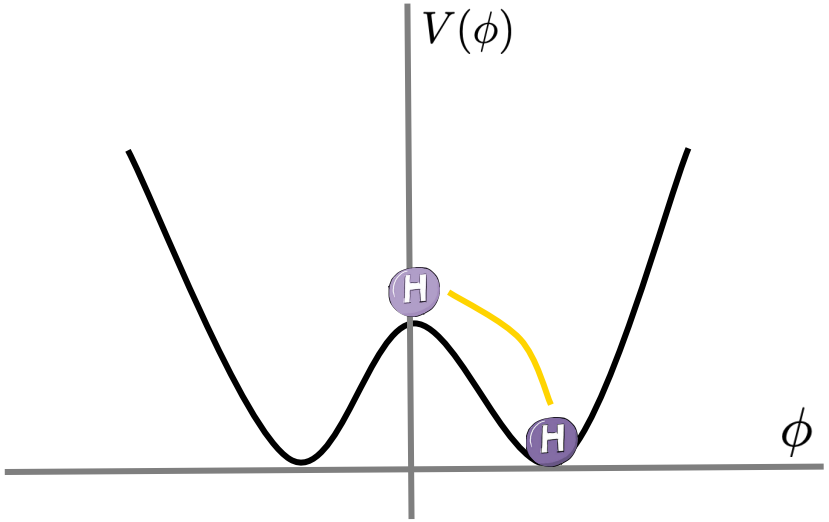
Our universe lives in the minimum:

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

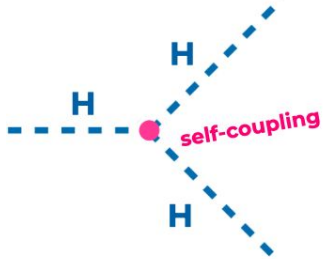
mass

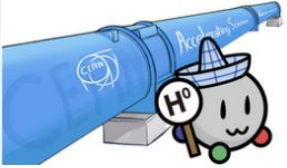
self-coupling

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



we can probe this via the HH production





Trilinear Higgs Coupling

Standard Model Higgs potential

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

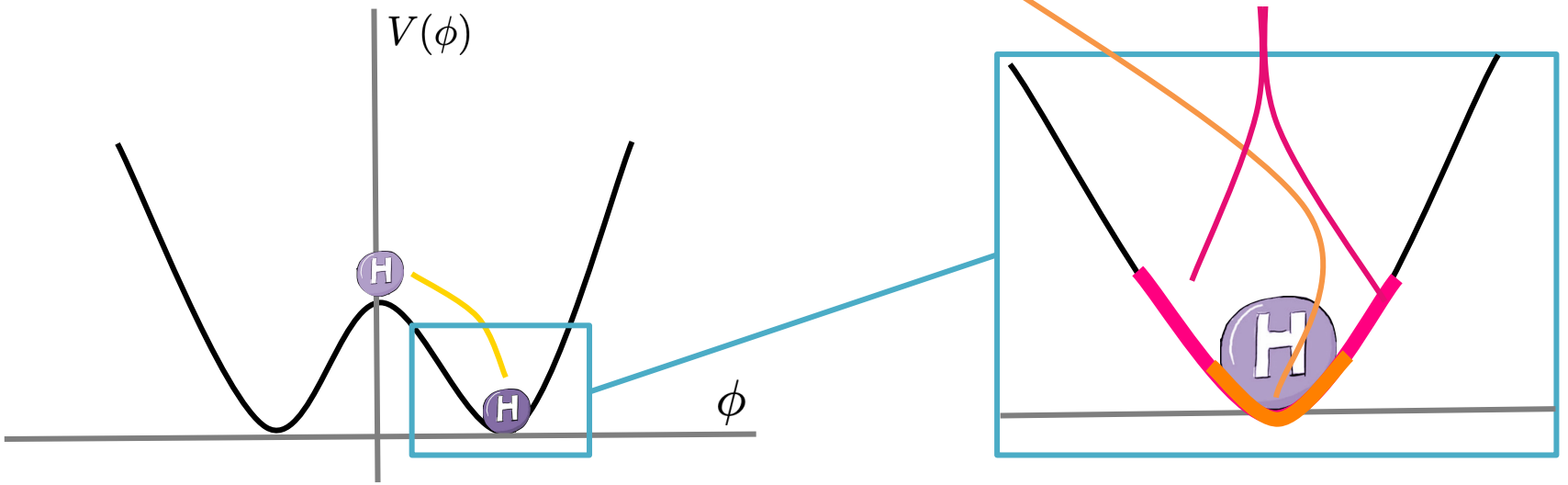
Our universe lives in the minimum:

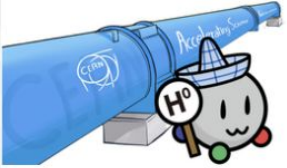
$$V = V_0 + \lambda\nu^2 h^2 + \lambda\nu h^3 + \frac{1}{4}\lambda h^4 - \frac{\lambda}{\nu^4}$$

mass

self-coupling

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





Trilinear Higgs Coupling

Standard Model Higgs potential

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

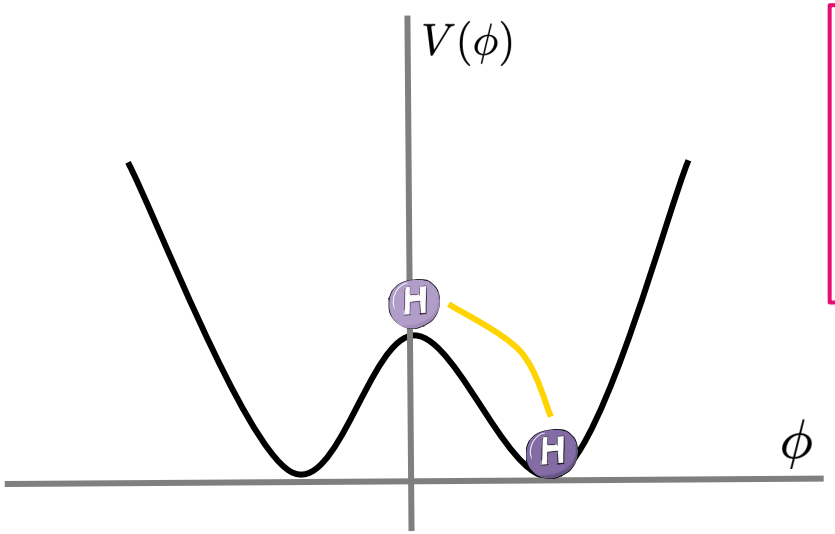
Our universe lives in the minimum:

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

mass

self-coupling

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

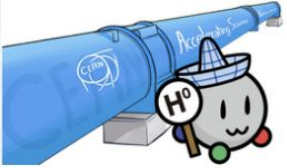


In the Standard Model:

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

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

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



Trilinear Higgs Coupling

Standard Model Higgs potential

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

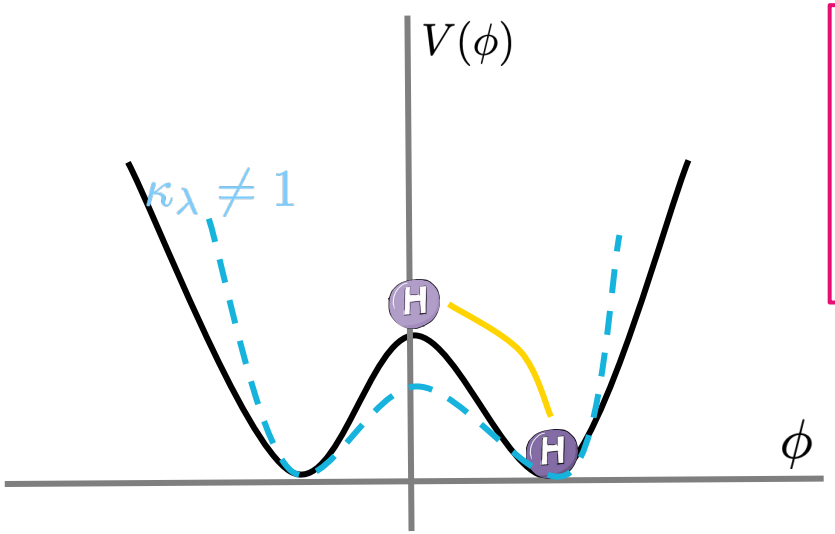
Our universe lives in the minimum:

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

mass

self-coupling

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

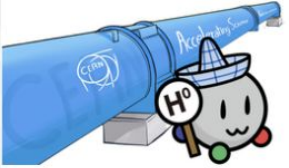


In the Standard Model:

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

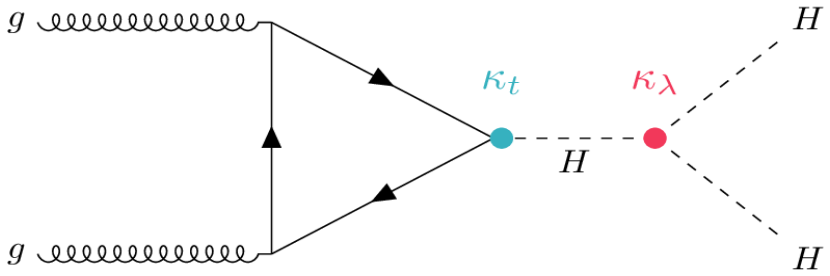
$$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{\mathrm{SM}}$$

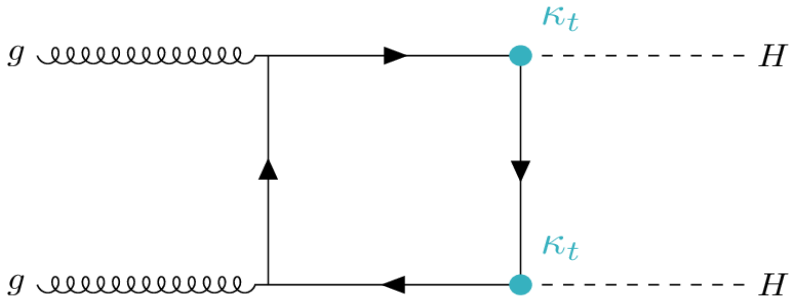
Non-resonant HH production searches probe the shape of the Higgs potential by measuring the Higgs self coupling: κ_λ.
$\kappa_\lambda \neq 1$ could indicate beyond Standard Model physics.

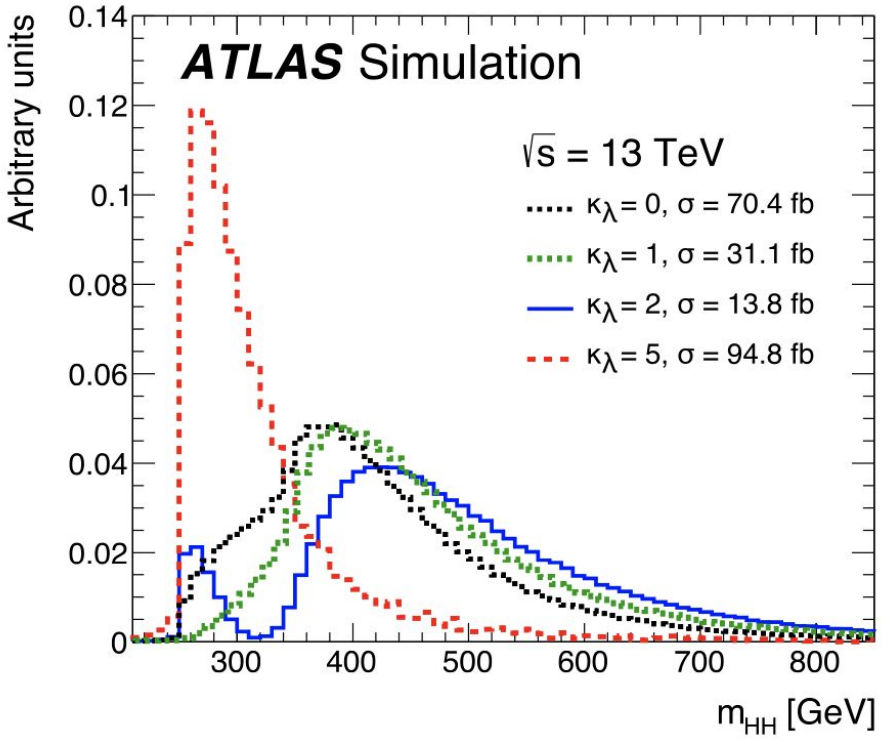


HH Production

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

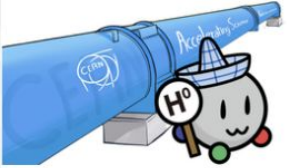




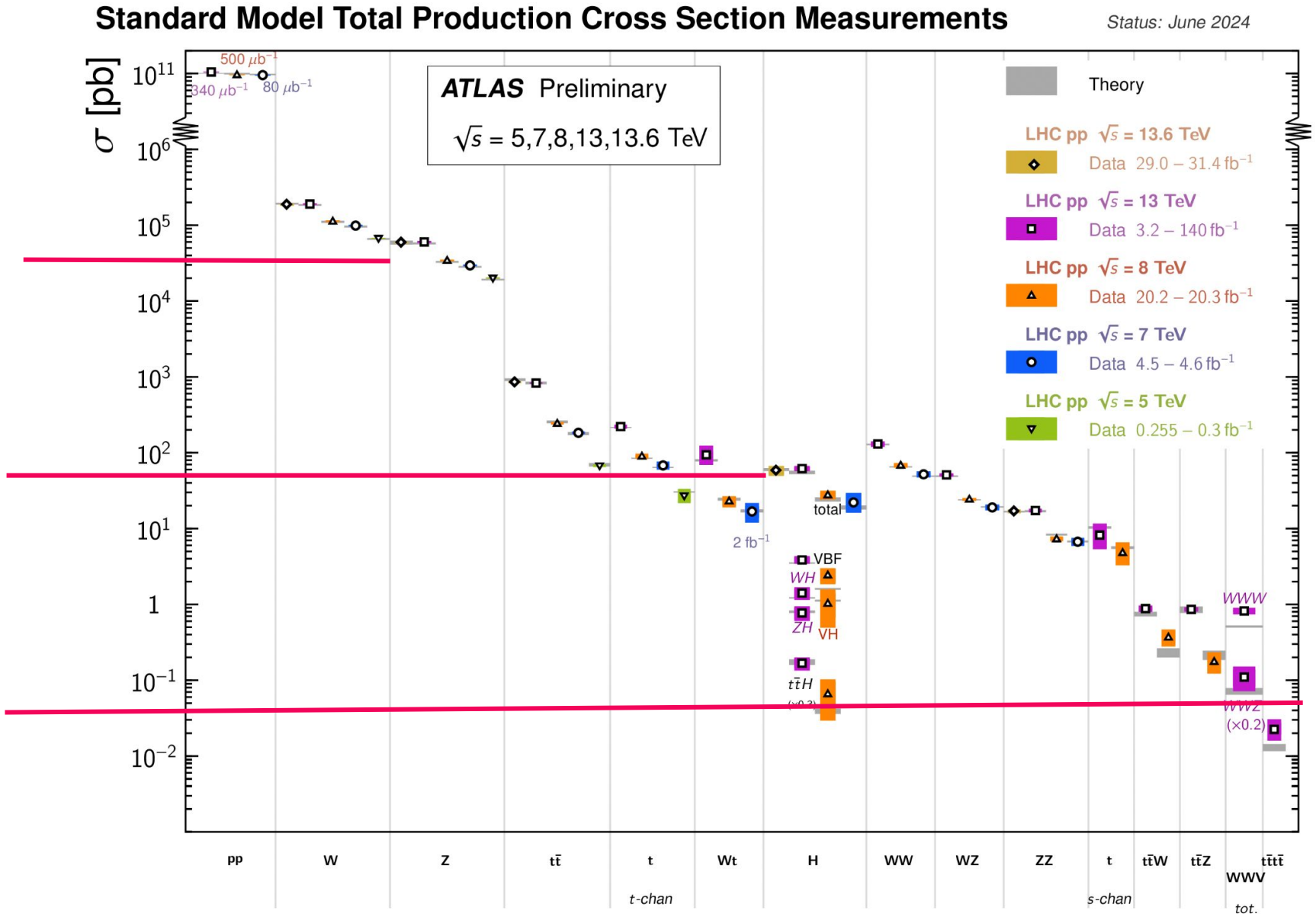


There is destructive interference between the box and triangle diagrams, thus the **cross section is suppressed** (~10^3 times smaller than single Higgs x-section). Deviations from SM can increase this cross section.

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



Higgs boson in the Standard Model



SM
Z production
x1000

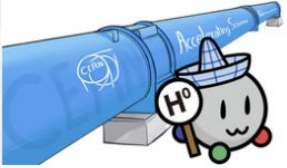
SM
Single Higgs
production

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

[ATLAS Public Results]

[CMS Public Results]

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Di-Higgs 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%

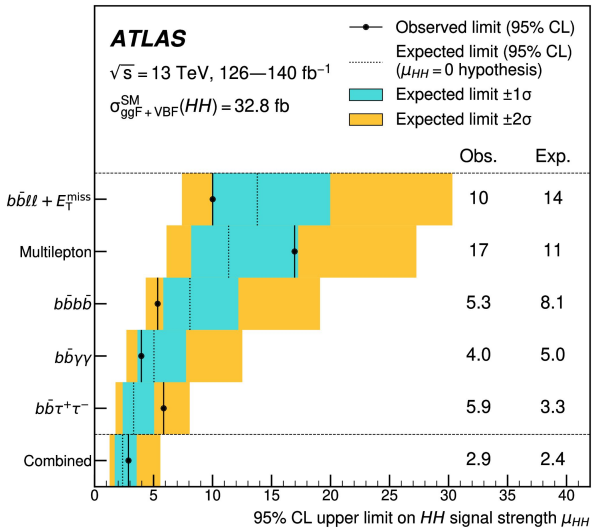
- Channels with large decay fractions may lead to challenging signatures.
- Exploring a mixture of different higgs decay channels to increase the sensitivity.
- Different analysis strategies developed.

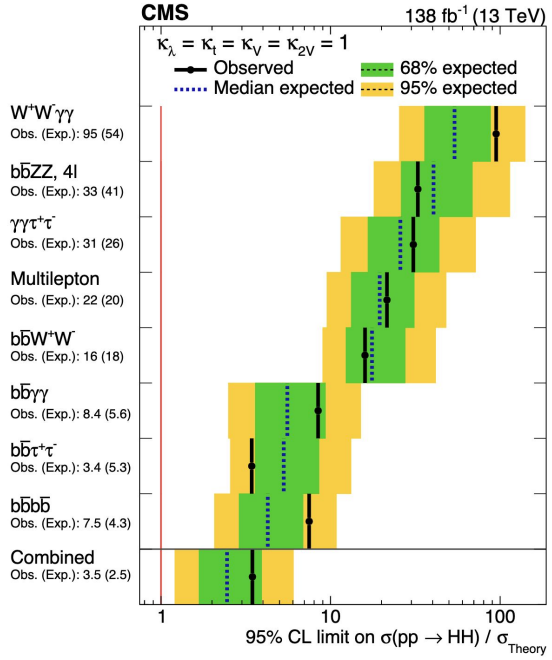
Combination is key in this search!

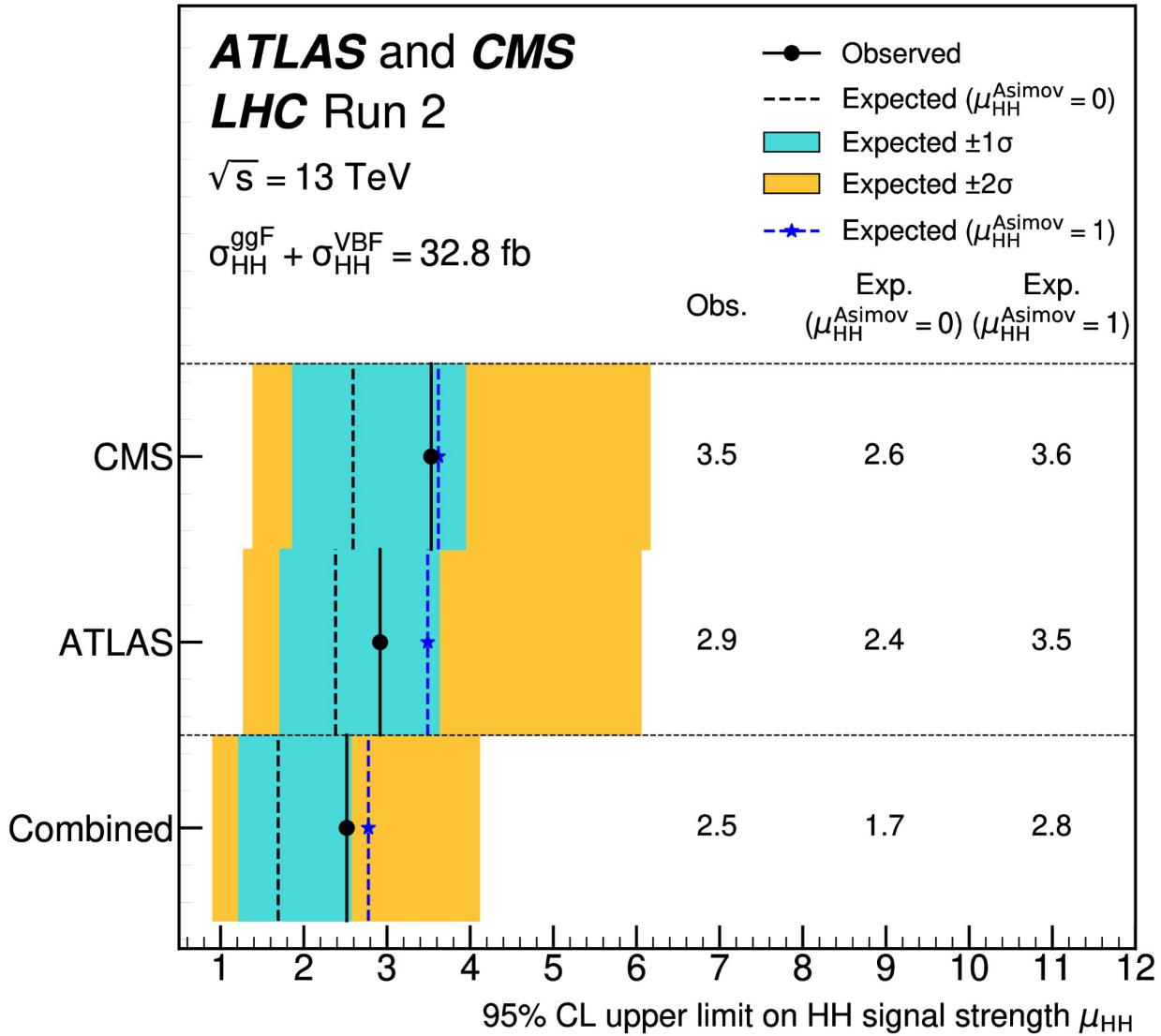
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ATLAS and CMS HH combination

Phys. Rev. Lett. 137 (2026) 131803





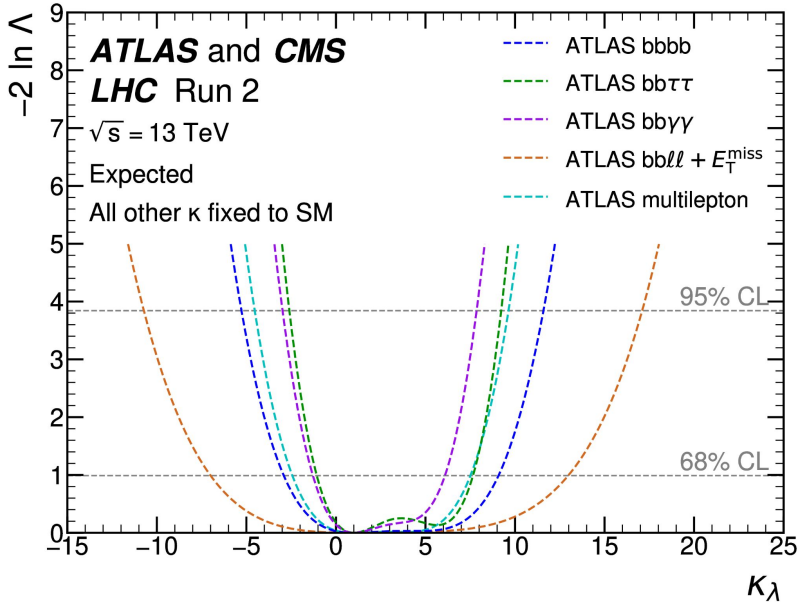


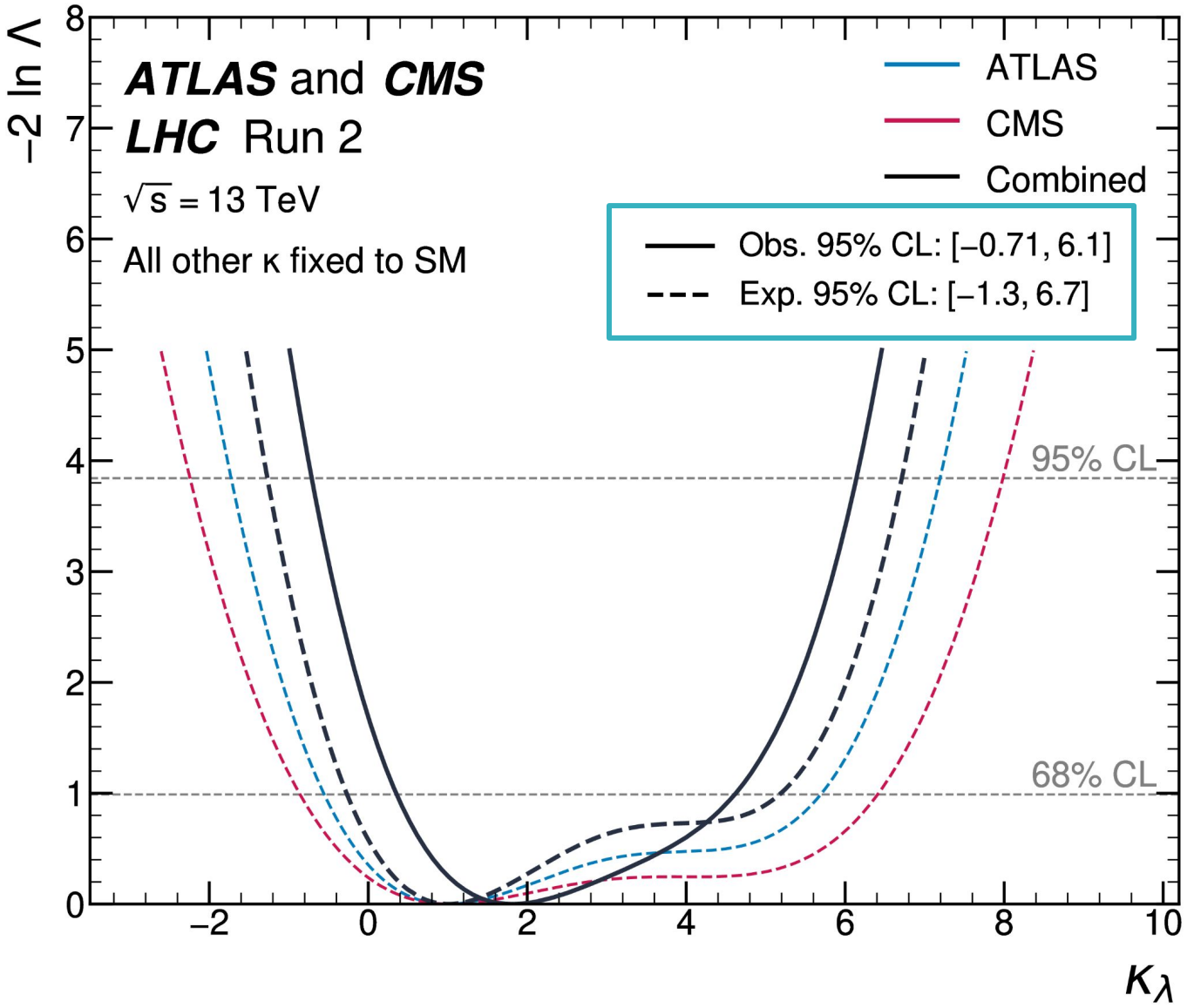
- ATLAS and CMS combination for searches of Higgs boson pair production!
  - Multiple channels explored in both collaborations.
- Best expected sensitivity to date on HH cross section:
  - $\mu_{HH} < 2.5$ (1.7 exp.)
- Observed (expected from SM) significance: 1.1σ (1.3σ)
- HH theory cross section uncertainty and Higgs + heavy flavour production become relevant for the sensitivity.

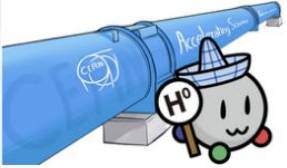
ATLAS and CMS HH combination

Phys. Rev. Lett. 137 (2026) 131803

Combination of different analyses, covering different kinematic regions play an important role in constraining κ_λ.

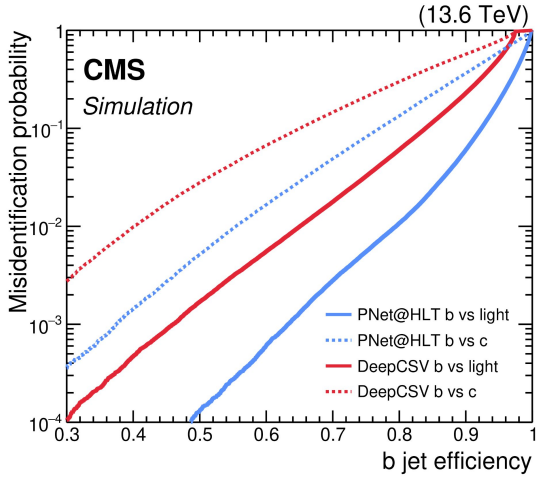






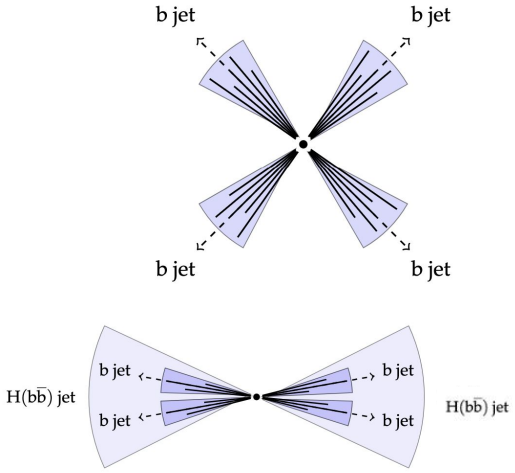
Latest HH searches

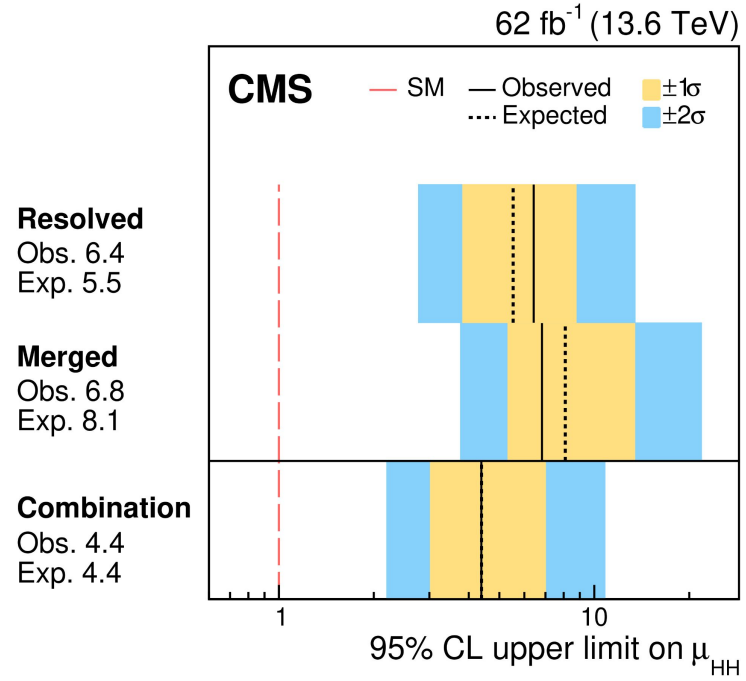
CMS-HIG-24-010



HH→4b

- Using Run 3 data: 62 fb^{-1}.
- Resolved and Boosted topologies.
  - Improved tagging techniques.
  - New b-jet triggers.
- Improvised analysis via ML.
- Measured ZZ and ZH production.
- 95% CL: $-2.26 < \kappa_\lambda < 8.83$

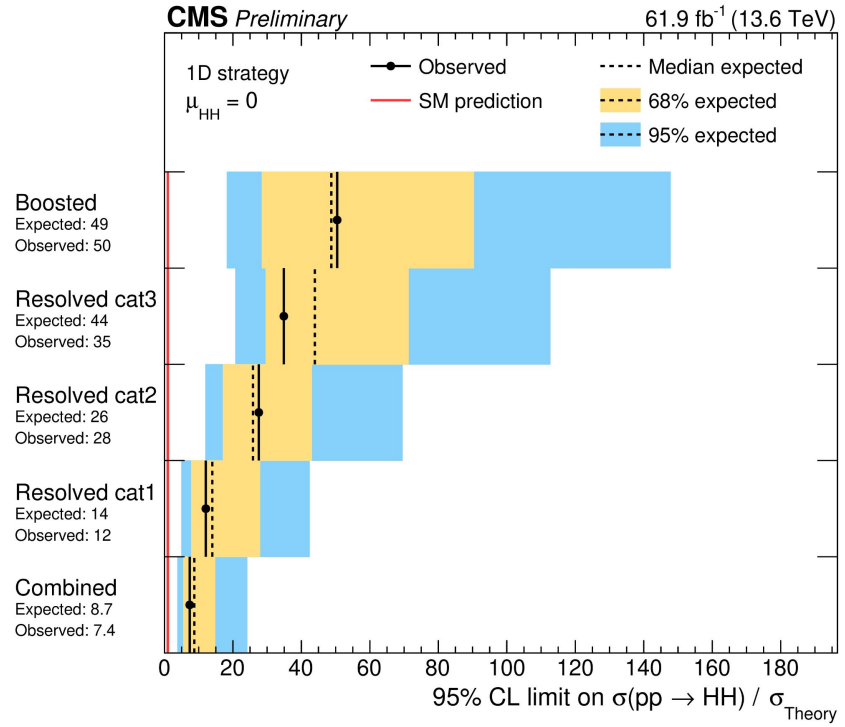


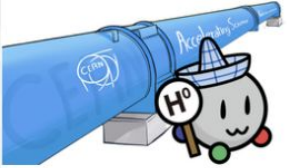


CMS-PAS-HIG-25-007

HH→bbyy

- Using Run 3 data: 62 fb^{-1}.
- 2D fit to di-photon and di-(b)-jet mass observables.
- Resolved and boosted topologies.
- 95% CL: $-3.9 < \kappa_\lambda < 10.4$



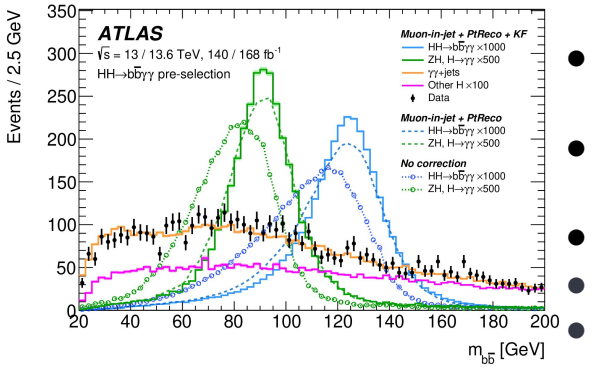


Latest HH searches

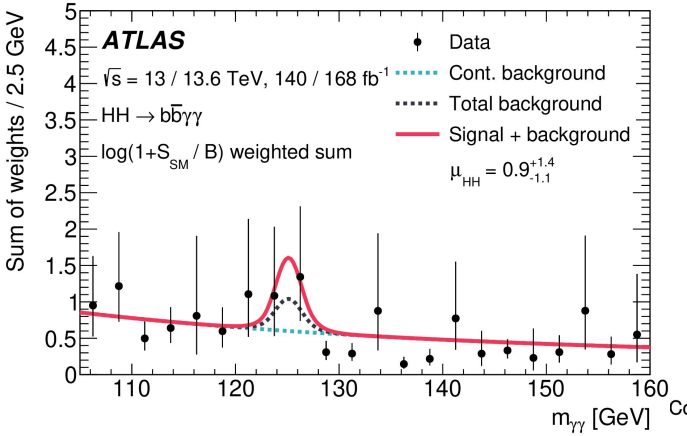
ATLAS-HIGP-2024-37

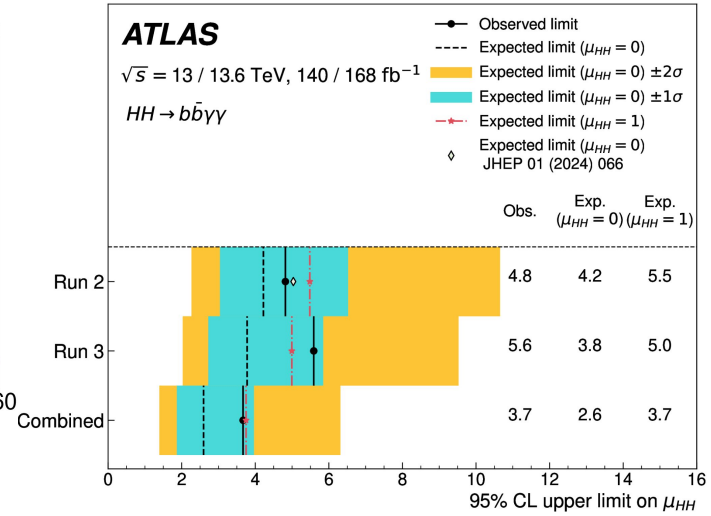
Phys. Lett. B 876 (2026) 140280

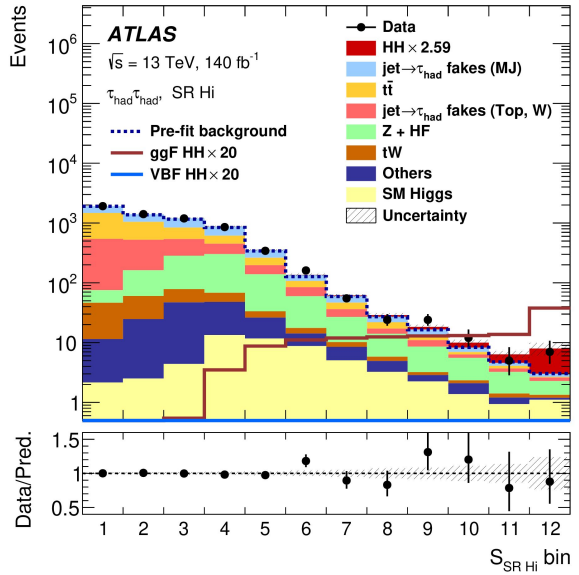
HH→bbyy



- Using Run 3 (168 fb^{-1}) and Run 2 (140 fb^{-1}) data re-analysis
- Improved b-tagging and m_{bb} reconstruction.
- Improved categorisation via ML.
- 95% CL: $-1.6 < \kappa_\lambda < 6.6$
- SM HH discovery significance: 0.78σ observed (1.01σ expected)



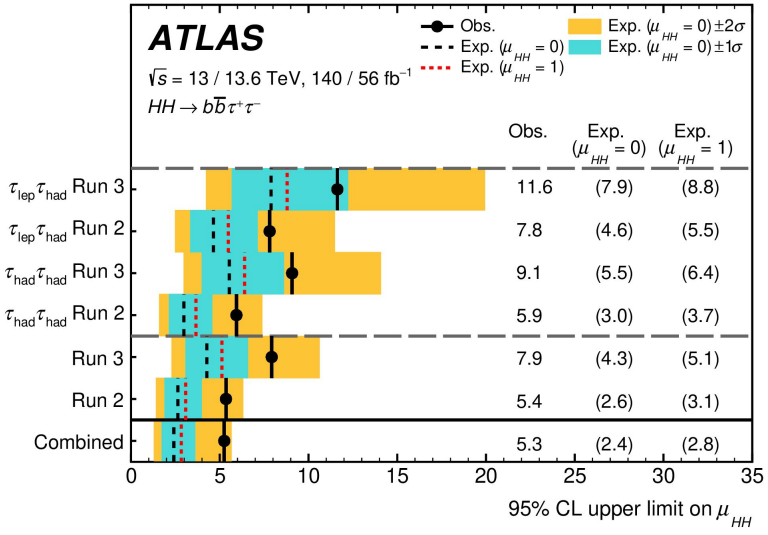


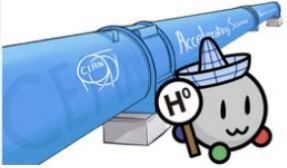


HH→bbττ

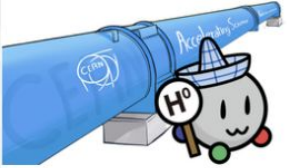
- Using Run 2 (56 fb^{-1}) and Run 2 (140 fb^{-1}) data re-analysis.
- Improved b-tagging and m_{bb} reconstruction.
- New b-jet triggers and tau-triggers in delay stream
- Improved categorisation via ML.
- Measured ZZ and ZH.

- κ_λ: [-3.4, 1.6] U [5.5., 10.1]
- SM HH discovery significance: 2.64σ observed (1.24σ expected)

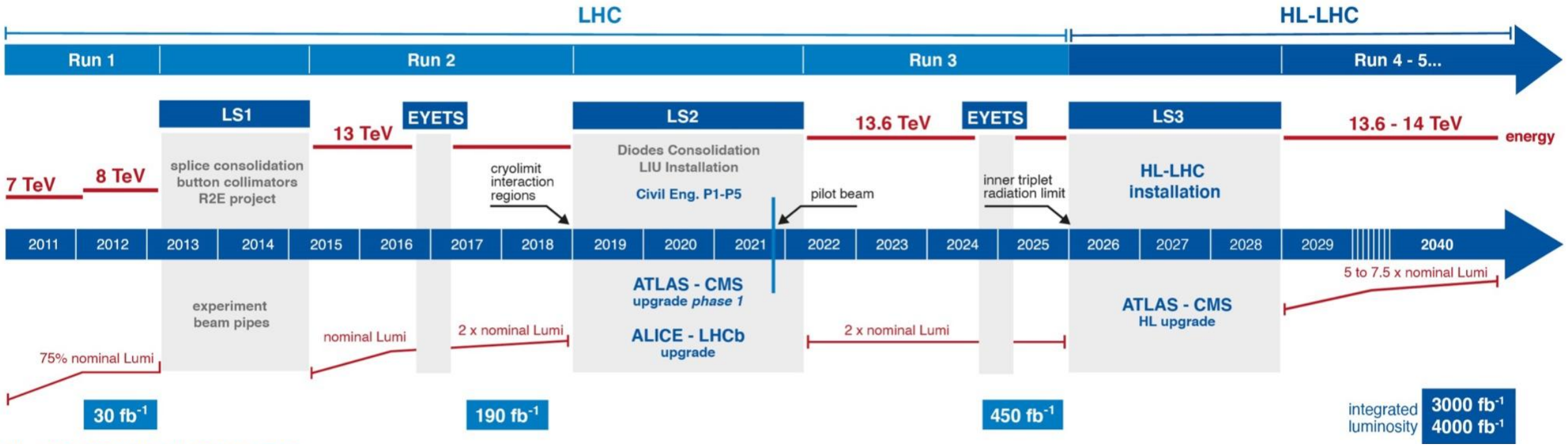




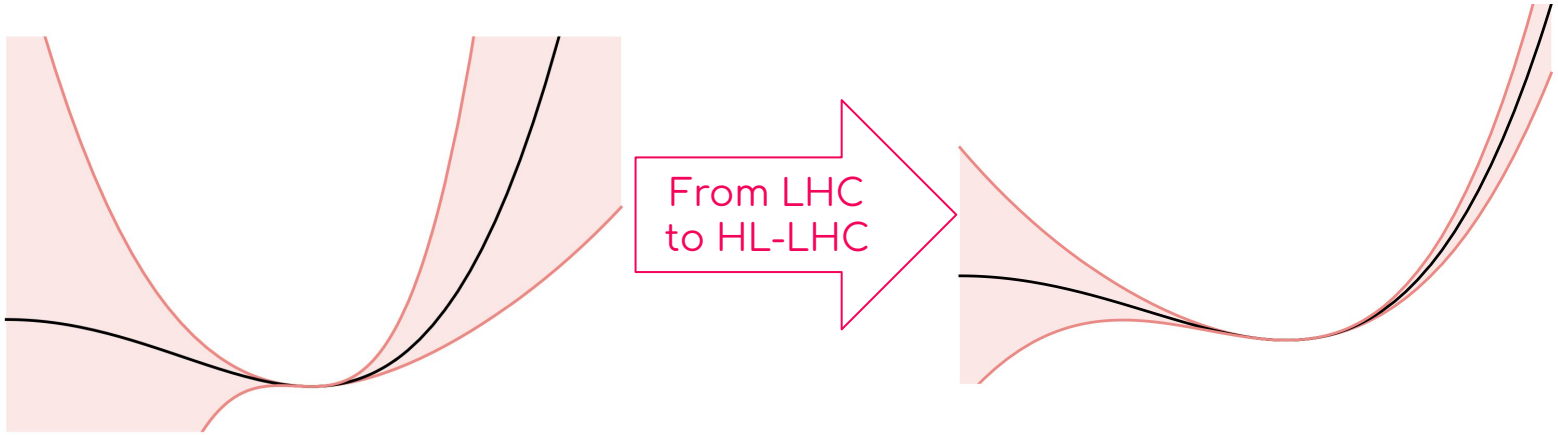
Towards HL-LHC



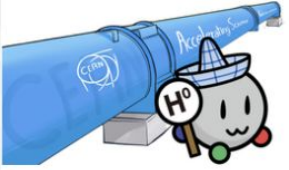
HL-LHC plan



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



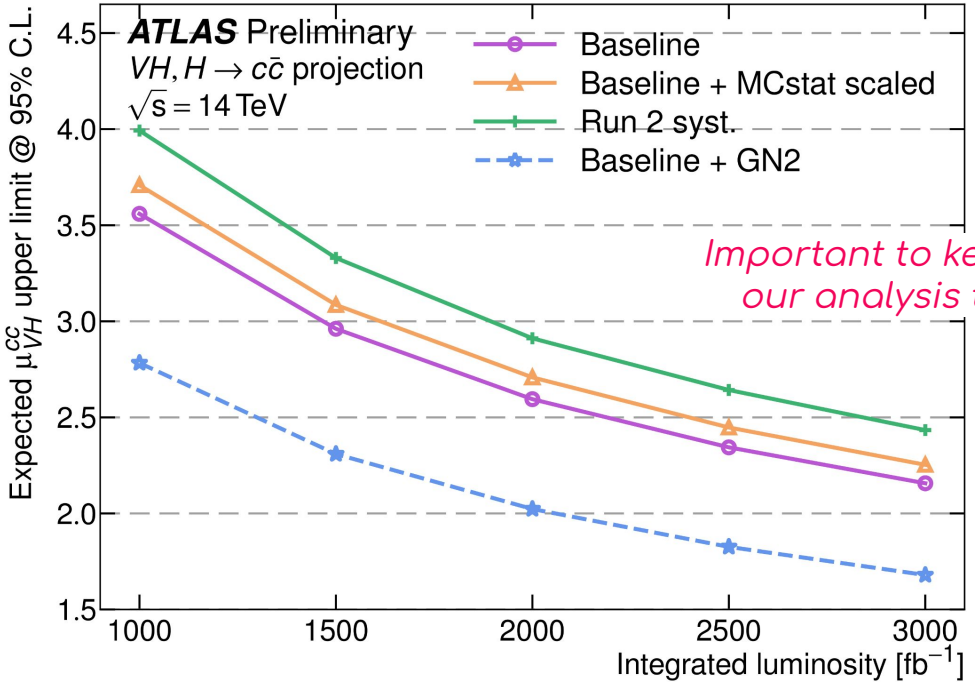
H/T N.Craig, R. Petrossian-Byrne



Higgs Measurements

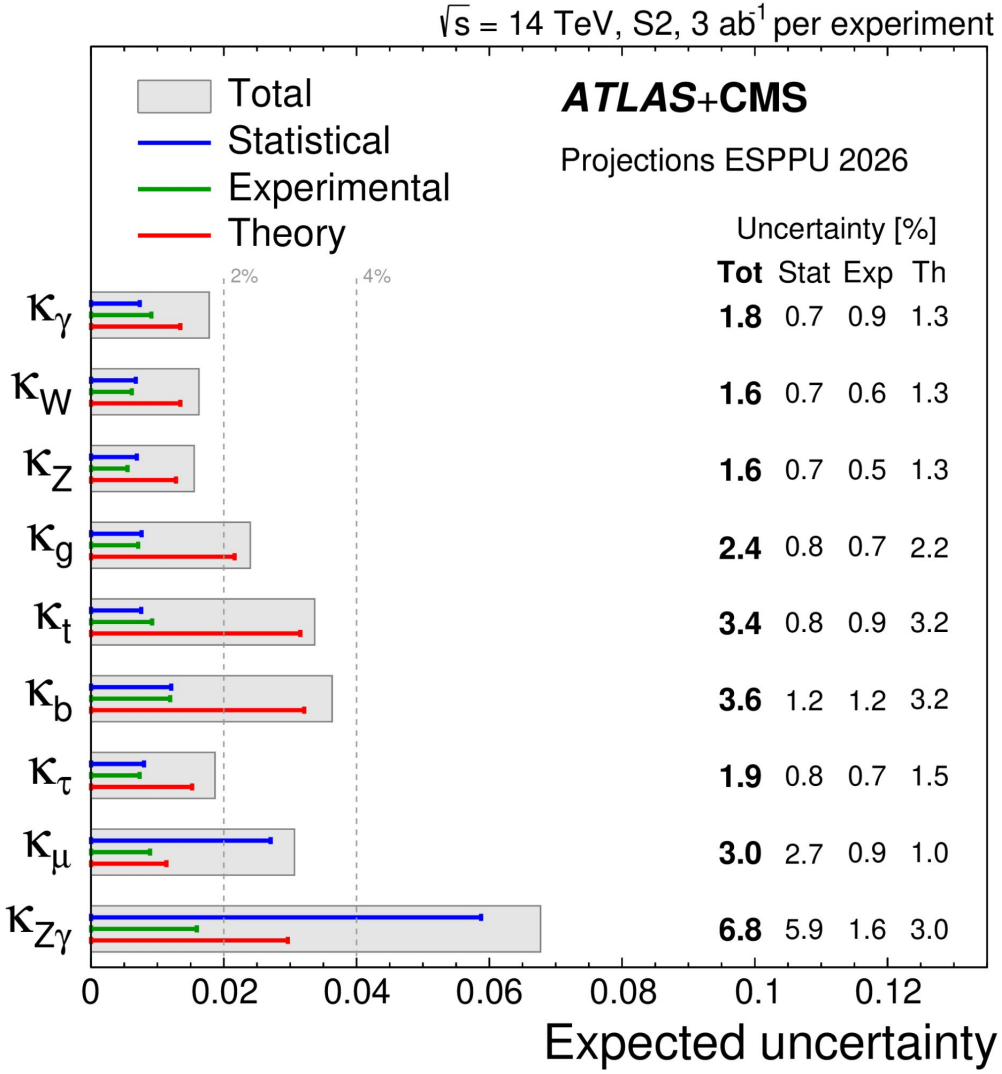
Statistically limited channels will profit immediately from Run 3

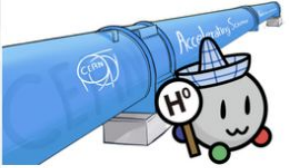
$\mathcal{L}$		$\delta\mu$ [%] $H \to Z\gamma$	$H \to \mu\mu$
2 ab^{-1}	ATLAS	21	13
	CMS	23	8.4
	ATLAS+CMS	15	7.1
3 ab^{-1}	ATLAS	17	11
	CMS	19	7.0
	ATLAS+CMS	14	5.9



Important to keep improving our analysis techniques!

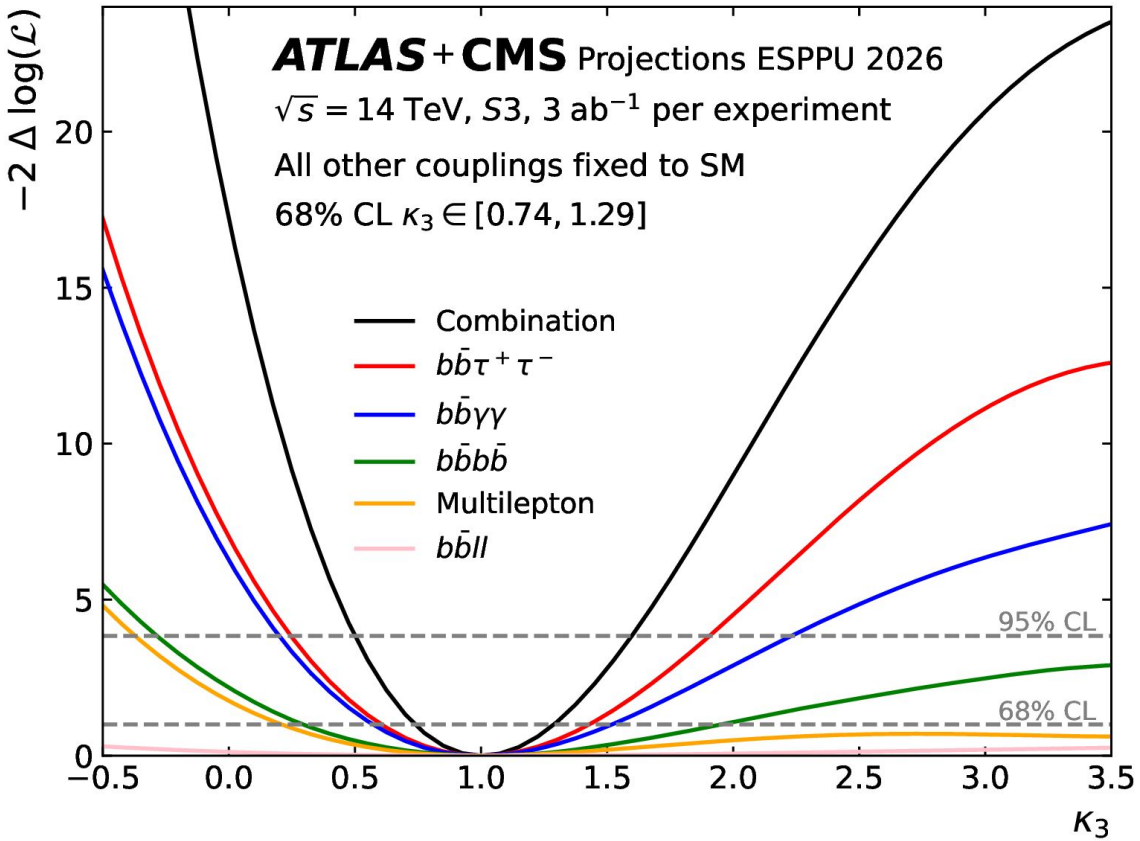
We will soon be dominated by theoretical uncertainties!





Di-Higgs ~~searches~~ measurement

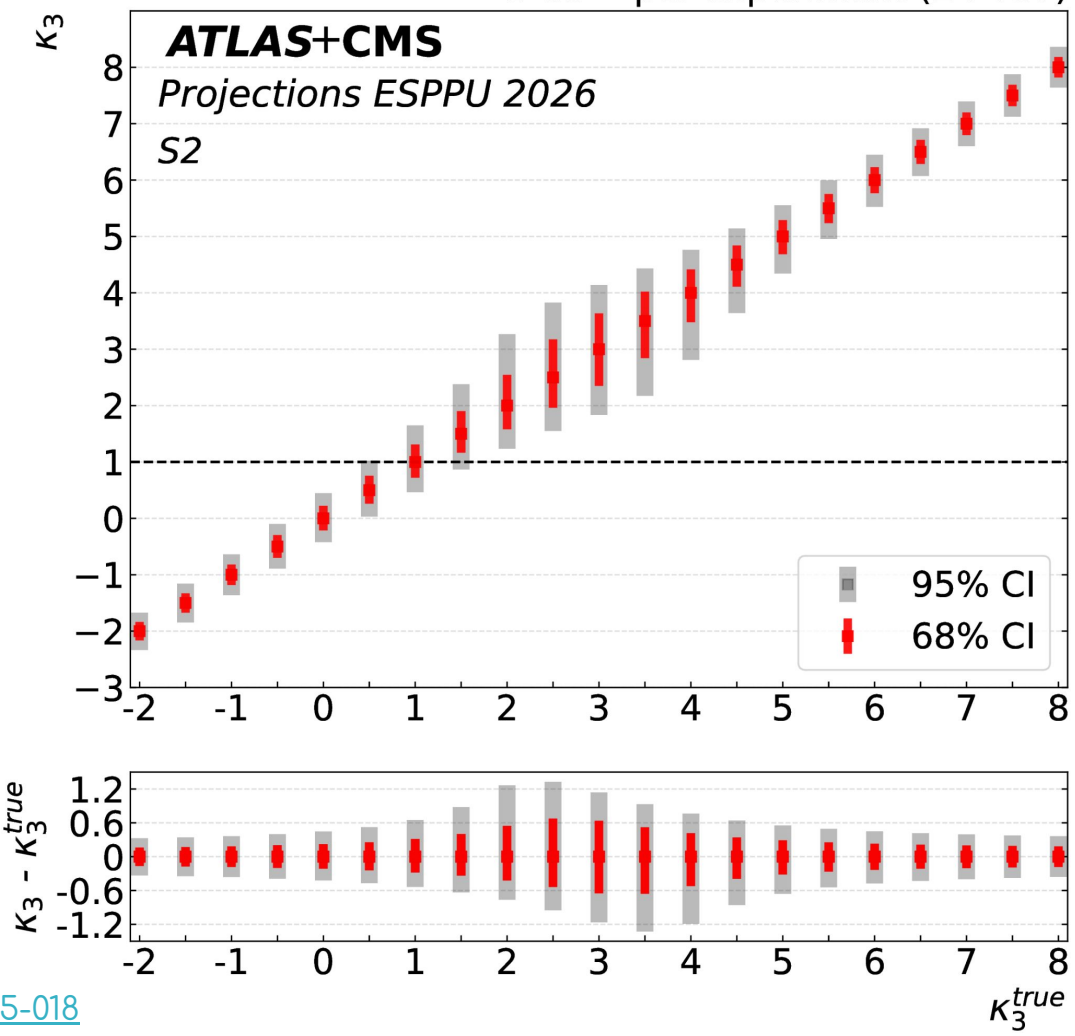
- A >5σ observation will be possible already with 2000 fb^{-1} combining both experiments.
  - 3000 fb^{-1} may allow a single-experiment observation.
- Including 5% improvement in the b-tagging identification and tau-identification will increase the precision by 5%.

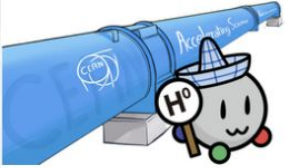


κ_λ is expected to be measured as $1.0^{+0.29}_{-0.26}$ if SM

Our precision will be determined by the self-coupling realised in Nature!

3 ab^{-1} per experiment (14 TeV)





Final remarks

- We have a very broad and rich Higgs physics program in ATLAS and CMS!
  - Very important **precision measurements** are being updated with the larger dataset of LHC Run 3.
  - Rare decays and production processes are now becoming more accessible: H→μμ, H→Zγ, etc.
  - Find all new results: ATLAS and CMS.

- 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.

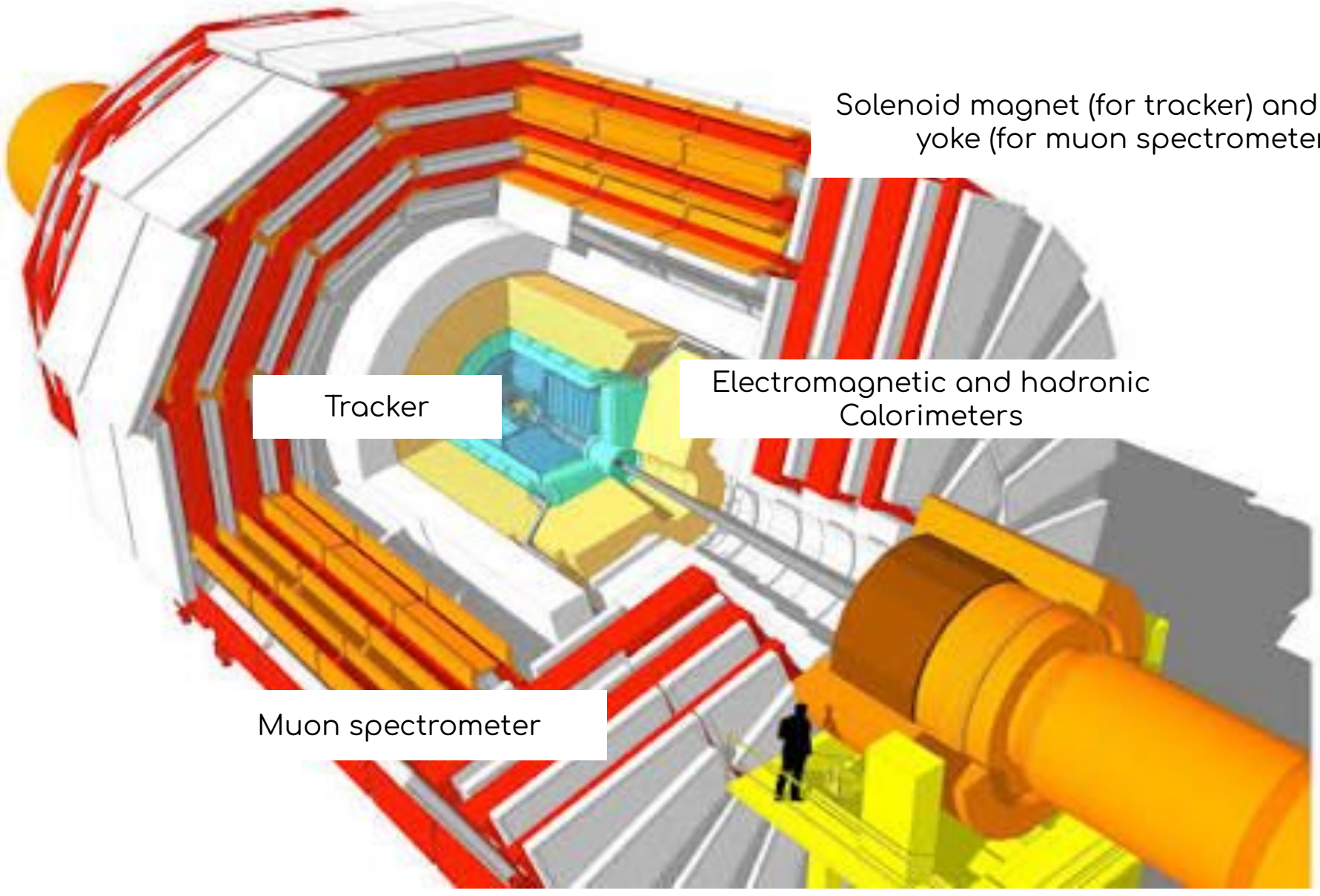
arelycg@cern.ch

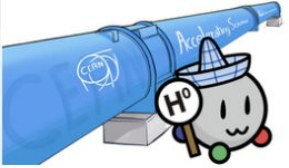
ありがとう



Credit: higgstan.com

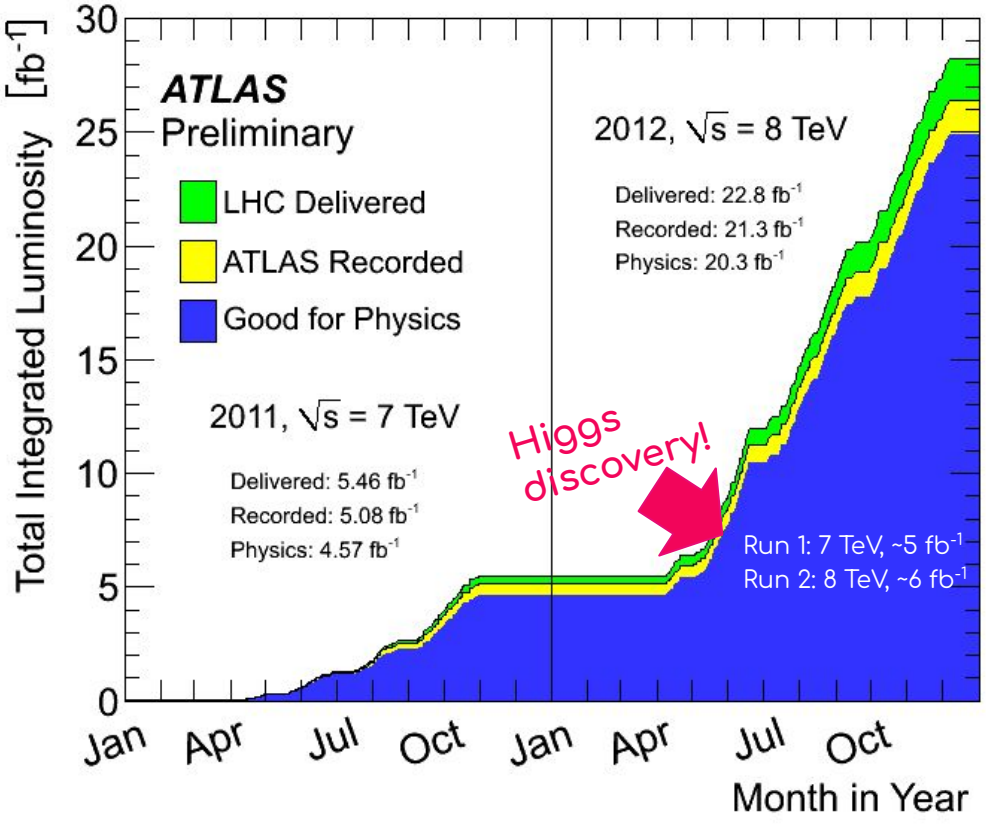
CMS

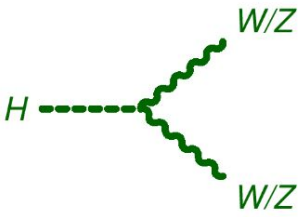

Solenoid magnet (for tracker) and return yoke (for muon spectrometer)
Tracker
Electromagnetic and hadronic Calorimeters
Muon spectrometer

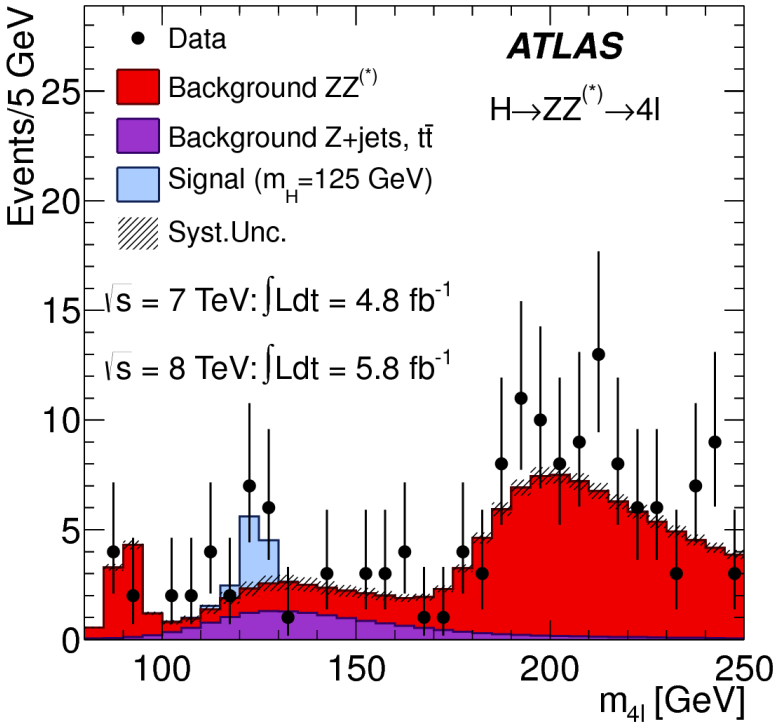


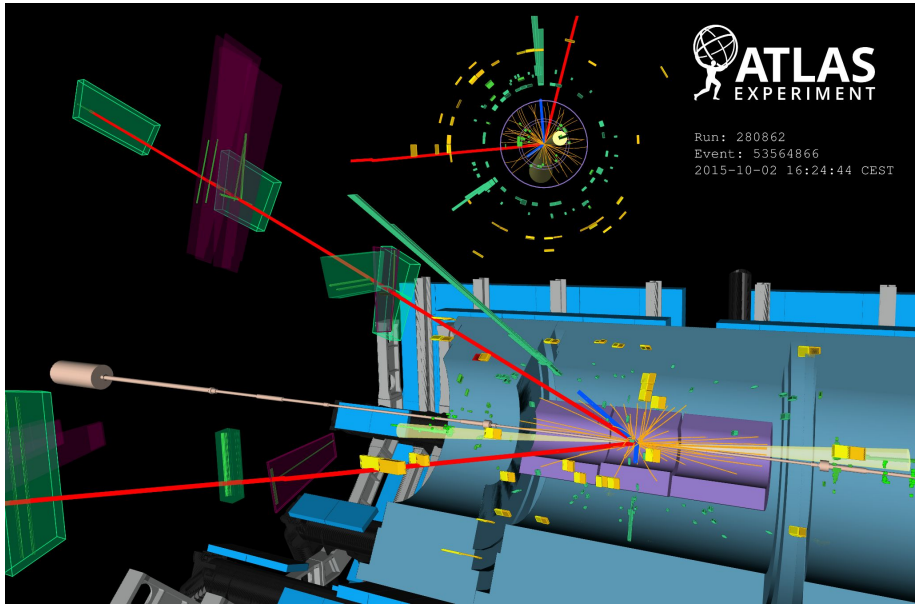
We found a Higgs!

ATLAS / CMS discovery papers

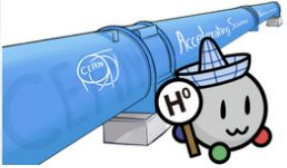








- A large search program in all decays channels from the start of the LHC Run 1.
- Main channels leading to the discovery:
  - H→ZZ*→4ℓ, H→γγ, H→WW→ℓνℓν.



Characterising the Higgs boson

Mass measurement

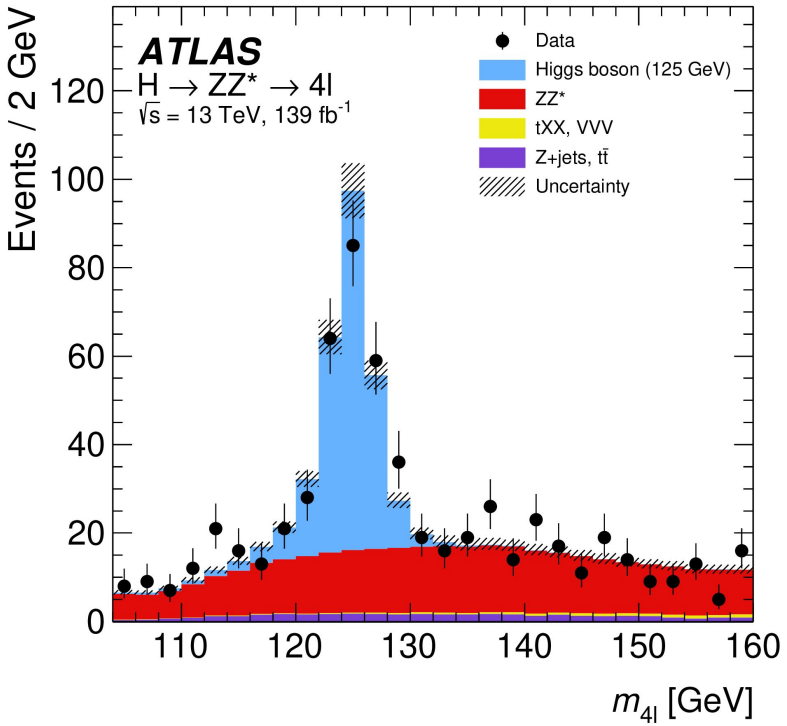
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

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

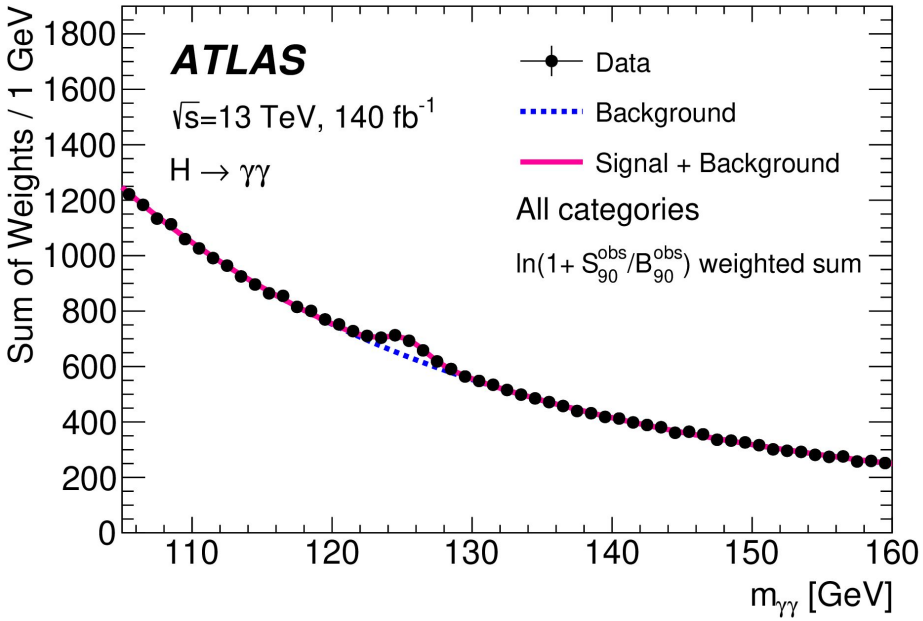
The mass is the only **free parameter** in the Higgs mechanism.

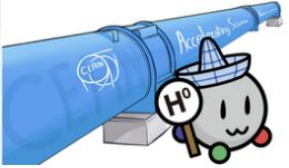
- Crucial input to predict Higgs production cross sections and decay rates
- Measurement in decay channels with good resolution:
  - H→ZZ*→4ℓ and H→γγ (fully reconstructable final states)
  - Relies on precise momentum calibration of muons, electrons and photons.

Phys. Lett. B 843 (2023) 137880



Phys. Lett. B 847 (2023) 138315





Characterising the Higgs boson

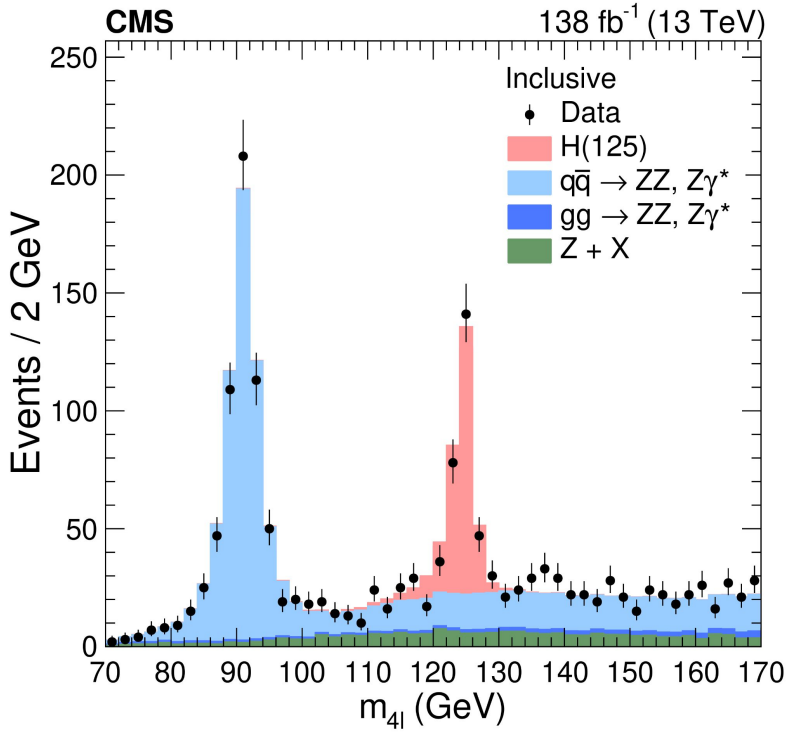
Mass measurement

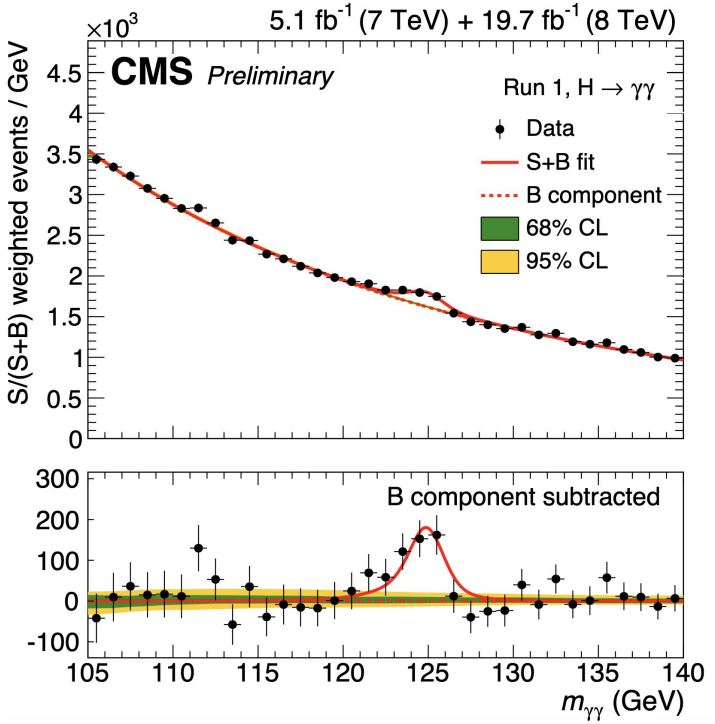
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

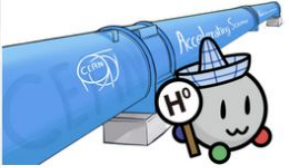
$$V = V_0 + \frac{1}{2}m_H^2 h^2 + \frac{m_H^2}{2v^2}vh^3 + \dots$$

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

- Crucial input to predict Higgs production cross sections and decay rates
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  - H→ZZ*→4ℓ and H→γγ (fully reconstructable final states)
  - Relies on precise momentum calibration of muons, electrons and photons.



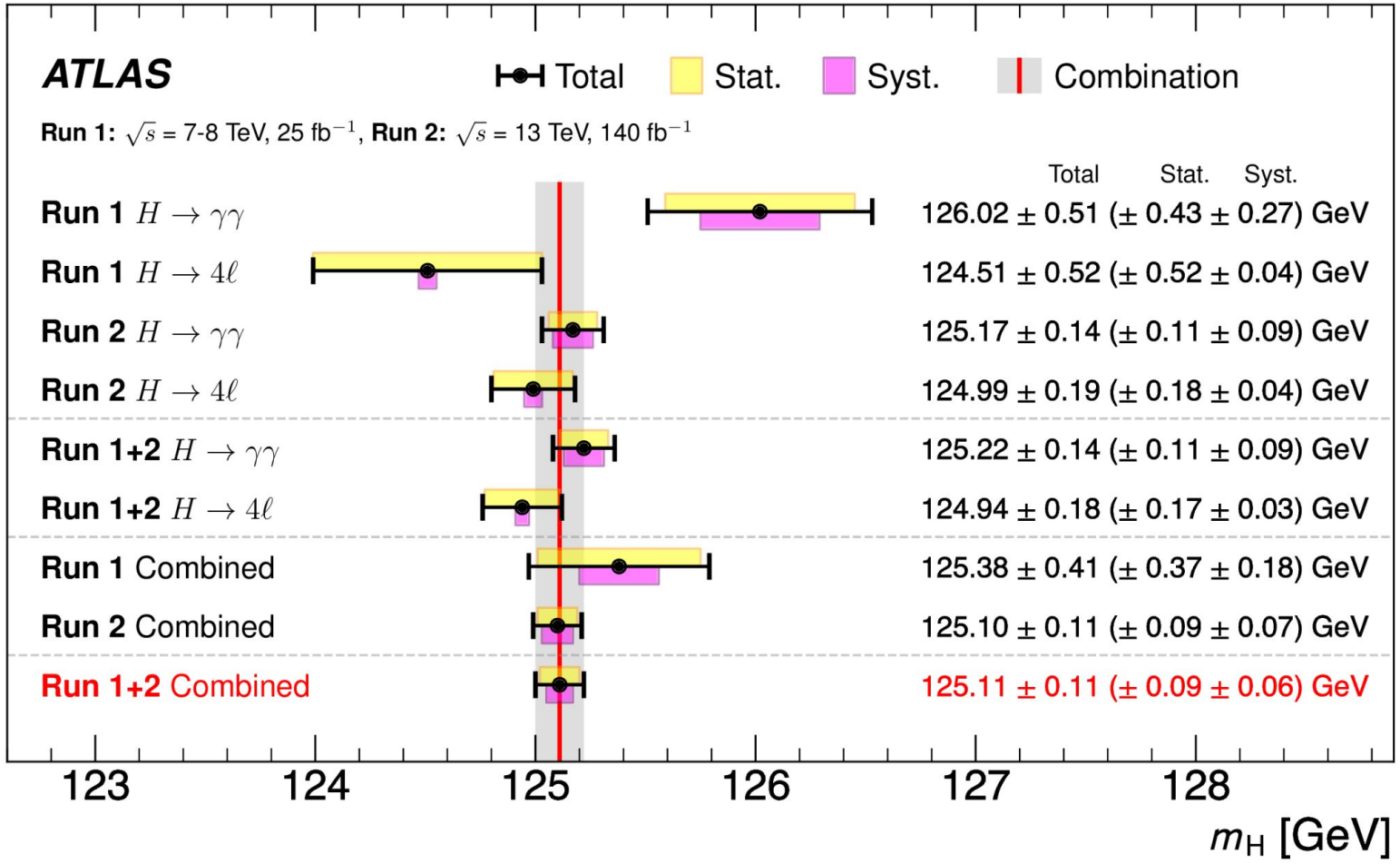




Characterising the Higgs boson

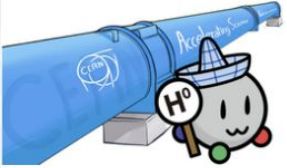
Mass measurement

Phys. Rev. Lett. 131 (2023) 251802



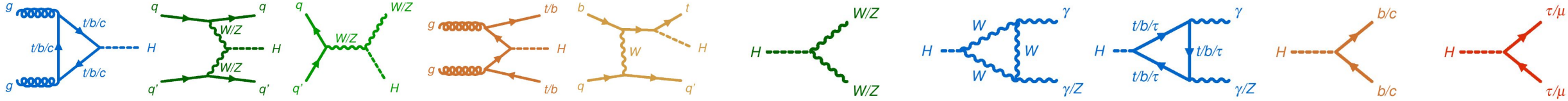
- First precision measurement at the LHC!
  - Current precision at 0.09%!
- Compare to Run 1, Run 2 combined measurement ($H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$) is equally limited by statistical and systematic uncertainties.
- Precise calibration of energy/momentum scale of leptons and photons.

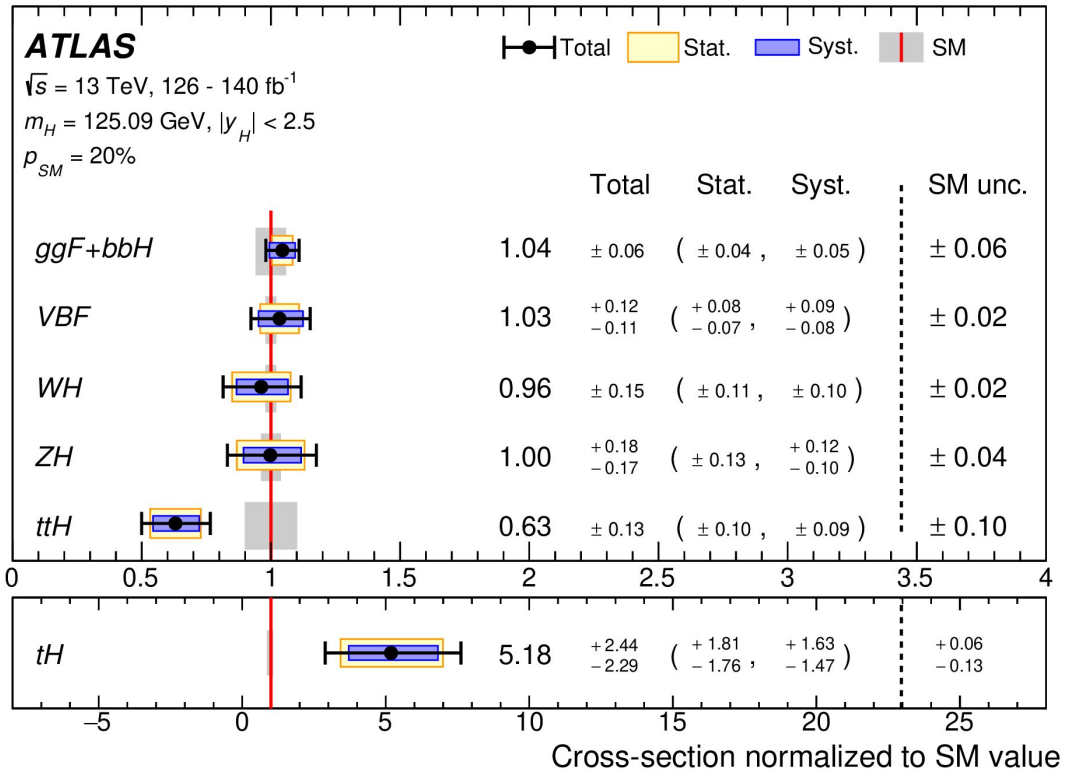
Source	Systematic uncertainty on m_H [MeV]
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background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

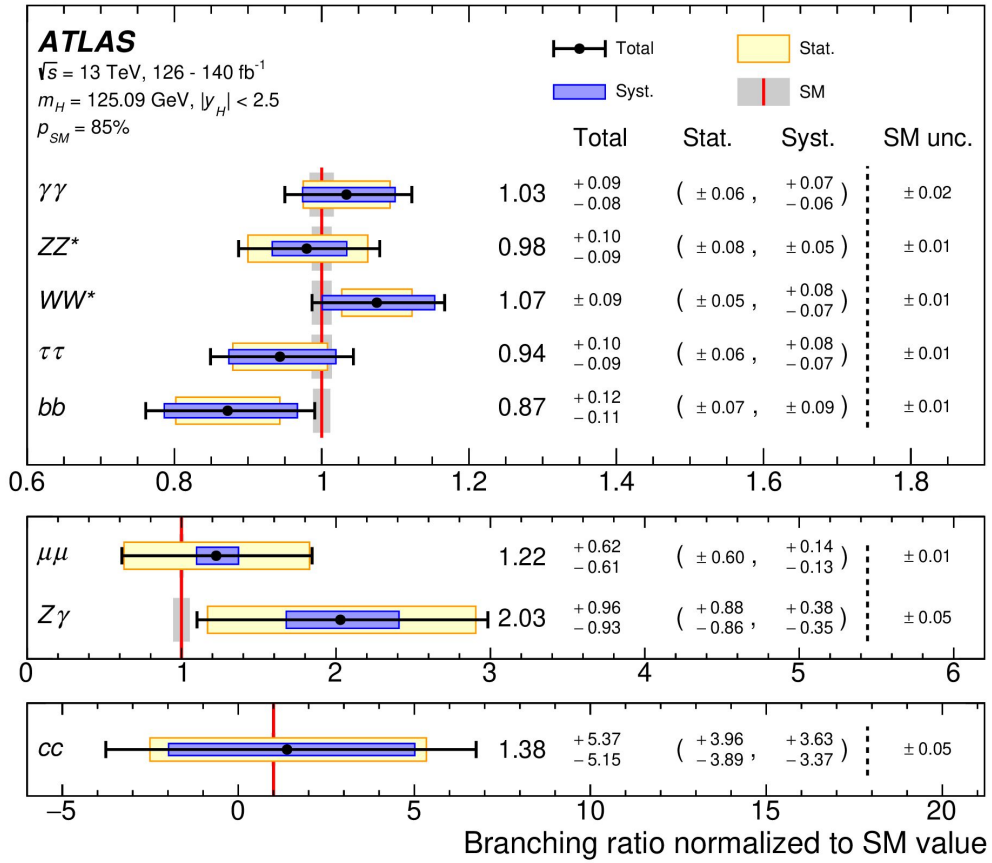


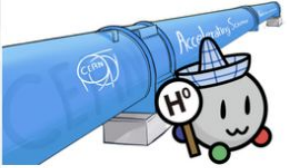
Higgs Couplings

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









Trilinear Higgs Coupling

Standard Model Higgs potential

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

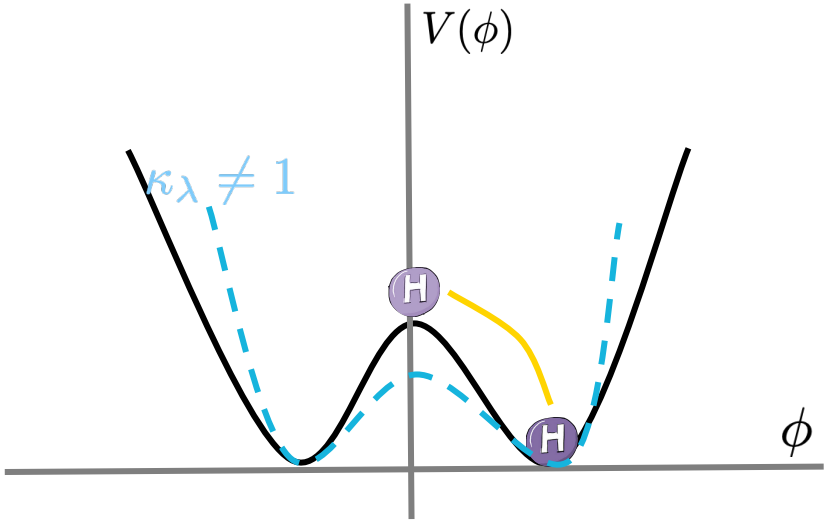
Our universe lives in the minimum:

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

mass

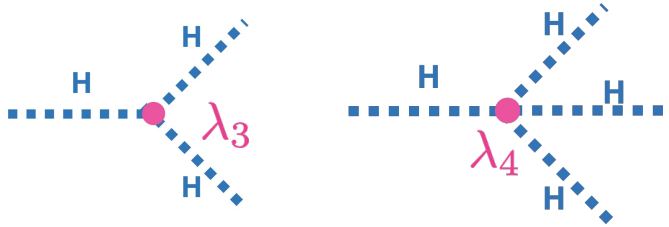
self-coupling

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

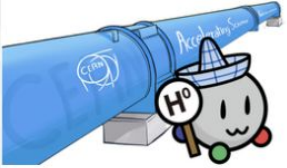


Moreover, in the SM:

$$\lambda_3 = \lambda_4$$

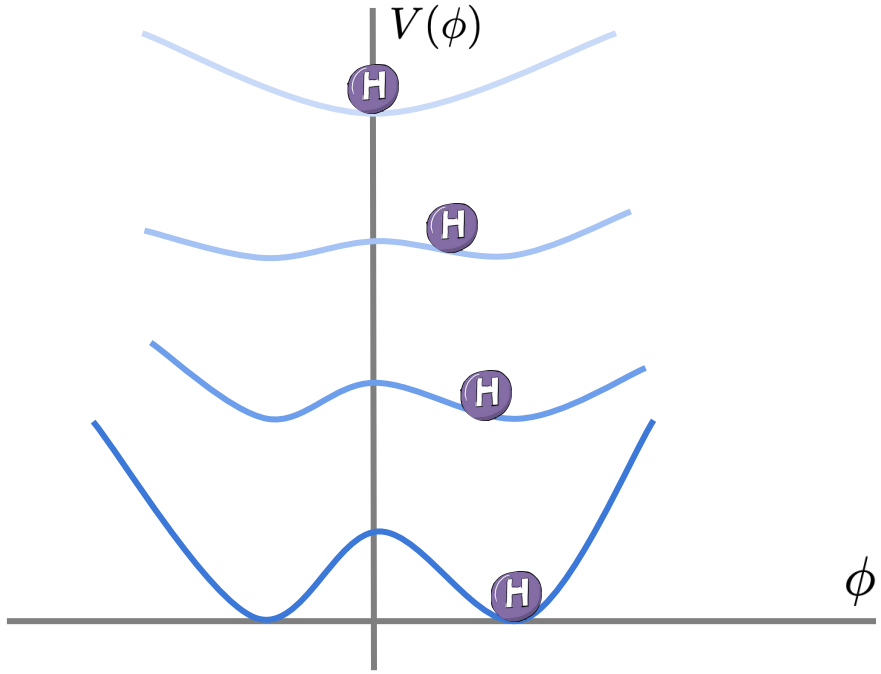


We can use **HHH** searches to independently constrain $\boldsymbol{\lambda_4}$

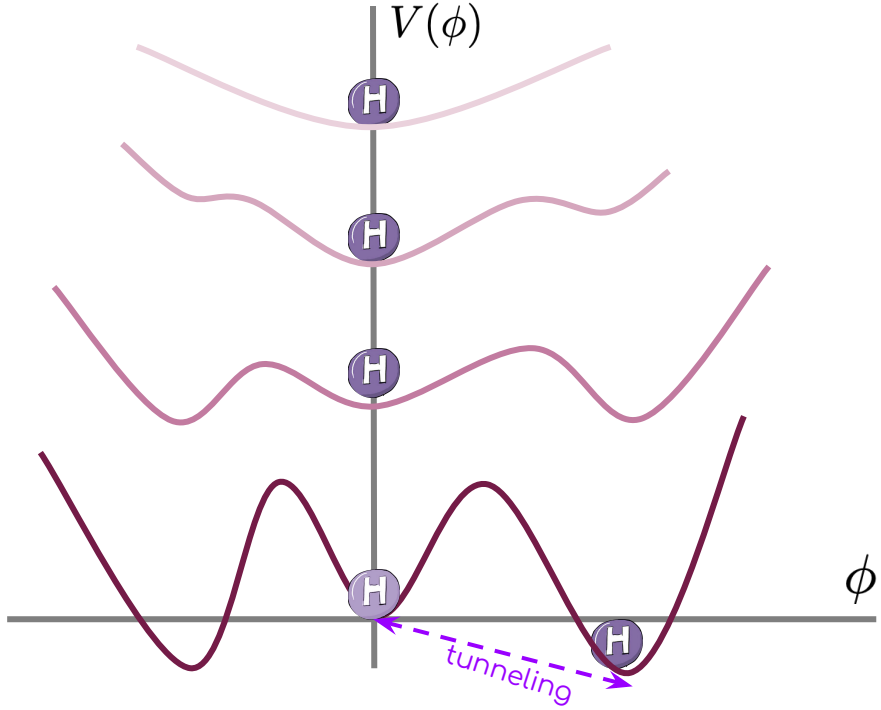


Electroweak phase transition

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

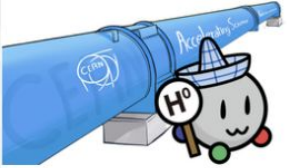


SM: 2nd order phase transition. Continuous cross-over from one phase to the other.



BSM: 1st order phase transition.

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

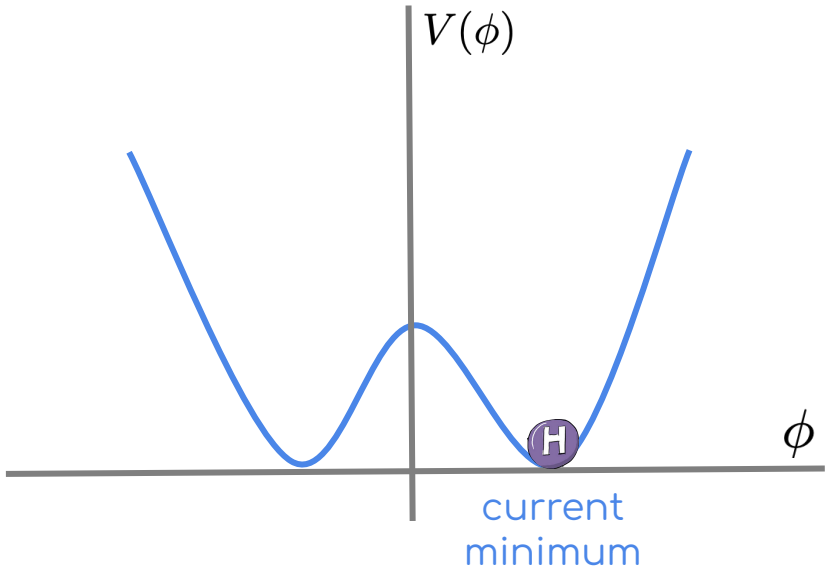


Stability of the universe

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

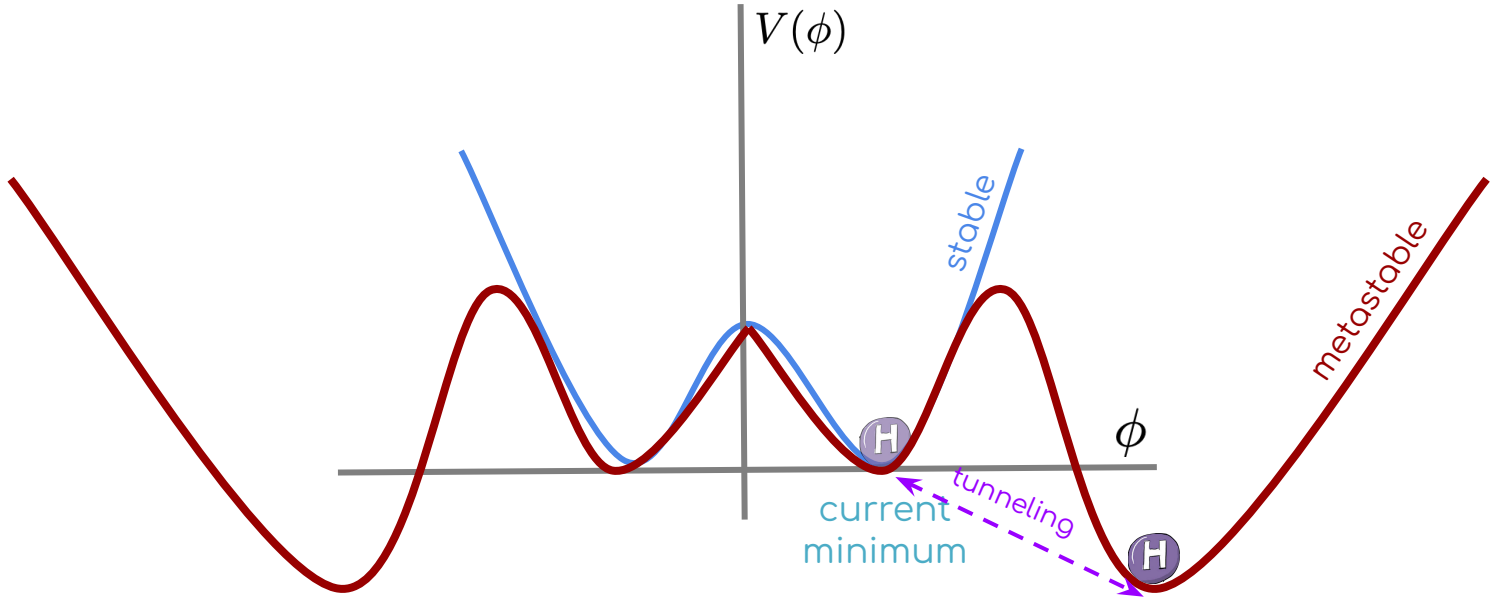
Stable universe

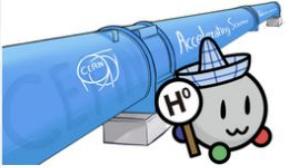
- Current minimum is the absolute minimum.
- Higgs fields will remain like this forever.



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...

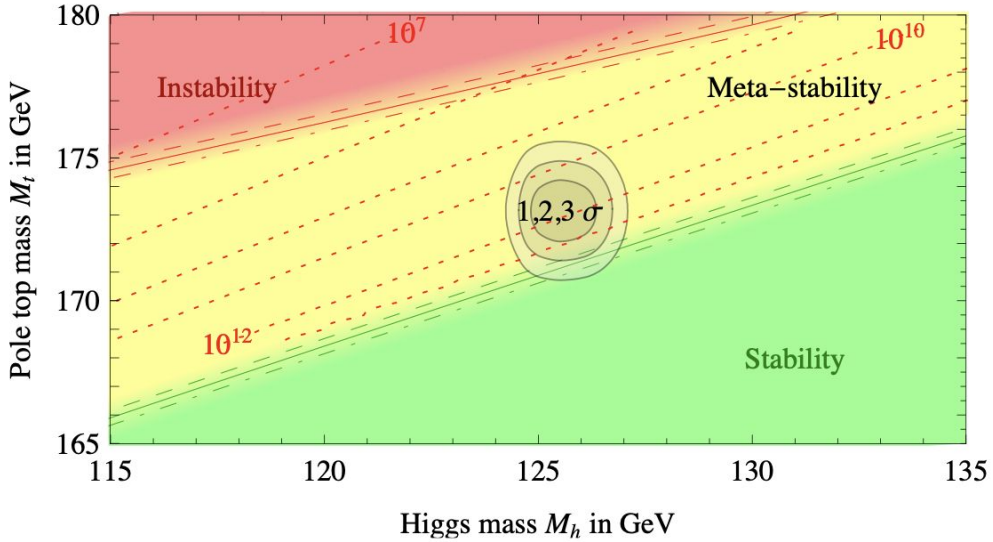




Stability of the universe

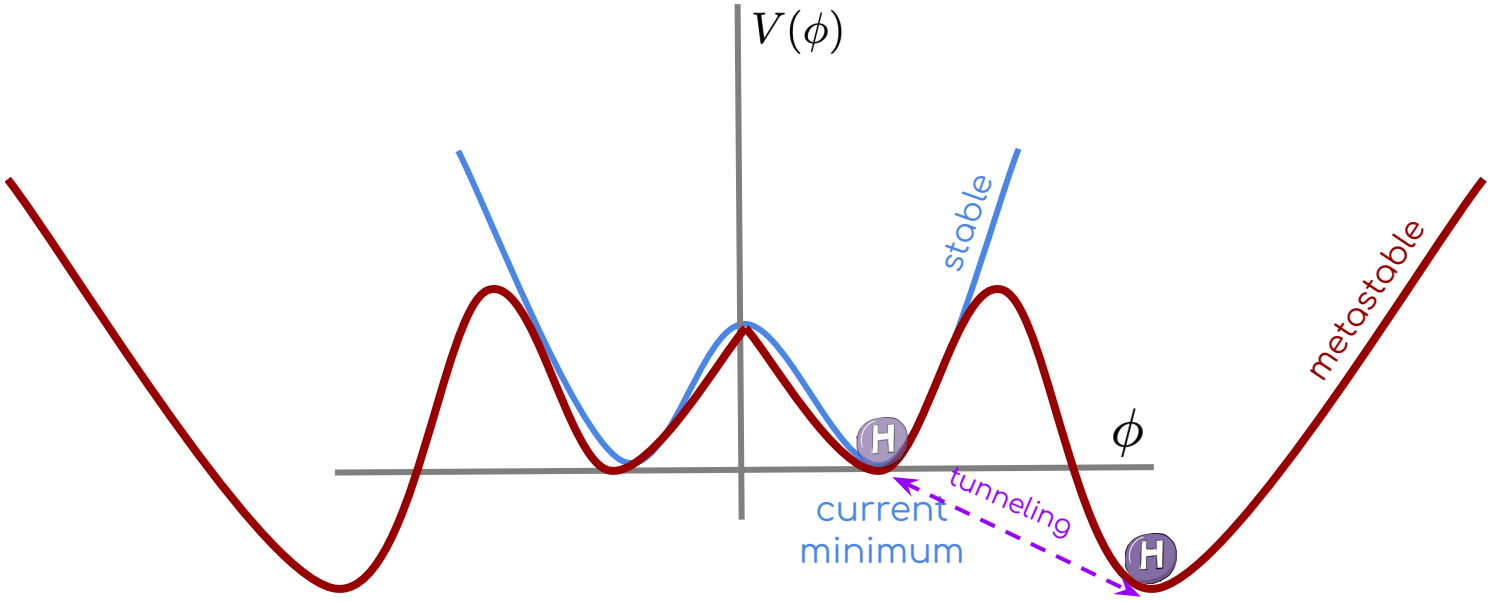
Measurements of the Higgs self-coupling can give insight about our universe!

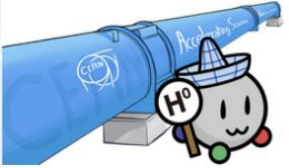
Precision on top mass is also fundamental to answer the question on the **metastability** of the universe.
arXiv:1205.6497



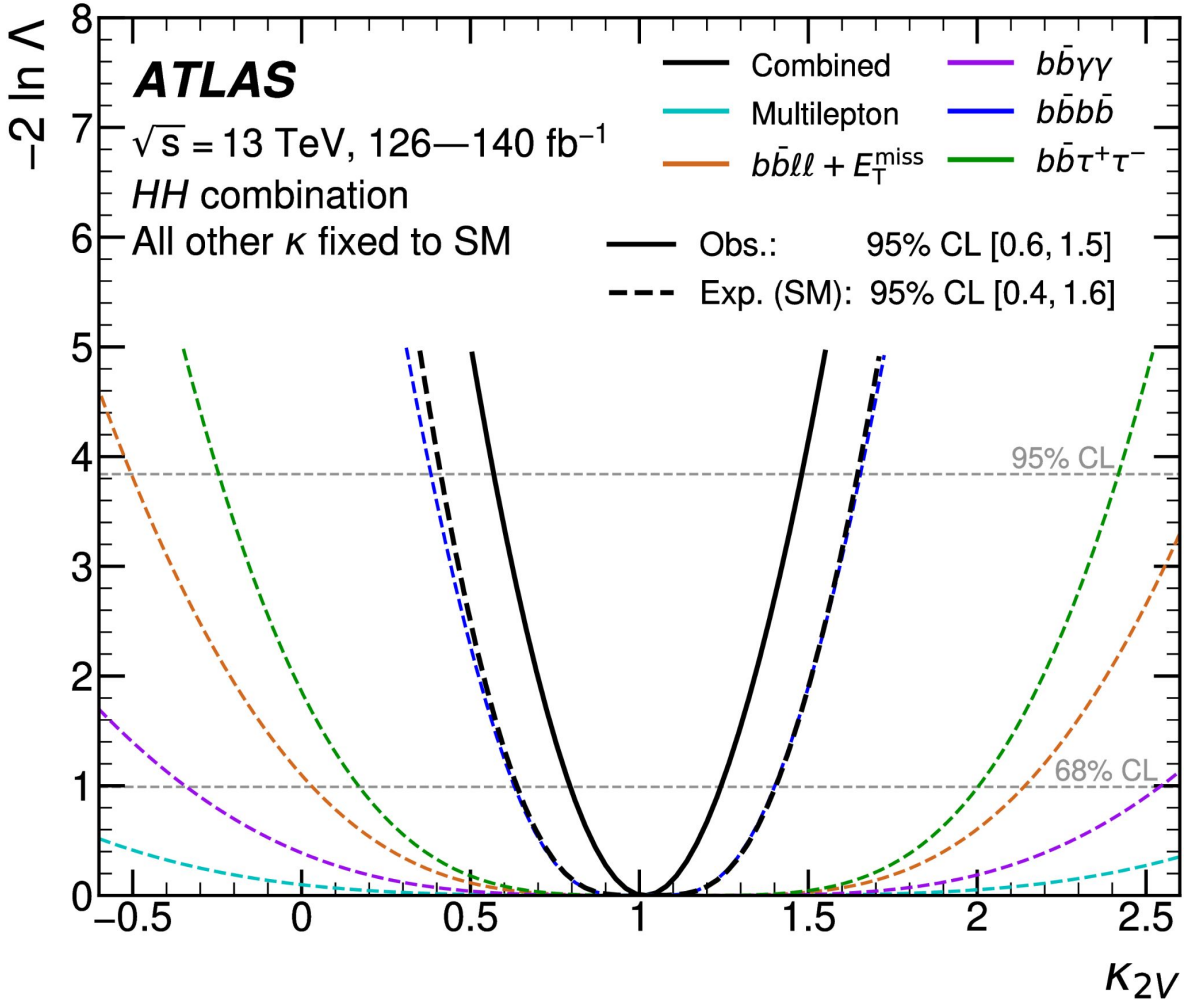
Metastable universe

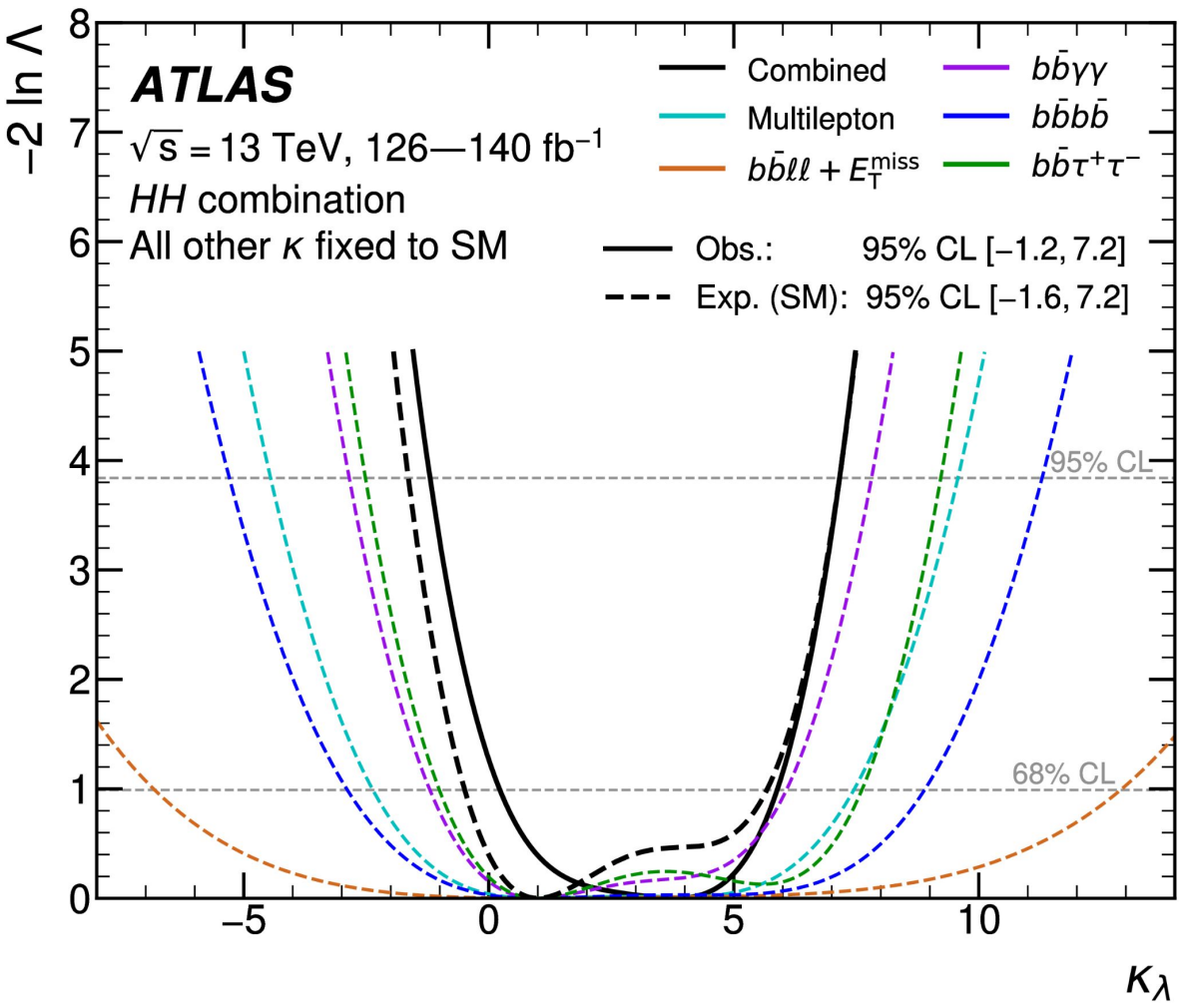
- Current minimum is a *false* vacuum.
- Lifetime is larger than the age of the universe, but eventually it will decay to the new minimum...

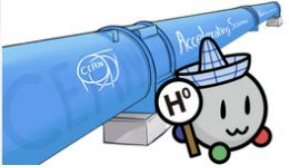




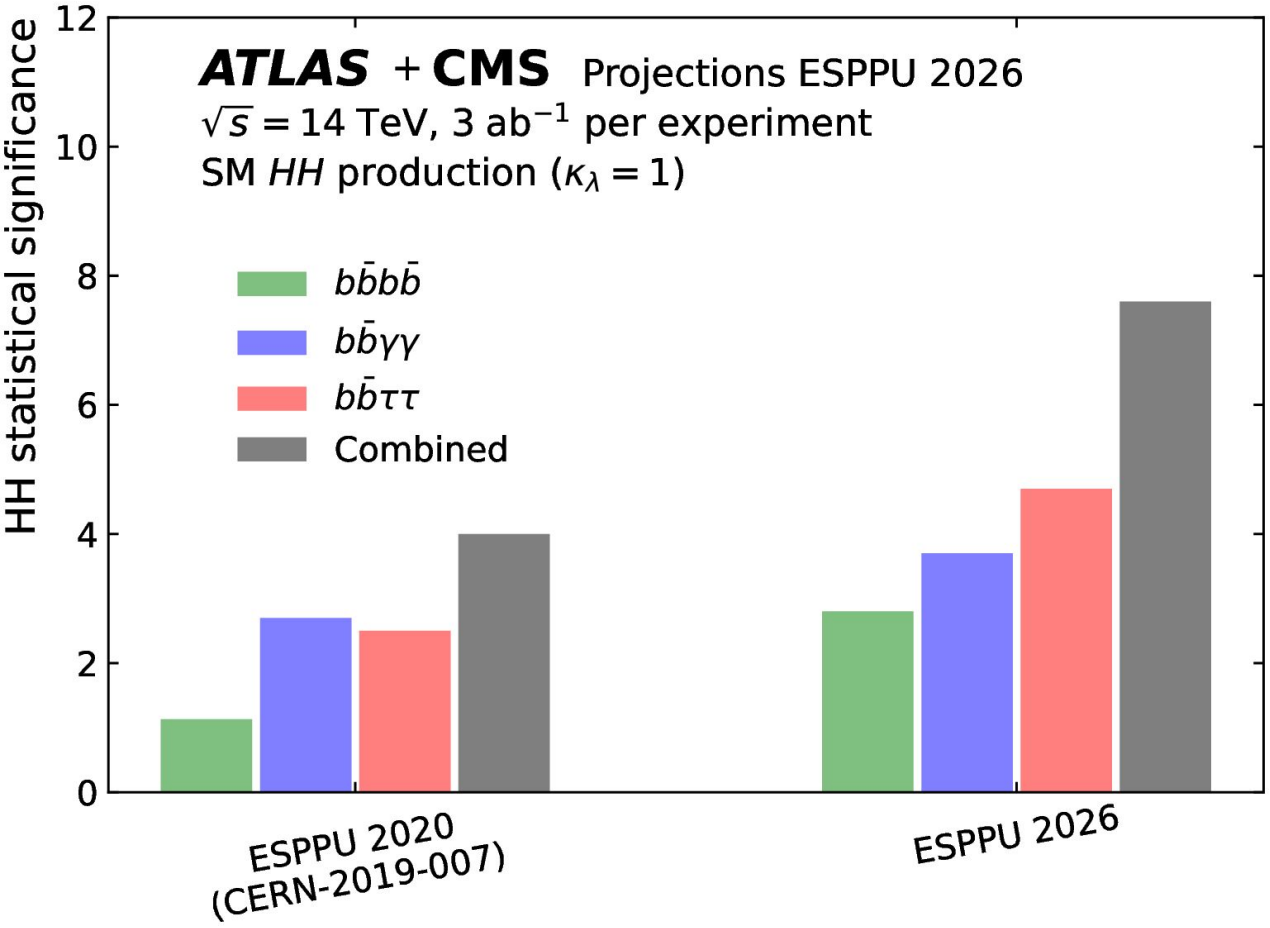
ATLAS and CMS HH combination







Di-Higgs ~~searches~~ measurements

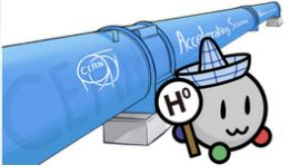


	3 ab^{-1} (*S2*)		3 ab^{-1} (*S3*)	
	ATLAS	CMS	ATLAS	CMS
HH statistical significance				
$b\bar{b}\tau^+\tau^-$	$3.5^\dagger$	2.4	**$3.8^\dagger$**	**2.7**
$b\bar{b}\gamma\gamma$	$2.4^\dagger$	$2.4^\dagger$	**$2.6^\dagger$**	**$2.6^\dagger$**
$b\bar{b}b\bar{b}$ resolved	1.0	$1.2^\dagger$	**1.0**	**$1.3^\dagger$**
$b\bar{b}b\bar{b}$ boosted	–	$2.2^\dagger$	–	**$2.2^\dagger$**
Multilepton	$1.0^\dagger$	–	**$1.0^\dagger$**	–
$b\bar{b}\ell^+\ell^-$	$0.5^\dagger$	–	**$0.5^\dagger$**	–
Combination	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	7.2		**7.6**	
κ_3 68% confidence interval				
ATLAS+CMS uncertainty	-27% / $+31\%$		**-26% / $+29\%$**	

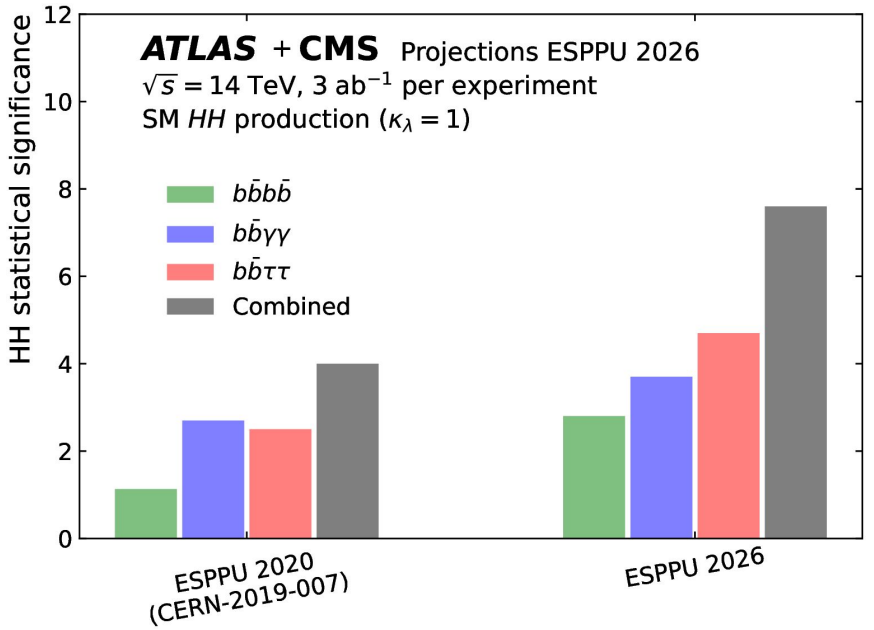
- A >5σ observation will be possible already with 2000 fb^{-1} combining both experiments in the baseline scenario (S2).
  - 3000 fb^{-1} may allow a single-experiment observation.
- Including 5% improvement in the b-tagging identification and tau-identification (S3) will increase the precision by 5%.

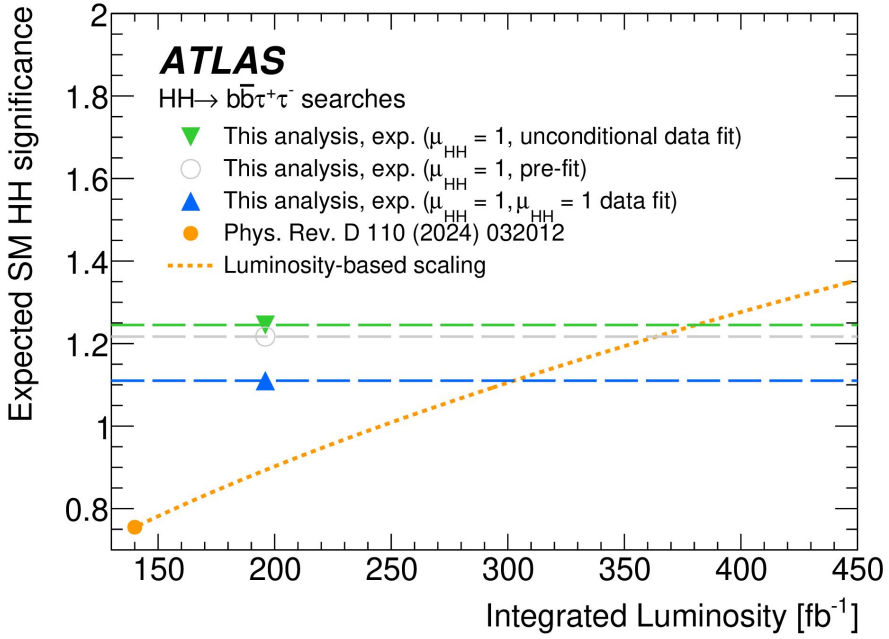
κ_λ is expected to be measured as $1.0^{+0.29}_{-0.26}$.

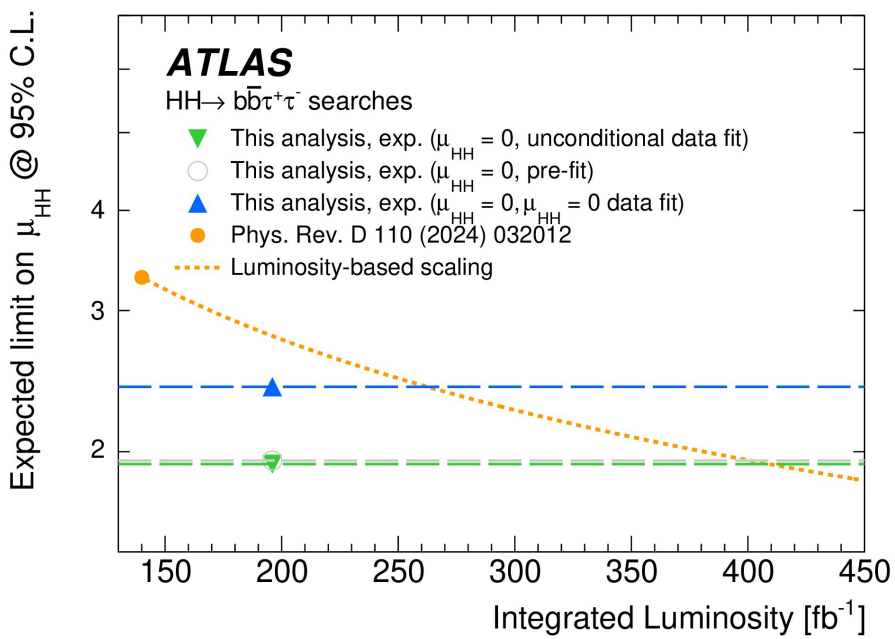
arelycg@cern.ch

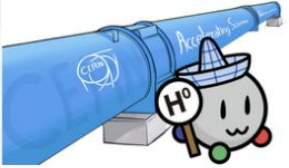


Di-Higgs ~~searches~~ measurements

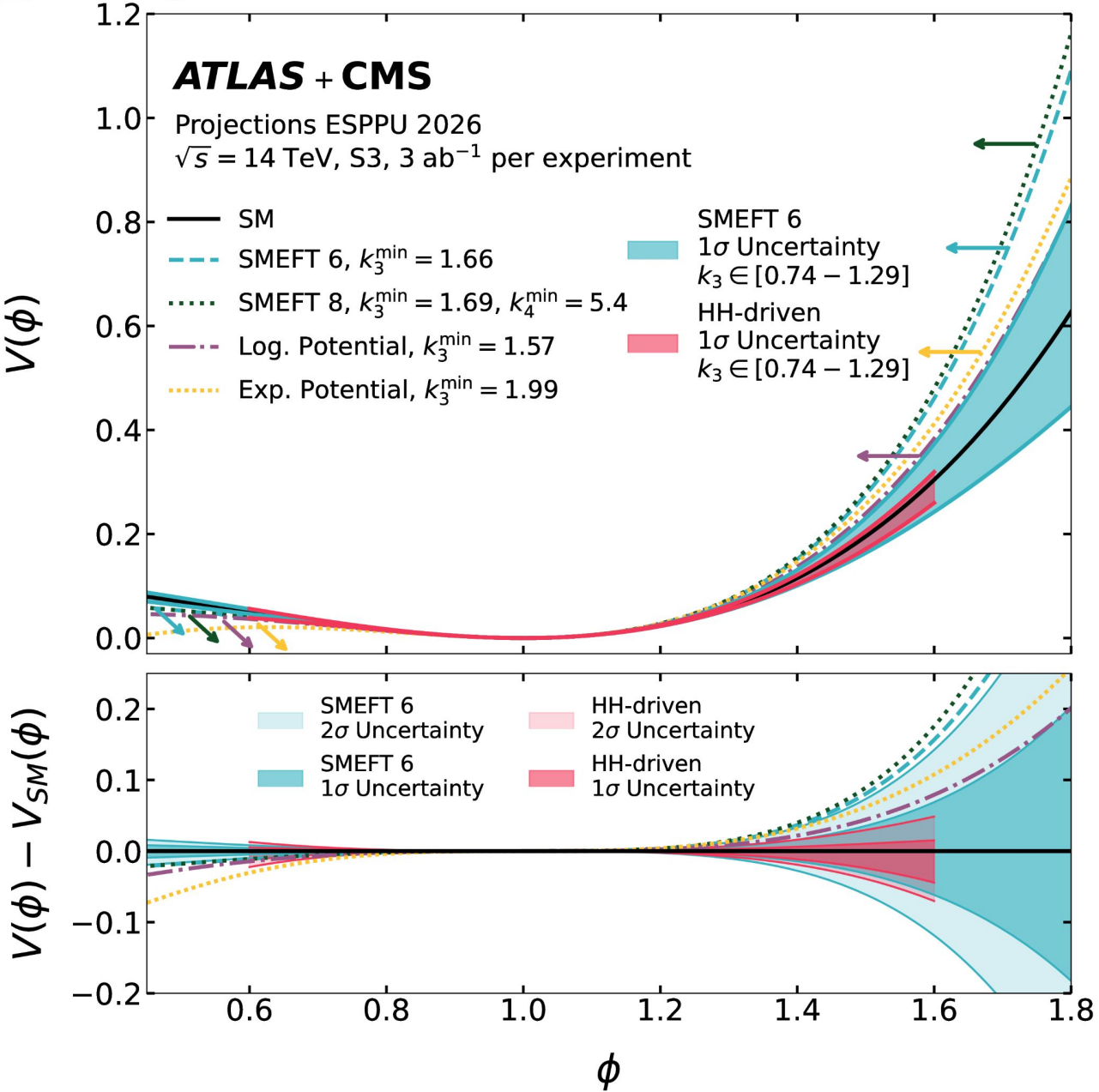








Di-Higgs ~~searches~~ measurements



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 defamation 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 $\kappa_\lambda > \kappa_{min}$.