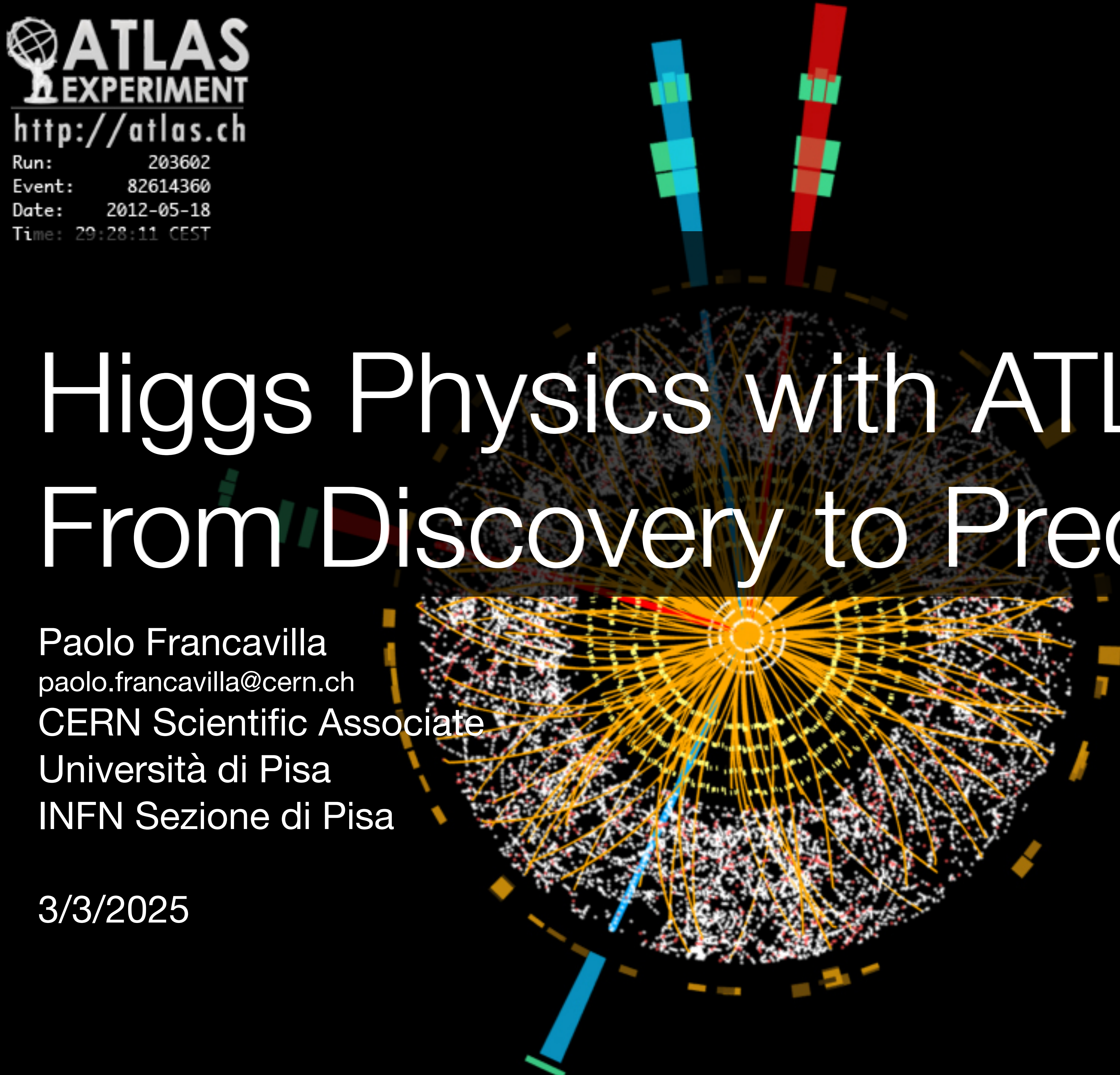

Higgs Physics with ATLAS: From Discovery to Precision

Paolo Francavilla
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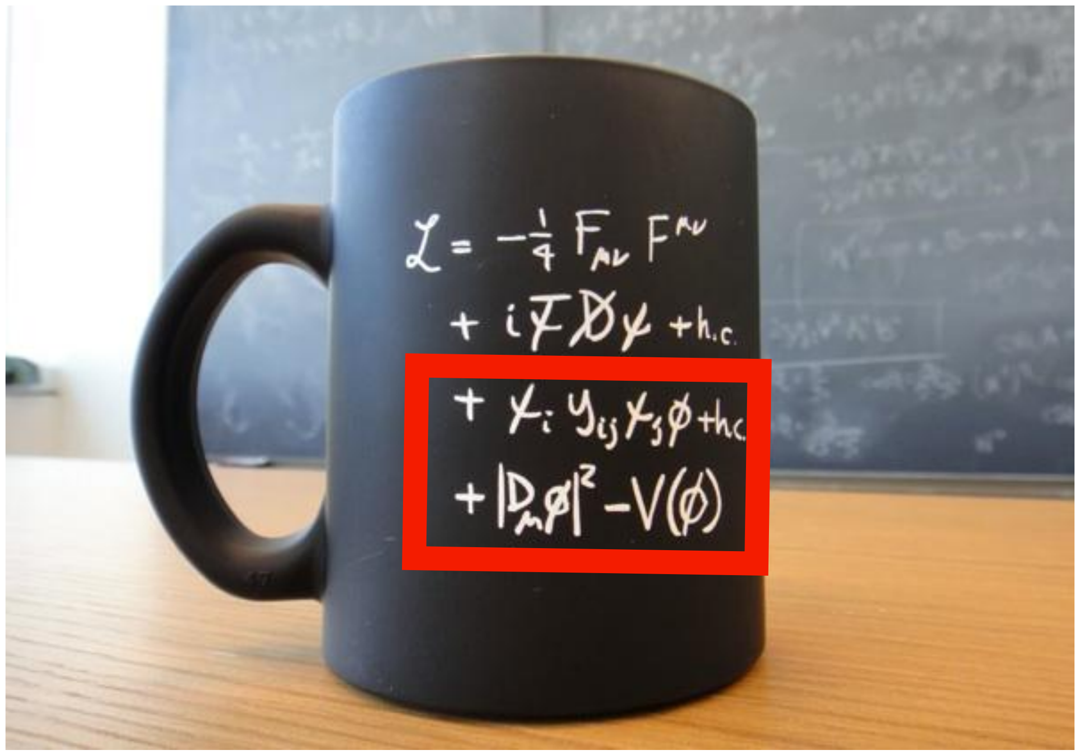
CERN Scientific Associate
Università di Pisa
INFN Sezione di Pisa

3/3/2025

The standard model and the Higgs field



There are parameters of the SM

g_1, g_2, g_3 3 gauge couplings

+QCD vacuum angle θ_{QCD}

θ_{ij}, δ_{CP} 3 CKM angles +1 phase

m_{q_i}, m_{l_j} 6 quark masses+3 charged leptons

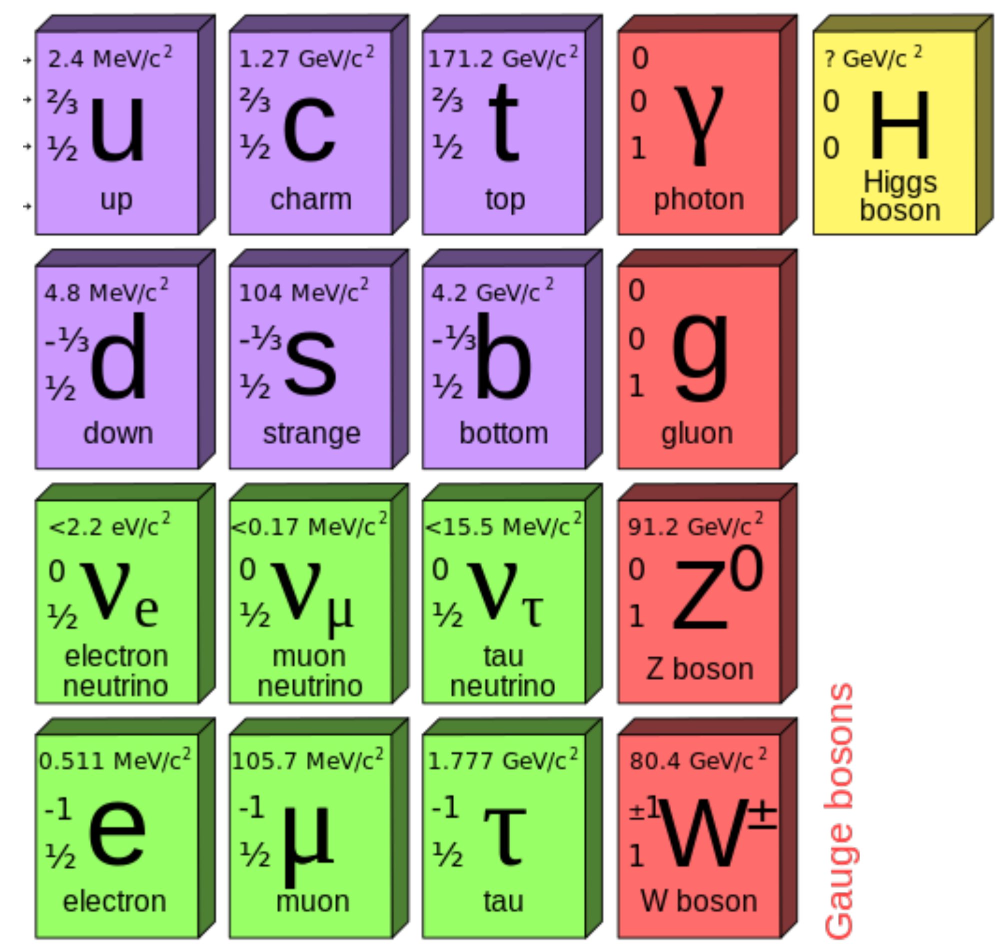
m_h, v Higgs mass and VEV

- In the Standard Model, the Higgs field plays a special role.

- In fact, its presence introduces most of the **free parameters** of the theory.

Higgs Boson production

- The perturbation of this new field manifest as a new particle: the Higgs boson.
- In the zoo of fundamental particles, the Higgs boson is one of the strangest:
    - The only scalar particle.
    - It couples with the massive fermions of the Standard Model without following any apparent symmetry rules.
    - …



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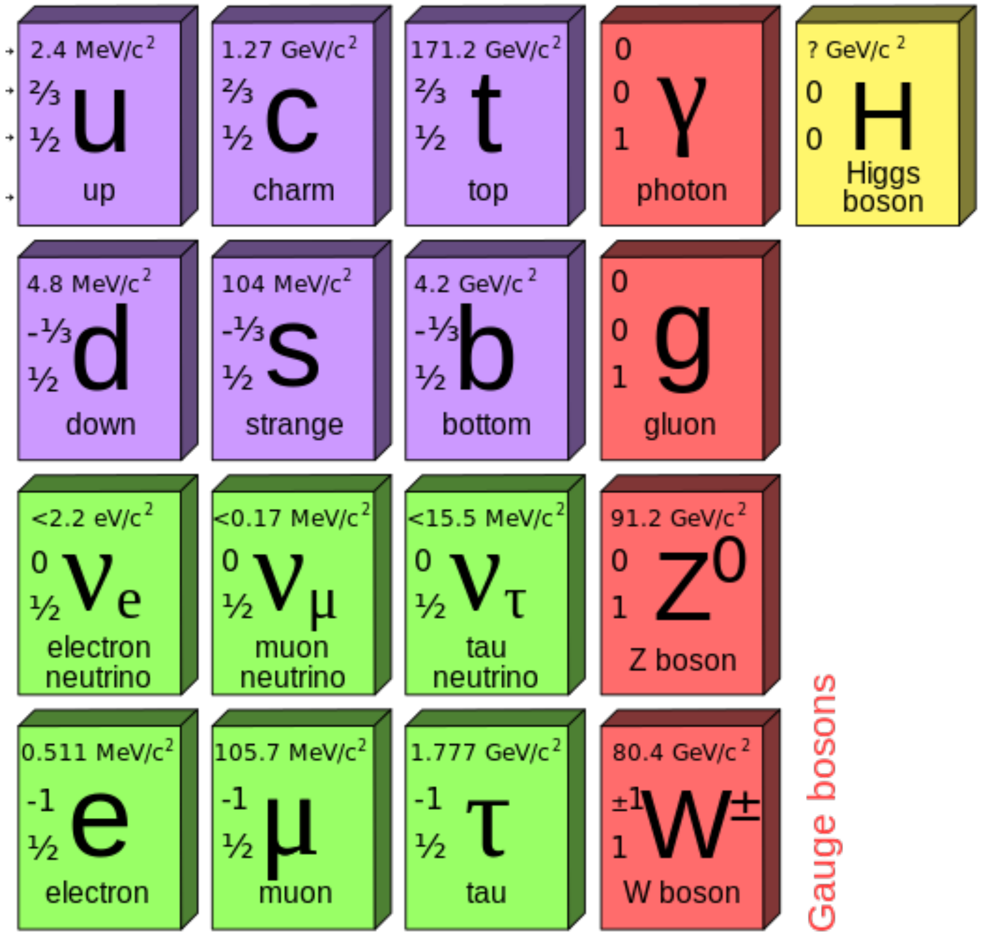
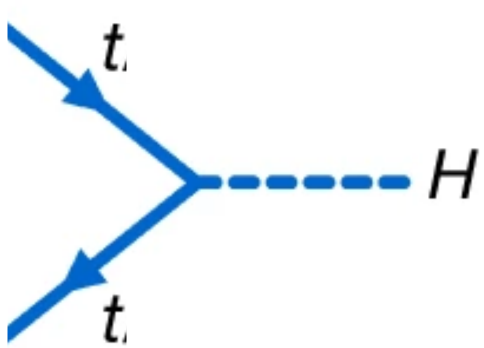
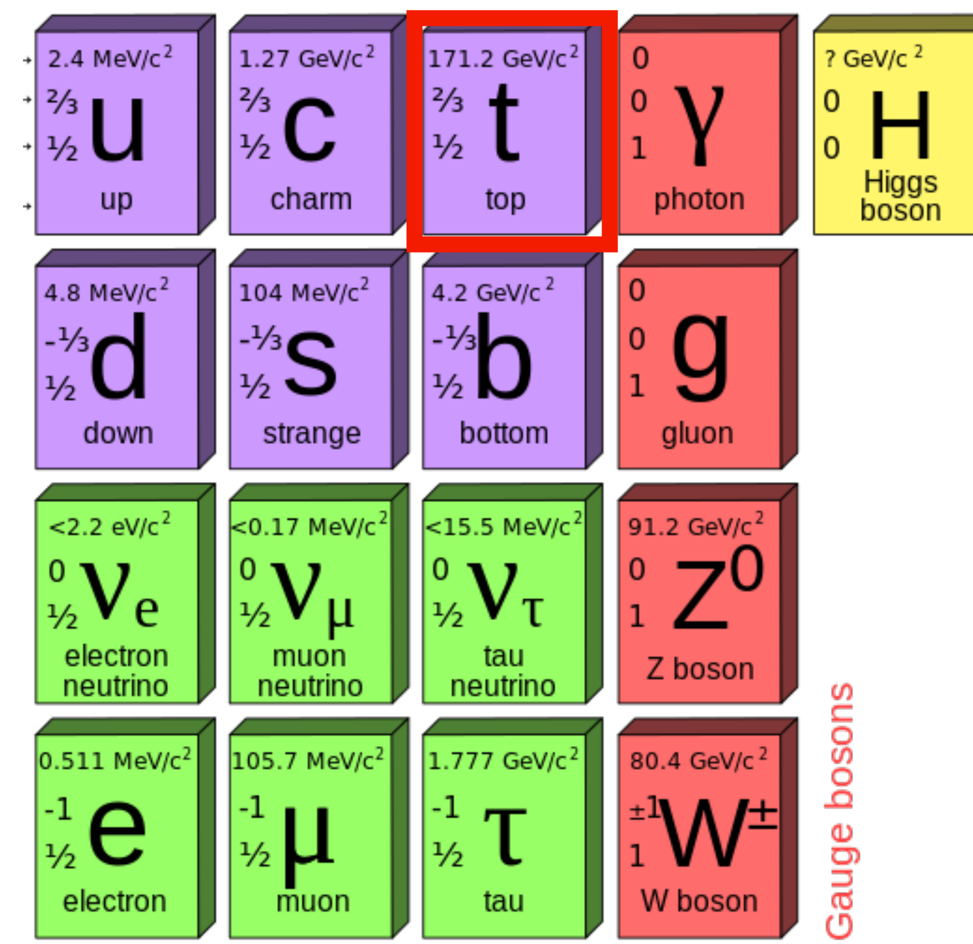
    - The only scalar particle.
    - It couples with the massive fermions of the Standard Model without following any apparent symmetry rules.
    - …
- **Measuring the characteristics of the Higgs boson with precision allows us to verify the consistency of the Standard Model description or highlight deviations that may indicate new physics.**



Higgs Boson production

- How can we “perturbate" the Higgs field to generate the Higgs boson?
- Idea: We could collide the most massive particles of the Standard Model.





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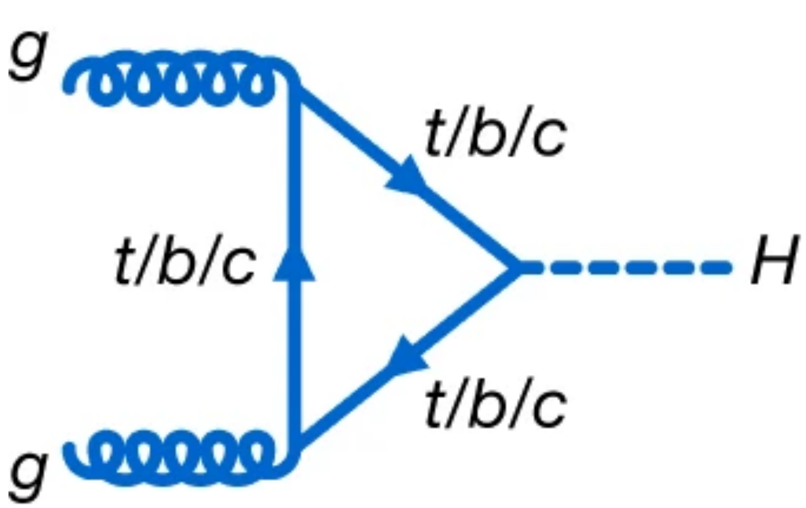
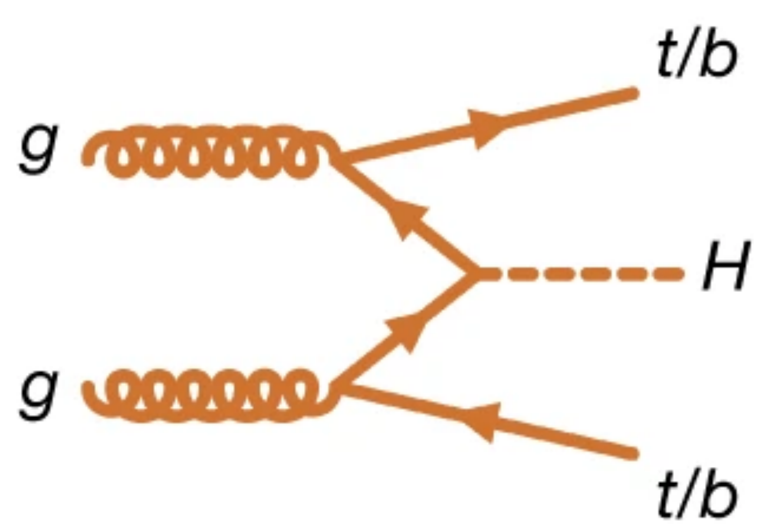
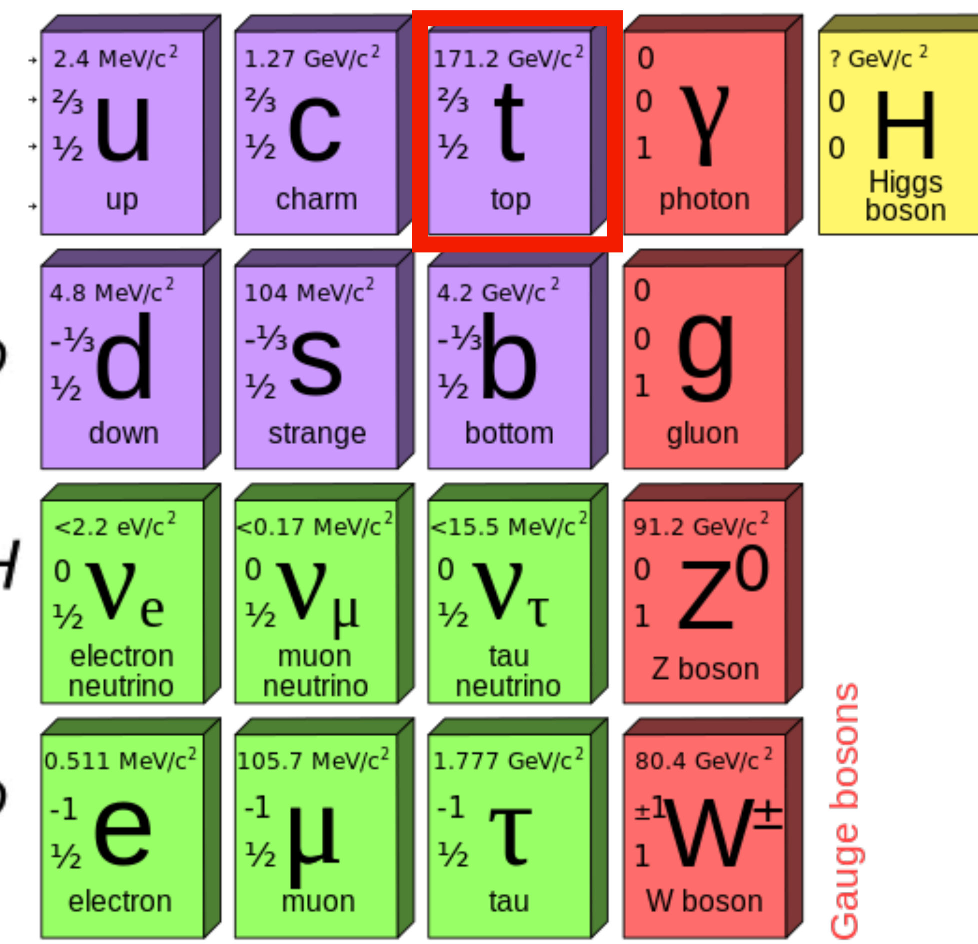


gluon-gluon fusion



ttH



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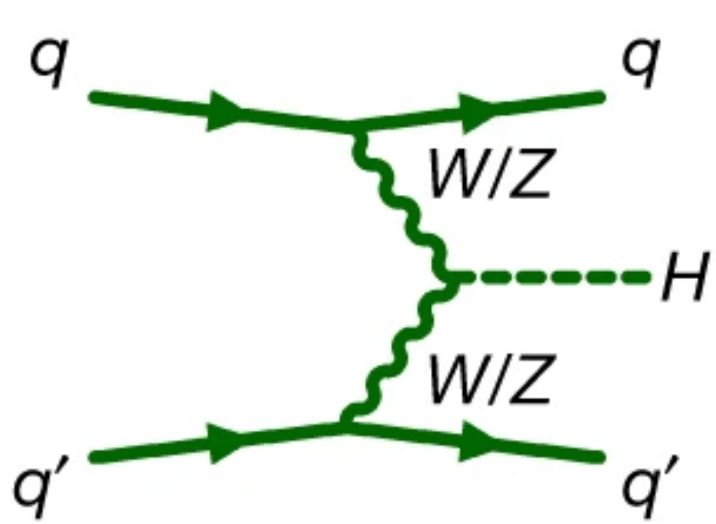
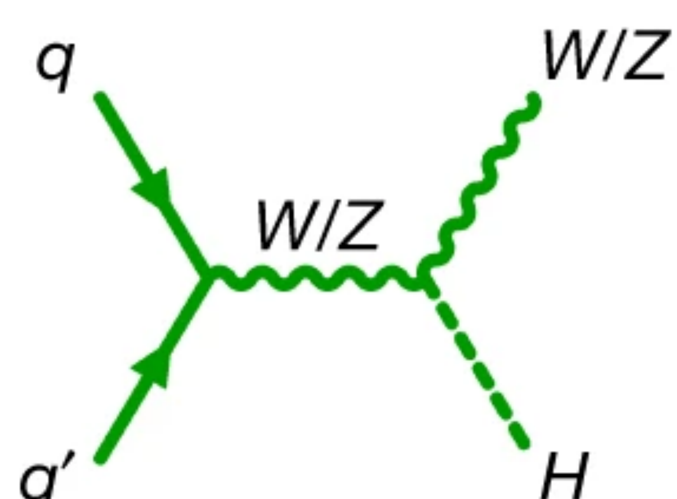
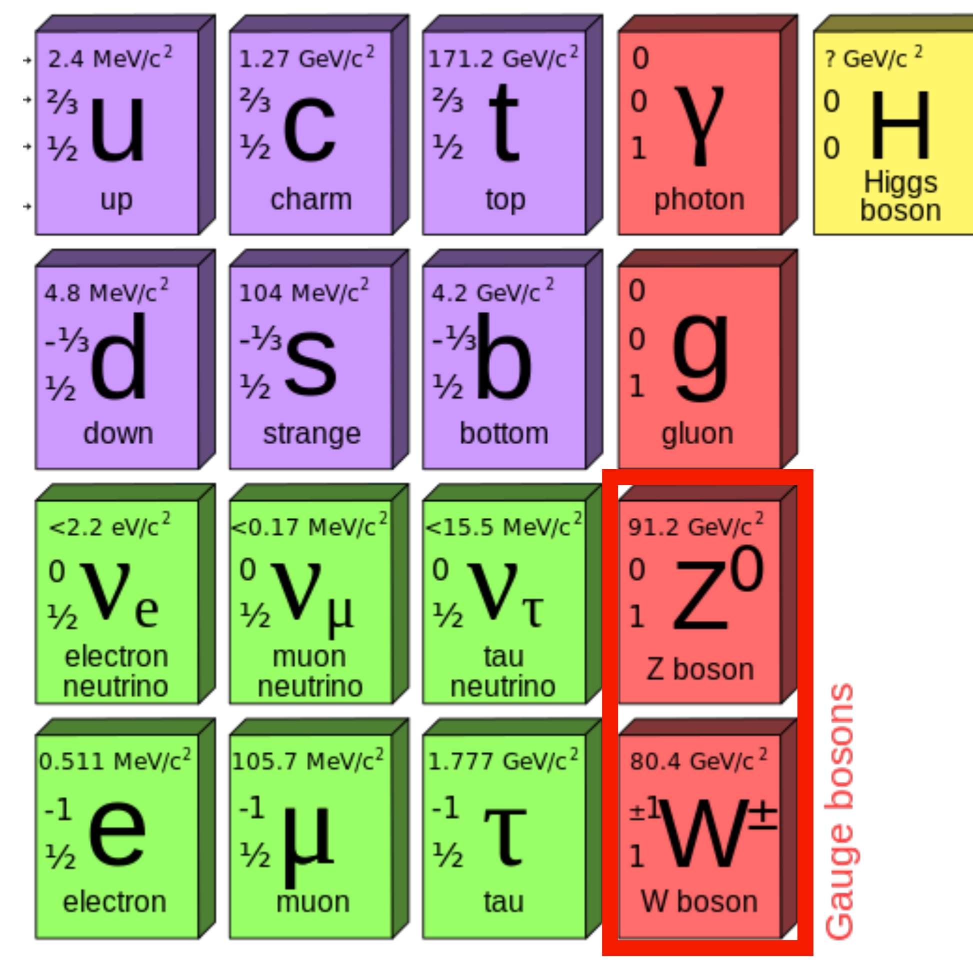


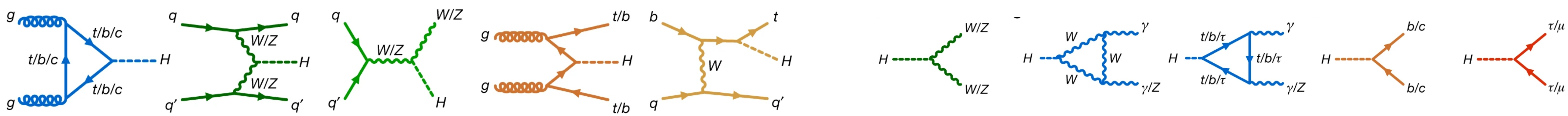
Vector boson fusion

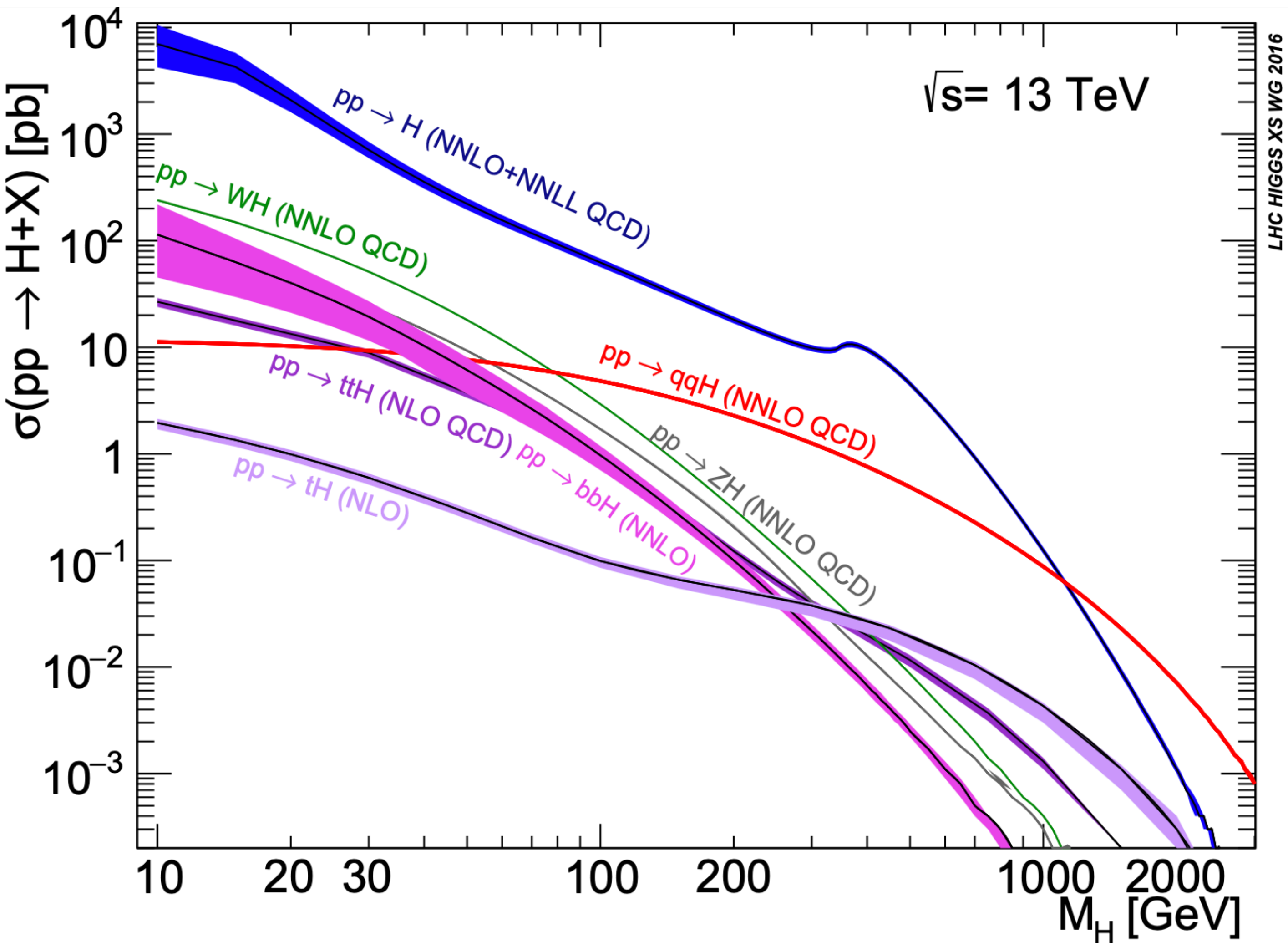


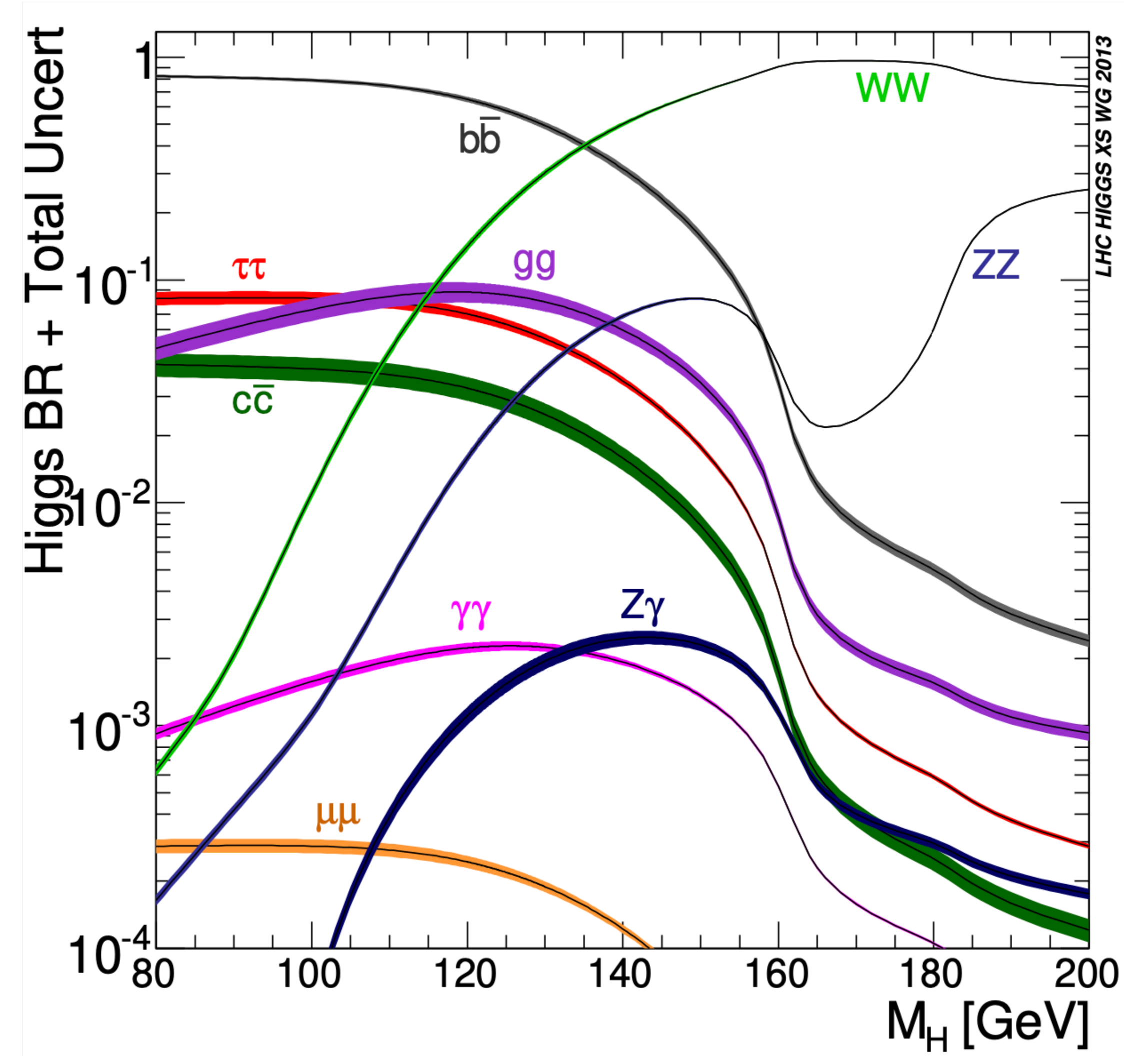
Higgs-strahlung



Higgs Boson production and decay modes

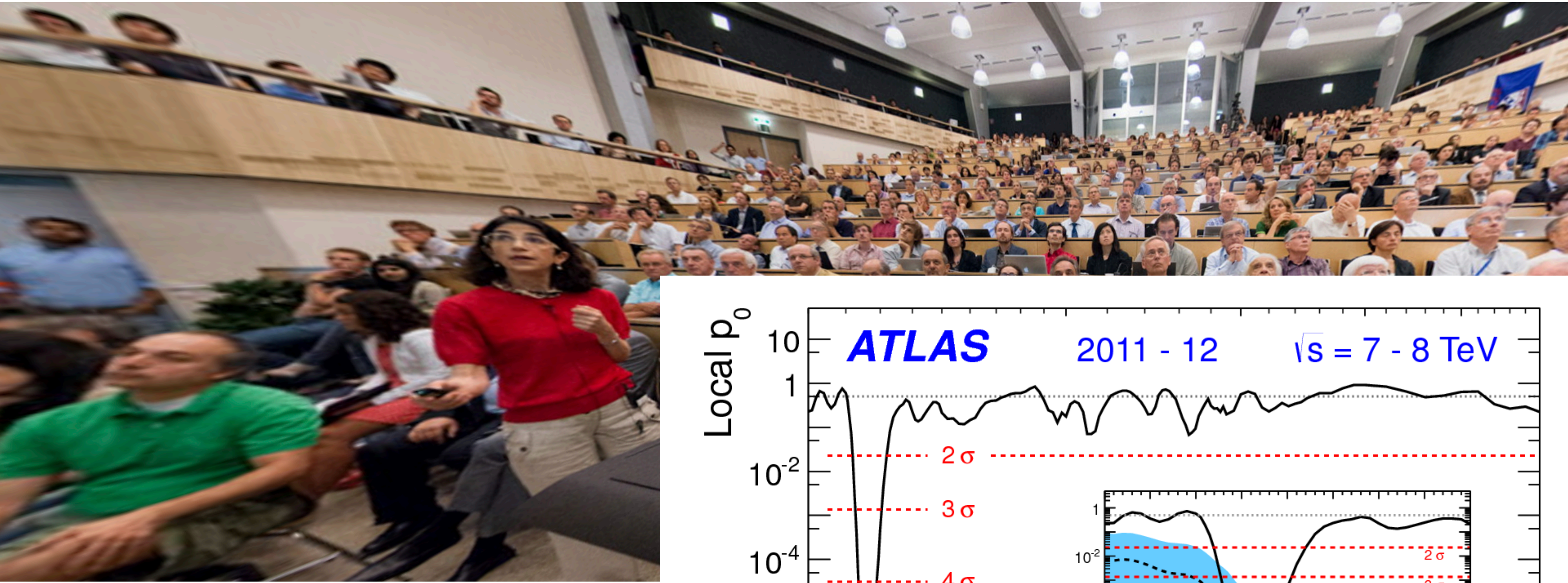


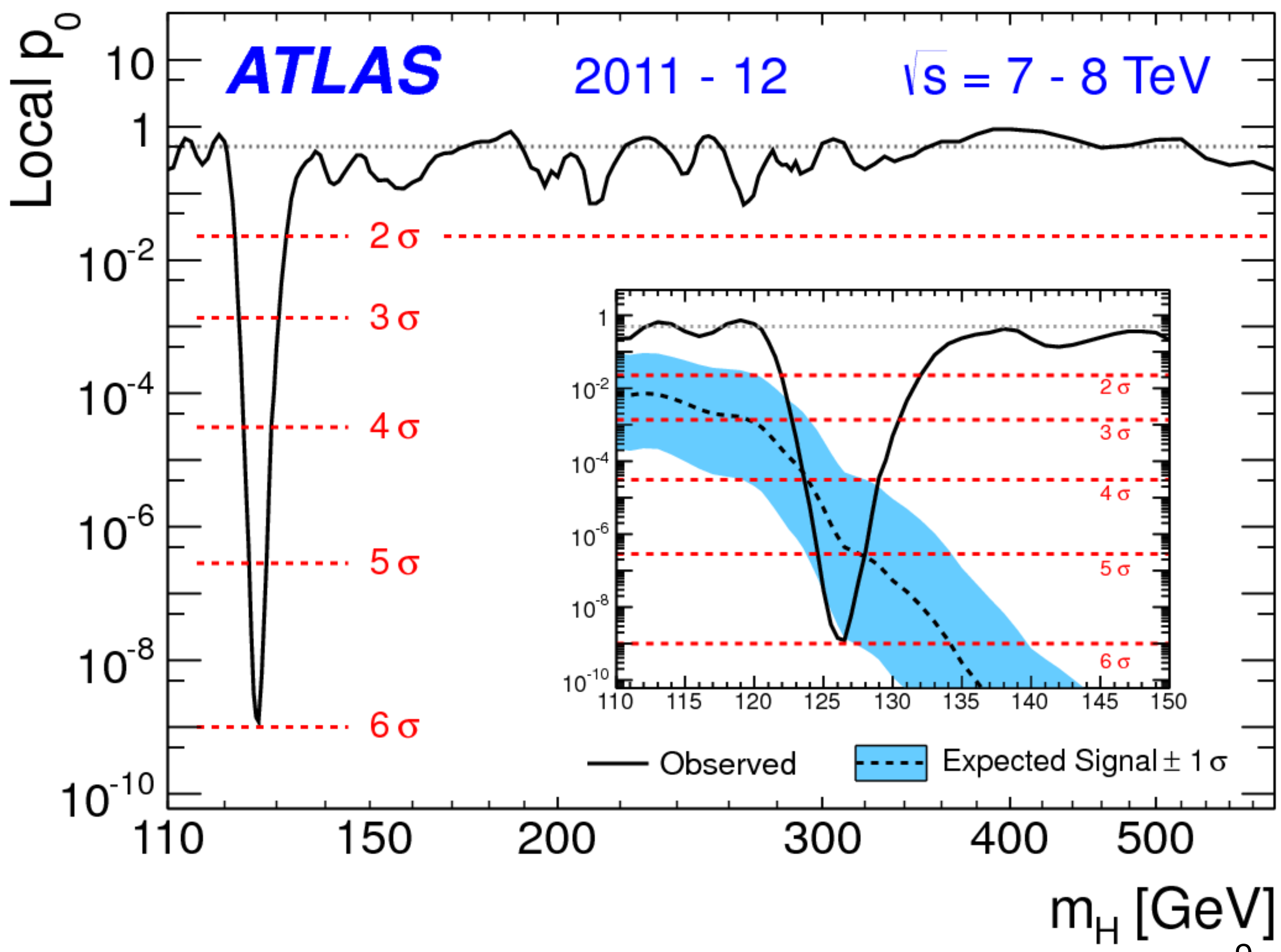




The theory is predictive if we know the mass of the Higgs boson.

2012: The discovery

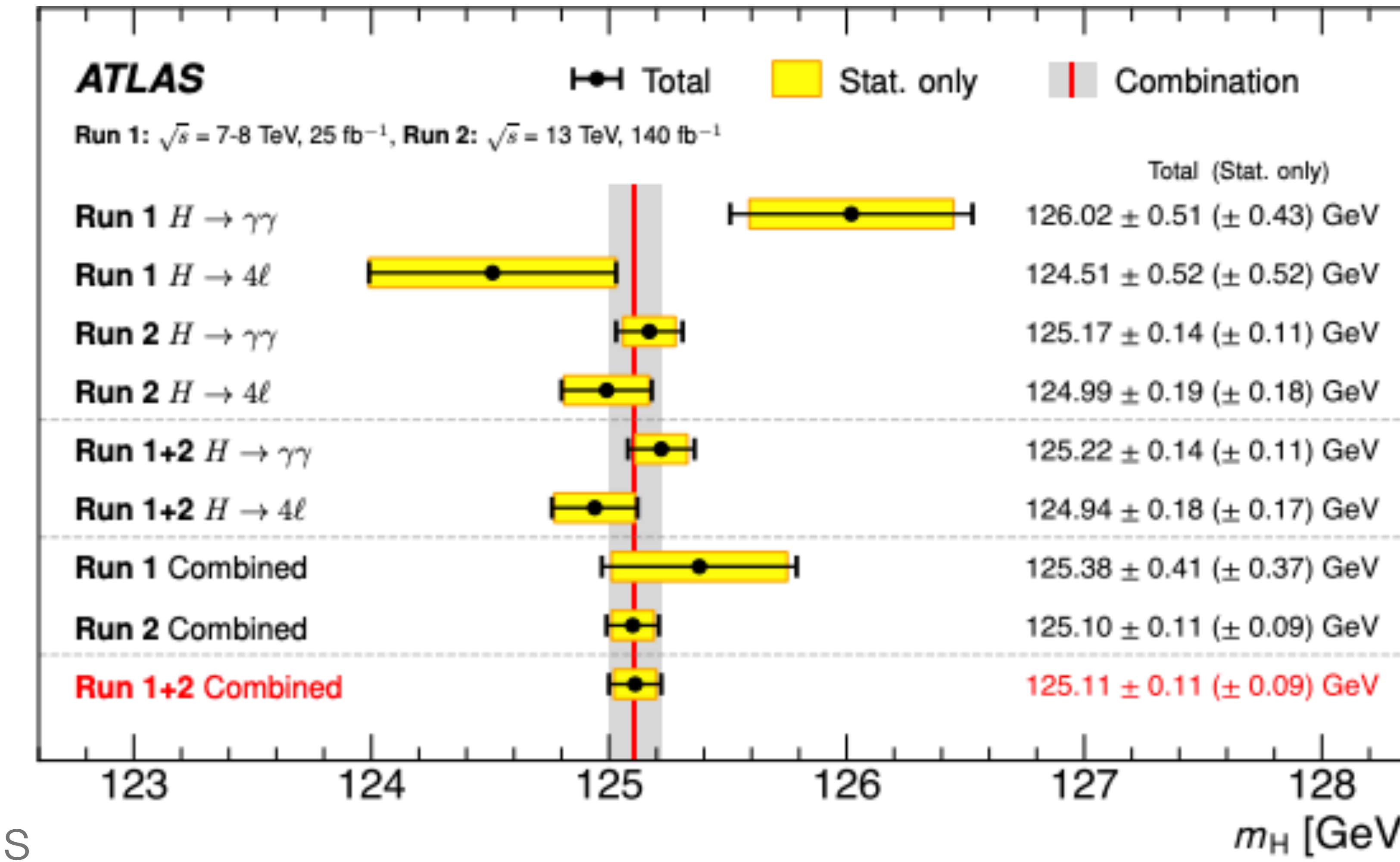




- First estimate of the mass ~126 GeV
- 2014: first "precise" measurement of the mass:
    - 125.36 ± 0.41 GeV
- (130 times the mass of the proton)

The Higgs boson mass

- m_H it is not predicted by the SM
- A central parameter for calculating the rest of the theoretical predictions for the Higgs boson in the Standard Model.



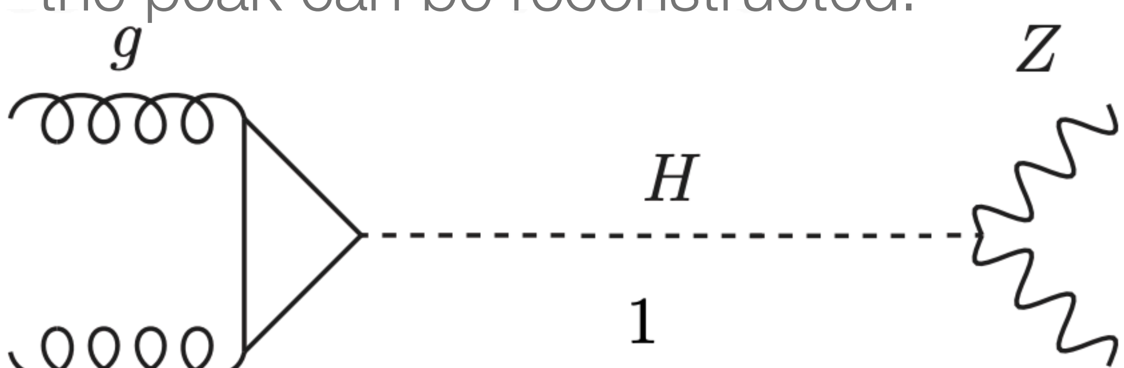
- The mass of the Higgs boson is measured with an accuracy of up to 0.1% using data from Run 2.

125.11±0.11 GeV (ATLAS).
125.08±0.12 GeV (CMS) (4l only)

Four times more precise than the first measurement in 2014, with an expected improvement due to a 2.5-fold increase in data.

The Higgs boson width

- The natural width Γ_H (4.1 MeV) of the Higgs boson is too small to be directly measured from a resonance where the peak can be reconstructed.

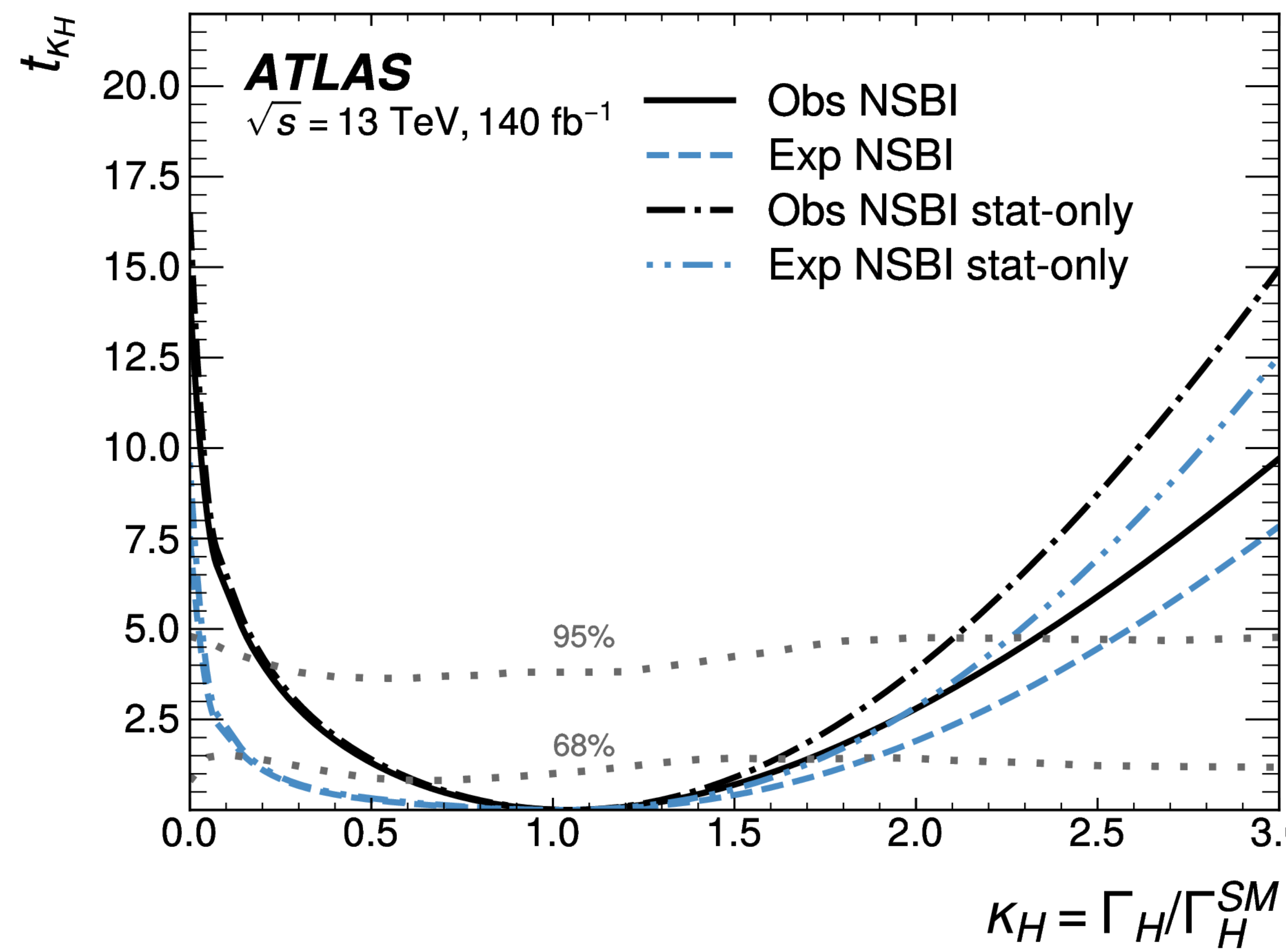


$$\frac{1}{(m^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}$$

- The ratio between the events reconstructed at $m \gg m_H$ and $m \sim m_H$ provides access to the width Γ_H

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

(τ: 1.6 x 10-$^{-22}$ s)



ATLAS

$4.3^{+2.7}_{-1.9}$ MeV.

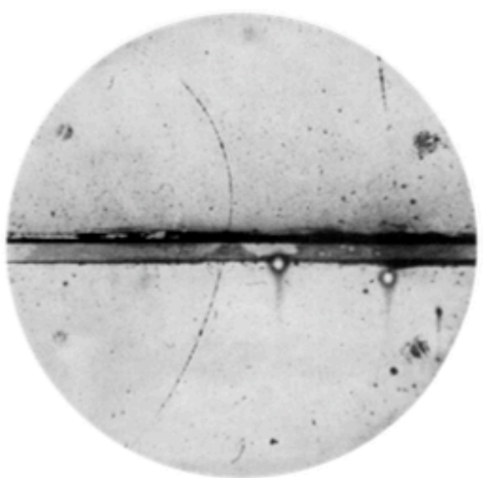
CMS

$3.2^{+2.4}_{-1.7}$ MeV

Evolution of analysis techniques

From A. Ghosh's slides

Positron discovery (1930s)



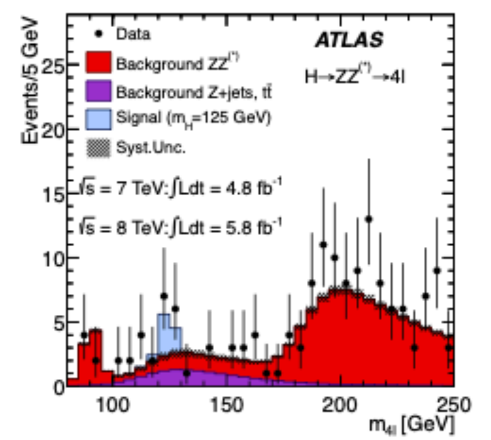
Single event

Top quark discovery (1990s)

Channel:	SVX
observed	27 tags
expected background	6.7 ± 2.1
background probability	2×10^{-5}

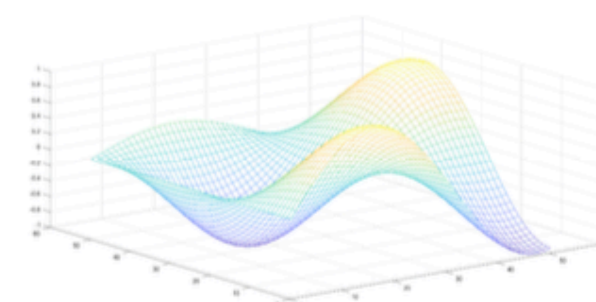
Multiple events:
Cut-and-count

Higgs boson discovery (2010s)



Shape information:
Histogram

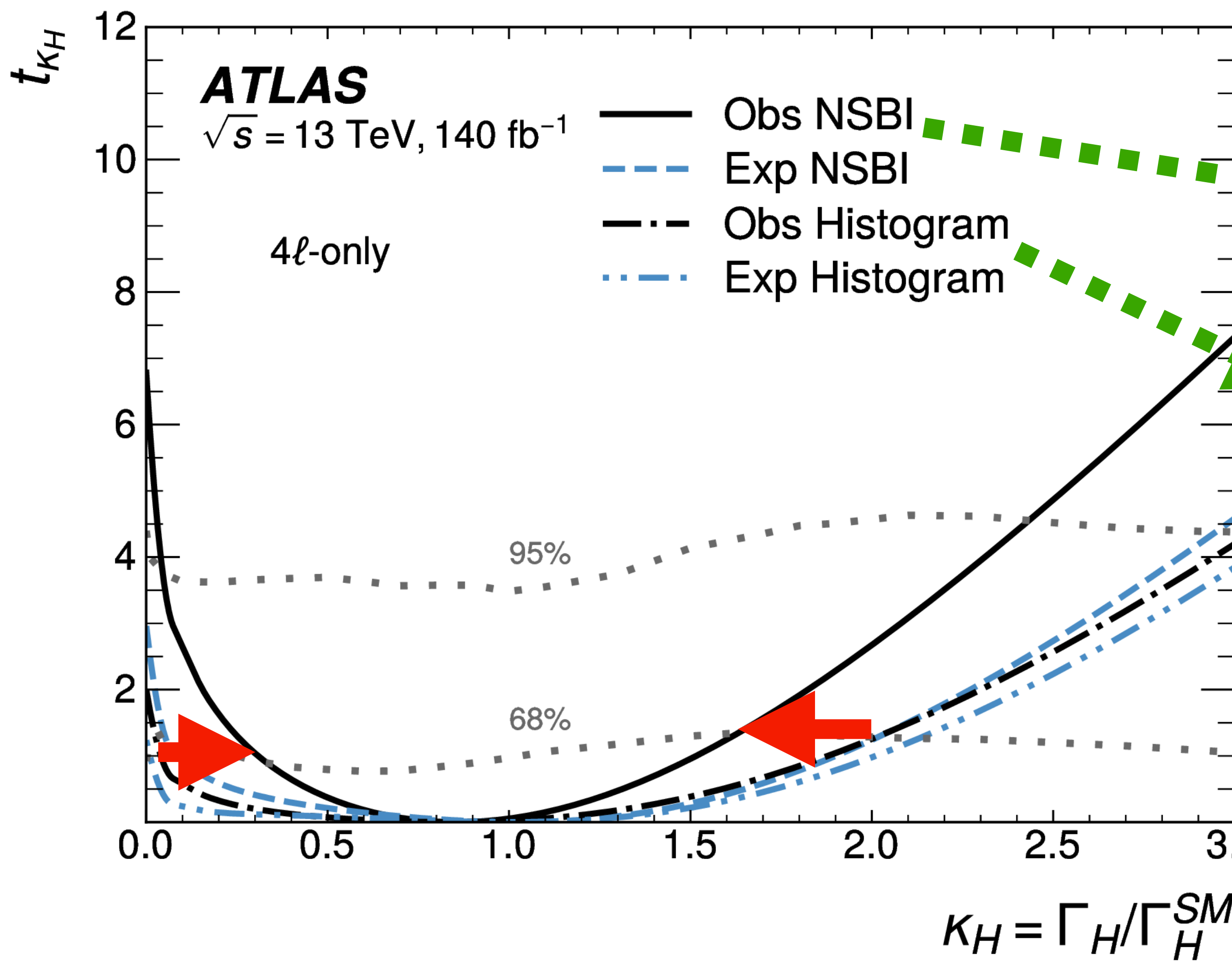
Future discovery (2020s ?)



High-dim shape information,
continuous (i.e. unbinned):
Neural inference

HIGP-2024-14/

Evolution of analysis techniques



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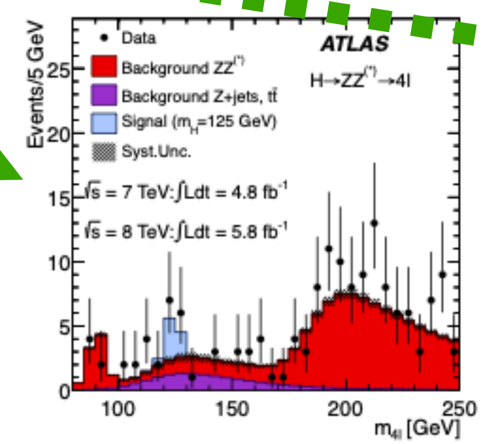
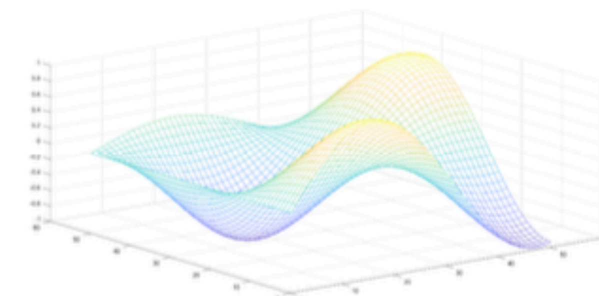


Shape information: Histogram

Future discovery (2020s ?)

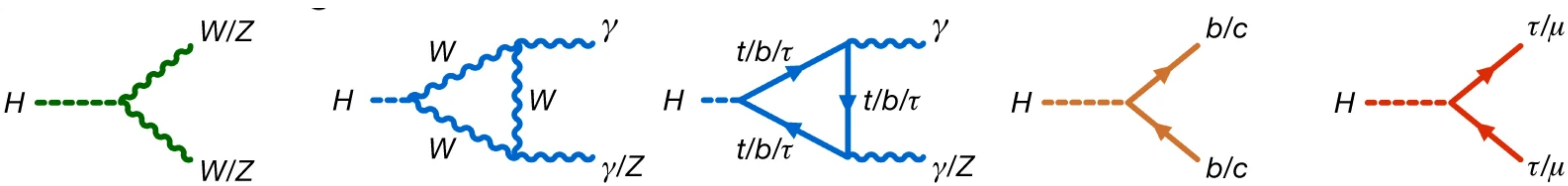


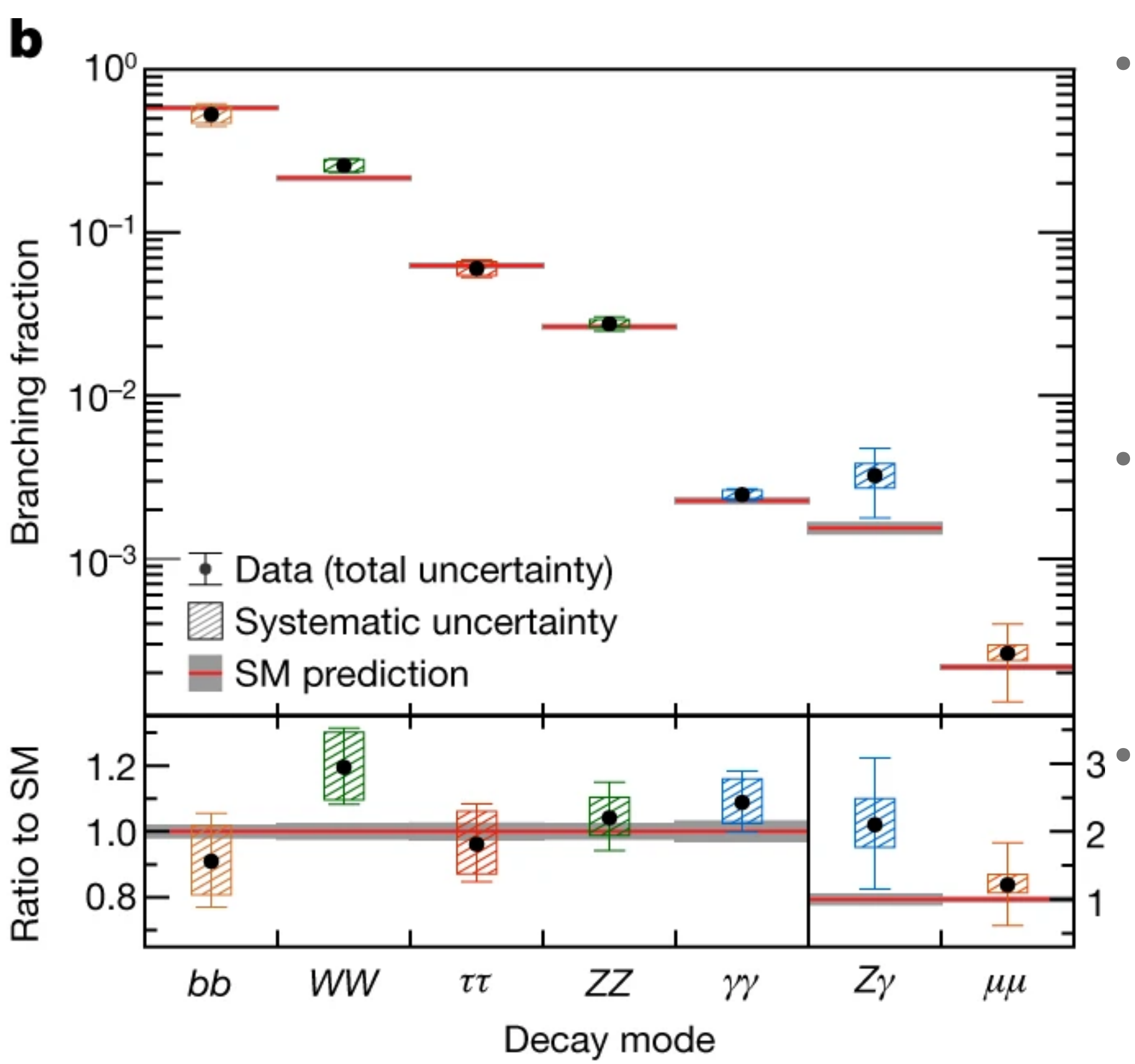
High-dim shape information, continuous (i.e. unbinned): Neural inference

- Significant reduction on the precision of the measurement

Nature 607, 52 (2022)

How does the Higgs boson decay?





- Precision in decays to vector bosons and b-quarks and τ-hadrons: ~10%
- Uncertainty in rare decays still significant
- => The data we will collect in the coming years will be interesting.

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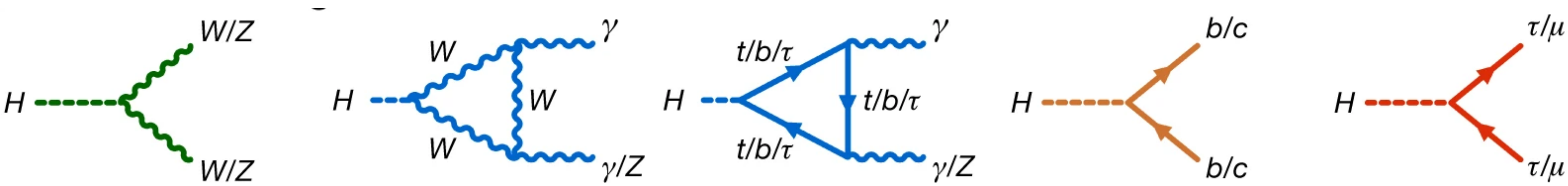

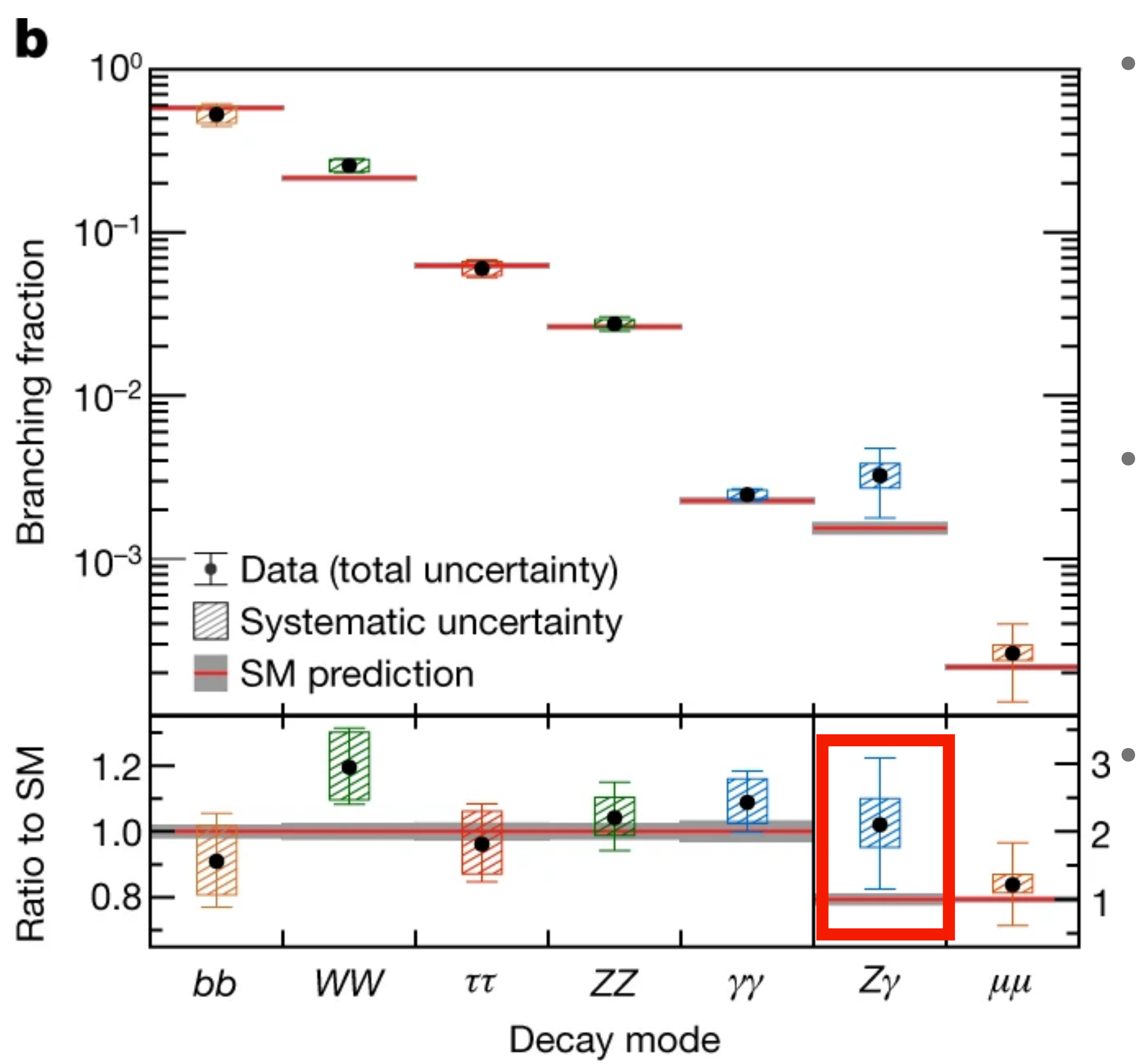

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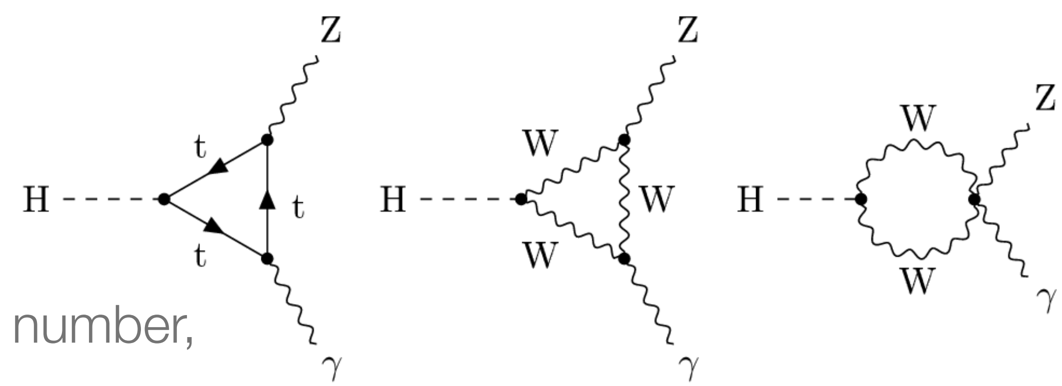
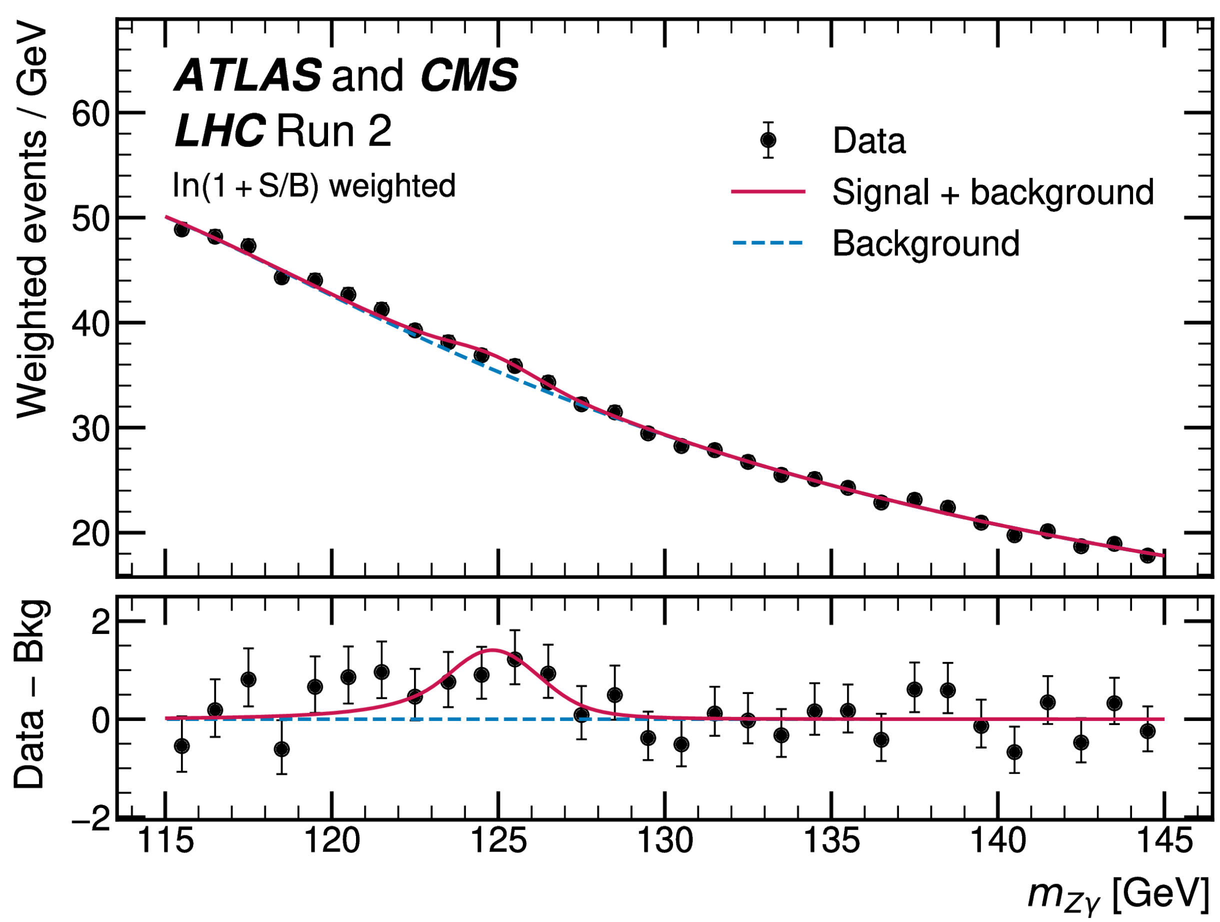
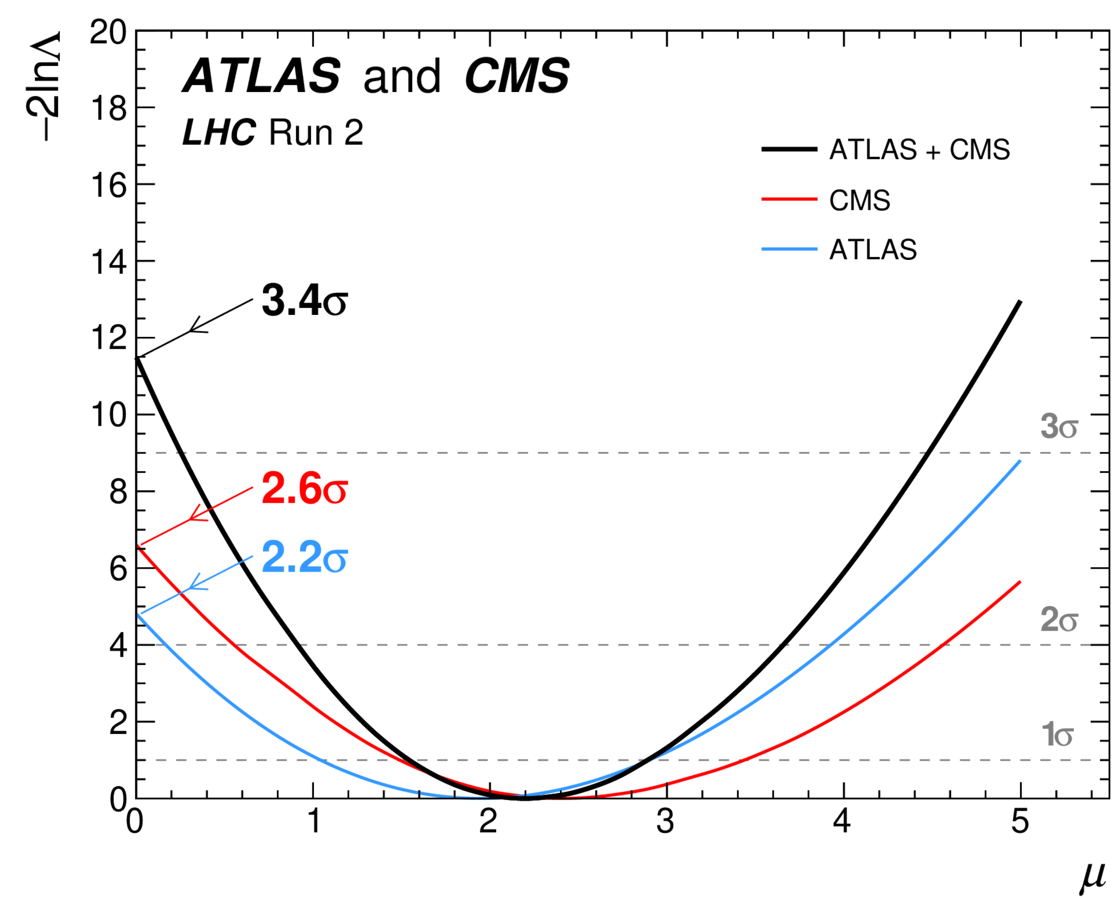
Phys. Rev. Lett. 132 (2024) 021803

First Run2 Combinations ATLAS & CMS (2015-2018 data) H→Zγ

- An elusive decay that we have been trying to measure for about 10 years.
- Sensitive to new physics.
- First evidence by combining the results from ATLAS and CMS.
- The number of measured events is 2.2 ± 0.7 times the expected number, still compatible with the Standard Model.

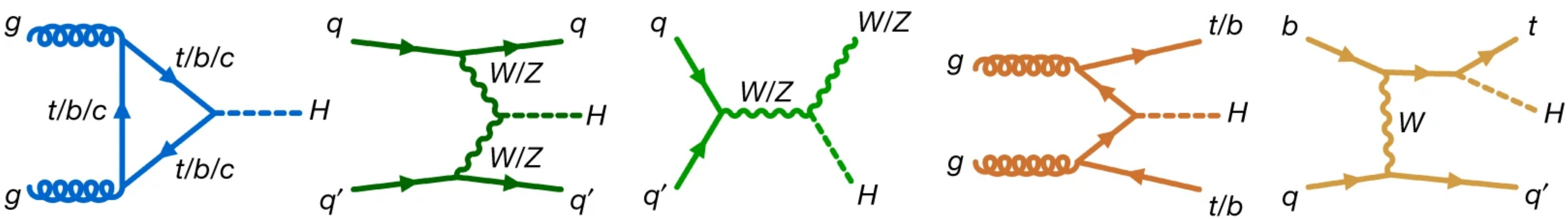


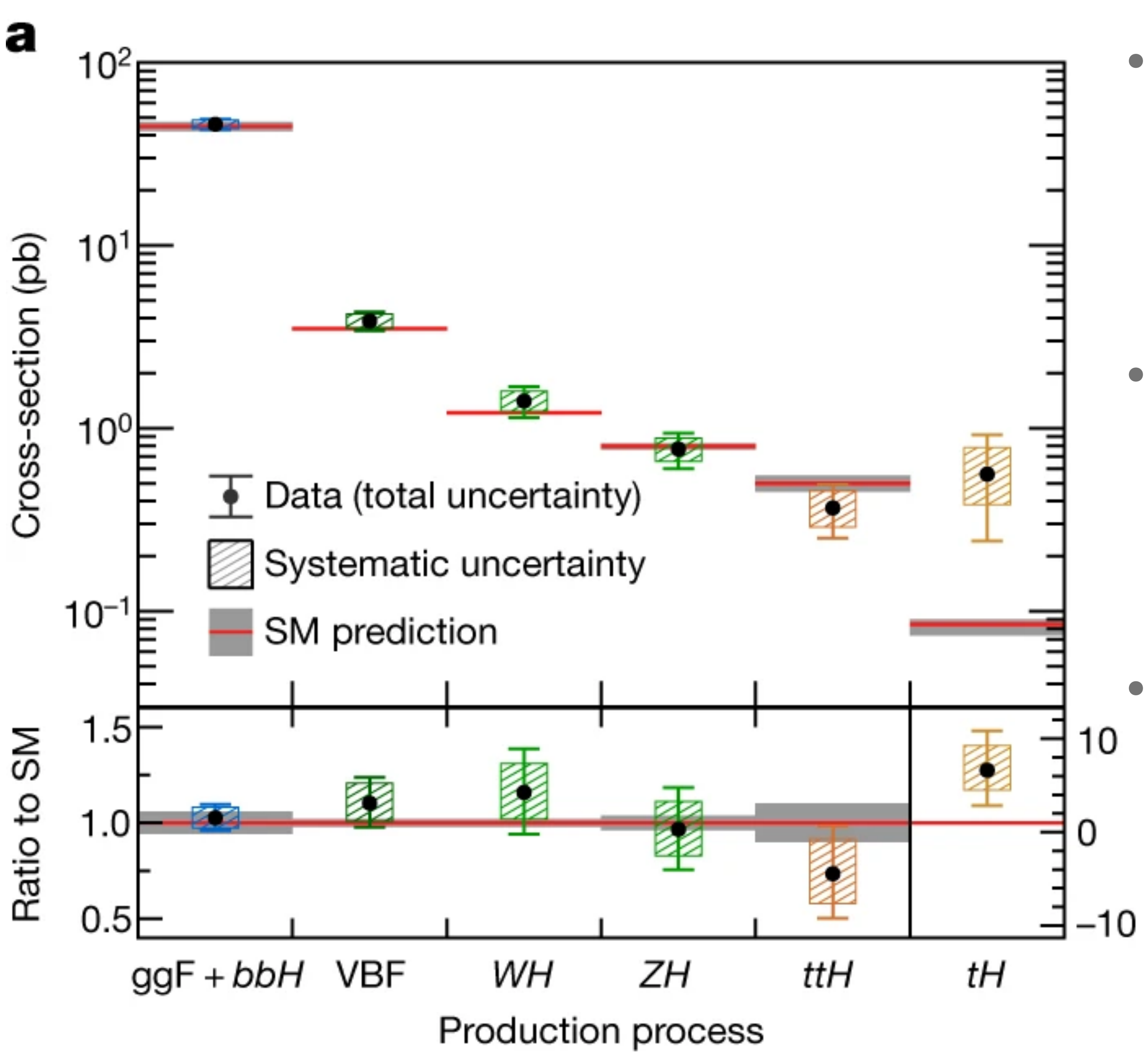




Nature 607, 52 (2022)

Measuring the Higgs boson production

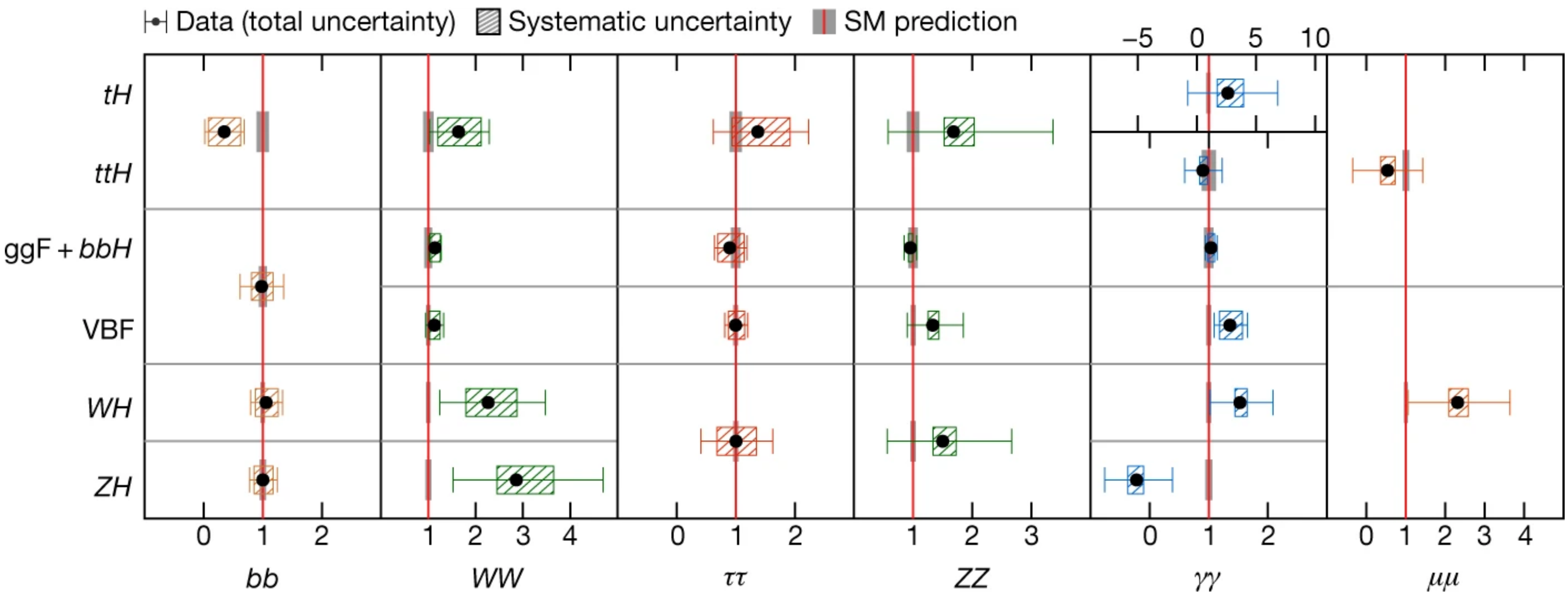




- Gluon-gluon fusion: Precision better than 10%!
- Precision of 10-20% for other production modes.
- Measurement of σ_{tH} ➔ Rare production modes are starting to be tested.

Nature 607, 52 (2022)

How many ways are there to measure the Higgs boson?



- ... and the following already published (or submitted to a journal) analyses are not yet included in the plot:
  - H→Zγ
  - pp→WH/ZH with H→ττ
  - pp→WH/ZH with H→bb and W/Z→qq
  - Vector boson fusion WH with H→bb
  - …

Nature 607, 52 (2022)

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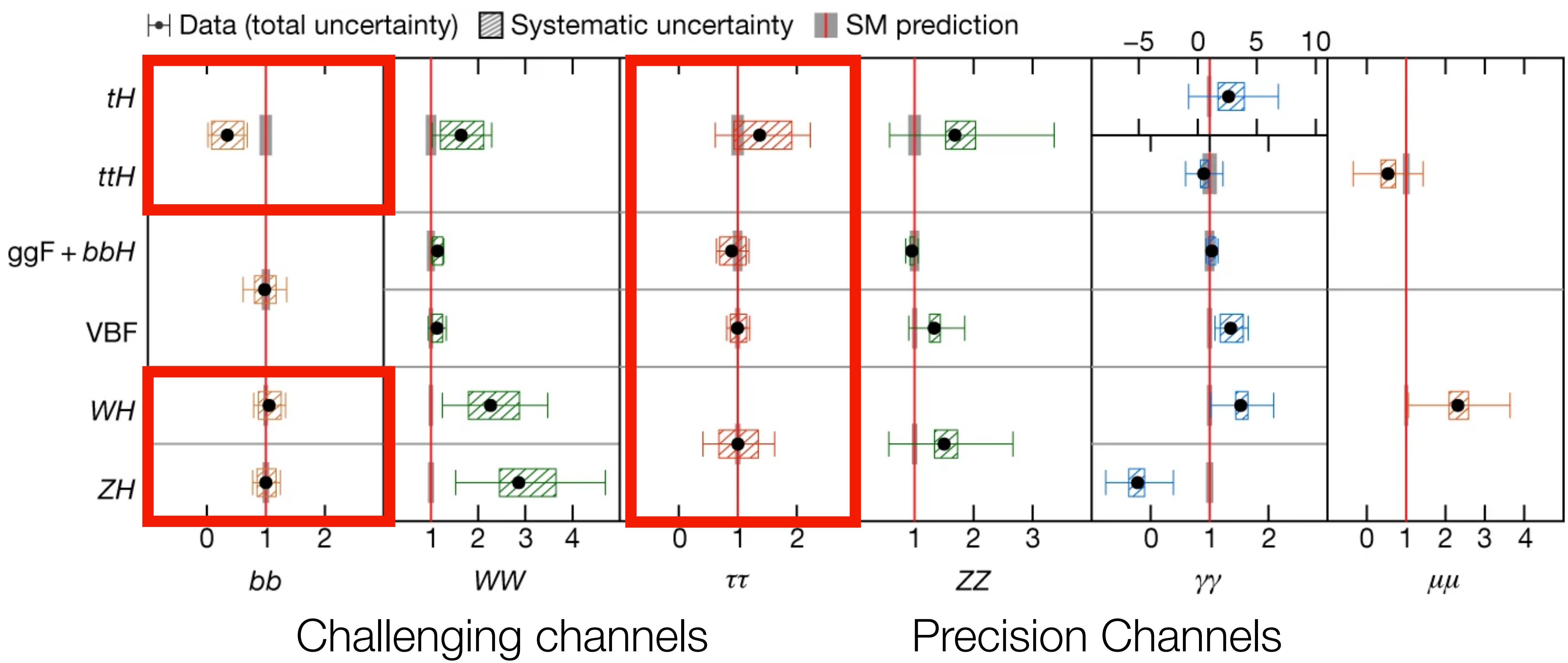

- Hot off the press:
  - **Updated channels in 2024**
  - **other to come (in the next months)**

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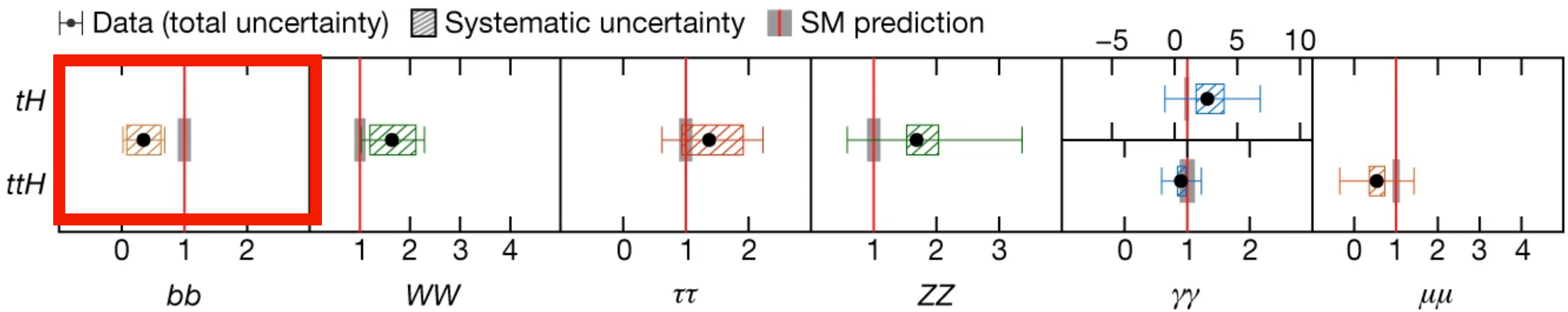

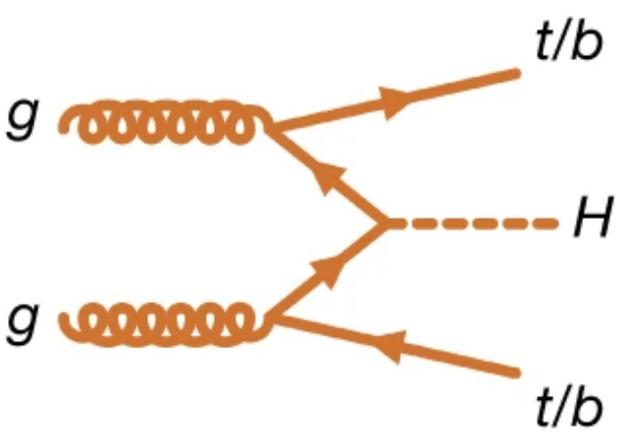

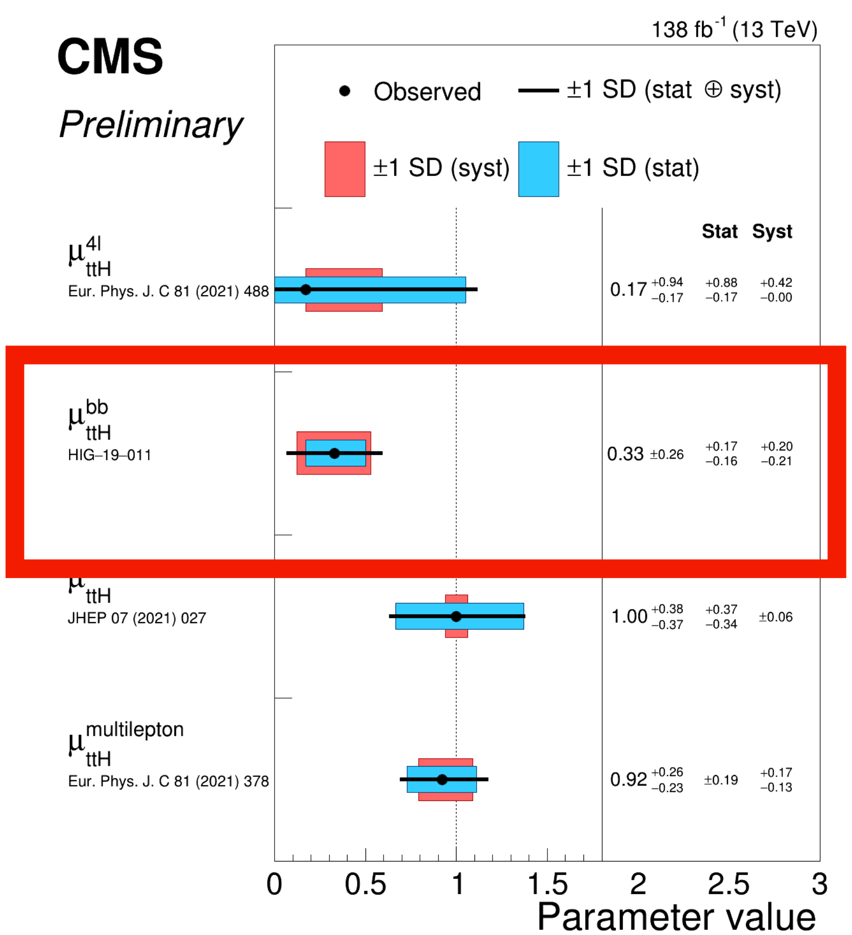

Higgs PAG Summary Plots

ttH ⇒ tree-level Higgs-top coupling

⇒Exploit the different decay channels.

Precisions per experiments in Run2 :

- H→γγ: ~35%
- H→ML: ~25%
- H→bb: ~26-27%,

H→bb has the largest Higgs BR (58%)
BUT: it is a complex signature:
4b + 2 W (1 or 2 leptons (e|μ))
Can we do better?

Nature 607, 52 (2022)

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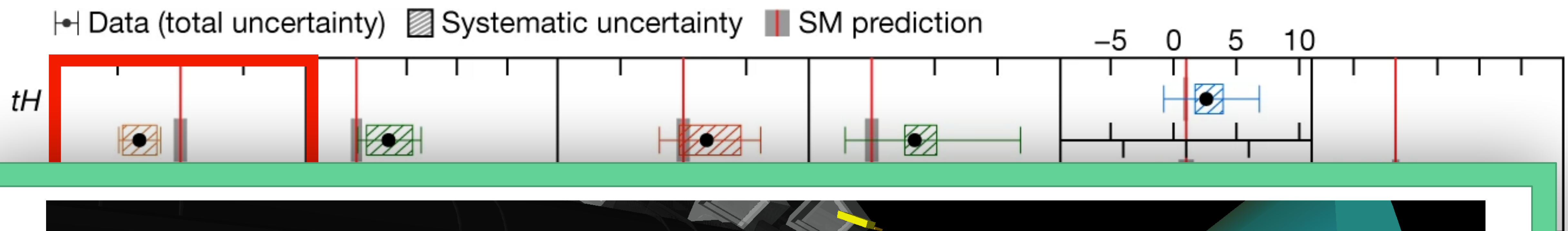

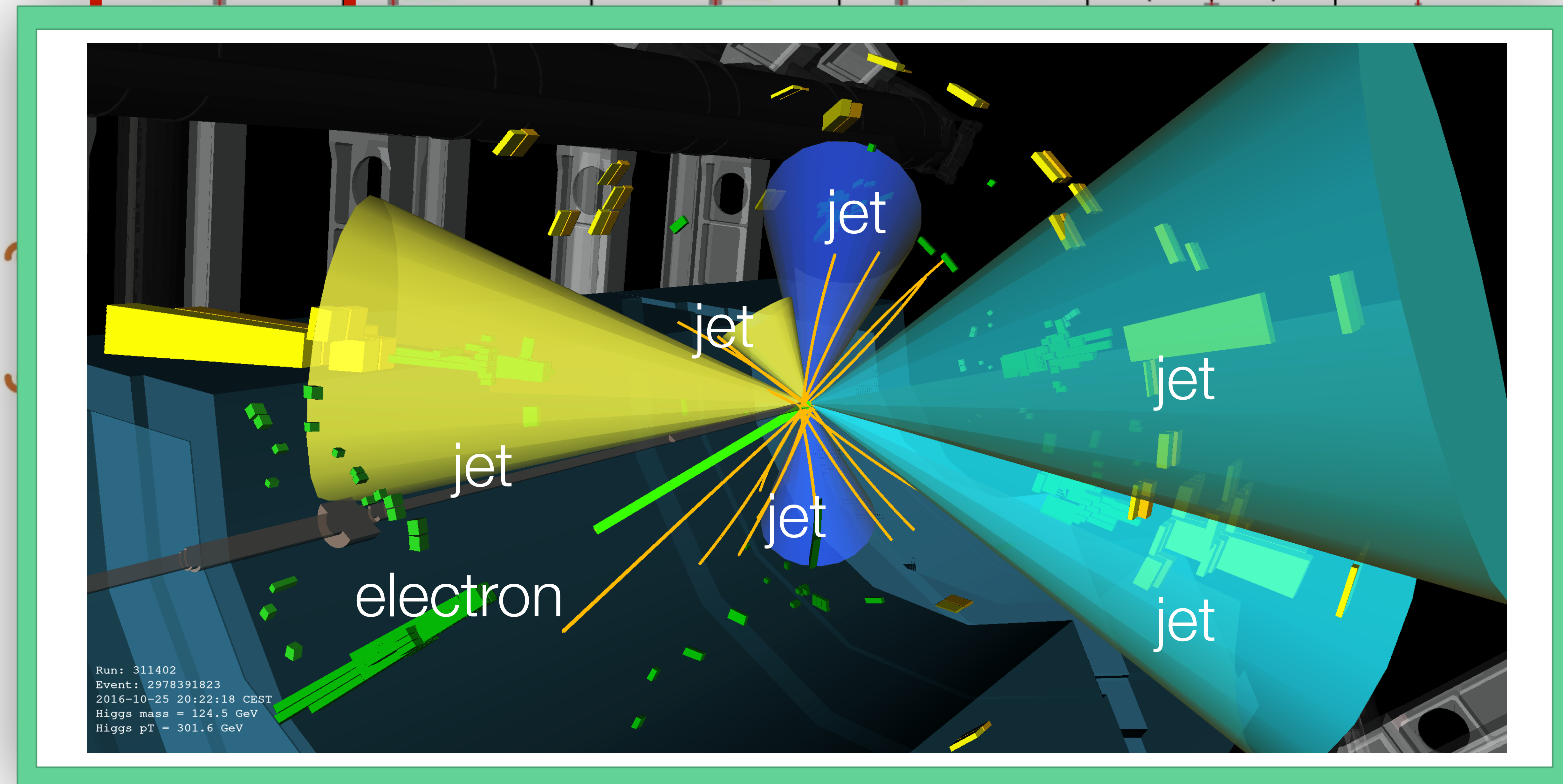

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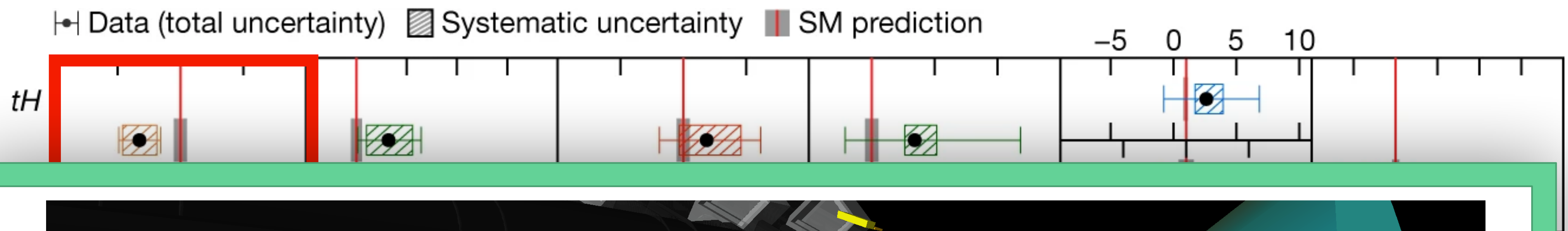

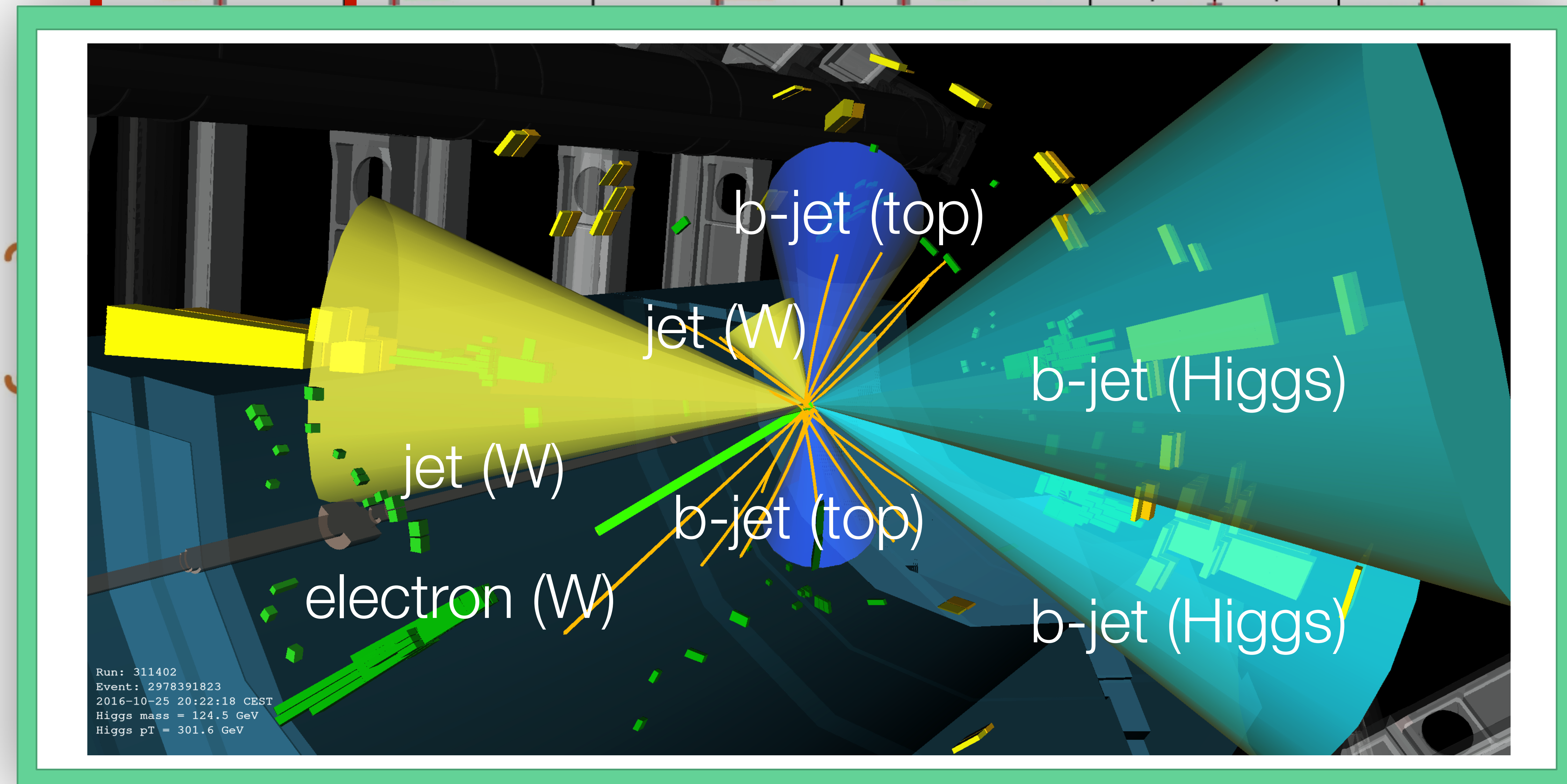

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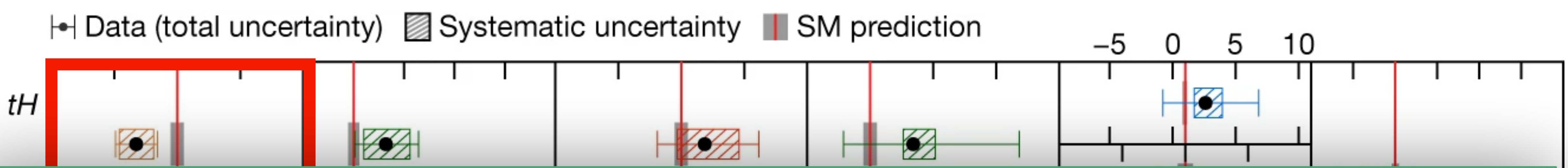

Eur. Phys. J. C 85 (2025) 210

- Improved b-jet identification (DL1r)
- Improved modelling of backgrounds (tt+b(b)…),
- Looser selection for better control.
- Use of transformer networks to separate signal and background, reconstruct $p_T(H)$

$$\mu_{ttH} = 0.81 \,^{+0.22}_{-0.19} \left(^{+0.20}_{-0.16} \text{ syst.} \right)$$

Overall uncertainty improved by factor 1.8,

4.6σ observed

Higgs PAG Summary Plots

Can we do better?

Nature 607, 52 (2022)

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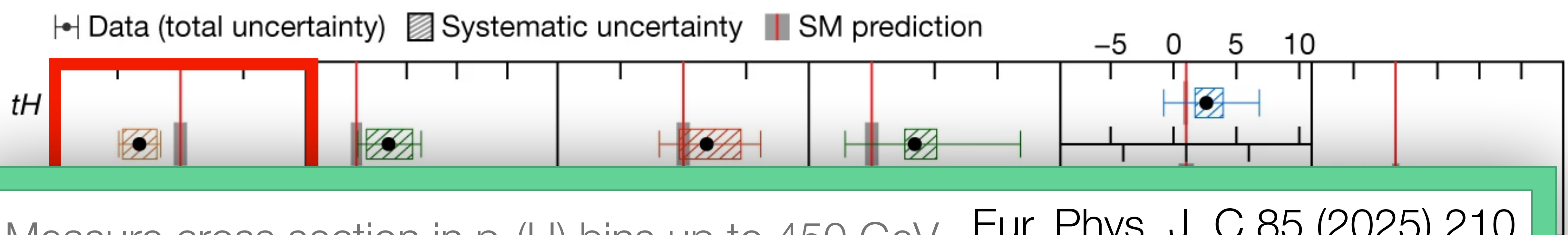
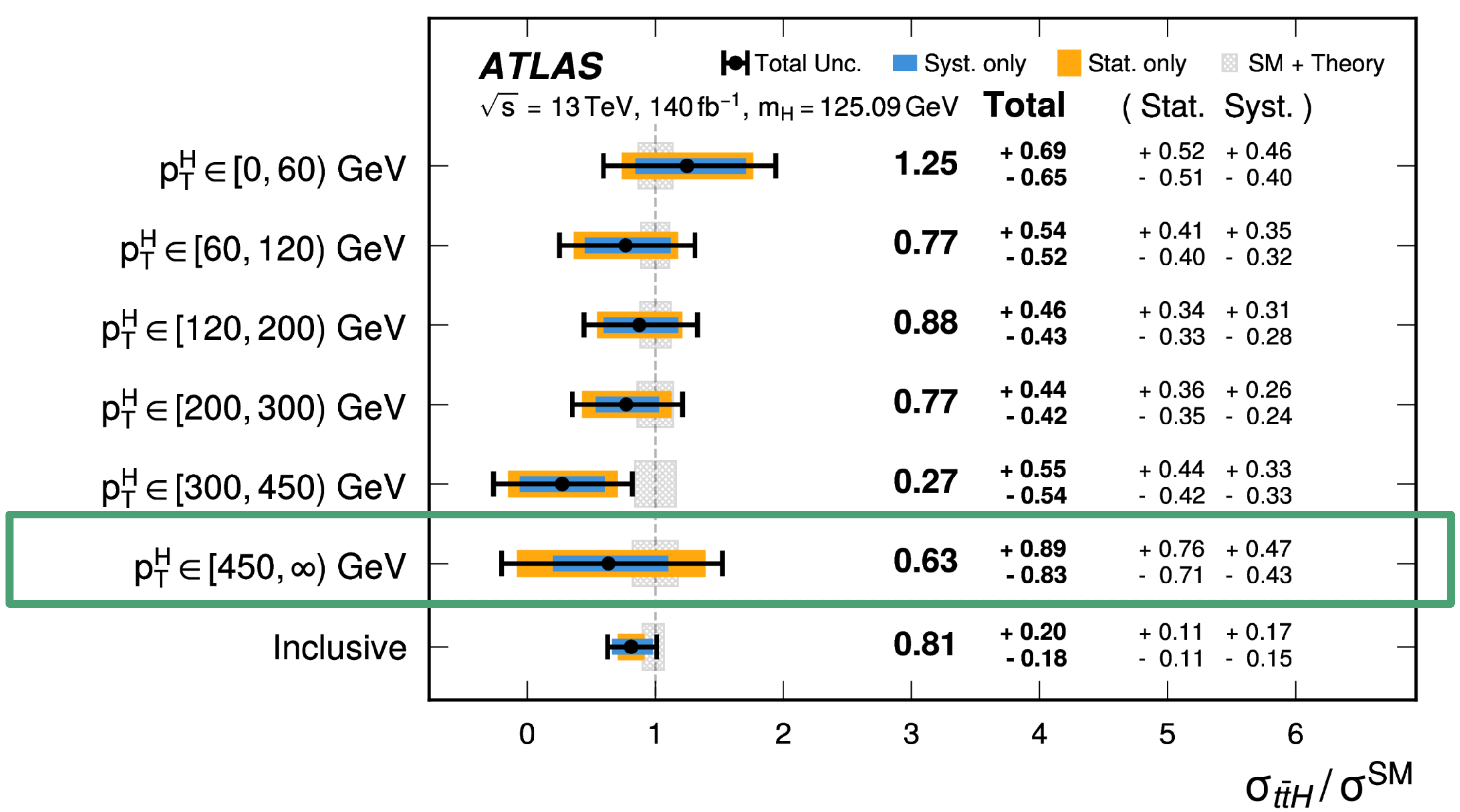


Eur. Phys. J. C 85 (2025) 210

Measure cross section in $p_T(H)$ bins up to 450 GeV.
Best single measurement to date.
⇒ Test SM in extreme phase-space



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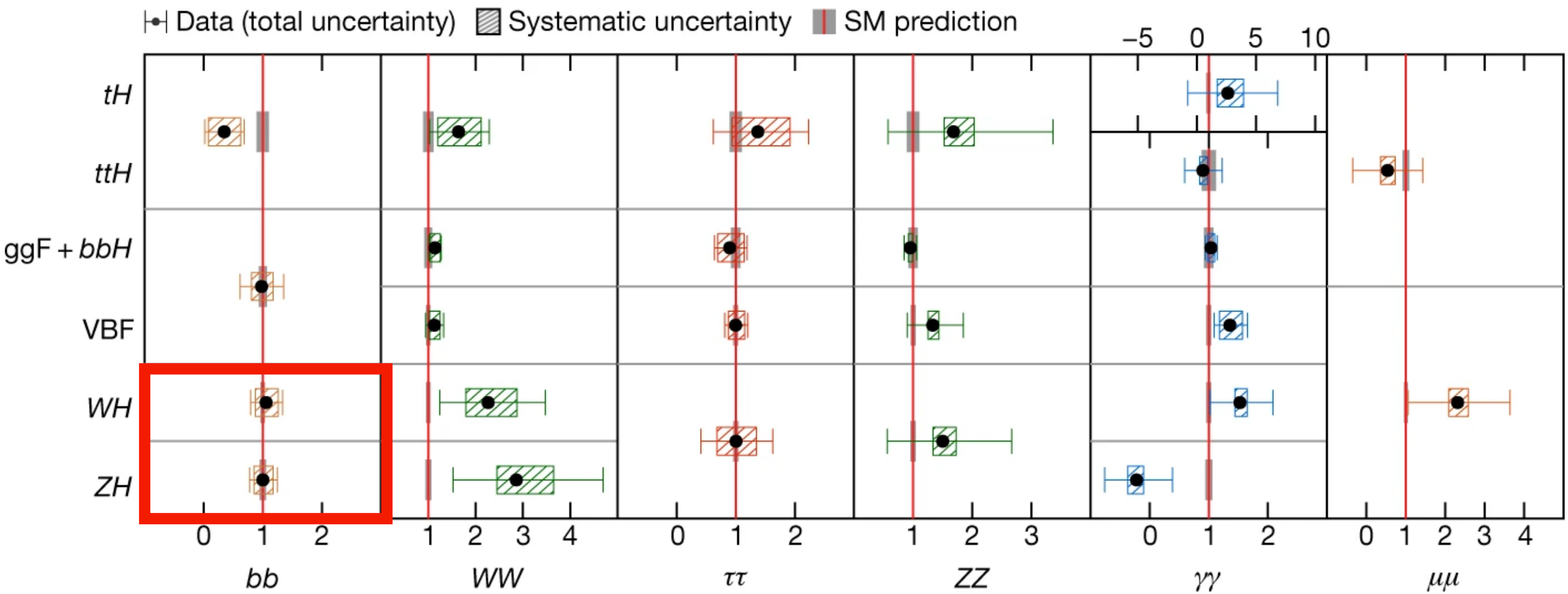

Challenging channels

Precision Channels

Nature 607, 52 (2022)

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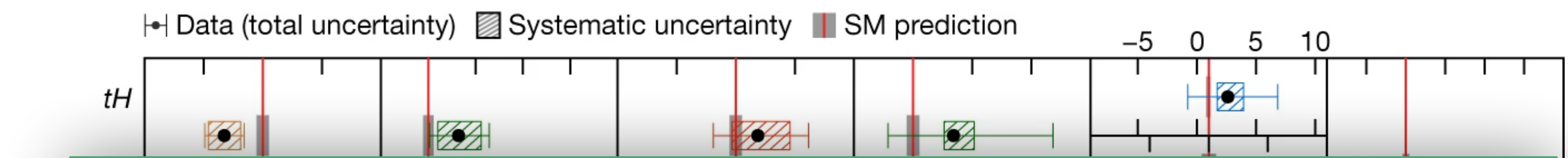


H→bb largest Higgs BR (58%)

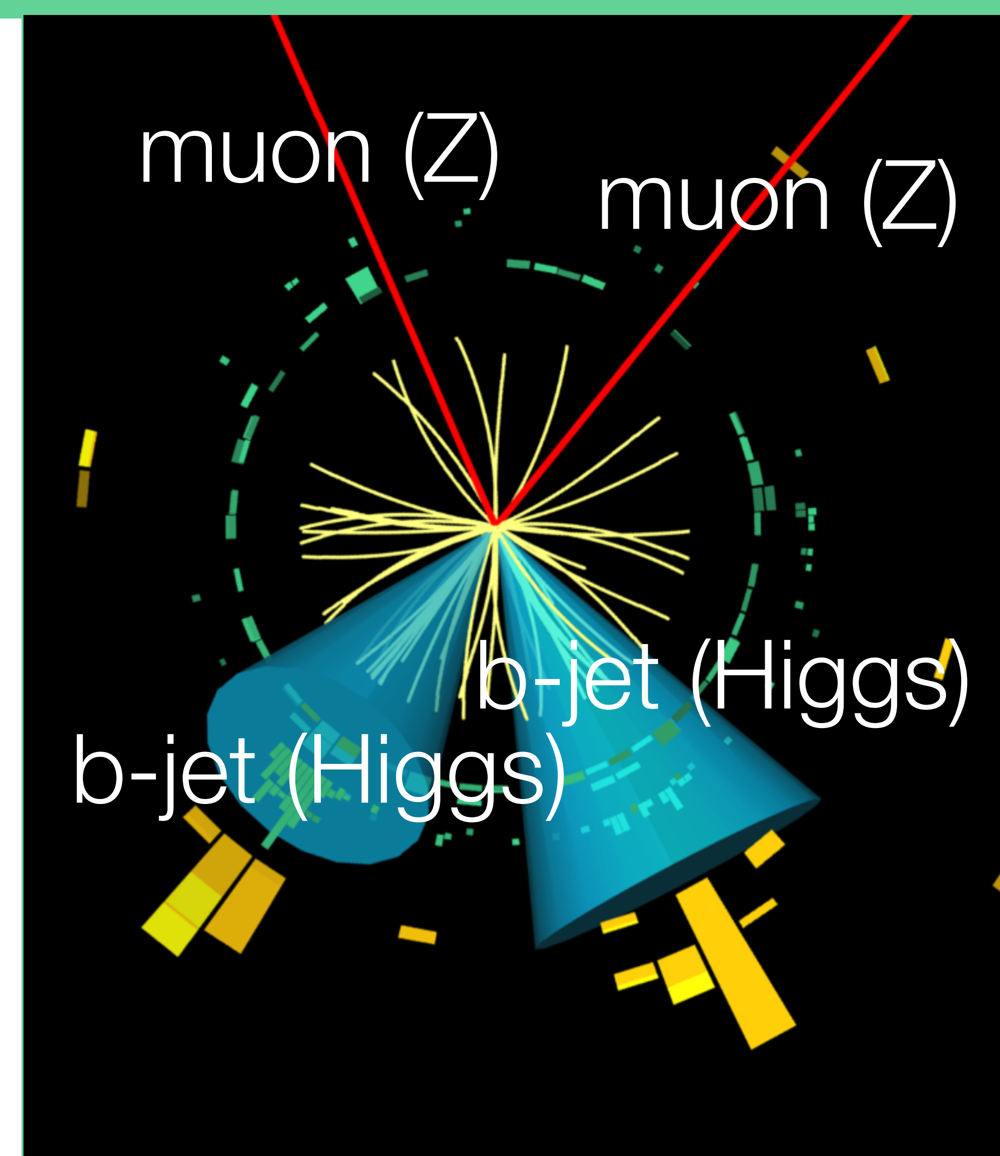
H→cc largest BR to 2nd gen. fermions (2.9%)

(V→lep)H most sensitive mode to access both.

Require b-jets or c-jets,

split signal in $N_{leptons}$:

- 0 (Z→νν),
- 1 (W→lν)
- 2 (Z→ll)



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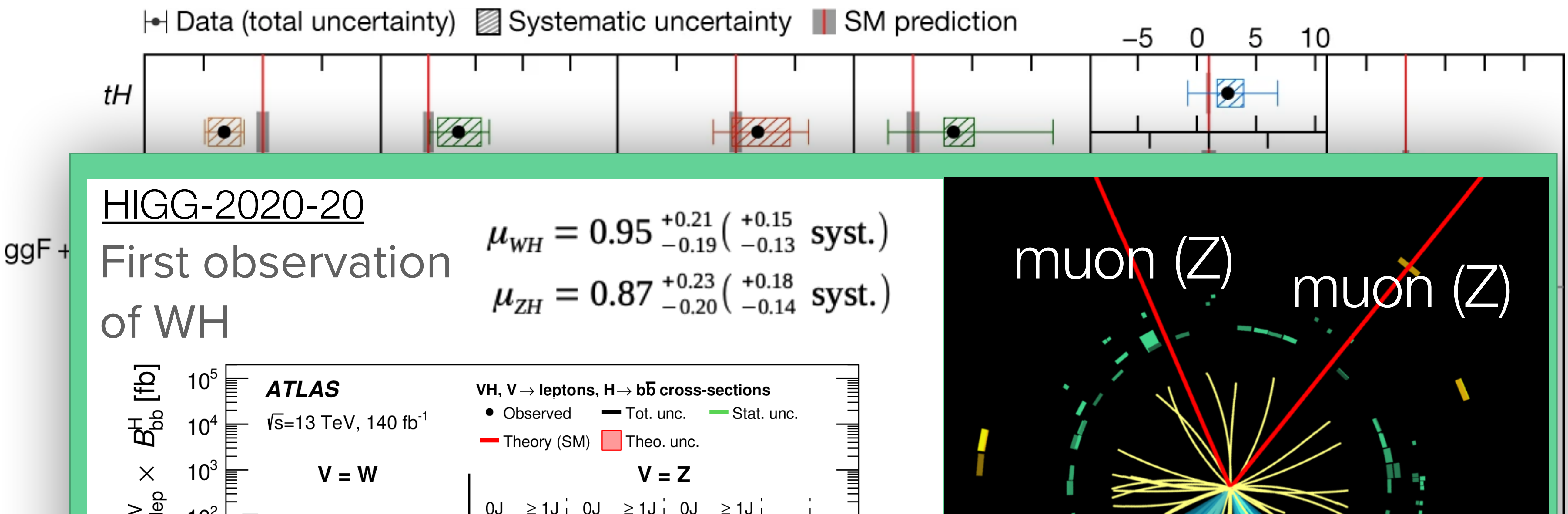
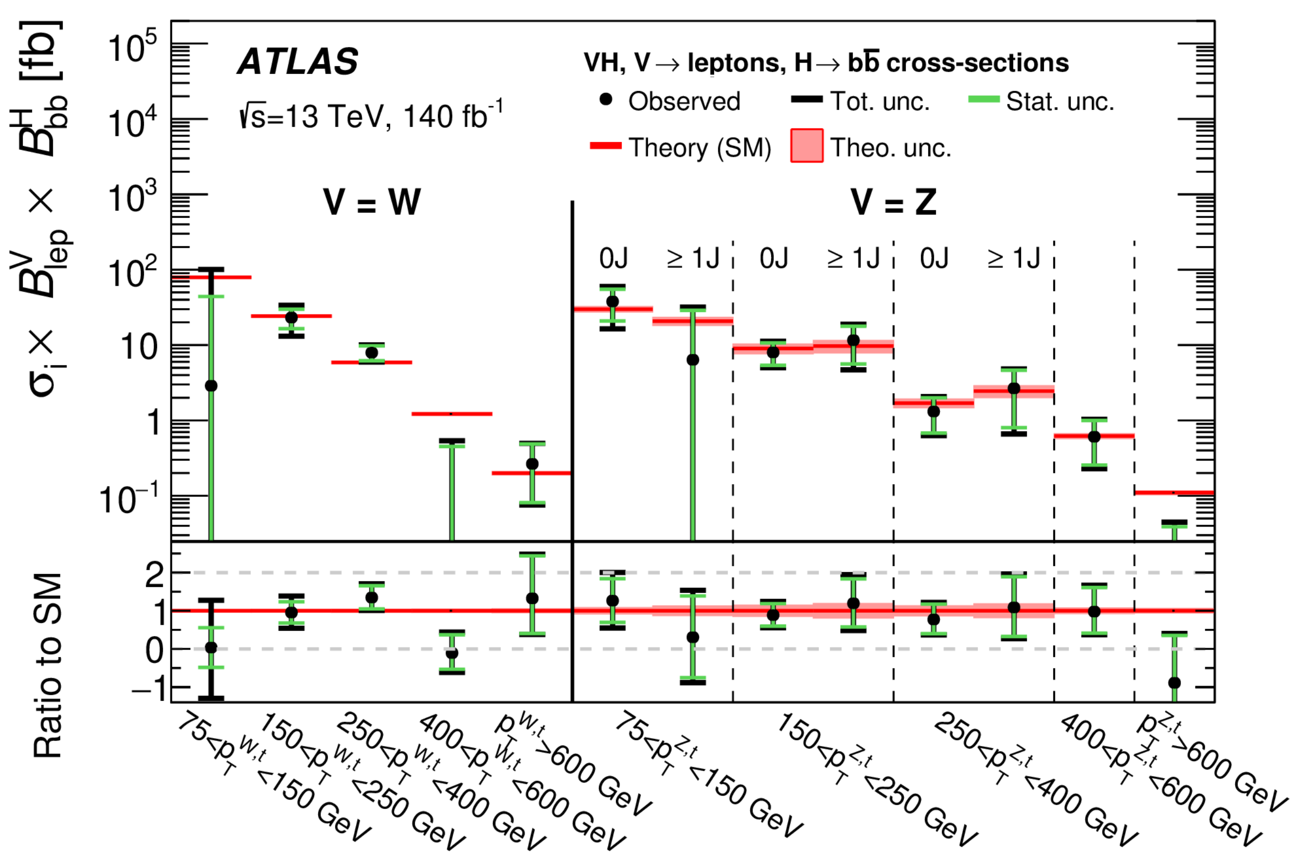


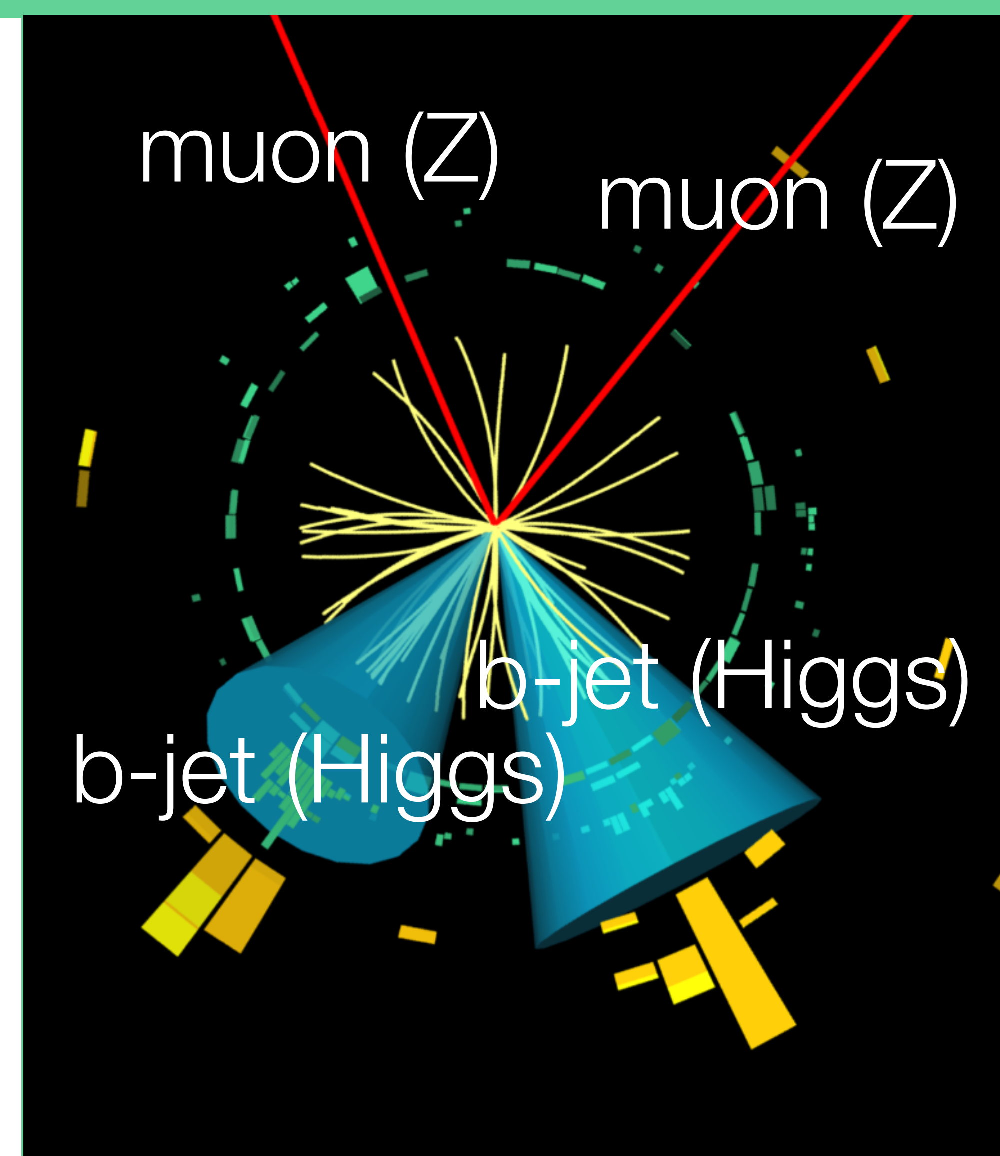
HIGG-2020-20

First observation of WH

$$\mu_{WH} = 0.95\,^{+0.21}_{-0.19}\left(\,^{+0.15}_{-0.13}\text{ syst.}\right)$$

$$\mu_{ZH} = 0.87\,^{+0.23}_{-0.20}\left(\,^{+0.18}_{-0.14}\text{ syst.}\right)$$





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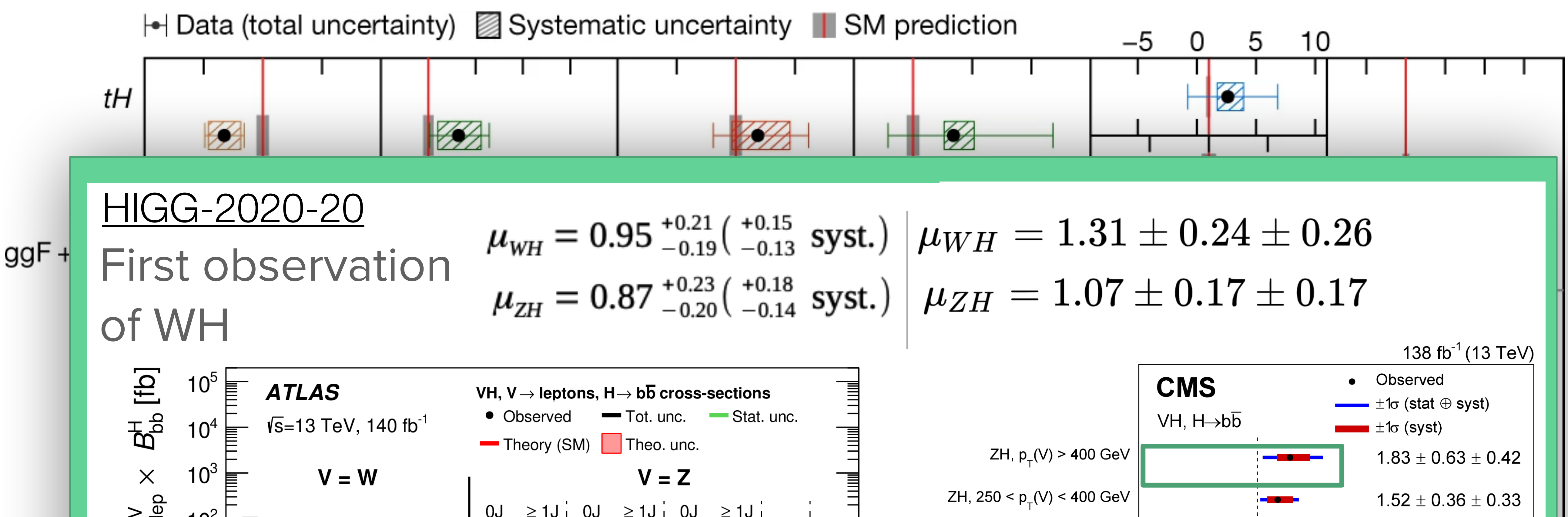

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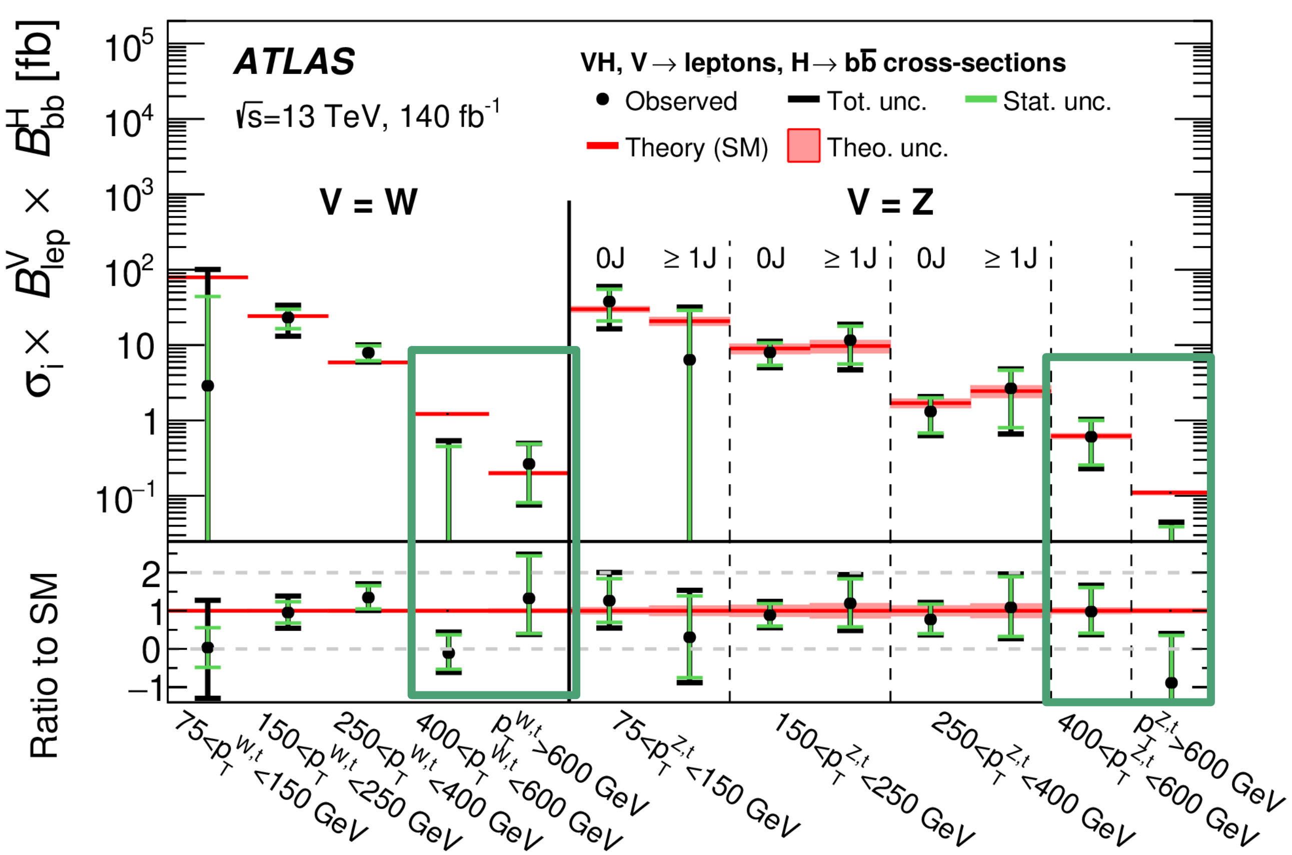
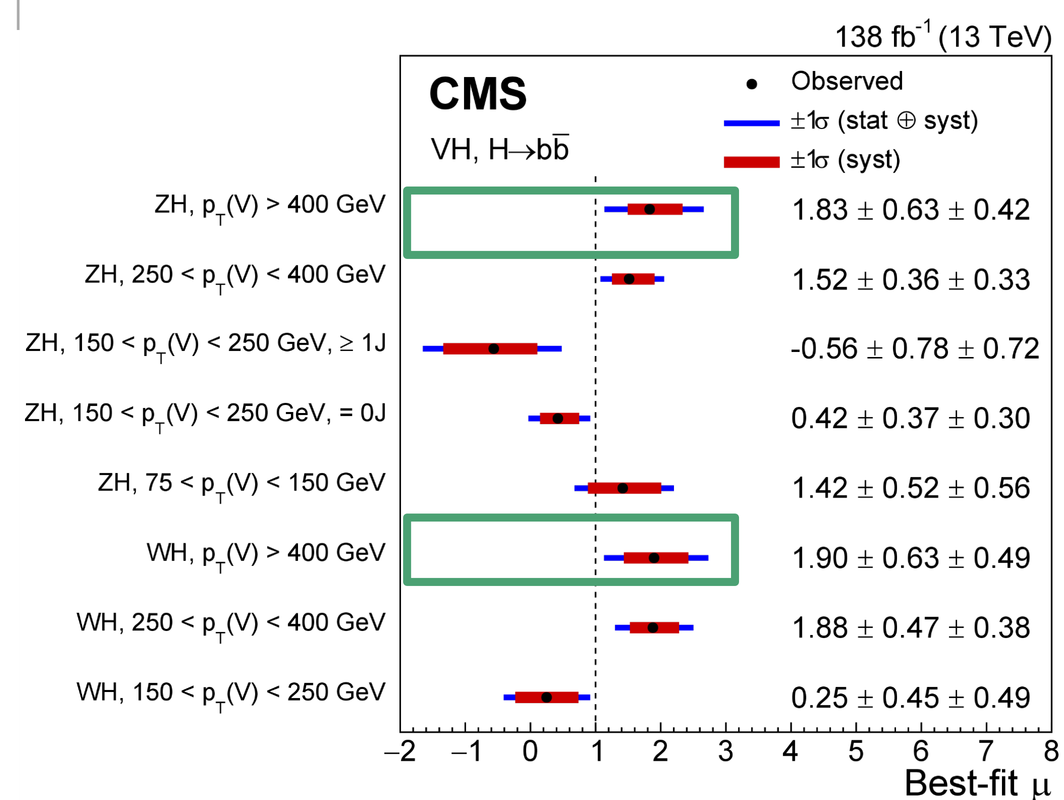
$$\mu_{ZH} = 0.87\ ^{+0.23}_{-0.20}\left(\ ^{+0.18}_{-0.14}\ \text{syst.}\right)$$

$$\mu_{WH} = 1.31 \pm 0.24 \pm 0.26$$

$$\mu_{ZH} = 1.07 \pm 0.17 \pm 0.17$$

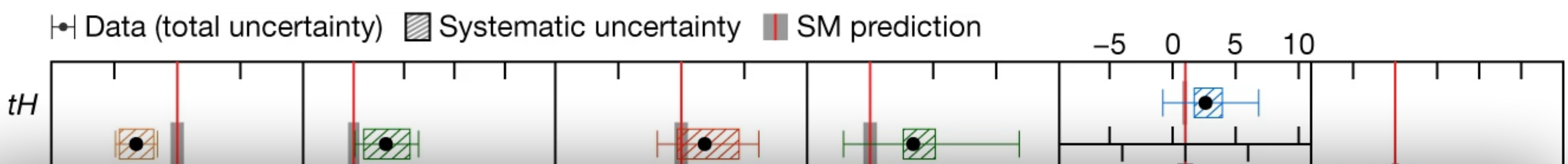




Phys. Rev. D 109 (2024) 092011

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

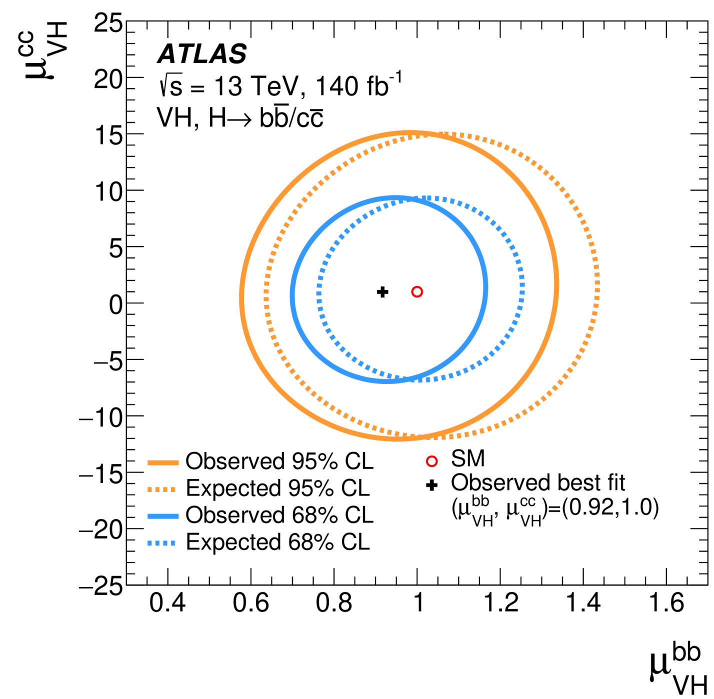
How many ways are there to measure the Higgs boson?



HIGG-2020-20

Higgs and Charm

Simultaneous fit with VH→bb



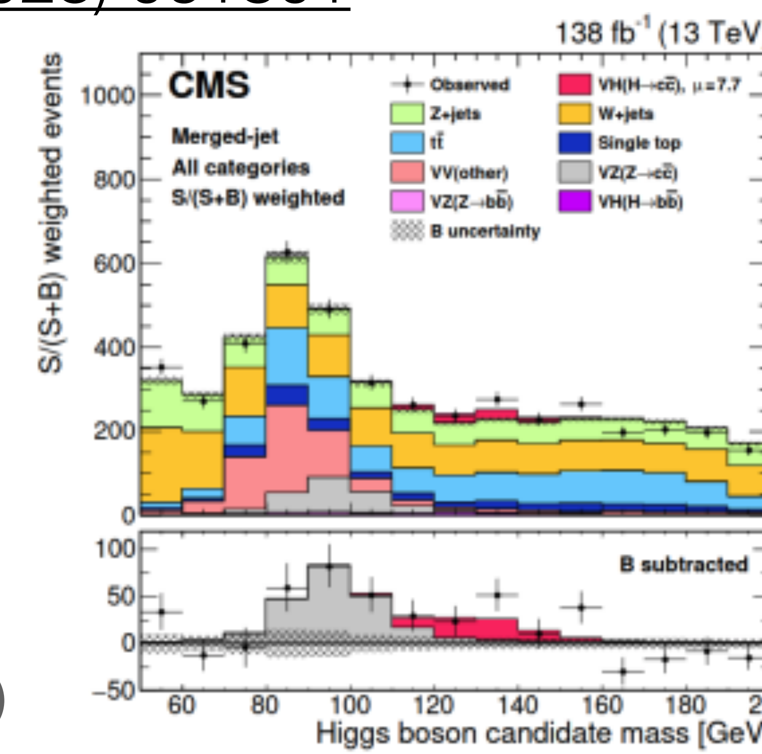
Best limit to date

Factor 2.5 improv. over previous limit !

⇒ **|κc| < 4.2 @ 95% CL**

X2 improvement over previous

PRL 131 (2023) 061801



Boosted H→cc (p_T(H) >300 GeV)

Best expected sensitivity

⇒ **1.1 < |κc| < 5.5**

First observation of Z→cc in had. coll.

Four (among the various) questions...

- How can we improve our current understanding?
- Does the Higgs boson interact with particles in a manner consistent with how they interact with the condensate?
- Does the Higgs field (and the Higgs boson) also interact with particles that are not part of the Standard Model?
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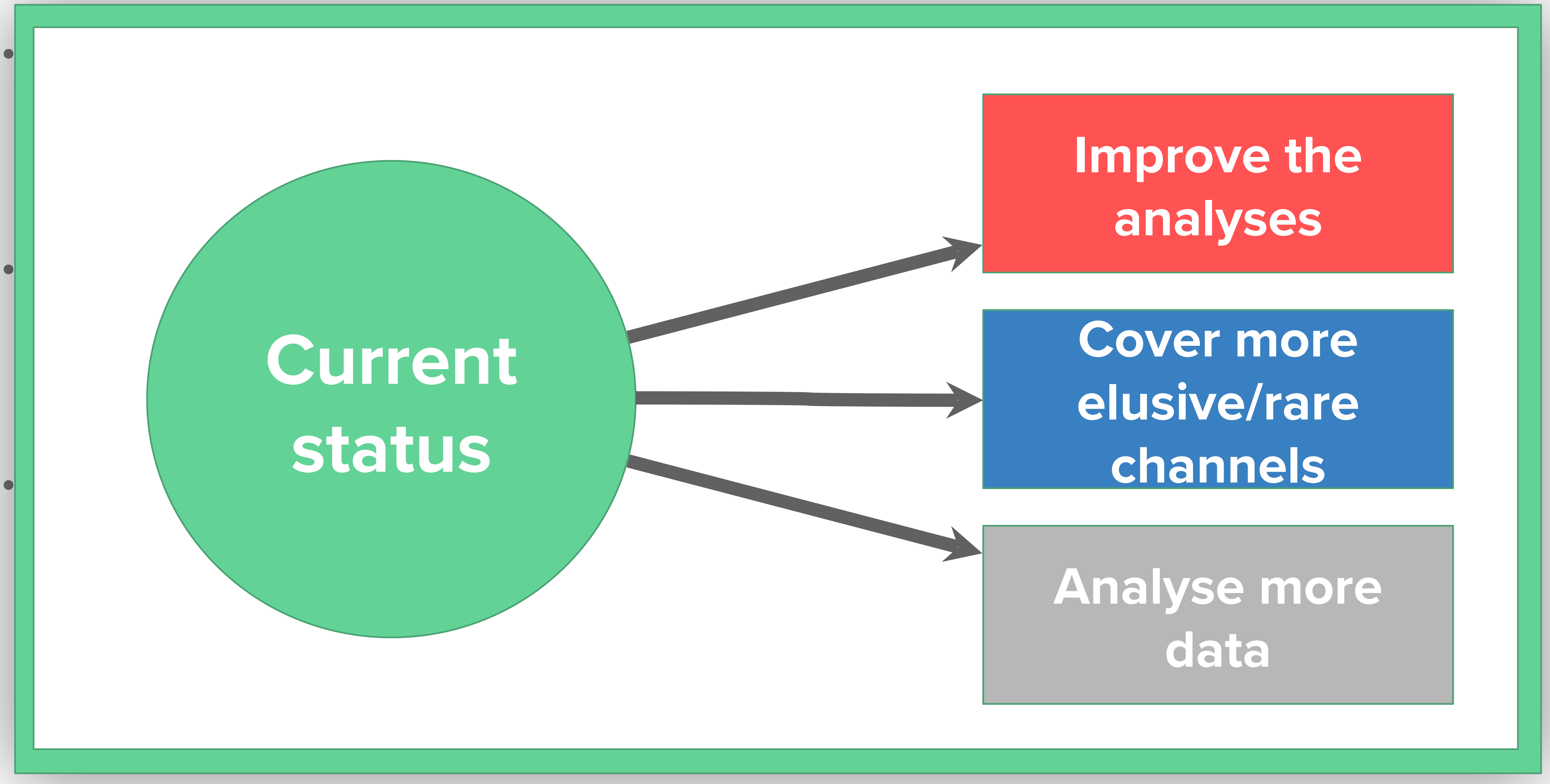
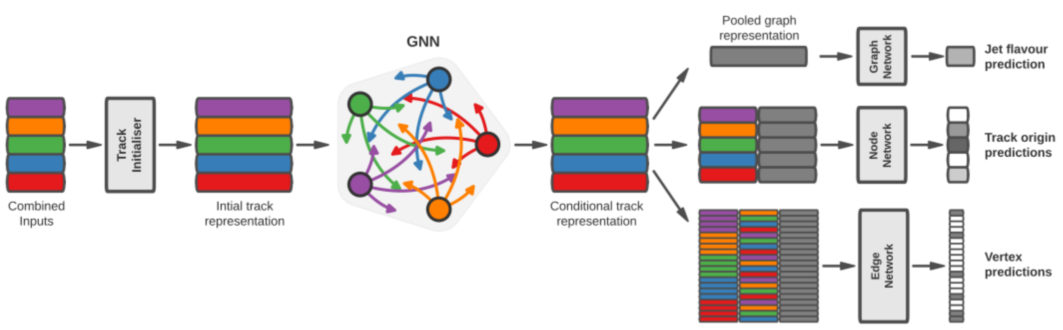


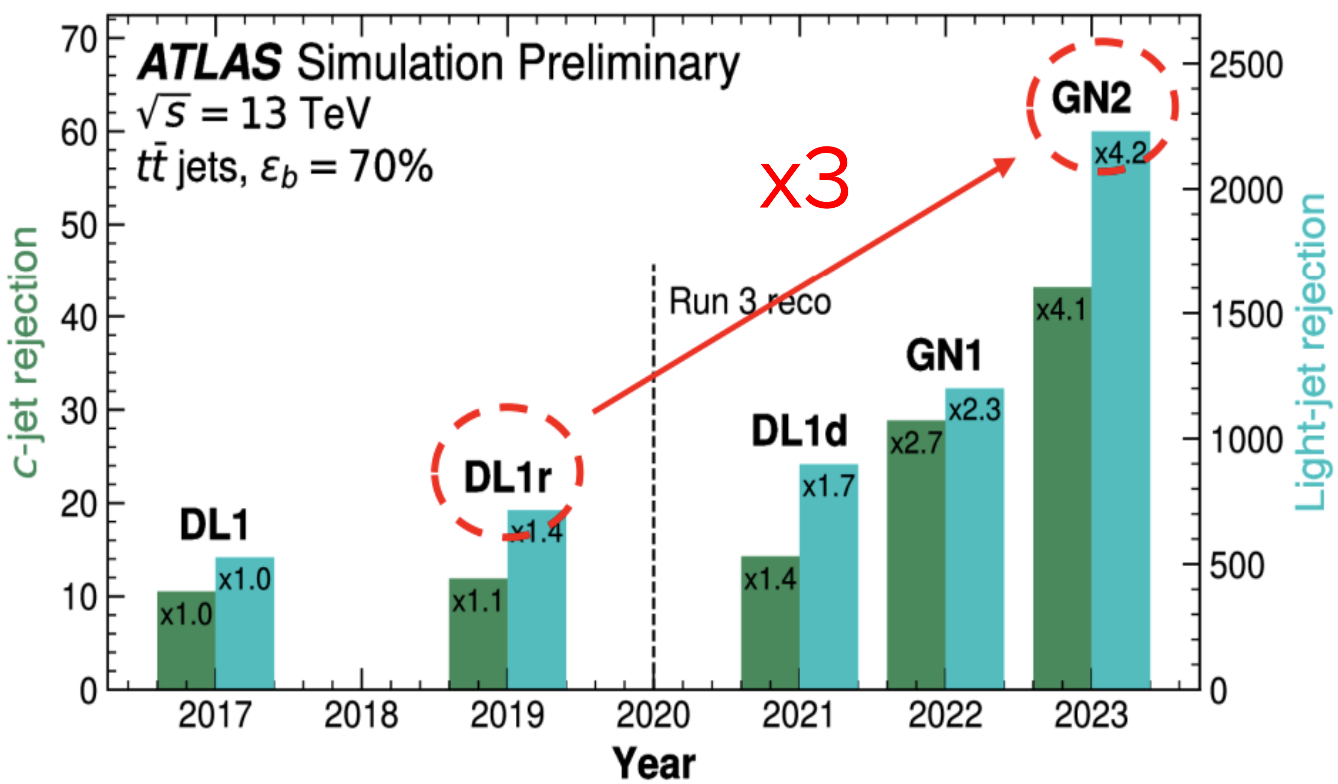
Improvements in experimental techniques: An example

Improve the analyses

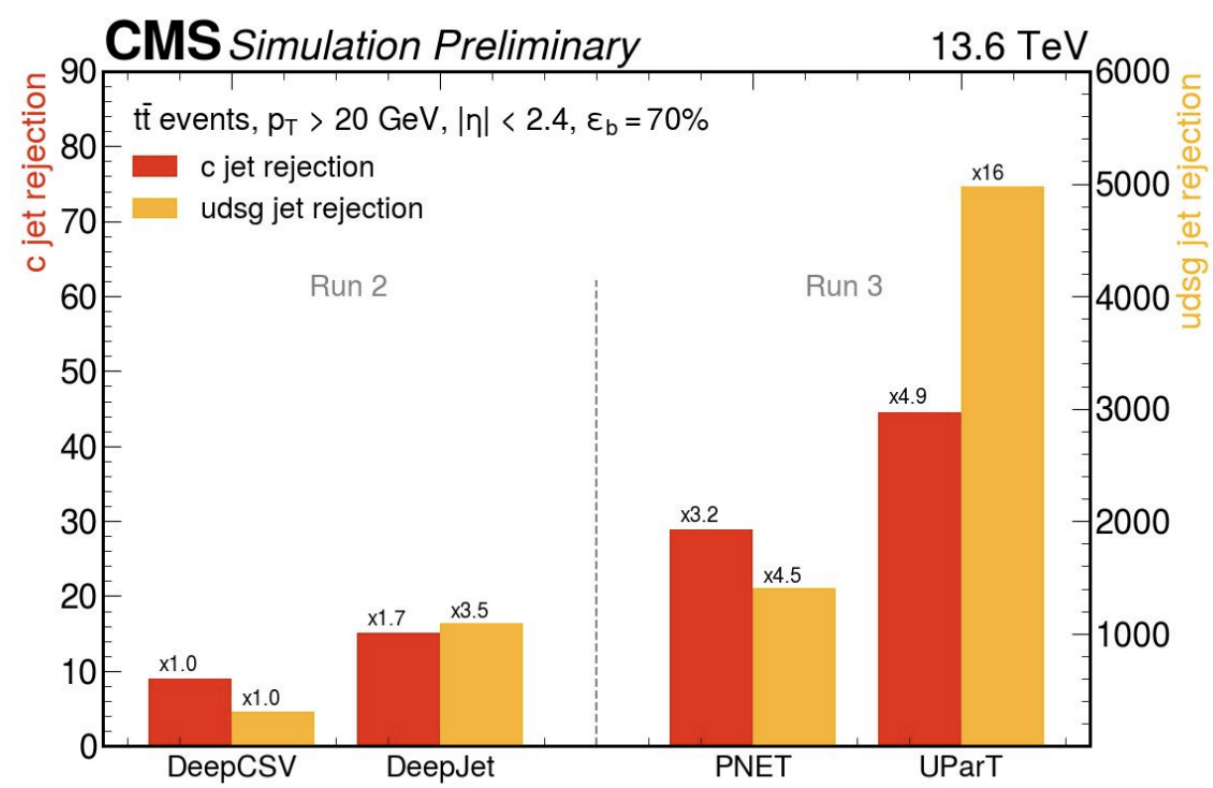
Rapid progress in techniques:

- **BDT => DNN => GNN,Transformers, etc.**





FTAG-2023-01



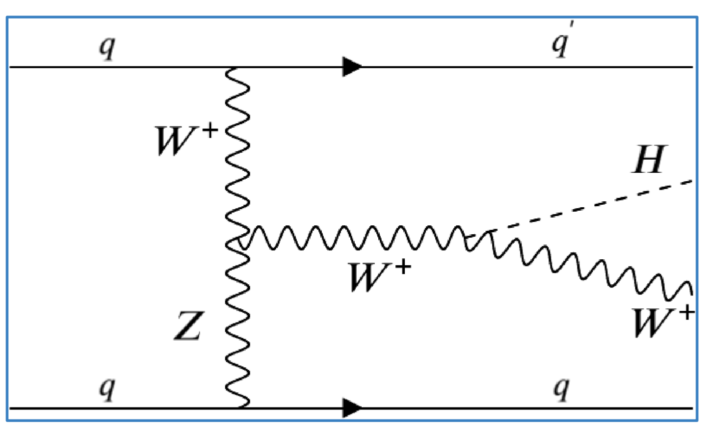
CMS-DP-2024-066

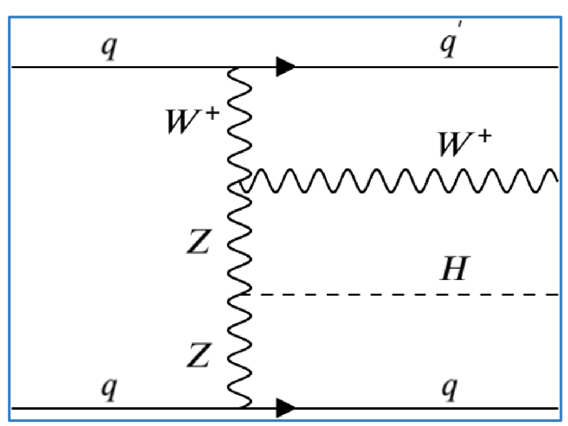
An elusive/rare channel: WH produced via VBF

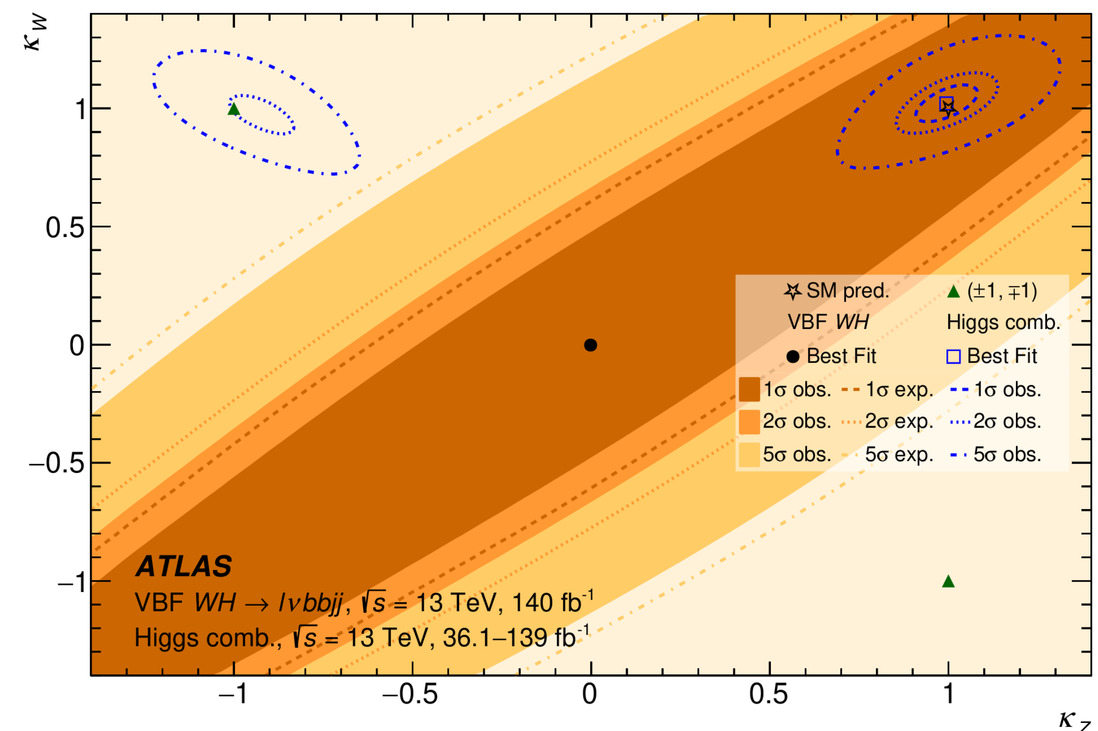
Cover more elusive/rare channels

Thanks to the interference in the VBF WH production, we can determine the relative sign of κ_W and κ_Z.

Different relative sign excluded with > 5 σ







Phys. Rev. Lett. 133 (2024) 141801

Editor selection of the year

Similar results from CMS

Phys. Lett. B 860 (2025) 139202

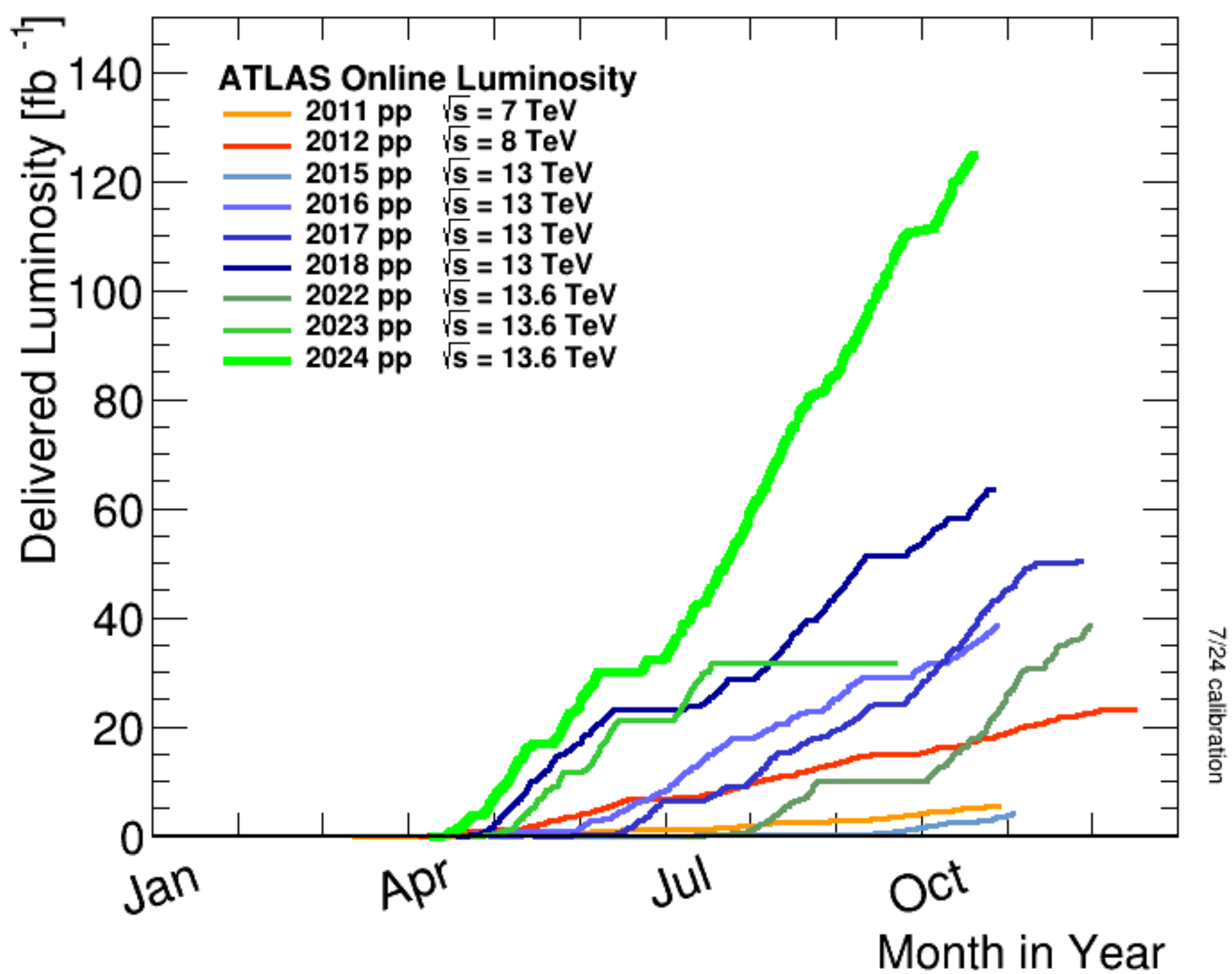
Data collected and plans

Analyse more data

A total of about 150 fb^{-1} (approximately 9 million Higgs events) recorded by the end of 2024, more than those analyzed in Run 2.

Combining partial Run3 results with the Run2 measurement will give us a net improvement in precision (at least for the statistically limited processes)

The plan for 2025/2026 is to continue taking data, with the target of ~ doubling this statistics



Four (among the various) questions...

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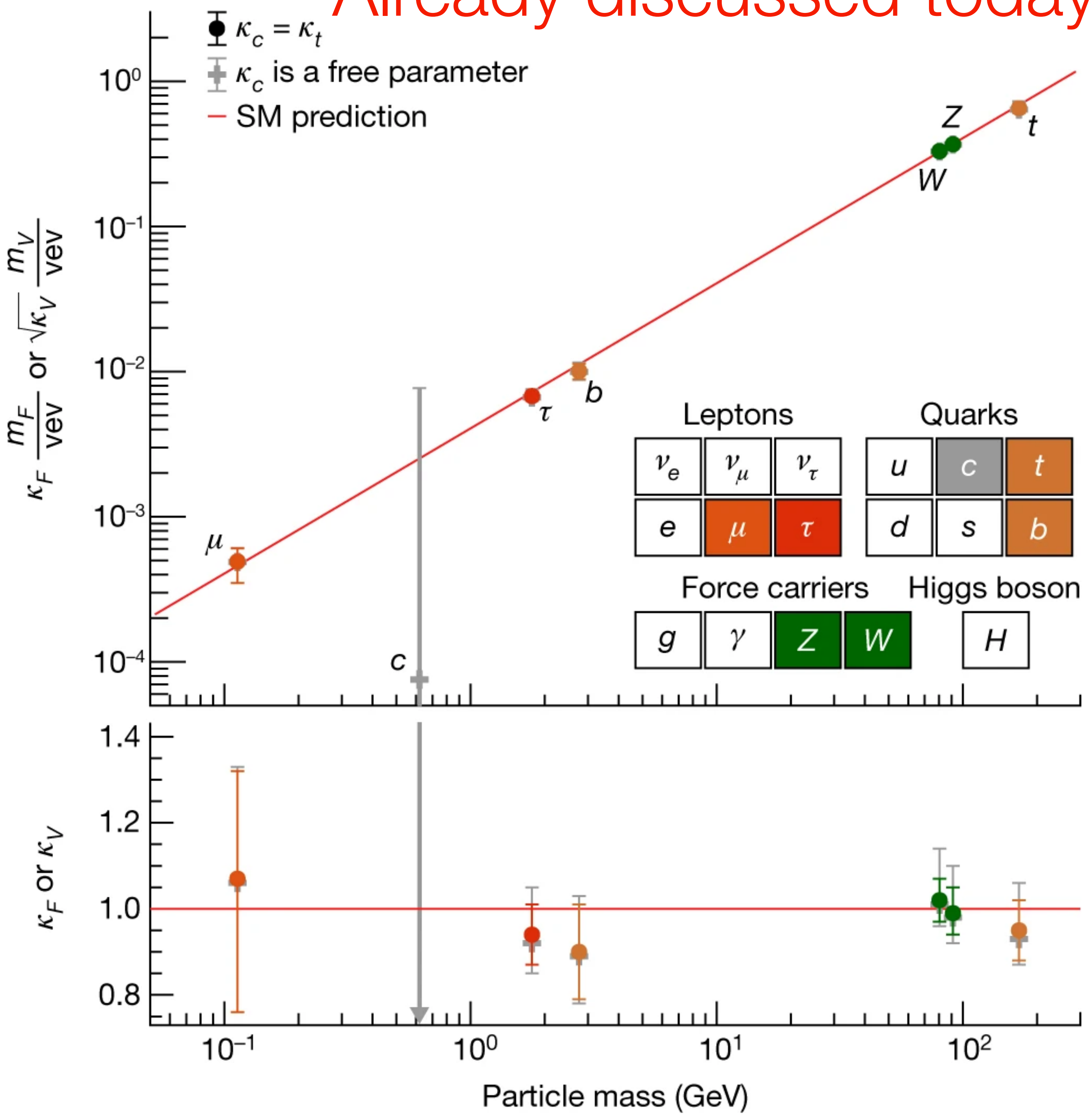
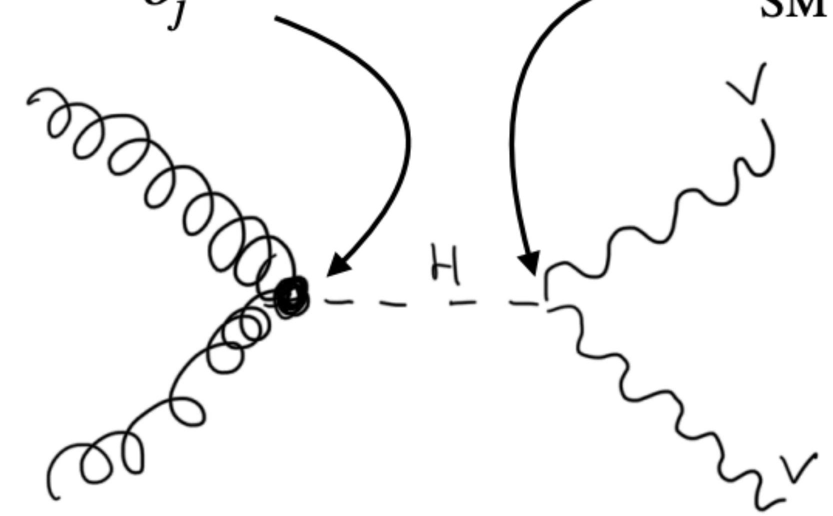
Nature 607, 52 (2022)

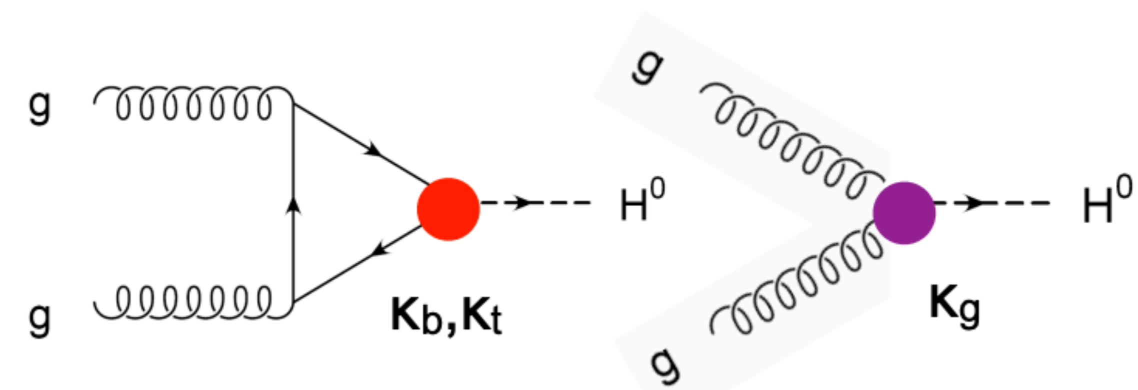
Coupling modifiers

Already discussed today!



$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \qquad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}}$$



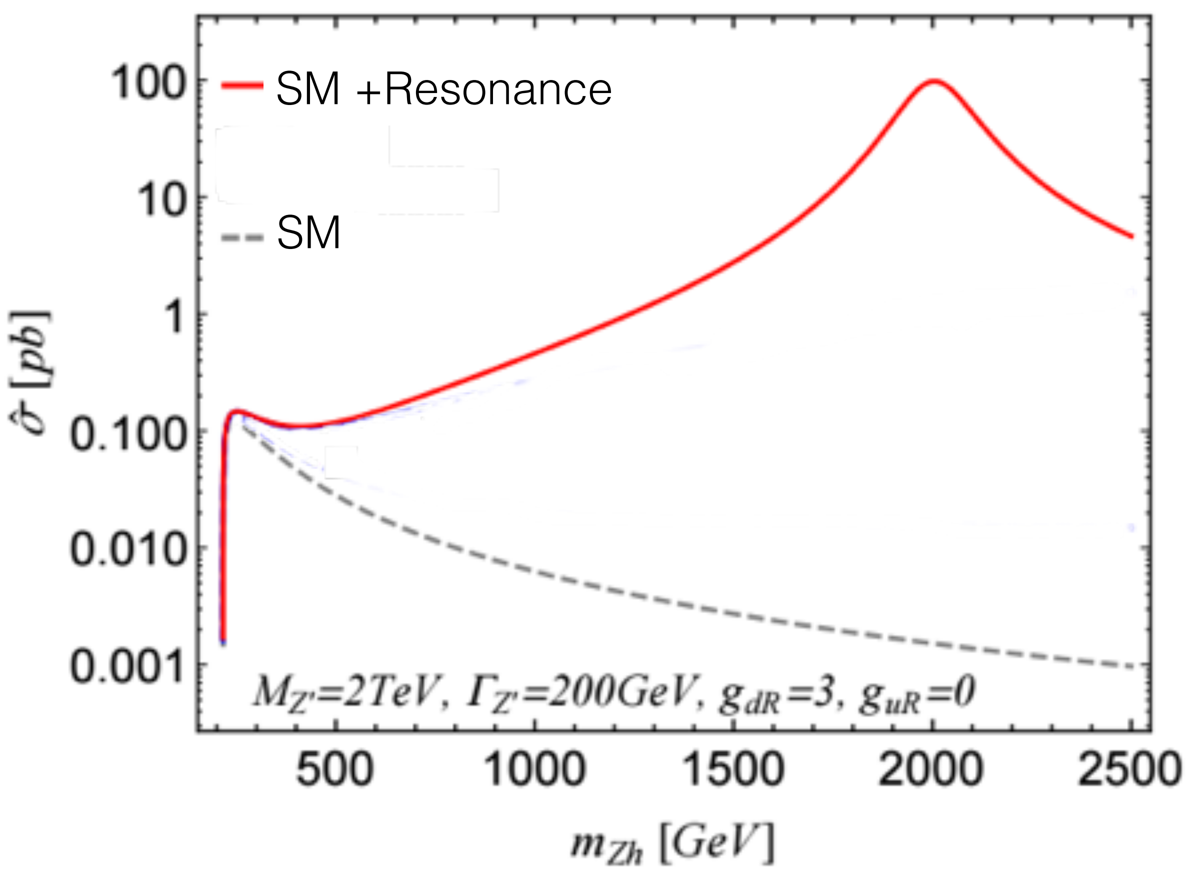


- Consistency test over 4 orders of magnitude!
- It should be noted that the measurement of vector bosons and the third fermion family is very precise.
- Run 3 and the HL-LHC will help us better measure the second family (μ and charm).

Four (among the various) questions...

- How can we improve our current understanding?
- Does the Higgs boson interact with particles in a manner consistent with how they interact with the condensate?
- **Does the Higgs field (and the Higgs boson) also interact with particles that are not part of the Standard Model?**
- What is the dynamics that led to this "special" vacuum state?

Resonances, but not only...

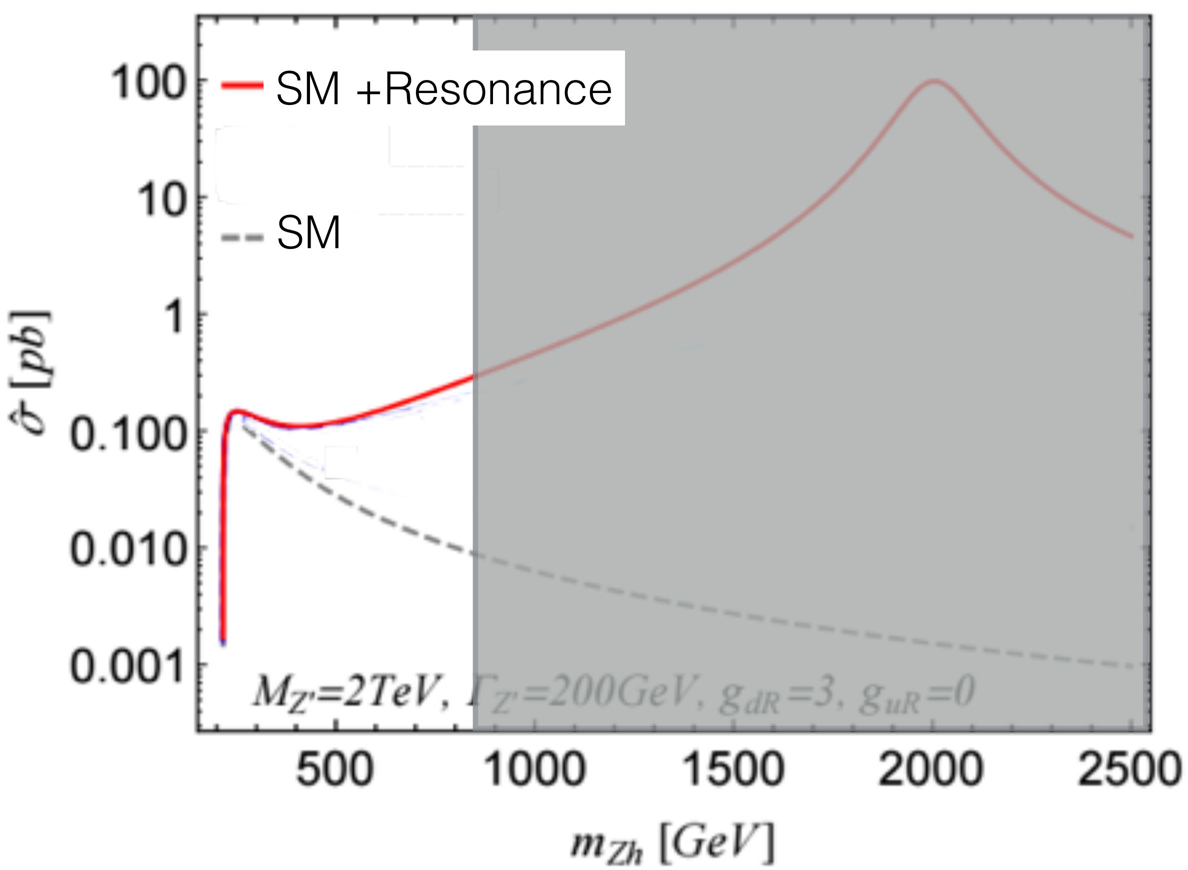


A natural way to search for new particles that interact with the Higgs boson is to look for:

- Resonances decaying into H + X;
- Exotic decays of the Higgs boson;

So far, no other bumps have been found (I will not cover them in this seminar).

Resonances, but not only...



A natural way to search for new particles that interact with the Higgs boson is to look for:

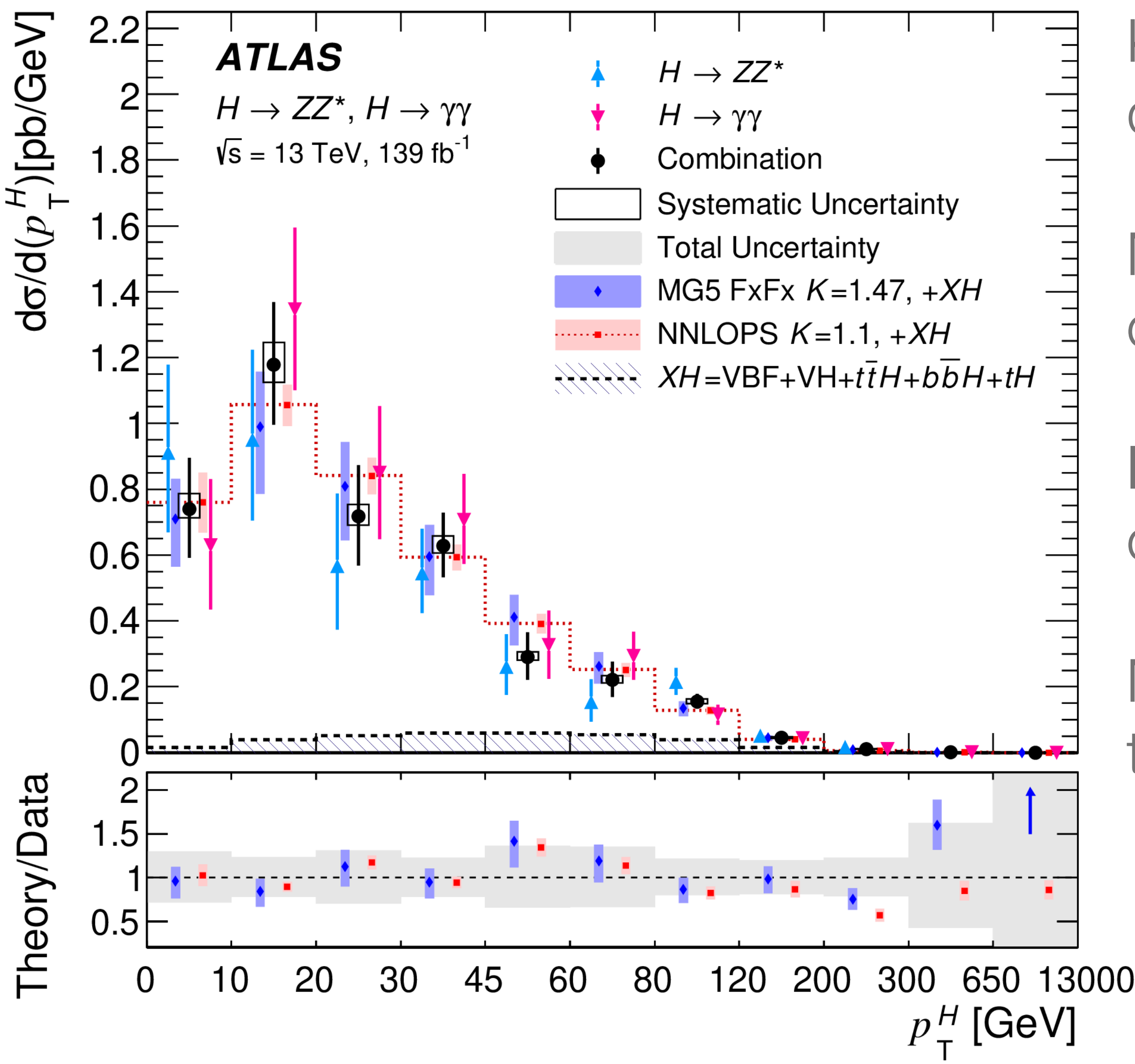
- Resonances decaying into H + X;
- Exotic decays of the Higgs boson;

So far, no other bumps have been found (I will not cover them in this seminar).

But what if these particles had a mass greater than what we can measure today?

Deviations in the kinematic distributions compared to the Standard Model predictions.

Differential measurements



Kinematic distributions measured through differential measurements.

Measurements made in different decay channels (γγ, ZZ, WW, ττ, bb).

In ATLAS, the results from γγ and ZZ have been combined.

Measurements used to extract information on the presence of deviations due to new physics.

Differential measurements

Combine measurements using

- **$H \to \gamma\gamma$**
- **$H \to ZZ^* \to 4l$**
- **$H \to WW^*$**
- **$H \to \tau\tau$**
- **$H \to \tau\tau$ boosted**

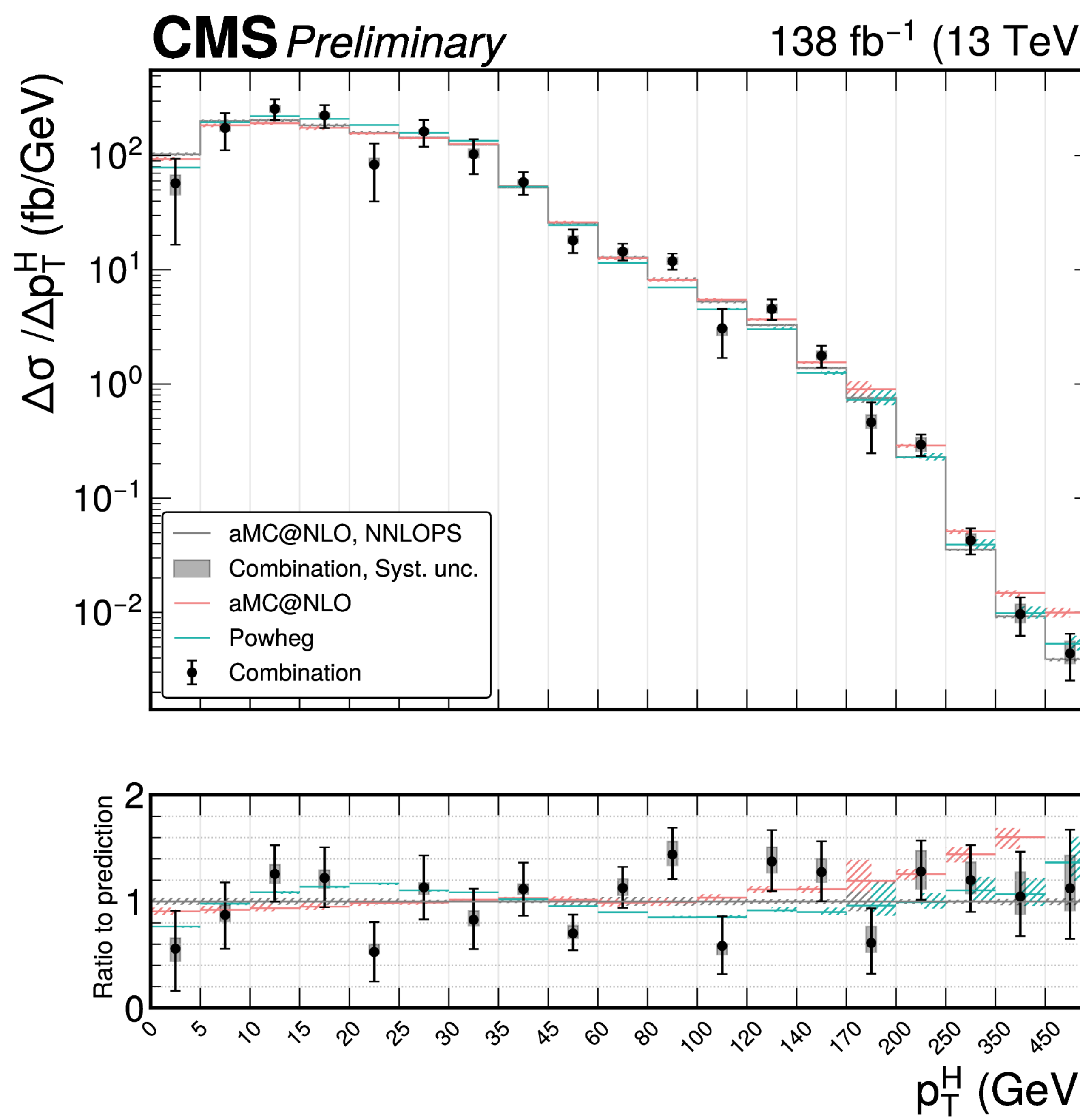
High-precision channels ($H \to \gamma\gamma$, $H \to ZZ^* \to 4l$)

Sensitive to high-p_T^H region ($H \to \tau\tau$, $H \to \tau\tau$ boosted)

Test of the SM over a wide $p_T(H)$ range.

Also N_{jets}, $p_T(j_1)$, $\Delta\phi_{jj}$, …

Good agreement of the distributions with the SM



Differential measurements

Combine measurements using

- **H→γγ**
- **H→ZZ*→4l**
- **H→WW***
- **H→ττ**
- **H→ττ boosted**

High-precision channels (H→γγ, H→ZZ*→4l)

Sensitive to high-p_T^H region (H→ττ, H→ττ boosted)

Test of the SM over a wide $p_T(H)$ range.

Also N_{jets}, $p_T(j_1)$, $\Delta\phi_{jj}$, …

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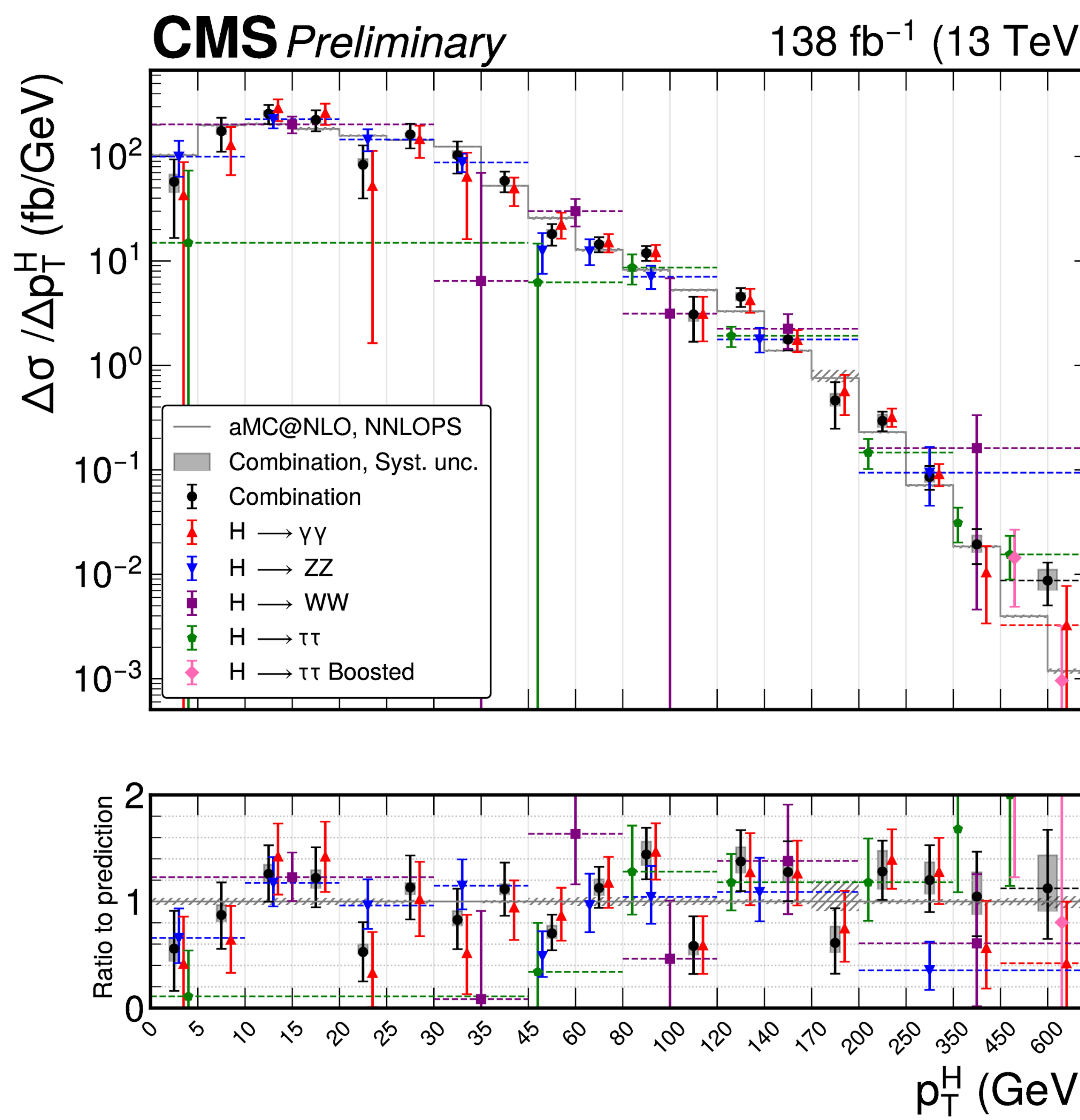
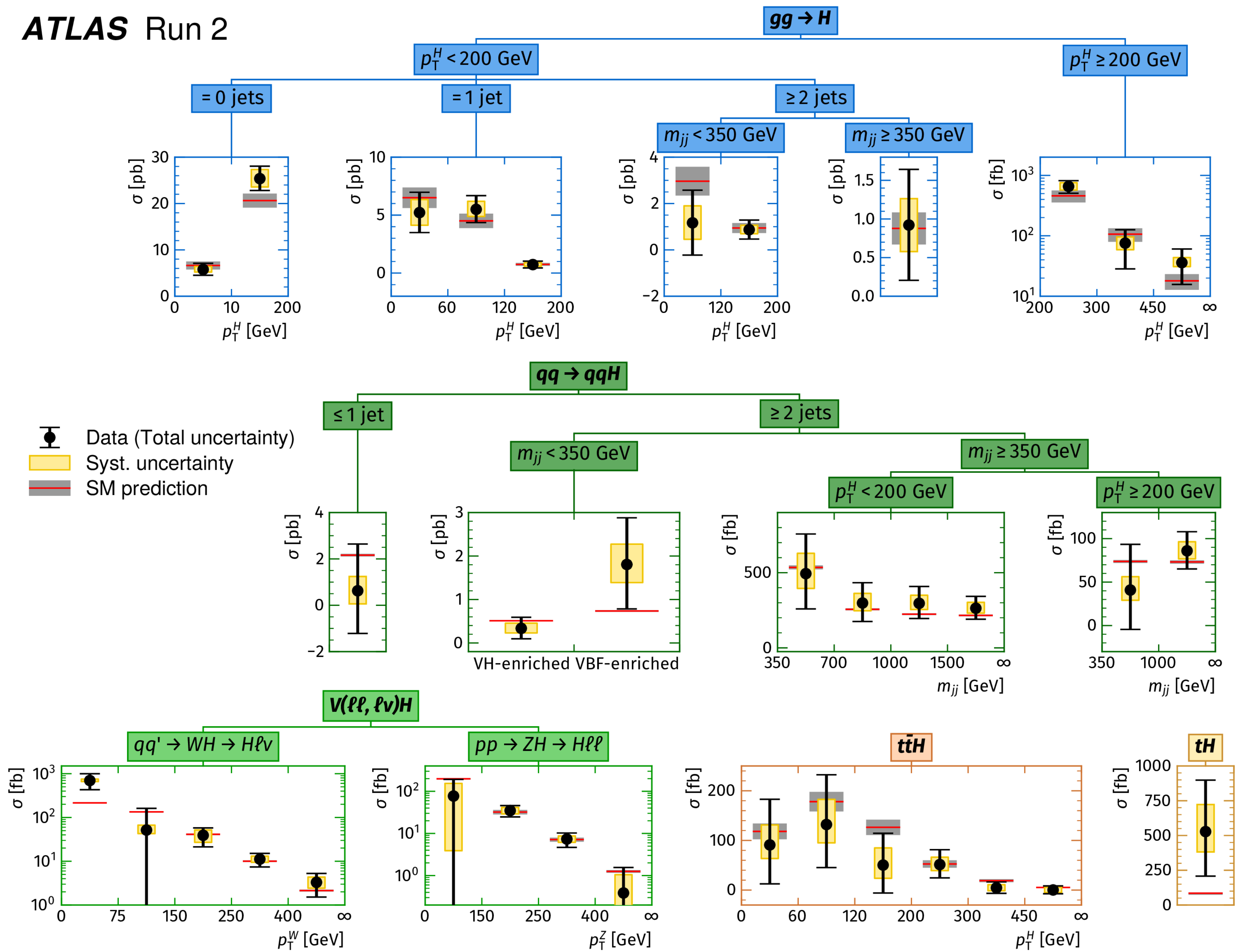


Nature 607, 52 (2022)

Other differential measurements: Simplified Template Cross Sections (STXS)



Nature 607, 52 (2022)

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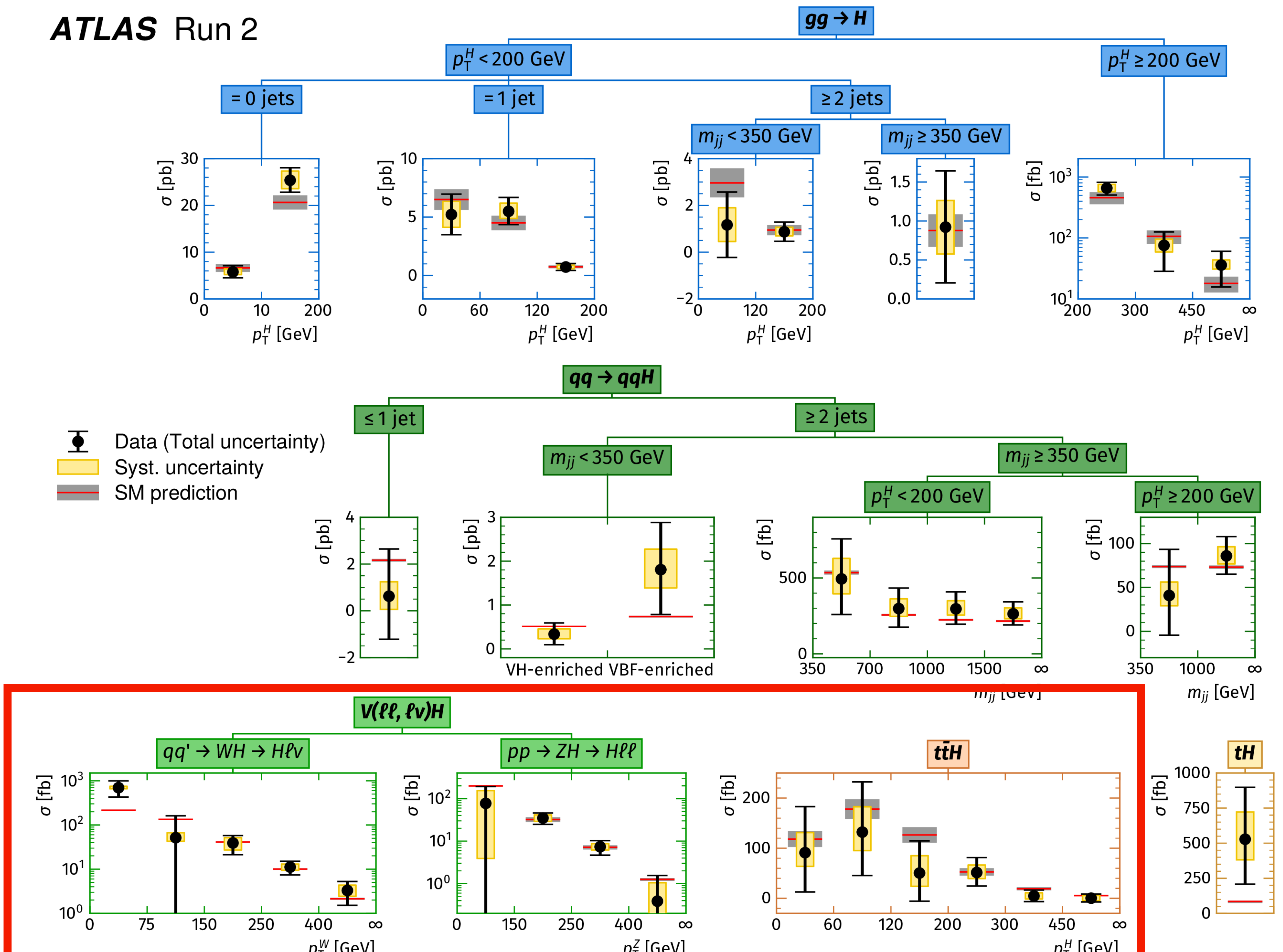
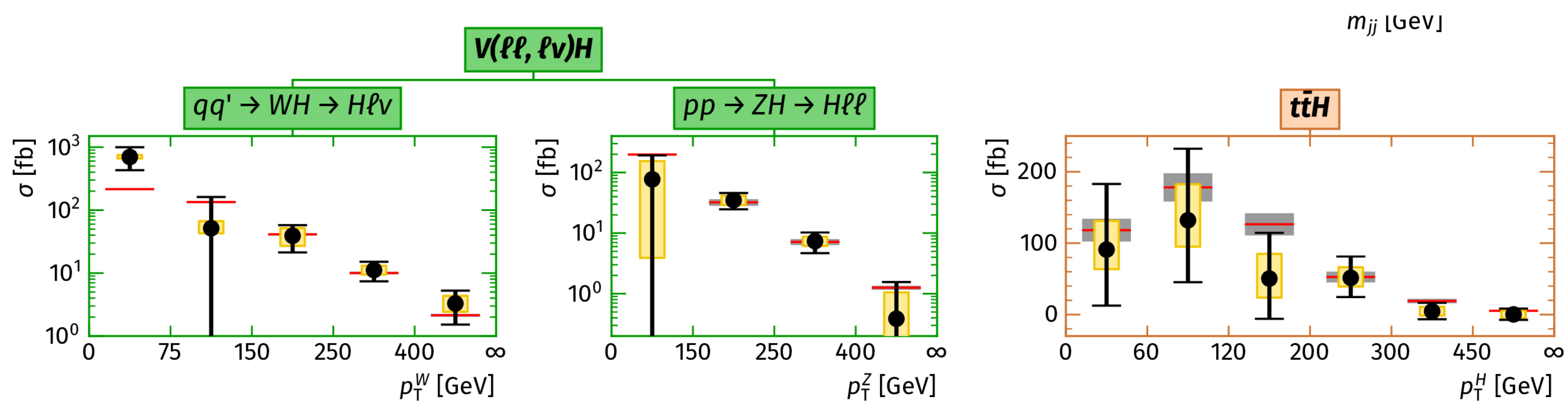
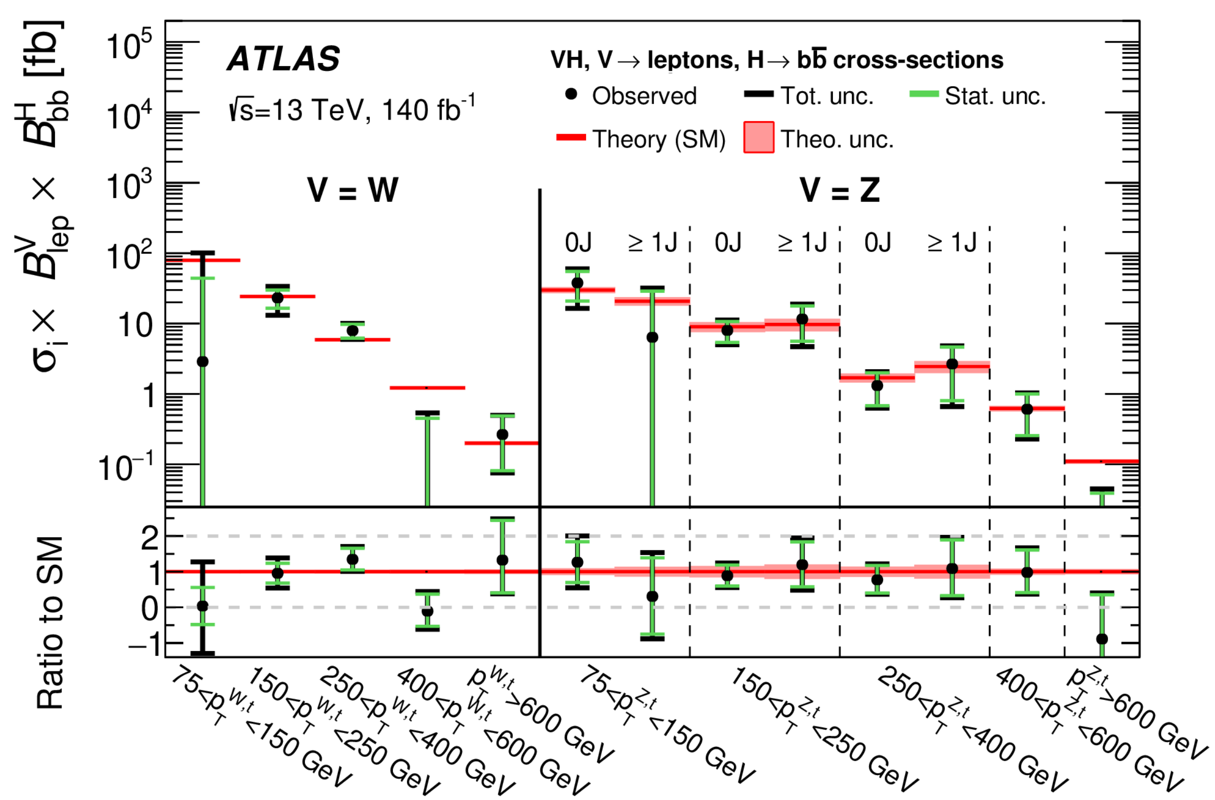
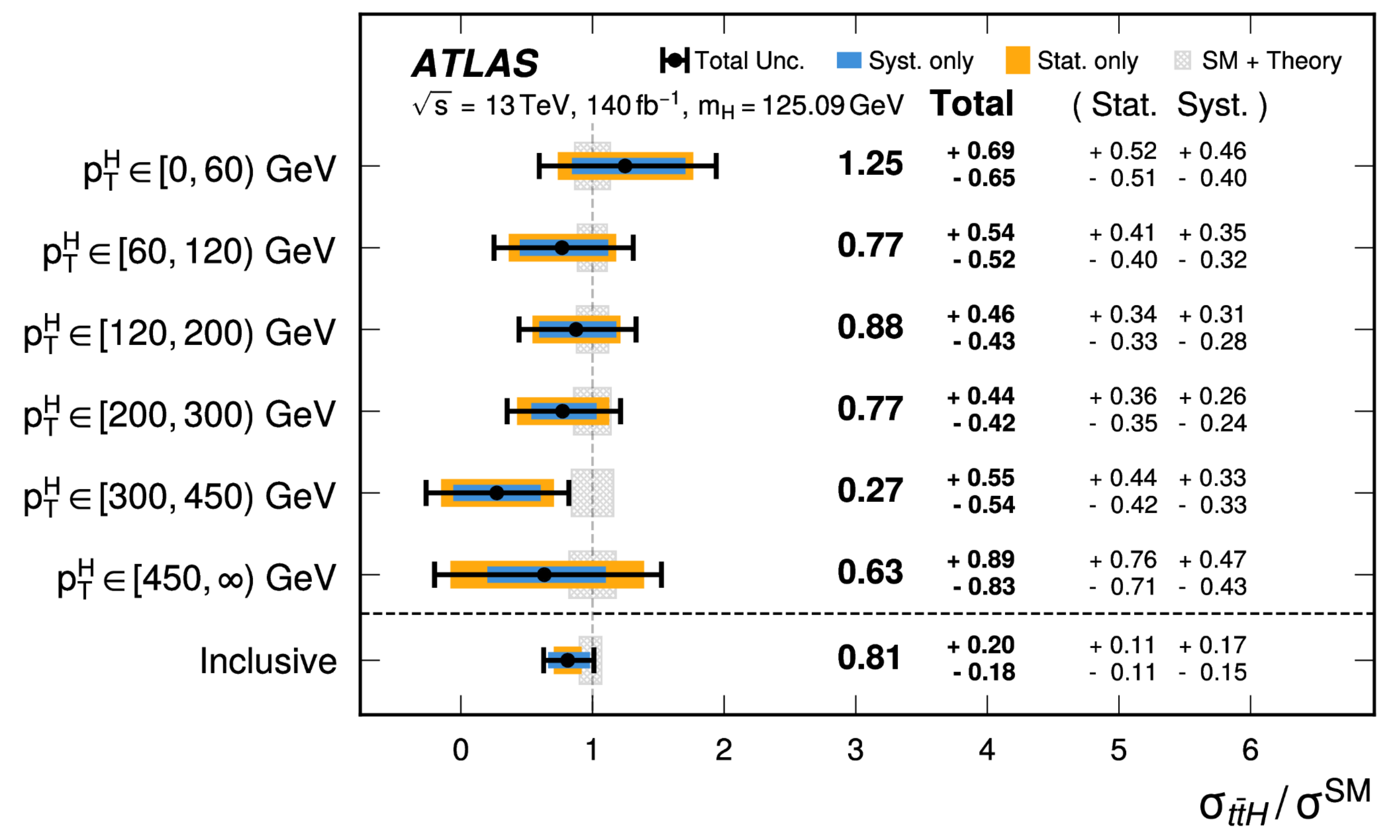


You have already seen them…



To be updated to include…

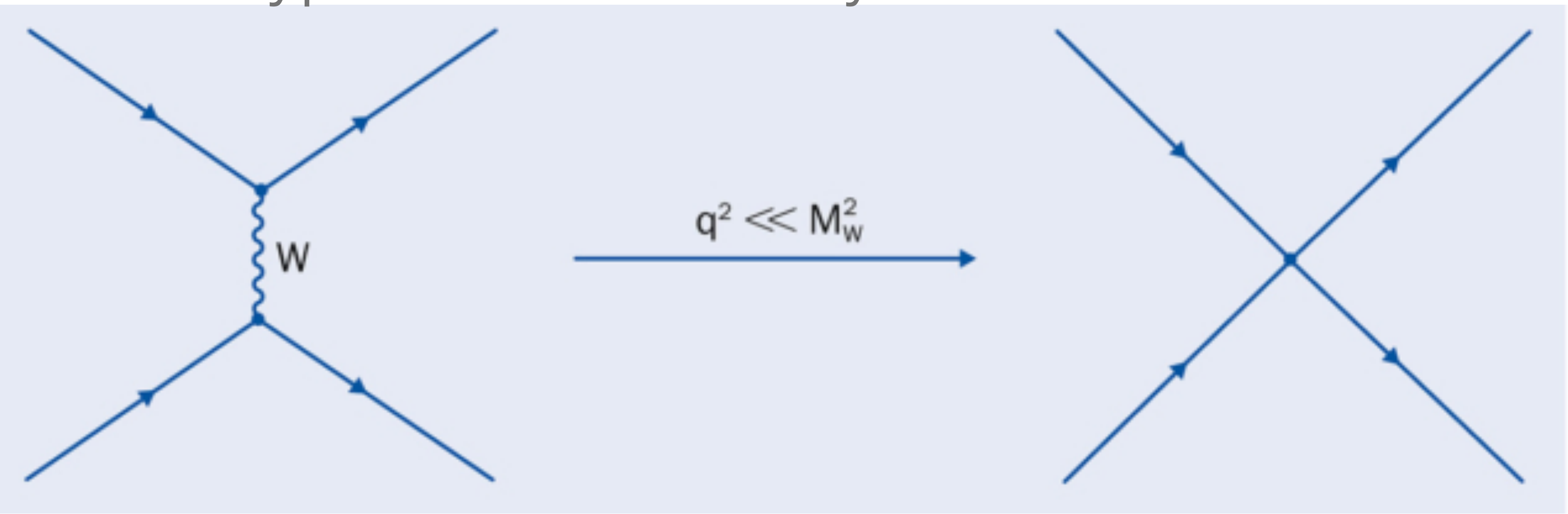




work ongoing…

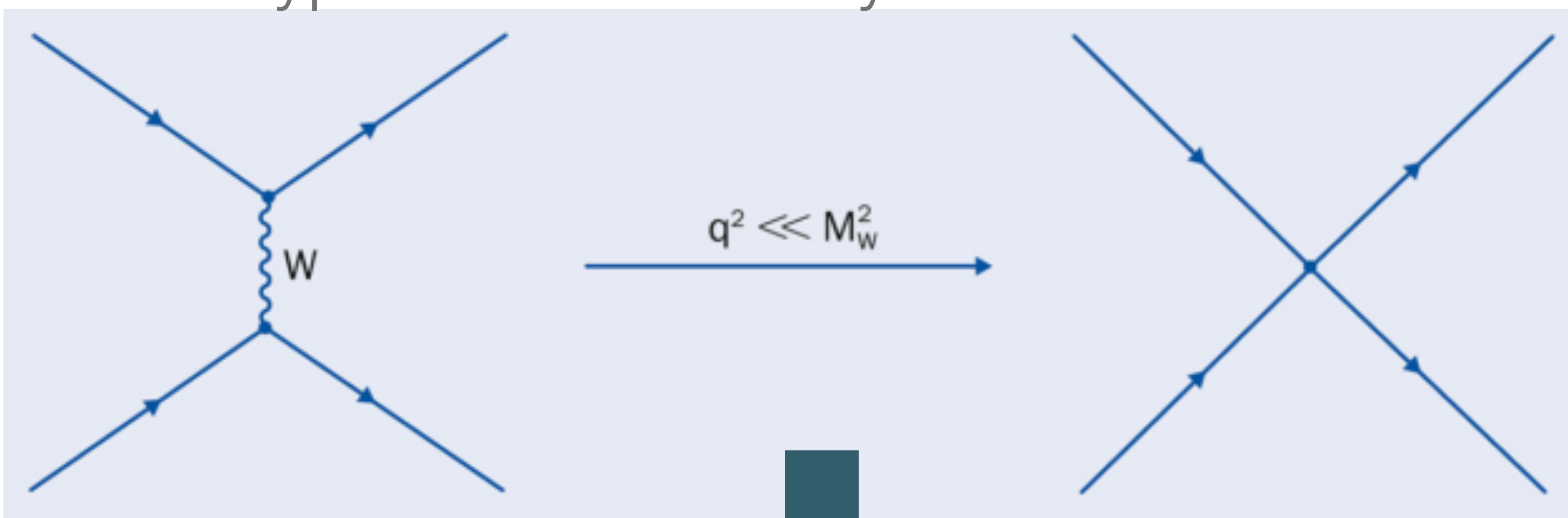
Beyond the coupling modifiers: Effective field theory

Prototype: Fermi's theory of weak interactions



Beyond the coupling modifiers:
Effective field theory

Prototype: Fermi's theory of weak interactions



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{j}^{N_{d=8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots,$$

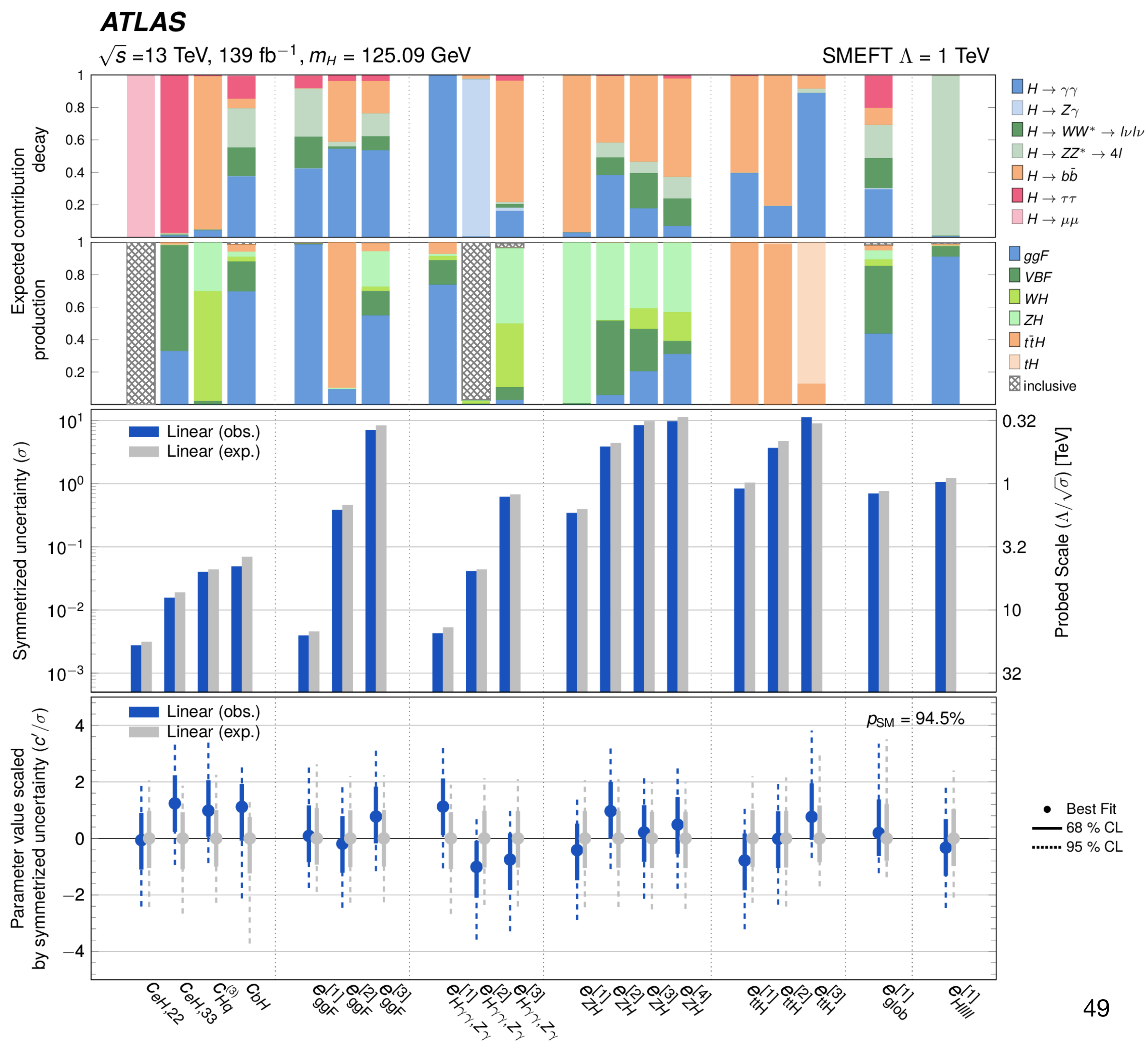
- Effective Lagrangian maps measured deviations into effective operators between the fields of the Standard Model.
- Systematic development of all possible contributions in series of $1/\Lambda$, where Λ represents the characteristic scale of new physics.
- BSM models with sufficiently high scales Λ are mapped into these developments.

Beyond the coupling modifiers: Effective field theory

[JHEP 11 (2024) 097](#)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

- Results obtained by combining all production and decay channels.
- The results include kinematic information.
- It is interesting to note the overall contribution of each production and decay channel.
- There are no significant deviations from the Standard Model.



Beyond the coupling modifiers: Effective field theory

JHEP 11 (2024) 097

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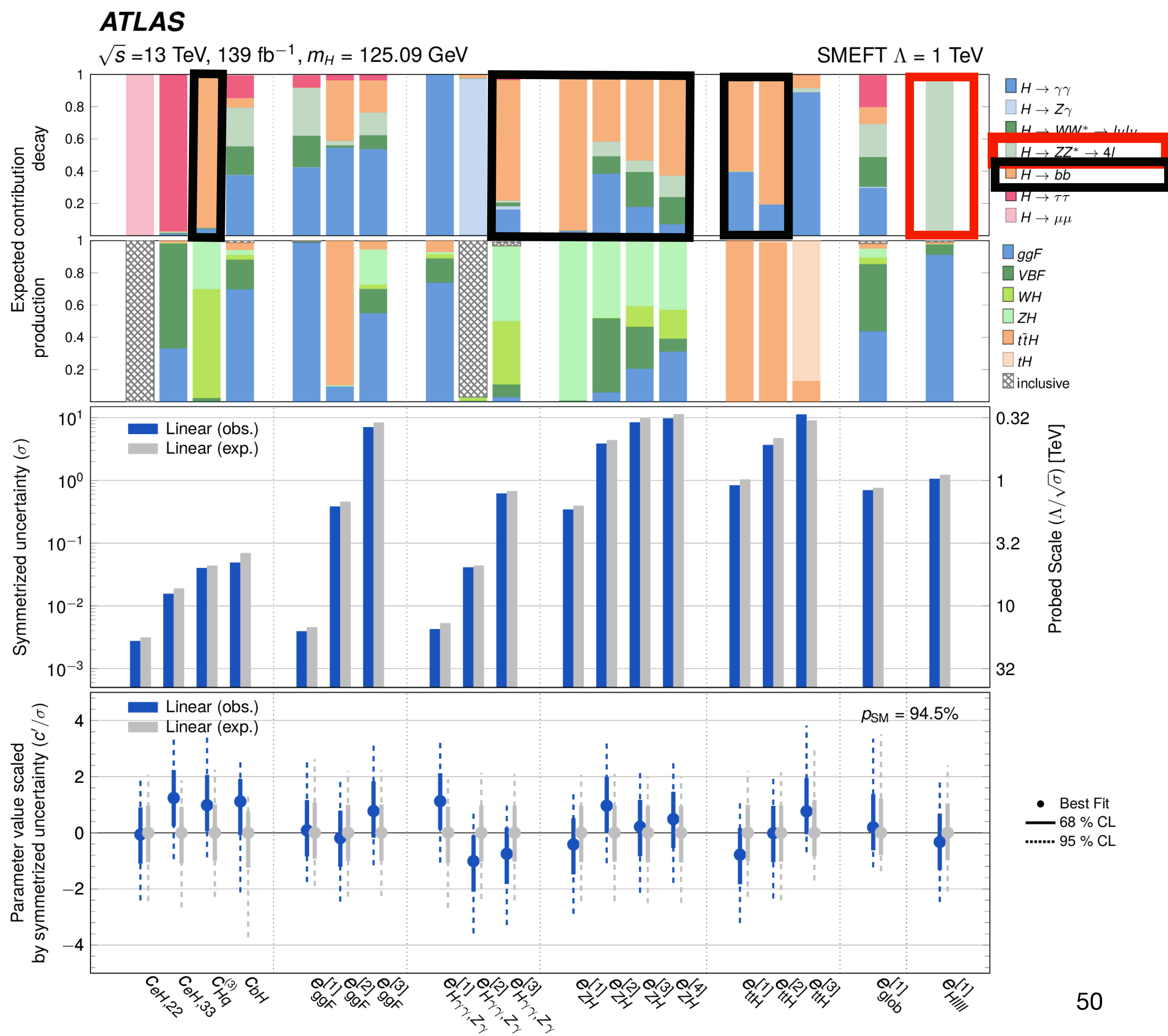

Four (among the various) questions...

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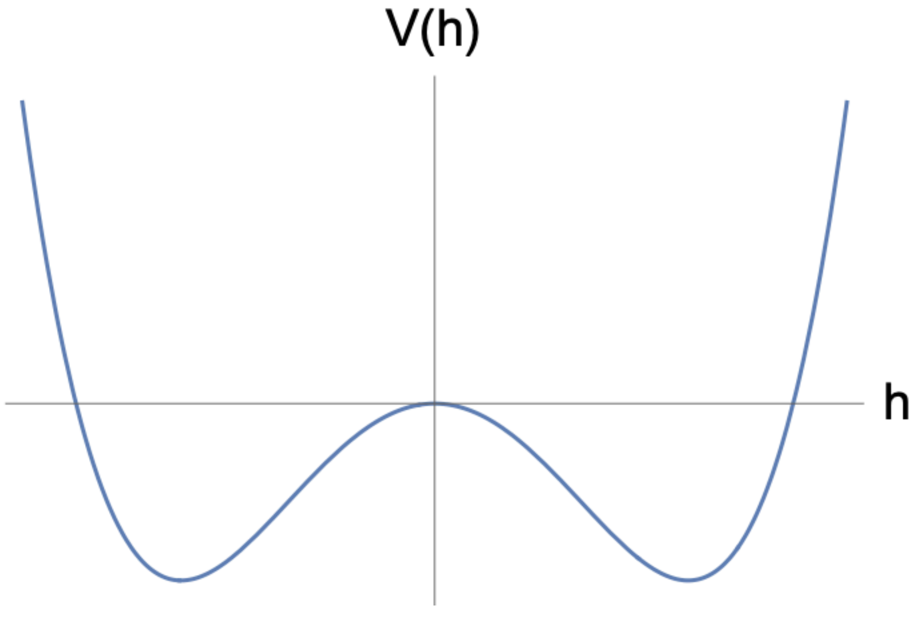
- **What is the dynamics that led to this "special" vacuum state?**

The potential

All the peculiarities of the Higgs field and the Higgs boson arise from the form of its potential.

A similar potential is present to describe superconductivity in the Ginzburg-Landau model (1950).



$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$

$$V(\Phi) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda \nu H^3 + \frac{1}{4} \lambda H^4$$

$$m_H = \sqrt{2}\mu$$

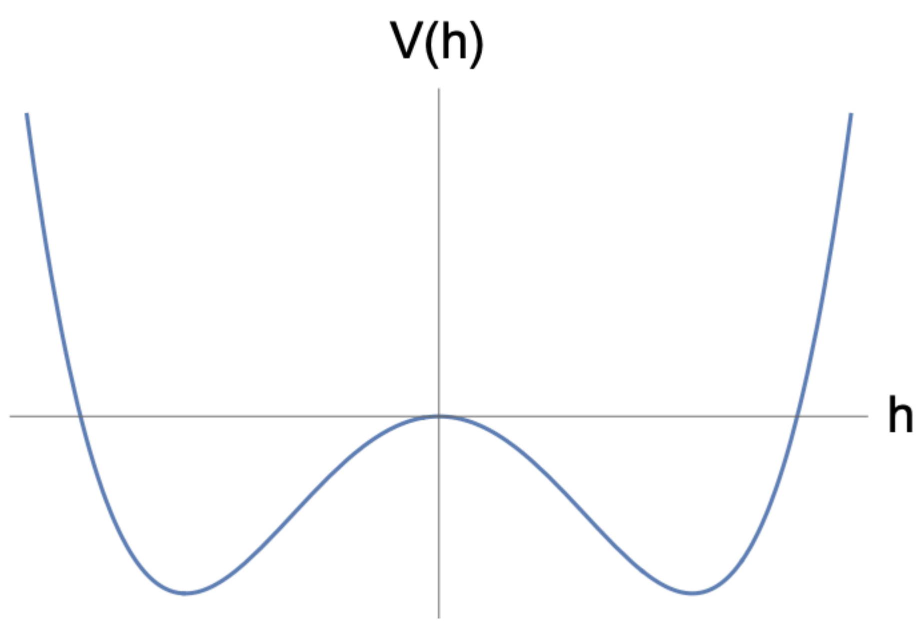
The potential

All the peculiarities of the Higgs field and the Higgs boson arise from the form of its potential.

A similar potential is present to describe superconductivity in the Ginzburg-Landau model (1950).

As in GL, the potential is introduced "by hand."

BUT in superconductivity, in 1957, a motivation for the potential came with the BCS theory.



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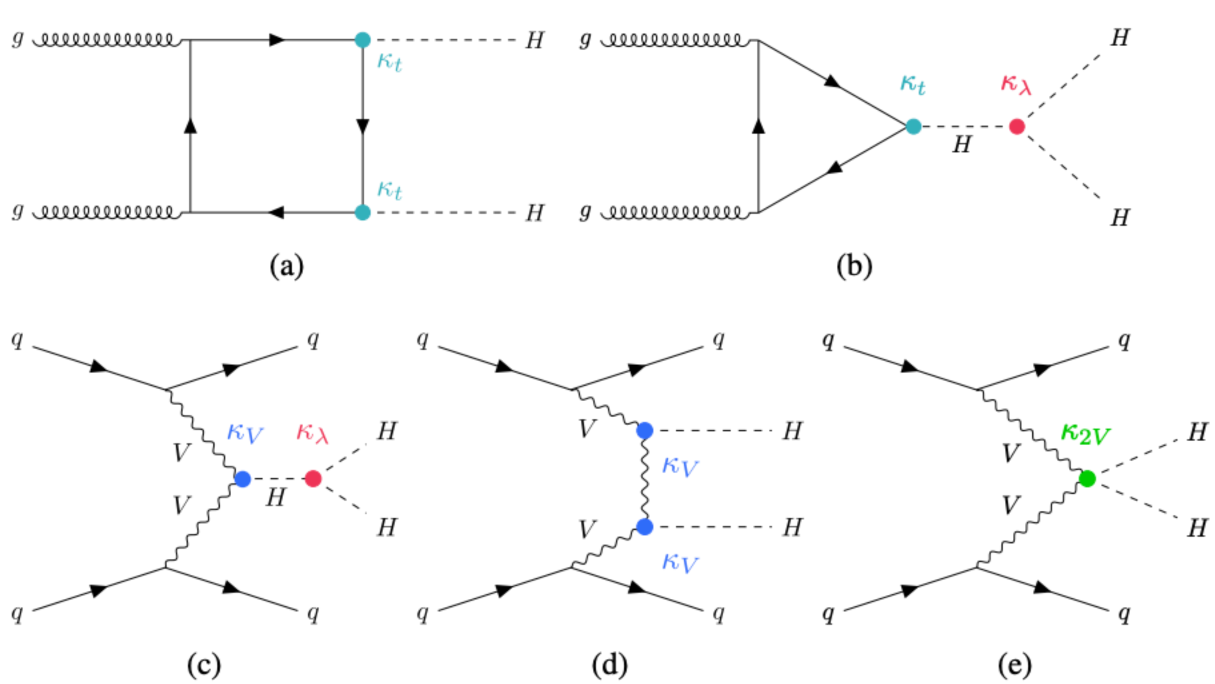
$$m_H = \sqrt{2}\mu$$

Phys. Rev. Lett. 133 (2024) 101801

Double Higgs

$$V(\Phi) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda \nu H^3 + \frac{1}{4} \lambda H^4$$



	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%

The measurement of the production of 2 (or more) Higgs bosons is the main tool to verify if the parameter λ is equal to the value expected from the theory.

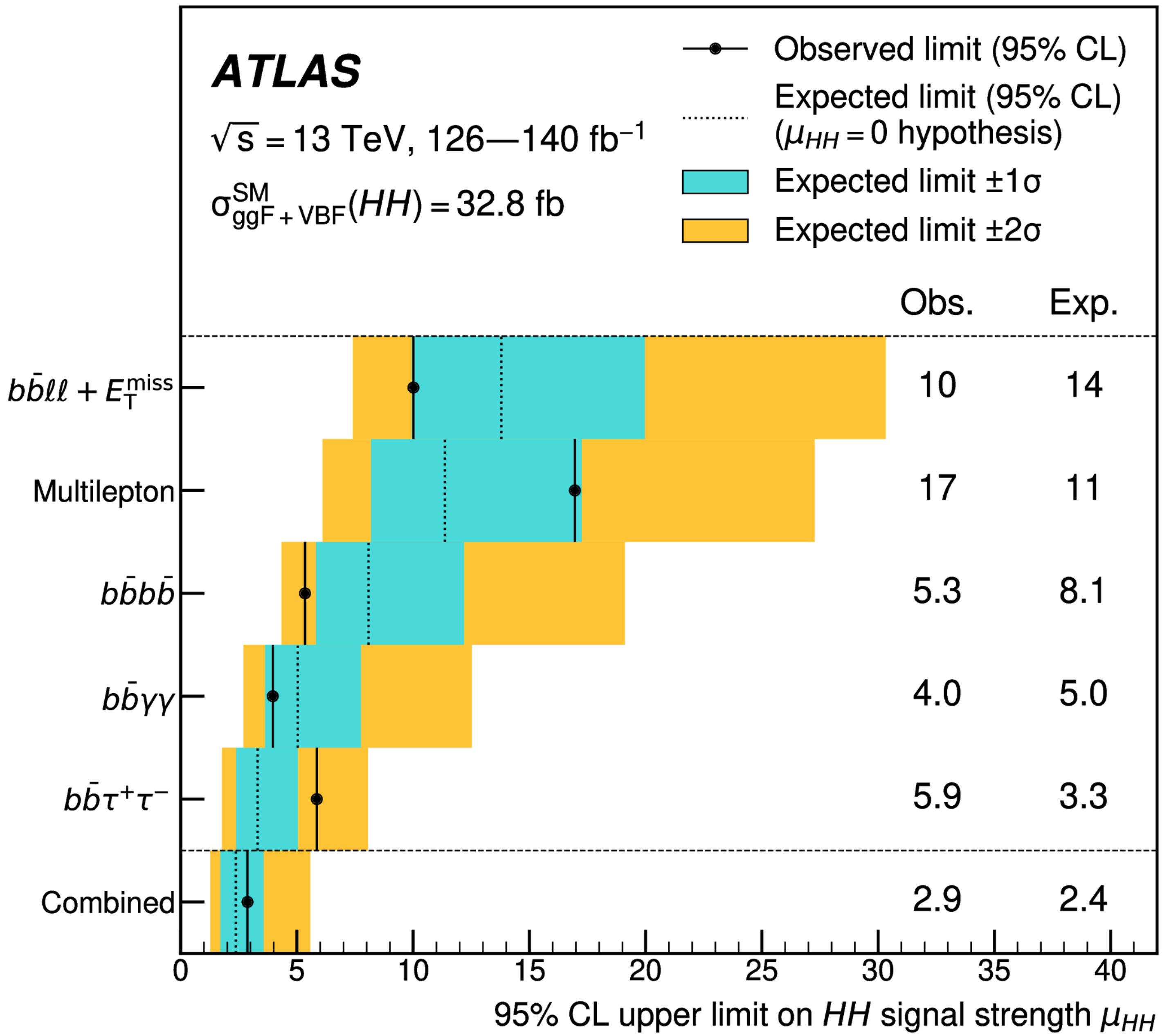
Phys. Rev. Lett. 133 (2024) 101801

ATLAS Run 2 combinations

Combine HH→bbττ + bbγγ + bbbb + multileptons + bbll+MET:

$$\mu_{HH} = 0.5\,^{+1.2}_{-1.0}\left(\,^{+0.7}_{-0.6}\ \text{syst.}\right)$$

Uncertainty comparable to SM signal!

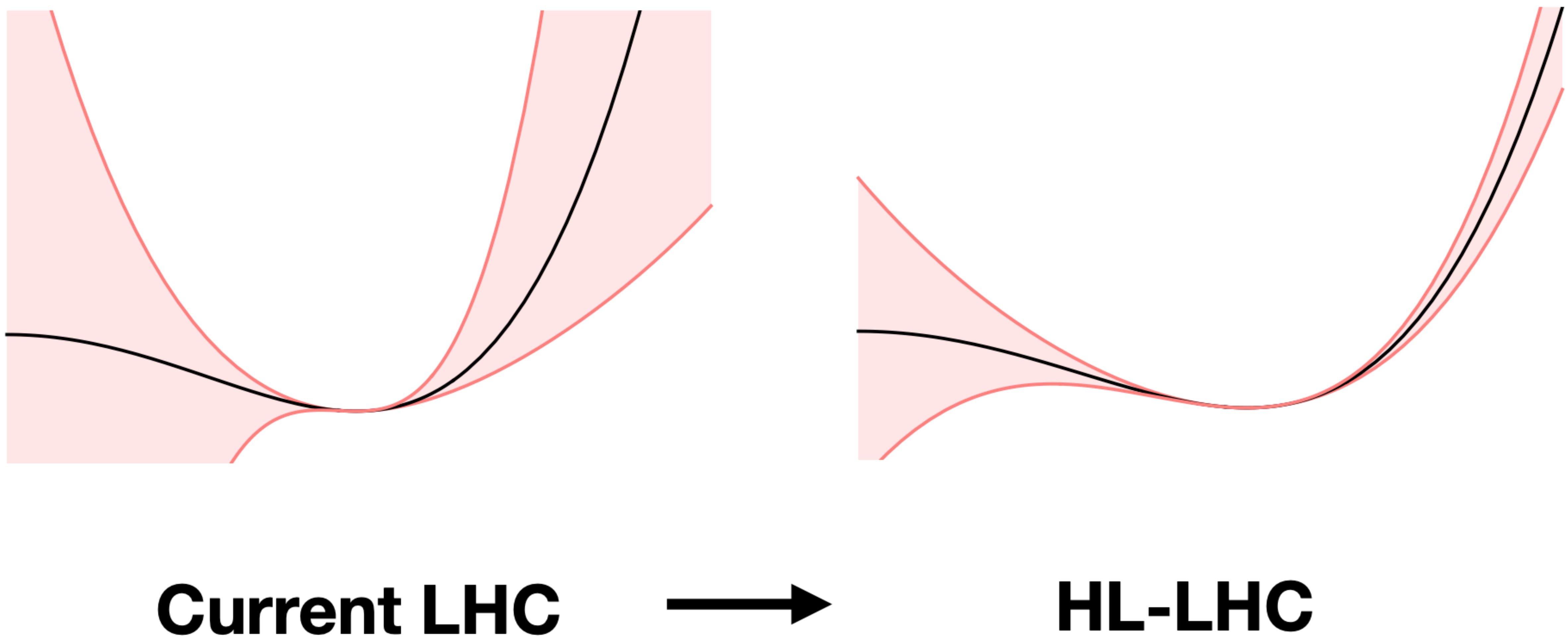


Self coupling

-1.2 < κ_λ < 7.2 @ 95% CL

Dominated by γγbb + ττbb Best constraint to date on k_λ coupling!

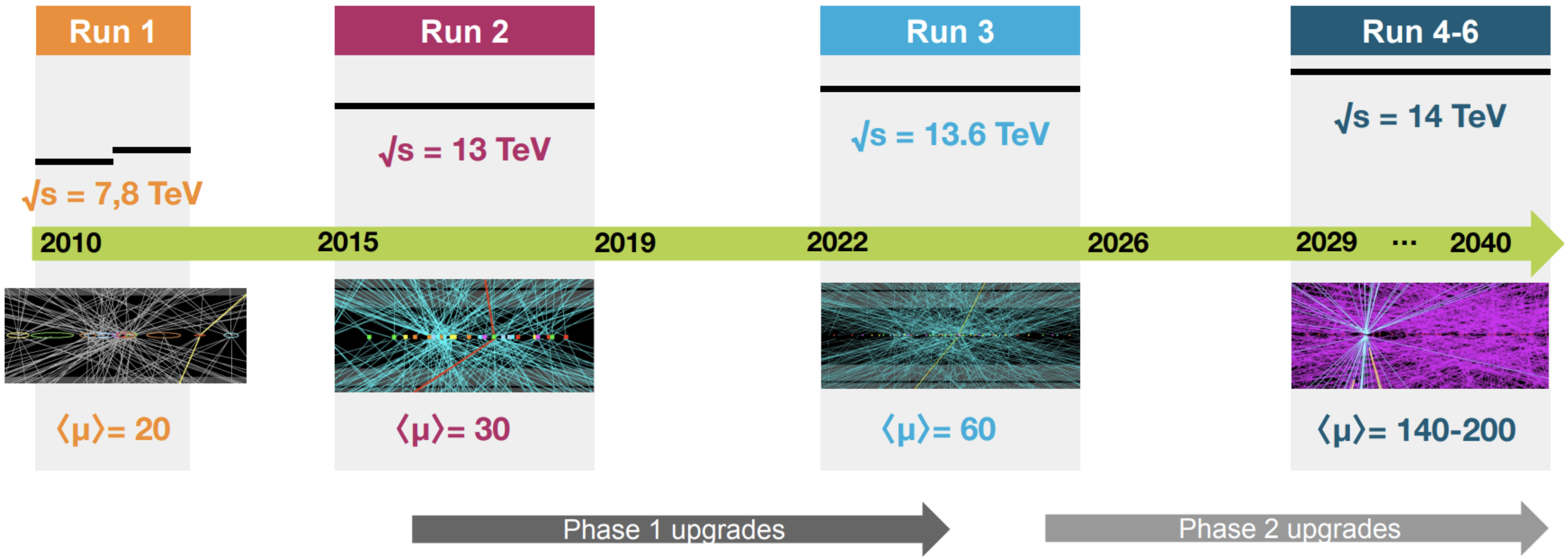
How well do we know the potential today?



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

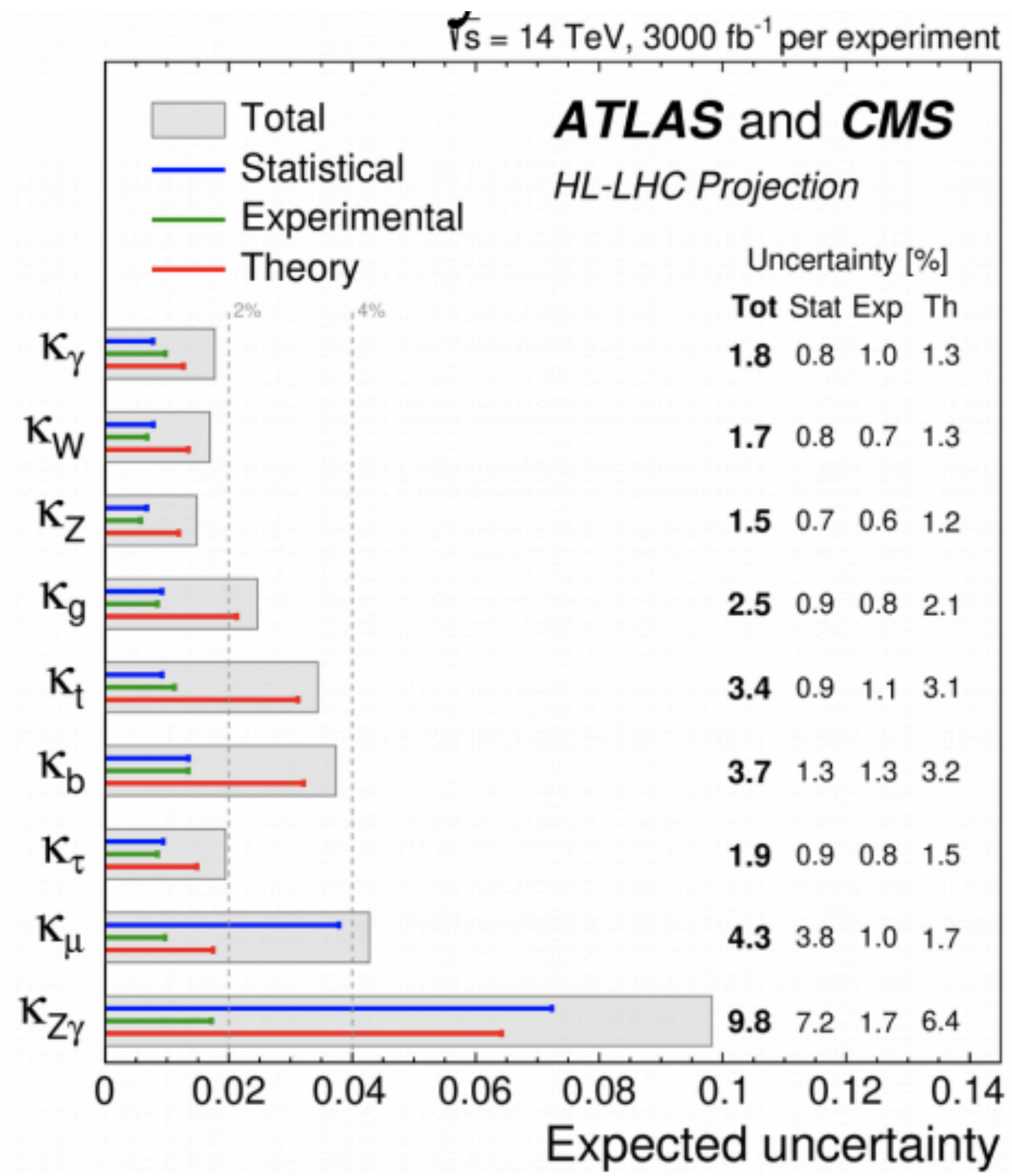
LHC schedule

From L. Brost's slides



- Instantaneous luminosity: 5–7.5 times higher
  - Pile up will increase from 60 (now) to 140-200 (levelled)
  - Beam induced cavern background increases linearly
  - Much larger radiation to detectors
  - Larger data sample: big challenges for computing and data storage
- Require improvements for experiments in all areas
  - Detectors, Electronics & Trigger, Software and computing

Projections: Higgs couplings



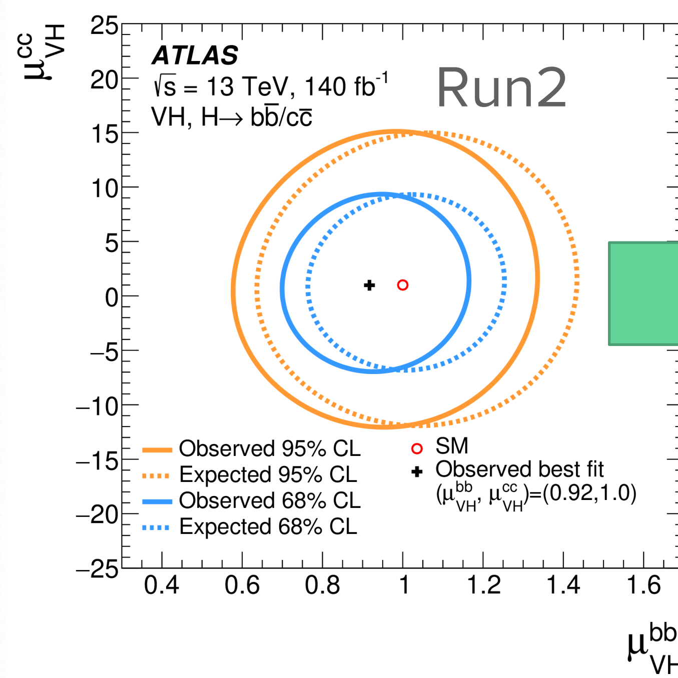
CERN-2019-007, 2019

Higgs couplings move into precision regime

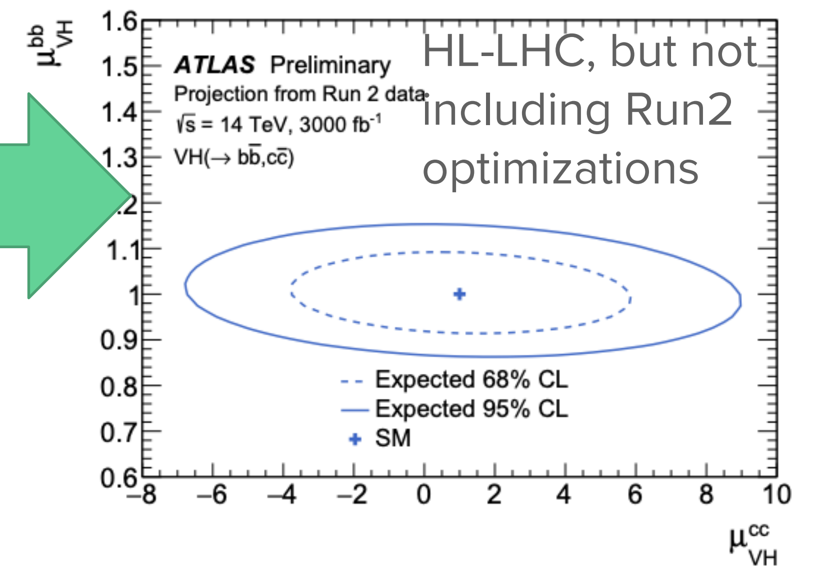
- Bosons and τ: <2% level
- 3rd generation quarks: 3.5%

Most of them dominated by theory uncertainties

HIGG-2020-20

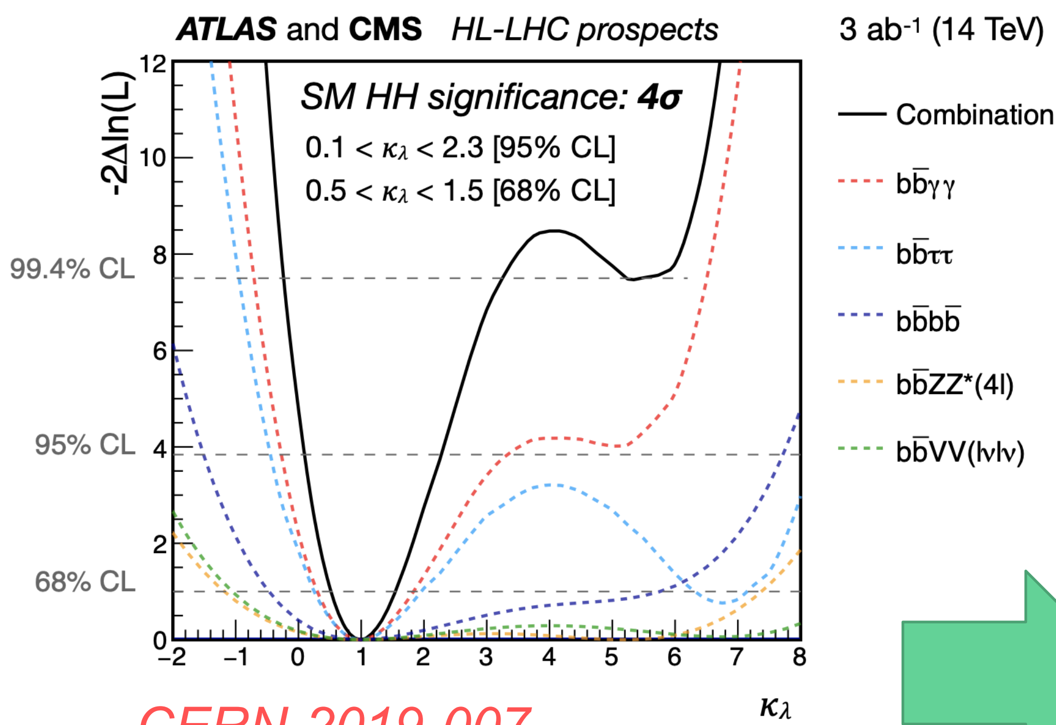


ATL-PHYS-PUB-2021-039

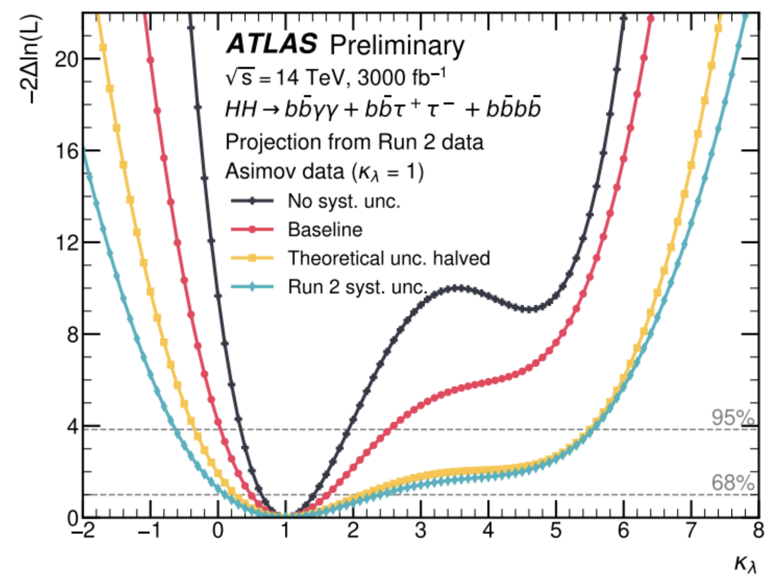


Do we already know we can do better?

Projections: Higgs self-coupling



CERN-2019-007, 2019



ATL-PHYS-PUB-2022-053

and today ?

European Strategy (2018)

Combination of 5 HH channels, based on partial Run2 results

50% precision in self coupling

4σ for SM HH (ATLAS + CMS)

Snowmass+ (2022)

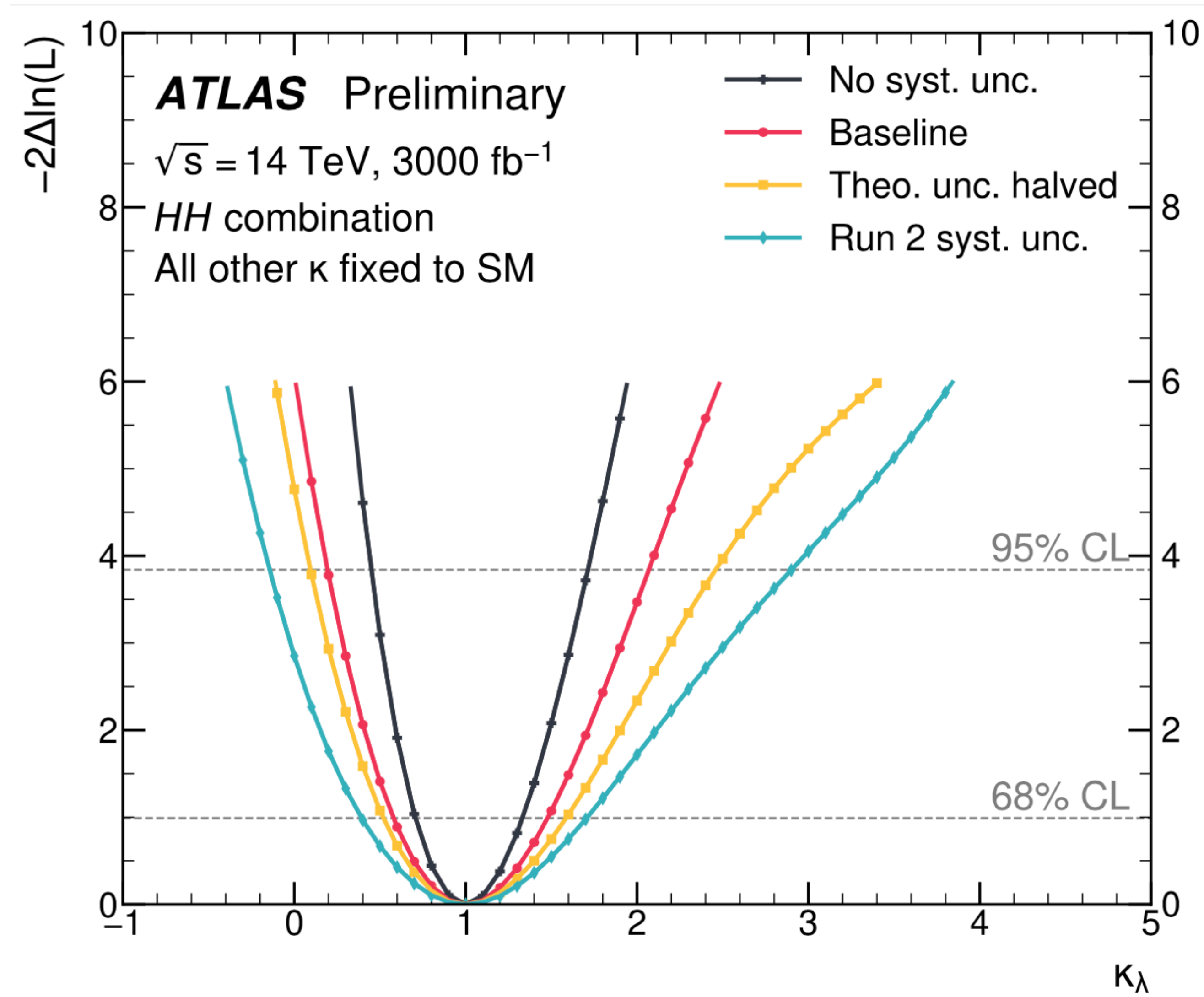
ATLAS Updated bbbb, bbγγ, and bbττ,
CMS updated bbγγ, γγWW, γγττ, ttHH

Likely 5σ from back of the envelope estimations

Off Press!

- @3ab-1 ATLAS alone will get to 45% accuracy on Higgs self-couplings, with conservative assumptions.

- To be presented today for the first time at the 161st LHCC Meeting OPEN Session



Conclusions

Very broad physics program on the Higgs boson at the LHC.

- Reaching an unforeseen level of precision for the amount of data we analysed!
- Significant reduction of uncertainties on all the couplings,
    - Second generation fermions are not anymore beyond our reach
- Di-Higgs is already reaching the SM sensitivity with Run2 data
    - And we have more Run3 collisions already on our disks!
- Completing the Run2 physics program
    - Final Run2 Combinations between LHC experiments
- Run3 offers us a unique opportunity to improve the precision of our measurements,
    - and surprises can always come….

Grazie dell’attenzione !

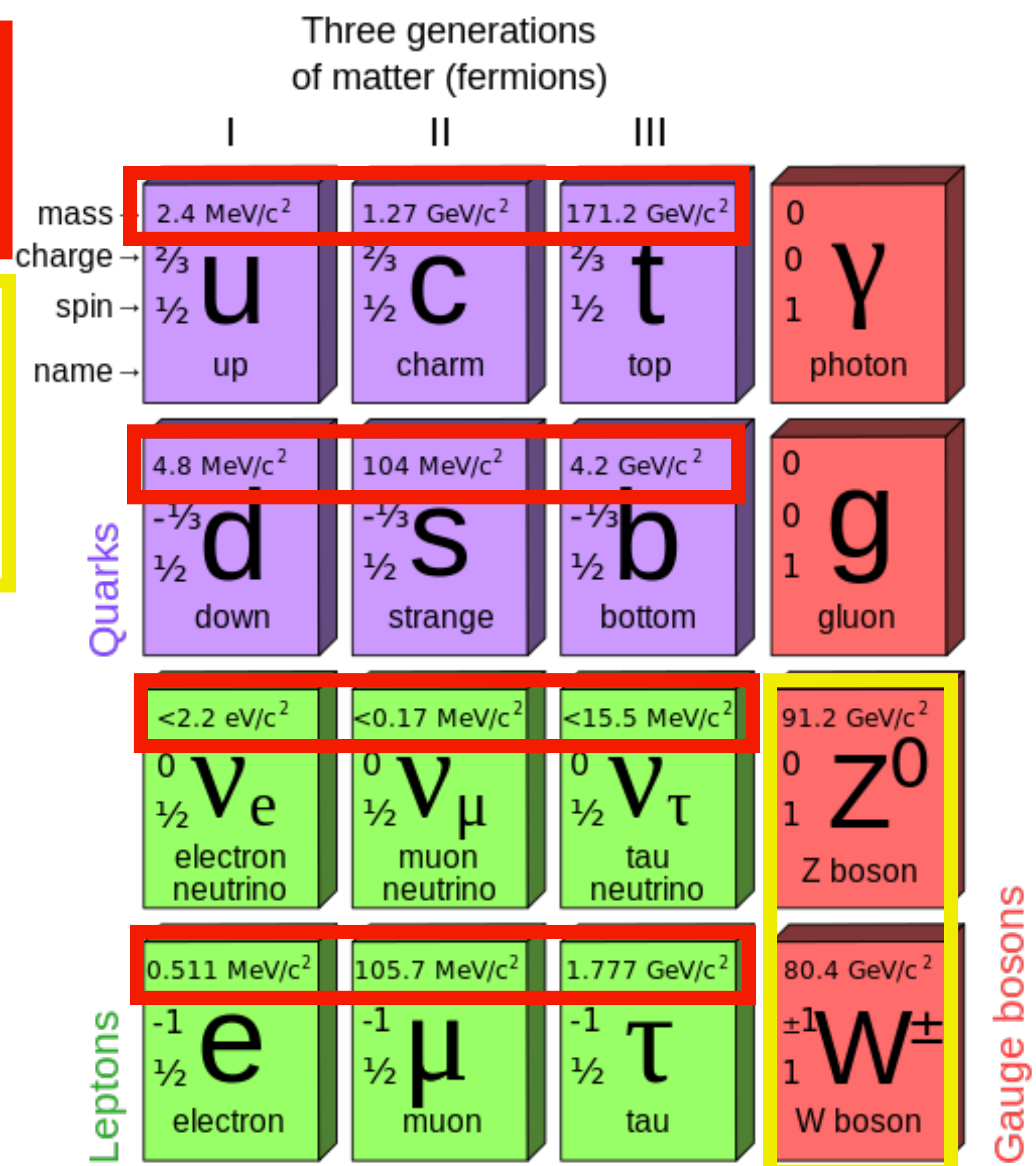
paolo.francavilla@cern.ch

Introduction

- Strangely, the masses appear to be more or less random numbers and do not seem to follow symmetry rules.

- Local symmetries at the foundation of the SM predict that the vector bosons should have zero mass.

- So why do the W and Z bosons have mass?



Introduction

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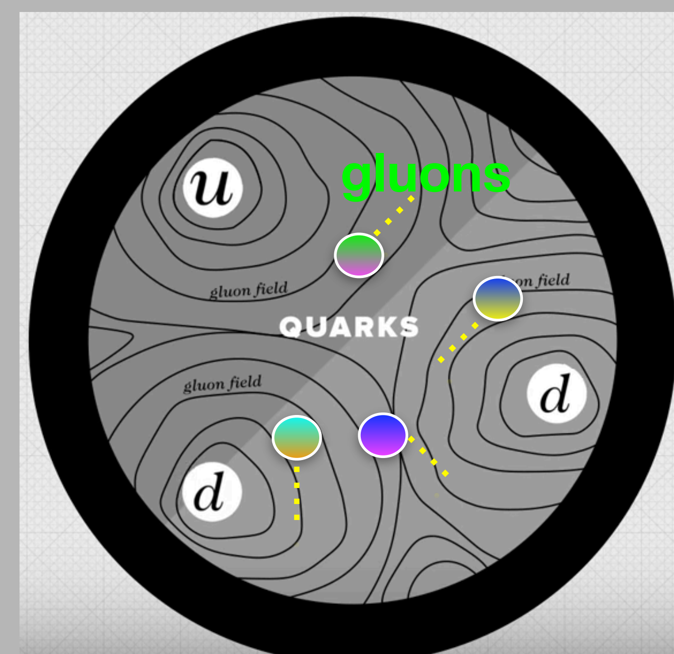
- Local symmetries at the foundation of the SM predict that the vector bosons should have zero mass.
- So why do the W and Z bosons have mass?
- Mass is an emergent property of a system, resulting from some type of interactions.

Example - the neutron



The mass of quarks accounts for only about

of the mass of neutrons and protons.

99% of an object's mass is due to strong interactions.

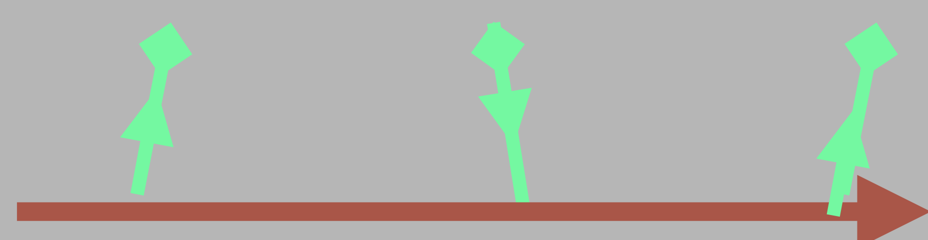
Introduction

- Strangely, the masses appear to be more or less random numbers and do not seem to follow symmetry rules.
- Local symmetries at the foundation of the SM predict that the vector bosons should have zero mass.
- So why do the W and Z bosons have mass?
- Mass is an emergent property of a system, resulting from some type of interactions.
- The Higgs field is introduced precisely to provide these interactions for fundamental particles.

The assumptions in the Brout-Englert-Higgs mechanism are:

- Existence of a new **fundamental scalar field**, **the Higgs field;**
- In nature, the Higgs field exists in a **condensate state**;

  in fact, this state is present everywhere and determines **some of the peculiar properties of the vacuum.**
- The Higgs condensate **continuously interacts** with the **particles of the Standard Model**.
- The **interaction** between the Higgs field and the particles of the Standard Model is **stronger the greater the mass of the particle.**



Introduction

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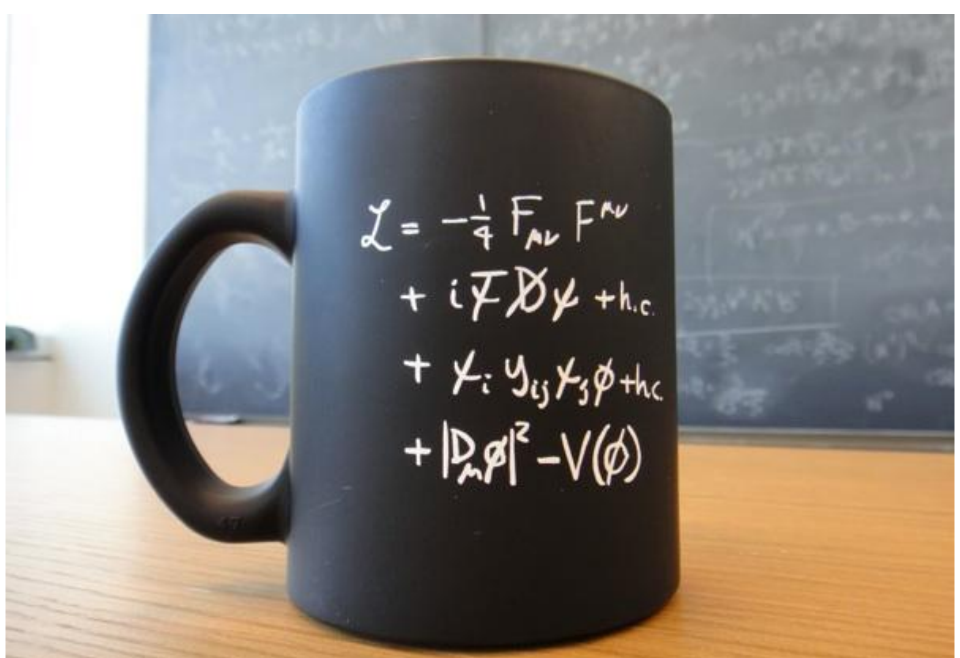
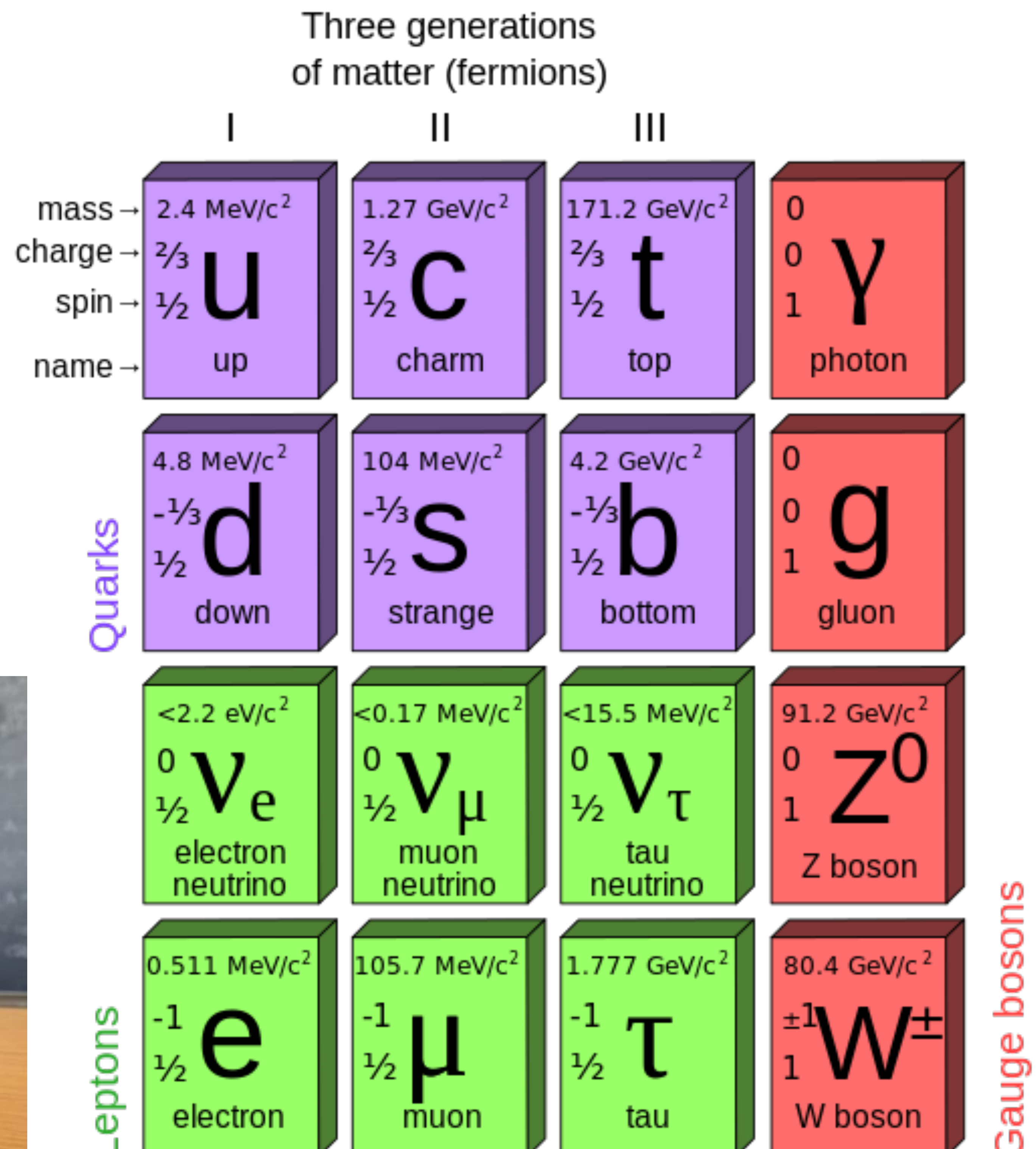
Predicted Higgs Boson – The mechanism implies the existence of a new scalar particle, the Higgs boson, which was later discovered at the LHC in 2012.

Introduction

- The Standard Model (SM) describes the fundamental interactions tested so far in the laboratory.
- Electromagnetic, weak, and strong interactions are mediated by photons (γ), W and Z bosons, and gluons (g).
- Among the foundational ideas of the SM is the concept of symmetry (gauge symmetry), which plays a central role.

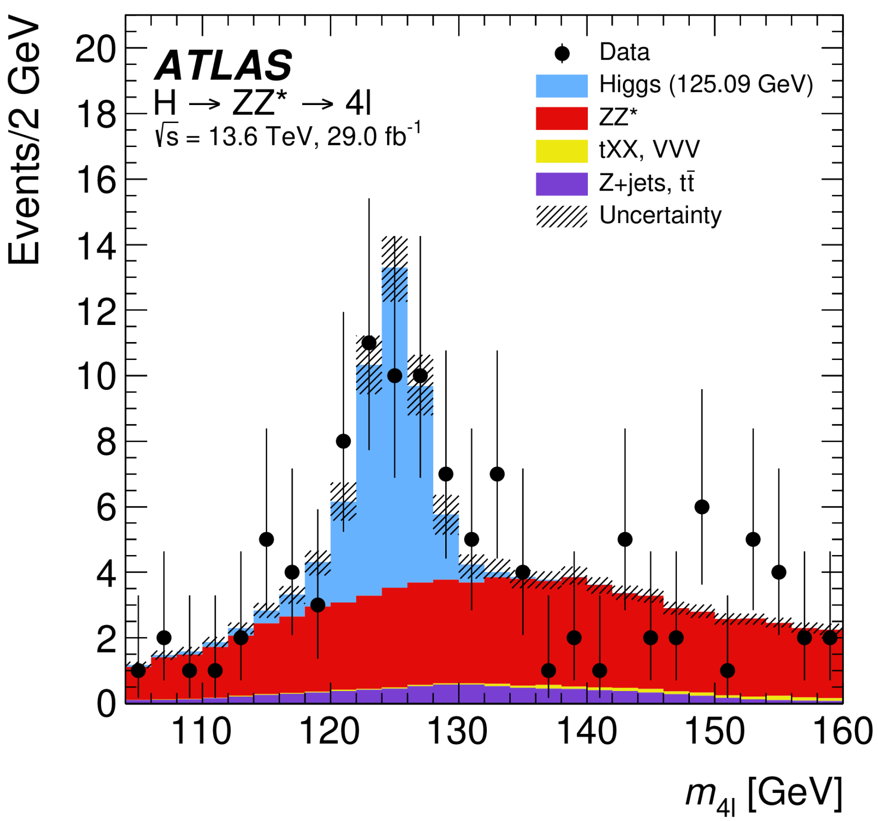


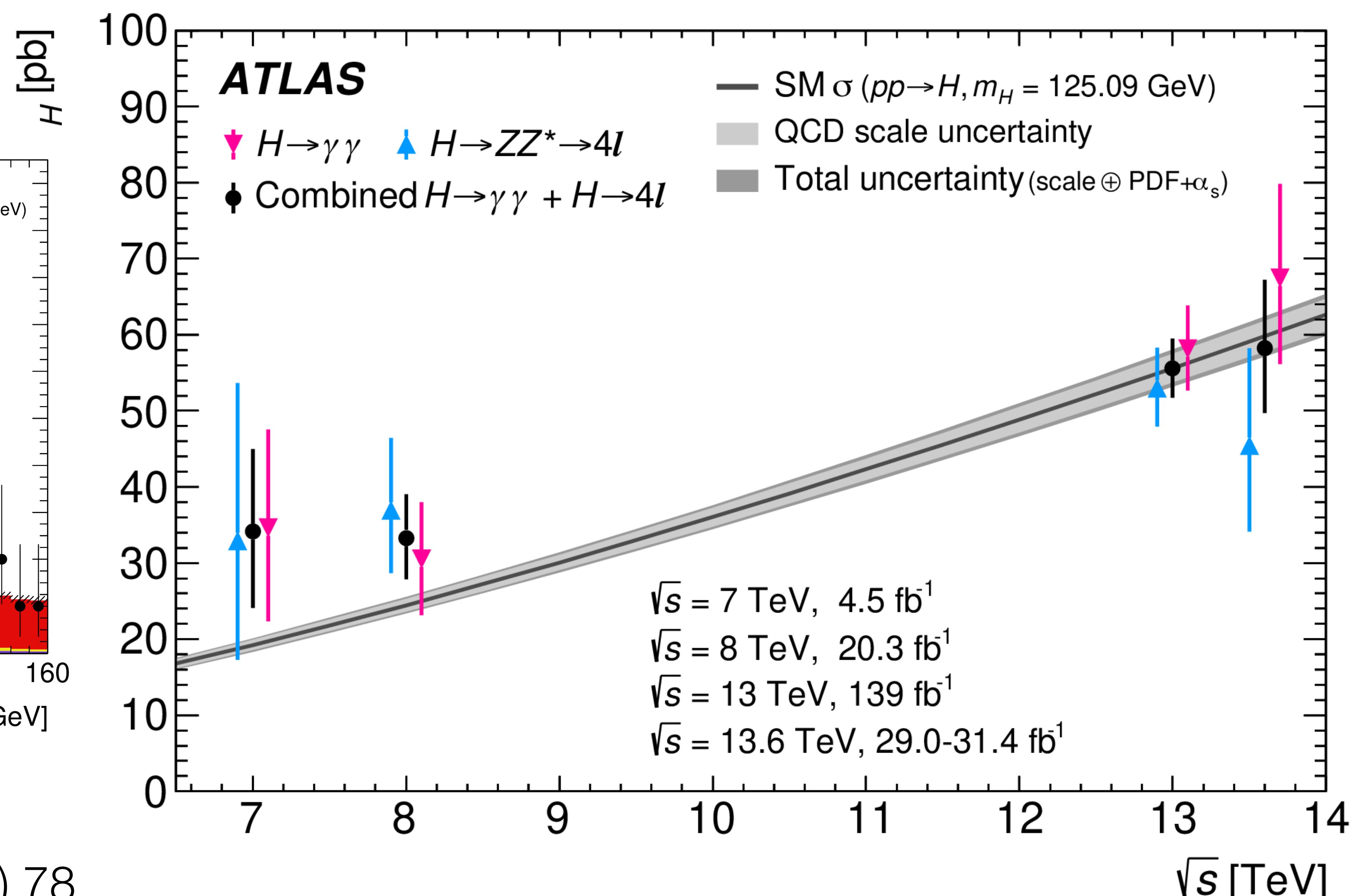


First measurement of the Run3

Analyse more data

With the 2022 data, a first measurement of the production cross-section at 13.6 TeV was made.



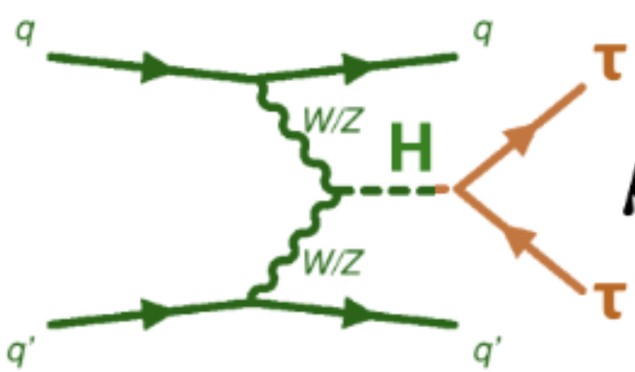


Eur. Phys. J. C 84 (2024) 78

Higgs-tau coupling

H ➔ ττ largest BR to leptons (6%)

Sufficient statistics and low enough backgrounds for precise measurements for **VBF**:

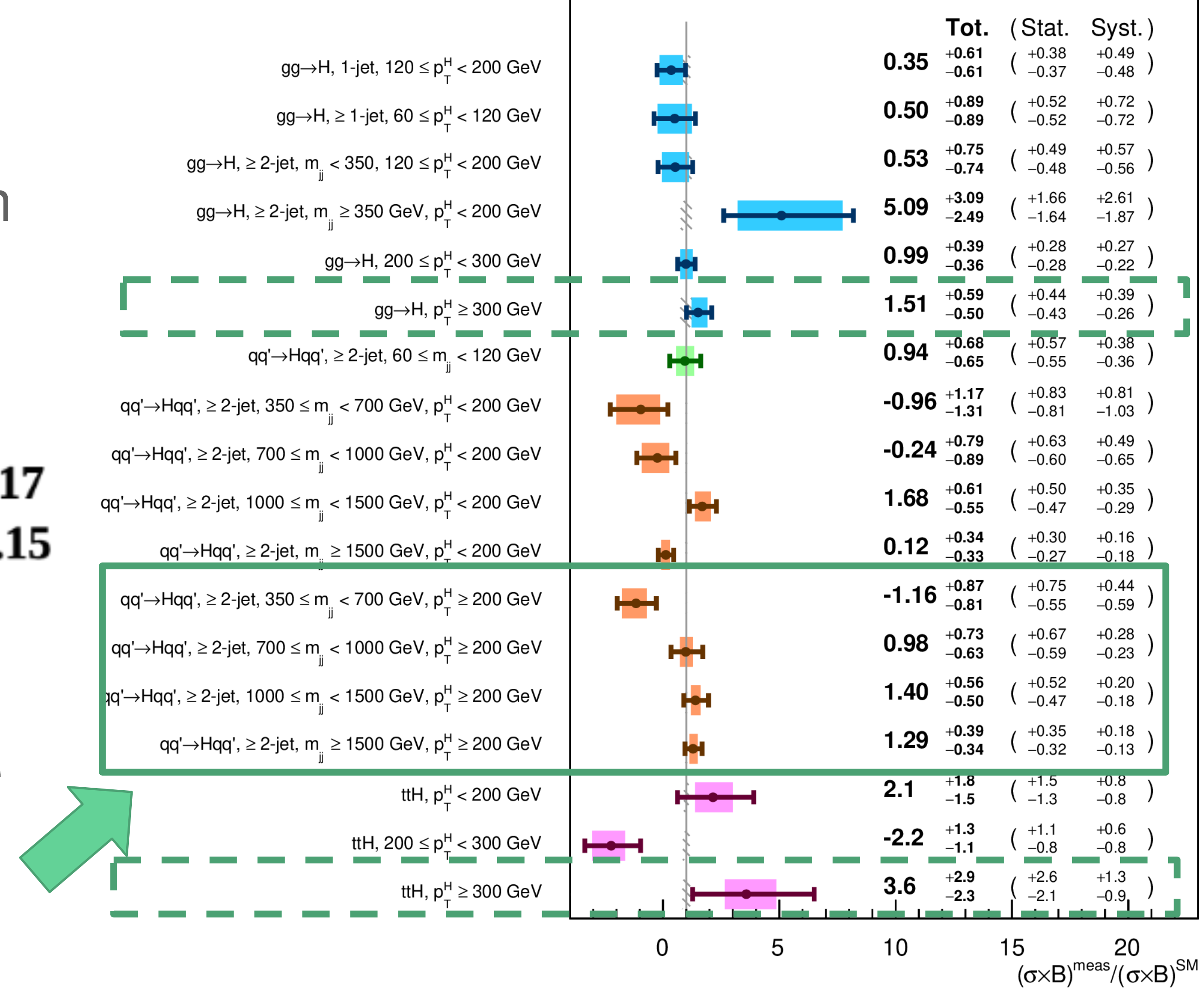


$$\mu_{\mathrm{VBF}} = 0.93\,^{+0.17}_{-0.15}$$

Most precise measurement to date

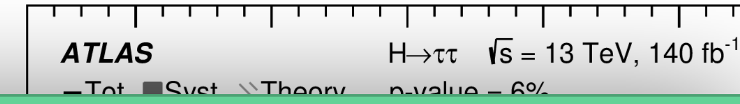
First measurement in multiple m_{jj} bins for the higher $p_T(H)$

HIGG-2022-07



Higgs-tau coupling

[HIGG-2022-07]

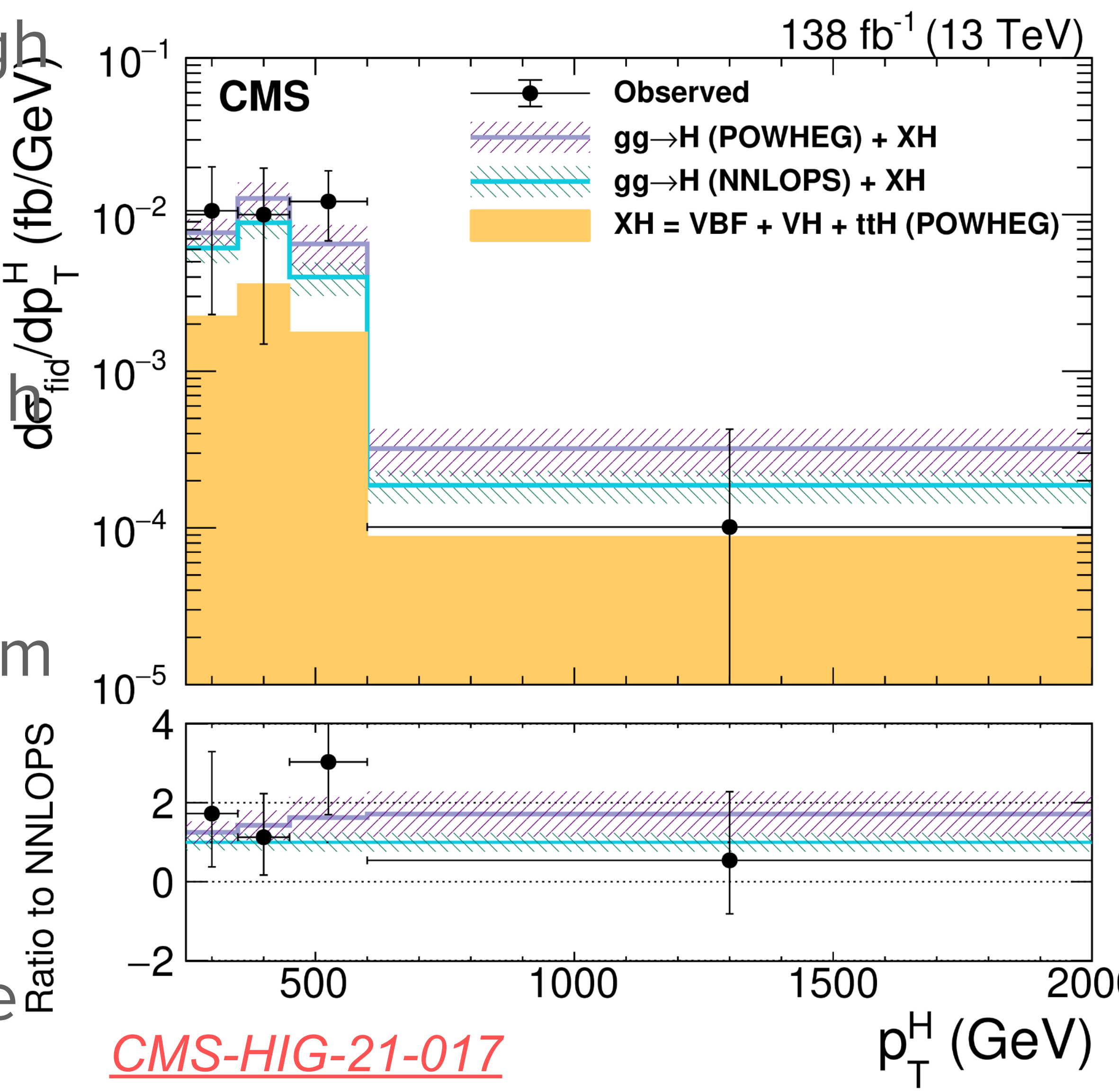


Sufficient statistics and low enough backgrounds for precise measurements at **high p_T(H)**:

First measurement of boosted high p_T(H) using the H → ττ

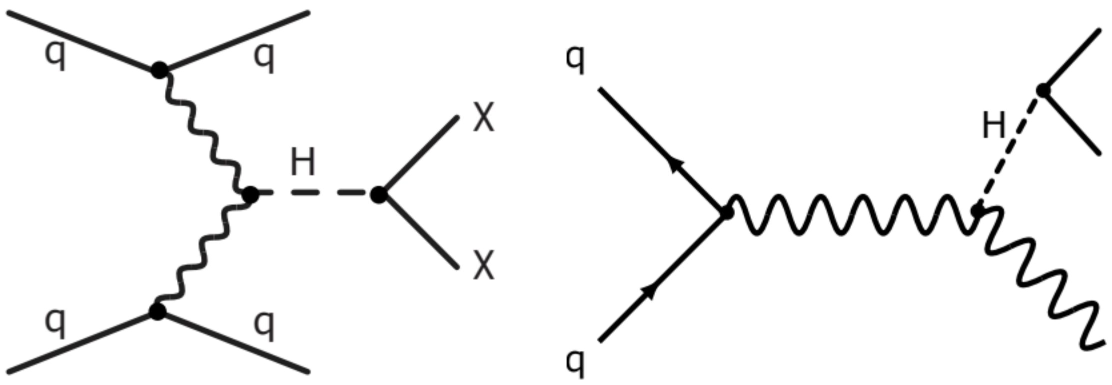
Dedicated reconstruction algorithm for the boosted ττ topologies

Among the most precise measurements in the p_T(H) regime



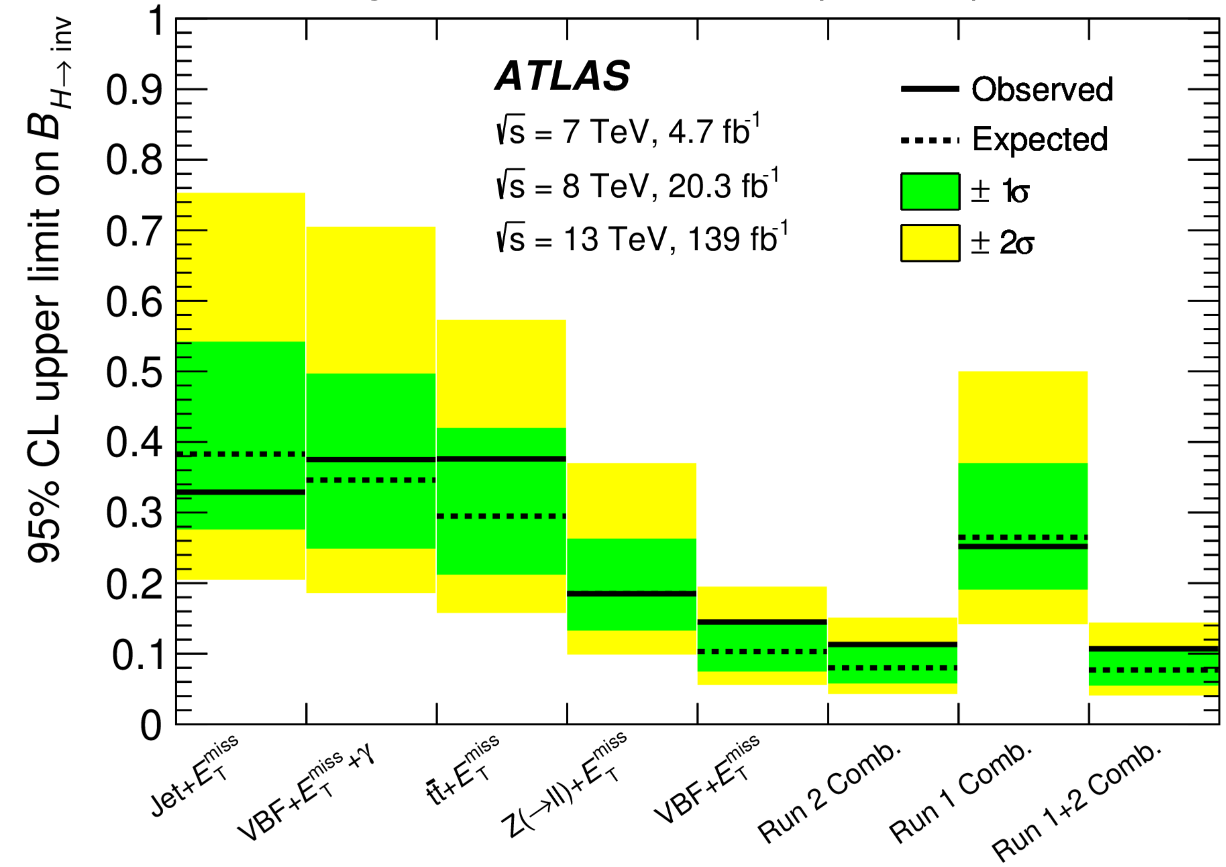
[CMS-HIG-21-017]

Higgs Invisibile

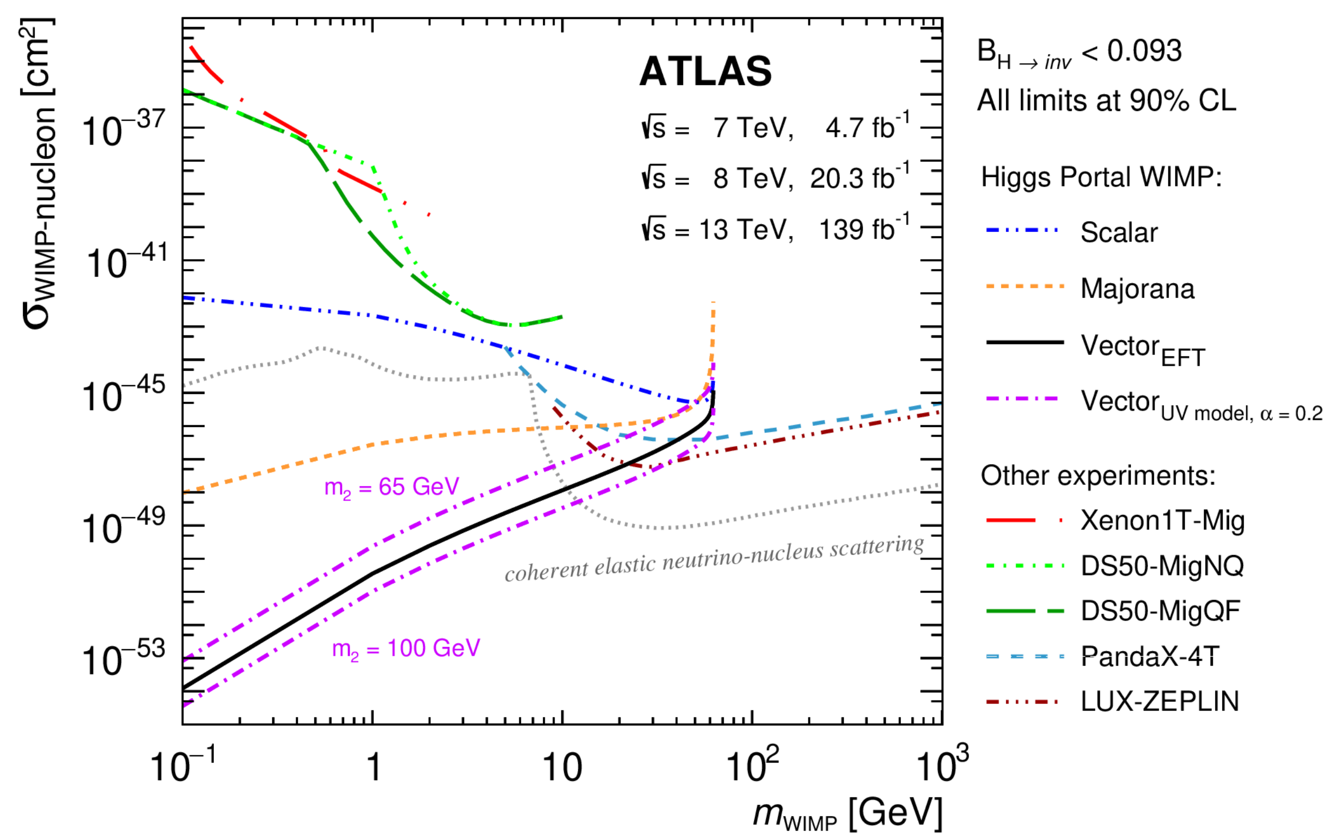


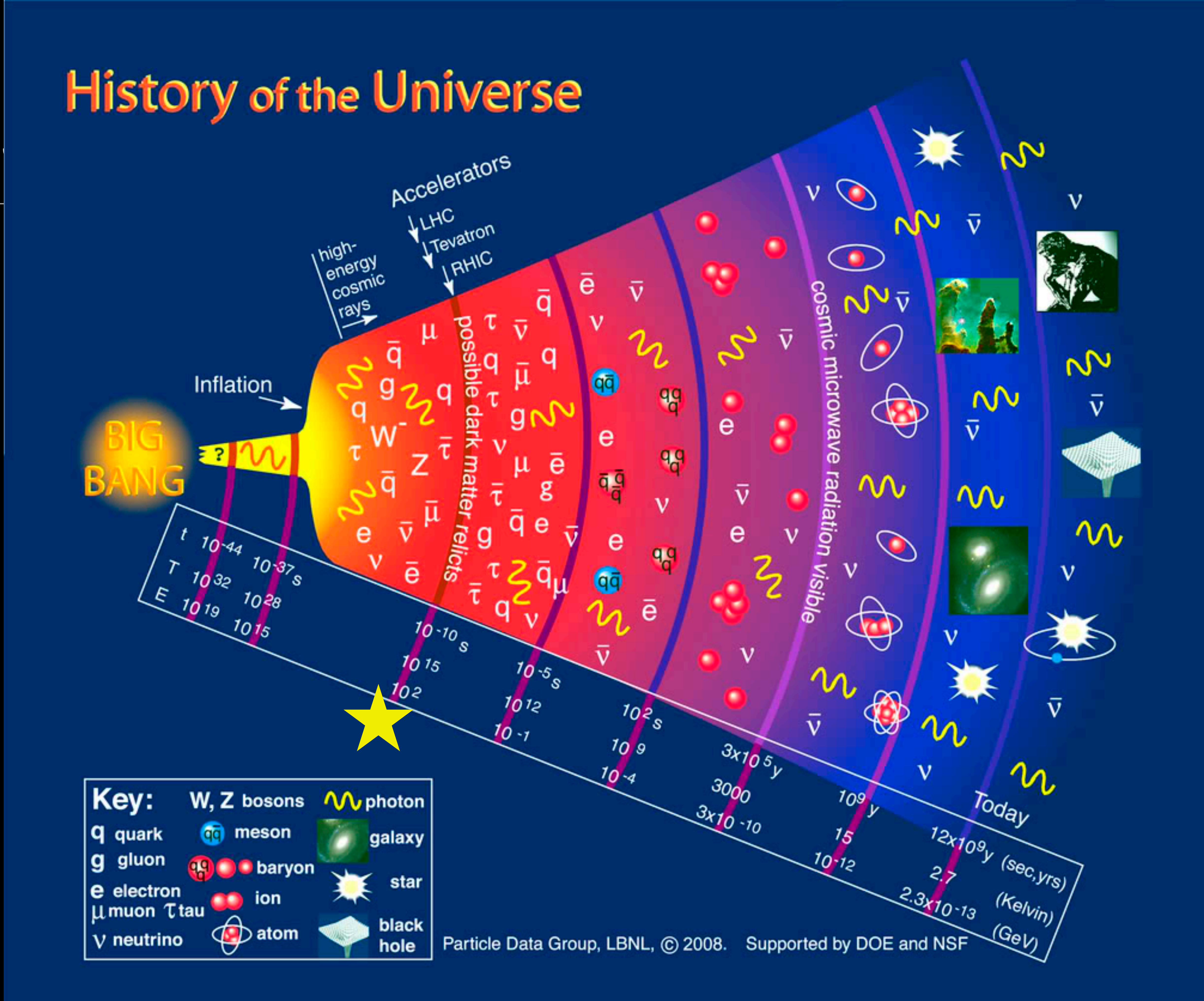
(a) VBF topology (b) $Z + H$ topology

Phys. Lett. B 842 (2023) 137963

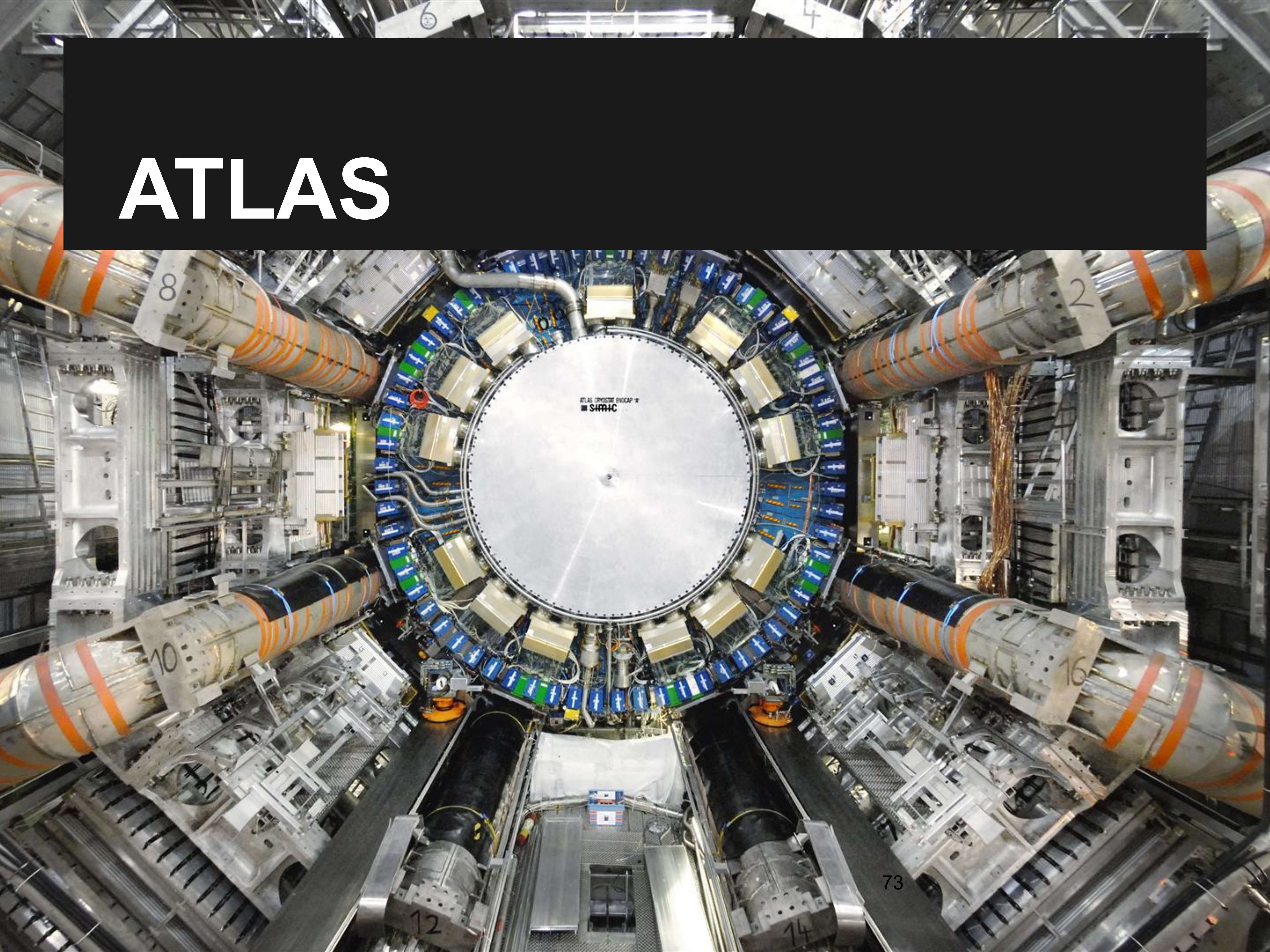


- Can the Higgs boson be a portal to new particles that do not interact with the rest of the Standard Model?
- If the new particle has mass $m<m_H/2$ => Invisible decay of the Higgs boson.
- And if this invisible particle was responsible for dark matter?




History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Today
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

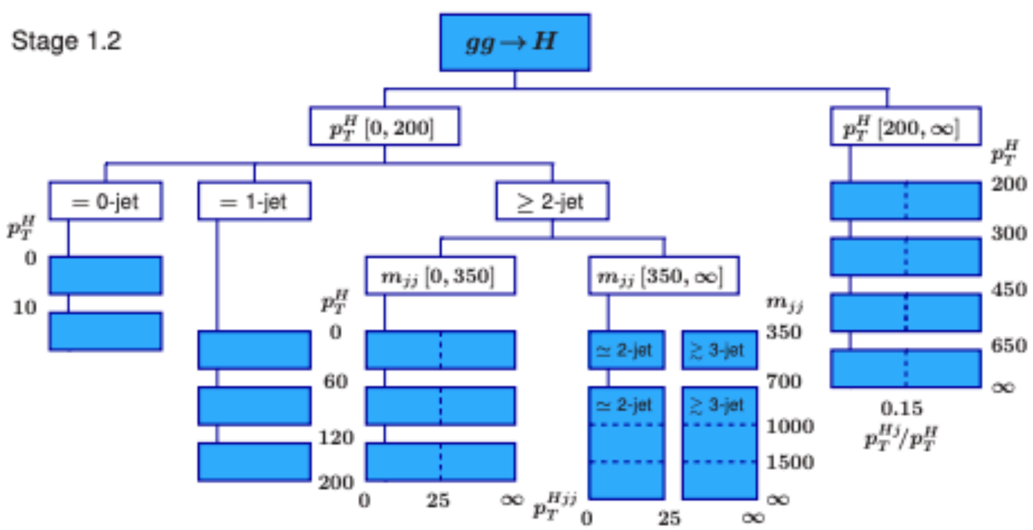
ATLAS

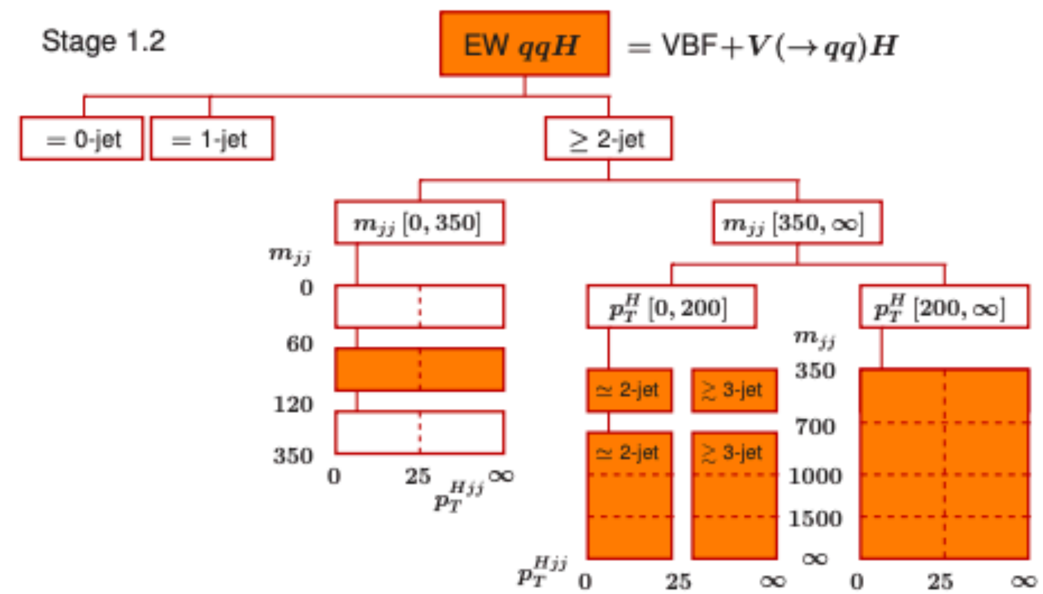


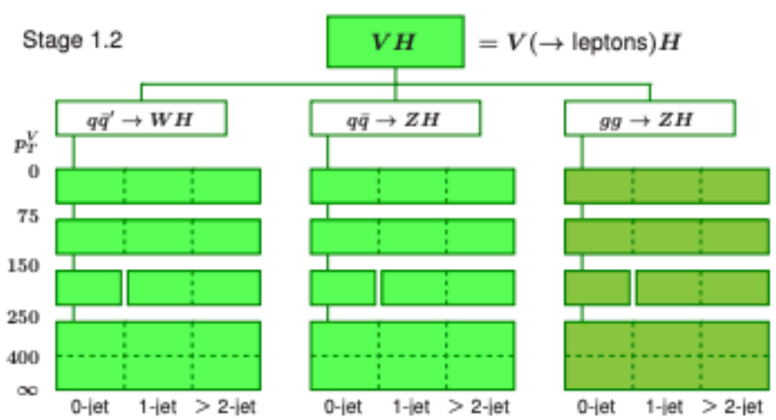
Simplified template cross sections (STXS)

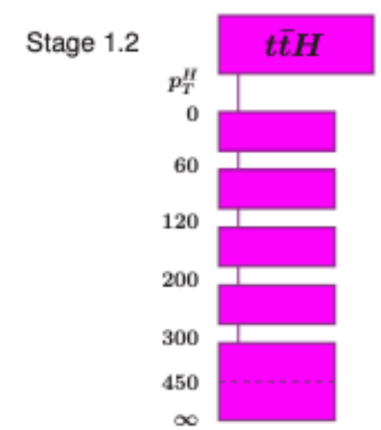
- STXS reveals the kinematic properties of Higgs production processes with associated jets to maximize the experimental sensitivities while at the same time minimizing their theory dependence.

LHCHXSWG



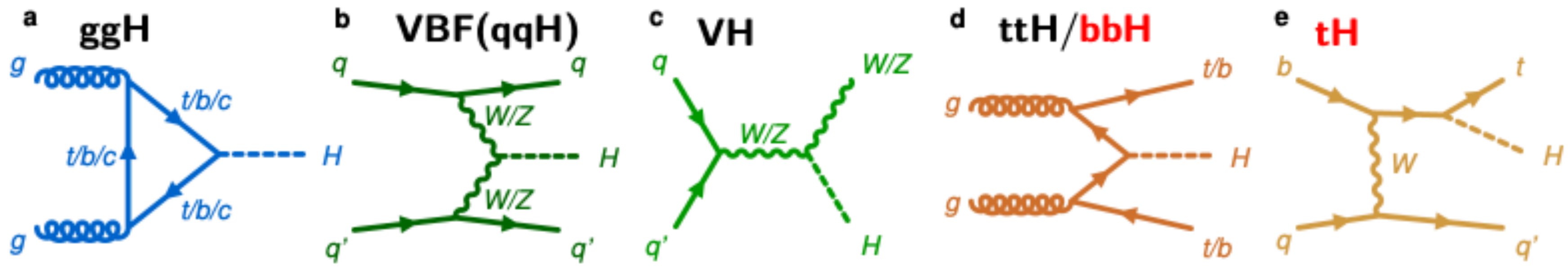






Single Higgs production

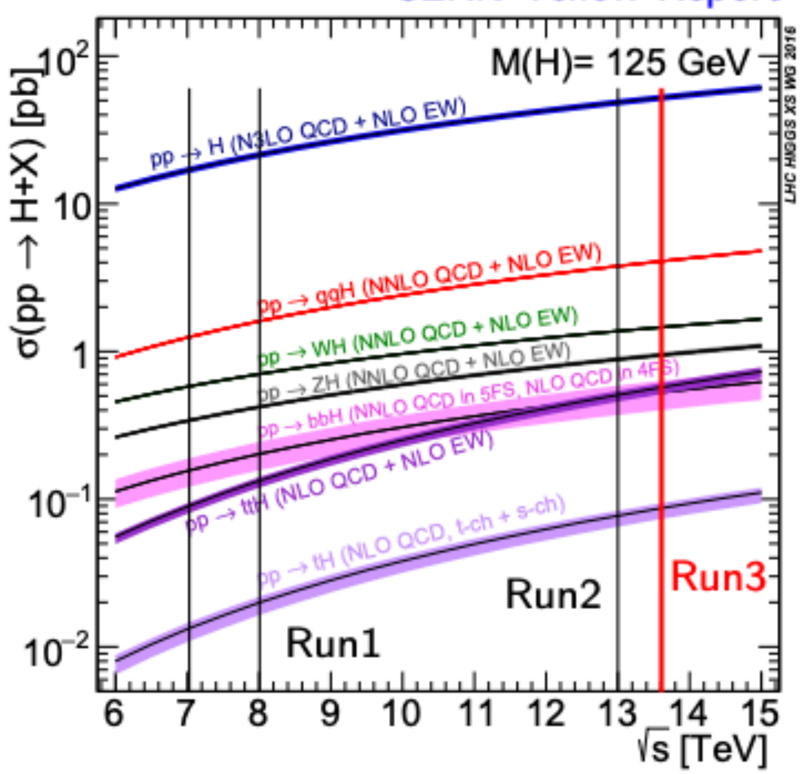
Nature 607, 52 (2022)



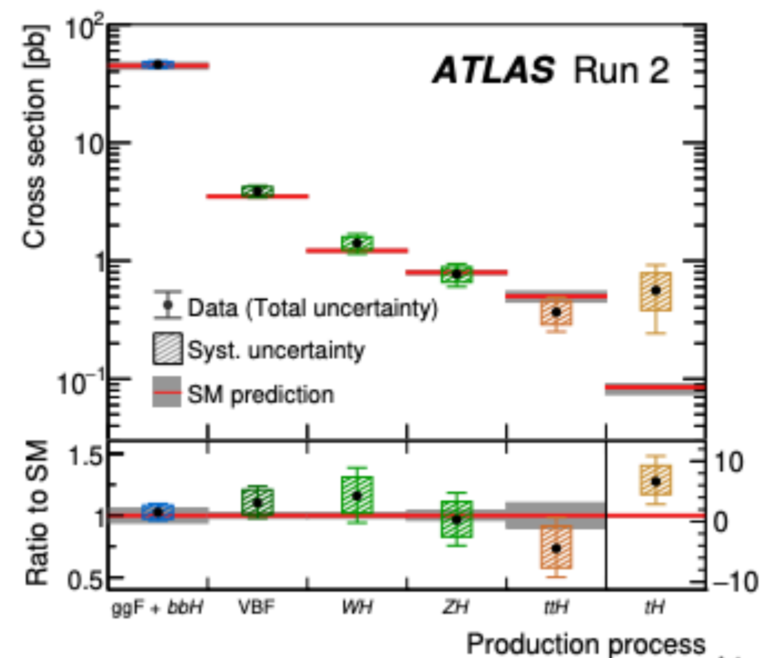
- Global signal strength:
  - $\mu = 1.05 \pm 0.06$ (ATLAS)
  - $\mu = 1.002 \pm 0.057$ (CMS)

- **bbH** and **tH** are not yet discovered.

CERN Yellow Report 4

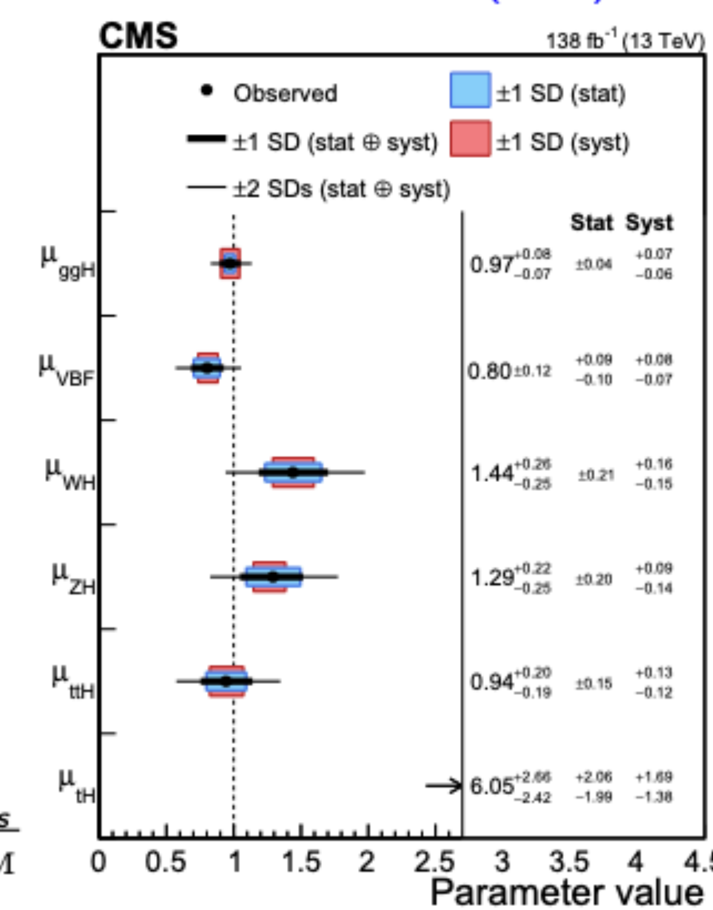


Nature 607, 52 (2022)



$$\mu_i = \frac{\sigma_{obs}}{\sigma_{SM}}$$

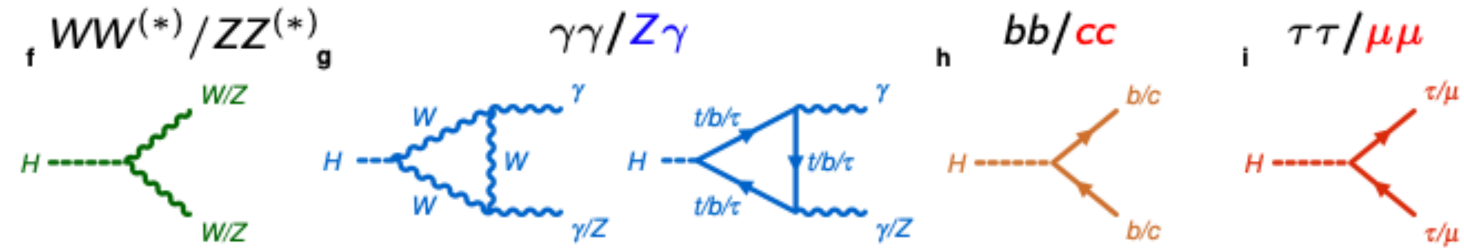
Nature 607 (2022) 60-68



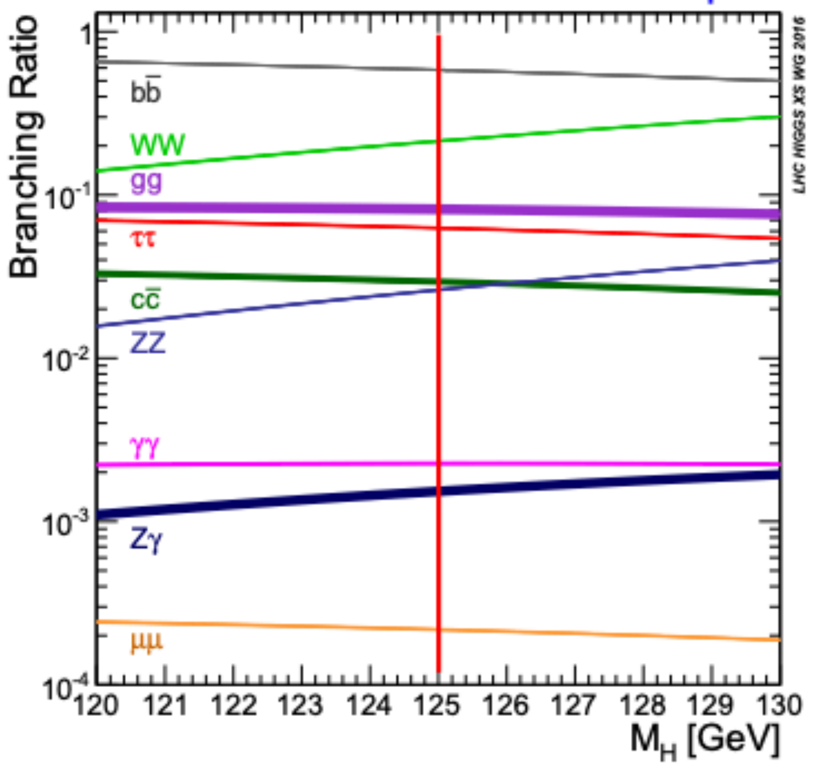
Higgs decay

- *cc* and $\mu\mu$ are still under searching.
- $Z\gamma$ is above 3σ in the combination of ATLAS and CMS.

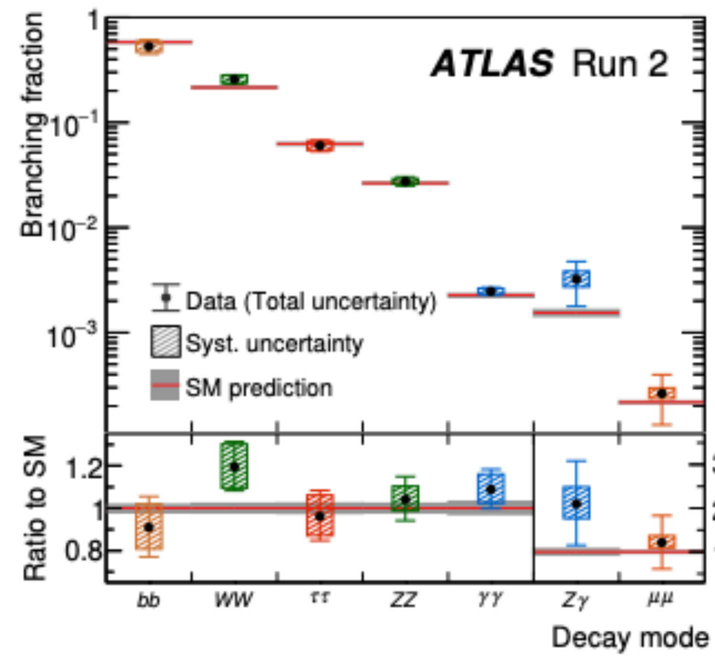
Nature 607, 52 (2022)



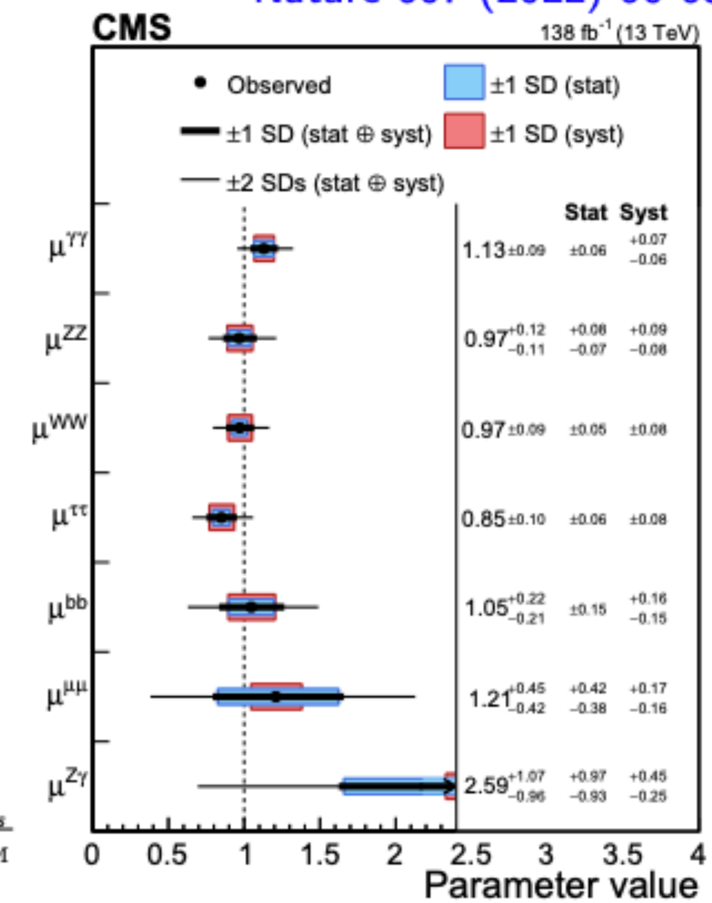
CERN Yellow Report 4



Nature 607, 52 (2022)



Nature 607 (2022) 60-68

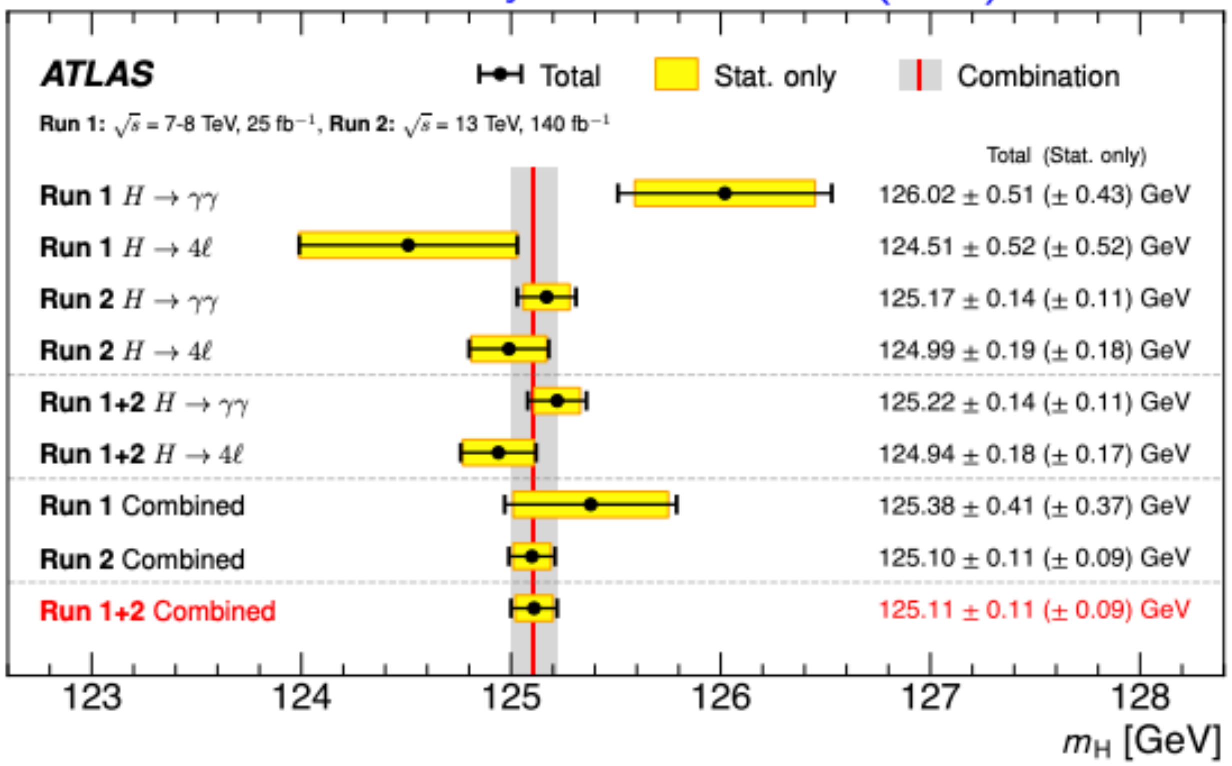


$$\mu_i = \frac{\mathcal{B}_{obs}}{\mathcal{B}_{\mathrm{SM}}}$$

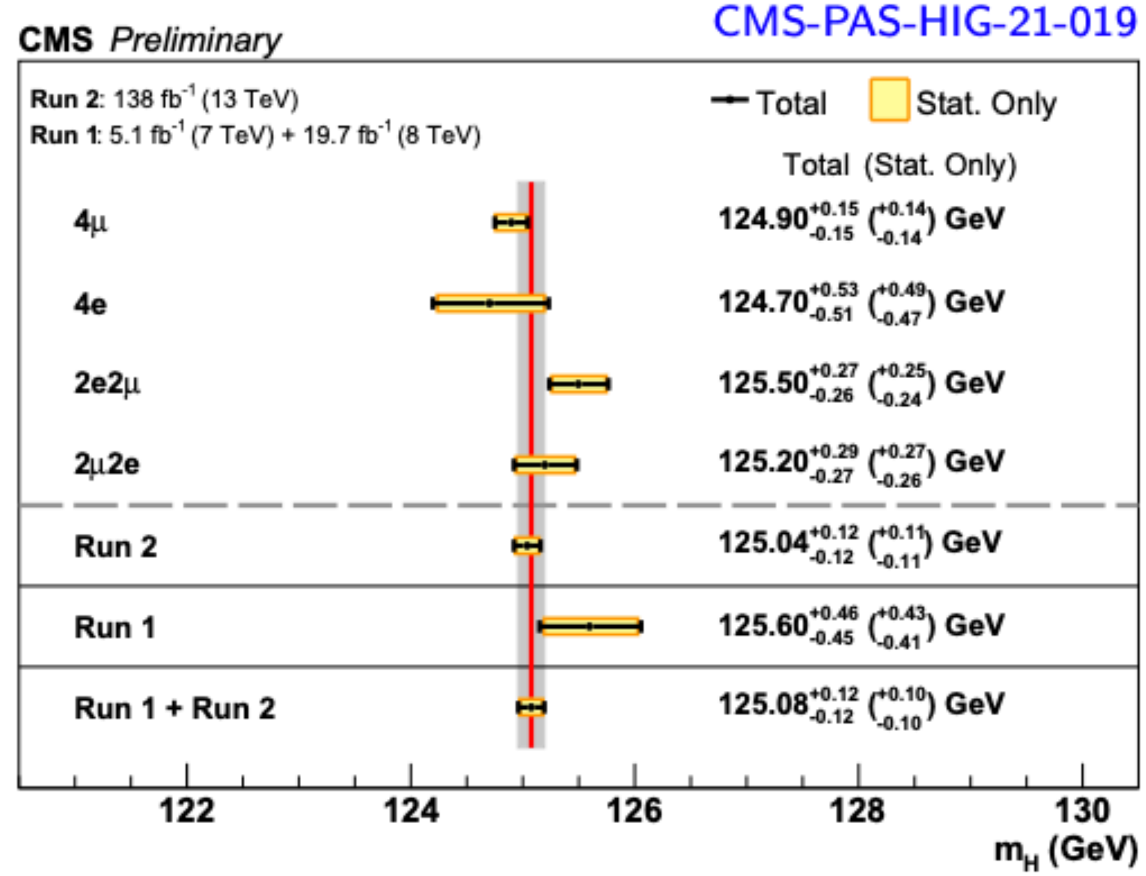
Higgs mass

- ATLAS and CMS measured the Higgs mass with full Run2 data combined with the Run1 results, achieving an accuracy of less than 0.1%.
  - 125.11±0.09 (stat.)±0.06(syst.) = **125.11±0.11** GeV (ATLAS).
  - 125.08±0.10 (stat.)±0.07(syst.) = **125.08±0.12** GeV (CMS).

Phys. Rev. Lett. 131 (2023) 251802



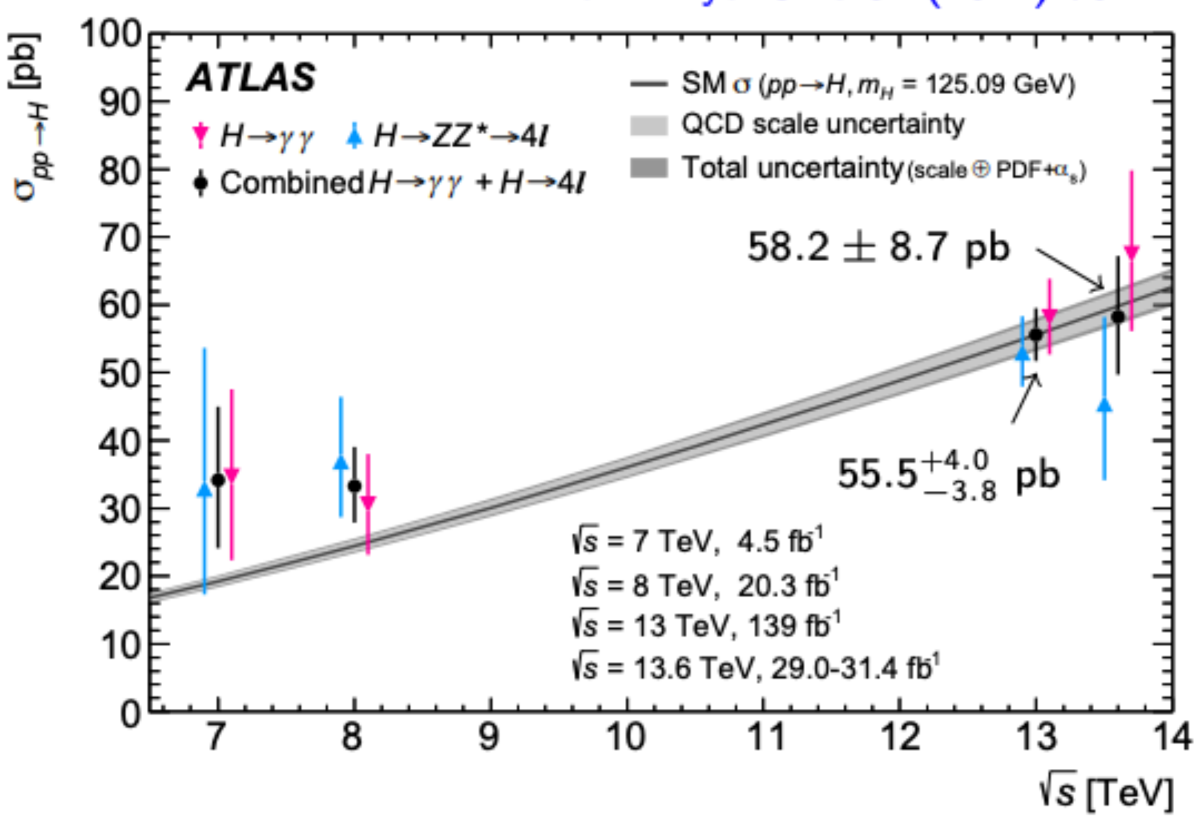
CMS-PAS-HIG-21-019



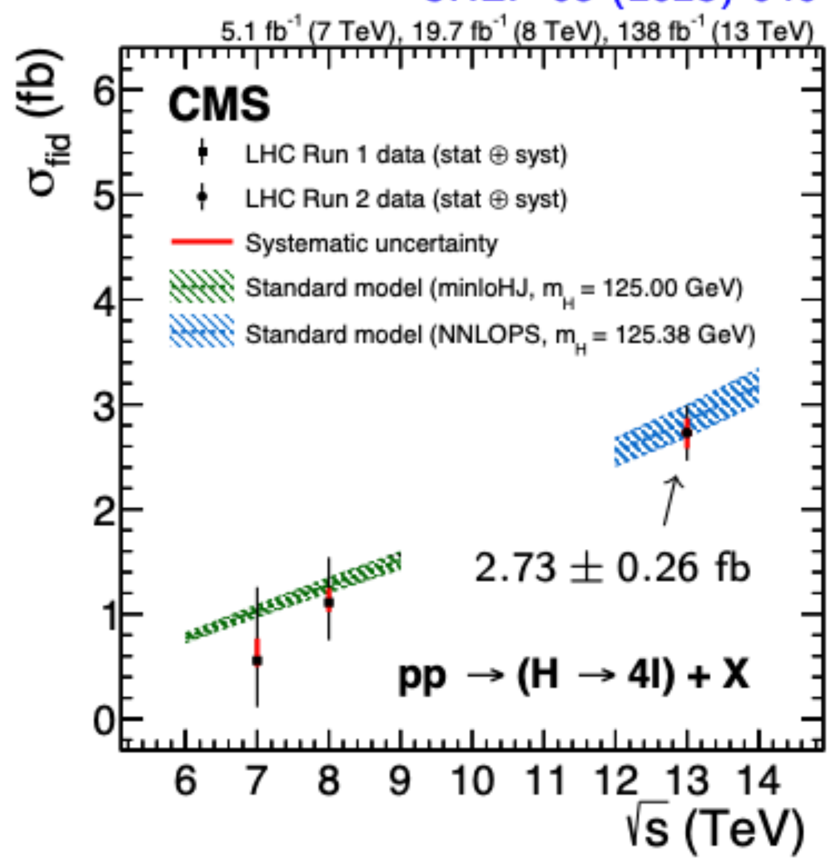
Inclusive cross section measurement

- ATLAS published the measurements of the total cross section in $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ with Run1, Run2 and Run3 (2022) data.
  - Relative uncertainties: $\sim$**7 % for Run2**, $\sim$**15 % for Run3**.
- CMS has the results in $H \to ZZ^* \to 4\ell$ with Run1 and Run2 datasets.
  - $\sigma_{\text{fid}} = 73.4^{+5.4}_{-5.3}(\text{stat})^{+2.4}_{-2.2}(\text{syst})$ fb in agreement with 75 ± 4.1 fb in $H \to \gamma\gamma$ with Run2 data.

Eur. Phys. J. C 84 (2024) 78



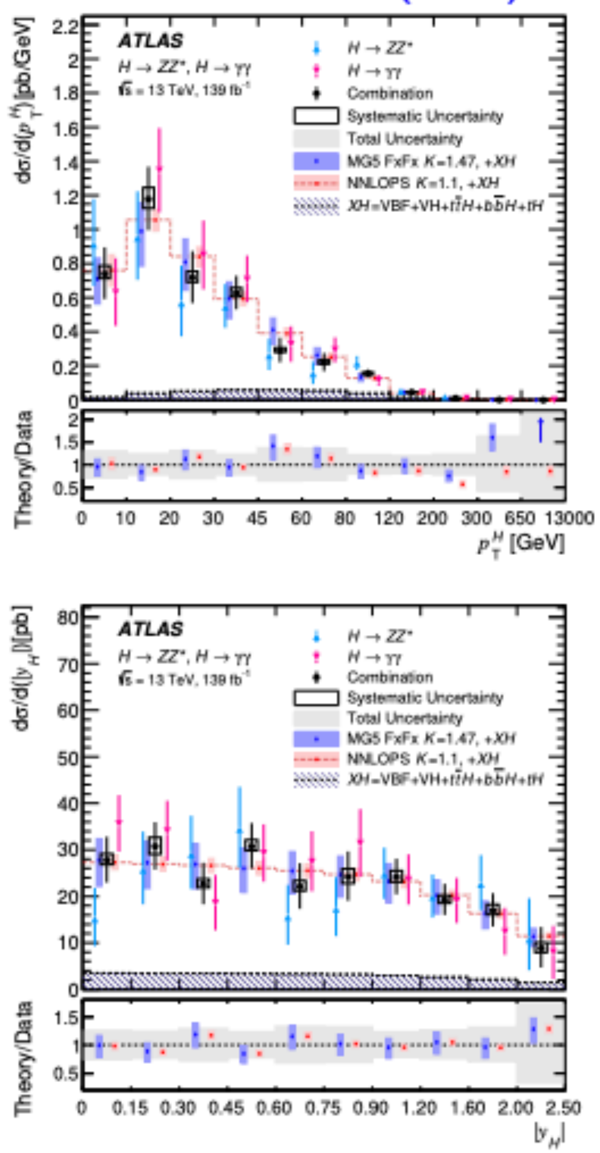
JHEP 08 (2023) 040



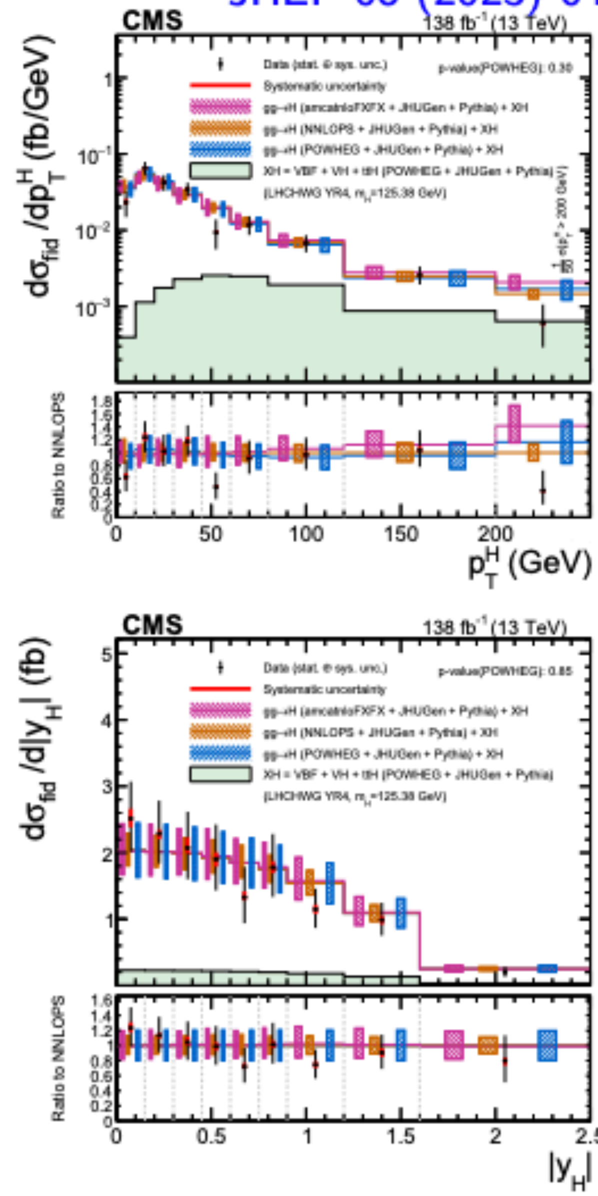
Differential cross sections

- $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ show comparable results of Higgs kinematics with full Run2 data.
- ATLAS further combined the Run2 results of two channels.
- There are $H \to WW^*$ results from ATLAS and CMS and $H \to \tau\tau$ results from CMS.

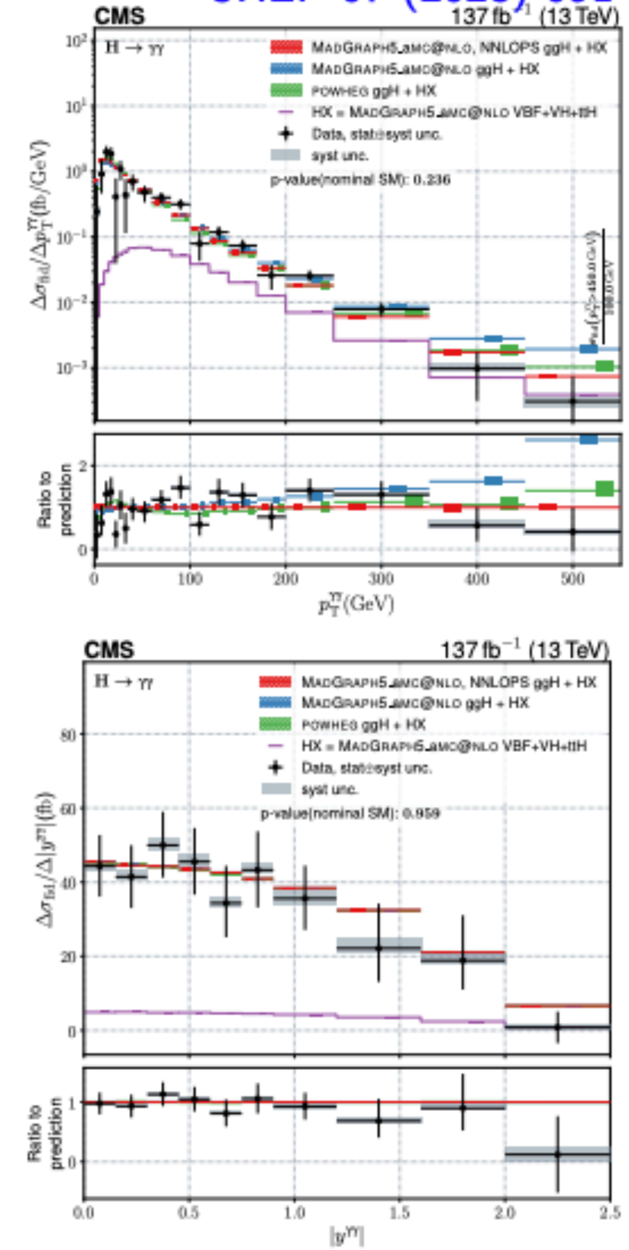
JHEP 05 (2023) 028



JHEP 08 (2023) 040



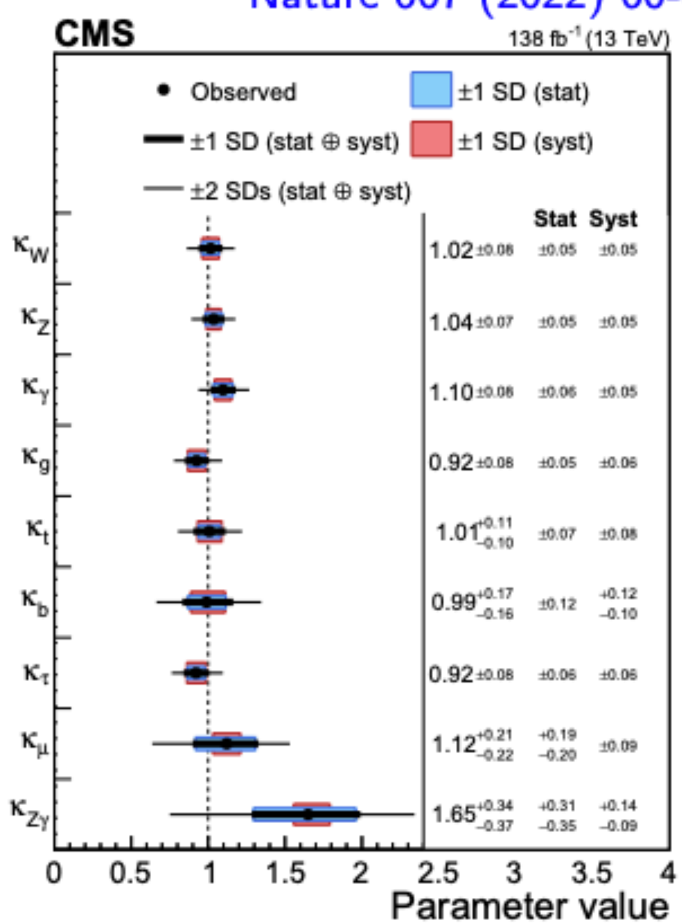
JHEP 07 (2023) 091

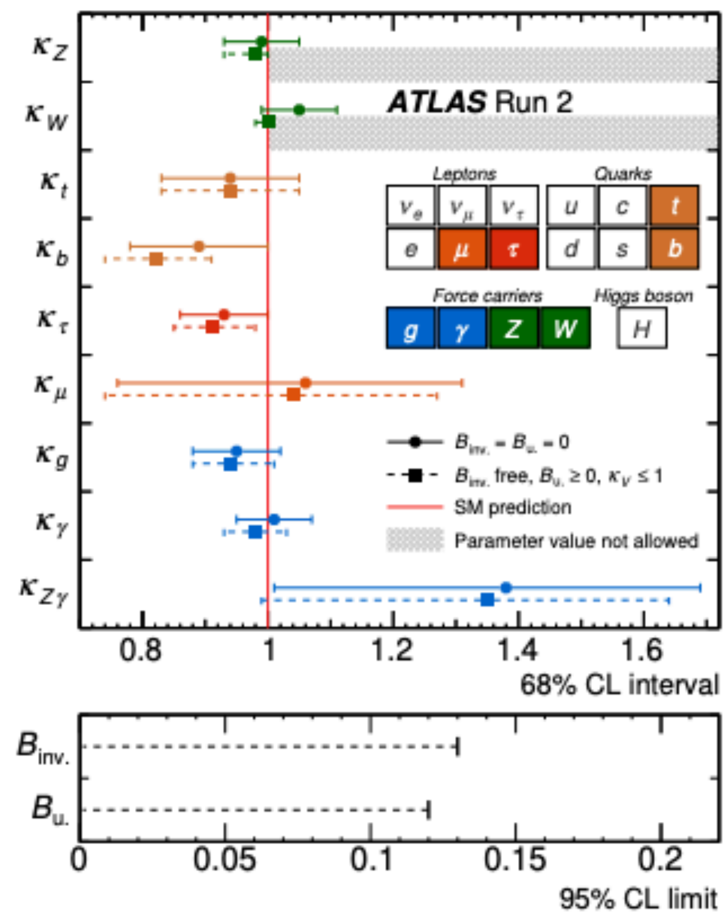


Higgs coupling

- The loop-induced processes are treated using effective coupling strength modifiers (κ_g, κ_γ and $\kappa_{Z\gamma}$).
- $\mathcal{B}_{inv}$ and $\mathcal{B}_u$ are the branching ratios of invisible particles and other decay which are undetected owing to a large background, respectively.

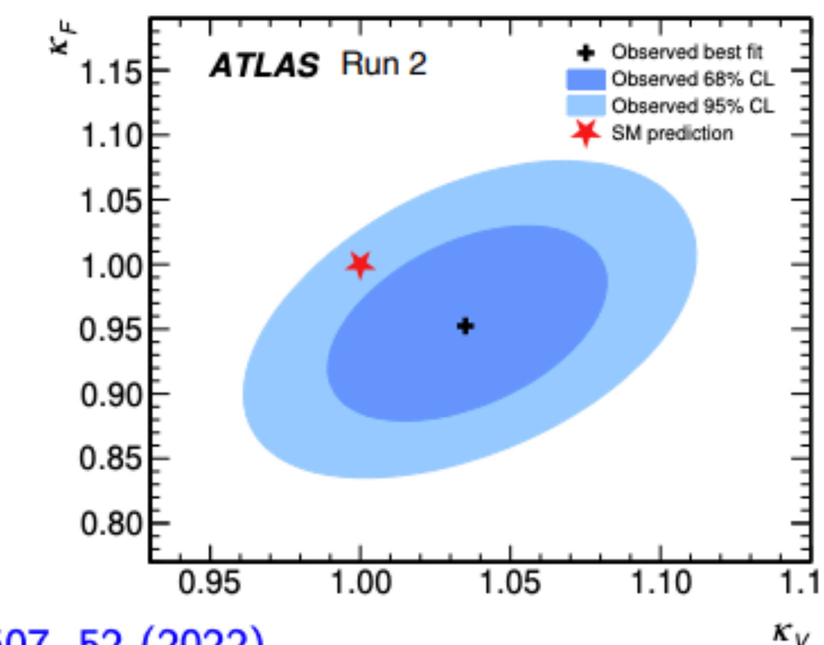
Nature 607 (2022) 60-68





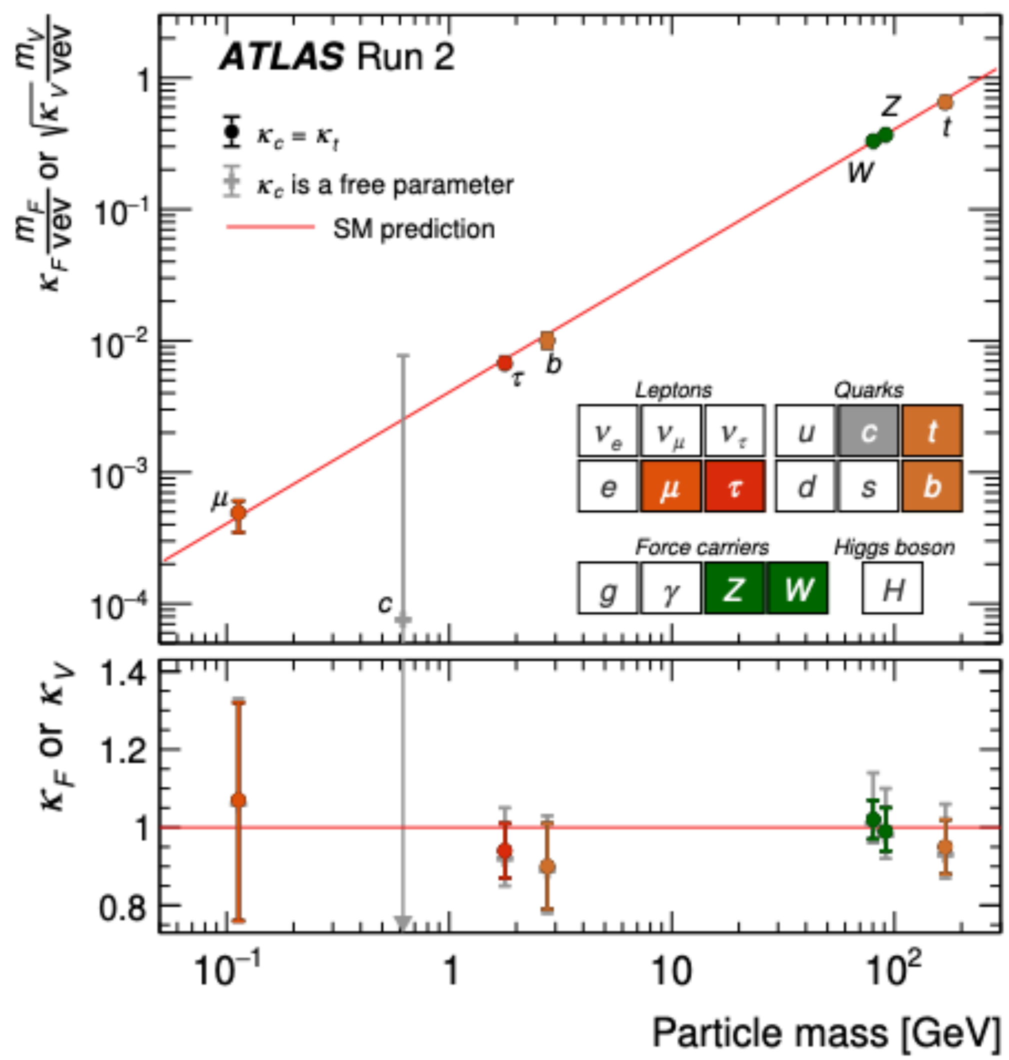
Nature 607, 52 (2022)

- ATLAS and CMS checked κ_F vs. κ_V with $\kappa_V = \kappa_Z = \kappa_W$ and κ_F for all fermions.

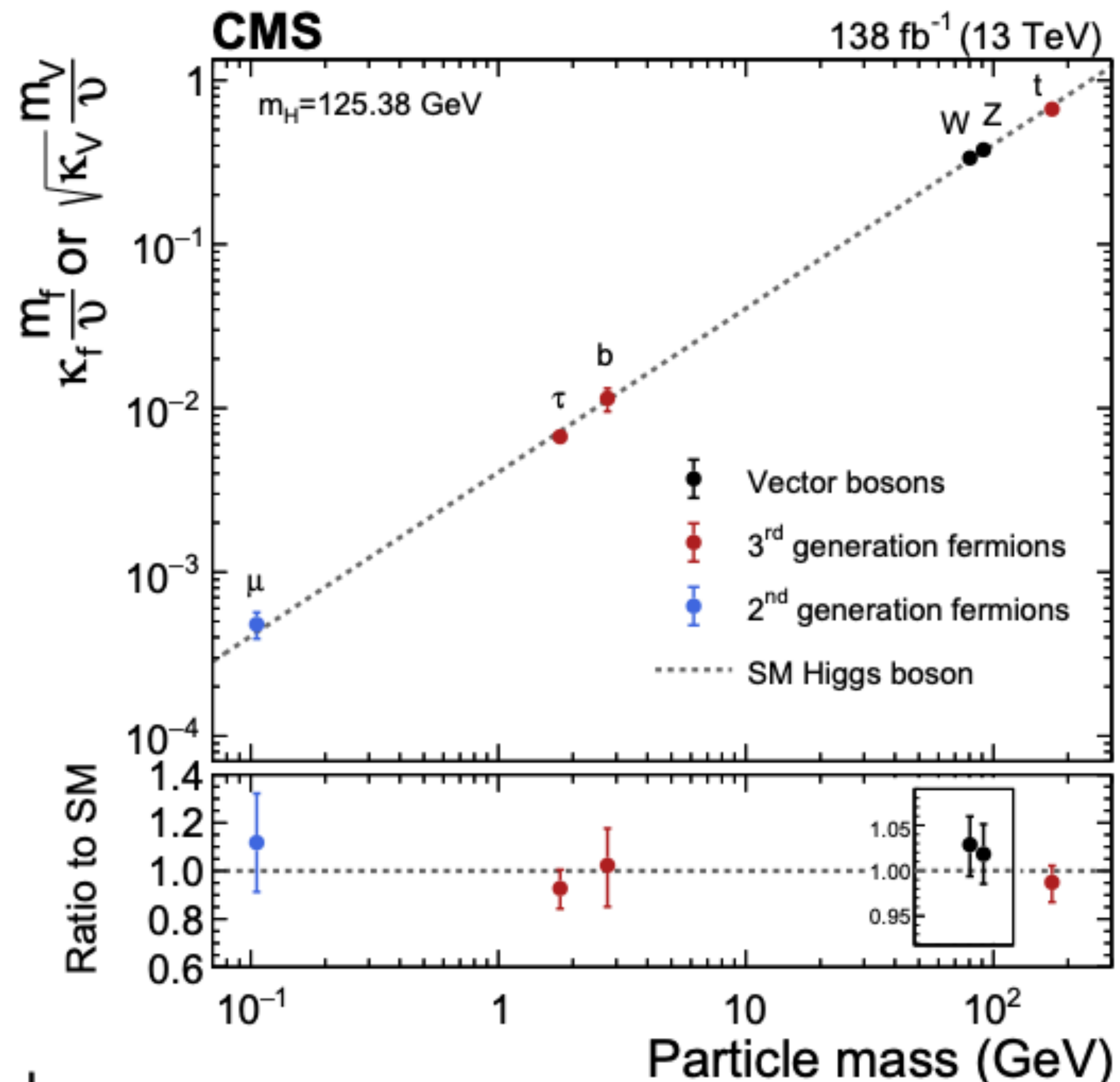


Higgs coupling strength

Nature 607, 52 (2022)



Nature 607 (2022) 60-68



- κ_c is obtained from the fit with floating κ_c and fixed the other κ parameters.

Higgs width

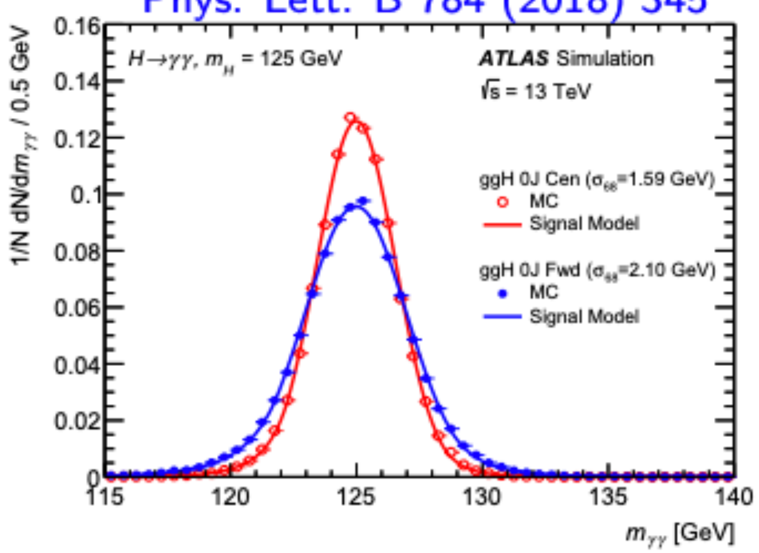
- The SM prediction of total Higgs width is 4.1 MeV, which is inaccessible from direct measurements.
- The total width can be extracted from the ratios of yields of on-shell and off-shell Higgs boson events.
- $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV (ATLAS) and $3.2^{+2.4}_{-1.7}$ MeV (CMS)

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggF}g^2_{HZZ}}{m_H\Gamma_H}.$$

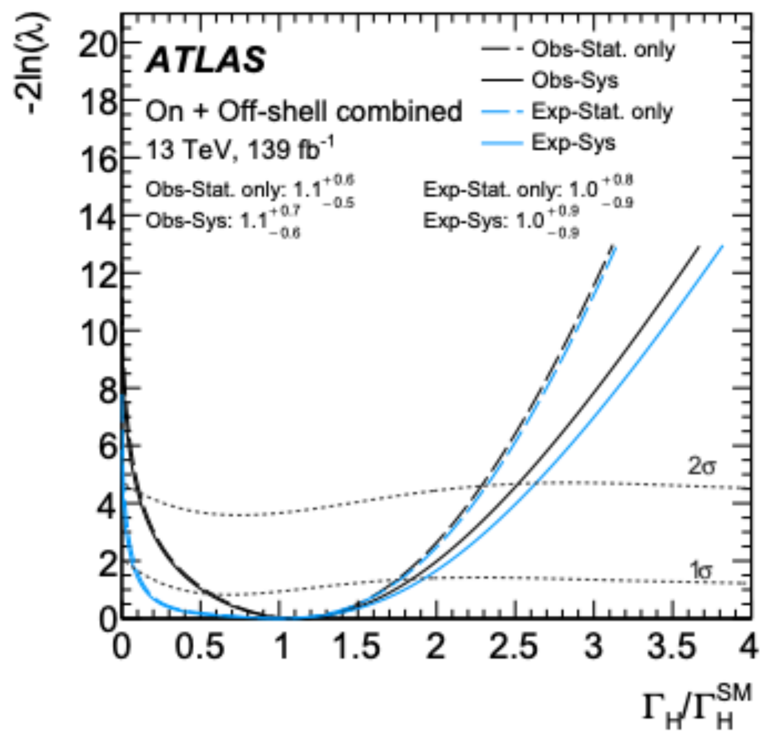
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggF}g^2_{HZZ}}{m^2_{ZZ}}$$

$$\Gamma_H = \frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}}$$

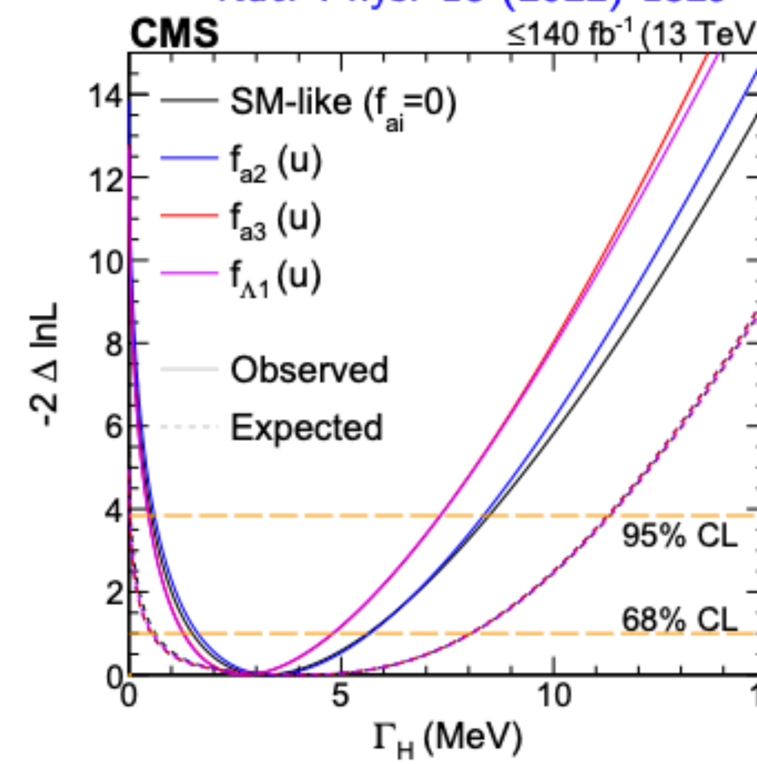
Phys. Lett. B 784 (2018) 345



Phys. Lett. B 846 (2023) 138223



Nat. Phys. 18 (2022) 1329



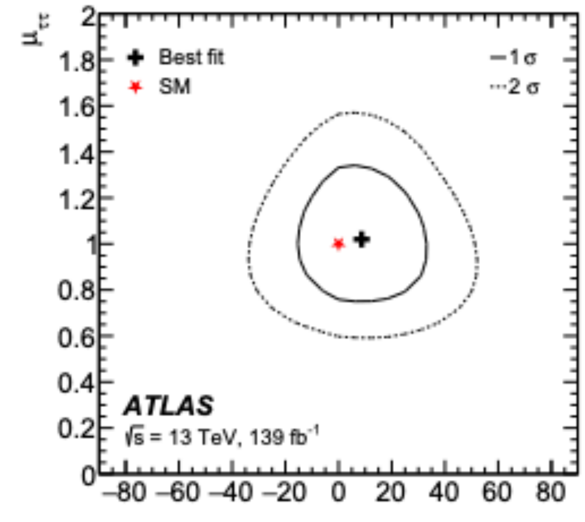
Anomalous couplings of *Hff*

- The spin-parity quantum numbers of the Higgs boson are consistent with $J^{PC} = 0^{++}$.
- The anonmalous effects of Hff can be parameterized with the amplitude as:

$$A(Hff) = -\frac{m_f}{v}\bar{\psi}(\kappa_f + i\tilde{\kappa}_f\gamma_5)\psi$$

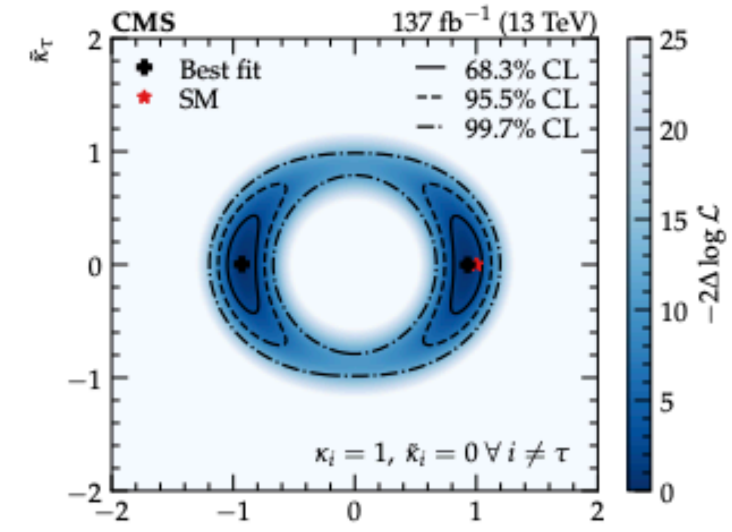
- No deviation from SM has been found.

Eur. Phys. J. C 83 (2023) 563



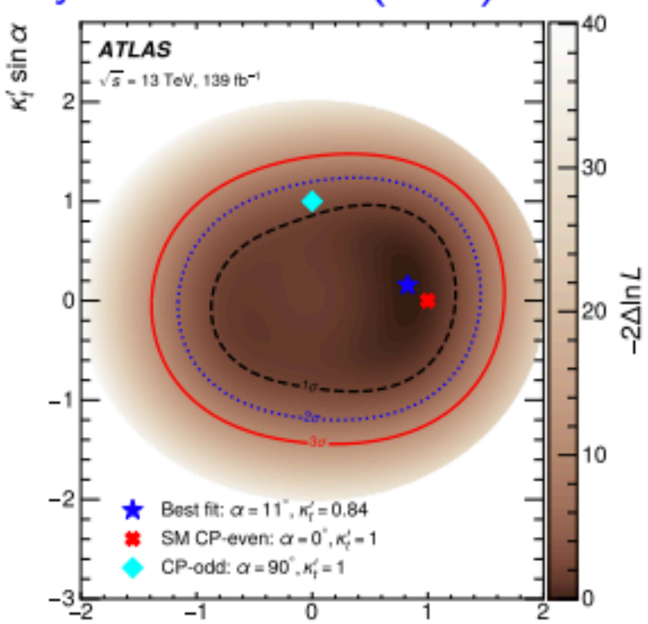
$H \to \tau\tau$

JHEP 06 (2022) 012



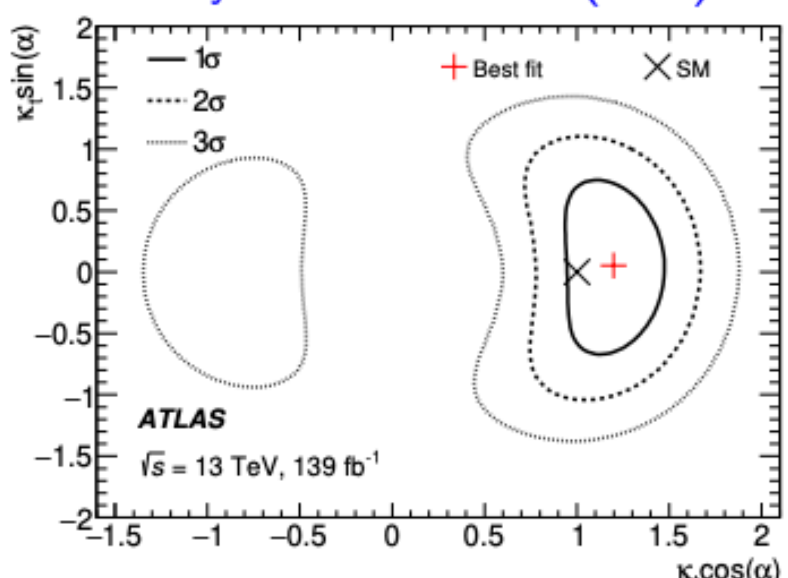
$H \to \tau\tau$

Phys. Lett. B 849 (2024) 138469



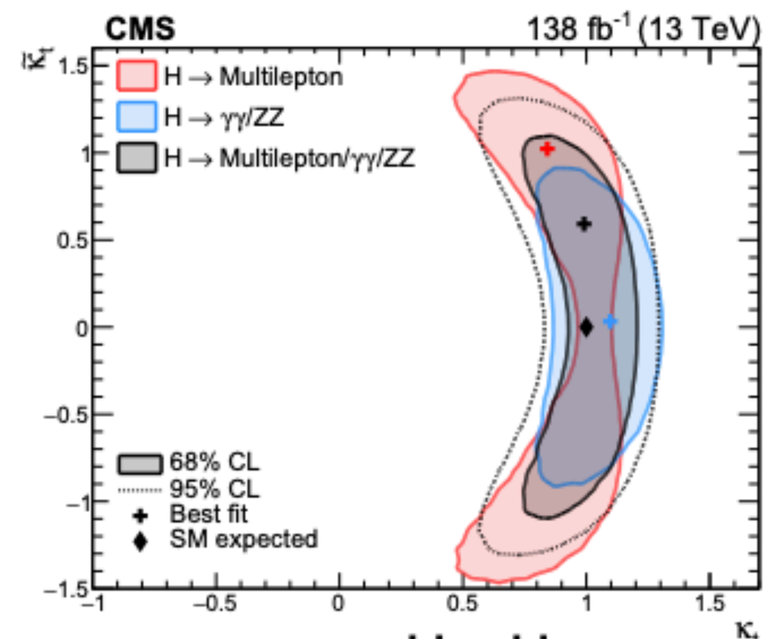
ttH, tH, $H \to bb$

Phys. Rev. Lett. 125 (2020) 061802



ttH, tH, $H \to \gamma\gamma$

JHEP 07 (2023) 092



ttH, tH