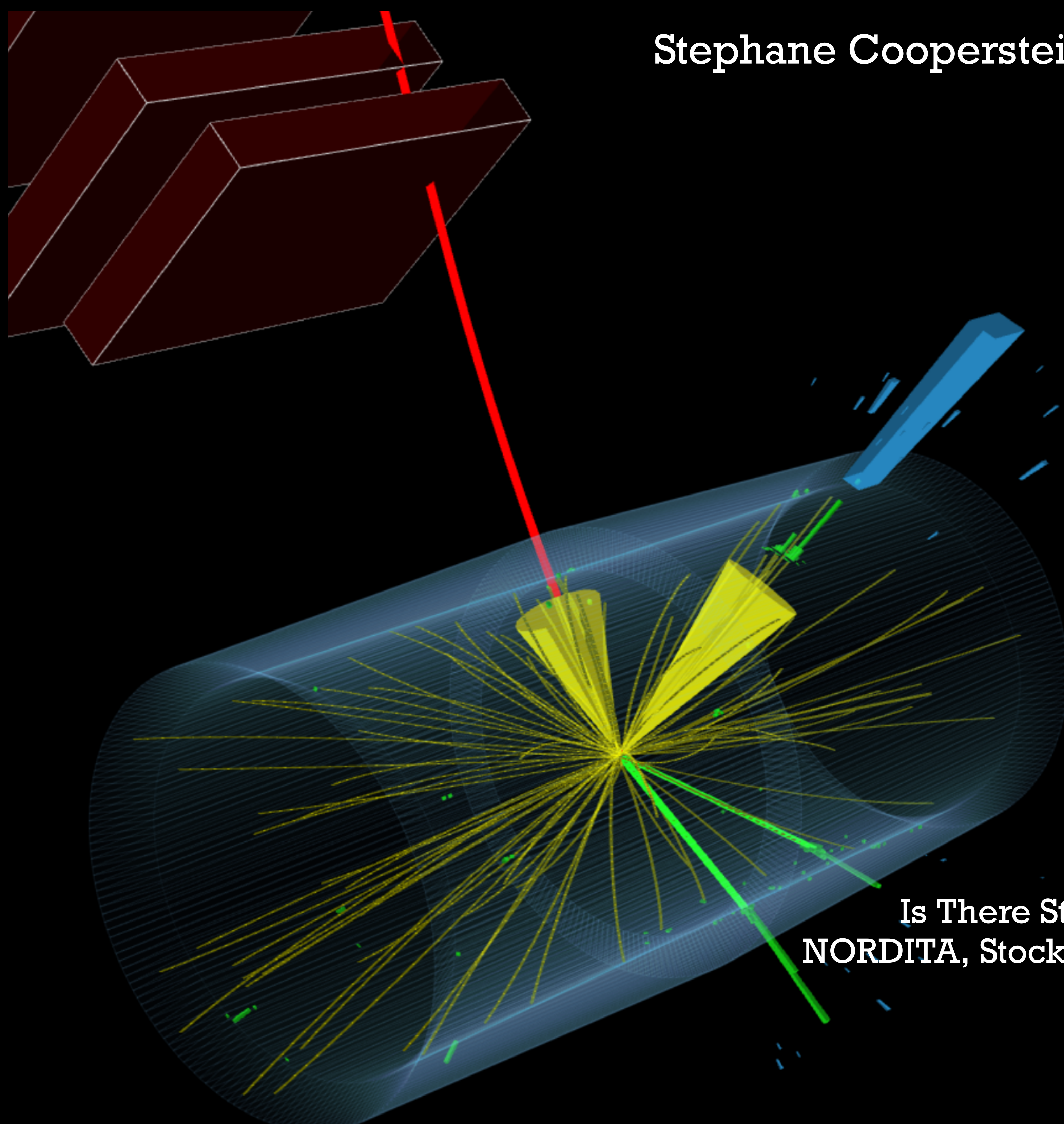
Rare Higgs Boson Decays and Extensions of the Higgs Sector

Stephane Cooperstein (UC San Diego)



Is There Still Room for Naturalness?
NORDITA, Stockholm, Sweden 18-29 April 2022

Higgs sector in the Standard Model

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
&+ i \bar{\Psi} \not{D} \psi + h.c. \\
&+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
&+ |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

Higgs sector in the Standard Model

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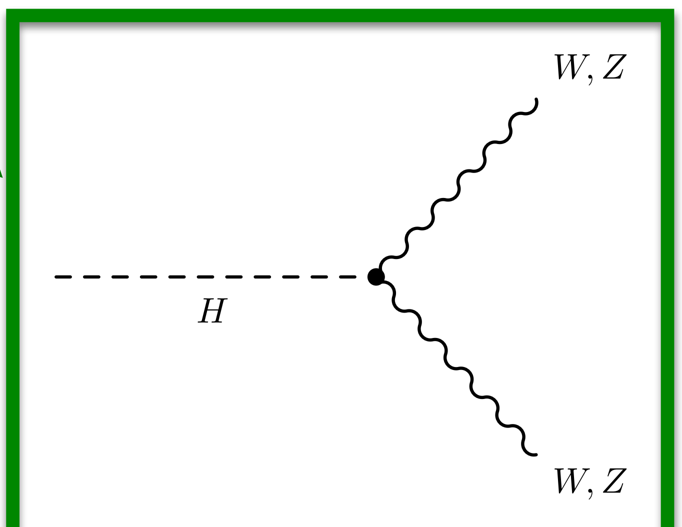
$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

- Mass generation for and Higgs interactions with gauge bosons are a direct consequence of electroweak symmetry breaking.
- Tells us how much the symmetry is broken, but not whether this is accomplished by one Higgs doublet, or two, or ten, or some mixture of Higgs doublets and other symmetry breaking mechanisms…

Bosonic Couplings



Higgs sector in the Standard Model

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$$+ i \bar{\Psi} \not{D} \Psi + h.c.$$
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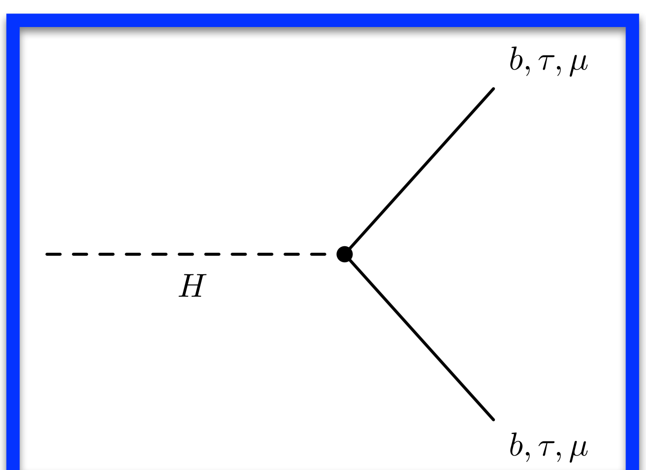
$$+ |D_\mu \phi|^2 - V(\phi)$$

- Adjustable parameters, fermion masses are a linear sum of coupling strength times VEV of anything that breaks the electroweak symmetry.
- Yukawa couplings for heavy fermions cannot be too large, or perturbation theory would break down.
- Yukawa interactions of first and second generation probe a very different scale ⇒ *measuring these is critical to understanding full nature of electroweak symmetry breaking*.



$$L_{\text{Yuk}} = (1 + \frac{H}{v}) m_f \bar{f}_L f_R$$

Higgs sector in the Standard Model

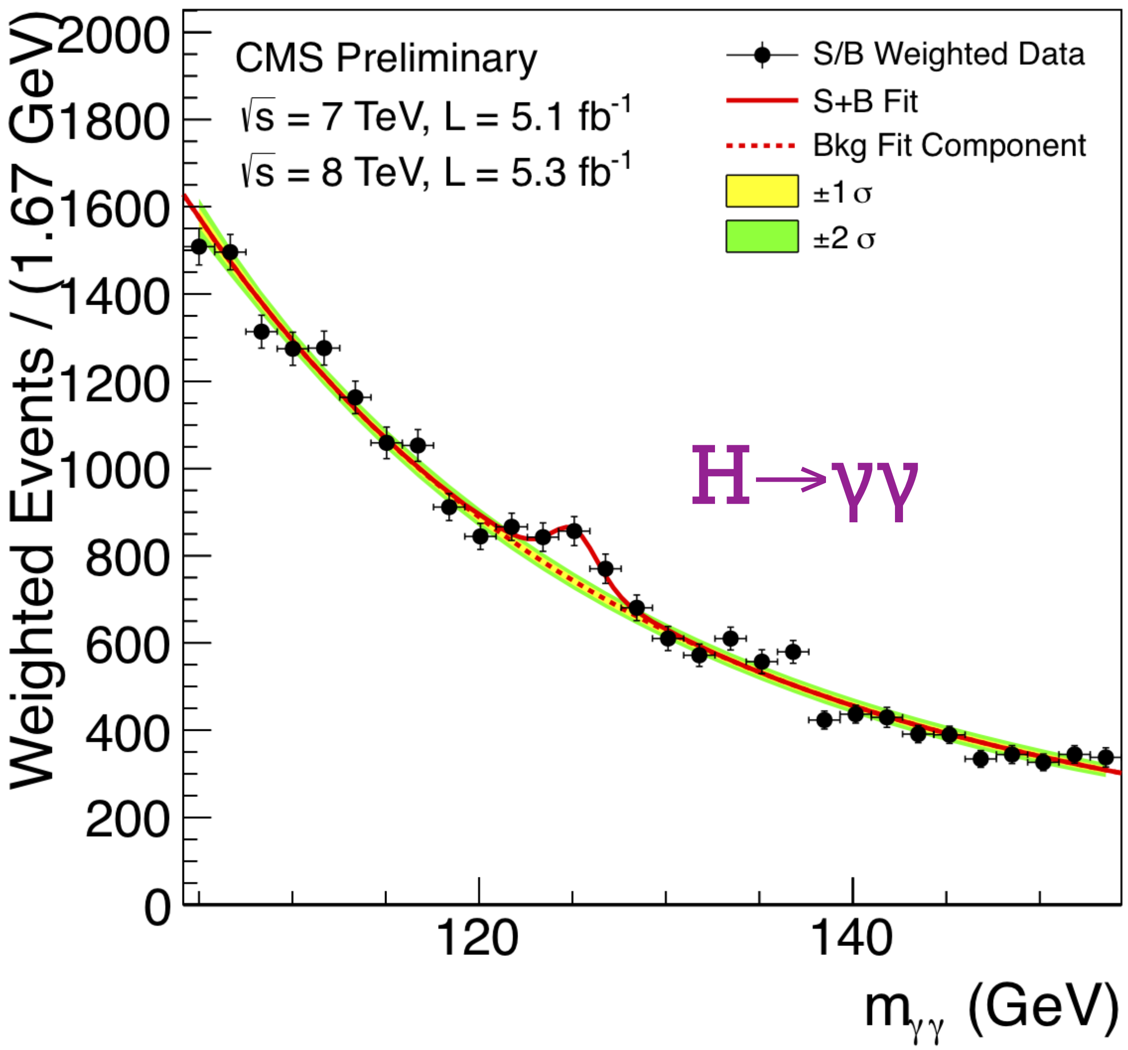
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

+? ...

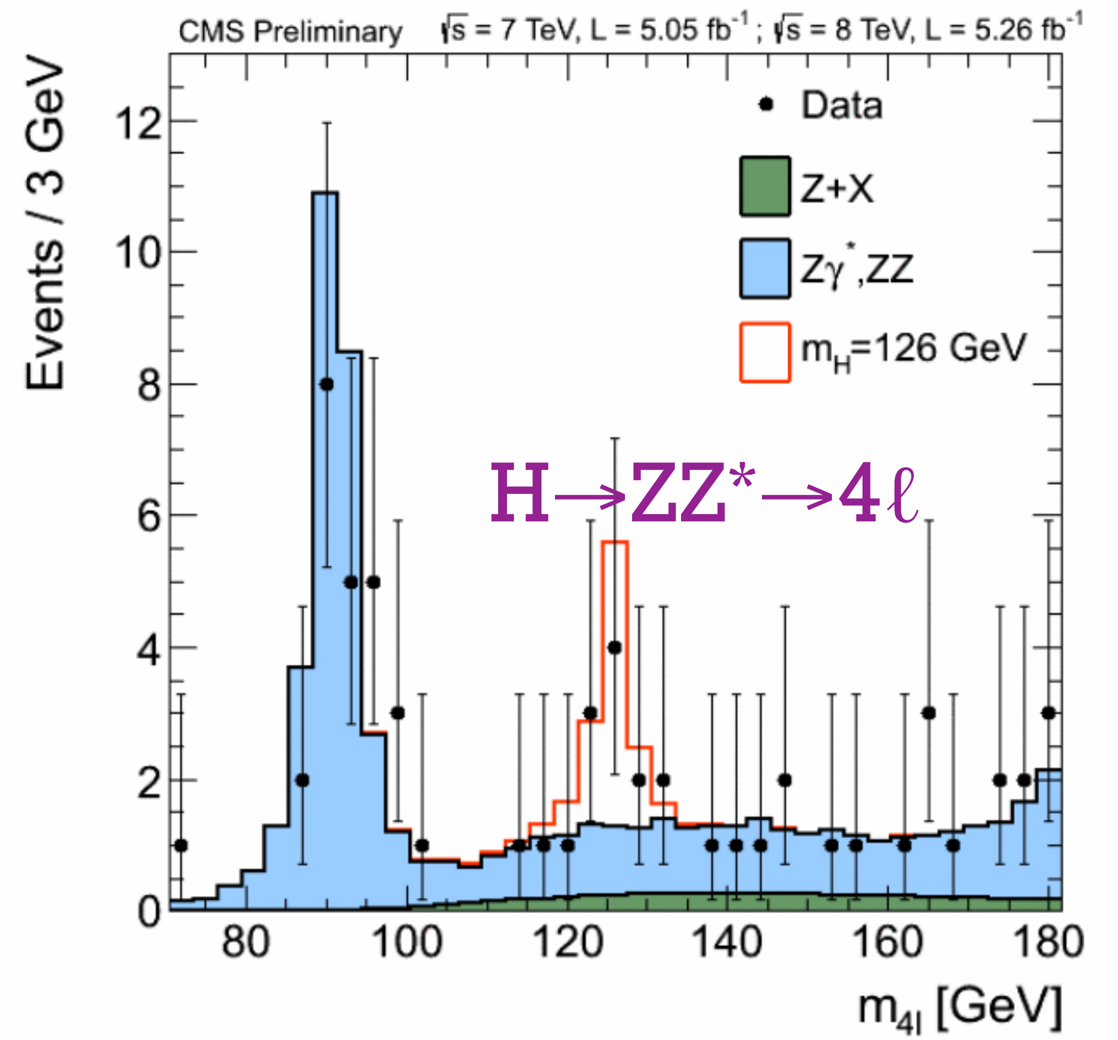
- What else could be (is?) out there?
- Higgs sector plays in integral role in many BSM models.
- Additional (pseudo)scalars? Charged Higgs? Composite Higgs? …

Higgs boson discovery (July 2012)

- Observation of new boson with mass 125 GeV by both ATLAS and CMS Collaborations.
- Relied primarily on H→ZZ and H→γγ decay channels.



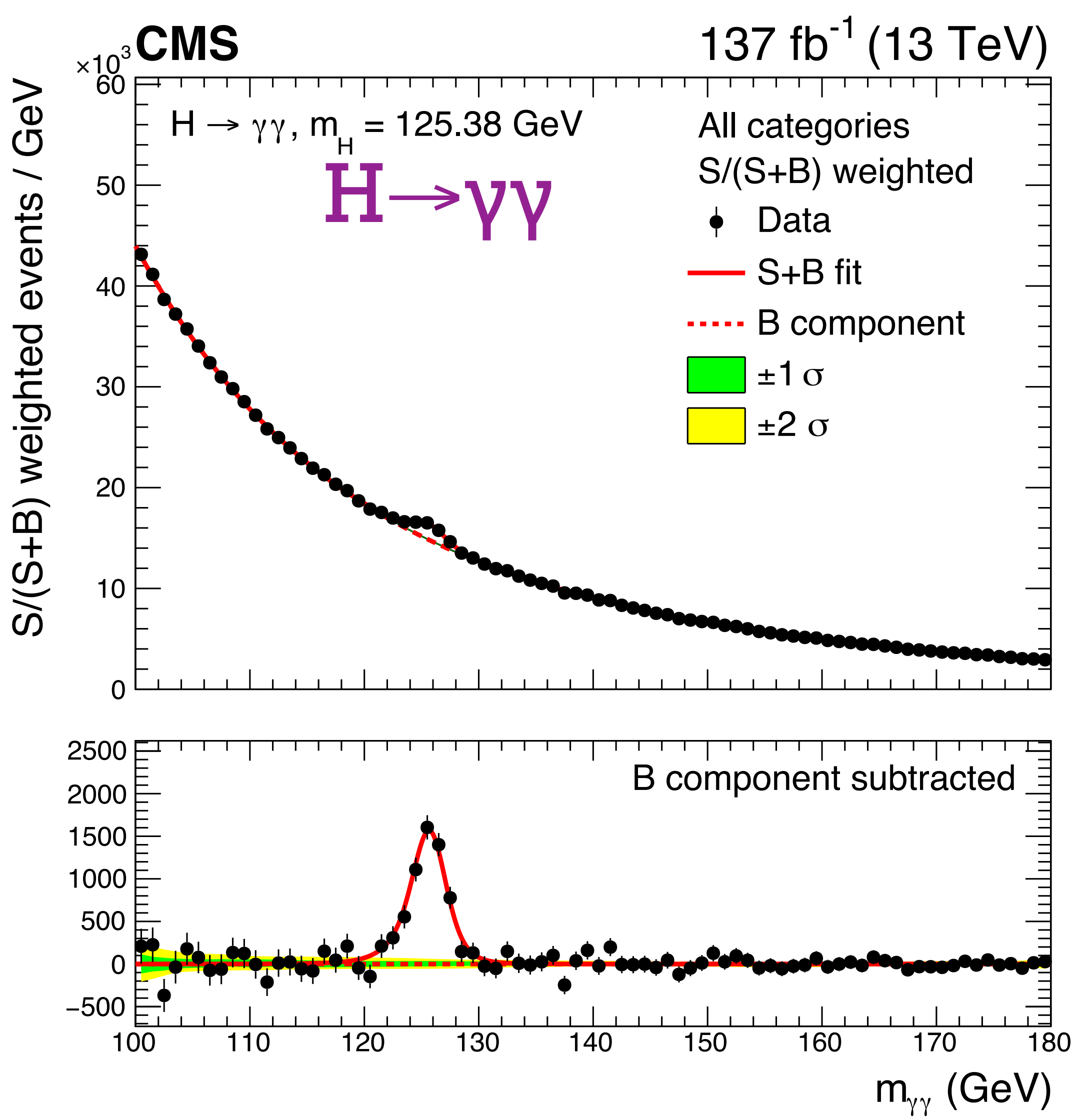
H→γγ

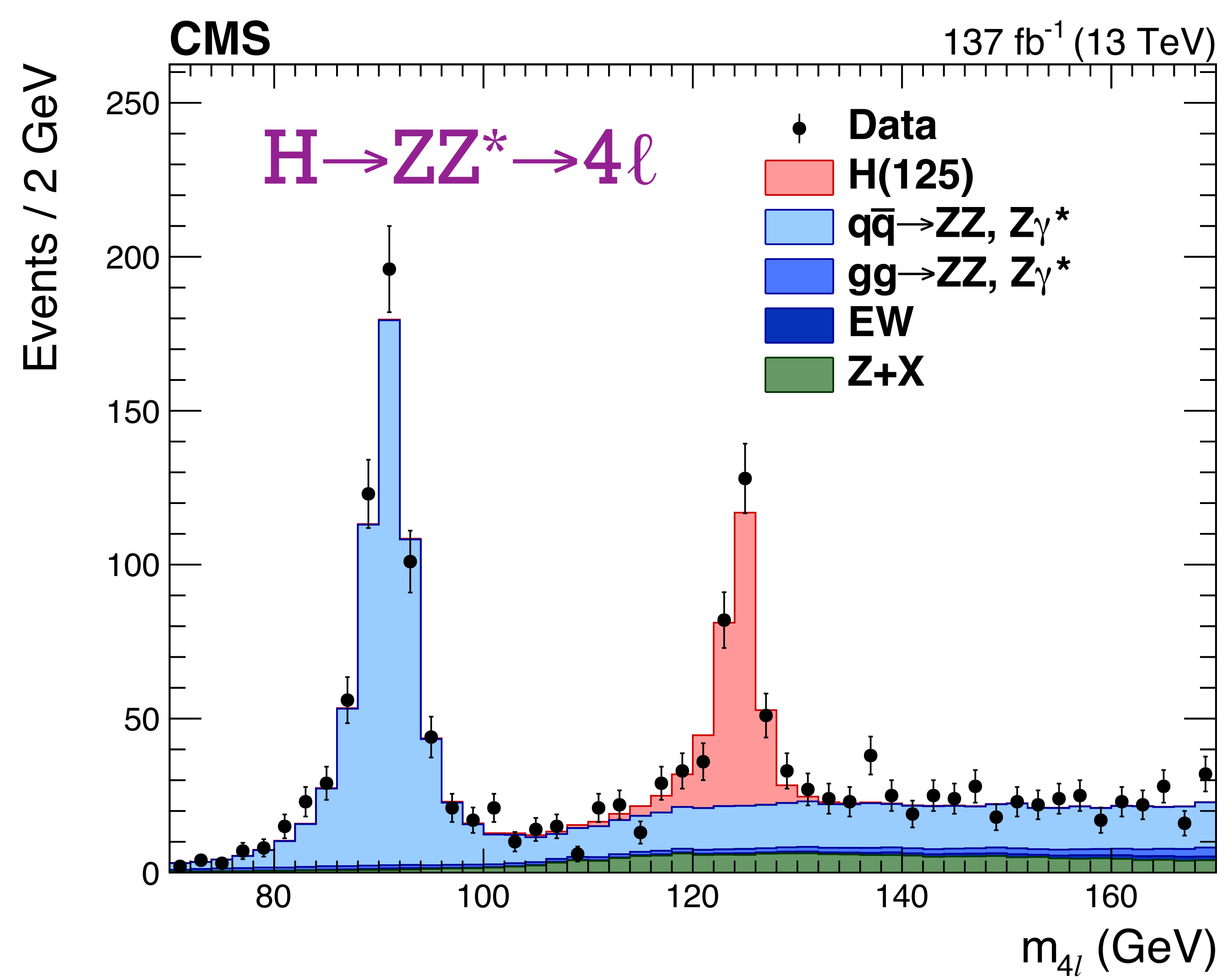


H→ZZ*→4ℓ

- Millions of Higgs bosons have now been produced at the LHC, enabling a huge variety of tests of Higgs boson properties.

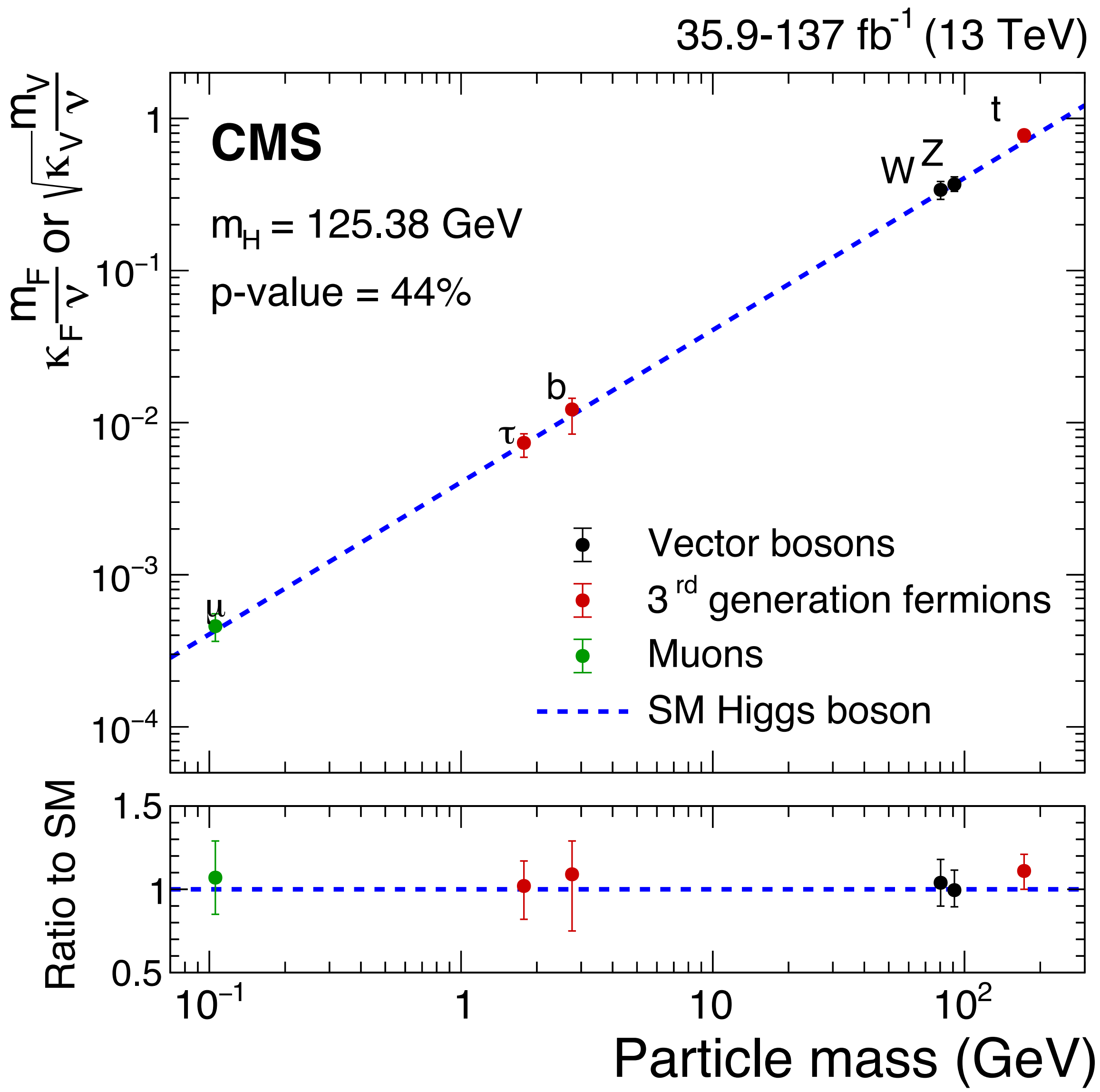
- *Where do we go from here?*





The next frontier(s) in Higgs physics

- What we have achieved so far:
  - Measurement of m_H to nearly per-mille precision.
  - Observation of all third-generation H couplings (t, b, τ).
  - Detailed measurements of H properties (differential, STXS, CP, …)
- This unprecedented data set opens a *new window in exploration of H sector*:
  - Honing in on Yukawa interactions of first and second generation (H→μμ, H→cc, H→ee)
  - Constraining H→invisible at 5-10% level.
  - Searching for BSM within H sector at TeV scale (resonant and non-resonant).

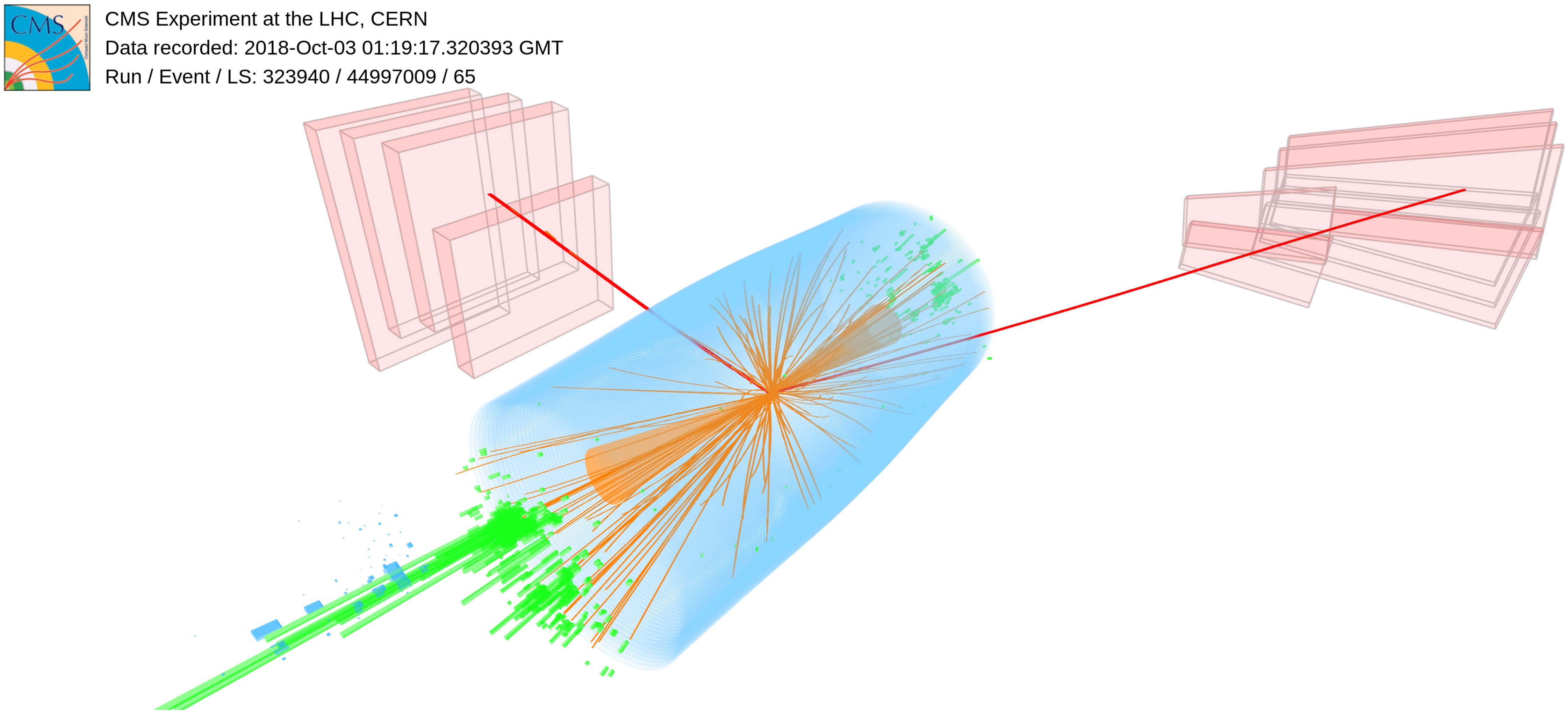


Outline for this talk

- Searches for **Higgs boson rare decays** (H→μμ, H→cc, H→Zγ, H→ee, H→quarkonia)
  - Probing Yukawa interactions of first and second generation.
  - Predicted by the SM, but generally with very small branching ratios.

- Searches for **extensions of the Higgs sector** (H→invisible, H→aa, ϕ→ττ, …)
  - Probing exotic properties of the SM-like Higgs boson and/or looking for additional Higgs-like particles near TeV scale.

- *A few disclaimers:*
  - *The scope is vast and my selection is biased (mostly CMS), talk is not meant to be exhaustive.*
  - *I give preference to the newest results (most results shown today were released in 2022).*
  - *There is much more going on than what I present today - if interested, let's discuss!*



- *Measuring H→μμ is the most promising probe of second-generation Yukawas at the LHC.*

- Muons are reconstructed with very high efficiency and excellent momentum resolution.

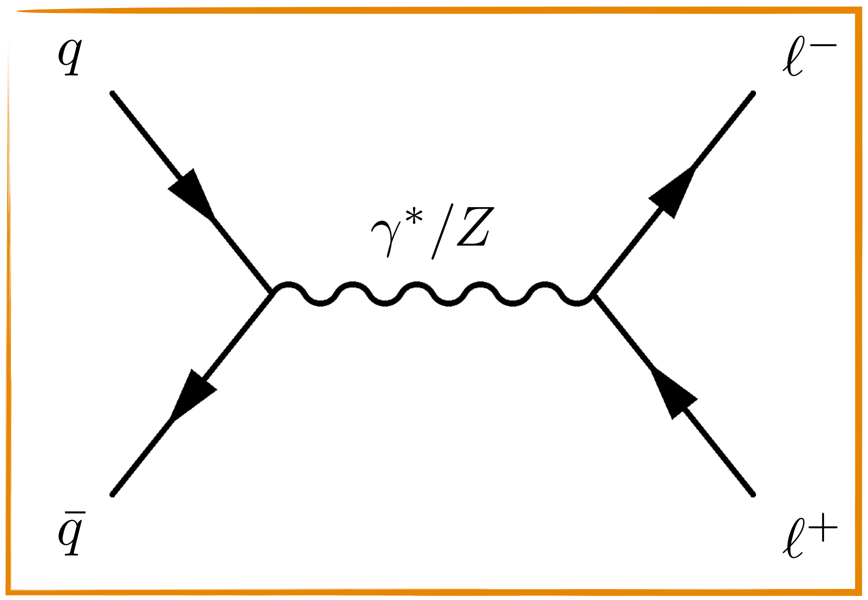
- SM prediction is BR(H→μμ) ~ $2.2*10^{-4}$ ⇒ finding a (very very small) needle in a haystack.

Challenge(s) in measuring H→μμ

Effective cross section

Drell-Yan (DY) production

σ_{eff}(DY) ~ 15 pb

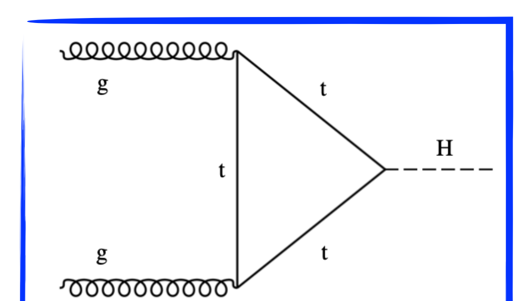


- S/B ~ one per-mille with $m_{\mu\mu}$ near 125 GeV
- Large additional background rejection necessary to measure H→μμ signal.

Three orders of magnitude more DY background than H→μμ signal in preselected search region.

H→μμ signal

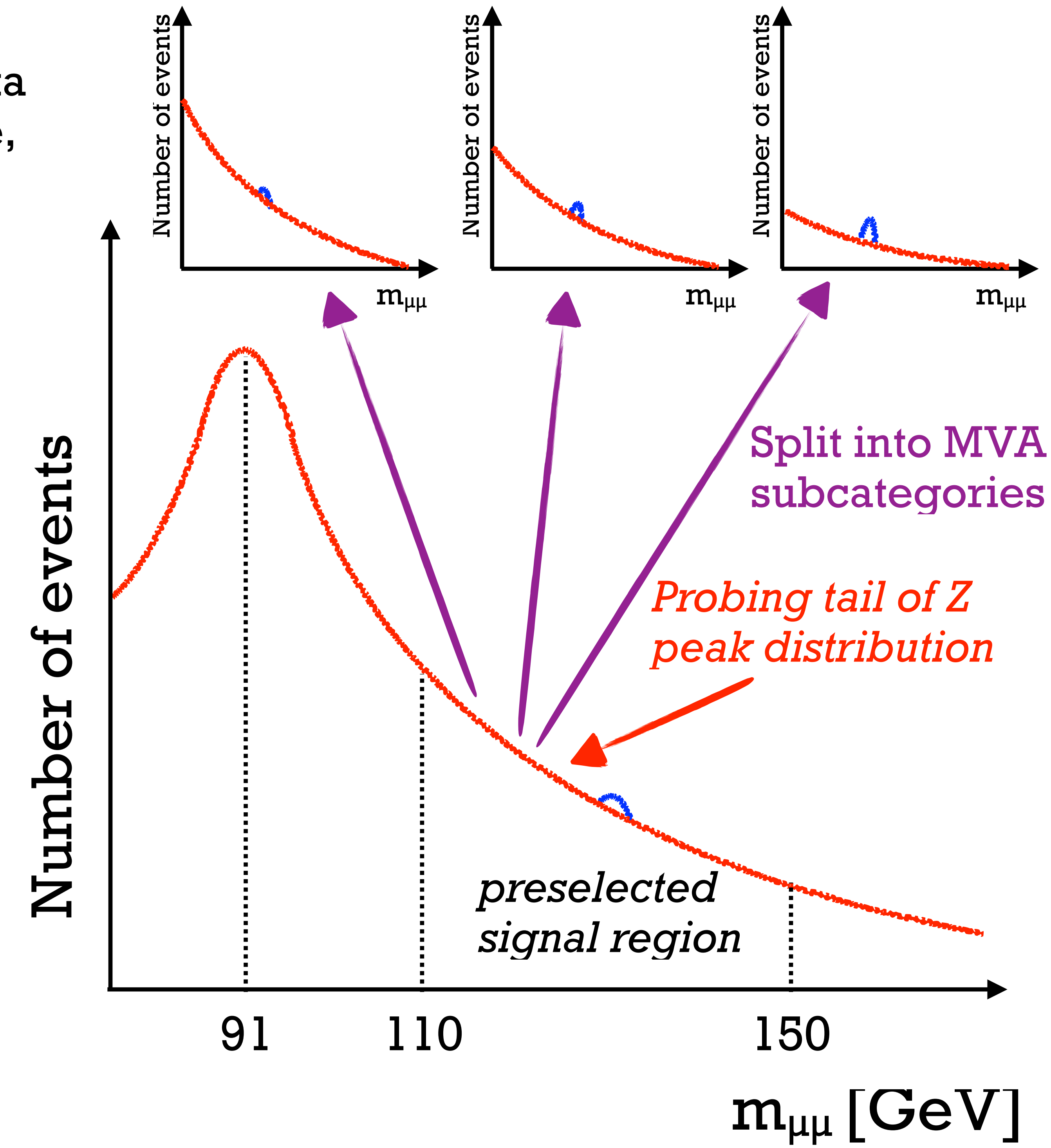
σ_{eff}(H→μμ) ~ 0.01 pb



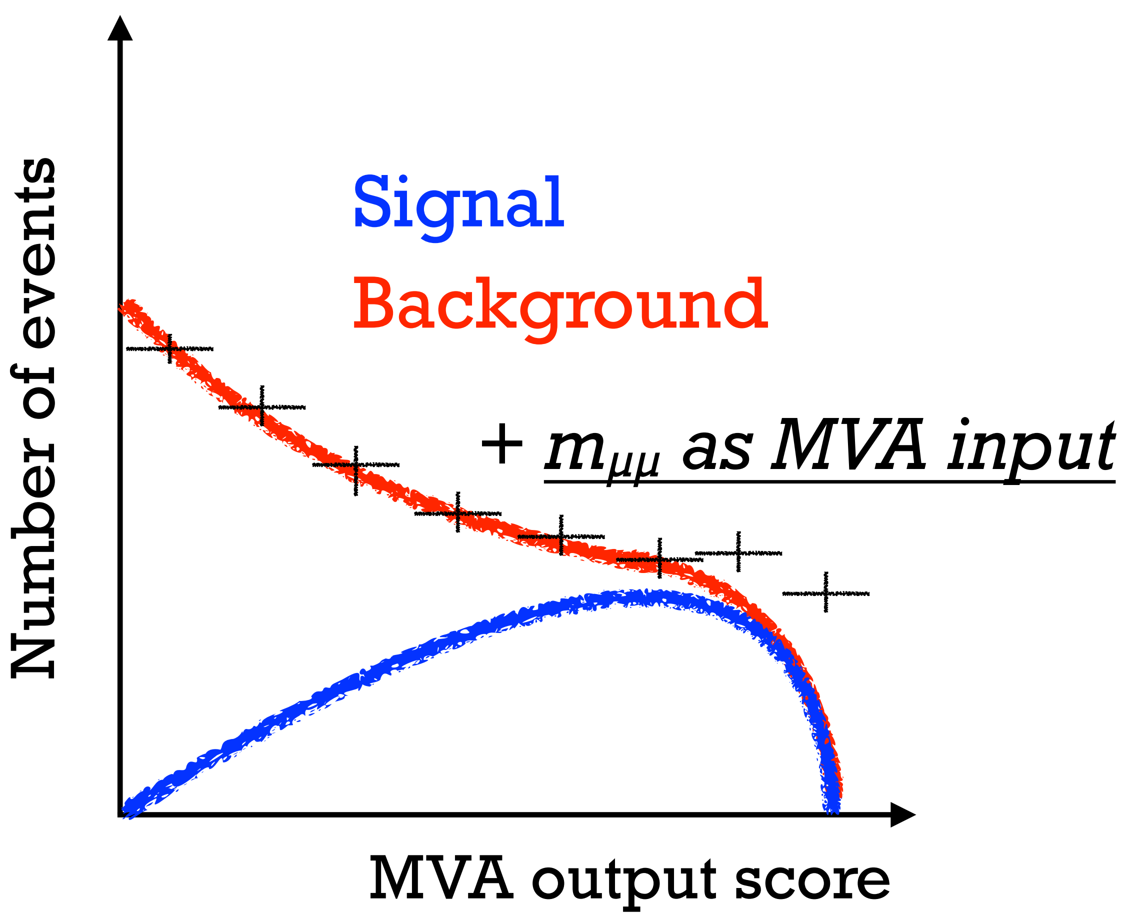
H→μμ in a nutshell

- Analysis strategy optimized per H production mode, with similar contribution to overall H→μμ precision from gluon-fusion and VBF categories.
- Huge effort to make the most of the Run-2 data (won't focus on the experimental details here, there are many…)

Data-driven categories (ggH, ttH, VH)



Simulation-based VBF category

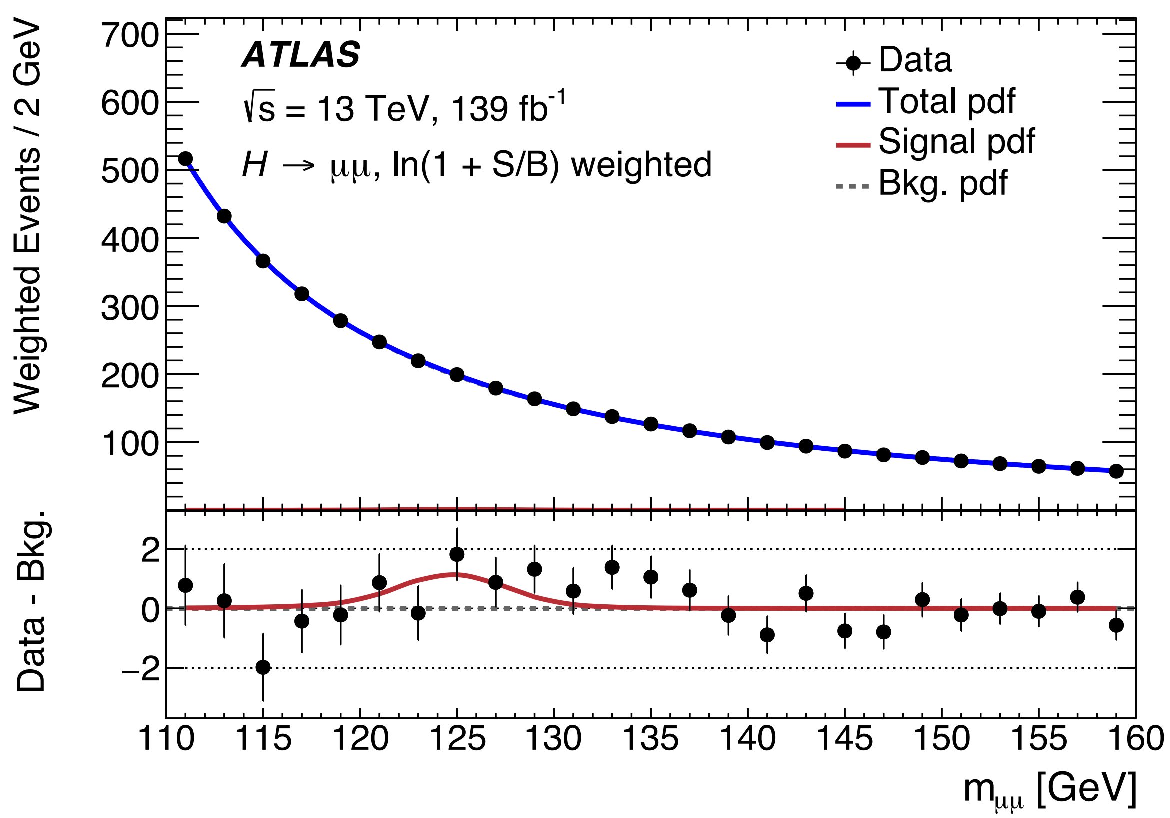


Putting it all together

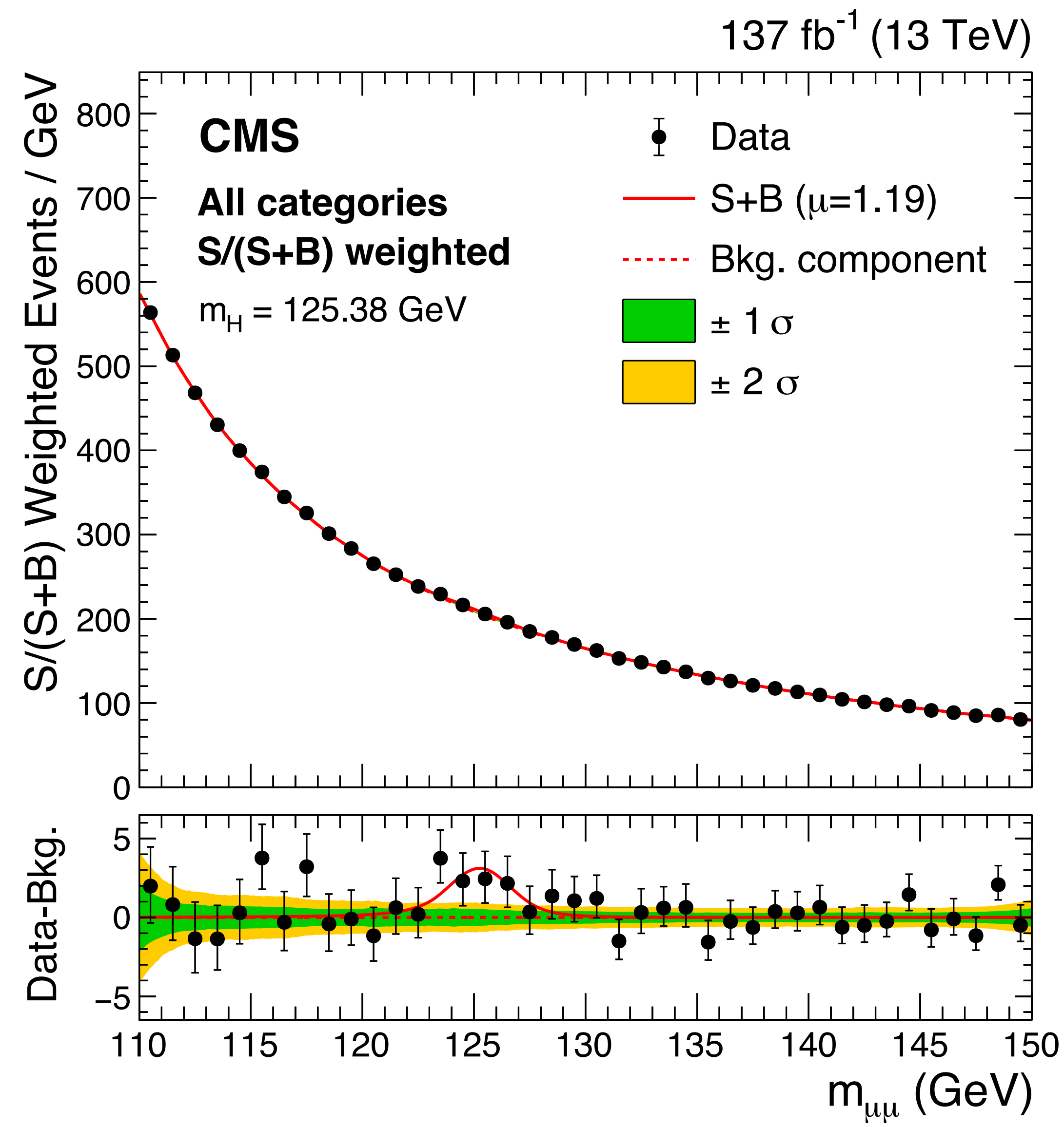
- *Evidence for H→μμ with LHC Run-2 data!*

- *What exactly does this imply about the muon Yukawa?…*

ATLAS Run-2 result*: **2.0σ** (1.7σ) obs. (exp.)



CMS Run-2 result: **3.0σ** (2.5σ) obs. (exp.)



*I don't cover the details of ATLAS measurement in this talk, refer to Phys. Lett. B 812 (2021) 135980

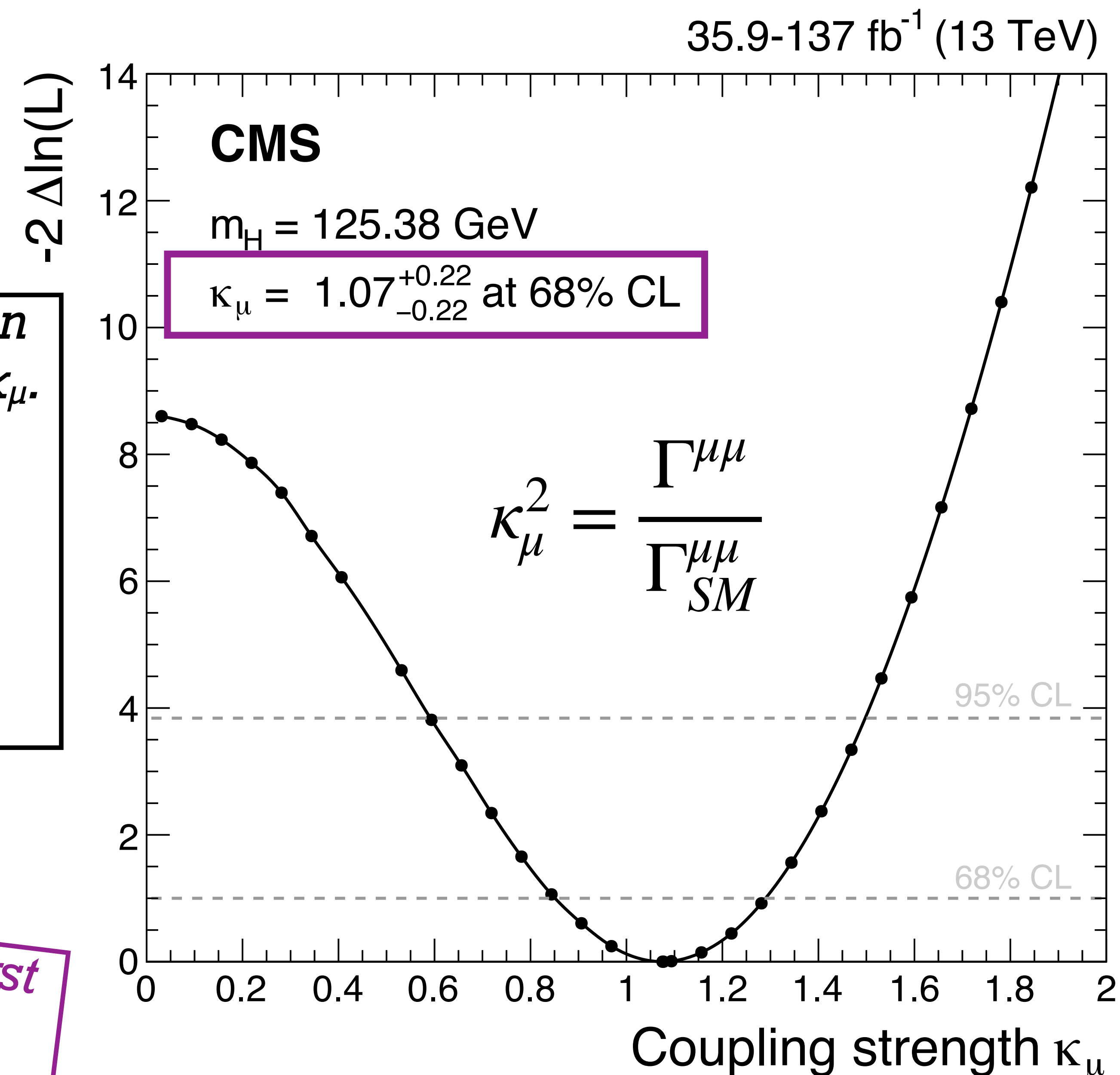
Direct constraints on H-μ interaction

Direct access to H-μ interaction

$$\mu = \sigma_H \cdot BR(H \rightarrow \mu\mu)$$

Depends on Higgs boson interaction strength with t, W, Z, …

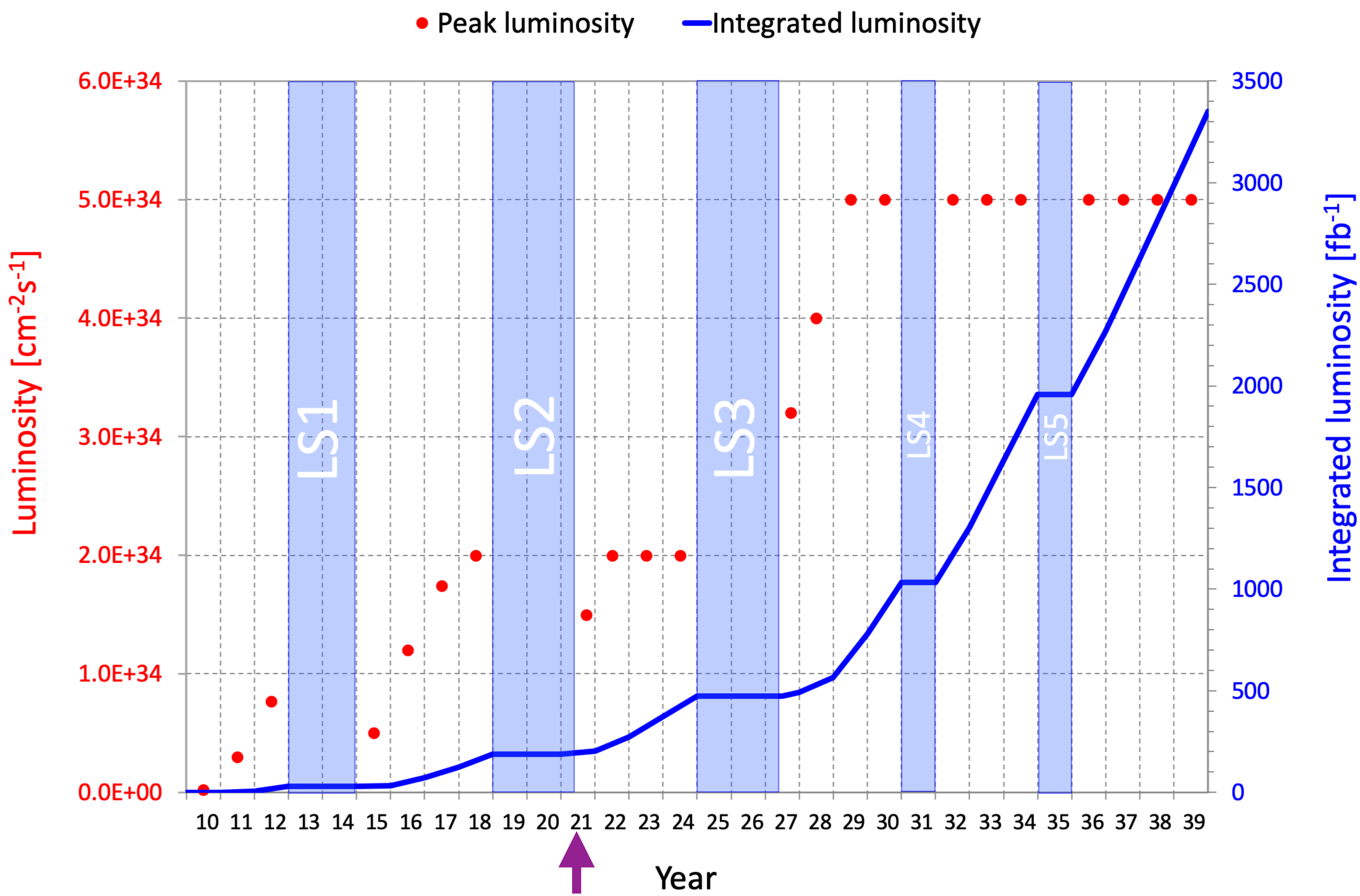
H-μ coupling strength from combination with measurements of other Higgs channels (EPJC 79 (2019) 421)



- *Combine with other Higgs channels to obtain direct constraints on H-μ coupling strength κ_μ.*
- *Coupling strength of Higgs boson to muon measured with nearly 20% precision at 68% confidence level.*

- *Muon Yukawa looks very much SM-like at first look (20-30% precision), but we are just getting started!*

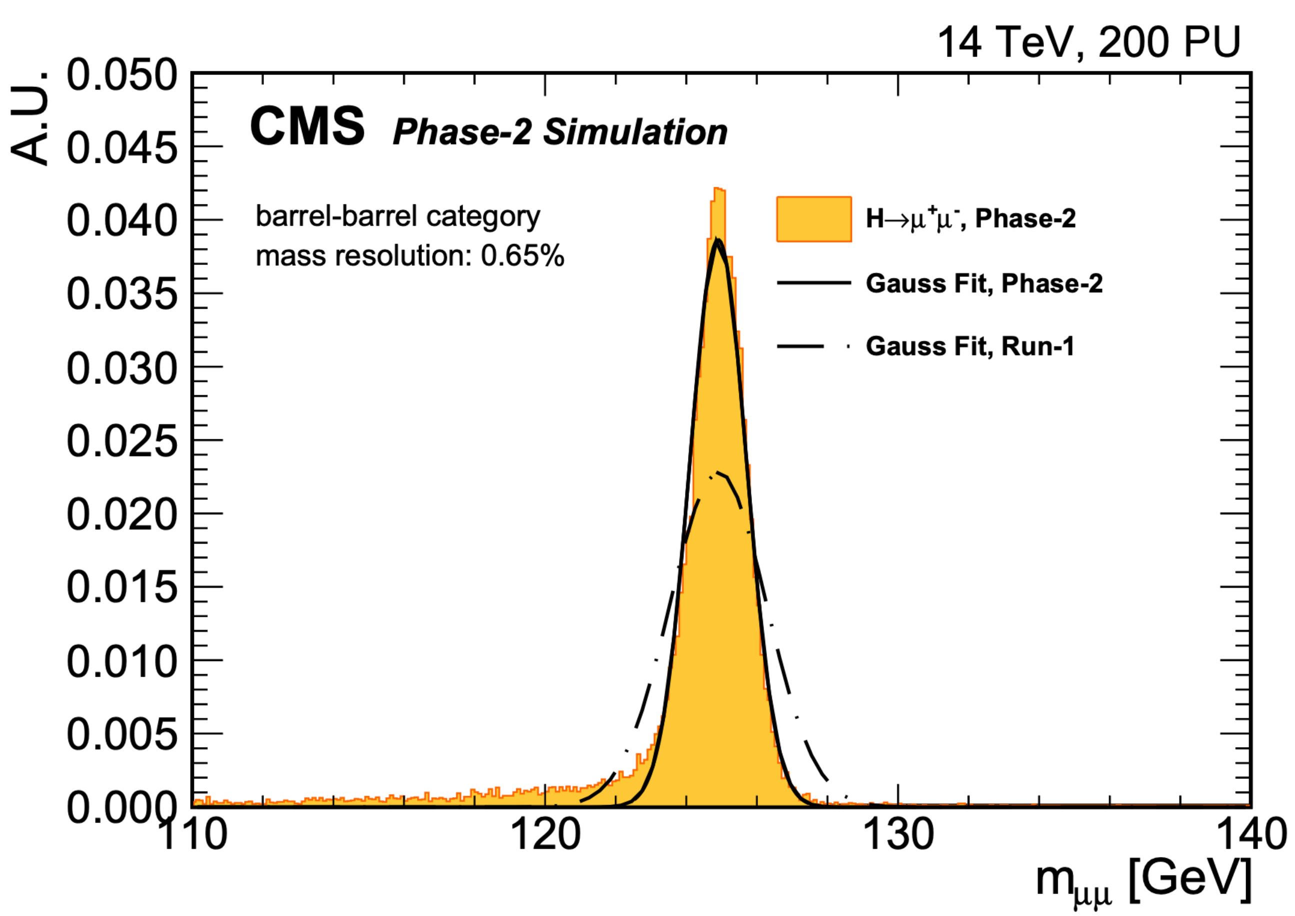
(HL) LHC schedule

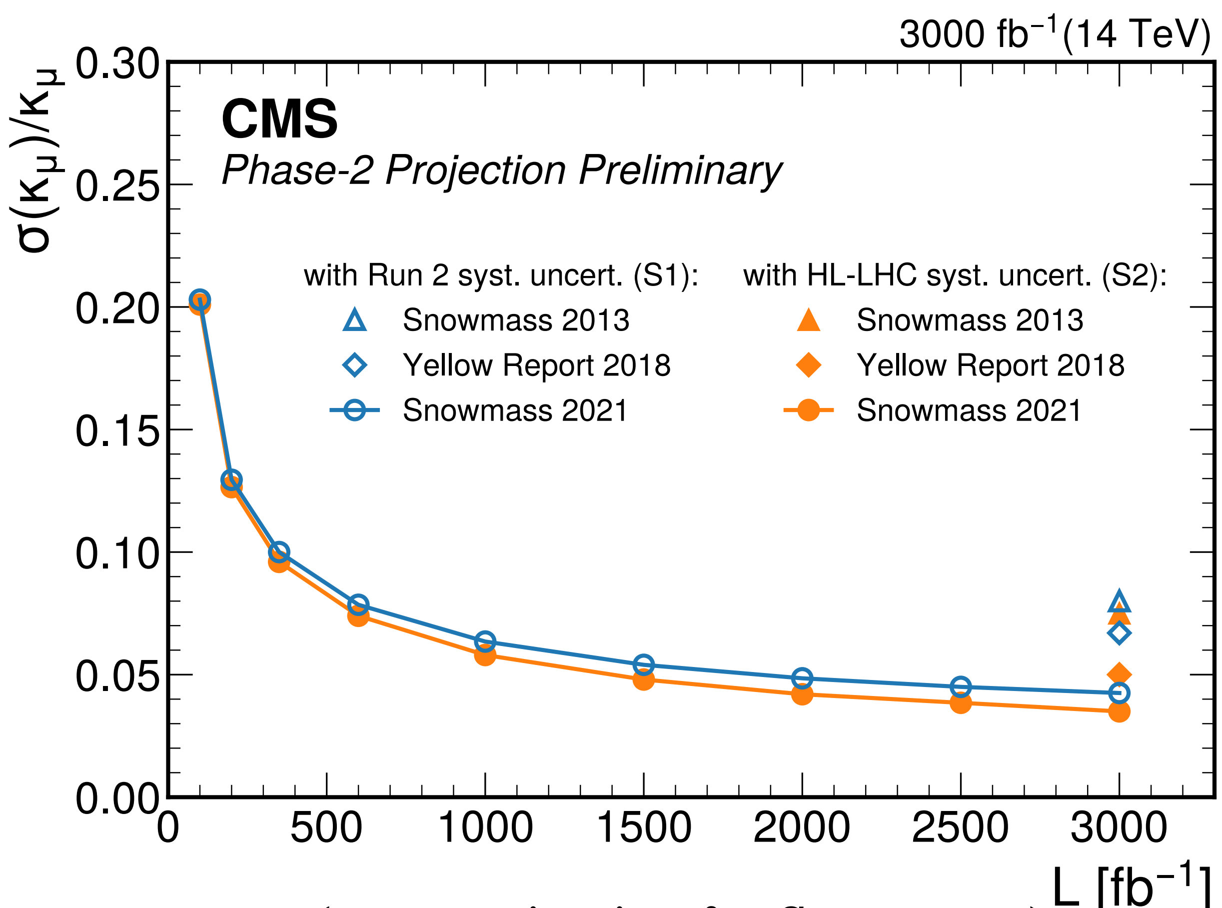


We are here (few % of final dataset)

What to expect

- (HL)-LHC: from evidence (20-30%) to precision (<5%) on muon Yukawa.
- Nature can be subtle!



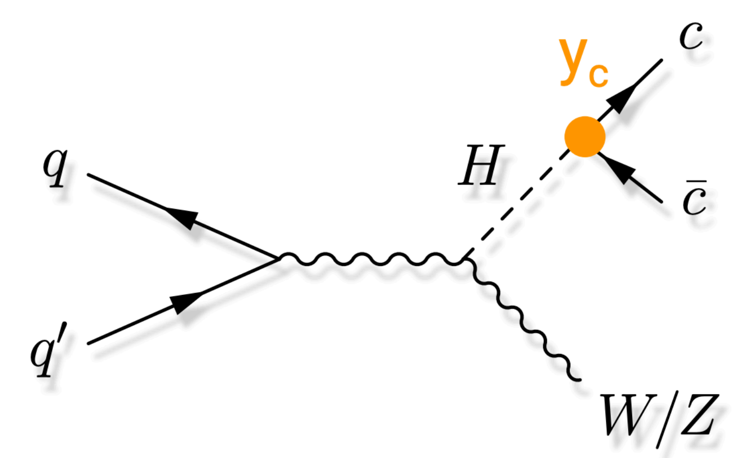


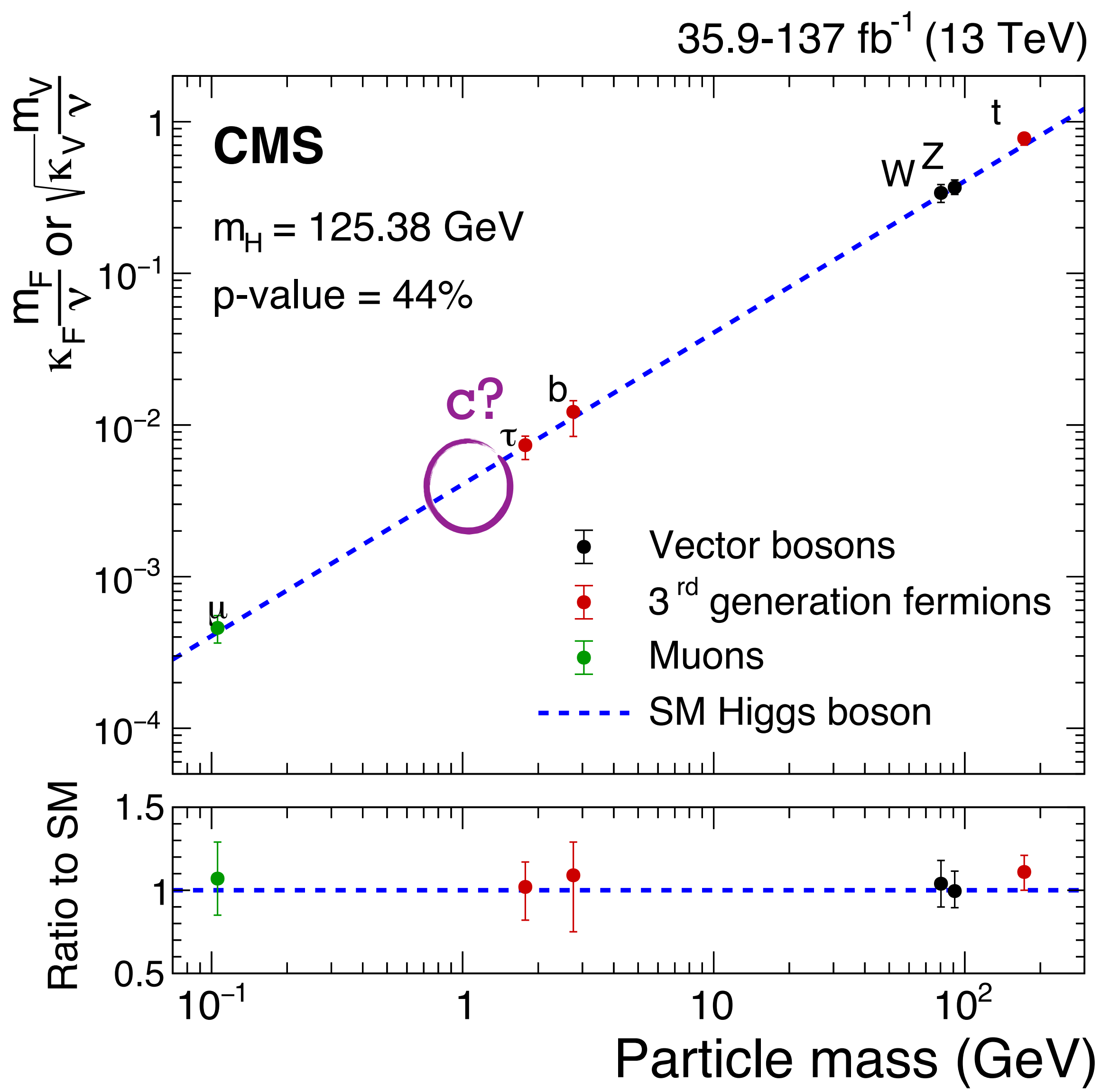
(new projection for Snowmass)

Constraining the Higgs-charm Yukawa

- Measuring H→cc at the LHC is extremely challenging:
  - Multijet background larger by many (7-9!) orders of magnitude.
  - Charm jet tagging is very difficult.
  - Until very recently, we not thought that measuring H→cc at the LHC would be possible.

- Today I highlight new results from CMS searching for H→cc in VH production (most sensitive channel).
  - It is also possible to constraint Y_c indirectly from production in differential H measurements, not covered today.
  - ATLAS also has a new VH, H→cc measurement this year, more details in backup.

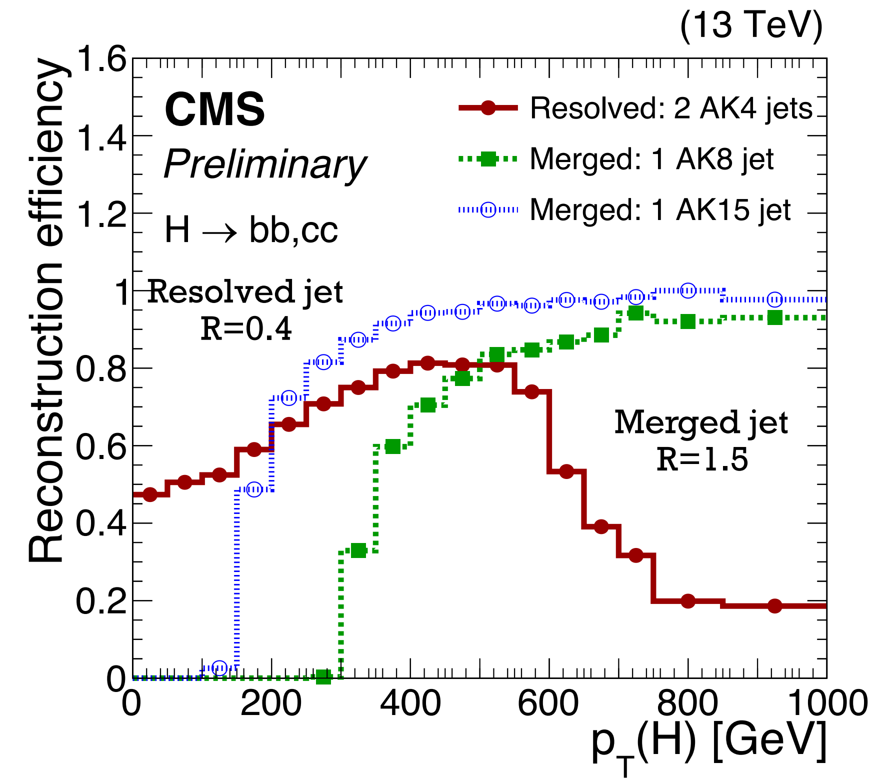


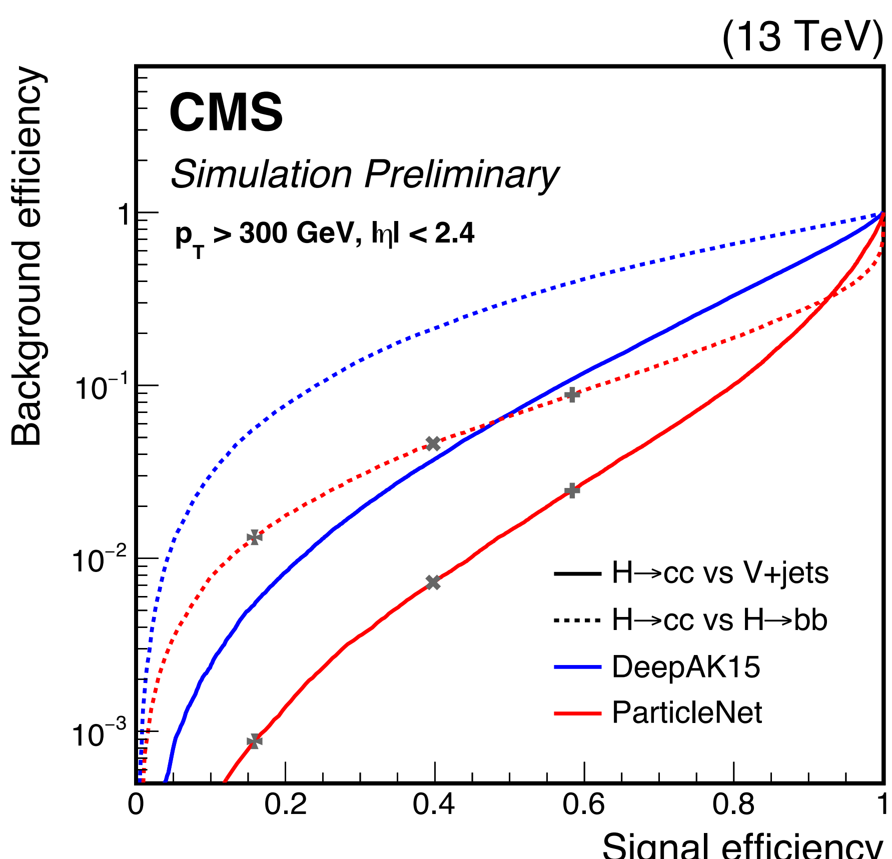


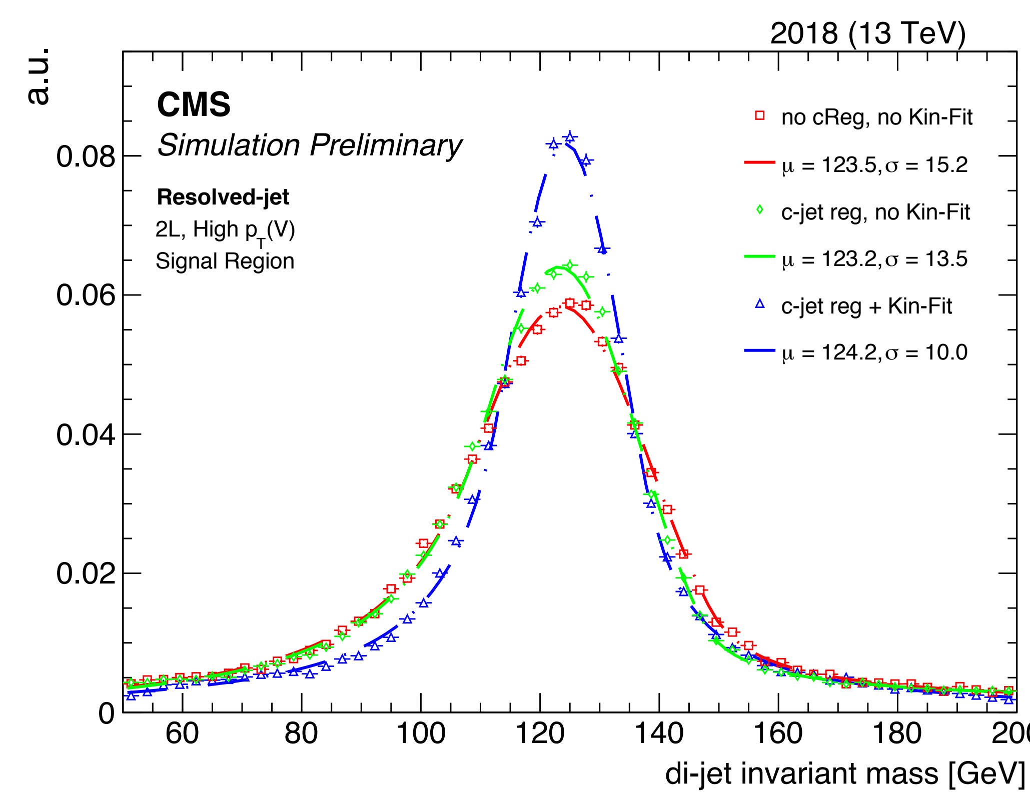
H→cc: maximizing the sensitivity

- *Huge effort to make the most of the data collected*:
    - Especially (but not only) in charm jet tagging, including the first application of graph neural networks to jet tagging (ParticleNet [1]).
    - Multiple applications of multivariate regression techniques, also kinematic fits, …)

- Factor ~5 improvement in sensitivity with respect to previous search:
    - Factor 2 from increased dataset, the rest from analysis improvements.



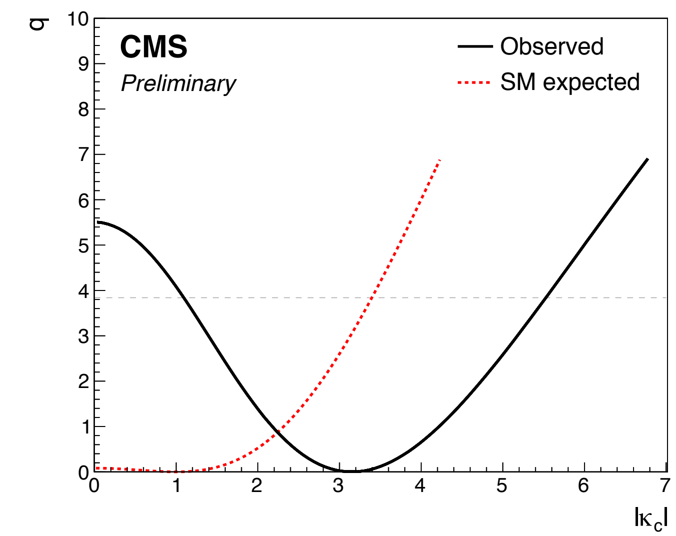




[1] Phys. Rev. D 101, 056019 (2020)

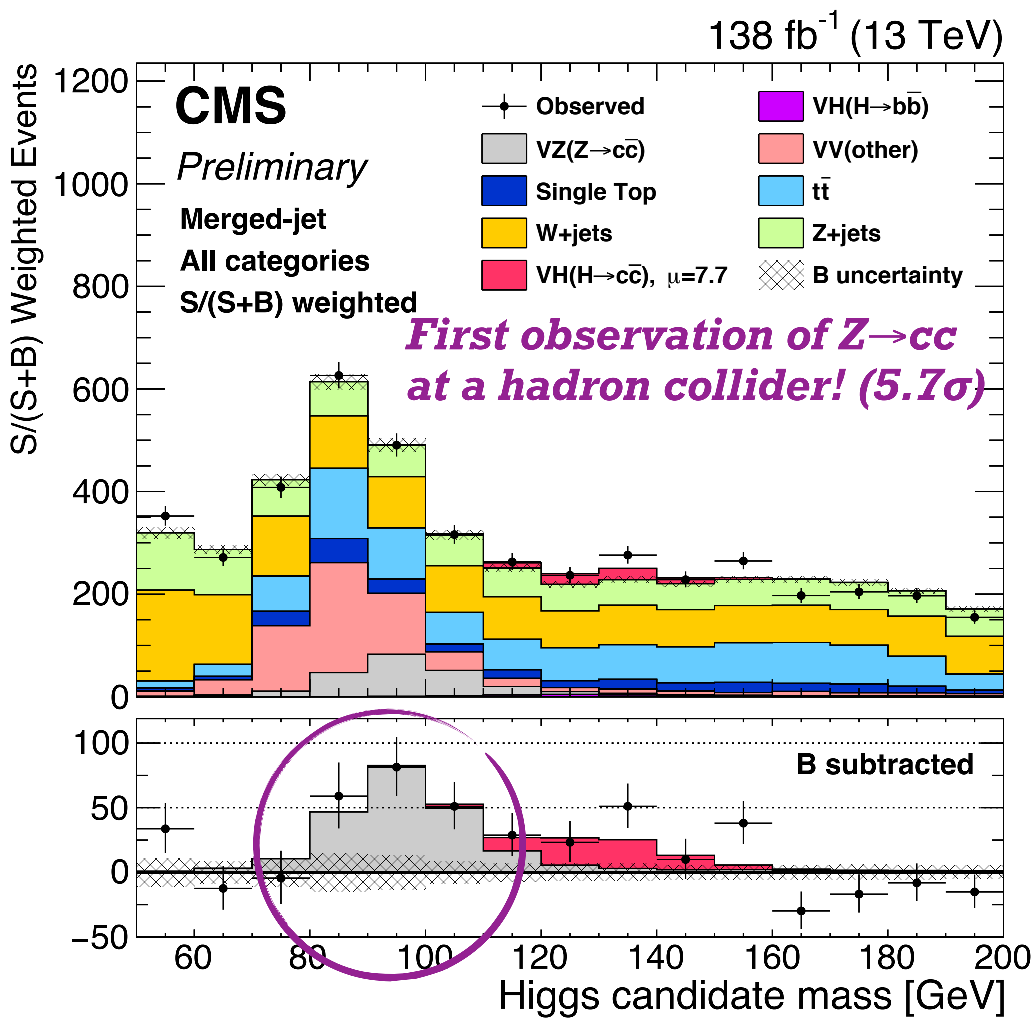
Putting it all together: H→cc results

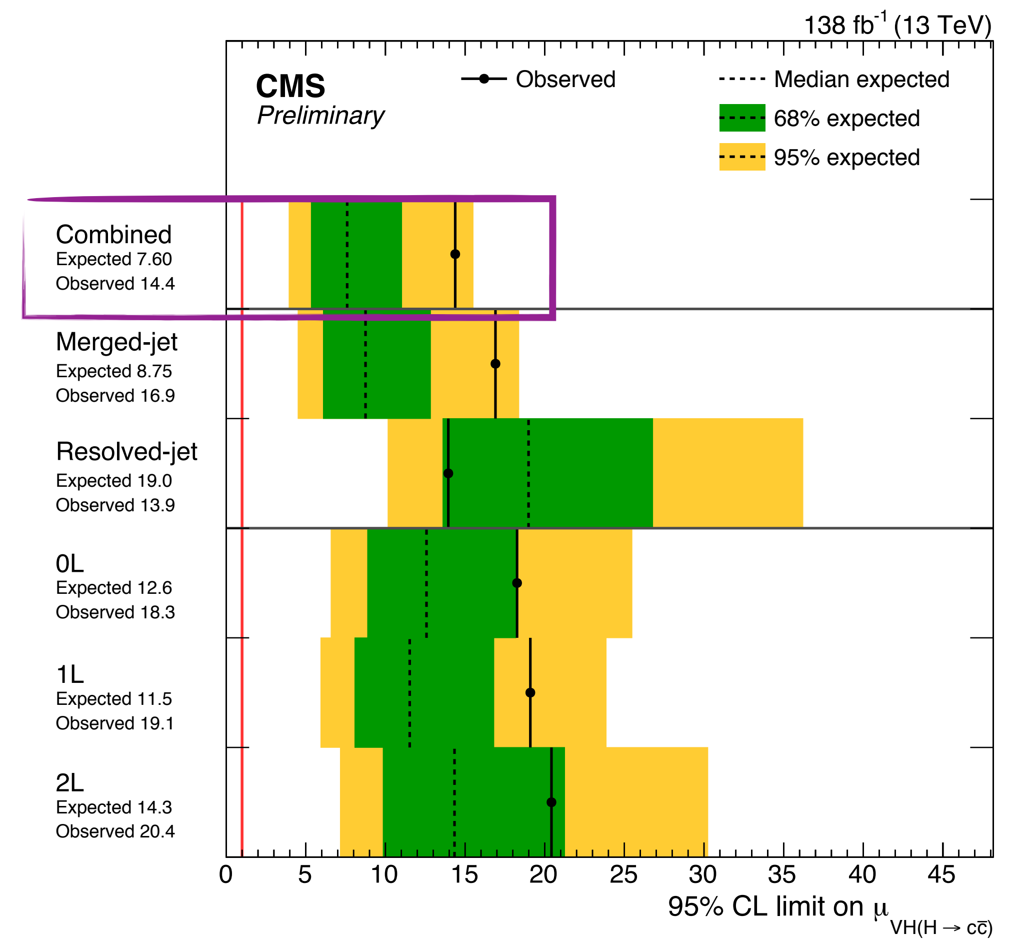
- Measurements of [W/Z]Z→cc signal demonstrates reliability of methods in data.
- Contraints on y_c comparable to what had previously been expected at end of HL-LHC!



1.1 < κ_c < 5.5 (<3.4 exp.)

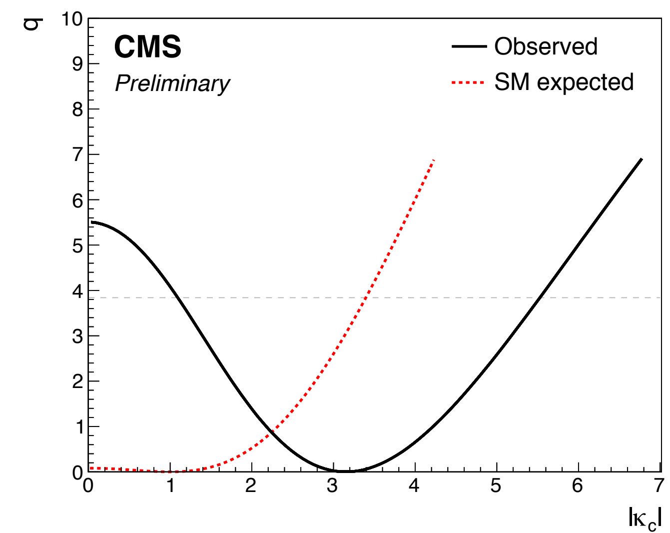
BR(H→cc) < 14 (8) x SM @95% C.L.





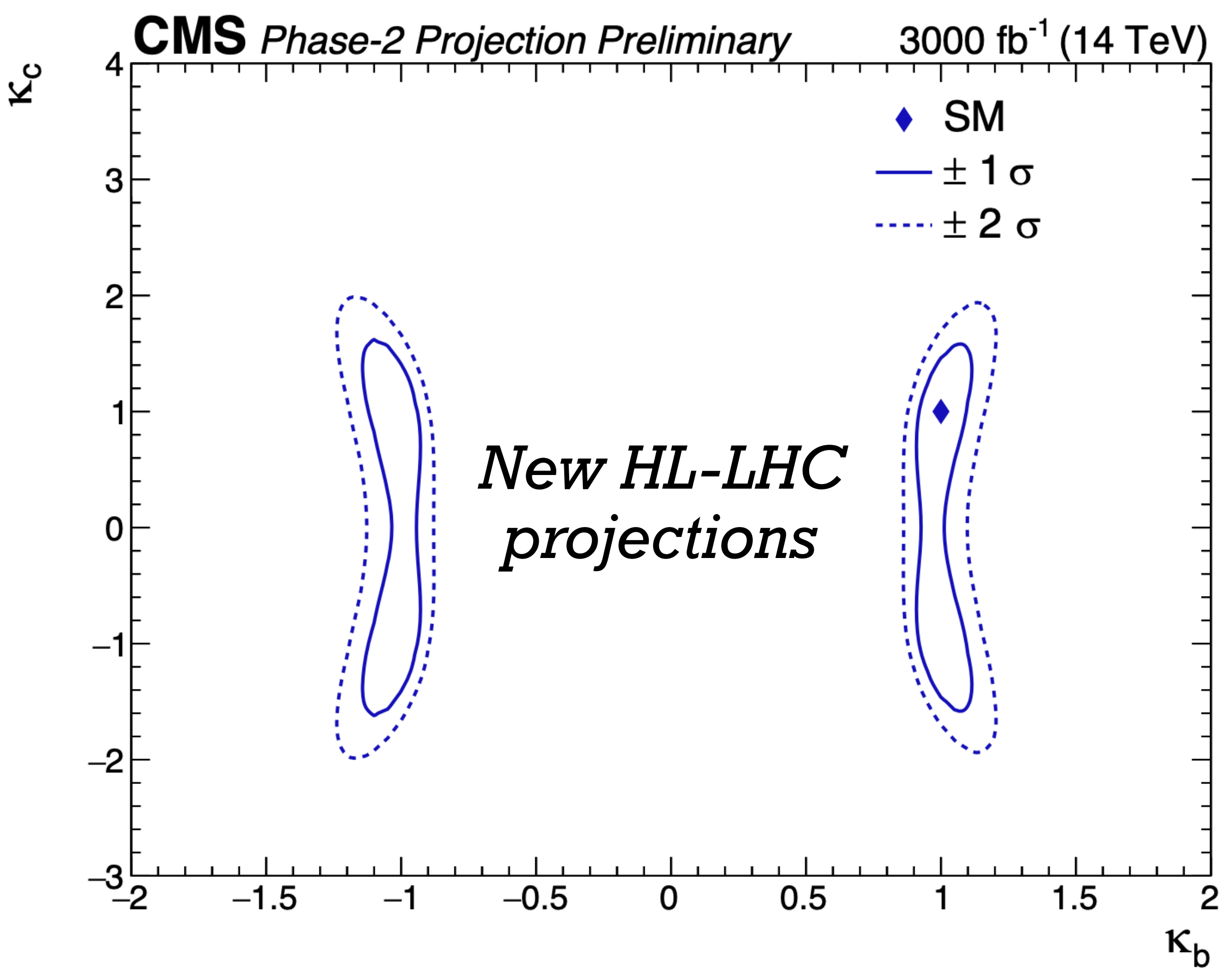
Putting it all together: $H \to cc$ results

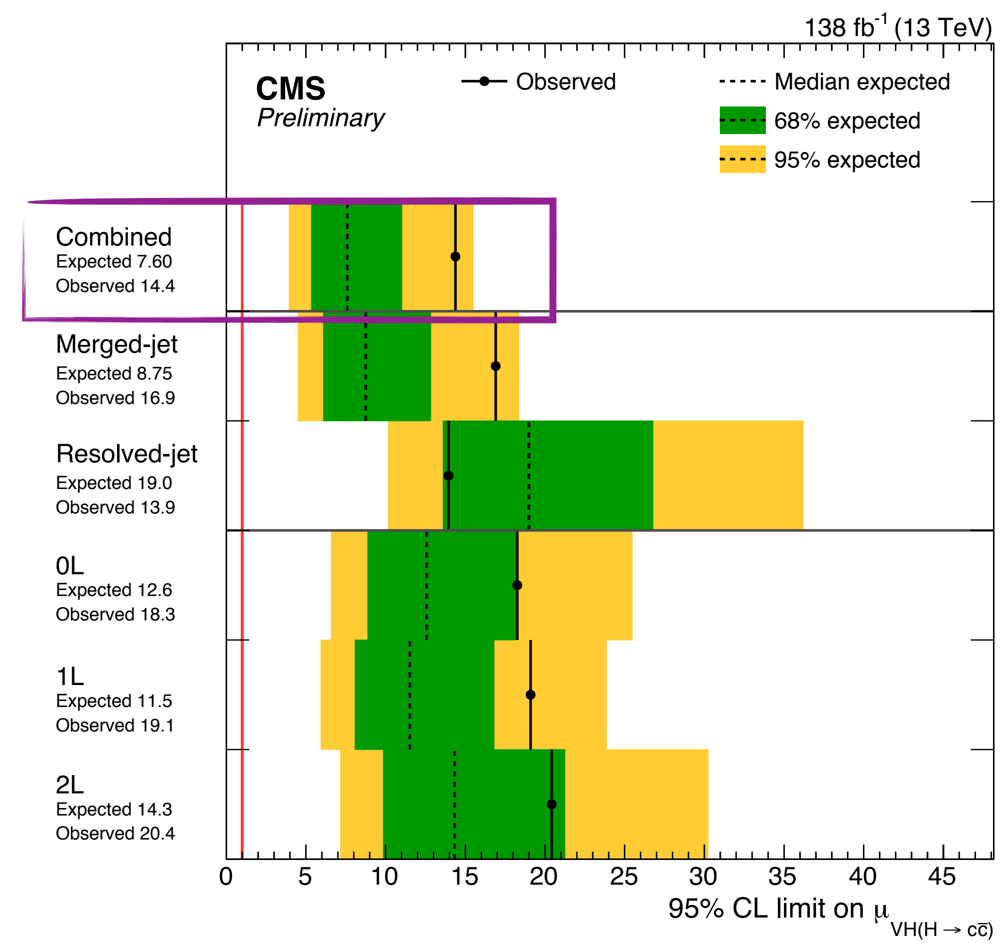
- Measurements of [W/Z]$Z \to cc$ signal demonstrates reliability of methods in data.
- Contraints on y_c comparable to what had previously been expected at end of HL-LHC!
- Updated projections for HL-LHC:
  - *With these results, a huge step forward towards measuring $H \to cc$ at the HL-LHC!*



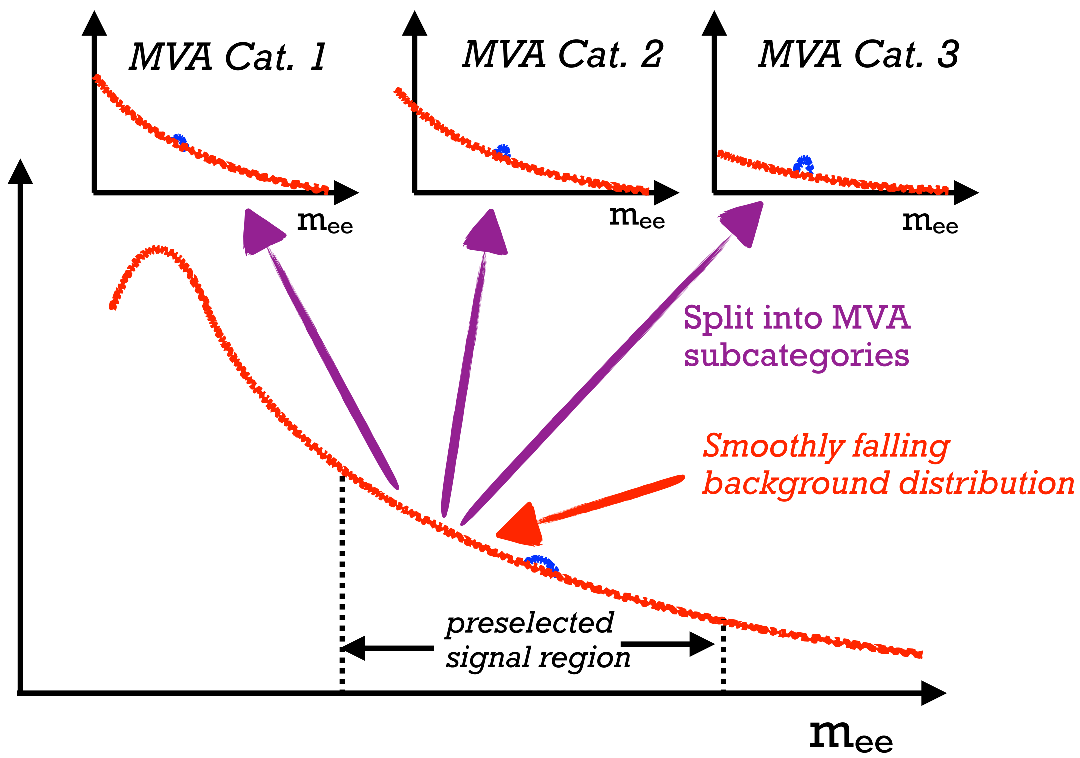
$1.1 < \kappa_c < 5.5$ (<3.4 exp.)

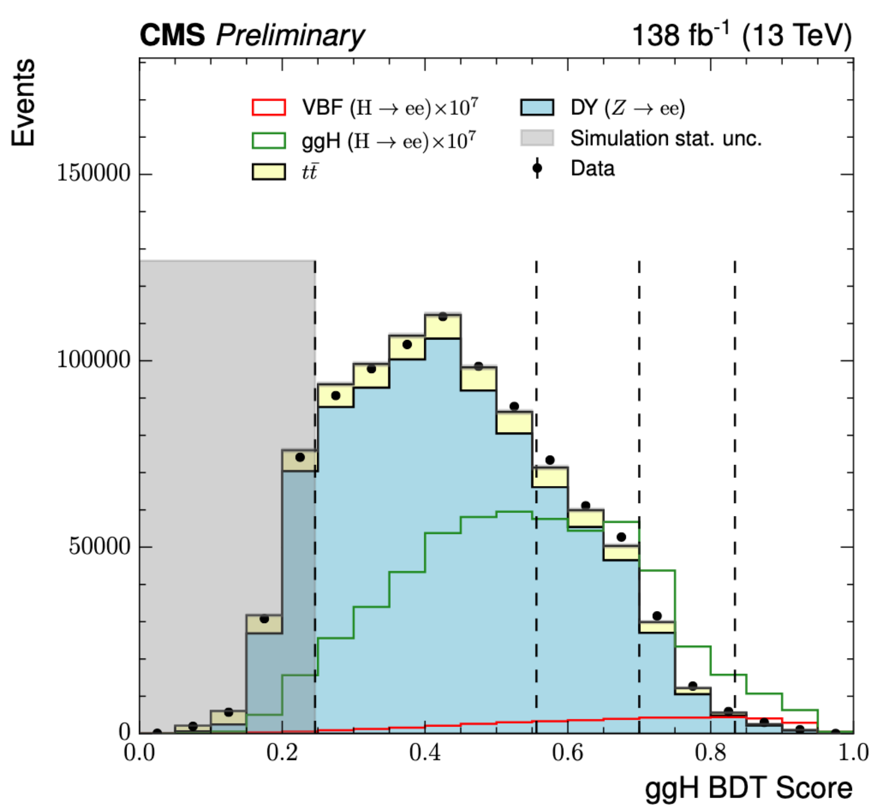
BR($H \to cc$) < 14 (8) x SM @95% C.L.

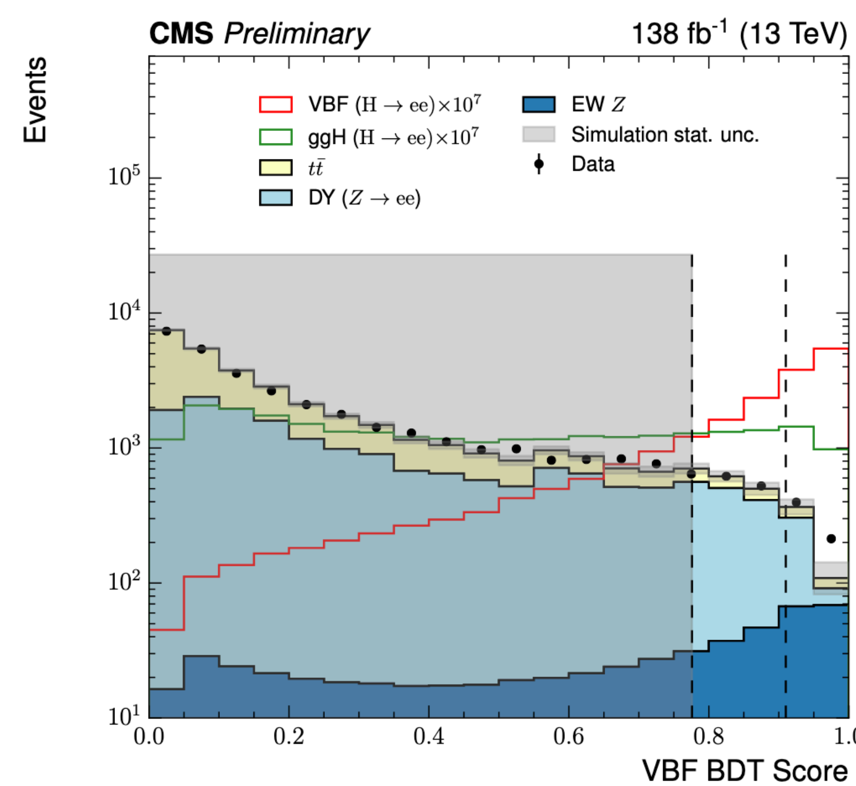




- H→ee only direct probe of Higgs-electron Yukawa.
  - SM prediction for BR(H→ee) ~ 5 * 10^{-9}.
  - ⇒ H→ee signal observation at the LHC would be a clear sign of BSM physics in Higgs sector.
- Dedicated MVA categories targeting gluon-fusion and vector boson fusion (VBF) H production modes.
- Multivariate classifiers used to isolate regions of high expected signal purity.



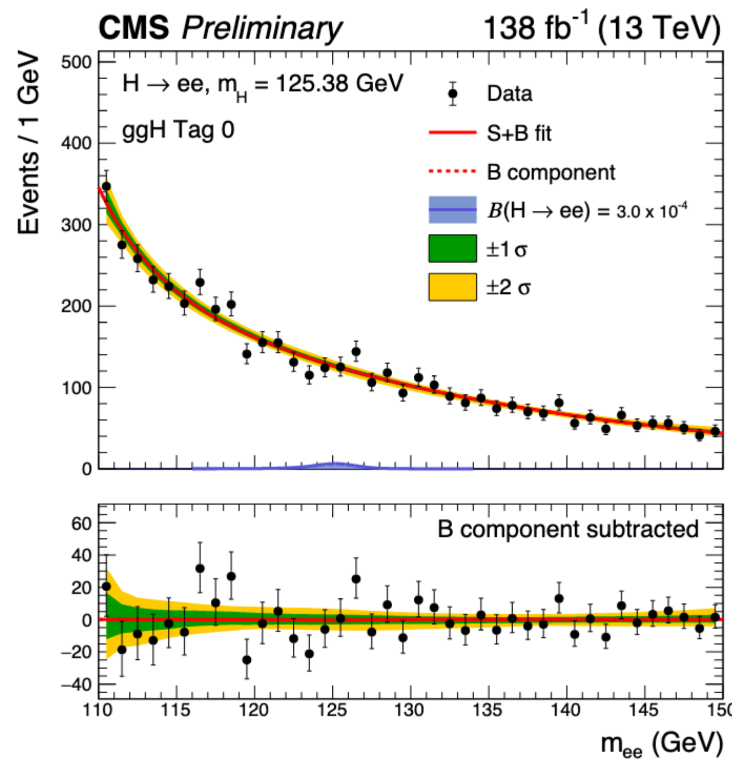




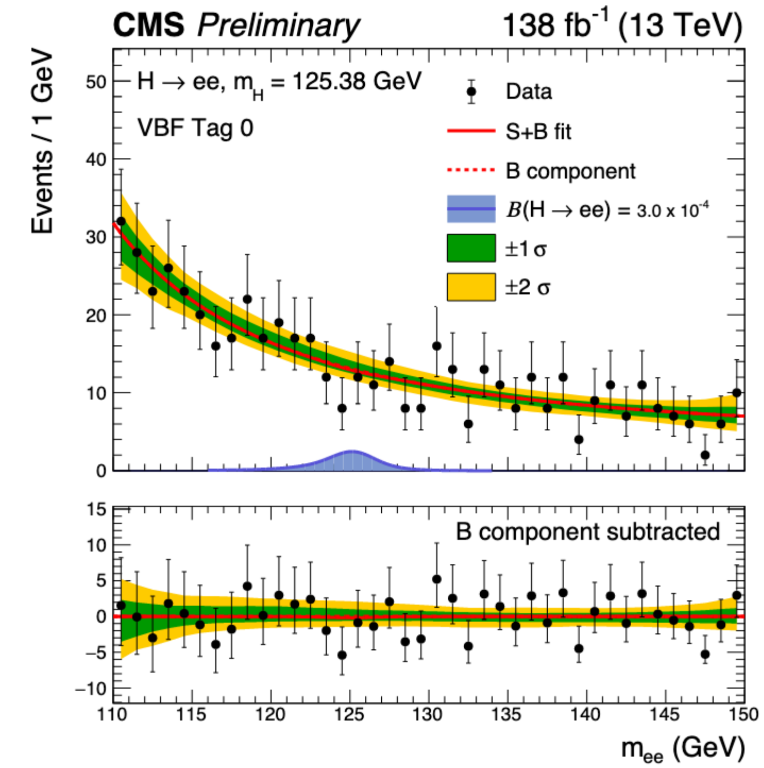
H→ee: results

- Parametric fits to m_{ee} distribution simultaneously across MVA categories .
- No significant excess above background-only expectation ⇒ best limit to date on BR(H→ee).
- Upper limit on BR(H→ee) scanned as a function of m_H.

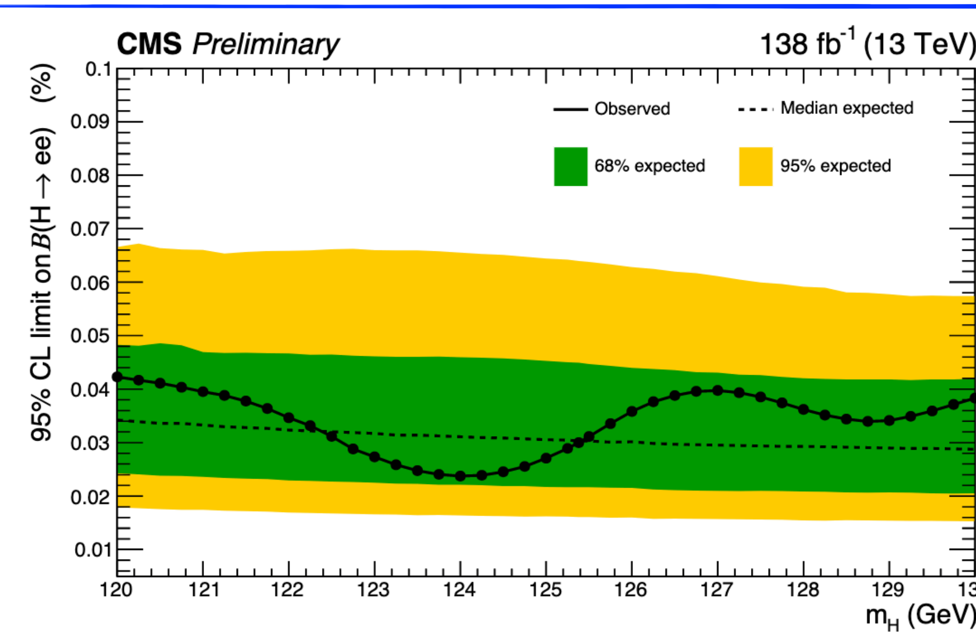
Most sensitive
ggH category



Most sensitive
VBF category

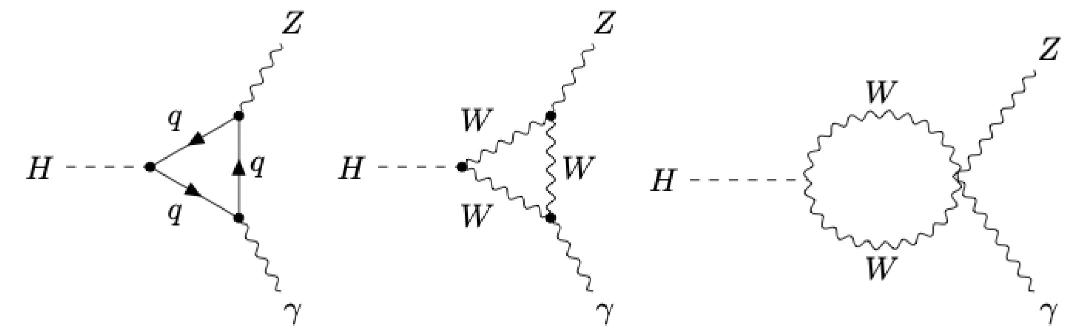


BR(H→ee) < 3.0 (3.0 exp.) * 10^{-4} @95% C.L.



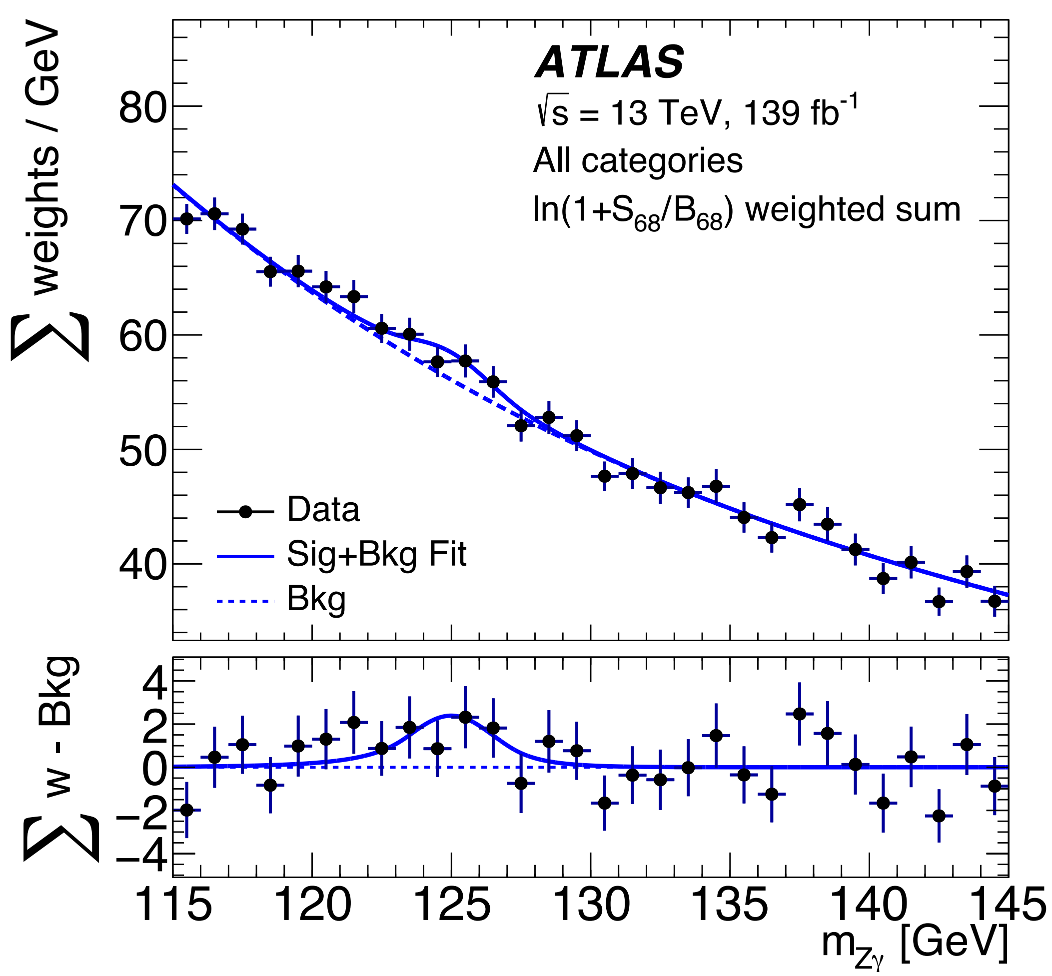
H→Zγ

- SM B(H→Zγ) = 1.6×10^{-3}, ratio between H→Zγ and H→γγ potentially sensitive to BSM.

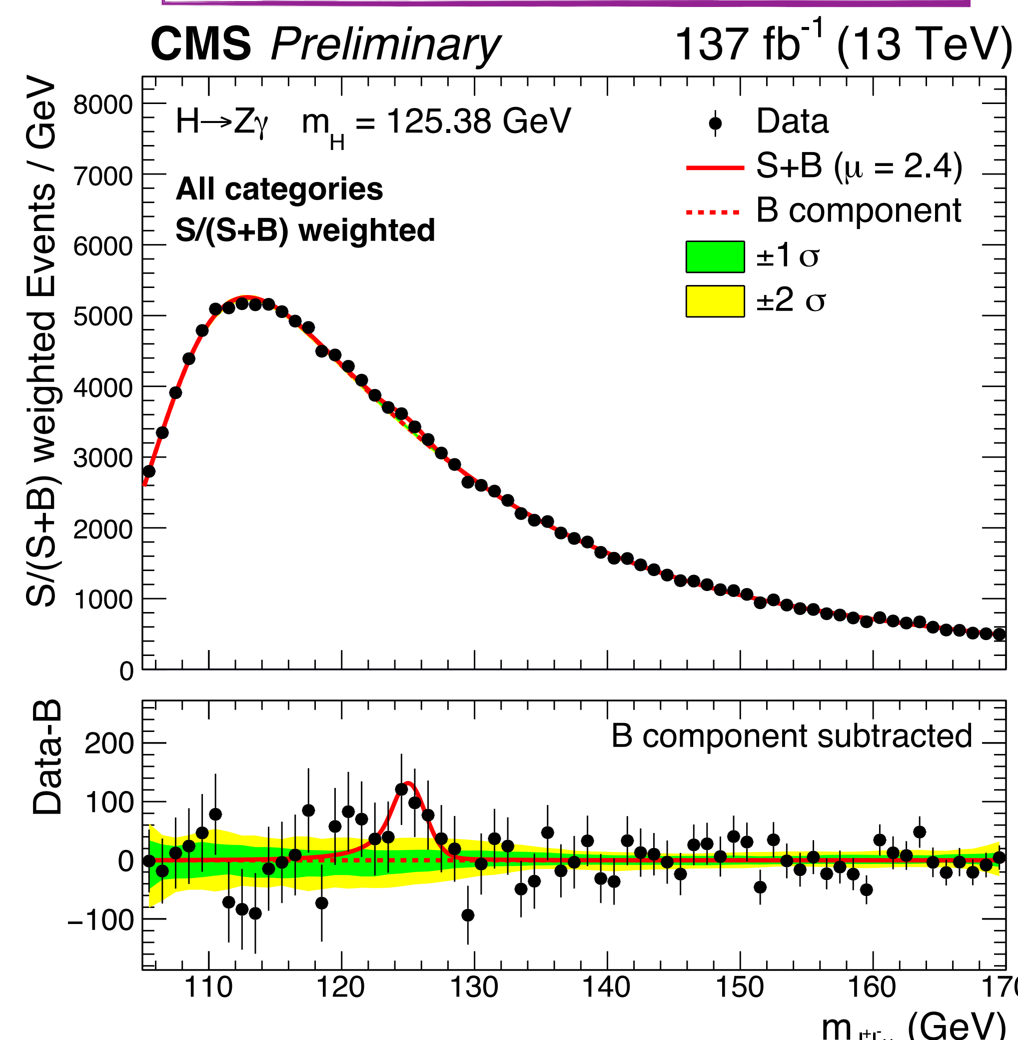


- Both experiments observe rate higher than SM expectation, with significance of 1-2σ.
- Statistically limited measurement ⇒ Run-3 data critical to pinpoint this potential signal.

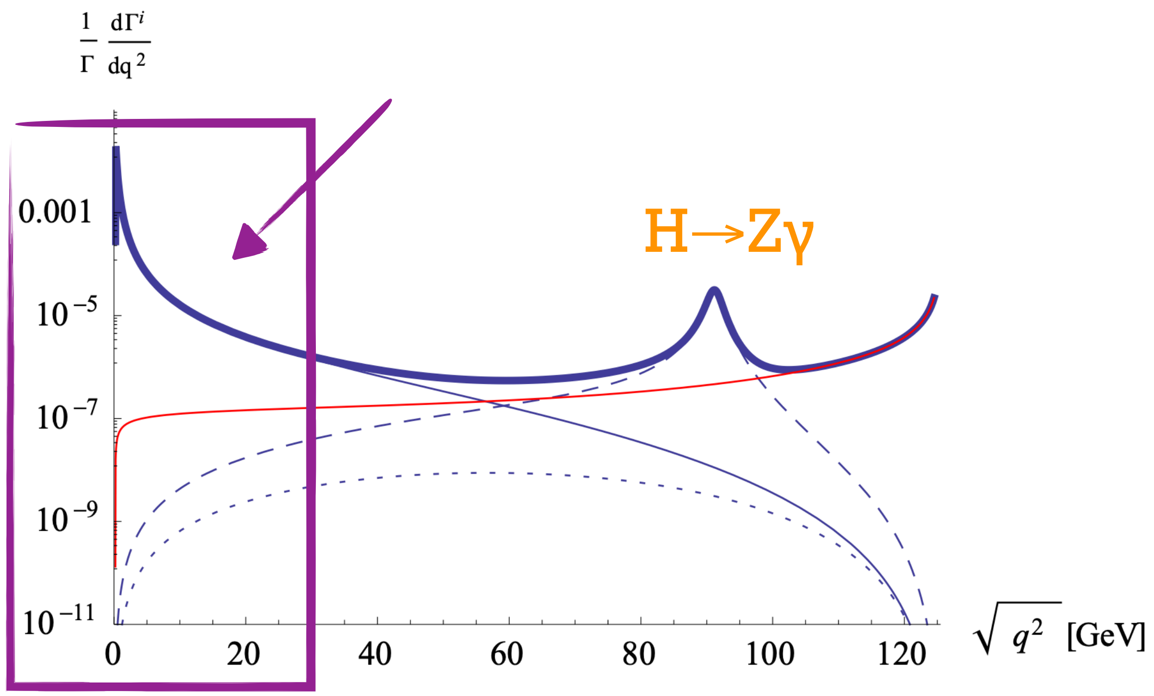
ATLAS Run-2 result: 2.2σ (1.1σ) obs. (exp.)

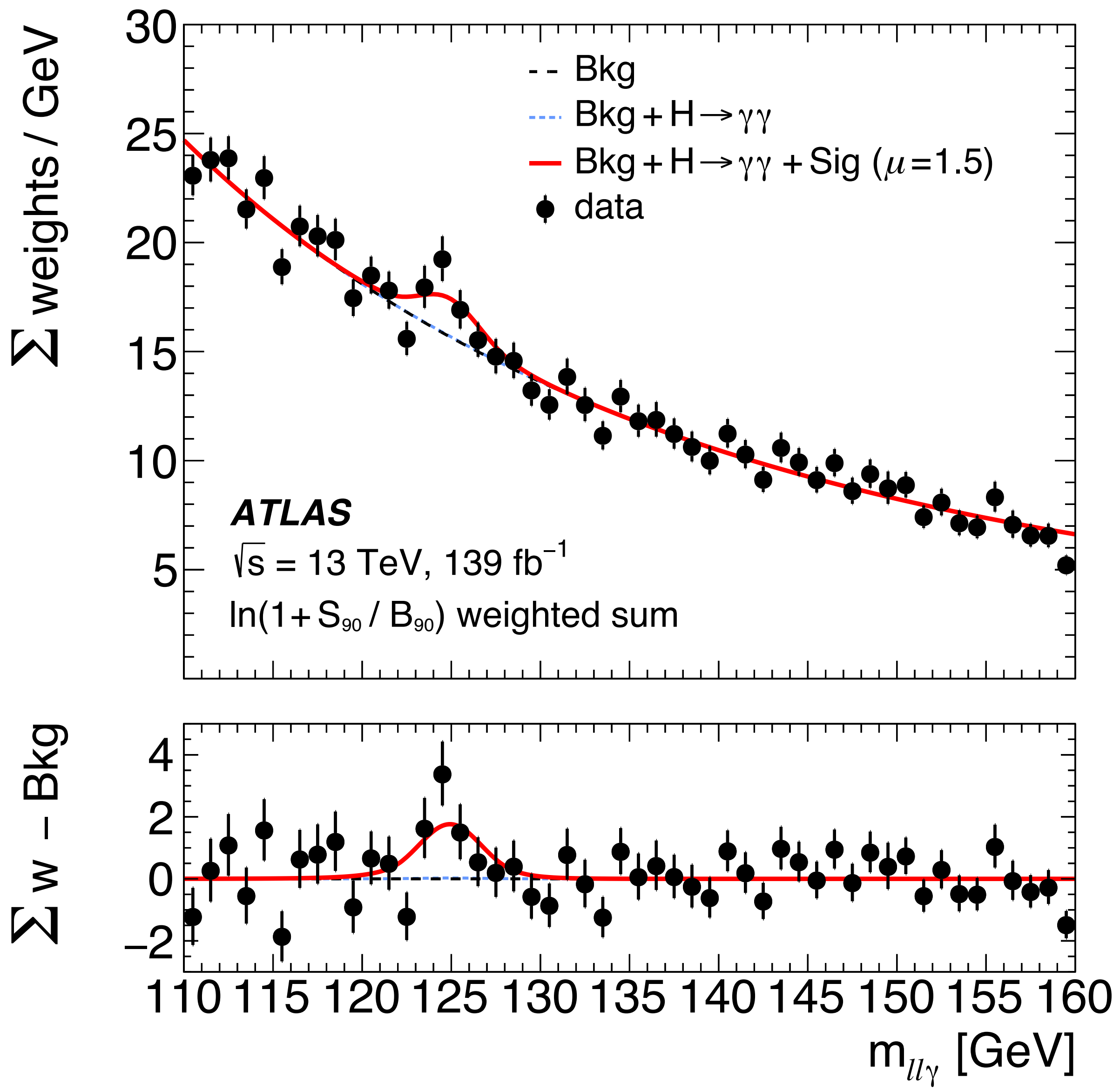


2.7σ (1.2σ) observed (expected for SM H) over b-only



H→llγ Dalitz decay

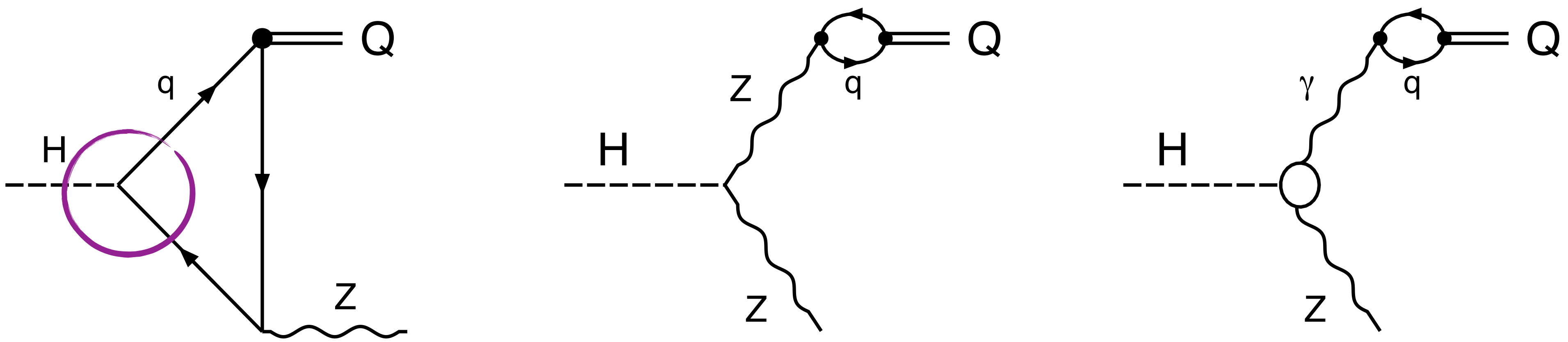




- Target low-m_{ll} region dominated by virtual photon contribution.
- ATLAS deployed in Run-2 dedicated trigger and reconstruction for merged-ee categories.
  - eeγ roughly factor 2 larger than μμγ at low mass.
  - Electron and muon categories contribute very similarly to overall sensitivity.

3.2σ (2.1σ) observed (expected for SM H) over b-only

H decays to quarkonia



- Exclusive H decays to X+quarkonia are an *important indirect probe of Yukawa interactions otherwise inaccessible* at LHC (Y_u, Y_d, Y_s).
  - Multiple diagrams that interfere, with Yukawa-sensitive contribution typically highly subdominant.
    - Can change significantly if Yukawa coupling is enhanced.
- Experimentally clean signature with small SM backgrounds.
- SM rates inaccessible by orders of magnitude ⇒ any excess would be a clear indication of (large) enhancement in Yukawa coupling.

H→Υ[Z/γ]

H→J/Ψ/[Z/γ]

H→J/Ψ(2S)/[Z/γ]

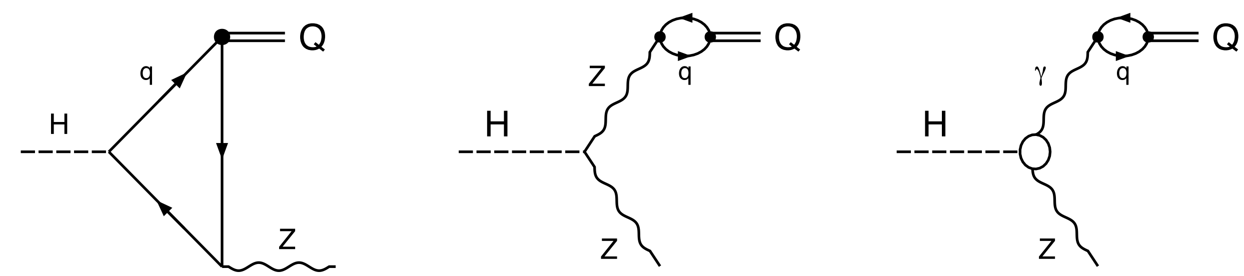
H→ϕ[Z/γ]

H→ρ[Z/γ]

H→J/Ψ J/Ψ

H→ ΥΥ

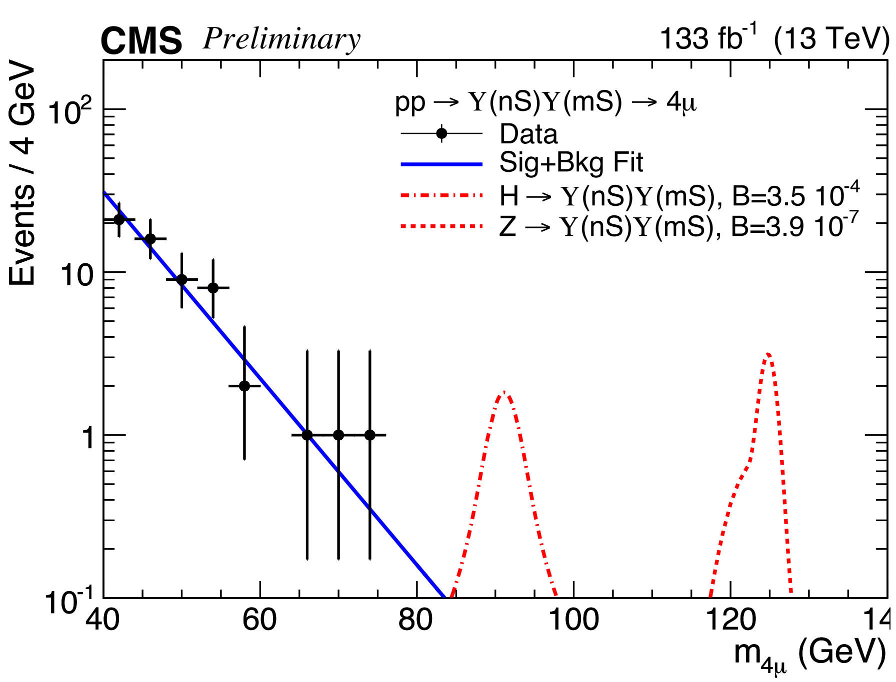
The latest: search for H→Z J/ψ / J/ψ J/ψ / ϒϒ



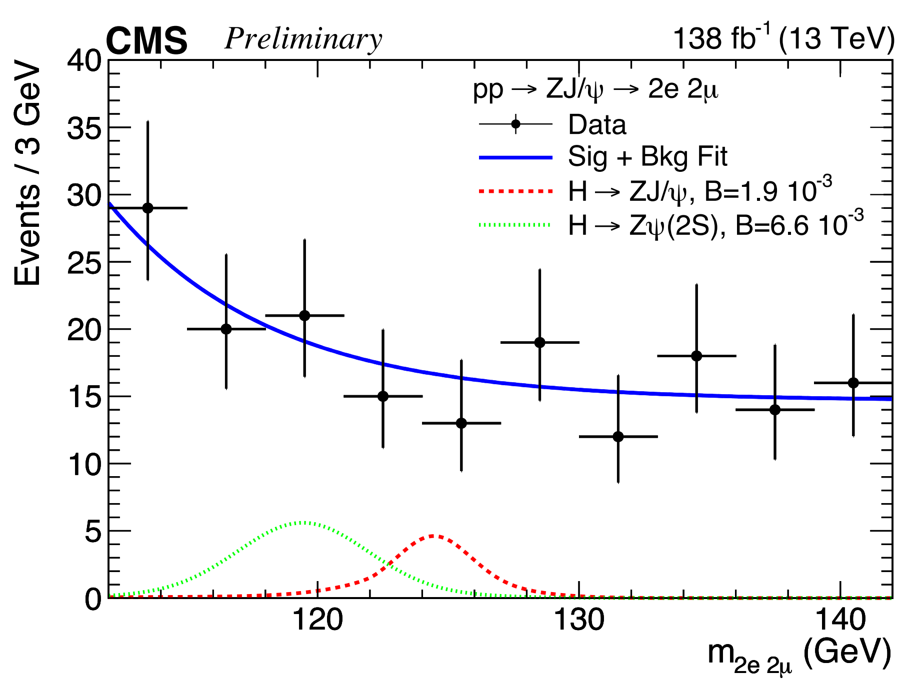
- Most recent result, including first search for H→Z J/ψ.
- These searches are generally statistically limited ⇒ will be a continually improving probe of otherwise inaccessible Higgs-quark interactions.

Decay mode	95% C.L. upper limit on BR
h→Z J/ψ	< 1.9 * 10^{-3}
h→ J/ψ J/ψ	< 3.8 * 10^{-4}
h→ϒ(nS)ϒ(mS)	< 3.5 * 10^{-4}

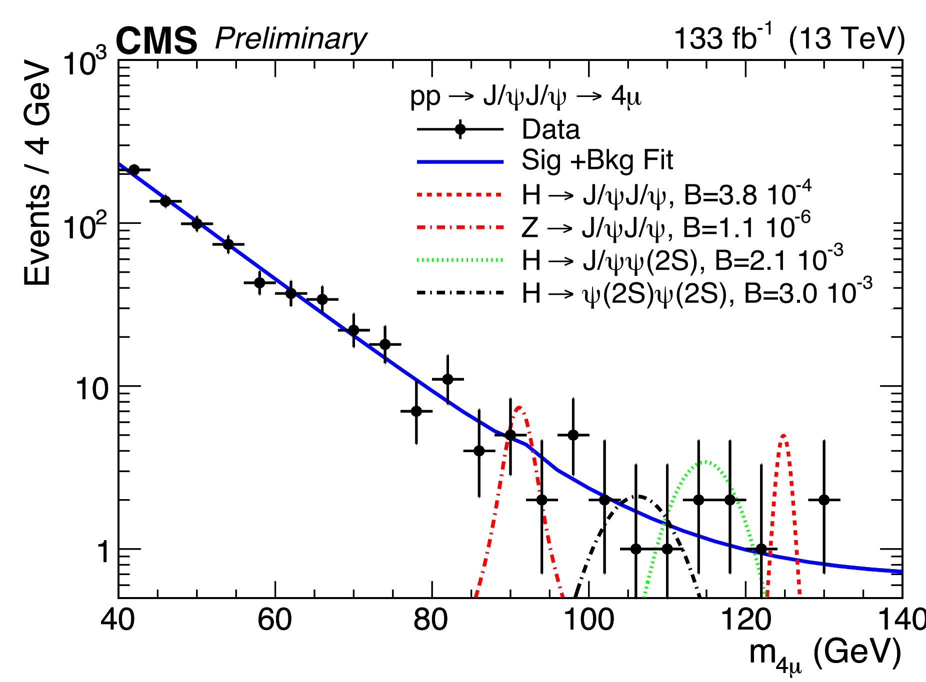
h→ϒ(nS)ϒ(mS)



h→Z J/ψ



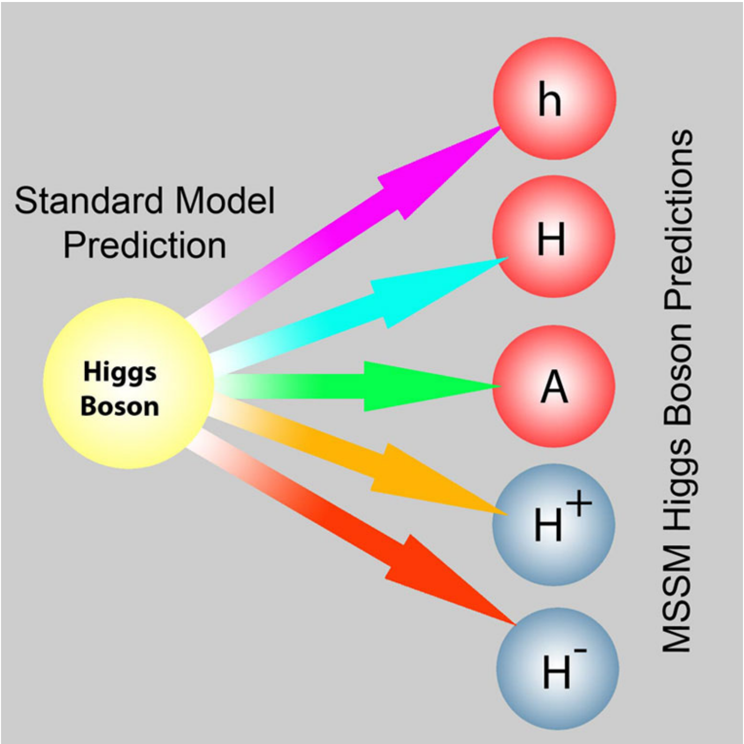
h→ J/ψ J/ψ



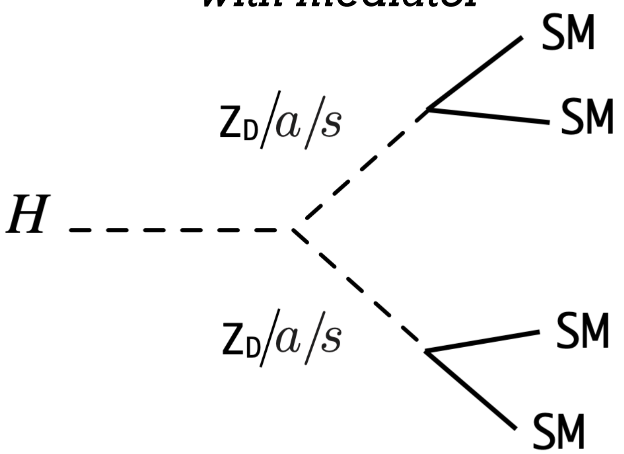
Higgs sector and BSM

- *Higgs sector* plays an integral role in many BSM models:
  - *As a mediator* to hidden sectors (dark matter?)
  - Through *interactions with mediator* (dark photon, additional singlet, …)
  - With *additional Higgs bosons* with mass near electroweak scale (e.g. (N)MSSM).
- Very large and diverse search program pursued by both ATLAS and CMS.
  - I highlight just a few selected examples, with a (strong) bias for excesses :)

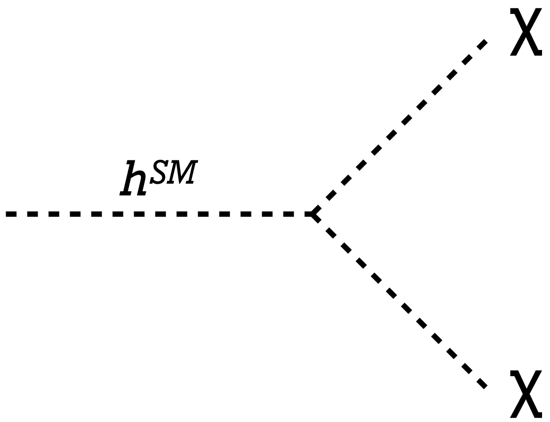
Additional Higgs bosons (MSSM)

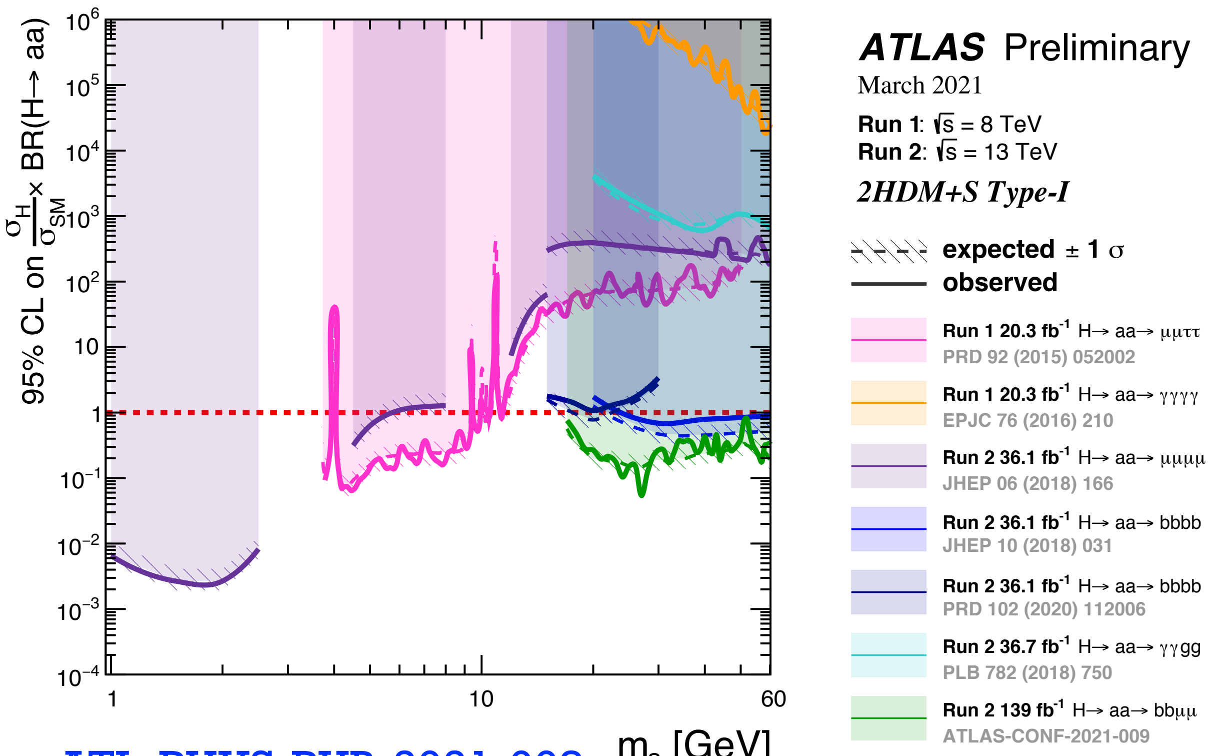


Higgs interaction with mediator



Higgs portal



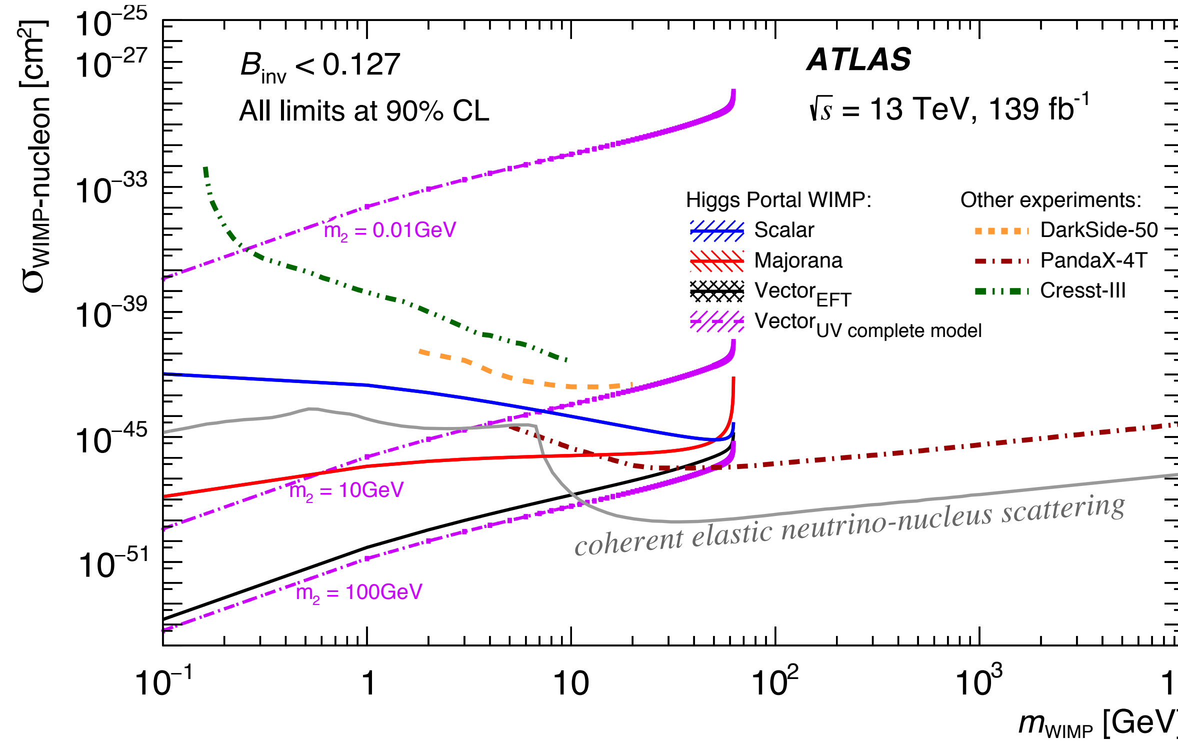


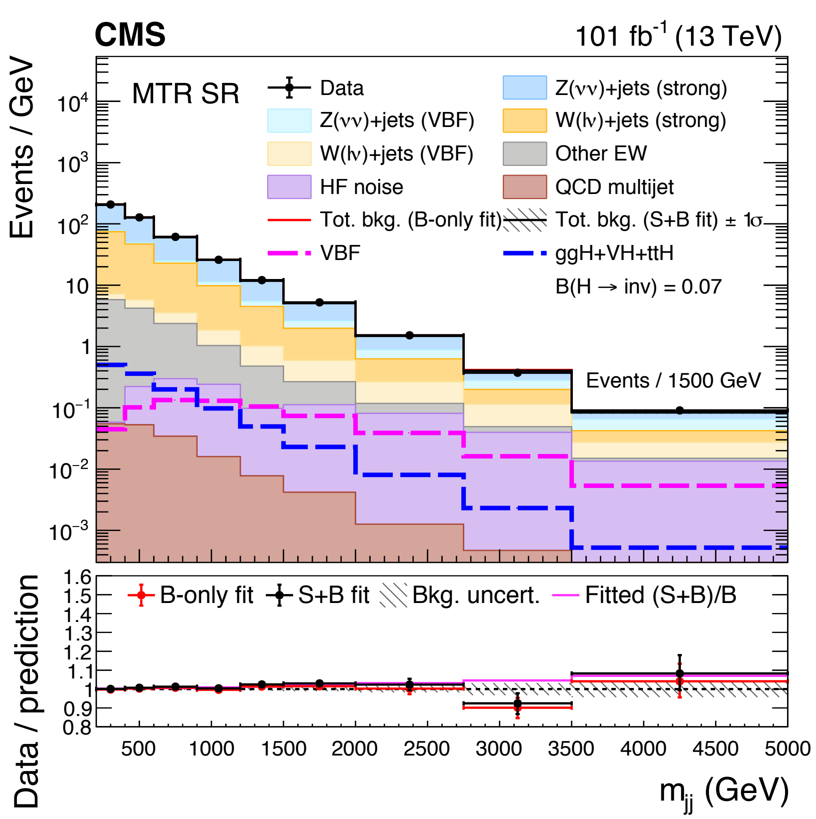
ATL-PHYS-PUB-2021-008

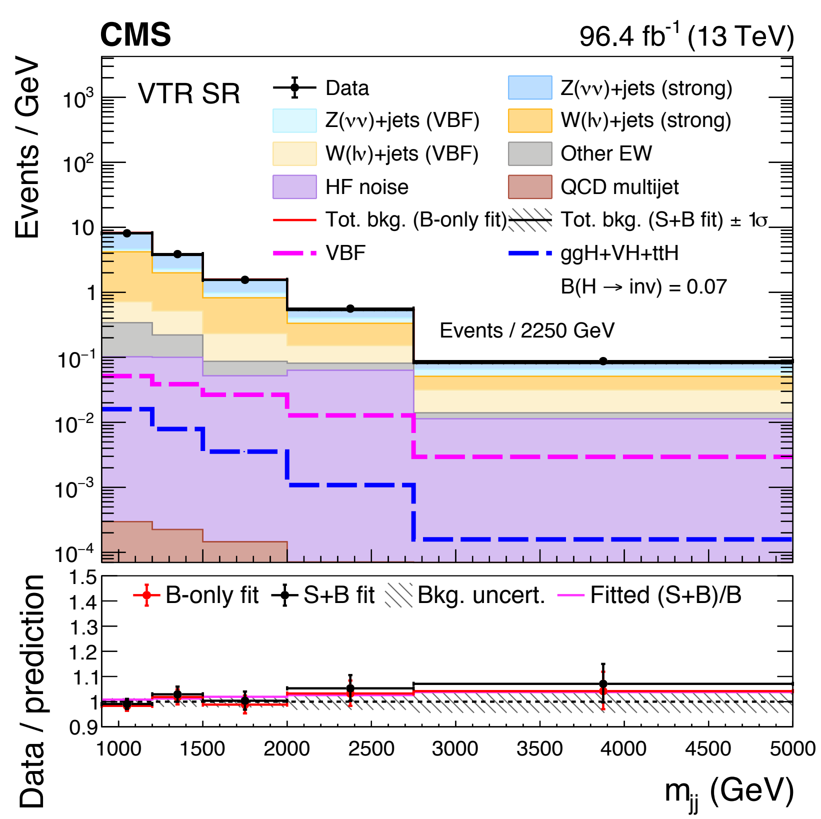
Constraining H→invisible

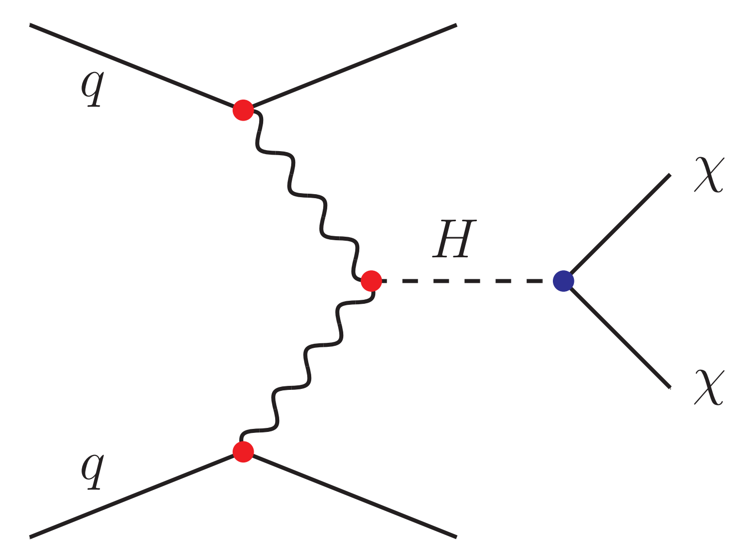
- Select region with large p_T^{miss} and two jets, look for excess over background at large m_{jj}.
- Dominant background from V+jets (strong and EW production).
- Additional interpretation: DM-nucleon scattering cross section in Higgs portal models.
  - LHC H→invisible searches probe m_{WIMP} from $m_H/2$ down to significantly lower mass than most direct detection experiments, but limit depends on model/assumptions.

ATLAS Run-2:
B_{inv} < 0.15 (0.10) @95% CL





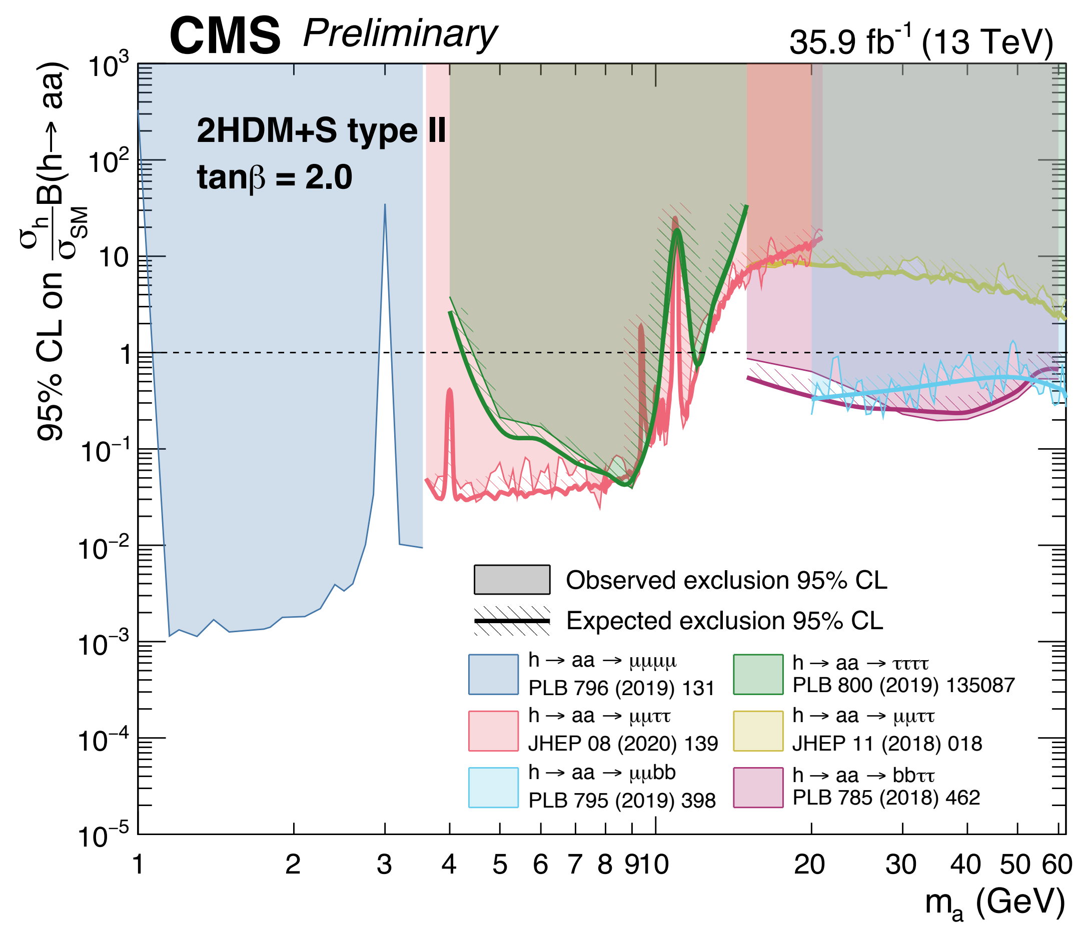


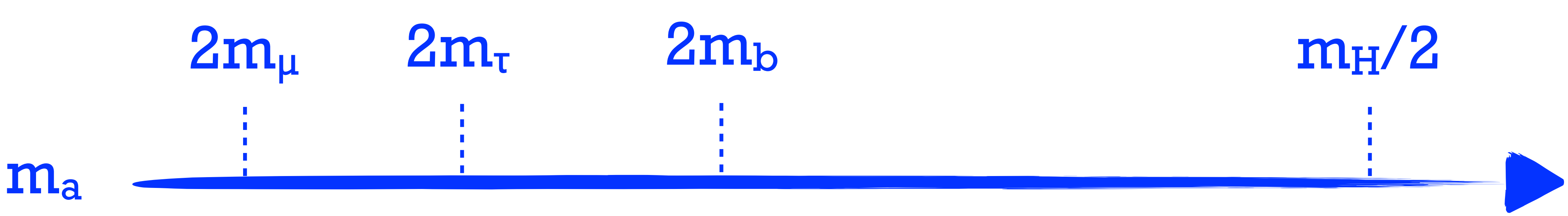


CMS Run-2:
B_{inv} < 0.18 (0.10) @95% CL

H→aa searches

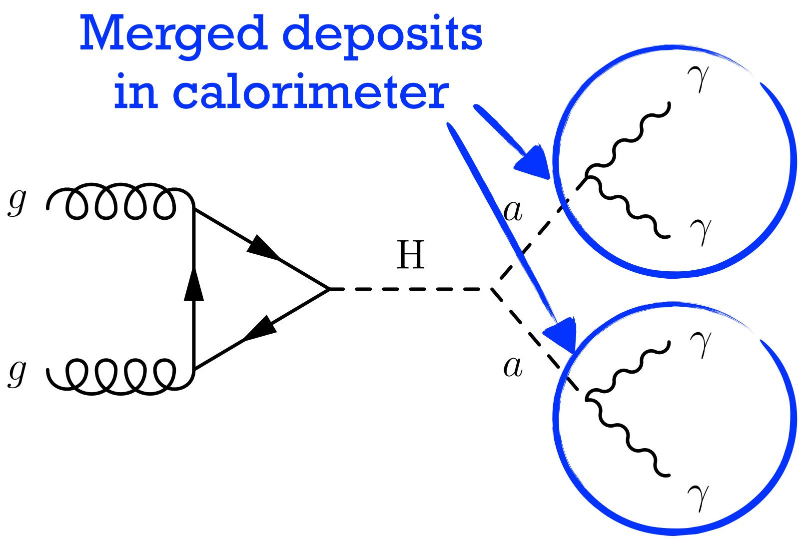
- H→aa searches probe additional particles in H sector for masses up to 60 GeV, such as those predicted by (N)MSSM
- Huge variety of potential experimental signatures, depending on m_a and (pseudo)scalar decay mode.
- Mass of (pseudo)scalar can be comparable to mass of decay products ⇒ different varieties of challenging "boosted" signatures with collimated/overlapping decay products.

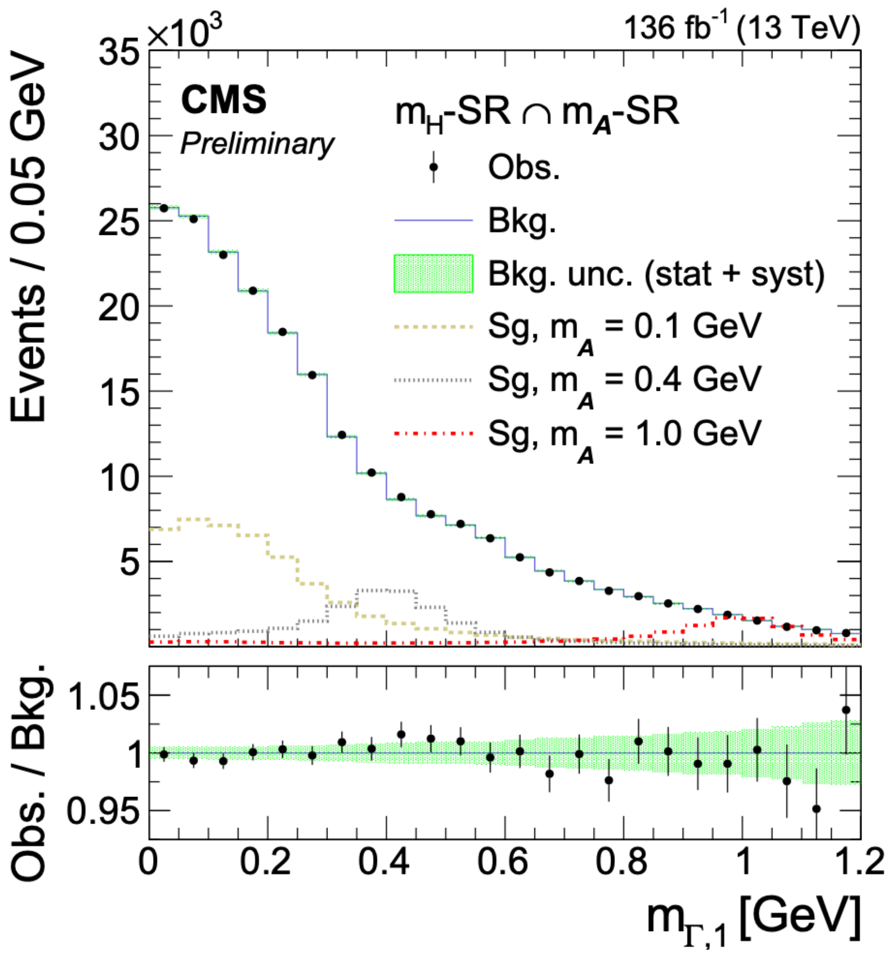


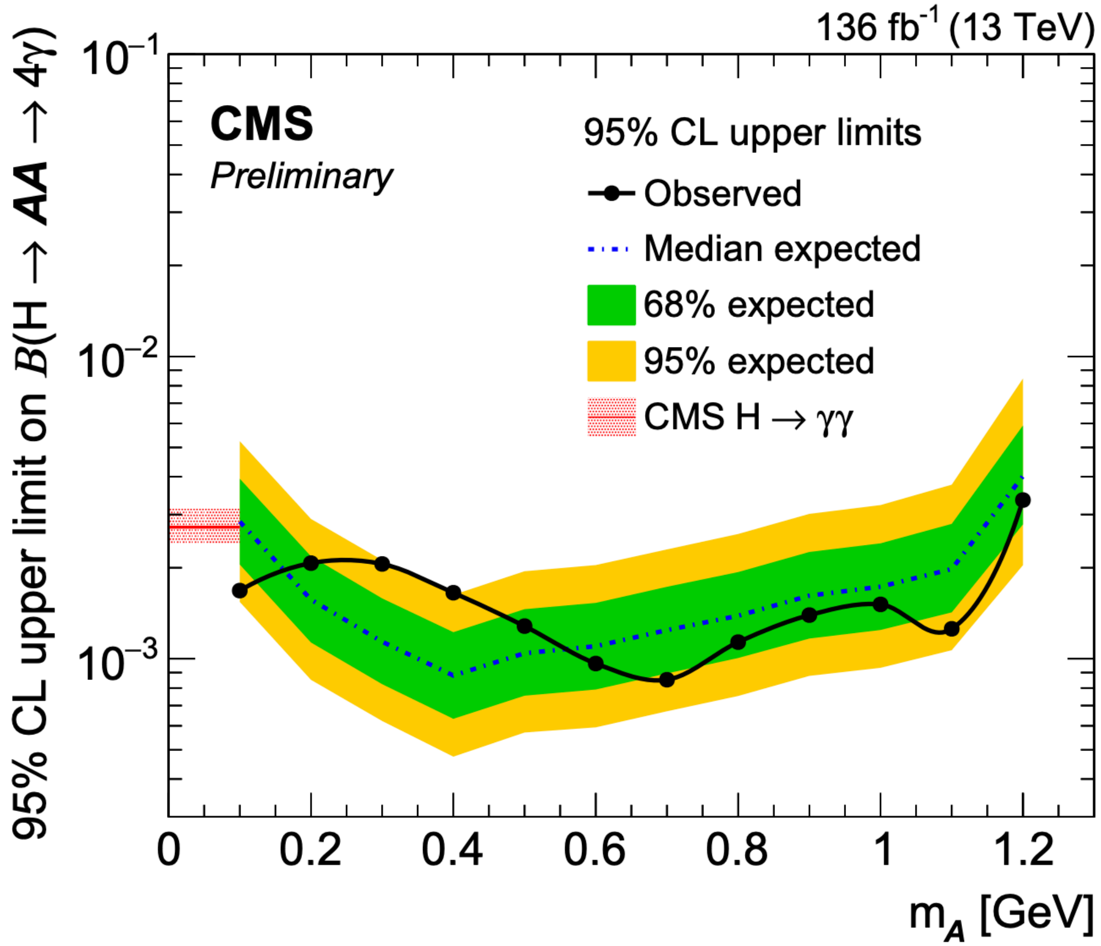


One (novel) example: boosted h→aa→4γ

- New search for h→aa→4γ at very low mass ($0.1 < m_a < 1.2$ GeV).
- Photon energy deposits are merged in calorimeter ⇒ novel end-to-end deep learning algorithm to identify merged a→2γ candidates.
- Search is also sensitive to displaced signatures up to cτ~10mm.

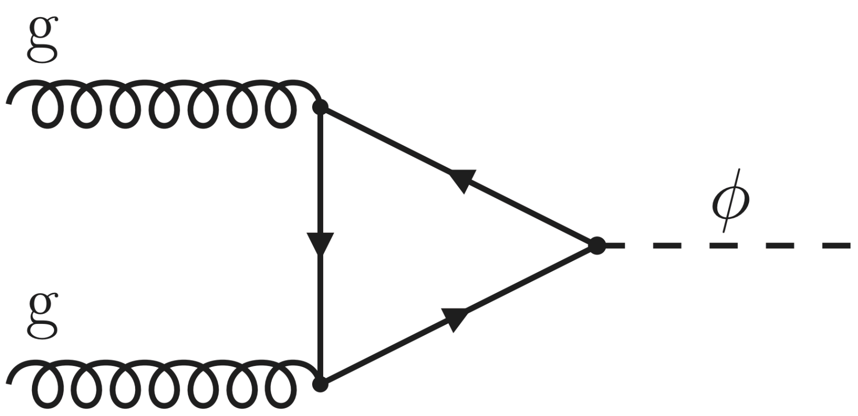


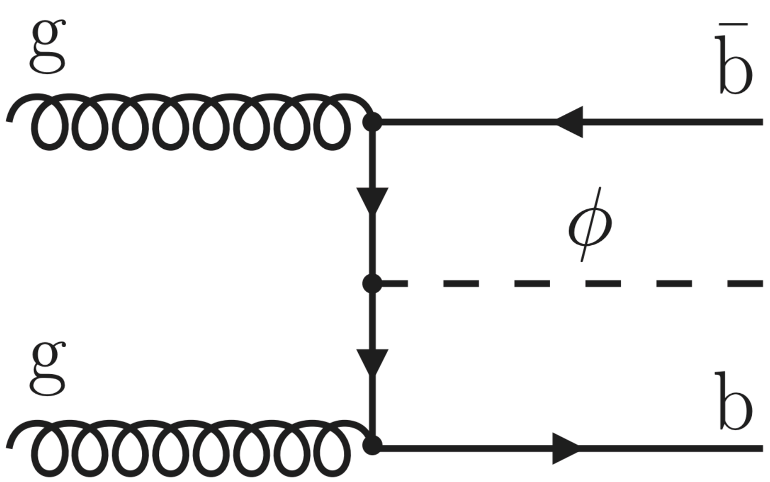


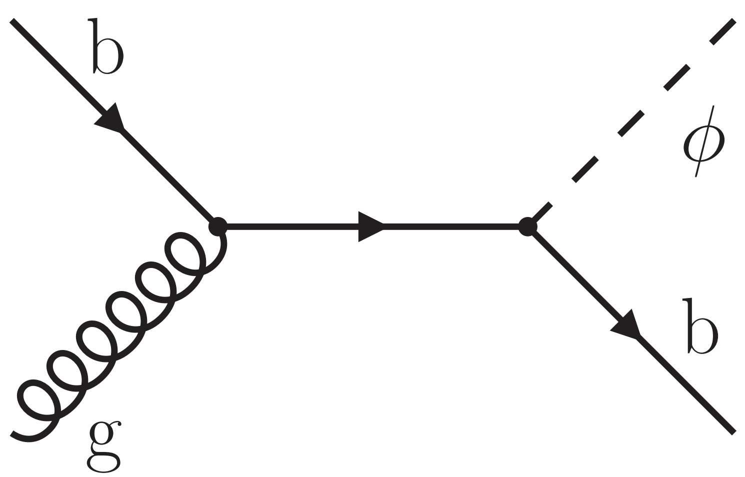


- The ττ final state is a key channel in search for additional particles in H sector
  - Background many orders of magnitude smaller than bb final state.
  - Larger mass ⇒ larger couplings, gives advantage with respect to μμ searches.

- Search for resonance in ττ (gluon-fusion and bbϕ)
  - "low mass": 60 GeV < m_ϕ < 250 GeV
  - "high mass": 250 GeV < m_ϕ < 3.5 TeV



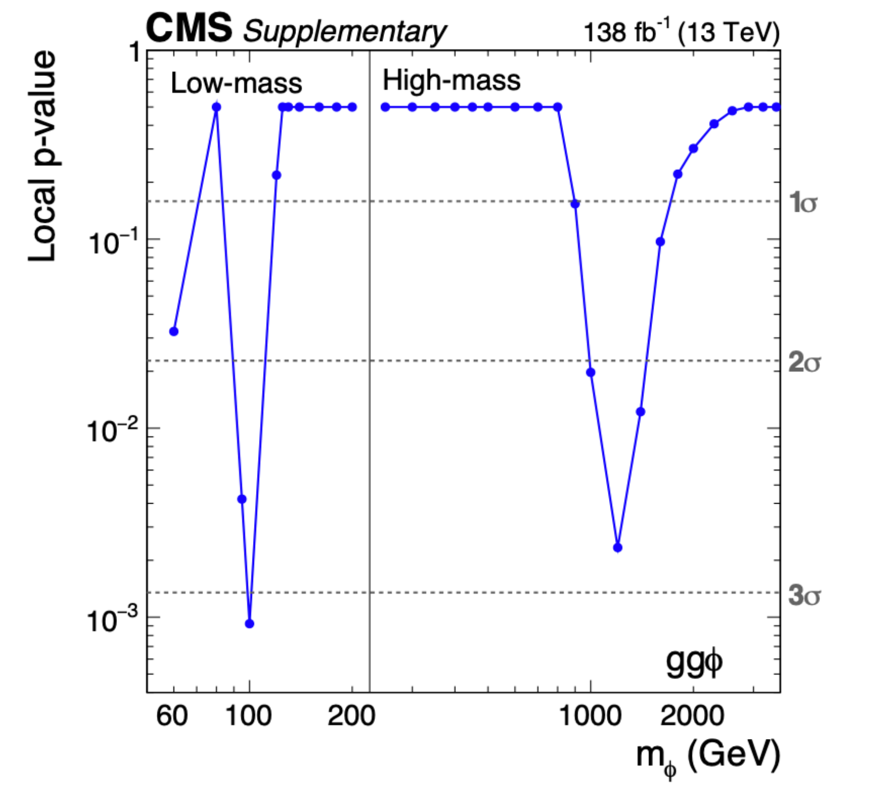


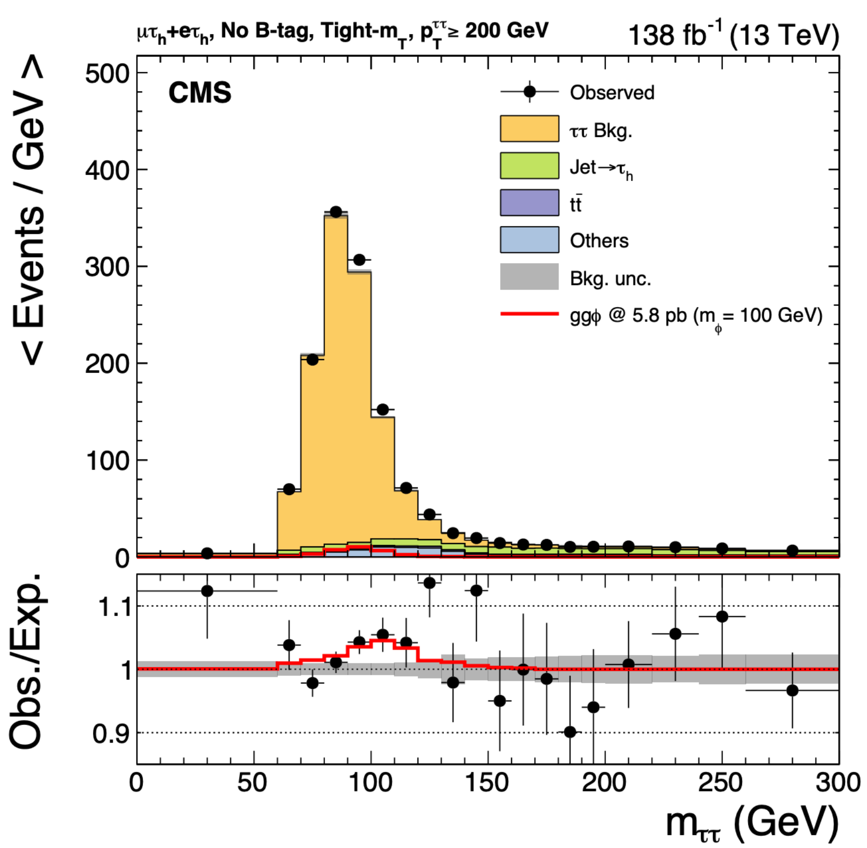


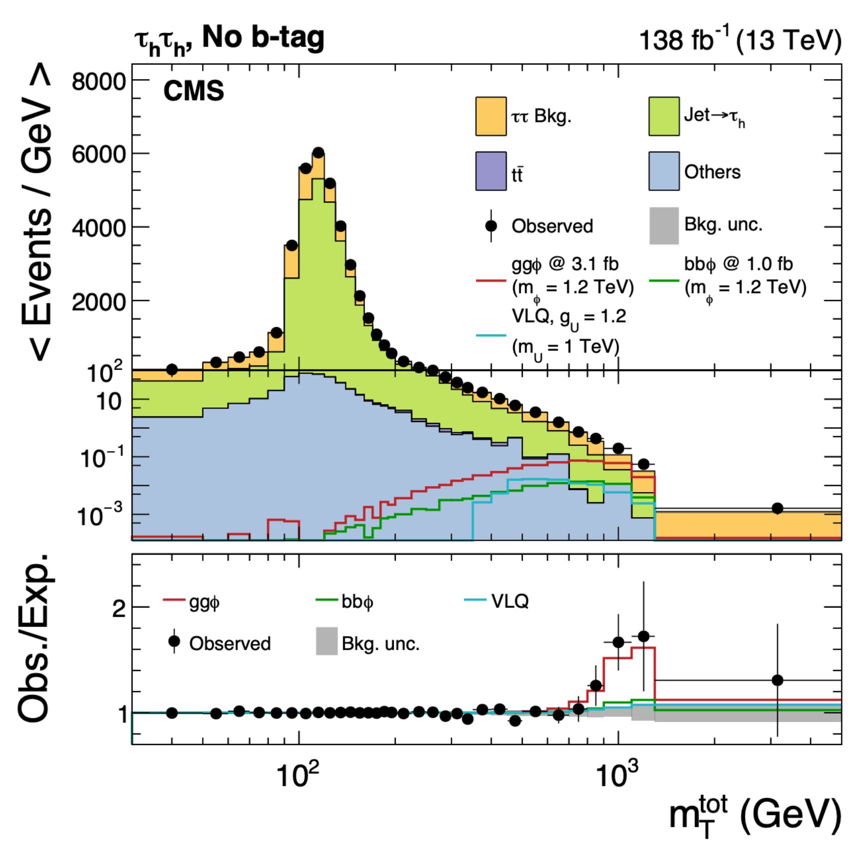
- Combination of eμ, $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$ channels.

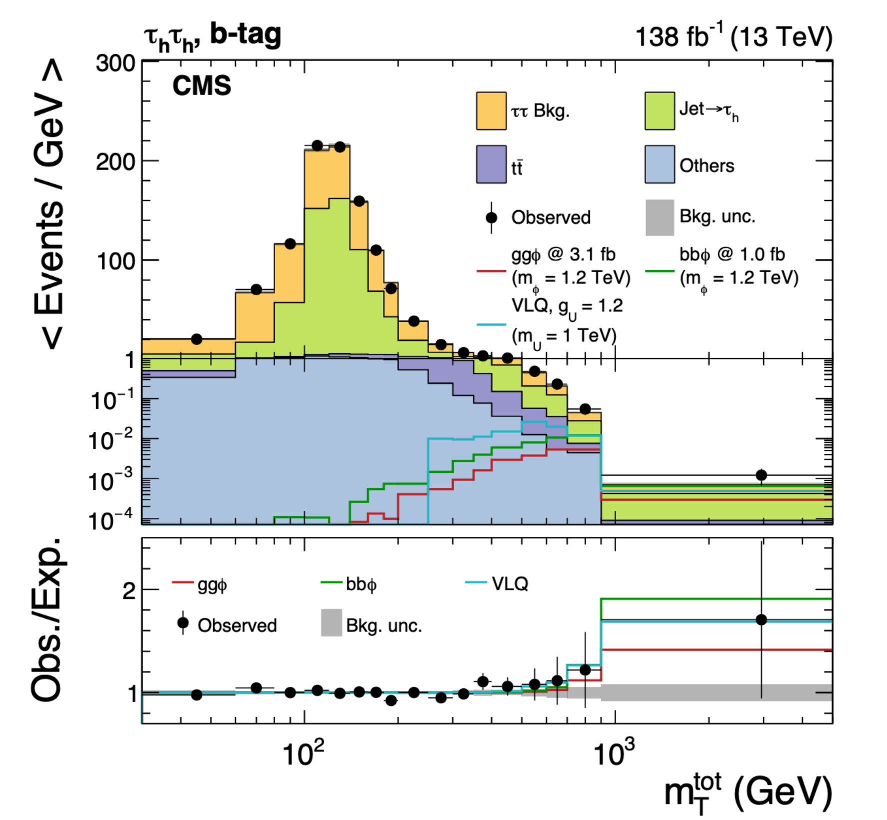
- Two localized excesses observed:
  - At 100 GeV, local significance: 3.1σ
    - Considering LEE within low mass search range ⇒ 2.7σ
  - At 1.2 TeV in ggϕ regions, local significance: 2.8σ
    - Considering LEE within high mass search range ⇒ 2.4σ

- Intriguing, but we need more data.



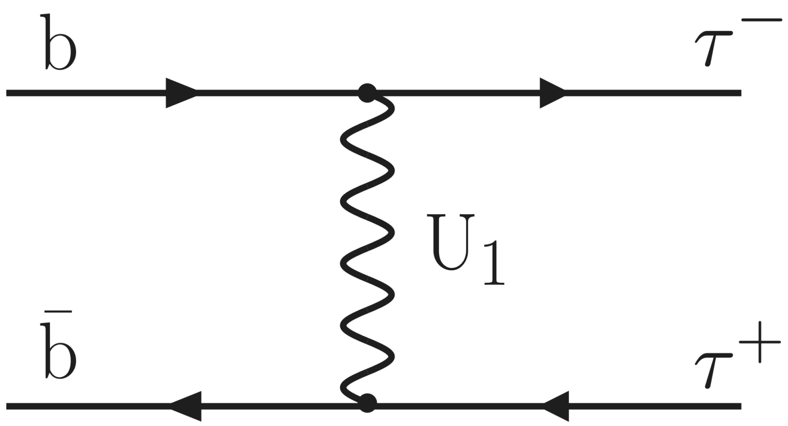


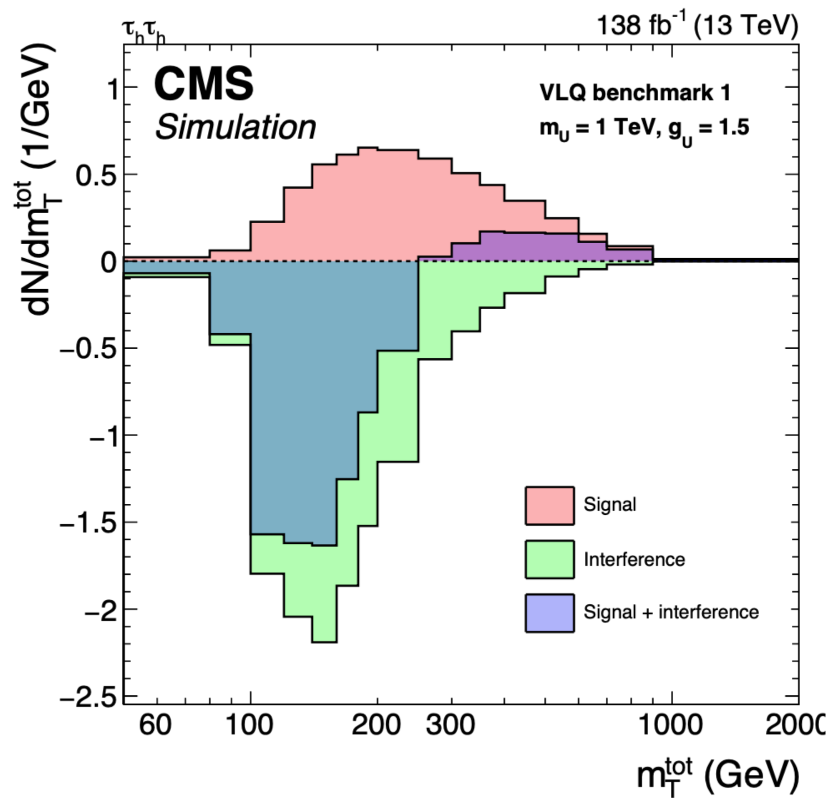




Extending the reach to leptoquarks

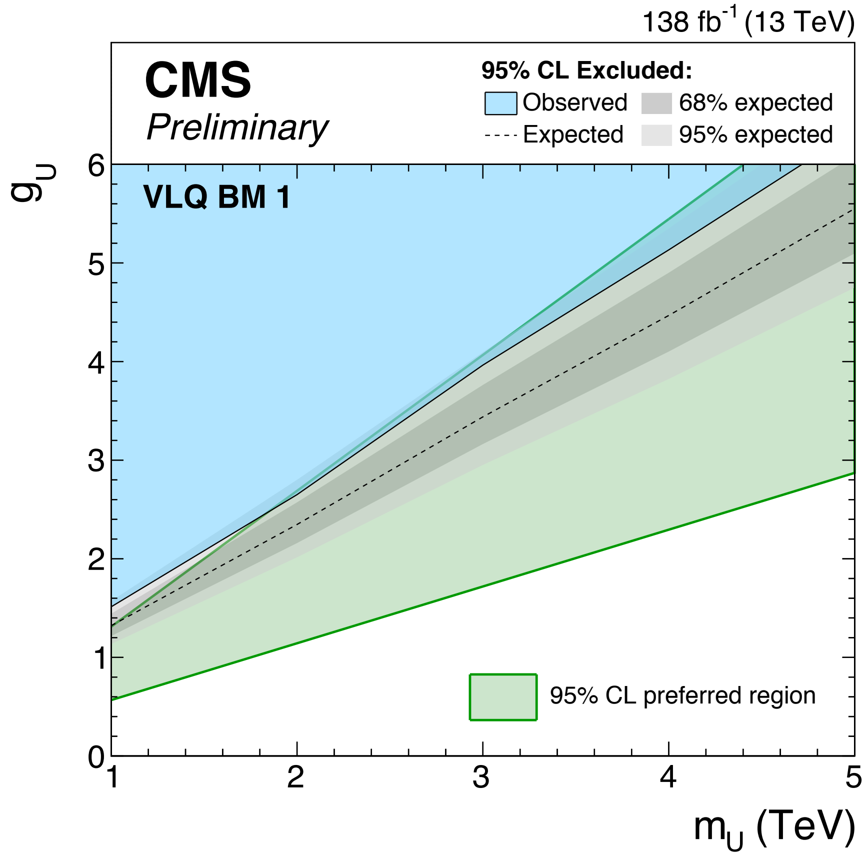
- *New for this analysis*: search for non-resonant signature of t-channel leptoquark exchange.
  - Presence of vector leptoquark (VLQ) would lead to enhancement in non-resonant production rate at high ττ invariant mass.
- LO Madgraph with 5FS to simulate t-channel VLQ exchange.
- Interference with Z→ττ is significant and generated separately.

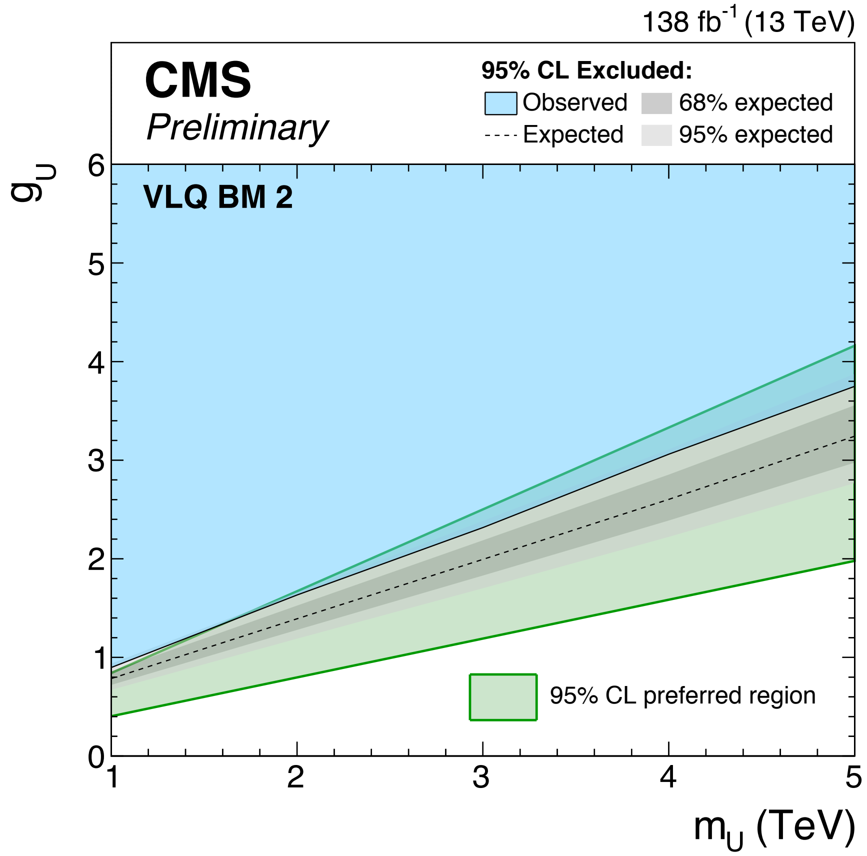




VLQ interpretation results

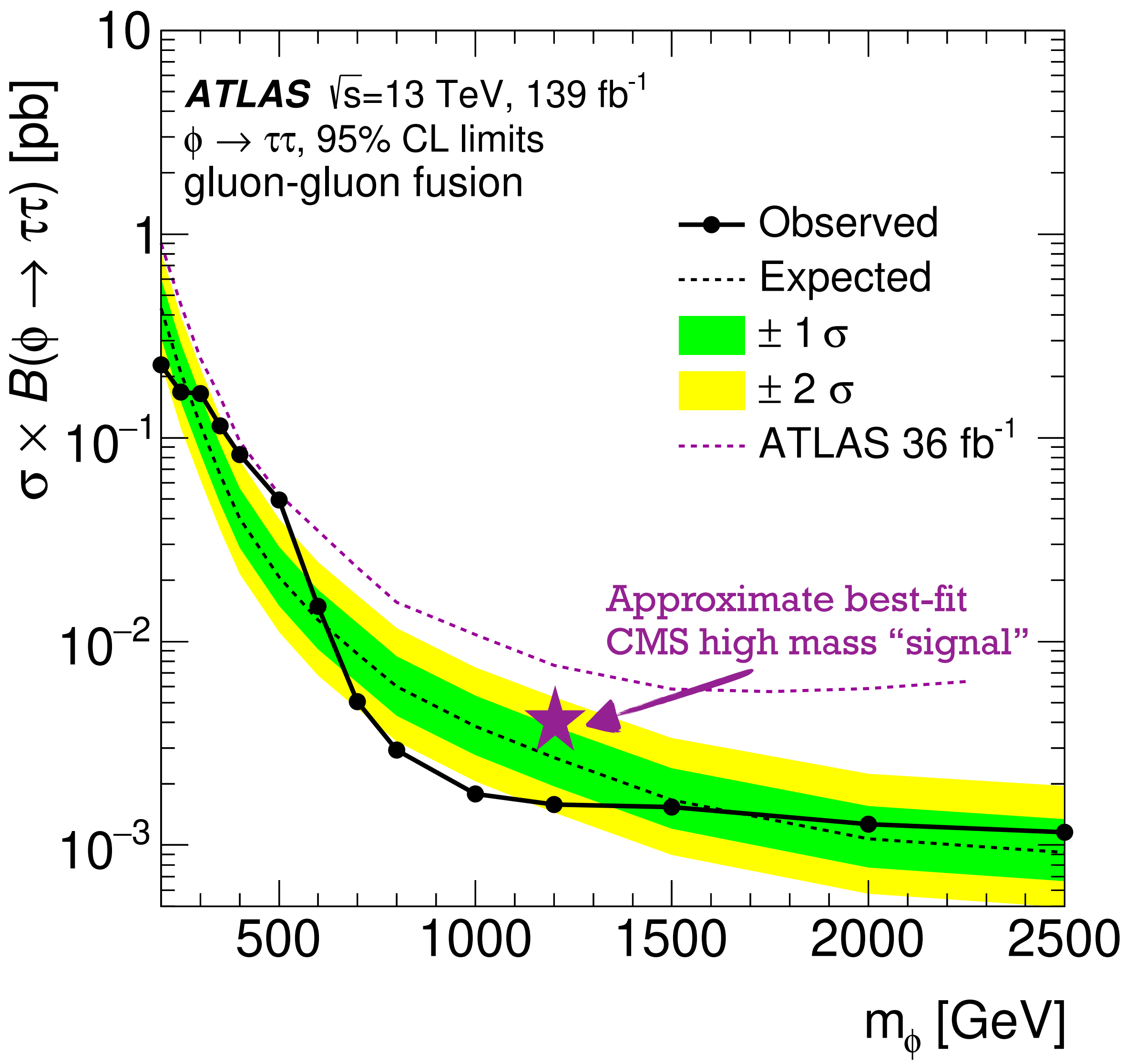
- Expected limits well within preferred region for B physics anomalies.
  - Such searches will be an important input in understanding the source of the B anomalies if they persist.
- This analysis is sensitive to VLQ signatures in category requiring at least one b jet.
  - There is a <2σ excess over the background at high mass in this b-enriched category, so limits are weaker than expected.
- Clearly this is a very interesting channel to continue to probe, in which we will either:
  - a) begin to exclude the VLQ parameter space preferred by B physics anomalies.
  - b) ~2σ excess observed in Run-2 could start to become statistically significant.

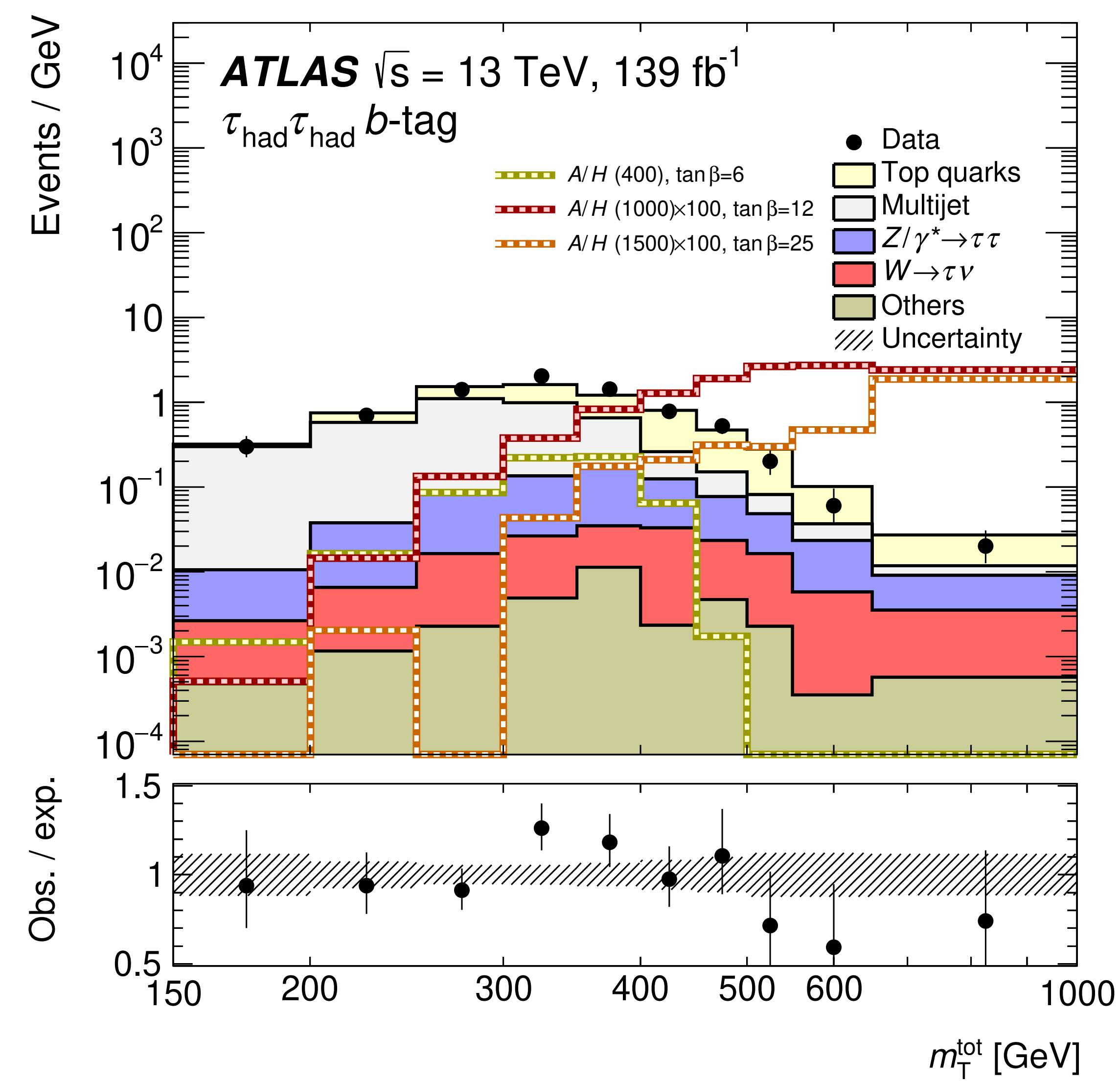




Comparison with ATLAS

- Excess at 1.2 TeV in b-veto (ggϕ) region appears to be excluded by comparable ATLAS $\phi \rightarrow \tau\tau$ search.
- On the other hand, no directly comparable low-mass $\phi \rightarrow \tau\tau$ search from ATLAS to gain insight on ~100 GeV excess.
- No sign of excess over background at high mass in b-enriched categories sensitive to VLQ, but very difficult to quantitatively compare or interpret in context of VLQ (none provided by ATLAS).

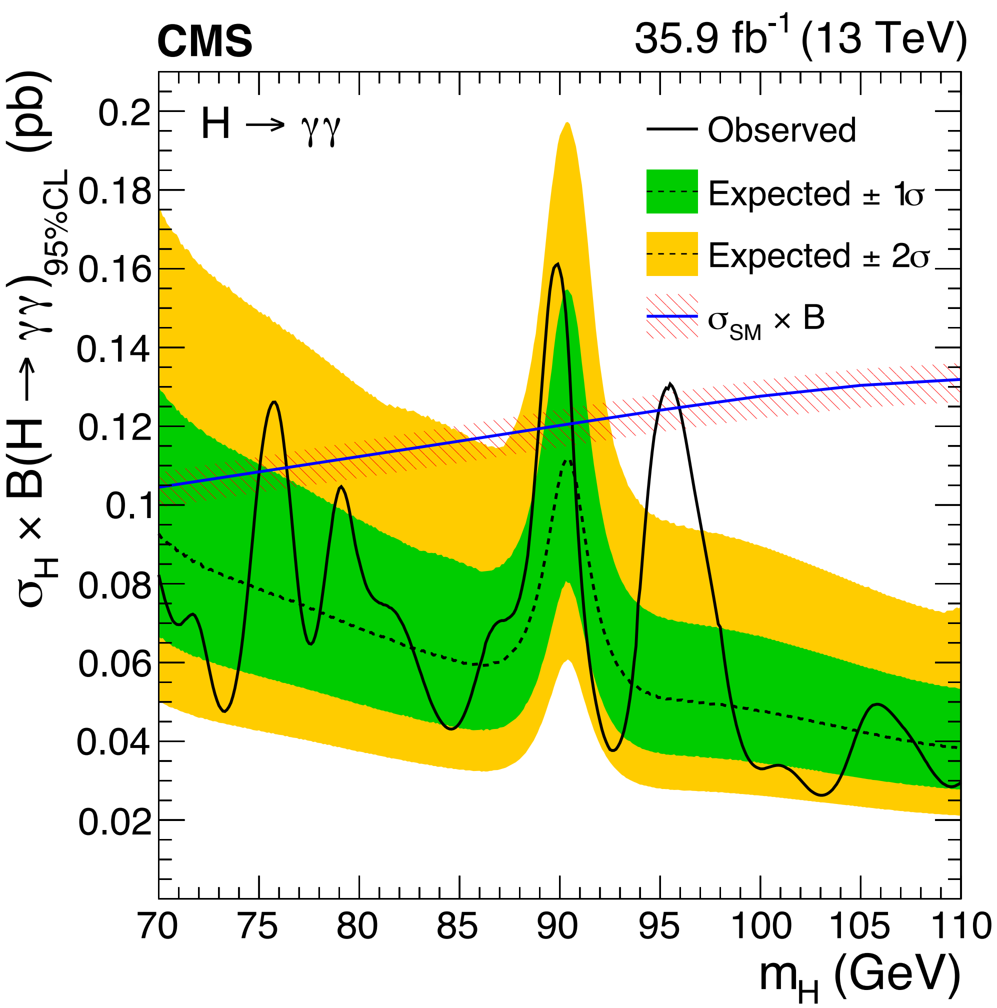


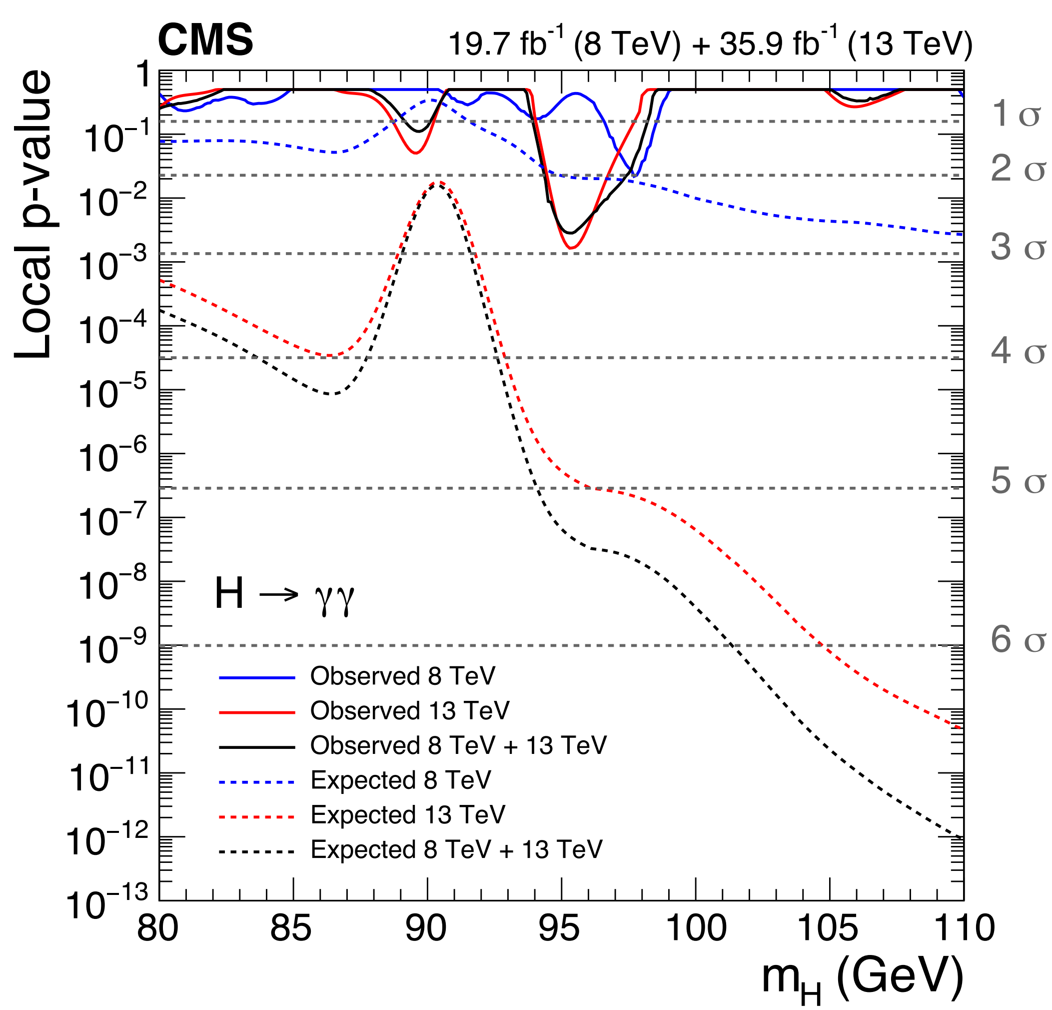


- Search for resonance in γγ mass spectrum between 70 and 110 GeV, from CMS with partial Run-2 13 TeV data.
  - Other results released so far consider 8 TeV data.

- Main challenges: selecting events at trigger level and background from misidentified Z→ee.

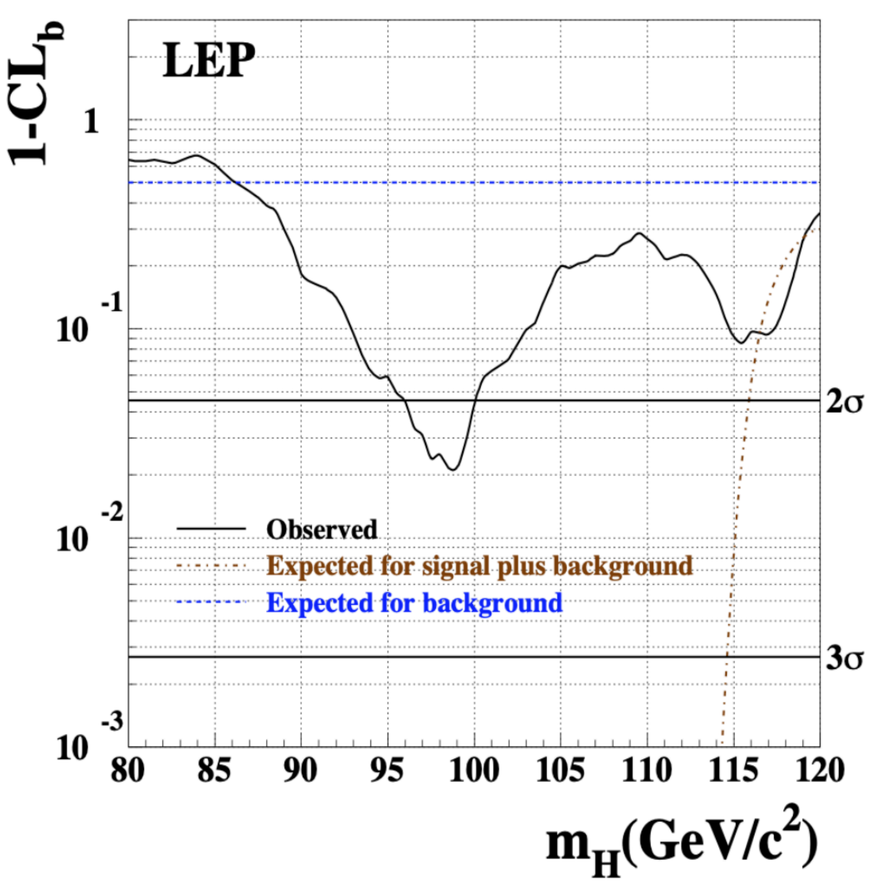
- Largest excess observed at $m_{\gamma\gamma}$ = 95.3 GeV, with a local (global) significance of 2.8σ (1.3σ).

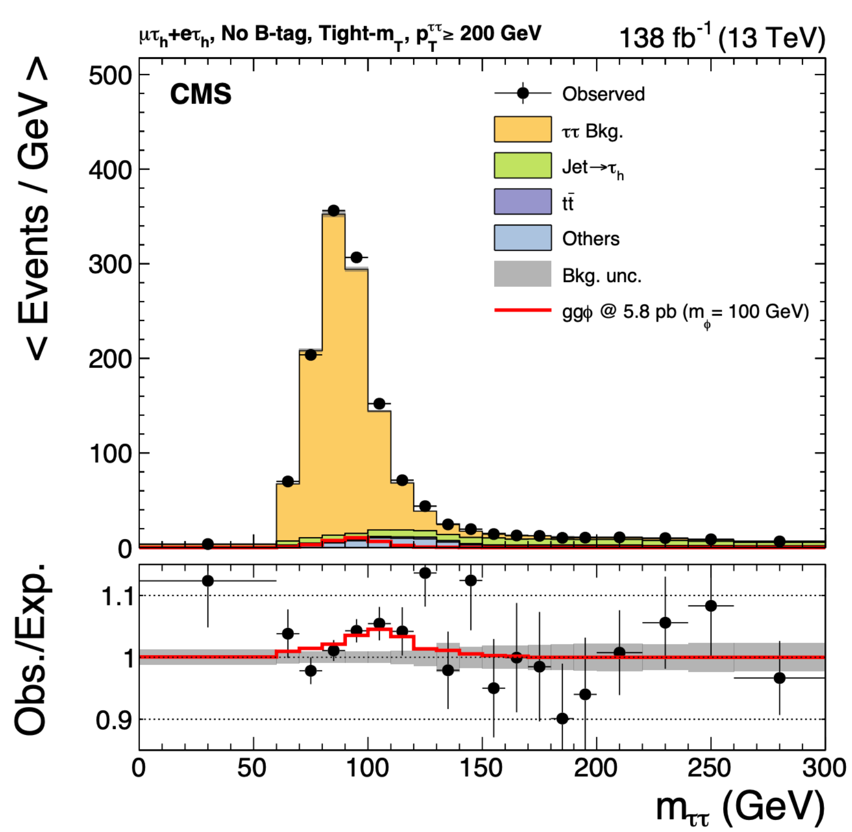


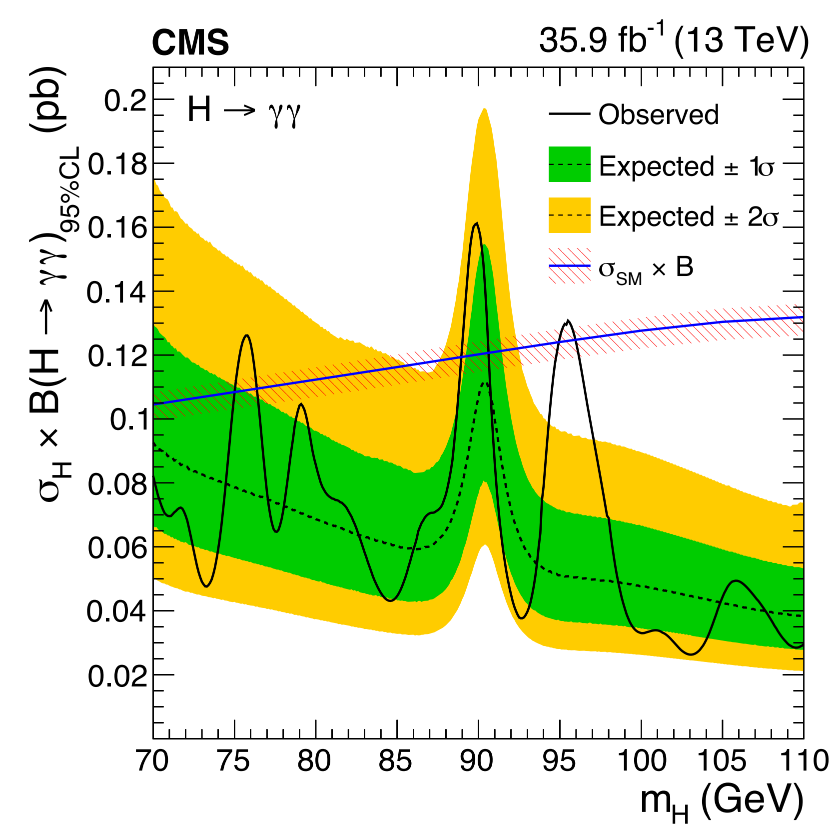


An excess near 95 GeV?

- A few 2-3σ (local) excesses consistent with Higgs-like scalar with mass about 95 GeV.
- Interesting, but definitely not conclusive.
- In the meantime…are there additional signatures we should be looking for?



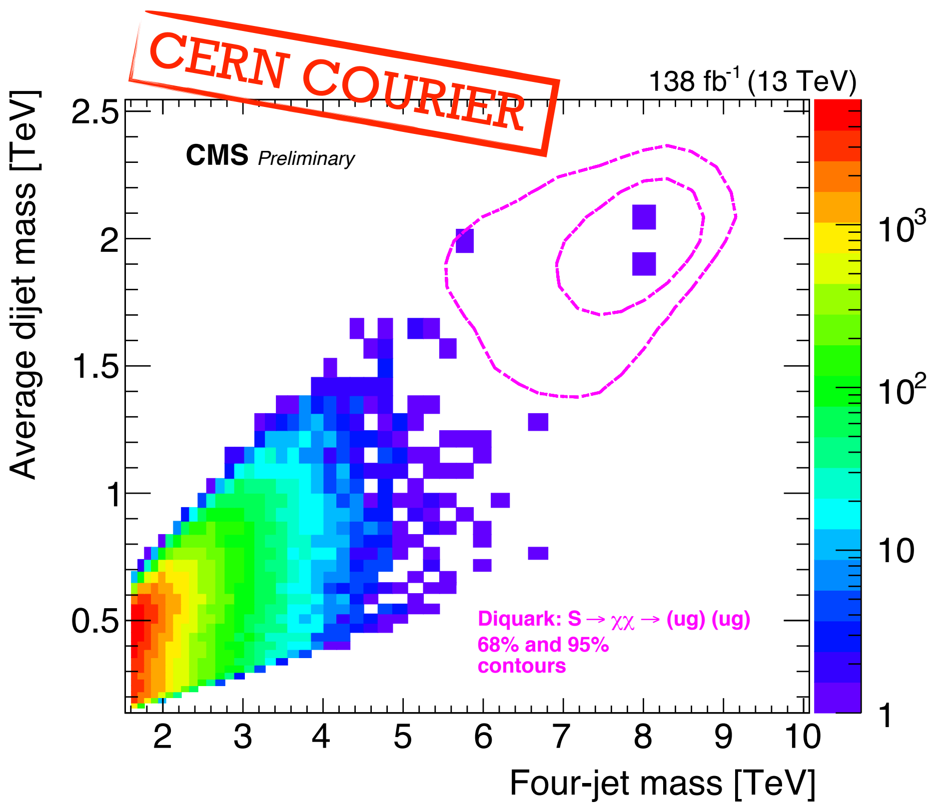




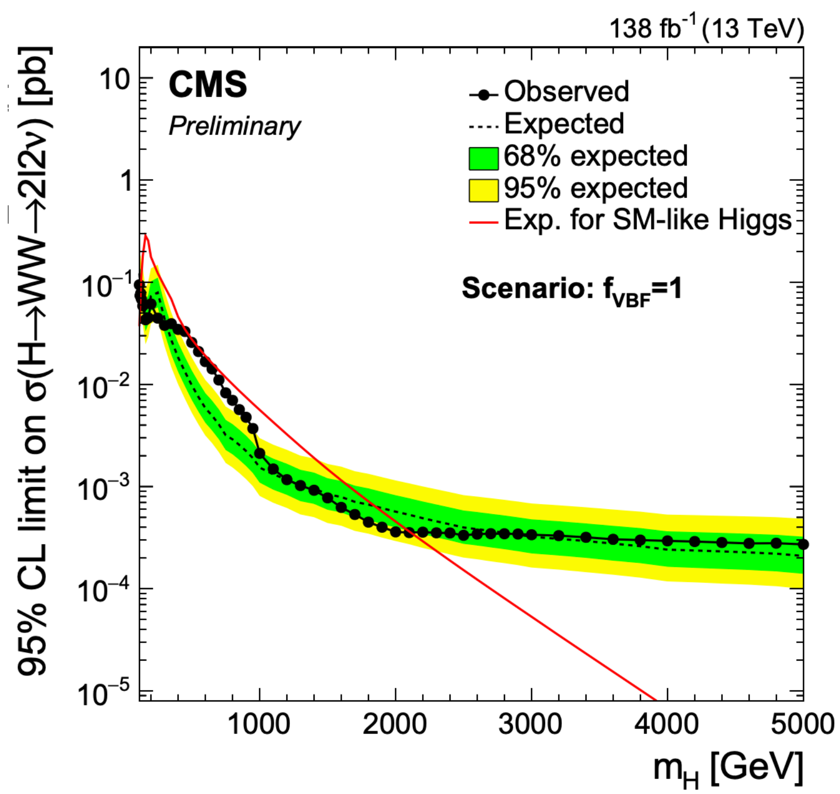
Pick your favorite bump

- Nothing necessarily striking in itself, but several new results with >3σ excesses, ~2σ considering look-elsewhere effect.
- Intriguing, but we need more data.

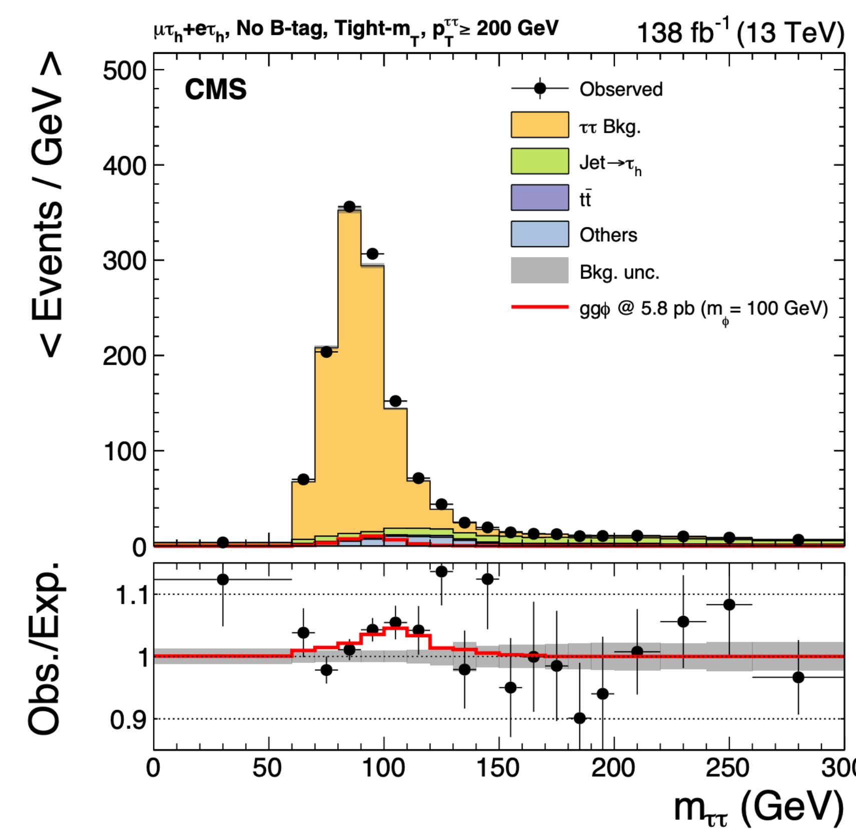
$Y \to XX \to (jj)(jj)$	VBF $H \to WW$	$\phi \to \tau\tau$
3.9σ (1.6σ global) at 8 TeV in four-jet mass	3.8σ (2.6σ global) in VBF WW broadly in mass ~700 GeV	3.1σ local excess for $m_{\tau\tau}$ ~100 GeV



CMS-PAS-EXO-21-010



CMS-PAS-HIG-20-016

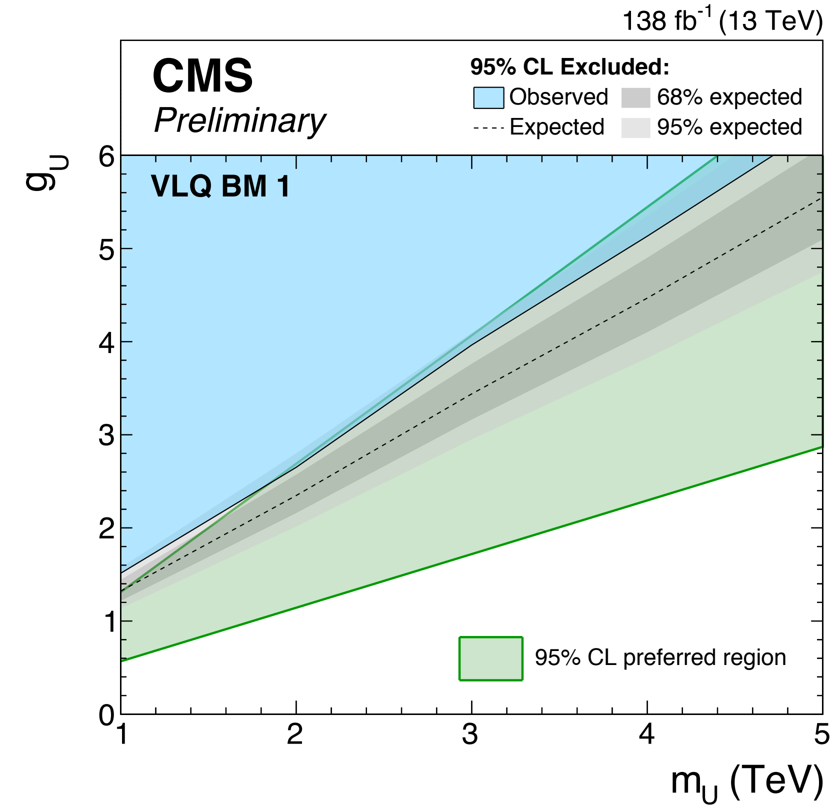


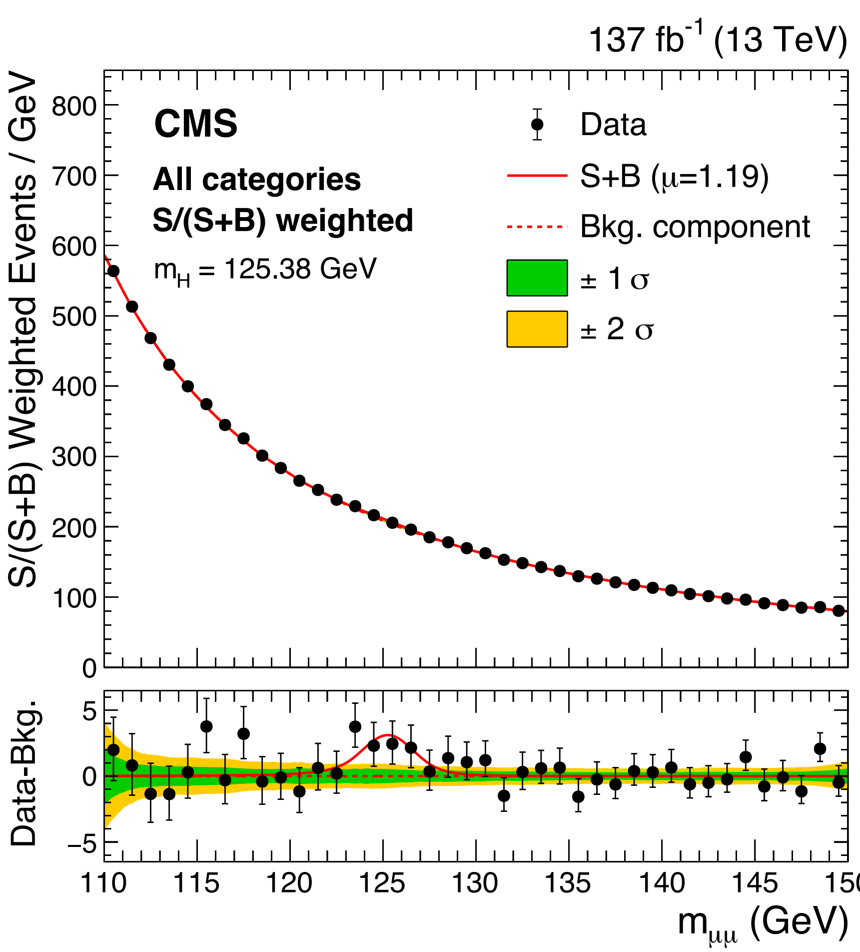
CMS-PAS-HIG-21-001

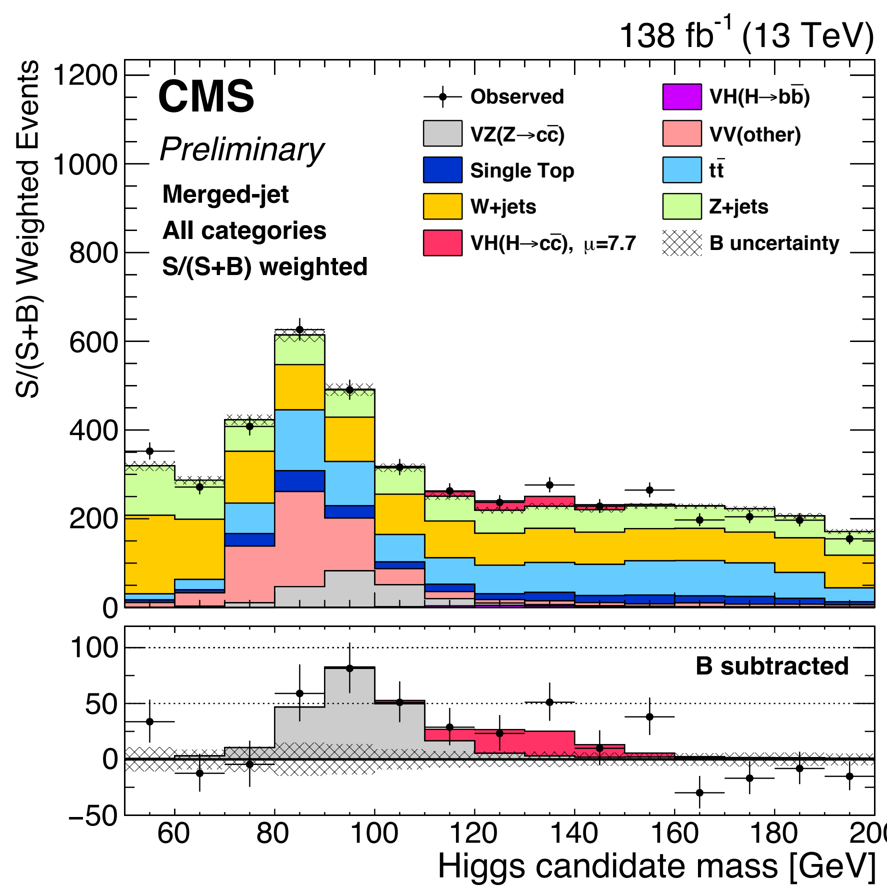
Summary

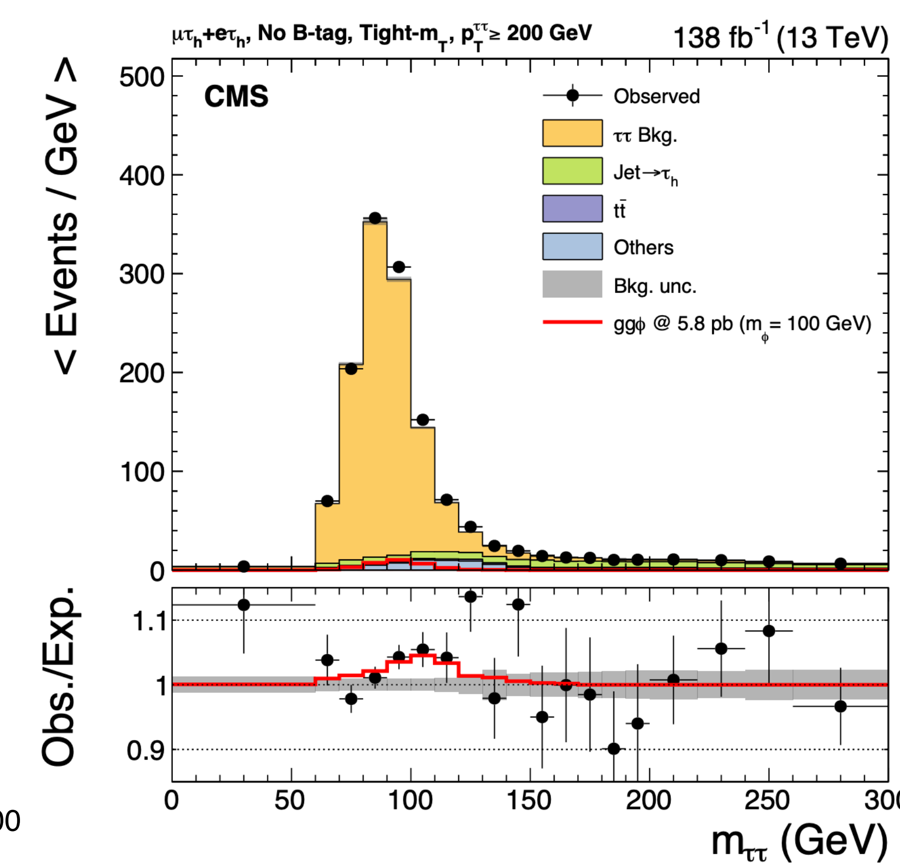
- We are just beginning to explore many aspects of the Higgs sector:
  - Yukawa interactions beyond the third generation, Higgs self-interaction, Higgs as a mediator to dark matter, additional H bosons up to TeV scale, …

- Enormous progress made in recent years in exploring these new frontiers in the Higgs sector
  - We are just getting started!

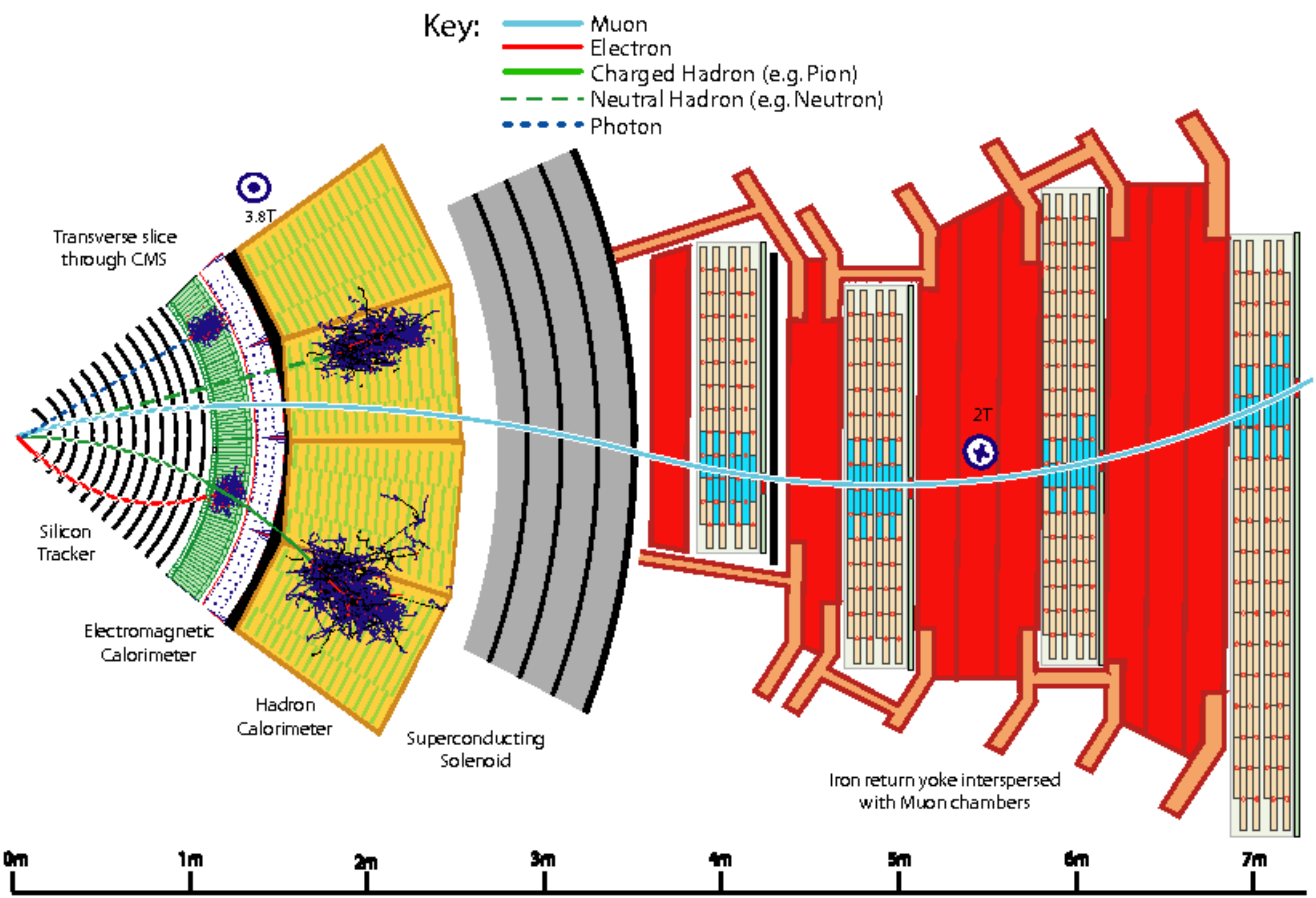








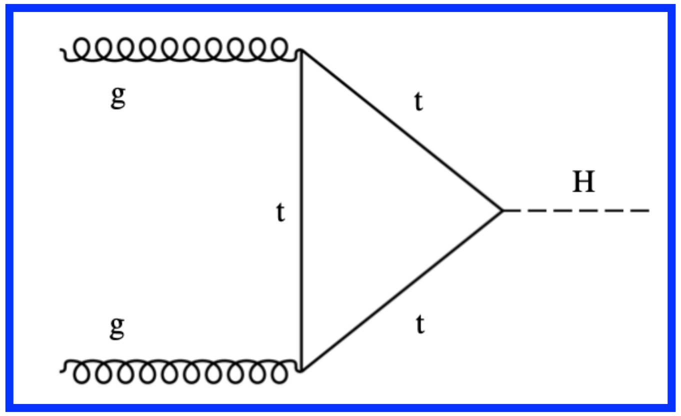
Additional Material


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
3.8T
Transverse slice through CMS
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

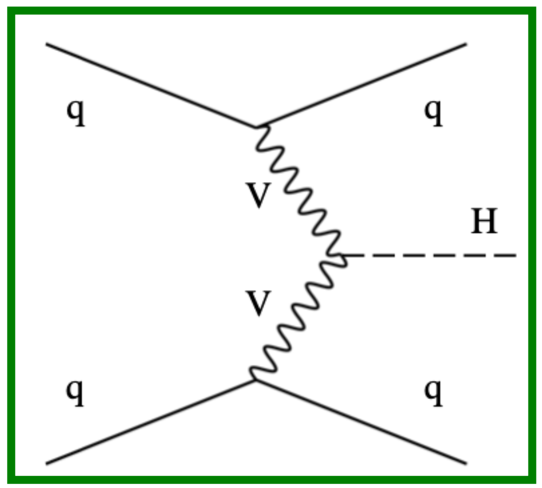
Higgs boson production modes at LHC

Improve signal-to-background separation by splitting events into exclusive categories, each targeting a particular Higgs boson production mode.

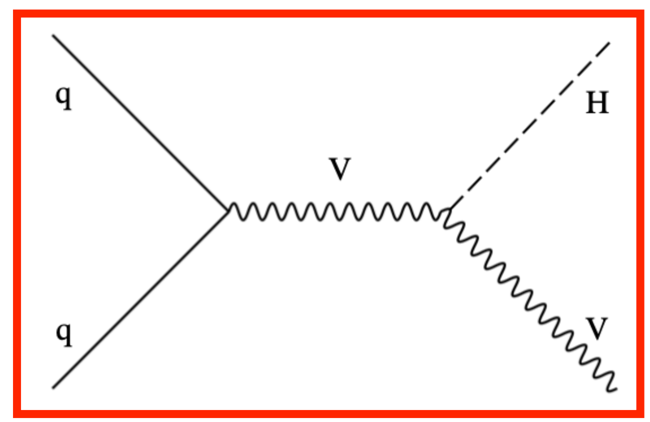
Gluon-gluon fusion (ggH)



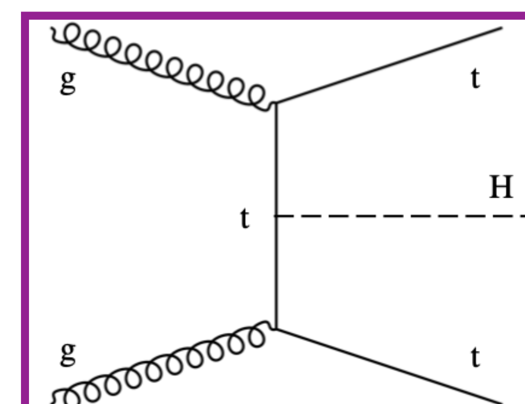
Vector boson fusion (VBF)



Associated production with W or Z (VH)



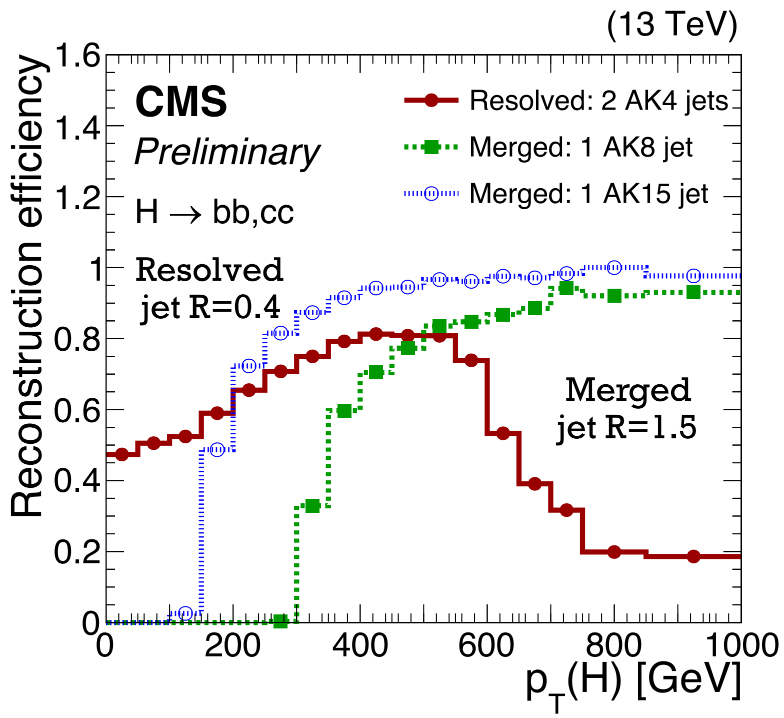
Associated production with top quarks (ttH)

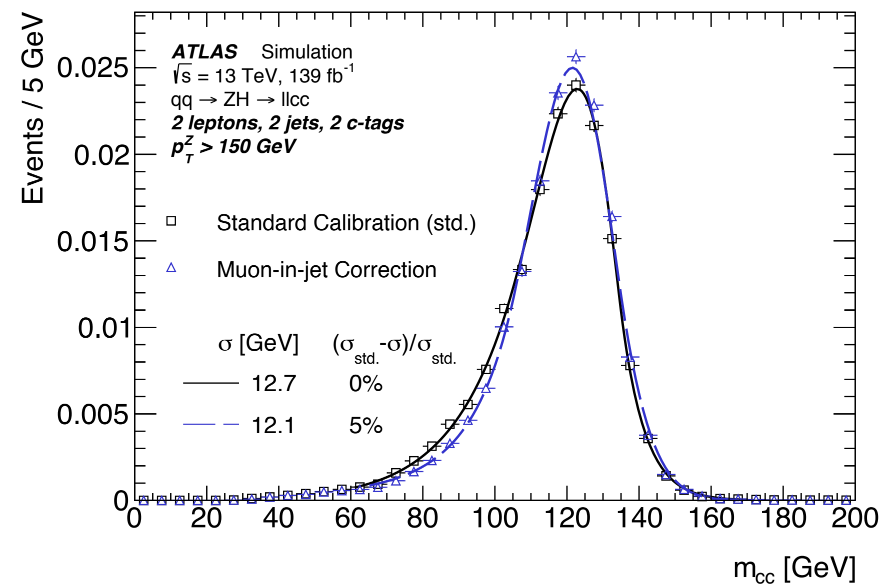


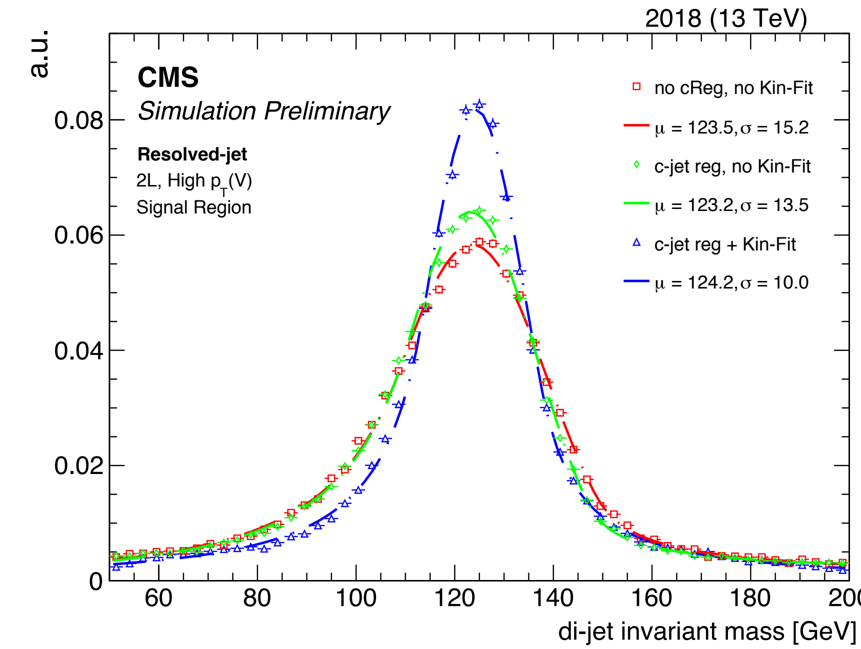
Effective cross section (rate)

Level of achievable signal purity

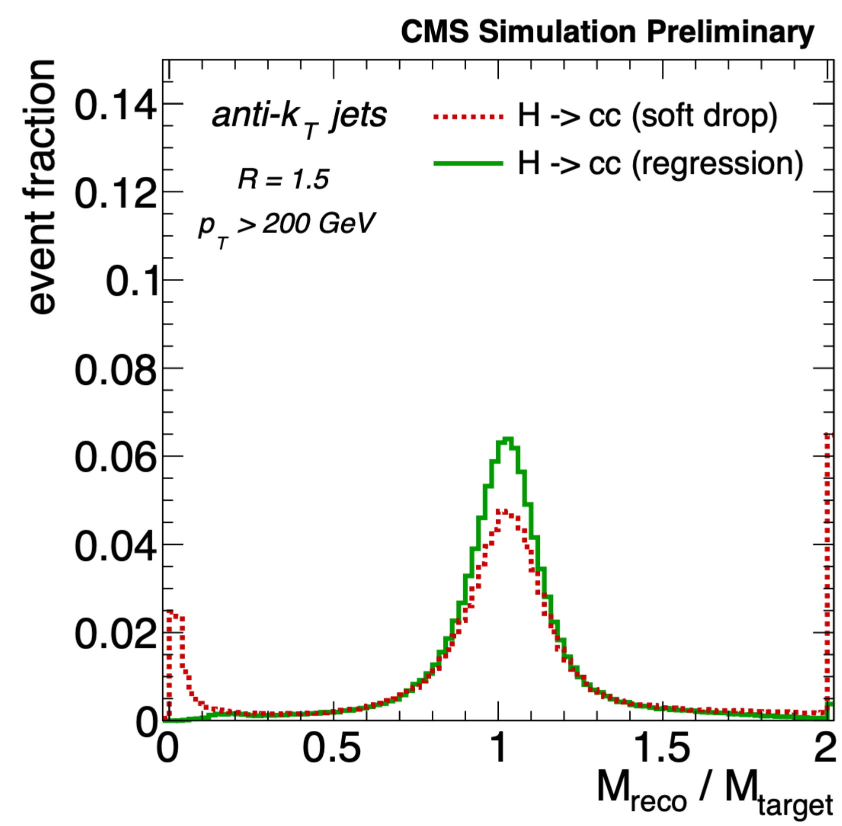
H→cc: Maximizing the sensitivity







- *Huge effort to make the most of the data collected*:
  - Very large improvement in *c-tagging** performance with respect to previous taggers.
  - Deep neural network-based *regression* to estimate resolved charm-jet p_T.
  - Graph neural network-based *regression* to estimate cc-jet mass.
  - *Kinematic fit* in resolved 2-lepton channel to better constrain H→cc candidate mass.



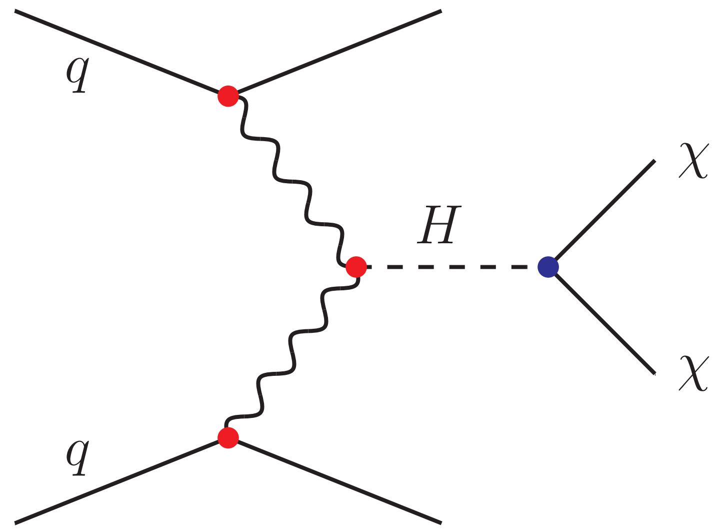
CMS-DP-2020-002

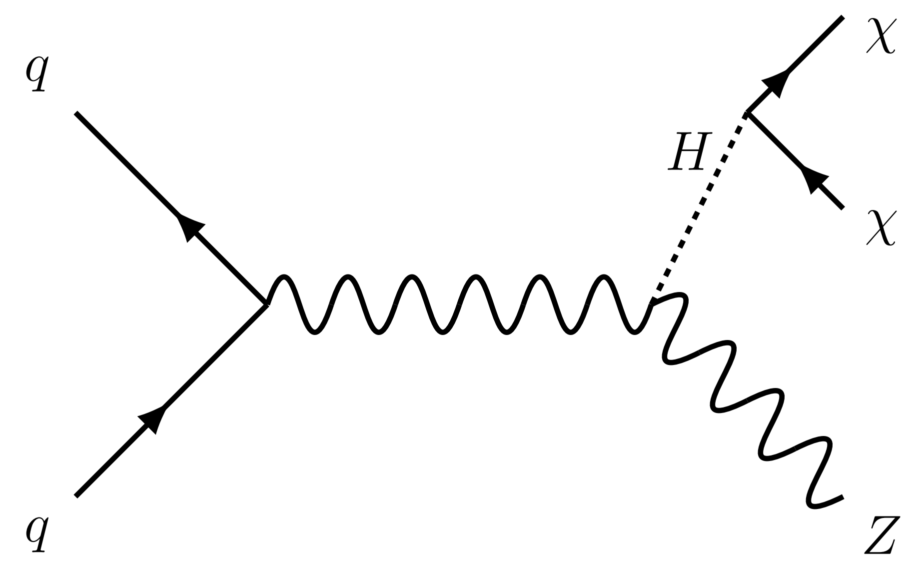
Novel method to calibrate charm jet taggers: arXiv:2111.03027, accepted for publication in J. Instrum.

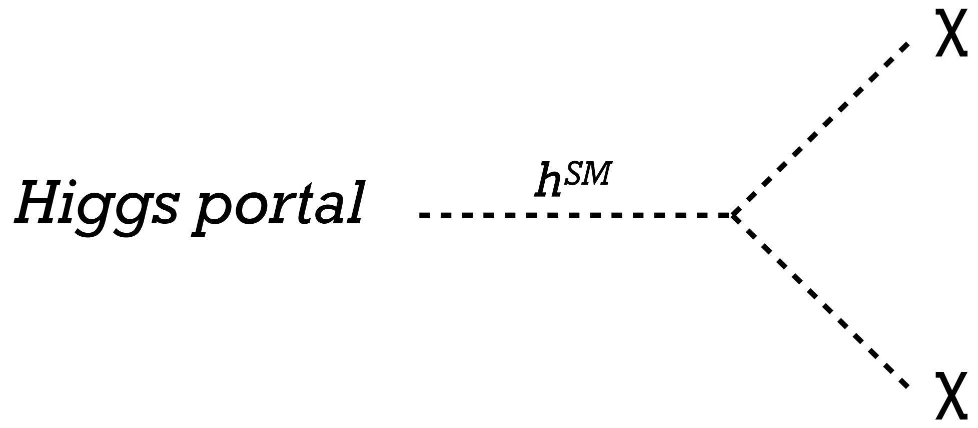
*including the first application of graph neural networks to jet tagging: Phys. Rev. D 101, 056019 (2020)

H→invisible

- SM prediction for H→ZZ*→4ν ~0.1%
- BR(H→invisible) can be highly enhanced under various BSM models, including Higgs portal models where H serves as mediator between SM particles and dark matter.
- Challenging experimental signature of missing E_T and additional (mainly hadronic) objects.
- VBF H production is the most sensitive H→invisible channel, balancing production rate with experimental challenges.







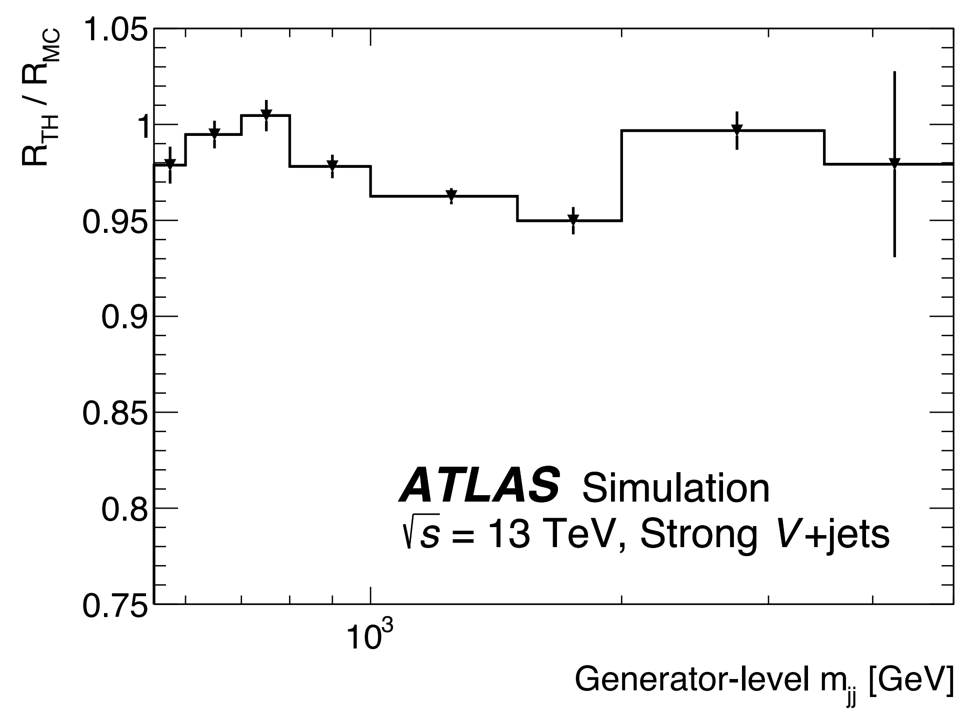
Pushing further on H→invisible

- We are starting to hit the systematic uncertainty limit in H→invisible
  - ⇒ to push further than ~10% on H→invisible, we need both more data and new ideas.

- Ratio of W+jets/Z+jets at large m_{jj} (~TeV) is a key input in background estimation.
  - Uncertainty in this ratio has been the leading uncertainty in multiple searches.

- Recent calculation of W+jets/Z+jets ratio as a function of m_{jj} at NLO EW + NLO QCD is a key step towards continuing to improve these measurements.

Group of systematic uncertainties	Impact on $\mathcal{B}(H \to inv)$ Observed	Impact on $\mathcal{B}(H \to inv)$ Expected
Theory	$^{+0.026}_{-0.025}$	±0.024
Simulated event count	±0.022	$^{+0.021}_{-0.022}$
Triggers	$^{+0.018}_{-0.019}$	±0.018
Jet calibration	$^{+0.014}_{-0.012}$	±0.011
QCD multijet mismodelling	±0.012	±0.013
Leptons/photons/b-tagged jets	$^{+0.011}_{-0.010}$	$^{+0.009}_{-0.010}$
Integrated luminosity/pileup	±0.004	±0.004
Other systematic uncertainties	$^{+0.013}_{-0.009}$	±0.009
Statistical uncertainty	±0.028	±0.028



Vector leptoquark modeling

$$\mathcal{L}_U = \frac{g_U}{\sqrt{2}} U^\mu \left[\beta_L^{i\alpha}(\bar{q}_L^i \gamma_\mu l_L^\alpha) + \beta_R^{i\alpha}(\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \text{h.c.}$$

$$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & \beta_L^{s\mu} & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & \beta_L^{b\tau} \end{pmatrix}, \quad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{b\tau} \end{pmatrix}$$

- Normalization of g_U chosen such that $\beta_L^{b\tau} = 1$.
- Couplings $\beta_L^{b\mu}$, $\beta_L^{s\mu}$, and $\beta_L^{d\tau}$, are small and neglected.
- Two benchmark (BM) scenarios are considered:
  - "VLQ BM 1": $\beta_R^{b\tau} = 0$ - no right-handed couplings
  - "VLQ BM 2": $\beta_L^{b\tau} = -1$ - Pati-Salam-like leptoquark
- Value of $\beta_L^{s\tau}$ taken from best-fit of B physics data: $\beta_L^{s\tau} = 0.19$ (BM1), $\beta_L^{s\tau} = 0.21$ (BM2)

Interpretation based on arXiv:2103.16558: Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert

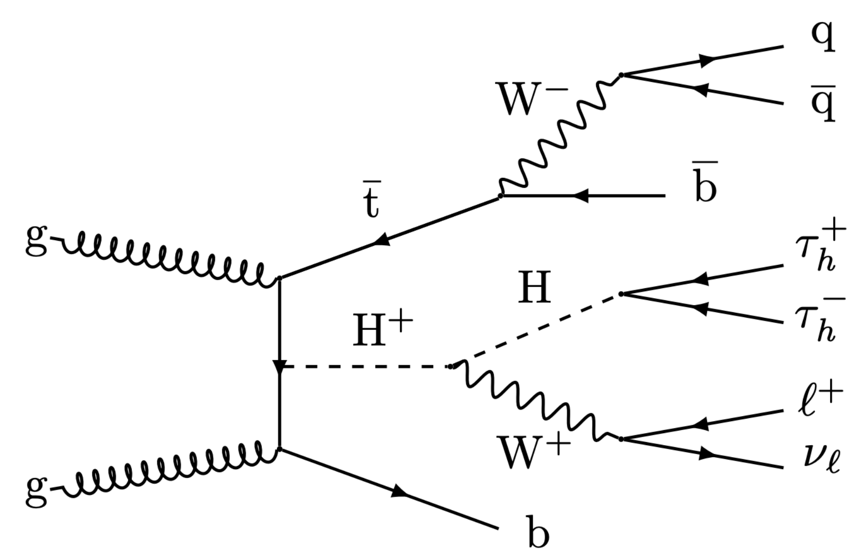
$\phi \rightarrow \tau\tau$: where we could use further input(s)

- VLQ interpretation given for two BM scenarios for VLQ couplings
  - Is it possible to interpret these results for other coupling scenarios?
  - If not, what additional inputs would be helpful?
- Extending the interpretation to include scalar leptoquarks
  - Here some guidance on a handful of model + coupling scenarios to focus on would be very helpful!
- Are there additional models/interpretations that we should include? i.e. what model(s) are we missing that are the most relevant and probed by such searches?

*with input from D. Winterbottom, A. Gottmann

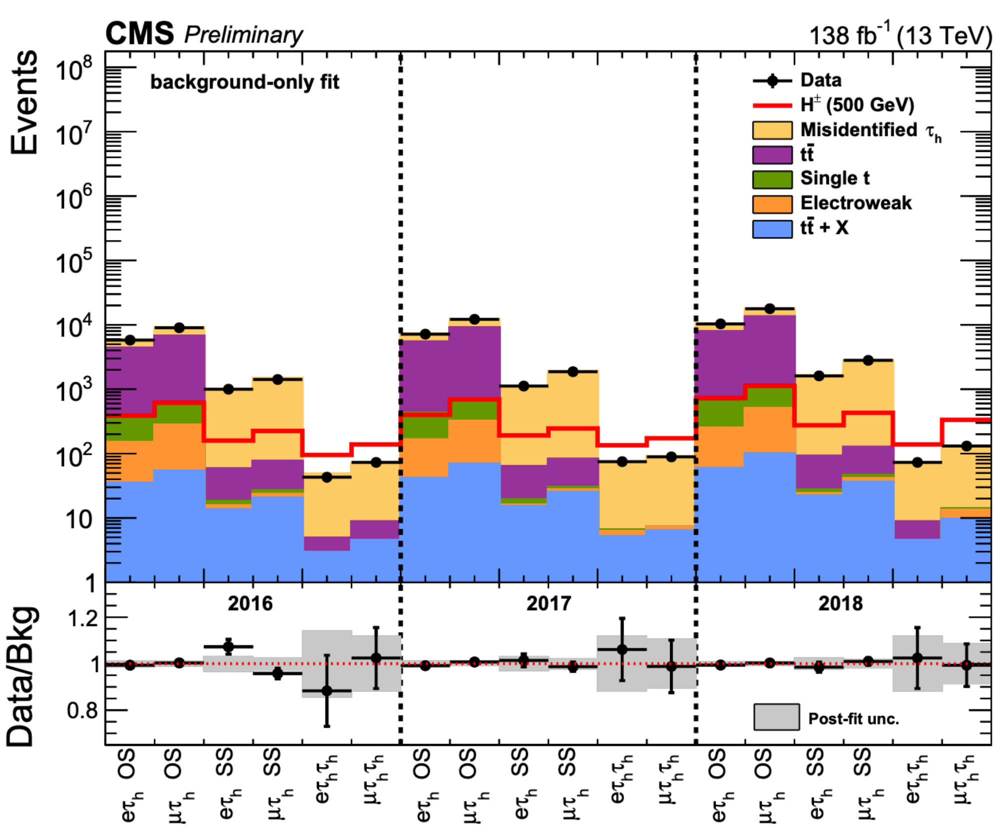
Search for $H^{\pm} \rightarrow HW^{\pm}$, $H \rightarrow \tau\tau$

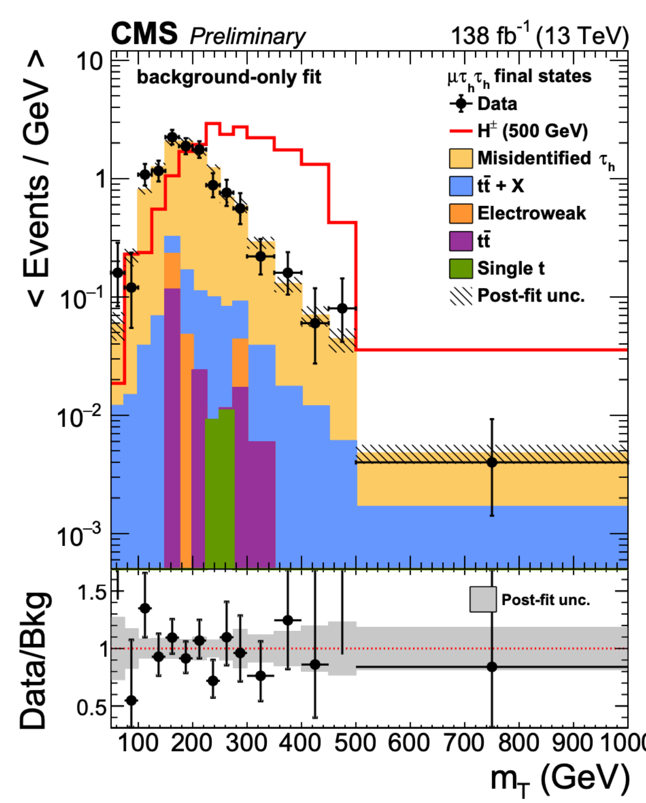
- Combination of $e\tau_h$, $\mu\tau_h$, $e\tau_h\tau_h$, and $\mu\tau_h\tau_h$ final states
  - 43% of total branching fraction.
  - In $e\tau_h$ and $\mu\tau_h$ channels, perform fit to output of MVA classifier.
  - In $e\tau_h\tau_h$ and $\mu\tau_h\tau_h$ channels, fit traverse mass of charged H candidate.

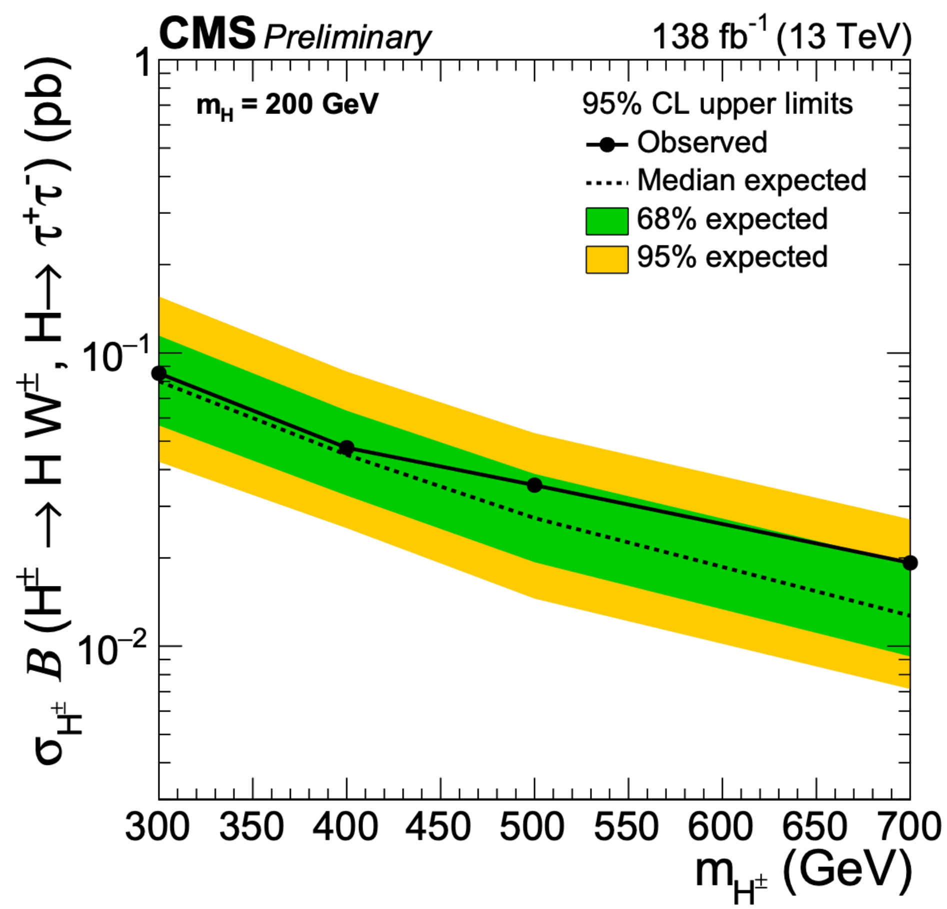


- Hadronic decays of top quark identified with mass-decorrelated neural network tagger.

- No significant excess observed ⇒ limits set on σ*BR for $H^{\pm} \rightarrow HW^{\pm}$, $H \rightarrow \tau\tau$ from 20 fb to 80 fb.

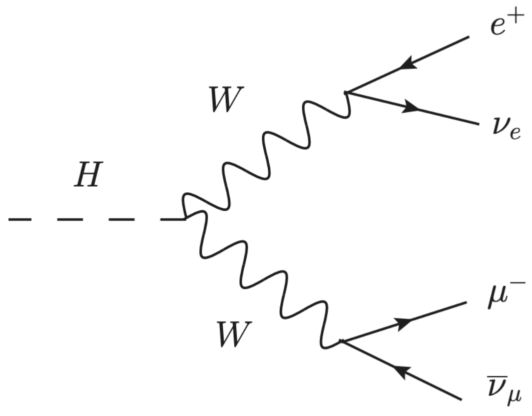




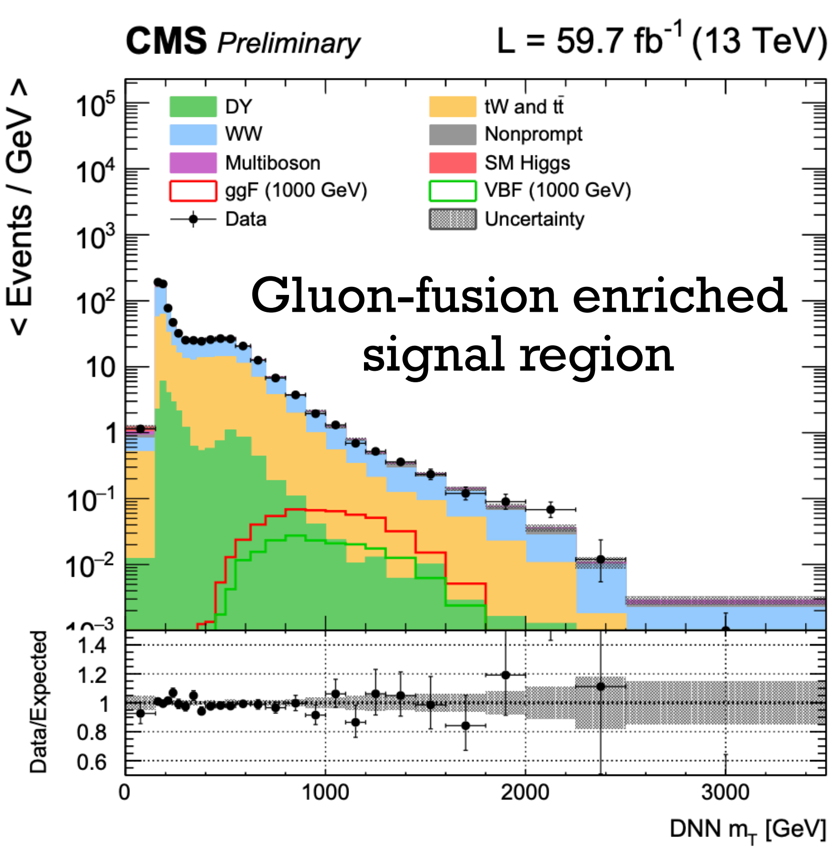


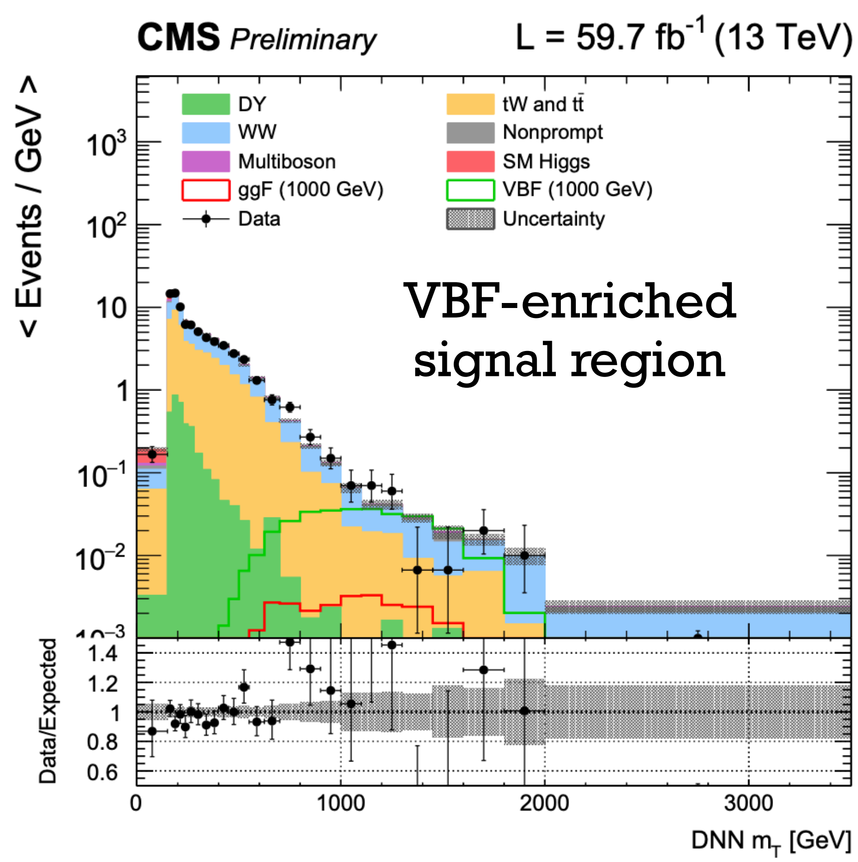
H→WW high mass search

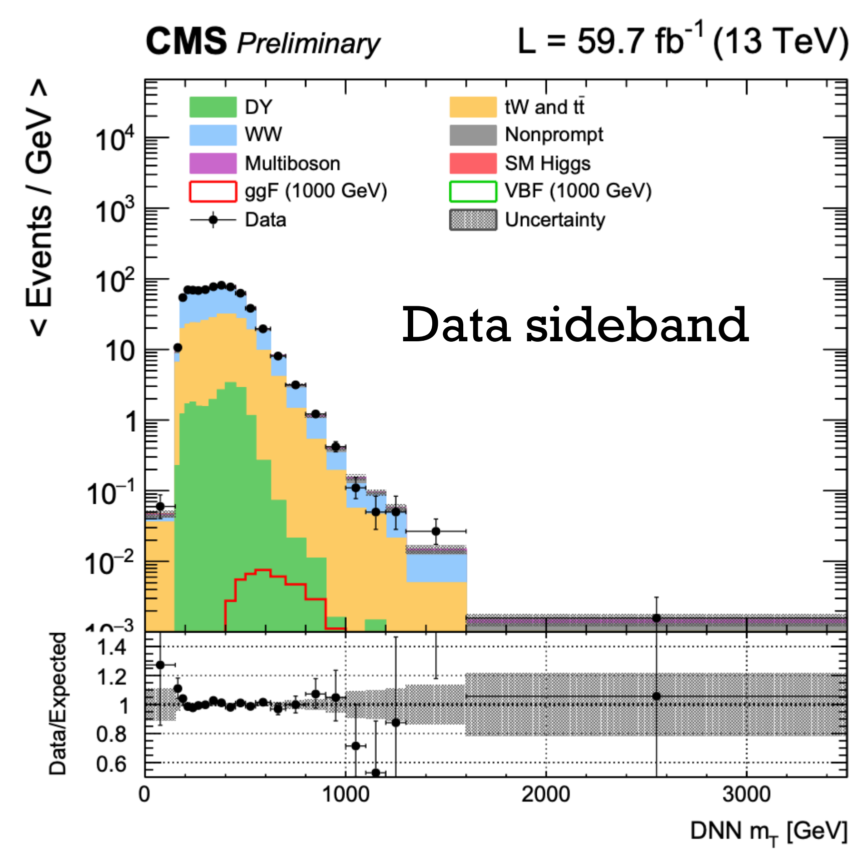
- Search for resonances in WW mass from 115 GeV to 5 TeV.
  - Separate categories for gluon-fusion and VBF production.
- Combination of searches in eμ, μμ, and eμ final states.
- Deep neural networks developed to:
  - Define high signal purity categories (classification)
  - Estimate signal resonance mass (regression)



Search region:
115 GeV < m_ϕ < 5 TeV



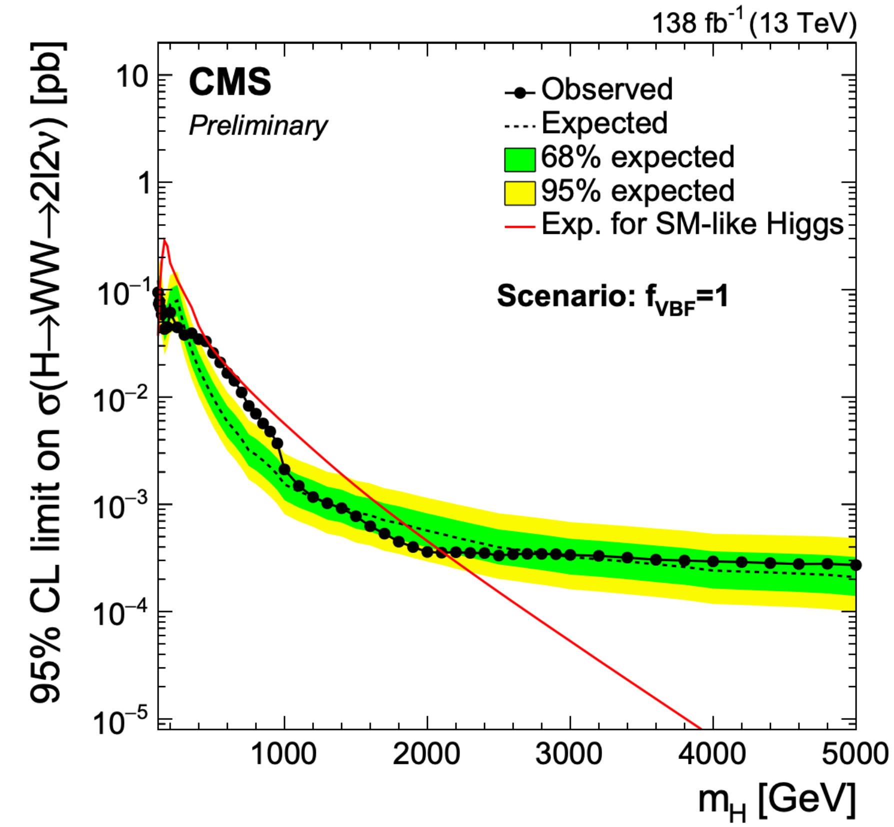


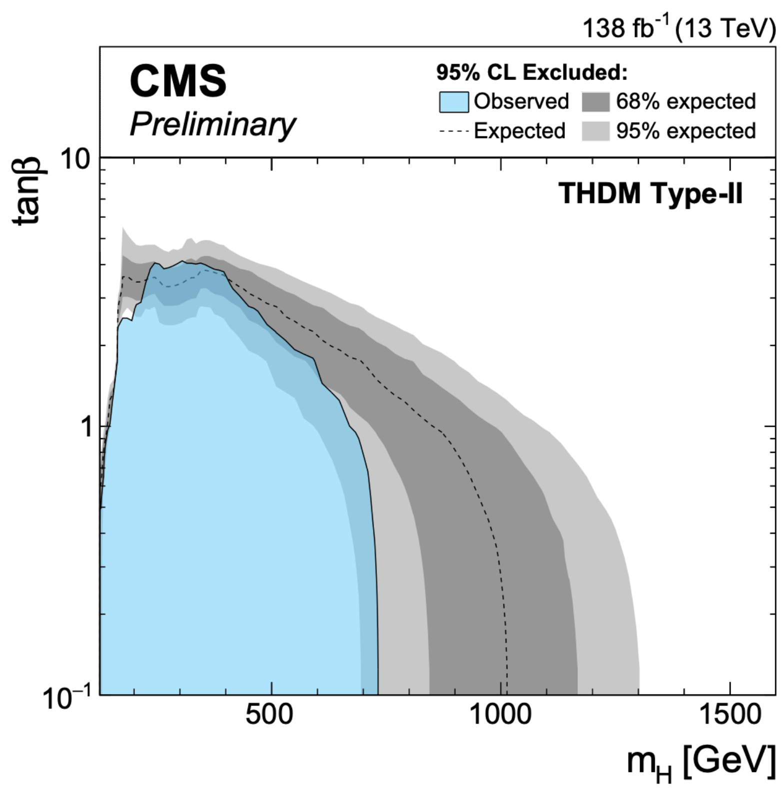


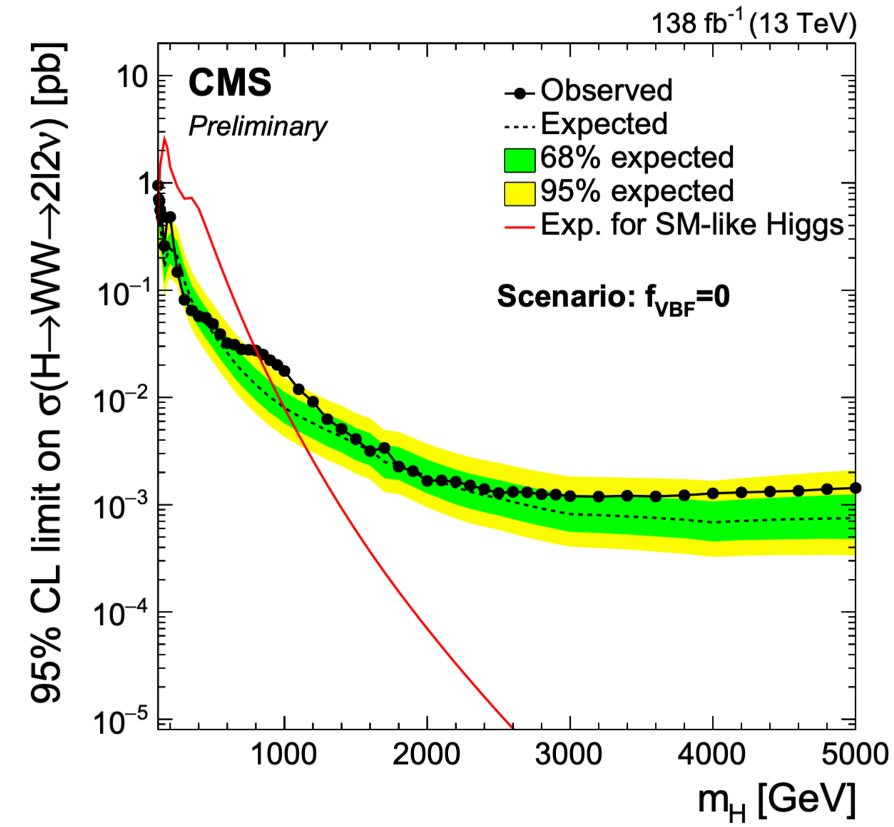
H→WW high mass search: results

- Many interpretations provided:
  - Model-independent, for range of width hypotheses.
  - MSSM (six scenarios in total).
  - Two Higgs Doublet Models (THDM).

- Largest excess over background observed near 650 GeV, with local (global) significance of 3.8σ (2.6σ).
  - Excess is concentrated in vector boson fusion production categories.
  - Something to keep an eye on!





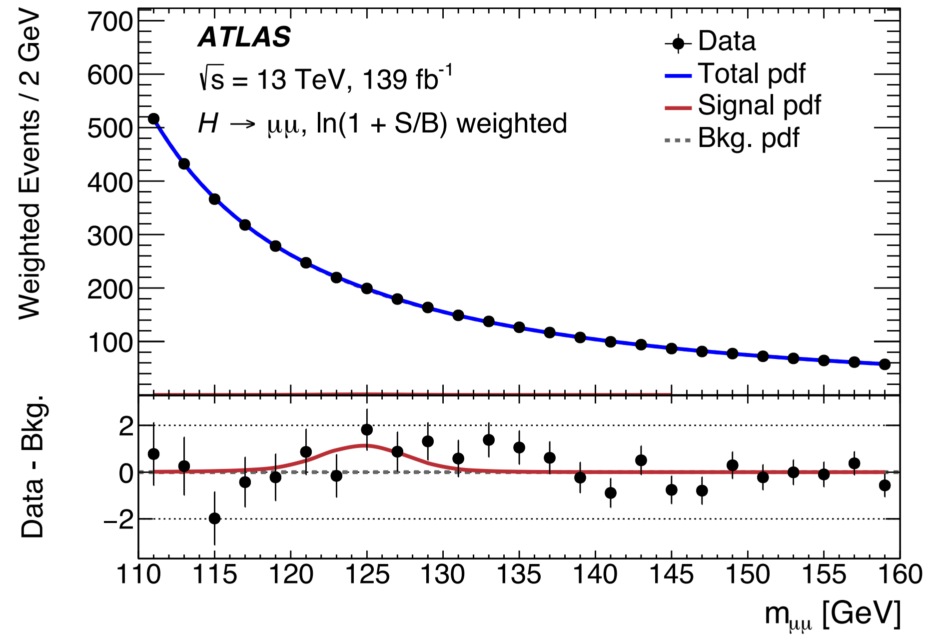


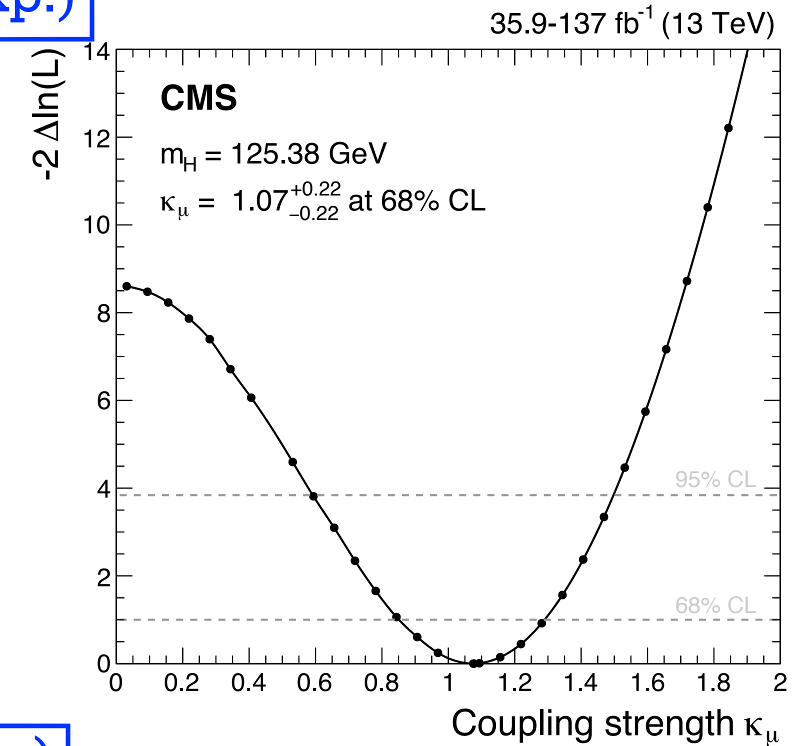
H→μμ: more details

- Most experimentally accessible probe of Yukawa interactions beyond third generation.

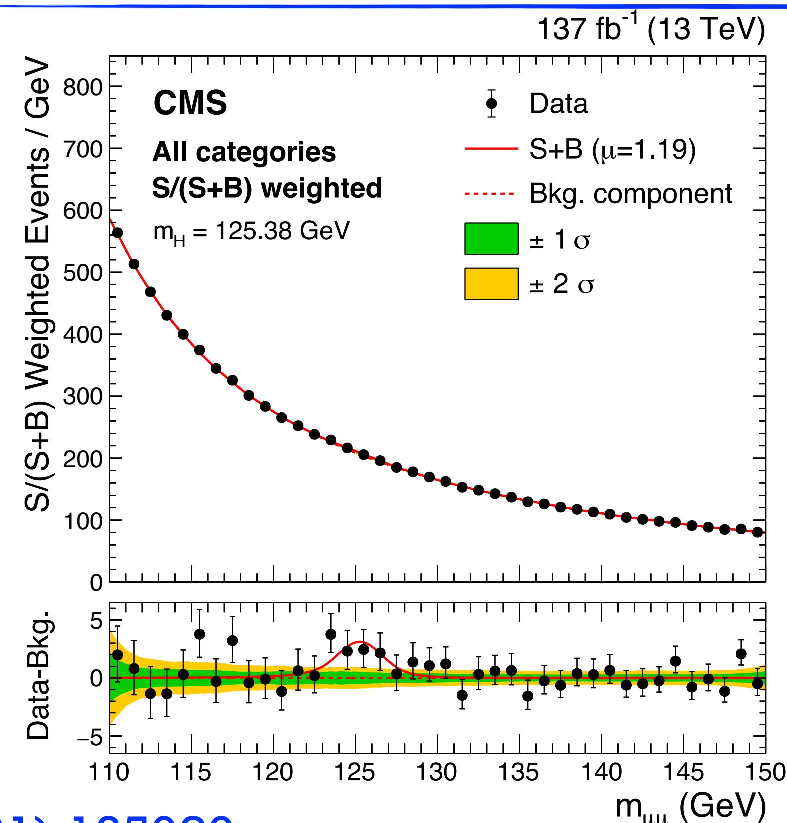
- *Evidence for H→μμ with LHC Run-2 data!*

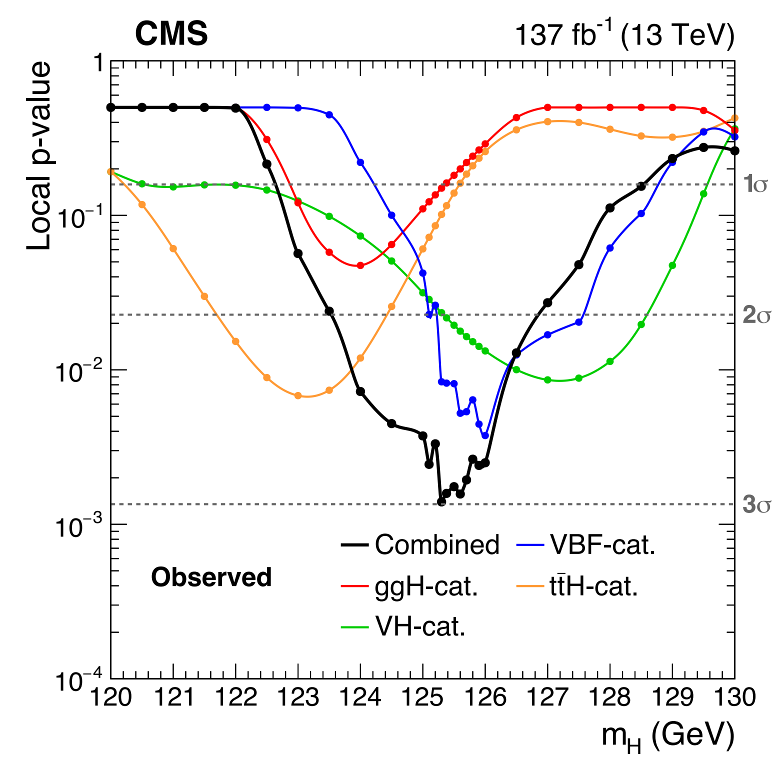
ATLAS Run-2 result: 2.0σ (1.7σ) obs. (exp.)





CMS Run-2 result: 3.0σ (2.5σ) obs. (exp.)





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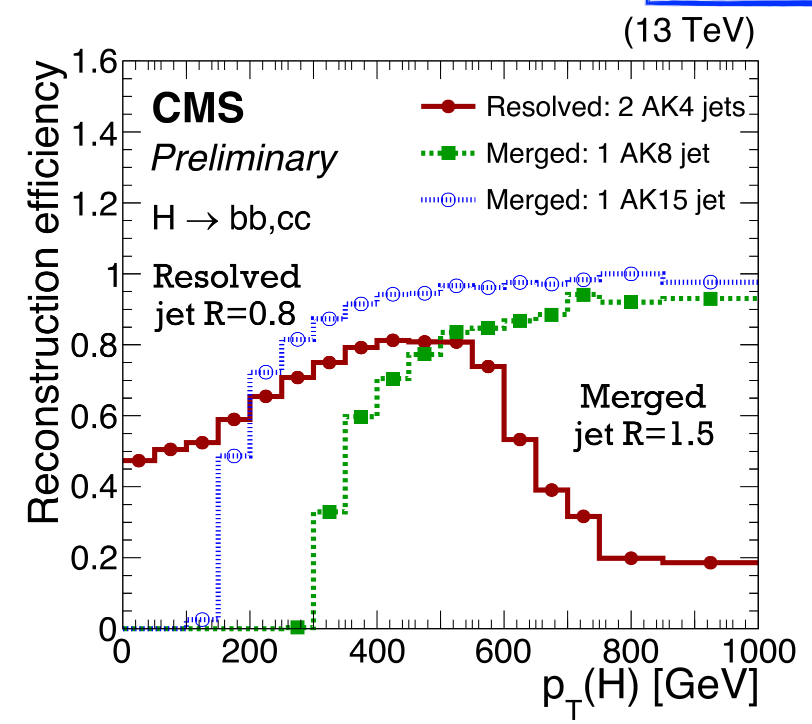
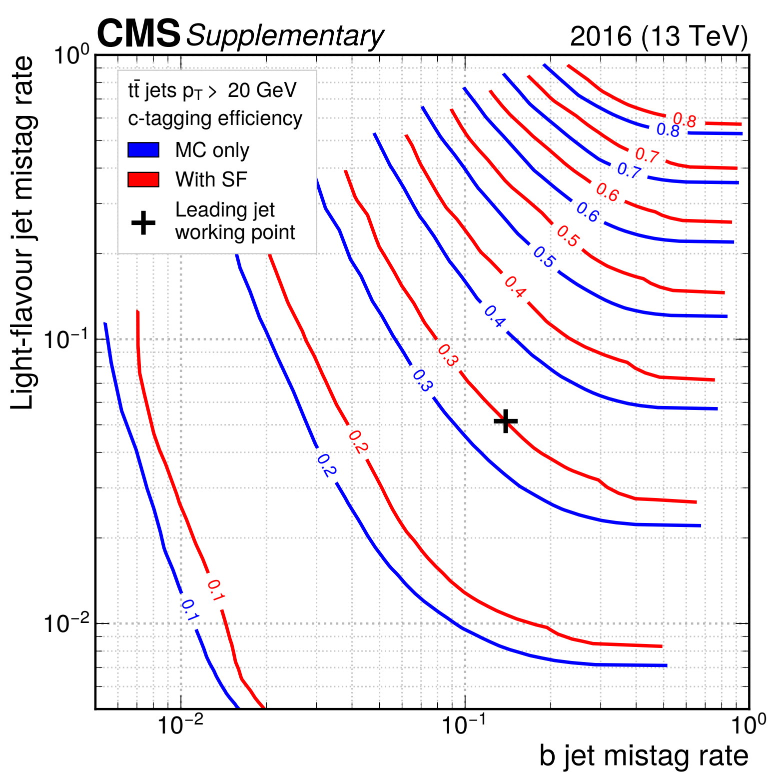
Charm jet tagging

NEW 2022!

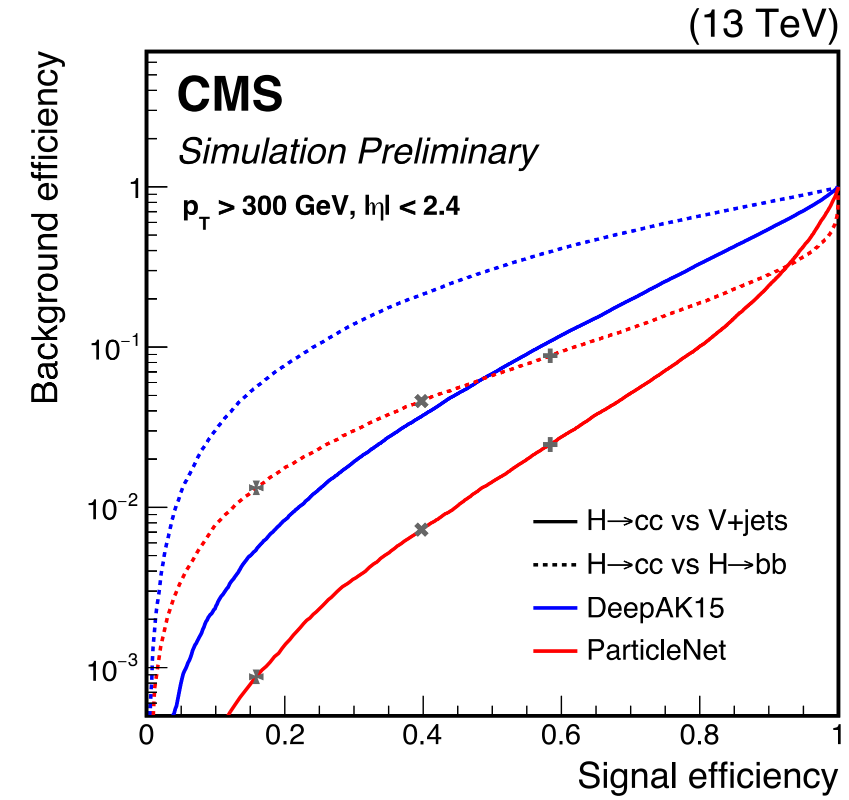
- Jets originating from charm quarks have properties intermediate between udsg and b jets ⇒ difficult to isolate.
- Enormous effort to maximize charm jet tagging performance in Run-2:
  - Using latest developments in machine learning*.
  - Exploring multiple jet topologies, including large-radius jets.
- Dedicated calibrations performed with data.



"Resolved" jet c-tagger (vs. udsg and vs. b)



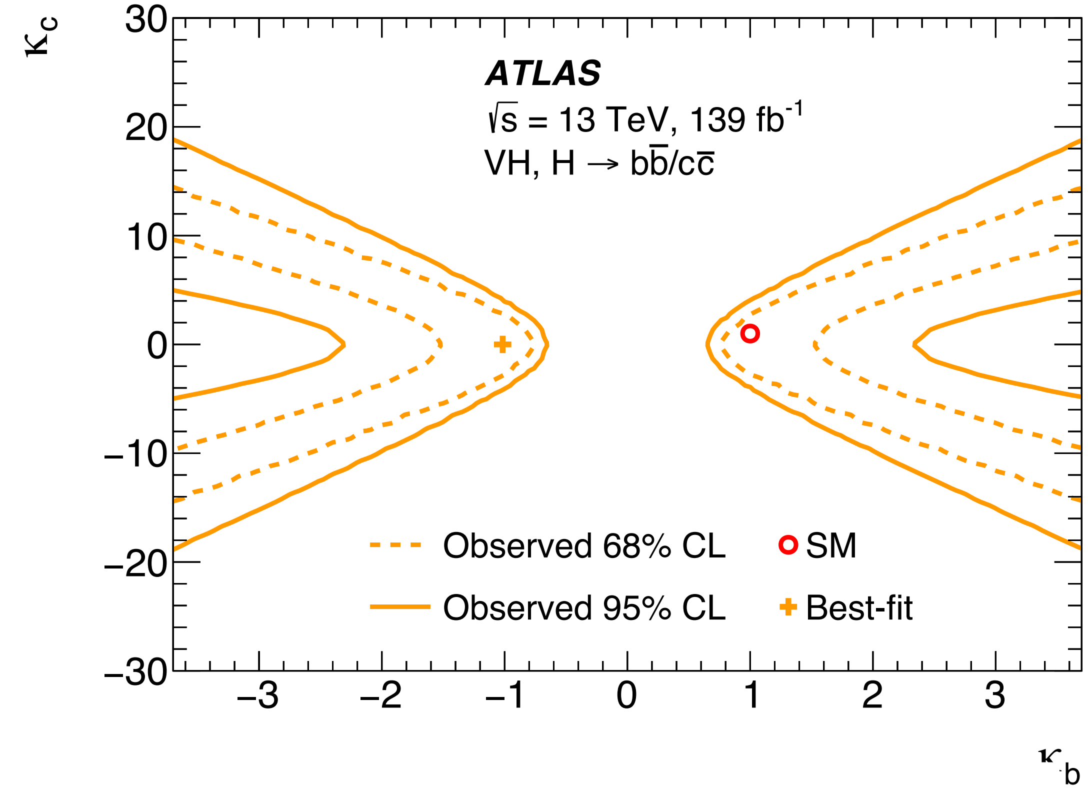
"Merged" jet cc-tagger (vs. bb, qq, …)



arXiv:2111.03027, accepted for publication in J. Instrum.

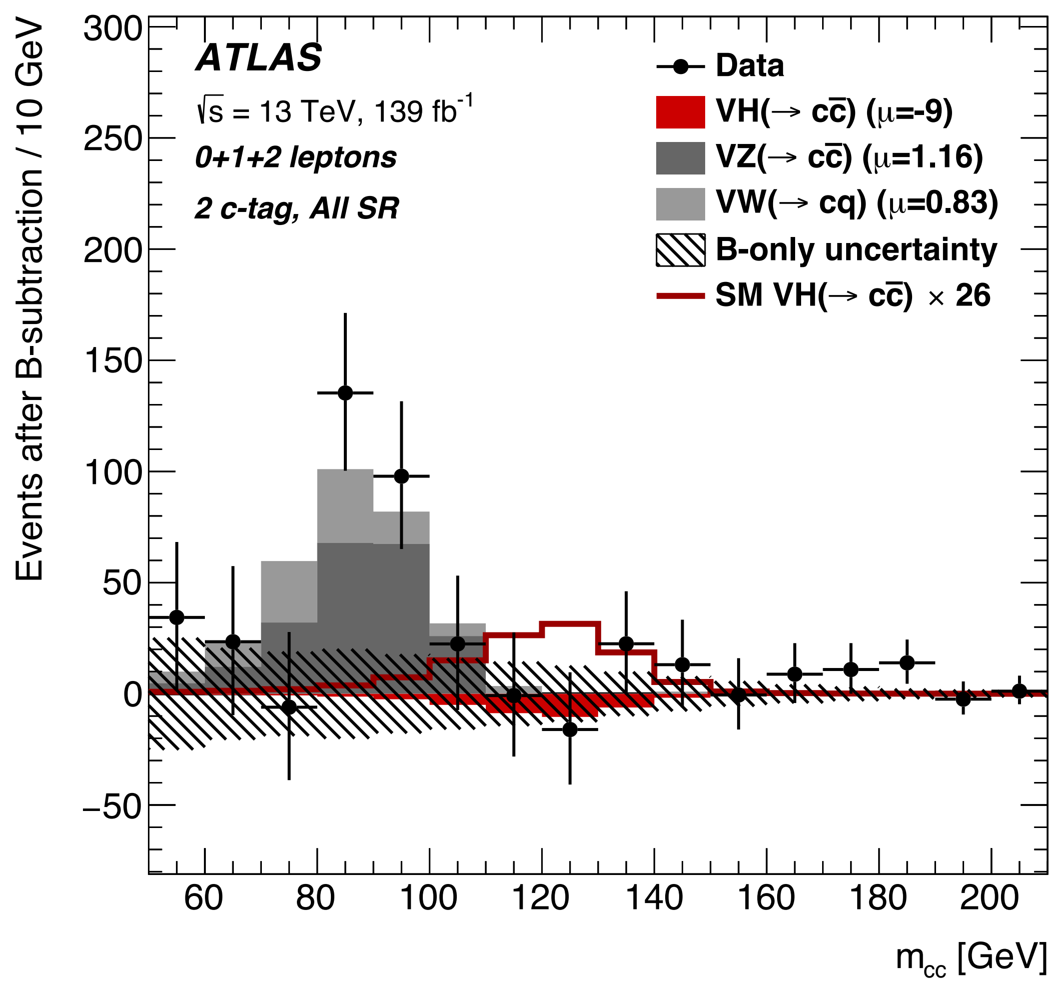
*including the first application of graph neural networks to jet tagging: Phys. Rev. D 101, 056019 (2020)

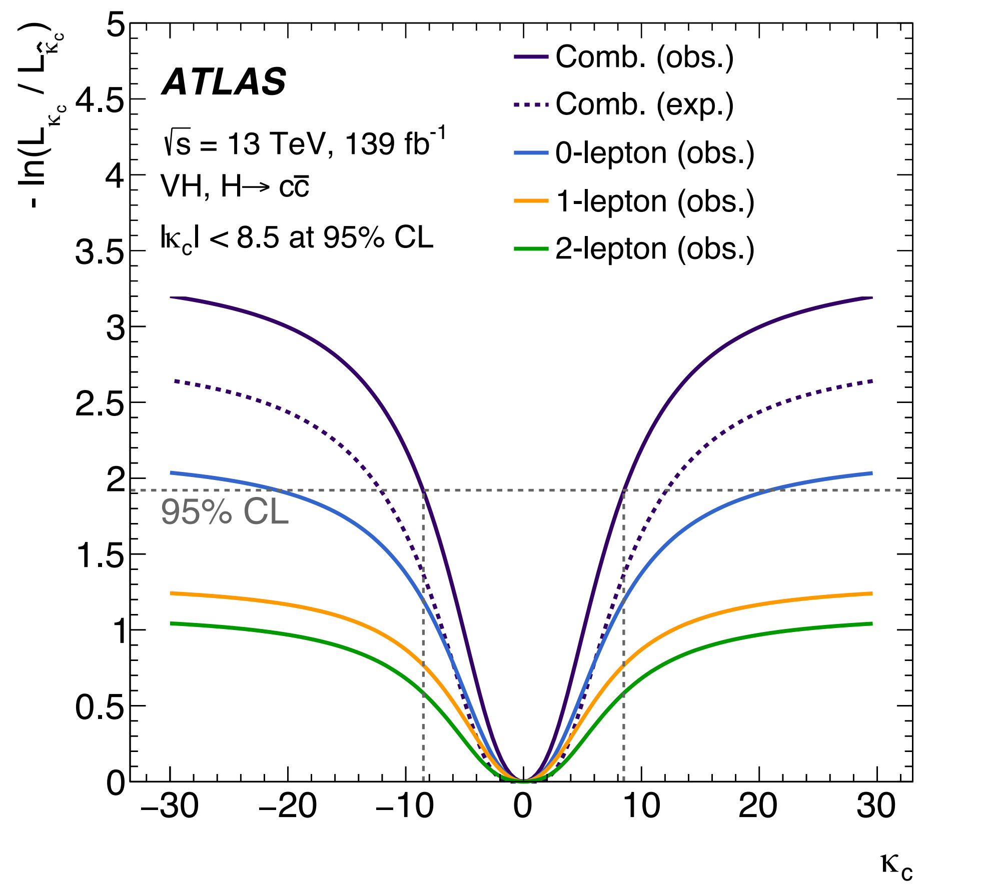
- Combination of 0-,1-, and 2-lepton channels using resolved jet topology (no boosted merged-jet analysis).



95% CL obs. (exp.) $\mu < 26(31)$

$\kappa_c < 8.5$ (12.4 exp.)

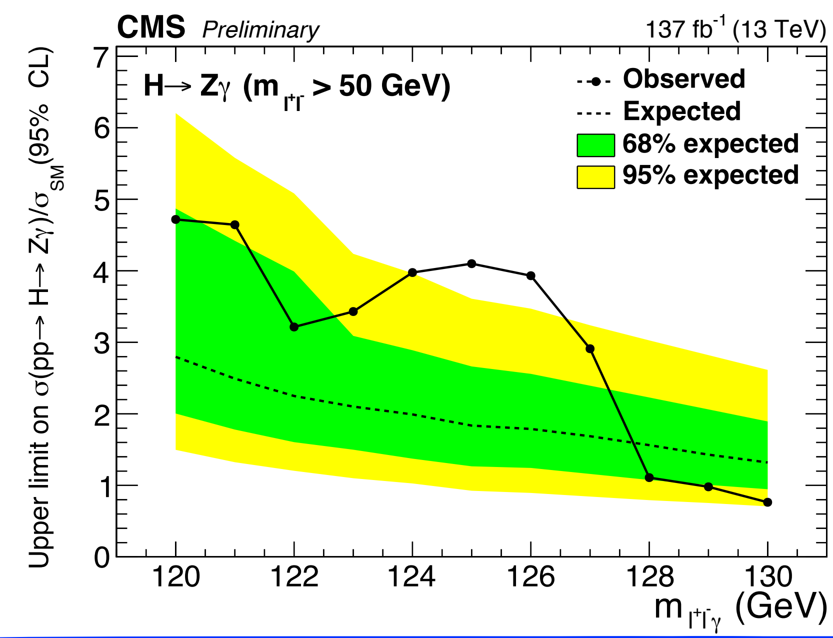




ATLAS-CONF-HIGG-2021-12

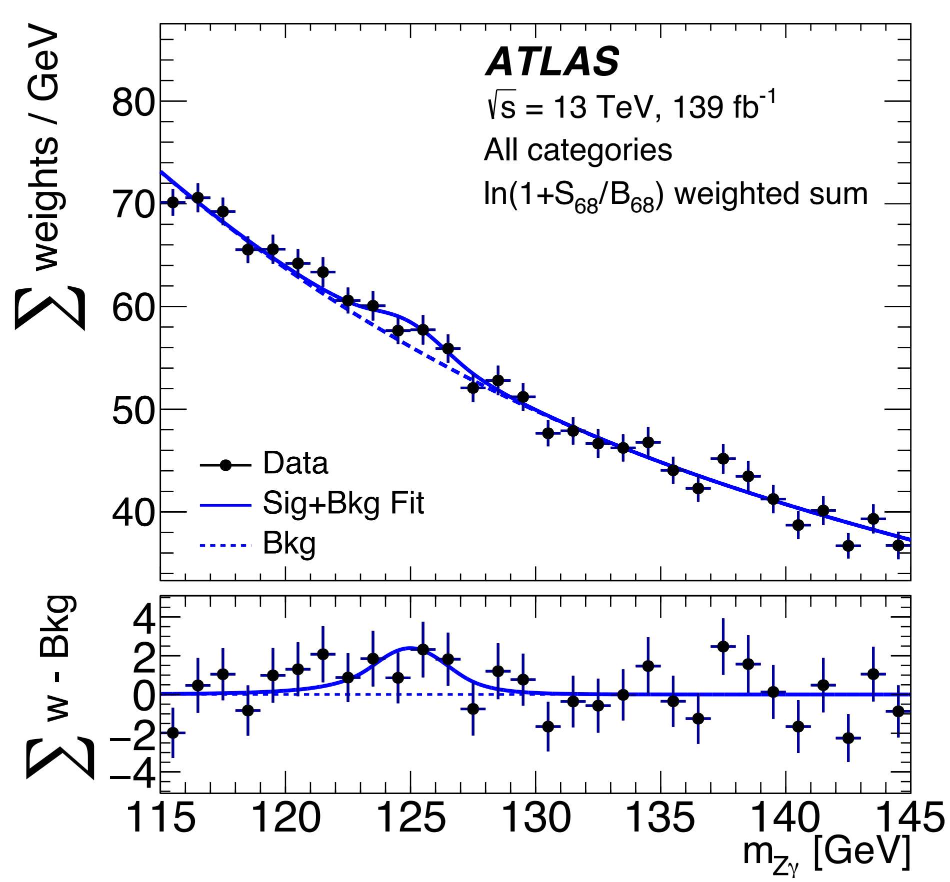
H→Zγ: further details

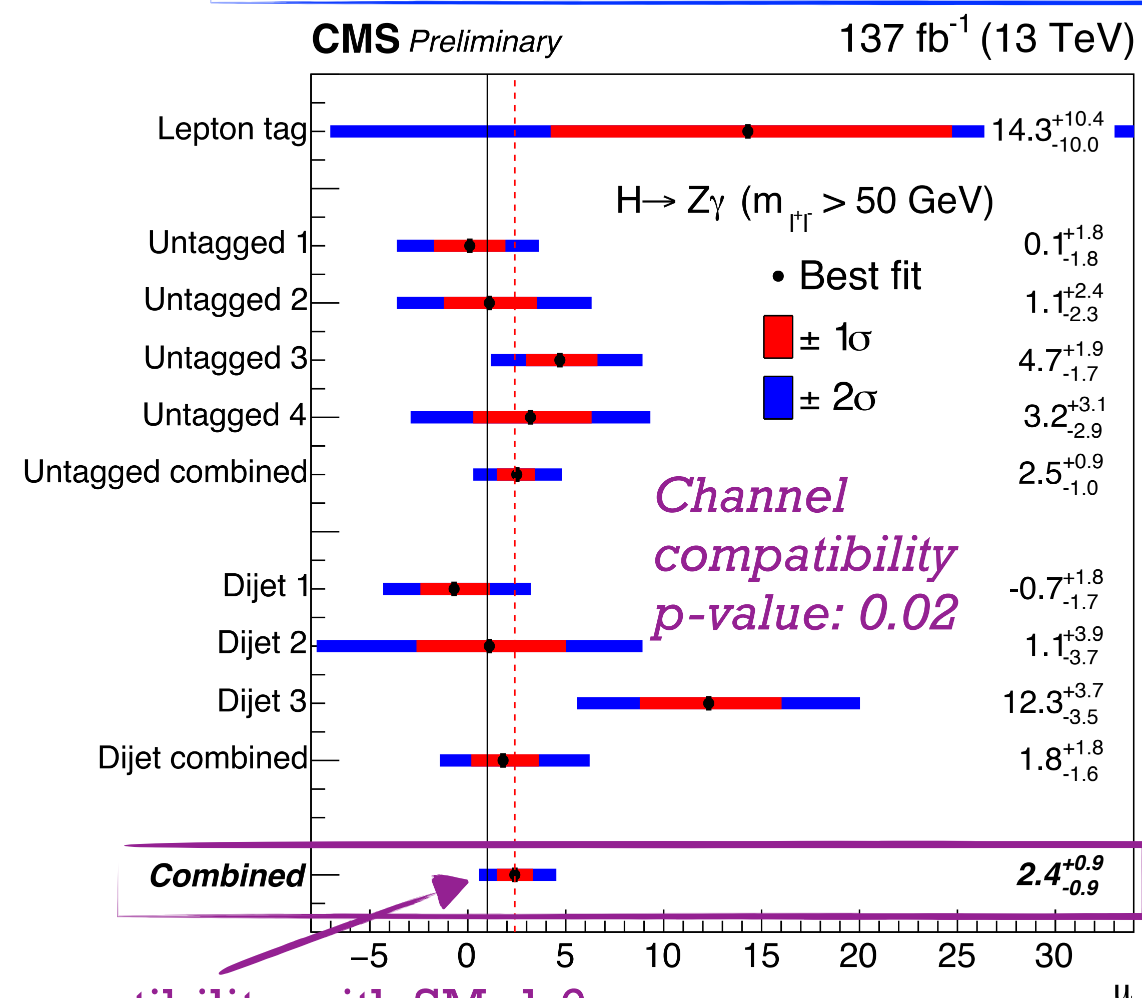
- ATLAS signal strengths “compatible within their total uncertainties” (paper).
- Compatibility tests from CMS at ~2σ level ⇒ need Run-3 data to understand if this is a statistical effect or a real discrepancy.



ATLAS Run-2 result: 2.2σ (1.1σ) obs. (exp.)

CMS Run-2 result: 2.7σ (1.2σ) obs. (exp.)





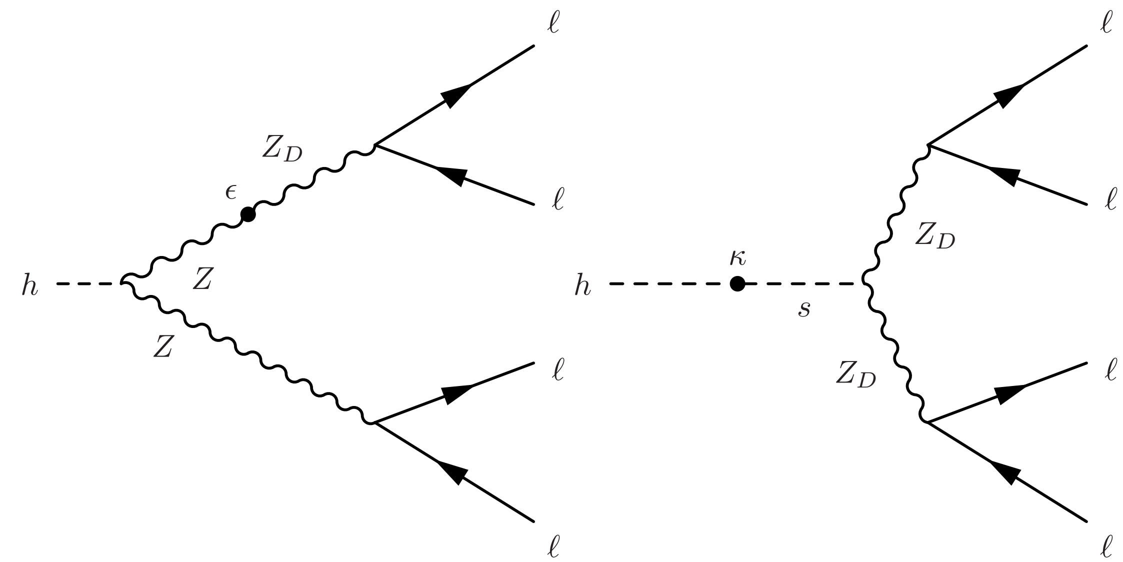
Compatibility with SM: 1.6σ

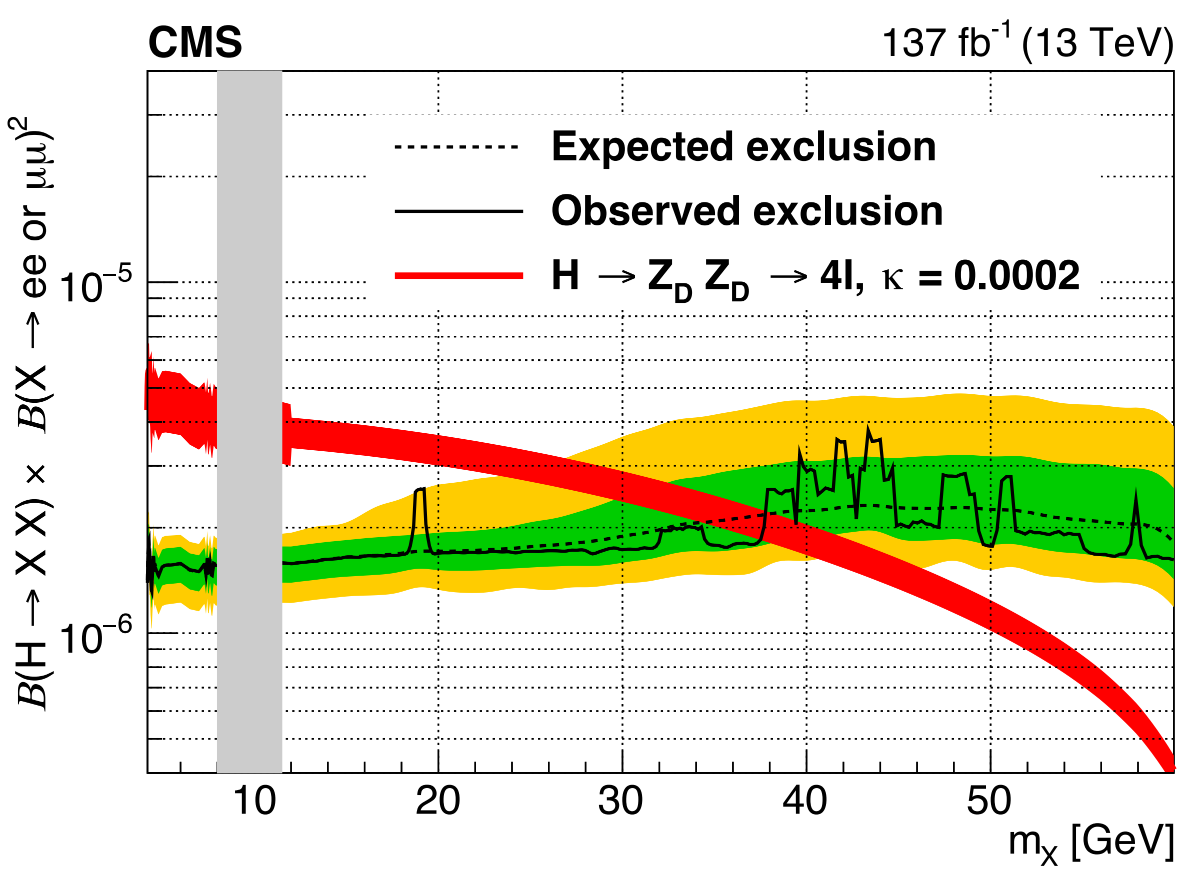
Exotic h→4l decays

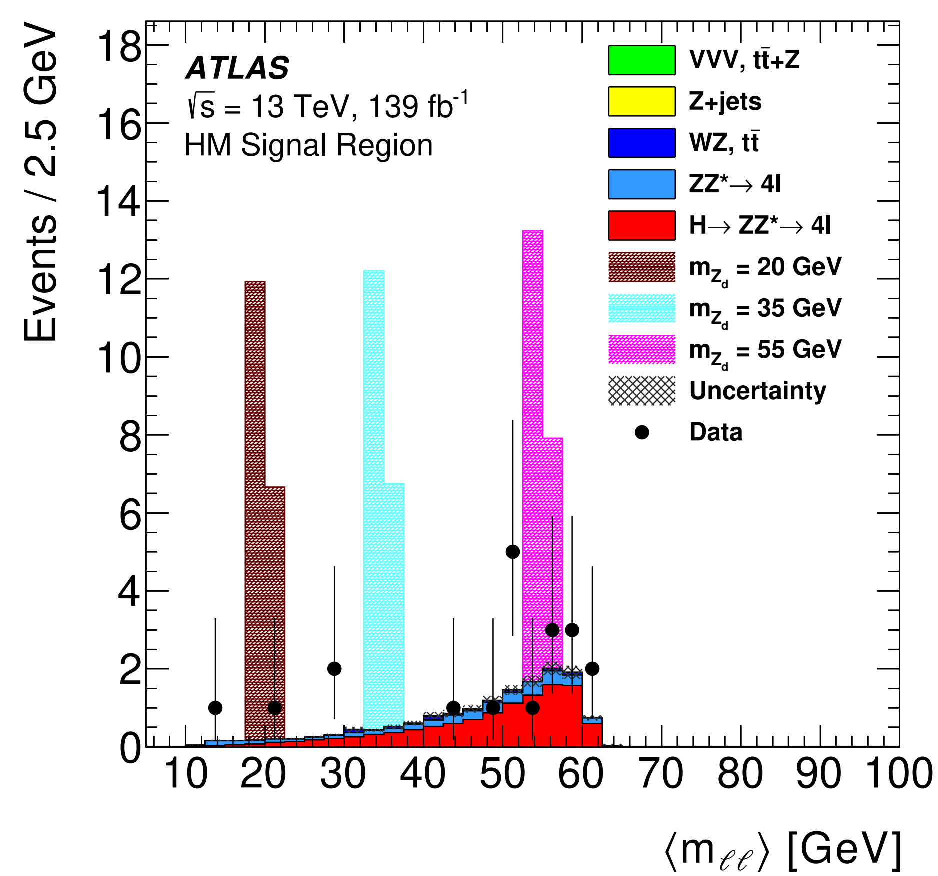
- Search for h→[XX/ZX]→4l
  - X = dark photon Z_D, neutral pseudoscalar a, …

- No significant excesses observed by ATLAS or CMS.

- Results interpreted as model-independent limits and for a range of BSM models (dark photon, MSSM, axion-like particles).

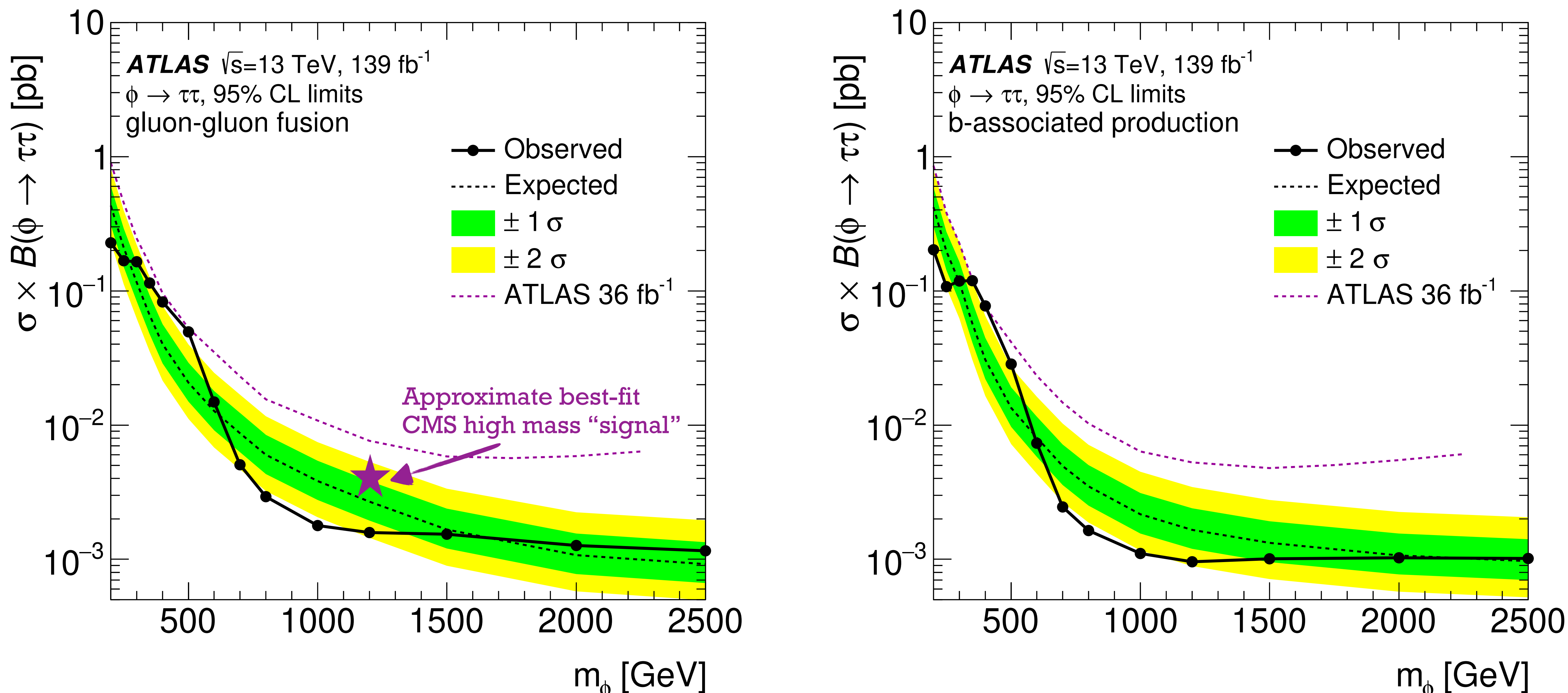






ATLAS $\phi \to \tau\tau$ at high mass

- Local 2.8σ excess observed by CMS in ggϕ @1.2 TeV appears to be excluded by ATLAS search @>95% C.L.
- No directly comparable low-mass $\phi \to \tau\tau$ search from ATLAS.



Phys. Rev. Lett. 125 (2020) 051801