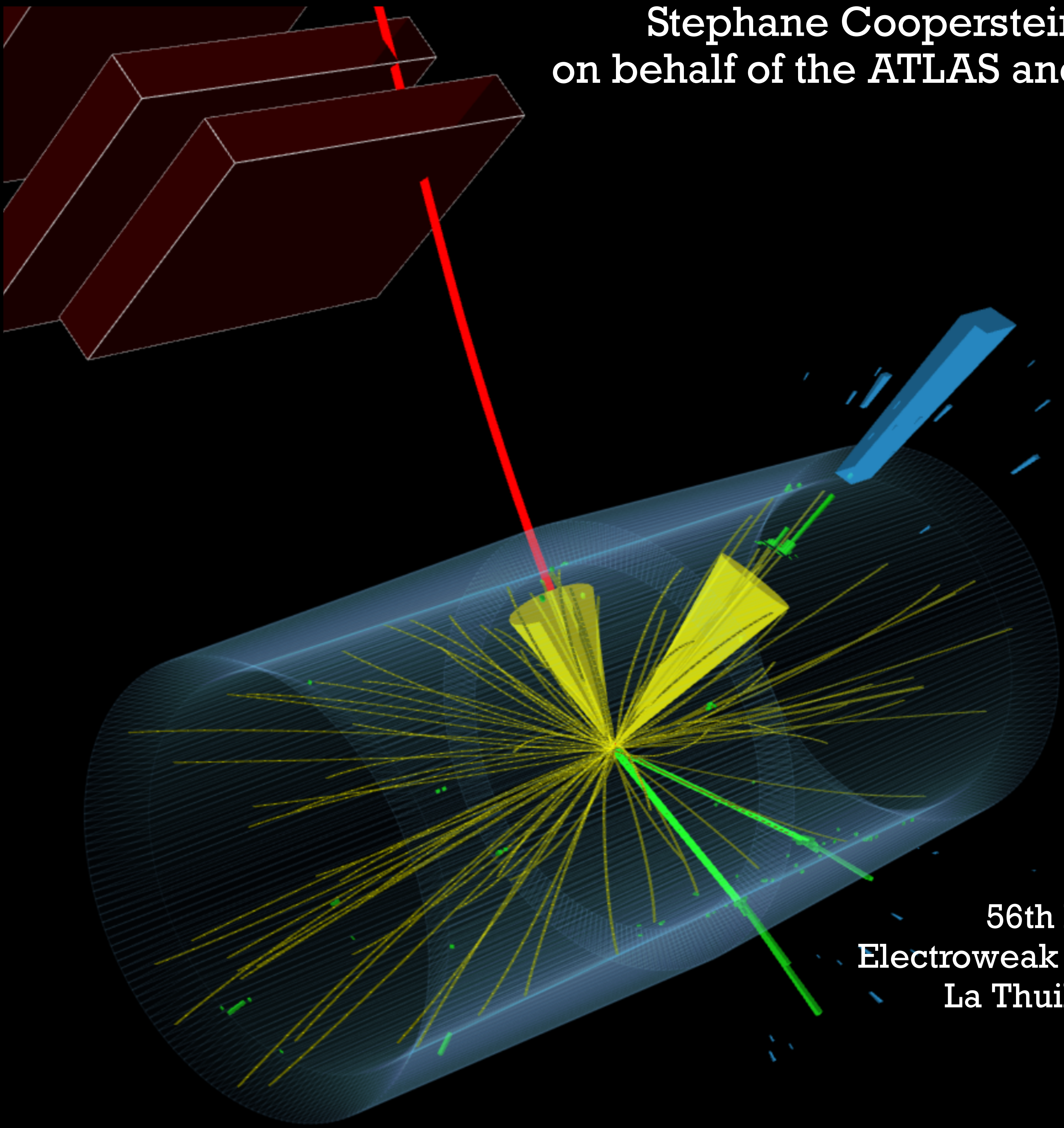
BSM H searches and rare H decay searches

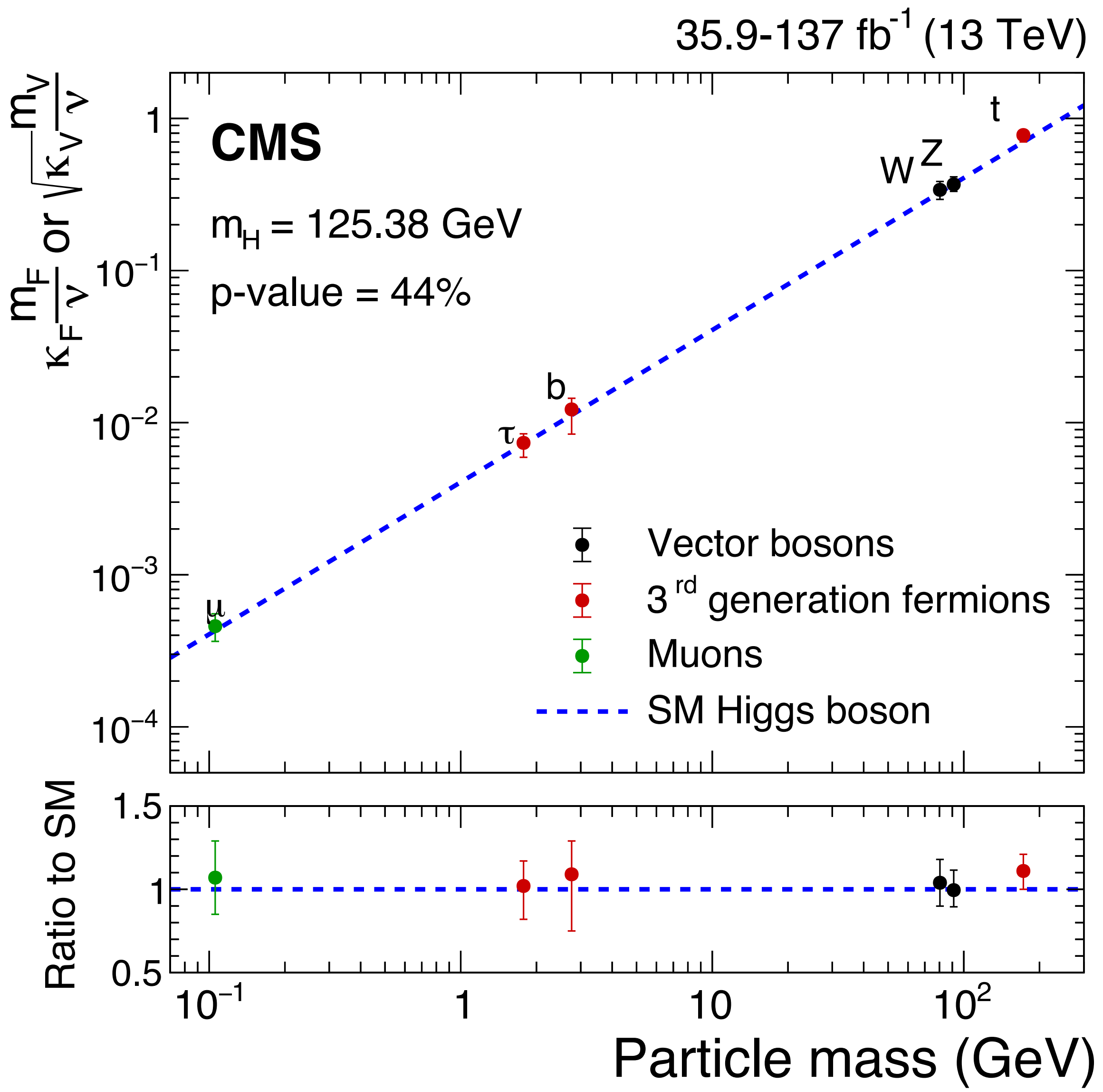
Stephane Cooperstein (UC San Diego)
on behalf of the ATLAS and CMS Collaborations



56th Rencontres de Moriond
Electroweak unification and unified theories
La Thuile, Italy, 12-19 March 2022

The next frontier(s) in Higgs physics

- Millions of Higgs bosons have now been produced at the LHC, enabling:
  - Measurement of m_H to nearly per-mille precision.
  - Observation of all third-generation H couplings.
  - Detailed measurements of H properties (differential, STXS, CP, …)
- This unprecedented data set opens a *new window in exploration of H sector*:
  - **Rare H decays** (H→μμ, H→Zγ, H→cc, H→ee,…)
  - **Exotic H decays** (H→invisible, H→aa, H→X+quarkonia …)
  - **Extended H sector** (MSSM, …)



Outline

H Rare Decays

- VH, H→cc:
  - CMS: CMS-PAS-HIG-21-008
  - ATLAS: arXiv:2201.11428, submitted to EPJC

Dedicated talk by V. Dao

NEW March 2022!

NEW January 2022!

- H→ee: CMS-PAS-HIG-21-015

NEW FOR MORIOND!

H Exotic Decays

Covered by R. Toro

- H→invisible:
  - VBF H→invisible CMS: CMS-PAS-20-003, submitted to PRD.
  - VBF H→invisible ATLAS: arXiv:2202.07953, submitted to JHEP
  - ZH (mono-Z) ATLAS: arXiv:2111.08372, submitted to PLB

NEW January 2022!

NEW February 2022!

November 2021

- H→aa→4γ (boosted): CMS-PAS-HIG-21-016

NEW FOR MORIOND!

- Exclusive H decays to quarkonia:
  - H→Z J/ψ / J/ψ J/ψ / YY: CMS-PAS-20-008

Covered by R. Toro

NEW January 2022!

Extended H sector

- MSSM/VLQ ϕ→ ττ: CMS-PAS-HIG-21-001

NEW FOR MORIOND!

- H→WW high mass: CMS-PAS-HIG-20-016

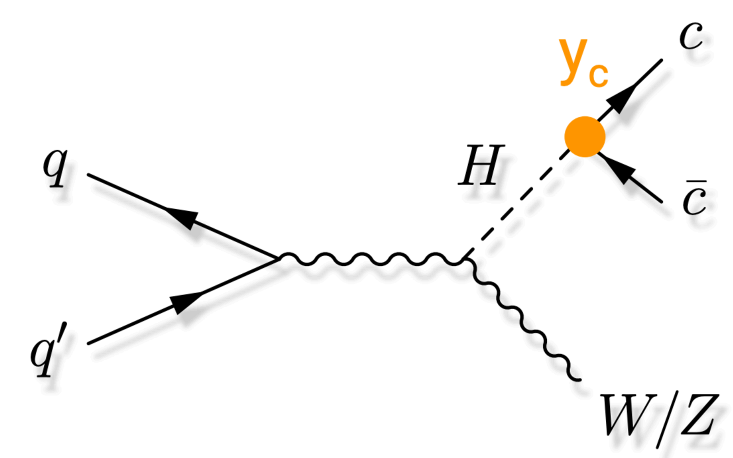
NEW FOR MORIOND!

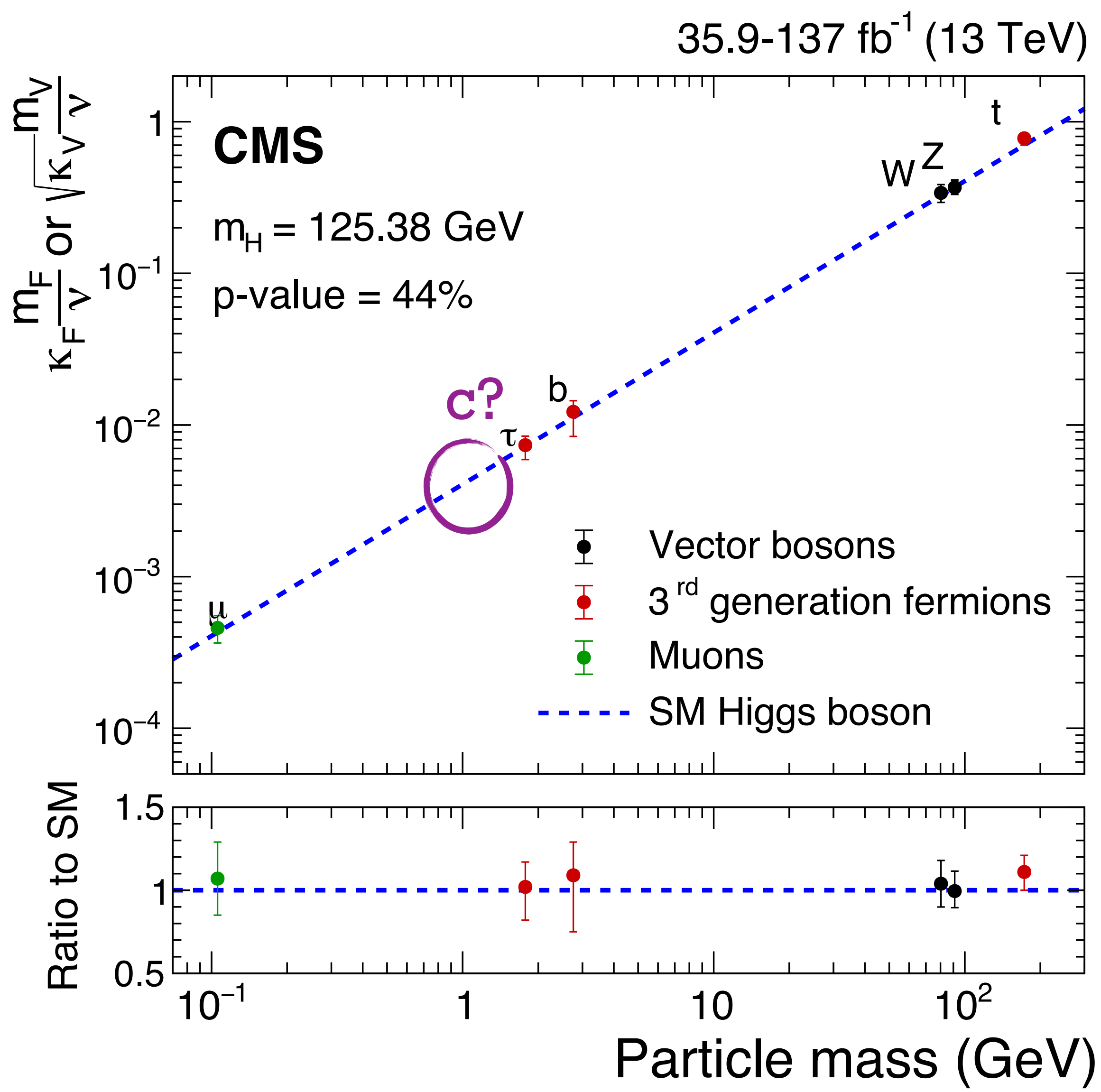
- H±→HW±, H→ττ: CMS-PAS-HIG-21-010

NEW FOR MORIOND!

Constraining the Higgs-charm Yukawa

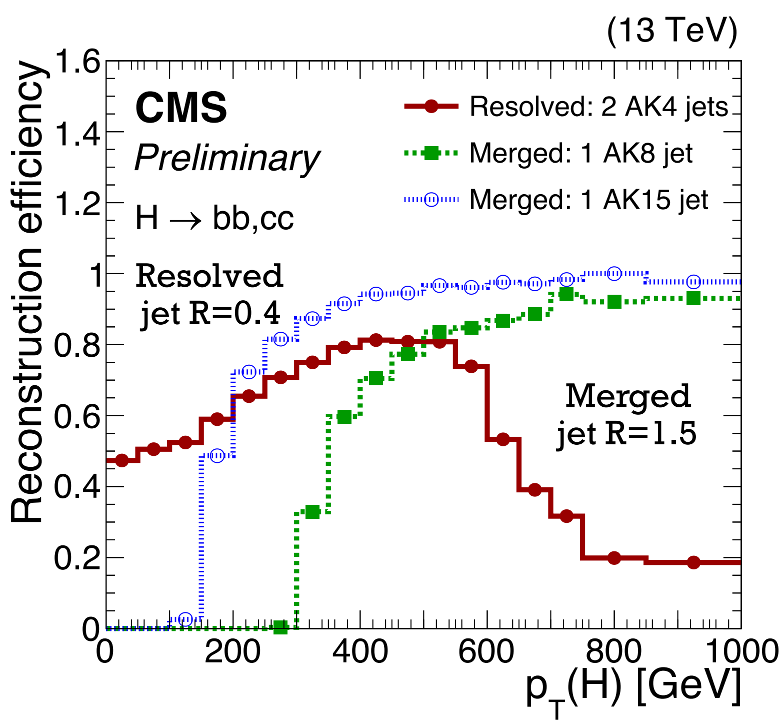
- Measuring Yukawa interactions beyond third generation is critical test of Higgs sector.
- Measuring H→cc at the LHC is extremely challenging:
  - Multijet background larger by many (~9!) orders of magnitude.
  - Charm jet tagging is very difficult.
- Today I highlight new results from CMS searching for H→cc in VH production (most sensitive channel).
  - ATLAS results covered this morning in dedicated talk by V. Dao.

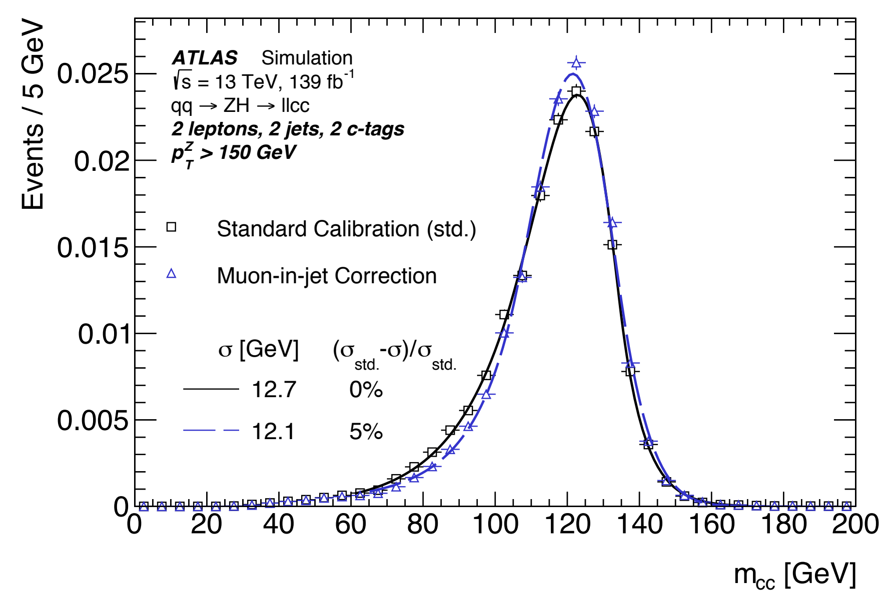


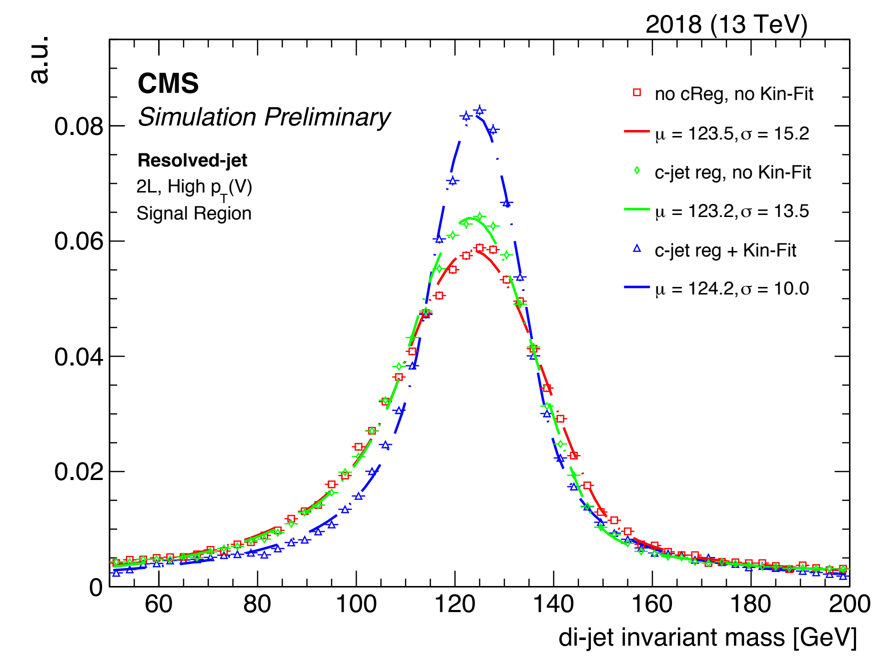


Maximizing the sensitivity

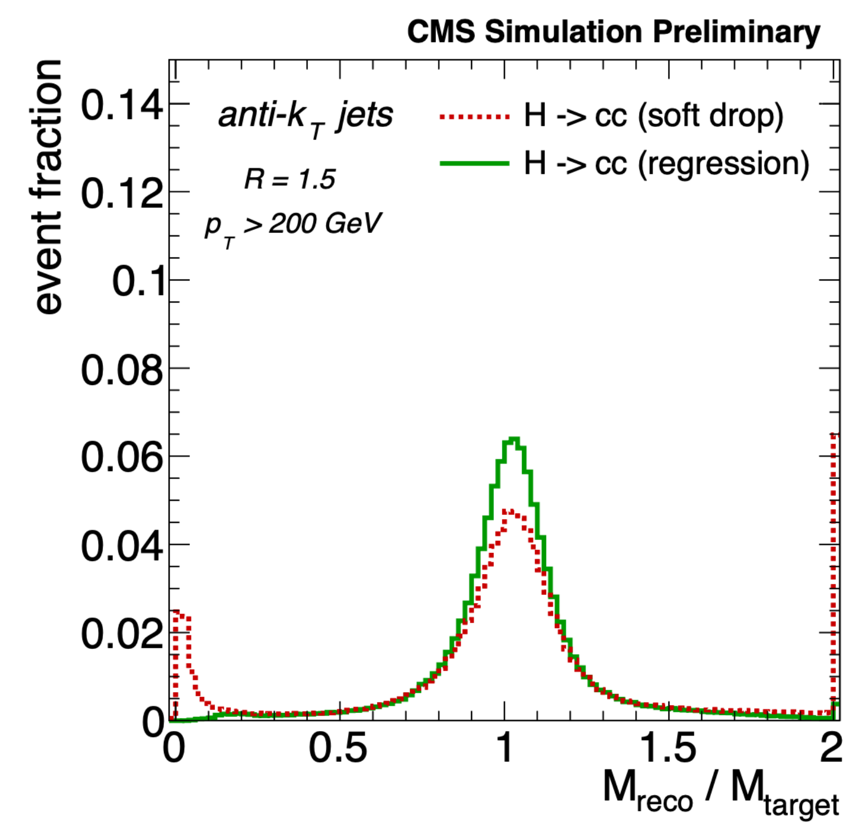
NEW 2022!







- *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

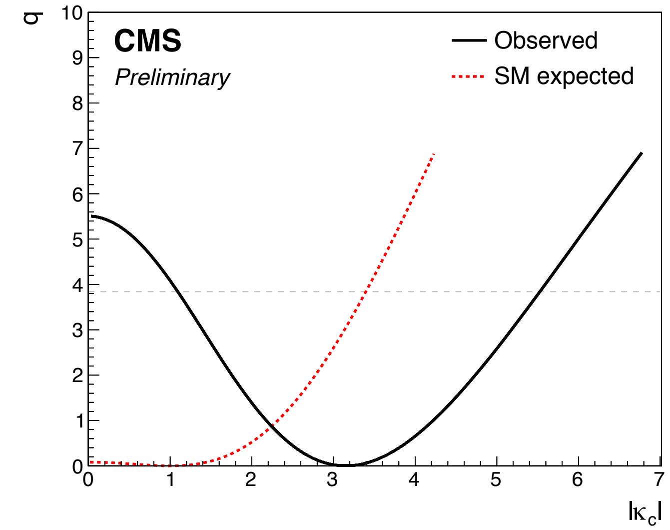
Novel method to calibrate charm jet taggers: arXiv:2111.03027, accepted for publication in J. Instrum.

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

Putting it all together: H→cc results

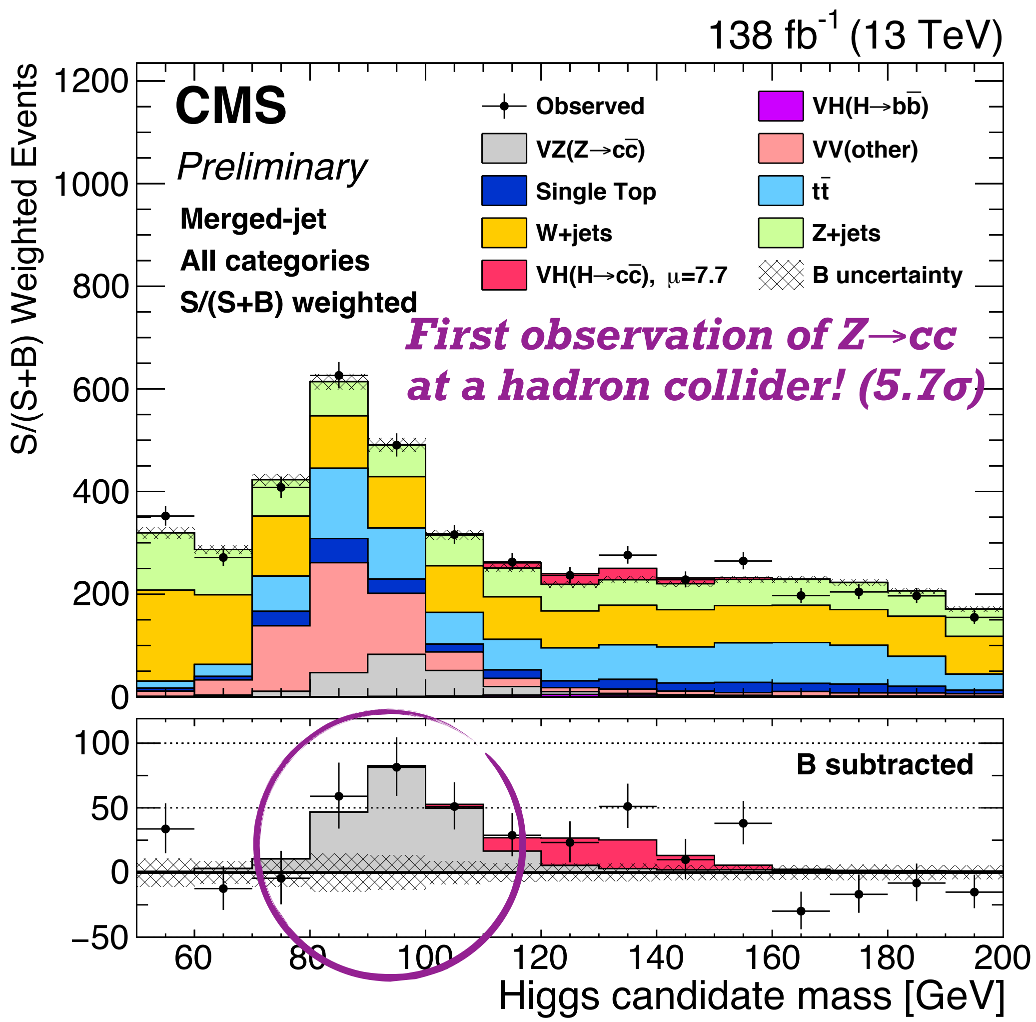
- Measurements of [W/Z]Z→cc signal demonstrates reliability of methods in data.
- Contraints on y_c comparable to what had previously been expected at end of HL-LHC!

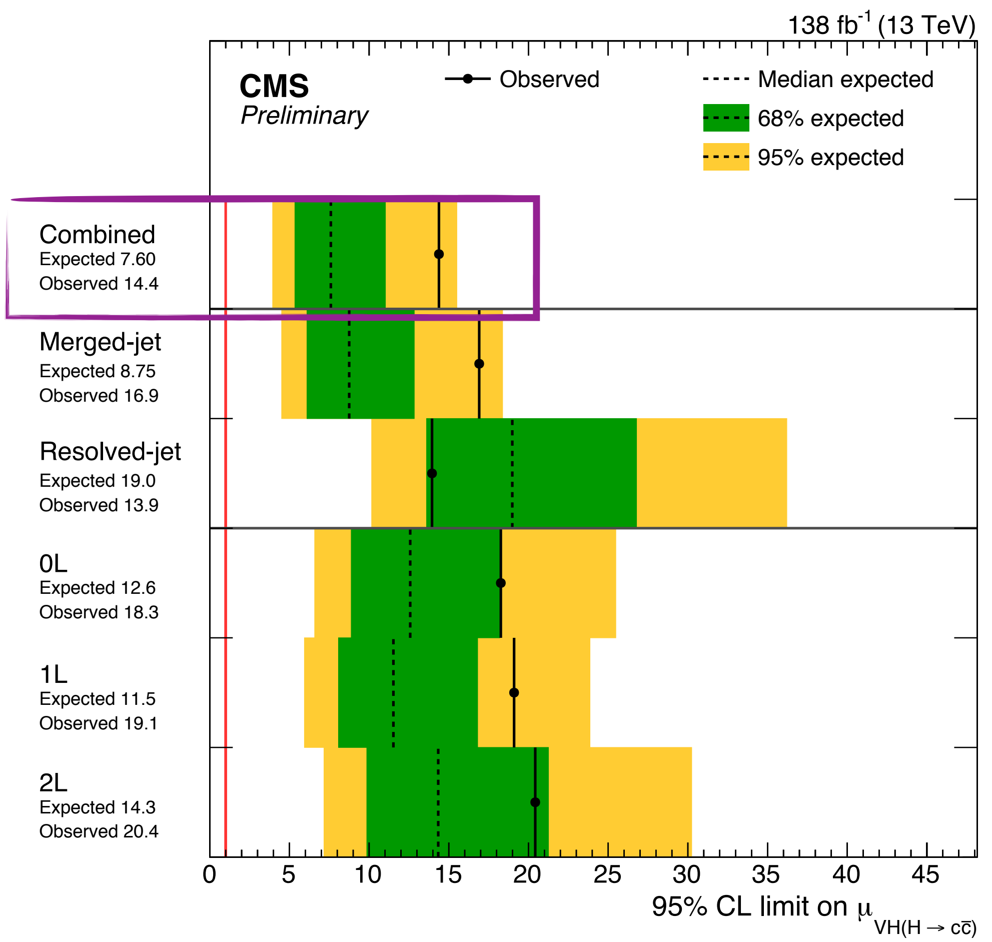
NEW 2022!



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

BR(H→cc) < 14 (8) x SM @95% C.L.

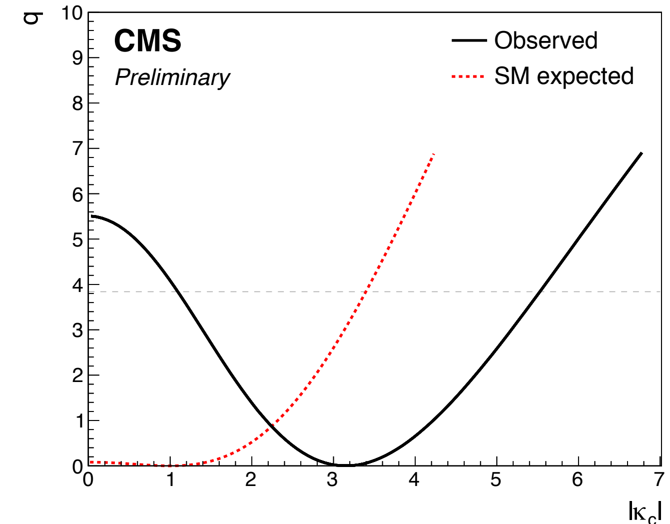




Putting it all together: H→cc results

NEW 2022!

- 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!
- Updated projections for HL-LHC:
    - *With these results, a huge step forward towards measuring H→cc at the HL-LHC!*



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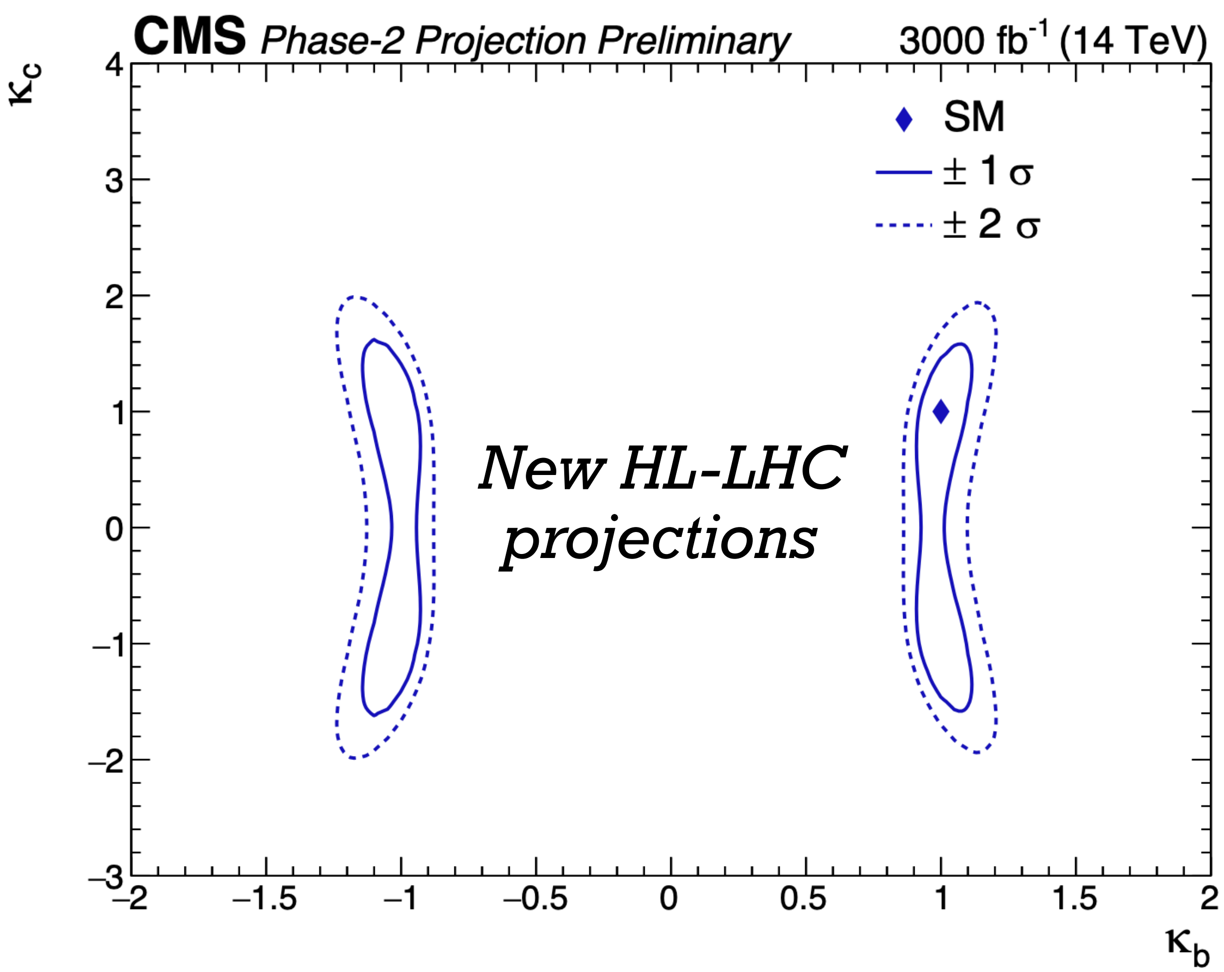
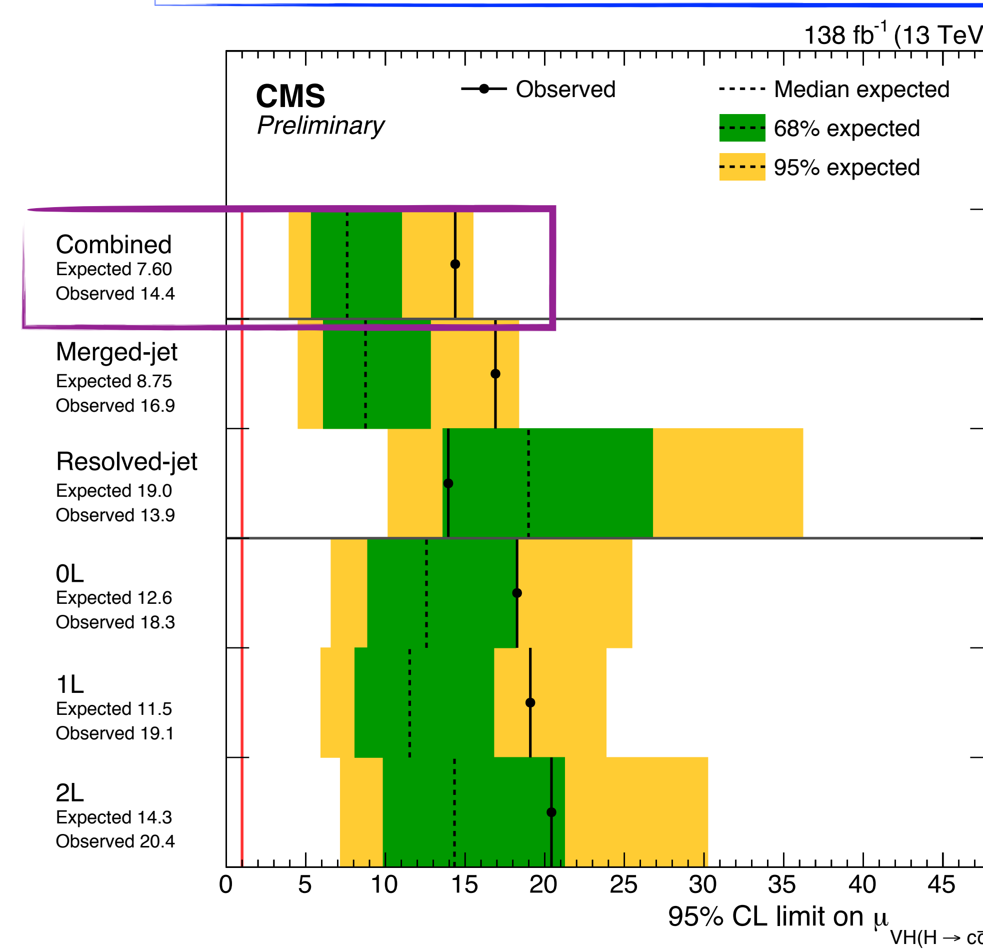




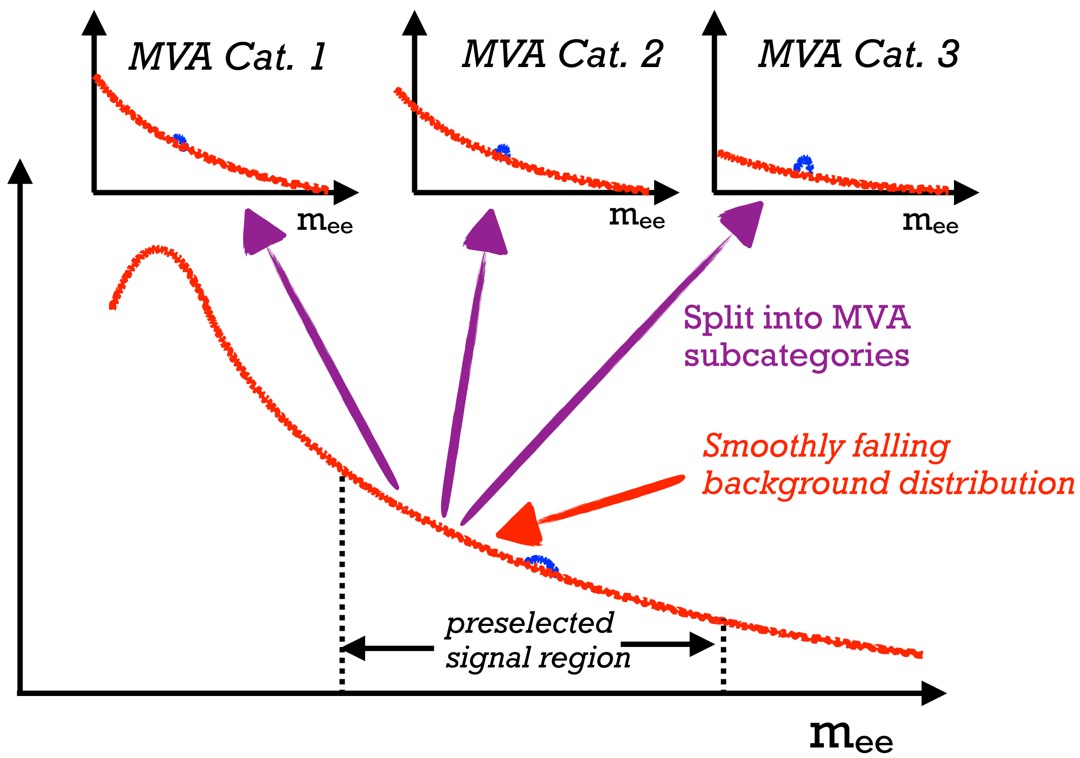
H→ee

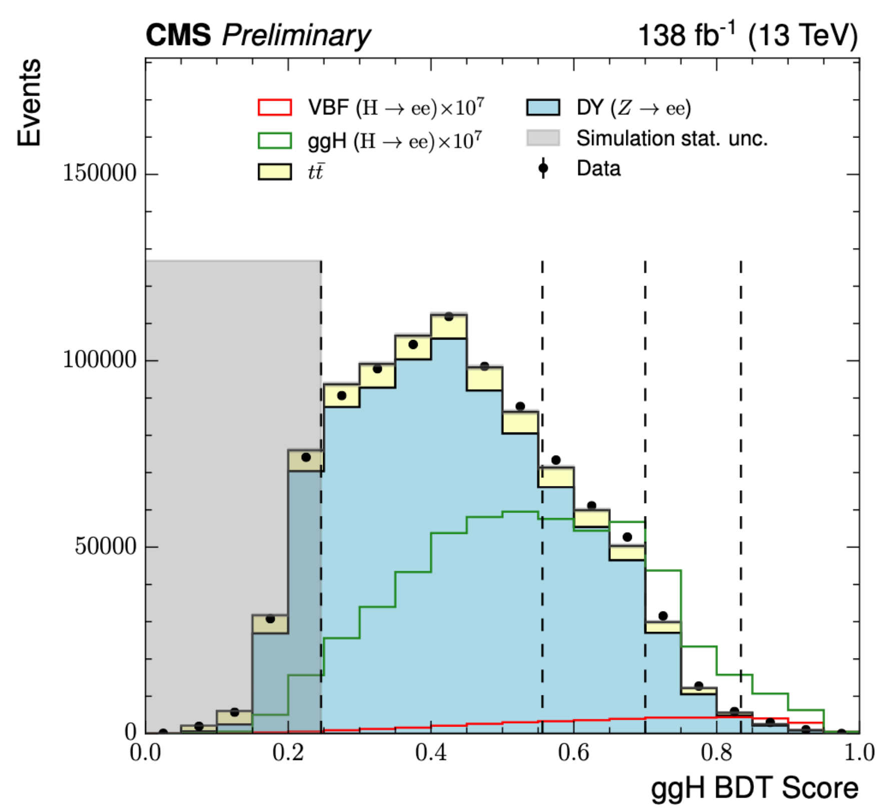
NEW FOR MORIOND!

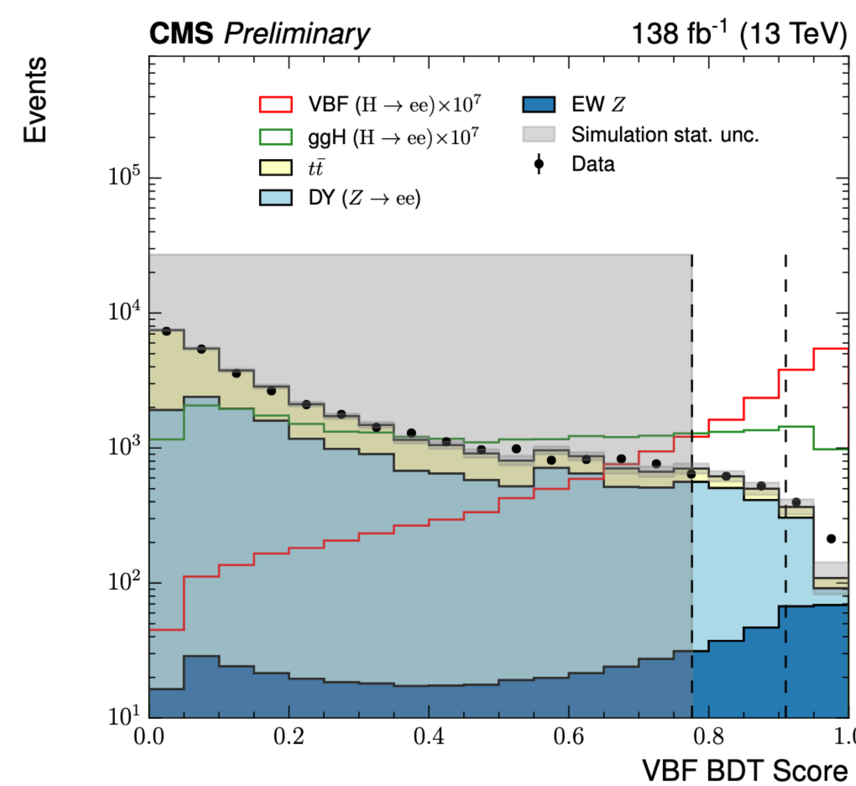
- H→ee only direct probe of Higgs-electron Yukawa.
  - SM prediction for BR(H→ee) ~ 5 * 10^{-9}.
  - ⇒ H→ee signal observation at the LHC would be a clear sign of BSM physics in Higgs sector.

- 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.





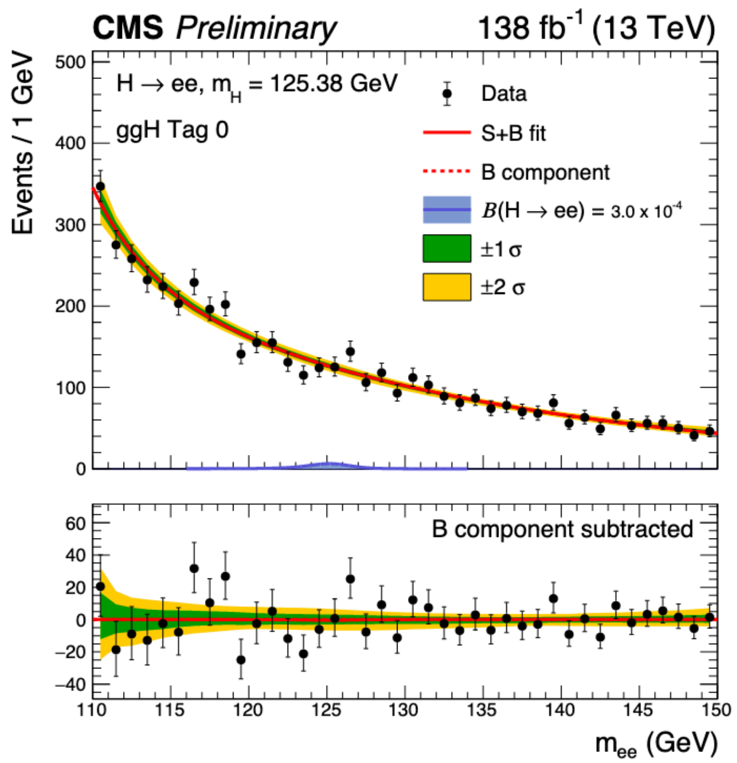


H→ee: results

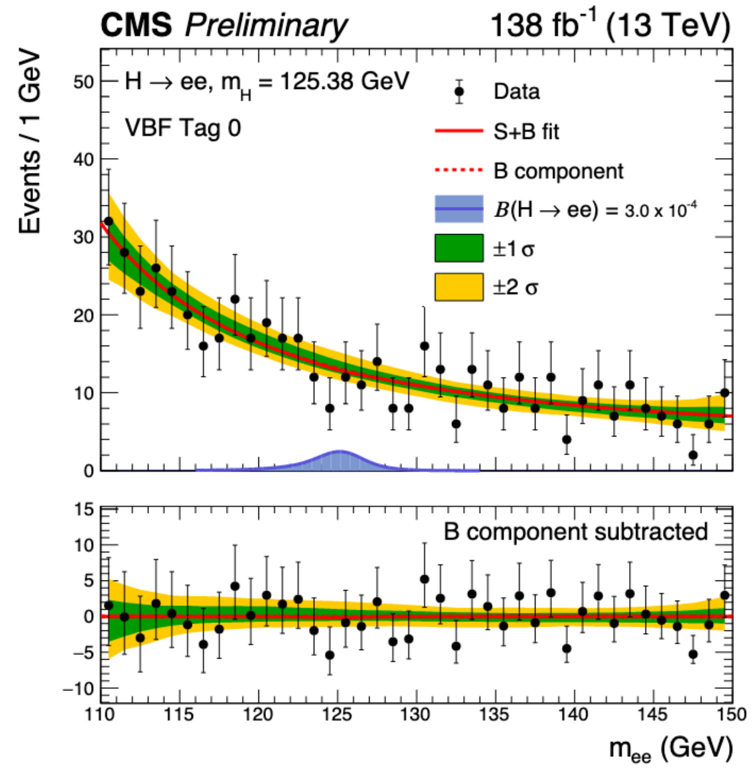
NEW FOR MORIOND!

- 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.

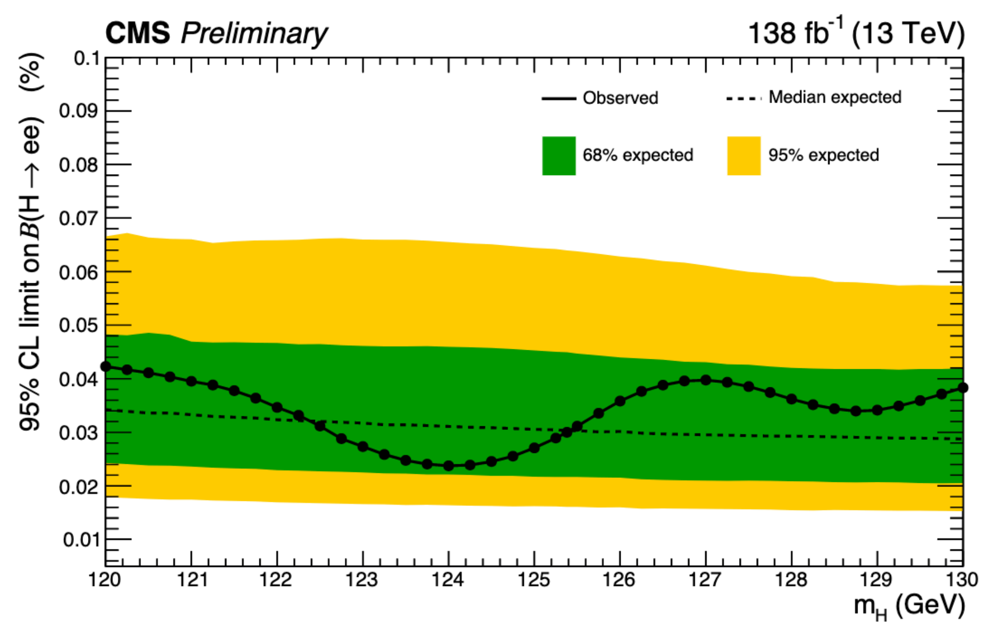
Most sensitive ggH category



Most sensitive VBF category



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

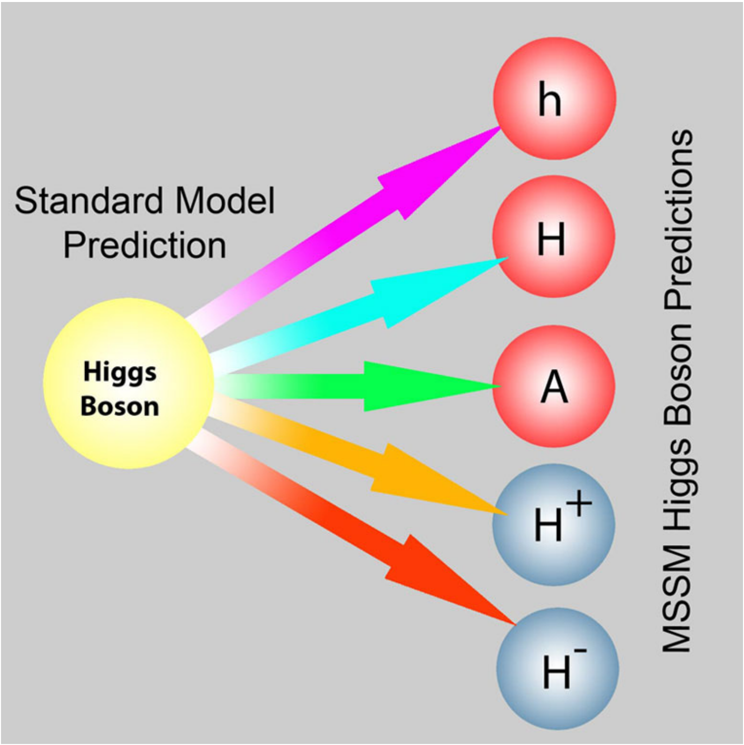


Higgs sector and BSM

- *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. MSSM).

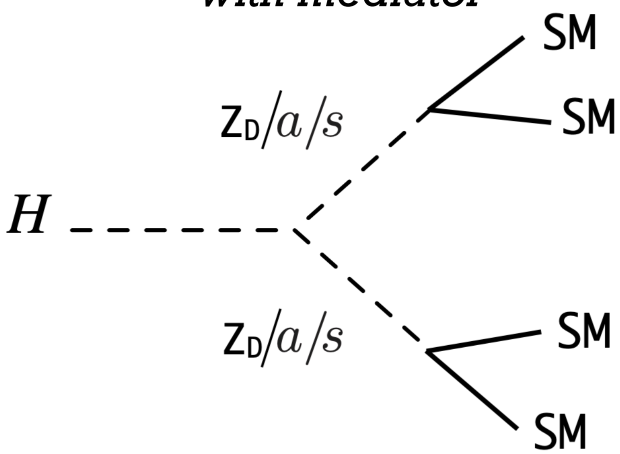
- Very large and diverse search program pursued by both ATLAS and CMS.

Additional Higgs bosons (MSSM)

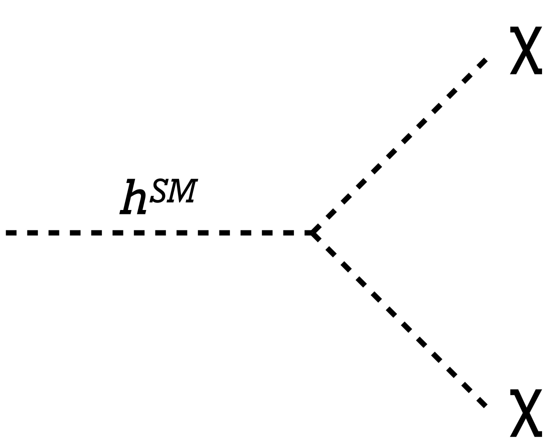


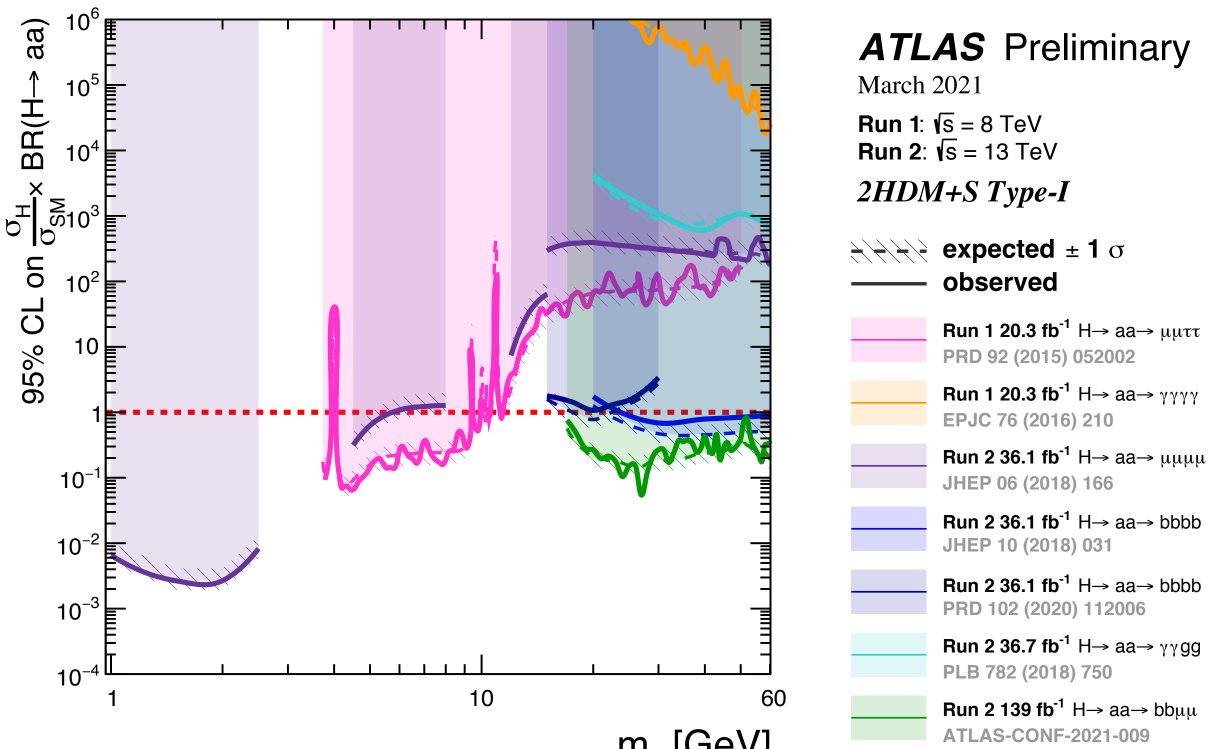
Standard Model | mediator? | Hidden sectors

Higgs interaction with mediator



Higgs portal



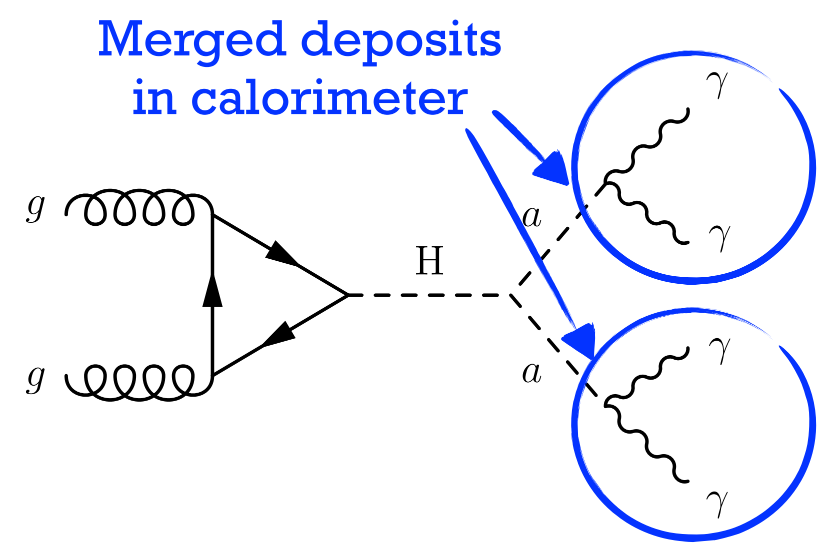


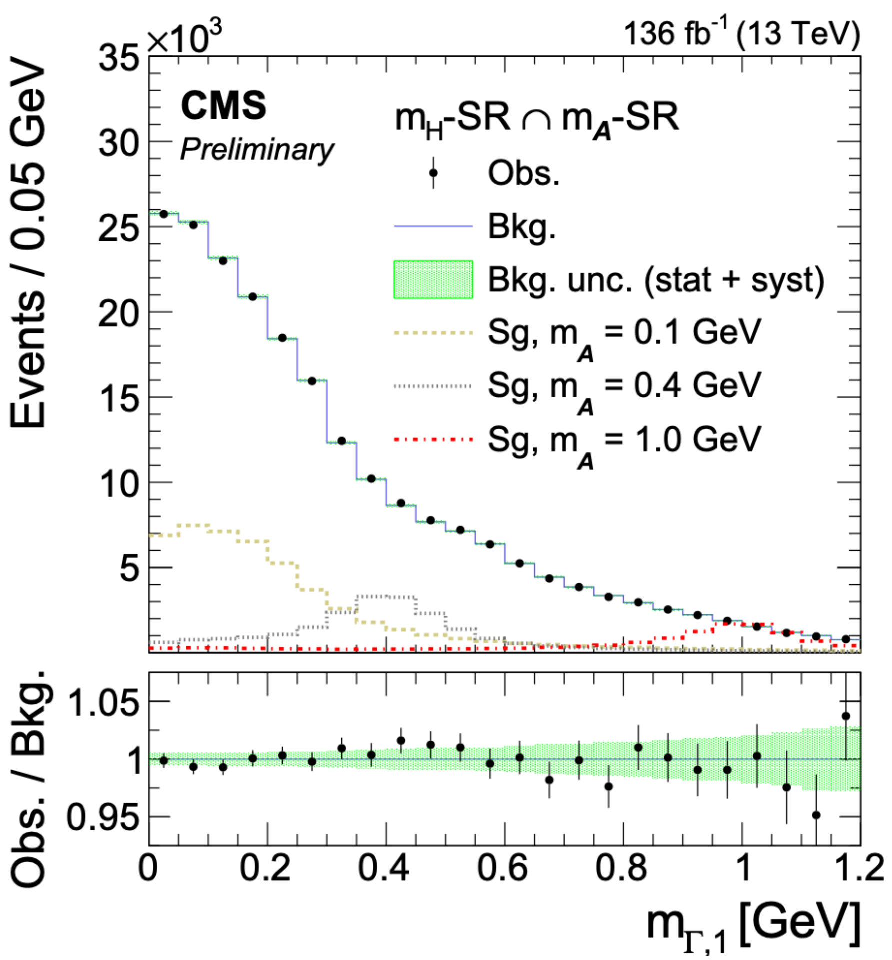
ATL-PHYS-PUB-2021-008

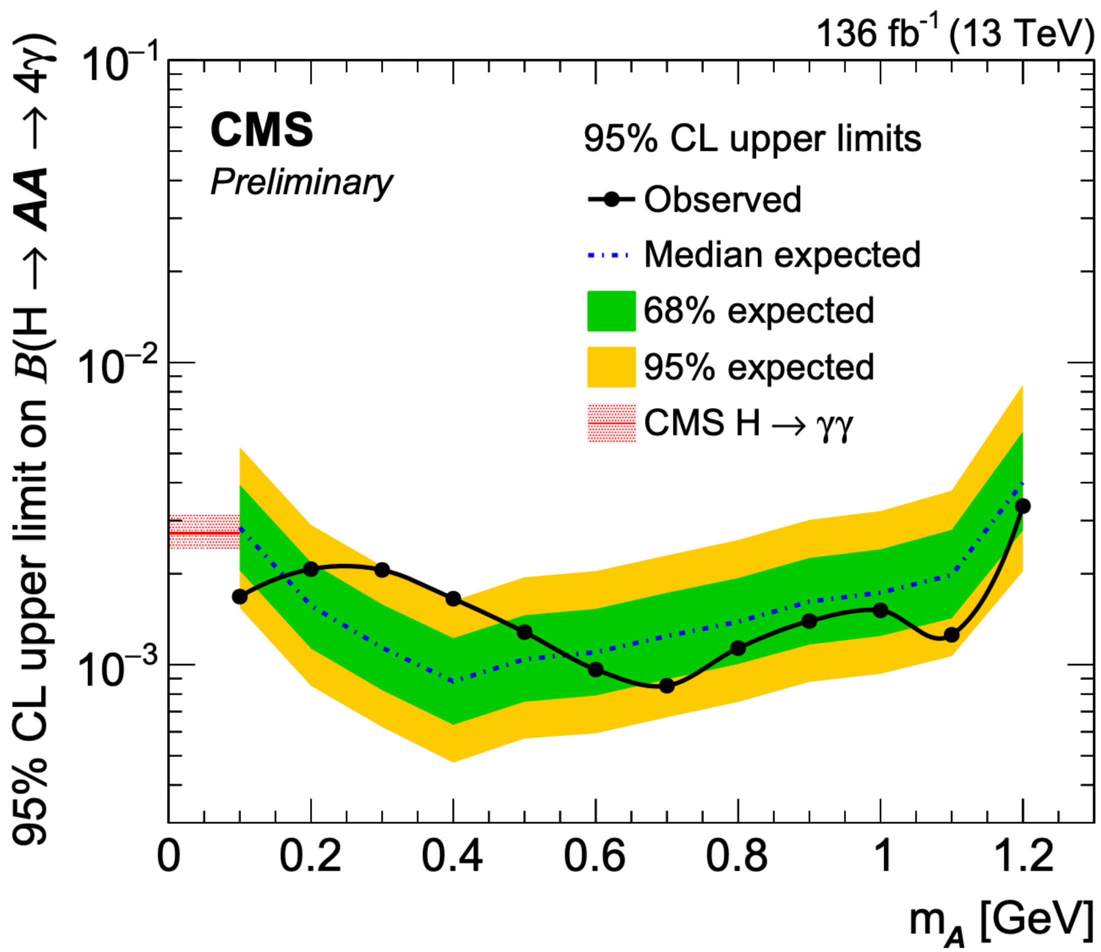
Boosted h→aa→4γ

NEW FOR MORIOND!

- 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.





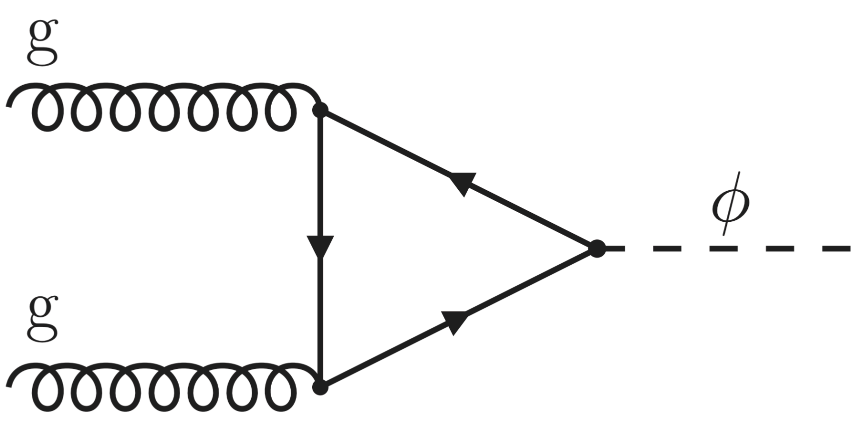


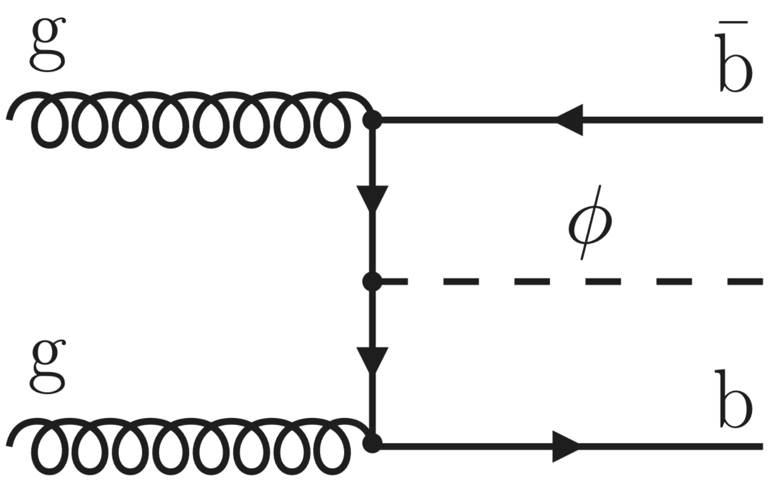
Search for $\phi \rightarrow \tau\tau$

NEW FOR MORIOND!

- The $\tau\tau$ 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 $\mu\mu$ searches.

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

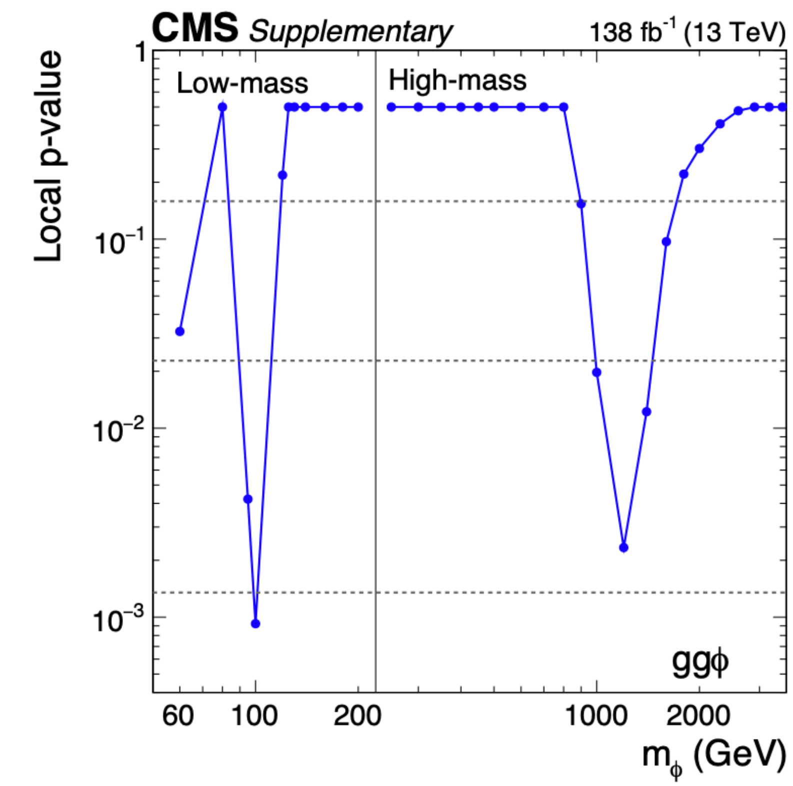


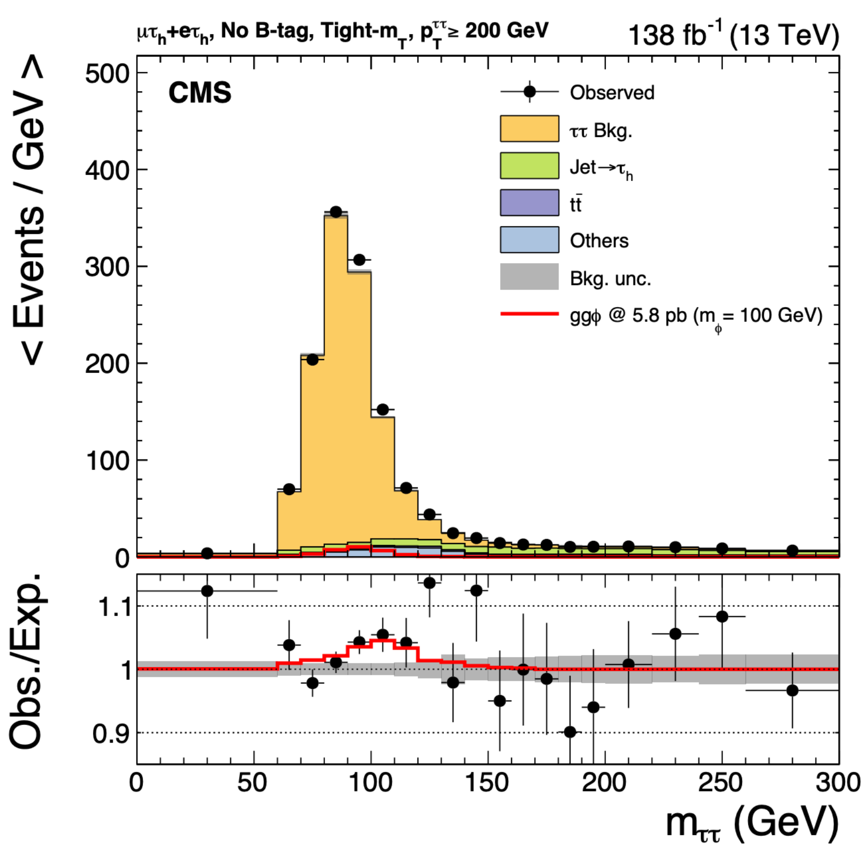


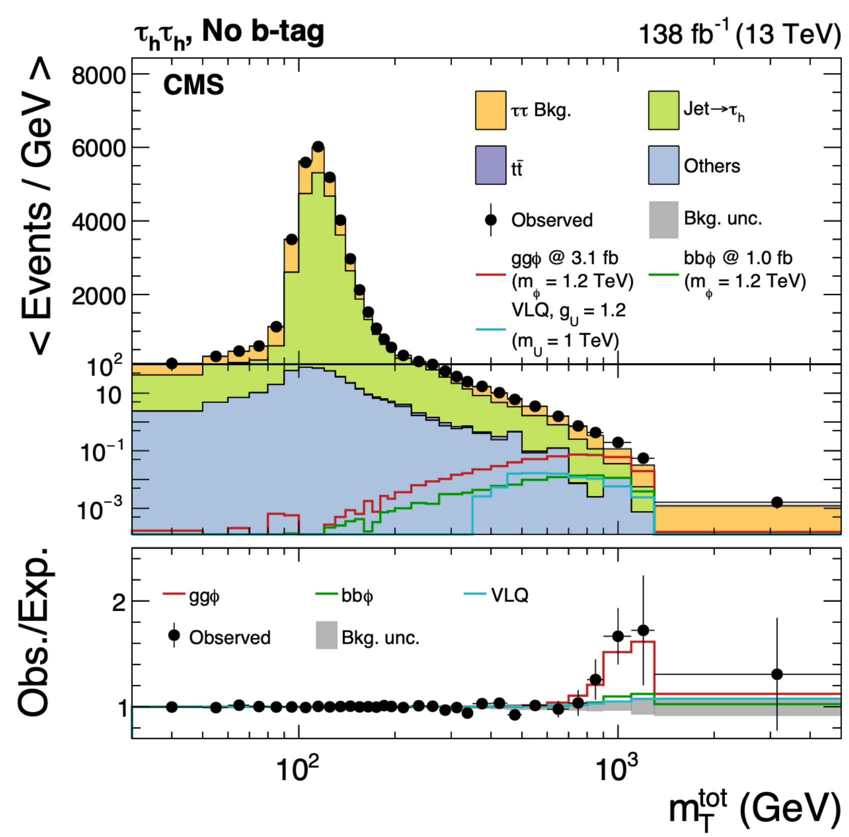
Search for ϕ→ ττ: results

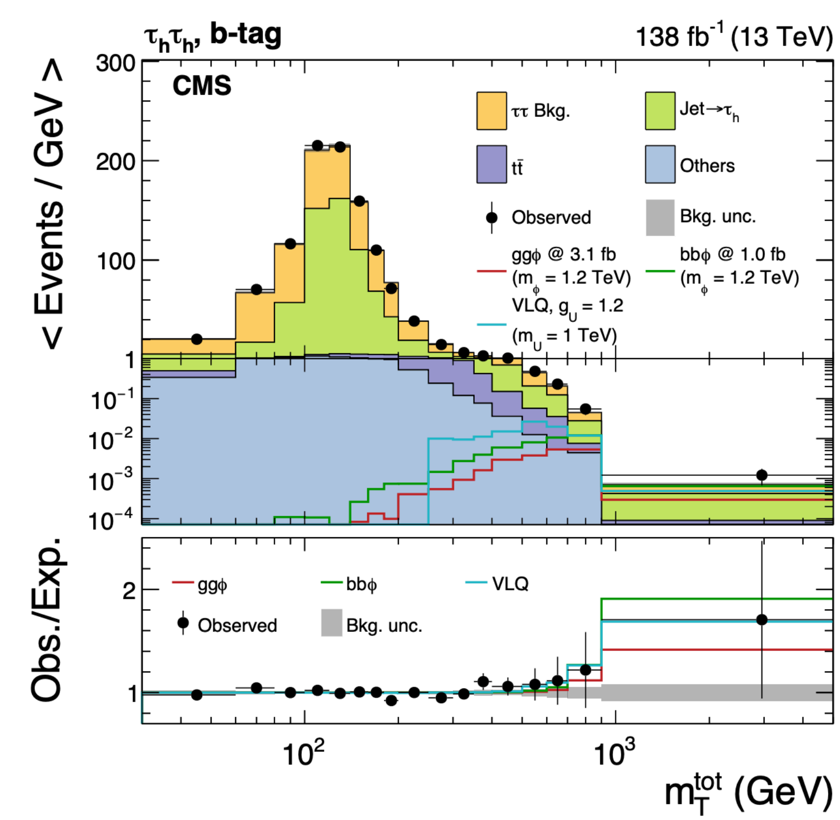
NEW FOR MORIOND!

- 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.





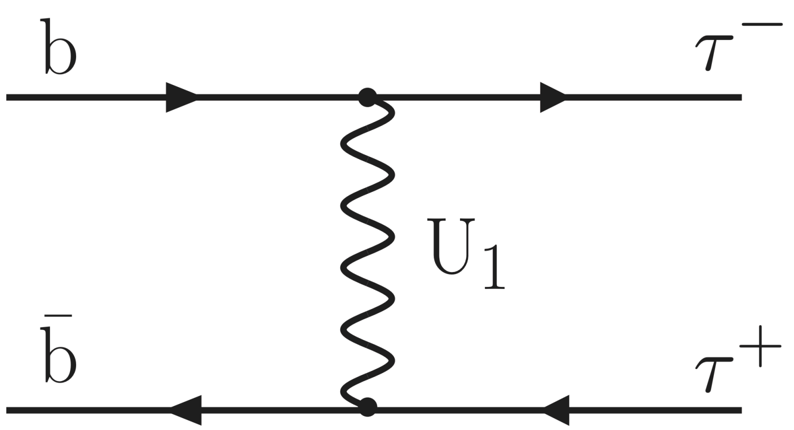


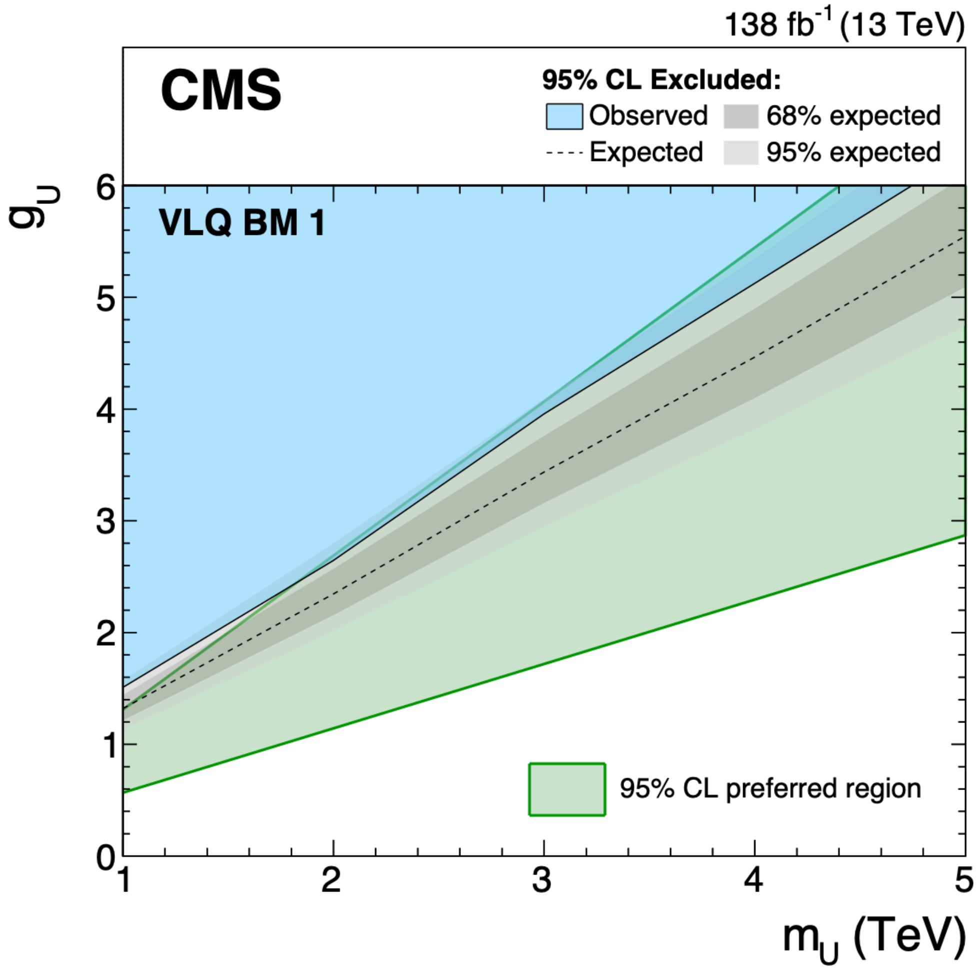


Extending the physics reach to VLQ

NEW FOR MORIOND!

- *New for this analysis*: search for non-resonant signature of t-channel leptoquark exchange.
    - Presence of VLQ would lead to enhancement in non-resonant production rate at high ττ invariant mass.
- Expected limits well within preferred region for B physics anomalies.
    - Slight excess observed in data, so constraints are weaker than expected.
- Something to keep in mind: high-mass (~1.2 TeV) excess driven by 0 b-jet category, which is not favored by VLQ model.
    - VLQ signal contribution primarily expected in region requiring b-tagged jets.

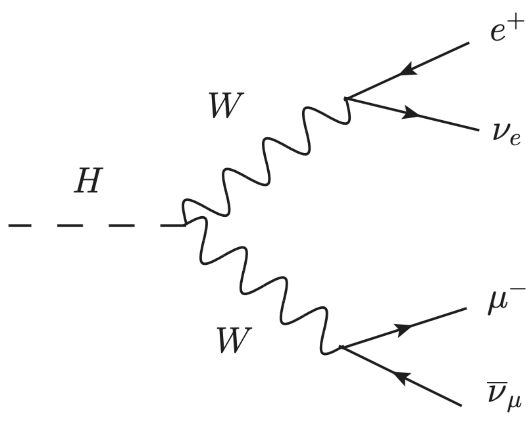




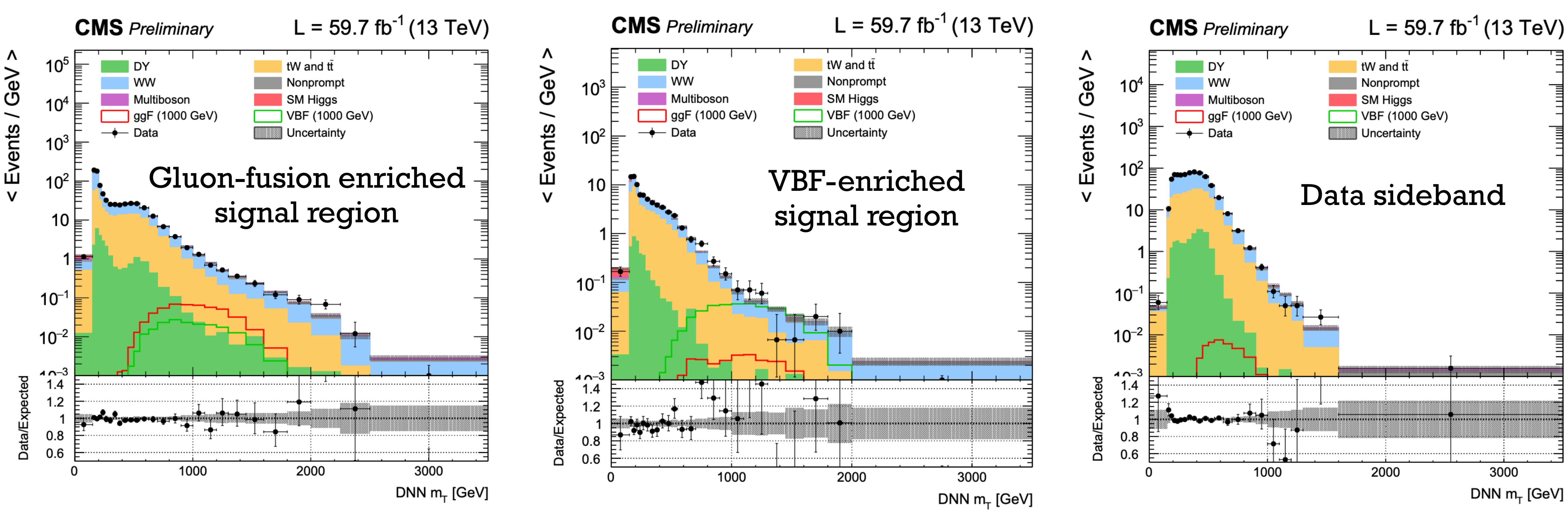
H→WW high mass search

NEW FOR MORIOND!

- 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)



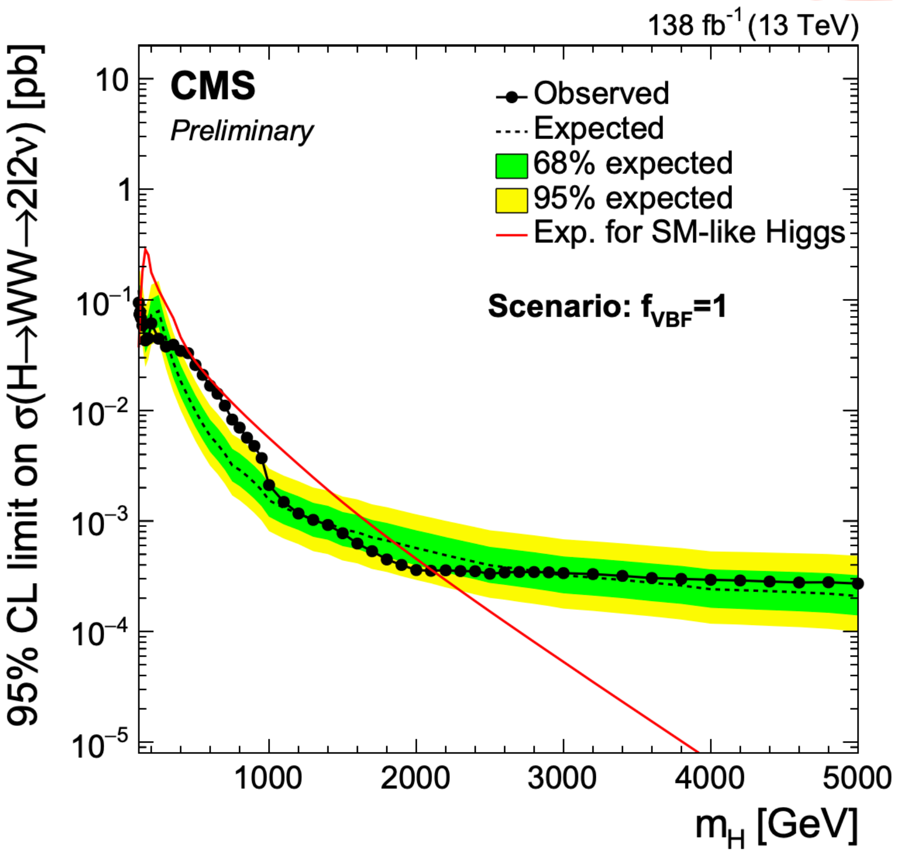
Search region:
115 GeV < m_ϕ < 5 TeV

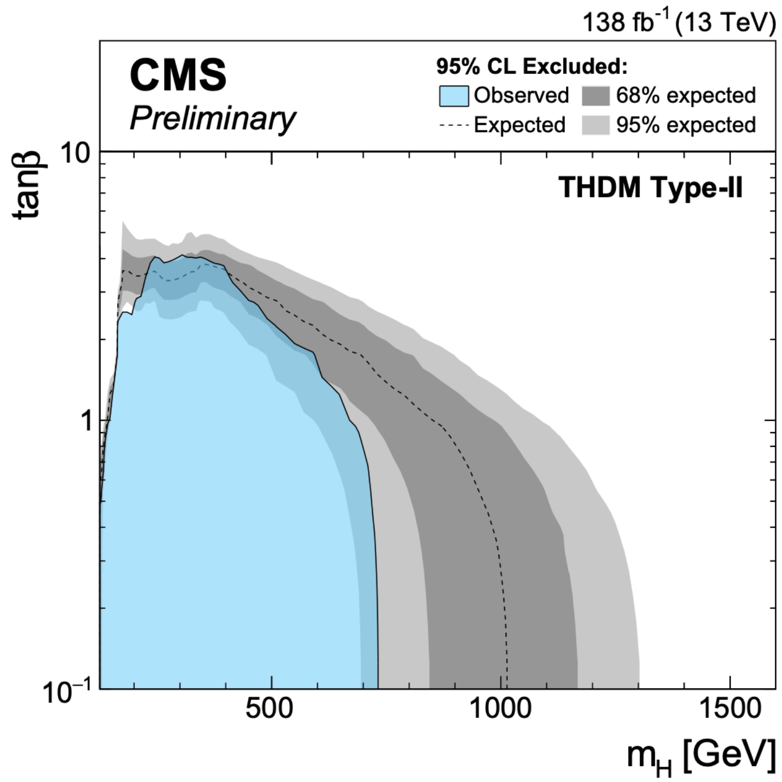


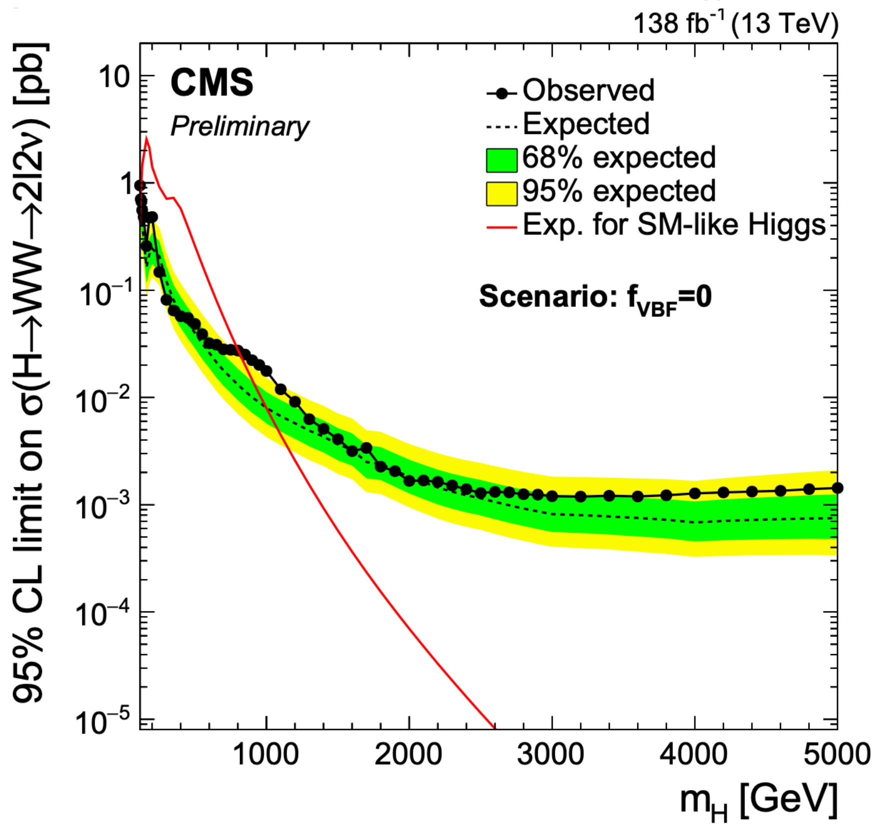
NEW FOR MORIOND!

- 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 categories.
  - Something to keep an eye on!



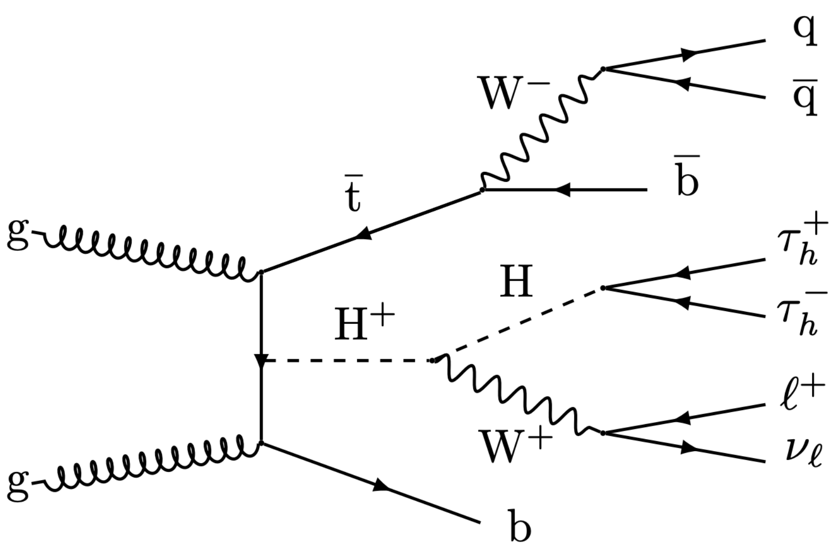




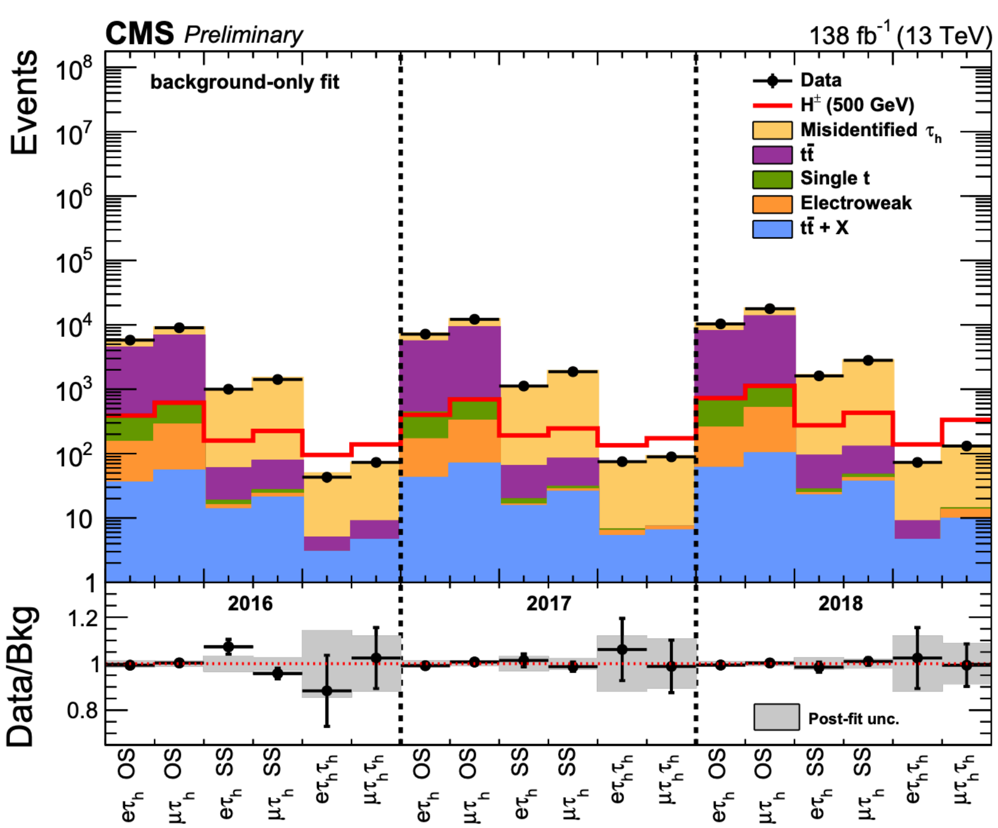
Search for $H^{\pm} \to HW^{\pm}$, $H \to \tau\tau$

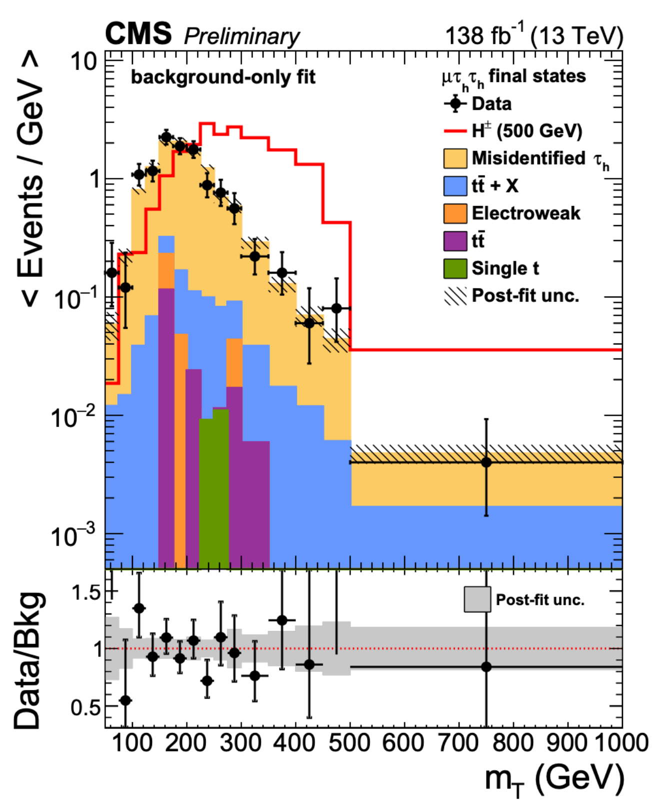
NEW FOR MORIOND!

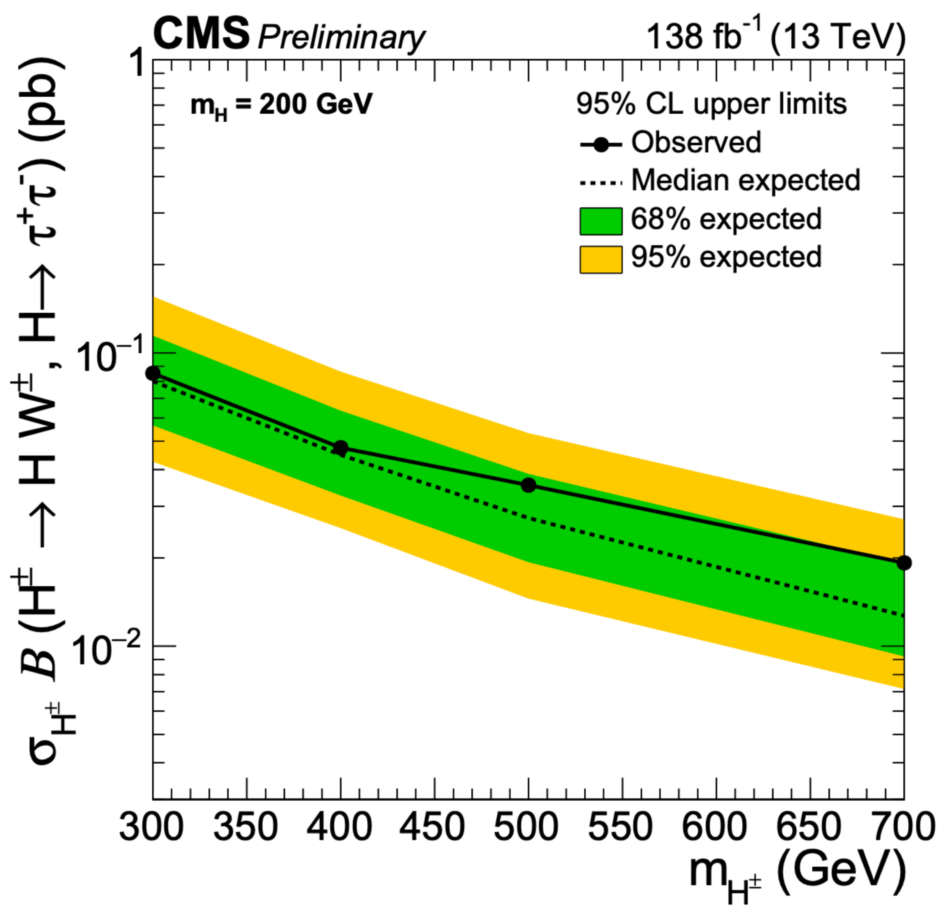
- Combination of $e\tau_h$, $\mu\tau_h$, $e\tau_h\tau_h$, and $\mu\tau_h\tau_h$ final states
  - 43% of total branching fraction.
  - In $e\tau_h$ and $\mu\tau_h$ channels, perform fit to output of MVA classifier.
  - In $e\tau_h\tau_h$ and $\mu\tau_h\tau_h$ channels, fit traverse mass of charged H candidate.



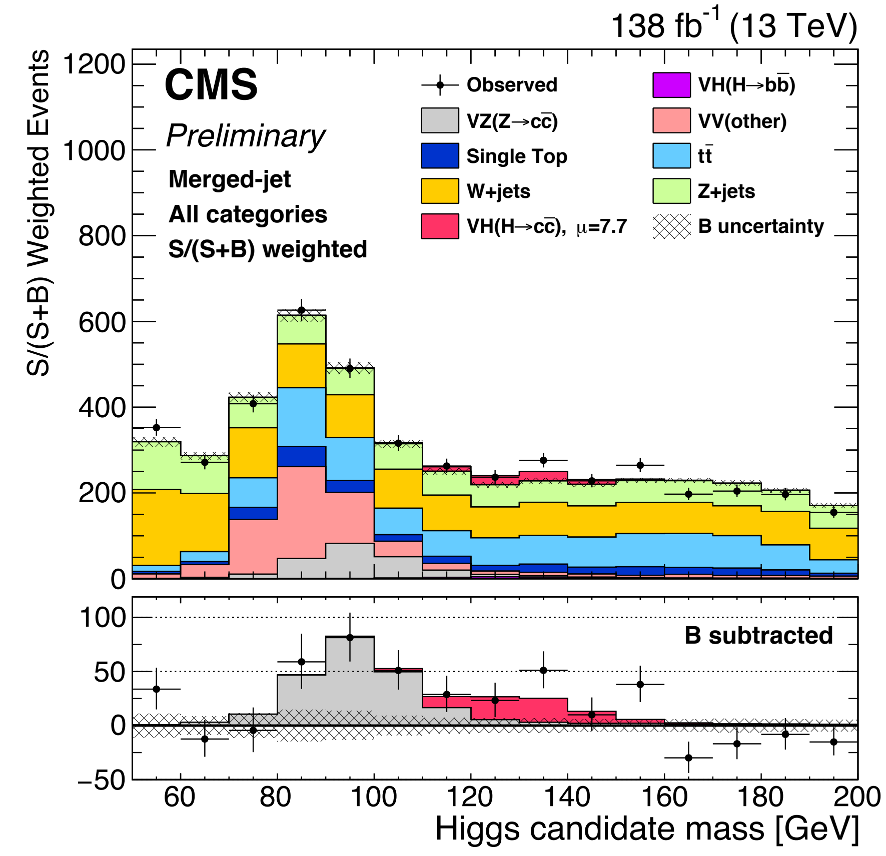
- Hadronic decays of top quark identified with mass-decorrelated neural network tagger.
- No significant excess observed $\Rightarrow$ limits set on σ*BR for $H^{\pm} \to HW^{\pm}$, $H \to \tau\tau$ from 20 fb to 80 fb.

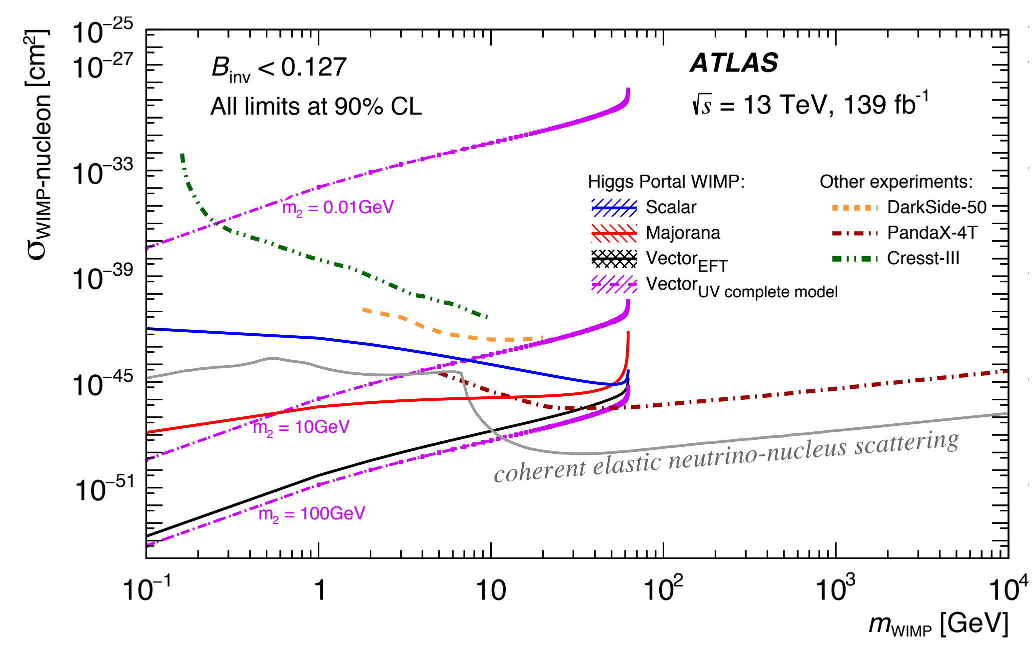






- We are just beginning to explore many aspects of the H sector:
  - Yukawa interactions beyond the third generation, Higgs self-interaction, Higgs as a mediator to dark matter, additional H bosons up to TeV scale…
- Enormous progress made in the past year:
  - Huge step forward in path to potentially measuring H→cc at the HL-LHC.
  - Multiple novel reconstruction methods and analysis improvements using ML.
- A bright future ahead for Run-3 and beyond!





Additional Material

Results not shown

- Unfortunately there were quite a few additional results, new since Moriond 2021, that could not be shown today in either my talk or Reina's this morning.

- Priority was given to the newest results.

H Rare Decays

- $H \to Z\gamma$: CMS-PAS-HIG-19-014 — October 2021

H Exotic Decays

- Exotic $h \to XX \to 4l$ decays:
  - ATLAS: arXiv:2110.13673, accepted by JHEP — October 2021
  - CMS: arXiv:2111.01299, accepted by EPJC — November 2021

Extended H sector

Spring/Summer 2021

- $H \to bb + p_T^{miss}$: JHEP 01 (2022) 063 (ATLAS)
- $H \to \gamma\gamma + p_T^{miss}$: JHEP 10 (2021) 13 (ATLAS)
- $t \to H^{\pm}b$, $H^{\pm} \to cb$: ATLAS-CONF-2021-037
- $H^{\pm} \to aW^{\pm}, a \to \mu\mu$: ATLAS-CONF-2021-047
- VBF $H^{\pm} \to VV$: Eur. Phys. J. C 81 (2021) 723 (CMS)

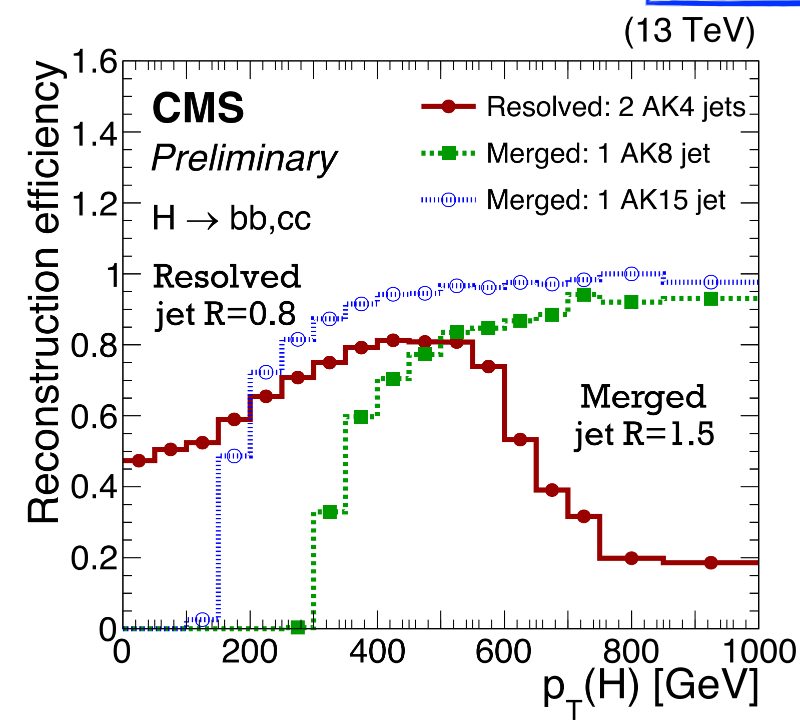
Charm jet tagging

NEW 2022!

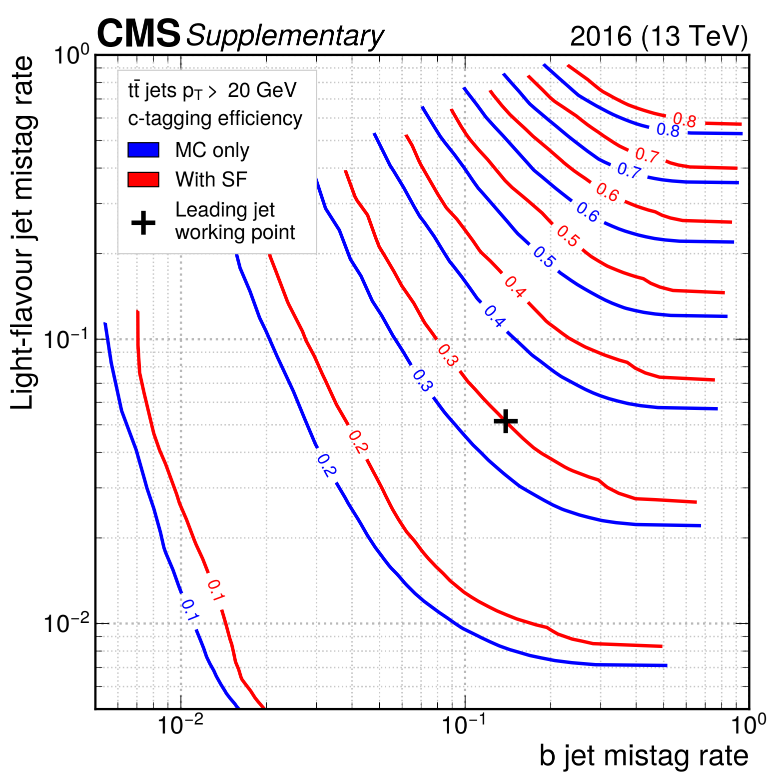
- Jets originating from charm quarks have properties intermediate between udsg and b jets ⇒ difficult to isolate.

- 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.

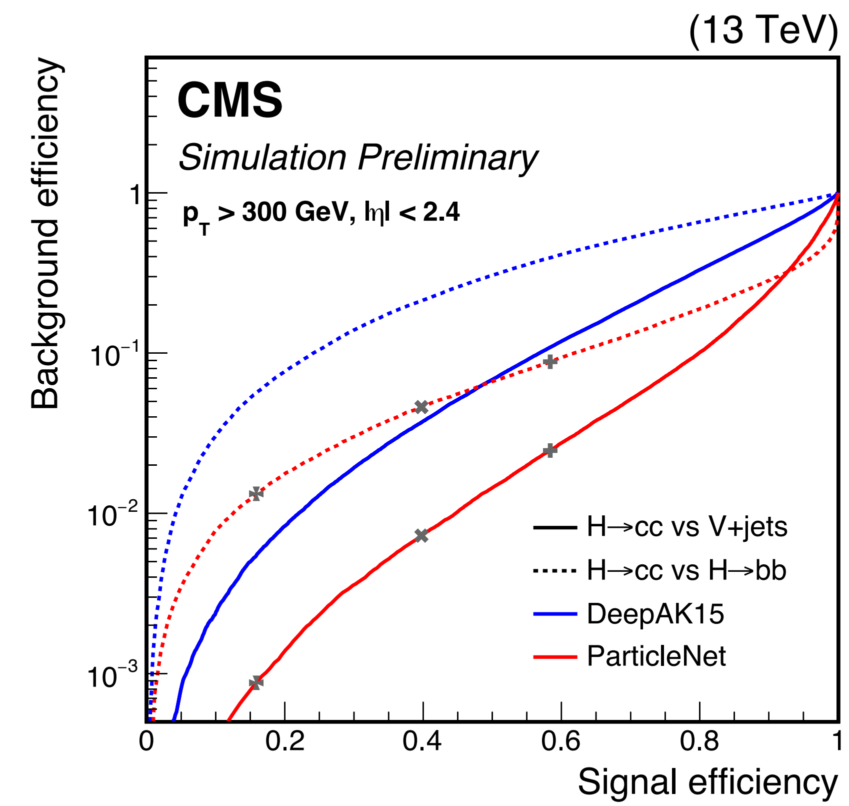
- Dedicated calibrations performed with data.



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



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

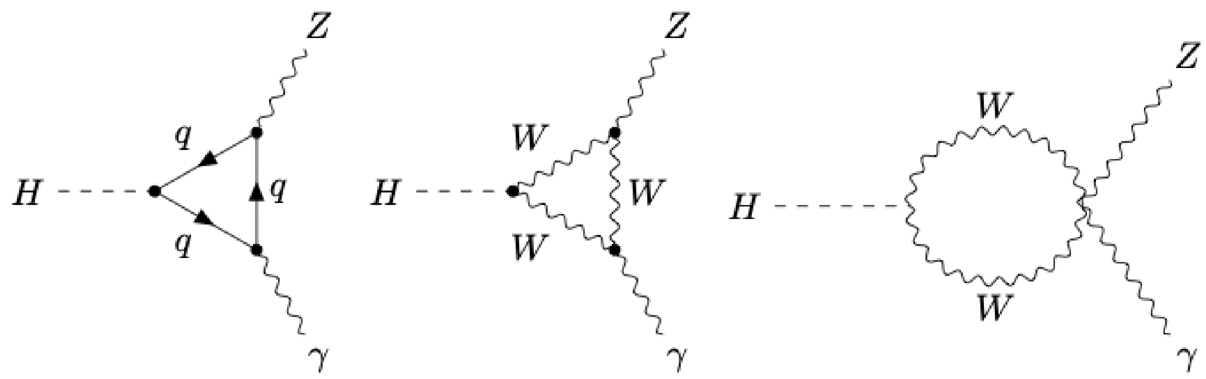


arXiv:2111.03027, accepted for publication in J. Instrum.

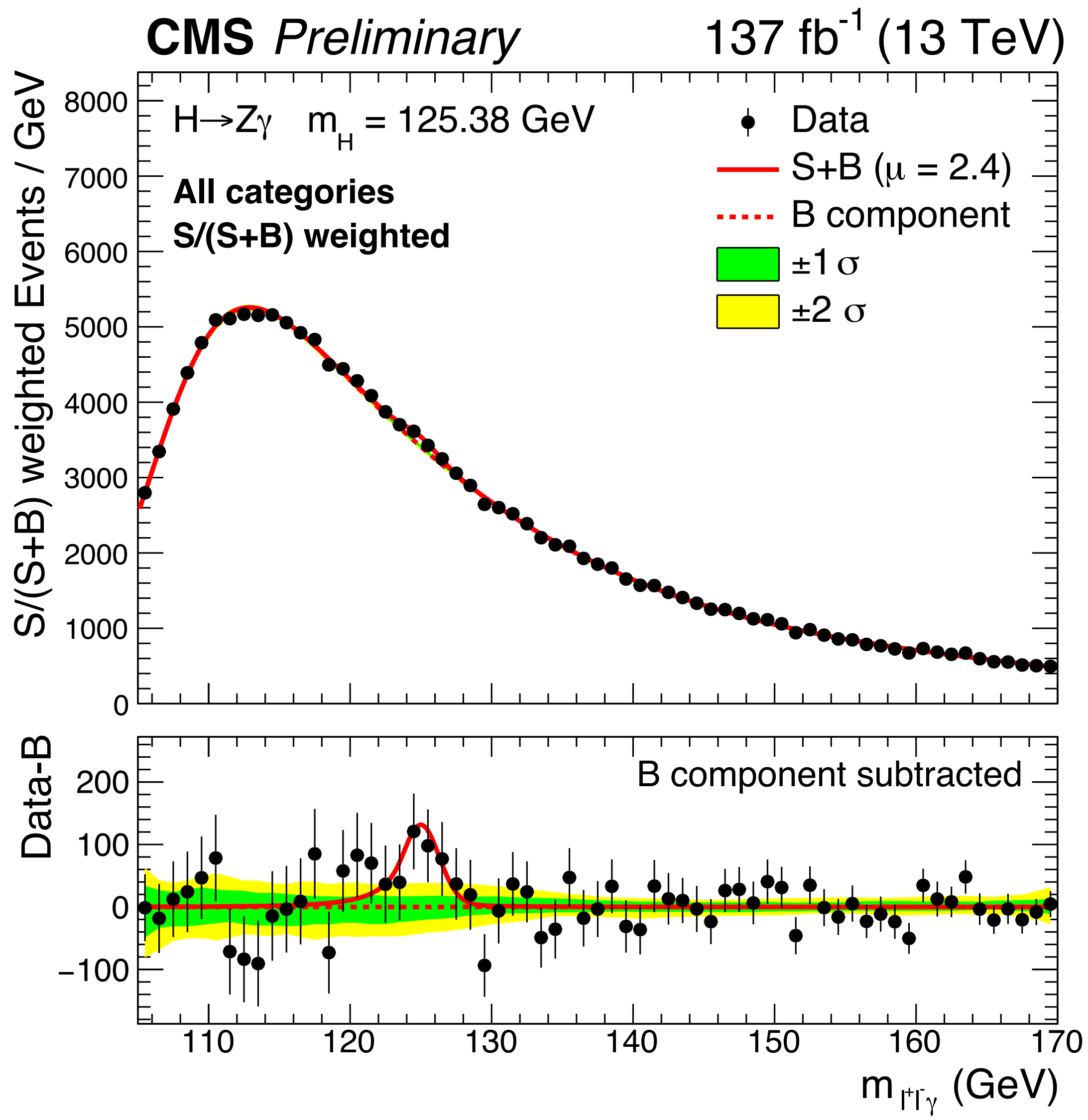
*including the first application of graph neural networks to jet tagging: Phys. Rev. D 101, 056019 (2020)

H→Zγ

- SM B(H→Zγ) = $1.6*10^{-3}$
- Ratio between H→Zγ and H→γγ potentially sensitive to BSM.
- Select Z→μμ and Z→ee events with additional photon and use MVA categorize events.
- Parametric fit to $m_{ll\gamma}$ to extract signal.
- Statistically limited measurement ⇒ Run-3 data critical to pinpoint this potential signal.



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

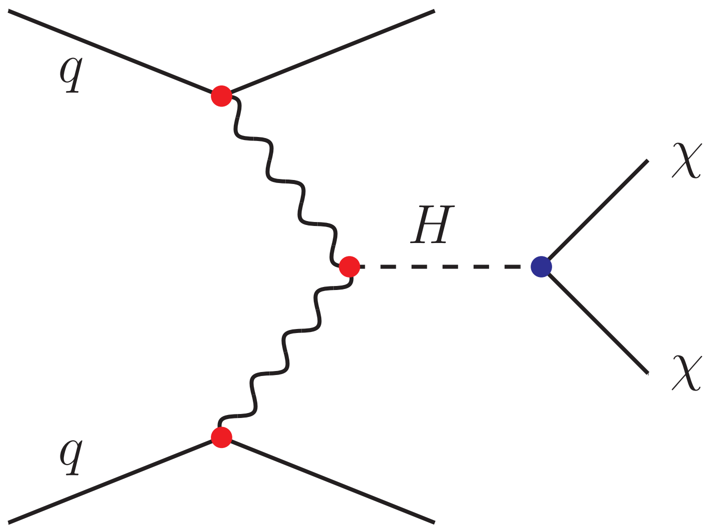


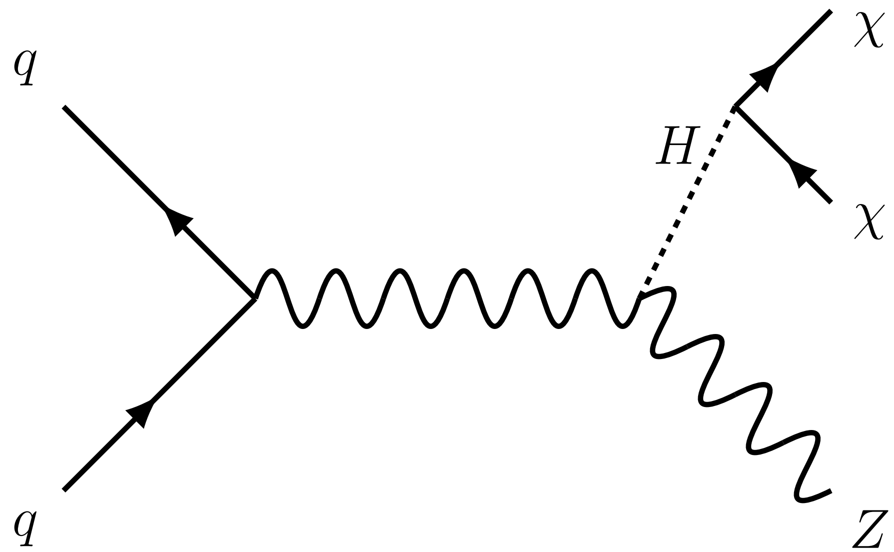
ATLAS Run-2 result: 2.2σ (1.1σ) obs. (exp.)

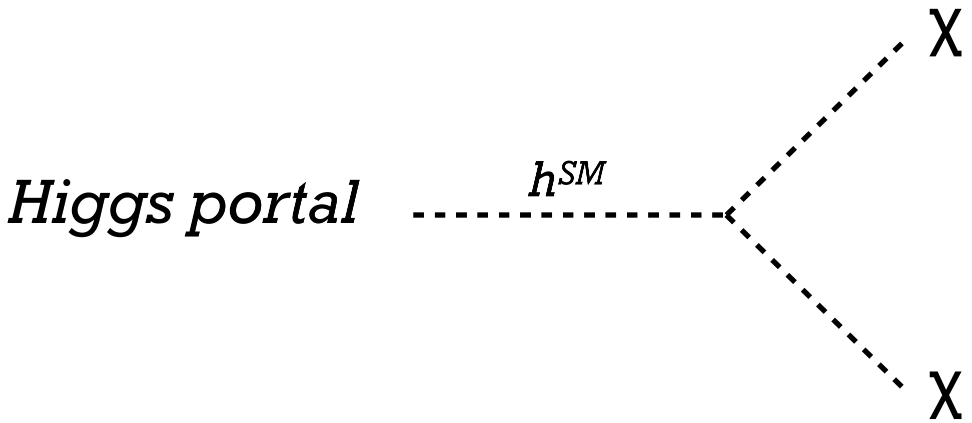
Phys. Lett. B 809 (2020) 135754

H→invisible

- SM prediction for $H \rightarrow ZZ^* \rightarrow 4\nu$ ~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.



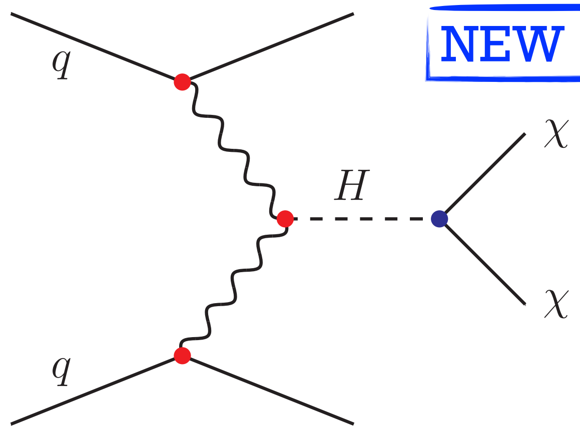


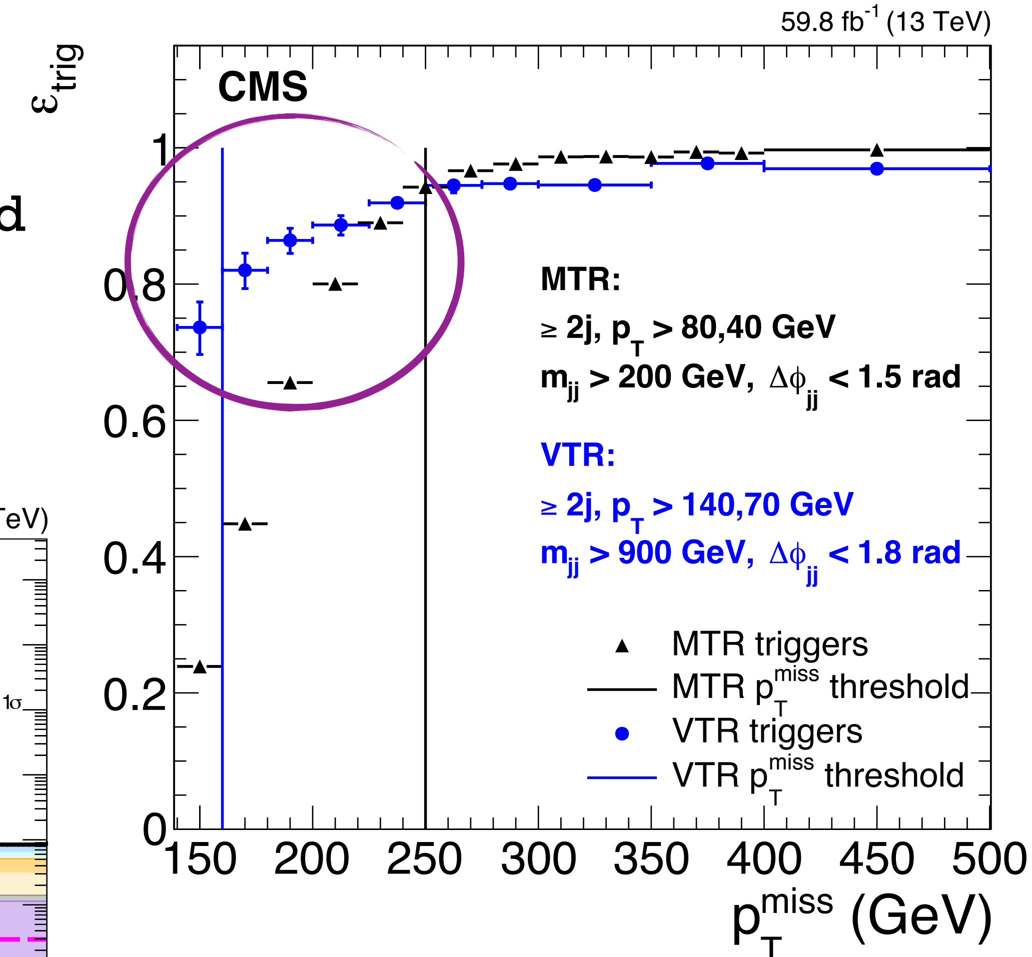


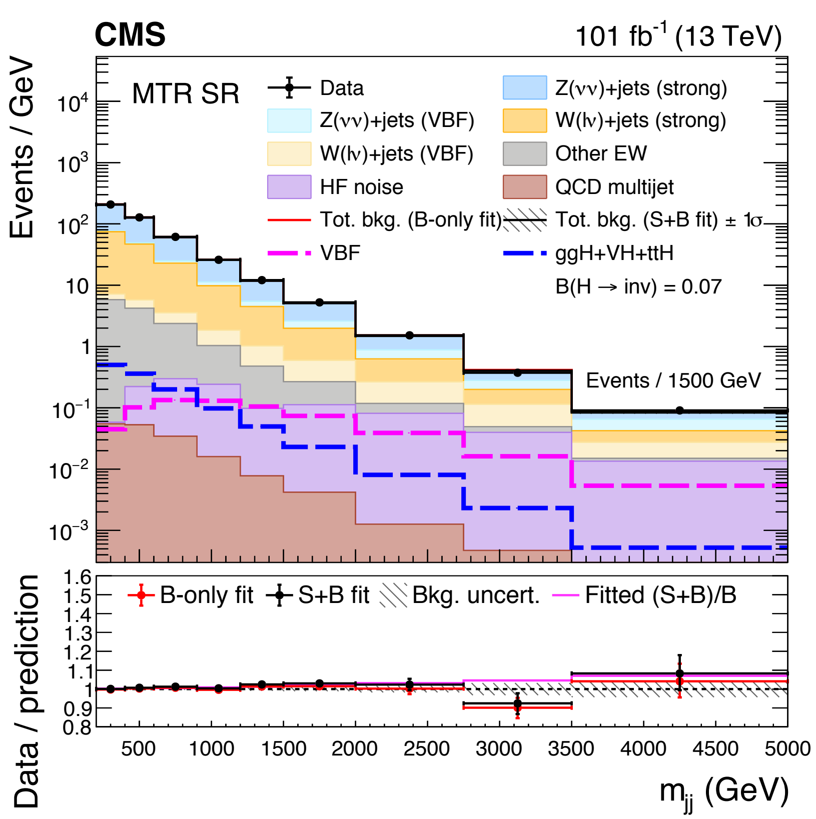
VBF H→invisible

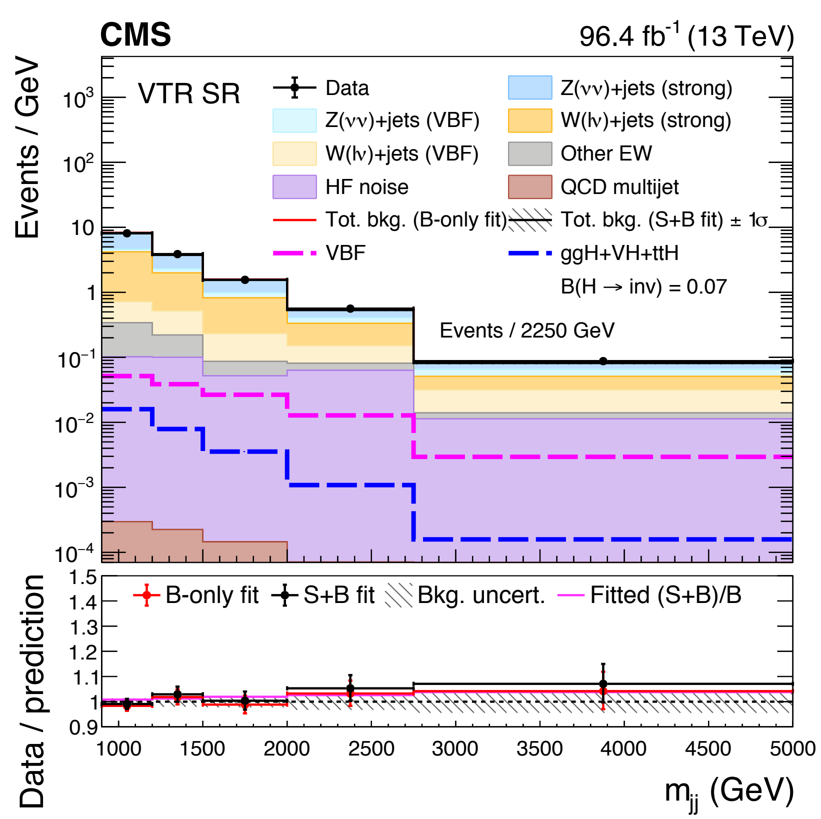
NEW 2022!

- Select region with large p_T^{miss} and two jets, look for excess over background at large m_{jj}.
- New from CMS: dedicated VBF trigger to recover signal efficiency for 160 GeV < p_T^{miss} < 250 GeV.
- Dominant background from V+jets (strong and EW production).
  - Extrapolate background from 1- and 2-lepton control sideband data to high-p_T^{miss}, high-m_{jj} signal region.







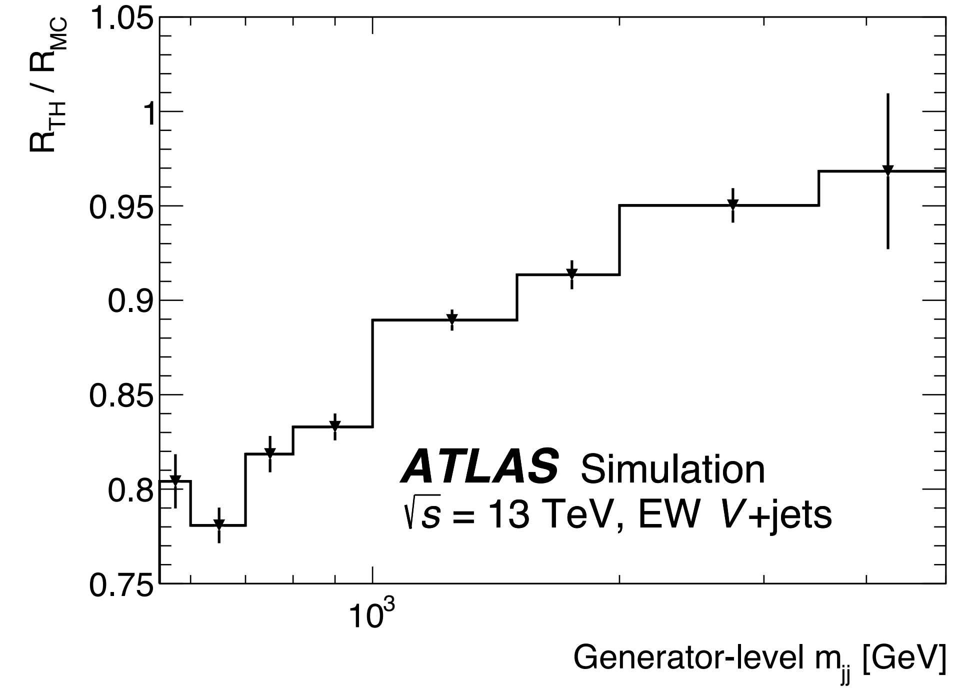


B_{inv} < 0.18 (0.10) @95% CL

Honing in on H→invisible

NEW 2022!

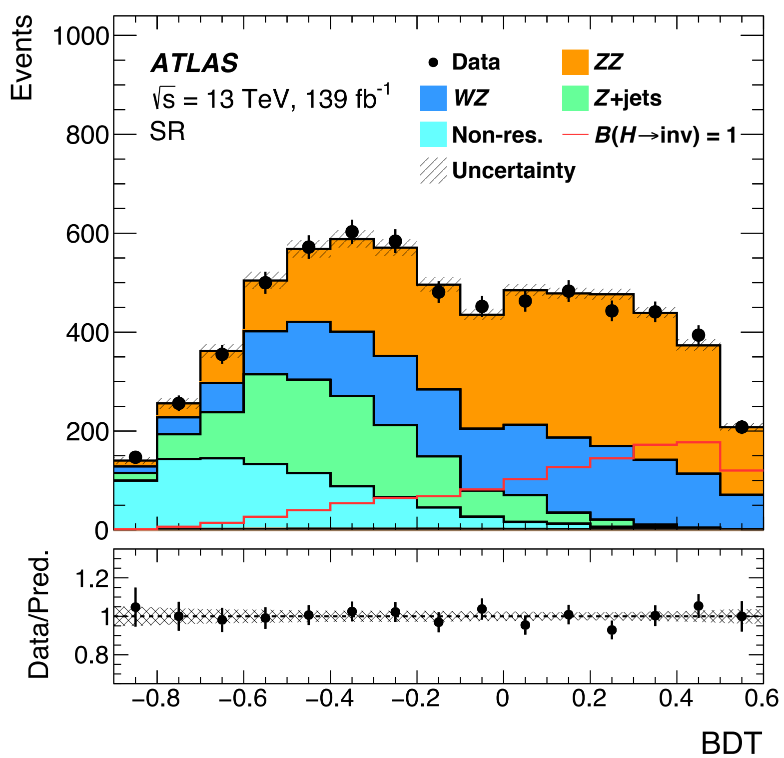
- Updated/improved ATLAS VBF H→invisible just submitted to JHEP:
    - Improved selection and signal region binning (in $\Delta\phi_{jj}$, N_j.)
    - Improved multijet background estimation.
    - Improved V+jets background estimation based on new theory calculation to constrain Z+jets from W-enriched CRs.



- New H→invisible limits from ZH production will further improve overall H→invisible constraints.

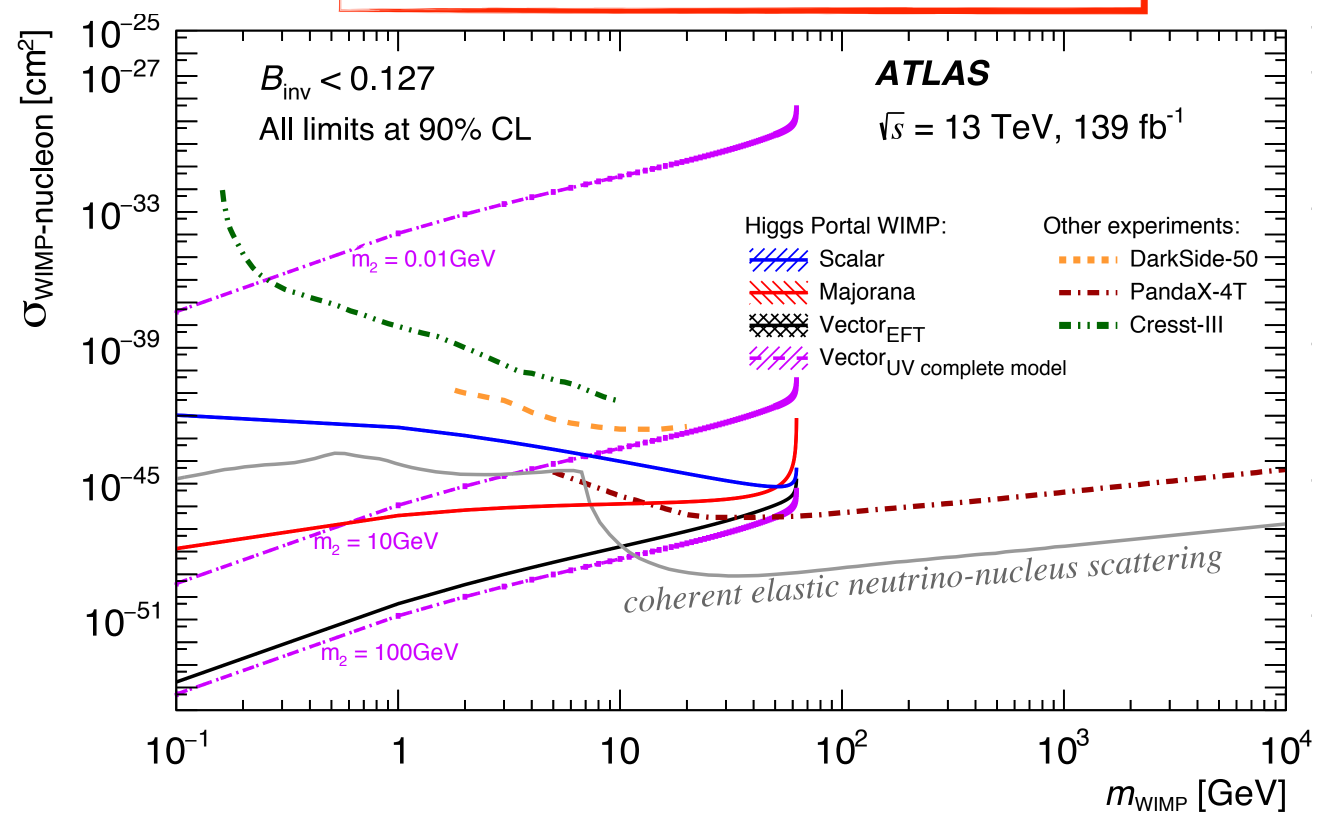
New ZH, H→invisible result:

$B_{inv} < 0.19$ (0.19) @95% CL



Updated VBF H→invisible result:

$B_{inv} < 0.15$ (0.10) @95% CL

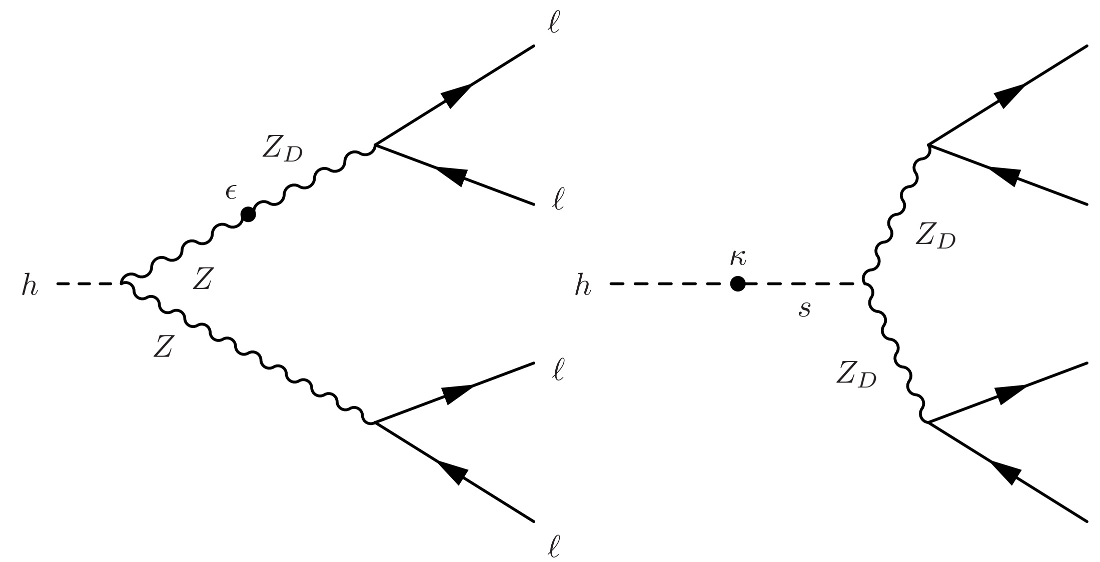


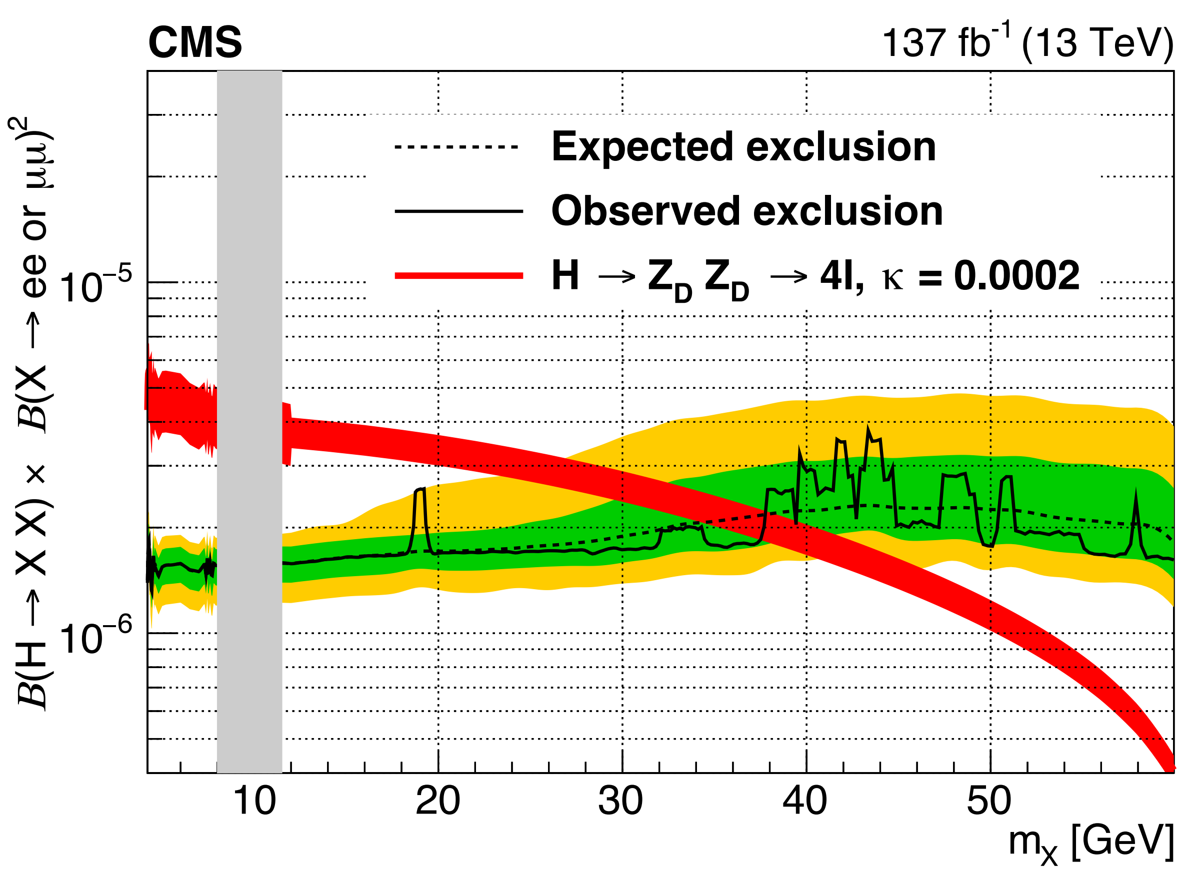
Exotic h→4l decays

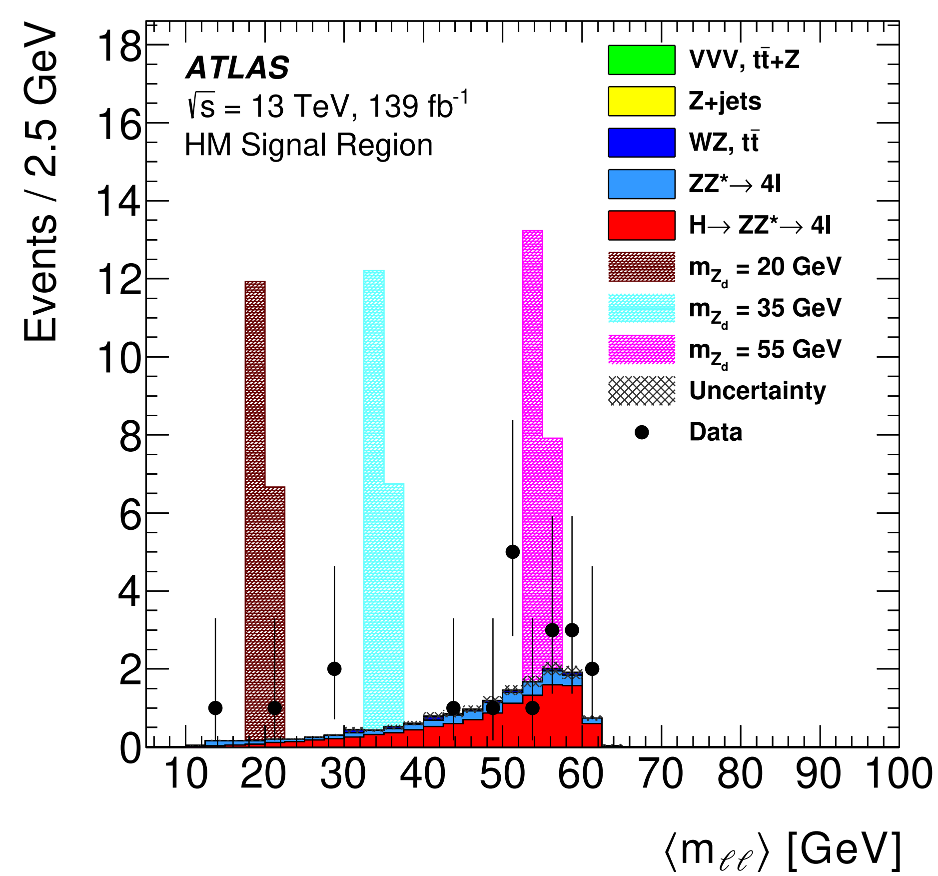
- Search for h→[XX/ZX]→4l
  - X = dark photon Z_D, neutral pseudoscalar a, …

- 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).



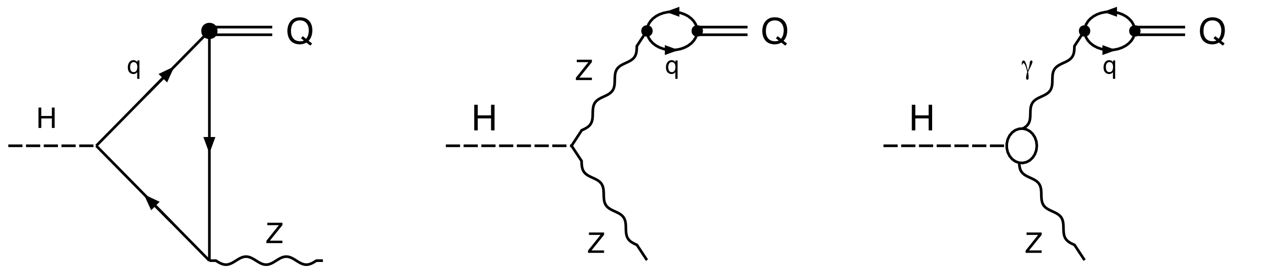




Search for h→Z J/ψ / J/ψ J/ψ / ΥΥ

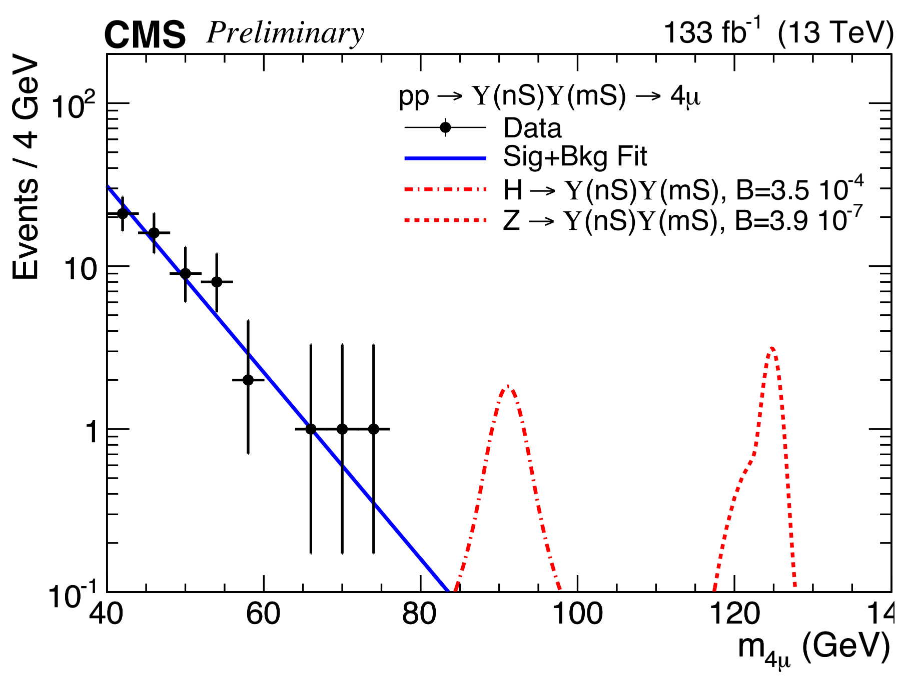
NEW 2022!

- First search for h→Z J/ψ.
- Experimentally clean signature with small SM backgrounds.
- SM rates inaccessible by orders of magnitude ⇒ any excess would be a clear indication of BSM physics.

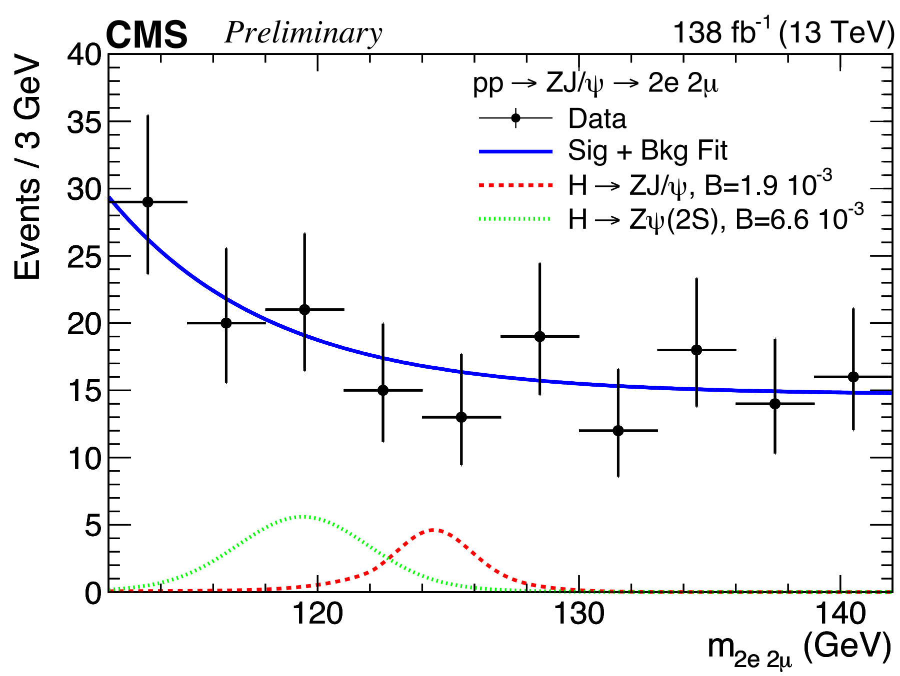


Decay mode	95% C.L. upper limit on BR
h→Z J/ψ	< 1.9 * 10^{-3}
h→ J/ψ J/ψ	< 3.8 * 10^{-4}
h→Υ(nS)Υ(mS)	< 3.5 * 10^{-4}

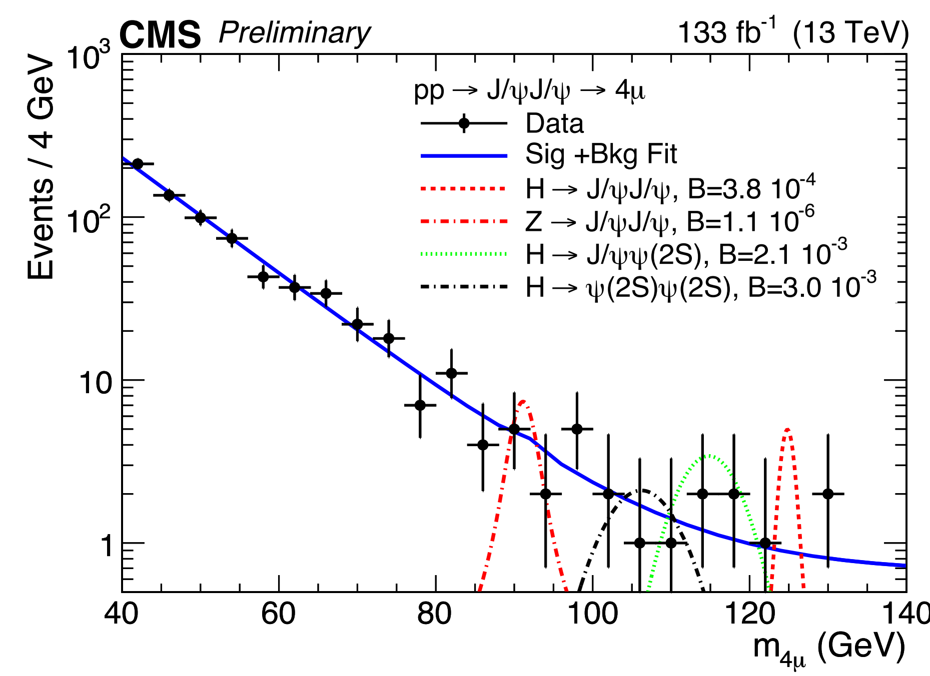
h→Υ(nS)Υ(mS)



h→Z J/ψ



h→ J/ψ J/ψ

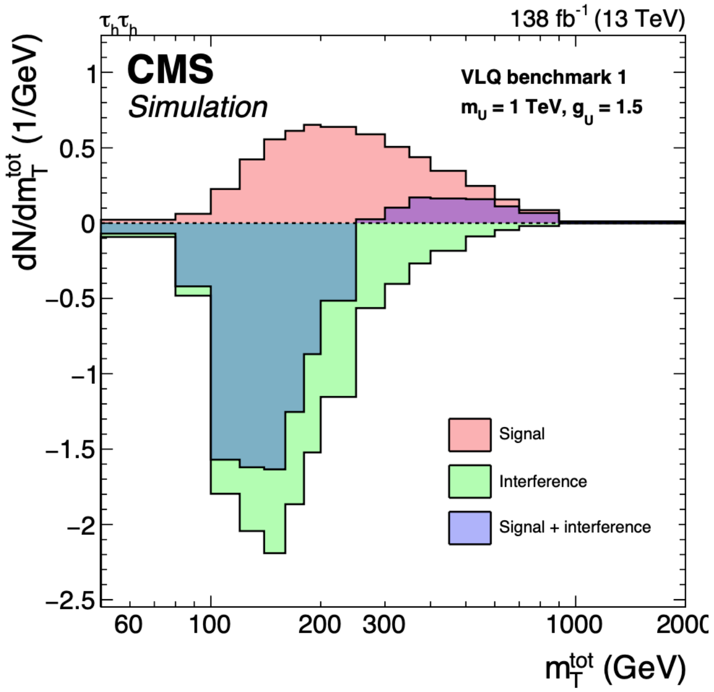


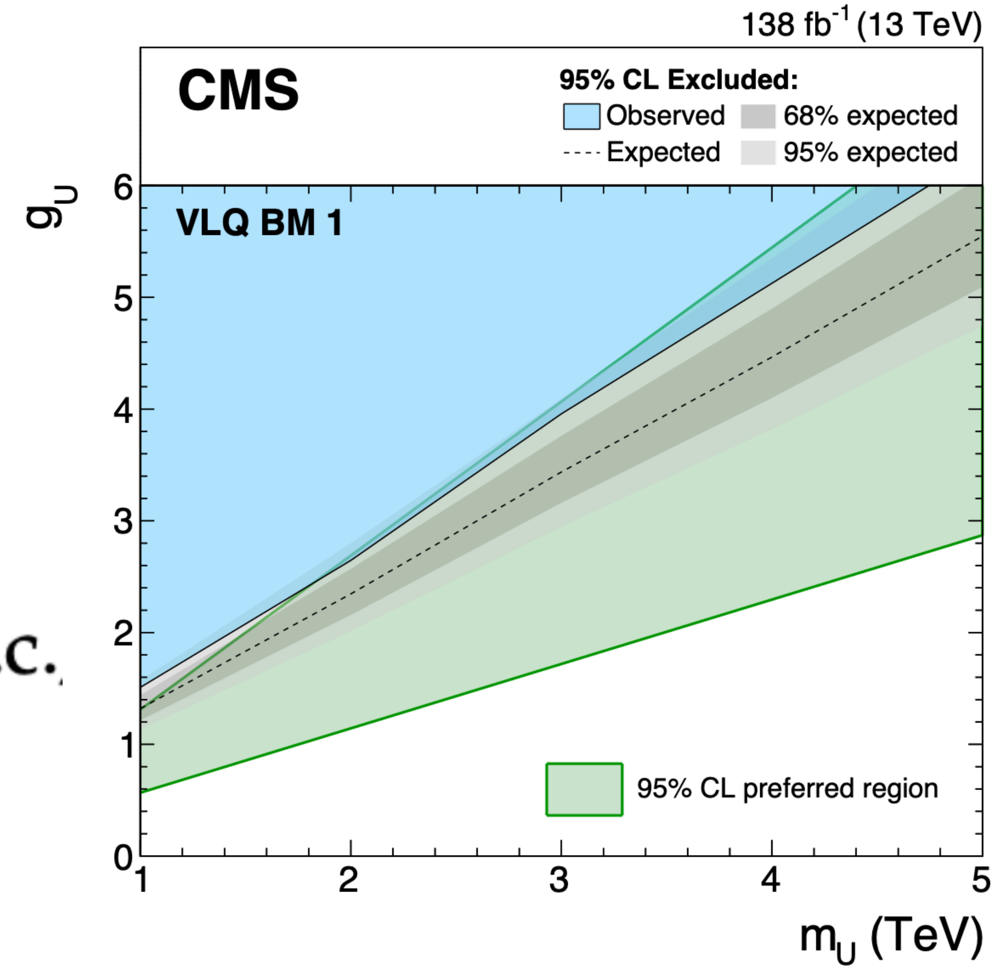
Extending the physics reach to VLQ: details

NEW FOR MORIOND!

- LO Madgraph with 5FS to simulate t-channel VLQ exchange.
- Interference with Z→ττ is significant and generated separately.
- Expected limits well within preferred region for B physics anomalies.
  - Slight excess observed in data, so constraints are weaker than expected.

$$\mathcal{L}_{\mathrm{U}} = \frac{g_{\mathrm{U}}}{\sqrt{2}} \mathrm{U}^{\mu} \left[\beta_{\mathrm{L}}^{i\alpha} (\bar{q}_{\mathrm{L}}^{i} \gamma_{\mu} l_{\mathrm{L}}^{\alpha}) + \beta_{\mathrm{R}}^{i\alpha} (\bar{d}_{\mathrm{R}}^{i} \gamma_{\mu} e_{\mathrm{R}}^{\alpha}) \right] + \mathrm{h.c.}$$



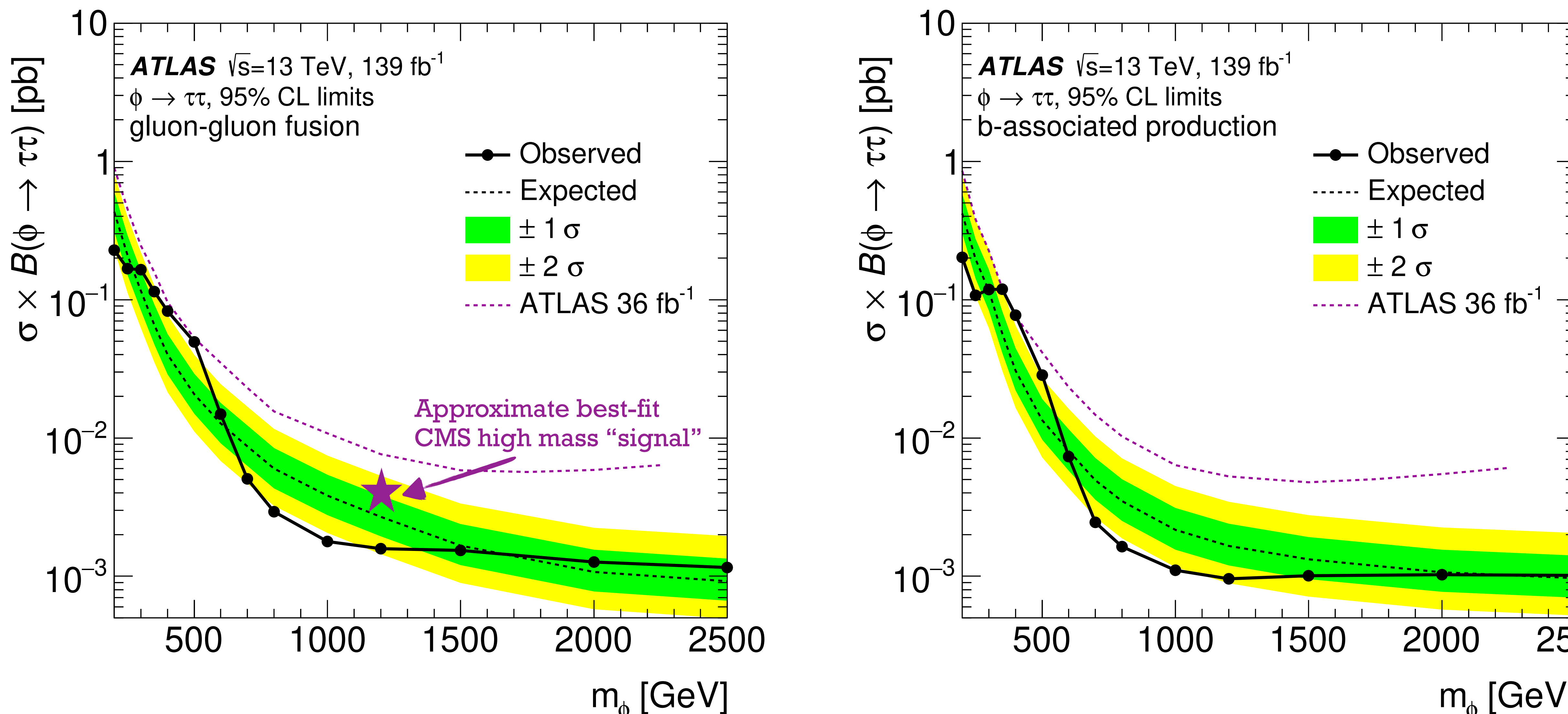


arXiv:2103.16558

ATLAS $\phi \rightarrow \tau\tau$ 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 $\phi \rightarrow \tau\tau$ search from ATLAS.



Phys. Rev. Lett. 125 (2020) 051801

Results new since Moriond 2021 not shown

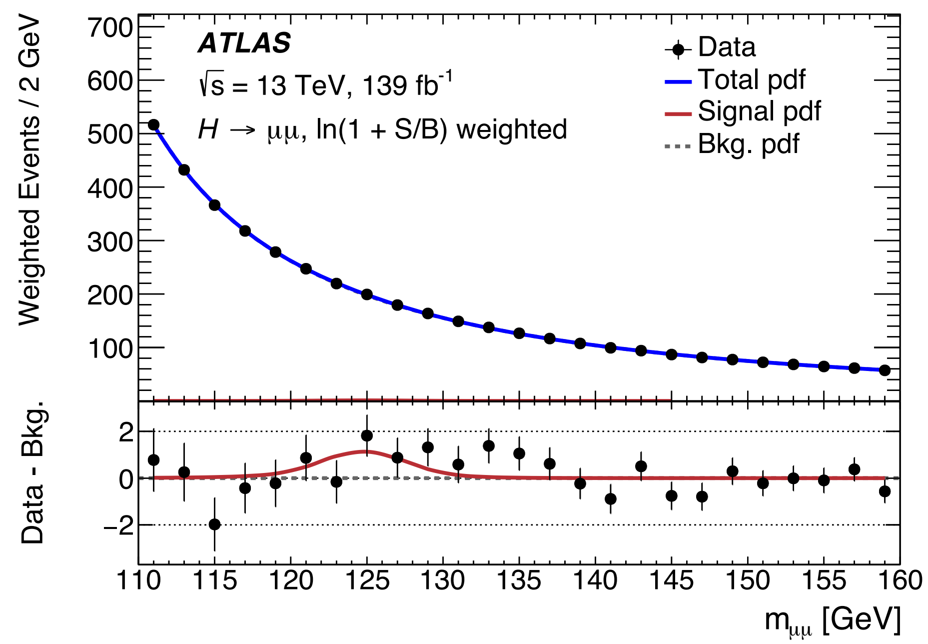
- Unfortunately I could not cover the full extent of new results since Moriond 2021.
- These results are listed here for reference.

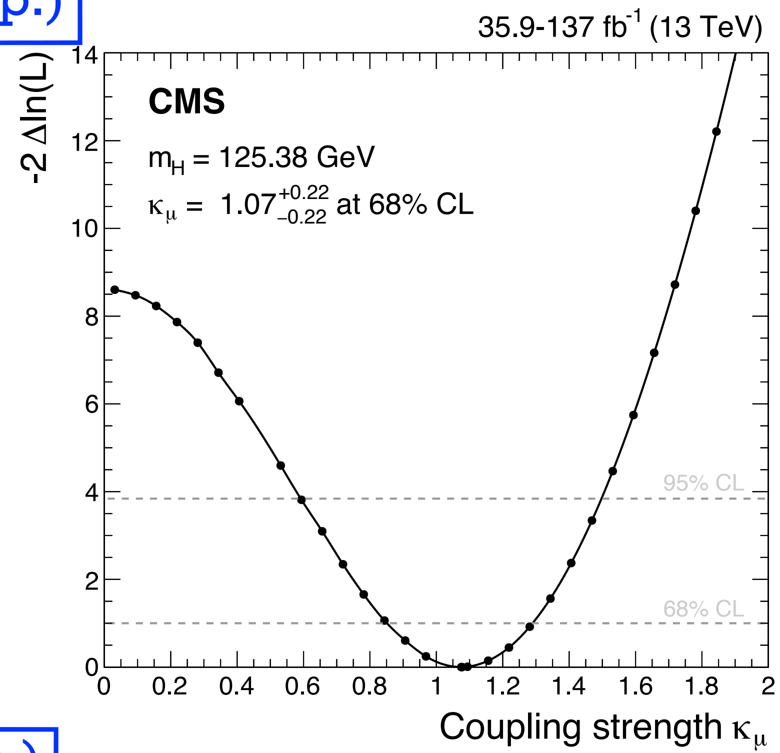
- $H \to bb + p_T^{miss}$: JHEP 01 (2022) 063 (ATLAS)
- $H \to \gamma\gamma + p_T^{miss}$: JHEP 10 (2021) 13 (ATLAS)
- $t \to H^{\pm}b$, $H^{\pm} \to cb$: ATLAS-CONF-2021-037
- $H^{\pm} \to aW^{\pm}, a \to \mu\mu$: ATLAS-CONF-2021-047
- VBF $H^{\pm} \to VV$: Eur. Phys. J. C 81 (2021) 723 (CMS)

H→μμ

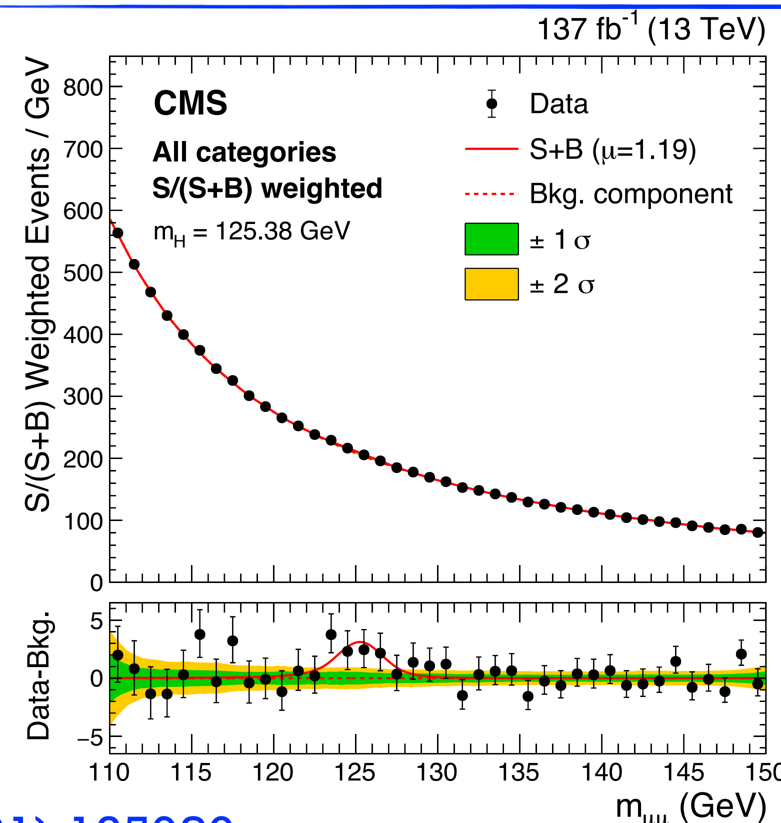
- Most experimentally accessible probe of Yukawa interactions beyond third generation.
- *Evidence for H→μμ with LHC Run-2 data!*

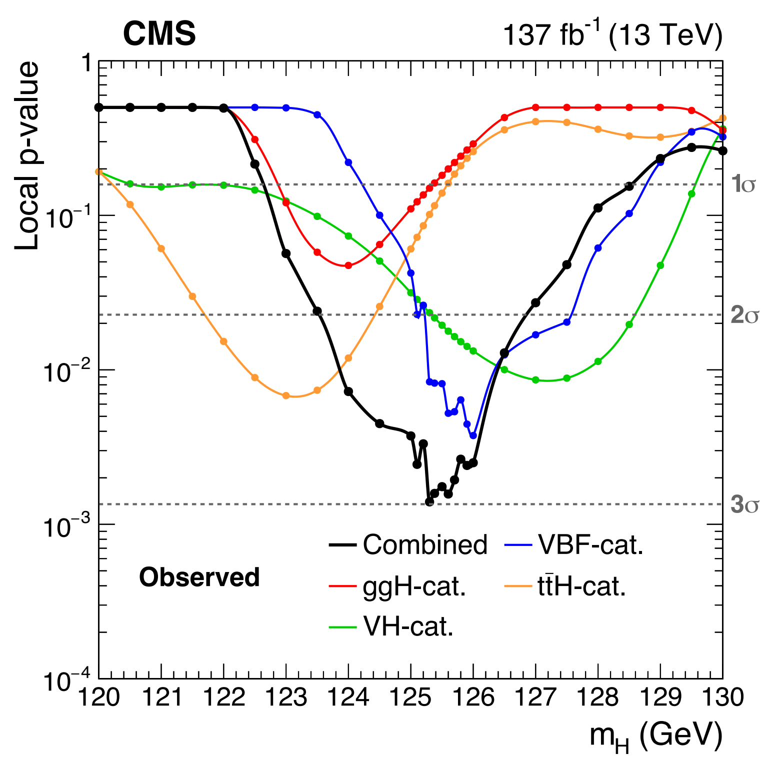
ATLAS Run-2 result: 2.0σ (1.7σ) obs. (exp.)





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

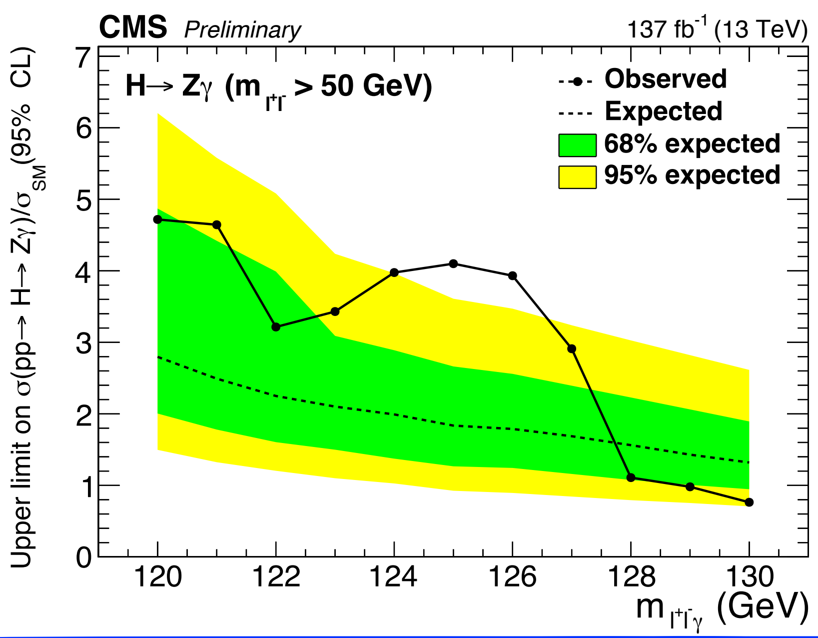




[JHEP 01 (2021) 148] [Phys. Lett. B 812 (2021) 135980]

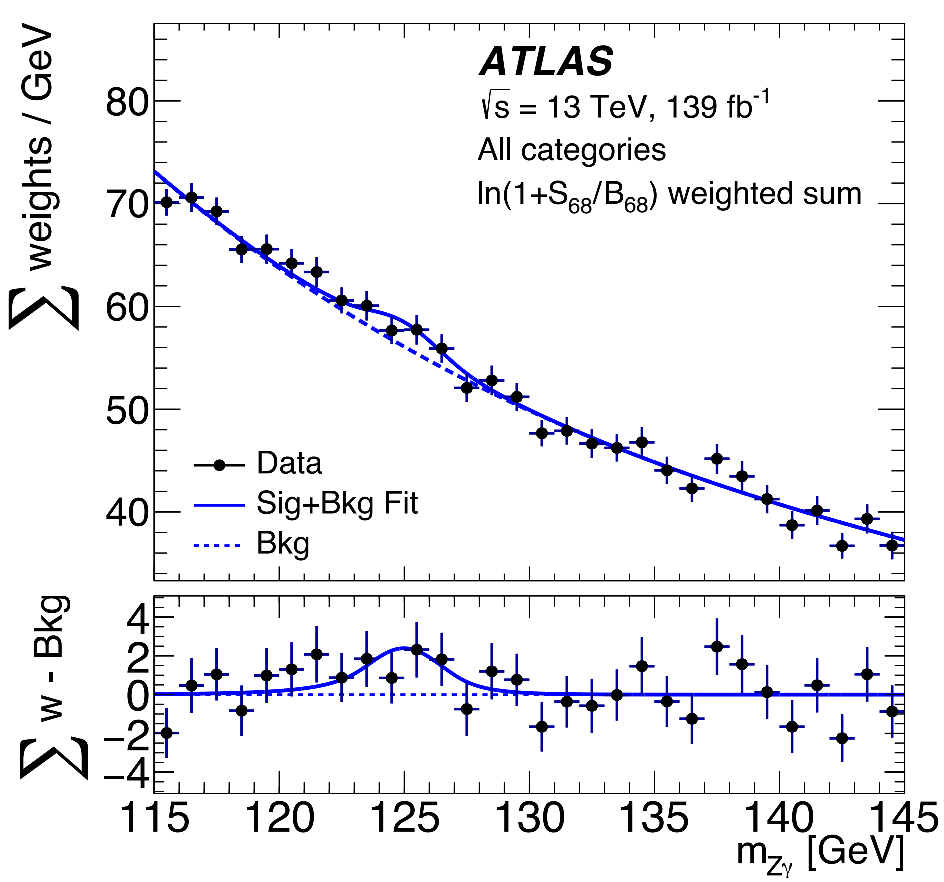
H→Zγ: further details

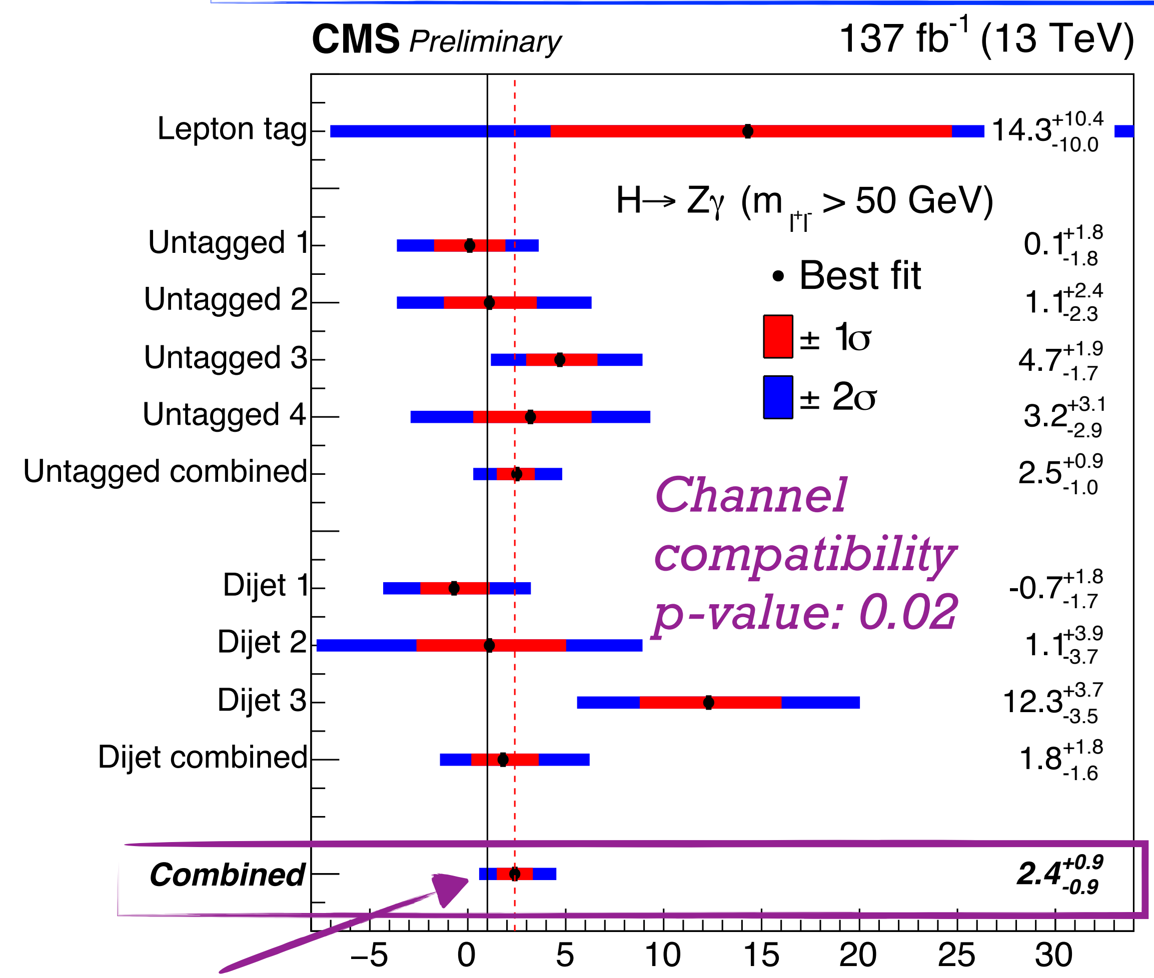
- ATLAS signal strengths “compatible within their total uncertainties” (paper).
- Compatibility tests from CMS at ~2σ level ⇒ need Run-3 data to understand if this is a statistical effect or a real discrepancy.



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

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

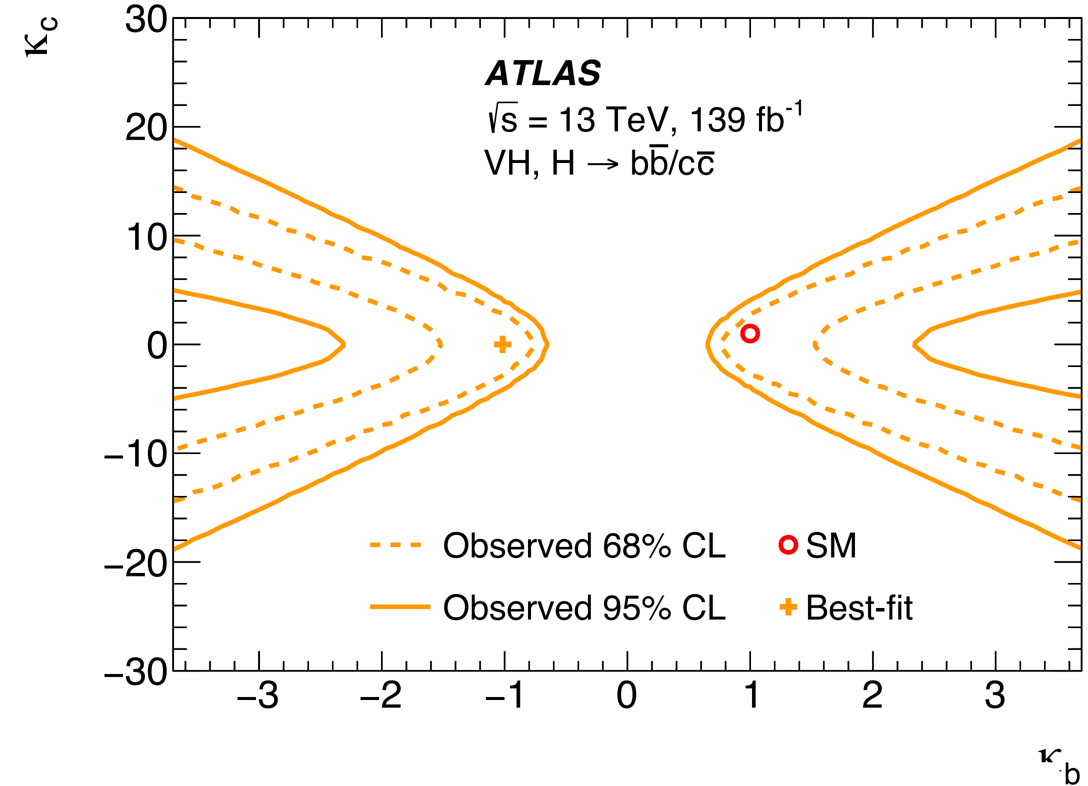




Compatibility with SM: 1.6σ

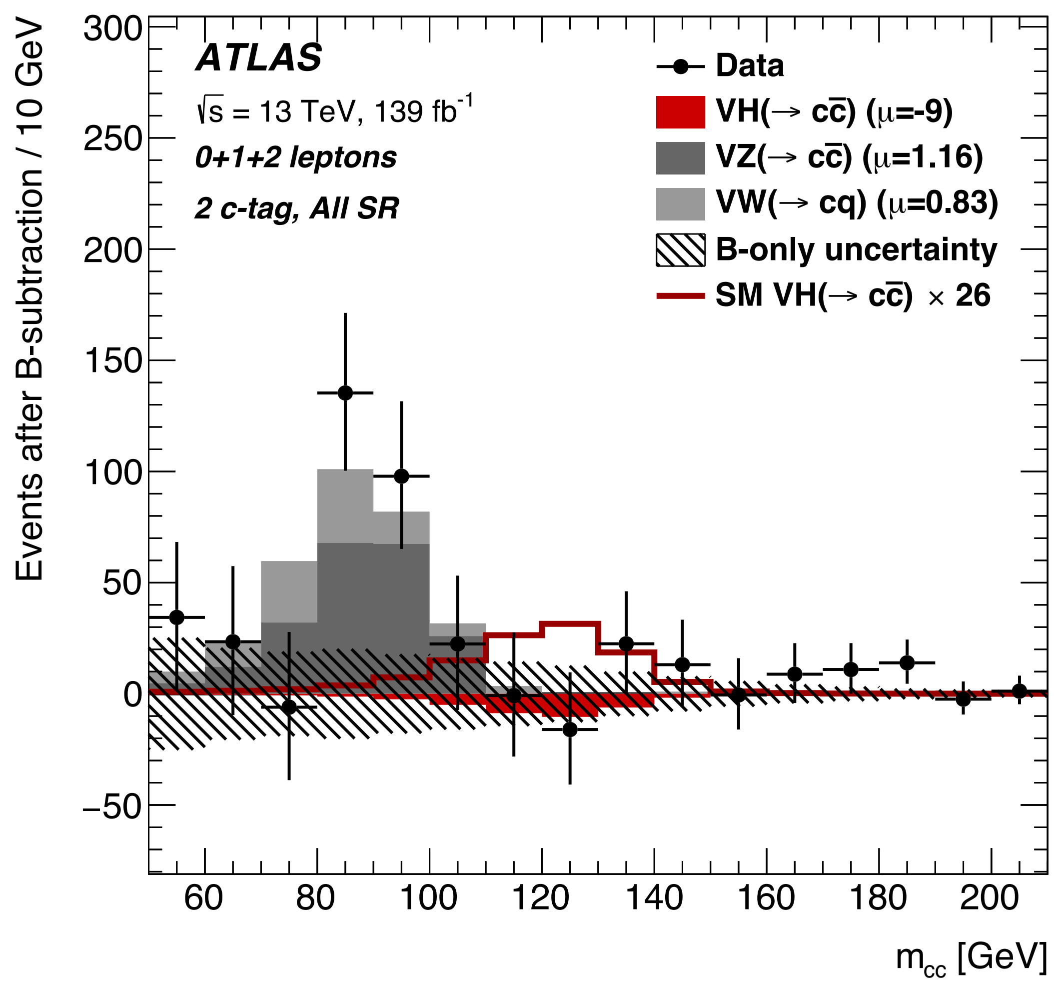
ATLAS VH, $H \rightarrow cc$

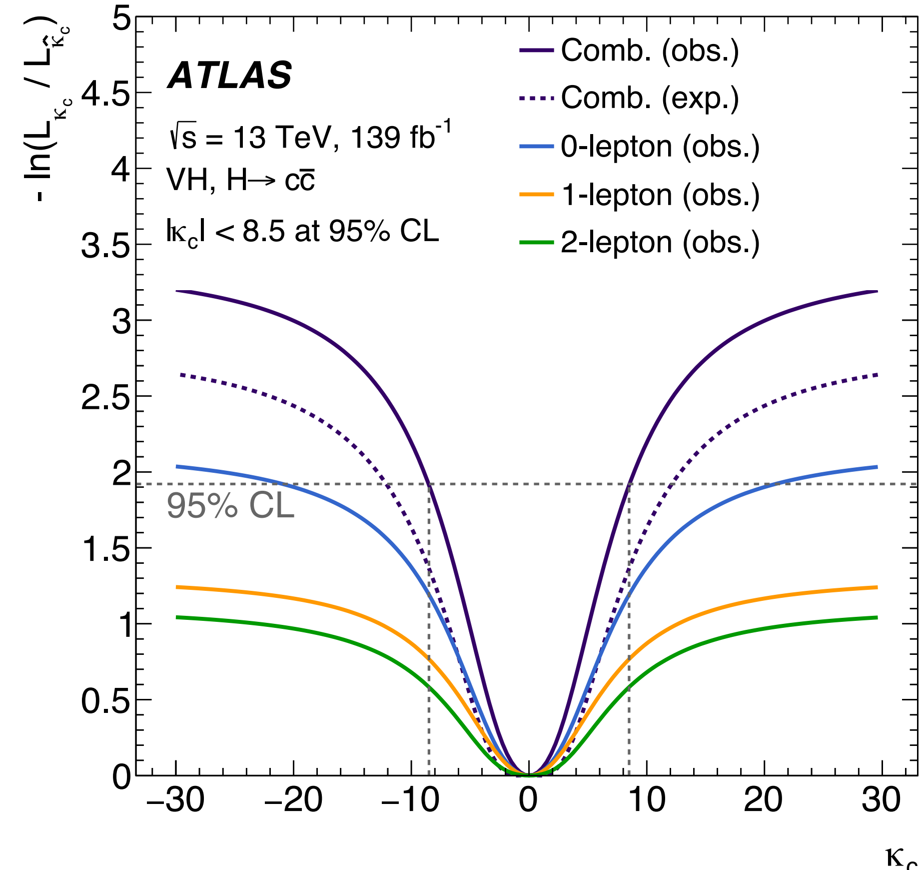
- For (many) more details, see V. Dao's talk in the morning session.



$\boxed{\text{95\% CL obs. (exp.) } \mu < 26(31)}$

$\boxed{\kappa_c < 8.5 \text{ (12.4 exp.)}}$





Search for low mass H→γγ

- 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).