Searches for Beyond-SM Higgs Sector at the LHC

Santeri Laurila
CERN

Spåtind 2023 – Nordic Conference on Particle Physics – 6 January 2023

BSM Higgs: Why Bother?

BSM Higgs: Why Bother?

- The Higgs discovery confirmed the existence of the predicted electroweak symmetry breaking mechanism, and so far the experimental results from LHC are consistent with the SM Higgs boson (as detailed by Sara)

BSM Higgs: Why Bother?

- The Higgs discovery confirmed the existence of the predicted electroweak symmetry breaking mechanism, and so far the experimental results from LHC are consistent with the SM Higgs boson (as detailed by Sara)
- However, **many of the shortcomings of the SM seem to be connected to the Higgs sector**:
  - Hierarchy problem, fermion generations, CP violation and baryogenesis (David's talk), dark matter...
  - Models aiming to address these issues often include an extended Higgs sector (e.g. all SUSY models)

BSM Higgs: Why Bother?

- The Higgs discovery confirmed the existence of the predicted electroweak symmetry breaking mechanism, and so far the experimental results from LHC are consistent with the SM Higgs boson (as detailed by Sara)
- However, **many of the shortcomings of the SM seem to be connected to the Higgs sector**:
  - Hierarchy problem, fermion generations, CP violation and baryogenesis (David's talk), dark matter...
  - Models aiming to address these issues often include an extended Higgs sector (e.g. all SUSY models)

BSM Higgs: Why Bother?

- The Higgs discovery confirmed the existence of the predicted electroweak symmetry breaking mechanism, and so far the experimental results from LHC are consistent with the SM Higgs boson (as detailed by Sara)
- However, **many of the shortcomings of the SM seem to be connected to the Higgs sector**:
  - Hierarchy problem, fermion generations, CP violation and baryogenesis (David's talk), dark matter...
  - Models aiming to address these issues often include an extended Higgs sector (e.g. all SUSY models)
- Key question: **is the Higgs sector indeed minimal**, **unlike any other sector in SM**, with only one complex Higgs doublet – or is it more complex?

BSM Higgs: Why Bother?

- The Higgs discovery confirmed the existence of the predicted electroweak symmetry breaking mechanism, and so far the experimental results from LHC are consistent with the SM Higgs boson (as detailed by Sara)
- However, **many of the shortcomings of the SM seem to be connected to the Higgs sector**:
  - Hierarchy problem, fermion generations, CP violation and baryogenesis (David's talk), dark matter...
  - Models aiming to address these issues often include an extended Higgs sector (e.g. all SUSY models)
- Key question: **is the Higgs sector indeed minimal**, **unlike any other sector in SM**, with only one complex Higgs doublet – or is it more complex?

BSM Higgs: Why Bother?

- The Higgs discovery confirmed the existence of the predicted electroweak symmetry breaking mechanism, and so far the experimental results from LHC are consistent with the SM Higgs boson (as detailed by Sara)
- However, **many of the shortcomings of the SM seem to be connected to the Higgs sector**:
  - Hierarchy problem, fermion generations, CP violation and baryogenesis (David's talk), dark matter...
  - Models aiming to address these issues often include an extended Higgs sector (e.g. all SUSY models)
- Key question: **is the Higgs sector indeed minimal**, **unlike any other sector in SM**, with only one complex Higgs doublet – or is it more complex?
- The list of interesting BSM Higgs models is wide and would earn its own lecture series:
  - **Singlet** models: Additional **neutral** scalar bosons (e.g. DM), strong first-order phase transition
  - **Doublet** models: Additional **neutral and charged** scalar bosons, more CP violation, FCNCs
    - E.g. **two-Higgs-doublet models** (2HDMs) with 5 Higgs bosons: h, H, A, H^+, H^-
  - **Doublet+singlet** models to combine the nice features of both
  - **Triplet** models: Similar consequences to doublet models [no FCNCs] and a spectrum of new scalars
    - E.g. **Georgi-Machacek**: Two extra triplets → several neutral, charged and **doubly-charged** scalars

From Early Run 2 to Early Run 3

- Throwback to Spåtind 2016:

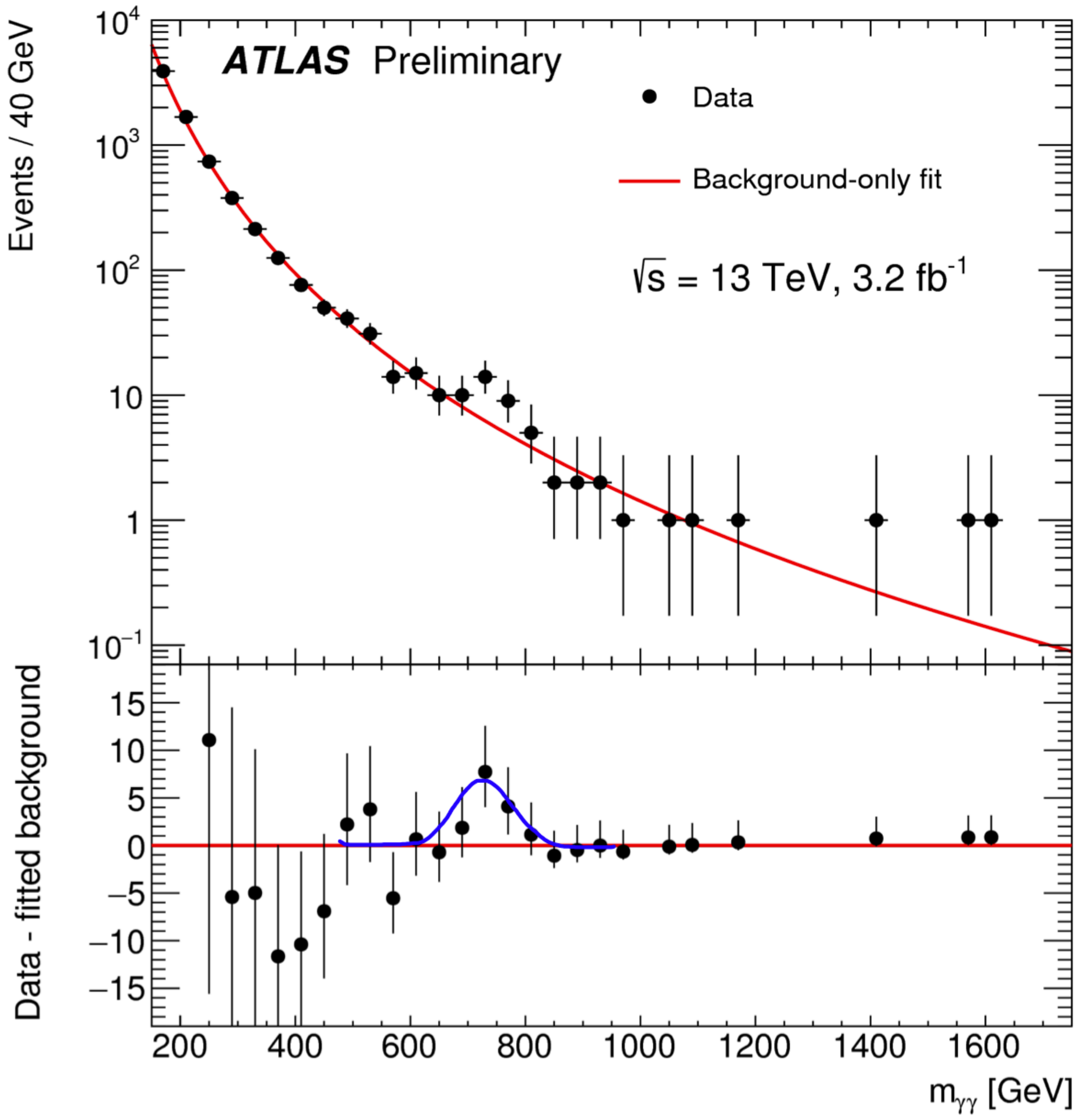
Chorus:
BSM particles
Show us who you are
Stop hiding, start coupling
The energy is high
Gathering at Spåtind
No need to wear a tie
Days they turn, more we learn
The energy is high

From Early Run 2 to Early Run 3

- Throwback to Spåtind 2016:

Chorus:
BSM particles
Show us who you are
Stop hiding, start coupling
The energy is high
Gathering at Spåtind
No need to wear a tie
Days they turn, more we learn
The energy is high

At seven-hundred-fifty
We indeed see a bump
It's time to ask the question
How significant?

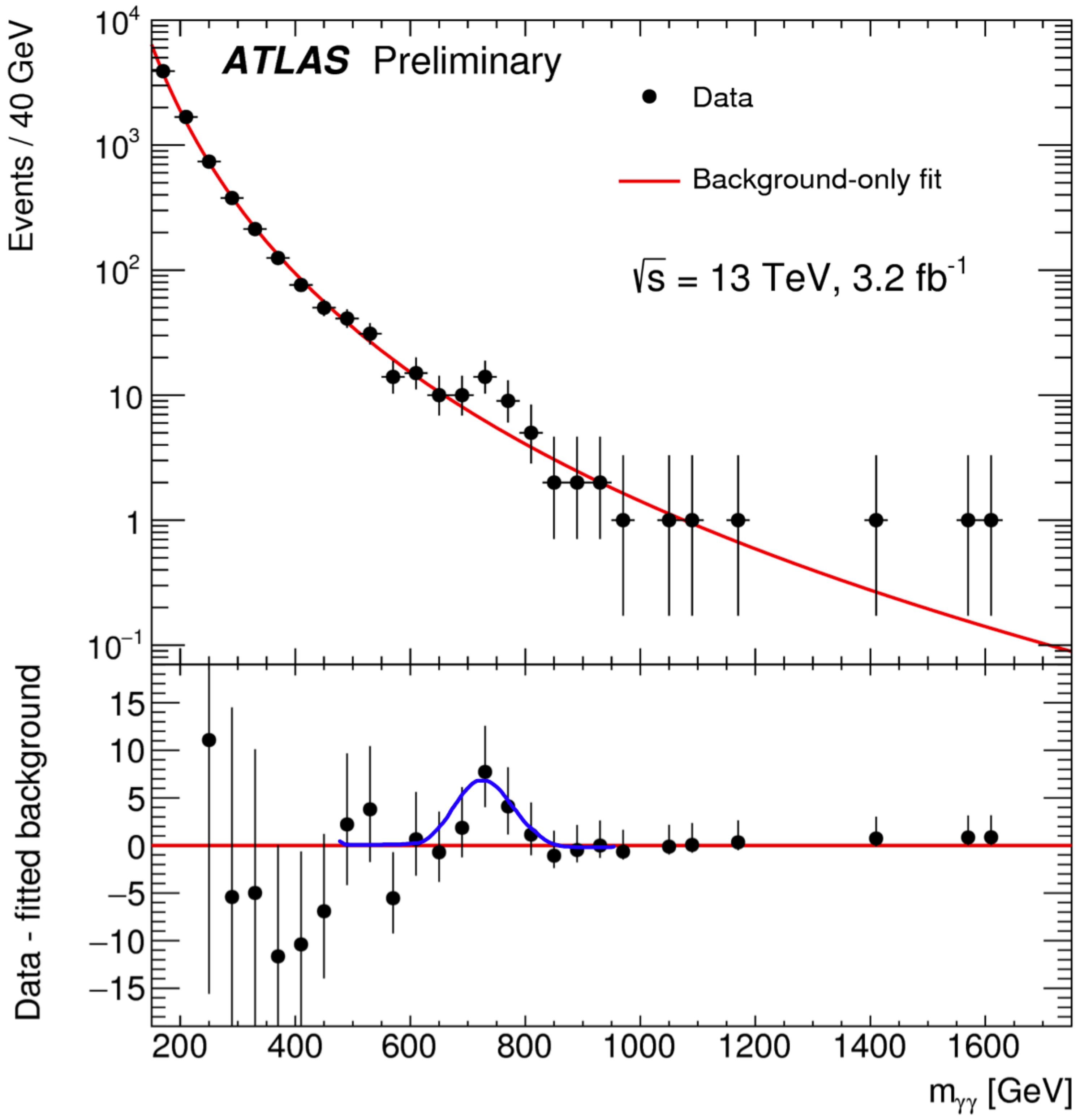


From Early Run 2 to Early Run 3

- Throwback to Spåtind 2016:

Chorus:
BSM particles
Show us who you are
Stop hiding, start coupling
The energy is high
Gathering at Spåtind
No need to wear a tie
Days they turn, more we learn
The energy is high

At seven-hundred-fifty
We indeed see a bump
It's time to ask the question
How significant?



- In this talk, I aim to give an **overview of where we stand with BSM Higgs searches** at the LHC
  - Very wide topic, so I have hand-picked a bunch of recent results [in a completely personally biased way]
  - Recent advances and innovations in search methods are **highlighted** (lots of ML as explained by Thea)
  - Some (mild) current **excesses** are mentioned too
    - Let's remember the 750 GeV lesson and not jump to conclusions!

BSM Higgs at the

BSM Higgs at the

- How to discover an extended Higgs sector at the LHC?
  - **"Do the Higgs trick again"**
    Searches for H_{BSM} with production and decay processes similar to H_{125}

  - **"Do the Higgs trick, but this time with electric charge"**
    Searches for charged Higgs bosons
  - **"Search as low as possible"**
    Searches for low-mass H_{BSM} (or other light BSM particles) *produced in H_{125} decays*
  - **"Search as high as possible"**
    Search for high-mass H_{BSM} (or other heavy BSM particles) *decaying to H_{125}*

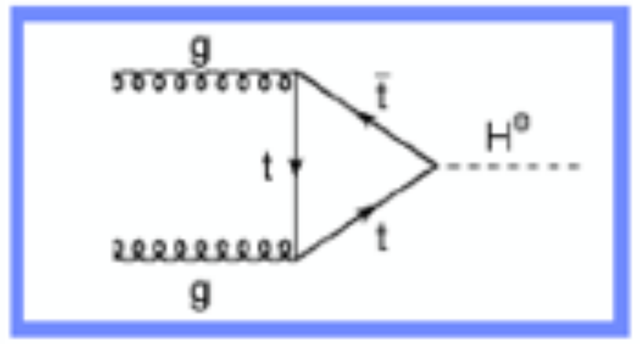
BSM Higgs at the

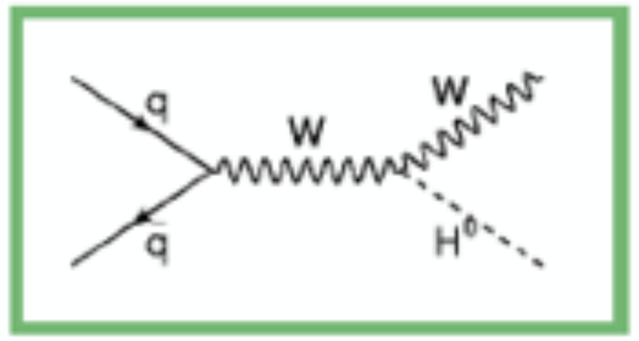
- How to discover an extended Higgs sector at the LHC?
  - **"Do the Higgs trick again"**
    Searches for H_{BSM} with production and decay processes similar to H_{125}
  - **"Do the Higgs trick, but this time with electric charge"**
    Searches for charged Higgs bosons
  - **"Search as low as possible"**
    Searches for low-mass H_{BSM} (or other light BSM particles) *produced in H_{125} decays*
  - **"Search as high as possible"**
    Search for high-mass H_{BSM} (or other heavy BSM particles) *decaying to H_{125}*
- All these scenarios are **constrained not excluded** by the previous searches and the H_{125} measurements

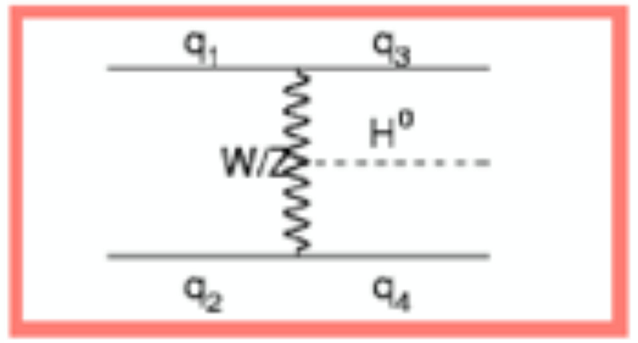
Neutral BSM scalars

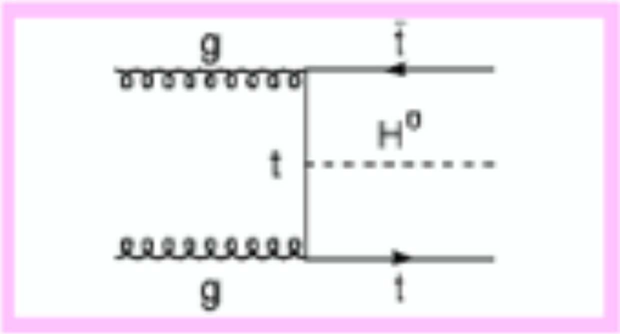
Neutral Higgs Production & Decays

- Just as for H_{125}, we need to consider several potential **production modes**: gluon-gluon fusion, vector boson fusion, WH and WZ, ttH...



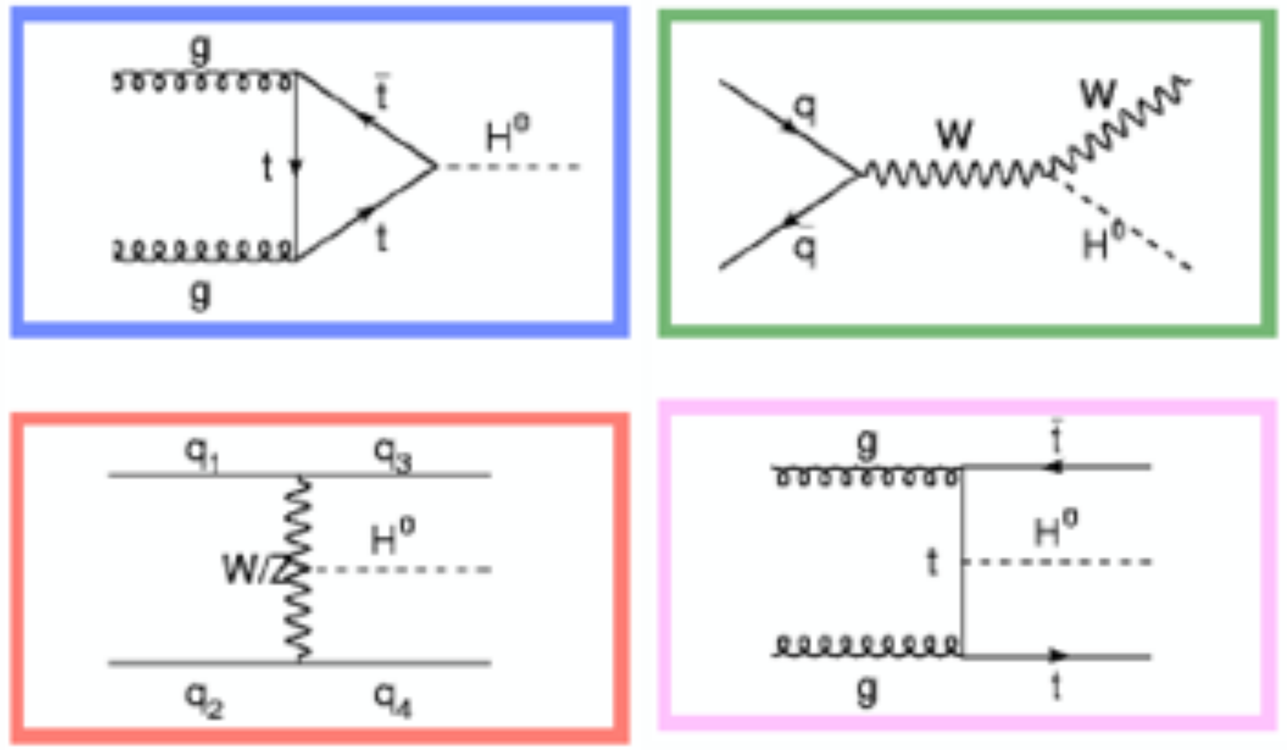


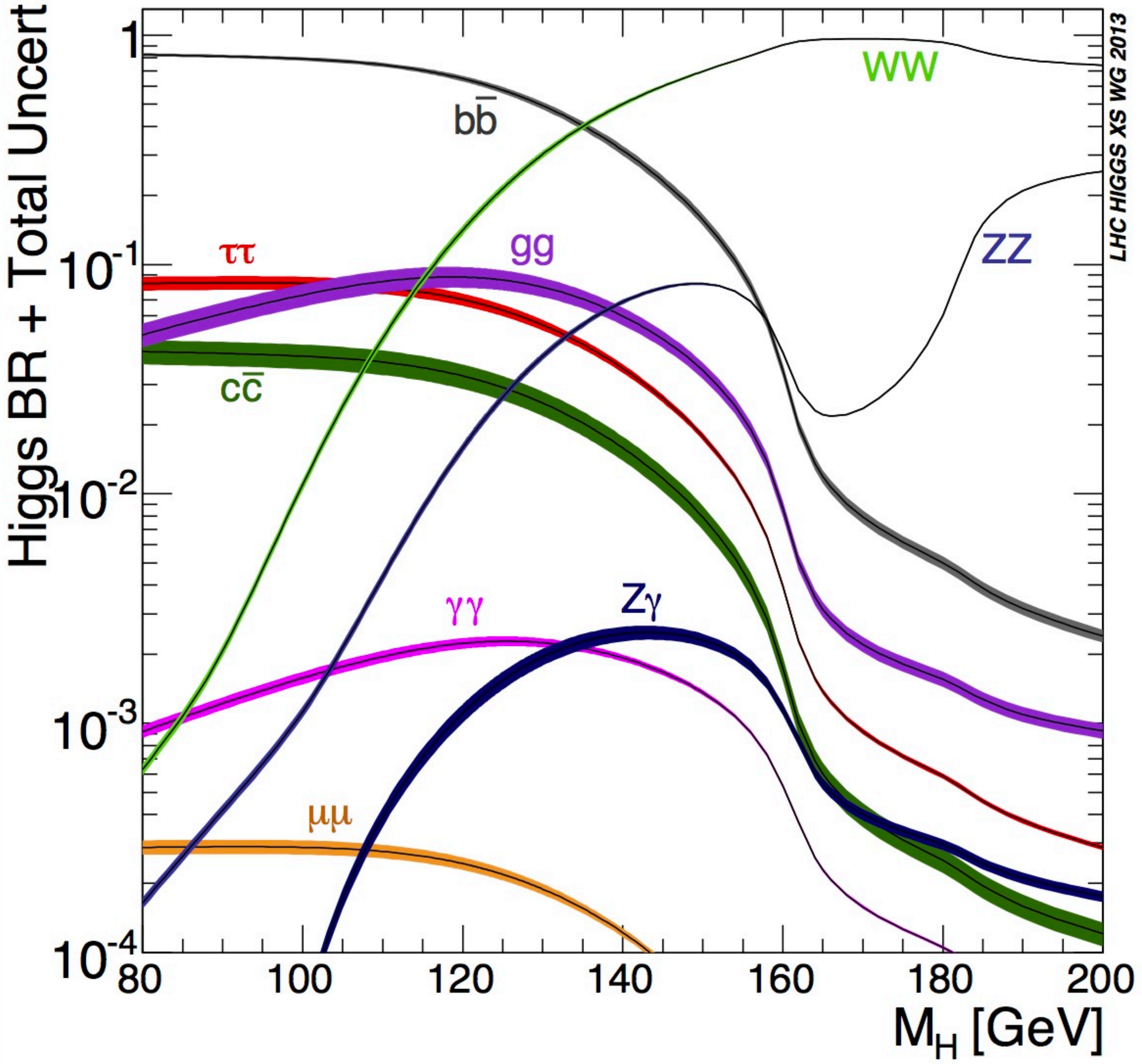




Neutral Higgs Production & Decays

- Just as for H_{125}, we need to consider several potential **production modes**: gluon-gluon fusion, vector boson fusion, WH and WZ, ttH…

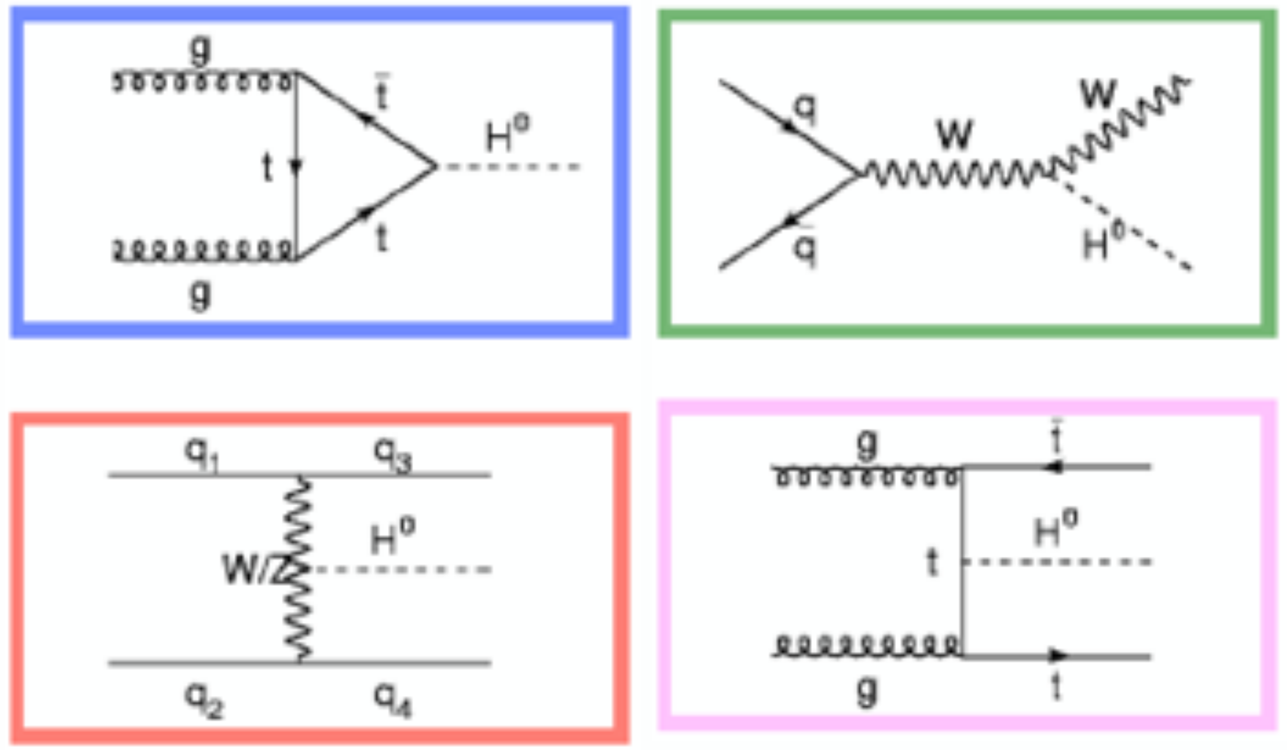


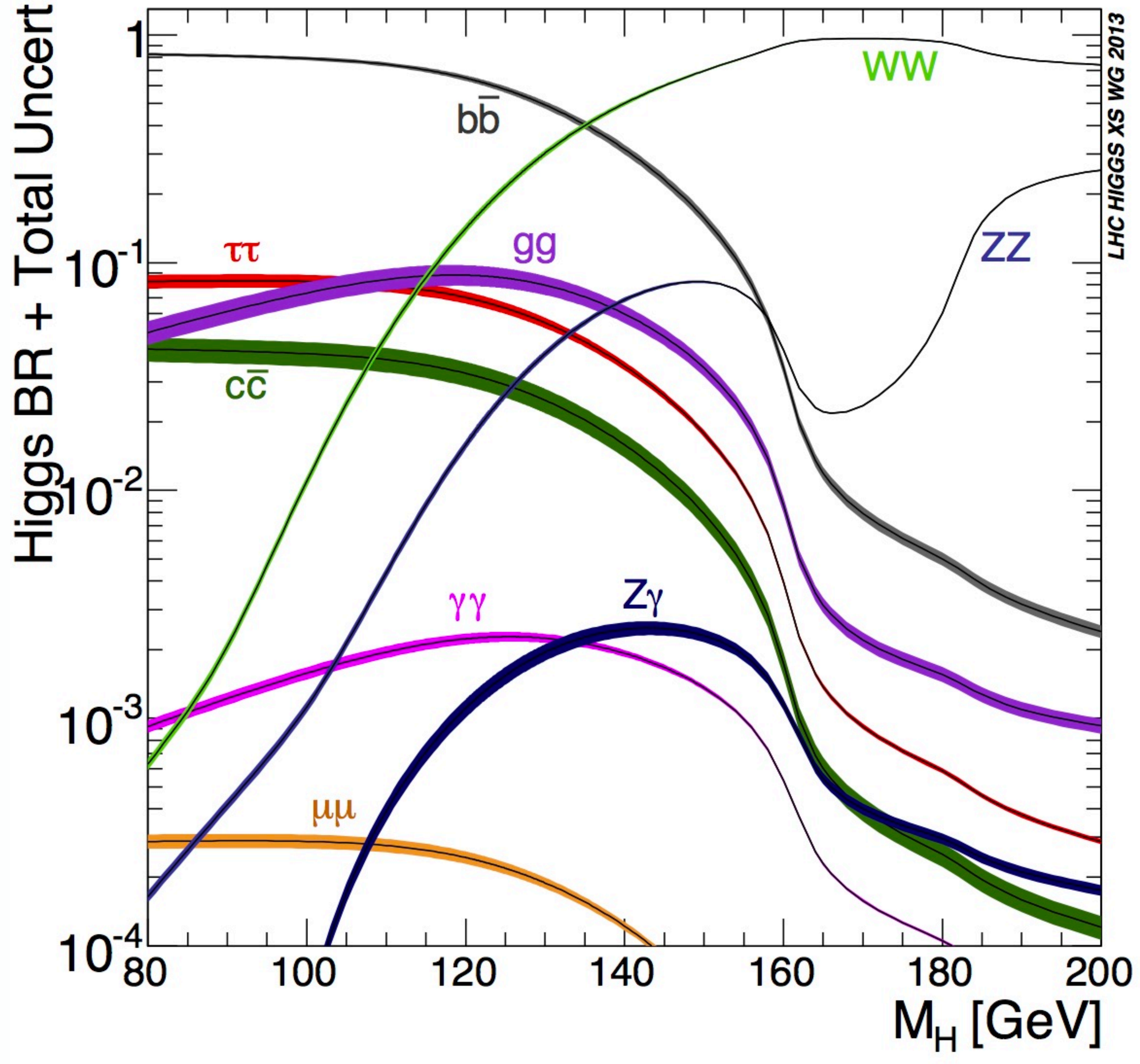


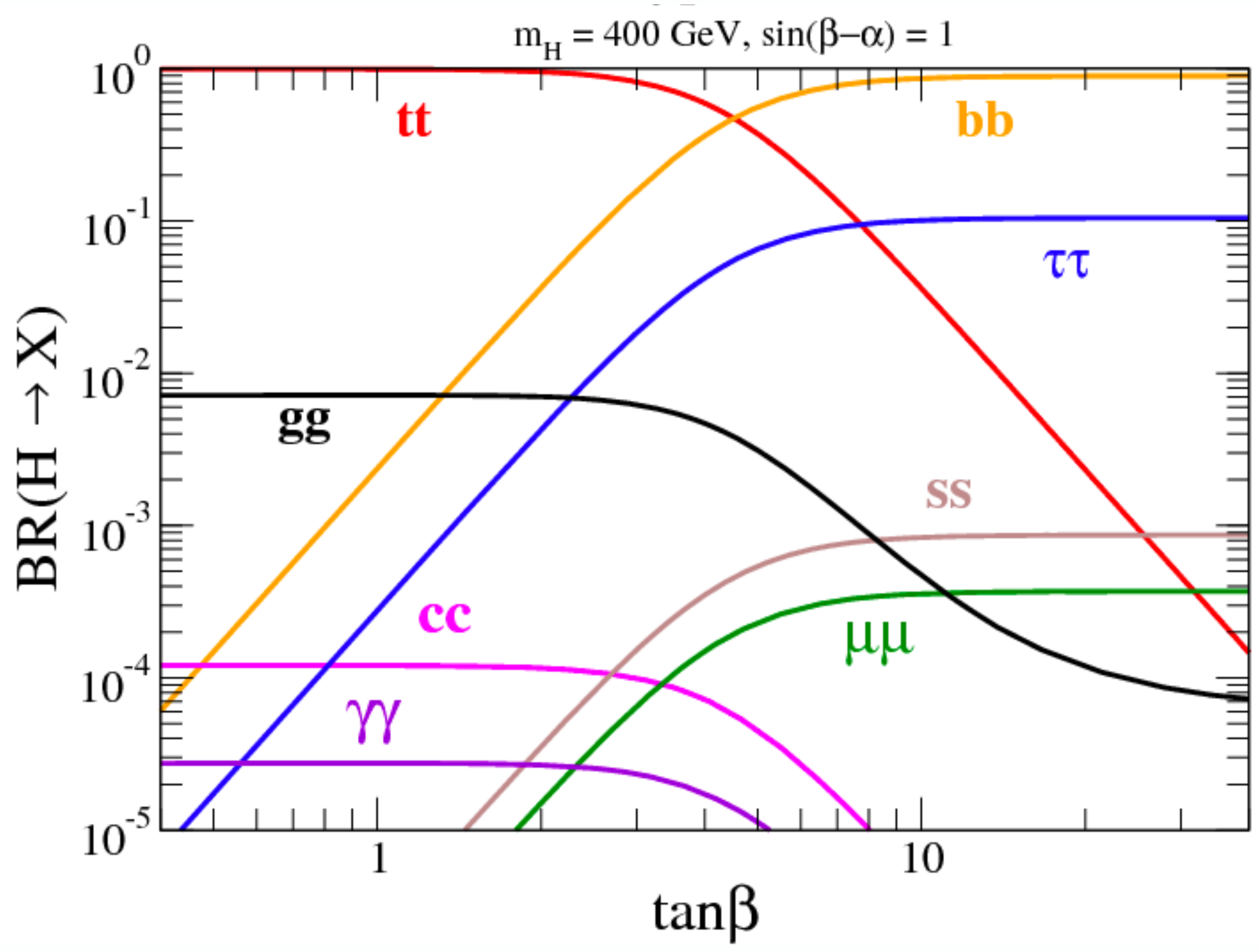
- **Branching fractions** depend on the BSM scalar mass, and often differently than in the SM!

Neutral Higgs Production & Decays

- Just as for H_{125}, we need to consider several potential **production modes**: gluon-gluon fusion, vector boson fusion, WH and WZ, ttH…



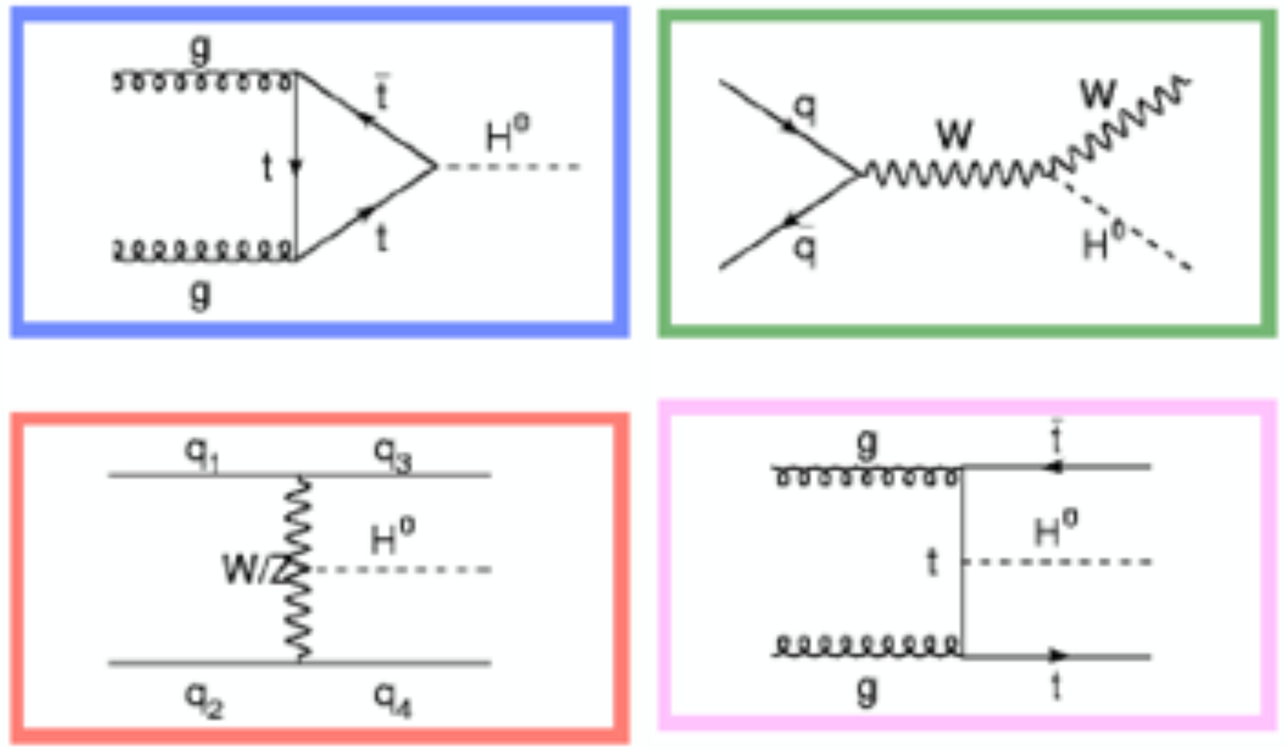


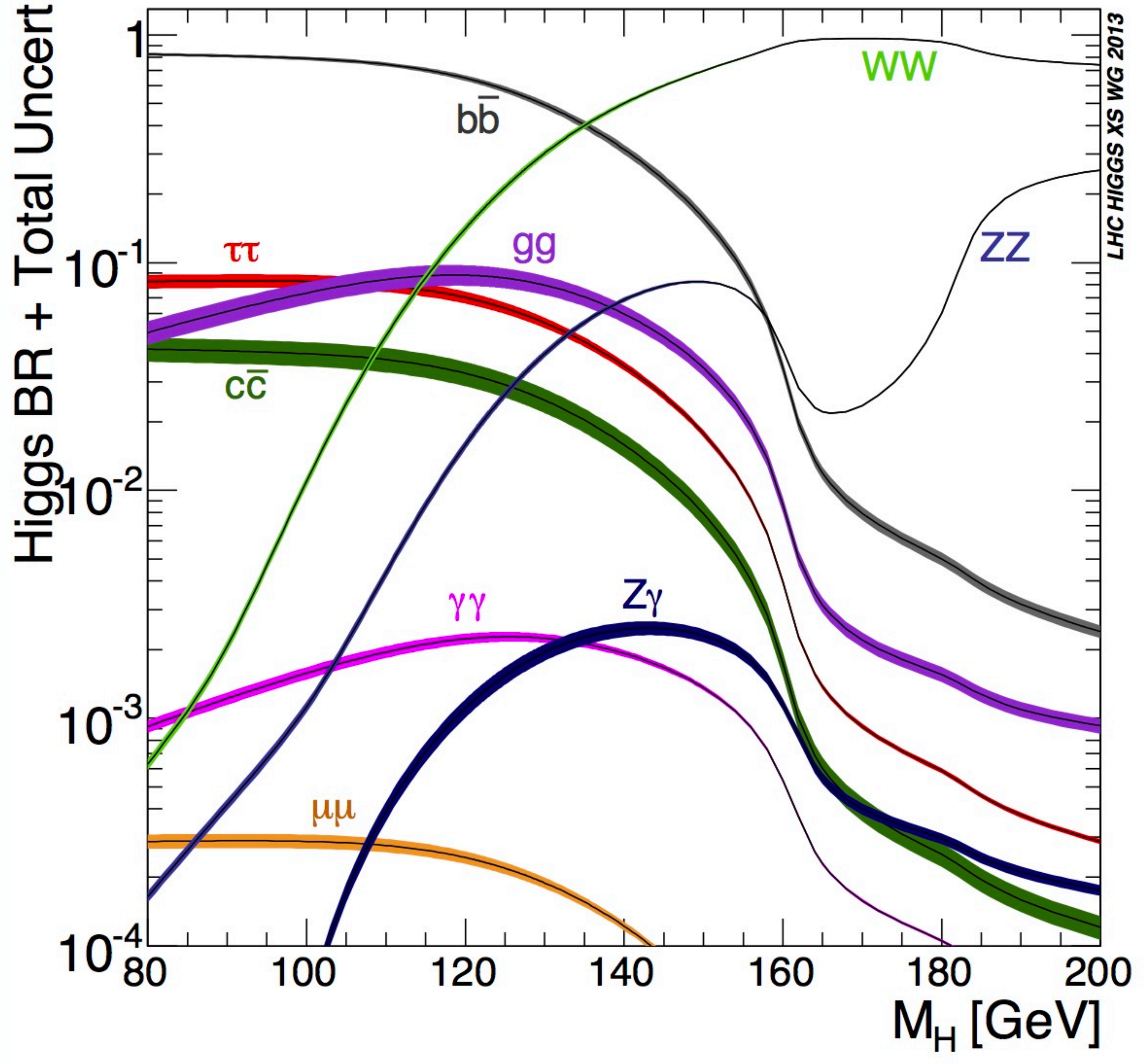


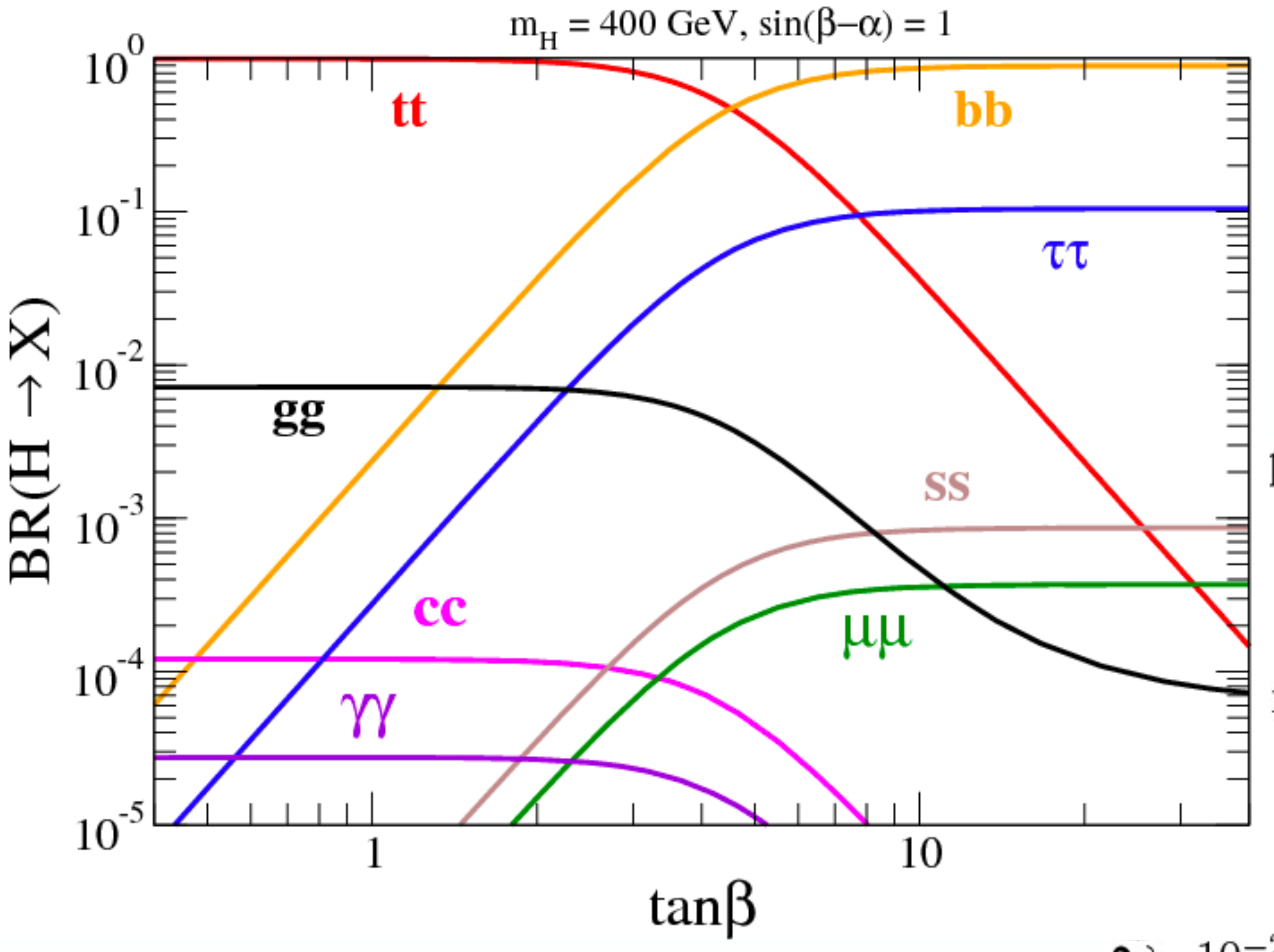
- **Branching fractions** depend on the BSM scalar mass, and often differently than in the SM!

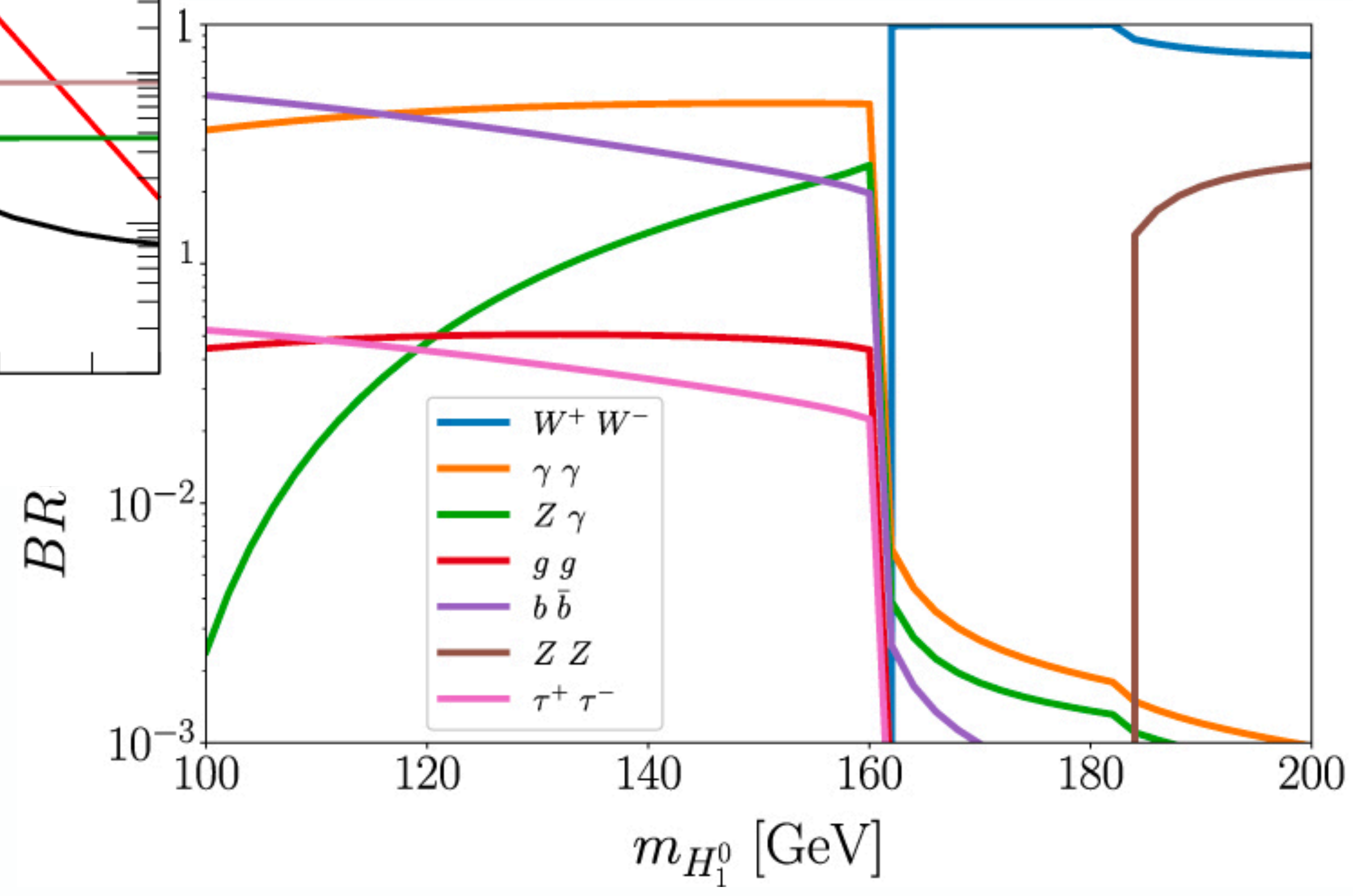
Neutral Higgs Production & Decays

- Just as for H_{125}, we need to consider several potential **production modes**: gluon-gluon fusion, vector boson fusion, WH and WZ, ttH…







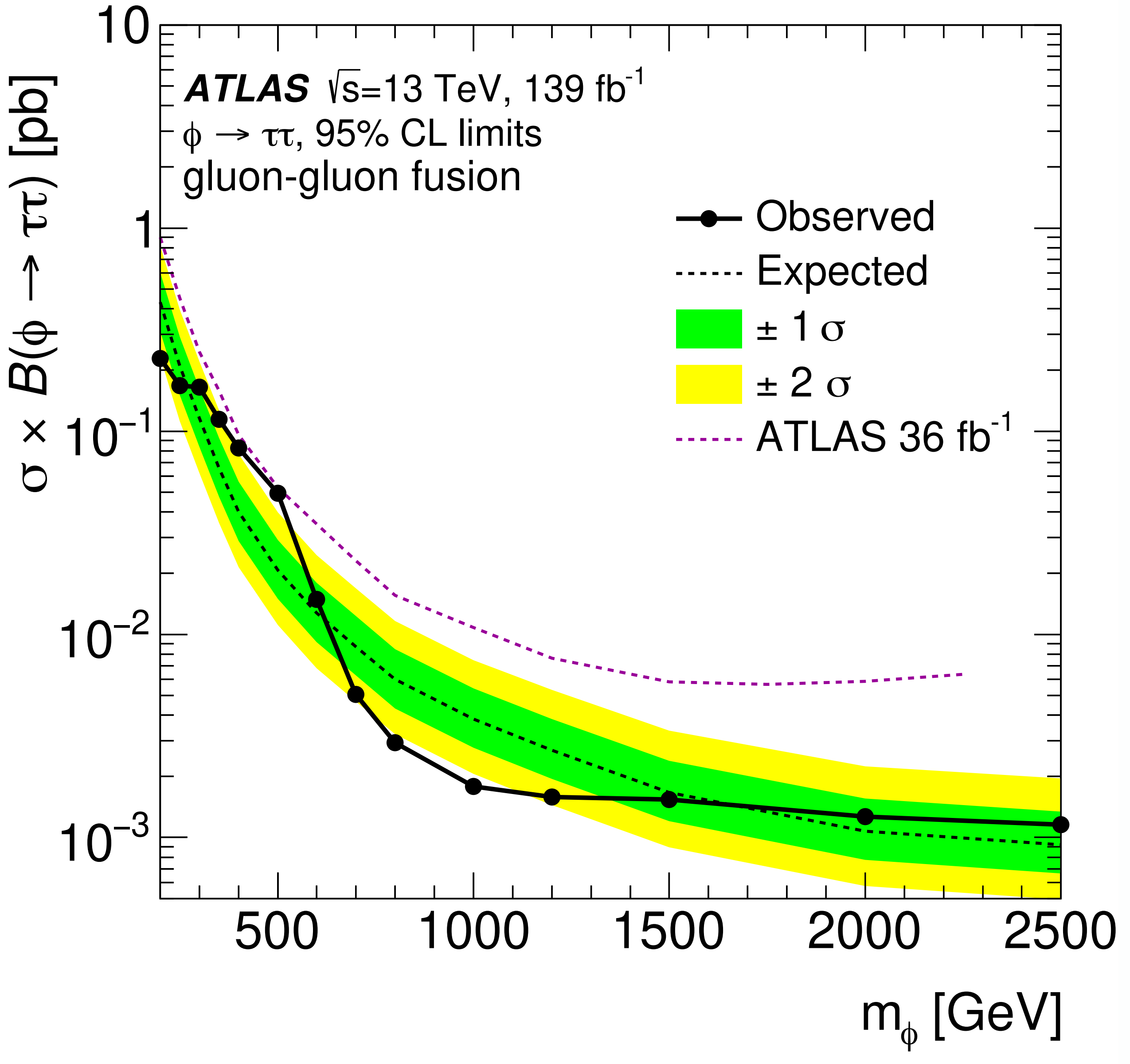


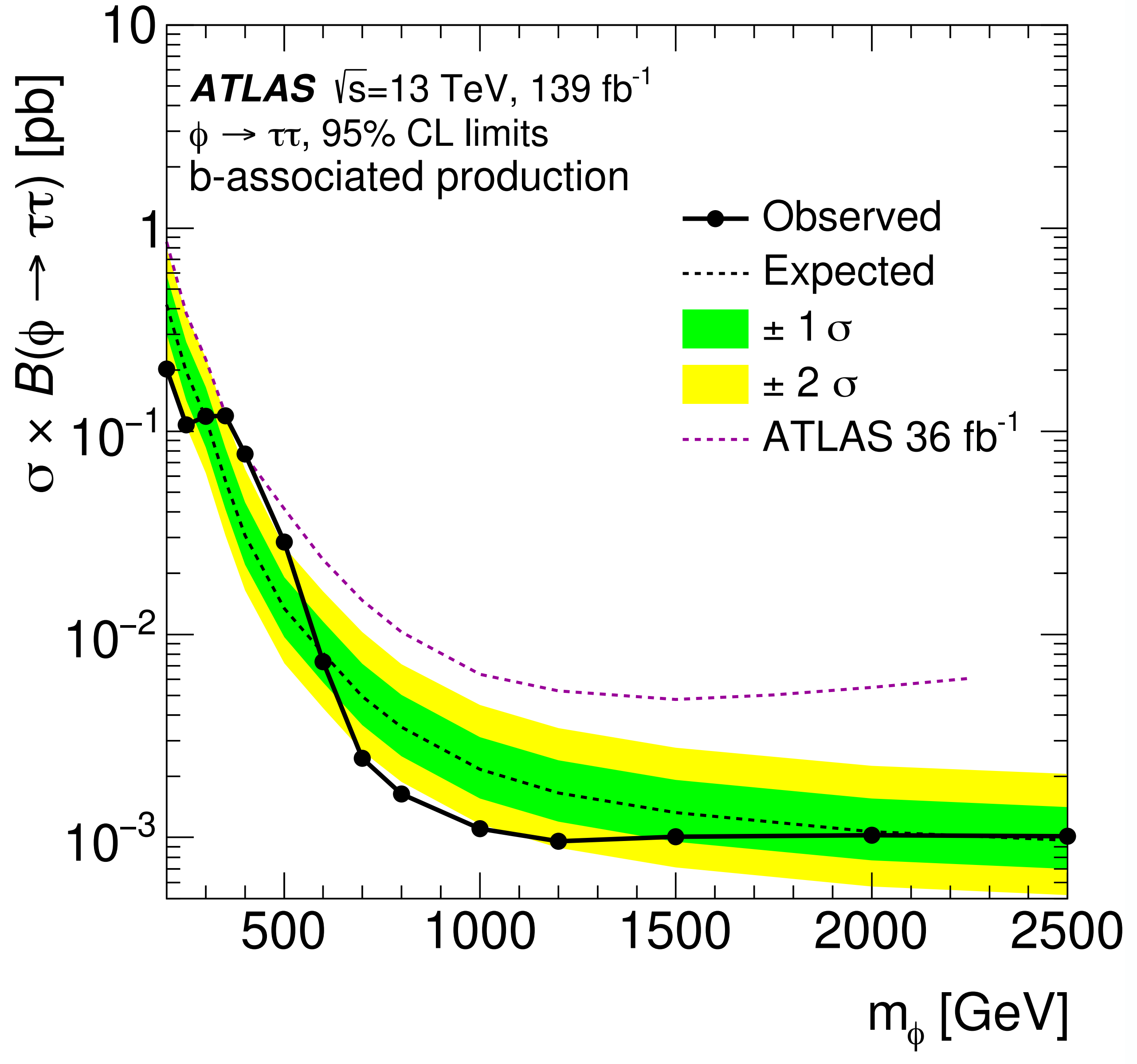
- **Branching fractions** depend on the BSM scalar mass, and often differently than in the SM!

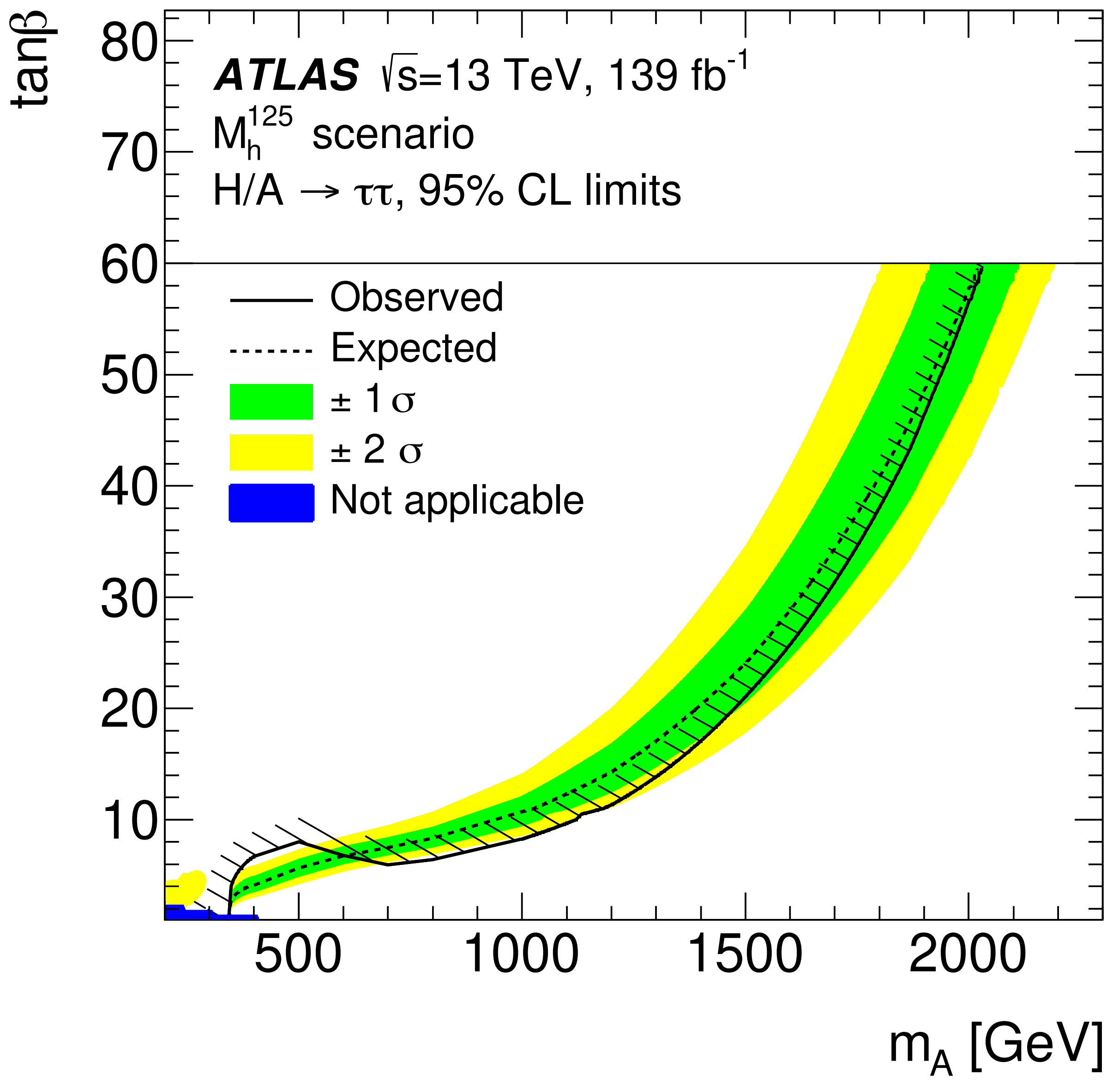
ATLAS & CMS H/A→ττ

ATLAS: arXiv:2002.12223

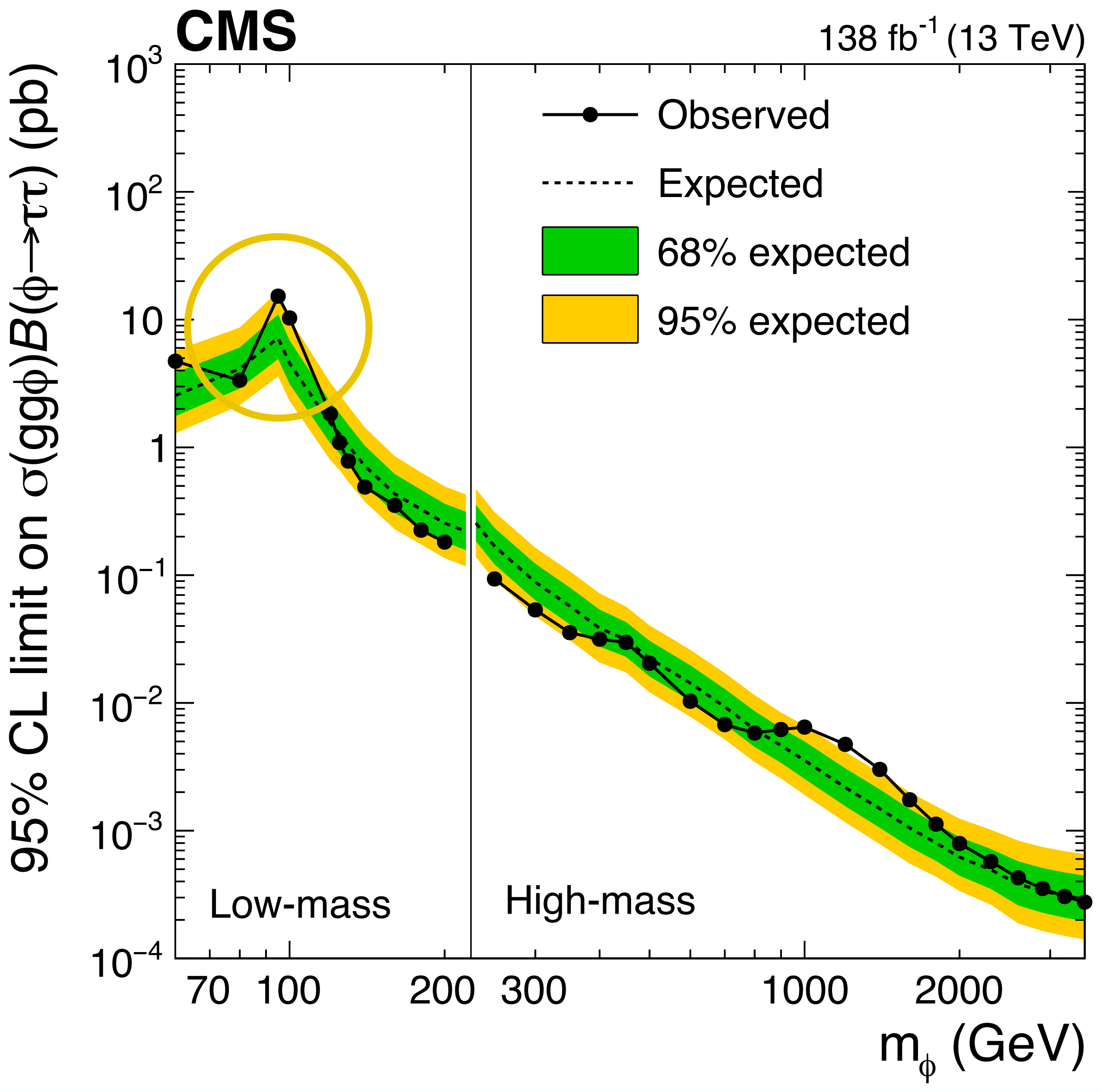
CMS: arXiv:2208.02717

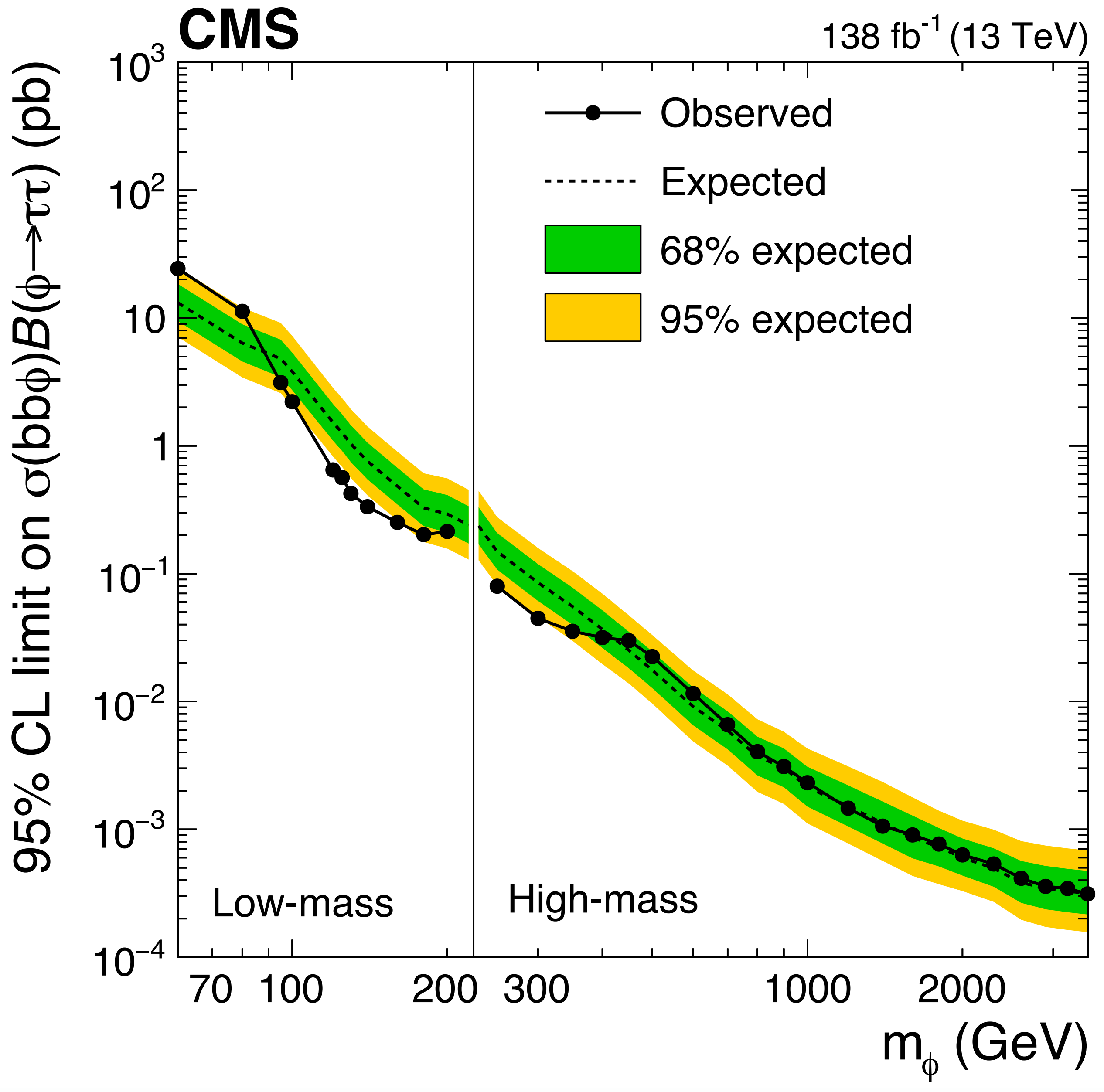


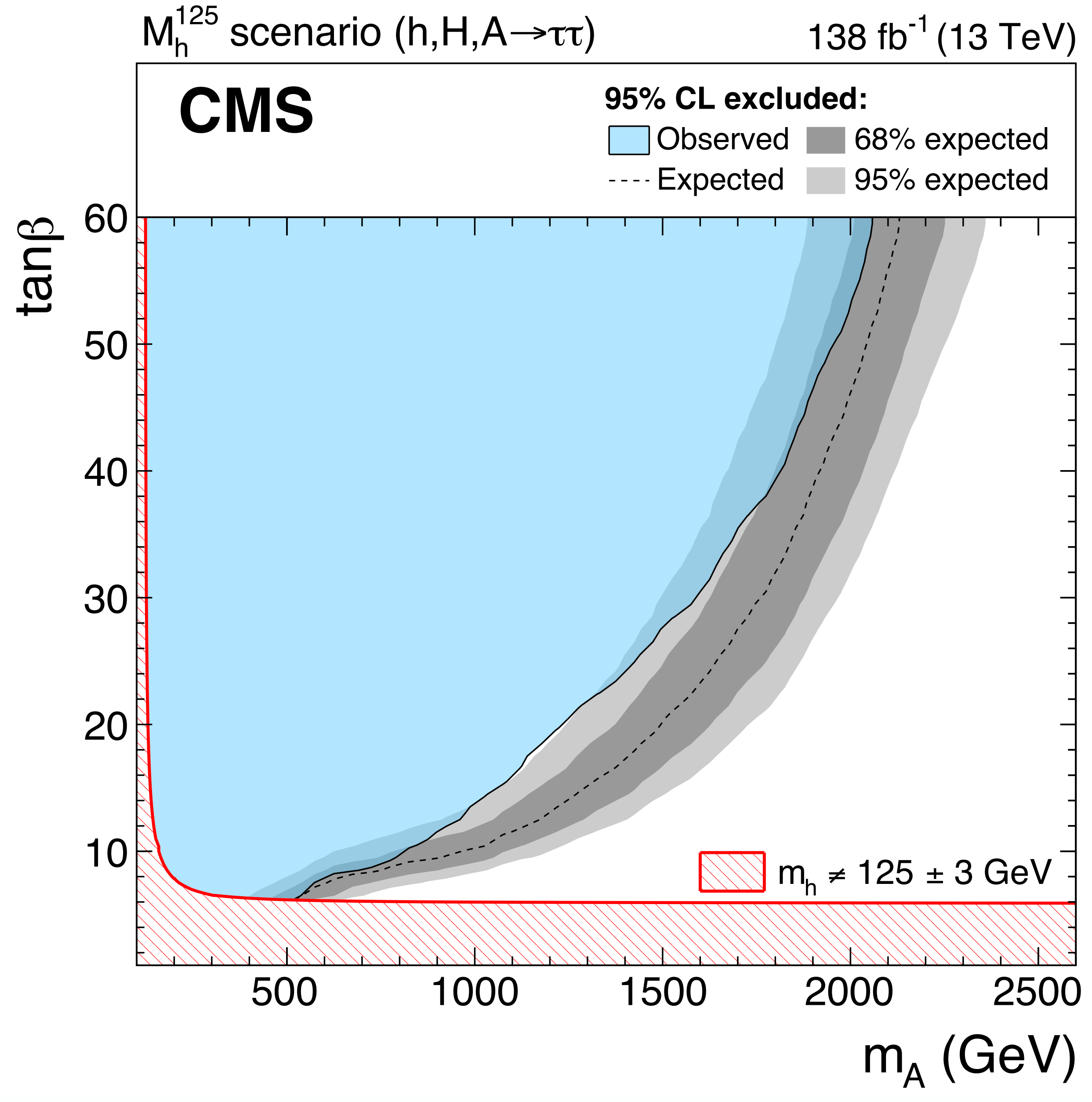




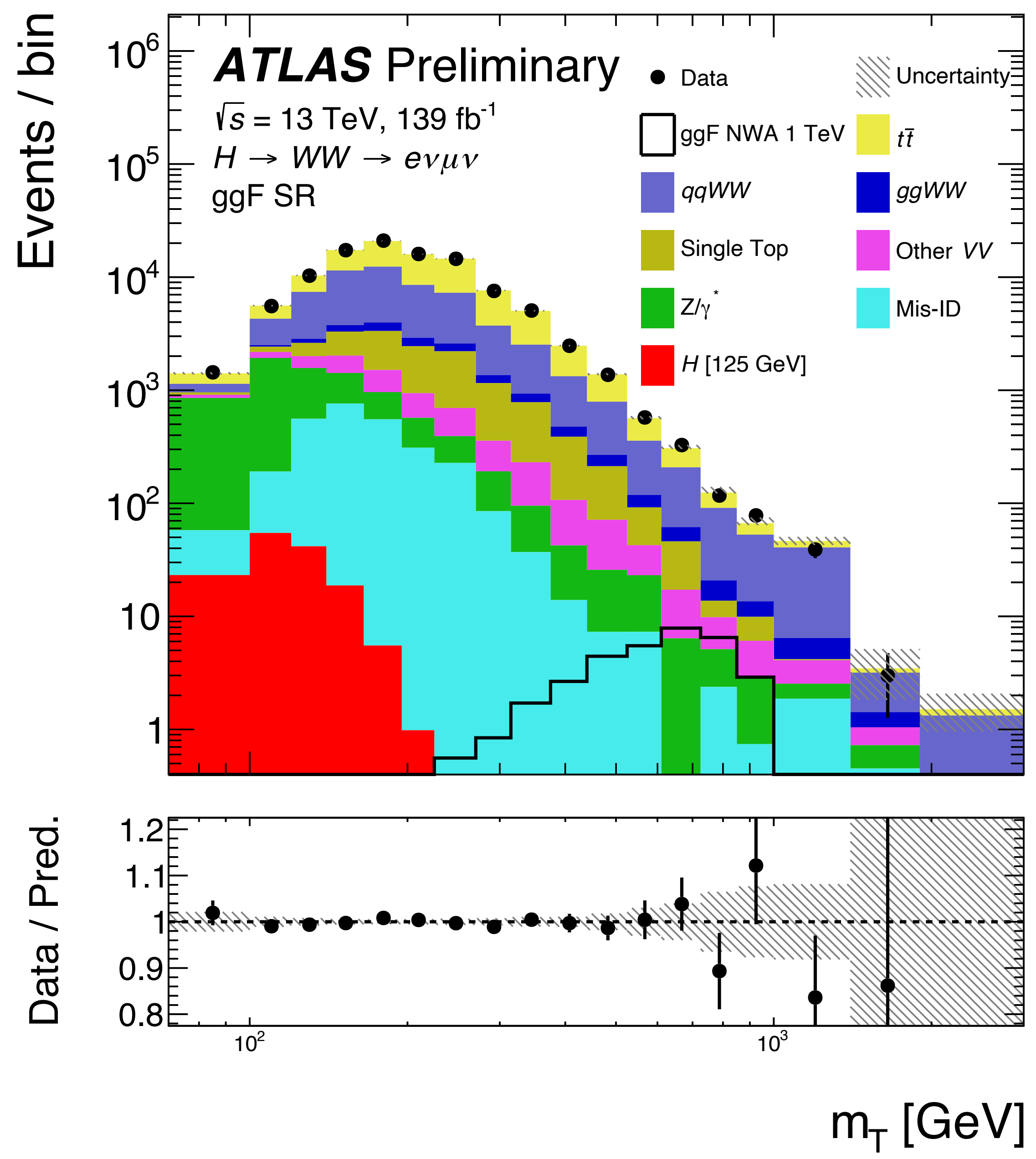
- H/A→ττ results are out with full Run 2 dataset
- CMS sees an excess of ~3σ (local) around 95 GeV
  - The other ~3σ one at 1.2 TeV is ruled out by ATLAS



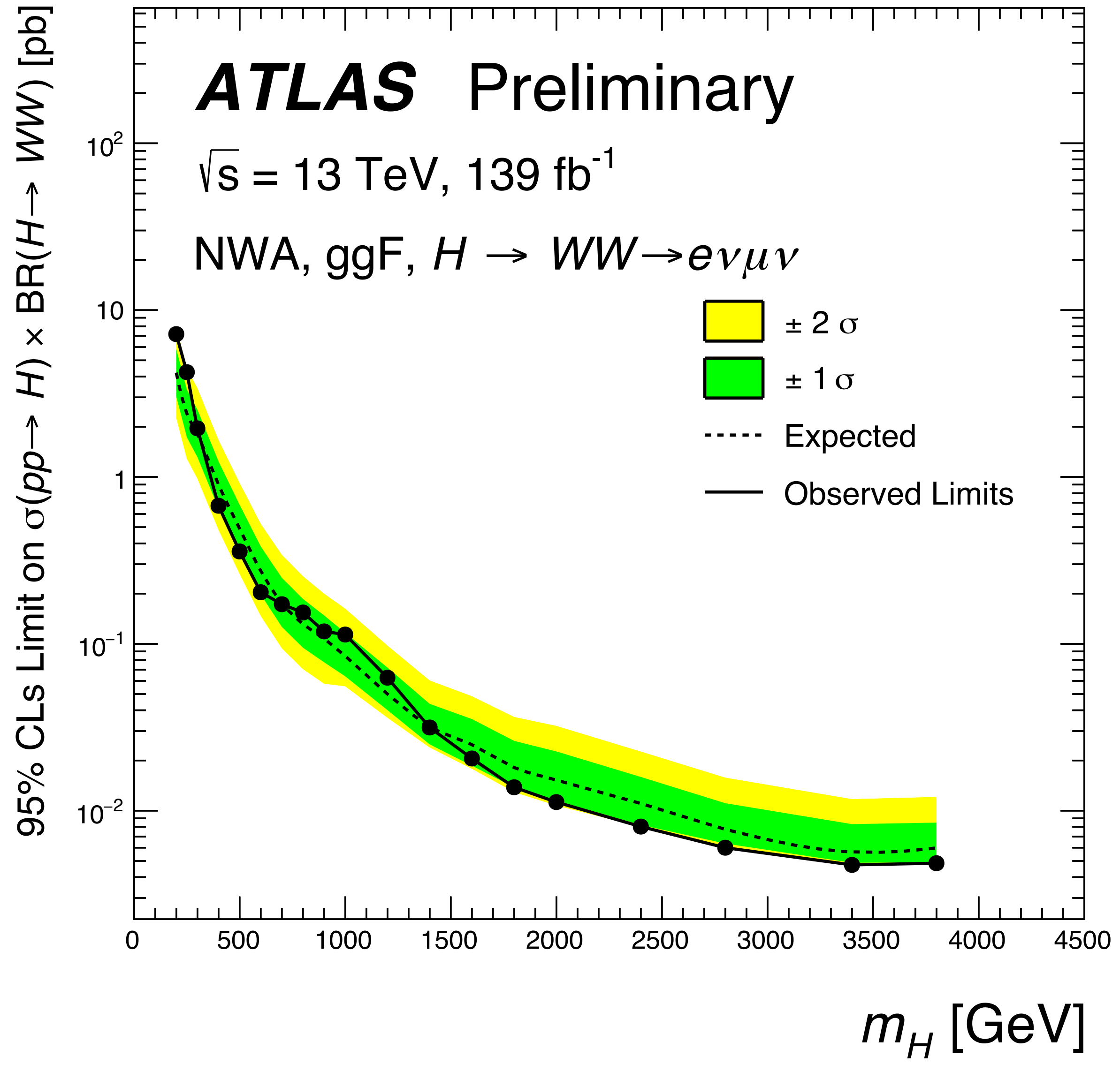


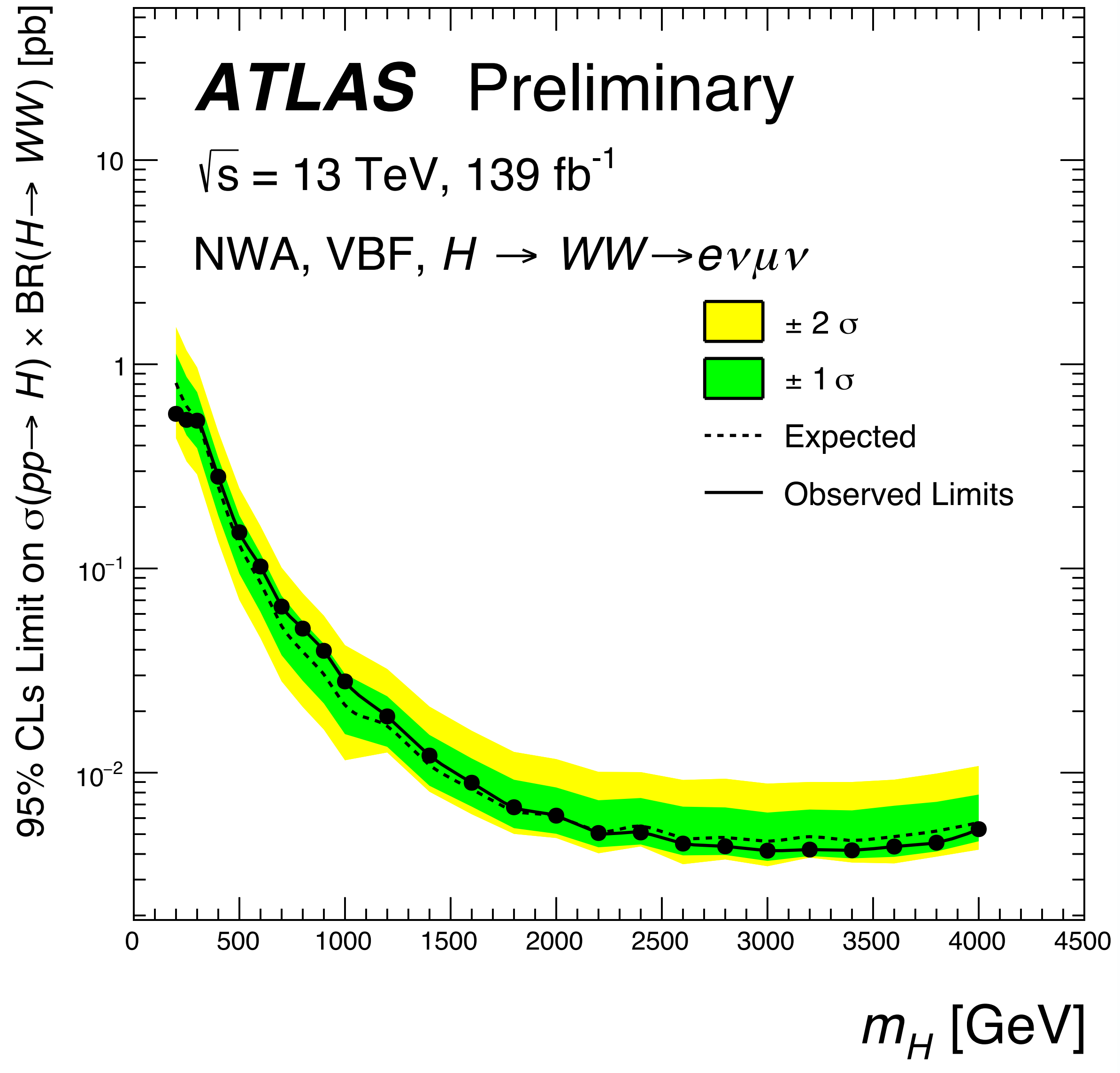


ATLAS & CMS H→WW



- Recent results in **dilepton** channel from both ATLAS & CMS, with search range **up to ~5 TeV**
  - ATLAS focuses on eμ+p_T^{miss}, CMS uses also ee and μμ
  - **Transverse mass** of leptons+p_T^{miss} as the discriminant
  - CMS uses a DNN for transverse mass regression
- No significant excess
  - CMS sees 3.8 (2.6) sigma local (global) VBF-like excess at **650 GeV**, not ruled out by the ATLAS limit

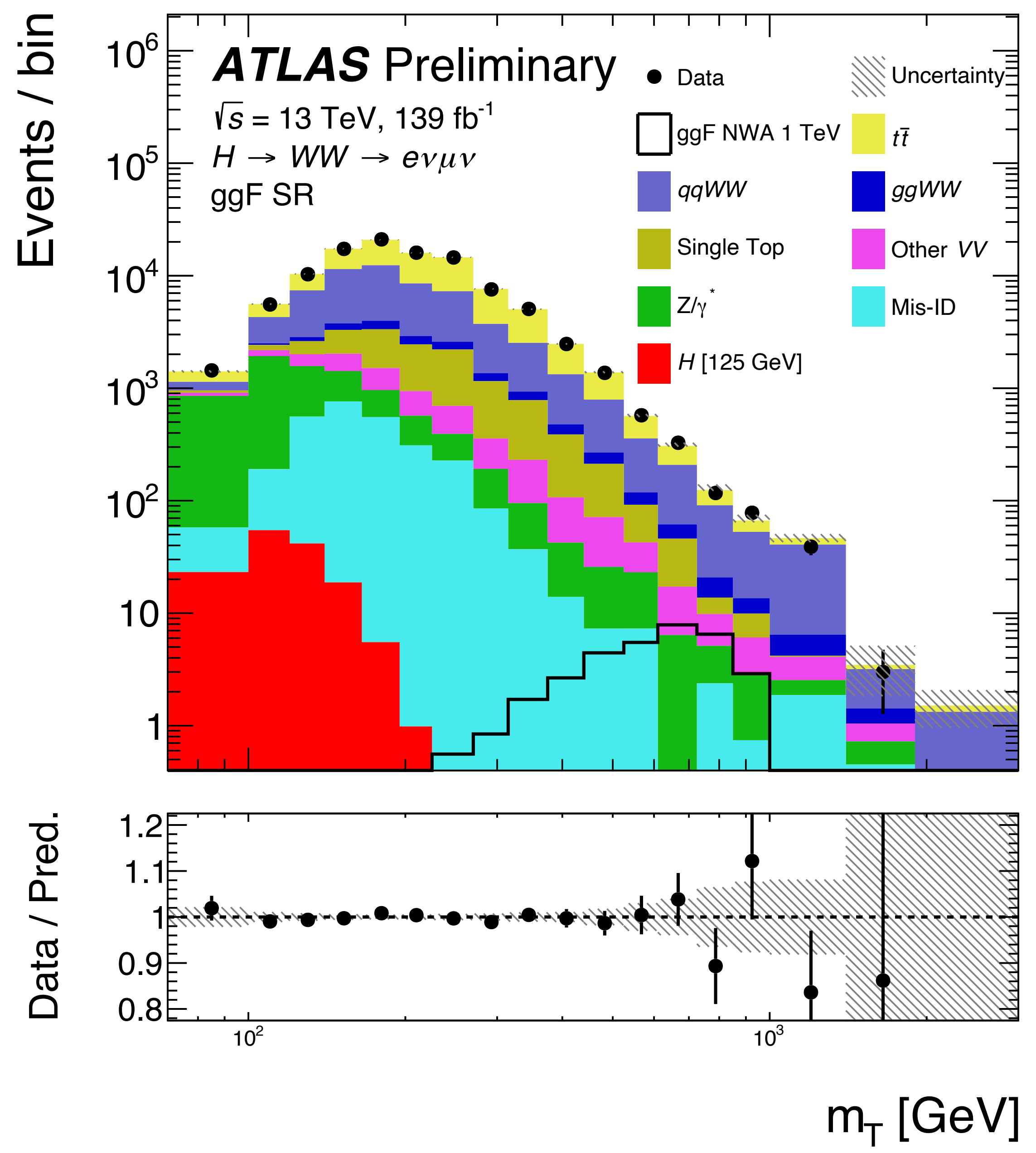




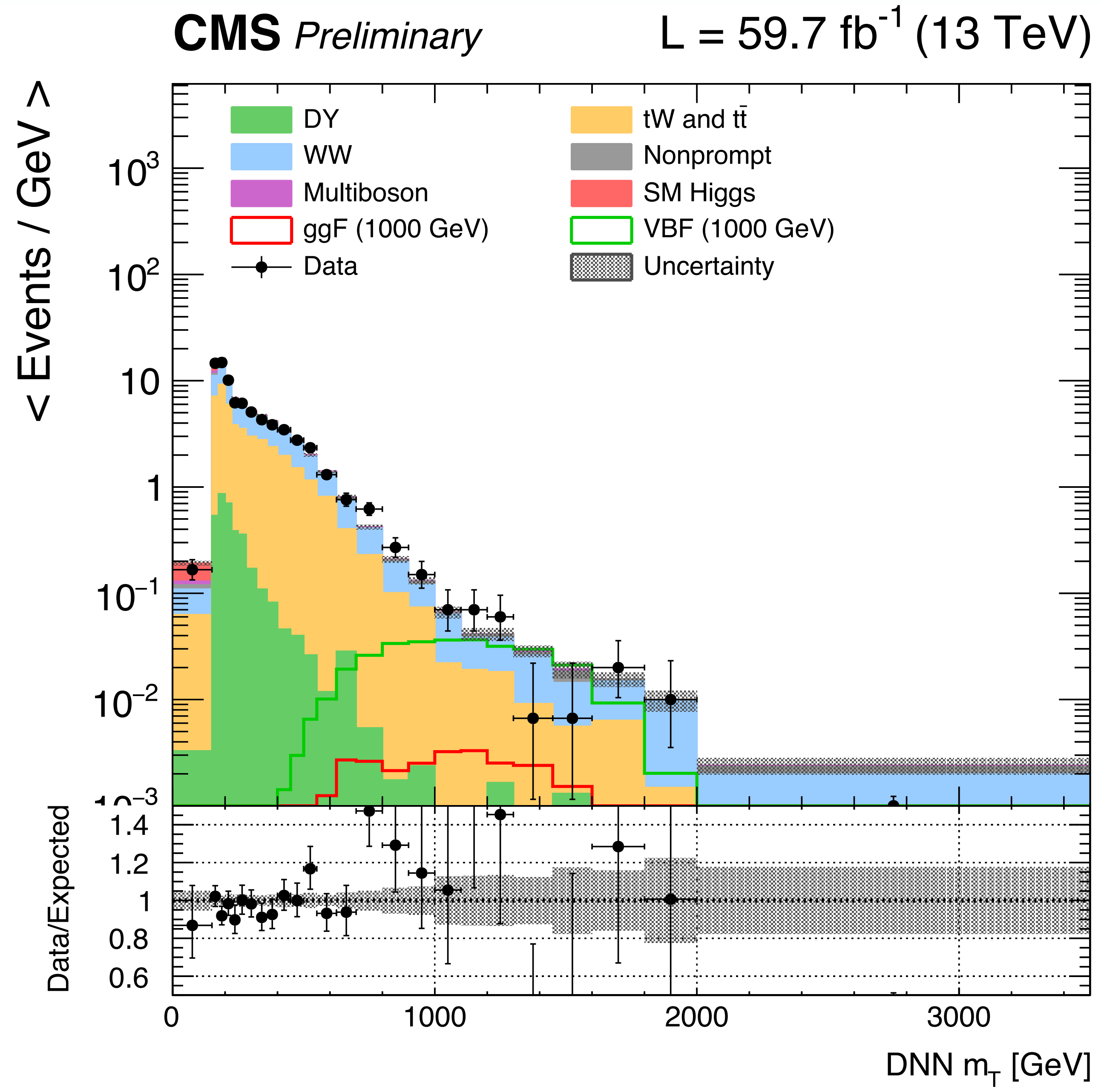
ATLAS & CMS H→WW

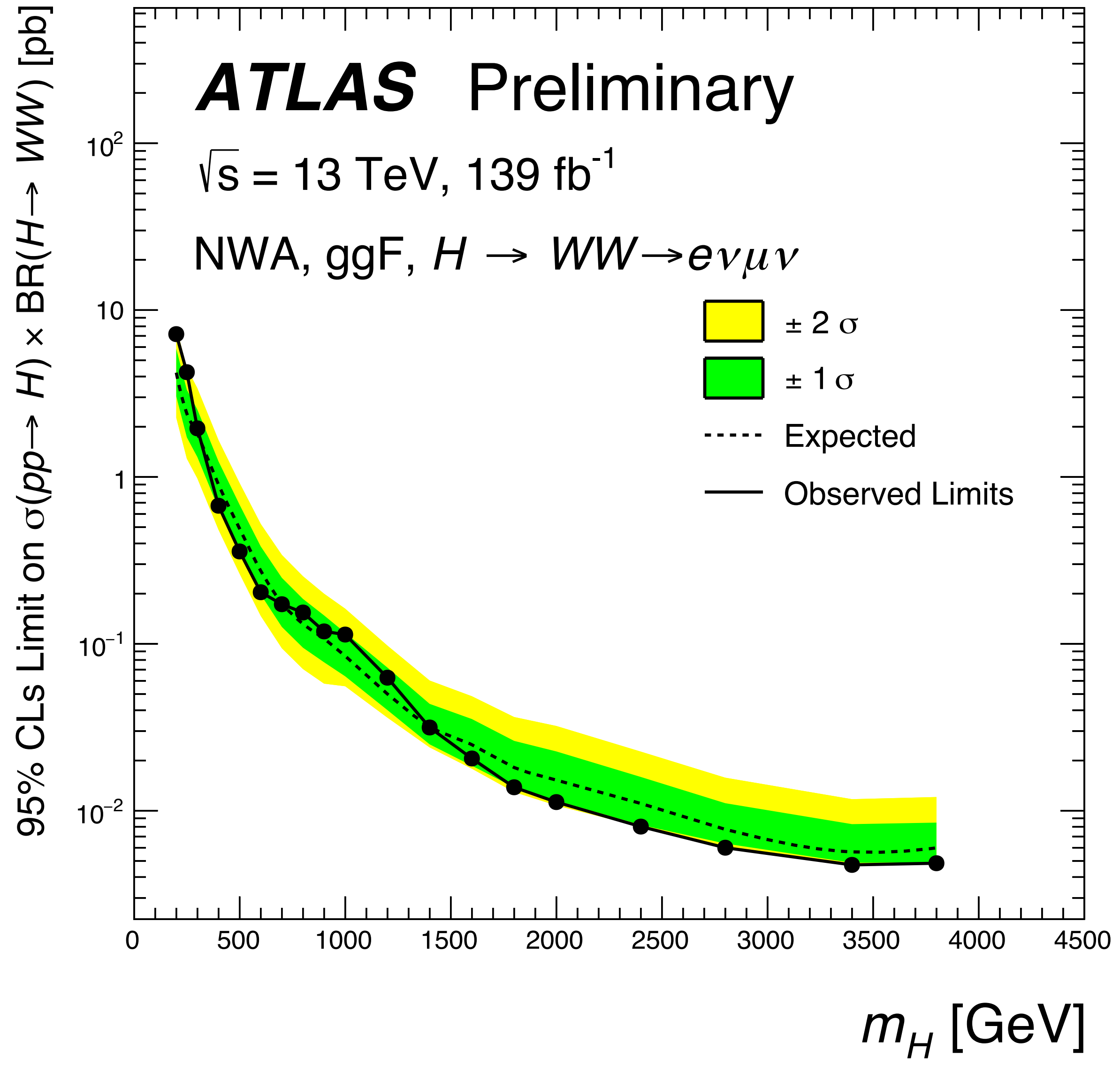
ATLAS-CONF-2022-066

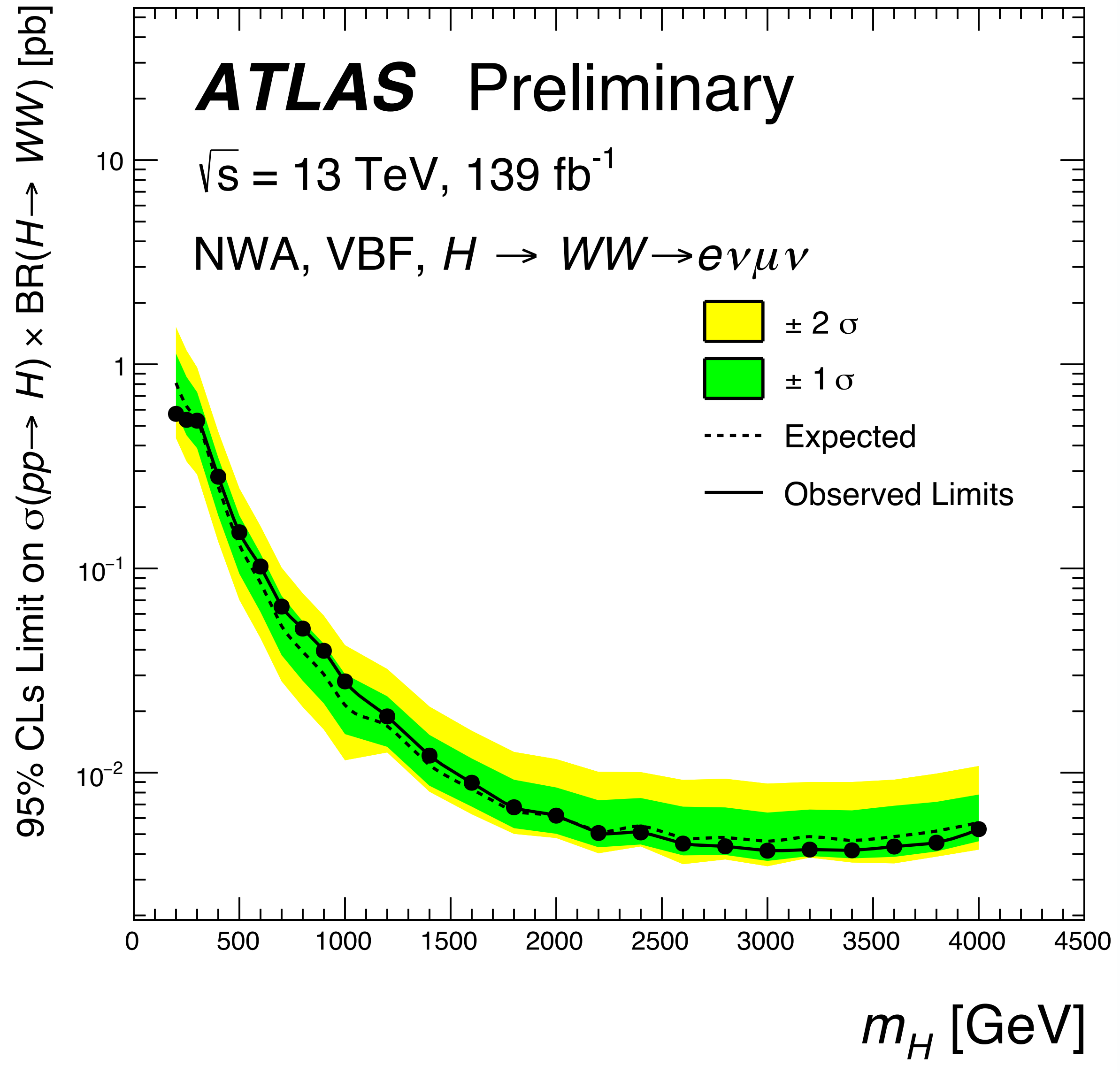
CMS-PAS-HIG-20-016



- Recent results in **dilepton** channel from both ATLAS & CMS, with search range **up to ~5 TeV**
  - ATLAS focuses on eμ+p_T^{miss}, CMS uses also ee and μμ
  - **Transverse mass** of leptons+p_T^{miss} as the discriminant
  - CMS uses a DNN for transverse mass regression
- No significant excess
  - CMS sees 3.8 (2.6) sigma local (global) VBF-like excess at **650 GeV**, not ruled out by the ATLAS limit



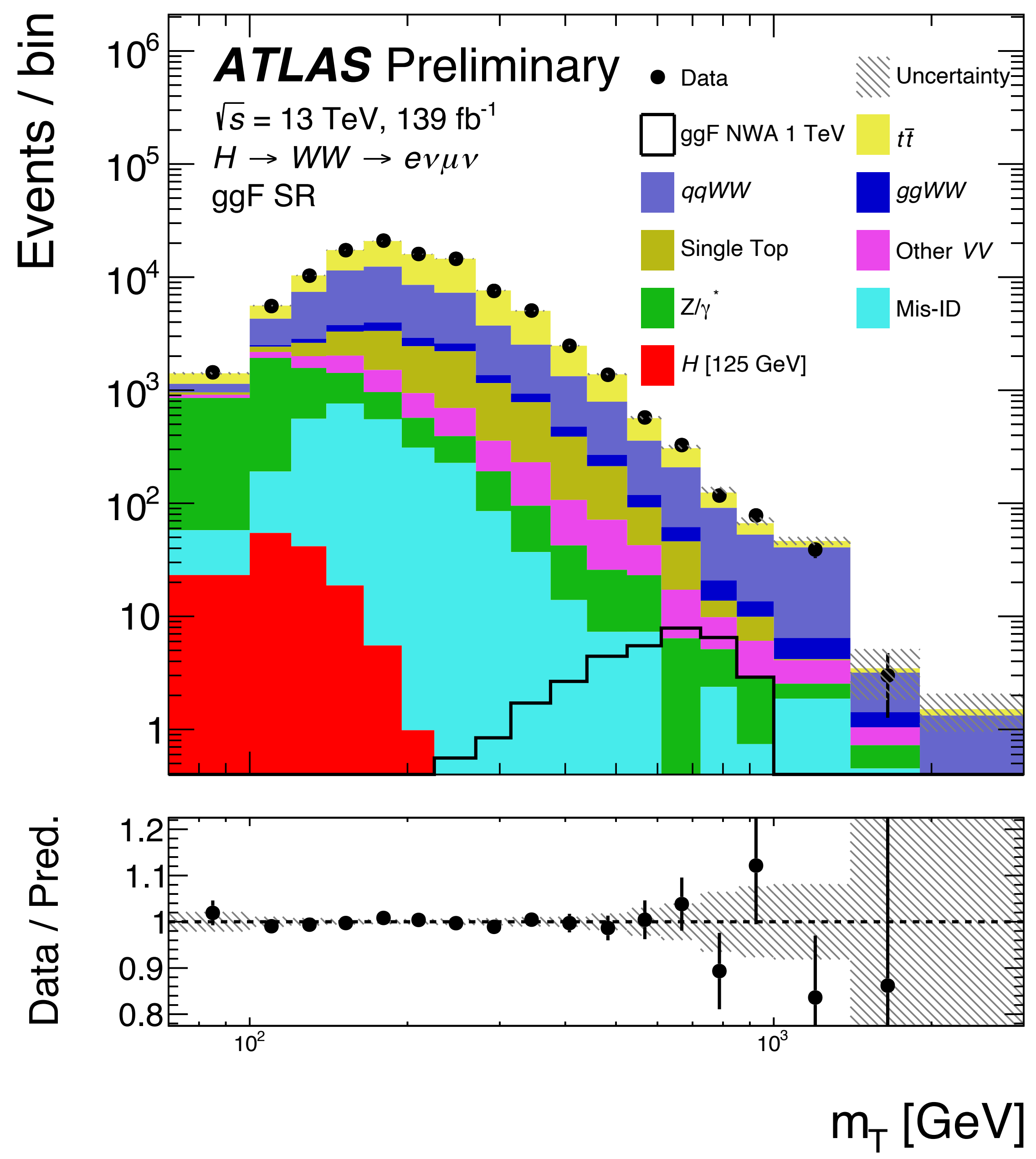




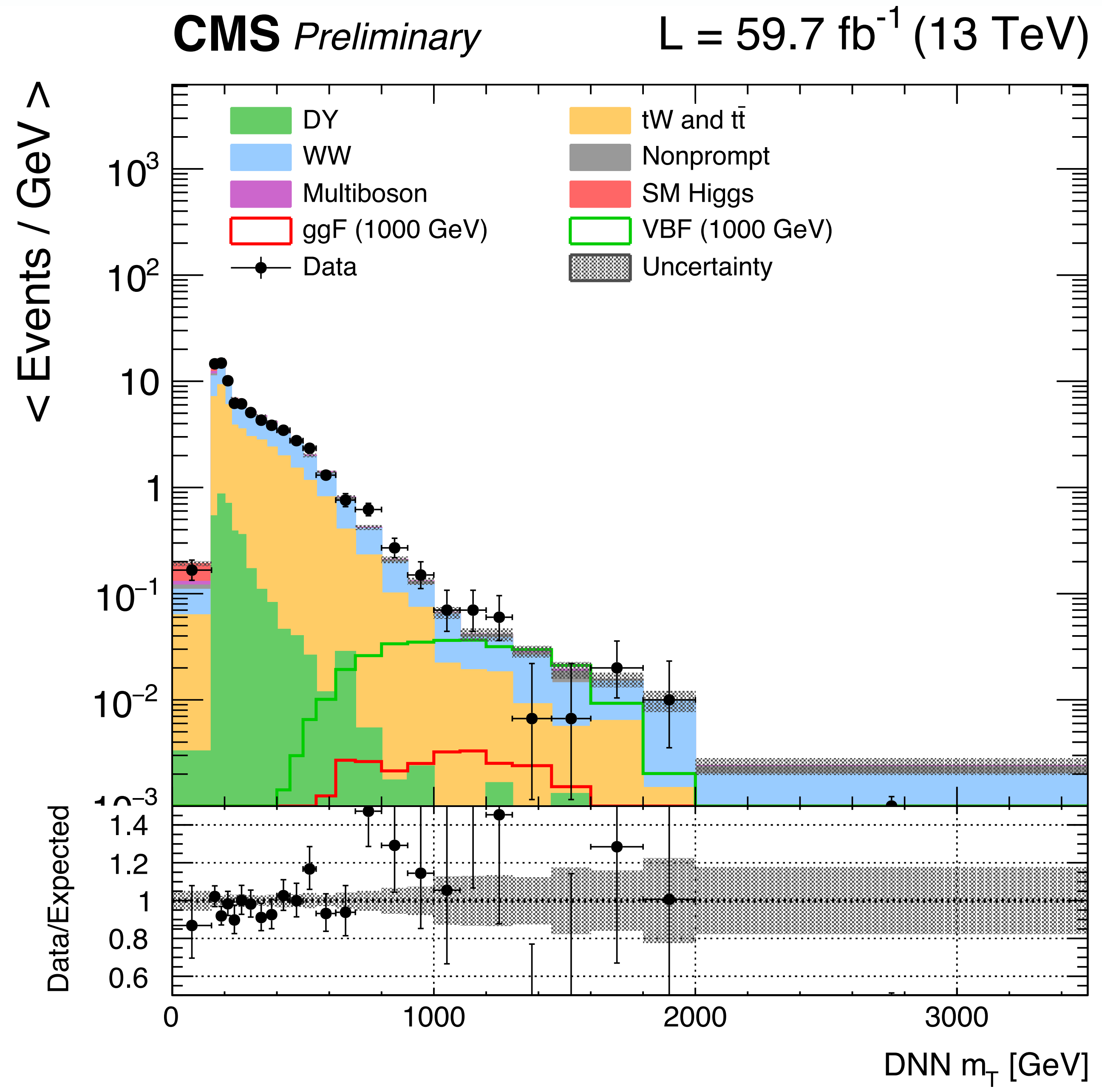
ATLAS & CMS H→WW

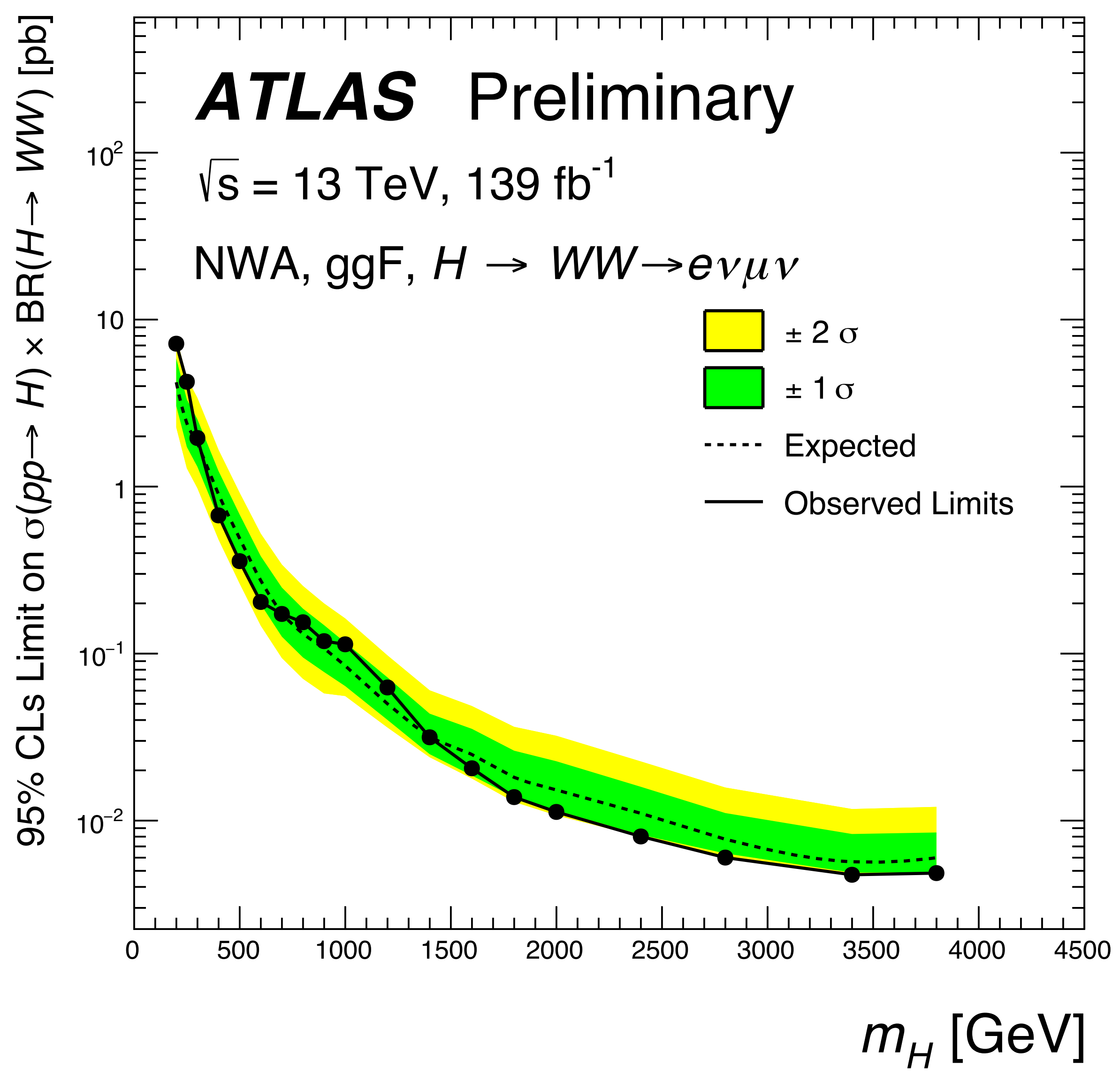
ATLAS-CONF-2022-066

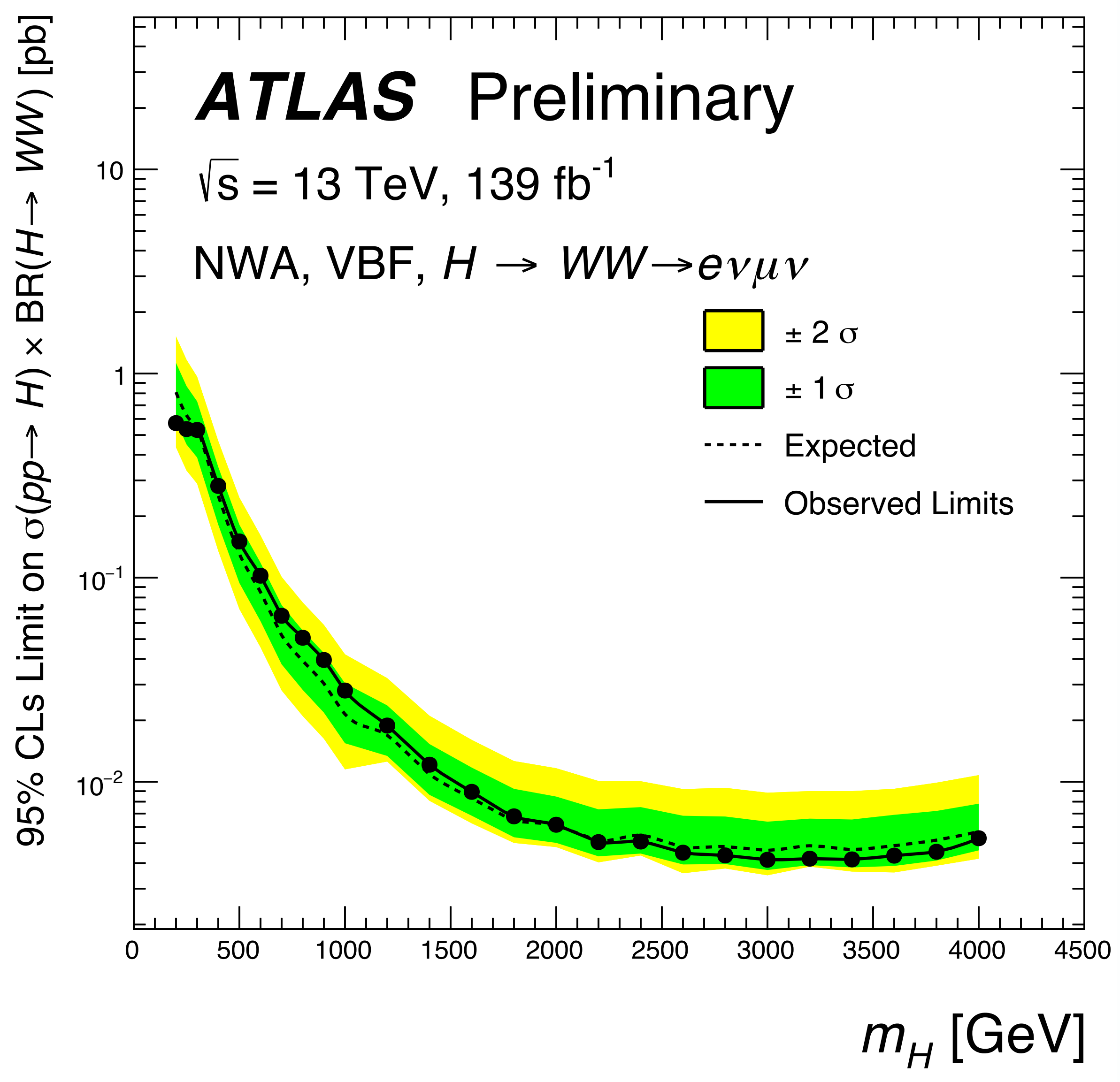
CMS-PAS-HIG-20-016

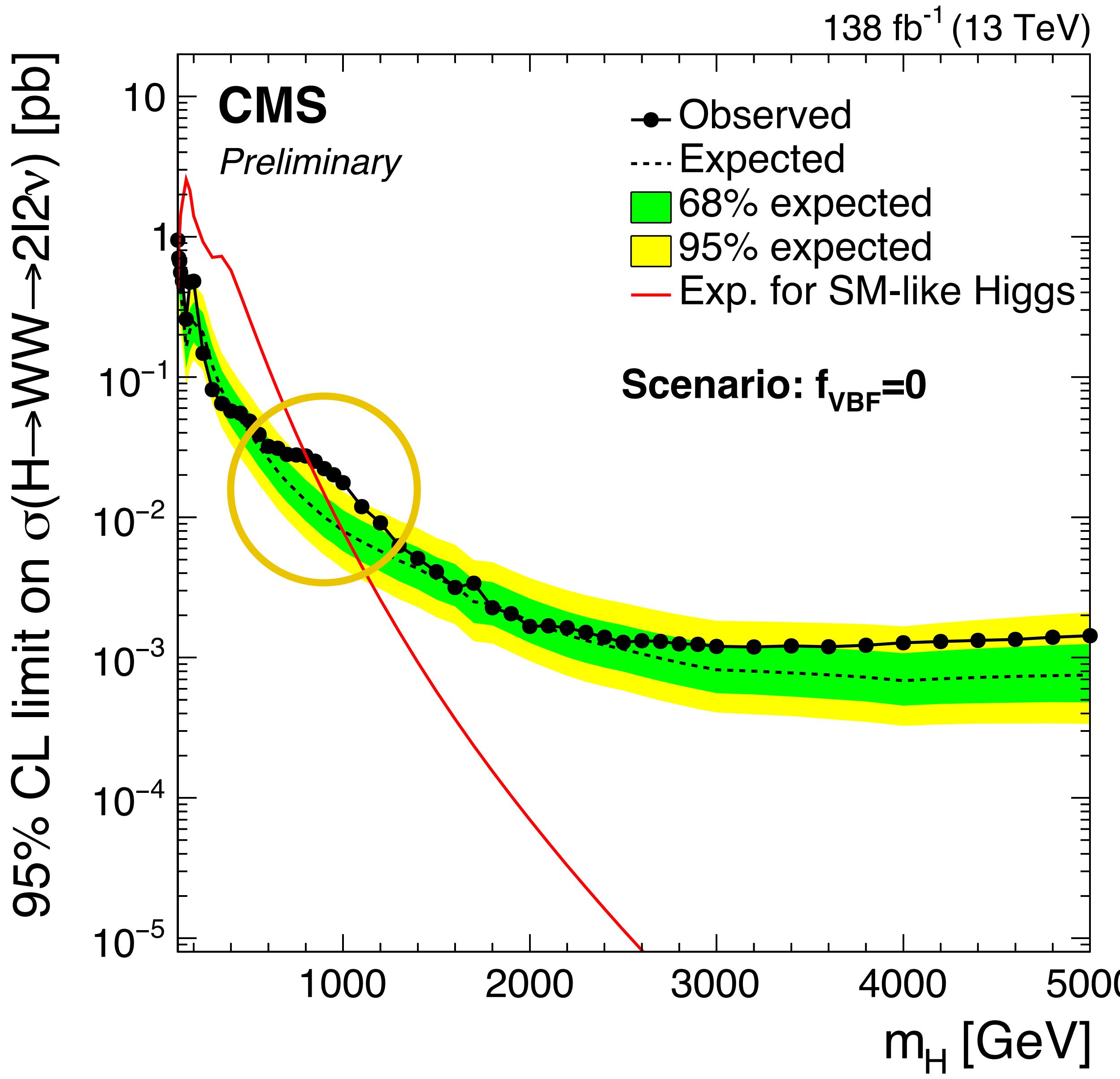


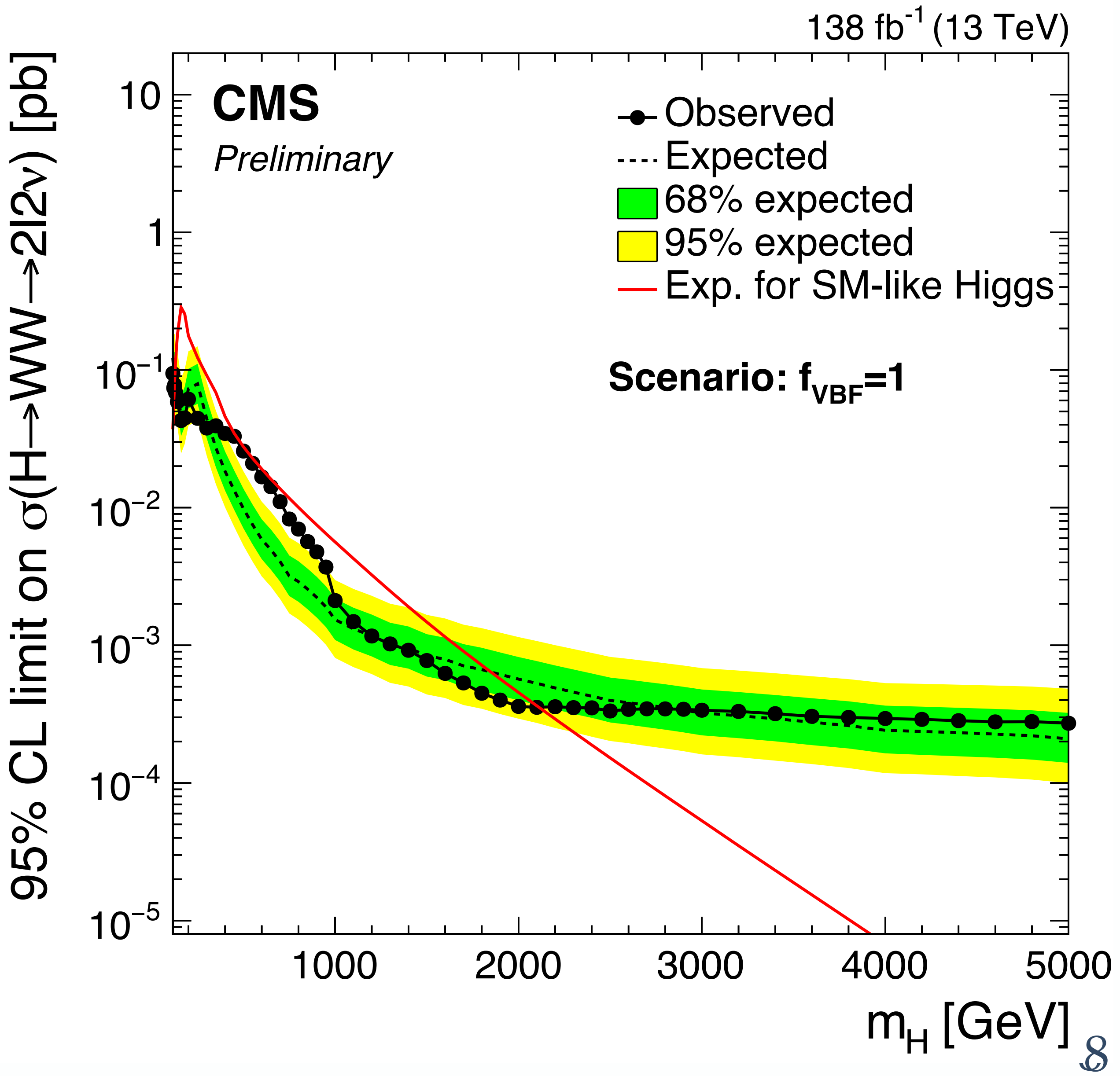
- Recent results in **dilepton** channel from both ATLAS & CMS, with search range **up to ~5 TeV**
  - ATLAS focuses on eμ+p_T^{miss}, CMS uses also ee and μμ
  - **Transverse mass** of leptons+p_T^{miss} as the discriminant
  - CMS uses a DNN for transverse mass regression
- No significant excess
  - CMS sees 3.8 (2.6) sigma local (global) VBF-like excess at **650 GeV**, not ruled out by the ATLAS limit







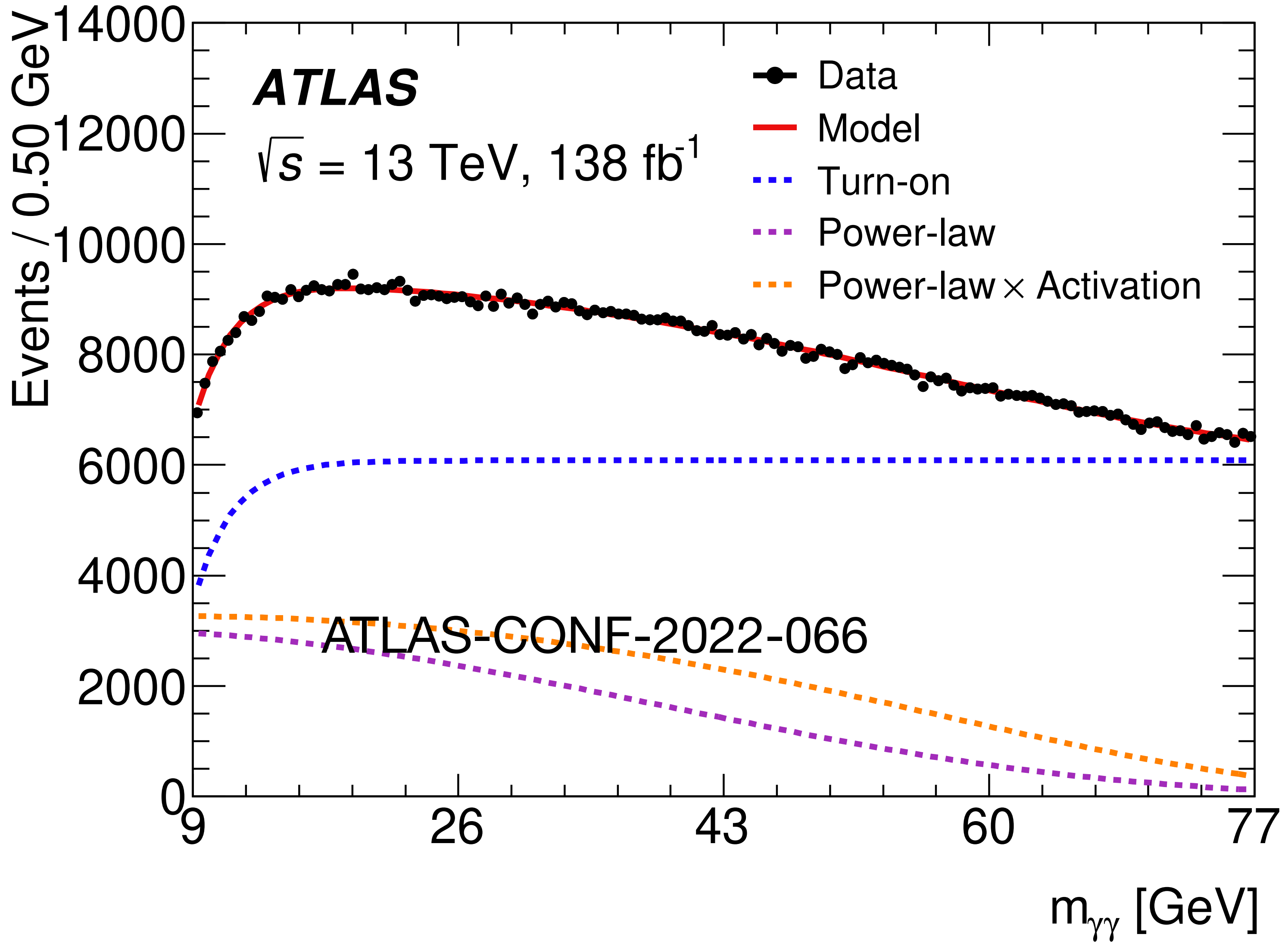


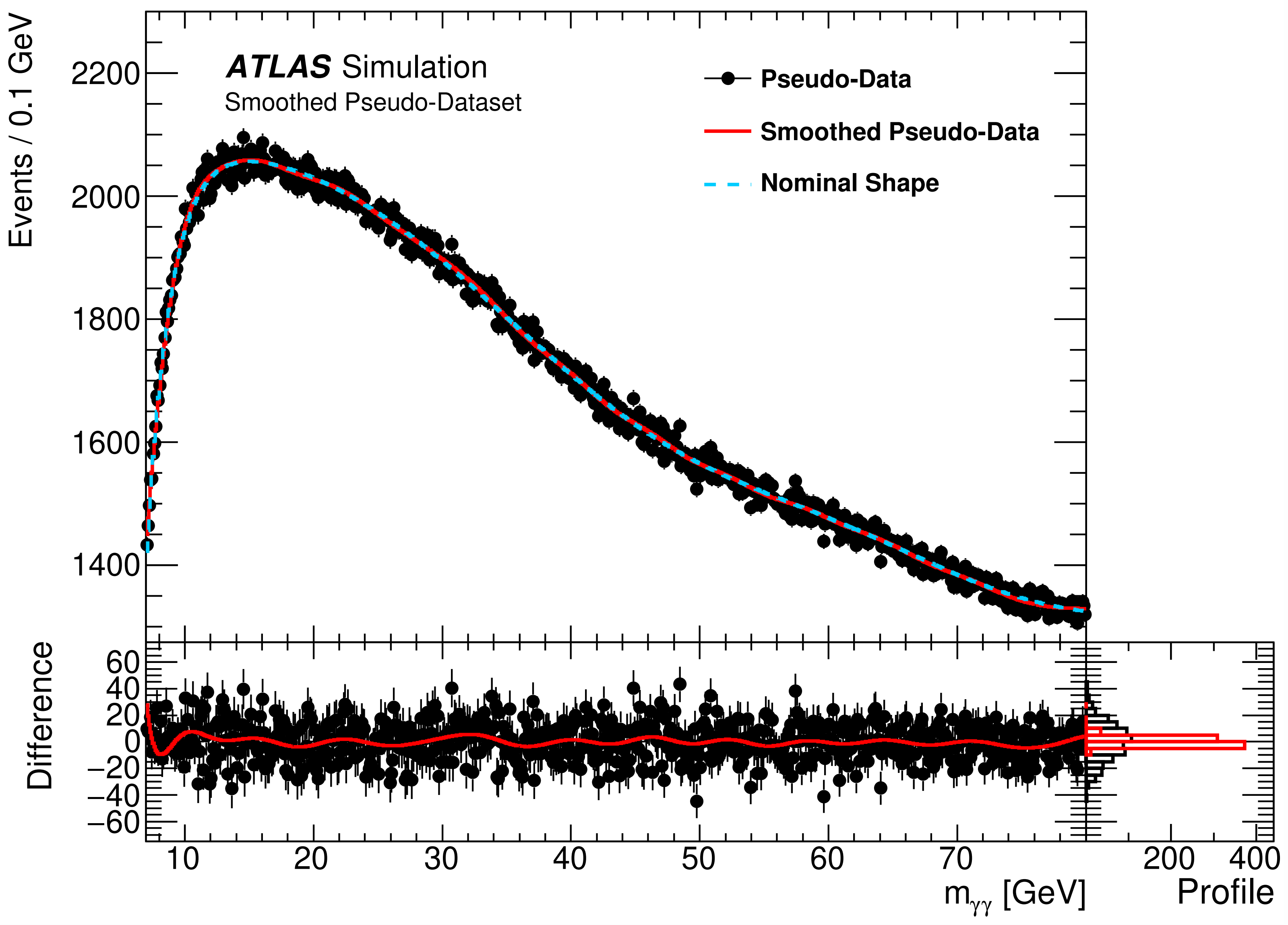


ATLAS H→γγ at low mass

arXiv:2211.04172

- First LHC search for generic low-mass γγ resonances reaching below 65 GeV and **down to 10 GeV**
- Select **closely spaced photon pairs** boosted against a jet, with **$p_T(\gamma\gamma)$ > 50 GeV**
- Background modeling based on a **parametric fit**
  - Smoothing based on **Gaussian Process regression** reduces the modeling systematics
  - Uncertainty in smoothing estimated with pseudo-data

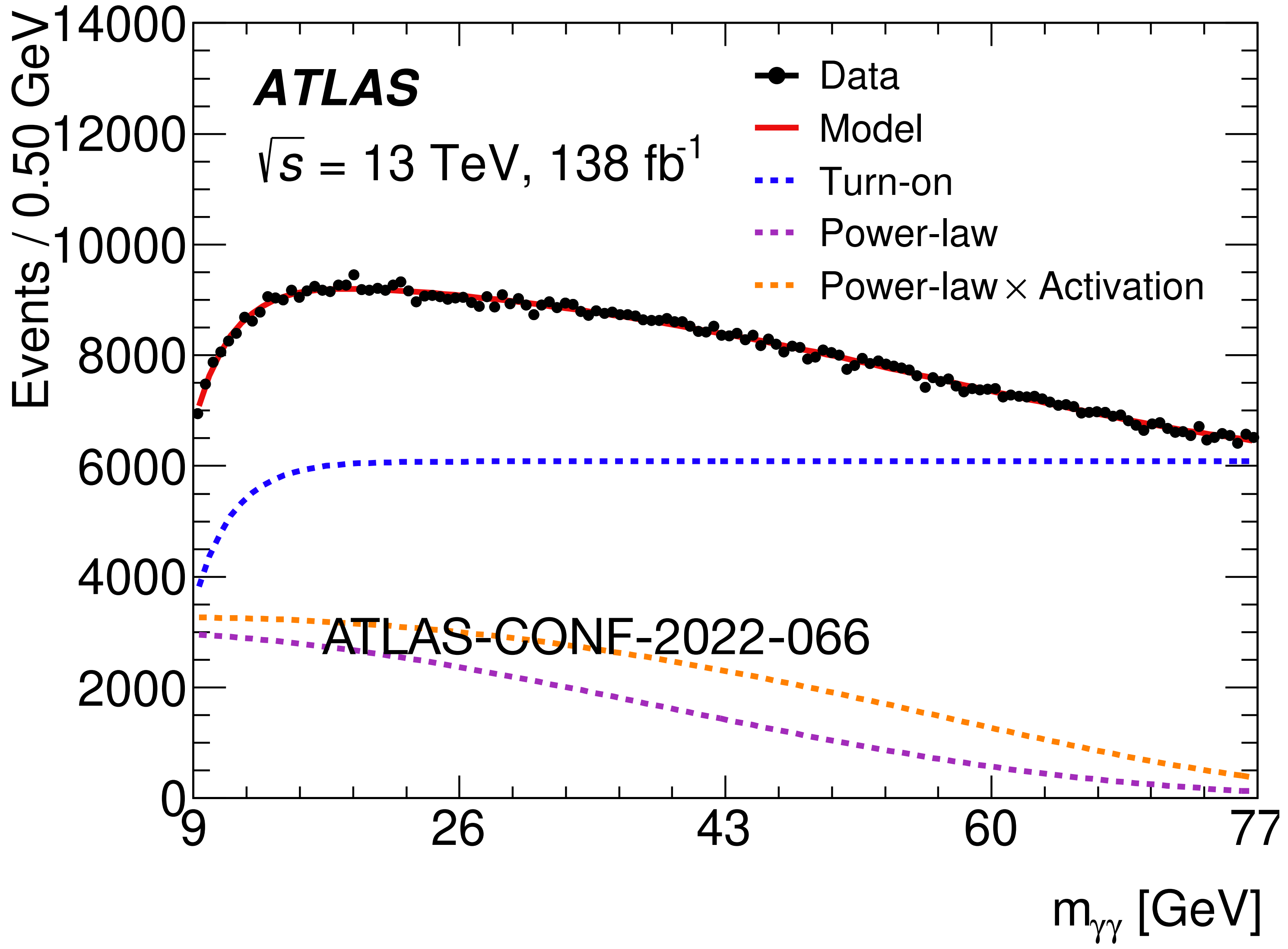


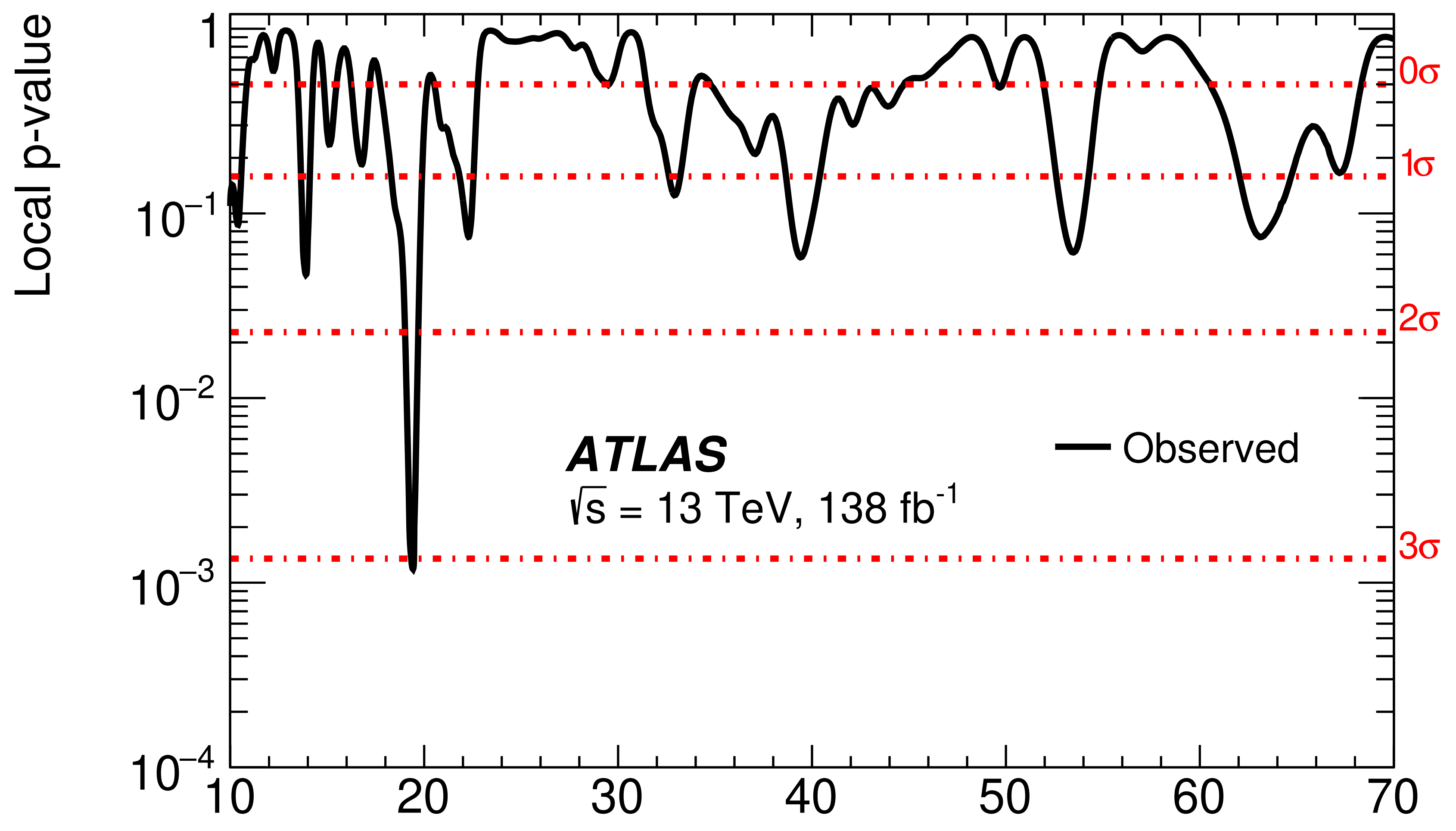


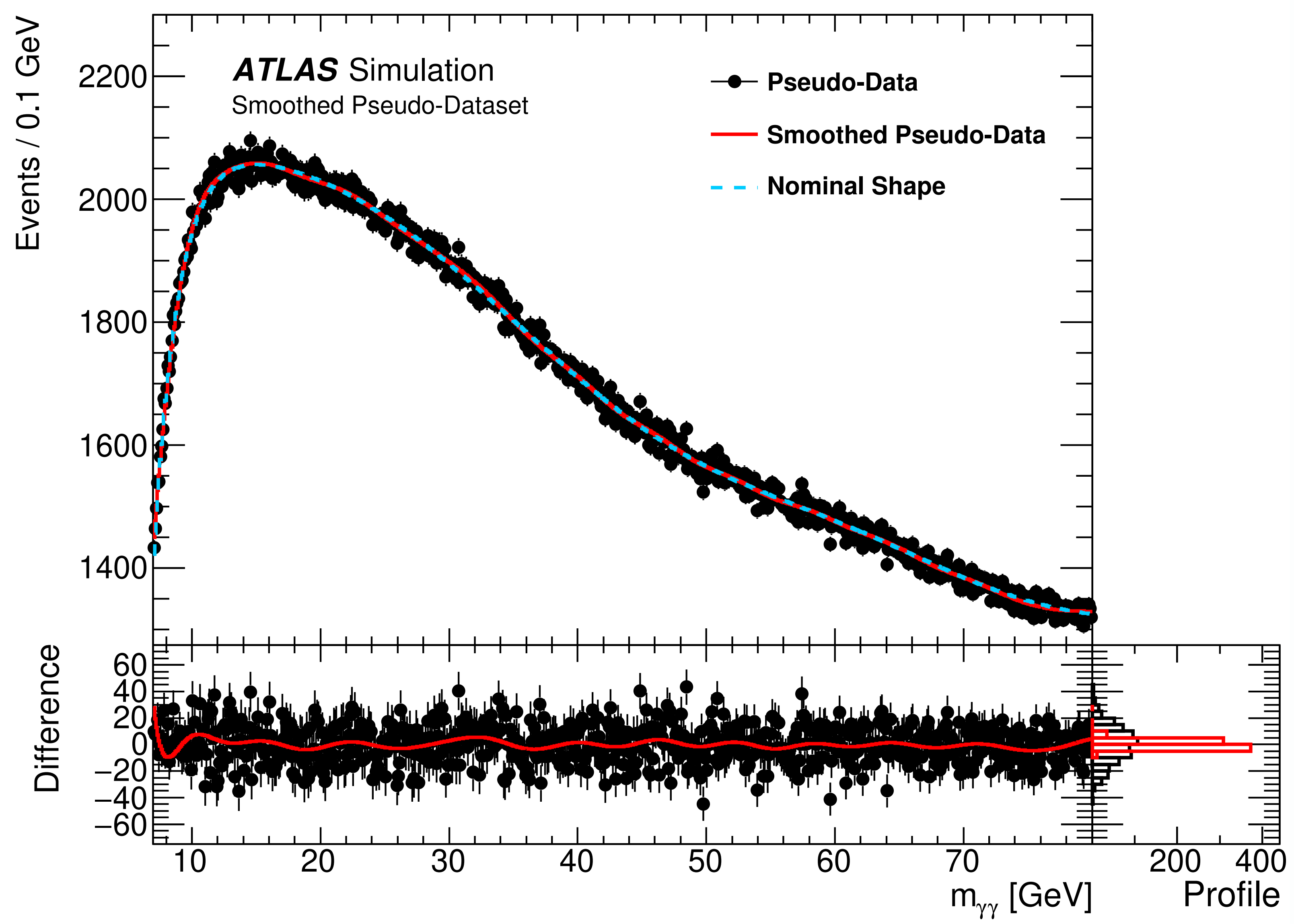
ATLAS H→γγ at low mass

arXiv:2211.04172

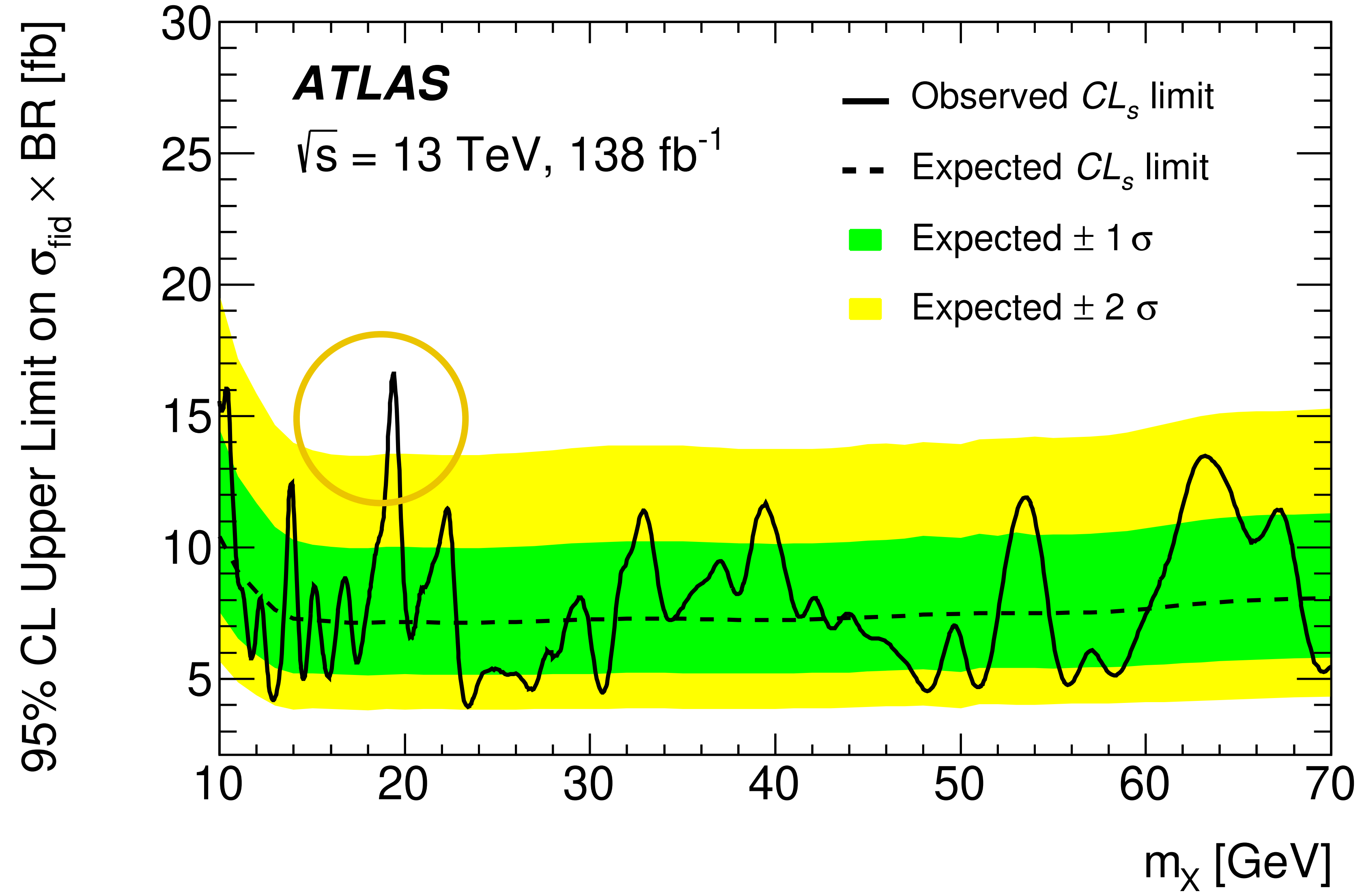
- First LHC search for generic low-mass γγ resonances reaching below 65 GeV and **down to 10 GeV**
- Select **closely spaced photon pairs** boosted against a jet, with **$p_T(\gamma\gamma)$ > 50 GeV**
- Background modeling based on a **parametric fit**
  - Smoothing based on **Gaussian Process regression** reduces the modeling systematics
  - Uncertainty in smoothing estimated with pseudo-data







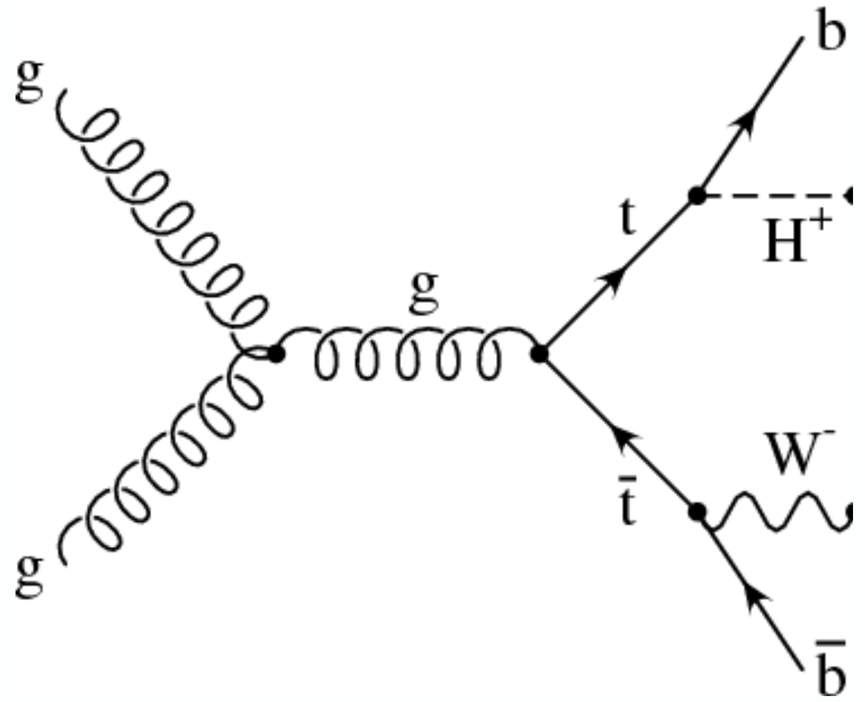
- Final discriminant: **diphoton invariant mass**
- No significant excess
  - The largest is 3.1σ (1.5σ) local (global) at 19.4 GeV

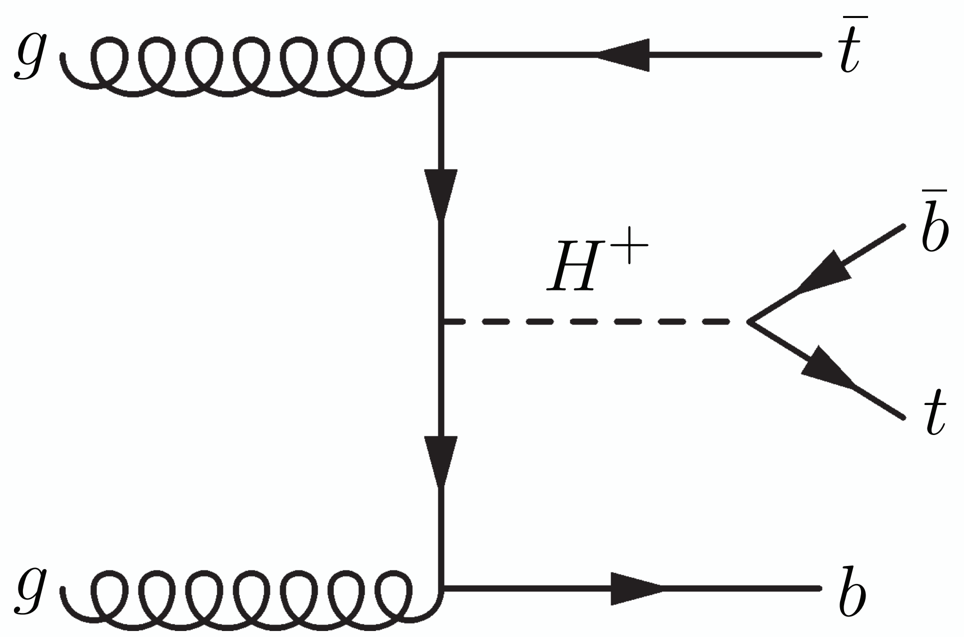


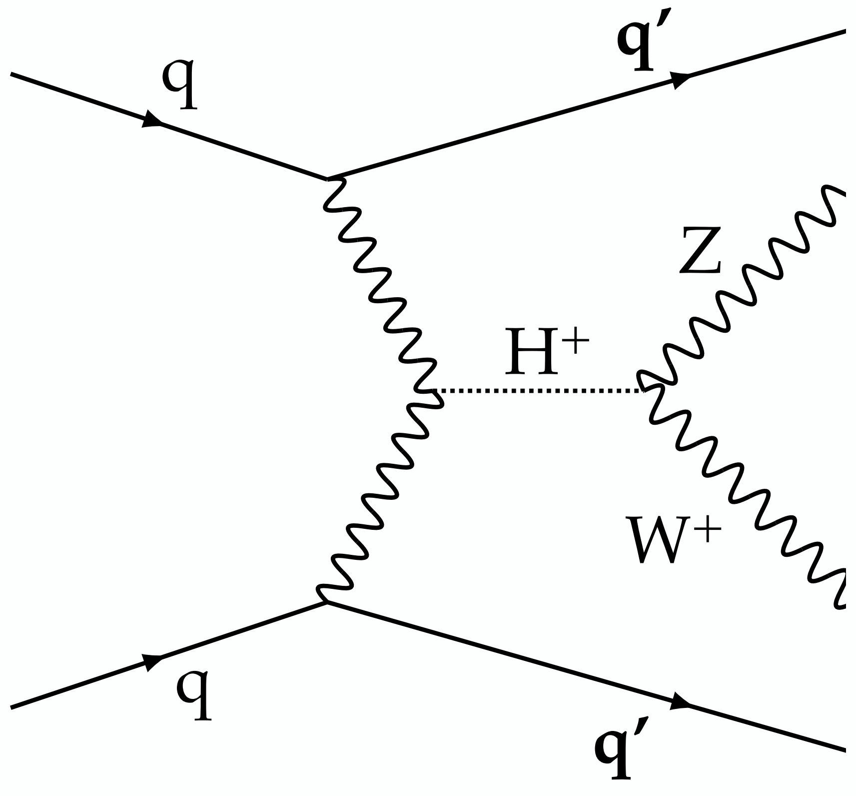
Charged BSM scalars

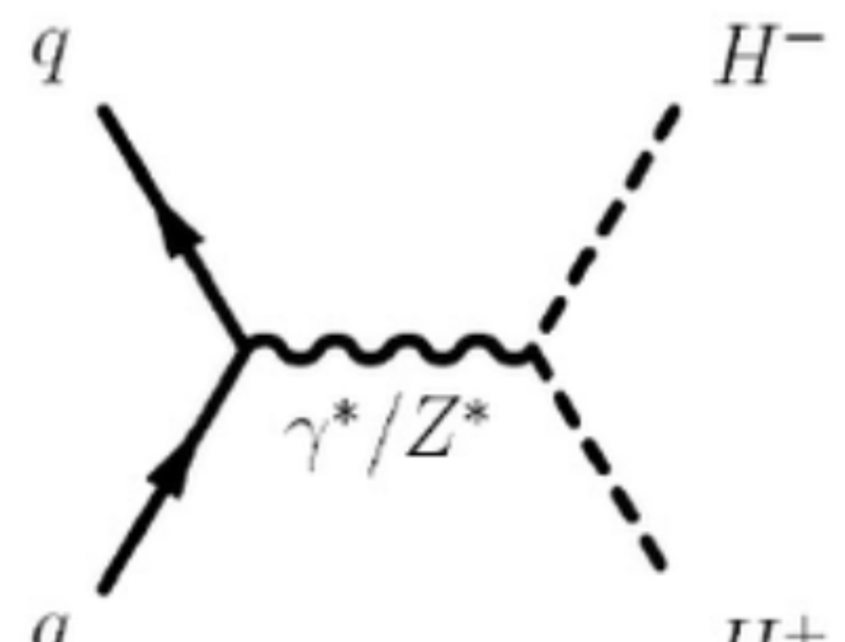
Charged Higgs production and decays

- Many possible production modes:
  - Top quark decays
  - Top associated production
  - Vector boson fusion
  - S-channel production





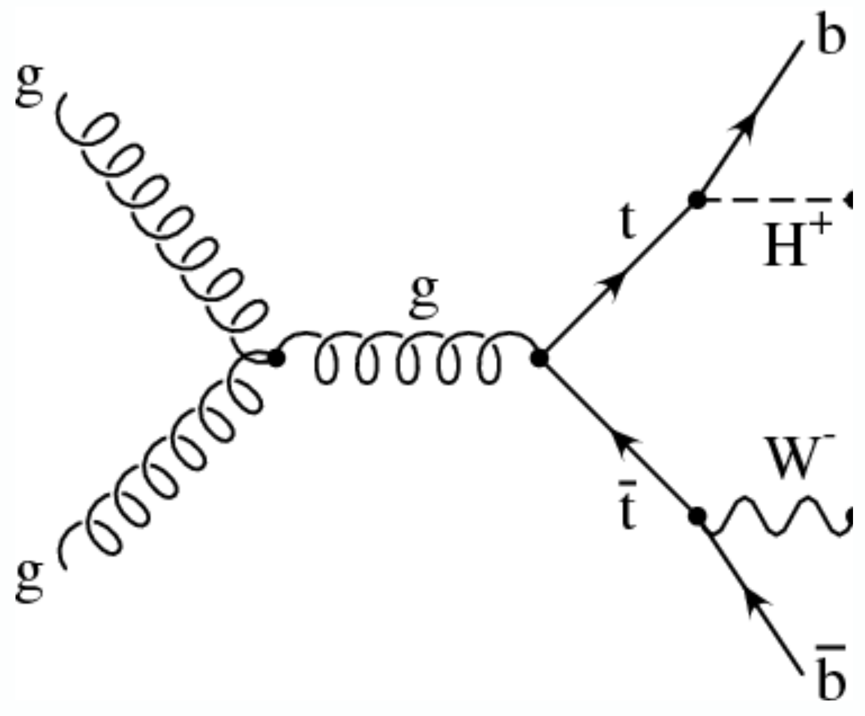


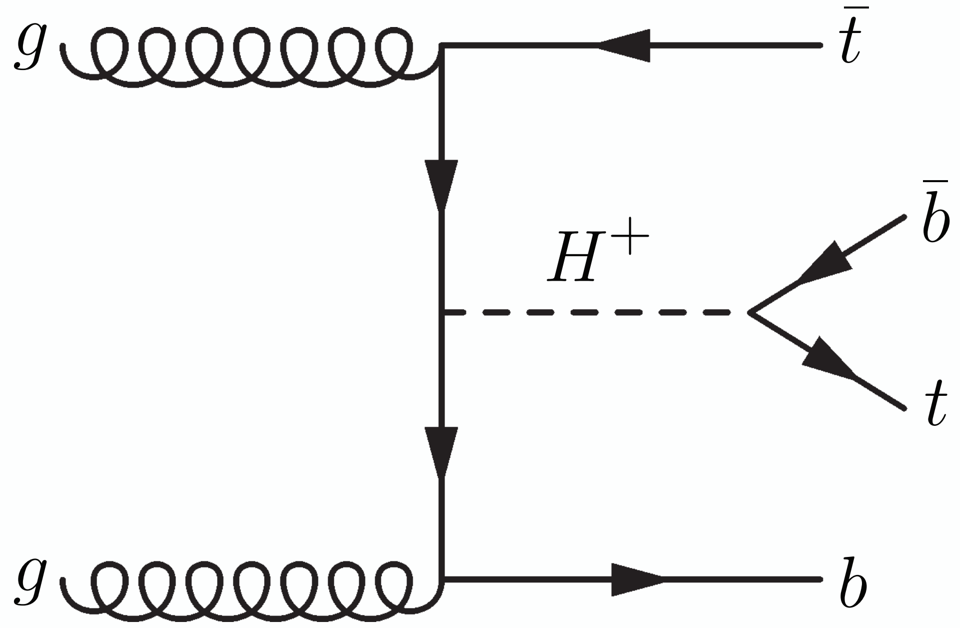


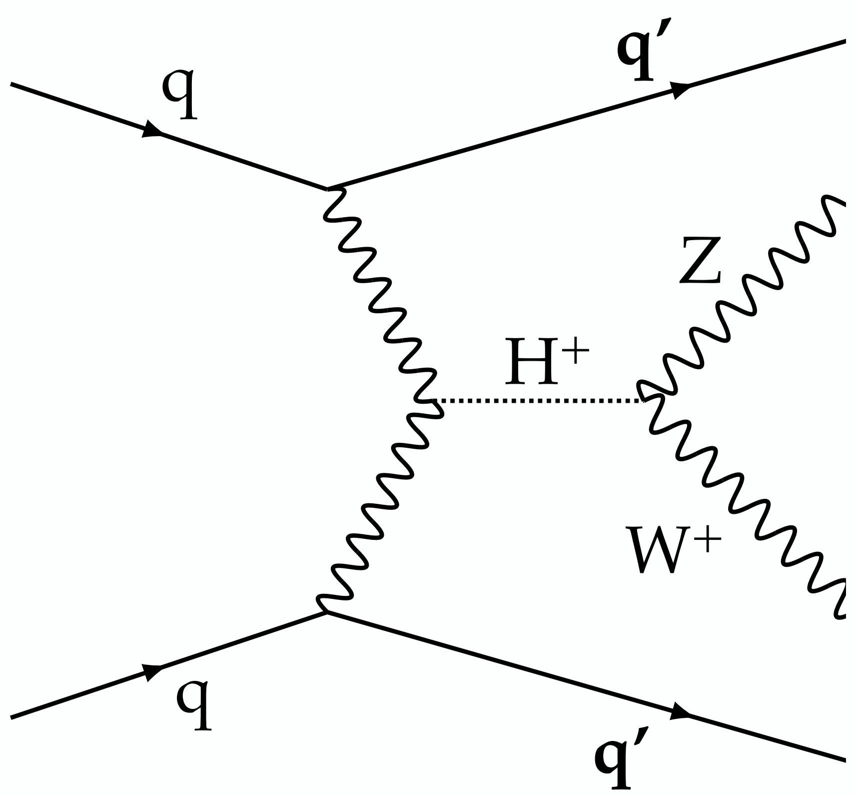
(a)

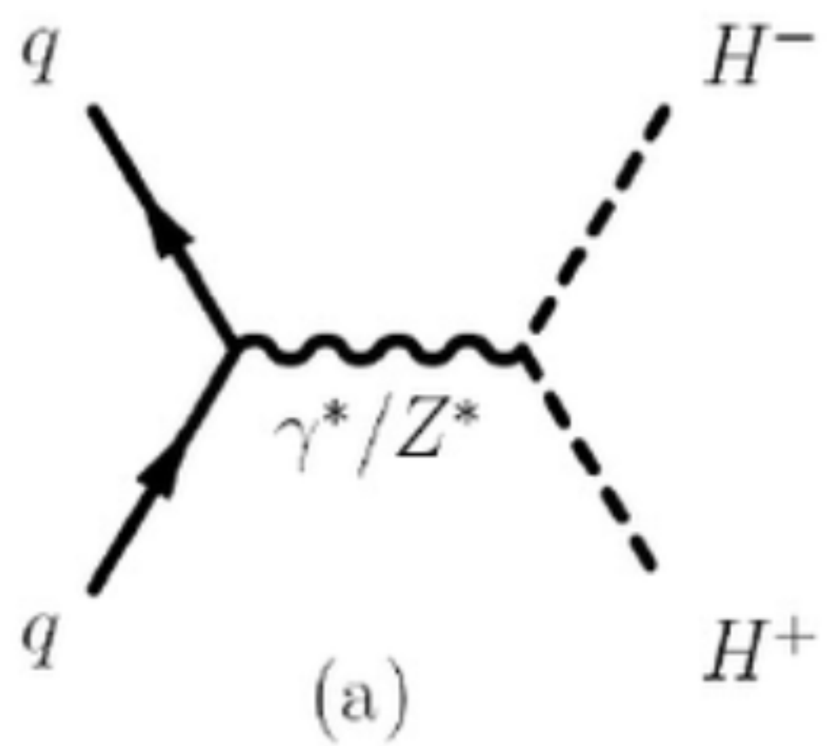
Charged Higgs production and decays

- Many possible production modes:
  - Top quark decays
  - Top associated production
  - Vector boson fusion
  - S-channel production

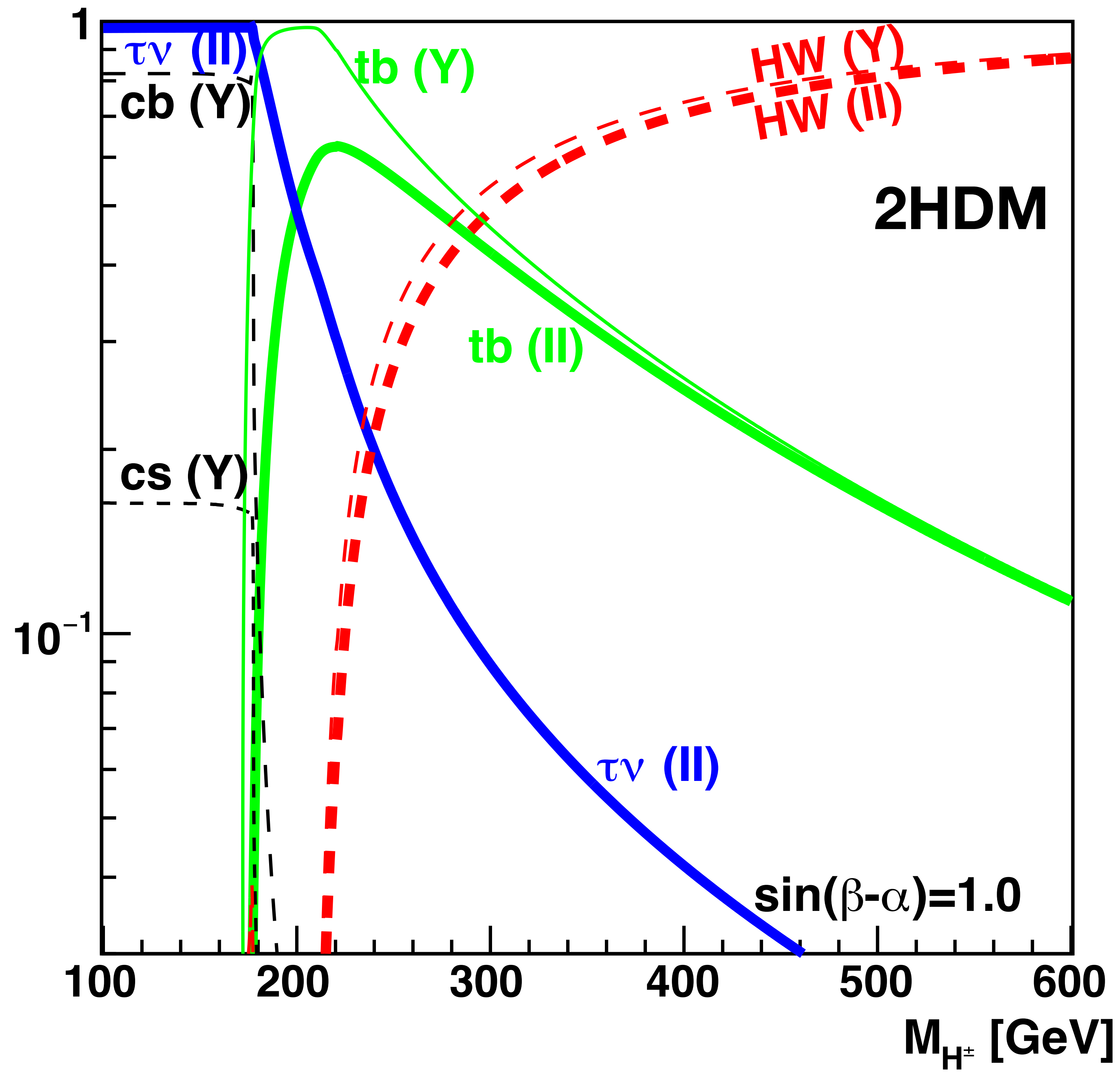


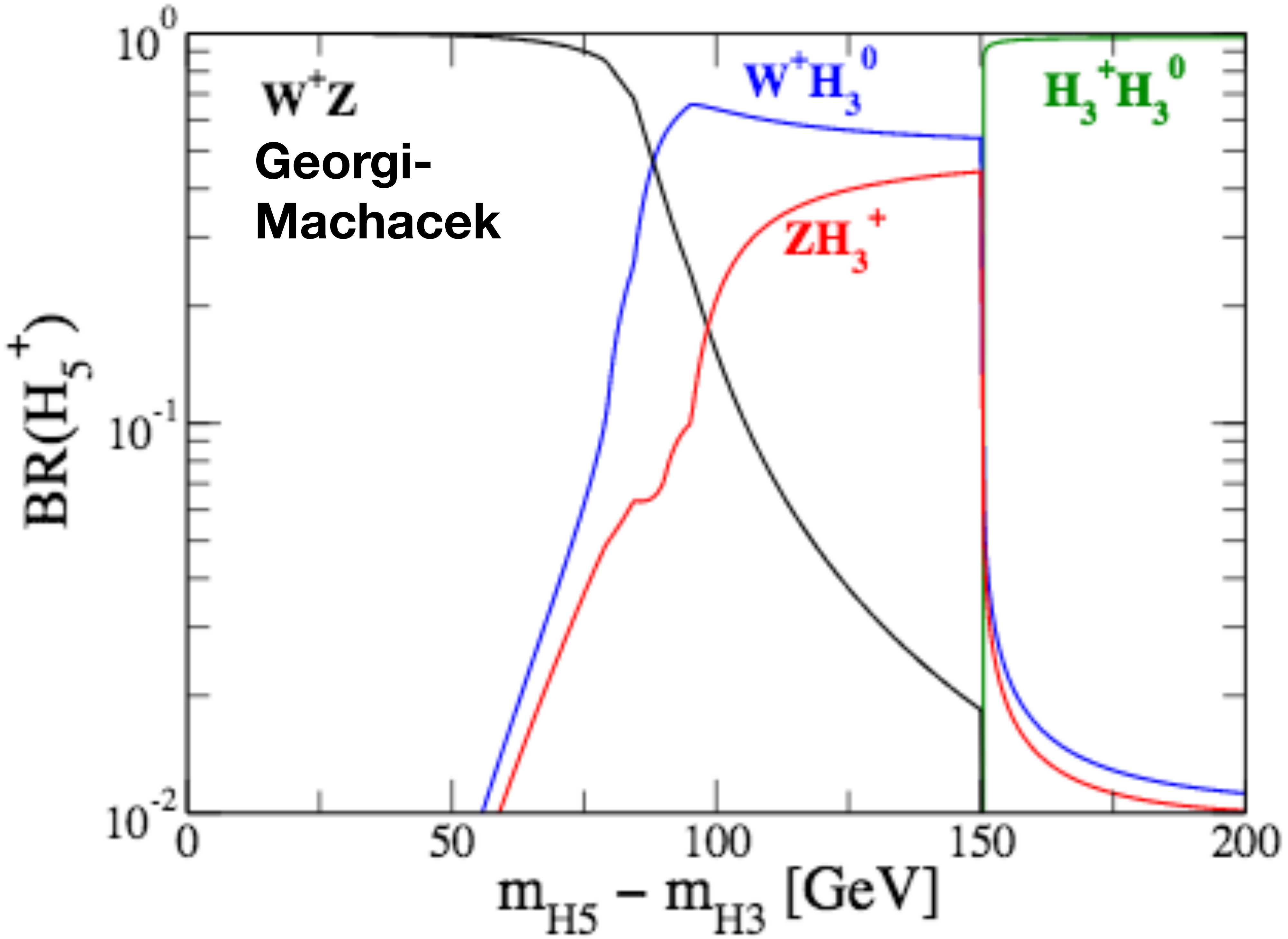






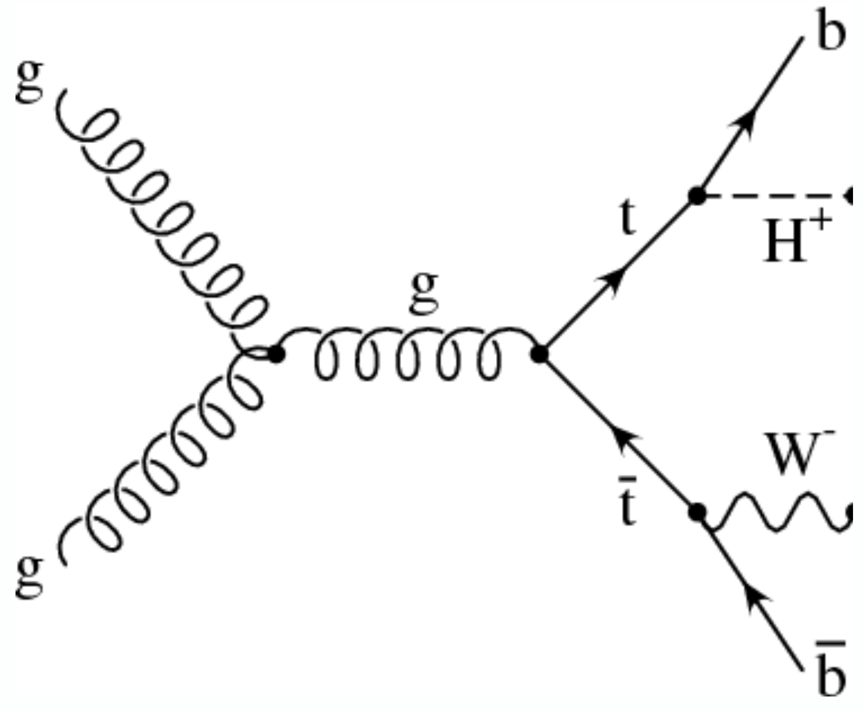
- And various decay channels:

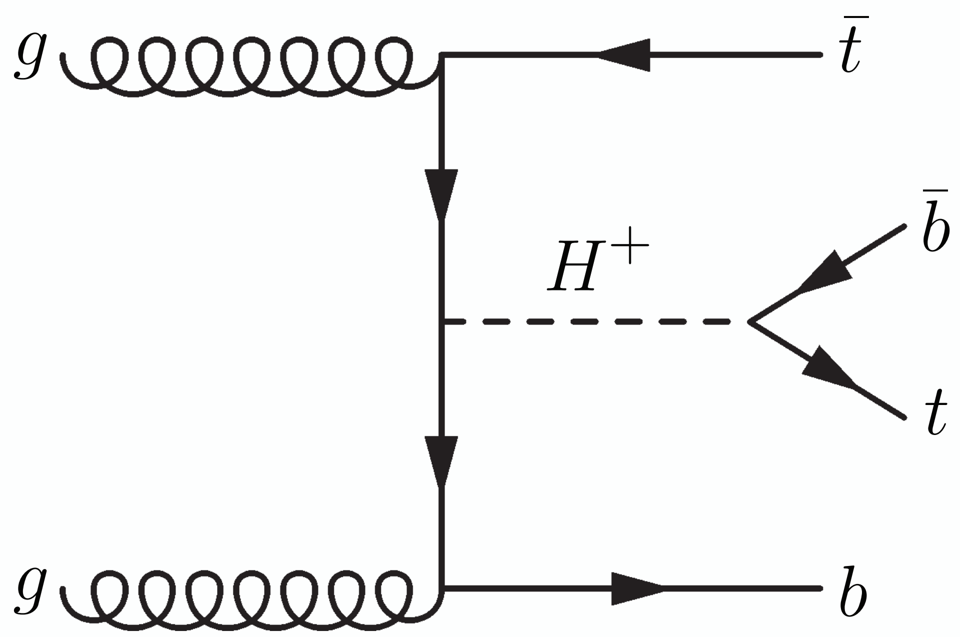


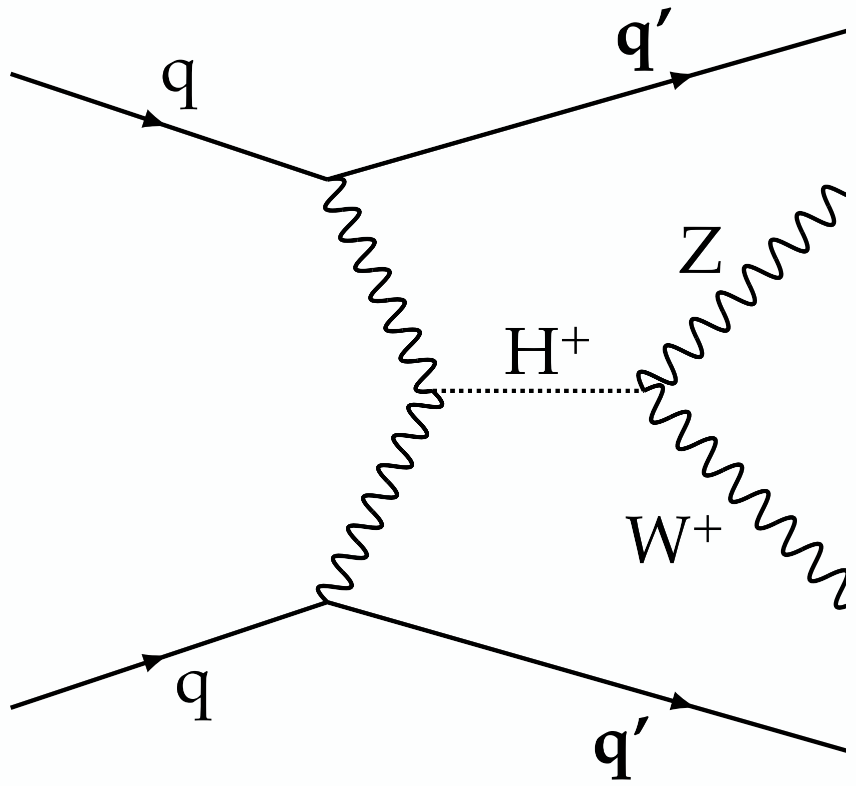


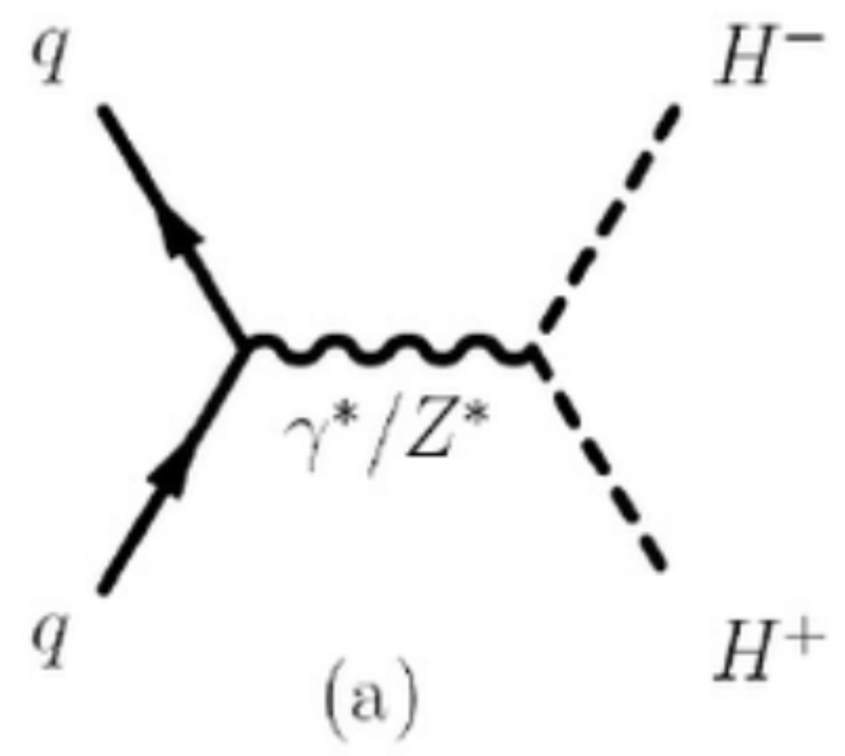
Charged Higgs production and decays

- Many possible production modes:
  - Top quark decays
  - Top associated production
  - Vector boson fusion
  - S-channel production

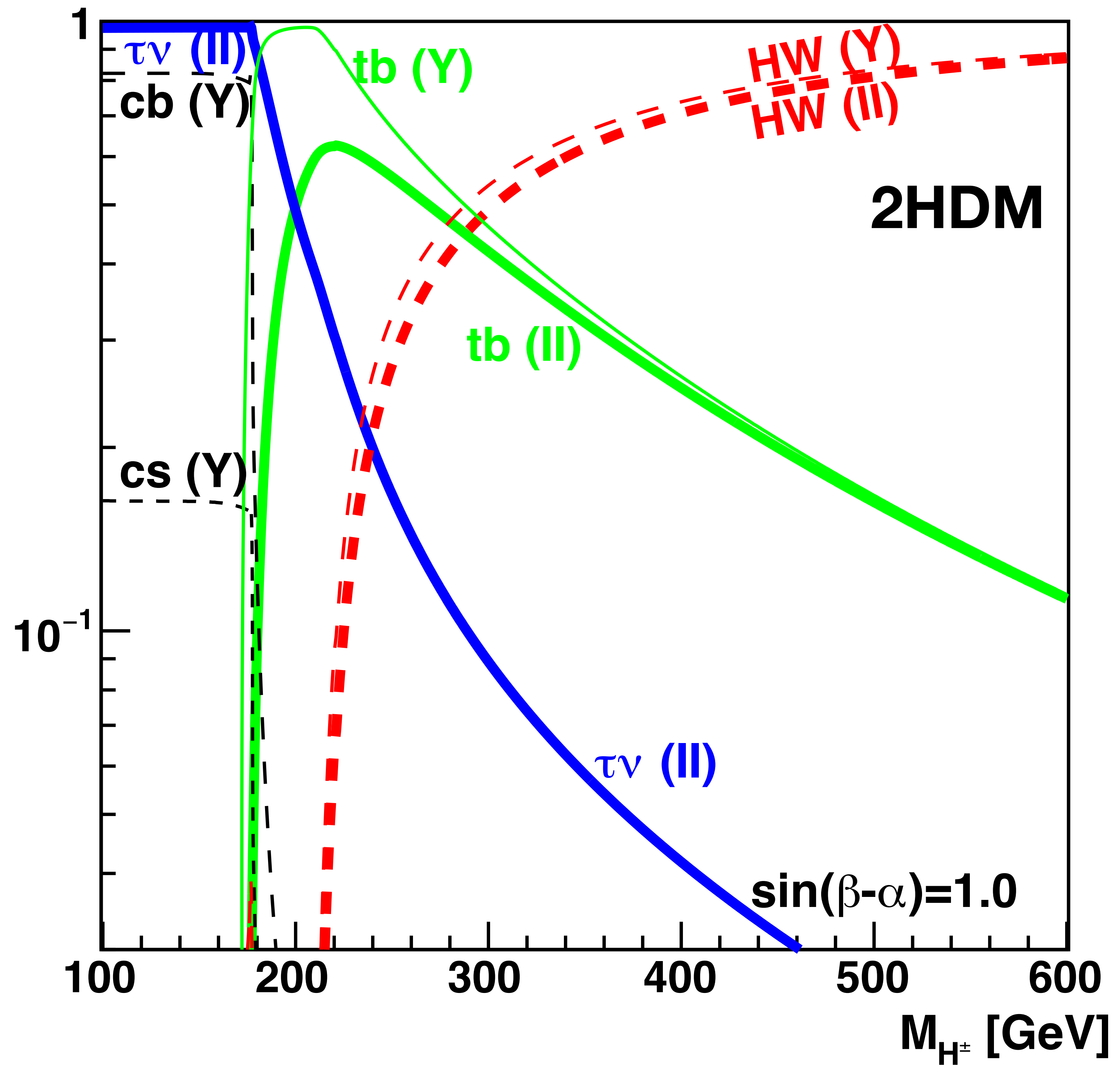


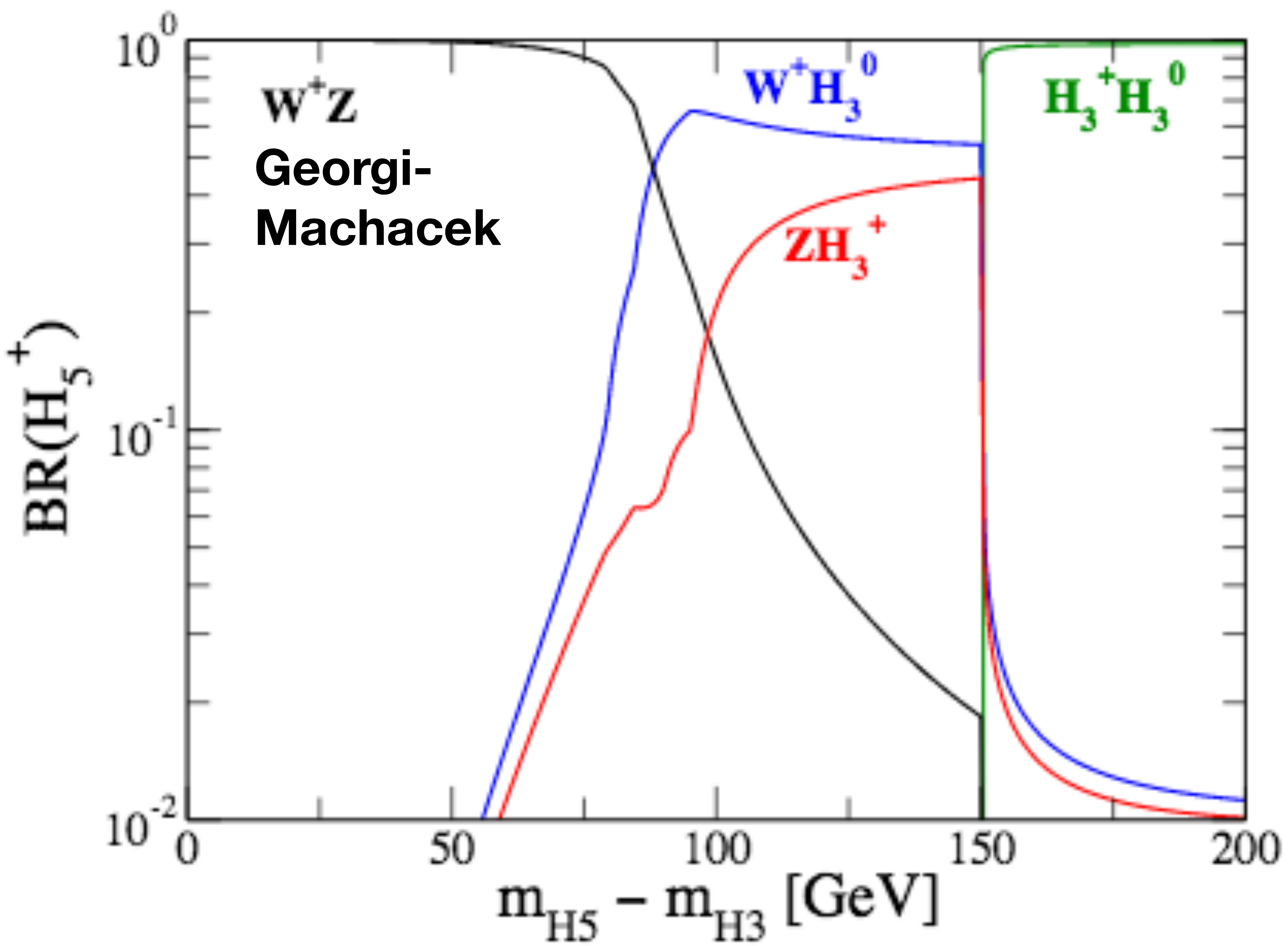






- And various decay channels:

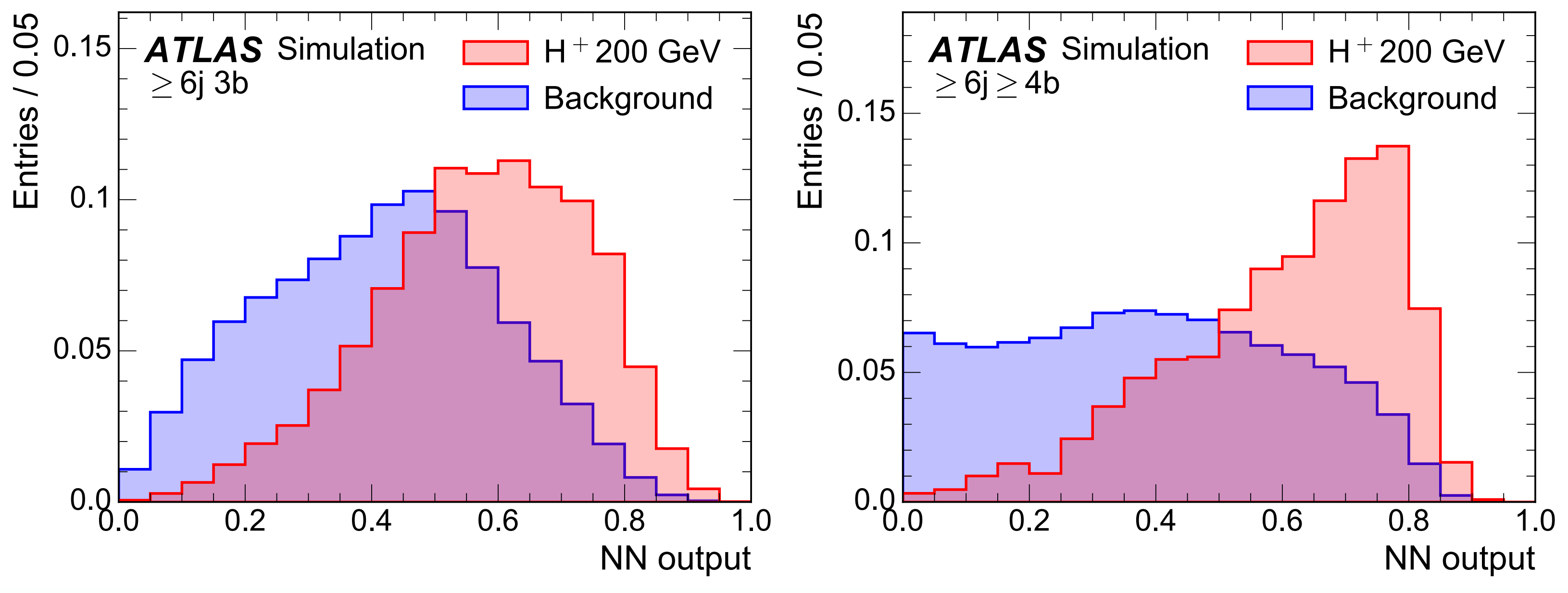




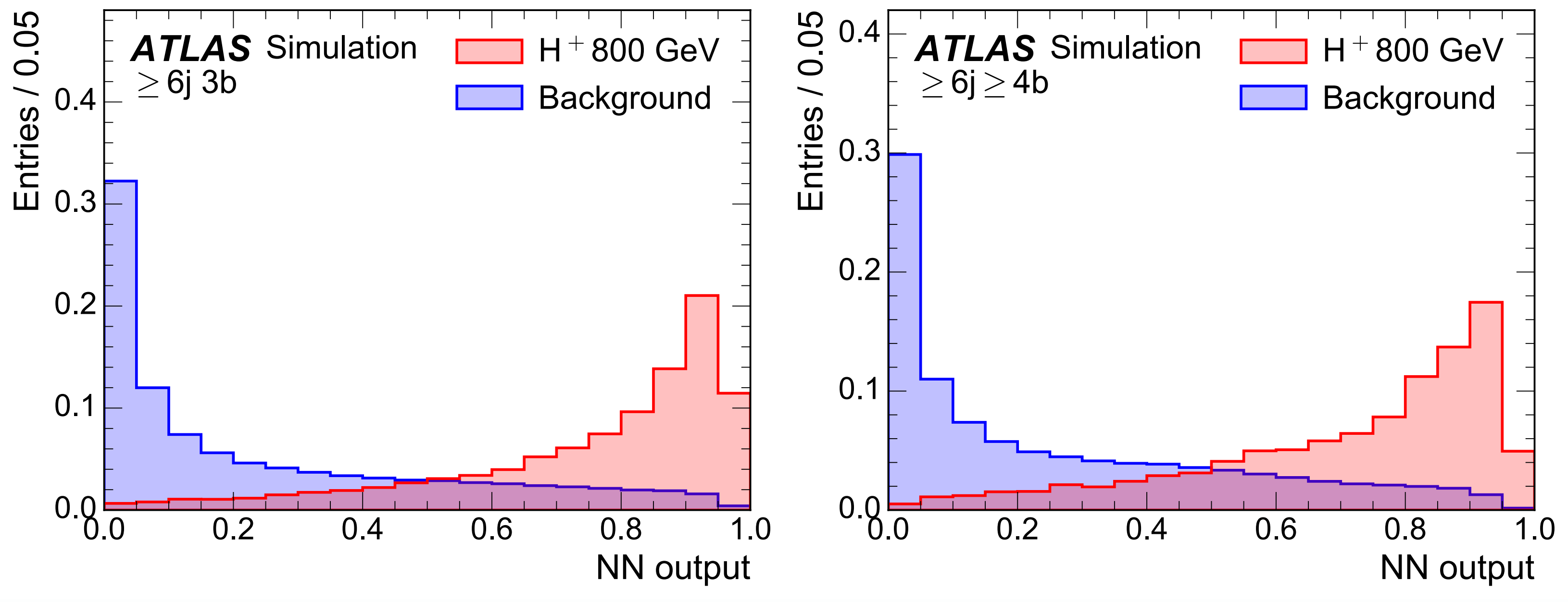
- ATLAS and CMS have wide search programs to cover ~all of this
- For today, two recent examples suffice

ATLAS H⁺⟶tb

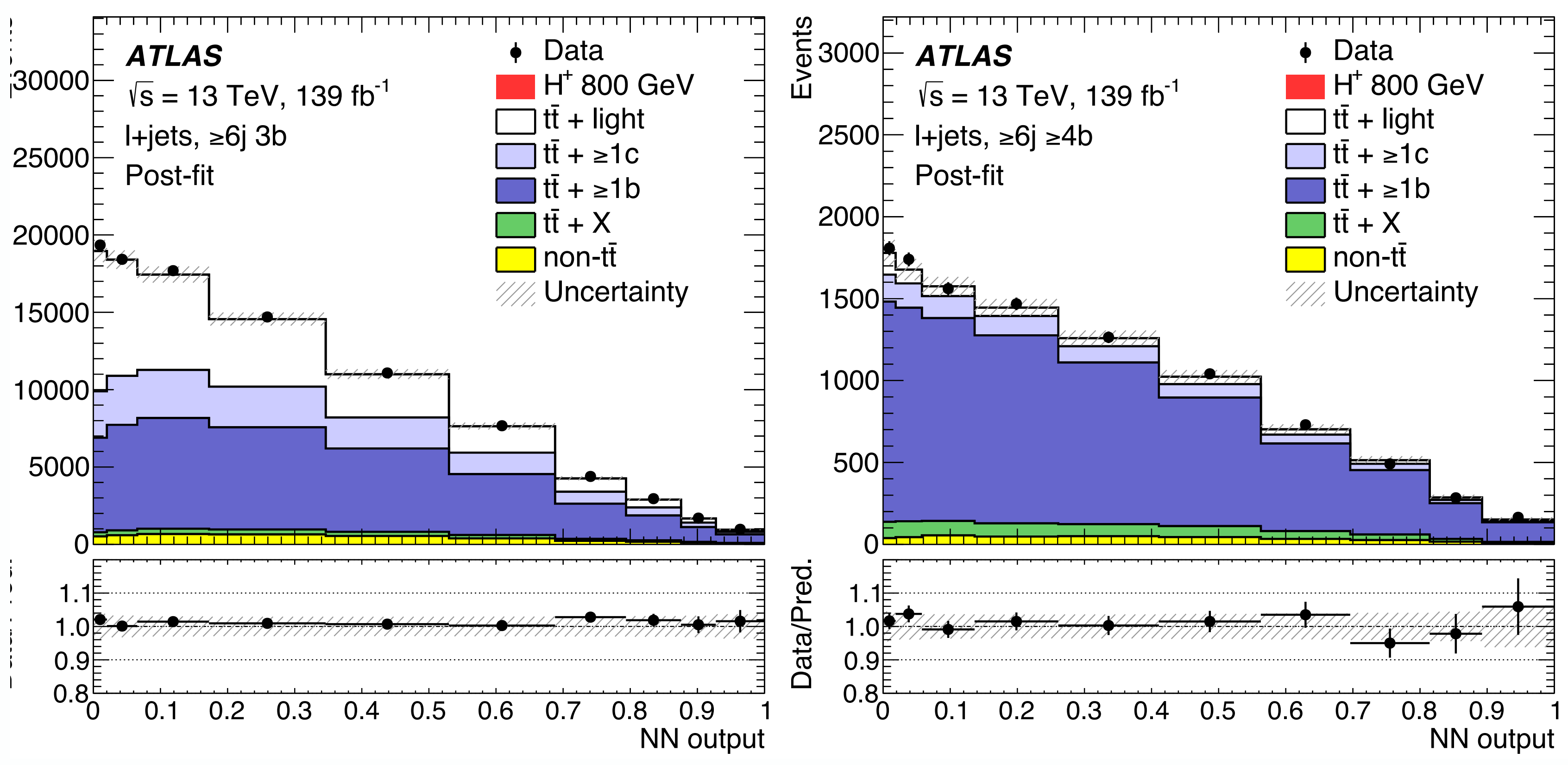
arXiv:2102.10076



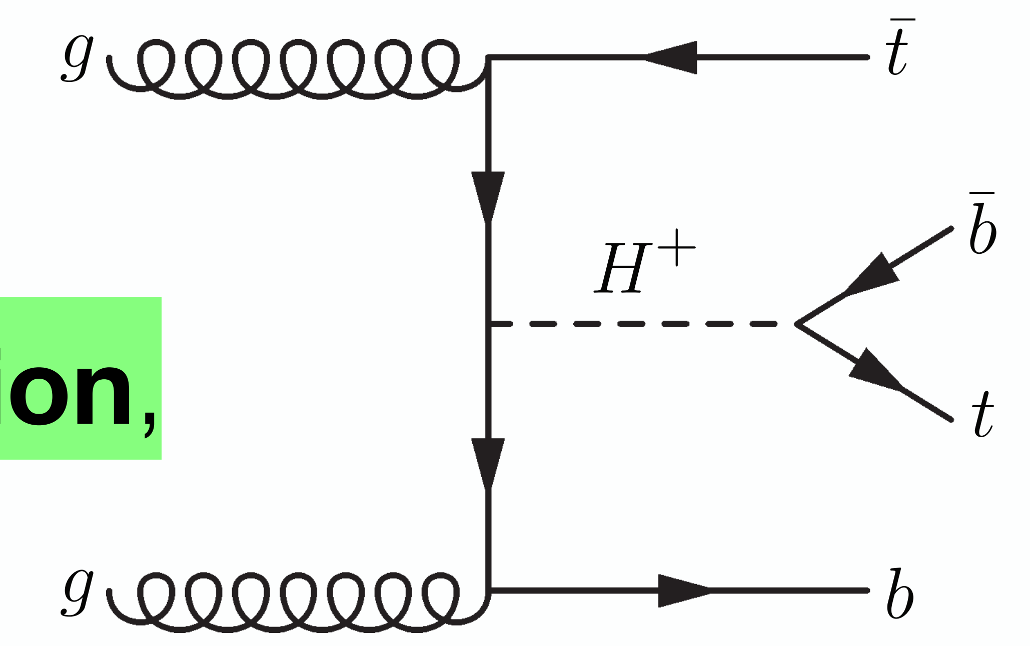
(c) ≥6j3b (d) ≥6j≥4b



(g) ≥6j3b (h) ≥6j≥4b

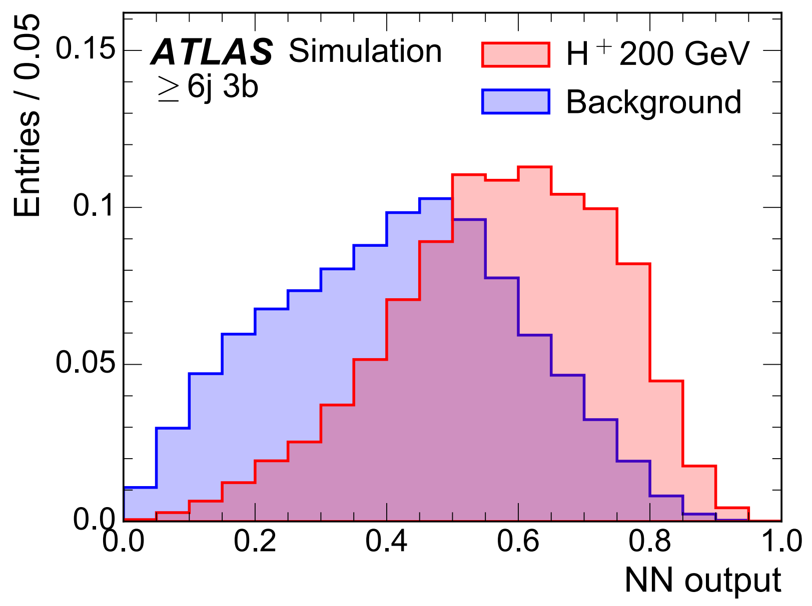


- Search for H^+ with mass **up to 2 TeV** in e/μ+jets final state
- First H^+ search with **NN-based limit extraction**, in categories of jet and b-jet multiplicity
- Background estimation from MC, with normalizations fitted from data
- No excess observed

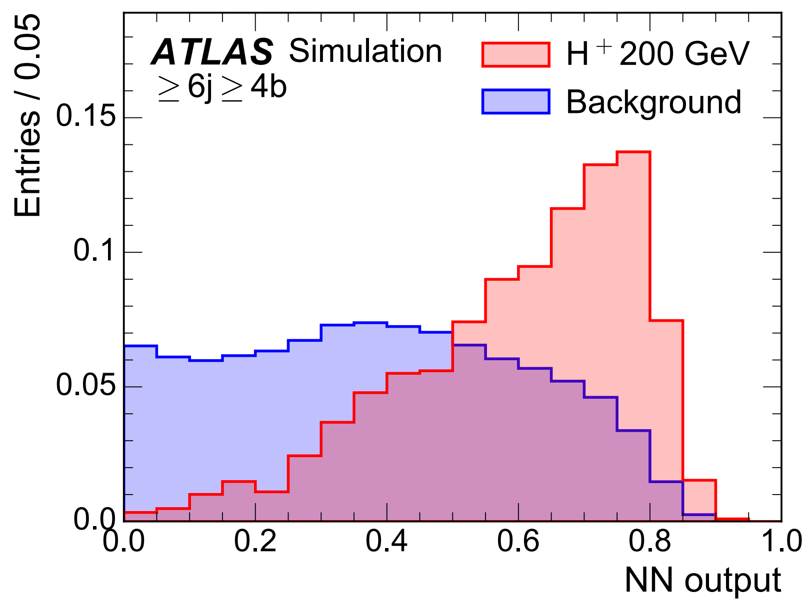


ATLAS H+⟶tb

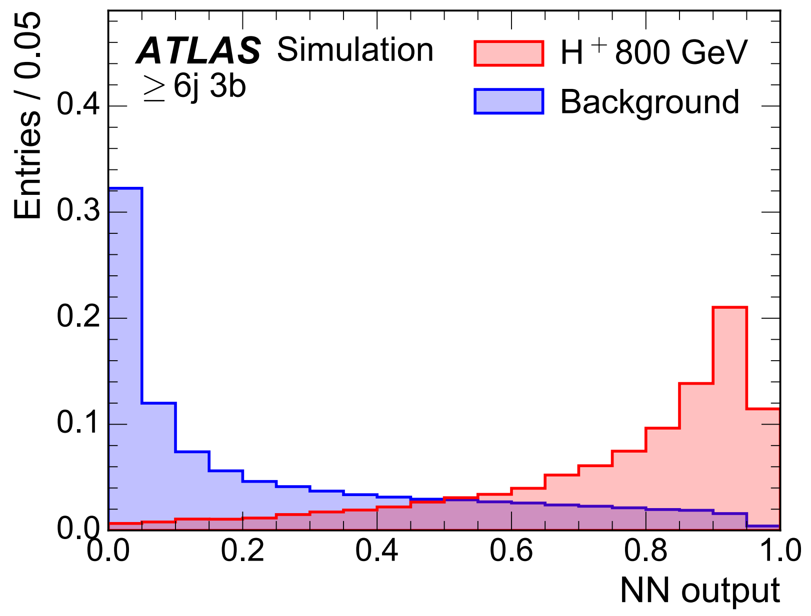
arXiv:2102.10076



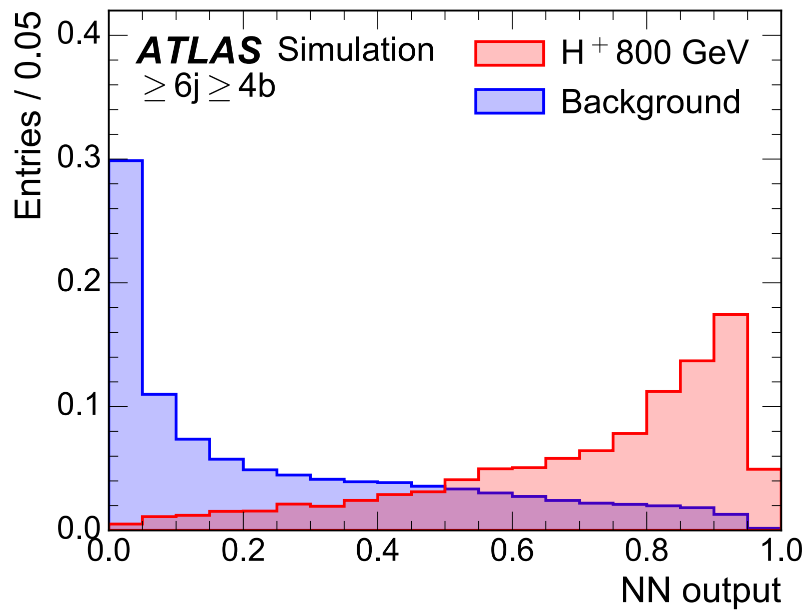
(c) ≥6j3b



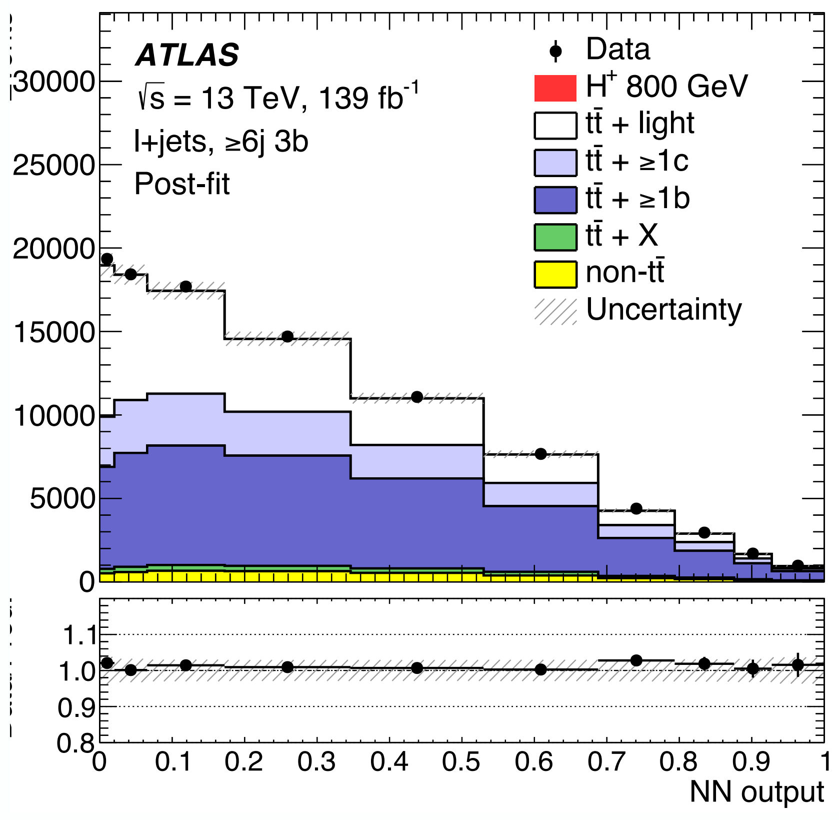
(d) ≥6j≥4b

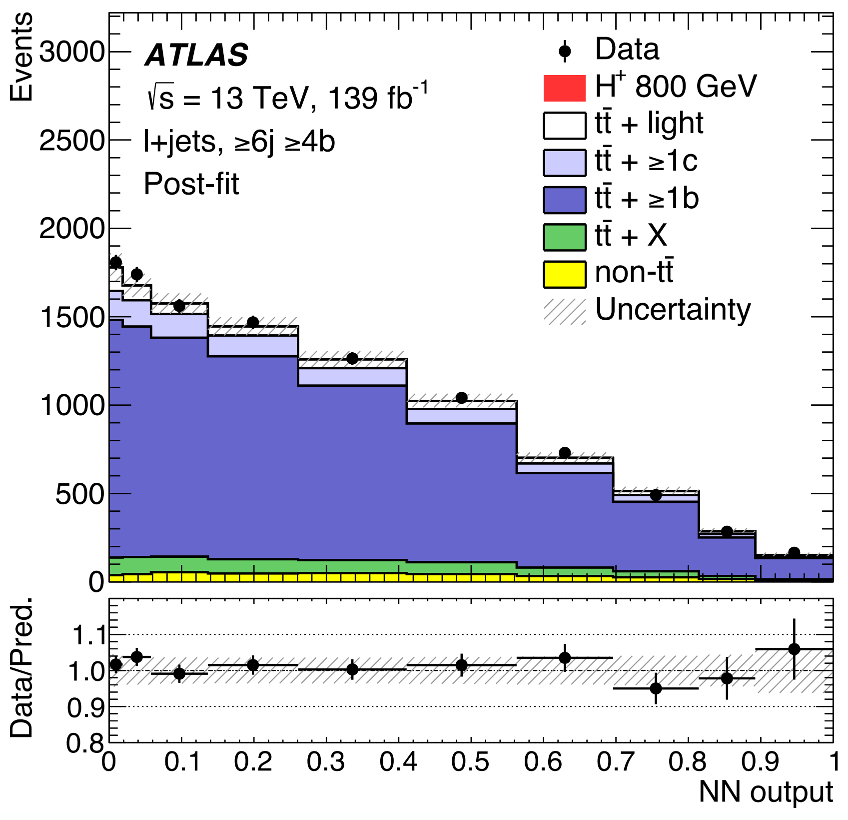


(g) ≥6j3b

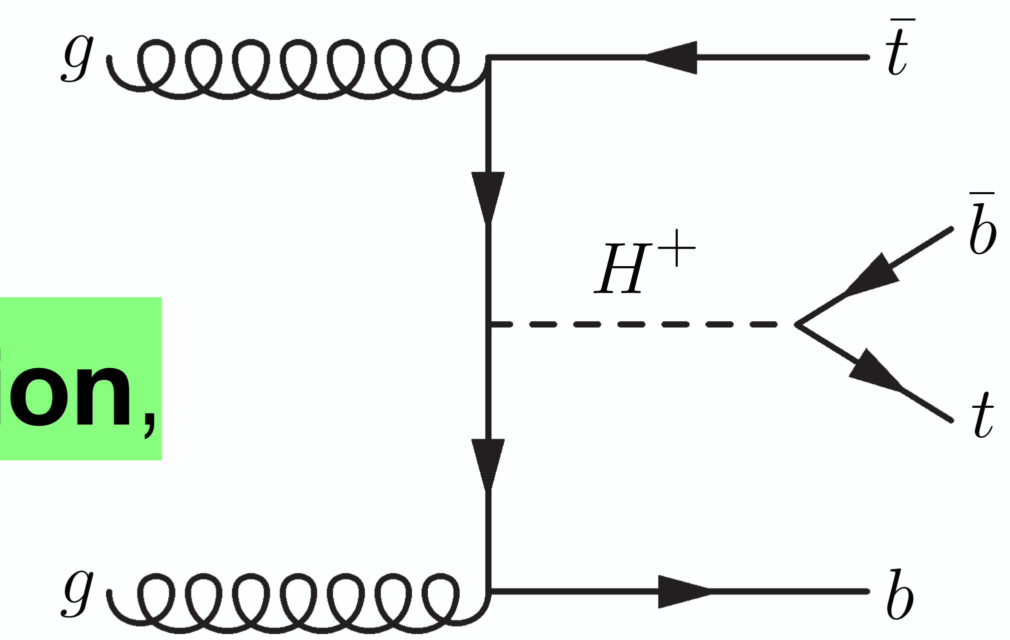


(h) ≥6j≥4b

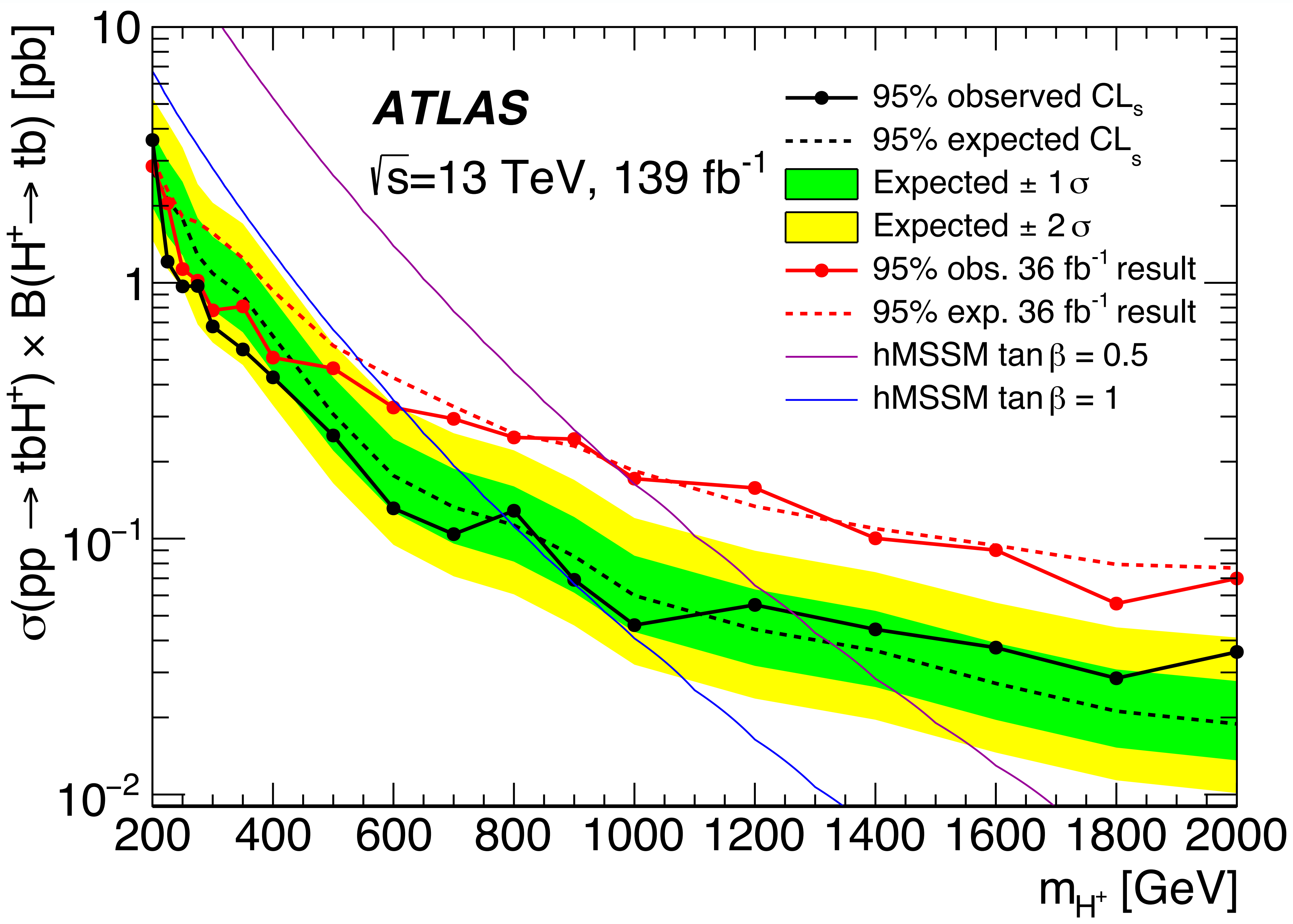


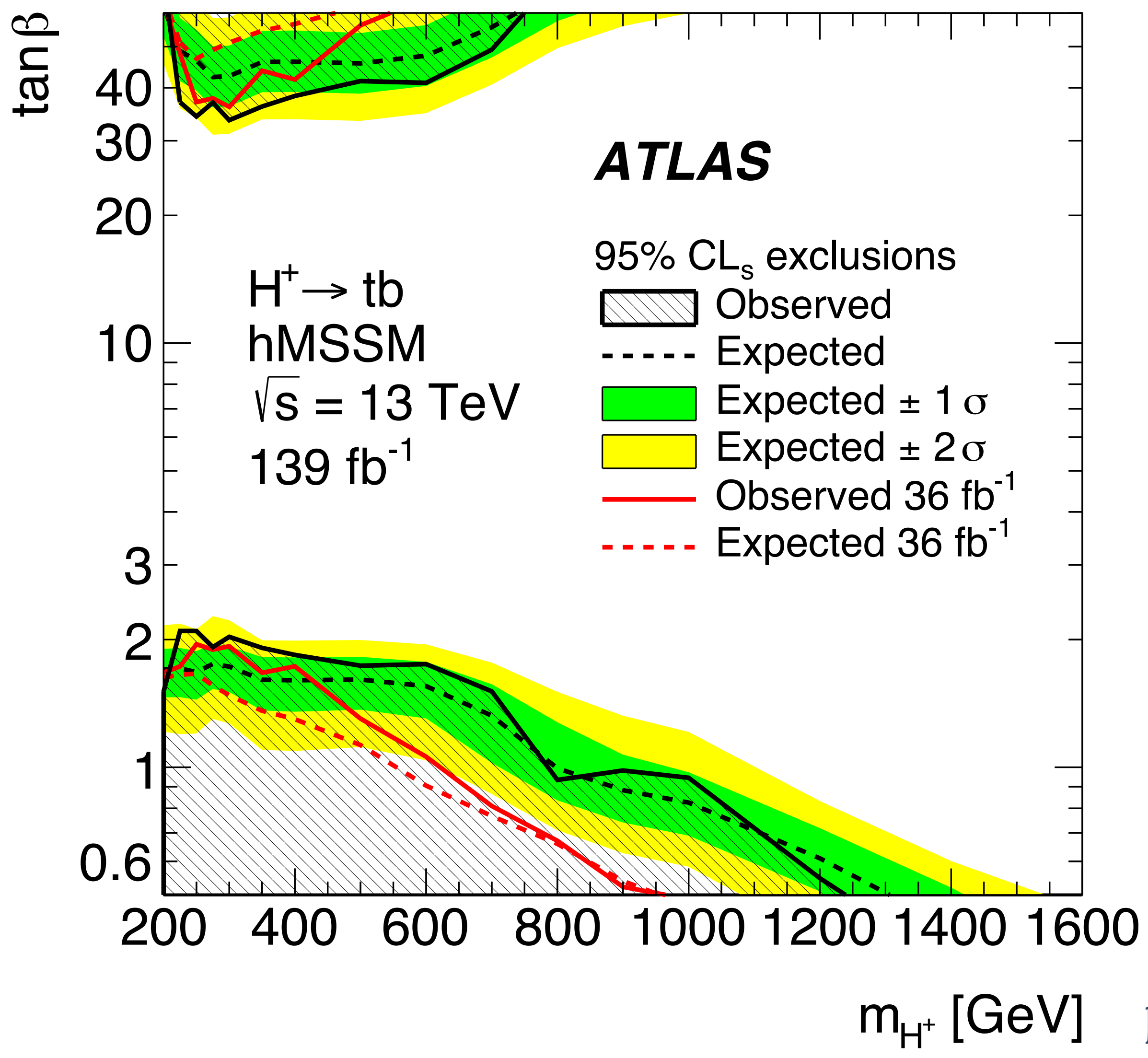


- Search for H+ with mass **up to 2 TeV** in e/μ+jets final state
- First H+ search with **NN-based limit extraction**, in categories of jet and b-jet multiplicity
- Background estimation from MC, with normalizations fitted from data
- No excess observed



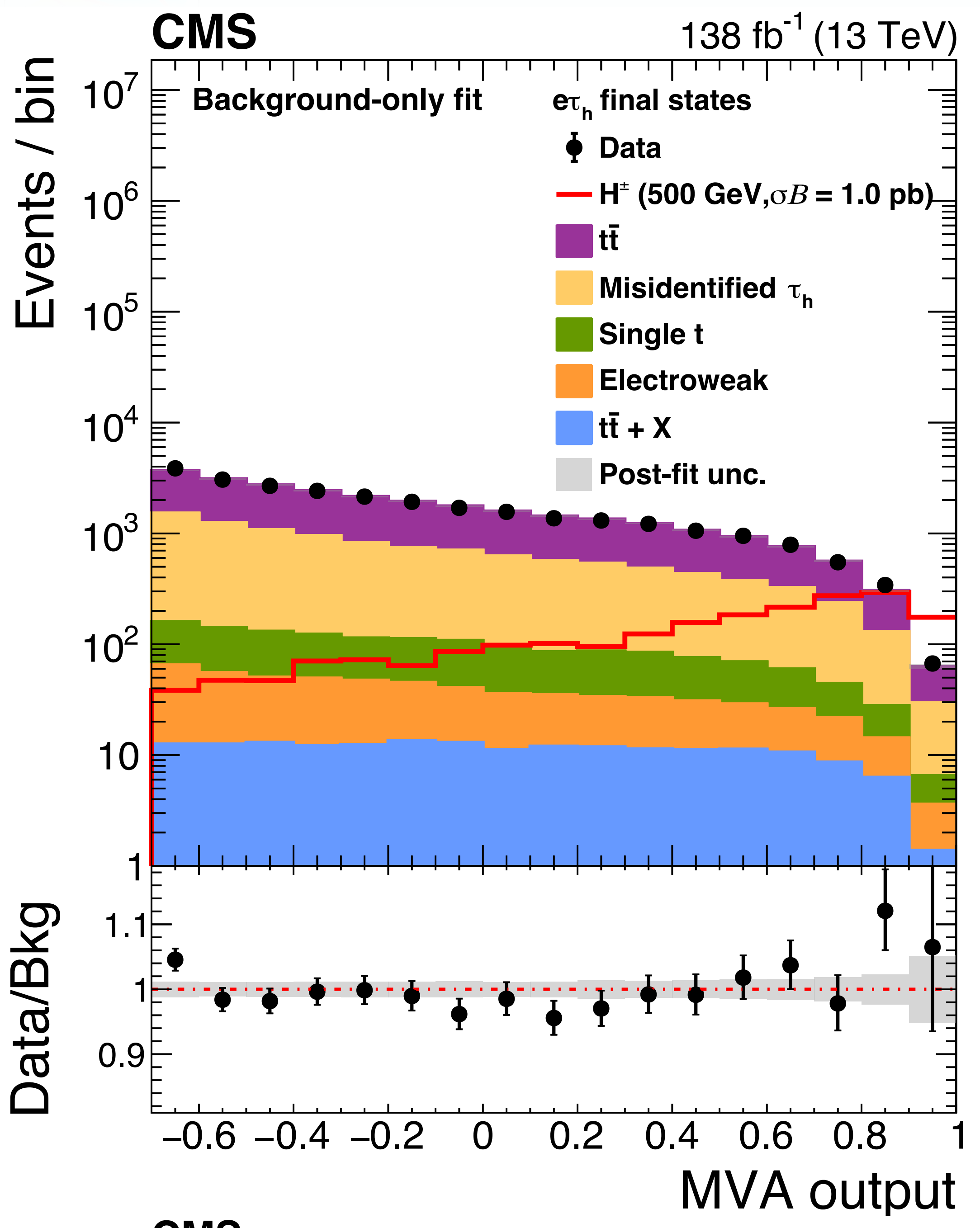
- Limits improved by **5%** (in systematics-driven low-mass region) to **70%** (at high mass)

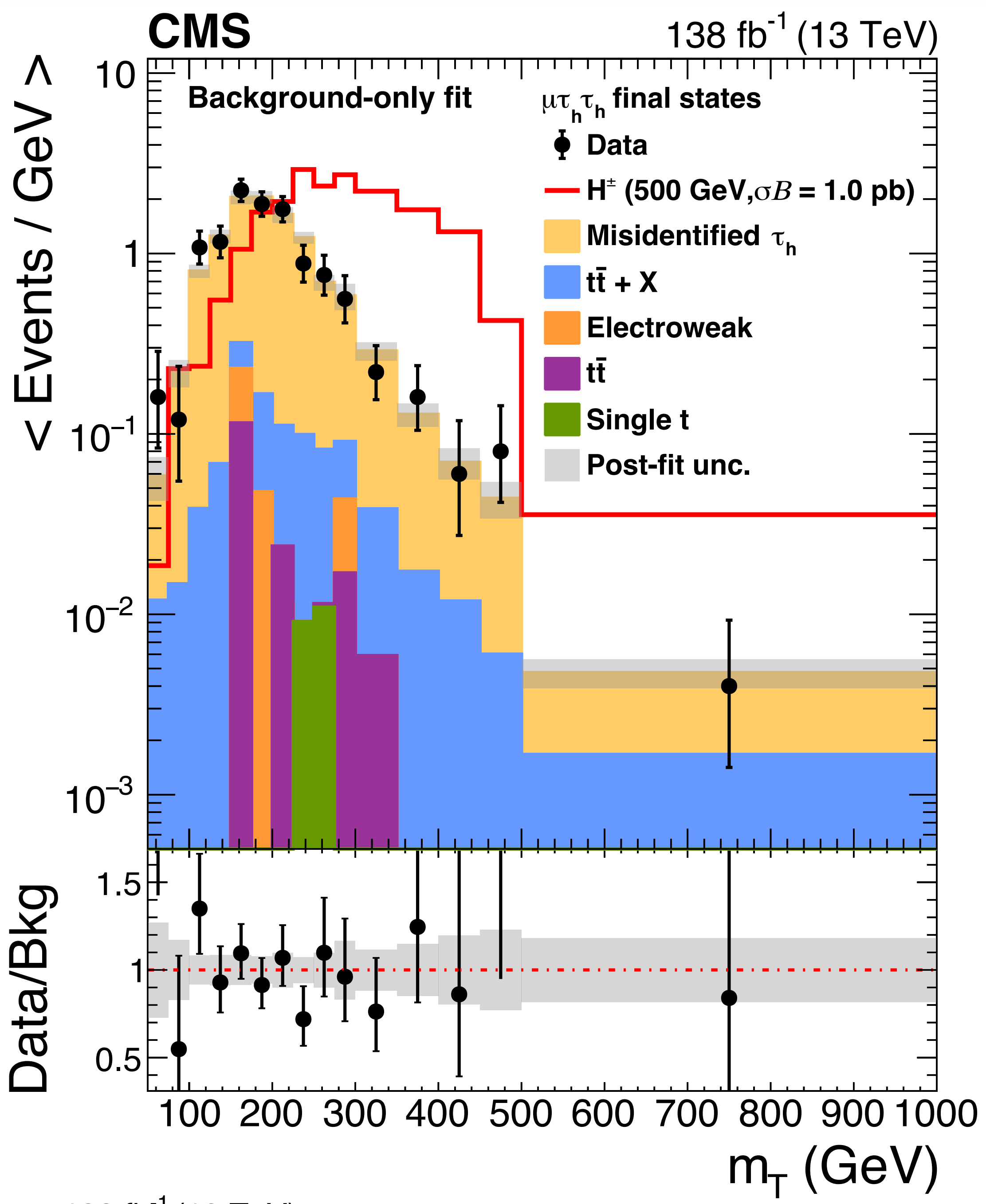




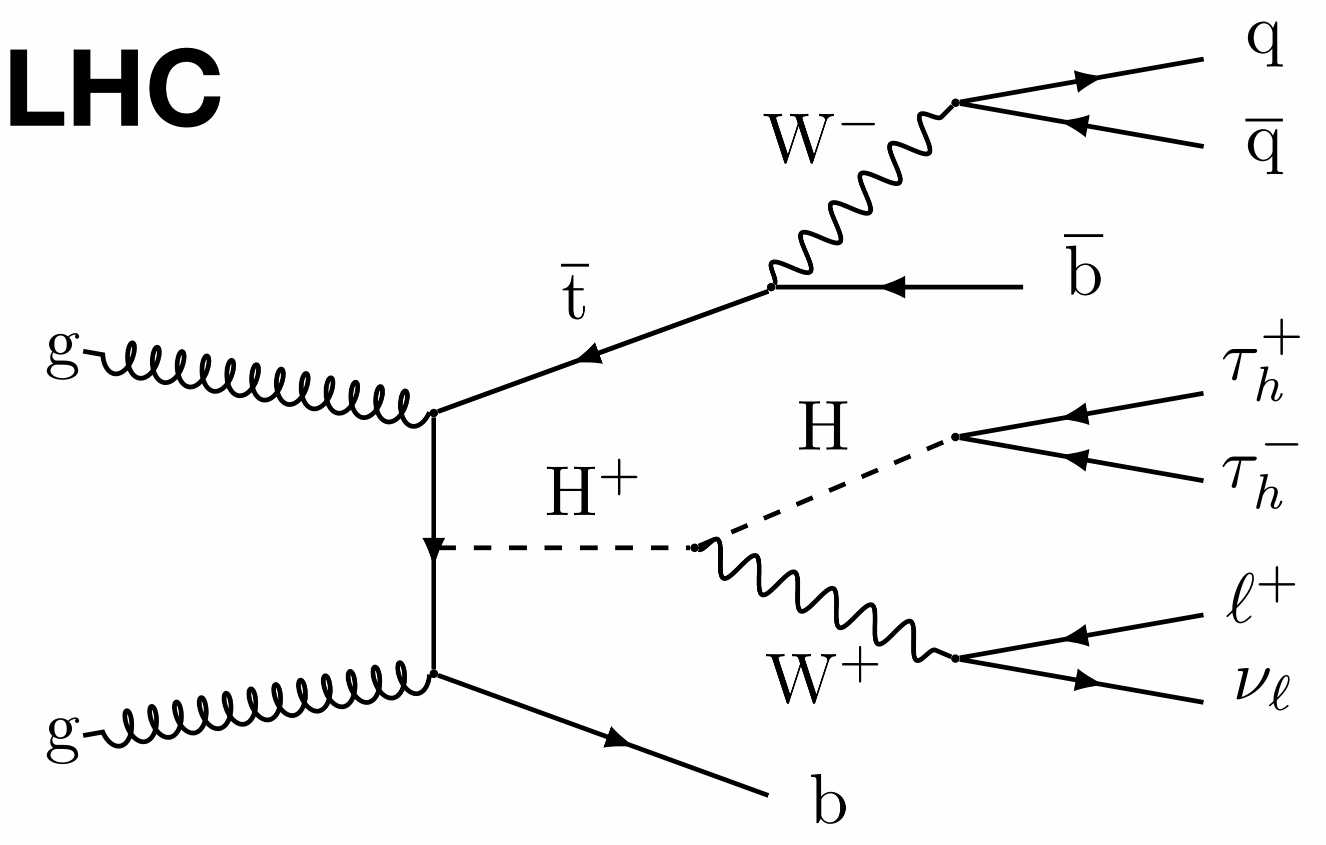
CMS H+⟶WH

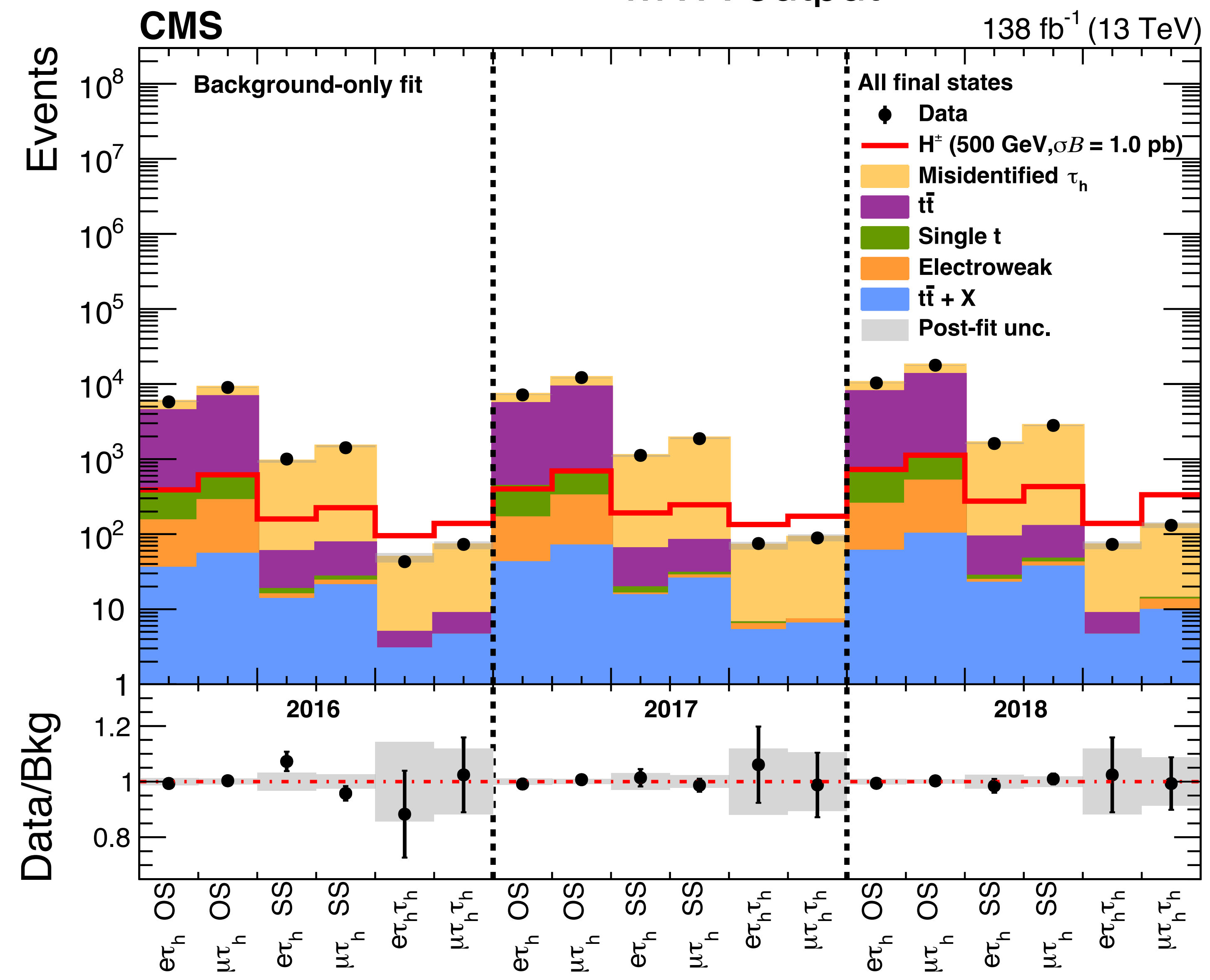
arXiv:2207.01046





- **First search for H+⟶WH at LHC**
  - H+ mass **300-700 GeV**
  - m_H set to **200 GeV**, targeting H(ττ) decay
- Data-driven estimation of jet⟶τ_h (QCD) background

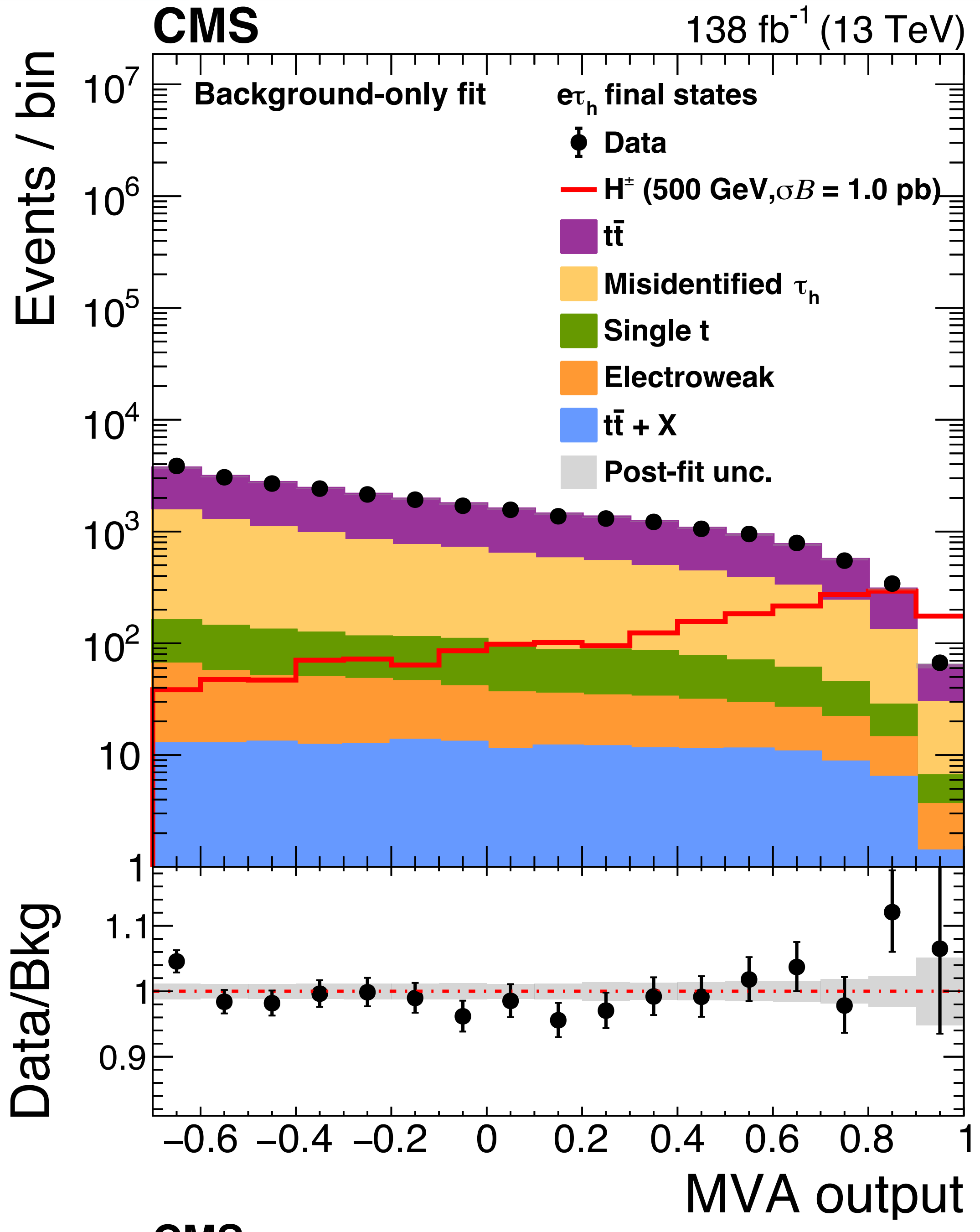


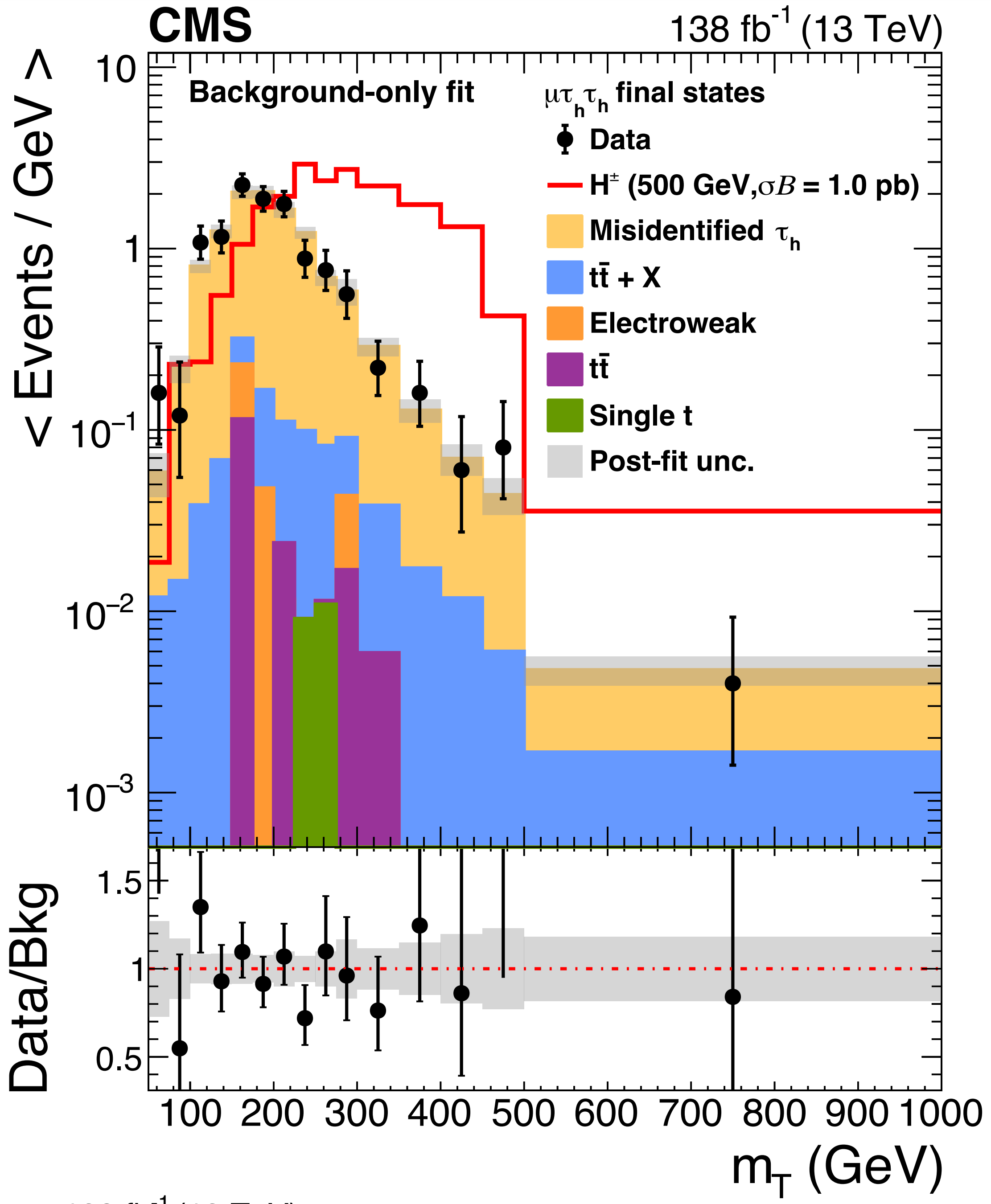


- Simultaneous fit to 18 categories, with **BDT output** or **transverse mass** as the discriminant

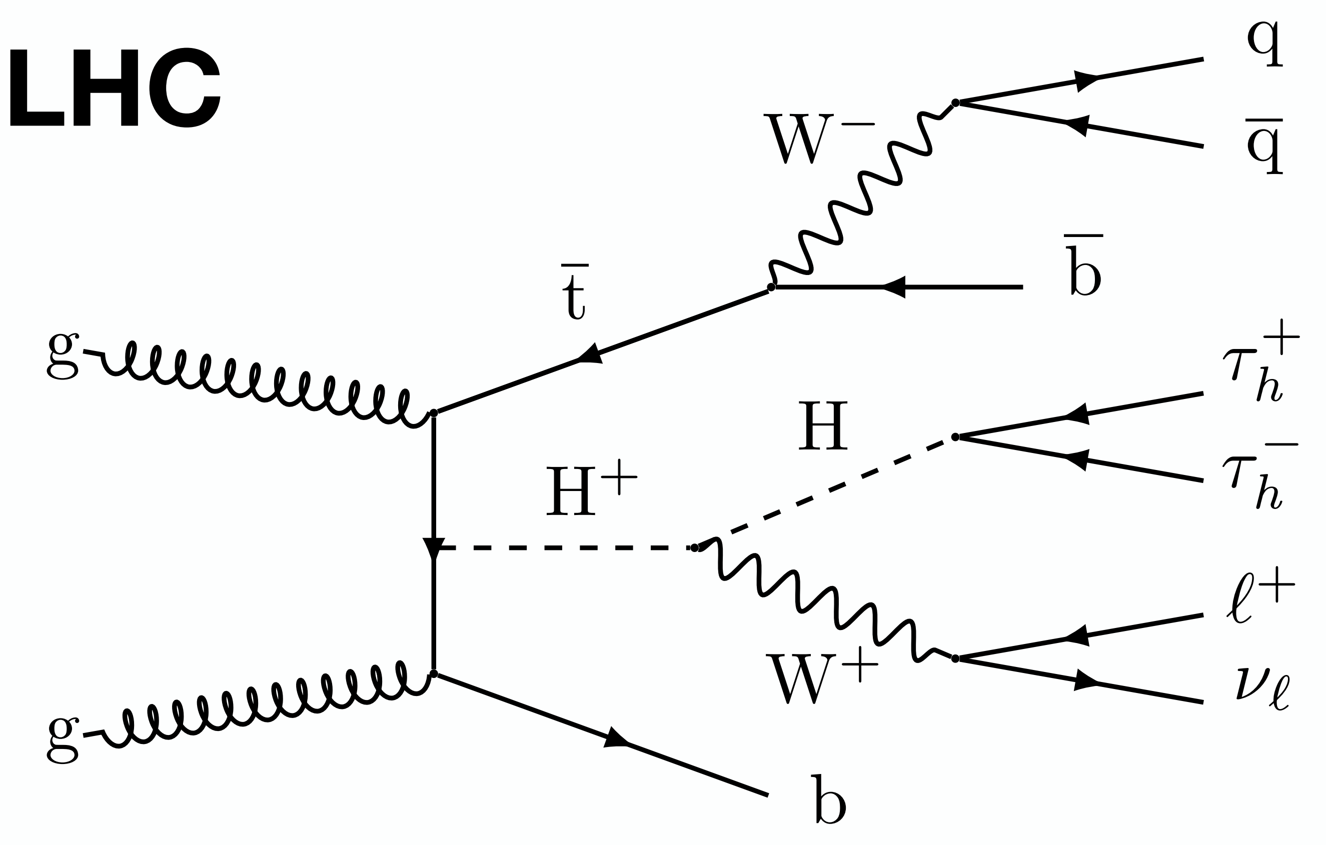
CMS H+→WH

arXiv:2207.01046

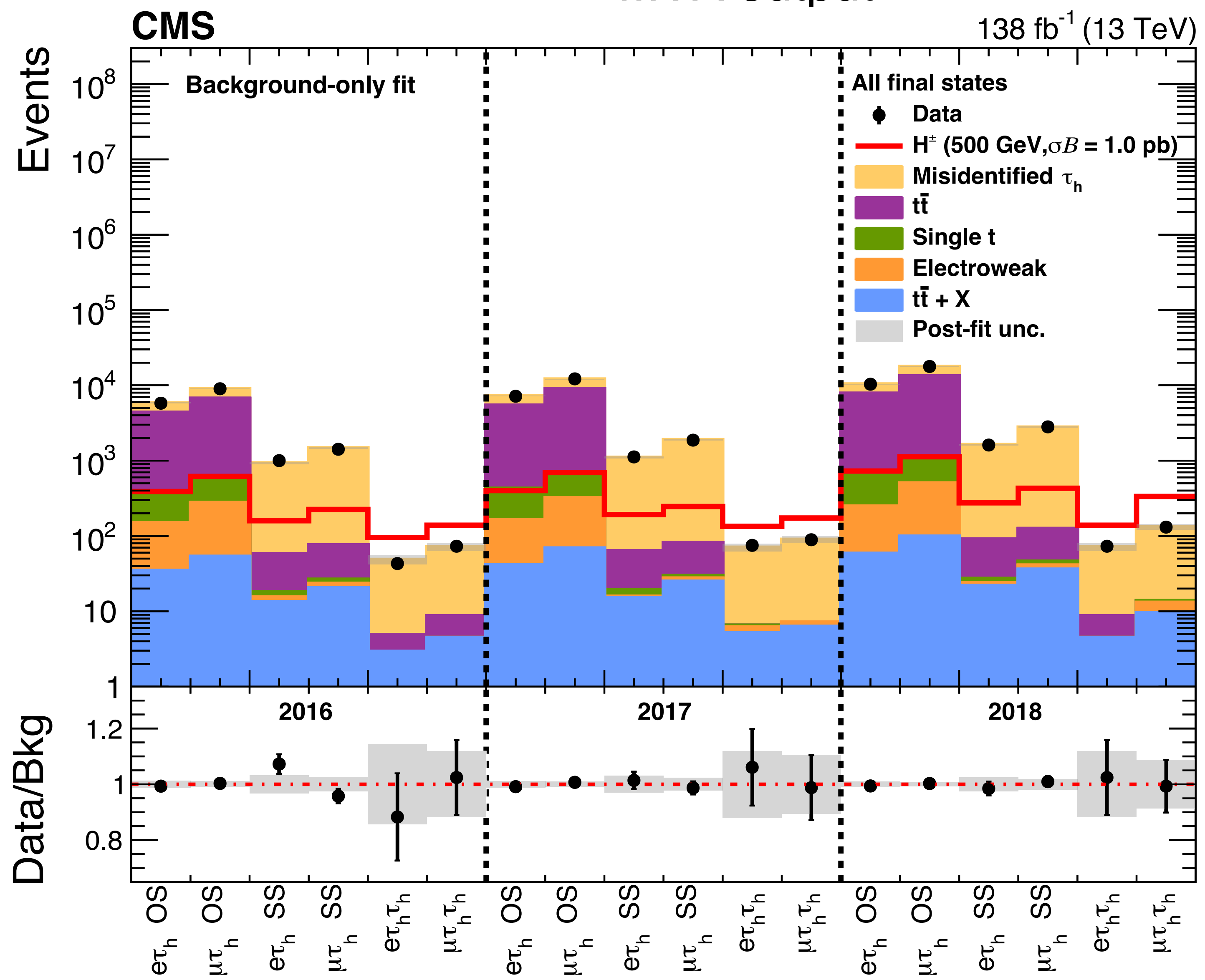




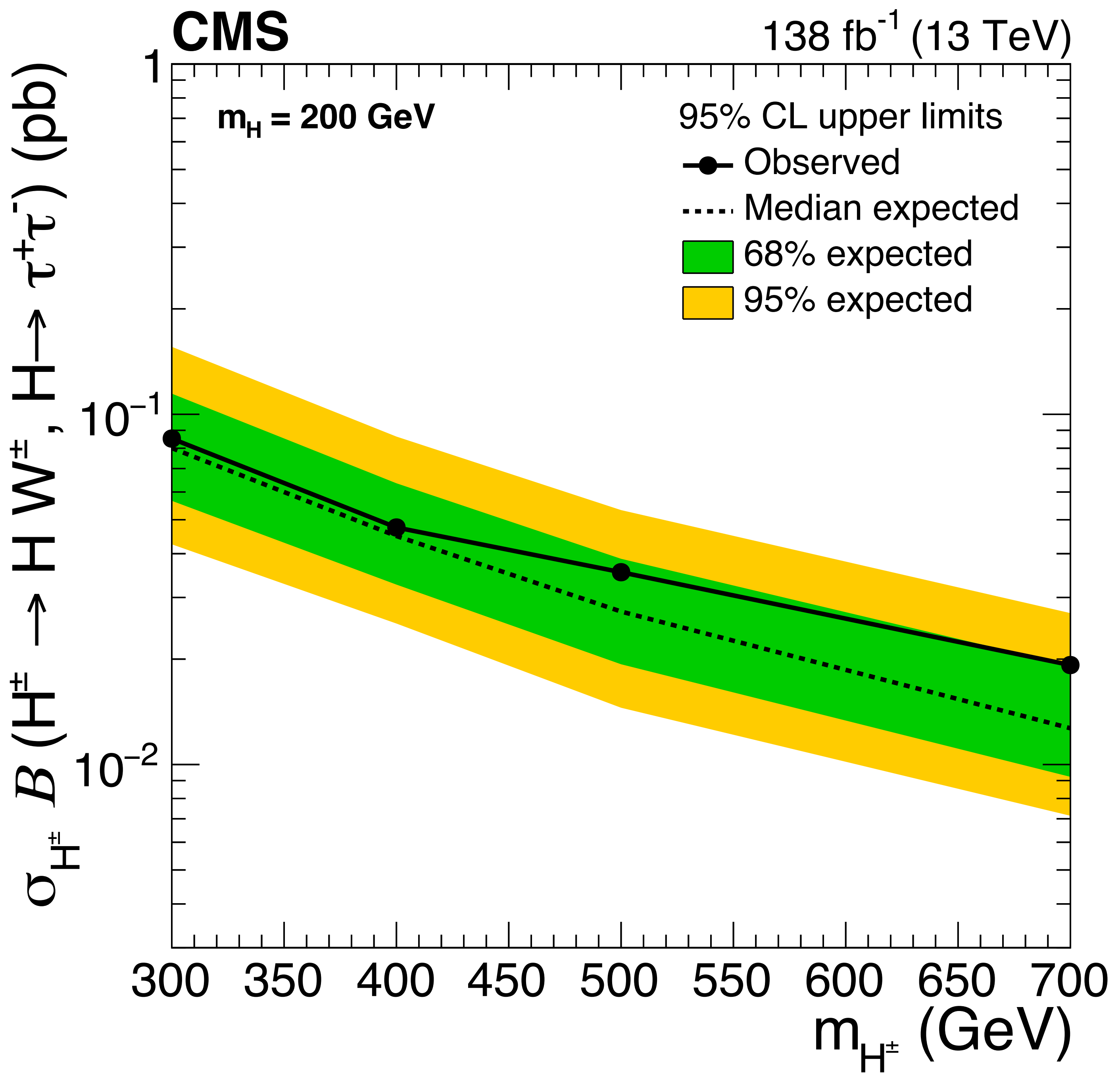
- **First search for H+→WH at LHC**
  - H+ mass **300-700 GeV**
  - m_H set to **200 GeV**, targeting H(ττ) decay
- Data-driven estimation of jet→τ_h (QCD) background

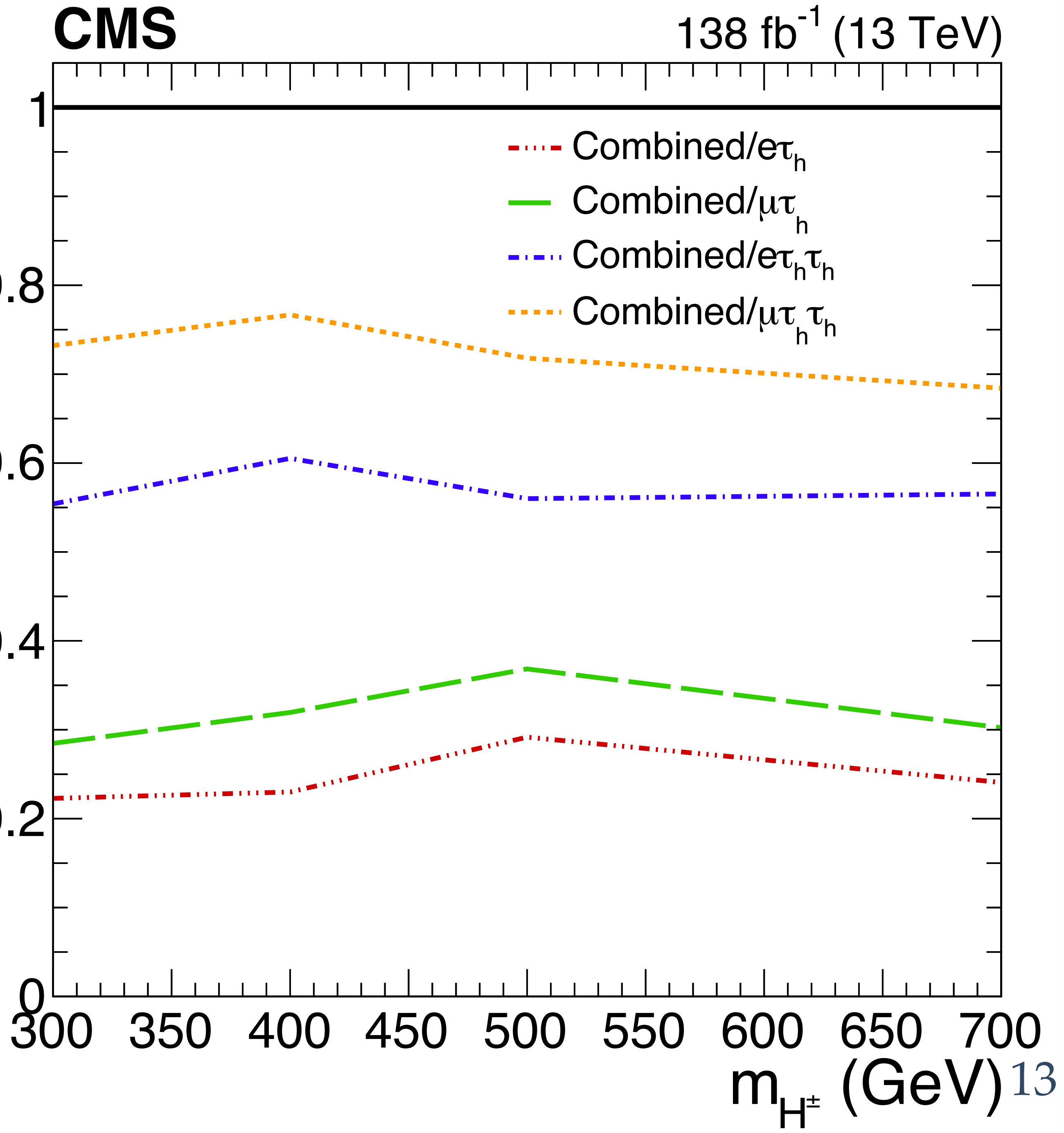


- No excess observed, sensitivity driven by l+$\tau_h\tau_h$ final state



- Simultaneous fit to 18 categories, with **BDT output** or **transverse mass** as the discriminant





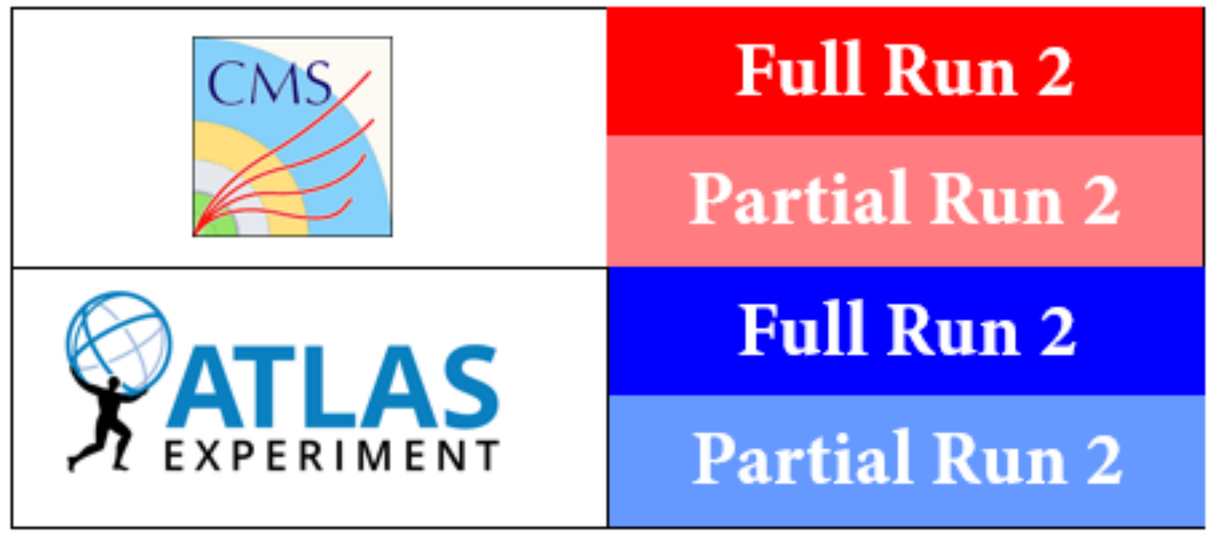
H_{125} decays to light BSM particles

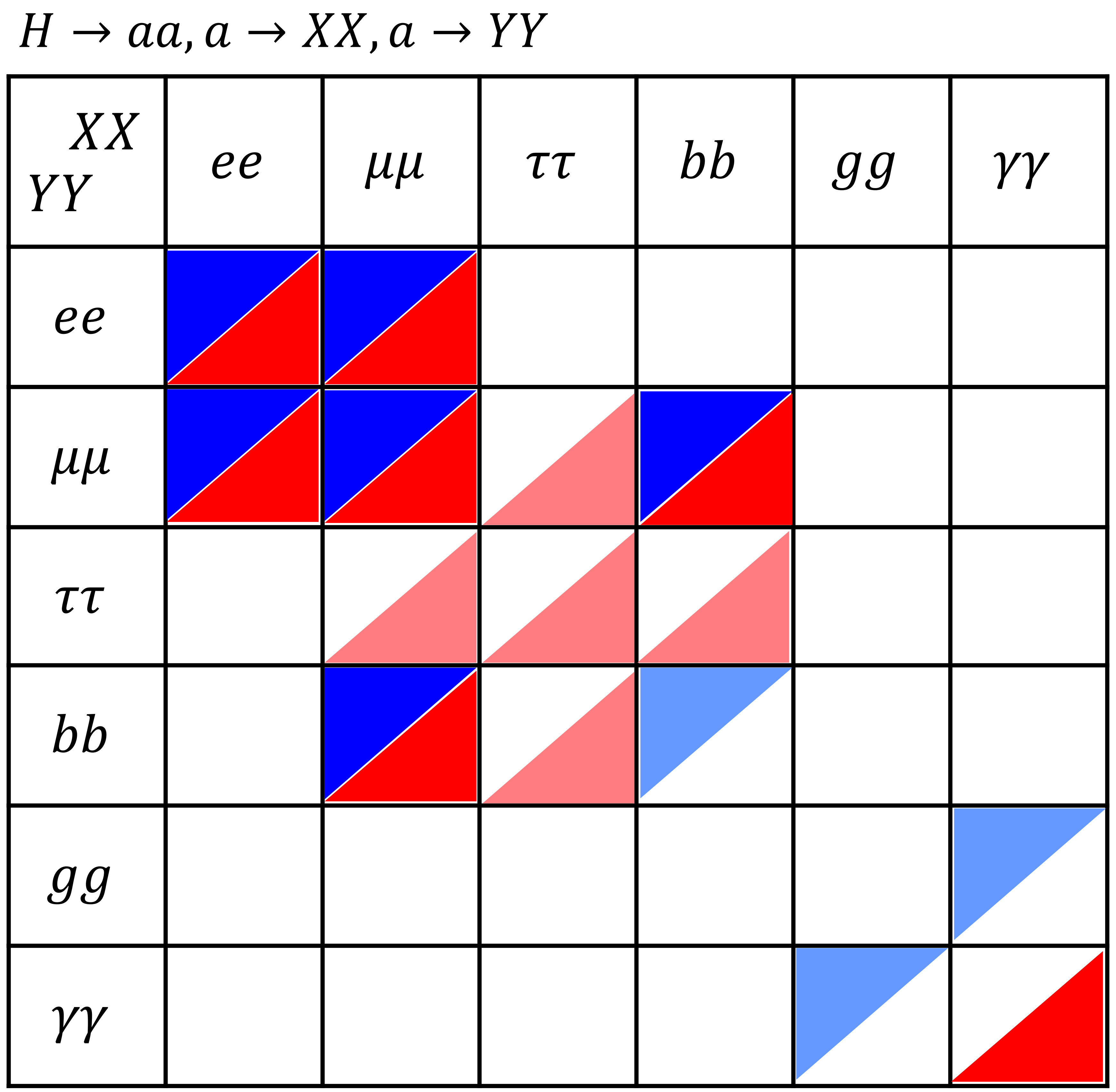
$H_{125} \rightarrow x_{BSM} x_{BSM}$ experimental summary

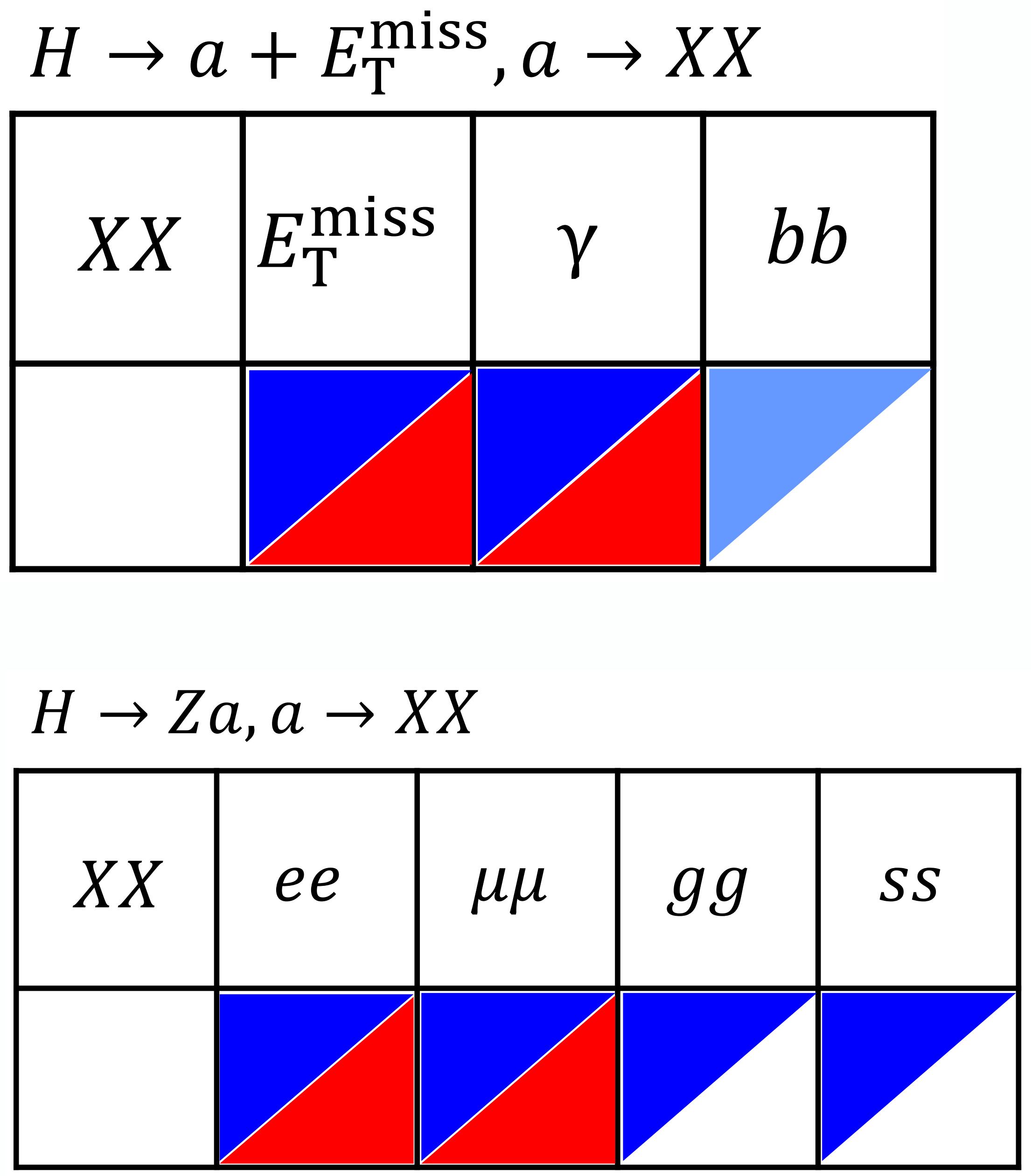
- Thanks to the small total width of **H_{125}**, it **could have notable branching fraction to even very weakly coupled BSM particles**, e.g.
  - One **extra singlet** coupling to H_{125} would generate **$H_{125} \rightarrow h_{BSM} h_{BSM}$**$\rightarrow$XXYY decays
  - Models with **axion-like particles** typically contain **$H_{125} \rightarrow aa$** decays to CP-odd BSM scalars a
- Very active and diverse search program at the LHC

$H_{125} \rightarrow X_{BSM}X_{BSM}$ experimental summary

- Thanks to the small total width of **H_{125}**, it **could have notable branching fraction to even very weakly coupled BSM particles**, e.g.
  - One **extra singlet** coupling to H_{125} would generate **$H_{125} \rightarrow h_{BSM}h_{BSM}$**$\rightarrow XXYY$ decays
  - Models with **axion-like particles** typically contain **$H_{125} \rightarrow aa$** decays to CP-odd BSM scalars a
- Very active and diverse search program at the LHC



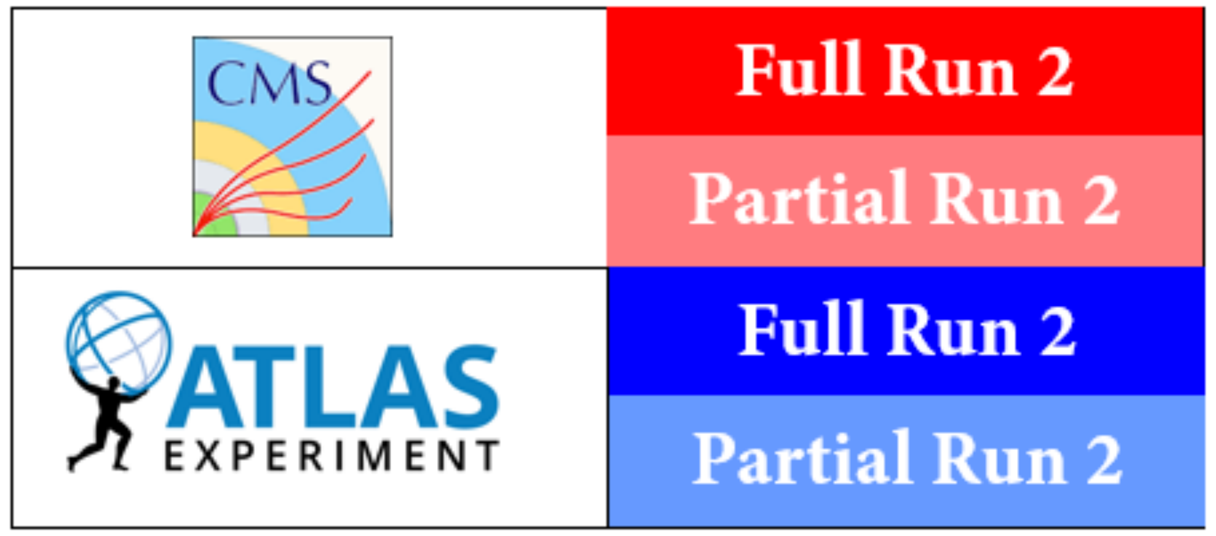




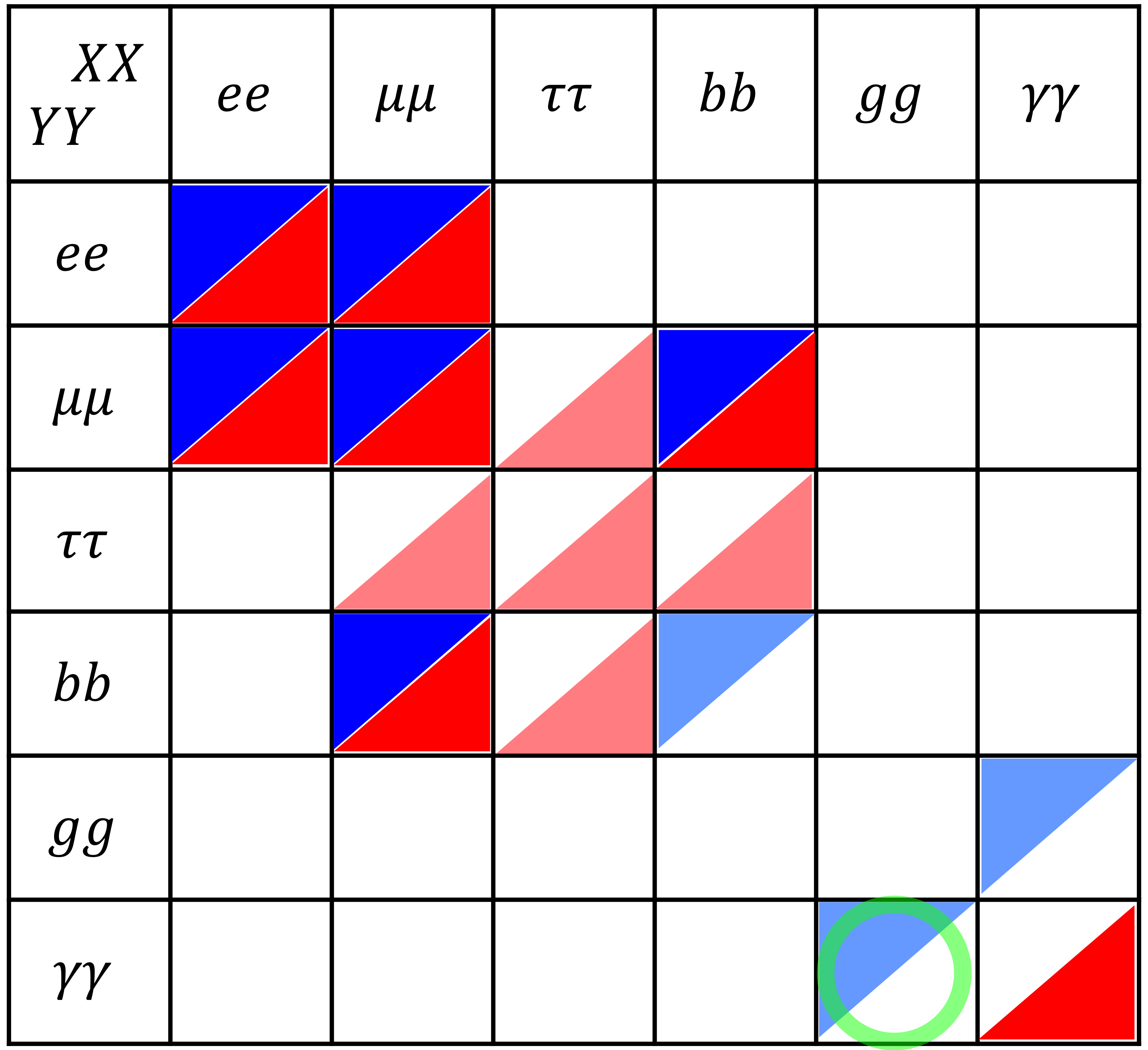
Overview tables by
Rafael Coelho Lopes de Sá
(for details see this talk)

$H_{125} \rightarrow X_{BSM} X_{BSM}$ experimental summary

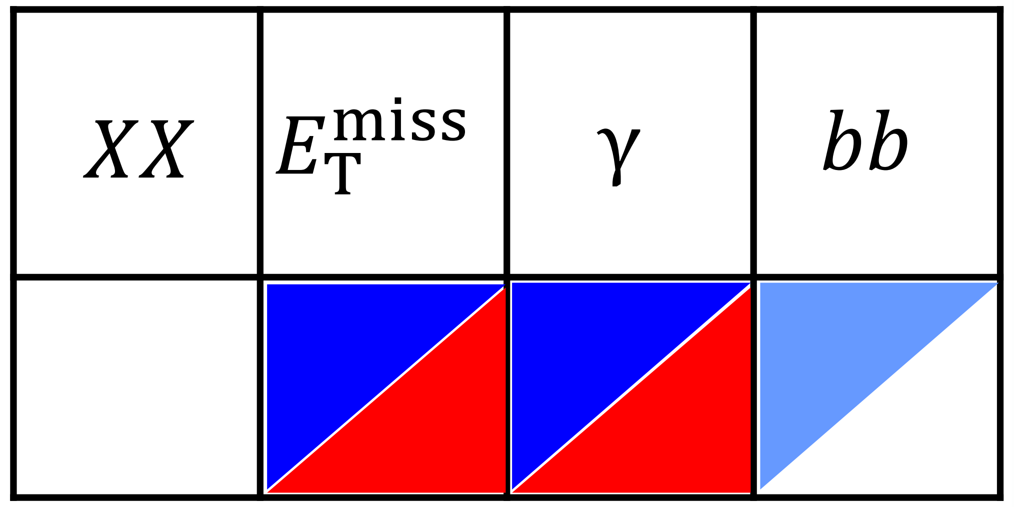
- Thanks to the small total width of **H_{125}**, it **could have notable branching fraction to even very weakly coupled BSM particles**, e.g.
  - One **extra singlet** coupling to H_{125} would generate **$H_{125} \rightarrow h_{BSM} h_{BSM}$**$\rightarrow XXYY$ decays
  - Models with **axion-like particles** typically contain **$H_{125} \rightarrow aa$** decays to CP-odd BSM scalars a
- Very active and diverse search program at the LHC



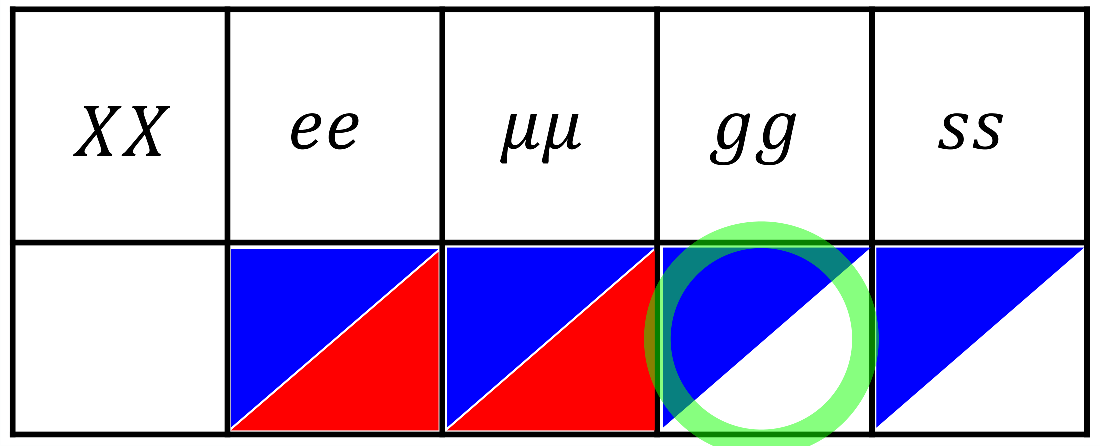
$H \rightarrow aa, a \rightarrow XX, a \rightarrow YY$



$H \rightarrow a + E_T^{miss}, a \rightarrow XX$



$H \rightarrow Za, a \rightarrow XX$

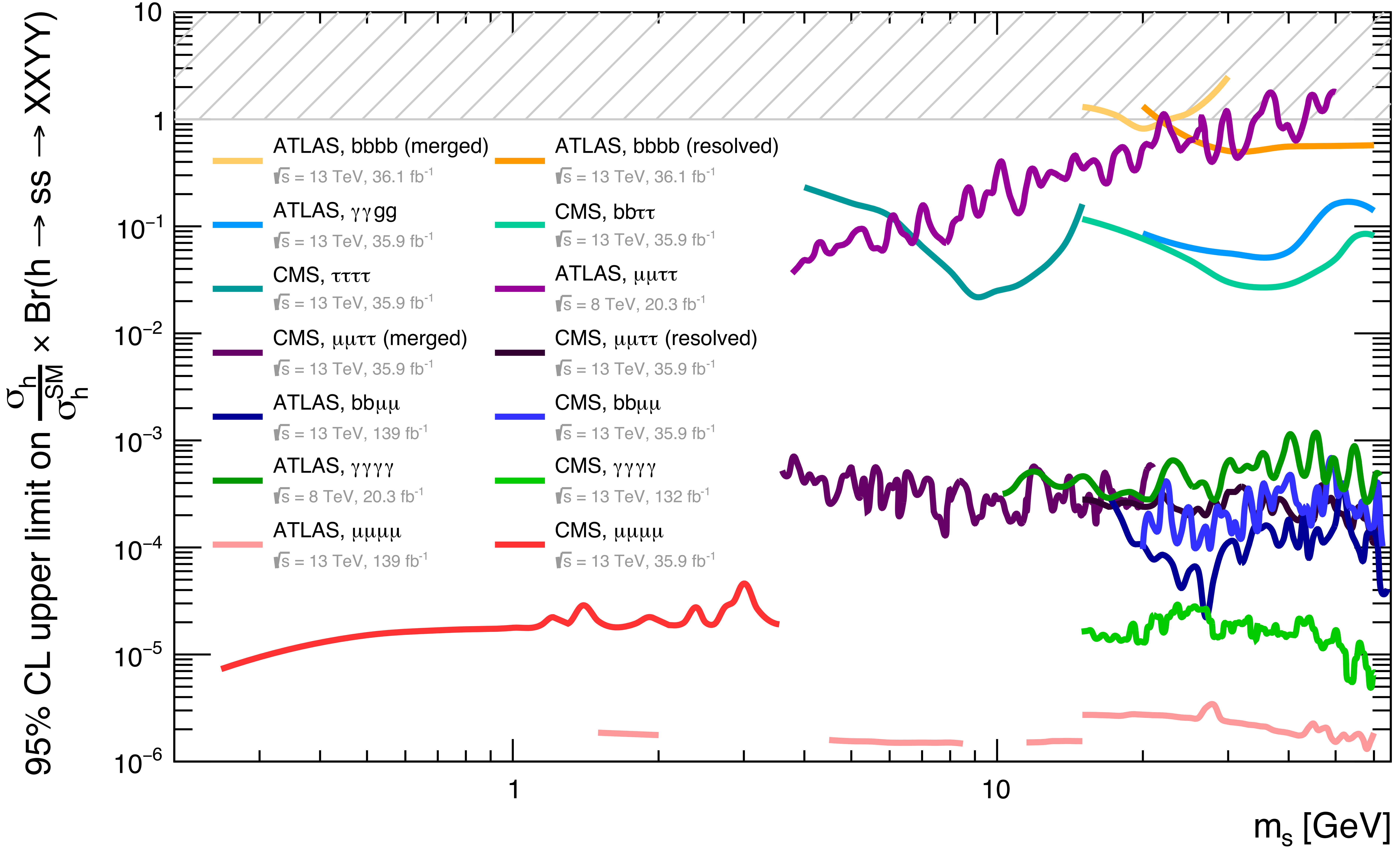


- ATLAS has introduced a dedicated DNN tagger for merged digluon jets

Overview tables by Rafael Coelho Lopes de Sá (for details see this talk)

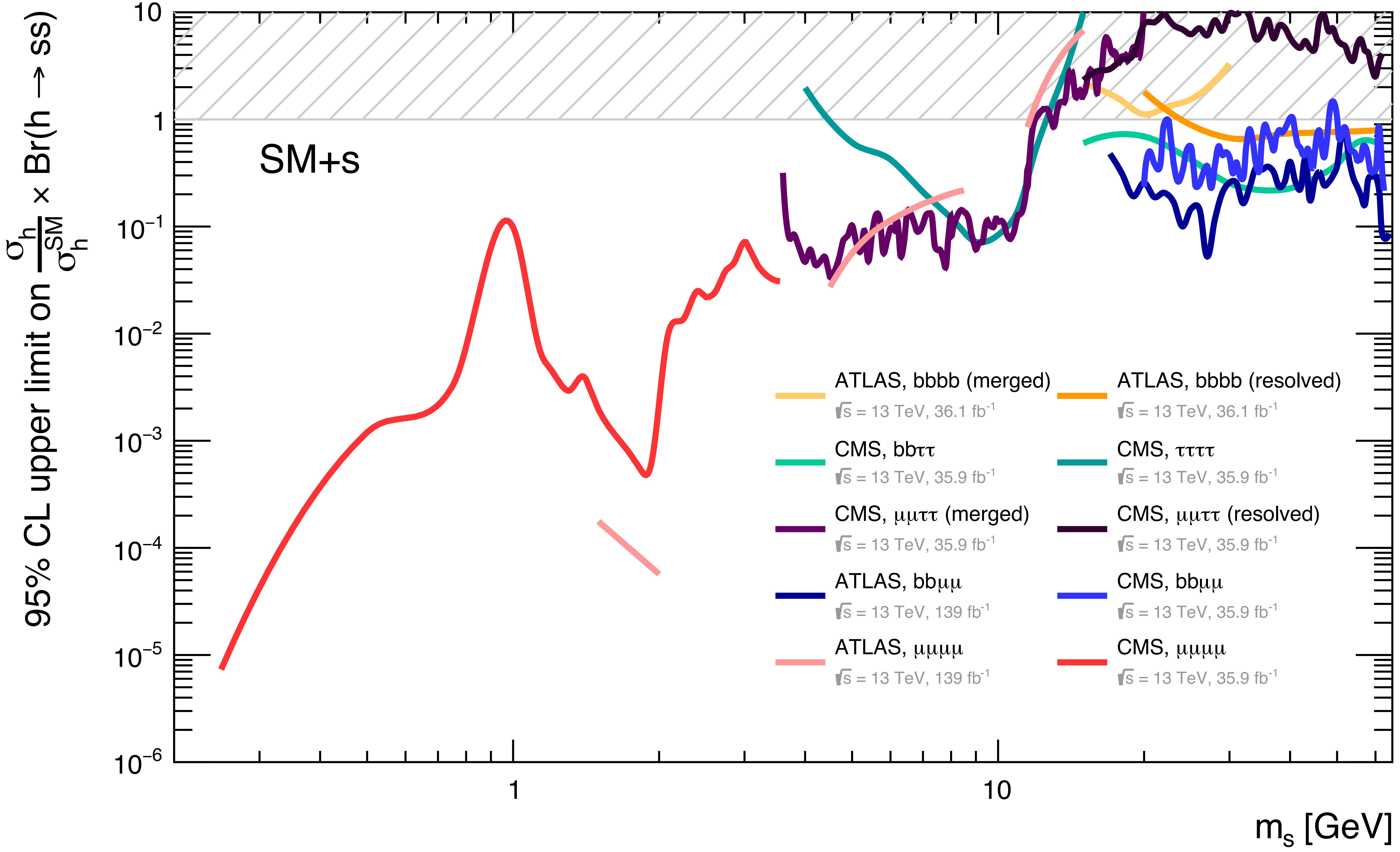
Summary of current upper limits

arXiv:2111.12751



- NB! To compare these upper limits, need to plug in (model-dependent) branching fractions to XX and YY

Limit comparisons in SM+s model



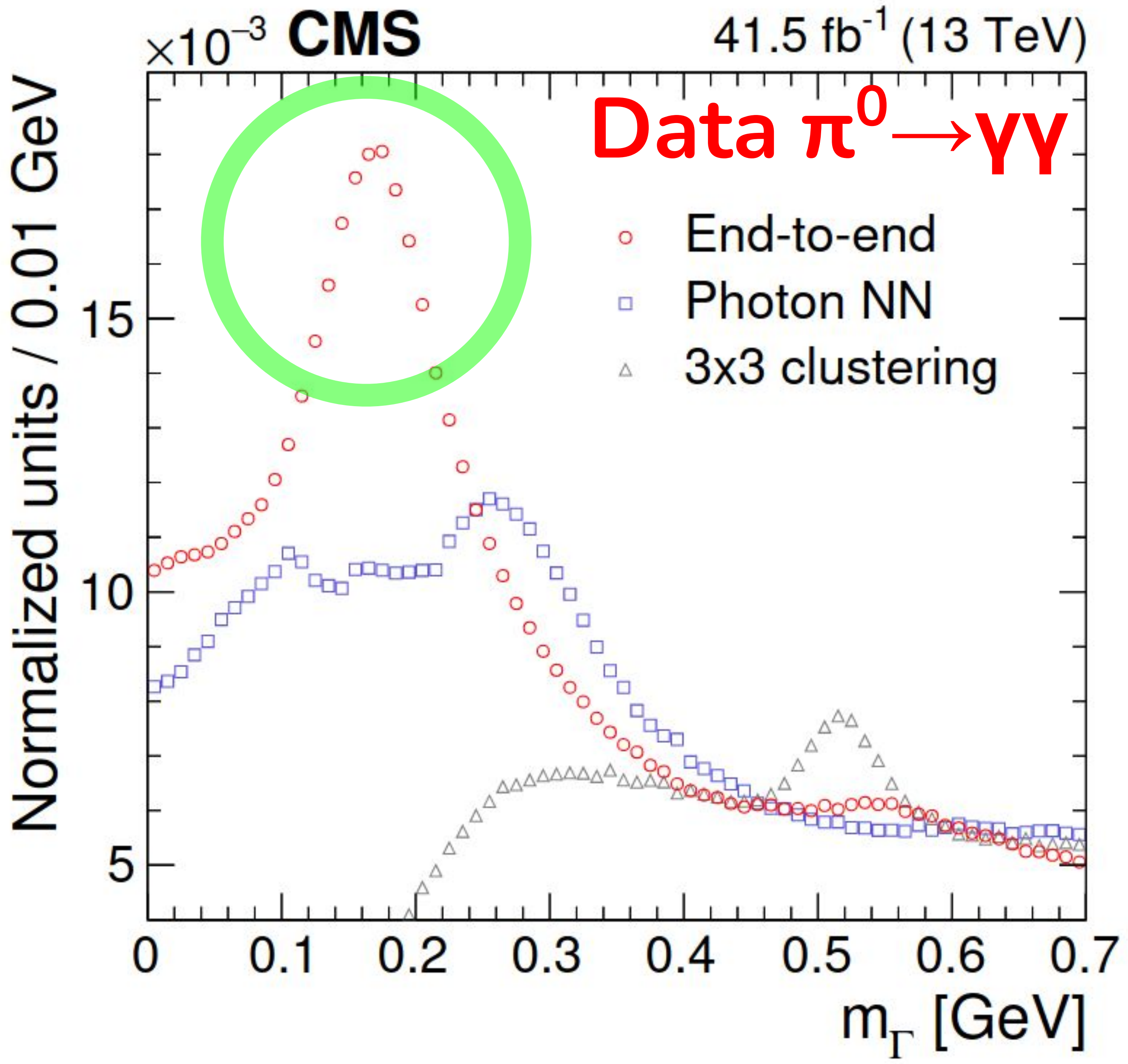
See the overview paper for other interesting benchmarks, e.g. case where s is long-lived

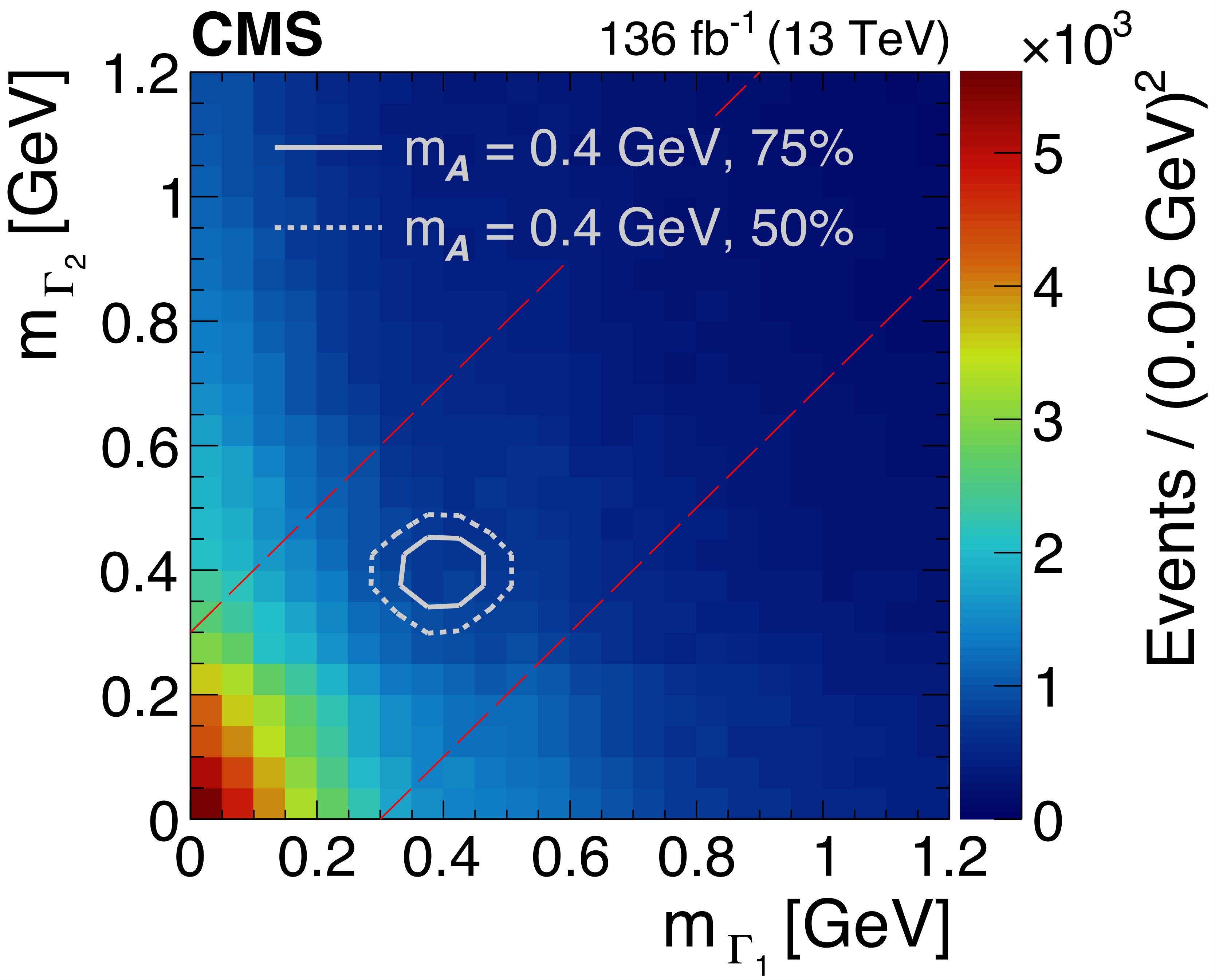
- Limit comparison assuming **SM+singlet benchmark model** with one extra real scalar singlet

CMS Boosted $H \rightarrow x_{BSM} x_{BSM} \rightarrow 4\gamma$

arXiv:2209.06197

- Targets **very low masses** (0.1-1.2 GeV) with a highly boosted signature
- $h_{BSM} \rightarrow \gamma\gamma$ decay reconstructed as **one merged diphoton object** in ECAL
  - **End-to-end ML reconstruction**: DNN trained on ECAL energy deposits to estimate diphoton invariant mass
- Signal extraction with **2D mass templates**
- Background estimation from sidebands → sideband statistics limit sensitivity

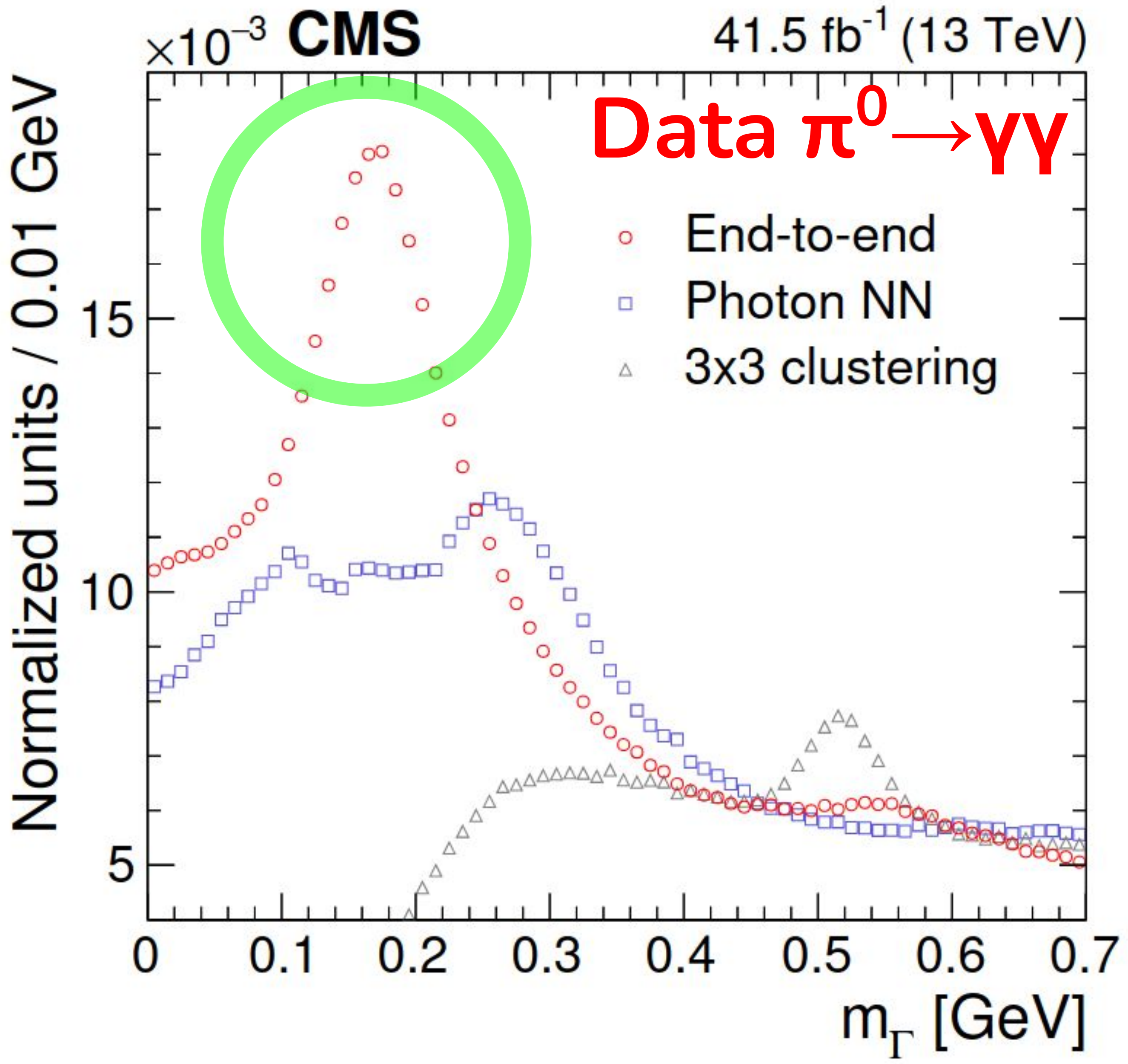


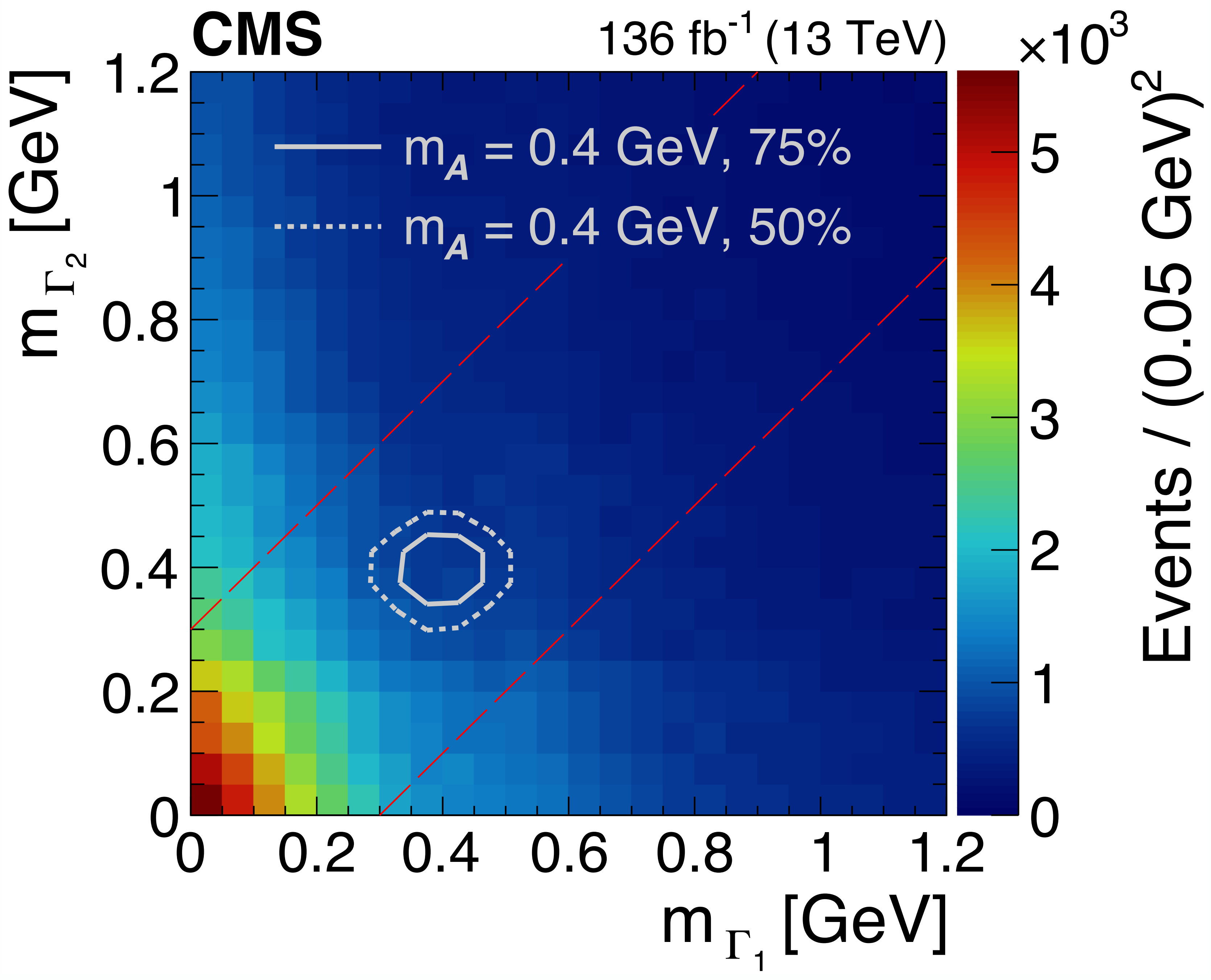


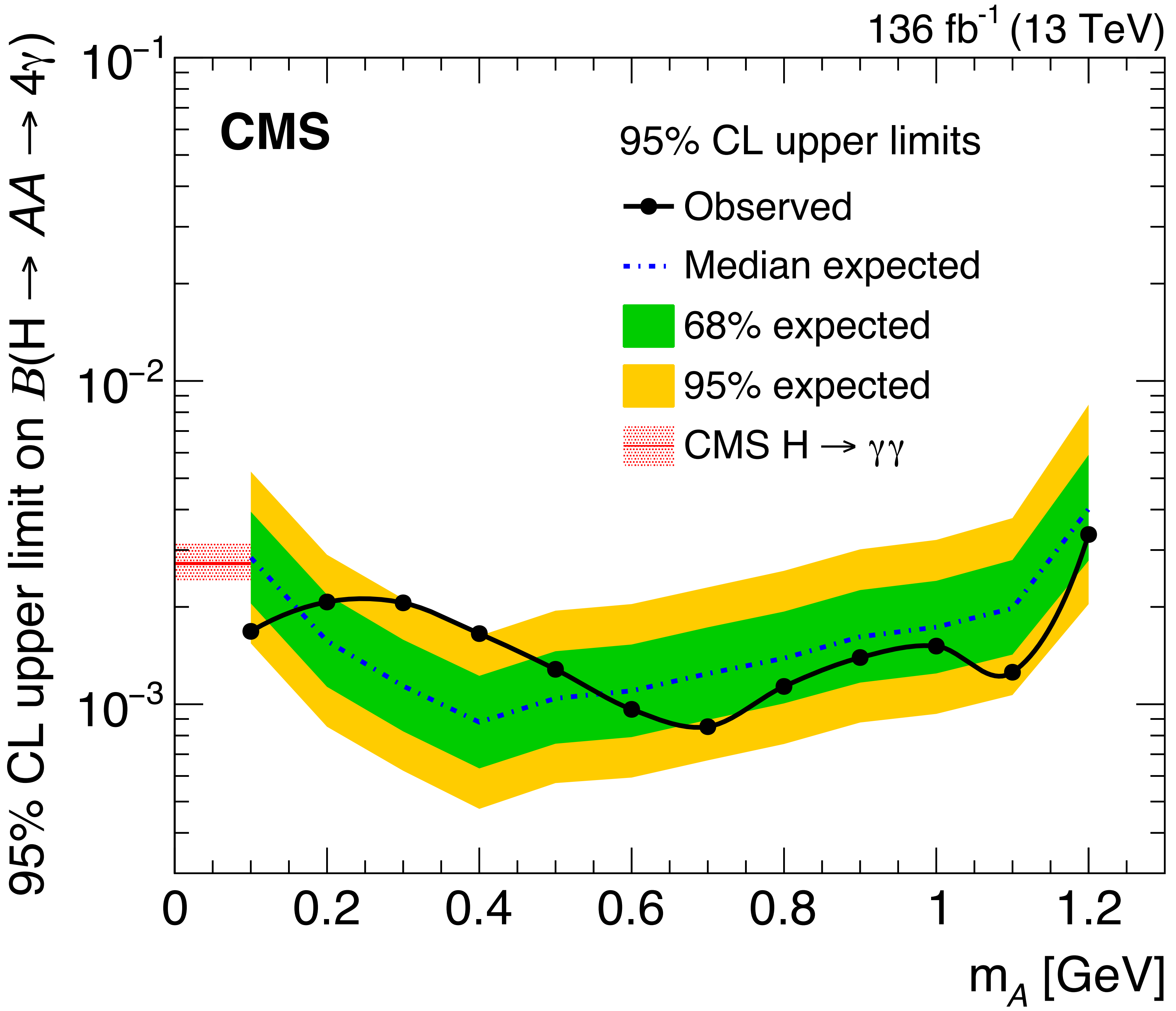
CMS Boosted $H \to x_{BSM} x_{BSM} \to 4\gamma$

arXiv:2209.06197

- Targets **very low masses** (0.1-1.2 GeV) with a highly boosted signature
- $h_{BSM} \to \gamma\gamma$ decay reconstructed as **one merged diphoton object** in ECAL
  - **End-to-end ML reconstruction**: DNN trained on ECAL energy deposits to estimate diphoton invariant mass
- Signal extraction with **2D mass templates**
- Background estimation from sidebands → sideband statistics limit sensitivity



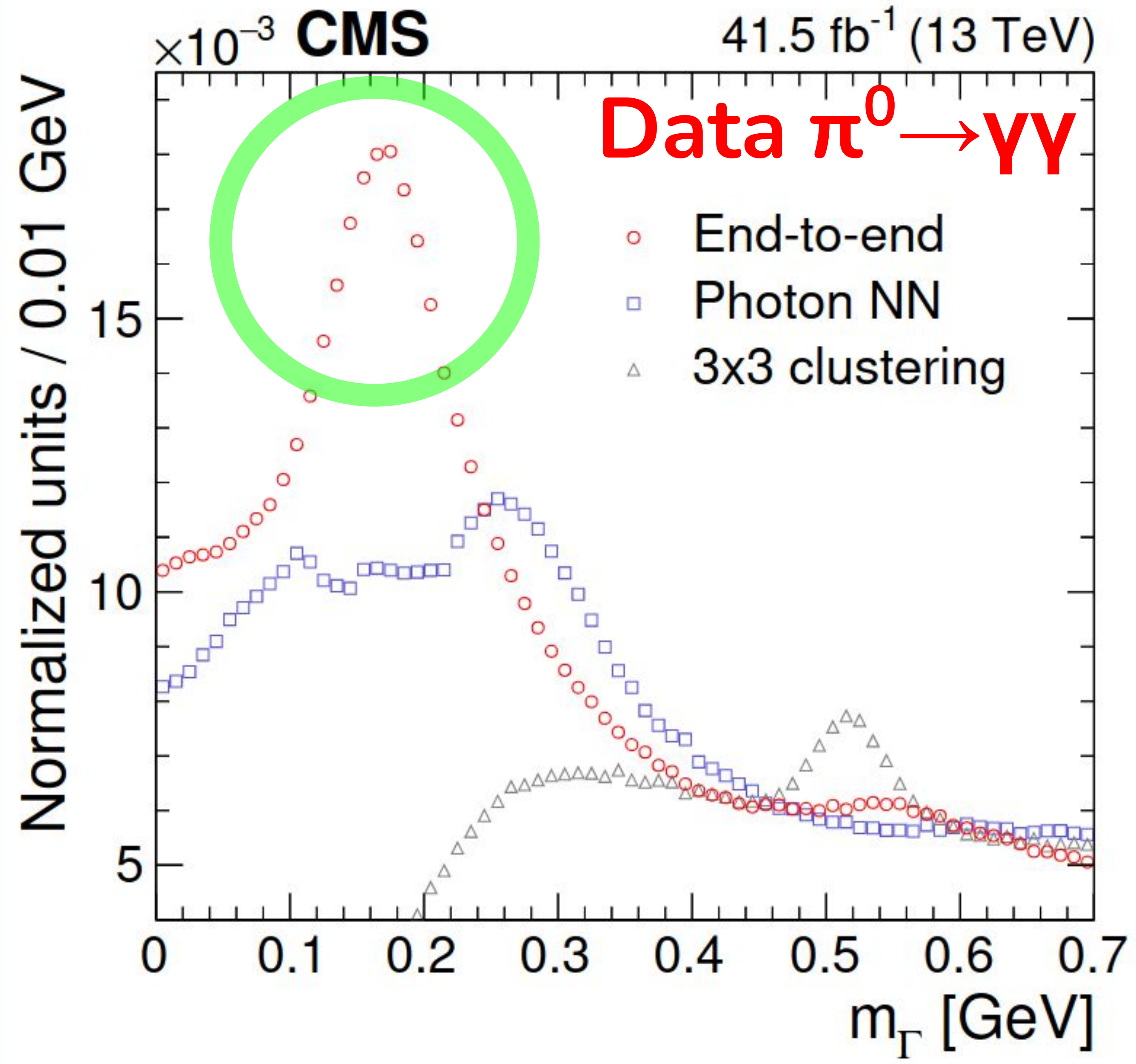


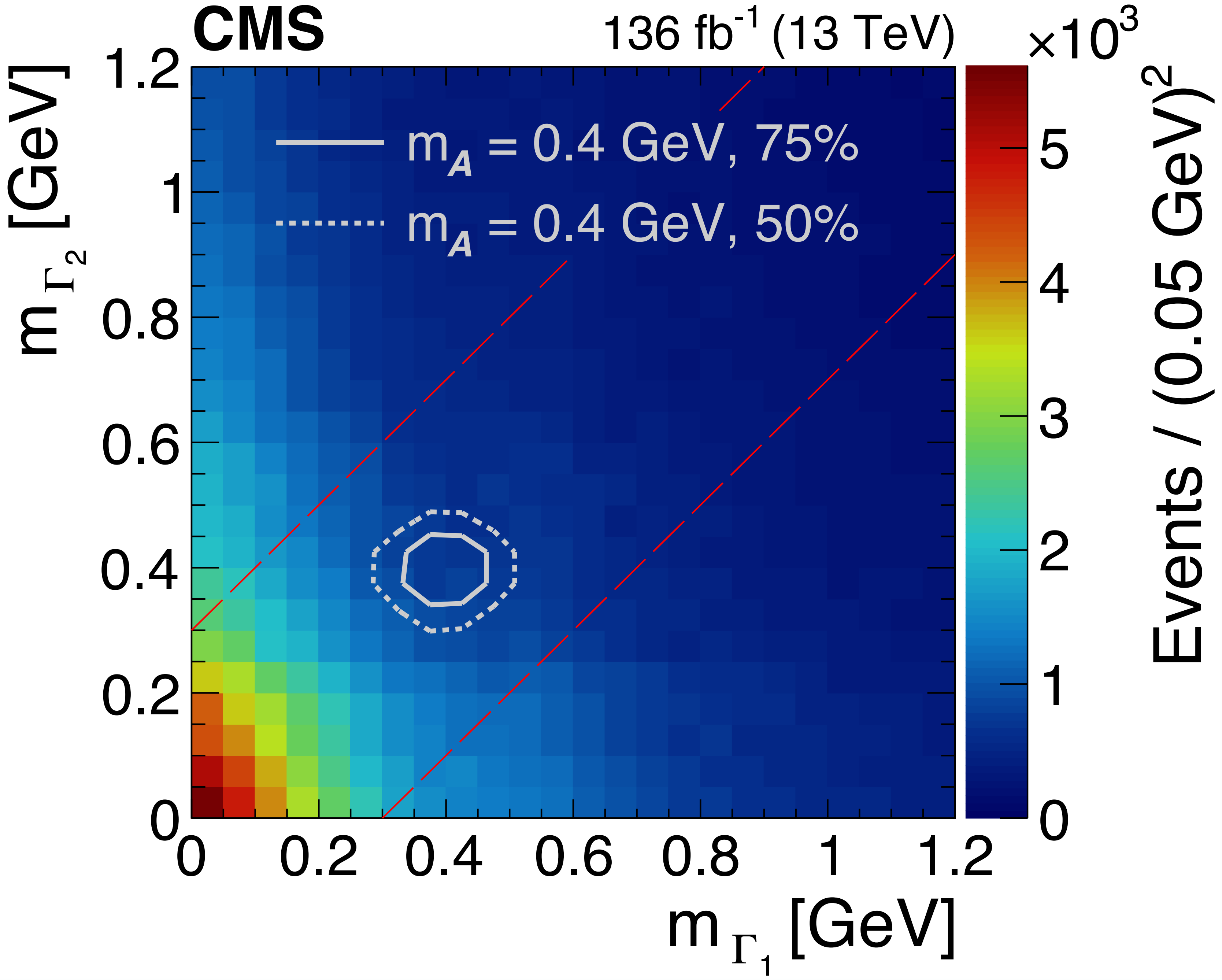


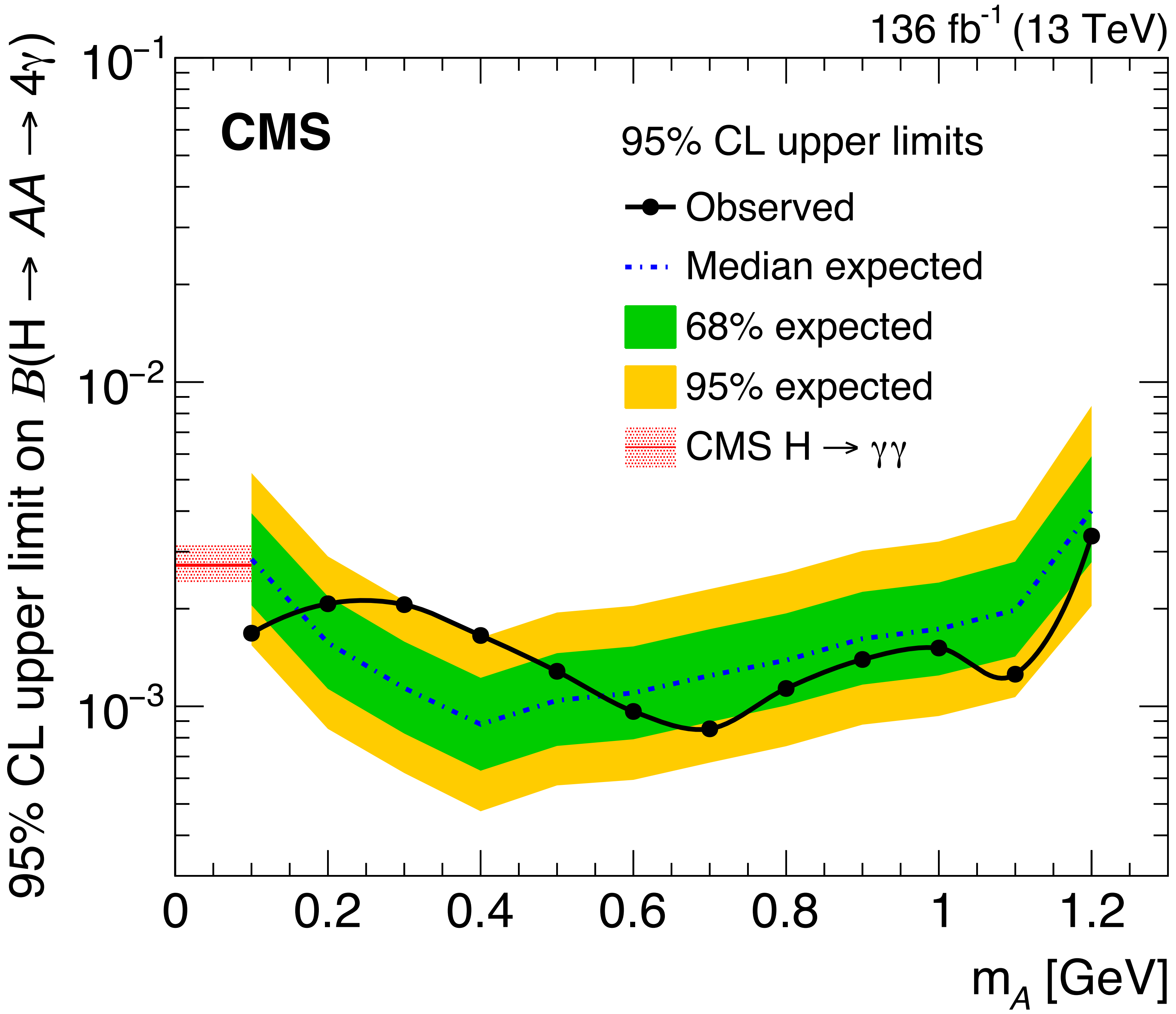
CMS Boosted H→$x_{BSM}x_{BSM}$→4γ

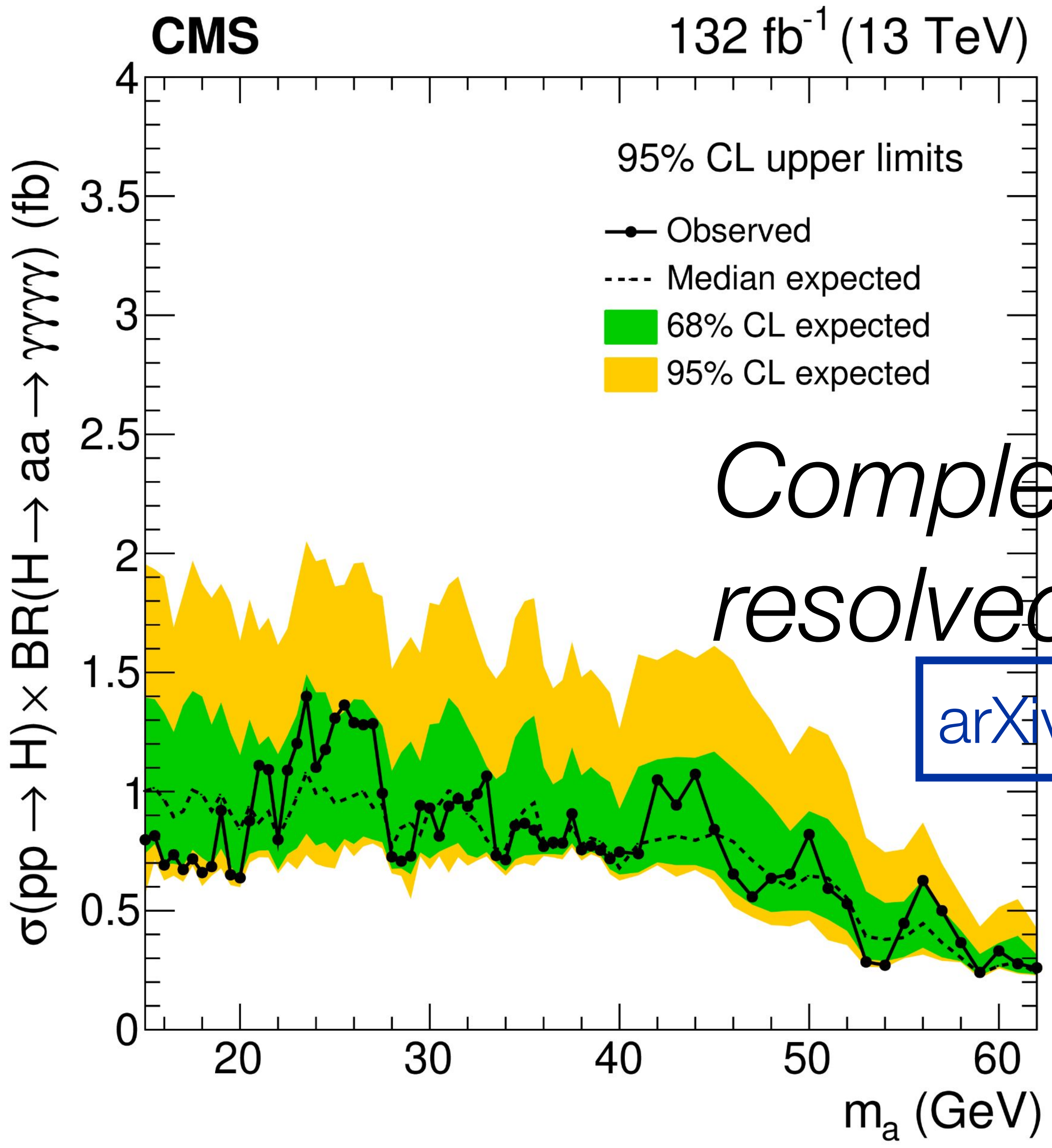
arXiv:2209.06197

- Targets **very low masses** (0.1-1.2 GeV) with a highly boosted signature
- h_{BSM}→γγ decay reconstructed as **one merged diphoton object** in ECAL
  - **End-to-end ML reconstruction**: DNN trained on ECAL energy deposits to estimate diphoton invariant mass
- Signal extraction with **2D mass templates**
- Background estimation from sidebands → sideband statistics limit sensitivity









Complementary resolved analysis

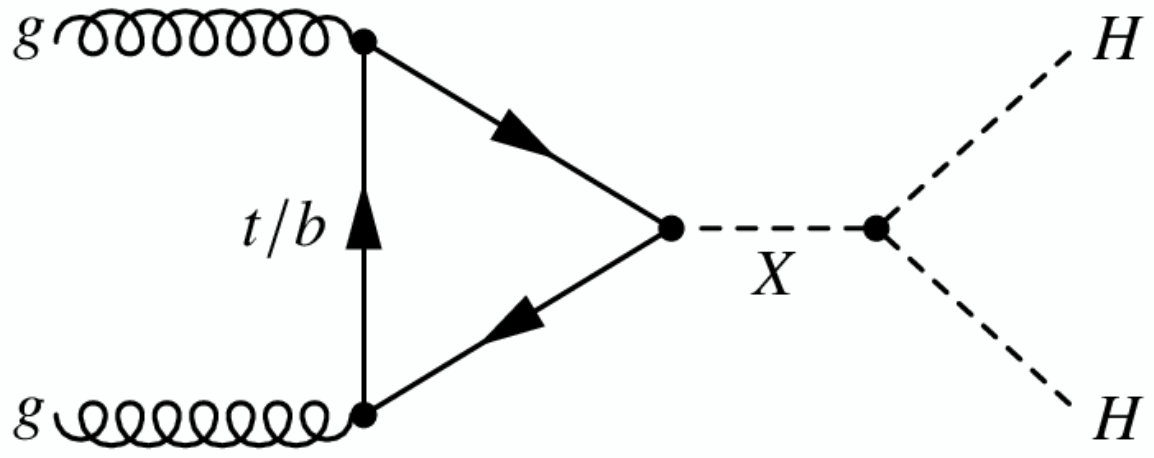
arXiv:2208.01469

Heavy resonances decaying to H_{125}

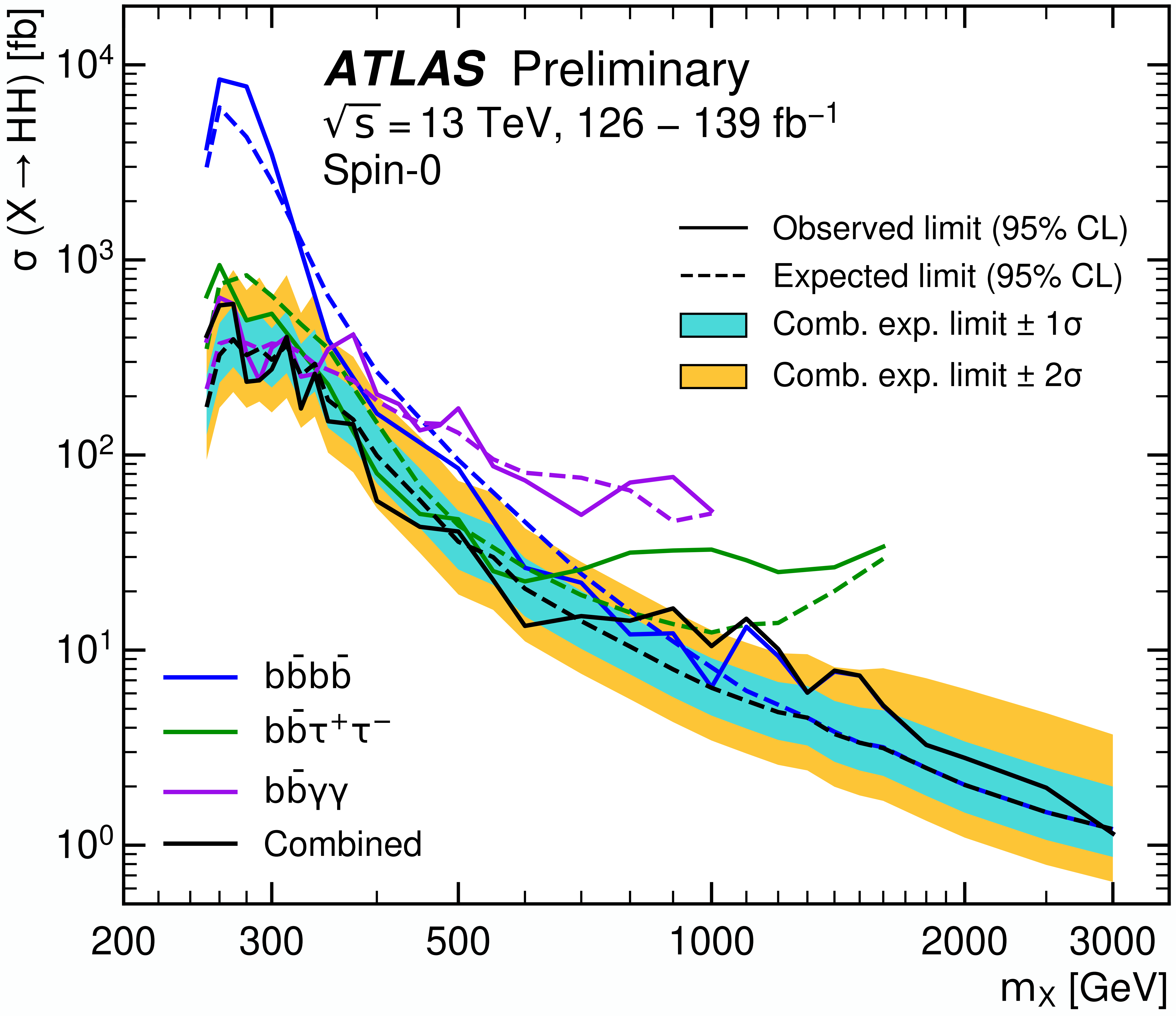
$H_{BSM} \rightarrow H_{125}H_{125}$

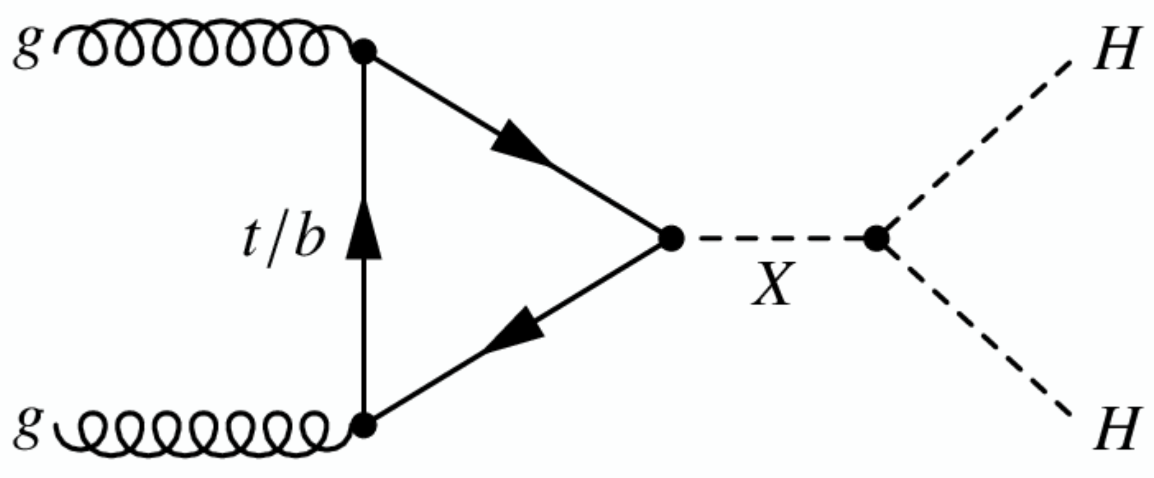
ATLAS-CONF-2021-052

CMS public web pages



$H_{BSM} \rightarrow H_{125}H_{125}$

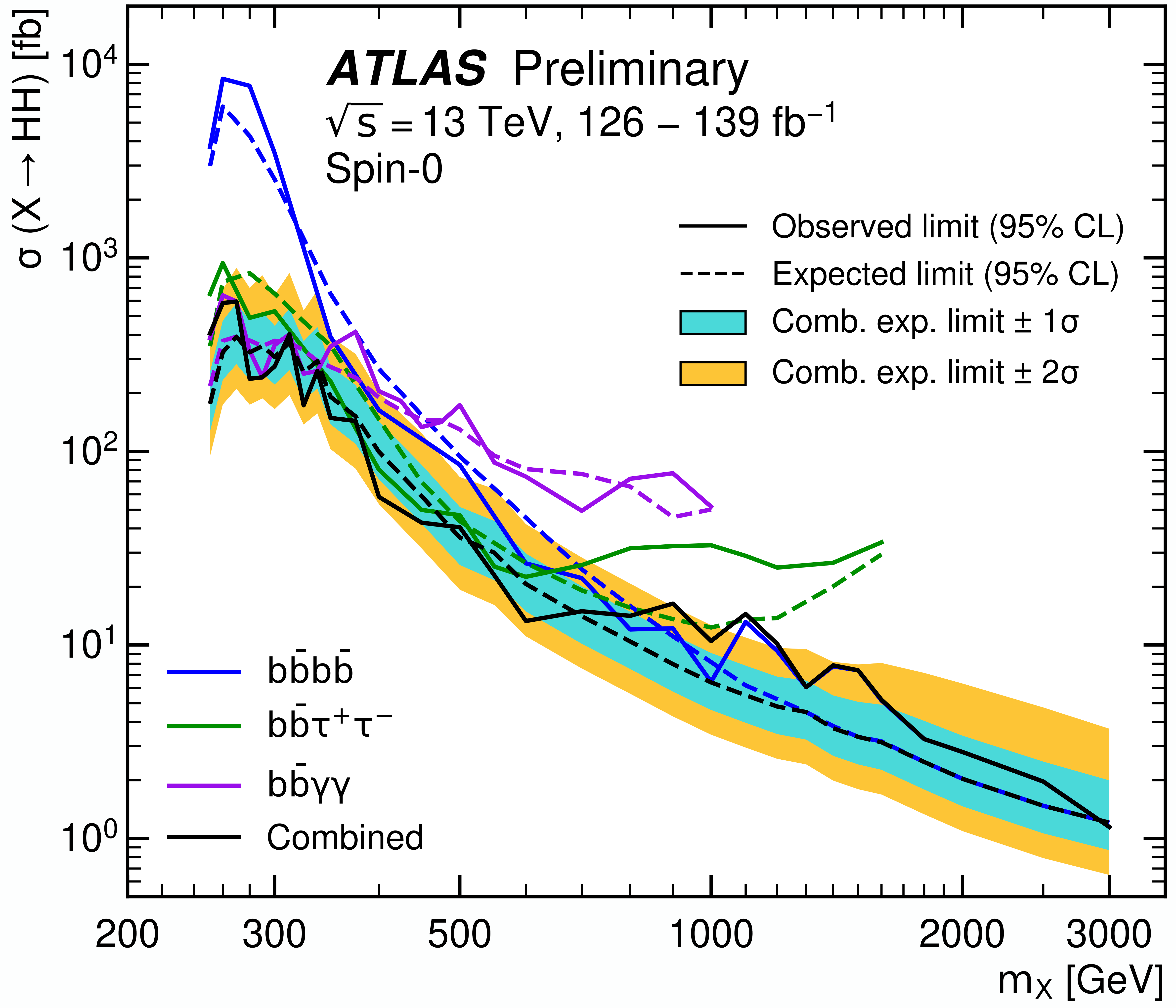


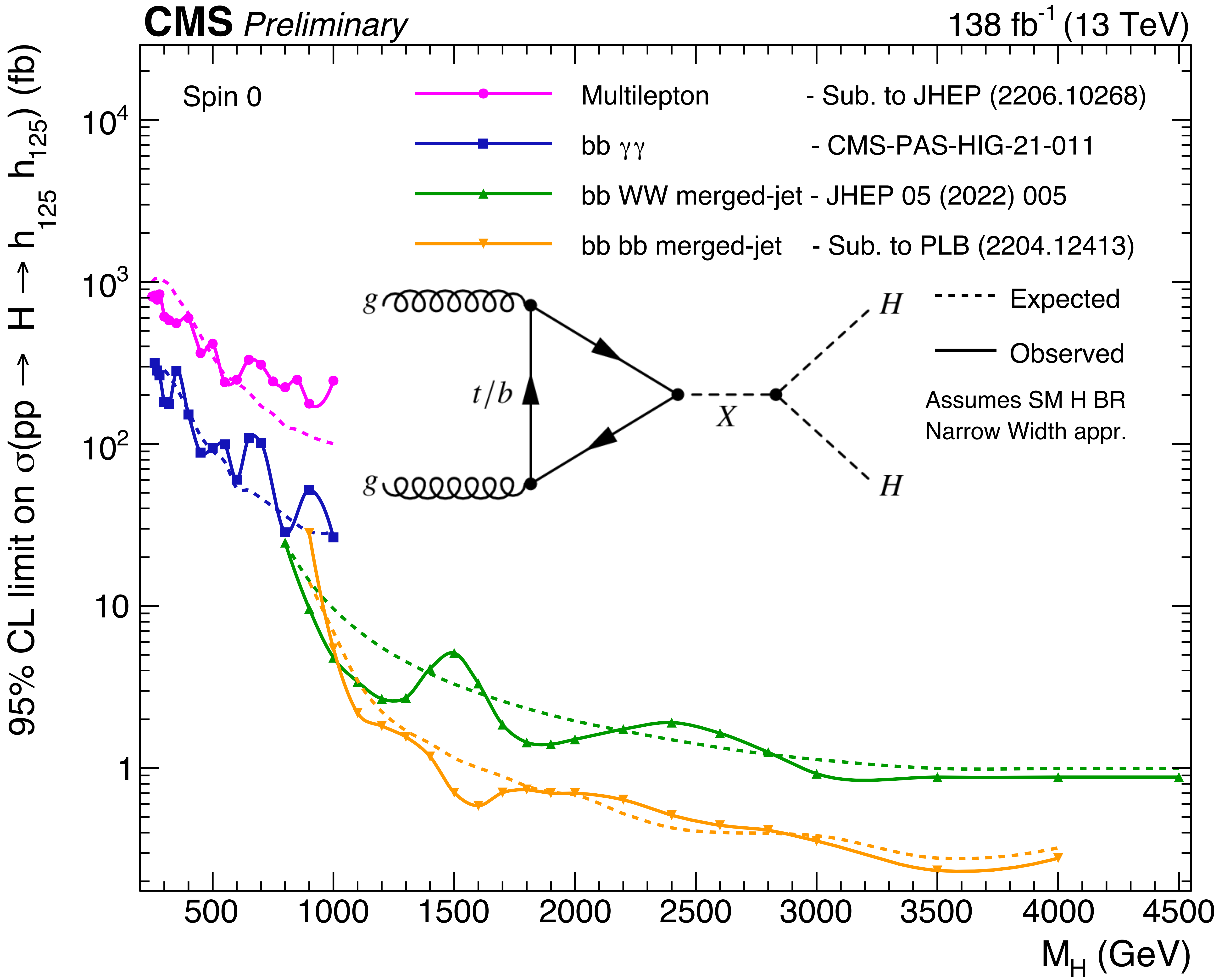


$H_{BSM} \rightarrow H_{125} H_{125}$

ATLAS-CONF-2021-052

CMS public web pages

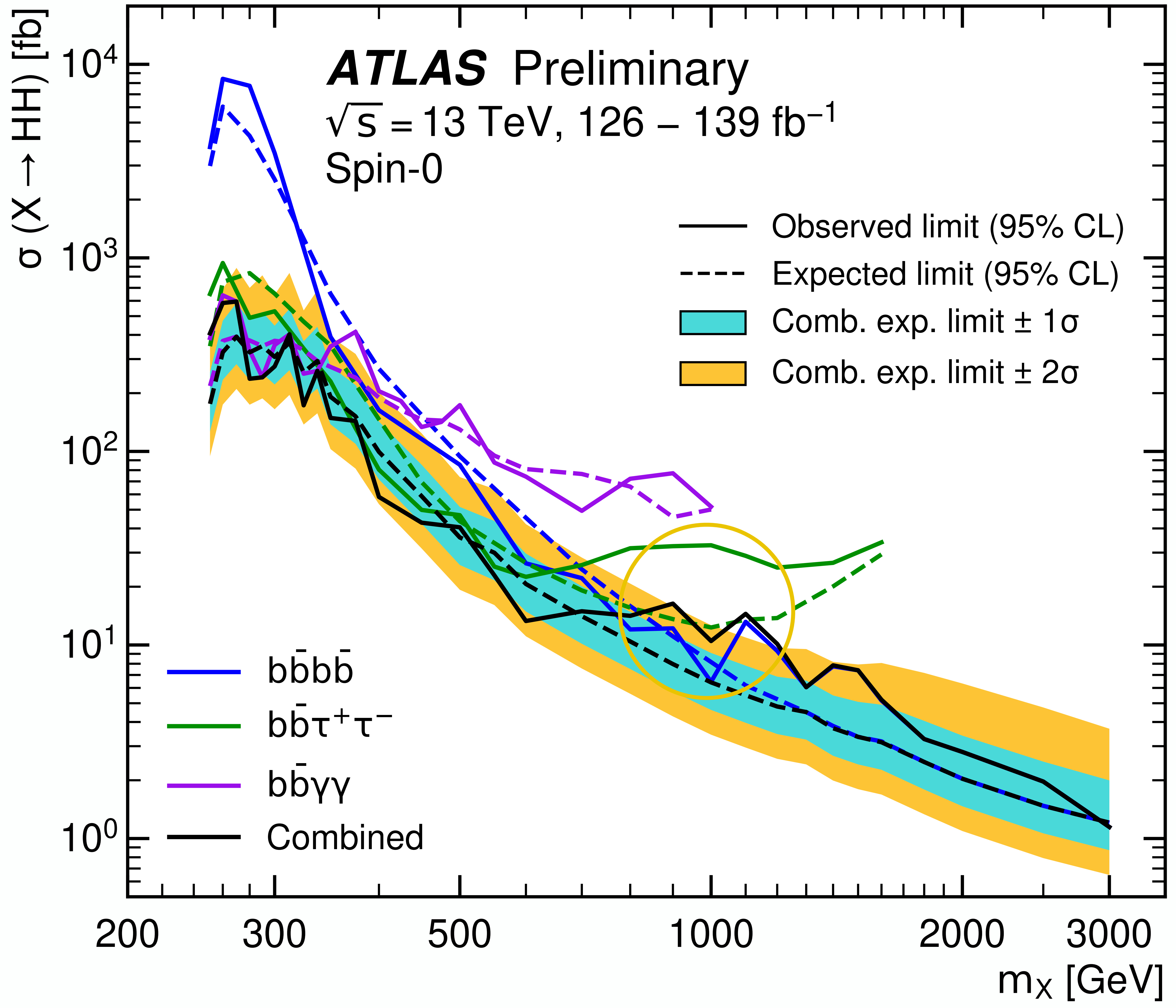


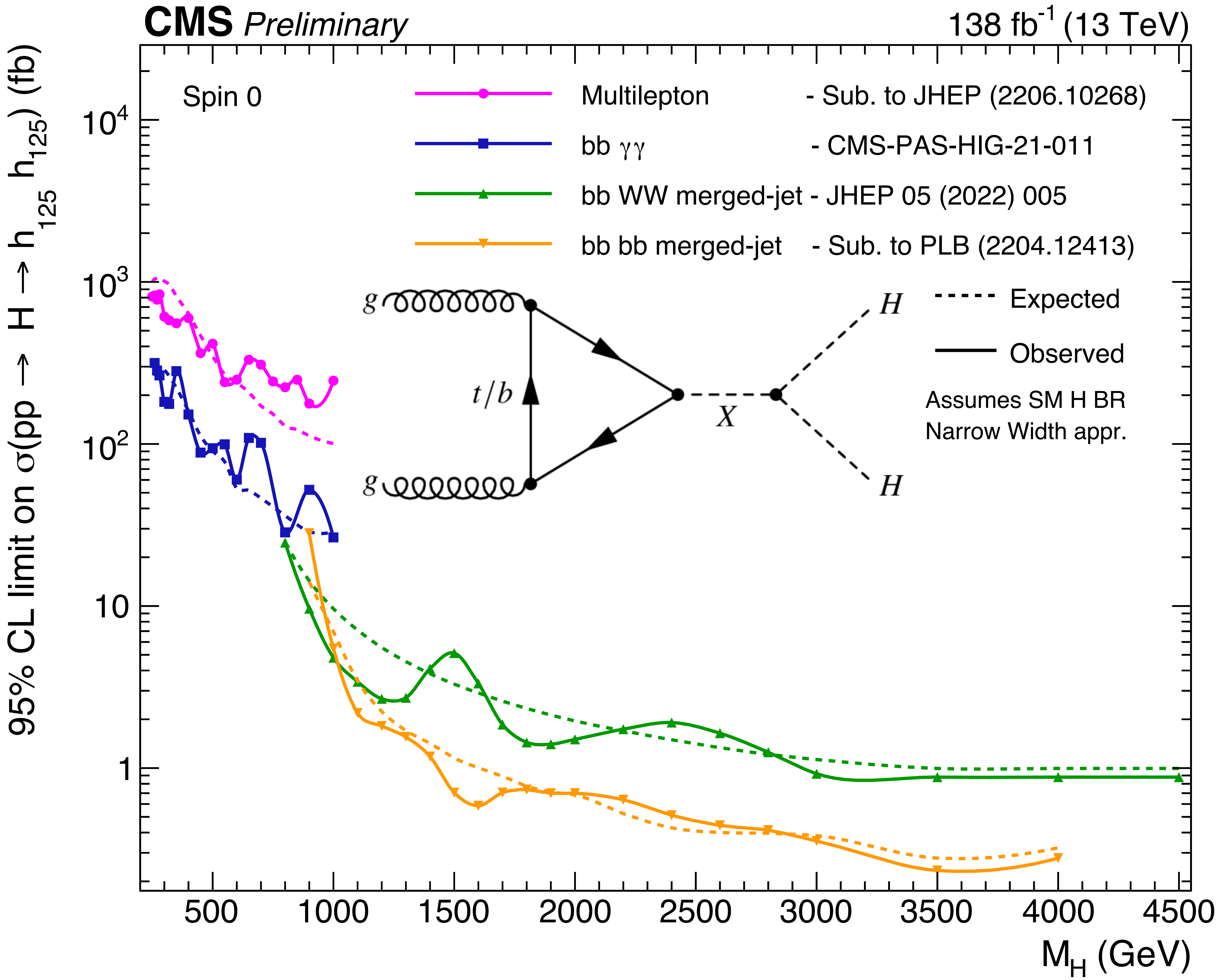


$H_{BSM} \rightarrow H_{125}H_{125}$

ATLAS-CONF-2021-052

CMS public web pages



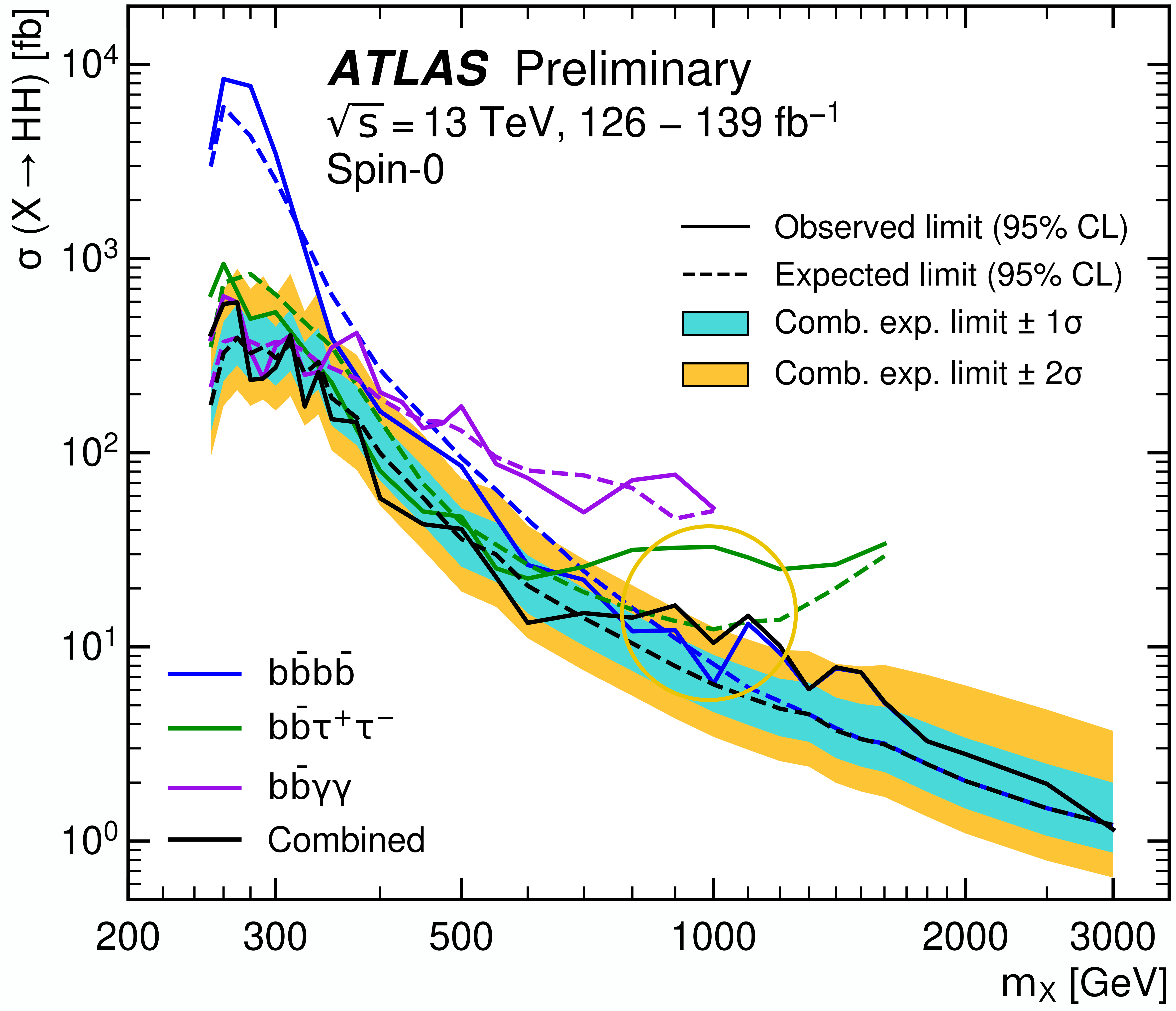


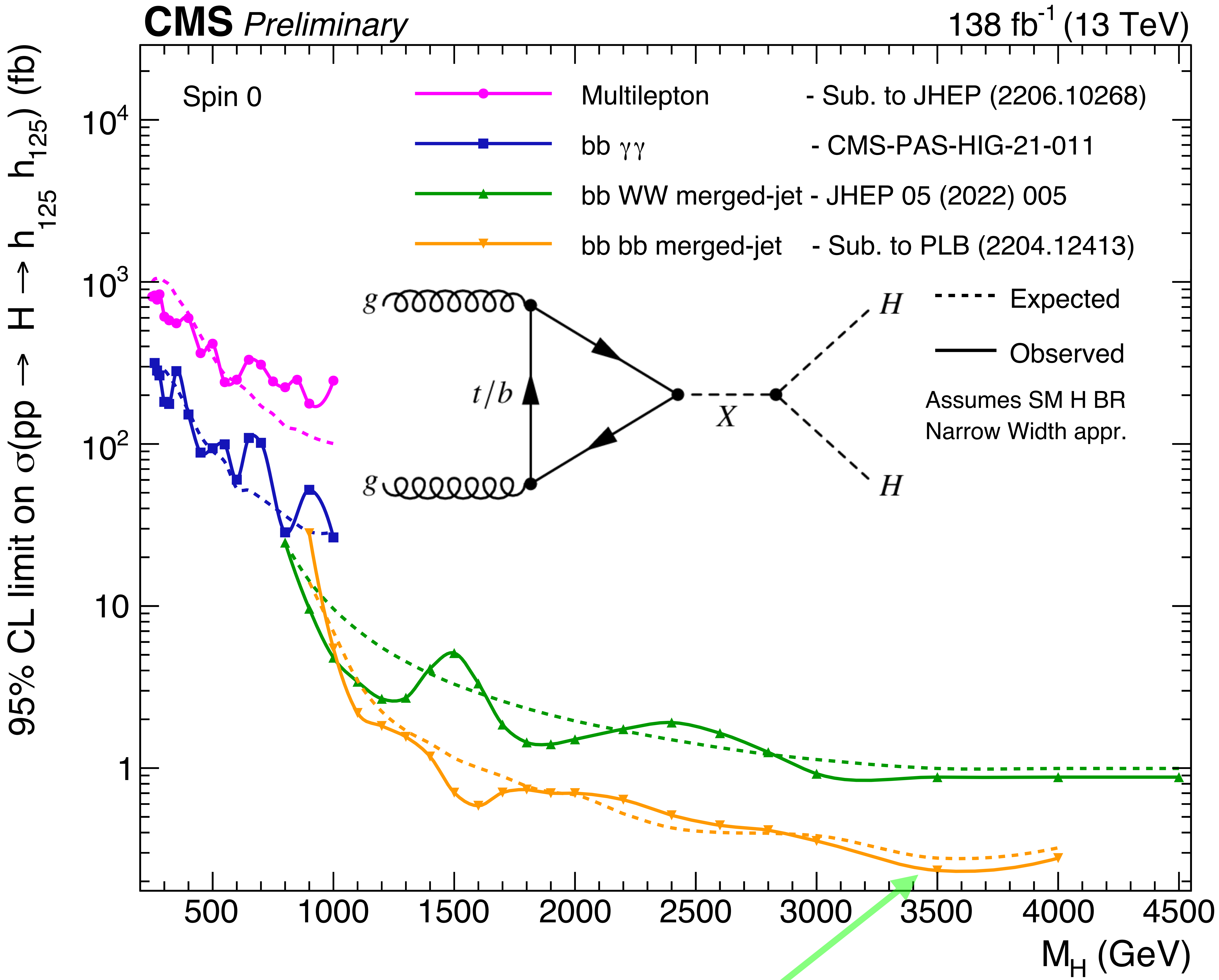
- ATLAS combined limit has 3σ (2σ) global (local) excess around **1.1 TeV**, not confirmed by CMS
- **bbττ** has a 3σ (2σ) excess around **1.0 TeV**

$H_{BSM} \rightarrow H_{125}H_{125}$

ATLAS-CONF-2021-052

CMS public web pages



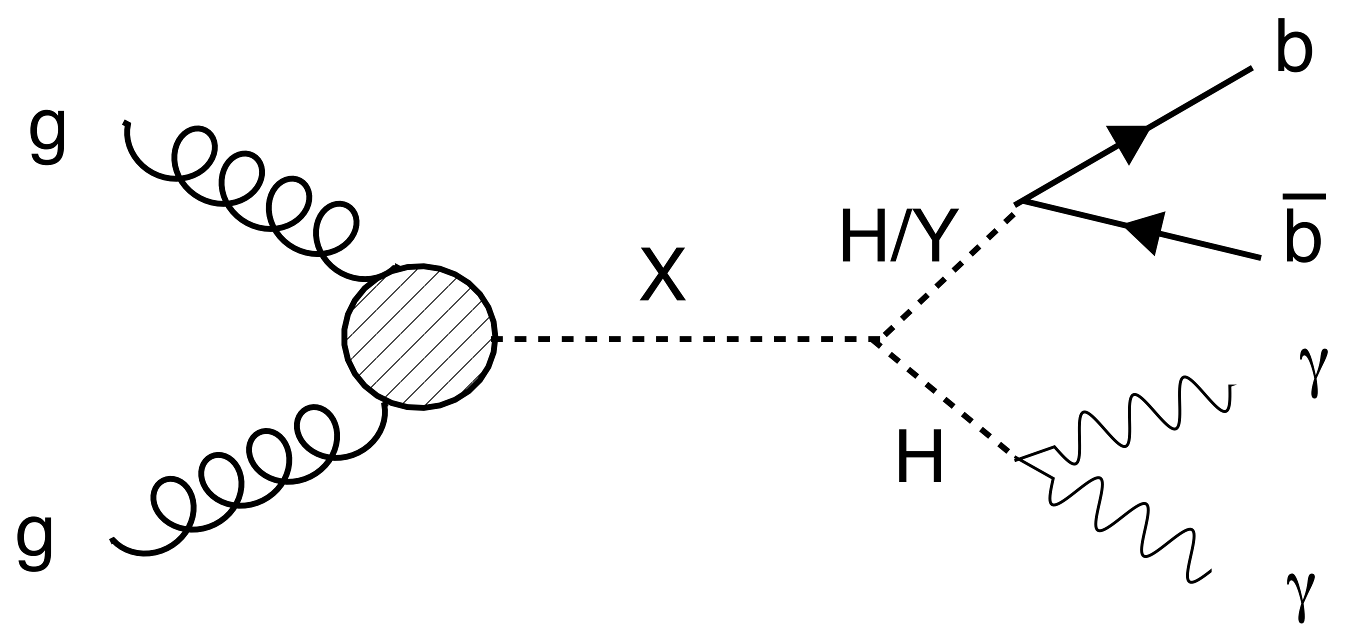


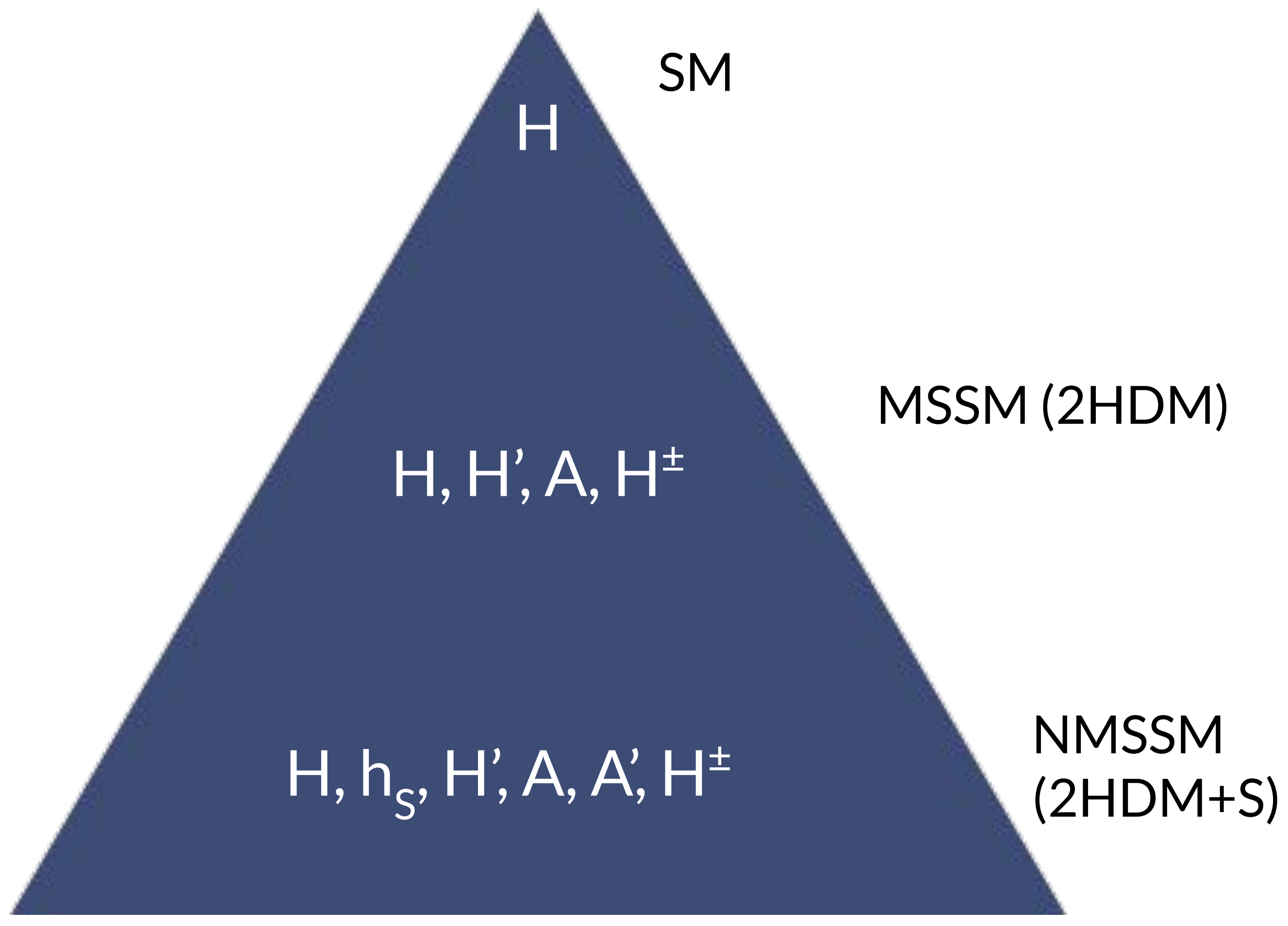
- ATLAS combined limit has 3σ (2σ) global (local) excess around **1.1 TeV**, not confirmed by CMS
- **bbττ** has a 3σ (2σ) excess around **1.0 TeV**

- Merged-jet bbbb channel has a recent improvement by a **factor of ~2** thanks to **graph neural network** based jet tagging

CMS $H_{BSM} \rightarrow H_{125}h_{BSM}$

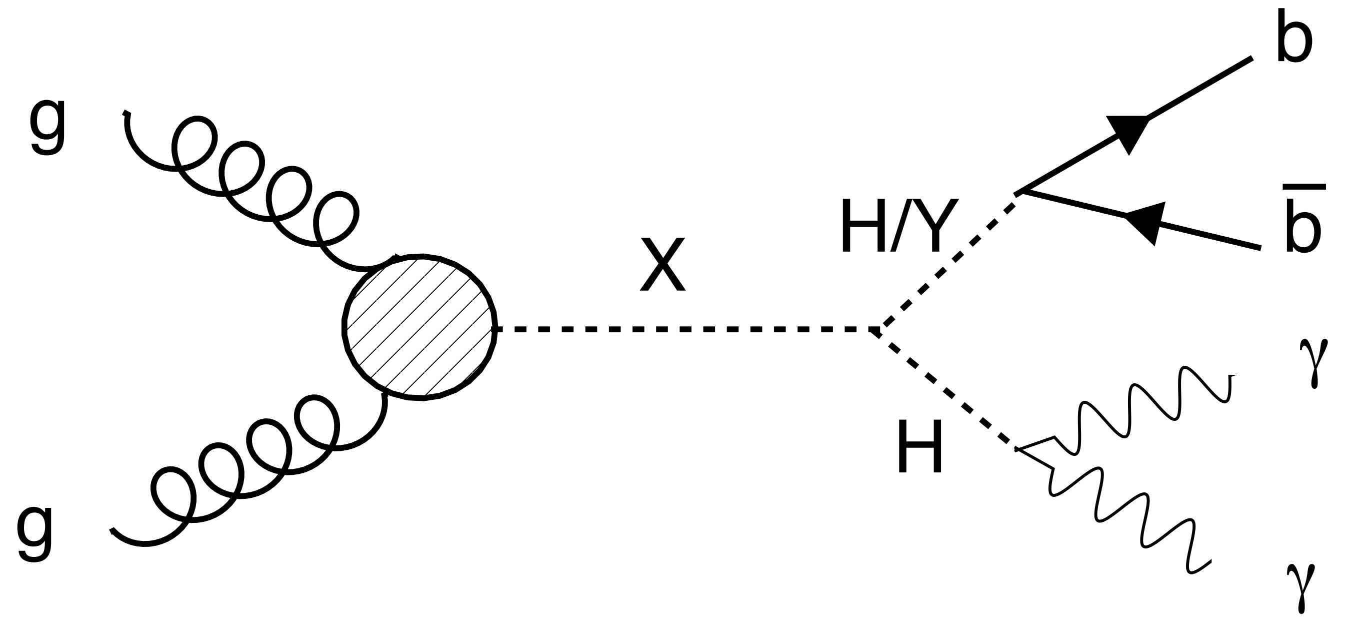
- $H_{BSM} \rightarrow H_{125}h_{BSM}$ **can be the dominant production process for h_{BSM}** e.g. in 2HDM+singlet models and in two-real-scalar-singlet models
- CMS has recently preformed the **first LHC searches for this process**, targeting different H_{125} decay modes :
  - $H_{125}(bb)h_{BSM}(bb)$ arXiv:2204.12413
  - $H_{125}(\tau\tau)h_{BSM}(bb)$ arXiv:2106.10361
  - $H_{125}(\gamma\gamma)h_{BSM}(bb)$ CMS-PAS-HIG-21-011

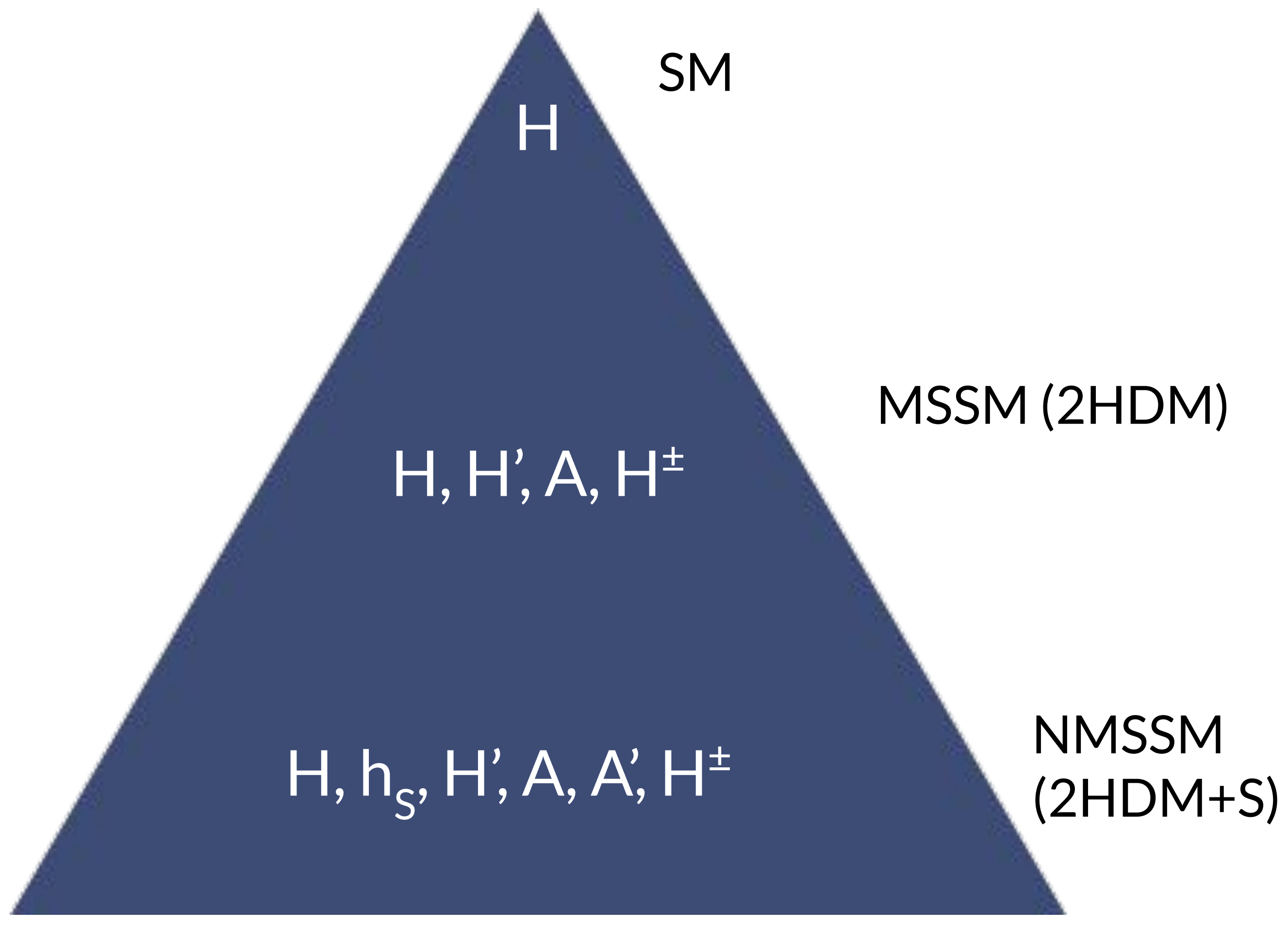


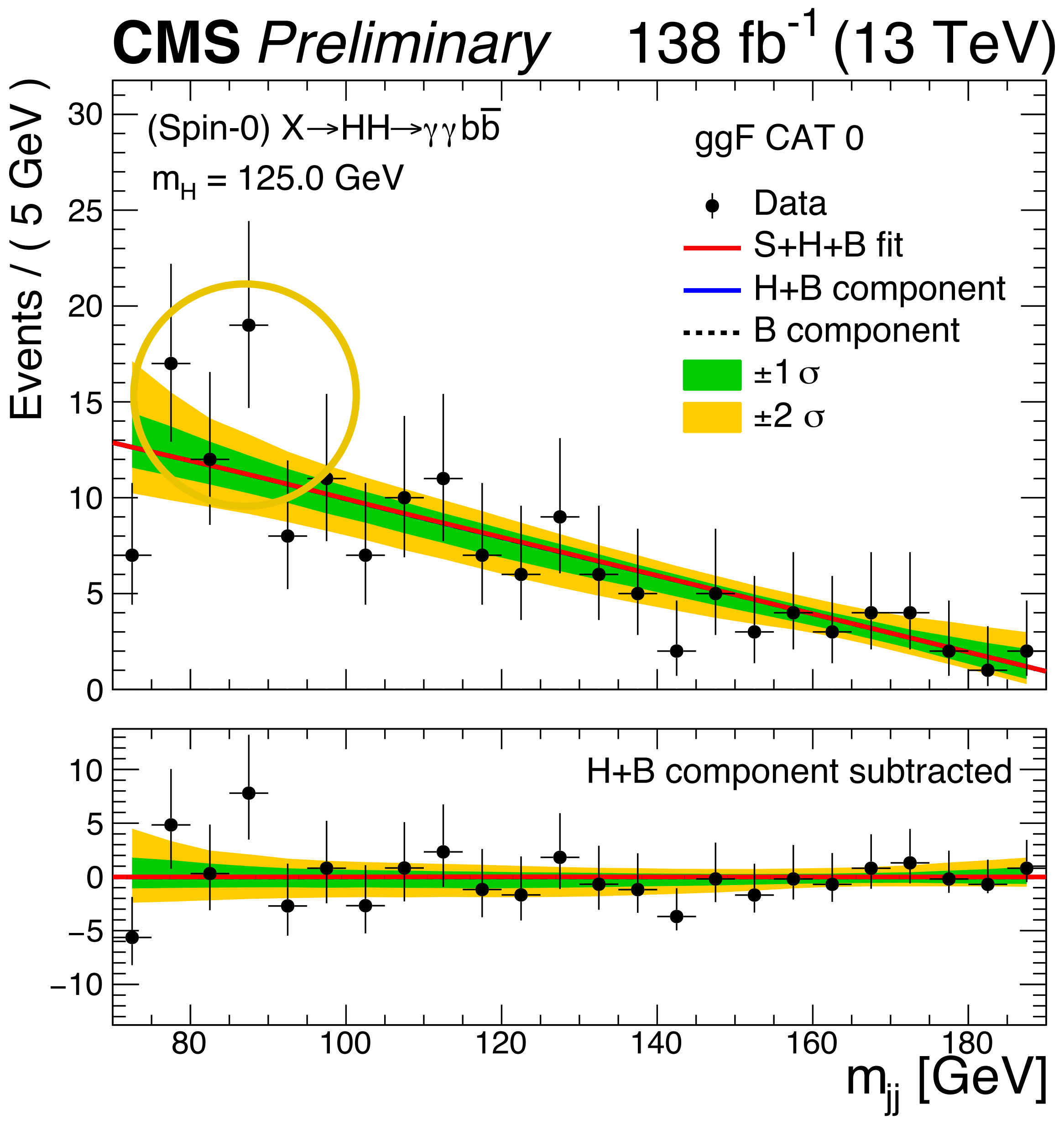


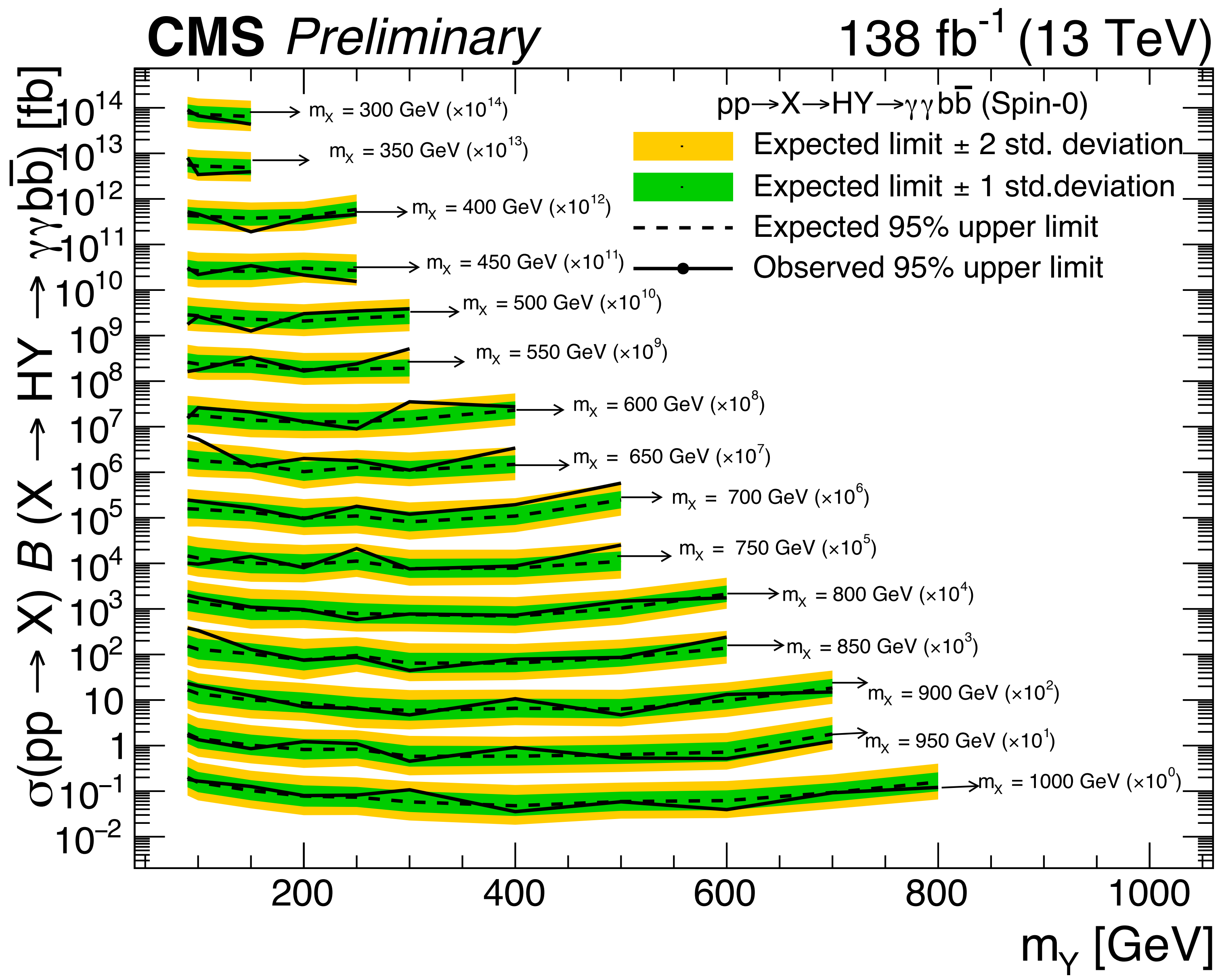
CMS $H_{BSM} \rightarrow H_{125} h_{BSM}$

- $H_{BSM} \rightarrow H_{125} h_{BSM}$ **can be the dominant production process for h_{BSM}** e.g. in 2HDM+singlet models and in two-real-scalar-singlet models
- CMS has recently preformed the **first LHC searches for this process**, targeting different H_{125} decay modes :
  - $H_{125}(bb)h_{BSM}(bb)$ arXiv:2204.12413
  - $H_{125}(\tau\tau)h_{BSM}(bb)$ arXiv:2106.10361
  - $H_{125}(\gamma\gamma)h_{BSM}(bb)$ CMS-PAS-HIG-21-011
    - The **γγbb** channel has a local (global) excess of **3.8σ** (**2.8σ**) at $m(H_{BSM})$=**650 GeV**, $m(h_{BSM})$=**90 GeV**



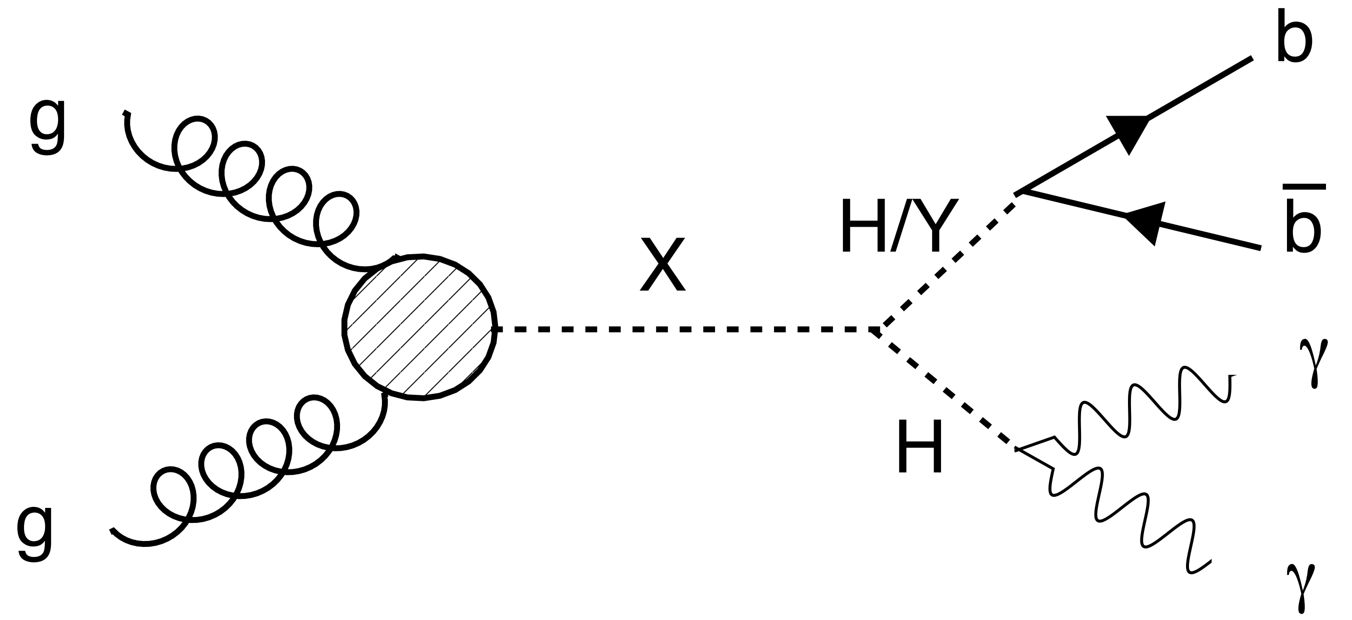


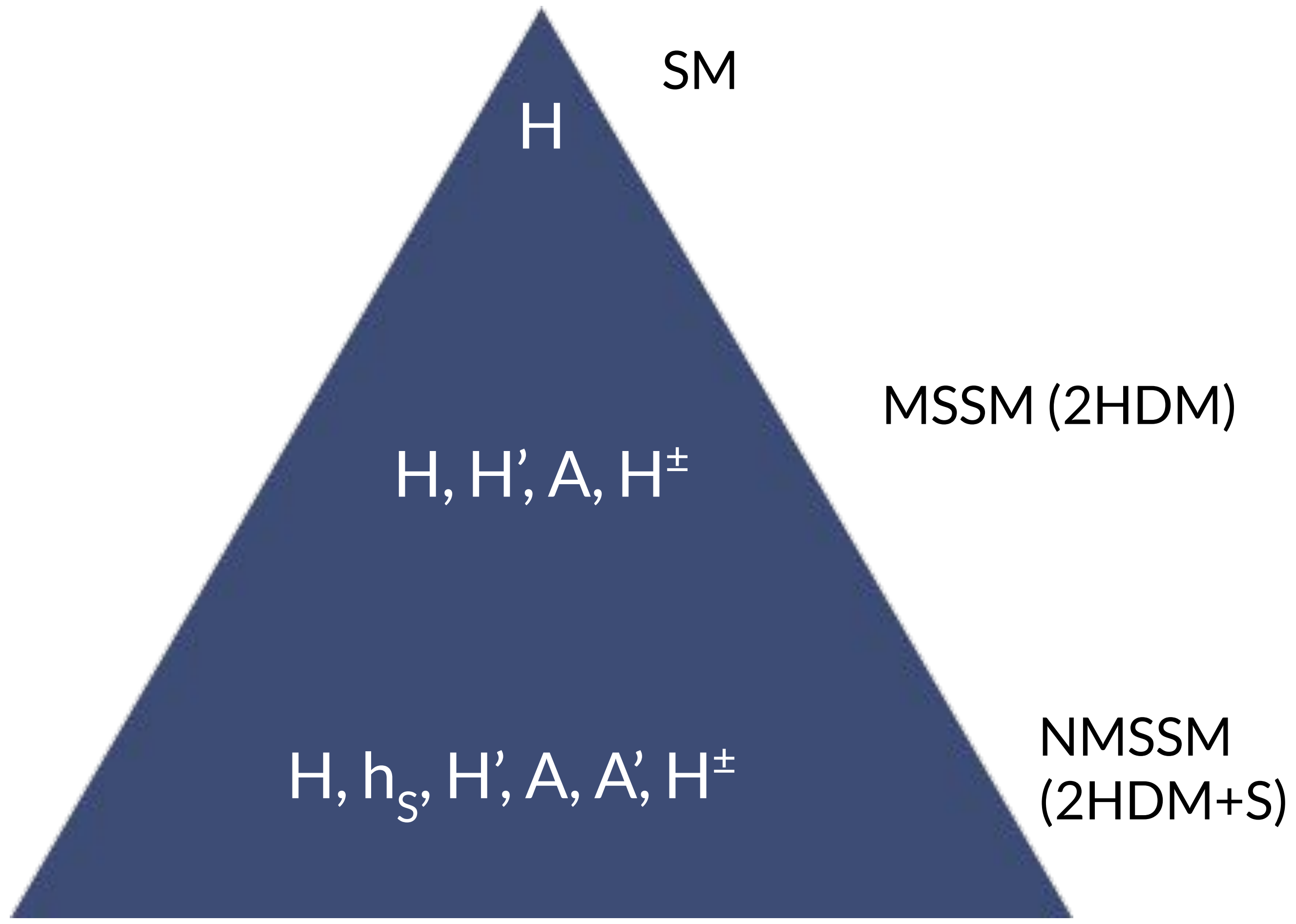


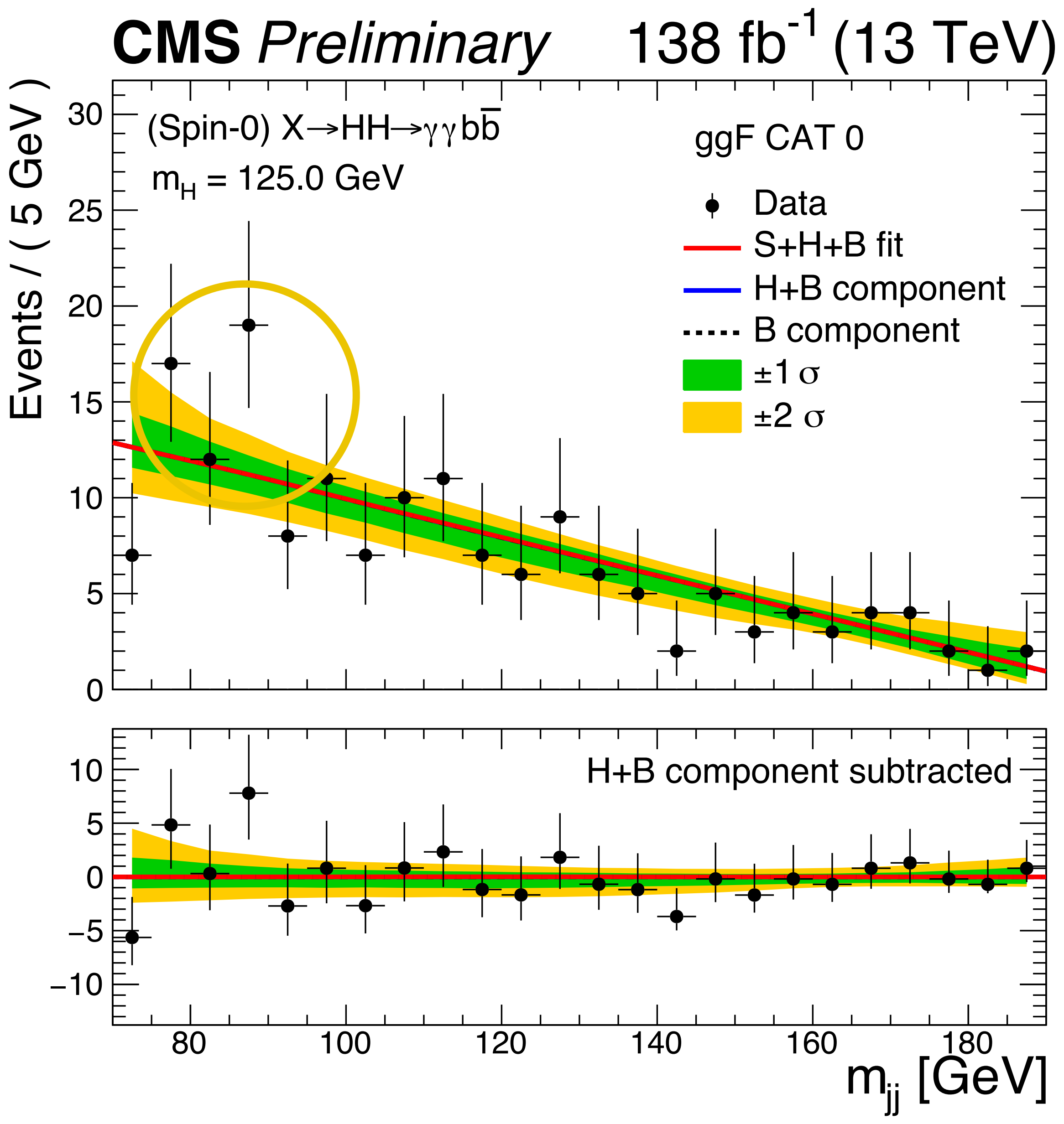


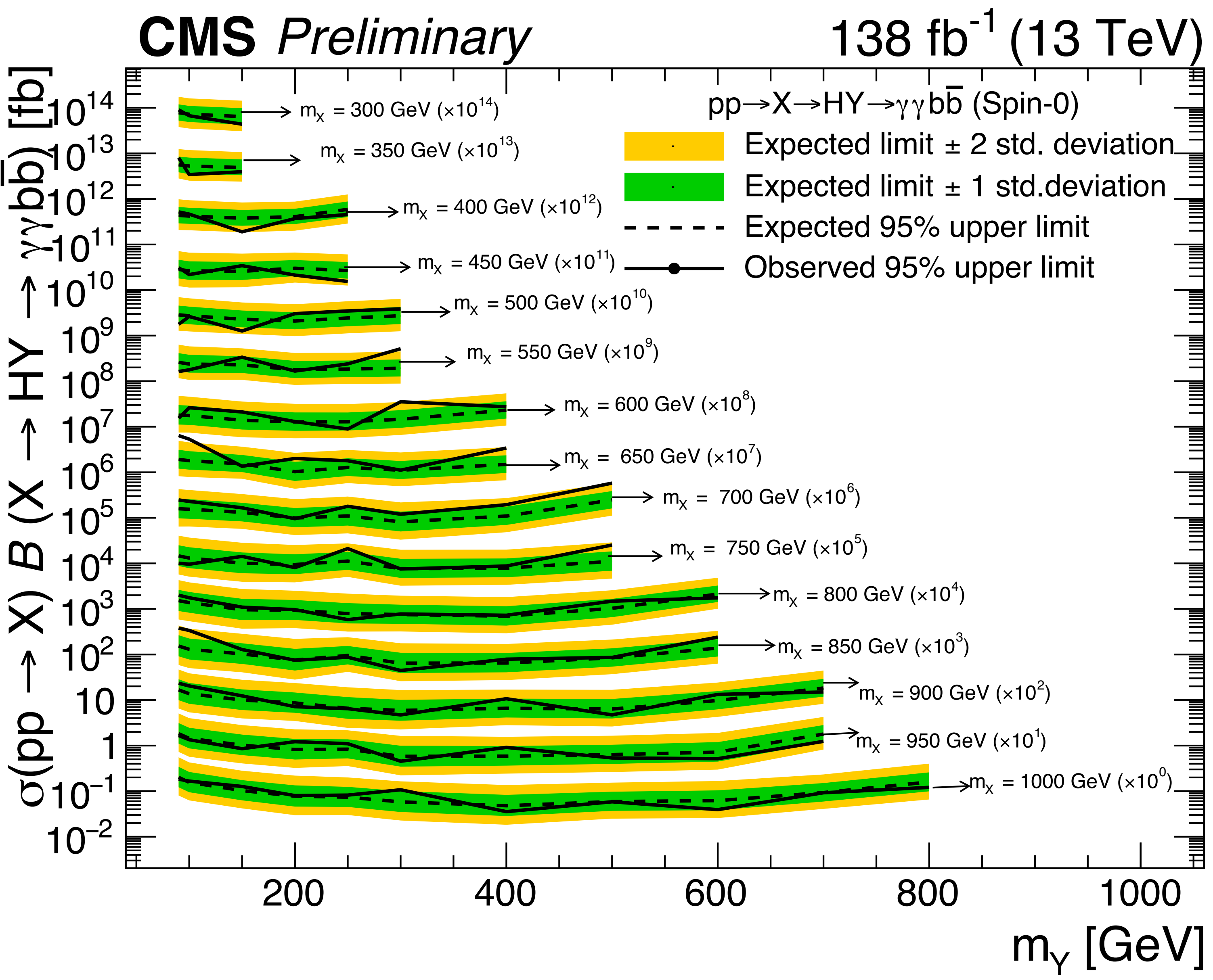
CMS $H_{BSM} \rightarrow H_{125} h_{BSM}$

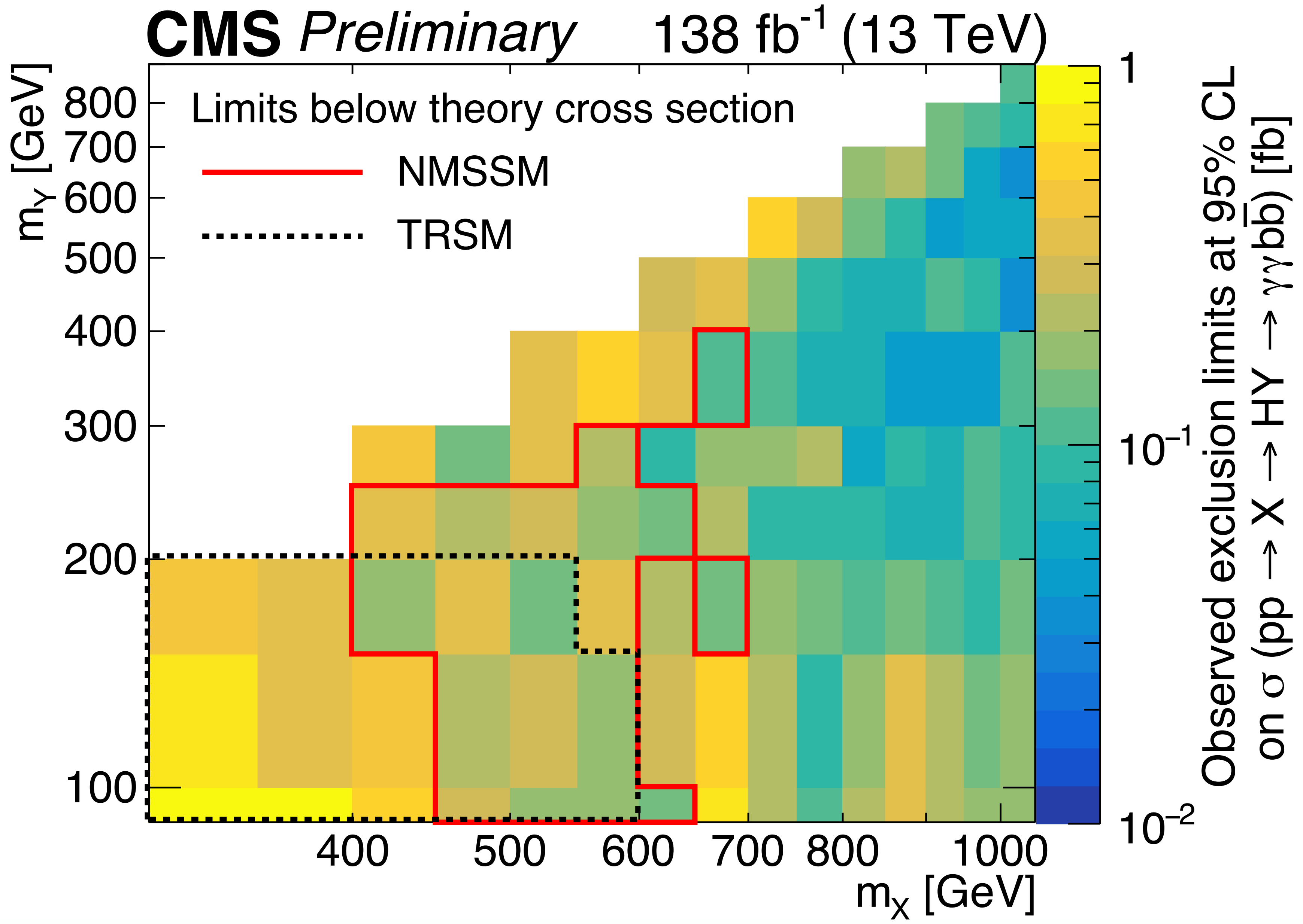
- $H_{BSM} \rightarrow H_{125} h_{BSM}$ **can be the dominant production process for h_{BSM}** e.g. in 2HDM+singlet models and in two-real-scalar-singlet models
- CMS has recently preformed the **first LHC searches for this process**, targeting different H_{125} decay modes :
  - $H_{125}(bb)h_{BSM}(bb)$ arXiv:2204.12413
  - $H_{125}(\tau\tau)h_{BSM}(bb)$ arXiv:2106.10361
  - $H_{125}(\gamma\gamma)h_{BSM}(bb)$ CMS-PAS-HIG-21-011
    - The **γγbb** channel has a local (global) excess of **3.8σ** (**2.8σ**) at m(H_{BSM})=**650 GeV**, m(h_{BSM})=**90 GeV**





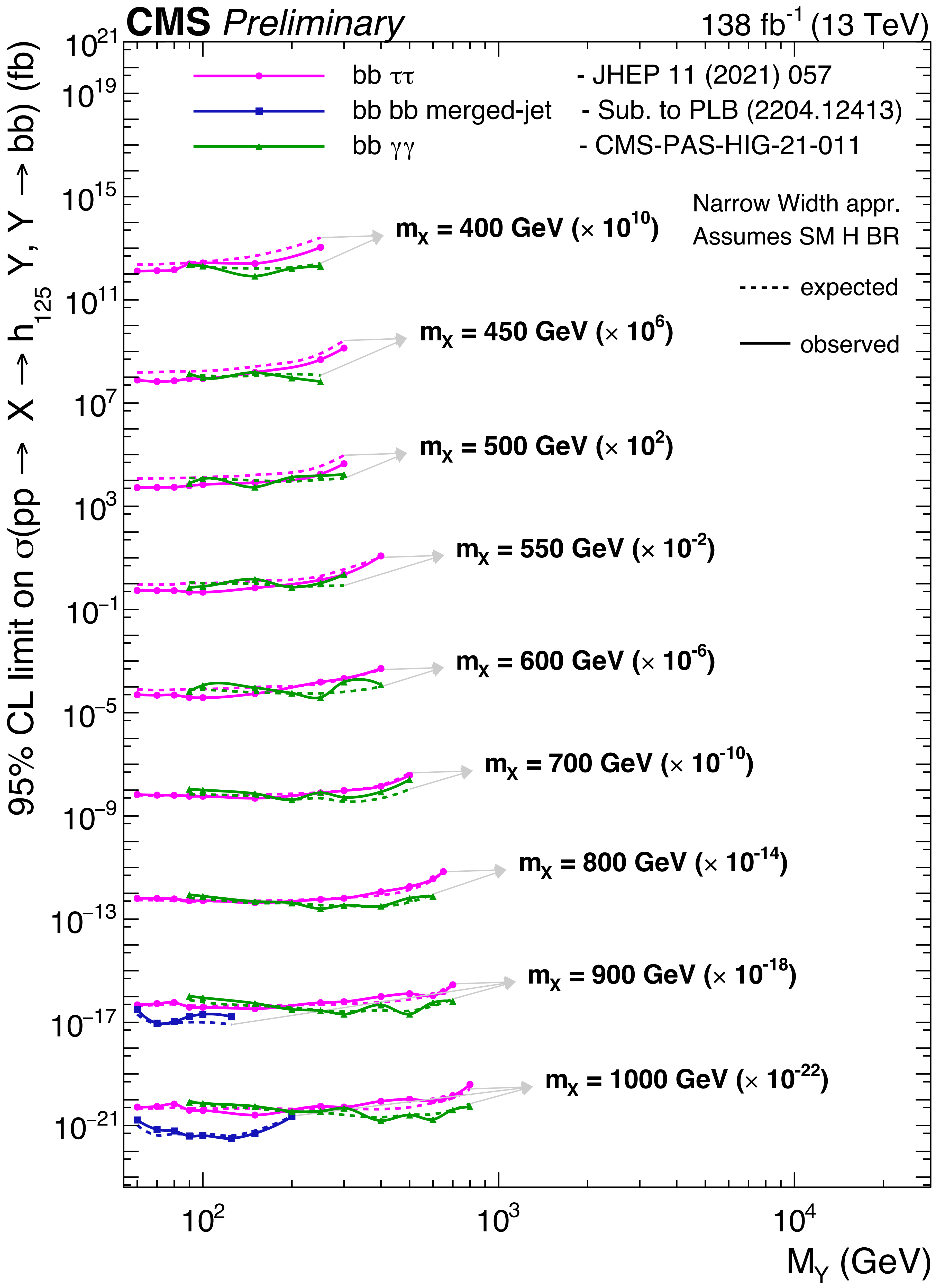


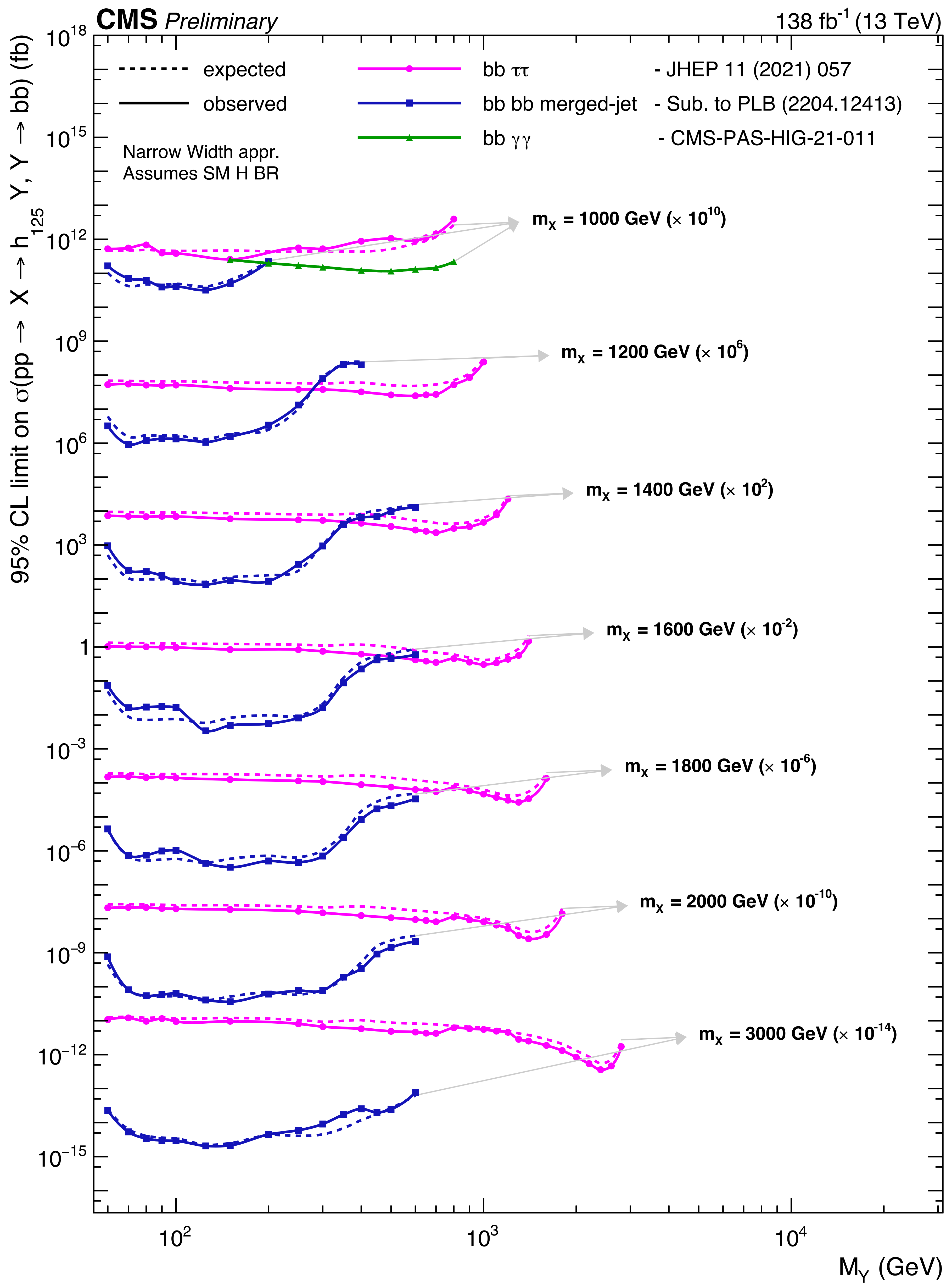


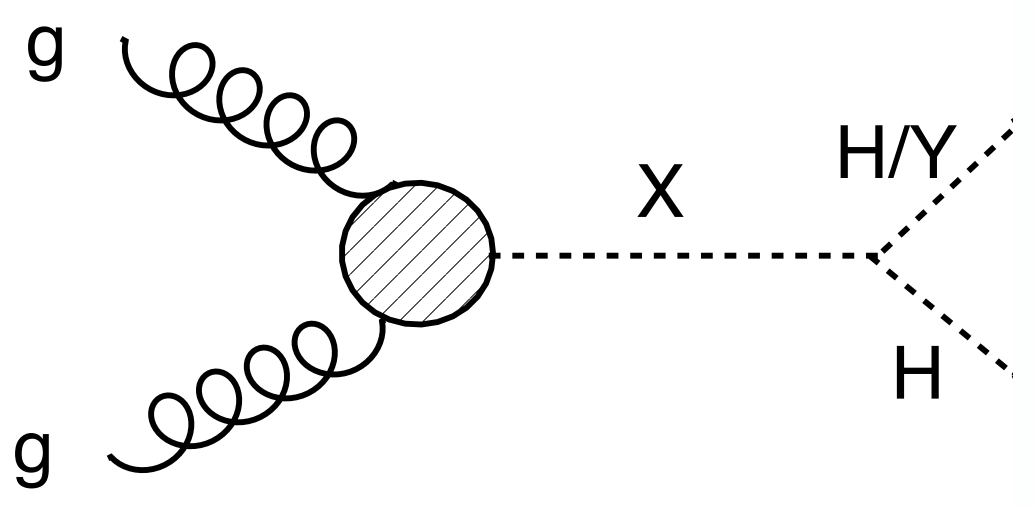


CMS $H_{BSM} \to H_{125} h_{BSM}$

CMS public web pages

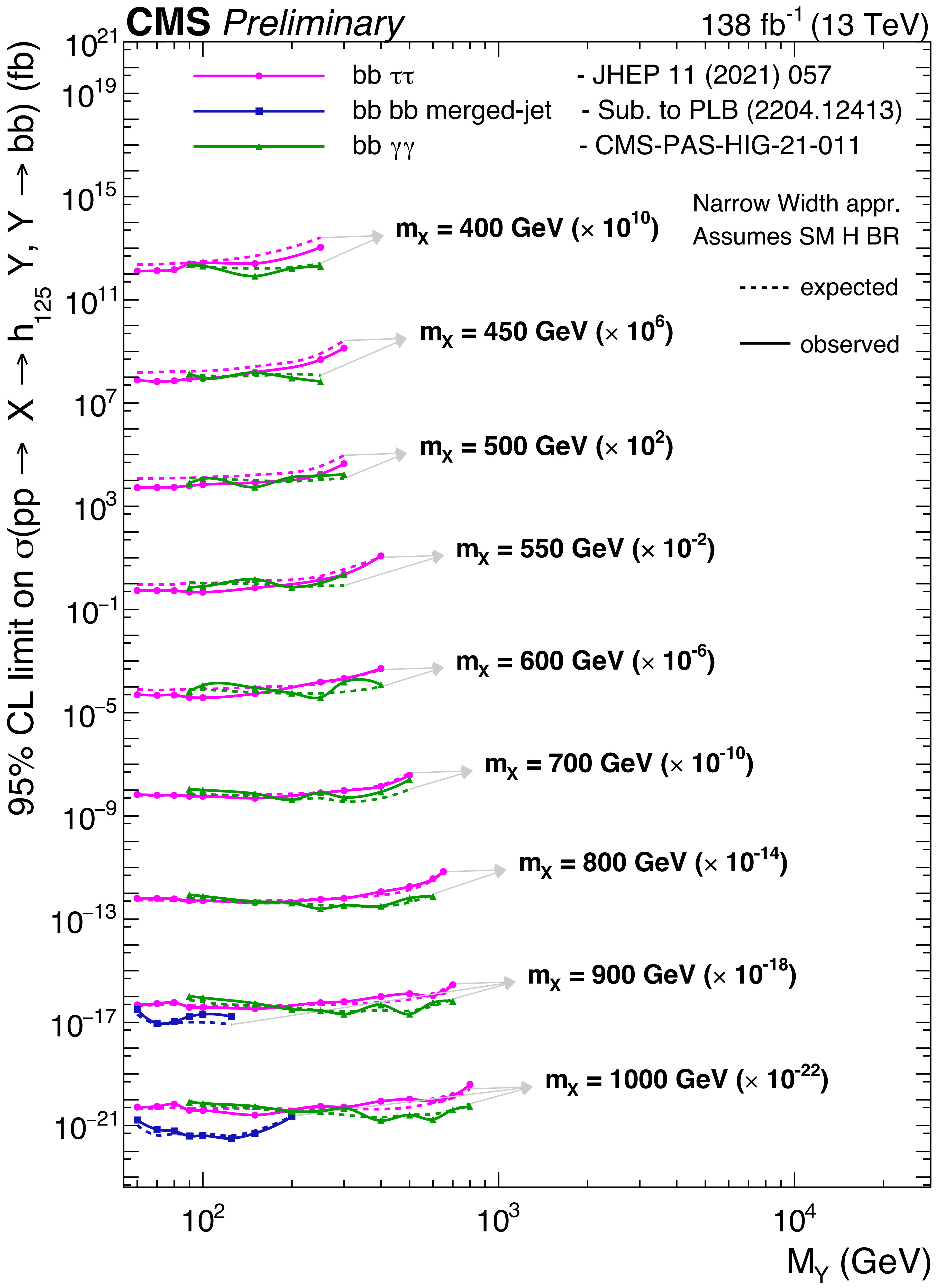


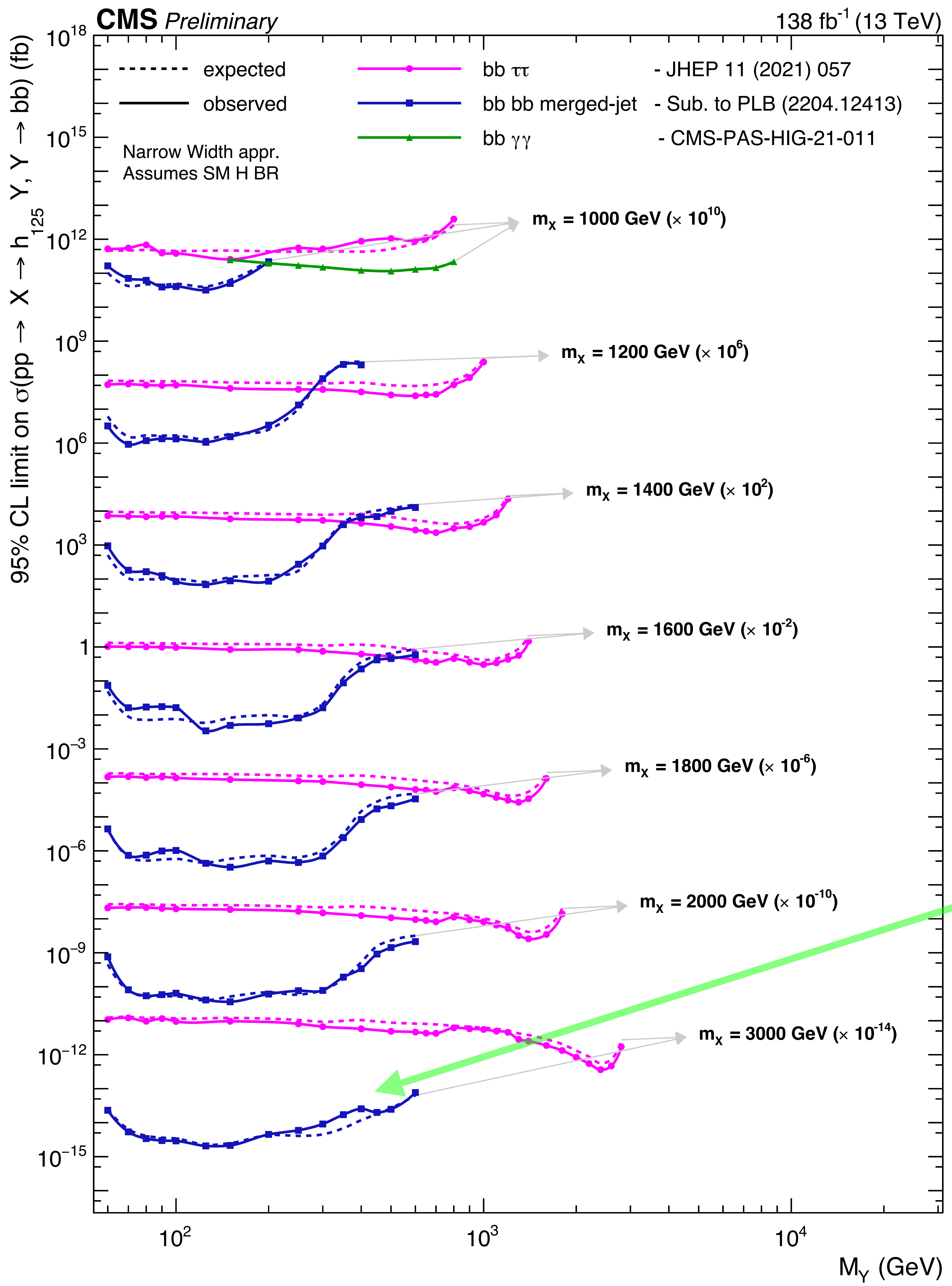


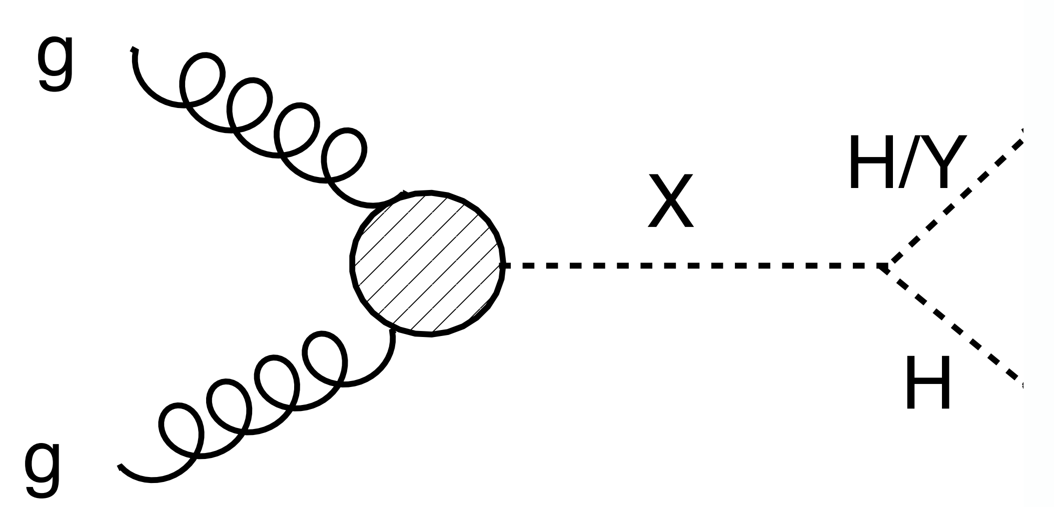


CMS $H_{BSM} \rightarrow H_{125} h_{BSM}$

CMS public web pages





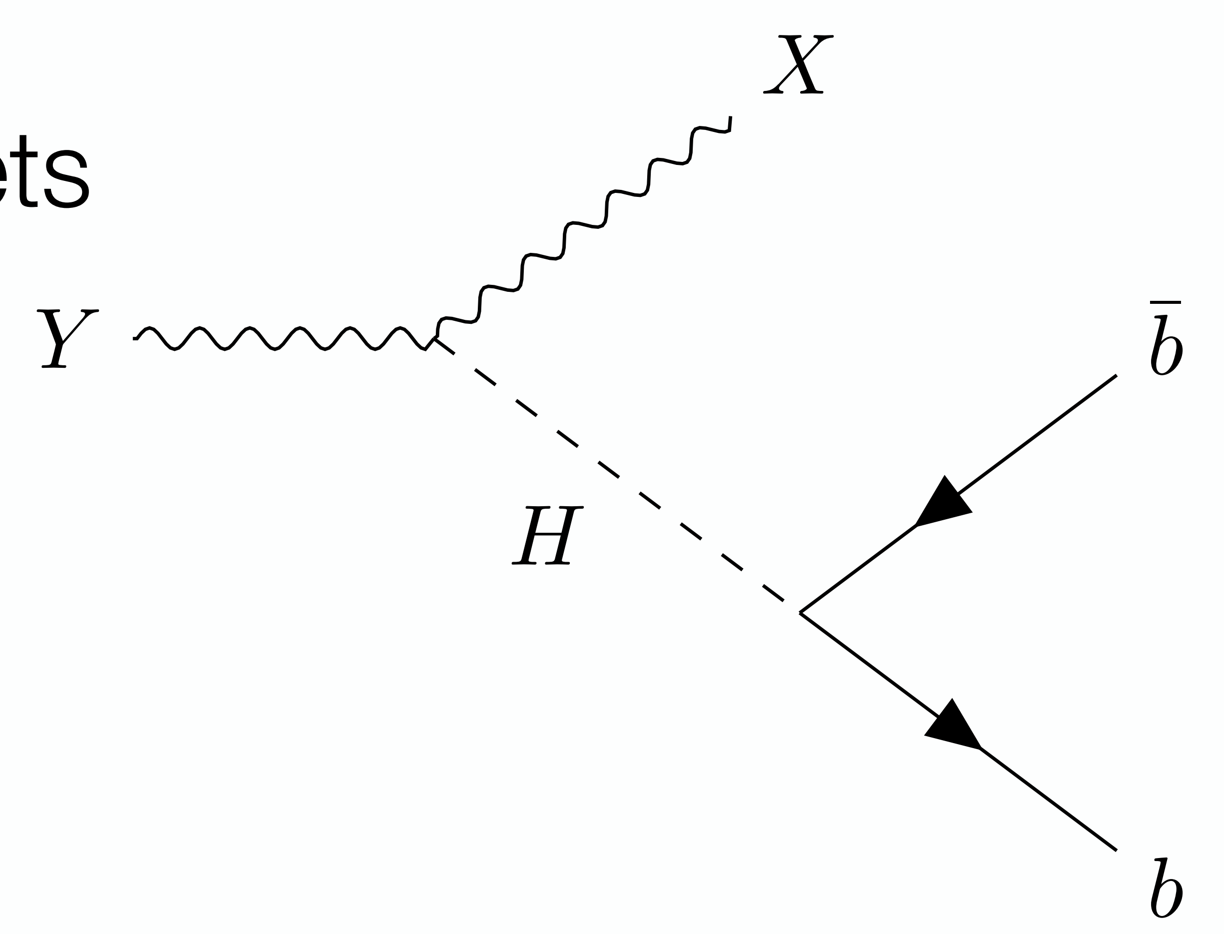


- Nice **complementarity** of the tree channels
- bbbb analysis focuses on merged-jet topology, benefitting from novel **H(bb) tagging with a graph neural network**

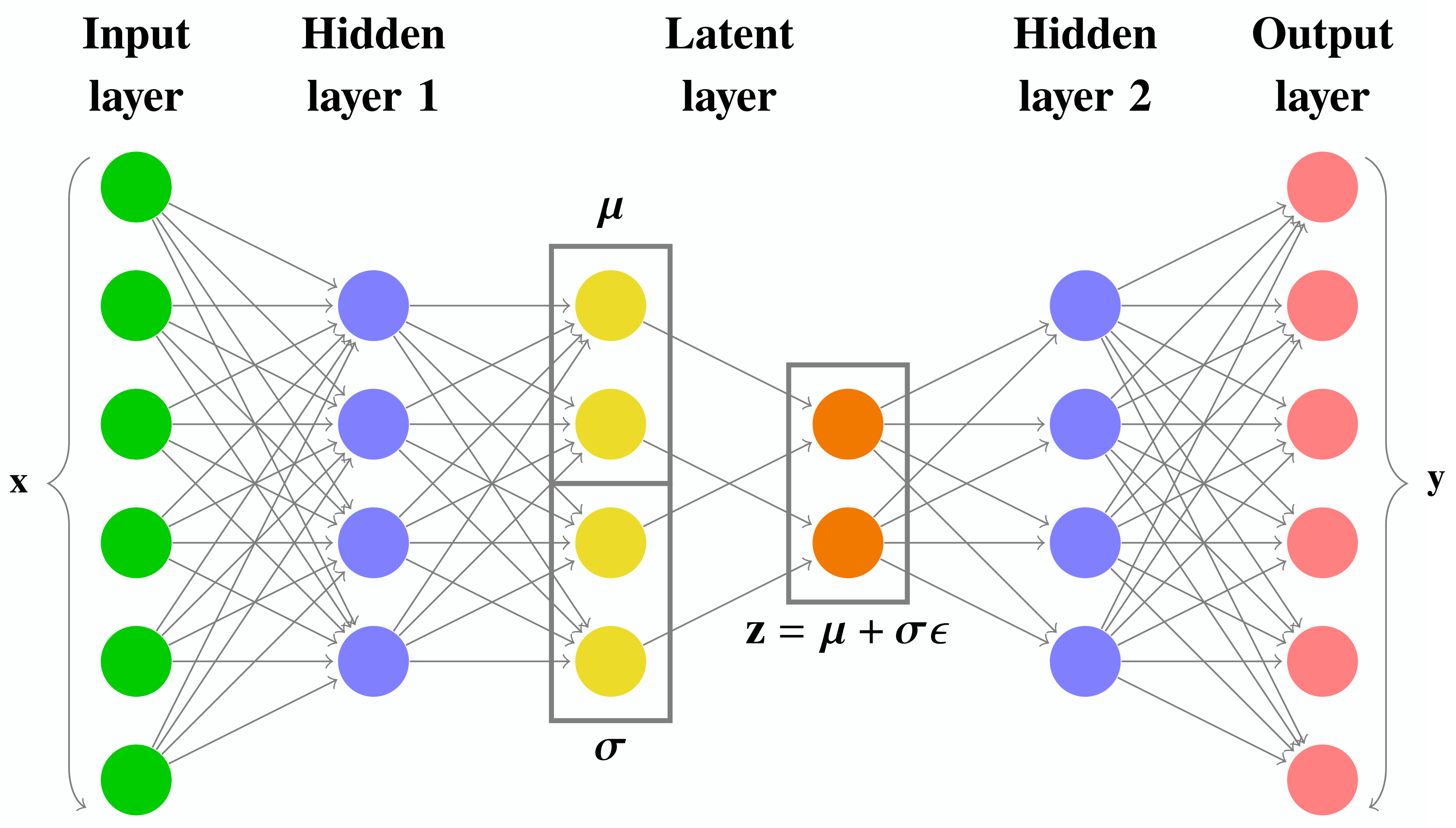
ATLAS $X \to YH_{125}$ anomaly search

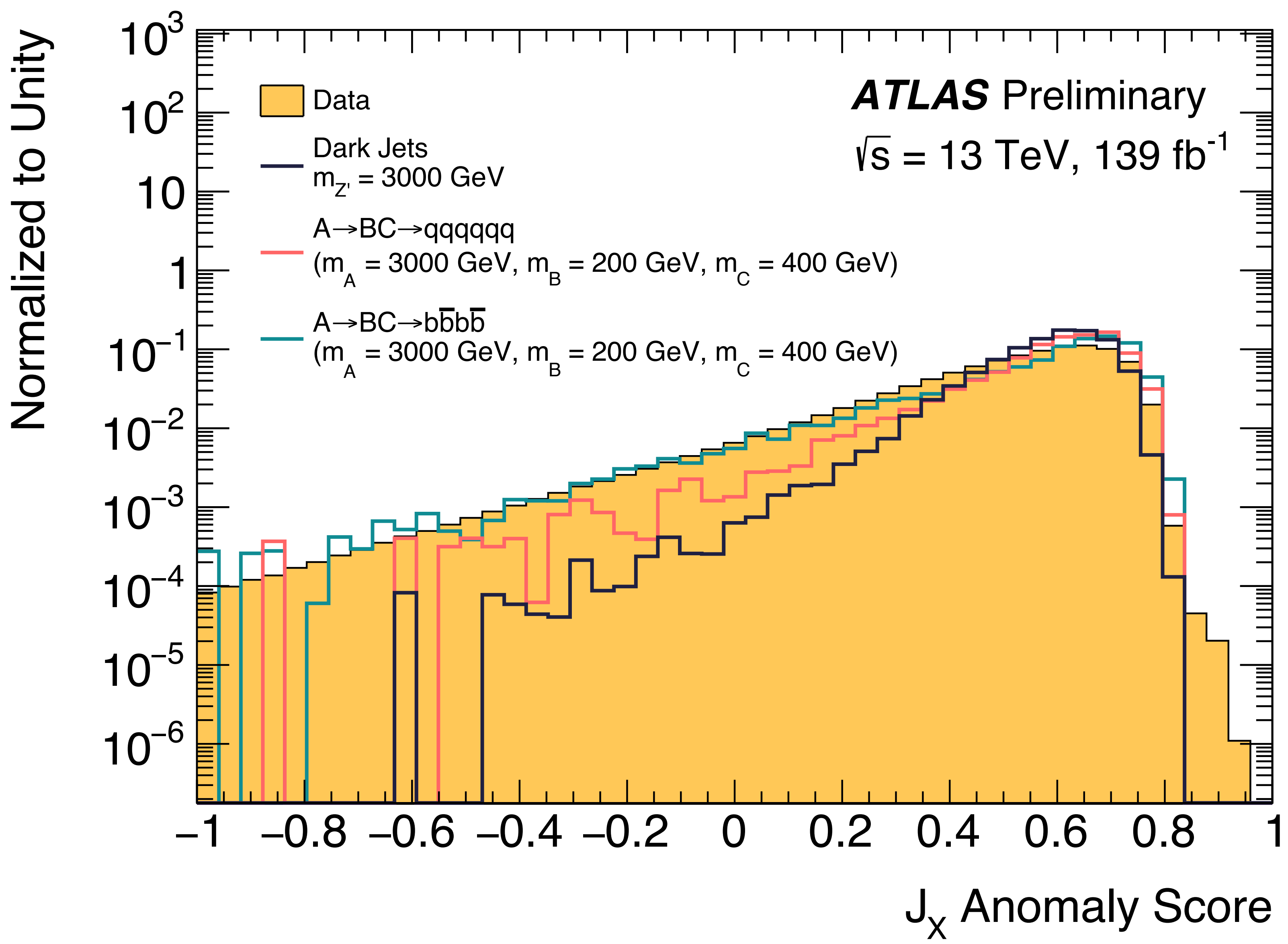
ATL-PHYS-PUB-2020-019

- Search for a heavy resonance **Y** (mass 1.5–6 TeV), decaying to H(bb) and a new particle **X** (mass 65-3000 GeV), both reconstructed as large-radius jets



- First application of **fully unsupervised ML** in an ATLAS analysis
  - Training on **unlabeled** jets, no particular signal hypothesis
  - Jets modeled as sequences of constituent four-vectors
  - **Variational autoencoder** used to define an **anomaly score** for each jet
  - Requiring anomaly score >0.5 leads to S/B enhancement by **~25%**

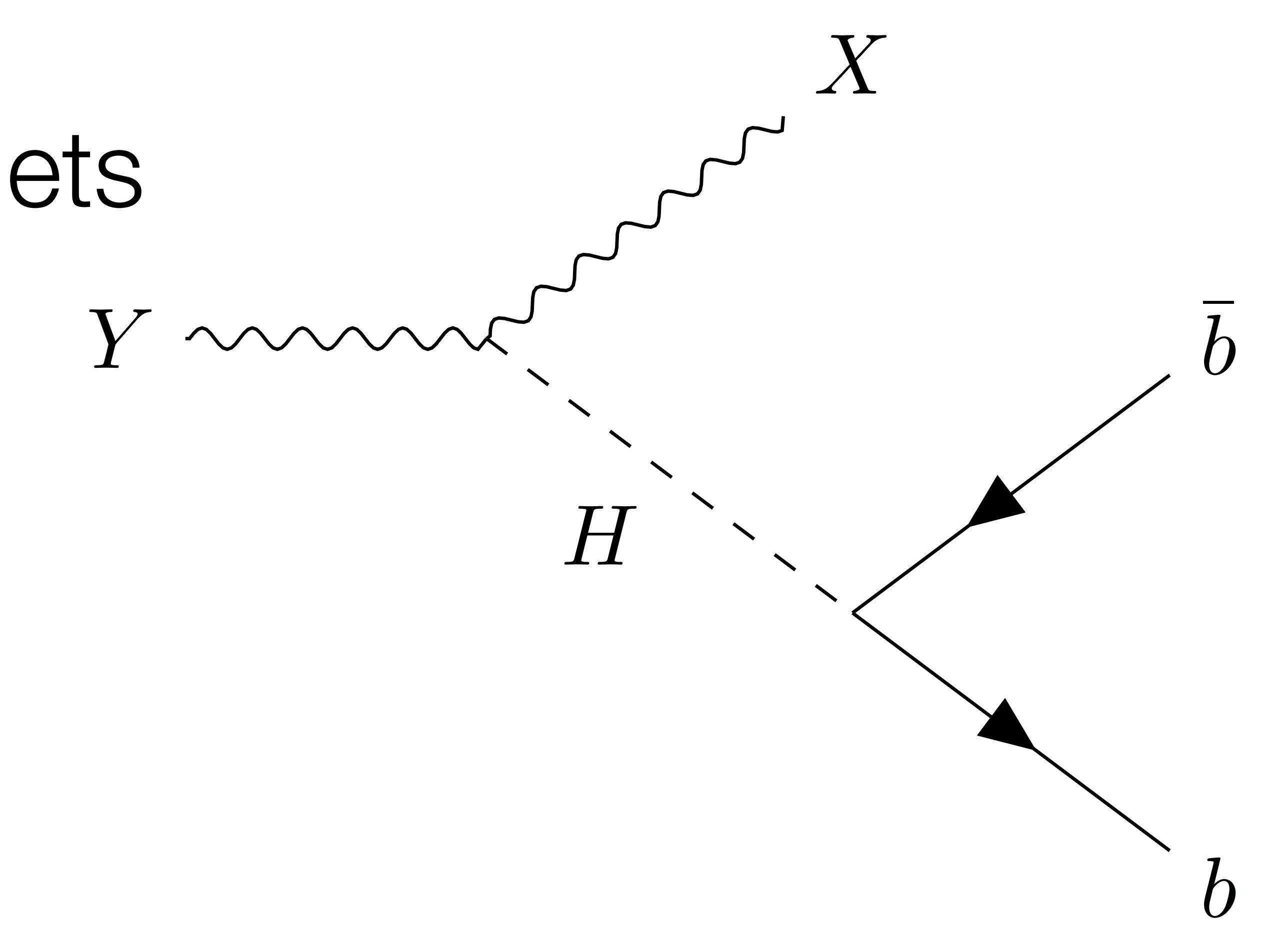




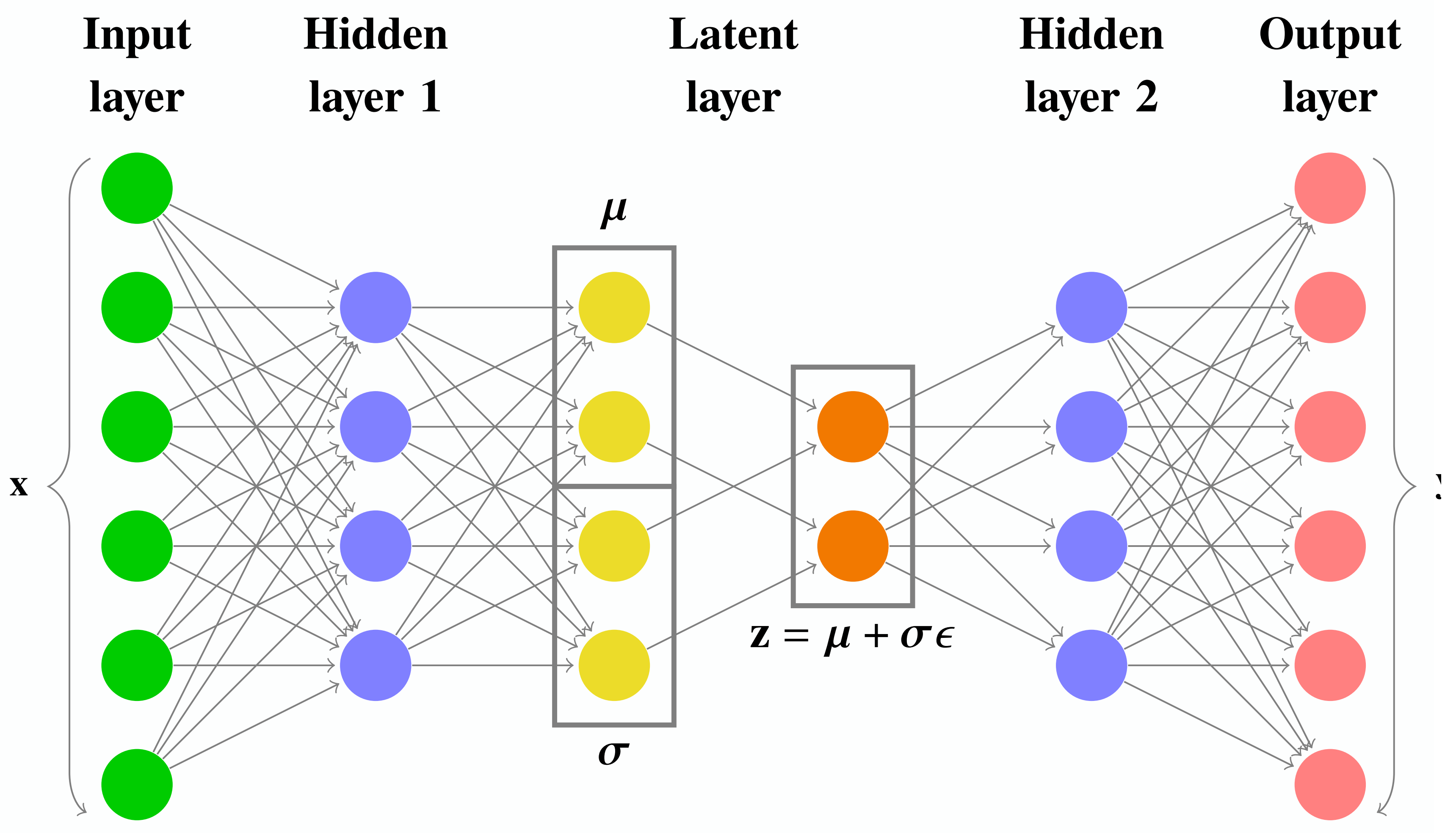
ATLAS X→YH_{125} anomaly search

ATL-PHYS-PUB-2020-019

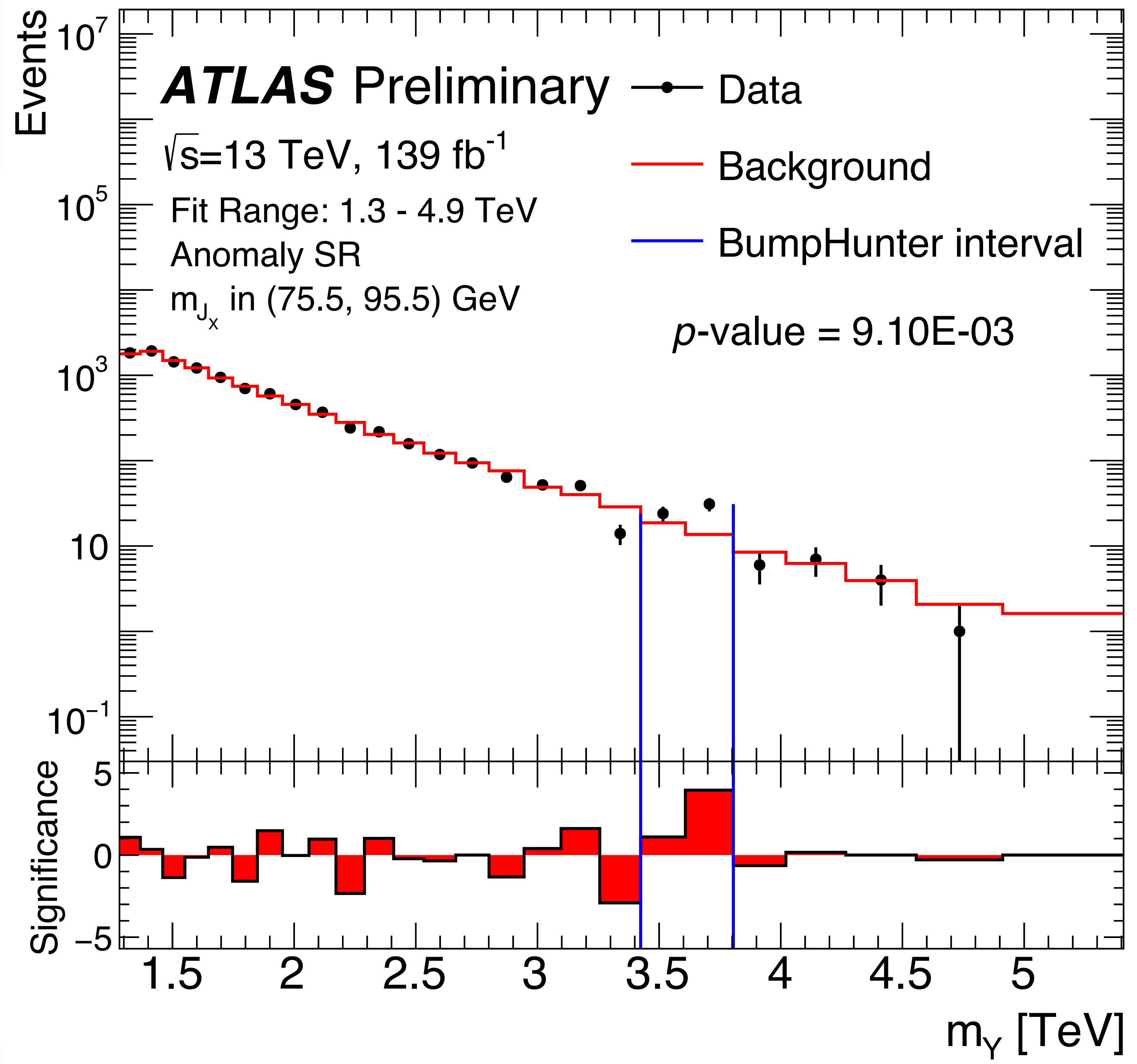
- Search for a heavy resonance **Y** (mass 1.5–6 TeV), decaying to H(bb) and a new particle **X** (mass 65-3000 GeV), both reconstructed as large-radius jets



- First application of **fully unsupervised ML** in an ATLAS analysis
  - Training on **unlabeled** jets, no particular signal hypothesis
  - Jets modeled as sequences of constituent four-vectors
  - **Variational autoencoder** used to define an **anomaly score** for each jet
  - Requiring anomaly score >0.5 leads to S/B enhancement by **~25%**



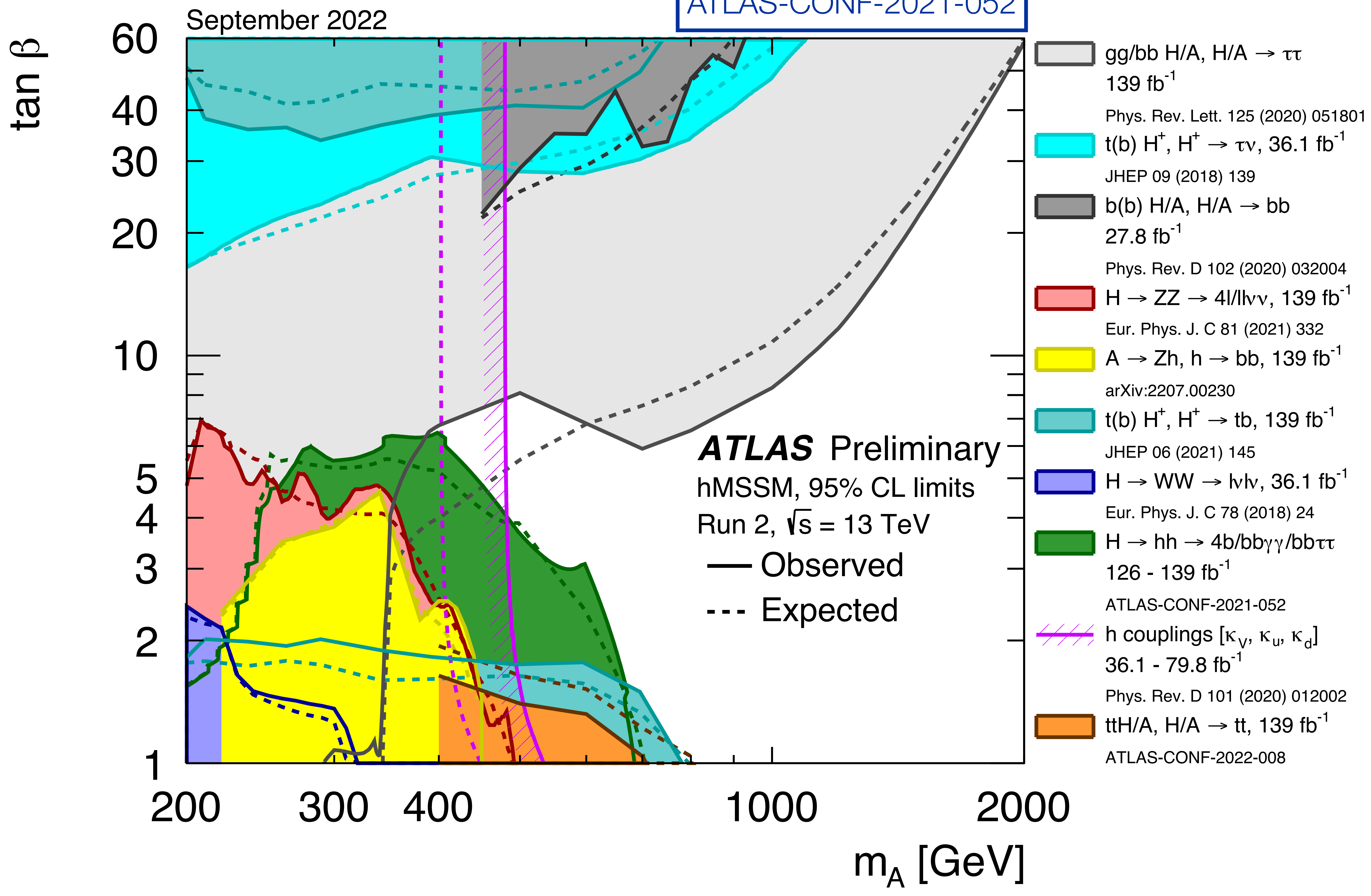
- Bump hunt performed in slices of (mX, mY)
- No significant excess (the largest has a global significance of 1.4σ)



Summary & Outlook

Putting pieces together: 2HDM

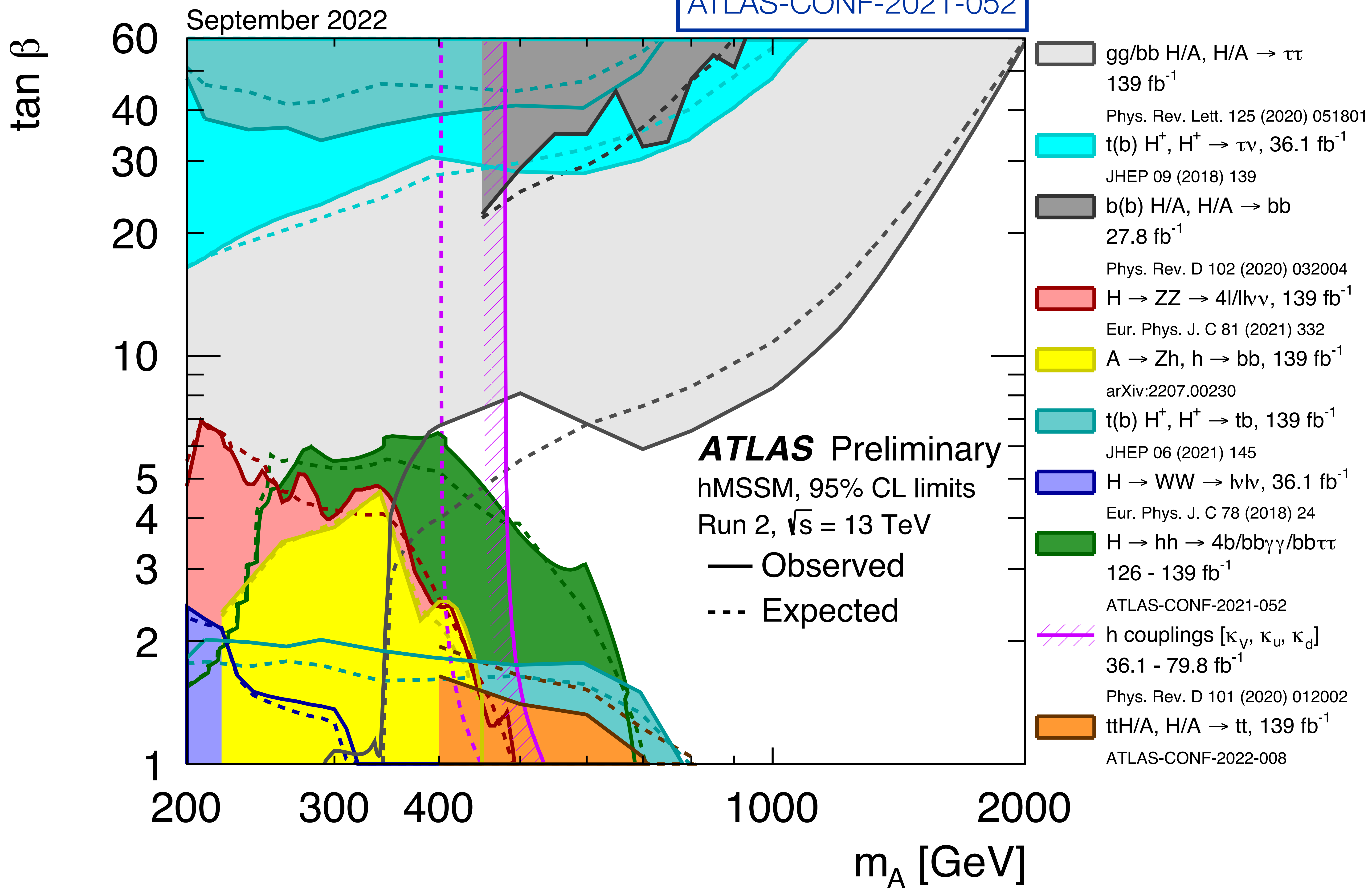
ATLAS-CONF-2021-052

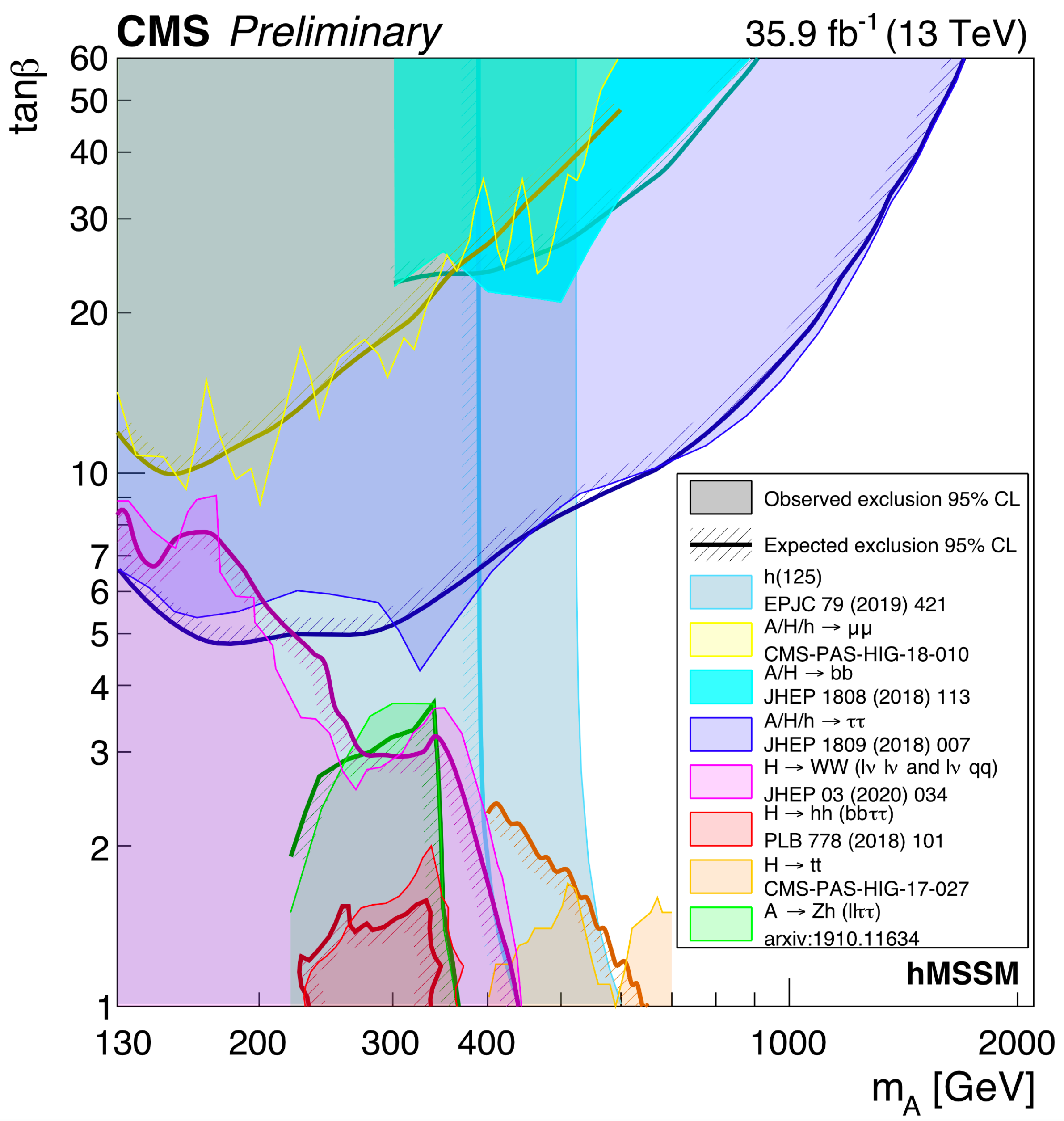


- **Neutral** and **charged** Higgs boson searches in various production and decay modes and H_{125} precision measurements **complement** each other

Putting pieces together: 2HDM

ATLAS-CONF-2021-052

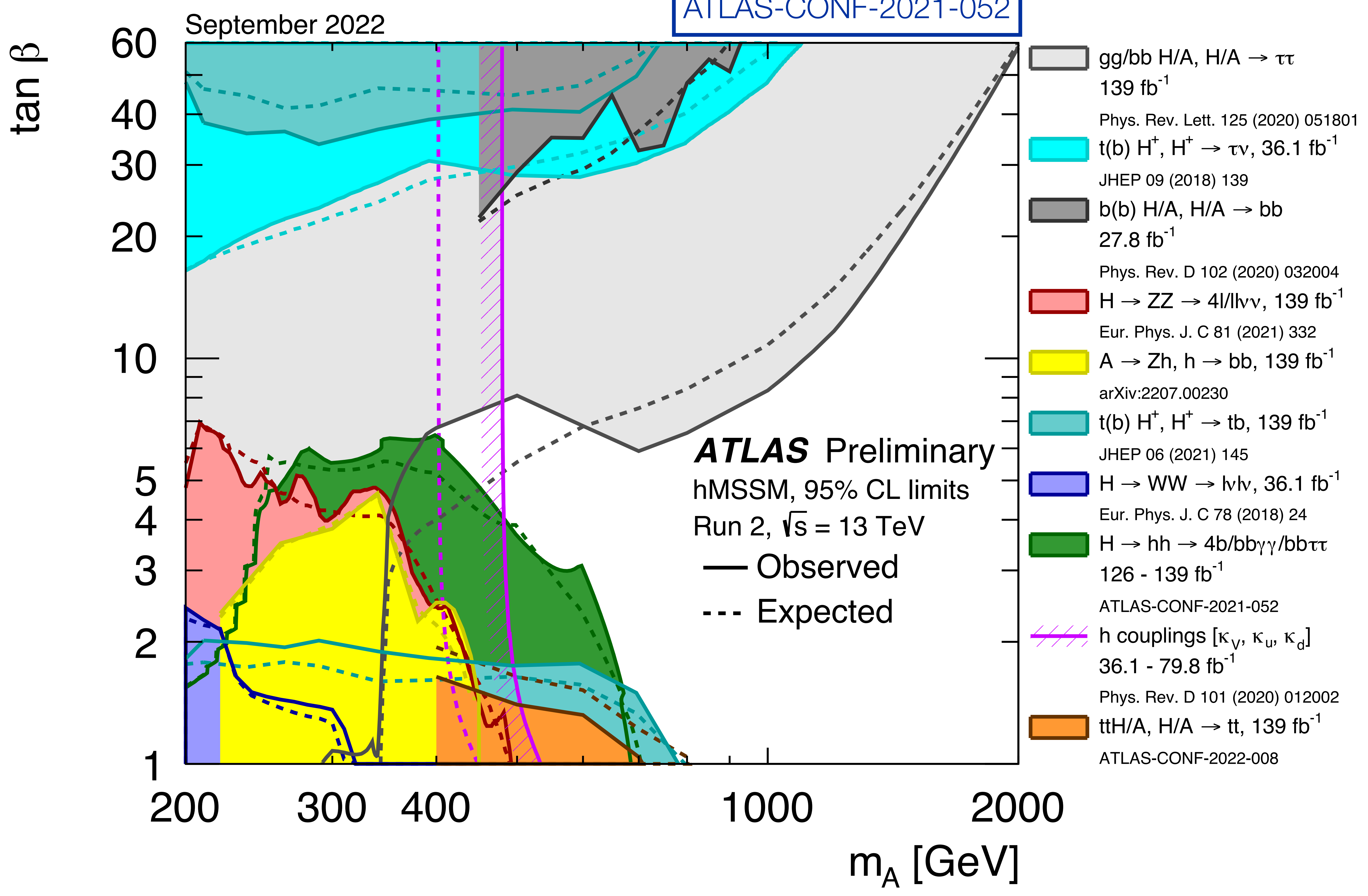


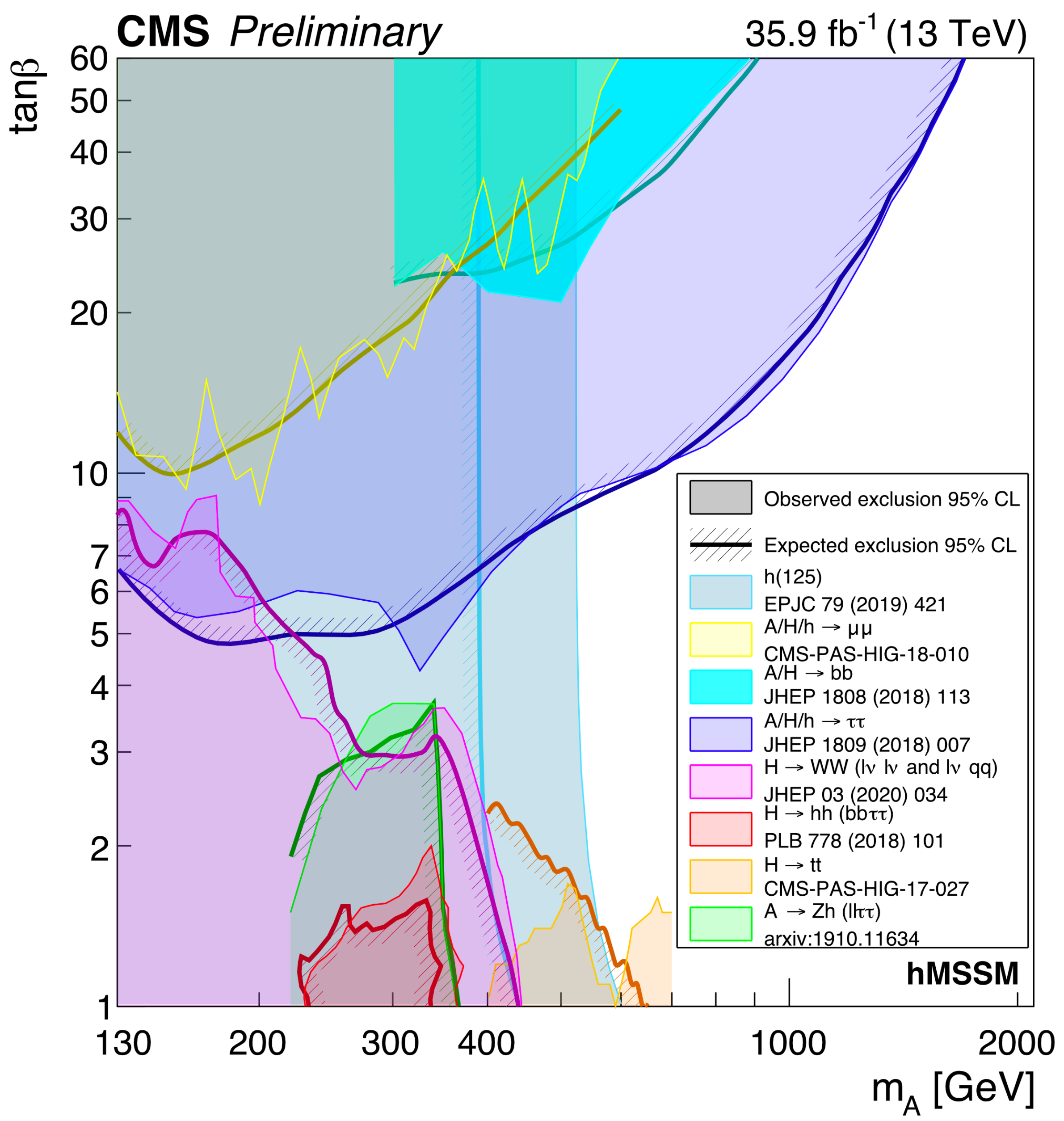


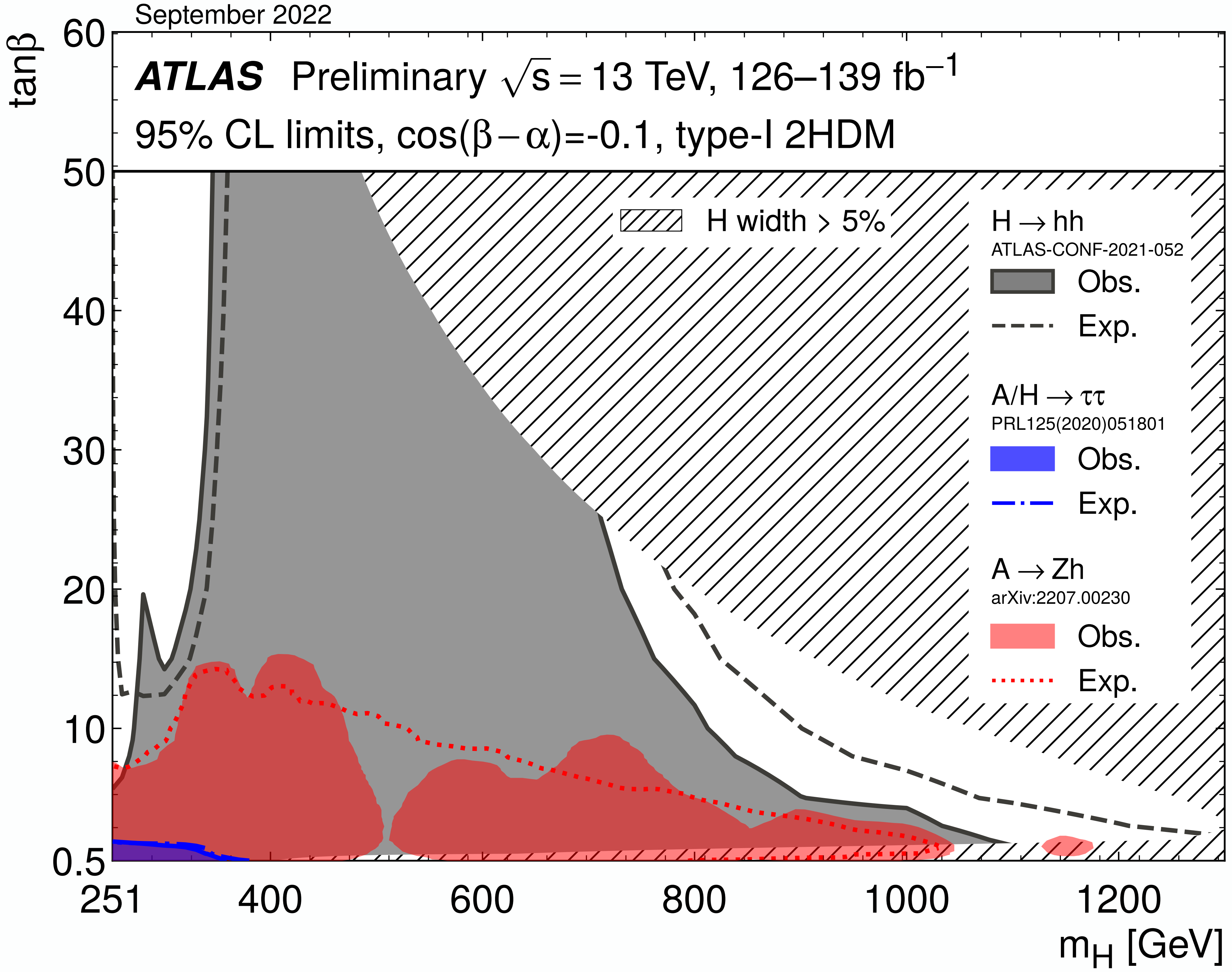
- **Neutral** and **charged** Higgs boson searches in various production and decay modes and H_{125} precision measurements **complement** each other

Putting pieces together: 2HDM

ATLAS-CONF-2021-052

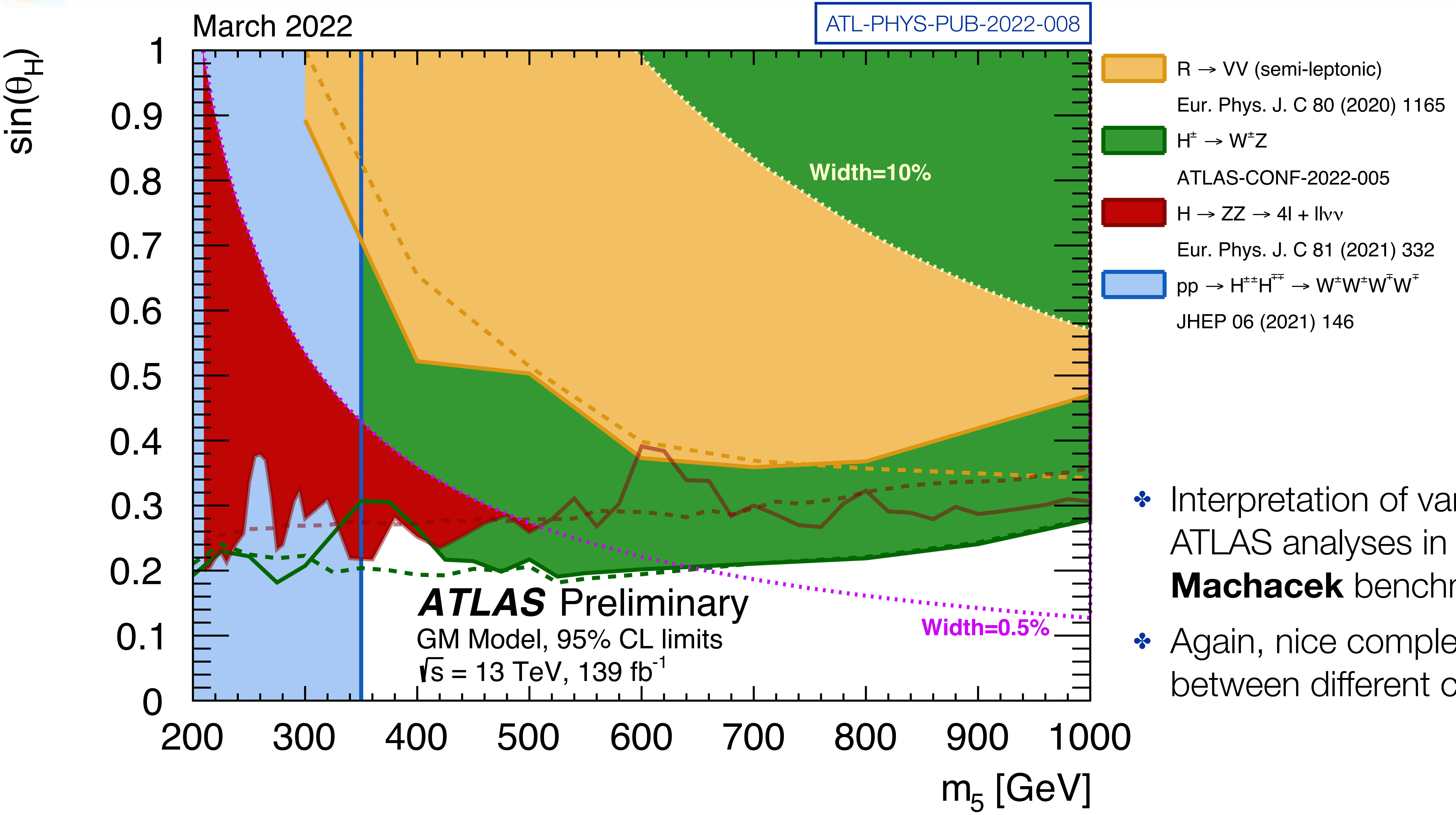






- **Neutral** and **charged** Higgs boson searches in various production and decay modes and H_{125} precision measurements **complement** each other

Putting pieces together: Triplet models



- Interpretation of various ATLAS analyses in a **Georgi-Machacek** benchmark
- Again, nice complementarity between different channels

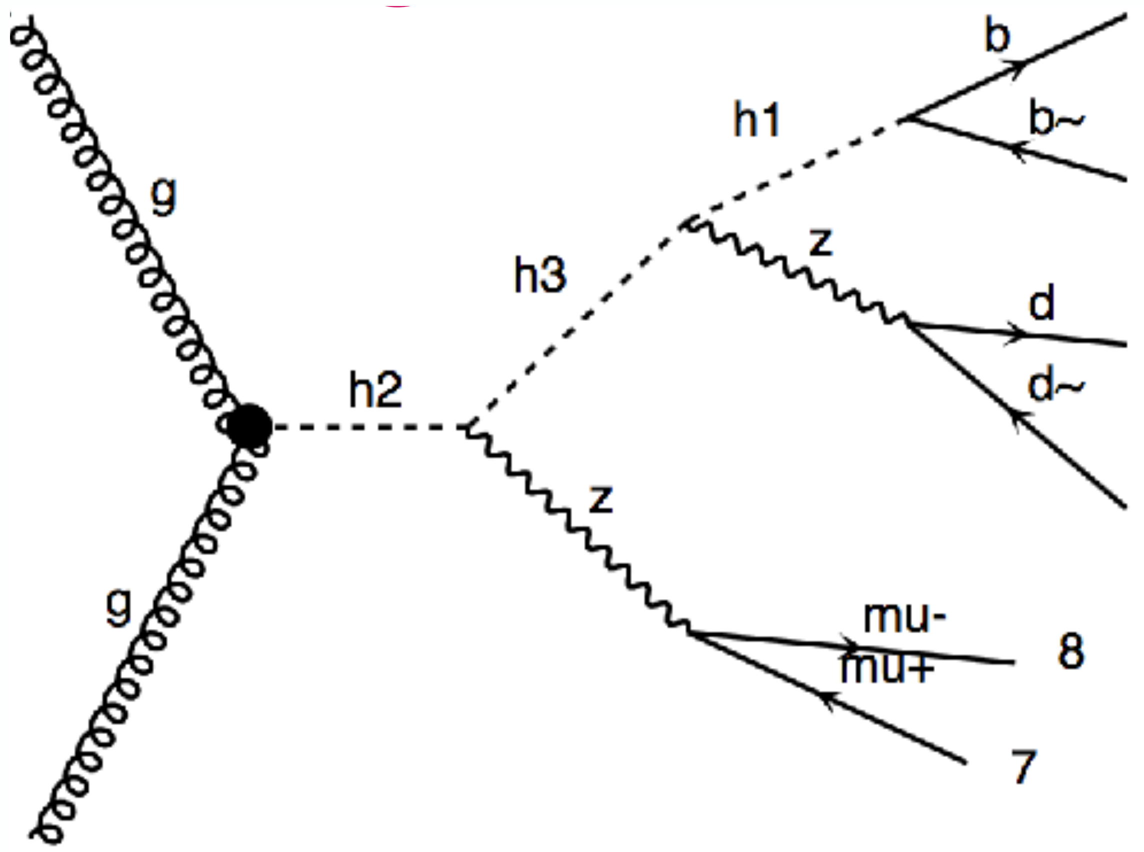
Recent proposals for new search channels

- Not a comprehensive list, just a few ideas that have been recently discussed in LHC Higgs WG

Recent proposals for new search channels

- Not a comprehensive list, just a few ideas that have been recently discussed in LHC Higgs WG

arXiv:2207.03007

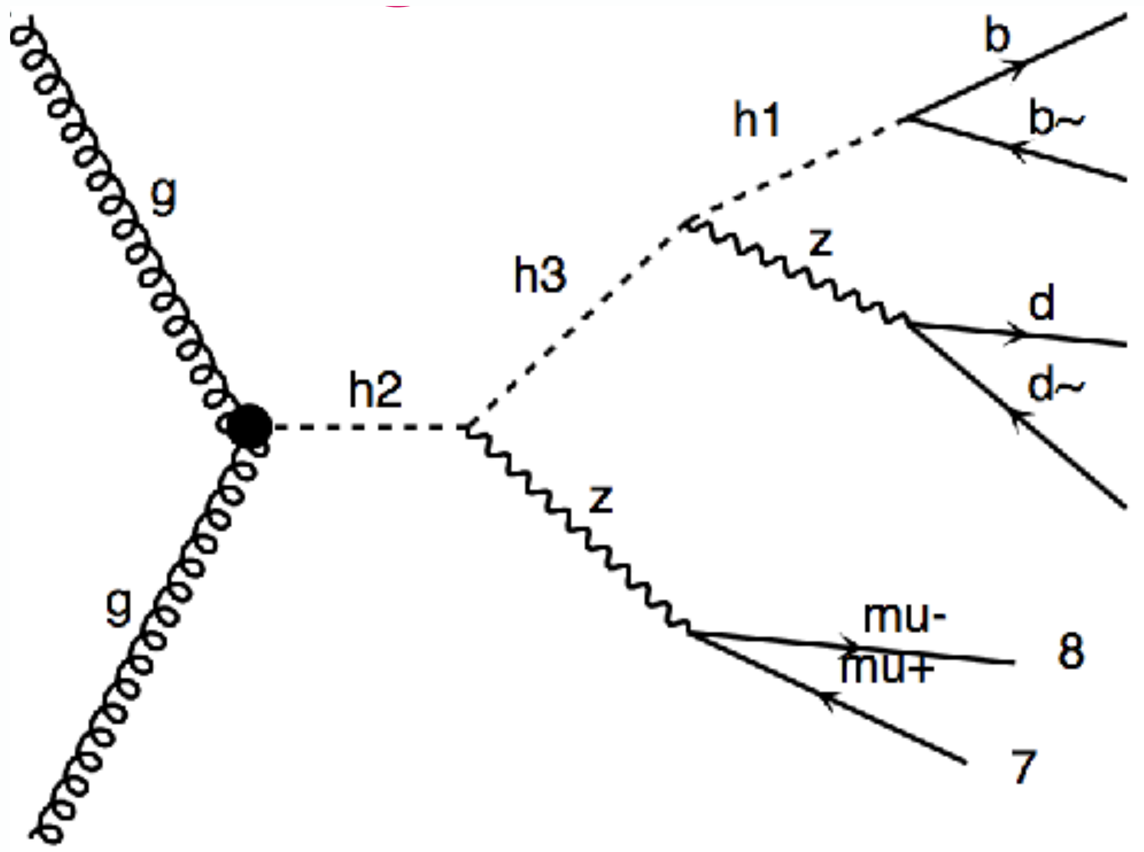


- gg → $\mathbf{H_{125}}$ → $\mathbf{Z^{*}a_{BSM}}$ → $\mathbf{Z^{*}Z^{*}h_{BSM}}$ → μμjjbb
  motivated by Type-1 2HDM

Recent proposals for new search channels

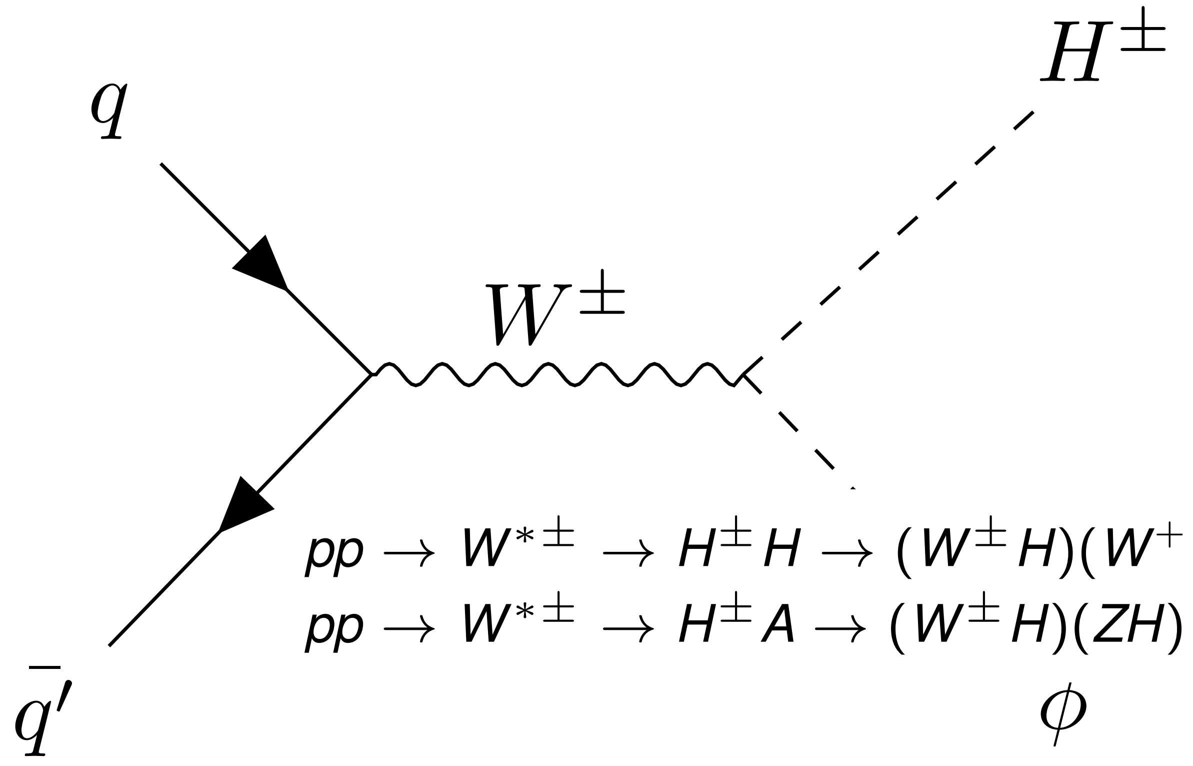
- Not a comprehensive list, just a few ideas that have been recently discussed in LHC Higgs WG

arXiv:2207.03007



- gg → H_{125} → Z^*a_{BSM} → $Z^*Z^*h_{BSM}$ → μμjjbb motivated by Type-1 2HDM

arXiv:2109.05682



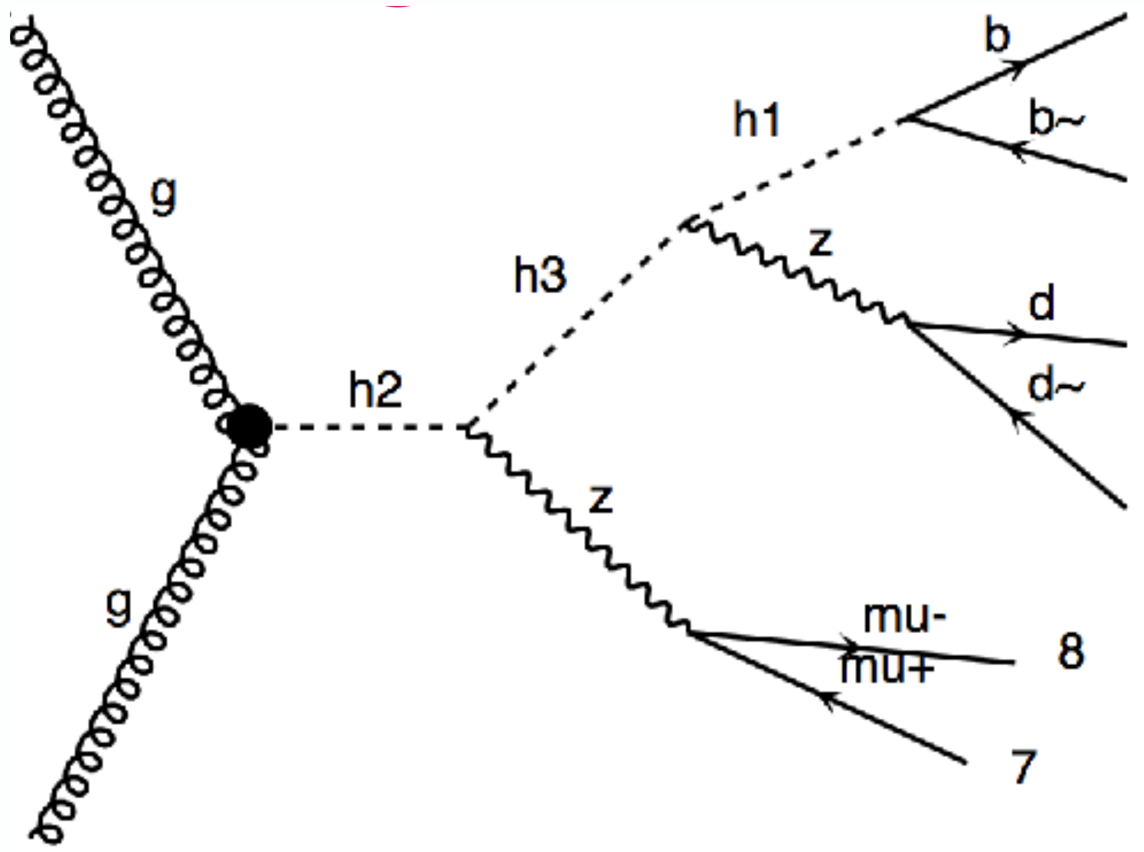
$$pp \to W^{*\pm} \to H^{\pm}H \to (W^{\pm}H)(W^{+}W^{-}) \to (W^{\pm}W^{+}W^{-})(W^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$$
$$pp \to W^{*\pm} \to H^{\pm}A \to (W^{\pm}H)(ZH) \to (W^{\pm}W^{+}W^{-})(ZW^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$$

- **Trilepton** final states of **H±H** and **H±A** pairs motivated by Type-1 2HDM

Recent proposals for new search channels

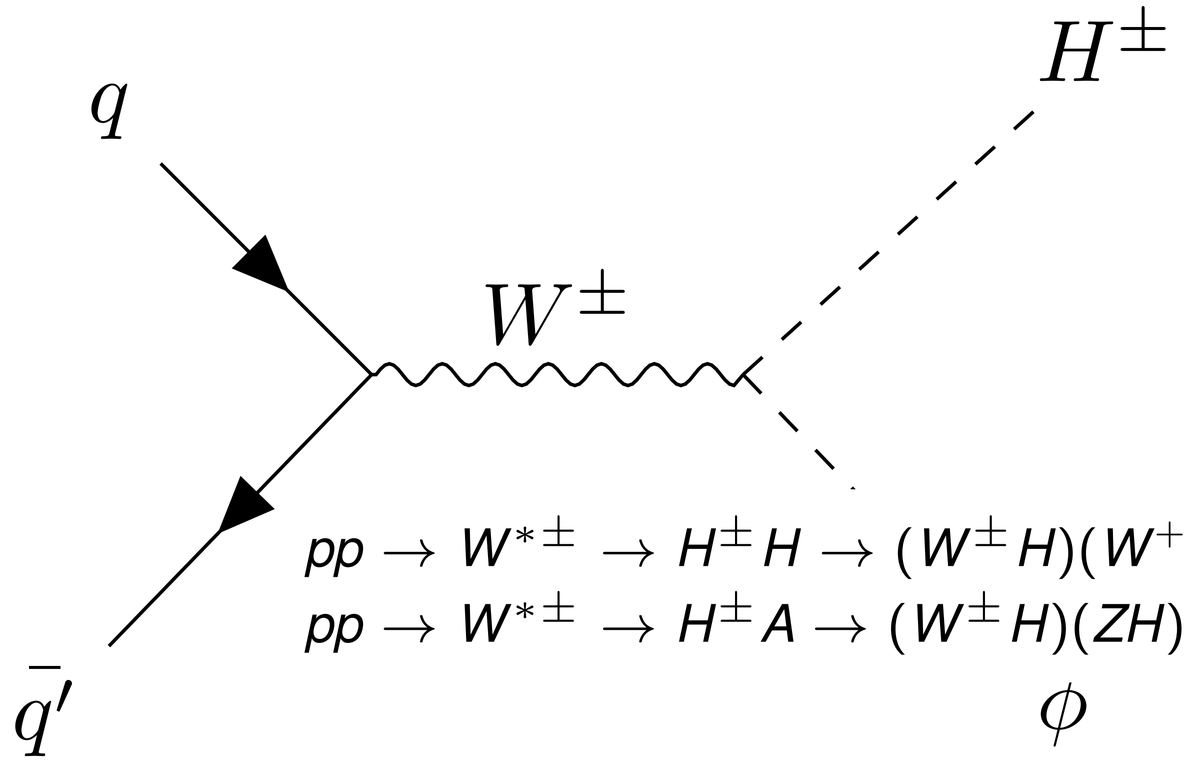
- Not a comprehensive list, just a few ideas that have been recently discussed in LHC Higgs WG

arXiv:2207.03007



- gg → $\mathbf{H_{125}}$ → $\mathbf{Z^{*}a_{BSM}}$ → $\mathbf{Z^{*}Z^{*}h_{BSM}}$ → μμjjbb motivated by Type-1 2HDM

arXiv:2109.05682

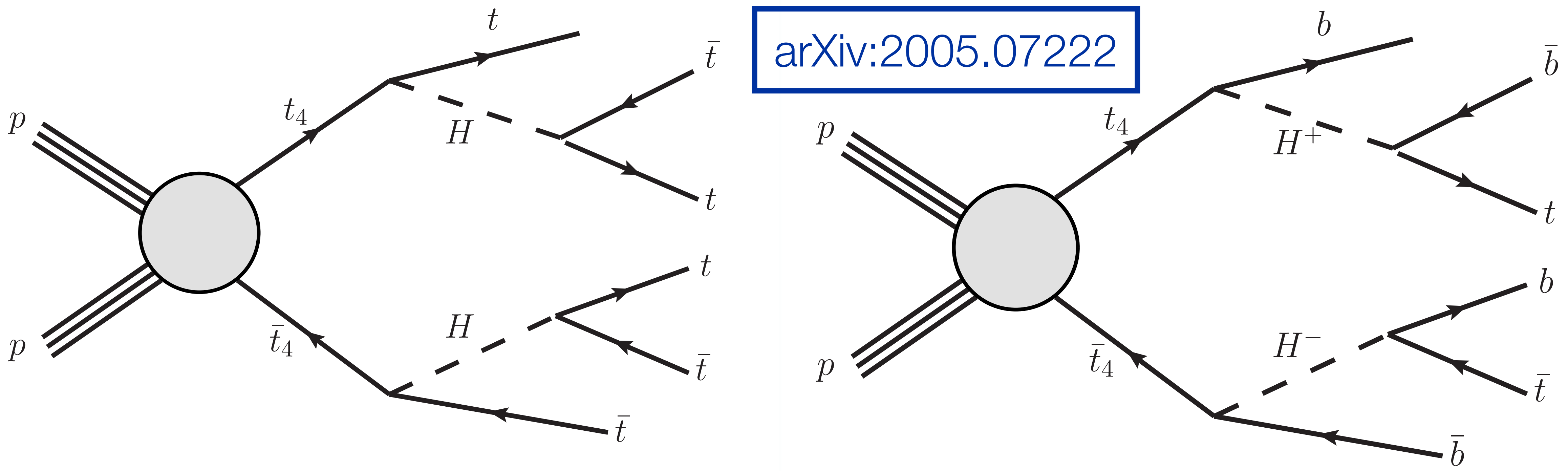


$pp \to W^{*\pm} \to H^{\pm}H \to (W^{\pm}H)(W^{+}W^{-}) \to (W^{\pm}W^{+}W^{-})(W^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$

$pp \to W^{*\pm} \to H^{\pm}A \to (W^{\pm}H)(ZH) \to (W^{\pm}W^{+}W^{-})(ZW^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$

- **Trilepton** final states of **H±H** and **H±A** pairs motivated by Type-1 2HDM

arXiv:2005.07222

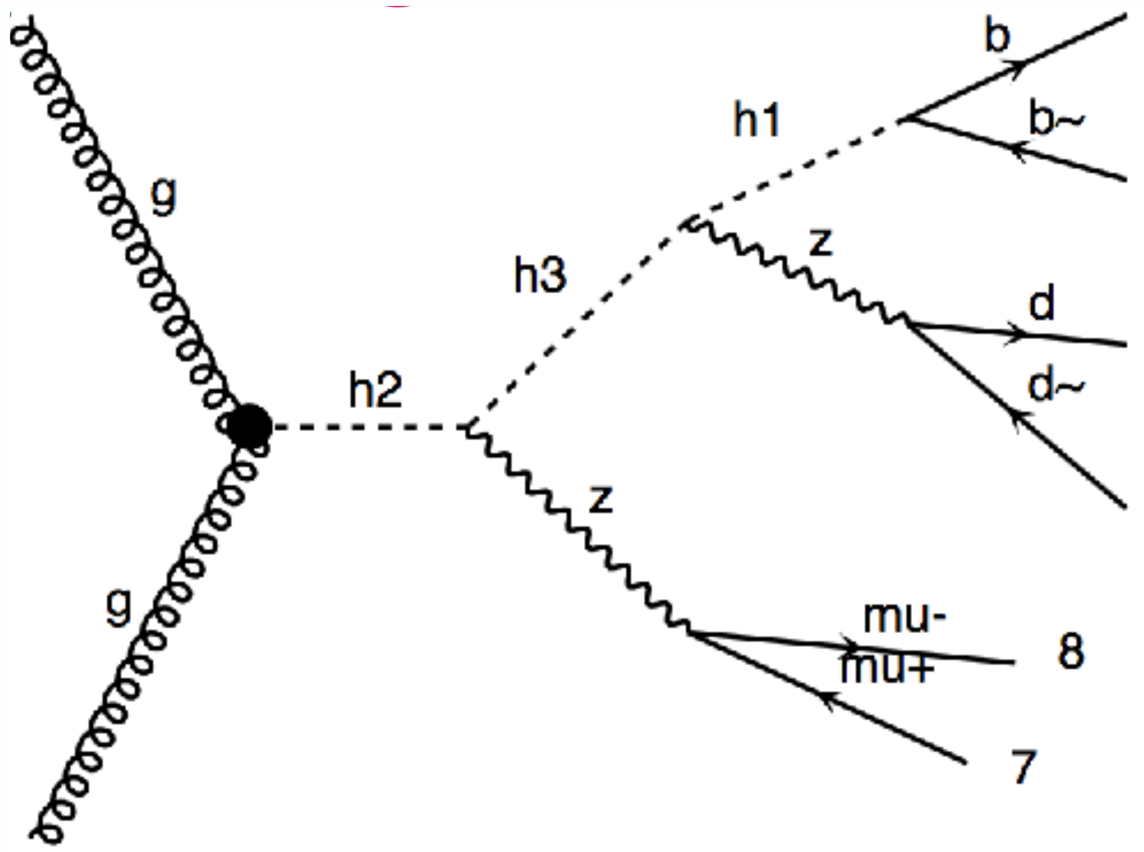


- Multi-top and multi-b final states from intermediate **vector-like quarks and H±/$\mathbf{H_{BSM}}$**

Recent proposals for new search channels

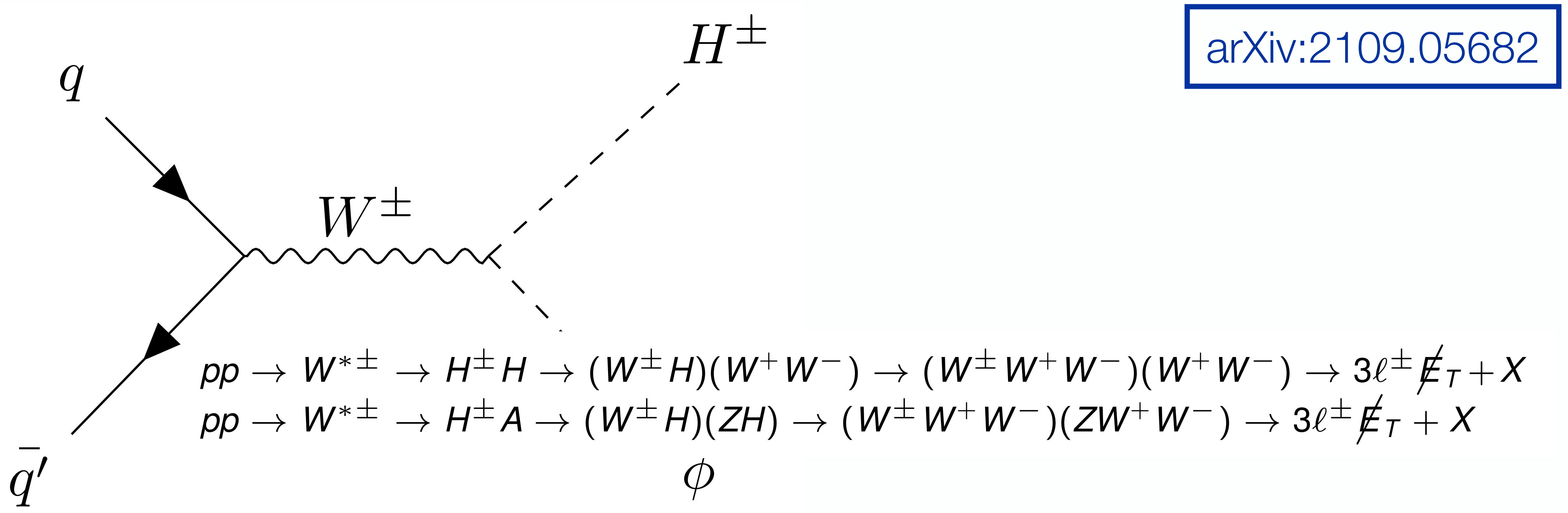
- Not a comprehensive list, just a few ideas that have been recently discussed in LHC Higgs WG

arXiv:2207.03007



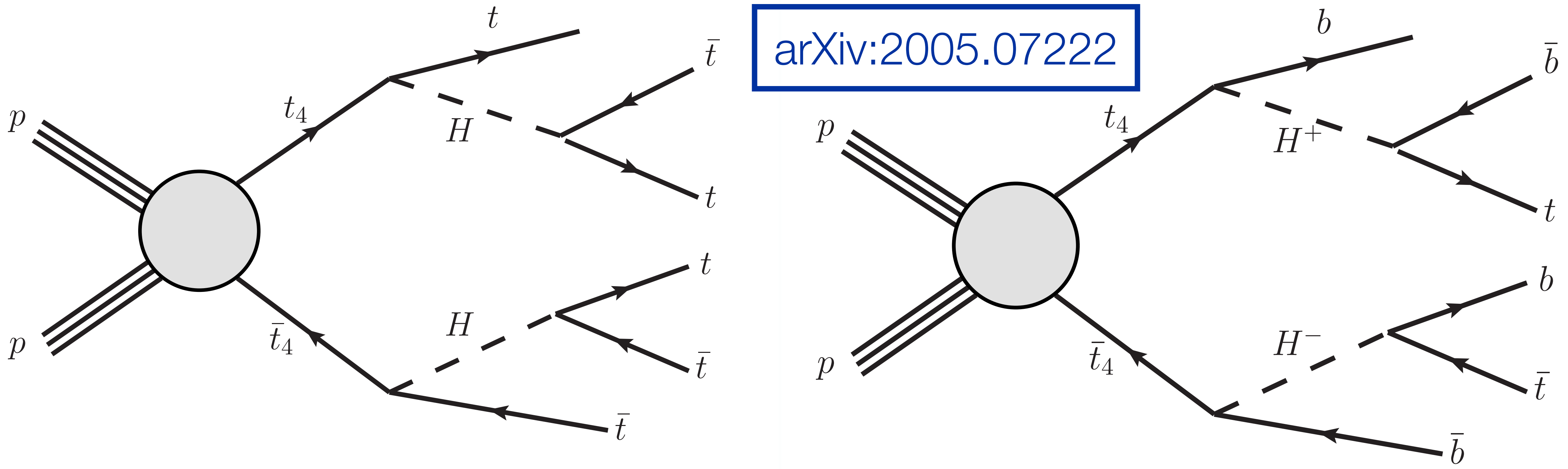
- gg → **H_{125}** → **Z^*a_{BSM}** → **$Z^*Z^*h_{BSM}$** → μμjjbb motivated by Type-1 2HDM

arXiv:2109.05682



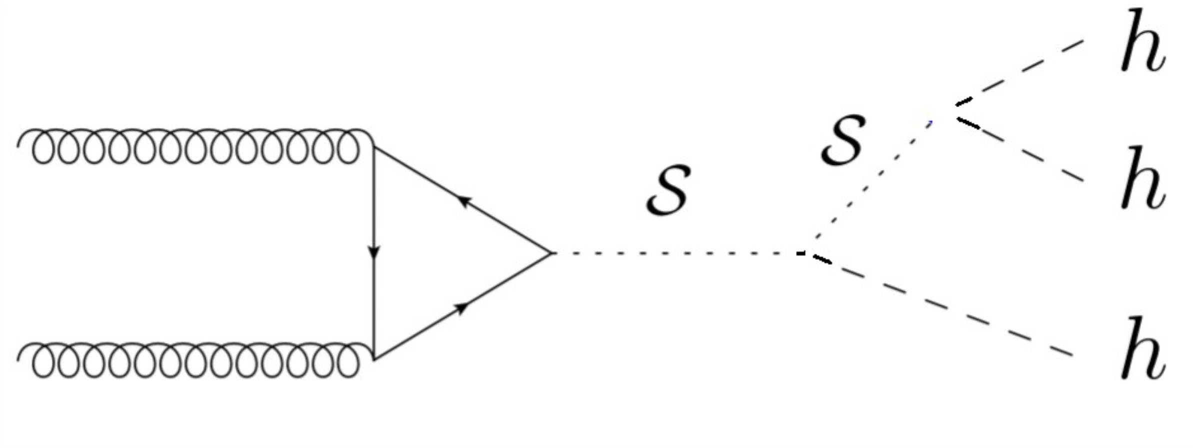
- **Trilepton** final states of **H±H** and **H±A** pairs motivated by Type-1 2HDM

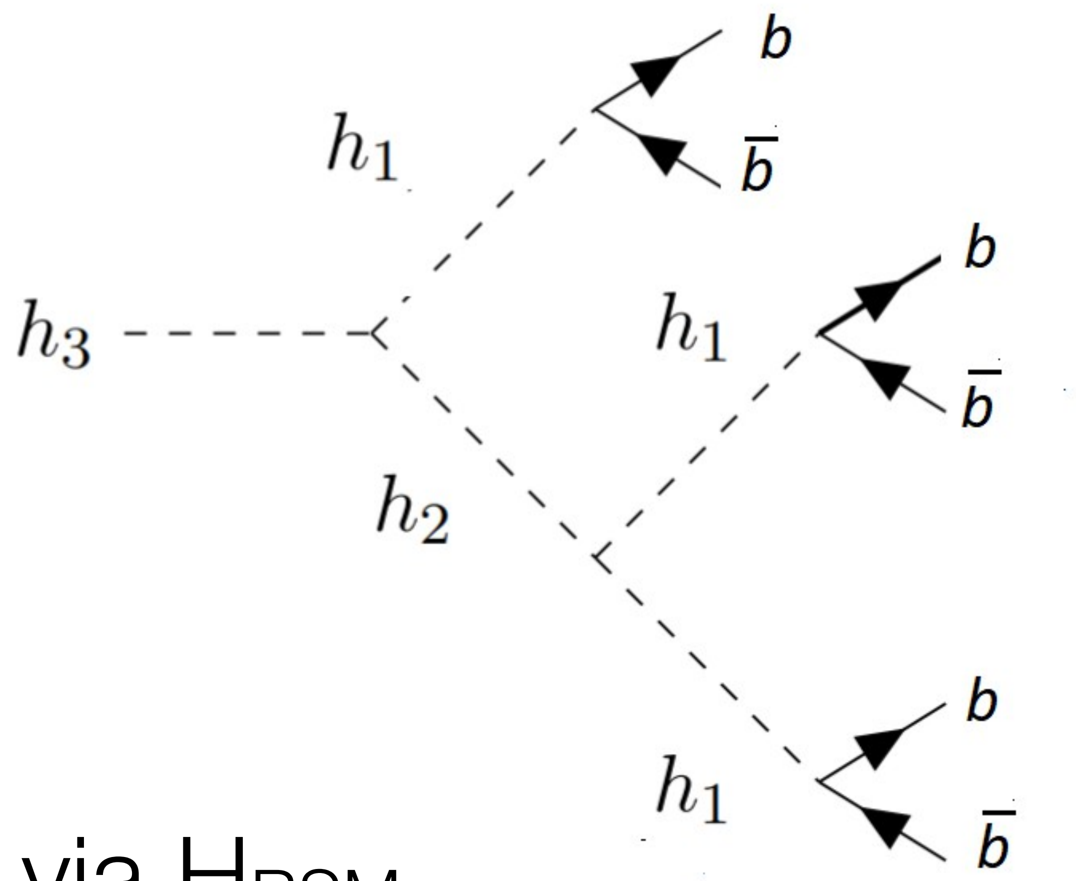
arXiv:2005.07222



- Multi-top and multi-b final states from intermediate **vector-like quarks and H±/H_{BSM}**

arXiv:2101.00037





- **Triple Higgs** production via H_{BSM} motivated by e.g. singlet or doublet models

Summary (metaphorical)

- There could be beautiful mountains in the horizon for us to observe, Beyond the Standard Mountain
- Experimentally, skiing around the area has so far not revealed any evidence of these BSM mountains
  - We set stronger and stronger exclusion limits, ruling out larger areas of our maps
- We keep improving our skiing techniques, and there is no shortage of possible trails
  - Most importantly, skiing can be lots of fun, and we learn a lot about the world along the way!