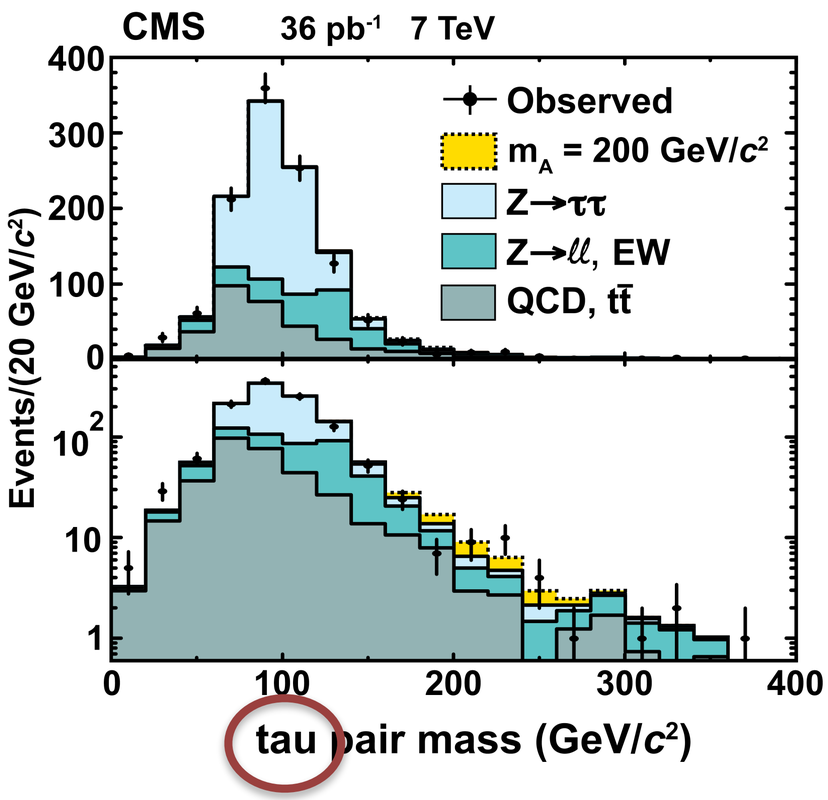
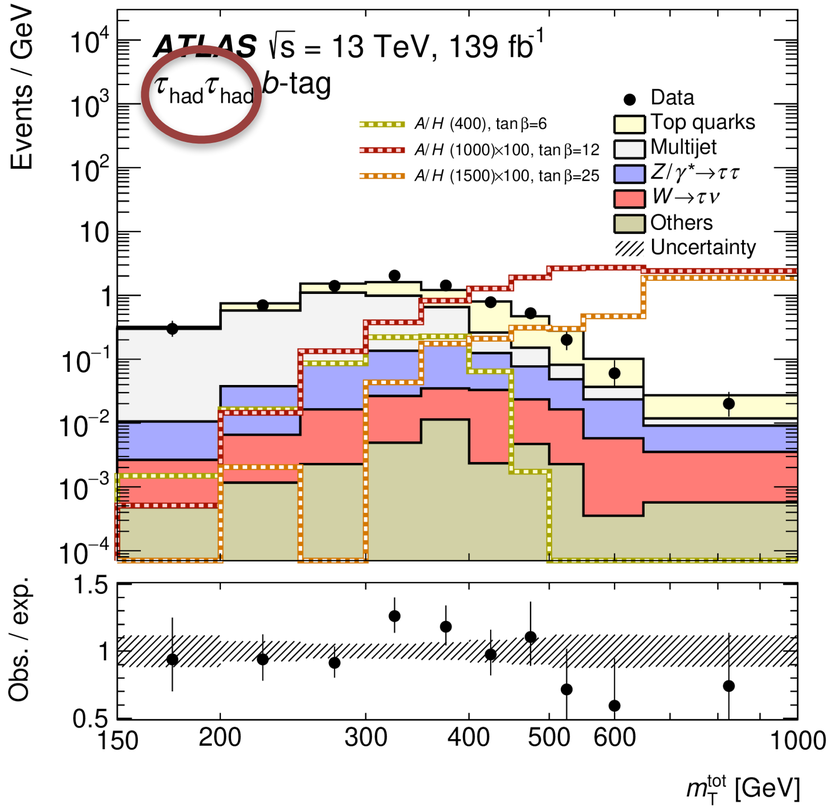




Beyond the Standard Model Higgs Searches

49th SLAC Summer Institute - The Higgs State Fair

Jan Steggemann

20 August 2021

The BSM Higgs Landscape

SM-like

h_{125} measurements

Rare h_{125} decays

BSM-like

Additional Higgs bosons

h_{125} BSM decays

Higgs as a tool

Marumi's lectures
TH: Stefania, Bernhard

This lecture!
TH: Nausheen, Jessie

The BSM Higgs Landscape

SM-like

h_{125} measurements: Is it really SM-like? E.g. coupling deviations, EFT

Rare h_{125} decays: Rate much higher than in SM?

It's all BSM!

BSM-like

Additional Higgs bosons

h_{125} BSM decays

Higgs as a tool

The BSM Higgs Landscape

SM-like

h_{125} measurements

Rare h_{125} decays

BSM-like

Additional Higgs bosons:
Scalar h/H,
Pseudoscalar a/A,
Charged scalar $H^{\pm}$,
Doubly charged scalar $H^{\pm\pm}$

h_{125} BSM decays:
h_{125}→aa/hh,
h_{125}→invisible,
h_{125}→long-lived,
LFV decays

Higgs as a tool - e.g. other new particles decaying to Higgs

ADDITIONAL HIGGS BOSONS

Main part of the lecture - will go through different extended Higgs sectors and discuss how we look for them

Extended Higgs sectors - 1-slide reminder

Slightly simplified view

Additional singlets, doublets, triplets, …, and **combinations** of them in addition to SM doublet

Singlet	**Doublet**	**Triplet**
Additional scalar H (or h/A/a)	Two additional scalars A/H (*) Charged scalar $H^{\pm}$	Fermiophobic scalars H_3 and $H_3^{\pm}$ Doubly charged scalar $H^{\pm\pm}$

generally violate custodial symmetry at tree level - need some mechanism to evade (e.g. Georgi-Machacek)

Generally **mixing with SM doublet**, modifying the h_{125} couplings
➡h_{125} is SM-like so mixing must be small

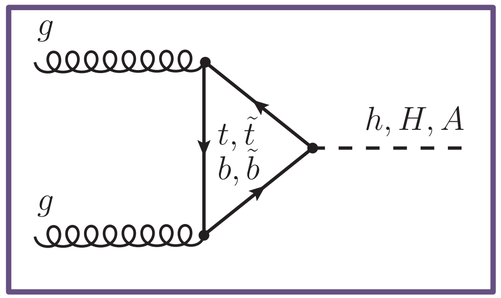
Sum rule for singlets and doublets:

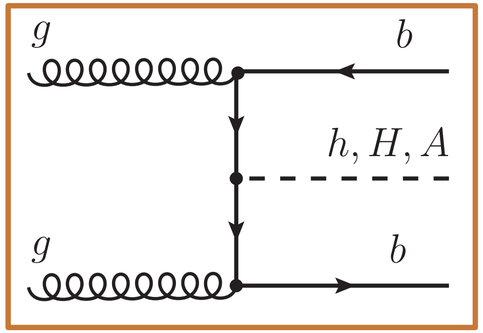
$$\Sigma_i (k_{VV}^{h_i})^2 = 1$$

(*) we most often look at CP eigenstates, but there can also be models with CP admixtures (not covered)

How to look for additional Higgs bosons

“Heavy” neutral scalars (<~ 100 GeV to ~ TeV):

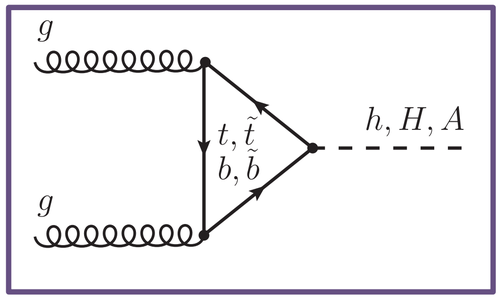


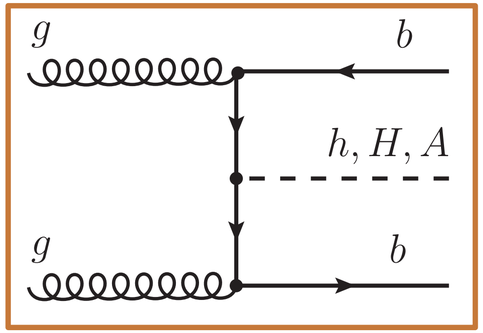


Produced like h_{125}:
gluon fusion, vector boson fusion, or t- or **b-associated**
➡ Need the **LHC** (or future high-energy collider) and multi-purpose experiment (currently **ATLAS** or **CMS**)
➡ Cross sections typically smaller than h_{125}: **Searches L_{int}-limited**

How to look for additional Higgs bosons

"Heavy" neutral scalars (<~ 100 GeV to ~ TeV):





b-jet tagged

Produced like h_{125}:
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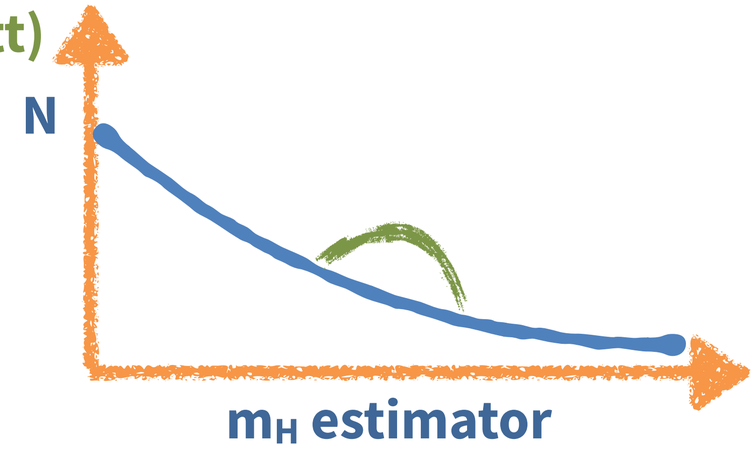
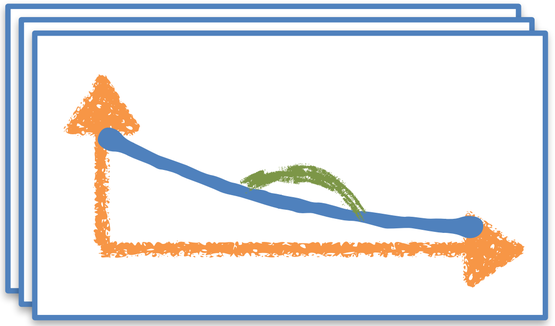
➡ Need the **LHC** (or future high-energy collider) and multi-purpose experiment (currently **ATLAS** or **CMS**)
➡ Cross sections typically smaller than h_{125}: Searches L_{int}-limited

Decays:
Either into SM like h_{125} **(ZZ, WW, γγ; ττ, bb, …)**
or heavier **(tt)**



Or into boson pairs $H \to h_{125}h_{125}/hh/h_{125}h/aa/ZA/\ldots$
$A \to Zh_{125}/ZH/ha/\ldots$



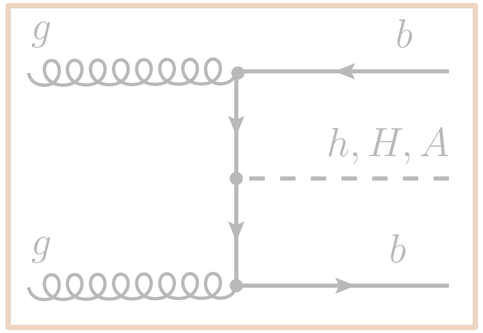
x 3

How to look for additional Higgs bosons

"Heavy" neutral scalars (<~ 100 GeV to ~ TeV):

Produced like h_{125}:
gluon fusion, vector b
➡ Need the **LHC** (or fu
multi-purpose experi
➡ Cross sections typic

A plethora of interesting final states and searches, experimentally very rich!



b-jet tagged

Decays:
Either into SM like h_{125} **(ZZ, WW, γγ; ττ, bb, …)**

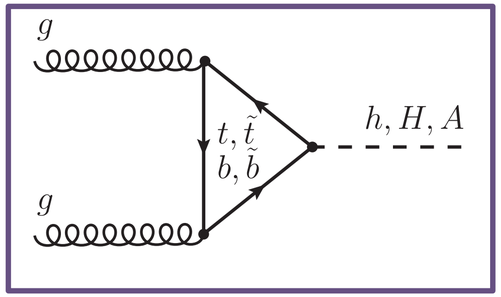
Or into boson pairs $H \to h_{125}h_{125}/hh/h_{125}h/aa/ZA/\ldots$
$A \to Zh_{125}/ZH/ha/\ldots$

Nowadays, most of the searches aren't "simple" bump hunts anymore, but increase the sensitivity by using **multiple event categories** or **multivariate classifiers (BDTs, DNNs)**

x 3

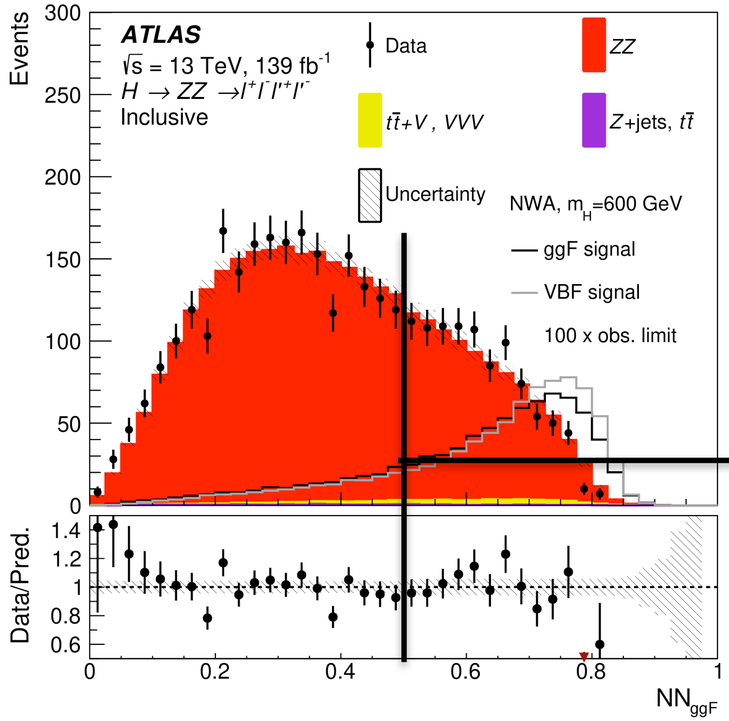
m_H estimator

Search for H→ZZ→4 leptons

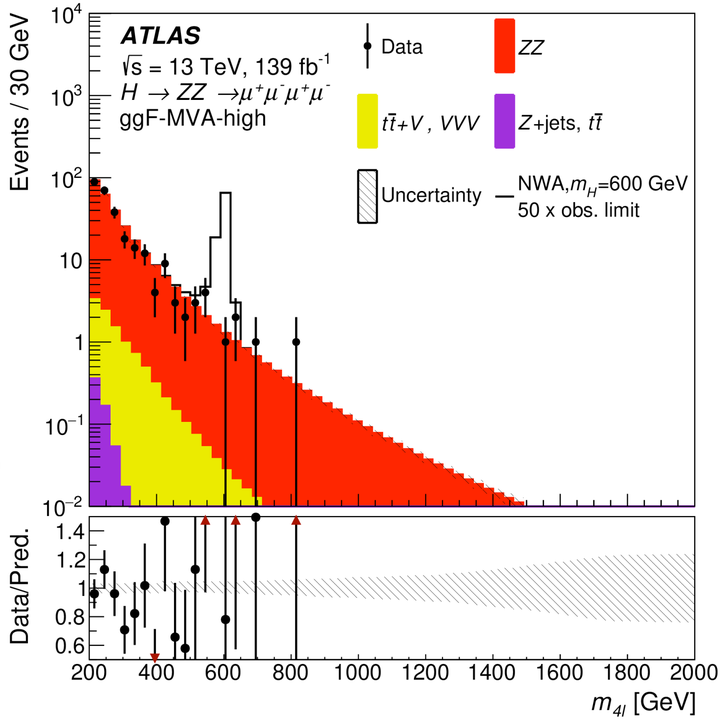


Kinematics of the 4 leptons and a possible jet

DNN classifier discriminates gluon fusion against SM ZZ production

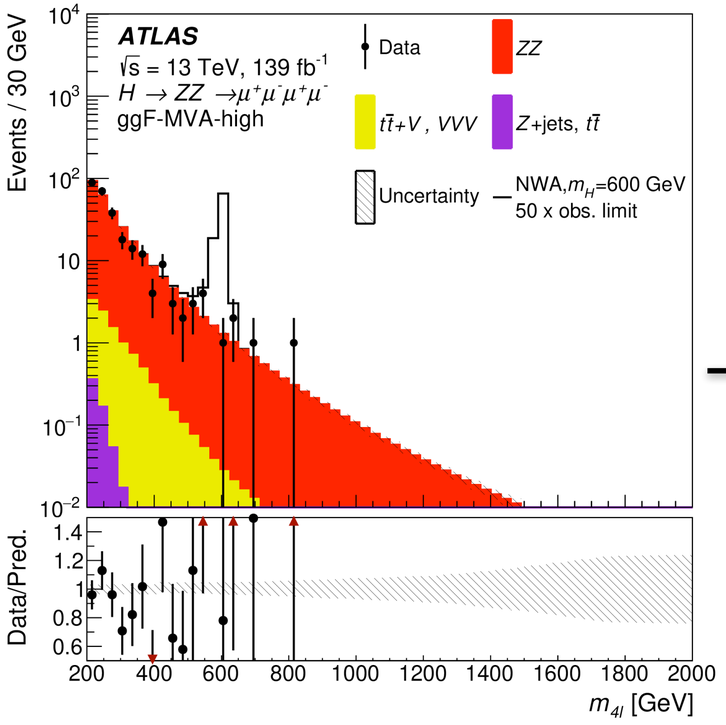


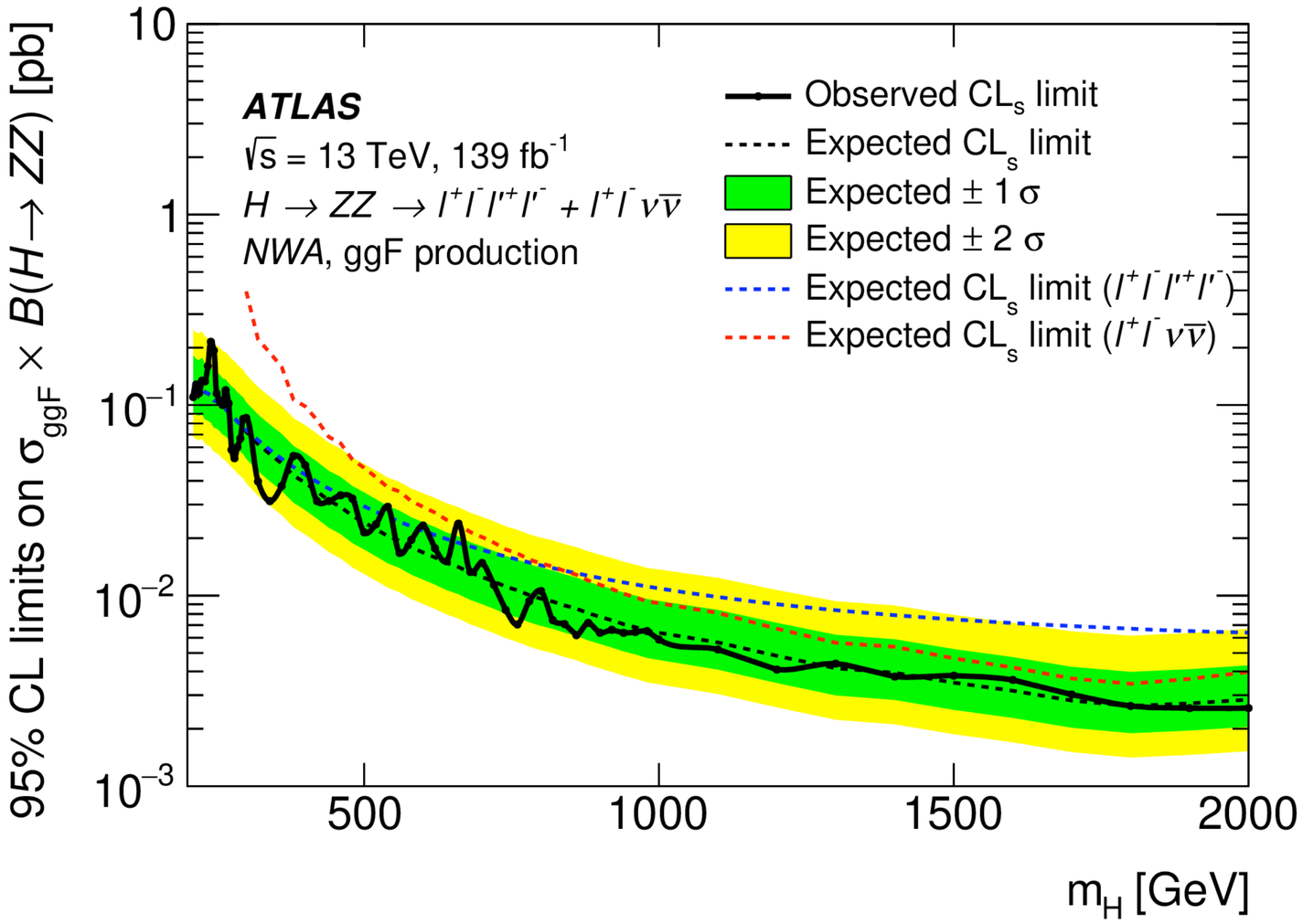
“Bump hunt” with 4-lepton mass distribution



ATLAS Eur. Phys. J. C 81 (2021) 332

Search for H→ZZ





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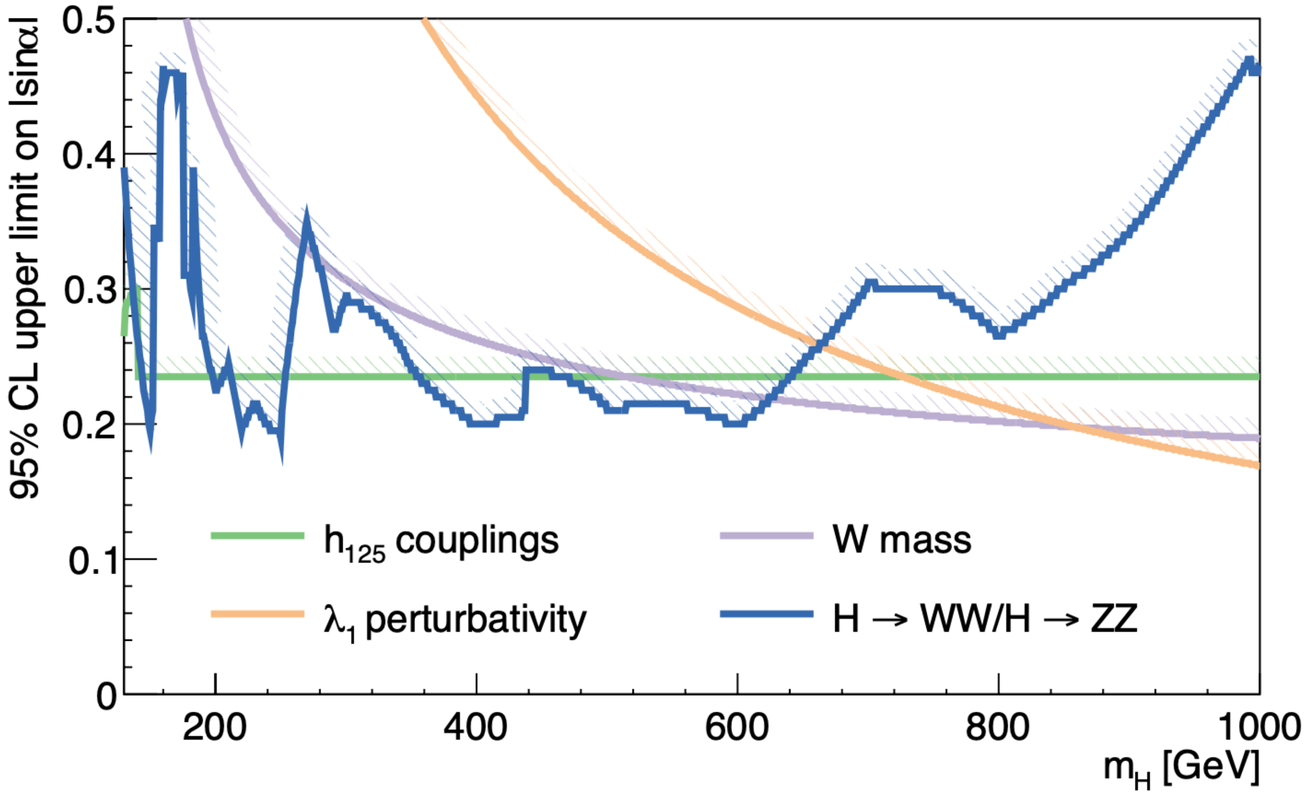
Connecting it to the simplest extended Higgs model: Additional real scalar singlet

Three parameters:

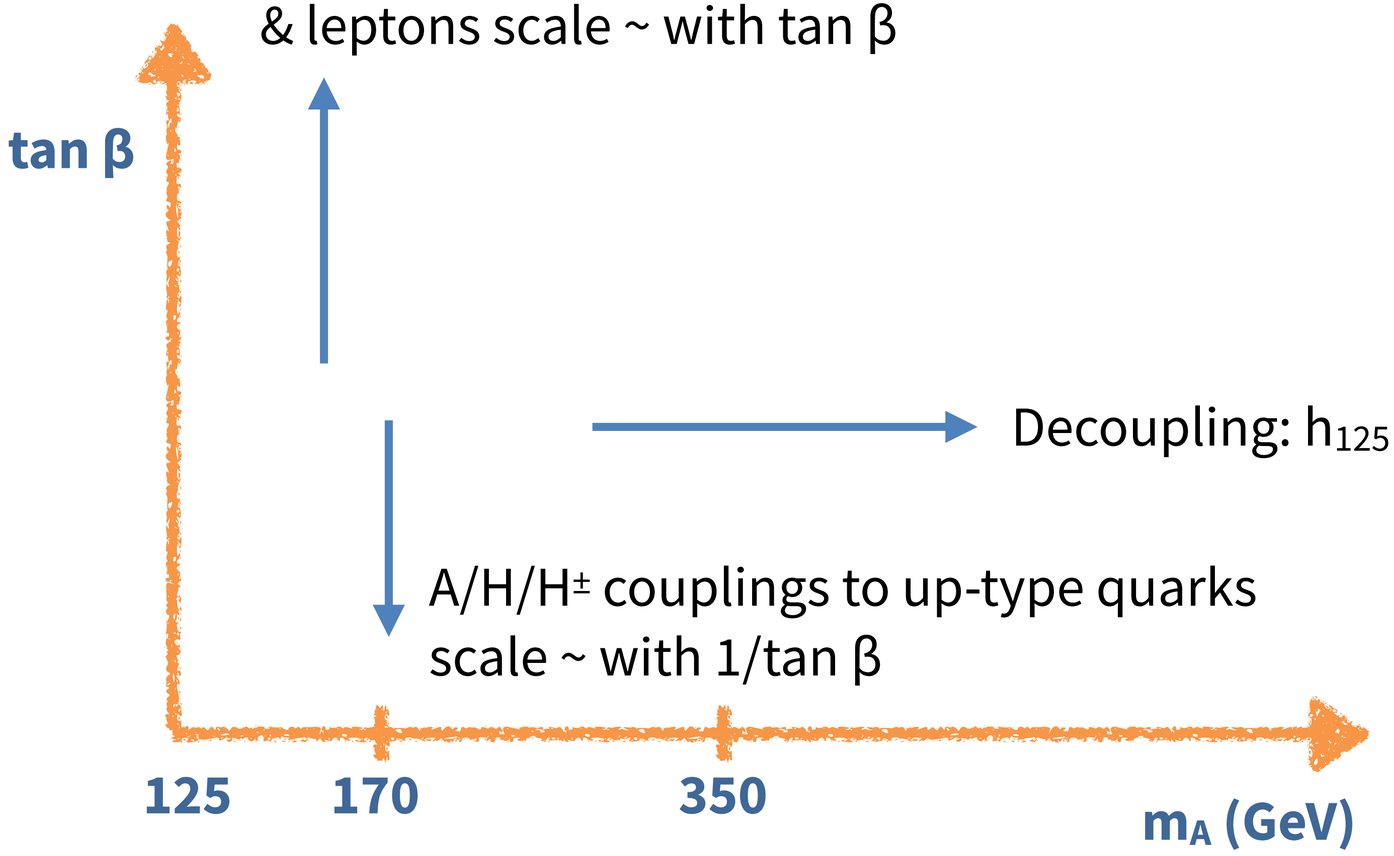
- **m_H**
- **Mixing angle α**:
  - ➡h_{125} couplings universally suppressed by cos(α)
  - ➡H couplings same as h_{125} but scale with sin(α)
- **Ratio of v.e.v.s tan(β)**
  - ➡Only important for mH > 250 GeV, where H →$h_{125}h_{125}$ mode opens (subsensitive but reduces branching fractions to WW/ZZ, up to 30% effect on limits)



adapted from [T Robens PoS(LHCP2019)138]

The MSSM Higgs sector: a 2HDM of type II

A/H/H± couplings to down-type quarks & leptons scale ~ with tan β



Decoupling: h_{125} naturally SM-like, $\cos(\beta - \alpha) \to 0$

A/H/H± couplings to up-type quarks scale ~ with 1/tan β

2HDM (Two-Higgs-Doublet Model) **Yukawa sector**

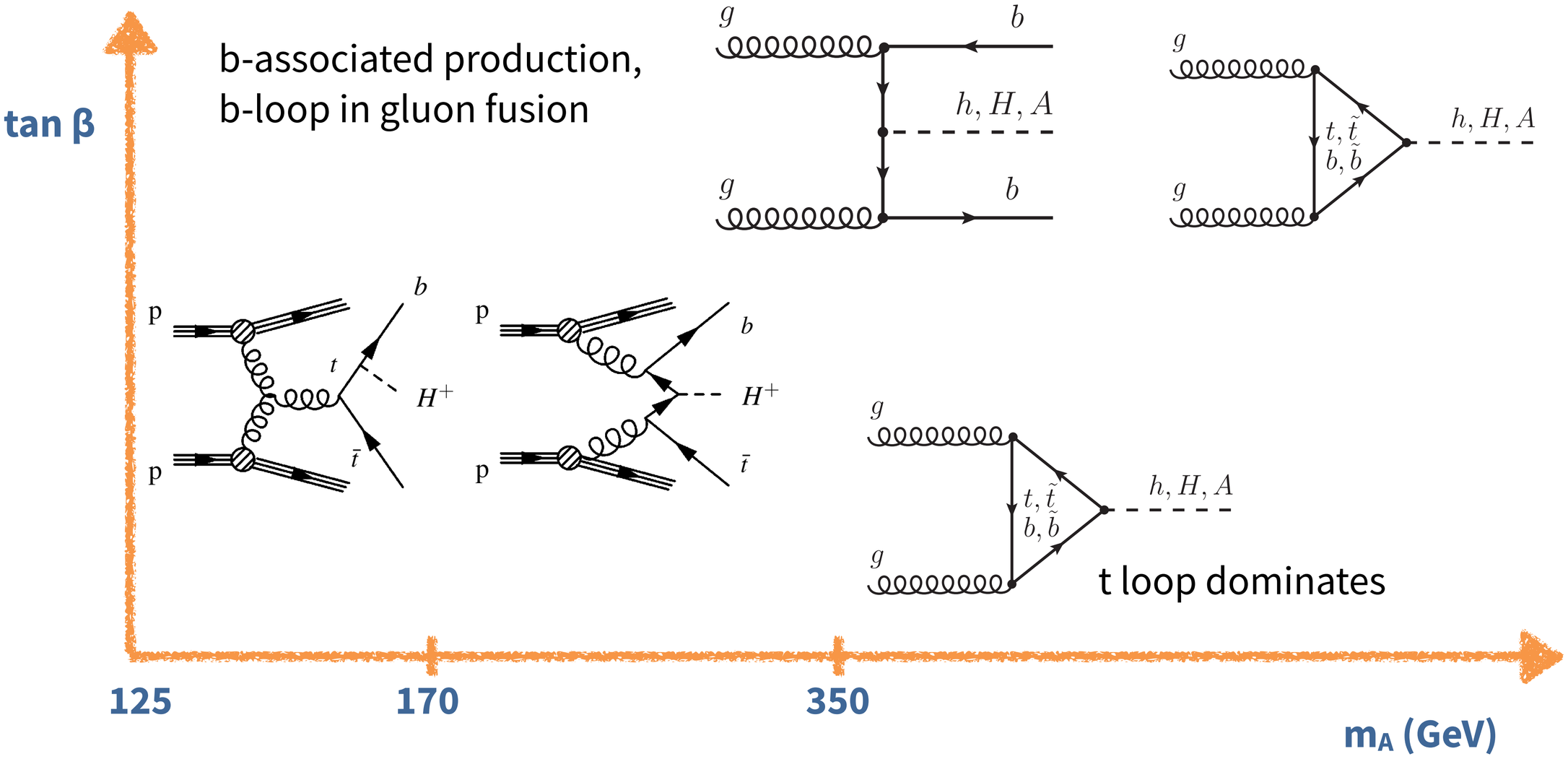
Model	u_R	d_R	ℓ_R
Type I	ϕ_2	ϕ_2	ϕ_2
Type II	ϕ_2	ϕ_1	ϕ_1
Lepton-specific	ϕ_2	ϕ_2	ϕ_1
Flipped	ϕ_2	ϕ_1	ϕ_2

Φ	$g^{\Phi}_{f(\phi_2)}$	$g^{\Phi}_{f(\phi_1)}$	g^{Φ}_{VV}
$H_{\rm SM}$	1	1	1
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A	$\pm 1/\tan\beta$	$\tan\beta$	0

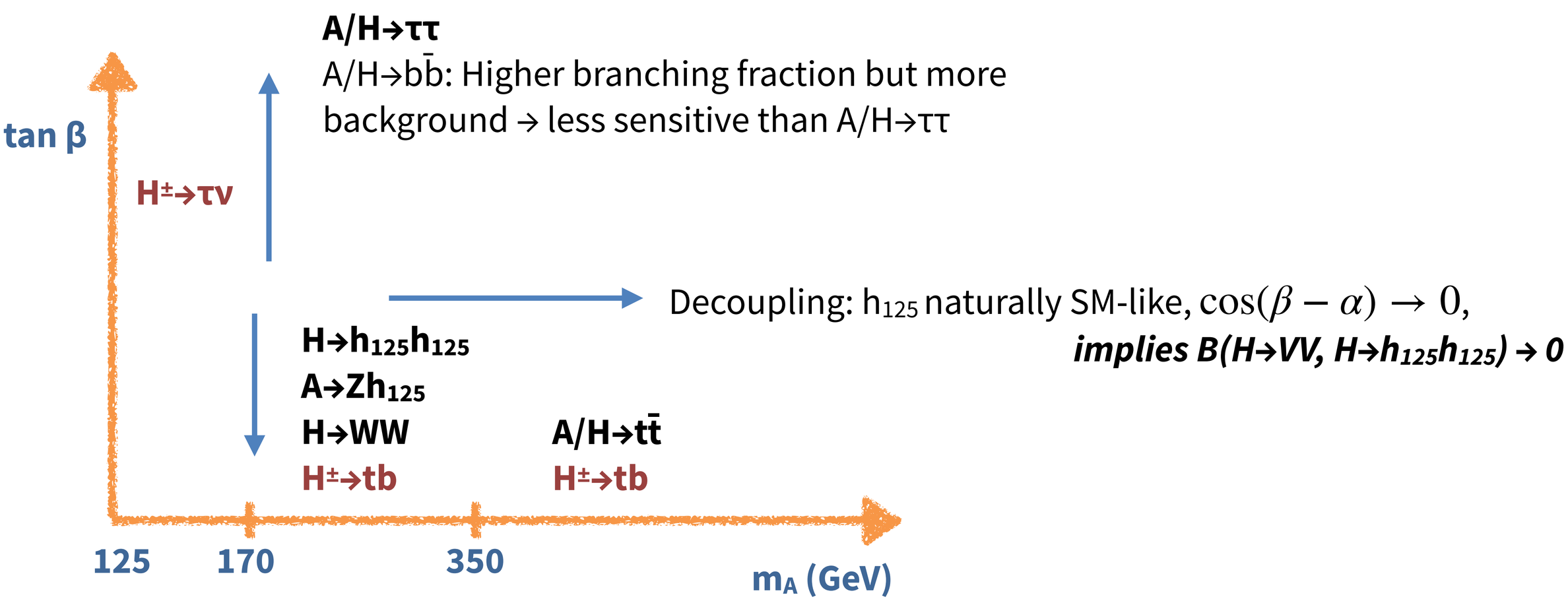
A/H/H± nearly mass-degenerate for sufficiently high m_A

MSSM: Minimal Supersymmetric Standard Model
2 free parameters at tree level: m_A, tanβ

Production


tan β
b-associated production,
b-loop in gluon fusion
g
b
h, H, A
g
b
g
t, t̃
b, b̃
h, H, A
g
p
b
t
H+
t̄
p
p
b
H+
t̄
p
g
t, t̃
b, b̃
h, H, A
g
t loop dominates
125
170
350
mA (GeV)

Most important decays

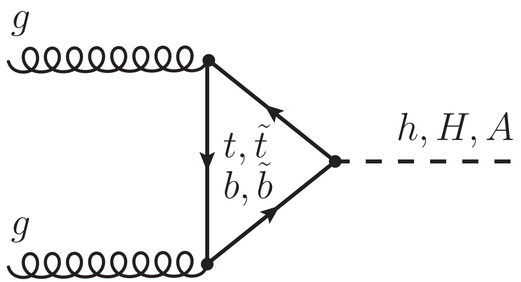


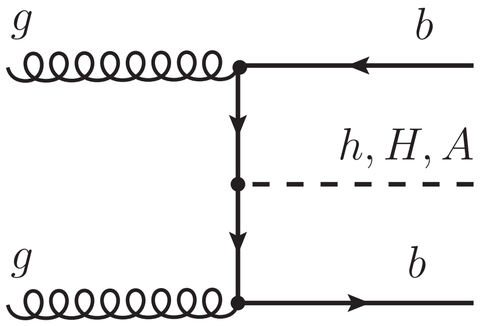
A/H→ττ: Experimental approach

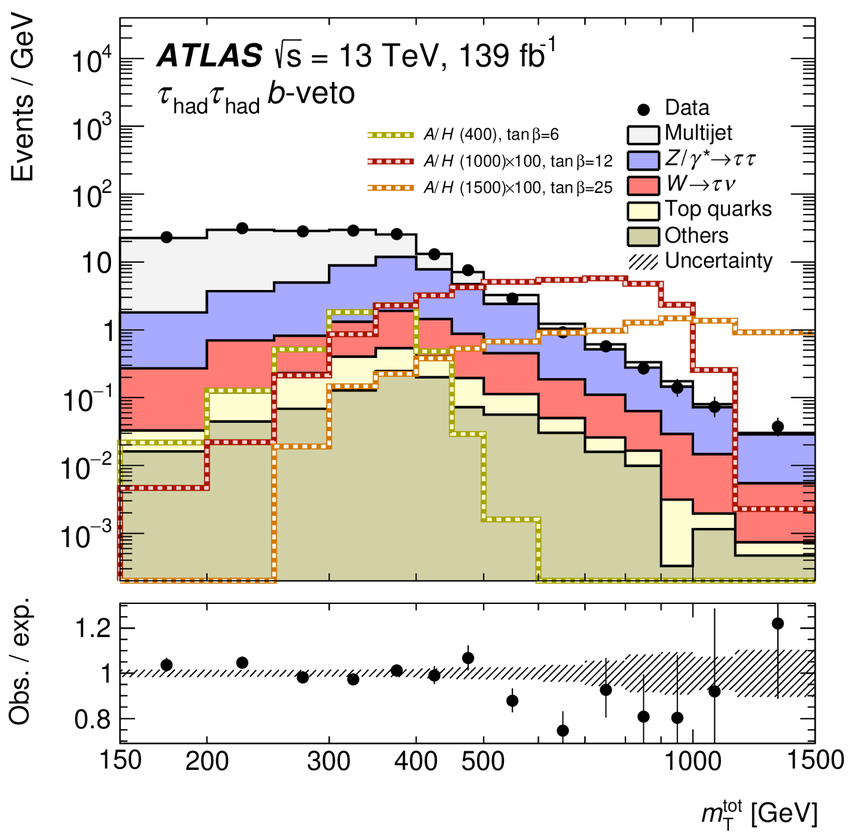
τ decays:
65% hadrons + **ν** (**τ_h**)
35% e/μ + **2ν**

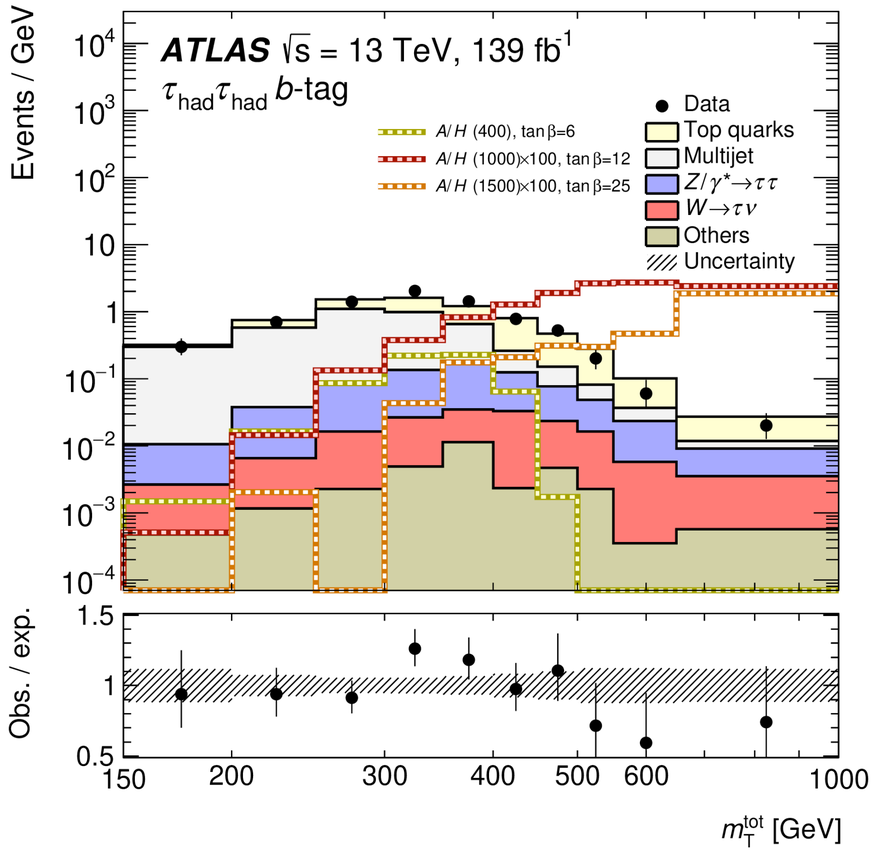
3 (4) interesting final states: μ**τ_h**, e**τ_h**, **$\tau_h\tau_h$** (eμ)

Challenges:
τ_h reconstruction/ID/ trigger, **p_T^{miss}**, related background







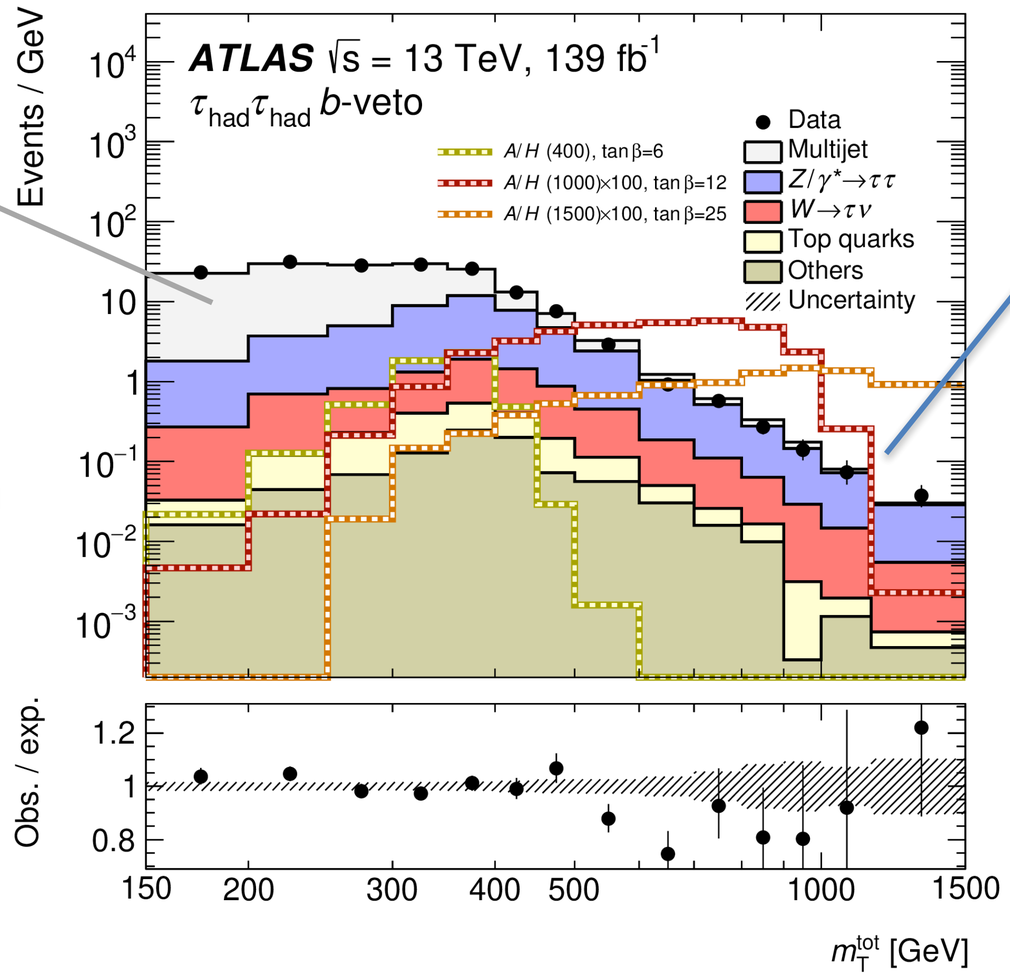


ATLAS Phys. Rev. Lett. 125 (2020) 051801

A/H→ττ: Experimental challenges

Multijet background:
Jets misidentified as τ_h

Measure jet→τ_h misID rate in data control region & apply in data sideband

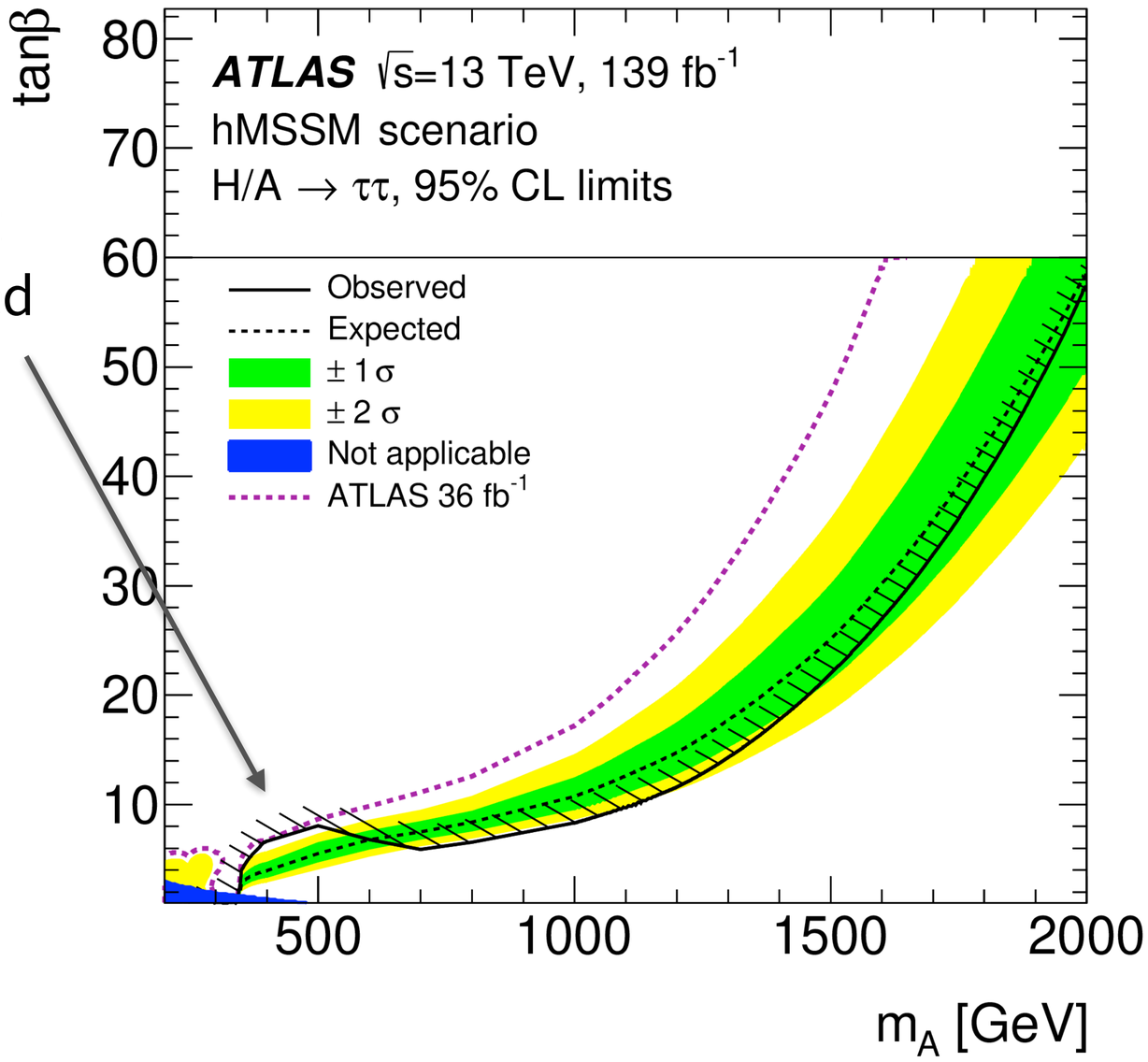


Irreducible Z/γ*→ττ background:
Estimated from simulation (ATLAS) or from **τ embedding** (CMS): replacing reconstructed μ in data (typically from Z/γ*→μμ) by simulated τ

m_T^{tot}: Square sum of m_T of three $\tau_h/\tau_h/p_T^{miss}$ combinations
Worse resolution for signal but shifts background to lower values

A/H→ττ: Limits extend to 2 TeV at high tan β

Observed limits a bit weaker than expected around 400-500 GeV



hMSSM

Assume m_h = 125 GeV and make a few simplifying assumptions

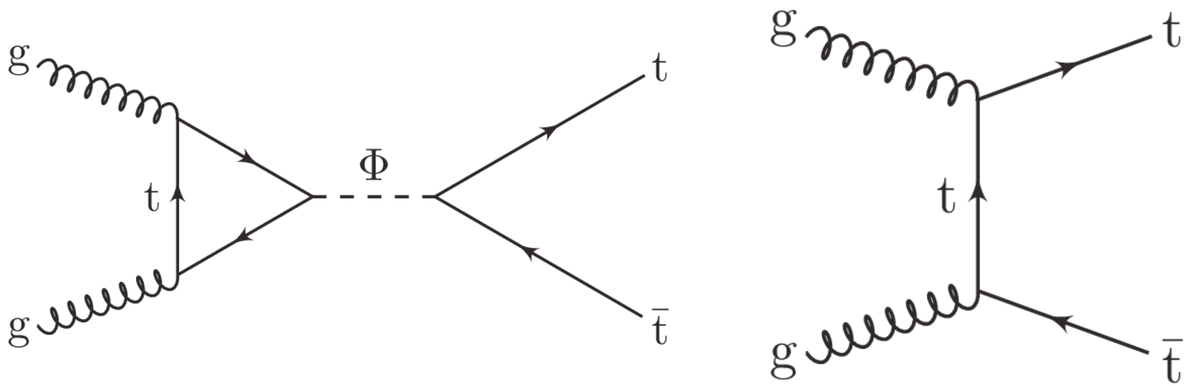
➡ only 2 free parameters

➡ low tan β open (at expense of high SUSY scale)

More benchmarks exist

ATLAS Phys. Rev. Lett. 125 (2020) 051801

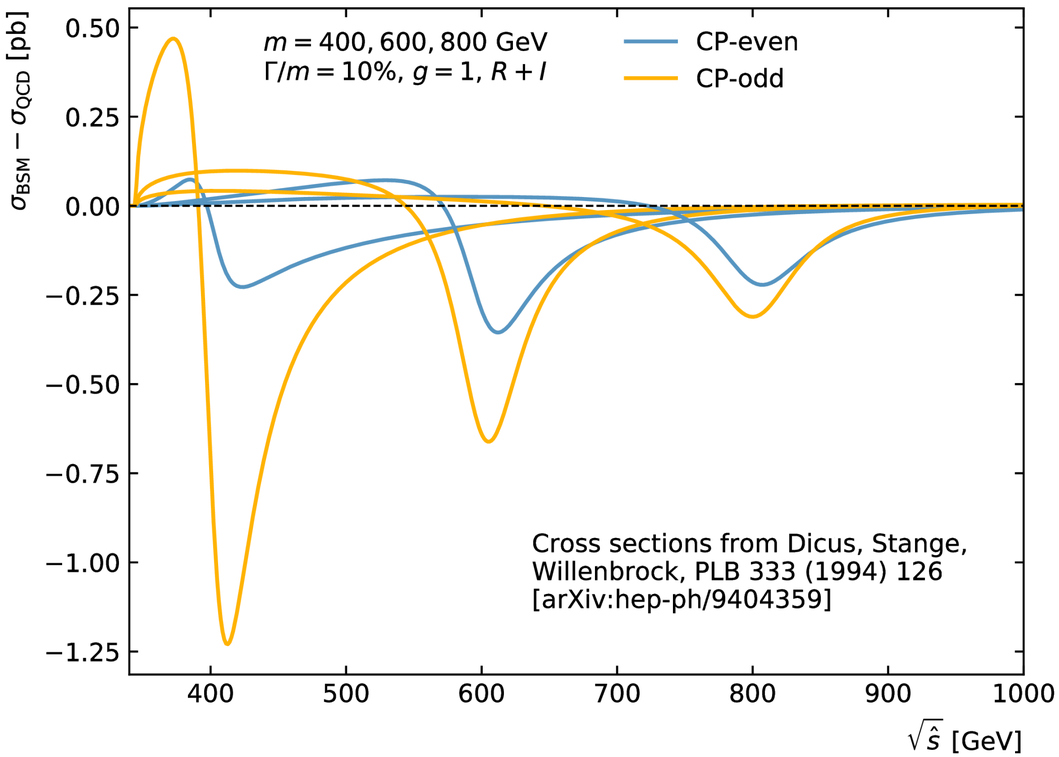
A/H→$t\bar{t}$:
Tackling low tan β



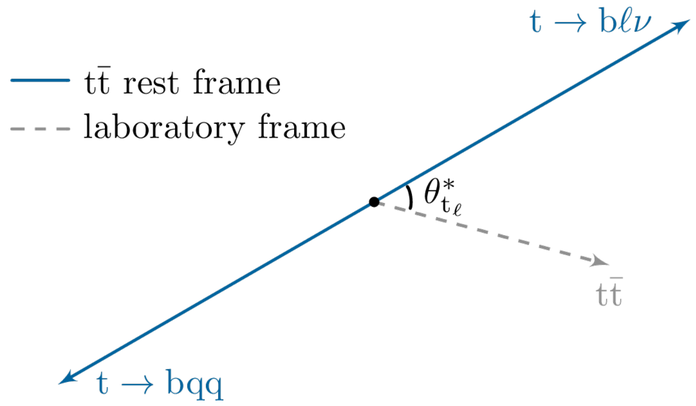
Beyond $t\bar{t}$ production threshold of around 350 GeV: A/H decays nearly 100% to $t\bar{t}$

Lineshape depends on coupling (~ 1/tan β)

Interference leads to complicated lineshape



A/H→$t\bar{t}$



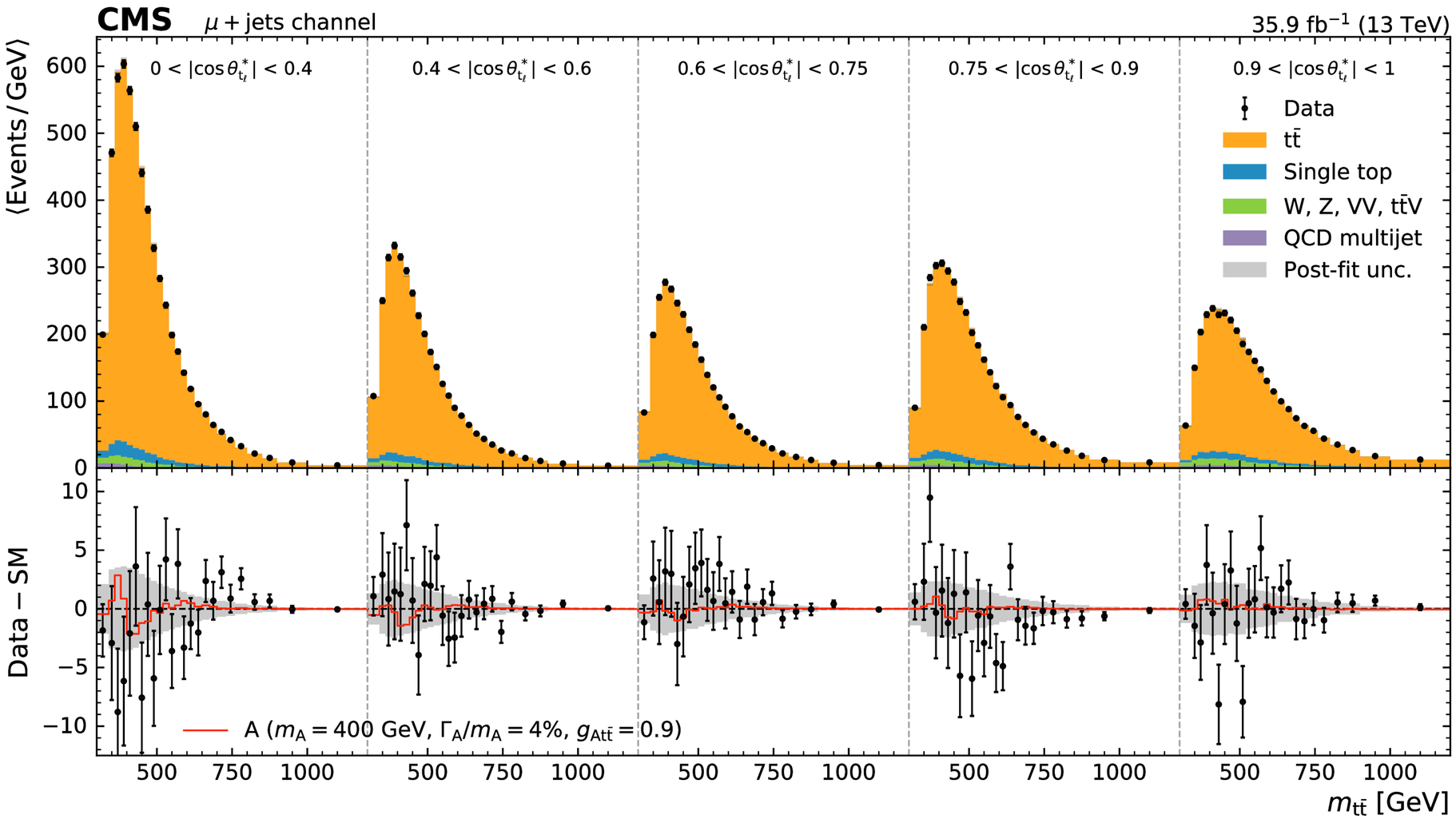
Three $t\bar{t}$ final states:

$\mu + p_T^{miss} + bbjj$

$e + p_T^{miss} + bbjj$

$\mu\mu/e\mu/ee + p_T^{miss} + bb$

Reconstruct $m(t\bar{t})$ using W mass constraint



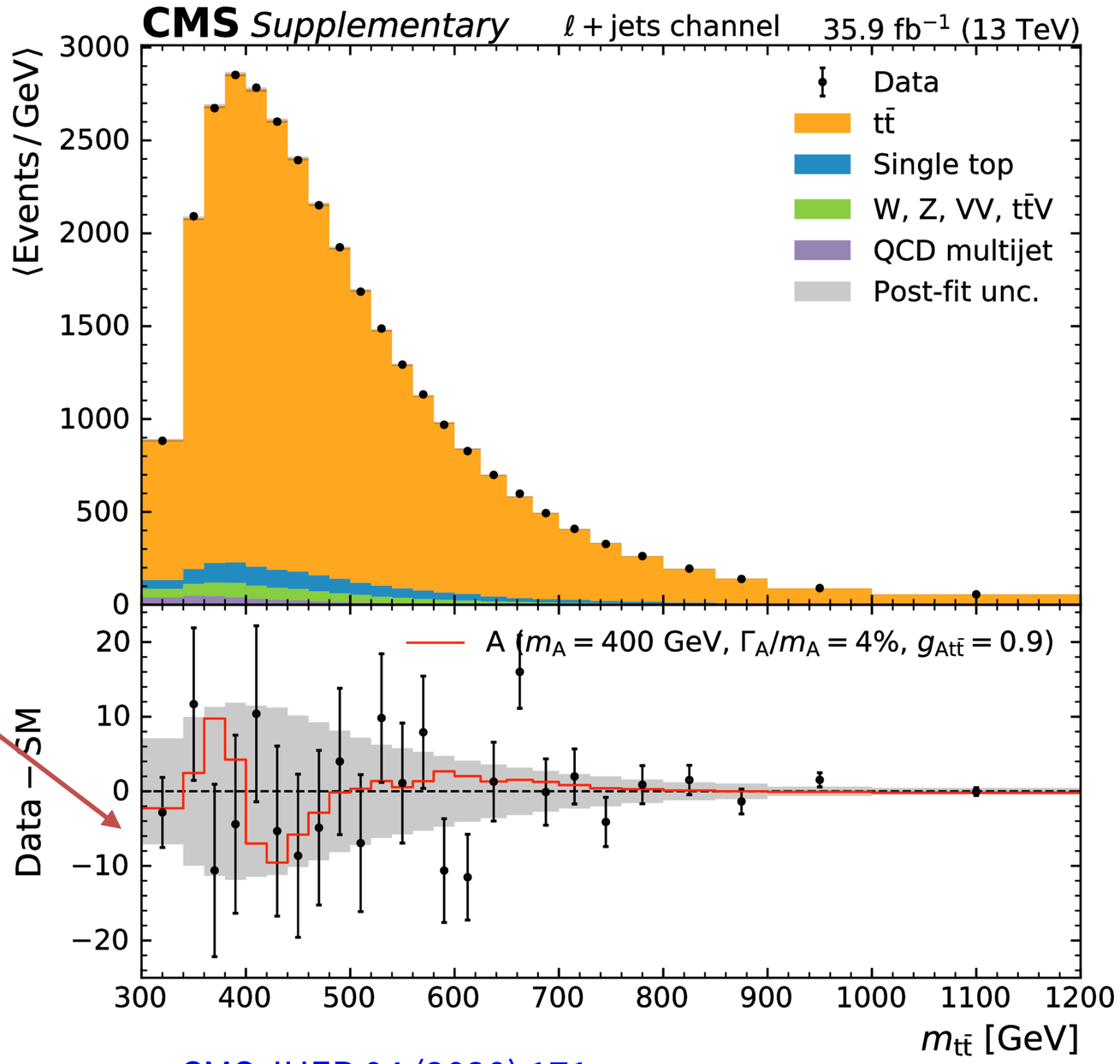
CMS JHEP 04 (2020) 171

A/H→$t\bar{t}$

Irreducible $t\bar{t}$ background from simulation: Requires very careful evaluation of all experimental & theoretical/modelling uncertainties

Need to be able to resolve < 1% level deviations in lineshape

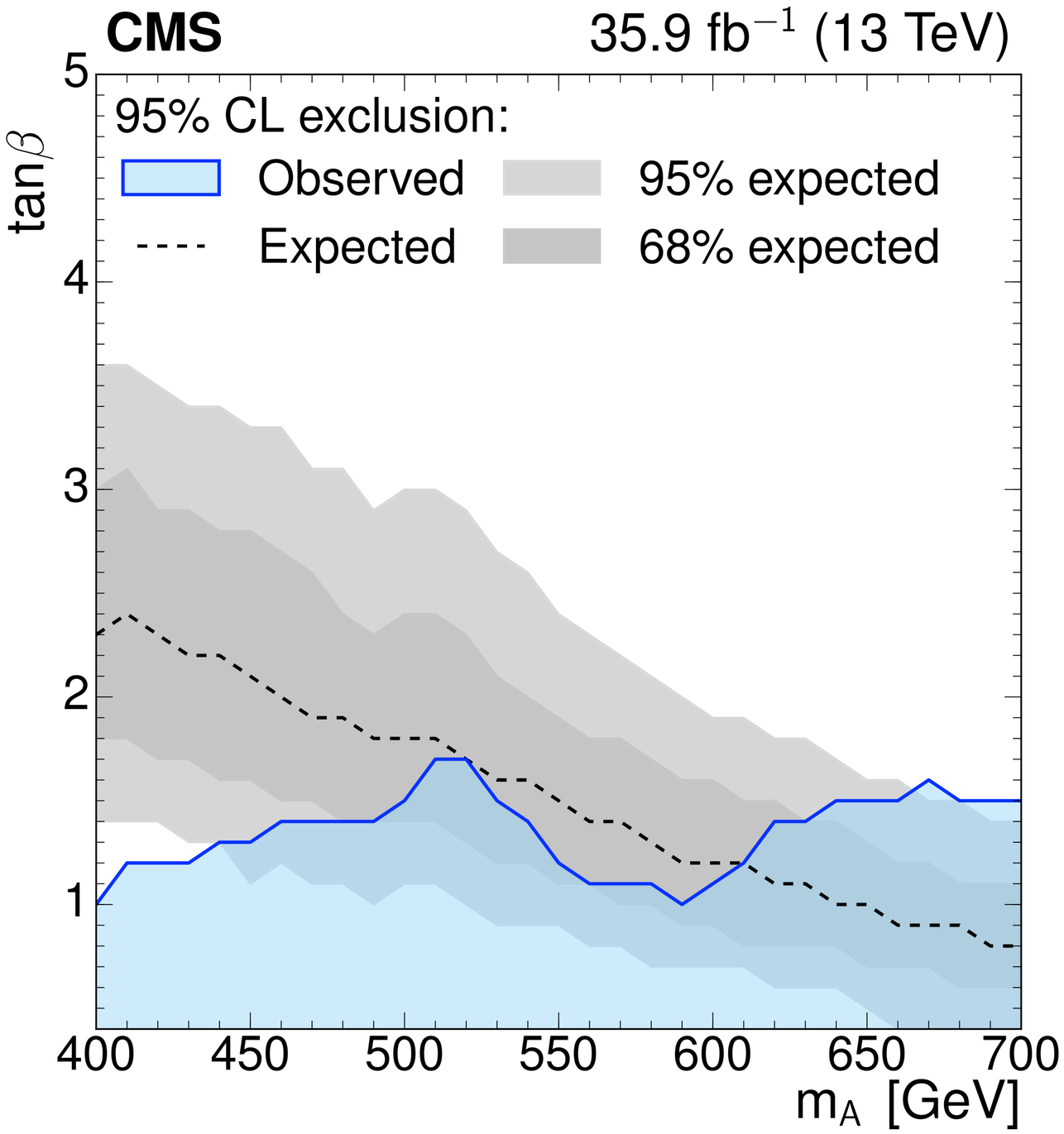
Systematic uncertainties do luckily not give rise to shapes like the ones we expect for signal: not systematically limited



CMS JHEP 04 (2020) 171

A/H→$t\bar{t}$

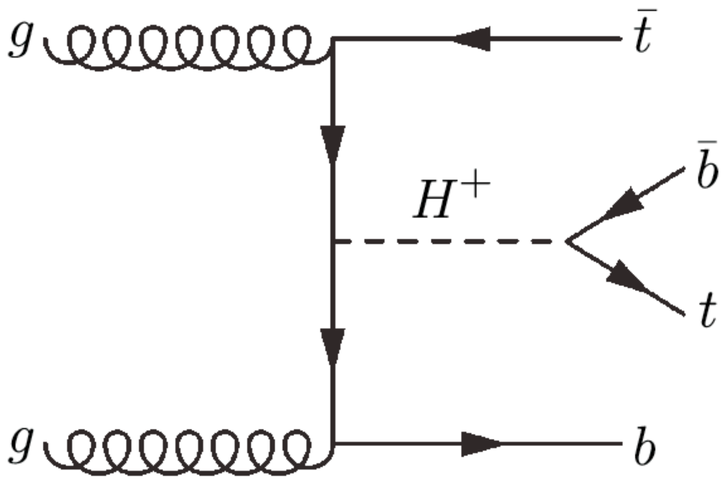
Sensitivity at low tanβ beyond 400 GeV

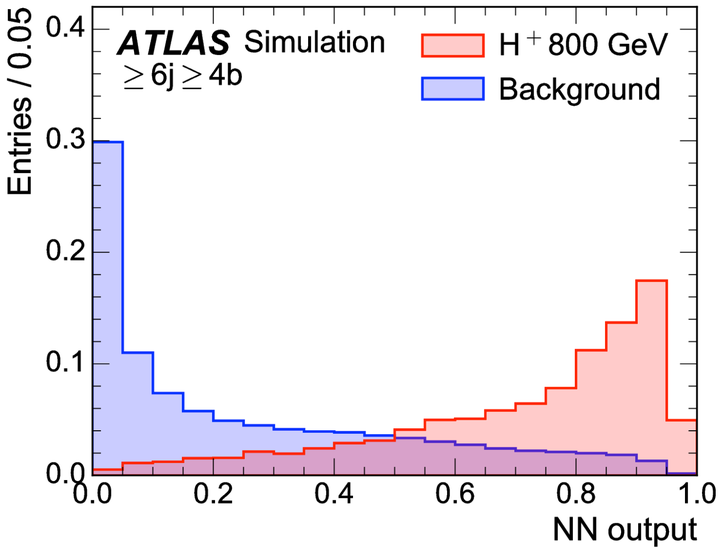


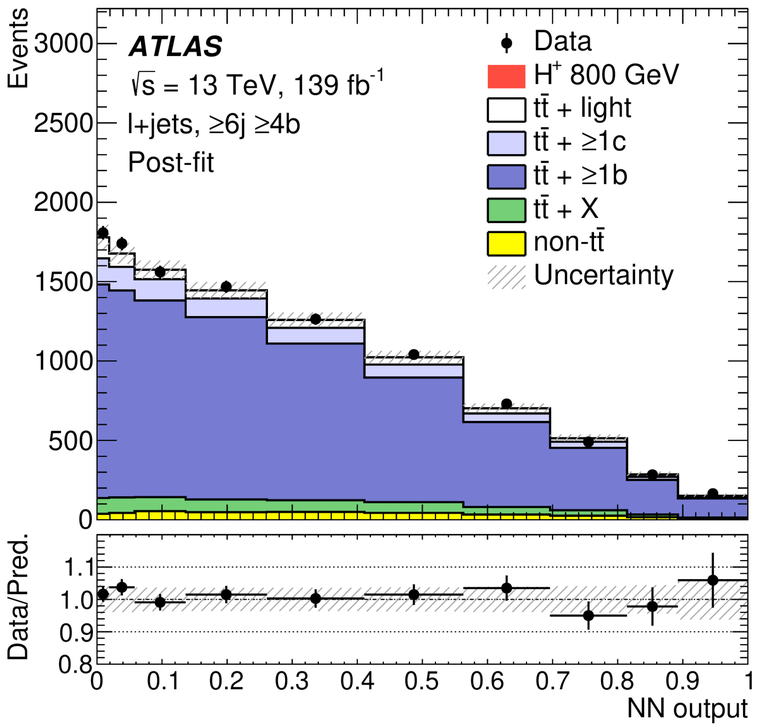
CMS JHEP 04 (2020) 171

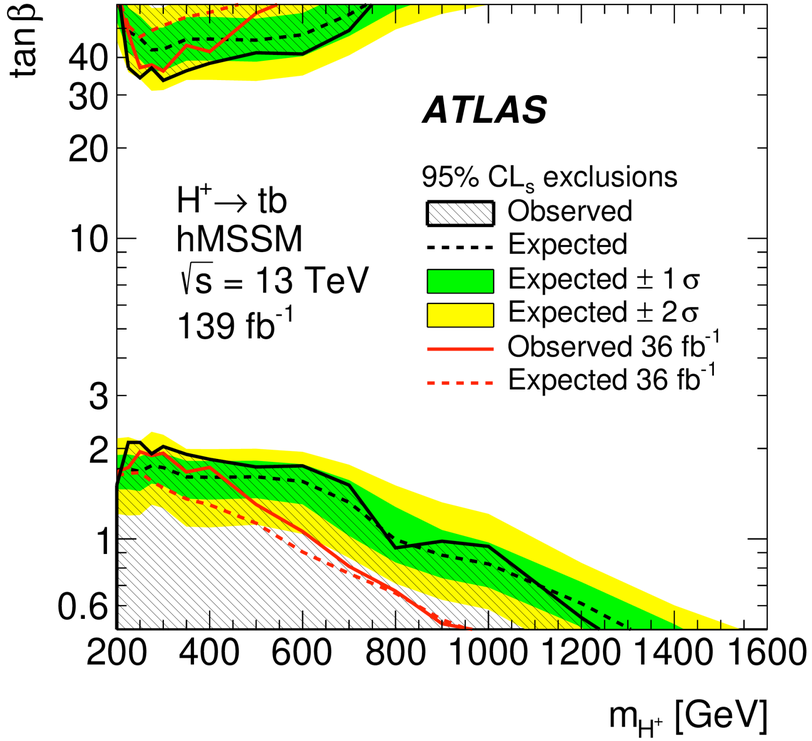
$H^{\pm} \to tb$

ttbb→μ/e + p_T^{miss} + **4b** + 2j final state (lepton + jets)
Categorise in n(jets) and n(b-tagged jets)









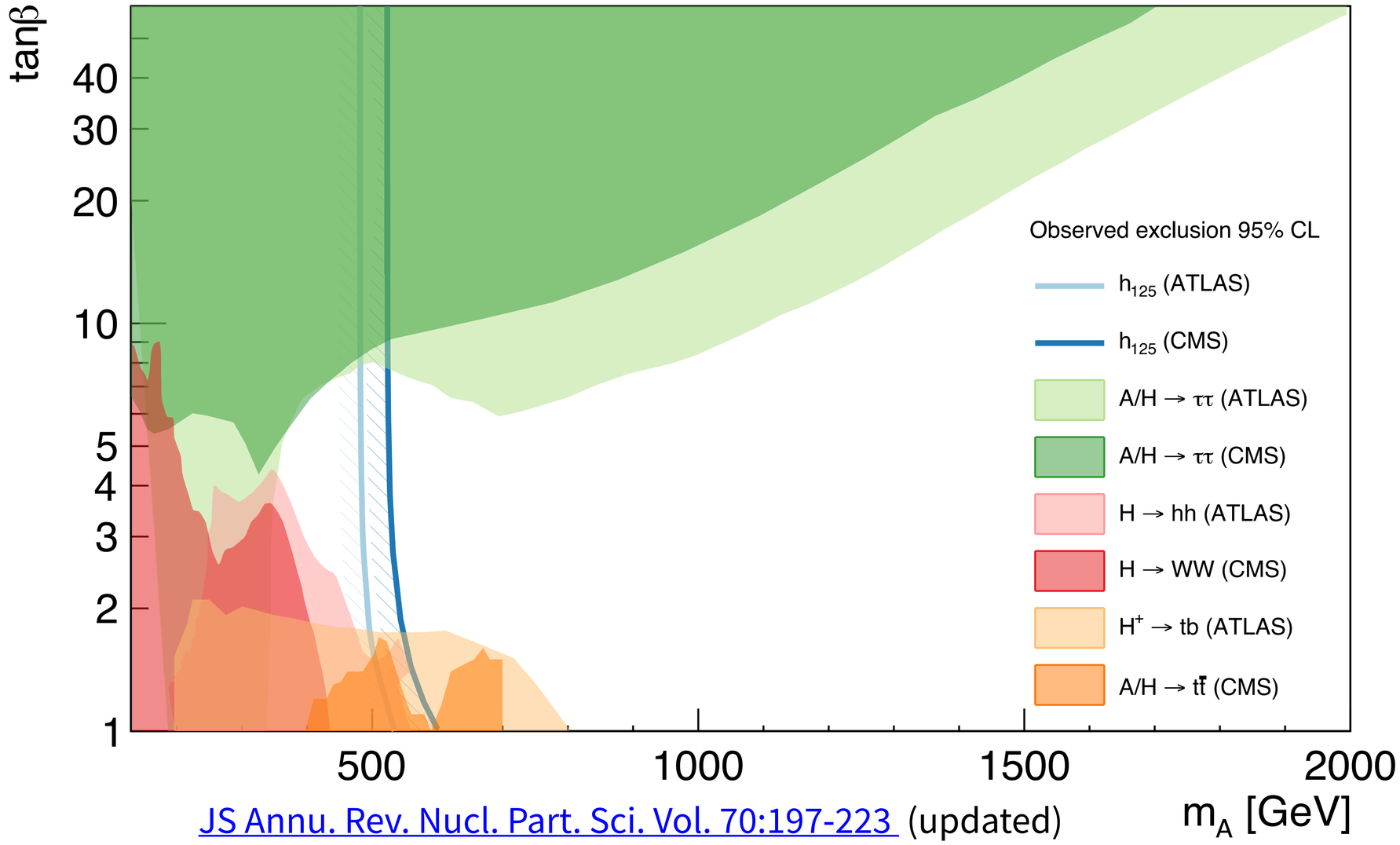
ATLAS JHEP 06 (2021) 145

Reach extends to higher $m_{H\pm} \sim m_A$

MSSM Summary

h_{125}: k_u, k_d, k_V coupling modifiers

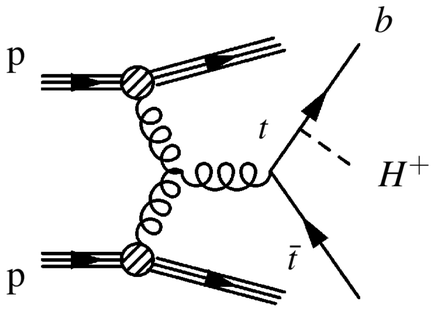
Complementarity between direct searches and h_{125} coupling measurements



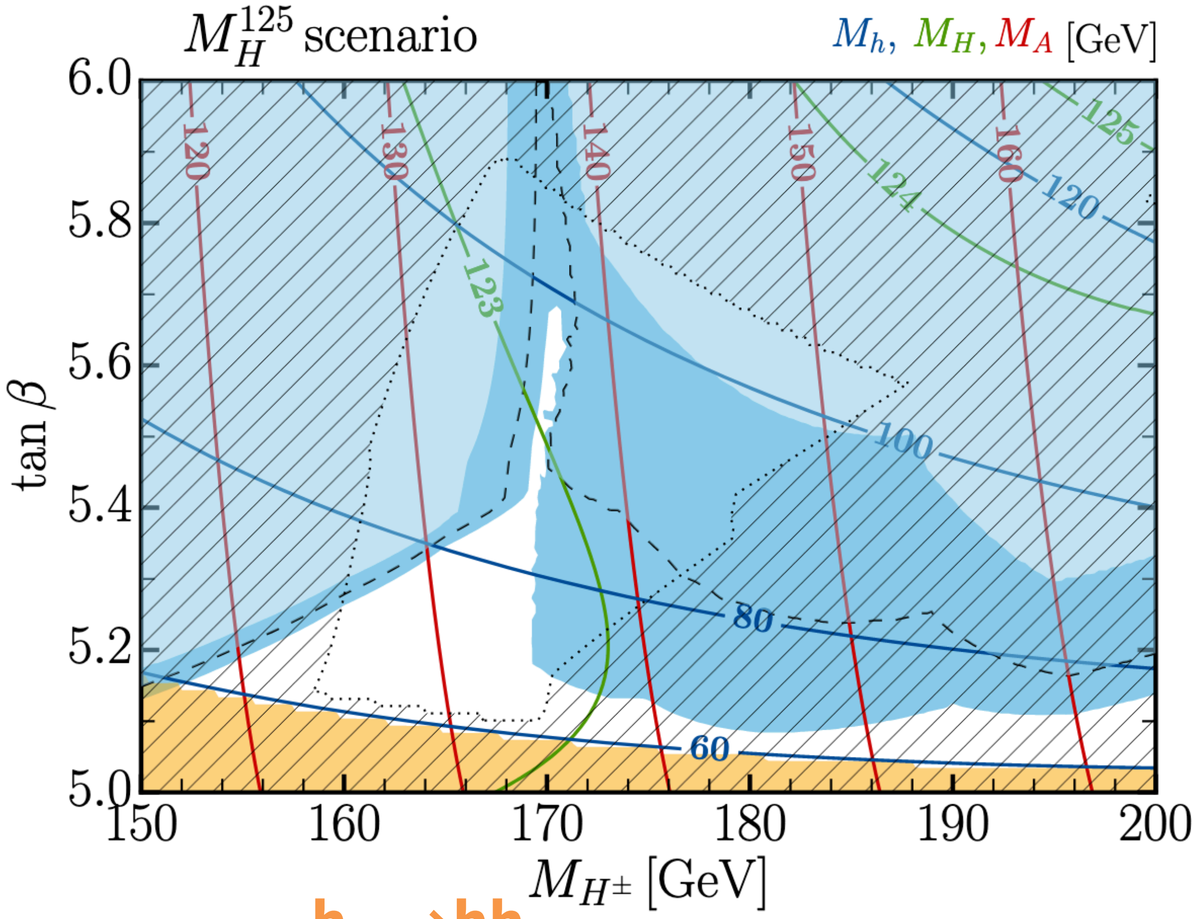
JS Annu. Rev. Nucl. Part. Sci. Vol. 70:197-223 (updated)
code on github

A brief note on MSSM with other mass hierarchy

Bagnaschi et al (Eur.Phys.J.C 79 (2019) 7, 617)



H±→τν



A/h→ττ

Hatched: h125 couplings

h125→hh

Heavier of the two neutral scalars takes role of h_{125}:

Mostly excluded, important role of $H^\pm\to\tau\nu$ searches in top quark decays

Large $H^\pm\to W^\pm h$ branching fraction in (small) allowed phase space, with $h\to\tau\tau$ or $h\to bb$

CMS Eur. Phys. J. C 79 (2019) 421

ATLAS Phys. Rev. D 101 (2020) 012002

General 2HDMs

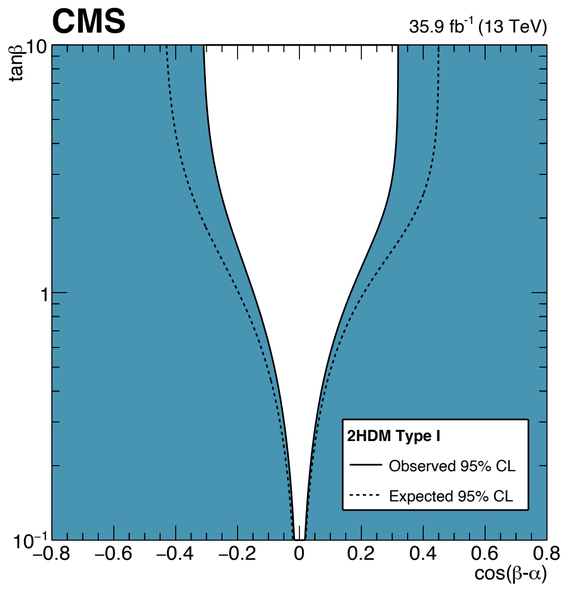
Compared to MSSM:

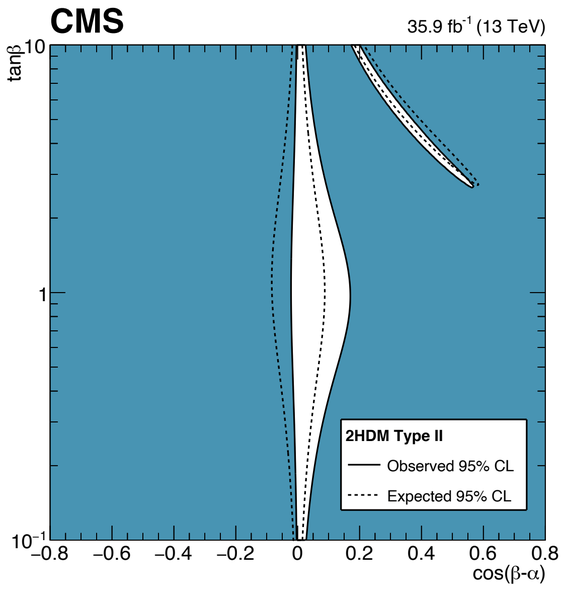
- Alignment not natural - but **h_{125} couplings imply small |cos(β-α)|** *(still slightly higher H→WW/ZZ/$h_{125}h_{125}$ and A→Zh_{125} rates possible)*
- A priori no mass degeneracy (*): **A→ZH/ H→ZA** can be possible and are not suppressed by alignment

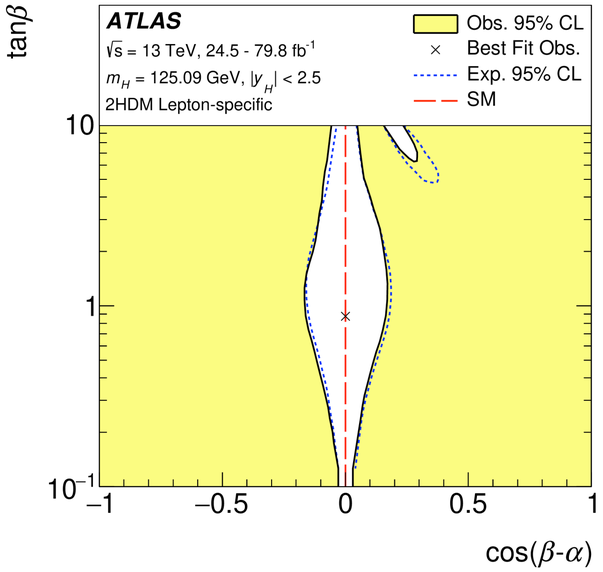
Type I: Decoupled at high tanβ

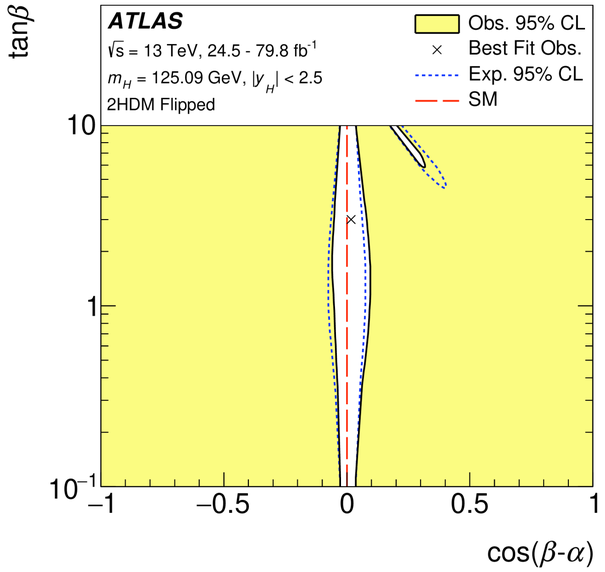
Flipped: high tanβ probed by **A/H→bb**

Lepton-specific: difficult to probe at high tan β







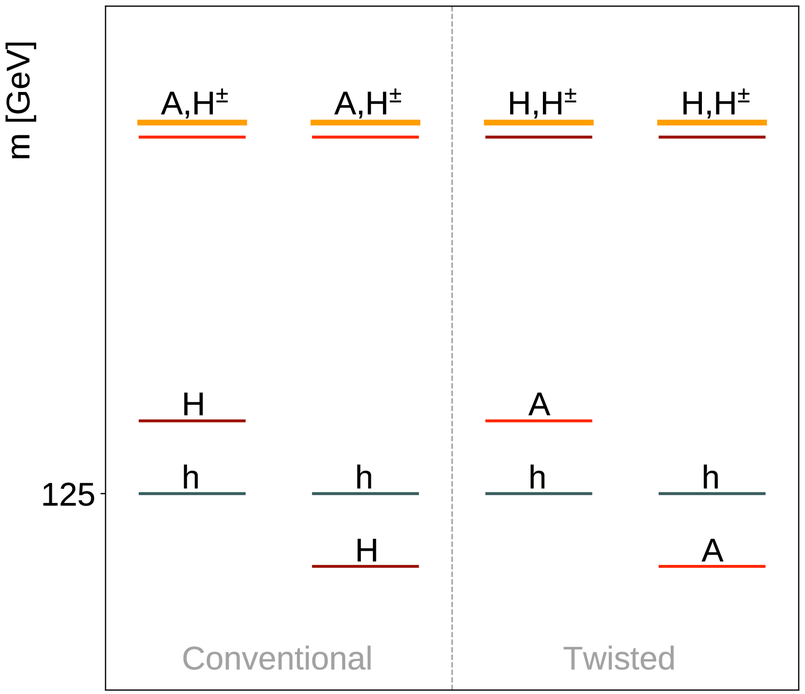


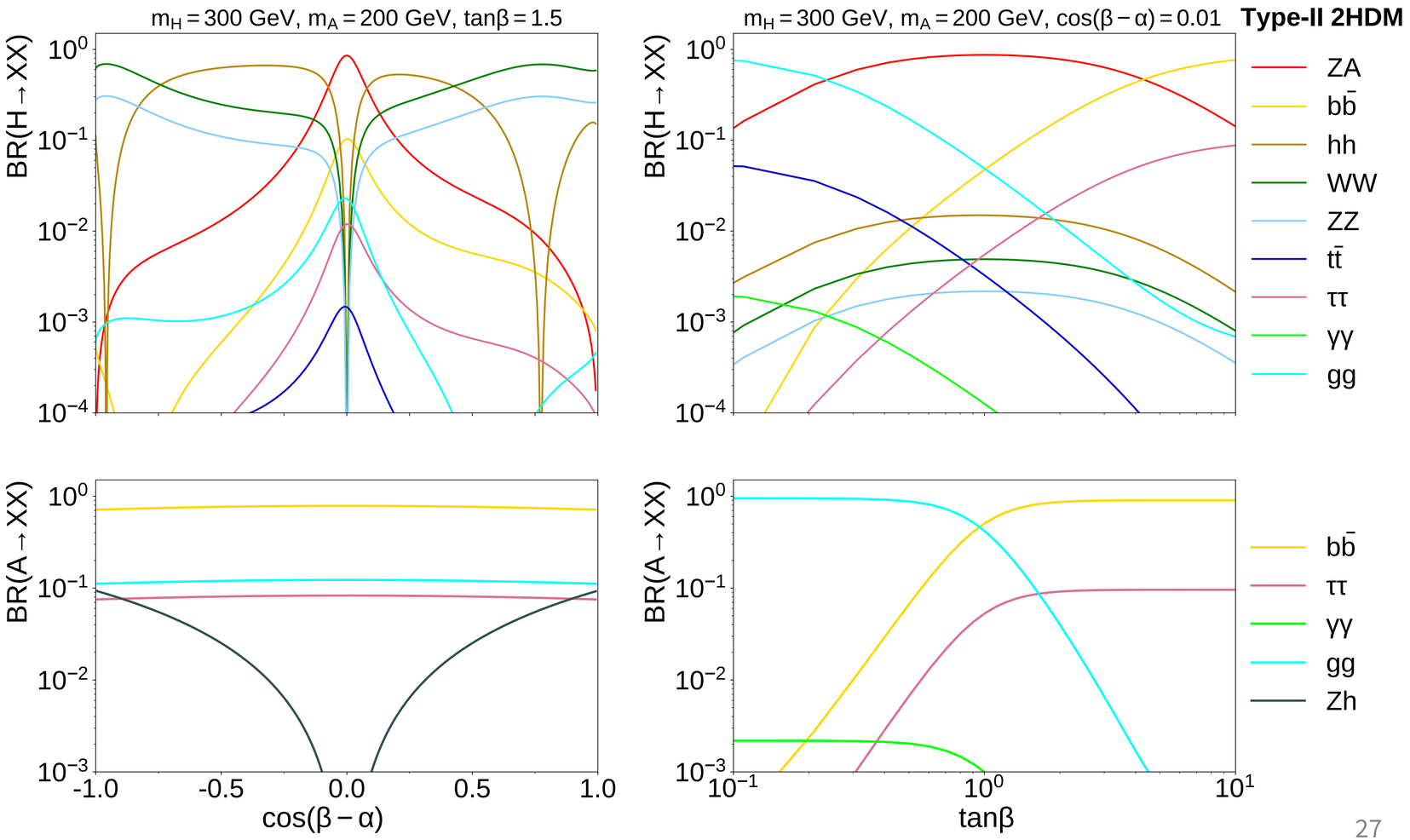
(*) but EWK precision constraints imply that 2 out of 3 additional Higgs bosons are close in mass

H→ZA/A→ZH

H→ZA unsuppressed in alignment limit

dominates over wide tanβ range (very high tanβ covered by **ττ**)

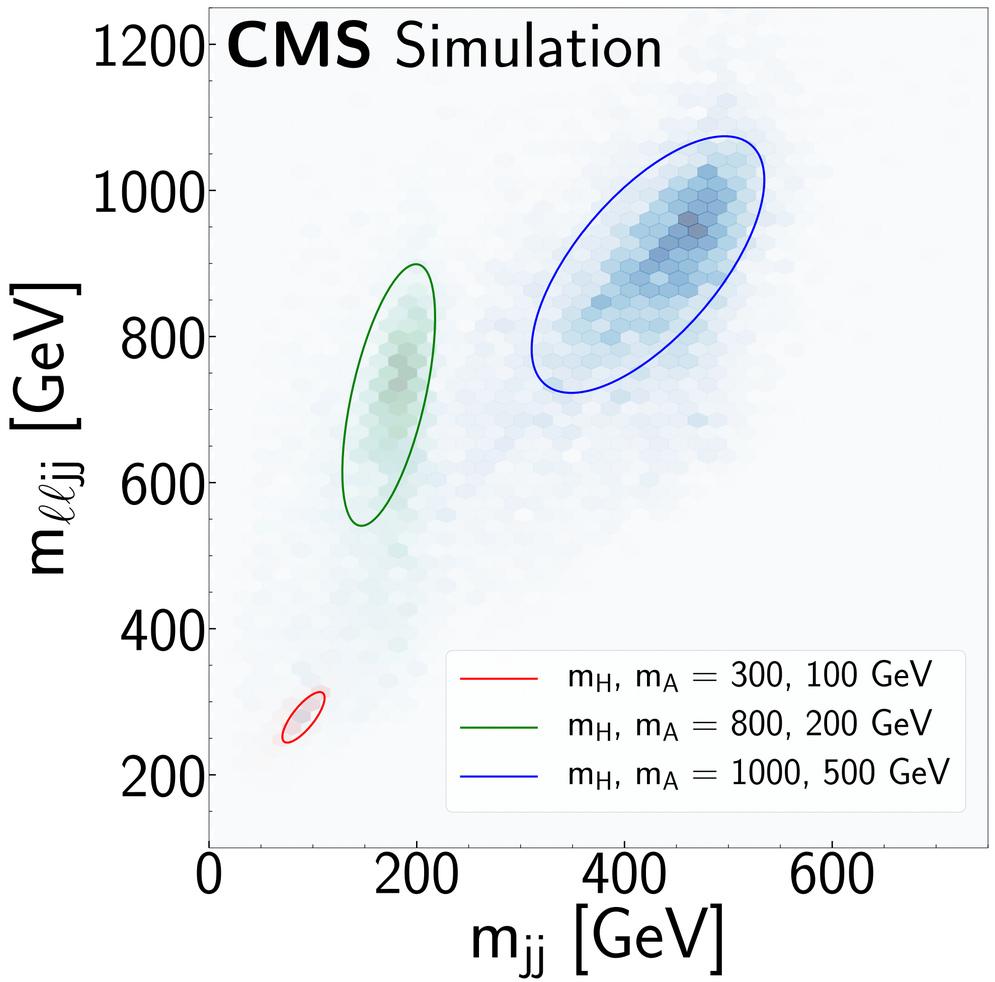




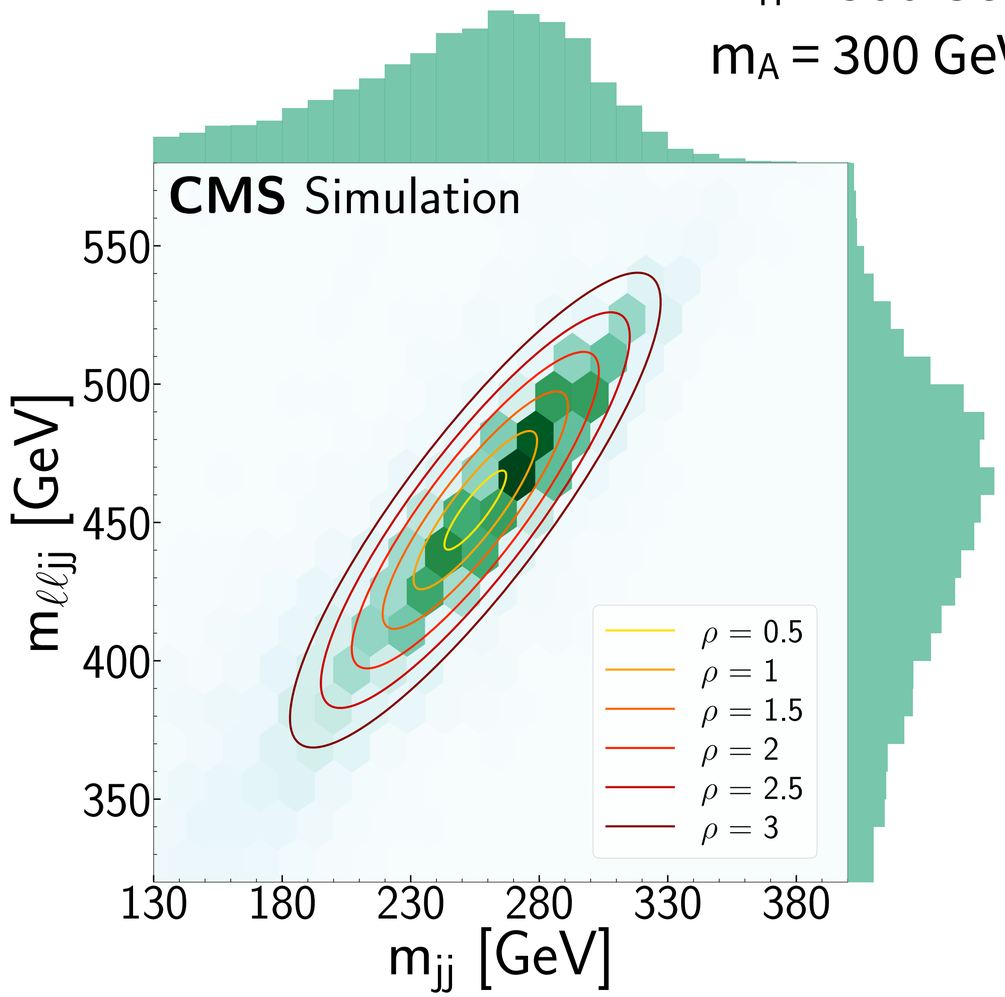
CMS JHEP 03 (2020) 055

H→ZA/A→ZH: Z→ll, A/H→$b\bar{b}$

m(ll) required to be compatible with nominal Z boson mass

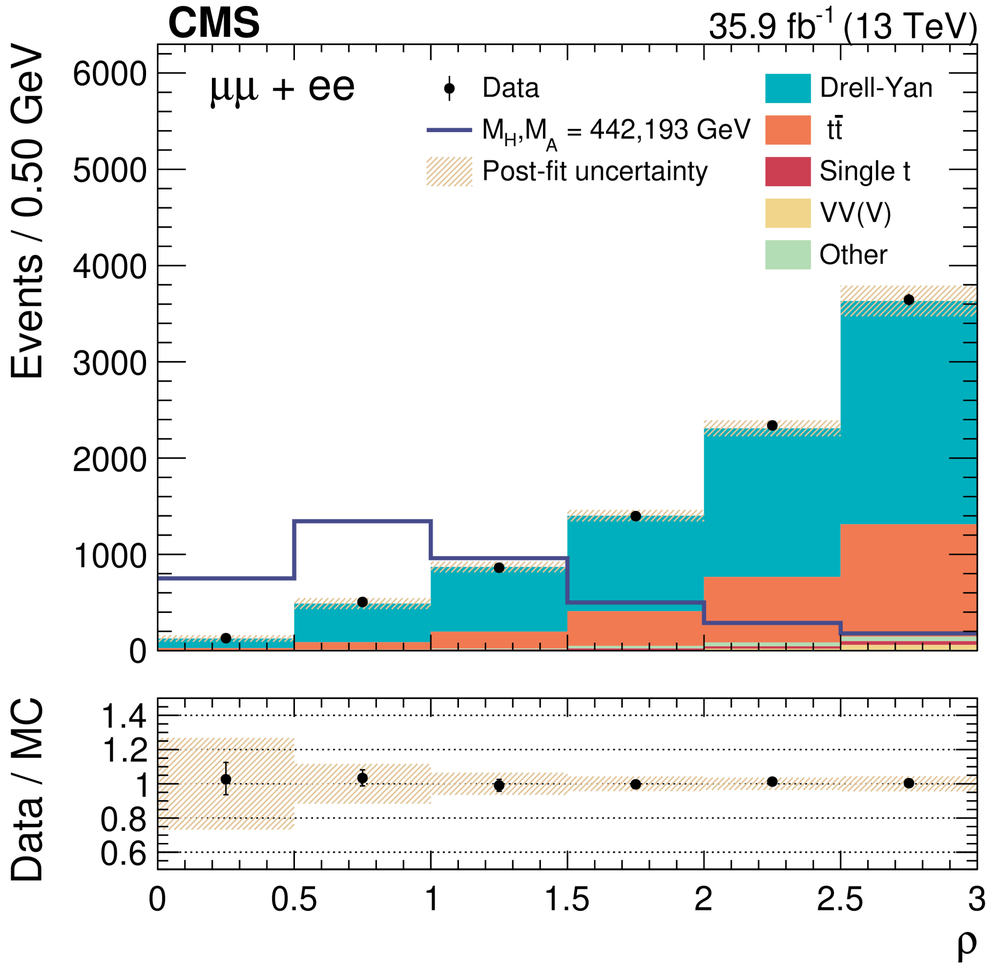


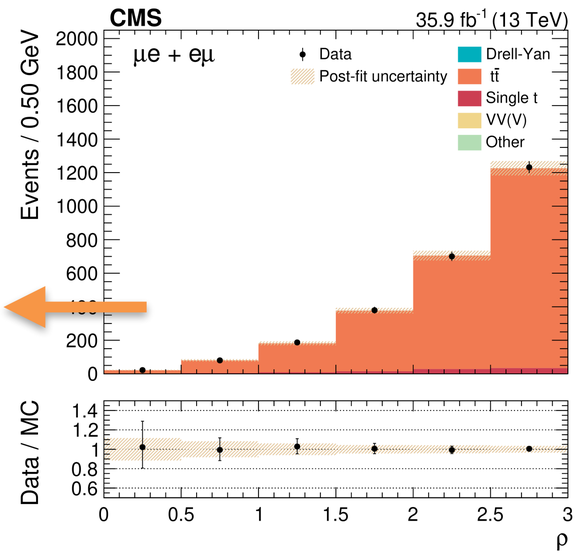
m_H = 500 GeV
m_A = 300 GeV



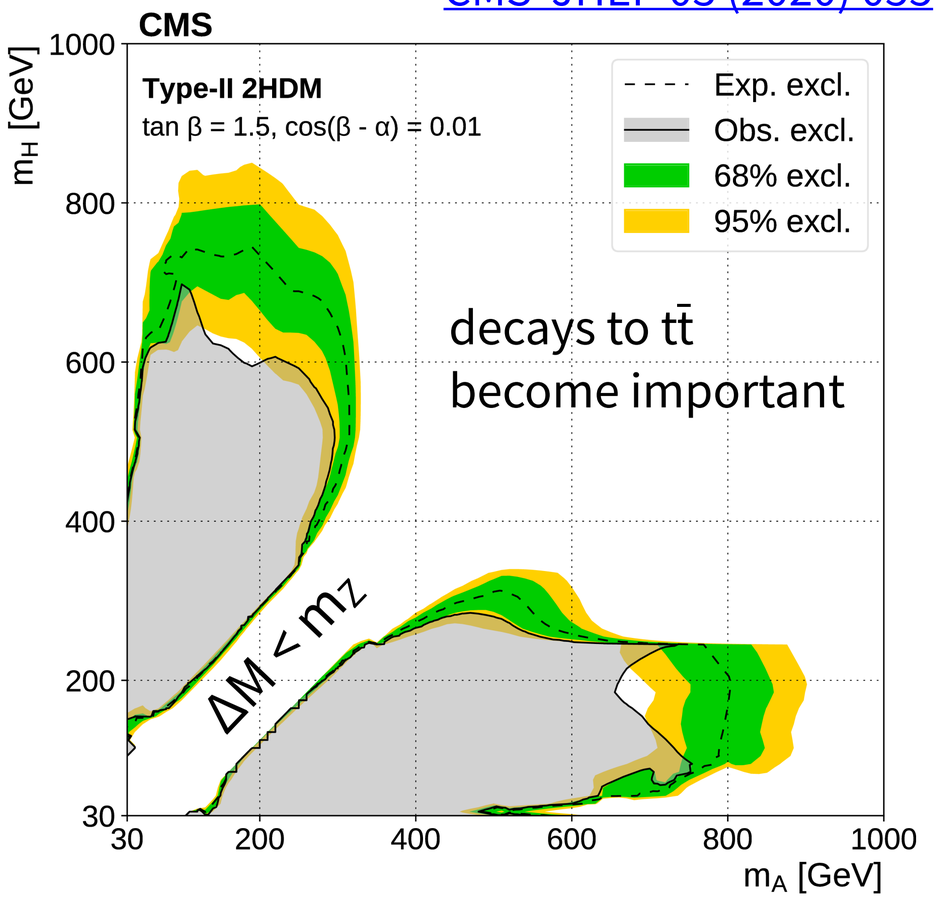
H→ZA/A→ZH: Z→ll, A/H→b$\bar{b}$

CMS JHEP 03 (2020) 055





tt̄ background estimated from eμ events



2HDM+S/NMSSM

Compared to 2HDM/MSSM:
Two additional singlet-like scalars, which can be light

Signatures:

- Lower-mass a/**h→SM** searches
- **Higgs-to-Higgs decays - have received a lot of attention lately since they lead to many interesting signatures**
  - ➡**h_{125}→aa/hh**
  - ➡**H→h_{125}h, A→h_{125}a**
  - ➡H→hh, A→Zh, h_{125}→Za, …

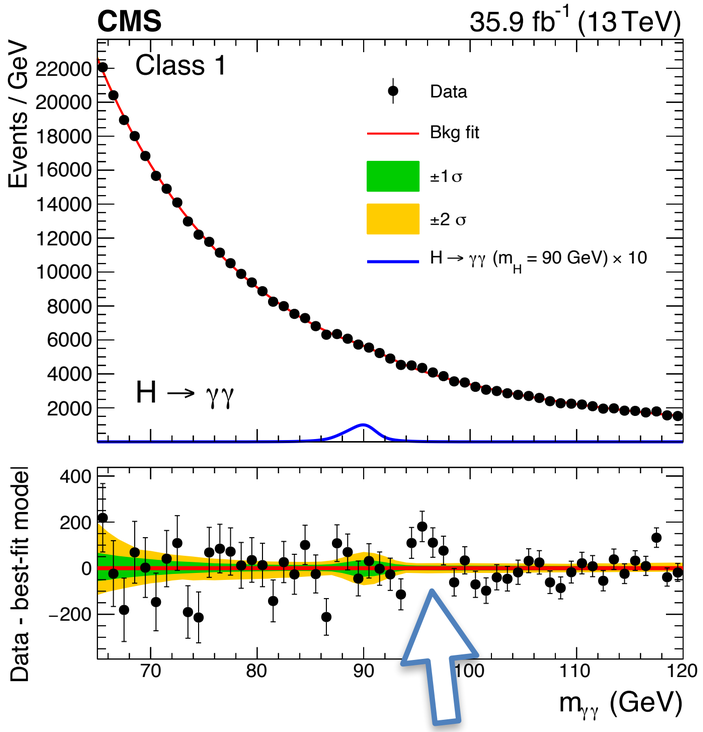
Aside: Higgs-to-Higgs signatures can appear in models as simple as two additional singlets, and additional decays like h_{125}→Hh might be interesting
There can also be cascade decays with 3 or 4 Higgs bosons in the final state Robens, Stefaniak, Wittbrodt

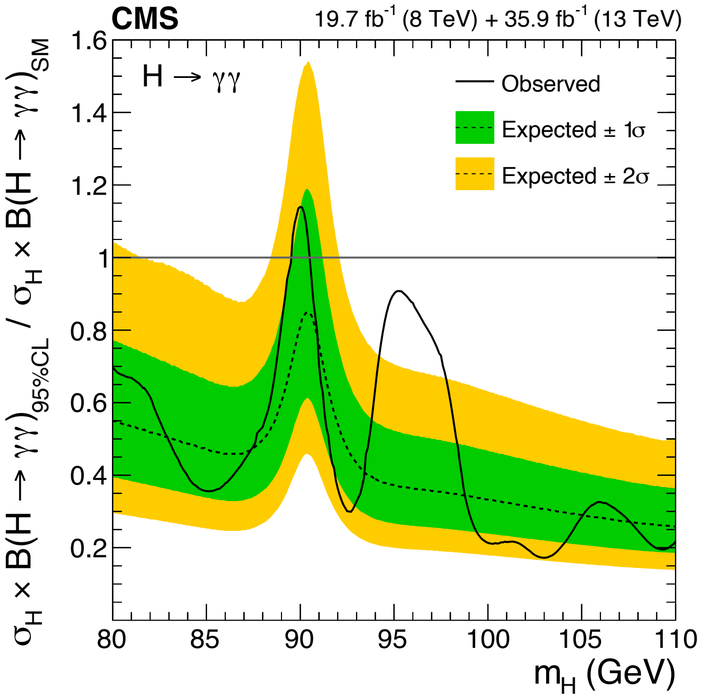
CMS Phys. Lett. B 793 (2019) 320

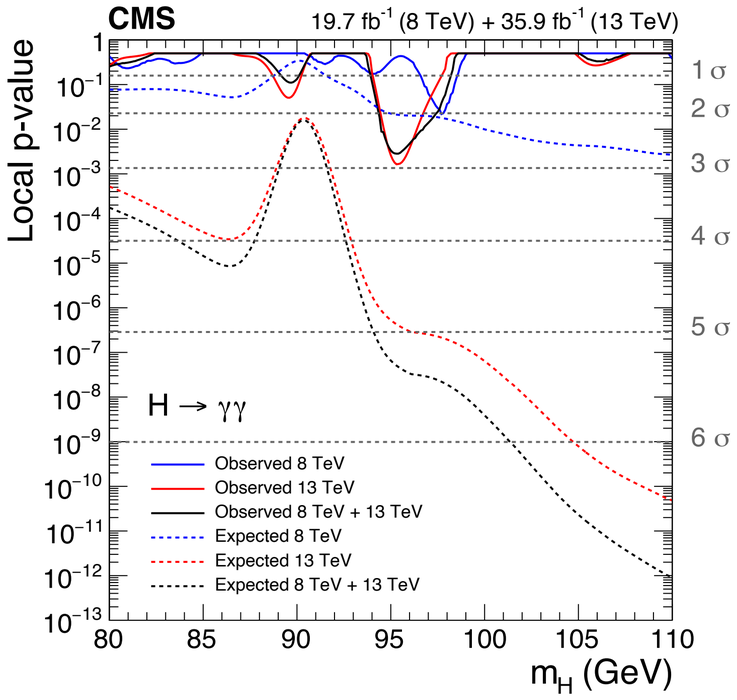
A search for H→γγ with 70 < m_H < 110 GeV

Fit m(γγ) spectrum in three categories defined by BDT that separates photon pairs from Higgs decays from those from the continuum

Excess has spurred some interest in theory community, though accounting for look-elsewhere-effect leads to significance of only 1.5σ





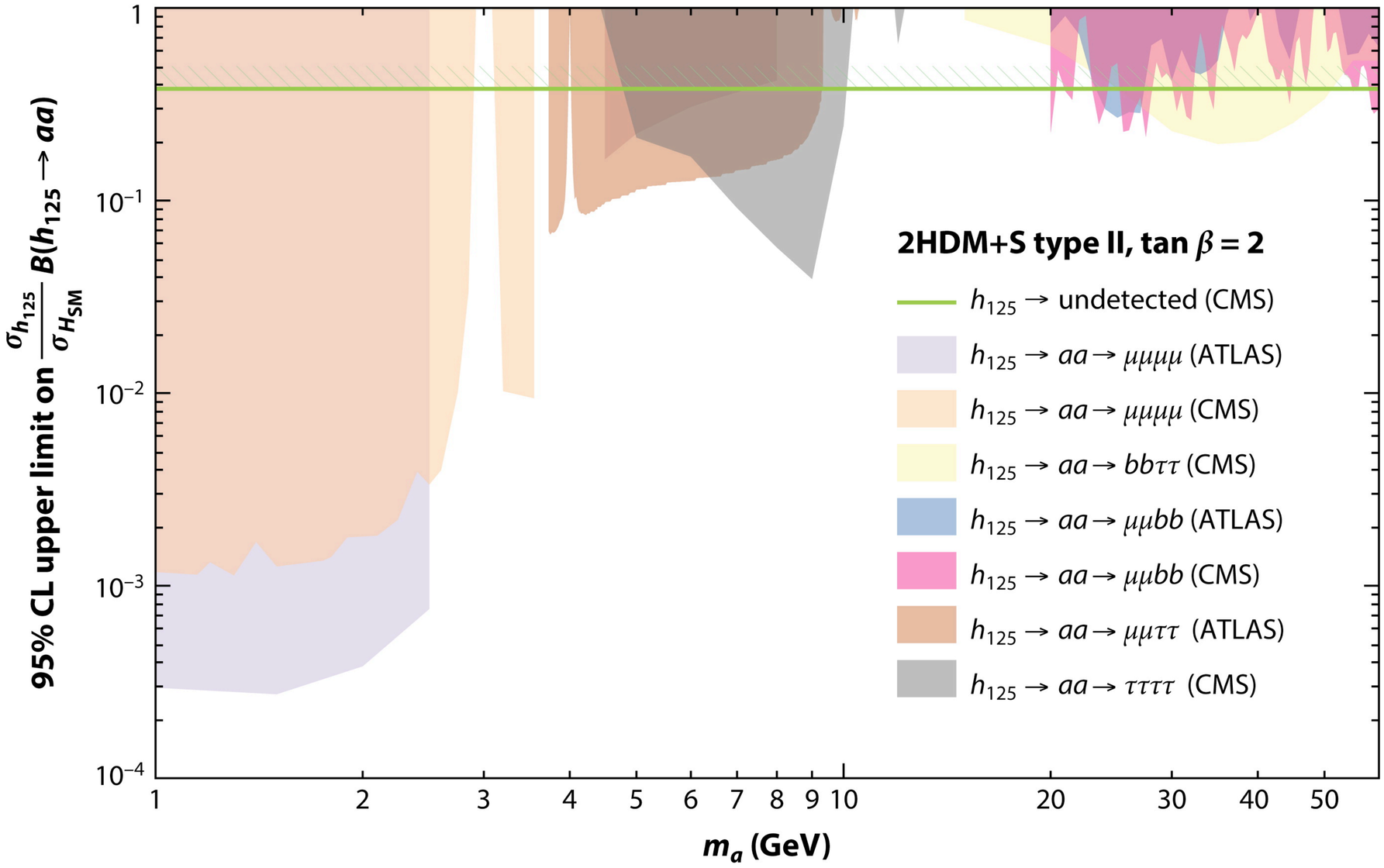


h_{125}→aa summary

Excellent reach for h_{125}→4μ analyses

Higher masses will become more interesting with more data

Experimentally very interesting/diverse



Steggemann J. 2020.
Annu. Rev. Nucl. Part. Sci. 70:197–223

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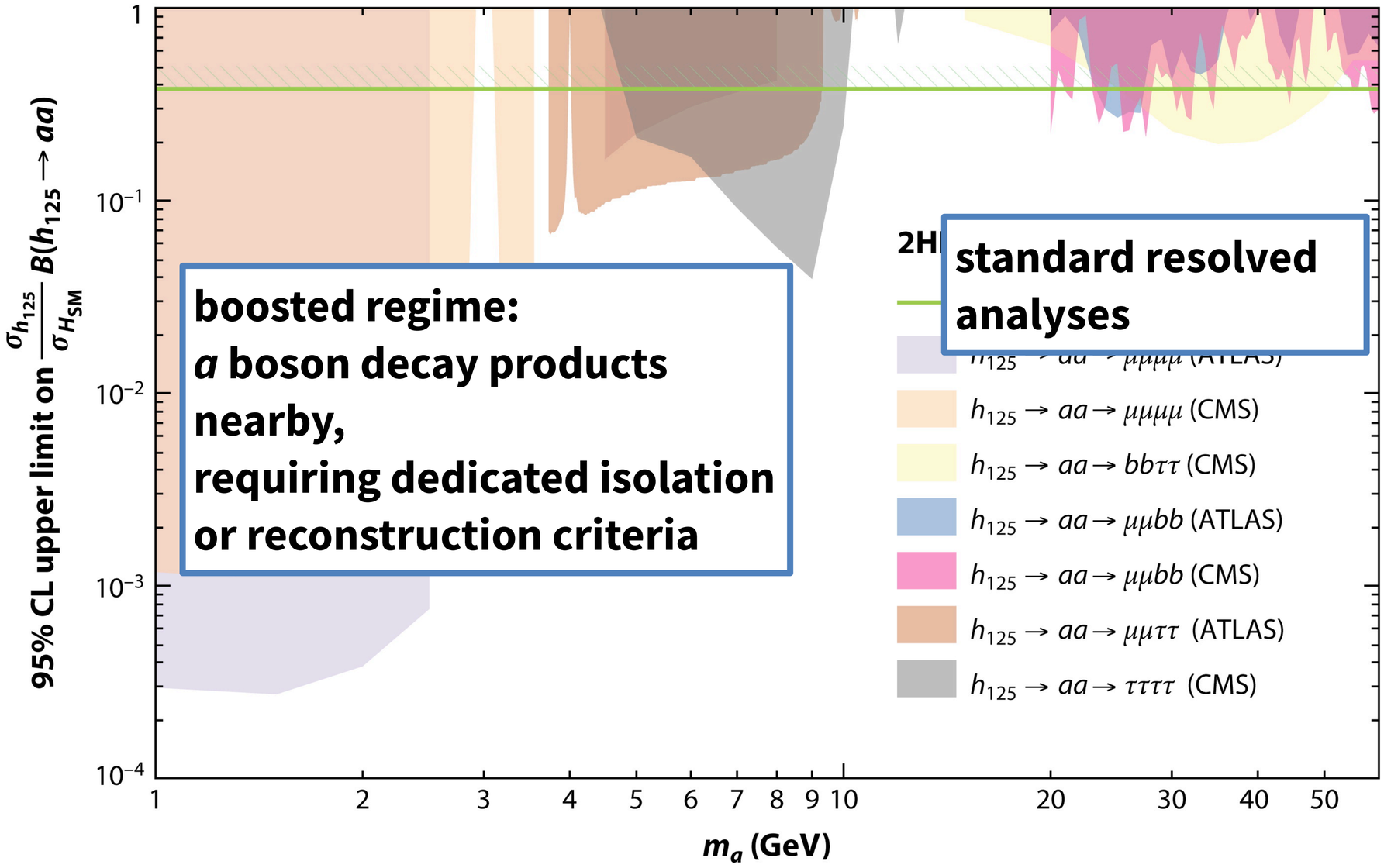
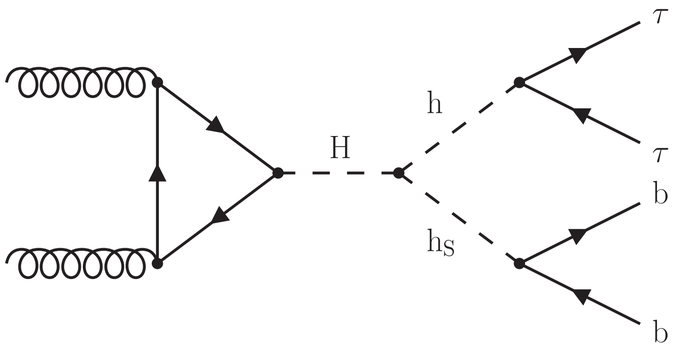
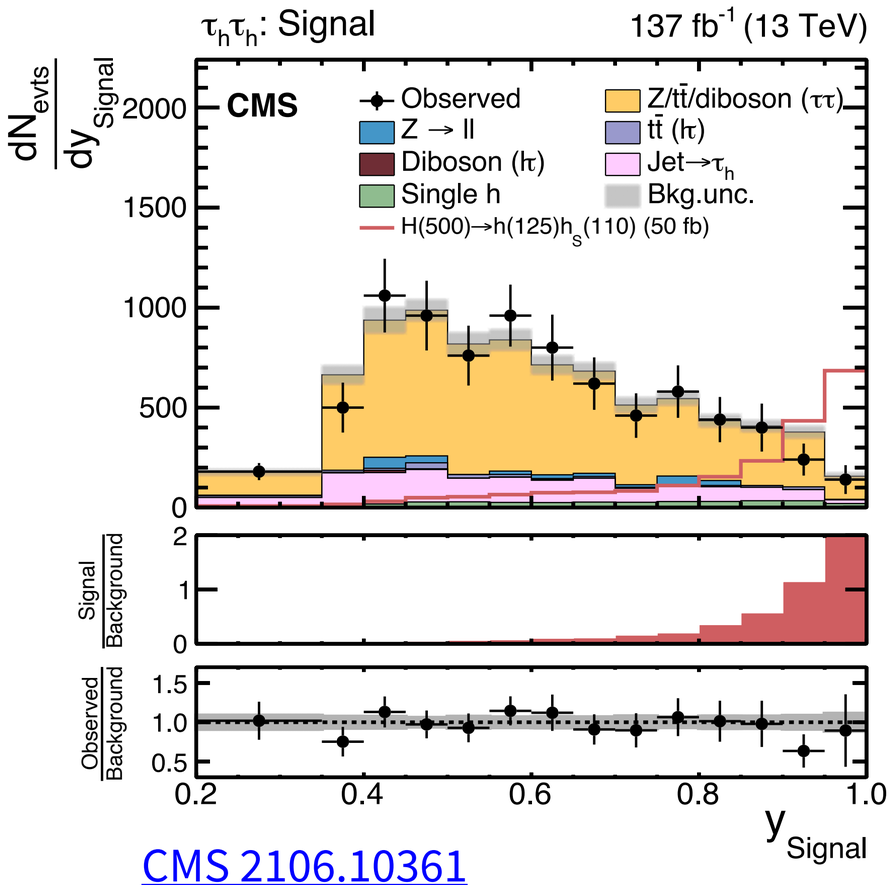


Steggemann J. 2020.
Annu. Rev. Nucl. Part. Sci. 70:197–223

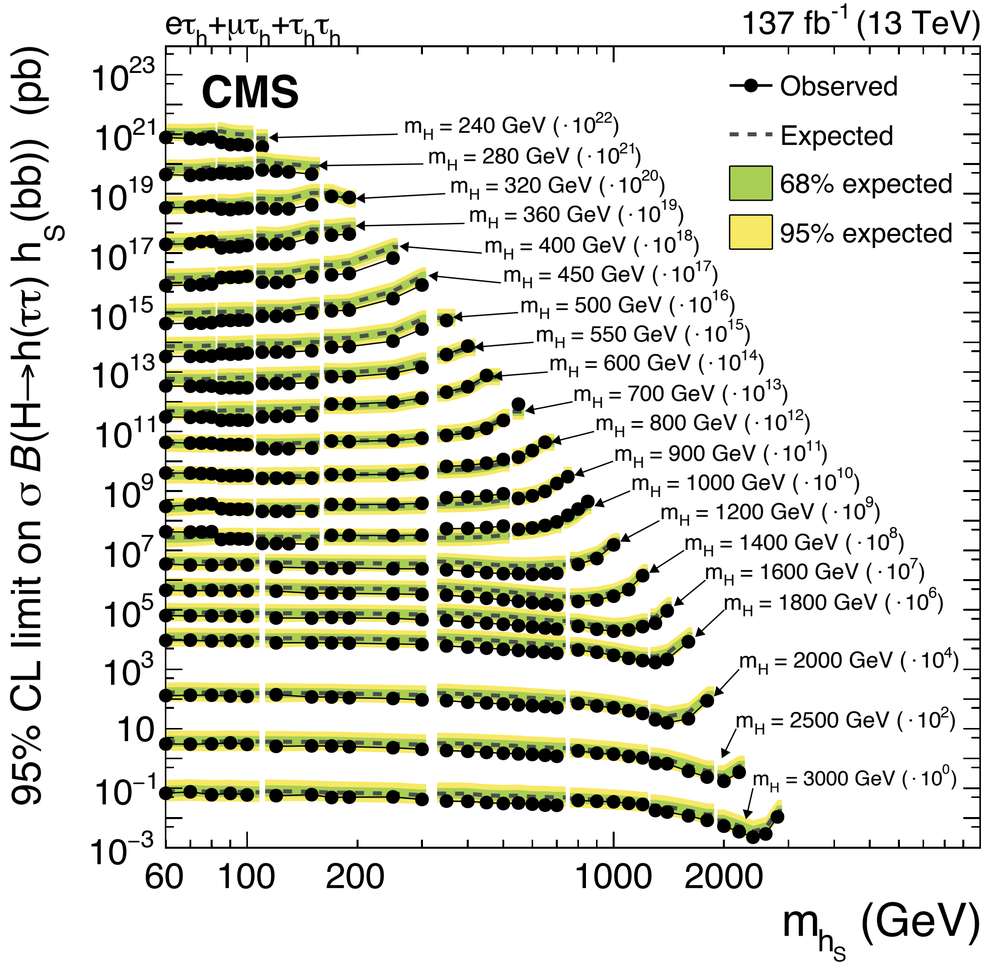
First H→h_{125}h result (ττbb)



Separate DNNs trained for several sets of nearby mass hypotheses



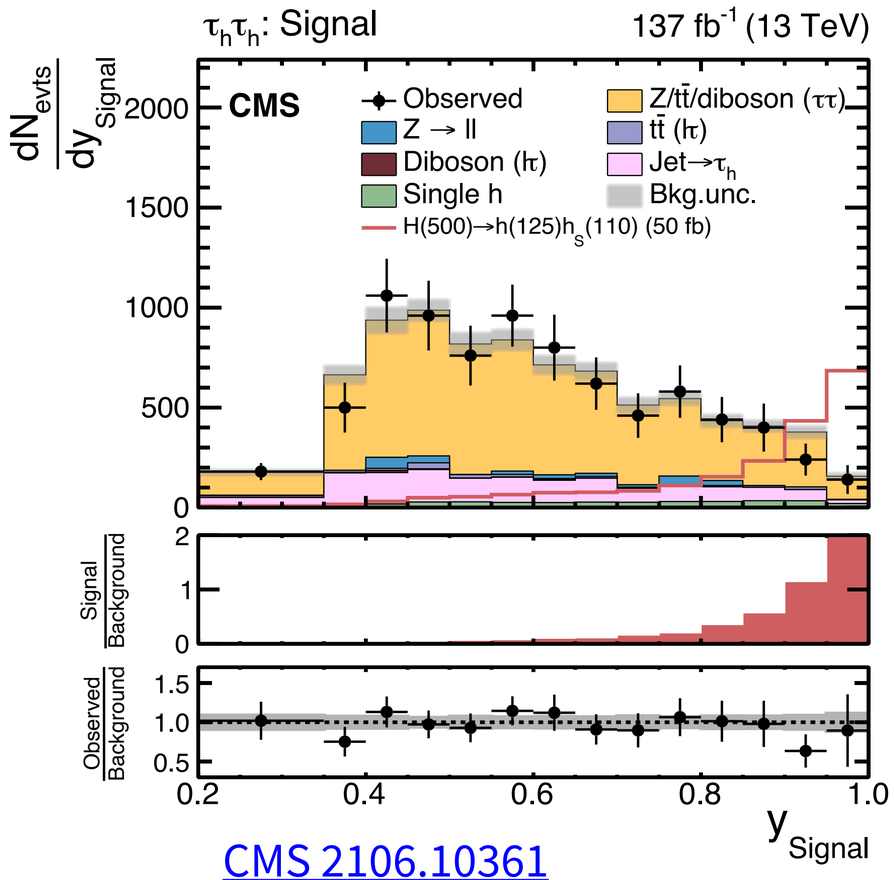
CMS 2106.10361



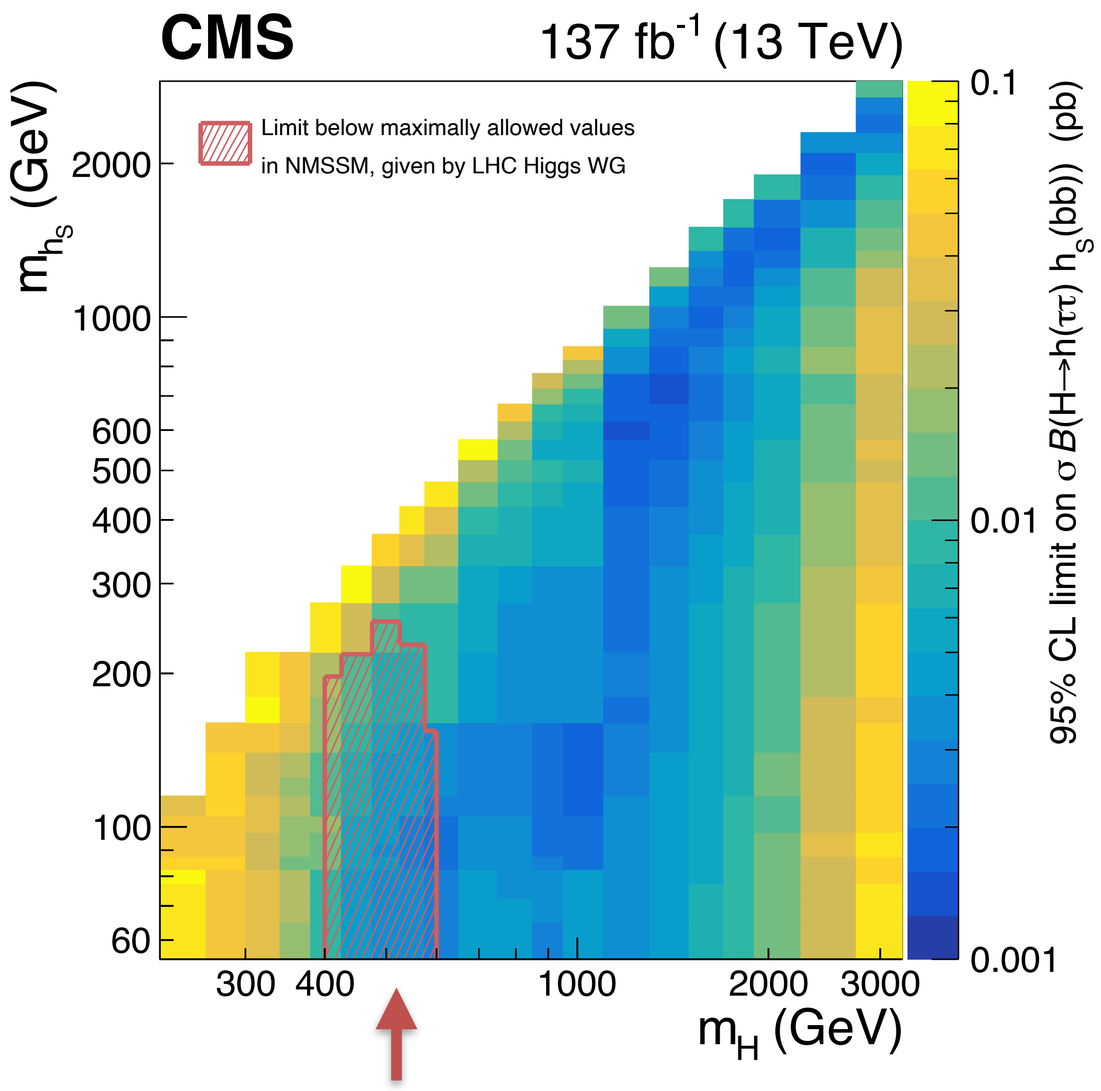
Many pairs of mass hypotheses to consider

First H→h_{125}h result (ττbb)

Separate DNNs trained for several sets of nearby mass hypotheses

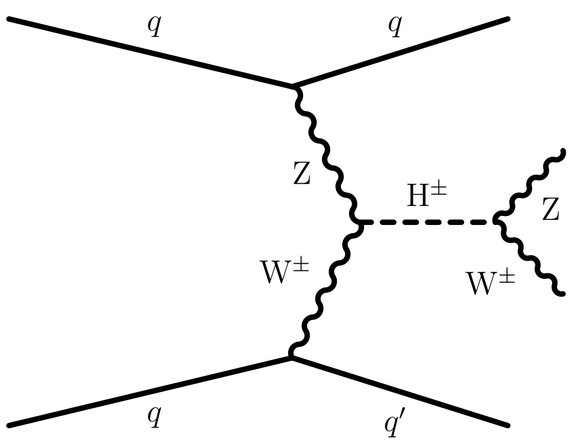


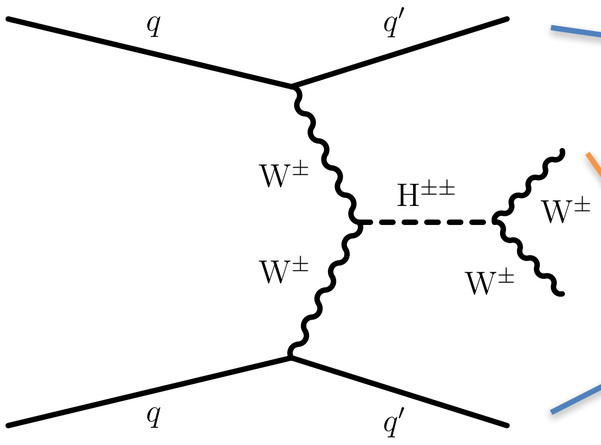
CMS 2106.10361

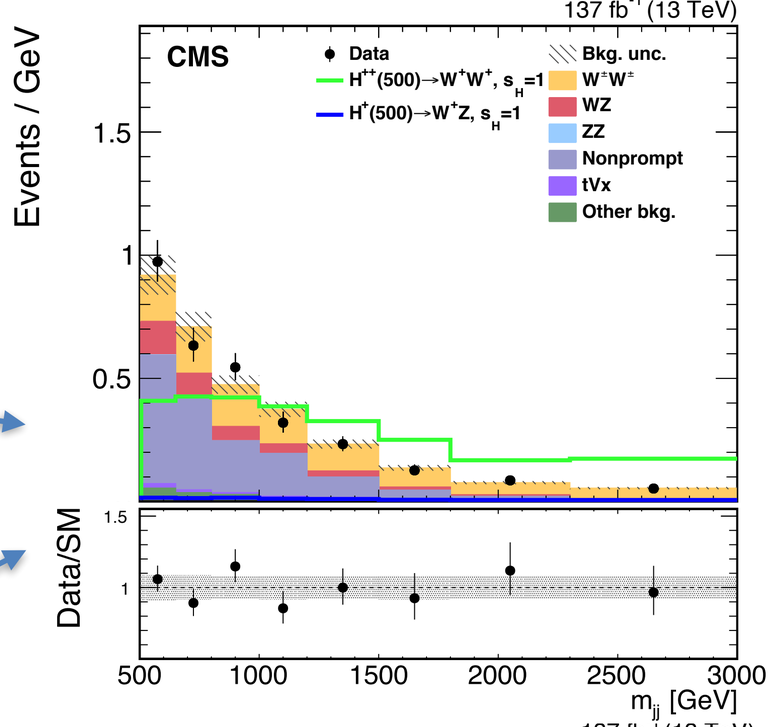


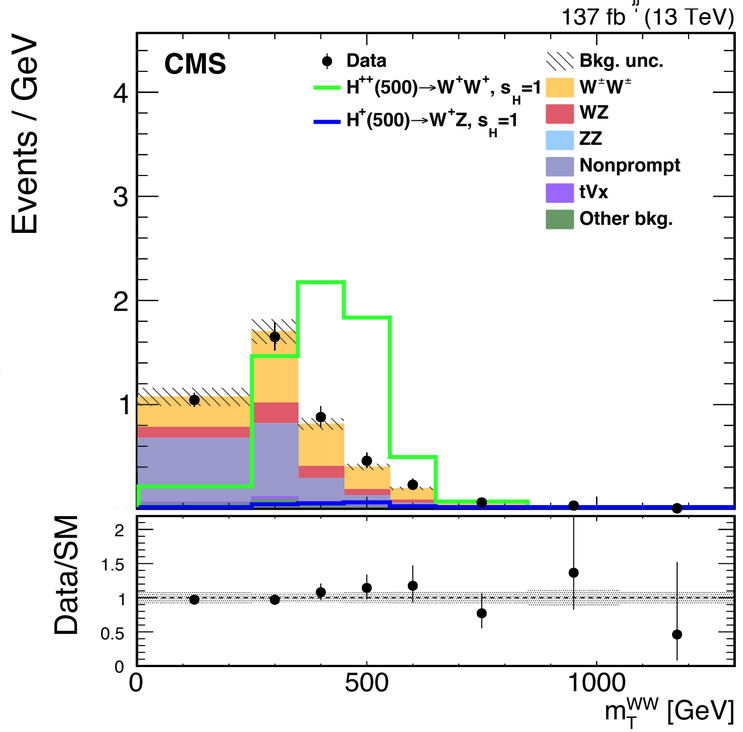
Sensitive to NMSSM parameter space

Higgs triplet: striking signatures









Vector boson fusion production: **2 forward jets +**
$H^{\pm\pm}\rightarrow W^{\pm}W^{\pm}$: **either same-sign leptons**
$H^{\pm}\rightarrow WZ$: **or a three-lepton final state**

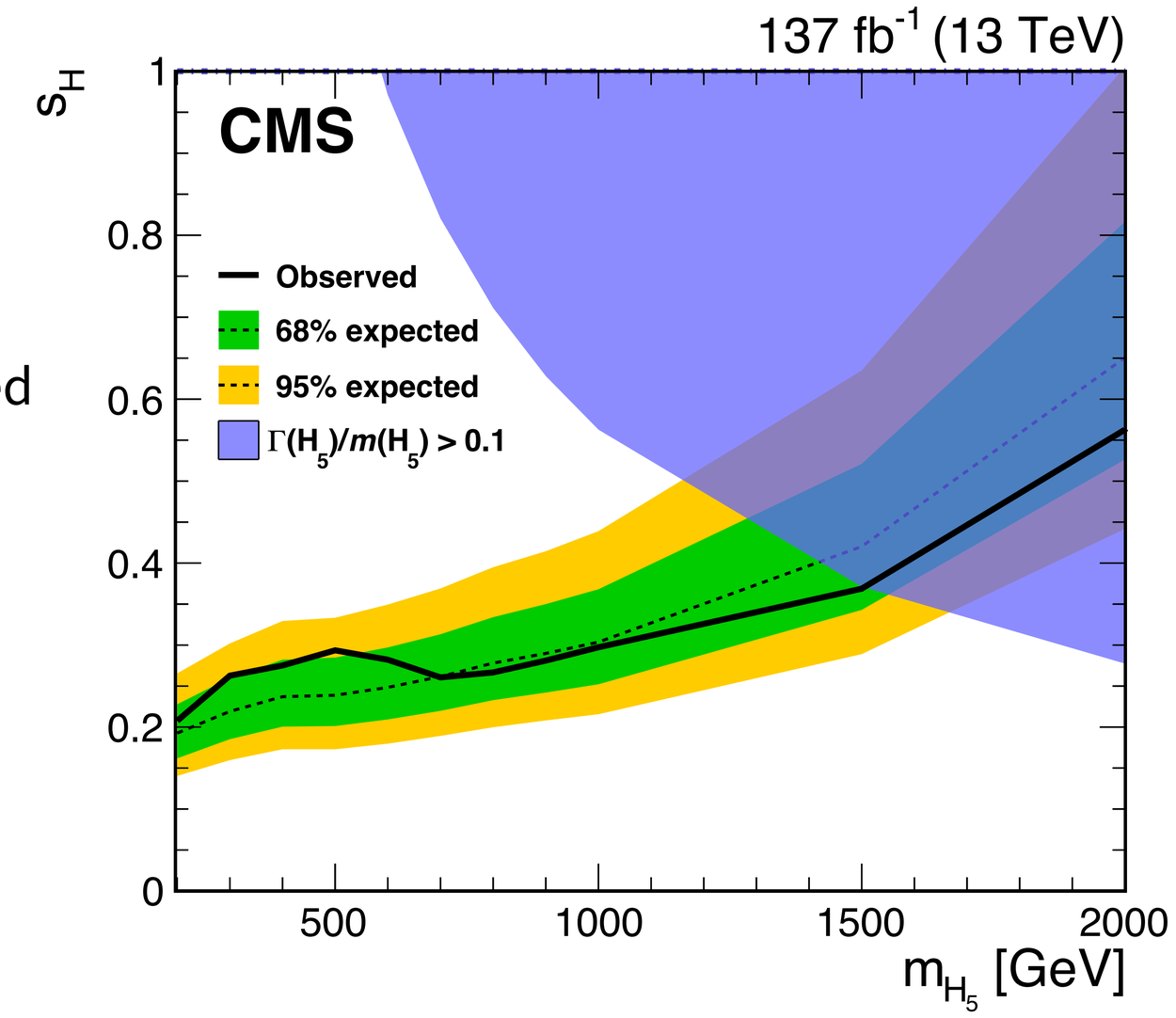
Signal extracted from 2D fit to (m_{jj}, m_T) + control regions

CMS HIG-20-017 (acc. by EPJC)

Higgs triplet: Constraint on Georgi-Machacek model

s_H: sets fraction of gauge boson mass generated by the triplet Higgs fields
H_5: Mass of (degenerate) additional fermiophobic heavy Higgs bosons (H, $H^{\pm}$, $H^{\pm\pm}$)

Comparably high mass reach



CMS HIG-20-017 (acc. by EPJC)

EXOTIC DECAYS

A vast field!
Will briefly discuss a few interesting signatures if time allows *(also already covered by Marumi)*

(Lepton-) flavour violation (LFV): Very active field in light of LHCb anomalies - connection to Higgs sector would be very exciting!

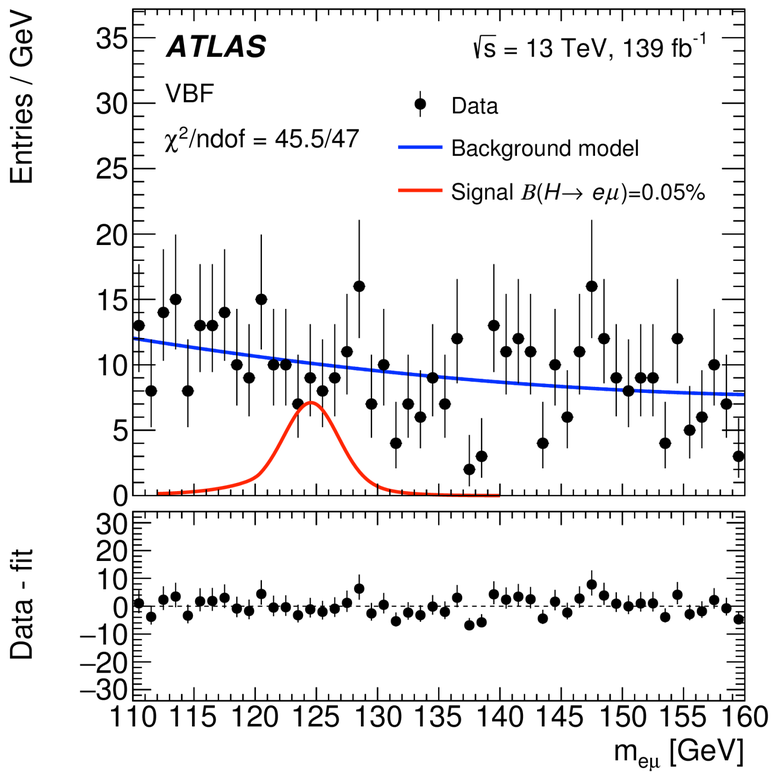
Invisible decays: Higgs as portal to dark matter - one of the big questions of (particle?) physics

There are also many well-motivated searches for h_{125}→long-lived, semi-invisible, mesonic final states, and others (axion-like particles, dark photons, …)

LFV decays

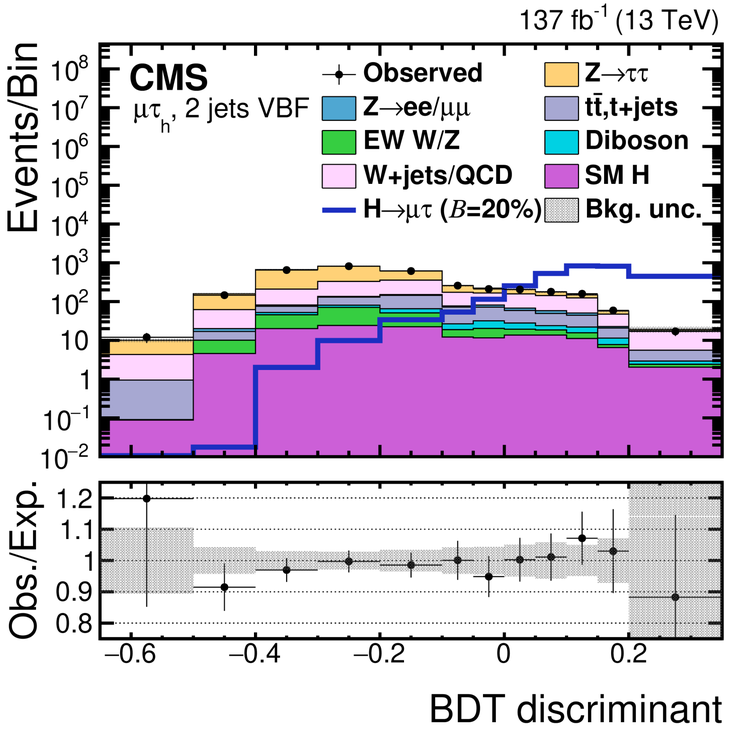
$h_{125}\to e\mu$

Fit to m(eμ) in 8 categories



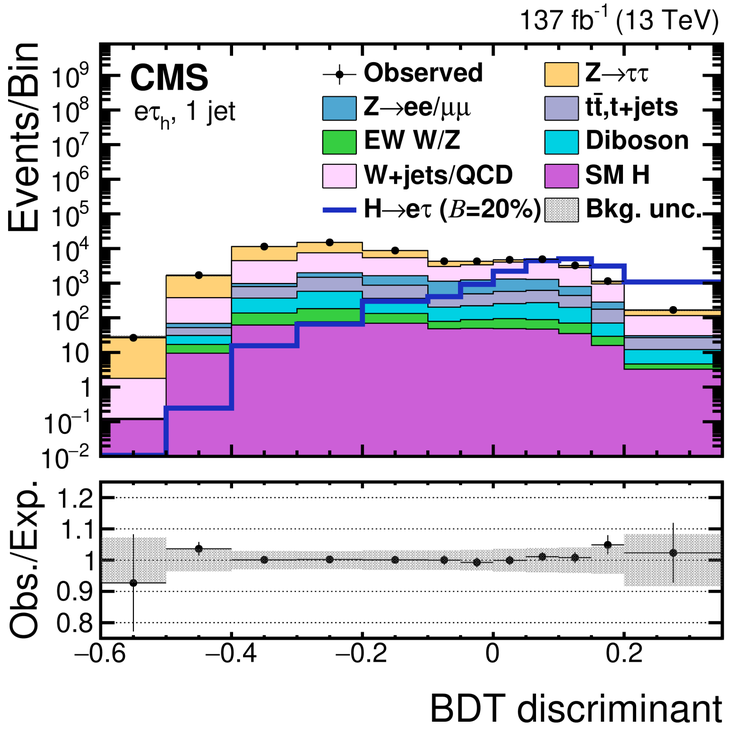
$h_{125}\to\mu\tau$

Fit to BDT discr. in 4 categories x 2 final states ($\mu\tau_h$, μe)



$h_{125}\to e\tau$

Fit to BDT discr. in 4 categories x 2 final states ($e\tau_h$, eμ)

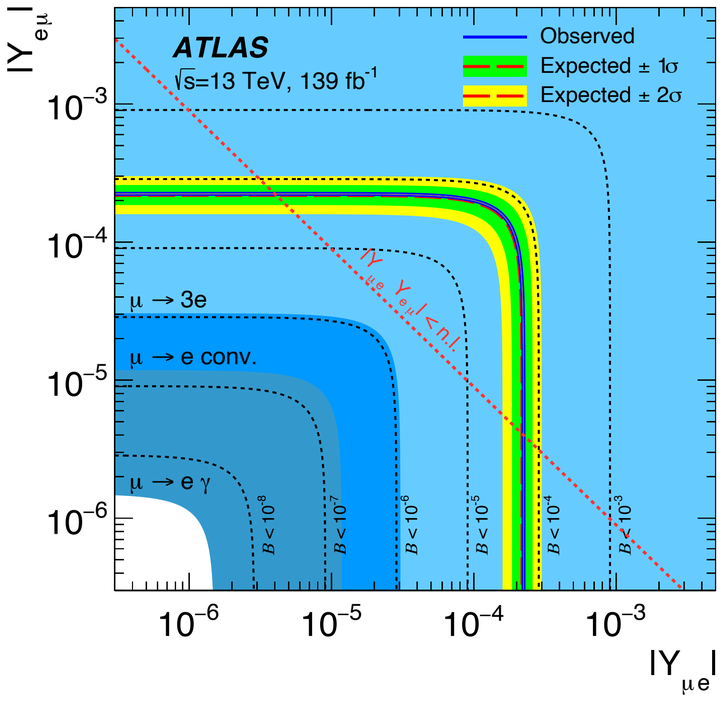


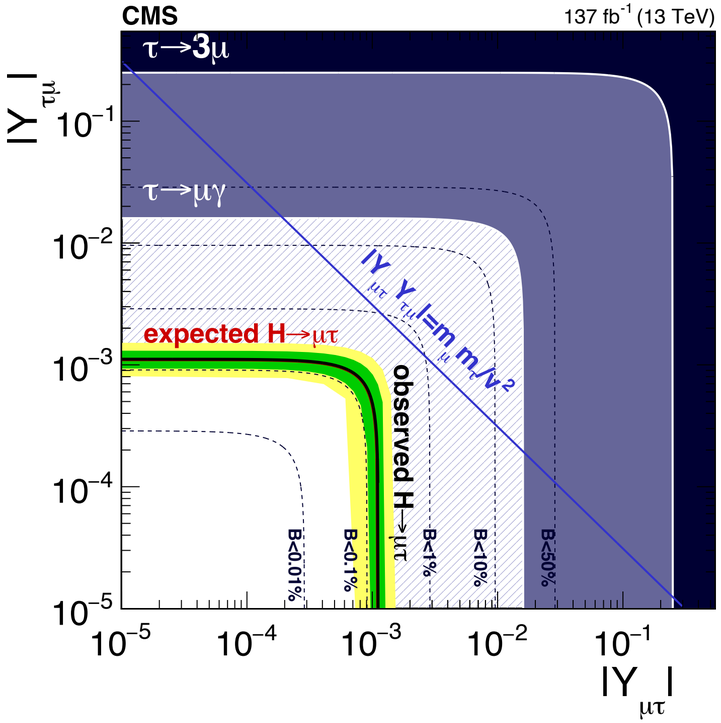
ATLAS Phys. Lett. B 801 (2020) 135148

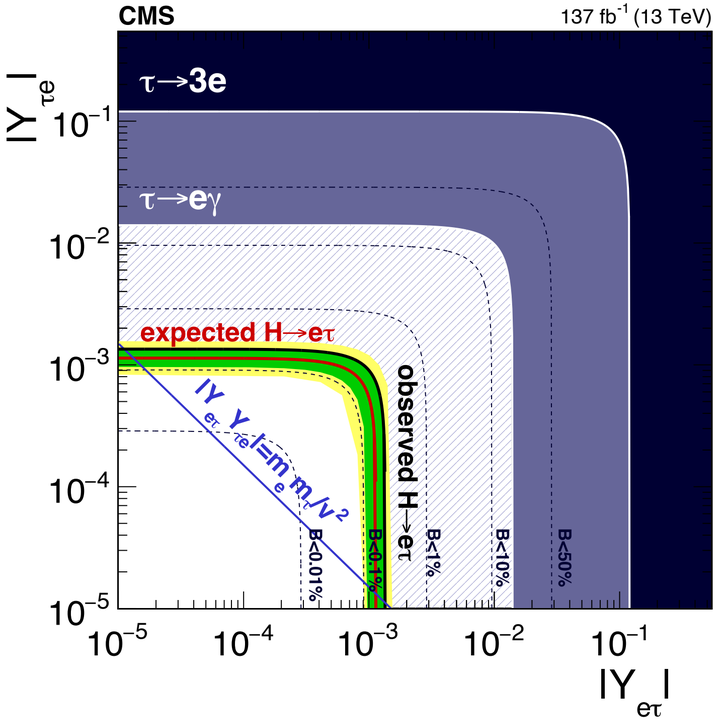
CMS 2105.03007

LFV decays - constraints

Limits set on off-diagonal Yukawa coupling terms







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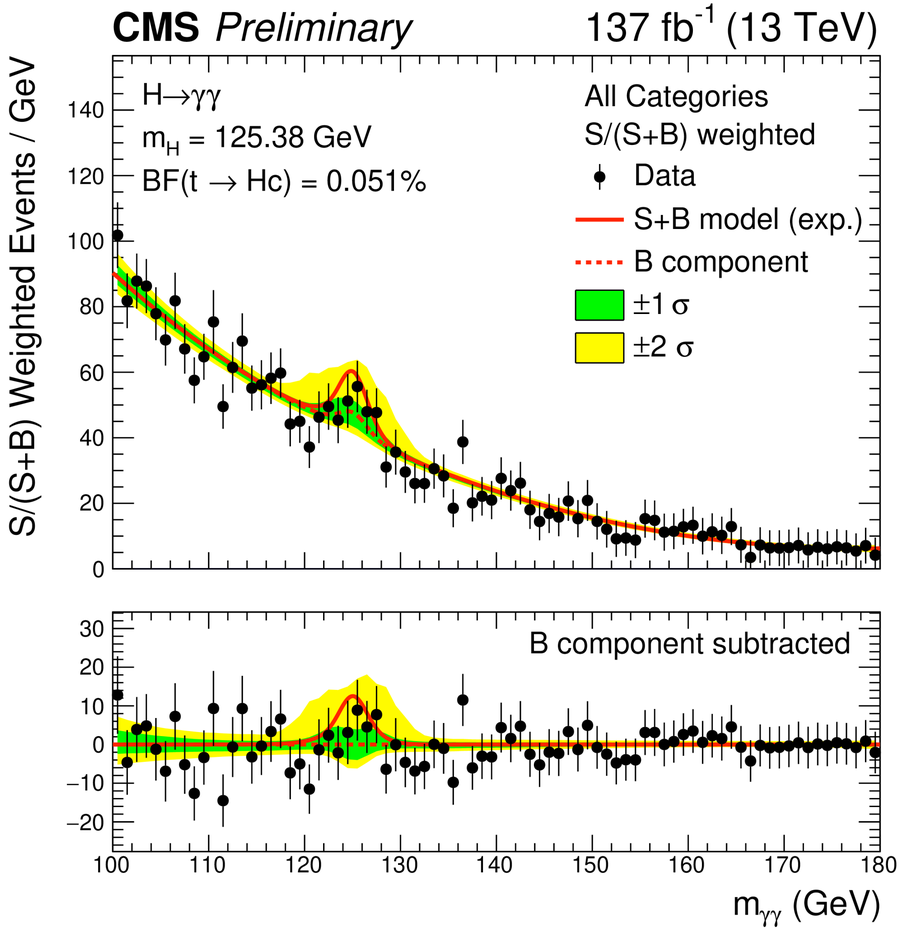
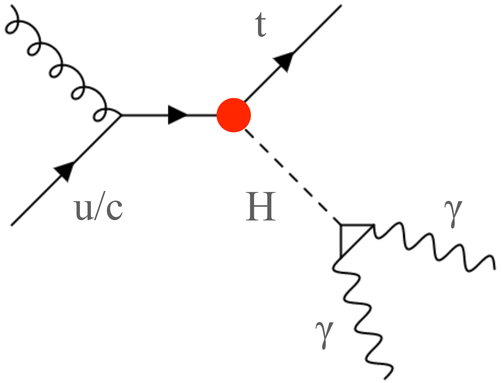
CMS 2105.03007

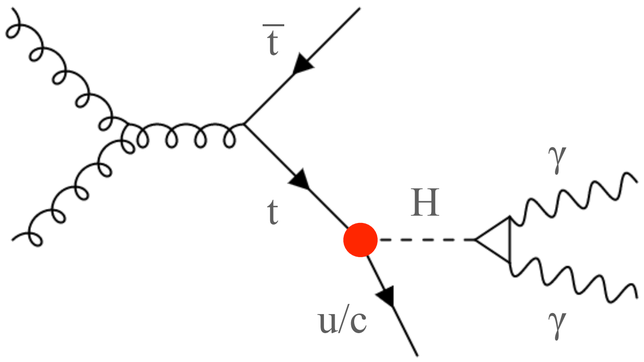
CMS PAS-TOP-20-007

Higgs as flavour-changing neutral current

Fit to m(γγ) distribution in 14 BDT categories

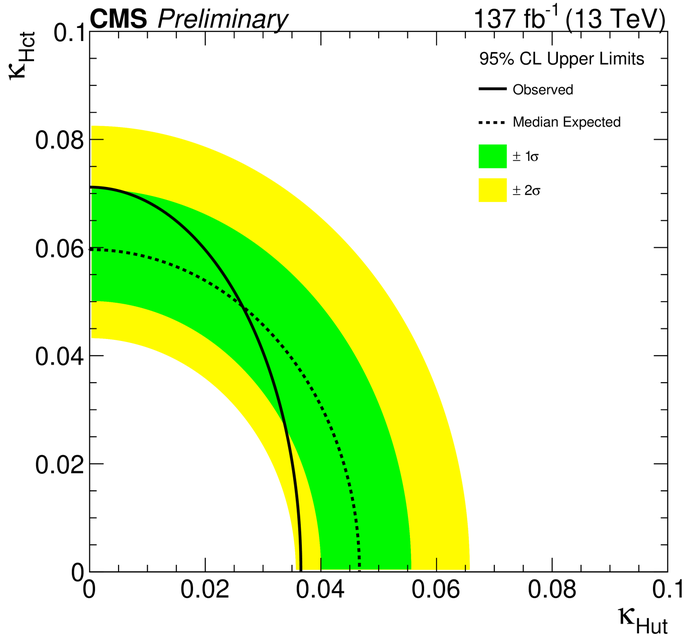






$B(t \to Hu) < 1.9 \times 10^{-4}$

$B(t \to Hc) < 7.3 \times 10^{-4}$



$h_{125} \rightarrow$ invisible

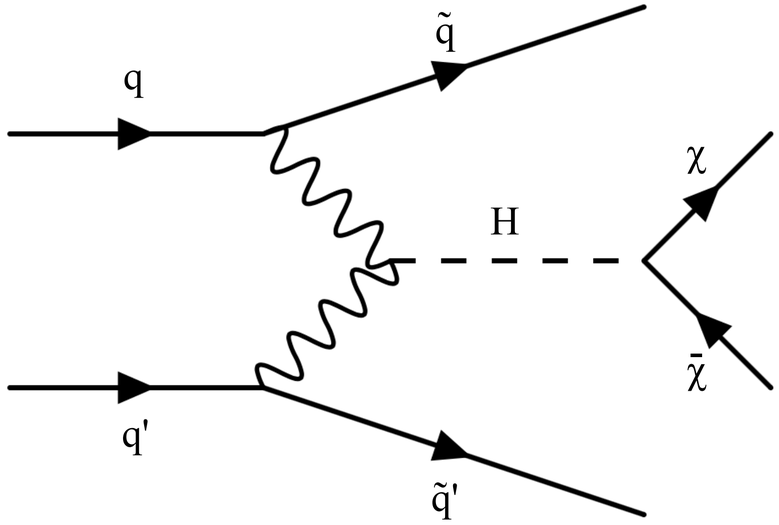
Experimentally challenging: Insufficient discrimination with p_T^{miss} alone

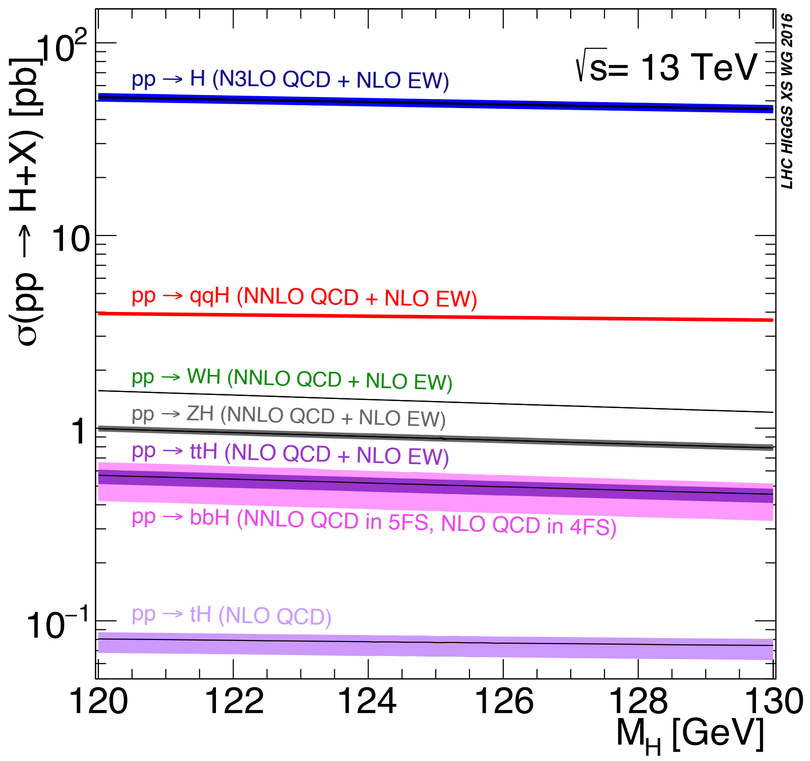
Best sensitivity with vector boson fusion production:

- Distinct tag
- Reasonably high cross section

(but other channels studied as well)

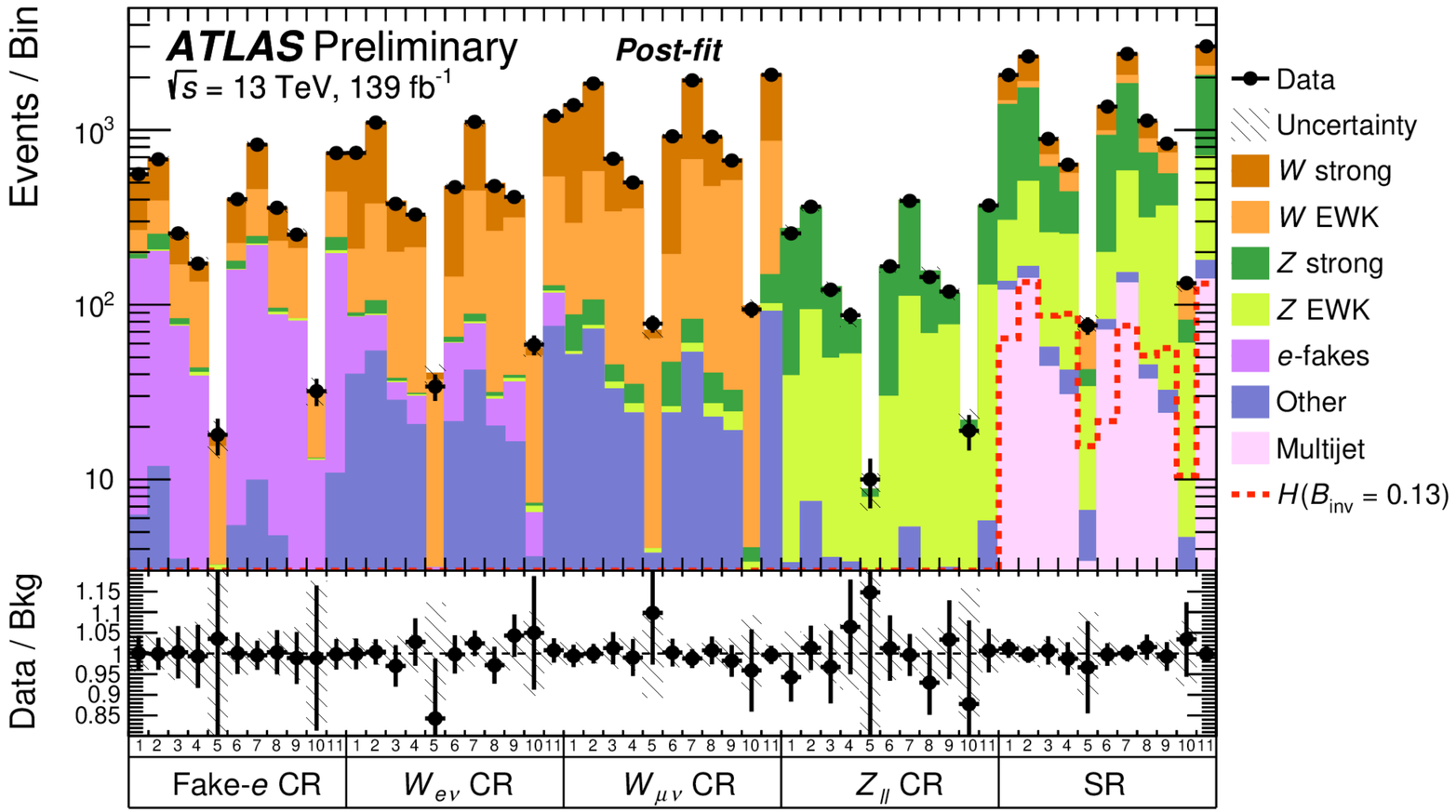
Rely on **p_T^{miss} trigger**



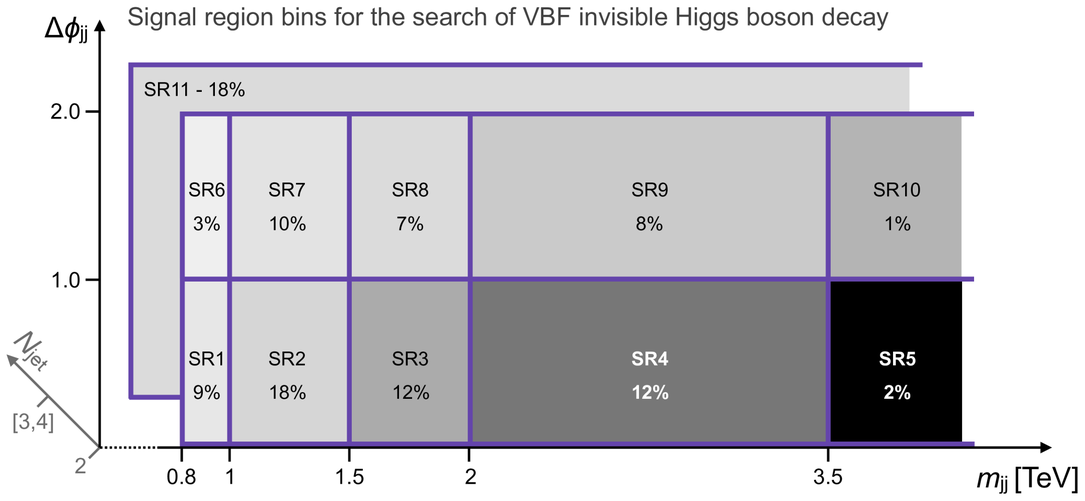


h_{125}→invisible

Involved background estimation with multiple control regions



B(h_{125}→inv) < 0.13 (0.13 exp.)



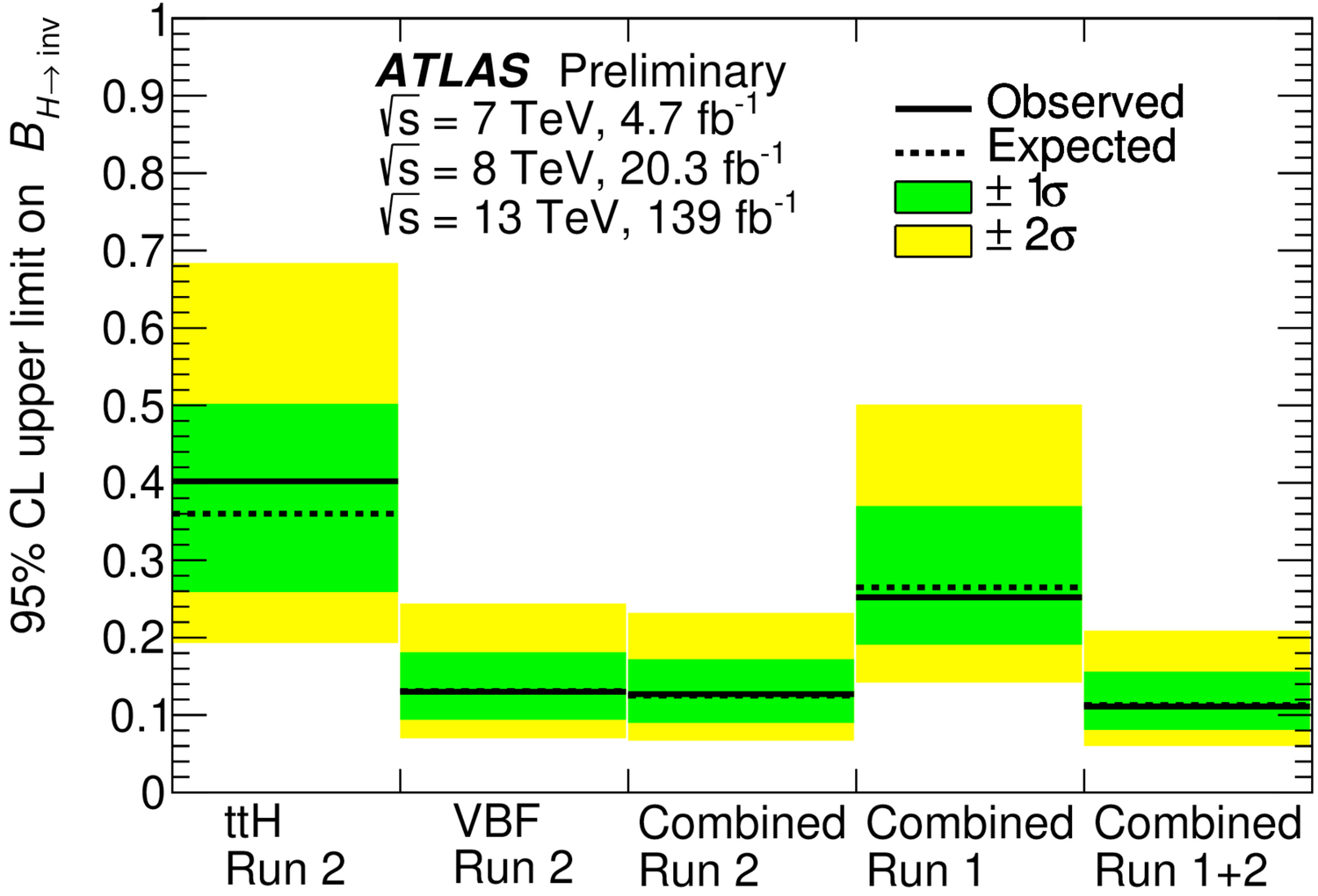
ATLAS-CONF-2020-008

h_{125}→invisible

VBF channel main contributor to current best limits

May crack the 10% barrier soon

Combined:
B(h_{125}→inv) < 0.11 (0.11 exp.)



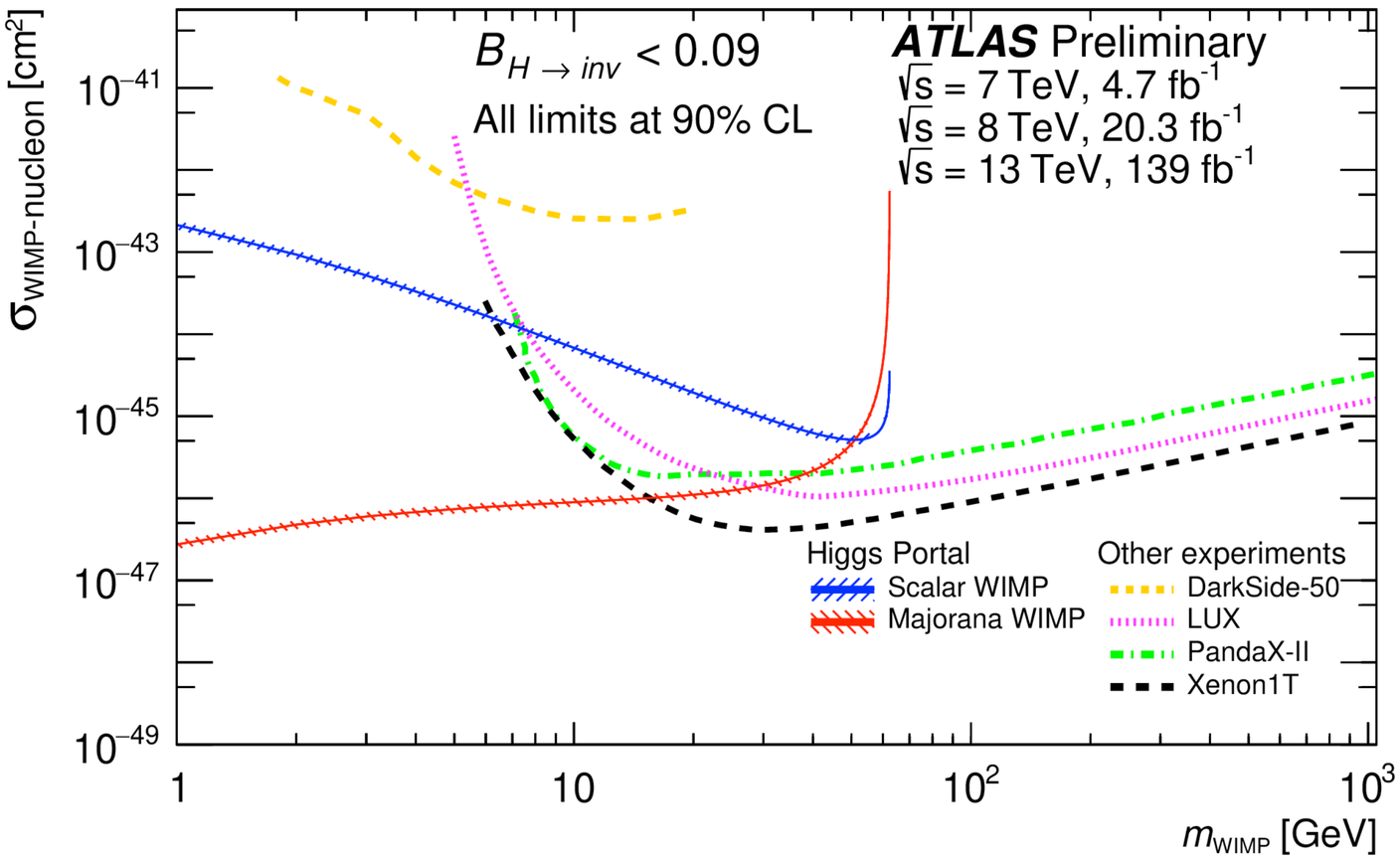
ATLAS-CONF-2020-052

h_{125}→invisible

VBF channel main contributor to current best limits

May crack the 10% barrier soon

Combined:
B(h_{125}→inv) < 0.11 (0.11 exp.)



provides sensitivity to dark matter candidates with mass up to ~ 60 GeV

ATLAS-CONF-2020-052

Summary

This lecture covered

- **Searches for additional Higgs bosons**, motivated by extended scalar sectors
- **Exotic Higgs boson decays**, in particular lepton-flavour violating decays and decays to invisible

Various other BSM Higgs possibilities, e.g. CP violation, decays to BSM/long-lived

A very active field of research:

- Well more than 5% of ATLAS and CMS publications
- Searches limited by integrated luminosity - essential for HL-LHC programme and future colliders
- A few interesting hints: a great time to be or get involved!

Experimental results and related information:

- ATLAS results HDBS Higgs
- CMS results HIG
- LHCb results Exotica
- LHC Higgs WG 3: LHCHWG3