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Searches for Higgs Beyond the Standard Model and Higgs pair-production

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OUTLINE

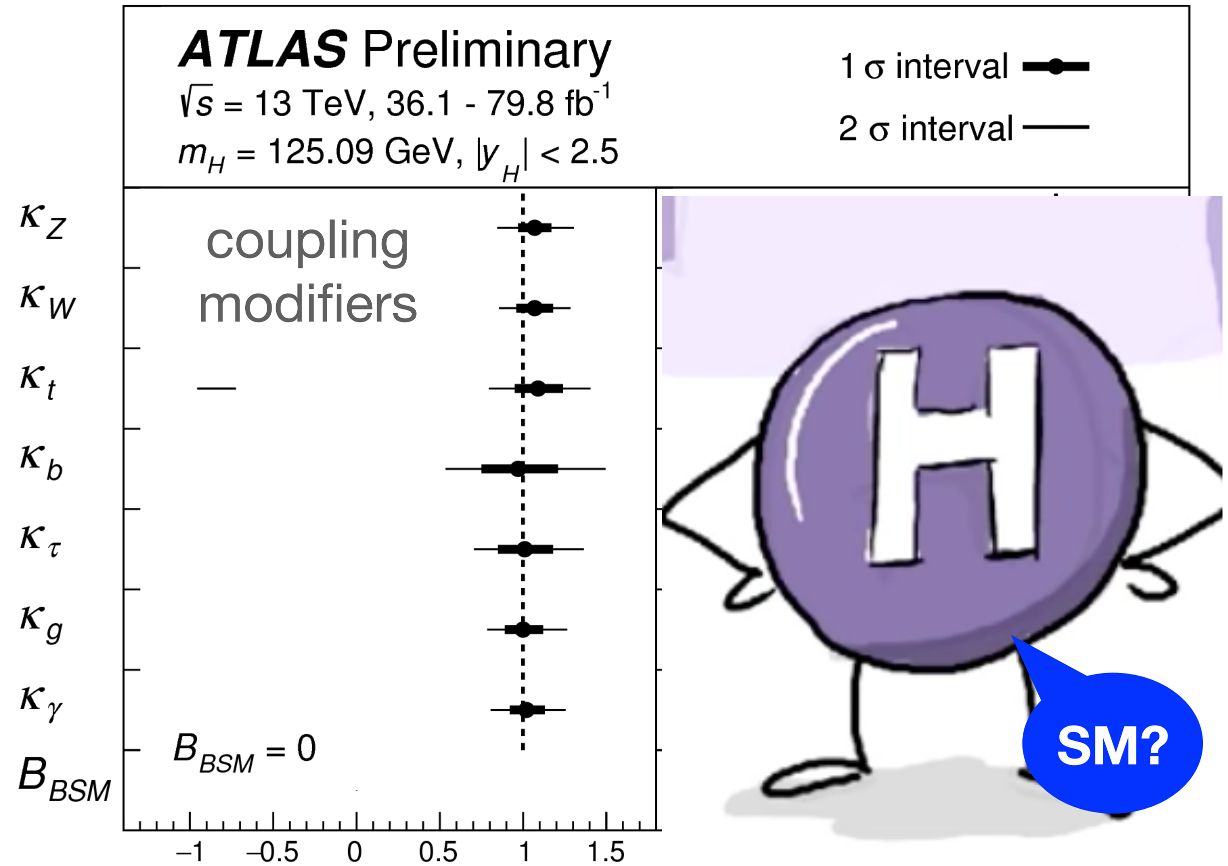
- **Searches for BSM Higgs**
  - searches for new Higgs bosons (neutral and charged)
    anomalous Higgs (125 GeV) decays
- **Searches for Higgs pair-production**
  - resonant and non-resonant
- *and interpretation*
  - guiding paradigms: 2HDM, 2HDM + a scalar Singlet, Higgs portal to a Hidden Sector

- Based on **results of data analyses from ATLAS and CMS** with
  - LHC **pp collisions at 13 TeV** (+8, 7 TeV), typically **~36 fb^{-1}**
    - in a some cases full Run2 statistics: ***13 TeV, 139 fb^{-1}***
  - selection based on results issued in the ~last year (others in backup)

Generalities of BSM Higgs

Is the 125 GeV boson the SM Higgs ?

Why a so simple scalar sector along with a complex fermion sector ?



Any extra scalar ?

a compelling constraint: custodial SU(2), i.e. ρ~1

any scalar multiplet must satisfy $I(I+1)=3Y^2/4$

the easiest solutions:

SU(2) doublet with Y=±1

or

SU(2)singlet with Y=0

$$\Phi_1 = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}_1 \quad \Phi_2 = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}_2$$

Dark matter

Composite Higgs

anomaly cancellation and m to q=2/3 and q=-1/3 quarks

SUSY

PQ axion models

CP violation sources

Baryogenesis

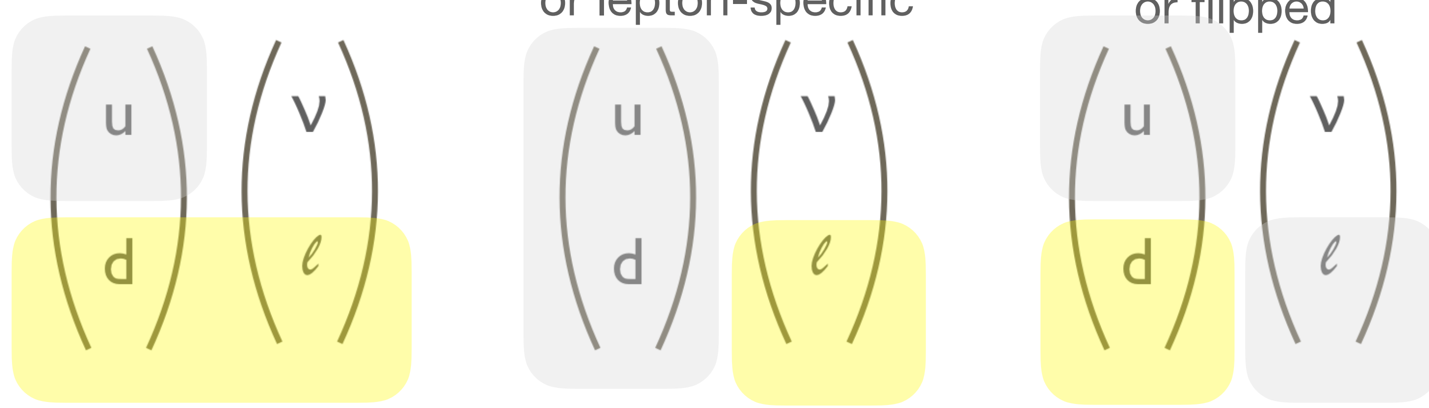
many tree-level or loop-induced CP violation sources

2HDM is ***viable*** and ***theoretically well motivated***

2 Higgs Doublet Models

Type I | II | X (or lepton-specific) | Y (or flipped)

Φ_1 gives mass to all fermions



MSSM

Yukawa couplings depend on **tanβ** and **cos(α−β)**

4 types of 2HDM are protected by symmetries from tree-level FCNC

a problem: Higgs-induced FCNC

a few parameters:

tanβ = v_2/v_1 ratio of vevs

α mixing angle of scalar bosons

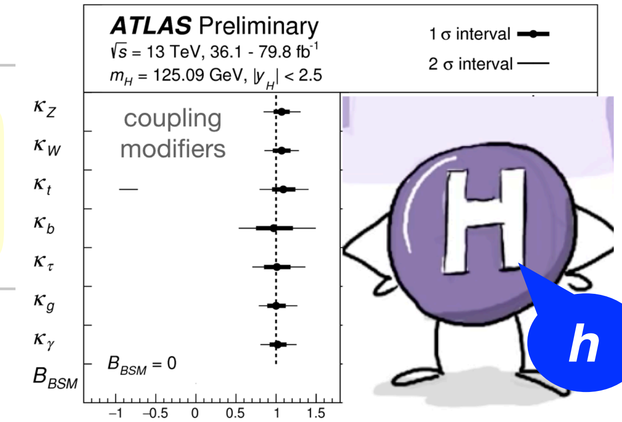
2HDM is ***viable*** and ***theoretically well motivated***

Φ_1 **Φ_2**

h *scalar* $m_h < m_H$ ***H*** *scalar* ***A*** *pseudo-scalar* ***H±*** *charged*

2 Higgs Doublet Models

Φ_1 Φ_2



Yukawa couplings depend on **tanβ** and **cos(α − β)**

Type I	II	X (or lepton-specific)	Y (or flipped)
Φ_1 gives mass to all fermions	(u, d) (ν, ℓ)	(u, d) (ν, ℓ)	(u, d) (ν, ℓ)

125 GeV boson = h

h SM like =>

cos(α − β) = ε ≈ 0

alignement limit

H,A Yukawa couplings, *normalized to those of h(SM)* *alignement limit*

	$H\bar{U}U$	$H\bar{D}D$	$H\bar{E}E$	$iA\bar{U}\gamma_5 U$	$iA\bar{D}\gamma_5 D$	$iA\bar{E}\gamma_5 E$
I	$-(\frac{1}{t_\beta}-\epsilon)$	$-(\frac{1}{t_\beta}-\epsilon)$	$-(\frac{1}{t_\beta}-\epsilon)$	$-\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
II	$-(\frac{1}{t_\beta}-\epsilon)$	$t_\beta+\epsilon$	$t_\beta+\epsilon$	$-\frac{1}{t_\beta}$	$-t_\beta$	$-t_\beta$
X	$-(\frac{1}{t_\beta}-\epsilon)$	$-(\frac{1}{t_\beta}-\epsilon)$	$t_\beta+\epsilon$	$-\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$-t_\beta$
Y	$-(\frac{1}{t_\beta}-\epsilon)$	$t_\beta+\epsilon$	$-(\frac{1}{t_\beta}-\epsilon)$	$-\frac{1}{t_\beta}$	$-t_\beta$	$\frac{1}{t_\beta}$

$t_\beta = \tan\beta = v_2/v_1$ in the table

high tanβ
ττ -> type II and X
bb -> type II and Y

low tanβ
tt -> all types

Favoured decay channels

H,A couplings to WW, ZZ are suppressed
*Searches must concentrate on decays to **3rd generation fermions***

α mixing angle of CP-even bosons

h $m_h < m_H$ ***H*** ***A*** ***H±***

scalar *scalar* *pseudo-scalar* *charged*

SEARCH FOR A/H IN TYPICAL 2HDM SCENARIOS

Search for heavy A/H decays to fermions

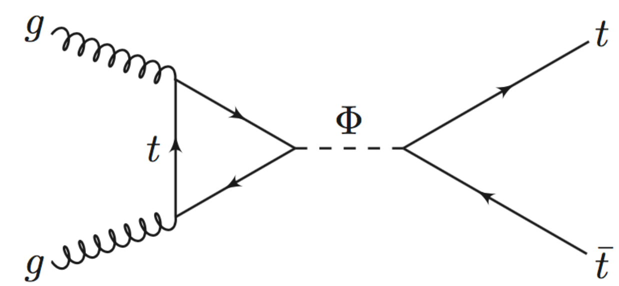
No recent updates of:
searches for charged Higgs
see in backup
searches for A ➛ ZH ➛ll bb
in backup

SEARCH FOR HEAVY A/H ➛ tt

CMS: ArXiv:1908.01115

ATLAS: PRL119 (2017) 191803, **@8TeV**

- A/H➛tt by CMS (Aug. 2019) with 36fb^{-1} at 13 TeV (1 lepton or 2 leptons final states)
- ***Interference*** with SM top-pair production ***may be >0 or <0***
  - All signal samples (MADGRAPH5 aMC@NLO) reweighed to NNLO (SUSHI) include interference terms;
    SM tt simulation by POWHEG reweighed to NNLO+NNLL

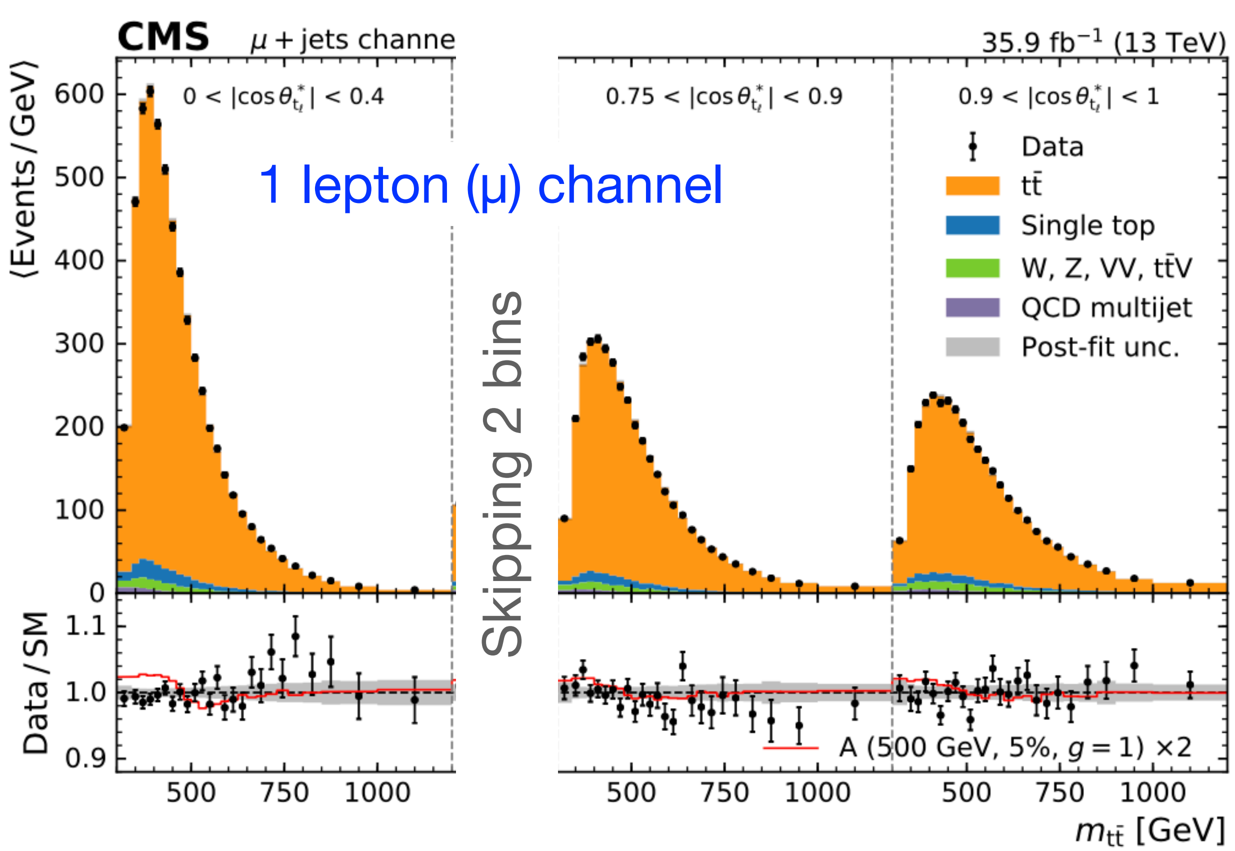


dominant @ low tanβ

- Info on ***spin correlation*** between top retained in decay products
- A complex analysis taking advantage of ***angular variables*** in a complete event reconstruction

2 leptons

chel cosine of the angle between the charged lepton momenta in their respective helicity frames



1 lepton

$\cos\theta_{tl}^{*}$ cosine of the angle in the tt rest frame between the t decaying semileptonically and the tt-direction in the lab frame

Search for signal based on max. likelihood fit of 2D binned distributions of:

m_{tt} x $\cos\theta_{tl}^{*}$	1 lepton
m_{tt} x chel	2 leptons

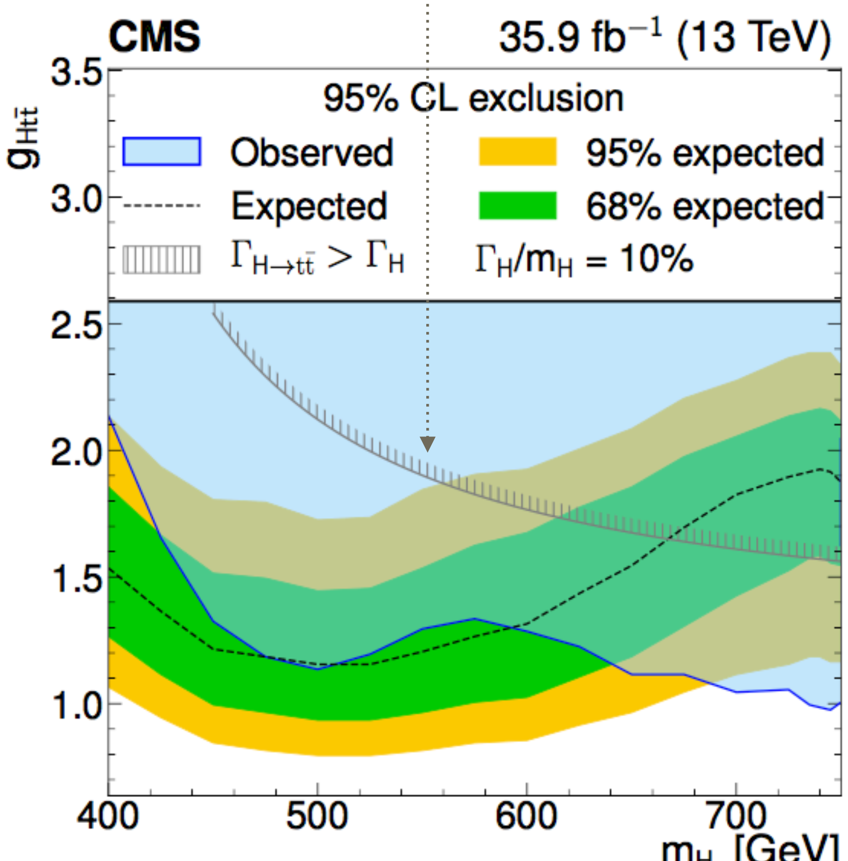
SEARCH FOR HEAVY A/H ➝ tt

CMS: ArXiv:1908.01115

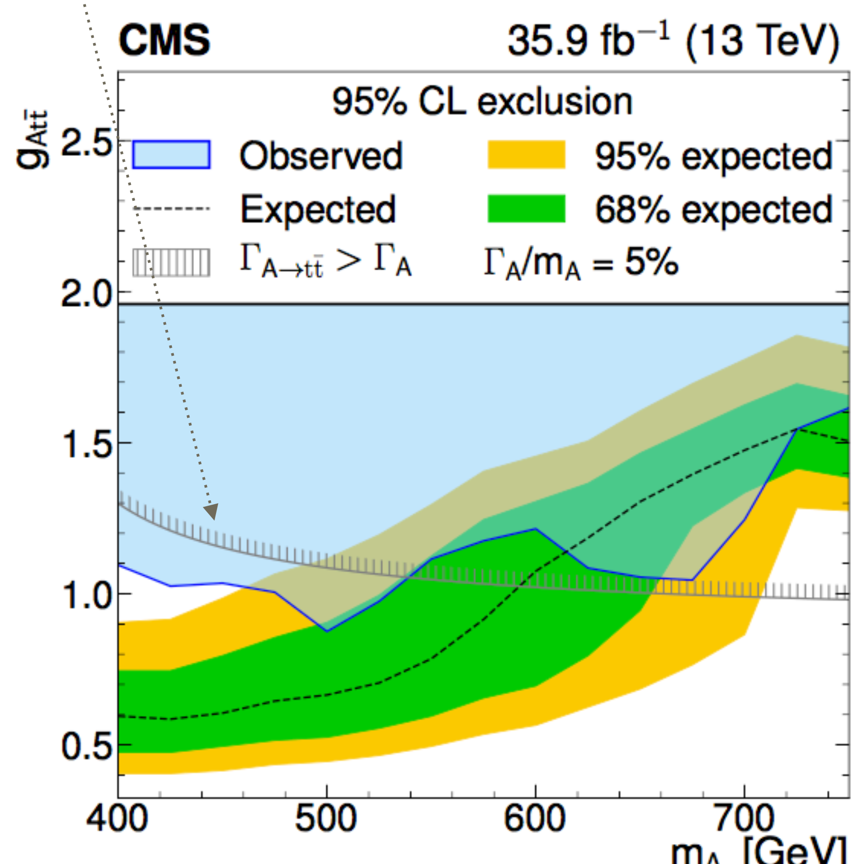
ATLAS: PRL119 (2017) 191803 **@ 8 TeV**

- model independent constraints on H/A couplings to top vs mass for various Γ_A/m_A
  - 0.5%, 1%, 2.5%, 5%, 10%, 25%
  - better sensitivity for large values of Γ_A/m_A

grey shaded curves give the boundary of sensitivity, corresponding to partial width to tt greater than the total width

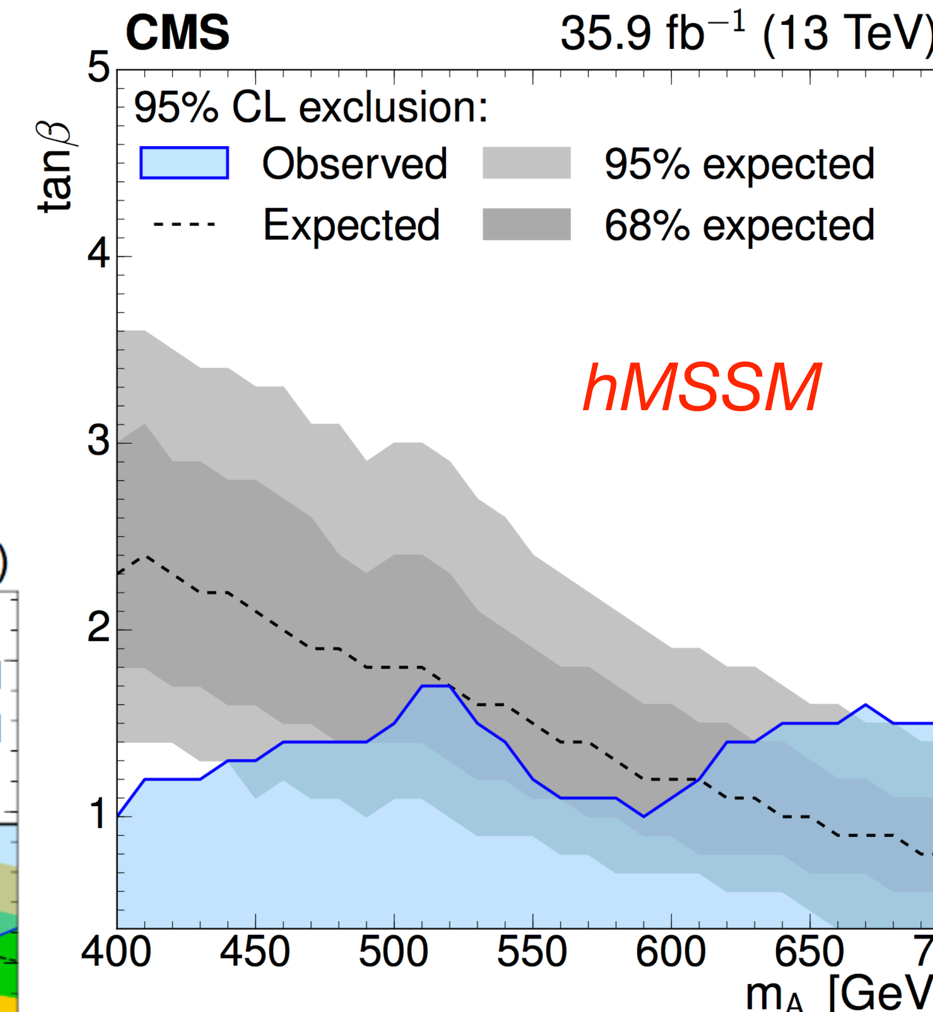


Htt



Att

sensitive @ low tanβ



A signal-like excess at m_A~400GeV

(1.9 σ global significance)

to be watched out with more statistics

CMS JHEP08(2018)113

SEARCH FOR HEAVY H IN *b(b)H→bb*

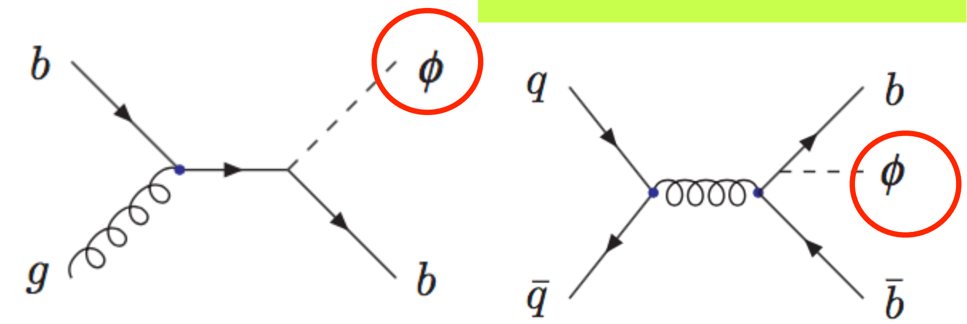
ATLAS ArXiv:1907.02749

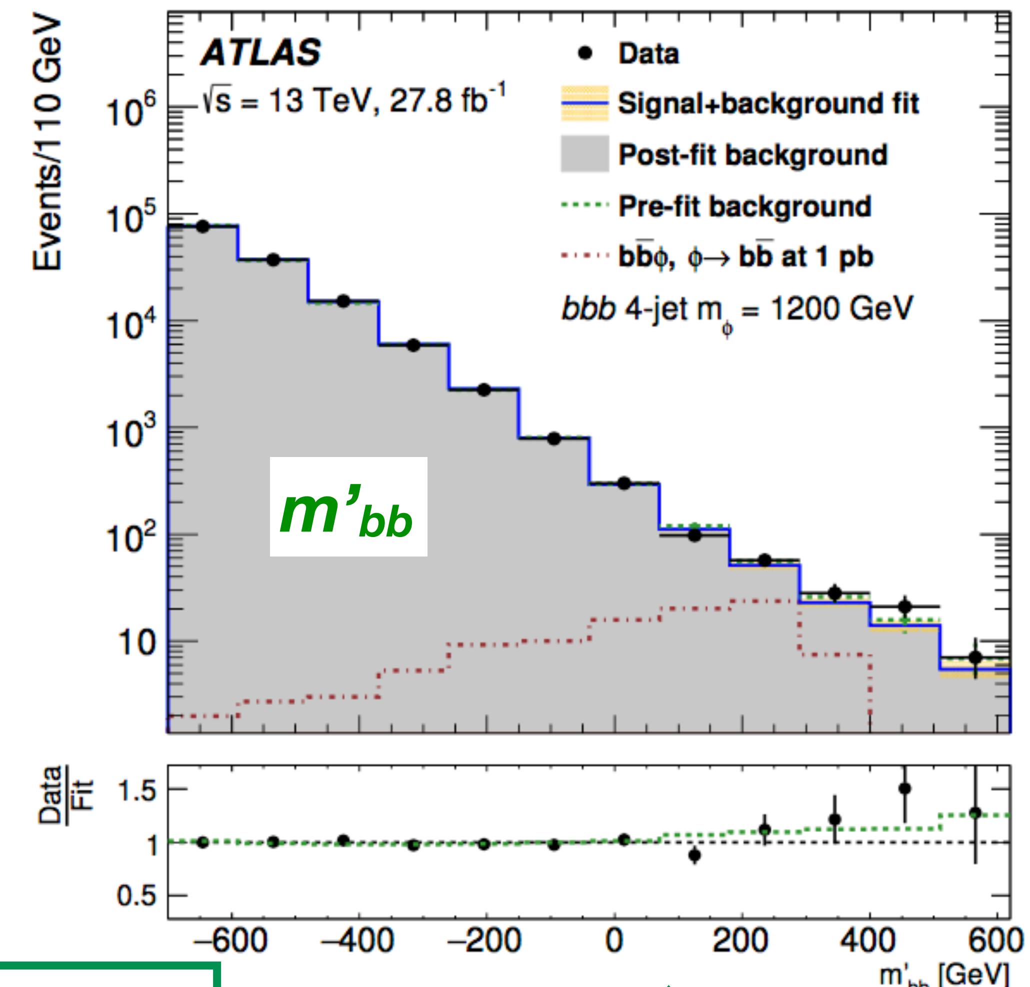
sensitive to type II and Y flipped, for high tanβ

- ATLAS search for a scalar ϕ [CP-even or CP-odd or a combination] produced in association b-quark(s) with ***36 fb^{-1} at 13 TeV***
  - a selection for ≥3 b-jets optimizes S/B
    - events with only 2 b-tagged jets used for QCD CRs, constraining the shape of the background in the SRs
  - trigger based on high E_T *b*-tagged (1 or 2) jets
  - *signal for 15 m_H values is emulated in a point of the MSSM corresponding to high BR to bb, and suppressed tt and ττ coupling*
- ***p_{T1}, p_{T2}*** and ***m_{bb}*** are studied with a ***Principal Component Analysis*** for each mass point, ***m'_{bb}*** *used as discriminating variable in a binned maximum likelihood fit*

$$\sigma(pp \to b\bar{b}\phi) \times \mathcal{B}(\phi \to b\bar{b}) < 0.6\text{–}4.0 \text{ pb}$$

for M_ϕ in 450–1400 GeV. @ 95% CL





m'_{bb} = def.

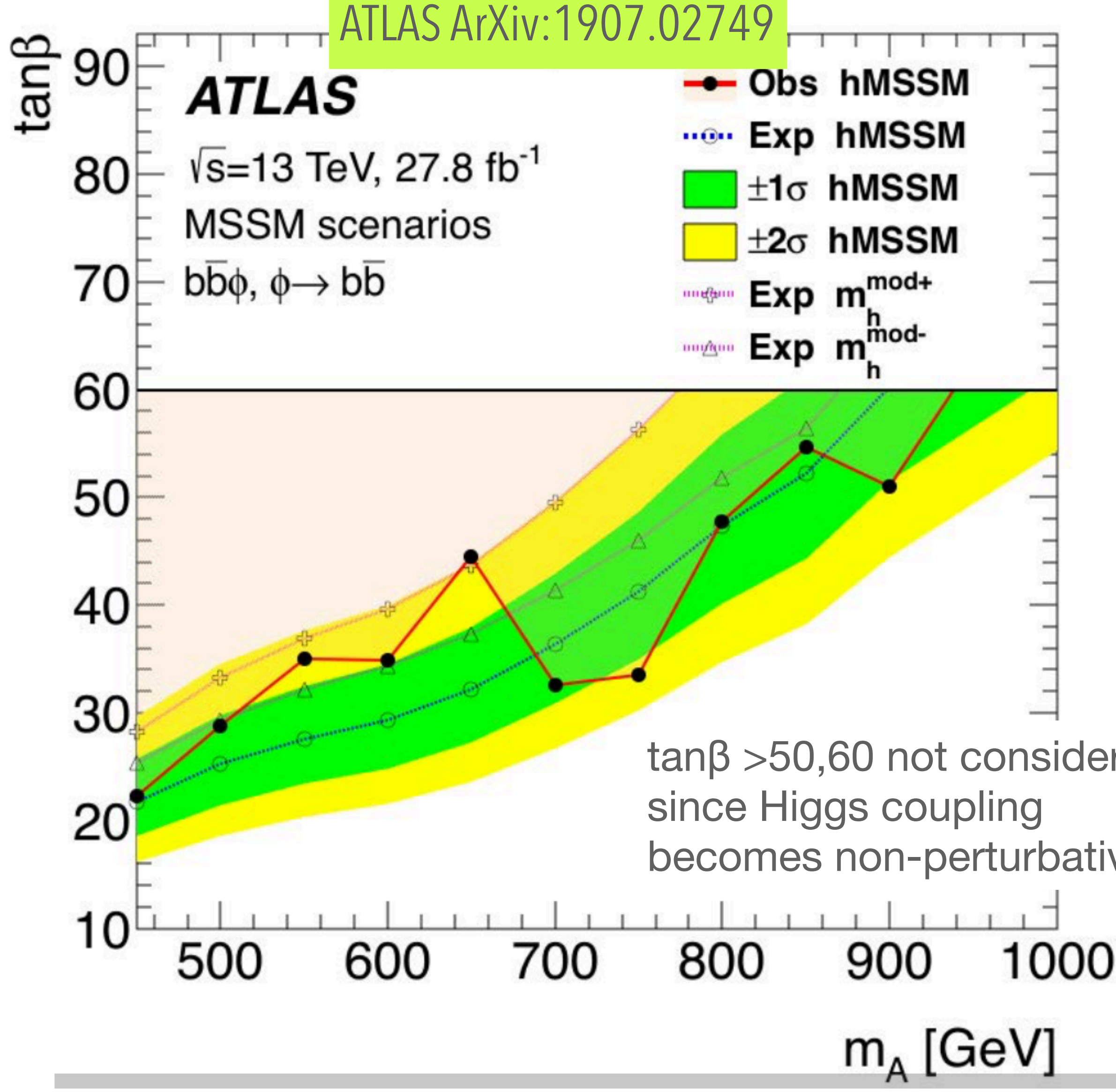
$$c_{m_{bb}}(m_{bb} - \langle m_{bb}\rangle) + c_{p_{T1}}(p_{T1} - \langle p_{T1}\rangle) + c_{p_{T2}}(p_{T2} - \langle p_{T2}\rangle)$$

SEARCH FOR HEAVY H IN *b(b)H➛bb*

$\sigma(pp \to b\bar{b}\phi) \times \mathcal{B}(\phi \to b\bar{b}) < 0.6\text{–}4.0$ pb
for Mϕ in 450–1400 GeV. @ 95% CL

sensitive to type II and Y flipped, for high tanβ
=> interpretation in Y model and
several MSSM benchmark scenarios

ATLAS ArXiv:1907.02749



tanβ >50,60 not considered,
since Higgs coupling
becomes non-perturbative

b(b)H➛bb VS b(b)H➛ττ

experimentally easier, published earlier on

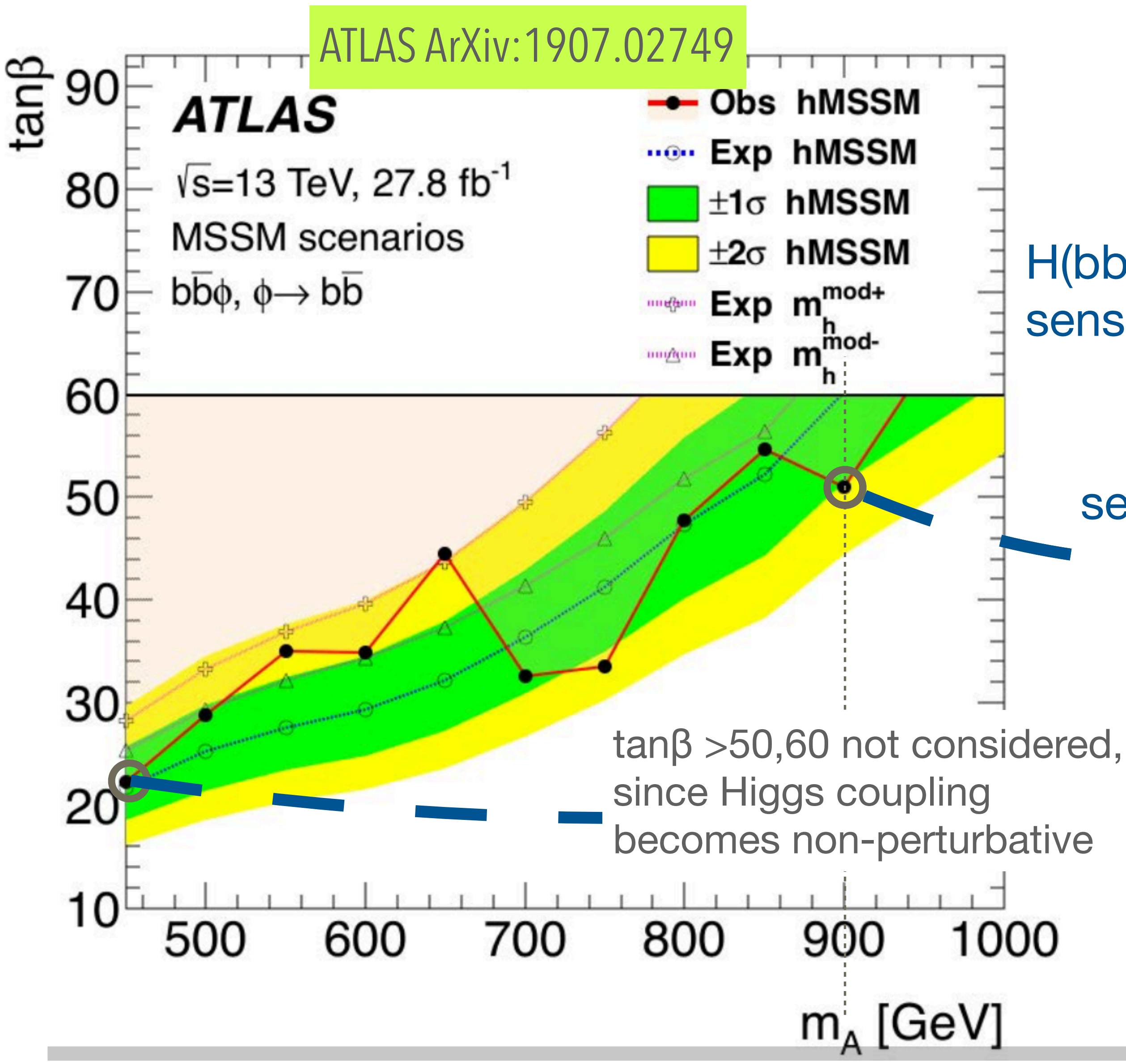
$\sigma(pp \rightarrow b\bar{b}\phi) \times \mathcal{B}(\phi \rightarrow b\bar{b})$ < 0.6–4.0 pb for Mϕ in 450–1400 GeV. @ 95% CL

same data set

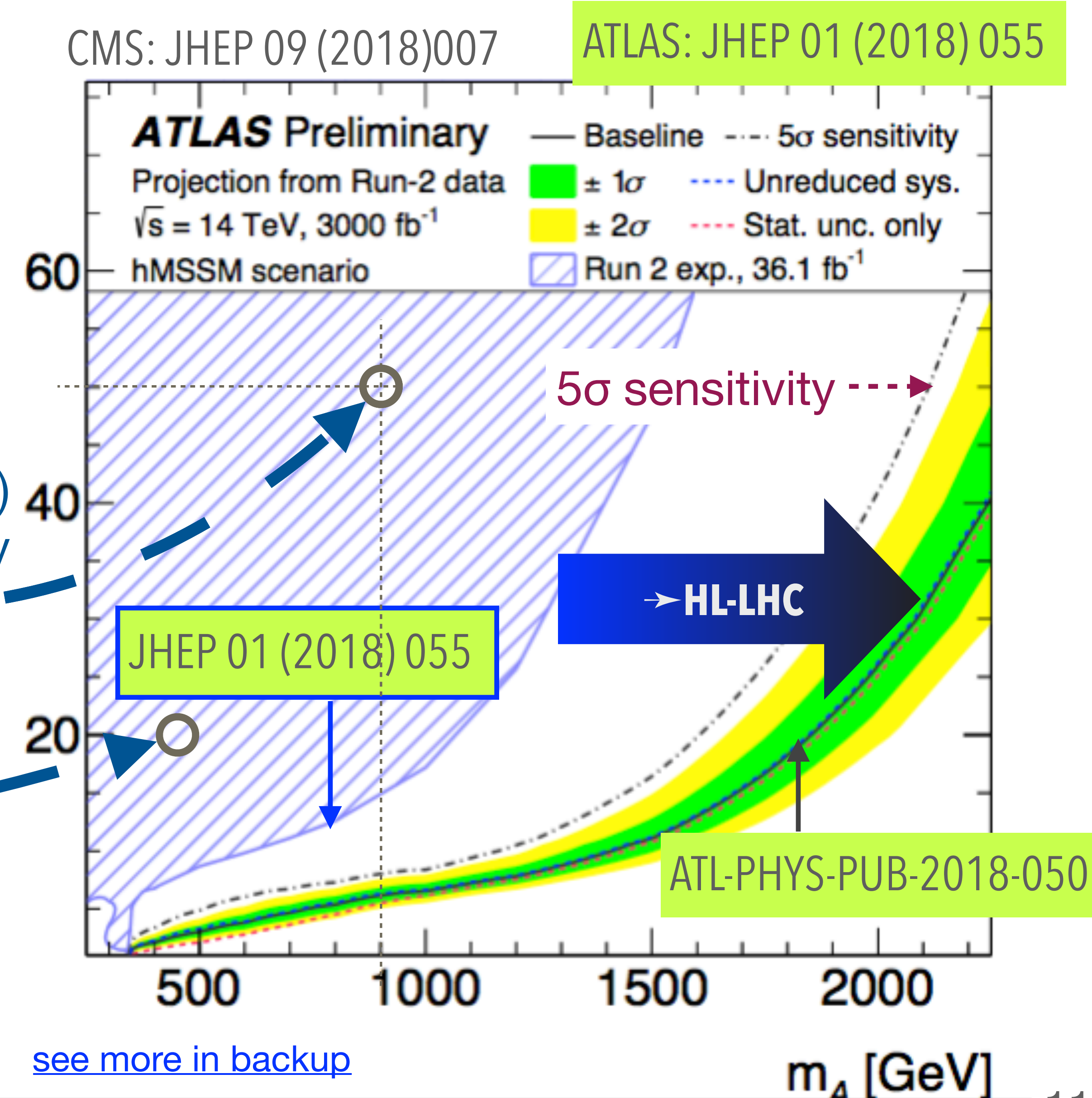
σ x $\mathcal{B}(\phi \rightarrow \tau\tau)$ < **1.0 pb-0.6x10^{-2} pb** for **ggF**
< **0.7 pb-0.4x10^{-2} pb** for **b-ass. pr.**
for Mϕ *in* 0.2-2.25 TeV @ 95% CL

sensitive to type II and Y flipped, for high tanβ
=> interpretation in Y model and several MSSM benchmark scenarios

sensitive to type II and X,Y for high tanβ
=> interpretation in *hMSSM*



H(bb) sensitivity << H(ττ) sensitivity



see more in backup

SEARCH FOR MSSM H ➤ μμ

CMS: arXiv:1907.03152

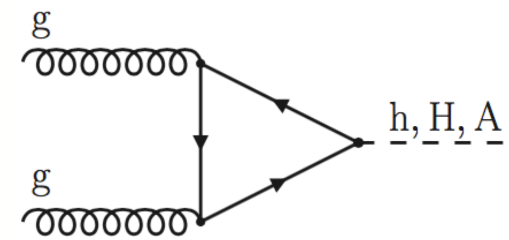
An MSSM devised analysis

H/A➤μμ is 300 times smaller than ττ but clear signature, close kinematics

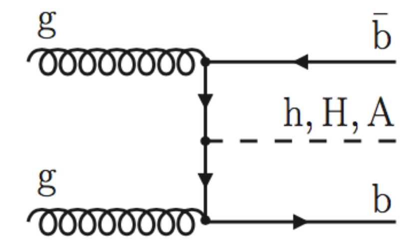
Two categories:
1) strictly one b-jets (to avoid large top bkg)
2) no b-tagged jet

No background simulation
Fit to
signal **(including all three neutral bosons** with mass and BR dictated by MSSM)
+ smooth analytical shape for the background

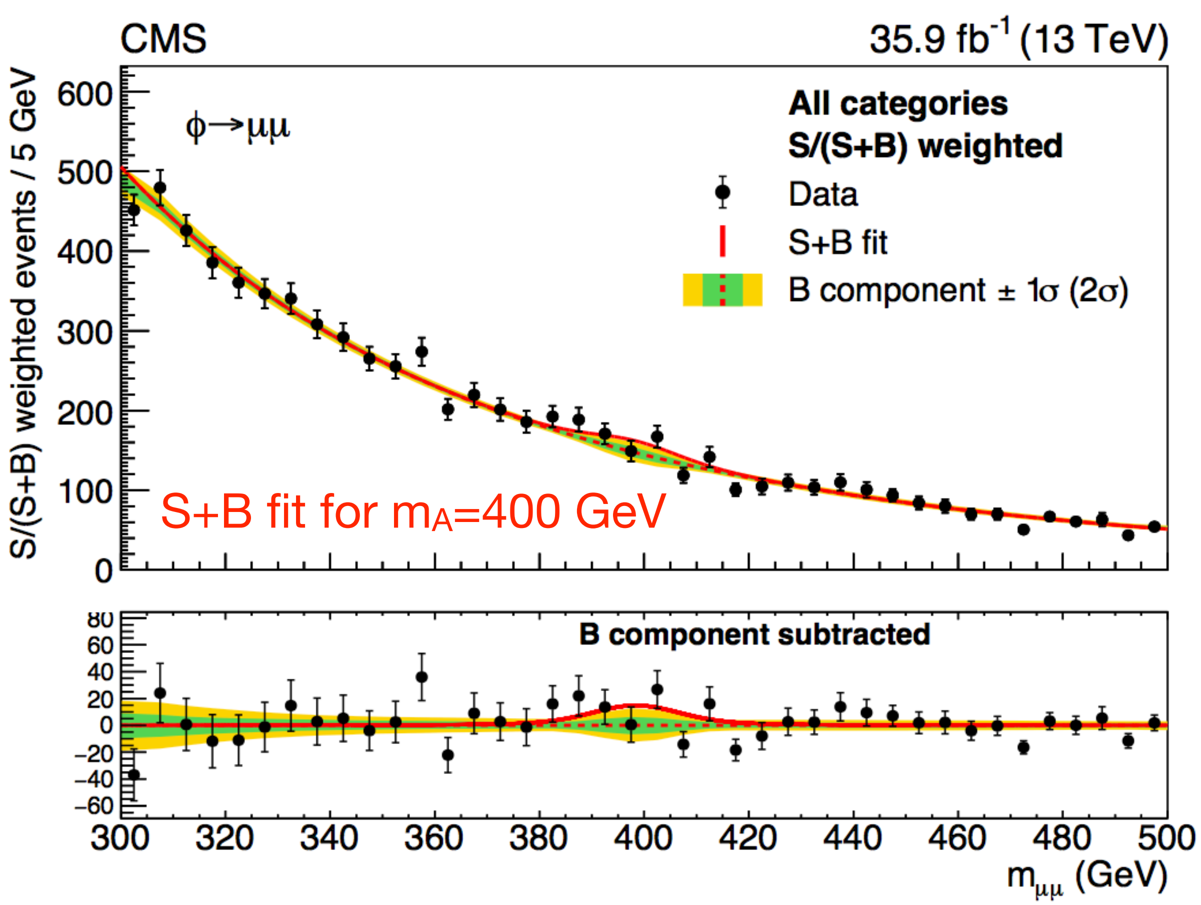
$$F_{\rm sig} = w_{\rm h} F_{\rm h} + w_{\rm H} F_{\rm H} + w_{\rm A} F_{\rm A}$$



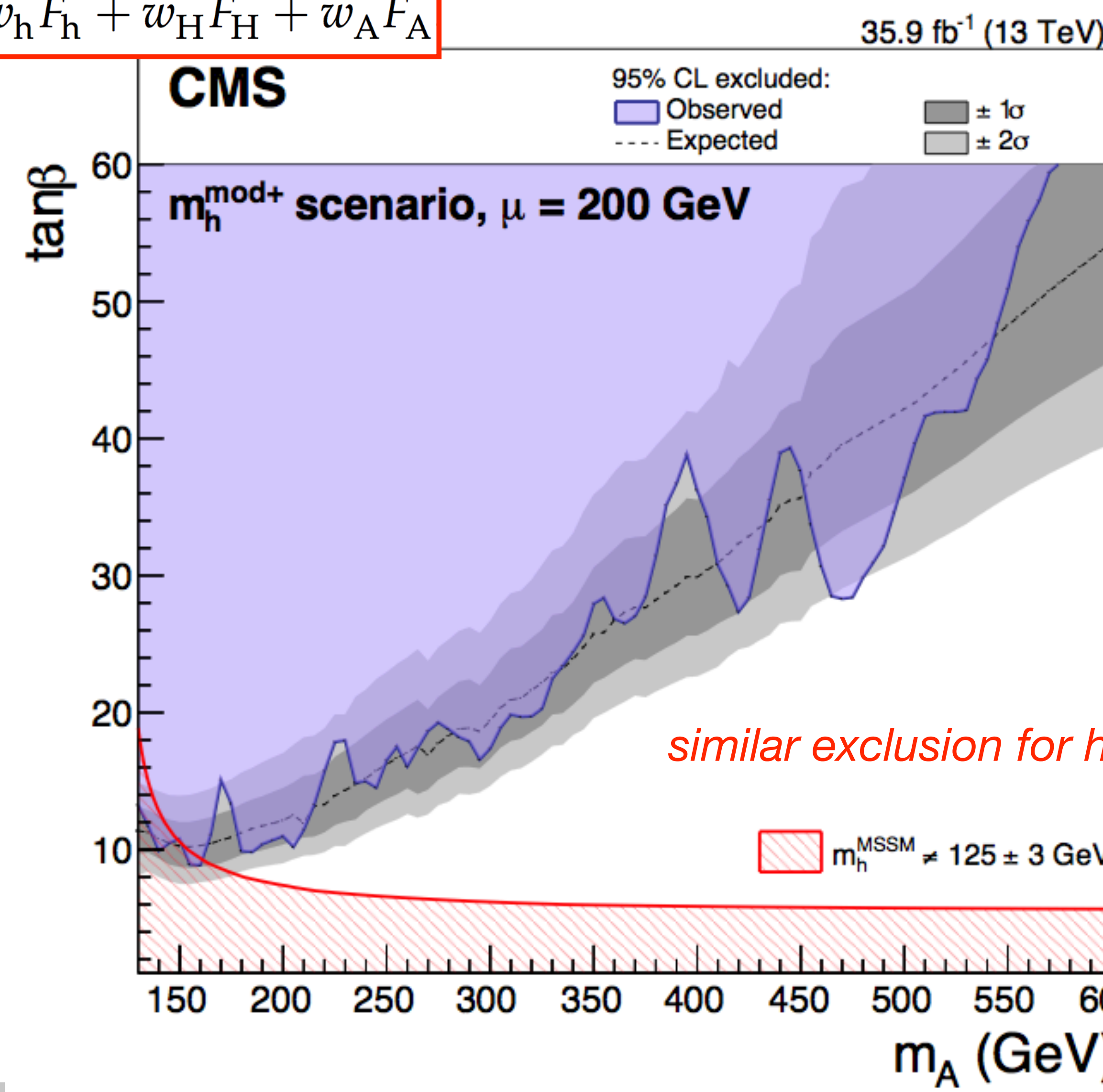
dominant for tan β <30



enhanced coupling to down-fermions at high tan β



S+B fit for m_A=400 GeV



similar exclusion for hMSSM

SEARCH FOR HEAVY H ➤ $\mu\mu$

ATLAS: arXiv:1901.08144

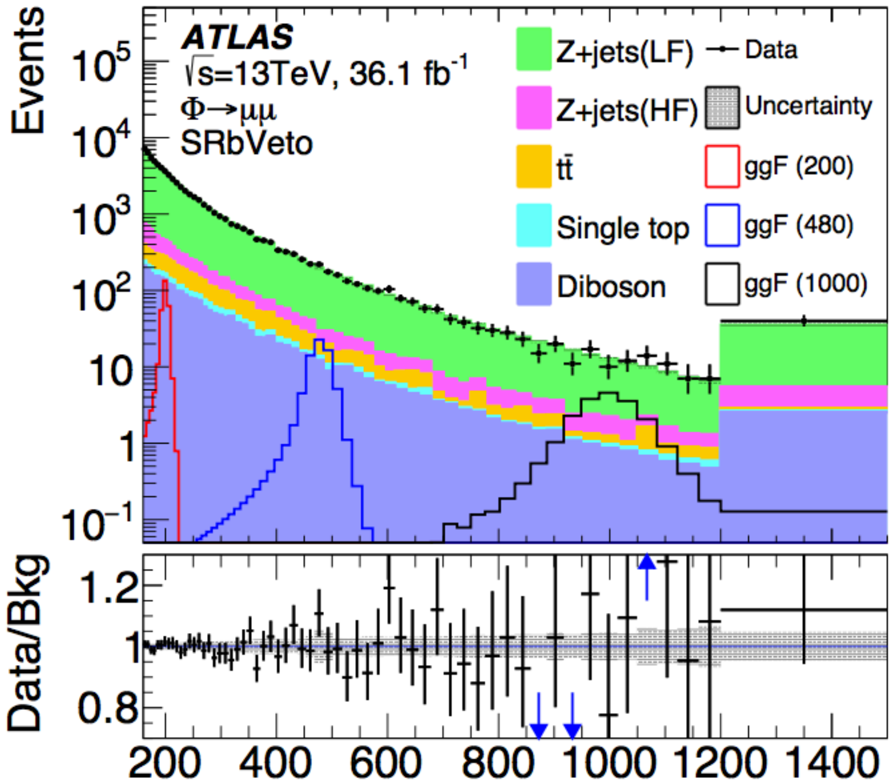
A model agnostic analysis

b-associated and **ggF** production modes

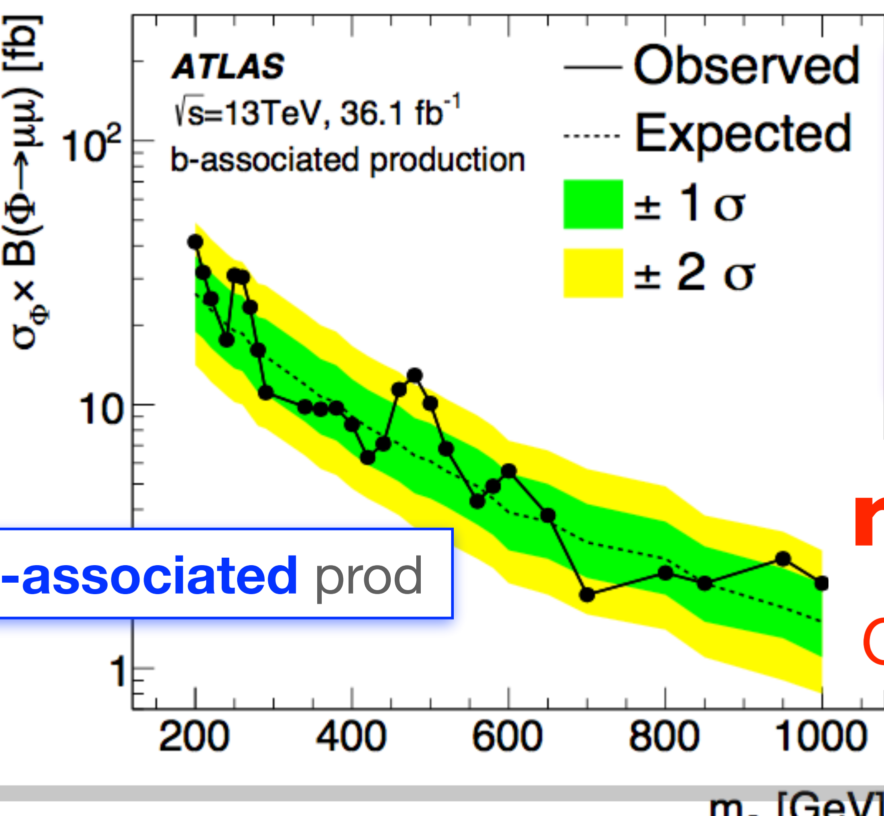
narrow width approximation

b-tag and **b-veto** categories

all background from simulations + control regions



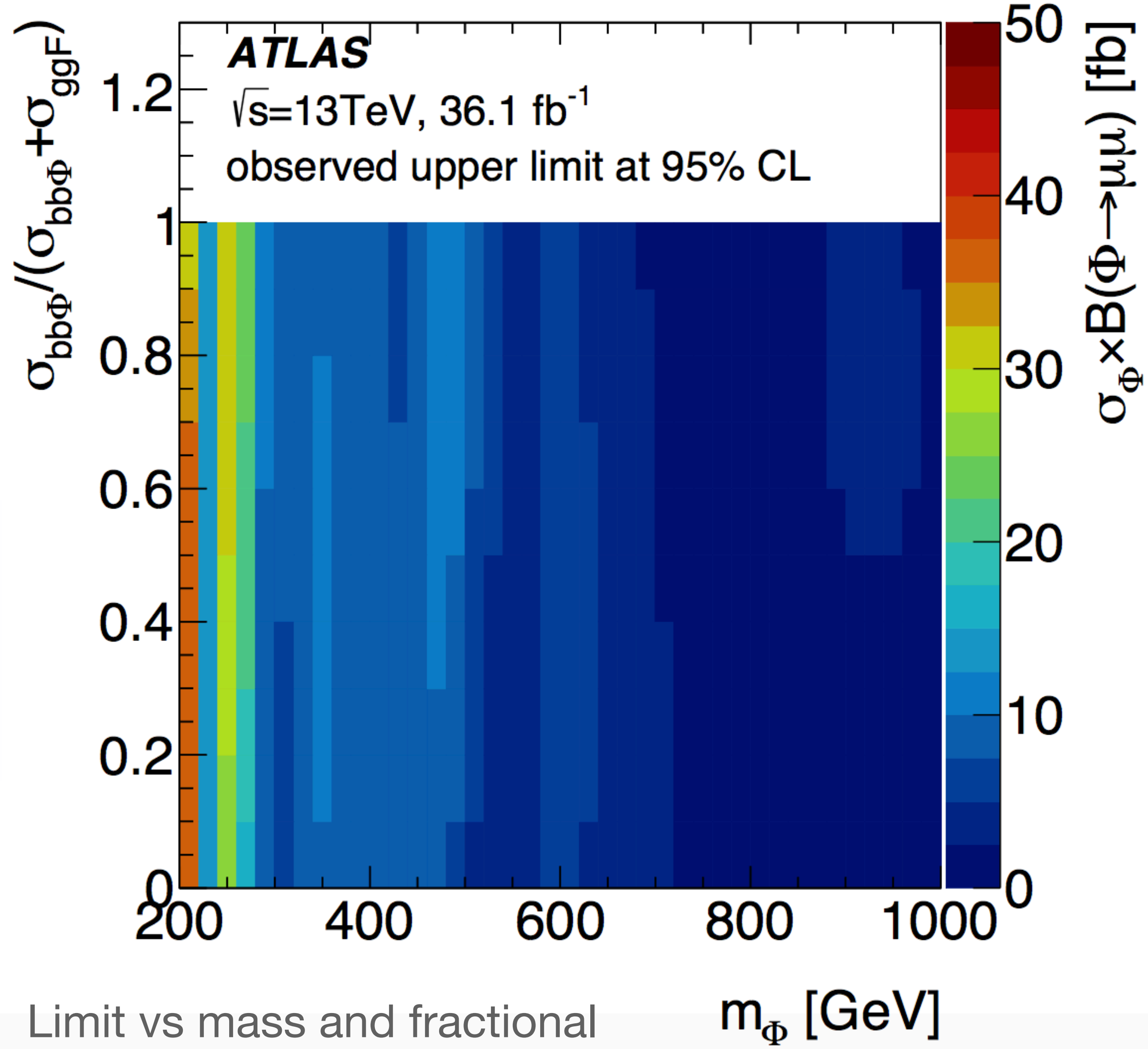
$m_{\mu\mu}$ GeV



b-associated prod

similar limits for **ggF** production mode

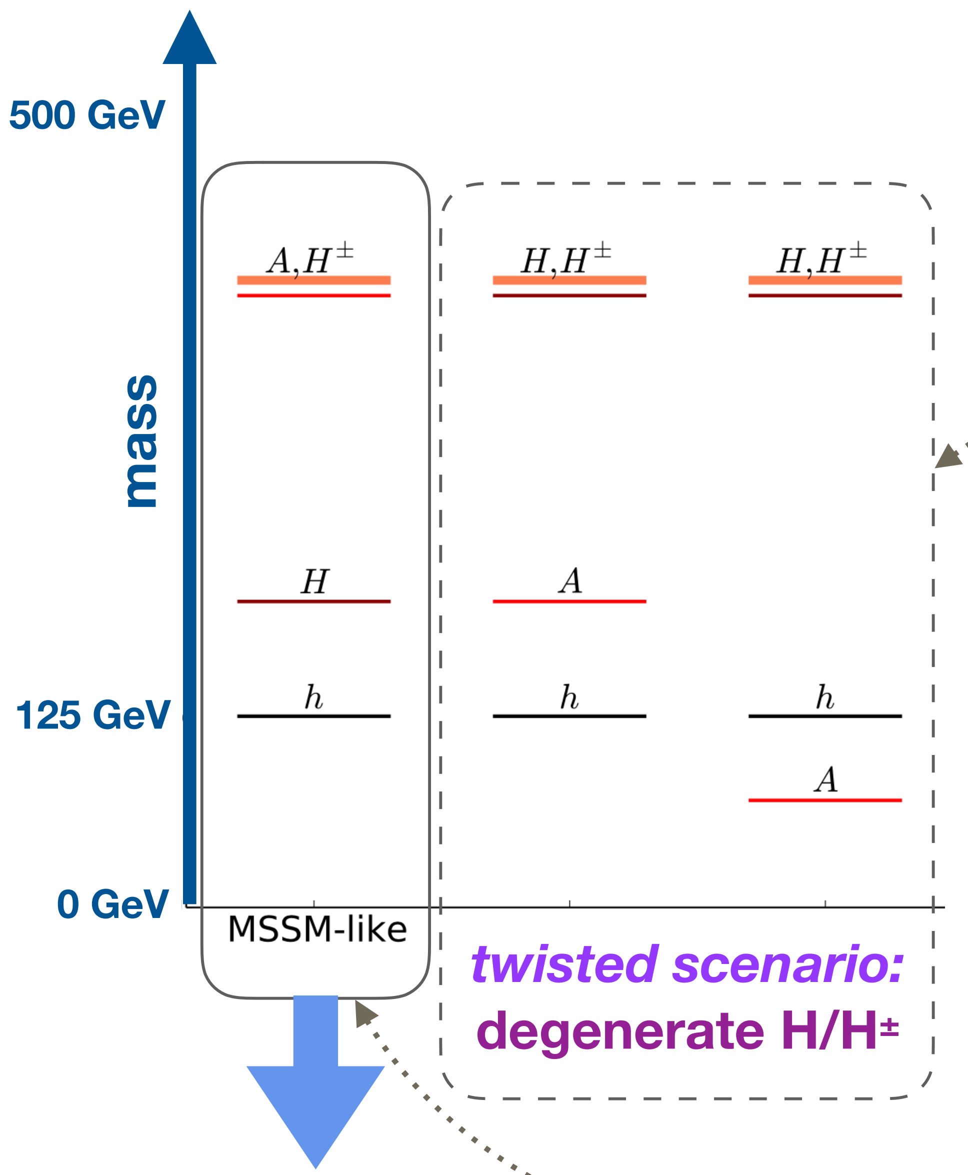
m_Φ GeV



Limit vs mass and fractional contribution of b-ass. production

SEARCH FOR A/H IN LESS TYPICAL SCENARIOS

UNCONVENTIONAL MASS HIERARCHY / COUPLINGS



classical scenario:
degenerate A/H±

in addition, H and A are typically assumed to be close in mass

light A in (b)A ➛ ττ

CMS: JHEP05(2019)210

H ➛ ZA ➛ ℓℓ bb

May 2019, CMS PAS HIG-18-012

unconventional mass hierarchy

hierarchy may reveal underlying physics: e.g. arXiv: 1803.01865 [hep-ph] see backup

~light H ➛ γγ

CMS: PLB 793 (2019) 320–347

unconventional / suppressed couplings

A ➛ Zh ➛ ℓℓ ττ

CMS: PAS-HIG-018-023, March 2019

H ➛ WW

CMS-PAS-HIG-17-033, March 2019

A ➛ Zh ➛ ℓℓ bb

CMS-PAS-HIG-18-005

A ➛ Zh ➛ (ℓℓ /νν) bb

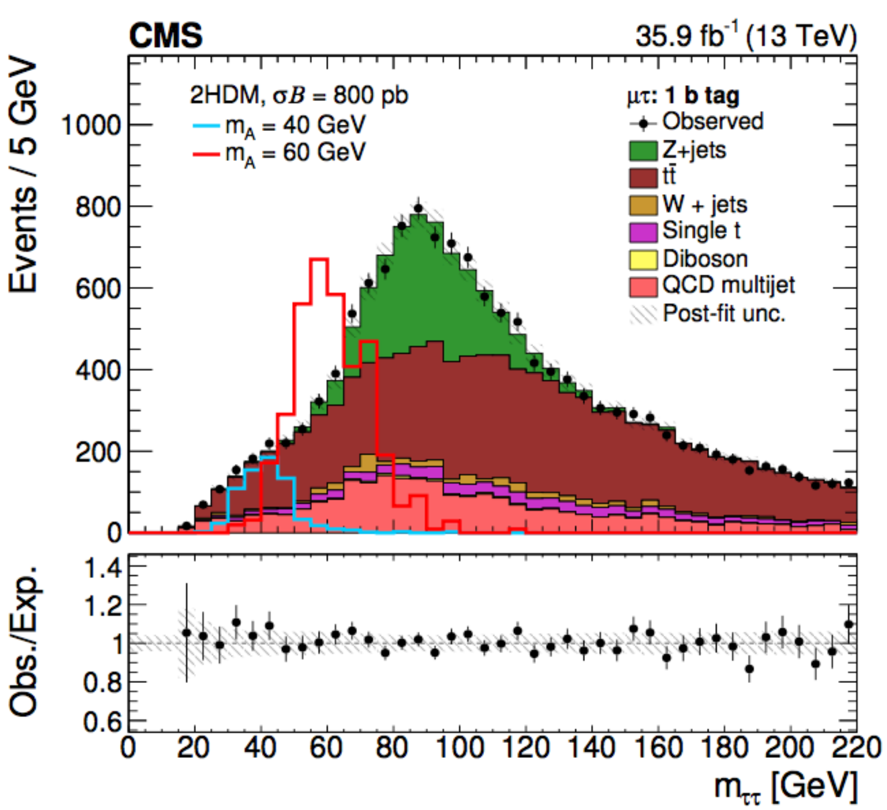
ATLAS: JHEP 03 (2018) 174

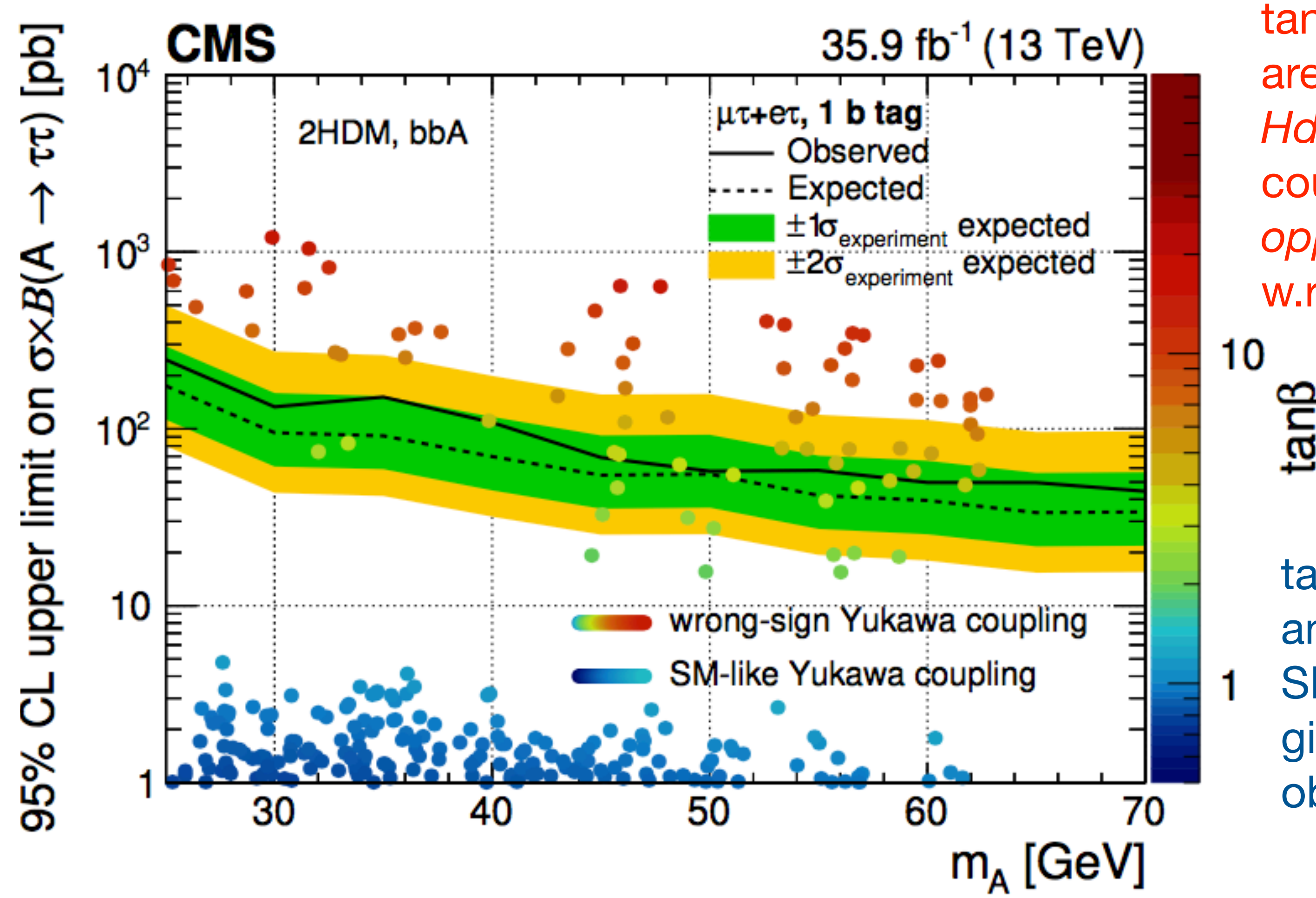
Light NEUTRAL A IN $b(b)A \rightarrow \tau\tau$

CMS: JHEP05(2019)210

*sensitive to type II and X, for high tanβ, **in canonical mass hierarchy scenarios***

- CMS studied also a less conventional scenario using 36 fb^{-1} at 13 TeV
  - a ***light*** *Higgs* **(20-70 GeV)** decaying to ττ and produced in association with b-quarks
    - selection requires one τ_{lep} and one τ_{had}
    - maximum likelihood fit of tau-pair invariant mass $m_{\tau\tau}$ to extract the signal strength





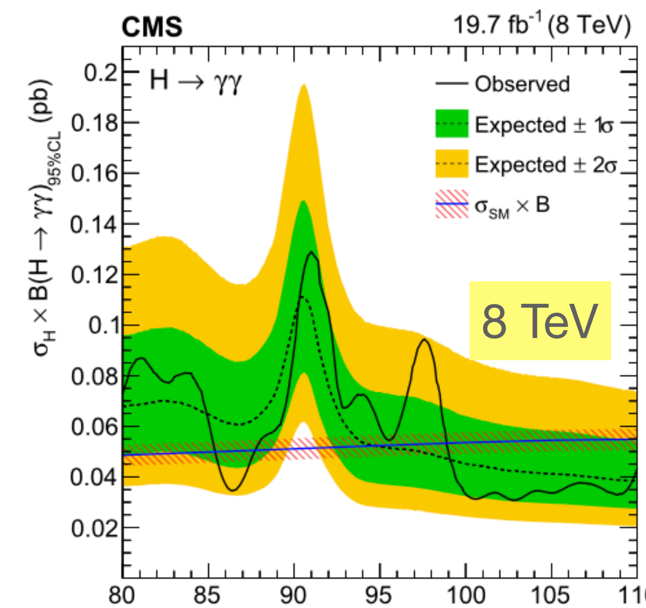
tanβ >1.6-37.0 are excluded for *Hdd* Yukawa coupling of *opposite sign* w.r.t. *SM hdd*

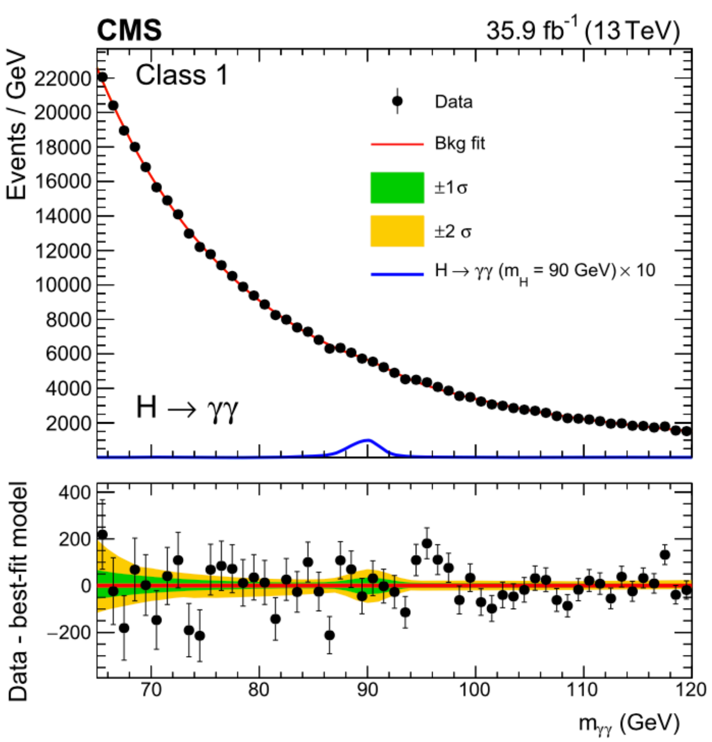
tanβ 0.6-2.0 and *Hdd* with SM-like sign give σxB < observed limit

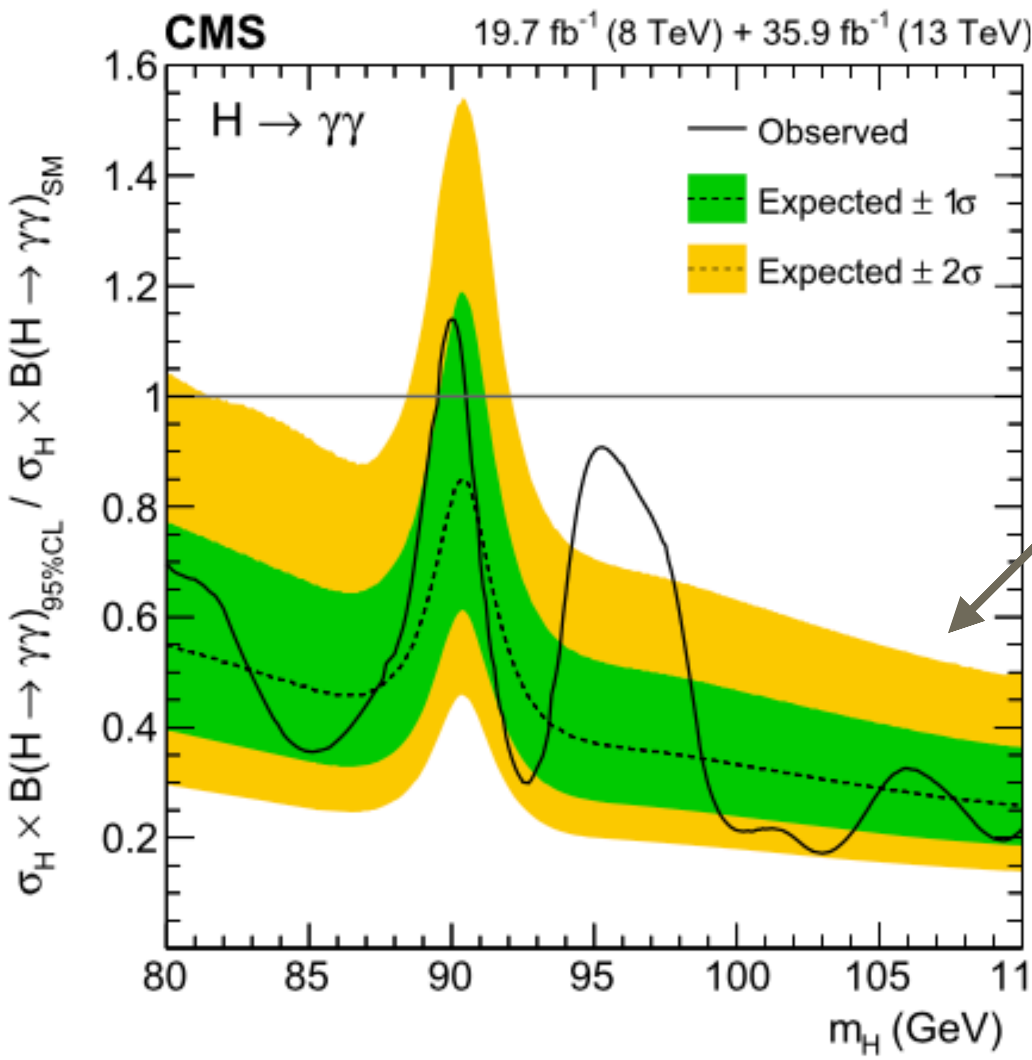
SM-LIKE H➛ γγ AT INTERMEDIATE MASS

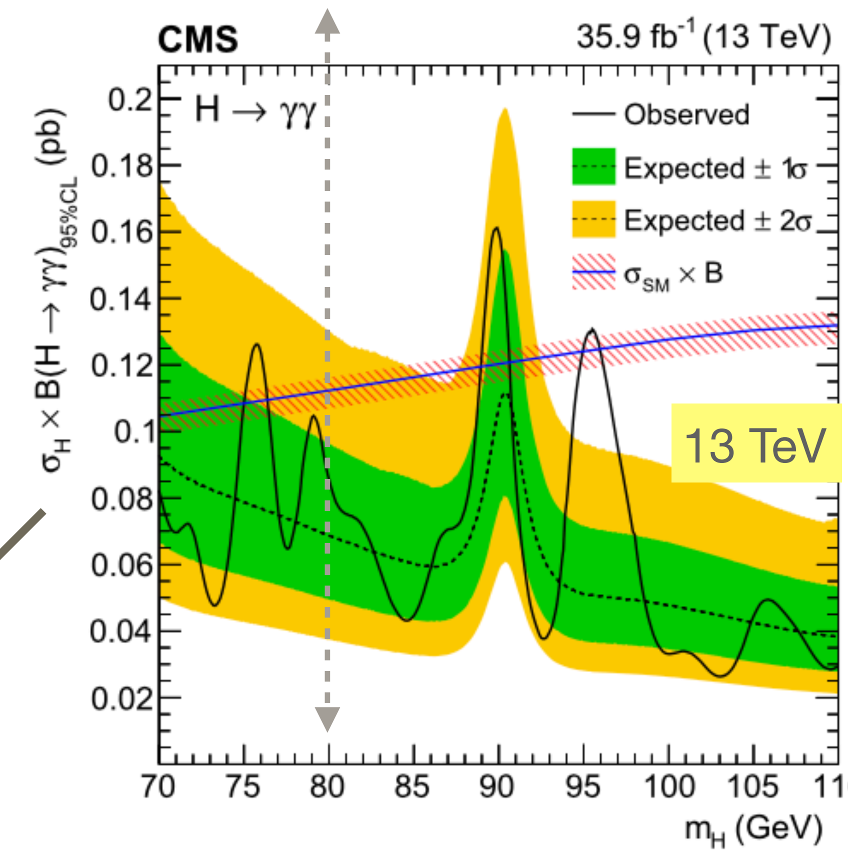
CMS: PLB 793 (2019) 320-347

- Search in the range 70-110 GeV with 8 TeV (20 fb^{-1}) and 13 TeV (36 fb^{-1}) data
- several categories to enhance sensitivity









analysis technique ~ SM h➛γγ

A small excess at ~ 95 GeV (local [global] significance ~2.8 [1.3])
to be watched out with more statistics

ATLAS published with 8 TeV, 20 fb^{-1}
In backup
PRL 113 (2014) 171801

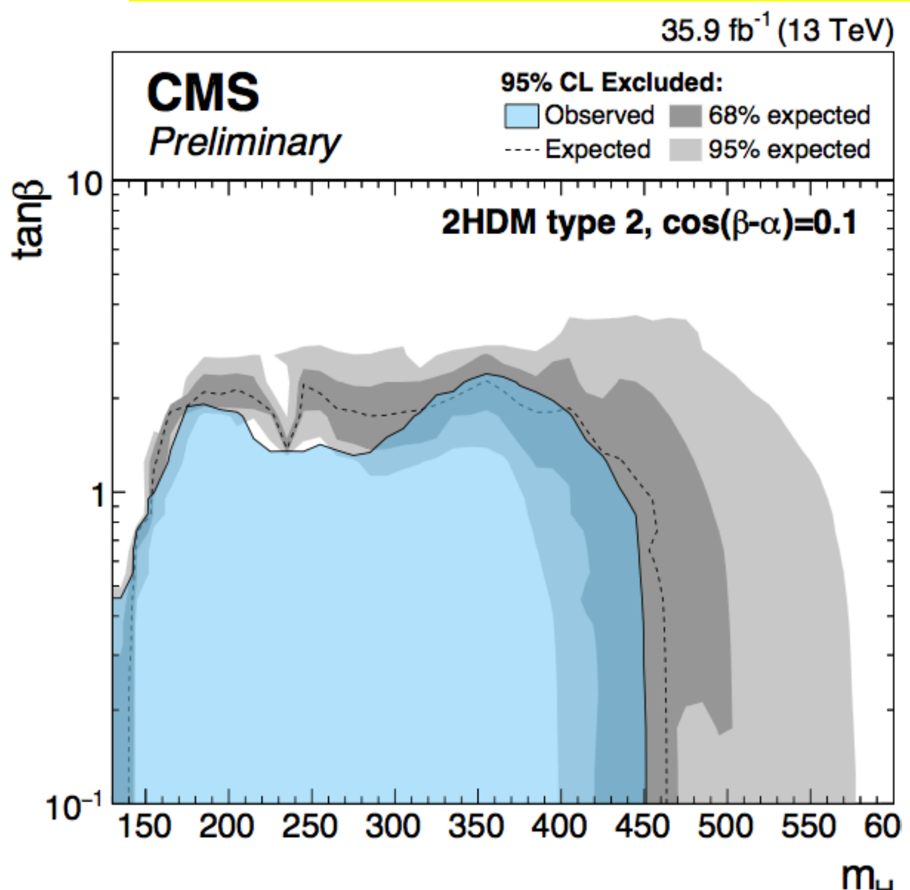
SEARCH FOR *HEAVY* *H* TO *WW*

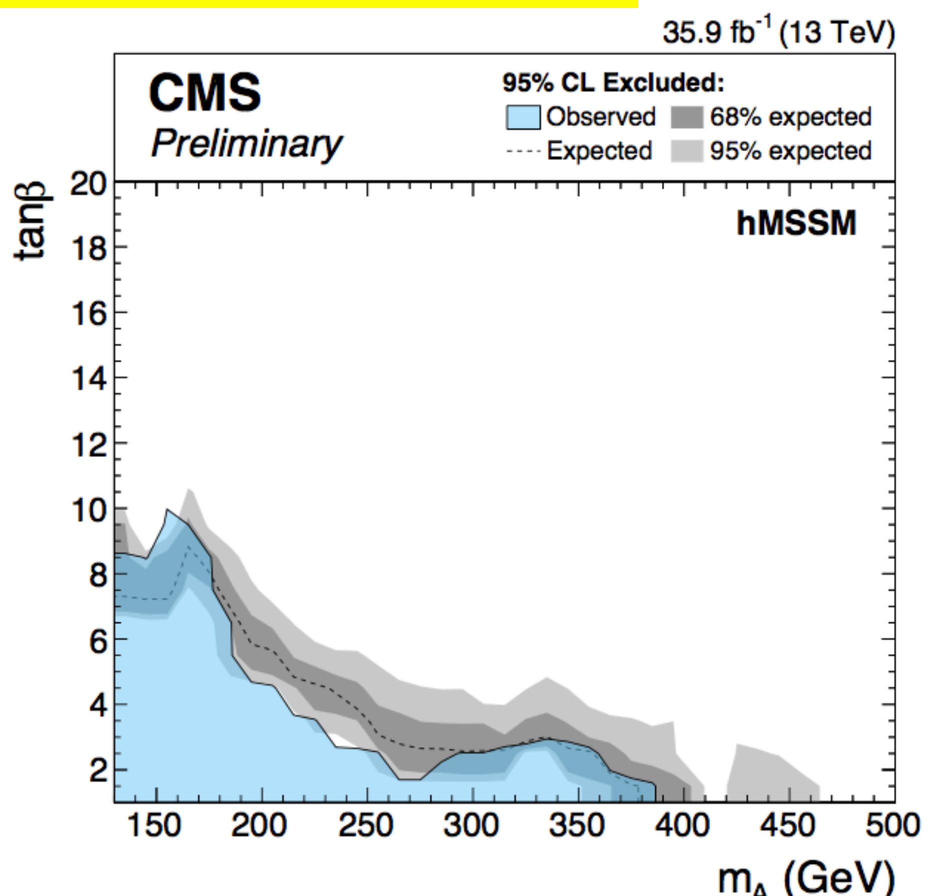
ATLAS: Eur. Phys. J. C 78 (2018) 24

March 2019 CMS: CMS-PAS-HIG-17-033

- ***H ➛ WW (VV in general) strongly suppressed in the alignment limit of 2HDM***
  - A ➛ WW and A ➛ ZZ are forbidden (at tree level) if the CP symmetry is assumed
  - several analyses in the past; the most recent preliminary by CMS (confirming results of ATLAS on the corresponding data set **36fb^{-1} at 13 TeV**) based on ***semi-leptonic and leptonic channels***
    mass range investigated 200 GeV to 3 TeV

a limited region of the parameter space is probed by this channel





VV resonance search at high mass still a must

see, for example, ATLAS VV resonance search in the fully hadronic channel:
arXiv:1906.08589 ***in Nadir D. talk***

no explicit interpretation in BSM Higgs scenarios

STATUS OF A BENCHMARK 2HDM SCENARIO: *hMSSM*

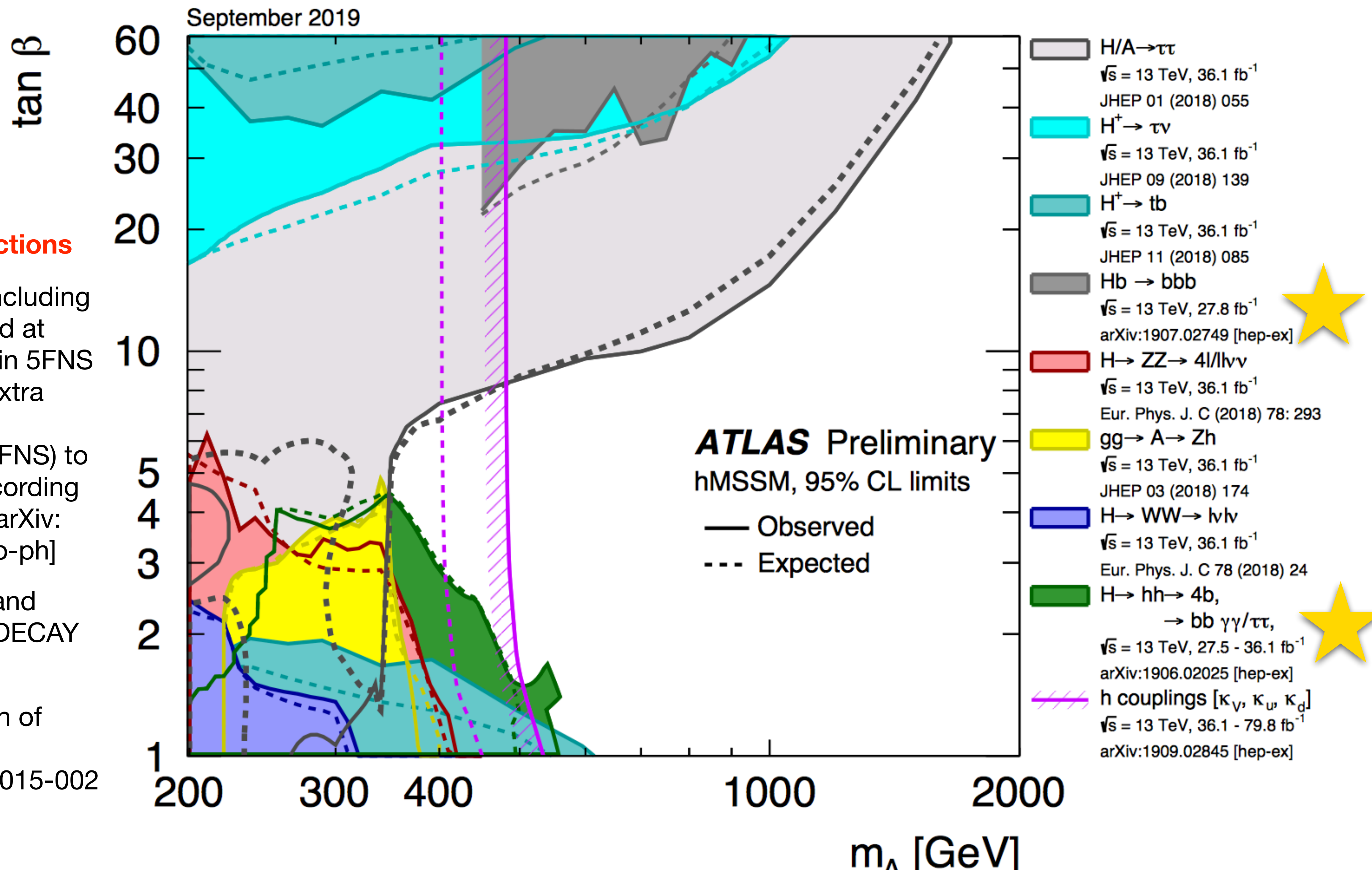
new ATLAS combination for PIC-2019

hMSSM predictions

σ with **SuShi** including ggF+b-ass.prod at NNLO in QCD in 5FNS corrected for extra contributions (estimated in 4FNS) to b-ass.prod according to recomm. in arXiv: 1112.3478 [hep-ph]

Partial widths and decays with HDECAY

for a discussion of hMSSM LHCHXSWG-2015-002



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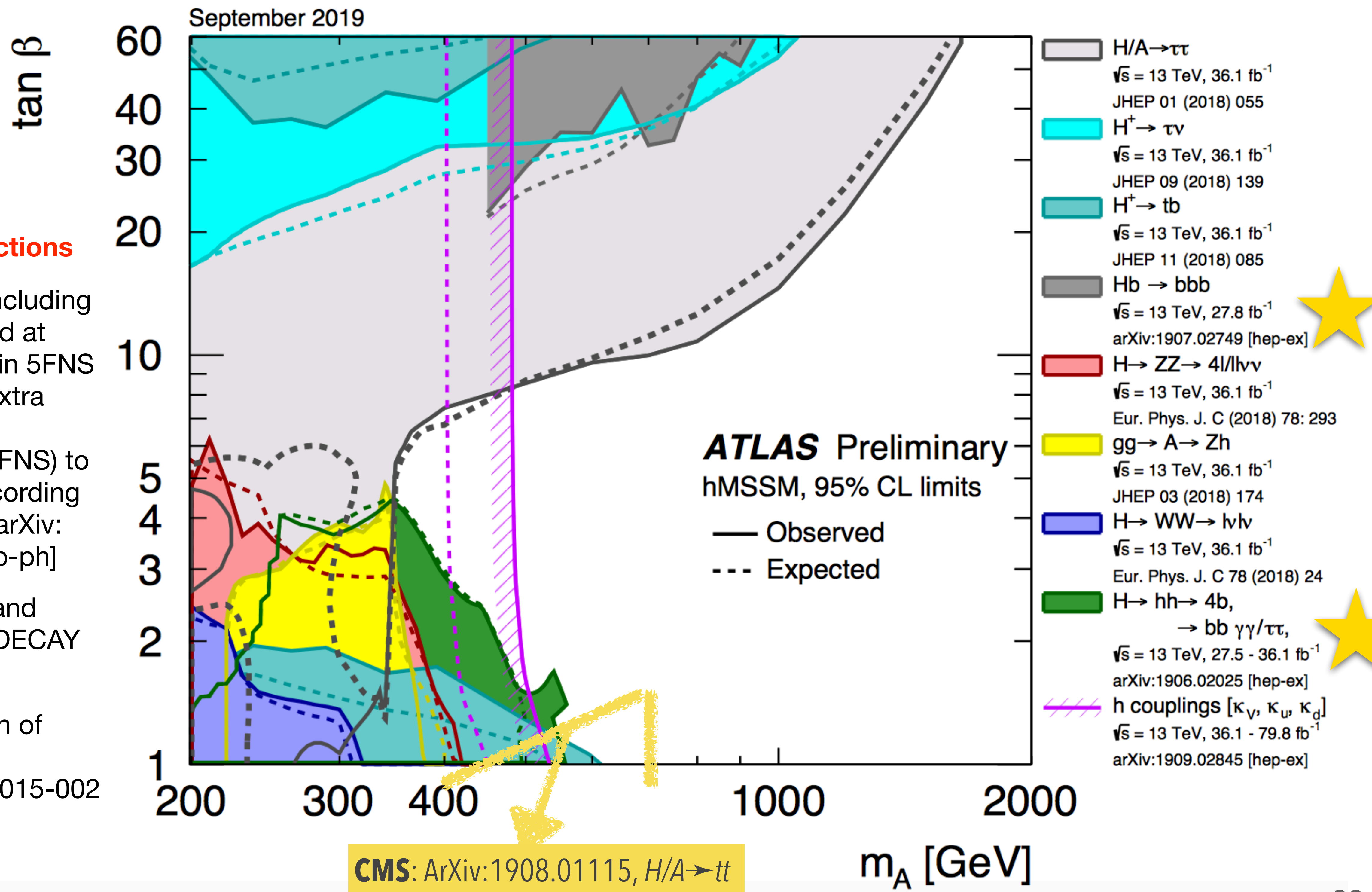

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Partial widths and decays with HDECAY

for a discussion of hMSSM LHCHXSWG-2015-002

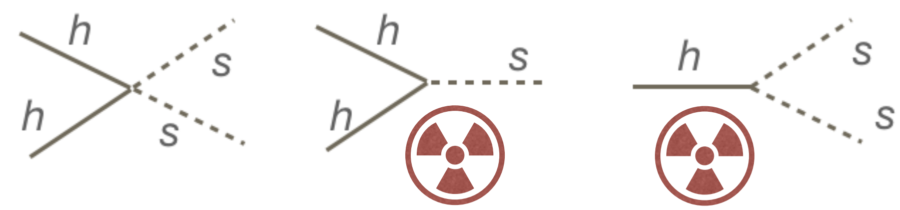
BEYOND 2HDM

Search for Higgs in next to minimal models
Higgs portal to a secluded sector
LFV Higgs decays

Back to generalities of BSM Higgs

Any extra scalar ?

SM+**s**
comes with many
CAVEAT
see, for example,
arXiv:1409.0005



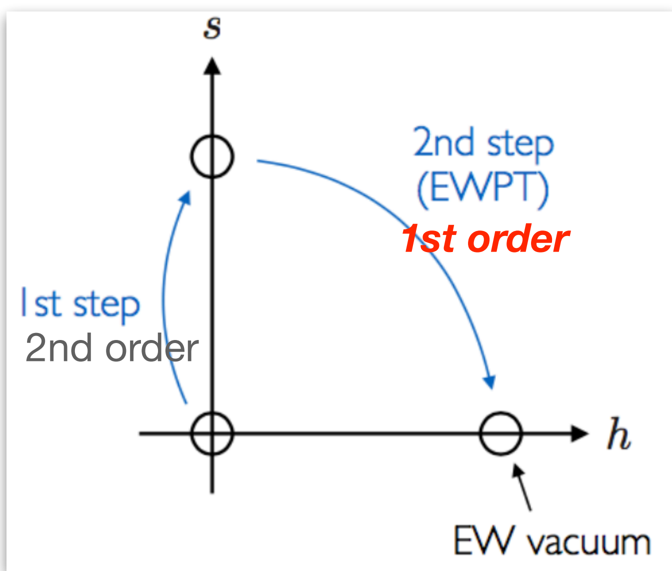
not testable at LHC if compatible with data

a compelling constraint:
custodial SU(2),
i.e. ρ~1

any scalar multiplet must satisfy $I(I+1)=3Y^2/4$

the easiest solutions:
SU(2) doublet with Y=±1
and
SU(2) singlet s with Y=0

see Panico @ EPS-HEP2019



out of eq. phase transition (Sakharov condition) not really possible with SM potential (smooth crossover)
a new scalar **s** allows for a 2-step EW phT

s can be dark matter or can couple to a hidden sector

Dark matter

***2HDM*+s**
is ***viable***
~simple and
theoretically motivated

All the known reasons for 2HDM

EW baryogenesis

gravitational wave signatures (LISA, future interferometers)

2HDM+S SIGNATURES AT LHC

next-to-minimal scenarios

ATLAS:PLB 782 (2018) 750, **h_{SM}→aa→jjγγ**

in backup ATLAS: JHEP06(2018)166, **h_{SM}→aa→4leptons**

in backup ATLAS: JHEP10 (2018) 031, **h_{SM}→aa→bbbb**

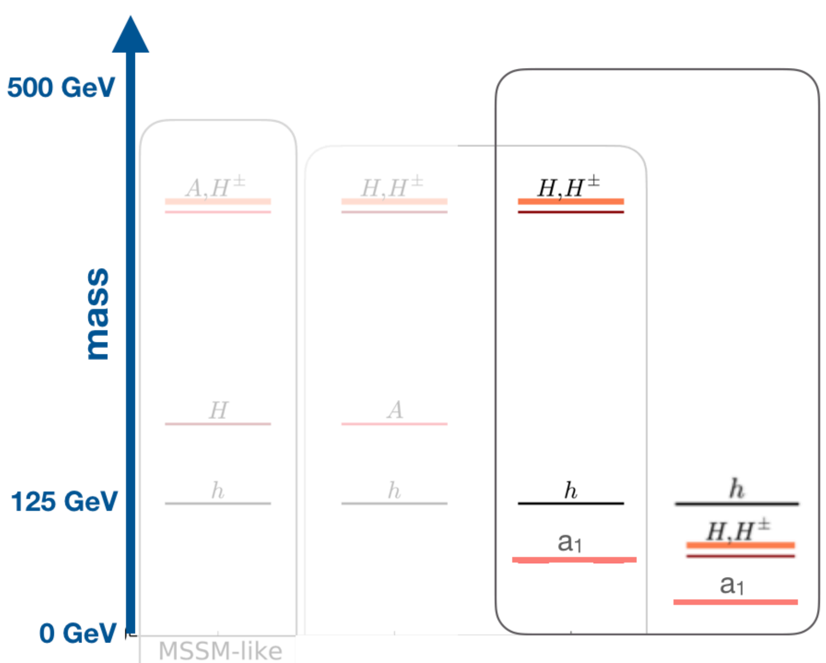
ATLAS: PLB 790 (2019) 1, **h_{SM}→aa→bbμμ**

CMS: PLB 795(2019)398, **h_{SM}→aa→bbμμ** see in backup

CMS: ArXiv:1907.07235, **h_{SM}→aa→μμ+2tracks**

CMS: ArXiv:1905.07453, **$H^{+/-}$→$W^{+/-}$a→μμμ/μee**

and many others



next-to-minimal SUSY models

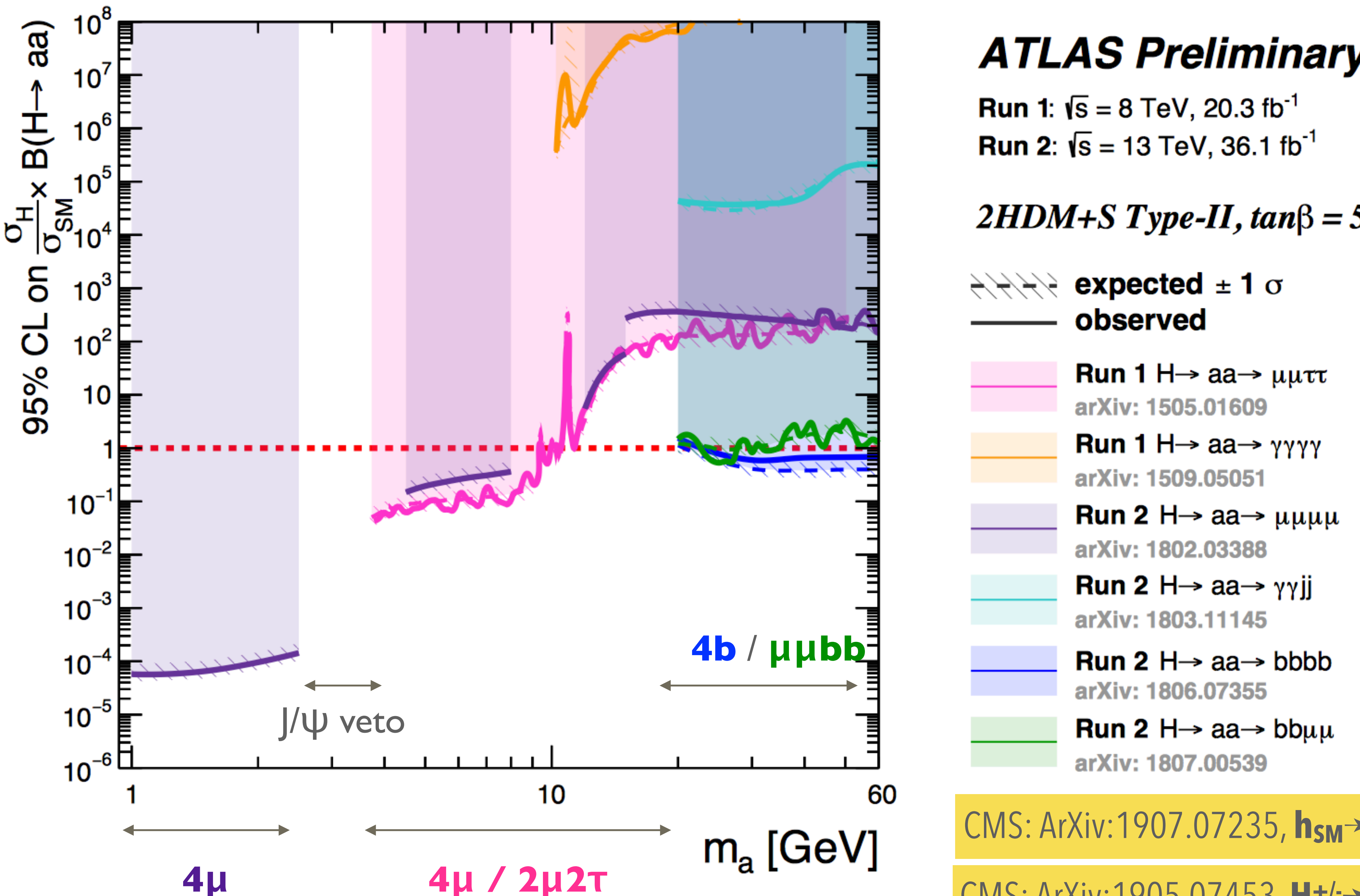
Models with dark matter in a secluded sector

- several processes allowed in non-minimal supersymmetric SM and the lepton specific and flipped ***2HDM+S*** (a 2HDM model extended with a scalar singlet)
  - ***3 CP-even, 2 CP-odd, H^+,H^-***
- *no S-fermion Yukawa couplings*
- if ***a_1 mass < 125 GeV***, **a_1 has large S component**
  - production via ggF and associated b production highly suppressed
  - ***h-> a_1a_1*** is accessible
    - h couplings measurement still allow for $\mathcal{B}$~30% to non-SM particles

STATUS OF A BENCHMARK 2HDM+S SCENARIO: type II tanβ=5

- December 2018 ~ PIC-2018
- *useful to get a feeling of the channel relative sensitivity*

see ATL-PHYS-PUB-2018-045 for constraints on many alternate scenarios



see backup

CMS: ArXiv:1907.07235, $h_{SM} \to aa \to \mu\mu$+2tracks

CMS: ArXiv:1905.07453, $H^{+/-} \to W^{+/-}a \to \mu\mu\mu/\mu ee$

STATUS OF A BENCHMARK 2HDM+S SCENARIO: type II tanβ=5

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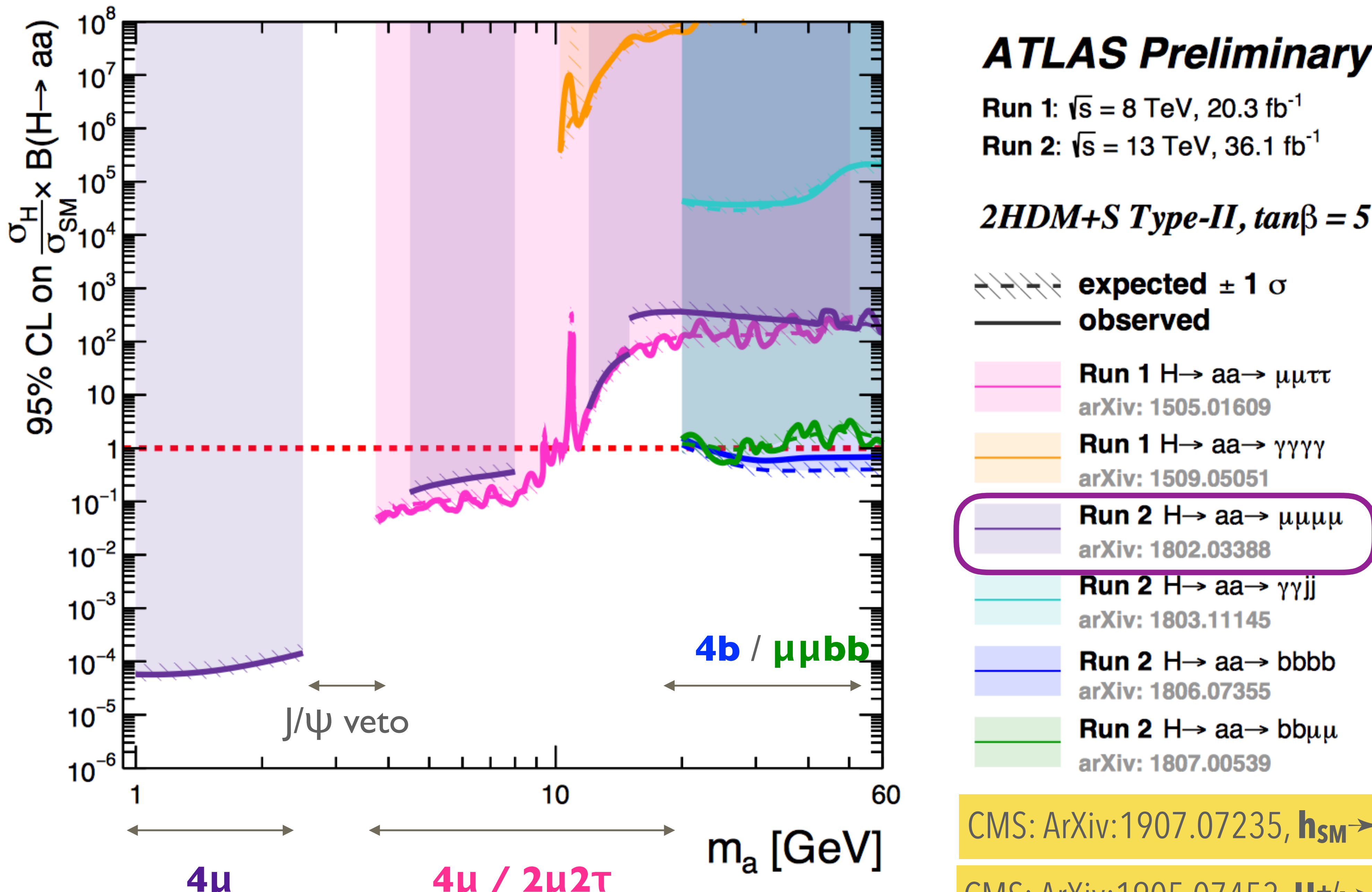


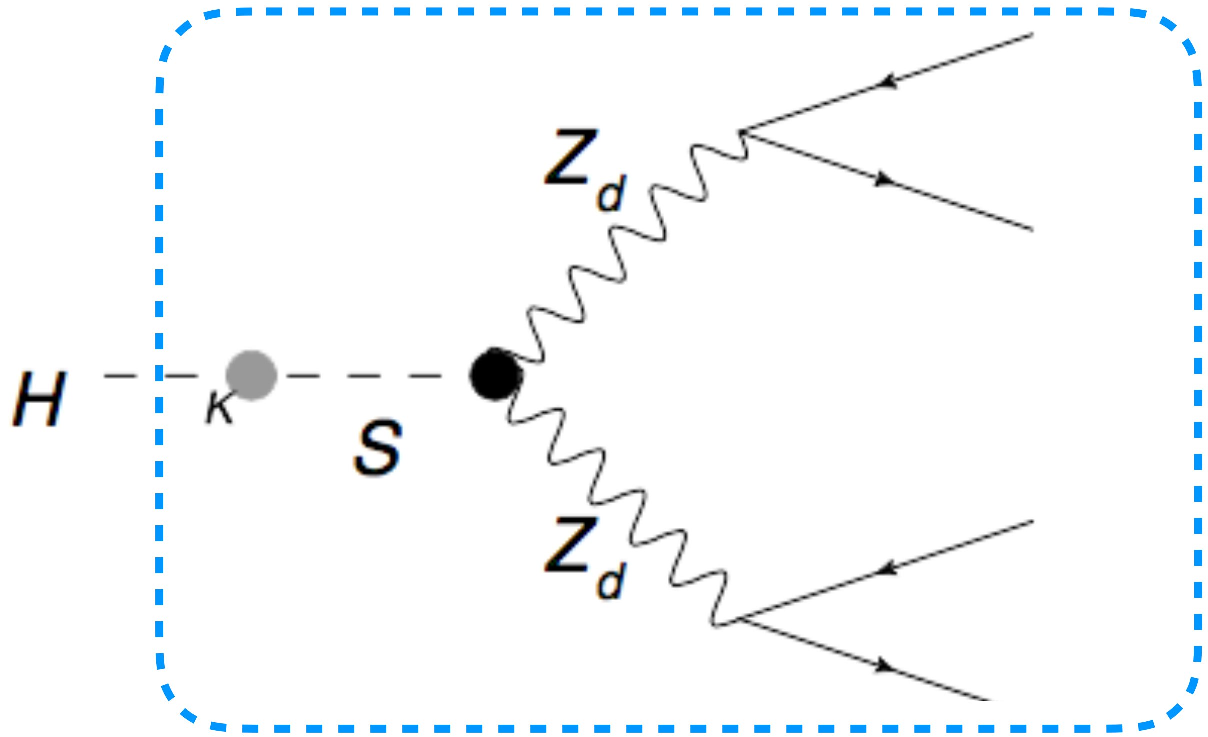
see backup

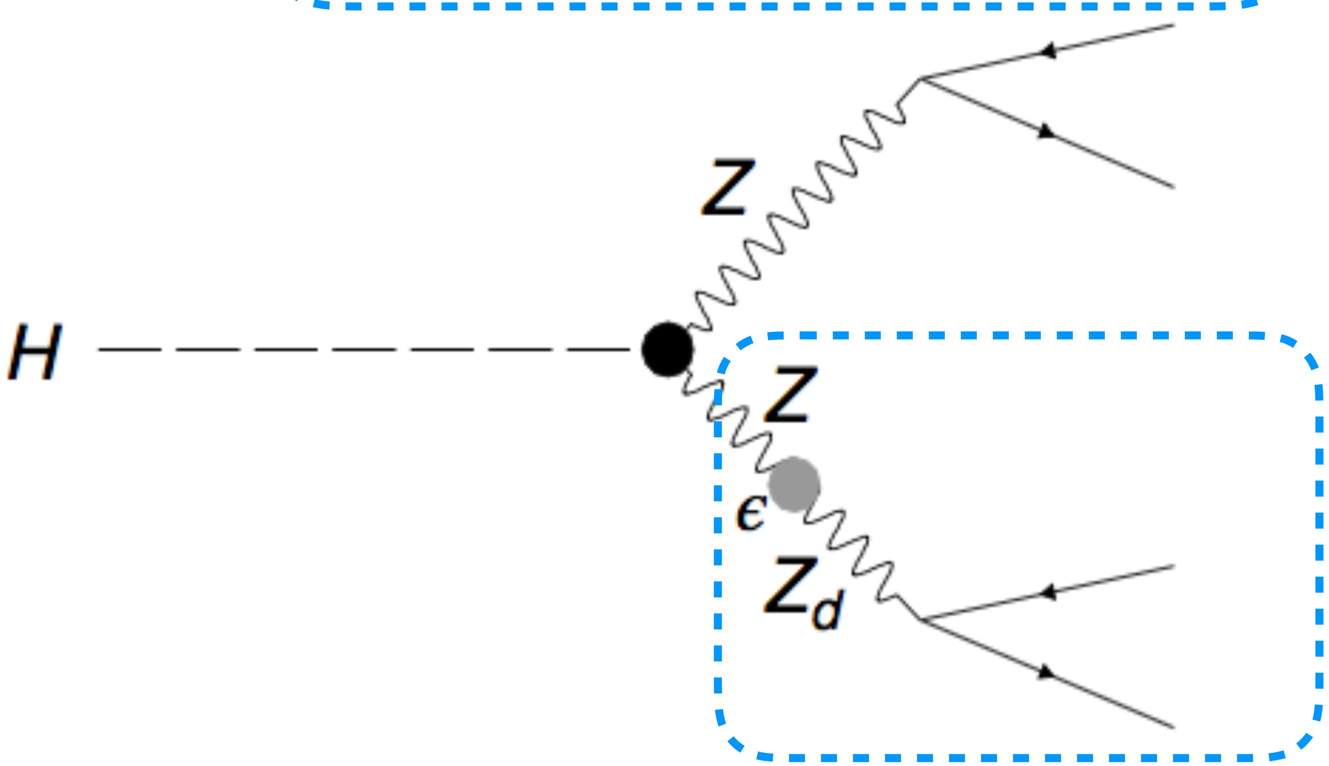
CMS: ArXiv:1907.07235, h_{SM}→aa→μμ+2tracks

CMS: ArXiv:1905.07453, $H^{+/-}$→$W^{+/-}$a→μμμ/μee

Another class of models:

Higgs portal to a Secluded/Hidden/Dark sector





particles of a hidden sector neutral under SM gauge interactions

Run 2 H→ aa→ μμμμ
arXiv: 1802.03388

not only H→aa

ATLAS: JHEP06(2018)166, **h_{SM}→aa→4leptons**

see in backup

constraints on the parameters of a **Hidden Abelian Higgs Model (HAHM)**

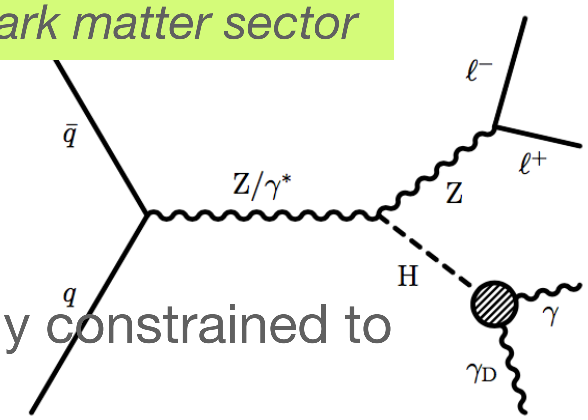
$h/H \to X\gamma \to \gamma$ + Invisible

for m_H in 125 - 300 GeV

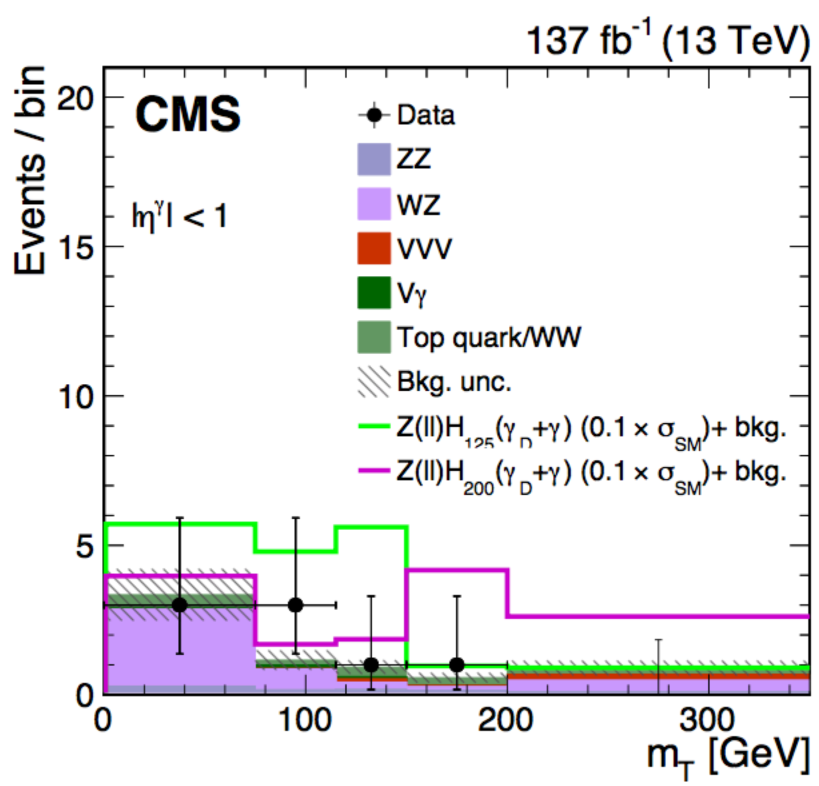
CMS: arXiv:1908.02699

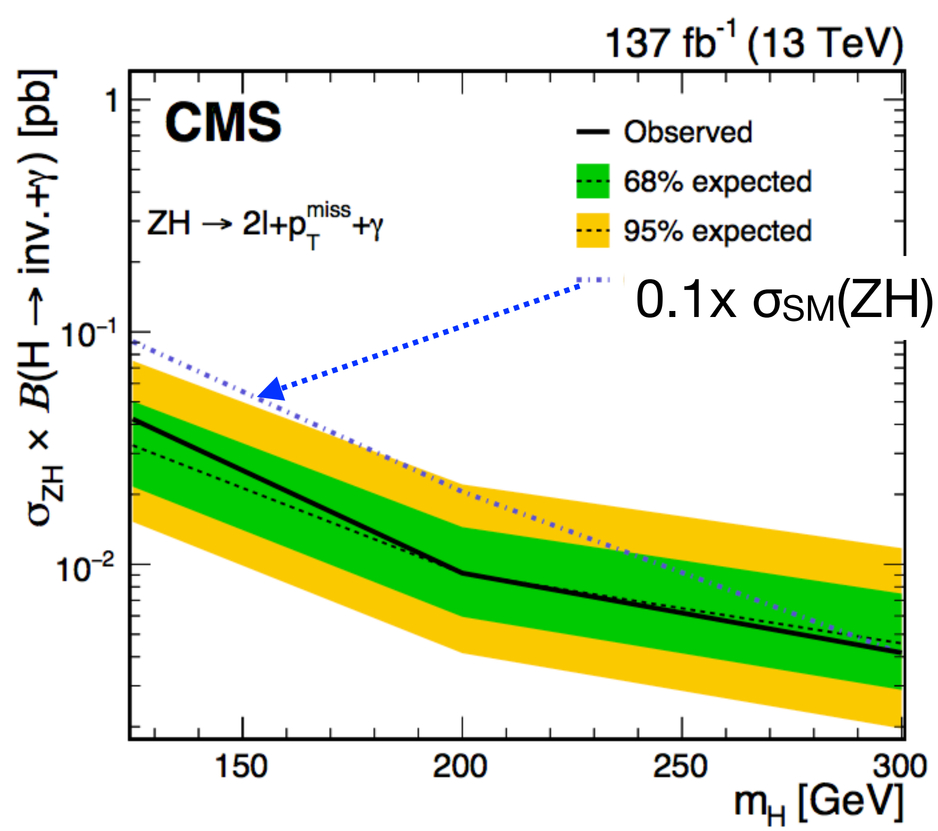
X= massless Dark Photon

in the realm of a secluded dark matter sector



- H produced in association with a Z decaying leptonically
- **137 fb^{-1} at 13 TeV**
- in the SM $\mathcal{B}(H \to \gamma Z(\nu\nu))$~3x10^{-4} below the sensitivity of this analysis and already constrained to ~3,4xSM prediction
- main background: WZ (or ZZ) -> $e\nu_e$Z (eeZ) with the electron reconstructed as a photon (the second *e* not reconstructed, undetected); next top, WW, etc
- binned maximum-likelihood fit to m_T distributions in 2($|\eta_\gamma|$< or >1) signal + 2x3(WZ,ZZ,top) control regions





Assuming SM production cross section for m_H=125GeV $\mathcal{B}(H \to \gamma$+massless invisible particle)>4.6(3.6) % is excluded at 95%CL

INVISIBLE HIGGS DECAYS

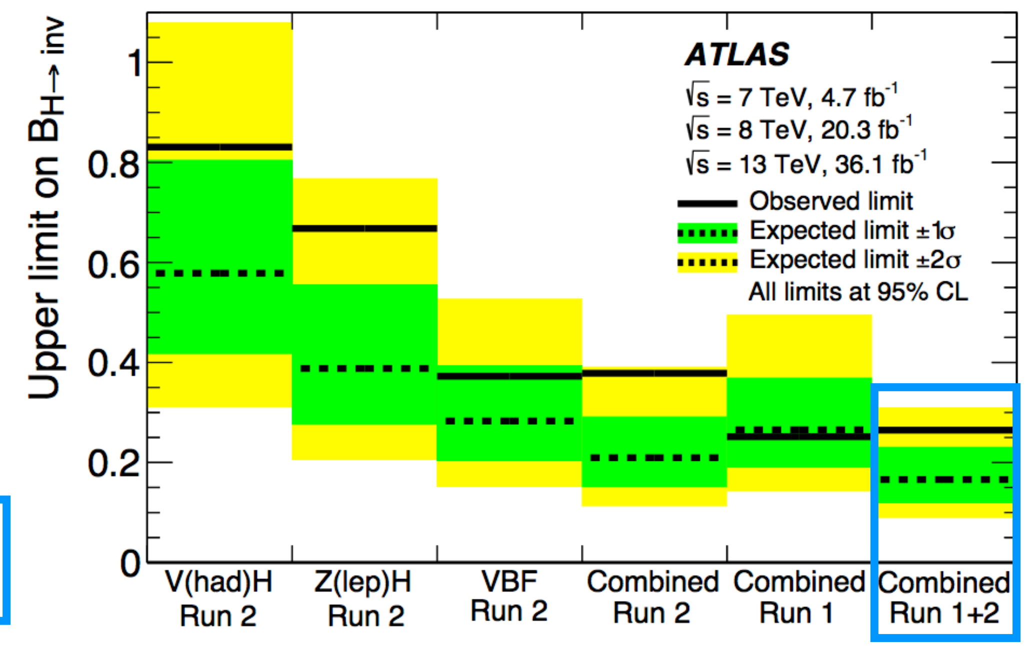
Higgs portal to Hidden Sector via Yukawa couplings to WIMPs

ATLAS: PRL 122 (2019) 231801 CMS: PLB 793 (2019) 520

- Searches for invisible decays of Higgs produced in VBF (CMS, ATLAS), in association with Z(ll) or Z/W(hadrons) (ATLAS) in 36 fb^{-1} at 13 TeV (and combined with 7 and 8 TeV data)

CMS: $\mathcal{B} < 0.19(0.15)$ @ 95% CL

ATLAS $\mathcal{B} < 0.26\ (0.17^{+0.07}_{-0.05})$ @ 95% CL
expected

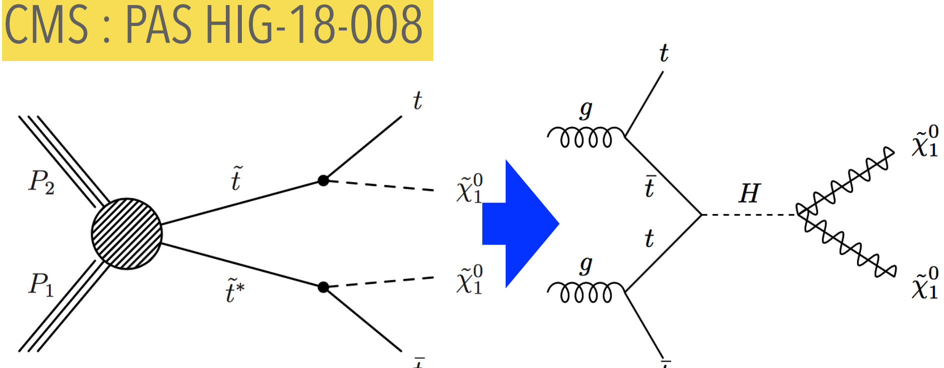


Interpreting H➛invisible as H➛χχ (χ=WIMP fermion or scalar) in an EFT approach and using f_N=0.308 ± 0.018

=> **limit on the WIMP-N cross section**

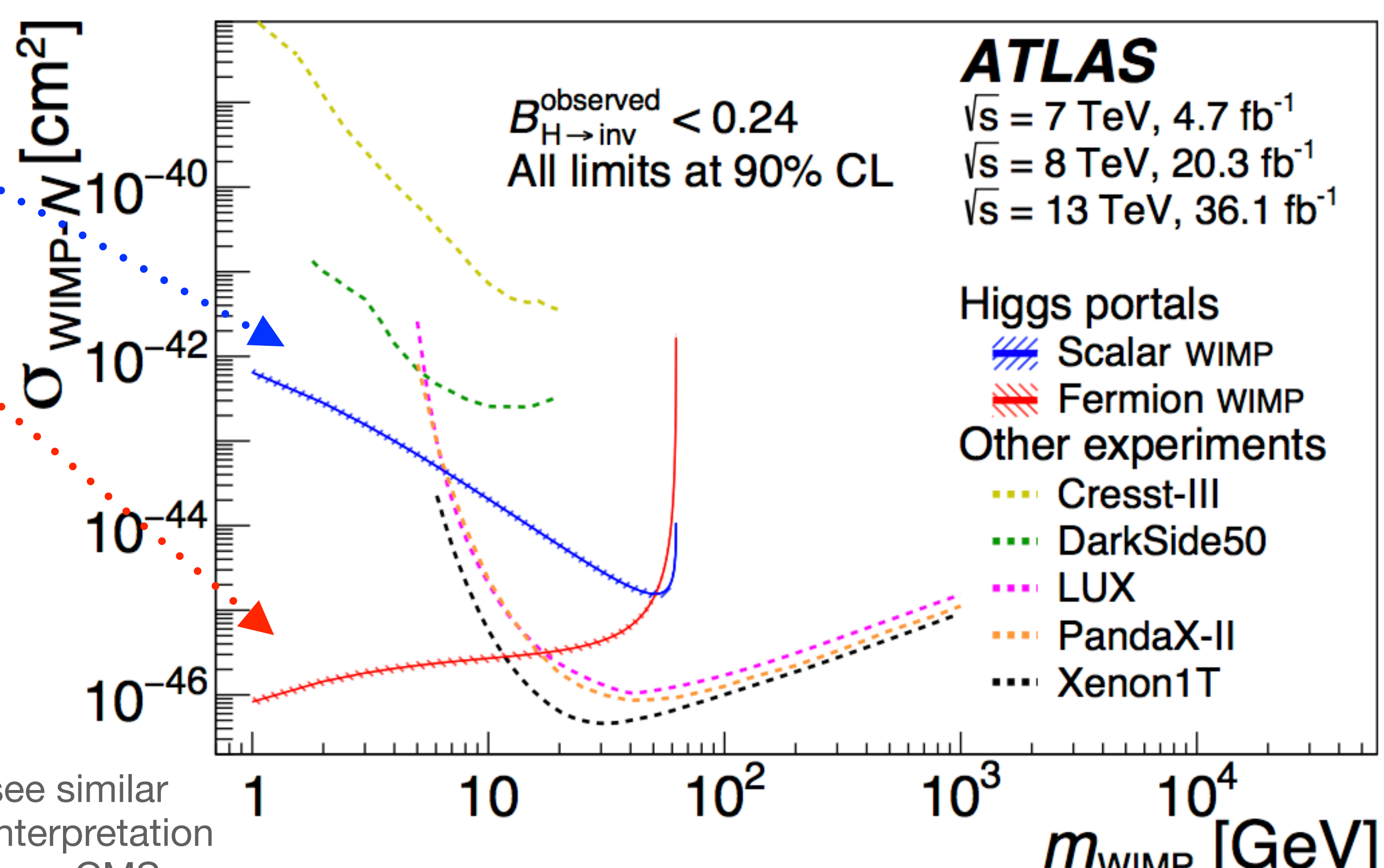
Recent recasting of results from a search for stop pair production in

CMS : PAS HIG-18-008



36 fb^{-1} at 13 TeV

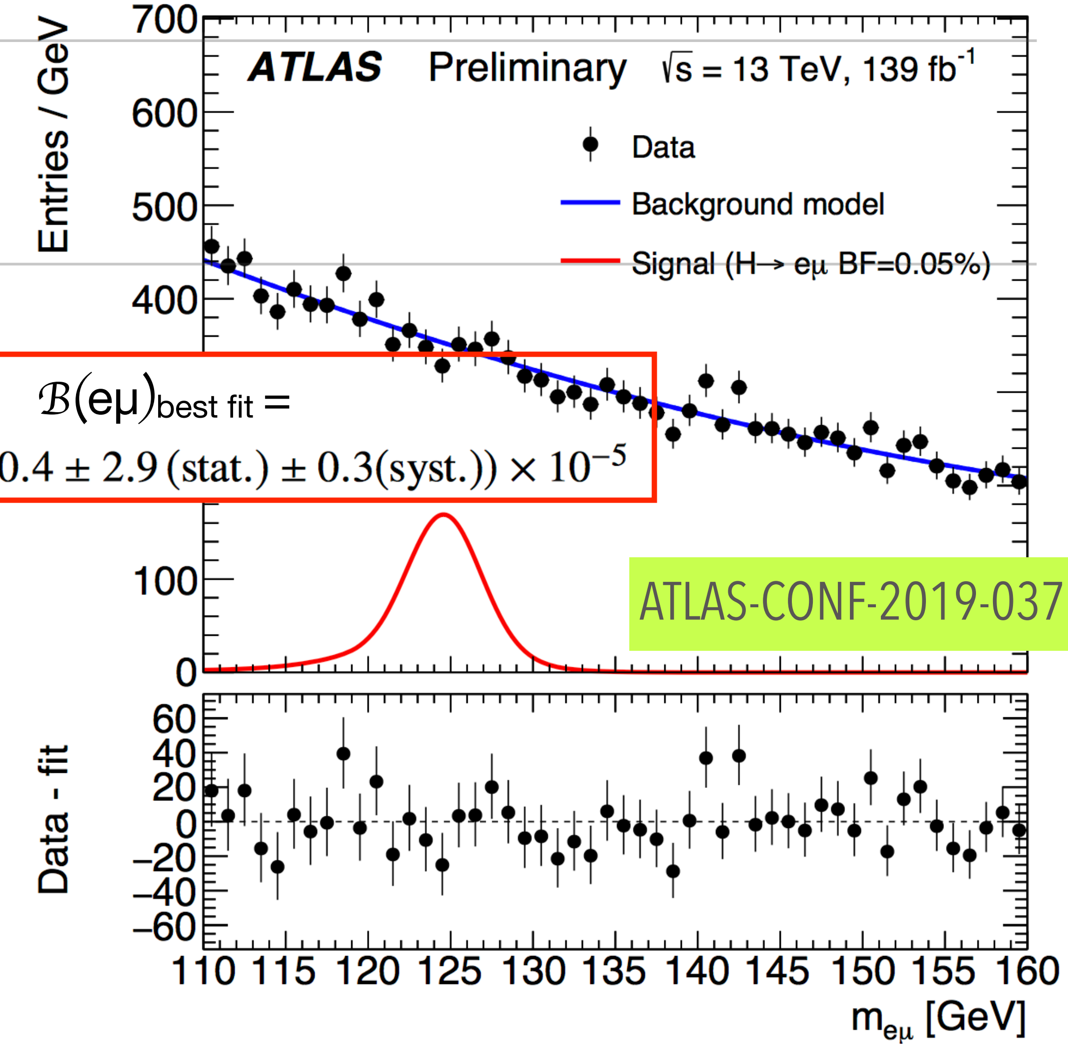
$\mathcal{B}(H \rightarrow inv) < 0.46\ (0.48)$



see similar interpretation from CMS. in backup

LFV DECAYS: *h*➛*eμ*

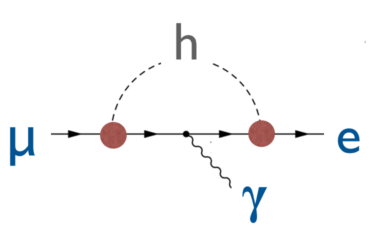
- ATLAS preliminary search for *h->eμ* decay with ***full Run2 statistics 139 fb^{-1} at 13 TeV***
- 8 categories of events corresponding to different $m_{e\mu}$ resolution
  - Combined fit of to the $m_{e\mu}$ binned spectra
  - Background (mainly from top-events) from data (sidebands)



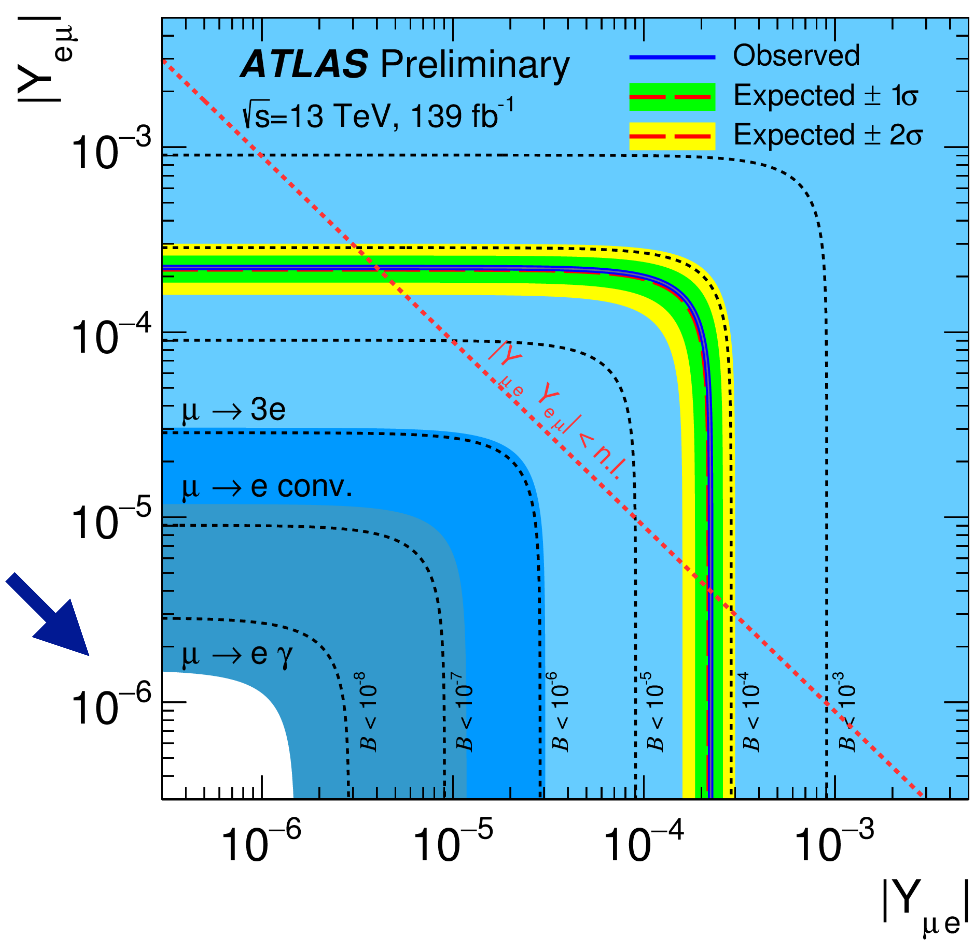
$\mathcal{B}(e\mu)_{\text{best fit}} = (0.4 \pm 2.9\,(\text{stat.}) \pm 0.3(\text{syst.})) \times 10^{-5}$

ATLAS-CONF-2019-037

Indirect constraints rely on SM values for the yet unmeasured Y_{ee}, $Y_{\mu\mu}$



Interpretation according to JHEP03(2013)026



$$\mathcal{B}(H \to ee) < 3.6 \times 10^{-4}\ (3.5 \times 10^{-4})$$
$$\mathcal{B}(H \to e\mu) < 6.1 \times 10^{-5}\ (5.8 \times 10^{-5})$$

36 fb^{-1} at 13 TeV

$H \to \mu\tau$	<0.25 (0.25)%	$0.47\%\ (0.34^{+0.13}_{-0.10}\ \%)$
$H \to e\tau$	<0.61 (0.37) %	$0.28\%\ (0.37^{+0.14}_{-0.10}\ \%)$

more in backup

CMS: JHEP06(2018)001

ATLAS: arXiv:1907.06131

see also heavy H (200-900 GeV) to τe or τμ CMS PAS HIG-18-017

in backup

HIGGS PAIR PRODUCTION

WHY DOES HIGGS PAIR PRODUCTION MATTER ?

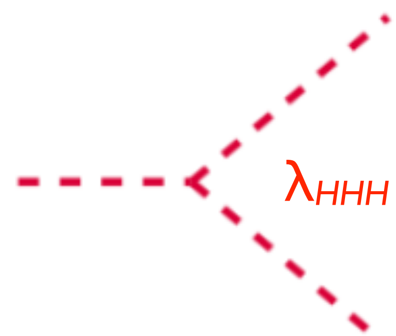
- ***SM prediction*** for 2H production (in ggF) known to NNLO + NNLL (QCD) and top-quark mass effect at NLO

$$\sigma_{HH} = 33.53^{+4.3\%}_{-6.0\%}(\text{QCD scale}) \pm 5.9\%(\text{other})\ \text{fb}$$

PDF uncertanities
α_s uncertanty
top-quark mass effect

- ***Higgs potential (non-resonant):***
  - a key/unknown parameter of the EW SSB mechanism: trilinear Higgs coupling gives contributions to Higgs pair-production

$$\lambda_{HHH} \stackrel{?}{=} \lambda_{SM} \sim m_h^2/(2v^2)$$

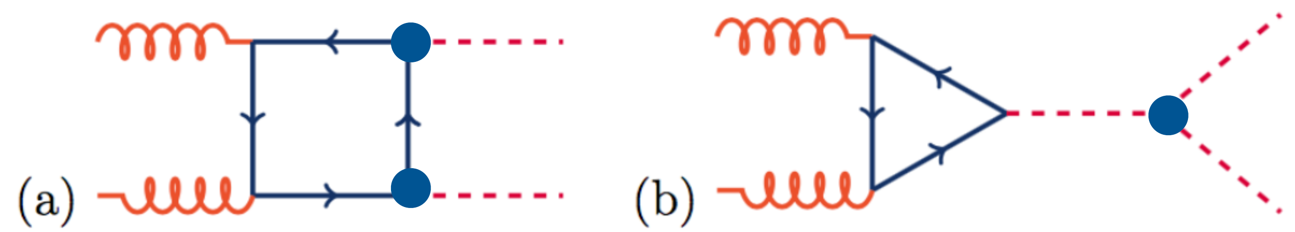


Precision electroweak observables
(oblique parameters: S,T affected via virtual loop by λ_{HHH}) imply
$\lambda_{HHH}/\lambda_{SM}$ in [-14, 17.4]
PRD 95, 093004 (2017)

- ***BSM physics (resonant, non-resonant):***
  - resonant or anomalous Higgs pair production foreseen in various scenarios:
    - 2HDM
    - Hidden sector models
    - bulk RS models

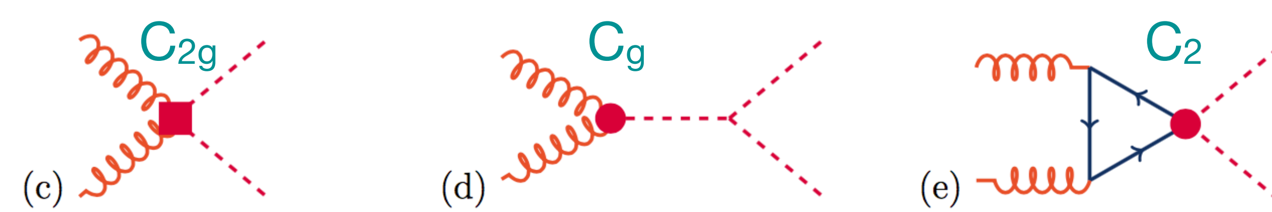
PROBING THE HIGGS POTENTIAL

- in the SM top-loop and 3-linear Higgs coupling diagrams are the dominant contributions
  - large negative interference ! Total cross section depends heavily on the intensity of λ_{HHH}
- a general strategy: probe the Higgs potential via non-resonant production in an EFT approach with dim-6 operators
  - *modifiers for the couplings* (Higgs-top and trilinear Higgs) in the SM diagrams + *3 new couplings*; ***5 parameters overall***



$\kappa_t = y_t/y_{tSM}$ $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$

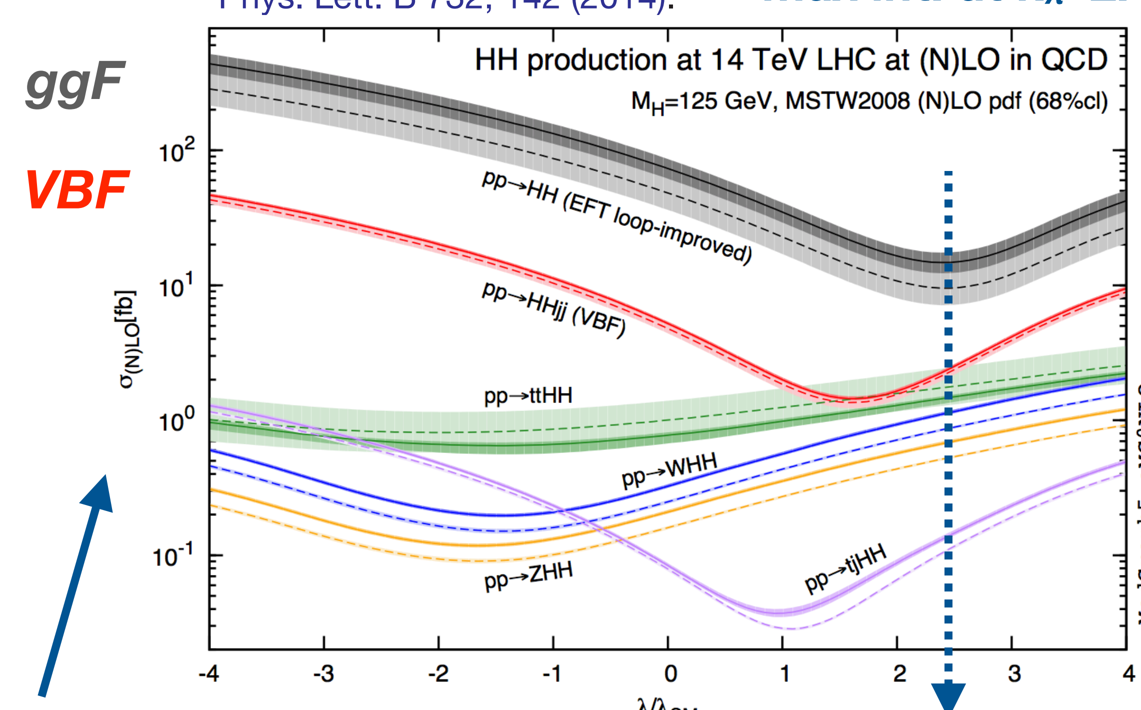
strength modified in EFT



new couplings in EFT

Phys. Lett. B 732, 142 (2014).

max int. at κ_λ=2.4



total cross section vs κ_λ

PRECISION HIGGS MEASUREMENTS AND λ_{HHH}

ATL-PHYS-PUB-2019-009

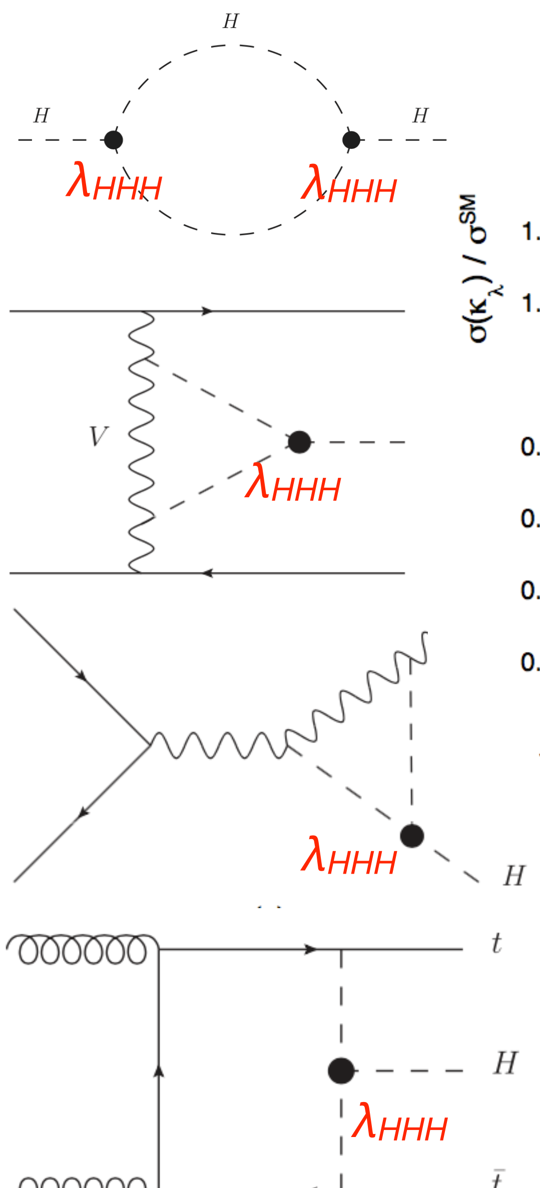
- single Higgs differential production (cross section and kinematics) and decay measurements provide insight onto Higgs self coupling via loop corrections
- decay channels γγ, ZZ*, WW*, ττ and bb studied at ***13 TeV*** with up to ***80 fb⁻¹***

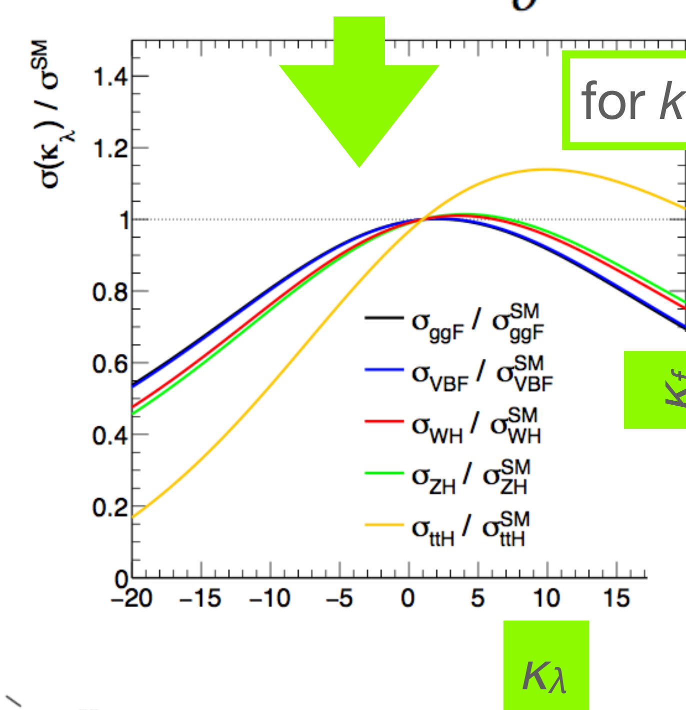
$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\rm BSM}}{\sigma^{\rm SM}} = Z_H^{\rm BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\rm EW}^i}\right]$$

following: 1709.08649 [hep-ph]
singling out the effect of Higgs self-couplings

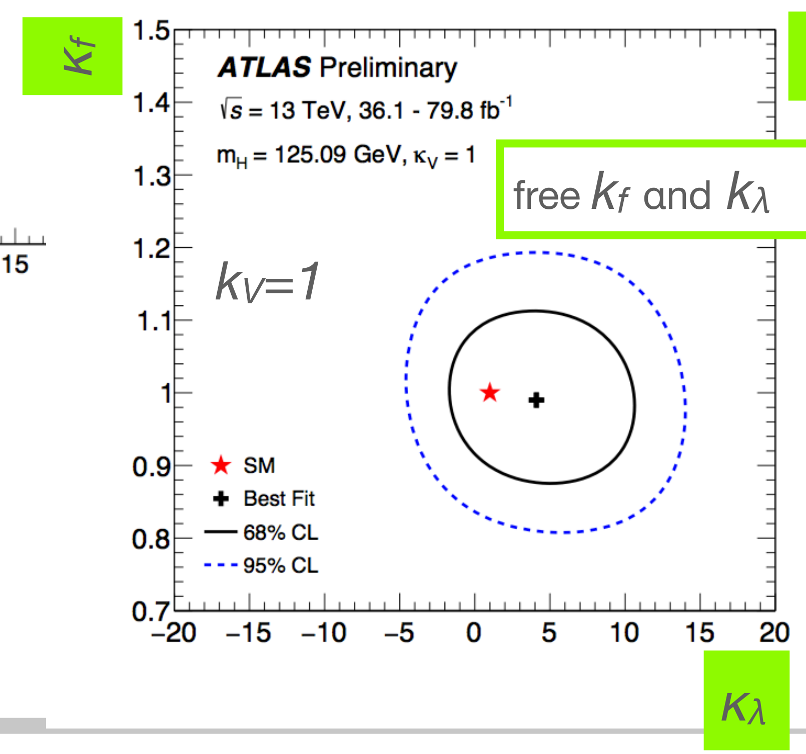
NLO ew corrections

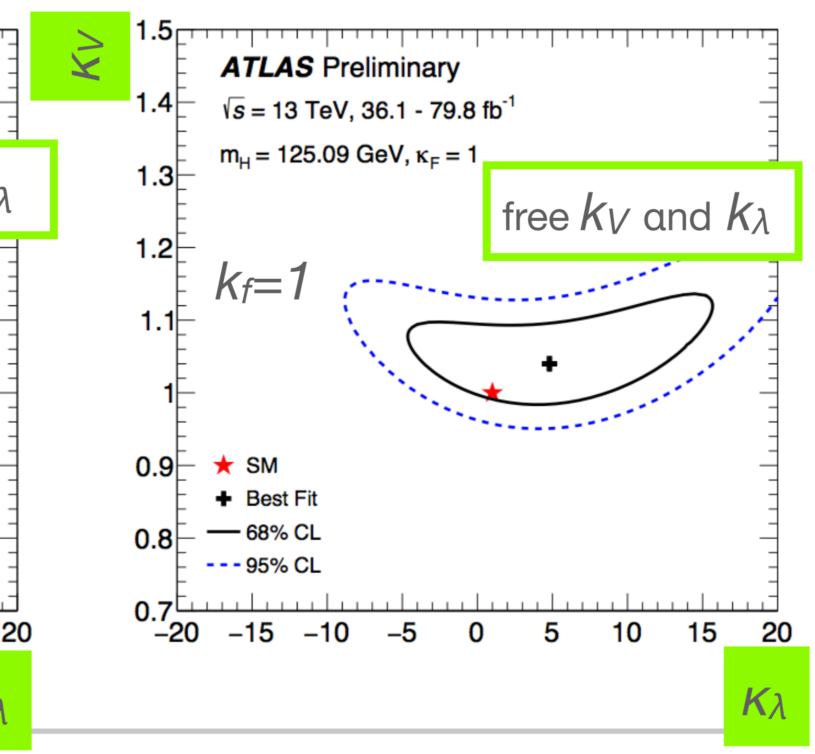
modifiers to Higgs couplings to vectors or fermions





$$\kappa_\lambda = 4.0^{+4.3}_{-4.1} = 4.0^{+3.7}_{-3.6}\,(\text{stat.})\,^{+1.6}_{-1.5}\,(\text{exp.})\,^{+1.3}_{-0.9}\,(\text{sig. th.})\,^{+0.8}_{-0.9}\,(\text{bkg. th.})$$





COMBINATION OF CROSS SECTION MEASUREMENTS

ATLAS: arXiv:1906.02025

13 TeV, ~36 fb^{-1}

CMS: PRL122 (2019) 121803

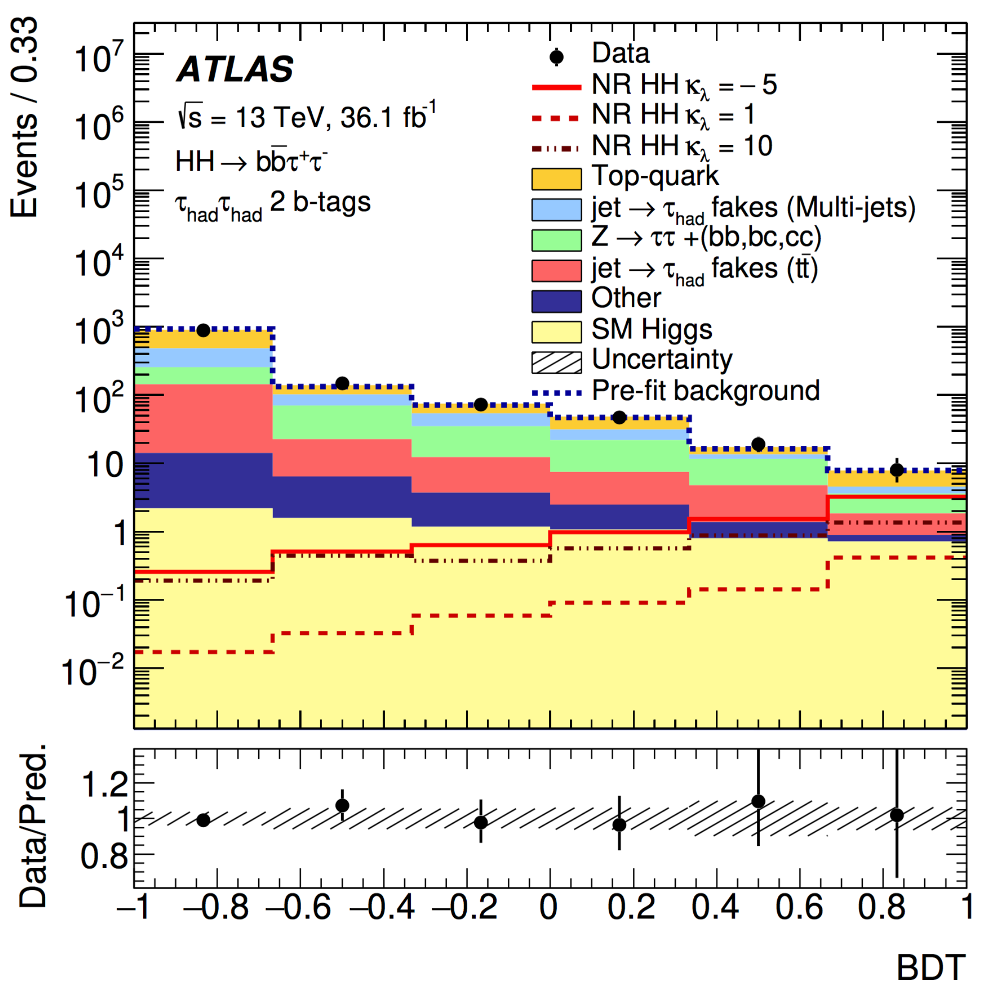
best sensitivity channels

		$\mathcal{B}$	S/B
	$bb\gamma\gamma$	$\mathcal{B}$(HH➛bbγγ) = 0.26%	S/B ≲ 5%
≥ 1 τ ➛had	$bb\tau\tau$	$\mathcal{B}$ = 7.4%	0.4%
	$bbbb$	$\mathcal{B}$ = 33.6%	~ 1%
	$bbVV$, in bbllvv or bblvlv, V=Z or W	$\mathcal{B}$ = 2.7%	S/B ~0.1%
WW➛lvqq	$bbWW$		
WW➛lvqq	$\gamma\gamma WW$		
	$WWWW$		

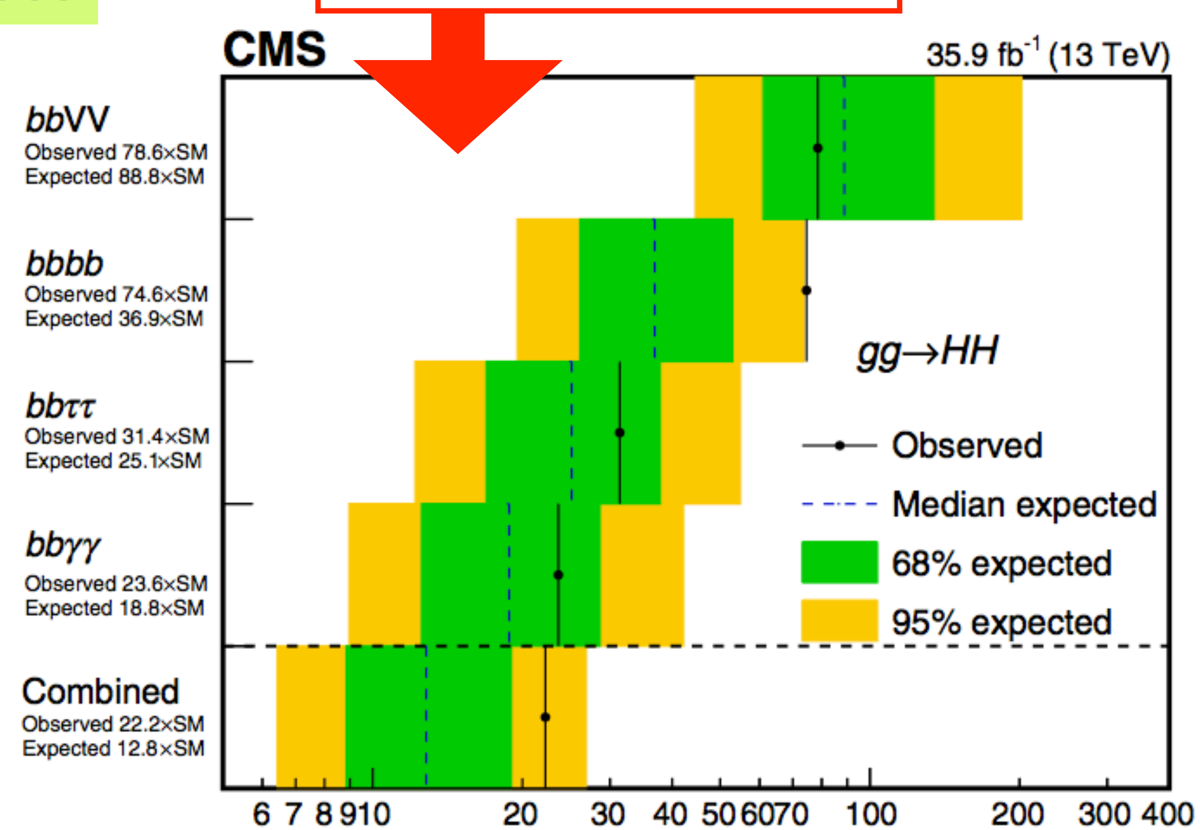
leptonic (no tau) and semileptonic final state

Several categories used in many of the analysis to maximize S/B

Discriminants:
m_{HH}, $m_{\gamma\gamma}$, BDT, ev. counts



95% CL on $\sigma_{HH}/\sigma_{HH}^{SM}$

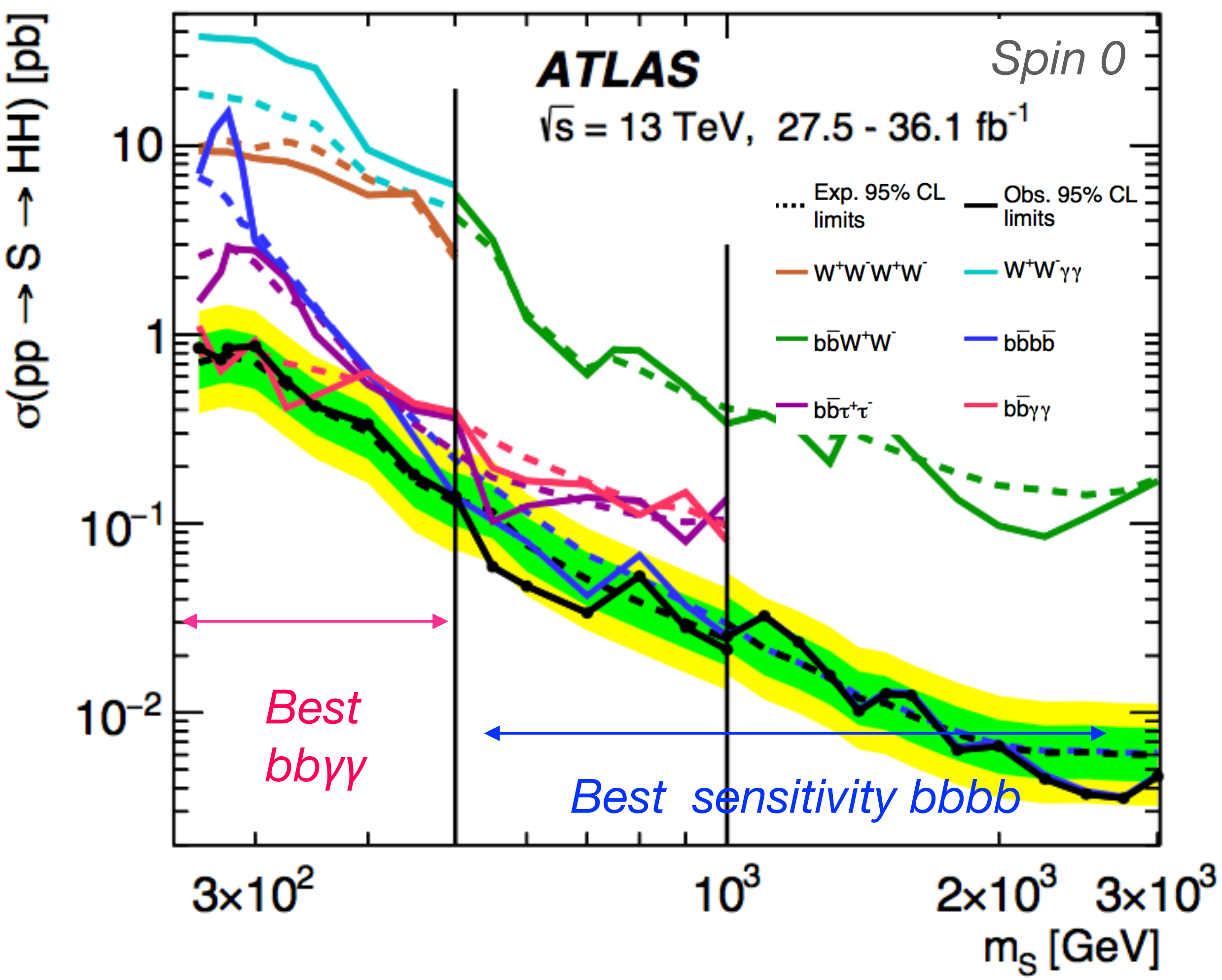


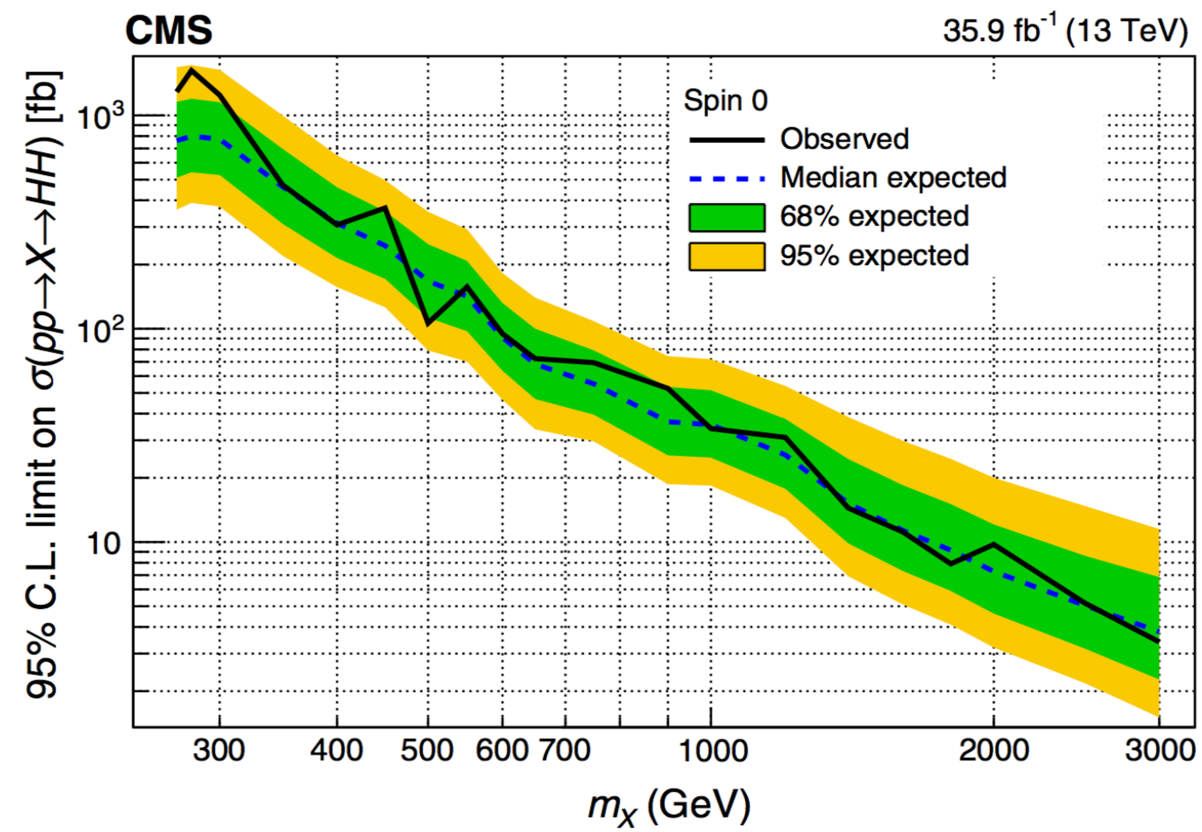
COMBINATION OF CROSS SECTION MEASUREMENTS

ATLAS: arXiv:1906.02025 — 13 TeV, ~36 fb^{-1} — CMS: PRL122 (2019) 121803

bbWW *γγWW* *WWWW* *bbγγ* *bbττ* *bbbb* *+ bbVV, in bbllνν or bblνlν, V=Z or W*

narrow width approximation





ATLAS interpretations (in backup)

EWK-singlet model: an extra singlet in addition to the SM scalar doublet

hMSSM a benchmark MSSM model

CMS also looked at another final state: CMS PAS HIG-18-013

HH➛bbZZ➛bb ℓℓ jj 13 TeV, ~36 fb^{-1}

➛bb ℓℓ νν (more in backup)

Search for **resonant production**: *no BSM Higgs interpretation*

Radion (spin 0 excitation in warped ED models)

Graviton Spin 2 KK-excitation

COMBINATION OF CROSS SECTION MEASUREMENTS

ATLAS: arXiv:1906.02025

13 TeV, ~36 fb^{-1}

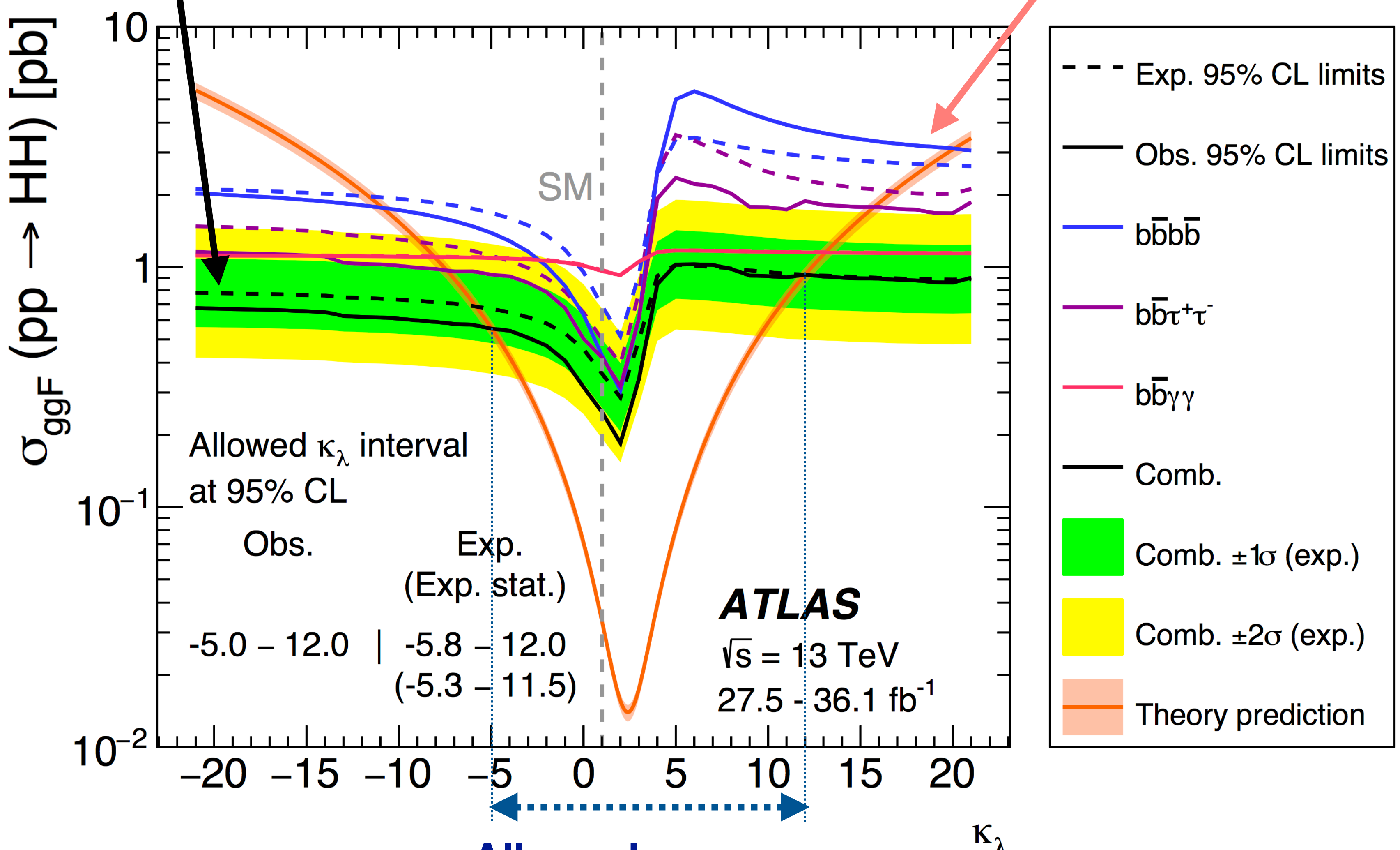
bbγγ
bbττ
bbbb

Limits on σ_{ggF} from a statistical interpretation of data based on κ_λ *dependent* cross section and (fully simulated) HH decay kinematics.

EFT theory prediction

Minimum at κ_λ=2.4 corresponds to the minimum σ, maximum interference

Scan on κ_λ with all other EFT param.s fixed at SM values.



Allowed κ_λ range

CMS: PRL122 (2019) 121803

Observed (expected) allowed range at 95% C.L.

$-11.8 < \kappa_\lambda < 18.8$

$(-7.1 < \kappa_\lambda < 13.6)$

Extrapolation to HL-LHC (14 TeV, 3ab^{-1})

κ_λ = 1 (0) would be determined with a significance of **~3 (4.5) σ (stat⊕syst) per exp.** assuming upgraded detectors

ATL-PHYS-PUB-2018-053

CMS PAS FTR-18-019

ANOTHER SEARCH FOR NON-RESONANT HIGGS PAIR-PRODUCTION

13 TeV, 139 fb^{-1}

ATLAS: arXiv:1908.06765

HH→bb ℓν ℓν

→WW/ZZ/ττ

→bb

e^+e^-, $\mu^+\mu^-$, $e^+\mu^-$, $e^-\mu^+$ + ≥2b-jets

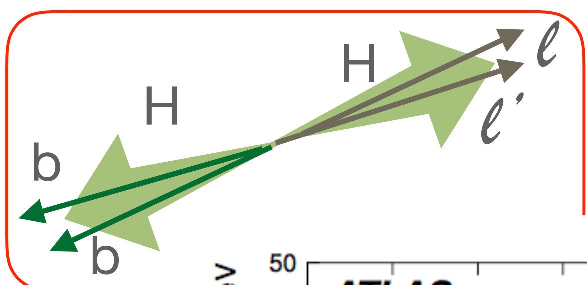
Search optimised for bbWW (largest BF) but bbZZ and bbττ included in the signal

Main background: Top (tt+Wt, interfering), Z(ll or ττ)+HF

Main S/B discriminants: m_{bb}, $m_{\ell\ell}$, *global properties of the event: d_{HH}*

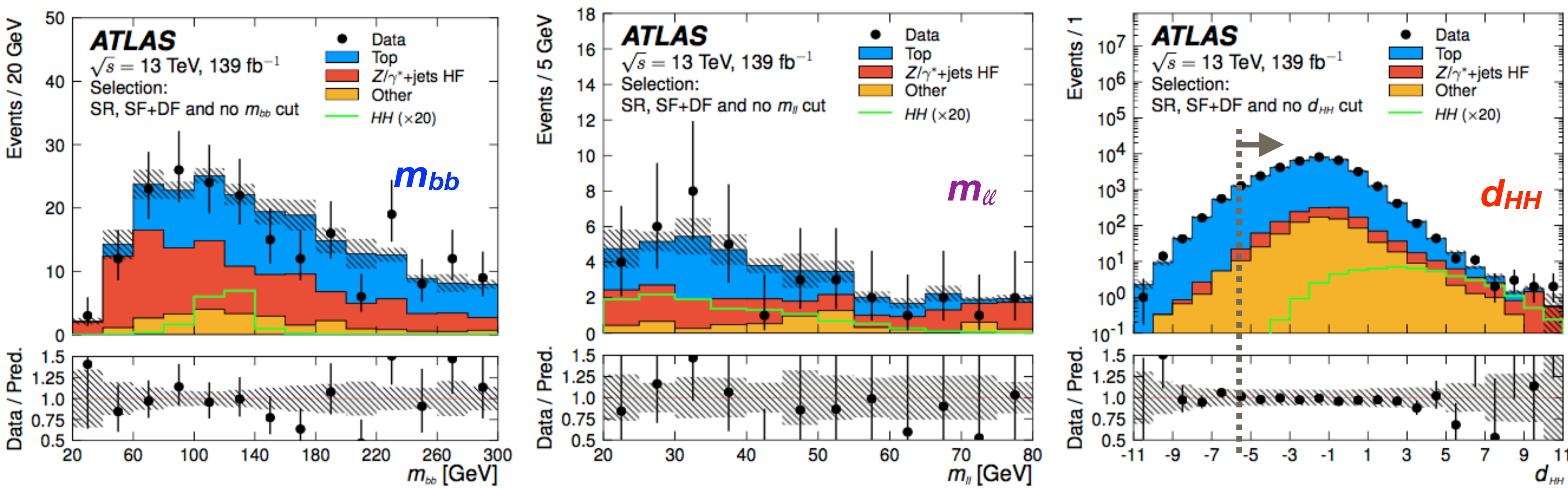
110-140 GeV *20-60 GeV*

>5.45 SF
>5.55 DF



$$d_{HH} = \ln\left[p_{HH} / \left(p_{\text{Top}} + p_{Z\text{-}\ell\ell} + p_{Z\text{-}\tau\tau}\right)\right]$$

p_i = probability for the event to be HH, Top, Z(ll), Z(ττ) according to a 4-output ***DNN classifier***



35 inputs, 2 layers, 125 nodes/ layer

SR Same Flavour *SR Diff. Flavour*

Event Yields	SR Same Flavour	SR Diff. Flavour
Data	16	9
Total Bkg.	14.9 ± 2.1	4.9 ± 1.2
Top	4.8 ± 1.4	3.8 ± 1.1
Z/γ^*+ HF	7.8 ± 1.4	0.21 ± 0.05
Other	2.3 ± 0.5	0.9 ± 0.4
HH (×20)	5.0 ± 0.6	4.8 ± 0.8

Scaling factor for Top and Z+HF from data in CRs

Post-fit Normalisation	
μ_{Top} = 0.79 ± 0.10	$\mu_{Z/\gamma^*+\text{HF}}$ = 1.36 ± 0.07

Limit on σ (gg → *HH*) ~ 40 σ$_{SM}$ @ 95% CL

	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$	Observed
$\sigma(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \to HH)/\sigma^{\text{SM}}(gg \to HH)$	14	20	29	43	62	40

HIGGS PAIR PRODUCTION VIA VBF

ATLAS-CONF-2019-030

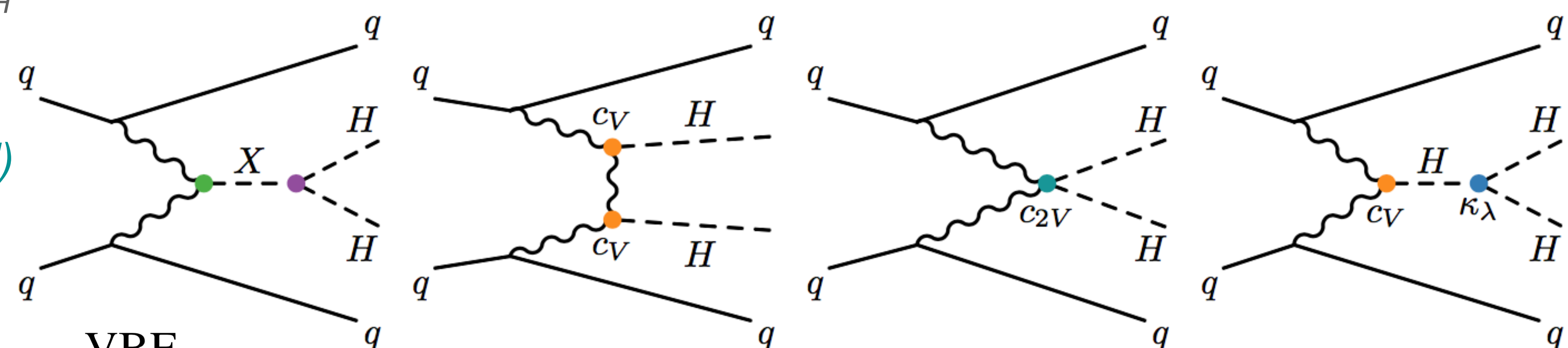
126 fb⁻¹ at 13 TeV

limited sensitivity to λ_{HHH} compared to ggF

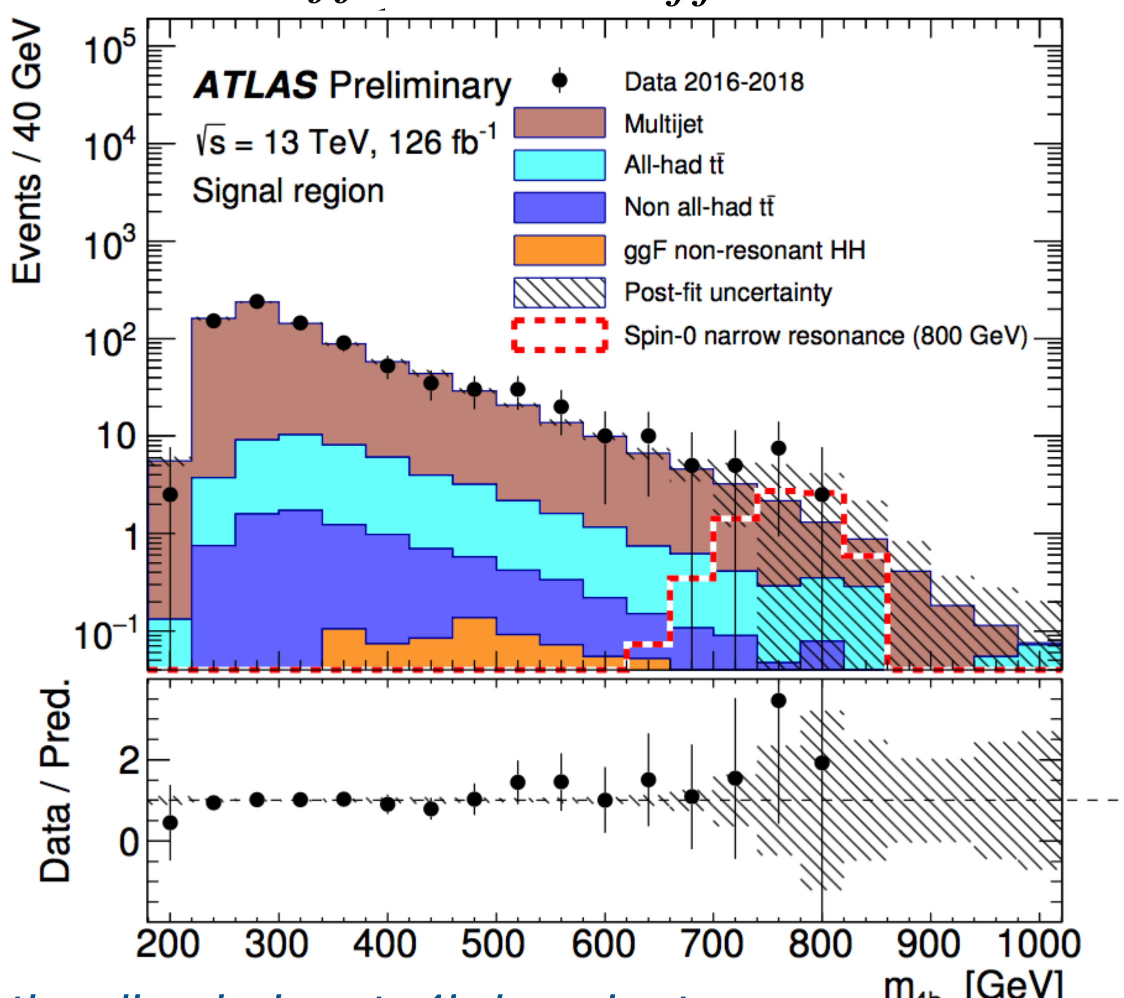
unique opportunity to access c_{2V}(=1 in the SM)

Higgs → bb only

σ(SM)=1.73 fb @ N³LO



$|\Delta\eta_{jj}^{VBF}| > 5 \quad m_{jj}^{VBF} > 1\,\text{TeV}$ **+4 b-tagged jets**



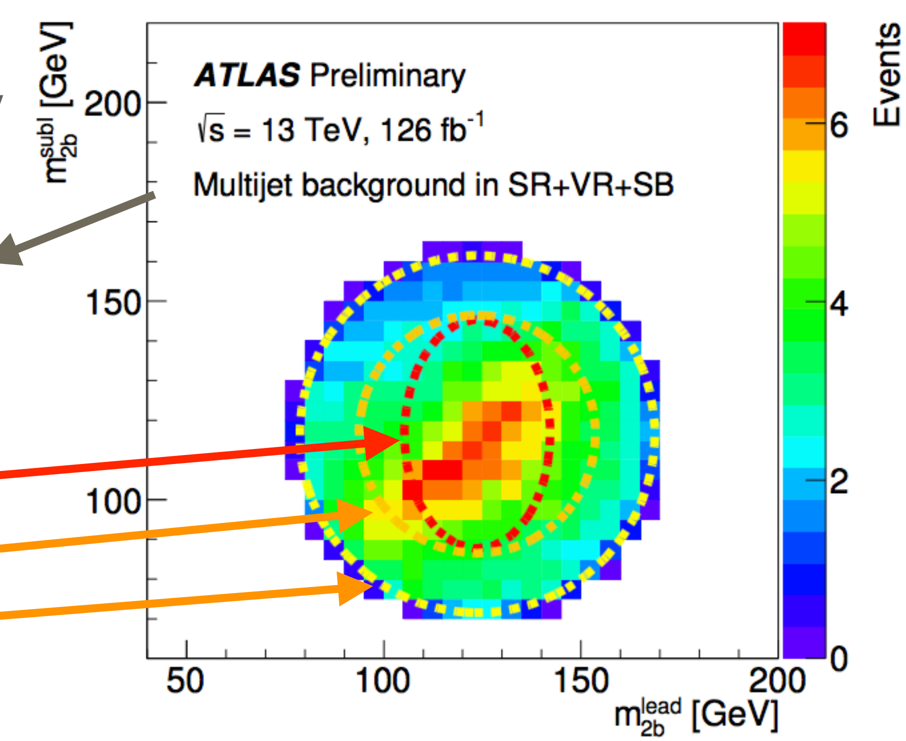
the discriminant: 4b invariant mass

non resonant σ studied for all couplings to SM values and varying c_{2V}

resonant study against two spin-0 benchmark models:

- broad width, tanβ=2, sin(β-α)=0.6
- narrow width, Γ=4MeV

dominant background obtained by reweighting a 2b+2j sample



HIGGS PAIR PRODUCTION VIA VBF

ATLAS-CONF-2019-030

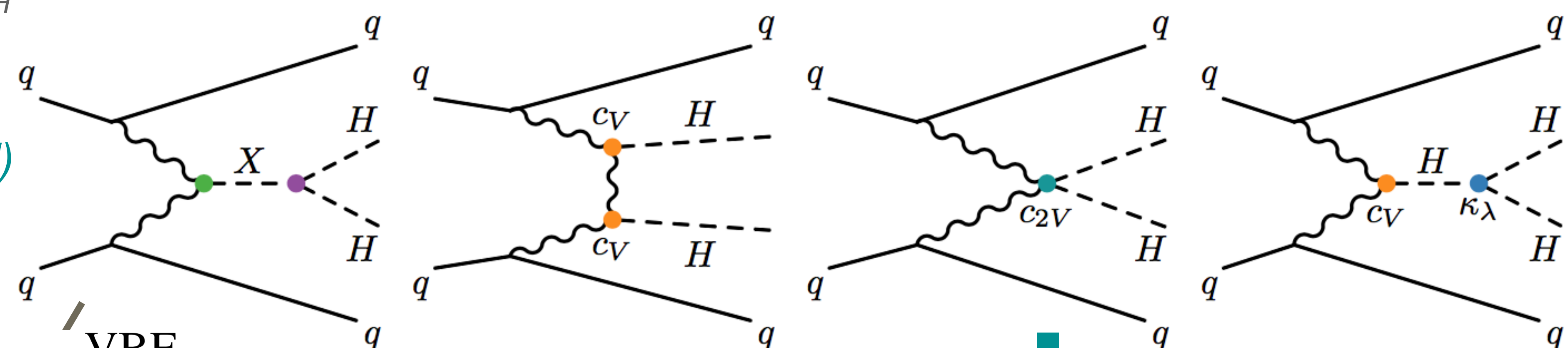
126 fb^{-1} at 13 TeV

limited sensitivity to λ_{HHH} compared to ggF

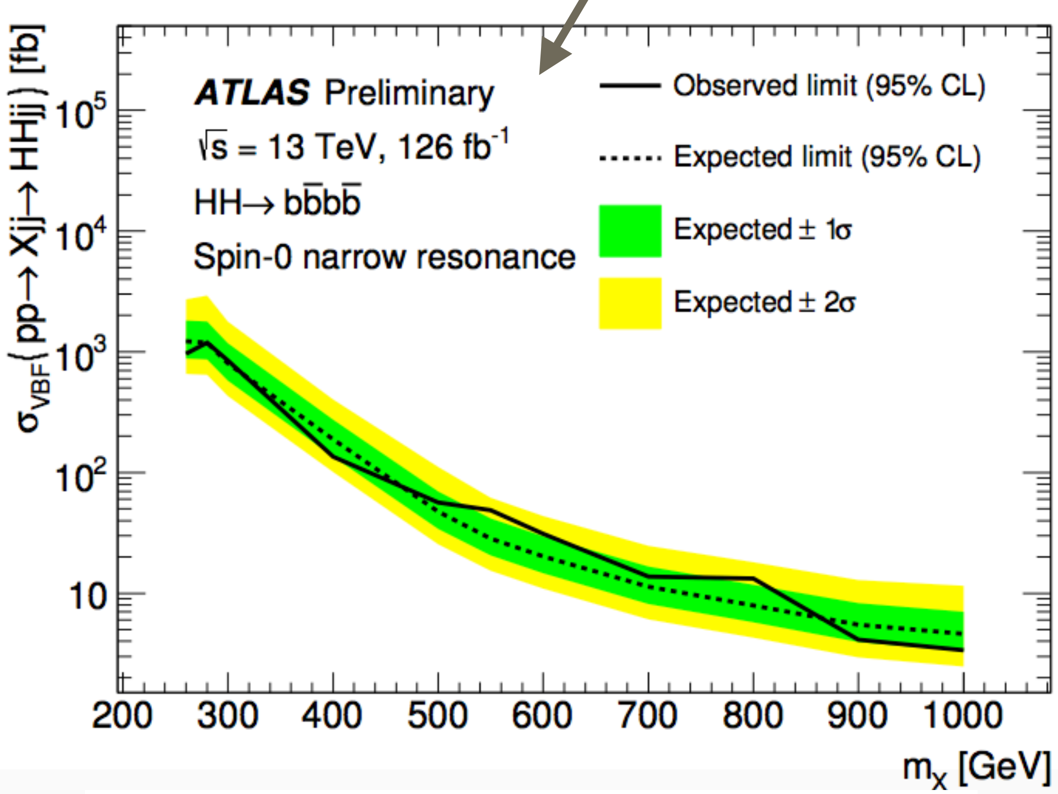
unique opportunity to access c_{2V}(=1 in the SM)

Higgs → bb only

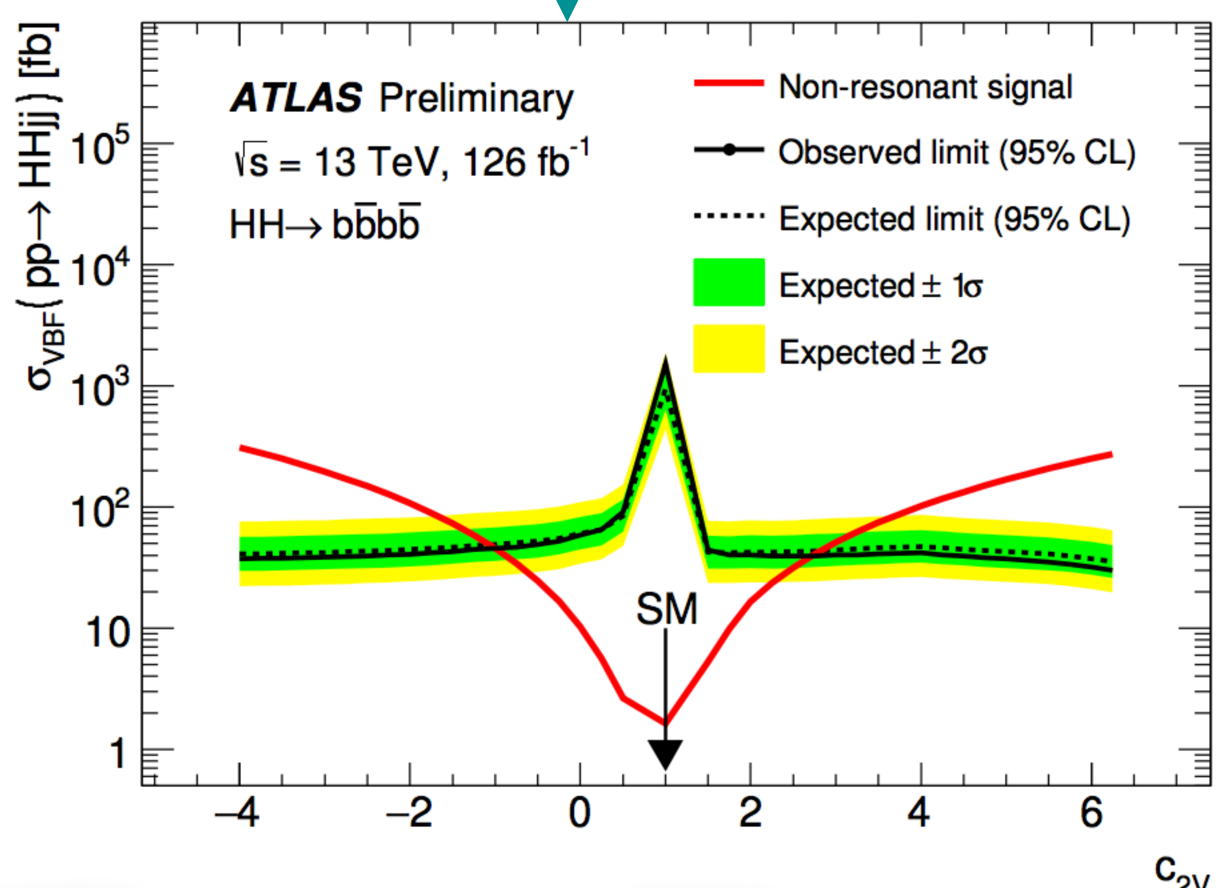
σ(SM)=1.73 fb @ N³LO



$|\Delta\eta_{jj}^{VBF}| > 5$ $m_{jj}^{VBF} > 1$TeV **+4 b-tagged jets**



slightly looser constraints for a broad resonance at 1 TeV



$c_{2V} < -1.02$ and $c_{2V} > 2.71$ *excluded @ 95% CL*

CONCLUSIONS

- The puzzles of the SM are likely to be related to the scalar sector
- No signs of deviations from SM so far, but still large room for data reconstruction and analysis improvements, new model testing, new data interpretation …
- LHC Run2 potential still to be exploited
  - from Run3 to HL-LHC, a long path for a deep scrutiny of tiny effects
- Find full list of available and future results in
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG/index.html

BACKUP

CMS: JHEP 09 (2018)007, heavy MSSM H➛ττ

sensitive to type II and X, for high tanβ

HEAVY NEUTRAL H IN b(b)H➛ττ

ATLAS: JHEP 01 (2018) 055

constraints already from LEP and Tevatron

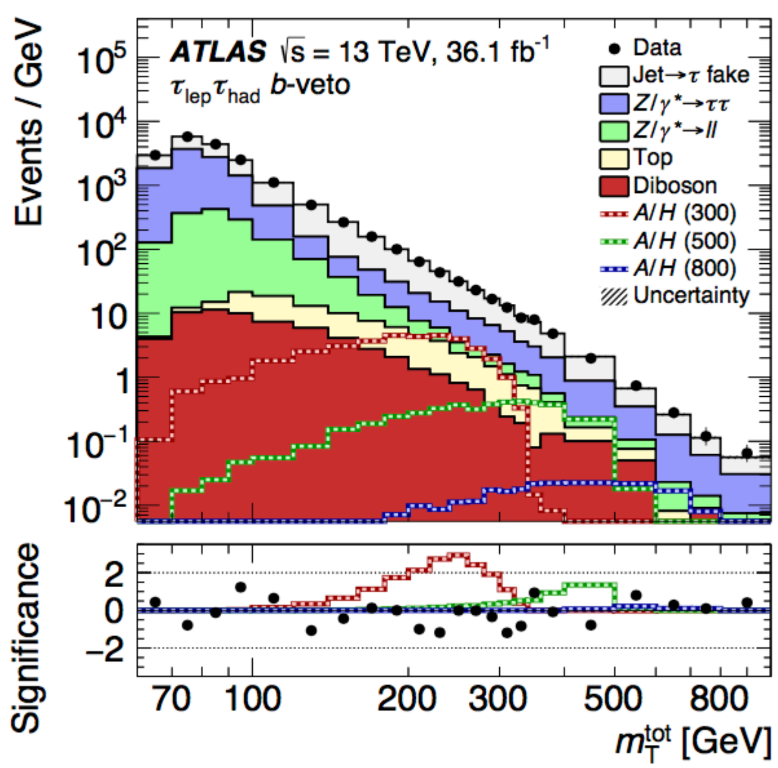
- experimentally easier that H->bb, published by ATLAS with **36 fb^{-1} at 13 TeV** mass range 0.2-2.25 TeV;

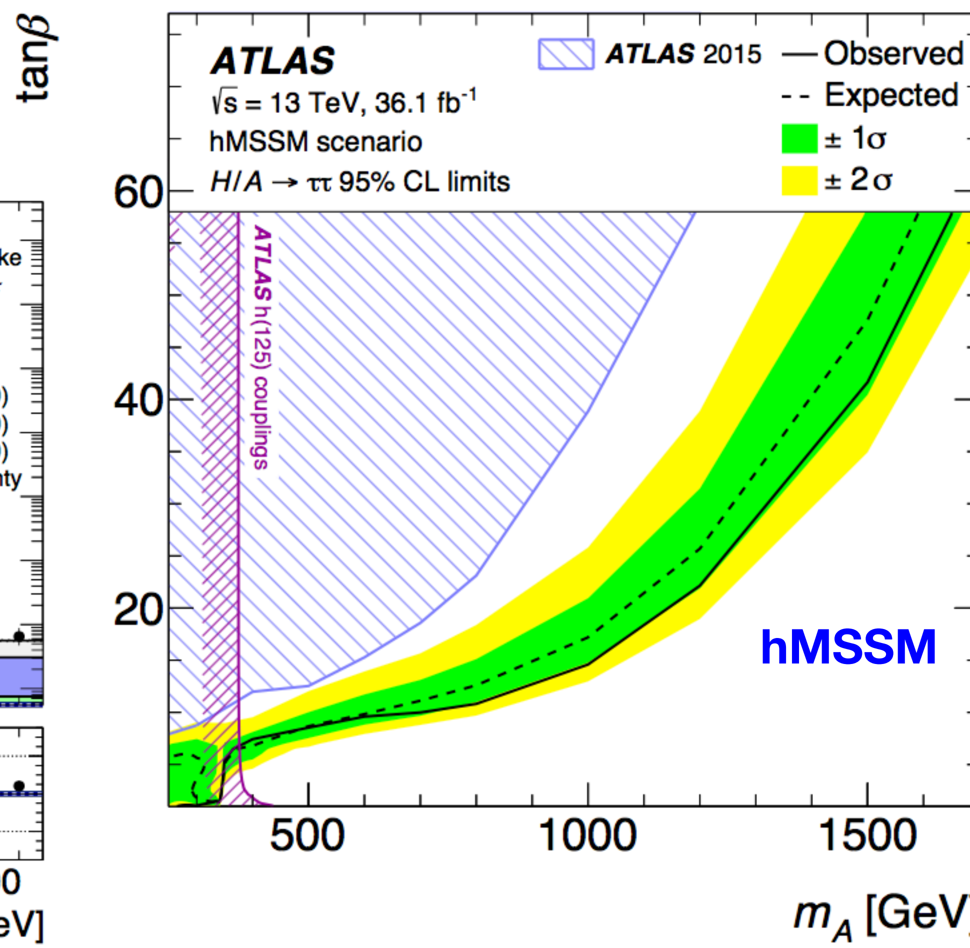
4 categories: $\tau_{lep}\tau_{had}$ → ≥ 1b-jet, no b-jet; $\tau_{had}\tau_{had}$ → ≥ 1b-jet, no b-jet

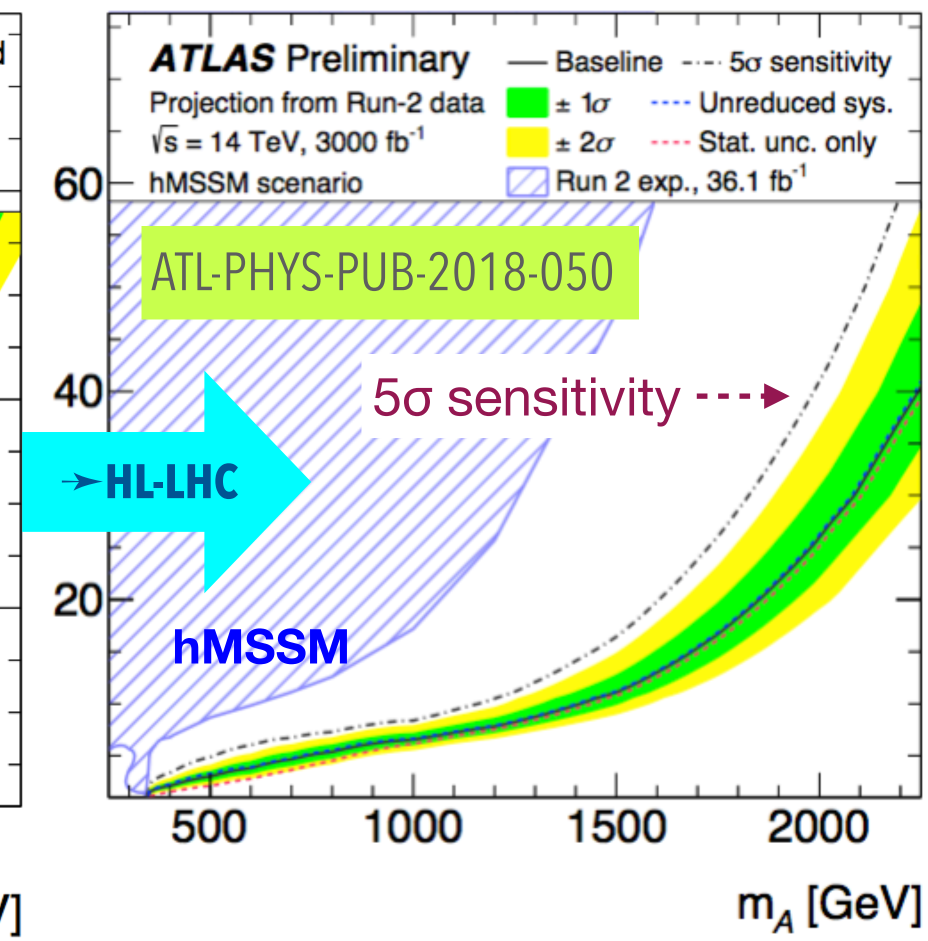
top, Z(ττ)+jets, multi-jet are the largest backgrounds depending on event category

upper limits on **σxB** between **1 and 0.6x10-2 pb** for **ggF** and **0.7-0.4x10-2 pb** for **b-ass. production**

best S/B discriminant: total transverse mass (from τ_1,τ_2, E_T^{miss})





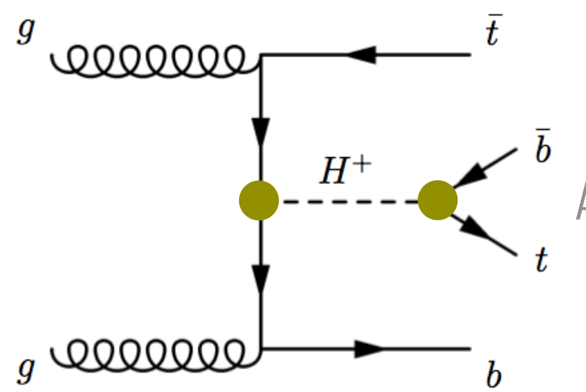


CHARGED HIGGS TO FERMIONS: *tb or τν*

for $m_H>m_t$

dominant production/decay mode

H± → tb



CMS PAS HIG-18-004

CMS PAS HIG-18-015

ATLAS: JHEP11(2018)085

$\sigma \times \mathcal{B} < 9.25$ to 0.005 pb.

200 GeV to 3 TeV.

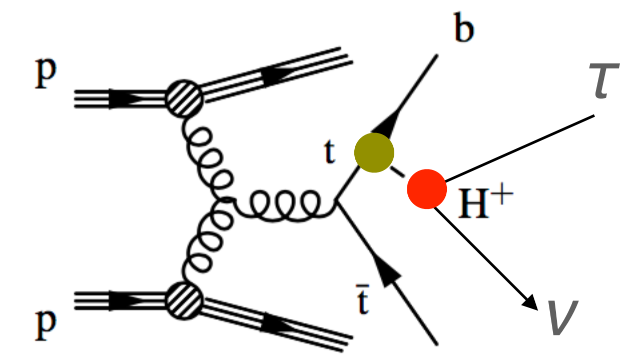
for $m_H<m_t$

dominant decay mode

H± → τν

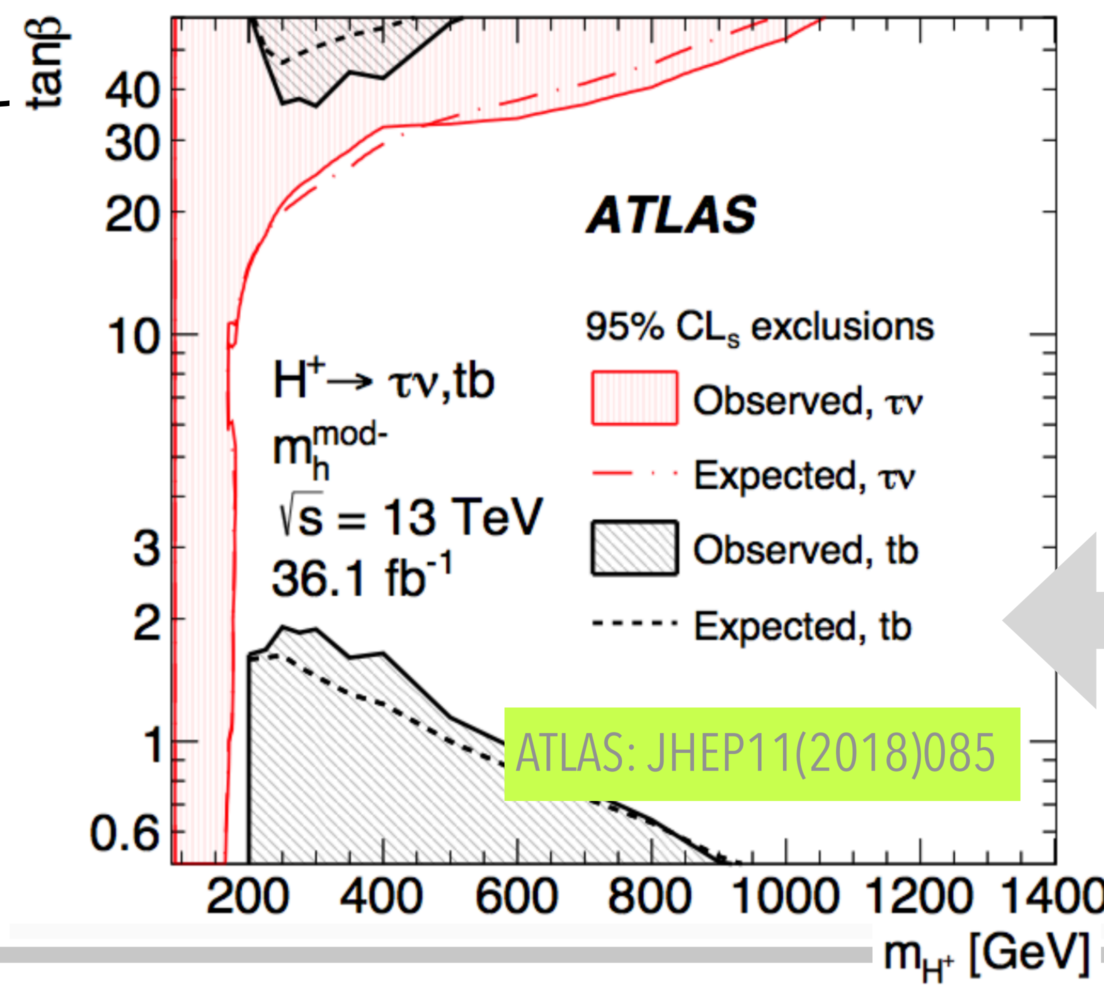
CMS: JHEP07(2019)142

ATLAS: JHEP09(2018)139



$\sigma \times \mathcal{B} < 5$ to 0.005 pb

80 GeV to 3 TeV



ATLAS: JHEP11(2018)085

ATLAS interpretation in a MSSM benchmark (type II) combines searches for decays to ***τν*** and decays to ***tb***

see the different roles in the plane tanβ-m_{H+}

Charged Higgs to fermions: *tb*, *τν*

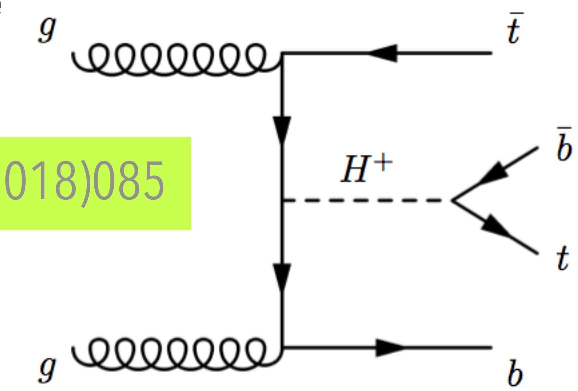
for $m_H > m_t$

dominant production/decay mode

$H^{\pm} \to tb$

complementary channels

ATLAS: JHEP11(2018)085

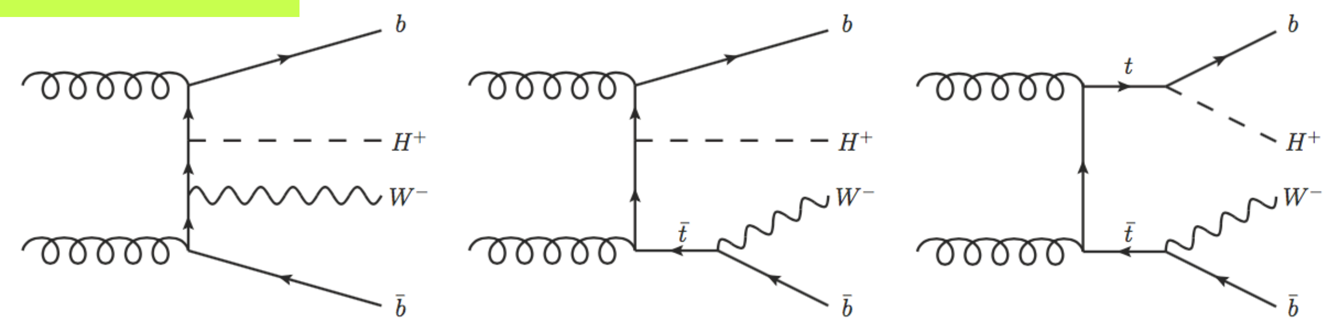


for $m_H < m_t$

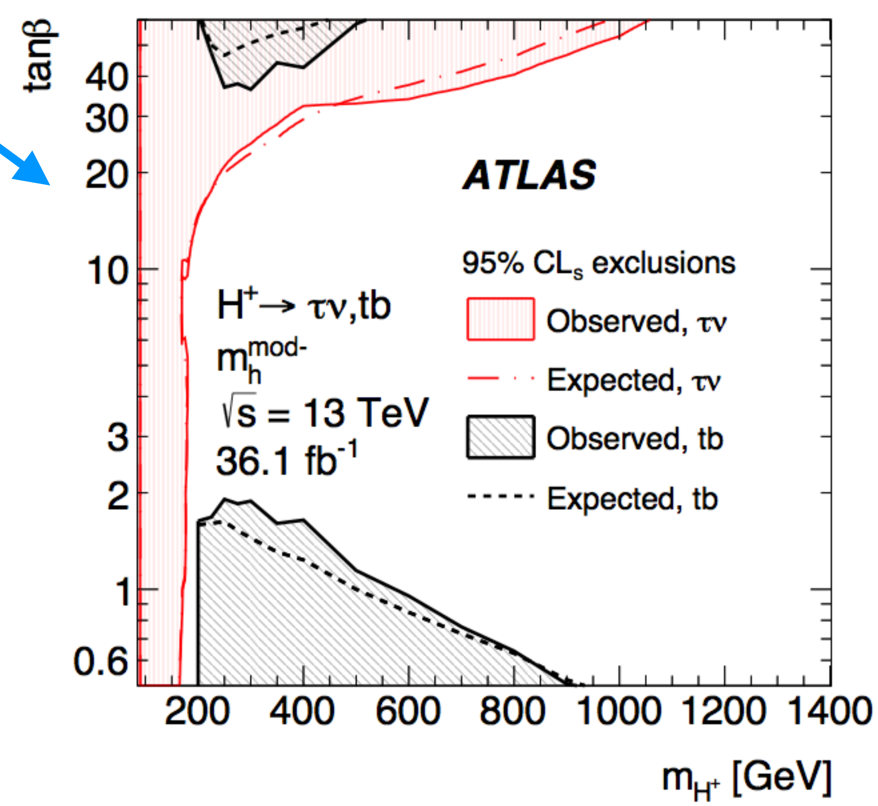
$H^{\pm} \to \tau\nu$ dominant decay

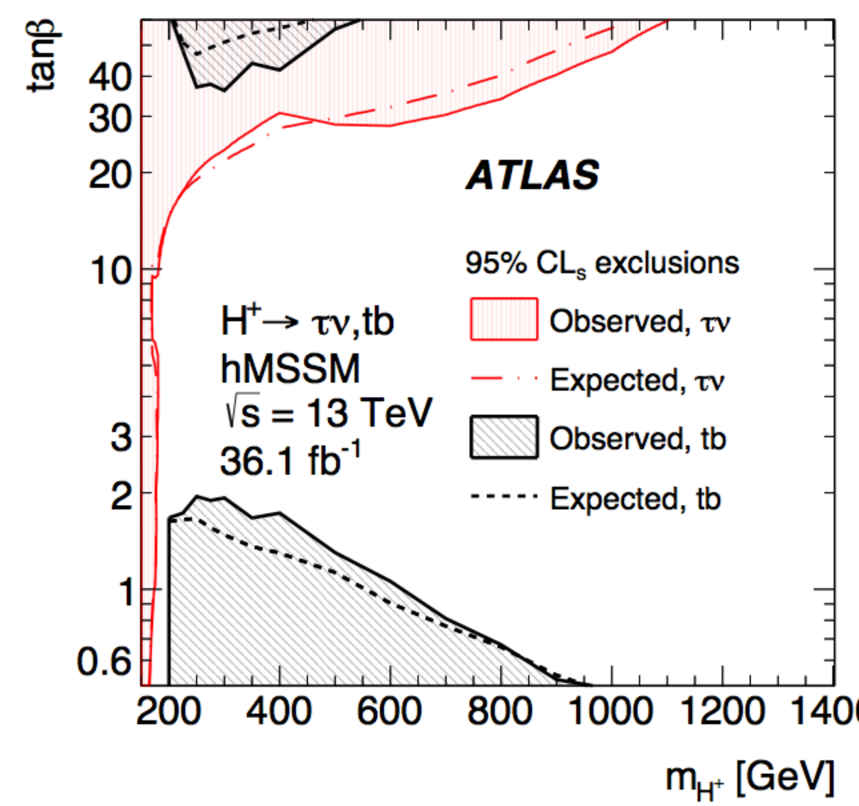
production mode: tH associated production (resonant or not) or top decay

ATLAS: JHEP09(2018)139



MSSM: m_h^{mod-}





MSSM: hMSSM

CHARGED HIGGS TO FERMIONS: *tb, τν*

for $m_H > m_t$

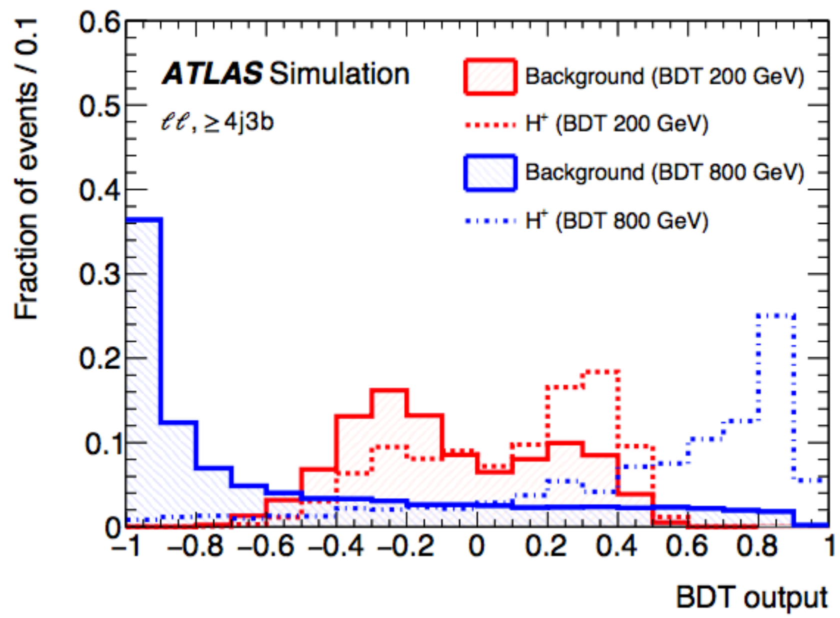
dominant production/decay mode

$H^\pm \to tb$

complementary channels

JHEP11(2018)085

many signal regions
(ℓ)ℓ +high mult. of (b-tagged)jets



profile likelihood fit of a binned distribution of a BDT output

$\sigma \times \mathcal{B} = 2.9\ (3.0)$ pb at $m_{H^+} = 200$ GeV to $\sigma \times \mathcal{B} = 0.070\ (0.077)$ pb at $m_{H^+} = 2$ TeV

95% CL exclusion limits

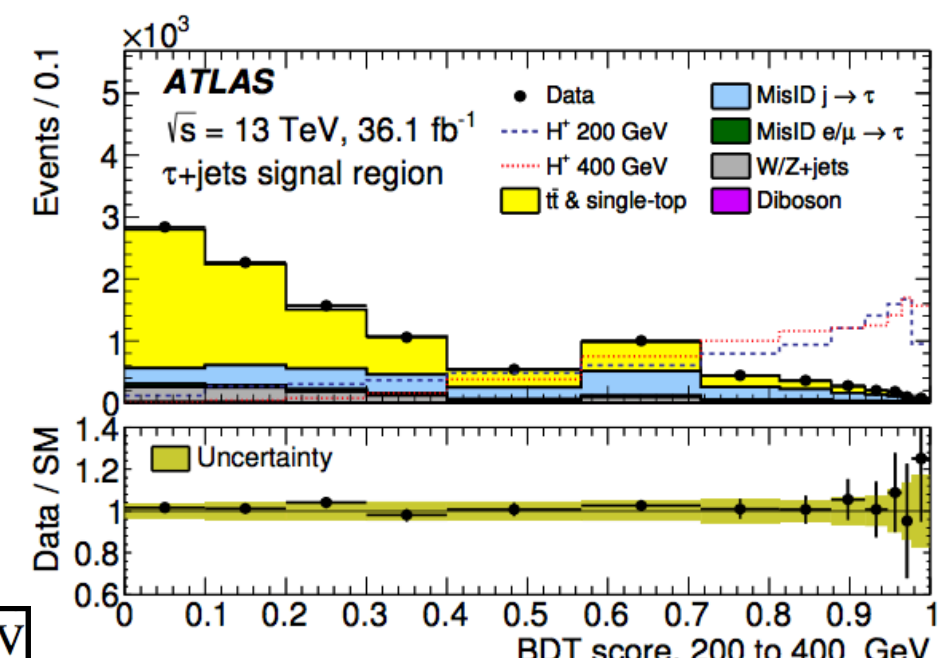
for $m_H < m_t$

$H^\pm \to \tau\nu$ dominant decay

production mode: tH associated production (resonant or not) or top decay

JHEP09(2018)139 **hadronic-τ decay** *+lepton or +jets depending on t-decay*

E_T^{miss} trigger
mass hypothesis dependent BDT output
to discriminate signal/background



BDT output in an example signal region

for $m_{H^\pm} = 90\text{–}2000$ GeV $\sigma \times \mathcal{B} < 4.2\text{–}0.0025$ pb @ 95% CL

CMS PAS HIG-18-004

CMS PAS HIG-18-015

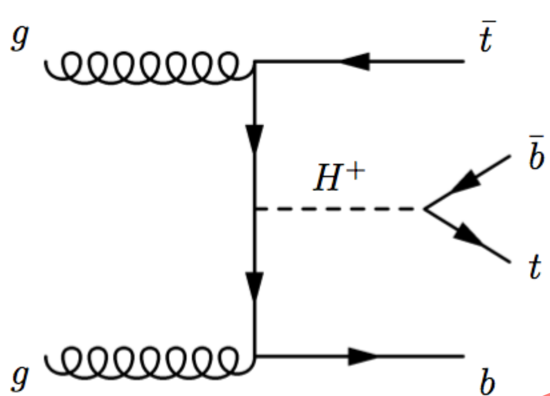
ATLAS: JHEP11(2018)085

CHARGED HIGGS TO FERMIONS: *tb*

for $m_H > m_t$

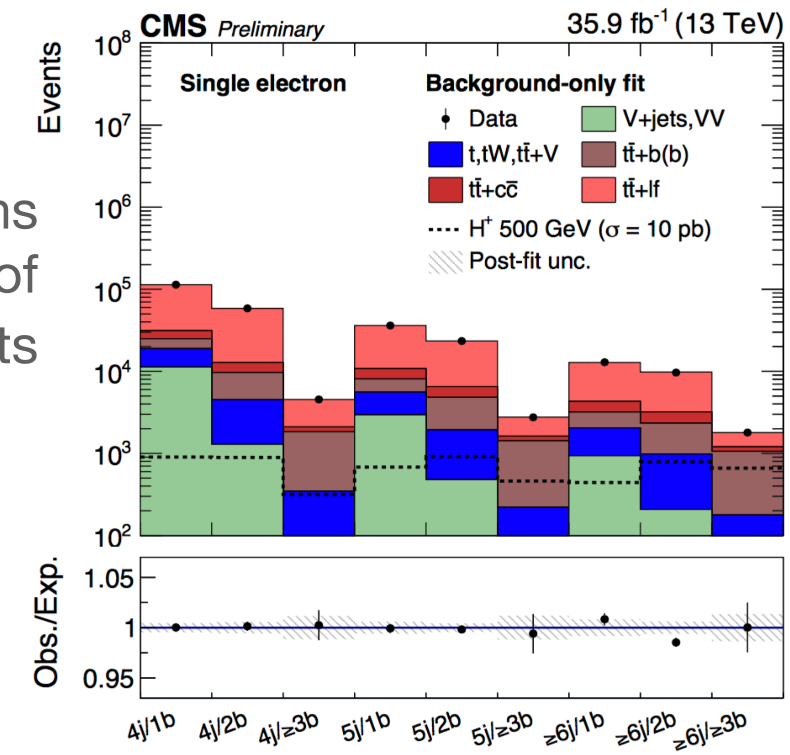
dominant production/decay mode

H±→tb



Preliminary CMS result HIG-18-004, March 2019

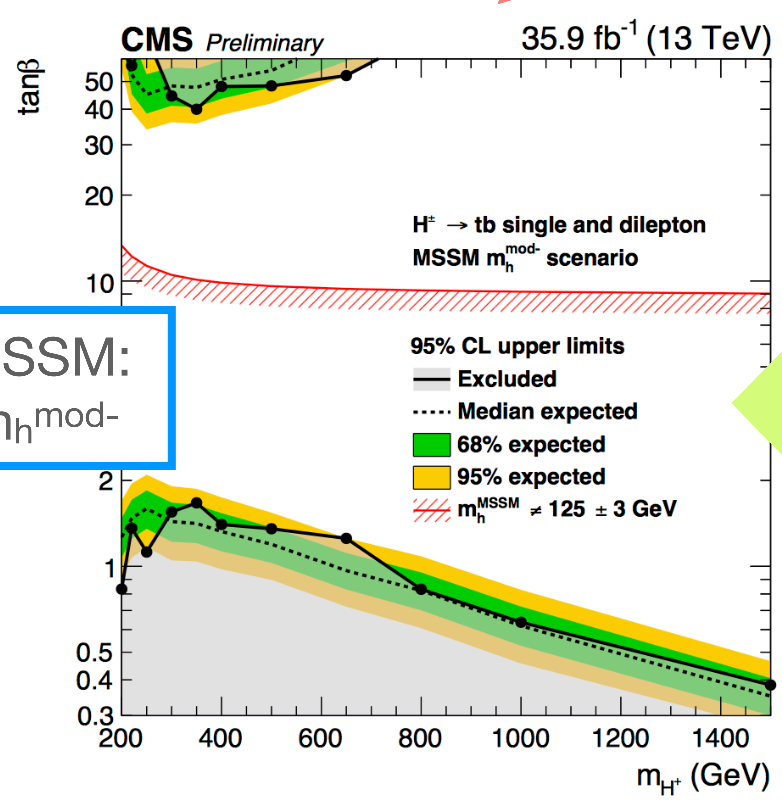
Many signal regions (ℓ)ℓ +high mult. of (b-tagged) jets



Updated in July (HIG-18-015) *with the addition of a fully hadronic analysis*

for more

Note: the region below the red curve is excluded if the observed Higgs is the CP-even h with m=125±3 GeV



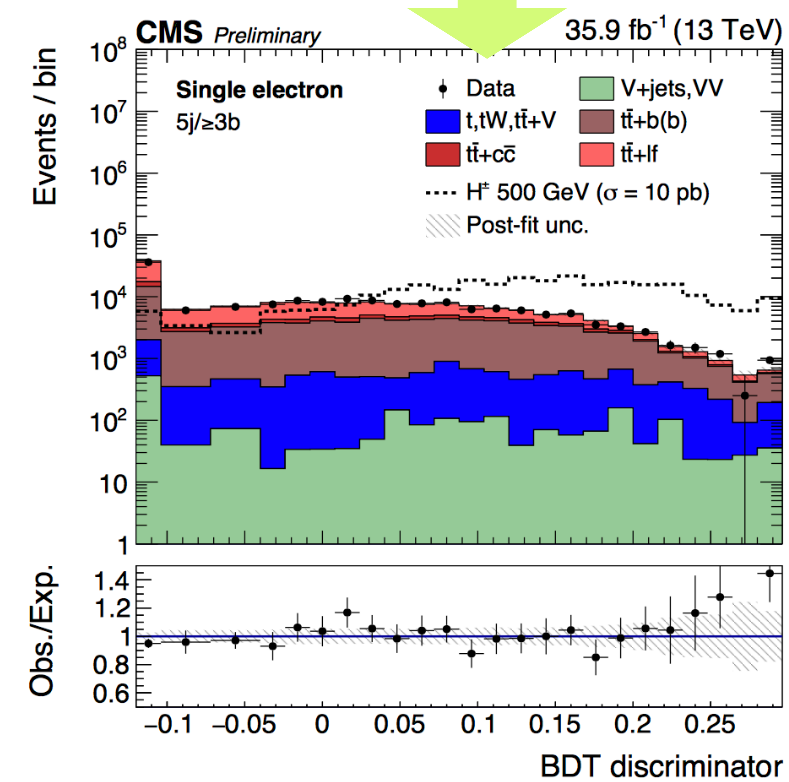
MSSM: m_h^{mod-}

@ 95% CL

$$\sigma \times \mathcal{B} < 9.25 \text{ to } 0.005 \text{ pb.}$$

leptonic + hadronic channels

200 GeV to 3 TeV.



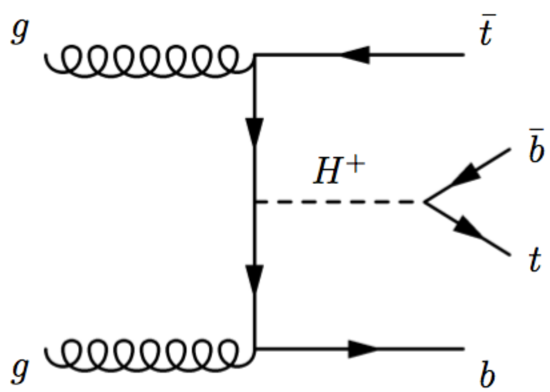
Consistent with ***ATLAS results in backup***

CHARGED HIGGS TO FERMIONS: *tb*

for $m_H > m_t$

dominant production/decay mode

$H^{\pm} \rightarrow tb$

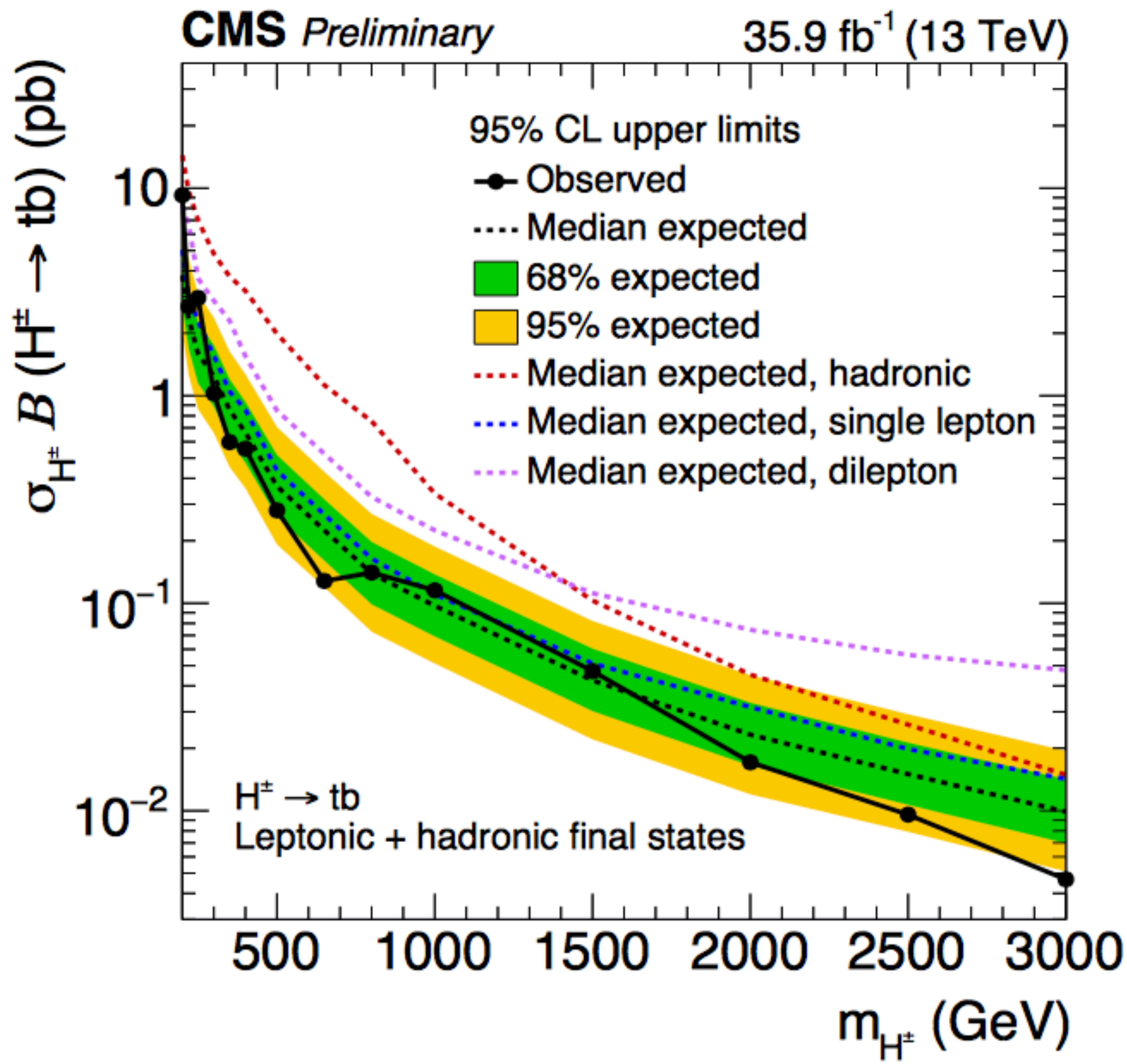


HIG-18-004, March 2019

Updated in July 2019
CMS PAS HIG-18-015,
with the addition of a fully hadronic analysis

@ 95% CL
$\sigma \times \mathcal{B} < 9.25$ to 0.005 pb.
200 GeV to 3 TeV.

leptonic + hadronic channels



Charged Higgs to fermions: τν

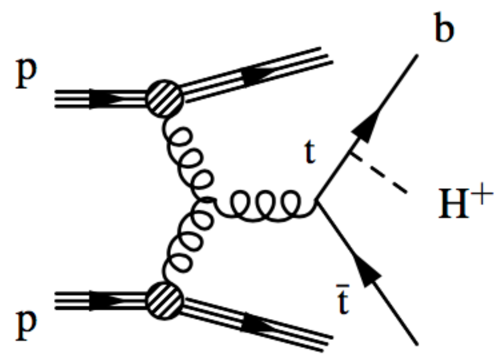
CMS: JHEP07(2019)142

ATLAS: JHEP09(2018)139

for $m_H < m_t$

dominant production mode

$H^\pm \rightarrow \tau\nu$



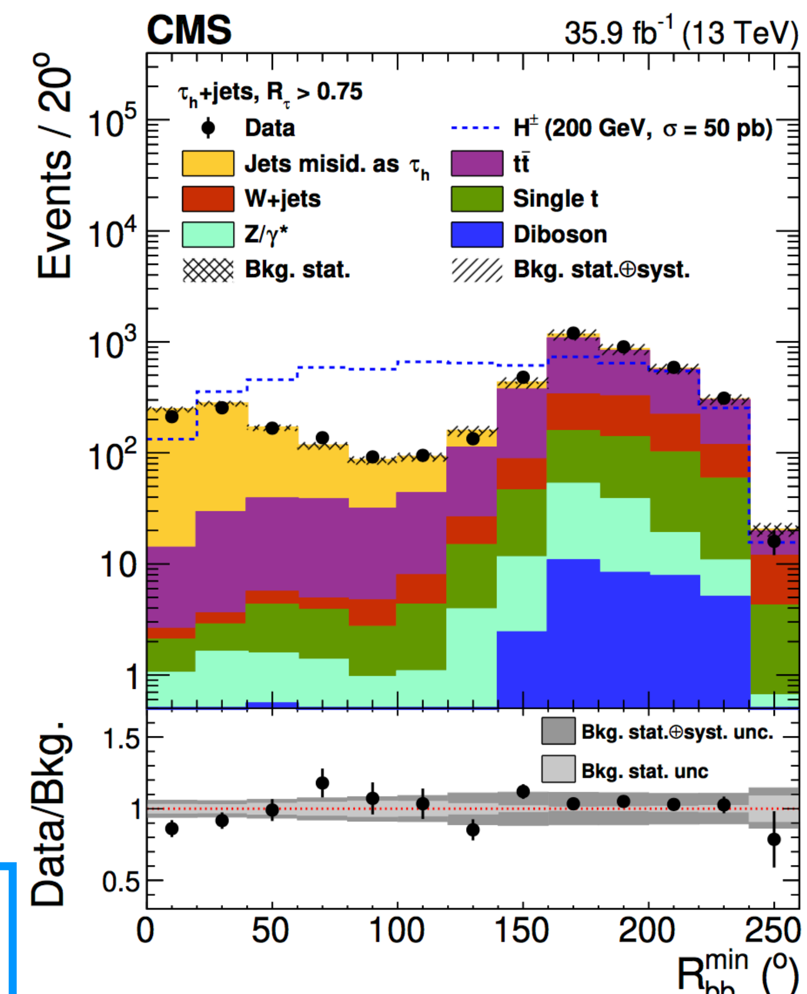
Recent CMS result July 2019

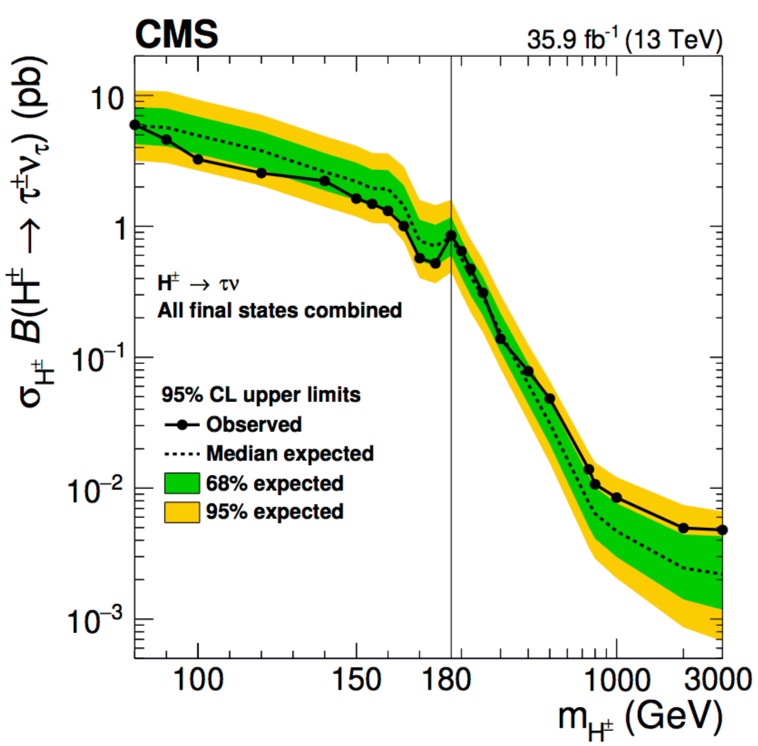
- ℓ + no τ_h:
- $\ell + \tau_h$: -> trigger efficiency at low m_H
- τ_h + jets:

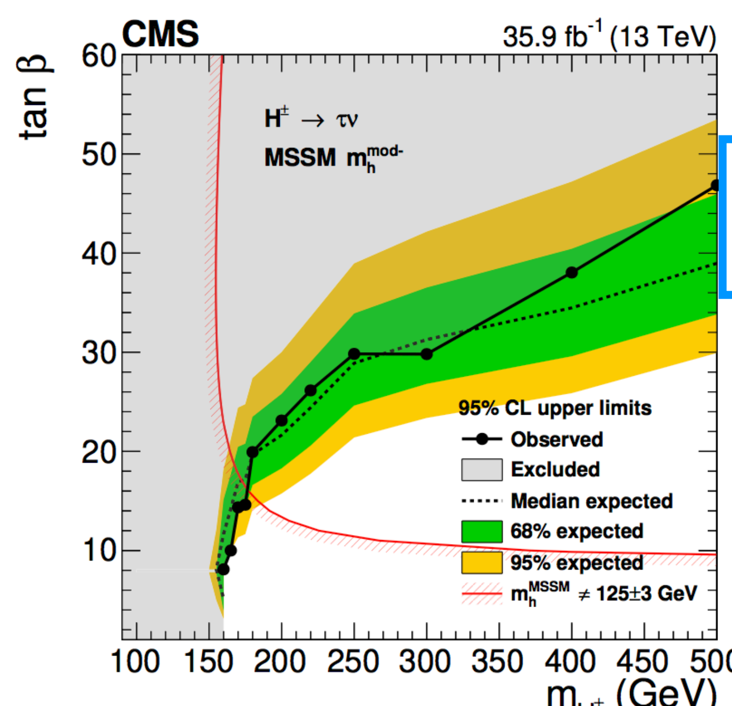
- Event selection uses hadronic and leptonic τ decays
- Cut based selection
- Likelihood fit to τ transverse mass

$$m_T(\tau_h/\ell) = \sqrt{2 p_T(\tau_h/\ell) p_T^{miss} [1 - \cos \Delta\phi(\vec{p}_T(\tau_h/\ell), \vec{p}_T^{miss})]}.$$

A S/B angular discriminant for the hadronic channel







MSSM: m_h^{mod-}

Note: the region below the red curve is excluded if the observed Higgs is the CP-even h with m=125±3 GeV

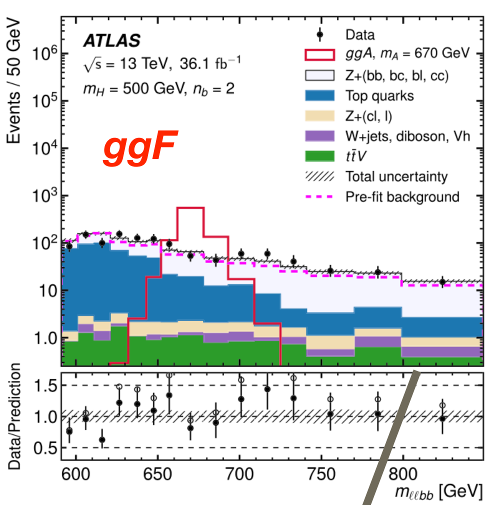
Consistent with ***ATLAS results in backup***

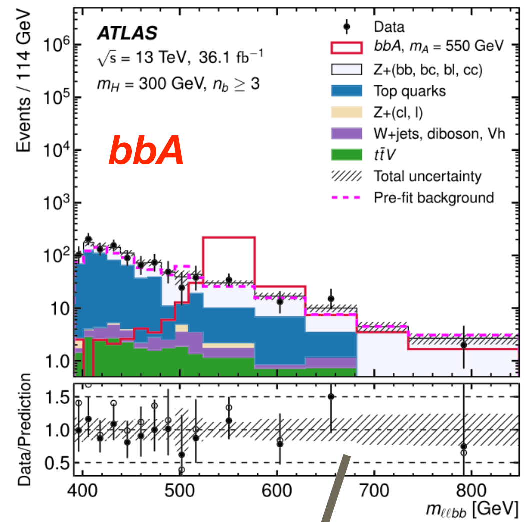
For backup

SEARCH FOR $A \rightarrow ZH \rightarrow \ell\ell\, bb$

large A, H mass splitting may be needed to accomodate electroweak baryogenesis scenarios in 2HDM

ATLAS: PLB 783 (2018) 392

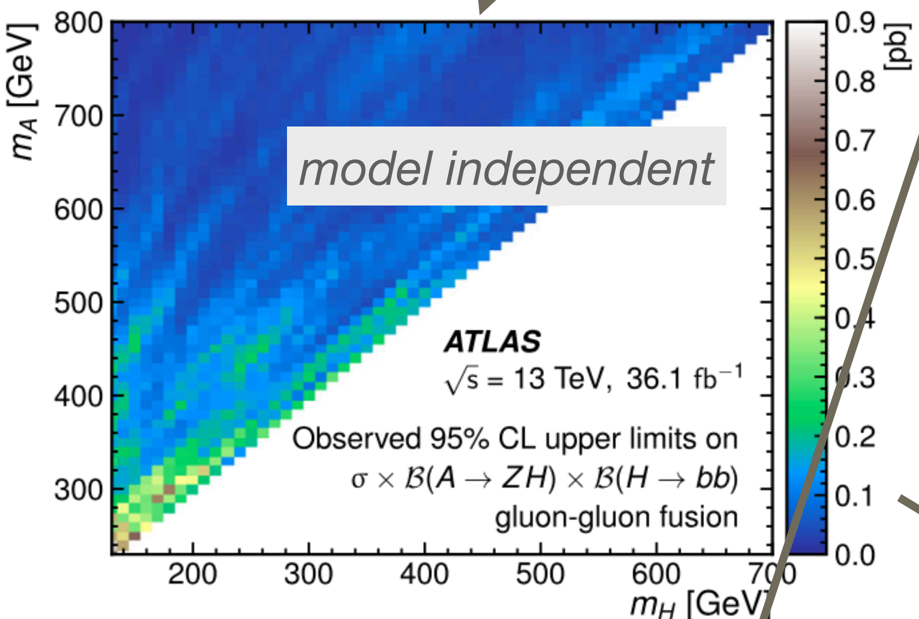




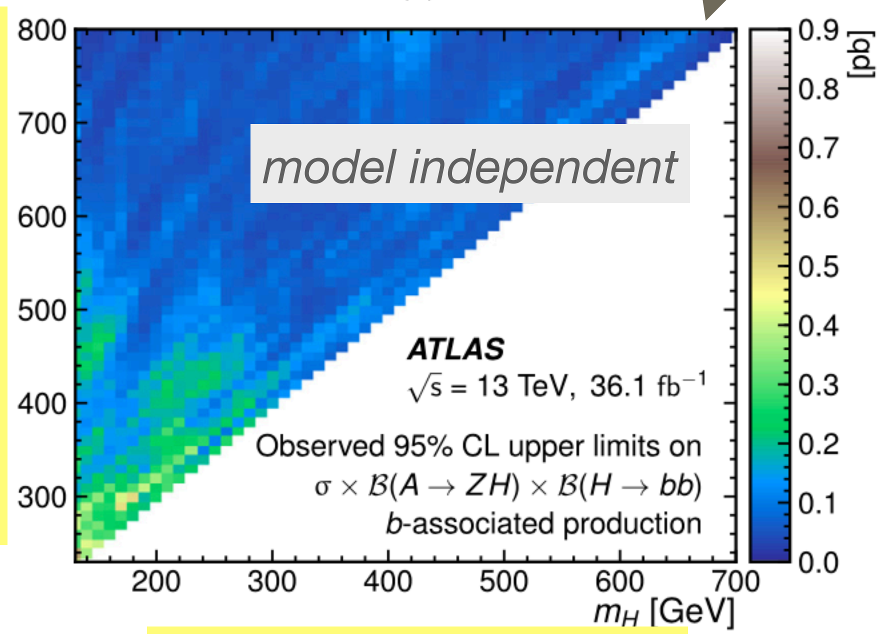
excluded

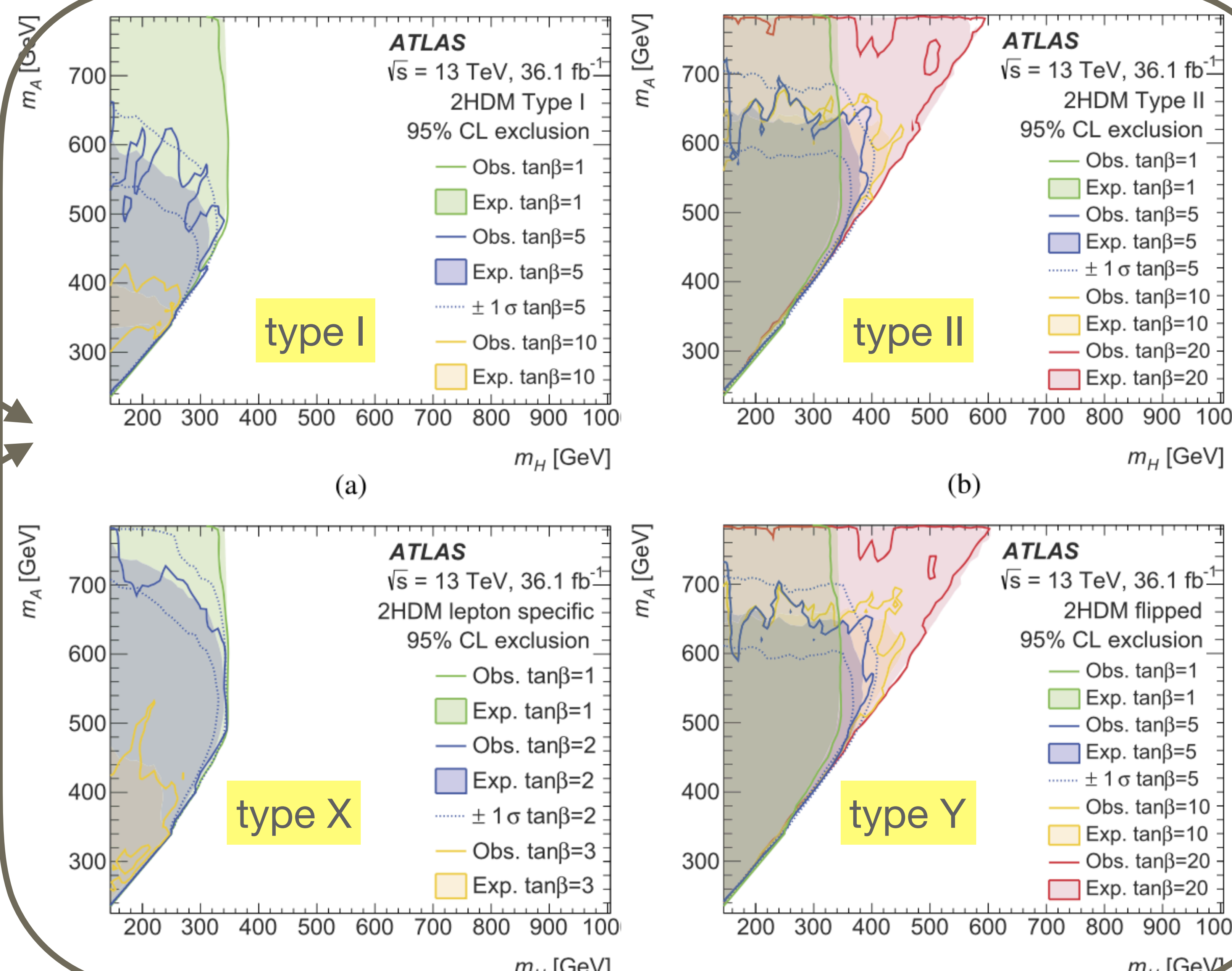
$\sigma \times \mathcal{B}(A \rightarrow ZH) \times \mathcal{B}(H \rightarrow bb)$ of 14–830 fb for *ggF*

26–570 fb for b-ass. prod. *bbA*



(b)





230-800 GeV, m_A range

130-700 GeV, m_H range

SEARCH FOR H ➛ ZA ➛ℓℓ bb

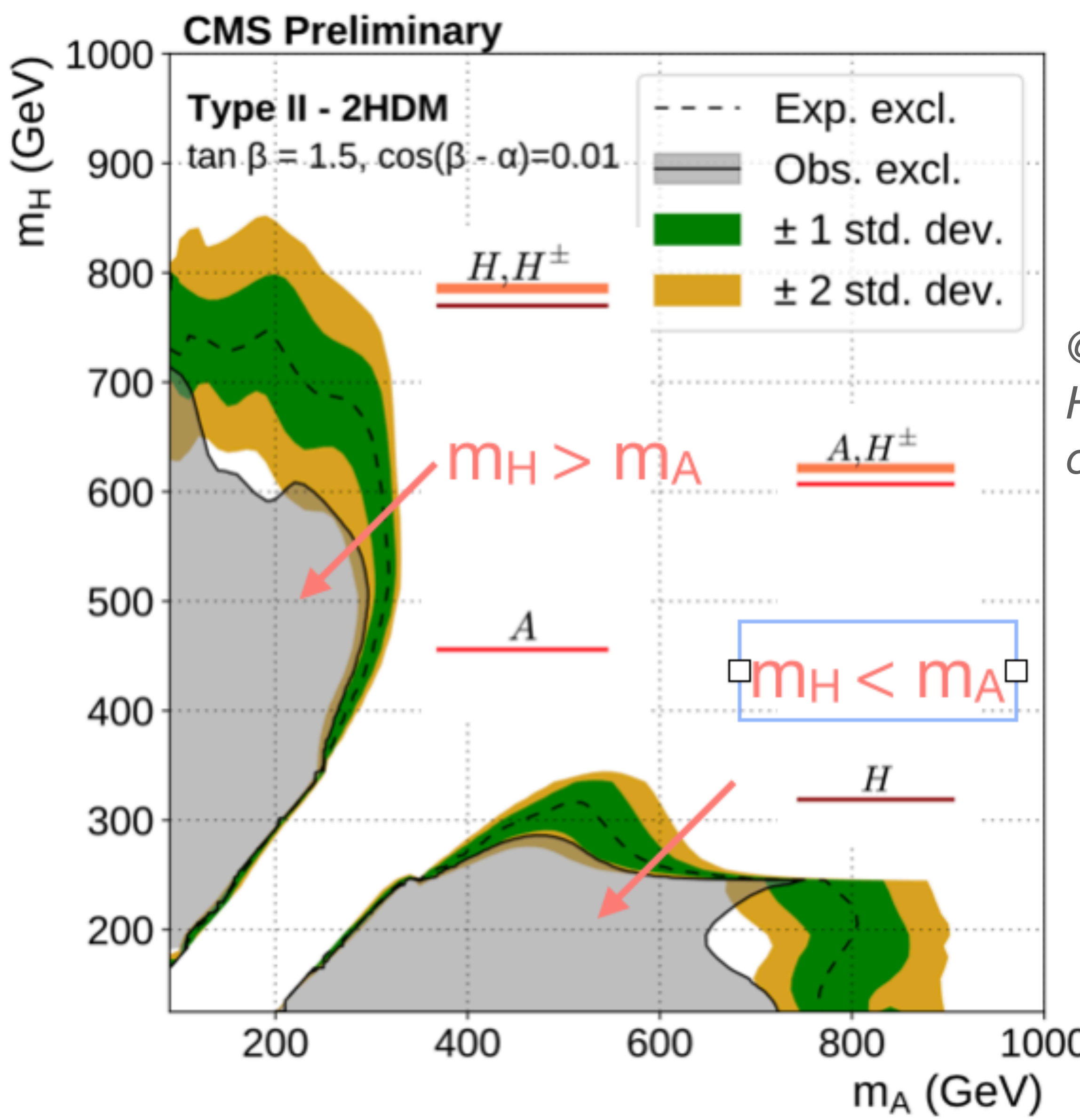
May 2019, CMS PAS HIG-18-012

μμ and ee channels

μe control region to constrain top background

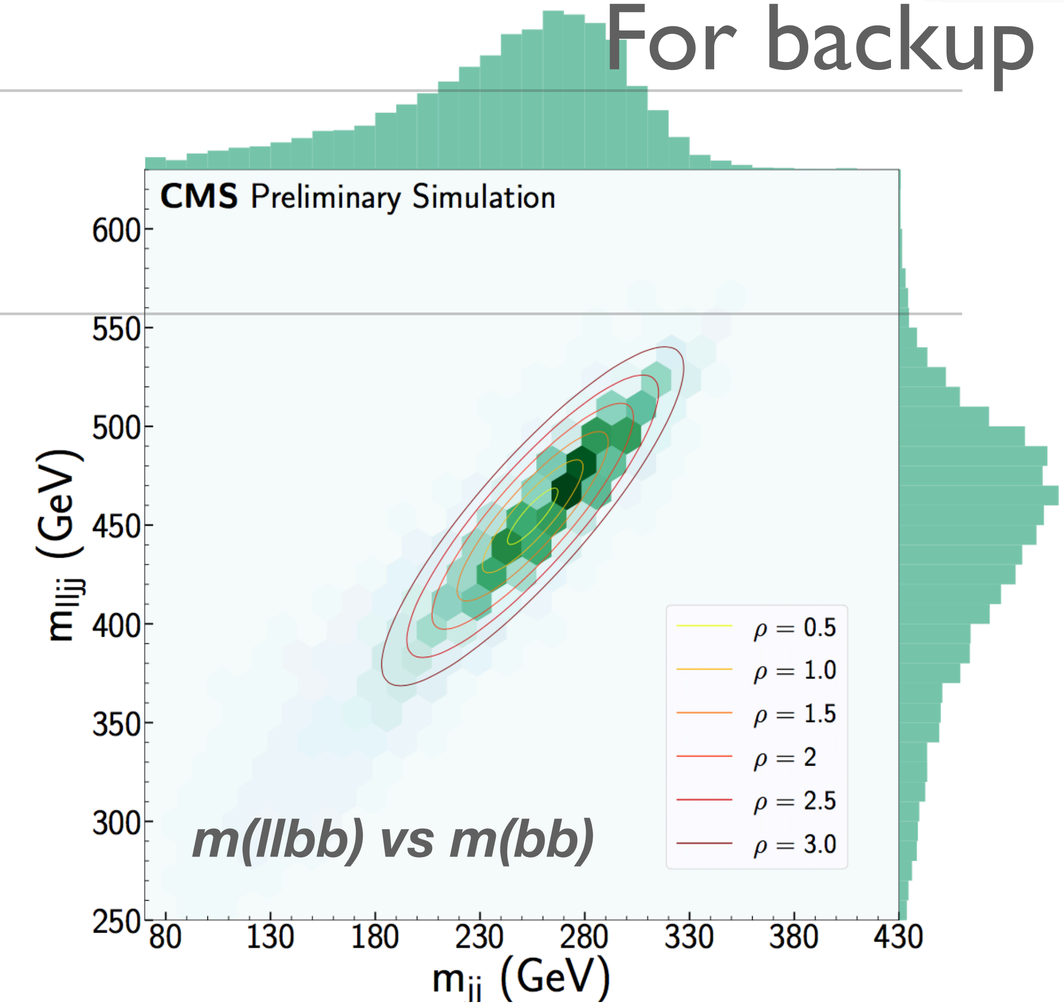
m(llbb) and m(bb) are correlated

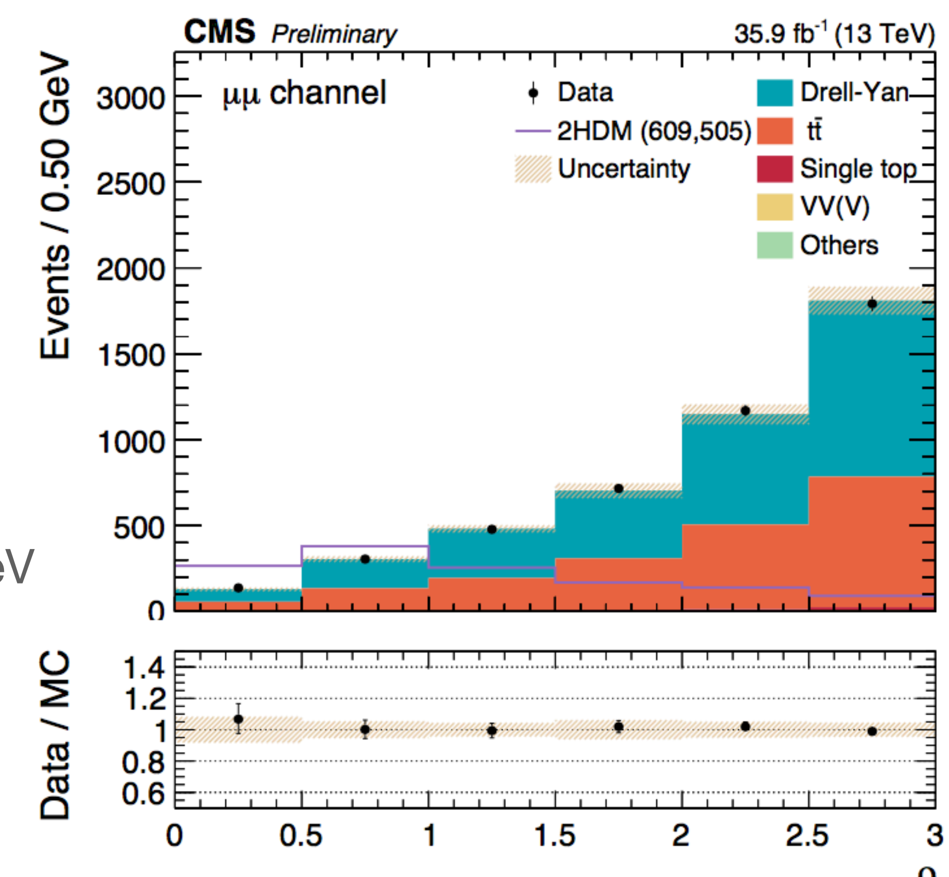
6 elliptically shaped bins in the 2D plane corresponding to fraction of the signal yield corresponding to ρ < 0.5,1, … 3σ of a ~2D gaussian pdf for each m hypo



@ analysis level H and A are not distinguishable

Local excess at m_H, m_A = 627, 126GeV with global significance ~1.3σ





SEARCH FOR A ➛ Zh➛$\ell\ell\,\tau\tau$

ATLAS: A➛Zh➛(ll/νν)bb: JHEP 03 (2018) 174

CMS: PAS-HIG-018-023

March 2019

$\ell\ell + \mu\tau_h$
$\ell\ell + e\tau_h$
$\ell\ell + \tau_h\tau_h$
$\ell\ell + e\mu$

4 channels used in the analysis

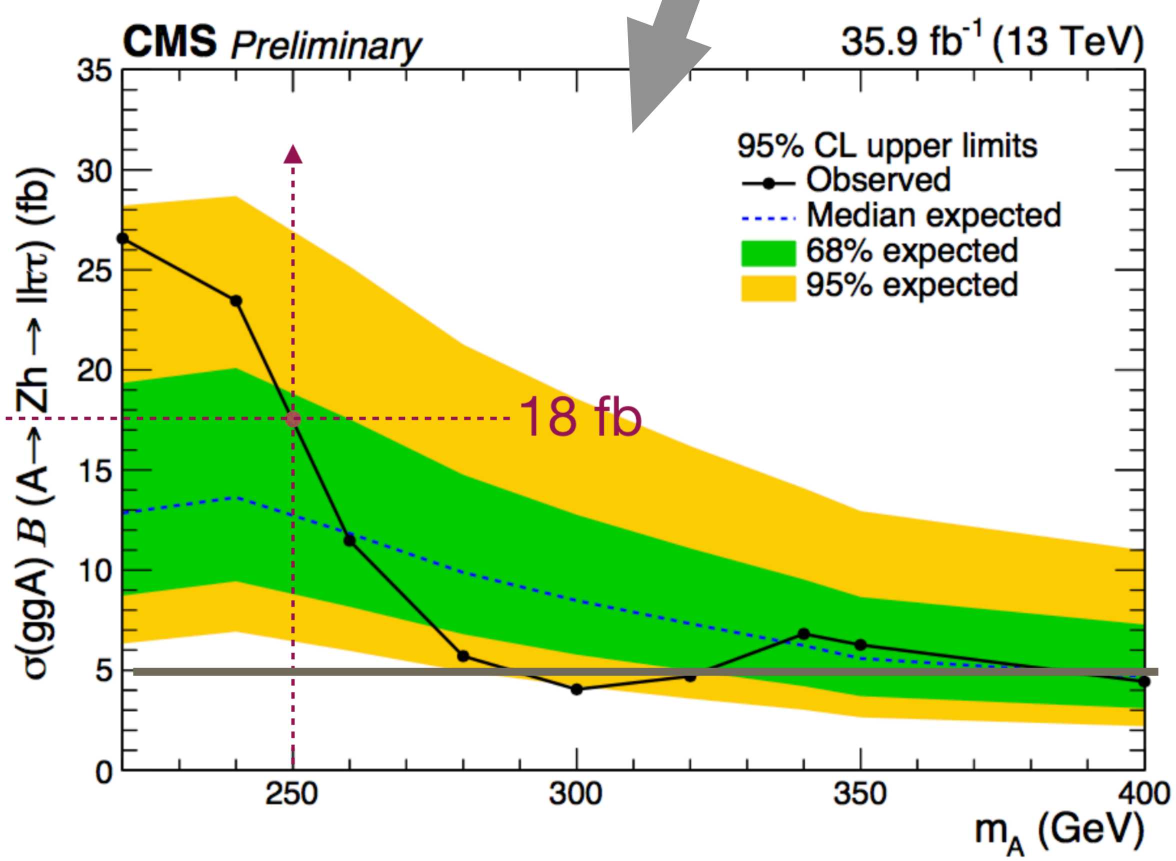
The selection target the *ggF* production mode (b-jet veto to suppress top background)

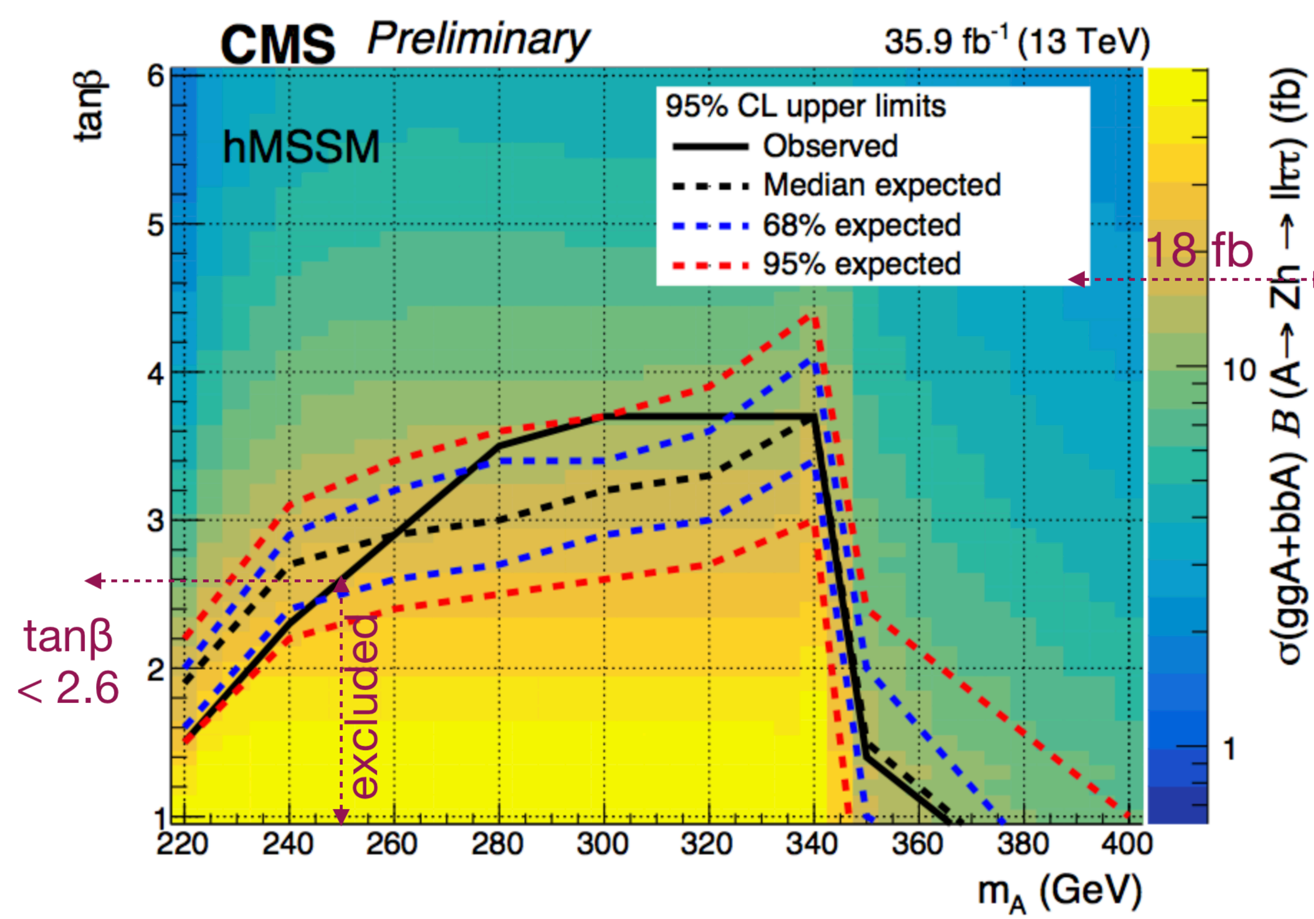
hZA, hW+H- couplings ~ cos(β-α) in MSSM

220-400 GeV, m_A range

No deviations w.r.t. SM predictions are observed
➥ limits on cross section x BR

interpretation in benchmark MSSM scenarios



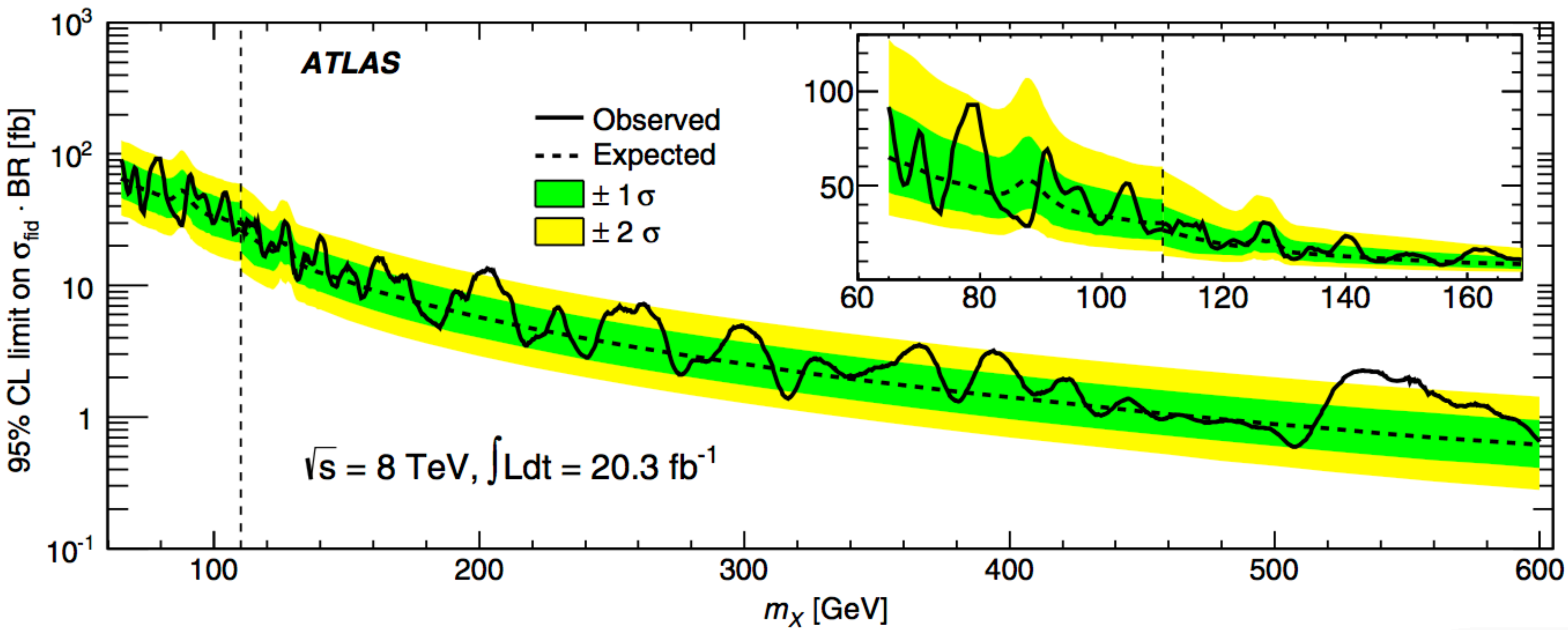


for example, at m_A=250 GeV, σxB > 18 fb is excluded => tanβ < 2.6 is excluded

SM-LIKE H→ γγ AT INTERMEDIATE MASS

ATLAS: PRL 113 (2014) 171801

- Search in the range 65-600 GeV with **8 TeV (20 fb^{-1})**
- two-γ final state



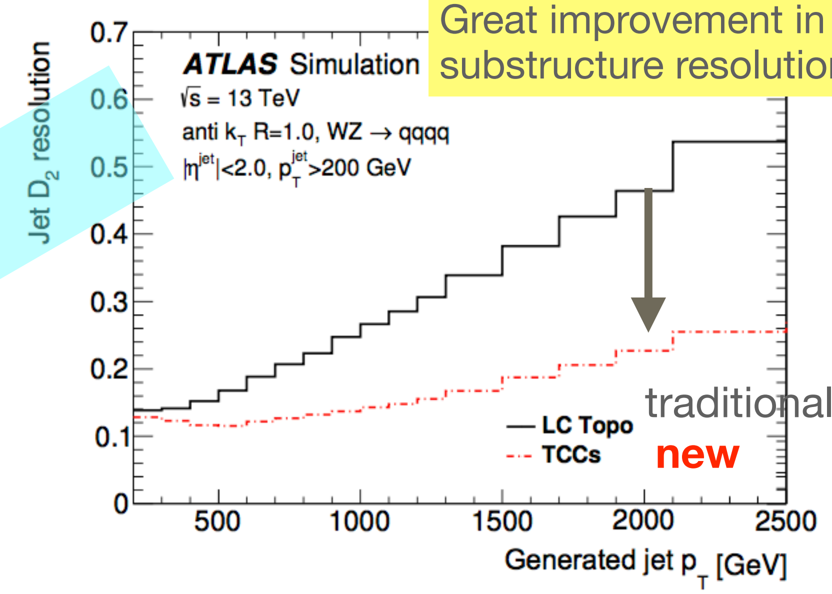
ATLAS: arXiv:1906.08589

SEARCH FOR *HIGH MASS VV* RESONANCES *(fully hadronic channel)*

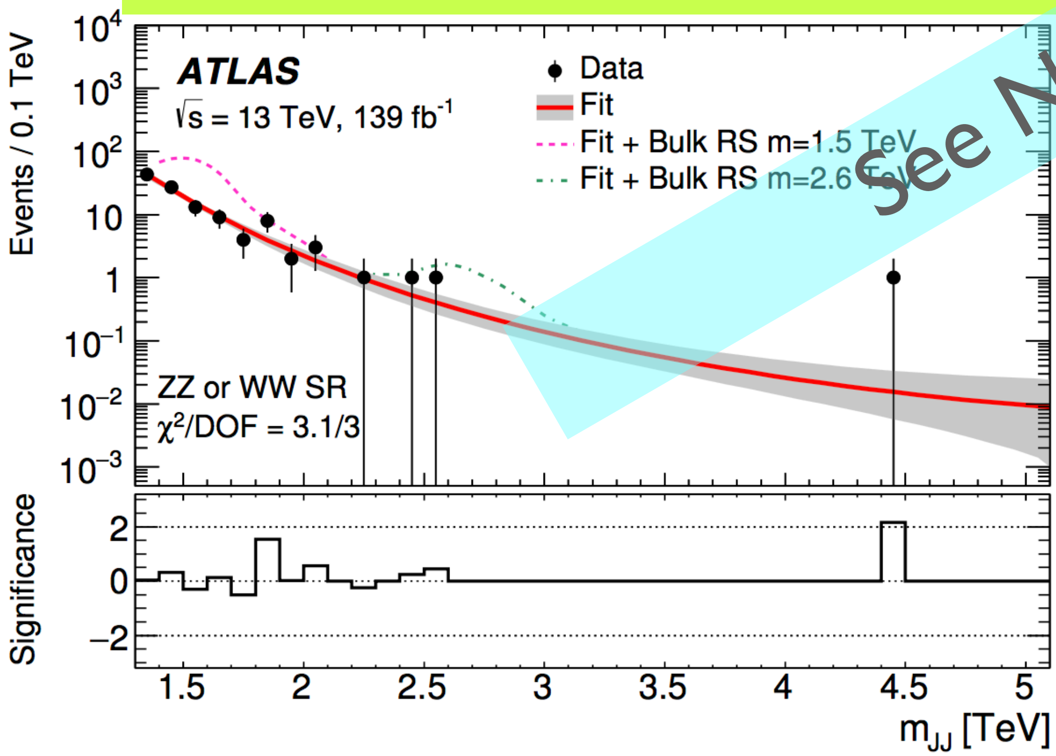
- ATLAS search for narrow di-boson resonances at m >1.3 TeV with ***139 fb^{-1} at 13 TeV*** in the fully hadronic final state ***two large-Radius jets, R=1.0***
  - Interpretation in benchmark ***spin-0***,1,2 model => ***Radion*** (in warped extra-dimensions) *decaying to WW or ZZ*…
  - Efficient V=Z,W tagging is crucial for S/B ➣ **Jet mass, substructure properties D2 => *new reco techniques***
    - jets from *TrackCaloClusters [combined and neutral]* *(merging direction info from tracking with energy info from Calo)*
    - **n_{trk} in jet** => lower in gluon-initiated jets
  - $|y_{12}| < 1.2$ and $A = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2}) < 0.15$ to suppress background
- ☑ Efficiency x acceptance is ~5% from m < 5 TeV
- ☑ For m=2 TeV, m_{JJ} distributions with a width of ~10% of the peak is obtained

See Nadir Daci's talk

Great improvement in jet substructure resolution



No explicit interpretation in BSM Higgs scenarios



In Randall-Sundrum warped Extra Dimension models ***Radions*** are scalar (spin 0) excitations of the gravitational field

Radions couple to fermions proportionally to m_f and to bosons proportionally to m_b^2

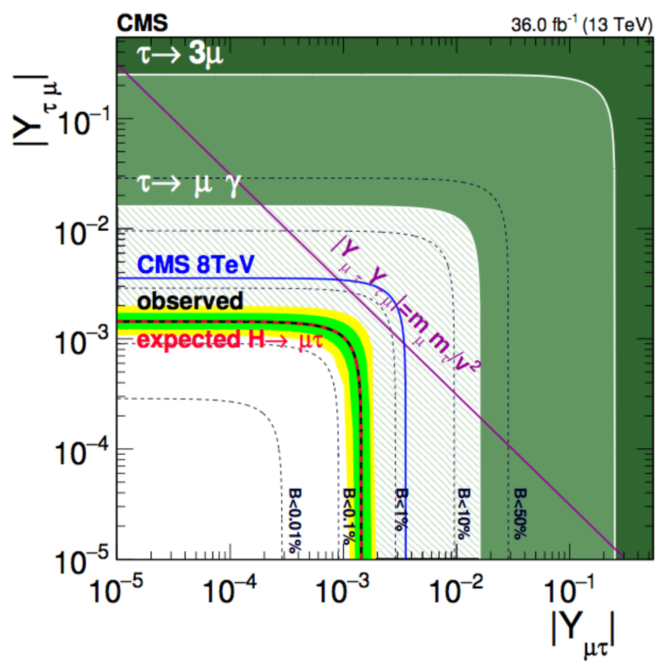
Mass [TeV]	Observed Limit [fb]		Expected Limit [fb]	Prediction [fb]
2.0	5.72		5.75	4.286
3.0	1.86	***Radion***	2.85	0.415
4.0	1.98		2.34	0.040
5.0	1.98		2.02	0.006

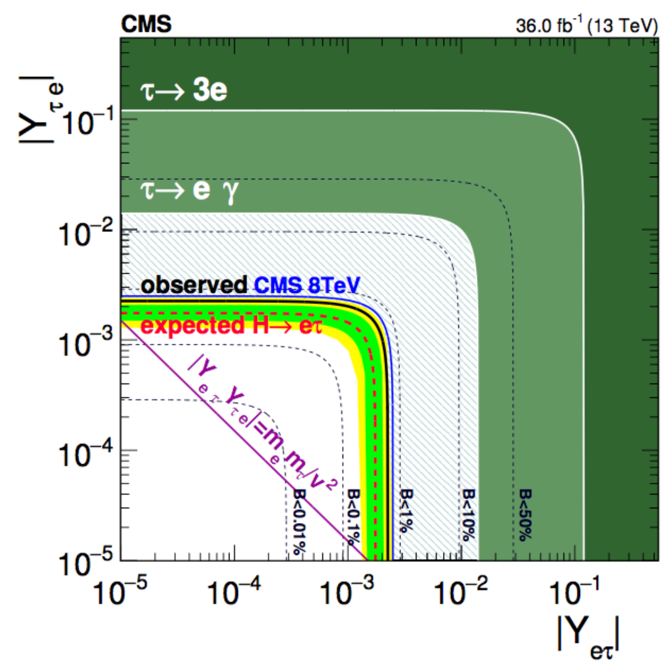
LFV DECAYS: $h \rightarrow \tau e, \tau\mu$

$H \to \mu\tau$ <0.25 (0.25)% $H \to e\tau$ <0.61 (0.37) % BR limits @ 95% CL

$\mu\tau_e$

$\mu\tau_h$





$e\tau_\mu$

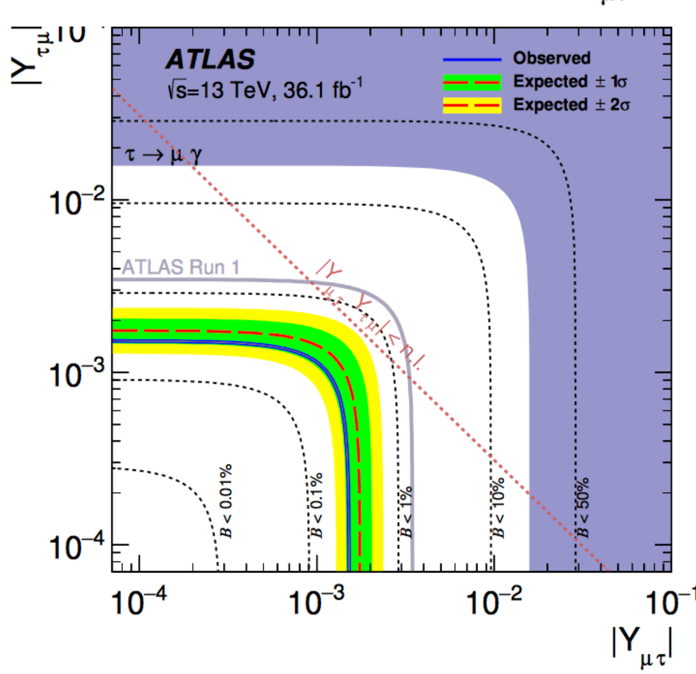
$e\tau_h$

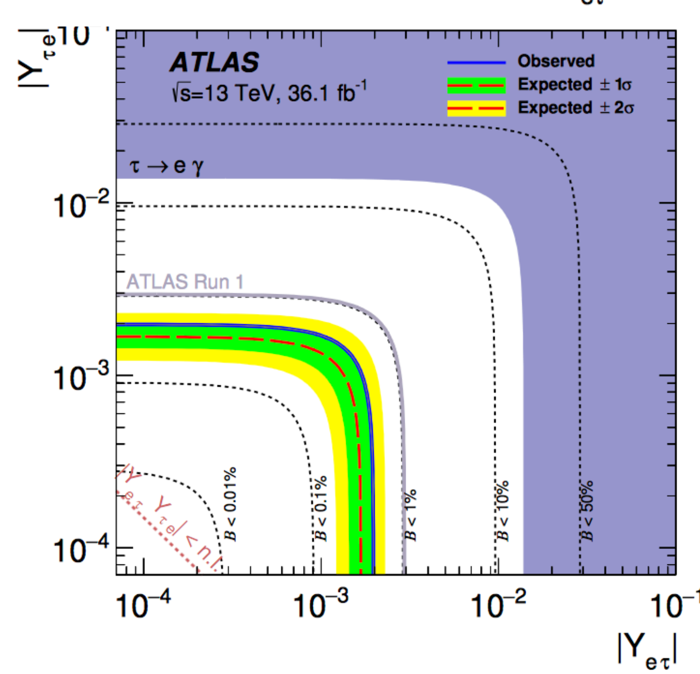
- **CMS** results on **13 TeV, 36fb^{-1}** May 2018 already at PIC2018

JHEP06(2018)001

Results from BDT score or M_{coll}

36 fb^{-1}, 13 TeV





- **ATLAS** results on **13 TeV, 36fb^{-1}** Jul 2019

arXiv:1907.06131, sub to PLB

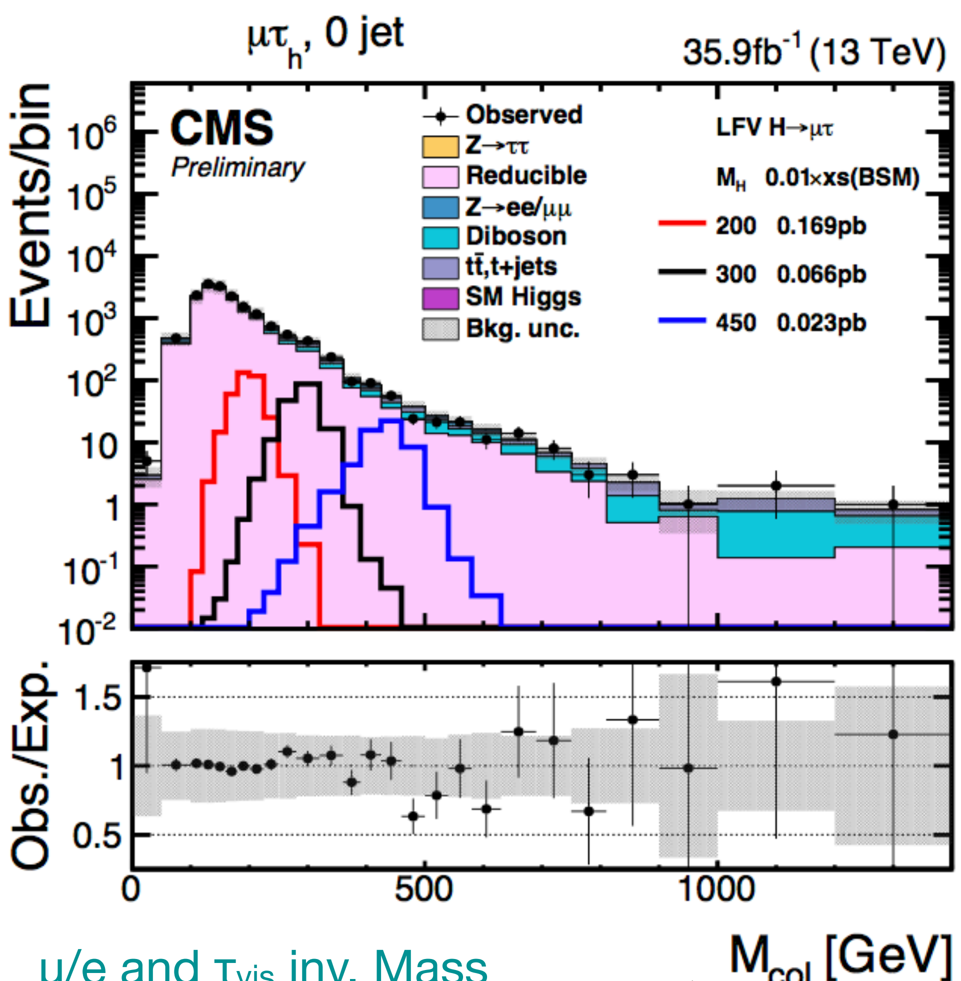
Results from BDT score

$0.47\% \ (0.34^{+0.13}_{-0.10}\ \%)$ $0.28\% \ (0.37^{+0.14}_{-0.10}\ \%)$ BR limits @ 95% CL

CMS PAS HIG-18-017

LFV DECAYS: HEAVY $h \to \tau e, \tau\mu$

- preliminary recent **CMS** results on **13 TeV, 36fb^{-1}** May 2019:
  - direct search for $H \to \mu\tau_h, H \to \mu\tau_e$, $H \to e\tau_h, H \to e\tau_\mu$

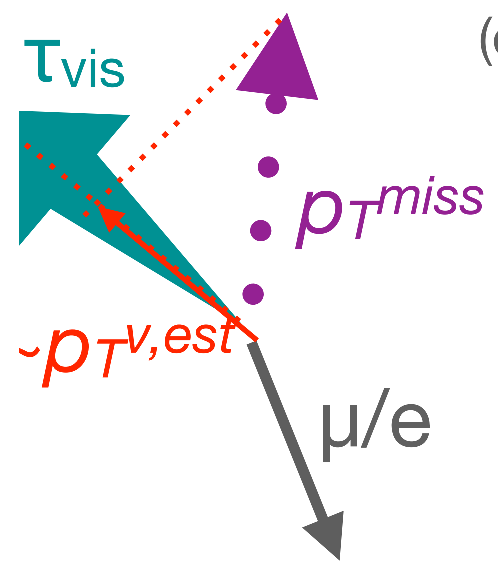


μ/e and τ_{vis} inv. Mass

$$M_{\text{vis}}/\sqrt{x_\tau^{\text{vis}}}$$

Visible fraction of τ energy

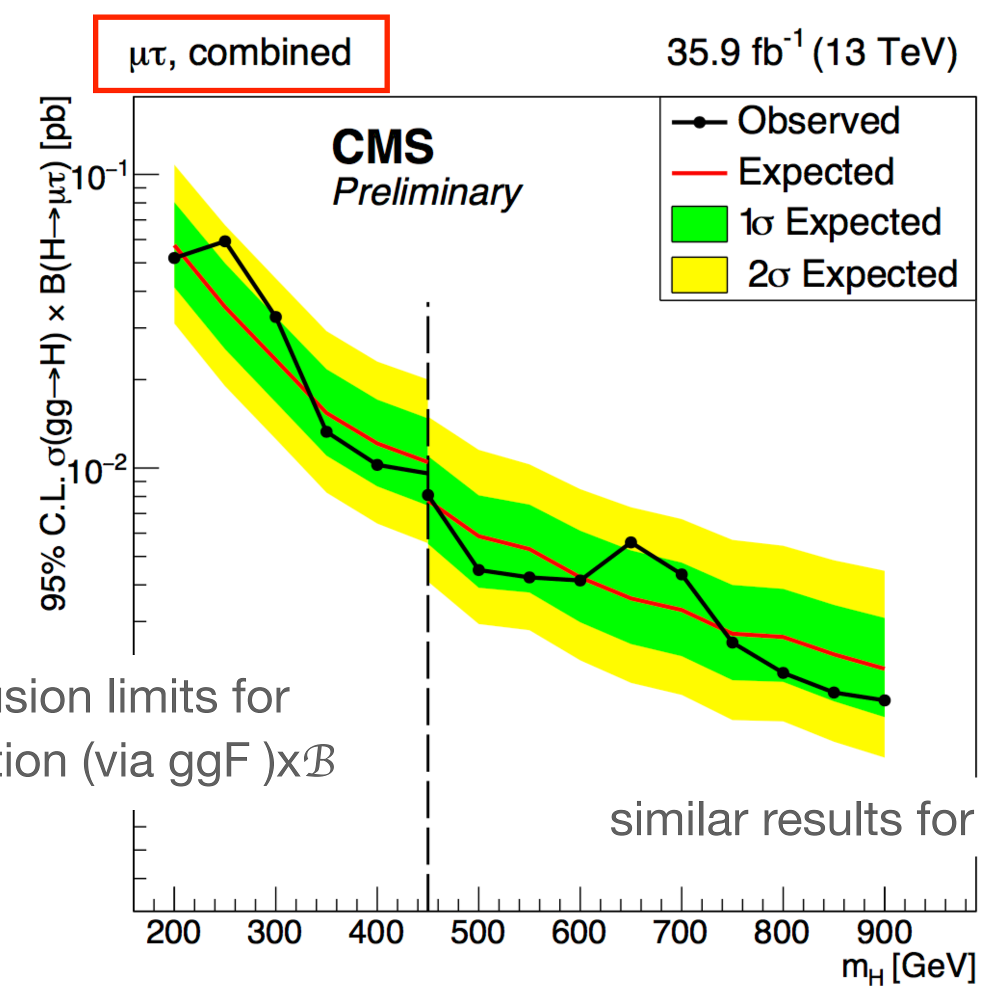
$$x_\tau^{\text{vis}} = p_T^{\vec{\tau}\,\text{vis}} / (p_T^{\vec{\tau}\,\text{vis}} + p_T^{\nu,\,\text{est}})$$



$m_H >> m_\tau$ ➜ τ decay products highly Lorentz boosted

Data driven estimate of W+j and multi-j background from j➛τ_h misidentification rate (estimated in Z+j and applied in control regions)

Main source of systematic error ~30%

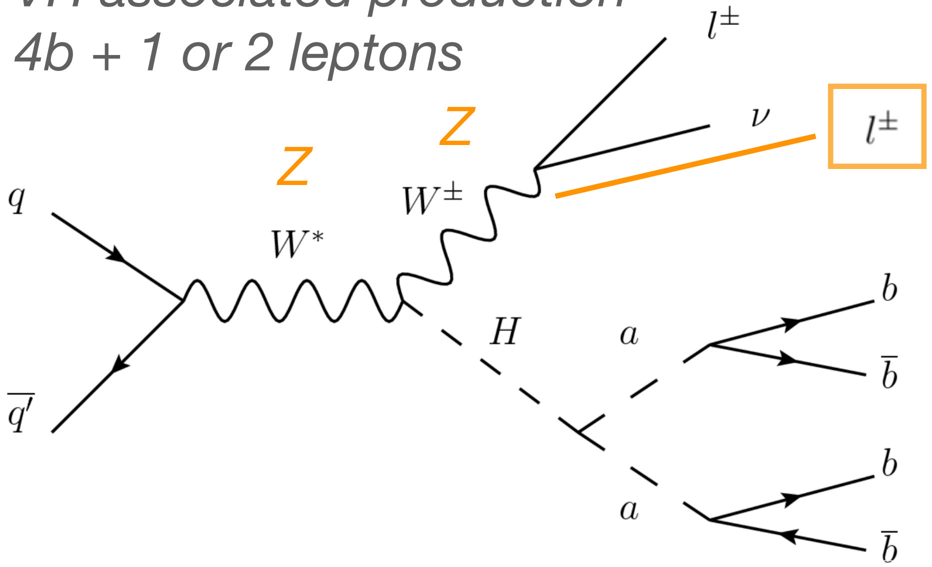


Exclusion limits for production (via ggF)x$\mathcal{B}$

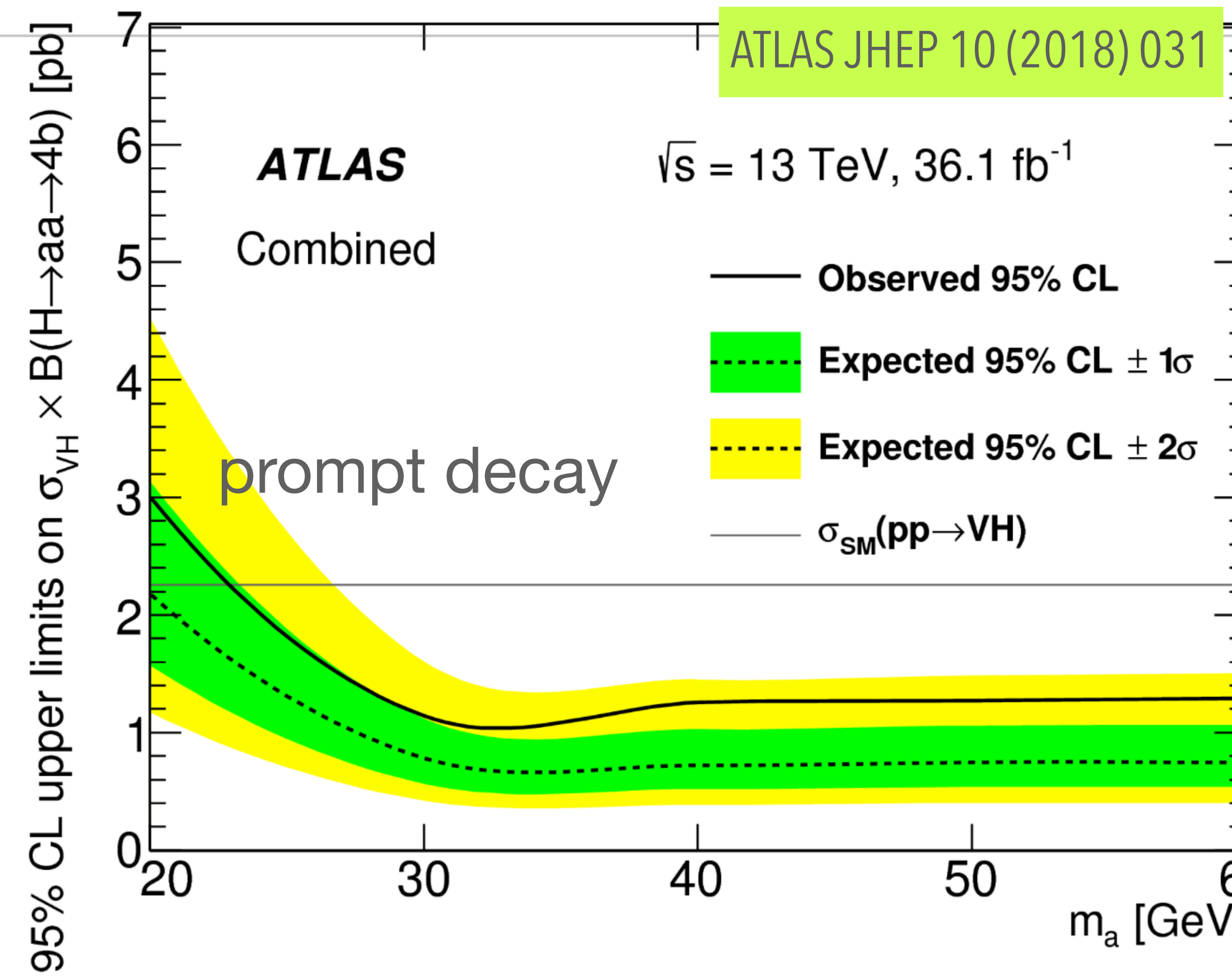
similar results for H➛eτ

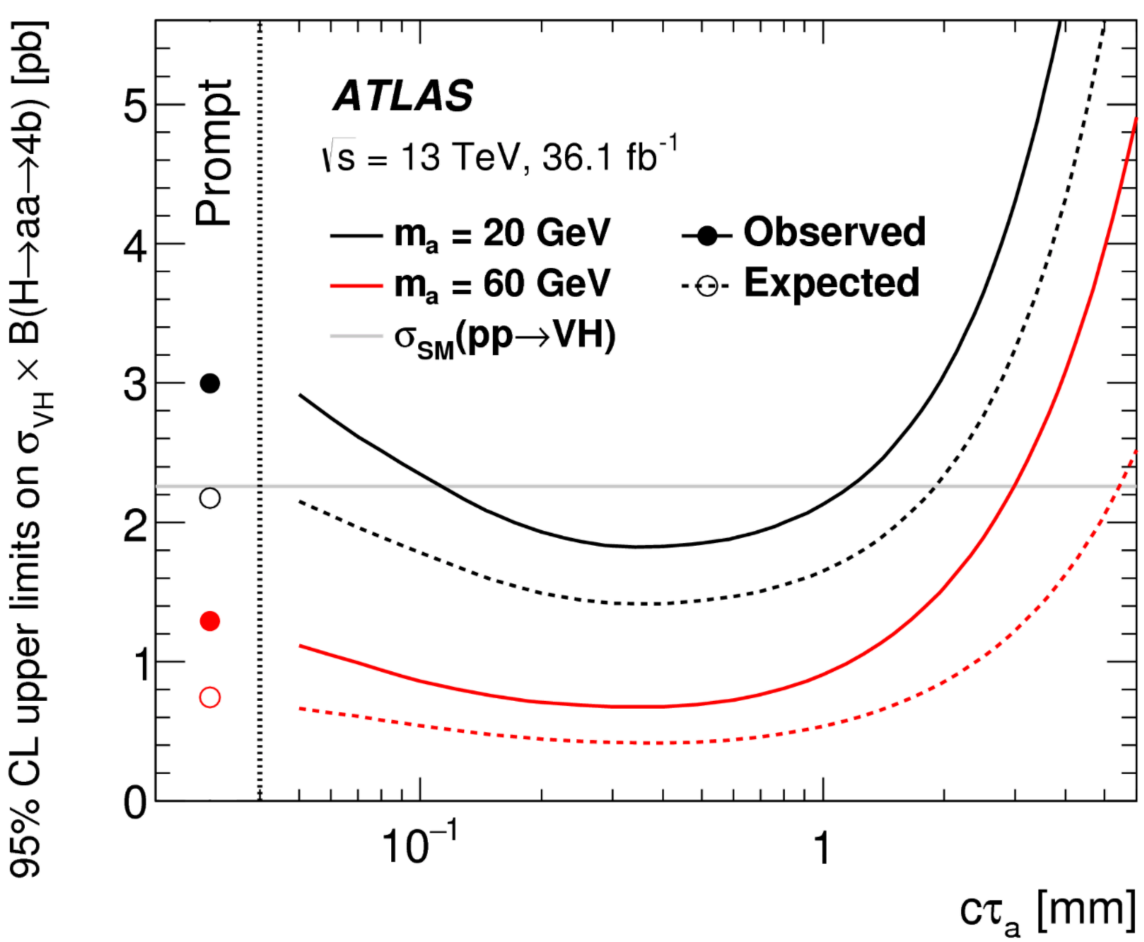
$h_{SM} \to aa \to 4b$ for $c\tau_a$<6mm, m_a in 20-60 GeV

VH associated production
4b + 1 or 2 leptons



ATLAS JHEP 10 (2018) 031





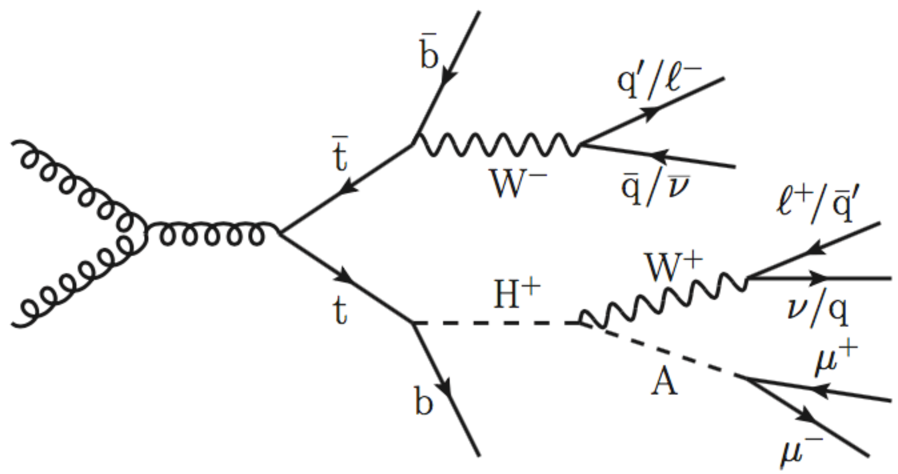
limit as a function of $c\tau_a$ for 20 and 60 GeV

enhancement of sensitivity at ~0.5 mm $c\tau_a$ due to higher b-tagging eff. for displaced b-production vertices

$H^{+/-} \to W^{+/-}A \to \mu\mu\mu/\mu ee$

CMS: ArXiv:1905.07453 May 2019

Inspired by R. Dermisek, E. Lunghi, A. Raval HEP04(2013)063

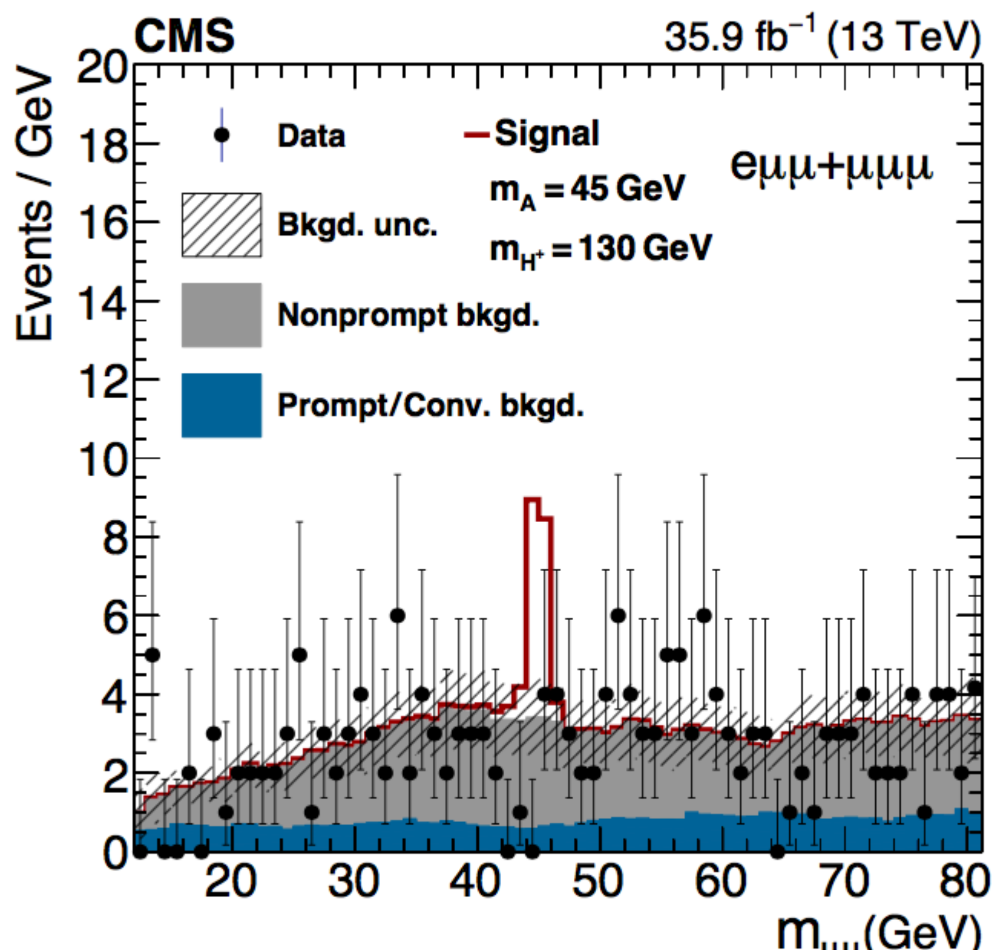


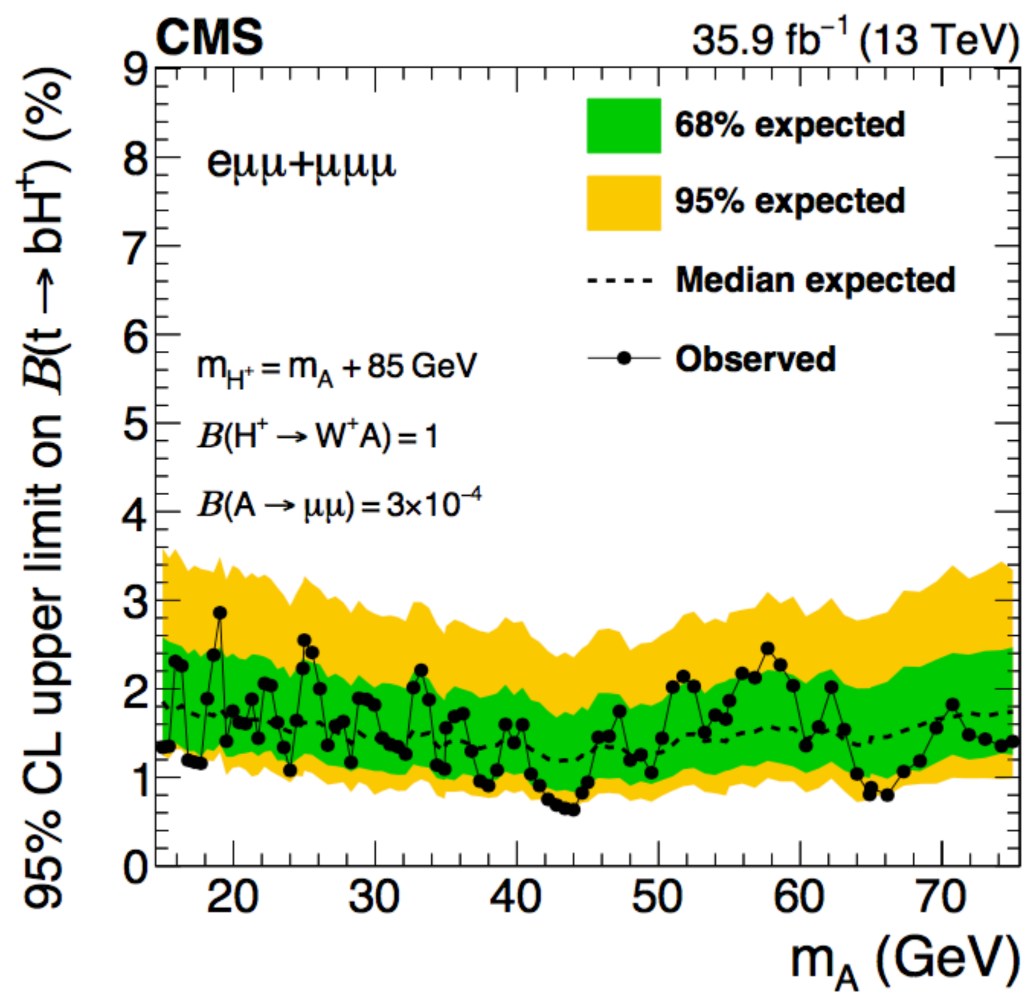
$H^{+/-}$ produced in a top decay

$H^{+/-} \to W^{+/-}A$ is the dominant decay mode if $H^{+/-}$ is lighter than the top

$A \to \mu\mu$ an easy signature

singlet extensions of the two Higgs doublet model allows for this decay mode of the charged Higgs, while being compatible with a SM-like scalar at ~125 GeV

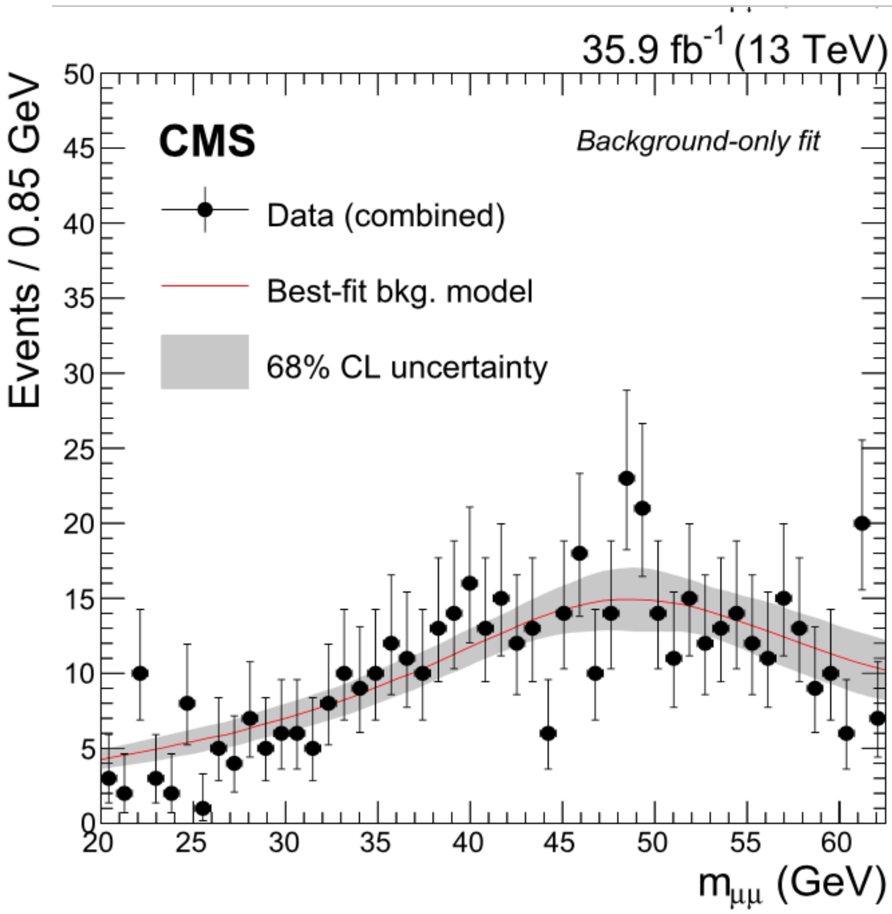




$h_{SM} \to a_1 a_1 \to bb\mu\mu$

CMS: arXiv:1812.06359, PLB795(2019)398, **$h_{SM} \to aa \to bb\mu\mu$**

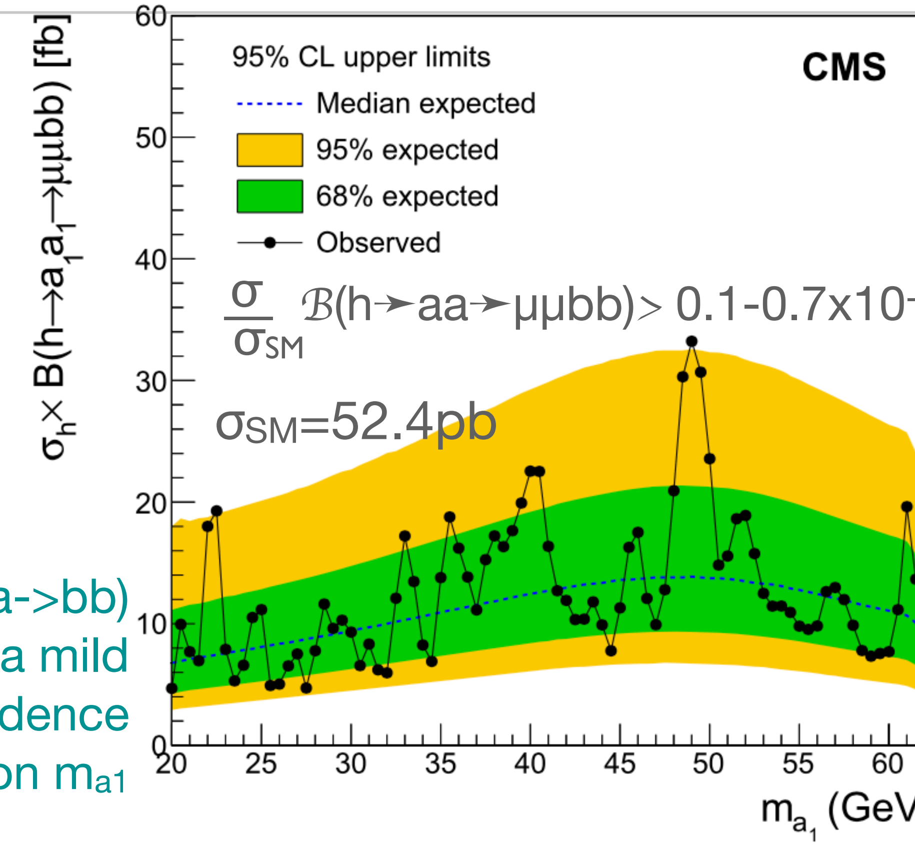
m_{a1} investigated range 20-62.5 GeV



signature:

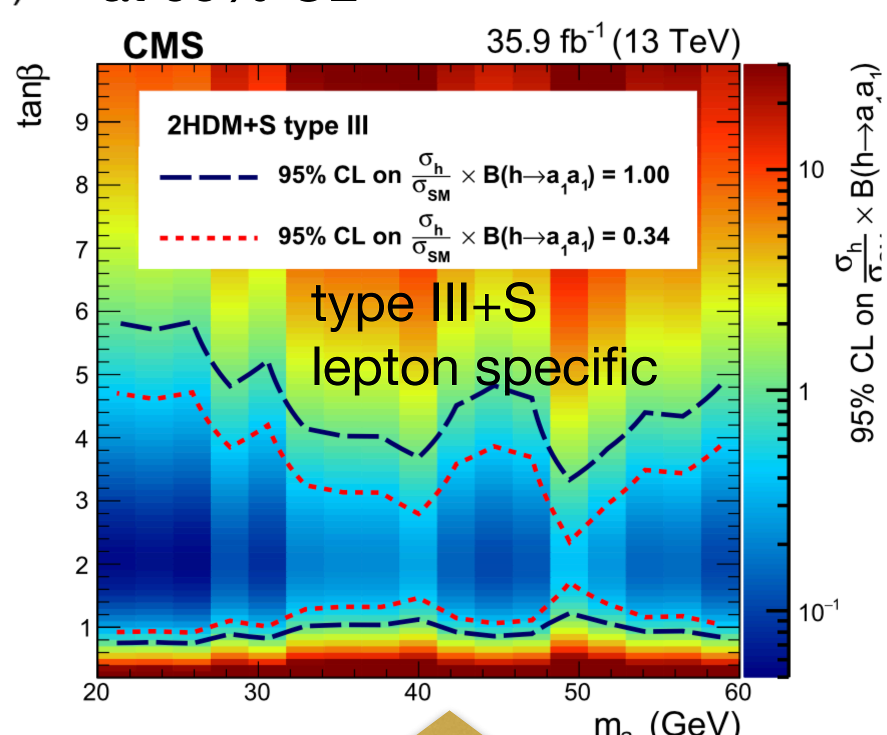
$m_{bb} \approx m_{\mu\mu} \approx m_{a_1}$

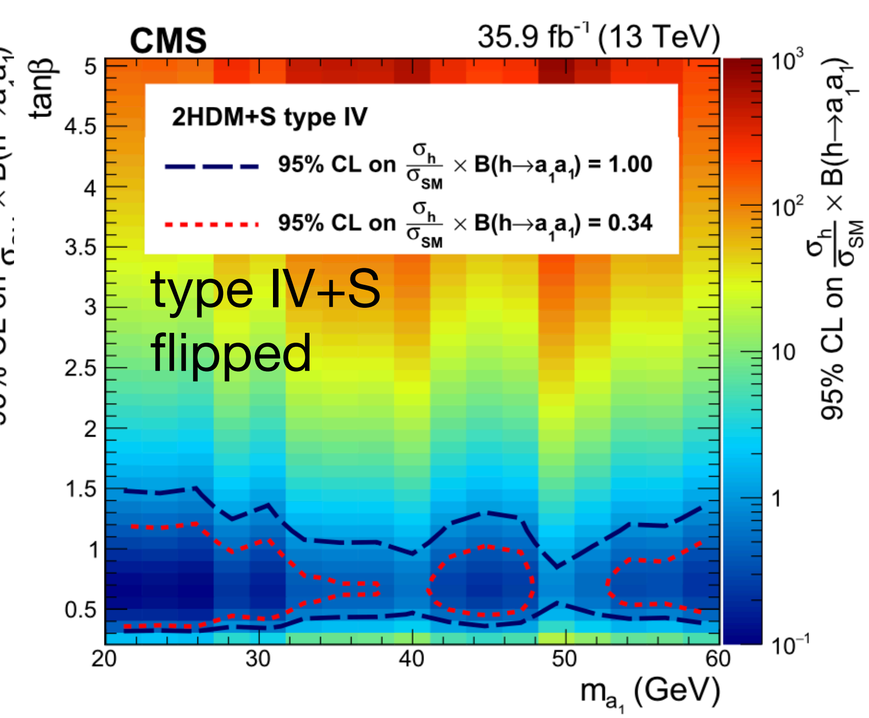
after the selection an un-binned maximum likelihood fit of $\boldsymbol{m_{\mu\mu}}$ is used for S/B discrimination



B(a->μμ)xB(a->bb) has a mild dependence on m_{a1}

at 95% CL





For a given m_{a1} value, changes of tanβ modify B(a→μμ)xB(a→bb)

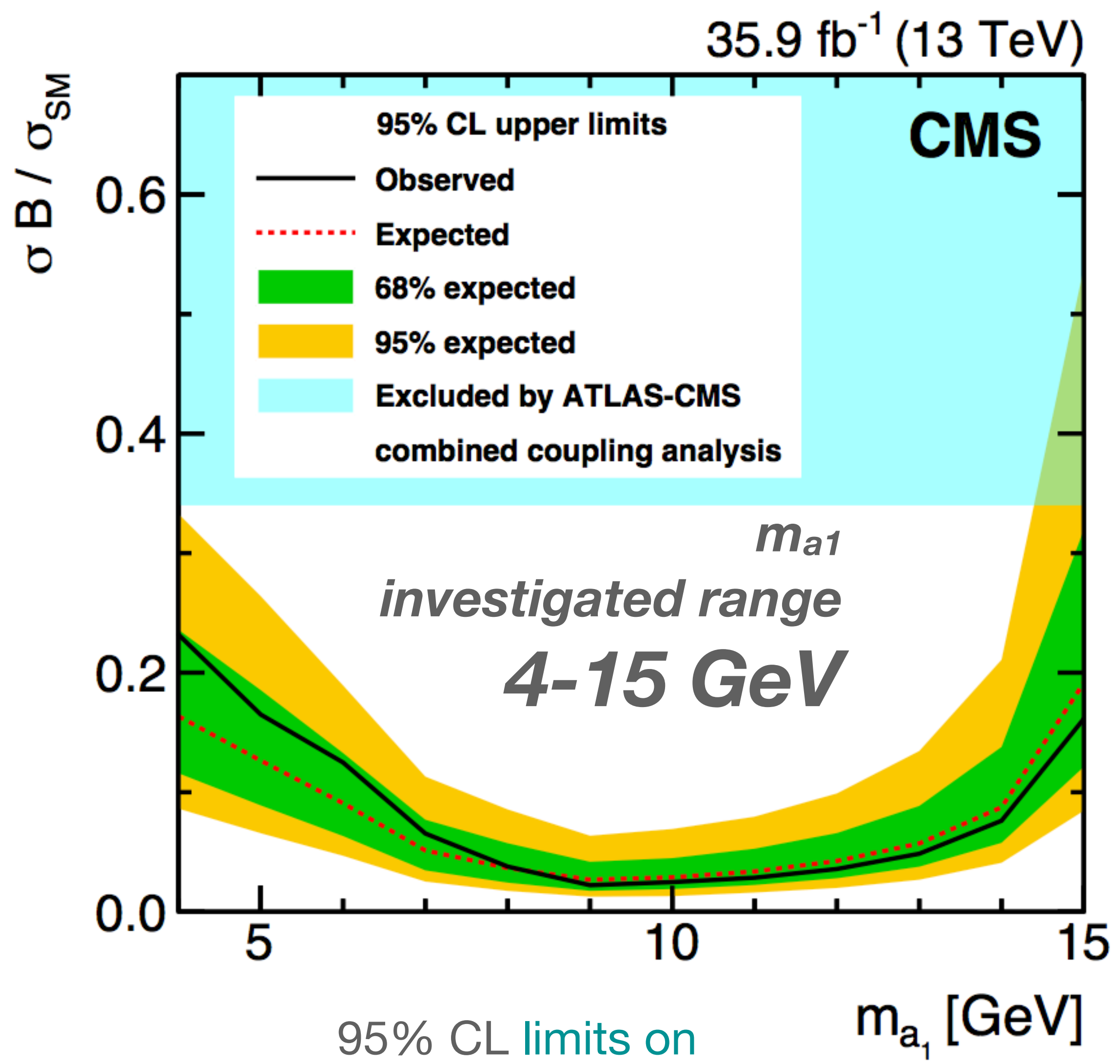
➡ limits on $\mathcal{B}(h \to a_1 a_1 \to \mu\mu bb)$ can be turned into a limit on $\mathcal{B}(h \to a_1 a_1)$

sensitivity region
exclusion region

$h_{SM} \to a_1 a_1 \to \mu\mu$+2tracks $\mu\mu\tau\tau$ $\tau\tau\tau\tau$

CMS: ArXiv:1907.07235, July 2019: H->aa->μμ+2tracks

- a process allowed in non-minimal supersymmetric SM and the lepton specific and flipped 2HDM+S (a 2HDM model extended with a scalar singlet)

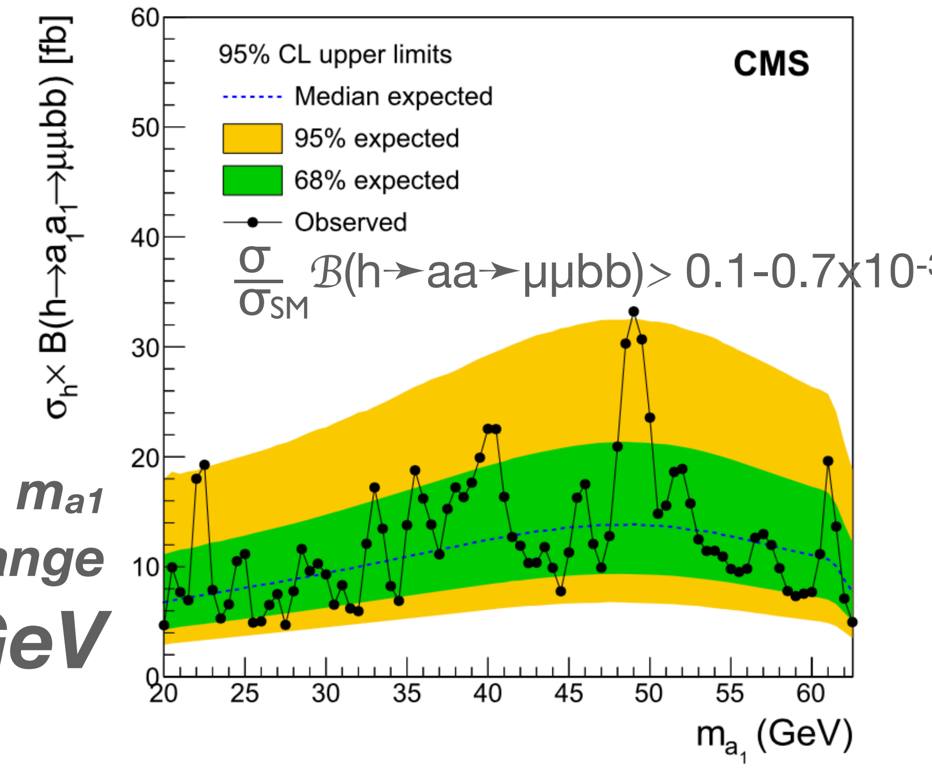


m_{a1} investigated range **4-15 GeV**

95% CL limits on

$\mathcal{B}(h_{SM} \to a_1 a_1) \times \mathcal{B}^2(a_1 \to \tau\tau)$

assuming SM production cross sections

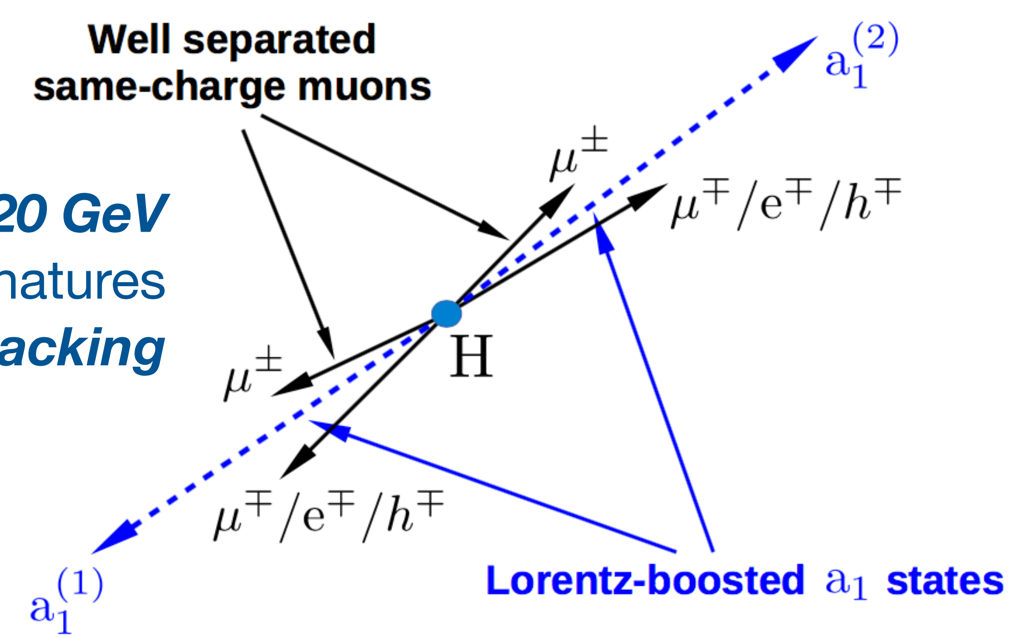


$\frac{\sigma}{\sigma_{SM}} \mathcal{B}(h \to aa \to \mu\mu bb) > 0.1\text{-}0.7 \times 10^{-3}$

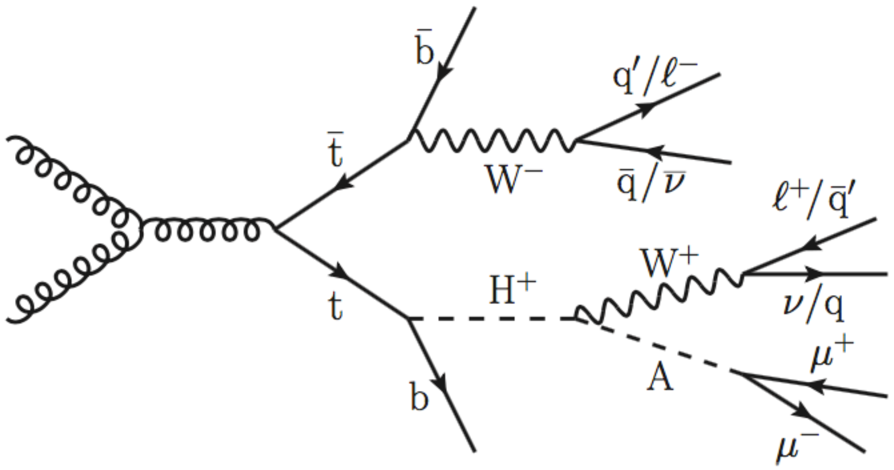
m_{a1} investigated range **20-62.5 GeV**

m_{a1}

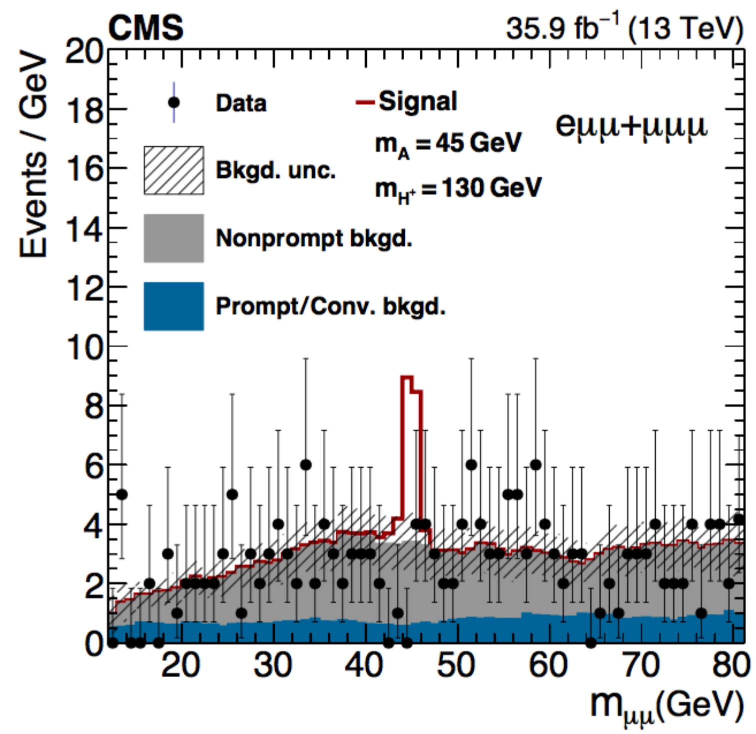
studying m_{a1}<20 GeV with signatures relying on *tracking*

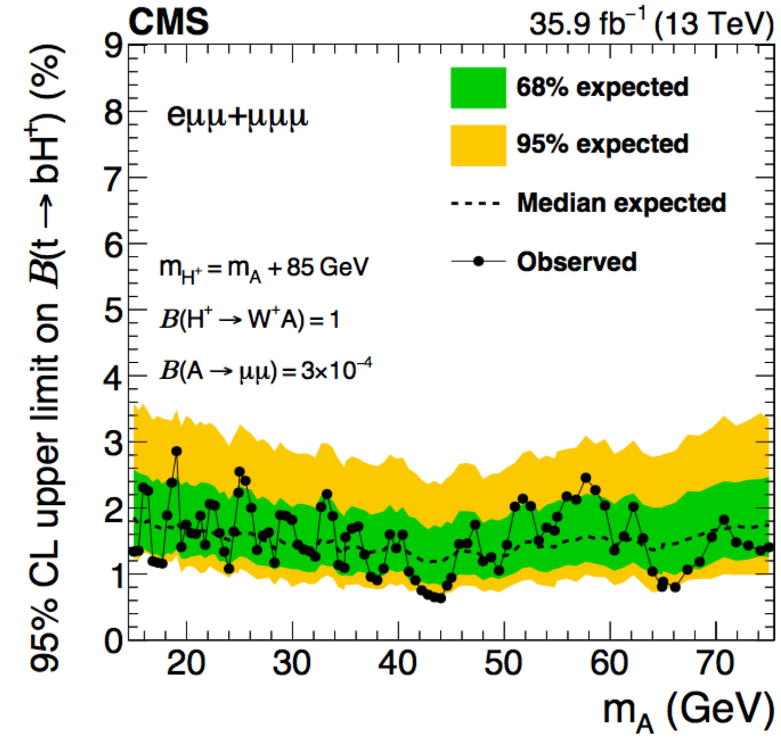


CMS: ArXiv:1905.07453, **$H^{+/-} \to W^{+/-} a \to \mu\mu\mu/\mu ee$**



m_{a1} in 15-75 GeV





$H^{+/-}$ produced in a top decay

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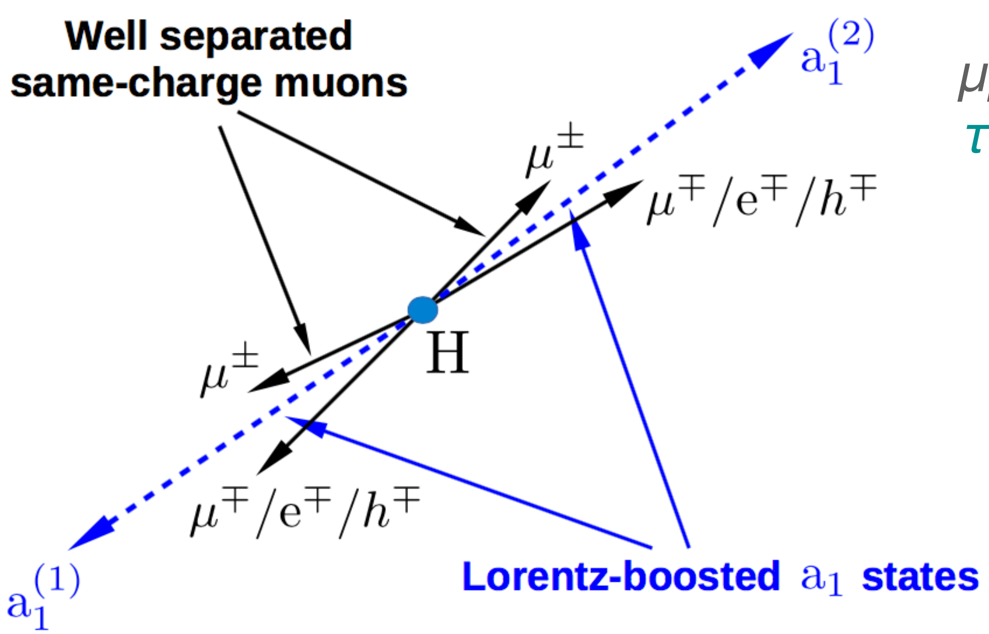


m_{a1} in 4-15 GeV

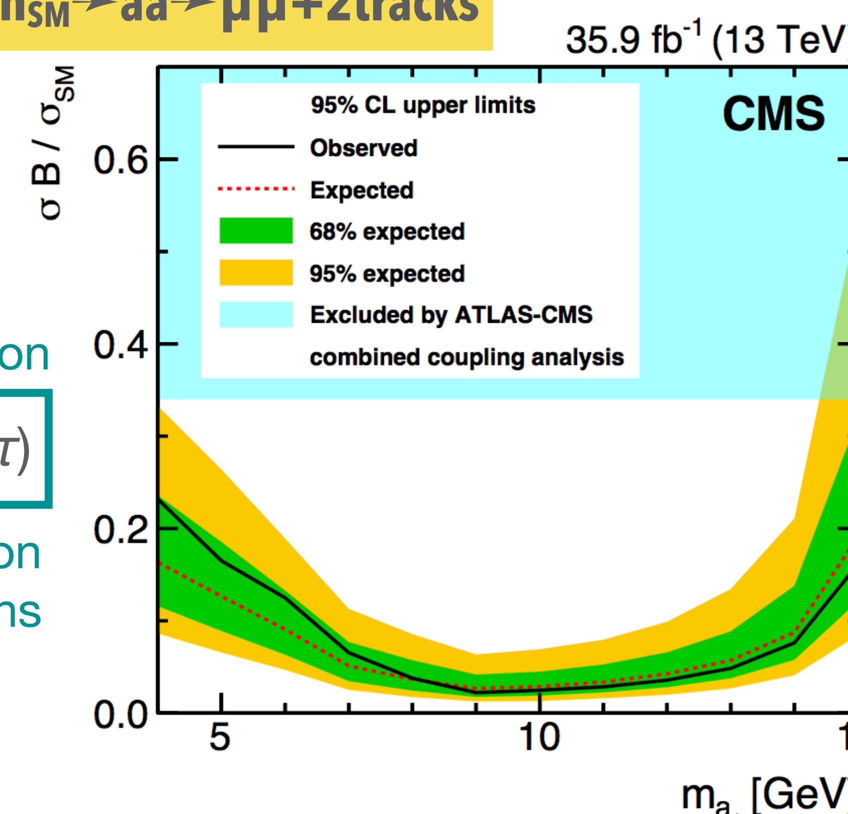
$\mu\mu\tau\tau$

$\tau\tau\tau\tau$

95% CL limits on

$\mathcal{B}(h_{SM} \to a_1 a_1) \times \mathcal{B}^2(a_1 \to \tau\tau)$

assuming SM production cross sections



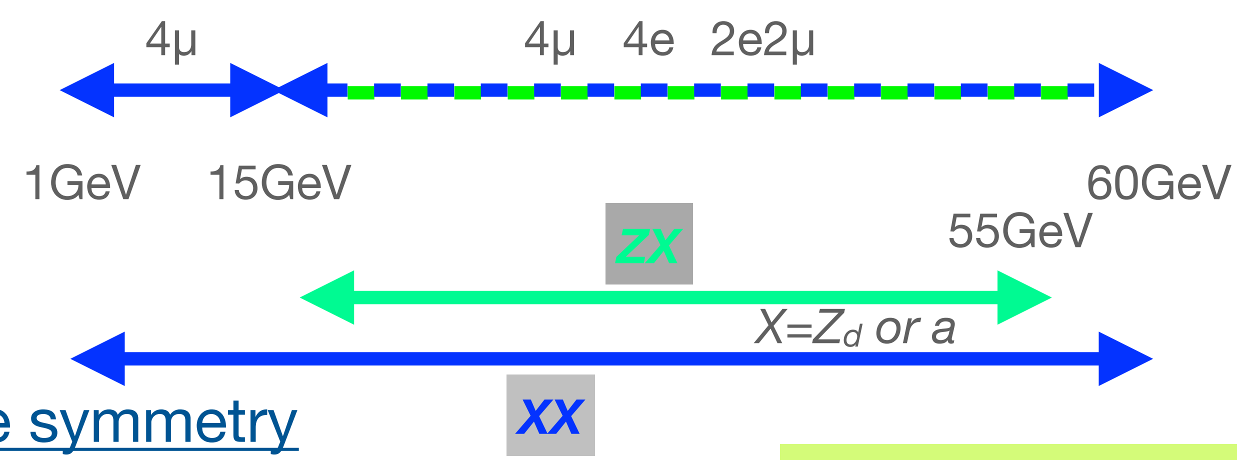
$H \to XX/ZX \to$ 4 leptons

for m_a, m_{Zd} in 1 and 60GeV

ATLAS: JHEP06(2018)166

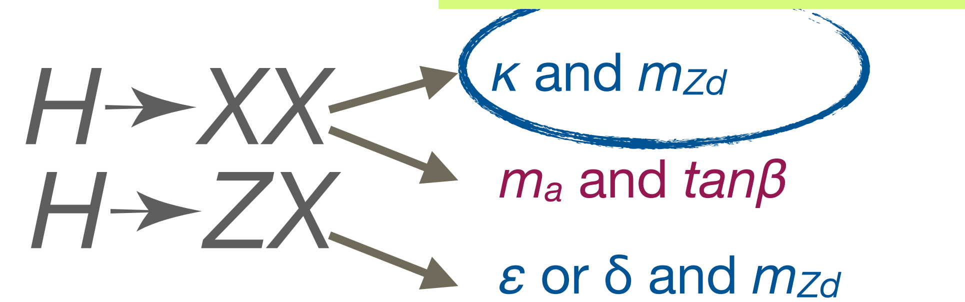
$X=a$ (pseudoscalar), $X=Z_d$ (vector)

three analyses

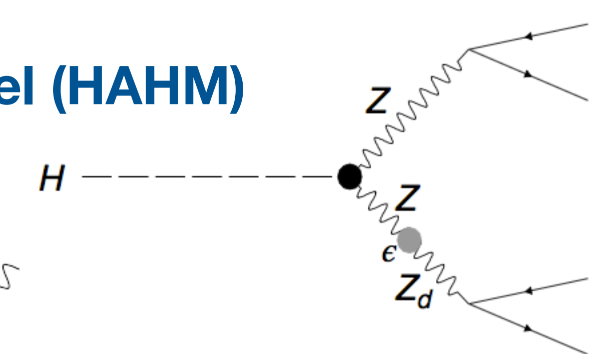


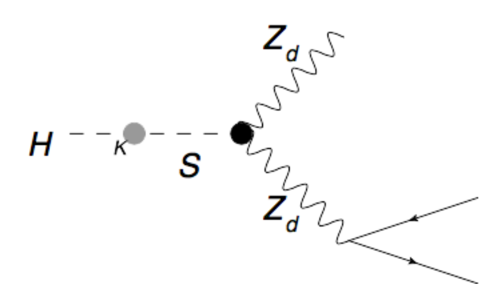
- the decay to 4 leptons occurs via a pair-production of a *vector* Z_d or a *pseudo-vector a*
- *two benchmark models:*
  - **2HDM+S** (as before);
    - type II (i.e. next to minimal SUSY)
  - spontaneously broken **U_d(1)** extra gauge symmetry holding for fermions / scalars not coupling to SM gauge bosons (secluded dark matter sector)
    - light gauge vector boson Z_d coupling can decay to ee, μμ via
      - kinetic mixing with the SM hypercharge gauge fields ε
      - mass mixing with the Z boson (δ)
    - Z_d production can proceed via mixing of the dark Higgs with the SM Higgs (κ) or $H \to ZZ \to ZZ_d$

accessible only at LHC



Hidden Abelian Higgs Model (HAHM)

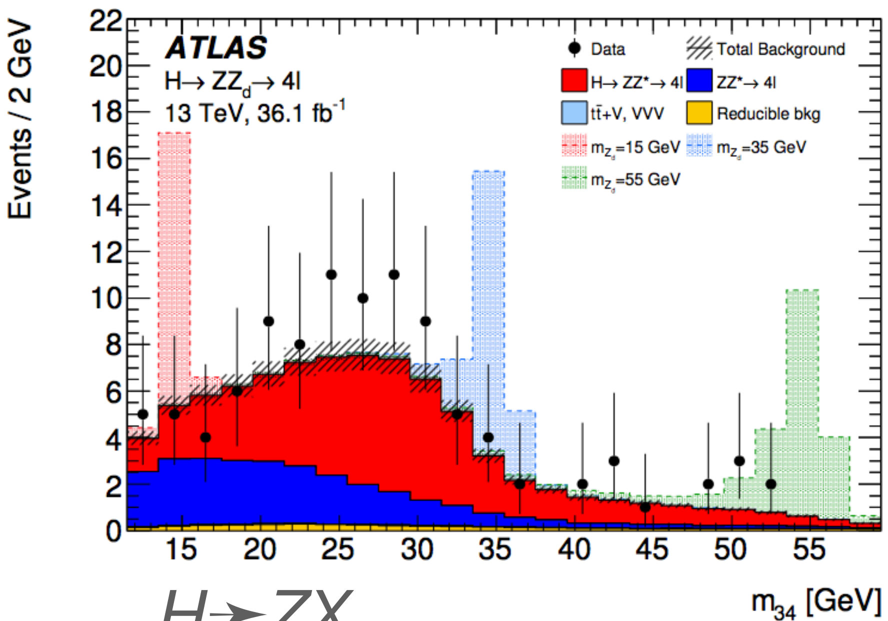




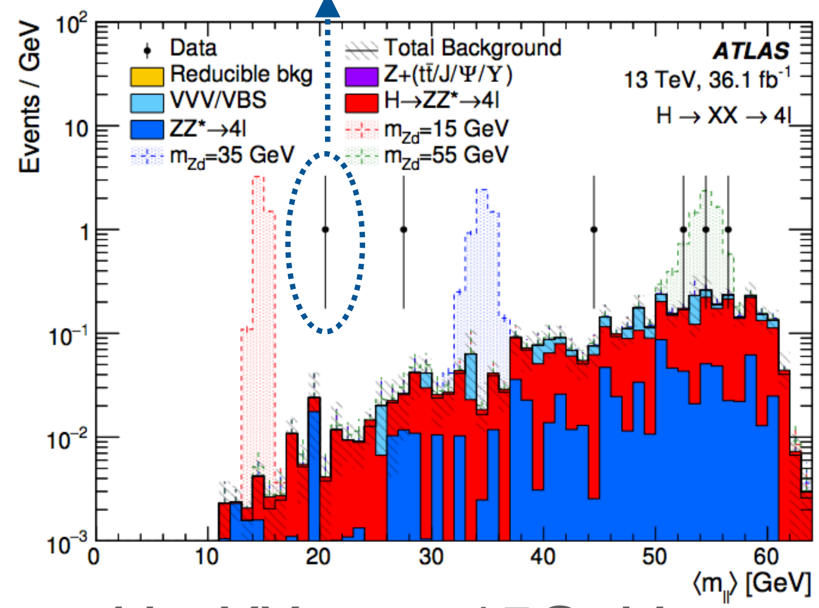
H➛XX/ZX➛ 4 leptons

ATLAS: JHEP06(2018)166

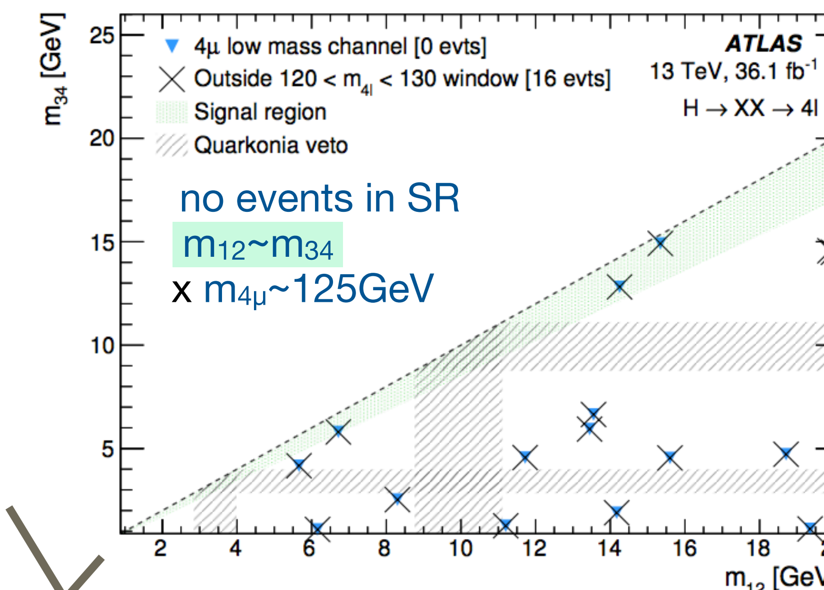
local (global) significance of 3.2(1.9) σ



H➛ZX



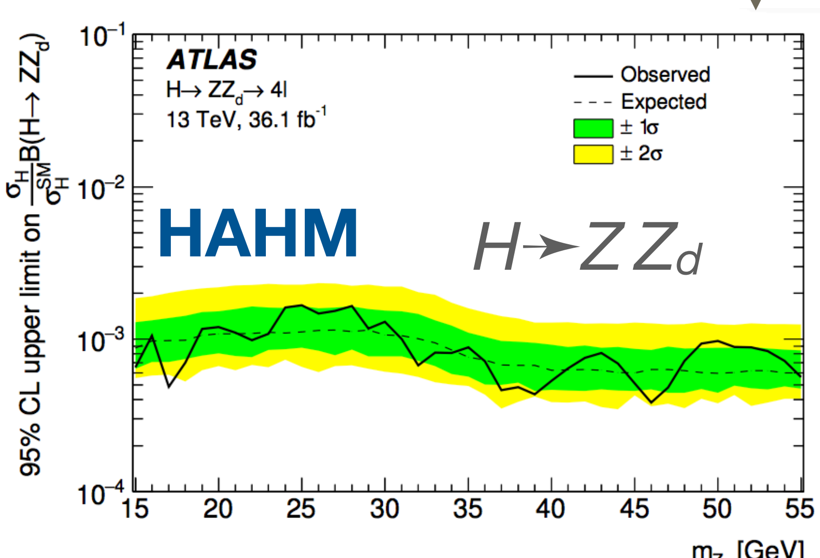
H➛XX, m_X>15GeV



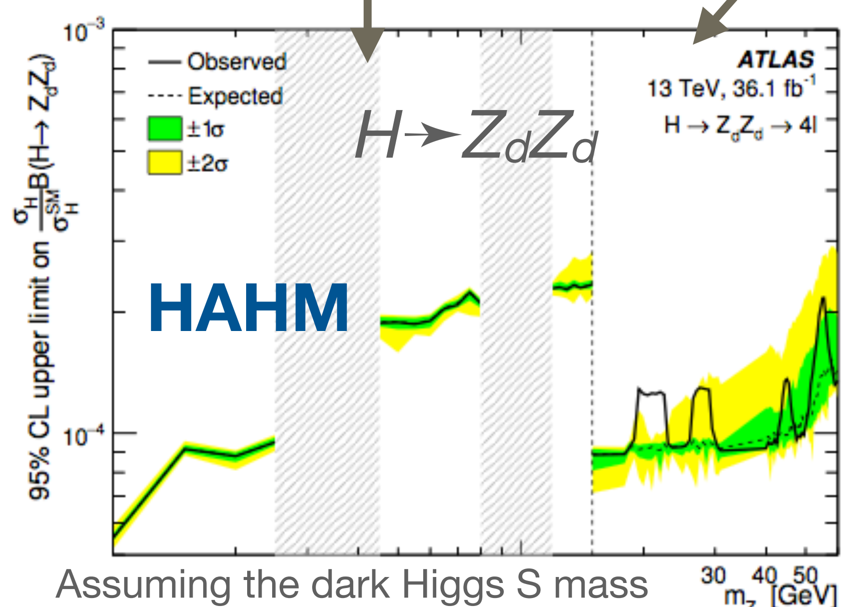
H➛XX, m_X<15GeV

using JHEP 02 (2015) 157 for B(Zd ➛ℓℓ) andPRD 90 (2014) 075004 for B(a➛ℓℓ)

Can be interpreted as a limit
~0.4-0.8x10^{-2} on ε,
the hypercharge-portal coupling

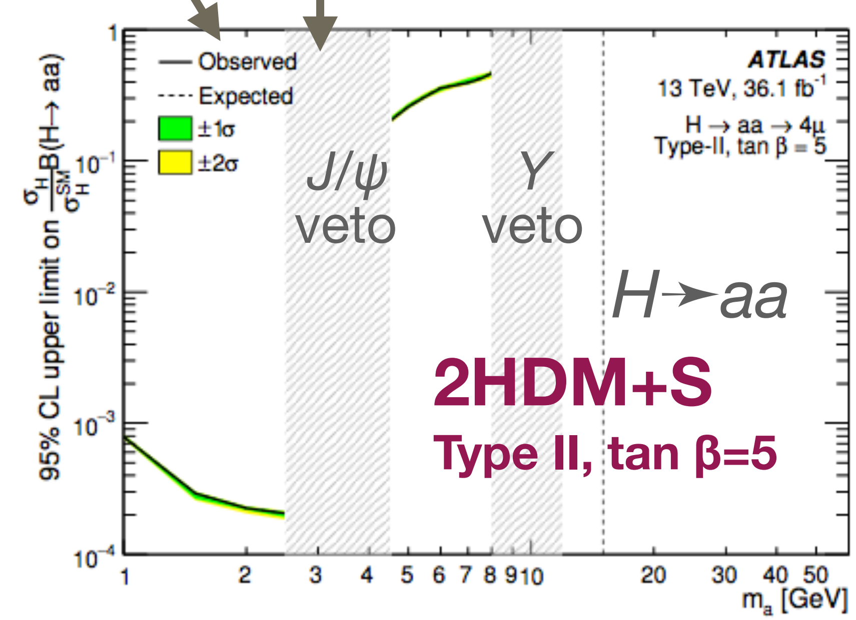


m_{Zd}



Assuming the dark Higgs S mass is $m_H/2<m_S<2m_H$, this limit can be turned into a limit on the Higgs portal coupling **κ ~ (1–10)×10^{-4}**

m_{Zd}



$\mathcal{B}$>1 (no sensitivity) above 15 GeV

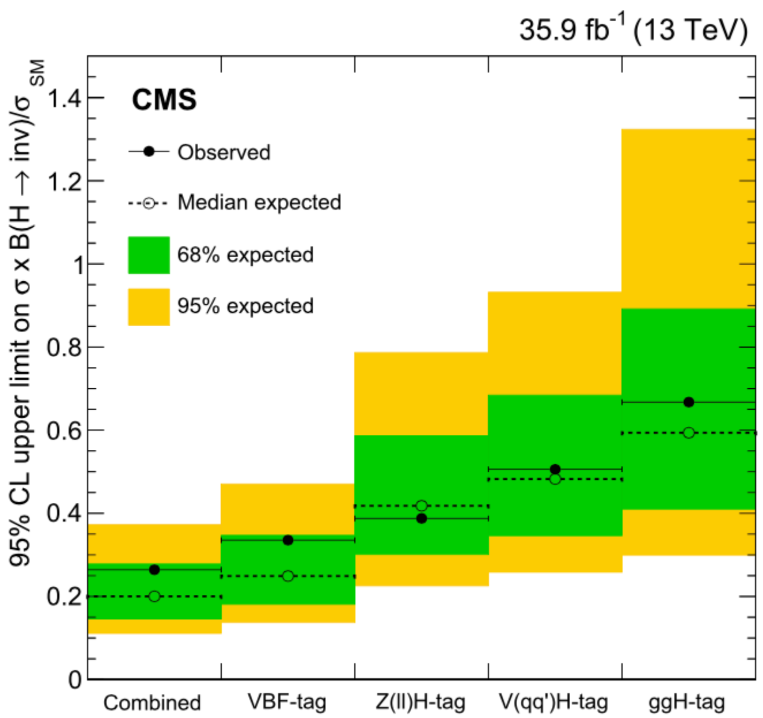
m_a

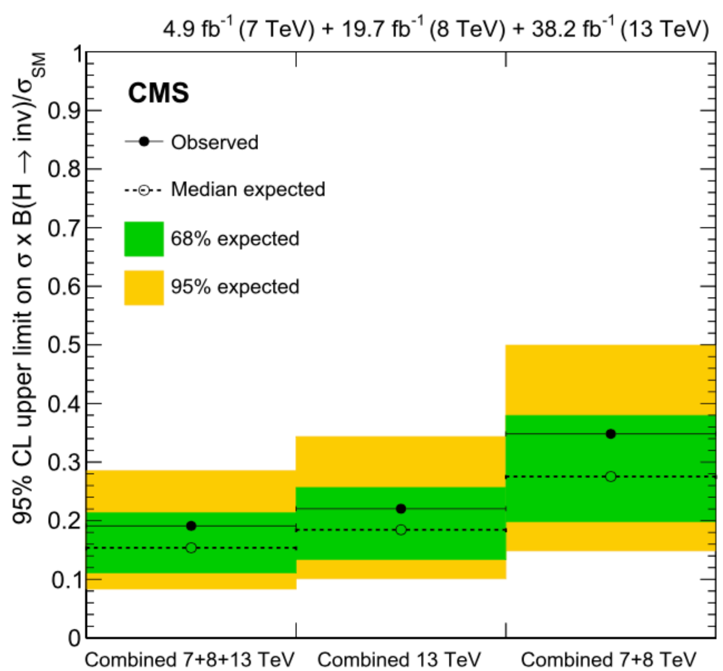
INVISIBLE HIGGS DECAYS

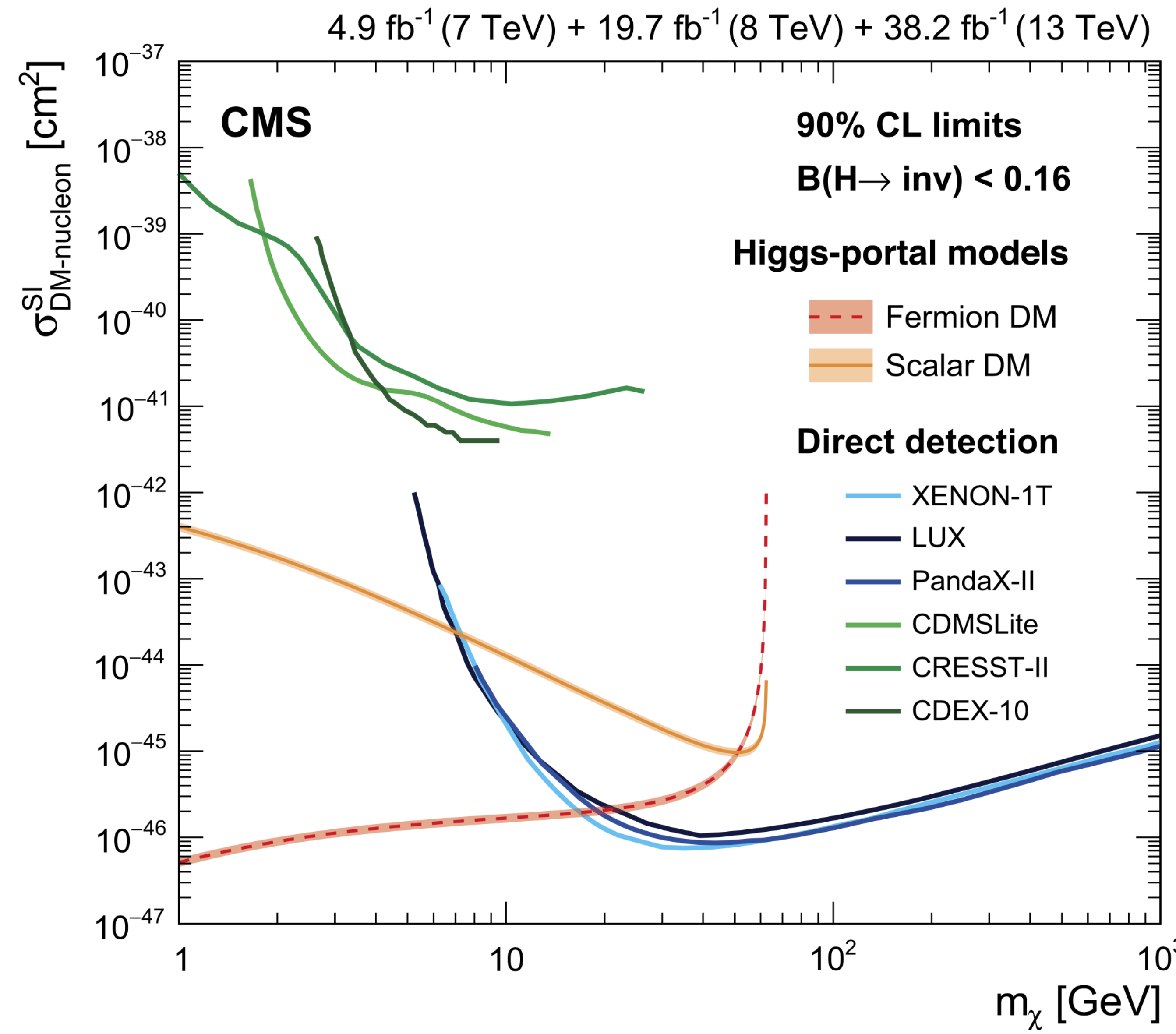
Higgs portal to Hidden Sector via Yukawa couplings to WIMPs

CMS: PLB 793 (2019) 520

- Combination of direct searches for invisible decays of Higgs produced in VBF, in association with Z(ll) or Z/W(hadrons) in 36 fb^{-1} at 13 TeV (and combined back with 7 and 8 TeV data)







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ATLAS: PRL 122 (2019) 231801

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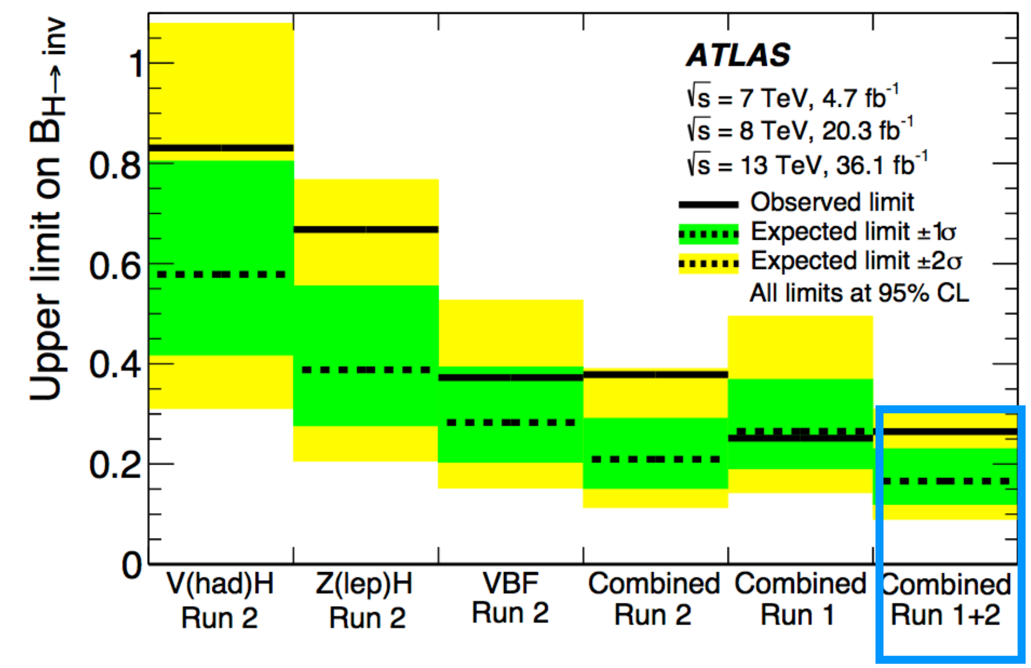
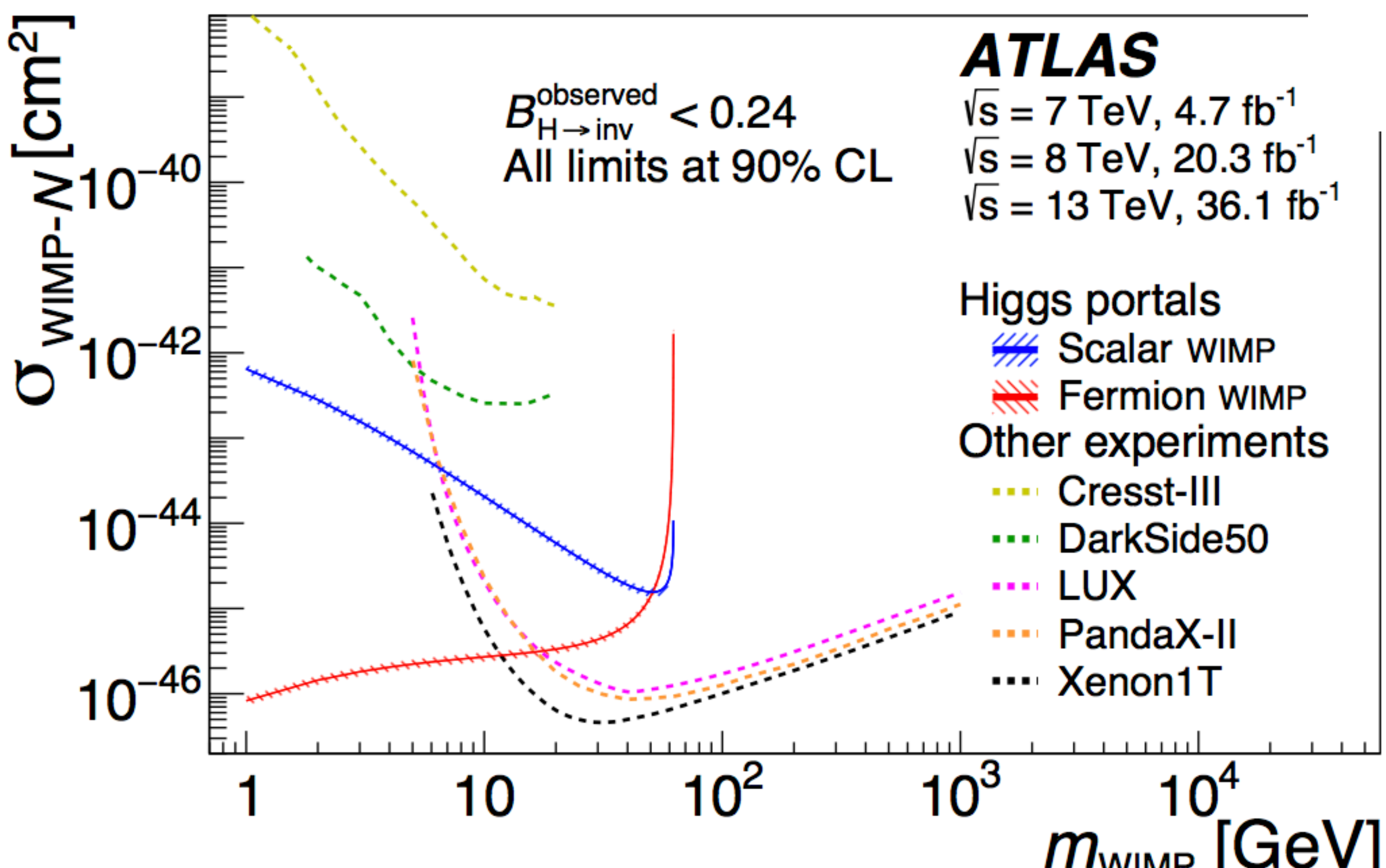




Interpreting H➛invisible as H➛χχ (χ=WIMP fermion or scalar) in an EFT approach and using f_N=0.308 ± 0.018 a limit on the WIMP-N cross section is derived

COMBINATION OF CROSS SECTION MEASUREMENTS

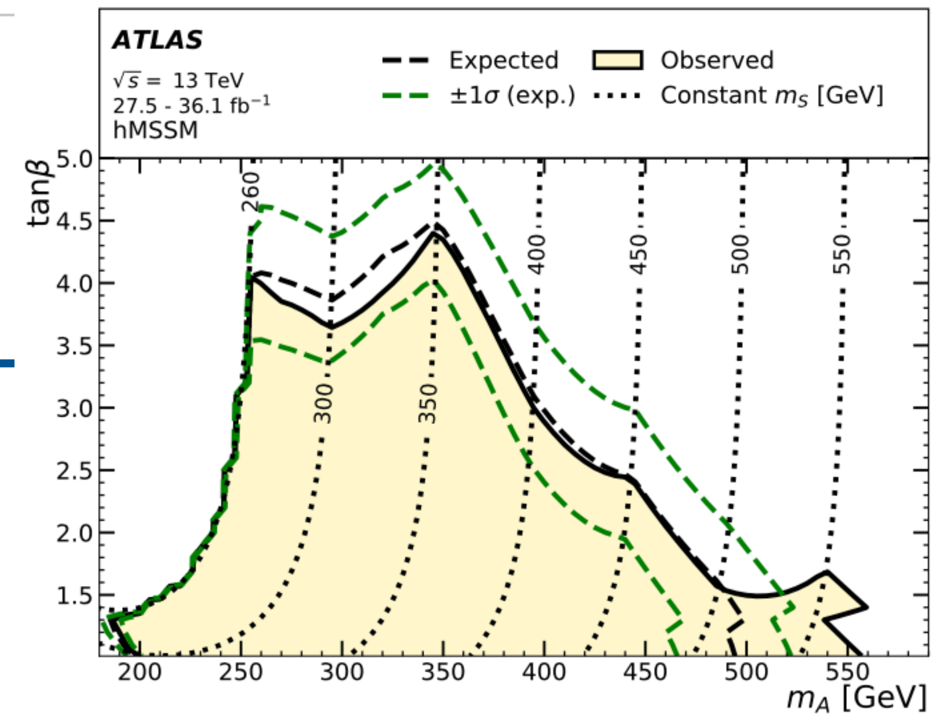
ATLAS: arXiv:1906.02025

13 TeV, ~36 fb^{-1}

only most sensitive channels used $bb\gamma\gamma$ $bb\tau\tau$ $bbbb$

Search for narrow width **spin-0 resonances** in two flavors:

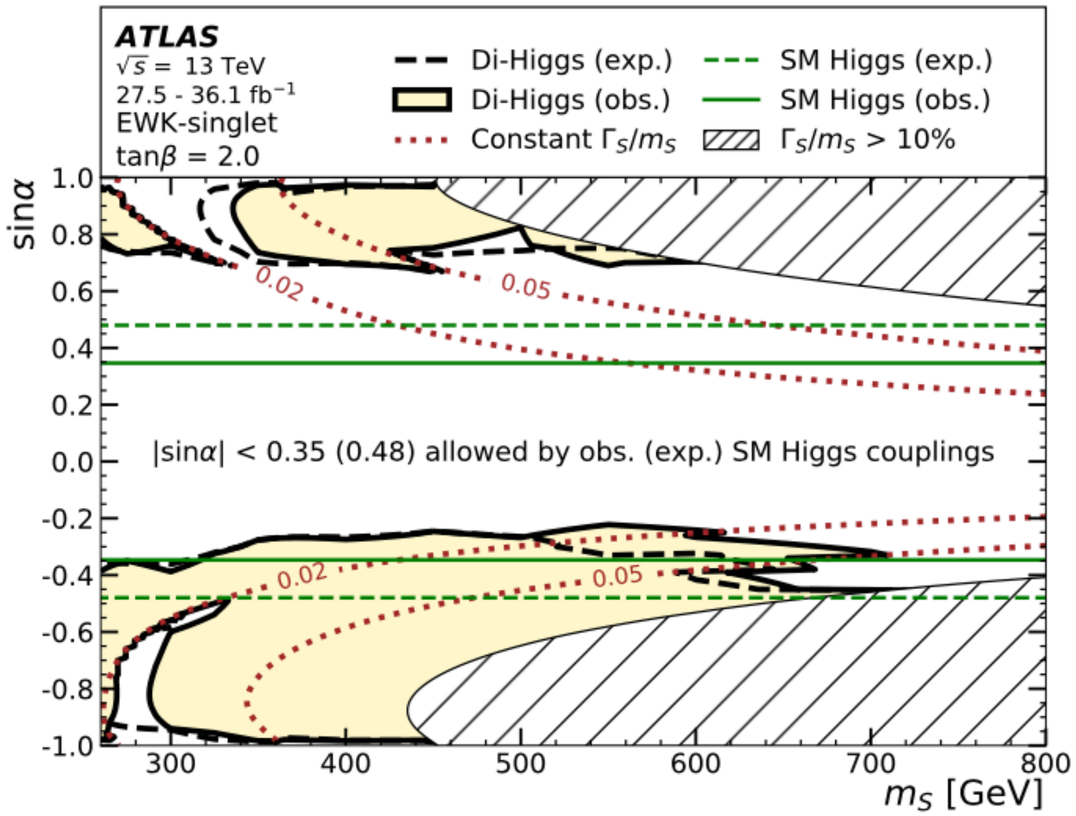
hMSSM



EWK-singlet model: an extra singlet in addition to the SM scalar doublet

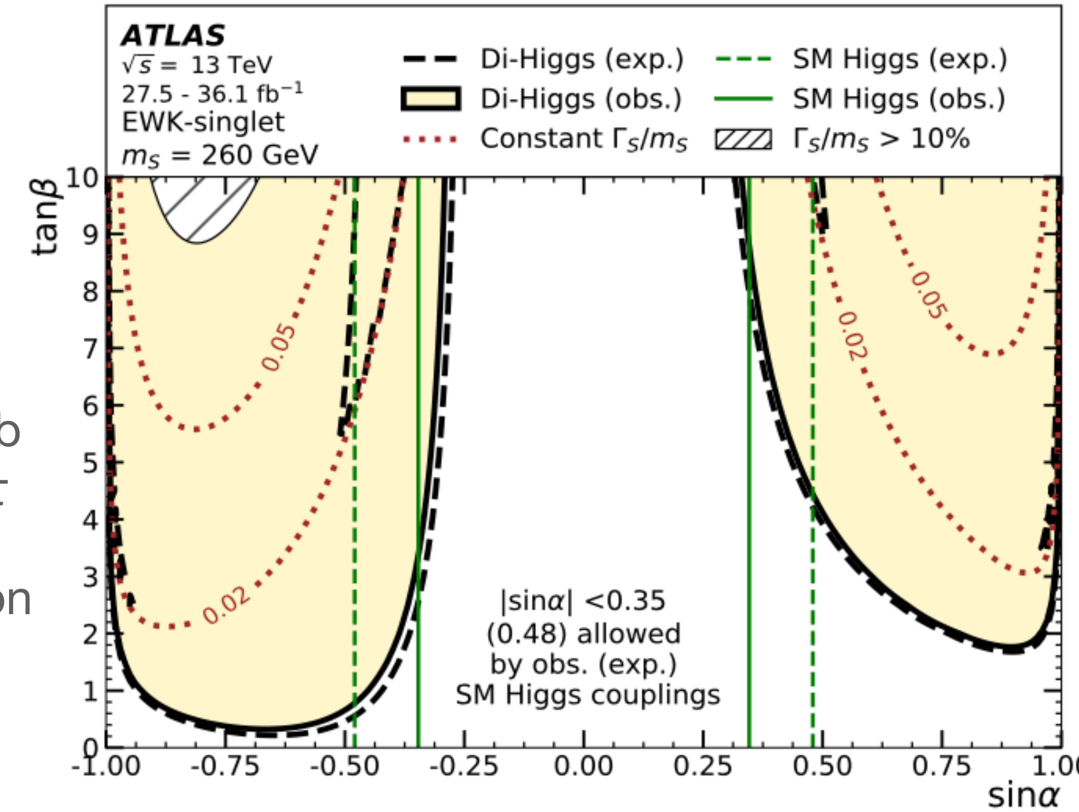
SM-like Higgs and the new (heavier) scalar mix (α) the ratio of vev (tan β) is a free parameter

$$m_h = 125\ \text{GeV}, M_H, \cos\alpha, v, \tan\beta = v/\langle s\rangle$$



Γ_S/M_S< 2% for $bb\gamma\gamma$
< 5% for bbbb
<10% for $bb\tau\tau$

Γ_S/M_S< M_S resolution



ANOTHER SEARCH FOR RESONANT HIGGS PAIR-PRODUCTION

HH➛bbZZ➛bb ℓℓ jj

➛bb ℓℓ νν

13 TeV, ~36 fb^{-1}

CMS PAS HIG-18-013

Parameter setting:

$1/\lambda^2_R$ is proportional to the radion production cross section (λ_R=1TeV)

Other parameters (relevant for the graviton production): KL=35 -> warp factor e^{-KL}

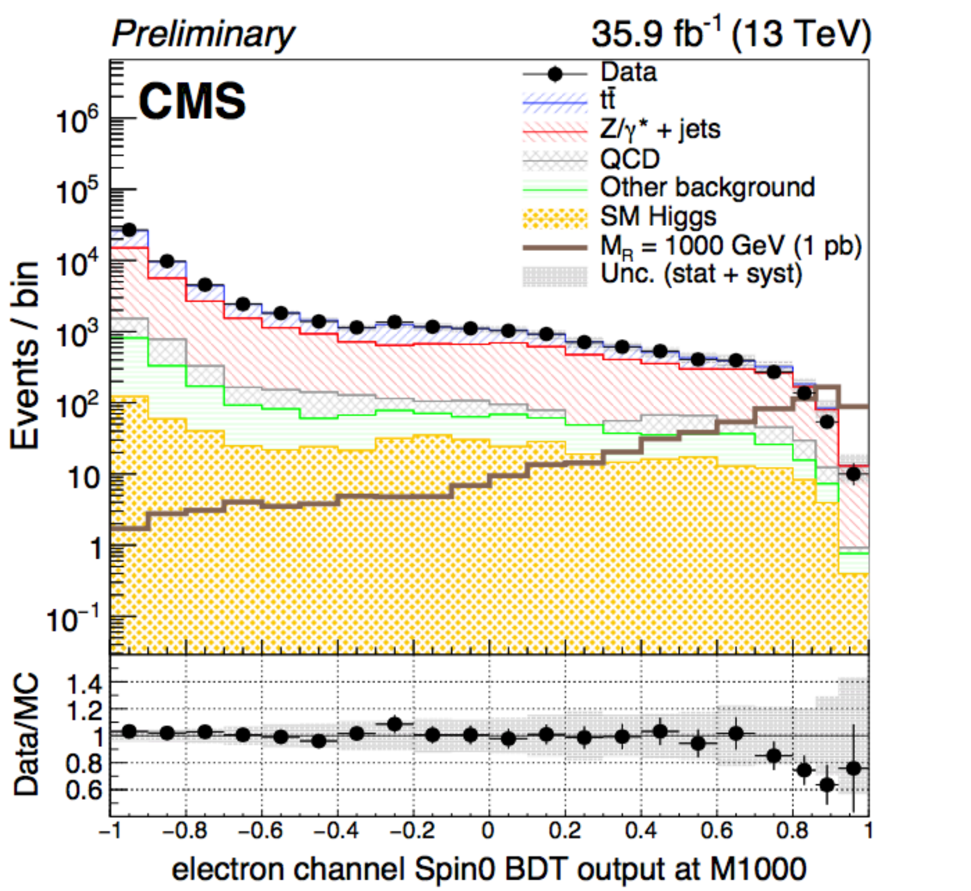
$\tilde{k} = k/M_{Pl}$ and we consider $\tilde{k}$ = 0.1

RS1: a RS model with one warped extradimension (with a non-factorizable geometry)

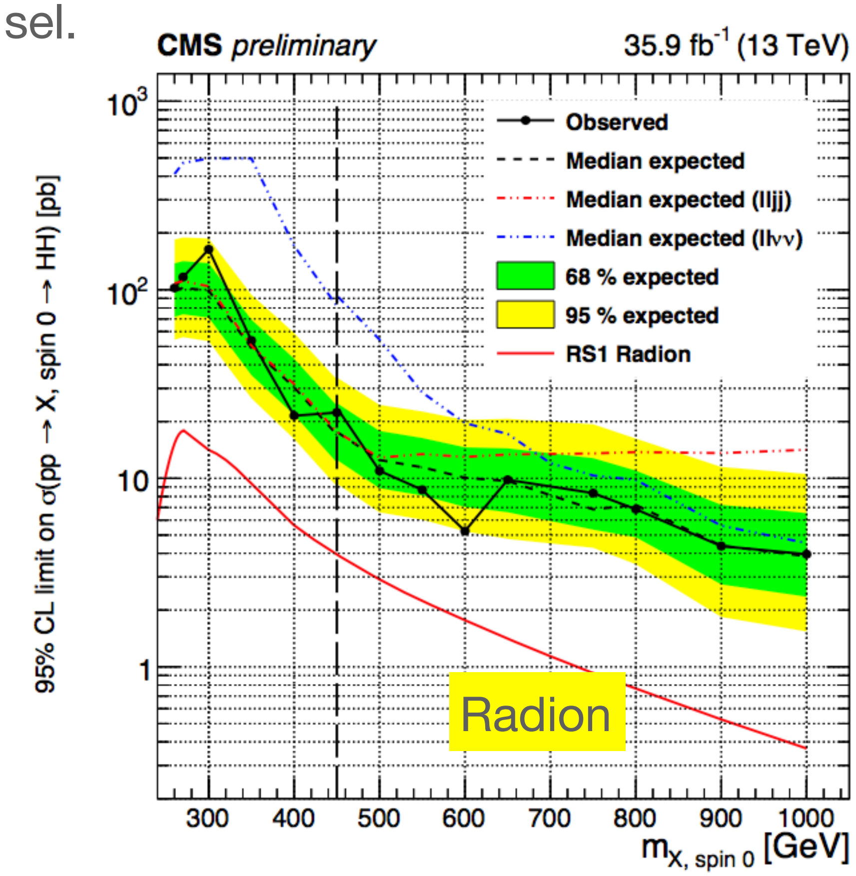
SM particles do not propagate in the extra dimension

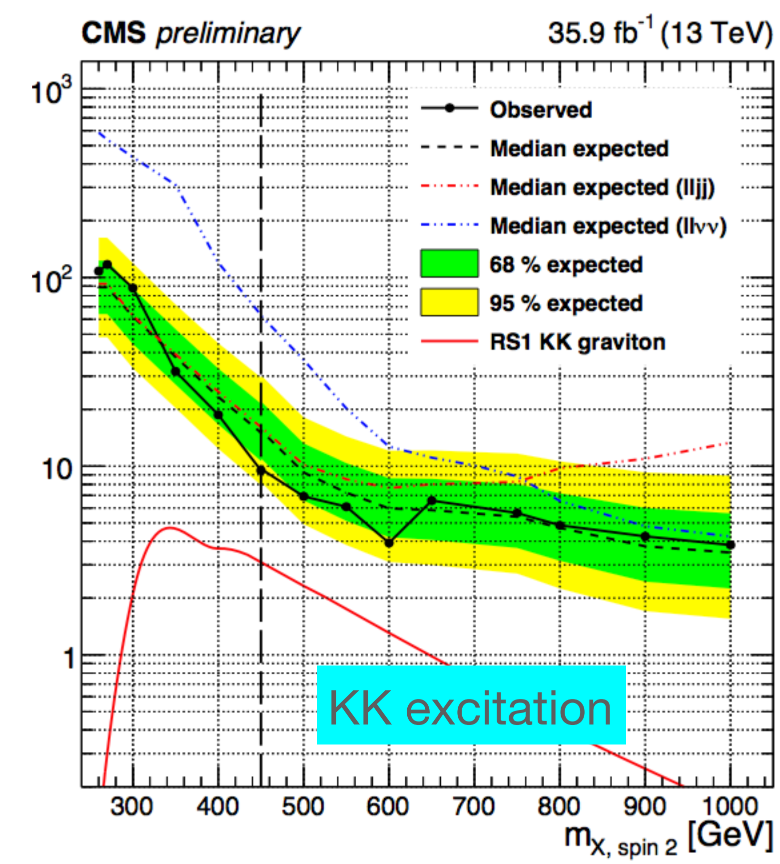
new particles can decay to Higgs pairs:
radion, spin 0,
first KK excitation, spin 2

top and Z+jet normalized to data in CRs
QCD from data, using SS leptons in dedicated sel.



DBT discriminant for *bblljj*,





HH transverse mass for bbllvv

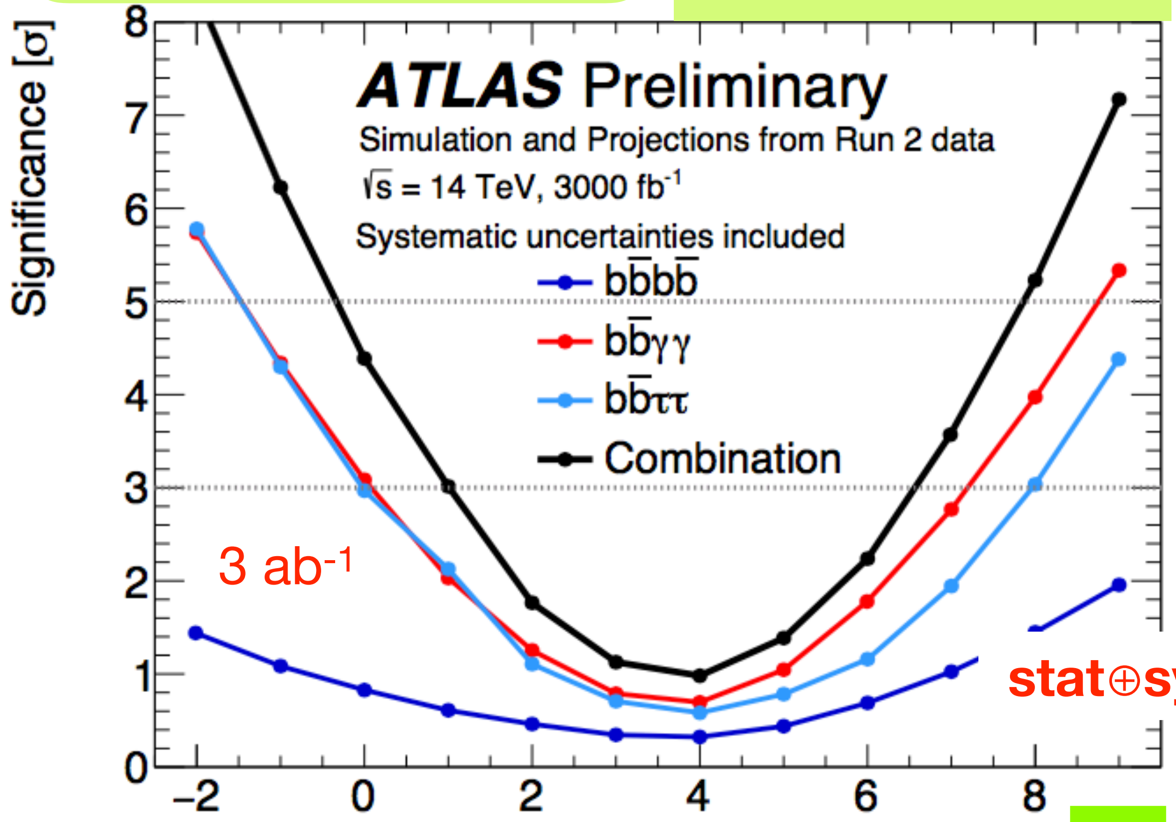
EXTRAPOLATION TO HL-LHC

13 TeV, ~36 fb^{-1} => κ_λ >7 (10) excluded at 95% CL today

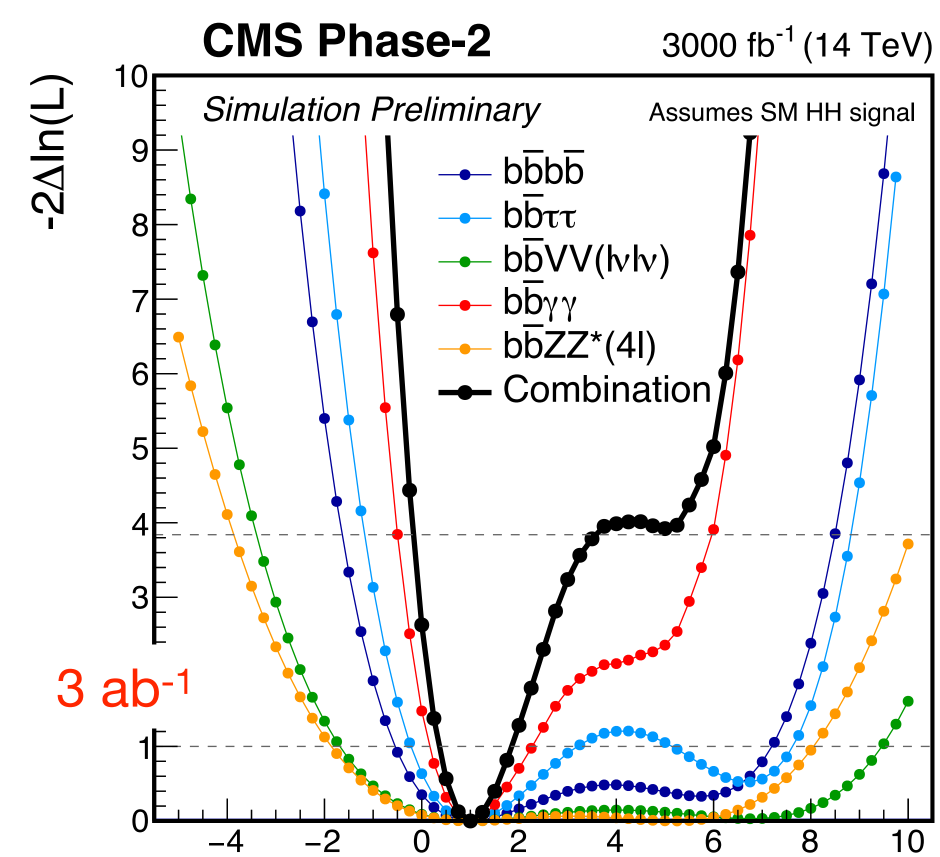
Extrapolation of the most sensitive analyses @ HL-LHC

bbγγ bbττ bbbb

ATL-PHYS-PUB-2018-053



CMS PAS FTR-18-019



HL-LHC: 3 ab^{-1} 14 TeV
κ_λ=1(0) will be determined with a significance of ***~3(4.5)σ per experiment***, including systematics (assuming the upgraded ATLAS detector)

HE-LHC scenario:
27 TeV, 15 ab^{-1}
bbγγ -> κ_λ=1.0±0.4
bbττ -> κ_λ=1.0±0.2

stat only

Single experiment

ATL-PHYS-PUB-2018-053

MSSM BENCHMARKS AFTER 2012

- **MSSM Higgs sector at tree level depends only upon m_A and tanβ**
  - at higher orders other parameters enter the play
    - dominant contributions: $\sim m^4_{top}$, $\sim\log M_S$, $\sim A^2_t$
- Carena et al., arXiv:1302.7033, evolution of benchmarks proposed before 2012, meant to guarantee compatibility with m_h ~125 GeV: **$m_h^{mod+/-}$** and others
    - SUSY breaking scale: M_S = 1TeV, higgsino mass parameter: μ = 200 GeV, stop coupling to Higgs: $A_t = X_t + \mu \cot\beta$, with X_t/M_S = 1.5 (-1.9) [stop mass mixing par.] in the on-shell scheme
- Djuadi et al., arXiv:1307.5205 imposes m_h = 125 GeV: **hMSSM**
  - if m_h = 125 GeV the MSSM Higgs sector with one loop and (most of) two-loop corrections to Higgs masses depends only on m_A and tanβ
    - underlying assumptions: the Higgs sector is CP conserving, all superparticles are too heavy to affect Higgs production and decays, any non-decoupling SUSY corrections to the Higgs couplings are negligible, the radiative corrections to the elements other than (2, 2) in the mass matrix of the neutral CP-even Higgs states are negligible

$m_H^{MOD+/-}$ MSSM BENCHMARK

Carena et al. : arXiv:1302.7033

	Parameter	$m_h^{\max}$	$m_h^{\mathrm{mod}+}$	$m_h^{\mathrm{mod}-}$	*light stop*	*light stau*	τ*-phobic*	*low-*M_H
	m_t	173.2	173.2	173.2	173.2	173.2	173.2	173.2
	M_A	varied	varied	varied	varied	varied	varied	110
	$\tan\beta$	varied	varied	varied	varied	varied	varied	varied
$M_{\tilde{t}_L} = M_{\tilde{b}_L} = M_{\tilde{t}_R} = M_{\tilde{b}_R} =:$	M_{SUSY}	1000	1000	1000	500	1000	1500	1500
	$M_{\tilde{l}_3}$	1000	1000	1000	1000	245 (250)	500	1000
stop mass mixing parameter	$X_t^{\mathrm{OS}}/M_{\mathrm{SUSY}}$	2.0	1.5	-1.9	2.0	1.6	2.45	2.45
	$X_t^{\overline{\mathrm{MS}}}/M_{\mathrm{SUSY}}$	$\sqrt{6}$	1.6	-2.2	2.2	1.7	2.9	2.9
couplings of susy partners of b, tau and top to the higgs	A_t	Given by $A_t = X_t + \mu\cot\beta$						
	A_b	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$
	A_τ	$= A_t$	$= A_t$	$= A_t$	$= A_t$	0	0	$= A_t$
higgsino mass parameter	μ	200	200	200	350	500 (450)	2000	varied
gaugino mass parameters, M_2 and M_1 related to M2 via tan β	M_1	Fixed by GUT relation to M_2						
	M_2	200	200	200	350	200 (400)	200	200
	$m_{\tilde{g}}$	1500	1500	1500	1500	1500	1500	1500
	$M_{\tilde{q}_{1,2}}$	1500	1500	1500	1500	1500	1500	1500
	$M_{\tilde{l}_{1,2}}$	500	500	500	500	500	500	500
	$A_{f\neq t,b,\tau}$	0	0	0	0	0	0	0

2HDM FEATURES AND UNDERLYING NEW PHYSICS

An example in arXiv:1803.01865 [hep-ph]

SUSY vs Compositeness

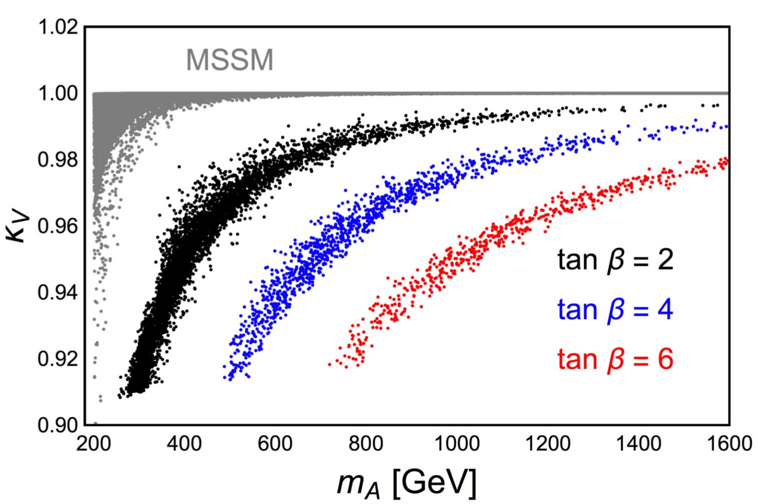
… actually ***MSSM*** vs an explicit **C2HDM** model based on a global SO(6) broken to SO(4)xSO(2) at a compositeness scale ***f***, $v = v_1^2 + v_2^2$, $v^2_{SM} = 1/(G_F\sqrt{2}) = f^2 \sin^2(v/f)$

$\tan\beta$ ~ free

$\tan\beta$ correlated to f

Using constraints from m_h = 125 GeV and m_t=175 GeV

arXiv:1803.01865



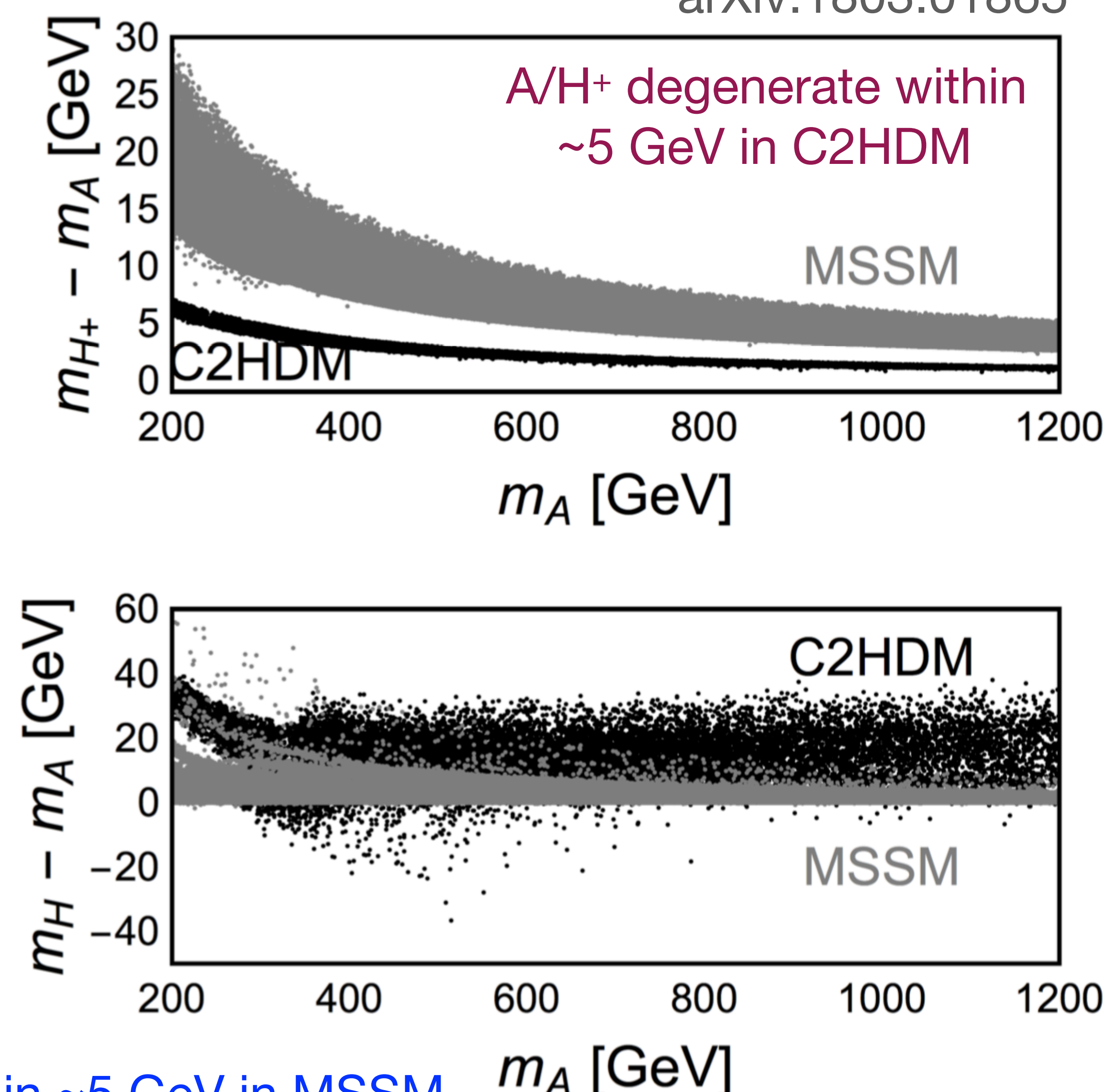
Deviations of κ_V from 1 are compatible with large (>400 GeV) values of $m_{A/H}$ only in C2HDM

$H^+ \to W^{+*}A$
points to MSSM

Higgs mass hierarchy and underlying new physics

$H \to Z^*A$ or $A \to Z^*H$
points to C2HDM

arXiv:1803.01865



A/H degenerate within ~5 GeV in MSSM