Searches for Beyond-the-SM Higgs bosons with ATLAS

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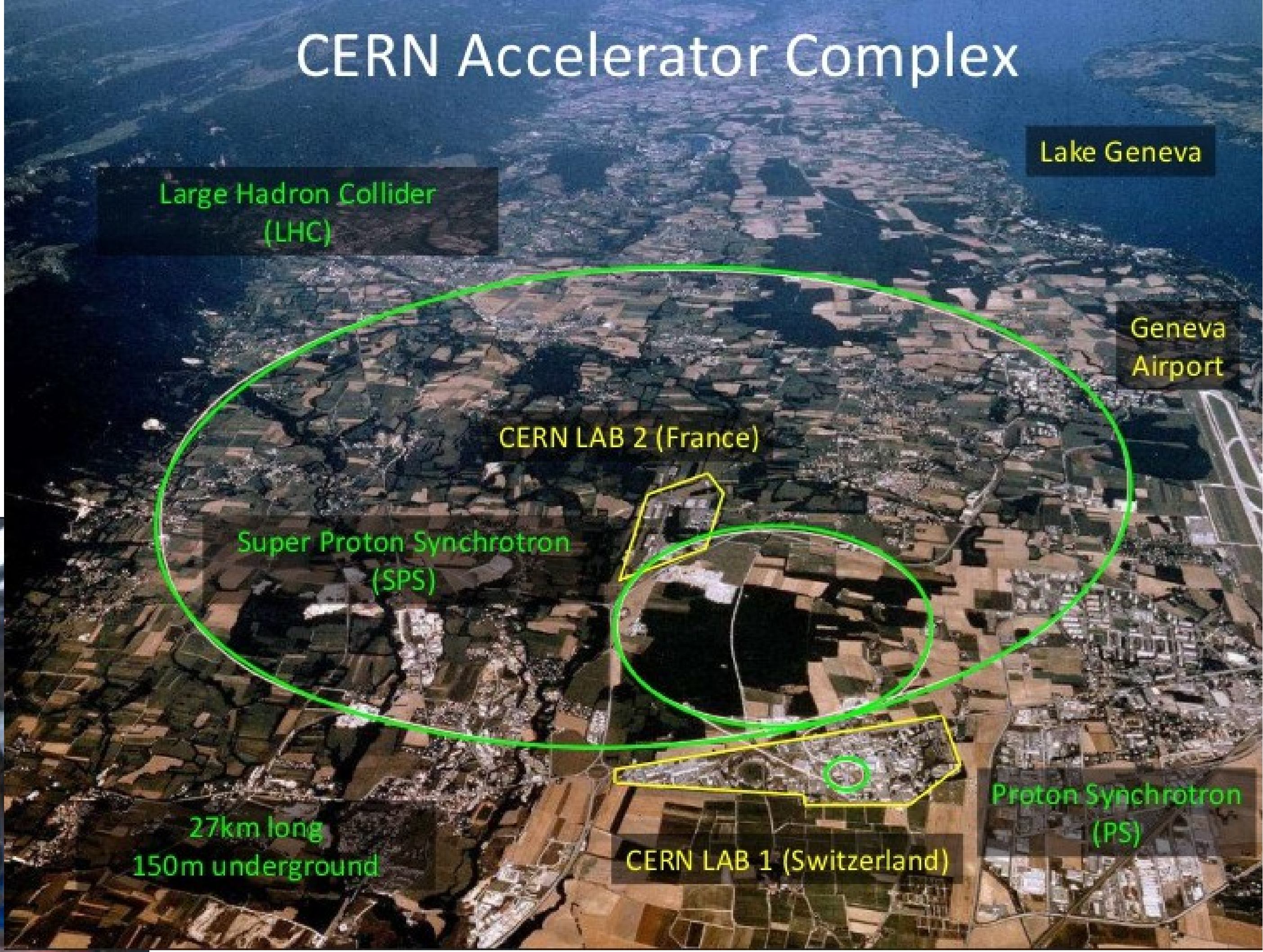
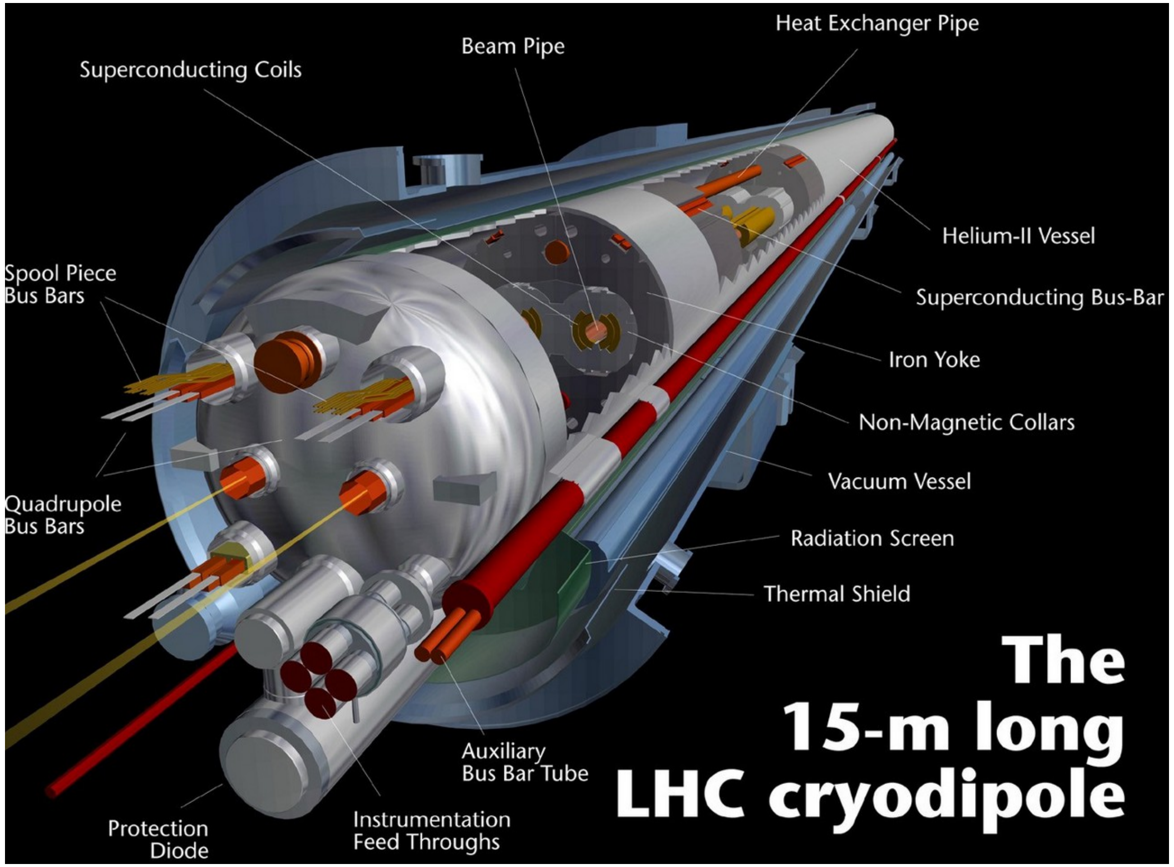
Dresden Seminar, January 10 2019



Large **H**adron **C**ollider (LHC)

Proton-proton collider



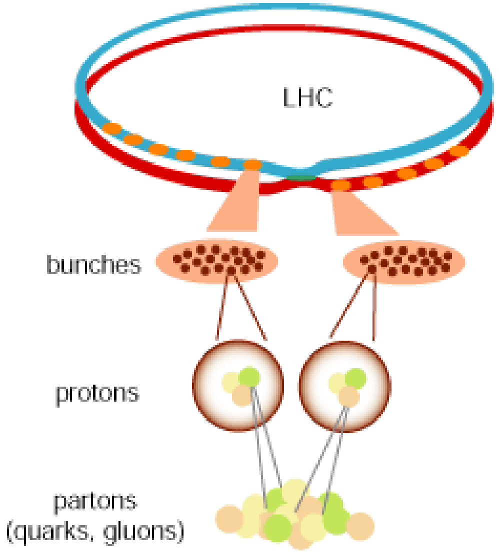
Super-conducting magnets operated with Helium at 1.9 K (colder than space!)

Vacuum in the beam pipe at 10^{-13} atm

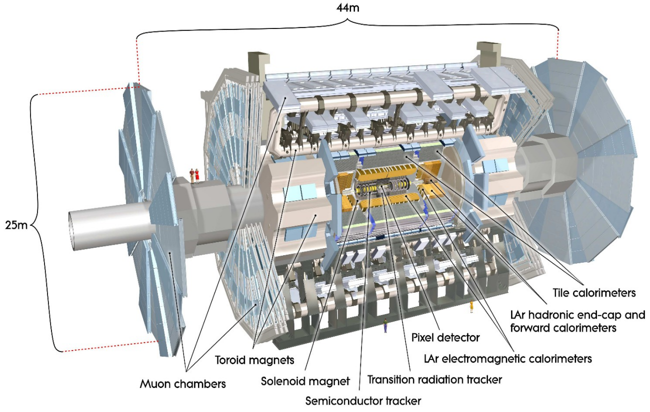
Protons accelerated to 99.999991% of the speed of light

10^{11} protons per bunch,
~2800 bunches per beam

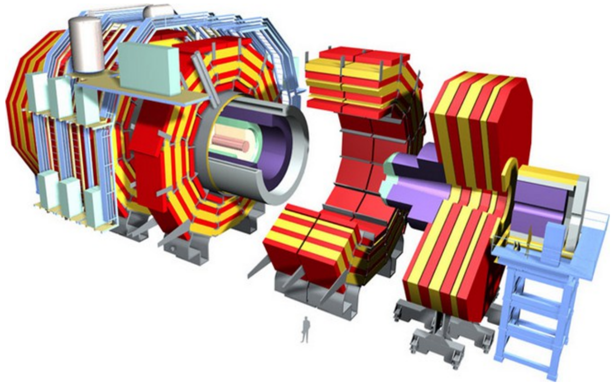
40 M bunch crossings per second



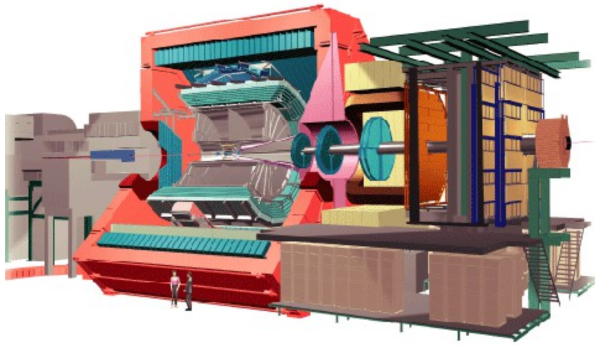
Four large detectors along the ring:



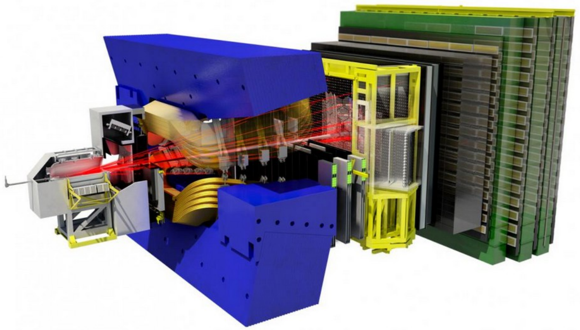
ATLAS



CMS



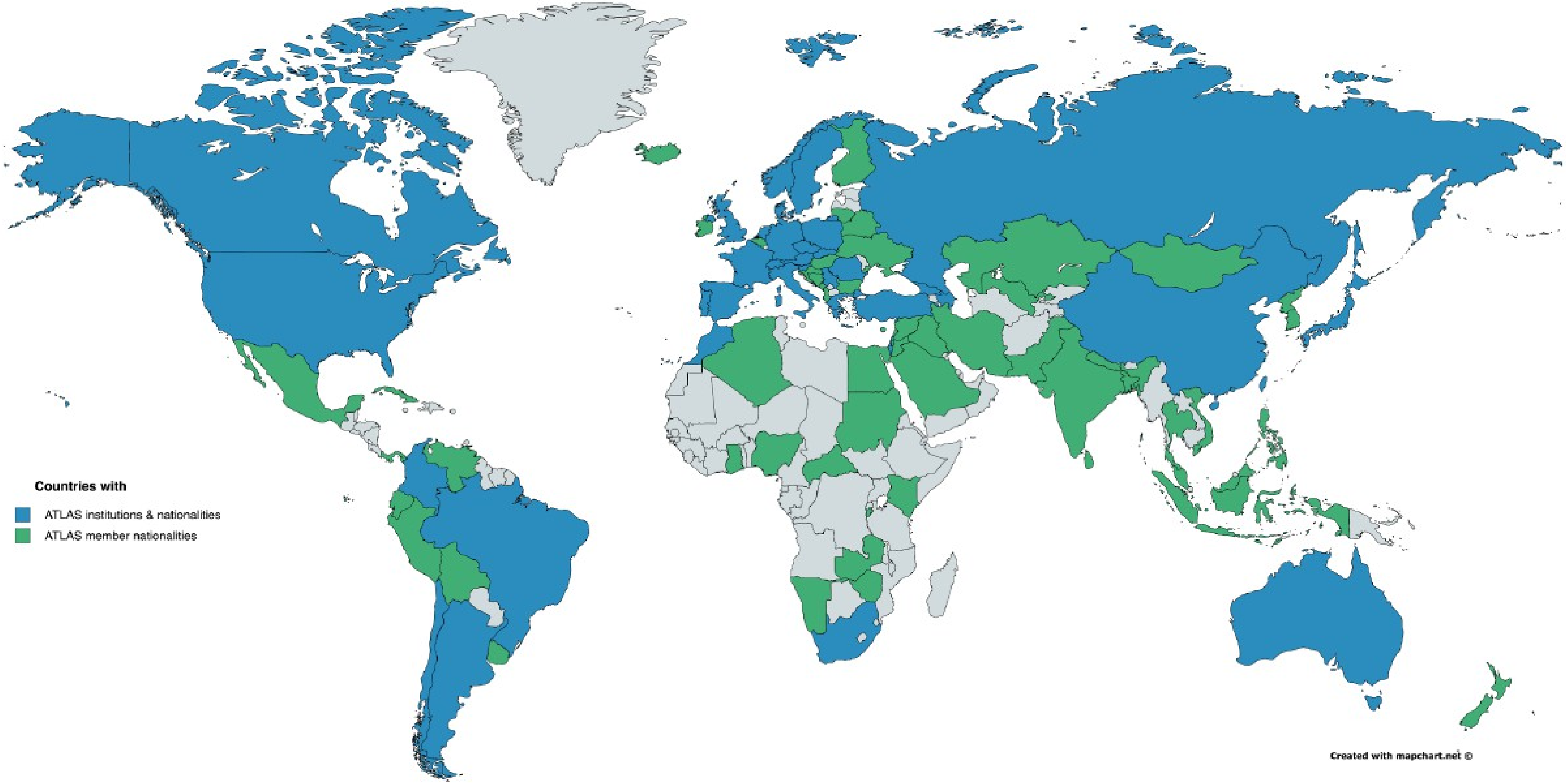
ALICE



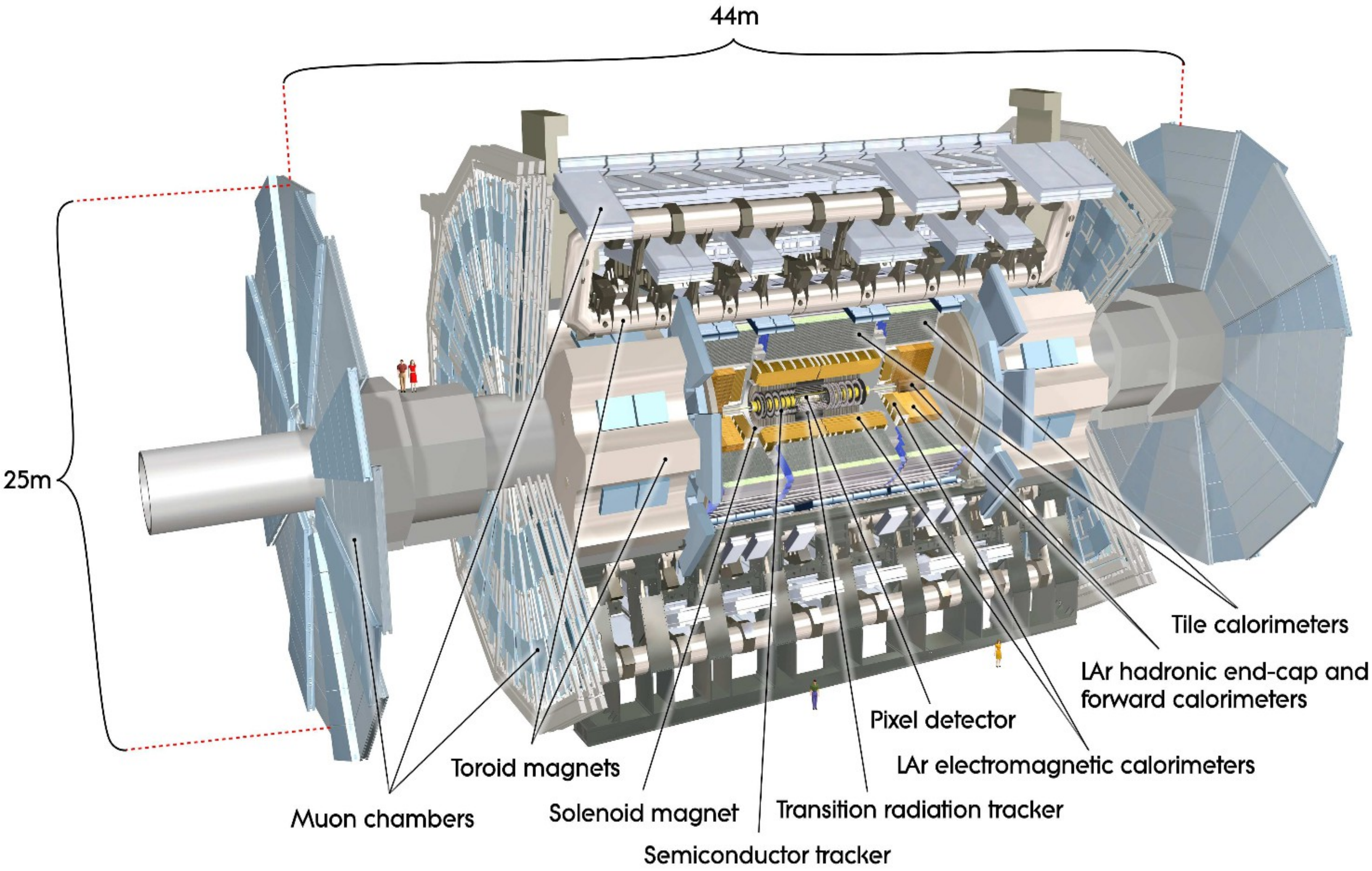
LHCb

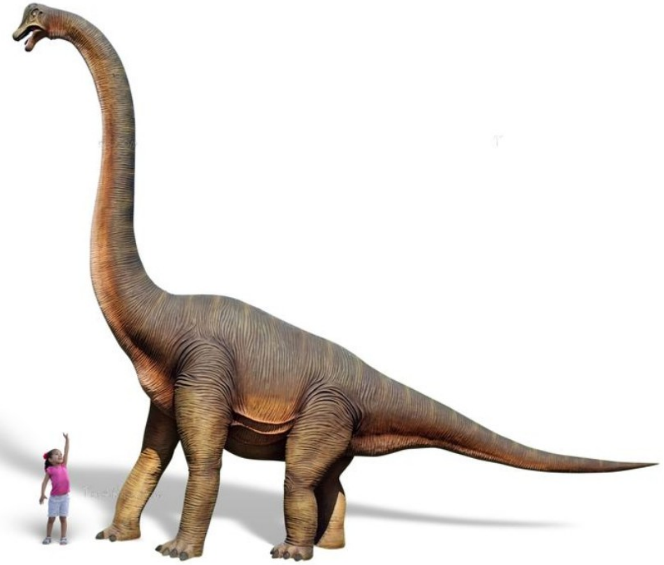
The ATLAS Collaboration in 2018

>5000 members: ∼3000 signing authors, >1000 students



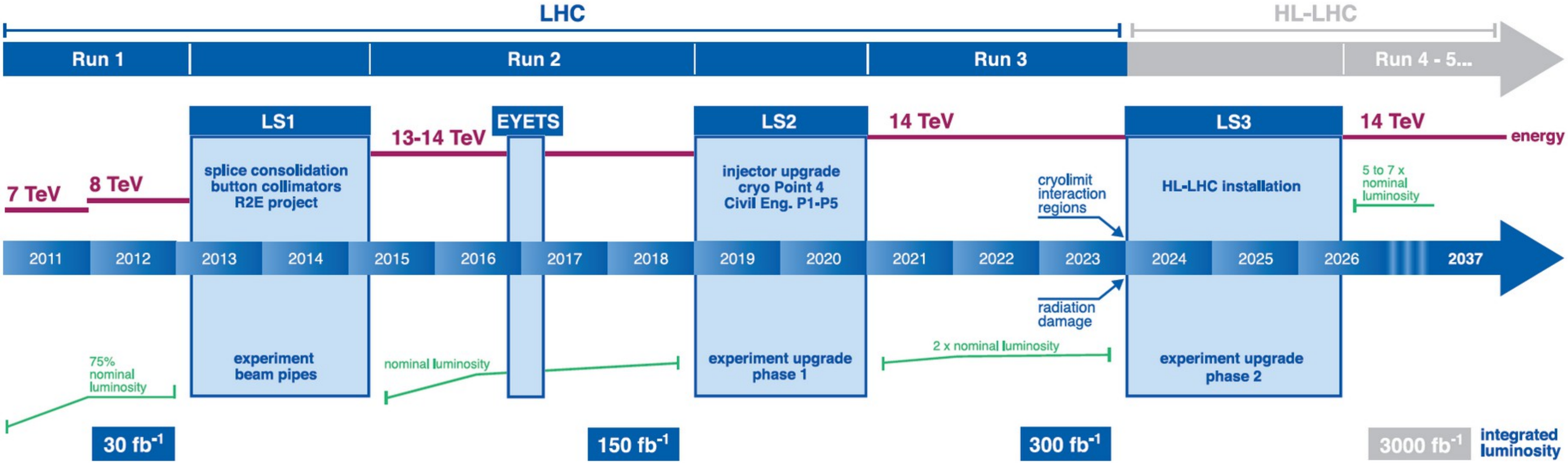
The ATLAS detector





LHC / HL-LHC Plan

High Luminosity LHC



LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

LS1

splice consolidation
button collimators
R2E project

experiment
beam pipes

EYETS

LS2

injector upgrade
cryo Point 4
Civil Eng. P1-P5

experiment upgrade
phase 1

LS3

HL-LHC installation

experiment upgrade
phase 2

7 TeV

8 TeV

13-14 TeV

14 TeV

14 TeV

energy

cryolimit
interaction
regions

radiation
damage

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2037

75%
nominal
luminosity

nominal luminosity

2 x nominal luminosity

5 to 7 x
nominal
luminosity

30 fb^{-1}

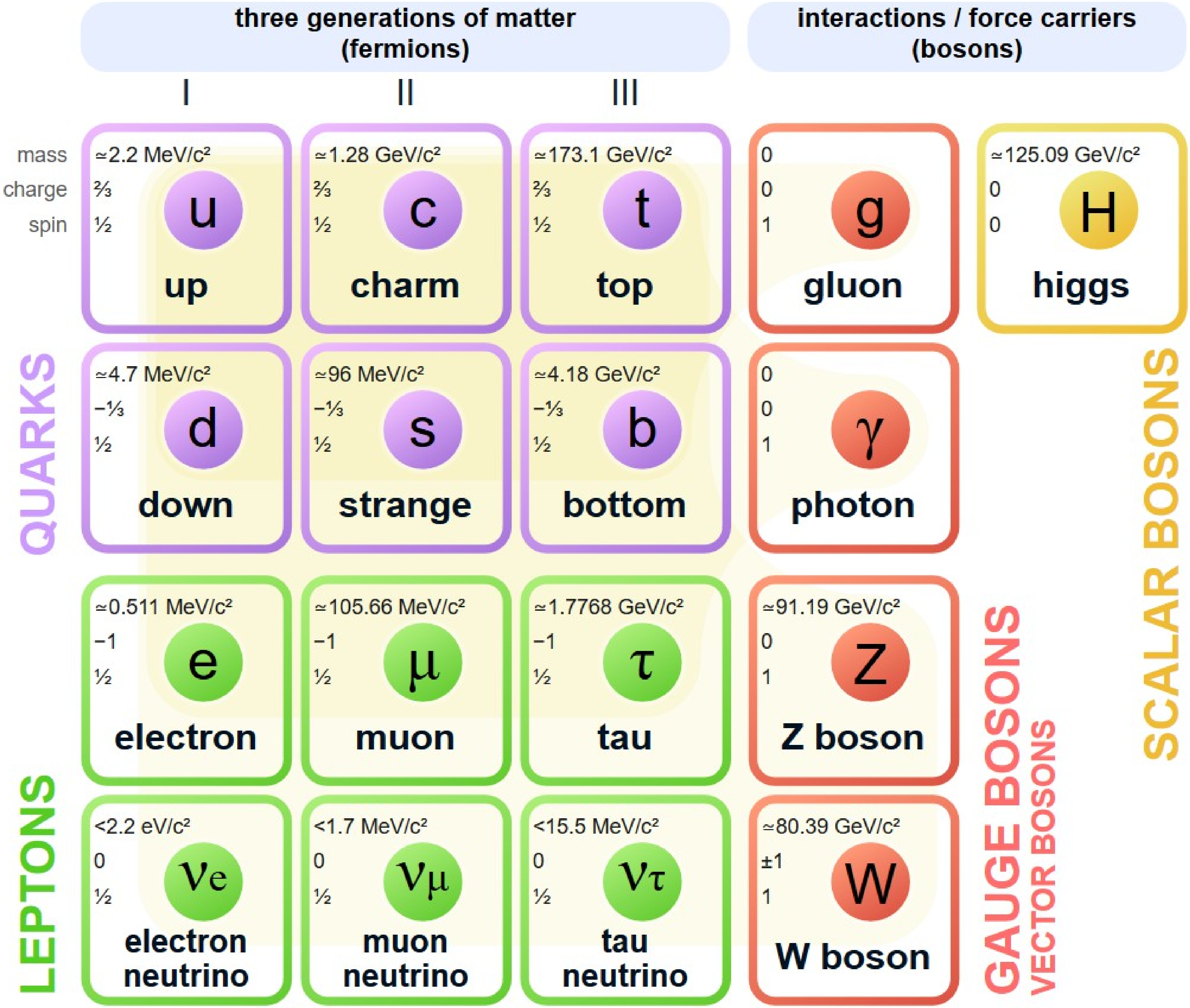
150 fb^{-1}

300 fb^{-1}

3000 fb^{-1}

integrated
luminosity

Standard Model of Elementary Particles



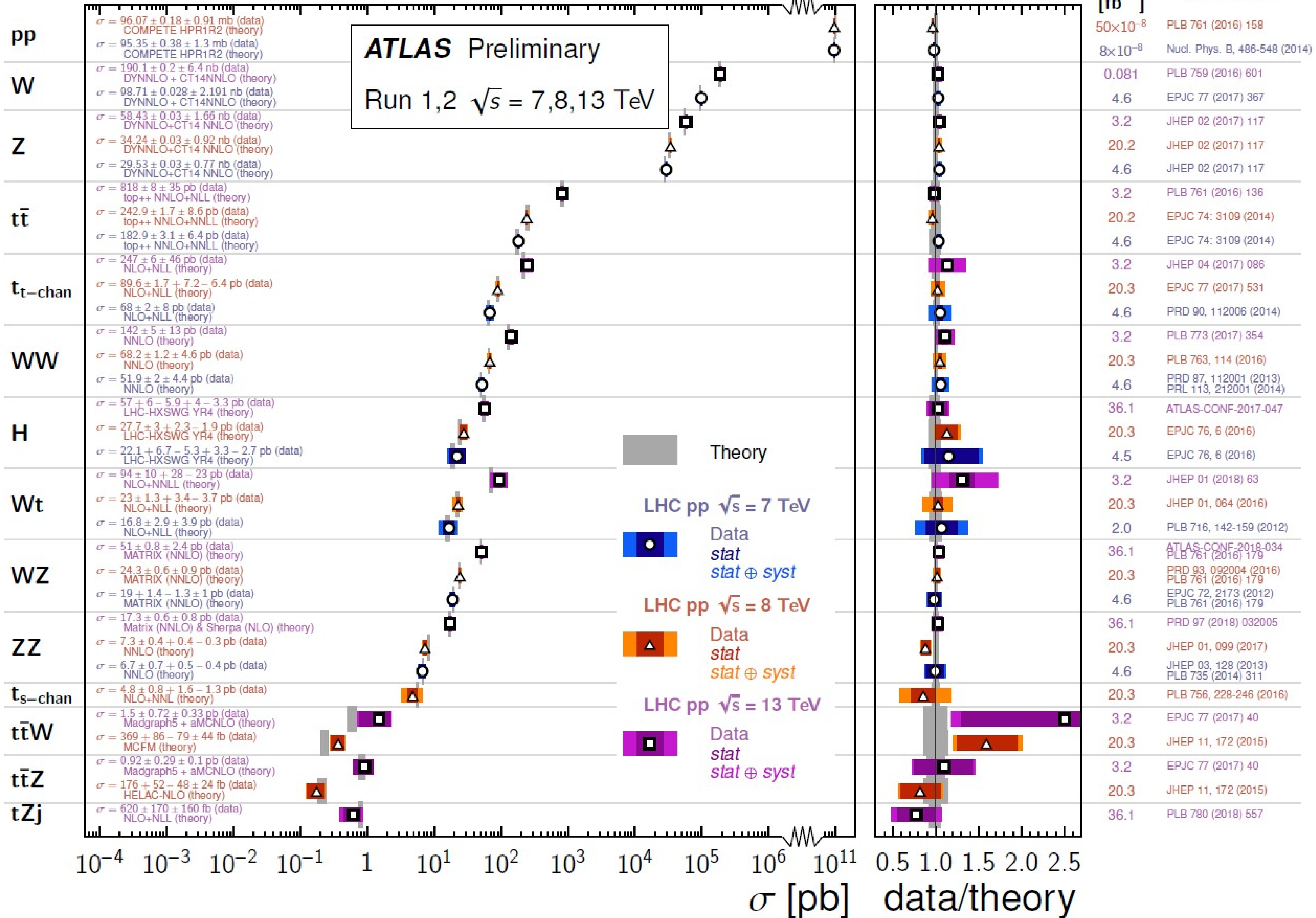
		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass charge spin	≃2.2 MeV/c^2 ⅔ ½ u **up**	≃1.28 GeV/c^2 ⅔ ½ c **charm**	≃173.1 GeV/c^2 ⅔ ½ t **top**	0 0 1 g **gluon**	≃125.09 GeV/c^2 0 0 H **higgs**
QUARKS		≃4.7 MeV/c^2 −⅓ ½ d **down**	≃96 MeV/c^2 −⅓ ½ s **strange**	≃4.18 GeV/c^2 −⅓ ½ b **bottom**	0 0 1 γ **photon**	
LEPTONS		≃0.511 MeV/c^2 −1 ½ e **electron**	≃105.66 MeV/c^2 −1 ½ μ **muon**	≃1.7768 GeV/c^2 −1 ½ τ **tau**	≃91.19 GeV/c^2 0 1 Z **Z boson**	
LEPTONS		<2.2 eV/c^2 0 ½ ν_e **electron neutrino**	<1.7 MeV/c^2 0 ½ ν_μ **muon neutrino**	<15.5 MeV/c^2 0 ½ ν_τ **tau neutrino**	≃80.39 GeV/c^2 ±1 1 W **W boson**	

GAUGE BOSONS

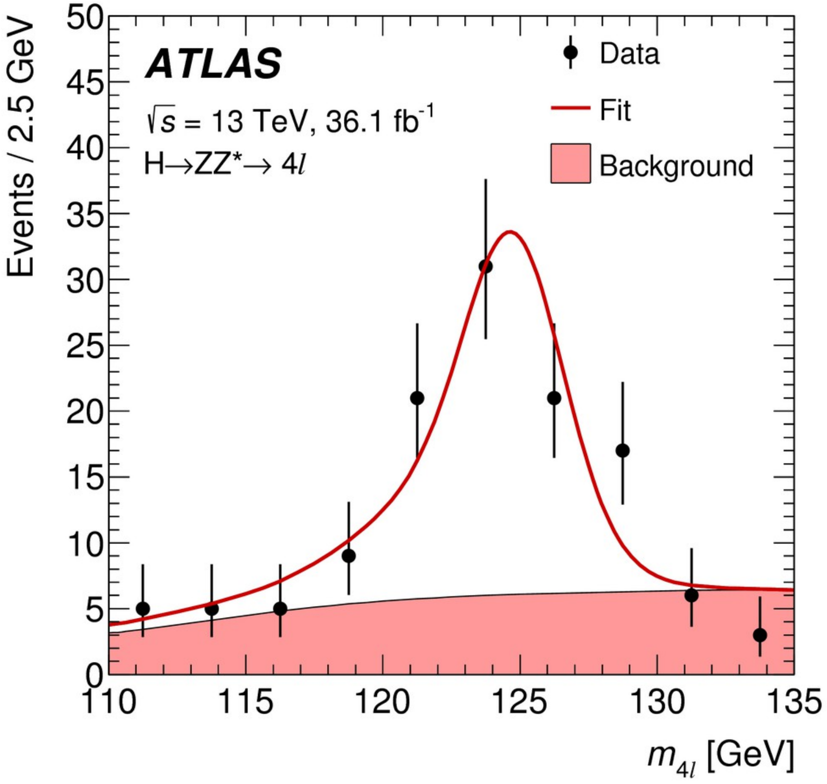
VECTOR BOSONS

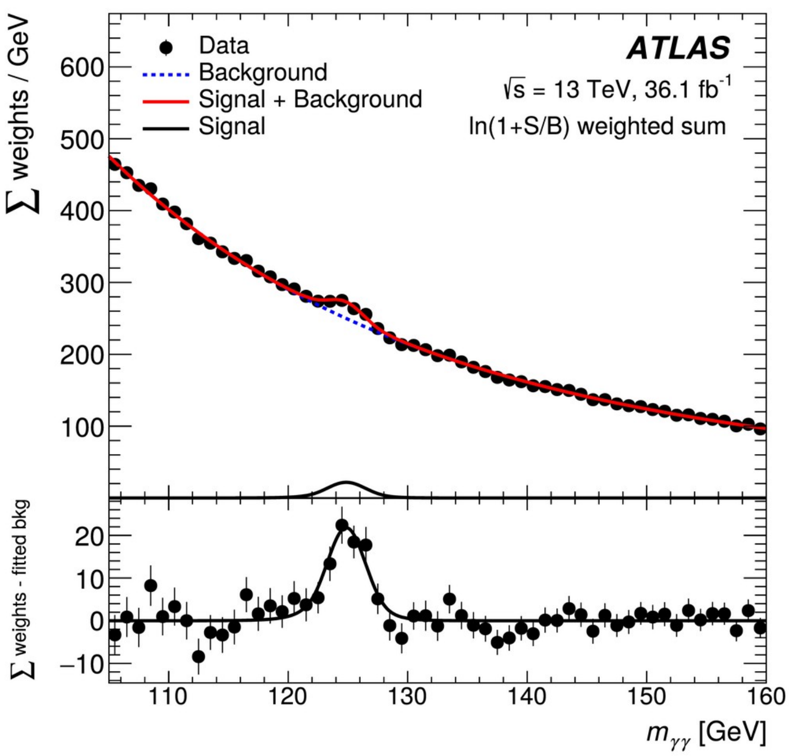
SCALAR BOSONS

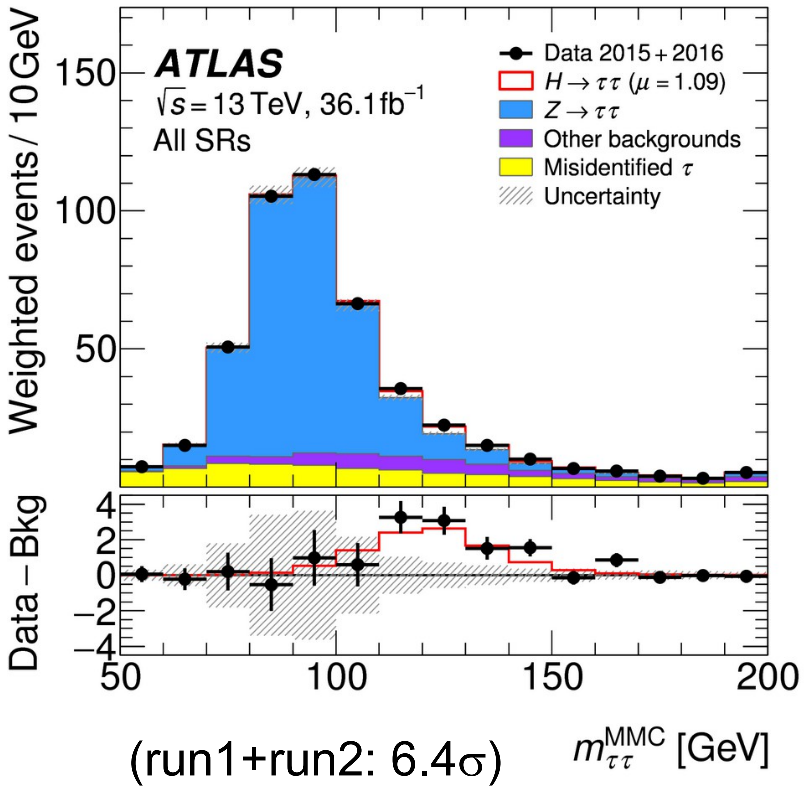
Standard Model Total Production Cross Section Measurements



SM Higgs Boson Status







(run1+run2: 6.4σ)

SM Higgs boson measurements:

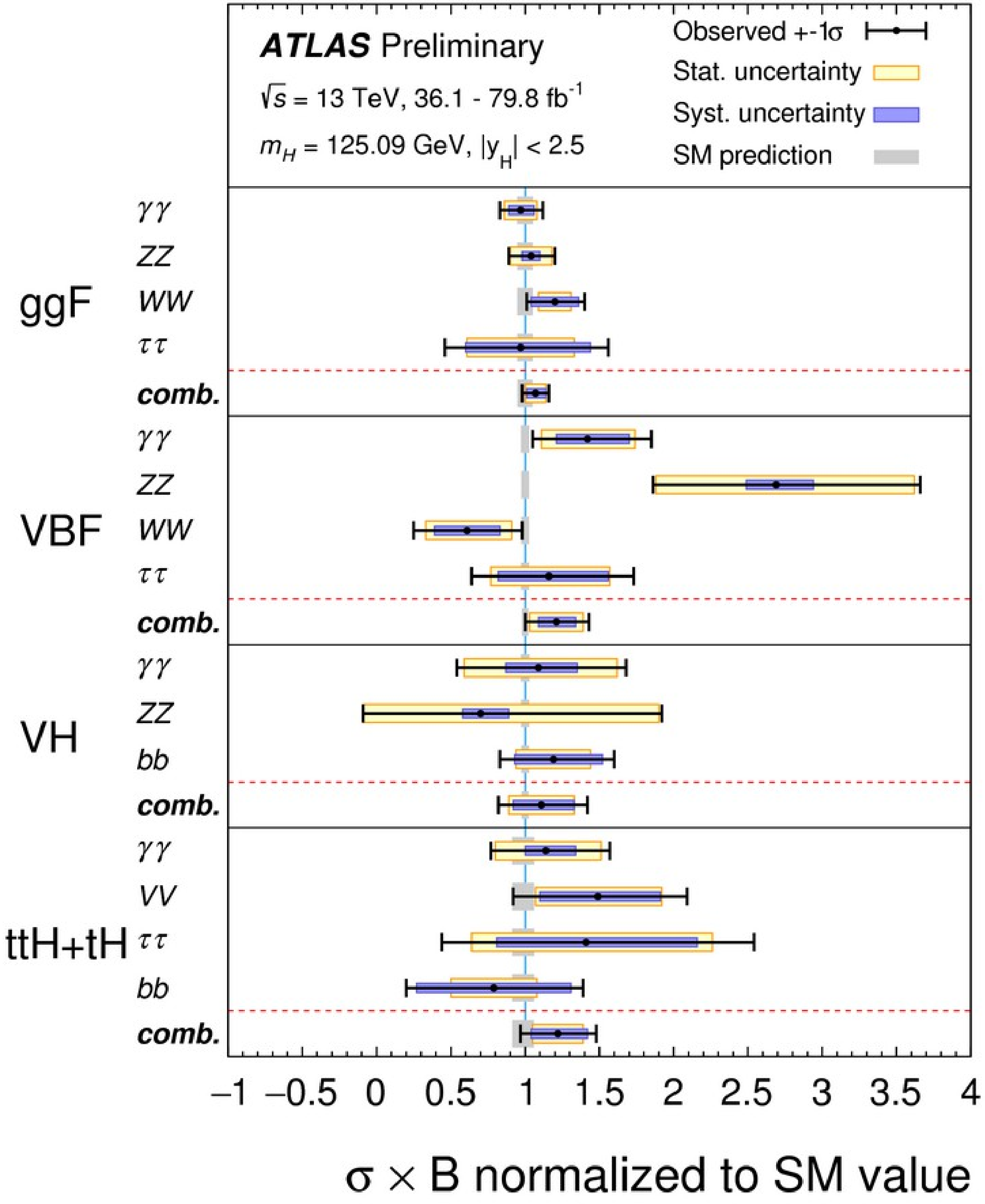
Signal strength: $\mu = 1.13^{+0.09}_{-0.08} = 1.13 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$

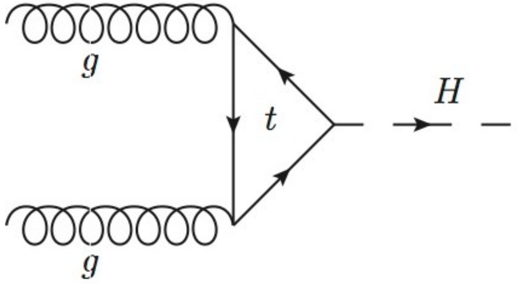
(ATLAS Run-2 combination with up to 80/fb)

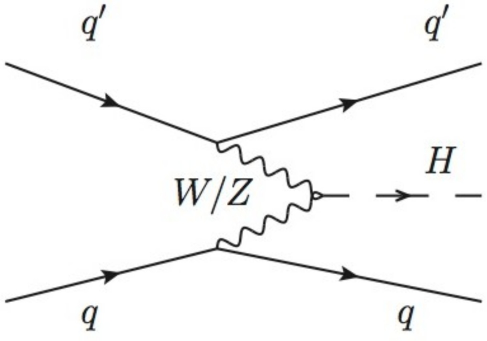
Mass: $m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})$ GeV

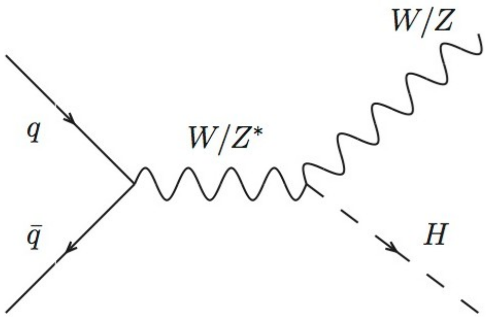
(Run-1 ATLAS+CMS combination)

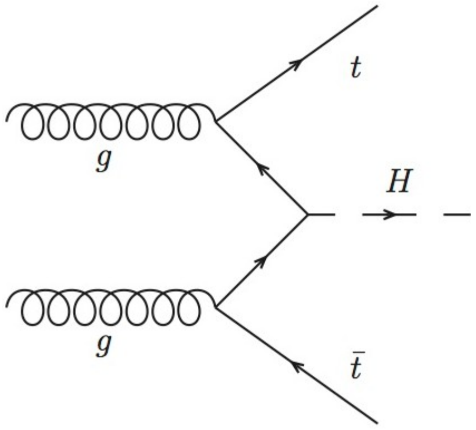
SM Higgs Boson Status



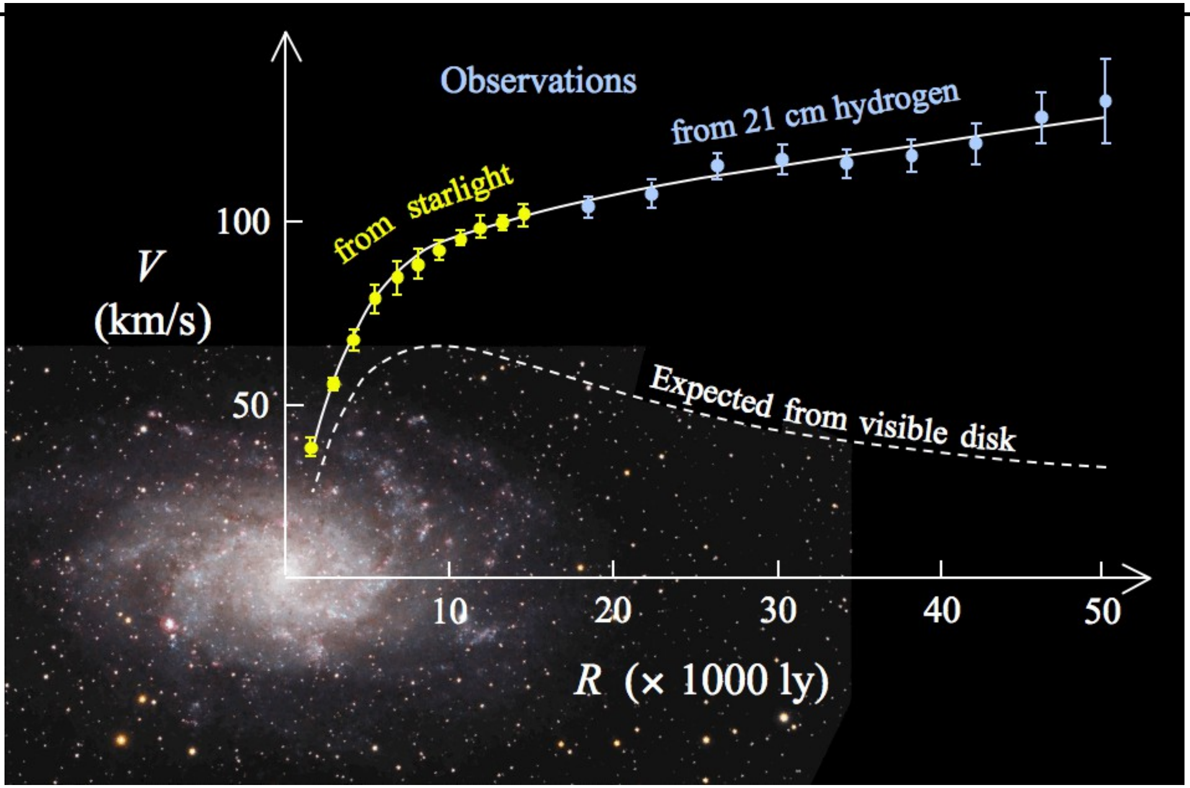








Motivation for Beyond-the-SM (BSM) Physics



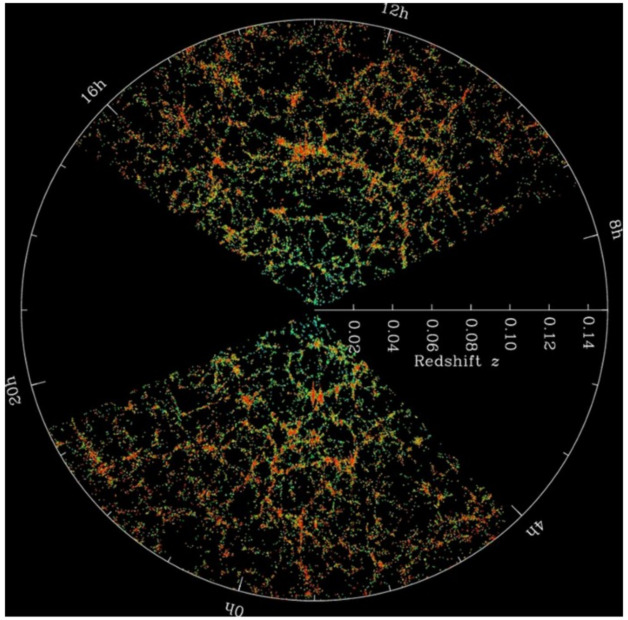
Dark Matter

Invisible matter, weakly interacting, massive, clumpy.

~85% of the universe's matter!

No particle of the SM is a convincing DM candidate

Large scale structure formation



Bound galaxy clusters

Motivation for Beyond-the-SM (BSM) Physics

Inflation

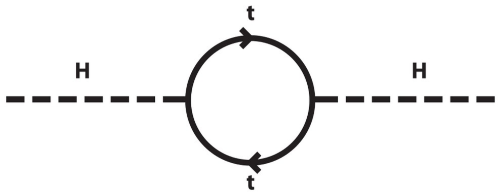
Grand Unified Theory

Neutrino Masses

Matter-antimatter asymmetry

Gravity

Higgs mass fine tuning



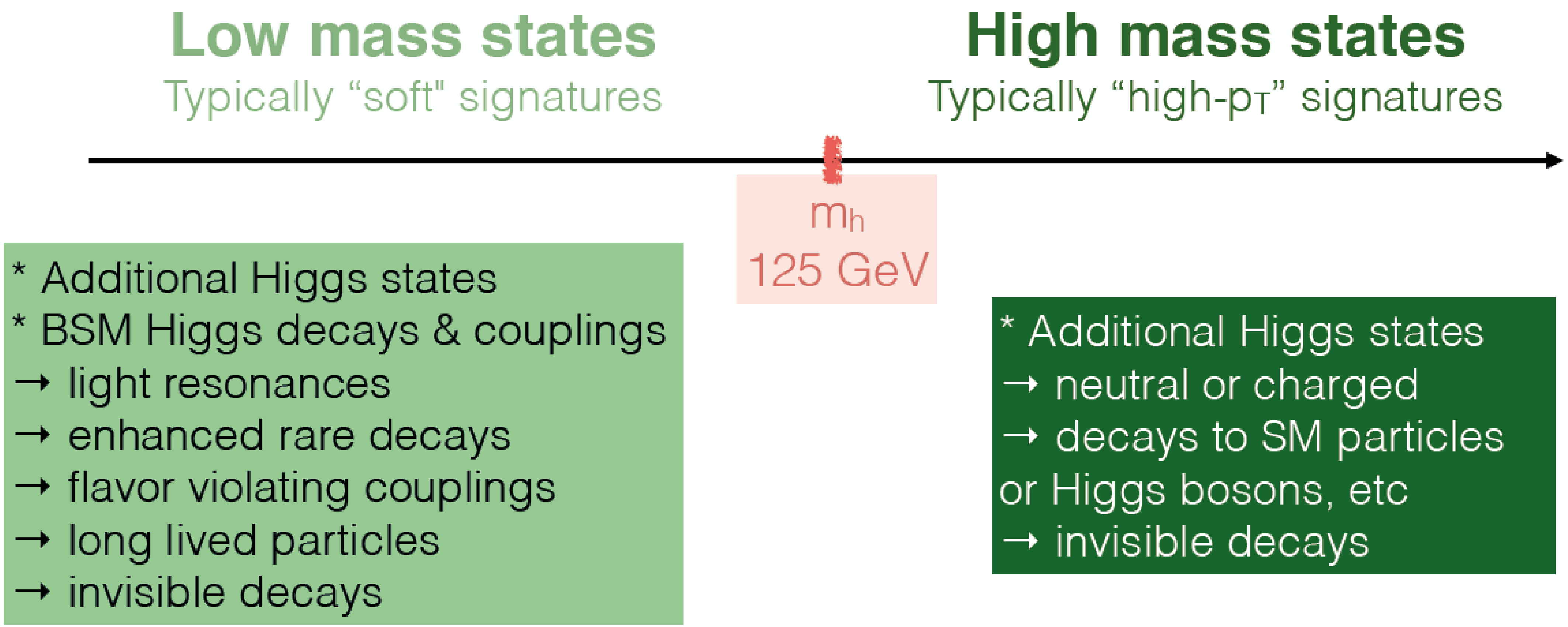
SM Parameters

Dark Energy

→ The Standard Model is not the final answer in physics, but it is a part of a greater theory

New Physics Associated to the Higgs Boson

Program of direct searches for BSM phenomena associated to the Higgs boson



Low mass states

Typically “soft" signatures

High mass states

Typically “high-p_T” signatures

m_h
125 GeV

* Additional Higgs states
* BSM Higgs decays & couplings
→ light resonances
→ enhanced rare decays
→ flavor violating couplings
→ long lived particles
→ invisible decays

* Additional Higgs states
→ neutral or charged
→ decays to SM particles or Higgs bosons, etc
→ invisible decays

Effort is complementary to measurements of Higgs boson properties (spin, CP, couplings, decays) to search for deviations from the SM

Program is not only in HBSM group, but also in other groups in Higgs and Exotics

Searches for BSM Higgs bosons: Overview

Neutral Heavy Higgs

A/H→$\tau\tau$
A/H→tt
A/H→bb
A/H→$\mu\mu$
H→WW
H→ZZ
H→$\gamma\gamma$
H→Zγ
H→$\chi\chi$
H→WH$^+$
A→Zh
A→ZH

Di-Higgs

H→hh
H→Sh
H→SS
NR HH

Charged Higgs

H$^+$→tb
H$^+$→$\tau\nu$
H$^+$→cs
H$^+$→cb
H$^+$→$\chi\chi$
H$^+$→Wγ
H$^+$→WH/Wh
H^{++}→W W
H^{++}→ll

Light Higgs, exotic Higgs decays

h→Za
h→aa
h→ss
tta, tts
H$^+$→Wa
h→meson+γ
LFV h
h→invisible
h→$\chi\chi$

Mono-Higgs

H→bb+MET
H→$\tau\tau$ + MET
H→Za→Z+MET

→ Rich and diverse physics program in the Higgs, Exotics, and Higgs/Dibosons physics groups of ATLAS

→ Find all results online: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

I. Additional Higgs Bosons

Art by Liron Barak

Benchmark Models

- Countless benchmark models on the market (→ see recommendations by the LHCHXSWG)
- Popular: MSSM (Minimal Supersymmetric SM), 2HDM (two Higgs Doublets), additional singlets, Higgs tripletts, ...
- **2HDM:** Two complex, hypercharge-one scalar doublets Φ_1 Φ_2 resulting in 8 degrees of freedom

SM:

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} \rightarrow H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}, H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

tanβ = v_1 / v_2

$$\begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

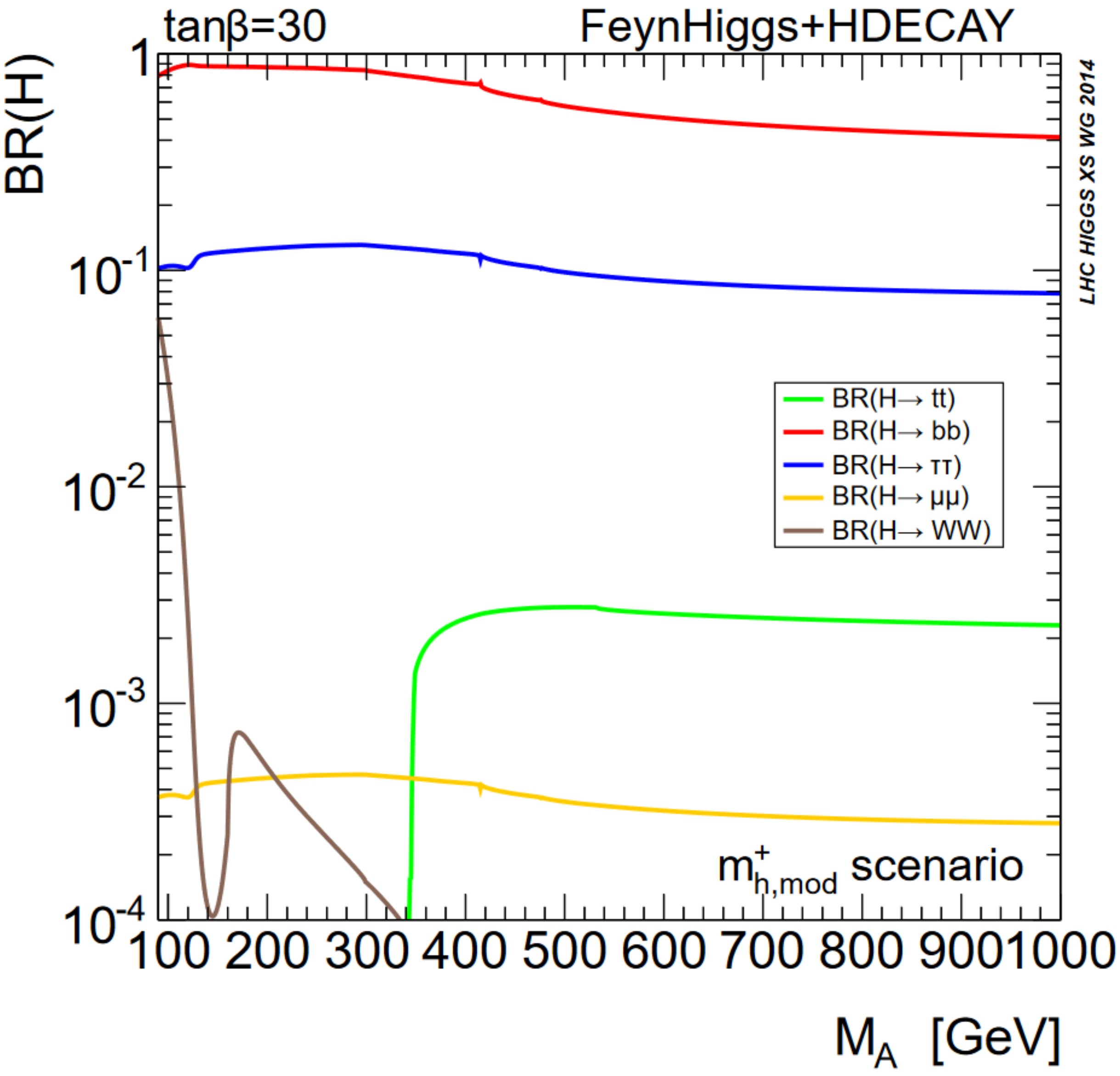
→ Five Higgs bosons: **h** (SM-like, CP even), **H** (heavy, CP-even), **A** (heavy, CP-odd), **H^+**, **H^-**

Mass hierarchy or mass degeneracy often imposed in the benchmarks,
leaving three parameters: Heavy Higgs mass, tanβ, mixing angle α

Four types for which no FCNC are allowed on tree level:

Type I:	All fermions couple with H_2, none with H_1
Type II:	Up-type quarks couple to H_2, down-type quarks and charged leptons to H_1
Flipped:	Up-type quarks and charged leptons couple to H_2, down-type quarks couple to H_1
Lepton-specific:	Charged leptons couple to H_1, all quarks couple to H_2

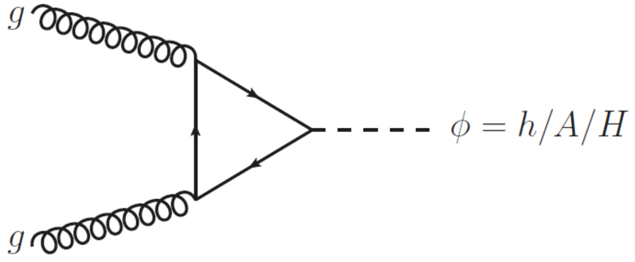
Heavy Higgs Decay in the MSSM: High tanβ

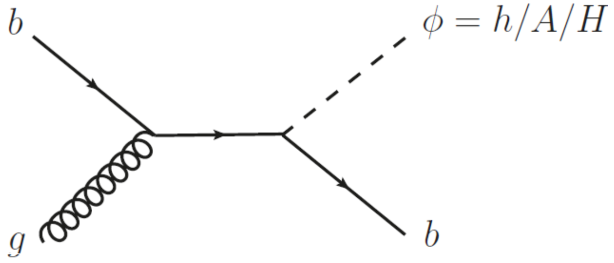


A/H → ττ

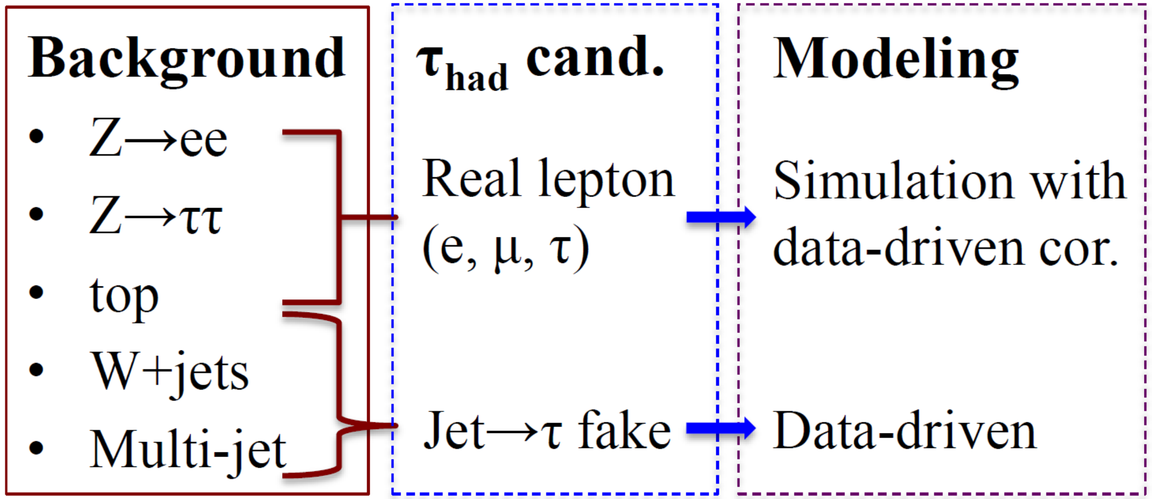
Selections

- $\tau_{had}\tau_{had}$: single τ trigger, $p_T(\tau_1)$>85/130/165 GeV depends on trigger , $p_T(\tau_2)$>65 GeV
- $\tau_{lep}\tau_{had}$: single e/μ trigger, $p_T(l/\tau_{had})$>30/25 GeV, $M_T(l, E_T^{miss})$<40 GeV
- Opposite Charge, ΔΦ(τ, τ)>2.4/2.7, Categorization: 0 or ≥1 b-tagged jet





Background modeling



Background
- Z→ee
- Z→ττ
- top
- W+jets
- Multi-jet

τ_{had} cand.

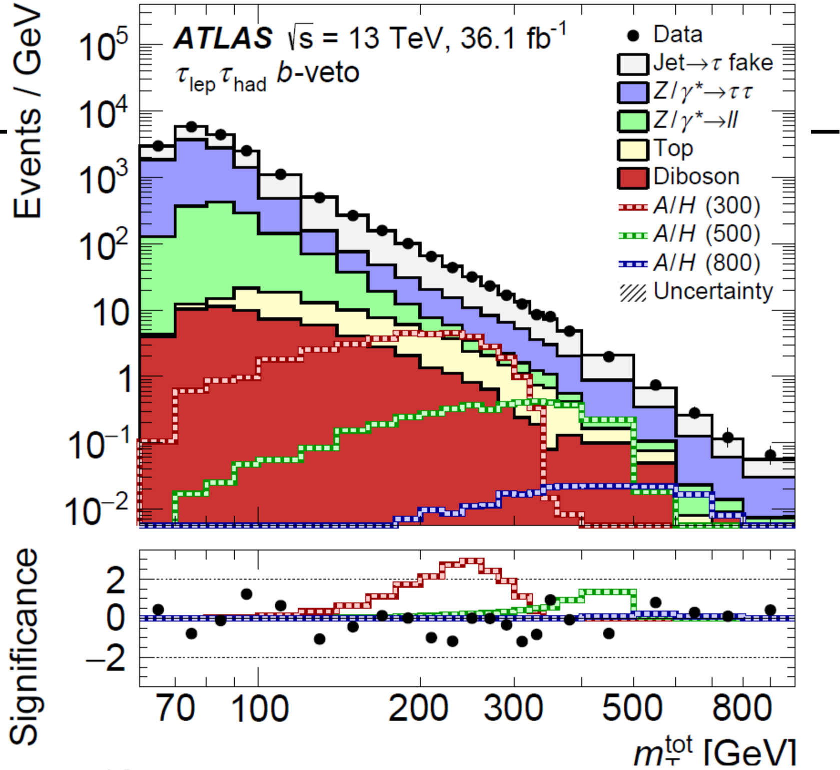
Real lepton (e, μ, τ)

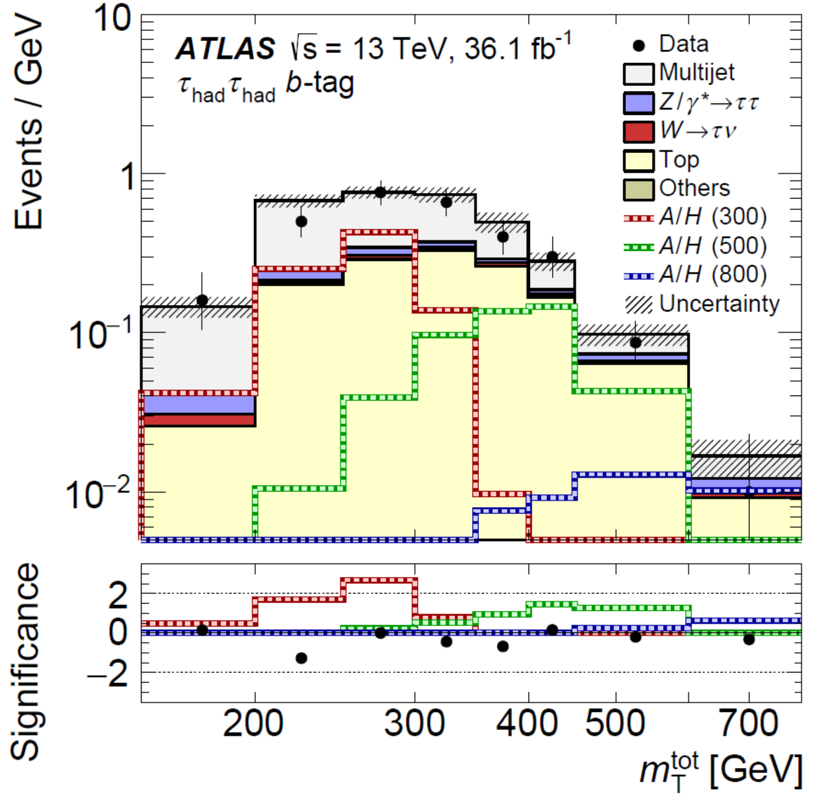
Jet→τ fake

Modeling

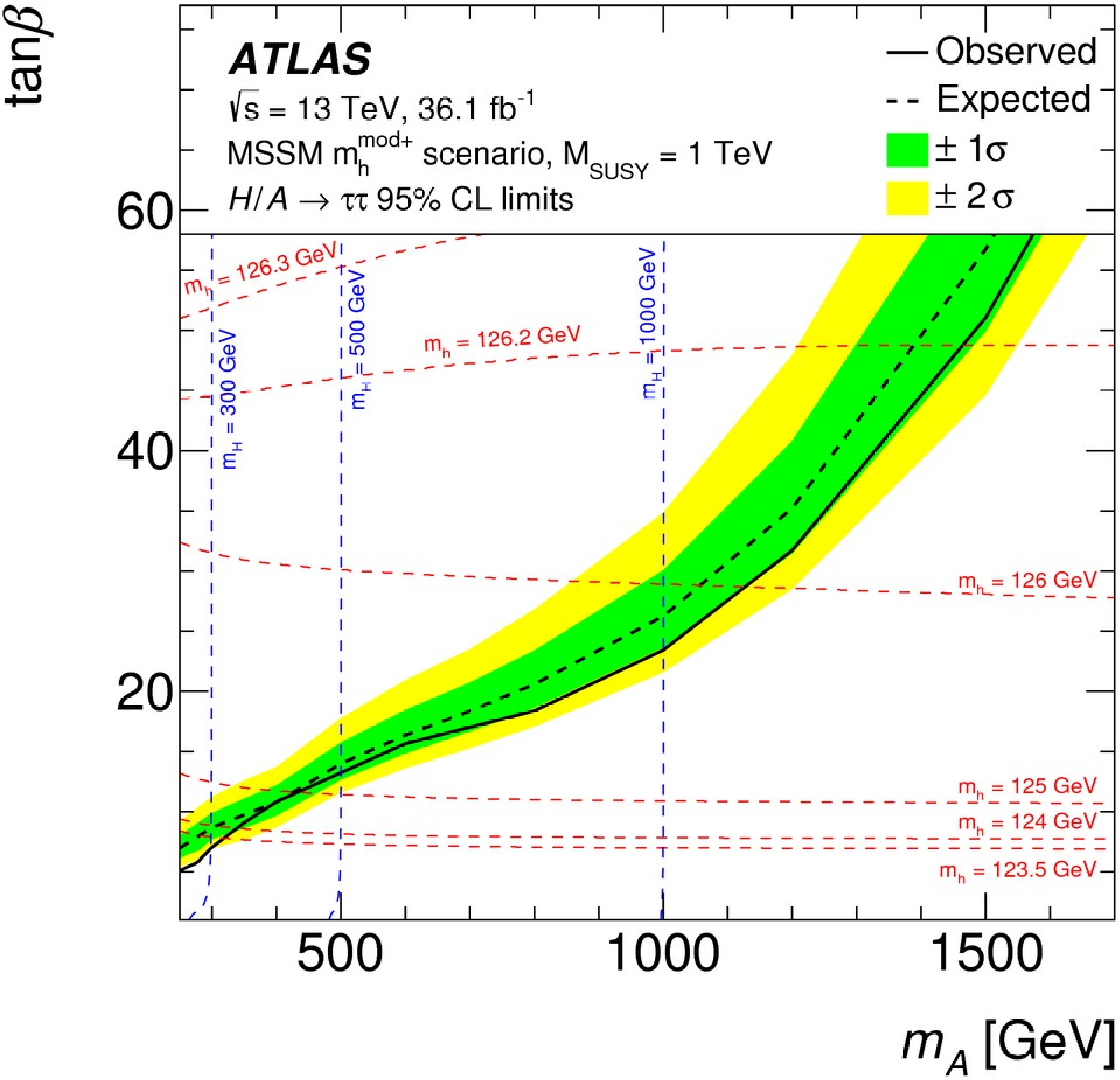
Simulation with data-driven cor.

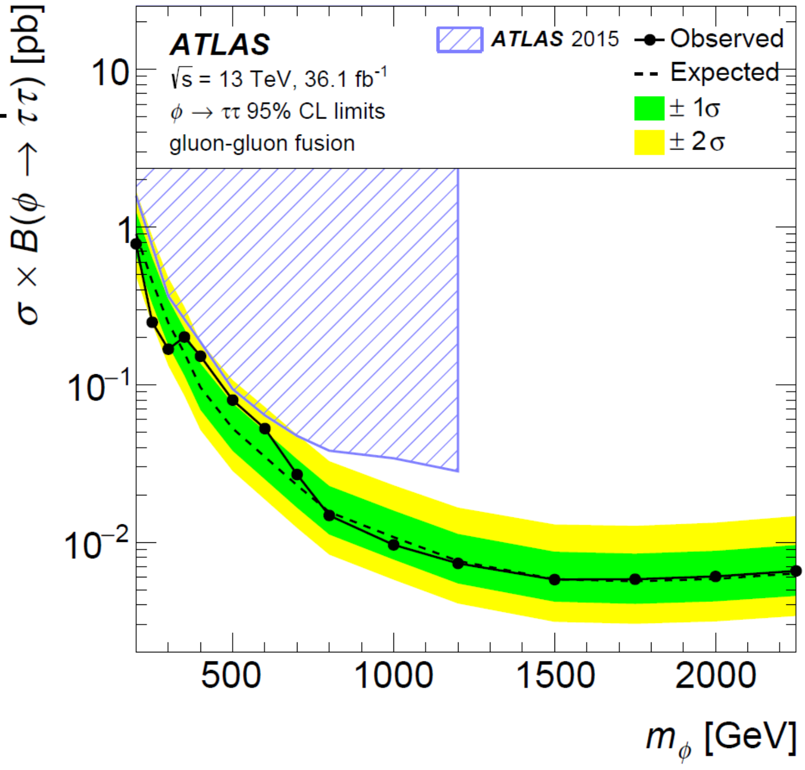
Data-driven

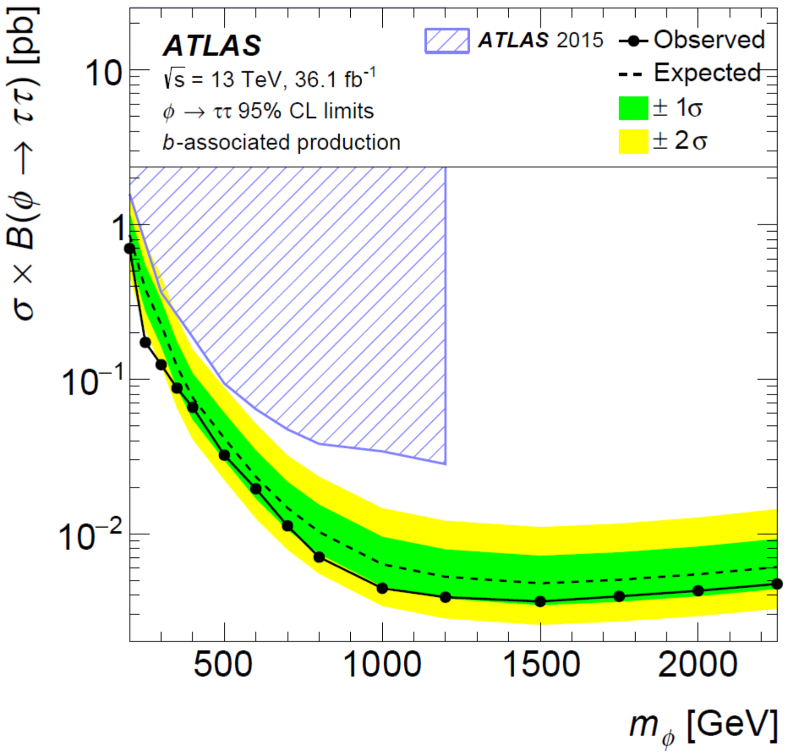




A/H → $\tau\tau$

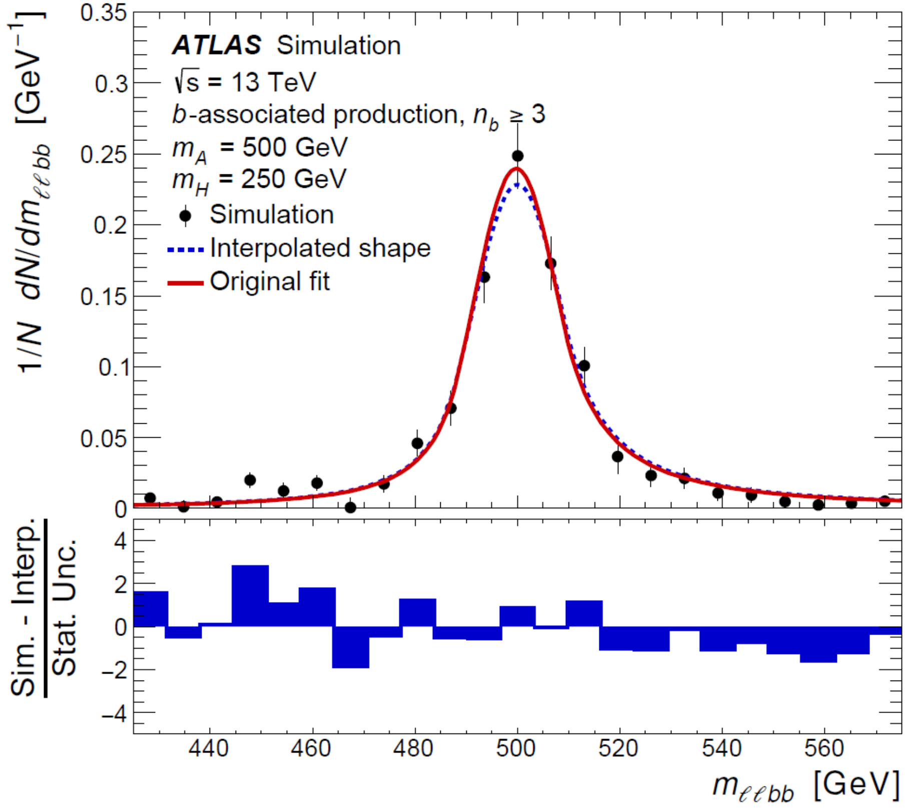

ATLAS
√s = 13 TeV, 36.1 fb-1
MSSM m_h^mod+ scenario, M_SUSY = 1 TeV
H/A → ττ 95% CL limits
Observed
Expected
± 1σ
± 2σ
m_h = 126.3 GeV
m_h = 126.2 GeV
m_h = 126 GeV
m_h = 125 GeV
m_h = 124 GeV
m_h = 123.5 GeV
m_H = 300 GeV
m_H = 500 GeV
m_H = 1000 GeV
tanβ
20
40
60
500
1000
1500
m_A [GeV]

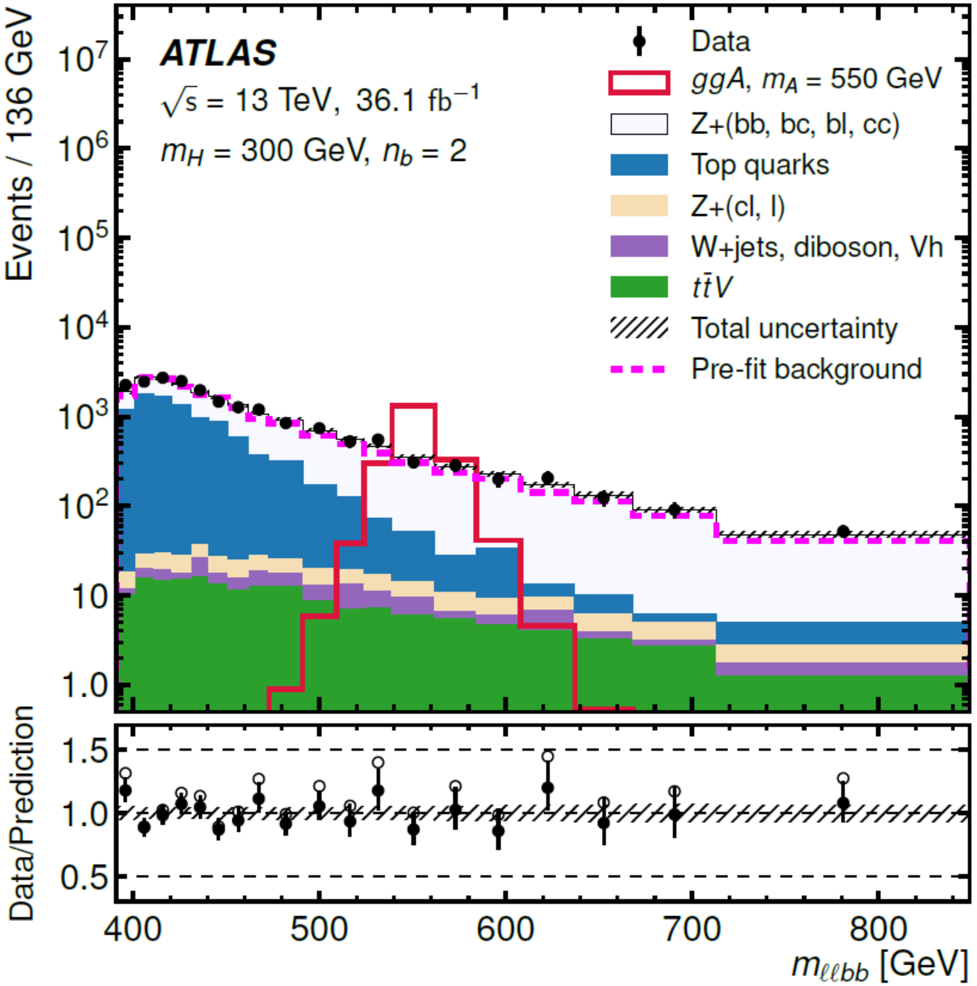

ATLAS
√s = 13 TeV, 36.1 fb-1
φ → ττ 95% CL limits
gluon-gluon fusion
ATLAS 2015
Observed
Expected
± 1σ
± 2σ
σ × B(φ → ττ) [pb]
10
1
10^-1
10^-2
500
1000
1500
2000
m_φ [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
φ → ττ 95% CL limits
b-associated production
ATLAS 2015
Observed
Expected
± 1σ
± 2σ
σ × B(φ → ττ) [pb]
10
1
10^-1
10^-2
500
1000
1500
2000
m_φ [GeV]

A → ZH → llbb

- H is not limited to 125 GeV → 2D scan in A and H mass, **mA > mH**
- Signal produced in gluon-fusion and through b-associated production
- Categories: nb=2, nb>=3 to access both production modes
- 80 < mll < 100 GeV, mbb must be close to the hypothesized H mass



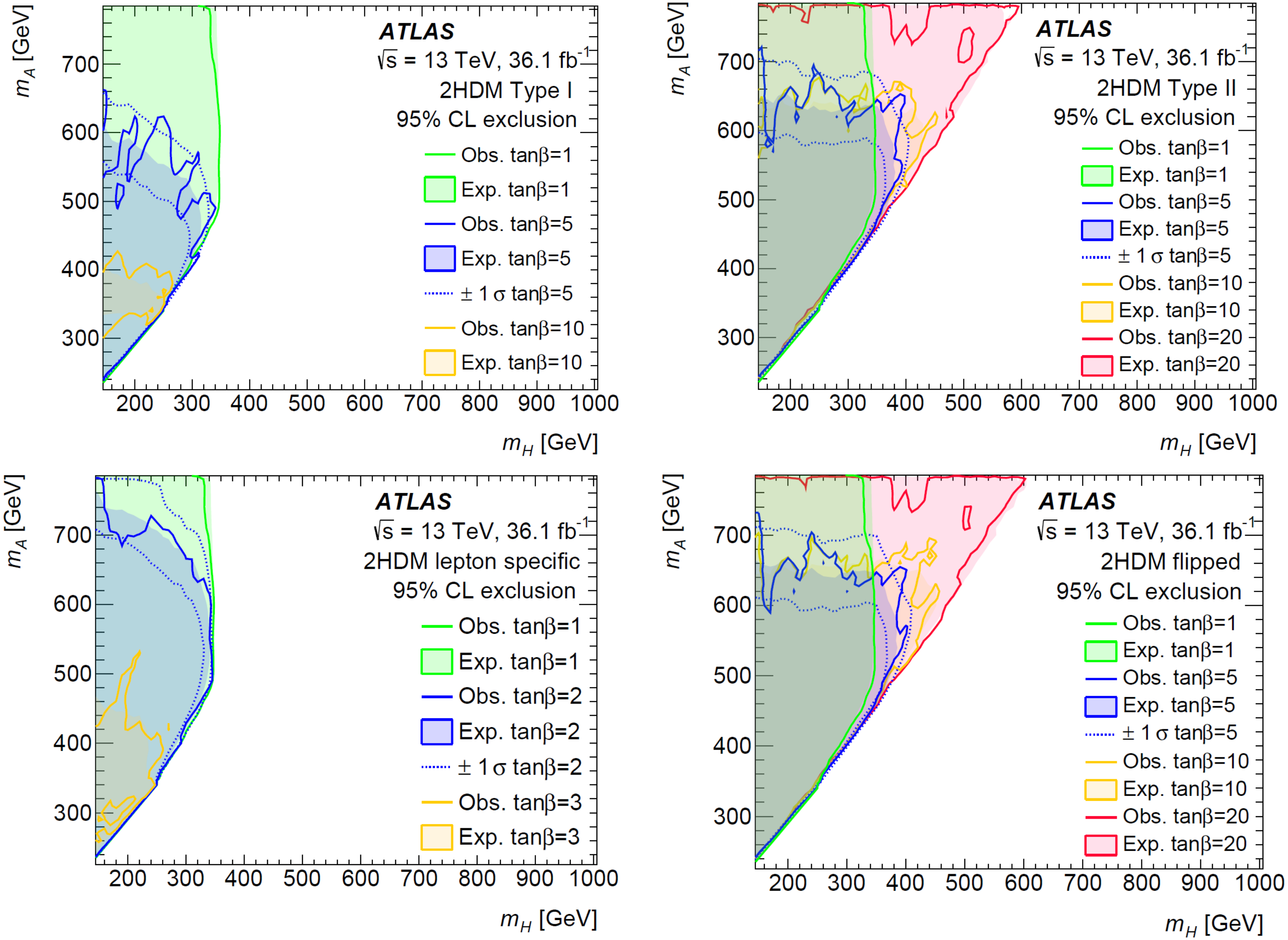


- mllbb final discriminant

Background estimation:

- ttbar: Shape taken from simulation, normalisation from data control region (eμ pair instead of ee or μμ pair) → 99% pure
- Z+jets: Shape from simulation, normalisation obtained from signal region mllbb fit (works well because shape is different from signal)
- Smaller backgrounds estimated entirely from simulation

A → ZH → llbb



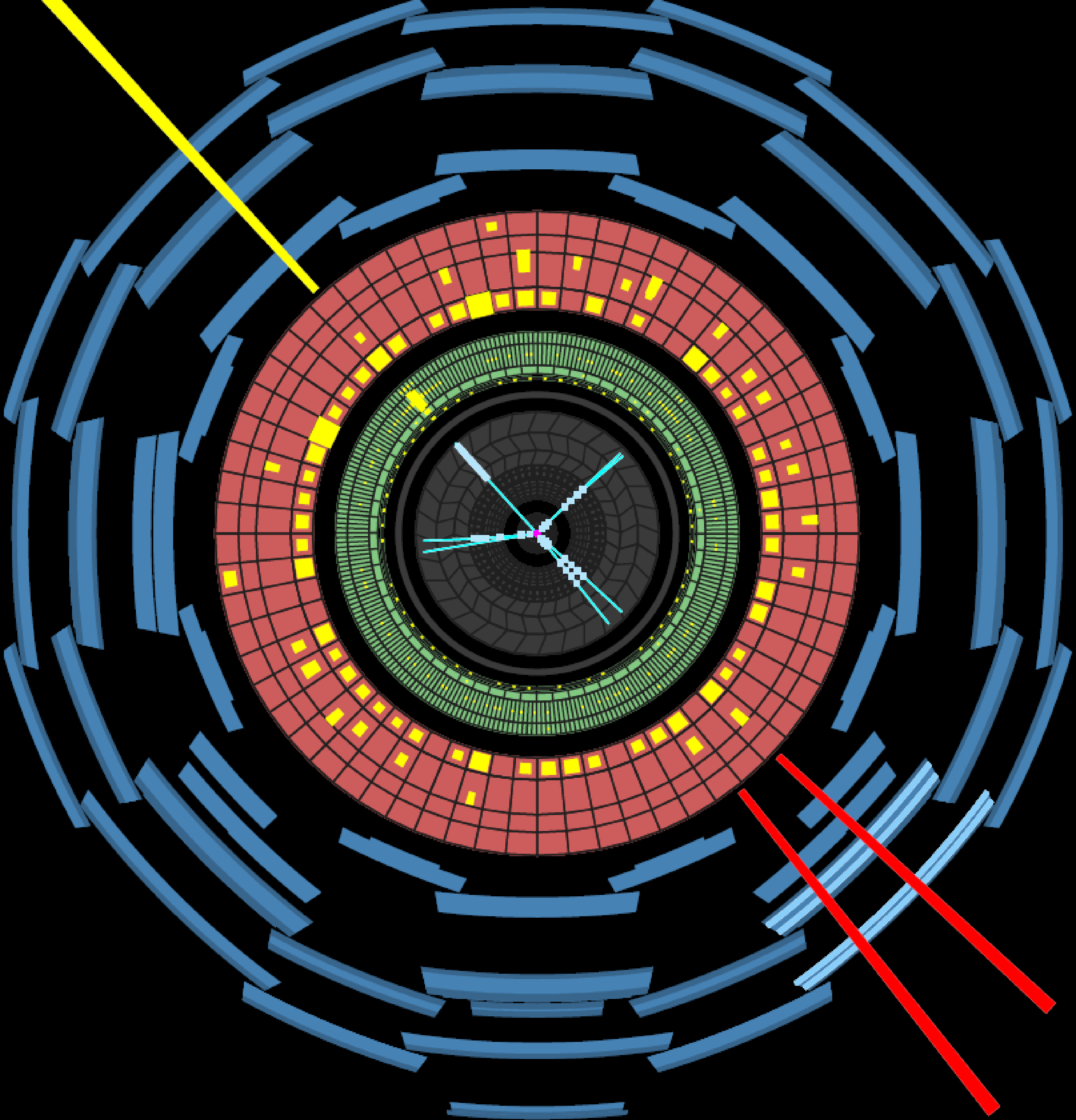
2D exclusions in 2HDM for cos(β–α)=0

Results similar for type-II and flipped (type-I and lepton-specific) because Yukawa couplings to quarks are the same, differences only for decay to leptons.

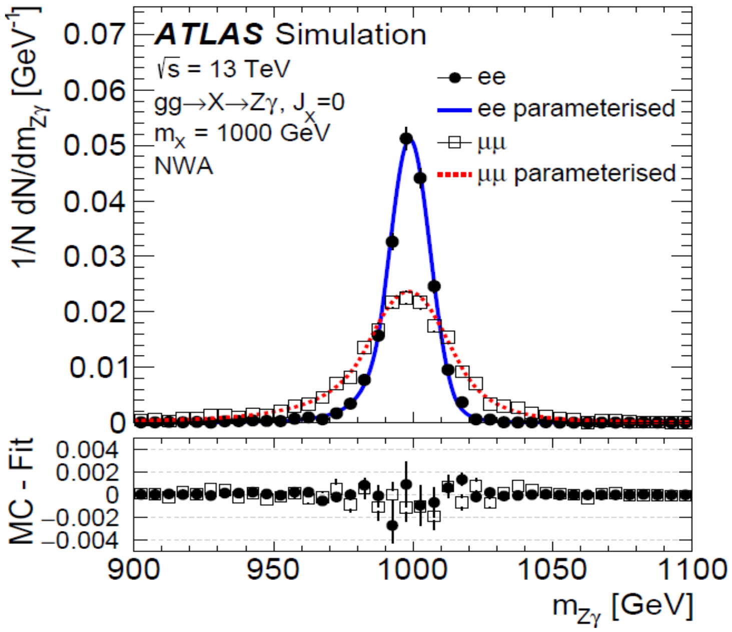
Type-I and lepton-specific sensitivity decreases for larger tanβ, because ggF cross section decreases (similarily, type-II and flipped sensitive to high tanβ due to enhanced bbA cross section)

$H \rightarrow Z\gamma$

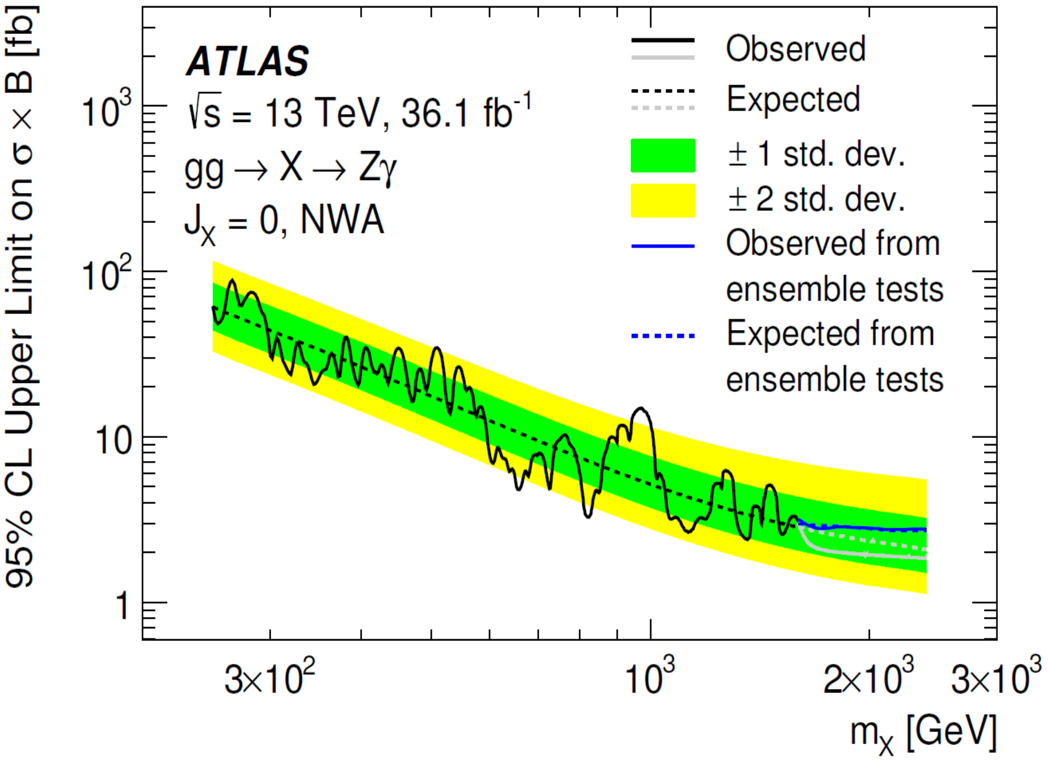
$m_{Z\gamma}$ = 1.57 TeV

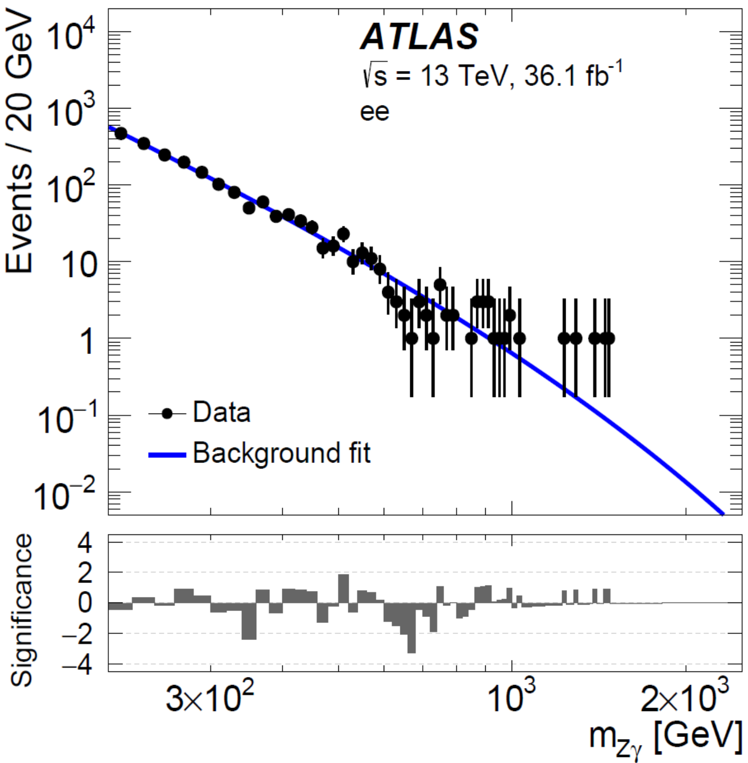


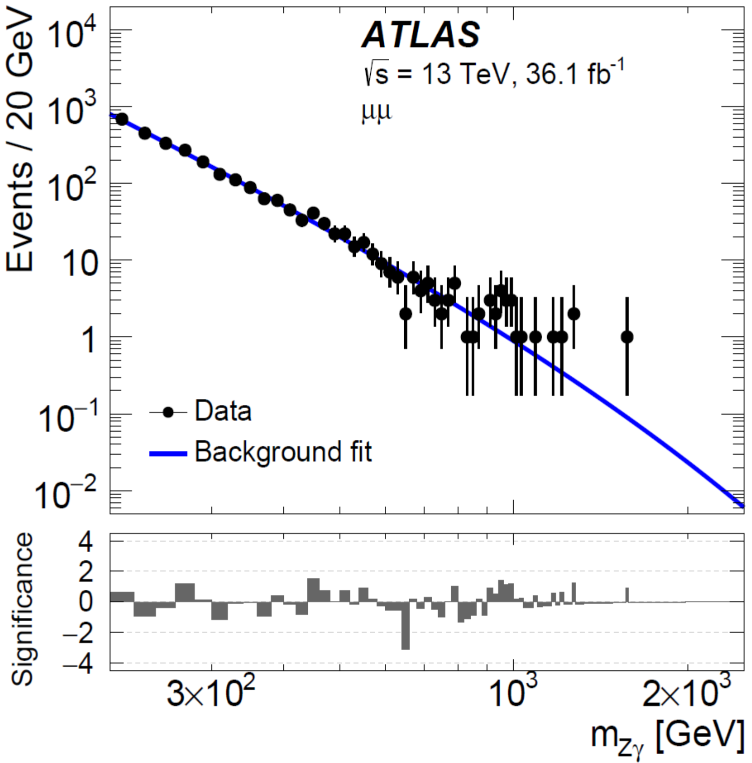
Additional Neutral Higgs Bosons: H → Zγ



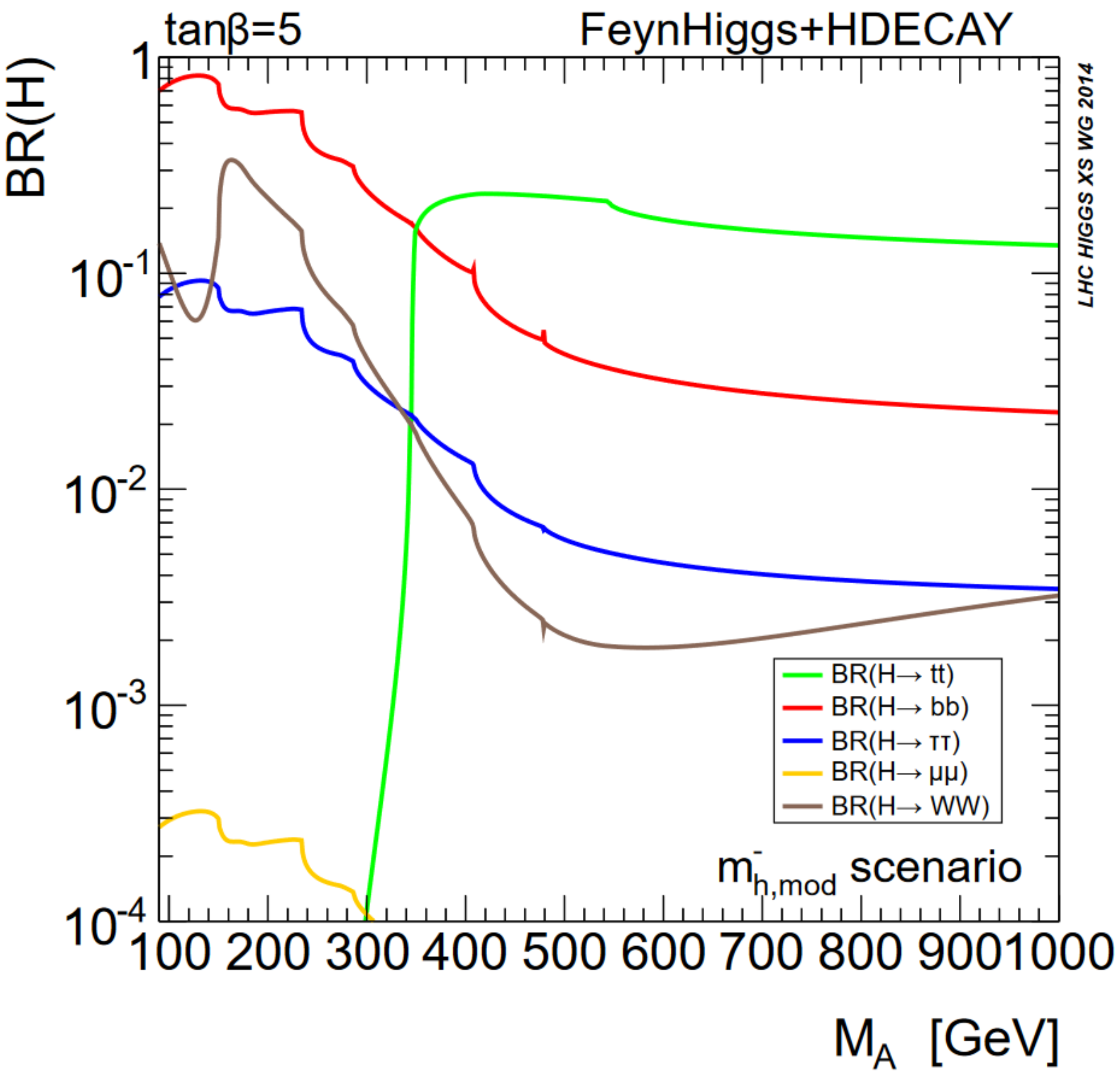
- Two catgeories for the high mass search: Z → ee and Z → μμ
- Signal shape modelled with double sided Crystal Ball
- Background shape modelled $f^{k}_{\mathrm{bkg}}(x; b, a_k) = N(1 - x^{1/3})^{b} x^{\sum_{j=0}^{k} a_k \log(x)^j}$ (k=0)
- Background model had to pass spurious signal tests and also an F-test
- No significant excess found, global significance 0.8σ
- SM limit: 6.6 (5.2) obs (exp) (SM analysis uses different categorisation)





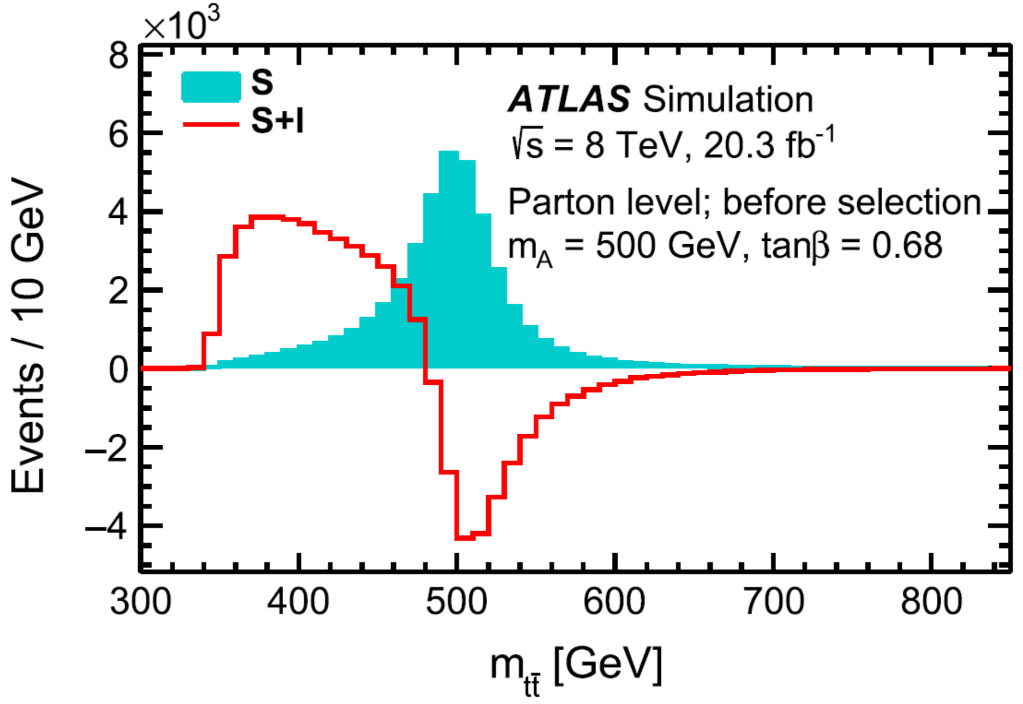


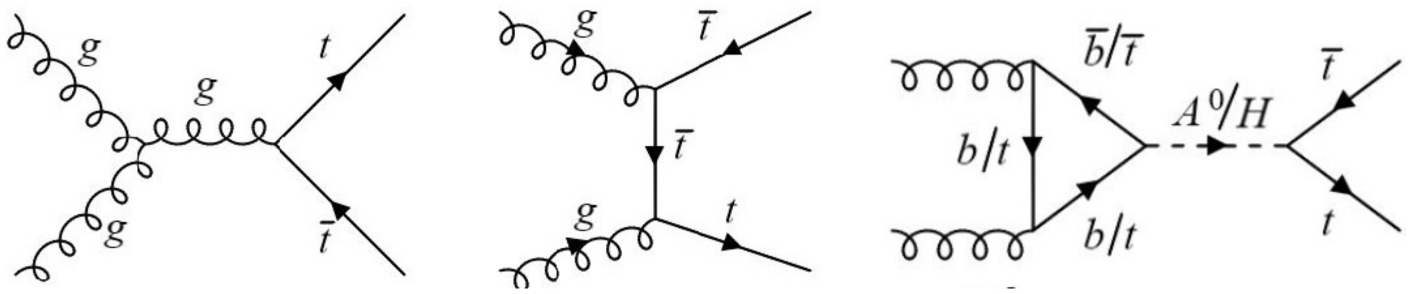
Heavy Higgs Decay in the MSSM: Low tanβ



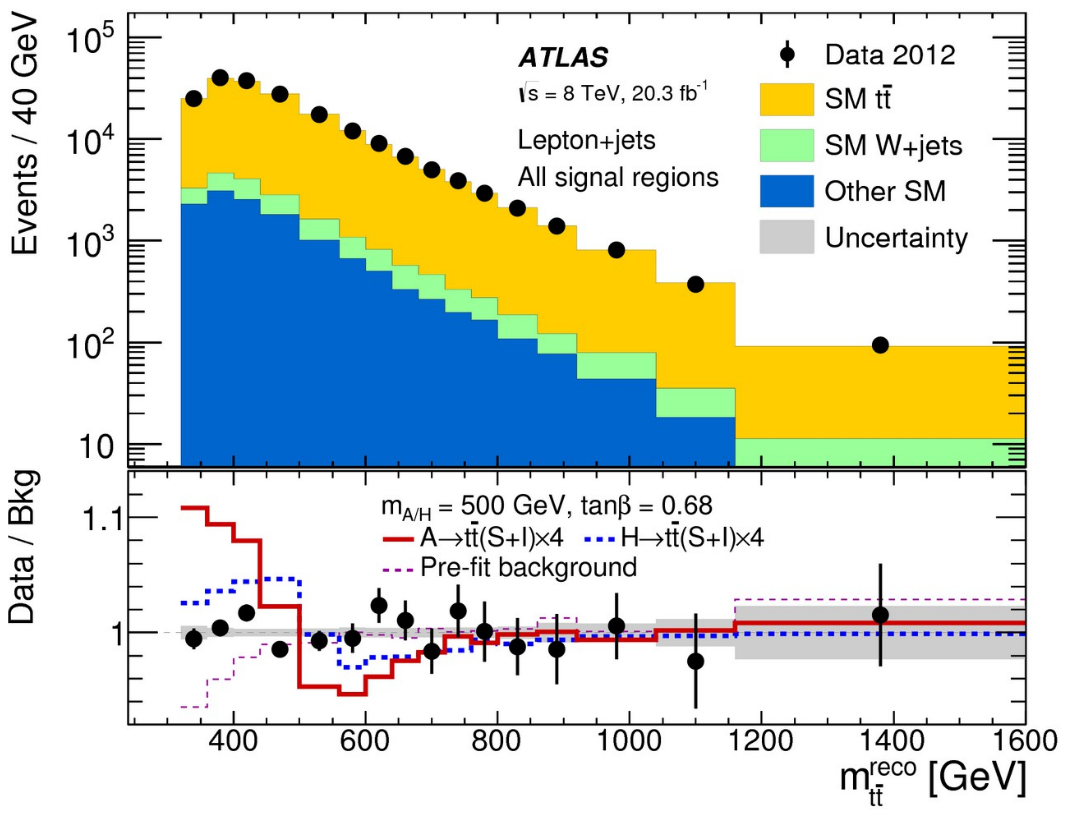
ttbar decay is dominant in many models for m_H > 350 GeV and low tanβ

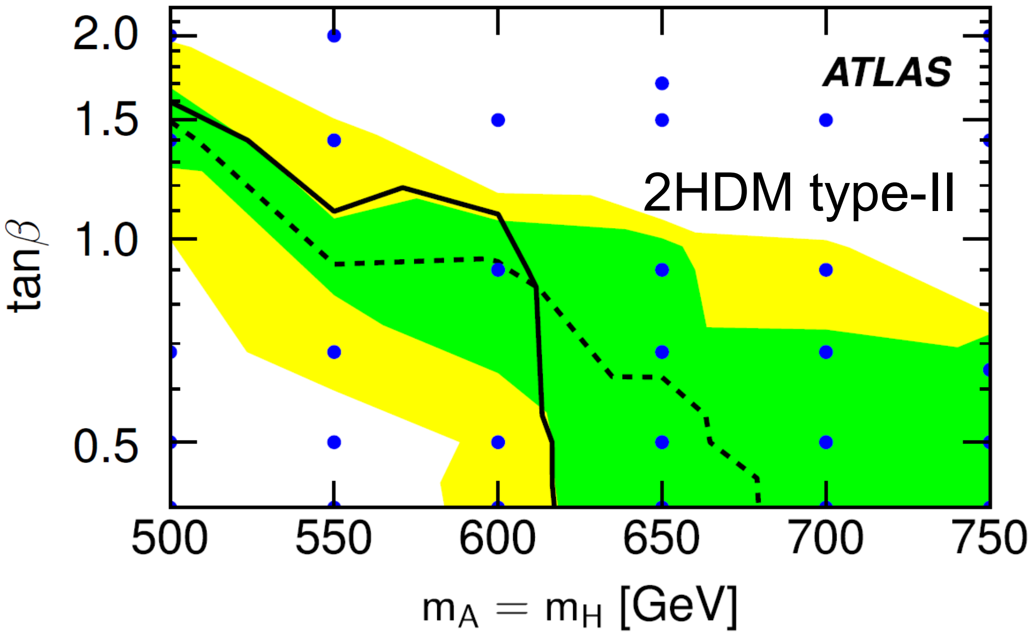
A/H → ttbar (8 TeV)





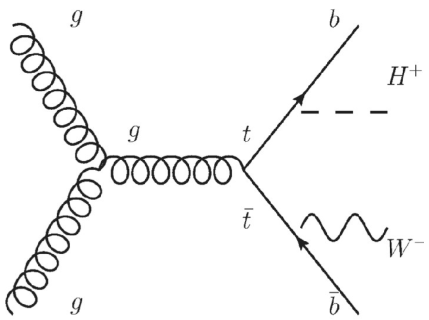
Huge signal-background interference, model-dependent





Charged Higgs Bosons: Production (2HDM)

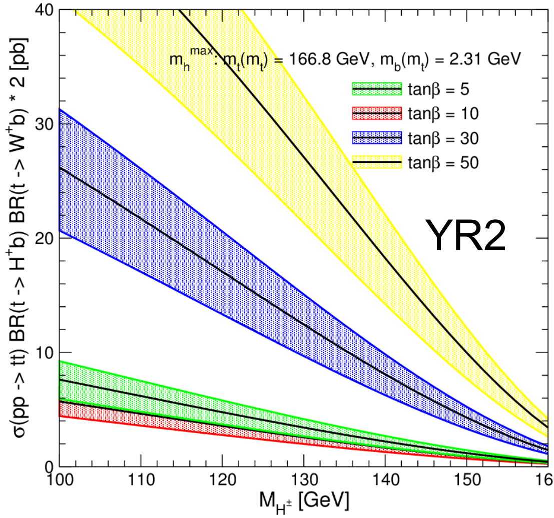
Low mass



$\sigma(pp \rightarrow tt) * BR(t \rightarrow bH^{+}) * BR(t \rightarrow bW)$

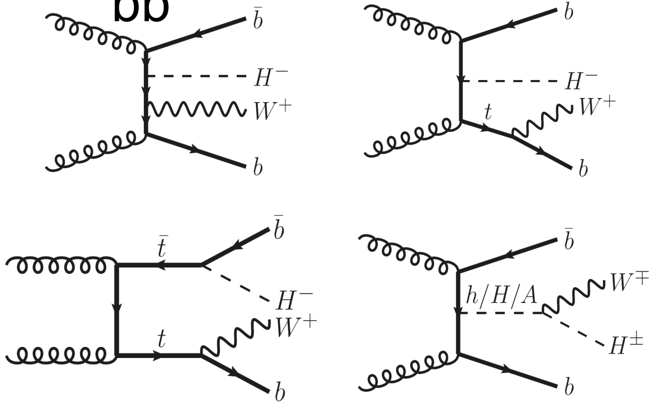
NNLO
PRL 110 (2013)

NLO: Phys. Rev. D76 (2007), hep-ph/9301237
NNLO: eg. hep-ph/9806244

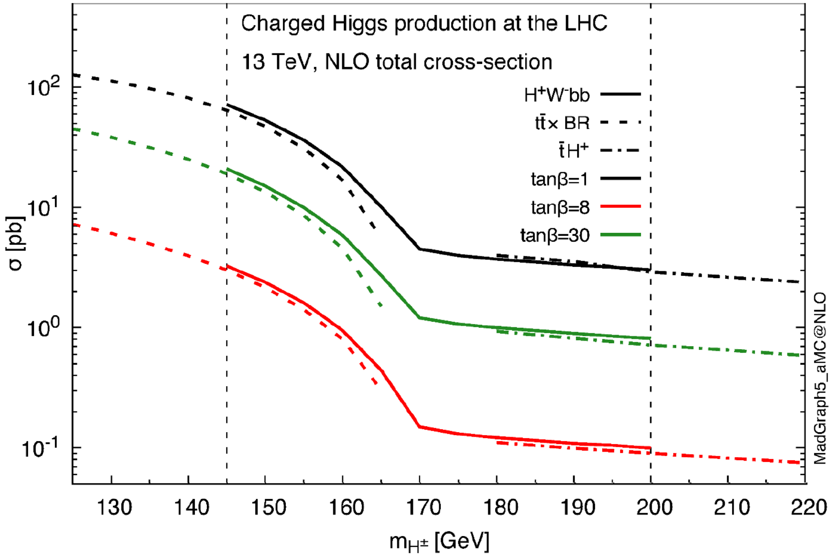


Intermediate mass

NLO $pp \rightarrow H^{+}W^{-}bb$

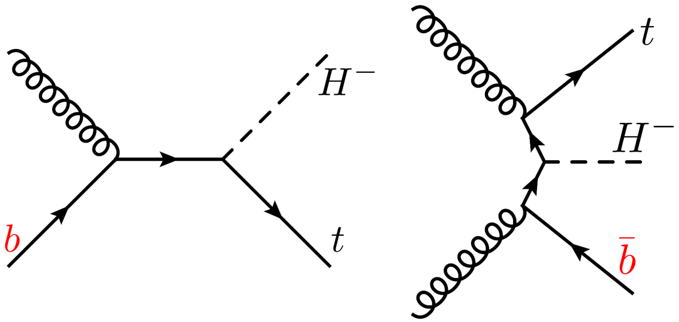


https://arxiv.org/abs/1607.05291

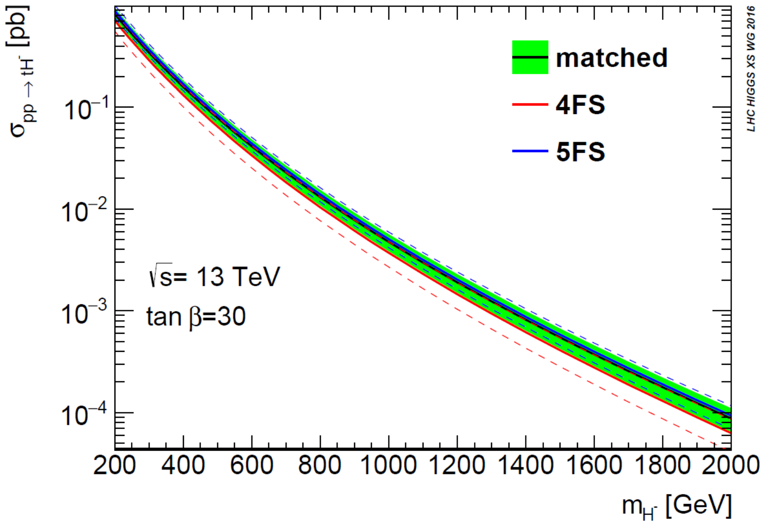


Differential cross sections at LO

High mass

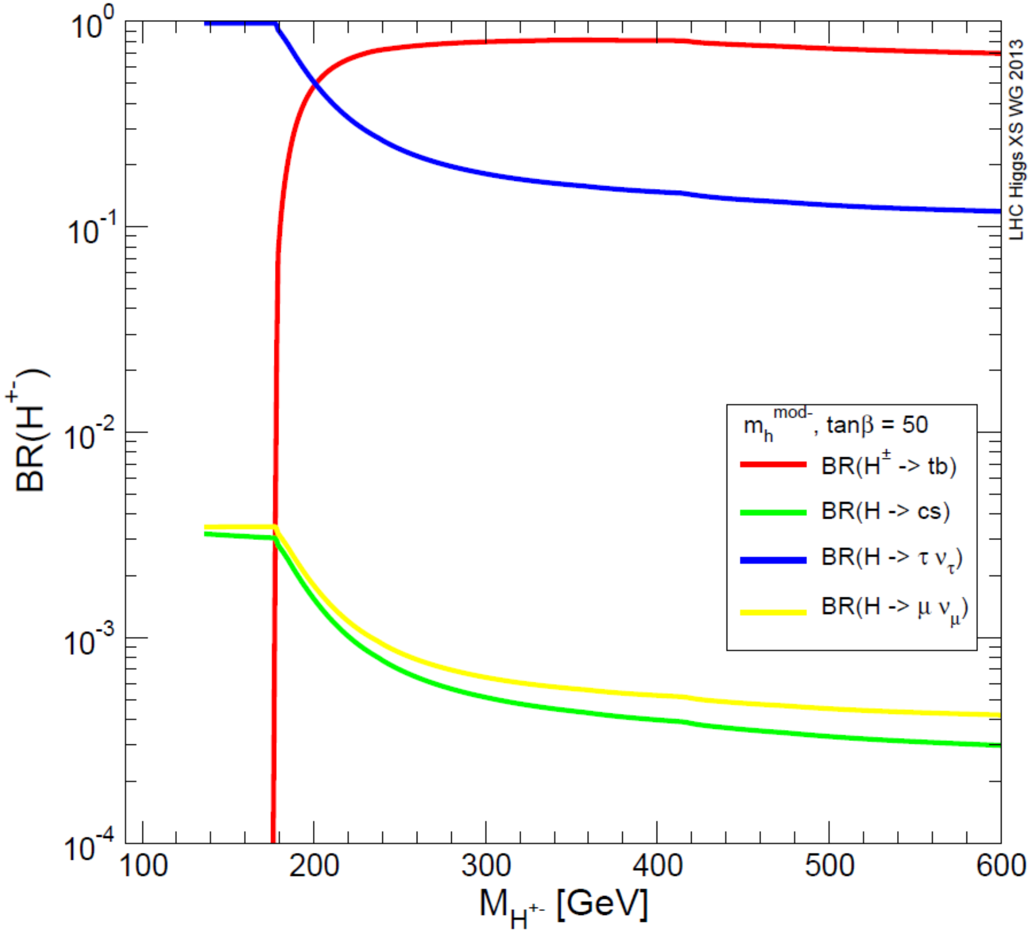


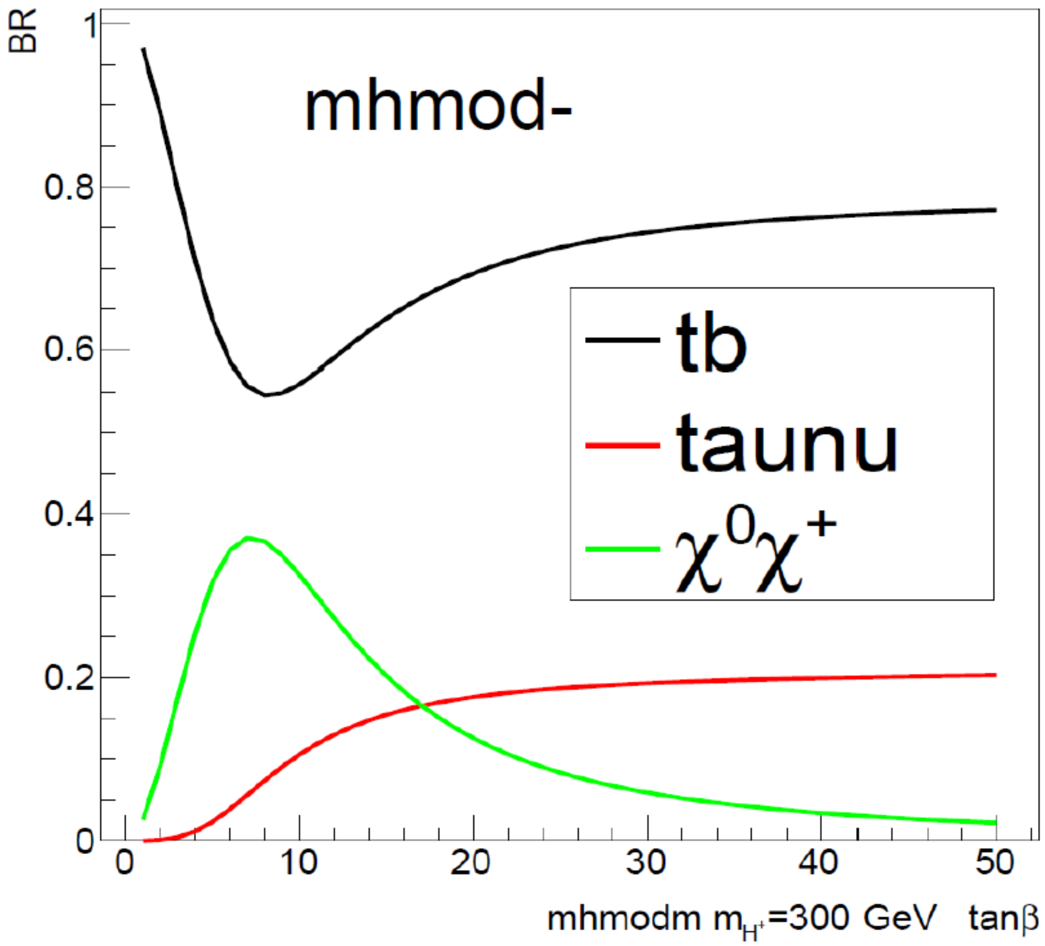
Tools: 4FS: MG5_aMCatNLO,
5FS: Prospino



Differential cross sections at NLO

Charged Higgs Decay in the MSSM

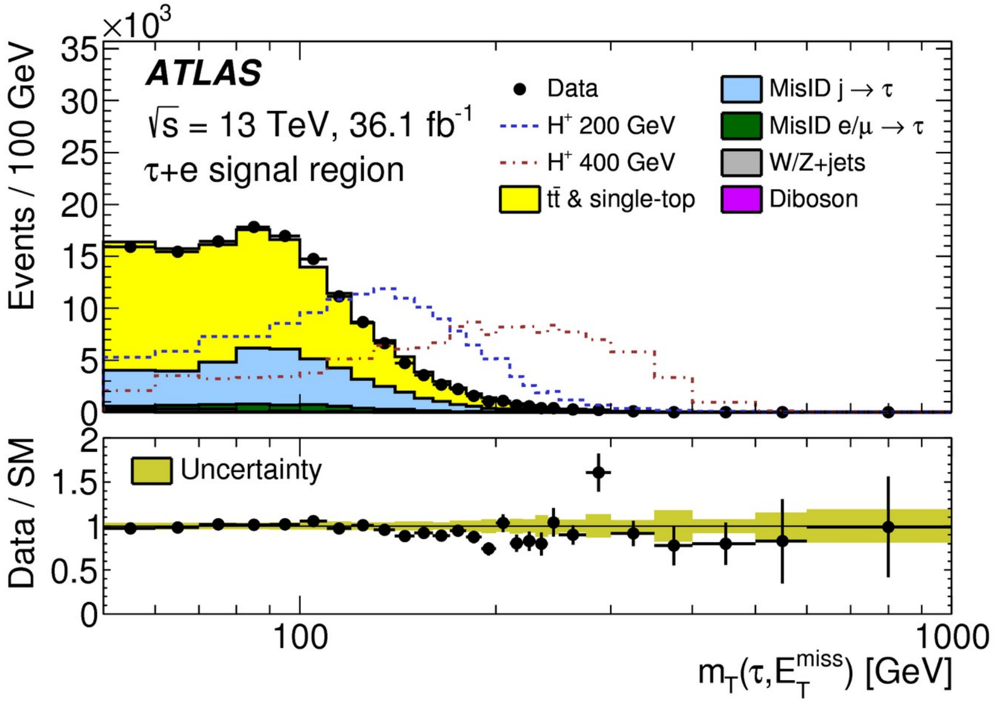


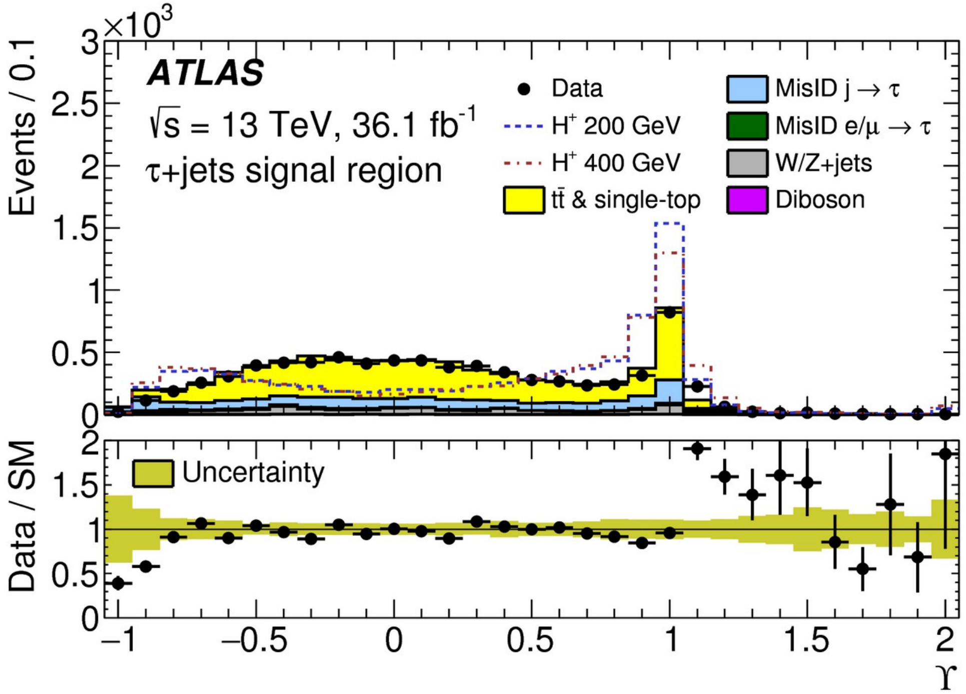


Charged Higgs Bosons: $H^+ \to \tau\nu$

τ_h-jet	τ_h-lep
$\not{E}_T$ trigger	single lepton trigger
$1\ \tau_h,\ p_T^\tau > 40 GeV$	$1\ \tau_h,\ p_T^\tau > 30 GeV$
$\geq$3 jets and $\geq$1 b-tag	$\geq$1 jets and $\geq$1 b-tag
no μ or e	1 mu or e, $p_T^\ell > 30 GeV$
$\not{E}_T > 150 GeV$	$\not{E}_T > 50 GeV$
$m_T(\tau, \not{E}_T) > 50 GeV$	opposite sign τ and e/μ

BDT input variable	$\tau_{\text{had-vis}}$+jets	$\tau_{\text{had-vis}}$+lepton
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓	✓
p_{T}^{τ}	✓	✓
$p_{\mathrm{T}}^{b\text{-jet}}$	✓	✓
p_{T}^{ℓ}		✓
$\Delta\phi_{\tau_{\text{had-vis}},\text{ miss}}$	✓	✓
$\Delta\phi_{b\text{-jet, miss}}$	✓	✓
$\Delta\phi_{\ell,\text{ miss}}$		✓
$\Delta R_{\tau_{\text{had-vis}},\ \ell}$		✓
$\Delta R_{b\text{-jet},\ \ell}$		✓
$\Delta R_{b\text{-jet},\ \tau_{\text{had-vis}}}$	✓	
Υ	✓	✓





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τ_h-jet	τ_h-lep
$\not{E}_T$ trigger	single lepton trigger
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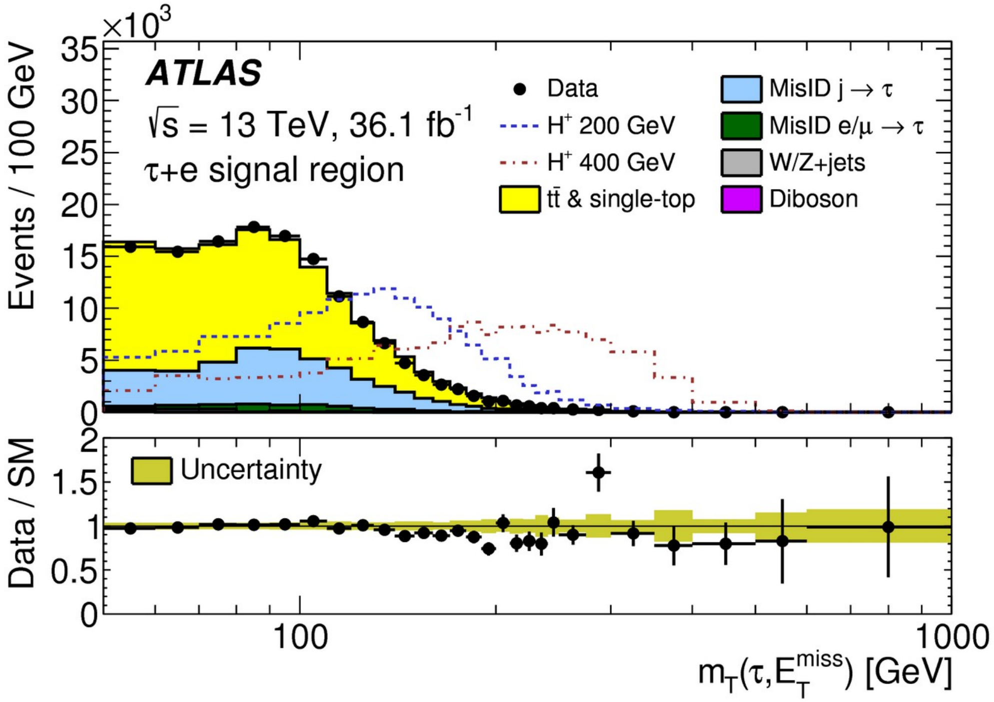
no μ or e	1 mu or e, $p_T^\ell > 30 GeV$
$\not{E}_T > 150 GeV$	$\not{E}_T > 50 GeV$
$m_T(\tau, \not{E}_T) > 50 GeV$	opposite sign τ and e/μ

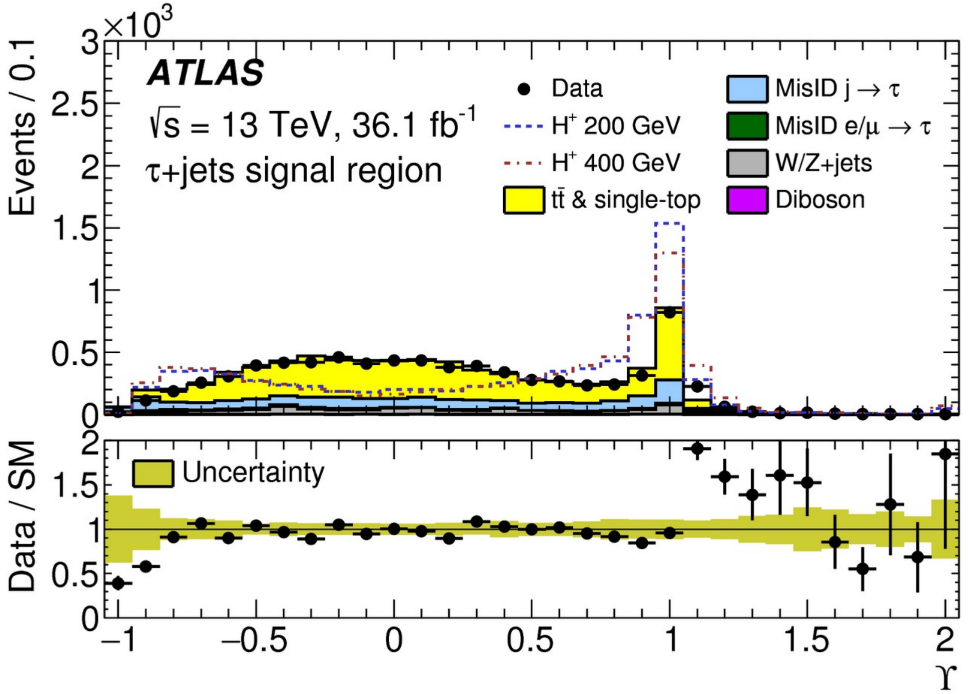
$$\Upsilon = \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{E_T^\tau} \approx 2\frac{p_T^{\tau\text{-track}}}{p_T^\tau} - 1$$

Polarization of the hadronic tau gives discrimination:

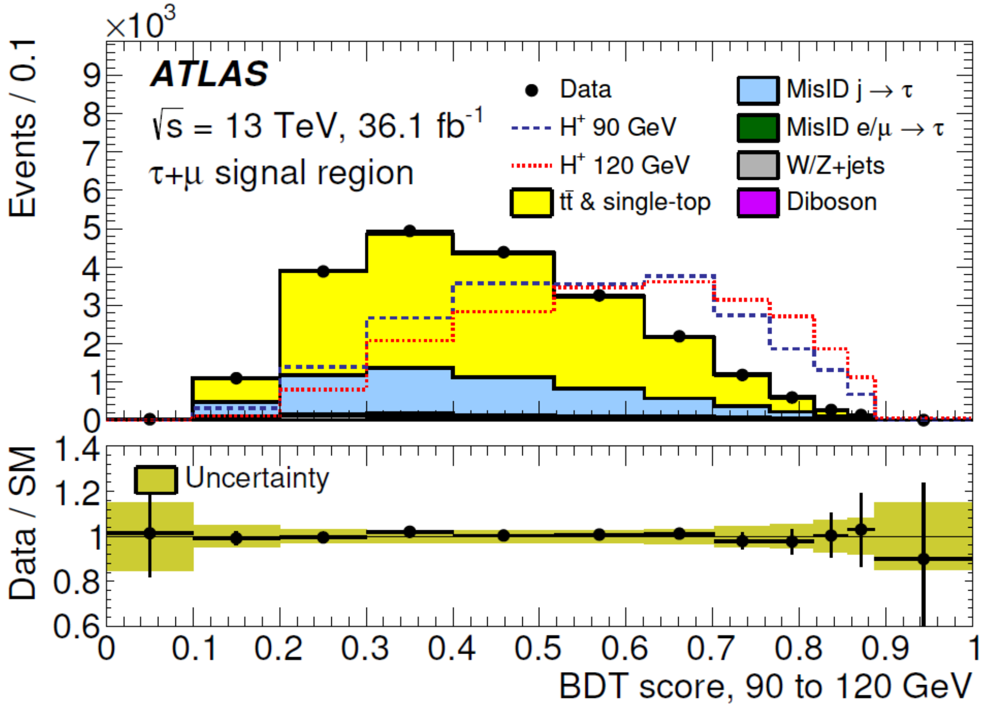
- In t → bW decay, tau comes from W decay
- In $H^+ \rightarrow \tau\nu$, tau comes from a scalar

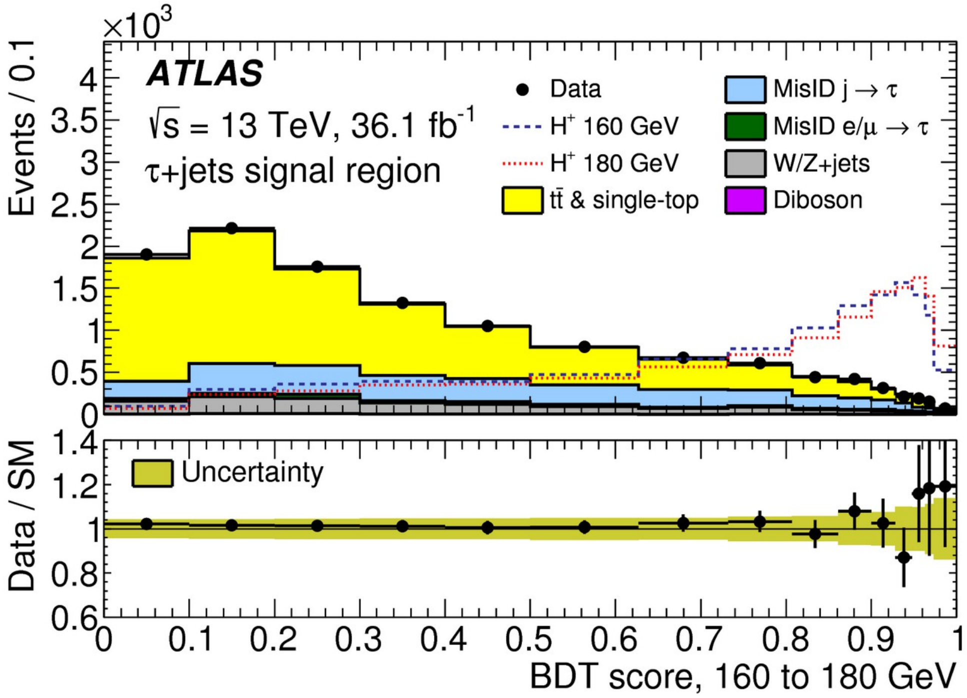
→ Difference in energy carried by the charged and neutral pions

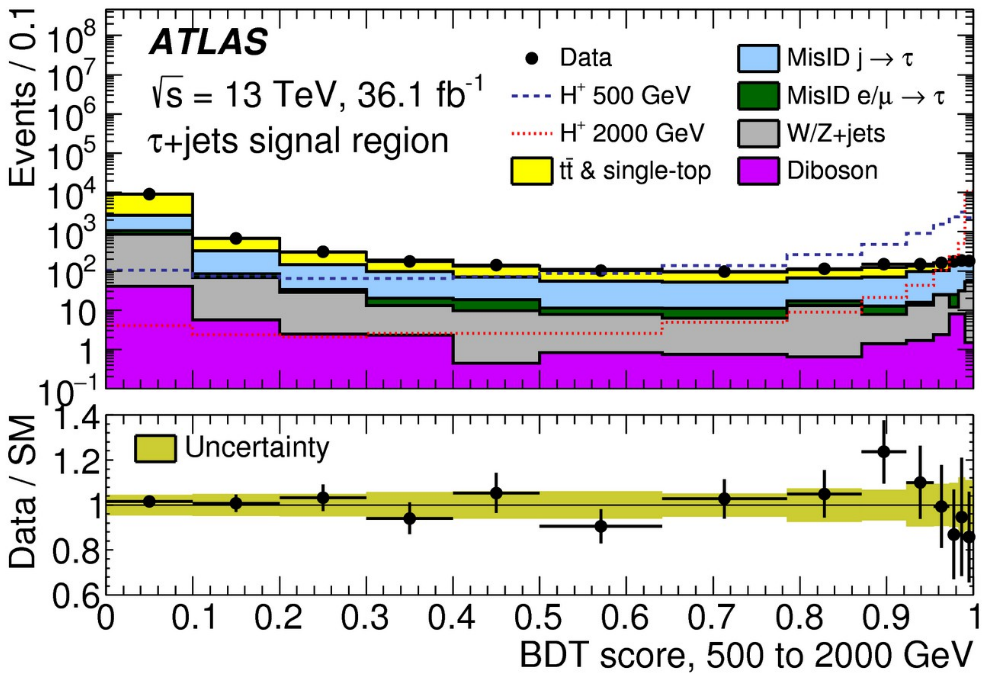




Charged Higgs Bosons: $H^+ \rightarrow \tau\nu$



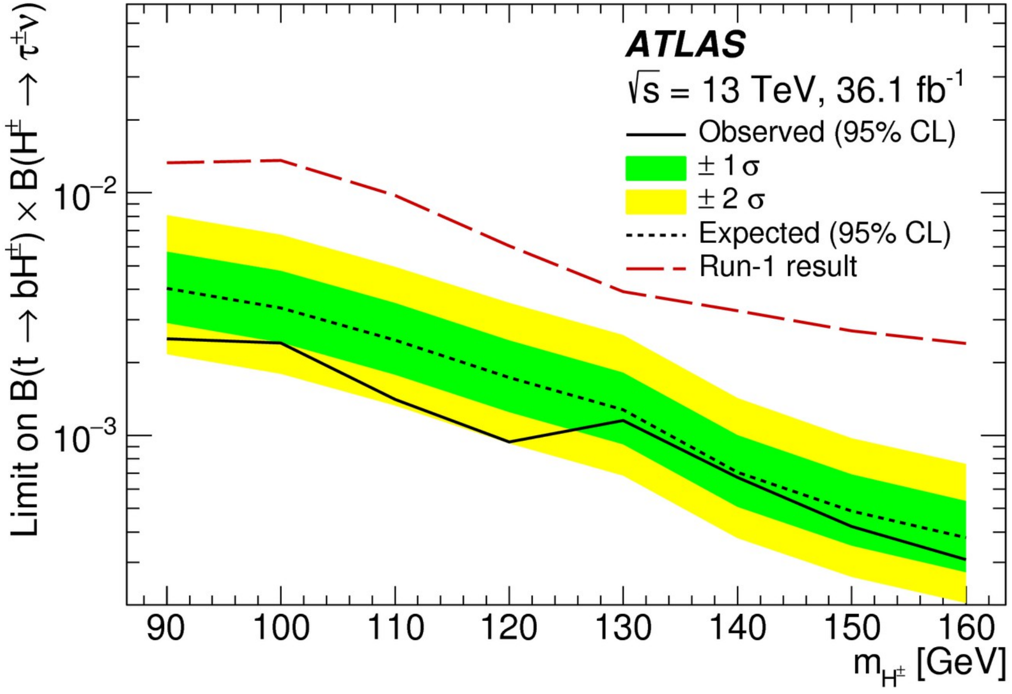




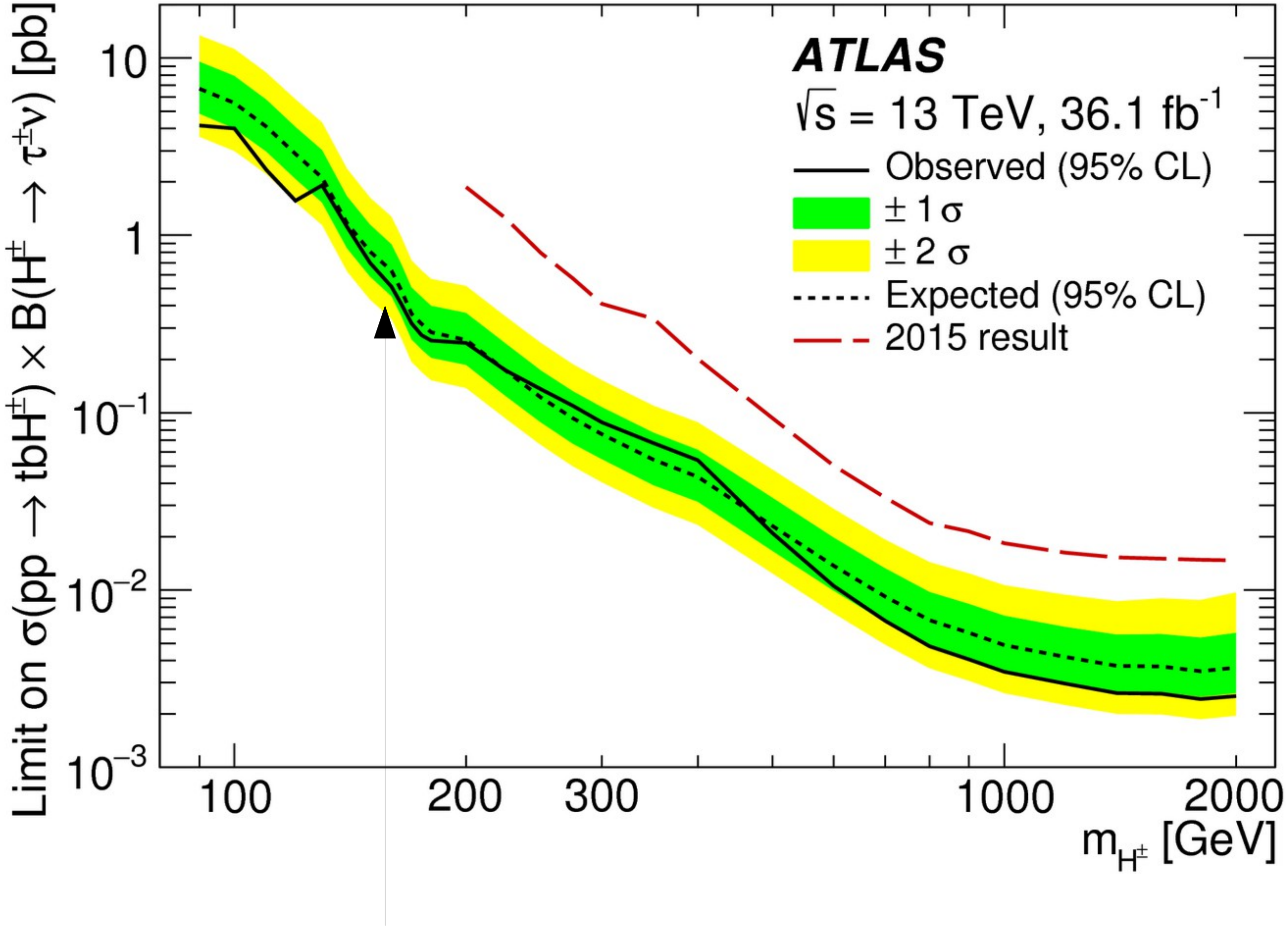
BDT trained separately in different $m(H^+)$ regions to exploit the changing kinematics as a function of $m(H^+)$

No cut on BDT applied, BDT shape is input to the fits

Charged Higgs Bosons: $H^+ \rightarrow \tau\nu$

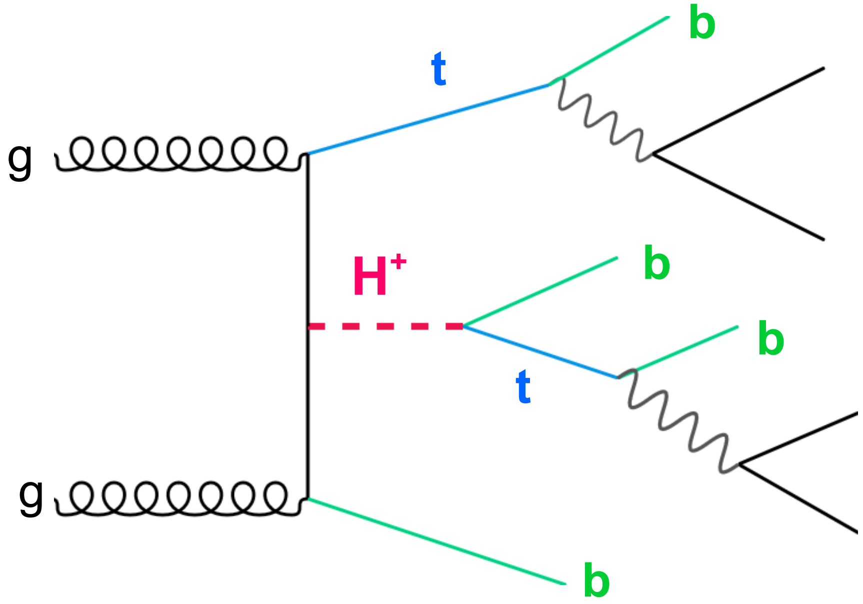


Huge improvement since run-1
from using MVA methods



No gap for m(H⁺)~m(t)
ATLAS explored this region for the first time ever

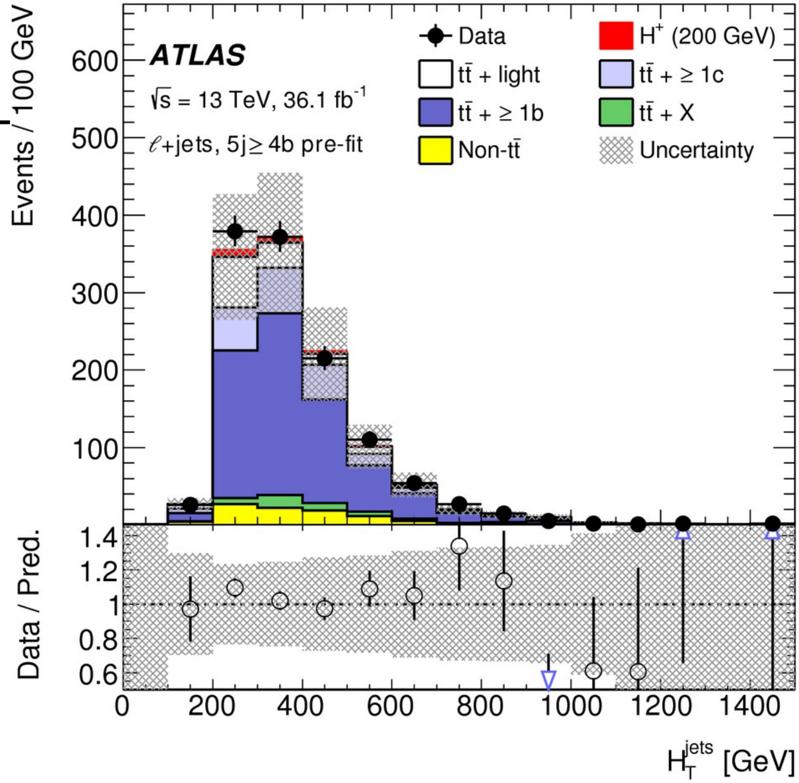
Charged Higgs Bosons: $H^+ \to tb$



Very difficult

Many (b-)jets

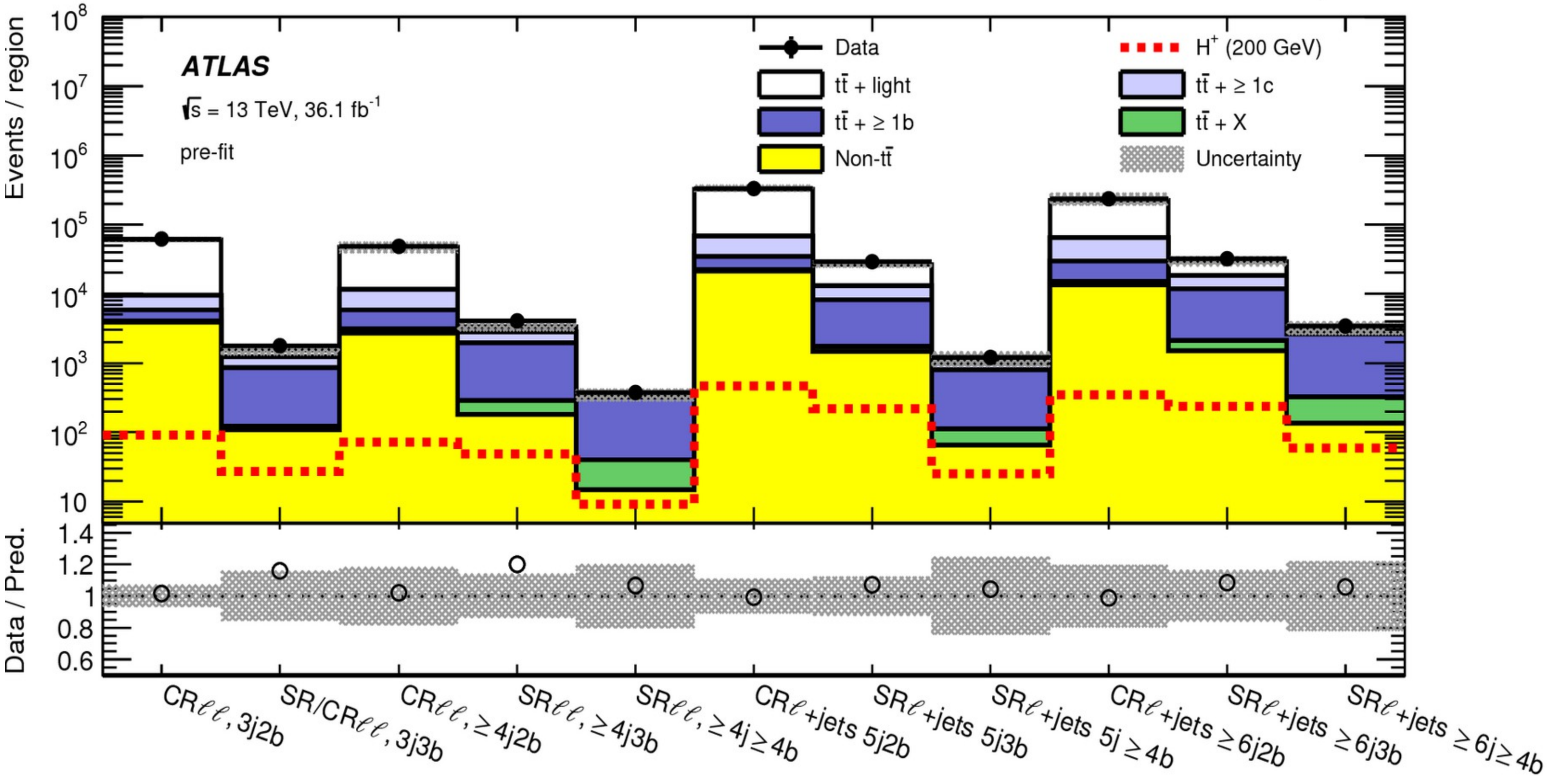
If H^+ mass is close to top mass, almost no discrimination



Explored in single-lepton and dilepton final states

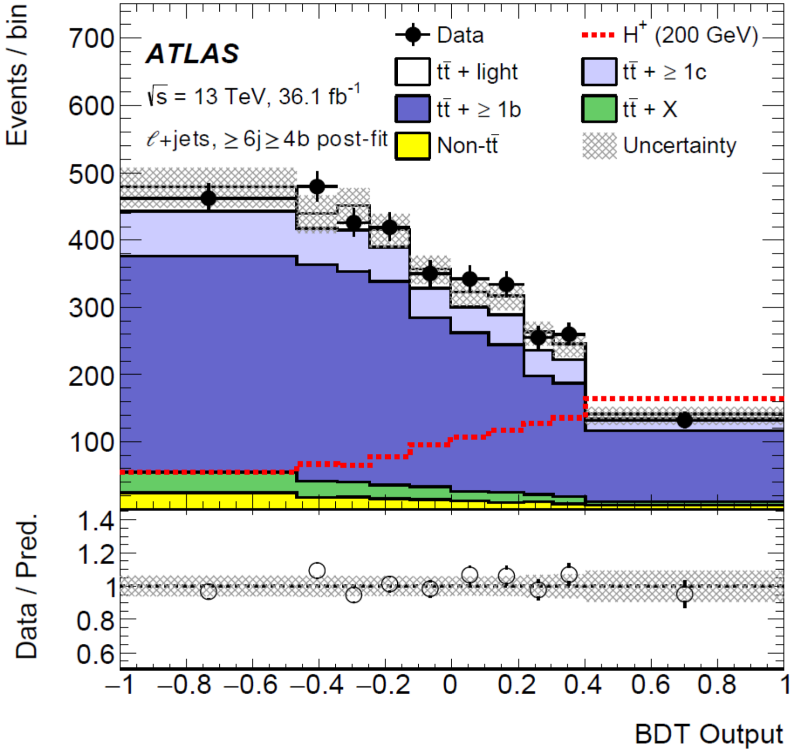
Events divided into many categories to increase sensitivity & background control

Backgrounds:
ttbar+light jets and ttbar+heavy quarks, modelled from simulation with huge uncertainties



Charged Higgs Bosons: $H^+ \to tb$

$p_{\mathrm{T}}(j_1)$
$m(b\text{-pair}^{\Delta R^{\min}})$
$p_{\mathrm{T}}(j_5)$
H_2
$\Delta R^{\mathrm{avg}}(b\text{-pair})$
$\Delta R(\ell, b\text{-pair}^{\Delta R^{\min}})$
$m(u\text{-pair}^{\Delta R^{\min}})$
$H_{\mathrm{T}}^{\mathrm{jets}}$
$m(b\text{-pair}^{p_{\mathrm{T}}^{\max}})$
$m^{\max}(b\text{-pair})$
$m^{\max}(j\text{-triplet})$
D

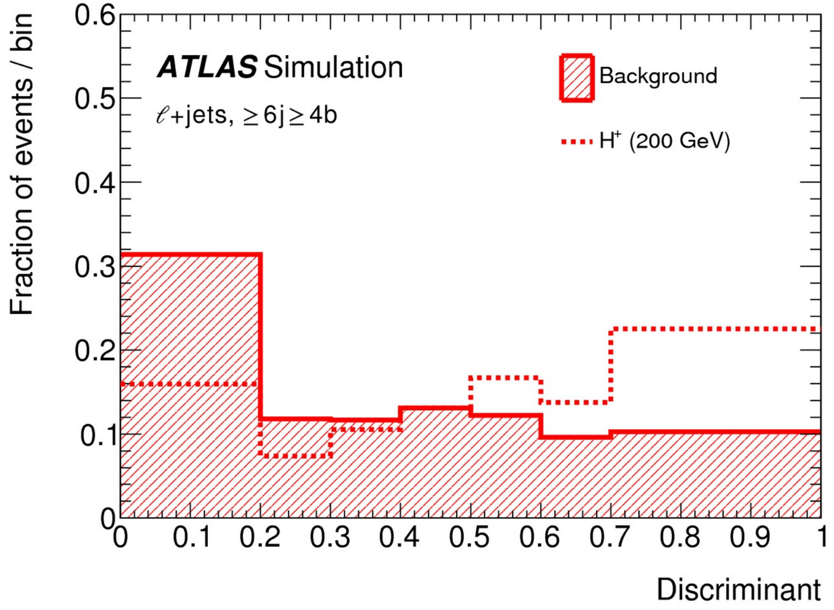


Very little discrimination at low mass (~200-300 GeV)

BDT trained for each mass point, in each SR

At low mass, kinematic discriminant added to training

$$D = P_{H^+}(\mathbf{x})/(P_{H^+}(\mathbf{x}) + P_{t\bar{t}}(\mathbf{x}))$$



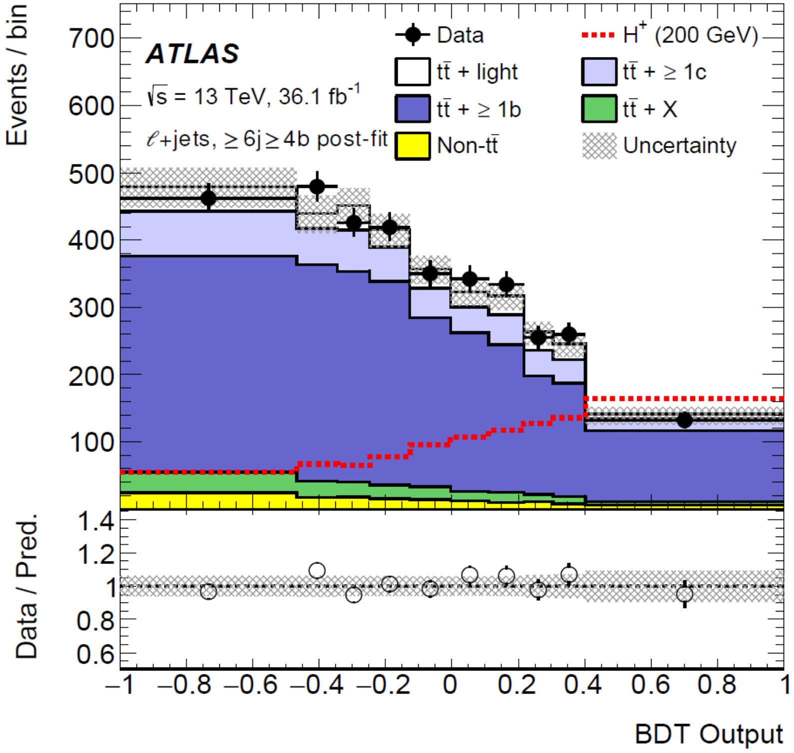
Discriminant D reflects the probability that an event is compatible with $H^+ \to tb$ or ttbar

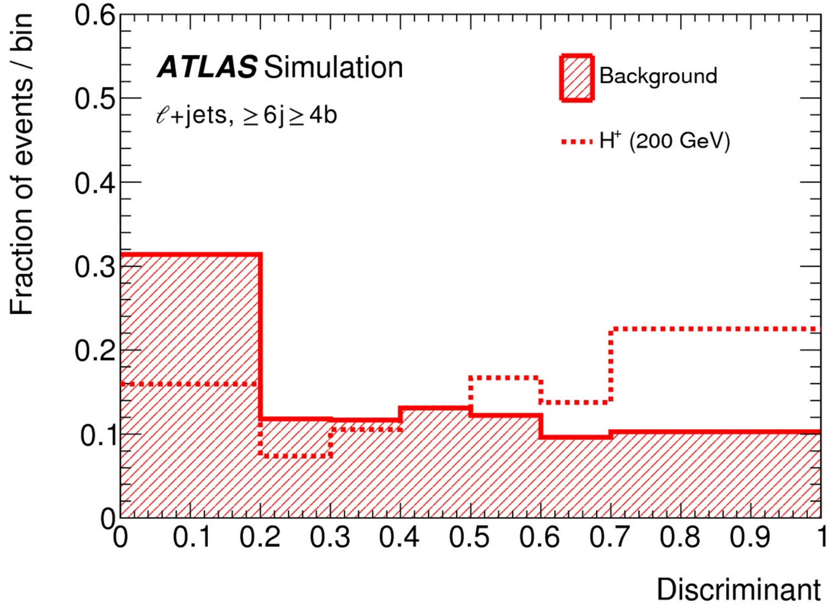
Inputs:

- mass of leptonic top
- mass of the hadronic W
- mass difference between leptonic top and hadronic W
- mass difference of the H^+ and one of the tops

Charged Higgs Bosons: $H^+ \rightarrow tb$

$p_T(j_1)$
$m(b\text{-pair}^{\Delta R^{\min}})$
$p_T(j_5)$
H_2
$\Delta R^{\text{avg}}(b\text{-pair})$
$\Delta R(\ell, b\text{-pair}^{\Delta R^{\min}})$
$m(u\text{-pair}^{\Delta R^{\min}})$
H_T^{jets}
$m(b\text{-pair}^{p_T^{\max}})$
$m^{\max}(b\text{-pair})$
$m^{\max}(j\text{-triplet})$
D





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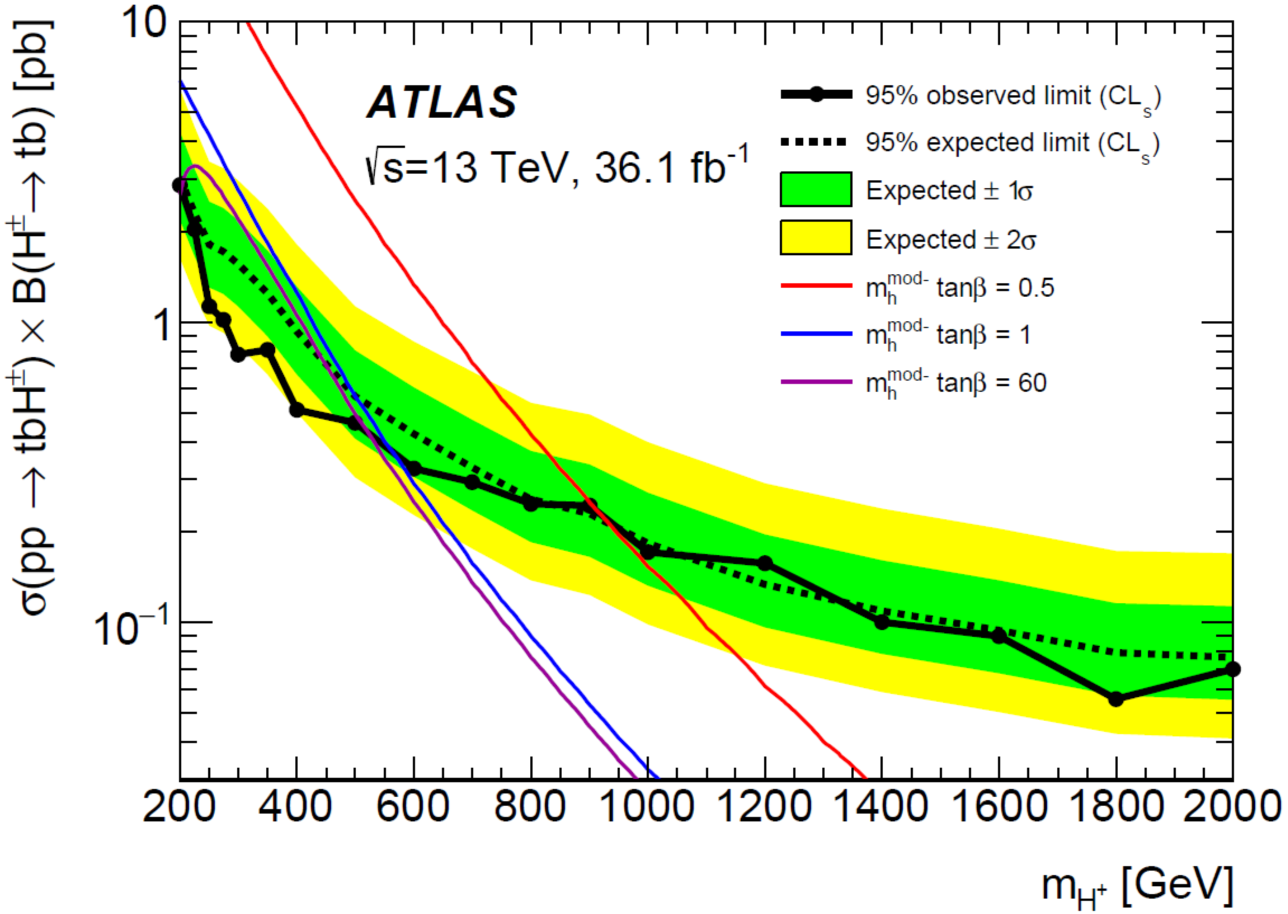
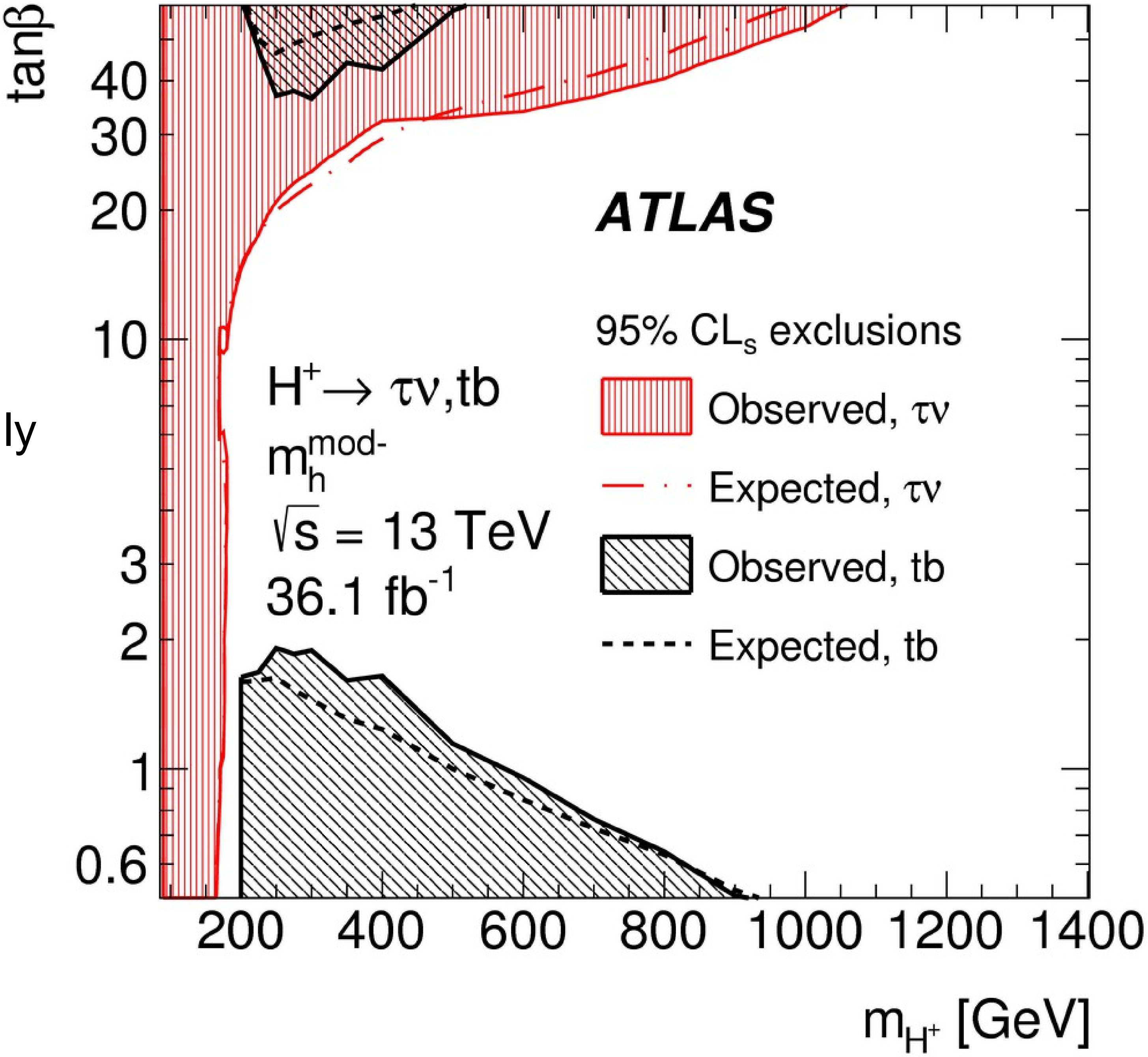


Charged Higgs Bosons: MSSM Interpretation

Low mass fully excluded!

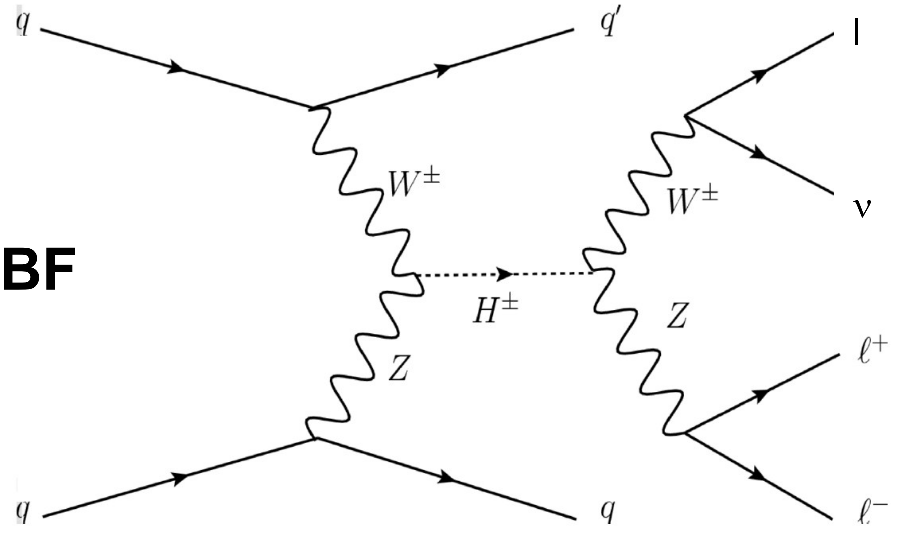


$H^+ \to tb$: uniquely sensitive to low and high tanβ

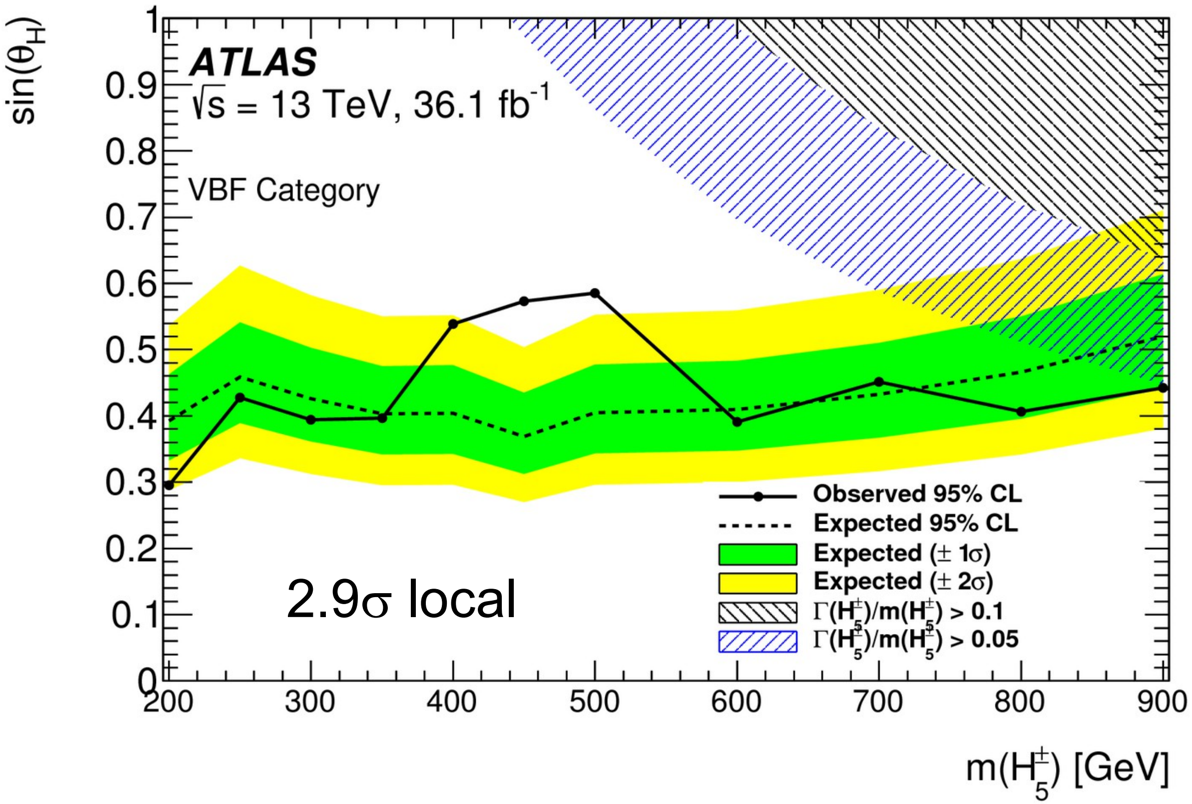
Overlap at high tanβ motivates a combination

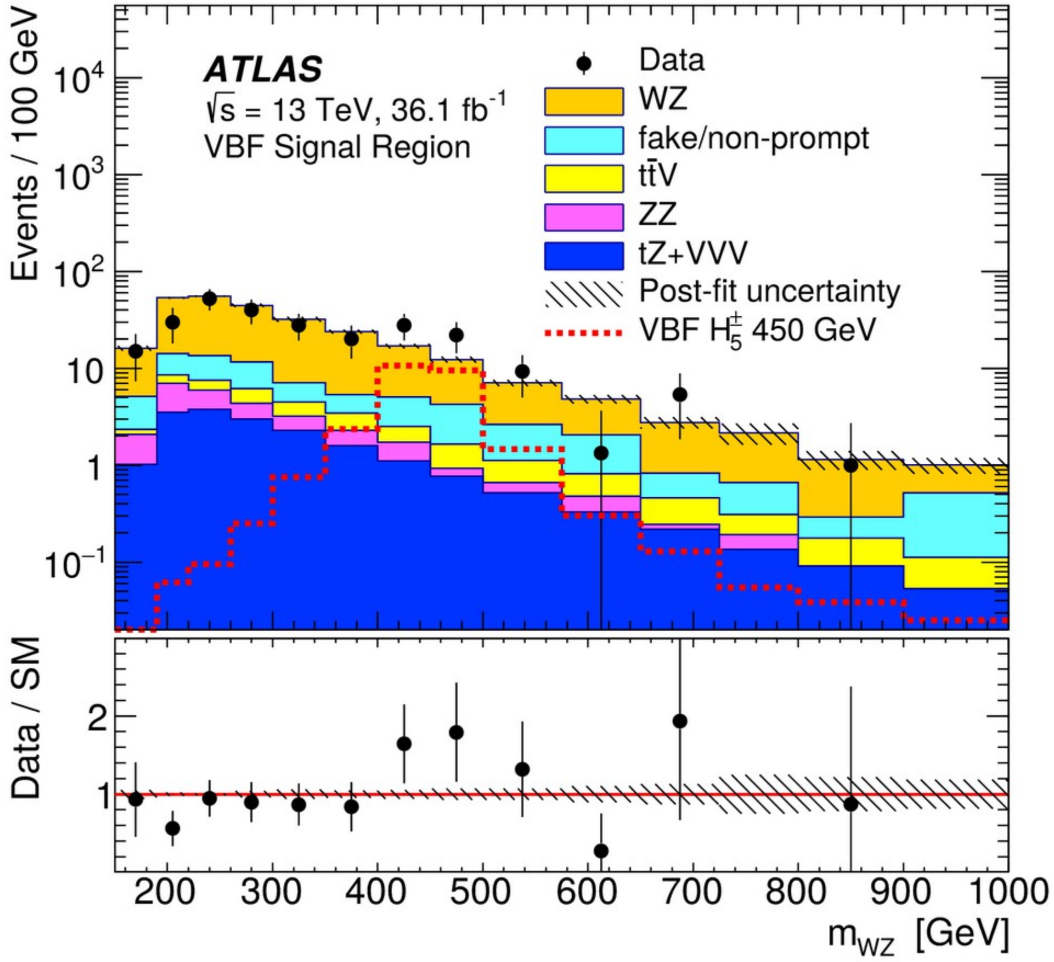
Charged Higgs Bosons in Triplett Models

VBF



- 3 leptons, MET > 25 GeV, b-jet veto
- m(WZ) reconstructed calculated with the solution for neutrino p_z that gives W mass
- VBF selection on jets (m_{jj}>500 GeV, $|\Delta\eta_{jj}|$>3.5)
- Georgi Machacek model Nucl. Phys. B 262 (1985) 463



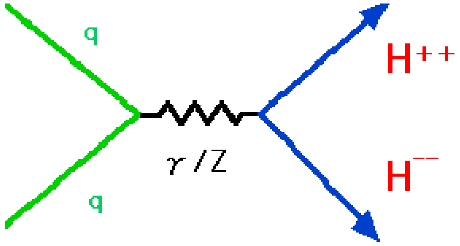


Doubly Charged Higgs Bosons $H^{++} \to W^+W^+$

Theory: arXiv:1105.1925

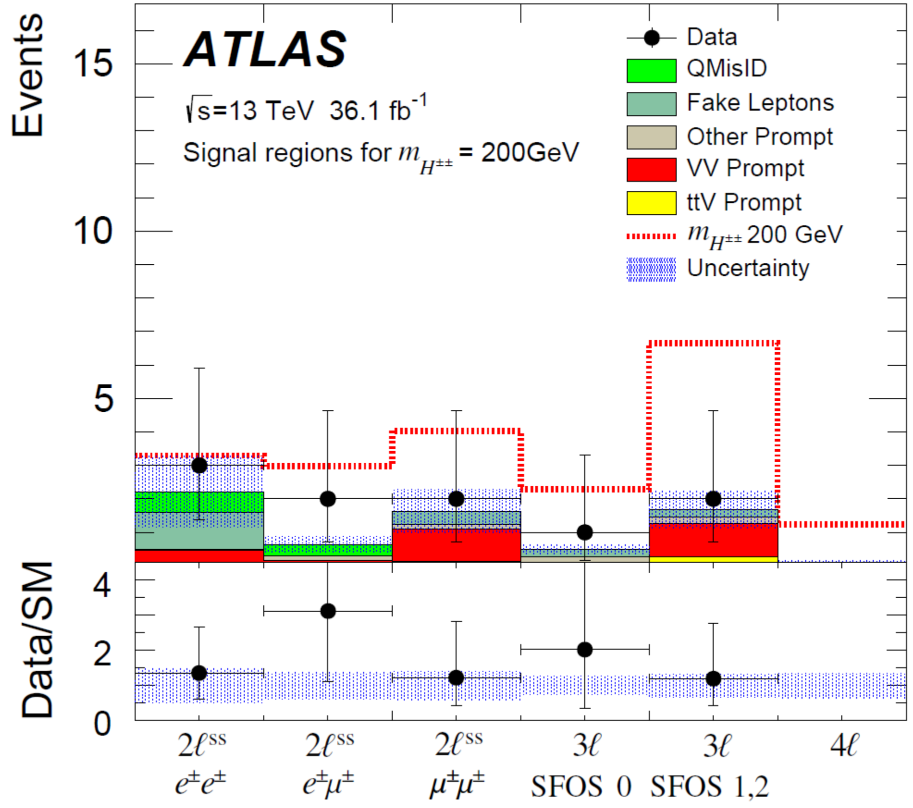
$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \quad \text{and} \quad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

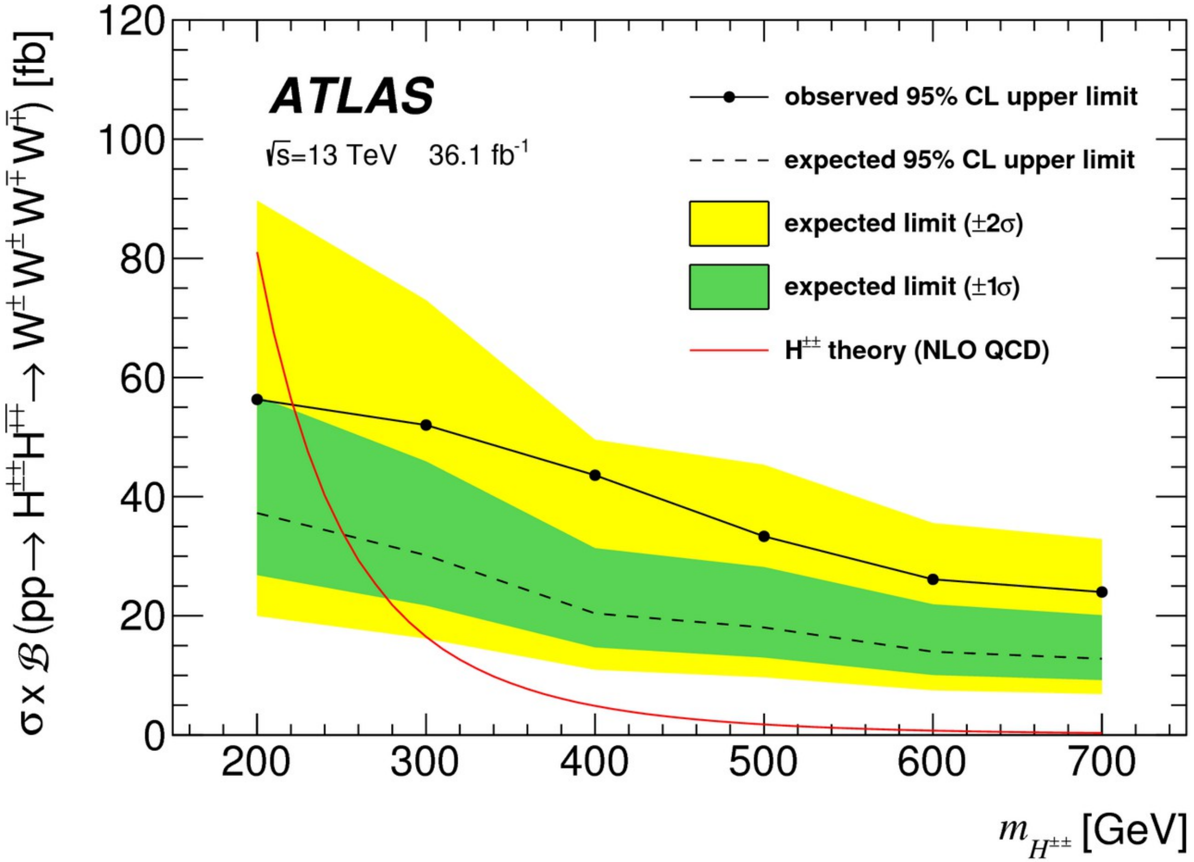
SM Higgs Doublet and additional hypercharge Y=2 scalar triplet
→ 7 Higgs bosons ($H^{\pm\pm}$, $H^{\pm}$, A, H, h), h is SM like
→ Triplet conveniently provides non-zero neutrino masses (type-II seesaw mechanism)



3 catgeories: 2l (same-sign), 3l, 4l   MET > 70 GeV (30 GeV) for 2l (3l, 4l)

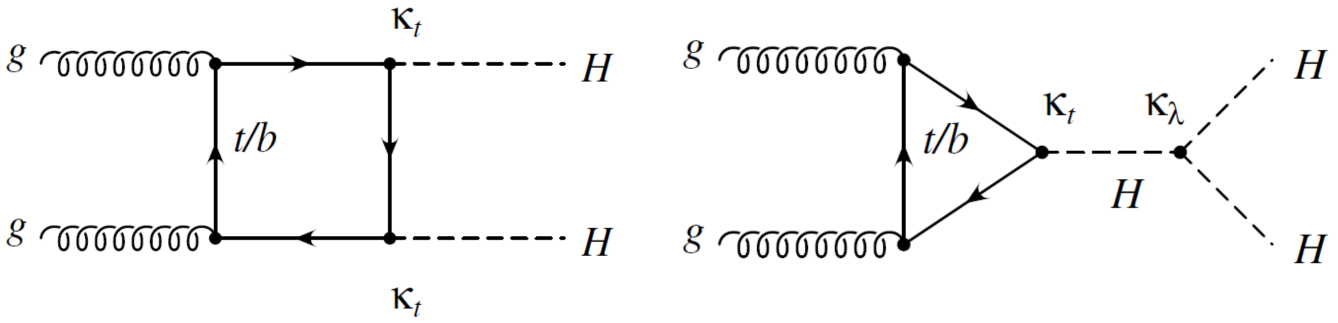
Cut-based selection, optimized with TMVA





Di-Higgs Searches

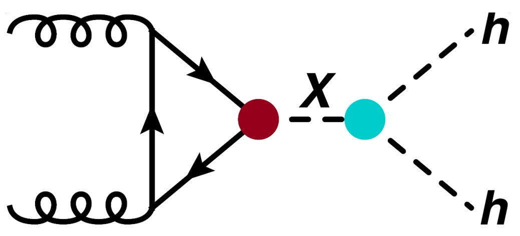
Non-resonant



SM ggF → HH cross section (κ_λ=1): 33.4 fb

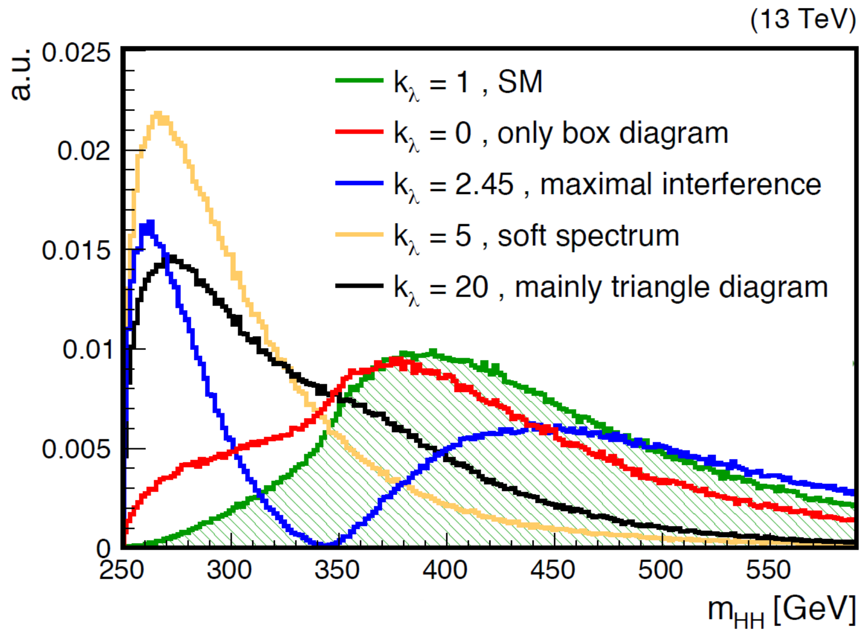
SM ggF → H cross section: 48.7 pb

Resonant

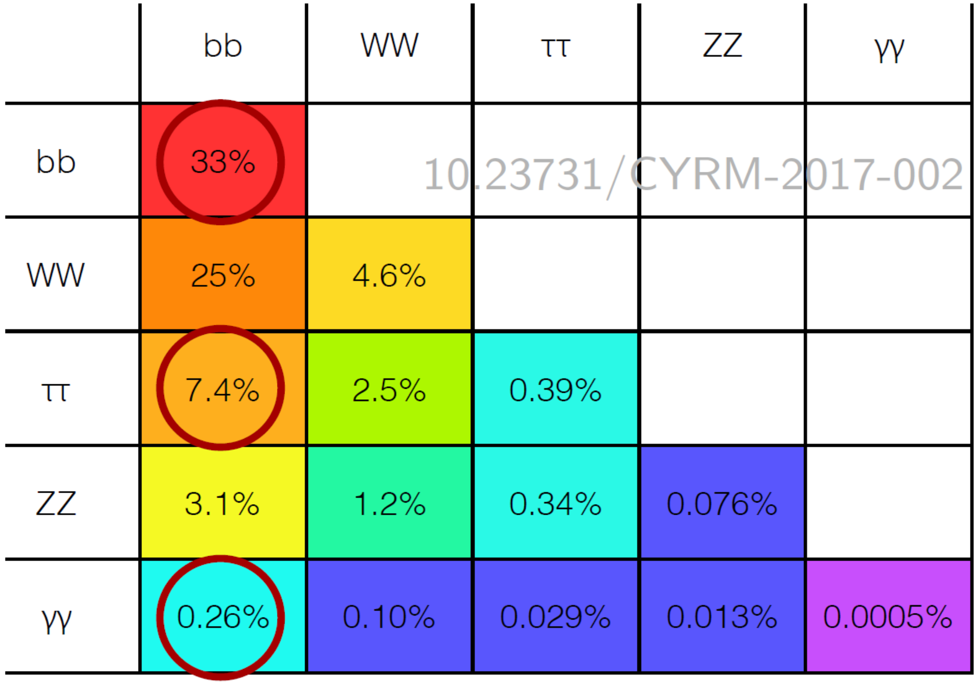


X can be a heavy Higgs (spin-0)
or a Graviton (spin-2)

Coupling variations lead to different shape and rates:



HH branching fractions:

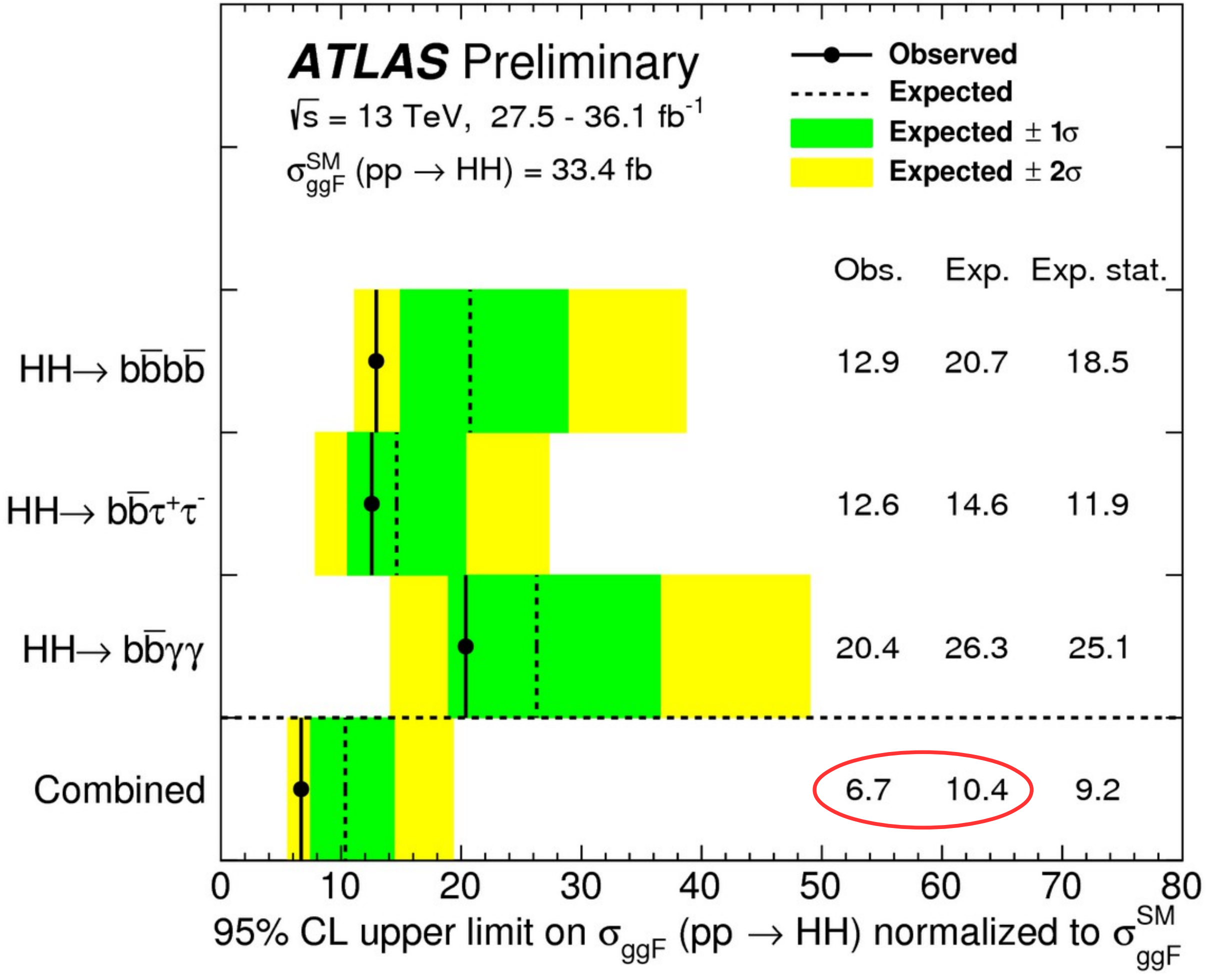


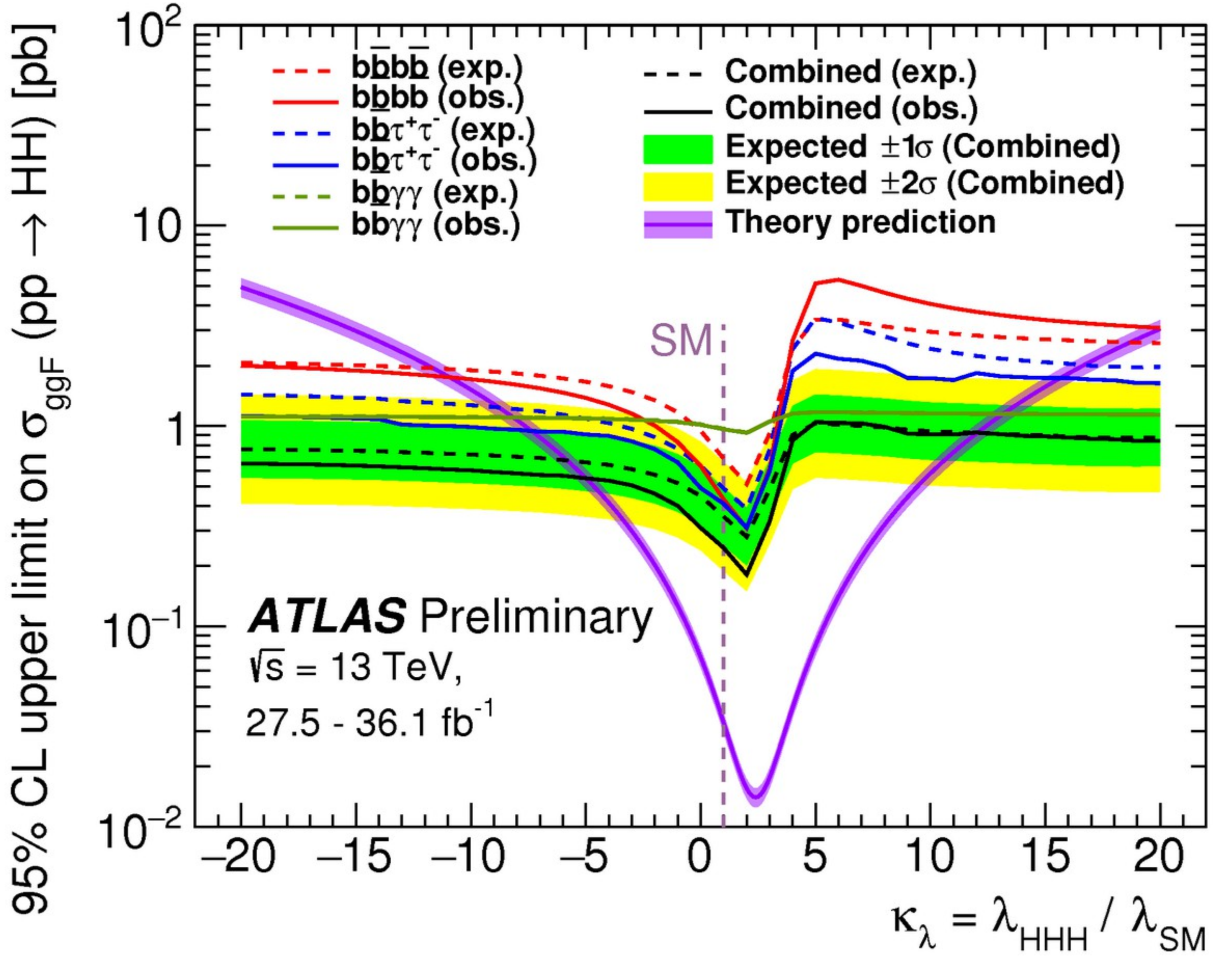
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

10.23731/CYRM-2017-002

Di-Higgs Searches: Non-resonant Results

ATLAS sets worlds-best limit on non-resonant HH production:



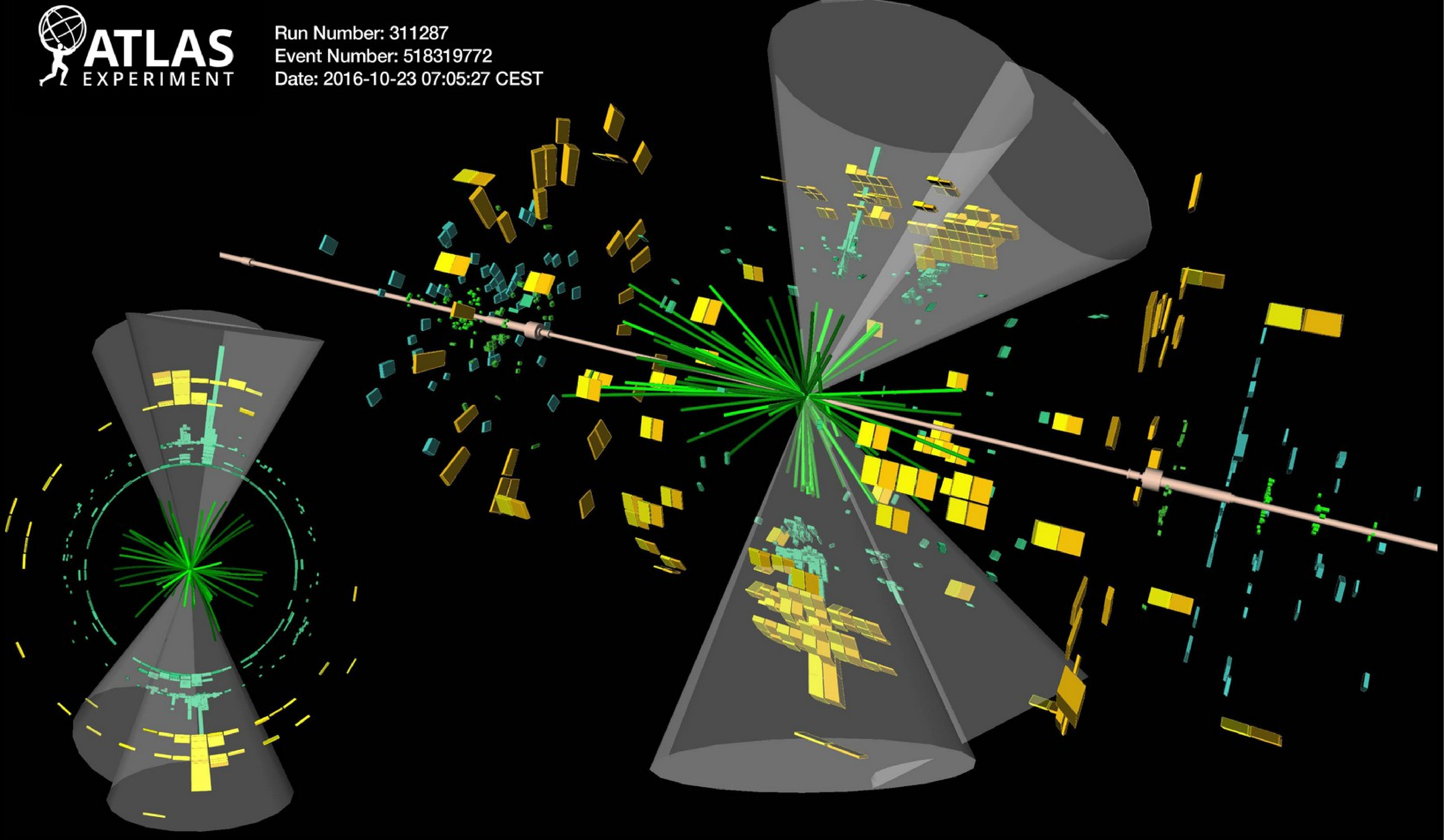


$$-5.0 < \kappa_\lambda < 12.1 \; (-5.8 < \kappa_\lambda < 12.0)$$

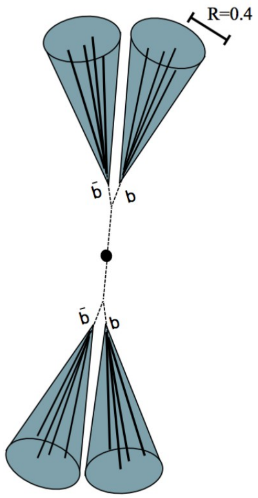
obs (exp)

CMS: **22.2 (obs), 12.8 (exp)**
$-7.1 < \kappa_\lambda < 13.6$ (exp)

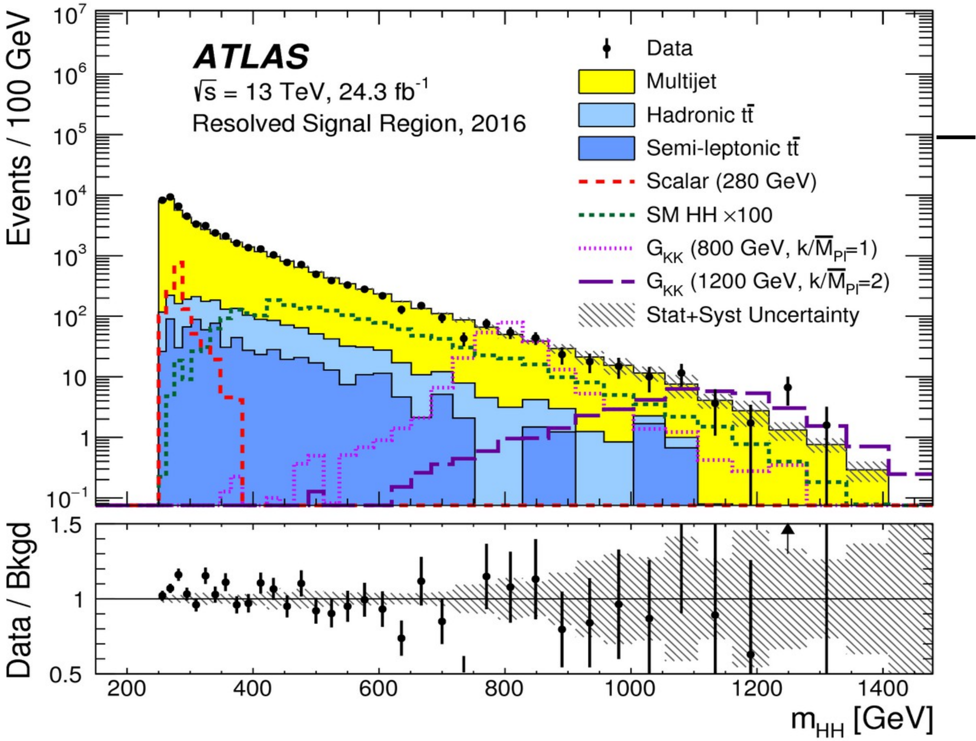
HH → 4b candidate

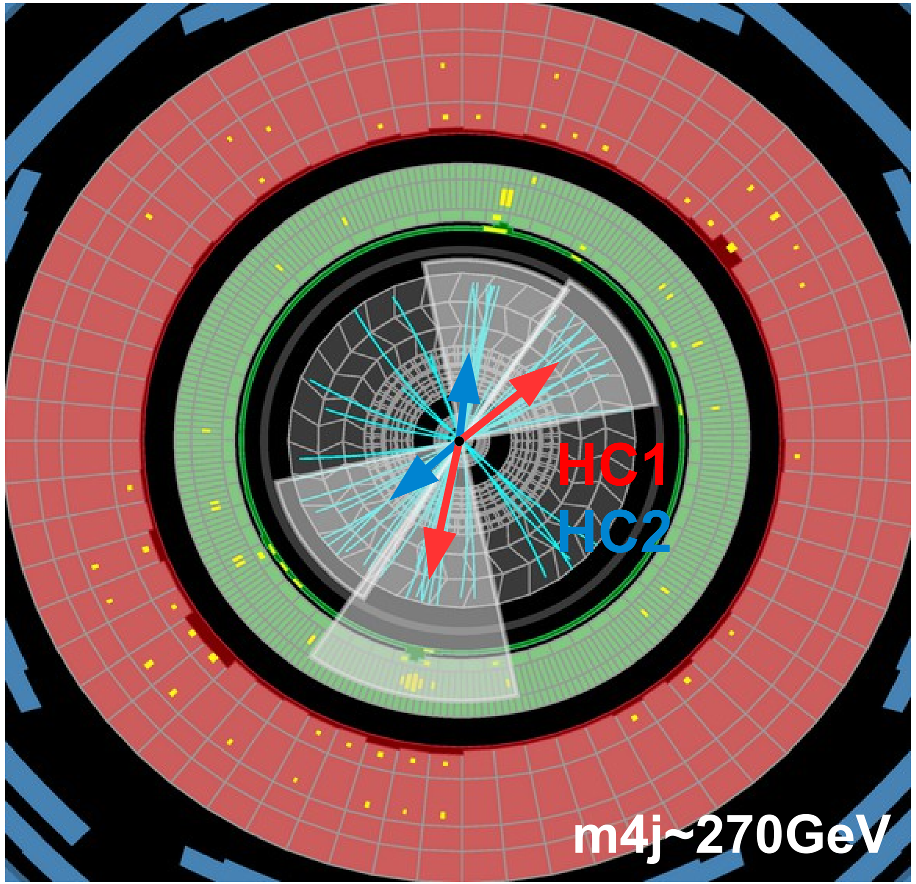


Di-Higgs Searches: HH → 4b

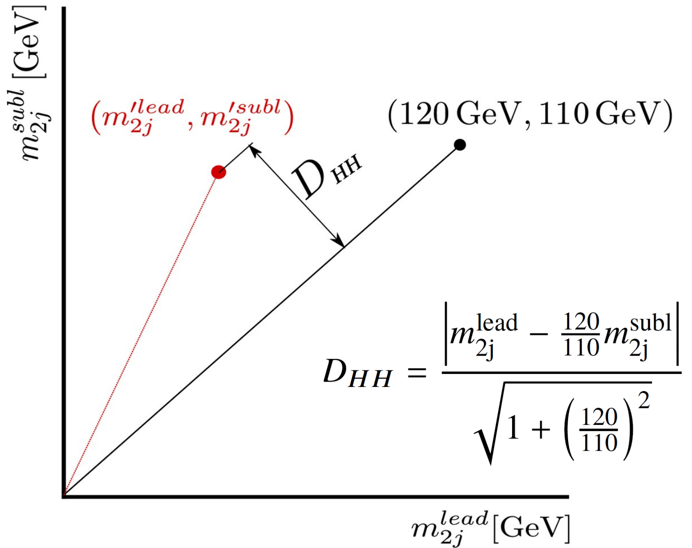


- Trigger: one or two jets passing online b-tagging (plus additional non b-tagged jets)
- Select events with 4 b-tagged jets (R=0.4), p_T> 40 GeV
- Not easy: Pairing the b-jets to Higgs candidates, use dijet mass to solve combinatorics



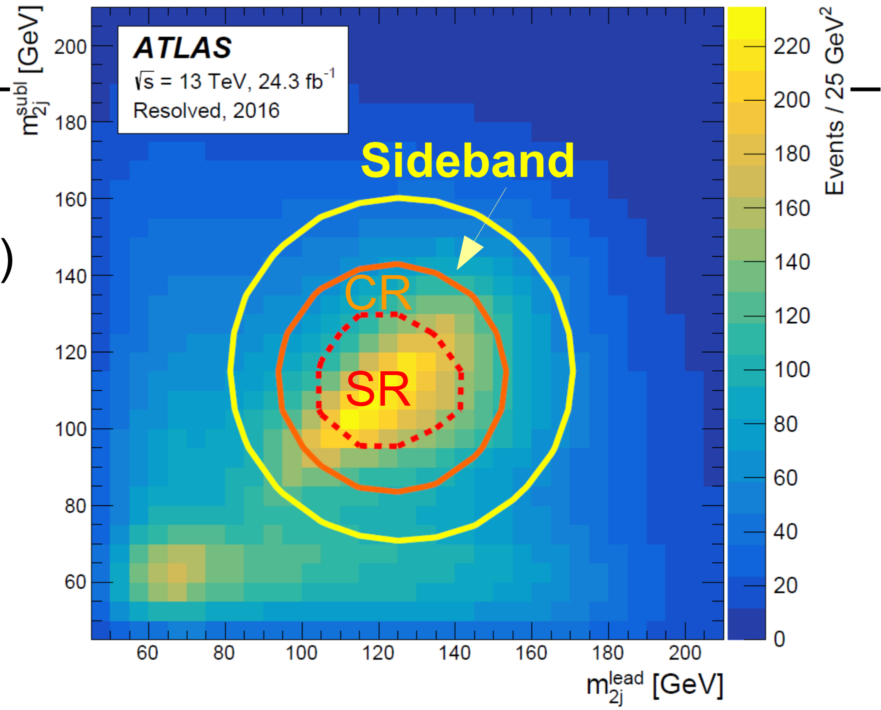


- Expected: decay of two particles of equal mass
- Semi-leptonic B-decays lead to energy loss → mass equality needs modification of expected masses (120 GeV, 110 GeV)
- D_{HH} quantifies the distance of the masses from the line connecting (0,0) and (120, 110) GeV
- Pairing that minimizes D_{HH} is chosen
- In simulation, this leads to at least 90% correct pairings



$$D_{HH} = \frac{\left| m_{2j}^{\text{lead}} - \frac{120}{110} m_{2j}^{\text{subl}} \right|}{\sqrt{1 + \left(\frac{120}{110}\right)^2}}$$

Di-Higgs Searches: HH → 4b



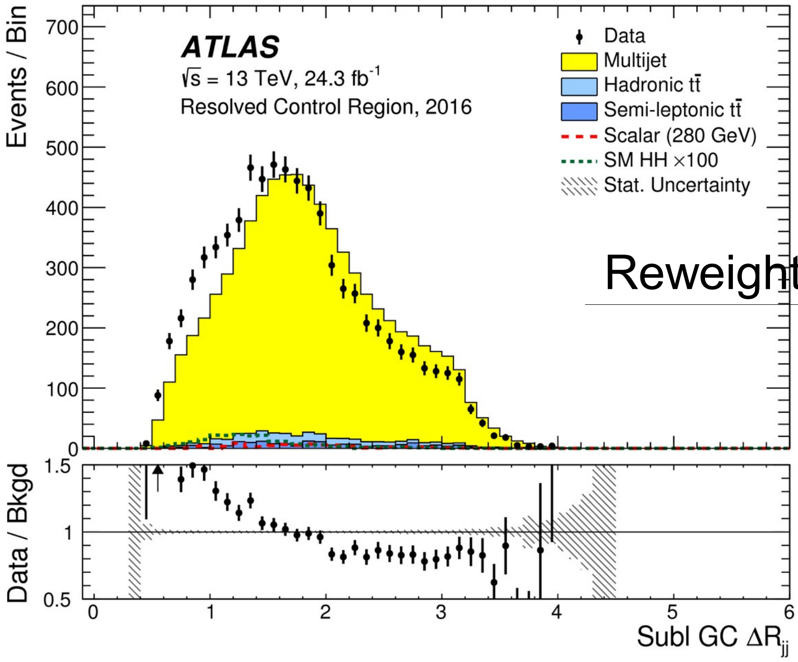
Data-driven estimation of the background model:

- Selection of the two-tag sample (contains ≥4 jets, exactly 2 of them b-tagged)

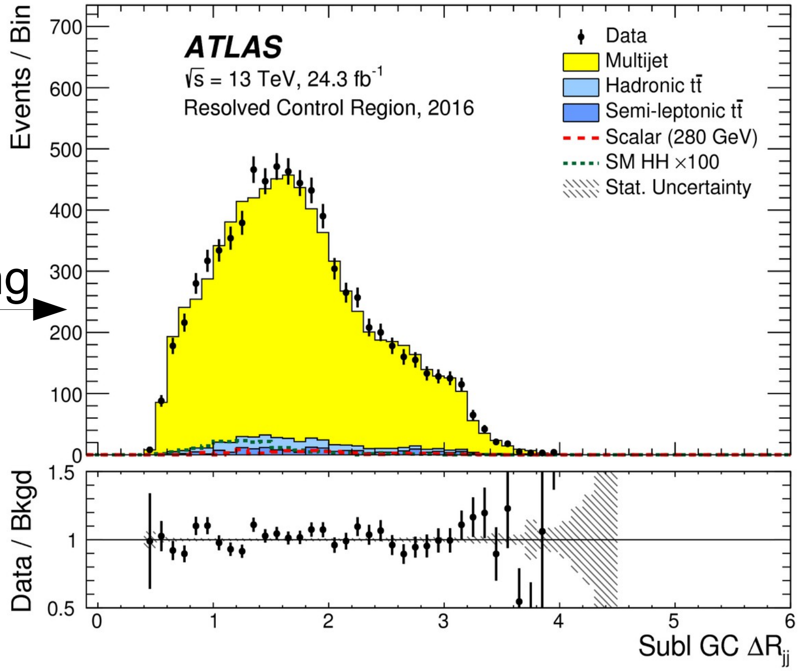
- Application of two weights (combinatorial, kinematic), obtained from the sideband, to make the 2b data look more like 4b data

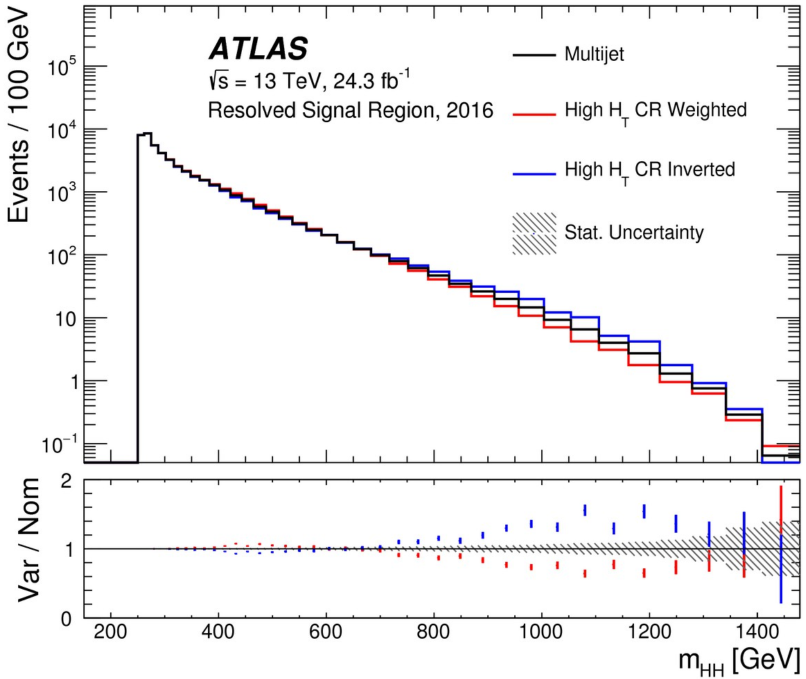
- Determining the normalization of multijet and ttbar by fitting event yields in background-enriched control regions

- An alternative background model is derived from the control region (CR), is used for validation and to derive a systematic uncertainty

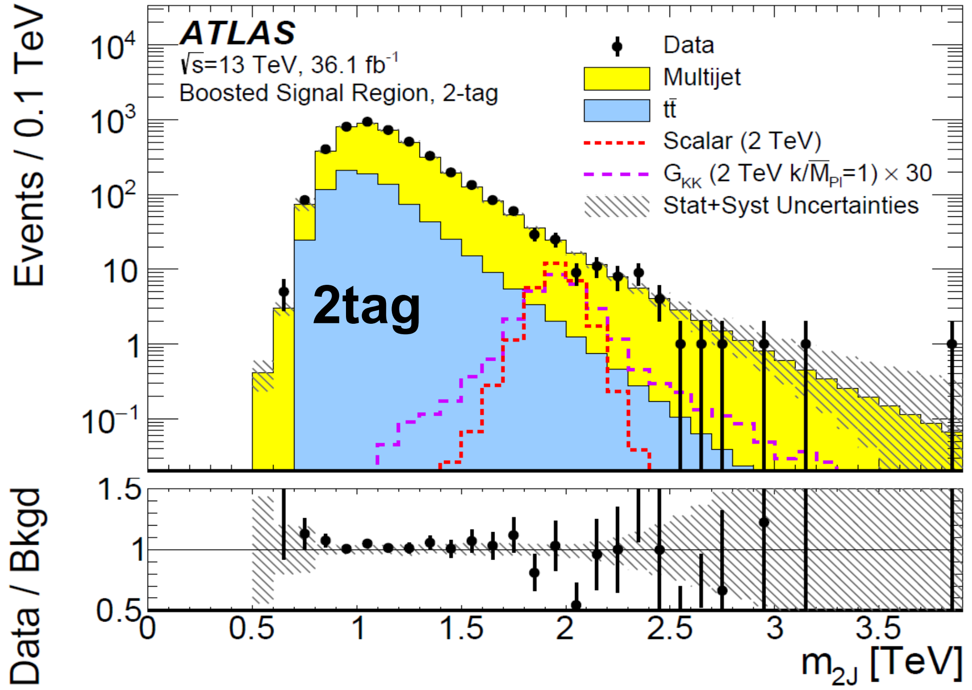


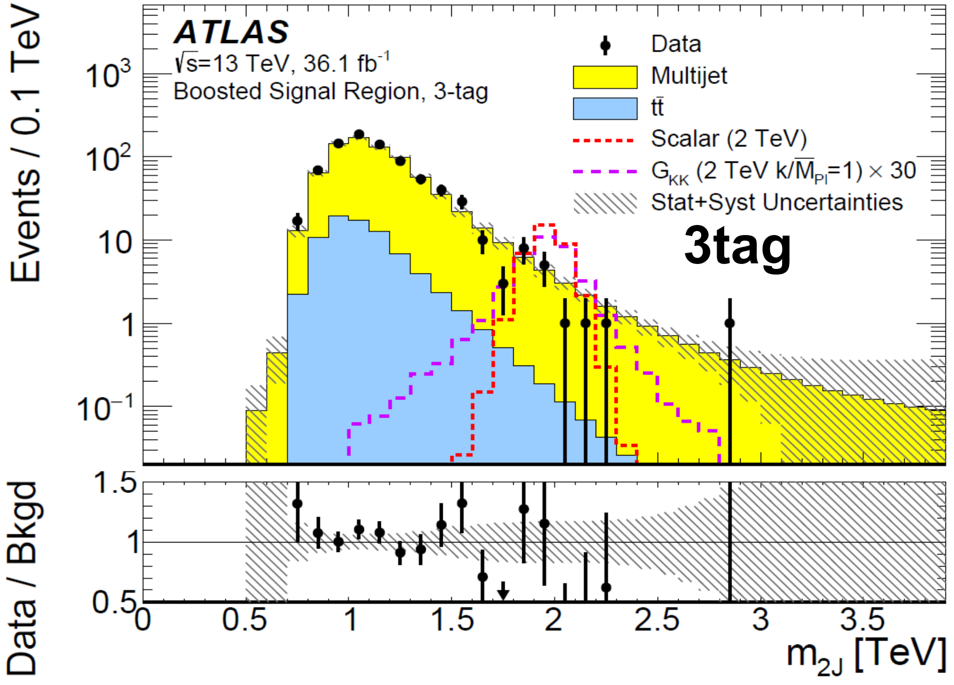
Reweighting

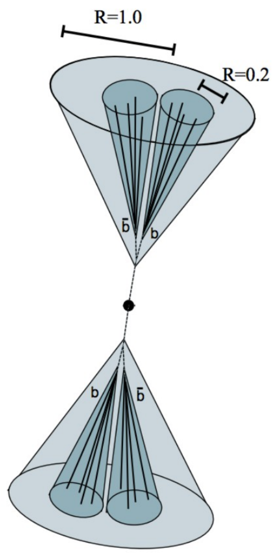


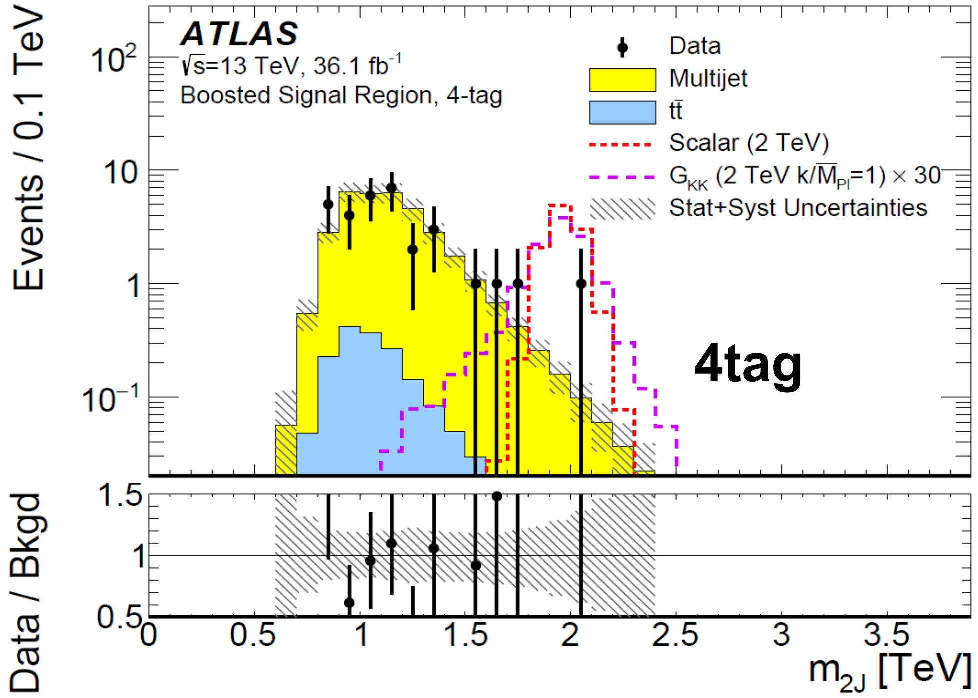


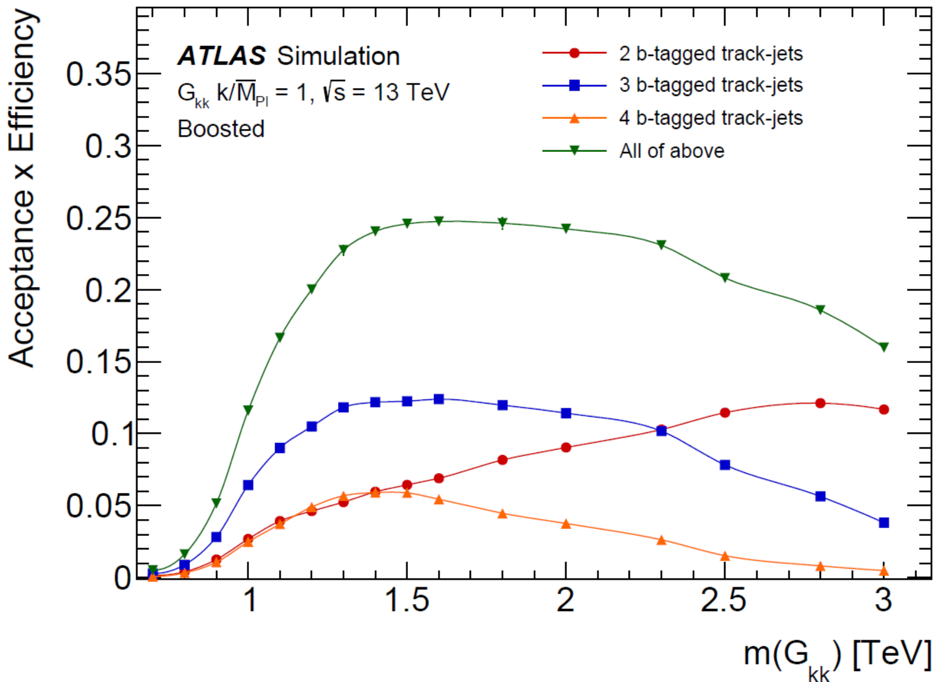
Di-Higgs Searches: HH → 4b (Boosted)

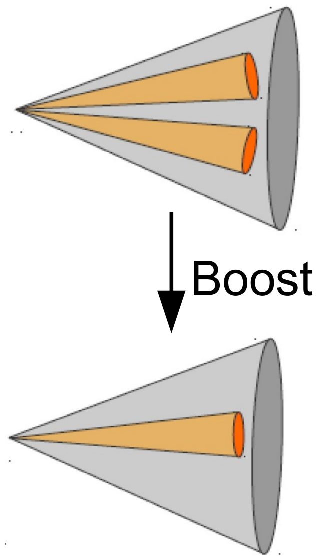






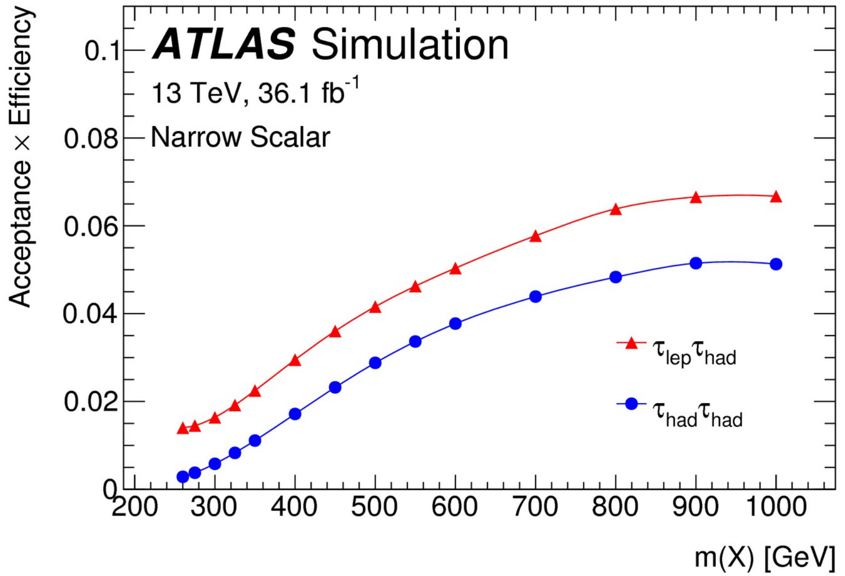




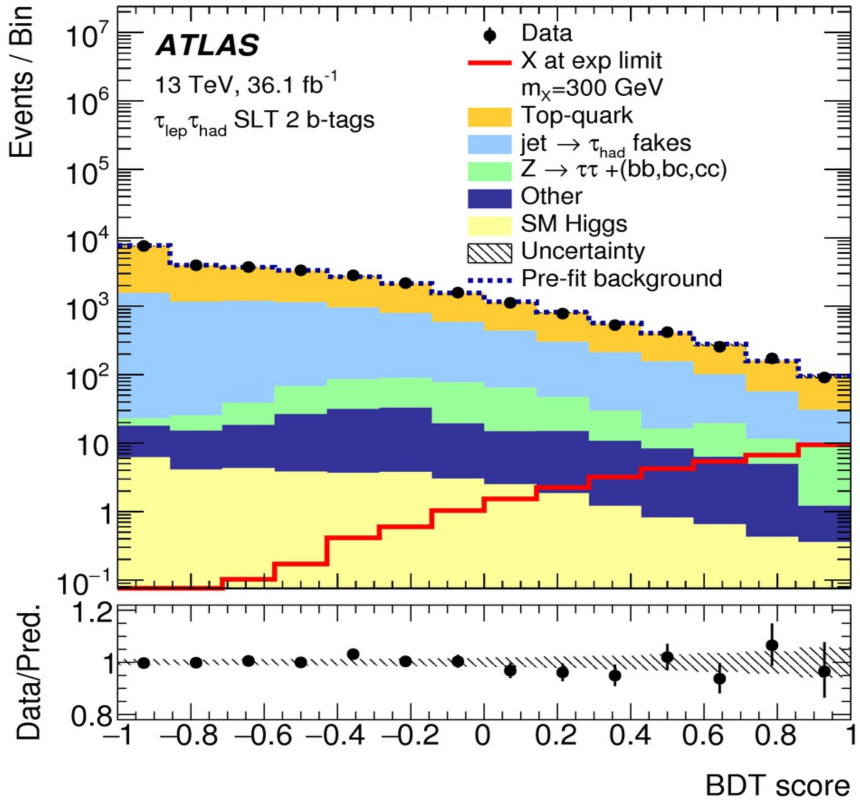


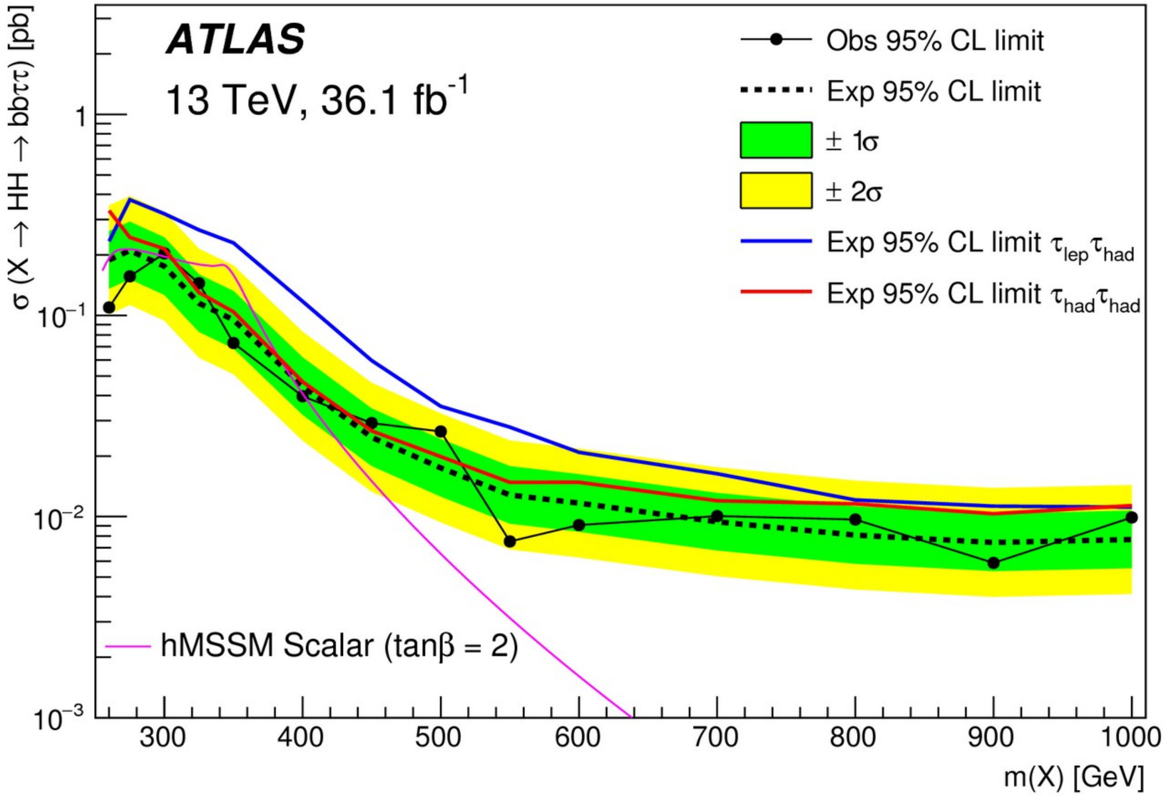
Di-Higgs Searches: HH → $bb\tau\tau$

- ATLAS' best HH channel for non-resonant
- 3 categories: Had-had, lep-had (single lepton trigger), lep-had (lepton+tau trigger)
- 2 bjets required in the SR, 0 and 1 b-tag regions used for validation
- BDT trained in each category, for each mass hypothesis
- Fits performed to the BDT output

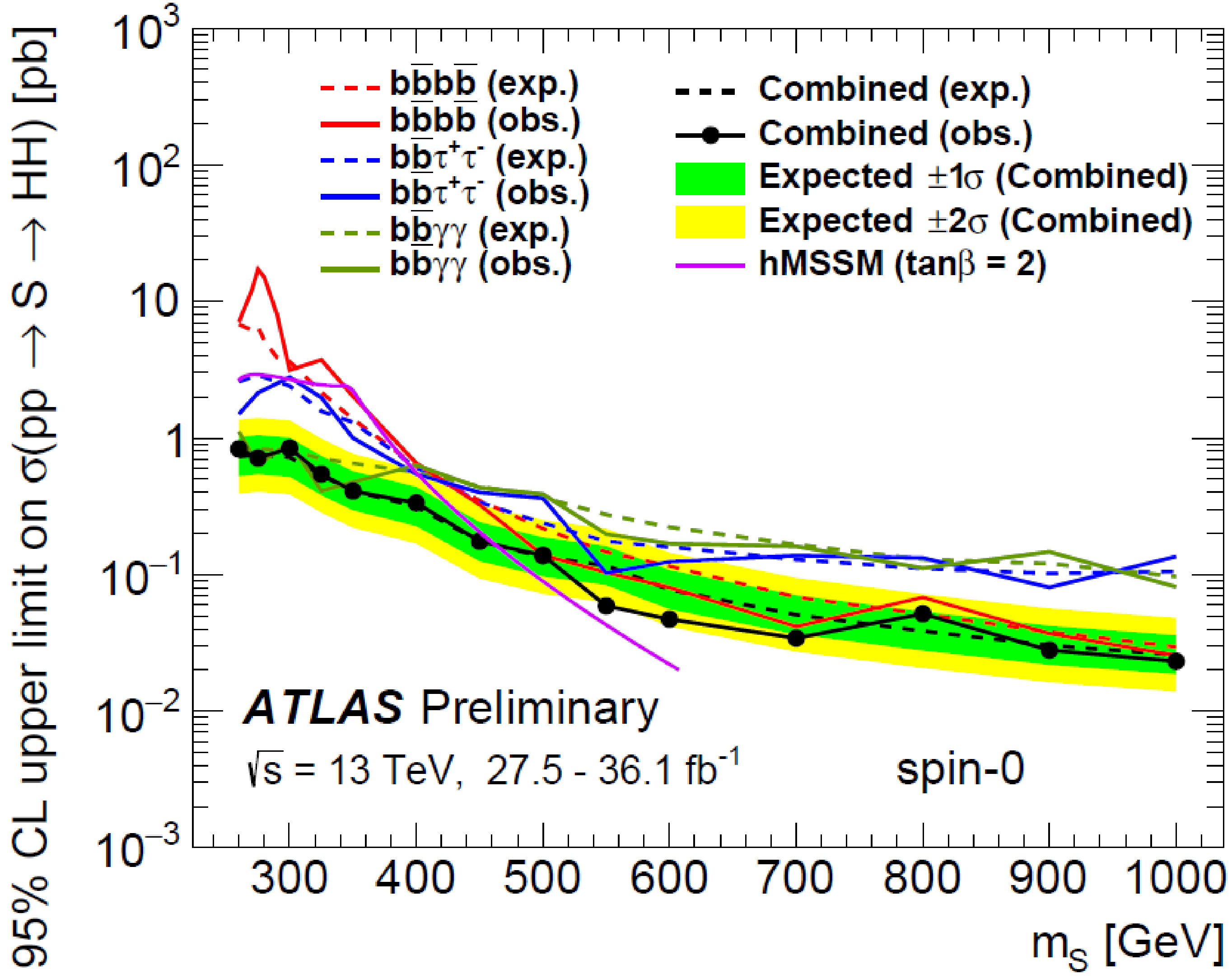


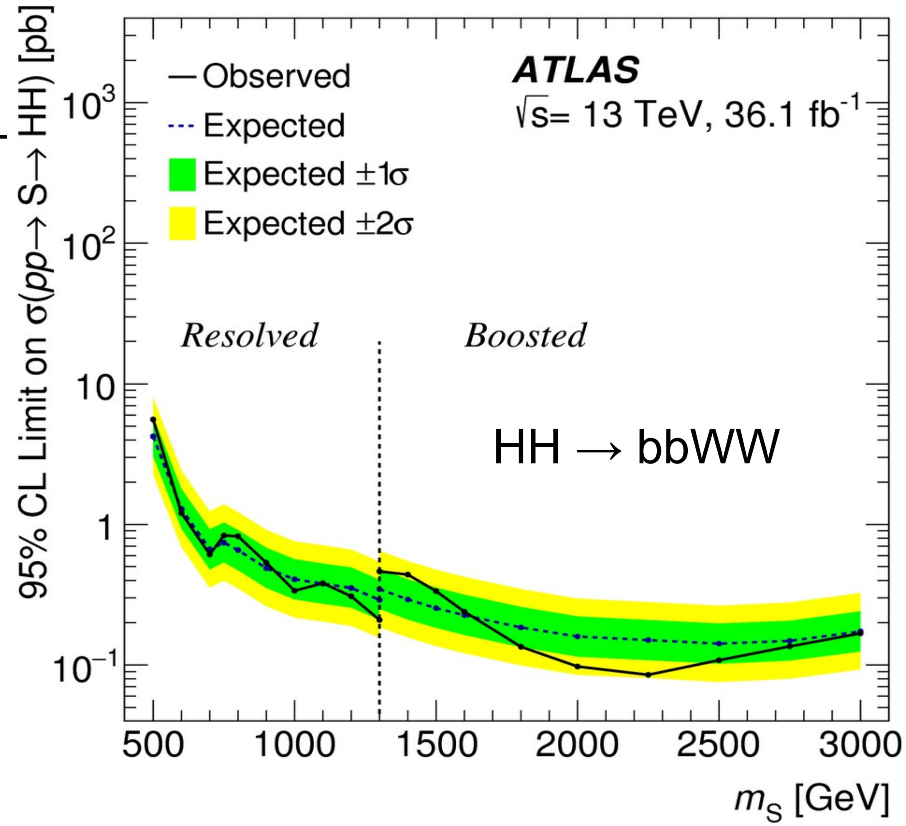
Variable
m_{HH}
$m_{\tau\tau}^{\text{MMC}}$
m_{bb}
$\Delta R(\tau,\tau)$
$\Delta R(b,b)$
$E_{\text{T}}^{\text{miss}}$
$E_{\text{T}}^{\text{miss}}$ ϕ centrality
m_{T}^{W}
$\Delta\phi(H,H)$
$\Delta p_{\text{T}}(\text{lep},\tau_{\text{had-vis}})$
Sub-leading b-jet p_{T}



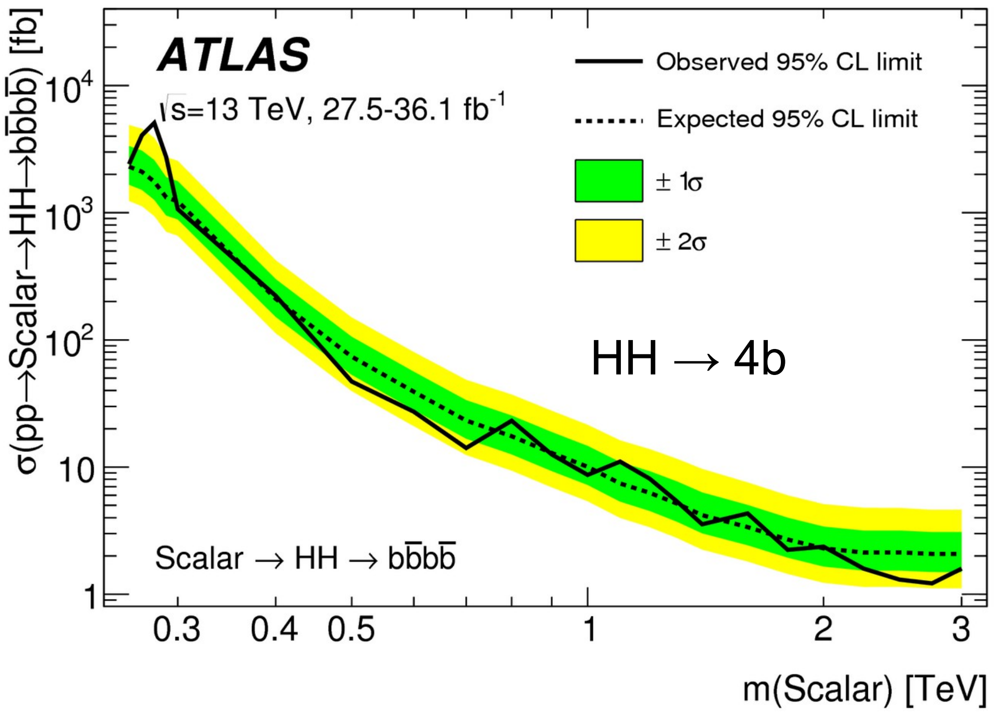


Di-Higgs: Resonant results

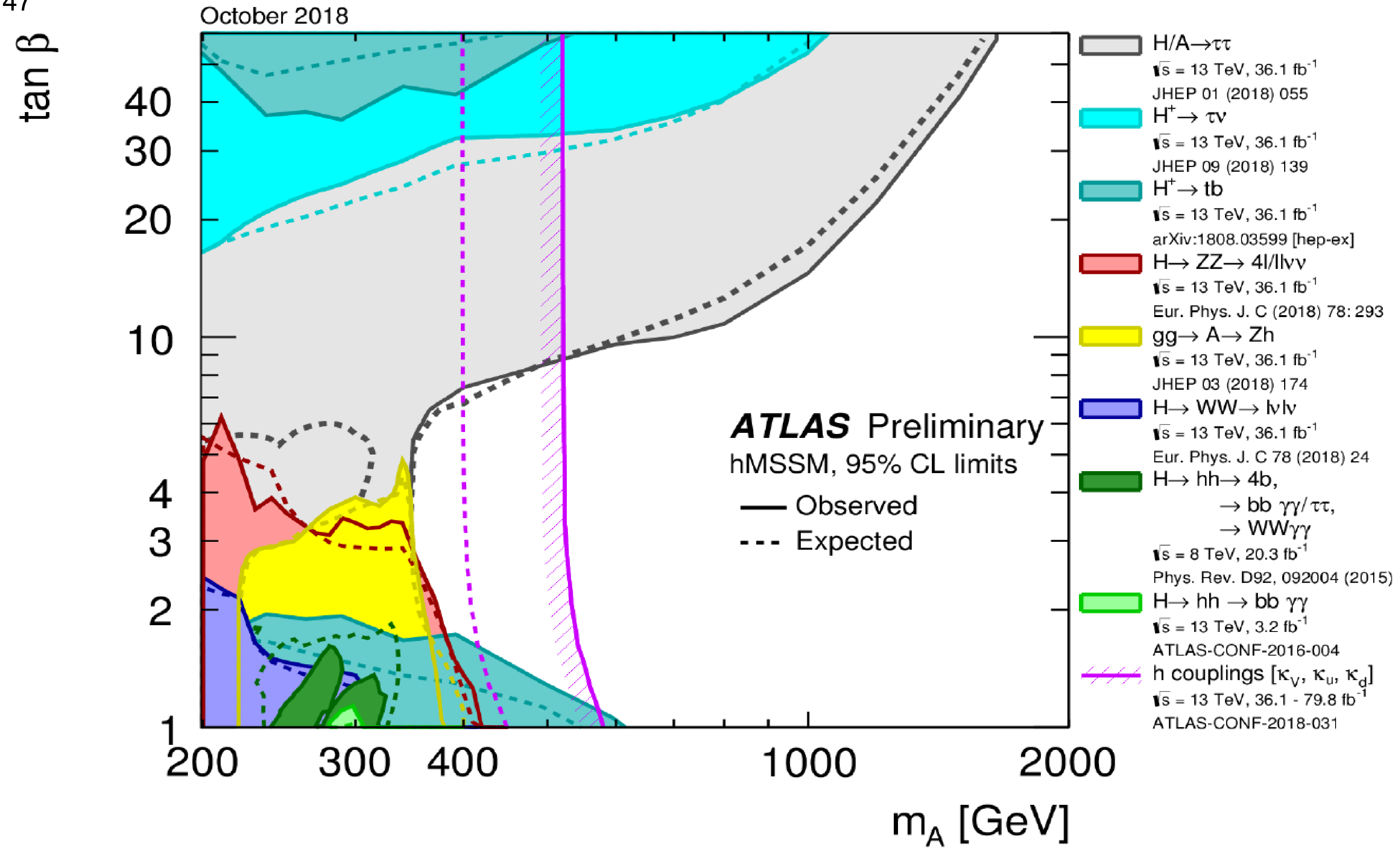




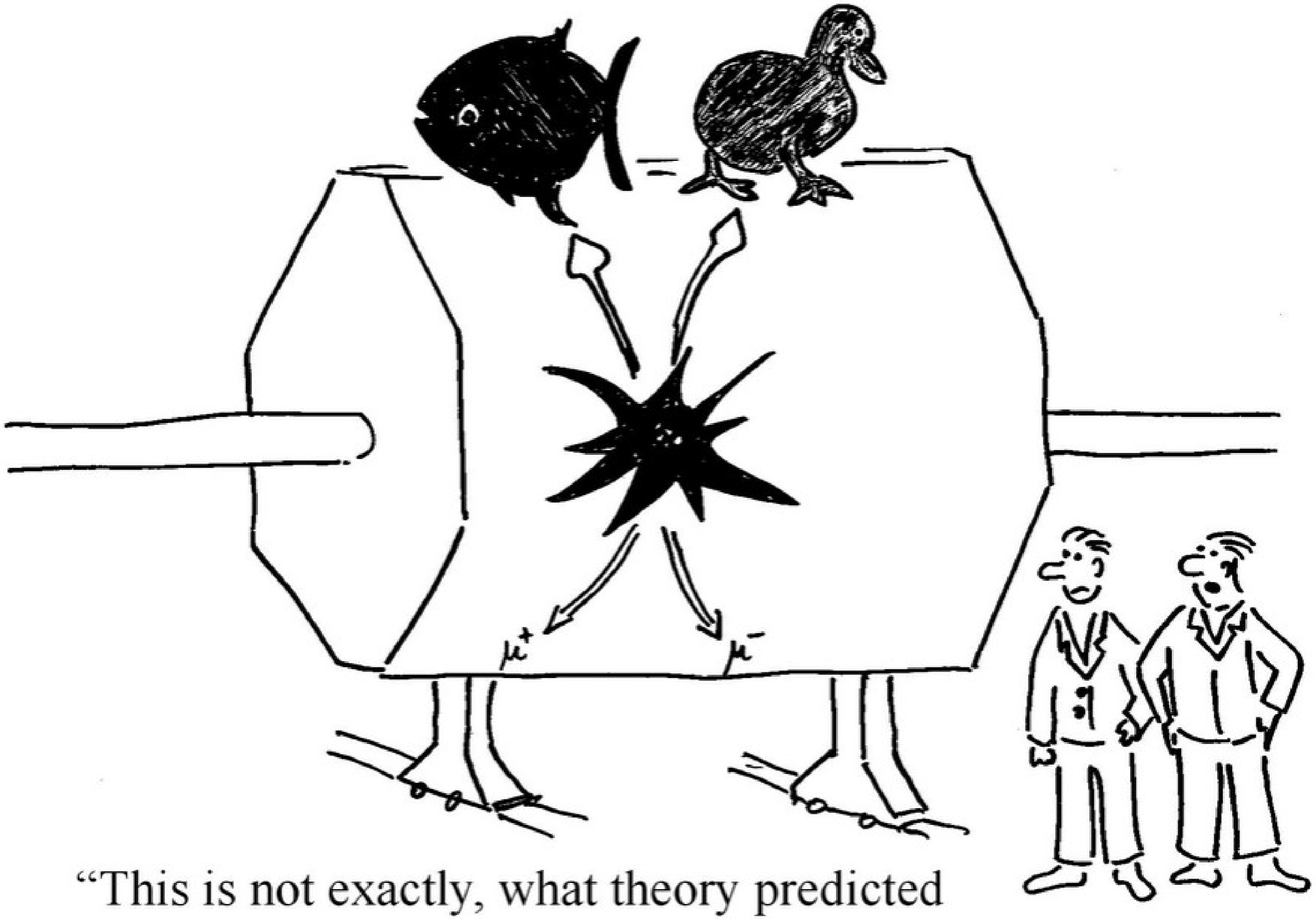
HH → bbWW



HH → 4b


October 2018
tan β
40
30
20
10
4
3
2
1
200
300
400
1000
2000
m$_A$ [GeV]
ATLAS Preliminary
hMSSM, 95% CL limits
Observed
Expected
H/A→ττ
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 01 (2018) 055
H$^+$→ τν
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 09 (2018) 139
H$^+$→ tb
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
arXiv:1808.03599 [hep-ex]
H→ ZZ→ 4l/llνν
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C (2018) 78: 293
gg→ A→ Zh
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 03 (2018) 174
H→ WW→ lνlν
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 78 (2018) 24
H→ hh→ 4b,
→ bb γγ/ττ,
→ WWγγ
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D92, 092004 (2015)
H→ hh → bb γγ
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
ATLAS-CONF-2016-004
h couplings [κ$_V$, κ$_u$, κ$_d$]
$\sqrt{s}$ = 13 TeV, 36.1 - 79.8 fb^{-1}
ATLAS-CONF-2018-031

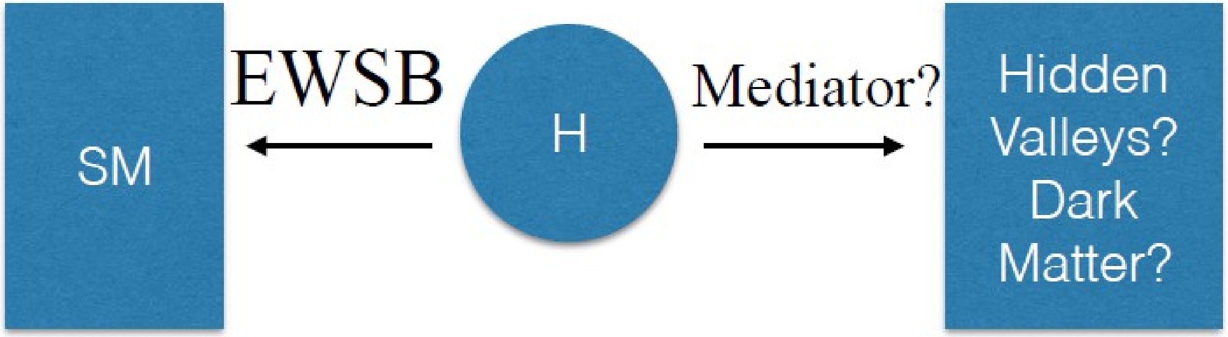
II. Exotic Higgs Decays



“This is not exactly, what theory predicted for the Higgs decay!”

Exotic Higgs Decays Overview

New particles might couple preferentially to the Higgs boson:



SM

EWSB

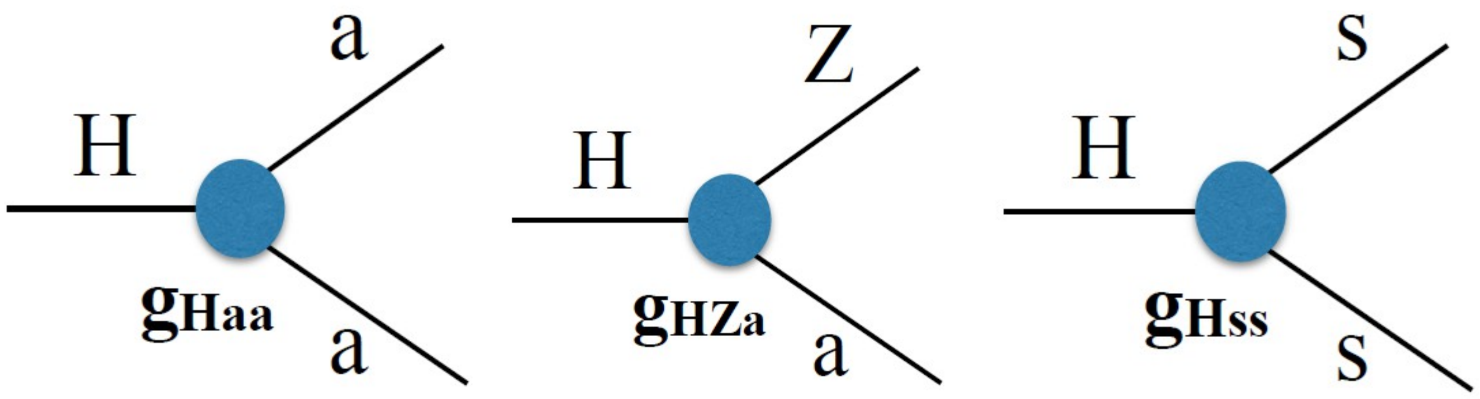
H

Mediator?

Hidden Valleys? Dark Matter?

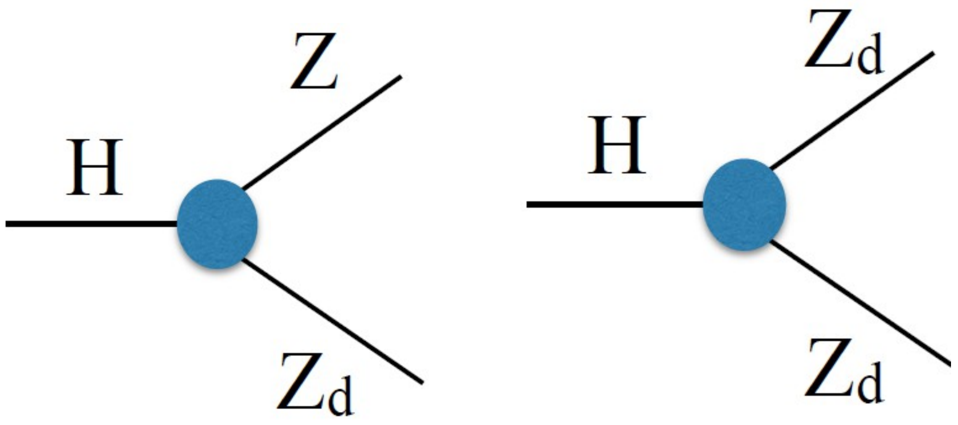
Typical benchmarks:
- SM + dark gauge symmetry $U(1)_d$
- 2HDM+S
- NMSSM

Extended Higgs sector contains light singlet (pseudoscalar a or scalar S)



H width is very small (4 MeV)
→ even a small new coupling could lead to sizable decay branching fractions

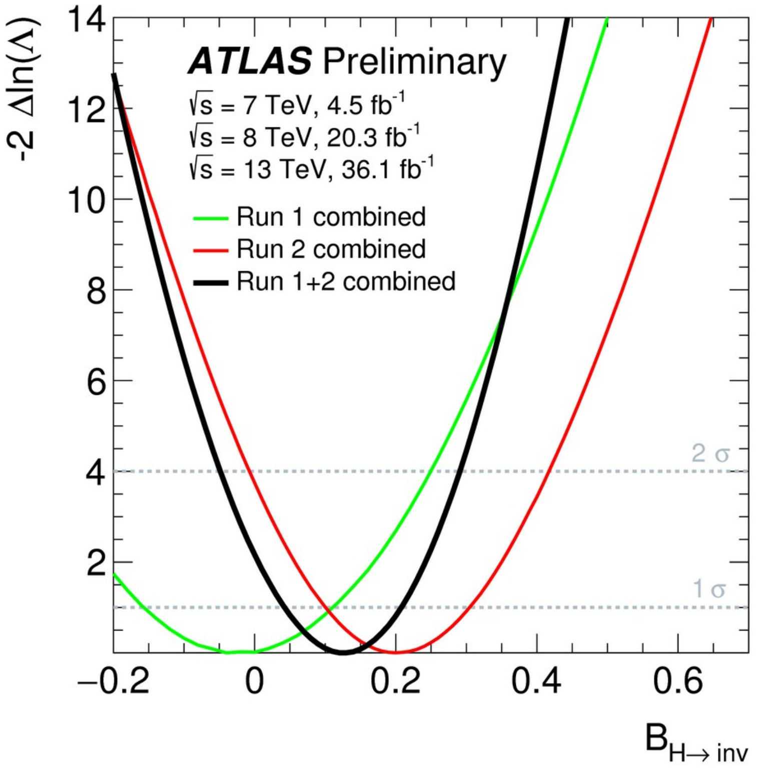
Hidden interaction, coupling to dark sector:

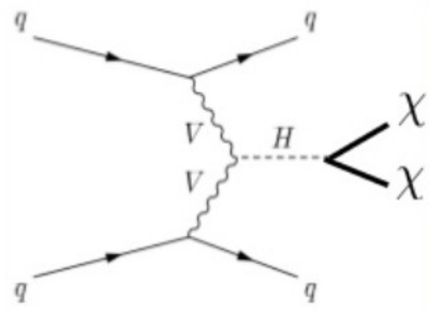


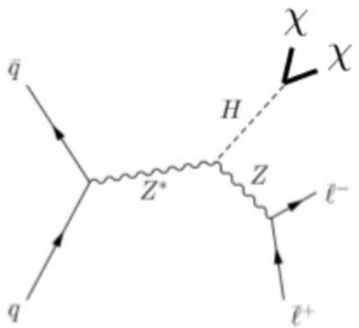
Exotic Higgs Decays Overview

Process	**Run-1**	**Run-2 2015**	**Run-2 2015+2016**
$H \to aa \to bb\mu\mu$			arXiv:1807.00539
$H \to aa \to 4b$		arXiv:1606.08391	arXiv:1806.07355
$H \to aa \to 2\tau 2\mu$	arXiv:1505.01609		
$H \to aa/ZZ_d/Z_dZ_d \to 4l$	arXiv:1505.07645		arXiv:1802.03388
$H \to aa \to 2j2\gamma$			arXiv:1803.11145
$H \to aa \to 4\gamma$	arXiv:1509.05051		arXiv:1808.10515 (0.2 < mX < 2 TeV)

H → invisible





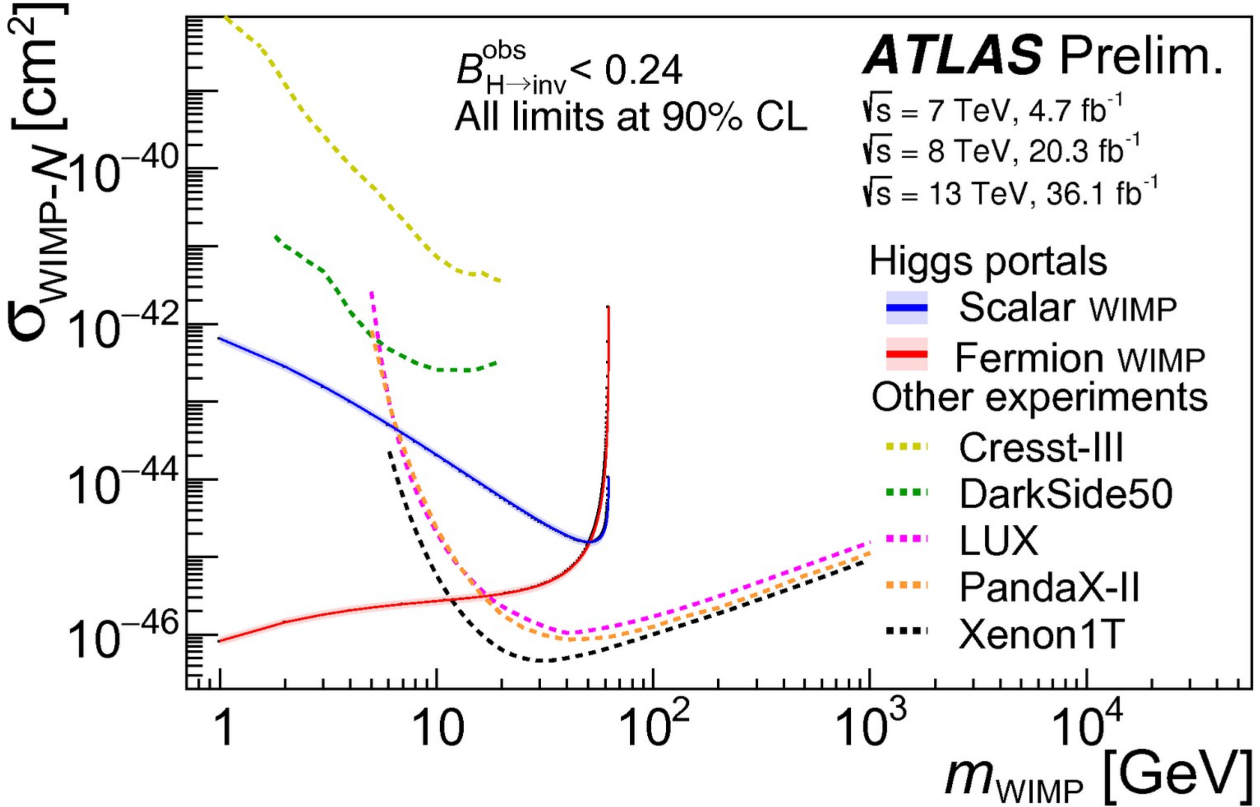


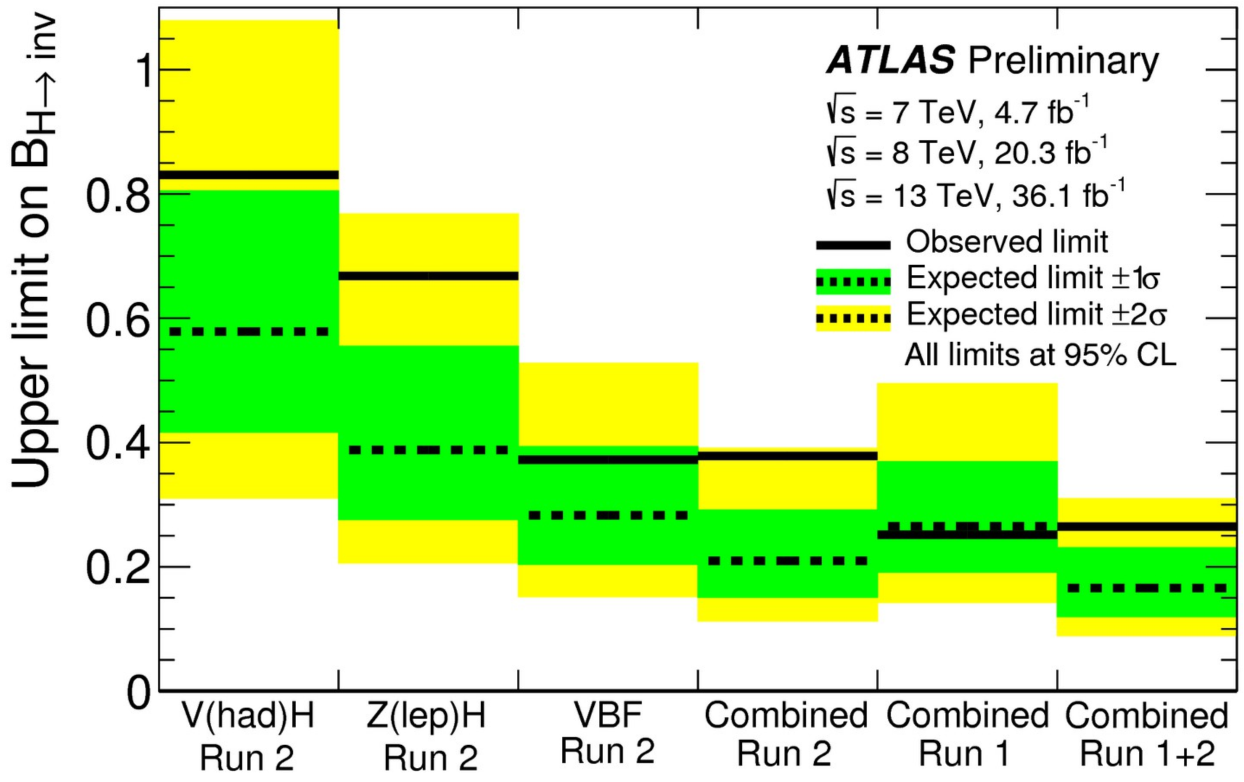
Higgs may decay to DM, can be identified indirectly via MET + the rest of the event

BR (H → inv) < 0.26 (obs)
(0.17 +0.07 -0.05 exp)

CMS: 24% obs (23% exp)

Interpretation also in Higgs portal models to set limit on WIMP-nucleon scattering cross section.

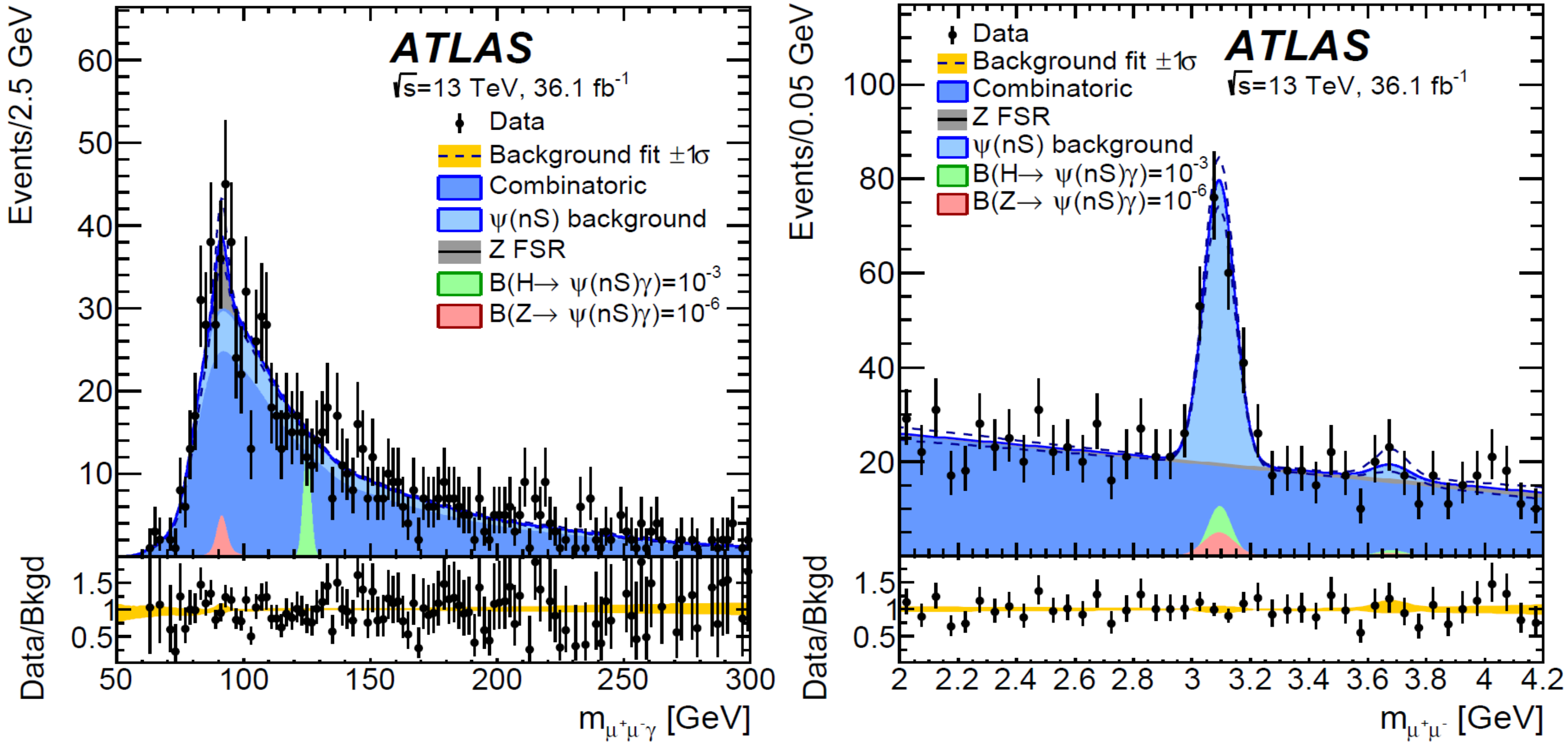




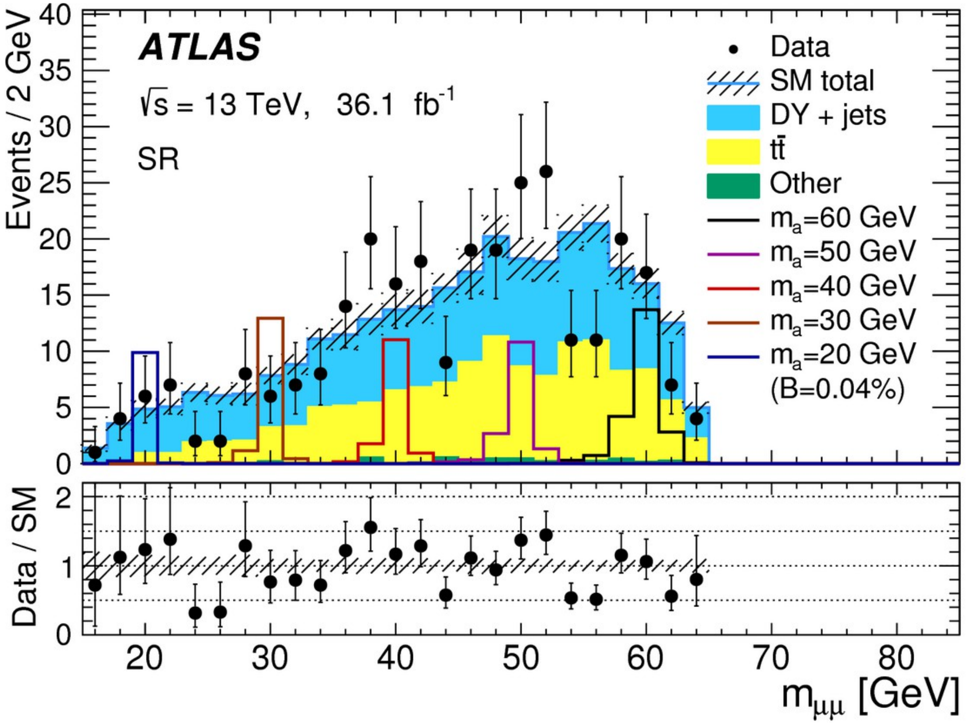
Rare Higgs Decays

- Search for H → J/ψ γ , H → ψ γ and H → Υγ probes c-quark and b-quark Yukawa coupling
- Rate predicted by the SM extremely small, an observation would hint new physics (eg. composite Higgs)
- Select events with OS muon pair (lead μ pT > 18 GeV), and a photon (pT > 35 GeV)
- 2D fits to the dimuon and dimuon+photon invarant mass spectra → no signal found on top of the SM predictions
- Rare decays of Z to the same final states searched as well, no deviation from prediction found

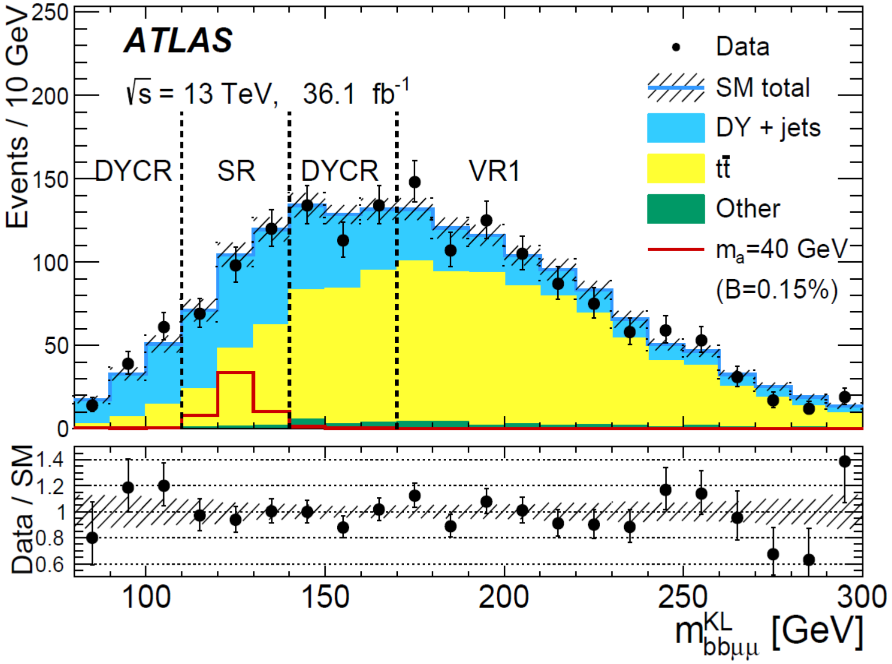
Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi\,(2S)\,\gamma)\,[\,10^{-4}\,]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi\,(2S)\,\gamma)\,[\,10^{-6}\,]$	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[\,10^{-6}\,]$	$2.8^{+1.2}_{-0.8}$	2.8
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[\,10^{-6}\,]$	$3.8^{+1.6}_{-1.1}$	1.7
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[\,10^{-6}\,]$	$3.0^{+1.3}_{-0.8}$	4.8



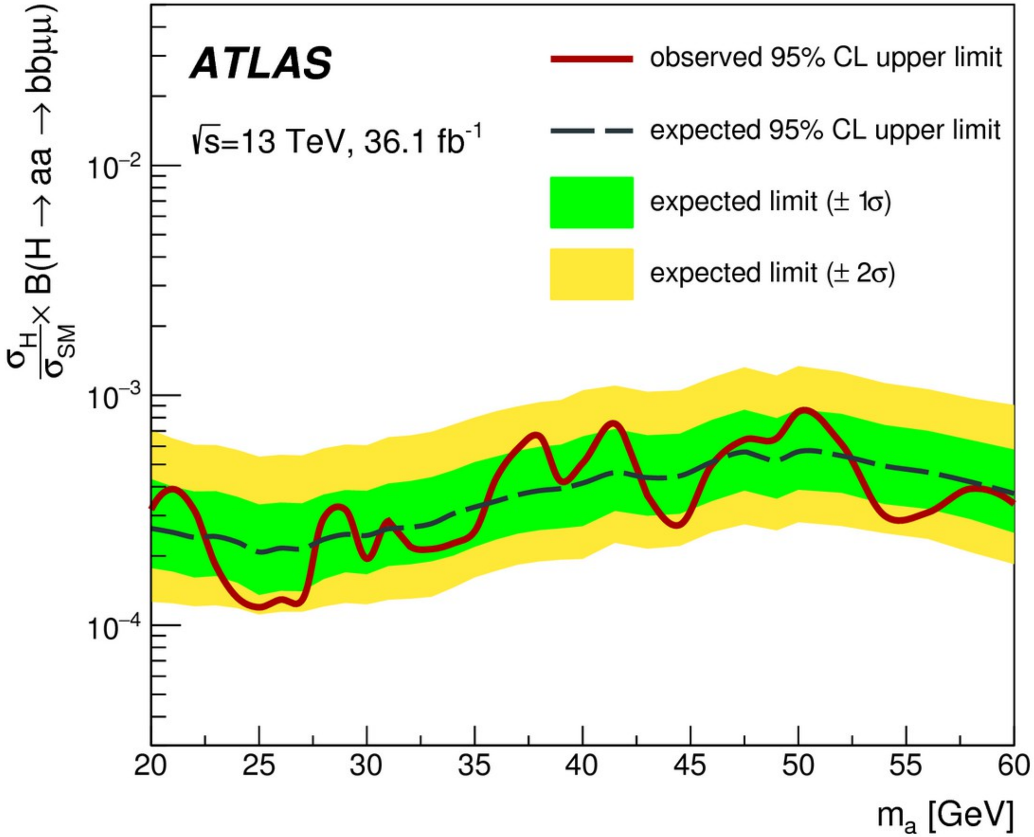
H(125) → aa → bbμμ



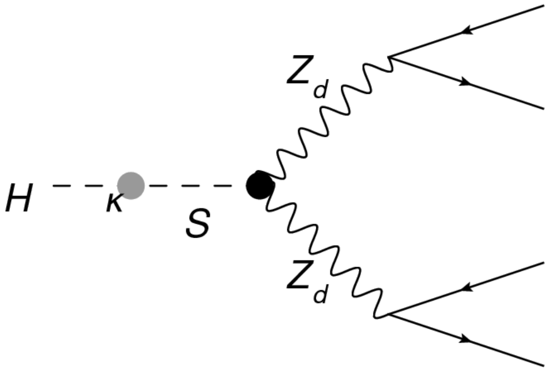
- Muons pT> 7 GeV, „medium“ ID, lead μ pT > 27 GeV, 0.4 anti-kt jets pT > 20 GeV, b-tagged with 77% WP
- Decay to two particles with equal mass → symmetric decay, but μμ mass resolution 10x better than the bb mass
- Kinematic fit to the energy of the b-jets improve bbμμ mass resolution, $|m_{bb\mu\mu}^{KL}$-125 GeV| < 15 GeV
- DY Background yield estimated from data from $m_{bb\mu\mu}$ **sidebands**, shape template from 0 b-tagged events.
- ttbar yield estimated from CR with large MET, shape from MC



No excess,
largest local significance
at 38 GeV (1.6σ)



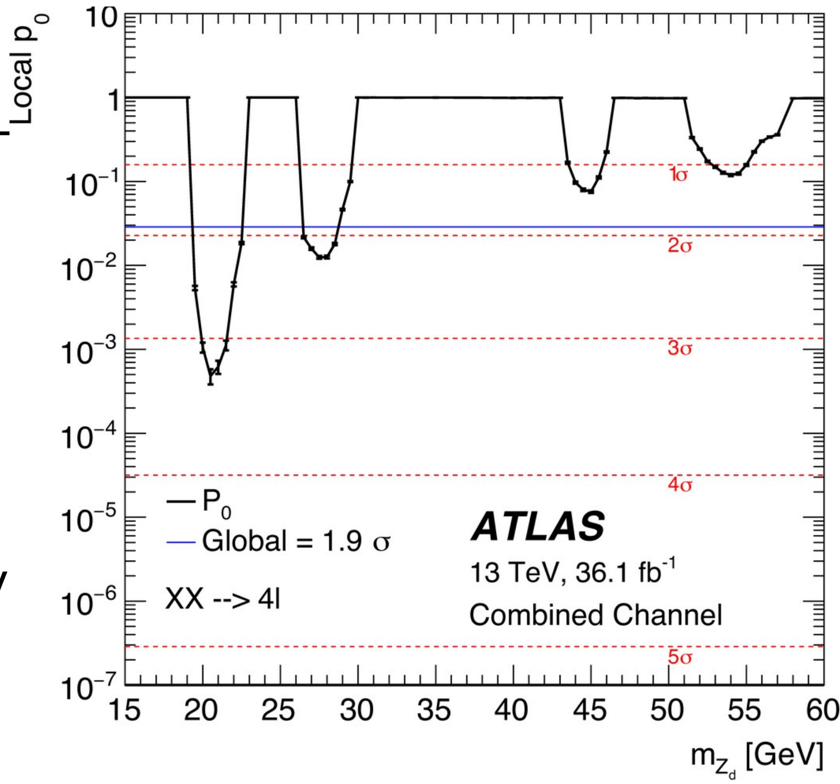
$H \rightarrow aa/ZZ_d/Za/Z_dZ_d \rightarrow 4l$

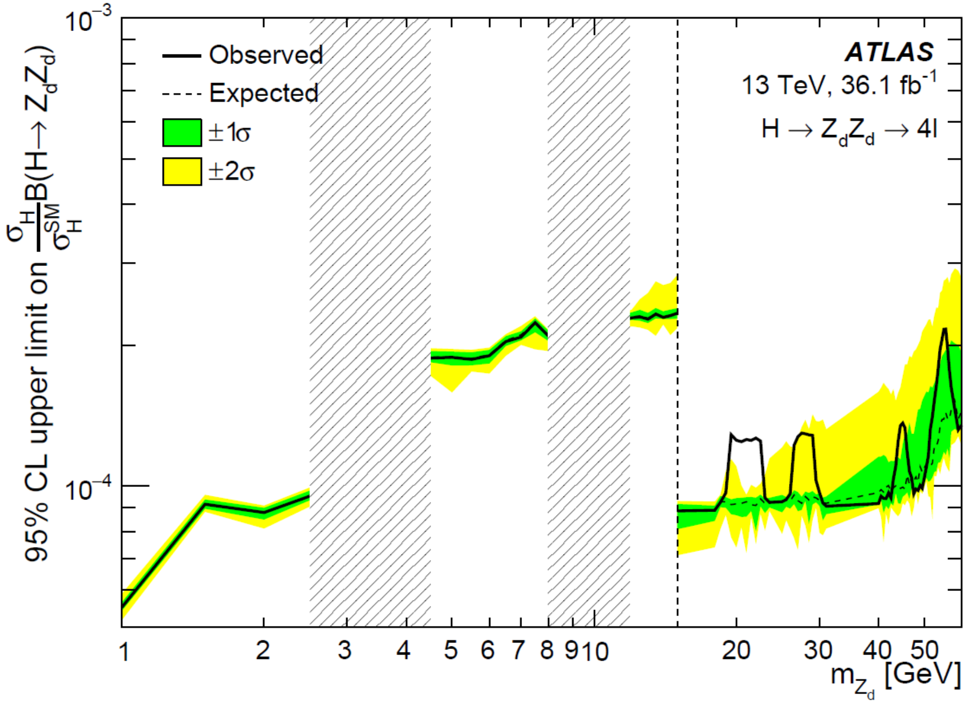


S: Dark Higgs boson

a is a pseudoscalar, Zd is a vector boson

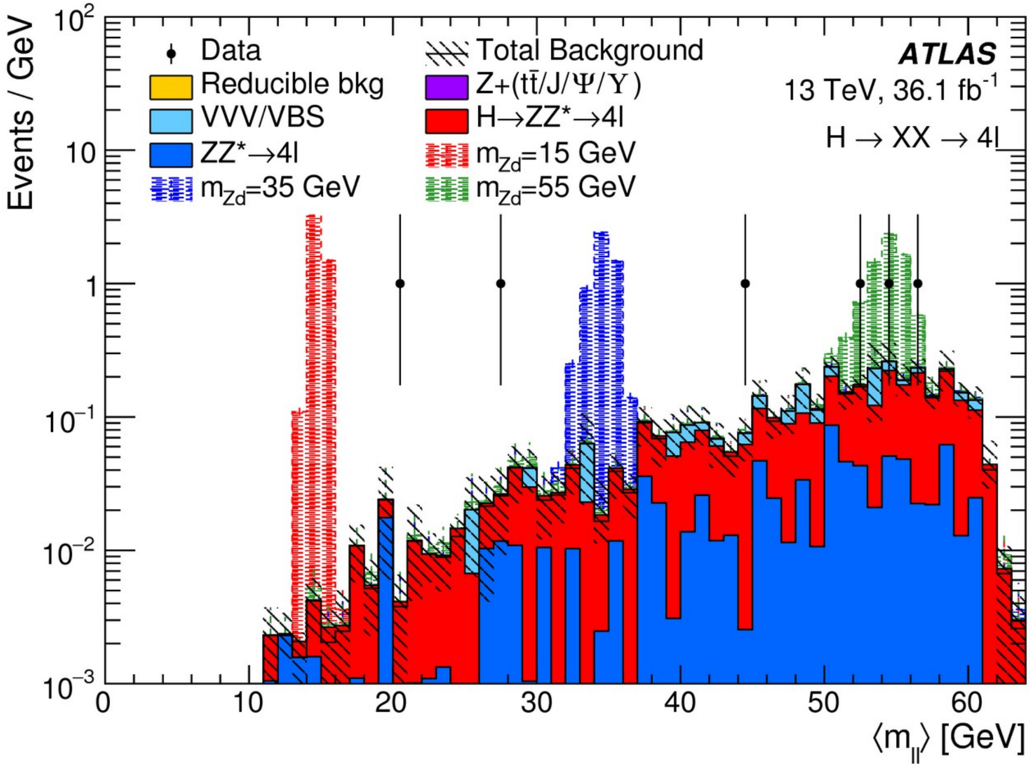
- Select events with 4e or 4μ, ie. 2 SFOS lepton pairs, lead lepton pT > 20 GeV
- m_{4l} must be close to Higgs mass $115 < m_{4l} < 130$ GeV
- For $H \rightarrow Z_dZ_d$, select lepton quadruplet that minimizes $|m_{12}-m_{34}|$

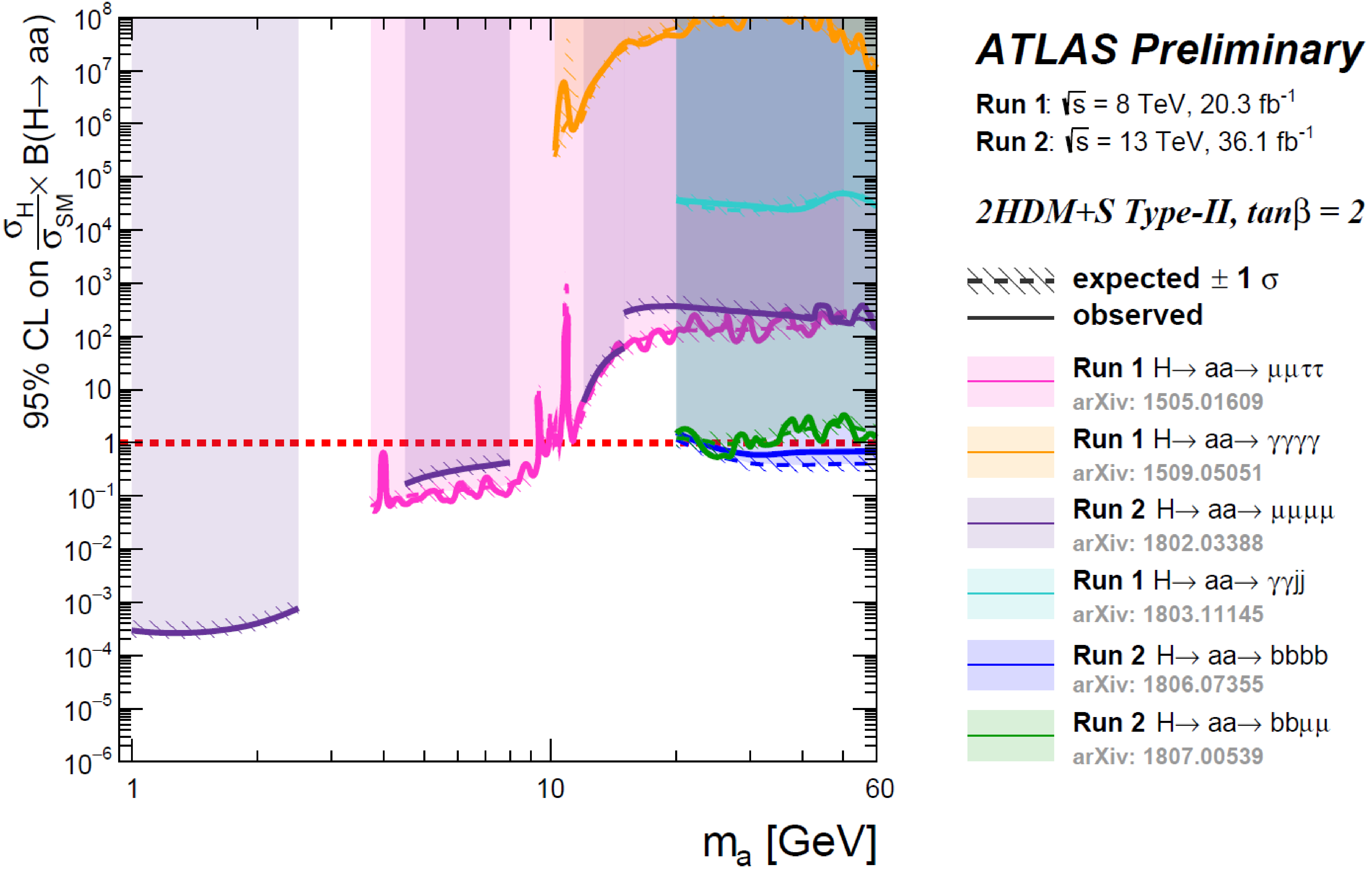




Largest excess at 20 GeV (1 event) 3.2σ local

Quarkonia regions excluded (vetoed during selection)




ATLAS Preliminary
Run 1: √s = 8 TeV, 20.3 fb^{-1}
Run 2: √s = 13 TeV, 36.1 fb^{-1}
2HDM+S Type-II, tanβ = 2
expected ± 1 σ
observed
Run 1 H→ aa→ μμττ
arXiv: 1505.01609
Run 1 H→ aa→ γγγγ
arXiv: 1509.05051
Run 2 H→ aa→ μμμμ
arXiv: 1802.03388
Run 1 H→ aa→ γγjj
arXiv: 1803.11145
Run 2 H→ aa→ bbbb
arXiv: 1806.07355
Run 2 H→ aa→ bbμμ
arXiv: 1807.00539
95% CL on $\frac{\sigma_H}{\sigma_{SM}} \times$ B(H→ aa)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
60
m_a [GeV]

Summary & Outlook

After two runs and 8 years of datataking...

- no sign of new physics found yet (but a few excesses here and there), no SUSY

- if new physics is accessible at the LHC energy scale, then it's hiding well

- We're entering a new era, doubling the luminosity will take a long time

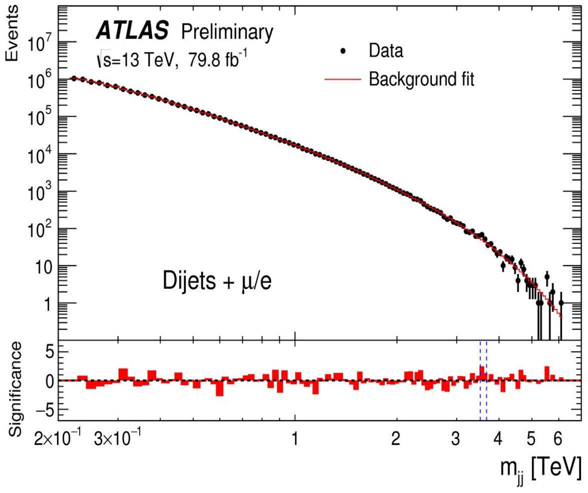
But, analyses get more and more sophisticated:

Clever and more powerful machine learning techniques, better signal-background discrimination, better control of systematic uncertainties for physics objects and theory

We have collected only a small part of the dataset yet (5%!)

- Run-3 and then HL-LHC enables probing especially the phase spaces where we're now very much statistically limited, and it leads to better precision of Higgs and other particles coupling measurements

- 14 TeV energy leads to larger cross sections and helps pushing into the high mass corners

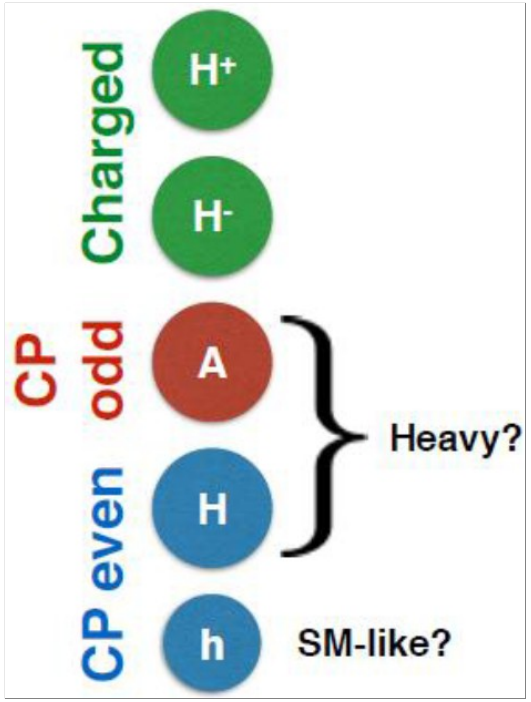


Backup

Minimal SUSY Extension of the SM (MSSM)

In the simplest SUSY extension, the Higgs sector consists of two Higgs doublets:

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} \to H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix}, H_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix} \quad \tan\beta = \frac{v_u}{v_d}$$



→ This leads to 5 observable Higgs bosons:

CP even **h, H**
CP odd: **A**
Charged: **H$^+$, H$^-$**

$$m_{h^0} \leq m_{A^0} \leq m_{H^0}$$

$$m_{h^0} \leq m_{Z^0} \leq m_{H^0}$$

(radiative corrections raise the masses)

The mass of the lightest CP even Higgs („h“) is constrained to be < 130 GeV

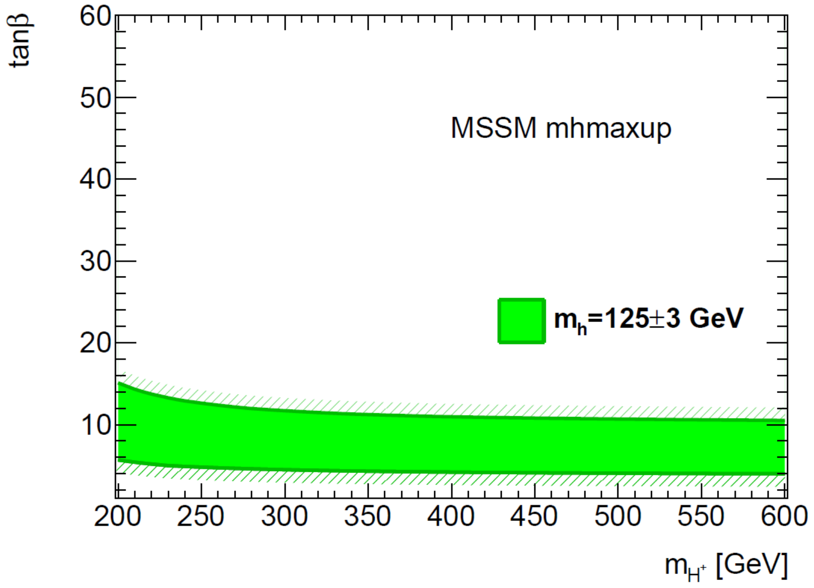
→ *Observation of the Higgs at 125 GeV does therefore not rule out the MSSM*

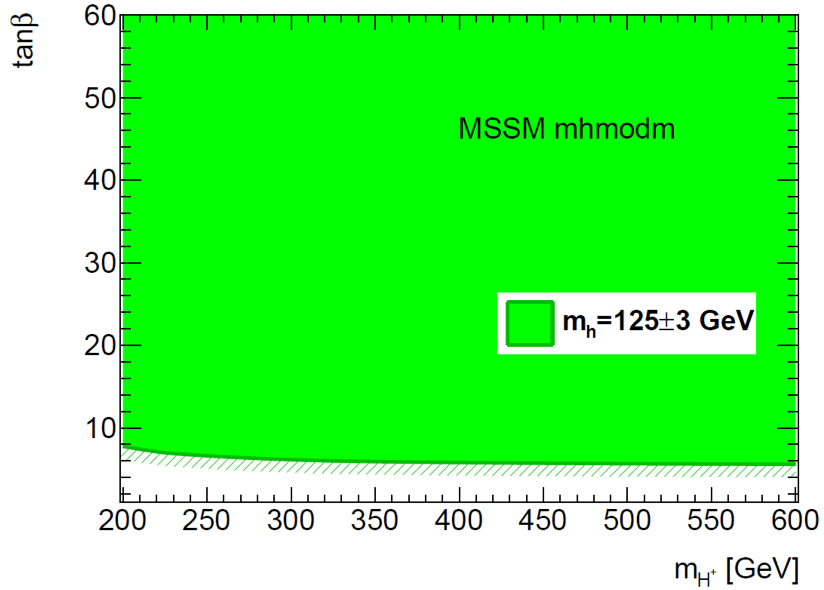
- SUSY introduces a lot of new parameters (to parametrize the mass breaking mechanism)
- The unconstrained MSSM has 109 new parameters → reduced by phenomenological considerations (eg. no FCNC) to 22 parameters
- MSSM benchmark models (such as m_h*mod* etc.) defined to study specific phenomenologies, leaving only two free parameters: **tanβ, A mass**

MSSM bechmark scenarios for the LHC

arXiv:1302.7033

mhmaxup	Higher order corrections maximize the h mass
mhmod±	Reduced stop mixing wrt. mhmax In mhmod+ the predictions are more in agreement with (g-2)μ, in mhmod- with b→sγ
light stop	ggh suppressed
light stau	Enhanced h → γγ at high tanβ
tauphobic	Suppressed couplings of h to down-type fermions
Low m_H	$m_h > m_H$ m_H= 125 GeV fixed





2HDM

Model	u_R^i	d_R^i	e_R^i
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

One doublet is fermiophobic

One doublet couples to up, other to down-type (=MSSM like)

One doublet couples to quarks as type-I, other with leptons as type-II

One doublet couples to quarks as type-II, other with leptons as type-I

Scale factors of Yukawa couplings	y_h^u	y_h^d	y_h^ℓ	y_H^u	y_H^d	y_H^ℓ	y_A^u	y_A^d	y_A^ℓ
Type-I	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	$\frac{s_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{c_\alpha}{c_\beta}$	$\frac{c_\alpha}{c_\beta}$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Flipped (Y)	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\cot\beta$	$\tan\beta$	$-\cot\beta$
Lepton Specific (X)	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{c_\alpha}{c_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\cot\beta$	$-\cot\beta$	$\tan\beta$

Significance, Limits, test statistics

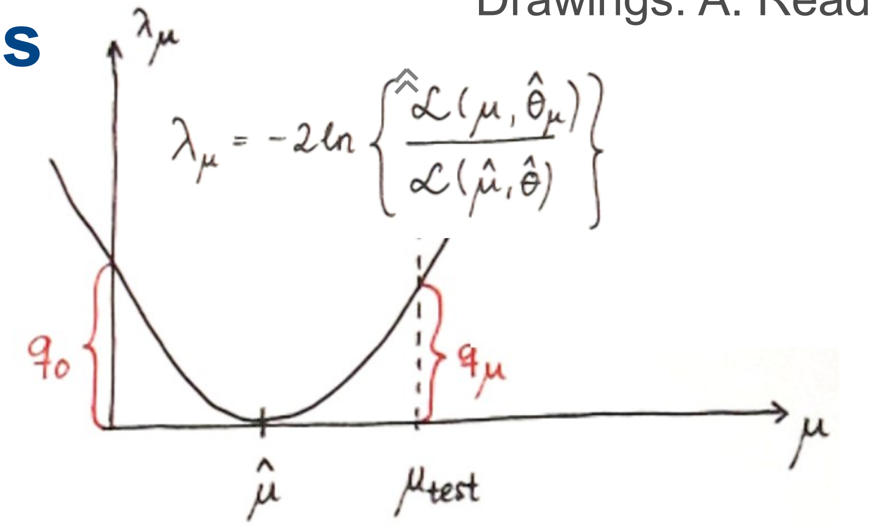
Drawings: A. Read

→ **Profile likelihood ratio** (used at the LHC):

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

„conditional fit“

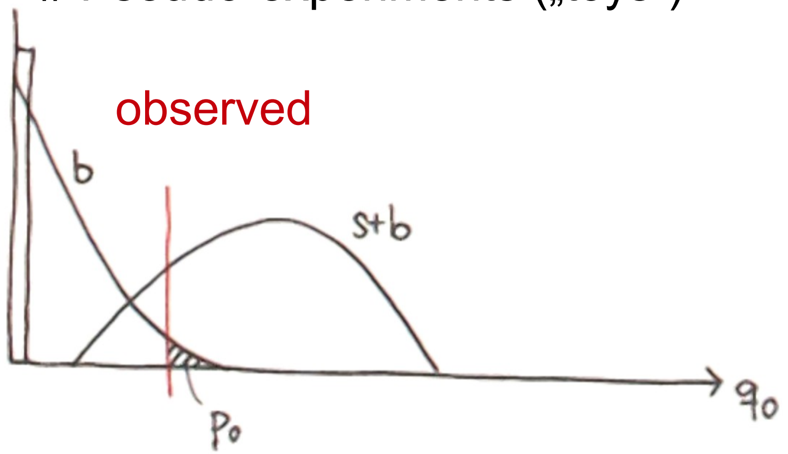
„unconditional fit“



Test-statistic to test the background-only hypothesis (→ discovery):

$$\tilde{q}_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} > 0 \\ +2\ln\lambda(0) & \hat{\mu} \leq 0 \end{cases}$$

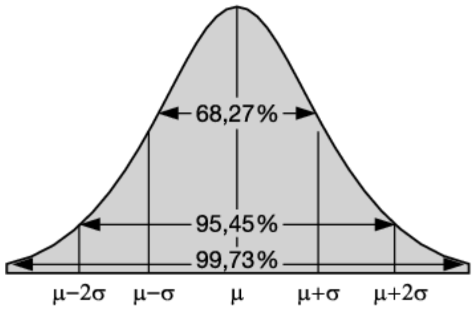
Pseudo-experiments („toys“)



The consistency with the background-only hypothesis is quantified with $\mathbf{p_0}$.

If p_0 is small, the consistency is poor → discovery.

The significance is the corresponding number of Gaussian standard derivations:



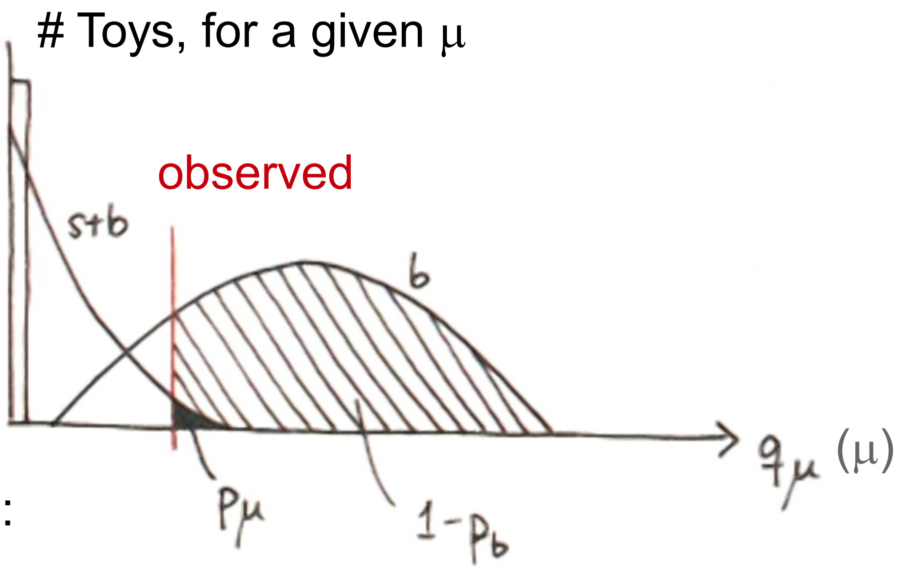
0σ ~ 0.5
1σ ~ 0.16
2σ ~ 0.022
3σ ~ 0.0013
4σ ~ 0.000032
5σ ~ 0.0000003

Significance, Limits, test statistics

Test-statistic to test the signal hypothesis
(→ exclusion limits):

(μ is scanned)

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ +2\ln\tilde{\lambda}(\mu) & \hat{\mu} > \mu \end{cases}$$



Define the quantity **CLs** (modified frequentiest limit):

$$CL_s(\mu) = \frac{p_\mu}{1-p_b}$$

CLs is the ratio of two p-values.
Sometimes, p_μ is also called CL_{S+B} and p_b is called CL_b (eg at LEP).

If eg. $CL_S(\mu) < 5\%$, the signal hypothesis (μ) is excluded at 1-5%=95% confidence level.
CL_s is known to be conservative, it prevents excluding hypotheses one is not sensitive to.

The observed p-values (p_0, p_μ and $1-p_b$) are integrals from the observed value of the test-statistic to infinity.

The expected p-values (suppose we had many LHC's, what is the average result we could expect) are obtained from integrating the medium of the test statistic distribution of the toys up to infinity.