Higgs Physics at the Large Hadron Collider

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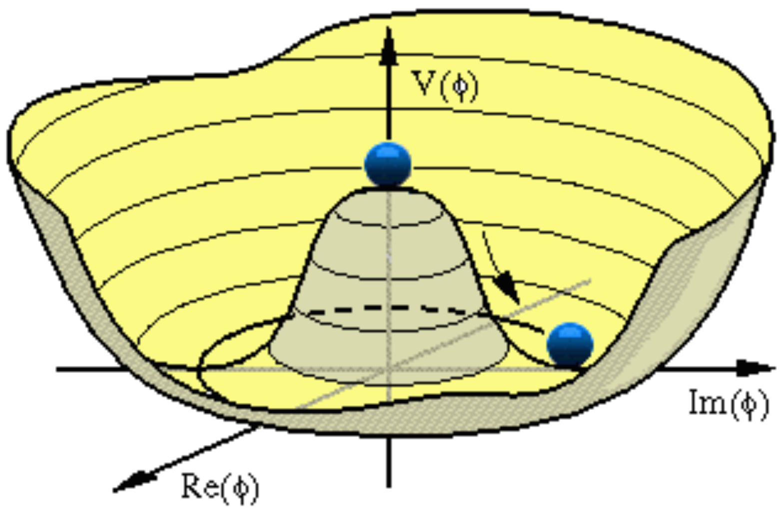
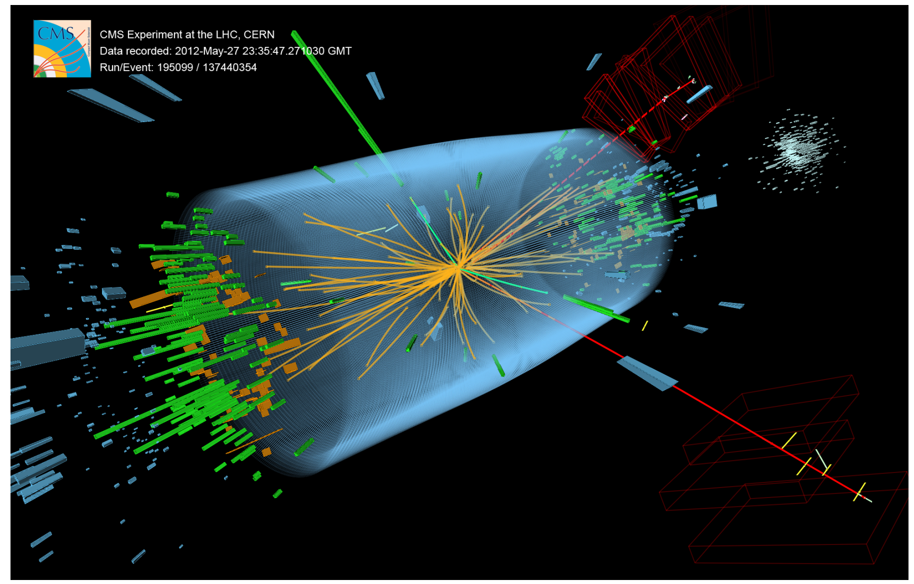
IoP HEPP 2019 — Imperial College London

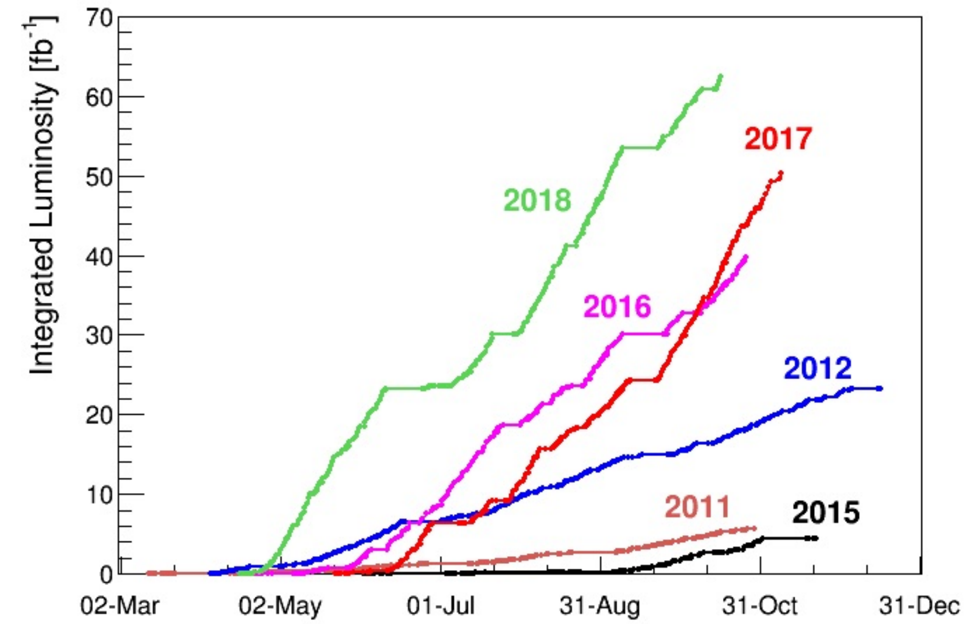
No Charge, No Spin, Only Mass…



Theory since 1964

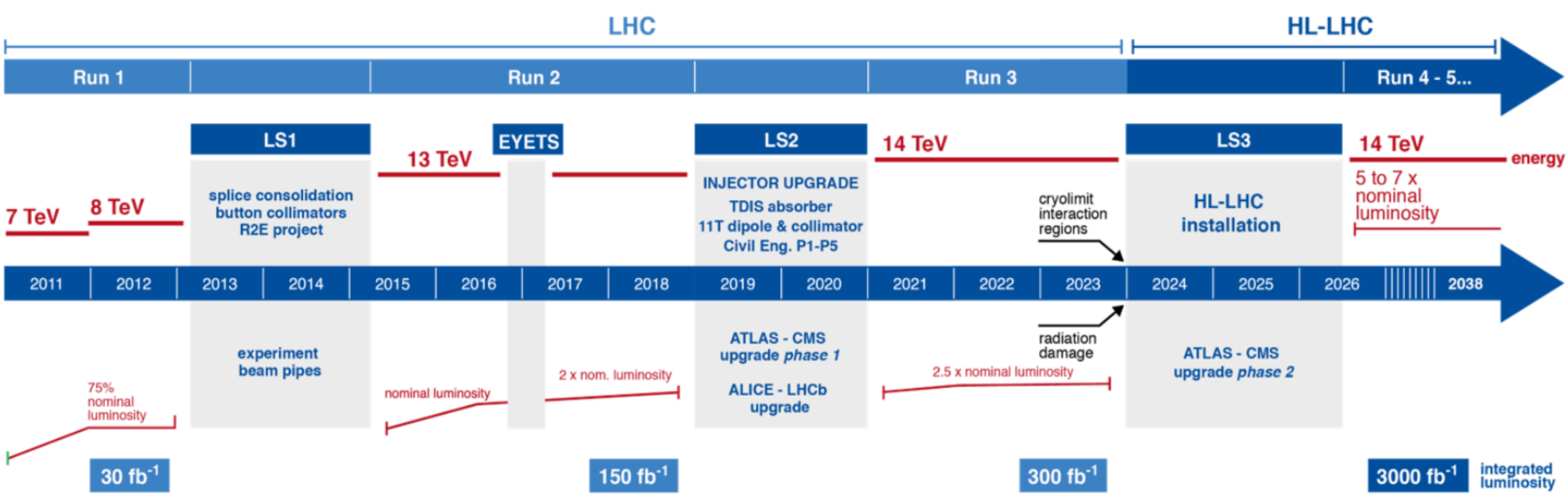


2012

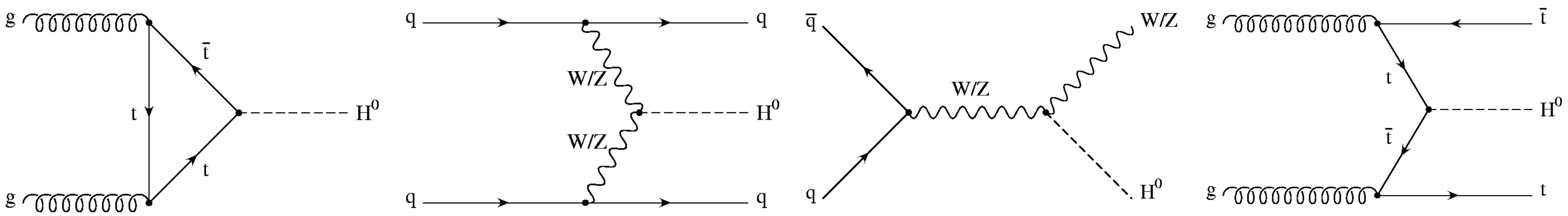


Today

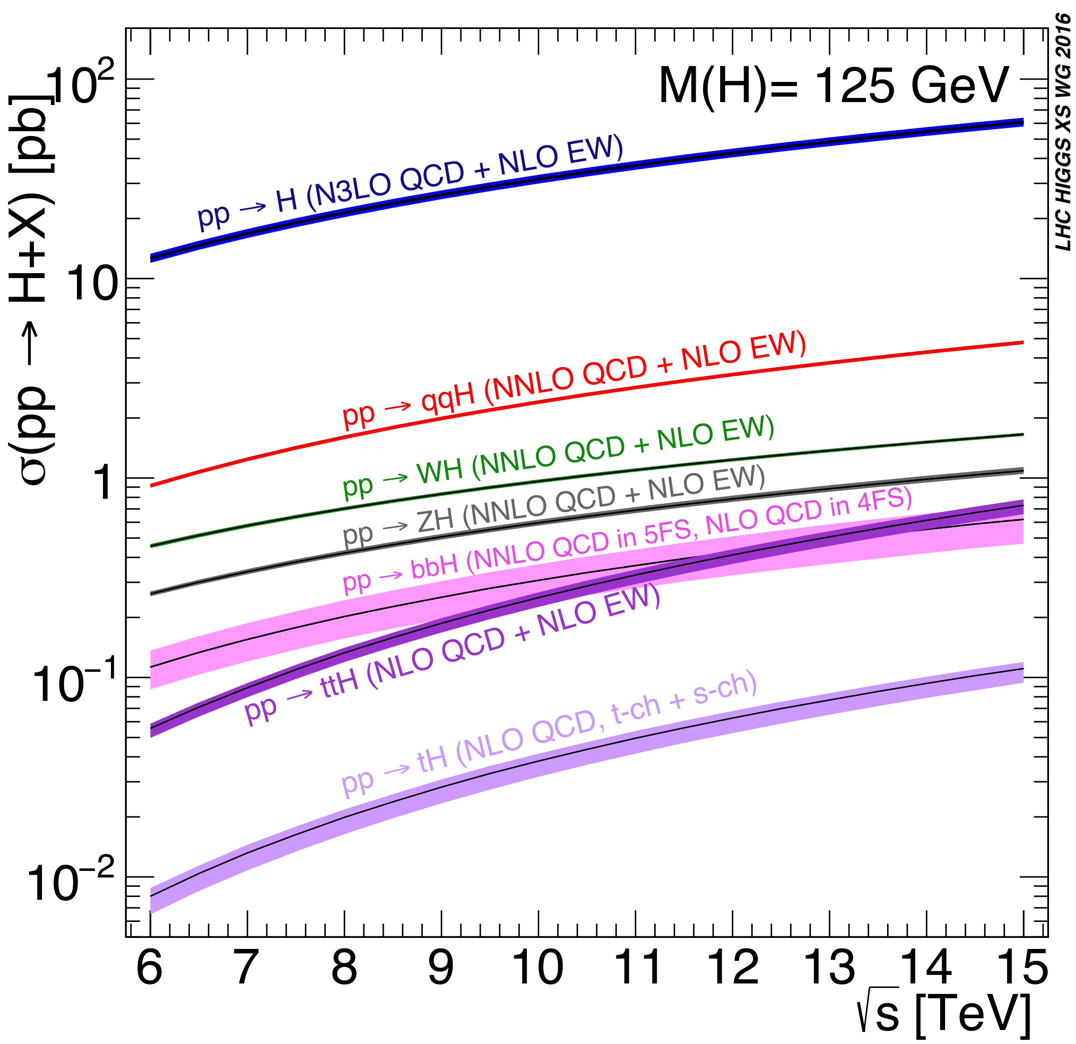
- CERN Large Hadron Collider provides us with a unique opportunity…

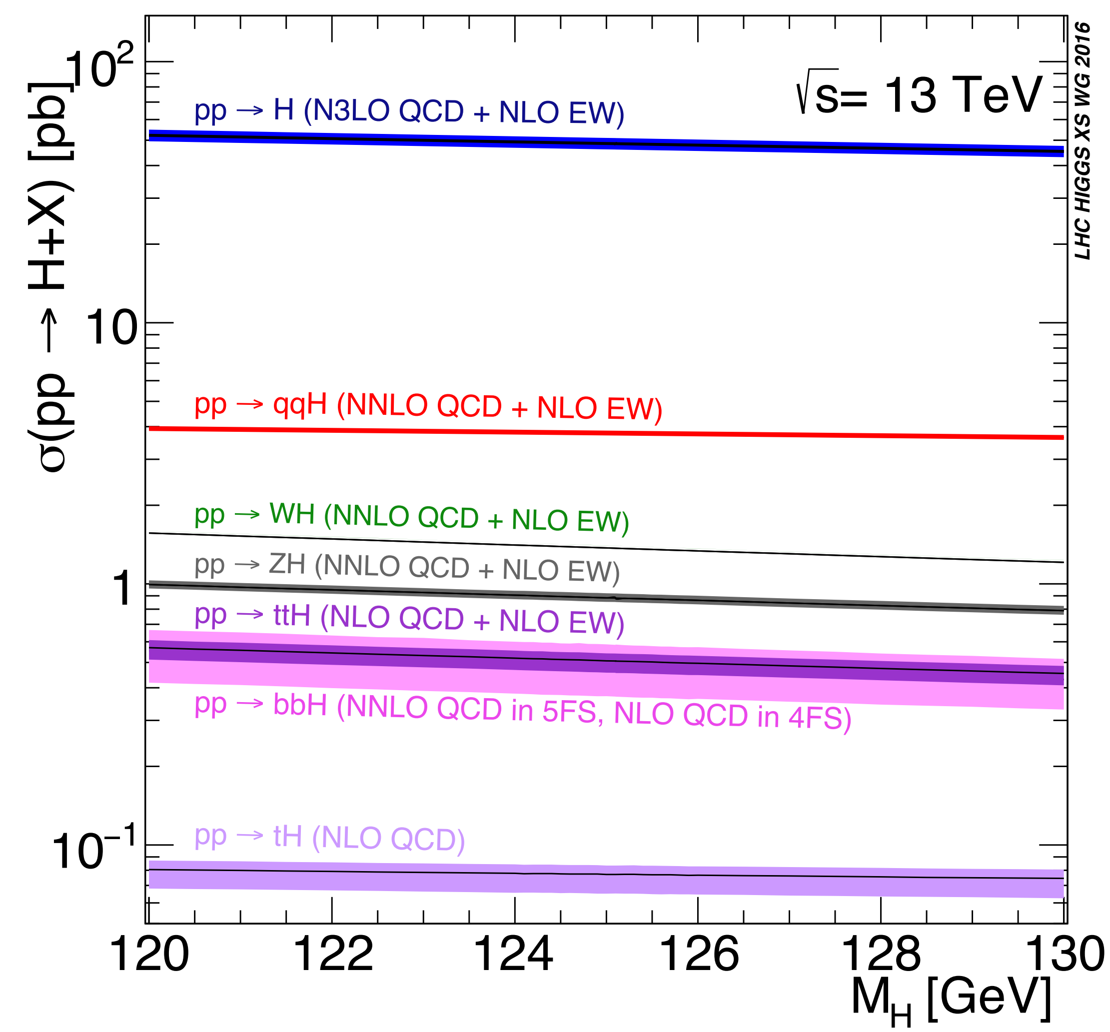


Higgs Boson Production at the LHC



- All major* production modes have now been observed…

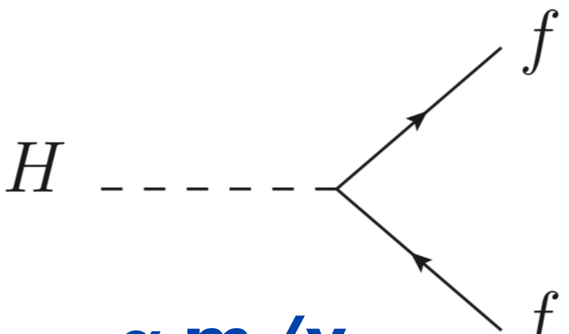




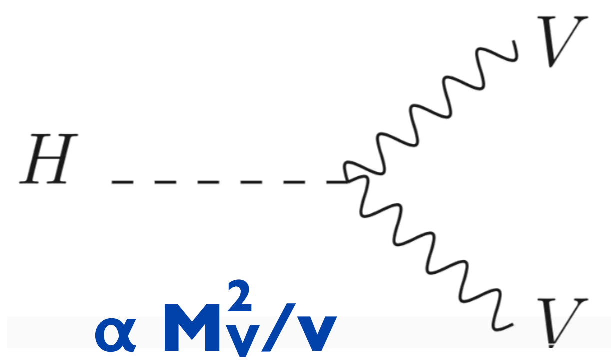
LHC Higgs XSWG YR4

***Not including bbH or tH**

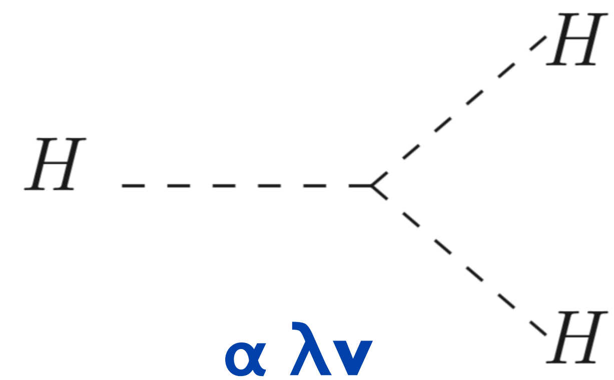
Higgs Boson Decay in the Standard Model



α m_f/v

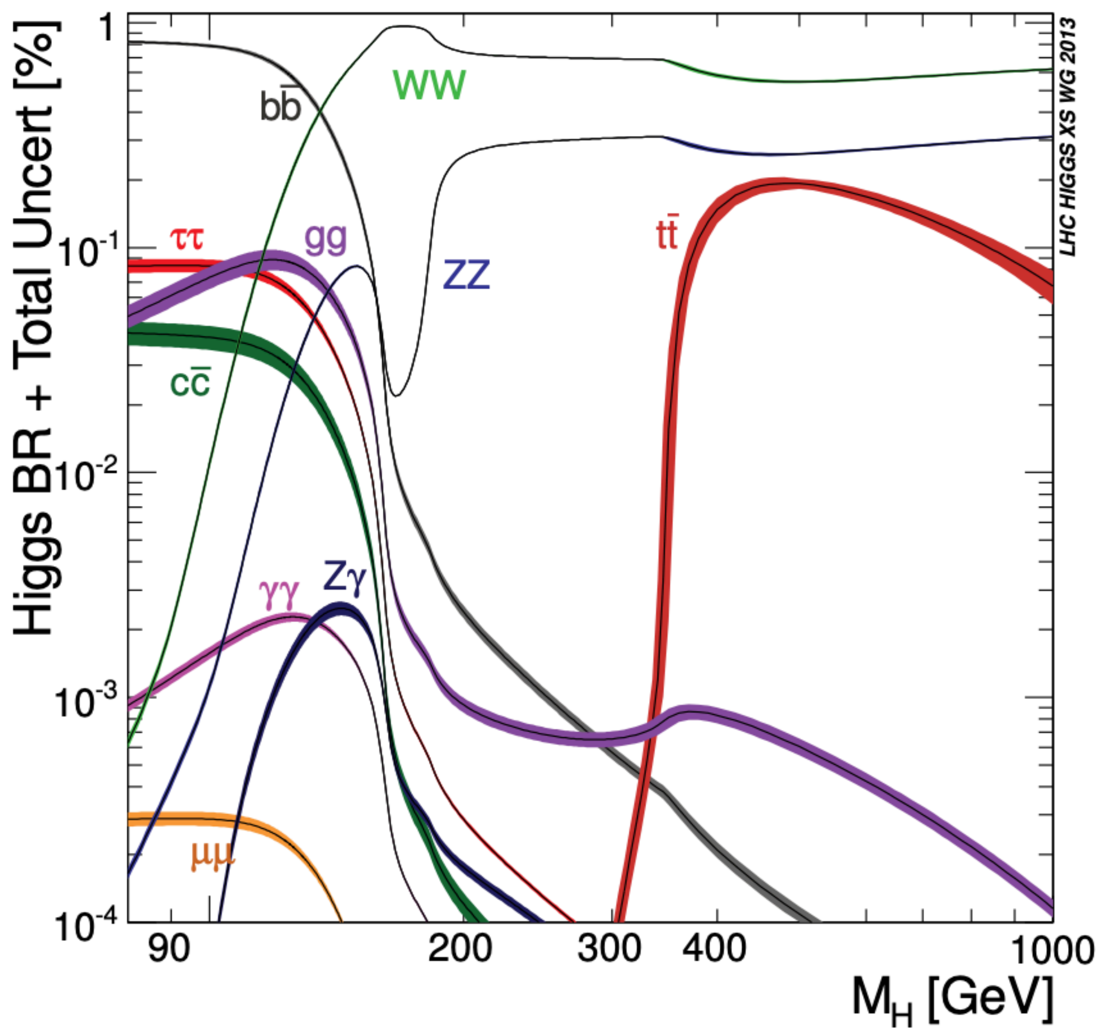


α M_V^2/v

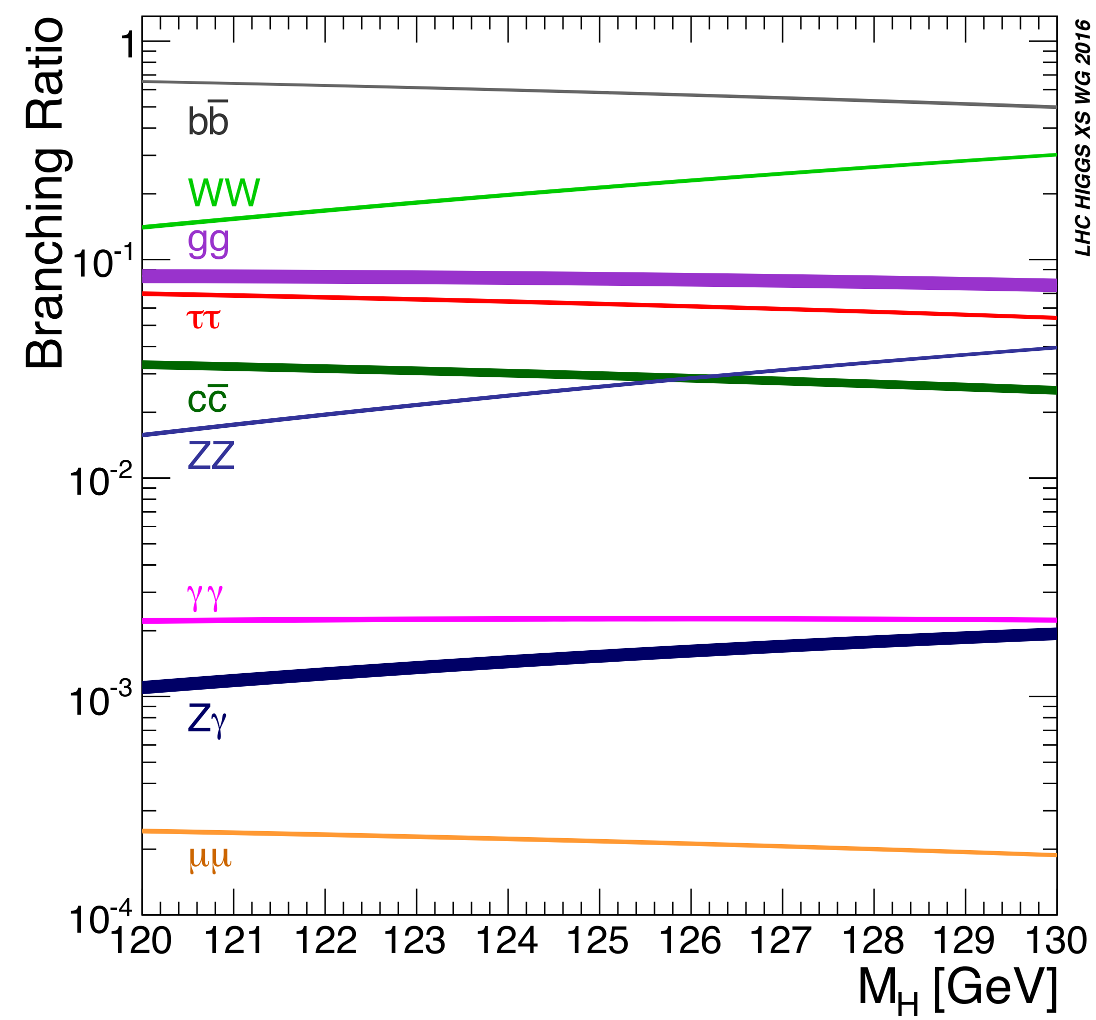


α λv

- Now in the era of precision measurements with some channels
- Searches move to looking for rare decays



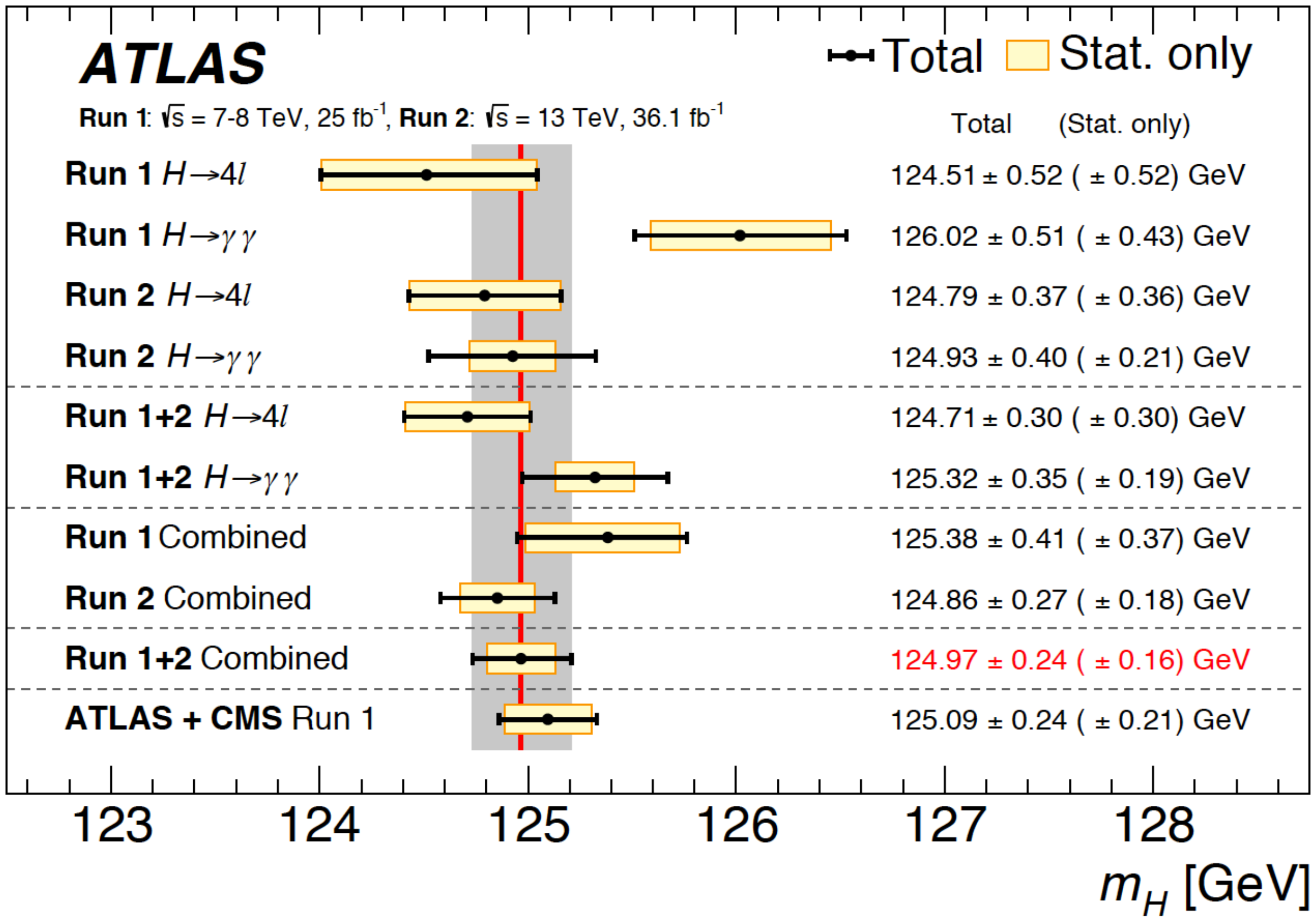
LHC Higgs XSWG YR3

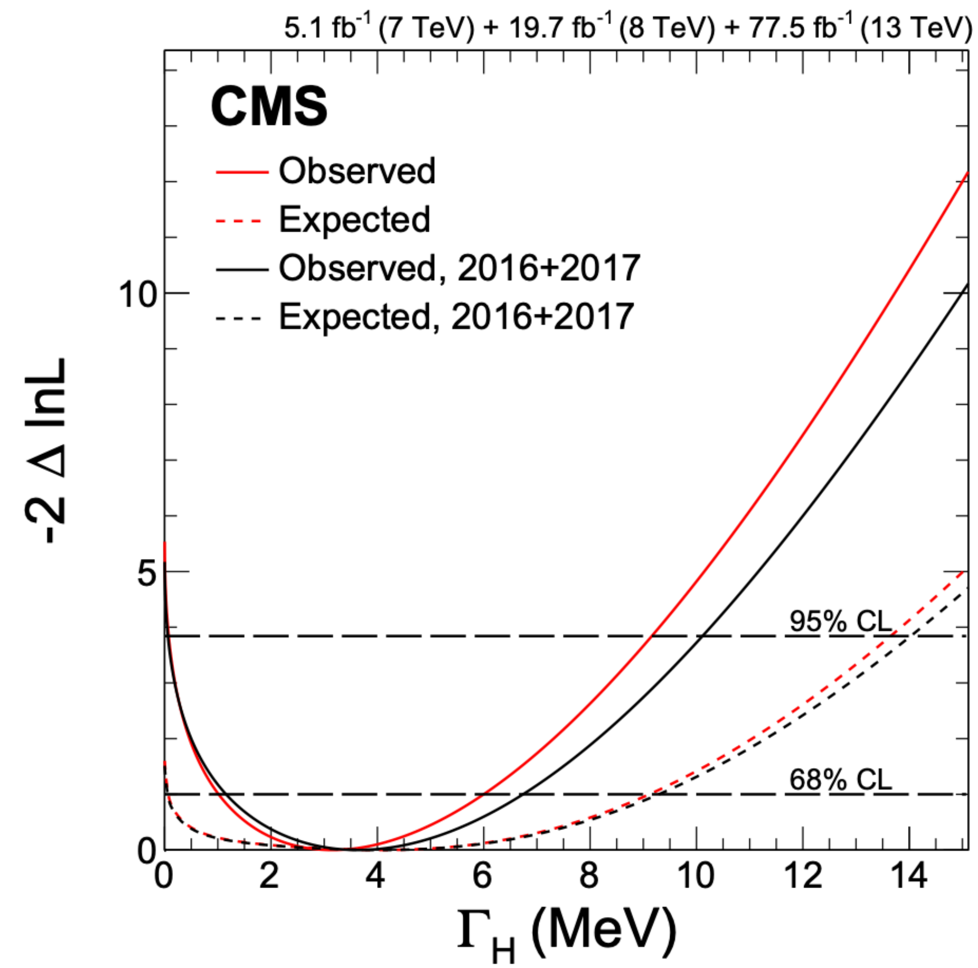


LHC Higgs XSWG YR4

Higgs Boson Properties: Mass and Width

- 125.09 ± 0.24 GeV (Run-1 ATLAS and CMS) **PRL 114 (2015) 191803**
- 124.97 ± 0.24 GeV (Run-1 and -2 ATLAS) **PLB 784 (2018) 345**
- 125.26 ± 0.21 GeV (Run-2 CMS 4l only) **JHEP 11 (2017) 047**



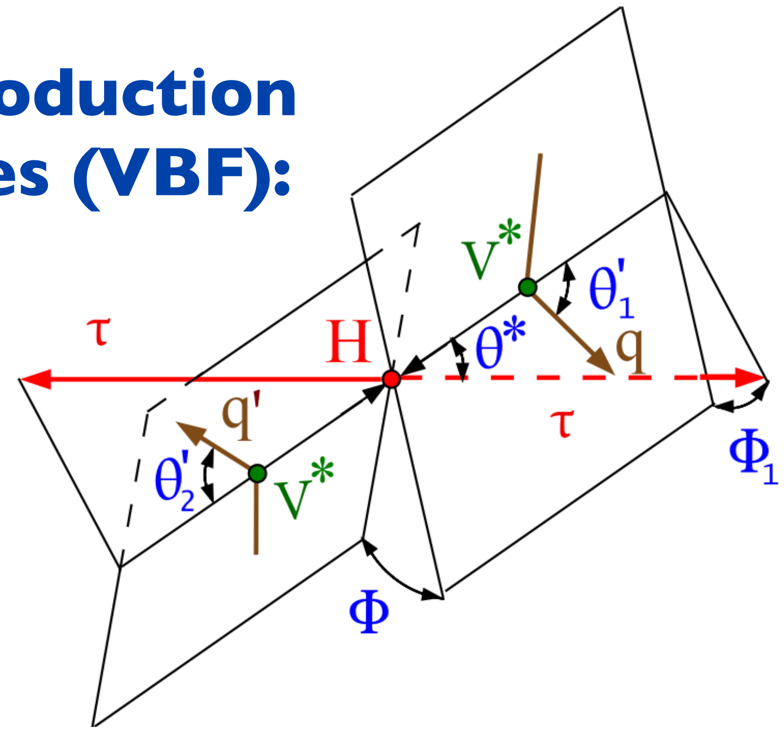


- Higgs width (indirect; includes off-shell Higgs signal strength, with assumptions)
- ATLAS width observed (expected): **PLB 786 (2018) 223**
  - < 14.4 MeV (15.2 MeV)
- CMS width observed (expected): **arXiv:1901.00174**
  - $3.2^{+2.8}_{-2.2}$ MeV ($4.1^{+5.0}_{-4.0}$ MeV)

Higgs Boson Properties: J^{CP}

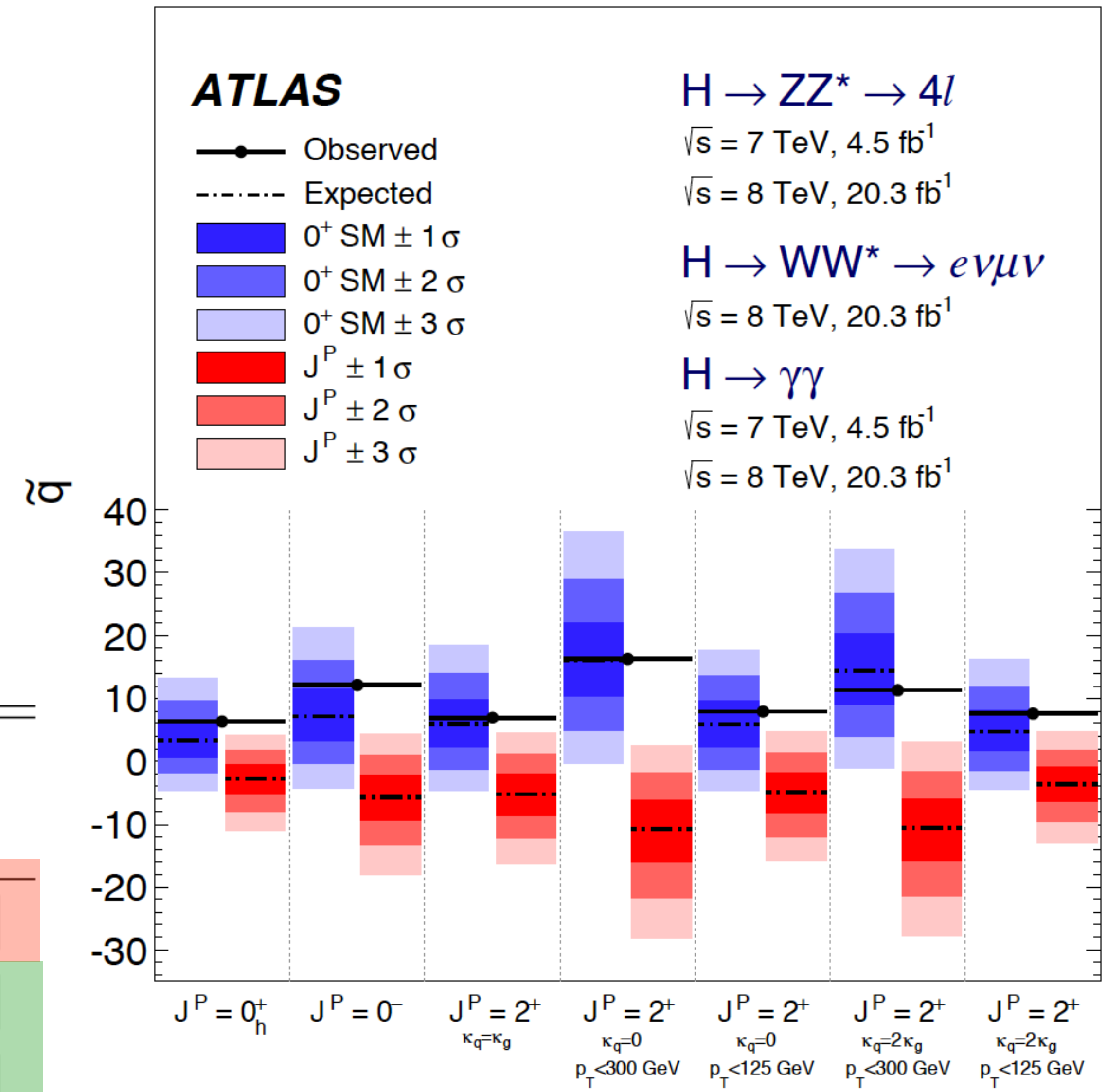
- Predicted by the Standard Model: CP-even with spin and parity $J^{PC} = 0^{++}$
- Most investigations to-date have focused on the couplings to bosons
- Admixtures of CP even and CP odd couplings are certainly still allowed

Definition of production and decay angles (VBF):



CMS

Parameter	Observed / (10^{-3}) 68% CL	Observed / (10^{-3}) 95% CL	Expected / (10^{-3}) 68% CL	Expected / (10^{-3}) 95% CL
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$	$[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$	$[-4.0, 4.2]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.53}_{-0.09}$	$[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$	$[-0.5, 1.7]$
$f^{Z\gamma}_{\Lambda 1}\cos(\phi^{Z\gamma}_{\Lambda 1})$	$0.0^{+1.1}_{-1.3}$	$[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$	$[-11, 8.0]$



EPJC 75 (2015) 476

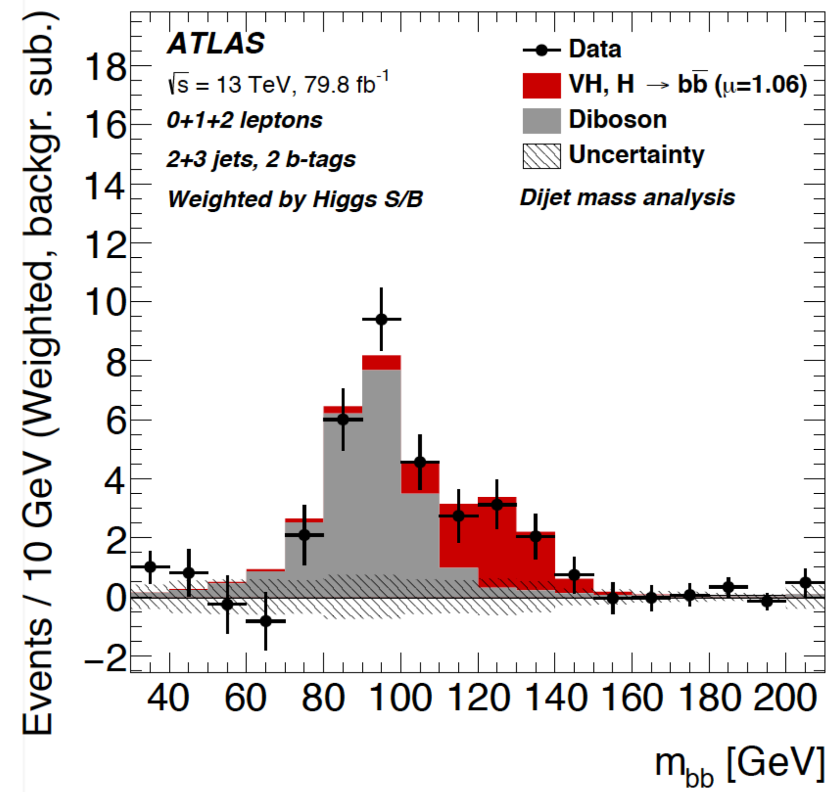
- Results from CMS for CP-violating and CP-conserving parameters (above) are consistent with the SM

arXiv:1903.06973

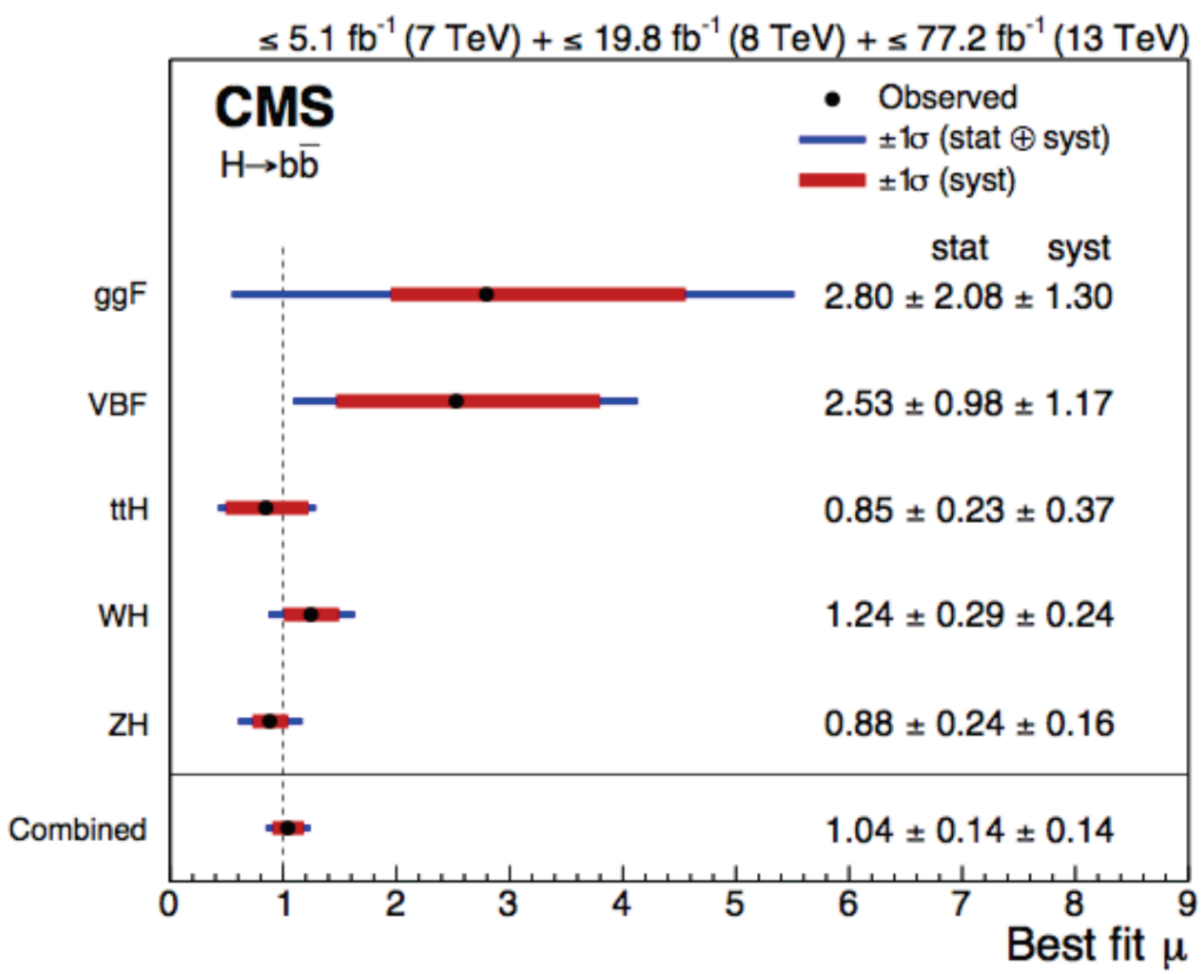
Higgs Boson Decays to Bottom Quarks

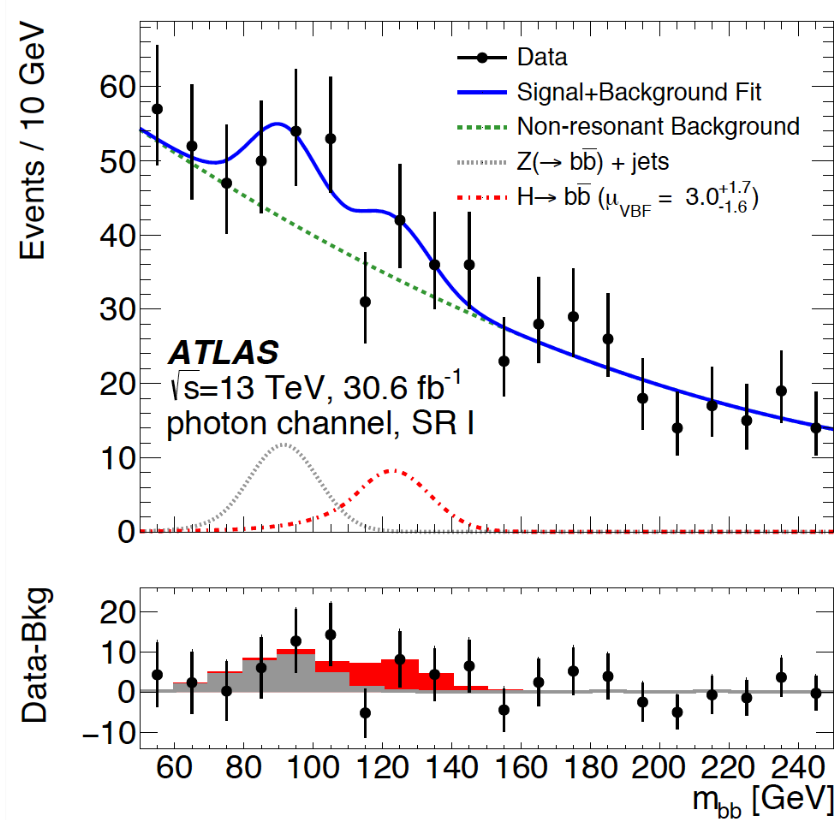
- Most sensitive production mode: VH
- Additional searches using ggF, VBF and ttH production
- Observed with 5.4σ (5.5σ) by ATLAS and 5.6σ (5.5σ) by CMS
- Observation of VZ(bb) production serves as a cross-check

PLB 786 (2018) 59



VH





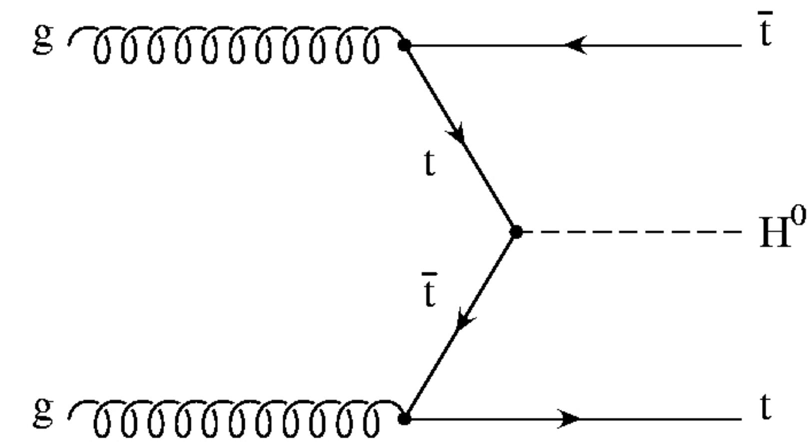
VBF

PRL 121 (2018) 121801

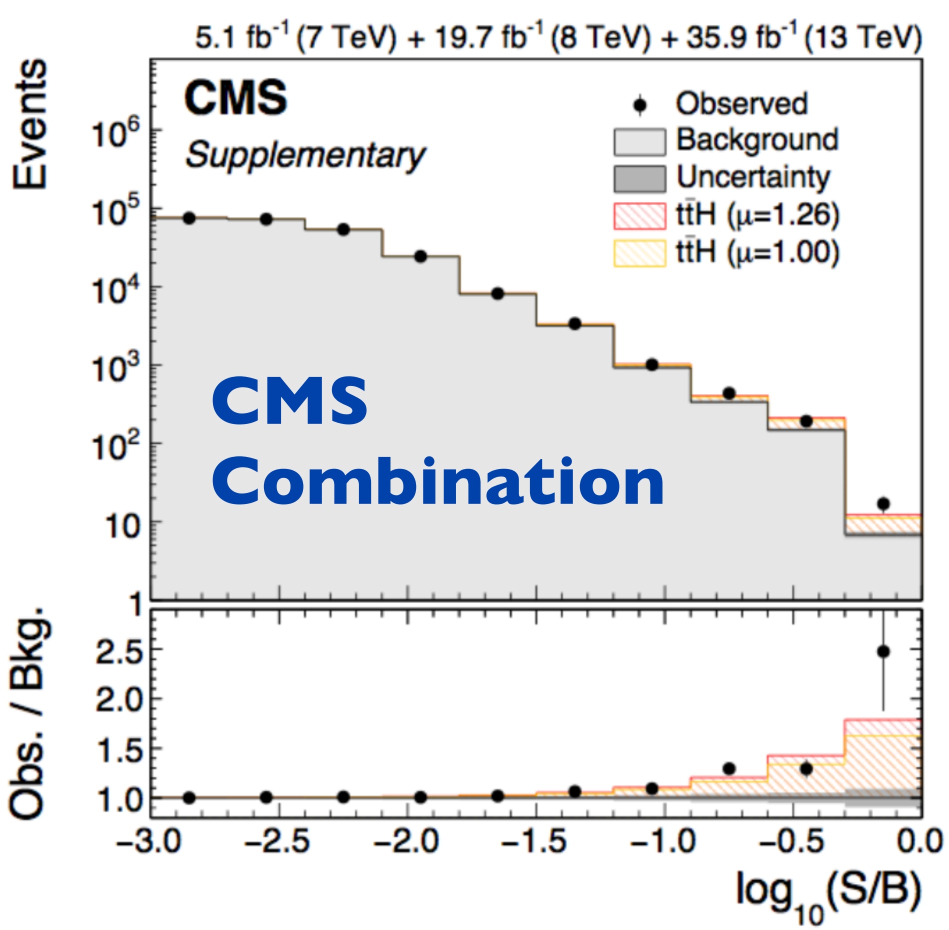
PRD 98 (2018) 052003

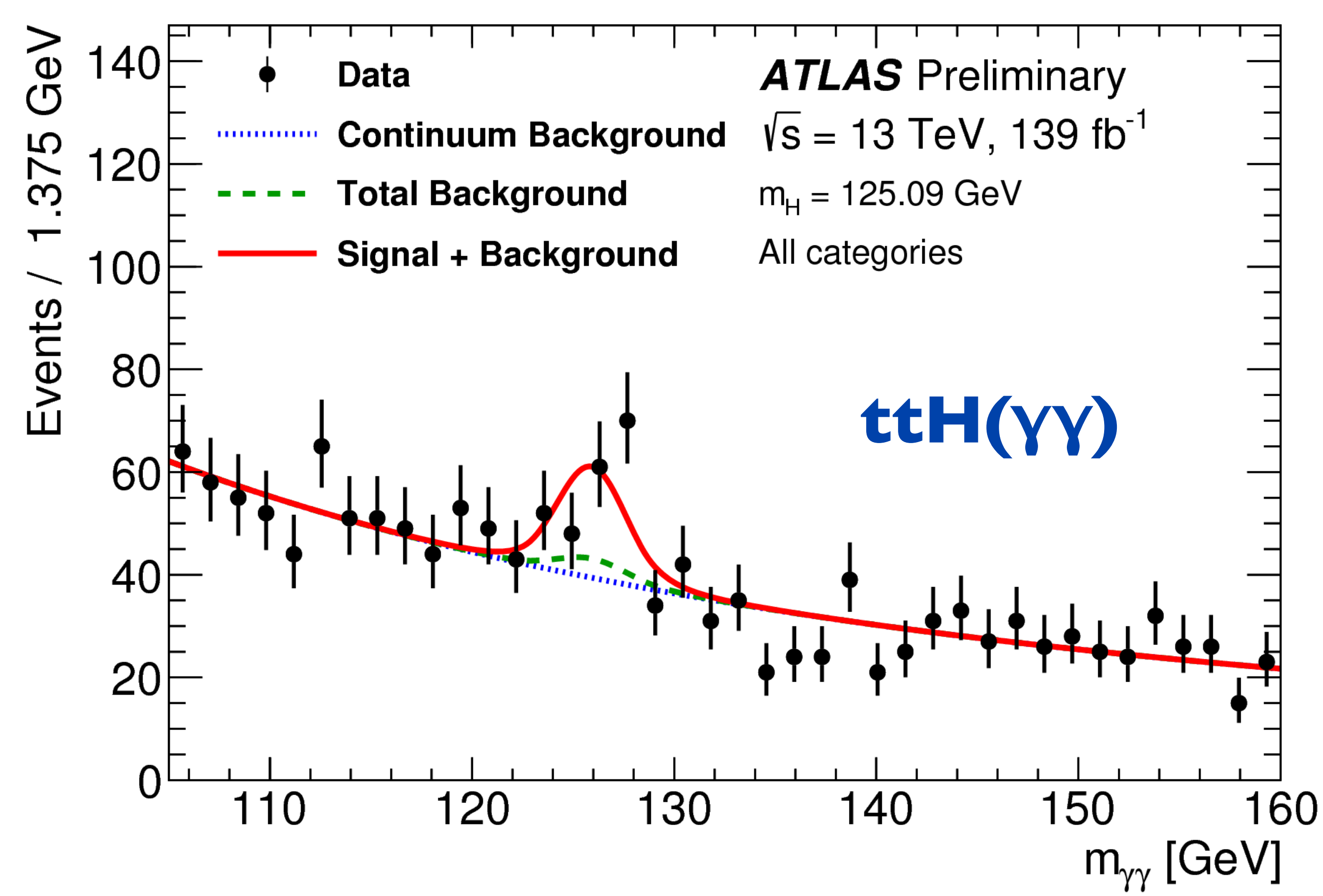
Higgs Production in Association with Top Quarks

- A direct probe of the coupling of the Higgs boson to top quarks is provided by ttH
  - Sensitive to contributions from new physics in the gluon-fusion loop
  - Combination of many decay channels: bb, WW*, ττ, γγ, ZZ*



- Observation at 6.3σ (5.1σ) from ATLAS **PLB 784 (2018) 173**
- CMS observation at 5.2σ (4.2σ) **PRL 120 (2018) 231801**



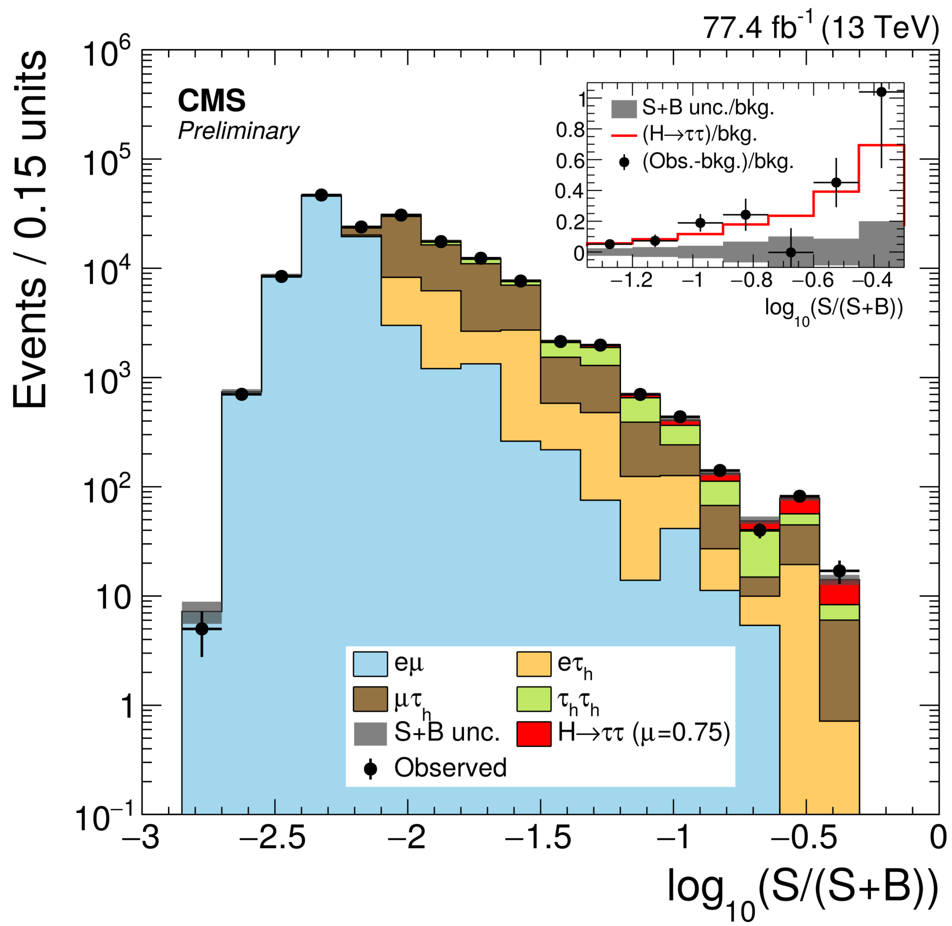


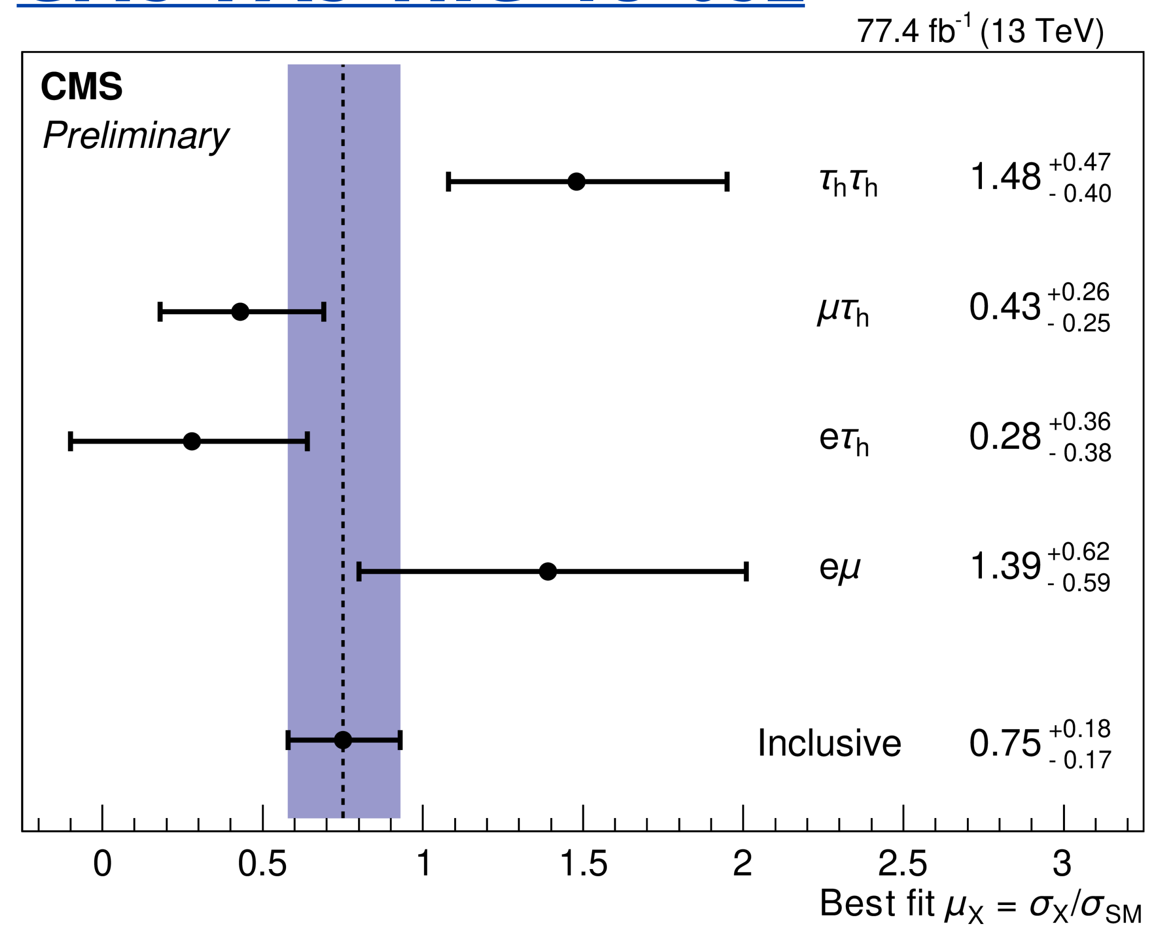
ATLAS-CONF-2019-004

Higgs Boson Decays to Tau Pairs

- New result from CMS which targets the ggF and VBF production modes
- After observation on 2016 data, new techniques applied on same + additional data
- Multi-class Neural Network: one category per process (ggF, VBF, each bkg), 10% improvement
- Improved background modeling for genuine taus (embedding) and reducible background (fake rate method)

CMS-PAS-HIG-18-032





Earlier CMS results on 36 fb^{-1} of data: $\mu = 1.09^{+0.27}_{-0.26}$

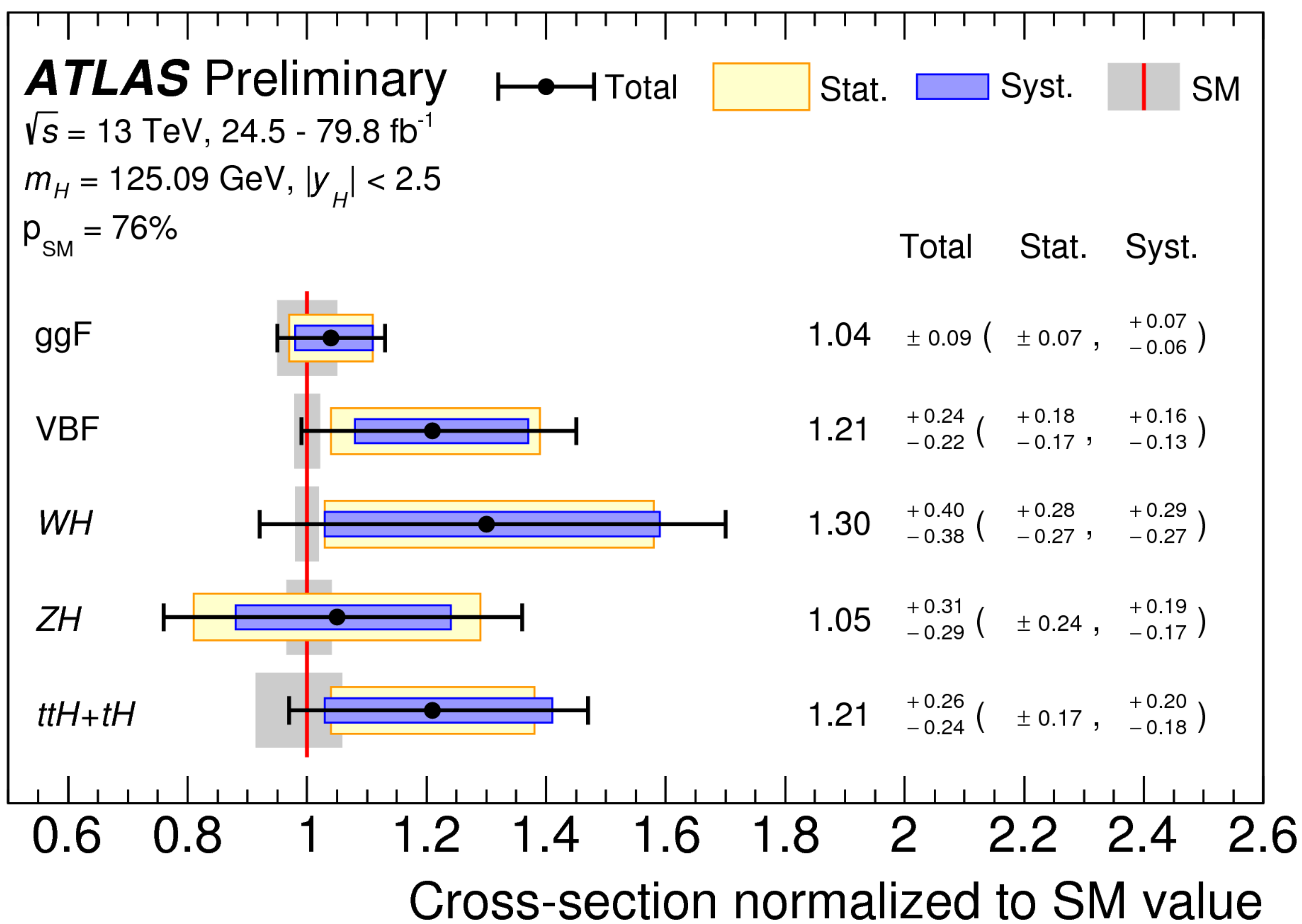
- Of course ATLAS also has results on this channel **arXiv: 1811.08856**

Higgs Boson Production and Couplings

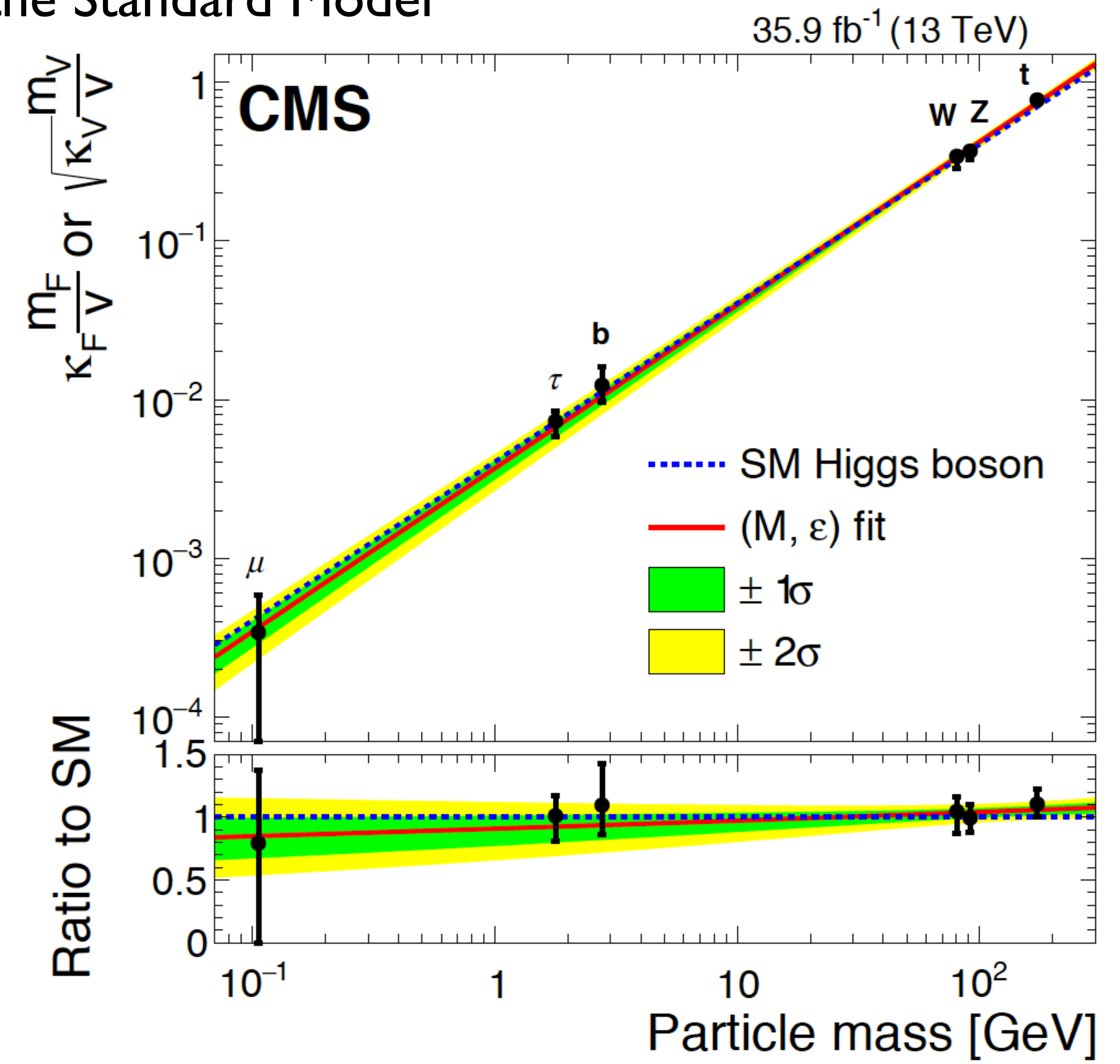
- Significances above 5σ are obtained for ggF, VBF (6.5σ), VH (5.3σ) and ttH (5.8σ) production modes when assuming SM branching ratios (ATLAS results are listed)
- Results are interpreted in the κ framework as a function of the particle mass (assuming no BSM contributions to the total width)

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}}$$

- Results are consistent with predictions from the Standard Model



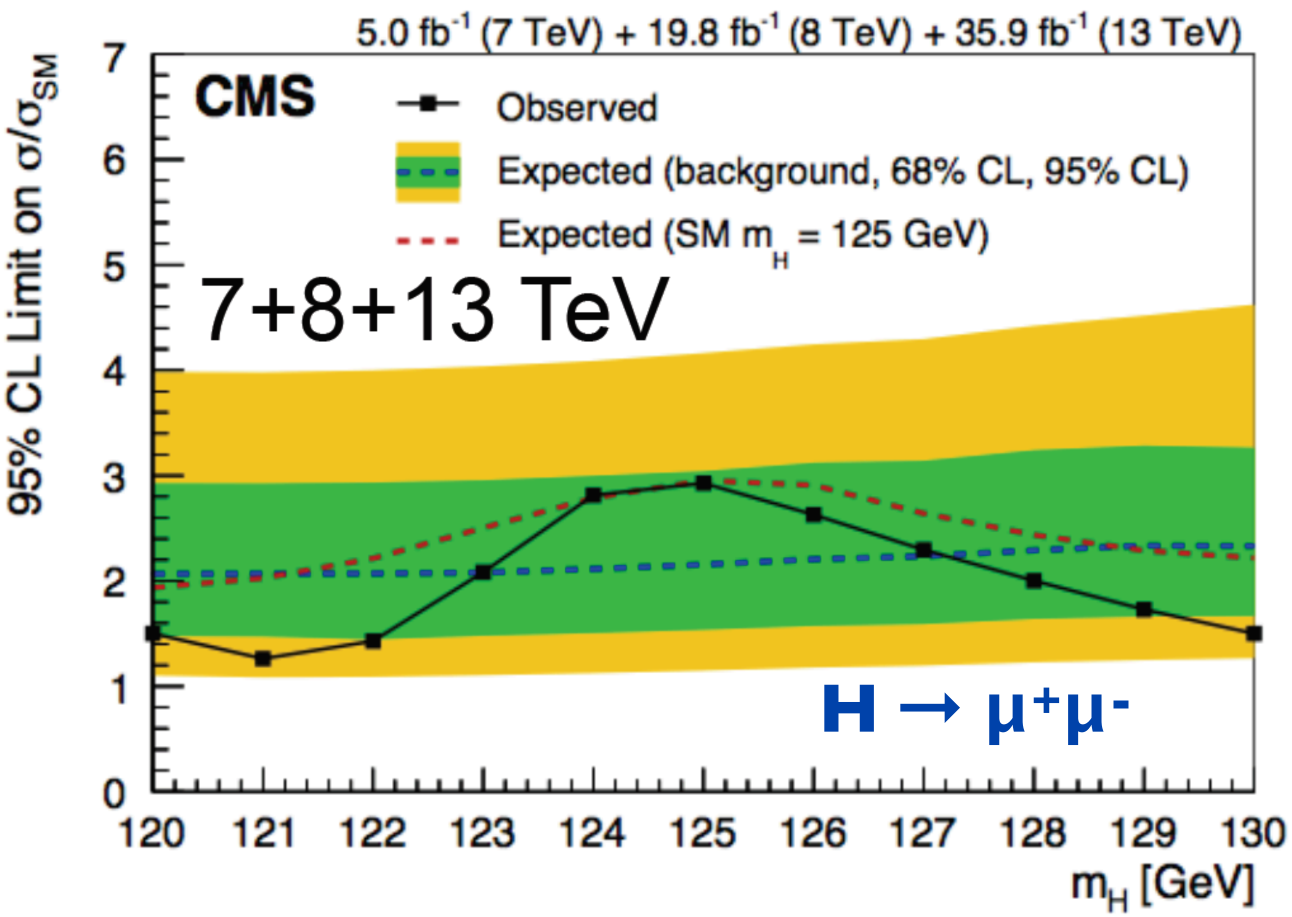
ATLAS-CONF-2019-005



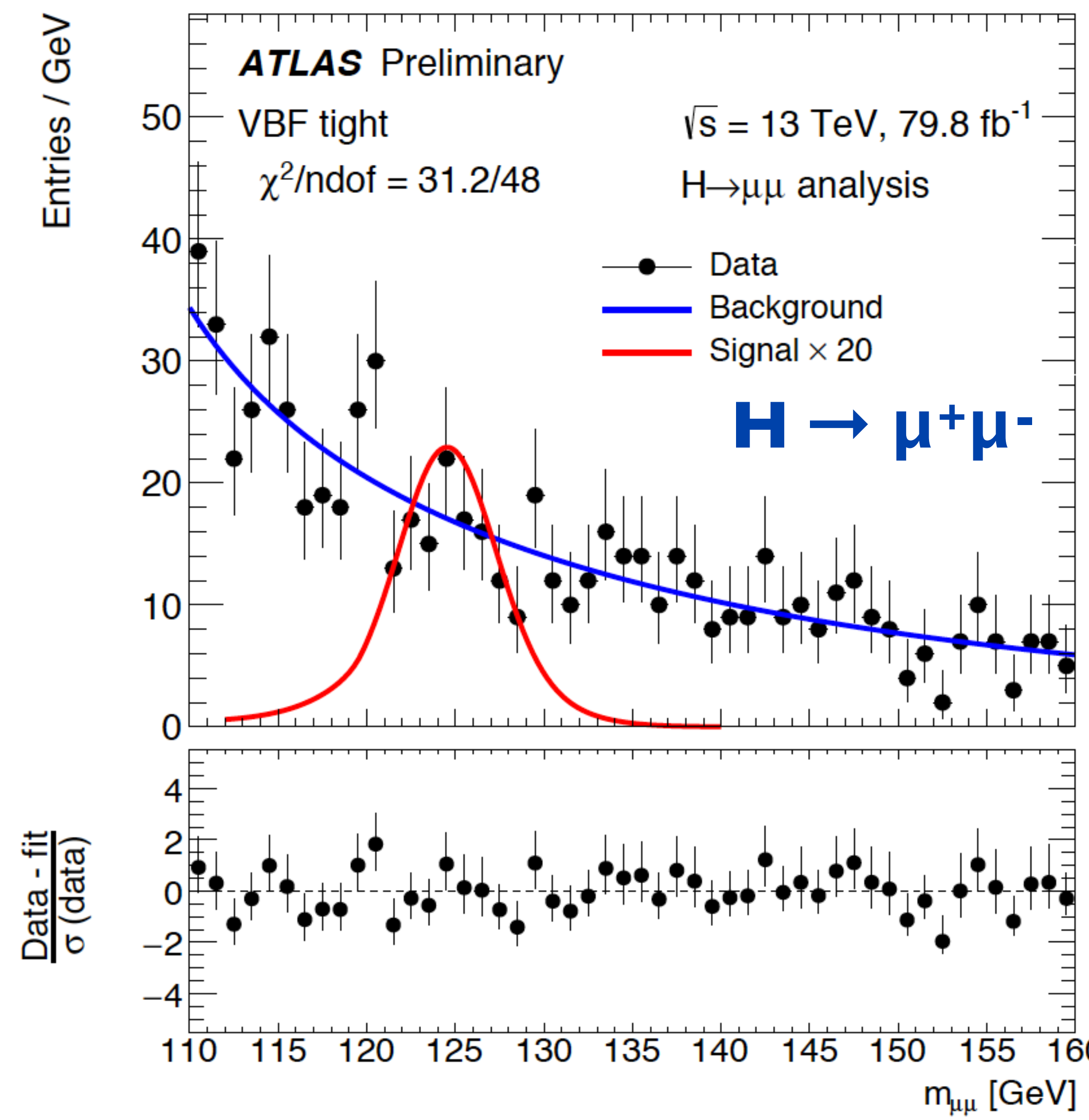
arXiv:1809.10733

Rare Decays of the Higgs Boson

- Getting closer to an observation; 95% CL upper limit on σ*BR:
  - ATLAS: $H \rightarrow \mu^+\mu^- < 2.1\ (2.0) \times$ SM
  - CMS: $H \rightarrow \mu^+\mu^- < 2.9\ (2.2) \times$ SM



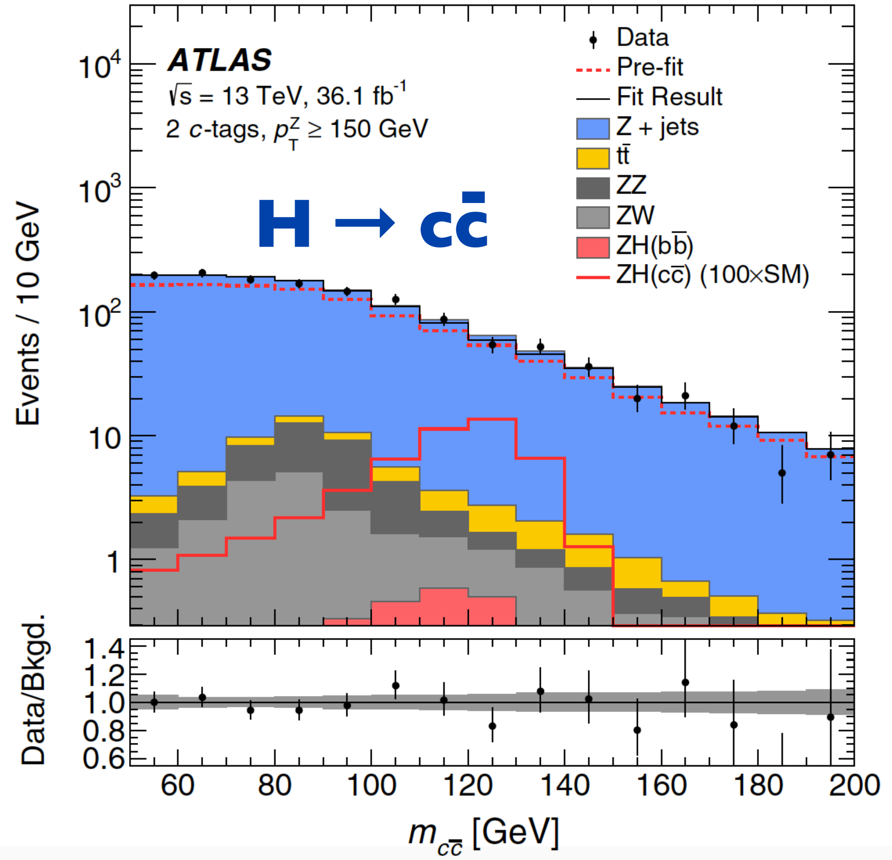
PRL 122 (2019) 021801



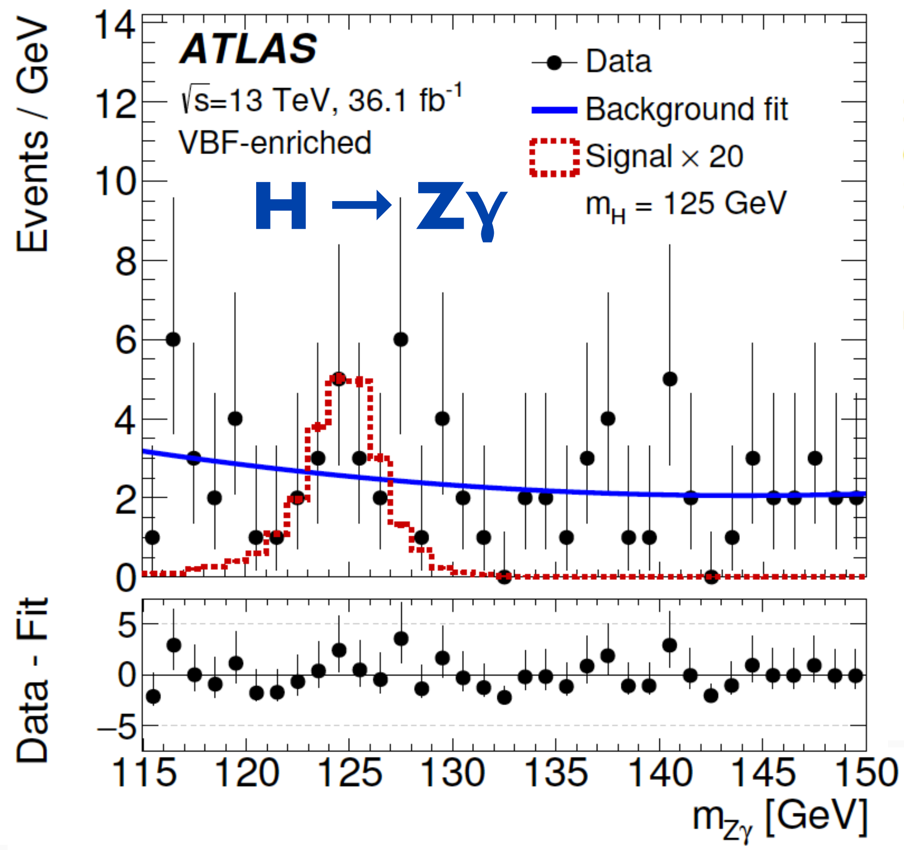
ATLAS-CONF-2018-026

Rare Decays of the Higgs Boson

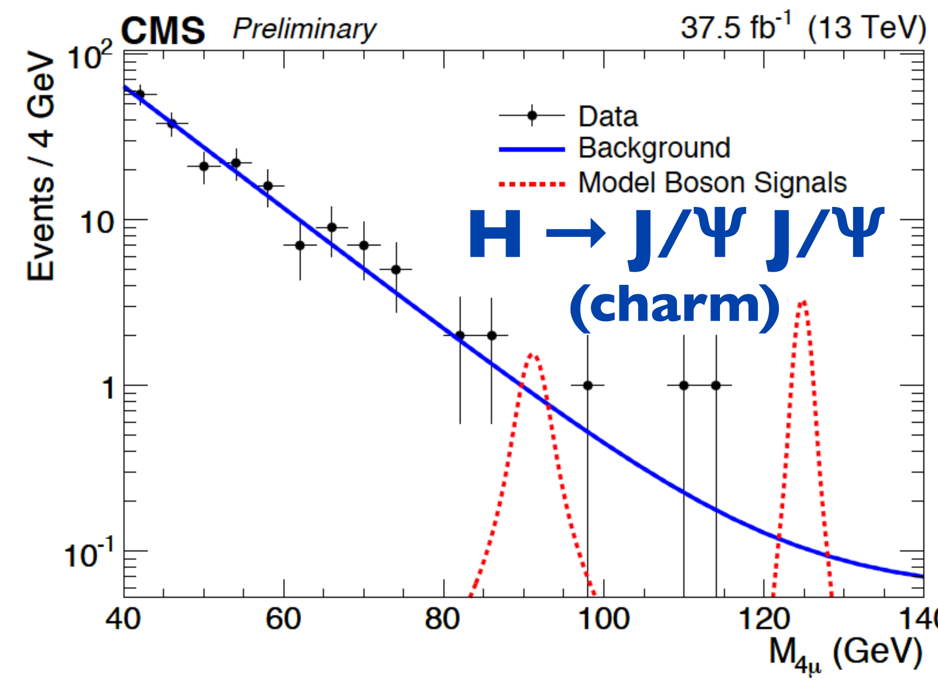
- Progressively stronger limits as the size of the LHC dataset grows…



PRL 120 (2018) 211802



JHEP 10 (2017) 112

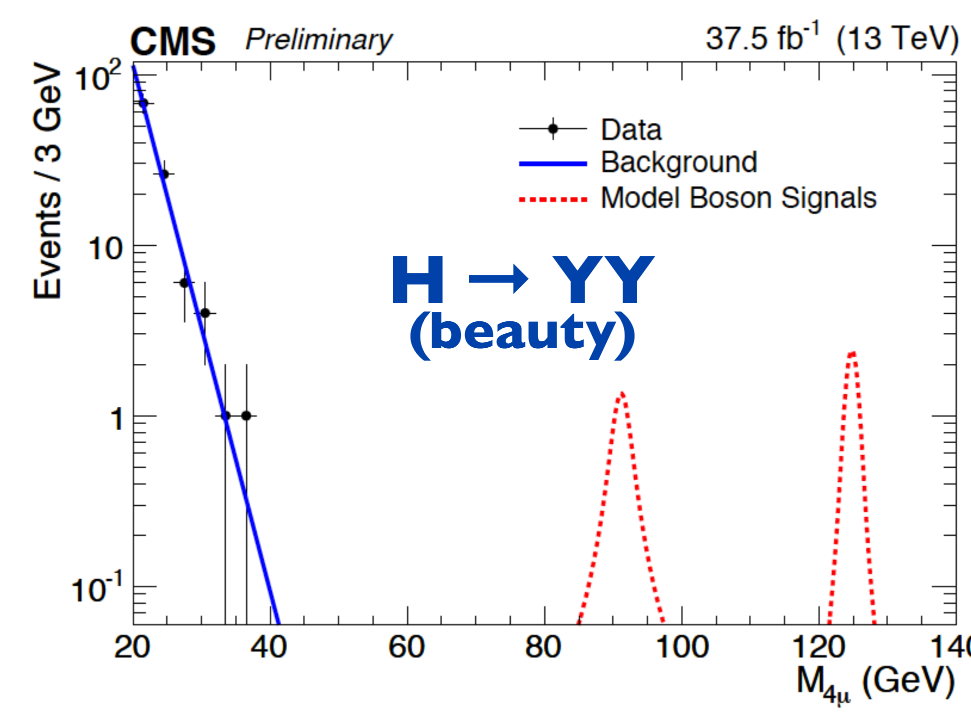


CMS-PAS-HIG-18-025

H → ϕγ (strange)

H → ργ (up/down)

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25

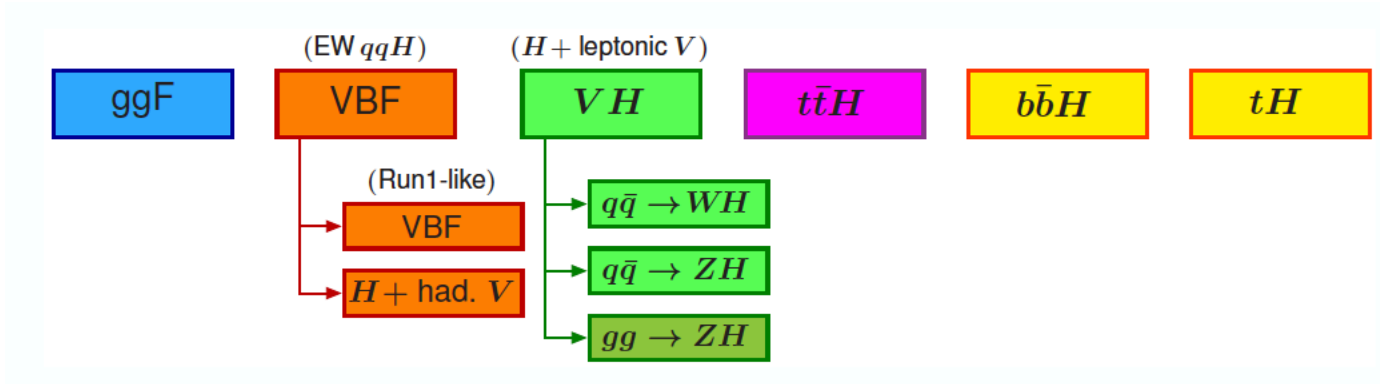


ATLAS JHEP 07 (2018) 127

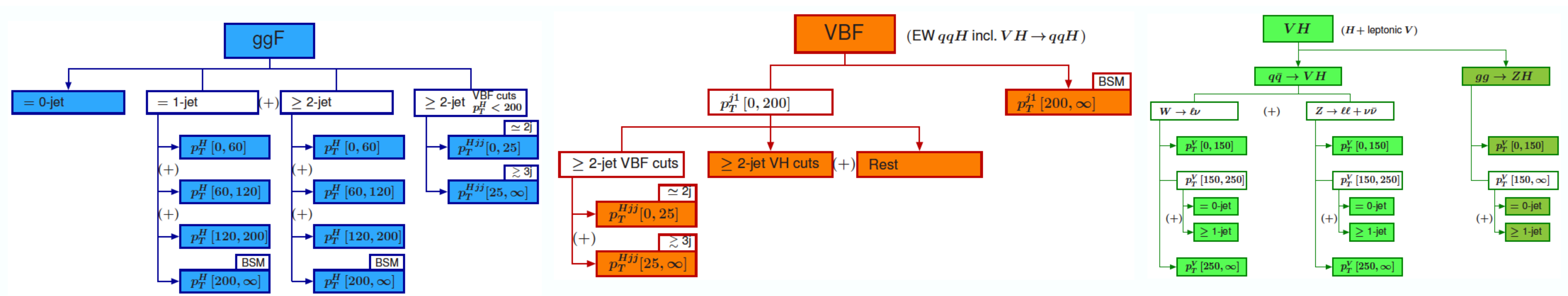
Higgs Boson Properties: Cross Section

- Simplified template cross-sections (STXS)
  - Defines the cross-sections in exclusive fiducial regions
  - Minimize theory dependence, maximize experimental sensitivity

Stage-0



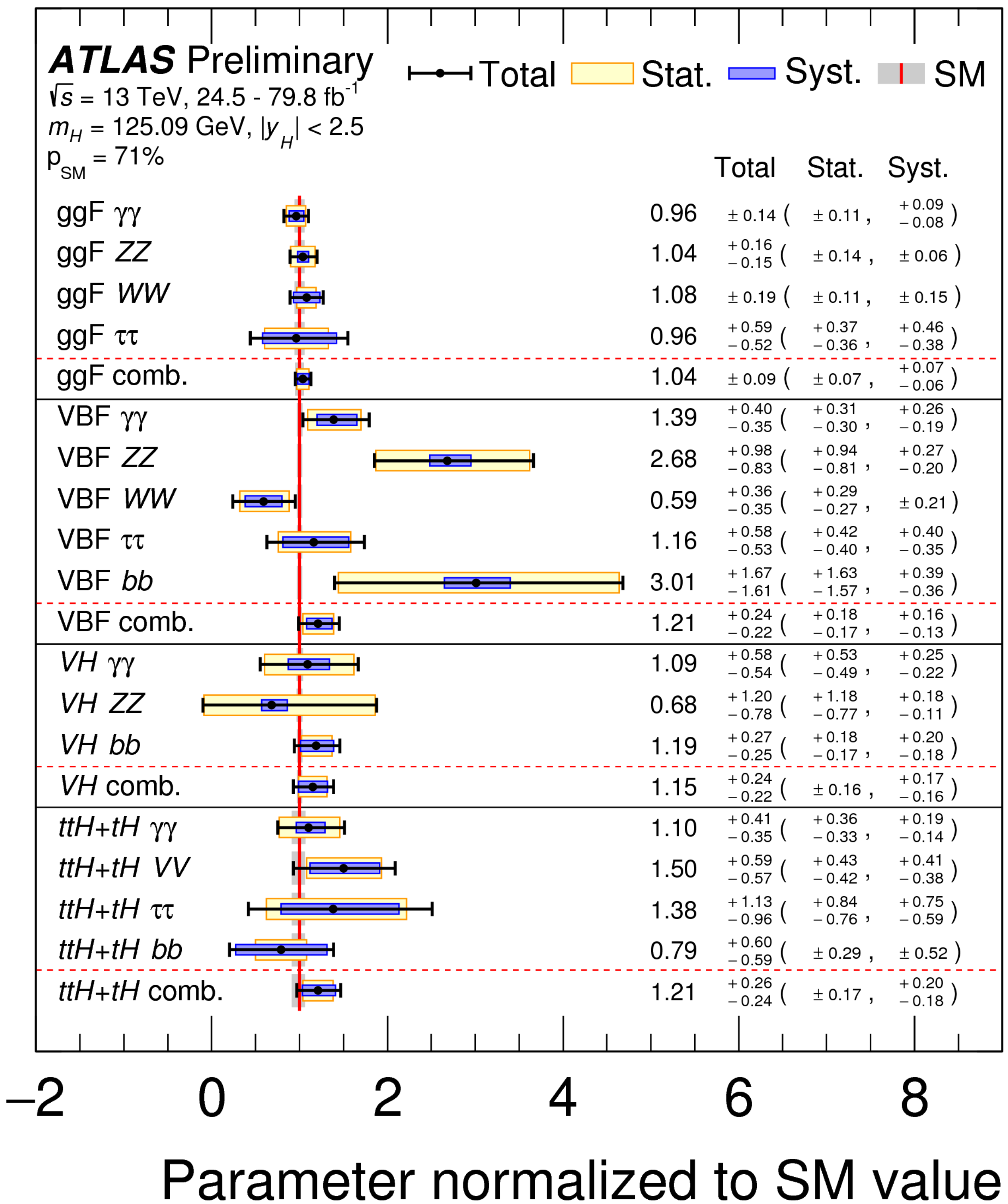
Stage-1

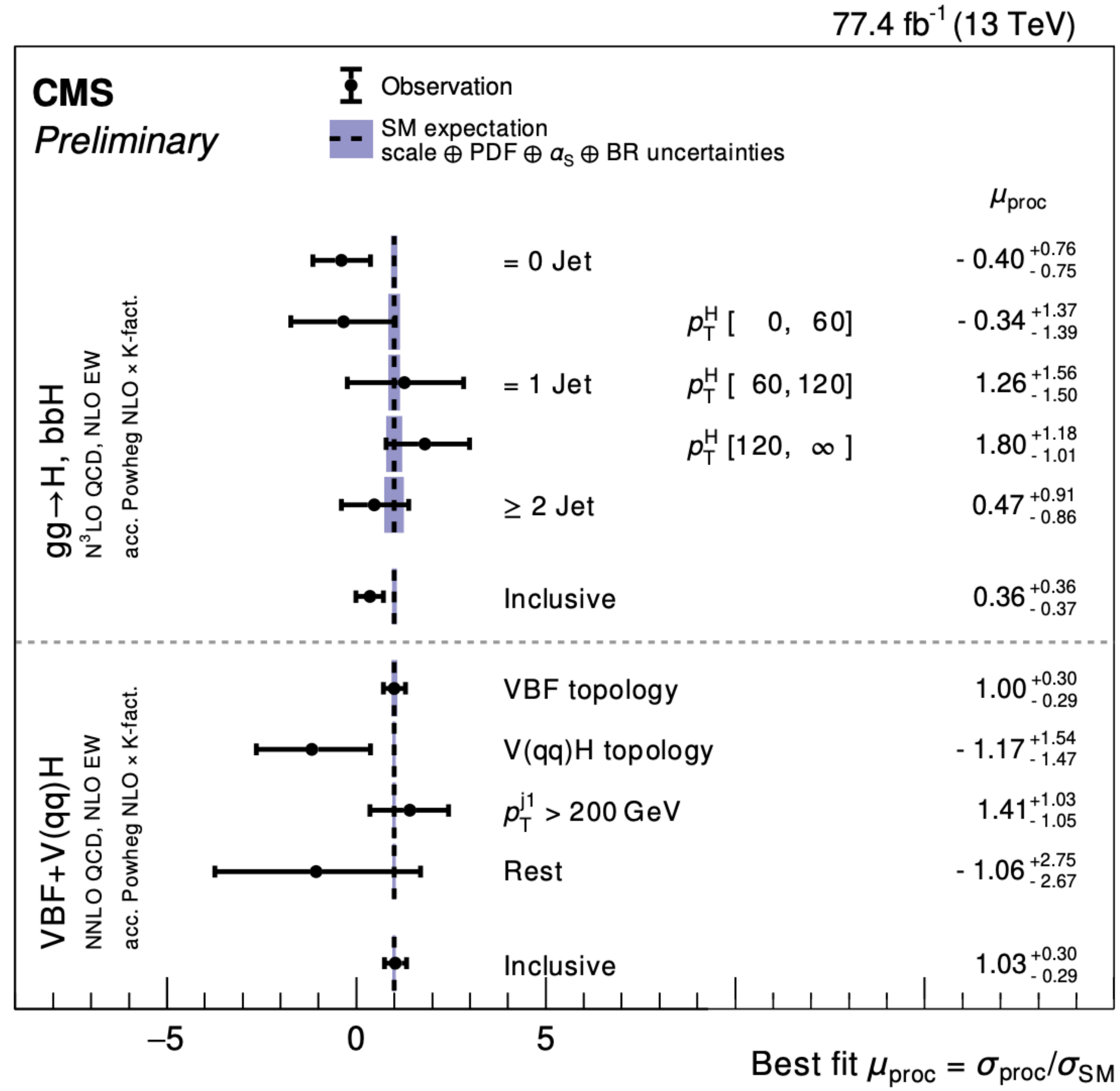


LHC Higgs XSWG YR4

Higgs Boson Properties: Cross Section

- ATLAS: first Stage 1 combination result with 5 main decay modes
- CMS: first Stage 1 $H \rightarrow \tau\tau$ measurement in multiple ggF and VBF bins
- STXS Stage 1.1 results now starting to be released (CMS $H \rightarrow ZZ \rightarrow 4l$)



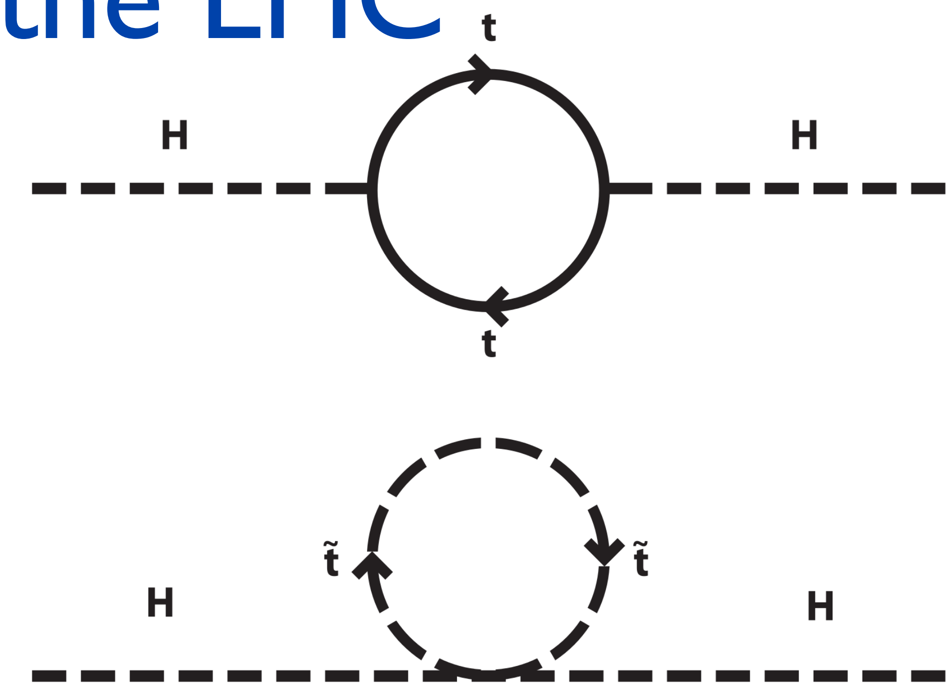


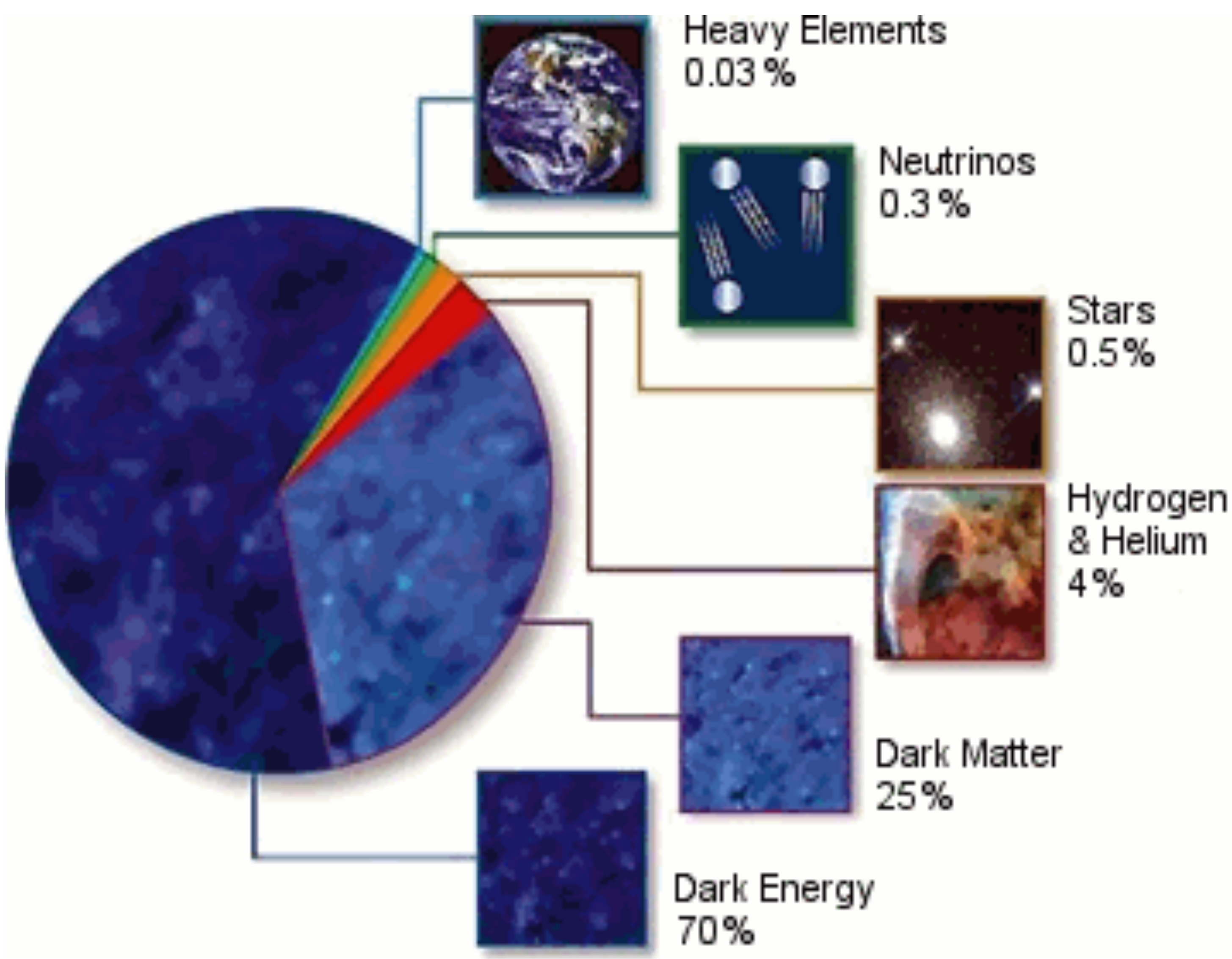
ATLAS-CONF-2019-005

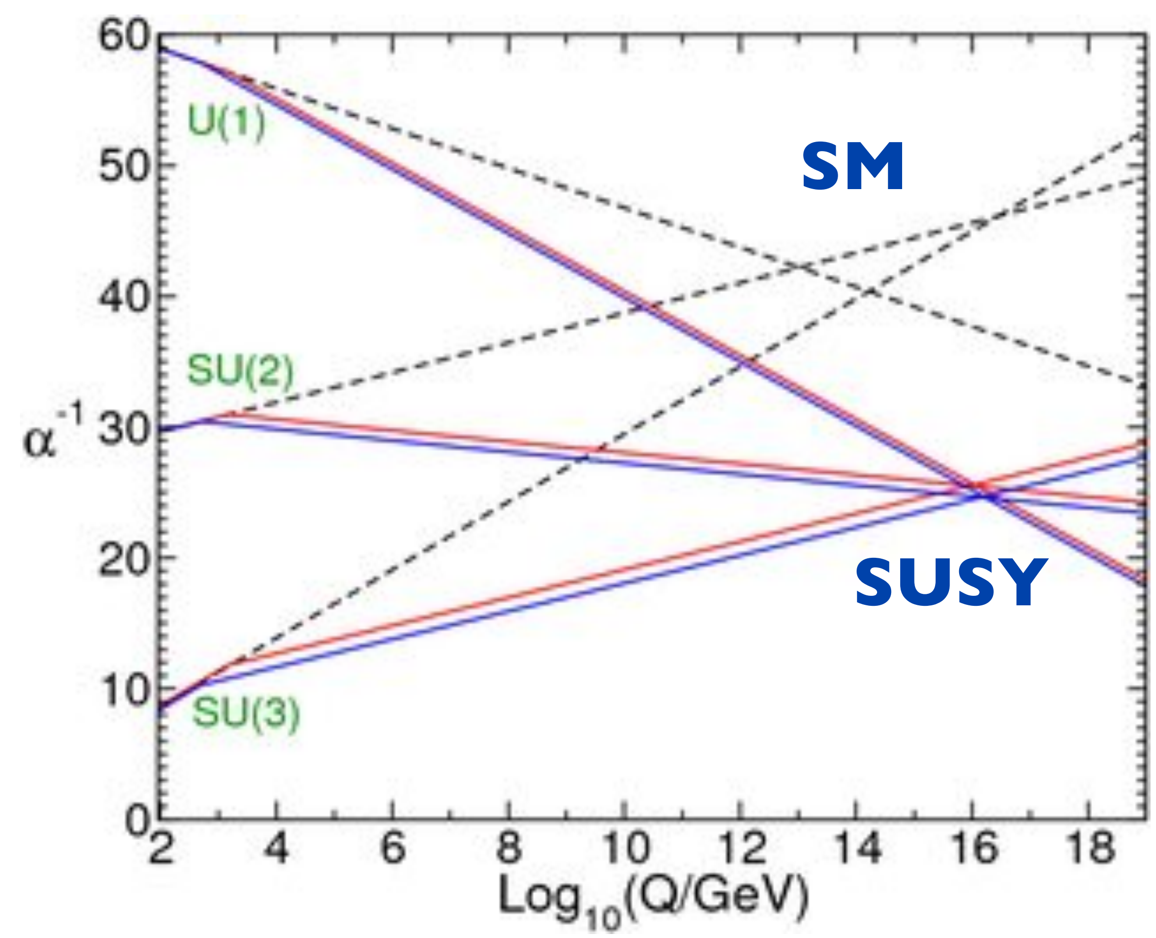
CMS-PAS-HIG-18-032

Breaking Physics at the LHC

- The Standard Model isn't perfect…
  - Naturalness (Hierarchy Problem)
  - Dark Matter
  - Unification of the forces (gauge couplings)

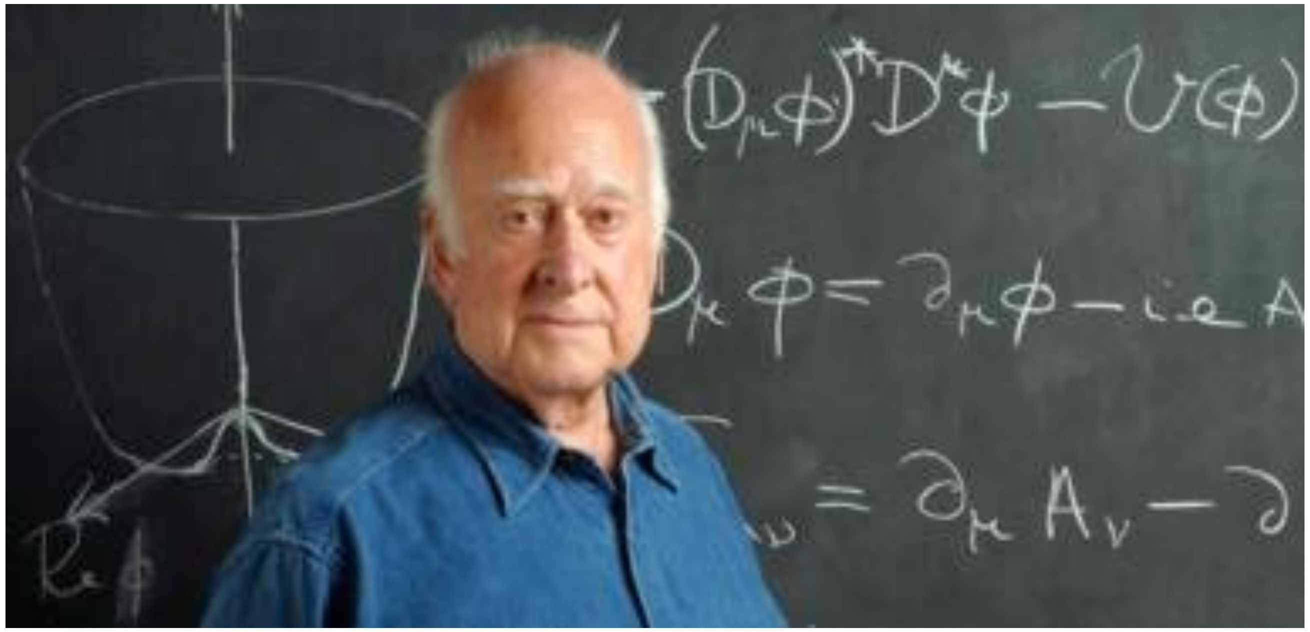




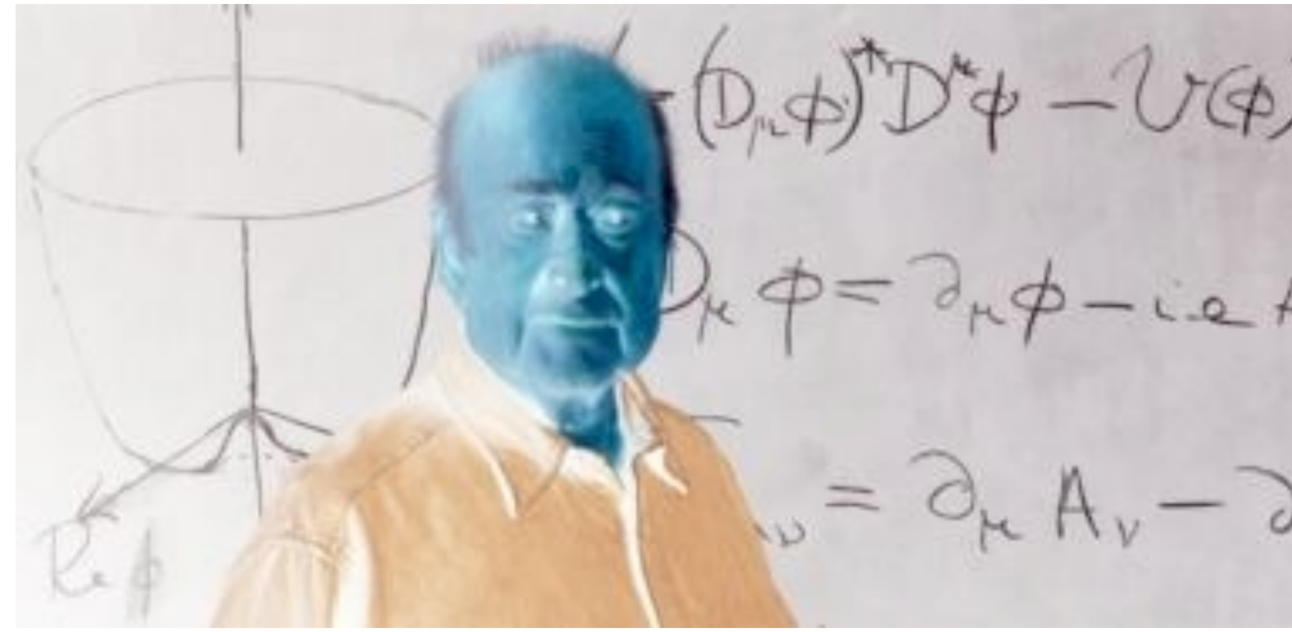


S. Martin SUSY Primer

<u>If</u> the (light) Higgs mass is ~125 GeV, what next?



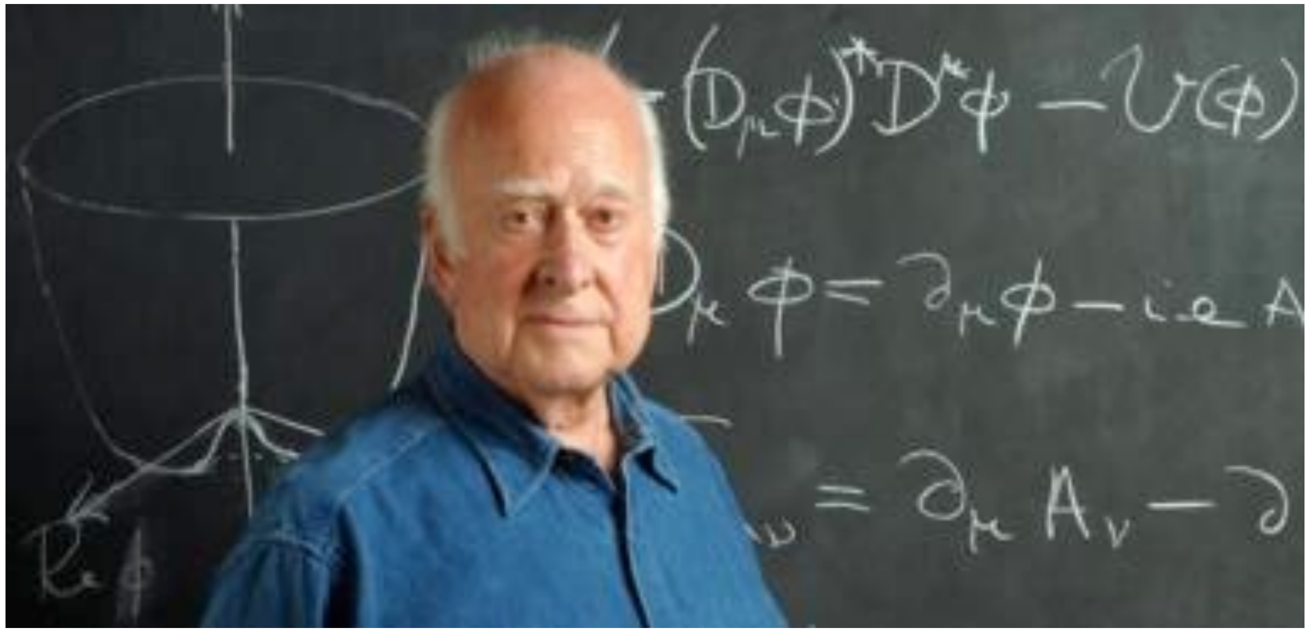
Standard Model Higgs



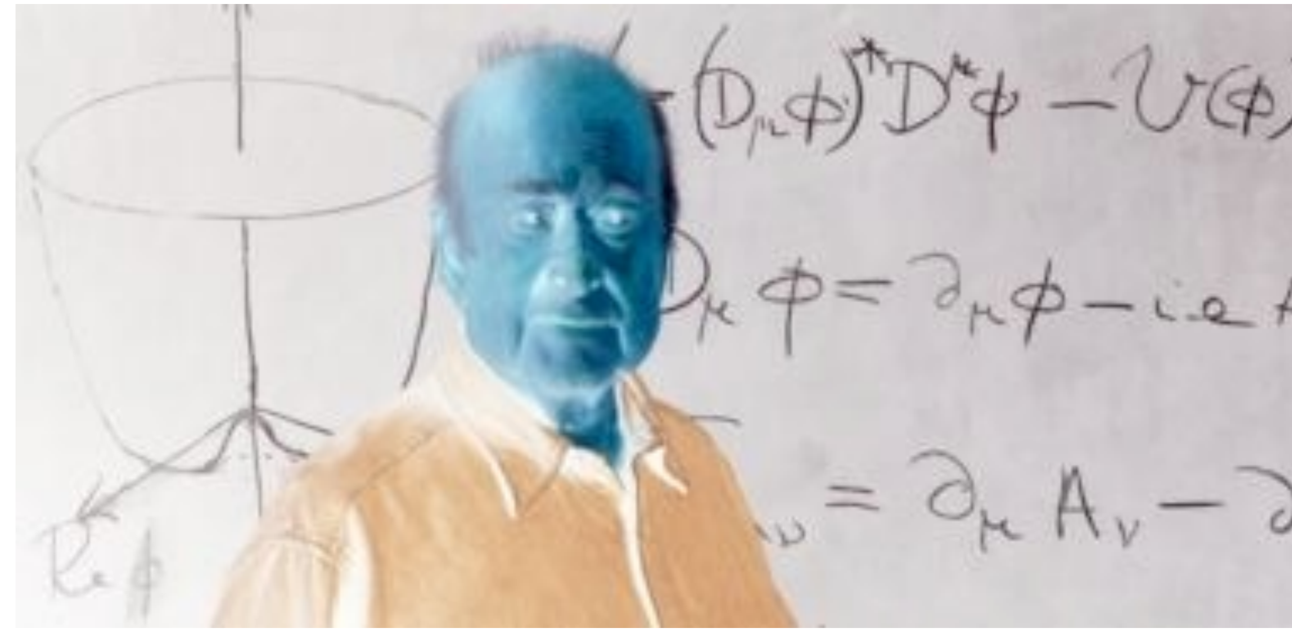
Beyond the SM Higgs

- Suppose that this is not the Standard Model Higgs…
  - In SM just one SU(2) doublet is assumed ⇒ 2HDMs from SUSY or axion models
  - Higgs Triplet Models ⇒ Can provide Majorana neutrinos with masses
  - Add a Singlet to the SM ⇒ Can provide a candidate for Dark Matter
  - Hidden sector particles ⇒ Candidates for Dark Matter
- Thankfully many of these scenarios are compatible with a 125 GeV Higgs…

If the (light) Higgs mass is ~125 GeV, what next?



Standard Model Higgs



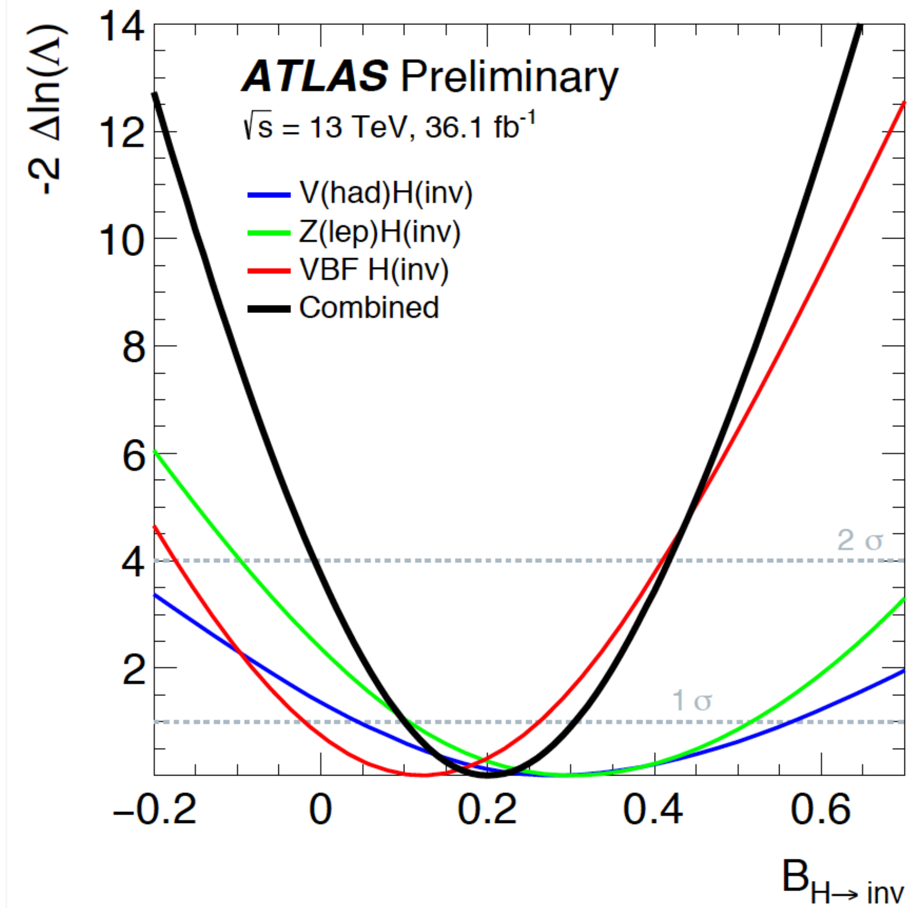
Beyond the SM Higgs

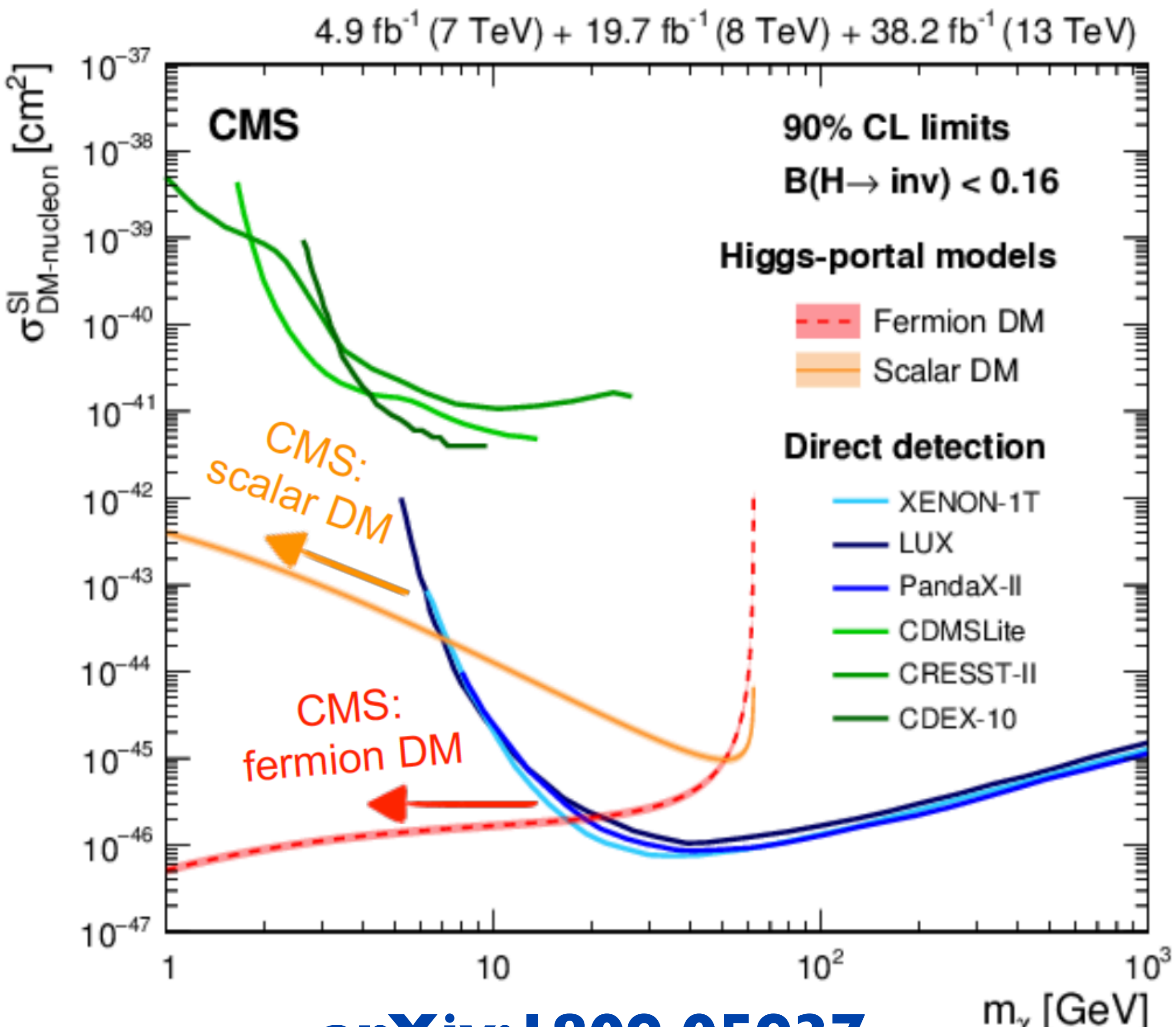
- For example, the MSSM (h, A, H, $H^{\pm}$) is compatible with a 125 GeV Higgs…
  - **hMSSM scenario:** the measured value of 125 GeV can be used to predict masses and decay branching ratios of the other Higgs bosons (m_h fixed; all SUSY particles are heavy)
  - **m_h^{mod} scenario:** top-squark mixing parameter is chosen such that the mass of the lightest CP-even Higgs boson is close to the mass of the one observed at the LHC (historical)
  - **New benchmarks:** six new scenarios proposed in August 2018 (**M_h^{125}**, **M_H^{125}**, etc.) see: **H. Bahl, E. Fuchs, T. Hahn, et al., arXiv: 1808.07542**

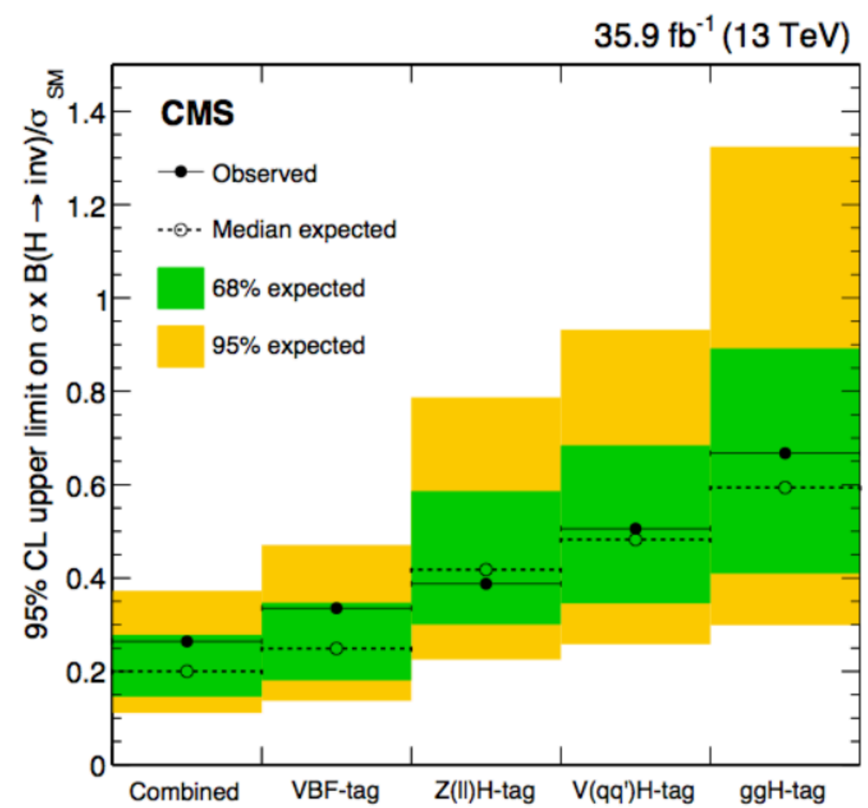
Higgs to Invisible Decays

- Coupling fits provide indirect constraints
- Direct searches for Higgs boson decays to 'invisible' particles
- ATLAS: V(had)H(inv), Z(lep)H(inv), VBF H(inv)
  - $B(H\rightarrow inv) < 0.26\ (0.17^{+0.07}_{-0.05})$ @ 95% CL
- CMS: Combine 7, 8 and 13 TeV results
  - $B(H\rightarrow inv) < 0.19\ (0.15)$ @ 95% CL

ATLAS-CONF-2018-054



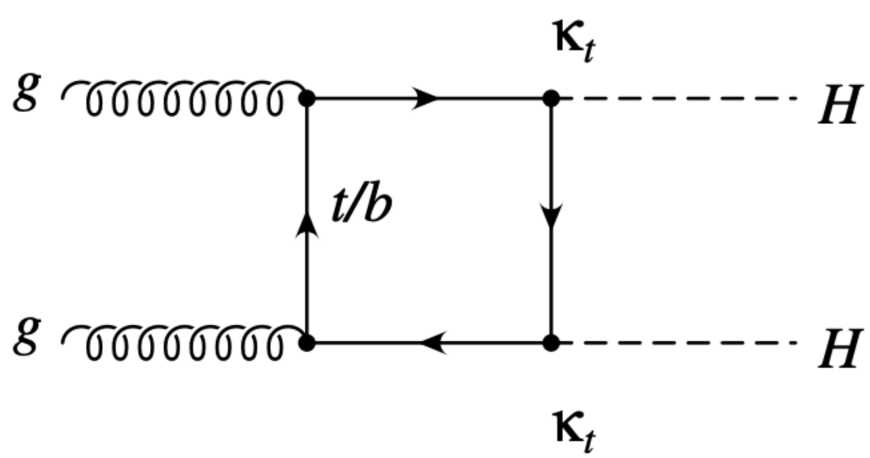


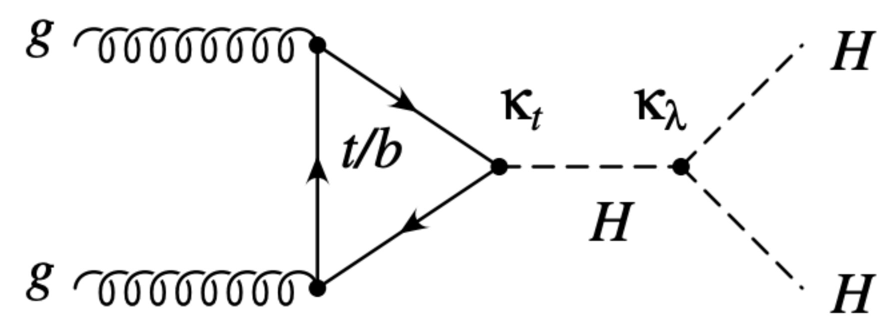


arXiv:1809.05937

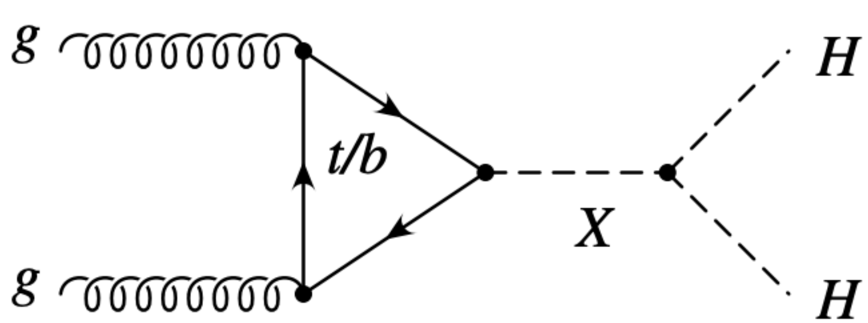
Di-Higgs Search

- Di-Higgs production is very small in the Standard Model due to destructive interference
  - 33.7 fb for proton-proton collisions with CME of 13 TeV (non-resonant)



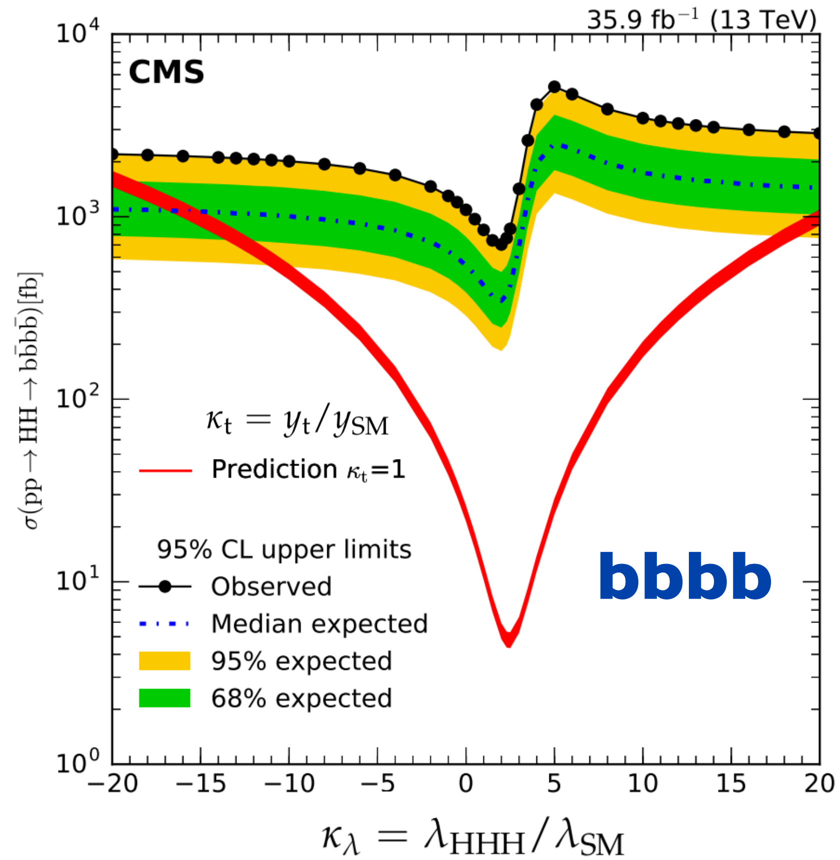


- With physics Beyond the Standard Model, this can be enhanced by:
  - Modified top Yukawa coupling or λ_{hhh} (non-resonant production)
  - Resonant production: 2HDM H→hh, Kaluza-Klein gravitons, etc.

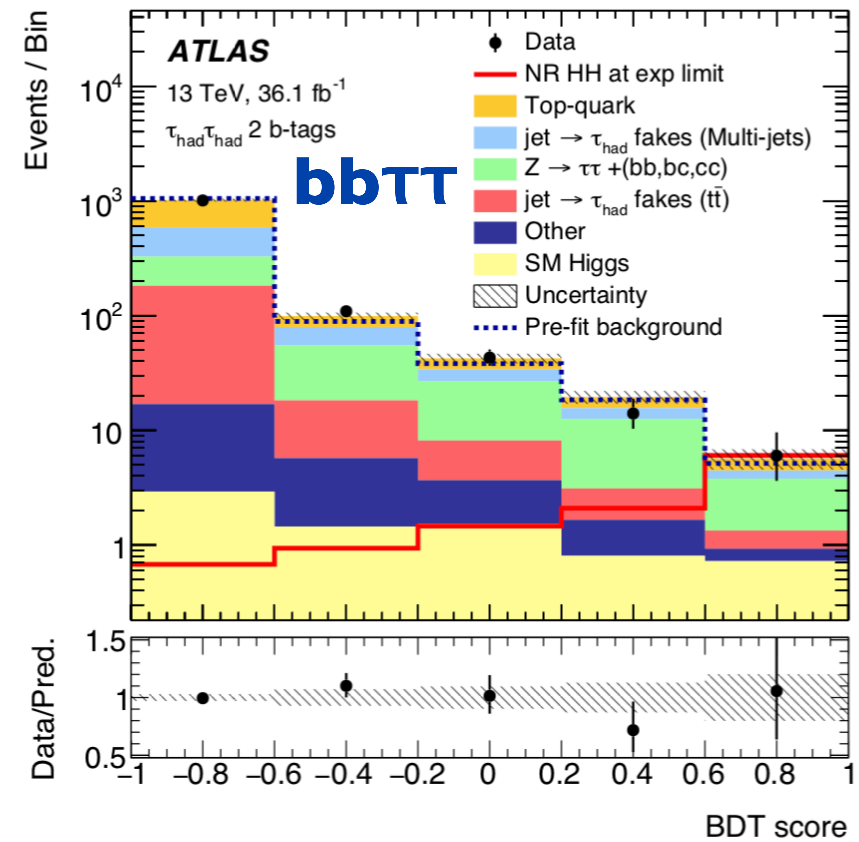


Di-Higgs Search

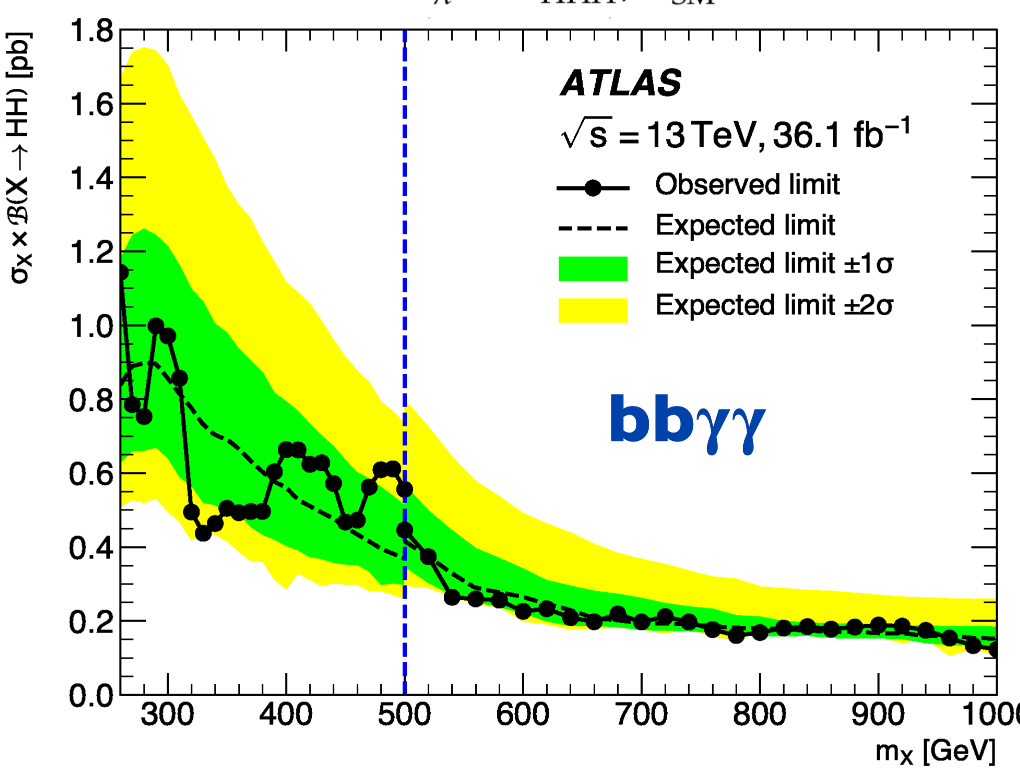
- ATLAS and CMS carry out di-Higgs searches in the bbbb, bbττ, bbγγ and bbVV channels
- A multivariate discriminant (BDT) is often used to separate signal from background
- For the resonant search a different training is used for each value of m_X



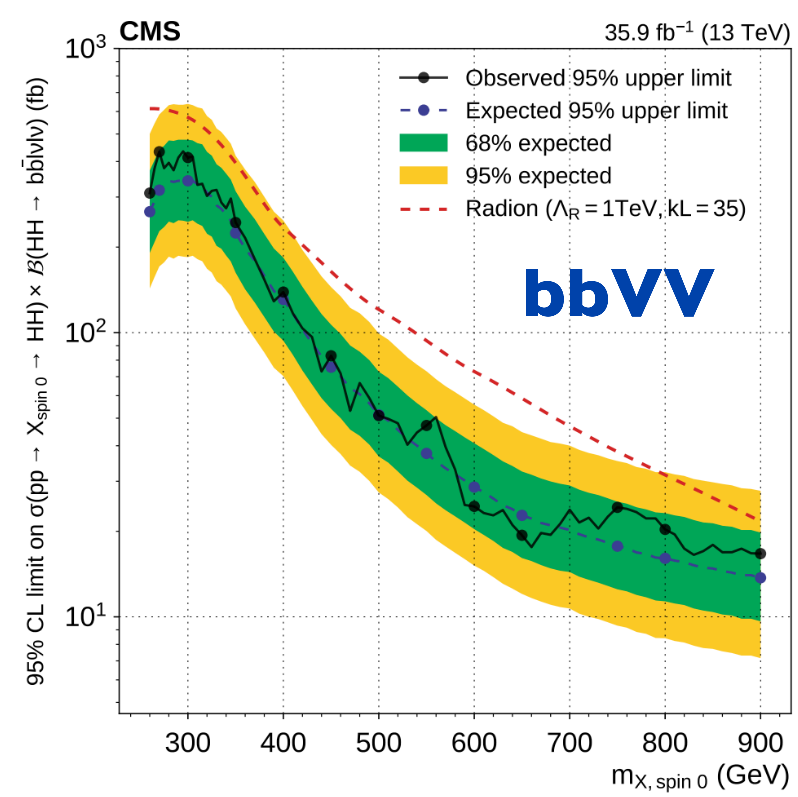
arXiv: 1810.11854



PRL 121 (2018) 191801



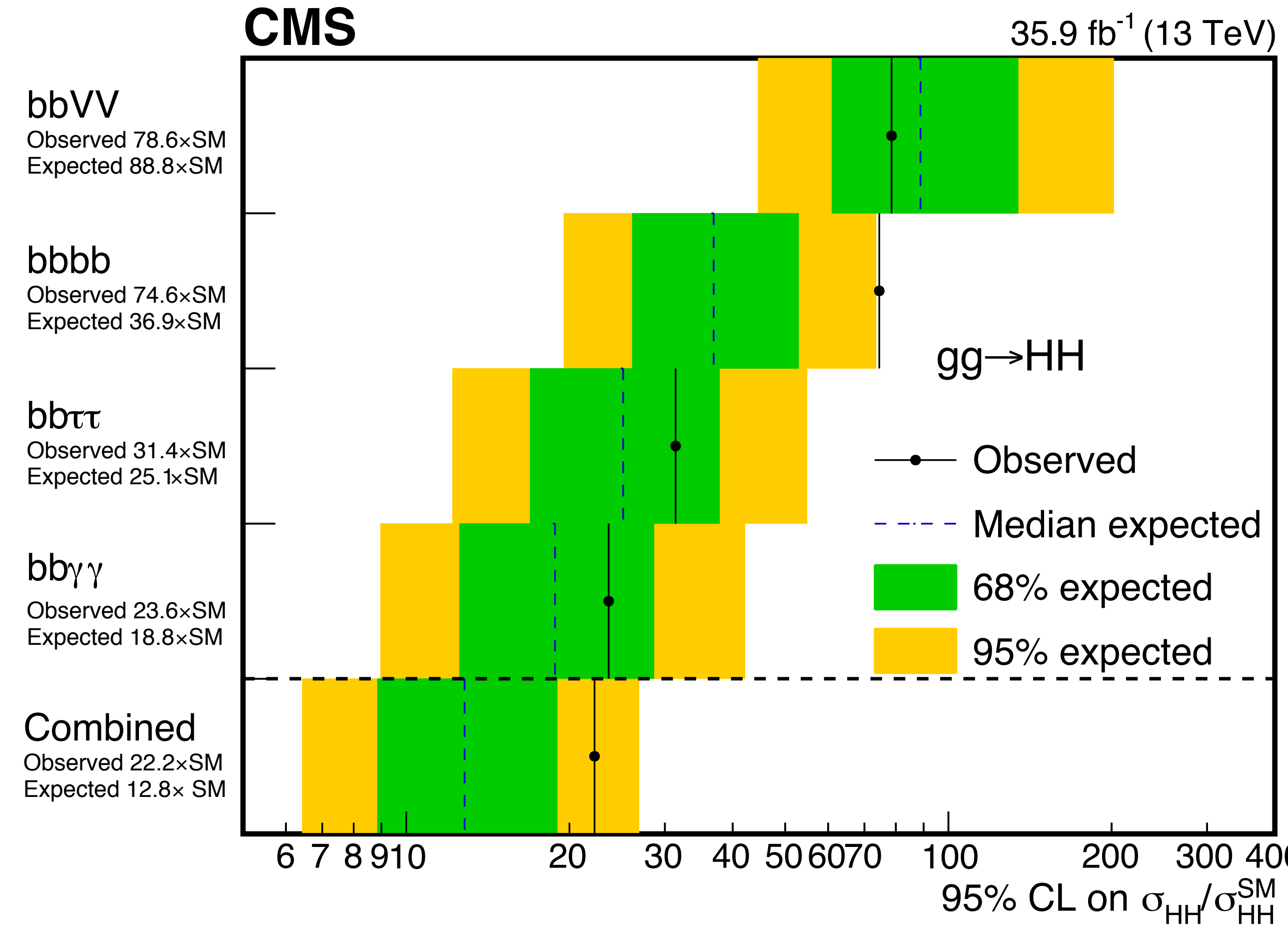
JHEP 11 (2018) 040



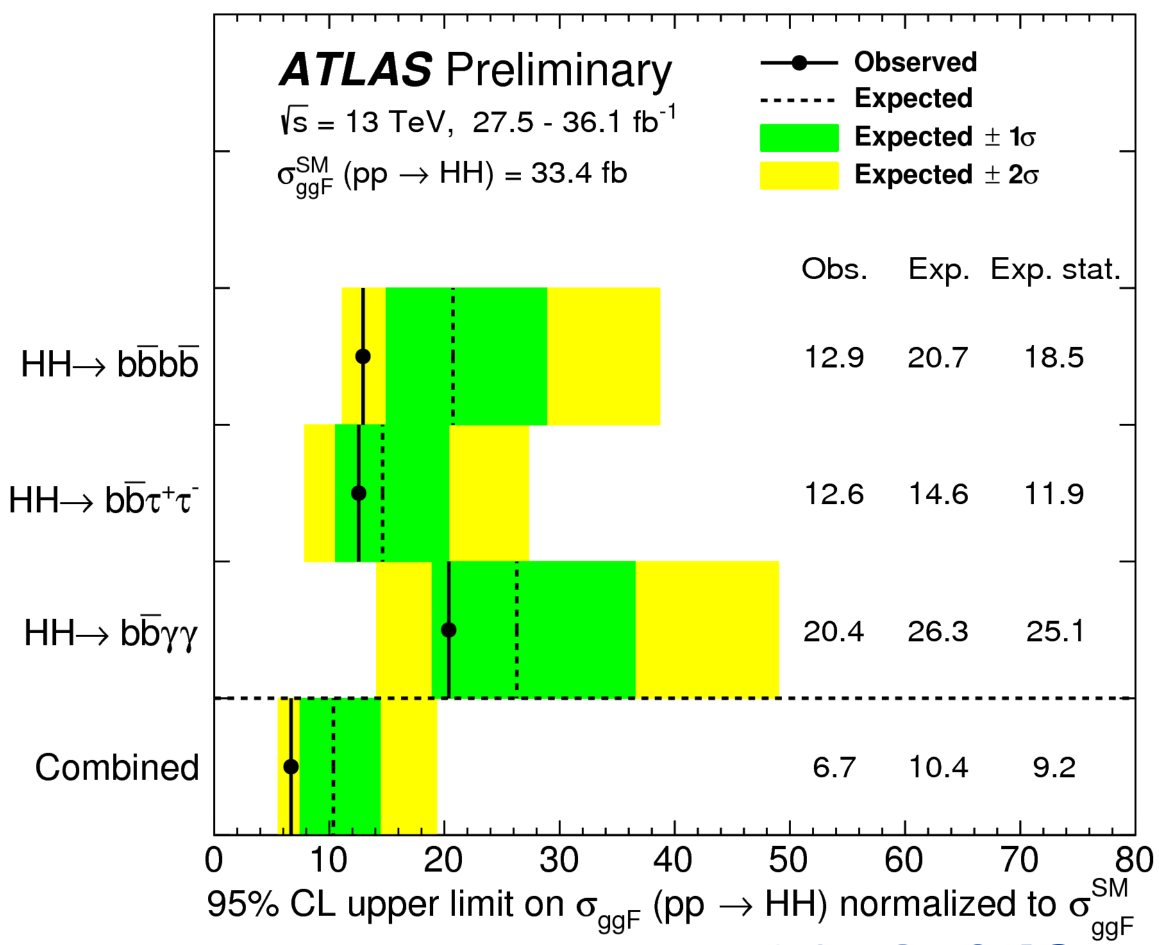
JHEP 01 (2018) 054

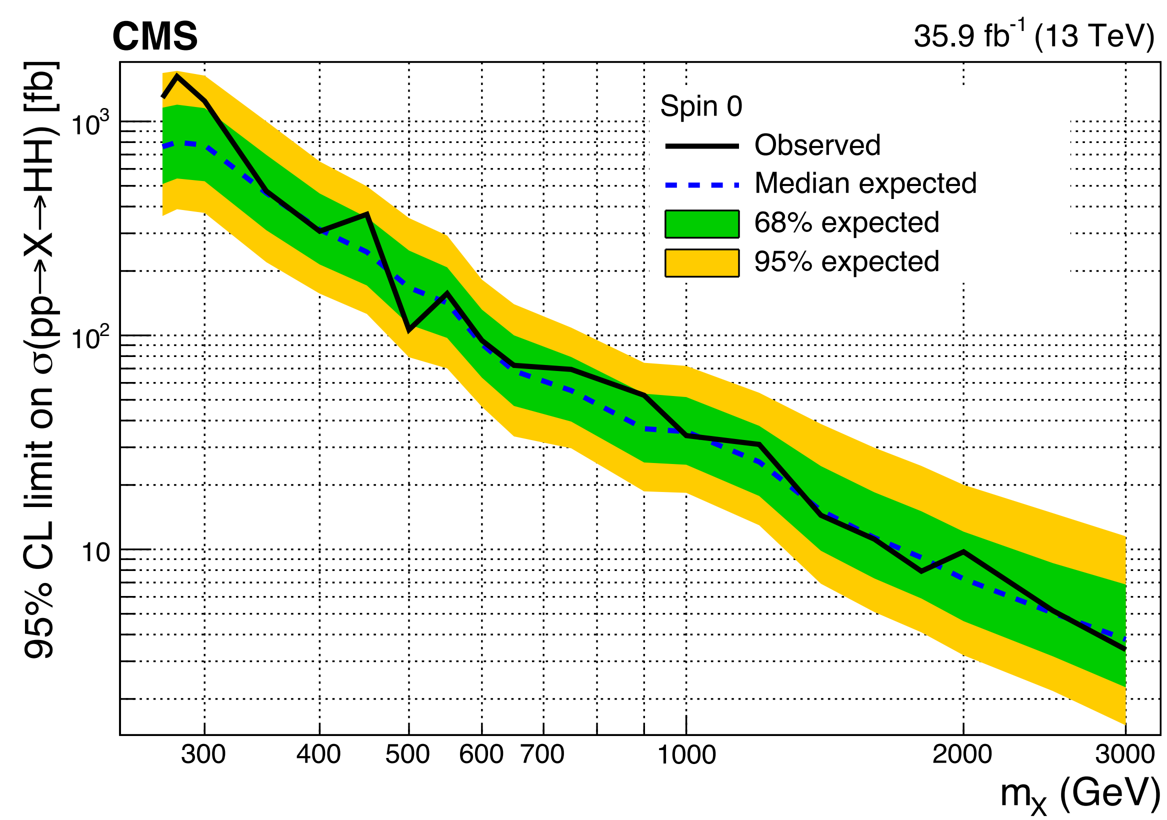
Di-Higgs Combinations

- ATLAS and CMS carried out statistical combinations of their di-Higgs search channels
- CMS has a combined limit of 22.2 (12.8) times the SM di-Higgs production cross-section at the 95% CL
- ATLAS combined limit is 6.7 (10.4) times the predicted Standard Model cross-section
- No significant excesses observed between 250 and 3000 GeV



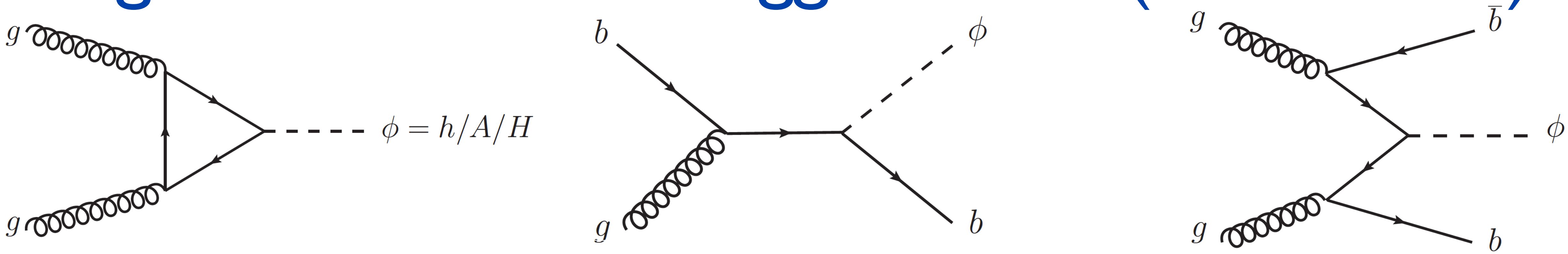
PRL 122 (2019) 121803



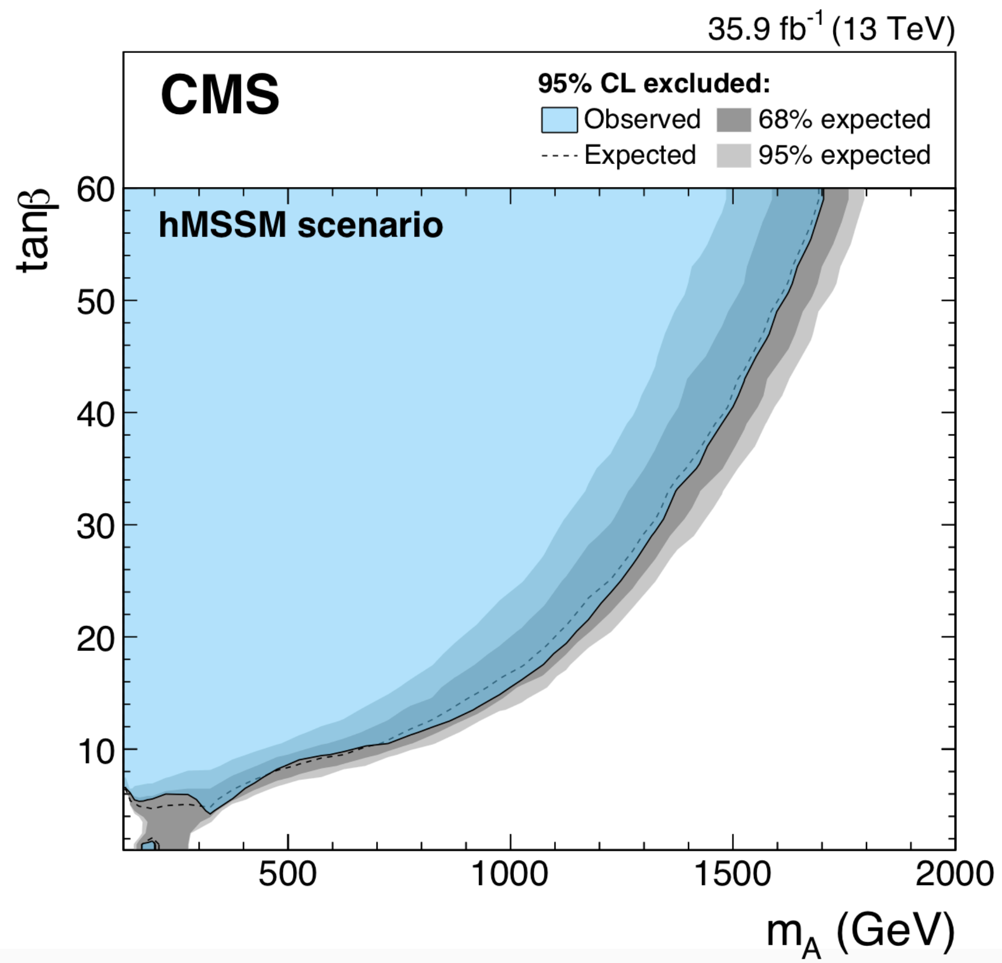


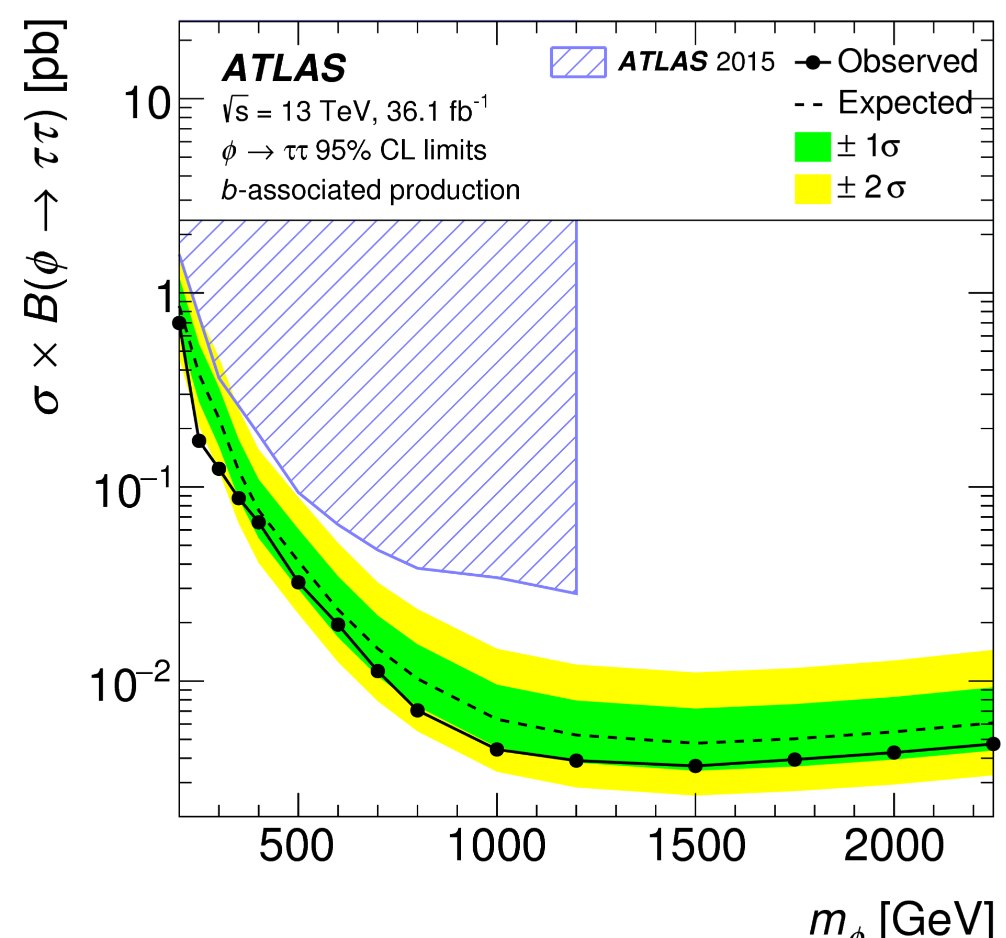
ATLAS-CONF-2018-043

High-mass Neutral Higgs Search ($A/H\to\tau^+\tau^-$)



- ATLAS and CMS both show limits in a model independent way and using benchmark scenarios
- CMS result: In the hMSSM, presence of a heavy neutral Higgs boson is excluded at the 95% CL for $\tan\beta > 6$ and m_A below 250 GeV. Exclusion contour reaches $m_A = 1.6$ TeV for $\tan\beta = 60$
- ATLAS result: In the hMSSM scenario the data exclude $\tan\beta > 1.0$ for $m_A = 250$ GeV and $\tan\beta > 42$ for $m_A = 1.5$ TeV at the 95% CL



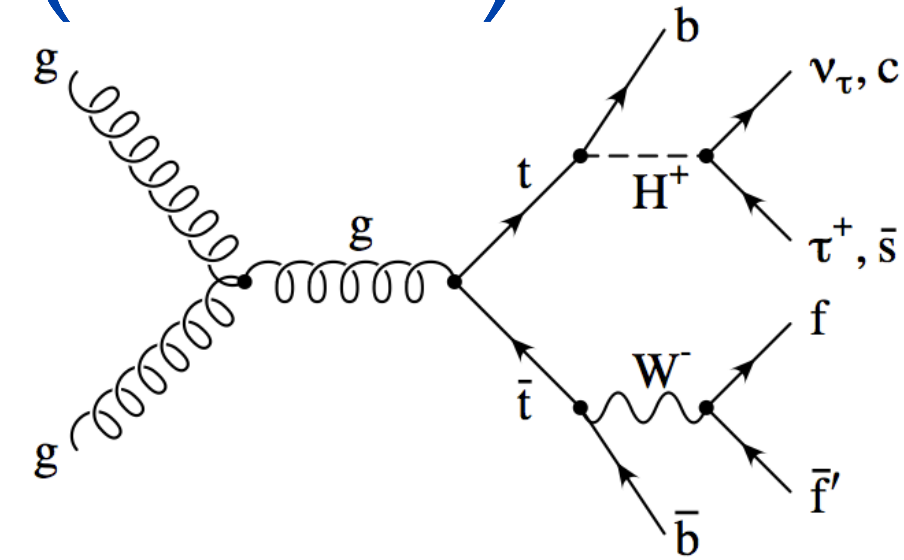


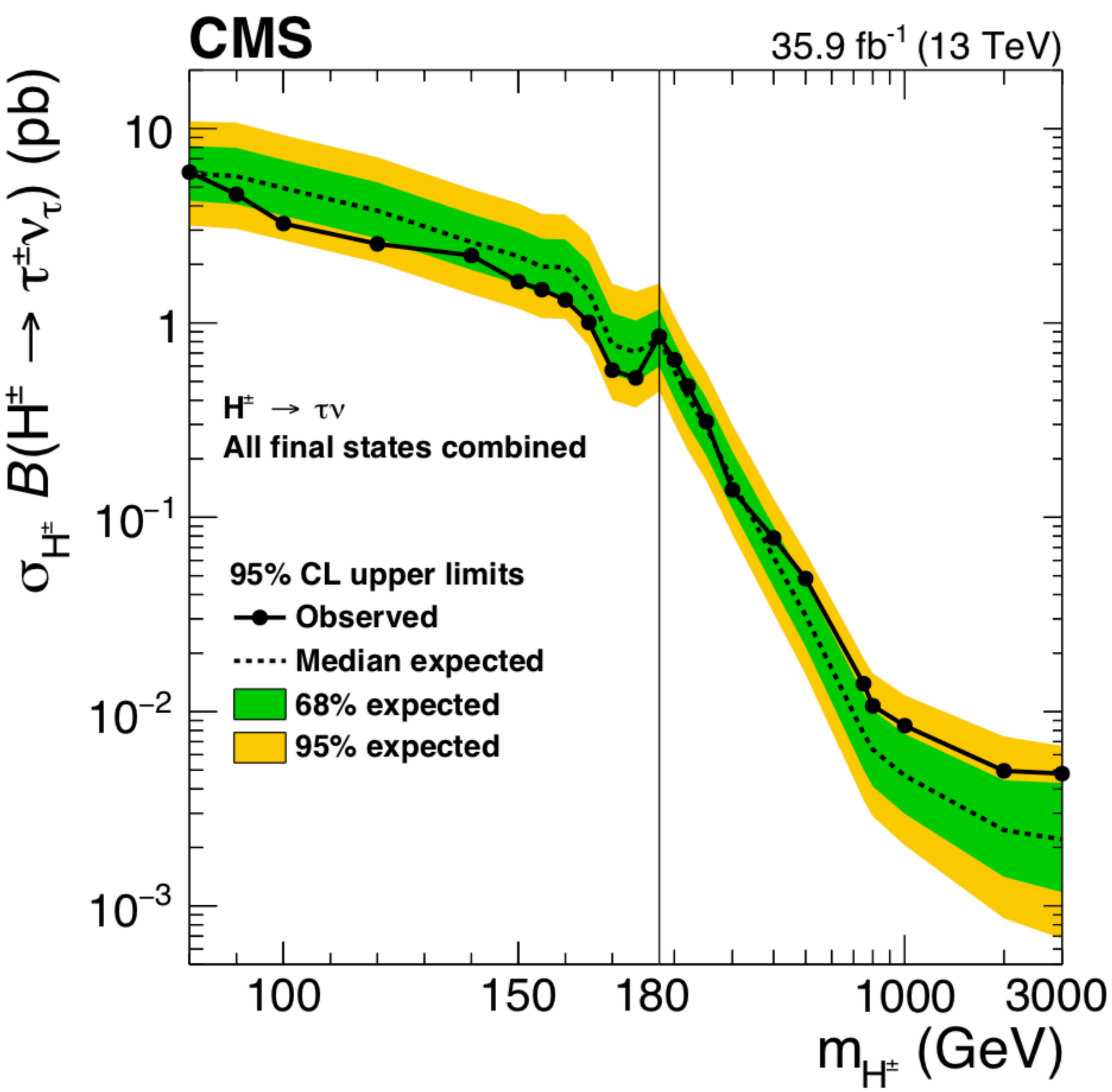
JHEP 09 (2018) 007

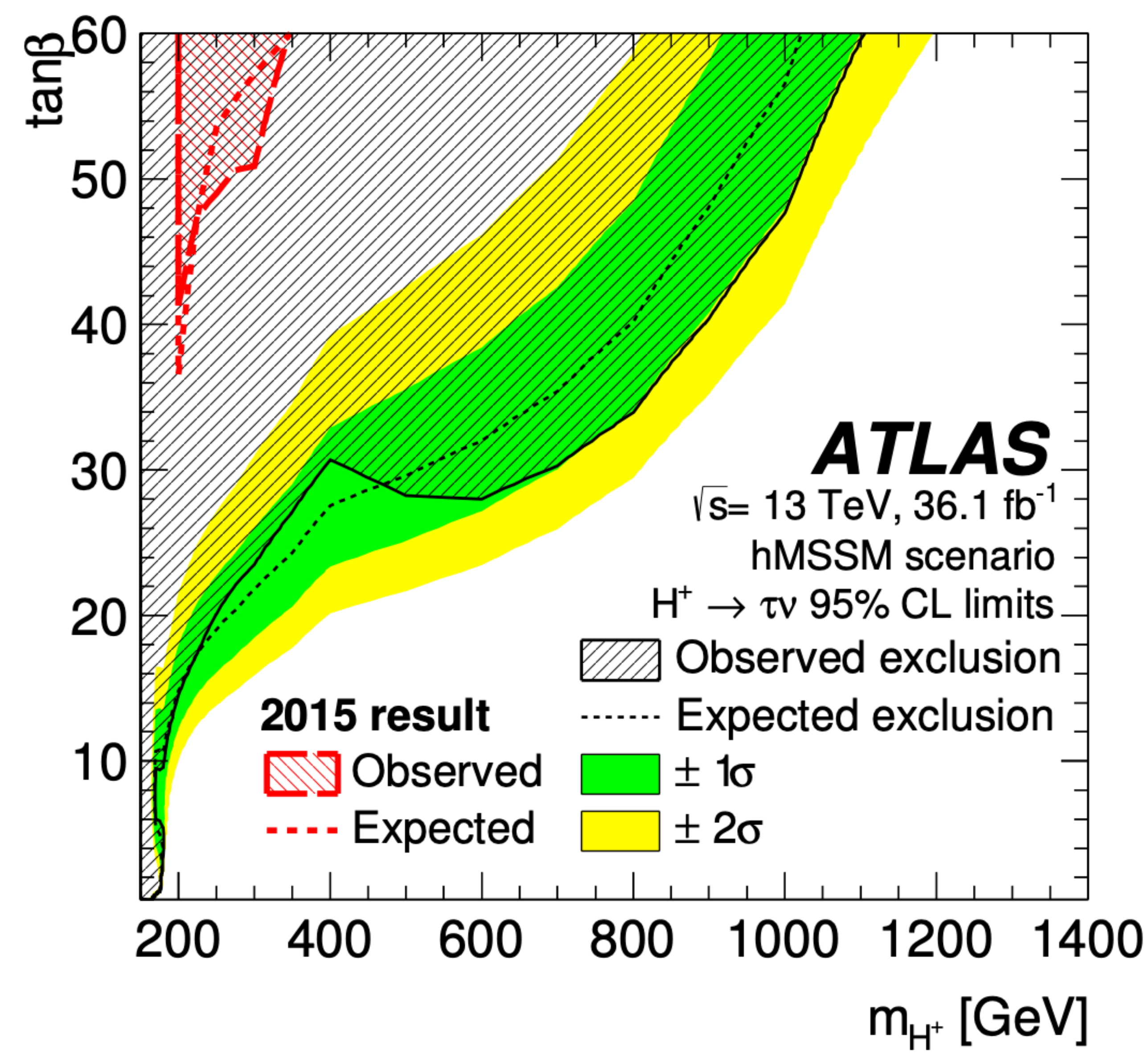
JHEP 01 (2018) 055

Charged Higgs Search ($H^+ \to \tau\nu$)

- For $M_{H+} < m_{top}$, main production mechanism is through the decay of a top quark ($t \to bH^+$)
- Search channels include the fully-hadronic and the leptonic decay modes of the tau
- Constraints in the intermediate mass region are now shown for the first time





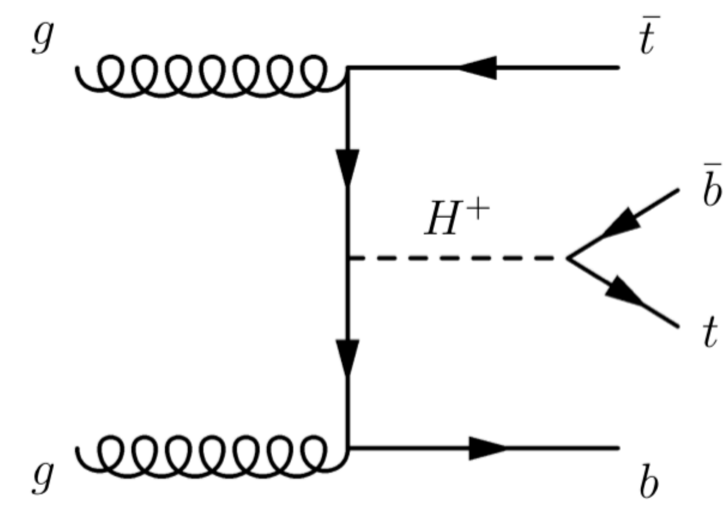


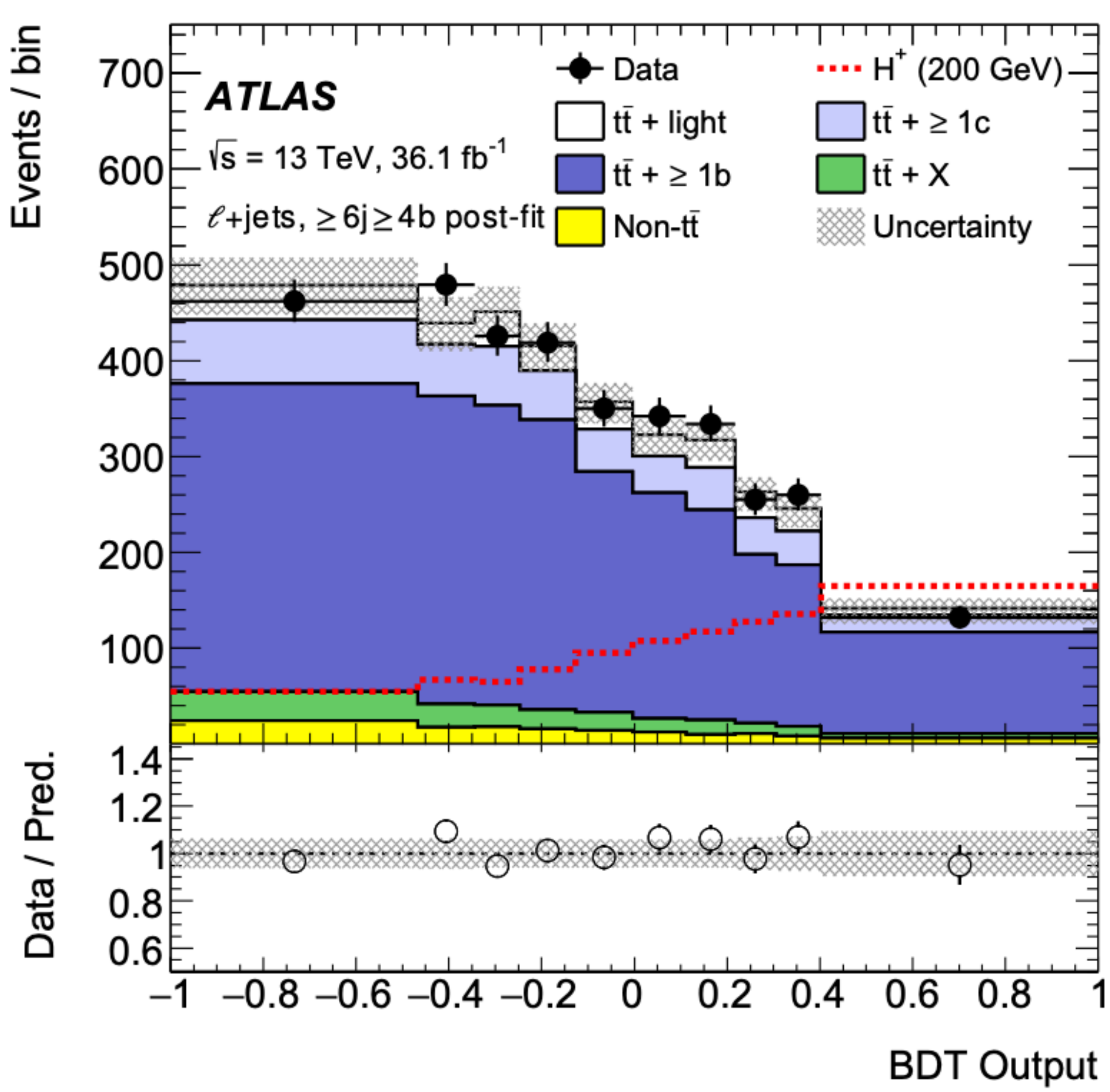
arXiv: 1903.04560

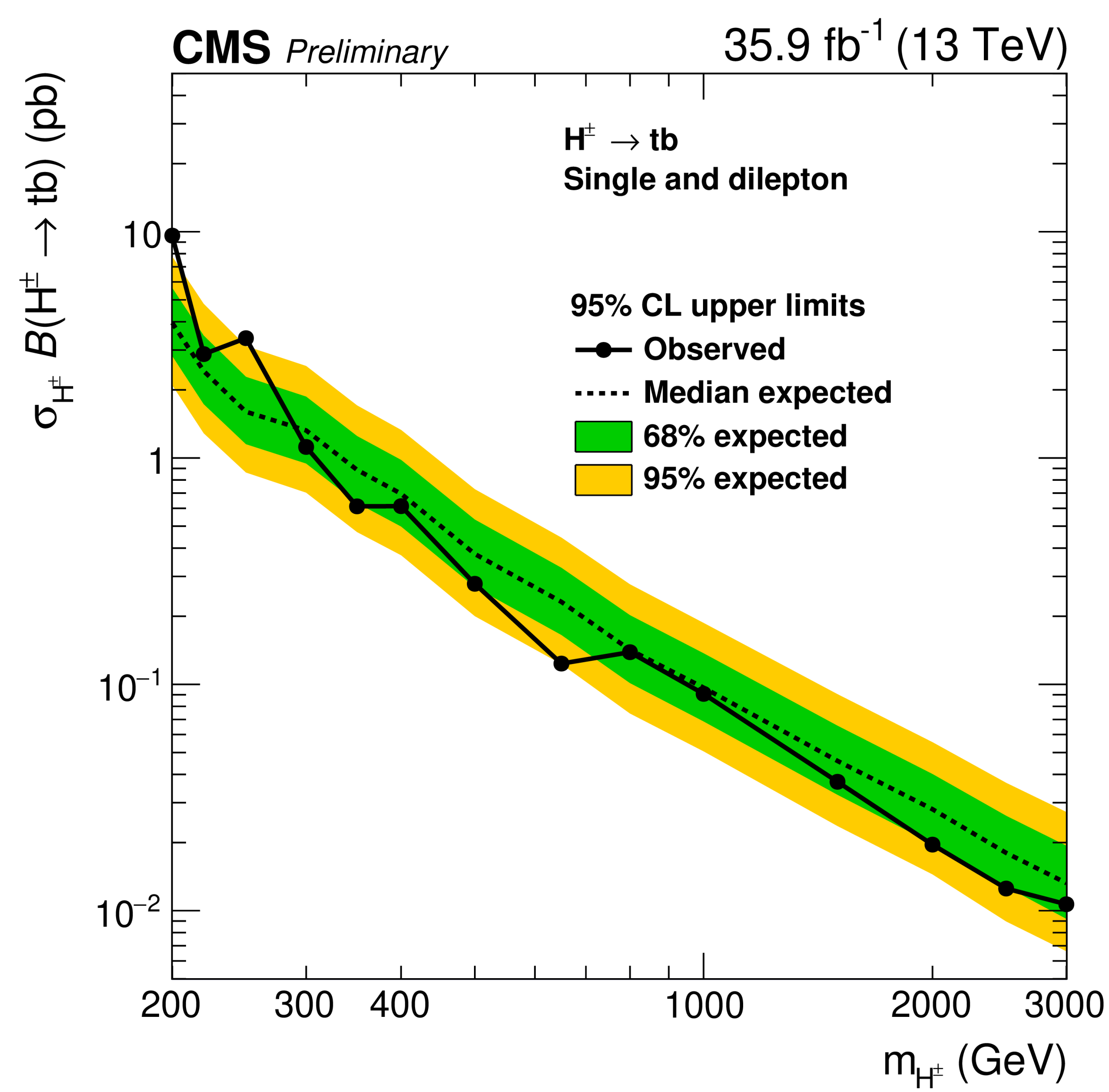
JHEP 09 (2018) 139

Charged Higgs Search ($H^+ \rightarrow tb$)

- This is the dominant decay mode for a heavy charged Higgs boson in a broad range of models
- Here the di-lepton (lepton = e, μ) and lepton+jets final states are used
- Discriminant formed from trained binary decision tree (BDT score) using ~dozen input variables





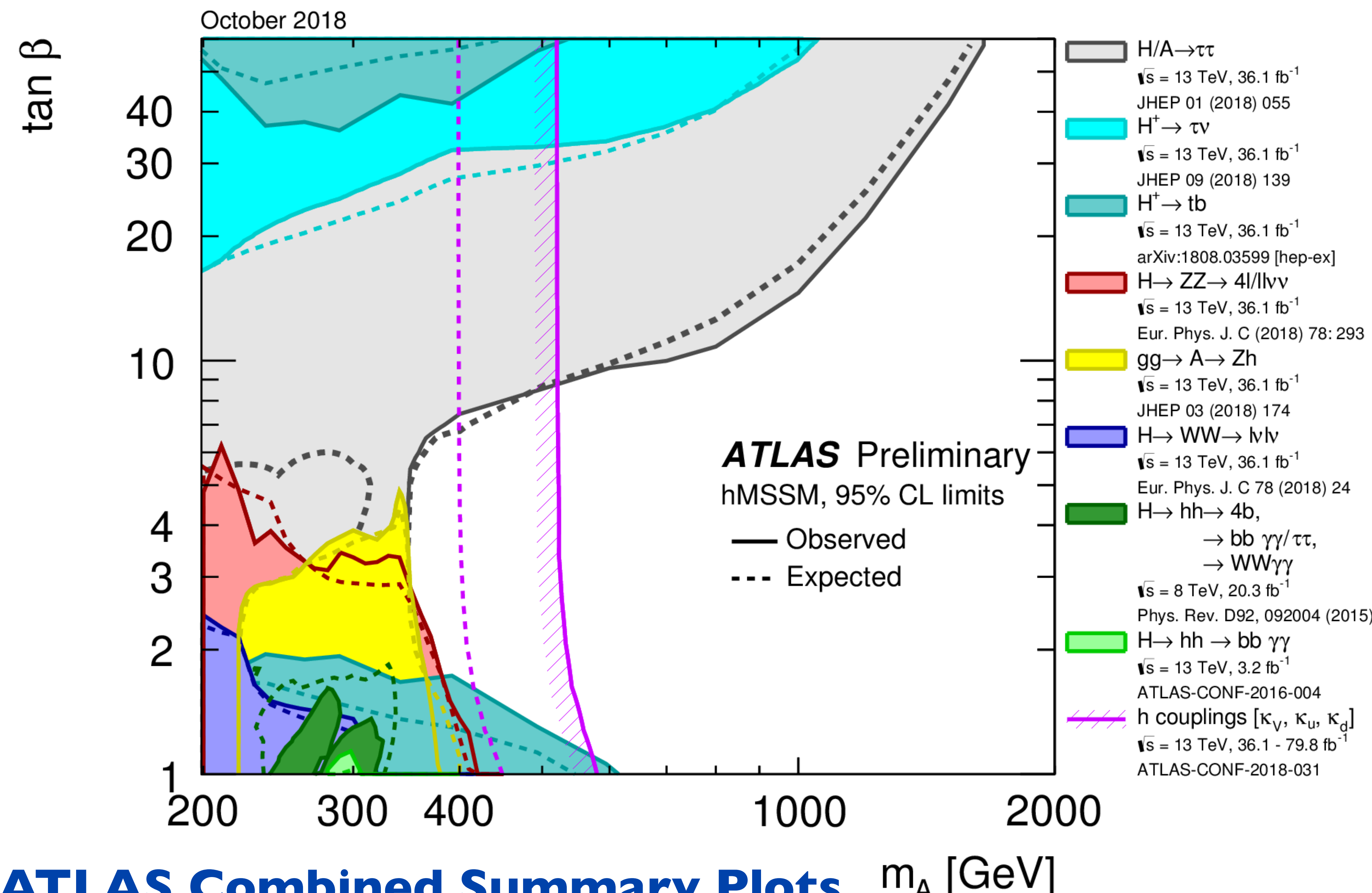


JHEP 11 (2018) 085

CMS-PAS-HIG-18-004

BSM Higgs Overlay

- ATLAS has released a preliminary plot showing the exclusion limits in the m_A-tanβ plane
- A large number of channels have been included, even some of the di-Higgs channels
- Also includes BSM interpretation of SM Higgs couplings limits
- Uses the hMSSM benchmark scenario



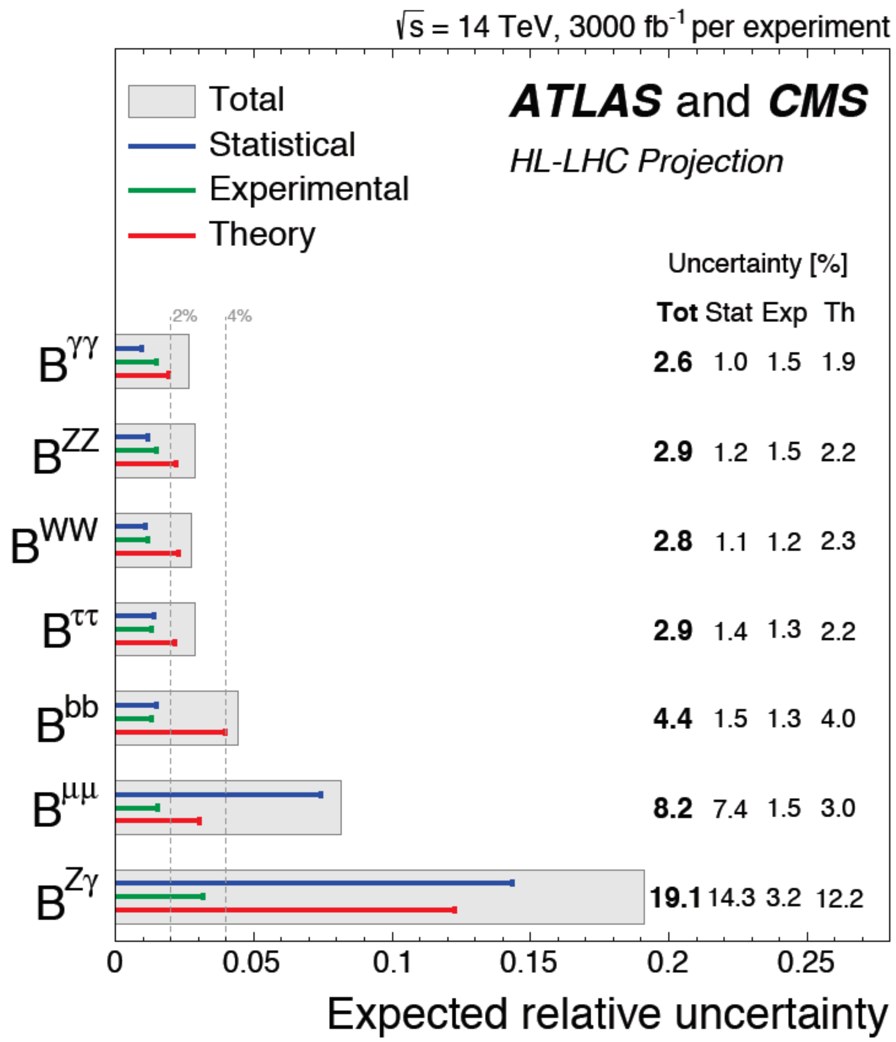
ATLAS Combined Summary Plots

Conclusions and Outlook

- Exploiting the current LHC dataset to learn as much as we can about this new particle
- Third generation Yukawa couplings firmly established
  - Direct observations of ttH, $H \to b\bar{b}$ and $H \to \tau^+\tau^-$
- Approaching sensitivity to second generation couplings, e.g., $H \to \mu\mu$
- Thus far the 125 GeV Higgs boson looks to be very SM-like
- Even with a SM-like Higgs observed, Beyond the Standard Model Higgs searches continue to be relevant (e.g., there are still regions of MSSM parameter space that are compatible with the observed Higgs at 125 GeV)
- ATLAS and CMS have a very active search program for BSM Higgs bosons and we've been exploring extended scalar sectors (among other BSM scenarios)
- We have at least one new boson… maybe more! These are very exciting times!

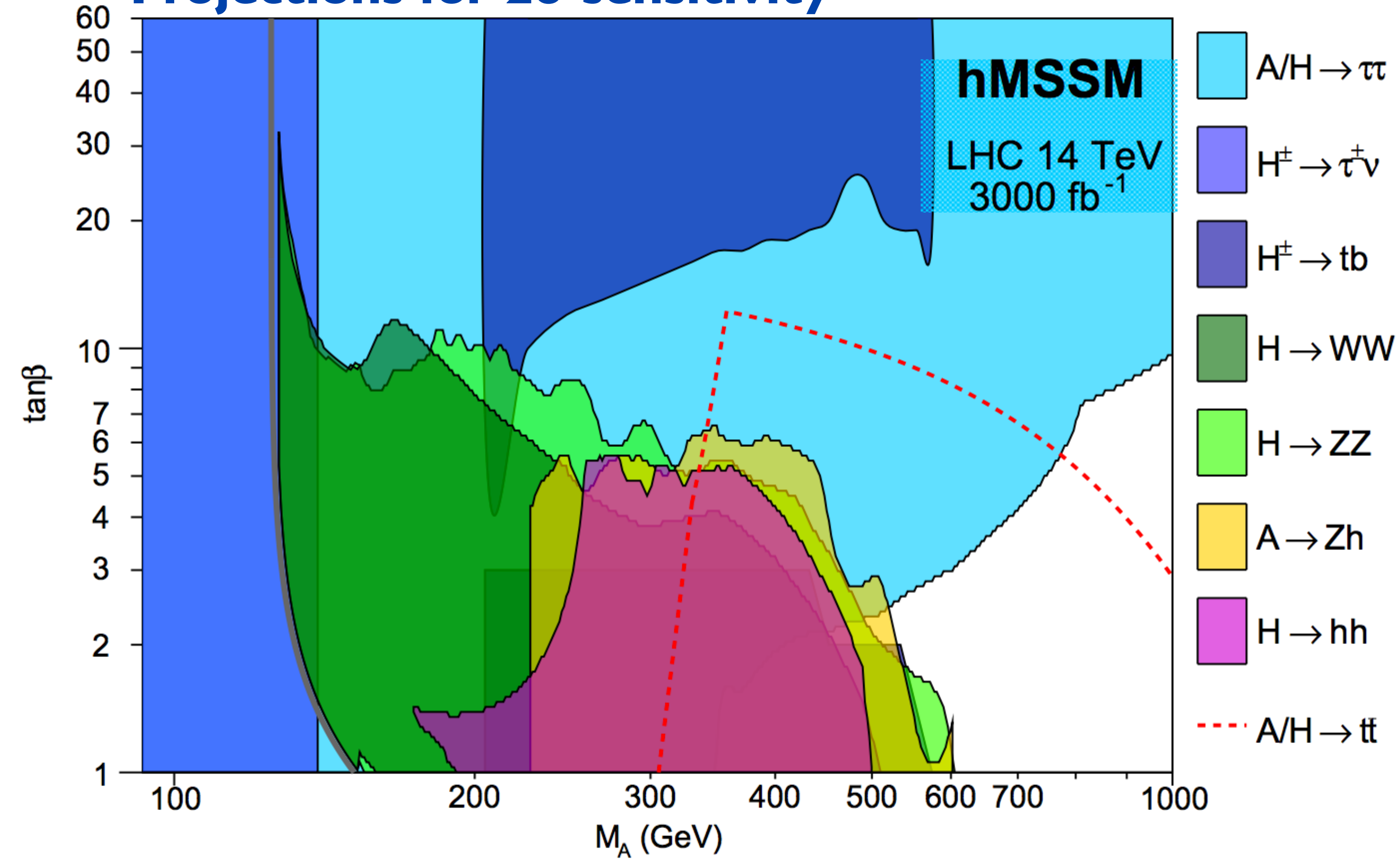
Back-up Slides

CERN LHC Plans for Run-3, 4-5,…



CERN-LPCC-2018-04

Projections for 2σ sensitivity



A. Djouadi, L. Maiani, A. Polosa, et al. JHEP 06 (2015) 168

ATLAS Higgs Combination (Run 2)

	$H\to\gamma\gamma$	$H\to ZZ^*$	$H\to WW^*$	$H\to\tau\tau$	$H\to b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 ℓ + 2 τ_{had} $t\bar{t}H$ multilepton 2 opposite-sign ℓ + 1 τ_{had} $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 4 ℓ (except $H\to ZZ^*\to 4\ell$) $t\bar{t}H$ leptonic, $H\to ZZ^*\to 4\ell$ $t\bar{t}H$ hadronic, $H\to ZZ^*\to 4\ell$			$t\bar{t}H$ 1 ℓ, boosted $t\bar{t}H$ 1 ℓ, resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH	VH 2 ℓ VH 1 ℓ, $p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} \geq 150$ GeV VH 1 ℓ, $p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} < 150$ GeV VH $E_{\text{T}}^{\text{miss}}$, $E_{\text{T}}^{\text{miss}} \geq 150$ GeV VH $E_{\text{T}}^{\text{miss}}$, $E_{\text{T}}^{\text{miss}} < 150$ GeV VH+VBF $p_{\text{T}}^{j1} \geq 200$ GeV VH hadronic (2 categories)	VH leptonic 0-jet, $p_{\text{T}}^{4\ell} \geq 100$ GeV 2-jet, $m_{jj} < 120$ GeV			$2\ \ell$, $75 \leq p_{\text{T}}^{V} < 150$ GeV, $N_{\text{jets}} = 2$ $2\ \ell$, $75 \leq p_{\text{T}}^{V} < 150$ GeV, $N_{\text{jets}} \geq 3$ $2\ \ell$, $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 2$ $2\ \ell$, $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} \geq 3$ $1\ \ell$ $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 2$ $1\ \ell$ $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 3$ $0\ \ell$, $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 2$ $0\ \ell$, $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 3$
VBF	VBF, $p_{\text{T}}^{\gamma\gamma jj} \geq 25$ GeV (2 categories) VBF, $p_{\text{T}}^{\gamma\gamma jj} < 25$ GeV (2 categories)	2-jet VBF, $p_{\text{T}}^{j1} \geq 200$ GeV 2-jet VBF, $p_{\text{T}}^{j1} < 200$ GeV	2-jet VBF	VBF $p_{\text{T}}^{\tau\tau} > 140$ GeV ($\tau_{\text{had}}\tau_{\text{had}}$ only) VBF high-m_{jj} VBF low-m_{jj}	VBF, two central jets VBF, four central jets VBF+γ
ggF	2-jet, $p_{\text{T}}^{\gamma\gamma} \geq 200$ GeV 2-jet, 120 GeV $\leq p_{\text{T}}^{\gamma\gamma} < 200$ GeV 2-jet, 60 GeV $\leq p_{\text{T}}^{\gamma\gamma} < 120$ GeV 2-jet, $p_{\text{T}}^{\gamma\gamma} < 60$ GeV 1-jet, $p_{\text{T}}^{\gamma\gamma} \geq 200$ GeV 1-jet, 120 GeV $\leq p_{\text{T}}^{\gamma\gamma} < 200$ GeV 1-jet, 60 GeV $\leq p_{\text{T}}^{\gamma\gamma} < 120$ GeV 1-jet, $p_{\text{T}}^{\gamma\gamma} < 60$ GeV 0-jet (2 categories)	1-jet, $p_{\text{T}}^{4\ell} \geq 120$ GeV 1-jet, 60 GeV $\leq p_{\text{T}}^{4\ell} < 120$ GeV 1-jet, $p_{\text{T}}^{4\ell} < 60$ GeV 0-jet, $p_{\text{T}}^{4\ell} < 100$ GeV	1-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 1-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV	Boosted, $p_{\text{T}}^{\tau\tau} > 140$ GeV Boosted, $p_{\text{T}}^{\tau\tau} \leq 140$ GeV	

Two Higgs Double Models (2HDM)

- We might have an extended scalar sector (i.e., multiple Higgs bosons) originating from two Higgs doublets… the 125 GeV particle could just be one of these Higgs bosons.
- **Type 1 2HDM:** All fermions couple to just one of the Higgs doublets
- **Type II 2HDM:** All up-type fermions couple to one Higgs doublet and all down-type fermions couple to the other
- **Lepton-specific 2HDM:** All quark couplings are like in the Type 1, lepton couplings are like in Type II
- **Flipped 2HDM:** All lepton couplings are like in the Type 1, quark couplings are like in Type II

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

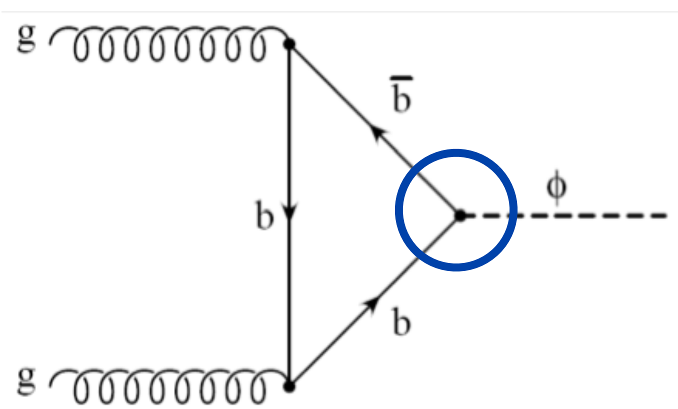
Tree-level coupling scale factors (BSM/SM) of a light Higgs boson to vector bosons, leptons, up-type and down-type quarks in 2HDMs

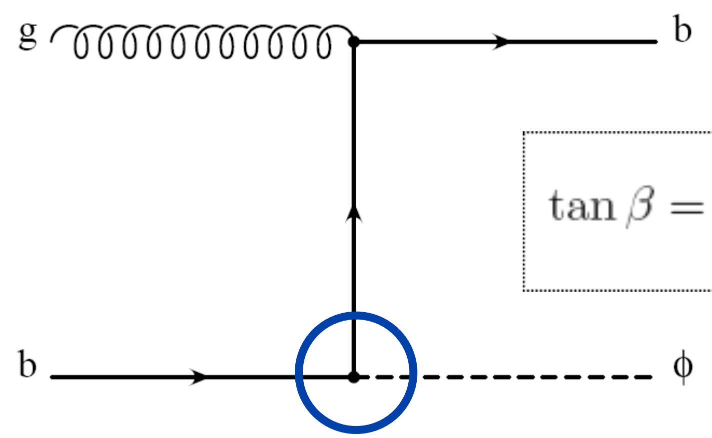
The ratio of the vacuum expectation values for the two Higgs doublets = *tan* β

The mixing angle between CP-even Higgs bosons = α

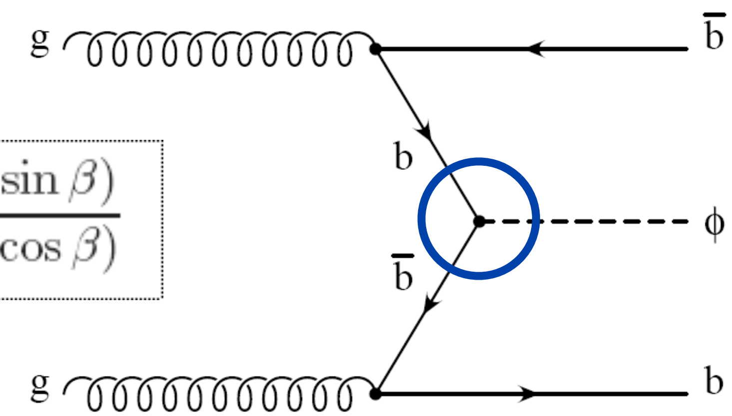
MSSM Higgs Sector

- Consider the case of an MSSM Higgs at the LHC
  - 2 Higgs doublets give rise to 5 physical Higgs bosons: h, H (CP-even), A (CP-odd), $H^{\pm}$
  - Enhanced coupling to 3rd generation; strong coupling to down-type fermions (at large $\tan\beta$ get strong enhancements to h/H/A production rates)
  - Diagrams with $bb\phi$ vertex enhanced proportional to $\tan^2\beta$ where ϕ=h,H,A

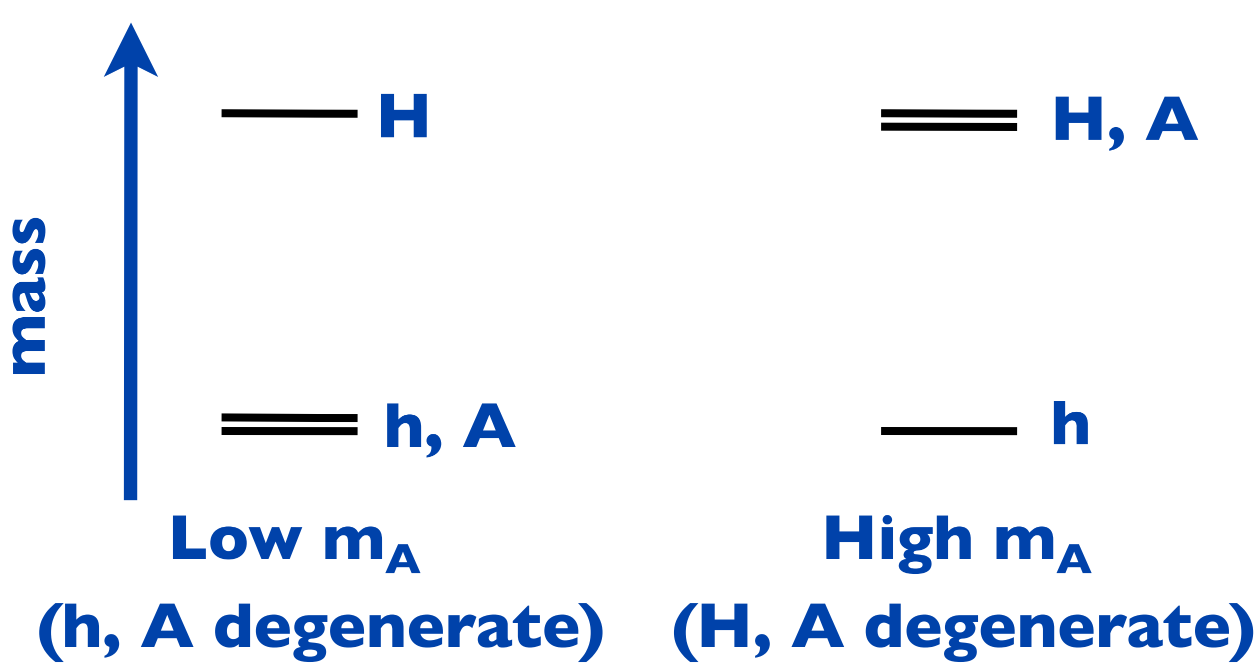


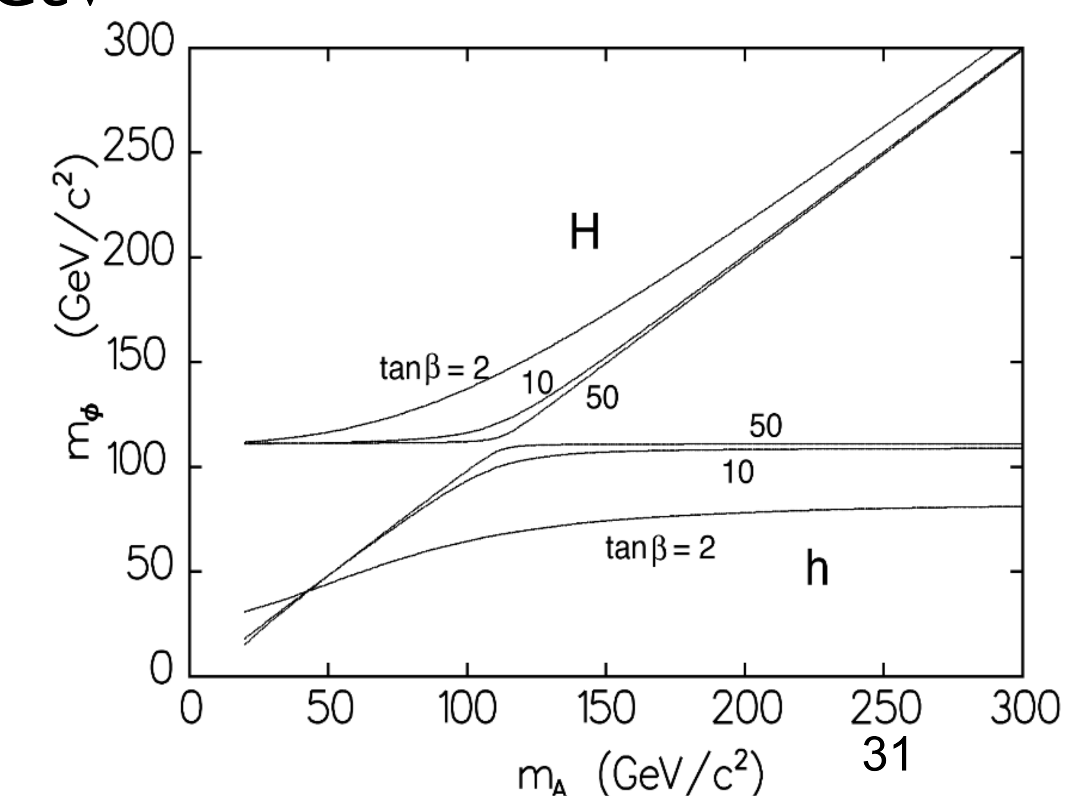


$$\tan\beta = \frac{v_2}{v_1} = \frac{(v\sin\beta)}{(v\cos\beta)}$$



- Can parameterize the masses of the Higgs bosons with two free parameters:
  - $\tan\beta$ and m_A; maximum value of m_h ~135 GeV





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Couplings in 2HDMs

4 types of 2HDMs with natural flavor conservation

Impose Z_2 to couple only one Higgs to each Yukawa type (d, e)

$\Phi_2(+), \Phi_1(-); t_R(+), d_R(\pm), e_R(\pm)$

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

	y_u^A	y_d^A	y_l^A	y_u^H	y_d^H	y_l^H	y_u^h	y_d^h	y_l^h
Type I	$\cot\beta$	$-\cot\beta$	$-\cot\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
Type II	$\cot\beta$	$\tan\beta$	$\tan\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type X	$\cot\beta$	$-\cot\beta$	$\tan\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type Y	$\cot\beta$	$\tan\beta$	$-\cot\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

$$-\mathcal{L}_{\rm Yukawa}^{\rm 2HDMs} = \sum_{f=u,d,l} \frac{m_f}{v}\left(y_f^h h\bar{f}f + y_f^H H\bar{f}f - iy_f^A A\bar{f}\gamma_5 f\right)$$

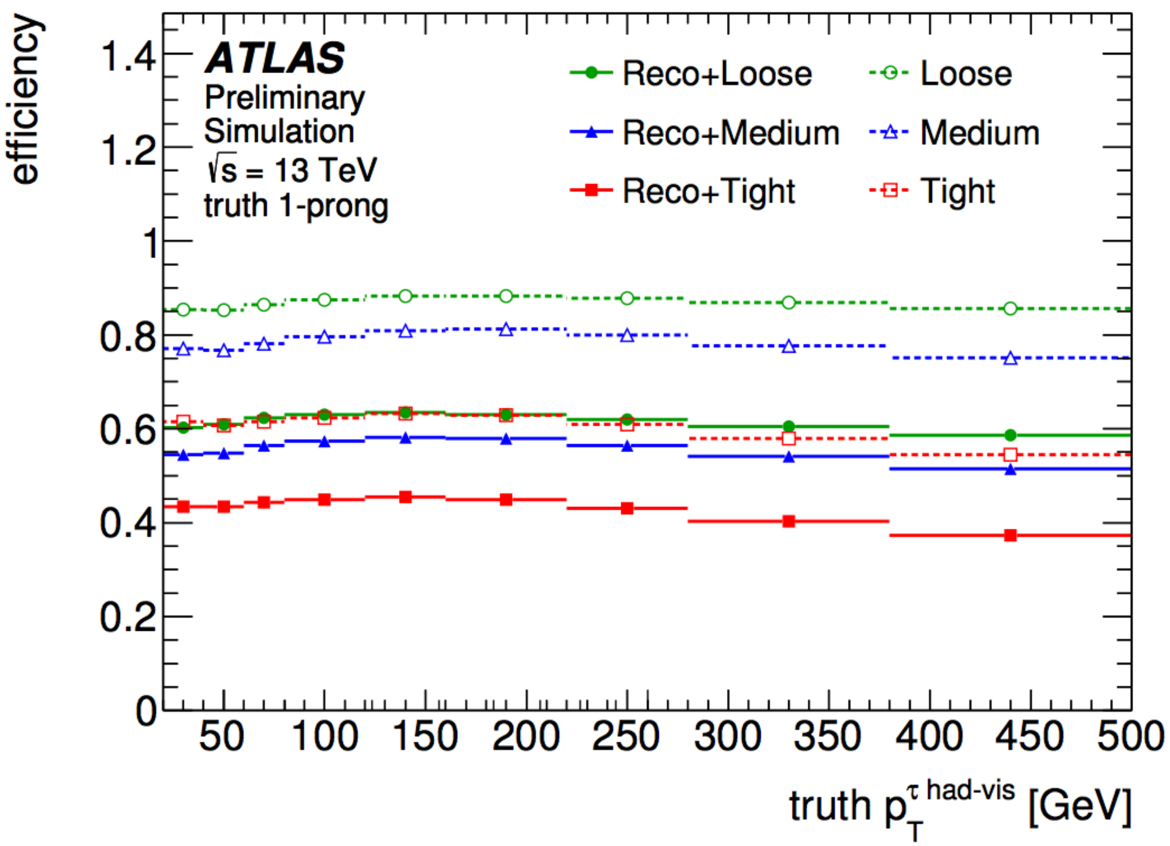
125 GeV

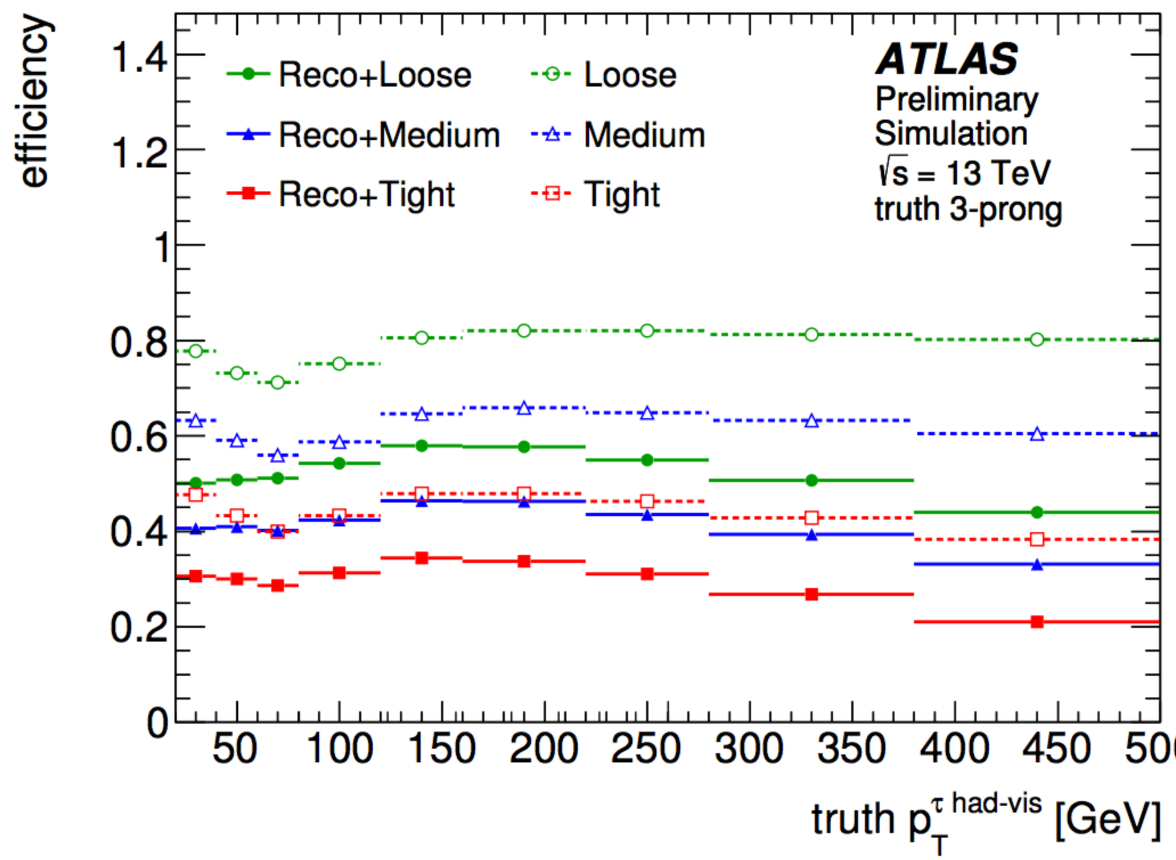
$$+\left[\sqrt{2}V_{ud}H^+\bar{u}\left(\frac{m_u}{v}y_u^A P_L + \frac{m_d}{v}y_A^d P_R\right)d + \sqrt{2}\frac{m_l}{v}y_l^A H^+\bar{\nu}P_R l + h.c.\right]$$

Reconstruction of hadronic τ decays

- The signature of hadronic τ decays are 1 or 3 tracks, collimated jet, possibly EM clusters

- Objects compatible with this signature are reconstructed
  - Seed from jet objects by considering each of them as a τ candidate
  - Identify a vertex consistent with a τ decay
  - Associate tracks within a core cone (ΔR≤0.2) of the τ axis to jet objects

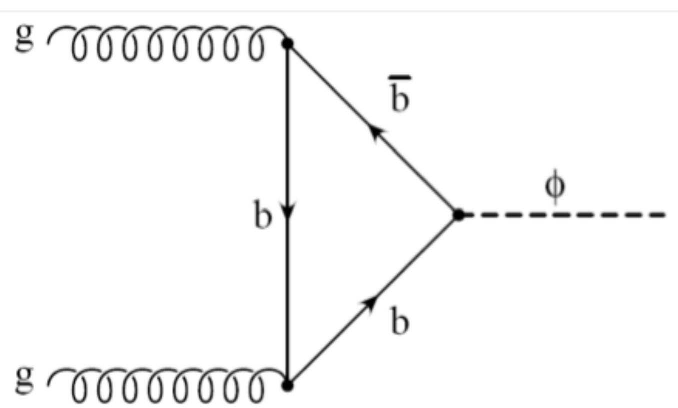


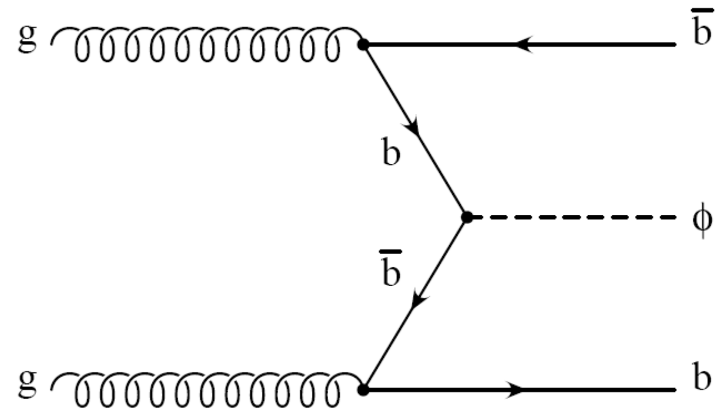


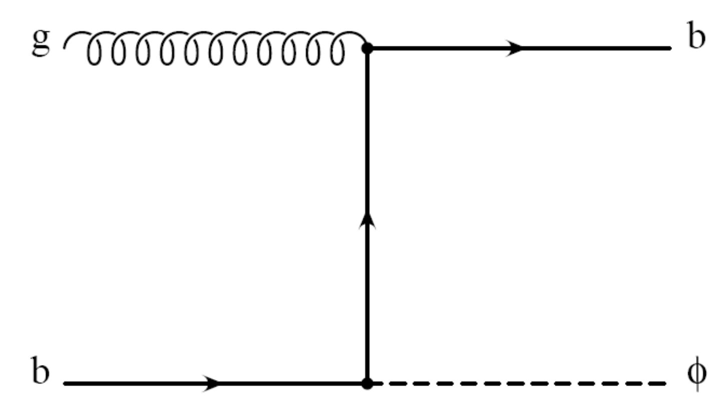
- Backgrounds from QCD jets, electrons and muons are rejected using dedicated algorithms (e.g., BDT used for rejection of jets) ATL-PHYS-PUB-2015-045
  - Discriminate using tracking information and cluster topology variables

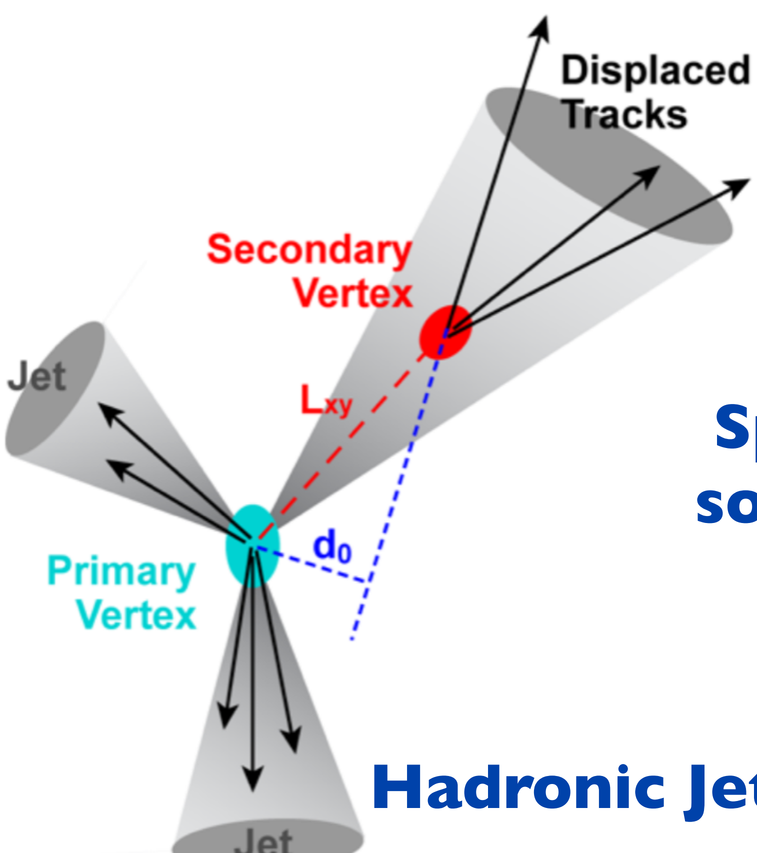
ATLAS MSSM Higgs Search ($A/H \rightarrow \tau^+\tau^-$)

- New ATLAS MSSM neutral Higgs search for 2017 uses 36.1 fb^{-1} of 13 TeV data
  - Strongest limits to-date (no recent update of the search released from CMS as of yet)
  - Improvement on the limits from the 2015 ATLAS result: Eur. Phys. J. C (2016) 76: 585
- Can use different categories to target main production mechanisms and different decays:
  - With or without b-quarks (b-jets; use of software for identification, i.e., "b-tagging")
  - With or without hadronic tau lepton decays (tau-jets; use software for identification)





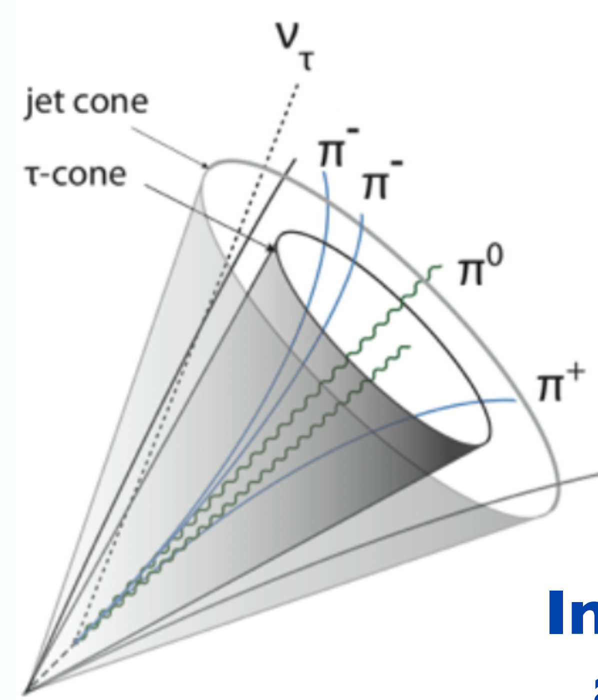




b-Quark decay (b-jet)

Specialized ATLAS software to identify these

Hadronic Jet



Hadronic Tau Lepton decay (tau-jet)

In total, 4 categories are considered by the analysis

ATLAS Background Estimation (A/H→τ+τ-)

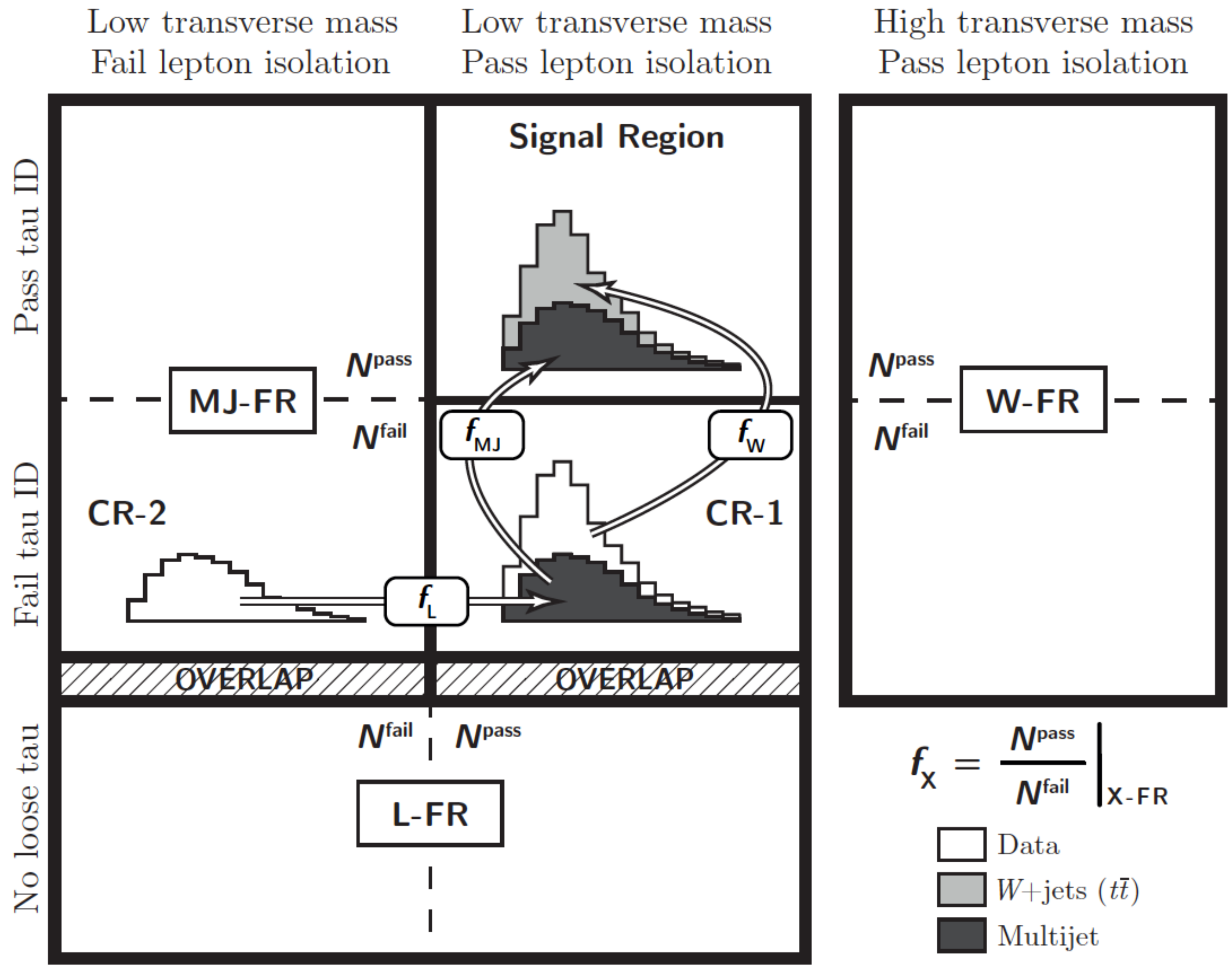


Figure 2: Schematic of the fake-factor background estimation in the $\tau_{lep}\tau_{had}$ channel. The fake-factors, f_X (X = MJ, W, L), are defined as the ratio of events in data that pass/fail the specified selection requirements, measured in the fakes-regions: MJ-FR, W-FR and L-FR, respectively. The multijet contribution is estimated by weighting events in CR-2 by the product of f_L and f_{MJ}. The contribution from W+jets and $t\bar{t}$ events where the $\tau_{had\text{-}vis}$ candidate originates from a jet is estimated by subtracting the multijet contribution from CR-1 and then weighting by f_W. There is a small overlap of events between L-FR and the CR-1 and CR-2 regions. The contribution where both the selected $\tau_{had\text{-}vis}$ and lepton originate from leptons is estimated using simulation (not shown here).

ATLAS Control Regions ($A/H \rightarrow \tau^+\tau^-$)

Table 1: Definition of signal, control and fakes regions used in the analysis. The symbol ℓ represents the selected electron or muon candidate and τ_1 (τ_2) represents the leading (sub-leading) $\tau_{\text{had-vis}}$ candidate.

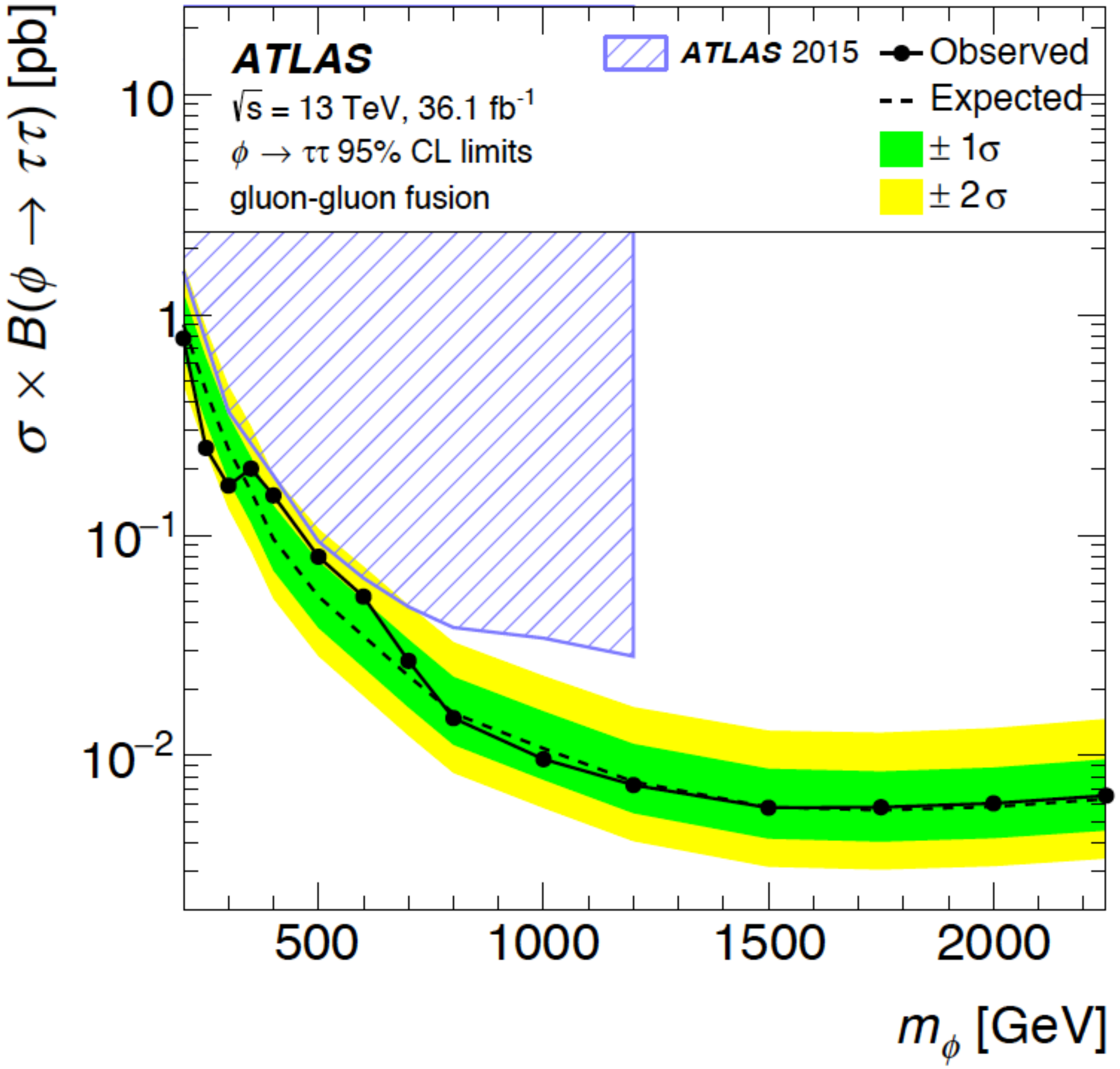
Channel	Region	Selection
$\tau_{\text{lep}}\tau_{\text{had}}$	SR	ℓ (trigger, isolated), τ_1 (medium), $q(\ell) \times q(\tau_1) < 0$, $\lvert\Delta\phi(\mathbf{p}_T^{\ell}, \mathbf{p}_T^{\tau_1})\rvert > 2.4$, $m_T(\mathbf{p}_T^{\ell}, \mathbf{E}_T^{\text{miss}}) < 40$ GeV, veto $80 < m(\mathbf{p}^{\ell}, \mathbf{p}^{\tau_1}) < 110$ GeV ($\tau_e\tau_{\text{had}}$ channel only)
	CR-1	Pass SR except: τ_1 (very-loose, fail medium)
	CR-2	Pass SR except: τ_1 (very-loose, fail medium), ℓ (fail isolation)
	MJ-FR	Pass SR except: τ_1 (very-loose), ℓ (fail isolation)
	W-FR	Pass SR except: $70\,(60) < m_T(\mathbf{p}_T^{\ell}, \mathbf{E}_T^{\text{miss}}) < 150$ GeV in $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$) channel
	CR-T	Pass SR except: $m_T(\mathbf{p}_T^{\ell}, \mathbf{E}_T^{\text{miss}}) > 110\,(100)$ GeV in the $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$) channel, b-tag category only
	L-FR	ℓ (trigger, selected), jet (selected), no loose $\tau_{\text{had-vis}}$, $m_T(\mathbf{p}_T^{\ell}, \mathbf{E}_T^{\text{miss}}) < 30$ GeV
$\tau_{\text{had}}\tau_{\text{had}}$	SR	τ_1 (trigger, medium), τ_2 (loose), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\mathbf{p}_T^{\tau_1}, \mathbf{p}_T^{\tau_2})\rvert > 2.7$
	CR-1	Pass SR except: τ_2 (fail loose)
	DJ-FR	jet trigger, $\tau_1+\tau_2$ (no identification), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\mathbf{p}_T^{\tau_1}, \mathbf{p}_T^{\tau_2})\rvert > 2.7$ $p_T^{\tau_2}/p_T^{\tau_1} > 0.3$
	W-FR	μ (trigger, isolated), τ_1 (no identification), $\lvert\Delta\phi(\mathbf{p}_T^{\mu}, \mathbf{p}_T^{\tau_1})\rvert > 2.4$ $m_T(\mathbf{p}_T^{\mu}, \mathbf{E}_T^{\text{miss}}) > 40$ GeV, b-veto category only
	T-FR	Pass W-FR except: b-tag category only

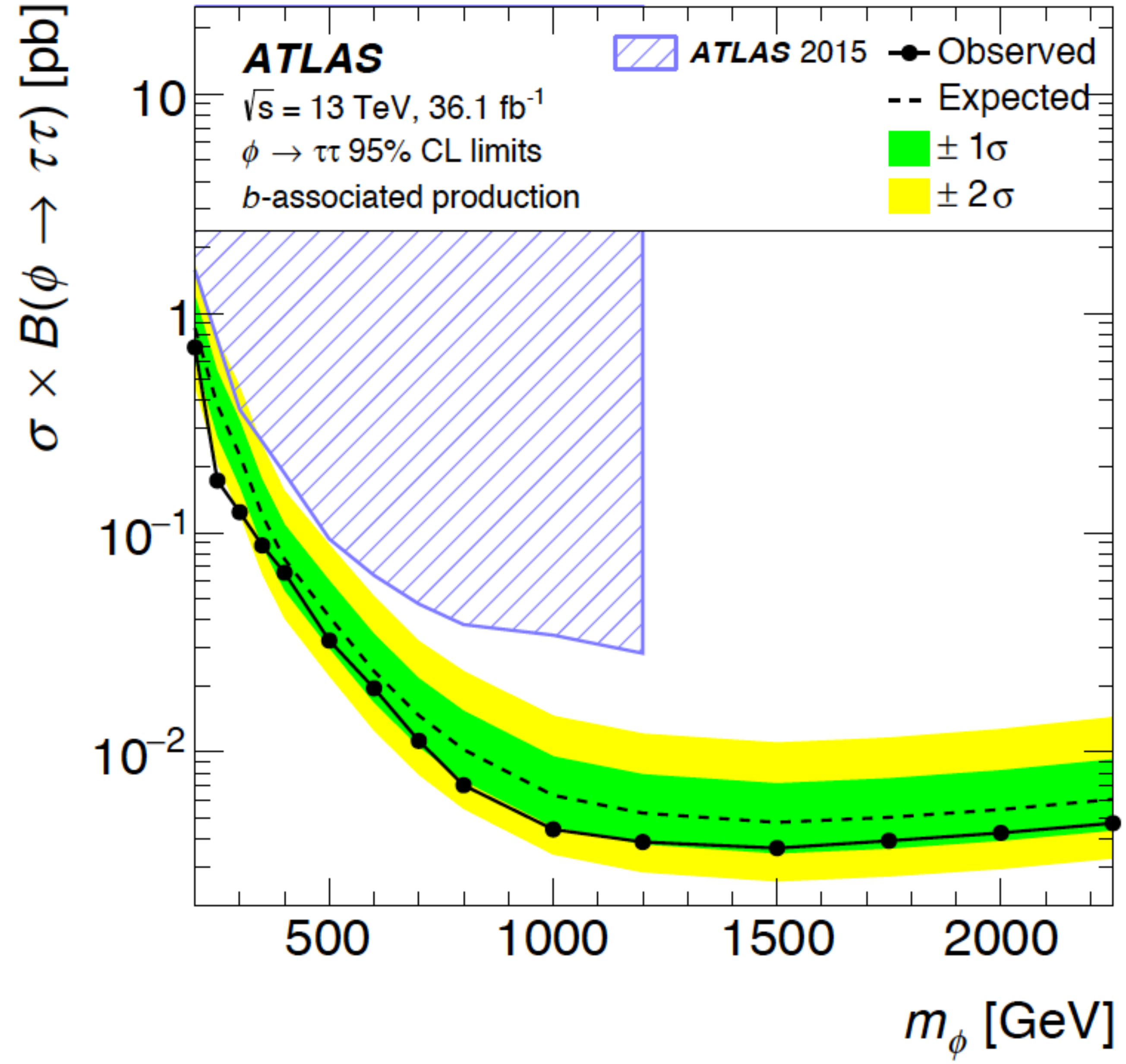
ATLAS Events ($A/H \to \tau^+\tau^-$)

Table 2: Observed number of events and predictions of signal and background contributions in the b-veto and b-tag categories of the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. The background predictions and uncertainties (including both the statistical and systematic components) are obtained before (pre-fit) and after (post-fit) applying the statistical fitting procedure discussed in Section 8. The individual uncertainties are correlated, and do not necessarily add in quadrature to the total background uncertainty. The label "Others" refers to contributions from diboson, $Z/\gamma^*(\to \ell\ell)$+jets and $W(\to \ell\nu)$+jets production. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, events containing a $\tau_{\text{had-vis}}$ candidate that originate from jets are removed from all processes other than Jet $\to \tau$ fake. The expected pre-fit contributions from A and H bosons with masses of 300, 500 and 800 GeV and $\tan\beta = 10$ in the hMSSM scenario are also shown.

		b-veto		b-tag	
Channel	Process	pre-fit	post-fit	pre-fit	post-fit
$\tau_{\text{lep}}\tau_{\text{had}}$	$Z/\gamma^* \to \tau\tau$	92 000 ± 11 000	96 400 ± 1600	670 ± 140	690 ± 70
	Diboson	880 ± 100	920 ± 70	6.3 ± 1.7	6.5 ± 1.4
	$t\bar{t}$ and single top-quark	1050 ± 170	1090 ± 130	2800 ± 400	2680 ± 80
	Jet $\to \tau$ fake	83 000 ± 5000	88 800 ± 1700	3000 ± 400	3390 ± 170
	$Z/\gamma^* \to \ell\ell$	15 800 ± 1200	16 200 ± 700	86 ± 21	89 ± 16
	SM Total	193 000 ± 13 000	203 400 ± 1200	6500 ± 600	6850 ± 120
	Data	203 365		6843	
	A/H (300)	720 ± 80	–	236 ± 32	–
	A/H (500)	112 ± 11	–	39 ± 5	–
	A/H (800)	10.7 ± 1.1	–	4.8 ± 0.6	–
$\tau_{\text{had}}\tau_{\text{had}}$	Multijet	3040 ± 240	3040 ± 90	106 ± 32	85 ± 10
	$Z/\gamma^* \to \tau\tau$	610 ± 230	770 ± 80	7.5 ± 2.9	8.6 ± 1.3
	$W(\to \tau\nu)$+jets	178 ± 31	182 ± 15	4.0 ± 1.0	4.1 ± 0.5
	$t\bar{t}$ and single top-quark	26 ± 9	29 ± 4	60 ± 50	74 ± 15
	Others	25 ± 6	27.4 ± 2.1	1.0 ± 0.5	1.1 ± 0.4
	SM Total	3900 ± 400	4050 ± 70	180 ± 60	173 ± 16
	Data	4059		154	
	A/H (300)	130 ± 50	–	44 ± 19	–
	A/H (500)	80 ± 33	–	28 ± 12	–
	A/H (800)	11 ± 4	–	5.1 ± 2.2	–

ATLAS Results ($A/H \to \tau^+\tau^-$)



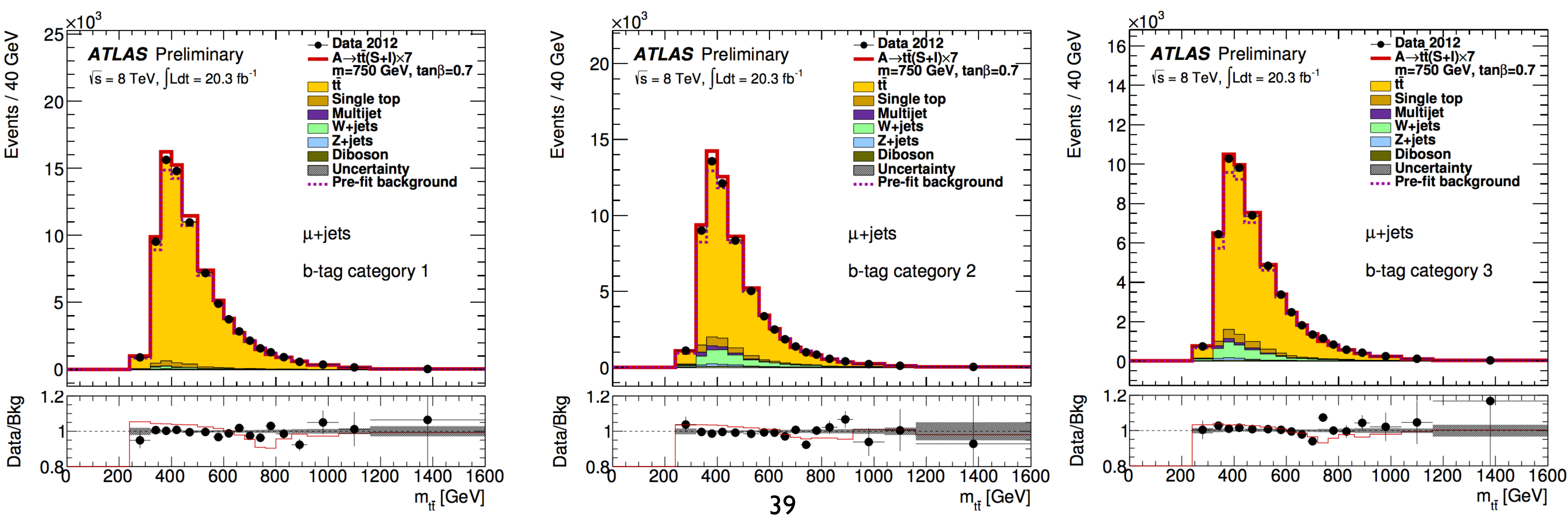


Event Selection / Mass Reconstruction (A/H→ttbar)

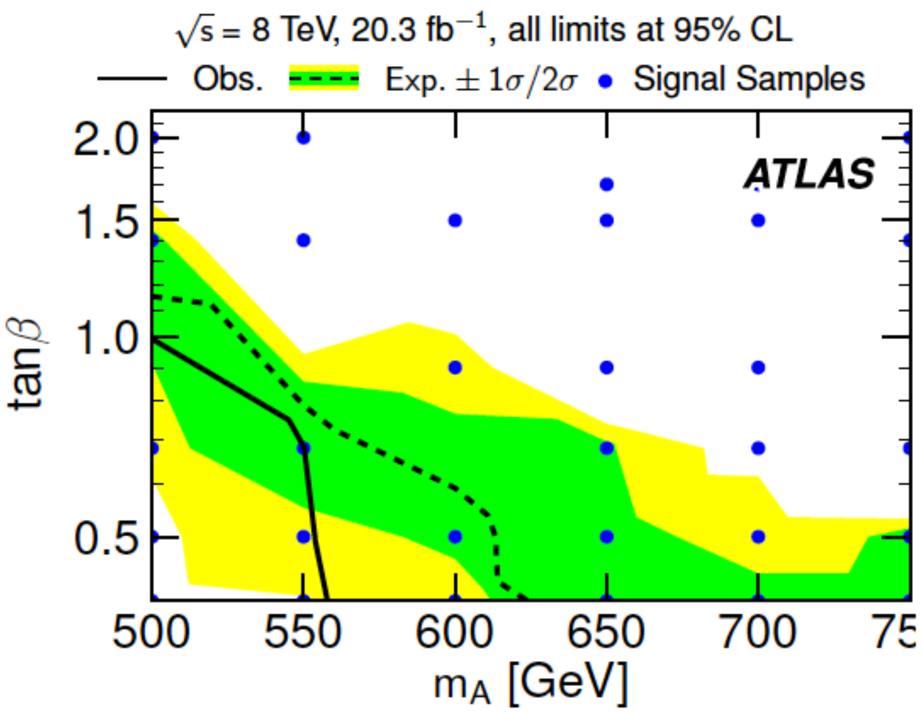
- Analysis targets the ttbar lepton+jets channel (one W to hadrons, one to leptons)
  - Single electron or single muon triggers are used—2 categories (one for e; one for μ)
  - One high p_T electron or muon; high MET from the escaping neutrino; presence of at least 4 high p_T jets in the event; at least one jet originating from b quarks must be tagged (70%); Sum of MET and m_T > 60 GeV (multi-jets suppression) $m_T^W = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{miss}} \cdot (1 - \cos\phi_{\ell\nu})}$
- A chi-squared fit is used for assignment of the decay products, then m_{tt} is reconstructed
  - Events further classified depending on the b-tagged jet(s) assignment—3 categories

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h - W}}{\sigma_{t_h - W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,j\ell\nu}) - (p_{T,t_h} - p_{T,t_\ell})}{\sigma_{\text{diff}\,p_T}}\right]^2$$

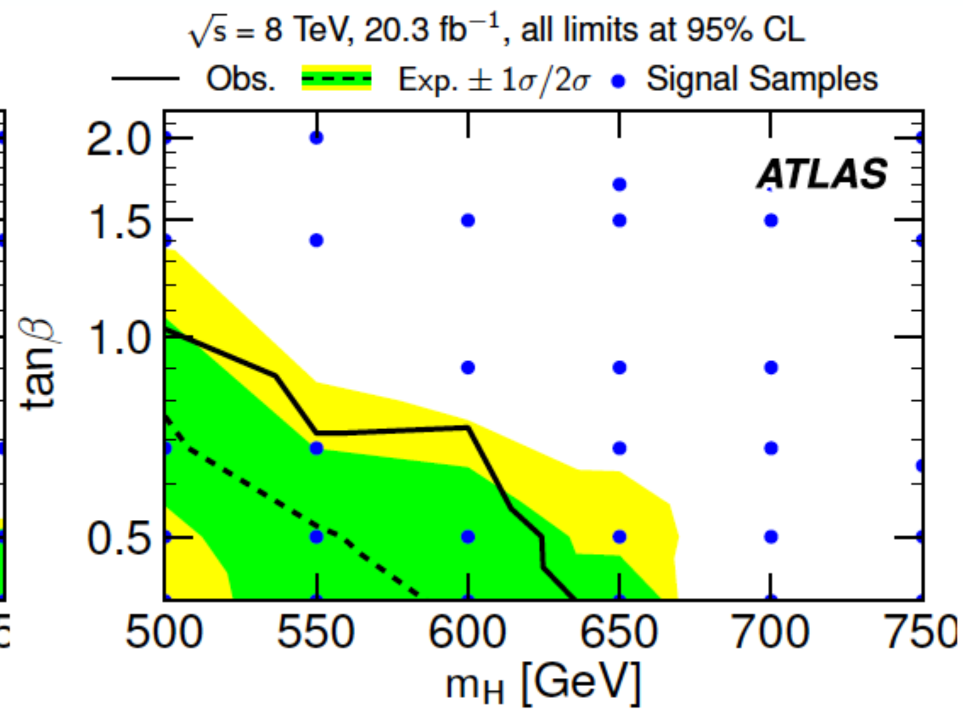
6 categories in total (2 lepton types) x (3 b-tagging classifications)



ATLAS High-mass Higgs Results (A/H→ttbar)



Pseudo scalar

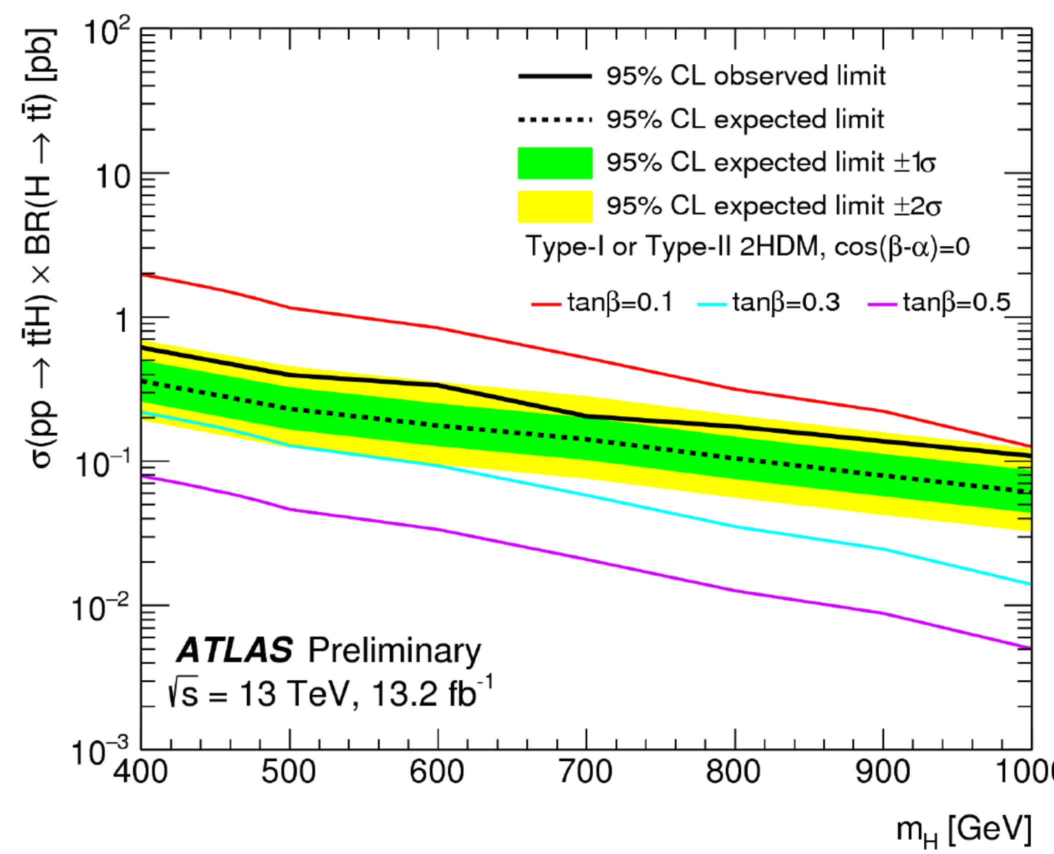


Scalar

[arXiv:1707.06025]

- No significant excess over Standard Model background expectation is observed in the Run-1 inclusive analysis at 8 TeV
- Type-II 2HDM shown

- ATLAS also looks into associated production of a heavy Higgs at 13 TeV using 13.2 fb^{-1}. We set upper limits on the signal production cross section x BR for a heavy Higgs mass between 400 GeV and 1000 GeV using the ttbar final state.
- Limit for Type-I or Type-II 2HDM shown.

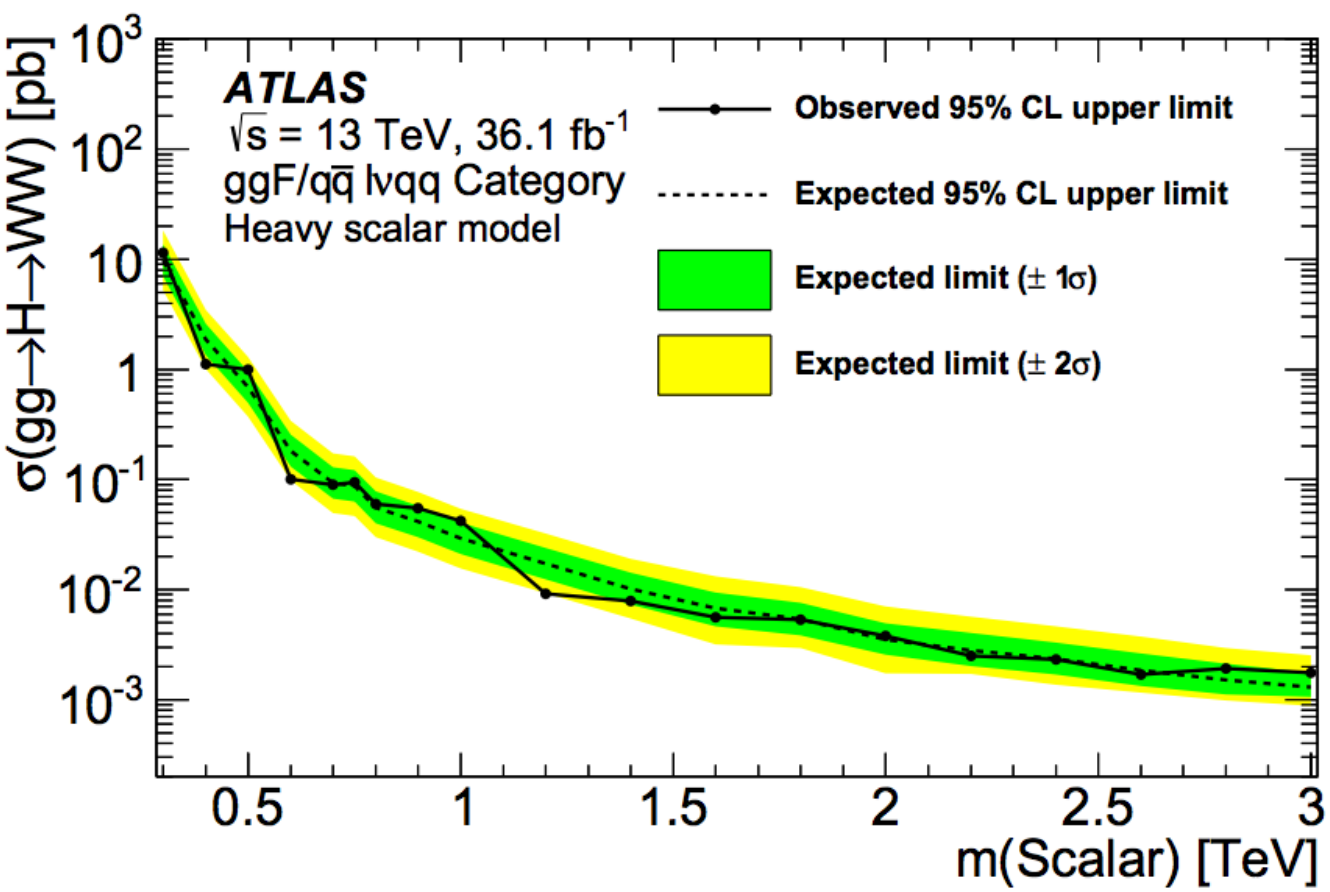


[ATLAS-CONF-2016-104]

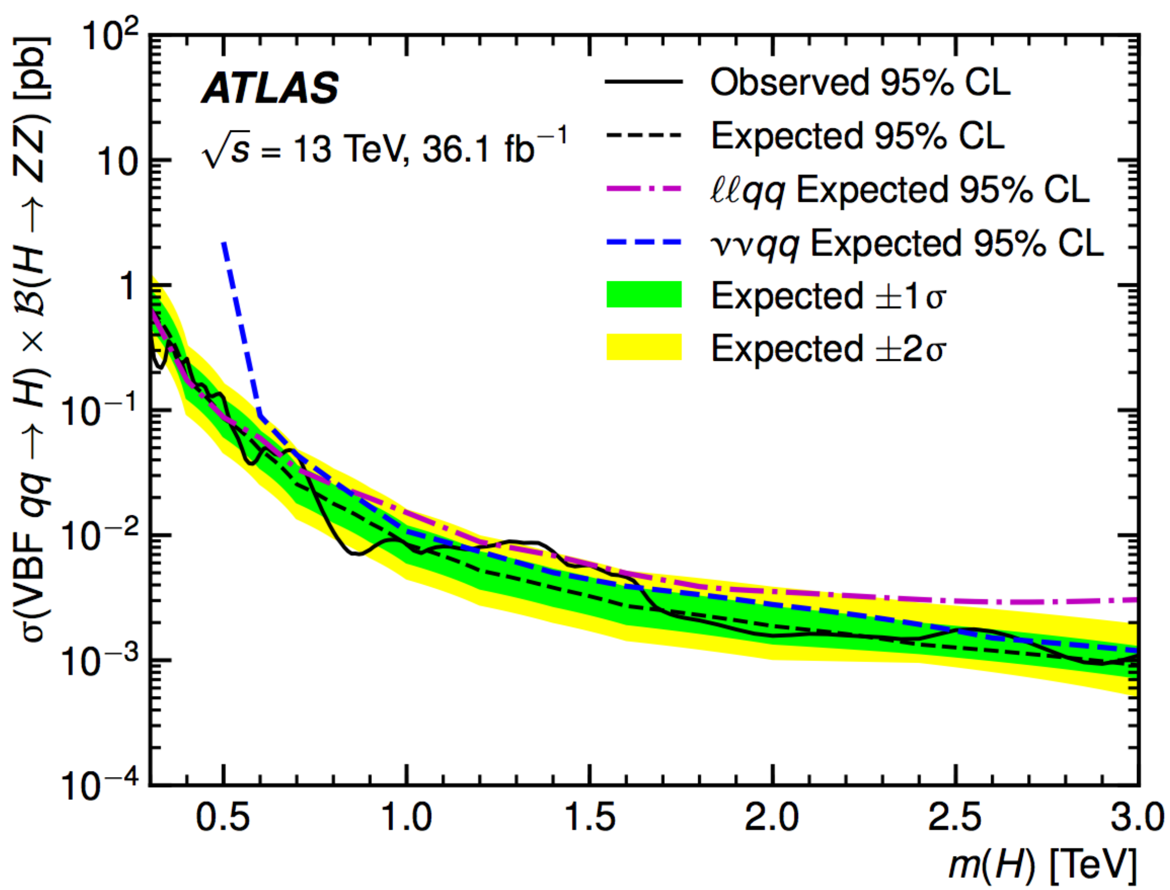
ATLAS High-mass Searches (H→WW or ZZ)

- ATLAS H→WW→lνqq (l=e,μ) uses 36.1 fb^{-1} of 13 TeV pp data
- Selection: e,μ + MET > 100 GeV, ≥1 jet
- Likelihood fit with dedicated control regions for ttbar and W+jets
- Signal Regions:
  - VBF and ggF/qq (merged and resolved)
  - Inclusion of a jet substructure variable for boosted boson vs. QCD separation

- H→ZZ→4l and llνν (l=e,μ) with ATLAS use 36.1 fb^{-1} of 13 TeV pp data
- Uses the same selection as the SM search, but requires both Z bosons to be on-shell
- Signal Regions:
  - VBF enriched category
  - ggF enriched category
- Limits are set using various widths



arXiv: 1710.07235/ATLAS-CONF-2017-058

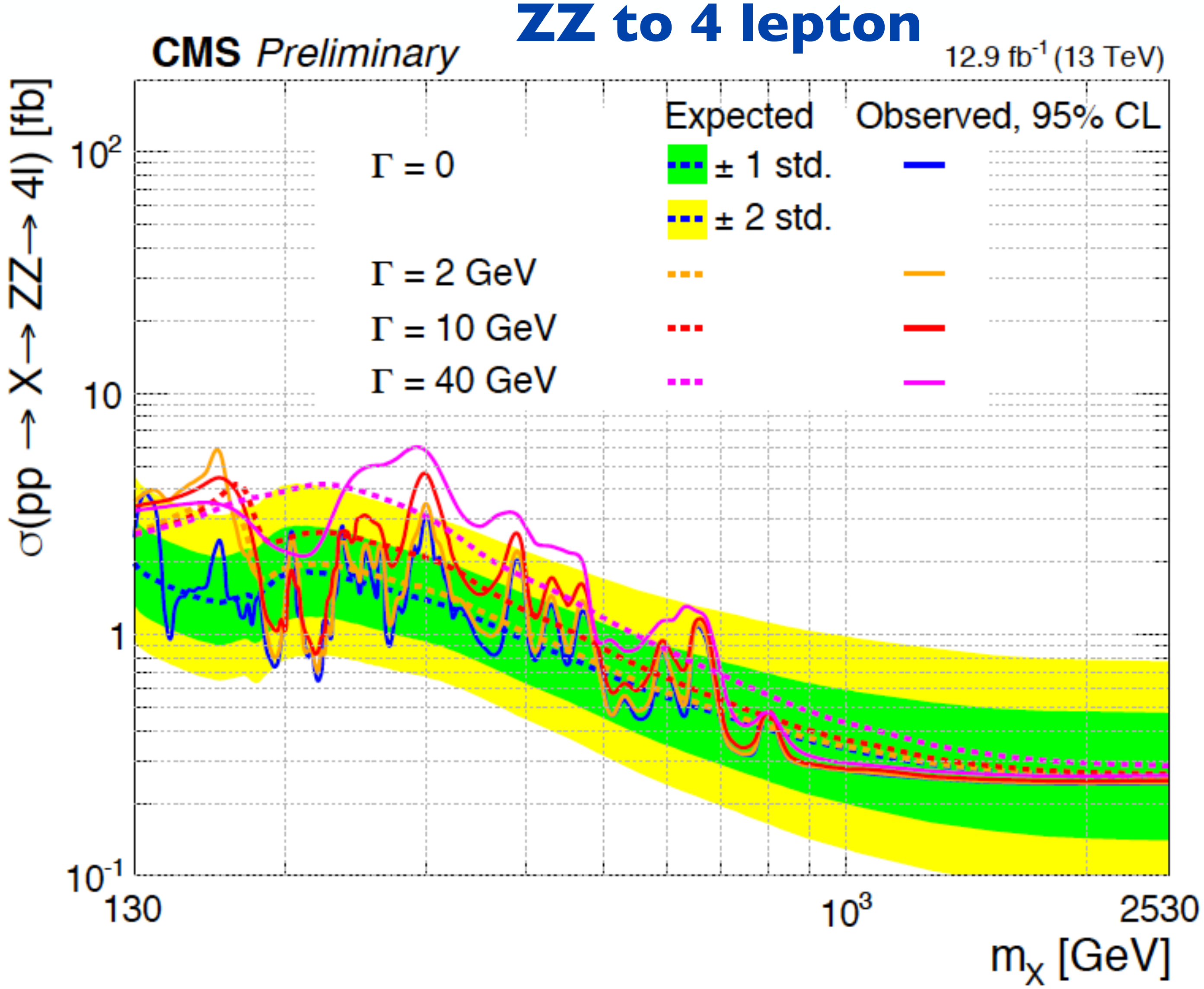


arXiv:1708:04445/arXiv: 1708:09638

CMS High-mass Searches (H→ZZ)

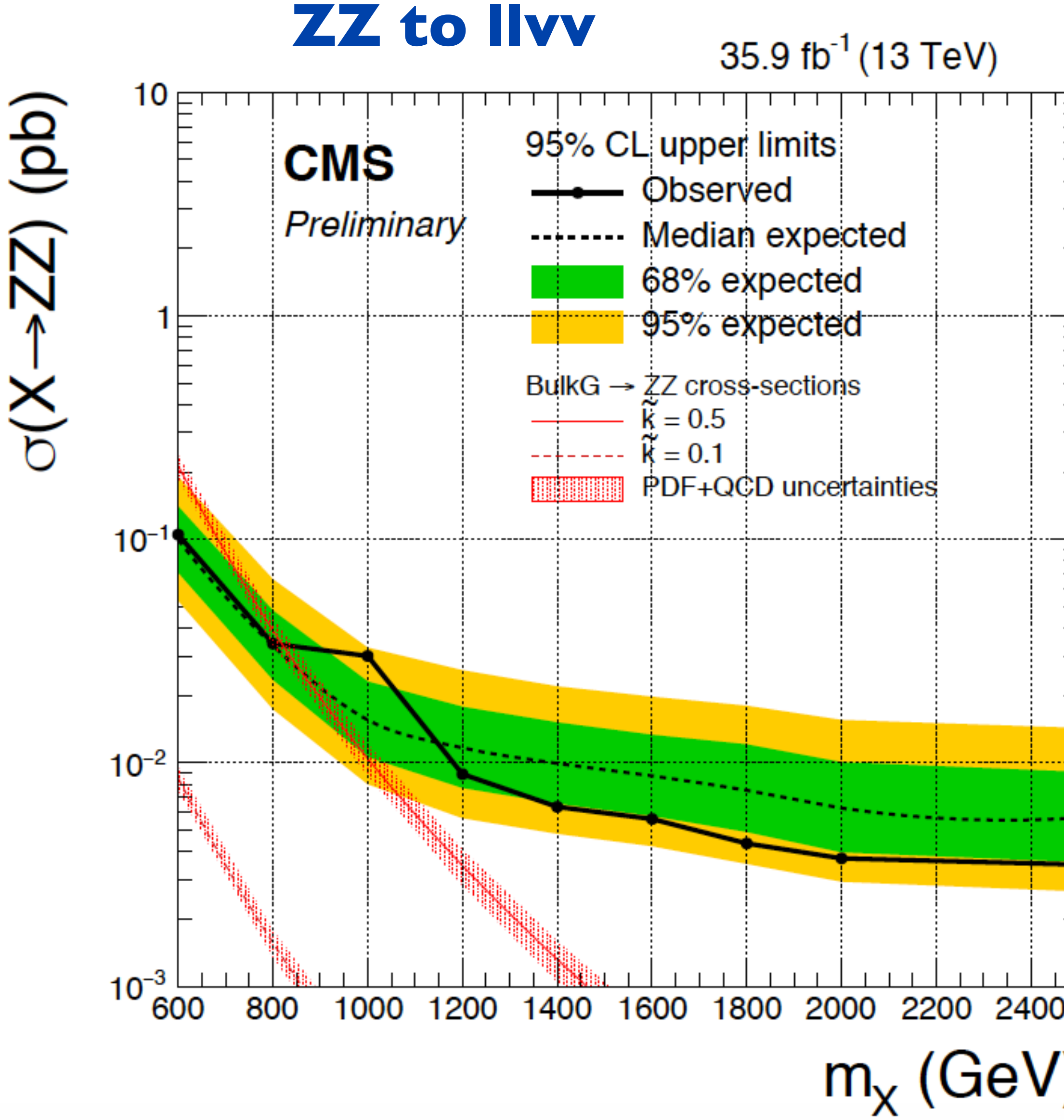
- CMS separates the searches into the H to ZZ to 4l and llvv final states
- The ZZ to 4l search is done as a function of Γ (with Γ < m_X) on m_{4l}
- The ZZ search in 4l uses a separate event categorization for ggF and VBF production
  - Matrix element calculations are used to form several kinematic discriminants

ZZ to 4 lepton



CMS PAS HIG-16-033

ZZ to llvv



CMS PAS B2G-16-023

Run-1: Doubly Charged Higgs (H^{++})

- Predicted by many models
  - Left-Right symmetric models, "Seesaw Type-II" models including Higgs triplet models (H^0, H^+, H^{++}) and "Little Higgs" models
  - Possible observation of H^{++} at the LHC could provide more insight into neutrino masses
  - Predominantly produced in pairs via Drell-Yan $pp \rightarrow H^{++}H^{--}$
- This is performed as a generic same-sign di-lepton spectrum search

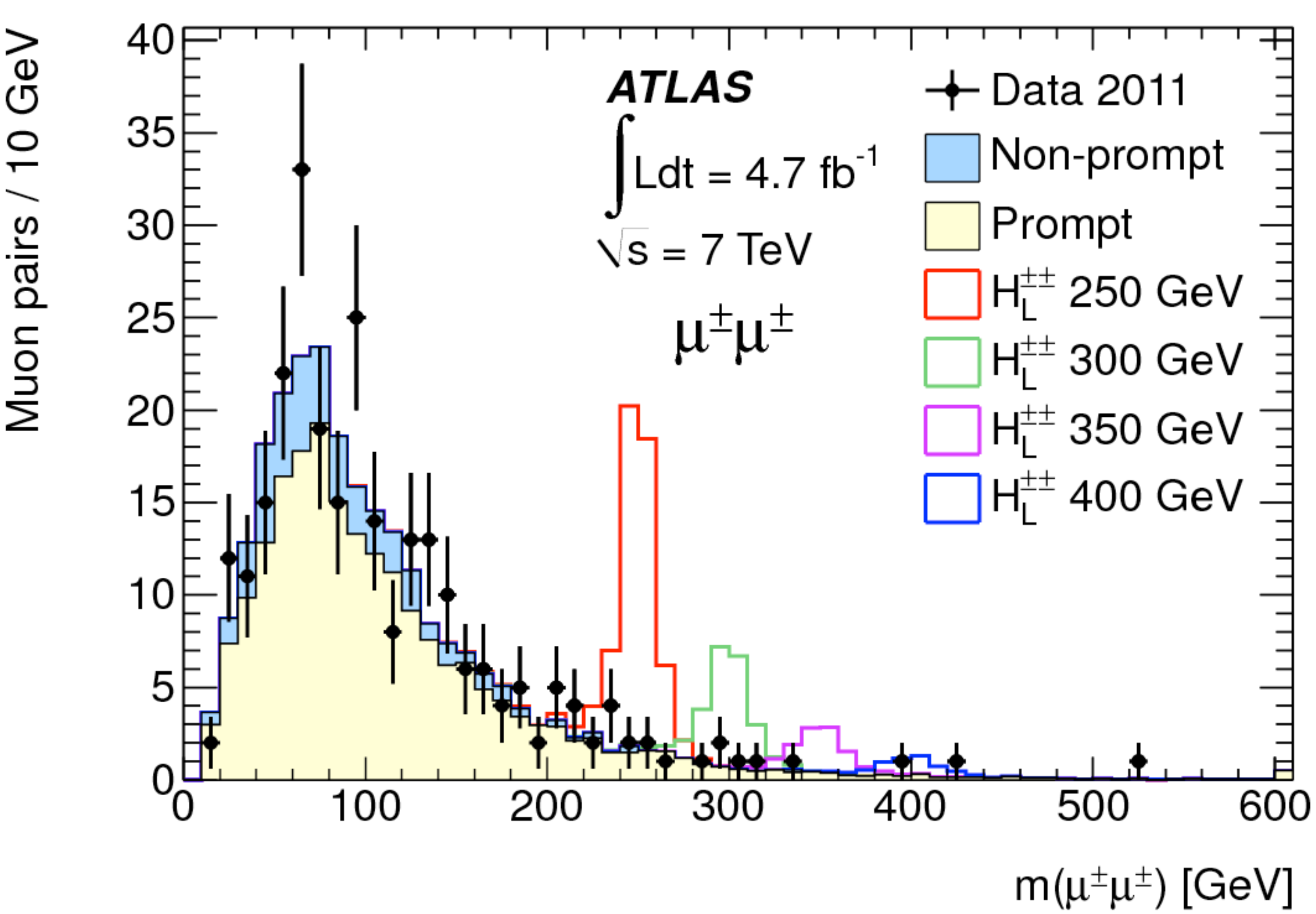
Dominant background to di-muon search at low masses comes from non-prompt muons (from heavy-flavor decays, or decays in-flight of pions or kaons)

- ATLAS Run-I paper on 7 TeV:

  Eur. Phys. J. C 72 (2012)

- And on 8 TeV:

  JHEP 03 (2015) 041

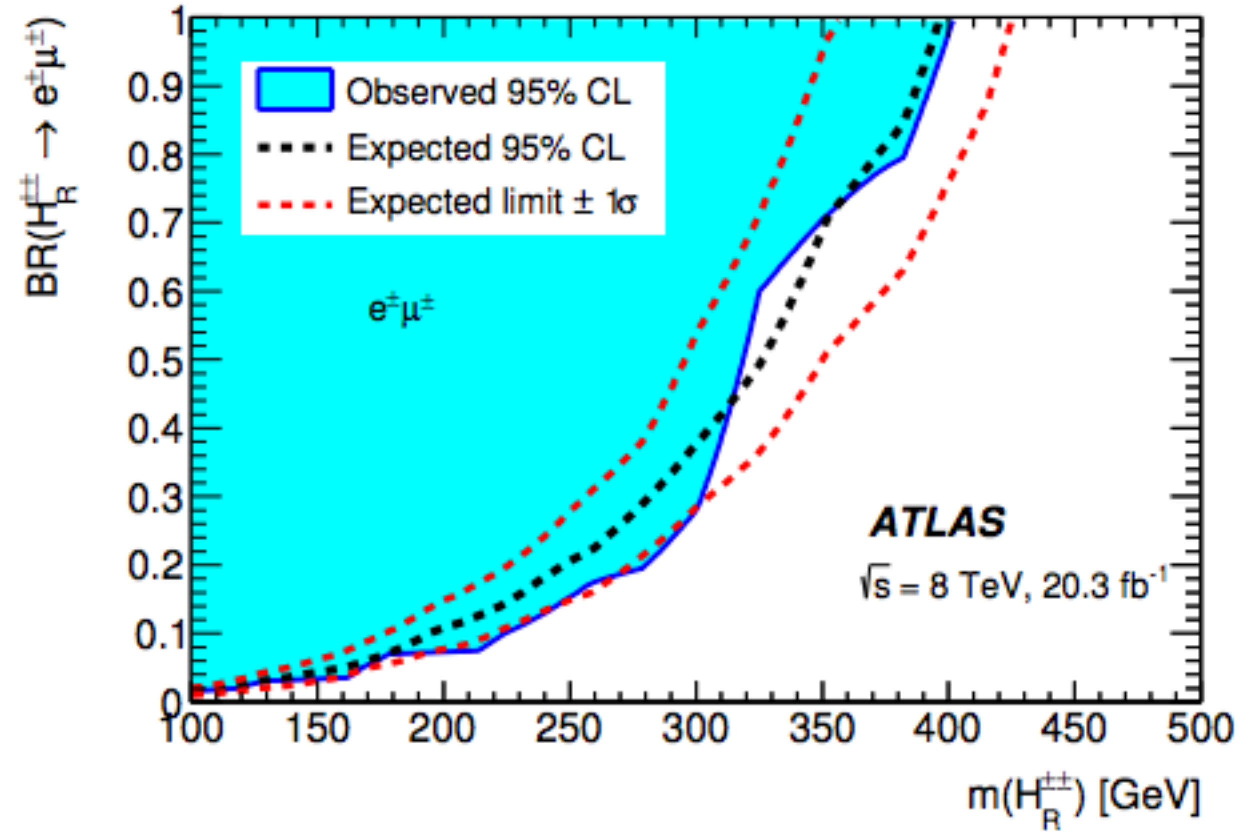


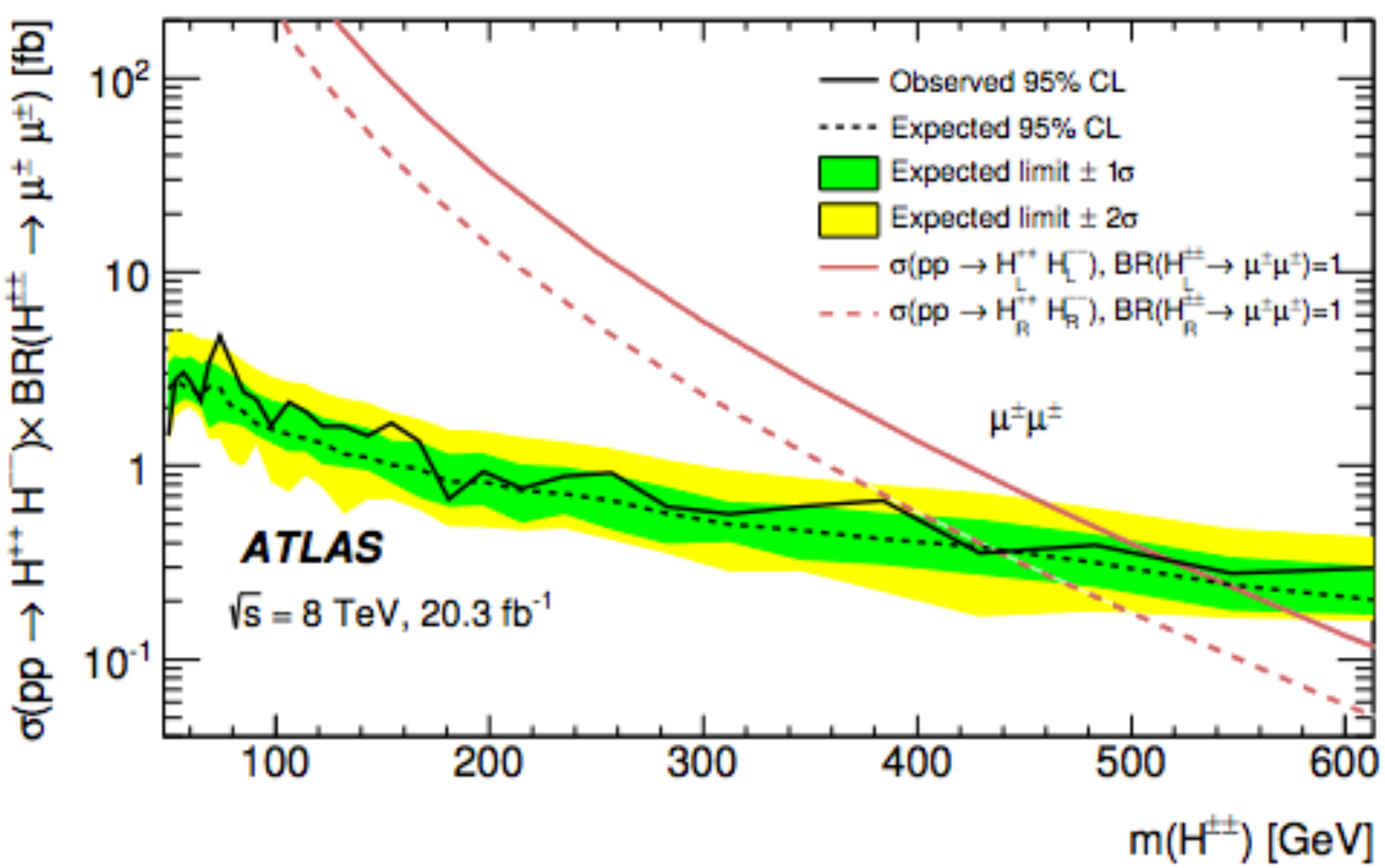
Run-1: Doubly Charged Higgs (H^{++})

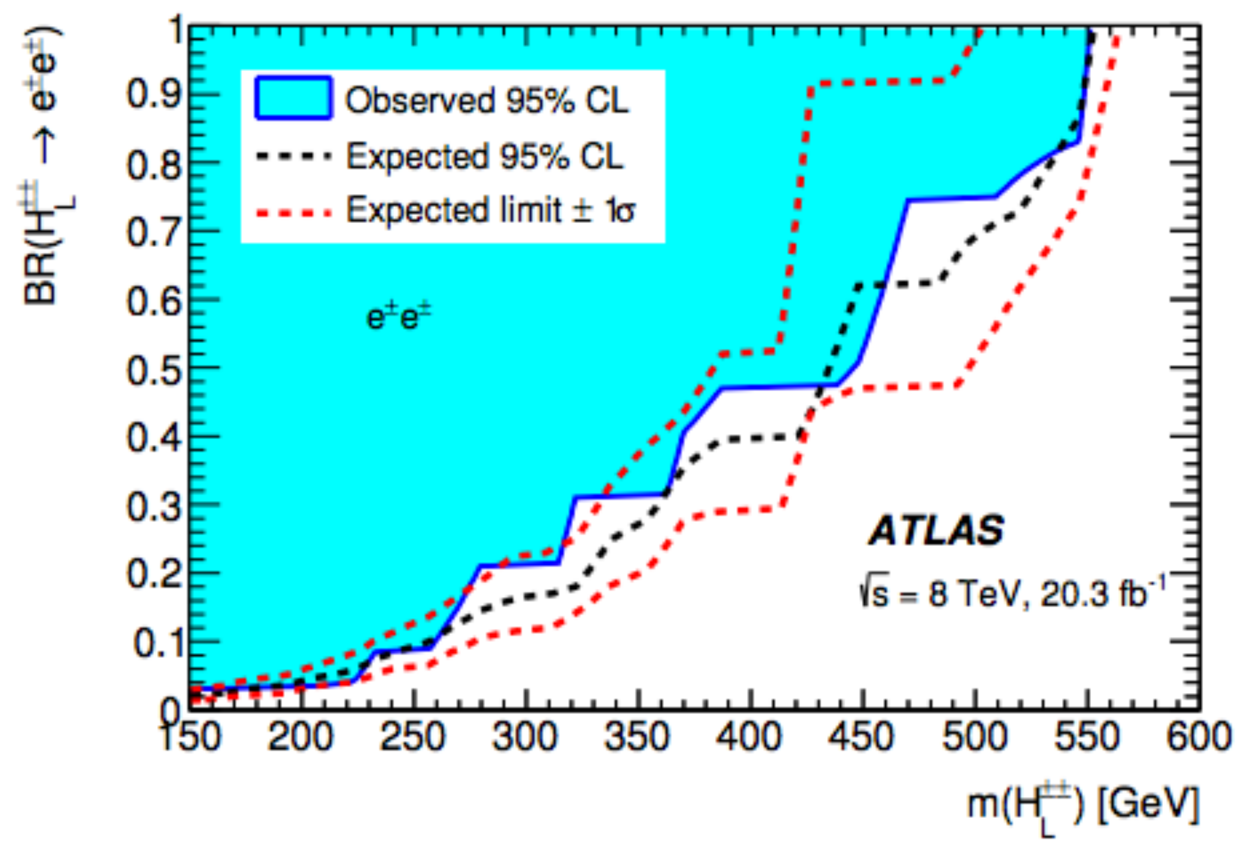
JHEP 03 (2015) 041

- Exclusion limits from 8 TeV in 20 fb^{-1}
  - Assuming $qq \rightarrow Z/\gamma^{*} \rightarrow H^{++}H^{--}$ to pairs of $\mu^{\pm}\mu^{\pm}$, $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$
  - Limits on $H^{\pm\pm}$ mass of 396 GeV - 553 GeV; BR=100%

$H_L^{\pm\pm}$ couple to both the Z and photons
$H_R^{\pm\pm}$ only couple to photons







Run-II: Doubly Charged Higgs (H^{++})

- Looks like $H^{++}H^{--}$ production cross section ~doubles going from 8 to 13 TeV
- Strong limits from 8 TeV data with 20 fb^{-1}… 13 TeV doubly charged Higgs searches start to get interesting in ~5 - 10 fb^{-1} range?

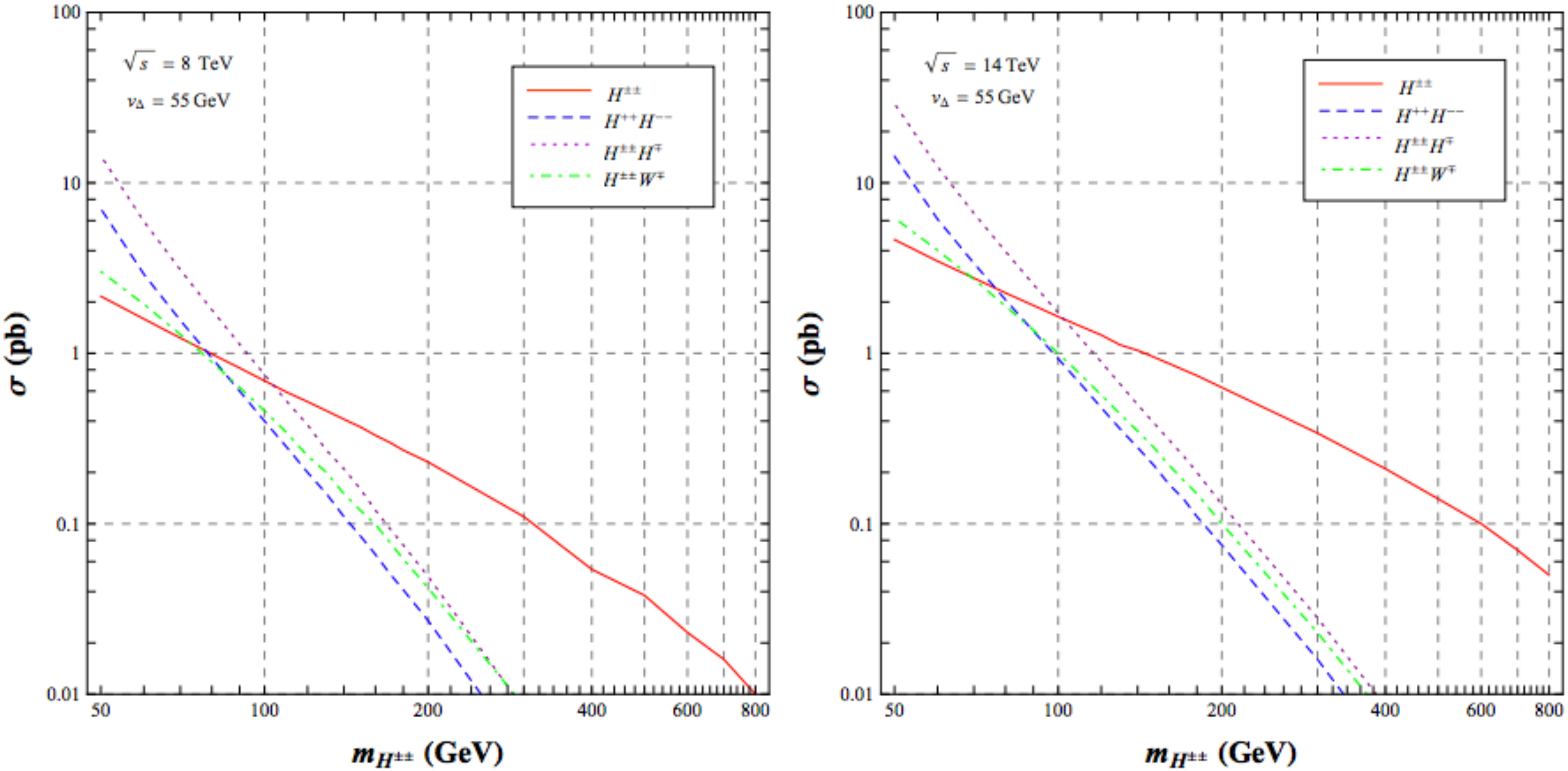
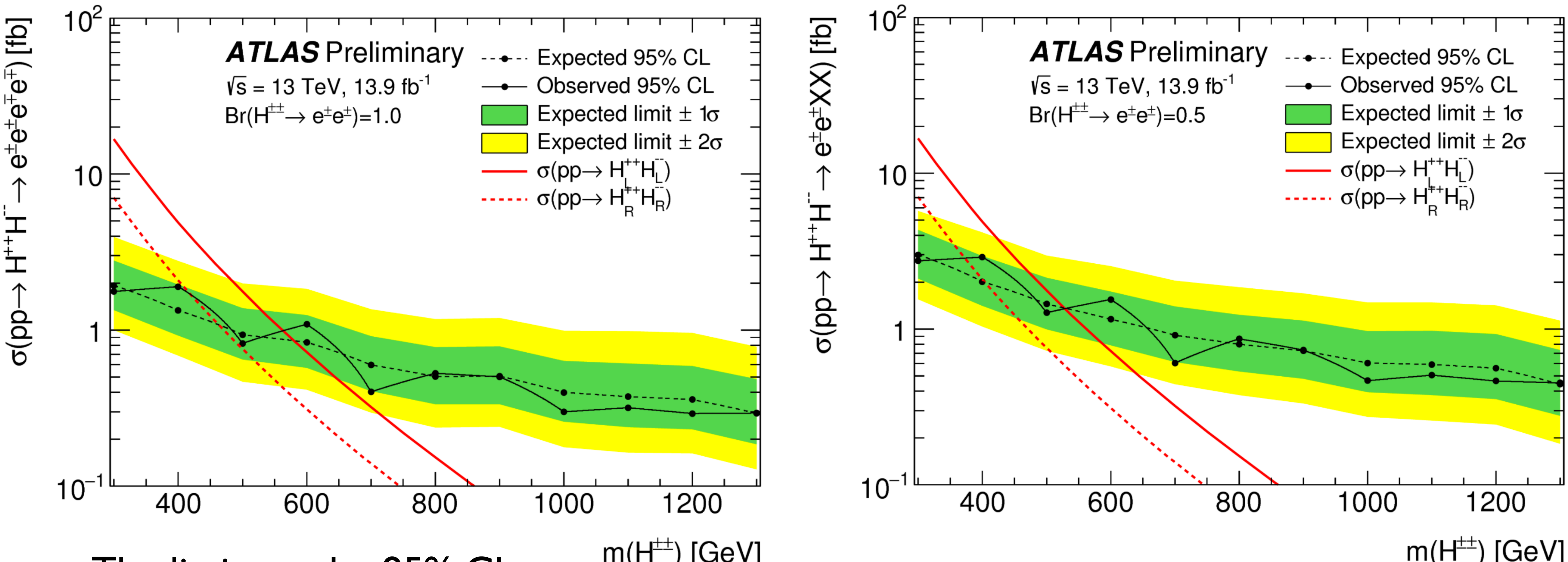


FIG. 1: Cross sections of the doubly charged Higgs bosons in various production channels for $v_\Delta = 55$ GeV. The collision energy is assumed to be 8 TeV in the left plot and 14 TeV in the right plot. The CTEQ6L PDF's are used. [Phys. Rev. D85 (2012) 095023]

Run-II: Doubly Charged Higgs (H^{++})

- Only publicly-available ATLAS result from Run-II for doubly charged Higgs is for the $e^{\pm}e^{\pm}$ channel… consider different fractions of the total BR.

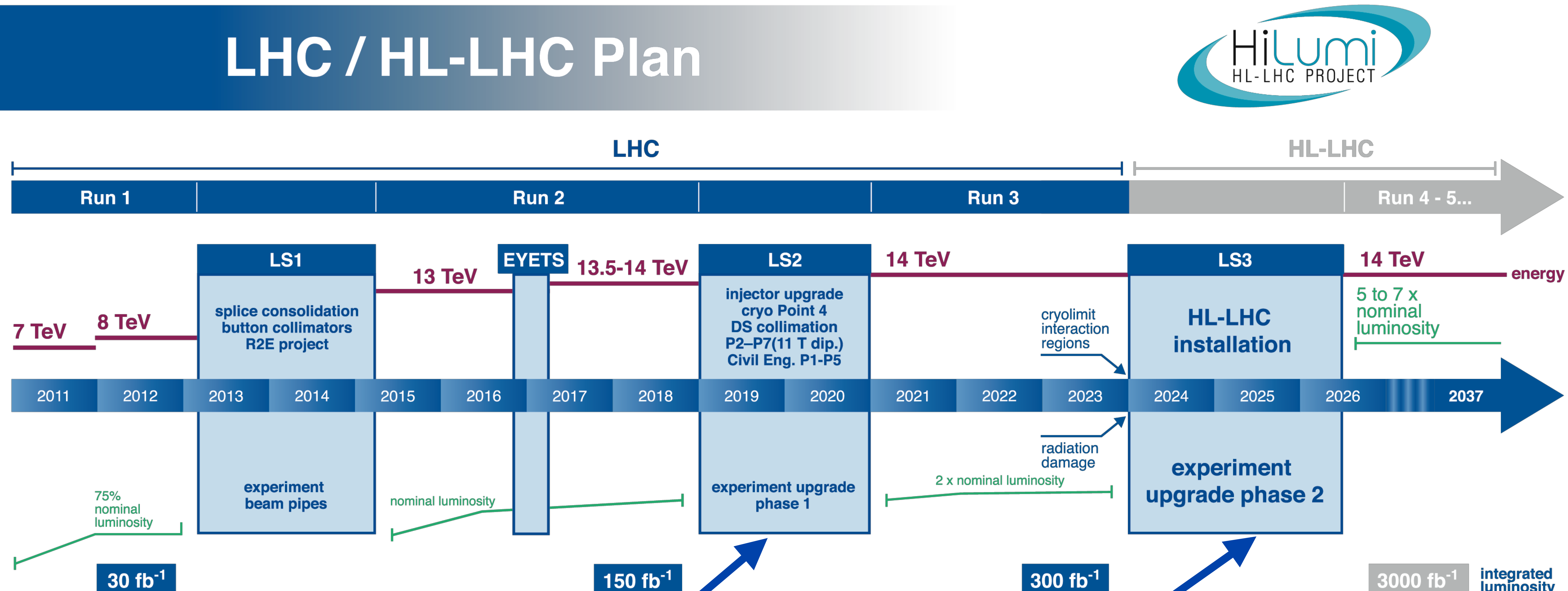


- The limits at the 95% CL are:
  - For 100% BR: Lower limit of 420 GeV for a doubly-charged Higgs boson coupling to right-handed leptons ($H^{\pm\pm}_R$) and 570 GeV for a doubly-charged Higgs boson coupling to left-handed leptons ($H^{\pm\pm}_L$).
  - For 50% BR: Lower limits of 380 GeV for $H^{\pm\pm}_R$ and 530 GeV for $H^{\pm\pm}_L$.

ATLAS-CONF-2016-051

CERN LHC Plans for Run-3, 4-5,…

- Run-2 pp running at 13 TeV finished in 2018… currently in long shut-down
- The long-term plan is to have about 3000 - 4000 fb^{-1} of integrated luminosity
- ATLAS and CMS will need upgrades for an era of high luminosity running…



Phase-I Upgrade for
L=2-3 x 10^{34} cm^{-2}s^{-1}
In the advanced stages… starting production

Phase-II Upgrade for
L=5-7.5 x 10^{35} cm^{-2}s^{-1}
In the design and prototyping stage