LHCP 2020, Paris (virtually)
27 May 2020

Higgs sector / 2 "What we would like to know"

Giovanni Petrucciani (CERN)
on behalf of the ATLAS and CMS Collaborations

Outline

- Part I: Higgs boson self-coupling
- Part II: Rare decays and beyond standard model physics
- Part III: Very brief outlook towards HL-LHC

In this talk I will focus only on a selection of the more recent results.

However, a very comprehensive set of studies on all these topics has been done by both collaborations on the early LHC Run 2 data from 2016 in the past. Results are available from the links below:

All ATLAS results: **Higgs**, **HDBS "Higgs and Diboson searches"**

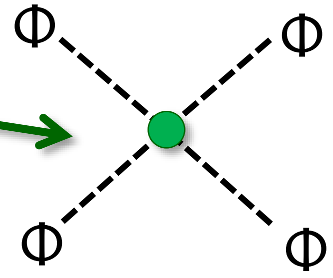
All CMS Higgs results: **papers**, **preliminary results**

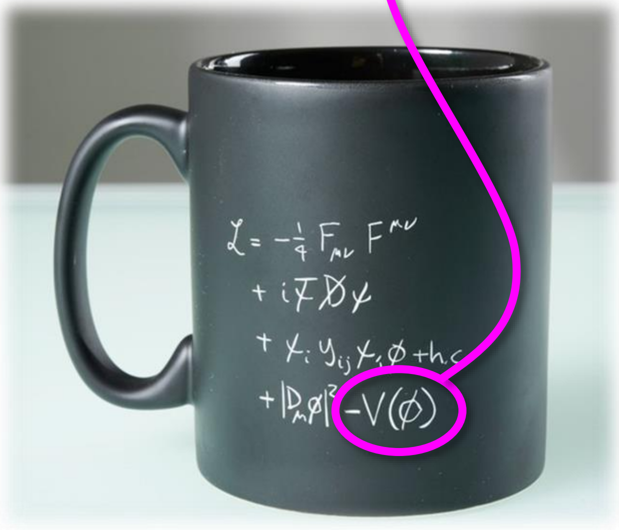
More info in the parallels: Daniel and Stefano (HH, Thursday), Andrey (2^{nd} gen, Thursday), Adam and Renje (BSM, Wednesday), Mariia (DM, Friday)

Part I: Higgs boson self-coupling

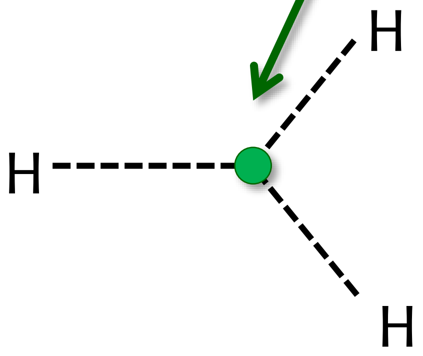
- An essential component of electroweak symmetry breaking

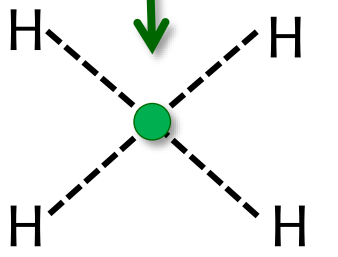
$$V(\Phi) = -\mu^2 |\Phi^\dagger \Phi| + \lambda |\Phi^\dagger \Phi|^2$$





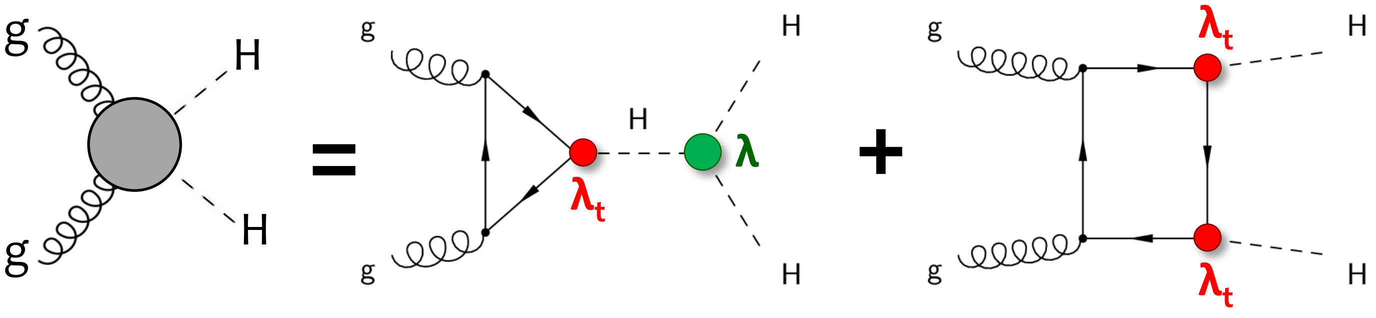
$$= V_0 + \tfrac{1}{2} m_H^2 H^2 + \lambda v H^3 + \tfrac{1}{4} \lambda H^4$$

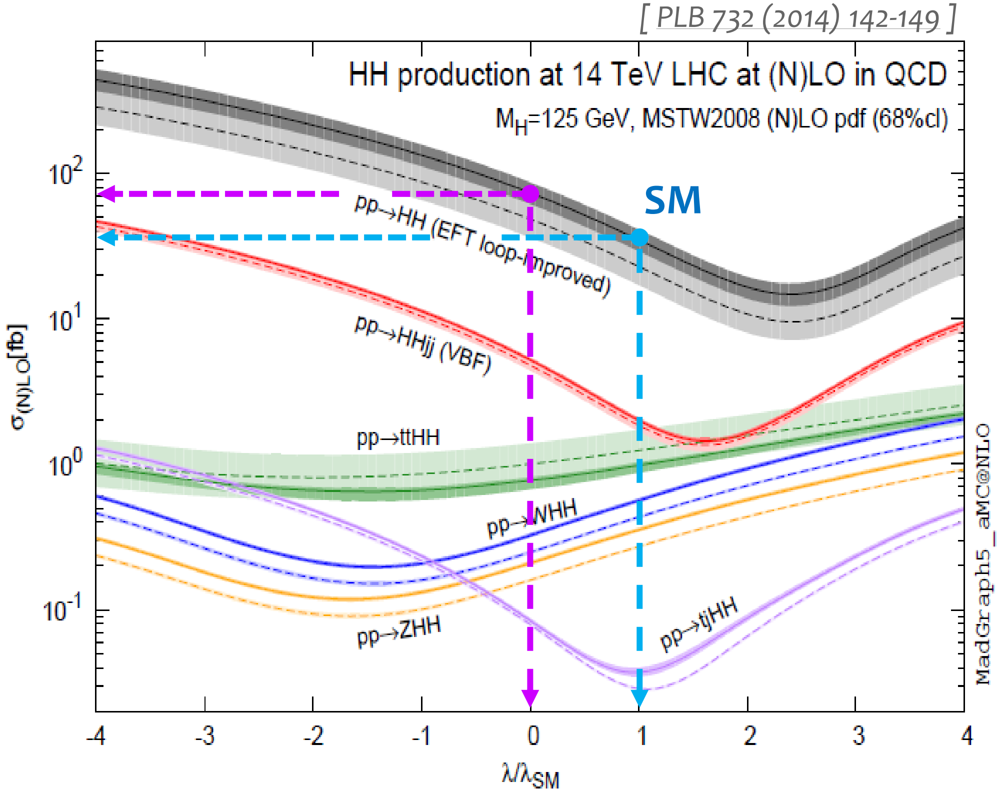




HH production in the SM: gluon fusion

- Dominant HH production mode in the SM is **gluon fusion,** driven by on **self-coupling λ** and **Higgs-top couplings λ_t**
  - $\sigma_{SM}(ggHH) = 31$ fb [~ 1/1500 of σ(ggH) !]





- **Destructive interference** between the two contributions: σ larger at λ = 0!

$$\sigma/\sigma_{SM} \sim 2.09\ \kappa_t^4 - 1.36\ \kappa_\lambda \kappa_t^3 + 0.28\ \kappa_\lambda^2 \kappa_t^2$$

$[\kappa_t := \lambda_t / \lambda_t^{SM}\ ;\ \kappa_\lambda := \lambda / \lambda_{SM}\ ]$

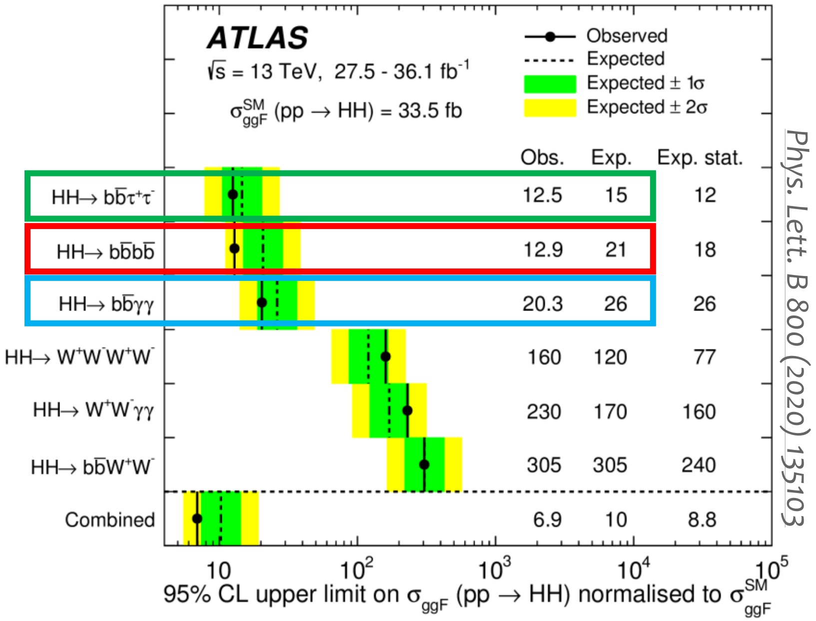
Phys. Rev. Lett. 122 (2019) 121803
Phys. Lett. B 800 (2020) 135103

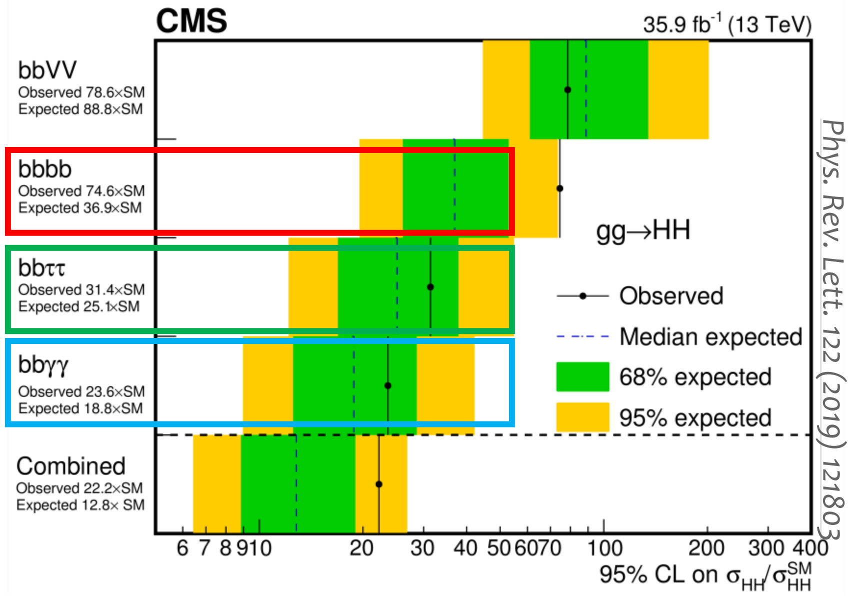
Double-Higgs production: early run 2 results

- Currently, the most stringent constraints on HH production are still the ones from the analysis of early LHC Run 2 (2016) data
  - Observed and expected upper limits on $\sigma(HH)/\sigma_{SM}(HH)$

ATLAS obs. 6.9 (exp. 10) **CMS obs 22.2 (exp. 12.8)**

  - Driven by the 3 most sensitive modes: **bb ττ**, **bb γγ**, **bb bb**



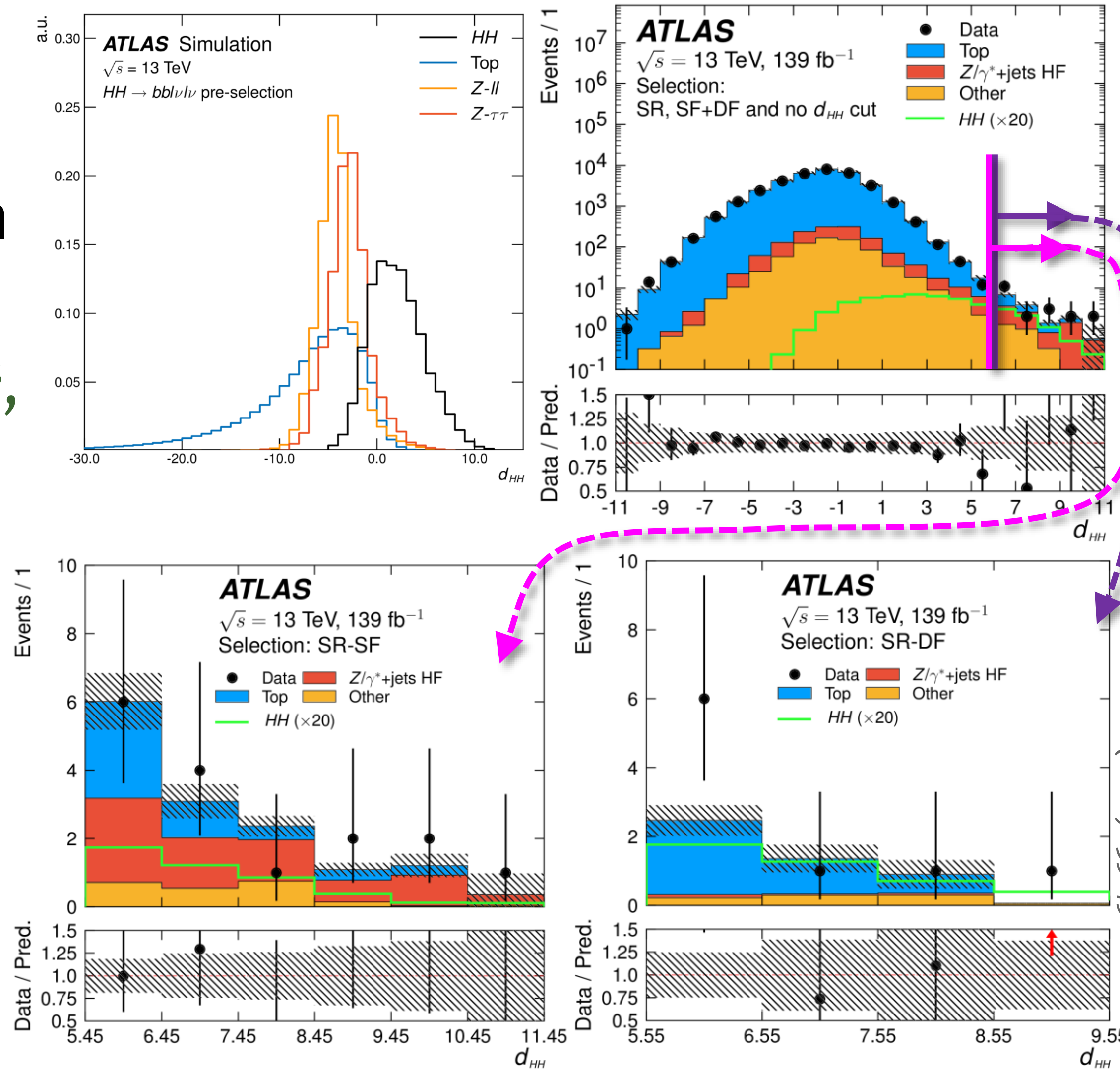


Differences across experiments for the same channel mainly driven by different level of complexity of the analyses.

ATLAS EXPERIMENT
$L = 139\ fb^{-1}$

Beyond 2016 data: HH → bb $W_{\ell\nu}W_{\ell\nu}$

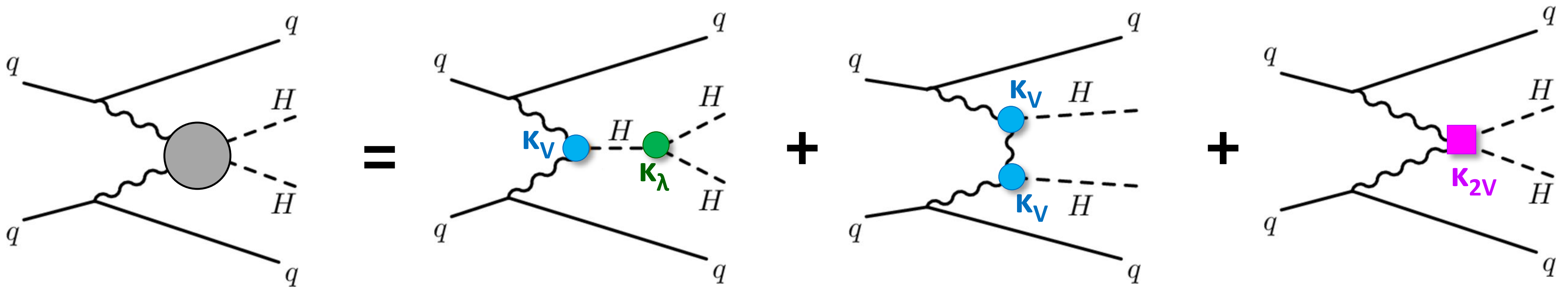
- First HH → bbℓνℓν analysis at ATLAS
- Multiclass DNN to separate **HH** from 3 main backgrounds: tt̄ , Z(ℓℓ), Z(ττ)
  - Inputs are individual leptons, jets, E_T^{miss}, high-level variables (e.g. $\Delta R_{\ell\ell}$, m_{T2}^{bb})
  - Output $\mathbf{d_{HH} := \ln(p_{HH} / \Sigma\, p_{bkg})}$
- Signal regions defined by d_{HH} cuts
- ×8/×3 better sensitivity than old 36 fb^{-1} analyses from ATLAS[*]/CMS:
  - Set limit at σ_{HH} < 40×SM (exp.: 29×SM)



[*] older analysis was for the H→ WW→ ℓνqq, qqqq decays

HH production: vector boson fusion

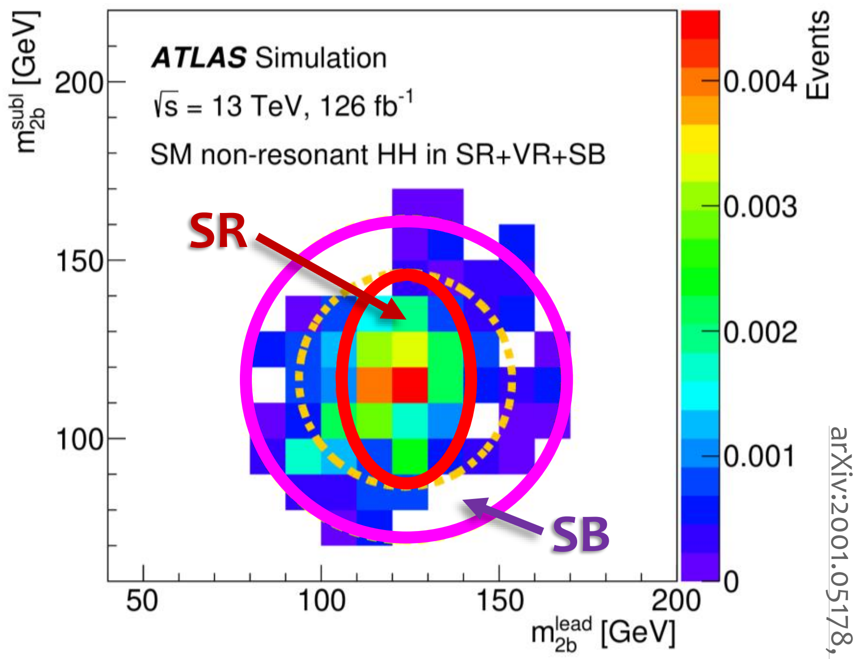
- VBF is the second production mode, with **σ_{SM} = 1.72 fb**
  - ~1/20 of ggHH, ~1/2000 of VBF H
- Receives contributions from **self-coupling** HHH, **HVV** coupling (κ_V, well measured in single Higgs), and **HHVV** quartic vertex (κ_{2V}).
  - $\kappa_{2V} = \kappa_V^2$ if H is part of a $SU(2)_L$ doublet, as in the SM or the SMEFT.
  - Otherwise, large increase in σ_{VBF} possible: $V_L V_L \rightarrow H H$ would violate unitary

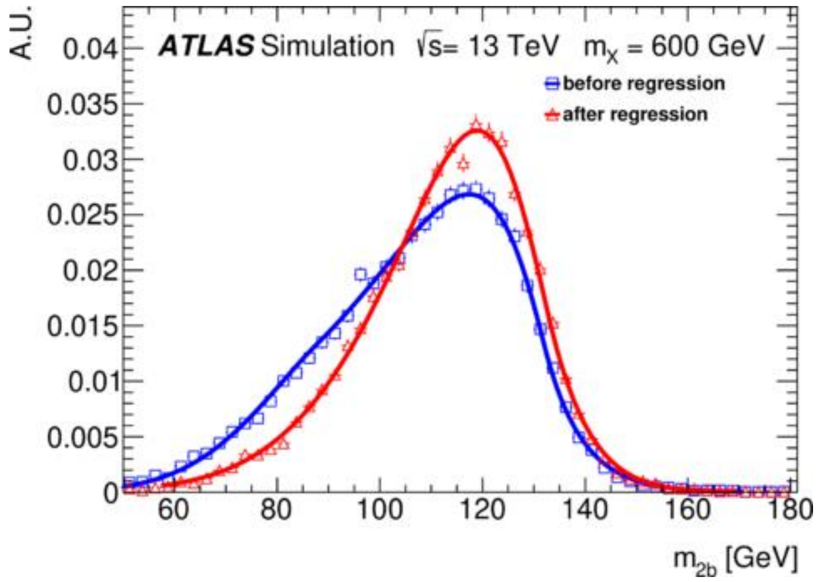


VBF HH → 4b

L = 126 fb^{-1}

- Target the more extreme kinematic of $\kappa_{2V} \neq 1$
  - **Tight cut-based VBF cuts: m_{jj} > 1 TeV, $|\Delta\eta_{jj}|$ > 5**
- Largely based on earlier HH → 4b search on 36 fb^{-1} dataset *[JHEP 01 (2019) 030]*
  - Same strategy used for HH → 4b selection: ΔR_{bb} cuts dependent on m_{4b}, elliptic **signal region** in the plane of the two m_{2b} masses
  - Same estimation of main QCD multi-jet and $t\bar{t}$ background: from events with 2 b-tags, with weights derived in **mass sideband**
- New b-jet energy regression using a BDT
  - ~10% better b-jet energy resolution





arXiv:2001.05178, sub. to JHEP

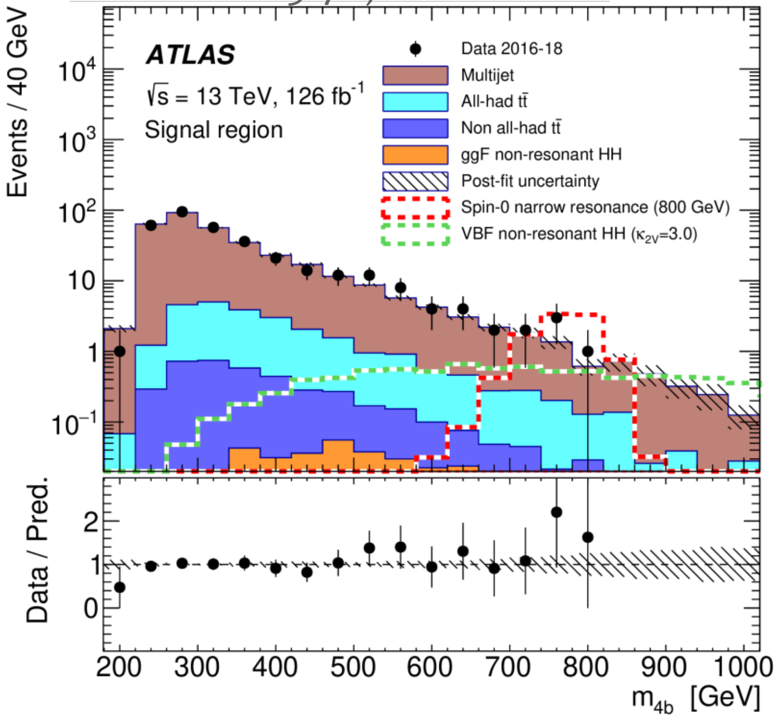
VBF HH → 4b

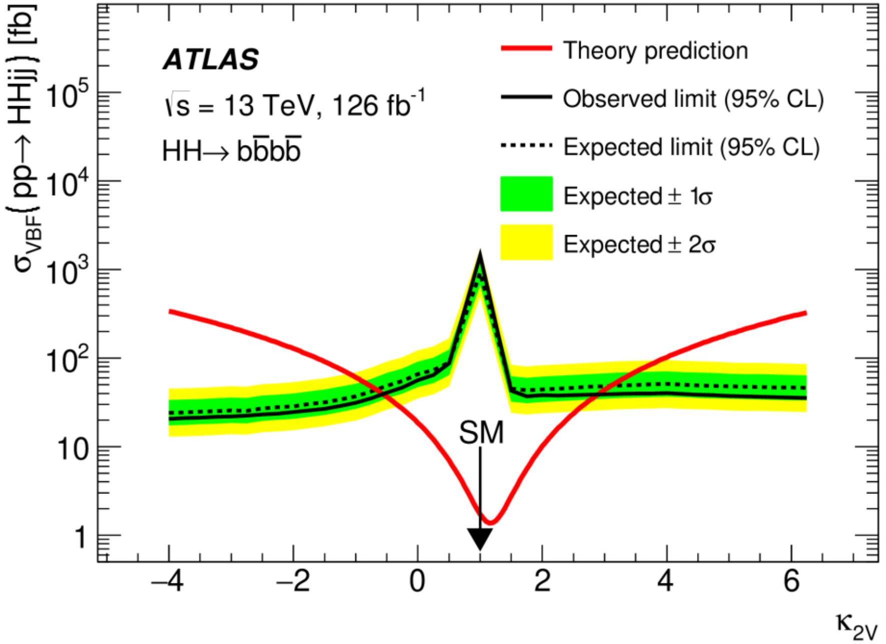
ATLAS EXPERIMENT

L = 126 fb^{-1}

- Use m(4b) as final discriminating variable
  - Searching also for resonant VBF X → HH
- Focus on probing **anomalous κ_{2V}**
  - Set $\kappa_V = 1$, $\kappa_\lambda = 1$
  - SM ggHH negligible with present sensitivity
- Set limit **$-0.56 < \kappa_{2V} < 2.89$** @ 95% CL (expected limit $-0.67 < \kappa_{2V} < 3.10$)
  - **First constraints on κ_{2V} at LHC !**
  - But still far from sensitivity to SM VBF HH. Set upper limit $\sigma/\sigma_{SM} < 840$ (exp. 540)

arXiv:2001.05178, sub. to JHEP

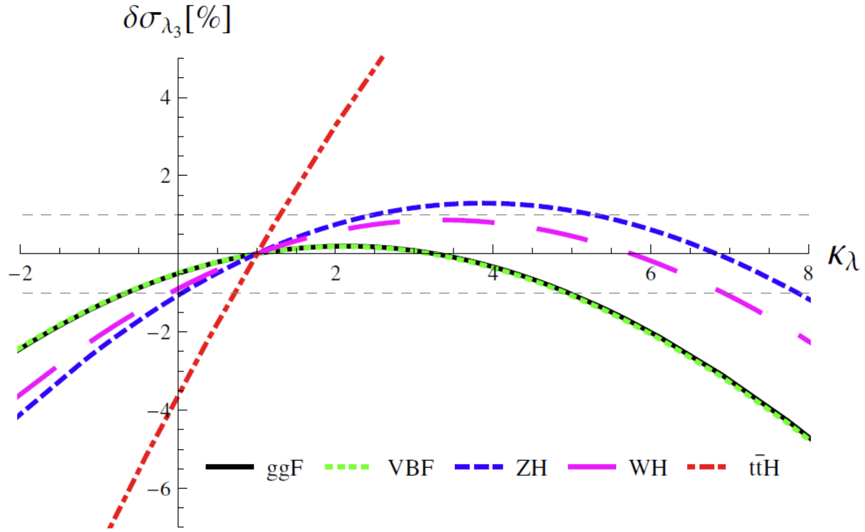




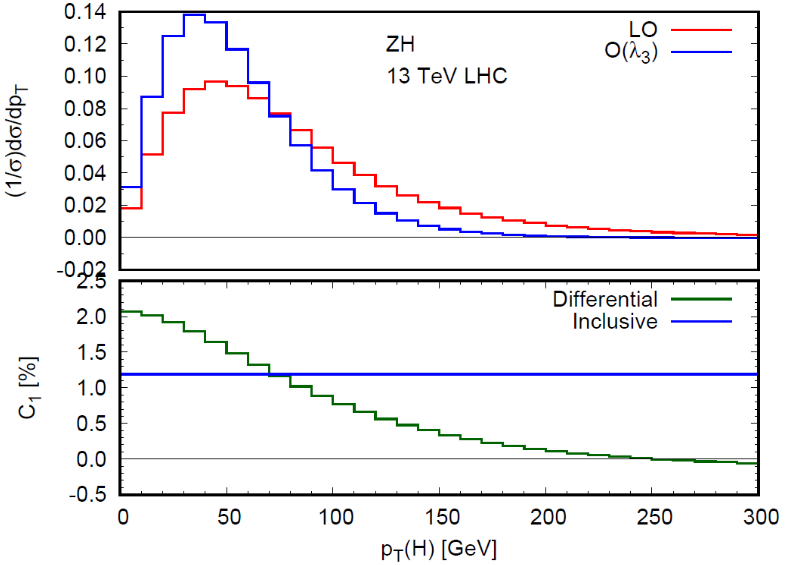
arXiv:2001.05178, sub. to JHEP

Constraining self-coupling from single H

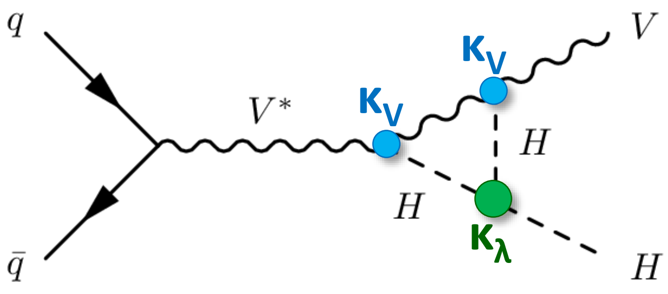
- At NLO, single Higgs observables are sensitive to Higgs boson self-coupling
  - O(1%) corrections to σ_H and BRs for $\Delta\kappa_\lambda = 1$
    Largest effect inclusively is ~3.5% on σ_{ttH}
  - Use of kinematic information, e.g. $p_T(H)$, can enhance the effect further (~×2–3)

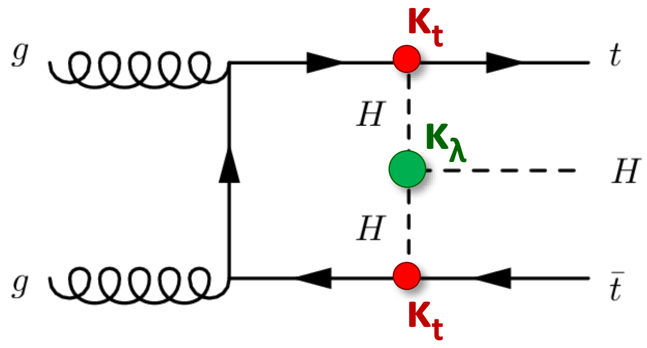


JHEP 12 (2016) 080



EPJC 77 (2017) 12, 887

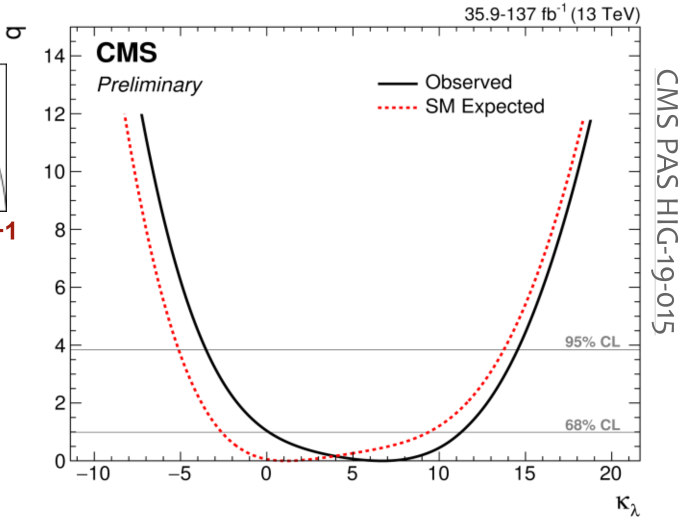




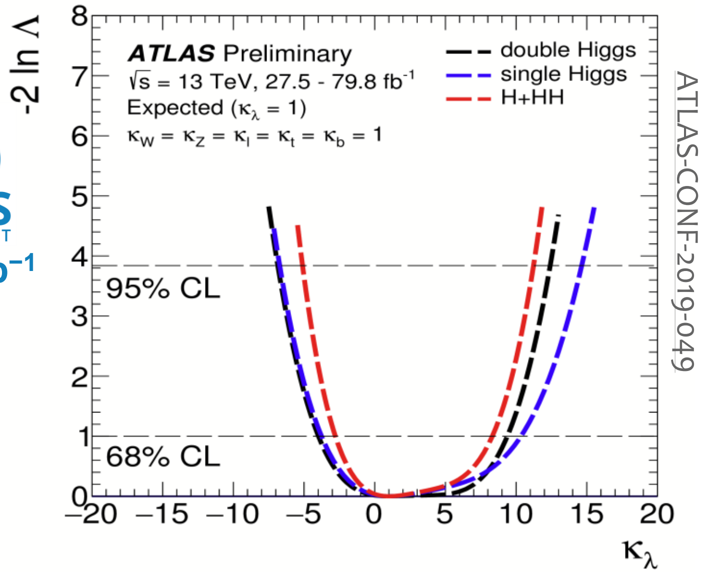
Constraining self-coupling from single H

- Explored by both ATLAS & CMS in the latest single-H combinations
  – ATLAS also including some kinematic information via STXS in VH & VBF prod.
- Constraints comparable to HH searches but only under tight mode assumptions
  – All other couplings fixed to SM, or only floating κ_V or only κ_f
- ATLAS: also combined H + HH fit*
  – Tighter constraint in κ_λ-only fit
  – Allow more general model with floating individual κ's and also κ_λ

CMS $L \leq 137\ \text{fb}^{-1}$



ATLAS EXPERIMENT $L \leq 80\ \text{fb}^{-1}$



*: ttH(γγ) dropped from H inputs due to large overlap with HH(bbγγ)

Phys. Rev. Lett. 122 (2019) 121803 ATLAS-CONF-2019-049
Phys. Lett. B 800 (2020) 135103 CMS PAS HIG-19-015

Overall summary of 95% CL limits on κ_λ

inputs	model.	ATLAS	*(expected)*	CMS	*(expected)*
Single H	only κ_λ	−3.2, 11.9	*−6.2, 14.4*	−3.5, 14.5	*−5.1, 13.7*
HH	only κ_λ	−5.0, 12.0	*−5.8, 12.0*	−11.8, 18.8	*−7.1, 13.6*
H + HH	only κ_λ	−2.3, 10.3	*−5.1, 11.2*		
H + HH	κ's & κ_λ	−3.7, 11.5	*−6.2, 11.6*		

More info in talks by Daniel and Stefano on Thursday

Disclaimer: these are still rather ad-hoc models; still a lot of work ahead for both theorists and experimentalists before we can have a more sounded global fit with full NLO SMEFT or HEFT

Part II: rare, forbidden and BSM

A selection, with higlights on ***new results from 2020***

• $H \rightarrow \mu\mu$, $c\bar{c}$	2nd gen fermion couplings
• **$H \rightarrow Z\ \rho/\varphi$**	enhanced light flavour couplings
• **$H \rightarrow Z\ \gamma$**	SU(2) structure of heavy BSM physics
• $H \rightarrow e\ \mu$[b]	lepton flavour violation
• **$H \rightarrow$ invis**[a], Z invis[b]	Higgs-coupled dark matter or dark sector
• **$H \rightarrow Z\ a$, $a\ a$, $Z_{(D)}\ Z_D$**	Light BSM particles coupled to the Higgs
• **Heavy $H \rightarrow \tau\ \tau$**	Extended Higgs sector, esp. MSSM

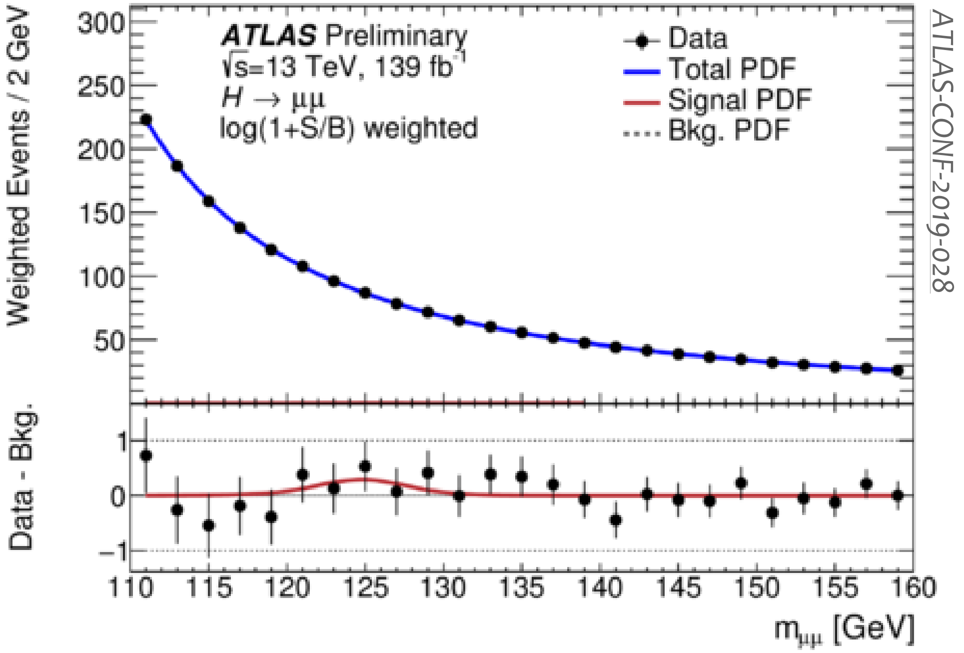
[a] in "Dark Matter" plenary talk by Katherine *[b] in the backup slides*

More info in the parallels: Andrey (2nd gen, Thursday), Adam and Renje (BSM, Wednesday)

$H \rightarrow \mu\mu$

L = 139 fb^{-1}

- $BR_{SM}(H\rightarrow \mu\mu) \sim 2.2 \times 10^{-4}$, and large irreducible DY → μμ background
  - S/B ~ 0.1% for inclusive events at 125 GeV
- Improvements to increase sensitivity:
  - Improved MVA categorization to select events at high S/B, e.g. from VBF
  - New FSR recovery to improve $\sigma(m_{\mu\mu})$
  - Improved rejection of jets from pileup
- Signal extraction from $m_{\mu\mu}$ fit
  - Improved background parametrization: inclusive "core" pdf + per-category empirical transfer function (with less free parameters)



Signal strength: $\mu = 0.5 \pm 0.7$

Significance: 0.8 obs. (1.5 exp.)

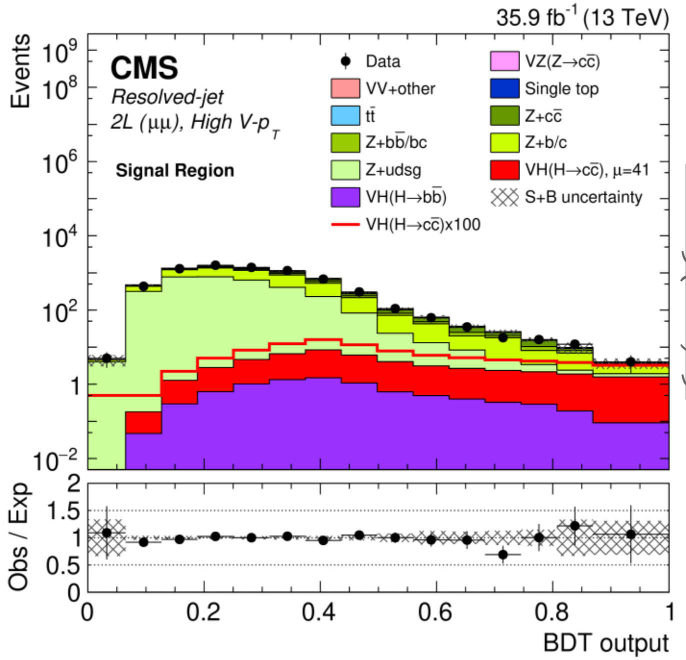
Upper limit on μ: 1.7 obs. (1.3 exp.)

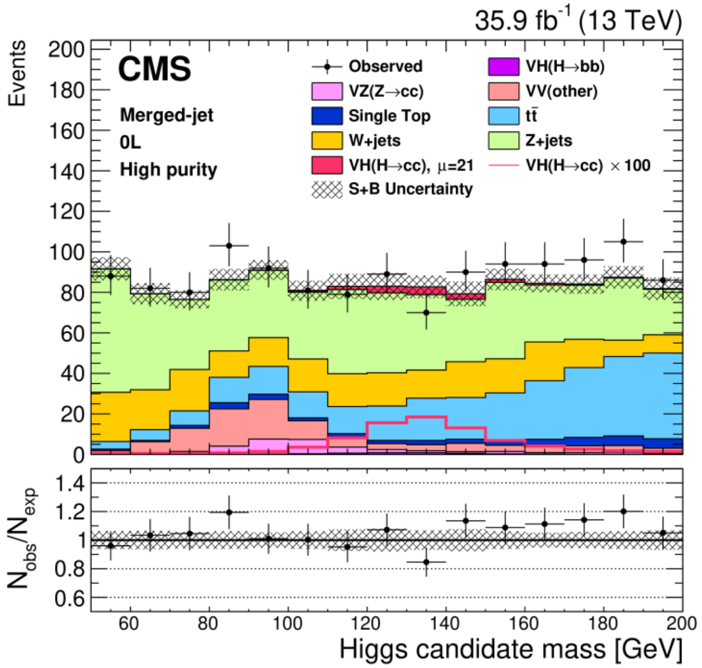
Also older CMS H → μμ result, 36 fb^{-1} + Run 1 [PRL 122 (2019) 021801]
$\mu = 1.0 \pm 1.0^{(stat)} \pm 0.1^{(syst)}$, significance 0.9 σ (expected 1.0 σ)

$H \to c\bar{c}$

L = 36 fb⁻¹

- $BR_{SM}(H \to c\bar{c}) = 2.9\%$ ~ 1/20 of $BR(H \to b\bar{b})$
- Target VH with $V = Z \to \ell\ell$, $W \to \ell\nu$, $Z \to \nu\nu$, with the combination of two strategies:
  - **Resolved analysis**: based on VH($b\bar{b}$) analysis, but with charm tagging. Signal extraction from fit to BDT
  - **Boosted analysis:** use anti-k_T(R=1.2) jets with advanced H→cc DNN tag (flavour + substructure), Signal extraction from groomed jet mass
- Multiple control regions to normalize in data the main backgrounds, i.e. V + jets and $t\bar{t}$
- **Set limits $\sigma \times BR(H \to c\bar{c}) < 70 \times SM$ (exp. $37 \times SM$)**

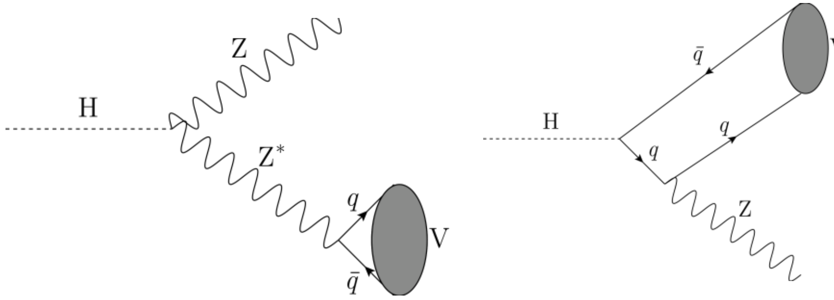




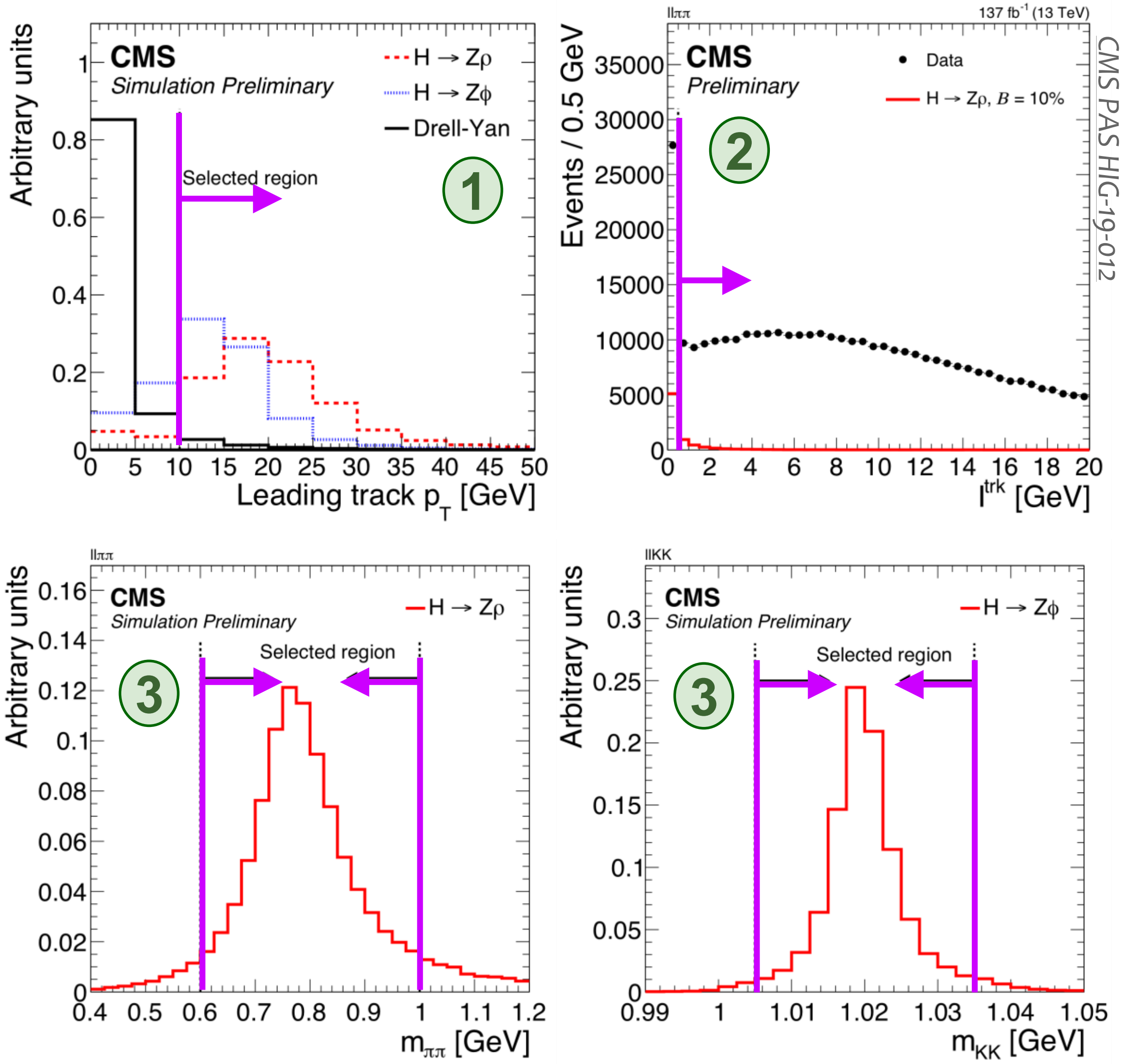
Also older ATLAS VH($c\bar{c}$), 36 fb⁻¹, only $Z \to \ell\ell$ channel and simpler analysis, Observed upper limit 110 × SM (expected 150 × SM) [PRL 120 (2018) 211802]

L = 137 fb^{-1}

$H \to Z + \rho/\varphi$

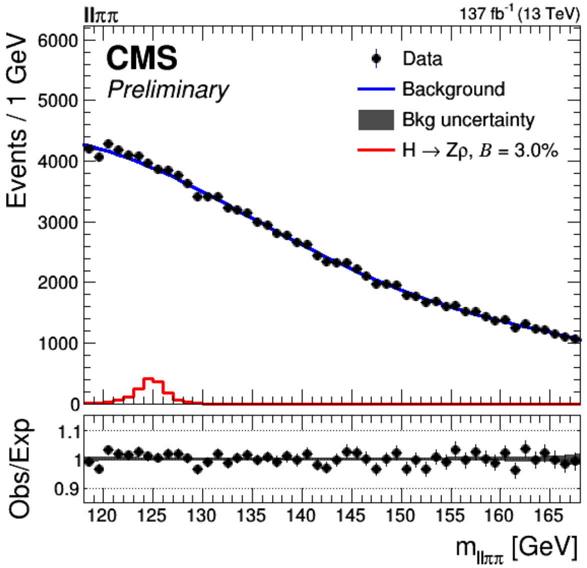


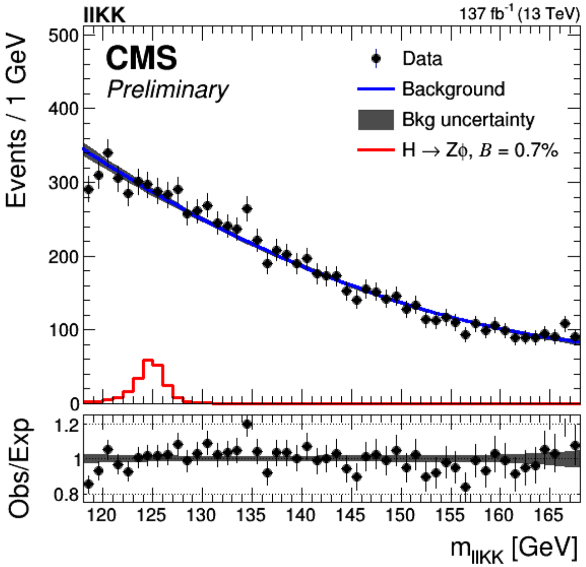
- SM BR mainly via $H \to Z\, Z/\gamma^* \to Z\, V$, but $H \to qq$ channel may have large enhancement in some BSM models
- Target $\boldsymbol{\rho \to \pi^+ \pi^-}$ and $\boldsymbol{\varphi \to K^+ K^-}$
  1. Select pairs of opposite-charge tracks, $\Delta R < 0.1$ and $p_T^{lead} > 10$ GeV
  2. Require di-track pair to be isolated
  3. Select window in di-track mass



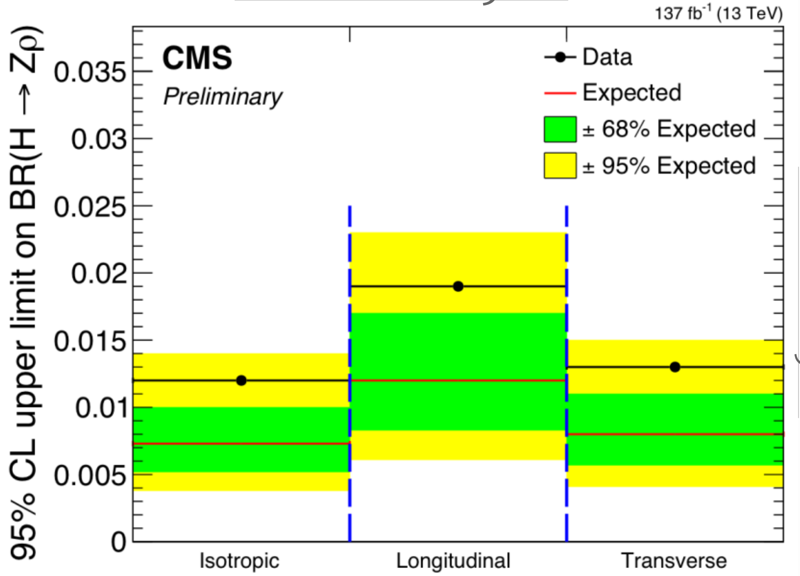
H → Z + ρ/φ

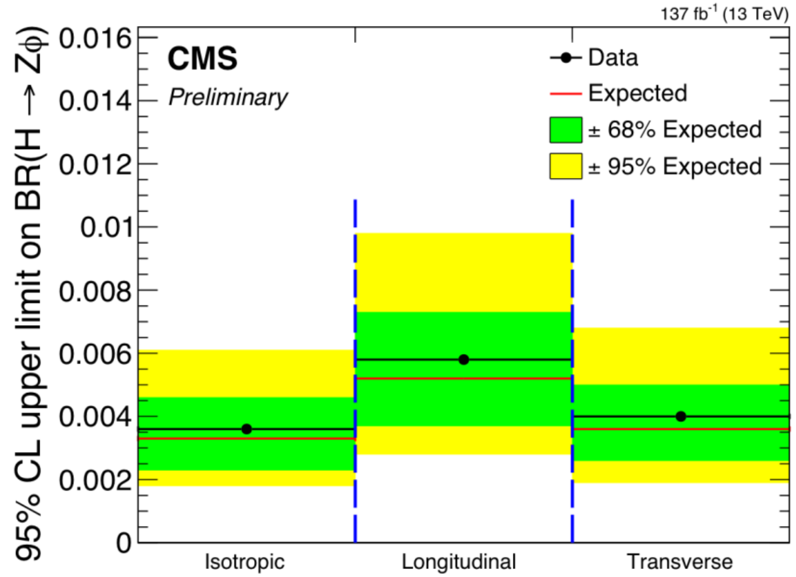
- **Fit m(ℓℓππ) or m(ℓℓKK)** to extract signal
  - Agnostic background model, *a la* H → γγ
- Set upper limits in the 0.3 – 2 % range
  - Acceptance depends on polarization, limits provided for different scenarios
  - Corresponding to ~ 860 – 1350 × SM BR





CMS PAS HIG-19-012



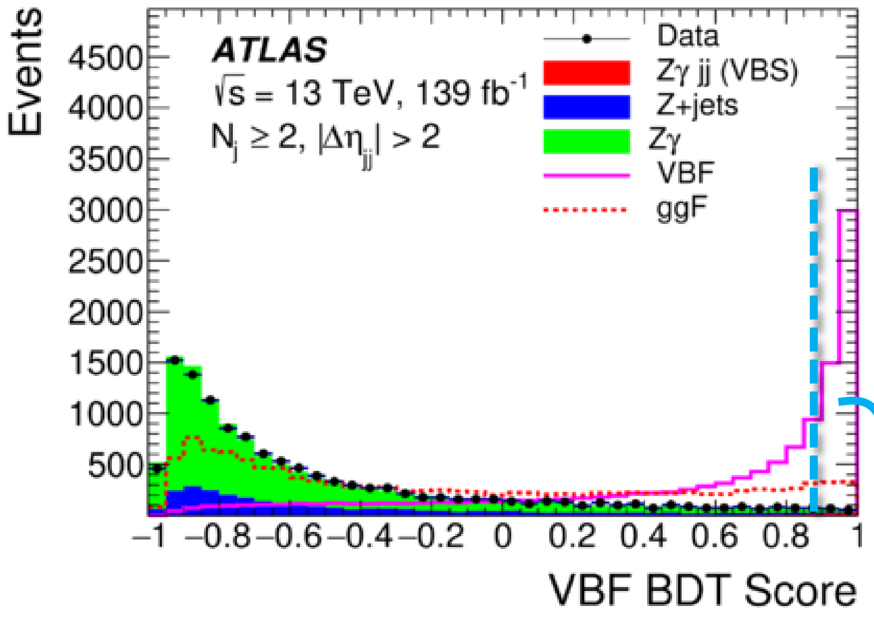


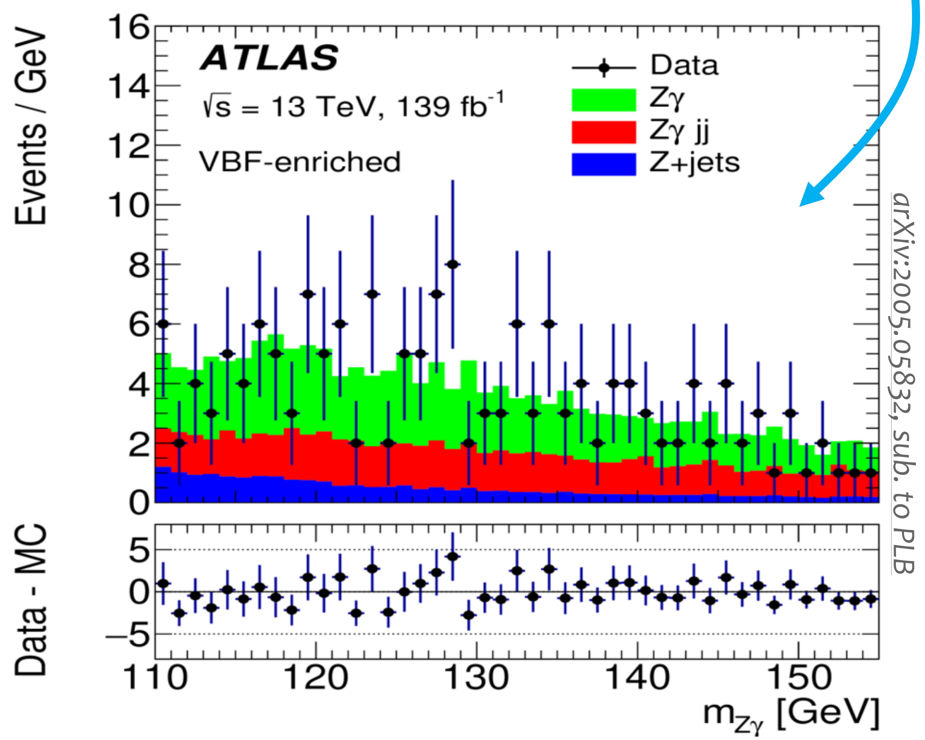
Also older ATLAS H → γ ρ/φ with 36 fb^{-1}
Set BR limits at 52 / 208 × SM for ρ / φ
[JHEP 07 (2018) 127]

H → Z γ

ATLAS EXPERIMENT
L = 139 fb^{-1}

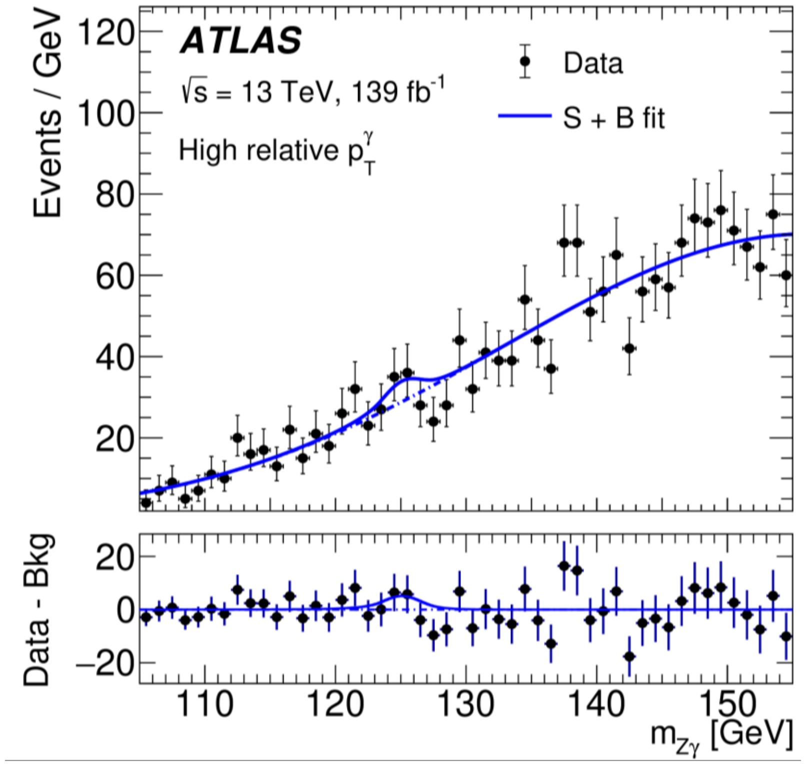
- SU(2)$_L$ symmetry ties together the HWW, HZZ, Hγγ, HZγ interactions
  - If heavy new physics respects SU(2)$_L$, correlated effects across the four
- BR(H → Z γ → ℓℓ γ) = 0.5 · 10^{-4}
  - Similar BR to H → 4ℓ, but larger background from Z γ production
- As in H → μμ, key ingredients are:
  - **Improve signal mass resolution:** FSR recovery, kinematic refit of Z → ℓℓ
  - **Improve S/B via categorization:** BDT targeting VBF production; p_T and p_{Tt}



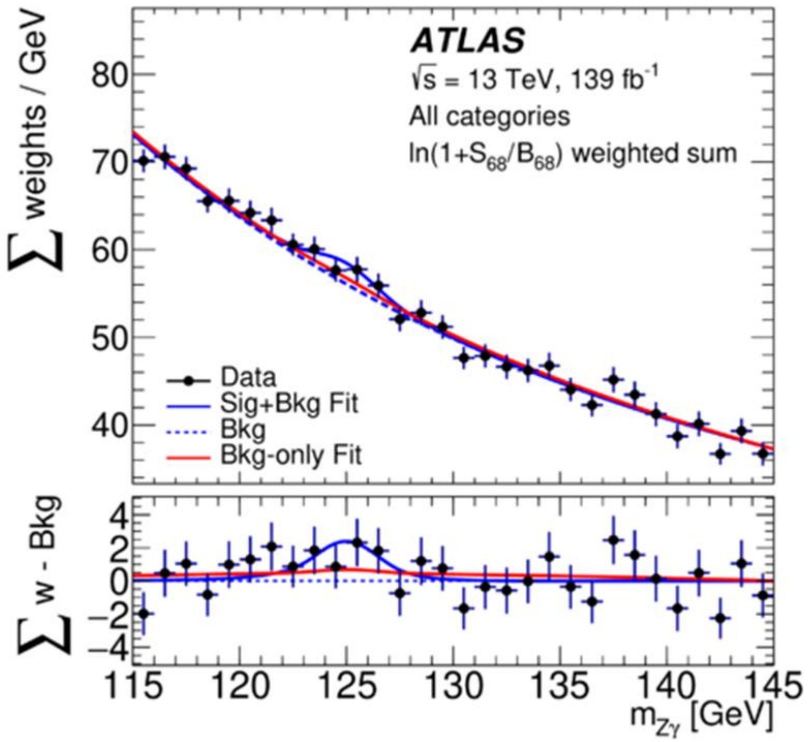


$H \to Z\gamma$: fit and results

High $p_T^\gamma / m_{Z\gamma}$ category (highest sensitivity)



Sum of all categories (sensitivity-weighted)



Fit results by category and combined

Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

arXiv:2005.05832, sub. to PLB

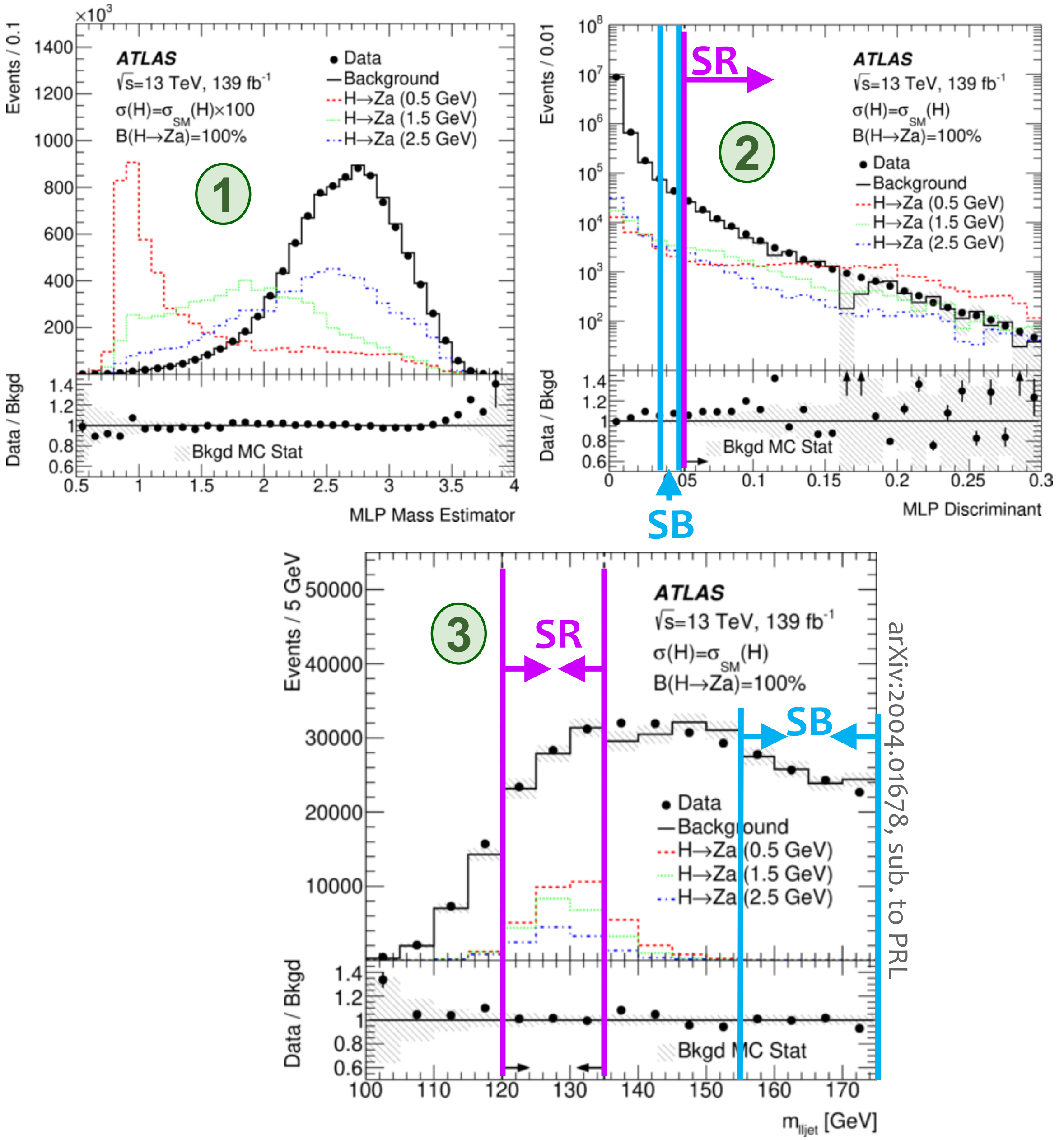
We may be starting to see the first hints of the signal

Also older CMS result on 36 fb⁻¹ for $H \to Z\gamma$ and $H \to \gamma^*\gamma \to \mu\mu\gamma$
Upper limit 3.9 × SM (expected 2.0 × SM). *[JHEP 11 (2018) 152]*

$H \to Z\,a \to \ell\ell\,j$

ATLAS EXPERIMENT
L = 139 fb^{-1}

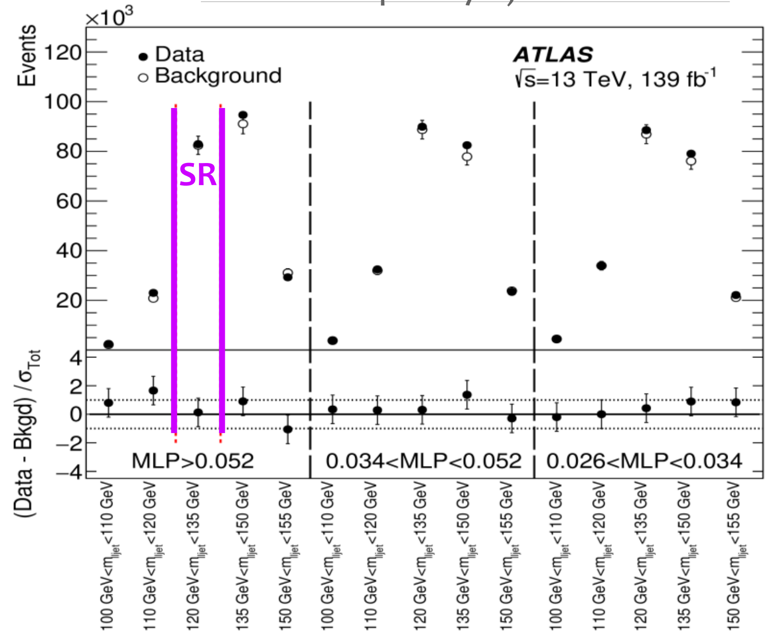
- Search for pseudoscalar "**a**"
  - e.g. in NMSSM or 2HDM+S models
- Target **inclusive hadronic decays**
  a → jet, for **m_a < 4 GeV**
  1. **MLP regression** to estimate a mass from jet substructure information
  2. **MLP discriminator** vs Z + jets bkg (using MLP regression as input)
  3. Define **signal region** by cutting on m(ℓℓj) and discriminator output
- Estimate backgrounds from data:
  - "ABCD" method with **sidebands** in m(ℓℓj) & MLP discriminant (+ corrections)

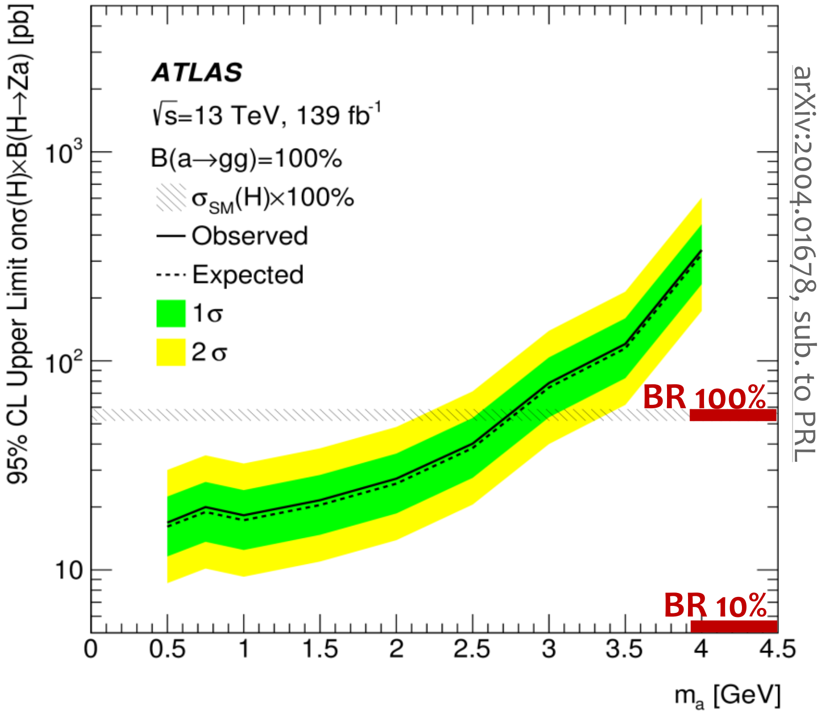


$H \to Z\,a \to \ell\ell\,j$

ATLAS EXPERIMENT
L = 139 fb^{-1}

- Search for pseudoscalar **"a"**
- Target **inclusive hadronic decays** **$a \to$ jet**, for **m_a < 4 GeV**
- Good agreement found between data and background predictions in signal region and validation regions
- Set upper limits on $\sigma \cdot BR(H \to Za)$
  - Interpreted separately for $a \to gg$ / $s\bar{s}$ (different efficiency of MLP discr. cut)
  - Also set upper limits on $BR(H \to Z\,\eta_c)$ and $BR(H \to Z\,J/\psi)$, but at BR ~ 200%



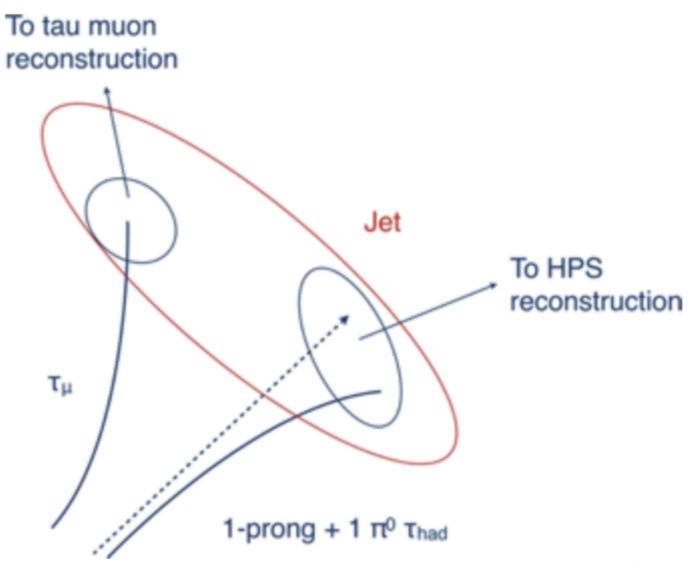


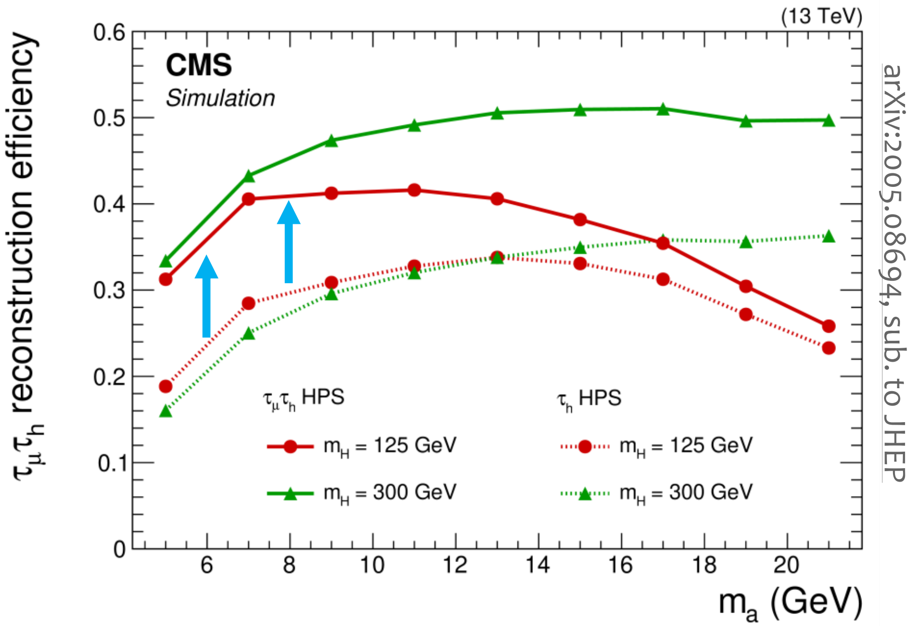
arXiv:2004.01678, sub. to PRL

$H \rightarrow a_{\mu\mu}\ a_{\tau\tau}$ at low m_a

L = 36 fb^{-1}

- Dedicated τ reco. for overlapping decay products of $a \rightarrow \tau_\mu\ \tau_h$
  - **Gain +50% efficiency at low m_a**





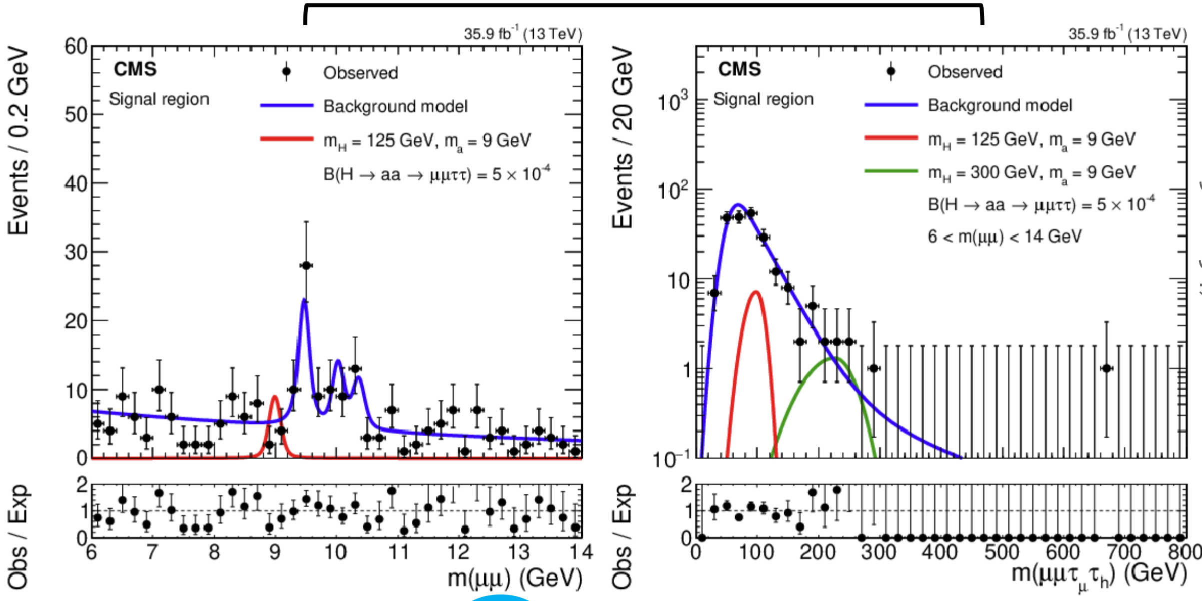
HPS (Hadrons Plus Strips) is the CMS algorithm for hadronic τ reconstruction using Particle Flow

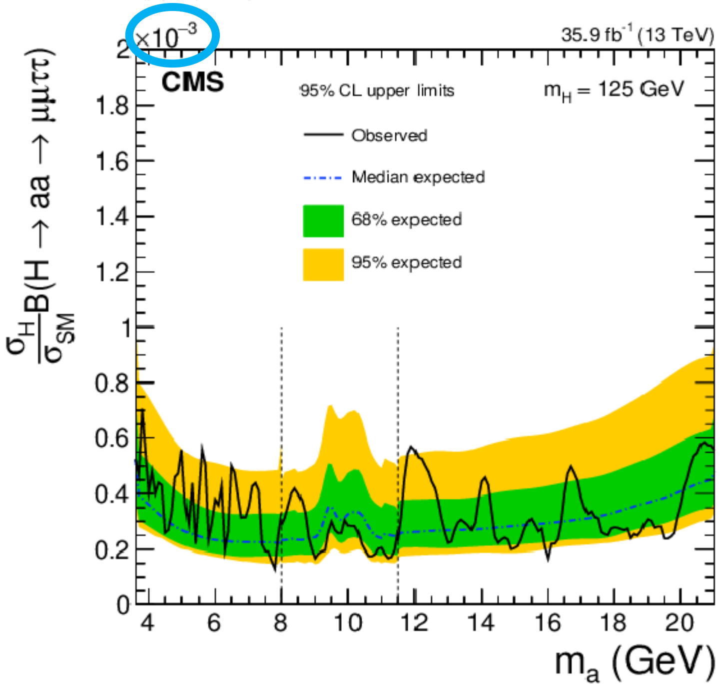
arXiv:2005.08694, sub. to JHEP

$H \rightarrow a_{\mu\mu}\ a_{\tau\tau}$ at low m_a

- Dedicated τ reco. for overlapping decay products of $a \rightarrow \tau_\mu \tau_h$
- 2D fit in $m(\mu\mu) \times m(\mu\mu\tau_\mu\tau_h)$ plane
  - Fit separately in 3 $m(\mu\mu)$ ranges, to reduce correlations with $m(\mu\mu\tau_\mu\tau_h)$
  - Control regions included to constrain the continuum and $\psi_{(2S)}$ and Υ peaks
- Set model-independent limits on $BR(H \rightarrow aa \rightarrow \mu\mu\tau\tau) \sim 0.02\text{–}0.08\%$
  - And in 2HDM+S benchmark models
  - Also demonstrate potential for $H_{Heavy} \rightarrow aa$ using m_H = 300 GeV

1D projections from 2D fit



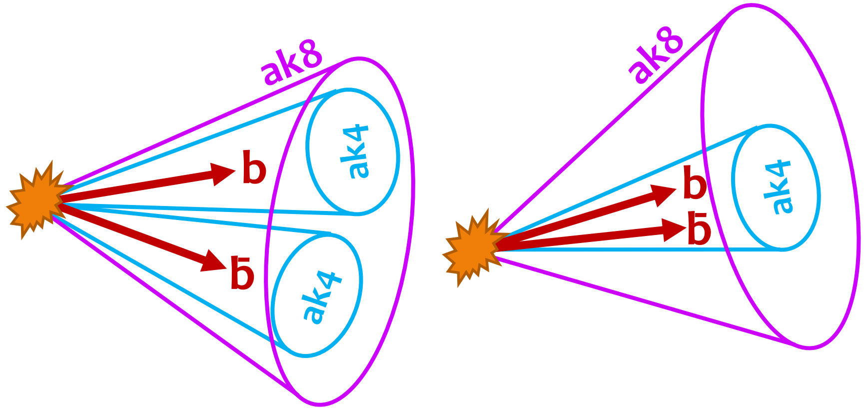


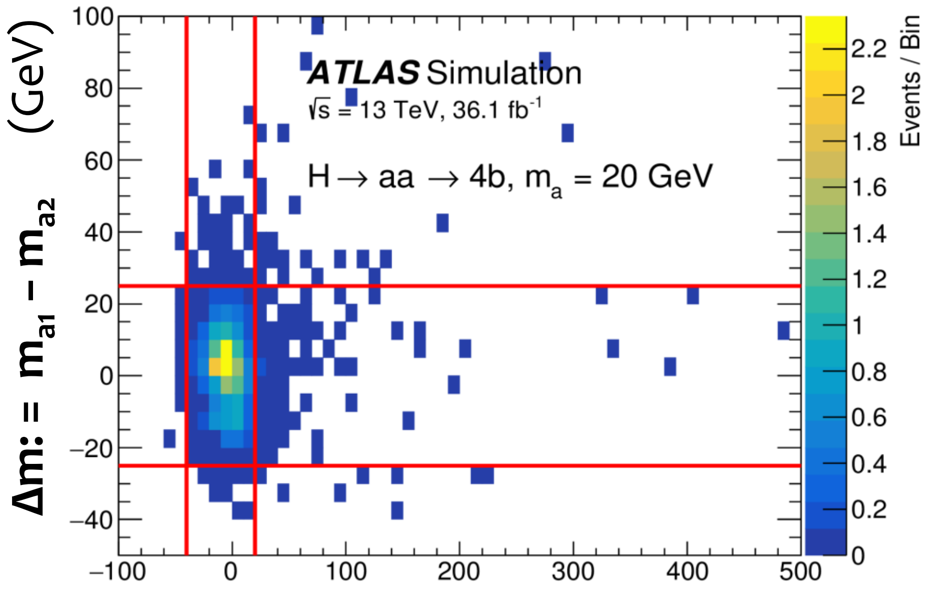
arXiv:2005.08694, sub. to JHEP

$H \to a_{b\bar{b}}\, a_{b\bar{b}}$ at low m_a

ATLAS EXPERIMENT
$L = 36\ fb^{-1}$

- Rely on $Z_{\ell\ell}H$ associated production
- Recluster jets with anti-k_T(R=0.8)
  - One ak8 jet for each $a \to b\bar{b}$ candidate
- Tag ak8 jets relying on substructure and b-tagging information from associated tracks and sec. vertices
  - Trained vs jets that contain a single b quark
  - ×100/×30 rejection of b-jets from $t\bar{t}$ & Z+jets at $a \to b\bar{b}$ signal efficiency of ~ 25% / 30%
- Select events with kinematic compatible with $H \to aa$ decay
  - Separately each m_a mass hypothesis





$m_{red} := [\, m_{aa} - (m_{a1} + m_{a2} - 2\, m_a)] - m_H$ (GeV)

correct reco m_{aa} for m_{ai} jet mismeasurement

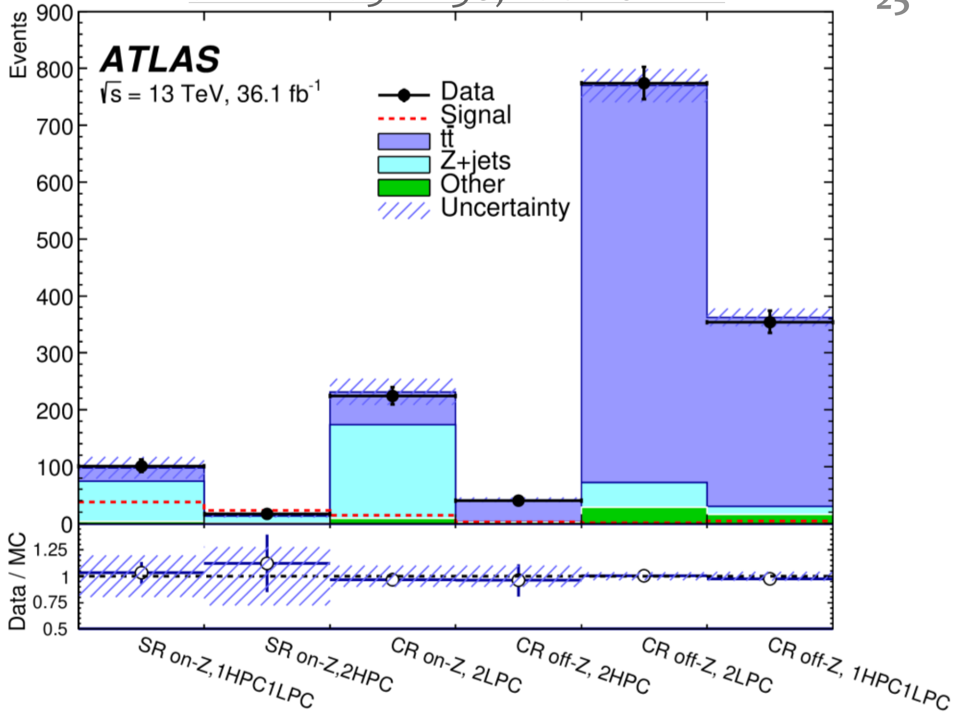
fixed inputs from signal hypothesis

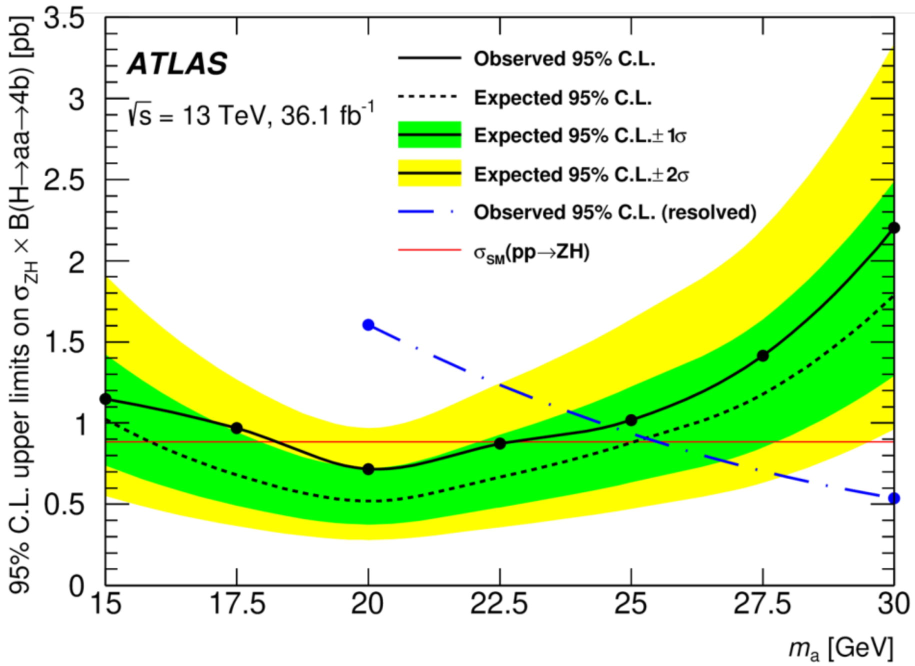
arXiv: 2005.12236, sub. to PRD

$H \rightarrow a_{bb}\ a_{bb}$ at low m_a

ATLAS EXPERIMENT
$L = 36\ fb^{-1}$

- Define signal and control regions depending on $m_{\ell\ell}$ and number of loose (LP) & tight (HP) ak8 tags
  - Constrain dominant backgrounds from Z+jets and ttbar
- Set limits on $\sigma_{ZH} \times BR(H \rightarrow aa \rightarrow 4b)$ for m_a in 15–30 GeV range
  - Best sensitivity at m_a = 20 GeV
    Set limit at 80%×σ_{ZH}^{SM} (exp. 60%×σ_{ZH}^{SM})
  - at large m_a, sensitivity taken over by older $H \rightarrow aa \rightarrow 4b$ "resolved" analysis [JHEP 10 (2018) 031]



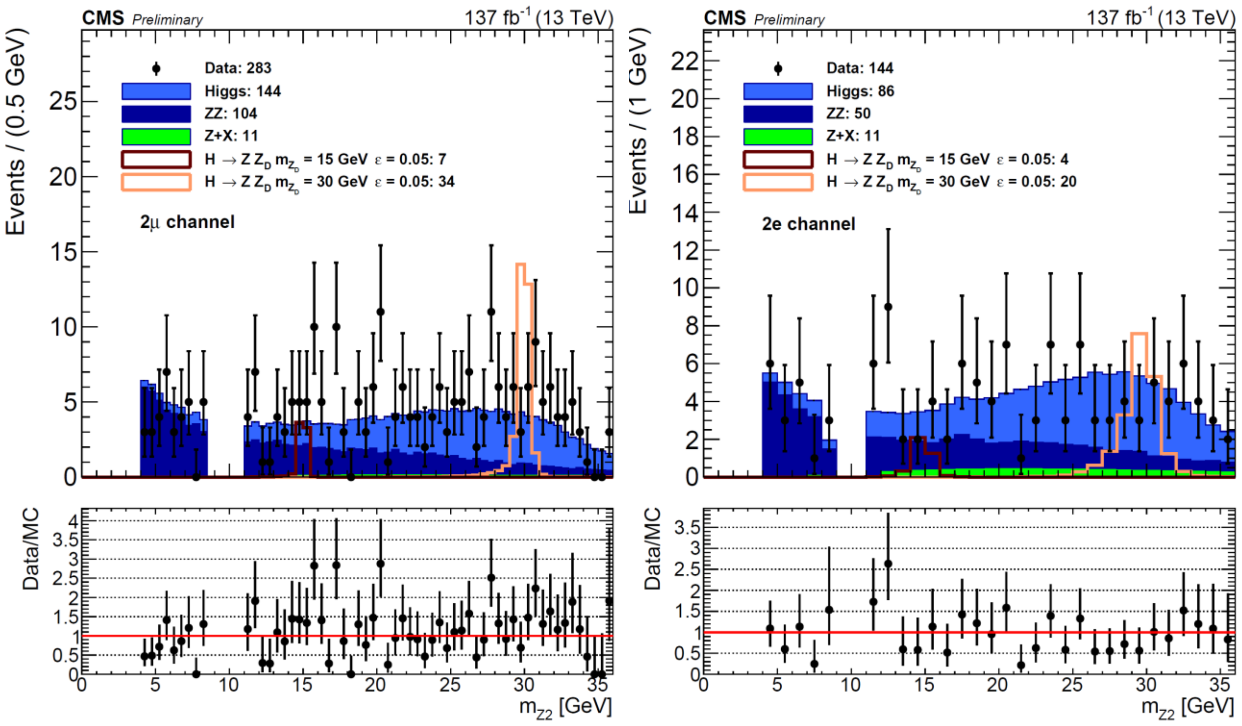


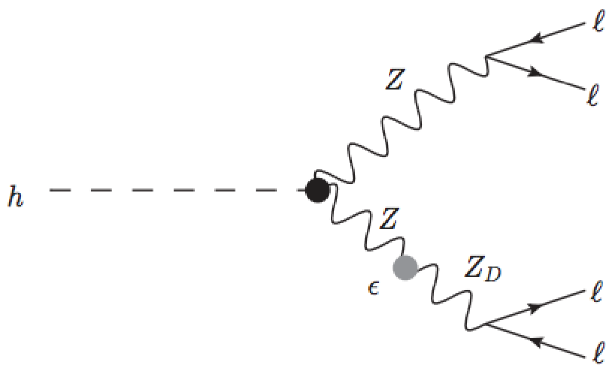
$H \to Z_{(D)} Z_D \to 4\ell$

L = 137 fb^{-1}

- Search for dark photons or ALPs
- Based on $H \to Z Z^* \to 4\ell$ analysis
  - objects, background estimation, …

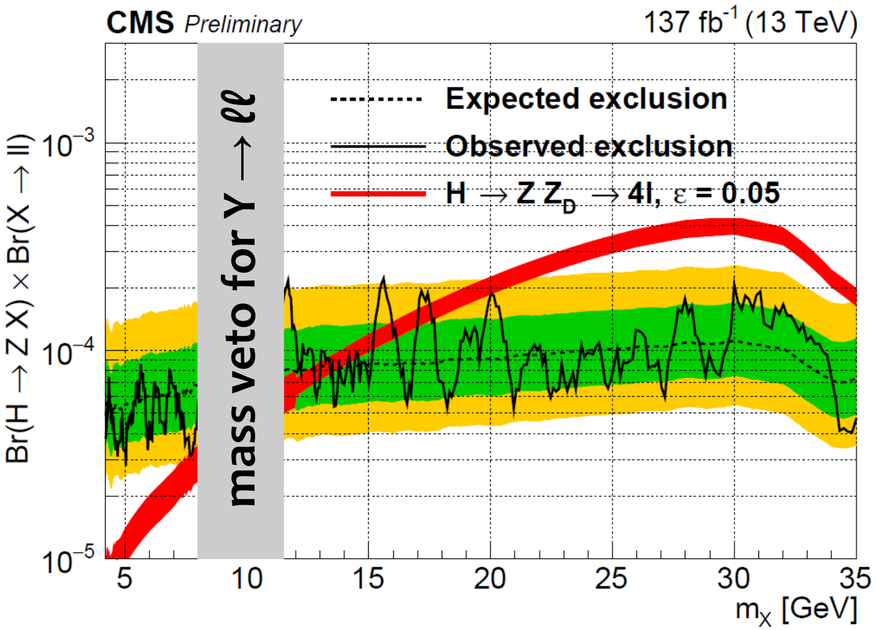
1. $H \to Z X \to 4\ell$ search:
   - $m_{Z1} > 40$ GeV, **$118 < m_{4l} < 130$ GeV**
   - Scan $\mathbf{m_{Z2}}$ distribution with window of size 4% / 10% for X $\to \mu\mu$ / ee
   - Set limits for $X \to \ell\ell$, $\mu\mu$, ee





Z_1 ($\ell\ell$ pair with $m_{\ell\ell}$ closest to m_Z^{PDG})

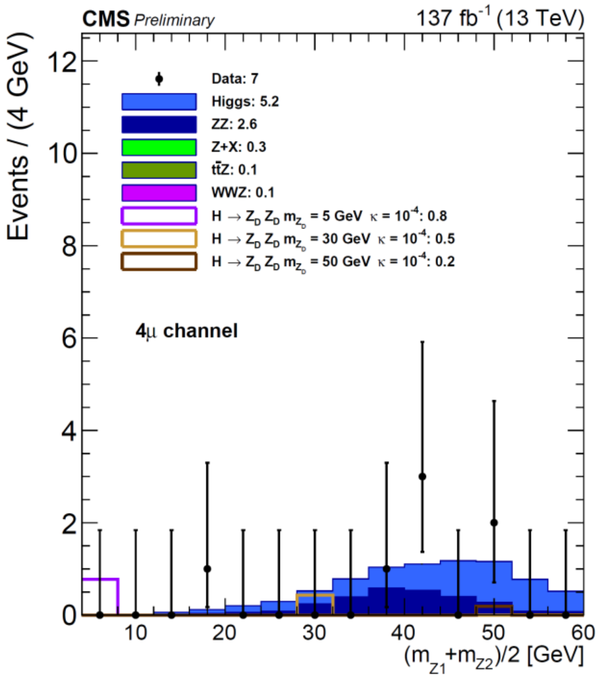
Z_2 (X)

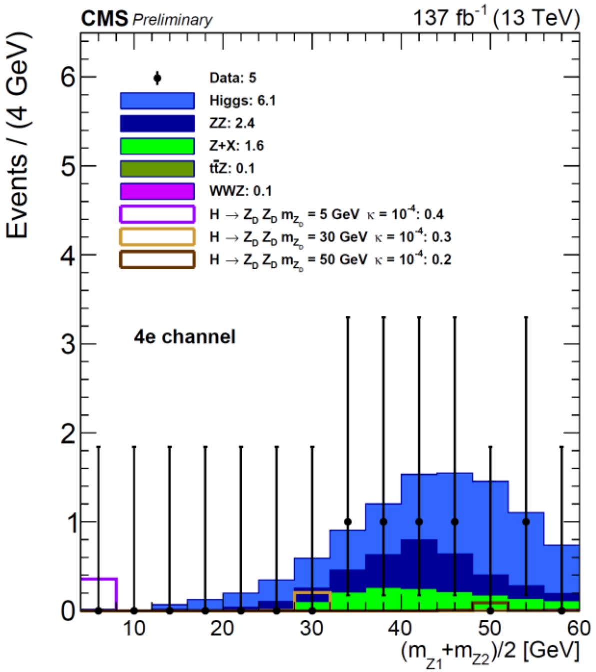


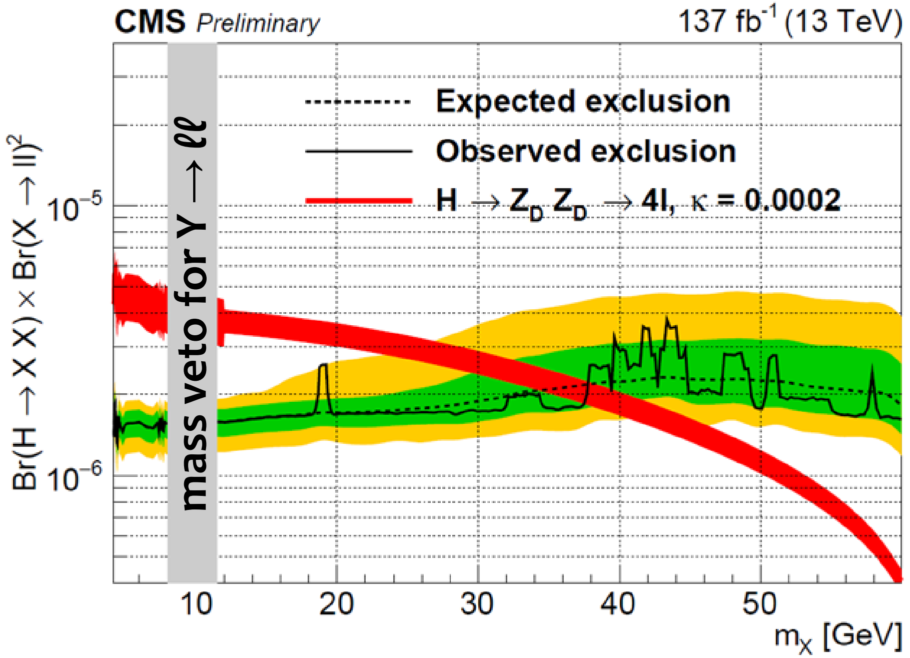
$H \rightarrow Z_{(D)} Z_D \rightarrow 4\ell$

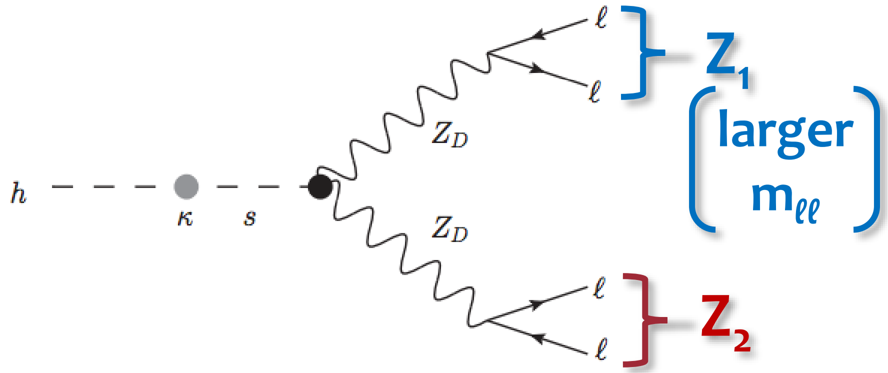
L = 137 fb^{-1}

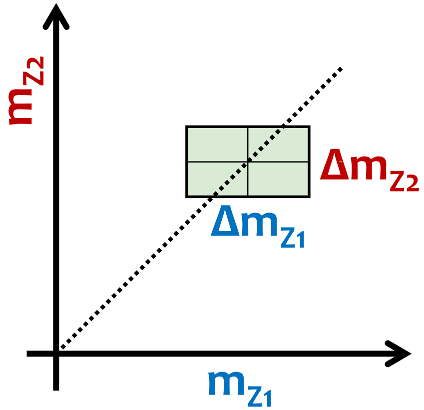
2. $H \rightarrow X X \rightarrow 4\ell$ search:
   - Select lepton pairings minimizing $|m_{Z_1} - m_{Z_2}| / (m_{Z_1} + m_{Z_2})$
   - $m_{Zi} \in$ 4–62.5 GeV, **$m_{4l} \in$ 118–130 GeV**
   - Scan m_{Z1}, m_{Z2} plane with 2D box centered on $m_{Z1} = m_{Z2} = m_X$ of size Δm_{Zi} = 4% / 10% for $Z_i \rightarrow \mu\mu$ / ee
   - Set limits for $X \rightarrow \ell\ell$, μμ, ee









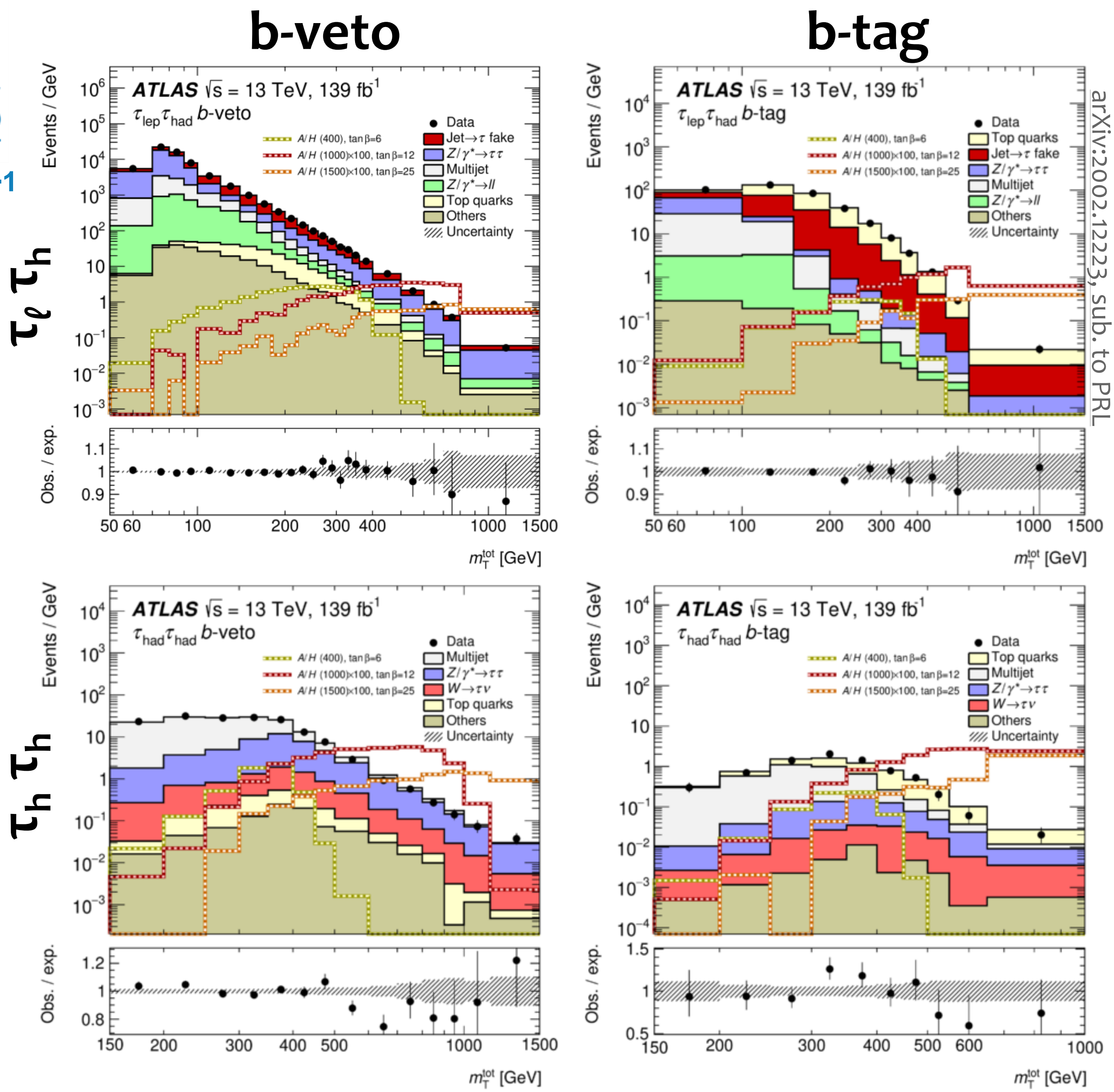


MSSM A/H → ττ

ATLAS EXPERIMENT
L = 139 fb⁻¹

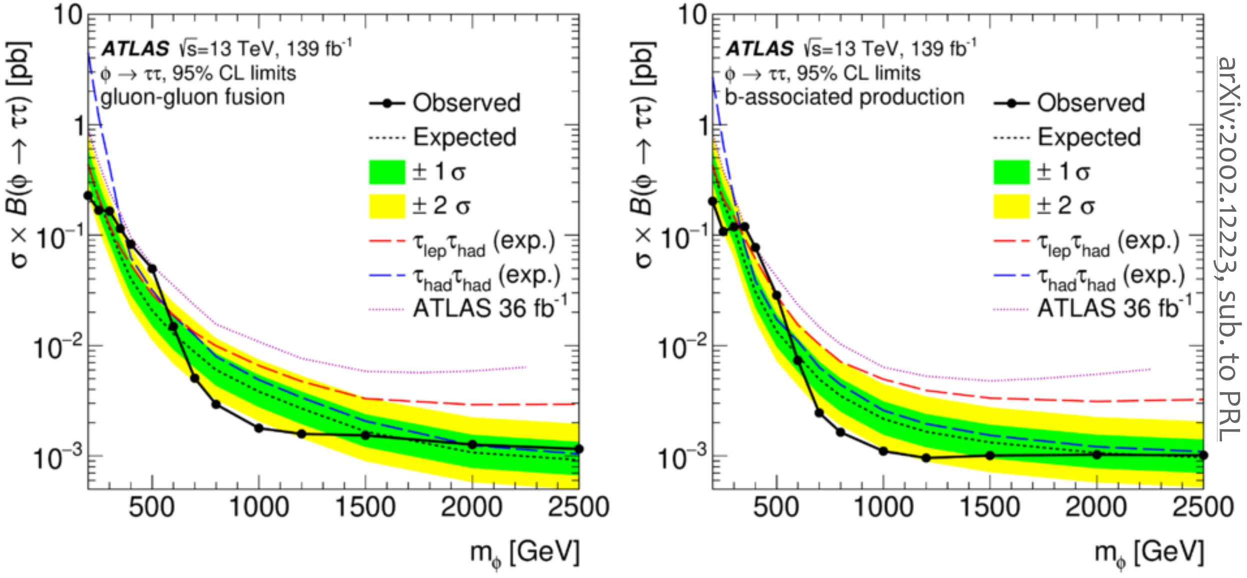
- Flagship mode at high tan(β)
  - Enhanced BR(A/H → ττ) and bbH production
- Main backgrounds:
  - Reducible jet → τ_h: from data using fake rate methods
  - Irreducible Z → ττ , tt̄: estimated from MC, plus CR at high $m_T^{\ell\nu}$ for tt̄
- Final discriminating variable

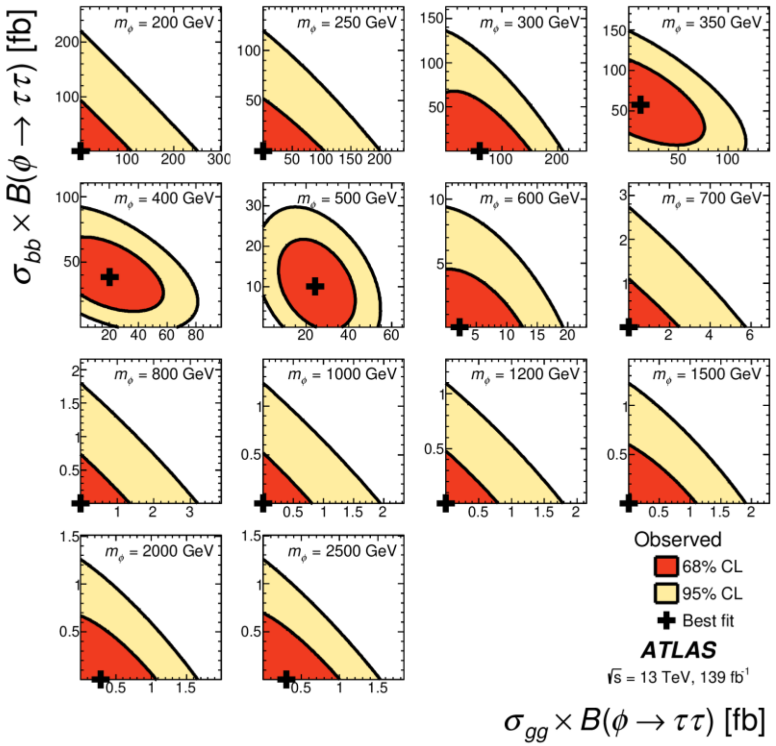
$$m_T^{tot} = \sqrt{\left(p_T^{\tau 1} + p_T^{\tau 2} + E_T^{miss}\right)^2 - \left(\overrightarrow{p_T^{\tau 1}} + \overrightarrow{p_T^{\tau 2}} + \overrightarrow{E_T^{miss}}\right)^2}$$



MSSM A/H → ττ

- Interpretation as limits on σ×BR for generic scalar φ
  - Provide 1D and 2D limits and likelihoods vs m_{φ}, σ_{ggF}, σ_{bbH}
  - Largest excess at m_{φ} ~ 400 GeV, local significance ~ 2 σ

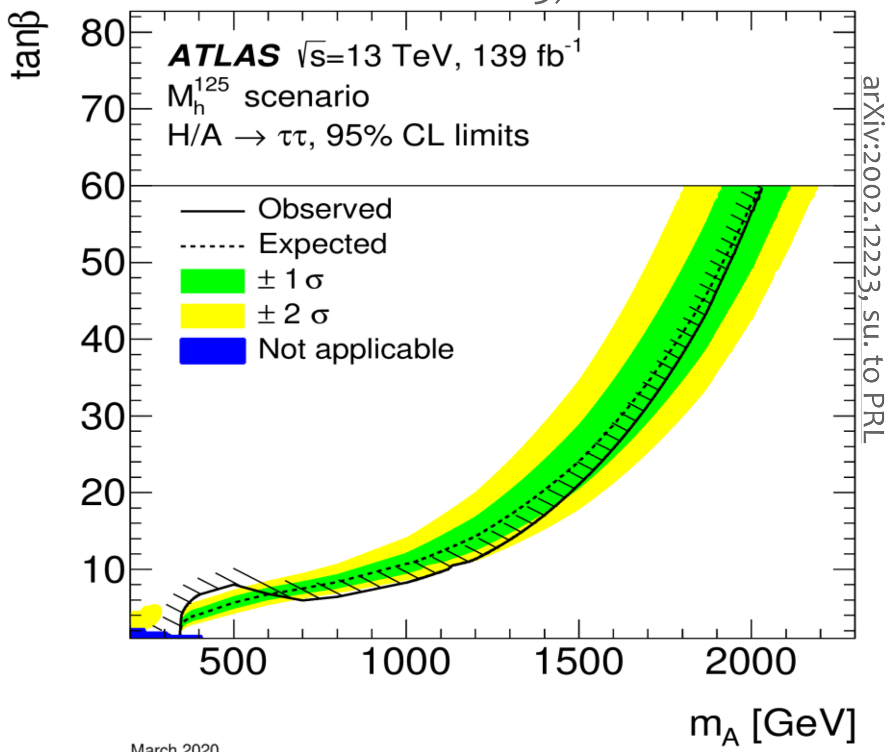




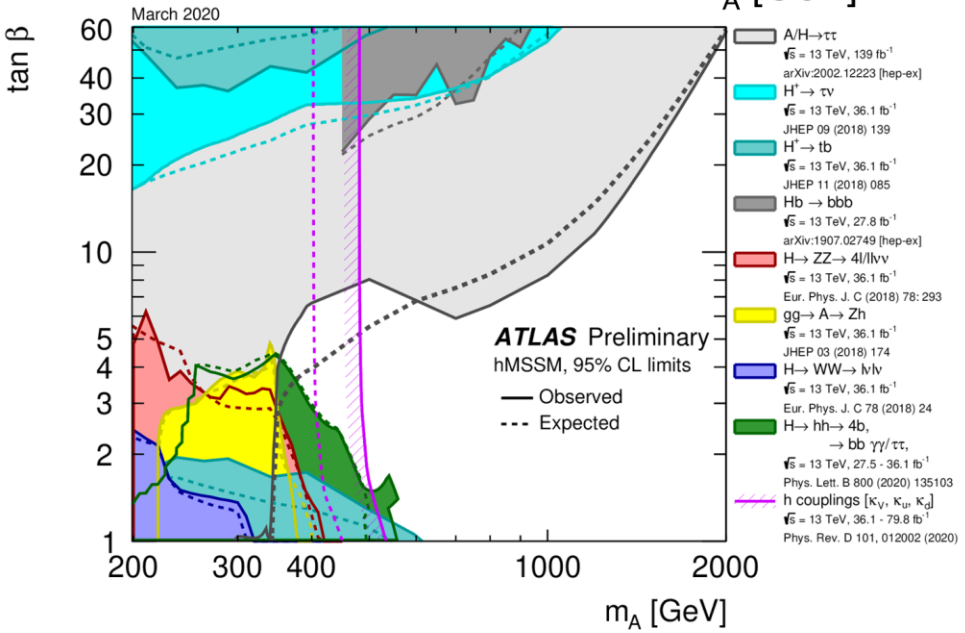
arXiv:2002.12223, sub. to PRL

MSSM A/H $\to \tau\tau$

- Interpretation as limits on $\sigma \times$BR for generic scalar φ
  - Provide 1D and 2D limits and likelihoods vs m_φ, σ_{ggF}, σ_{bbH}
  - Largest excess at $m_\varphi \sim 400$ GeV, local significance ~ 2 σ
- MSSM interpretations
  - New M_h^{125} benchmark scenarios e.g. tan(β) < 8 at 1 TeV (expected: < 10)
  - hMSSM, to compare with old result



arXiv:2002.12223, su. to PRL



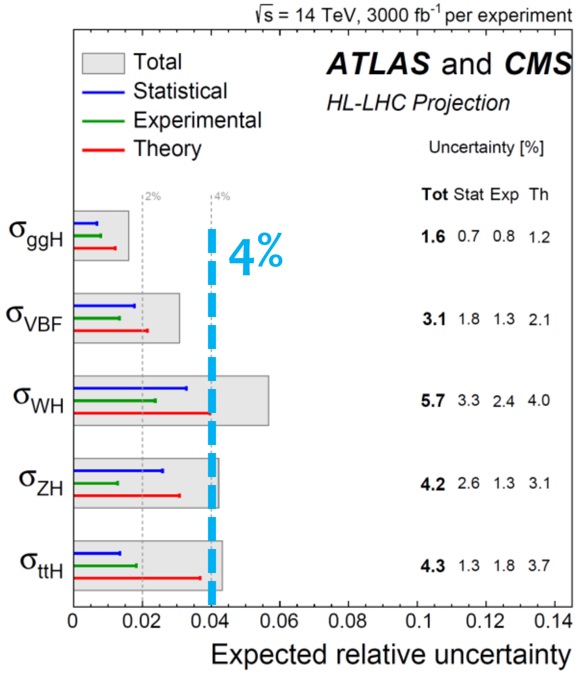
ATL-PHYS-PUB-2020-006

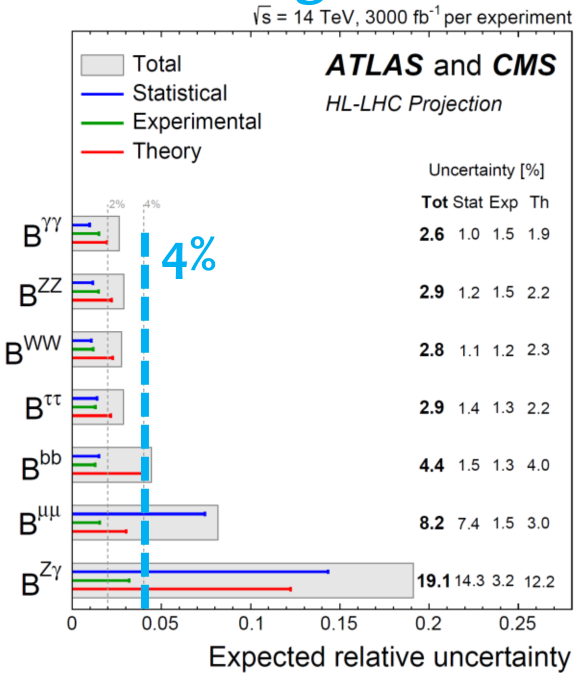
Also older CMS result on 36 fb⁻¹ [*JHEP 09 (2018) 007*]
M_h^{125} limits, e.g. tan(β) < 15 at 1 TeV (expected: < 16)

Part III: brief outlook at HL-LHC

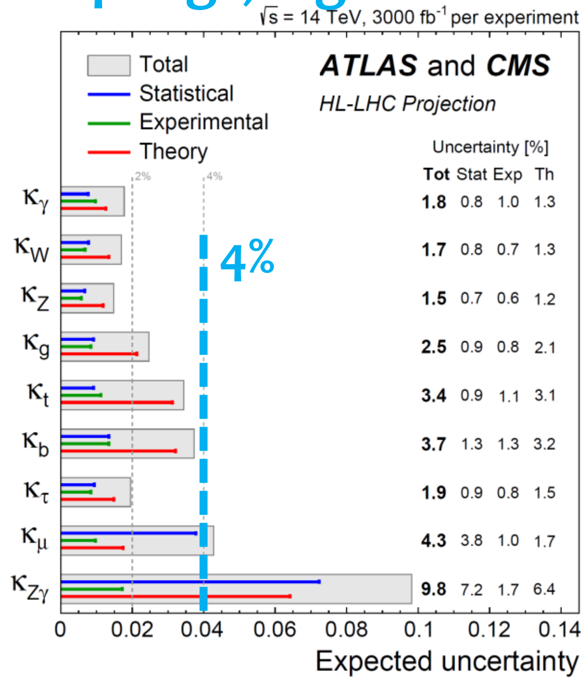
- Sensitivity for Higgs boson physics at HL-LHC evaluated back in 2018 in the context of the European Strategy update
  - Mostly based on knowledge from early LHC run 2 analyses (2016 data)
- Single Higgs boson observables: can reach few-percent precision

Cross sections and branching ratios

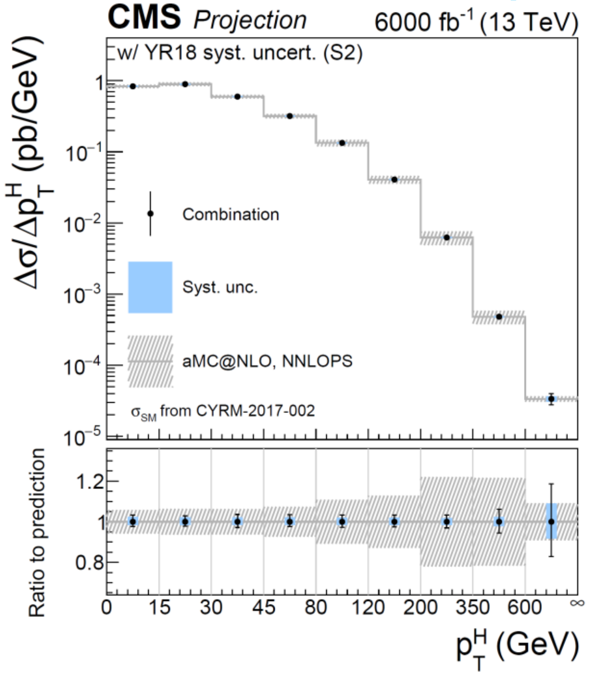




Couplings, e.g. κ fit



Differential $d\sigma/dp_T(H)$

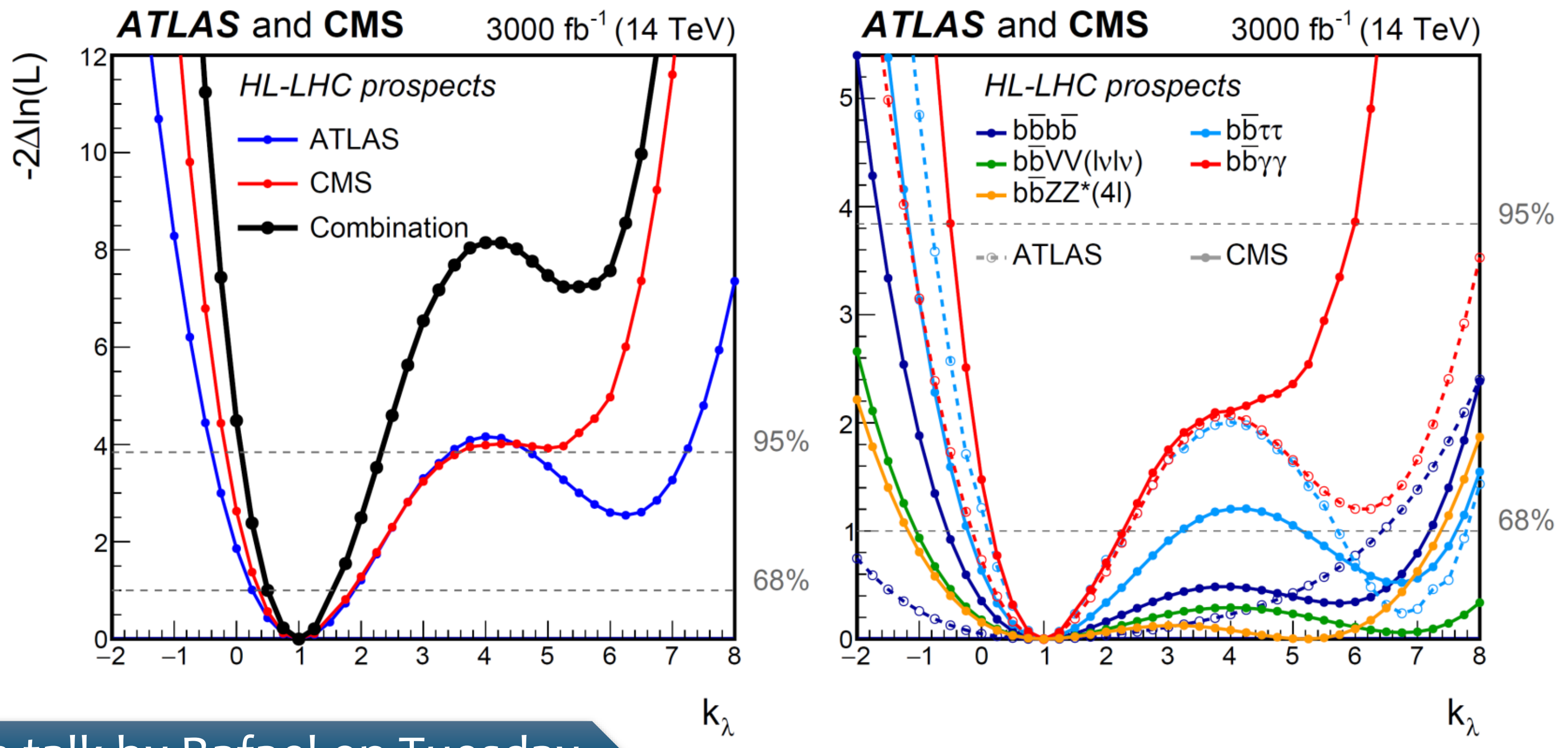


Part II: brief outlook at HL-LHC

- HH production: ~4σ evidence, measure κ_λ with ~ ±50% uncertainty
  - Projections based on a combination of extrapolations from Run 2 analyses and new analyses designed for HL-LHC

Expected significance for HH

	ATLAS	CMS
$b\bar{b}\,b\bar{b}$	0.61	0.95
$b\bar{b}\,\tau\tau$	2.1	1.4
$b\bar{b}\,\gamma\gamma$	2.0	1.8
$b\bar{b}\,VV(\ell\ell\nu\nu)$		0.56
$b\bar{b}\,ZZ(4\ell)$		0.37
combined	***3.0***	***2.6***
LHC comb.	**4.0**	



More info in talk by Rafael on Tuesday

Conclusions & outlook

- The quest for the Higgs boson self coupling goes on
  - Started probing new couplings in VBF HH, and deploying more advanced analysis methods to improve on past results
  - Expect strong results when LHC Run 2 data fully analysed!
  - and in the longer future, HH observation at HL-LHC
- Many new searches probing into the unknown:
  - Higgs boson decays into new yet unobserved particles
  - Rare decays that could be largely enhanced by new physics
  - Additional Higgs bosons from extensions of the standard model

… and still many more to try, with Run 2 data and beyond

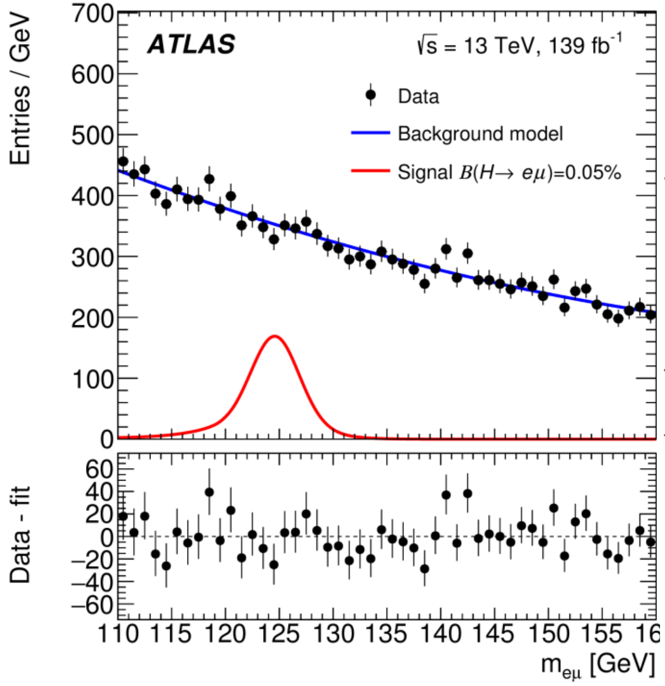
BACKUP

FIXME: this still needs work, of course….

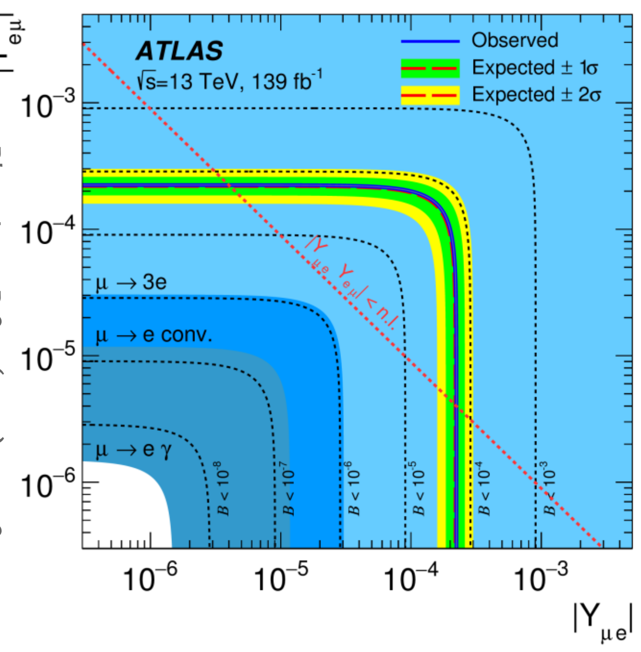
Lepton flavour violating decays

ATLAS EXPERIMENT
$L = 139\ fb^{-1}$

- Probe for $H \to e\mu$: direct test for LFV $y_{e\mu}$ Yukawa coupling
  - Very stringent limits from $\mu \to e\gamma$ and electron EDM, but depend on yet unobserved y_{ee} and $y_{\mu\mu}$
- Categorize by p_T^{ℓ}, $|\eta_\ell|$, $p_T^{\ell\ell}$
  - Select events with higher S/B or better dilepton mass resolution
- Set upper limit $BR_{e\mu} < 6.2 \times 10^{-5}$
  - Factor ~6 better than Run 1 limit
- Also set $BR(H \to ee) < 3.6 \times 10^{-4}$
  - $BR_{SM} \sim 5 \times 10^{-9}$ well out of reach

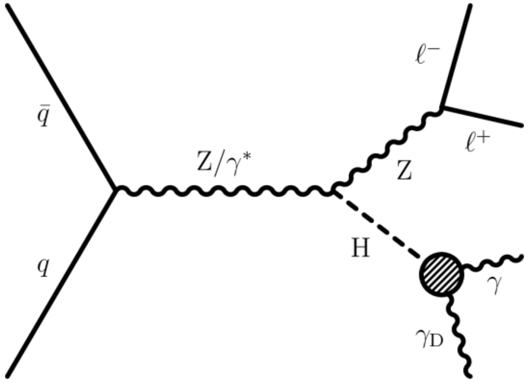


Phys. Lett. B 801 (2020) 135148



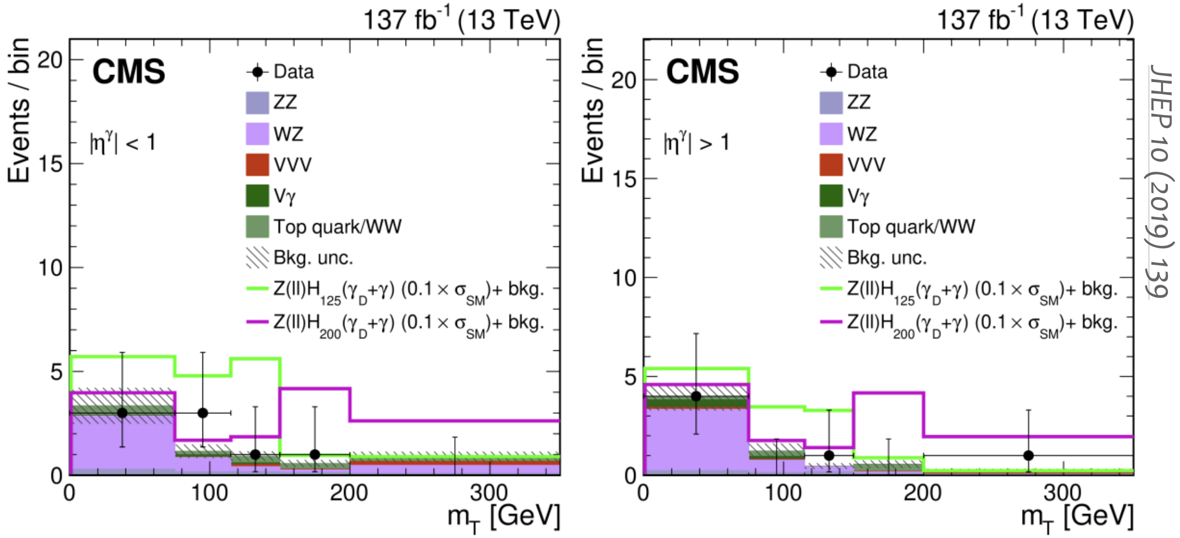
Also older 36 fb⁻¹ from CMS [JHEP 06 (2018) 001] and ATLAS [PLB 800 (2020) 135069] setting limits on $BR(H \to e\tau)$ and $BR(H \to \mu\tau)$ in the 0.25% – 0.6% range

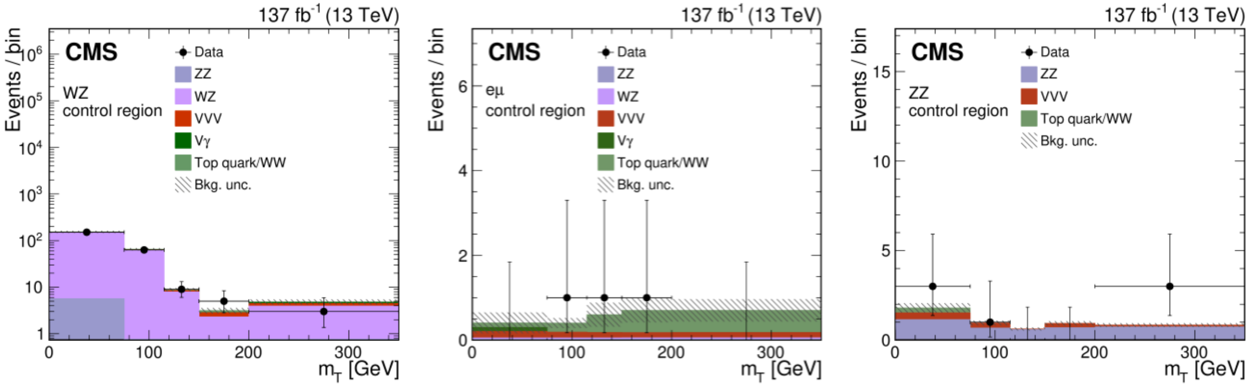
$H \to \gamma$ + invisible



L = 137 fb^{-1}

- Probe e.g. for $H \to \gamma\, \gamma_D$ (dark photon)
- Rely on $Z(\ell\ell)$ H associated production
  - Require high-p_T $Z_{\ell\ell}$, back-to-back and balanced with $\gamma + E_T^{miss}$ vector
- Dominant background: $WZ \to 3\ell\nu$
  - With electron mis-id as photon, or genuine γ from ISR/FSR and a lost ℓ
- Transverse mass m_T of $\gamma + E_T^{miss}$ system used to look for a signal
  - Control regions for **WZ**, **$t\bar{t}$/WW**, **ZZ**
- Set limits **BR($H \to \gamma$ + inv.) < 4.6%**
  - Tiny $BR_{SM}(H \to Z\gamma \to \nu\nu\gamma) \sim 3{\times}10^{-4}$



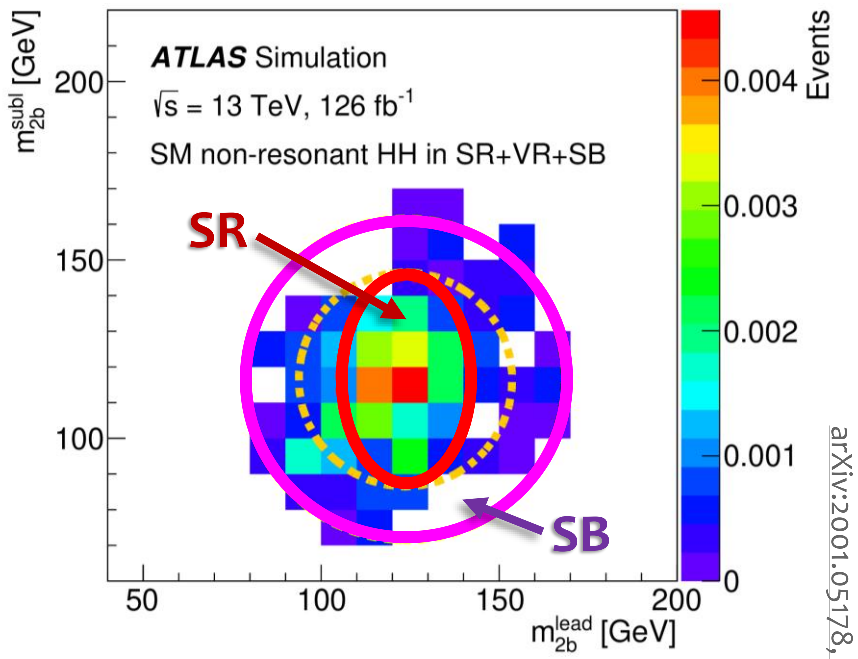


JHEP 10 (2019) 139

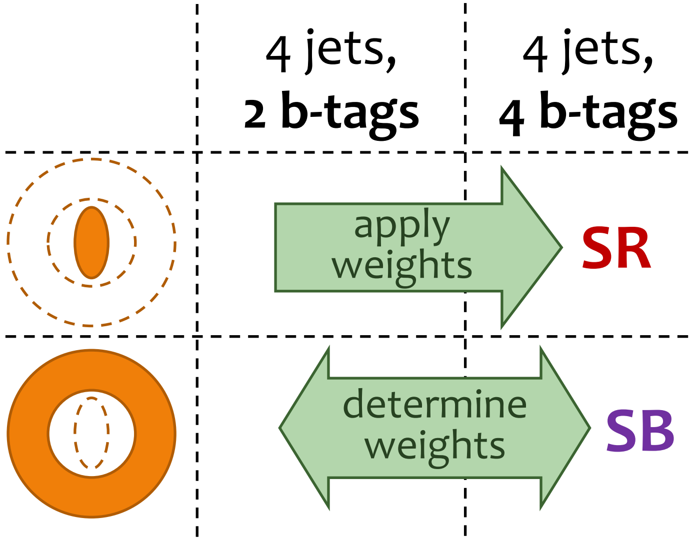
VBF HH → 4b

ATLAS EXPERIMENT
L = 126 fb^{-1}

- Target the more extreme kinematic of $\kappa_{2V} \neq 1$
  - **Tight cut-based VBF cuts: m_{jj} > 1 TeV, $|\Delta\eta_{jj}|$ > 5**
- Largely based on earlier HH → 4b search on 36 fb^{-1} dataset *[JHEP 01 (2019) 030]*
  - Same strategy used for HH → 4b selection: ΔR_{bb} cuts dependent on m_{4b}, elliptic **signal region** in the plane of the two m_{2b} masses
  - Same estimation of main QCD multi-jet and tt̄ background: from events with 2 b-tags, with weights derived in **mass sideband**
- New b-jet energy regression using a BDT
  - ~10% better b-jet energy resolution



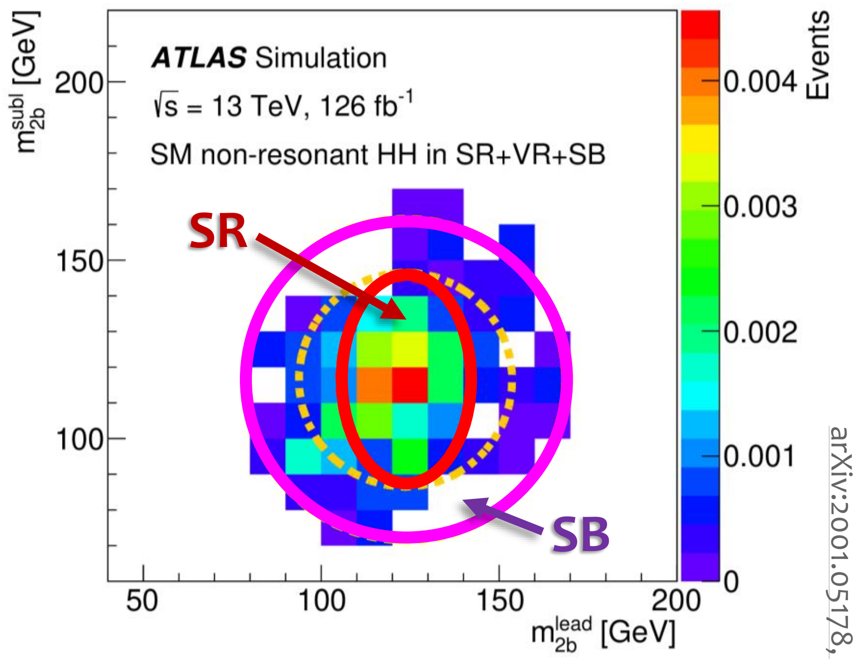
arXiv:2001.05178, sub. to JHEP

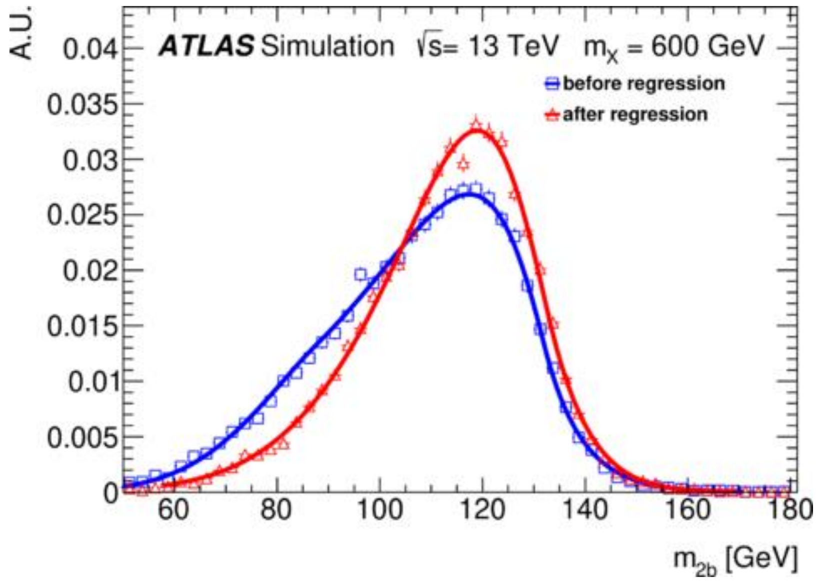


VBF HH → 4b

L = 126 fb^{-1}

- Target the more extreme kinematic of **$\kappa_{2V} \neq 1$**
  - **Tight cut-based VBF cuts: m_{jj} > 1 TeV, $|\Delta\eta_{jj}|$ > 5**
- Largely based on earlier HH → 4b search on 36 fb^{-1} dataset *[JHEP 01 (2019) 030]*
  - Same strategy used for HH → 4b selection: ΔR_{bb} cuts dependent on m_{4b}, elliptic **signal region** in the plane of the two m_{2b} masses
  - Same estimation of main QCD multi-jet and tt̄ background: from events with 2 b-tags, with weights derived in **mass sideband**
- New b-jet energy regression using a BDT
  - ~10% better b-jet energy resolution



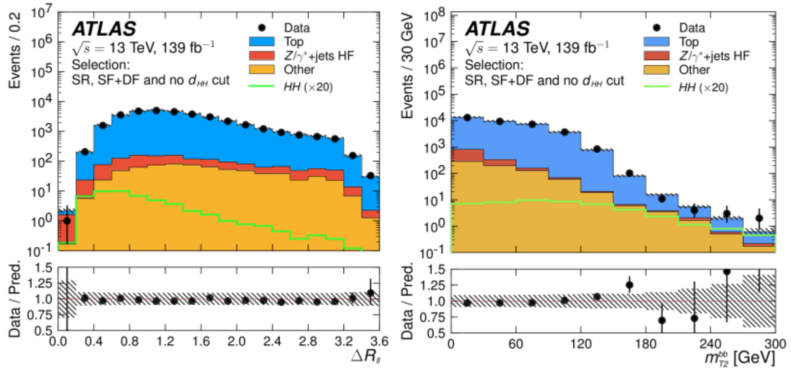


arXiv:2001.05178, sub. to JHEP

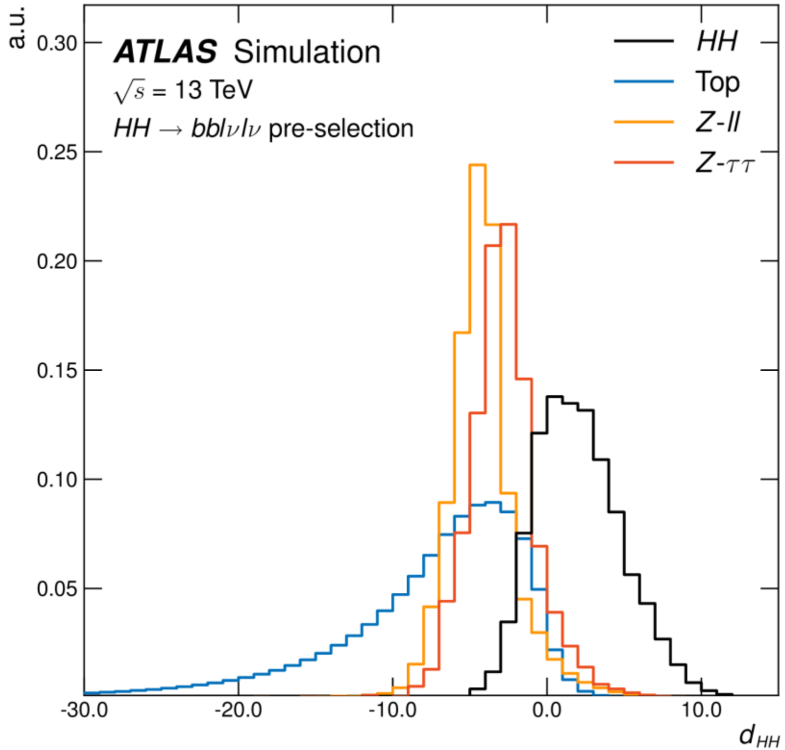
Beyond 2016 data: HH → bb $W_{\ell\nu}W_{\ell\nu}$

$L = 139\ fb^{-1}$

- Multiclass DNN to separate **HH** from 3 main backgrounds: **$t\bar{t}$** , **$Z(\ell\ell)$**, **$Z(\tau\tau)$**
  - Inputs are individual leptons, jets, E_T^{miss}, high-level variables (e.g. $\Delta R_{\ell\ell}$, m_{T2}^{bb})
  - Output **$d_{HH} := \ln(p_{HH} / \Sigma\, p_{bkg})$**



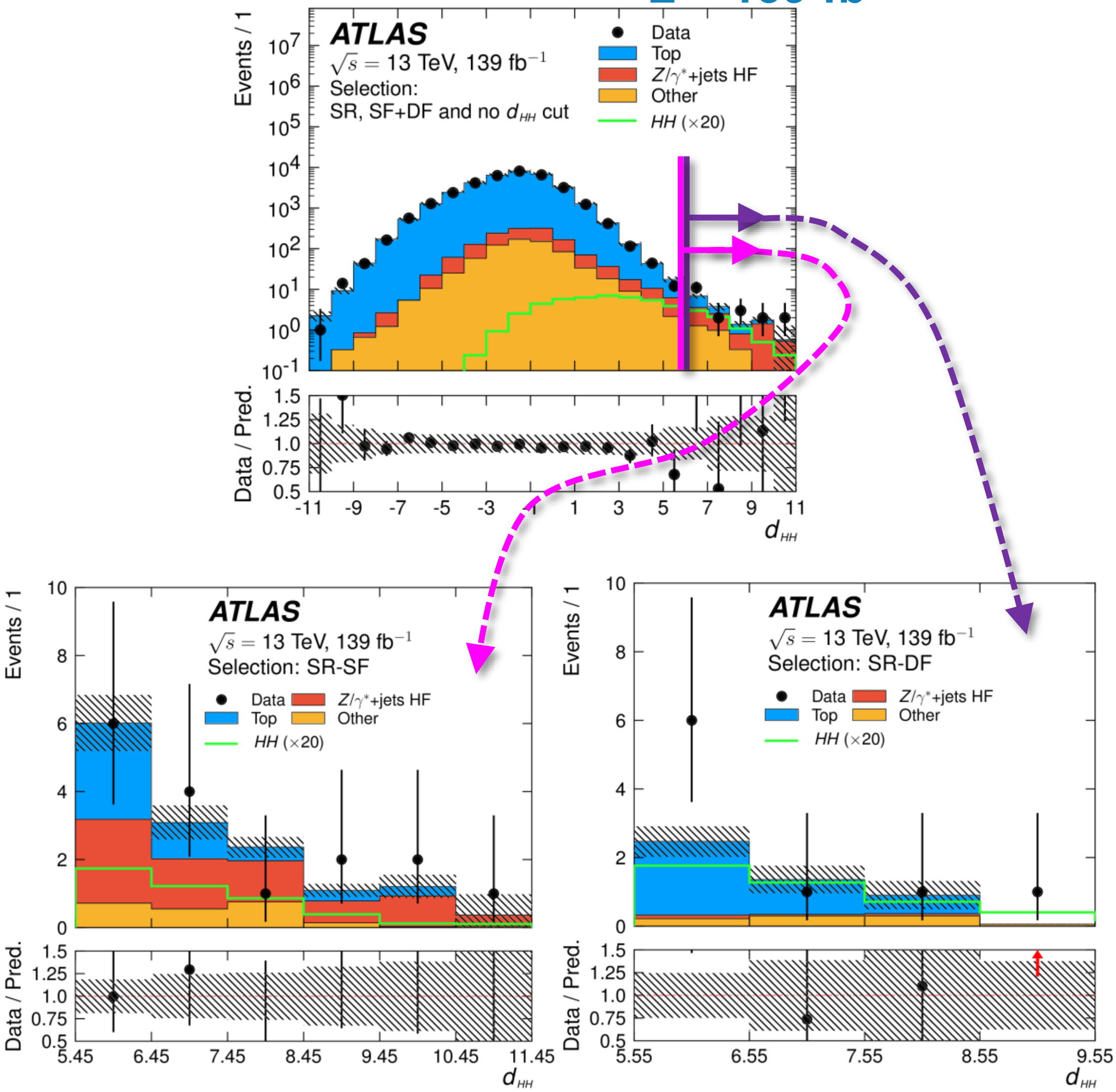
Phys. Lett. B 801 (2020) 135145



Beyond 2016 data: HH → bb $W_{\ell\nu}W_{\ell\nu}$

ATLAS EXPERIMENT
L = 139 fb^{-1}

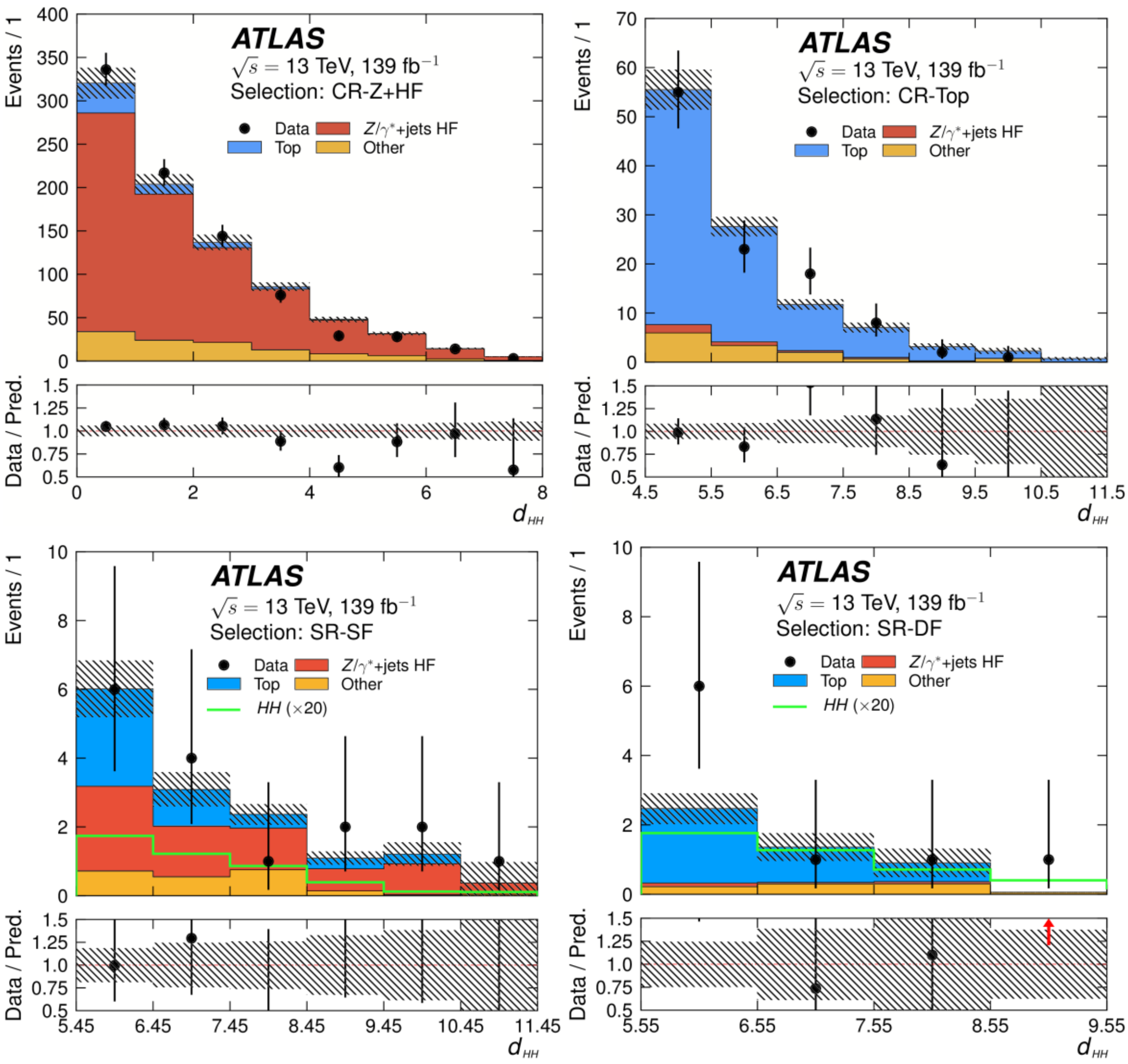
- Multiclass DNN to separate **HH** from 3 main backgrounds: **tt̄ , Z(ℓℓ), Z(ττ)**
  - Inputs are individual leptons, jets, E_T^{miss}, high-level variables (e.g. $\Delta R_{\ell\ell}$, m_{T2}^{bb})
  - Output $\mathbf{d_{HH} := \ln(p_{HH} / \Sigma\, p_{bkg})}$
- Signal regions defined by d_{HH}, split by lep. flavour: SF(ee+μμ), DF(eμ)



Beyond 2016 data: HH → bb $W_{\ell\nu}W_{\ell\nu}$

L = 139 fb^{-1}

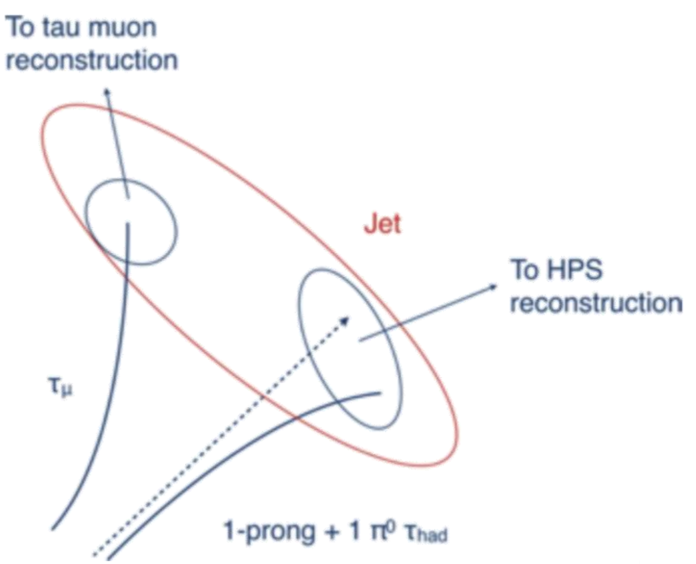
- Multiclass DNN to separate **HH** from 3 main backgrounds: **$t\bar{t}$** , **$Z(\ell\ell)$**, **$Z(\tau\tau)$**
  - Inputs are individual leptons, jets, E_T^{miss}, high-level variables (e.g. $\Delta R_{\ell\ell}$, m_{T2}^{bb})
  - Output $\mathbf{d_{HH} := \ln(p_{HH} / \Sigma\, p_{bkg})}$
- Signal regions defined by d_{HH}, split by lep. flavour: SF(ee+μμ), DF(eμ)
- Control regions inverting $m_{\ell\ell}$ and m_{bb} cuts for **Z + heavy flavour jets** and **$t\bar{t}$**
- ×8/×3 better sensitivity than older 36 fb^{-1} analyses from ATLAS/CMS:
  - Set limit at $\boldsymbol{\sigma_{HH}}$ **< 40×SM (exp.: 29×SM)**

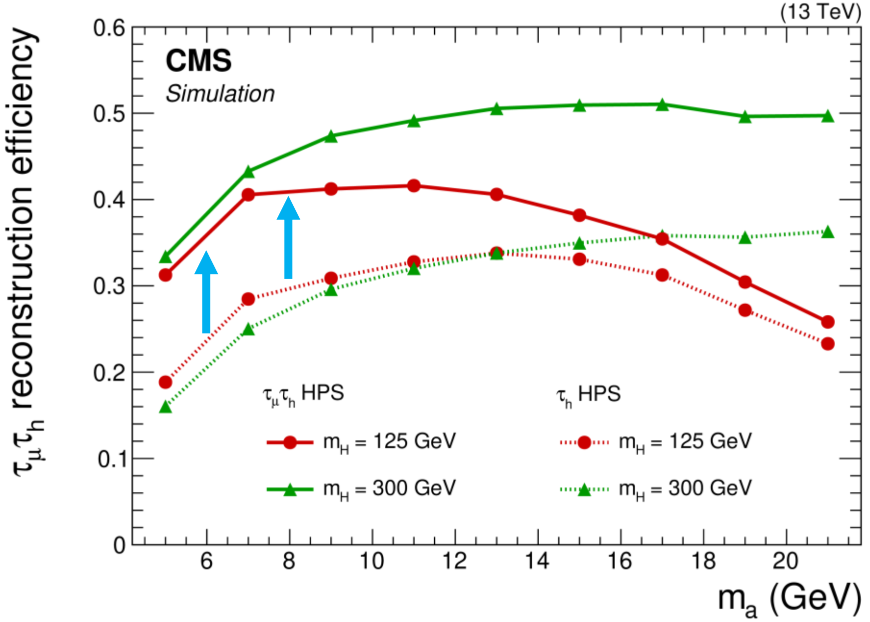


$H \rightarrow a_{\mu\mu}\ a_{\tau\tau}$ at low m_a

L = 36 fb^{-1}

- Dedicated τ reco. for overlapping decay products of $a \rightarrow \tau_\mu\, \tau_h$
  - **Gain +50% efficiency at low m_a**





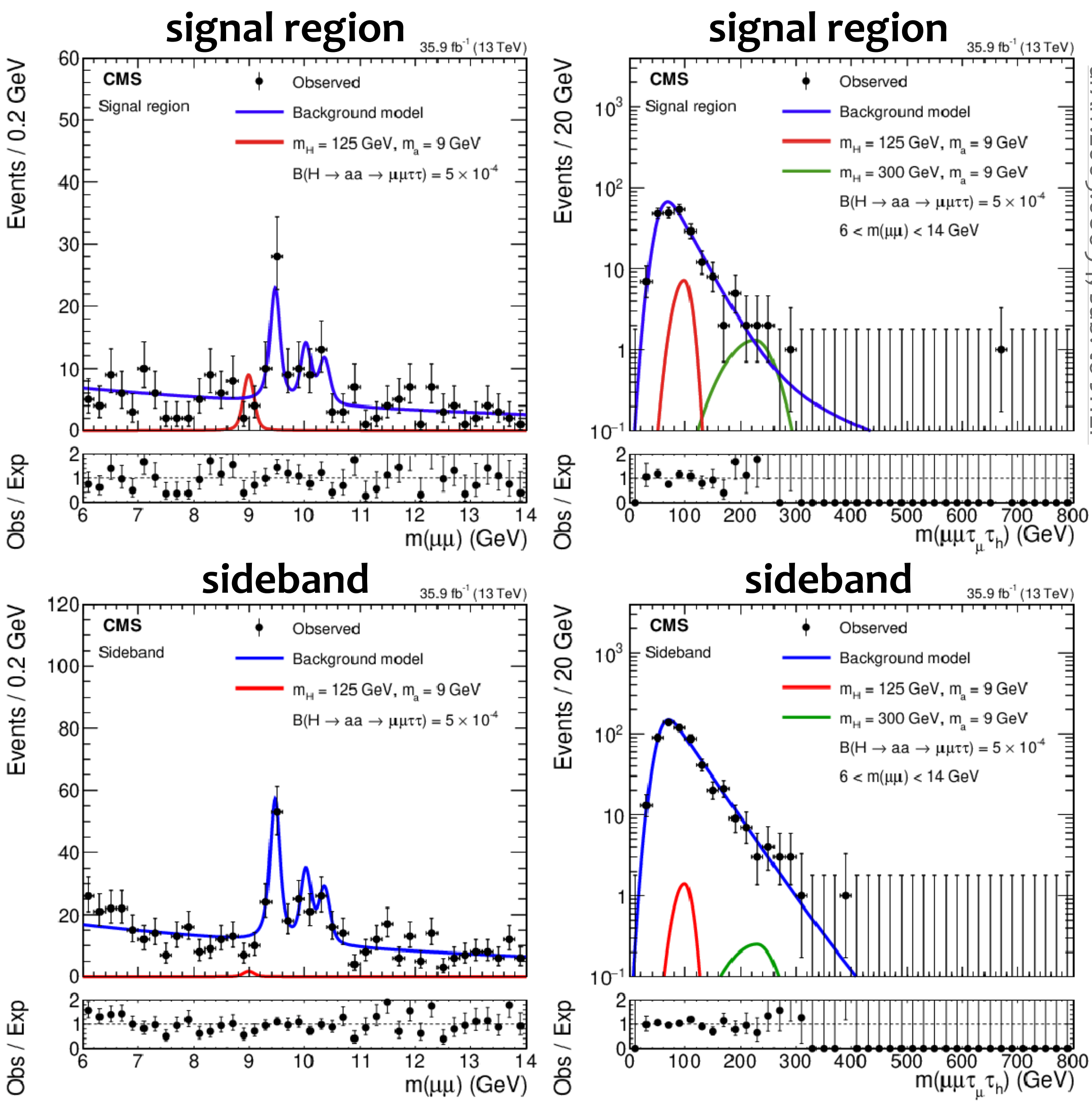
arXiv:2005.08694, sub. to JHEP

HPS (Hadrons Plus Strips) is the CMS algorithm for hadronic τ reconstruction using Particle Flow

$H \rightarrow a_{\mu\mu}\ a_{\tau\tau}$ at low m_a

- 2D fit in $m(\mu\mu) \times m(\mu\mu\tau_\mu\tau_h)$ plane
  - Fit separately in 3 $m(\mu\mu)$ ranges, to reduce correlations with $m(\mu\mu\tau_\mu\tau_h)$
  - Sideband with anti-isolated τ_h to constrain background, with transfer factor measured in $Z_{\mu\mu}$ + jet data
  - Additional 1D dimuon control region to constrain better $\psi_{(2S)}$ and Y peaks

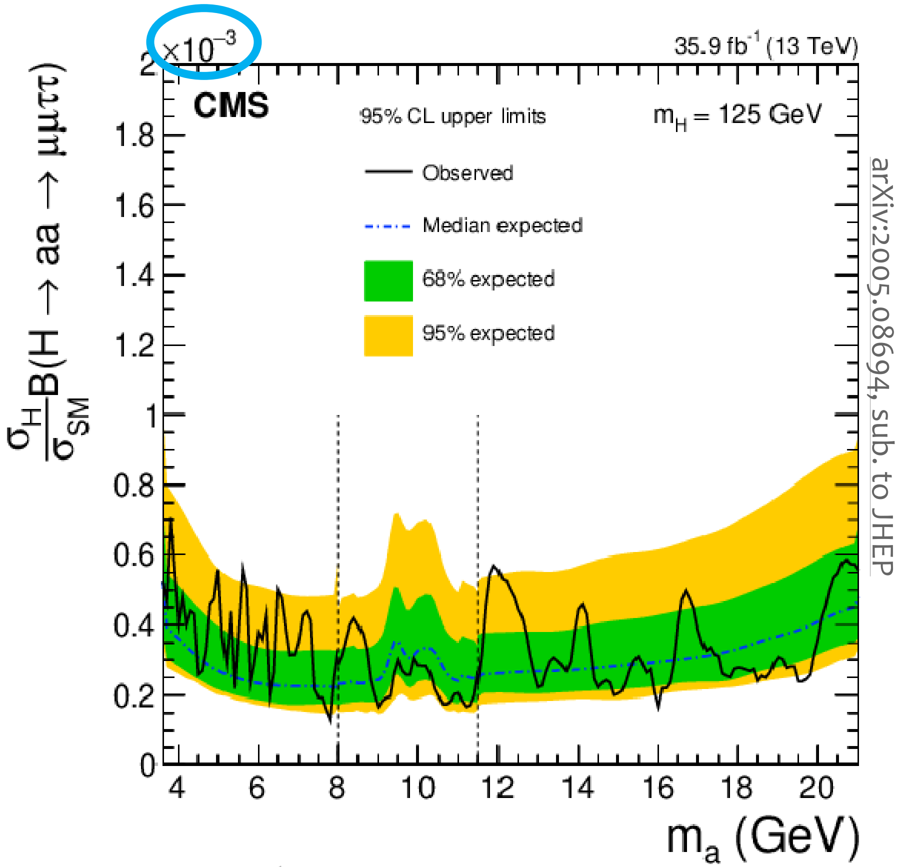
1D projections

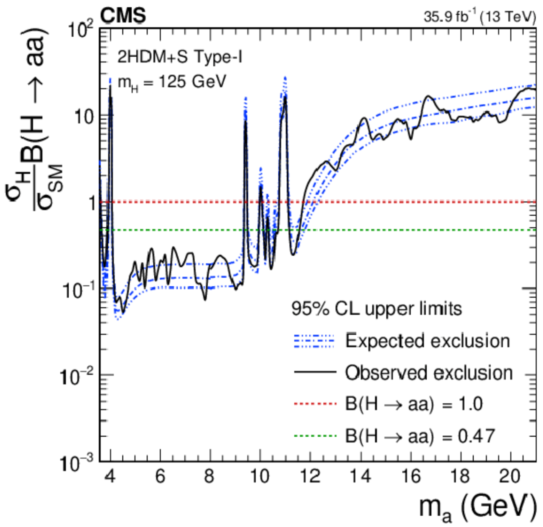


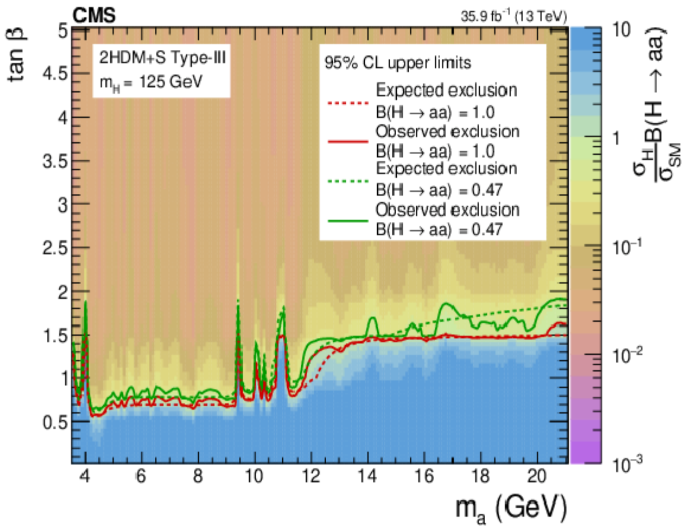
arXiv:2005.08694, sub. to JHEP

$H \to a_{\mu\mu}\ a_{\tau\tau}$ at low m_a

- Dedicated τ reco. for overlapping decay products of $a \to \tau_\mu \tau_h$
- 2D fit in $m(\mu\mu) \times m(\mu\mu\tau_\mu\tau_h)$ plane
- Set model-independent limits on BR(H→ aa→μμττ) ~ 0.02–0.08%
  - plus interpretations in different 2HDM+S benchmark models
- Showcase power of dedicated τ reco. also for heavier bosons
  - Demonstrated using a Higgs boson of mass 300 GeV as example



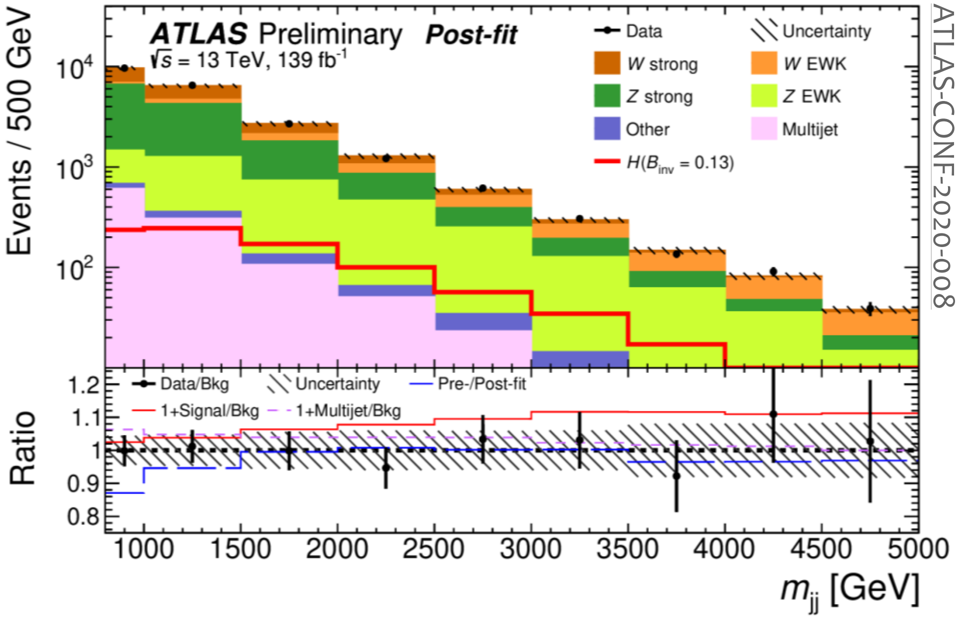


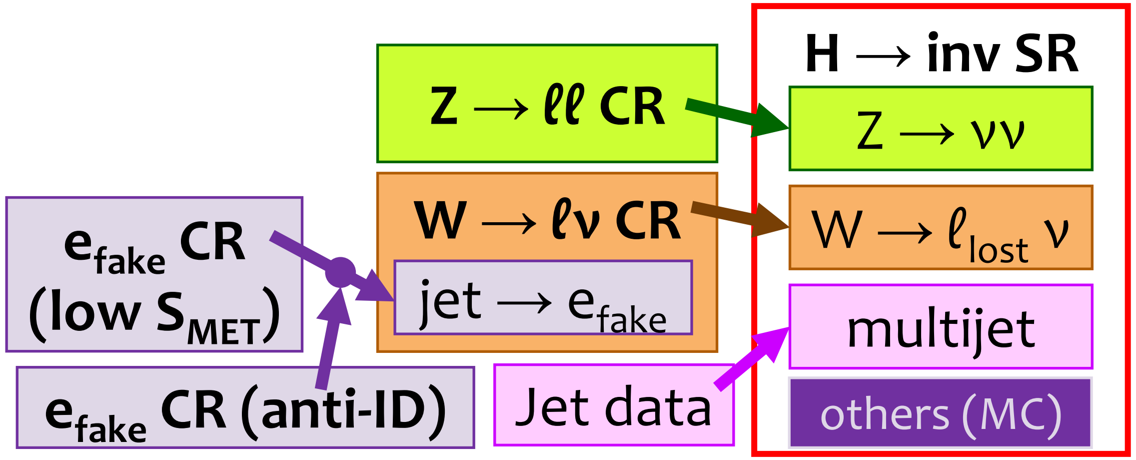


VBF H $\longrightarrow$ invisible

ATLAS EXPERIMENT
L = 139 fb^{-1}

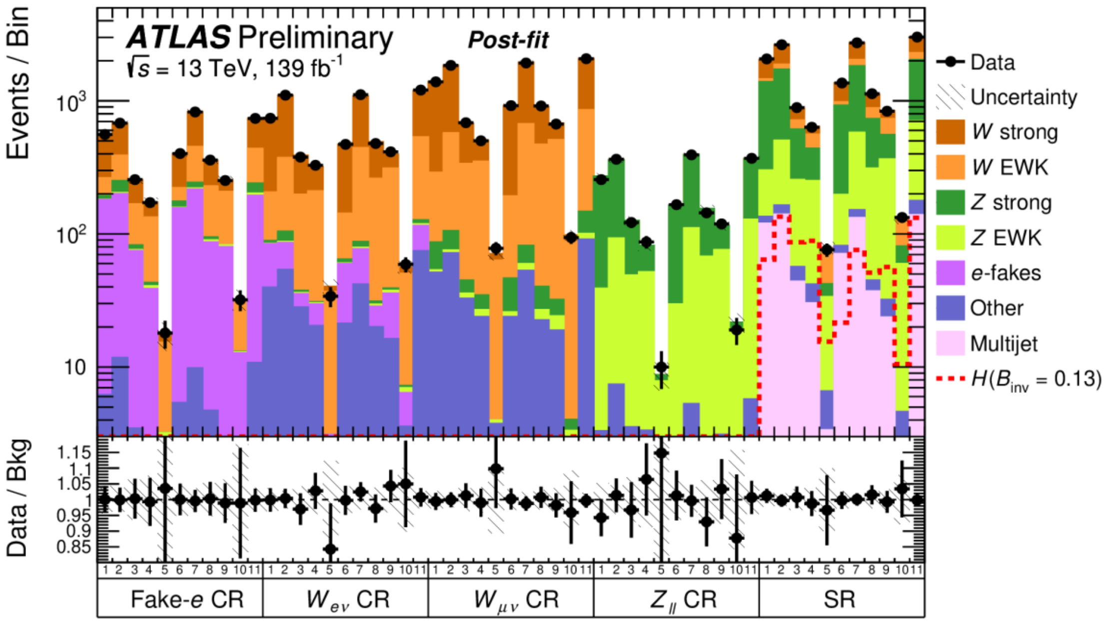
- Search for Higgs boson decays to Dark Matter ($m_{DM} < m_H/2$)
- VBF offers the best balance of cross section & purity
- Dominant backgrounds from $Z \rightarrow \nu\nu$ and $W \rightarrow \ell\nu$ (with lost ℓ)
  - Estimated from simultaneous fit using CRs of $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$
  - Further data-driven estimates for QCD multijet background in SR and in $W \rightarrow e\nu$ CR

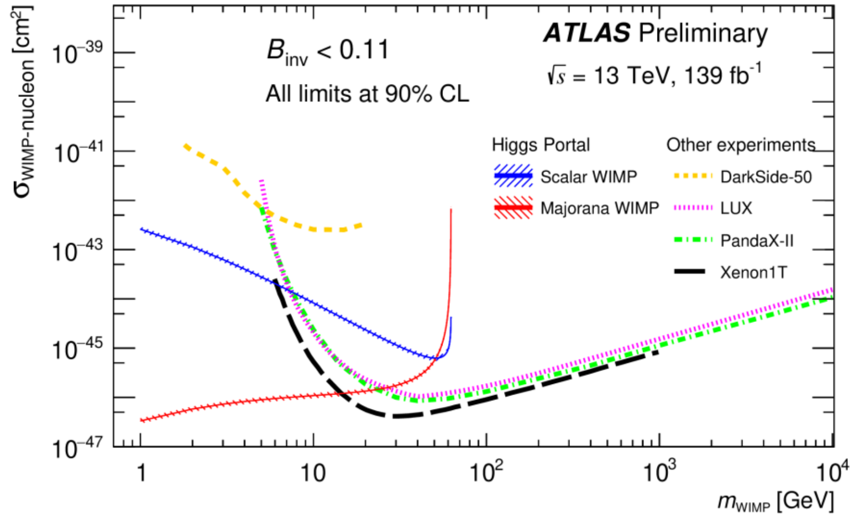




VBF H ⟶ invisible

- Several improvements compared to older 36 fb^{-1} ATLAS result
  - Improved acceptance & include events with 3rd jet from ISR/FSR
  - Finer SR binning in m_{jj}, $\Delta\varphi_{jj}$, n_{Jet}
  - Improved lepton selections (less $W \to \ell_{lost}\nu$, more $Z \to \ell\ell$ in CR)
  - Reduced MC stat. uncertainties (better filters, event weights, …)
- Sets world's best upper limit:
  - **BR(H→inv) < 0.13 (exp. 0.13)** @ 95% CL
  - (σ_{WIMP}, m_{WIMP}) limit interpretation



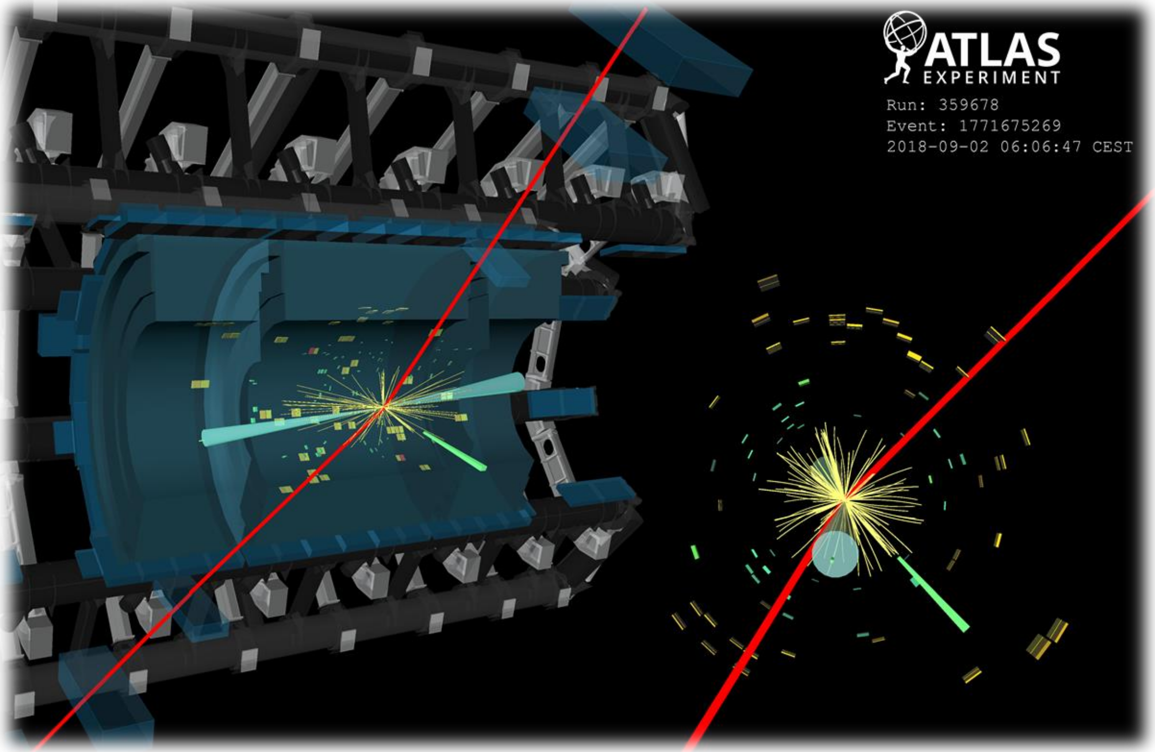


Also older 36 fb^{-1} + Run 1 combinations from CMS [PLB 793 (2019) 520] and ATLAS [PRL 122 (2019) 231801]
BR(H ⟶ invis) upper limits: CMS 0.19 (expected 0.15), ATLAS 0.26 (expected 0.17)

H → Z γ: the missing diboson decay

ATLAS EXPERIMENT
$L = 139\ fb^{-1}$

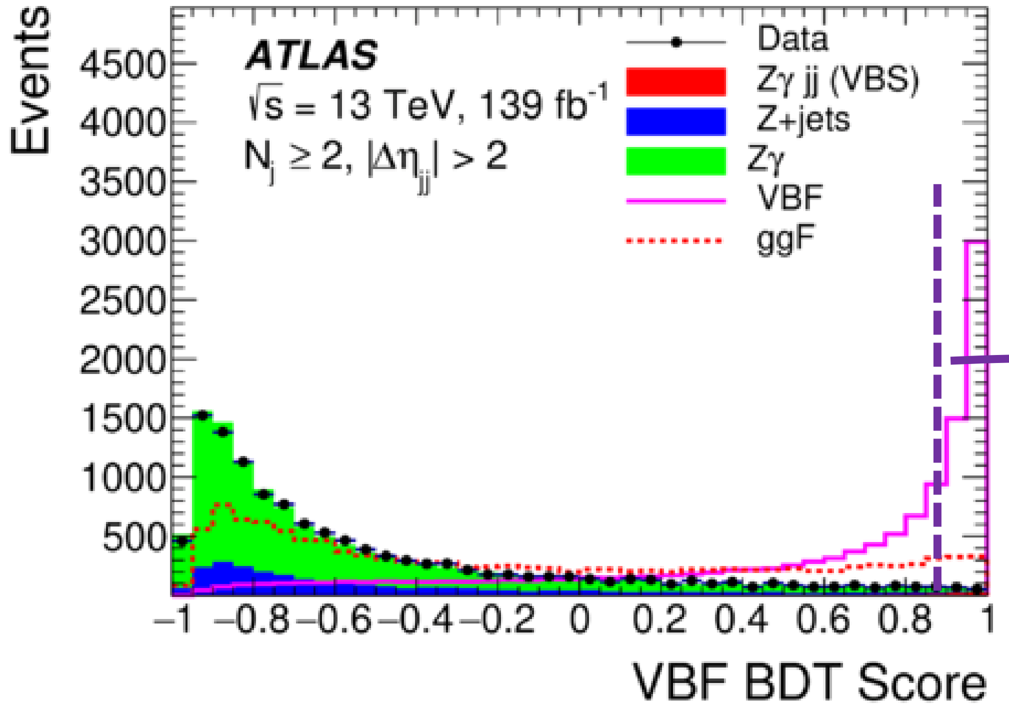
- $SU(2)_L$ symmetry ties together the HWW, HZZ, Hγγ, HZγ interactions
  - If heavy new physics respects SU(2), correlated effects across the four
- BR(H → Z γ → ℓℓ γ) = $0.5 \cdot 10^{-4}$
  - Similar BR to H → 4ℓ, but larger background from Z γ production
- As in H → μμ, key ingredients are:
  - **Improve signal mass resolution:** FSR recovery, kinematic refit of Z → ℓℓ
  - **Improve S/B via categorization:** BDT targeting VBF production; p_T and p_{Tt}

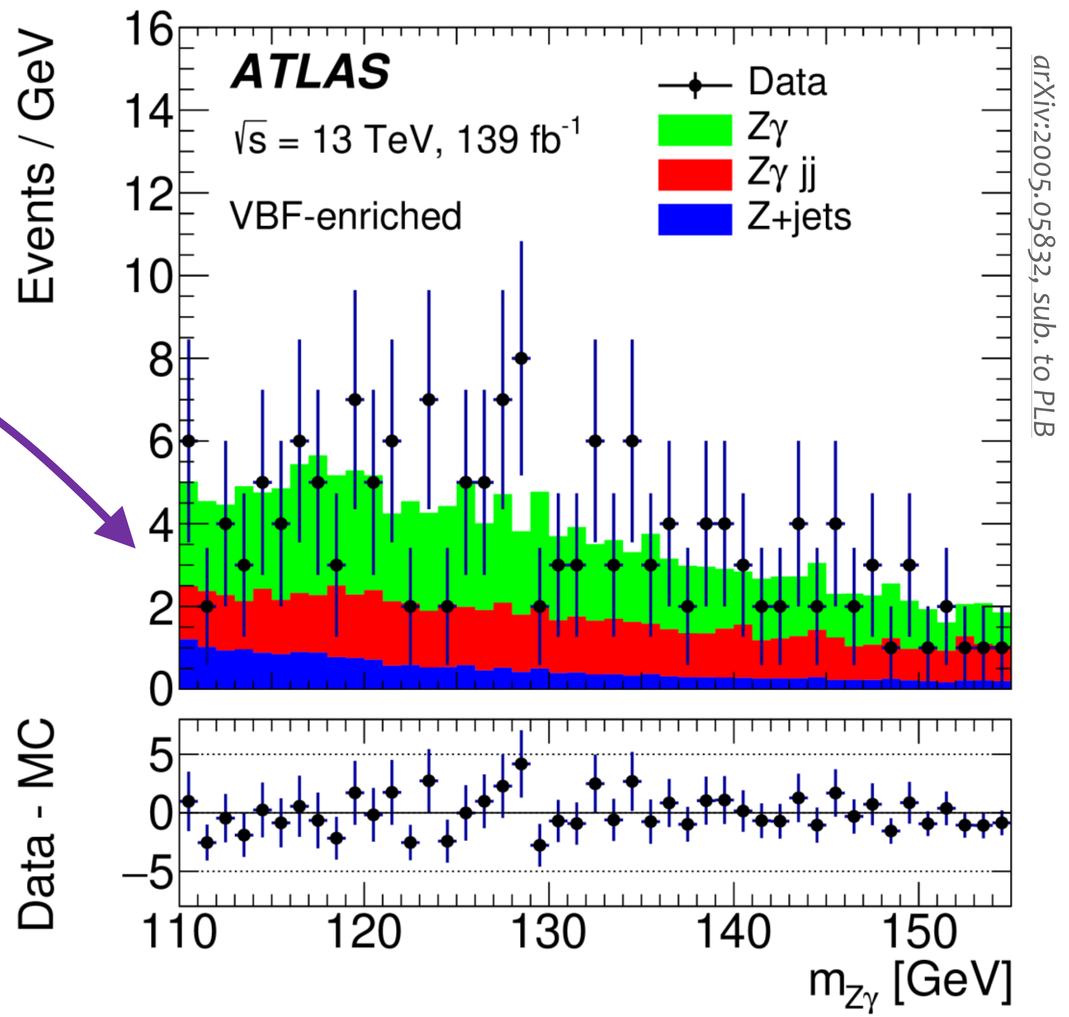


Event display of VBF H → Z γ → μμ γ candidate

arXiv:2005.05832, sub. to PLB

H → Z γ: VBF BDT

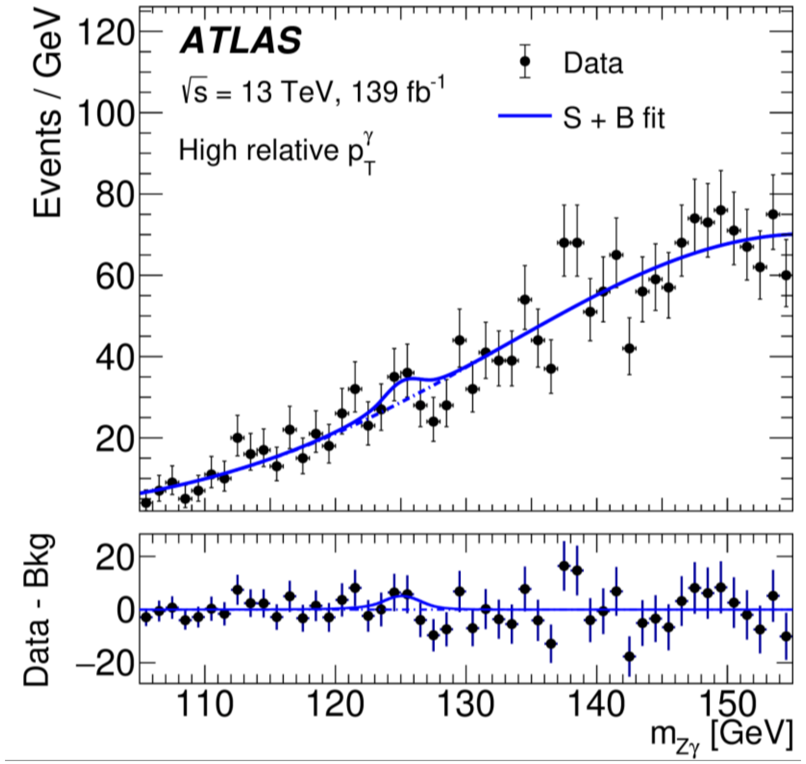




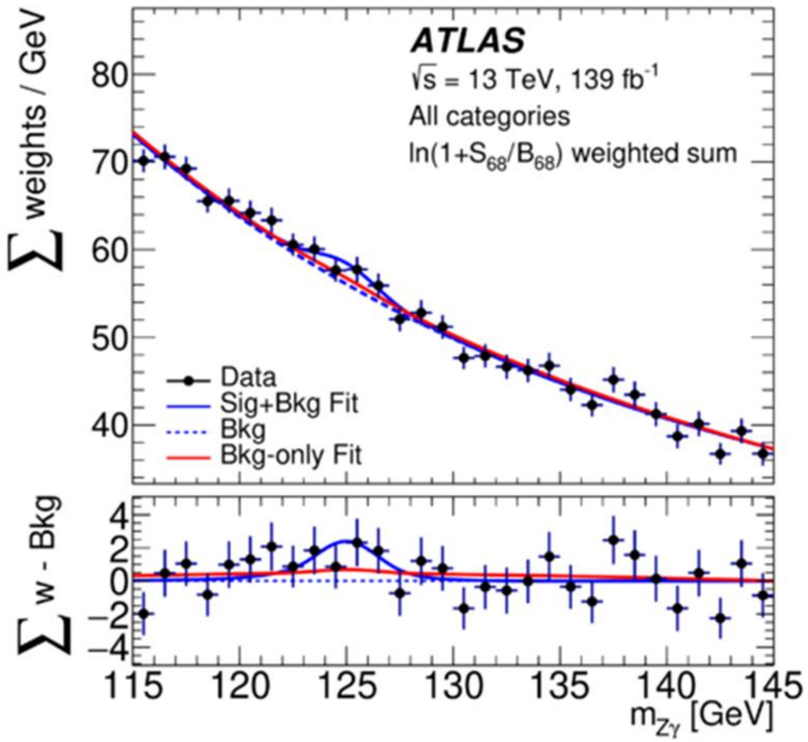
BDT with 8 inputs defined from the kinematics of the Zγ jj system: e.g. m(jj), Δφ(Zγ, jj), p_T(j1), …

H → Z γ: fit and results

High $p_T^\gamma / m_{Z\gamma}$ category (highest sensitivity)



Sum of all categories (sensitivity-weighted)



Fit results by category and combined

Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

arXiv:2005.05832, sub. to PLB

We may be starting to see the first hints of the signal

Also older CMS result on 36 fb⁻¹ for H → Z γ and H → γ* γ → μμ γ
Upper limit 3.9 × SM (expected 2.0 × SM). *[JHEP 11 (2018) 152]*