Studies of the CP properties of the Higgs boson at the ATLAS experiment

William Leight, for the ATLAS Collaboration
DESY

EPS-HEP2021
July 26, 2021

Outline

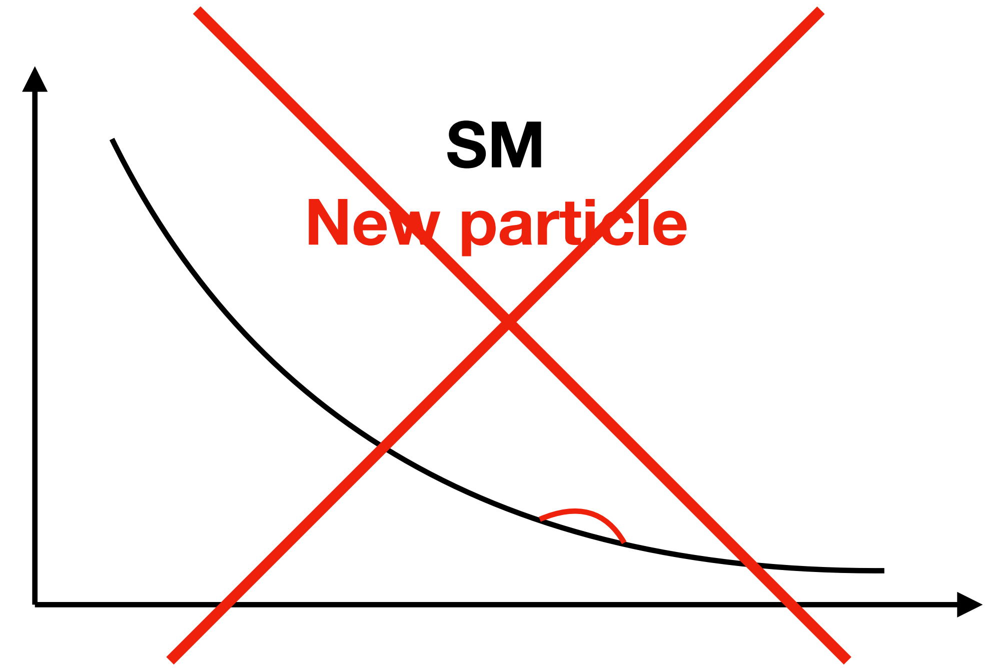
- Study of CP violation in VBF production using the $\tau\tau$ decay channel, *Phys. Lett. B 805 (2020) 135426*
- Study of CP violation in ttH production using the γγ decay channel, *Phys. Rev. Lett. 125 (2020) 061802*
- Study of CP violation in ggH production using the WW decay channel, ATLAS-CONF-2020-055

CP Violation and Effective Field Theories

- Matter-antimatter imbalance is not explained by the SM
  - Which only includes a small level of CP violation
- CP-violating BSM physics must be out there

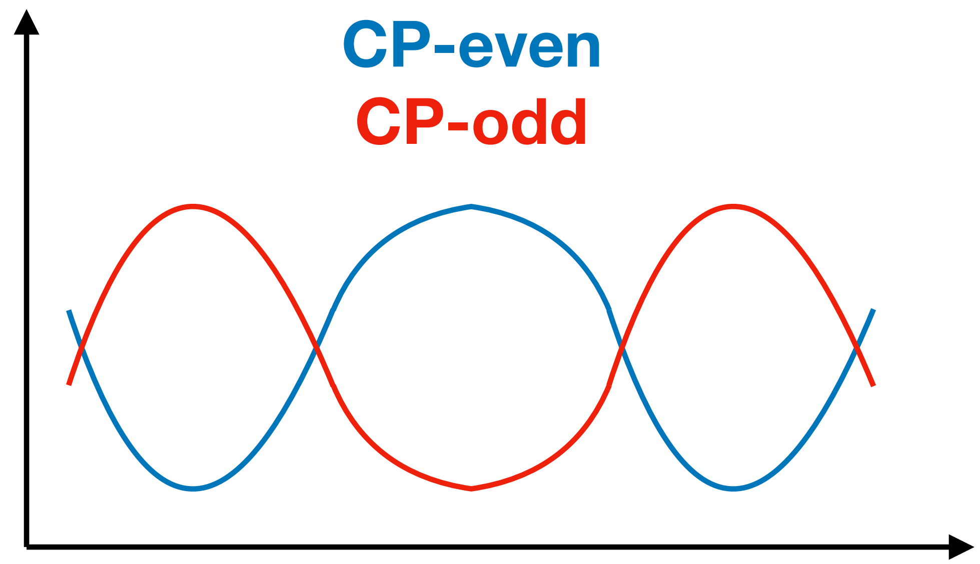
CP Violation and Effective Field Theories

- Matter-antimatter imbalance is not explained by the SM
  - Which only includes a small level of CP violation
- CP-violating BSM physics must be out there
  - Haven't been able to directly detect it so far



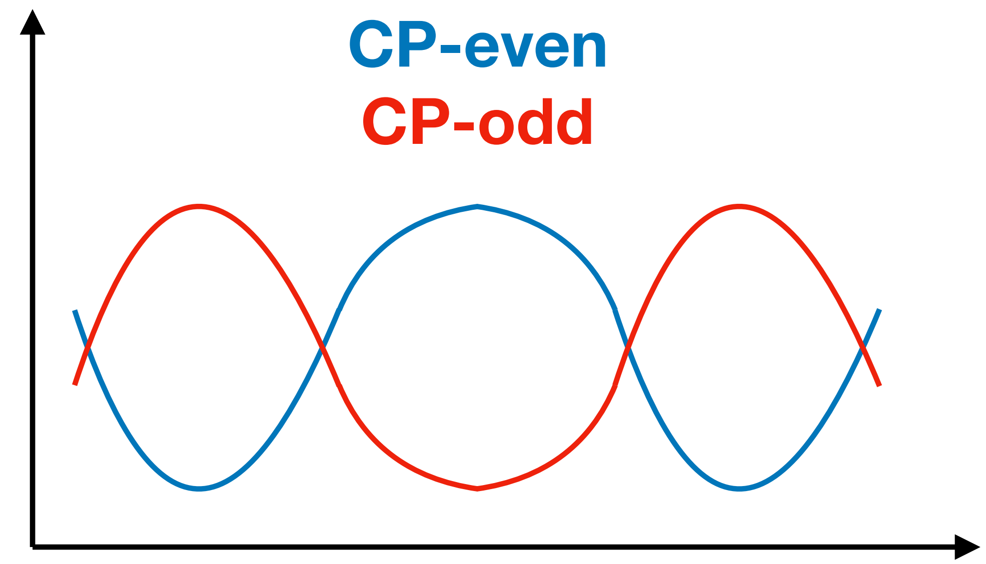
CP Violation and Effective Field Theories

- Matter-antimatter imbalance is not explained by the SM
  - Which only includes a small level of CP violation
- CP-violating BSM physics must be out there
  - Haven't been able to directly detect it so far
  - But we might be able to see its effects indirectly
- The couplings of the Higgs boson to other particles could be affected by physics at higher energies



CP Violation and Effective Field Theories

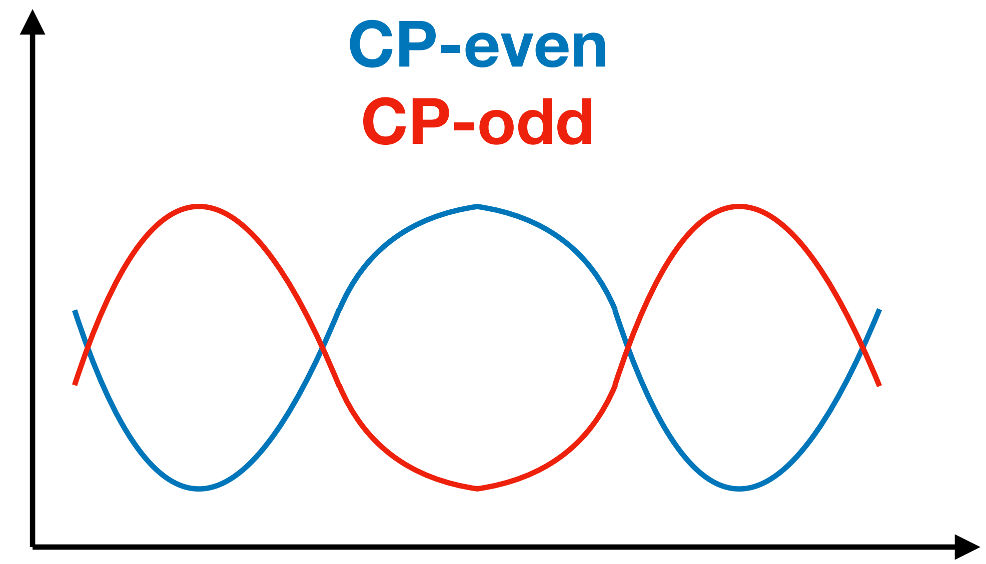
- Matter-antimatter imbalance is not explained by the SM
  - Which only includes a small level of CP violation
- CP-violating BSM physics must be out there
  - Haven't been able to directly detect it so far
  - But we might be able to see its effects indirectly
- The couplings of the Higgs boson to other particles could be affected by physics at higher energies



- Parameterize new physics with an EFT model
  - Higgs Characterization is the main one used for results shown here
- Allow for some admixture of a 0^- Higgs boson
- Include all possible interactions from gauge-invariant dimension-6 operators
  - For each analysis, focus on the operators that effect the relevant vertex
  - Assume SM holds for the rest

CP Violation and Effective Field Theories

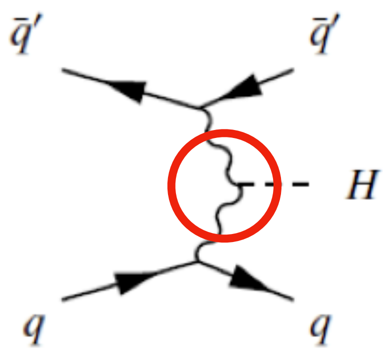
- Matter-antimatter imbalance is not explained by the SM
  - Which only includes a small level of CP violation
- CP-violating BSM physics must be out there
  - Haven't been able to directly detect it so far
  - But we might be able to see its effects indirectly
- The couplings of the Higgs boson to other particles could be affected by physics at higher energies



- Study of CP violation in VBF production using the $\tau\tau$ decay channel, *Phys. Lett. B 805 (2020) 135426*
- Study of CP violation in ttH production using the γγ decay channel, *Phys. Rev. Lett. 125 (2020) 061802*
- Study of CP violation in ggH production using the WW decay channel, ATLAS-CONF-2020-055

Phys. Lett. B 805 (2020) 135426

CP in the HVV Vertex



CPV described by single* parameter $\tilde{d}$

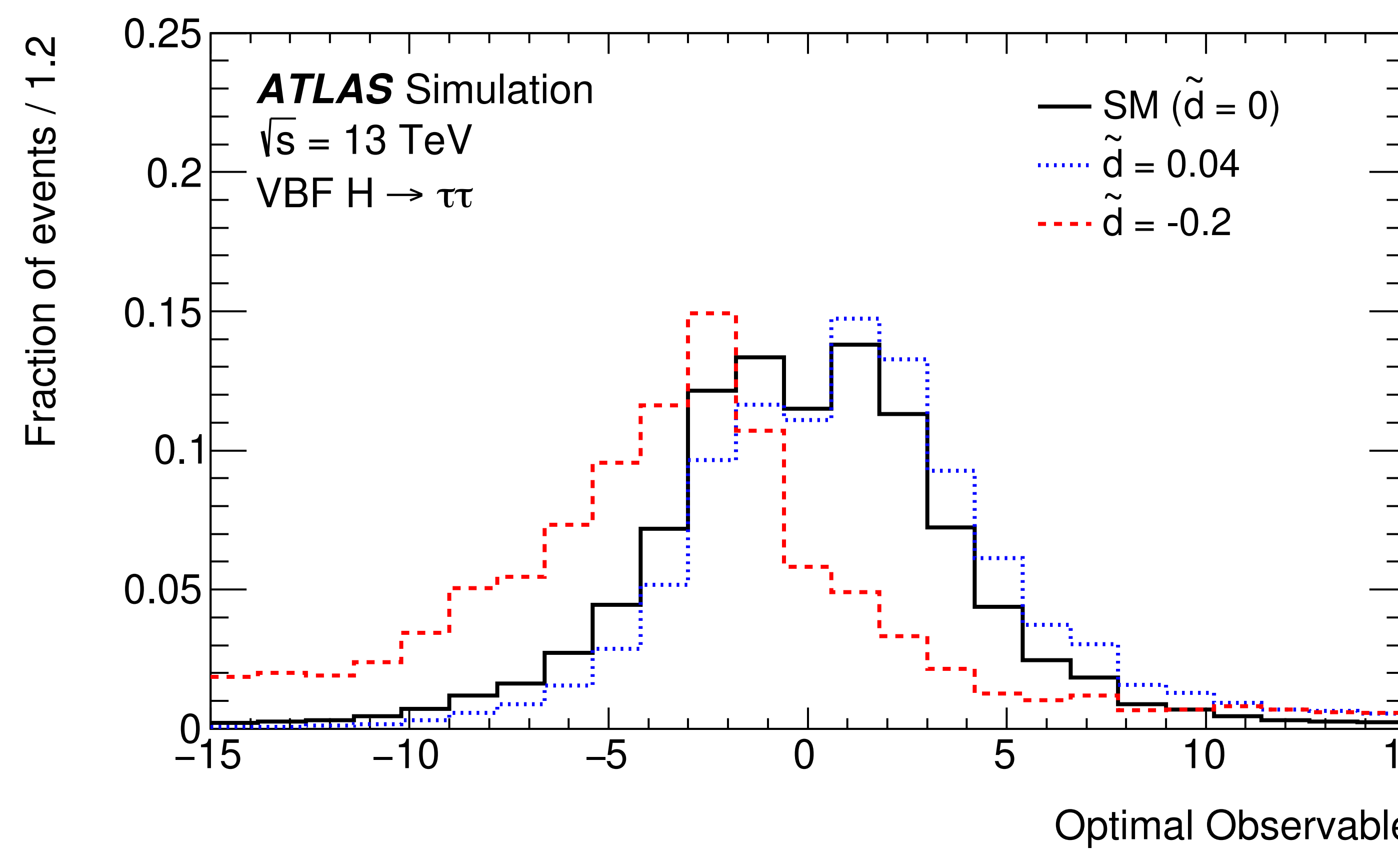
$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d} \cdot \mathcal{M}_{\mathrm{CP\text{-}odd}}$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d} \cdot 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\mathrm{CP\text{-}odd}}|^2$$

CP-odd contribution

$$\mathcal{O}_{\mathrm{opt}} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

- O_{opt} combines information from 7 variables characterizing the final state
  - $\langle O_{opt}\rangle=0$ if no CPV
  - More sensitive than $\Delta\phi_{jj}$
- $\tau\tau$ final state offers good S/B and reconstruction of the Higgs
  - More details in talk of M. Mlynarikova

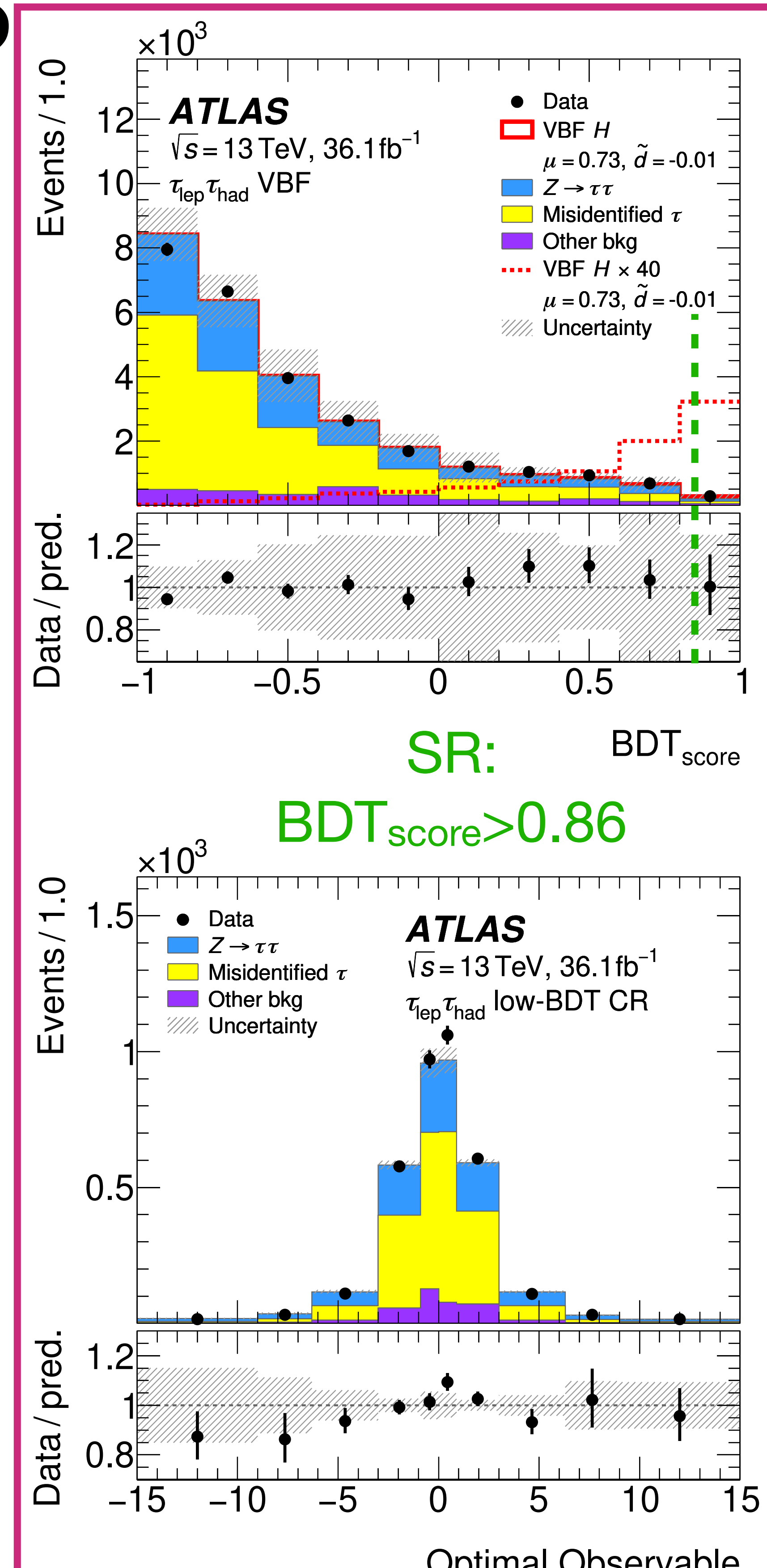


*Assuming BSM physics affects W and Z equally

Analysis

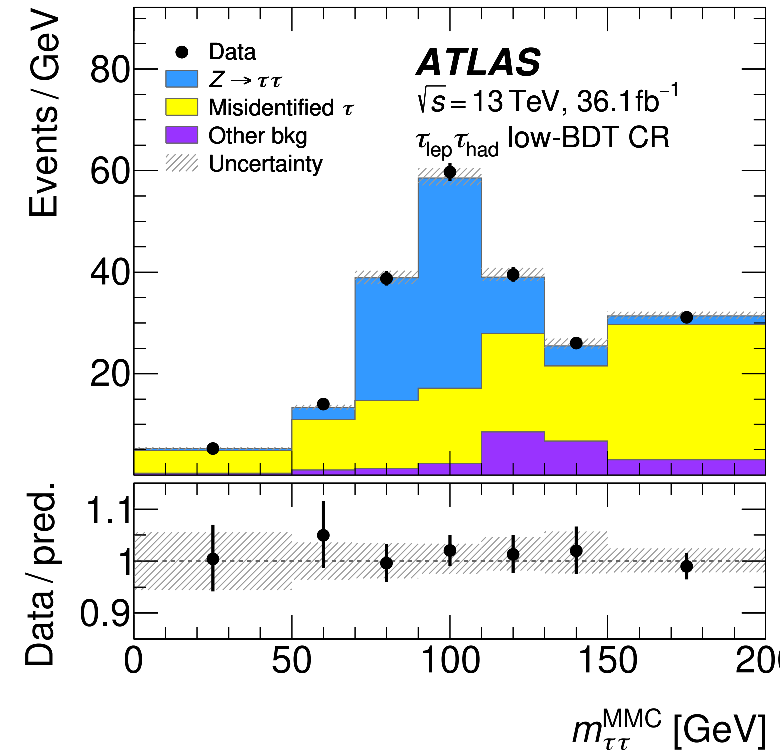
Phys. Lett. B 805 (2020) 135426

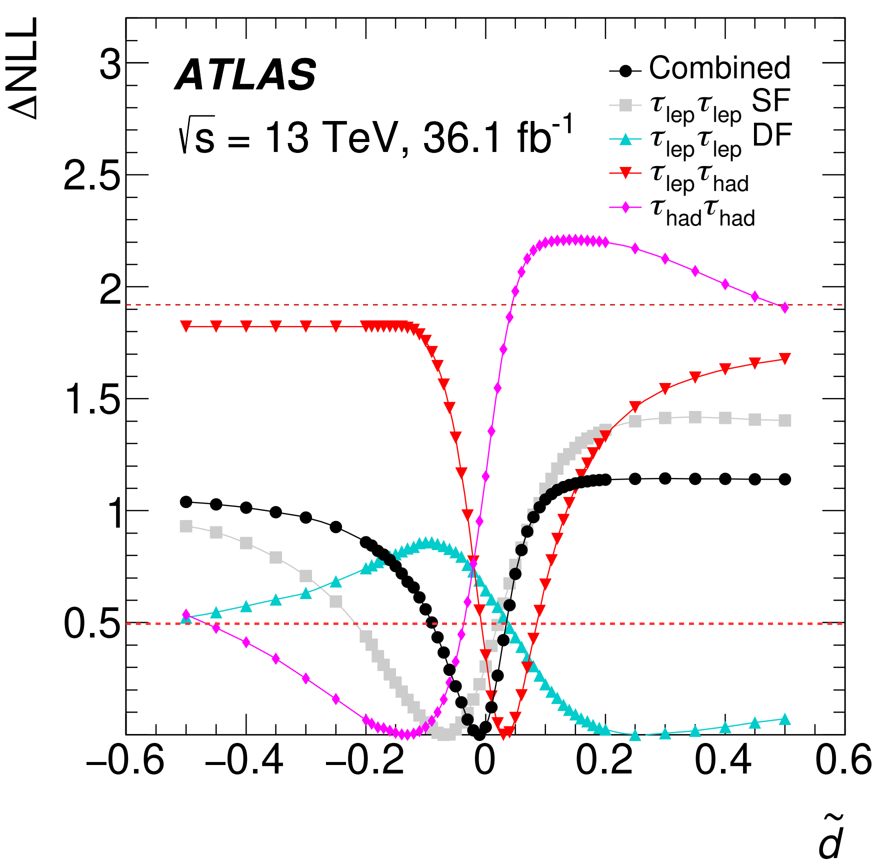
- All four $\tau\tau$ channels are used (dileptonic SF and DF, semileptonic, all hadronic)
- VBF topology selected by requiring two widely separated jets with m_{jj}>300 GeV
- BDT trained in each channel for further discrimination
  - Score used to define a SR
  - No dependence of O_{opt} on the BDT
- CRs used to constrain normalization of
  - $Z\rightarrow\tau\tau$ (all channels)
  - Z→ll (dileptonic SF)
  - top backgrounds (dileptonic)
  - Misidentified τ estimated using data-driven methods



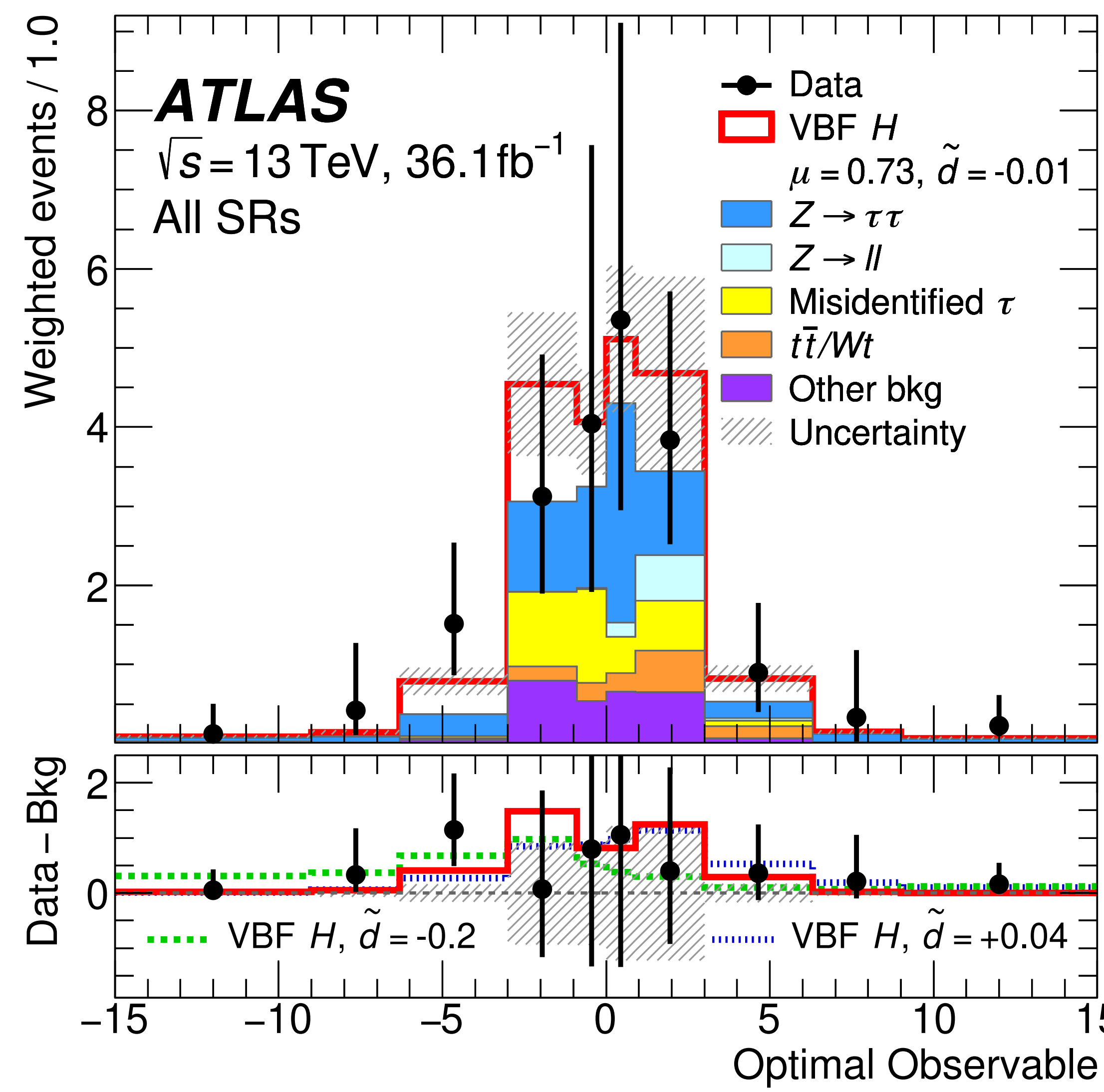
Results

- Fit to O_{opt} distributions performed simultaneously
  - Ditau mass in the low-BDT CR, event yields for others
  - Signal normalization is allowed to float
  - Also $Z\rightarrow\tau\tau$ or ll and top backgrounds
  - Fraction of H→WW decays fixed to SM value
- **Combined $<O_{opt}>=-0.19\pm0.37$**
- **68% CL for $\tilde{d}$ is [-0.090,0.035]**



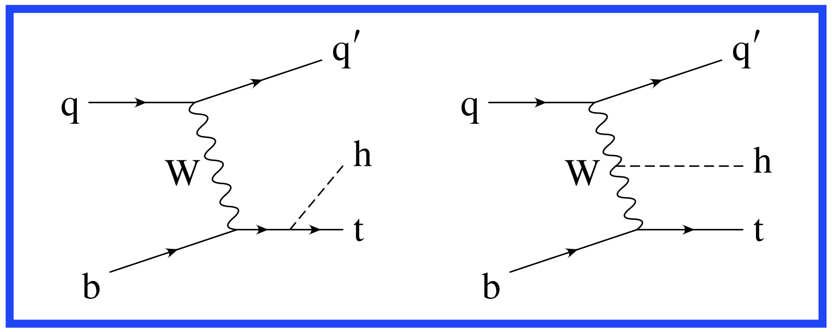


Phys. Lett. B 805 (2020) 135426



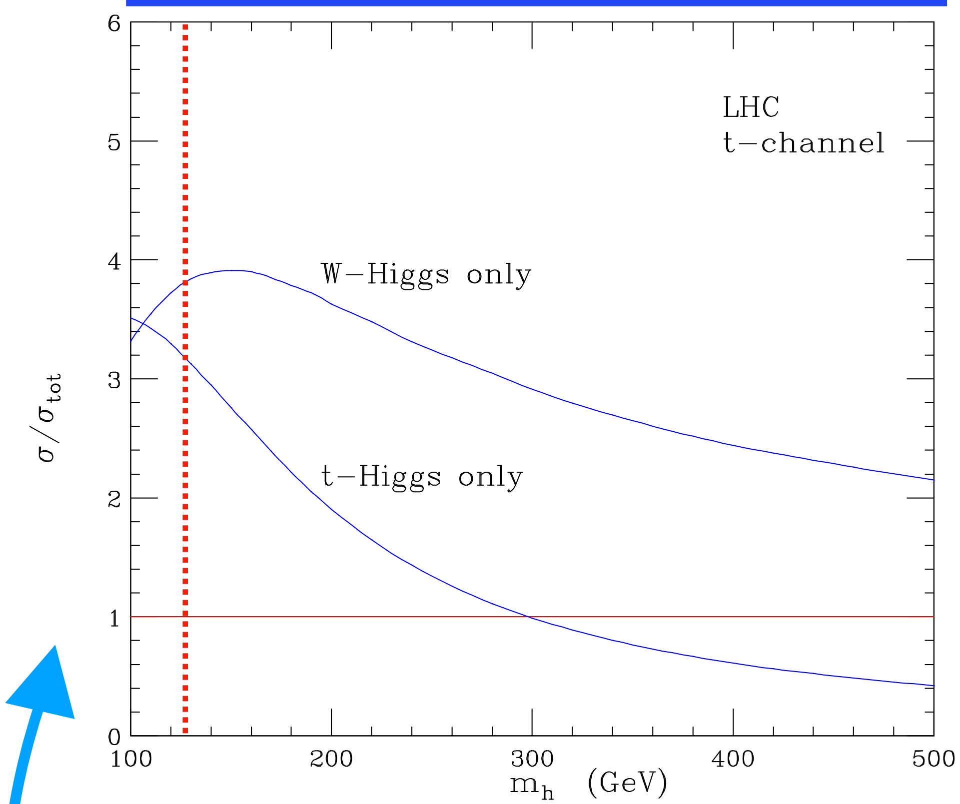
Phys. Rev. Lett. 125 (2020) 061802

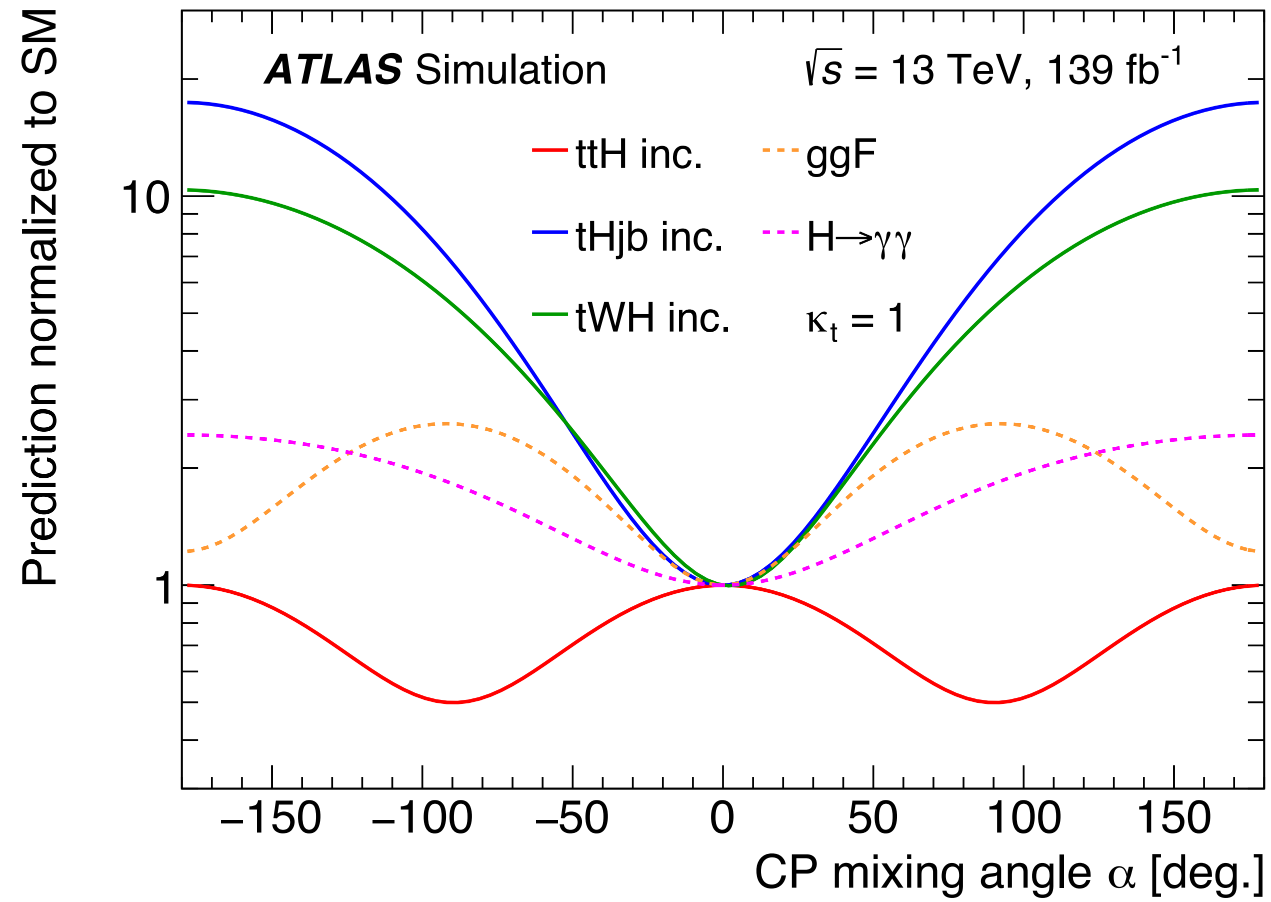
CP in the Top Yukawa



$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

Phys.Rev.D 64 (2001) 094023

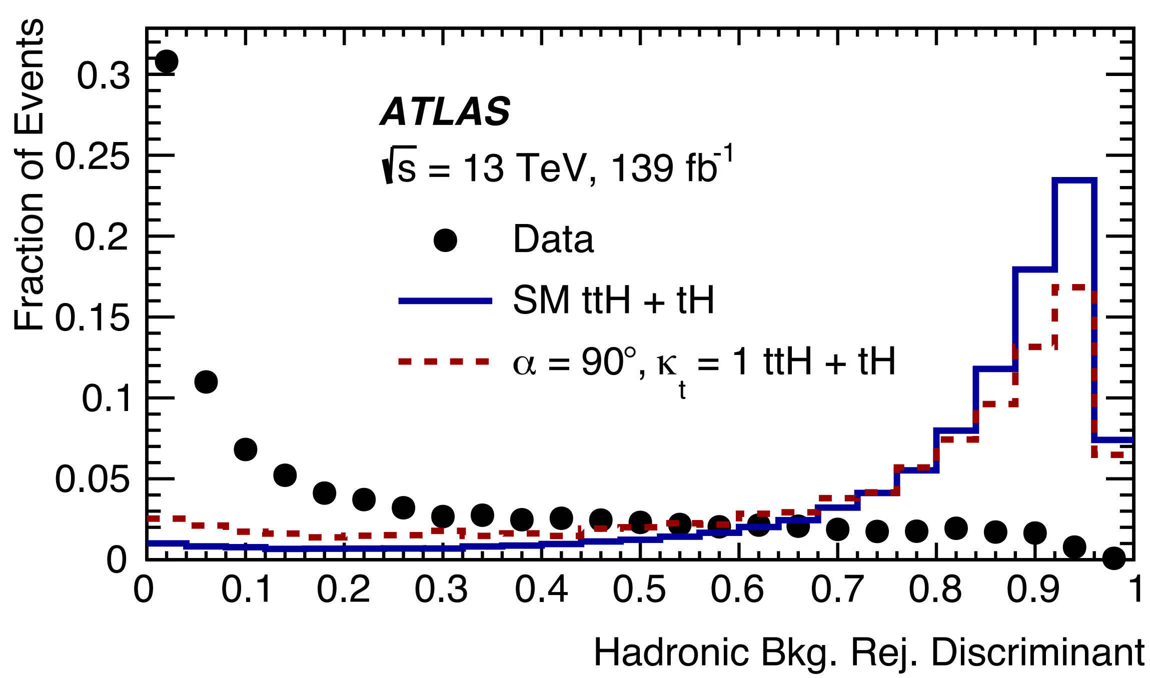


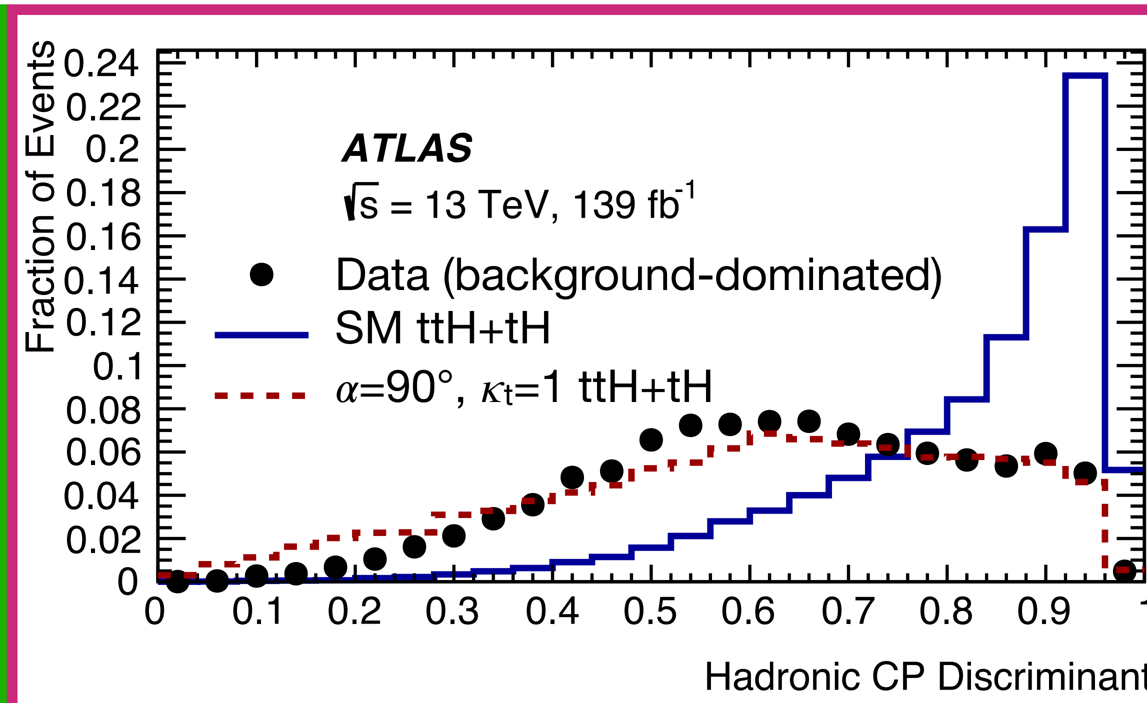


- New physics in HVV suppressed by $1/\Lambda^2$
- Assuming Higgs is partly 0^-, not the case for CP-odd contribution to top Yukawa
- Would strongly affect ttH and especially tH yields
  - tH suppressed in SM by interference

Analysis

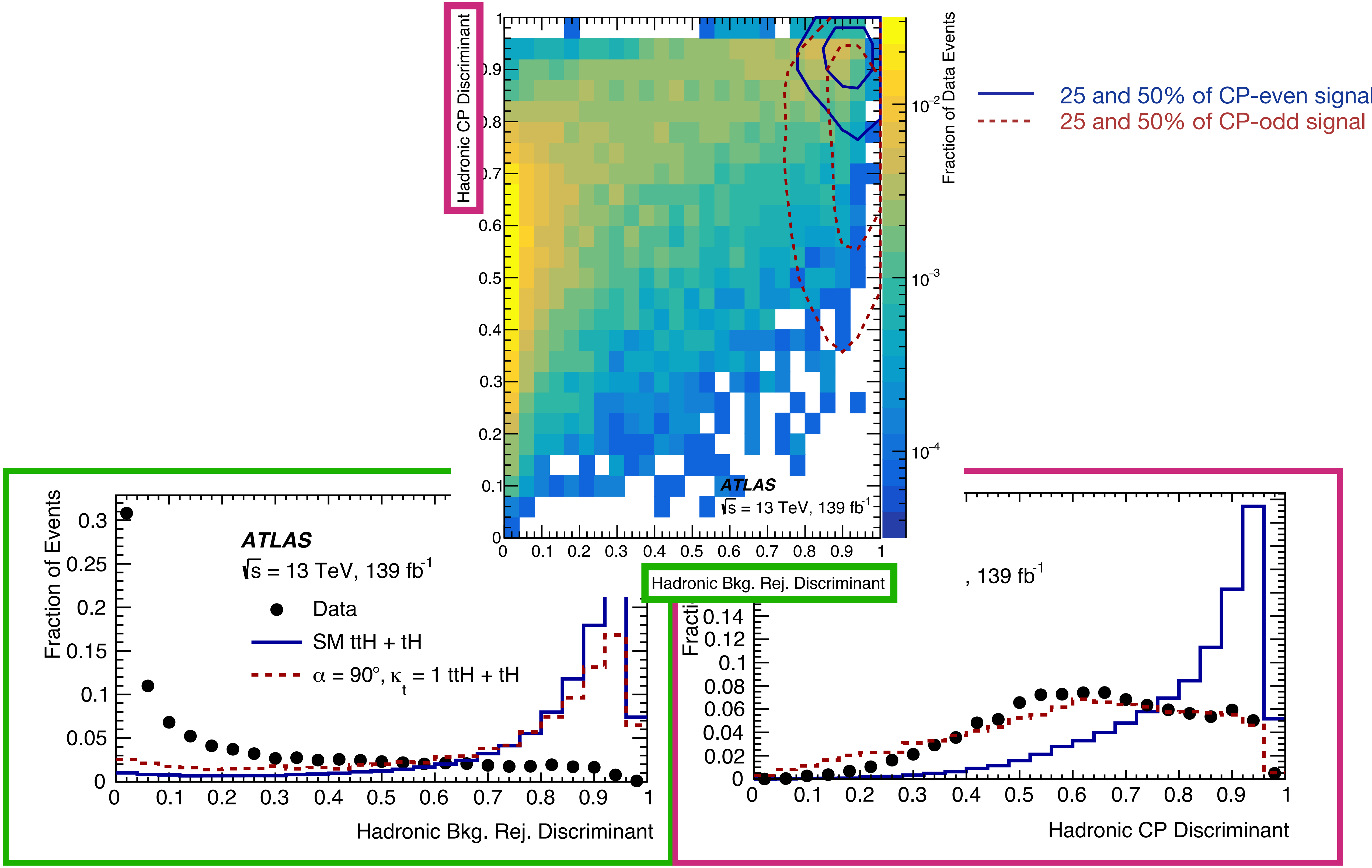
- γγ final state: high yield, clean, good mass resolution
  - For more details on γγ analysis, see talk by E. Rossi
  - For more details on ttH analyses, see talk by H. Yang
- Two BDTs for event categorization
  - Trained separately in hadronic and leptonic top-quark decays
  - One for discriminating against background
  - One for discriminating CP-even from CP-odd





Phys. Rev. Lett. 125 (2020) 061802

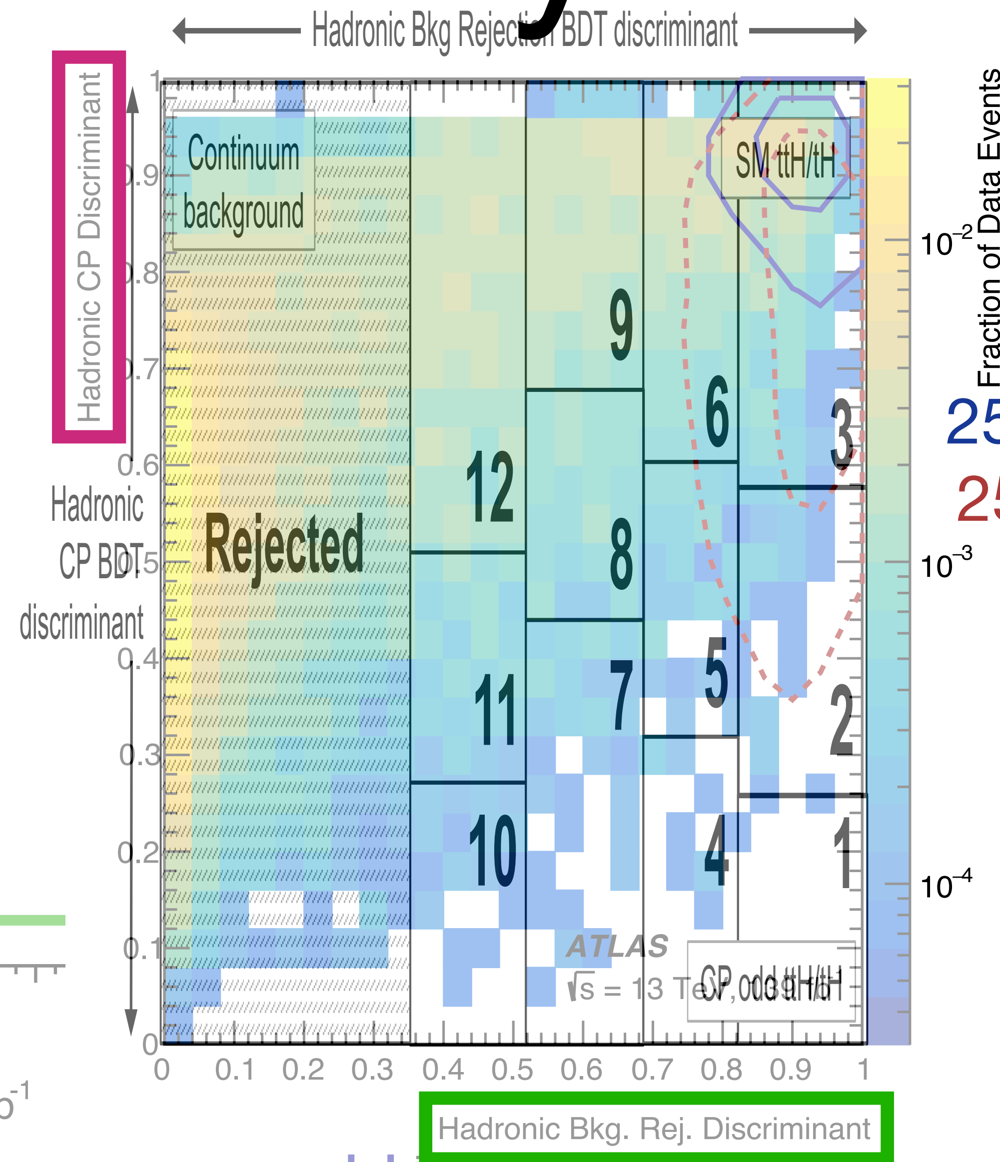
Analysis



Phys. Rev. Lett. 125 (2020) 061802

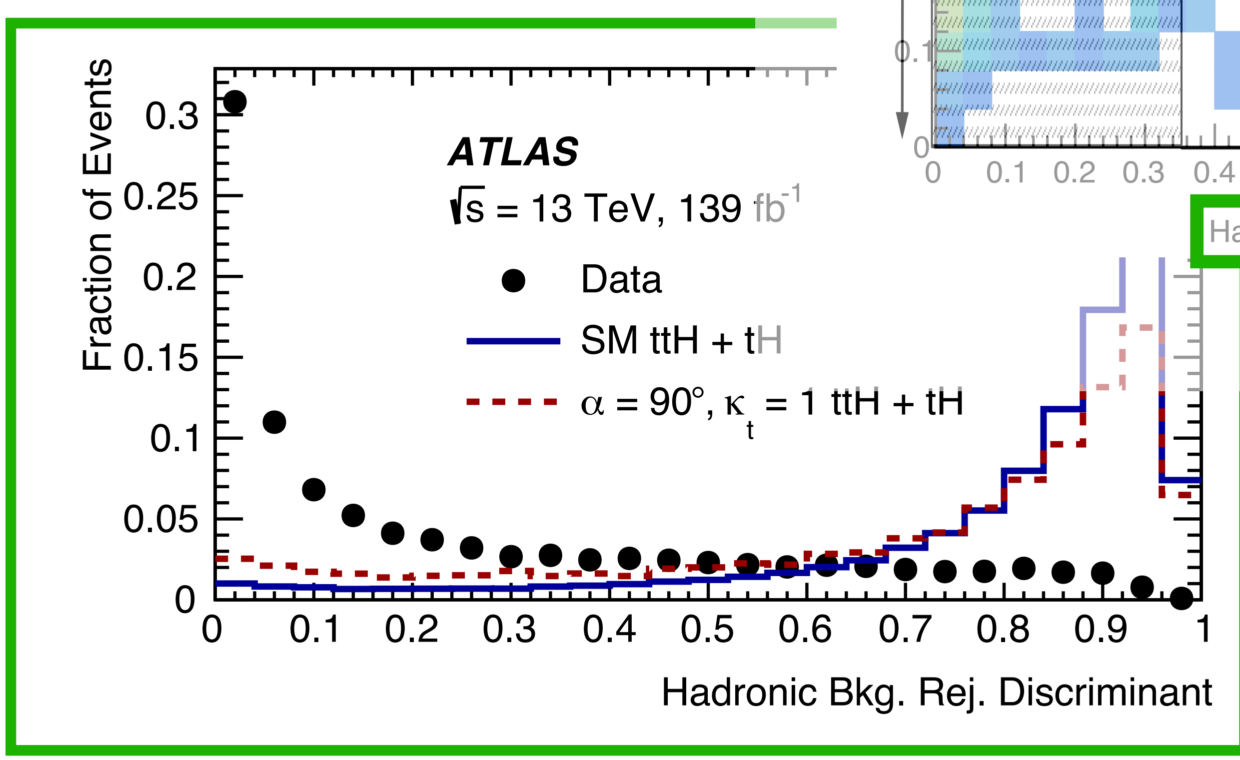
Analysis

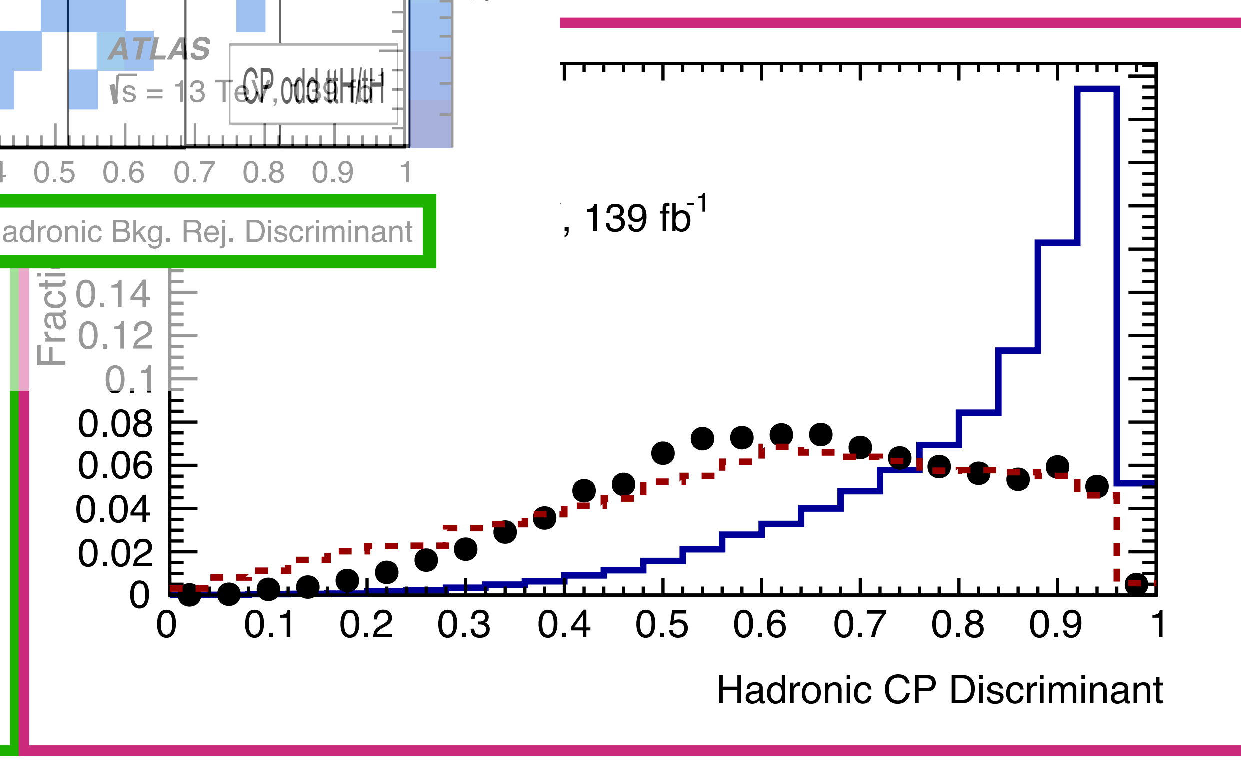
- Final categorization in 2d BDT plane
- Categories and boundaries chosen to optimize ttH significance and CP-even vs. CP-odd discrimination



25 and 50% of CP-even signal

25 and 50% of CP-odd signal

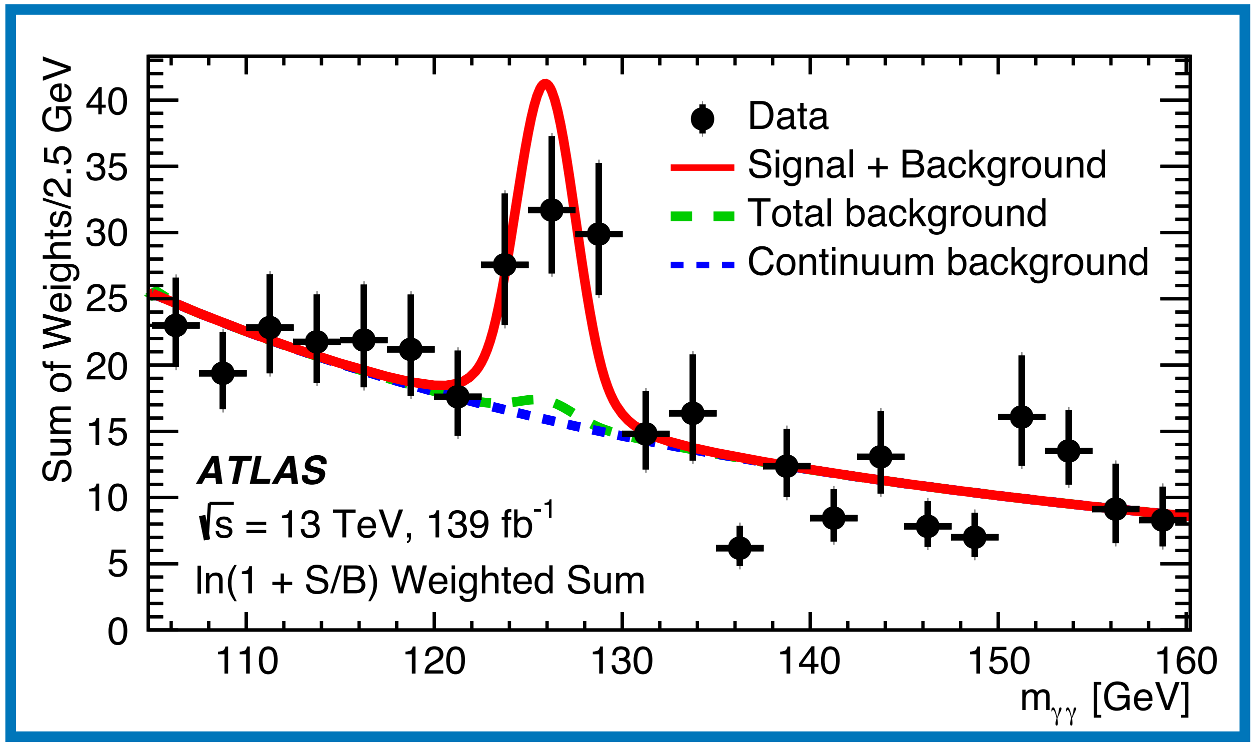




Phys. Rev. Lett. 125 (2020) 061802

Results

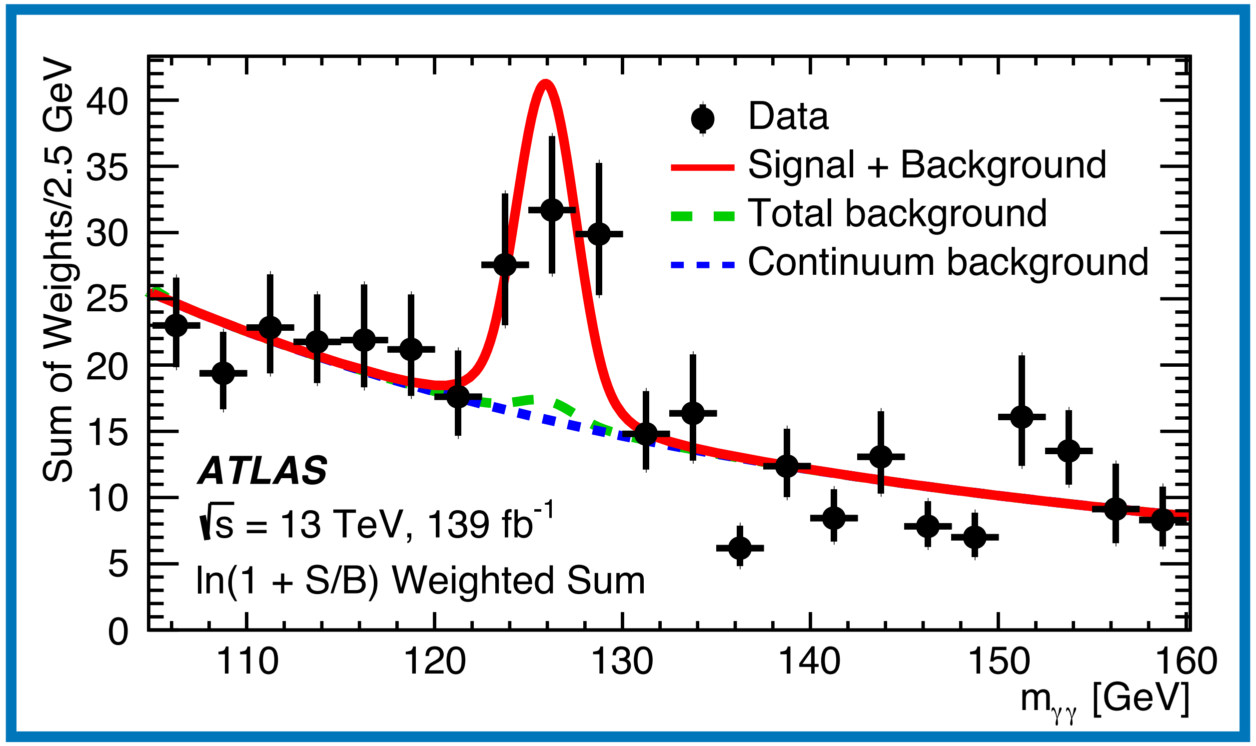
- Simultaneous fit in all categories

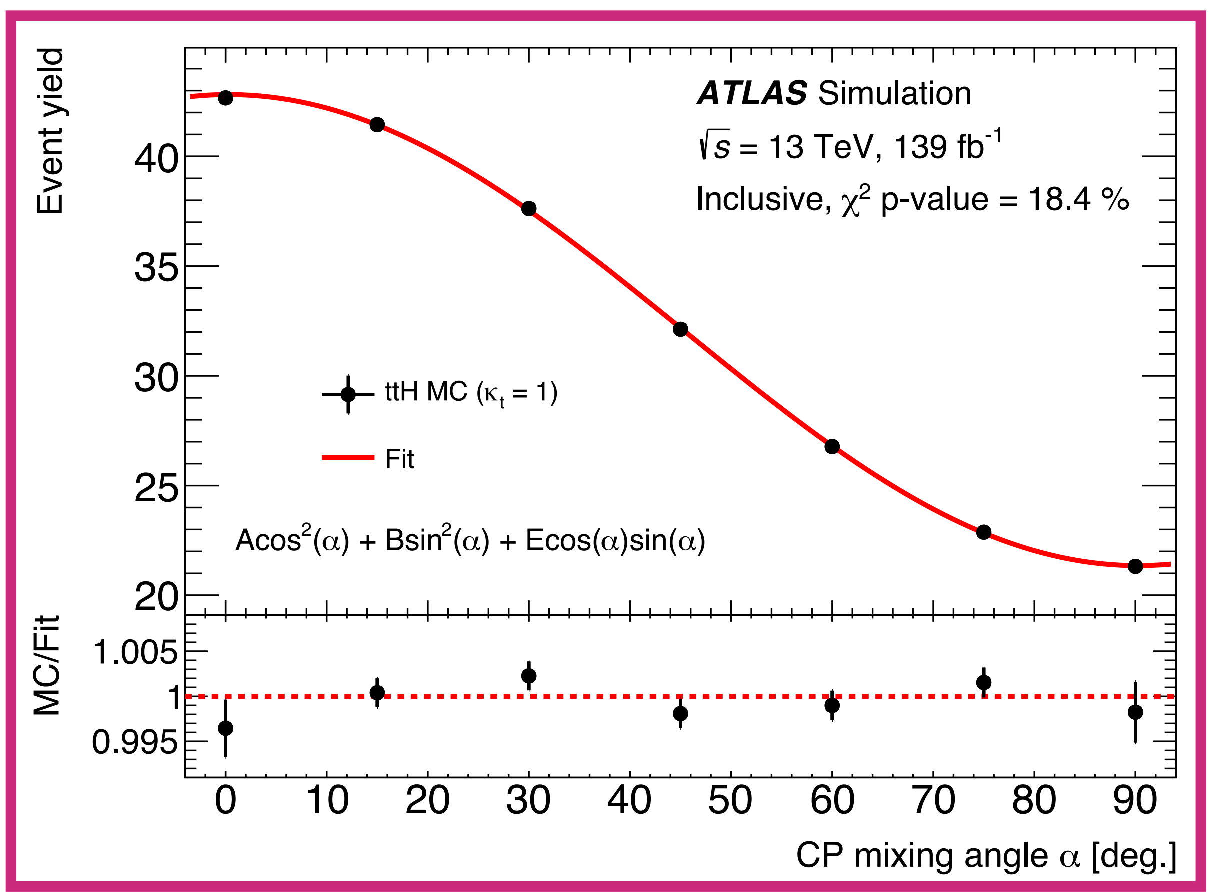


Phys. Rev. Lett. 125 (2020) 061802

Results

- Simultaneous fit in all categories
- ttH and tH yields parameterized in terms of α and κ_t

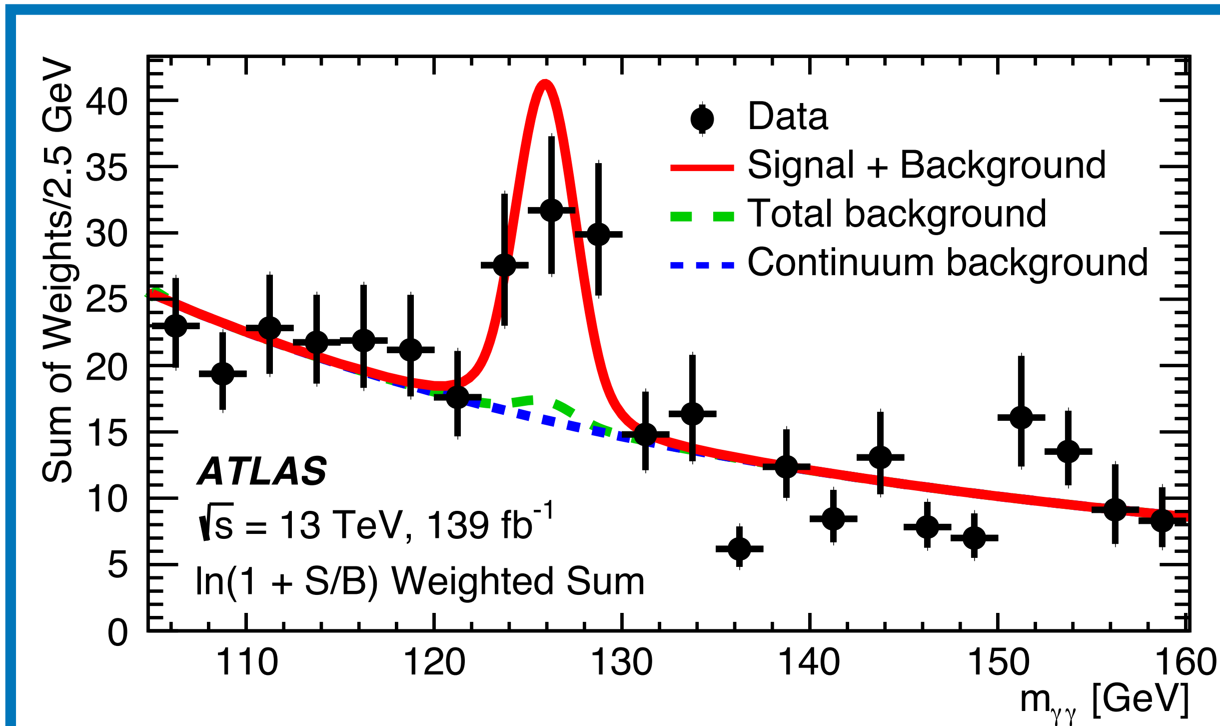


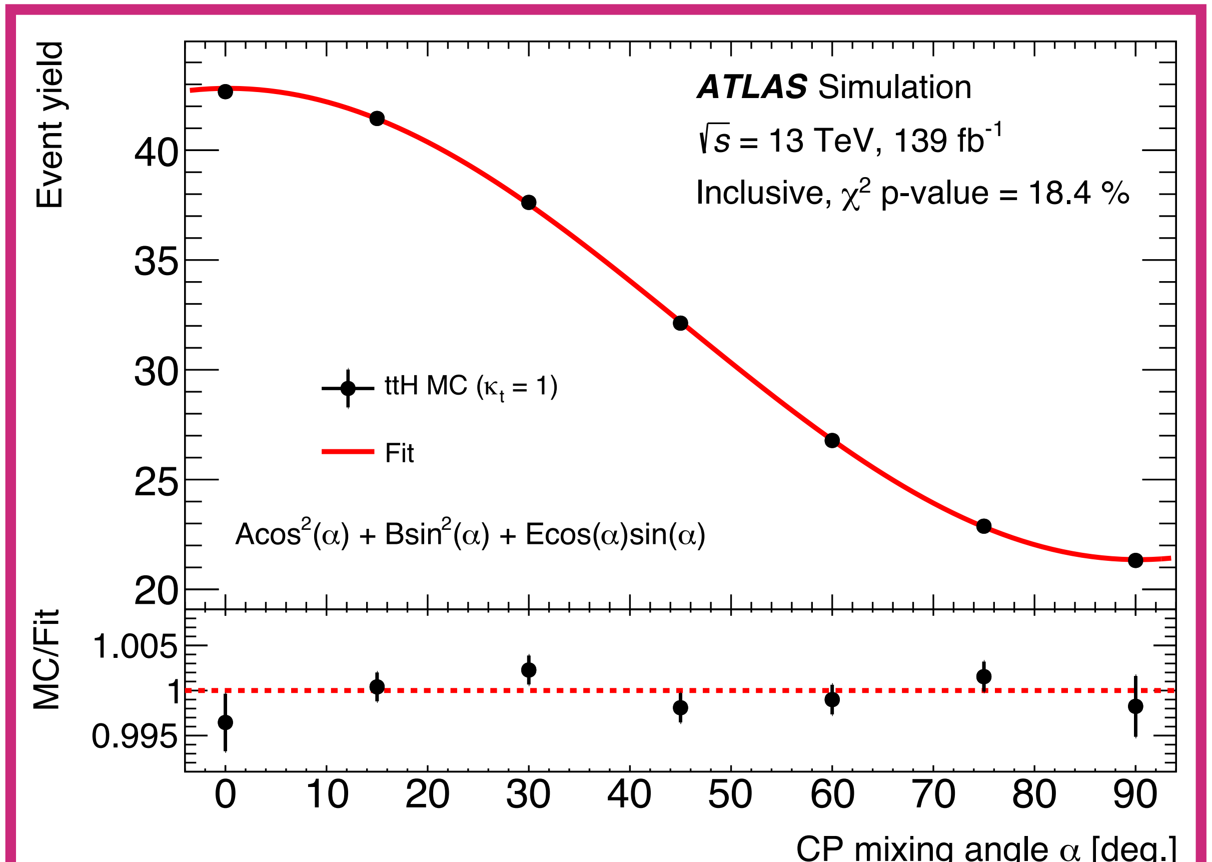


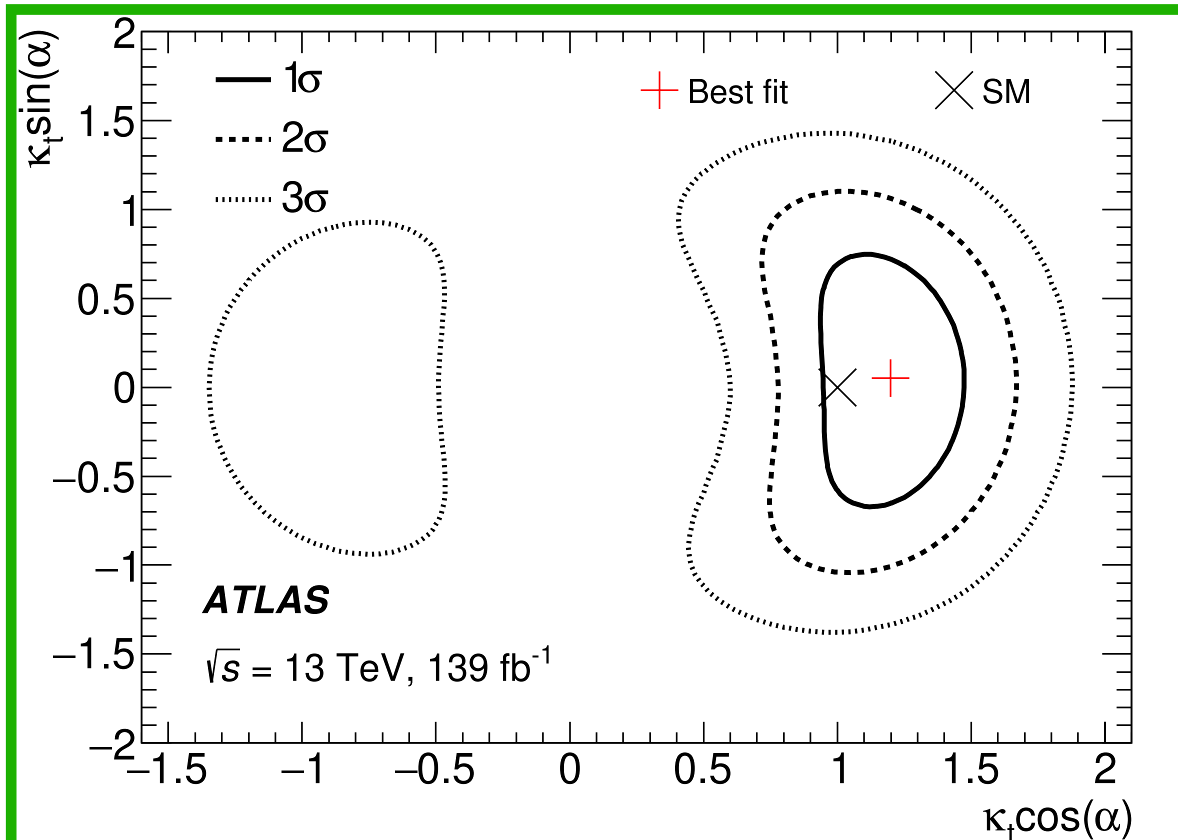
Phys. Rev. Lett. 125 (2020) 061802

Results

- Simultaneous fit in all categories
- ttH and tH yields parameterized in terms of α and κ_t
- ggF and H→γγ coupling modifiers constrained by other analyses
- 2d fit of $\kappa_t\sin(\alpha)$ vs. $\kappa_t\cos(\alpha)$

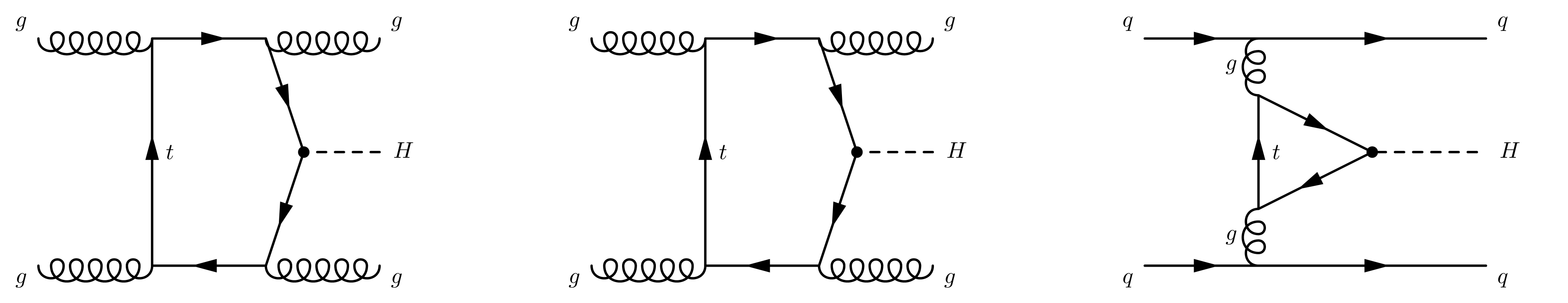






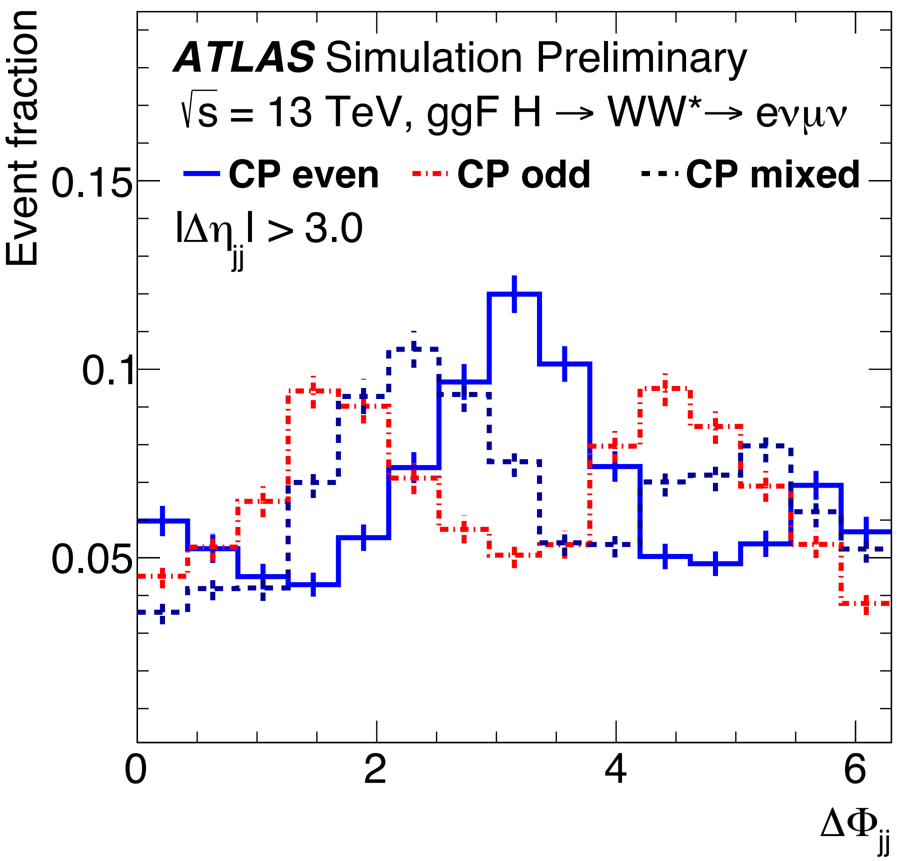
$|\alpha|$>43° excluded at 95% CL

CP in the ggH Vertex



$$\mathcal{L}_0^{\text{loop}} = -\frac{1}{4}\left(\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \kappa_{Agg} g_{Hgg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right) H$$

- In $m_{top} \rightarrow \infty$ limit, effective ggH vertex inherits the CP structure of the Higgs-top interaction
- Look for CP violation in ggH+2jet production
  - $\Delta\phi_{jj}$ distribution is highly sensitive
  - This analysis uses $H \rightarrow WW^* \rightarrow l\nu l\nu$ decay channel
    - ✦ Relatively large BR
    - ✦ See talk of Y. Lu for more details



$\kappa_{Hgg}=1$, $\kappa_{Agg}=0$ (SM)

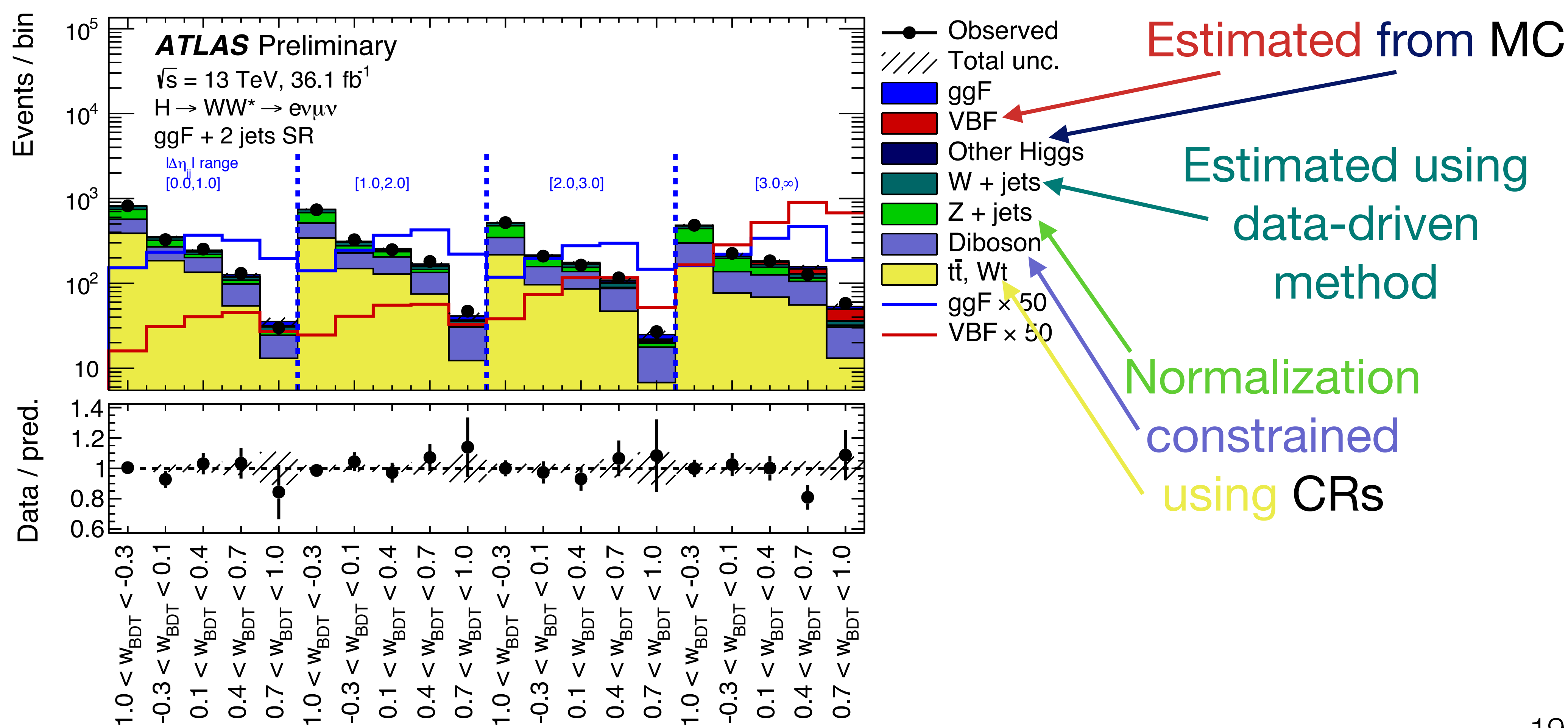
$\kappa_{Hgg}=1$, $\kappa_{Agg}=0$

$\kappa_{Hgg}=\kappa_{Agg}=1/\sqrt{2}$

Analysis

- Train a BDT to distinguish between ggF+2j signal and top, diboson, and $Z(\tau\tau)$+jets backgrounds
  - Input observables and BDT discriminant show no CP dependence
  - Define categories based on $\Delta\eta_{jj}$ and BDT to maximize sensitivity
    - ✦ CP discrimination increases with $\Delta\eta_{jj}$

ATLAS-CONF-2020-055

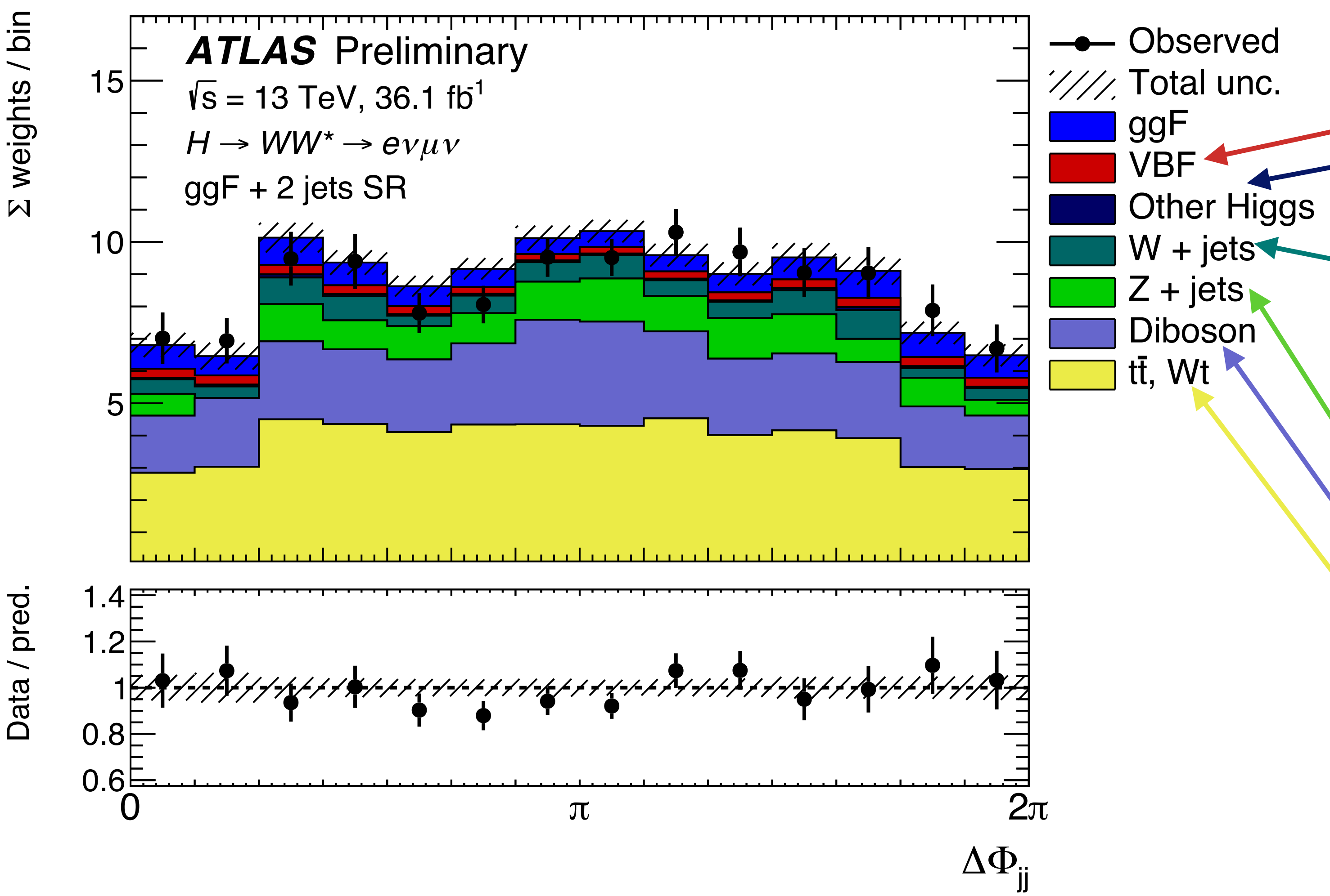


Analysis

- Train a BDT to distinguish between ggF+2j signal and top, diboson, and Z($\tau\tau$)+jets backgrounds
  - Input observables and BDT discriminant show no CP dependence
  - Define categories based on $\Delta\eta_{jj}$ and BDT to maximize sensitivity

ATLAS-CONF-2020-055

Weighted by ln(1+N_S/N_B) for each category



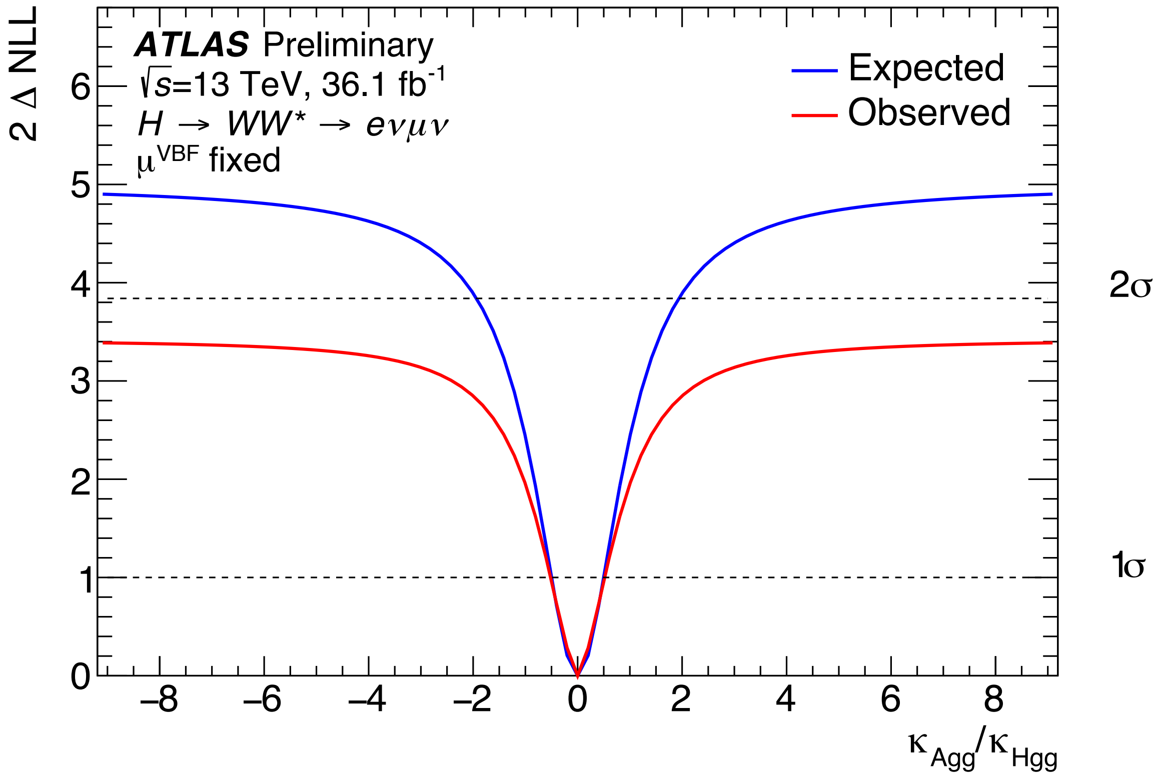
Estimated from MC

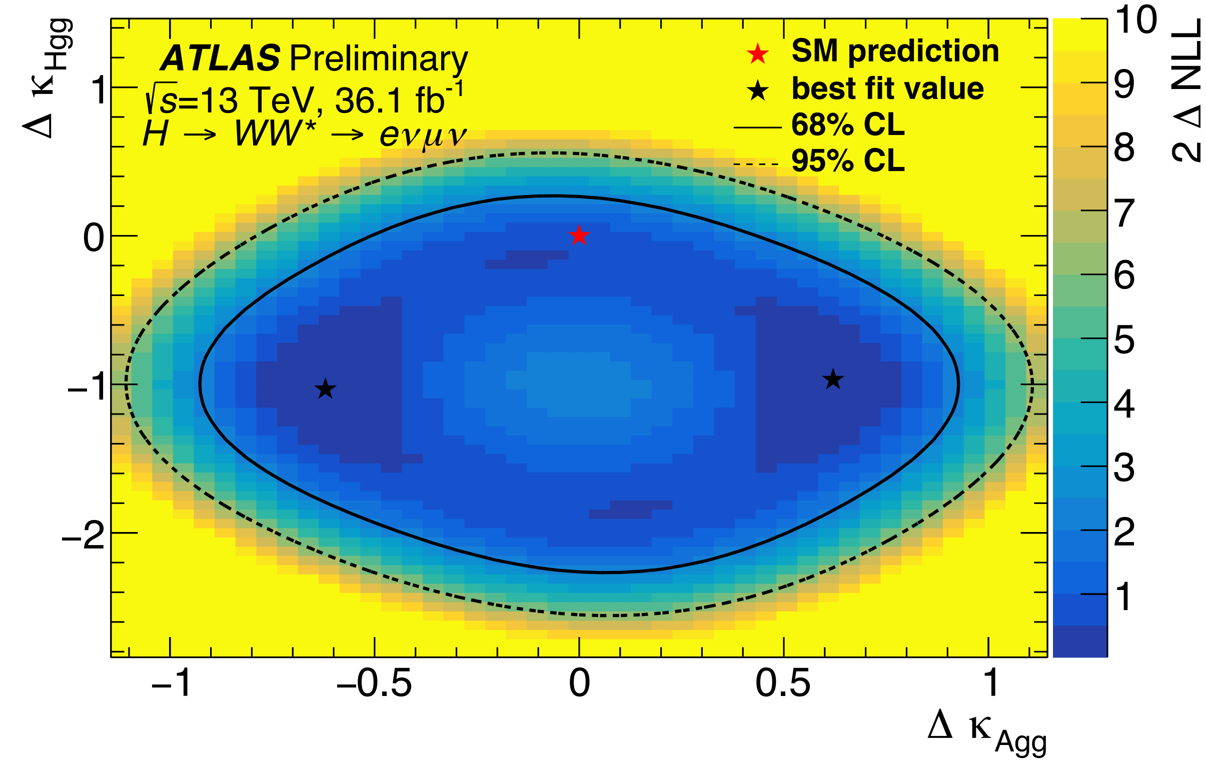
Estimated using data-driven method

Normalization constrained using CRs

Results

ATLAS-CONF-2020-055





- Parameter morphing used to interpolate between α values
- Perform fits using shape and rate, or only shape information
  - Rate could be affected by other BSM effects
  - Shape-only not sensitive with this dataset
  - Use both for simultaneous scan of CP-even and CP-odd parameters
- Shape and rate gives a best-fit value of:
  - **tan(α)=0±0.4(stat)±0.4(syst)**

Conclusion

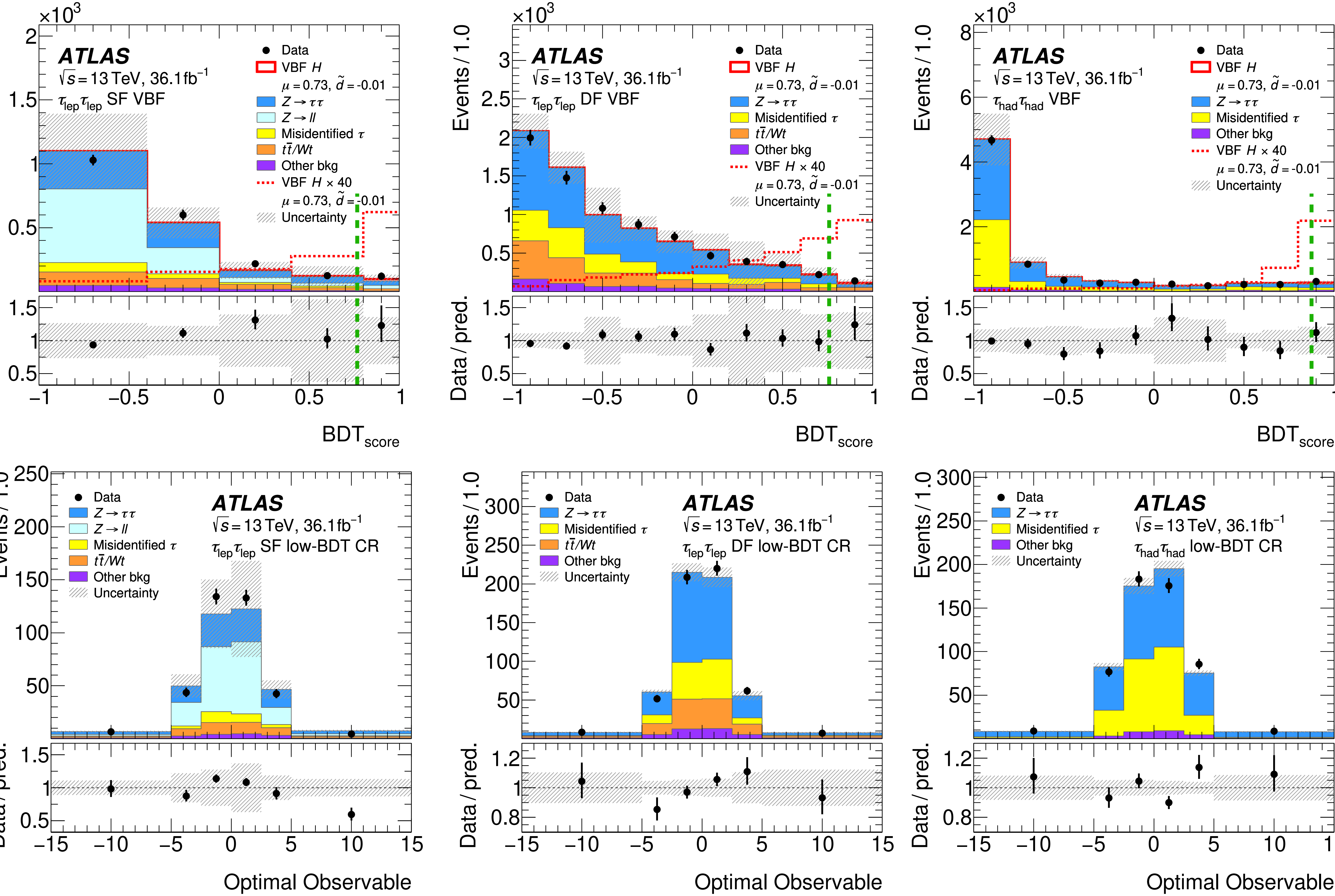
- Higgs couplings provide a potentially fruitful area of search for BSM CP-violating physics
    - With EFT's as the essential theoretical model
- Higgs couplings to V and top studied with different techniques
- No sign of CP violation yet
    - All results statistically dominated
    - Not all yet using the full Run-2 dataset
- More results using additional channels and approaches are coming, stay tuned!

Backup

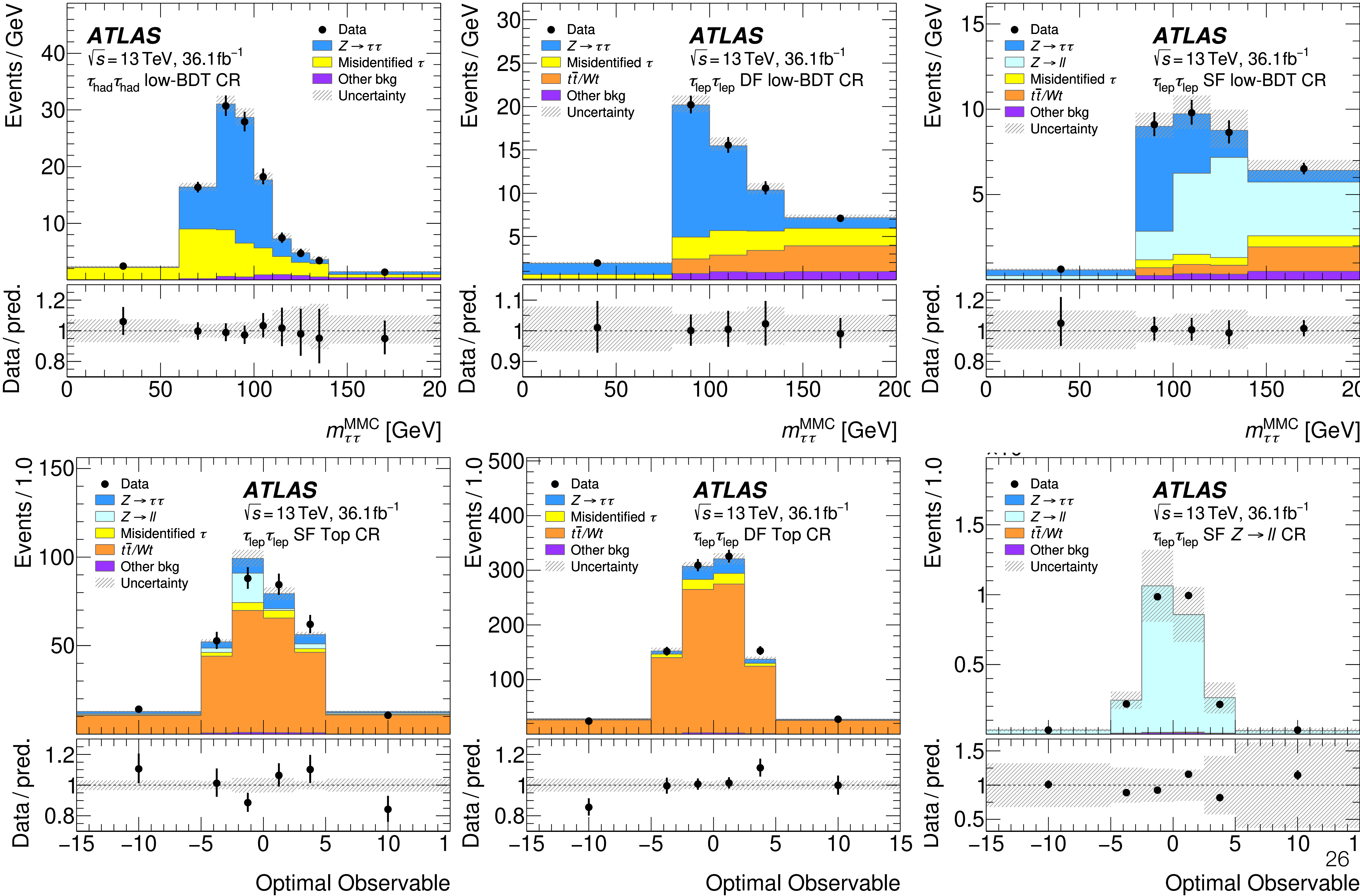
VBF H→$\tau\tau$ Event Selection

<table>
<tr><th>Channel</th><th>$\tau_{\text{lep}}\tau_{\text{lep}}$ SF</th><th>$\tau_{\text{lep}}\tau_{\text{lep}}$ DF</th><th>$\tau_{\text{lep}}\tau_{\text{had}}$</th><th>$\tau_{\text{had}}\tau_{\text{had}}$</th></tr>
<tr><td rowspan="7">Preselection</td><td colspan="4">Two isolated τ-lepton decay candidates with opposite electric charge</td></tr>
<tr><td>$p_{\text{T}}^{\tau_1} > 19^*/15^*$ GeV (μ/e)
$p_{\text{T}}^{\tau_2} > 10/15^*$ GeV (μ/e)</td><td>$p_{\text{T}}^{e} > 18$ GeV
$p_{\text{T}}^{\mu} > 14$ GeV</td><td>$p_{\text{T}}^{\tau_{\text{had}}} > 30$ GeV
$p_{\text{T}}^{\tau_{\text{lep}}} > 21^*$ GeV</td><td>$p_{\text{T}}^{\tau_1} > 40$ GeV
$p_{\text{T}}^{\tau_2} > 30$ GeV</td></tr>
<tr><td colspan="2">$m_{\tau\tau}^{\text{coll}} > m_Z - 25$ GeV</td><td>$m_{\text{T}} < 70$ GeV</td><td>$0.8 < \Delta R_{\tau\tau} < 2.5$</td></tr>
<tr><td>$30 < m_{\ell\ell} < 75$ GeV</td><td>$30 < m_{\ell\ell} < 100$ GeV</td><td></td><td>$|\Delta\eta_{\tau\tau}| < 1.5$</td></tr>
<tr><td>$E_{\text{T}}^{\text{miss}} > 55$ GeV</td><td>$E_{\text{T}}^{\text{miss}} > 20$ GeV</td><td></td><td>$E_{\text{T}}^{\text{miss}} > 20$ GeV</td></tr>
<tr><td>$E_{\text{T}}^{\text{miss, hard}} > 55$ GeV</td><td></td><td></td><td></td></tr>
<tr><td colspan="3">$N_{b\text{-jets}} = 0$</td><td></td></tr>
<tr><td rowspan="2">VBF topology</td><td colspan="4">$N_{\text{jets}} \geq 2$, $p_{\text{T}}^{j_2} > 30$ GeV, $m_{jj} > 300$ GeV, $|\Delta\eta_{jj}| > 3$</td></tr>
<tr><td colspan="3">$p_{\text{T}}^{j_1} > 40$ GeV</td><td>$p_{\text{T}}^{j_1} > 70$ GeV, $|\eta_{j_1}| < 3.2$</td></tr>
<tr><td rowspan="3">BDT input variables</td><td colspan="4">$m_{\tau\tau}^{\text{MMC}}$, m_{jj}, $\Delta R_{\tau\tau}$, $C_{jj}(\tau_1)$, $C_{jj}(\tau_2)$, $p_{\text{T}}^{\text{tot}}$</td></tr>
<tr><td colspan="2">$m_{\tau\tau}^{\text{vis}}$, $m_{\text{T}}^{\tau_1, E_{\text{T}}^{\text{miss}}}$, $p_{\text{T}}^{j_3}$</td><td colspan="2">$C(\phi^{\text{miss}})/\sqrt{2}$</td></tr>
<tr><td>$\Delta\phi_{\tau\tau}$</td><td>$E_{\text{T}}^{\text{miss}}/p_{\text{T}}^{\tau_1}$, $E_{\text{T}}^{\text{miss}}/p_{\text{T}}^{\tau_2}$</td><td>$m_{\tau\tau}^{\text{vis}}$, $|\Delta\eta_{\tau\tau}|$</td><td>$p_{\text{T}}^{\tau\tau E_{\text{T}}^{\text{miss}}}$, $|\Delta\eta_{\tau\tau}|$</td></tr>
<tr><td>Signal region</td><td colspan="2">$\text{BDT}_{\text{score}} > 0.78$</td><td>$\text{BDT}_{\text{score}} > 0.86$</td><td>$\text{BDT}_{\text{score}} > 0.87$</td></tr>
</table>

VBF H→ττ CRs

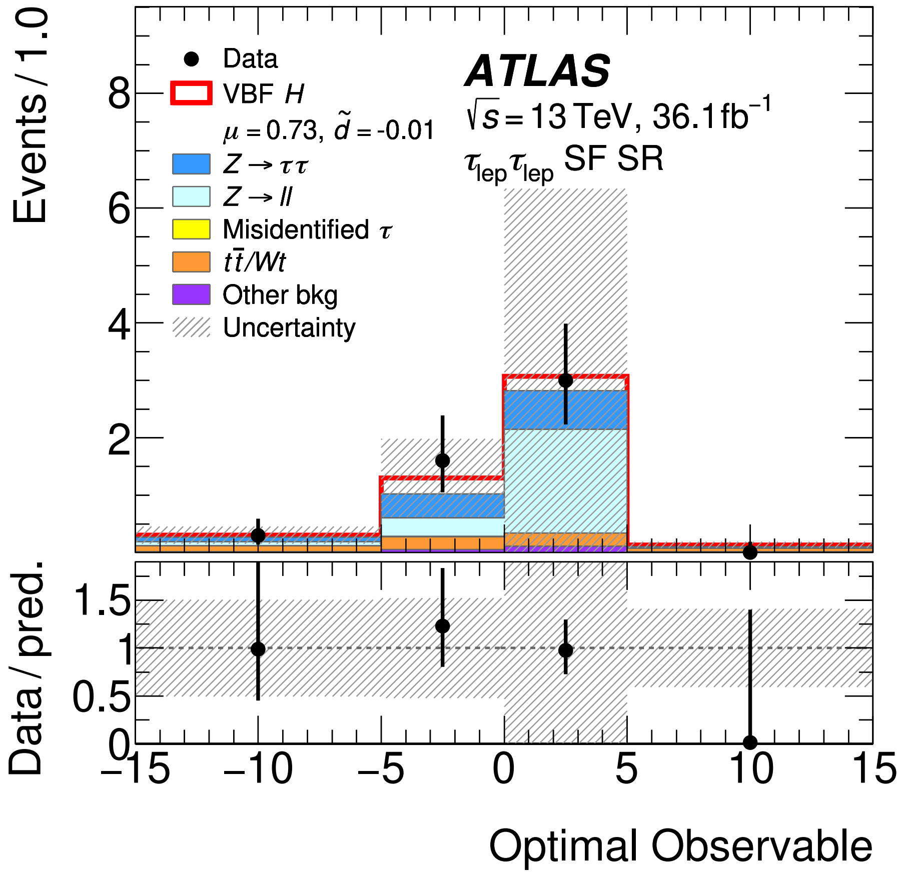

ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
$\tau_{lep}\tau_{lep}$ SF VBF
$\tau_{lep}\tau_{lep}$ DF VBF
$\tau_{had}\tau_{had}$ VBF
$\tau_{lep}\tau_{lep}$ SF low-BDT CR
$\tau_{lep}\tau_{lep}$ DF low-BDT CR
$\tau_{had}\tau_{had}$ low-BDT CR
Data
VBF H
μ = 0.73, $\tilde{d}$ = -0.01
$Z \rightarrow \tau\tau$
$Z \rightarrow ll$
Misidentified τ
$t\bar{t}/Wt$
Other bkg
VBF H × 40
Uncertainty
Events / 1.0
Data / pred.
BDT$_{score}$
Optimal Observable

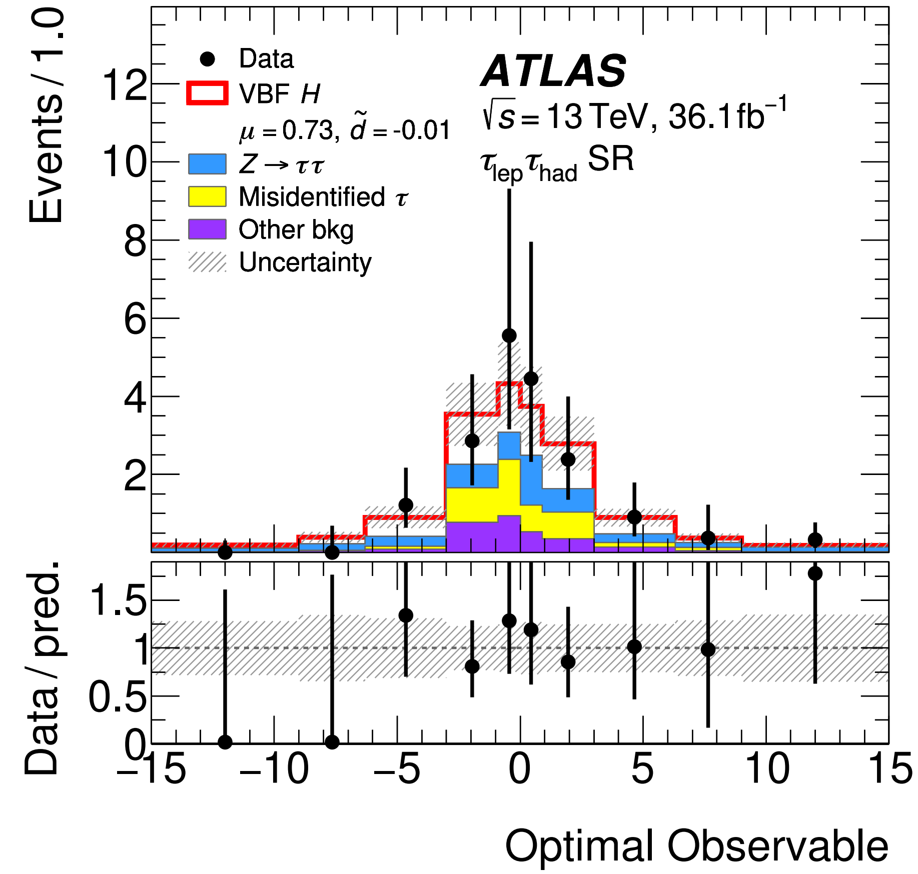
VBF H→ττ CRs

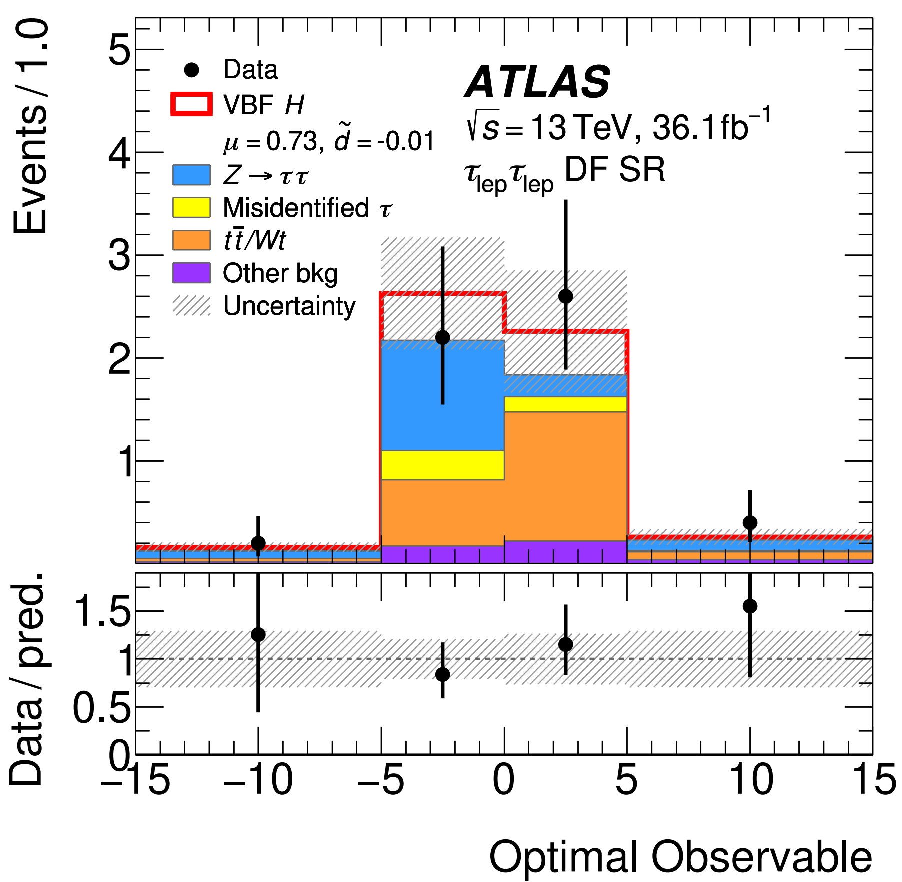


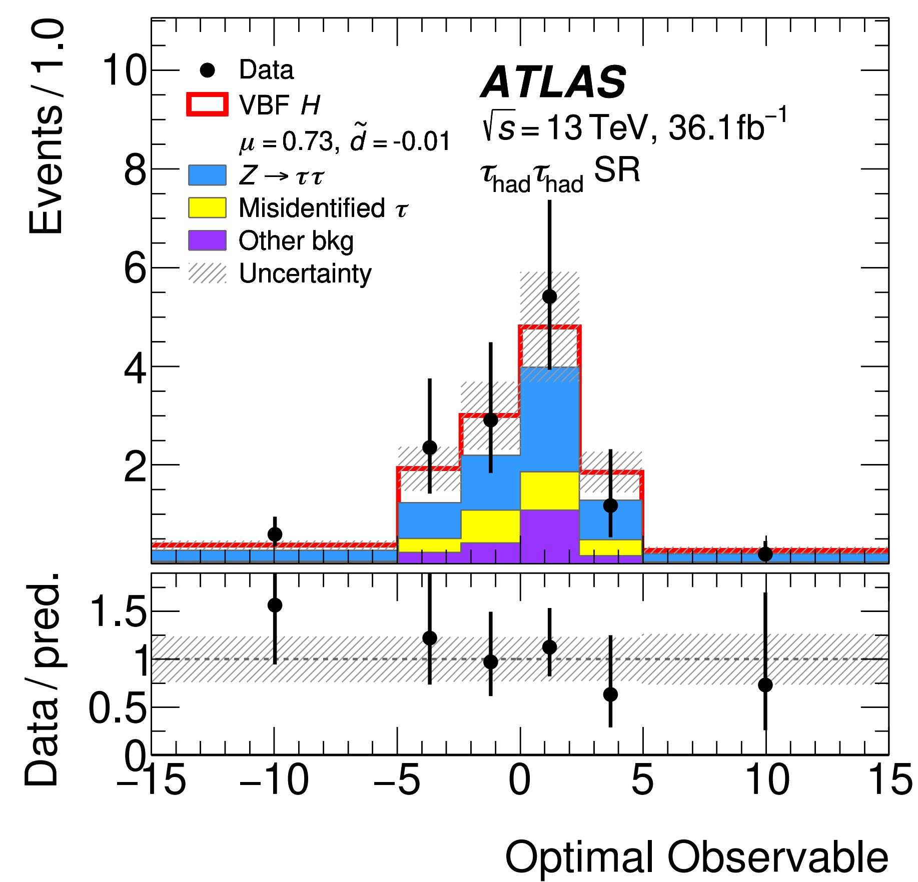
ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
$\tau_{had}\tau_{had}$ low-BDT CR
$\tau_{lep}\tau_{lep}$ DF low-BDT CR
$\tau_{lep}\tau_{lep}$ SF low-BDT CR
$\tau_{lep}\tau_{lep}$ SF Top CR
$\tau_{lep}\tau_{lep}$ DF Top CR
$\tau_{lep}\tau_{lep}$ SF $Z\to ll$ CR
Data
$Z\to\tau\tau$
$Z\to ll$
Misidentified τ
$t\bar{t}/Wt$
Other bkg
Uncertainty
Events / GeV
Events / 1.0
Data / pred.
$m_{\tau\tau}^{MMC}$ [GeV]
Optimal Observable

VBF H→ττ SRs

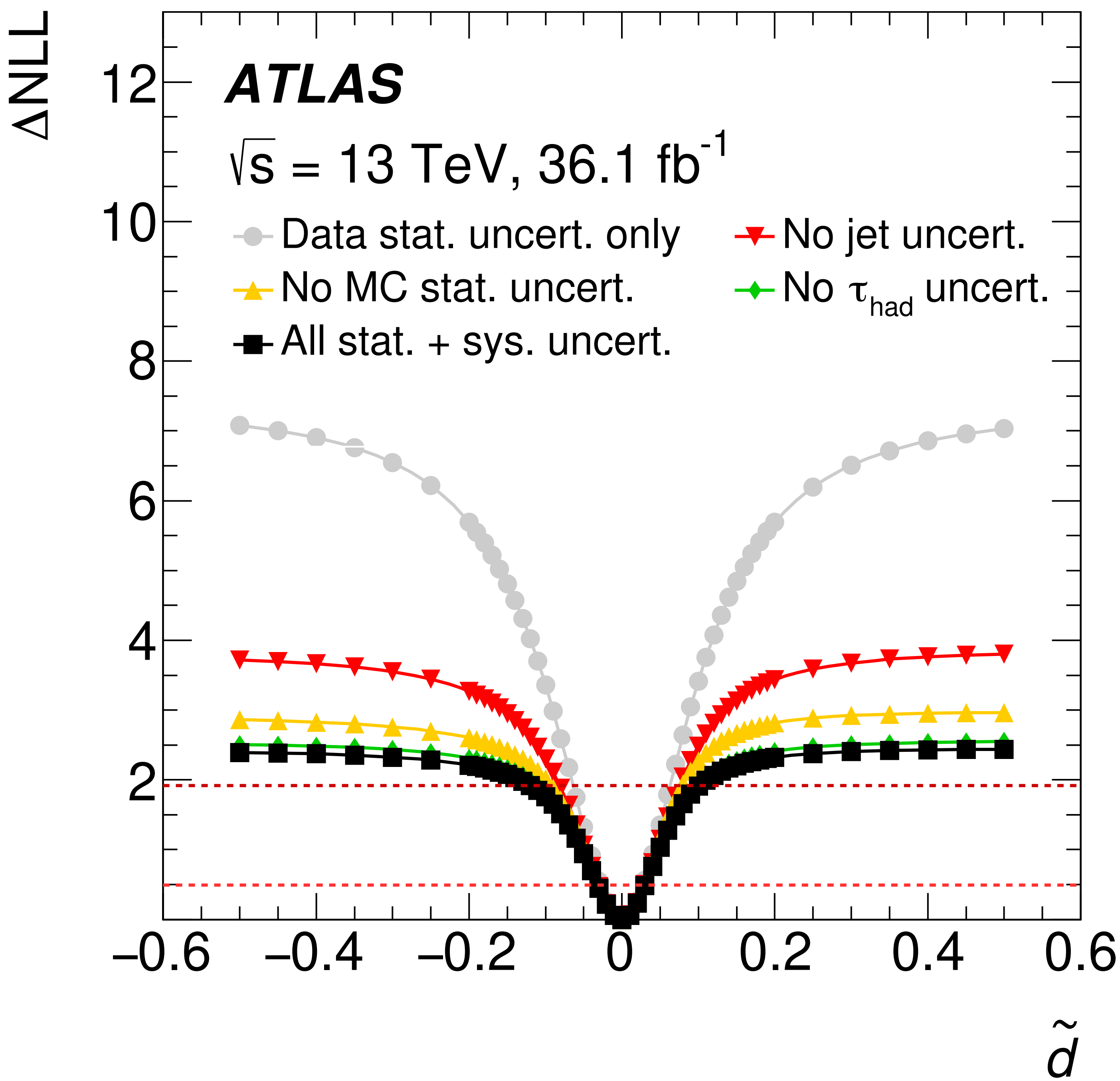

Data
VBF H
μ = 0.73, d̃ = -0.01
Z → ττ
Z → ll
Misidentified τ
tt̄/Wt
Other bkg
Uncertainty
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
τlep τlep SF SR
Events / 1.0
Data / pred.
Optimal Observable


Data
VBF H
μ = 0.73, d̃ = -0.01
Z → ττ
Misidentified τ
Other bkg
Uncertainty
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
τlep τhad SR
Events / 1.0
Data / pred.
Optimal Observable

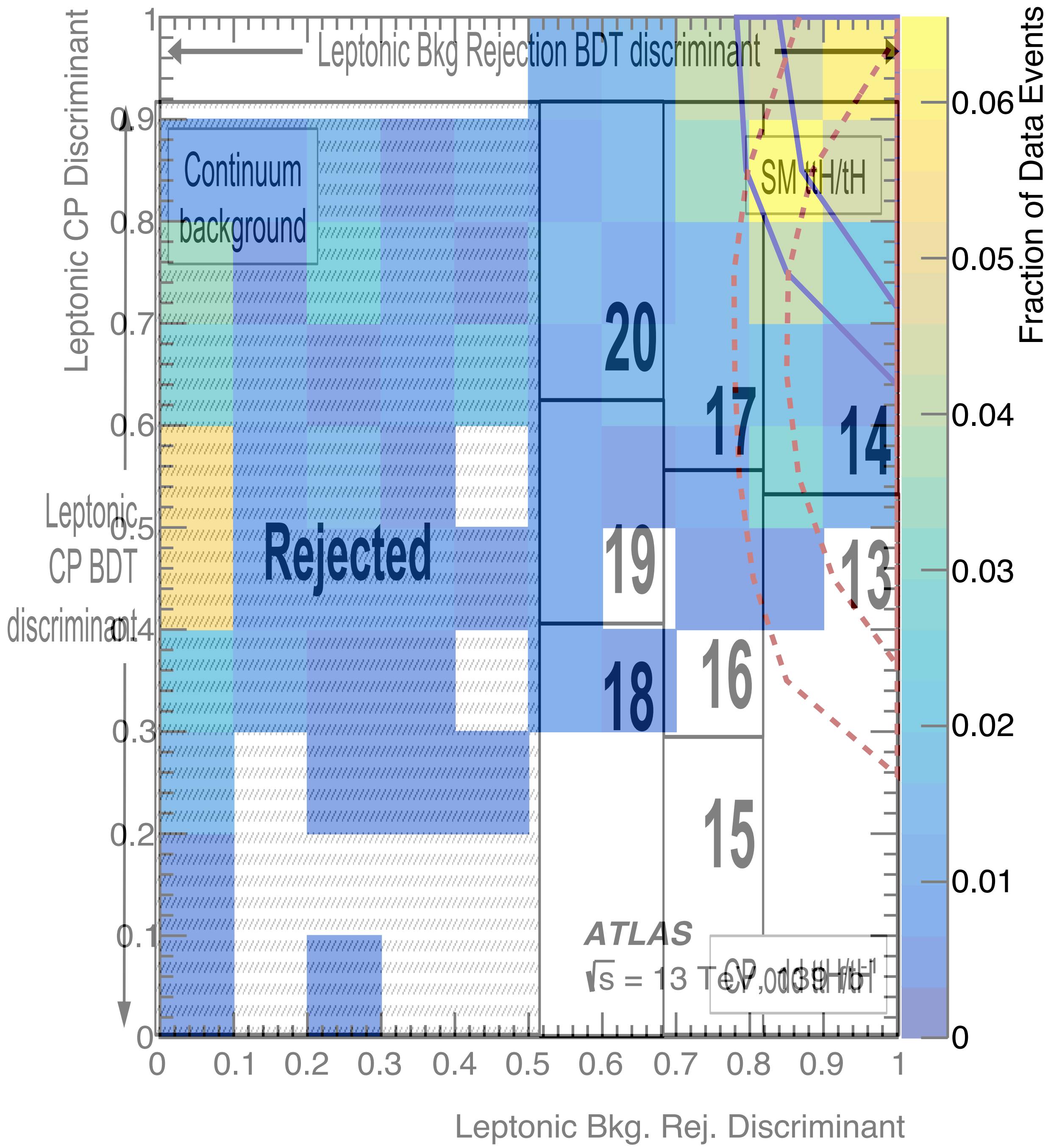

Data
VBF H
μ = 0.73, d̃ = -0.01
Z → ττ
Misidentified τ
tt̄/Wt
Other bkg
Uncertainty
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
τlep τlep DF SR
Events / 1.0
Data / pred.
Optimal Observable

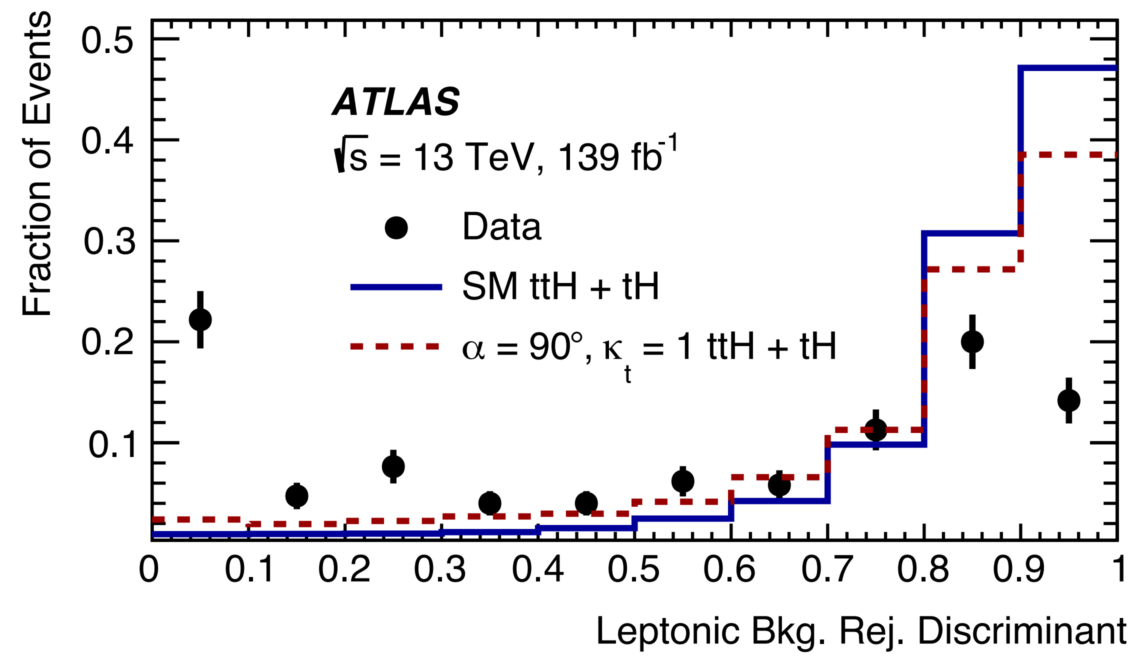

Data
VBF H
μ = 0.73, d̃ = -0.01
Z → ττ
Misidentified τ
Other bkg
Uncertainty
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
τhad τhad SR
Events / 1.0
Data / pred.
Optimal Observable

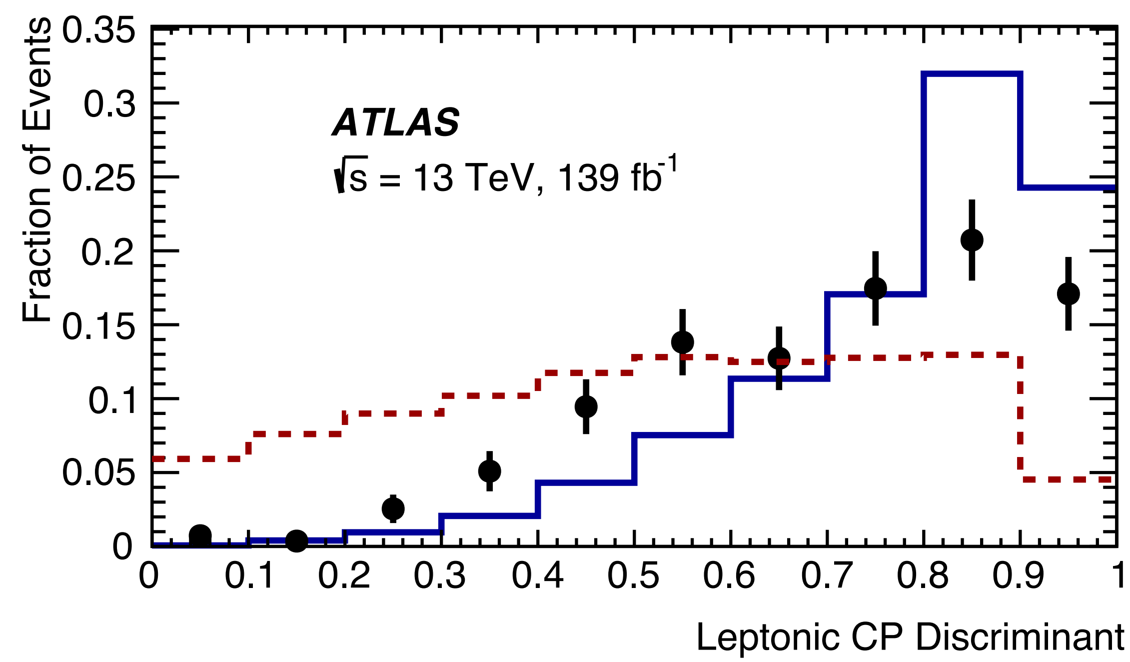
VBF H→$\tau\tau$ Systematics



ttH Leptonic Channel

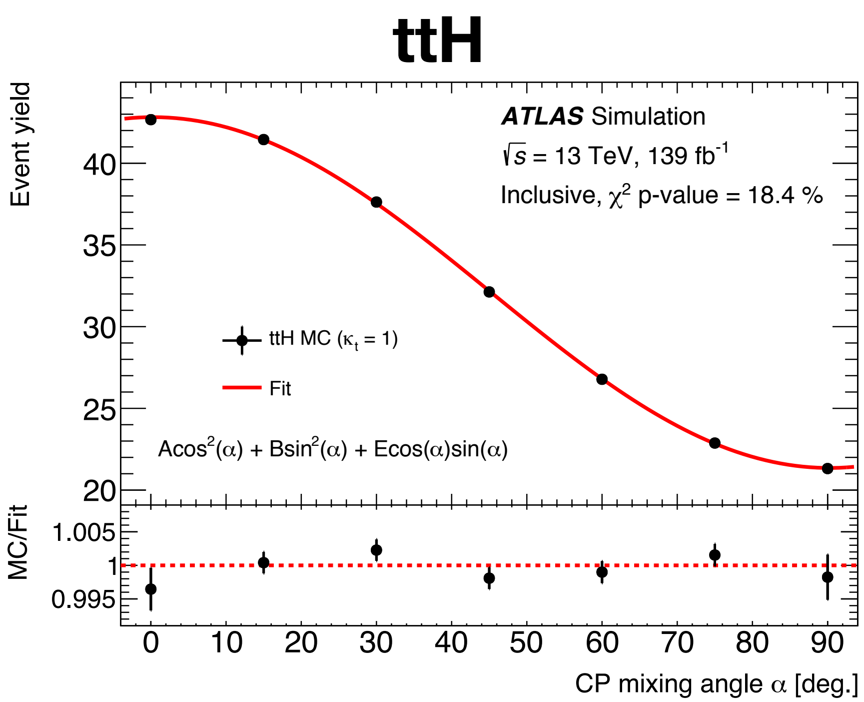




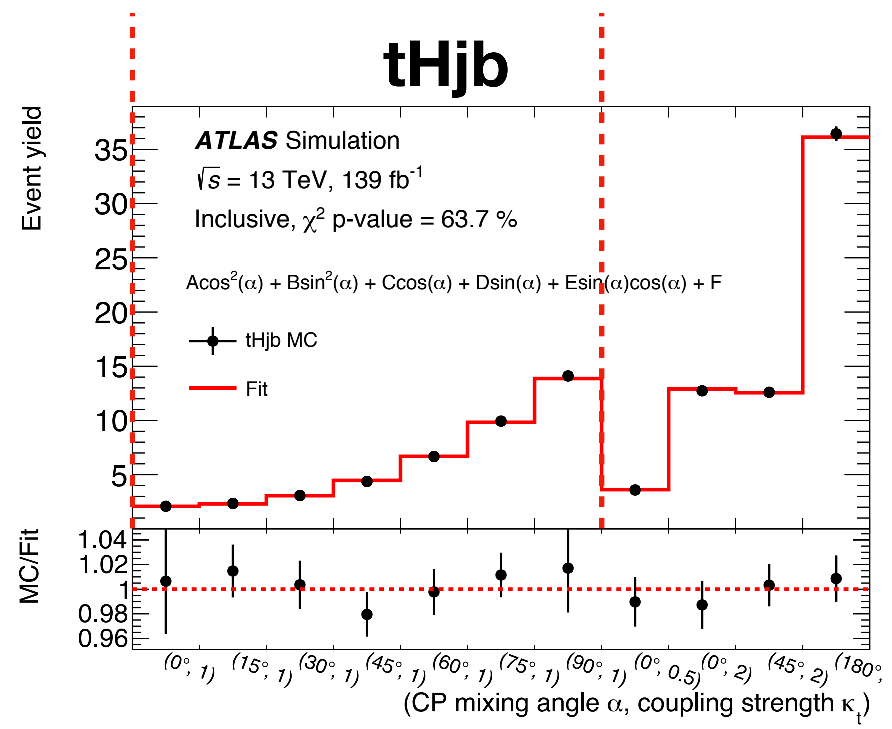


ttH Signal Parameterizations

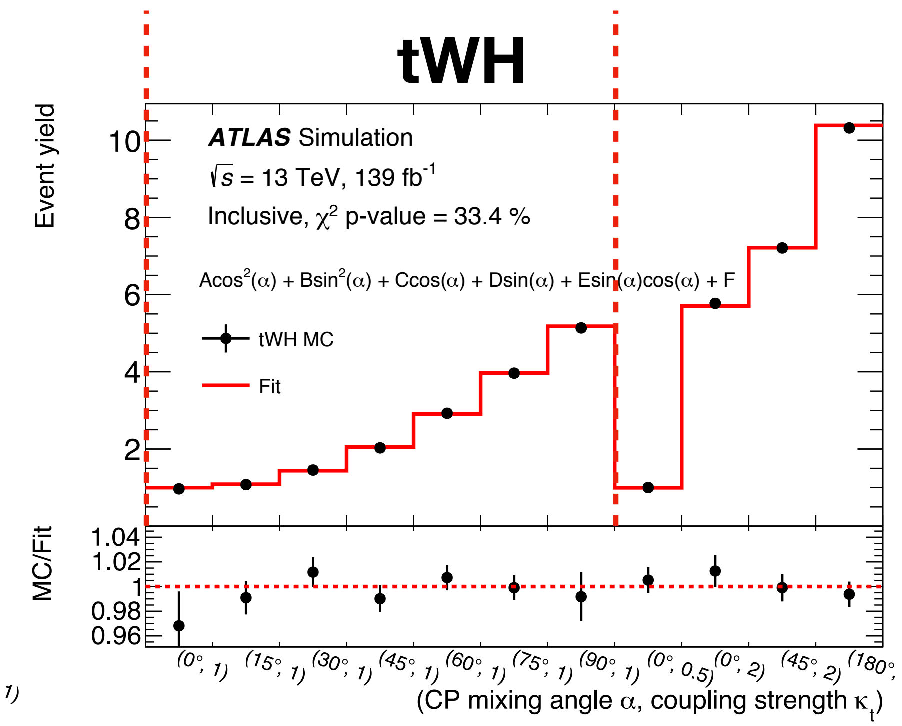
κ_t=1



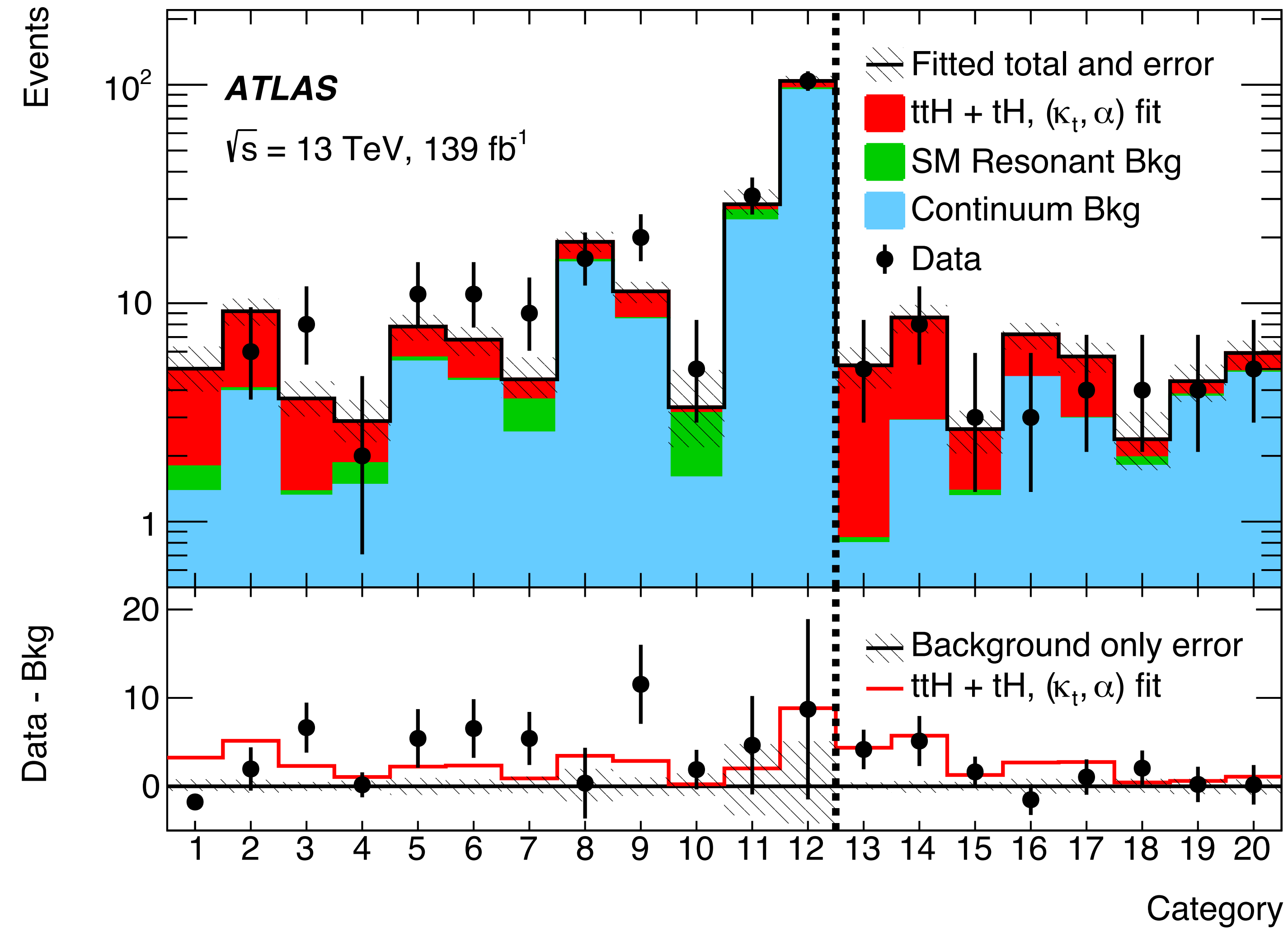
κ_t=1

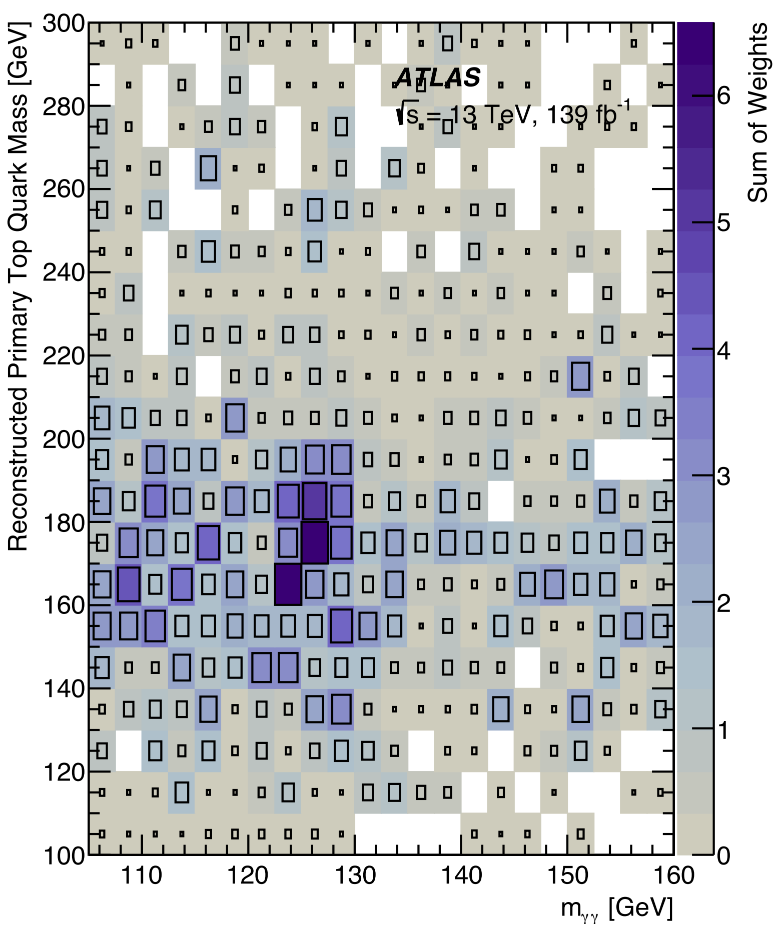


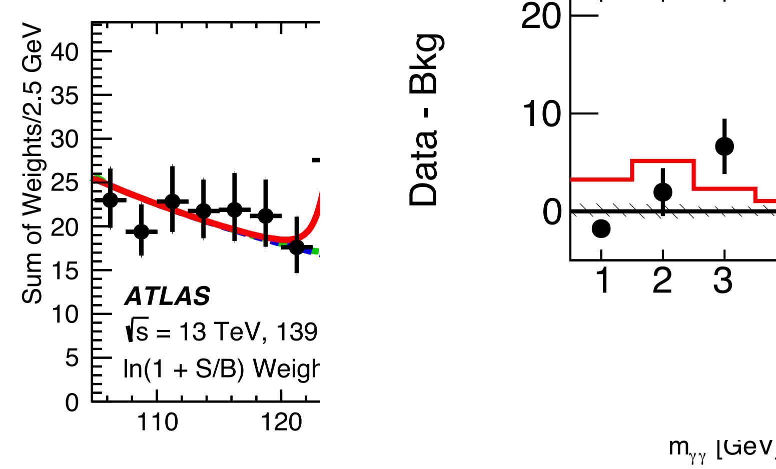
κ_t=1

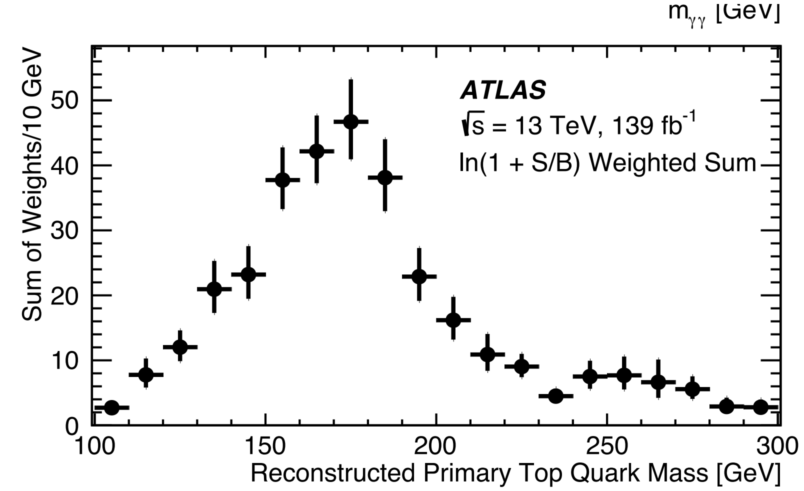


ttH Fit Results









ggF+2j HWW Systematics

Source	$\Delta\left(\kappa_{Agg}/\kappa_{Hgg}\right)$
Total data statistical uncertainty	0.4
SR statistical uncertainty	0.33
CR statistical uncertainty	0.10
MC statistical uncertainty	0.14
Total systematic uncertainty	0.28
Theoretical uncertainty	0.23
Top quark bkg.	0.15
ggF signal	0.14
WZ, ZZ, $W\gamma$, $Z\gamma$ bkg.	0.06
WW bkg.	0.06
Z/γ^* bkg.	0.016
VBF bkg.	0.015
Experimental uncertainty	0.21
b-tagging	0.16
Modelling of pile-up	0.10
Jets	0.07
Misidentified leptons	0.04
Luminosity	0.034
Total	0.5

ggF+2j HWW Shape-Only Scan