BSM perspectives in four-top final states at the LHC

Panagiotis Stylianou

based on work with Anisha, O. Atkinson, A. Bhardwaj, C. Englert and W. Naskar (2302.08281)

FH discussion
10 July 2023

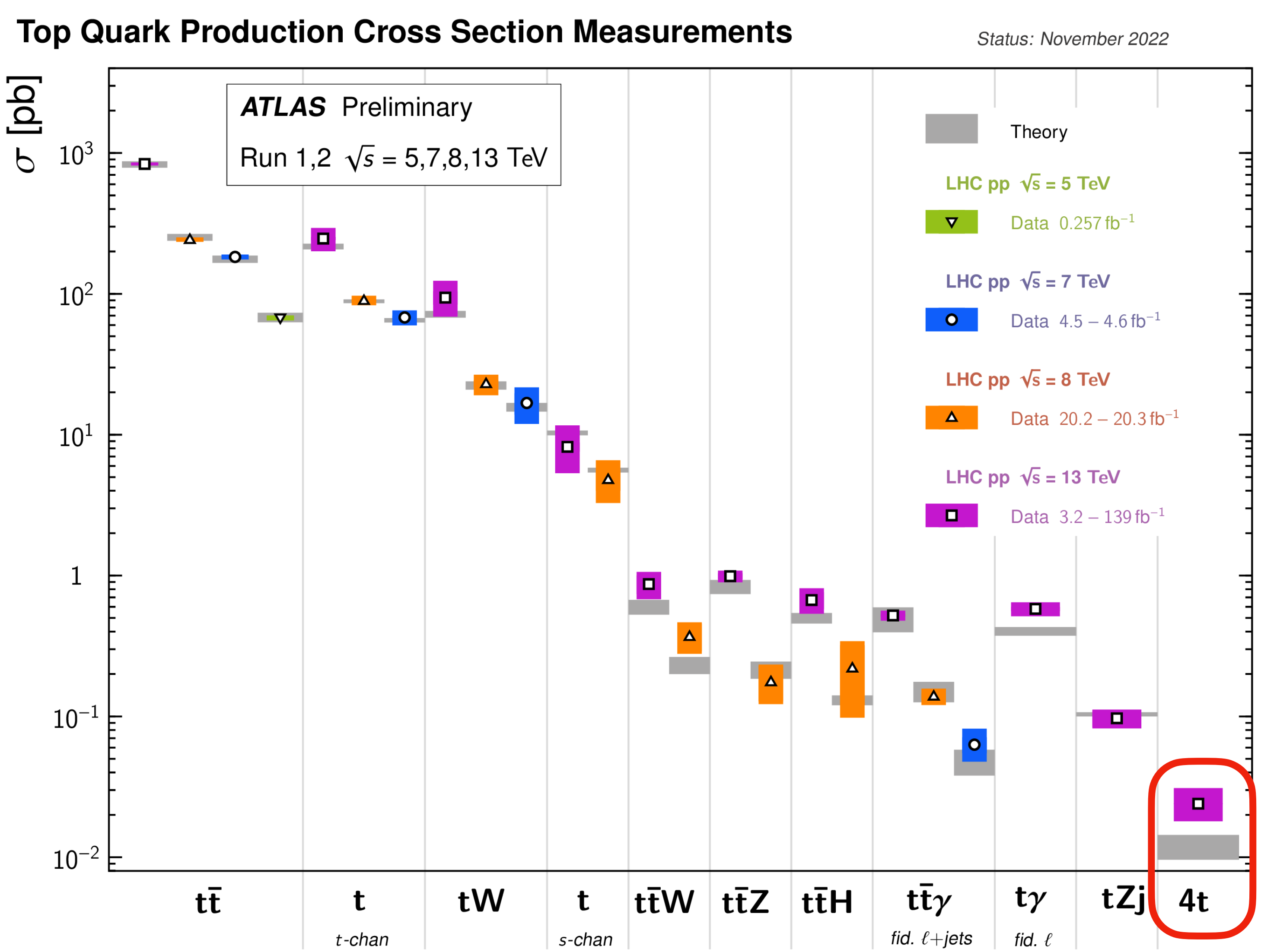
Outline

No BSM signal discovered at LHC

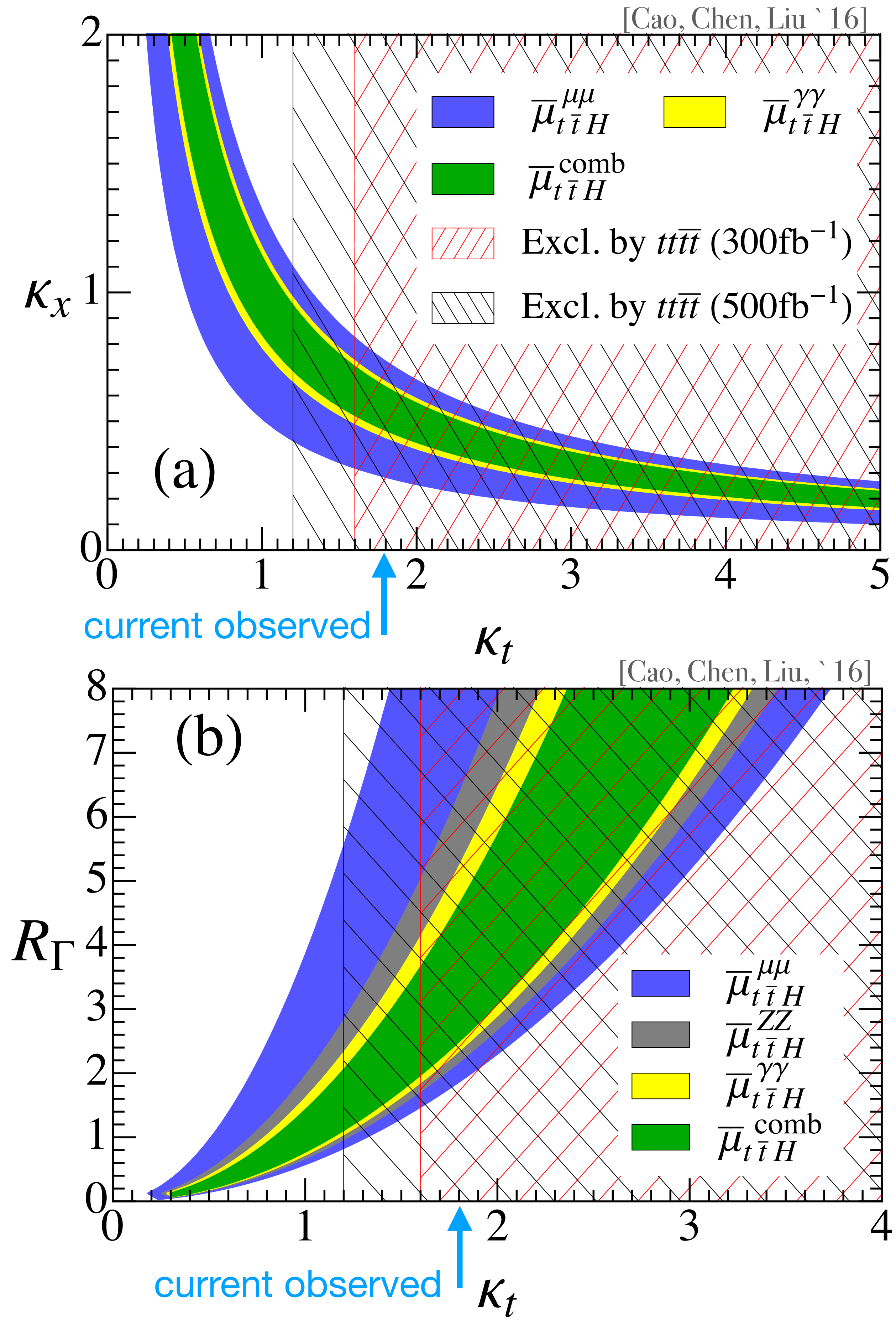
- Turn to less abundant processes for new-physics searches
- Efficient exploitation of correlations in data required
- Model-independent techniques

Content:

- Focus on 4-top production
  →GNN analysis
- BSM resonances in 4-top
  →2HDM example
- Non-resonant searches
  →Higgs-philic ALP



4-top at the LHC



$t\bar{t}t\bar{t}$ production

- Rare process, but recently observed by ATLAS, CMS [ATLAS 2303.15061] [CMS 2305.13439]
- SM cross section at NLL accuracy [Beekveld, Kulesza, Valero ` 22]
- Access to Yukawa coupling y_t
- Independent of Higgs width
- Combine with $t\bar{t}H$ for insights on other couplings / width [Cao, Chen, Liu ` 16]

Considered Processes for SM

- Two same-sign di-lepton (2SSDL) final state:

$$pp \to t\bar{t}t\bar{t} \to \ell^+\ell^+/\ell^-\ell^- + \text{jets} + \text{b-quarks}$$

- Three leptons (3L):

$$pp \to t\bar{t}t\bar{t} \to \ell\ell\ell + \text{jets} + \text{b-quarks}$$

Multiple final states with rich kinematics → Exploit correlations in data with Machine Learning

Pre-selection:

- $p_T(\ell) > 10$ GeV & $|\eta(\ell)| < 2.5$
- $p_T(b) > 20$ GeV & $|\eta(b)| < 2.5$
- $p_T(j) > 20$ GeV & $|\eta(j)| < 4.5$
- At least 20 GeV of missing energy

70% tagging efficiency

↓

nowadays pessimistic, but we neglect mis-tagging

Simulated SM Backgrounds

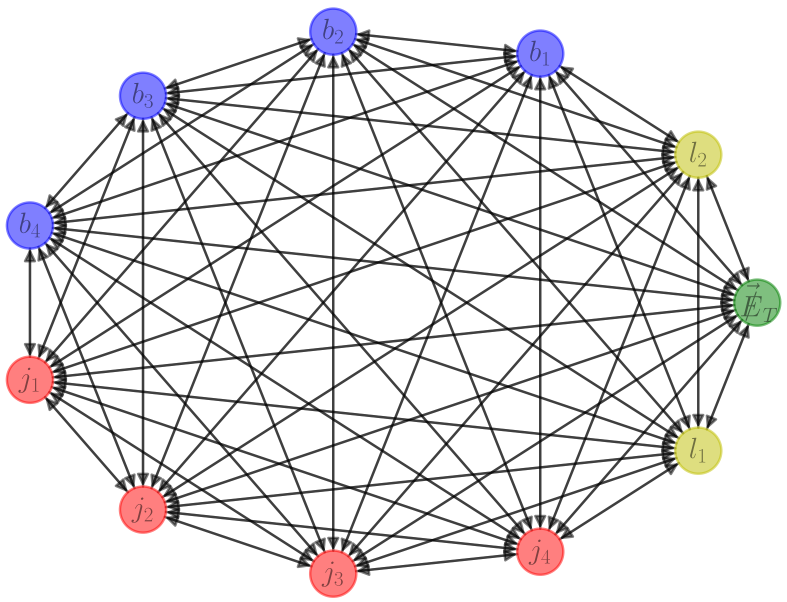
- 2SSDL backgrounds:

Processes	Cross Section (fb)
$pp \to t_{\ell^+}\bar{t}_h W^+_{\ell^+} + t_h \bar{t}_{l\_} W^-_{\ell^-}$	57.67±0.06
$pp \to t_{\ell^+}\bar{t}_h Z_{\ell^+\ell^-} + t_h \bar{t}_{\ell^-} Z_{\ell^+\ell^-} + t_{\ell^+}\bar{t}_{\ell^-} Z_{\ell^+\ell^-}$	10.65 ± 0.01
$pp \to (W^+_{\ell^+} W^-_h W^+_{\ell^+} + W^+_h W^-_{\ell^-} W^-_{\ell^-}) b\bar{b}$	43.29 ± 0.05
$pp \to (W^+_{\ell^+} W^-_h Z_{\ell^+\ell^-} + W^+_h W^-_{\ell^-} Z_{\ell^+\ell^-} + W^+_{\ell^+} W^-_{\ell^-} Z_{\ell^+\ell^-}) b\bar{b}$	12.65 ± 0.02

- 3L backgrounds:

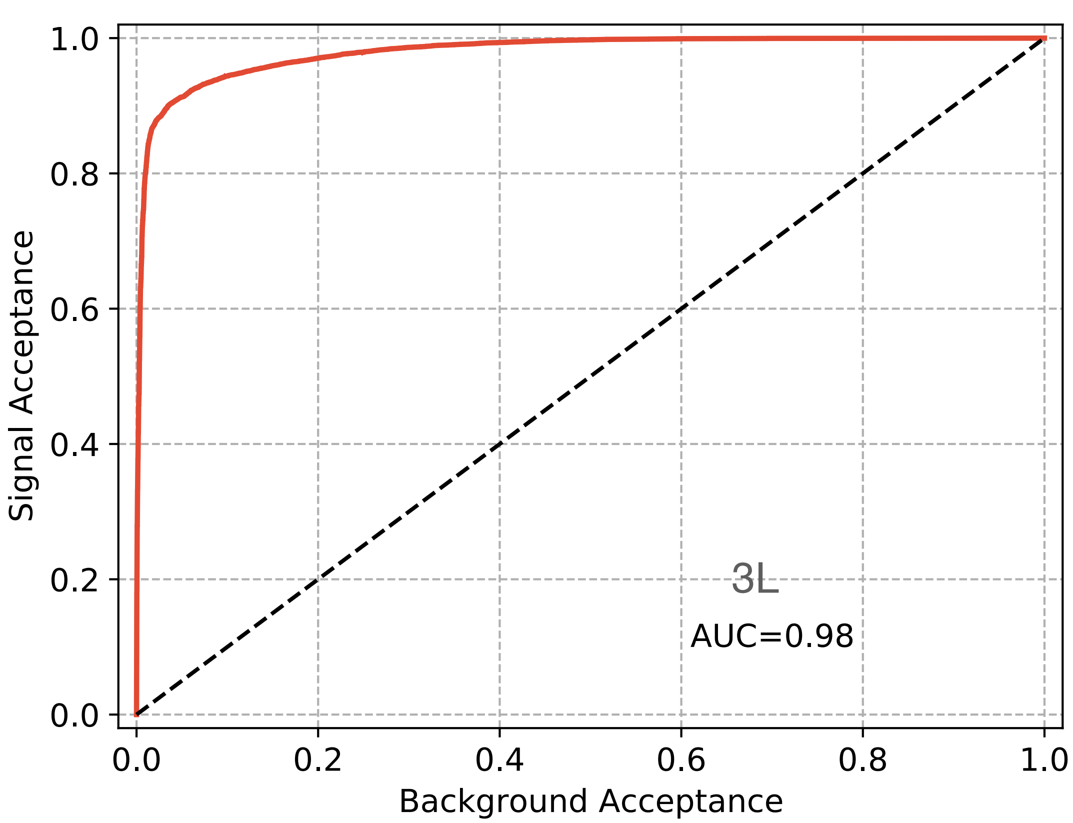
Processes	Cross Section (fb)
$pp \to t_{\ell^+}\bar{t}_{\ell^-} W^\pm_{\ell^\pm}$	3.421 ± 0.004
$pp \to t_{\ell^+}\bar{t}_h Z_{\ell^+\ell^-} + t_h \bar{t}_{\ell^-} Z_{\ell^+\ell^-} + t_{\ell^+}\bar{t}_{\ell^-} Z_{\ell^+\ell^-}$	10.65 ± 0.01
$pp \to Z_{\ell^+\ell^-} W^\pm_{\ell^\pm} b\bar{b}$	3.296 ± 0.003
$pp \to W^+_{\ell^+} W^-_{\ell^-} W^\pm_{\ell^\pm} b\bar{b}$	3.614 ± 0.004
$pp \to (W^+_{\ell^+} W^-_h Z_{\ell^+\ell^-} + W^+_h W^-_{\ell^-} Z_{\ell^+\ell^-} + W^+_{\ell^+} W^-_{\ell^-} Z_{\ell^+\ell^-}) b\bar{b}$	12.65 ± 0.02

SM Significance



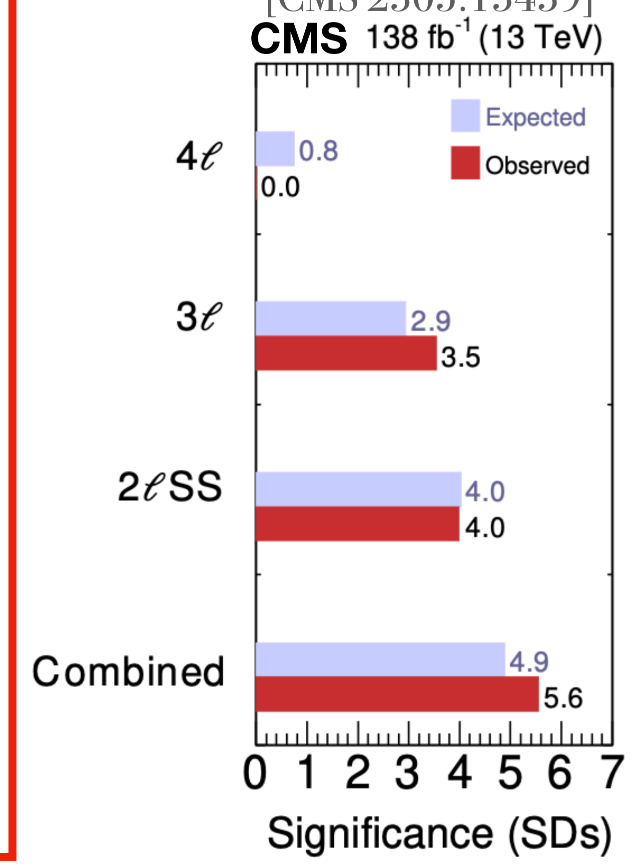
Input feature vector for node i:
$x_i^{(0)} = [p_{T,i}, \eta_i, \phi_i, E_i, m_i, \mathrm{PID}_i]$

$\left\{P(\mathrm{Signal}), P(\mathrm{Background})\right\}$



- Use ROC curves to obtain optimal working point →gives score threshold to accept event
- 'Simplified' significance $N_S/\sqrt{N_B + N_S}$ for our simulated gives ~ 4.6 for 2SSDL and ~ 3 for 3L
- Reasonable estimates for BSM expected with our analysis

[CMS 2305.13439]



Scalar resonances - why 4-top?

- Many works focus on different types of resonances (e.g. [Darme, Fuks, Maltoni `21], [Cao et al `21]) → **focus on scalar resonances**

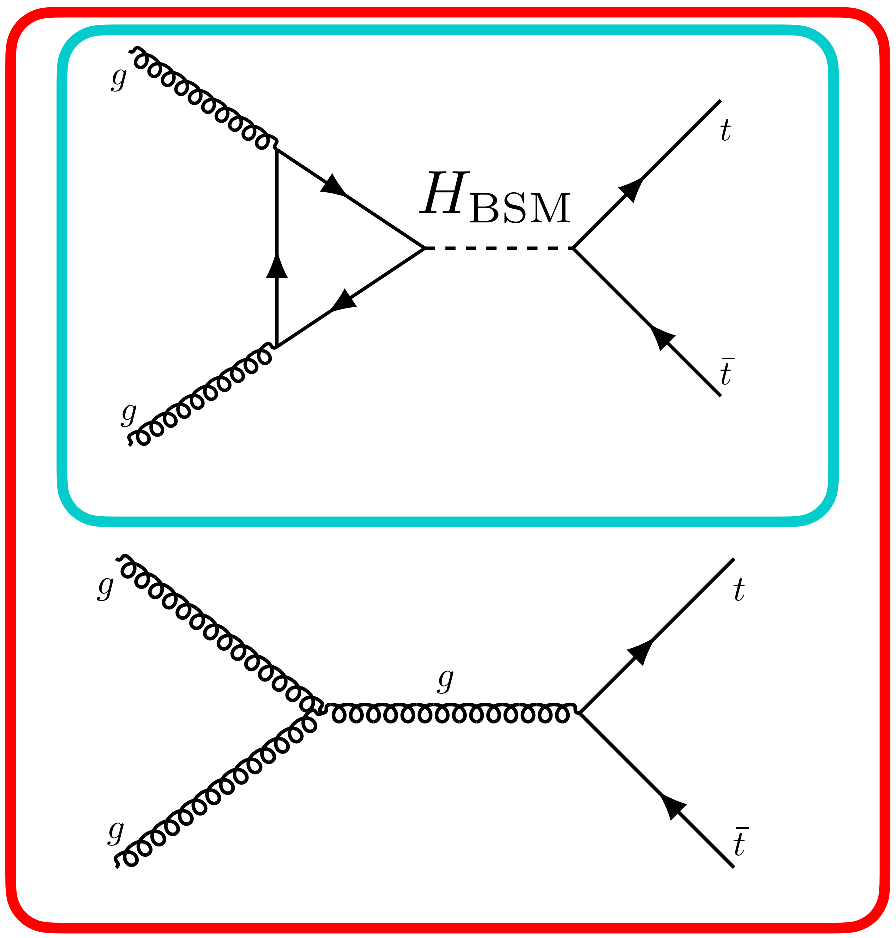
Fermion Yukawa couplings: $g_{f\bar{f}h} \sim m_f$

Heavier? →

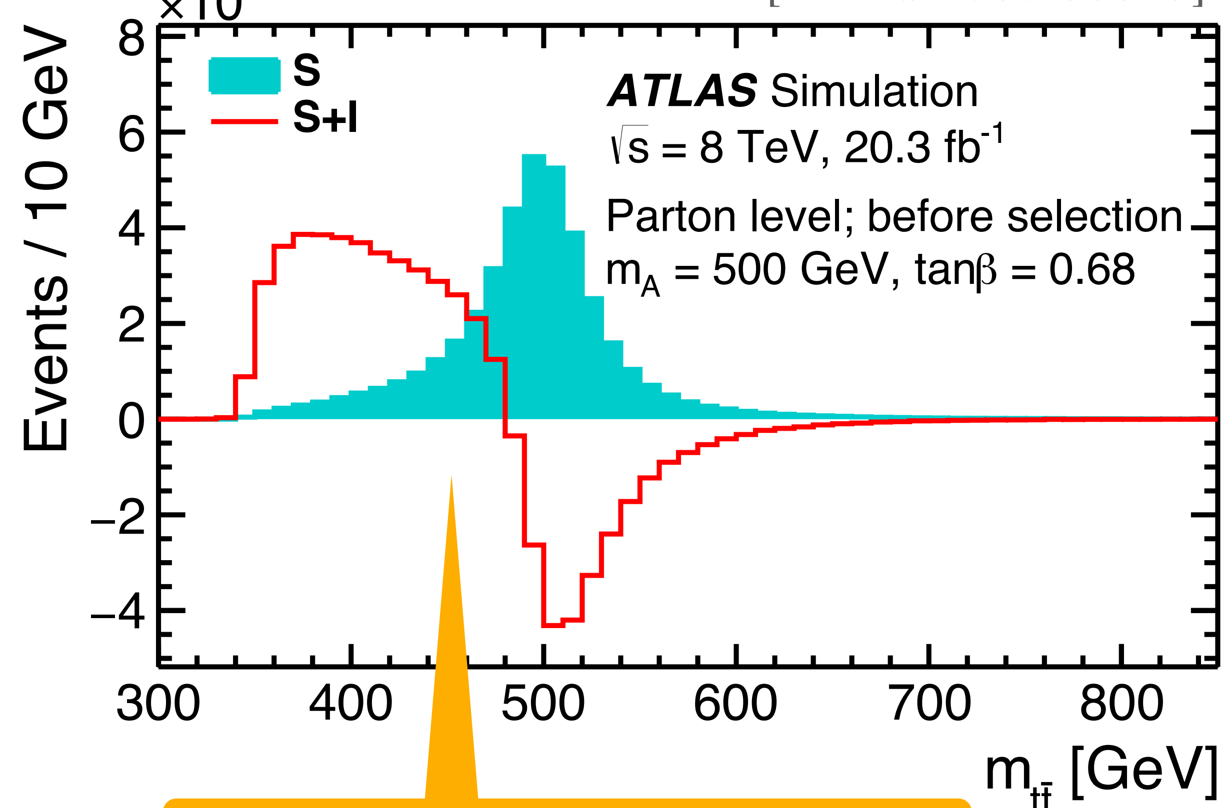
BSM scalars dominant coupling to tops?

$\Longrightarrow$ **Resonances in $t\bar{t}$!**

- However:



[ATLAS 1707.06025]



Distortion of peak from signal-background

Scalar Resonance searches

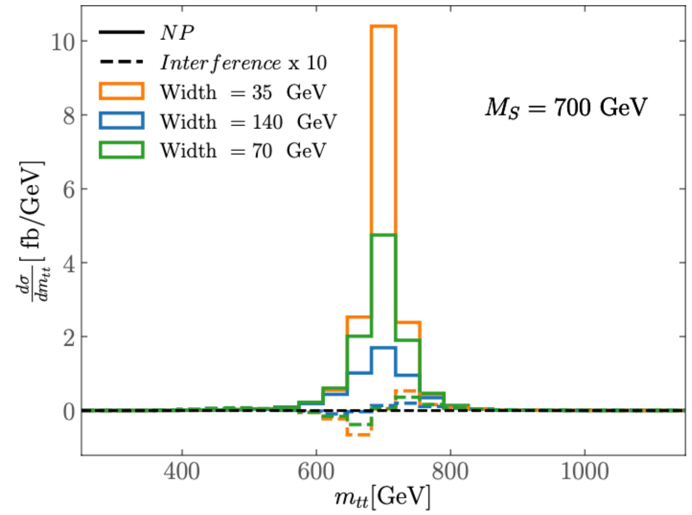
- Simplified Lagrangian:

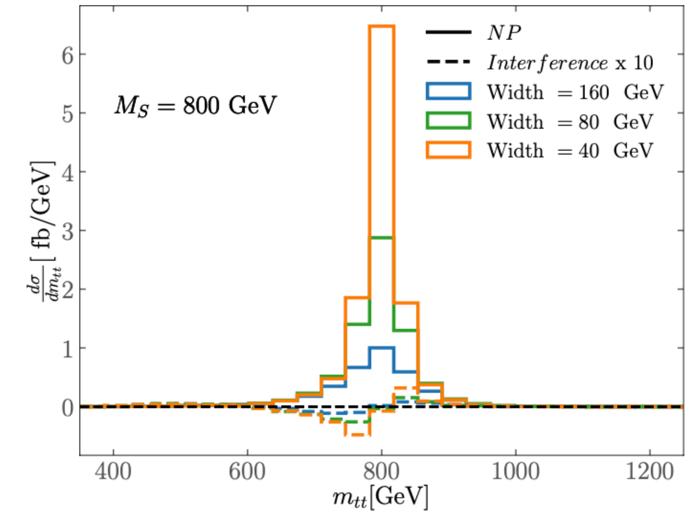
$$\mathcal{L}_{\text{simp}} = \frac{1}{2}(\partial S)^2 - \frac{M_S^2}{2}S^2 - \frac{m_t}{v}\left[\xi_S \bar{t}_L t_R S + \text{h.c}\right]$$

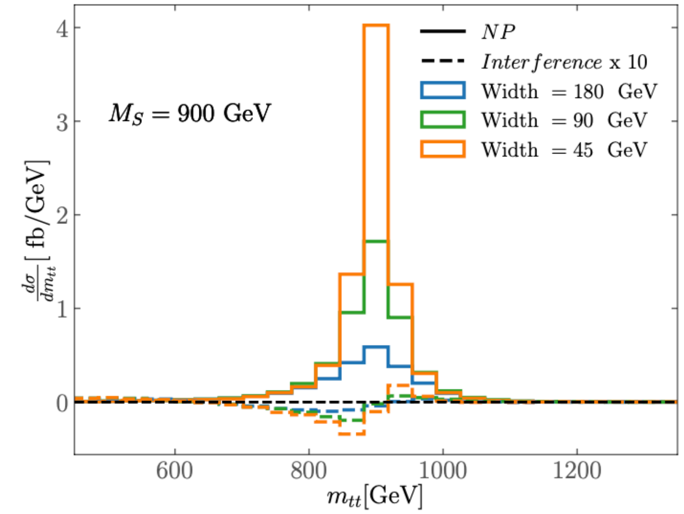
Resonant Contributions: $d\sigma^{\text{new}} \sim |\mathcal{M}_{\text{res}}|^2 \text{dLIPS}$

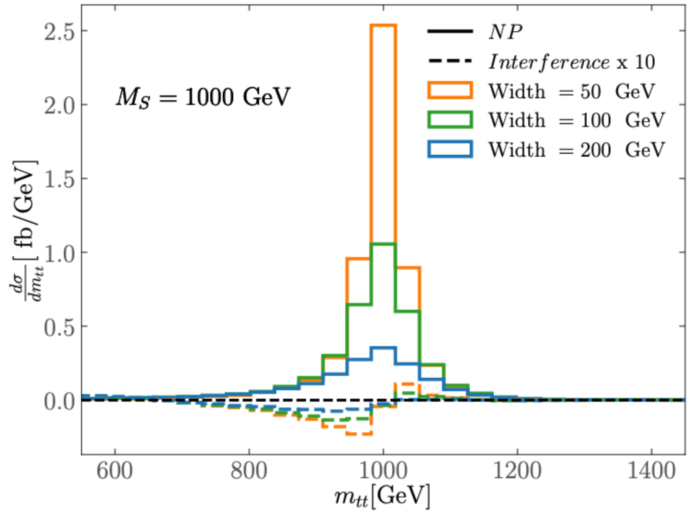
Interference Contributions: $d\sigma^{\text{inf}} \sim 2\text{Re}\left(\mathcal{M}_{\text{bkg}}\mathcal{M}^*_{\text{res}}\right)\text{dLIPS}$

- Interference effects that can distort mass peak are relatively small
- More significant for $\xi_S \to 0$ but in this case sensitivity is also limited
- For CP-odd case interference should be vanishing when studying CP-even observables







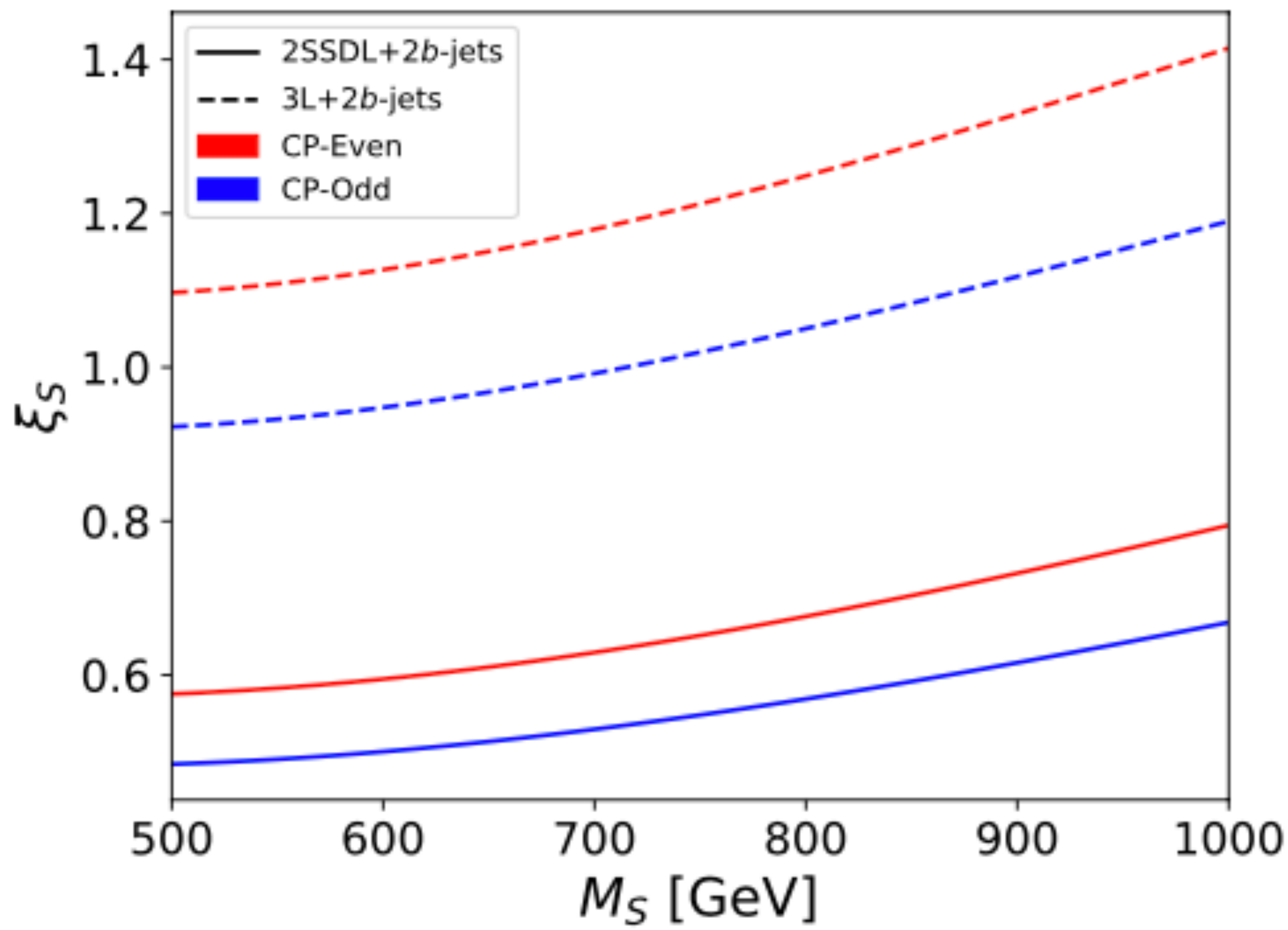


Results with GNN

- Train GNN for different masses M_S for fixed width ratios $\Gamma_S/M_S = 0.1$ and $\xi_S = 1$

- Can in principle set constraints on $\xi_S < 1$, however sensitivity is limited

- 2σ confidence limits on scalar mass with CP-even and CP-odd couplings (3/ab for 13TeV collisions)



Mapping to 2HDM

- Map to type-2 2HDM with particle content:
  - CP even: h (SM-like Higgs) , H and $H^{\pm}$
  - CP odd: A

$$\mathcal{L}_{2\text{HDM}} \supset -\frac{m_t}{v}\left(\xi_h \bar{t}th + \xi_H \bar{t}tH - i\xi_A \bar{t}\gamma^5 tA\right)$$

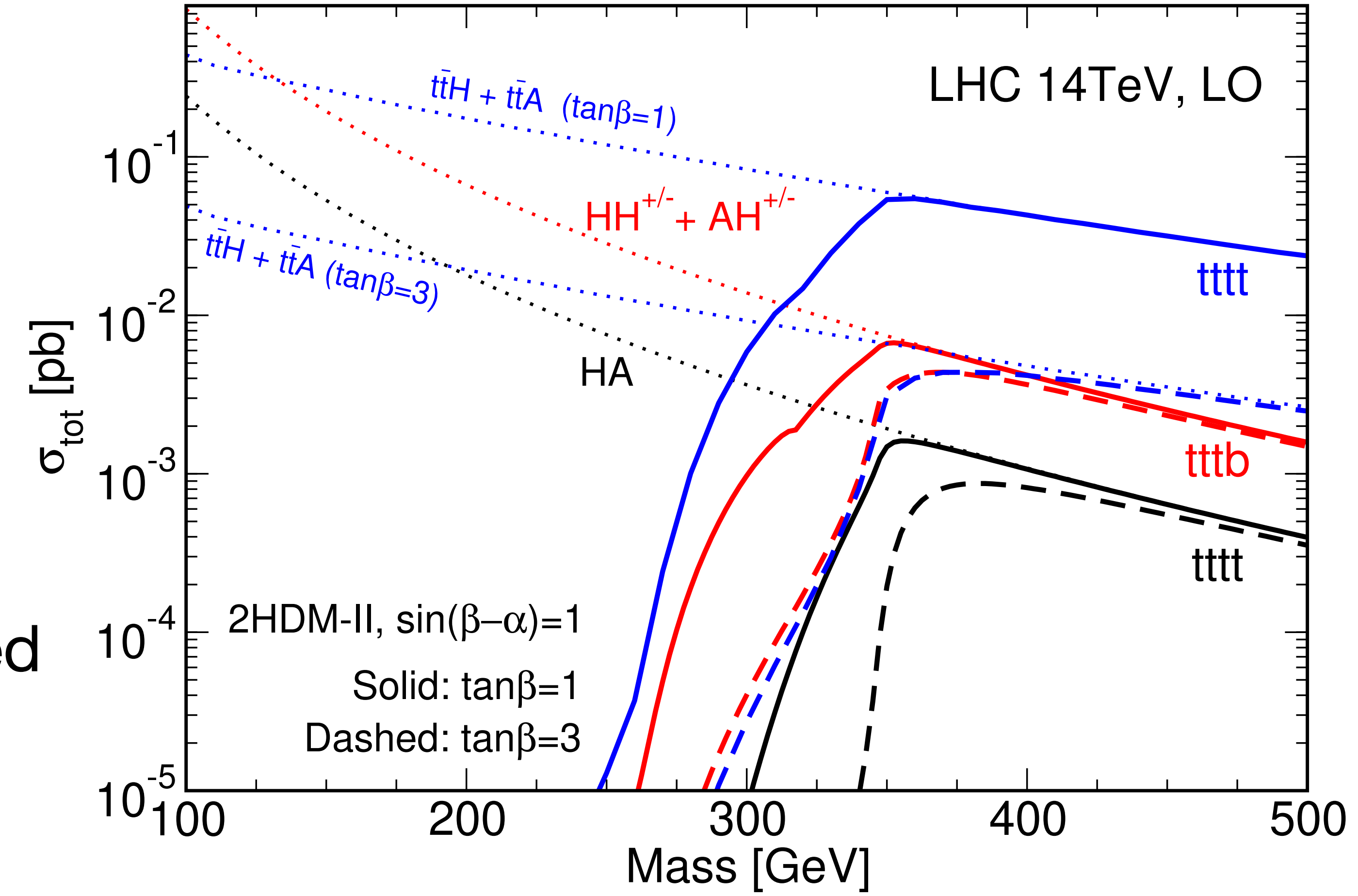
- Parameters in terms of 2HDM couplings:

$$\xi_h = \sin(\beta-\alpha) + \cos(\beta-\alpha)$$
$$\xi_H = \cos(\beta-\alpha) - \sin(\beta-\alpha)$$
$$\xi_A = \cot(\beta)$$

Alignment limit:
$\cos(\beta-\alpha) = 0$

- Sizeable multi-top interactions expected

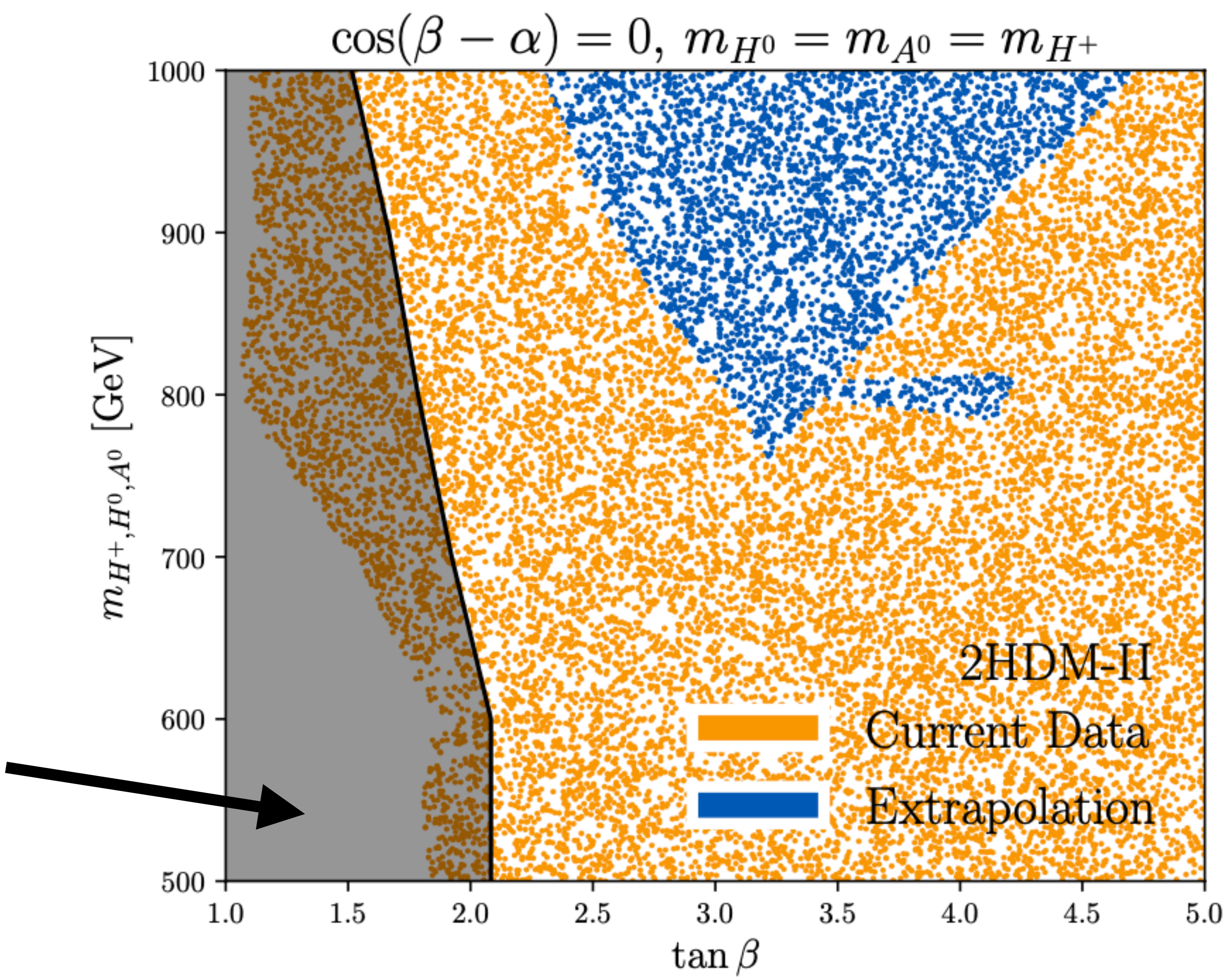
[Kanemura, Yokoya, Zheng `15]



Exclusions

- Scan parameter space (2HDecay and HiggsBounds) for current data and extrapolated
- Sensitivity improvements mostly lead by $H^+ \to t\bar{b}$ and $H \to \tau^+\tau^-$
- Overlay 2SSDL resonance search results

4-top 2SSDL exclusion at HL-LHC



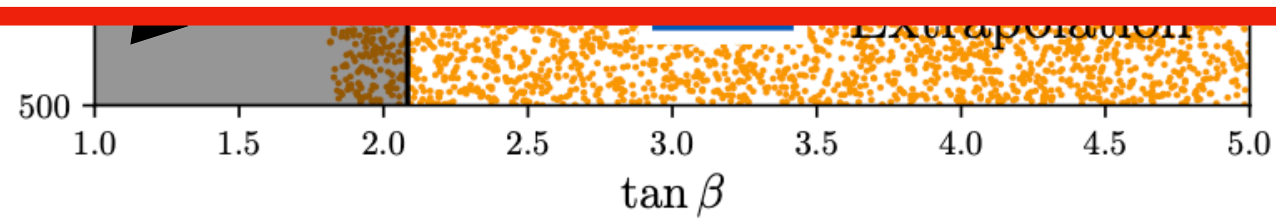
Exclusions

- Scan parameter space (2HDecay and HiggsBounds) for current data and extrapolated
- Sensitivity improvements mostly lead by $H^+ \to t\bar{b}$ and $H \to \tau^+\tau^-$
- Overlay 2S

- Effects from signal-signal interference?
- Possible mixing effects from BSM states?

- Currently investigating for Two-Higgs Doublet Models
- Collaborative effort with ATLAS experimentalists at DESY

4-top 2SSD
exclusion at
HL-LHC



SMEFT Prospects from four-tops

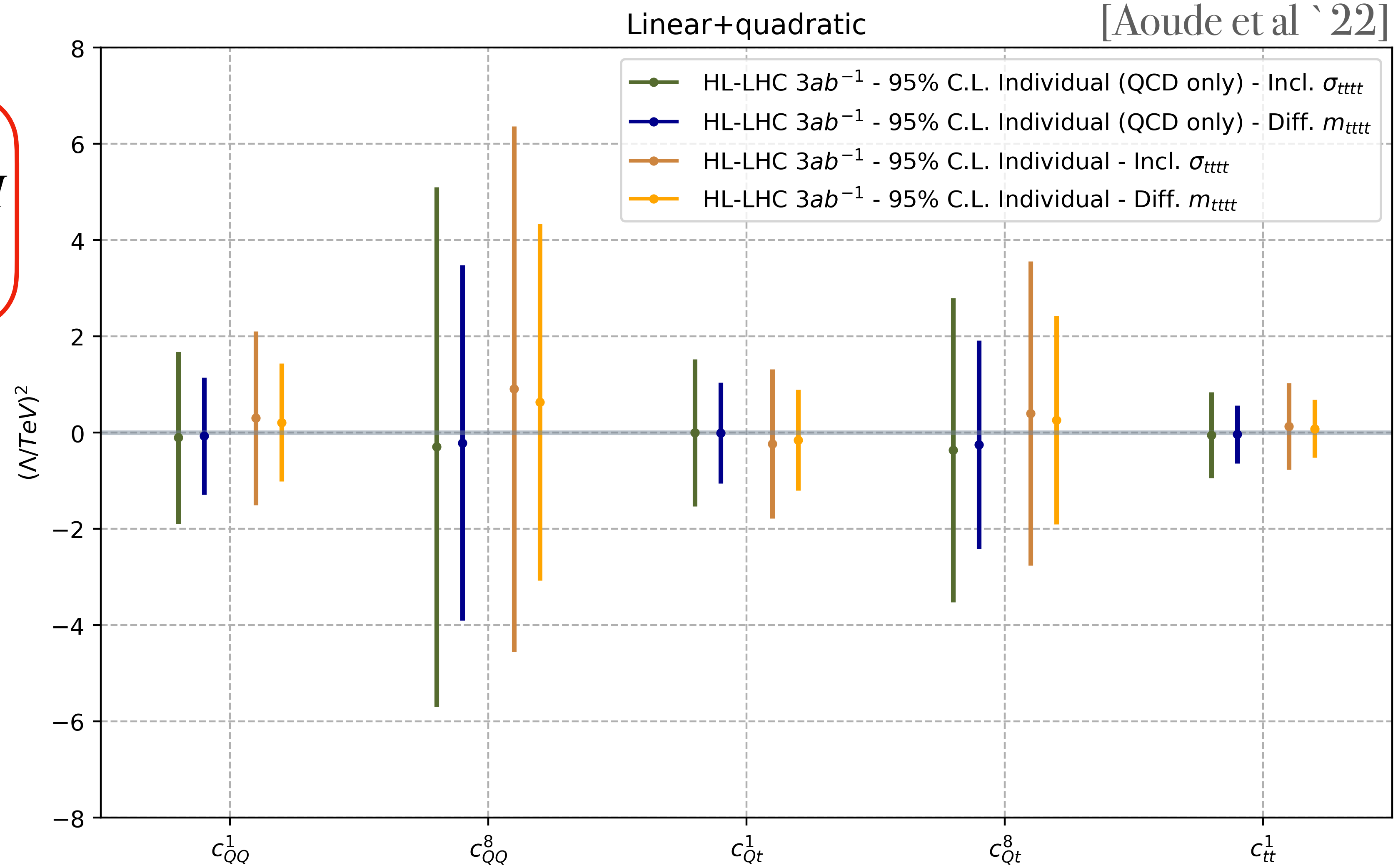
- SMEFT Lagrangian $$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{n\geq 5}\sum_i \frac{C_i^{(n)}}{\Lambda^{n-4}}\mathcal{O}_i^{(n)}$$
- Sensitivity to 4-heavy 4-fermion operators in SMEFT [Aoude et al `22]
- Complements top-fits from top-pair production

Care needed! Significant $\alpha_S^2\alpha_{EM}$ and $\alpha_S^2\alpha_t$ contributions

↓

Not unexpected, sizeable EW even at NLO [Frederix, Pagani, Zaro `18]

[Aoude et al `22]



Non-resonant new interactions

- Motivated EFT-related example: $\hat{H}$ parameter [Englert et al ` 19]
- Can be understood as an oblique correction:

$$\hat{H} = -\frac{M_H^2}{2}\Sigma''_H(M_H^2)$$

- Introduce through $\mathcal{L}_{\hat{H}} = \frac{\hat{H}}{m_H^2}|D_\mu D^\mu \Phi|^2$

Higgs propagator modification

$$-i\Delta(p^2, m_H^2) = \frac{1}{p^2 - m_H^2} - \frac{\hat{H}}{m_H^2}$$

- Associated modifications of couplings

$$\frac{g^{\hat{H}}_{VVH}(p^2)}{g^{\rm SM}_{VVH}} = 1 - \hat{H}\left(1 - \frac{p^2}{m_H^2}\right) \quad , \quad \frac{g^{\hat{H}}_{t\bar{t}H}}{g^{\rm SM}_{t\bar{t}H}} = 1 - \hat{H}$$

- Note: $\left(\frac{1}{p^2 - M_H^2} - \frac{\hat{H}}{M_H^2}\right)\left[1 - \hat{H}\left(1 - \frac{p^2}{M_H^2}\right)\right] = \frac{1}{p^2 - M_H^2} + \mathcal{O}(p^2 - M_H^2)$

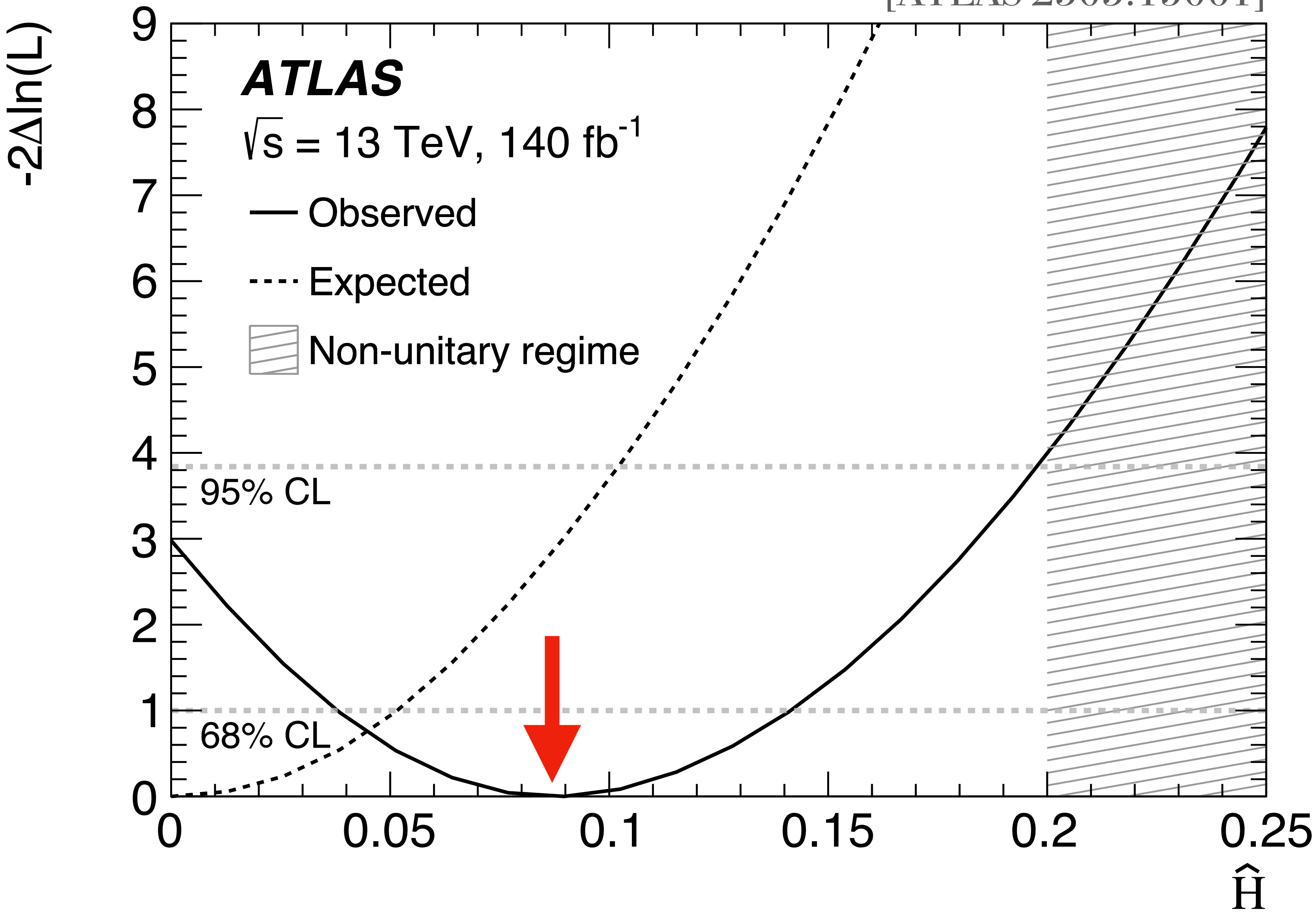
$\Longrightarrow$ Effect of $\hat{H}$ can be more important in 4-top

$\hat{H}$ bounds from experiments

- Previous CMS 95% upper limit: $\hat{H} < 0.12$ [CMS 1908.06463]
- Recent ATLAS paper also placed bounds on $\hat{H}$

Small excess from SM!

[ATLAS 2303.15061]



An example: 4-top for Higgs-philic ALP

[Anisha, Das Bakshi, Englert, PS `22 (preprint)]

- Chiral Electroweak Lagrangian (HEFT):

$$U = \exp(i\pi^a \tau^a / v)$$

$$\mathcal{L} = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \mathcal{L}_{\text{ferm}} + \mathcal{L}_{\text{Yuk}} + \frac{v^2}{4} \mathcal{F}_H \, \text{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2} \partial_\mu H \partial^\mu H - V(H) + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{FP}}$$

[Buchalla, Cata, Krause` 14]
[Brivio et al ` 14]
[Herrero, Morales `20,`21, `22]

Non-linear construction, **Higgs is a singlet**

$$\mathcal{F}_H = \left(1 + 2(1+\zeta_1)\frac{H}{v} + (1+\zeta_2)\left(\frac{H}{v}\right)^2 + \ldots\right)$$

Non-linear introduction of an Axion-Like Particle (ALP):

$$\mathcal{L}^{\text{ALP}}_{\text{LO}} = \frac{1}{2} \partial_\mu \mathcal{A} \partial^\mu \mathcal{A} - \frac{1}{2} M_{\mathcal{A}}^2 \mathcal{A}^2 + a_{2D} \left(i\, v^2 \text{Tr}[U \tau^3 U^\dagger \boldsymbol{\mathcal{V}}_\mu] \frac{\partial_\mu \mathcal{A}}{f_A} \mathcal{F}_{2D} \right)$$

ALP field

$$\boldsymbol{\mathcal{V}}_\mu = (D_\mu U) U^\dagger$$

How to constrain new couplings and mass?

$$\mathcal{F}_{2D} = \left(1 + 2\zeta_{12D}\frac{H}{v} + \zeta_{22D}\left(\frac{H}{v}\right)^2 + \ldots\right)$$

[Brivio et al ` 17]

An example: 4-top for Higgs-philic ALP

[Anisha, Das Bakshi, Englert, PS ` 22 (preprint)]

- Chiral Electroweak Lagrangian (HEFT):

$$U = \exp(i\pi^a\tau^a/v)$$

$$\mathcal{L} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \mathcal{L}_{\text{ferm}} + \mathcal{L}_{\text{Yuk}}$$

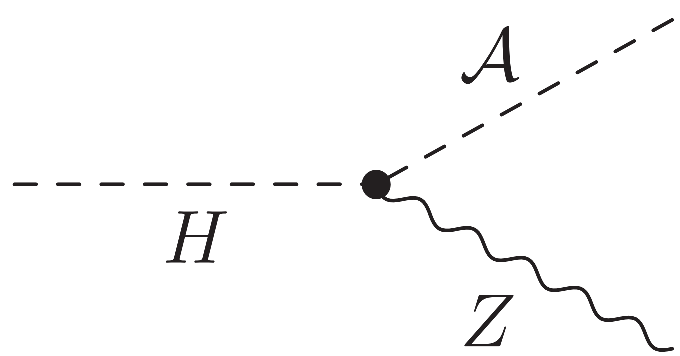
[Buchalla, Cata, Krause ` 14]
[Brivio et al ` 14]
[Herrero, Morales ` 20, ` 21, ` 22]

$$\ldots_{\text{GF}} + \mathcal{L}_{\text{FP}}$$

Non-... constr... Higgs is...

$$\ldots + \ldots)$$

In non-linear case ALP-Higgs-Z coupling is leading order



Non-linear i...

$$\mathcal{L}^{\text{AL}}_{\text{LO}} \ldots$$

ALP field

$$V_\mu = (D_\mu U)U^\dagger$$

How to constrain new couplings and mass?

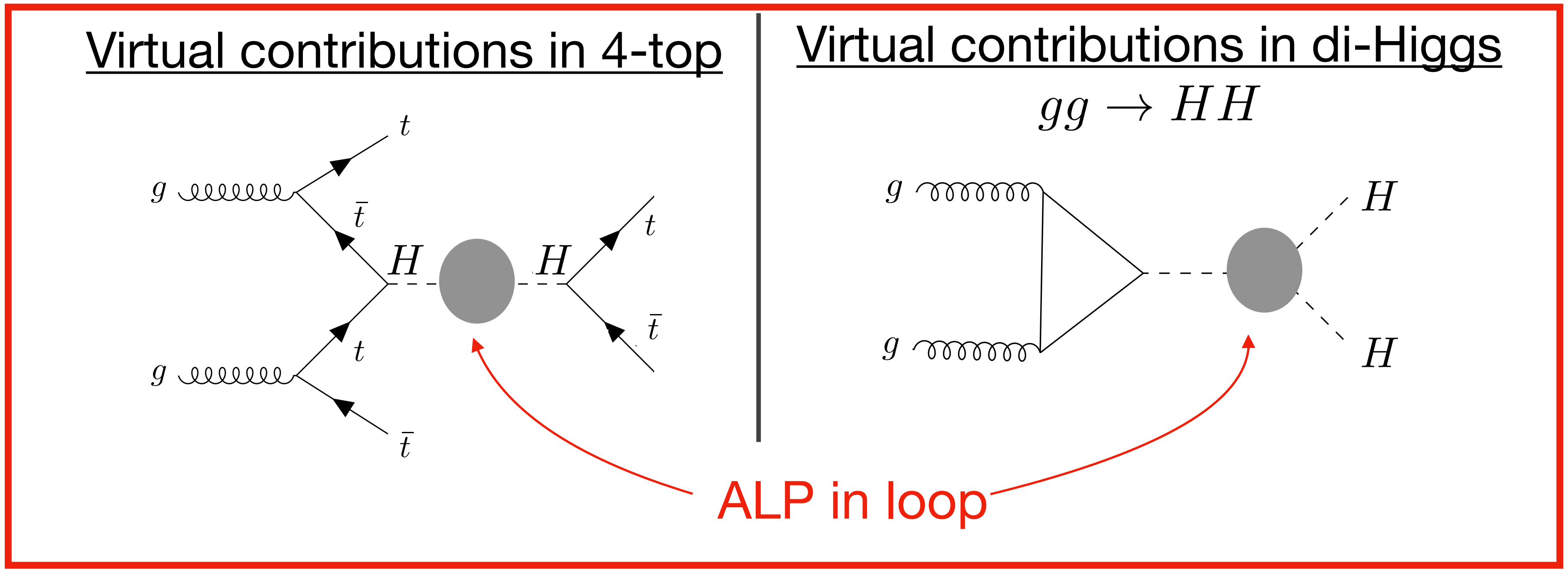
$$\mathcal{F}_{2D} = \left(1 + 2\zeta_{12D}\frac{H}{v} + \zeta_{22D}\left(\frac{H}{v}\right)^2 + \ldots\right)$$

[Brivio et al ` 17]

An example: 4-top for Higgs-philic ALP

[Anisha, Das Bakshi, Englert, PS `22 (preprint)]

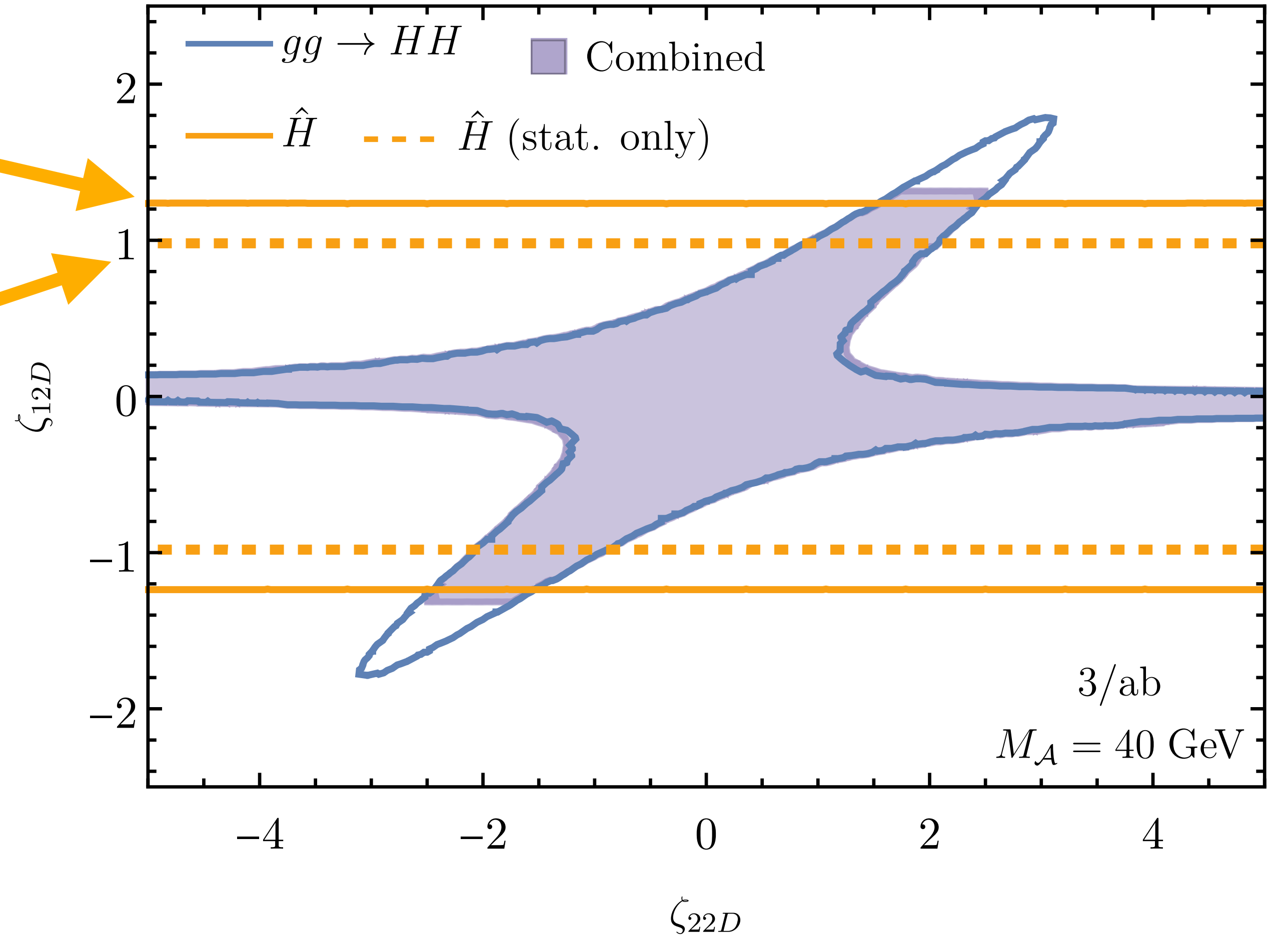
- Main probes for ALP mass $\gtrsim$ 34 GeV:



3/ab extrapolation

Projection with only statistics

[CMS-PAS-FTR-18-03]



Conclusions

- **ML techniques** enhance sensitivity to SM 4-top production

  → **utilised by experiments**

- **Sensitivity to resonances** → 4-top can complement searches of top-pair production suffering from destructive signal-SM interference

- Complementary information to parameter models of UV-complete models (e.g. representative 2HDM type II)

- Measurement of $\hat{H}$ can provide insights on non-resonant interactions: small deviation in observed data from ATLAS

- $\hat{H}$ particularly useful for models with new states coupled to Higgs

Thank you!

Backup: Edge Convolution

- Signal Region Selection:
  - represent events as fully-connected bidirectional graphs
  - Graph Neural Network (GNN) for signal-background discrimination
  - Supervised learning: background → 0, signal → 1
- Each node is assigned node features $\vec{x}_i^{(0)}$ as input
- Node features updated for each ‘message passing layer’ with <u>Edge Convolution</u>

Linear Layers

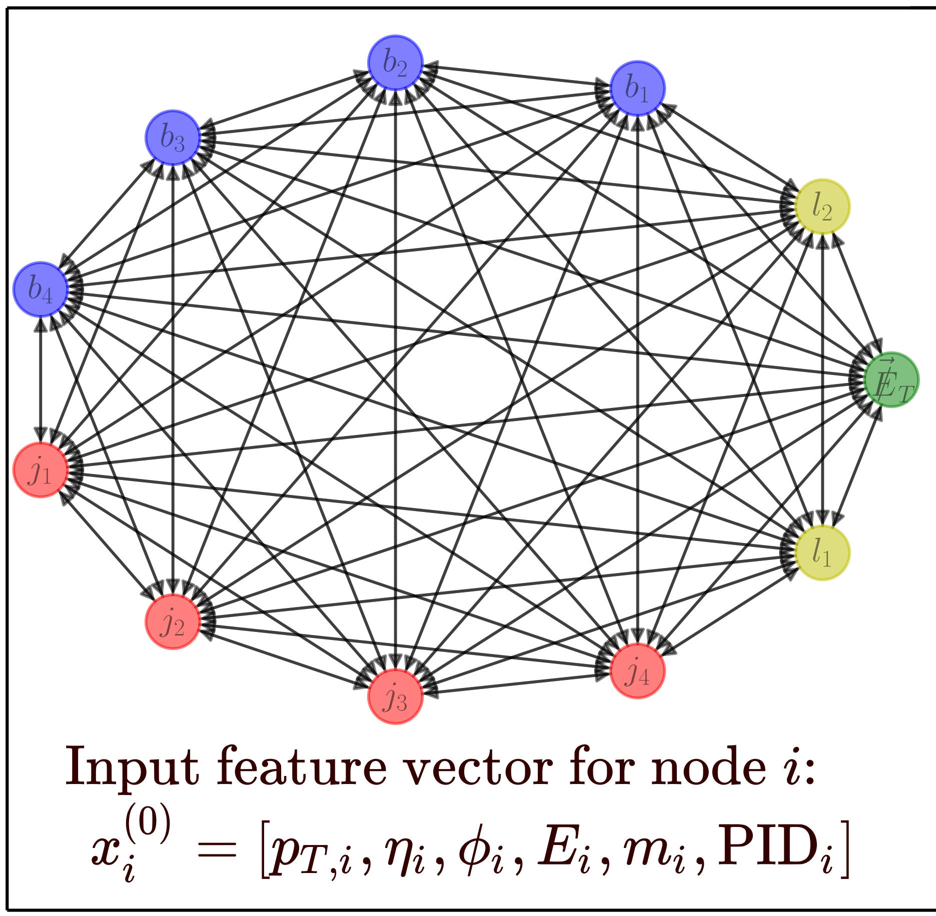
$$\vec{x}_i^{(l+1)} = \frac{1}{|\mathcal{N}(i)|} \sum_{j \in \mathcal{N}(i)} \textrm{ReLU}\left(\Theta \cdot (\vec{x}_j^{(l)} - \vec{x}_i^{(l)}) + \Phi \cdot (\vec{x}_i^{(l)})\right)$$

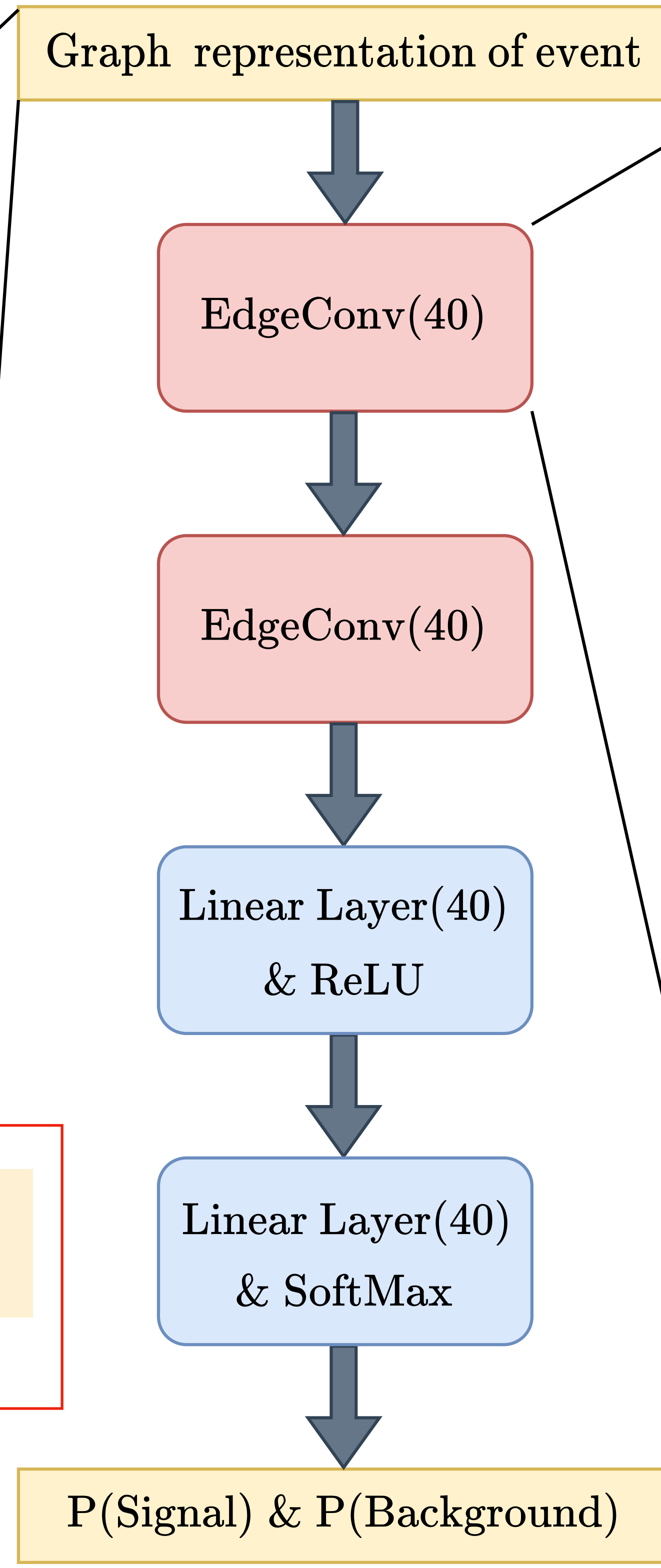
Nodes in ‘neighbourhood’ of i (connected)

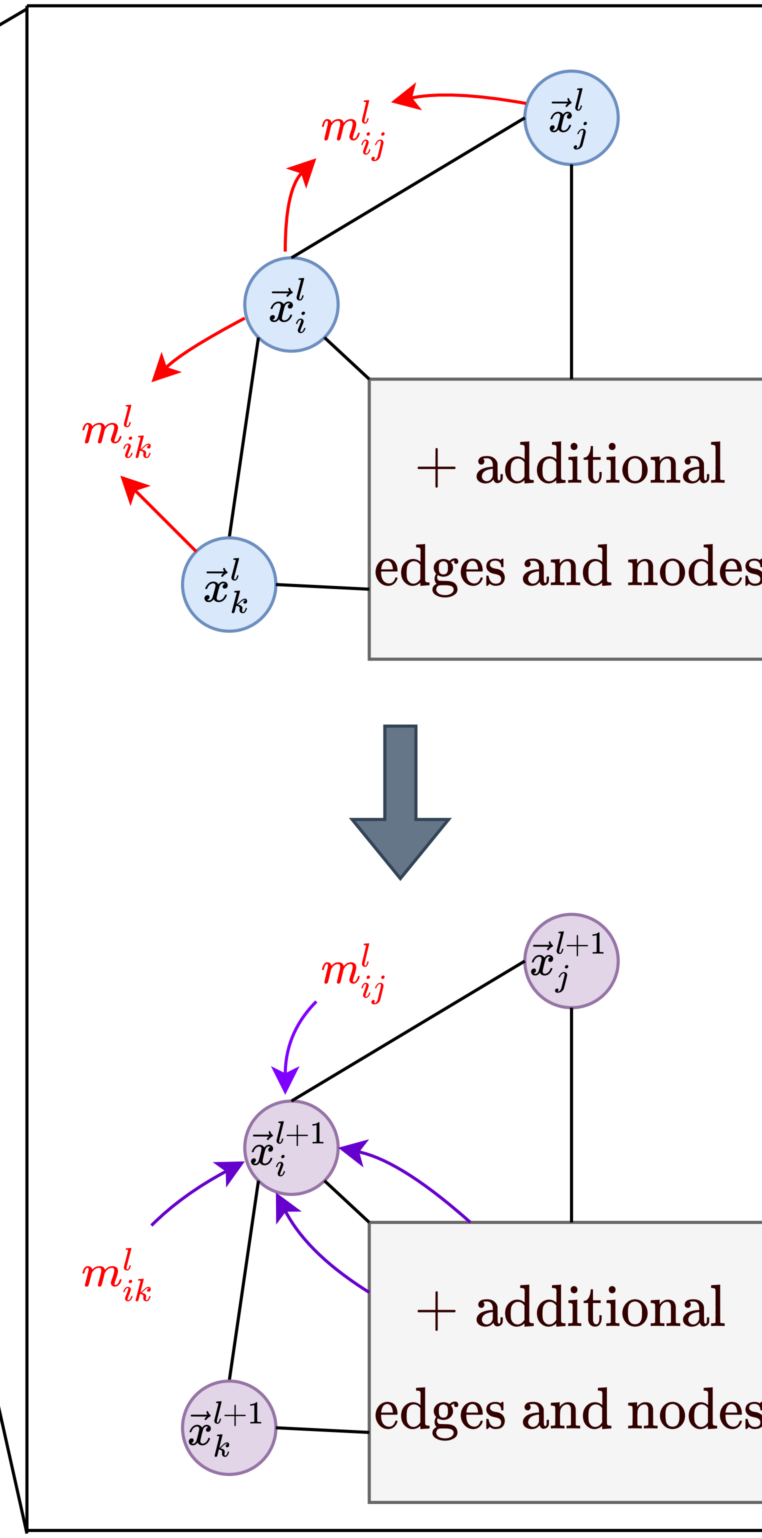
$m_{ij}^{(l)}$

- <u>‘Graph Readout Operation’:</u> mean → gives a vector for ‘graph properties’

Backup: Network Architecture







EdgeConv:

linear layers

$$\vec{x}_i^{(l+1)} = \frac{1}{|\mathcal{N}(i)|} \sum_{j \in \mathcal{N}(i)} \mathrm{ReLU}\left(\Theta \cdot (\vec{x}_j^{(l)} - \vec{x}_i^{(l)}) + \Phi \cdot (\vec{x}_i^{(l)})\right)$$

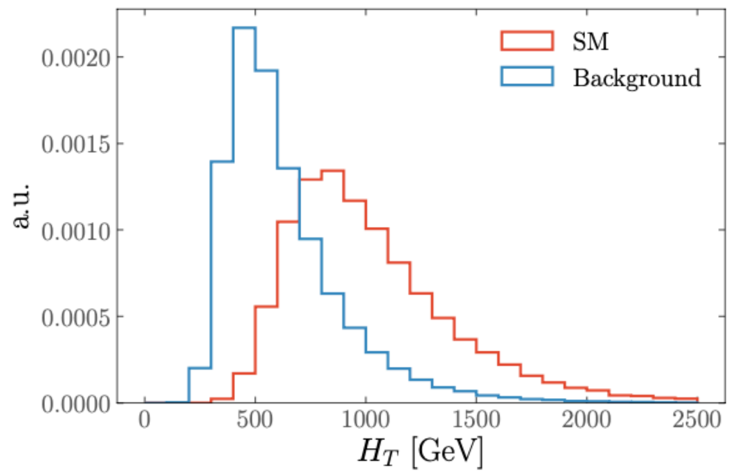
$m_{ij}^{(l)}$

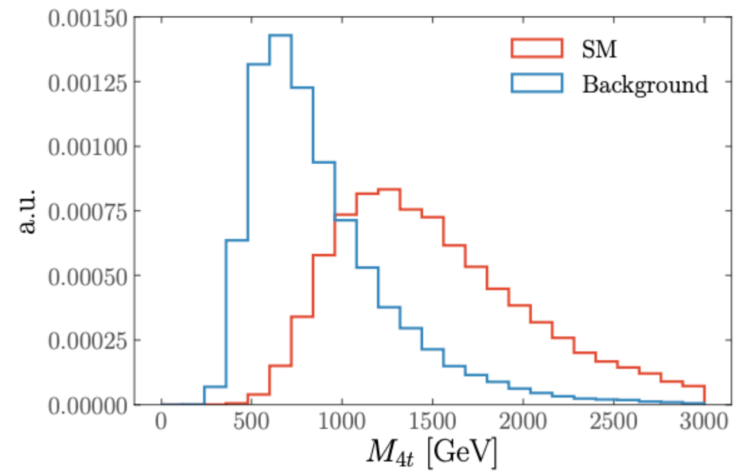
Signal: labeled as 1

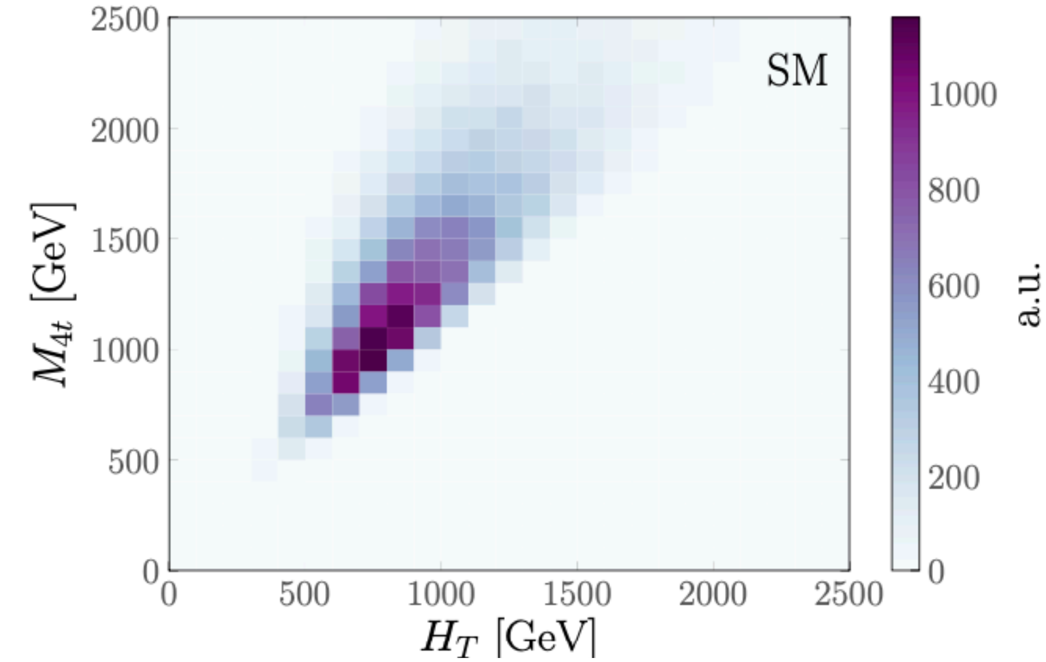
Background: labeled as 0

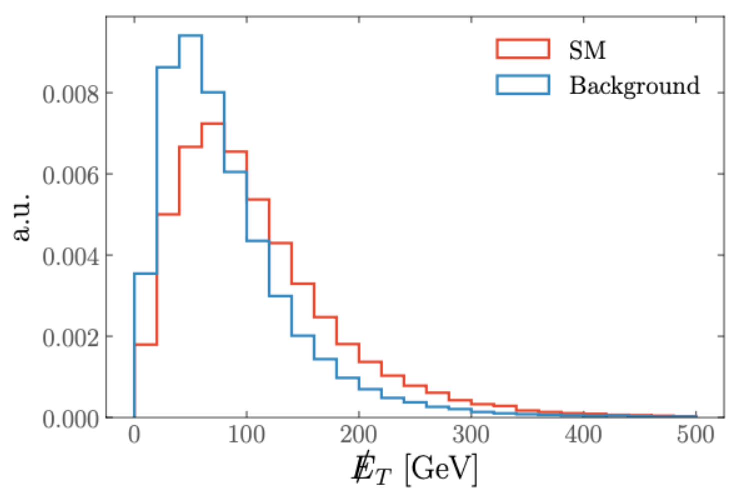
Backup: Representative Distributions

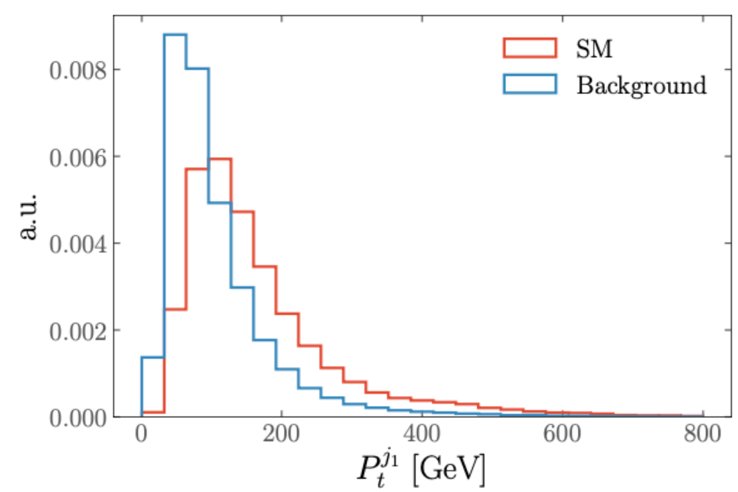
- Total visible invariant mass and H_T show the best discriminative features between SM signal and SM background for 2SSDL

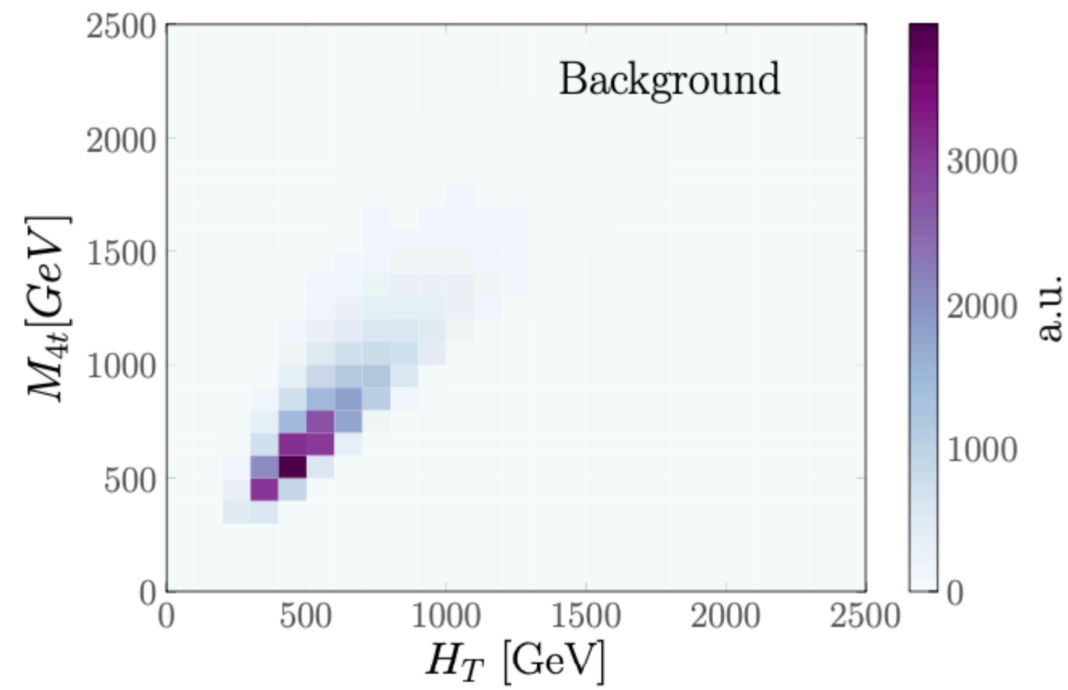


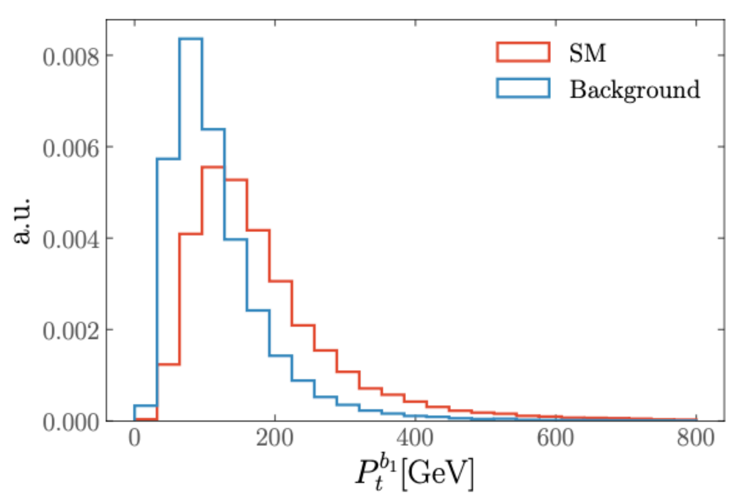


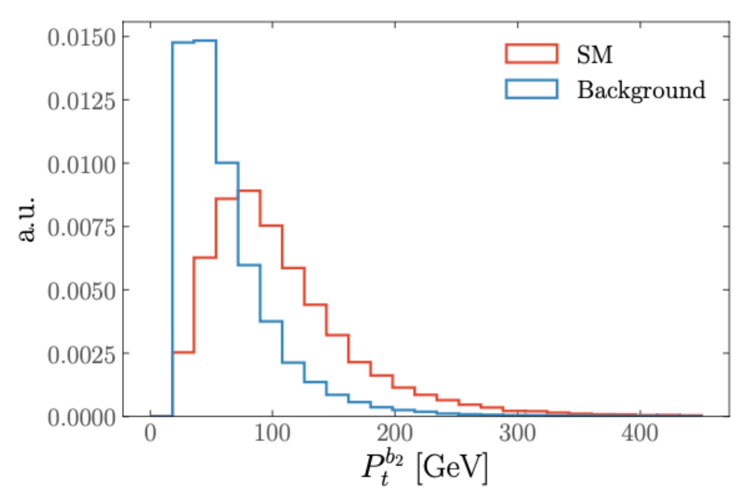












Backup: Resonances vs EFT in 4-top

- Simplified Lagrangians with scalars, pseudoscalars and vector resonances (e.g. [Darme, Fuks, Maltoni `21], [Cao et al `21])

- Scalar to EFT matching

Need dim-8 operators, e.g.

$$\mathcal{O}_S^1 = \bar{t}t\bar{t}t$$

- Differences between EFT and resonances **for small couplings and masses**