Constraining the Top Yukawa Coupling in tH Production with the ATLAS Experiment at the LHC

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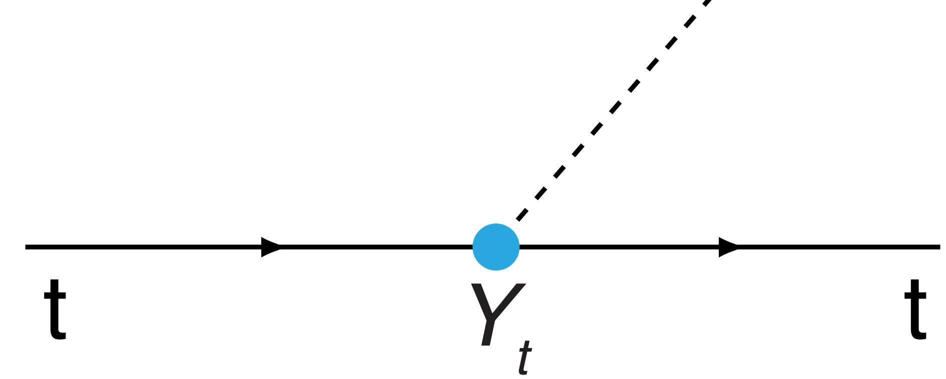
The Top Yukawa Coupling

- Yukawa coupling, Y, between Higgs and fermions.
- Strength of Yukawa coupling in SM directly proportional to fermion mass.
- Fundamental parameters of the SM.
- Top quark heaviest particle in SM; largest coupling strength to Higgs.

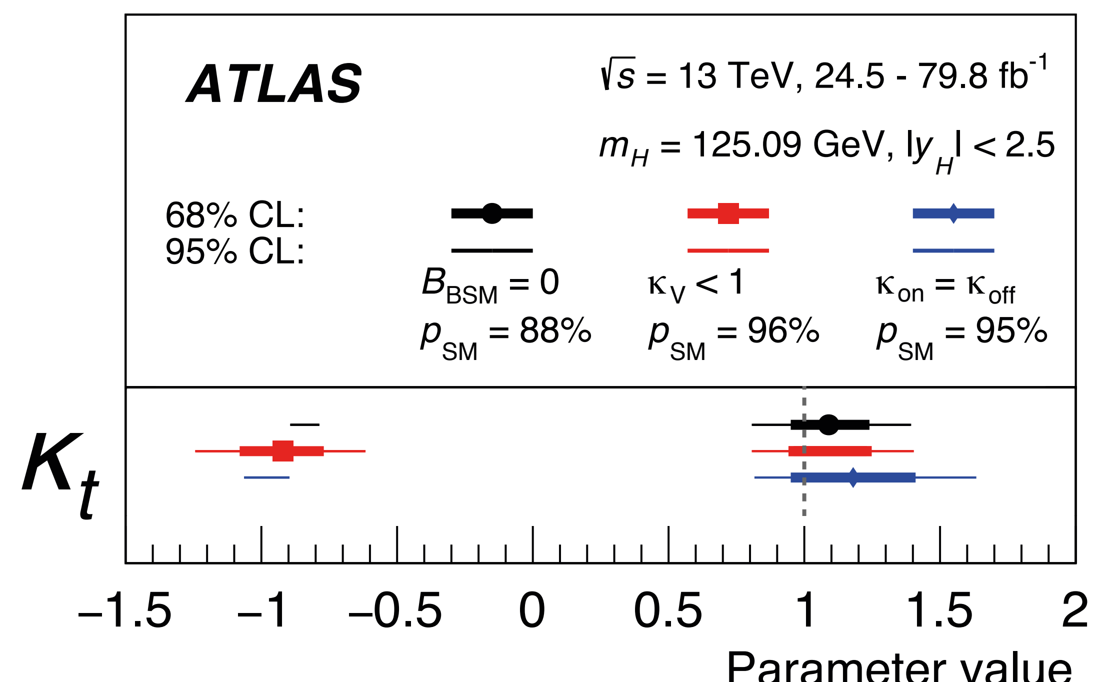
$$\mathscr{L}_t = -\frac{m_t}{v}\kappa_t \bar{\psi}_t \psi_t H$$



What do we know already?

- **Direct** constraints from $\mathrm{t\bar{t}H}$ production, not sensitive to sign.
- $\kappa_t = -1$ not yet directly excluded by ATLAS

ATLAS Run2 combination $80\ \mathrm{fb}^{-1}$



$$\kappa_t = Y_t^{obs} / Y_t^{SM}$$

The κ Framework

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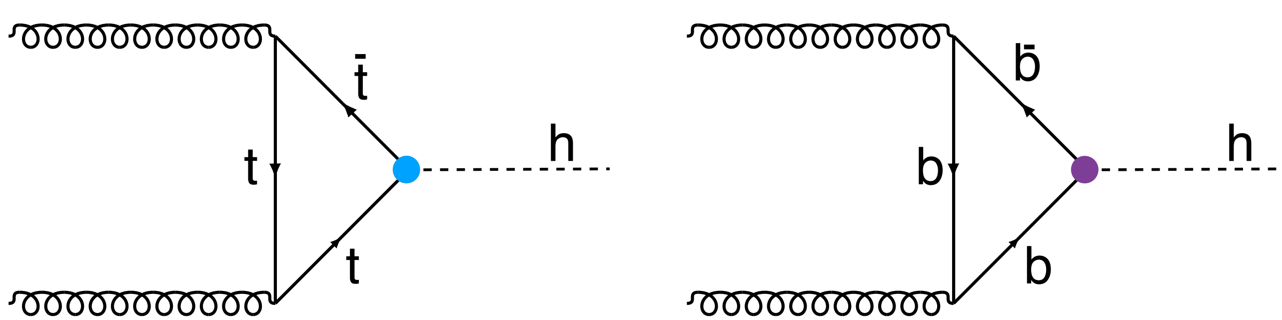
- Higgs coupling strength to other SM particles parameterised using κ modifiers.
- $\kappa_i^2 = \sigma_i/\sigma_i^{SM}$, $\kappa_i^2 = \Gamma_i/\Gamma_i^{SM}$
- Sensitivity to κ_t sign from loops and directly.
- Not using loop processes lets us directly probe κ_t.

Production	Resolved modifier
$\sigma(ggF)$	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(gg \to ZH)$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $-0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(tHW)$	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
Partial decay width	
Γ^{gg}	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\gamma\gamma}$	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$

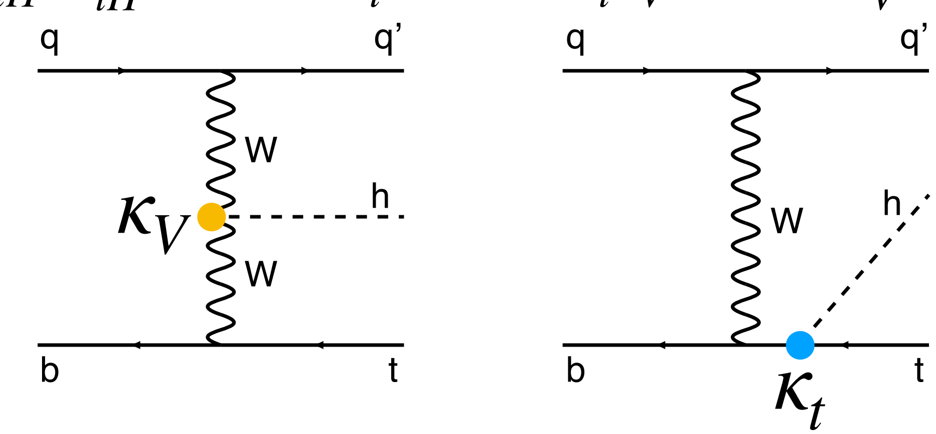
ggF production - indirect

$$\sigma_{ggF}/\sigma_{ggF}^{SM} = 1.040\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b - 0.005\kappa_t\kappa_c$$



tH production - direct

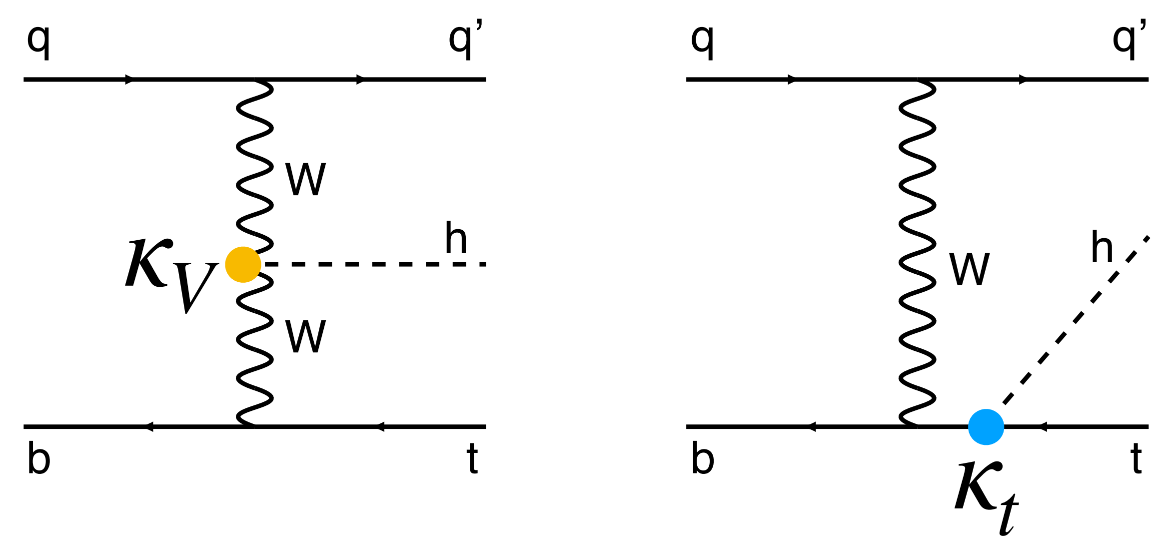
$$\sigma_{tH}/\sigma_{tH}^{SM} = 2.63\kappa_t^2 - 5.25\kappa_t\kappa_V + 3.58\kappa_V^2$$



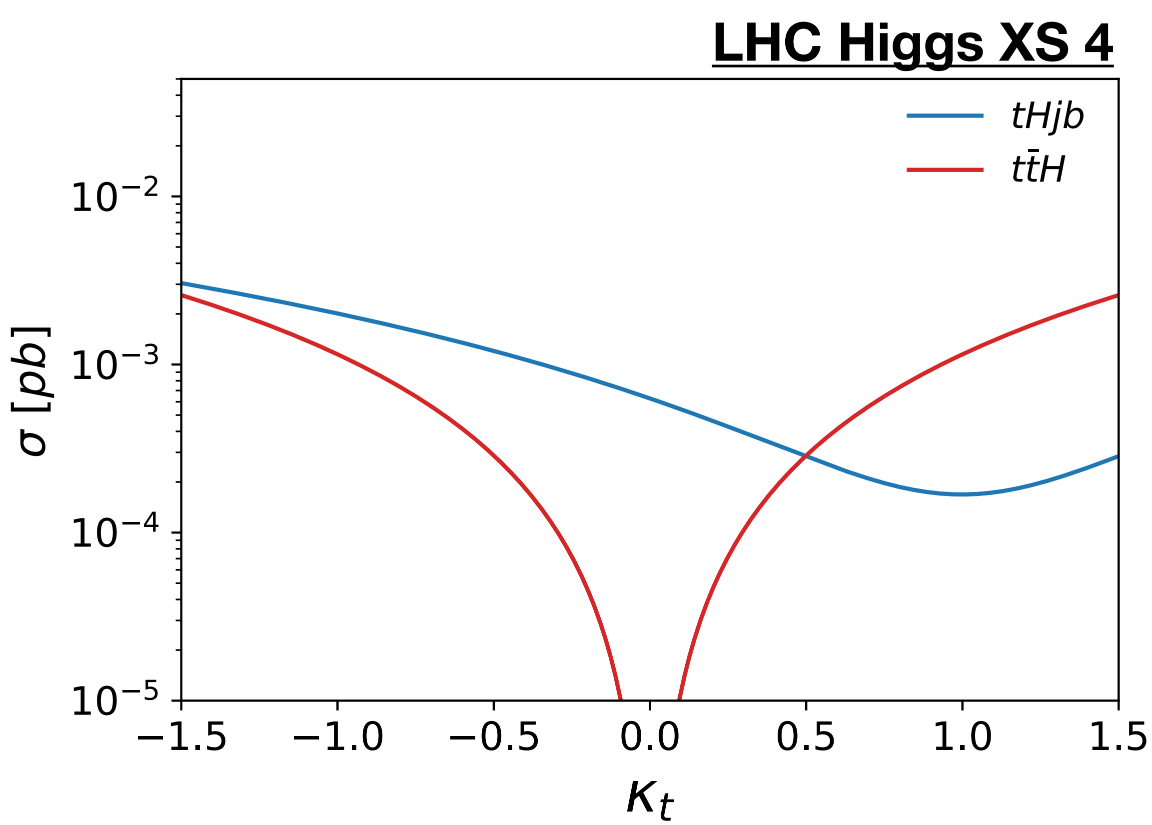
The tH Process

- As opposed to $t\bar{t}H$, tH is sensitive to sign of top Yukawa coupling.
- Sensitivity from interference between possible diagrams.
- Use process to directly exclude $\kappa_t = -1$ in ATLAS.

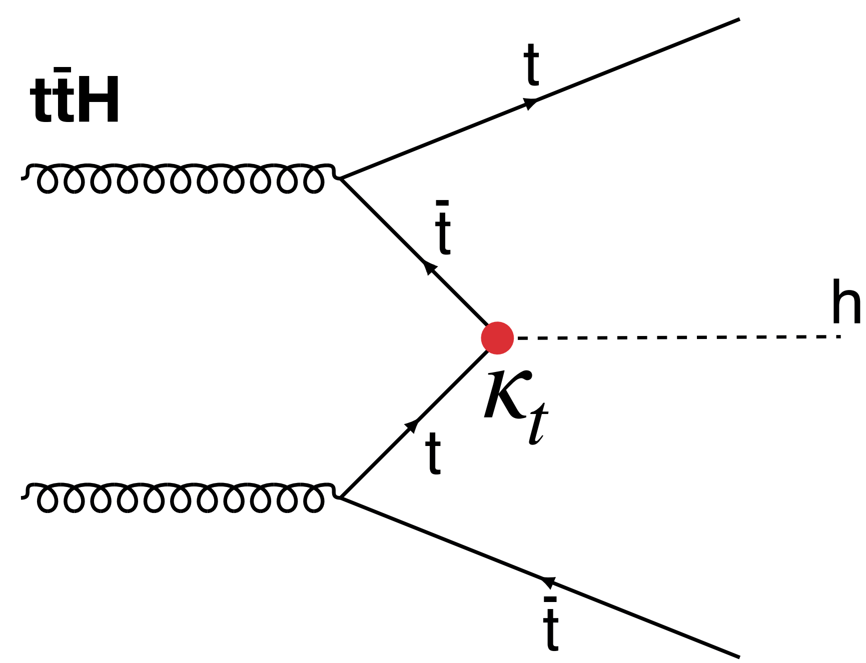
tH



$$\sigma_{tH}/\sigma_{tH}^{SM} = 2.63\kappa_t^2 - 5.25\kappa_t\kappa_V + 3.58\kappa_V^2$$

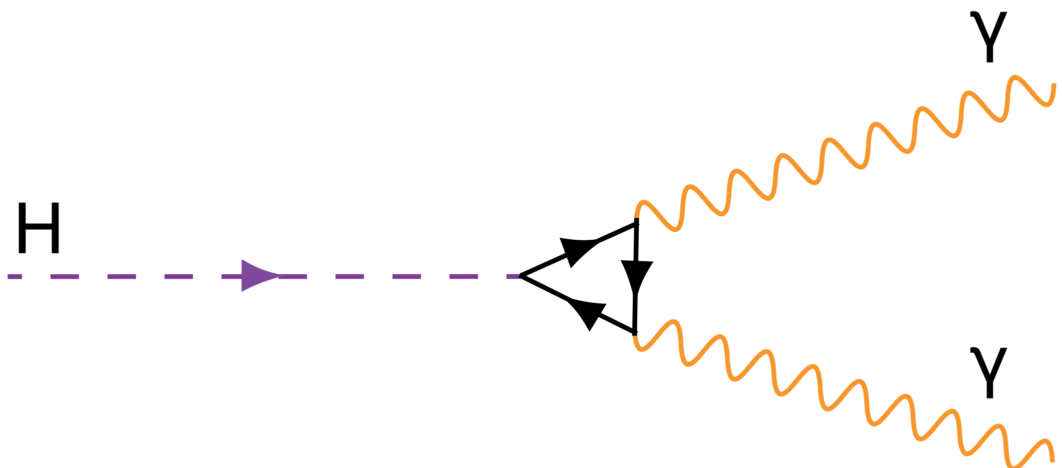


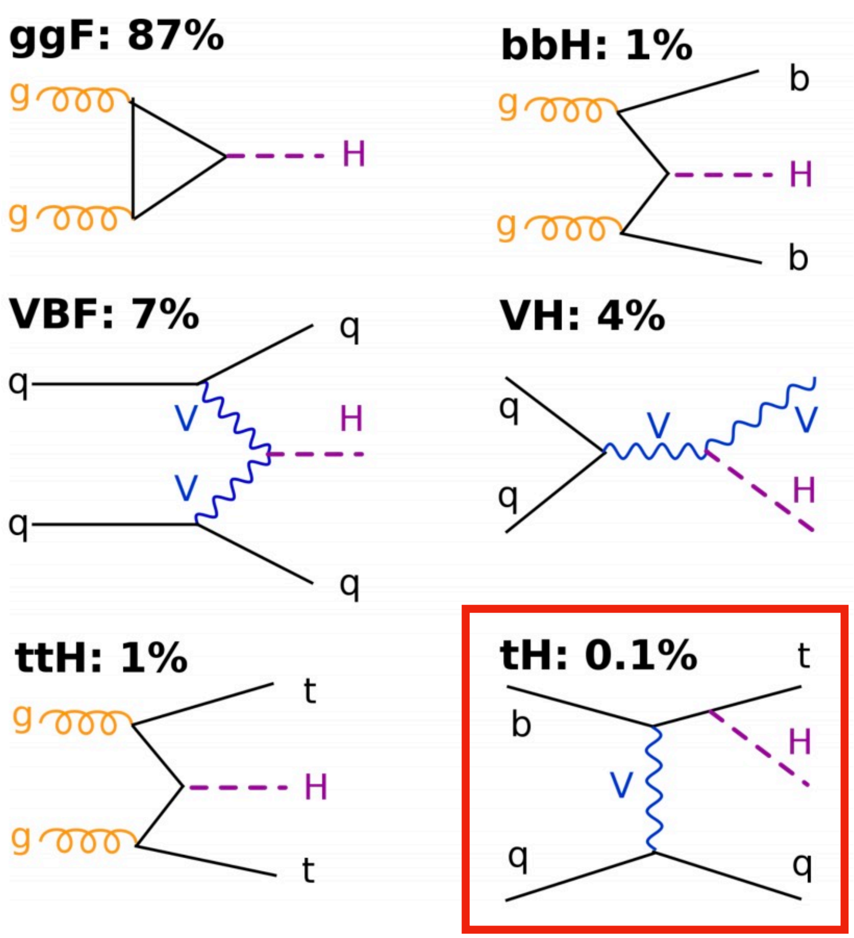
$t\bar{t}$H



$$\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{SM} = \kappa_t^2$$

The $\mathrm{H} \rightarrow \gamma\gamma$ Couplings Analysis Overview





% of Higgs production at LHC

- Full Run 2 ATLAS dataset $139\ \mathrm{fb}^{-1}$.
- $\mathrm{H} \rightarrow \gamma\gamma$ decay channel, fit in $m_{\gamma\gamma}$ spectrum.
- Measure key Higgs production cross-sections.
- How well can we constrain κ_t?

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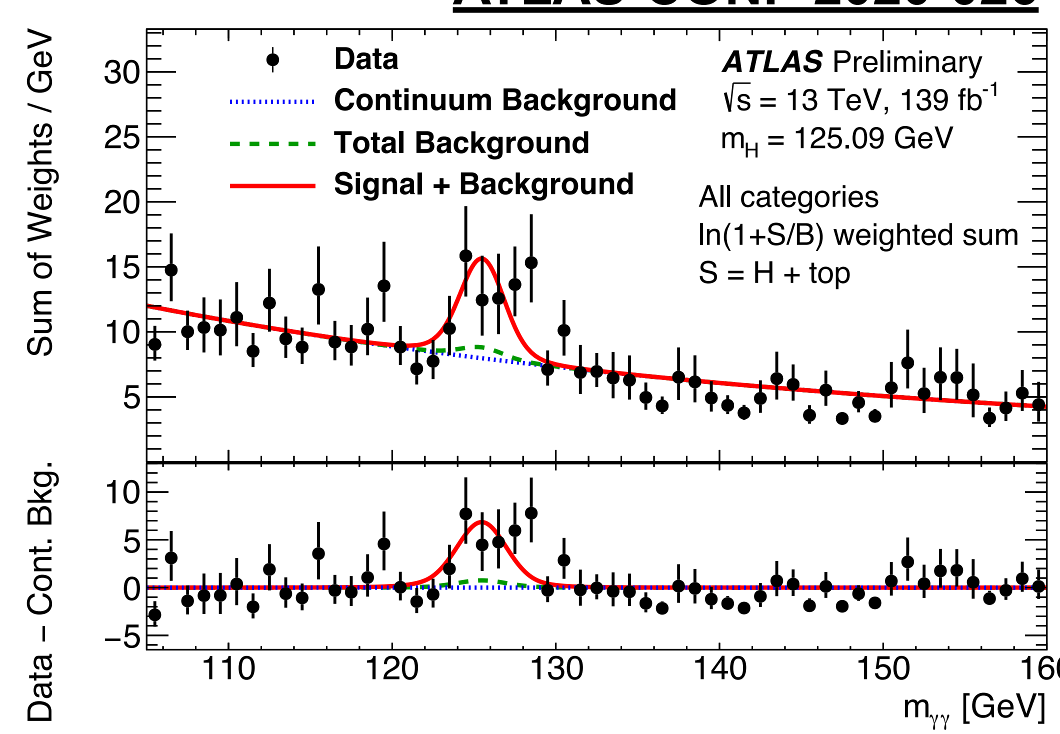


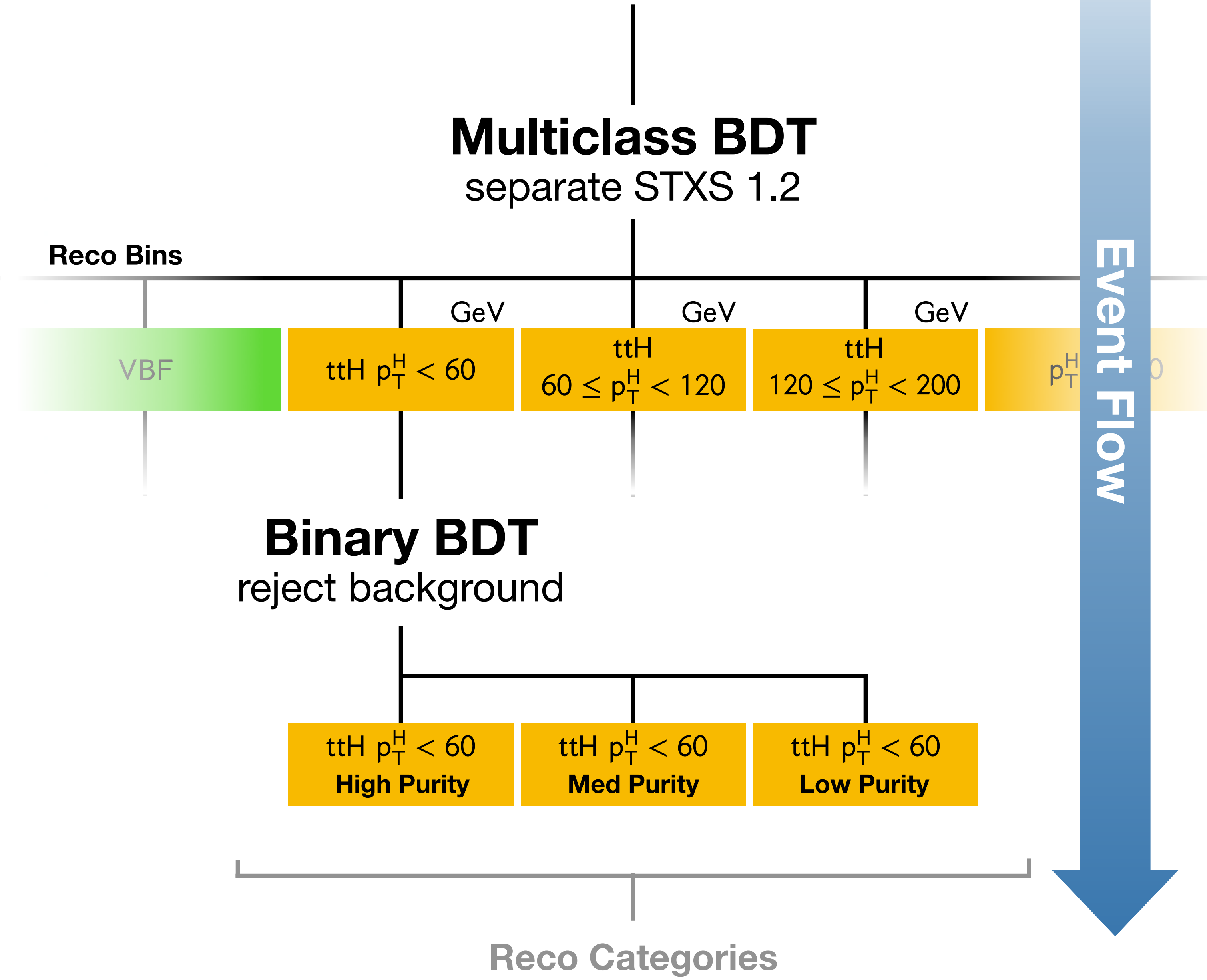
Categorisation Overview

Aims:

- Split events into categories sensitive to STXS 1.2 bins.
- Low correlation & high sensitivity.

Approach:

- Two “layered” categorisation:
  - **Multiclass BDT**: separate all signal classes.
  - **Binary BDT**: reject non-resonant background.



STXS = Simplified Template Cross-sections

Key Categorisation Components

Top Reconstruction

- BDTs trained with $\mathrm{t\bar{t}H}$ sample, using the XGBoost package
- Reconstructs up to two top candidates per event.
- Top candidate variables play a key role in categorisation performance for tH.
- Key in separating $\mathrm{t\bar{t}H}$ and tH.

top candidate ⟵ **max** $(BDT - score)_{triplet}$ ⟵ **BDT**

$P_4(W - \text{candidate})$

$P_4(b - \text{candidate})$

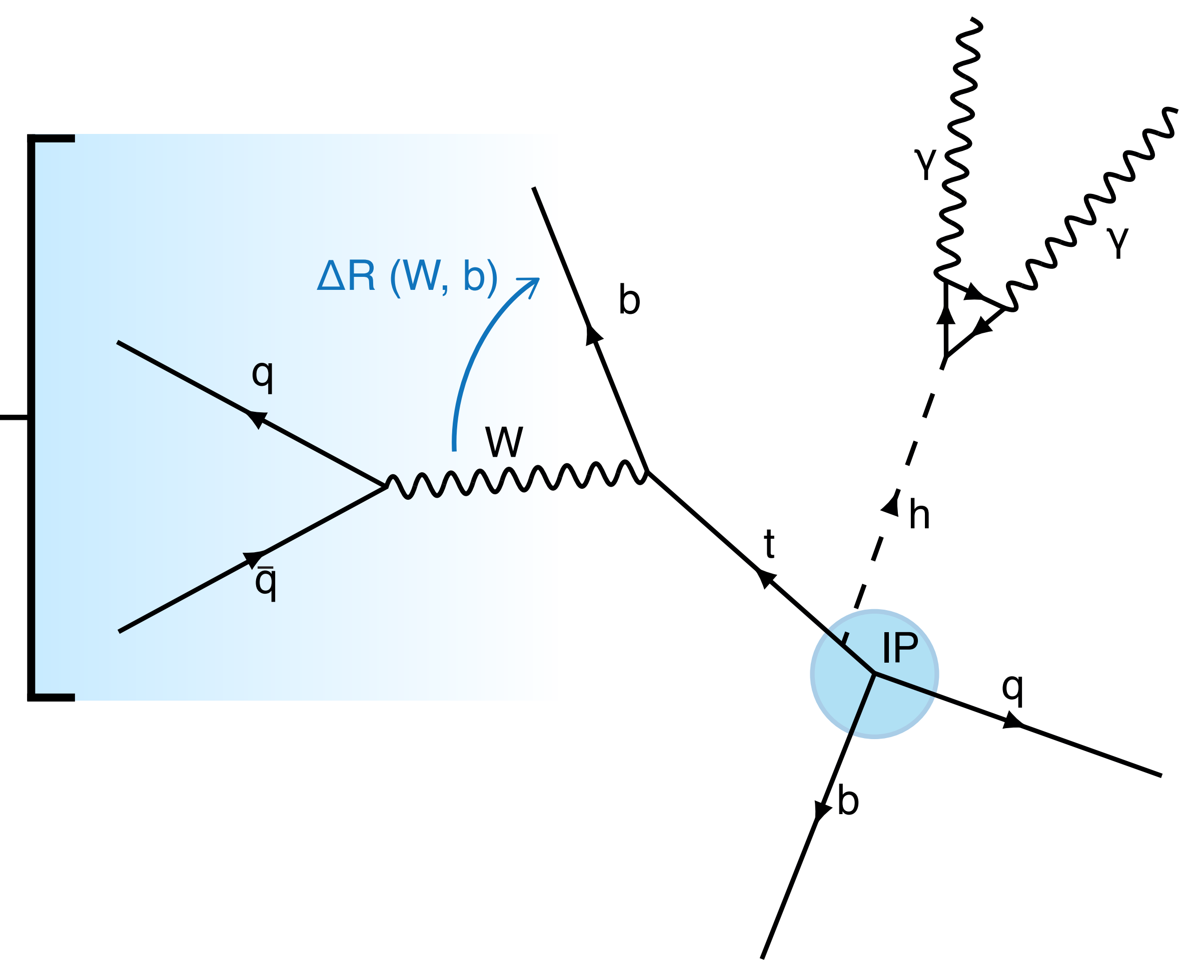
$\Delta R(W, b)$

$\Delta R(W_{j1}, W_{j2})$

$PCBtag_{jets}$

$m_{top-candidate}$

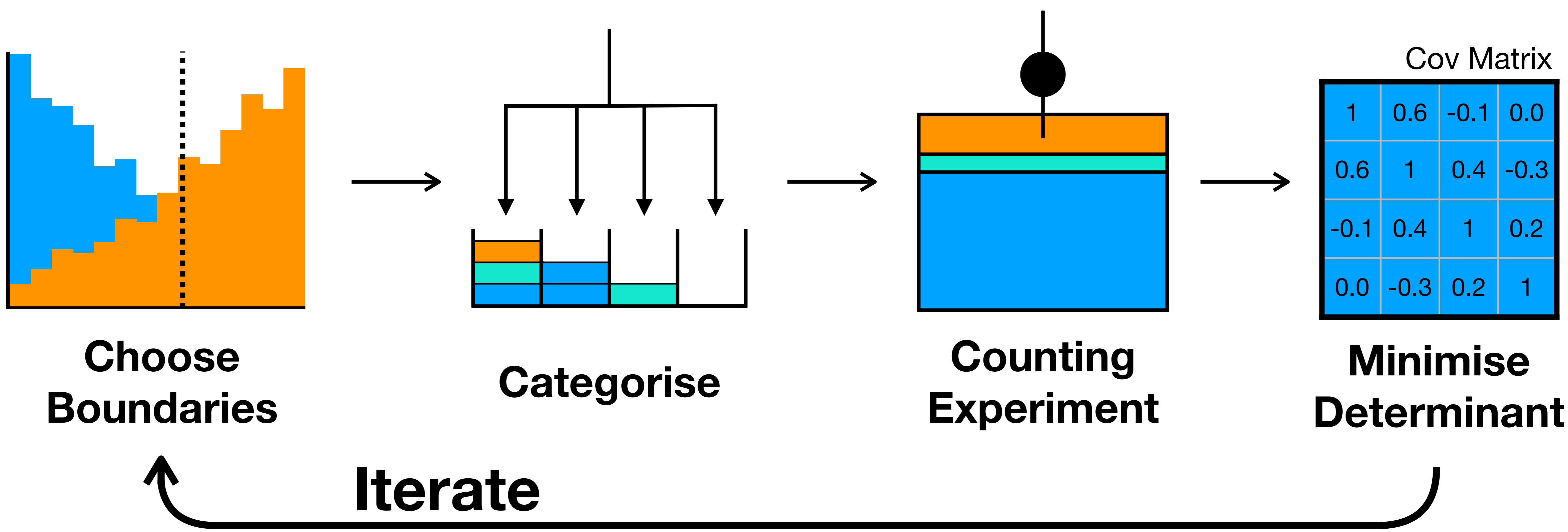
⟵



Key Categorisation Components

Multiclass D-Optimality (signal vs signal)

- Novel procedure to decide on **Multiclass BDT** category boundaries.
- Conduct counting experiment for each categorisation option.
- Minimise the determinant of the covariance matrix.
- Results in smallest overall uncertainty and correlation across cross-section measurement.



D-optimality

Key Categorisation Components

Top Binary BDTs (signal vs bkg)

- Three binary BDTs trained using XGBoost
- Separate top processes from non-resonant background.
- Make use of low level variables, including top candidate variables.

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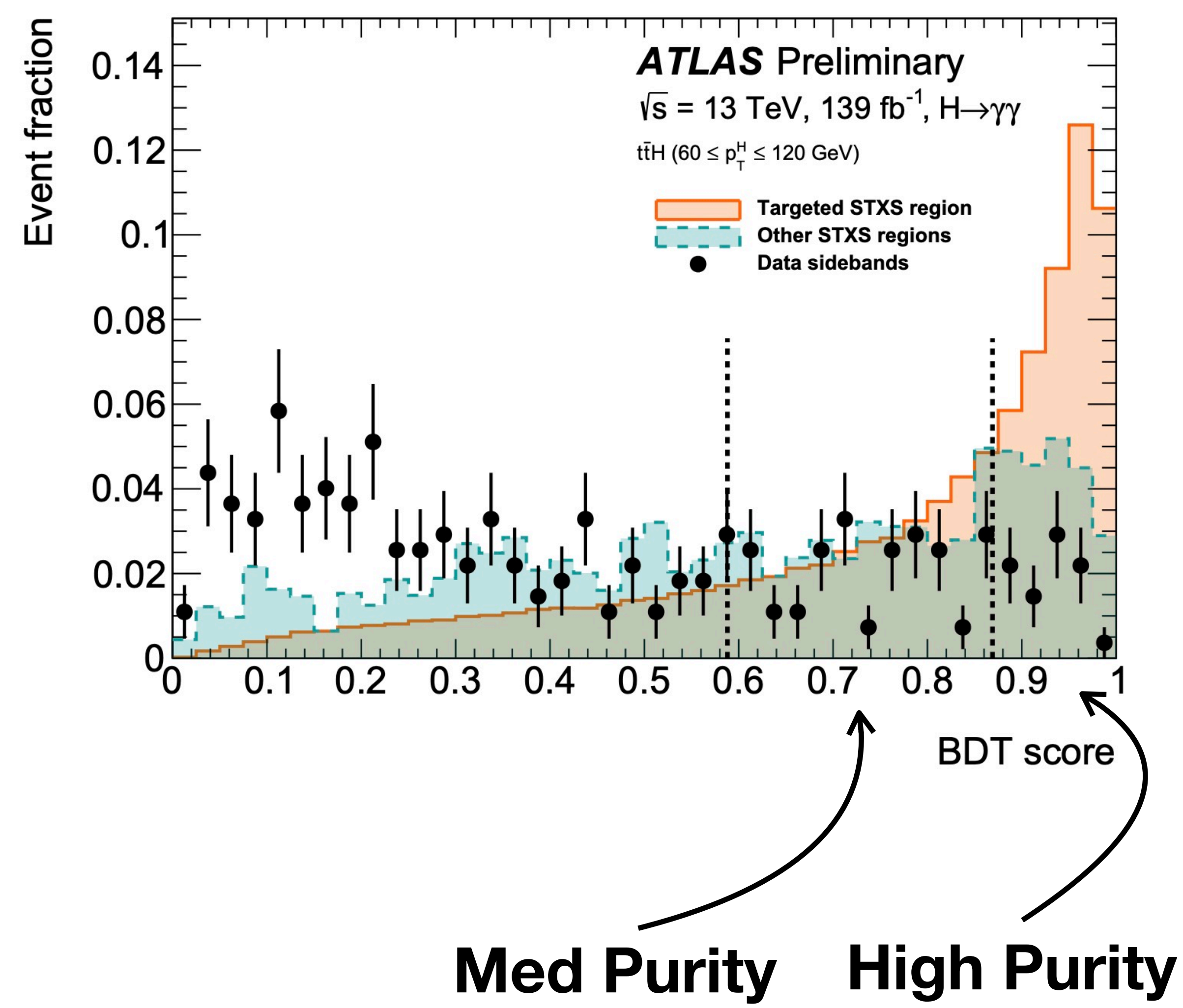
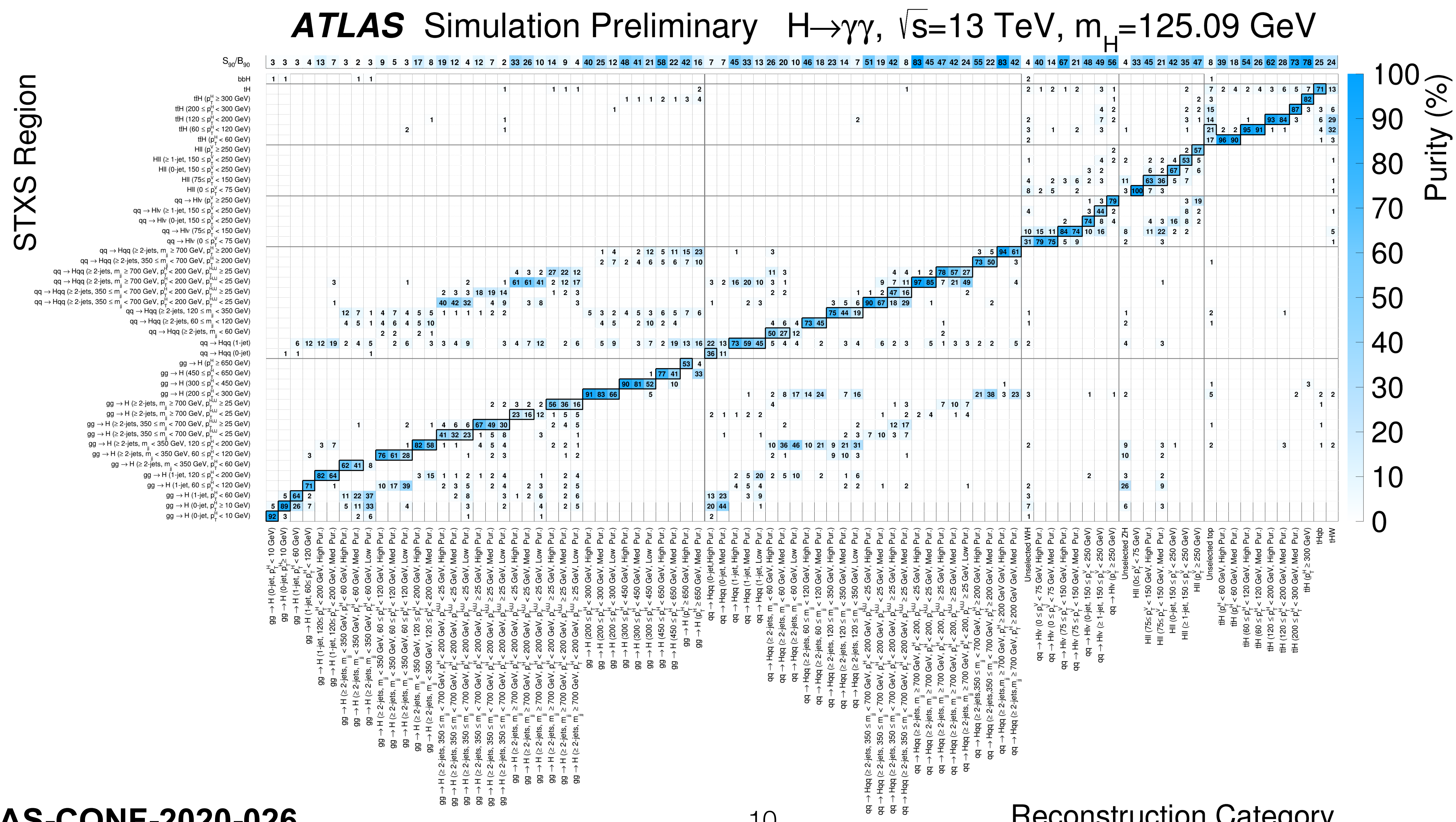


Categorisation Purities

- Results in 88 categories with high purity to targeted STXS 1.2 bins.



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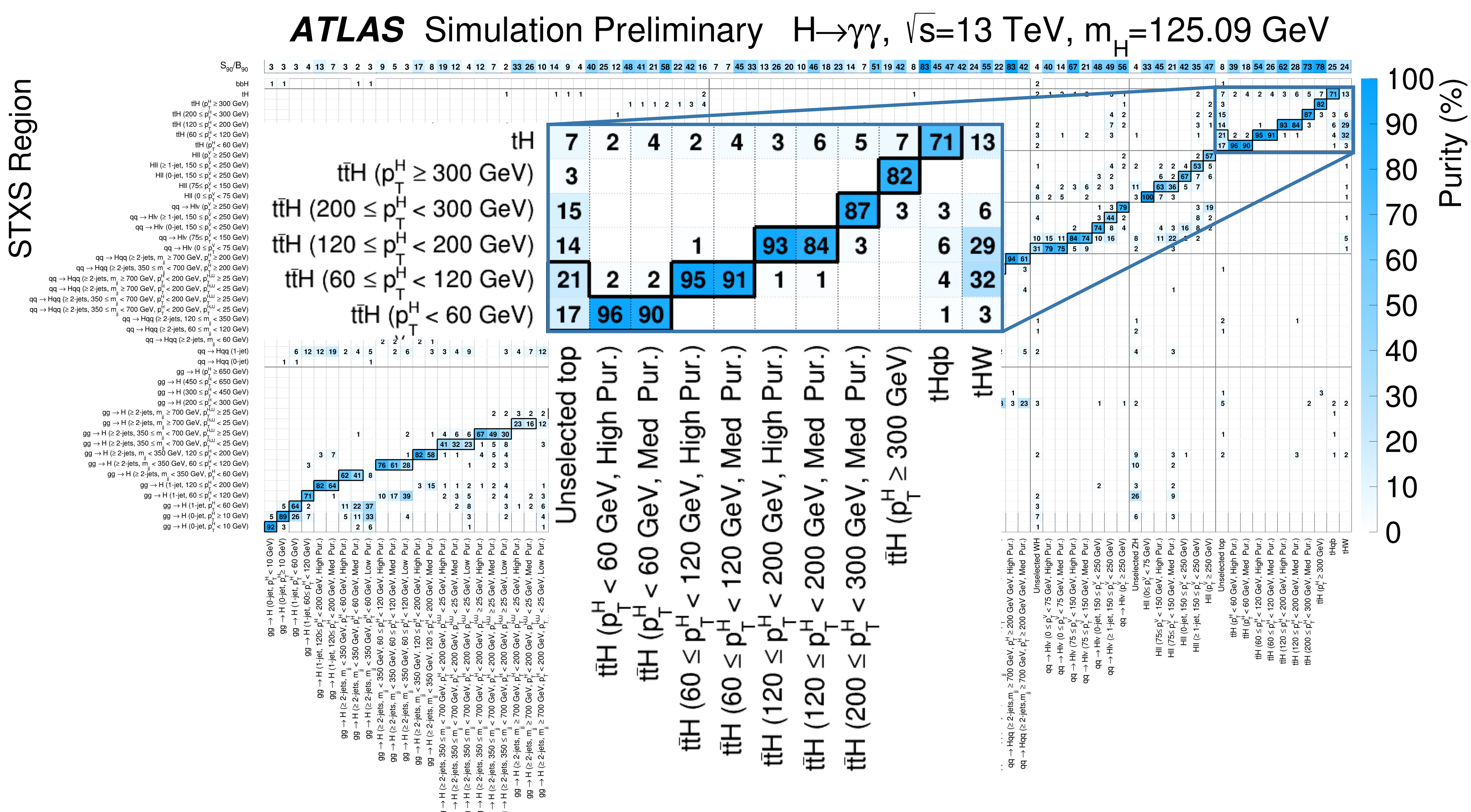

Results

- Results consistent with SM
- World-best tH SM sensitivity, $\sigma_{tH} < 8.3 \times \sigma_{tH}^{SM}$
- Lower than $12 \times \sigma_{tH}^{SM}$ expected for $\kappa_t = -1$ hypothesis [LHC Higgs XS 4]
- Low correlation between tH and $t\bar{t}H$

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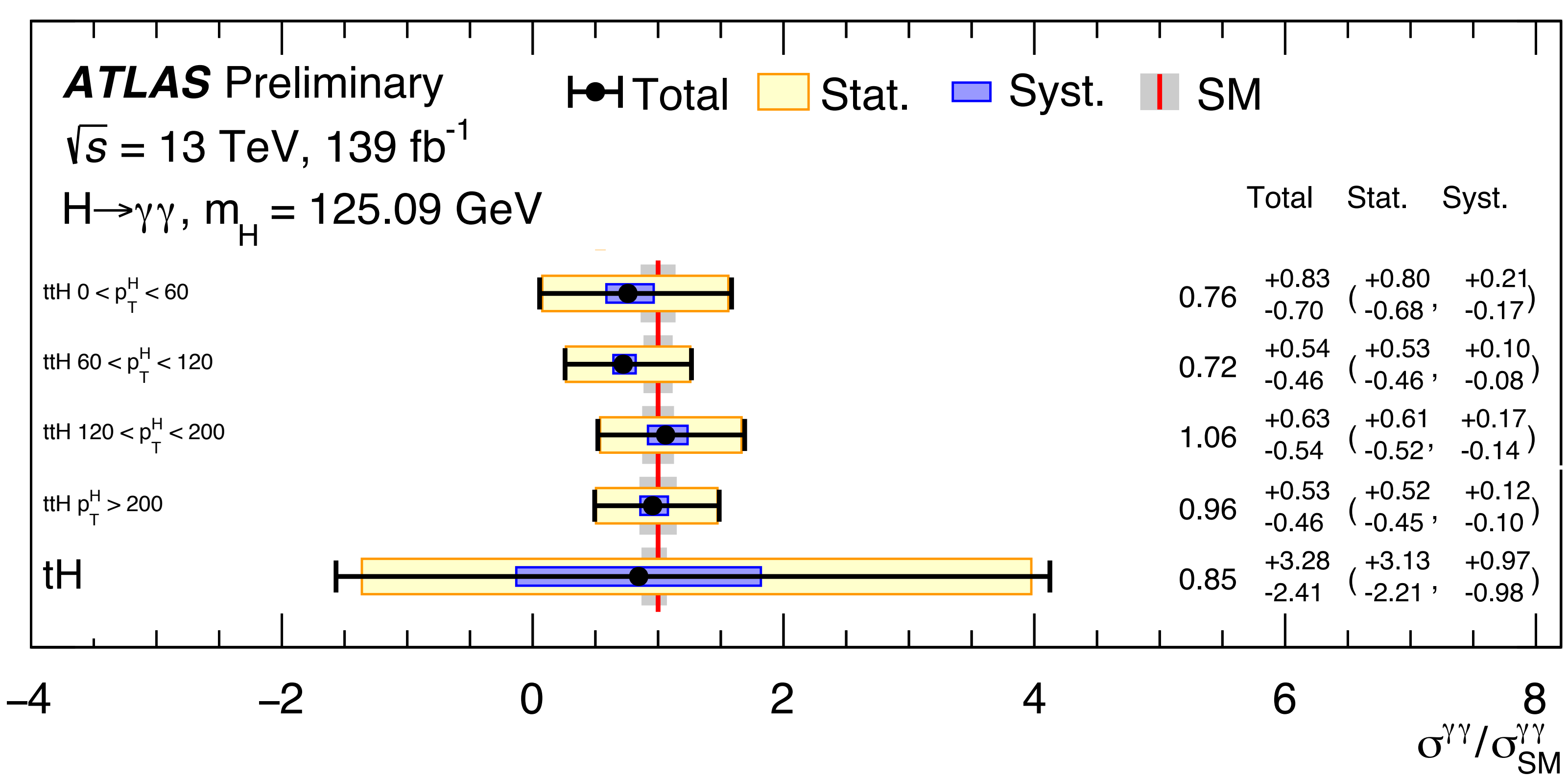

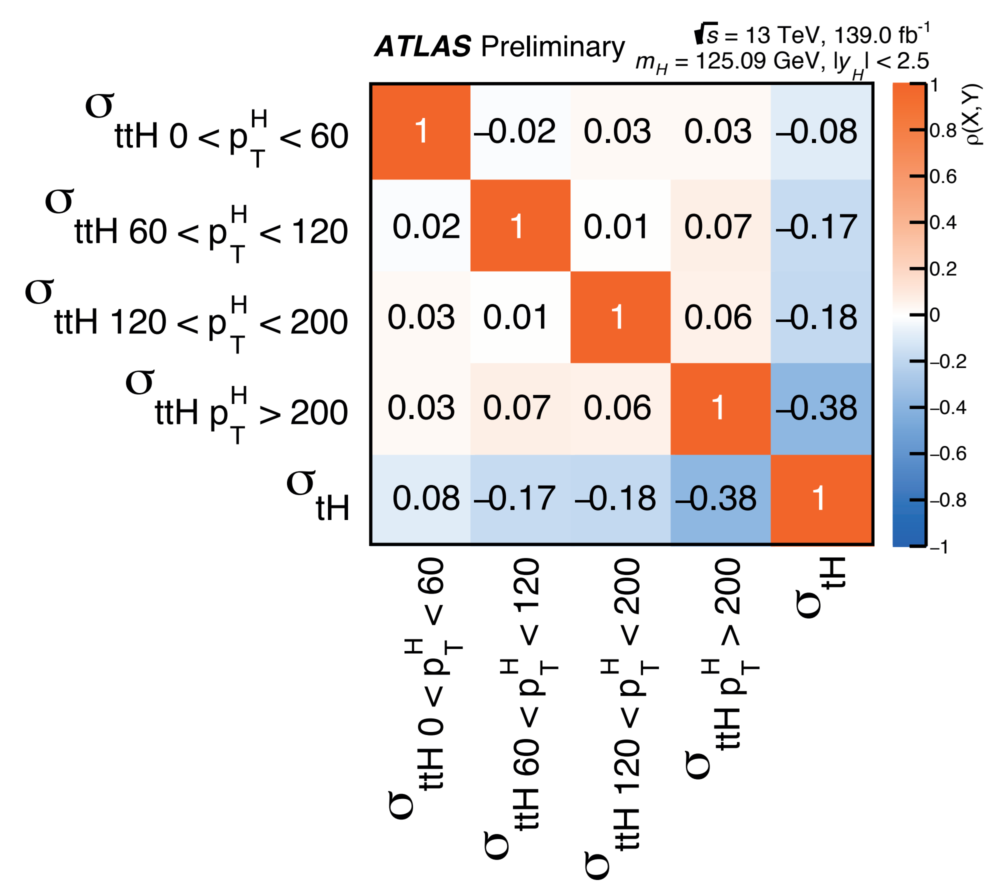

κ_t Results

Higgs Combination

- Combine results in different Higgs decay channels:
    - H $\rightarrow \gamma\gamma, ZZ^*, WW^*, \tau\tau, b\bar{b}, \mu\mu, inv$
- Contributions from gg → H and H $\rightarrow \gamma\gamma$ not considered
- Majority of sensitivity comes from tH in H $\rightarrow \gamma\gamma$ channel
- Small contribution from gg → ZH loop
- We can exclude negative values of κ_t at 2.9σ (2.7σ) obs (exp)!

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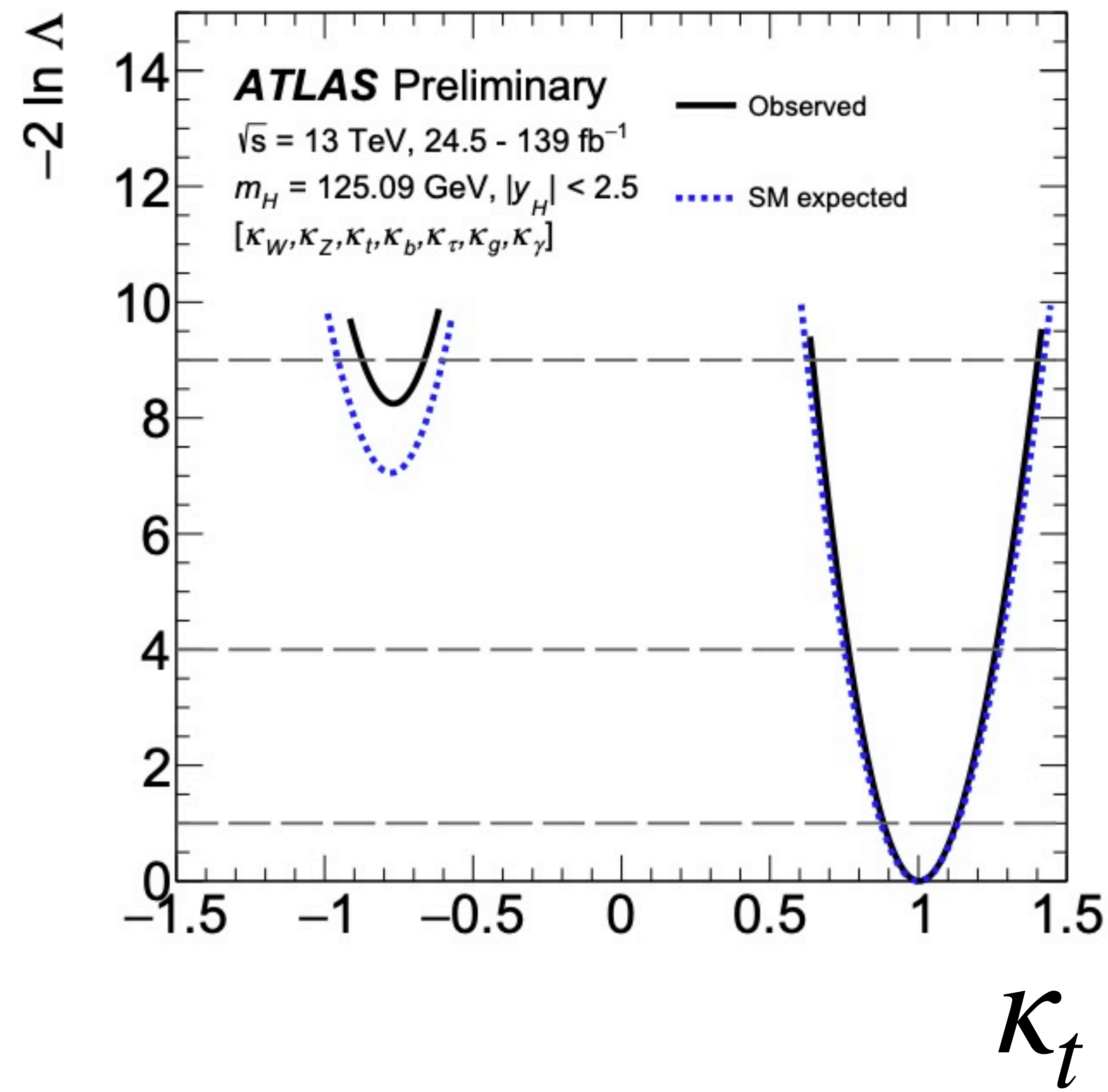
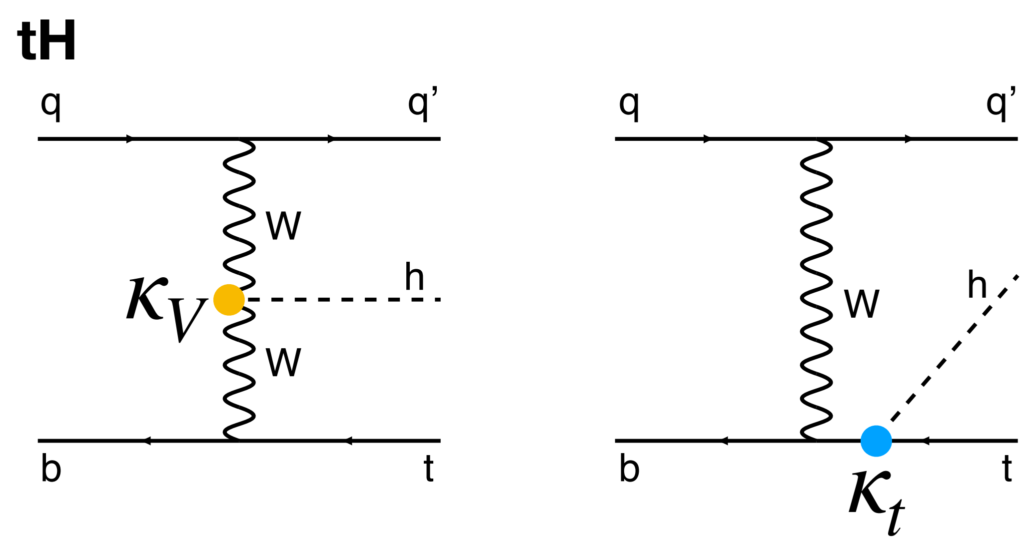


Summary

- Top Yukawa coupling Y_t is one of the 25 fundamental parameters of the Standard Model.
- Single-top Higgs process (tH) extremely sensitive to the sign of κ_t.
- H $\rightarrow \gamma\gamma$ analysis can set world-best constraint on $\sigma_{tH} < 8.3 \times \sigma_{tH}^{SM}$
- This sensitivity allows us to exclude negative κ_t at 2.9σ (2.7σ) obs (exp)



$$\sigma_{tH}/\sigma_{tH}^{SM} = 2.63\kappa_t^2 - 5.25\kappa_t\kappa_V + 3.58\kappa_V^2$$

Backup

Combination Generic Model

- gg → H and H → $\gamma\gamma$ loops are not resolved
- Using effective couplings κ_g and κ_γ

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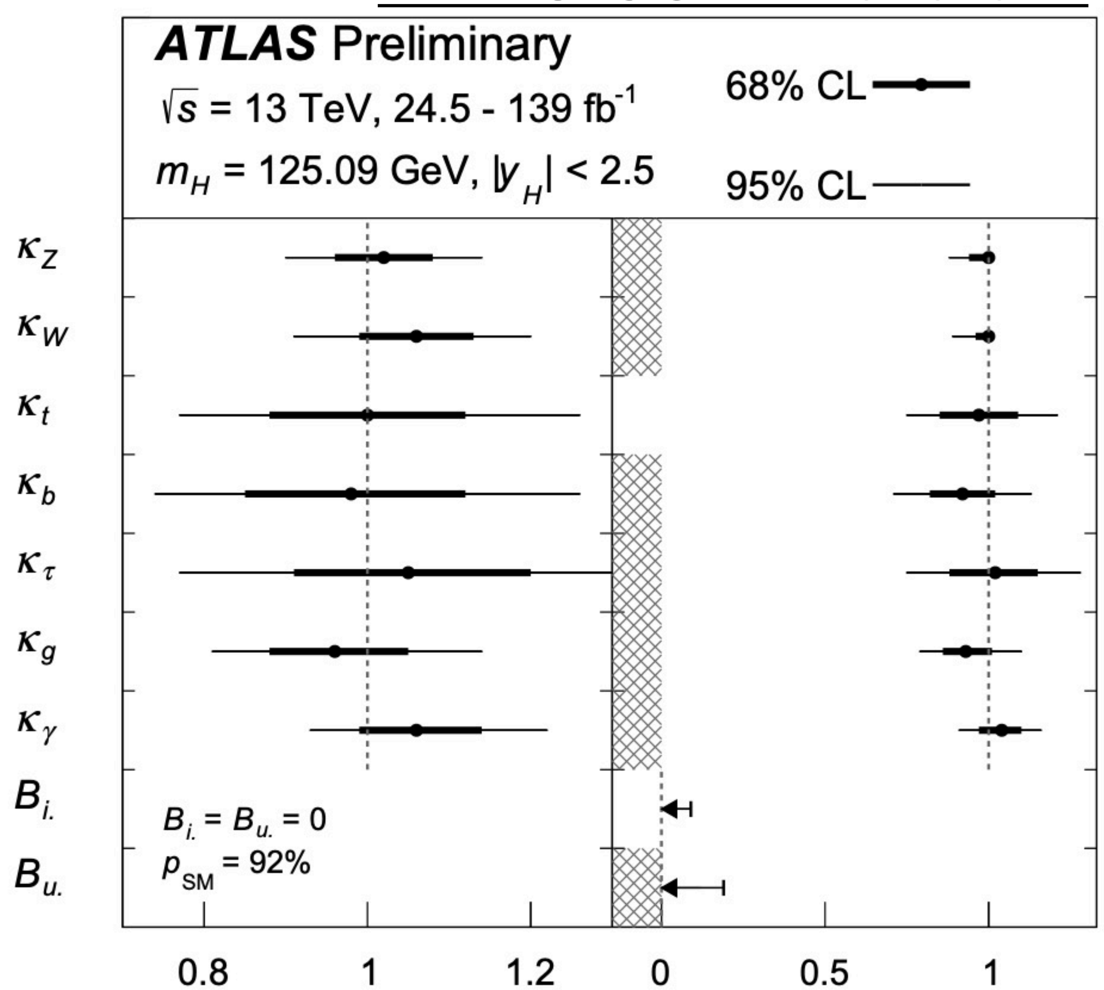
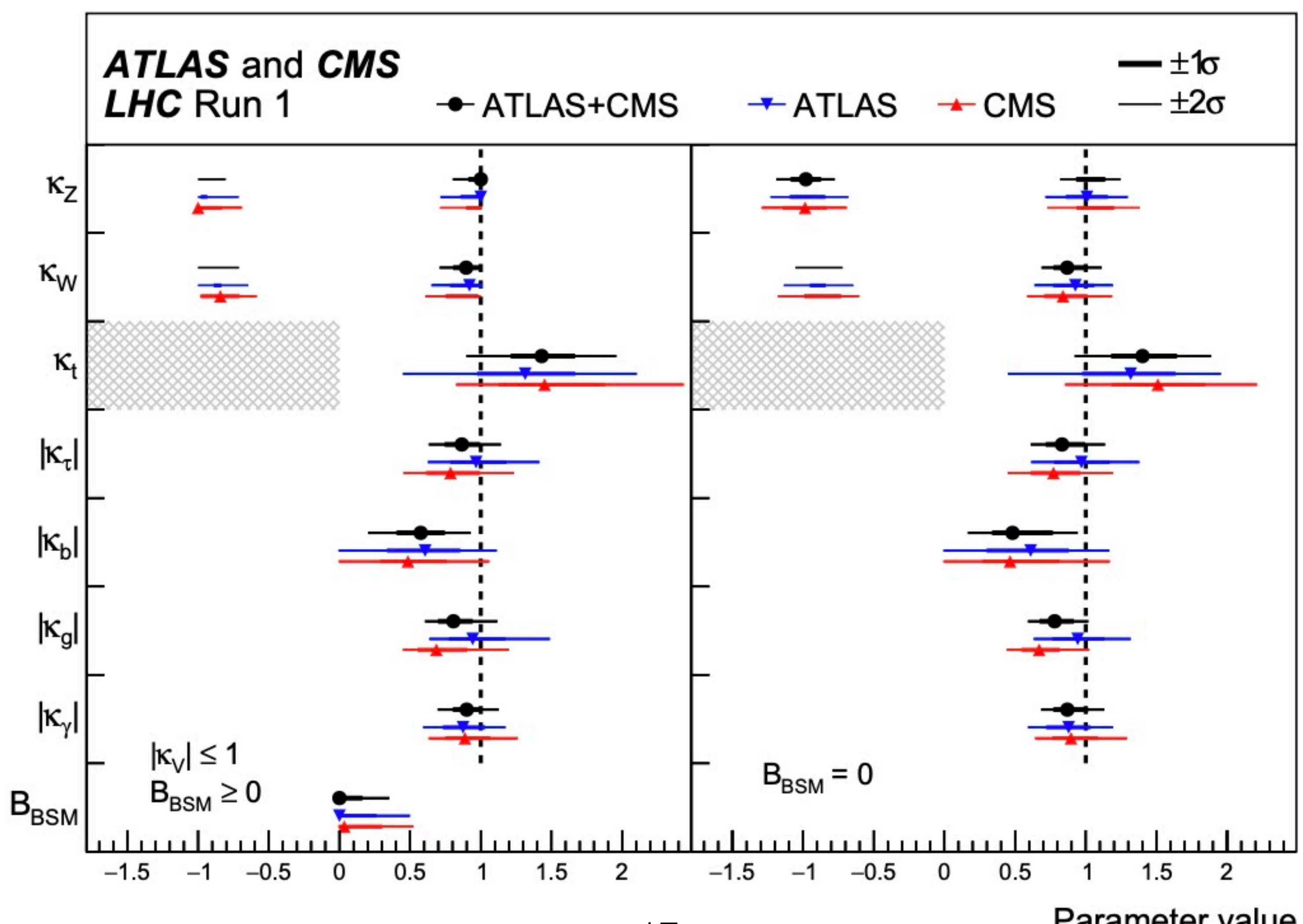


ATLAS + CMS Run1 Combination

- κ_t was fixed to be positive
- Probed the relative sign of κ_V and κ_t

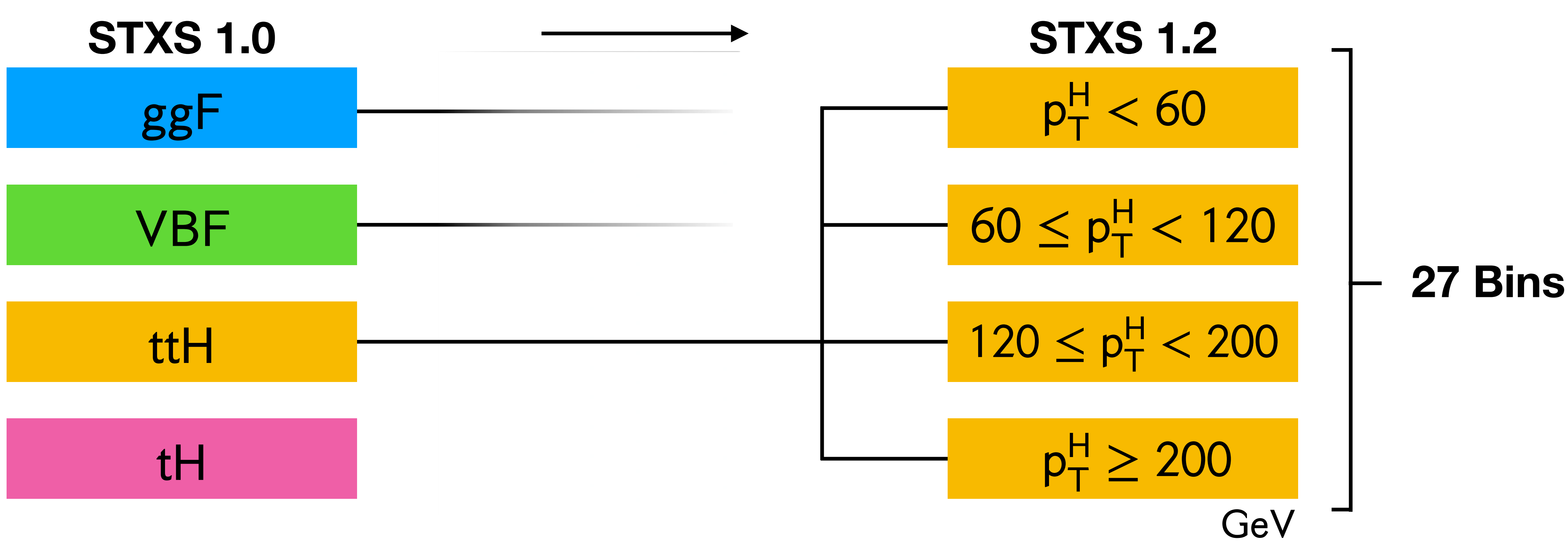
ATLAS + CMS Run1 Combination



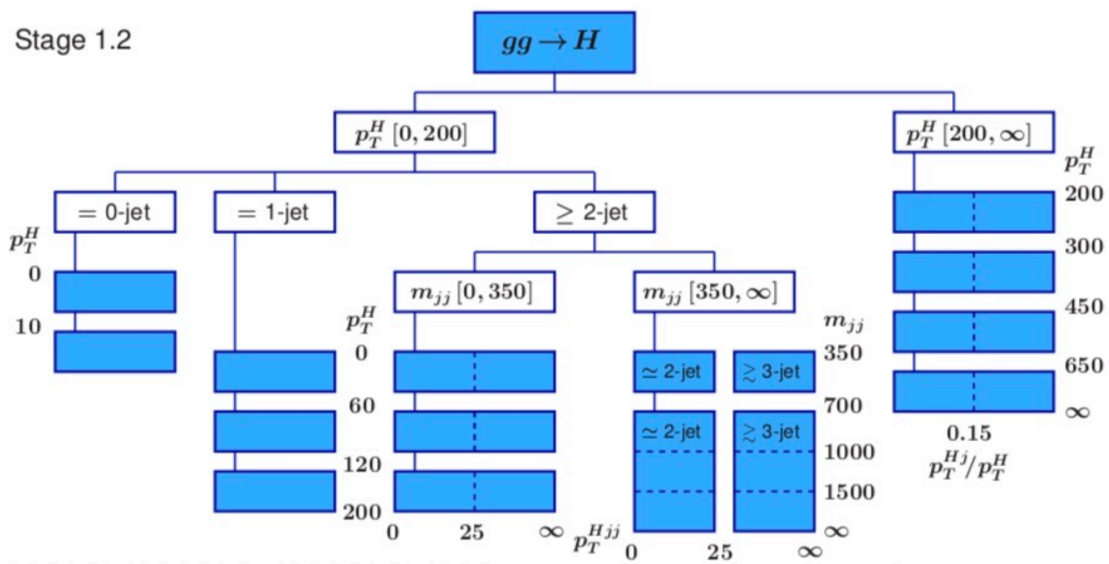
STXS 1.2

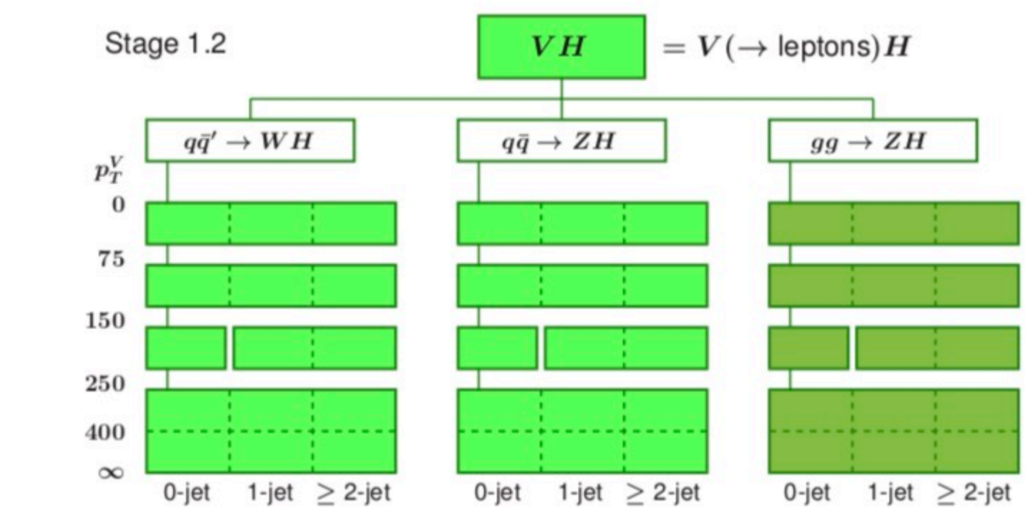
Simplified Template Cross-Sections

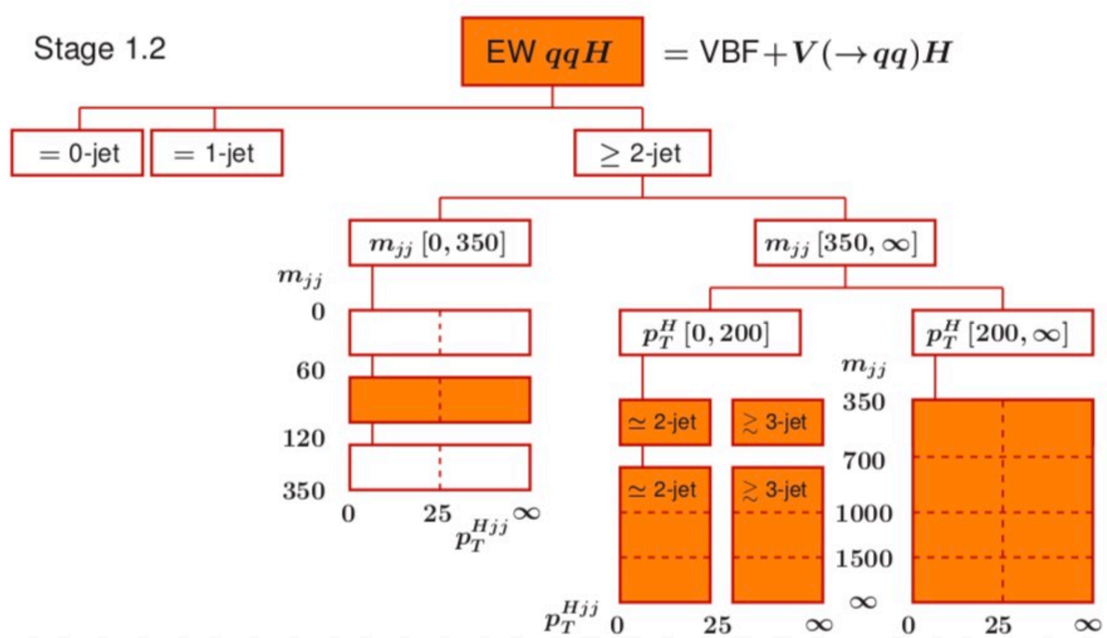
- Consistency in measurements across analyses and experiments for combinations.
- Targets Higgs production mode phase spaces to reduce theoretical uncertainty.

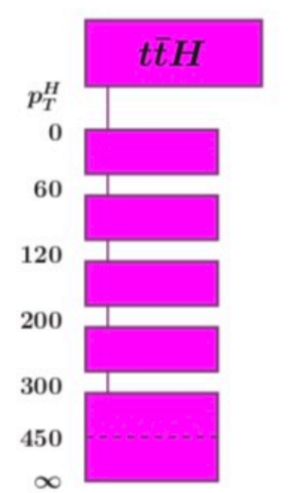


STXS 1.2


Stage 1.2
gg → H
p_T^H [0, 200]
p_T^H [200, ∞]
= 0-jet
= 1-jet
≥ 2-jet
m_jj [0, 350]
m_jj [350, ∞]
≃ 2-jet
≳ 3-jet
p_T^H
0
10
60
120
200
300
450
650
∞
m_jj
350
700
1000
1500
25
p_T^Hjj
0.15
p_T^Hj/p_T^H


Stage 1.2
VH
= V(→ leptons)H
qq̄′ → WH
qq̄ → ZH
gg → ZH
p_T^V
0
75
150
250
400
∞
0-jet
1-jet
≥ 2-jet


Stage 1.2
EW qqH
= VBF+V(→qq)H
= 0-jet
= 1-jet
≥ 2-jet
m_jj [0, 350]
m_jj [350, ∞]
p_T^H [0, 200]
p_T^H [200, ∞]
≃ 2-jet
≳ 3-jet
m_jj
0
60
120
350
700
1000
1500
∞
25
p_T^Hjj

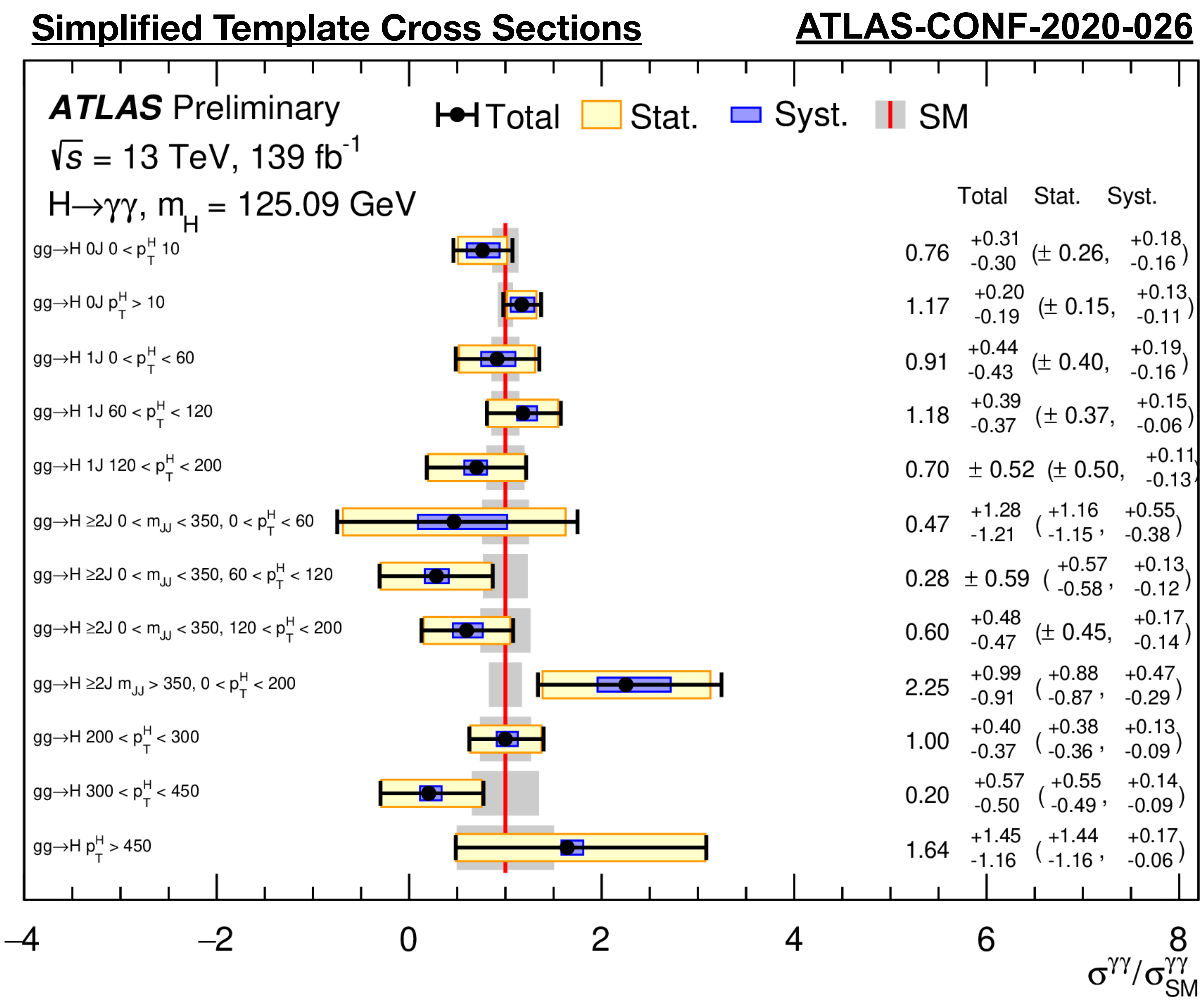

tt̄H
p_T^H
0
60
120
200
300
450
∞

D-Optimality

- Adjust weights applied to BDT category scores.
- Minimise using Powell algorithm.
- Does not need to be differentiable.
- BDT categorises events based on maximal score.

$$S \circ \vec{w} = (s_{ij} \cdot w_j) = \begin{bmatrix} s_{11} \cdot w_1 & \cdots & s_{1M} \cdot w_M \\ \vdots & \ddots & \vdots \\ s_{N1} \cdot w_1 & \cdots & s_{NM} \cdot w_M \end{bmatrix}$$

Results: 27 STXS



Results: 27 STXS

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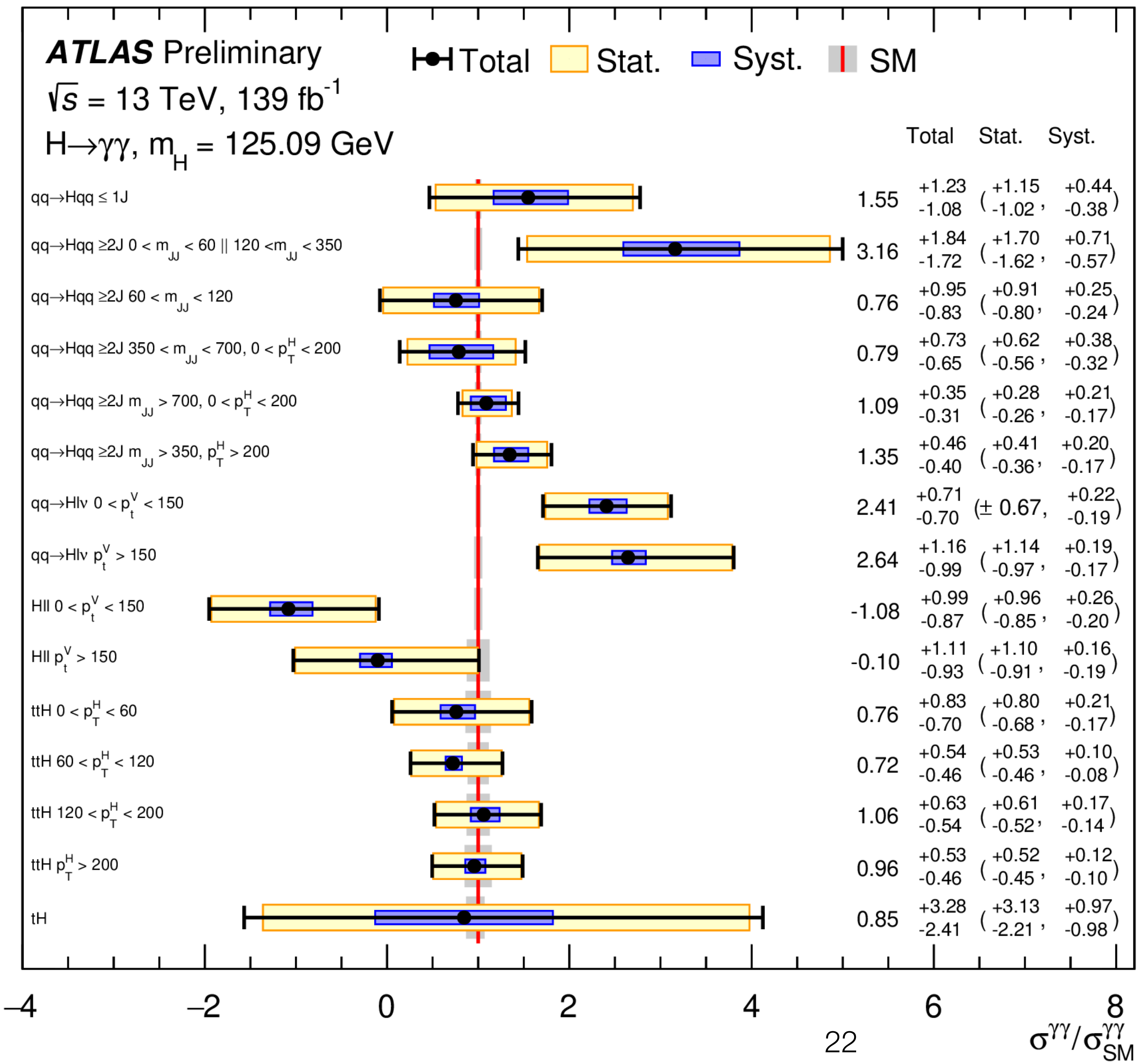
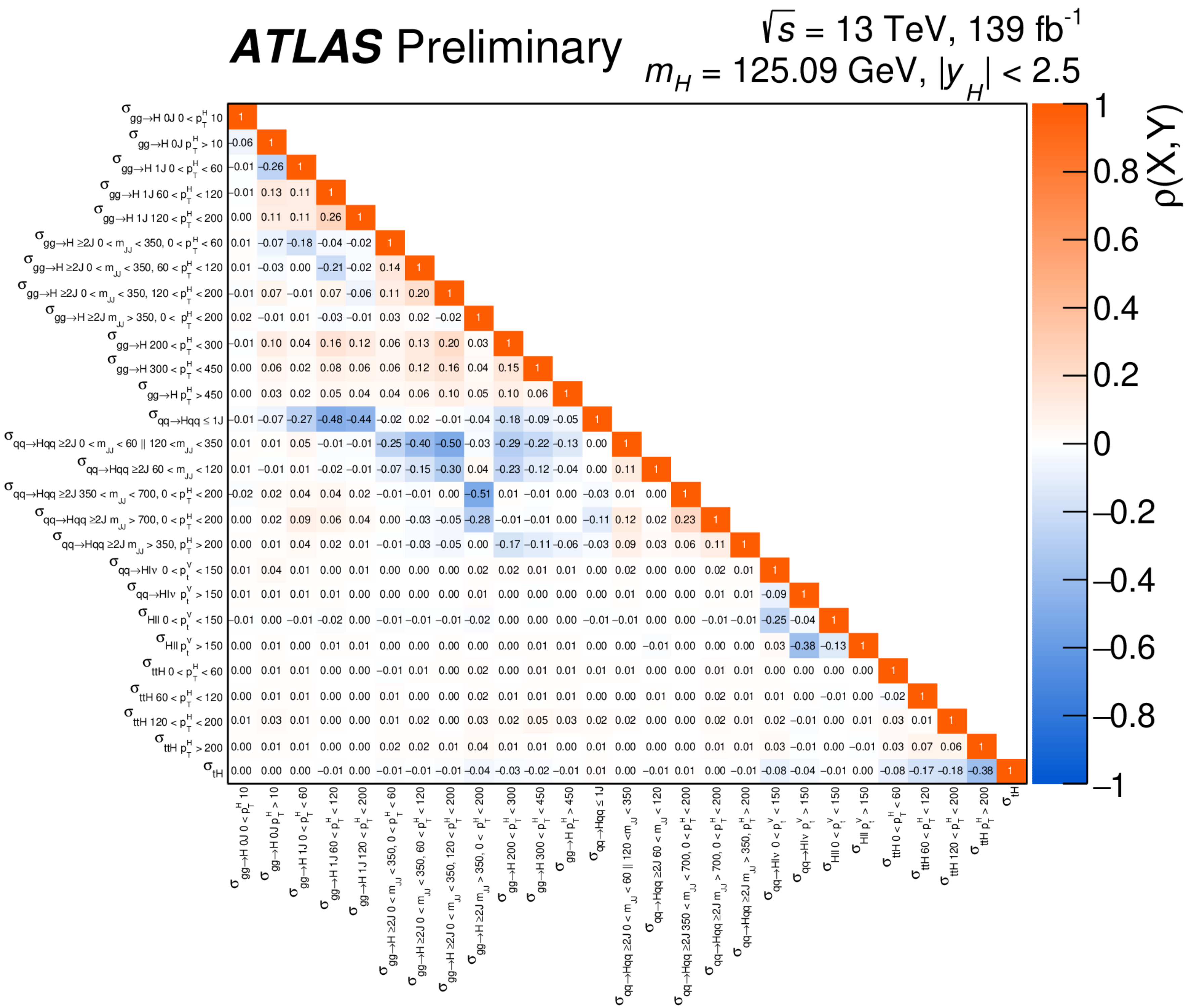
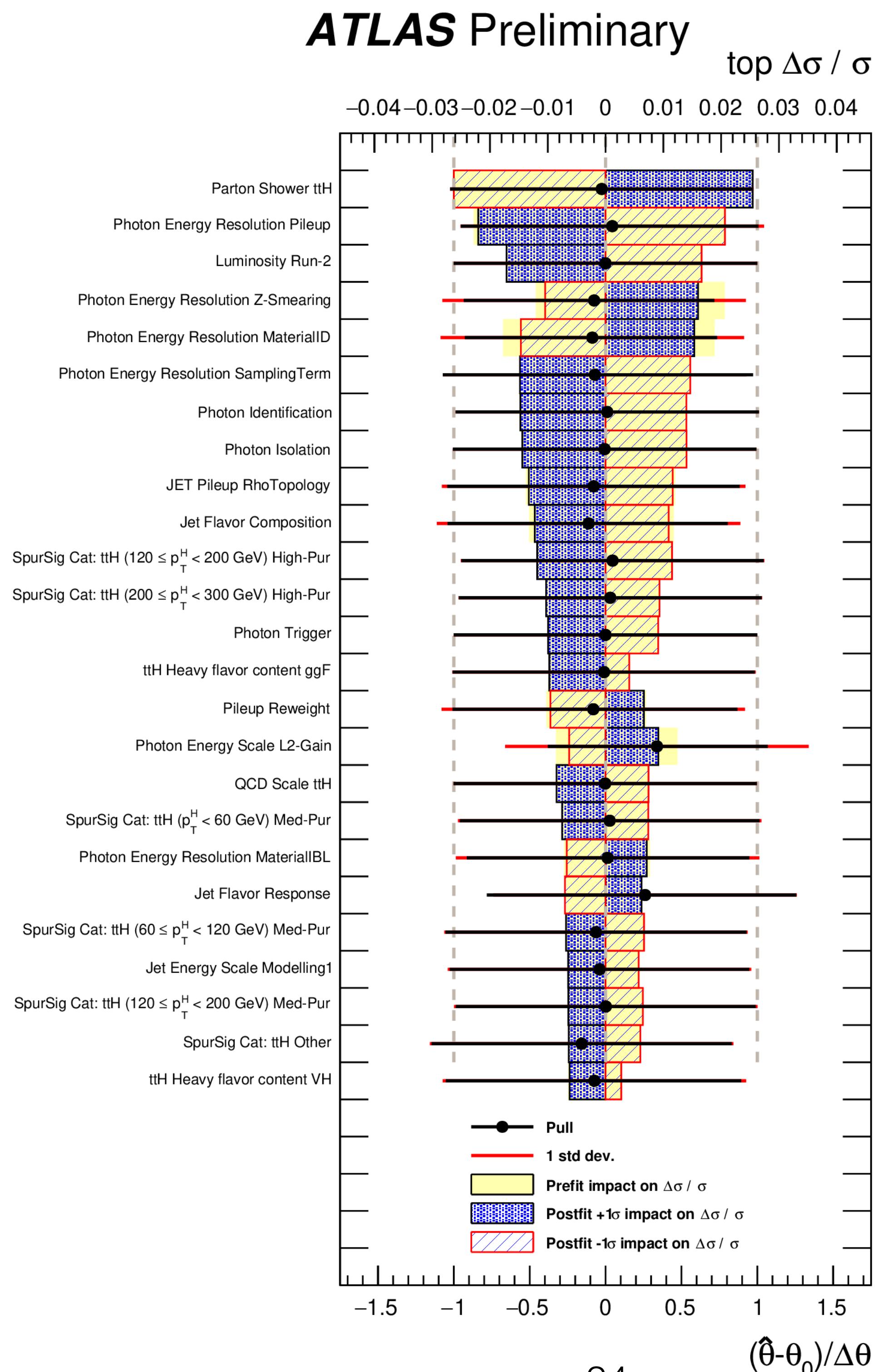


- Results consistent with SM (p-value 60%).
- ttH observed (expected) sensitivity 4.3σ (4.7σ)
- First analysis to keep tH as separate POI.
- Upper limit on $\mu_{tH} < 8.2$

Results: STXS Correlations



Results: Top Pulls



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Signal & Background Modelling

Signal:

- Fit Double-sided Crystal Ball function to MC in each analysis category.
- Parameters are then fixed in final fit to data.

Background:

- Data driven!
- Fit analytical function to data sideband.

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