$t\bar{t}$ and QCD Backgrounds in the $hh \to b\bar{b}b\bar{b}$ Boosted Analysis with ATLAS

Josephine Brewster, Max Swiatlowski, Marco Valente, Russell Bate, Dilia Portillo Quintero, Sebastien Rettie

August 7th, 2024

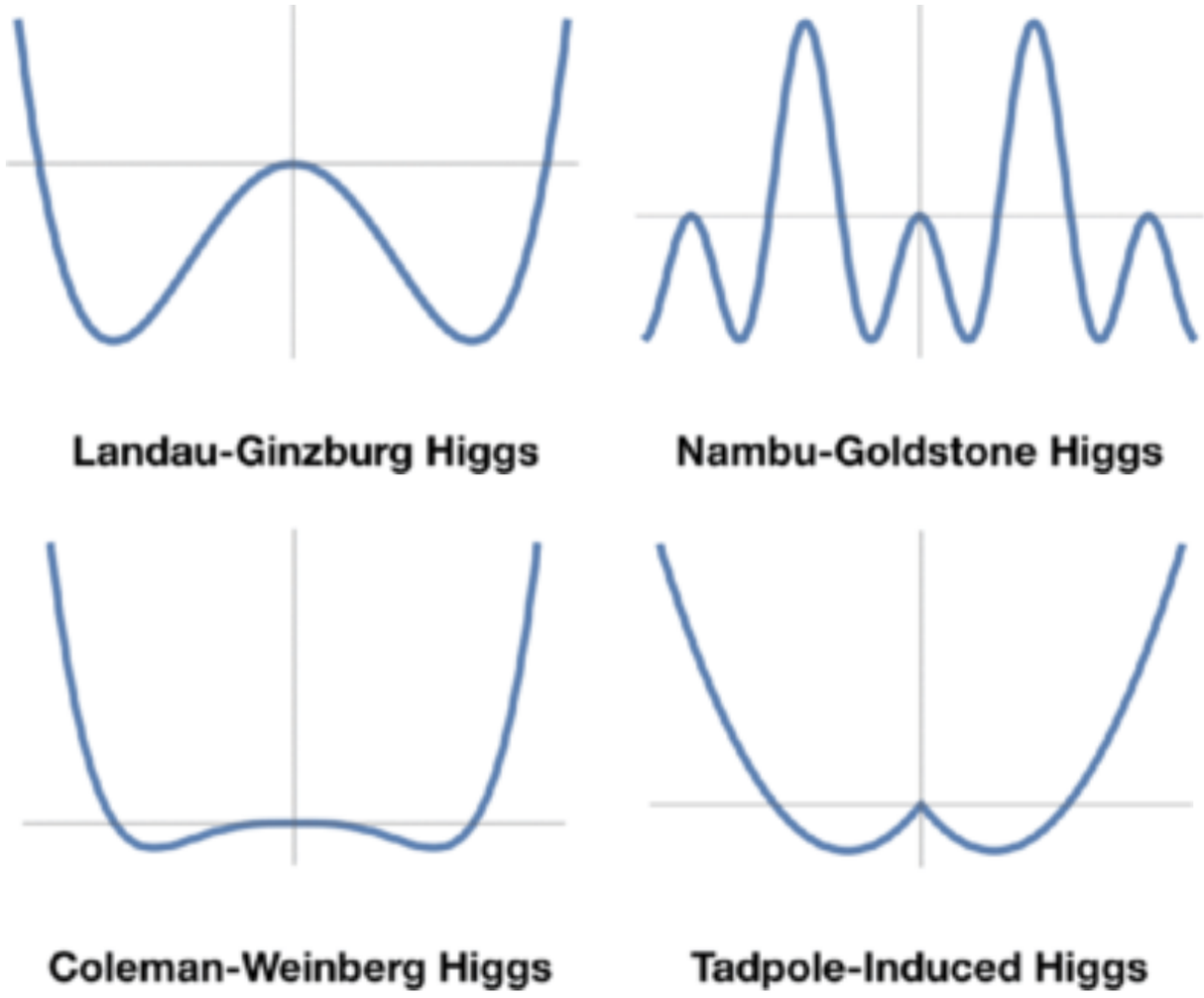
Why Measure the Higgs Self-Coupling?

Why Measure the Higgs Self-Coupling?

- Higgs self-coupling tells us about the shape of the Higgs potential

Why Measure the Higgs Self-Coupling?

- Higgs self-coupling tells us about the shape of the Higgs potential



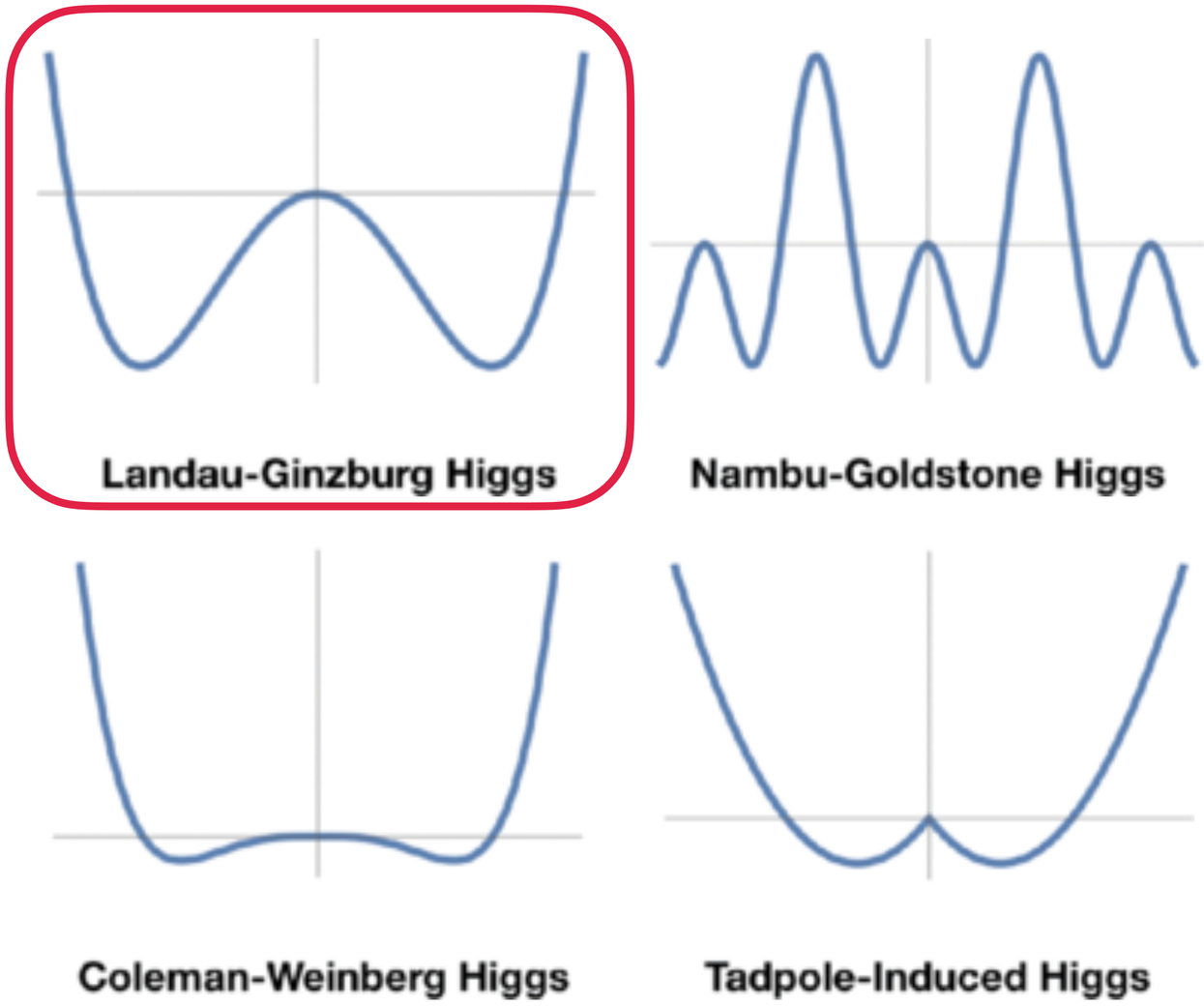
PhysRevD.101.075023

Why Measure the Higgs Self-Coupling?

- Higgs self-coupling tells us about the shape of the Higgs potential

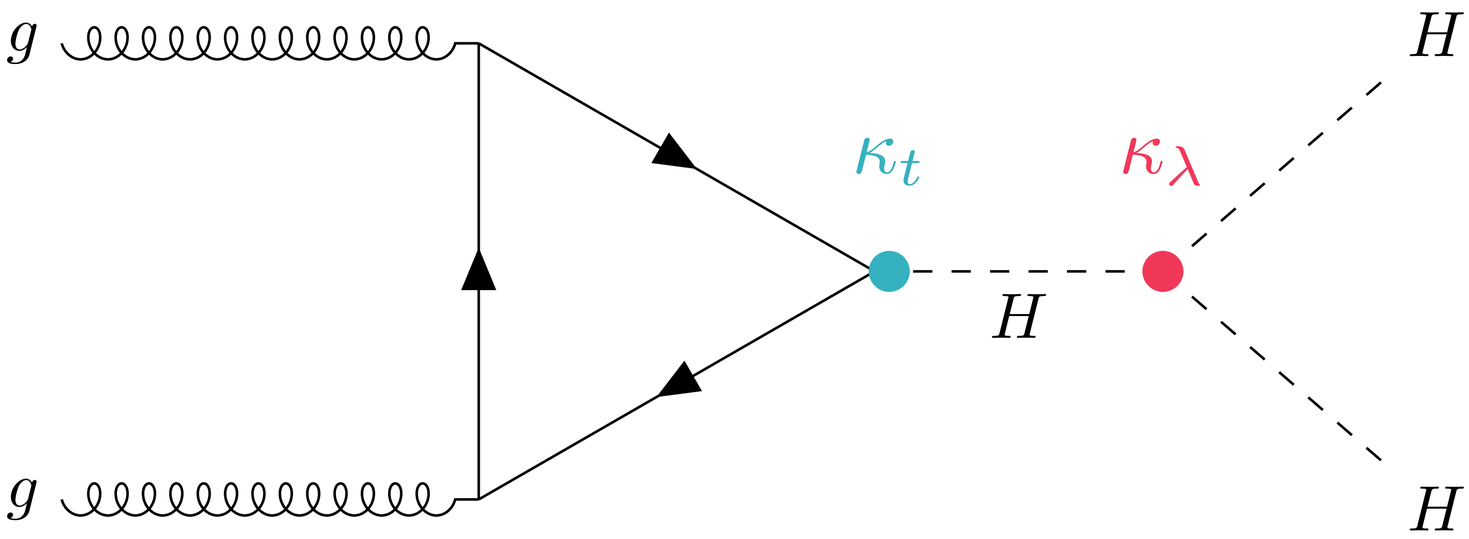
Standard Model Higgs:

$$\lambda H^4 - 2\lambda v^2 H^2 + \lambda v^4$$



PhysRevD.101.075023

How Do We Measure the Higgs Self-Coupling?



- This diagram lets us measure the Higgs self-coupling κ_λ by studying events with two Higgs bosons

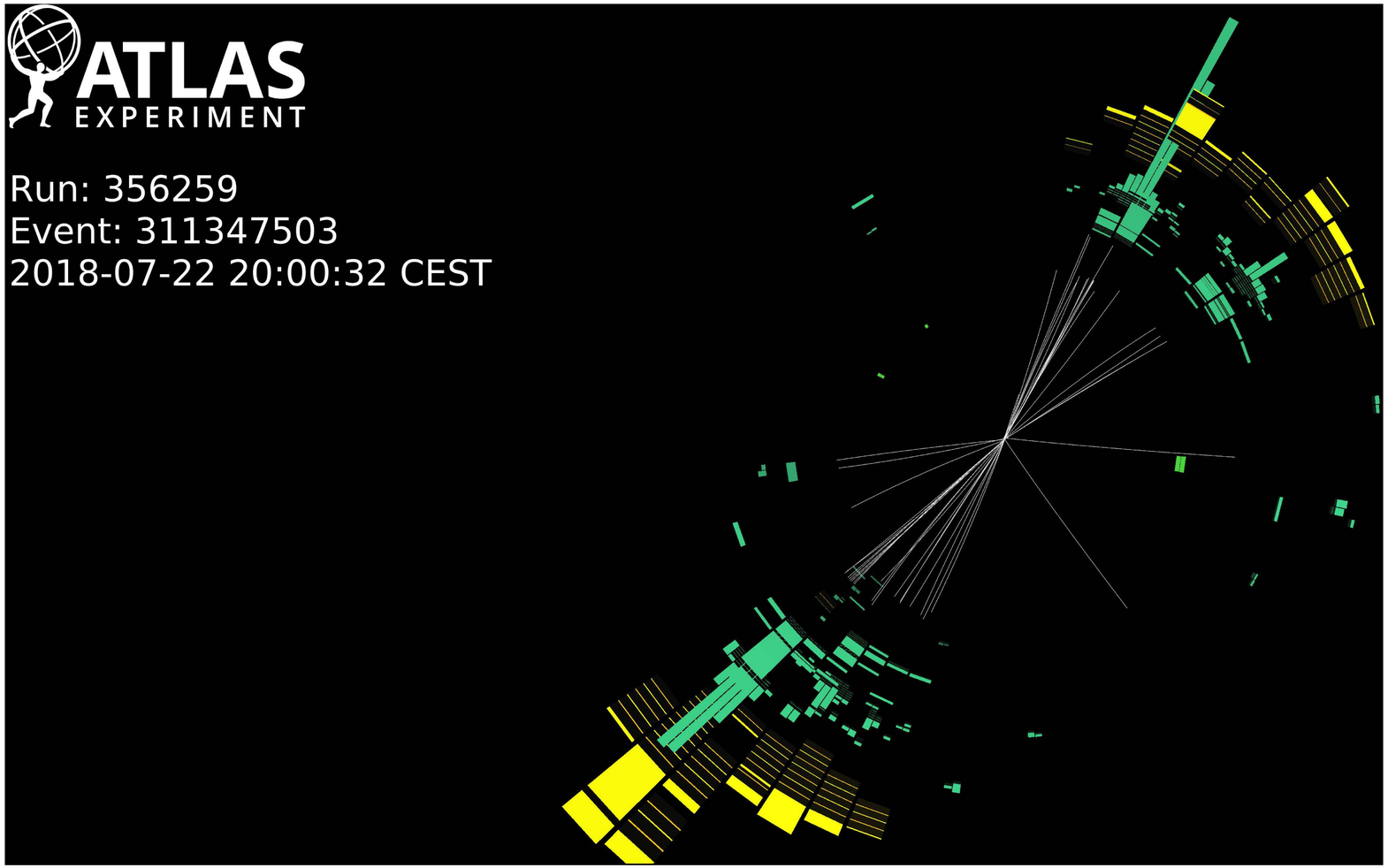
$hh \to b\bar{b}b\bar{b}$ Boosted Analysis

$hh \to b\bar{b}b\bar{b}$ Boosted Analysis

- $hh \to b\bar{b}b\bar{b}$ is the most common decay

$hh \rightarrow b\bar{b}b\bar{b}$ Boosted Analysis

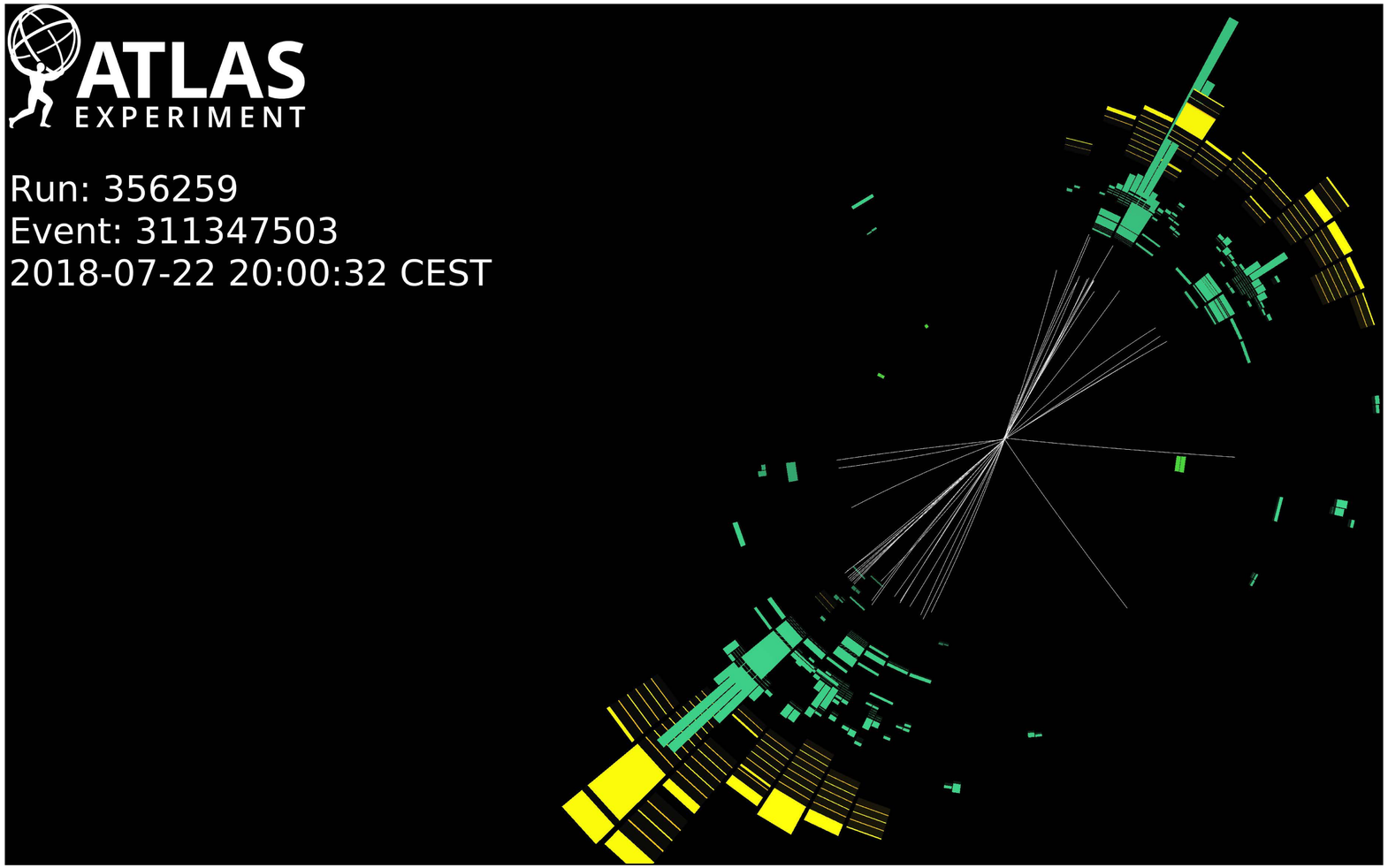
- $hh \rightarrow b\bar{b}b\bar{b}$ is the most common decay
- Boosted analysis: two large radius jets containing two b quarks each



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-41/figaux_11.png

$hh \rightarrow b\bar{b}b\bar{b}$ Boosted Analysis

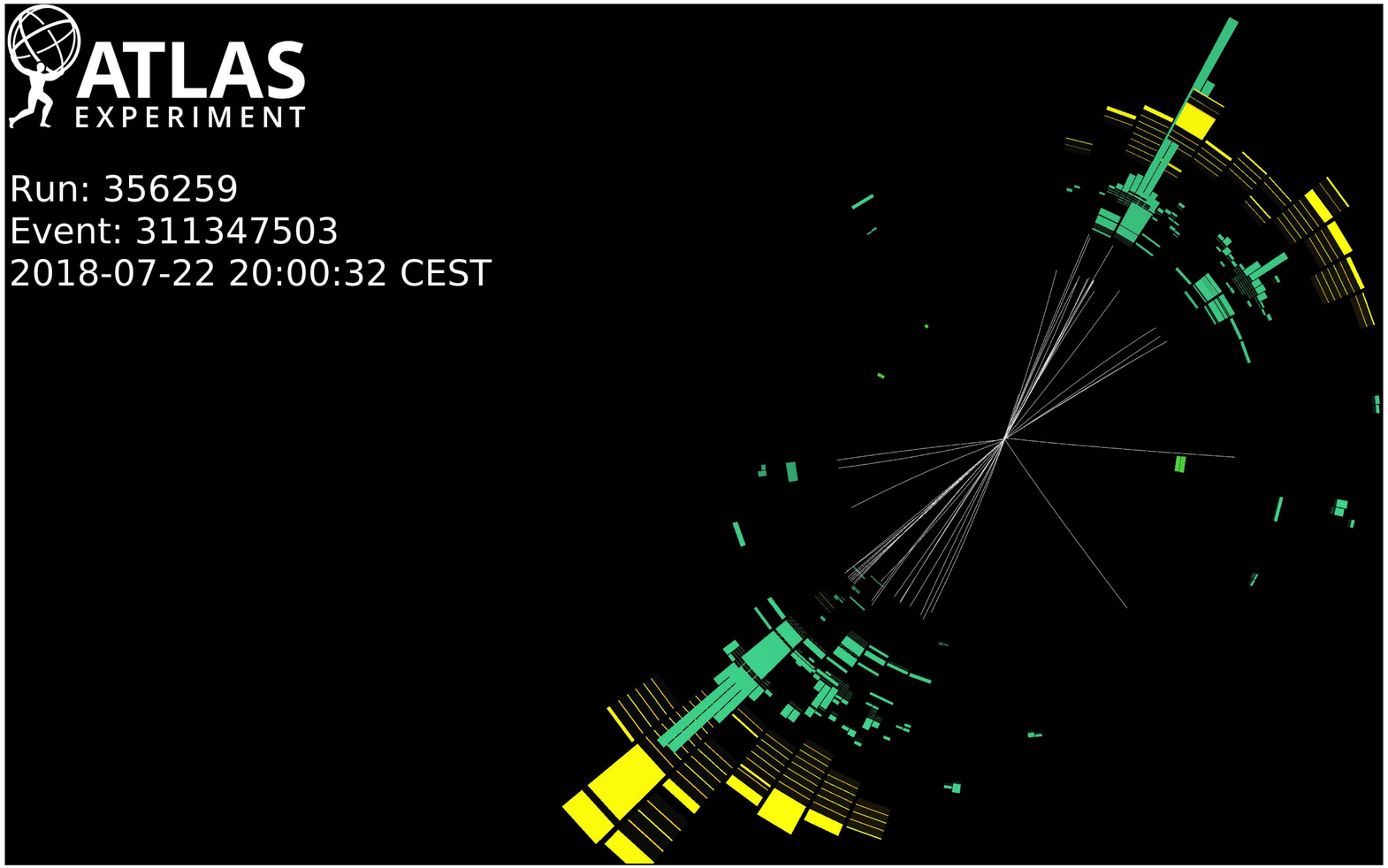
- $hh \rightarrow b\bar{b}b\bar{b}$ is the most common decay
- Boosted analysis: two large radius jets containing two b quarks each
  - this reduces backgrounds!



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-41/figaux_11.png

$hh \rightarrow b\bar{b}b\bar{b}$ Boosted Analysis

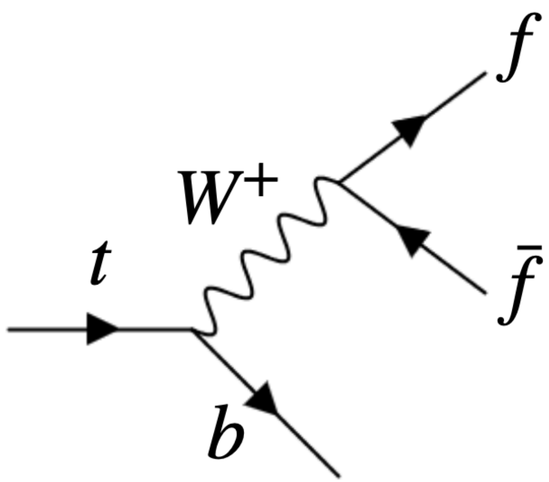
- $hh \rightarrow b\bar{b}b\bar{b}$ is the most common decay
- Boosted analysis: two large radius jets containing two b quarks each
  - this reduces backgrounds!
- Use a tagger to try to tell if jet is from a Higgs (GN2X *Hbb* Tagger https://cds.cern.ch/record/2866601)

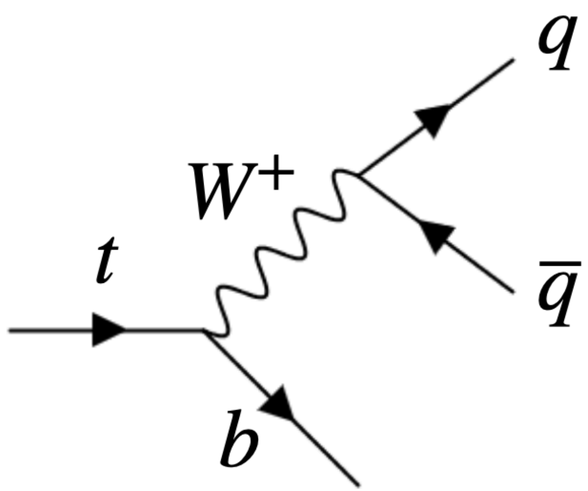


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-41/figaux_11.png

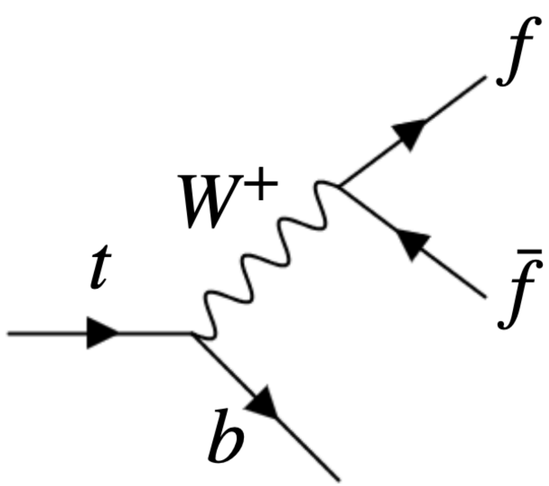
Why Study $t\bar{t}$?

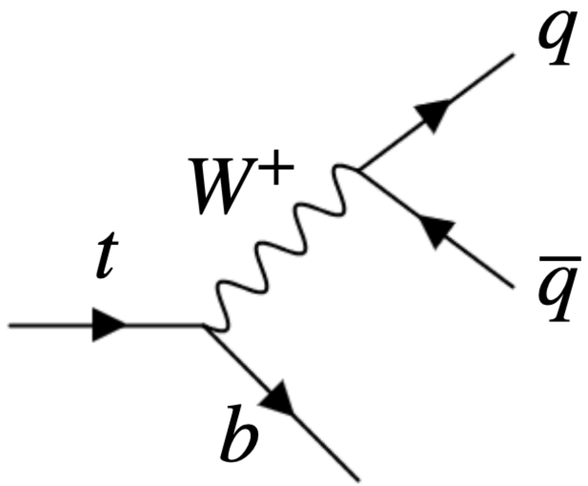
Why Study $t\bar{t}$?





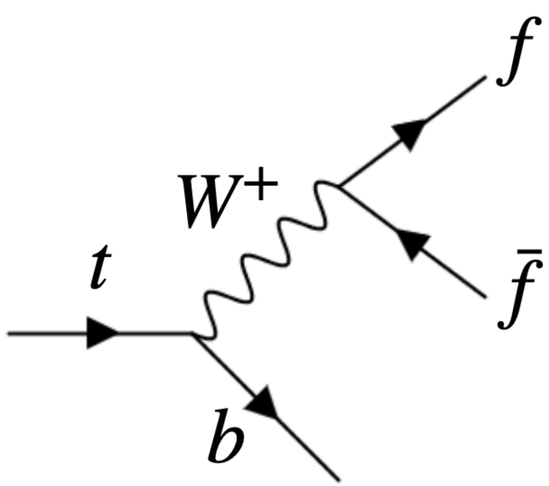
Why Study $t\bar{t}$?

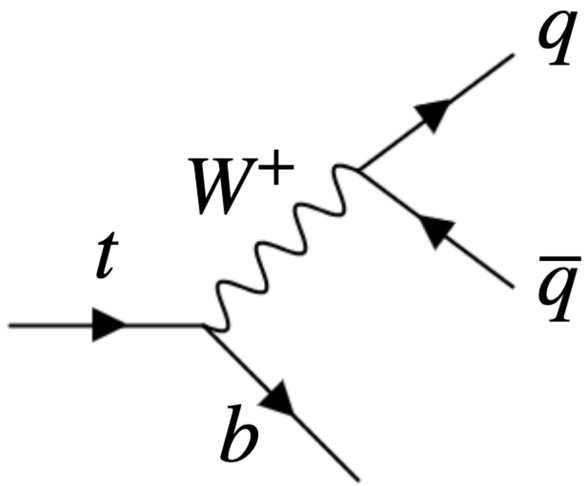




- From previous studies $t\bar{t}$ is a significant background (10-30%)

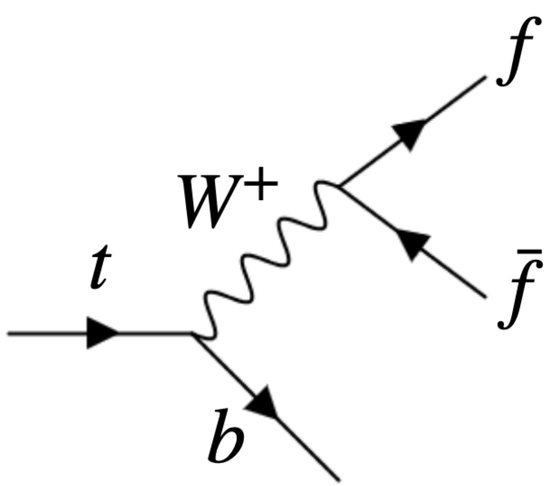
Why Study $t\bar{t}$?

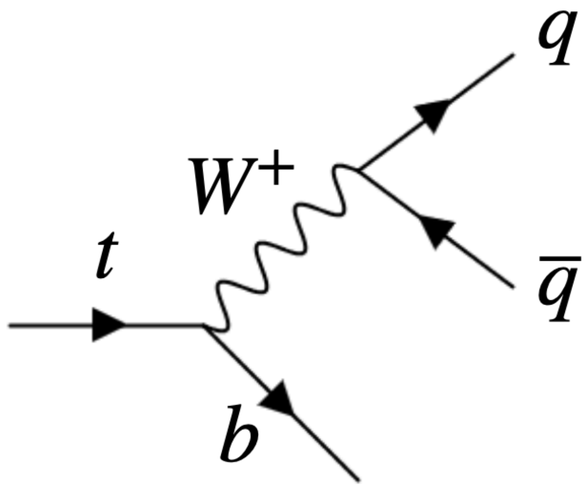




- From previous studies $t\bar{t}$ is a significant background (10-30%)
- Look at composition of jets making it past tagger: **What is faking a second b?**

Why Study $t\bar{t}$?



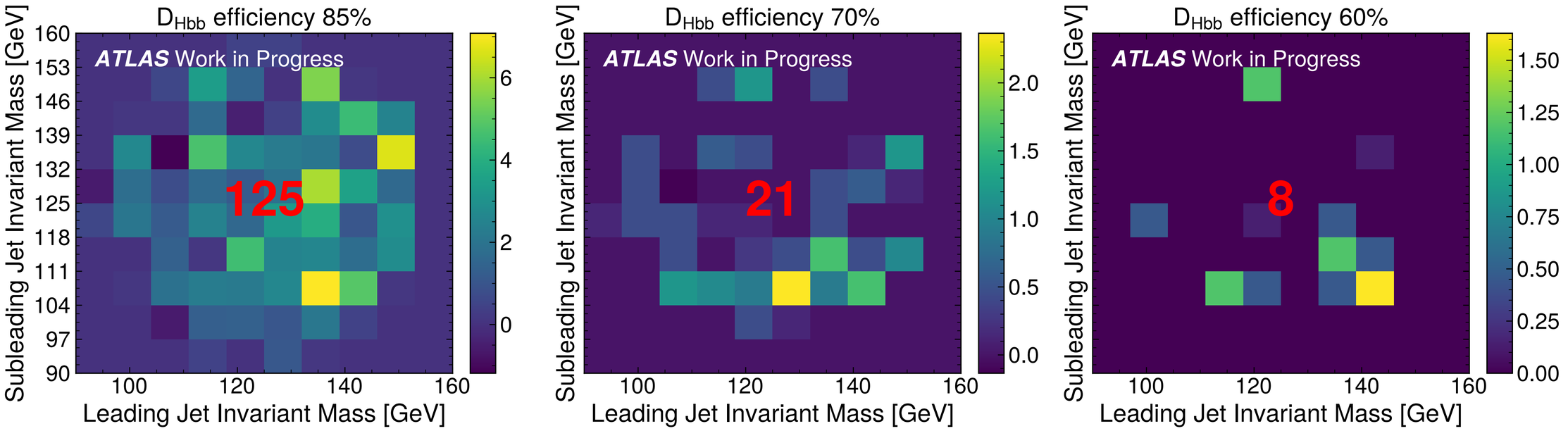


- From previous studies $t\bar{t}$ is a significant background (10-30%)
- Look at composition of jets making it past tagger: **What is faking a second b?**
- Compare to *QCD* backgrounds

Backgrounds After Tagger Cuts

Backgrounds After Tagger Cuts

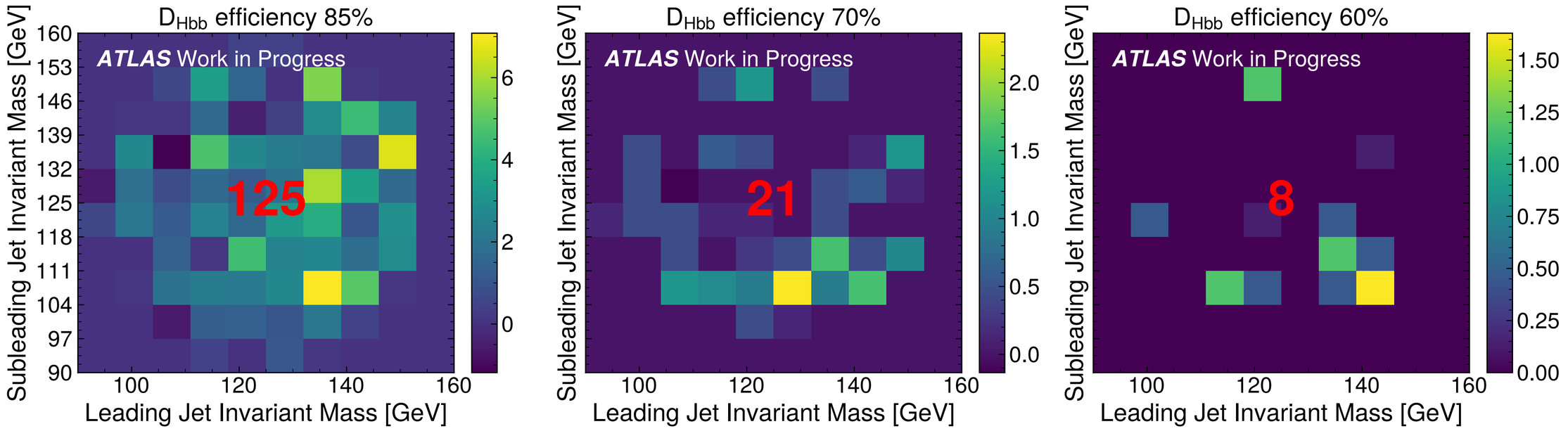
Histograms of $t\bar{t}$ Events with $p_T \geq 450$



- Total number of events in signal region (normalized to 140 ifb)

Backgrounds After Tagger Cuts

Histograms of $t\bar{t}$ Events with $p_T \geq 450$

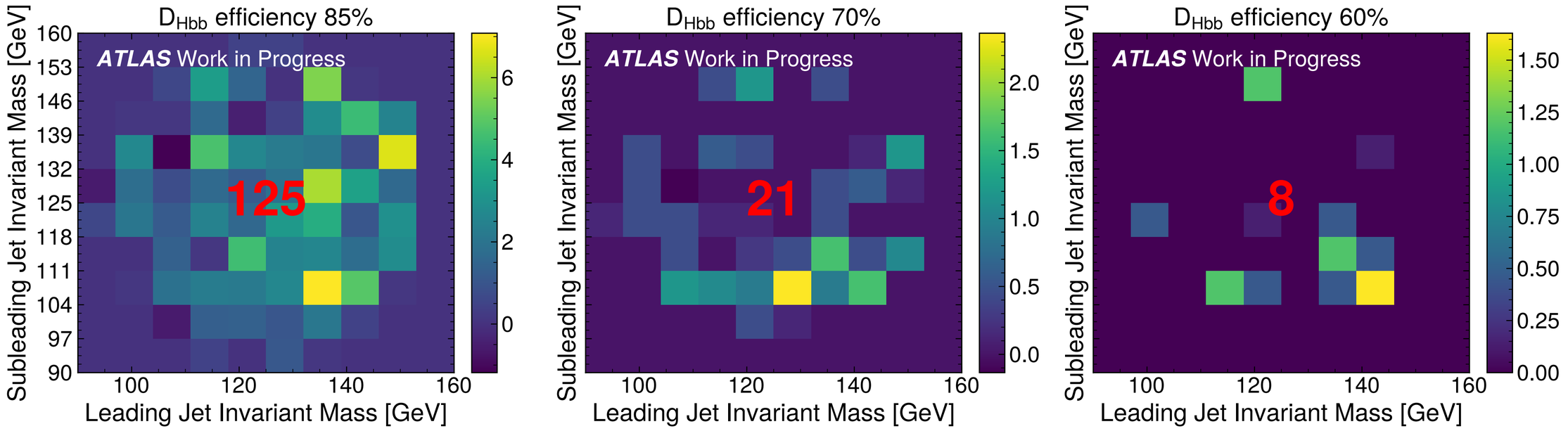


- Total number of events in signal region (normalized to 140 ifb)

- Previous study had number of $t\bar{t}$ events on the order of 10^3, 10^2, and 10^0 respectively
  - https://arxiv.org/abs/2202.07288

Backgrounds After Tagger Cuts

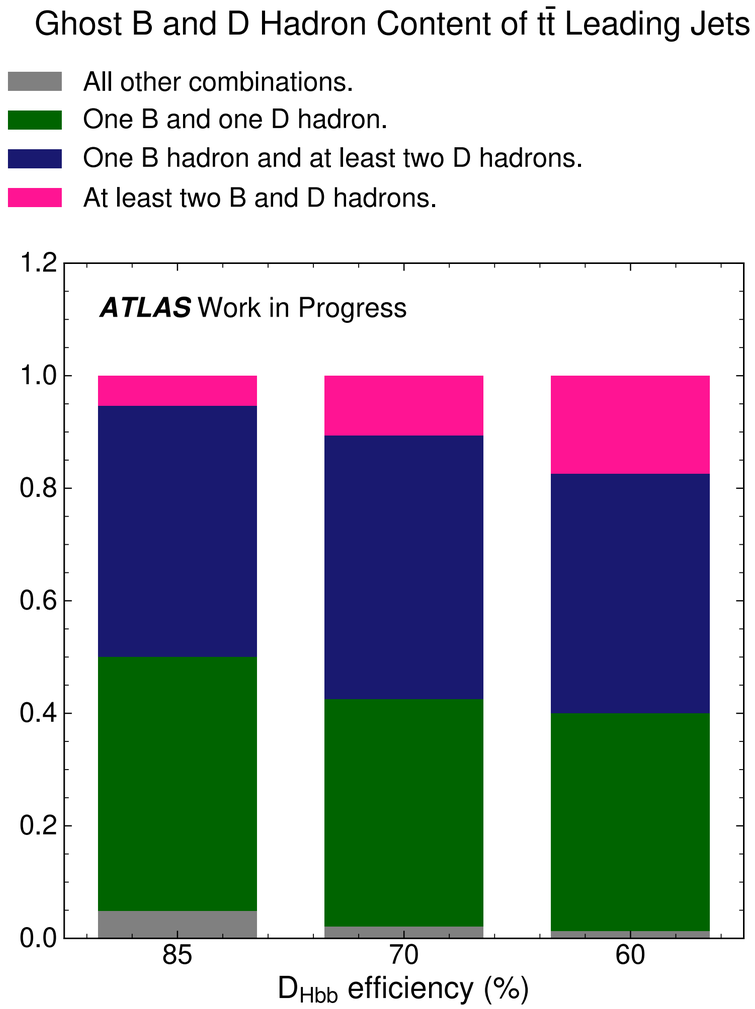
Histograms of $t\bar{t}$ Events with $p_T \geq 450$



- Total number of events in signal region (normalized to 140 ifb)

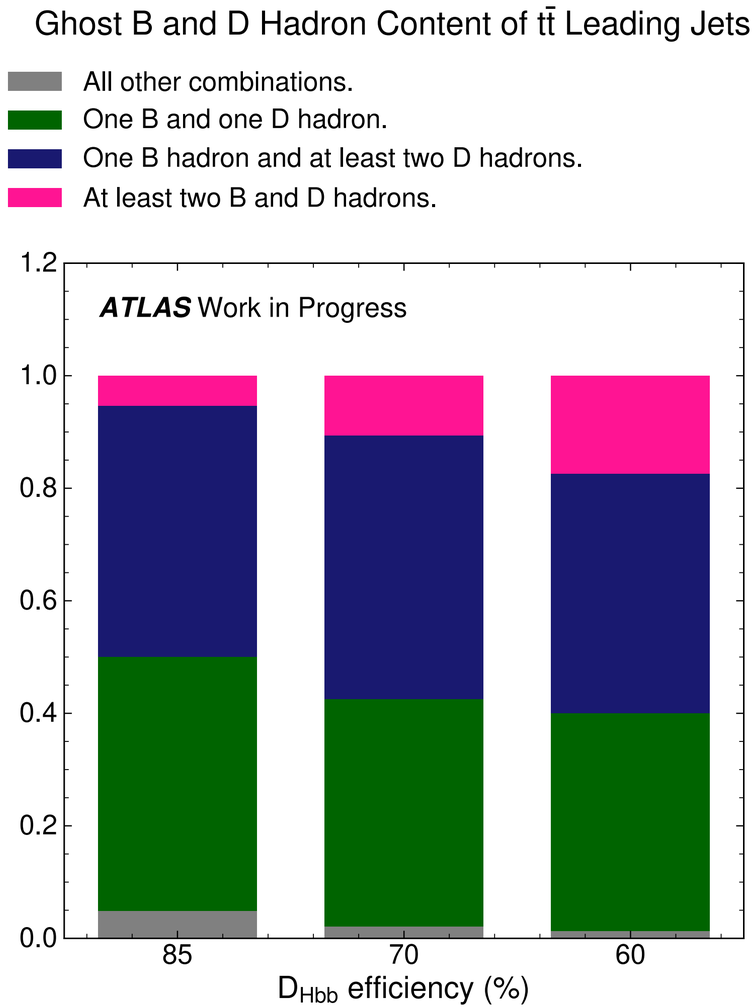
- Previous study had number of $t\bar{t}$ events on the order of 10^3, 10^2, and 10^0 respectively
  - https://arxiv.org/abs/2202.07288
- Significant reduction!

B and *D* Hadron Content of Leading Jets

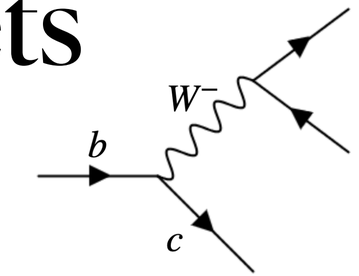


B and *D* Hadron Content of Leading Jets

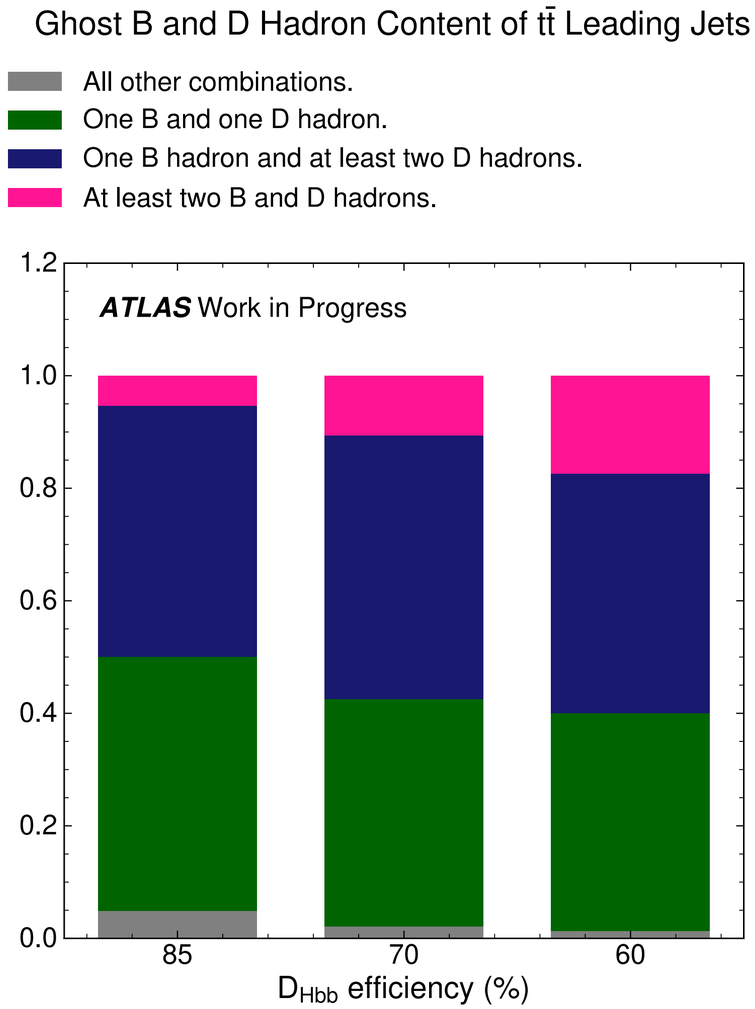
- As cuts get tighter, much more likely to have two *B* hadrons



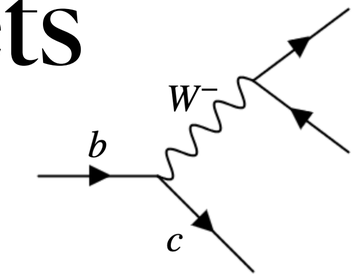
B and *D* Hadron Content of Leading Jets



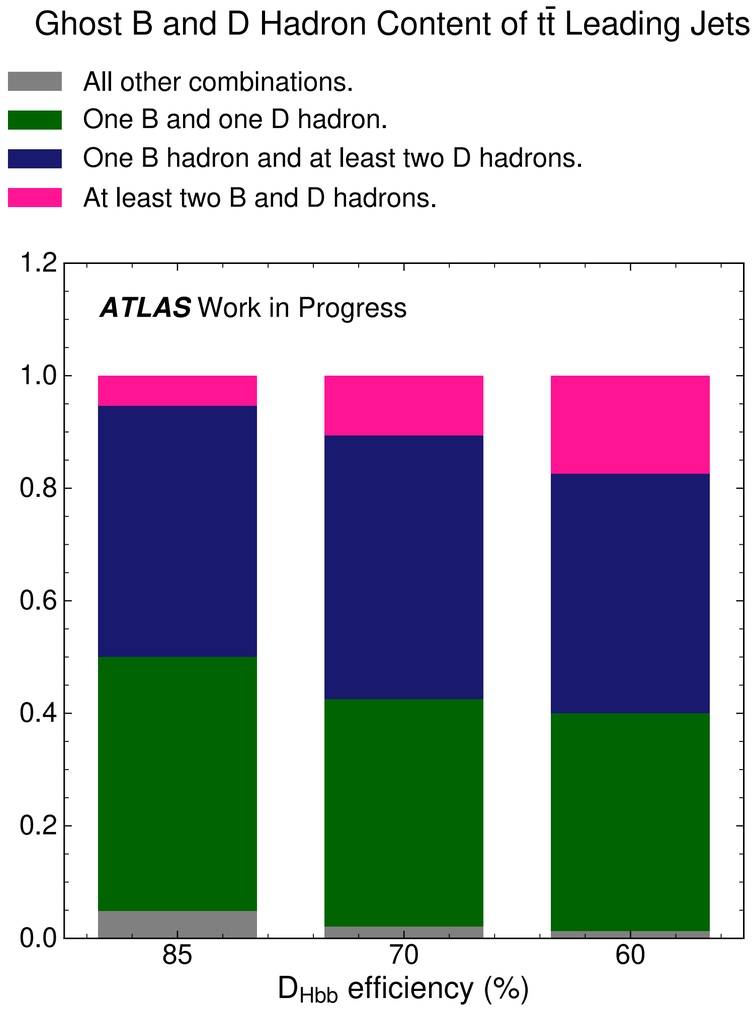
- As cuts get tighter, much more likely to have two *B* hadrons



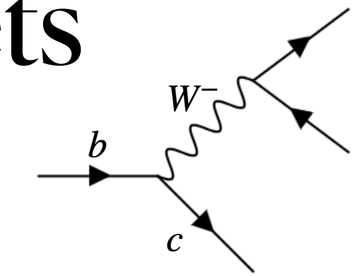
B and *D* Hadron Content of Leading Jets



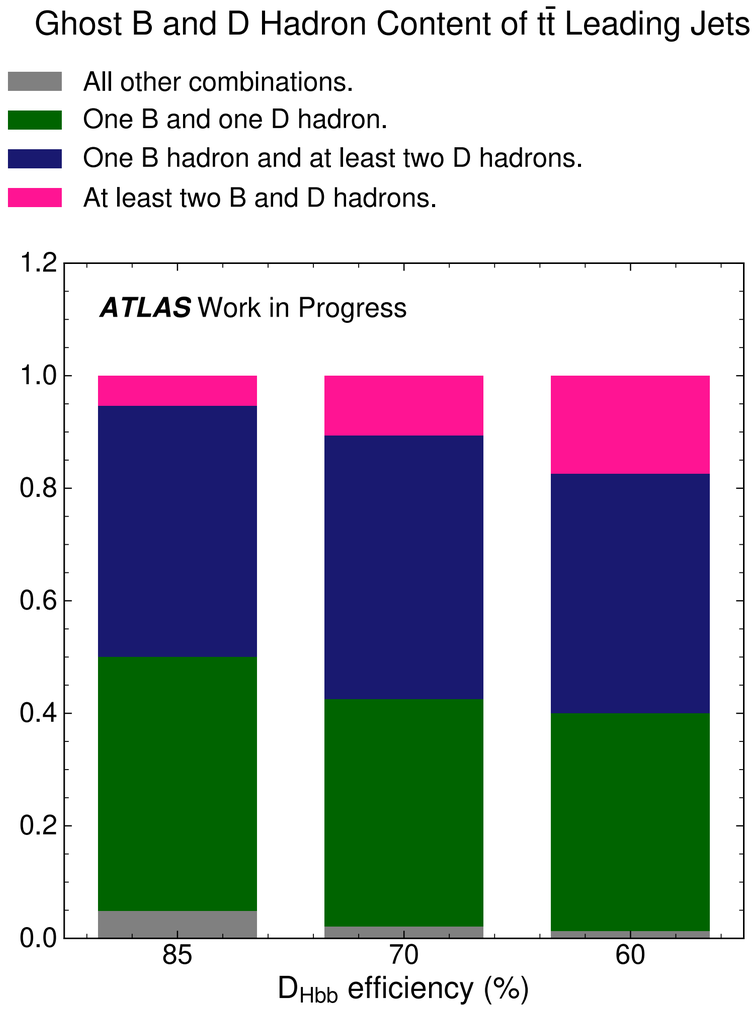
- As cuts get tighter, much more likely to have two *B* hadrons
- Presence of *D* hadron likely getting $t\bar{t}$ through cuts

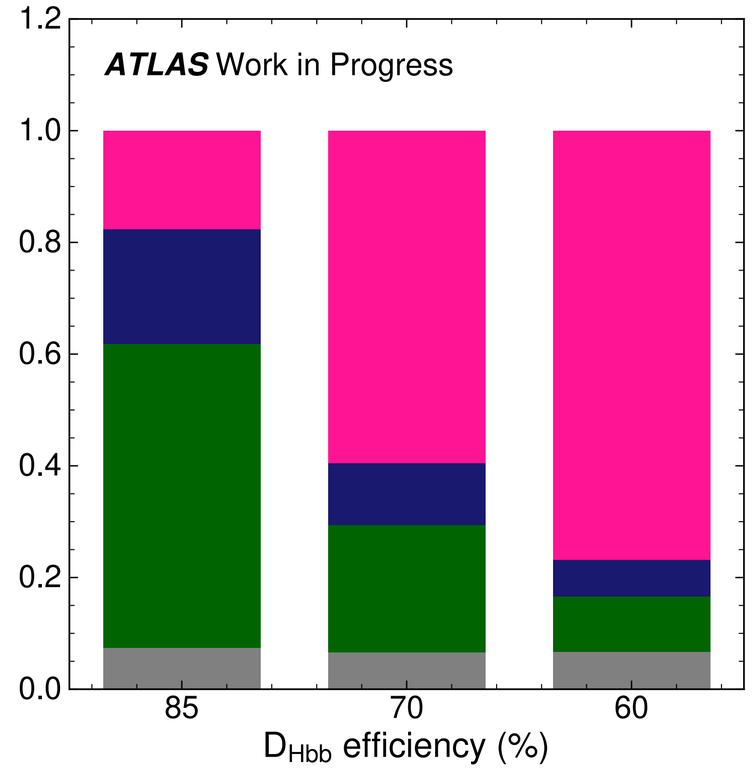


B and *D* Hadron Content of Leading Jets



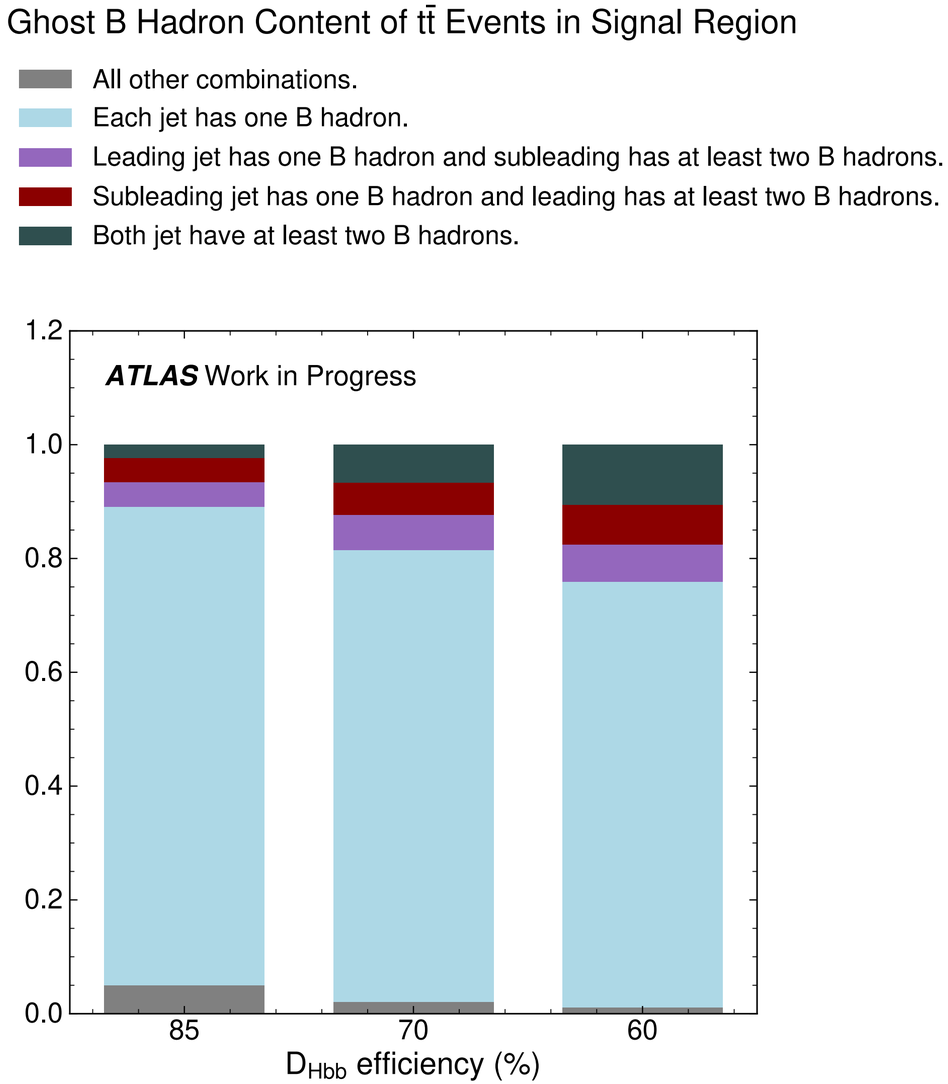
- As cuts get tighter, much more likely to have two *B* hadrons
- Presence of *D* hadron likely getting $t\bar{t}$ through cuts
- *QCD* much more likely to actually have two *B* hadrons





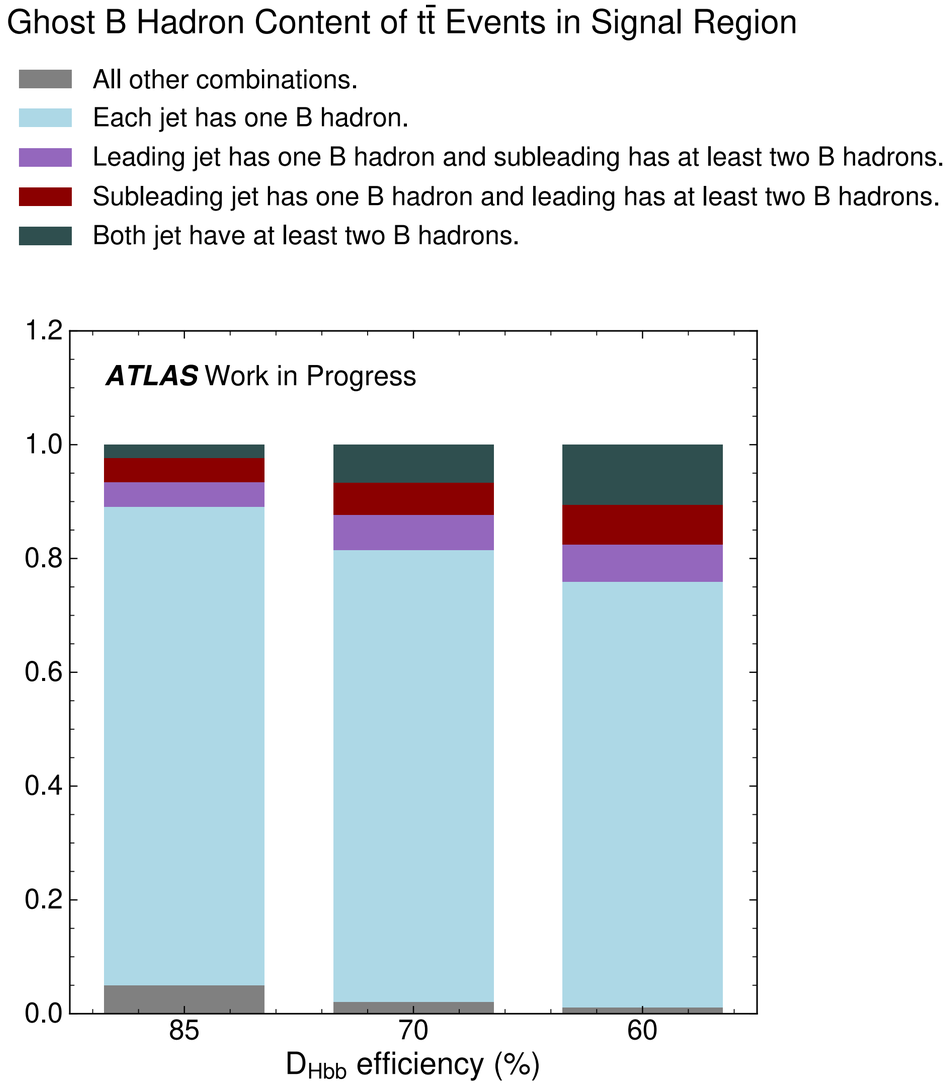
B Hadron Content of Events

B Hadron Content of Events



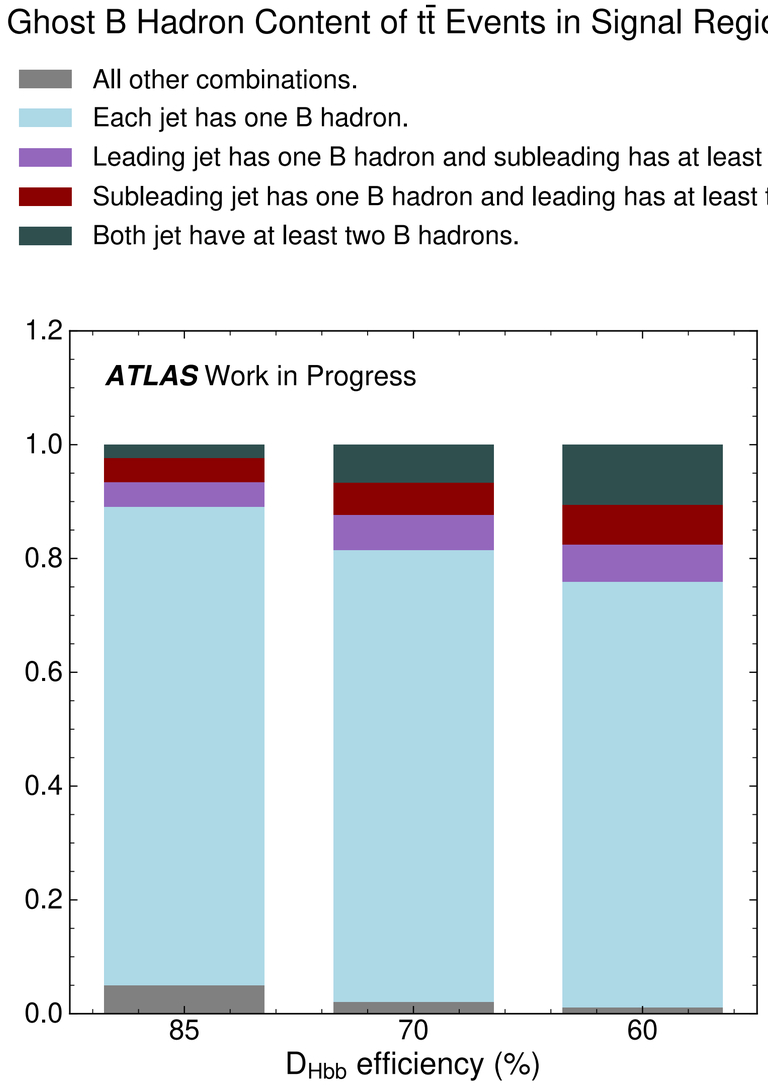
B Hadron Content of Events

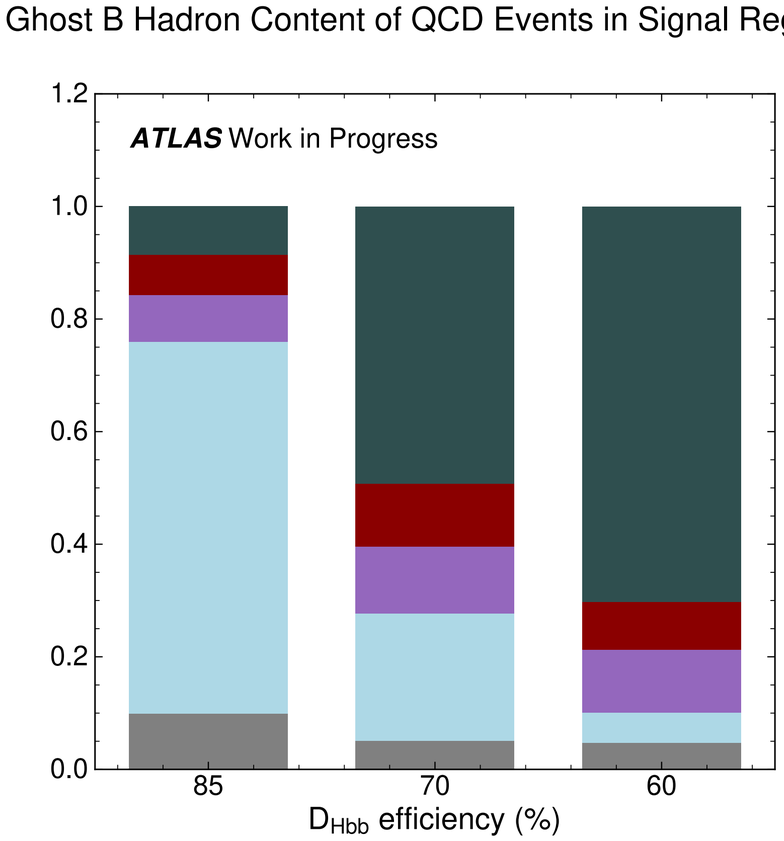
- $t\bar{t}$ mostly seeing events with one *B* hadron per jet (expected)



B Hadron Content of Events

- $t\bar{t}$ mostly seeing events with one *B* hadron per jet (expected)
- *QCD* much more likely to actually have two *B* hadrons





Conclusion

Conclusion

- $t\bar{t}$ is significantly reduced by GN2X *Hbb* Tagger

Conclusion

- $t\bar{t}$ is significantly reduced by GN2X *Hbb* Tagger
- It appears to be *D* hadrons faking the second *B* hadron in $t\bar{t}$ jets and true *B* hadrons in *QCD* jets

Conclusion

- $t\bar{t}$ is significantly reduced by GN2X *Hbb* Tagger
- It appears to be *D* hadrons faking the second *B* hadron in $t\bar{t}$ jets and true *B* hadrons in *QCD* jets

- Good feedback to provide for tagger group and for Run 3 analysis

Conclusion

- $t\bar{t}$ is significantly reduced by GN2X *Hbb* Tagger
- It appears to be *D* hadrons faking the second *B* hadron in $t\bar{t}$ jets and true *B* hadrons in *QCD* jets

- Good feedback to provide for tagger group and for Run 3 analysis
- Currently studying composition in control and validation regions to compare to signal region and validate extrapolations

Backup Slides

GN2x Tagger

- GN2X Hbb-tagger (D_{Hbb}) is defined as:

$$D_{Hbb} = \ln\left(\frac{p_{Hbb}}{f_{cc}p_{Hbb} + f_{top}p_{top} + (1 - f_{cc} - f_{top})p_{qcd}}\right), f_{cc} = 0.02, f_{top} = 0.25$$

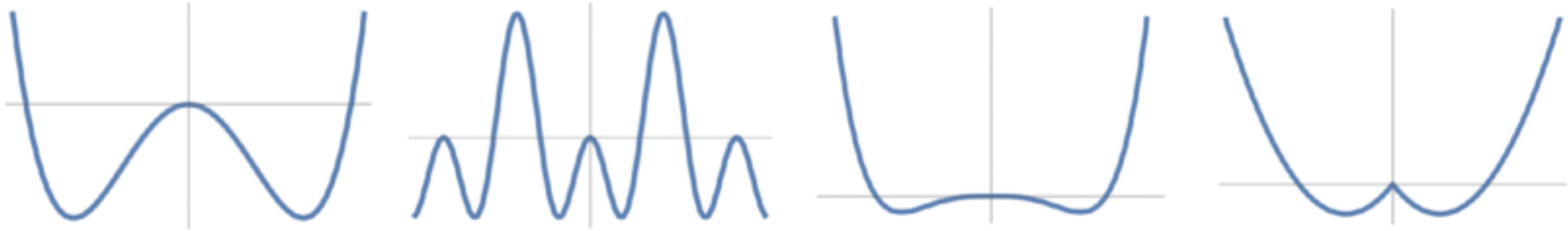
  - GN2X Documentation:
    - https://indico.cern.ch/event/1408775/contributions/5920971/attachments/2846772/4977631/R24_GN2Xv01_tagger_FlatMass_qcd_April292024-1.pdf
    - https://xbb-docs.docs.cern.ch/Xbb/GN2_track/

- GN2X is a Graph Neural Network (GNN) Tagger that is trained with tracks

Higgs Potentials

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2} (H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + e (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

Source: [PhysRevD.101.075023]



Landau-Ginzburg Higgs **Nambu-Goldstone Higgs** **Coleman-Weinberg Higgs** **Tadpole-Induced Higgs**

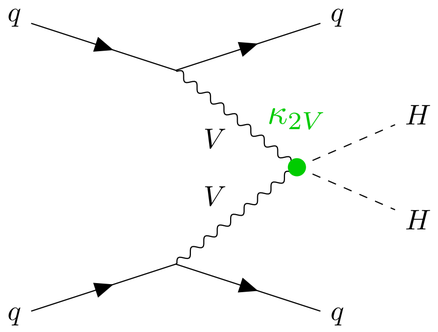
(1) Elementary Higgs boson, in which the Higgs boson is taken as an elementary scalar with rescaled self-couplings. The Higgs mass parameter is negative and thus triggers EWSB.

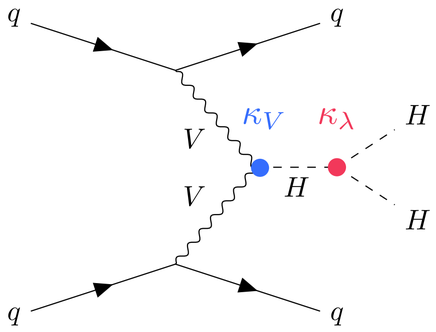
(2) Nambu-Goldstone Higgs, in which the Higgs boson is taken as a pseudo-Nambu-Goldstone (PNG) boson [9,10] emerging from strong dynamics at a high scale (see Refs. [11–13] for comprehensive reviews).

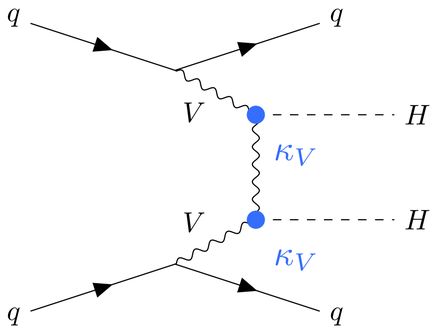
(3) Coleman-Weinberg (CW) Higgs, in which EWSB is triggered by renormalization group (RG) running effects [14–16] with classical scale invariance.

(4) Tadpole-induced Higgs, in which EWSB is triggered by the Higgs tadpole [17,18], and the Higgs boson mass parameter is taken to be positive.

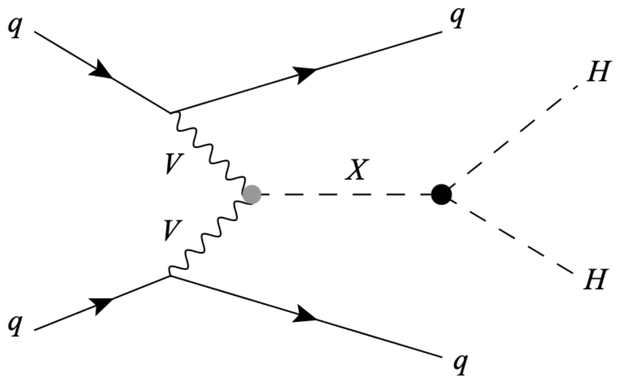
All *hh* Feynman Diagrams



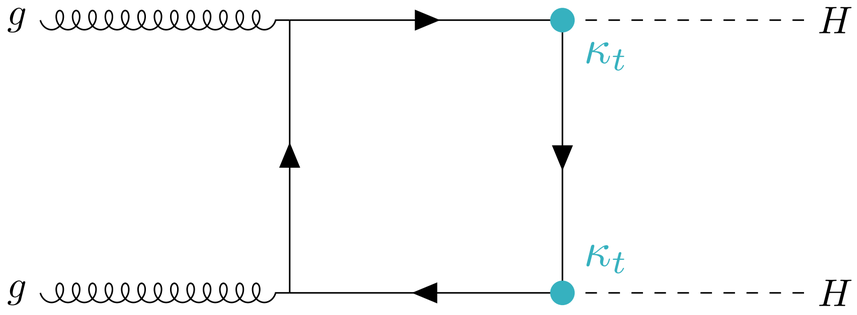


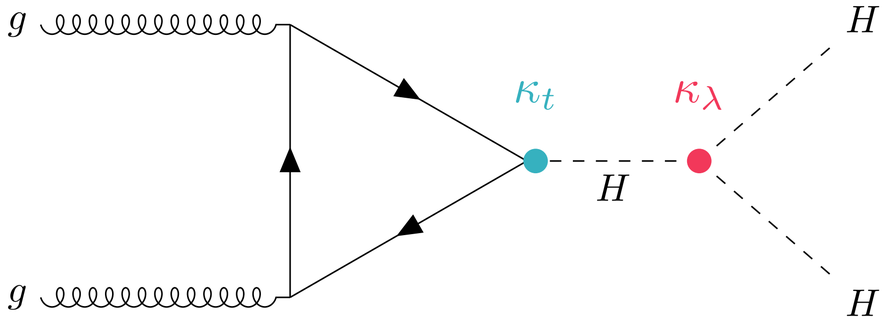


vector boson fusion



resonant production (BSM)

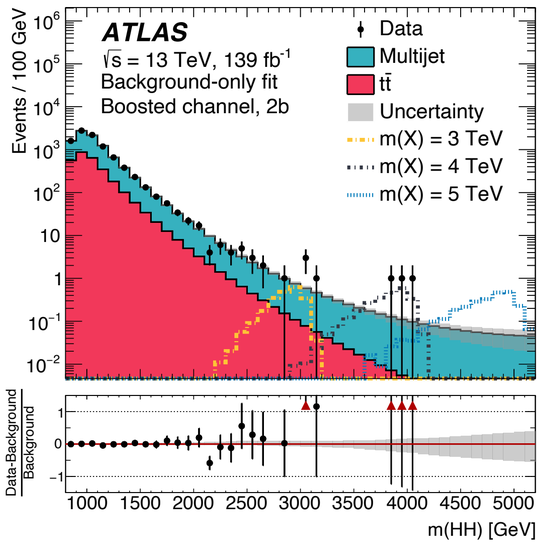


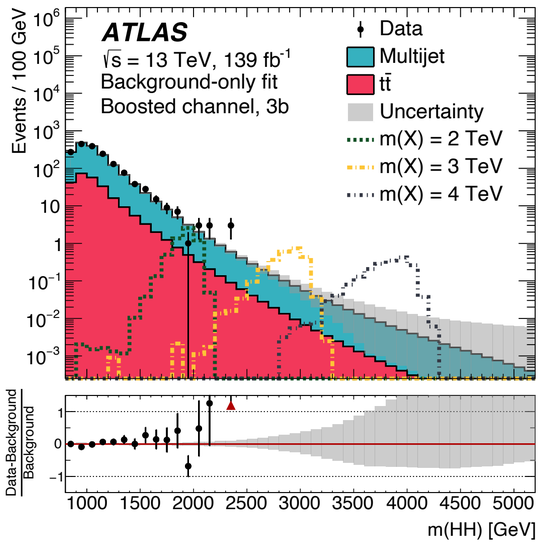


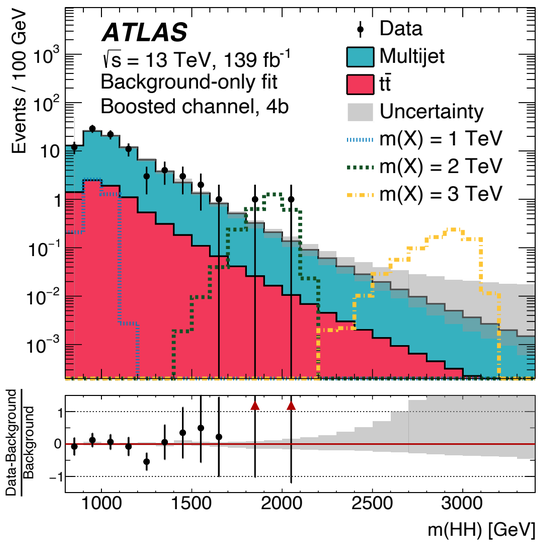
gluon-gluon fusion

Source: https://arxiv.org/abs/2404.17193

Previous Tagger Result Comparison







Total number of events in signal region (normalized to 140 ifb)