ATLAS EXPERIMENT

Exotic Higgs Decays:

ATLAS Search for Higgs Decays to Two Light Scalars

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With special thanks to
Claudia Seitz, Rickard Ström, Priscilla Pani, and Beate Heinemann

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DESY.

Overview

Process: Higgs decay to two light scalars

Objects used in the analysis

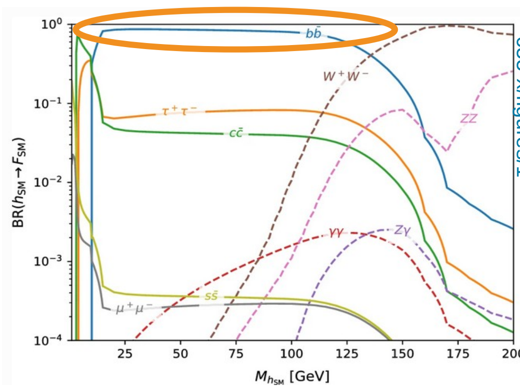
Event selection & categorization

Reconstruction methods

Exotic Higgs Decays

Two additional scalars: direct decays.

- Search for particles predicted by the Two Real Singlet Model [1]:
  - Predicts existence of two additional **Higgs-like particles**: a_1 and a_2
  - Large coupling to each other, other couplings inherited from H_{SM}
- In our search:
  - Consider them to be lighter that the H_{SM} ($m(H_{SM})$ = 125 GeV)
  - Look at the process $H_{SM} \rightarrow a_1\, a_2 \rightarrow 4b$



https://link.springer.com/article/10.1140/epjc/s10052-020-7655-x/figures/1

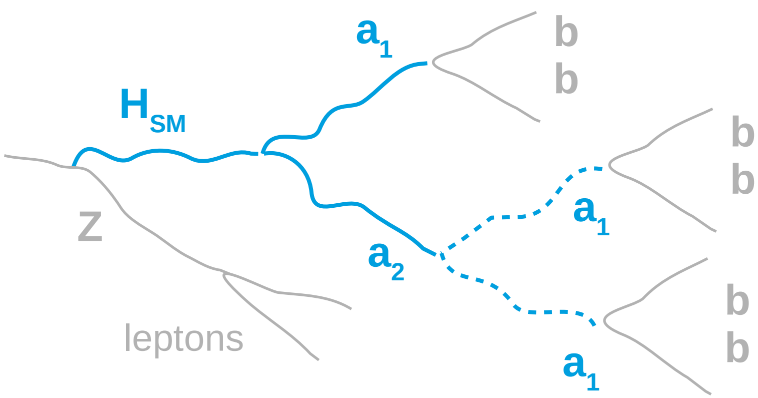
- Final state: 4 very low-p_T b quarks

[1] Robens, Stefaniak, Wittbrodt. Two-real-scalar-singlet extension of the SM: LHC phenomenology and benchmark scenarios. EUR PHYS J *C*, 80(2). 2020. arXiv:1908.08554

Exotic Higgs Decays

Two additional scalars: cascade decays.

- If $m(a_2) > 2\, m(a_1)$: cascade decay possible
- Final state: 6 very low-p_T b quarks



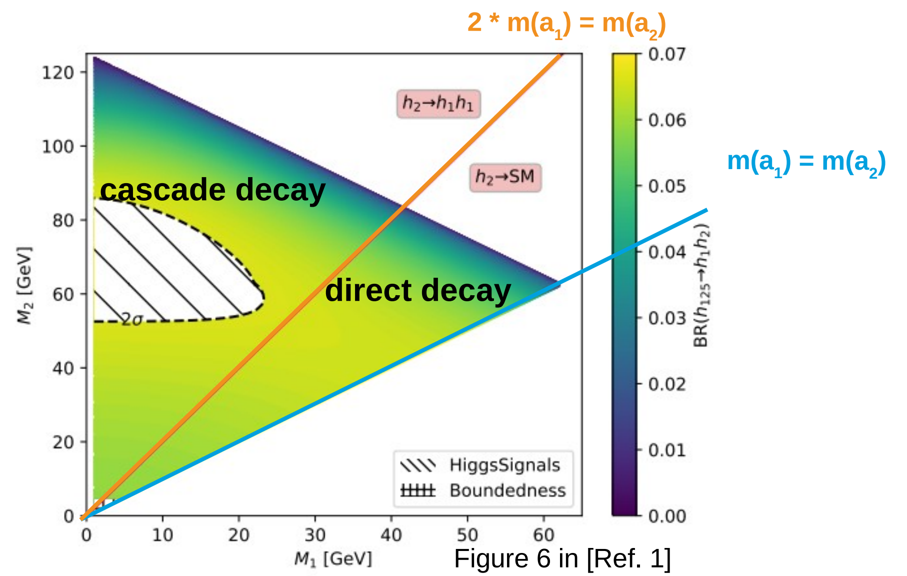


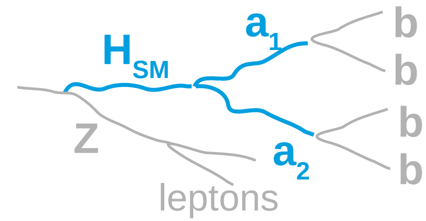
Figure 6 in [Ref. 1]

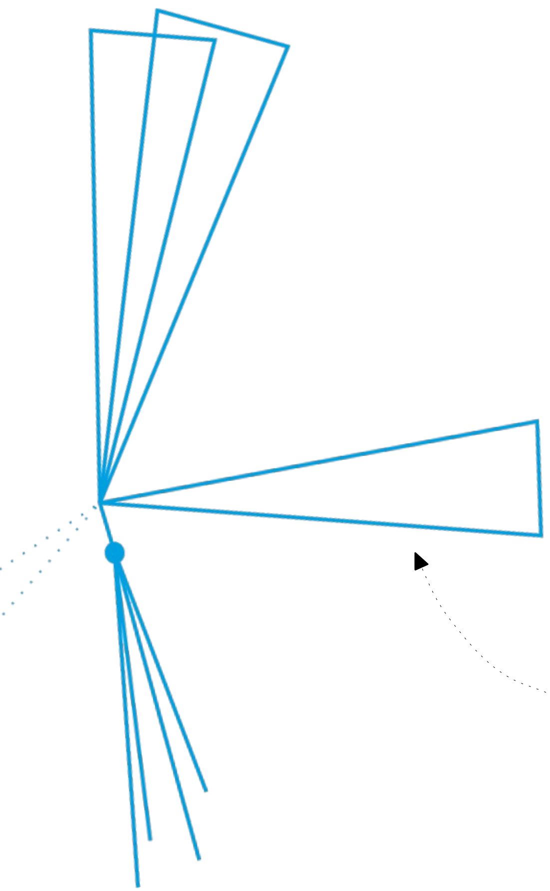
- Consider ZH_{SM} production

  → 2 leptons (e or mu) in final state to trigger on

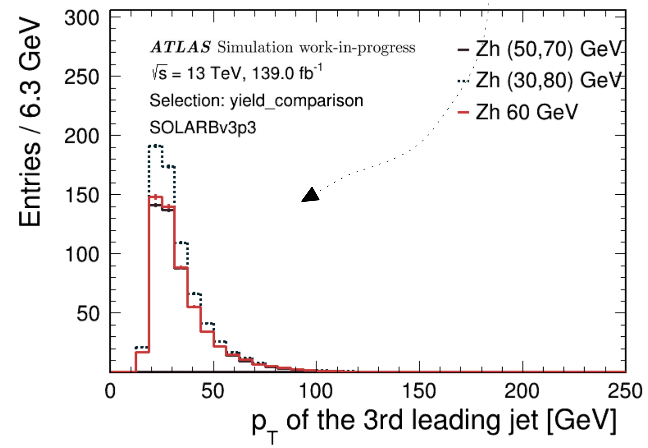
Low-p_T B Hadrons

Reconstruction of different b-objects.





- Signal characterized by two leptons and 4 (or 6) **low-p_T** b quarks in the final state



- Have different types of **b-objects** in the events

  1) regular b-jets (ATLAS DL1r tagger [2])

  with a p_T threshold lowered to 15 GeV

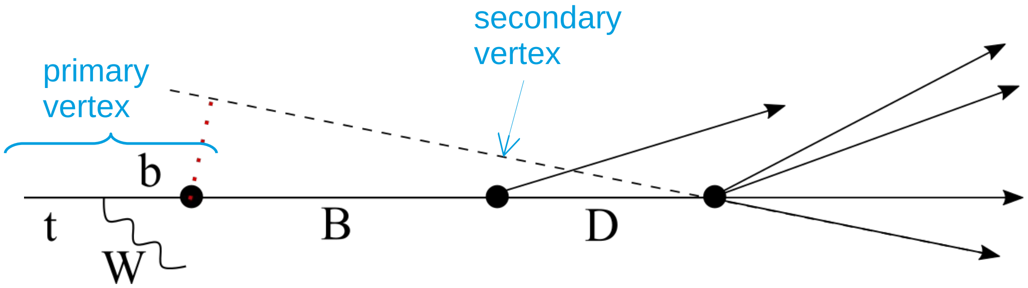
[2] ATLAS Collaboration. ATLAS b-jet identification performance and efficiency measurement with tt events in pp collisions at √s=13 TeV. Eur. Phys. J. C 79, 970, CERN, 2019.

FTag Interlude

b-tagging with the DL1r tagger.

- Hadrons containing b quarks tend to have a longer lifetime than other hadrons

  → jets from b hadrons have recognizable features



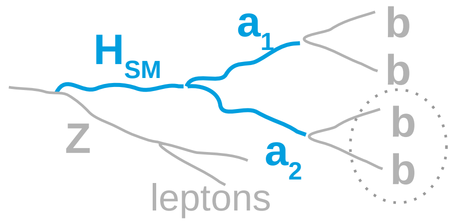
  1) **secondary vertices**

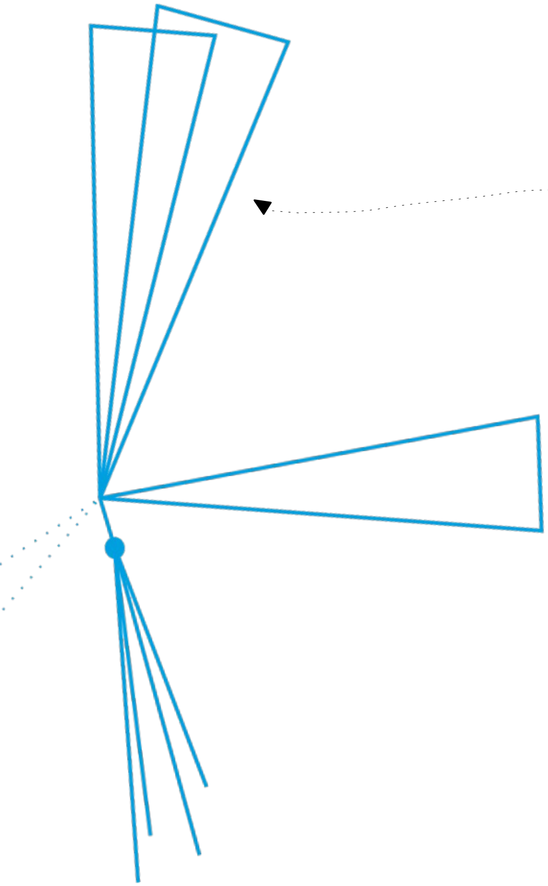
  2) tracks have larger **impact parameter**: distance of the track pass-by to the primary vertex

- DL1r tagger is a deep neural network, inputs are secondary vertex and track variables
- Output is a tagger discriminant: probability to be a b-jet
- Different working points: different cuts on discriminant

Low-p_T B Hadrons

Reconstruction of different b-objects.





- Have different types of **b-objects** in the events

  1) regular b-jets

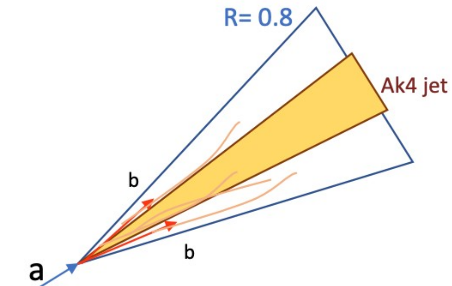
  2) bb-tagged jets

  - For low a_1/a_2 boson masses the boson is boosted and the decay products merge

    → reconstruct two b hadrons inside of **one** jet

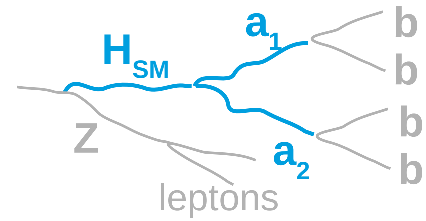
  - group developed a specialized bb-tagger for low-p_T region
    DeXTer: Deep Sets based Neural Networks for Low-p_T $X \rightarrow bb$ identification

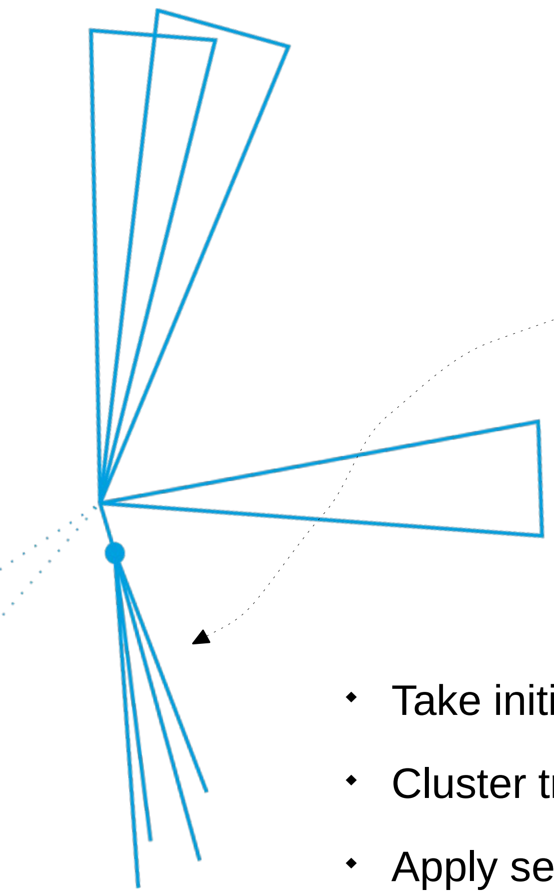
  - tagger runs on regular R = 0.4 jets, use tracks inside 0.8 cone as additional input



Low-p_T B Hadrons

Reconstruction of different b-objects.





- Have different types of **b-objects** in the events

  1) regular b-jets

  2) bb-tagged jets

  3) soft secondary vertices

tc-lvt tagger
[3] ATLAS Collaboration. Soft b-hadron tagging for compressed SUSY scenarios. Technical Report ATLAS-CONF-2019-027, CERN, 2019.

  - b hadron can be too low in p_T to reconstruct a jet

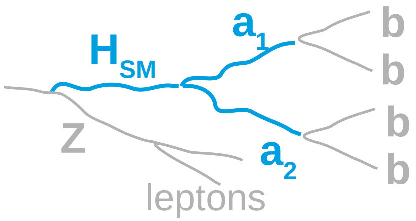
    → look for secondary vertices outside of jets

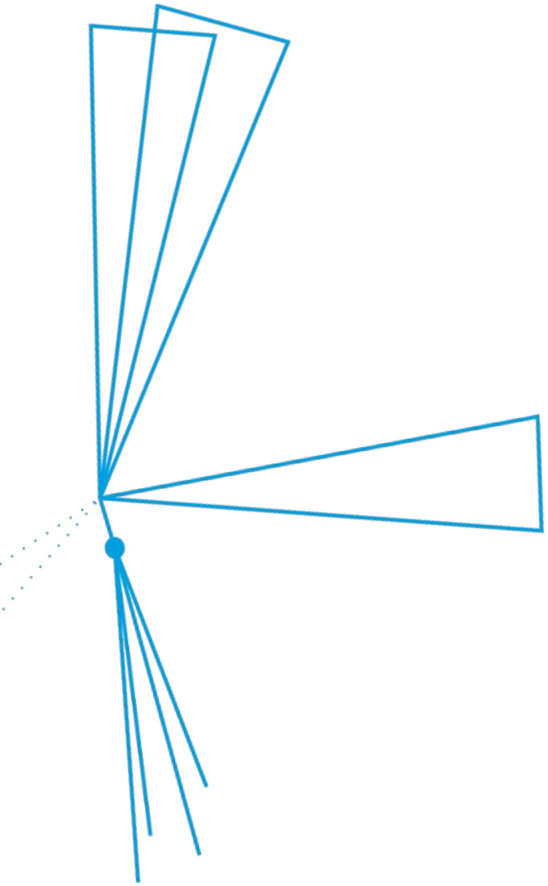
  - developed in the context of searches for compressed SUSY scenarios [3]:

- Take initial tracks: high momentum, high impact parameter
- Cluster tracks around initial track
- Apply secondary vertexing algorithm to the cluster (instead of a jet)

Low-p_T B Hadrons

Reconstruction of different b-objects.





- Have different types of **b-objects** in the events

  1) regular b-jets

  2) bb-tagged jets

  3) soft secondary vertices

- Ensure coherent event interpretation:

  - Remove overlap between jet collections

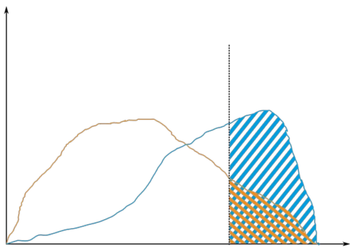
  - Remove any soft secondary vertex close to a jet

Calibration of Soft Secondary Vertices

Efficiency and fake rate scale factors.

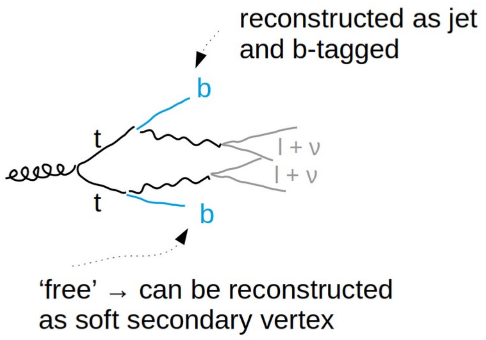
- Calibration = correction of the reconstruction efficiency in MC to data
- Get two scale factors:
  - An efficiency SF
  - A fake rate SF

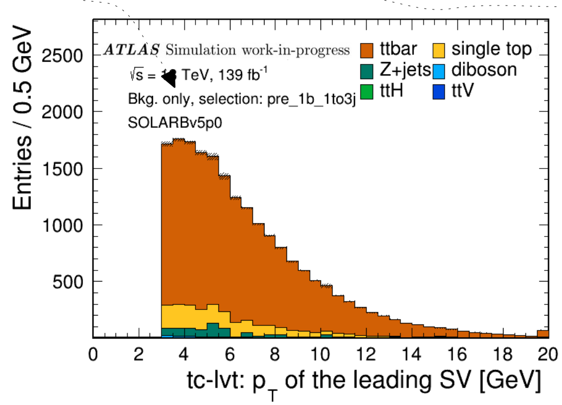
$$SF = \frac{\epsilon^{data}}{\epsilon^{MC}}$$

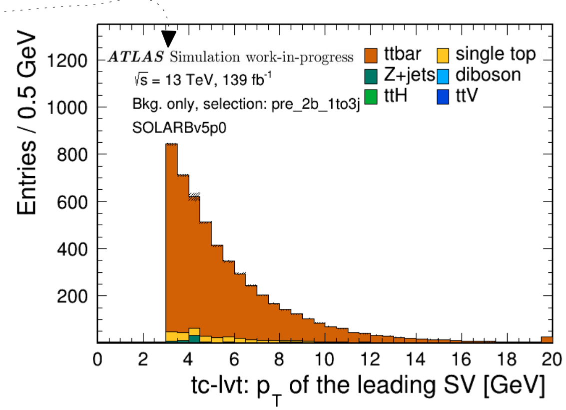


- Measure in data in a regions where we expect
  - many ‘true’ soft SVs → efficiency
  - few ‘true’ soft SVs → fake rate

di-leptonic ttbar with exactly 1 or exactly 2 b-jets





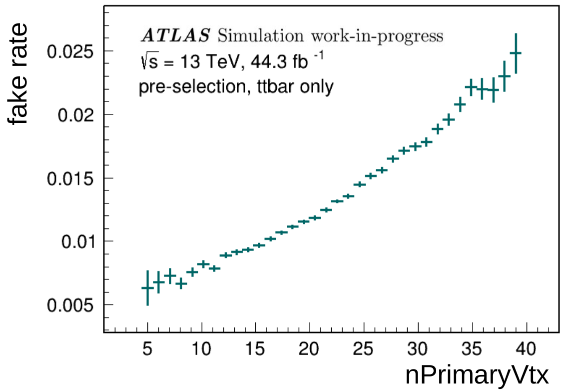


Calibration of Soft Secondary Vertices

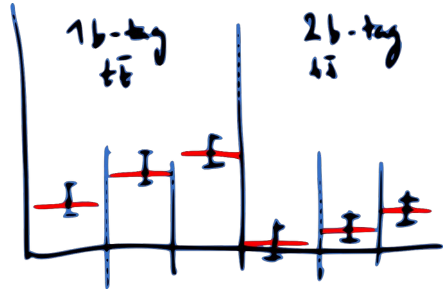
Extraction.

- Fake soft SVs are mostly random track crossings

  → fake rate depends on the pile-up / number of primary vertices

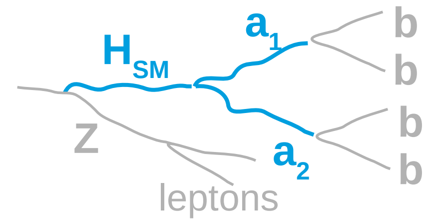


- Extract the efficiency SF and the fake rate SF in bins of the number of primary vertices
- Do a combined fit in the 1b and 2b region to extract them simultaneously

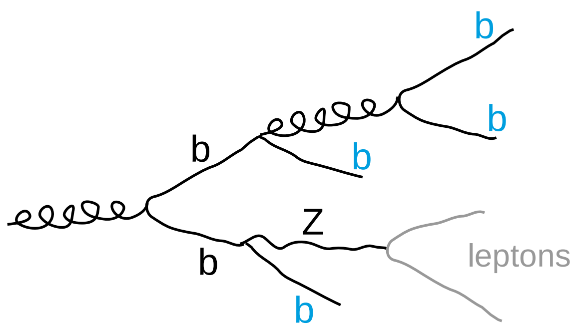


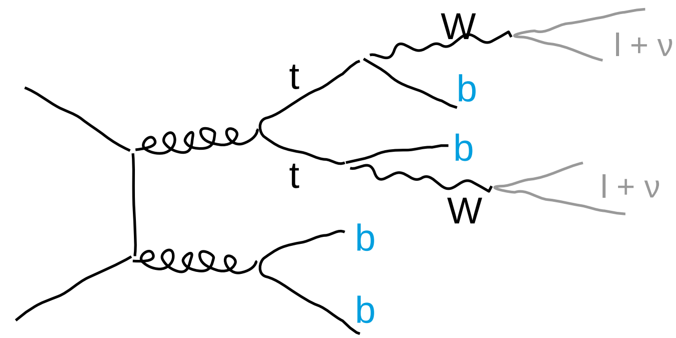
Event Selection

And background composition.



- Main backgrounds: Z+jets and ttbar (example diagrams)

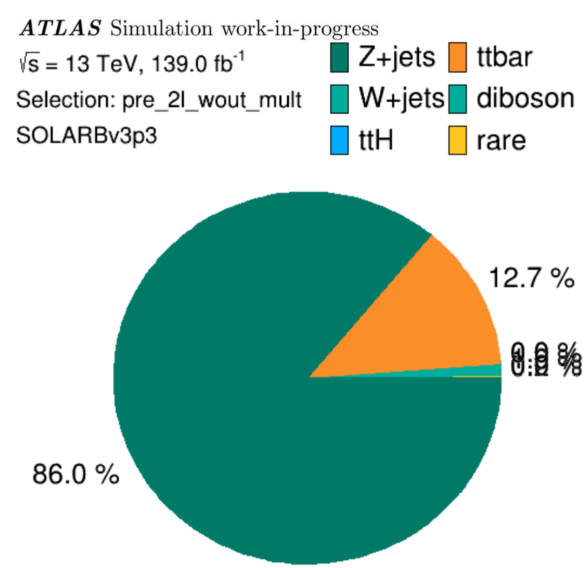




- Lepton pre-selection cuts: require
  - Leptons of same flavour, opposite charge
    in signal: Z → $e^+ e^-$ or $\mu^+ \mu^-$
  - Lepton invariant mass in Z mass window
    85 GeV < mll < 100 GeV

→ good rejection of ttbar

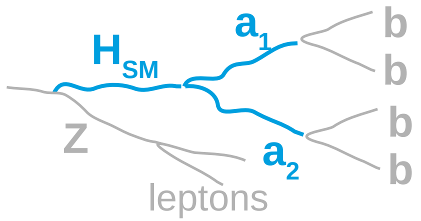
→ Z+jets main background



* single top and ttV still missing

Event Categories

Fully and partially reconstructed.



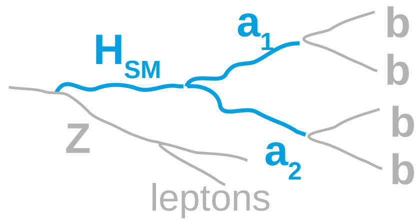
- b-tagged and bb-tagged jets are built from the same collection of 0.4 jets, so for each jet:
  - try if it bb-tagged
  - If not: try if it is b-tagged
  - If not: light jet
- Existence of bb-jets, b-jets and soft SVs leads to many multiplicity regions / **event categories**
- Events can be **fully** reconstructed: all b-quarks are in a reconstructed object

  2 bb, 1bb 2b, 1bb 1b 1 sv, 4b, 3b 1sv (for non-cascades)
- Or **partially** reconstructed: one or more objects are lost (detector acceptance, tagger efficiencies ...)

  1 bb 1b, 3 b, …

Reconstruction Methods

Variables to discriminate signal from background.

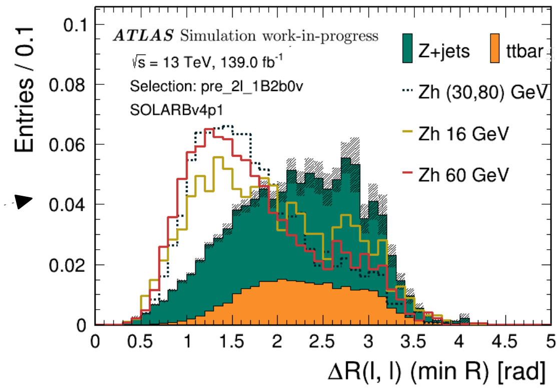


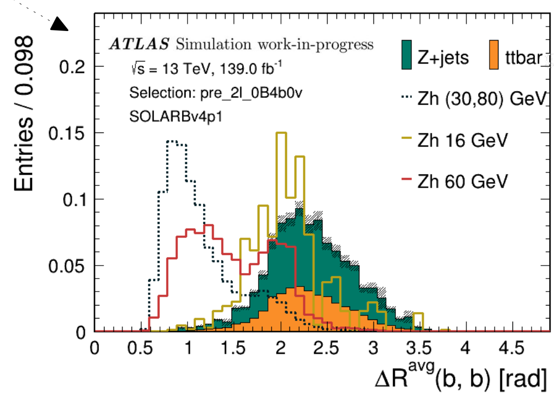
- In different event categories:

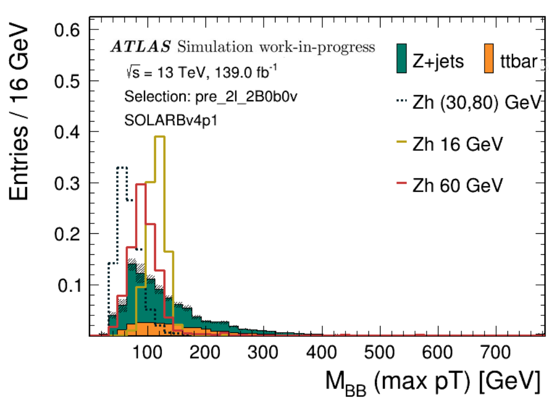
  Several variables have a strong separating power of signal vs. background

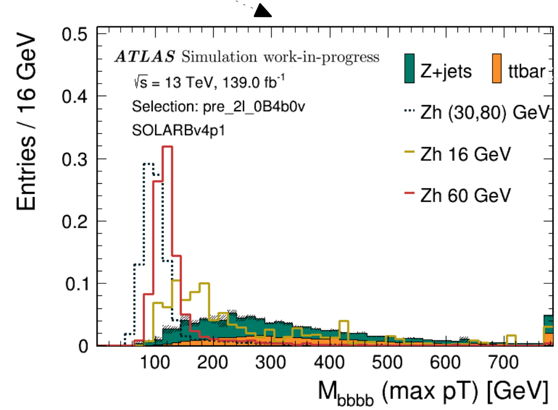
  example plots in different event categories; all plots **normalized**

  - angular distance of the leptons in the event
  - average over angular distance of each b-jet pair
  - Invariant mass of the b-objects



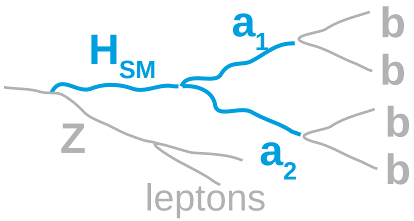






Reconstruction Methods

Cut and count study.



- Define signal regions: optimize cuts by maximizing the 'significance' [4] (approximation formula for p-value)

[4] Buttinger, Lefebvre.
Formulae for Estimating Significance. Technical Report
ATL-COM-GEN-2018-026, CERN, 2018.

$$Z = \begin{cases} +\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n \geqslant b \\ -\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & \text{if } n < b. \end{cases}$$

- Get expected exclusion limit with simplified fit:

ATLAS Simulation work-in-progress

signal mass	16 GeV	60 GeV	(30, 80) GeV
expected limit on signal strenght μ from simplified fit	10%	18%	8%

- assume BR(H → aa → bbbb) = 100 %
- fit only in signal regions (no control regions)
- assume flat 20% systematic uncertainty
- get limit on signal strength parameter µ

- Other (very promising) ideas for the event reconstruction:
  - Build a neural network that gives a suggestion of which objects to pair to reconstruct the light scalars
  - Use a BDT for signal – background discrimination

Summary

$H \rightarrow a_1 a_2 \rightarrow$ 4b or 6b

- Decays of the SM Higgs boson to light scalars (of different mass) could be important since there is still sizable room of ~ 20% [5] for non-SM Higgs decays
- Introducing multiple reconstruction methods for b-hadrons enhances the possibility to reconstruct the signal
- Several very promising variables with strong separating power of signal vs. background

[5] ATLAS Collaboration. A combination of measurements of Higgs boson production and decay using up to 139fb^{-1} of proton-proton collision data at $\sqrt{s}$= 13 TeV collected with the ATLAS experiment. Technical Report ATLAS-CONF-2020-027, CERN, 2020.
→ Table 8

Thanks for your time and attention!

Any questions? :)

Contact

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References

- [1] Tania Robens, Tim Stefaniak, and Jonas Wittbrodt. Two-real-scalar-singlet extension of the SM: LHC phenomenology and benchmark scenarios. *The European Physical Journal C*, 80(2): 15, Feb 2020. ISSN 1434-6052. doi: 10.1140/epjc/s10052-020-7655-x.
URL https://doi.org/10.1140/epjc/s10052-020-7655-x.

- [2] ATLAS Collaboration. ATLAS b-jet identification performance and efficiency measurement with tt¯ events in pp collisions at s√=13 TeV. Eur. Phys. J. C 79, 970, CERN, 2019.
URL https://doi.org/10.1140/epjc/s10052-019-7450-8

- [3] ATLAS Collaboration. Soft b-hadron tagging for compressed SUSY scenarios. Technical Report ATLAS-CONF-2019-027, CERN, Geneva, Jul 2019.
URL https://cds.cern.ch/record/2682131.

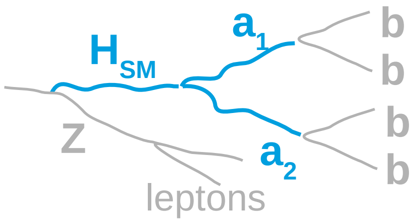
- [4] William Buttinger and Michel Lefebvre. Formulae for Estimating Significance. Technical Report ATL-COM-GEN-2018-026, CERN, Geneva, Oct 2018.
URL https://cds.cern.ch/record/2643488.

- [5] ATLAS Collaboration. A combination of measurements of Higgs boson production and decay using up to 139fb^{-1} of proton-proton collision data at √s= 13 TeV collected with the ATLAS experiment. Technical Report ATLAS-CONF-2020-027, CERN, Geneva, Aug 2020.
URL http://cds.cern.ch/record/2725733.

- [previous analysis] ATLAS Collaboration. Search for the Higgs boson produced in association with a vector boson and decaying into two spin-zero particles in the H → aa → 4b channel in pp collisions at √s = 13 TeV with the ATLAS detector. *Journal of High Energy Physics*, 2018 (10), Oct 2018. ISSN 1029-8479. doi: 10.1007/jhep10(2018)031.
URL http://dx.doi.org/10.1007/JHEP10(2018)031.

Discriminating Variables

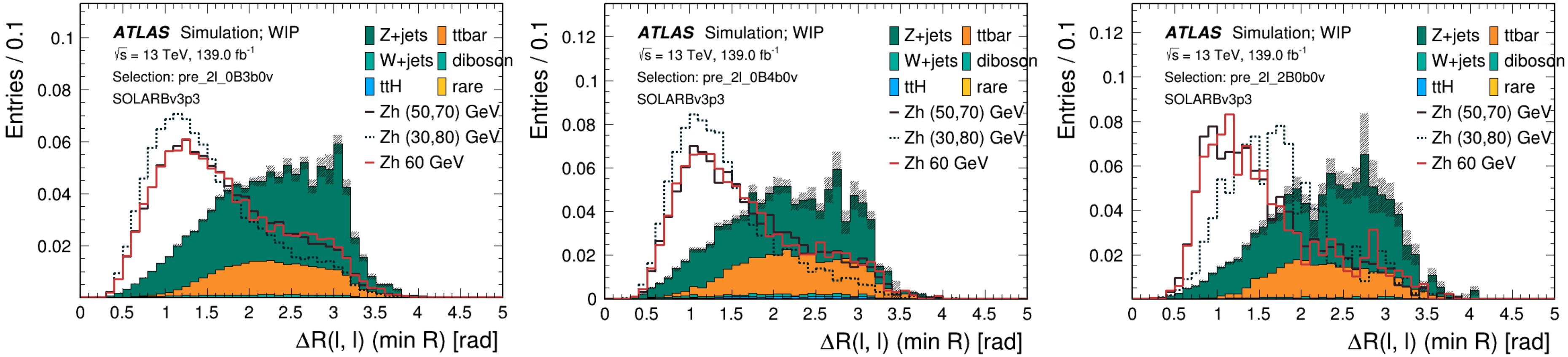
dR(l,l)



- dR(l,l) = angular distance of the leptons in the event
- In signal, Z comes from ZH process, which tends to have higher pT than in the Z+jets process

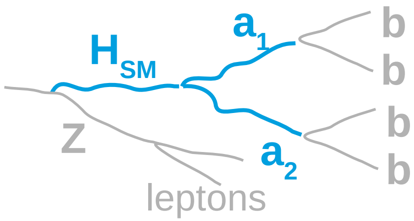
  → decay products (leptons) tend to be closer together in signal
- has separating power in all categories

  plots in different event categories; all plots **normalized**



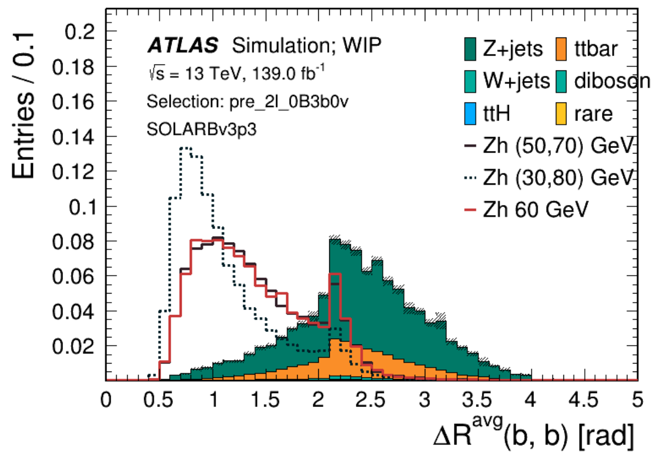
Discriminating Variables

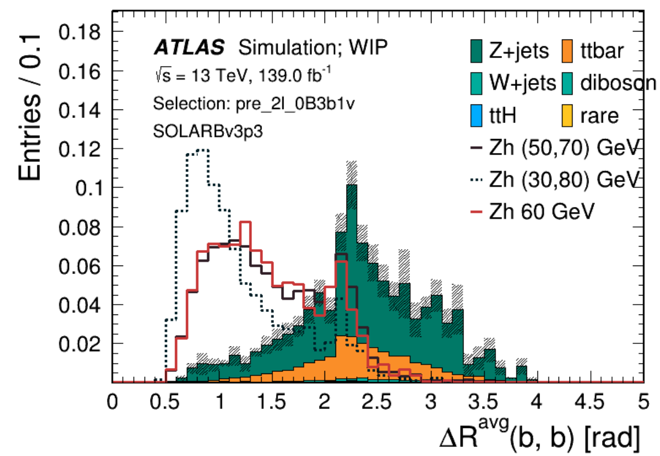
dR^{avg}(b,b)



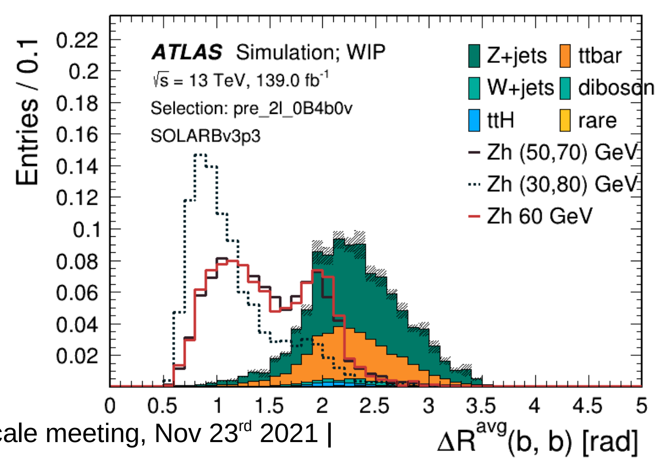
- In signal, the average over the dR of each b-jet pair tends to be smaller than in background, since bs come from one a boson
- All plots **normalized**

dR^{avg}(b,b) in 0bb 3b 0v and 0bb 3b 1v →



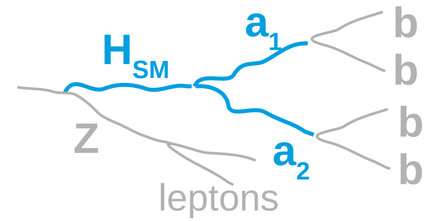


dR^{avg}(b,b) in 0bb 4b 0v →



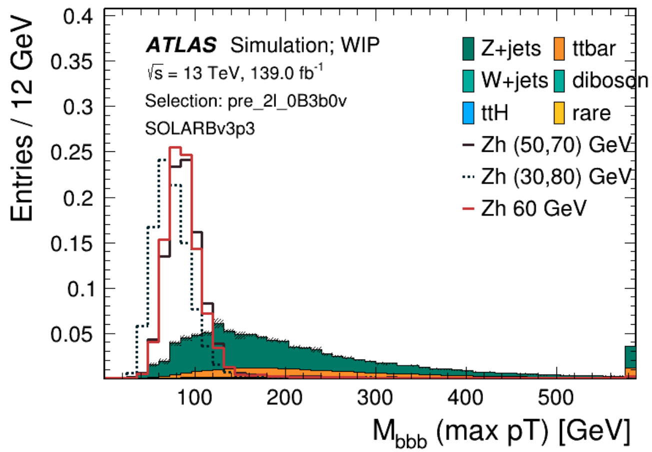
Discriminating Variables

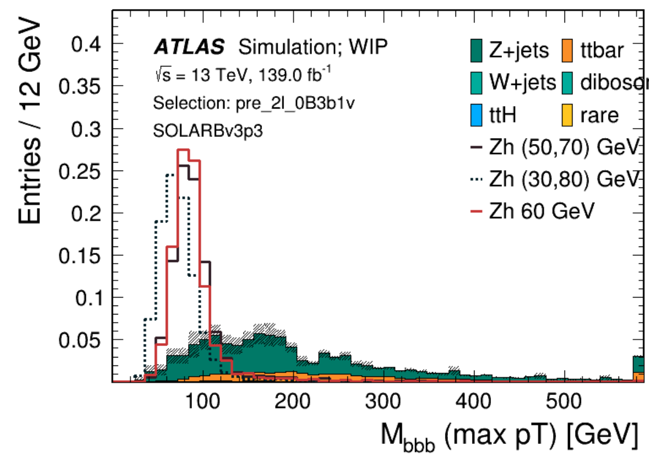
Invariant masses



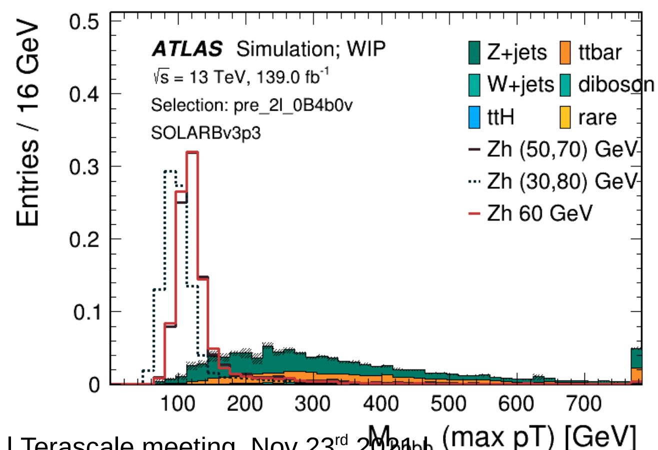
- In signal, the invariant mass of the b-jets (M_{bbb} and M_{bbbb}) reconstructs to ≤ or ~ the Higgs mass
- All plots **normalized**

M_{bbb} in 0bb 3b 0v and 0bb 3b 1v →



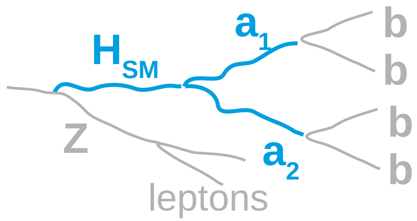


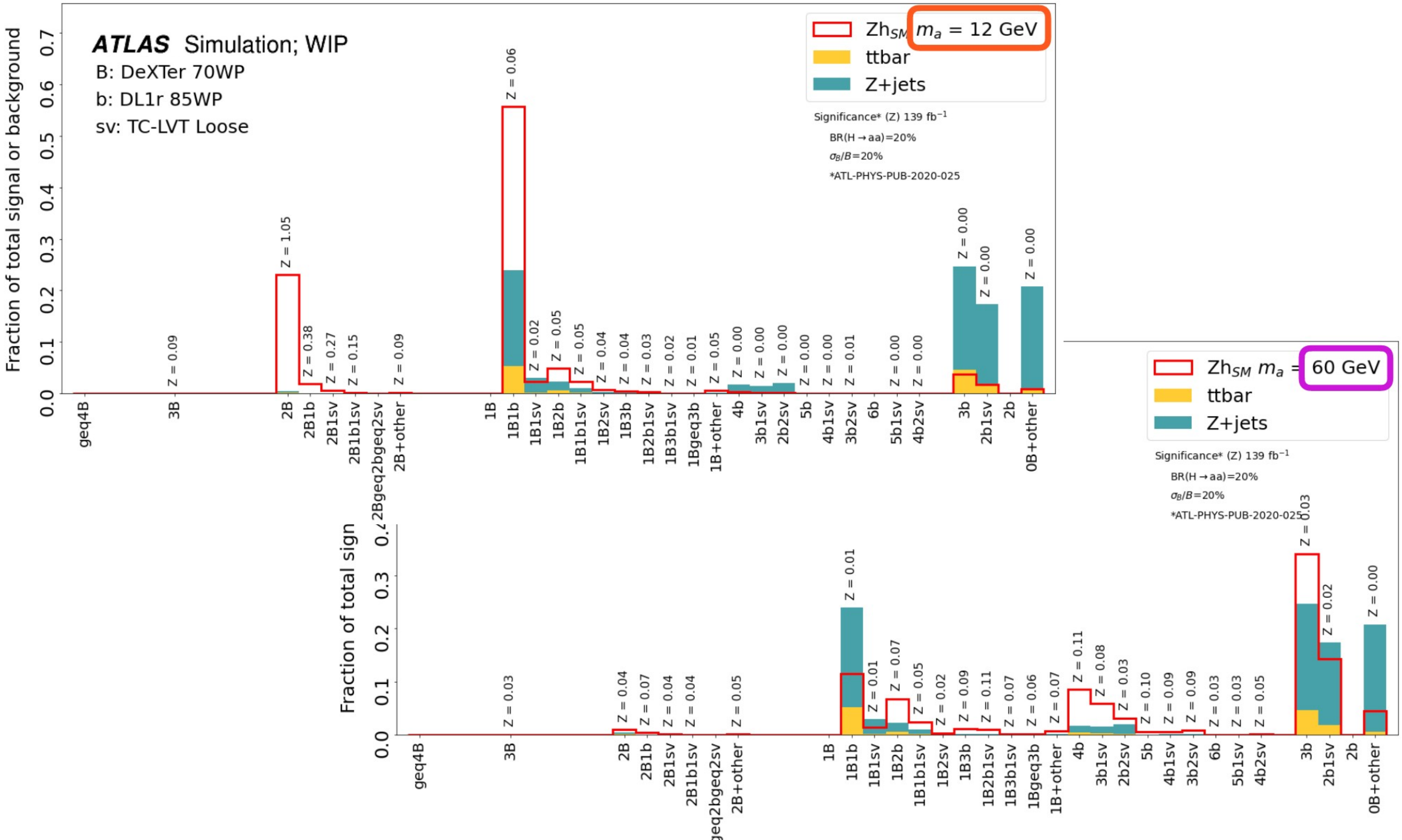
M_{bbbb} in 0bb 4b 0v →



Event Categories

Population studies.





- Go into the promising event categories and find discriminating variables