Boosted Higgs Tagging at ATLAS and CMS

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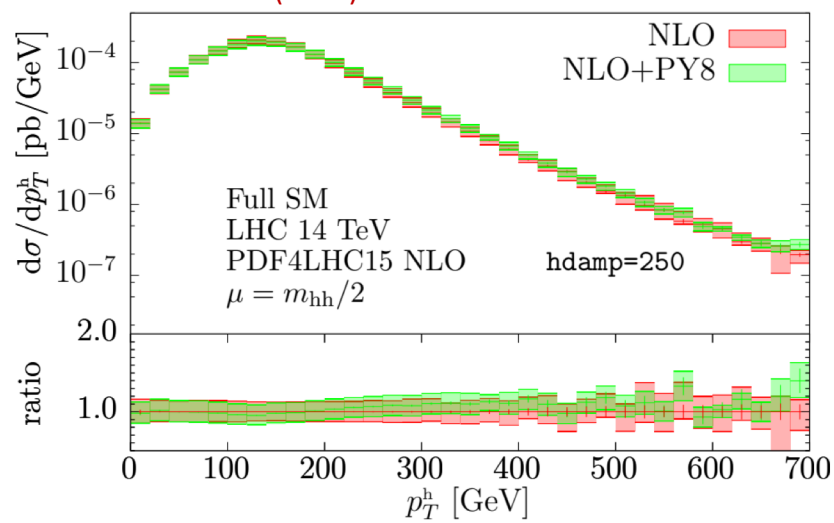
Why Boosted Higgs?

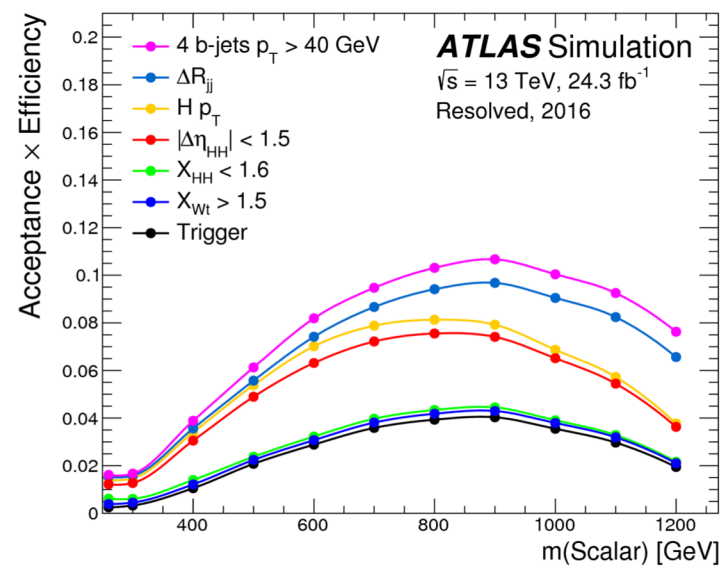
- High p_T Higgs bosons from:
  - Tails of SM hh distribution
  - Anomalous coupling enhancement
  - New heavy resonances

JHEP 1708 (2017) 088

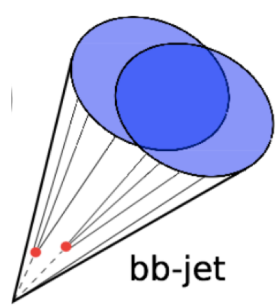


- Standard jet finding + b-tagging approaches fail when Higgs decay products merge due to Lorentz boost

arXiv:1804.06174

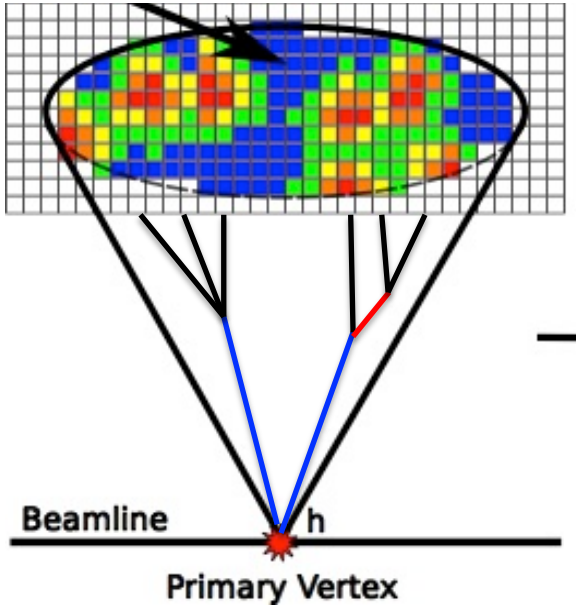


- Boosted jet approaches: large-R jets + jet substructure



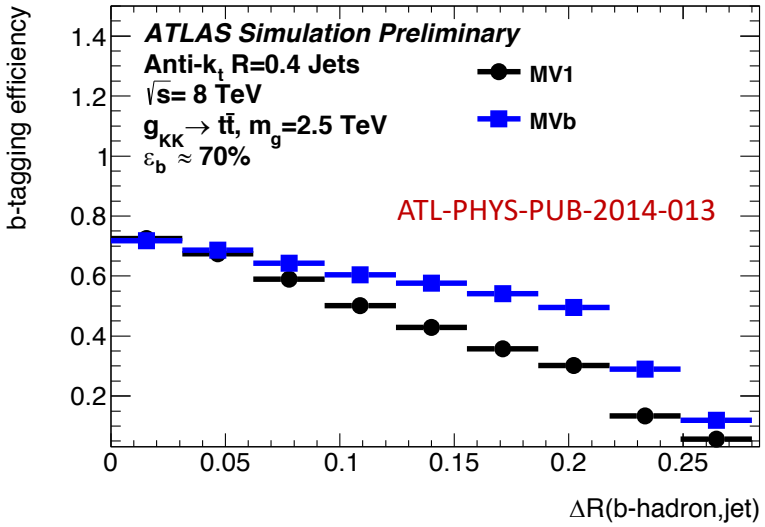
Higgs Tagging: B-tagging + Substructure

- Ingredients
  - Large-R jet, Jet Mass and substructure
  - B-hadron identification



- How to identify multiple b-jets in this dense environment?
  - How to identify regions of interest / seed axes to run b-tagging algorithms?

- How to combine jet substructure with b-tagging?



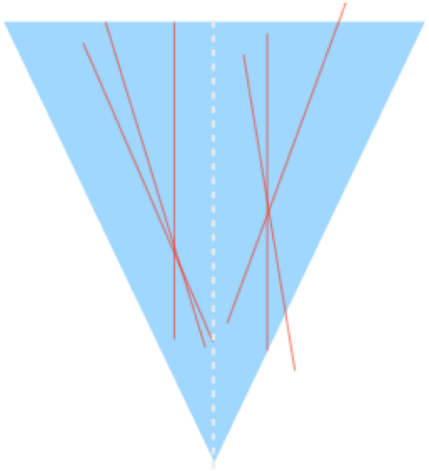
Higgs Tagging Methods

ATLAS	CMS
	Full Large-R jet
	Large-R jet soft-drop subjets
Fixed radius track jets	
Variable radius track jets	
Exclusive k_T subjets	τ-axis guided double tagging
Center of mass	
ML driven improvements	ML driven improvements

- Note: differences in mass window and jet pT ranges, make direct comparisons not possible

Large-R Jet and Subjet Based Higgs Tagging

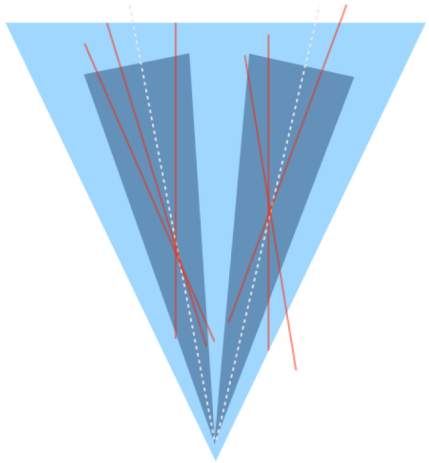
- Apply standard b-tagging algorithms to:
  - Entire large-R jet as region of interest
  - Subjets from clustering large-R jet constituents as regions of interest



Large-R jet tagging

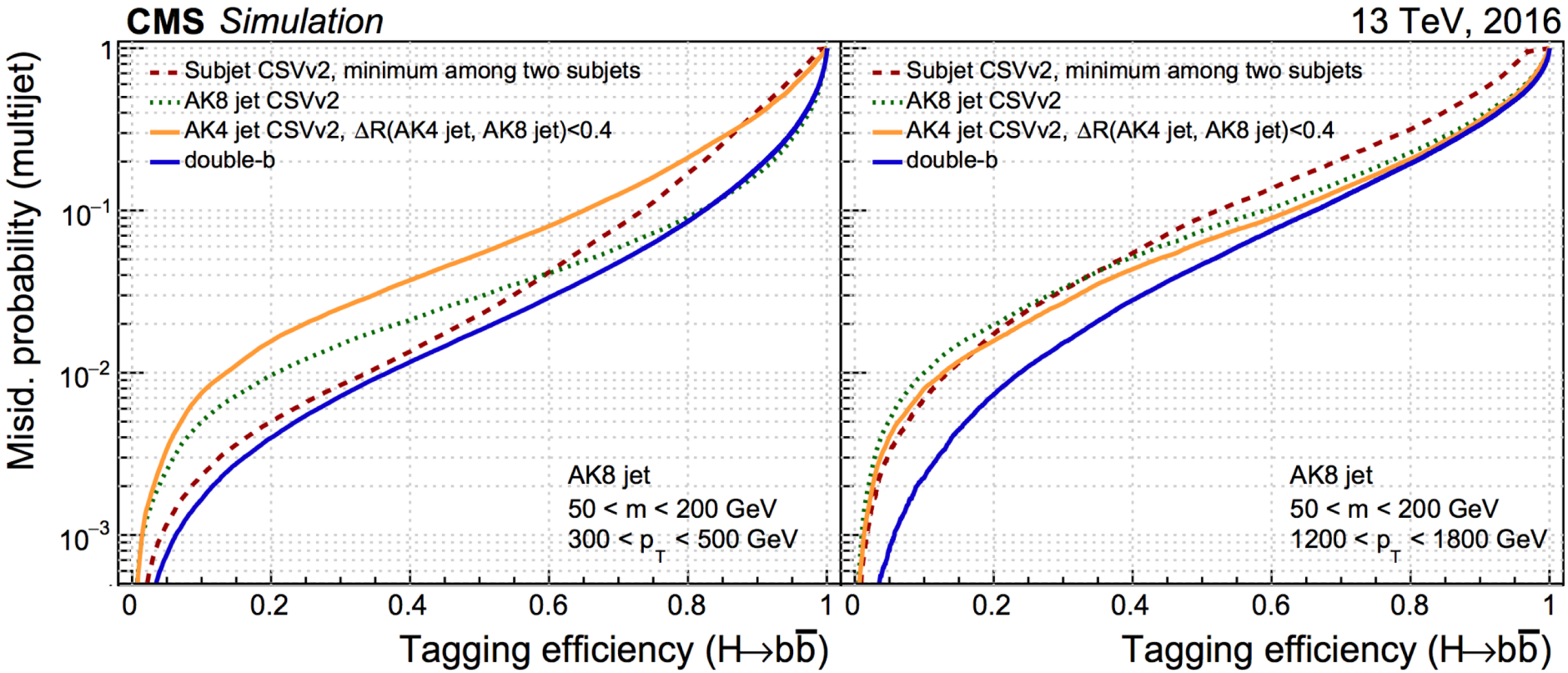
- Pros:
  - Internal structure of jet, including impact of neutrals, used to guide RoI finding

- Cons
  - Sensitive to grooming algorithm
  - For large-R jet tagging, lose the benefit of the two b-hadron RoI hypothesis to guide b-tagging
  - Harder to calibrate subjet independent of large-R jet



Subjet tagging

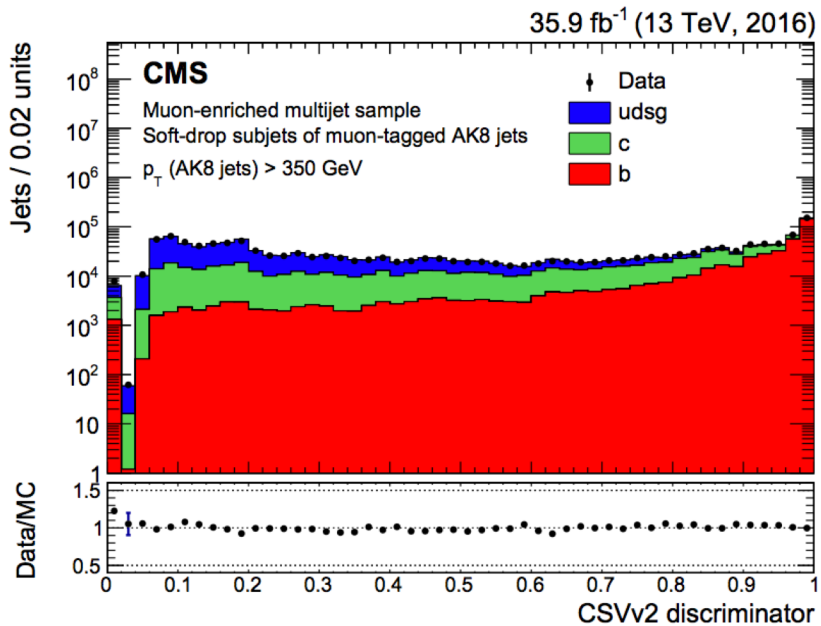
Large-R Jet and Subjet Based H-Tagging



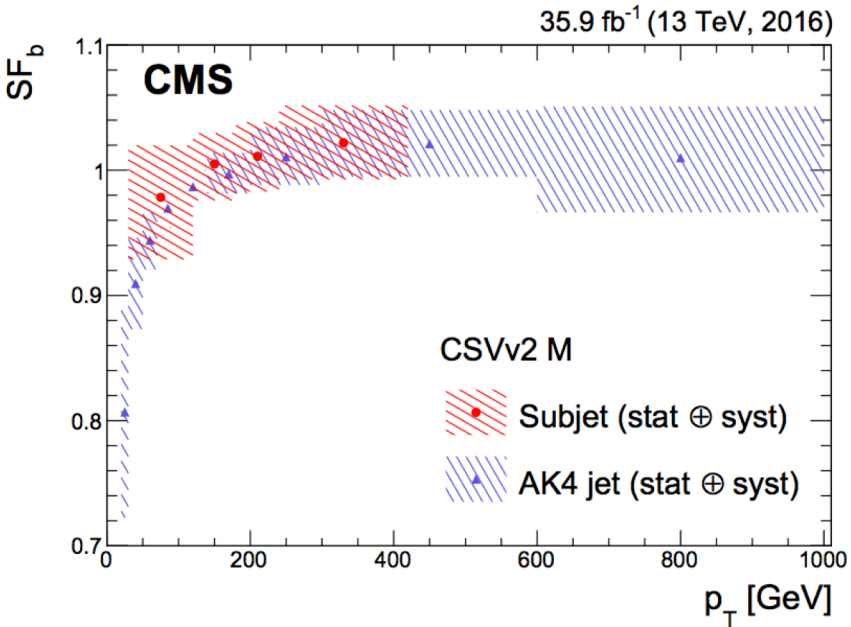
Note:
Will come back to blue line later

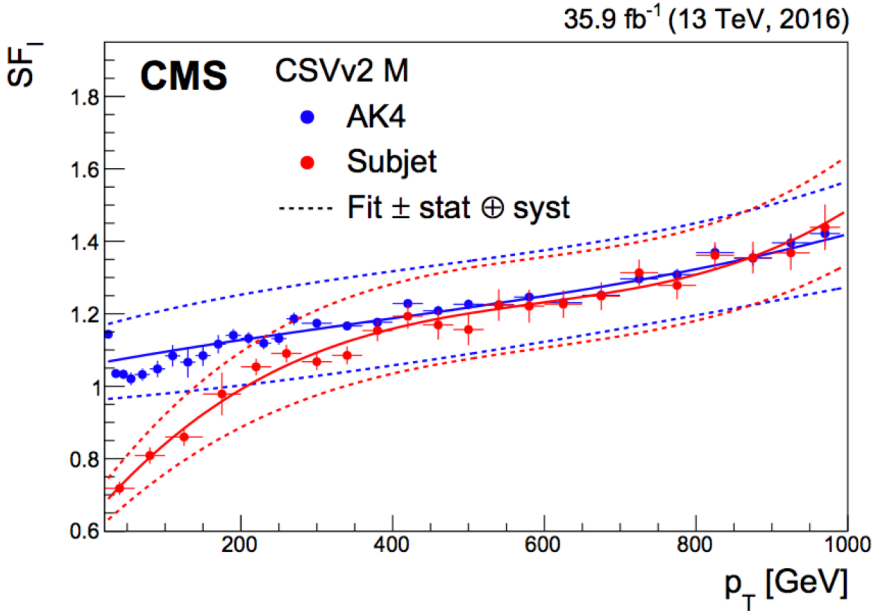
JINST 13 (2018) P05011

Data/MC for Subjet Tagging



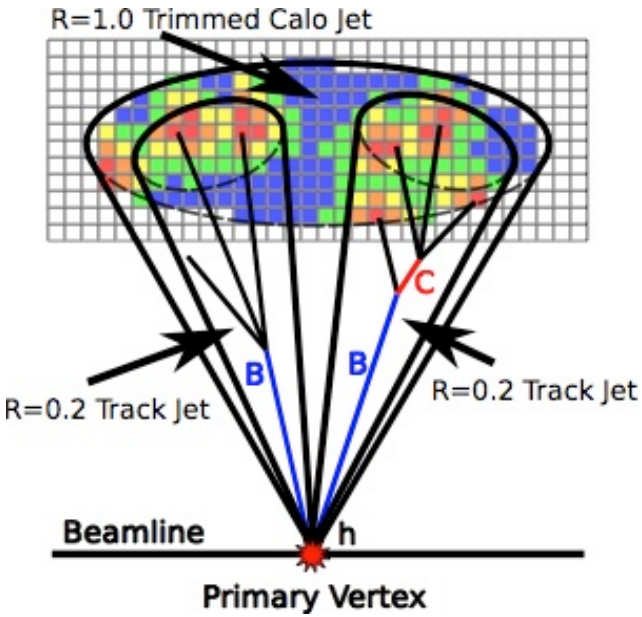
- b-jet calibration in muon enriched subjets of large-R jets in multijet events
- Light-jet calibration using "negative tagged" subjets

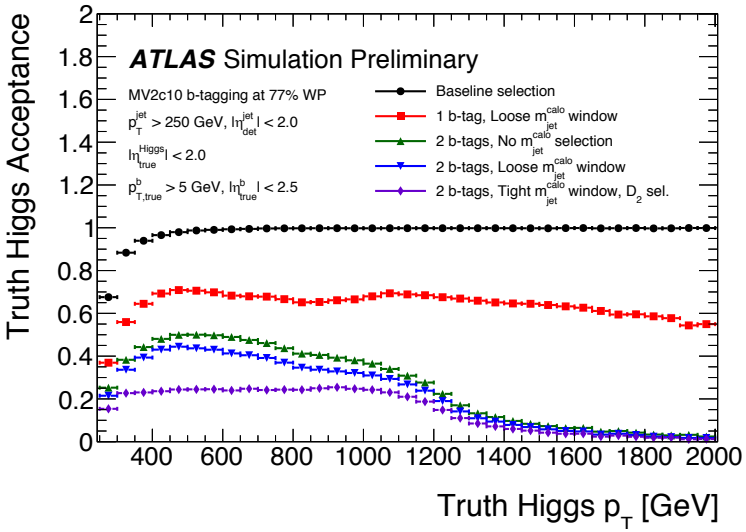




Track Jet based Boosted Higgs Tagging

- Jet clustering on tracks using small-R to resolve fine features
- Match track jets to larger-R jets
- Pros
  - Excellent track resolution allows for small-R clustering
  - Pileup insensitive
  - Independent of large-R jet
    - Insensitive to grooming algorithm
    - b-tagging calibration independent of large-R jet
- Cons:
  - No access to neutral particle information in finding direction





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H-Tagging with Fixed Radius Track Jets

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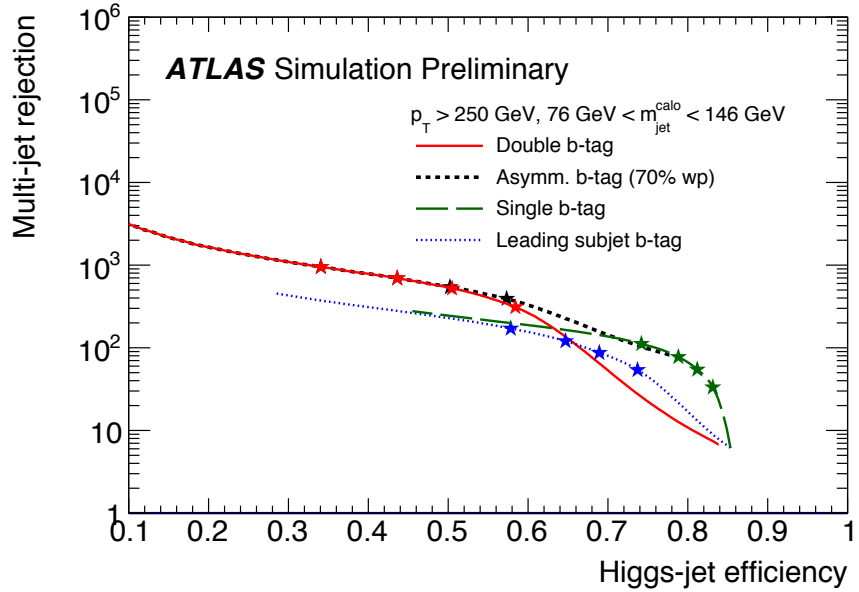
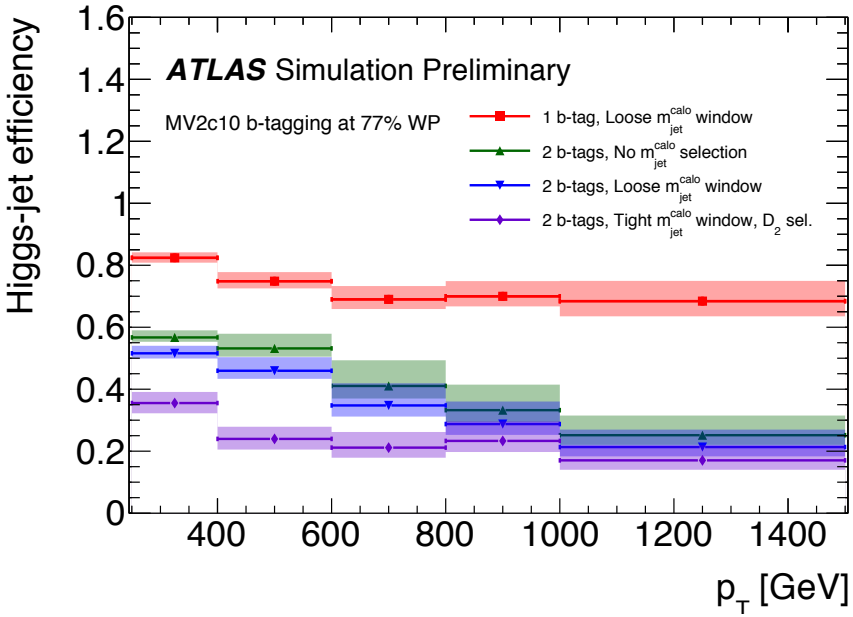
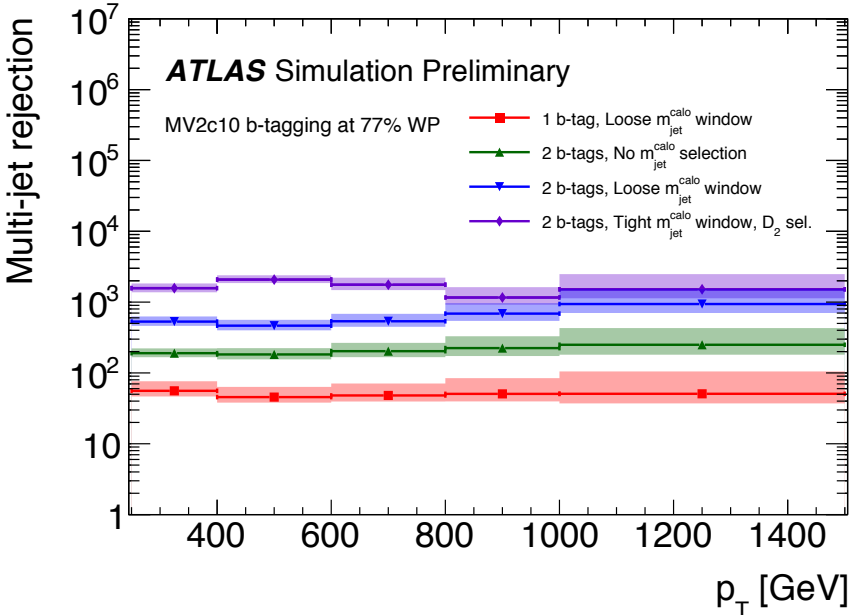
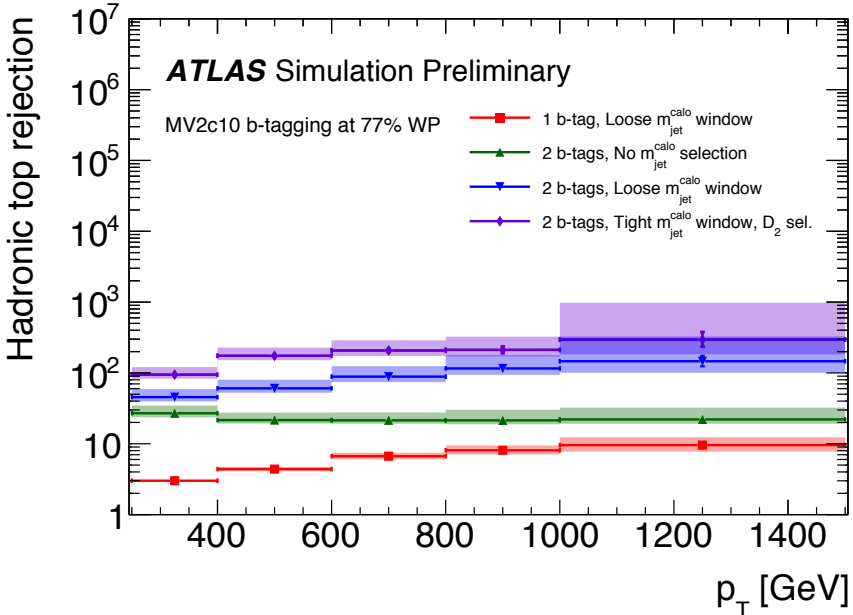


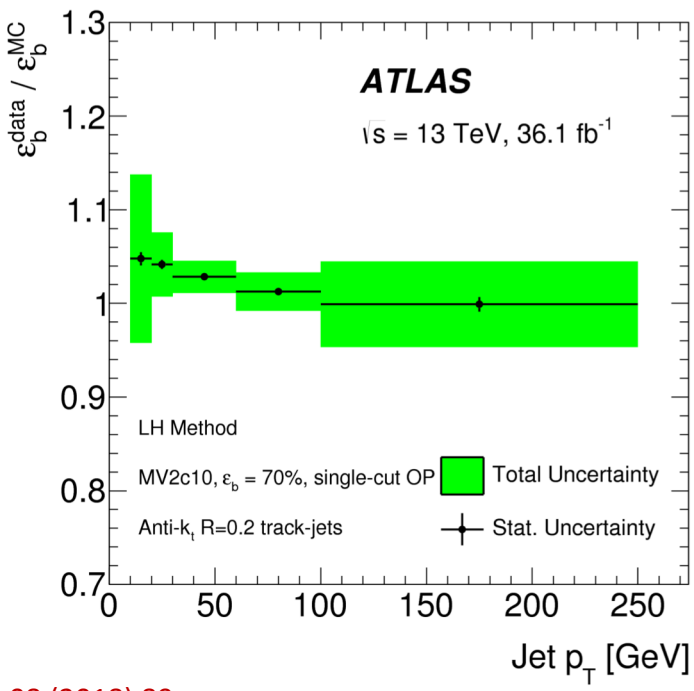


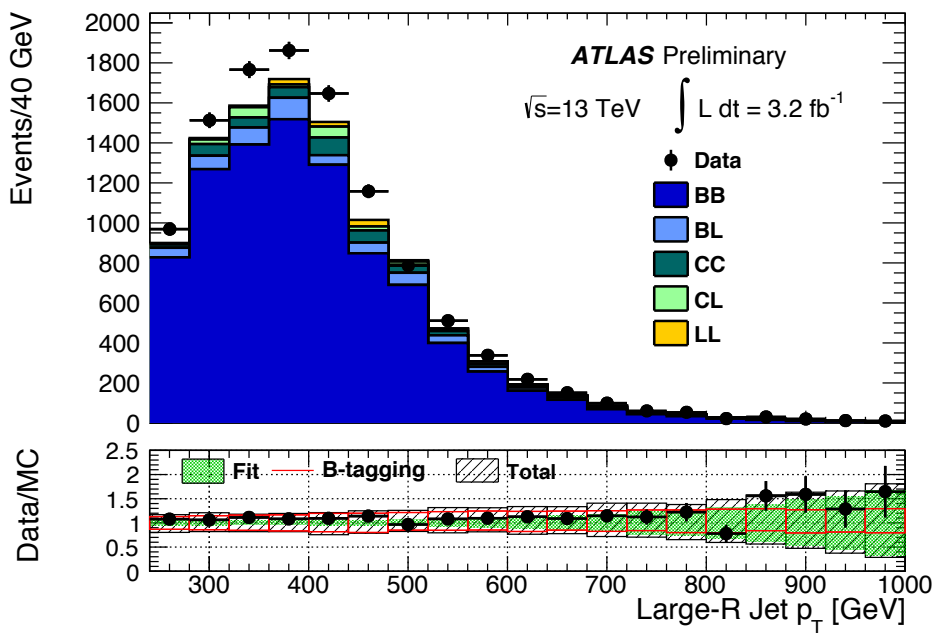




Performance in Data

- **Left**: Single jet b-tagging calibration in dilepton t-tbar events
- **Right**: Muon matched large-R jets in multijet events for double b-tagging validation in gluon→bb enriched sample
  - Useful to check for topological effects or "cross talk" between among the two b-tagged jets





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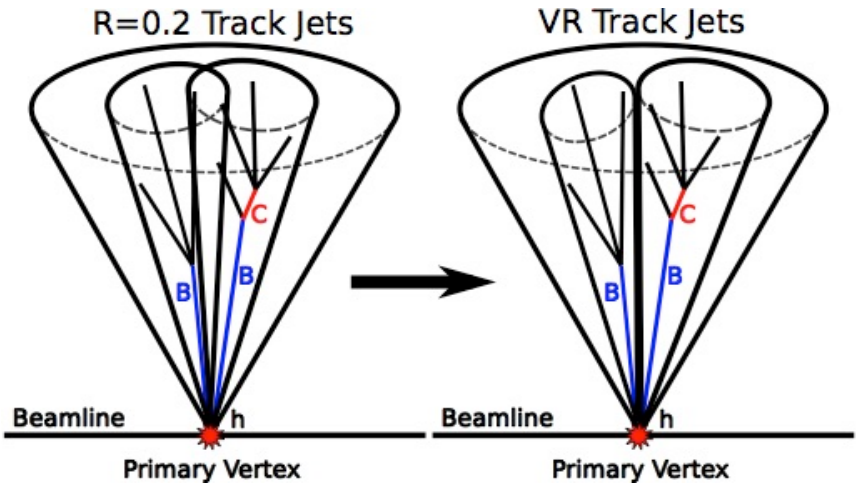
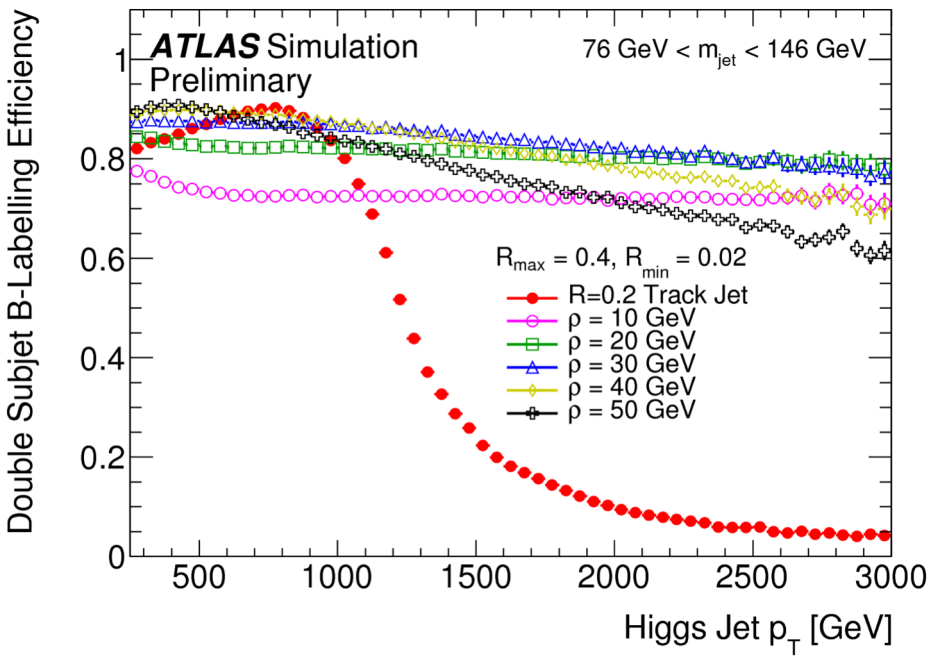
ATLAS-CONF-2016-039

VR Track Jet Based b-tagging

- At high Higgs jet p_T, fixed radius track-jets will merge
  - One option: use single and double track-jet selections
- Shrink track jet R with p_T
  - $R \rightarrow R_{eff}(p_T) = \frac{\rho}{p_T}$
- Pro:
  - Resolve and tag multiple b-jet region of interests up to higher Higgs jet p_T
- Cons:
  - Need to be careful about overlapping track jets





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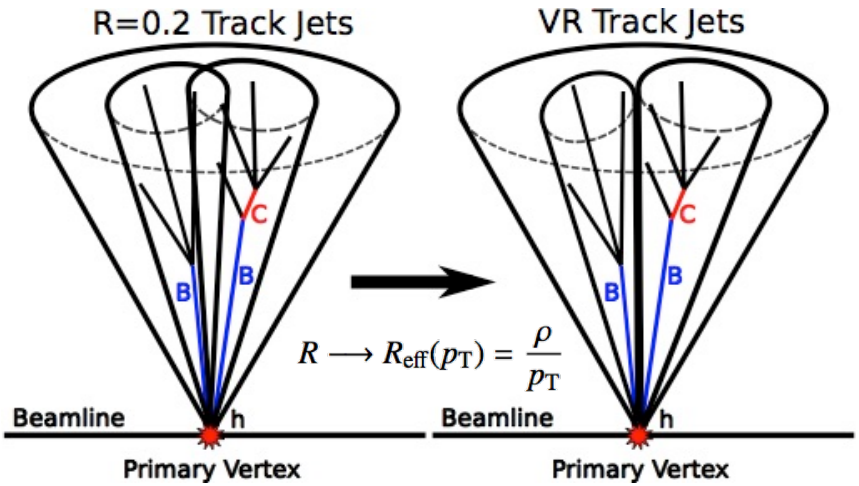
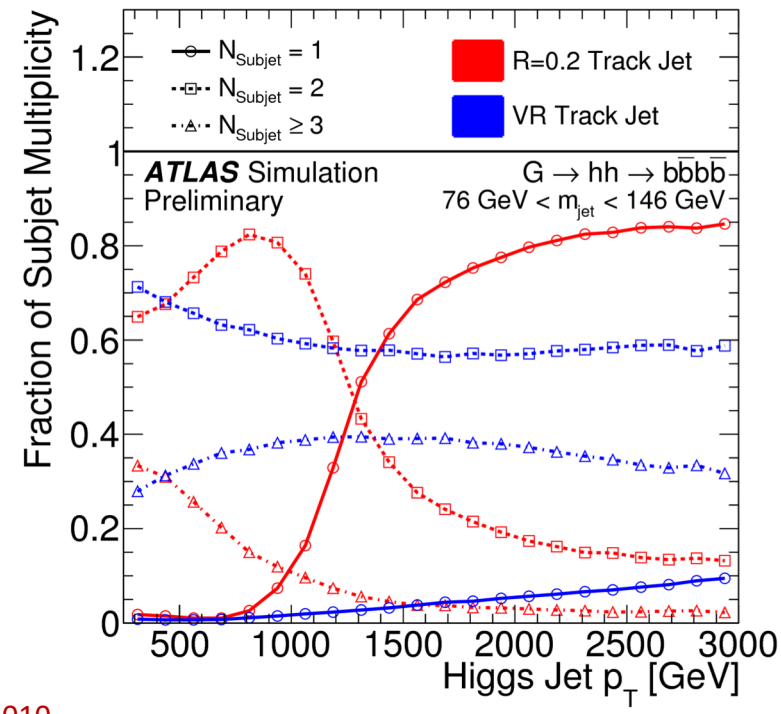
VR Track Jet Based b-tagging

- At high Higgs jet p_T, fixed radius track-jets will merge
  - Necessitates using single and double track-jet selections
- Shrink track jet R with p_T
- Pro:
  - Resolve and tag multiple b-jet region of interests up to higher Higgs jet p_T
- Cons:
  - Need to be careful about overlapping track jets





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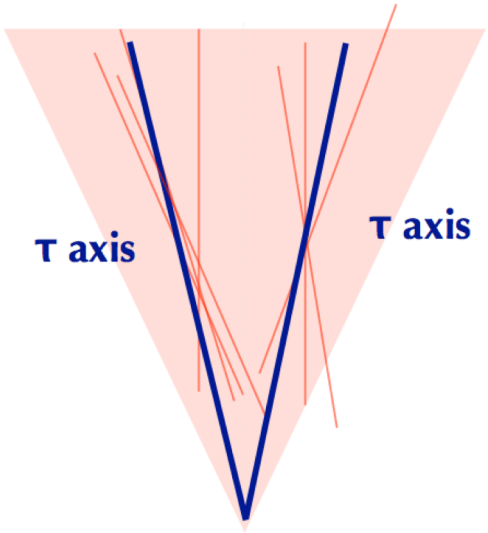
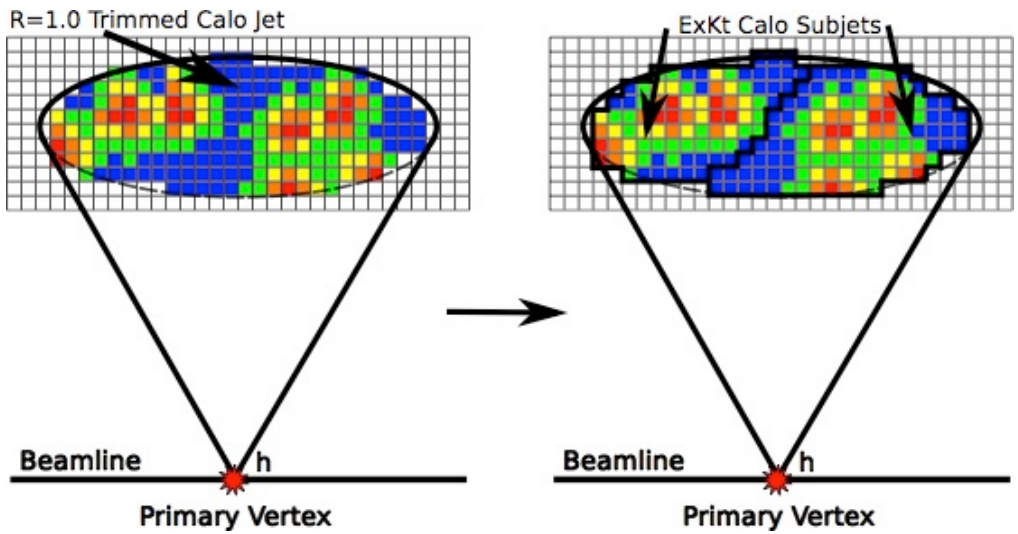
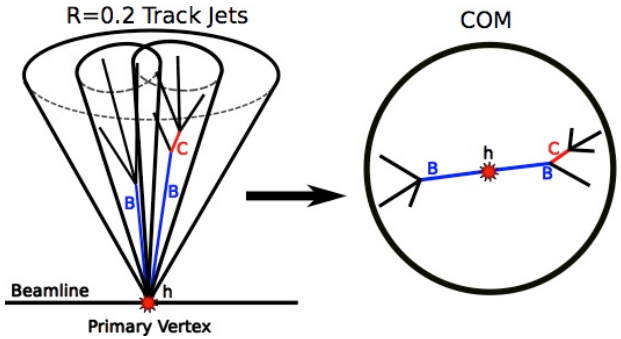
Exclusive subjet guided b-tagging



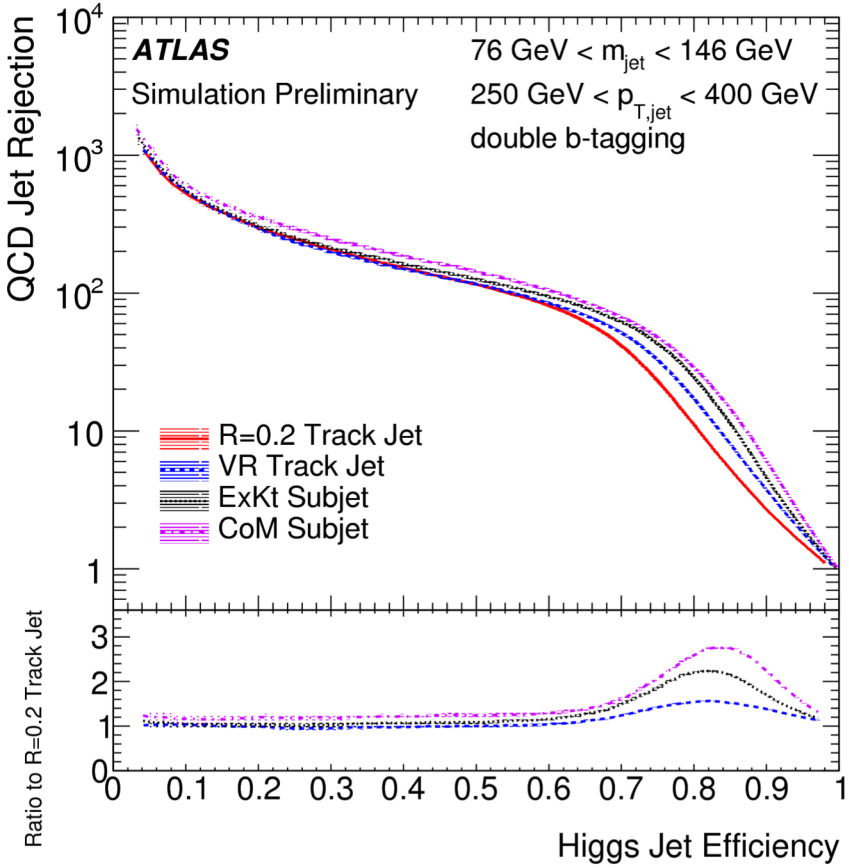


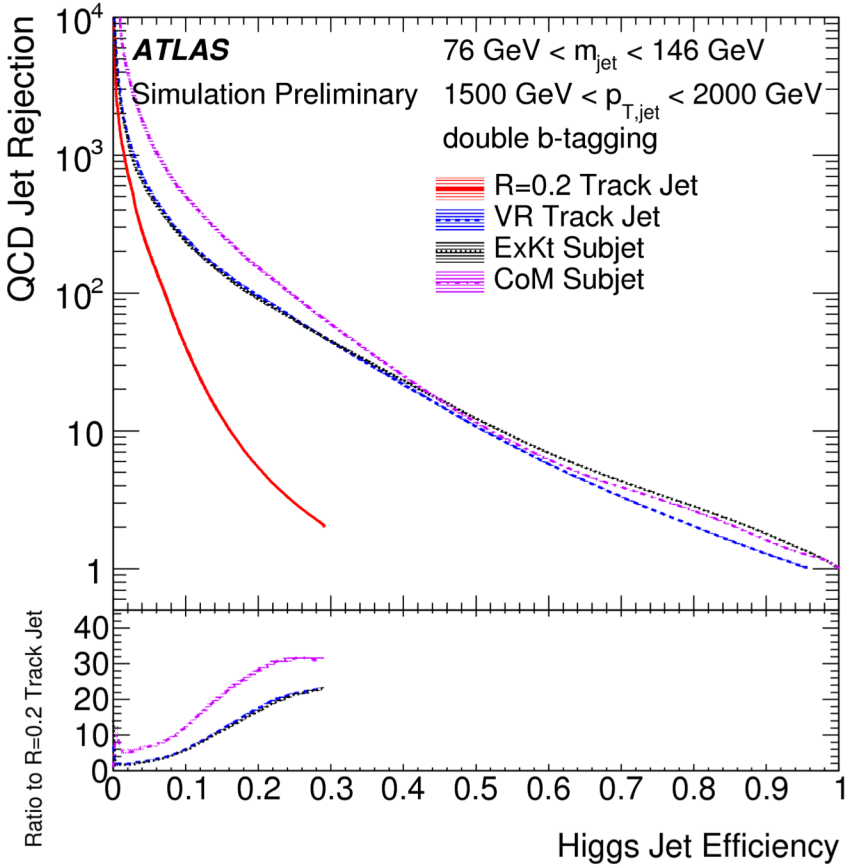
- Identify two exclusive regions of interest using exlcusive-k_T declustering of large-R jet
  - ATLAS: standard b-tagging on ExKt subjets
  - CMS: Tagger using RoIs based on τ axes (found with exclusive-k_T)

- Alternatively boost into center of mass frame and do exclusive clustering
  - E.g. with EECambridge algorithm, min $y_{ij} = 2(1-\cos\theta_{ij})$



ATLAS VR Track Jet, Exclusive K_T, and CoM





Note: Trainings are based on ttbar samples, and no specific training has yet been performed using jets in boosted topologies.

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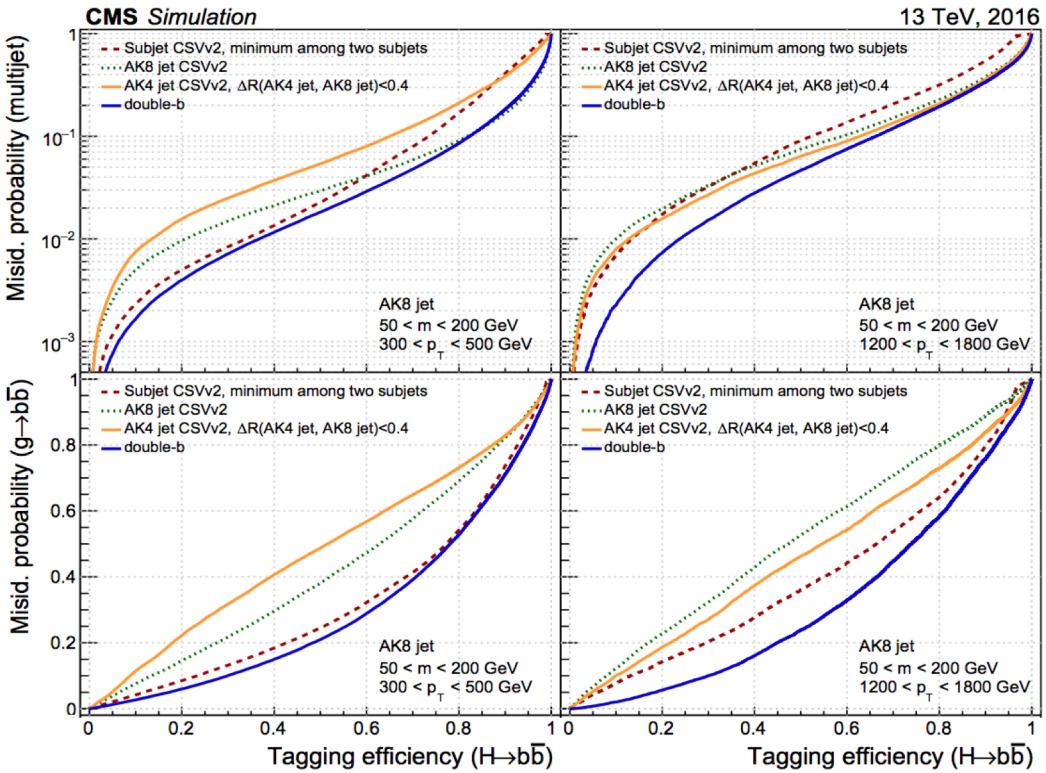
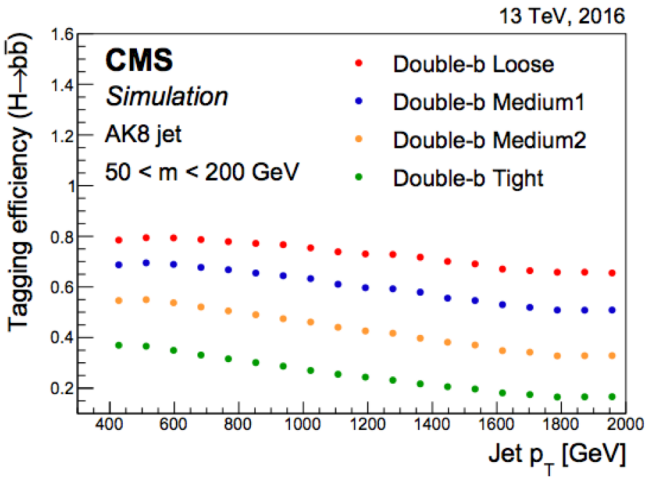
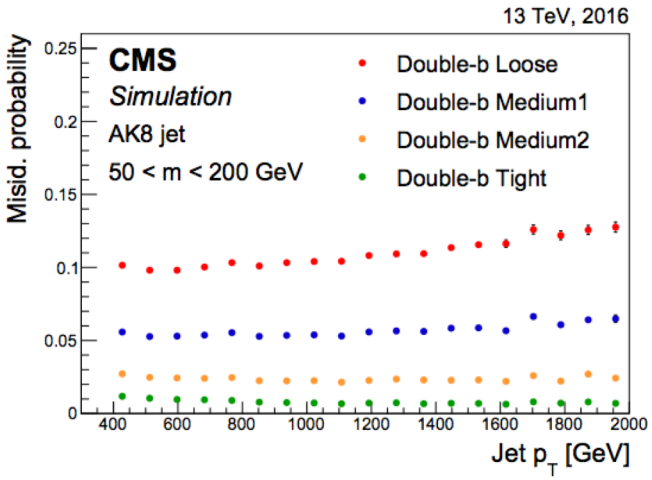
CMS DoubleB

- Associate tracks and vertices to τ-axes
- Combine in BDT: b-tagging information from both subjets and information relating the two subjets

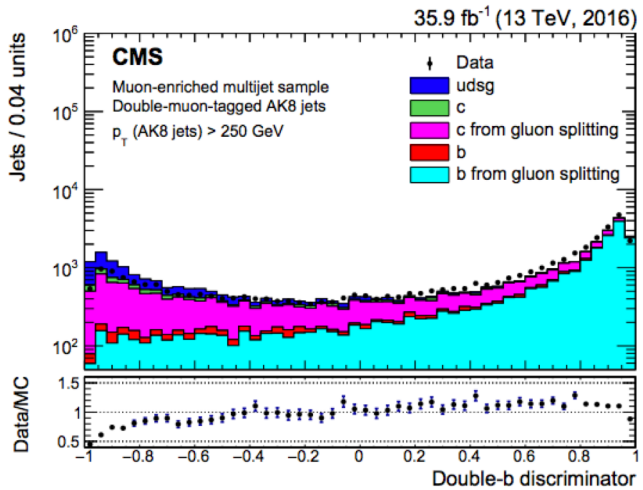


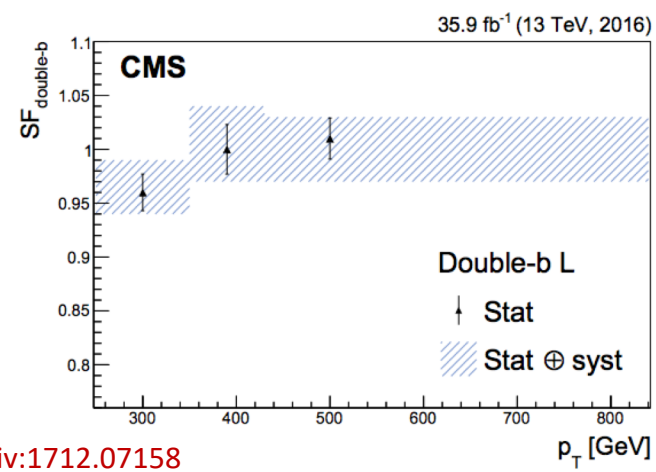




CMS DoubleB Scale factors

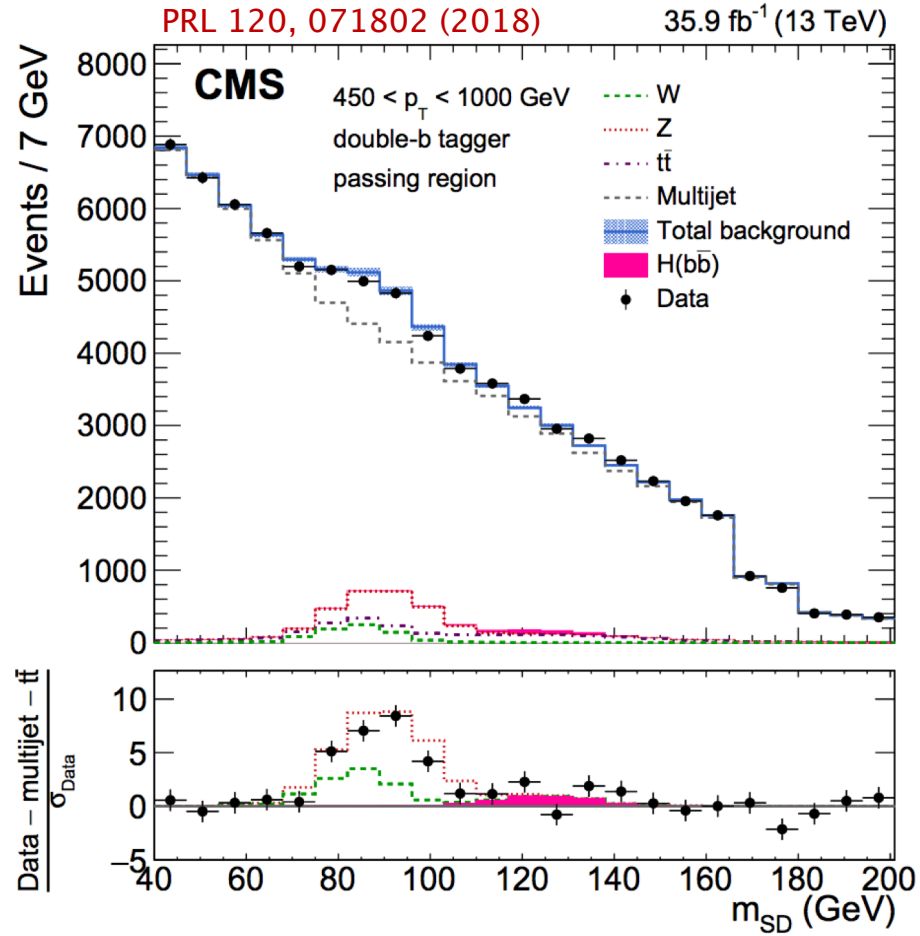
- Double-b calibration using muon matched large-R jets in multi-jet events
- Top jet mistag rate calibration in boosted top events





arXiv:1712.07158

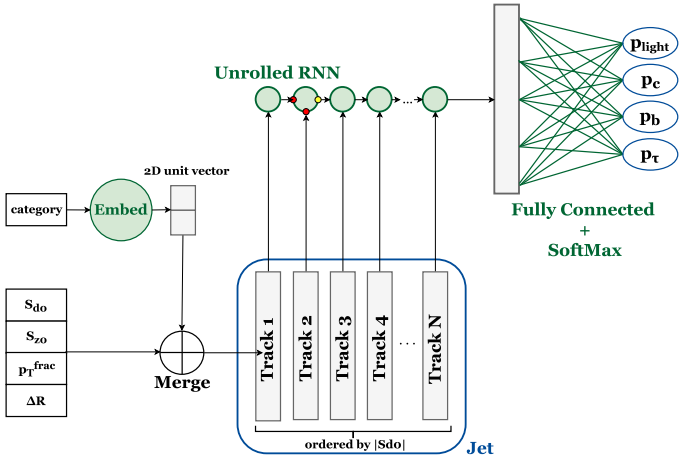
PRL 120, 071802 (2018)

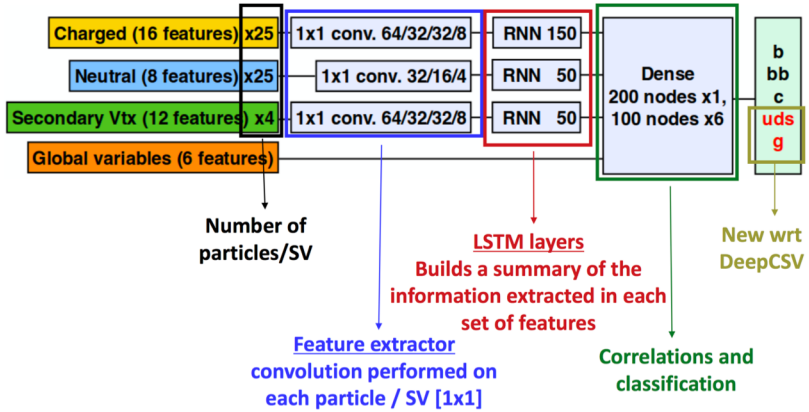


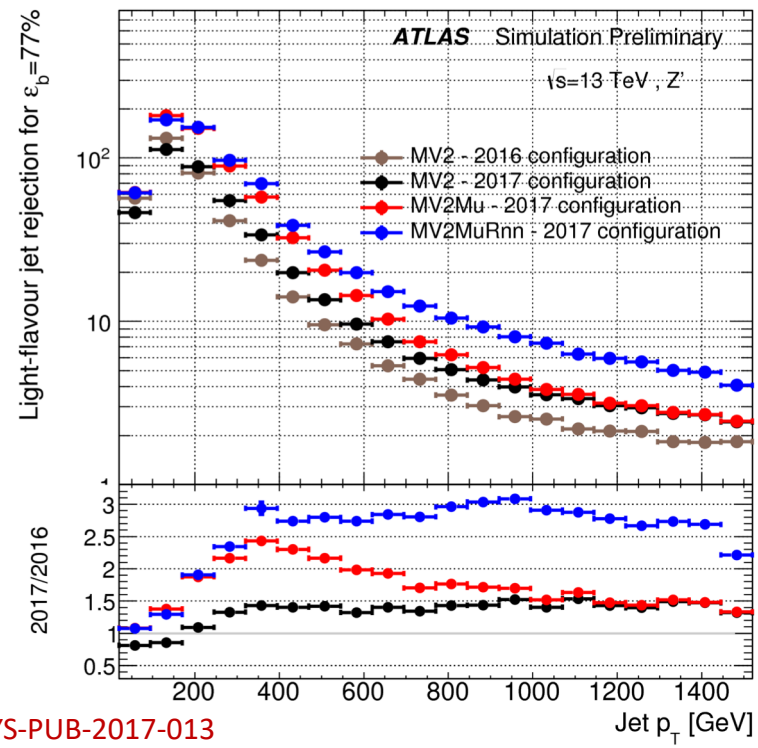
- Z-bosons identified with tagger in Higgs+ISR analysis

New Ideas in Development

ML improvements to single b-jet tagging







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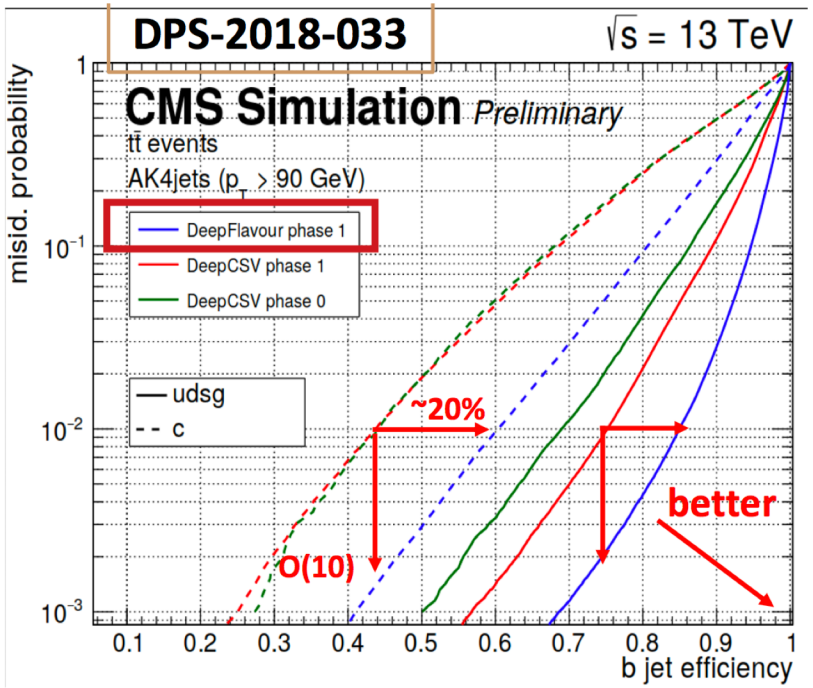
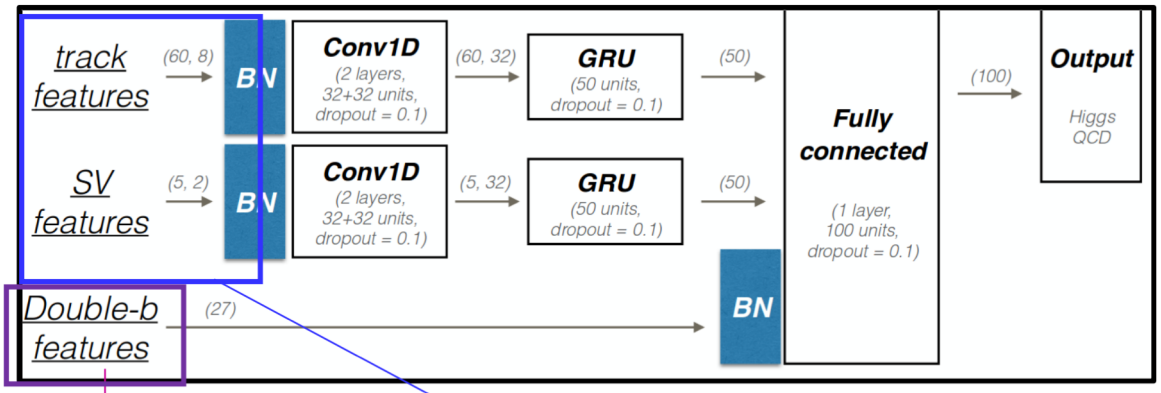


From L. Gouskos, BOOST 2018

CMS DeepDoubleB



Double-b features:

-> vertexing, tracking & substructure

-> inputs largely mass & p_T independent

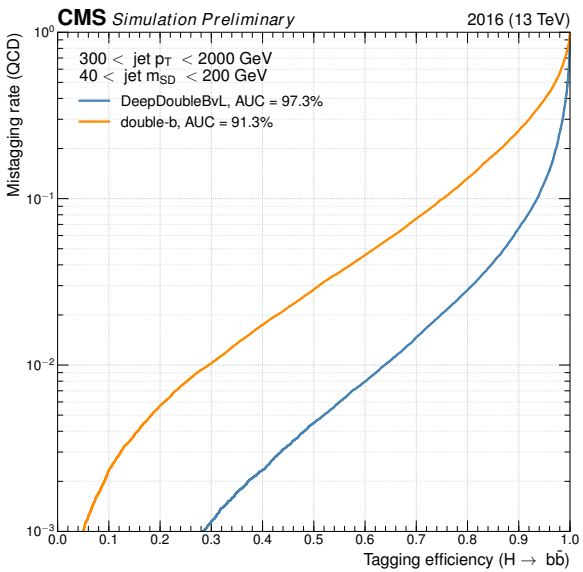
Inputs (differences wrt "slim" jet case):

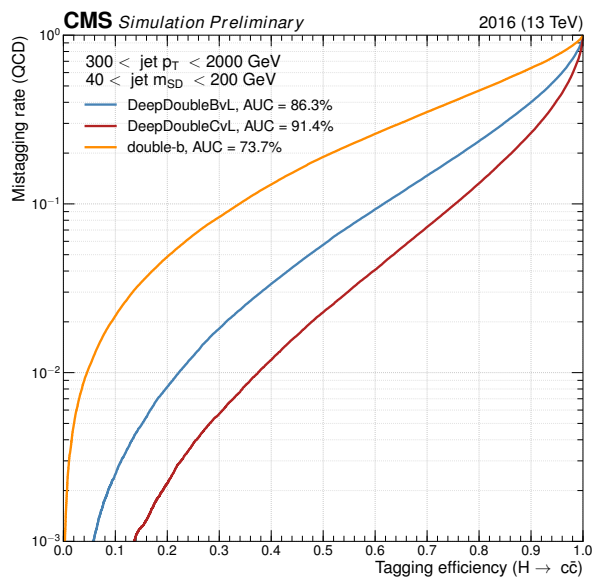
→ Increased num of particles/SV (larger R)

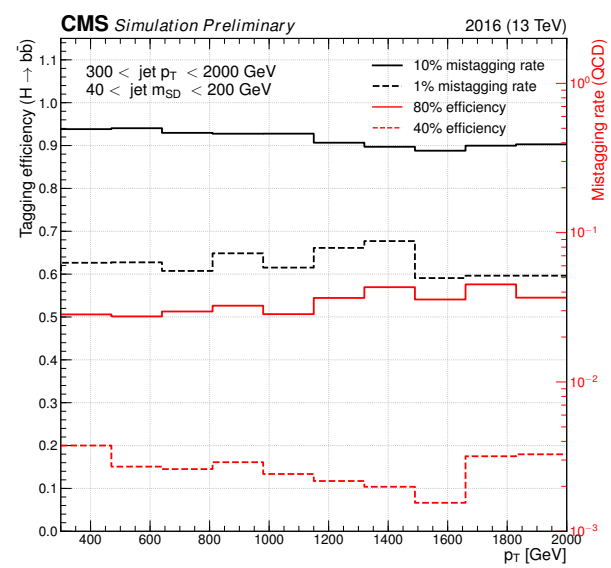
→ Reduced num of features (less mass sculpting)

→ Drop Neutral PF candidates

From L. Gouskos, BOOST2018







Conclusion

- Wide array of Higgs tagging approaches utilizing b-tagging and substructure in different ways

- Exciting new algorithms being deployed, while active development continues!
  - Including dedicated double b-tagging and utilizing modern machine learning methods
  - Need to understand if such approaches expose us to new and potentially larger modeling uncertainties.

- Methods to calibration / validate these methods are becoming fairly well established
  - Do we need to calibrate samples other than bb? What about b, cc, c, l?
  - Are there topology specific effects?