

# FCCJetBenchmarks: Jet performance benchmark toolkit for reconstruction algorithms

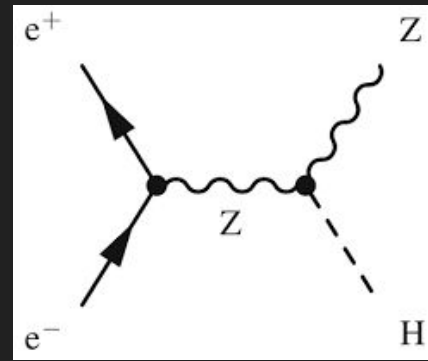
Gregor Krzmann, SLAC/Stanford

Advisor: Ariel Schwartzman

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# Motivation

- Several Higgs channels at FCC-ee rely on multi-jet final states:
  - $H \rightarrow WW^* \rightarrow 4$  jets
  - $H \rightarrow 2$  jets
- ZH production with
  - $Z \rightarrow qq \rightarrow$  additional 2 jets
  - $Z \rightarrow \nu\nu \rightarrow$  missing energy
- Jet energy resolution may be different depending on the number of jets in final state
- Key questions:
  - How do we compare different reconstruction (PF) algorithms for a wide range of final states?
  - What jet algorithm should be used?
- We want to develop a **comprehensive framework for jet performance** at FCC-ee
- This way, new detector designs and PF algorithms could be evaluated always in exactly the same way - using the same metrics



# Motivation

- Typical workflow for an analysis of events containing jets at the FCC-ee:

Event simulation



Reconstruction (e.g. PF)



Jet clustering



Event selection and Analysis

Using Key4HEP software stack and the FCCAnalyses framework

# The framework

Event simulation



Reconstruction (e.g. PF)



Jet clustering



Event selection and Analysis

Provided by the user

- e+e- anti-kt
- Durham

Compare various observables:  
 $m_H$ , jet energy resolution, jet angular resolution

- Everything implemented within the Key4HEP and FCCAnalyses frameworks
- Jet clustering implemented using FastJet
- Easy to add new PF methods, jet clustering, or detector concepts

# Provided samples - dataset and reconstruction

Event simulation

- Using Delphes IDEA card and PYTHIA 8 with Key4HEP software stack;  $\sqrt{s}=240$  GeV
- Various processes with 2, 4, and 6-jet final states (see below)
- 5M events per process

Reconstruction

Two options:

- Use the Delphes PF
- Use the calo hits directly

Jet Clustering

Process	Number of jets in final state
Z( $\rightarrow$ qq)H( $\rightarrow$ WW $\rightarrow$ qqqq) (p8_ee_ZH_6jet_ecm240) (all flavours)	6
Z( $\rightarrow$ bb)H( $\rightarrow$ WW $\rightarrow$ bqqq) (p8_ee_ZH_6jet_HF_ecm240)	6
Z( $\rightarrow$ qq)H( $\rightarrow$ WW $\rightarrow$ qqqq) (p8_ee_ZH_6jet_LF_ecm240)	6
Z( $\rightarrow$ bb)H( $\rightarrow$ bb) (p8_ee_ZH_bbbb_ecm240)	4
Z( $\rightarrow$ qq)H( $\rightarrow$ bb) (p8_ee_ZH_qqbb_ecm240)	4
Z( $\rightarrow$ bb)H( $\rightarrow$ gg) (p8_ee_ZH_bbgg_ecm240)	4
Z( $\rightarrow$ qq)H( $\rightarrow$ gg) (p8_ee_ZH_qqgg_ecm240)	4
Z( $\rightarrow$ qq)H( $\rightarrow$ qq) (p8_ee_ZH_qqqq_ecm240)	4
Z( $\rightarrow$ vv)H( $\rightarrow$ bb) (p8_ee_ZH_vvbb_ecm240)	2
Z( $\rightarrow$ vv)H( $\rightarrow$ gg) (p8_ee_ZH_vvgg_ecm240)	2
Z( $\rightarrow$ vv)H( $\rightarrow$ qq) (p8_ee_ZH_vvqq_ecm240)	2

**$e^+e^-$  generalized anti-kt (inclusive mode)**

$$d_{ij} = \min(E_i^{-2}, E_j^{-2})(1 - \cos\theta_{ij}), \quad d_{iB} = E_i^{-2}$$

- Option with energy recovery (will discuss later)

**Durham (exclusive mode)**

$$d_{ij} = 2 \min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$$

# Event processing details

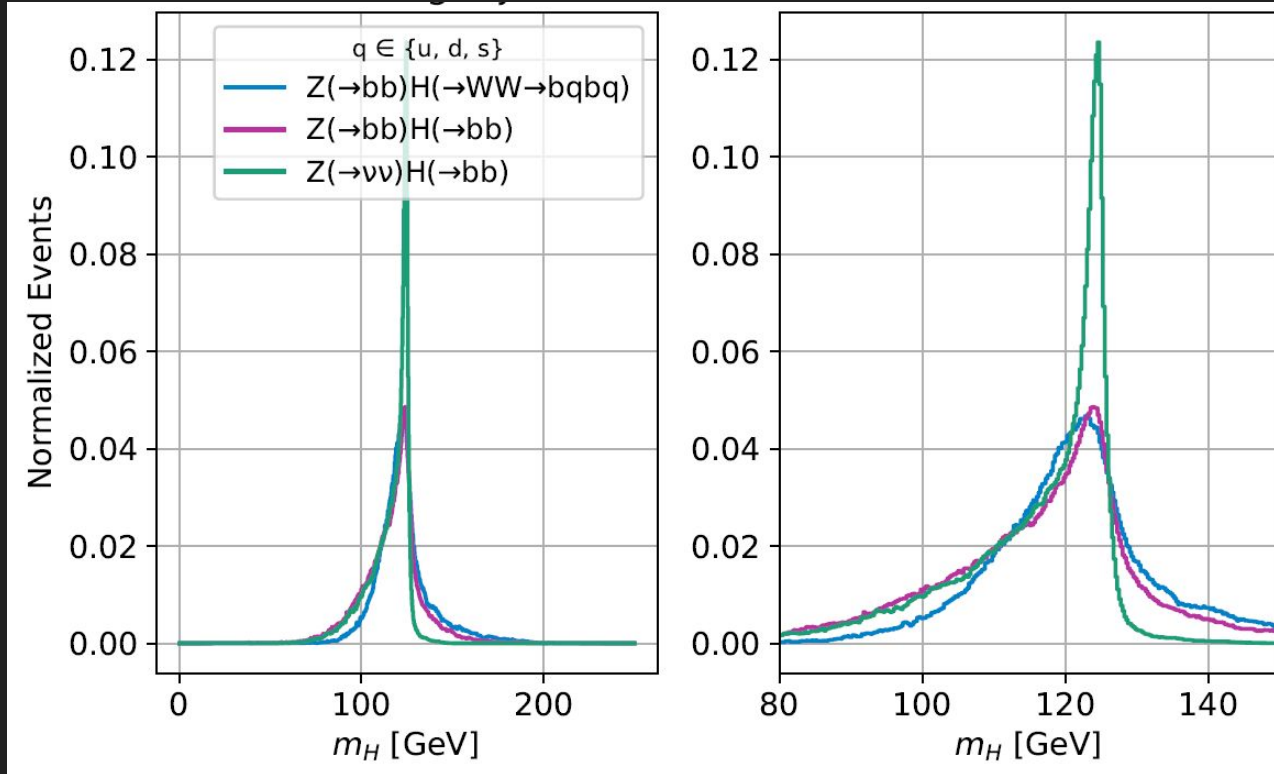
- Idealization: the expected number of jets in the event is known beforehand (input to the clustering algorithm).
- Truth: Jets clustered from final-state MC particles
- Jet matching: greedy matching using  $R_{\max} = 0.3$
- Simplified scenario: keep only events where all reco jets are matched to gen jets.
- Idealization: Compute  $m_H$  from jets that are matched to the truth quarks from H (from the Pythia decay tree)

# Results

- First, main results using PF objects clustered with Durham
- Then, comparison between PF jets and calo jets clustered with Durham
- Lastly, comparison between Durham and  $e^+e^-$  anti-kt

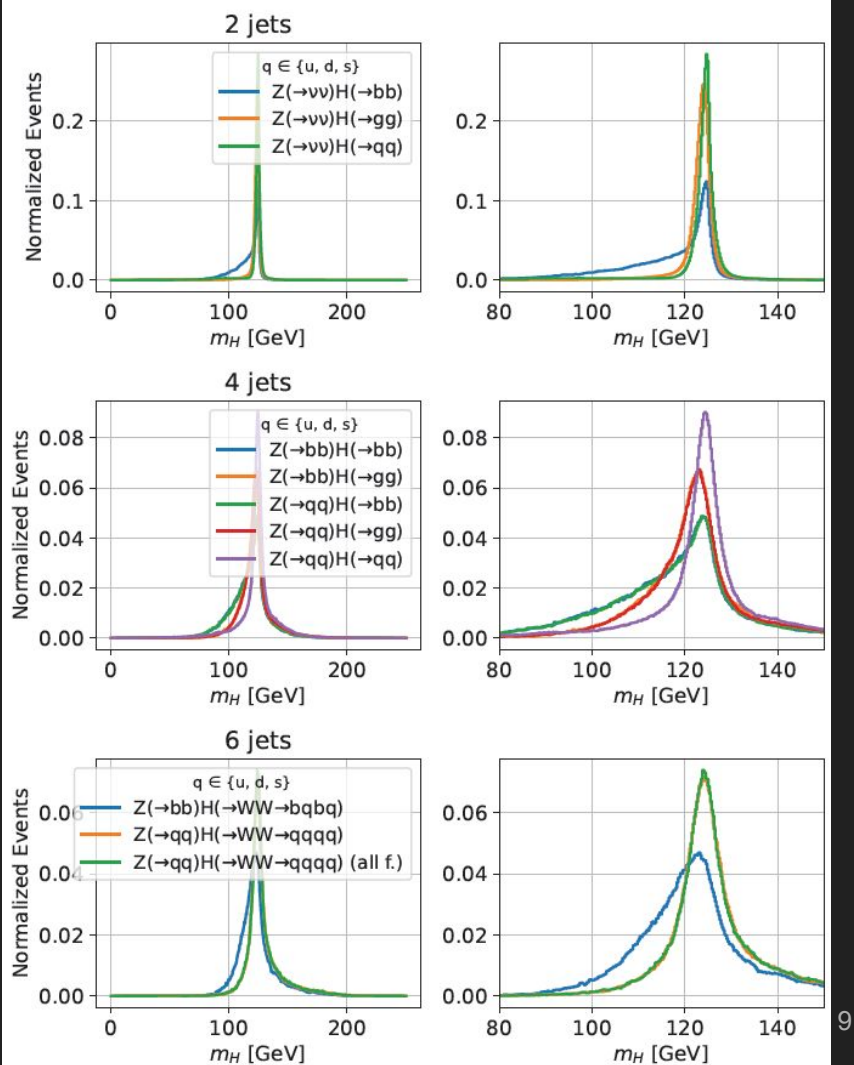
# Results: Durham algorithm with PFO

- $m_H$ : comparison for events with 2-, 4-, and 6-jet events (green, purple, blue)



# $m_H$ plots (Durham with PF)

- Long tail for processes where the Higgs final state contains b-jets (neutrinos)



# Jet Energy Resolution (Durham PF)

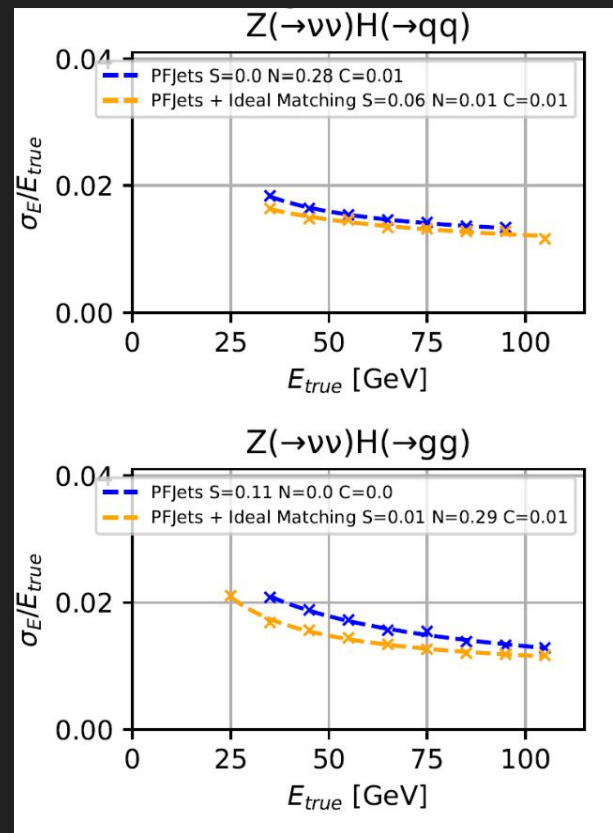
- Width: narrowest 68% interval / MPV
- Plot this vs. true jet E in bins of 10 GeV (\*where >50k jets in bin)  
With confusion term:

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

Without confusion term:

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus C$$

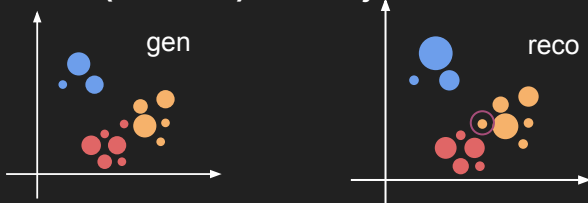
- Still working on the fits



# Jet definitions

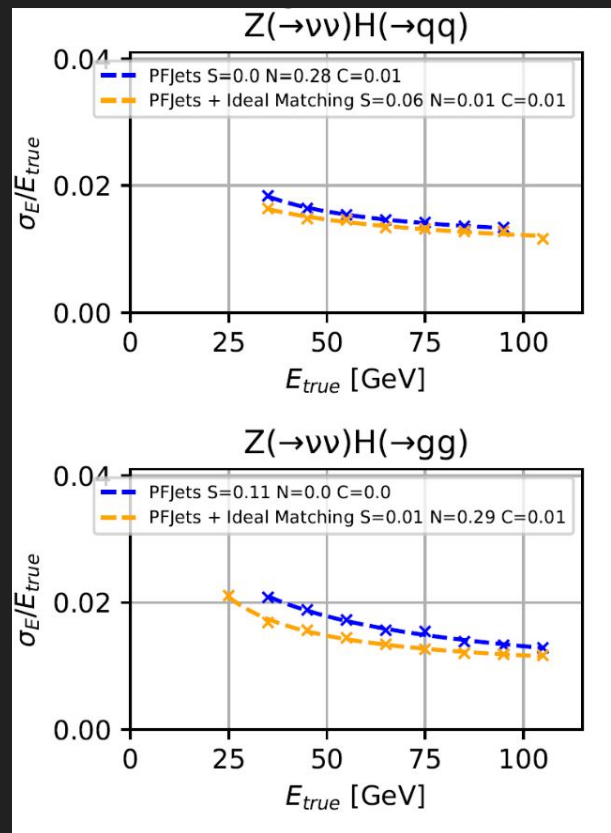
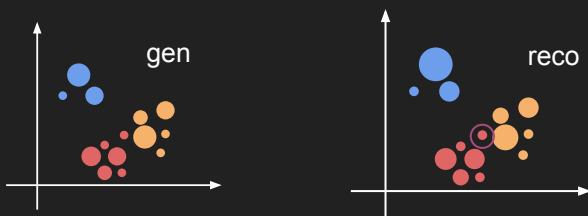
- **Gen jets: Run jet clustering on status-1 visible particles (no neutrinos)**
- **Reco jets**

- **Blue (PFJets)** - reco jets are clustered from reco particles



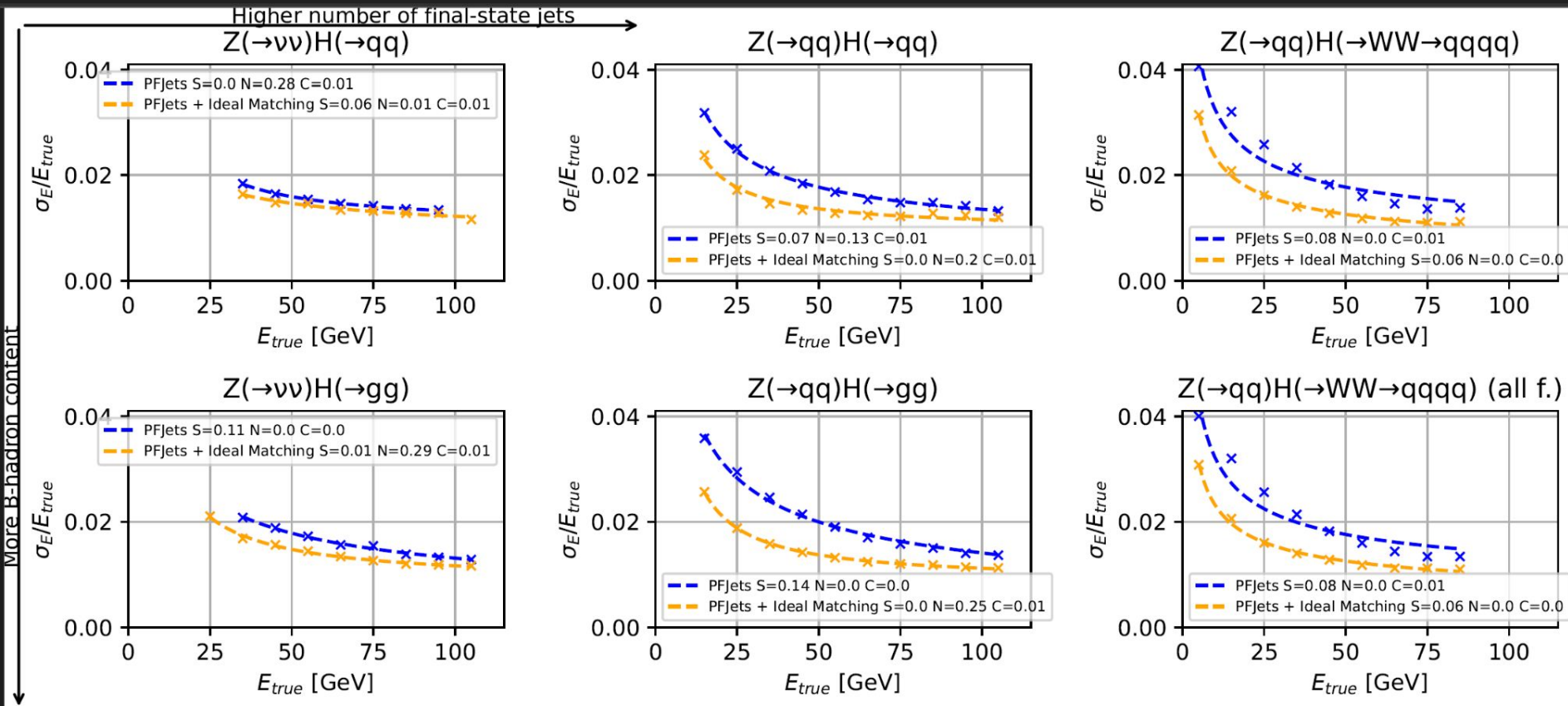
- **Yellow (PFJets + Ideal Matching)** - reco jets are defined from the gen jets, by taking for each MC particle the matched reco particle

- The only effect of confusion is in the truth definition - ideal jet clustering



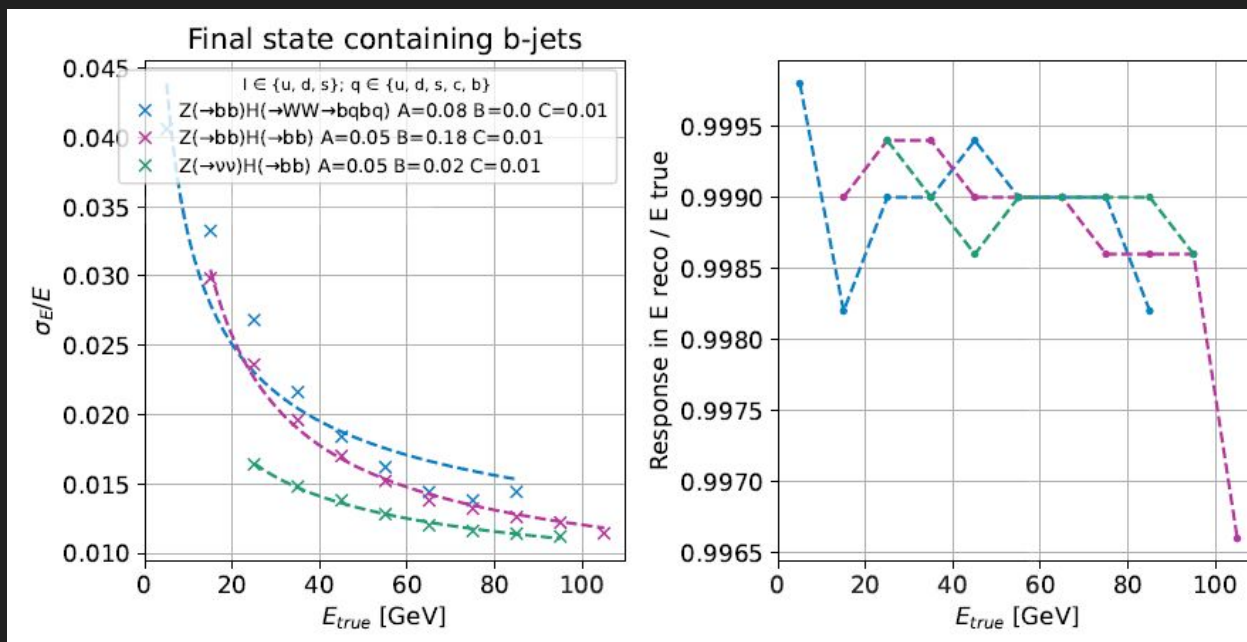


# Jet Energy Resolution ([full plots](#))



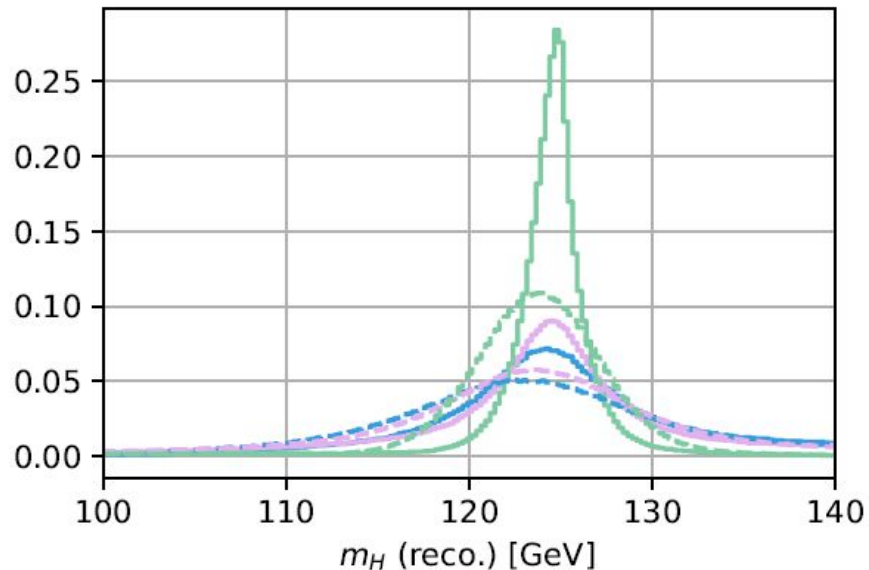
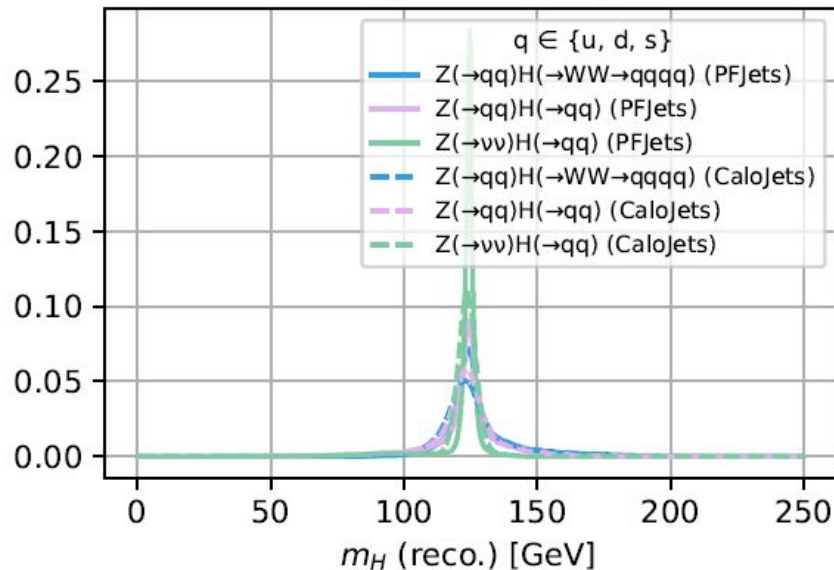
# Jet Energy Resolution (Durham PF)

- 2-, 4-, and 6-jet process



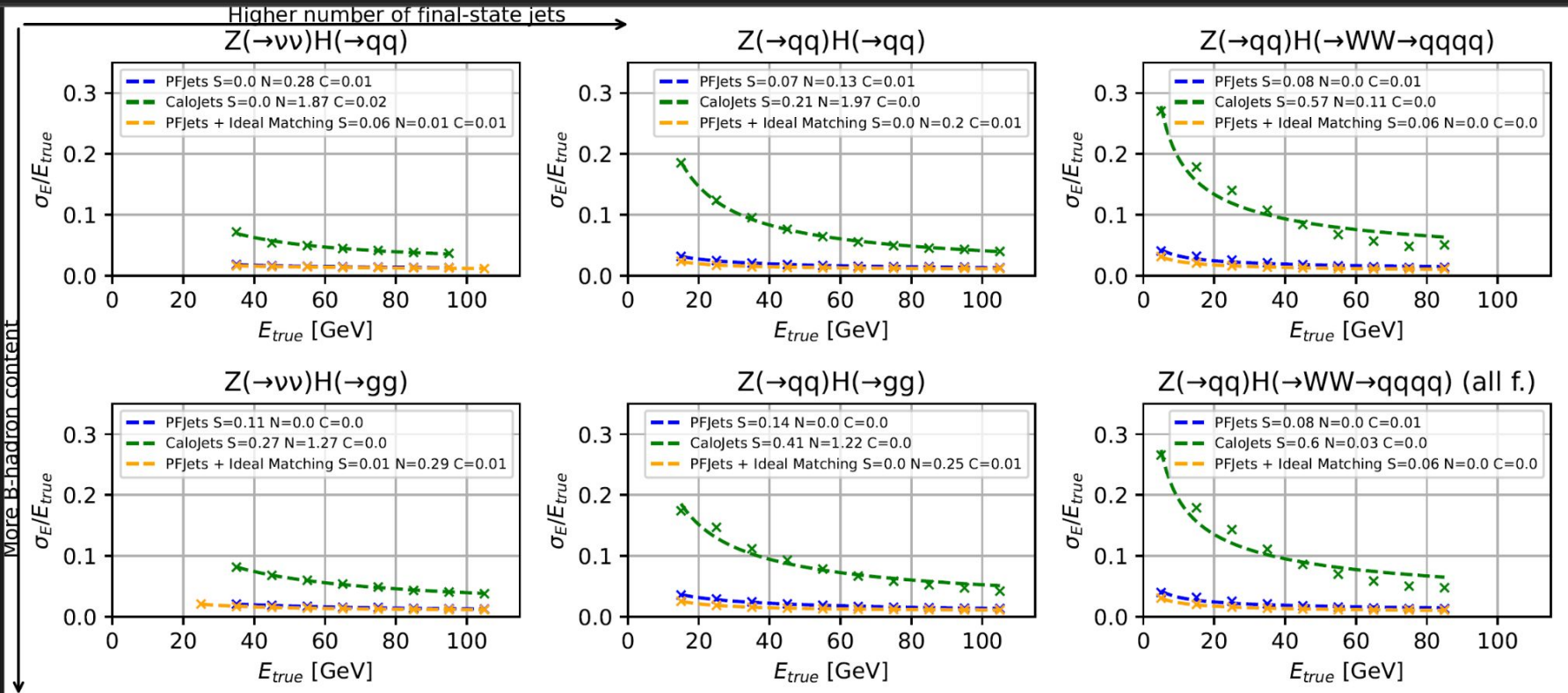
# Comparison Calo jets vs. PF jets (both Durham)

## H → Light-flavour jets

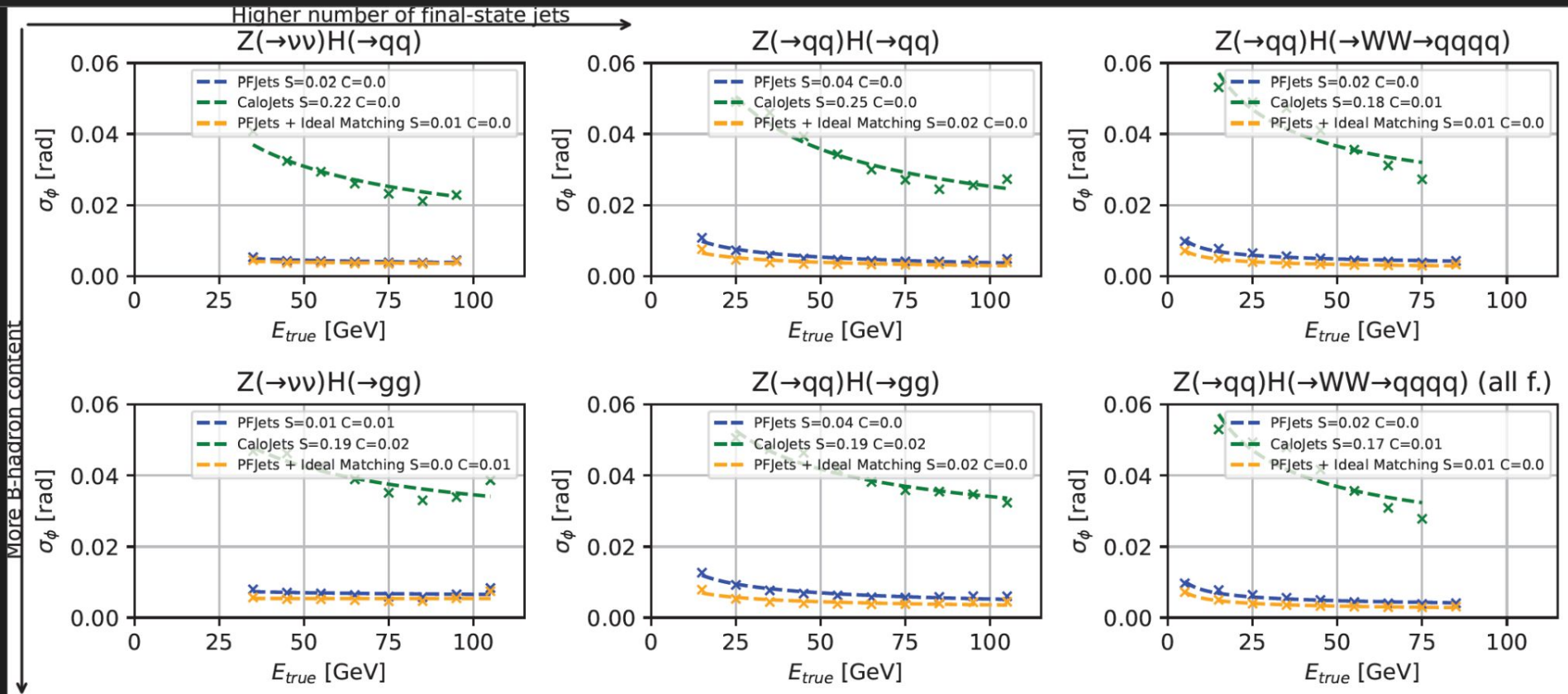


# Jet energy resolution: comparison with calo jets [\(full plots\)](#)

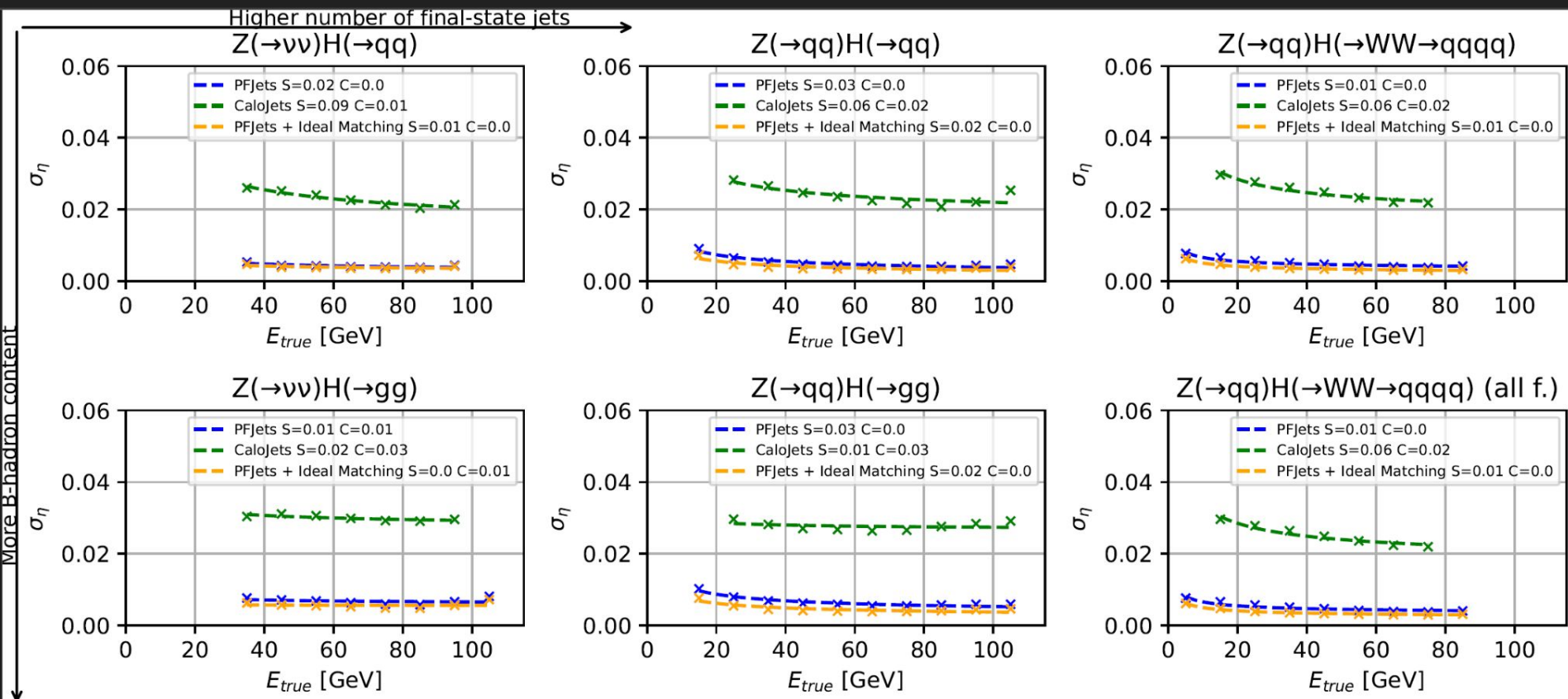
- Some issues with fitting (sometimes  $S \rightarrow 0$  as  $N$  term dominates, but setting  $N=0$  doesn't give a good fit)



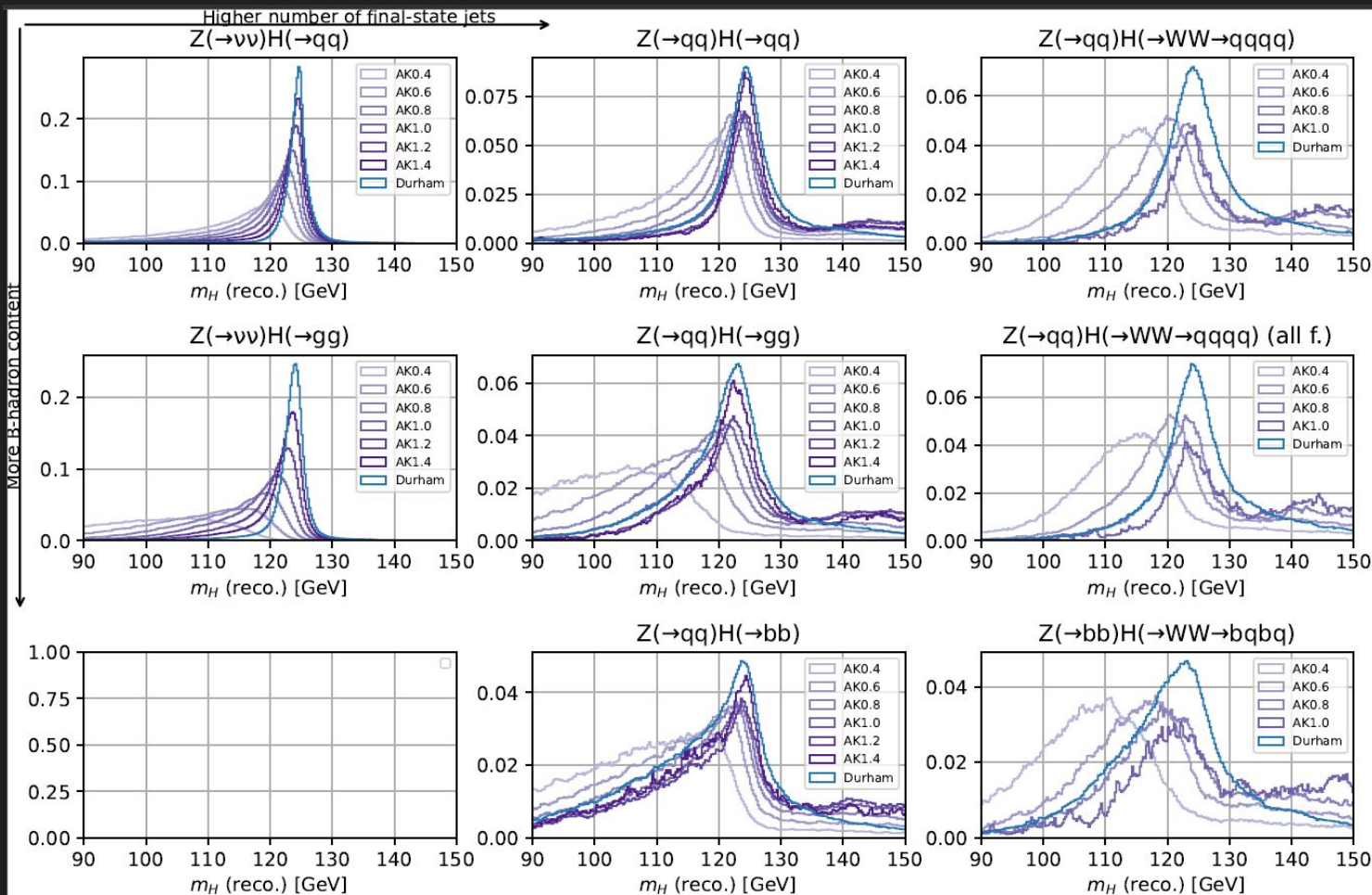
# Angular resolution - phi (full plots)



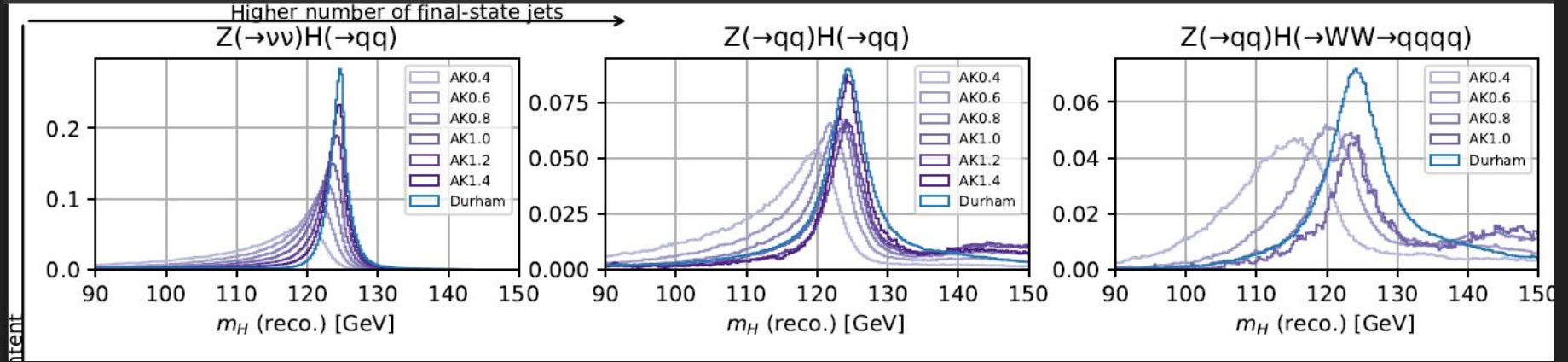
# Angular resolution - eta (full plots)



# anti-kt and Durham comparison (full plots)



# Anti-kt vs. Durham

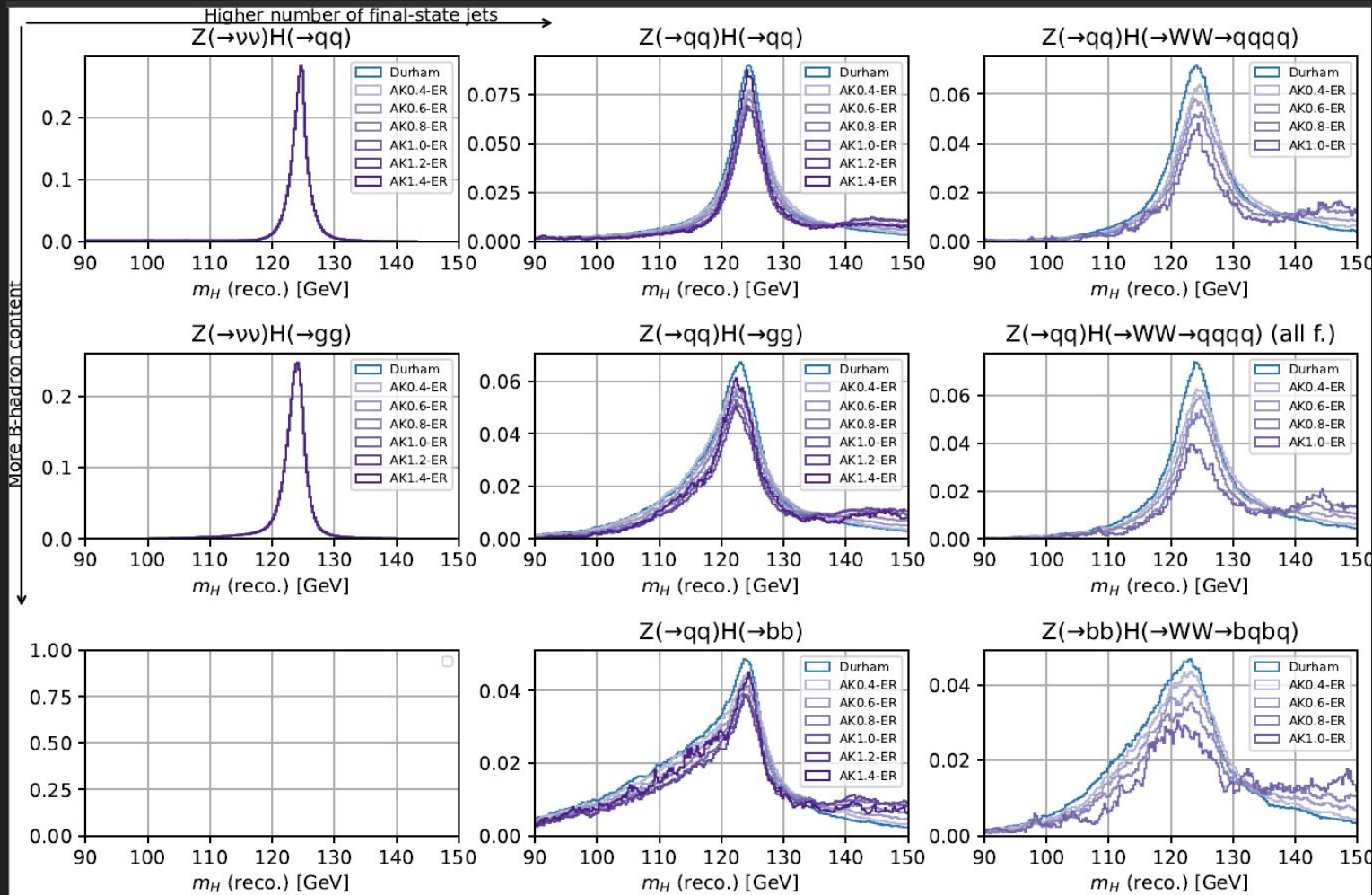


- Keep the  $N$  highest- $p_T$  jets
- We cluster either too little (left side of the peak) or too much (right side)
- Try energy recovery (next slide)

([https://indico.cern.ch/event/1439509/contributions/6289574/attachments/2997180/5280612/AEC\\_onnely\\_FCC.pdf](https://indico.cern.ch/event/1439509/contributions/6289574/attachments/2997180/5280612/AEC_onnely_FCC.pdf))

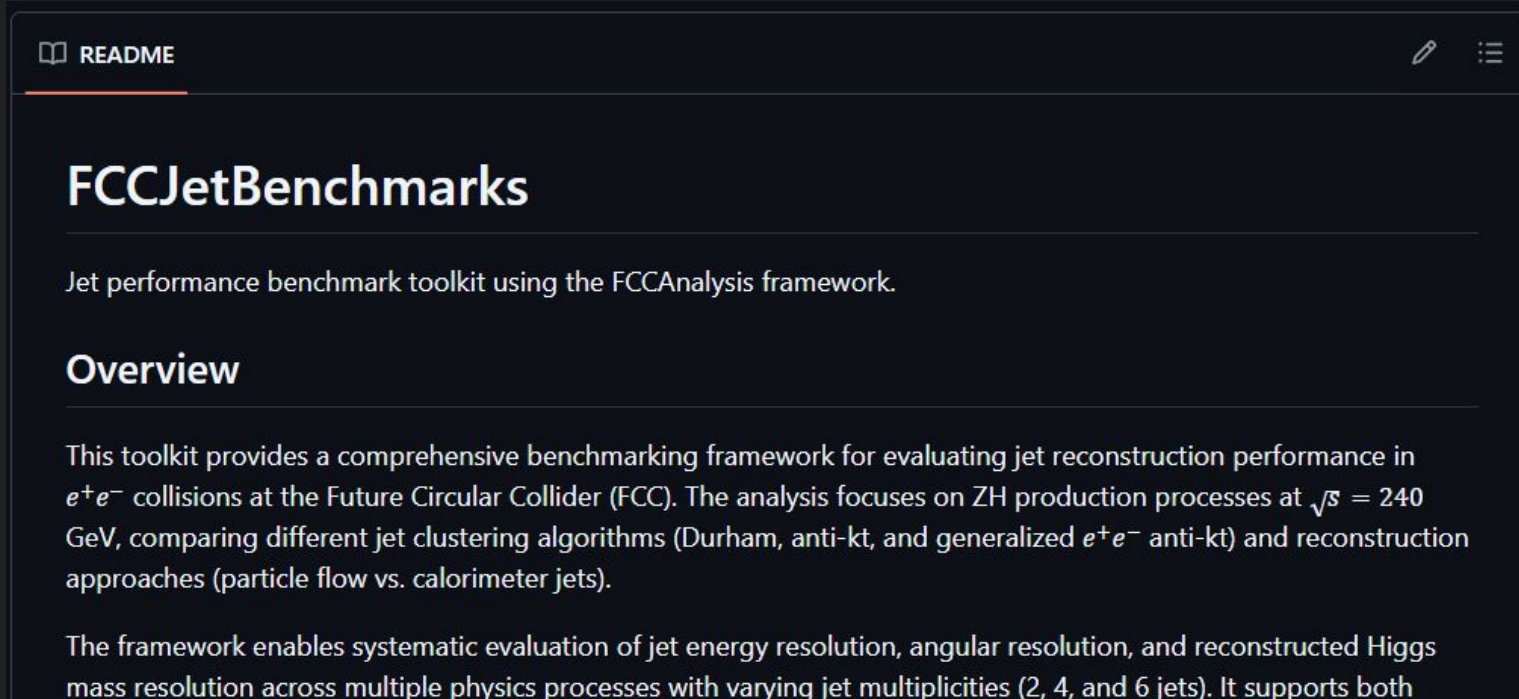
# Anti-kt with energy recovery vs. Durham (full plots)

(in the two-jet case, both jets are always used, and all particles are clustered in them, so the result is always the same)



# Code and manual

<https://github.com/gregorkrz/FCCJetBenchmarks> - includes main results, examples, and a tutorial, as well as current issues



The image shows a screenshot of the GitHub README page for the FCCJetBenchmarks repository. The page has a dark theme. At the top left, there is a 'README' label with a folder icon. At the top right, there are icons for editing and a menu. The main heading is 'FCCJetBenchmarks' in a large, bold font. Below the heading is a horizontal line, followed by a paragraph: 'Jet performance benchmark toolkit using the FCCAnalysis framework.' Below this is another horizontal line and the section heading 'Overview' in a bold font. The main text of the overview paragraph reads: 'This toolkit provides a comprehensive benchmarking framework for evaluating jet reconstruction performance in  $e^+e^-$  collisions at the Future Circular Collider (FCC). The analysis focuses on ZH production processes at  $\sqrt{s} = 240$  GeV, comparing different jet clustering algorithms (Durham, anti-kt, and generalized  $e^+e^-$  anti-kt) and reconstruction approaches (particle flow vs. calorimeter jets).'

The framework enables systematic evaluation of jet energy resolution, angular resolution, and reconstructed Higgs mass resolution across multiple physics processes with varying jet multiplicities (2, 4, and 6 jets). It supports both

# Conclusion

- Developed a comprehensive jet performance package to evaluate the performance of PF and jet reconstruction at FCC-ee - can be helpful to guide the optimization of detector concepts and PF algorithms
- At  $e^+e^-$  colliders, jet energy resolution strongly depends on the number of final state jets due to jet overlaps - important to test performance in different cases to cover full range of FCC physics
- Additional modules to create new plots can be added in future versions
- New metrics could be easily implemented; could also be extended to PF and tracking performance
- Plan to put out an FCC Note

# Conclusion

- Using the package, we already have learned (or verified) some interesting aspects of jet performance at FCC-ee
  - It seems that Durham works best for  $m_H$  measurement in our idealized scenario even when anti-kt is used with energy recovery in all cases.
  - PF works better in terms of jet energy resolution than using calorimeter hits only - expected
  - Energy recovery helps with anti-kt, although Durham still performs best
  - Some issues with jet energy resolution parametrization

# Backup

With confusion term:

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

# Calo jets energy resolution - fitting (A\*E)

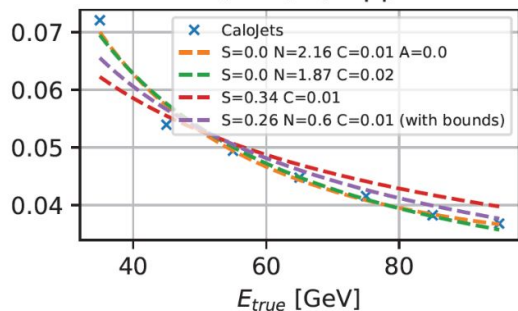
Bounds: C [0.005, 0.04]; N [0, 0.6]; S [0.01, 0.6]

Without confusion term:

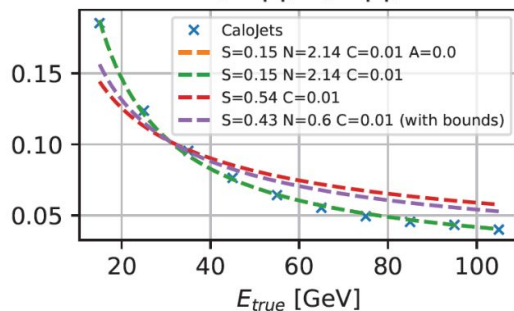
$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus C$$

Higher number of final-state jets →

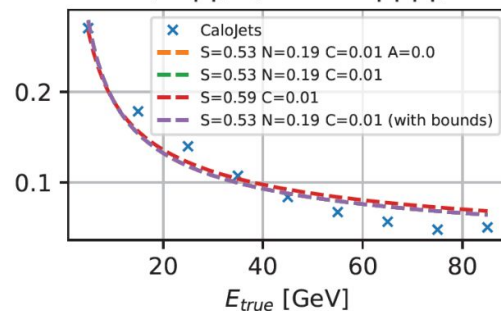
Z(→νν)H(→qq)



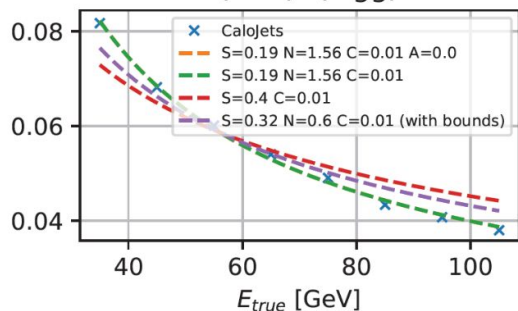
Z(→qq)H(→qq)



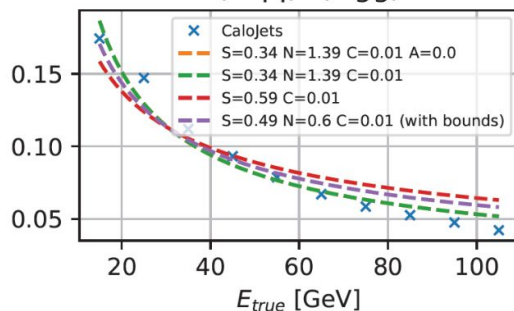
Z(→qq)H(→WW→qqqq)



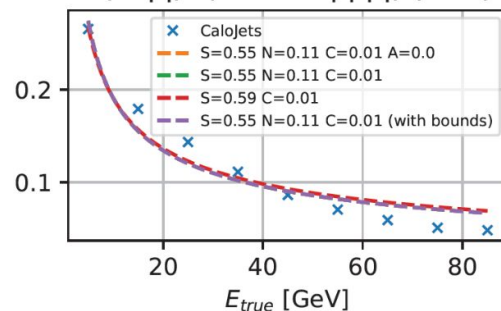
Z(→νν)H(→gg)



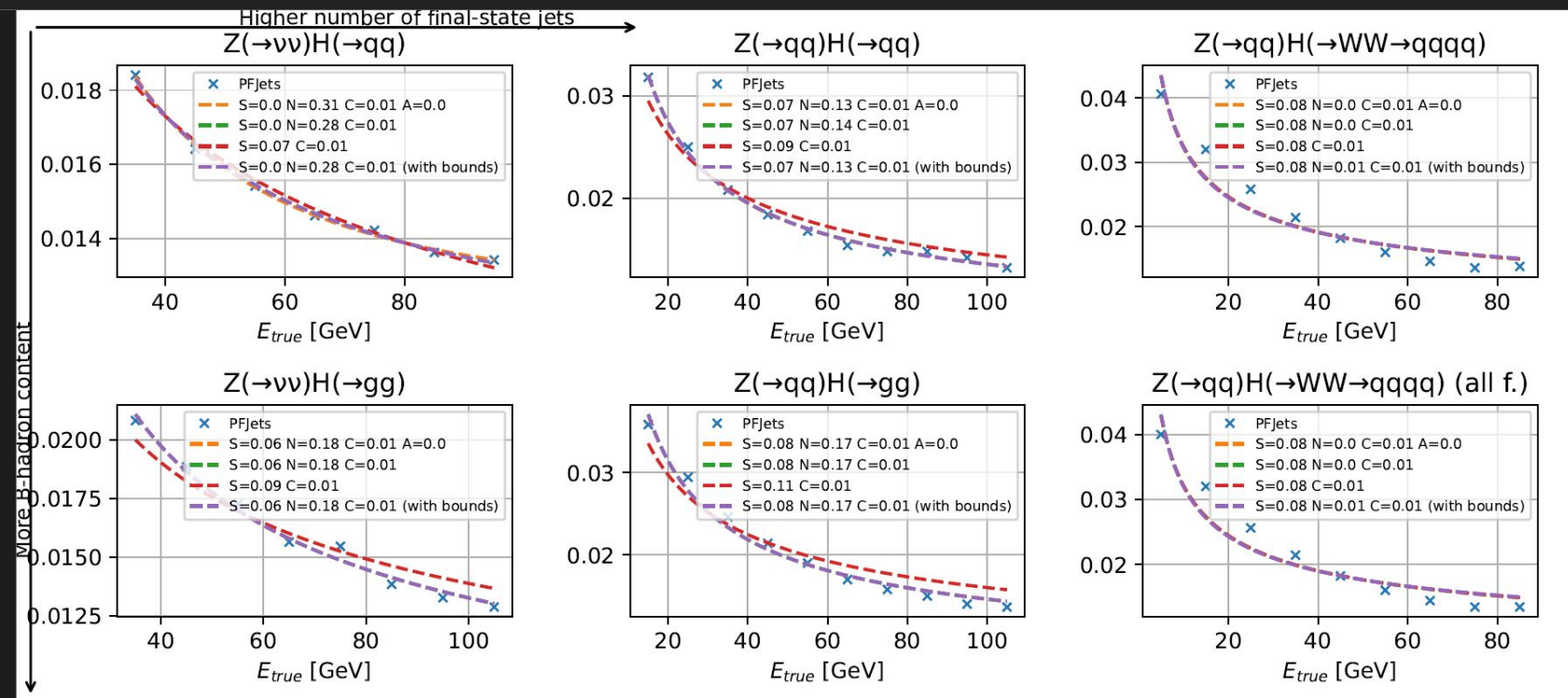
Z(→qq)H(→gg)



Z(→qq)H(→WW→qqqq) (all f.)



# PF jets JER fitting



# Fraction of events that pass the criteria

Process	PF Jets	Calo Jets	AK06-ER	AK08-ER	AK10-ER	AK12-ER
$Z(\rightarrow bb)H(\rightarrow WW\rightarrow bqbq)$	0.837	0.338	0.854	0.782	0.386	0.013
$Z(\rightarrow bb)H(\rightarrow bb)$	0.954	0.738	0.952	0.933	0.879	0.609
$Z(\rightarrow bb)H(\rightarrow gg)$	0.920	0.649	0.936	0.920	0.879	0.652
$Z(\rightarrow qq)H(\rightarrow WW\rightarrow qqqq)$	0.864	0.458	0.863	0.787	0.381	0.014
$Z(\rightarrow qq)H(\rightarrow WW\rightarrow qqqq)$ (all f.)	0.863	0.448	0.863	0.790	0.388	0.014
$Z(\rightarrow qq)H(\rightarrow bb)$	0.954	0.777	0.951	0.932	0.877	0.605
$Z(\rightarrow qq)H(\rightarrow gg)$	0.921	0.689	0.934	0.916	0.876	0.651
$Z(\rightarrow qq)H(\rightarrow qq)$	0.951	0.799	0.947	0.927	0.872	0.595
$Z(\rightarrow \nu\nu)H(\rightarrow bb)$	0.994	0.940	0.993	0.994	0.994	<b>0.994</b>
$Z(\rightarrow \nu\nu)H(\rightarrow gg)$	0.982	0.894	0.980	0.982	0.984	<b>0.985</b>
$Z(\rightarrow \nu\nu)H(\rightarrow qq)$	0.988	0.949	0.987	0.988	0.988	0.989

# Jet Energy Resolution parametrization

# Energy recovery

Similar to

[https://indico.cern.ch/event/1439509/contributions/6289574/attachments/2997180/5280612/AEConnelly\\_FCC.pdf](https://indico.cern.ch/event/1439509/contributions/6289574/attachments/2997180/5280612/AEConnelly_FCC.pdf),

the jets are sorted by energy and the expected number of jets with the highest energy is selected first.

Each extra jet gets recombined with the closest of these jets.

# Gen jet energy spectrum

