Studies of HCAL segmentation for FCC

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ANL

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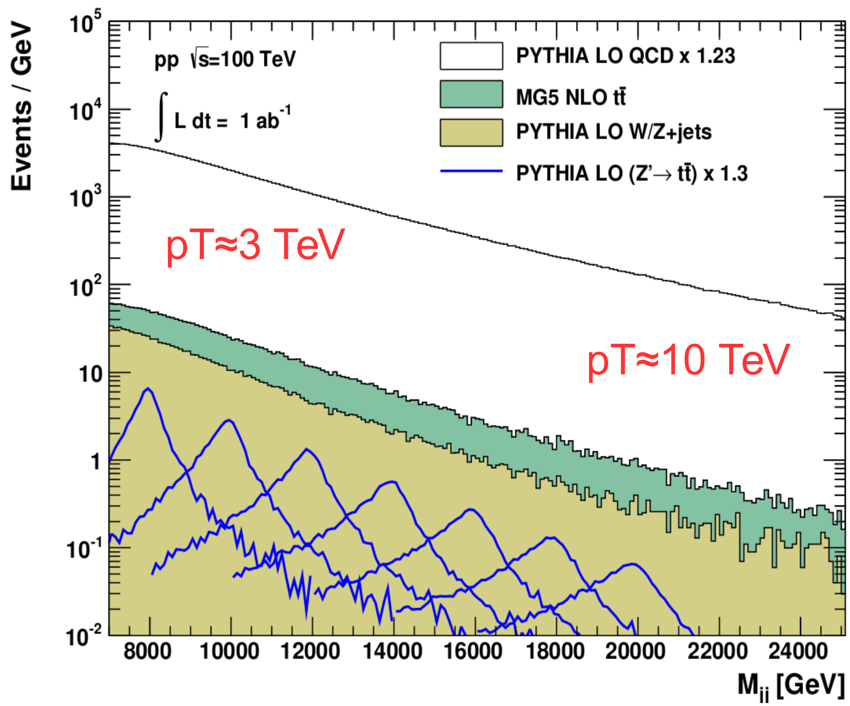
FCC-hh calorimeters informal meeting

Motivation

- 100 TeV collider can access particles with ~10-20 TeV masses
- Z'/gKK example:

Studies based on 100 fb-1 presented in Next steps in the Energy Frontier (FNAL, Aug. 2014)
https://indico.fnal.gov/getFile.py/access?contribId=34&sessionId=0&resId=0&materialId=slides&confId=7864

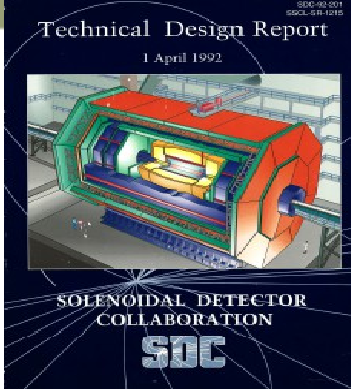


- Jet with R~0.4-0.6 contain decay products of heavy particles with M~10-20 TeV assuming hadronic decays (W/t)
  - R=0.5 was used for Snowmass studies for pT>1 TeV for HI-LHC
  - "Reconstructing top quarks at the upgraded LHC and at future accelerators" arXiv:1307.6908

- We need to use jet-substructure techniques for the standard jets!

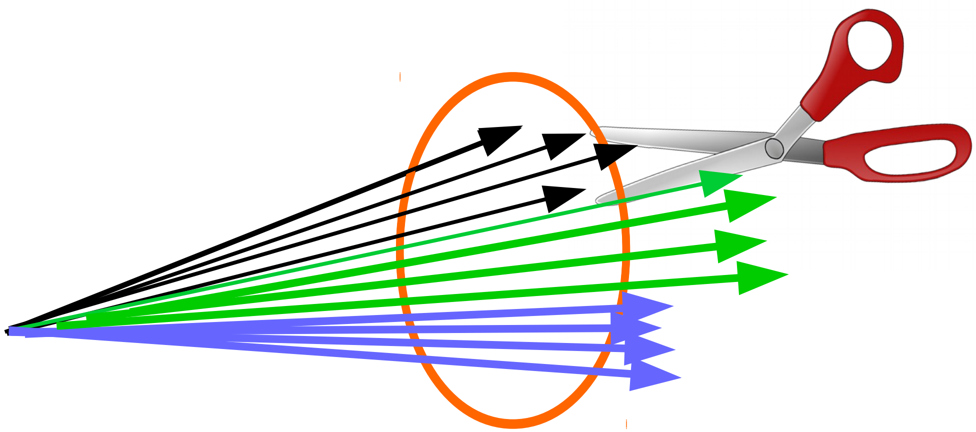
→ **a high-granular calorimeter**

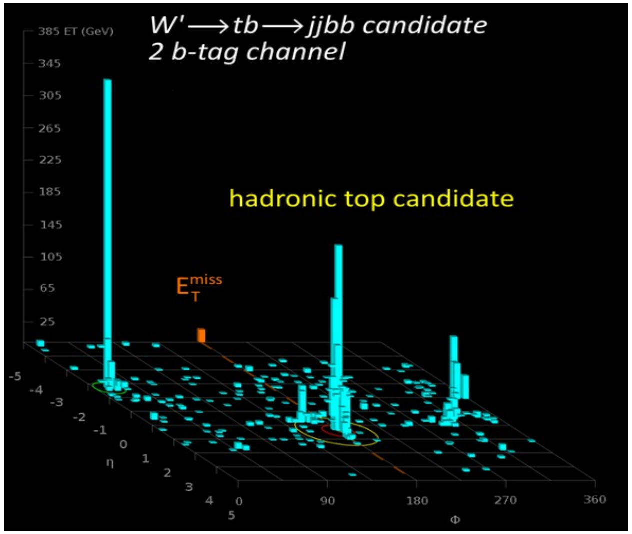
Discriminating variables



- Use jet substructure signatures (SSC-SR-1217 TDR 1992 p 3-26)
- Tremendous recent progress in advancing such approach
- Examples:
  - Jet mass ← This talk
  - τ_{32} and τ_{21} (N-subjettiness jet characteristics) ← This talk — J.Thaler, K. Van Tilburg, JHEP 1103:015, 2011
  - Jet shapes (eccentricity) — S.C., J.Proudfoot, Phys. Rev. D81 (2010) 114038
  - $\sqrt{d_{12}}$ splitting scale — J. M. Butterworth, B. E. Cox, and J. R. Forshaw, Phys. Rev. D65 (2002) 96014
  - R^{eff} effective jet radius (weighted with energy radial distance to jet center)

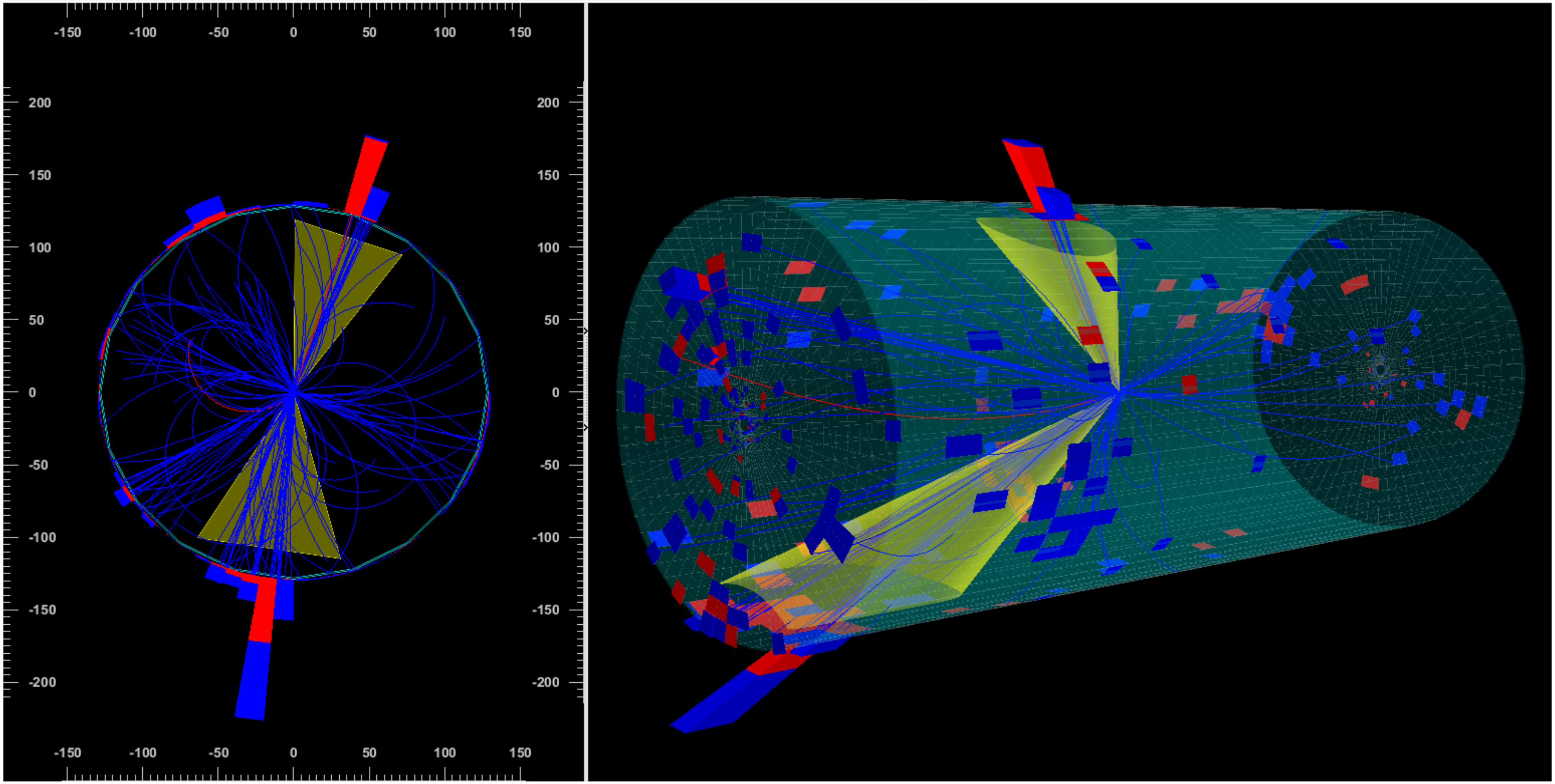
  .... many more!





Example: Z'(10 TeV) → $t\bar{t}$ → two antiKT05 jets (pT> 3 TeV)

2 antiKT5 jets (yellow) from boosted top quarks



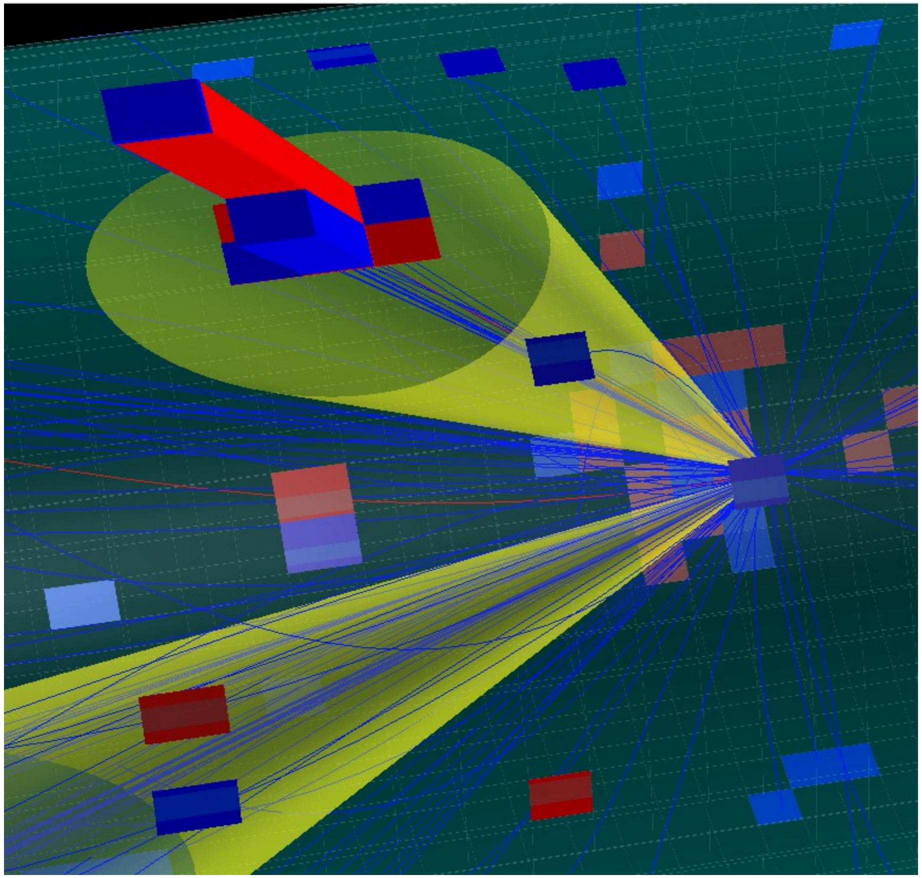
Using Delphes fast simulation + Snowmass detector + MC input from HepSim public database

Blue color → charged particles

Red → electrons

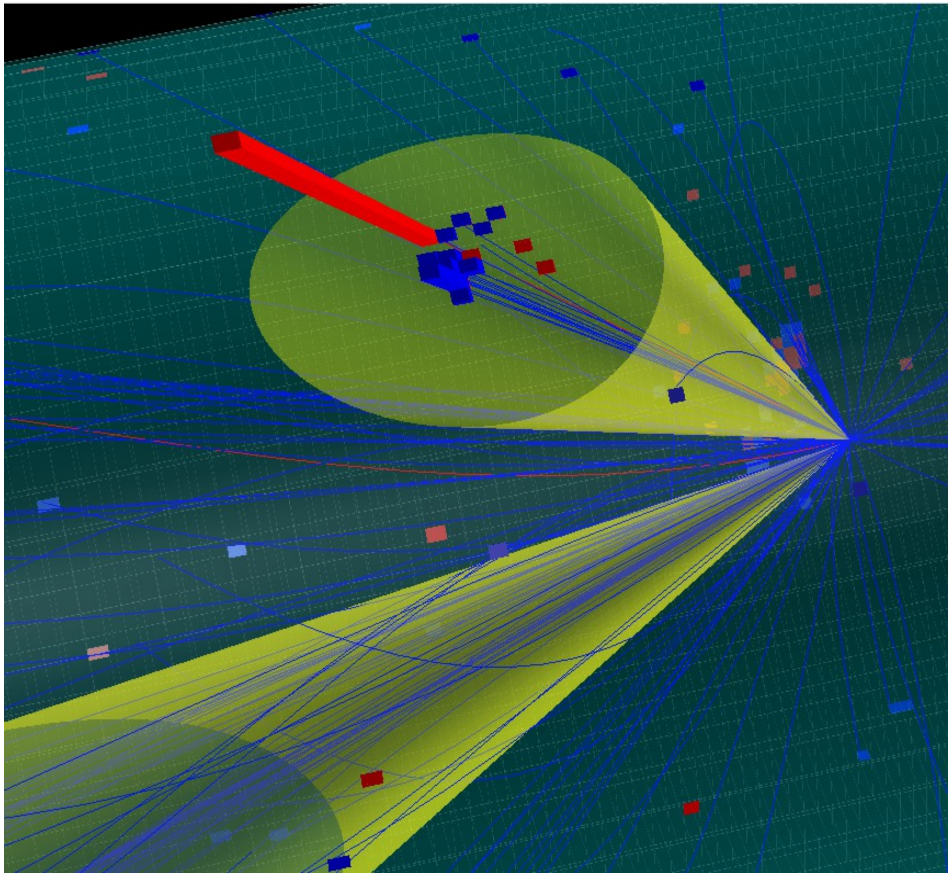
Example: Z'(10 TeV) → $t\bar{t}$ → 2 antiKT05 jets (pT> 3 TeV)

Snowmass-like CAL geometry



~ 5 deg :
Phi ~ 5 deg, Eta ~ 0.1

x4 smaller CAL cells



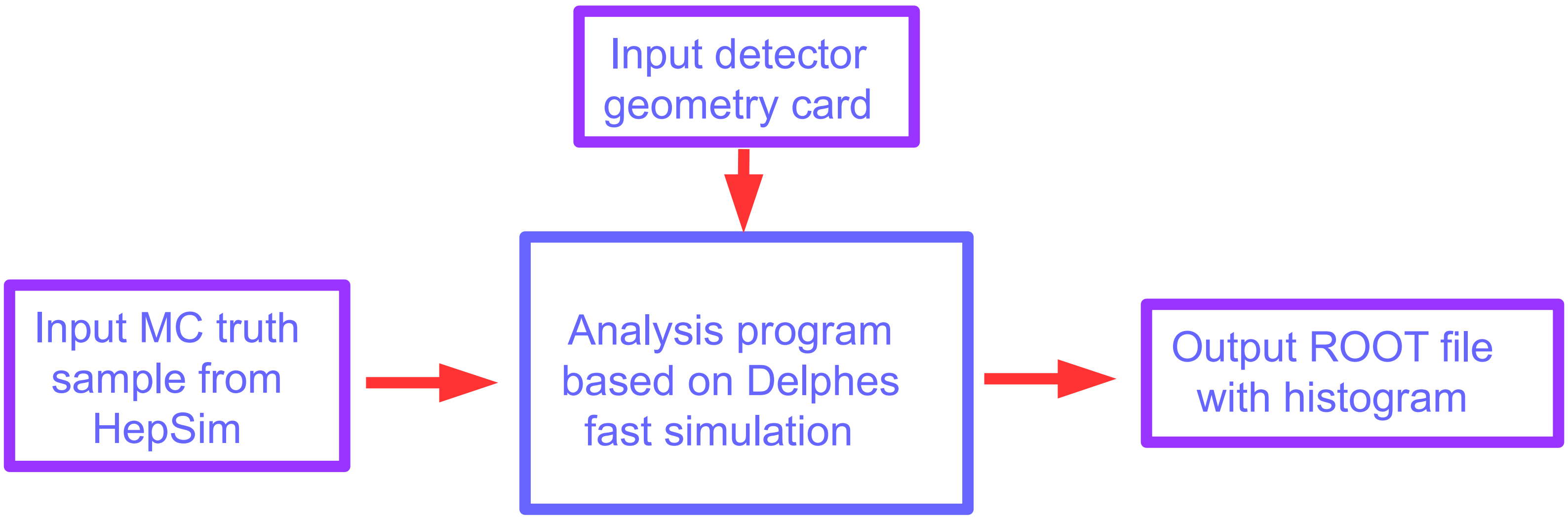
~ 1.25 deg :
Phi ~ 1.25 deg, Eta ~ 0.025

x 4 better →

Note: this study uses a Fast Simulation.
We ignore effects from Molière radius when considering transverse profile of showers!

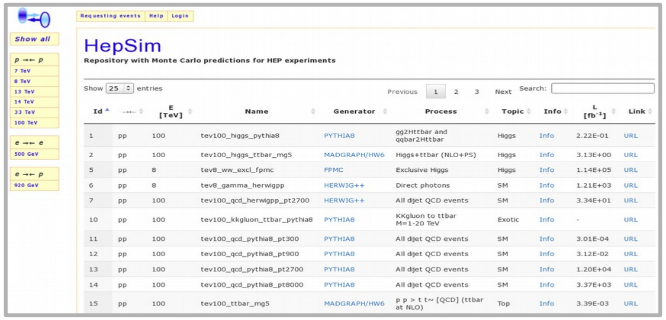
Analysis setup for a fast simulation

- Description: https://atlaswww.hep.anl.gov/asc/wikidoc/doku.php?id=vlhc:hcal
- It shows how to do the analysis on “the fly” (fast turnover!)



One can also created ROOT trees after the fast simulation and then run analysis program
Truth-level input files can be taken from the   HepSim public database

Monte Carlo used in this study:
- boosted top (pT>2.7 TeV)
- Z'/gKK for masses 8-20 TeV
- High-pT QCD (pt>2.7 TeV)
- Boosted W/Z (pT>2.7 TeV)



Detector geometry cards

- **Case 1:** ATLAS-like. Jets antiKT jets R=0.5 built from "Towers"
  - HCAL has 64 modules in **φ** and **η=0.1** in the central region
  - ECAL has x4 better segmentation

```
# HCAL
-1.6<Eta<1.6.                              Segment: 0.025 eta x 1.40625 deg phi
 -4.5<Eta<-1.7 and 1.7<Eta<4.5             Segment: 0.05  eta x 10 deg phi
 -4.6<Eta<4.6      and 4.6<Eta<6           Segment: 0.2 eta x 20 deg phi
# HCAL (64 modules in Phi):
-1.6<Eta<1.6.                              Segment: 0.1 eta x 5.625 deg phi
-4.5<Eta<-1.7 and 1.7<Eta<4.5              Segment: 0.2 eta x 11.25 deg phi
 -6.0<Eta<4.6      and 4.6<Eta<6           Segment: 0.2 eta x 20 deg phi
```

HCAL in Delphes:

$$\frac{\sigma_{E_T}}{E_T} = \frac{a}{\sqrt{E_T}} \oplus \frac{b}{E_T} \oplus c$$

a=0.5 (sampling)
c=0.03 (const)
b=0 (noise)

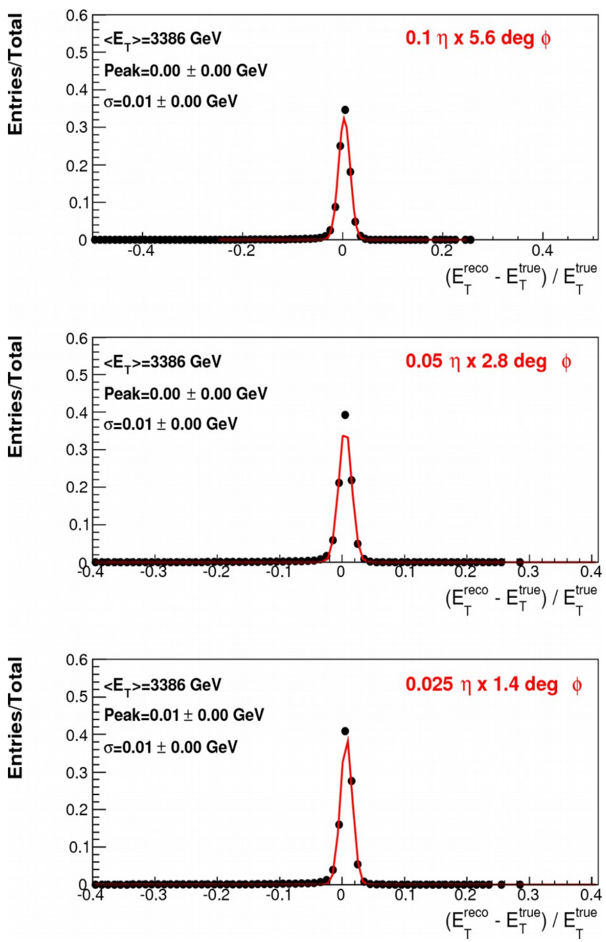
  - 60% of energy of charged/neutral hadrons are in HCAL
  - 100% energy from gamma & electrons are in ECAL
  - Smearing applied for towers (ECAL & HCAL, separately)
- **Case 2**: Same as before, but **η** is x2 and x4 better
- **Case 3:** Same as before but both Eta and Phi segmentation are x2 and x4 better

- **ATLAS-like. Jets R=0.5 from "EFlow"**
  - Using tracks (after resolution smearings)
  - Neutral particles are measured by ECAL & HCAL
  - 60% of energy of neutral hadrons are in HCAL

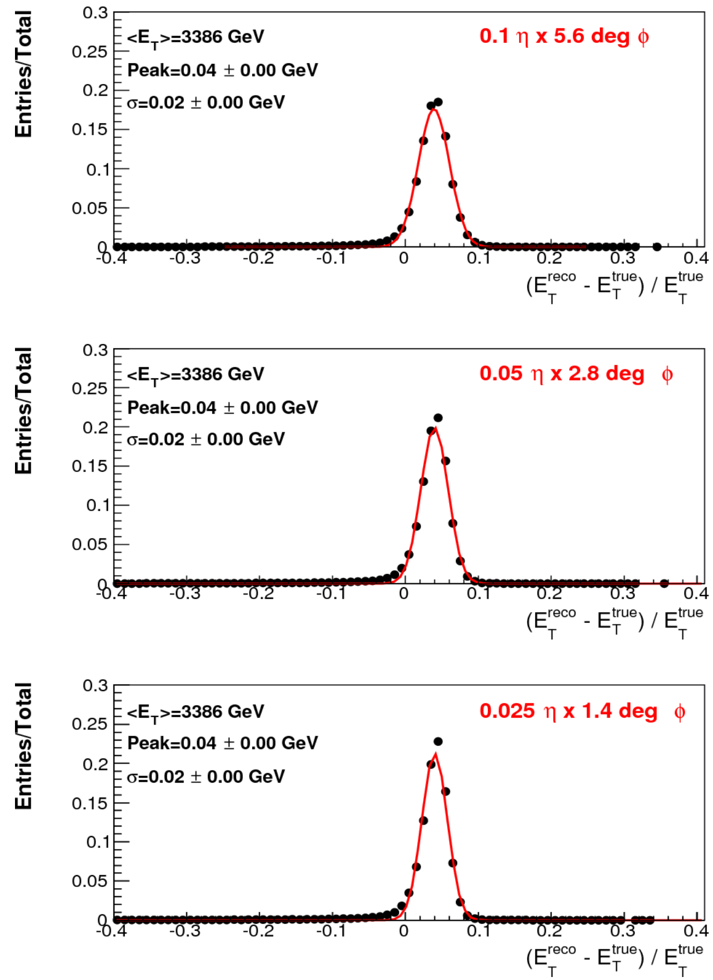
Tower jets are calibrated as:
1.06+400/(pt*pt*)

Jet resolutions (pT>3 TeV, antiKT5)

Jets from eFlow



Jets from Towers



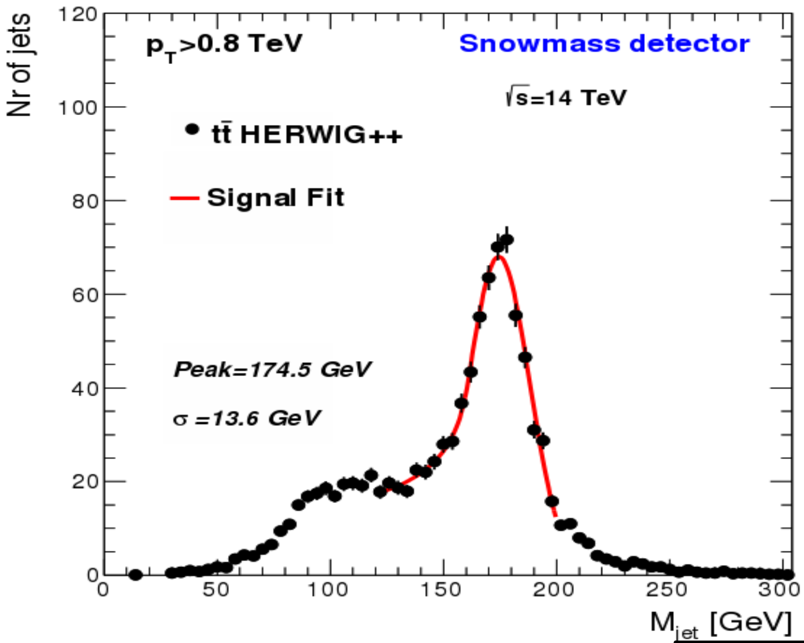
- High-pT jets are calibrated after using the jet resolution function: 1.06+400/(pt*pt*) for tower jets

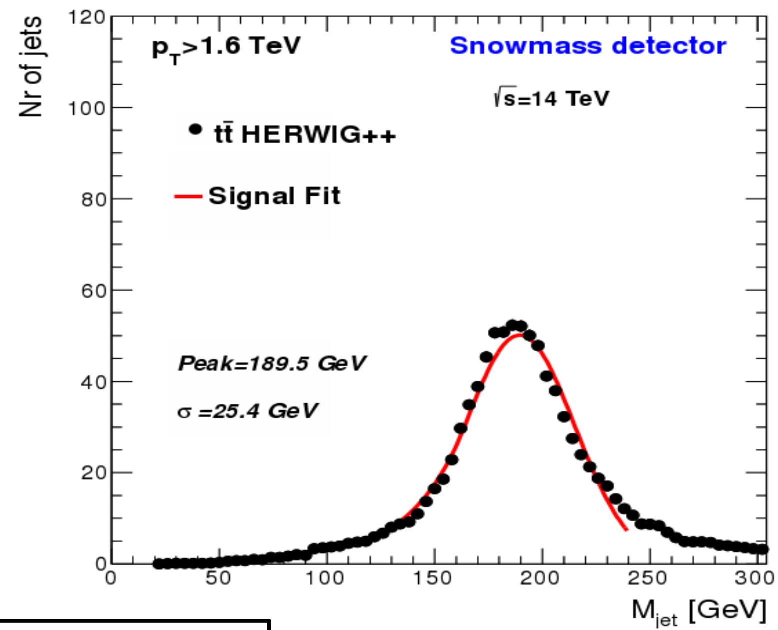
Studies of jet mass at Snowmass

arXiv:1307.6908

eFlow+CAL with 0.087x0.087 in Eta-Phi plane

- Several effects contribute to the jet mass reconstruction with increase of pT
  - detector
  - defuse soft radiation
  - hard radiation of extra jet

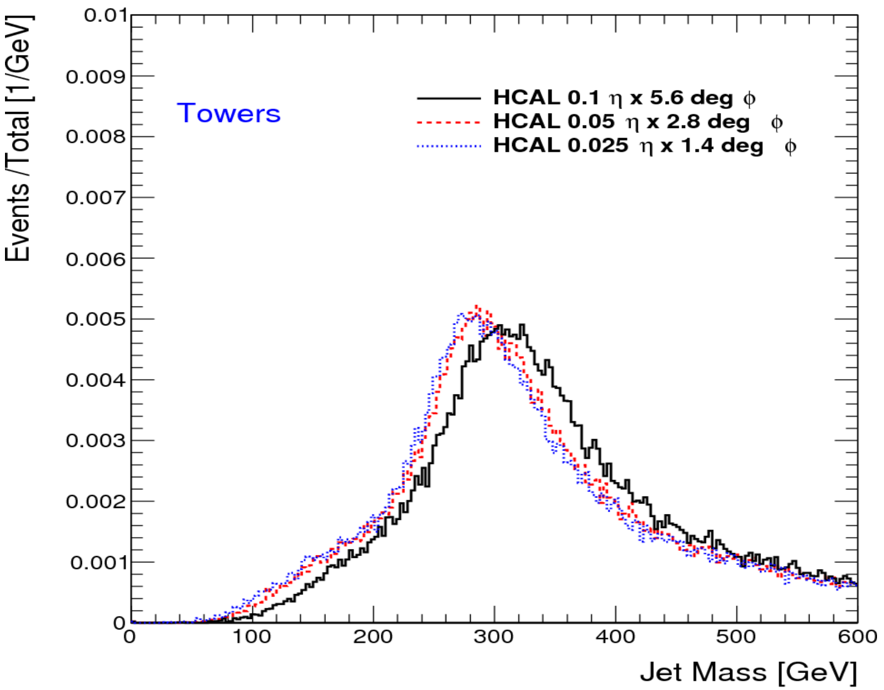


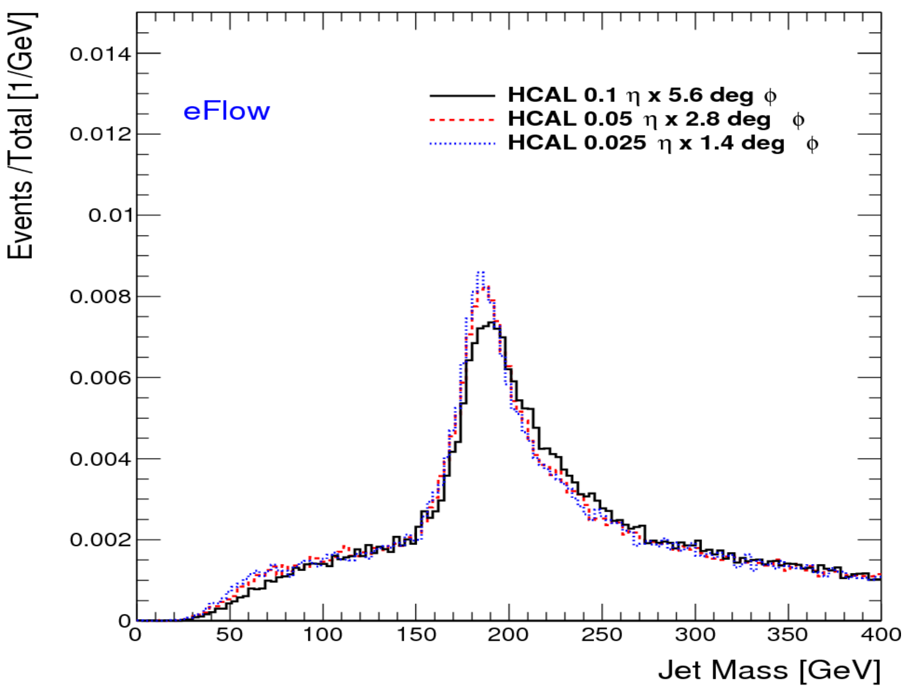


antiKT jets with R=0.5

Jet masses using a FCC detector setup (HCAL, ECAL)

- pp collisions at 100 TeV. Madgraph5+HERWIG. High-pT ttbar events
  - http://atlaswww.hep.anl.gov/hepsim/info.php?item=57
- antiKT5 jets. pT>3 TeV and |eta|<1.5

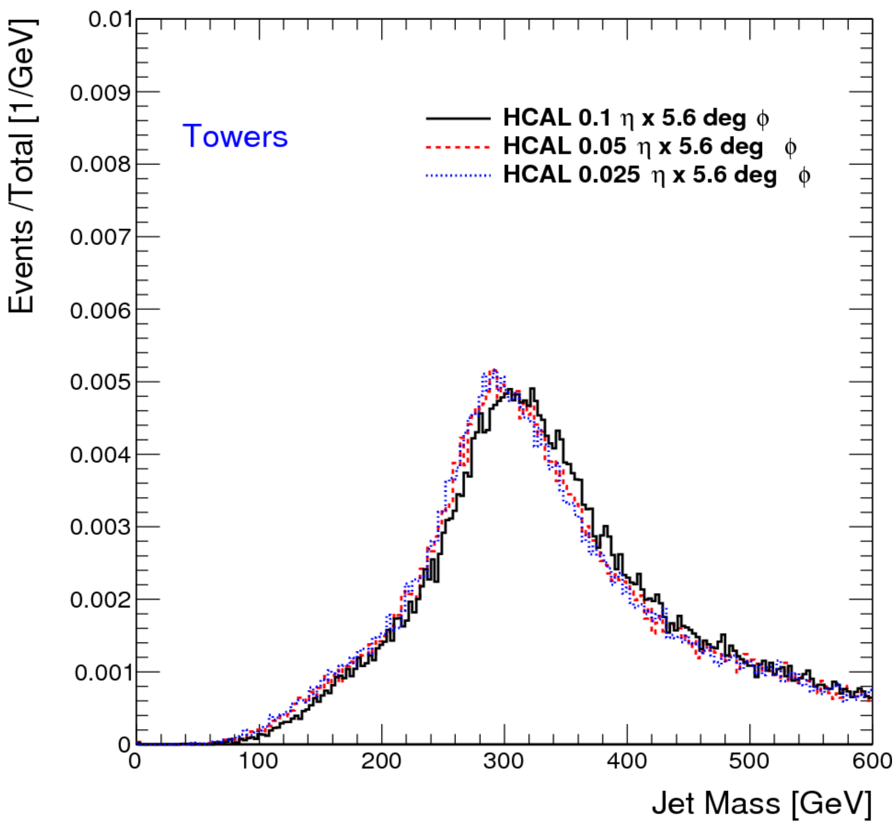


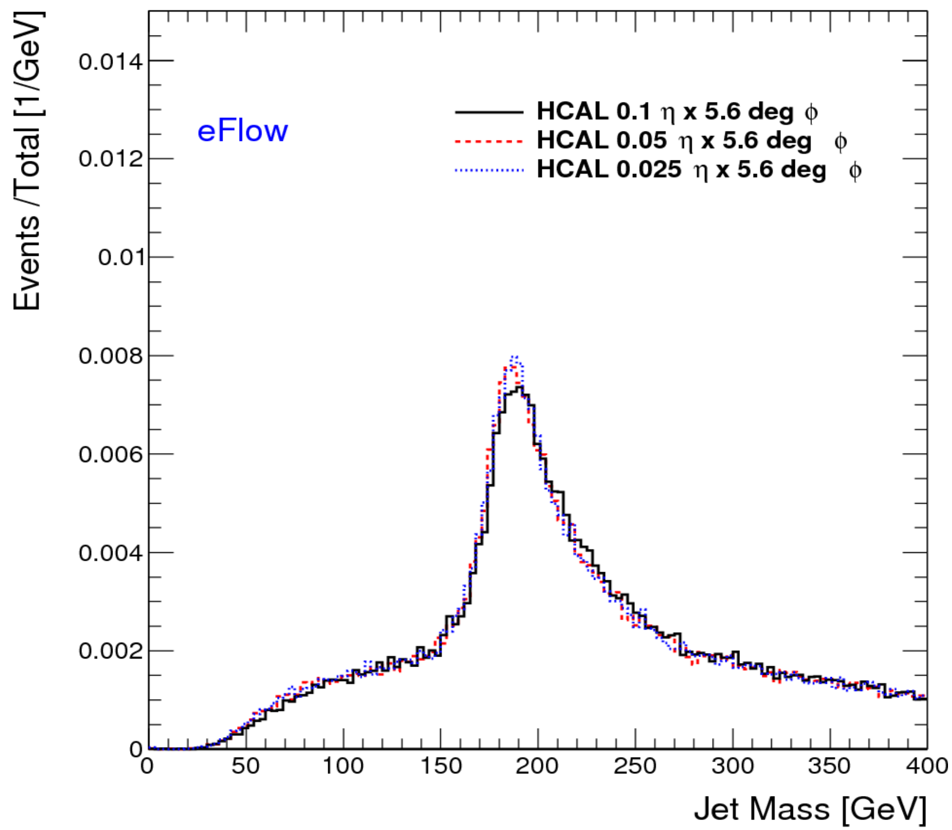


- Note: a large shift (~100 GeV) for tower jets using this setup
- Some improvements for 5.6 → 2.8 deg in the η-φ plane
- No significant effect when 2.8 deg → 1.4 deg

Jet masses. Changing only η cells

- 100 TeV. Madgraph5+HERWIG. High-pT ttbar events http://atlaswww.hep.anl.gov/hepsim/info.php?item=57
- antiKT5 jets. pT>3 TeV and |eta|<1.5



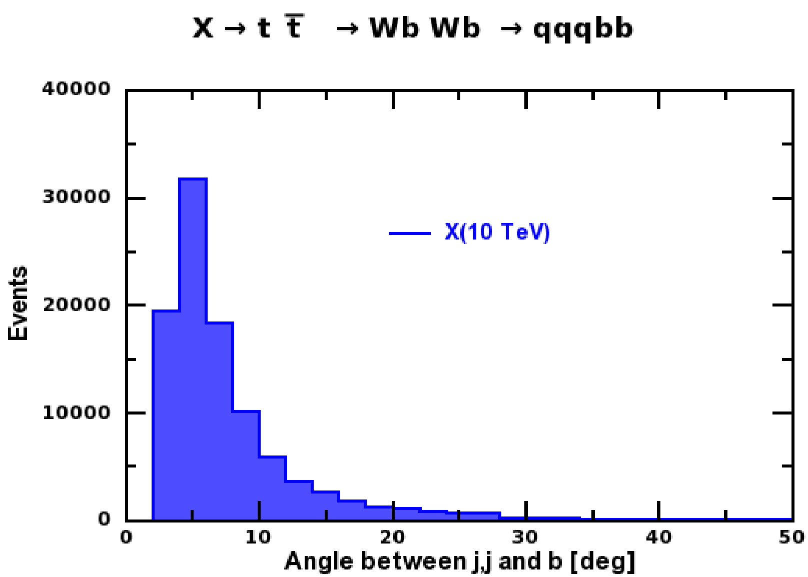


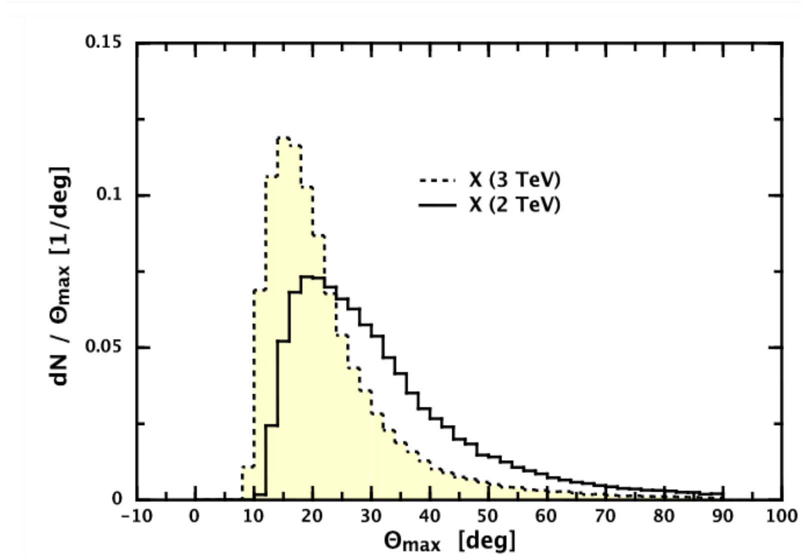
- Some improvements, but the effect is quite small

Jet substructure for boosted top

Separation of top decay products for X (10 TeV)→ $t\bar{t}$

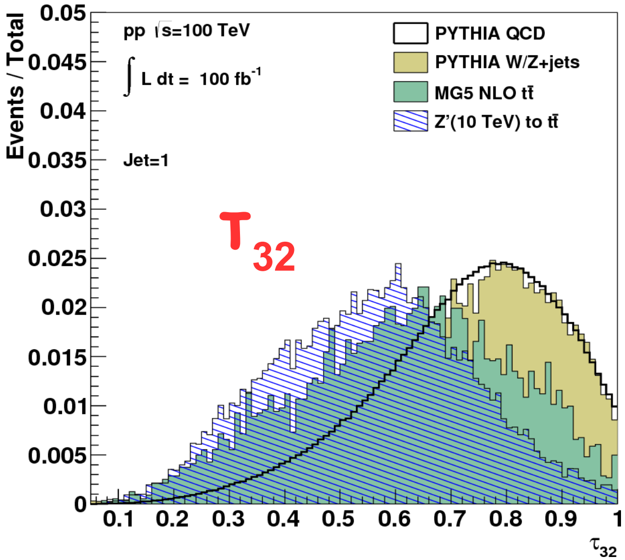
Phys. Rev. D81 (2010) 114038 S.C. J.Proudfoot

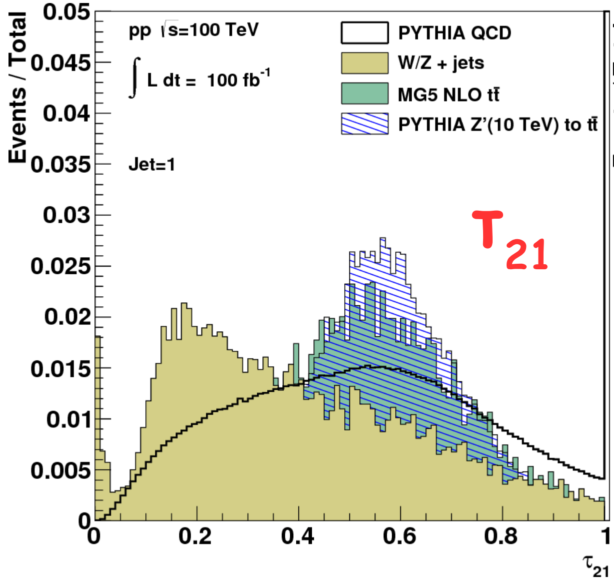


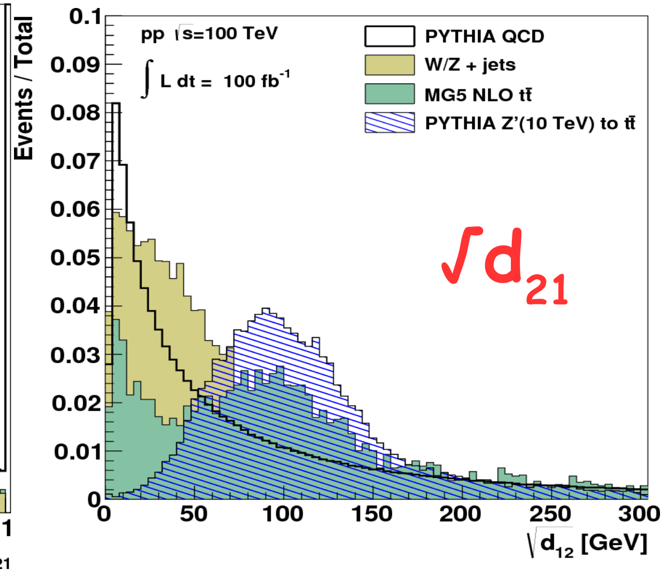


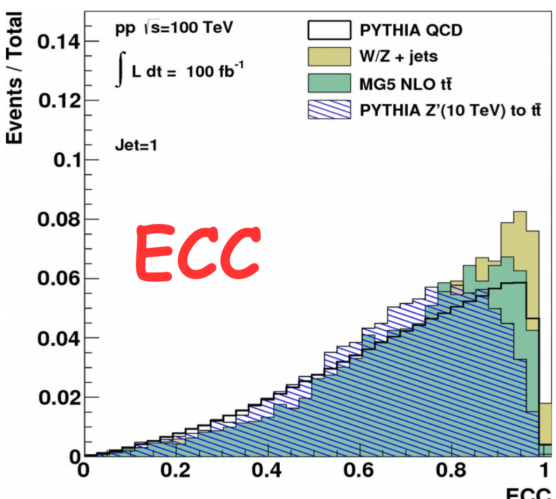
- For ~10 TeV object, typical opening angle between q, $\bar{q}$ and b from t ($\bar{t}$) is 5 degree
- "Highly boosted" regime: decay products are inside "standard" jets with R=0.5
- Event kinematics → "back-to-back" jets
  - top decays form a narrow "core"
  - large final-state gluon radiation introduces extra smearing (Snowmass13, arXiv:1307.6908)

Discriminating variables (lead. jet)









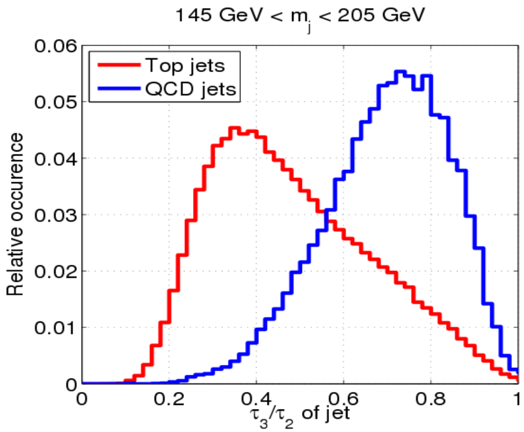
- τ_{32} **>0.75** reduces QCD and boosted W/Z
- τ_{21}**<0.3** reduces W/Z
- τ_{21}**>0.8** reduces QCD background
- $\sqrt{d_{12}}$**> 50 GeV** reduces QCD,W/Z, some $t\bar{t}$

Correlation between variables:
~10% for τ_{32} , τ_{21} , mass ~30% correlation between d_{12} mass, ECC

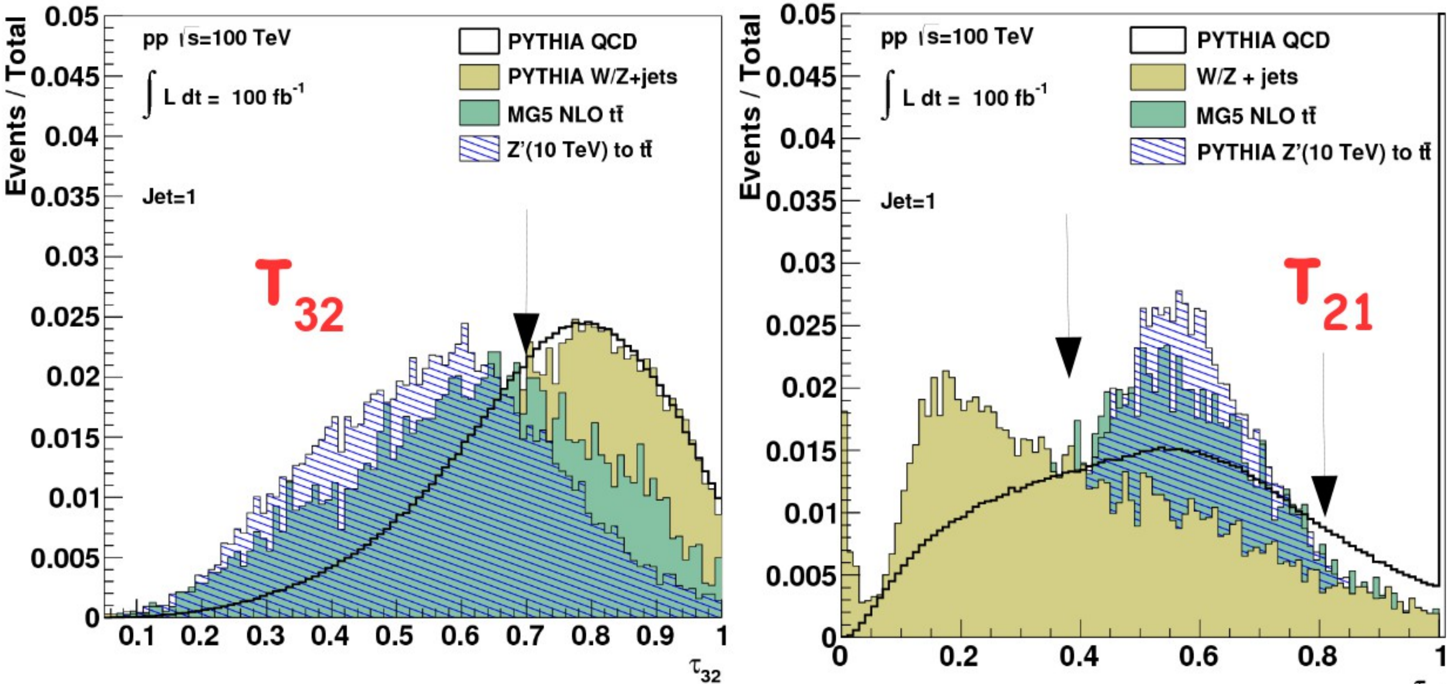
Studies based on 100 fb-1 presented in Next steps in the Energy Frontier (FNAL, Aug. 2014)
https://indico.fnal.gov/getFile.py/access?contribId=34&sessionId=0&resId=0&materialId=slides&confId=7864

This talk: N-subjettiness

- Jesse Thaler, Ken Van Tilburg (JHEP 1103:015,2011)
- tau32=tau3/tau2 is used for top reconstruction



Truth-level studies for Z'/gKK for 100 TeV pp



Studies based on 100 fb-1 presented in Next steps in the Energy Frontier (FNAL, Aug. 2014)
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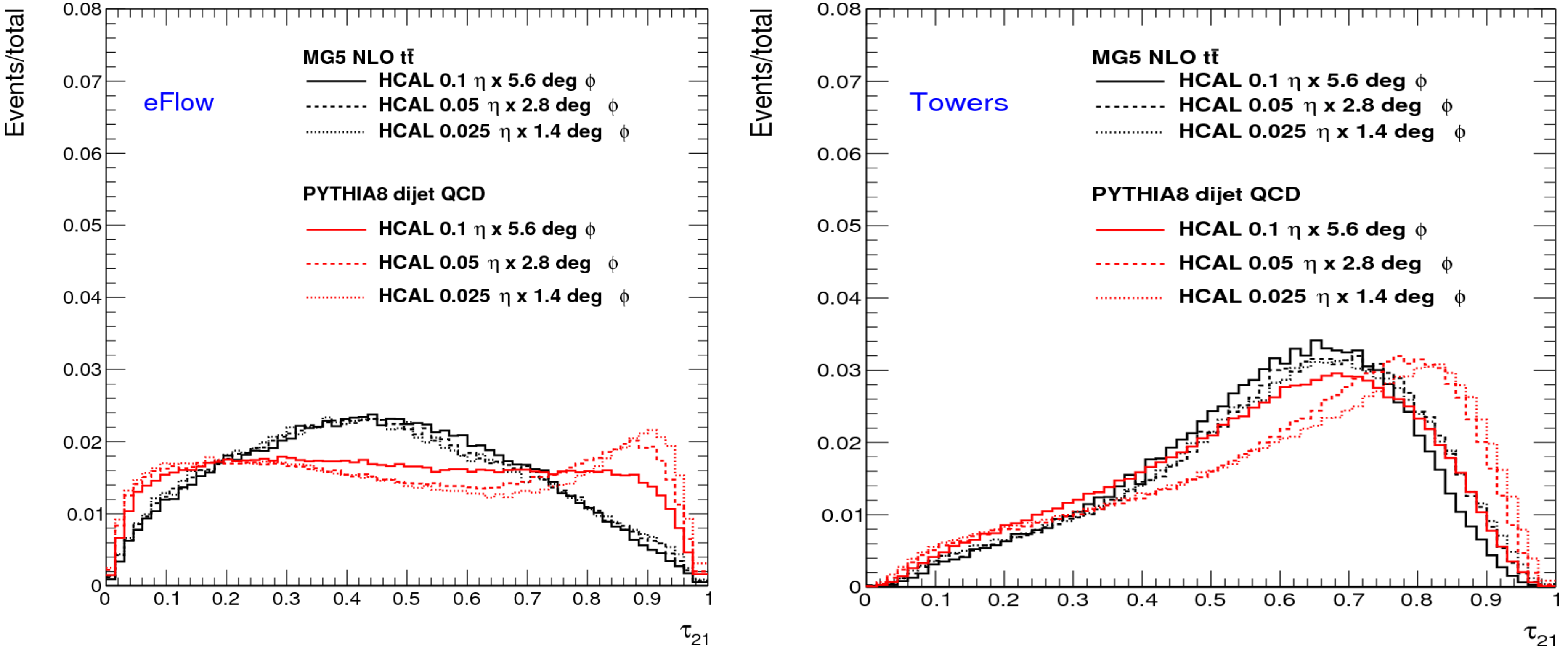
Jet substructure (pT>3 TeV)

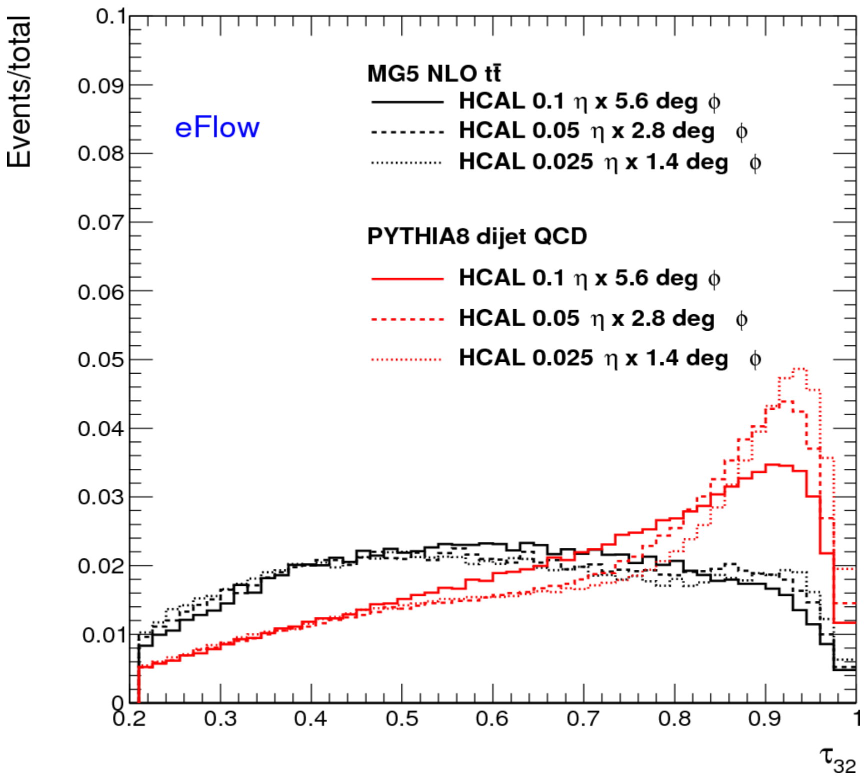
MC $t\bar{t}$ and QCD dijets for pT>3 TeV:
http://atlaswww.hep.anl.gov/hepsim/info.php?item=57
http://atlaswww.hep.anl.gov/hepsim/info.php?item=13

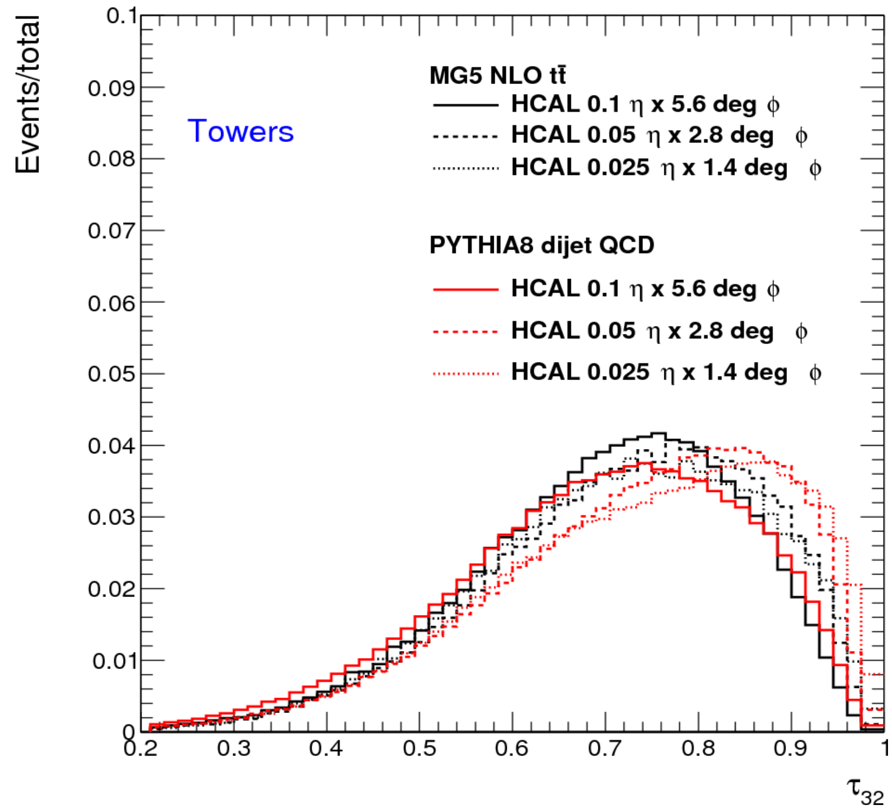
Delphes options:
- Option 7 ("winner-take-all", arXiv:1401.2158)
- antiKT5



- Comparing $t\,\bar{t} \rightarrow$ 2 boosted jets with dijet QCD jets for p>3 TeV
- Substantial improvements in separation between QCD and top quarks going from 5.6 to 2.8 degree. 1.4 degree case shows smaller change

Jet substructure (pT>3 TeV)





- Comparing $t\bar{t} \rightarrow$ 2 boosted jets with dijet QCD jets above 3 TeV
- Improvements in separation between QCD and top quarks going from 5.6 to 2.8 degree. 1.4 degree case shows smaller change

Conclusions

- 100 TeV collider will access ~10-20 TeV mass region for heavy particles
- Need to reconstruct jet substructure for p>3-10 TeV jets using the standard jets (R~0.5)
- Jet masses and jet substructure variable show sensitivity to HCAL segmentation using fast detector simulation based on Delphes
  - Largest improvement → going from 5.6 to 2.8 degrees in both **φ** and **η**
  - means 128 modules in **φ** and 0.05 in **η**
- Need to check other jet-shape variables
  - eccentricity is expected to show smaller sensitivity to CAL segmentation
  - but same angular segmentation in φ-η plane is preferred