Analysis of $ee \to t\bar{t}$ and first jet studies

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Keywords of the project

The focus of this project is analysing **top-quark electroweak couplings** in pair produced events. An **optimal observables analysis** is planned to be performed in order to gauge the sensitivity to **anomalous couplings of the top quark to the photon and the Z**. MC data is simulated using FCCSW where an **event selection and event reconstruction** is being developed with plans of performing a **kinematic fit**.

Optimal Observables (OO)

For a single coupling parameter C which is zero at Born level in SM

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right|_{SM} = 1 + \frac{OO_C^{(1)}}{SM}\cdot C + \frac{OO_C^{(2)}}{SM}\cdot C^2 \Rightarrow$$

$$\left\langle\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right\rangle = \langle SM\rangle + \langle OO^{(1)c}\rangle\cdot C + \langle OO_C^{(2)}\rangle\cdot C^2$$

– same statistical sensitivity as a maximum likelihood fit

– requires matrix elements from **MadGraph** $\leftrightarrow$ **Feynrules** $\leftrightarrow$ **SMEFT**

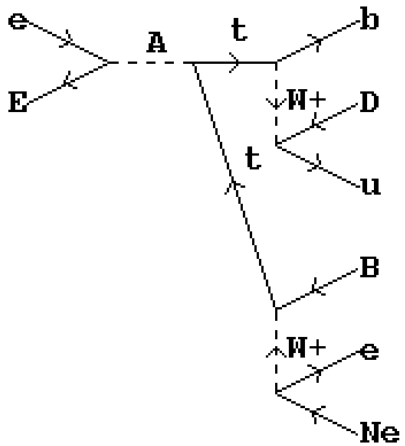
$\hookrightarrow$ functional – next comparison to Whizard

Signal:

Semileptonic channel

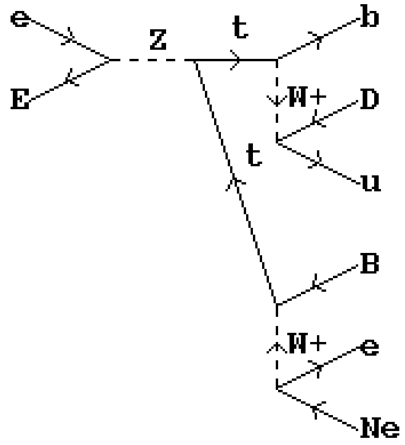
$$t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}q\bar{q}\ell\nu_\ell$$

3rd phase of FCC-ee @ $\sqrt{s} = 365\,GeV$



Backgrounds:

$\mu\mu$	γZ	ZW^+W^-
$b\bar{b}$	W^+W^-	ZZZ
$\sum q\bar{q}$	ZZ	single top
$q = u, d, c, s$		LHE files from MadGraph



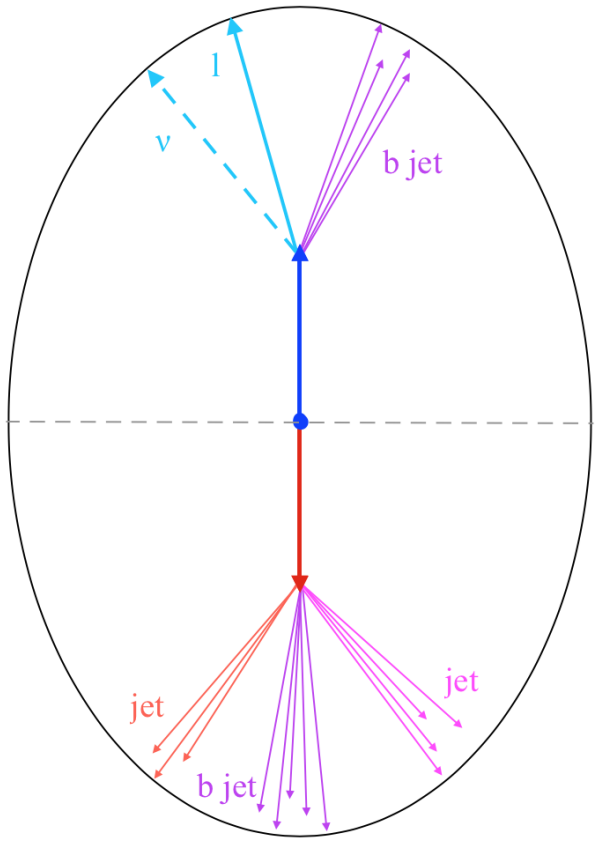
- All MC files are generated in the FCCSW framework with DelphesPythia8_EDM4HEP and ILD Delphes Card
  - Common baseline detector decision?

$$t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}q\bar{q}\ell\nu_\ell$$

Signature of semileptonic decay channel:

- At least 1 lepton
- Missing momentum
- 4 jets

- Invariant mass of lepton-neutrino pair $\sim M_W$
- Invariant mass of entire event
- Event shape: thrust, sphericity
- etc.



Event shapes: Thrust and sphericity are used for quantifying event shape by tracking quark directions. With a non-isotropic event shape, we can expect 1 jet+lepton+$\not{E}$ on one side of the semi-major axis and 3 jets on the other side.

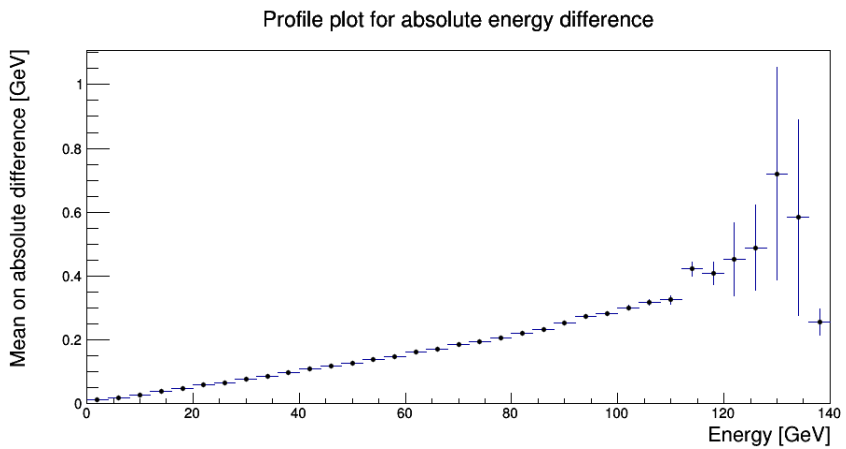
Highest energy lepton:

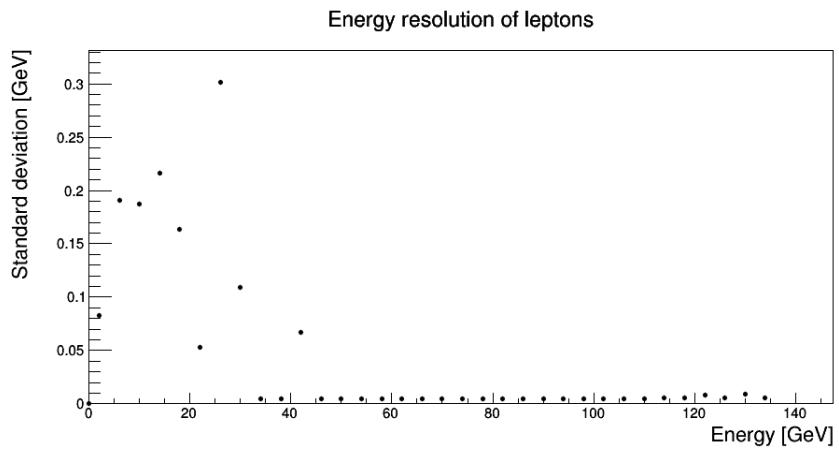
Assuming that the lepton from the W-decay will have the highest energy, it can be used as a selector. This selector has an acceptance of

$$\mathbf{96.6 \pm 0.7\ \%}$$

→ Find RP highest energy lepton
→ Match to MC particle
→ Parent history (EDM4Hep gives parent and daughter history for MCParticleData)
→ Stopping criteria with PDG and status code

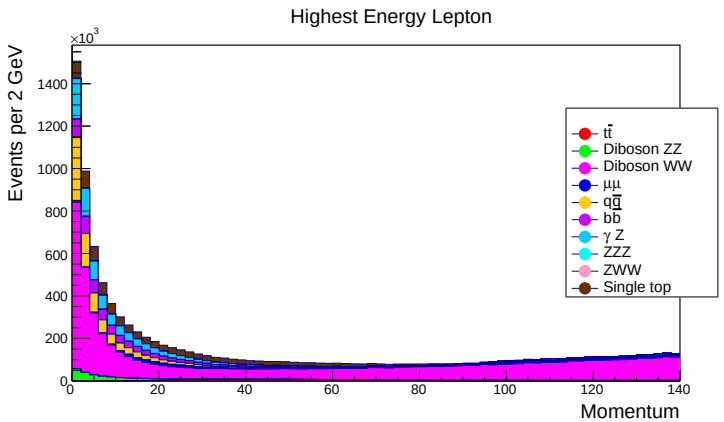
The majority of the highest energy leptons are originating from a W-boson with the same charge. 0.02% are originating from an opposite charge W-boson indicating a decay from a lighter-flavour non-b-quark. The remaining leptons are originating from a b-quark.

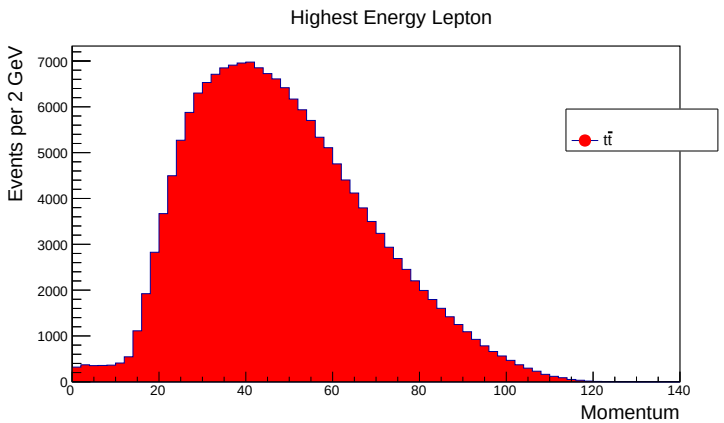




Strategy:

Iterative procedure based on maximum significance on a set of variables
→ choose variable with highest maximum significance
→ make cut and reiterate on remaining set

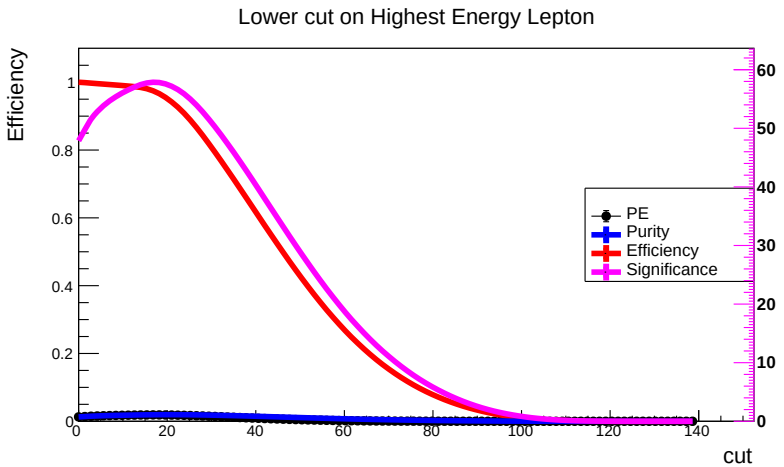




List of variables:

- Highest energy lepton
- 2nd highest energy lepton
- Lepton momentum
- Lepton momentum excluding highest energy lepton
- Momentum difference between highest and second highest energy lepton
- Missing momentum
- Invariant mass of lepton-neutrino pair
- Invariant mass of 1st and 2nd highest energy leptons
- Invariant mass of event excluding highest energy lepton
- Thrust of event excluding highest energy lepton
- Thrust of entire event

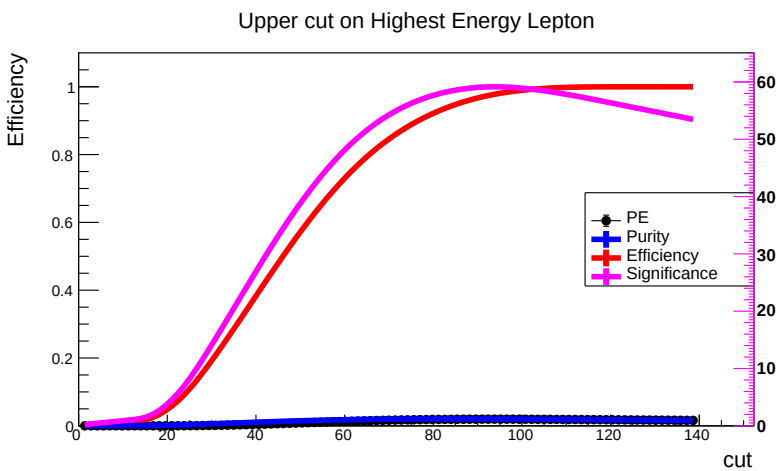
Significance-optimised selection cut strategy

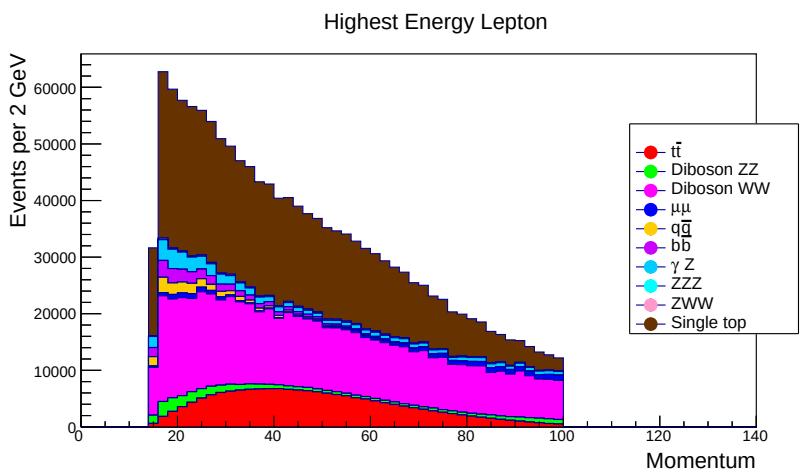


$$\textbf{Significance} = \frac{sig}{\sqrt{sig + bkg}}$$

$$\textbf{Efficiency} = \frac{sig}{sig_{\text{tot}}}$$

$$\textbf{Purity} = \frac{sig}{sig + bkg}$$





Significance-optimised selection cut strategy

Pre-selection cuts

- Exclude events with zero leptons
- Thrust for entire event < 0.85
- 15 GeV $<$Highest energy lepton $<$ 100 GeV
- 160 GeV $<$ Invariant mass of event excluding highest energy lepton $<$ 300 GeV
- 2nd highest energy lepton $<$ 40 GeV
- Jet specific cuts to be determined

Significance of signal for each background before and after Pre-Selection

Background	Sanity check	Pre-Selection
Total	48	192
$\mu\mu$	162	402
$\sum q\bar{q}$	169	400
$b\bar{b}$	198	400
γZ	152	399
WW	61	326
ZZ	234	392
ZWW	405	400
ZZZ	421	405
single top	157	211

Jet reconstruction:

- FastJet in FCCAnalyses $\text{analyzers/dataframe/JetClustering}\begin{cases}\text{.cc}\\ \text{.h}\end{cases}$
  - Thank you to Clement Helsens for providing this option
- So far, only "native"[1] FastJet algorithms are implemented.
  - k_t, anti-k_t, Cambridge, Durham (e^+e^- k_t) as well as e^+e^- versions of anti-k_t and Cambridge
- The "after burner" provides more flexibility.
- At least 1 lepton $\rightarrow$ Highest energy lepton is excluded from the clustering
- 4 jets $\rightarrow$ exclusive clustering up to *exactly* 4 jets

Jet matching:

From the 4 hard process quarks in the MC collection, a jet is matched to the MC quark that minimises the matching angle - smallest displacement

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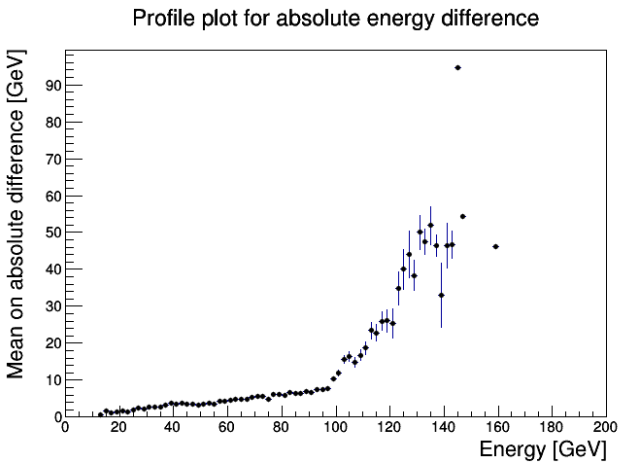
[1] FastJet User Manual: https://arxiv.org/pdf/1111.6097.pdf

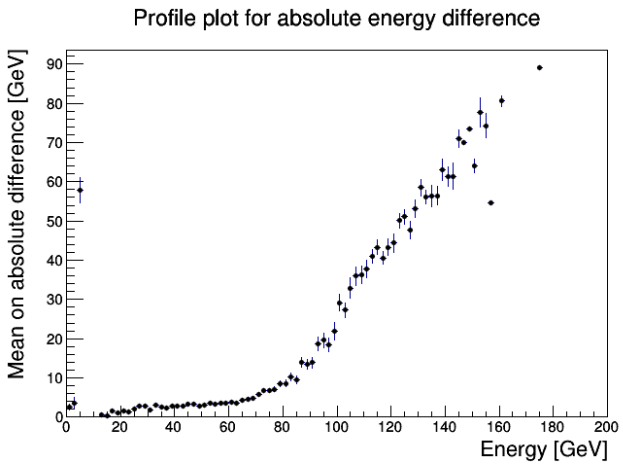
Jet Absolute Energy Difference

between true MC quark and reconstructed jet

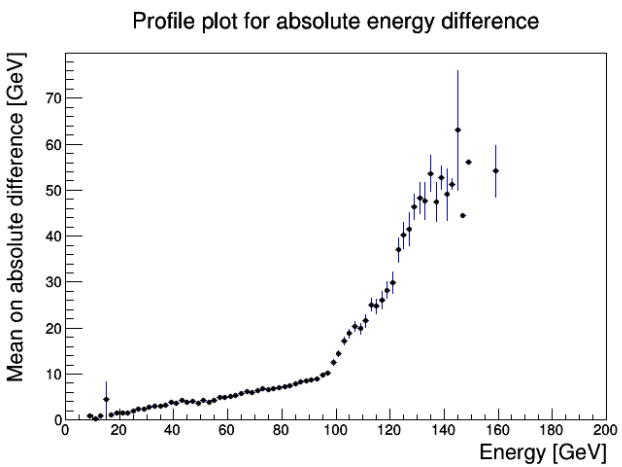
k_t Algorithm



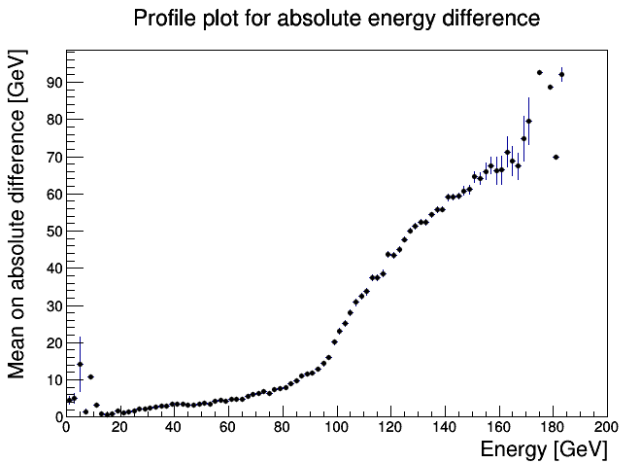
e^+e^- Anti-k_t Algorithm



Durham Algorithm (e^+e^- k_t)



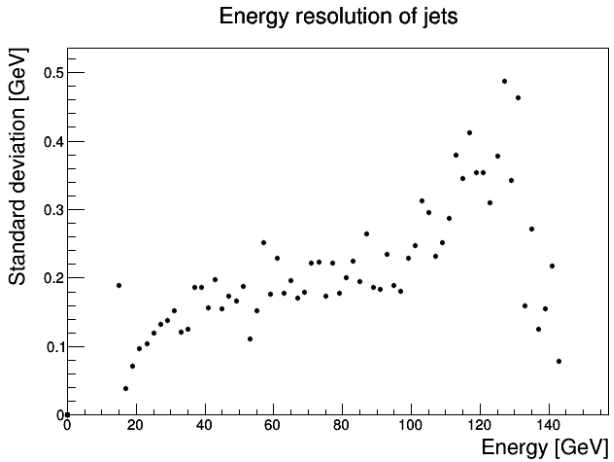
e^+e^- Cambridge



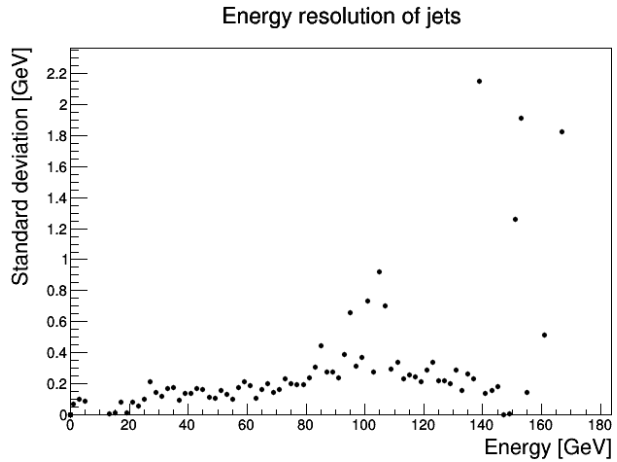
Jet Energy Resolution

from relative energy difference between true MC quark and reconstructed jet

k_t Algorithm



e^+e^- Anti-k_t Algorithm



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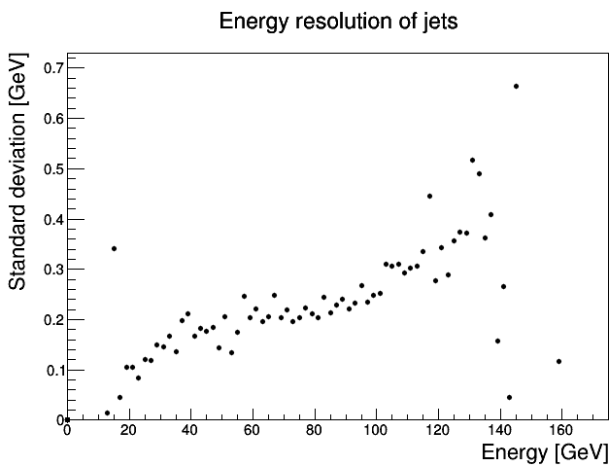
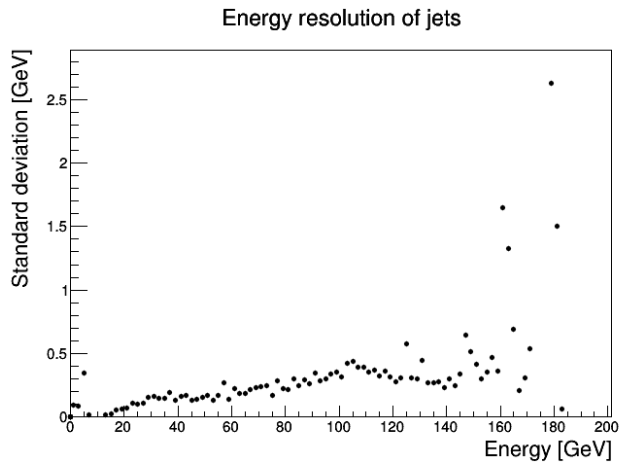


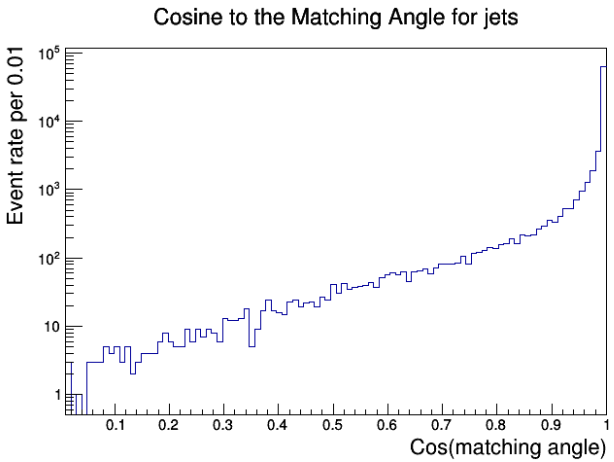
e^+e^- Cambridge



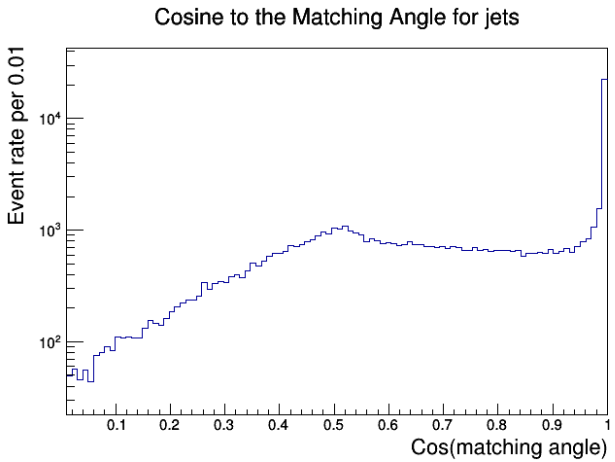
Jet Matching Angle

between true MC quark and reconstructed jet

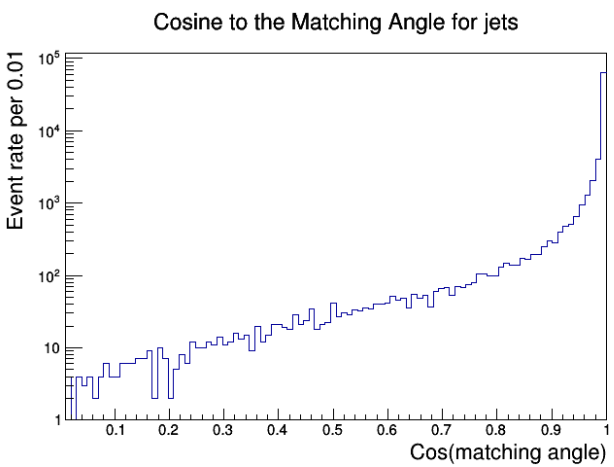
k_t Algorithm



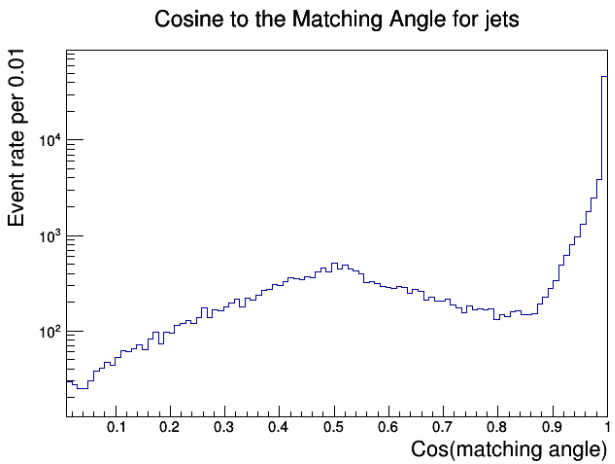
e^+e^- Anti-k_t Algorithm



Durham Algorithm (e^+e^- k_t)



e^+e^- Cambridge



Jet Matching Angle

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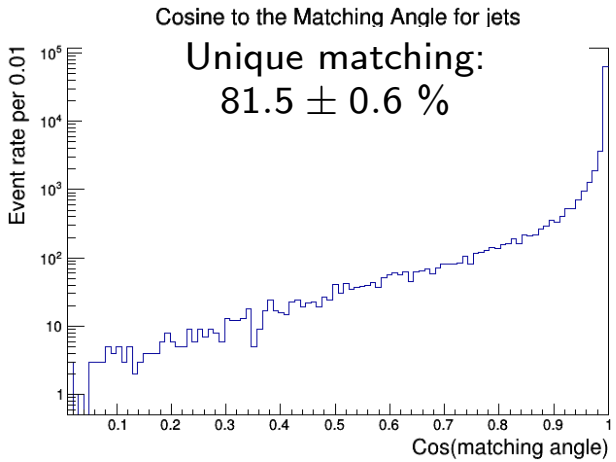
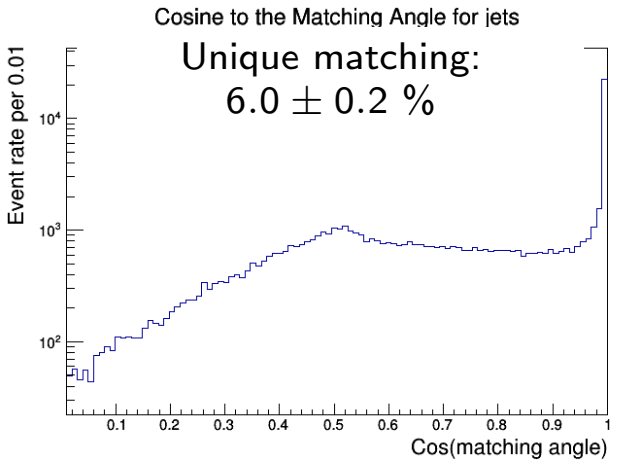
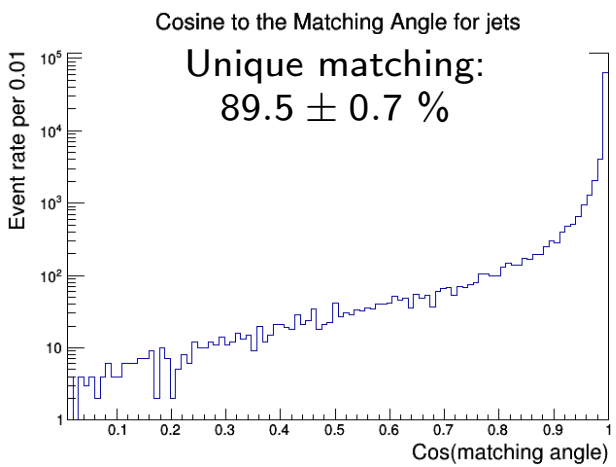
k_t Algorithm



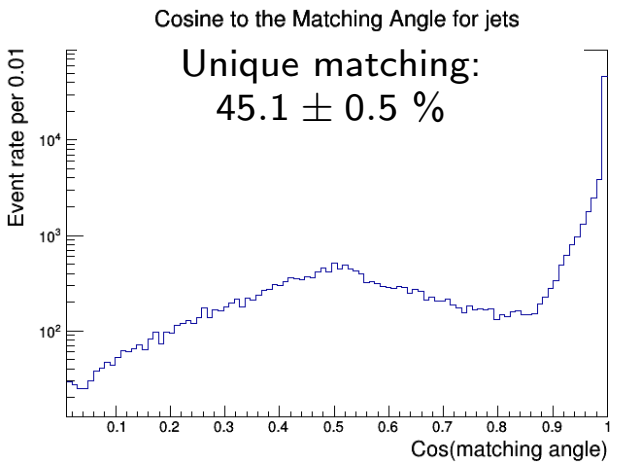
e^+e^- Anti-k_t Algorithm



Durham Algorithm (e^+e^- k_t)



e^+e^- Cambridge



Continuing Jet Studies

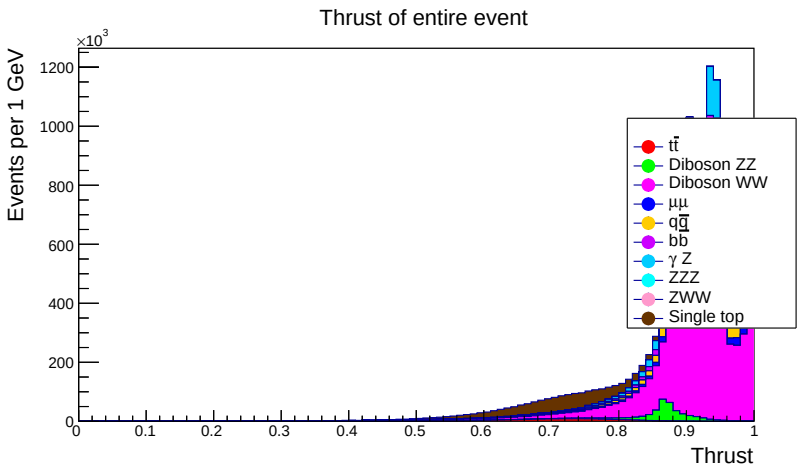
- Expand list of jet algorithms with "plugin" algorithms from FastJet:
  - Jade, (e^+e^- Cambridge)
- Energy normalisation methods provided by FastJet
- Merging schemes (default is E-scheme)
- Additional ideas?
- Jet Specific Selection Cuts
  - Thrust to test distribution of jets in event shape, invariant mass, etc.

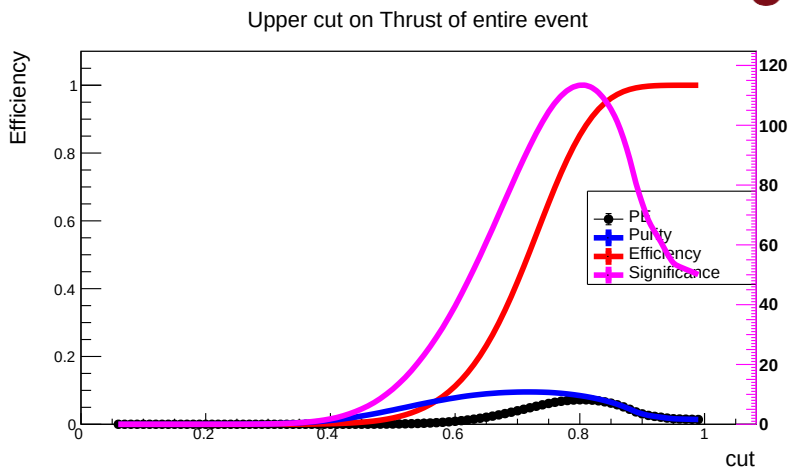
Kinematic Fit

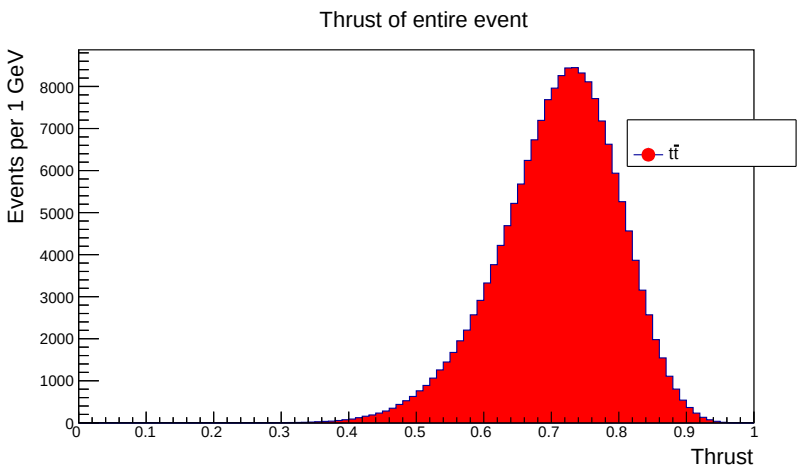
- Imposing constraints to improve resolution and reduce background for event selection and reconstruction of ttbar events
- Semileptonic $\rightarrow$ maximum kinematic information
- Complete reconstruction
  - Develop software inspired by ABC-fit compatible with FCCSW

Backup

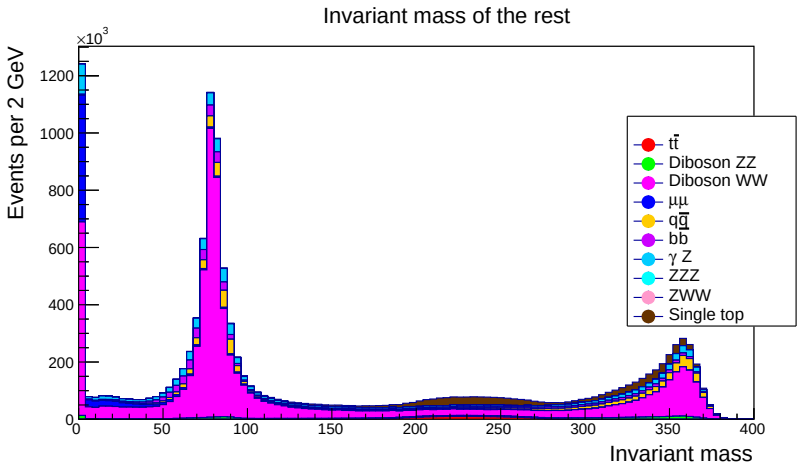
Thrust of entire event

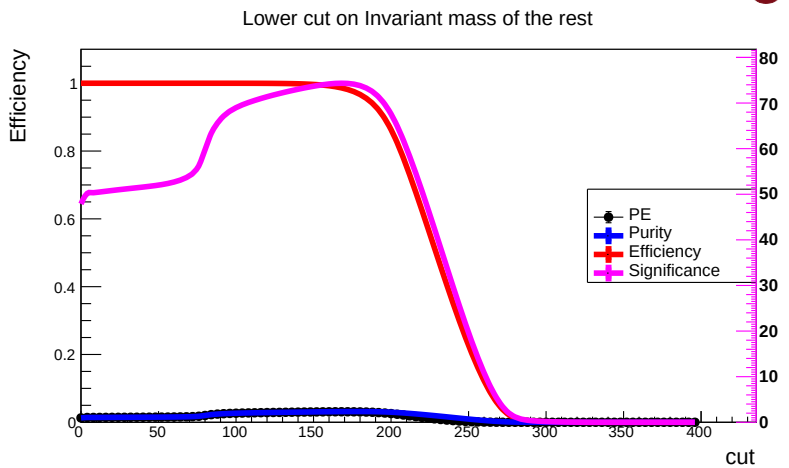


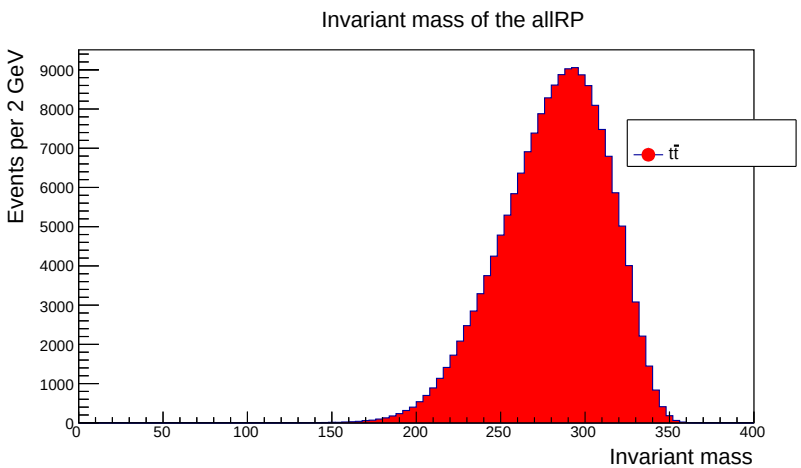


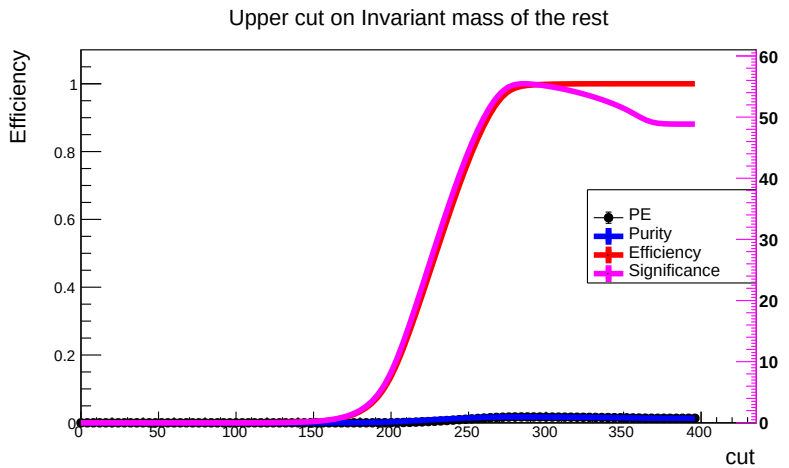


Invariant mass of the rest









2nd highest energy lepton