$t\bar{t}$

Towards $t\bar{t}$ Forward-Backward Asymmetry: Top Tagging at High Energies (1.4 TeV)

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Outline

- $t\bar{t}$ Forward-Backward Asymmetry
- Analysis Strategy
- Isolated Lepton Identification
- Top Tagging: Algorithm, Efficiency
- Summary and Conclusion

Goal: $t\bar{t}$ Forward-Backward Asymmetry

- Using CLIC-ILD, operating at 1.4 TeV with 1.5 ab^{-1} (1.3 γγ -> had. / BX)
- Determining top quark couplings through measurement of cross-sections and forward-backward asymmetries for different polarisations
- Increased boost → better separation between the decay products of the two top quarks, but new reconstruction techniques needed
- The sub-percent precision on anomalous electroweak couplings yields sensitivity to new physics, also at scales well beyond the direct reach

Experimentally

$$A^t_{FB} = \frac{N(0 < \theta_{top} \leq \pi/2) - N(\pi/2 < \theta_{top} \leq \pi)}{N(0 < \theta_{top} \leq \pi/2) + N(\pi/2 < \theta_{top} \leq \pi)}$$

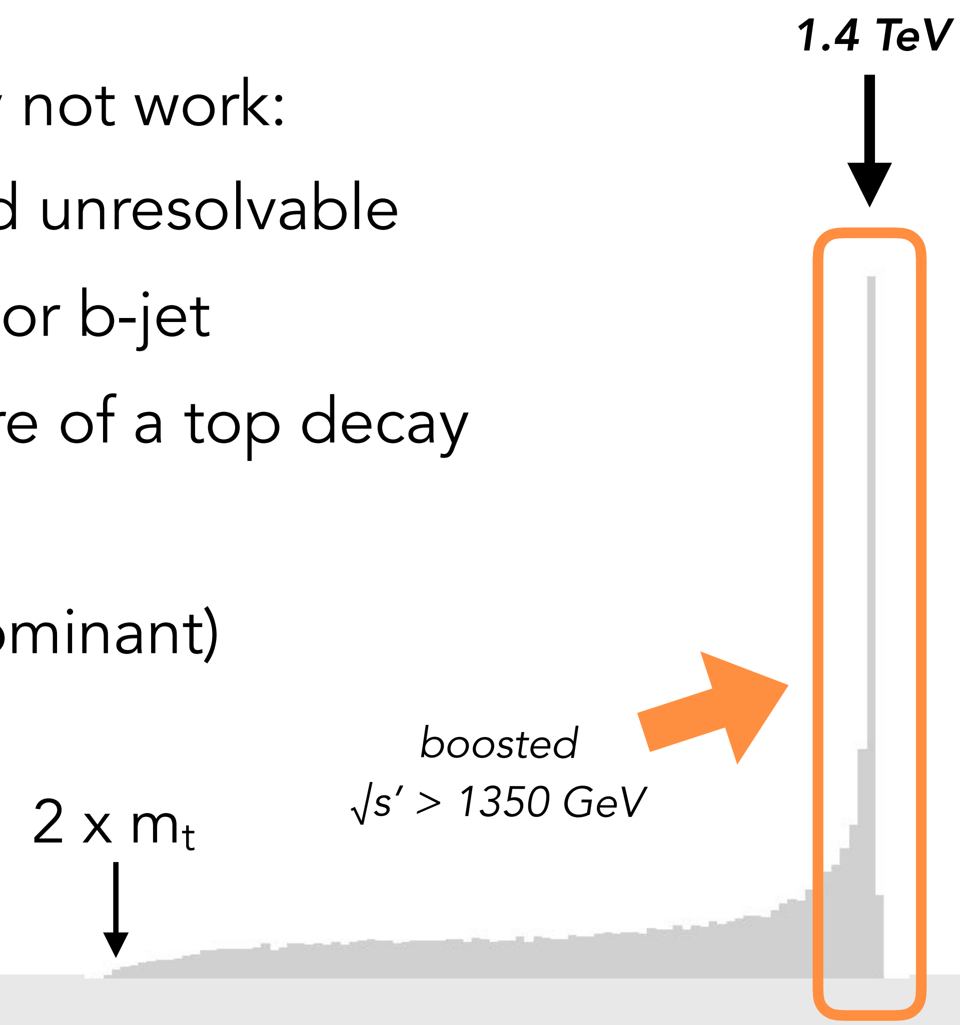
- Study of top quark couplings: form-factors or effective operators

$$\Gamma_\mu^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

Analysis Strategy @ 1.4 TeV

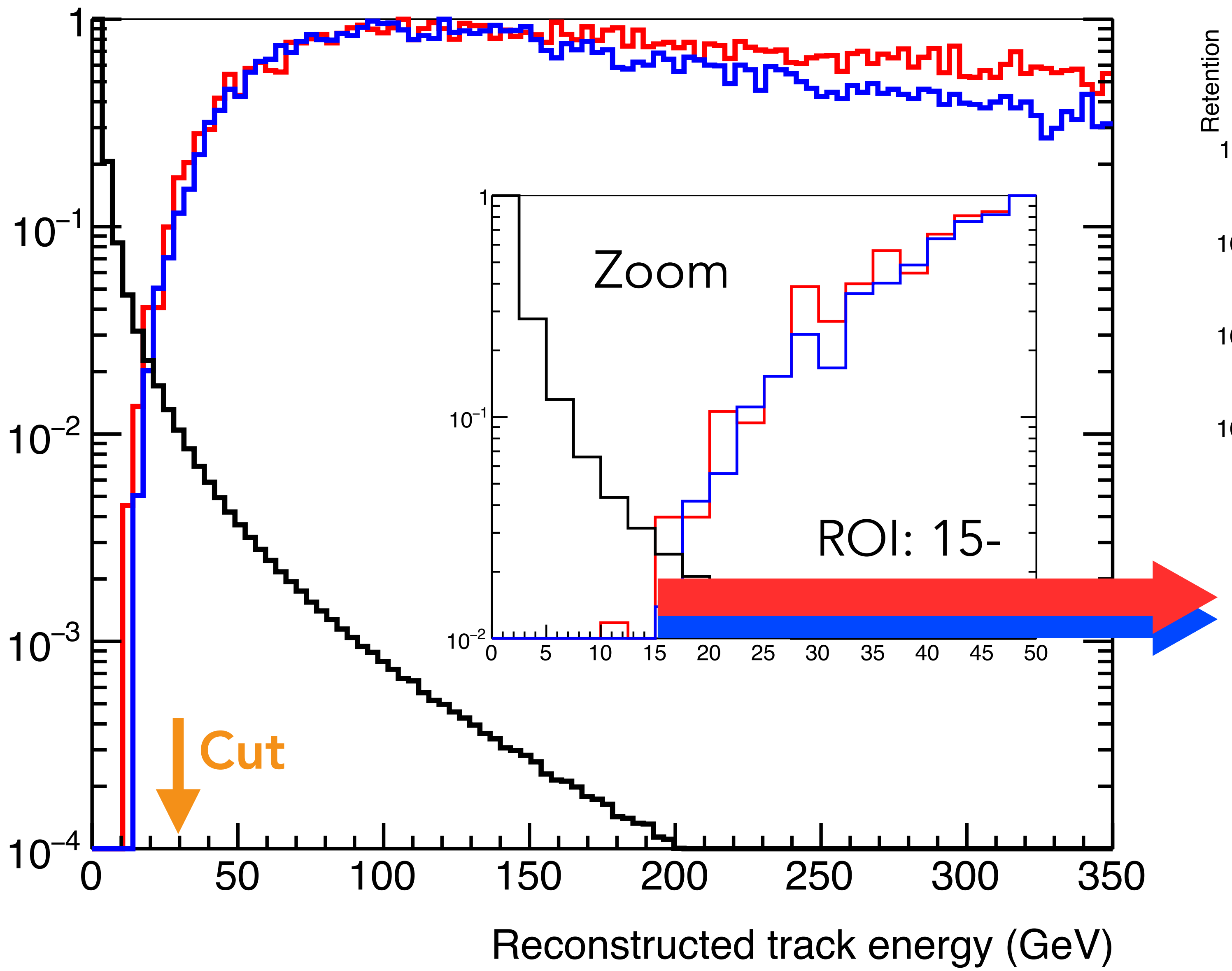
- *Resolved analysis*
  - Production near threshold (events with lower effective centre-of-mass due to ISR, beamstrahlung, and/or luminosity spectrum)
  - Use b-tagging, search for W, or 3 jets with a combined invariant mass near m_t
- *Boosted analysis (large R-jets/fat-jets)*
  - Standard top-quark identification techniques may not work:
    - b-tagging difficult since tracks are crowded and unresolvable
    - W decay product not isolated from each other or b-jet
  - Identify prongy structure that would be a signature of a top decay
  - Looking at $t \rightarrow W^{\pm}b$:
    - fully hadronic decays $W^{\pm} \rightarrow qq$ (light quarks dominant)
    - semi-leptonic decays $W^{\pm} \rightarrow l\nu$

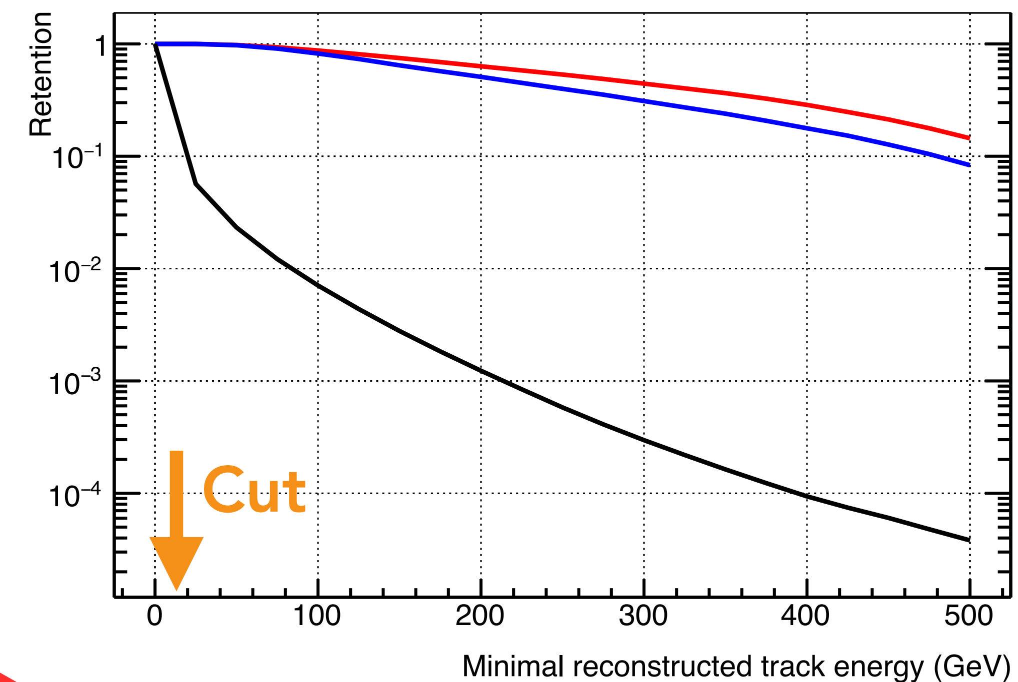


Isolated Lepton Identification

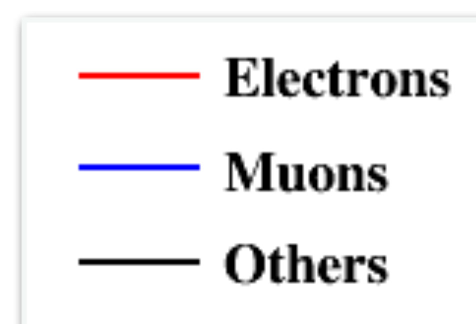
- Goal: Identify leptons from the $W^{\pm}$ decay
- Studying semi-leptonic decays with electron and muon vs. fully hadronic
- Using Marlin processor: *IsolatedLeptonFinder*
  - **Electron, muon**
    - Track energy
    - Impact parameter (should originate from PV due to short lifetime of top quarks and W, unlike decay products from b quarks that may originate from a displaced vertex)
    - Calorimeter energy (different interaction cross-sections leads to different deposition of energy in the sub-detectors)
    - Isolation information (jets are busier than electrons and muons)
  - **Tau** (rapid decay, mean life τ $2.9\text{x}10^{-13}$ s ⇨ different behaviour)
    - *LEAVE for later!*

Lepton ID Optimisation - Track Energy

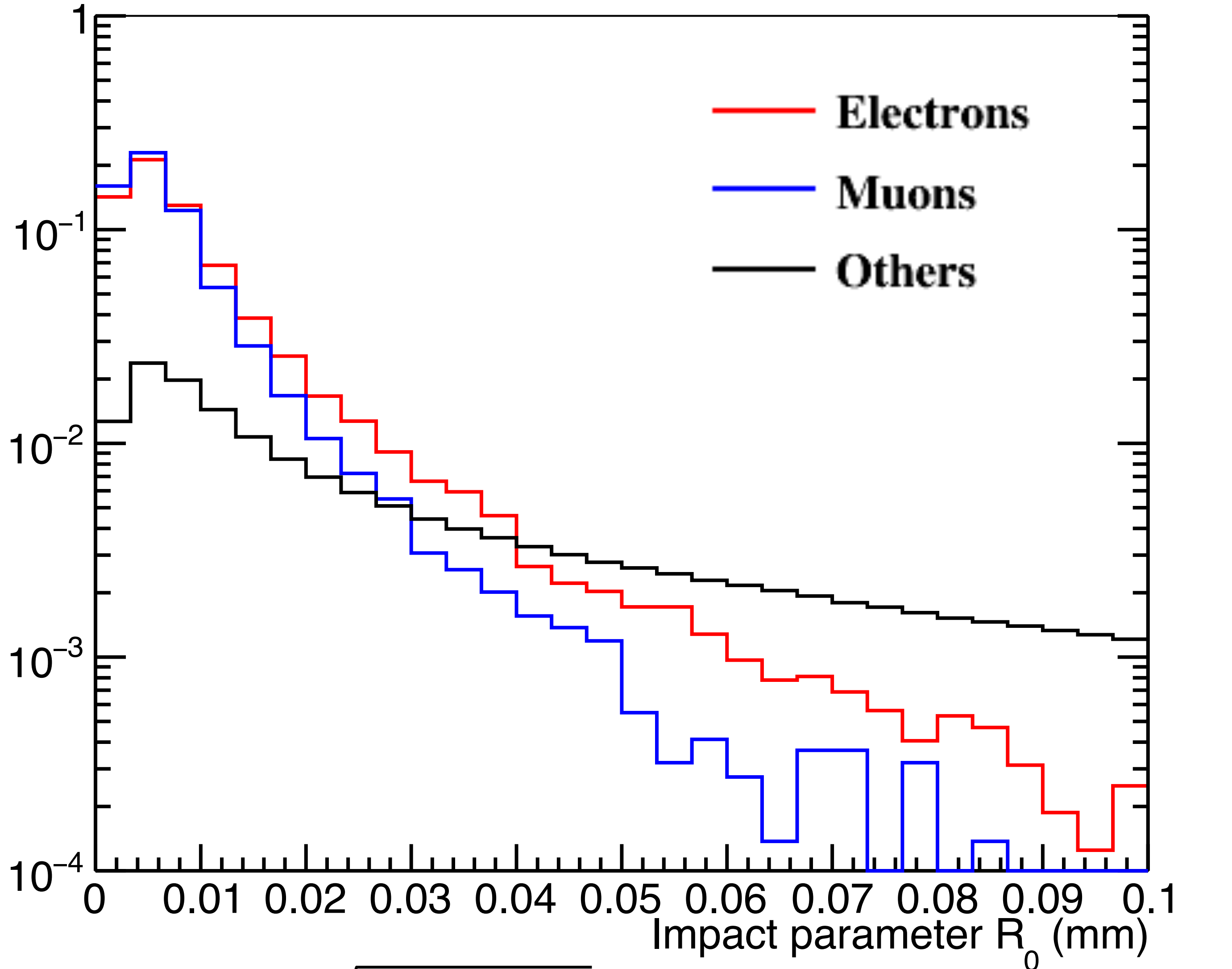


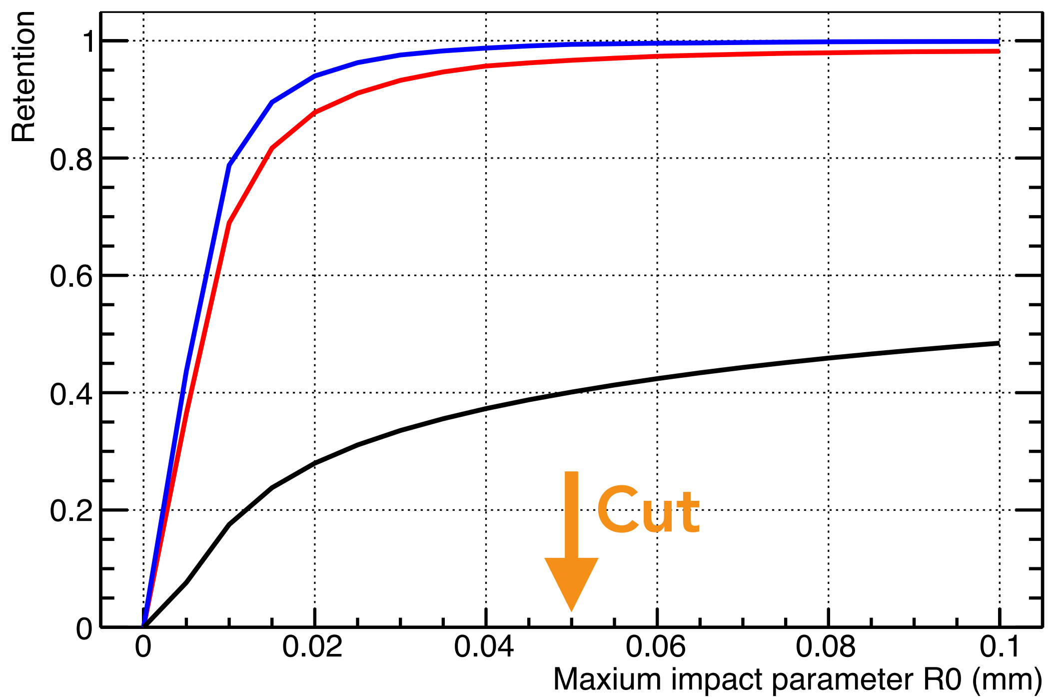


- Cut placed at 15 GeV



Lepton ID Optimisation - Impact Parameter





$$R_0 = \sqrt{Z_0^2 + d_0^2}$$

- Cut placed at 0.1 mm
- Cut also on Z_0 and d_0 (0.05)

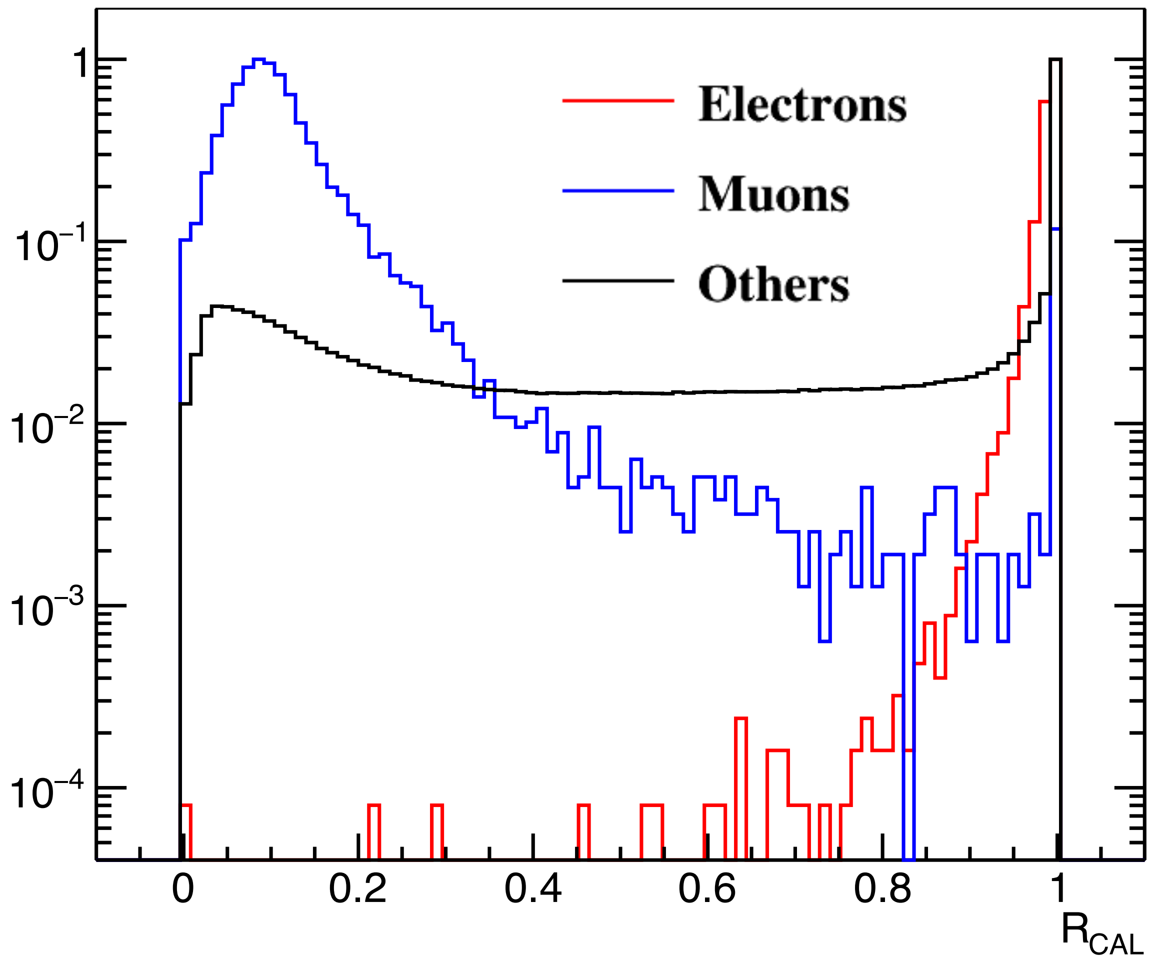
ROI:

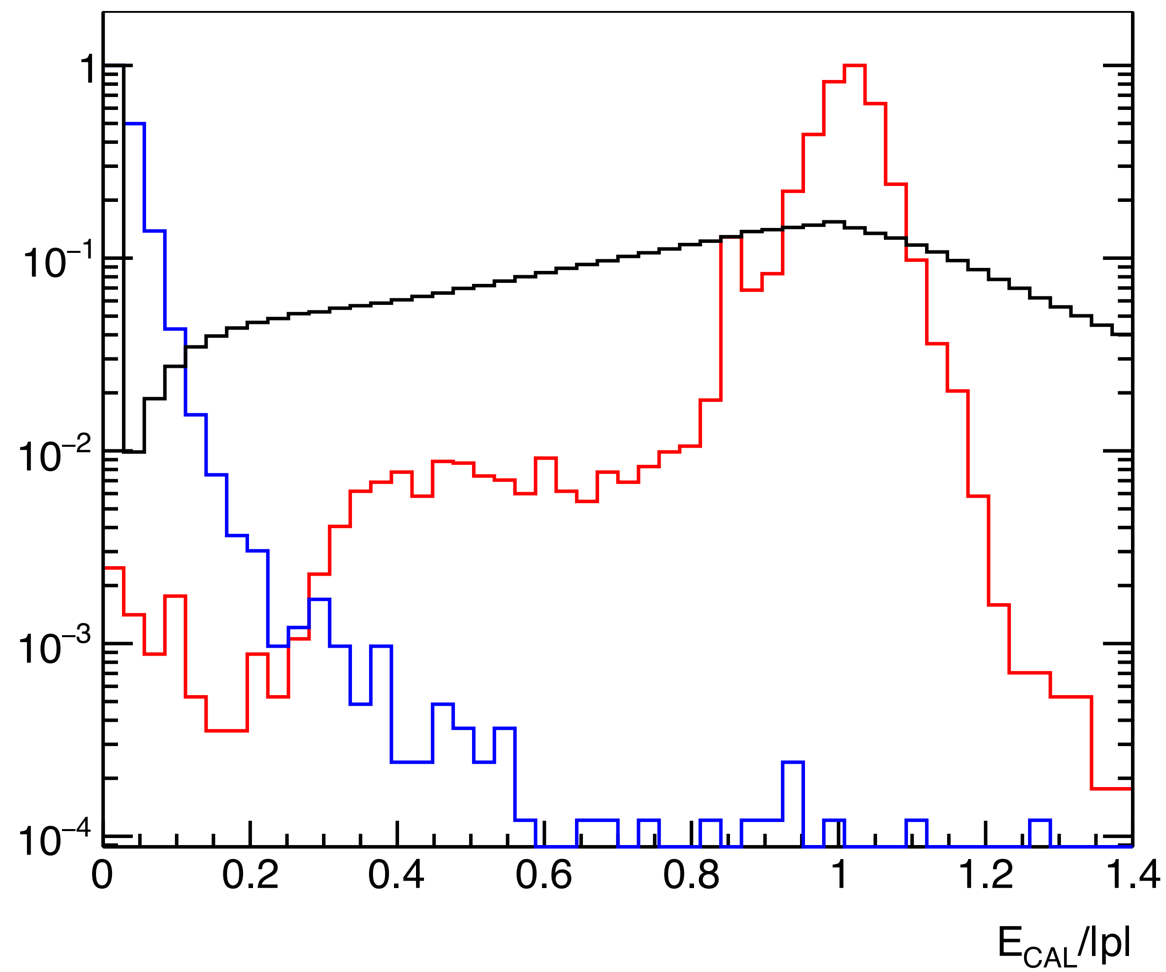
0.00 - 0.10

Lepton ID Optimisation - Calorimeter Info

Individual regions of interest (ROI) for electron and muon (zero charge PFOs removed)

"Fraction of total CAL energy that is observed in the ECAL"



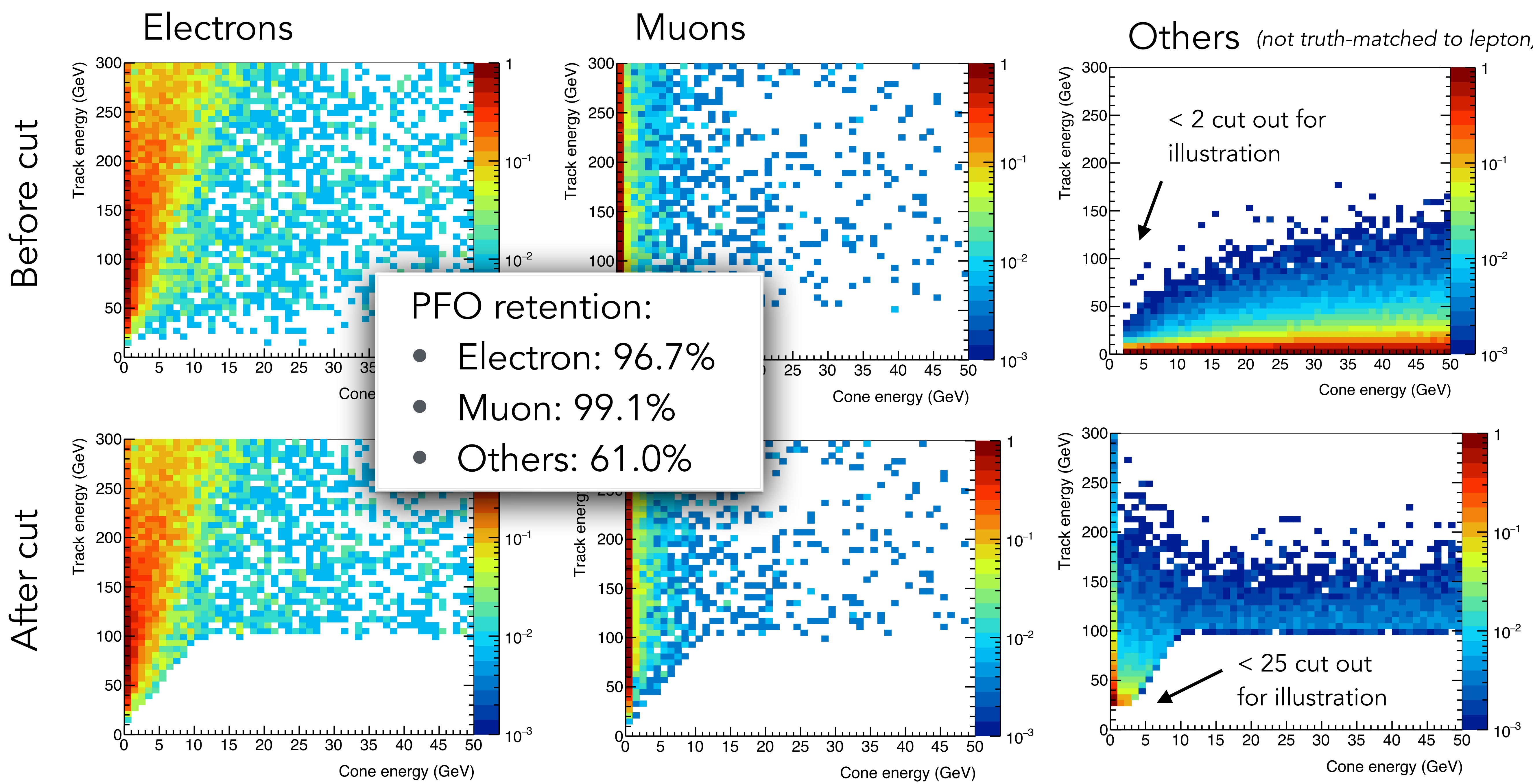


$$R_{Cal} = E_{ECal} / (E_{ECal} + E_{HCal})$$

ROI: 0.0 - 0.5 | 0.9 - 1.0 | 0.0 - 0.3 | 0.3 - 1.2

Lepton ID Optimisation - Cone Isolation

(Track energy) > 10 x (Cone energy) for (Cone energy) < 10 GeV, otherwise (Track energy) > 100 GeV - using cone opening angle of ~2.6 degrees (0.999)



PFO retention:

- Electron: 96.7%
- Muon: 99.1%
- Others: 61.0%

Lepton ID Optimisation - Performance

- The cuts on previous slides were applied + (zero charge)
- Muon veto is very efficient in identifying muons from initial W decay + remove fakes
- Electron veto is efficient but have a higher fake rate
- Cut on Pandora ID can help reducing the fake rate?

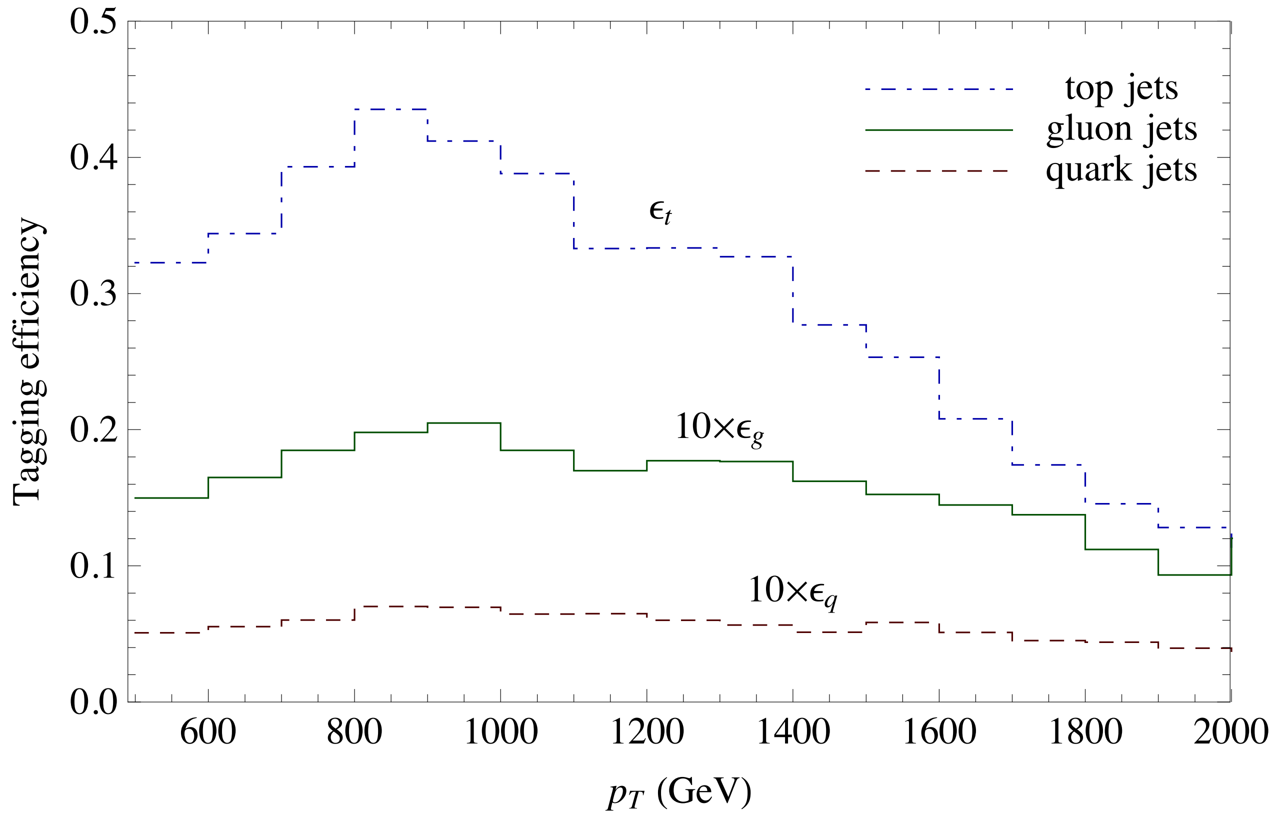
Processes	Muon Veto Correctly Identified	Electron Veto Correctly Identified
Semi-leptonic $W \rightarrow \nu_e + e$	fake ~0%	**82%**
Semi-leptonic $W \rightarrow \nu_\mu + \mu$	**92.5 %**	fake ~0%
Fully hadronic $W \rightarrow qq$	fake **4.4%***	fake **29.8%****

**5.2 % for event inv. mass > 1350 GeV*

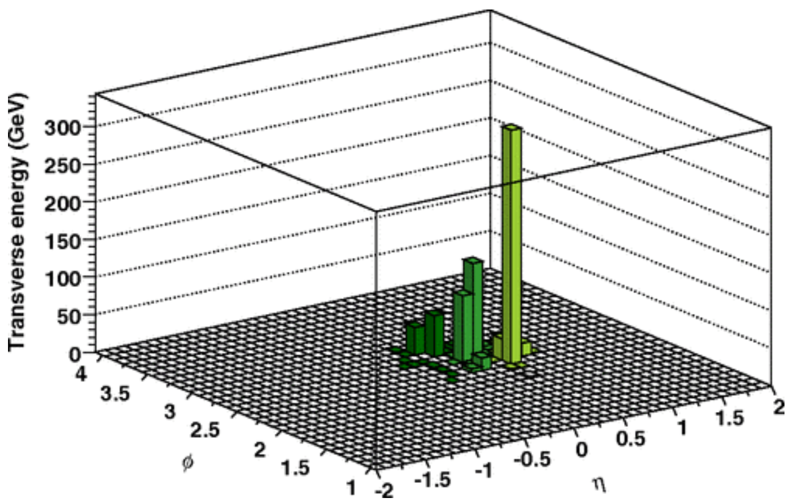
***36.4% for event inv. mass > 1350 GeV*

Top Tagging

- Goal: distinguish top quarks from QCD background
- Following the method from Kaplan et al, DOI: 10.1103/PhysRevLett.101.142001
- Distinguish boosted top jets from light-quark and gluon jets using jet substructure
  - Parsing jet cluster (Isolate events with three hard, nearby subjets)
  - Imposing kinematic constraints (exploit 3-body kinematics of top decay)



"A typical top jet with a p_T of 800 GeV at the LHC. The three subjets after top tagging are shaded separately."



DOI: 10.1103/PhysRevLett.101.142001

Top Tagging Algorithm

1) Cluster event using large jet radius R (catch 'em all) - Cambridge Aachen
   - Iteratively merge pair with closest $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ until $\Delta R < R$

2) Iteratively decluster each resulting jet to search for subjets
   - Split into two parts, reject softest if ……………………… $\frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}} < \delta_p$
   - Declustering continues on the harder object until:

Both subjets are harder than δ_p	✔	Both subjets are too close $\lvert\Delta\eta\rvert + \lvert\Delta\phi\rvert < \delta_r$	✗
Both subjets are softer than δ_p	✗	Only one calorimeter cell left	✗

3) Repeat step 2
   - Results in 2, 3, or 4 (additional soft gluon emission) subjets or the original jet

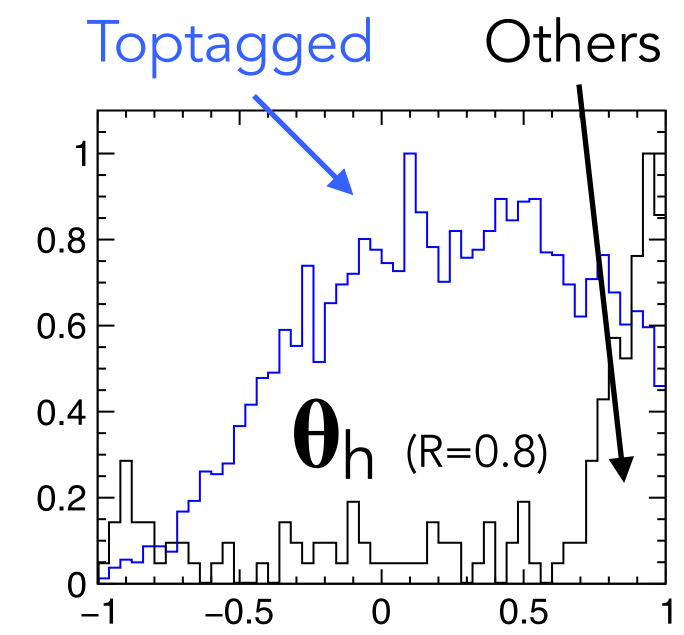
   { 2 ✗, 3 ✔, 4 ✔ }

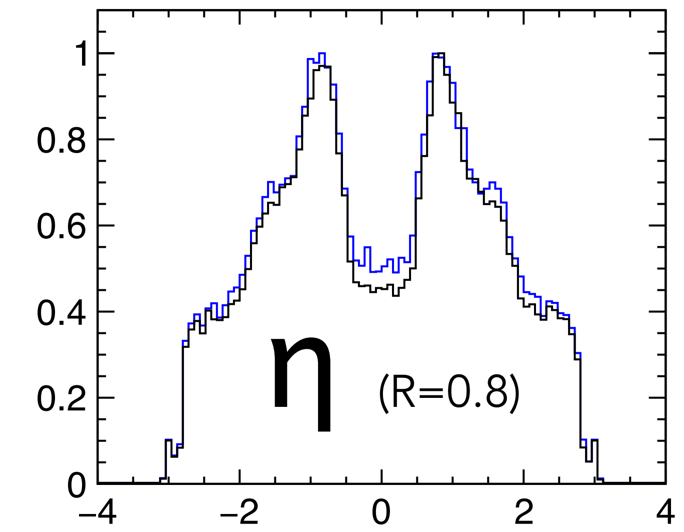
4) Additional kinematic cuts (next slide)

Top Tagging Algorithm

The following kinematic cuts are applied:

- Total invariant mass of 3-4 subjet system close to m_t:
  - 145 GeV ≤ m_t ≤ 205 GeV
- Two subjects which reconstruct the W mass within:
  - 65 GeV ≤ m_W ≤ 95 GeV
- W helicity angle consistent with top decay: $\cos\theta_h < 0.7$

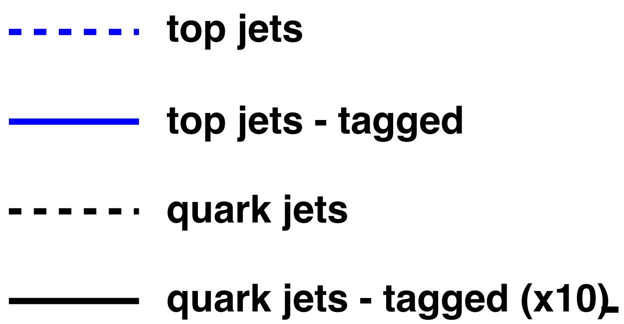




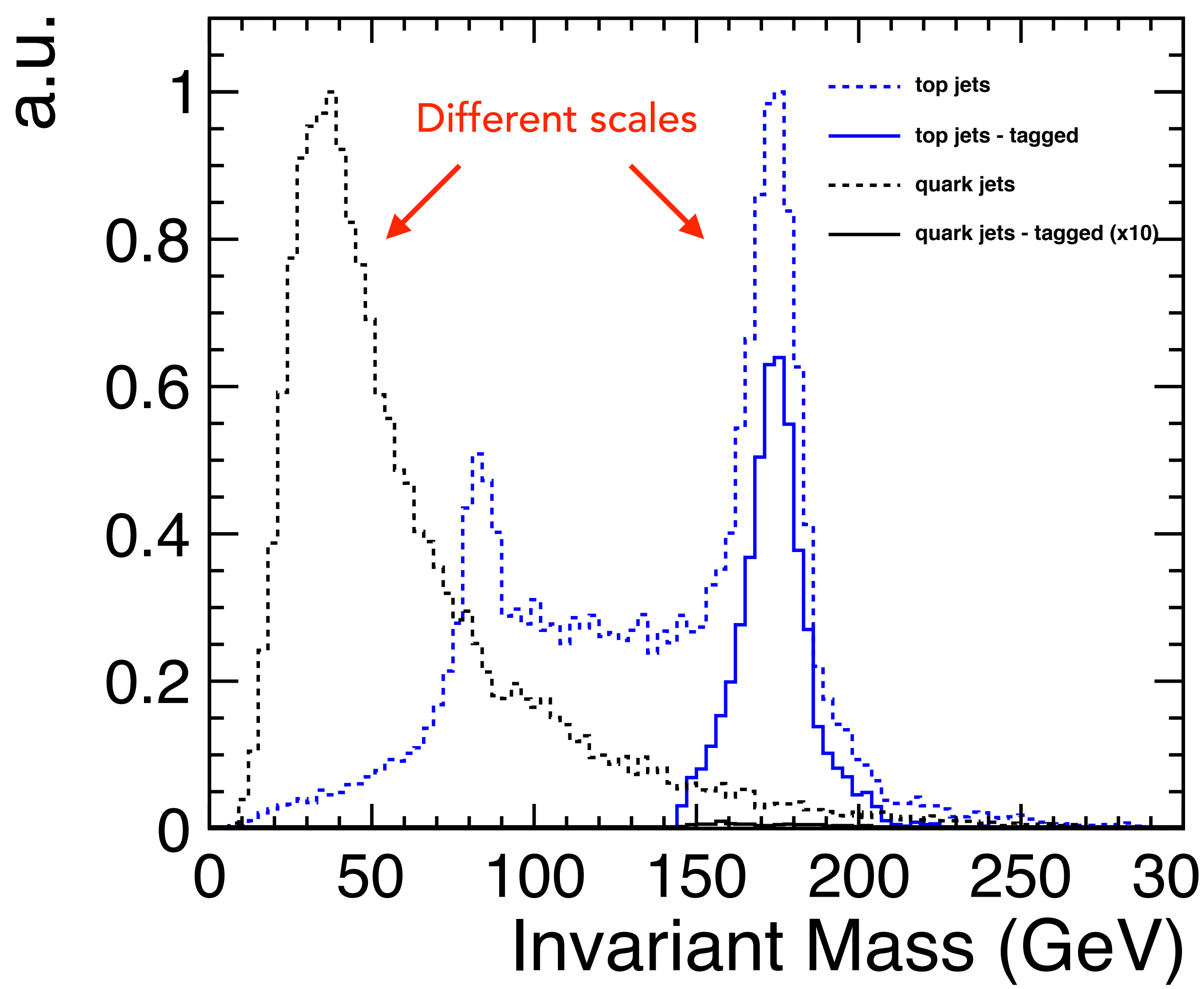
General:

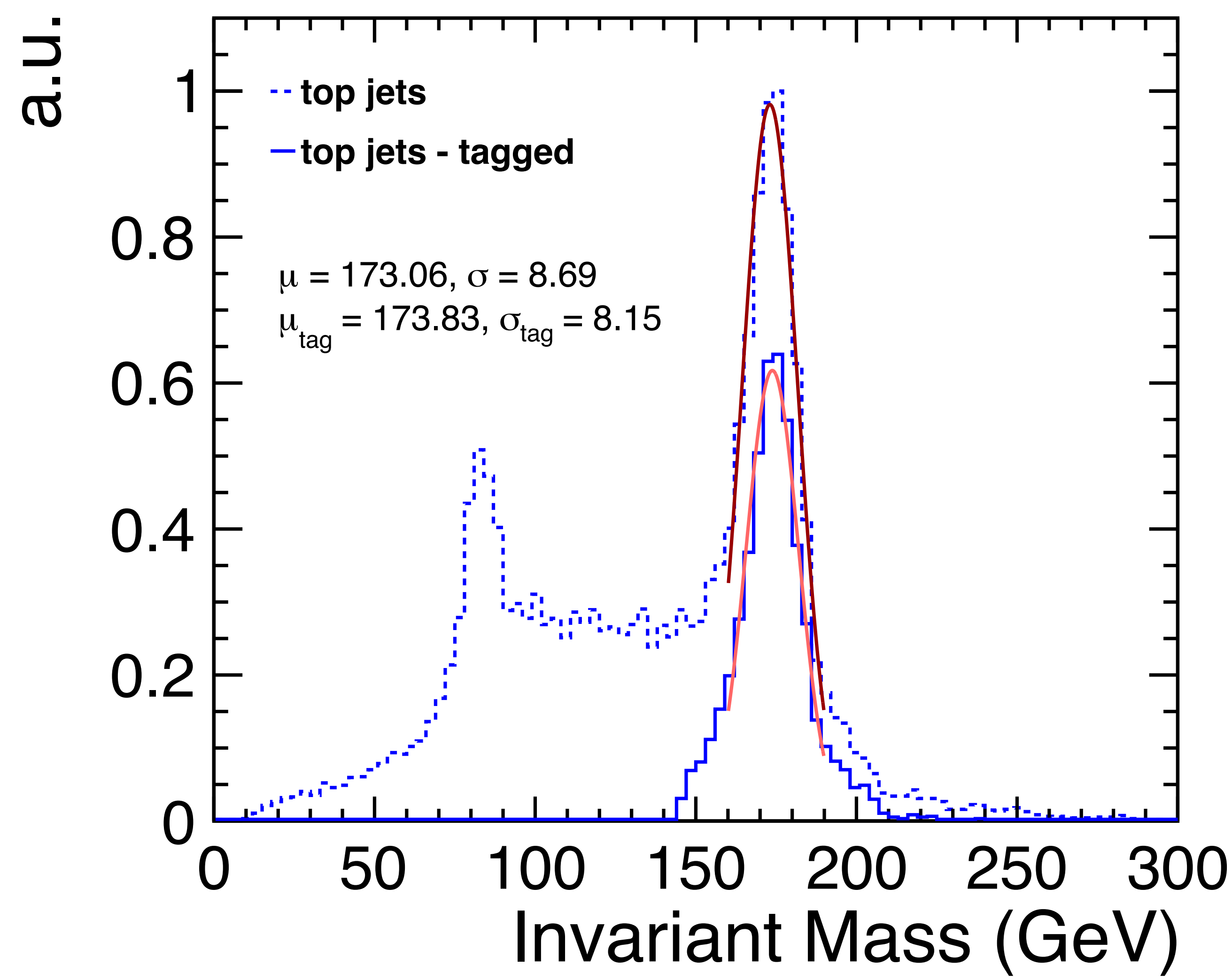
- Boosted events: Invariant mass > 1350 GeV
- At least two jets above 250 GeV
- And |η| < 2.5
- Default settings: R = 0.8, δ_p = 0.10, δ_r = 0.10
- Top tagger parameter optimisation (R, δ_p , $|\Delta\eta| + |\Delta\phi| < \delta_r$)

Top Tagging Results - Invariant Mass



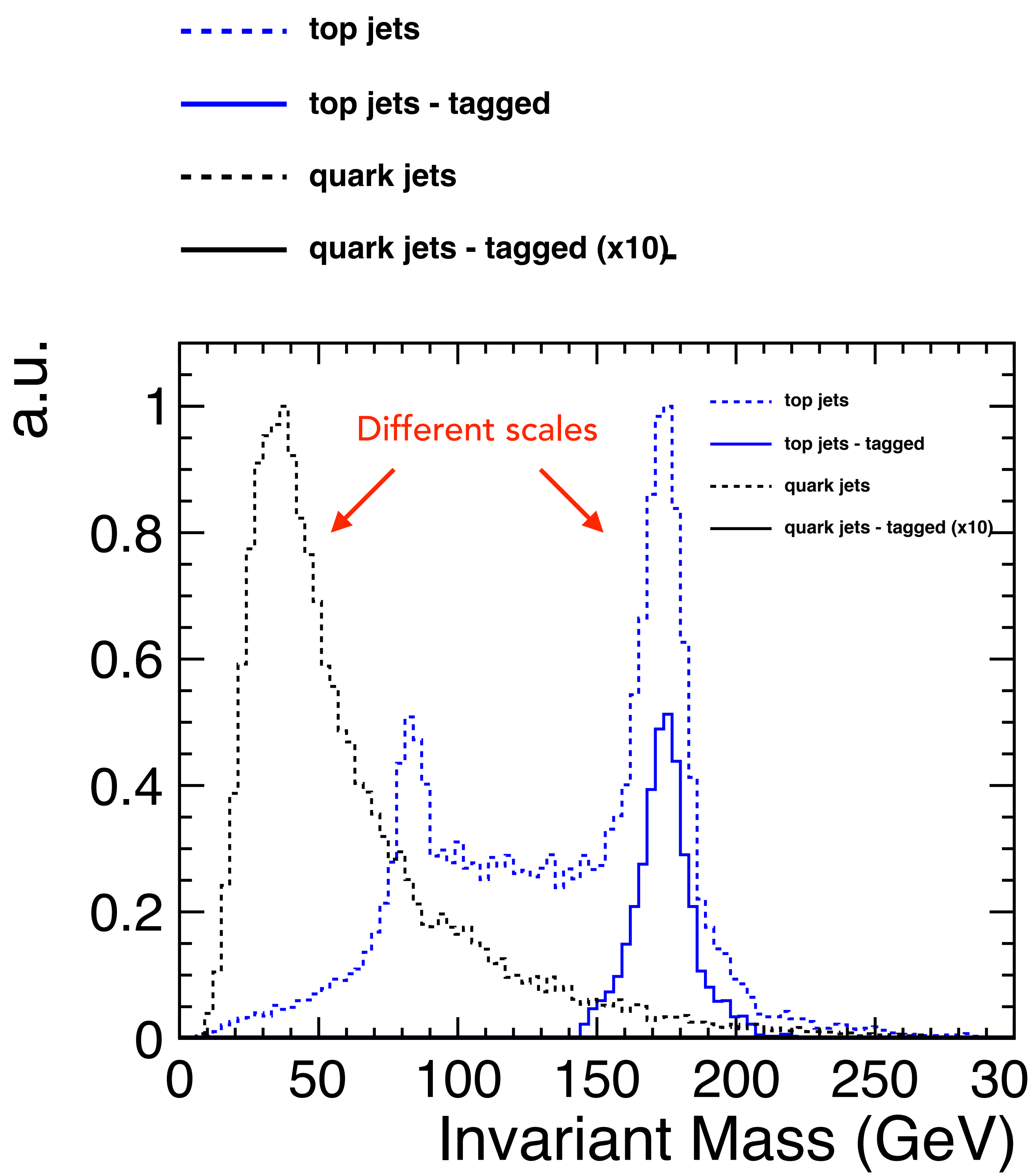
- w/o helicity cut
- Mass resolution in the order of 4.5%
- Optimisation pending

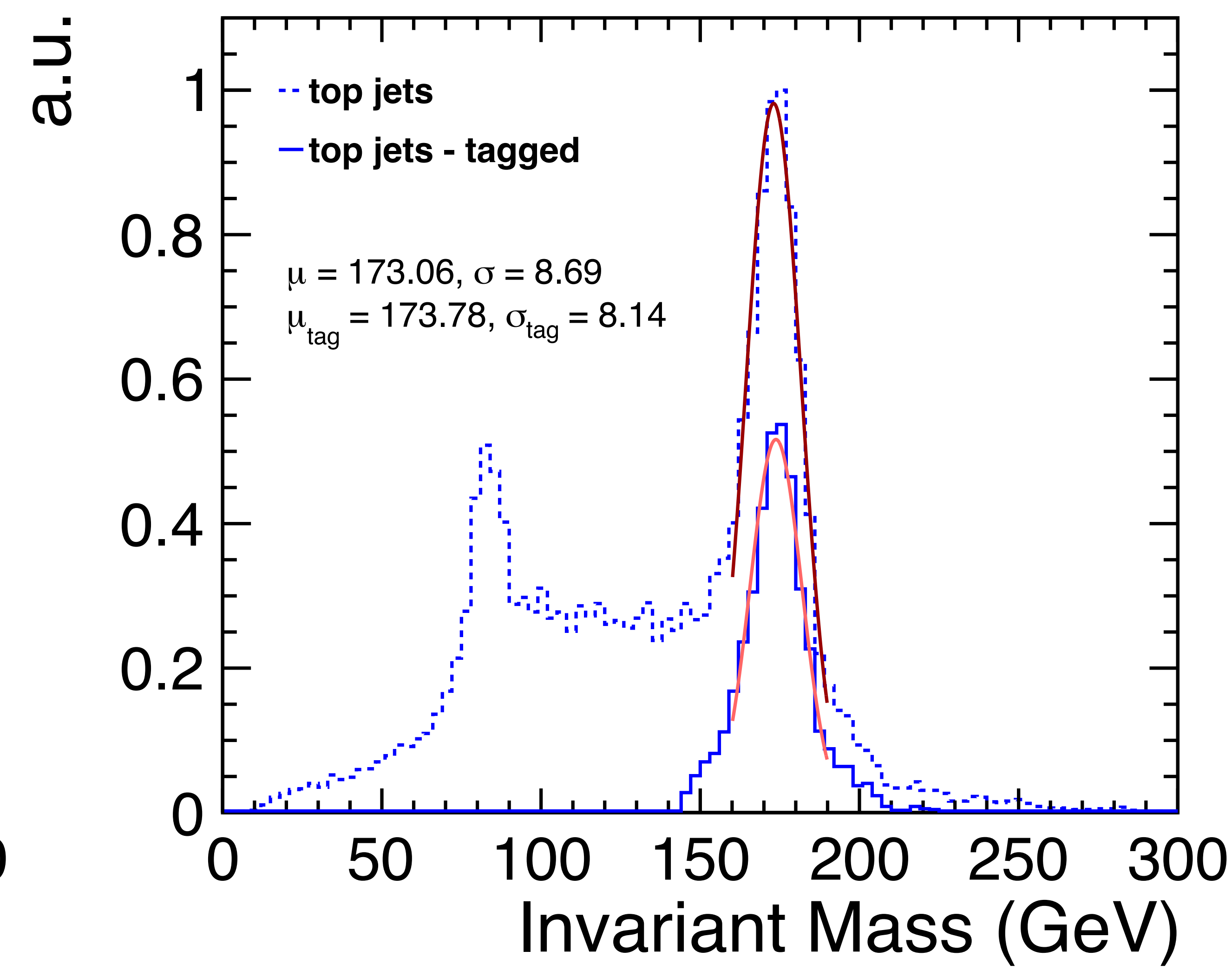




Top Tagging Results - Invariant Mass

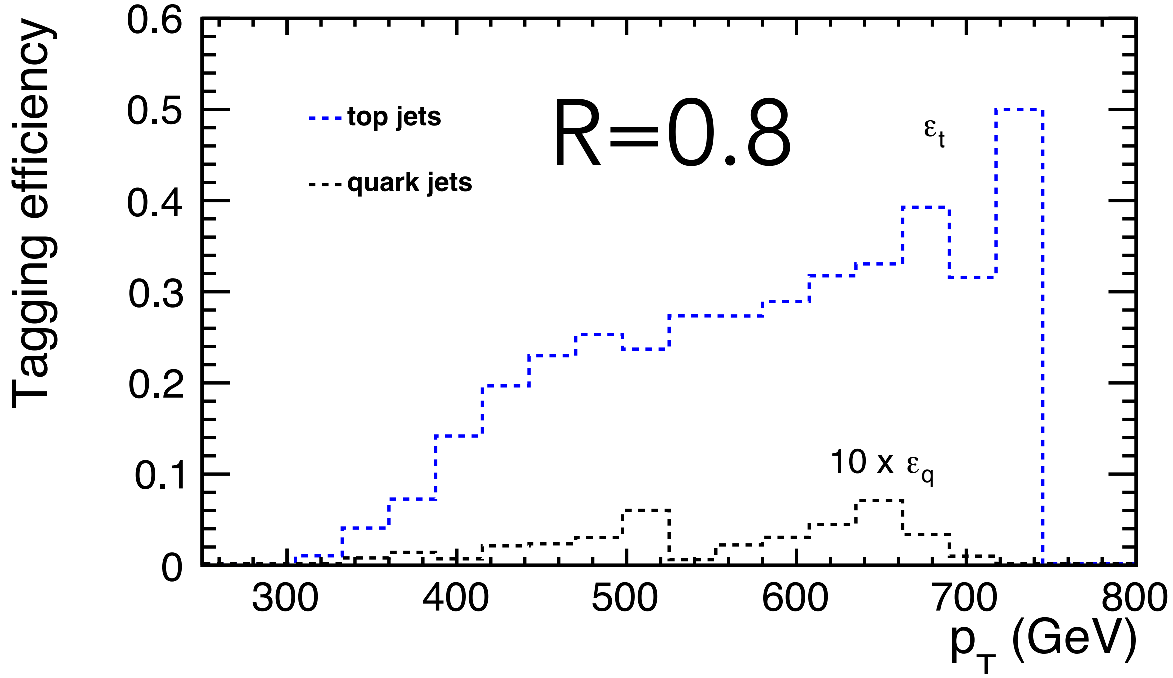
- w. helicity cut
- Mass resolution in the order of 4.5%
- Optimisation pending

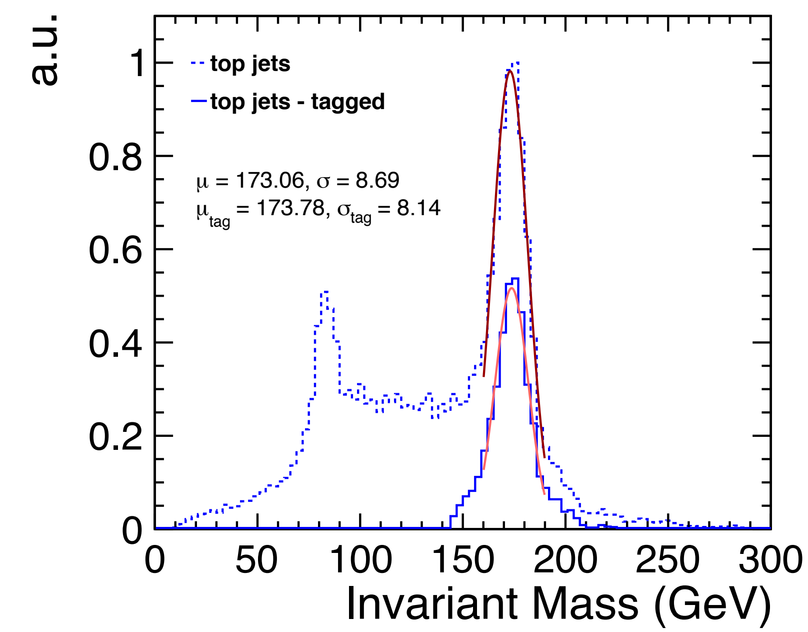


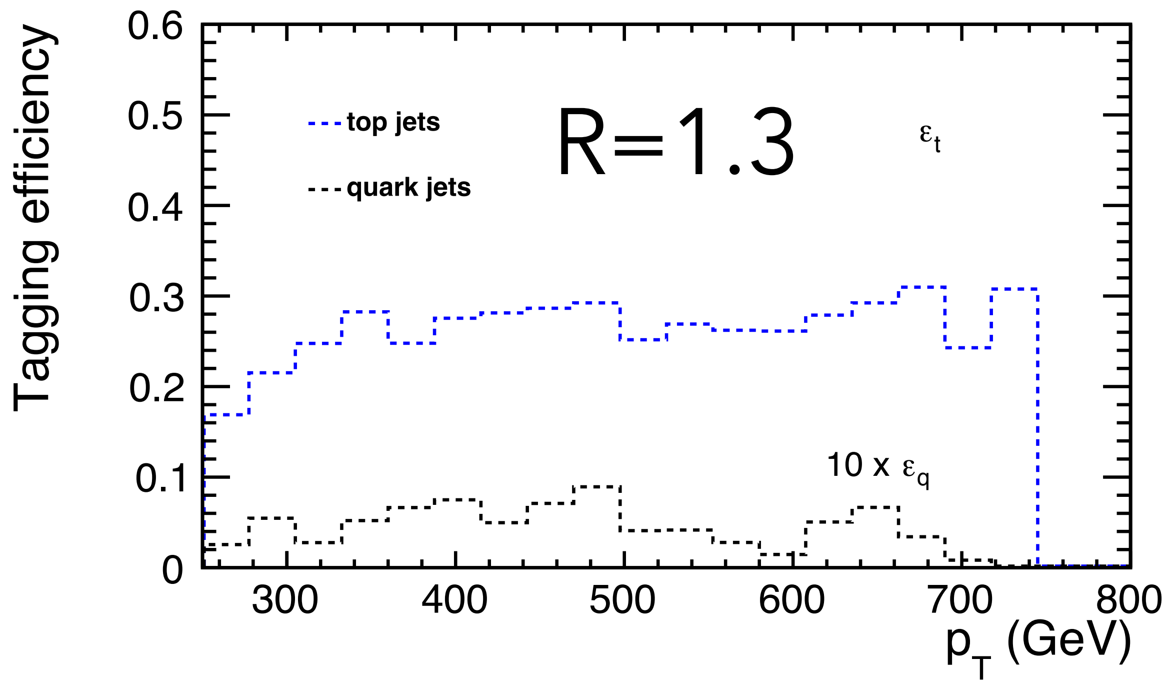


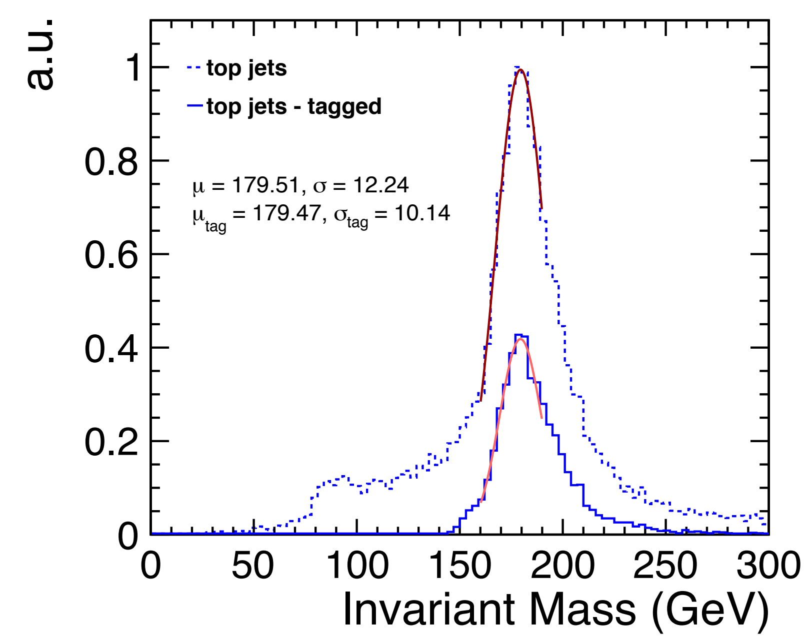
Top Tagging Results - Efficiency

Jet level efficiency



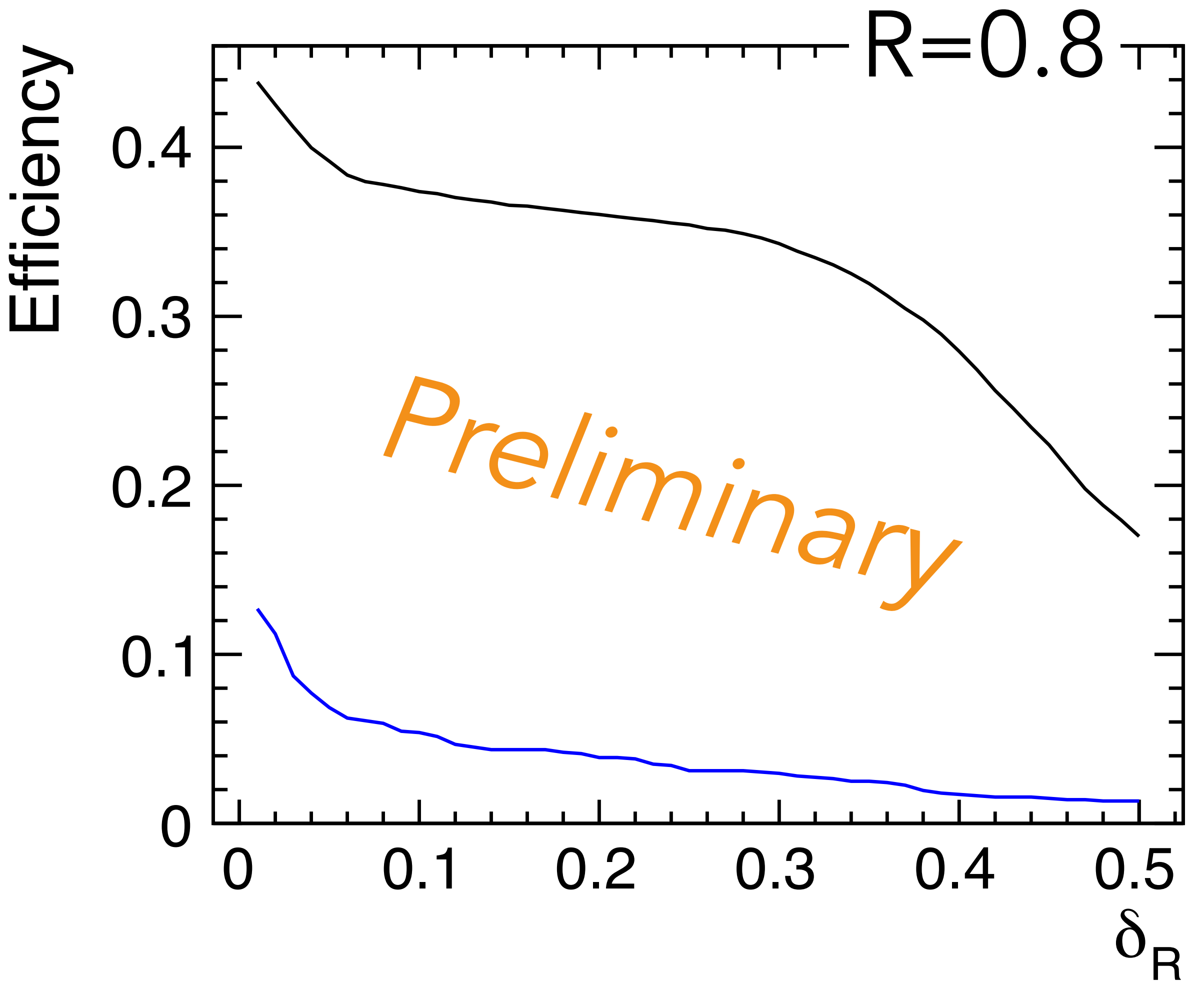


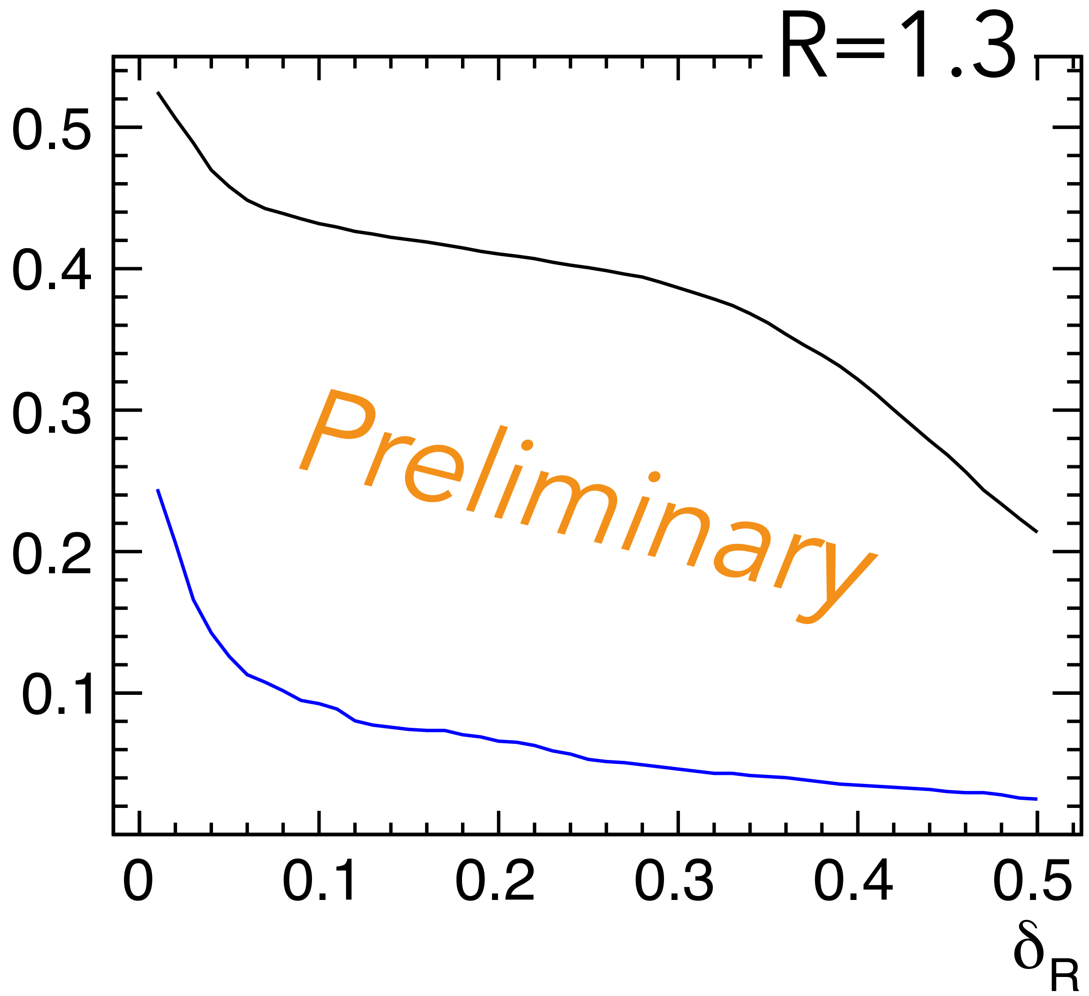




Top Tagging Results - Efficiency

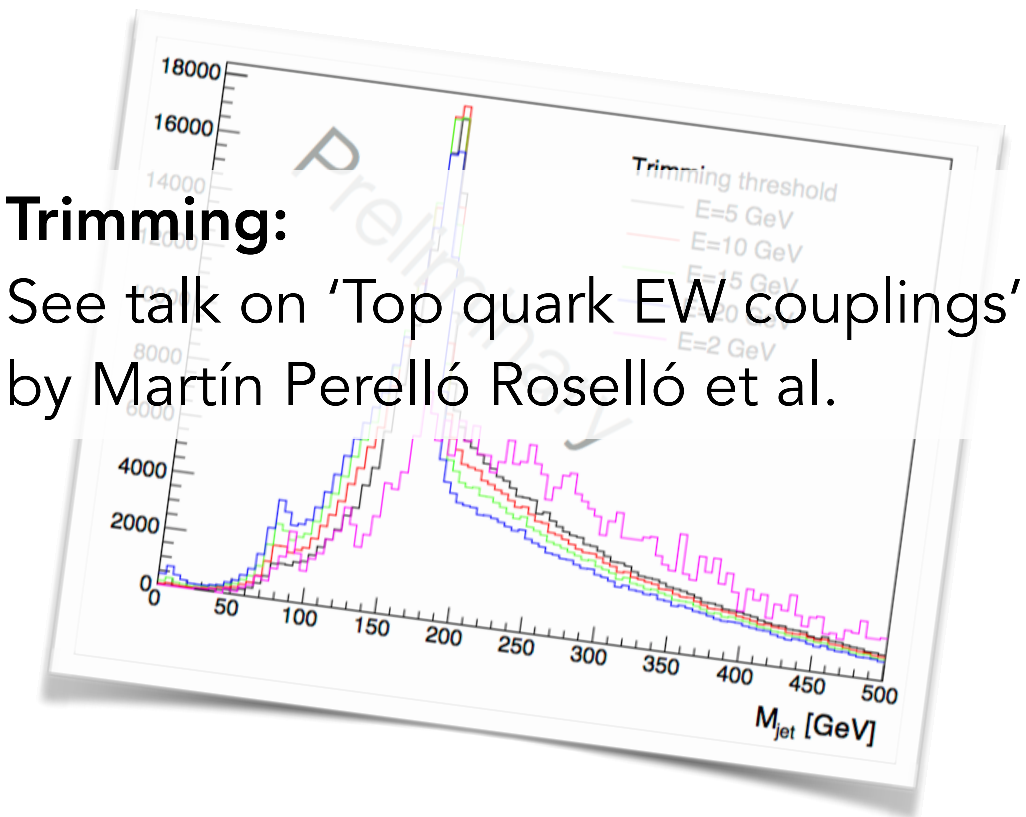
Event level efficiency - Optimisation pending





Summary and Conclusions

- Using CLIC-ILD, operating at 1.4 TeV
- Goal: Determining top quark couplings through measurement of cross-sections and forward-backward asymmetries for different polarisations
- New reconstruction techniques needed
    - Top tagging looks promising
    - Final optimisation pending
    - Incl. trimming (Ignacio Garcia, Martín Perelló Roselló, Marcel Vos)



Trimming:
See talk on ‘Top quark EW couplings’ by Martín Perelló Roselló et al.

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Backup Slides

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MC Samples

- **6 fermions final state samples:**
  - Fully hadronic - prod ID 6595, 6598, **6601**, 6604, 6607, 6610, 6613, 6616, 6619, 6622 (used for lepton isolation optimisation and top tagging optimisation), single top events cleaned out (~30 %)
  - Semi-Leptonic (electron) - prod ID **6589**+**6592** (used for lepton isolation optimisation)
  - Semi-Leptonic (muon) - prod ID **6634**+**6637** (used for lepton isolation optimisation)

- qq - prod ID **2091** (used for top tagging optimisation)

Signal sample (6-fermion production compatible with ttbar) at 1.4 TeV assuming P(e-) = -80%:

Type	ProdID	Events planned	Events produced	σ [fb]	Comments
ee -> yyveev	6586	15000	15600	7.91	
ee -> yyveyx	6589	50000	57600	31.9	NEW
ee -> yyxyev	6592	50000	61800	29.0	NEW
ee -> yyuyyc	6595	50000	50400	29.7	NEW
ee -> yycyyu	6598	50000	52200	29.7	NEW
ee -> dduyyu	6601	50000	76600	30.0	NEW
ee -> ssussu	6604	10000	11600	0.018	
ee -> ssubbu	6610	10000	11400	0.096	
ee -> bbubbu	6607	10000	12800	0.013	
ee -> ddcyyc	6613	10000	14400	1.82	
ee -> sscssc	6616	10000	11800	1.52	
ee -> sscbbc	6619	40000	58400	23.5	
ee -> bbcbbc	6622	10000	12000	0.013	
ee -> yyvelv	6625	20000	23800	10.8	
ee -> yyvlev	6628	20000	23600	9.82	
ee -> yyvllv	6631	30000	36400	15.6	
ee -> yyvlyx	6634	70000	91200	40.7	NEW
ee -> yyxylv	6637	70000	71800	40.7	NEW

https://twiki.cern.ch/twiki/bin/view/CLIC/MonteCarloSamplesForTopPhysics