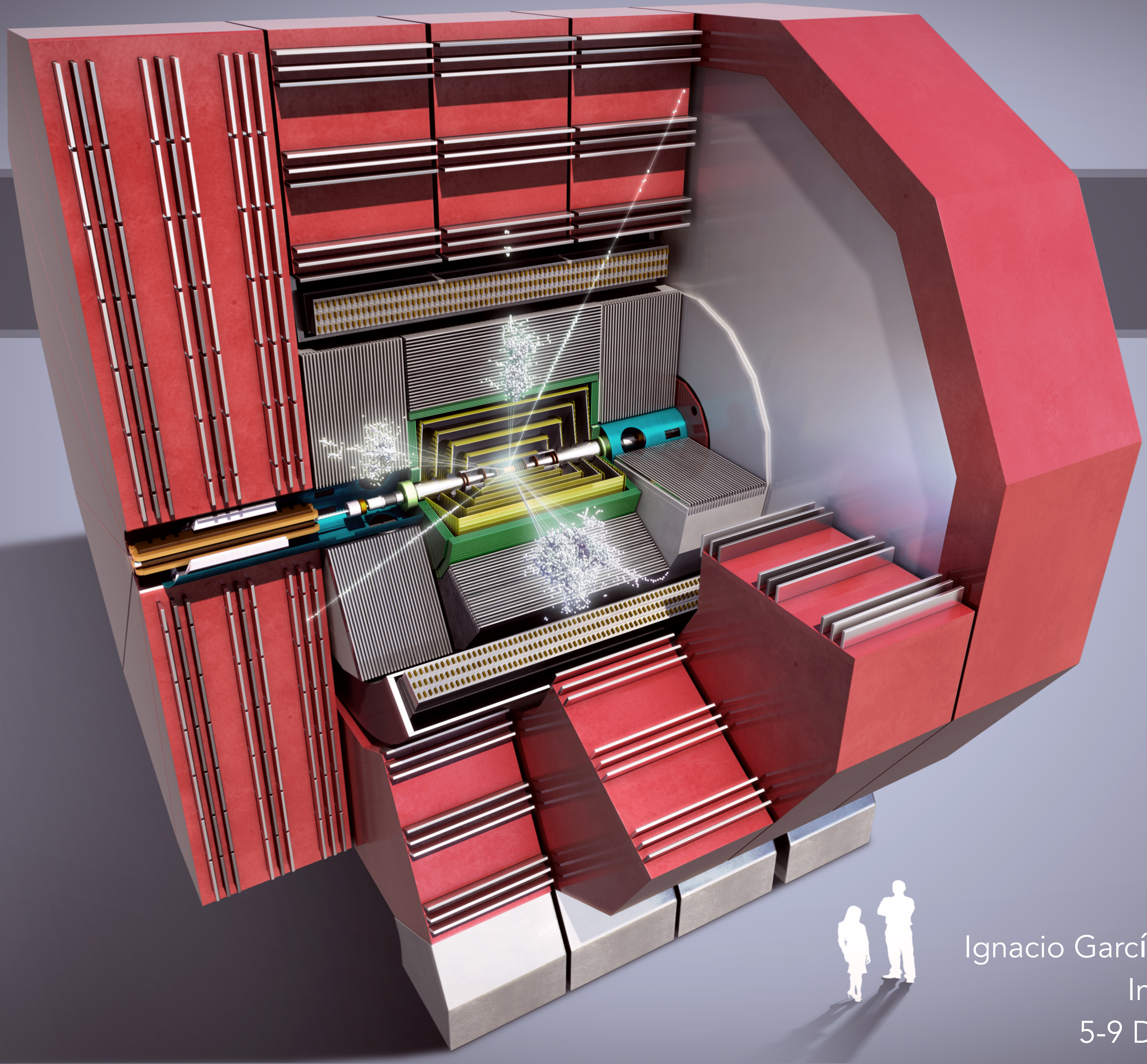

CLIC Detector

On behalf of the: CLICdp Collaboration:

Reconstruction of boosted top quarks at high-energy CLIC

Philipp Roloff and **Rickard Ström** (CERN)
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International Workshop on Future Linear Colliders
5-9 December 2016, MORIOKA CITY, IWATE, JAPAN

Outline

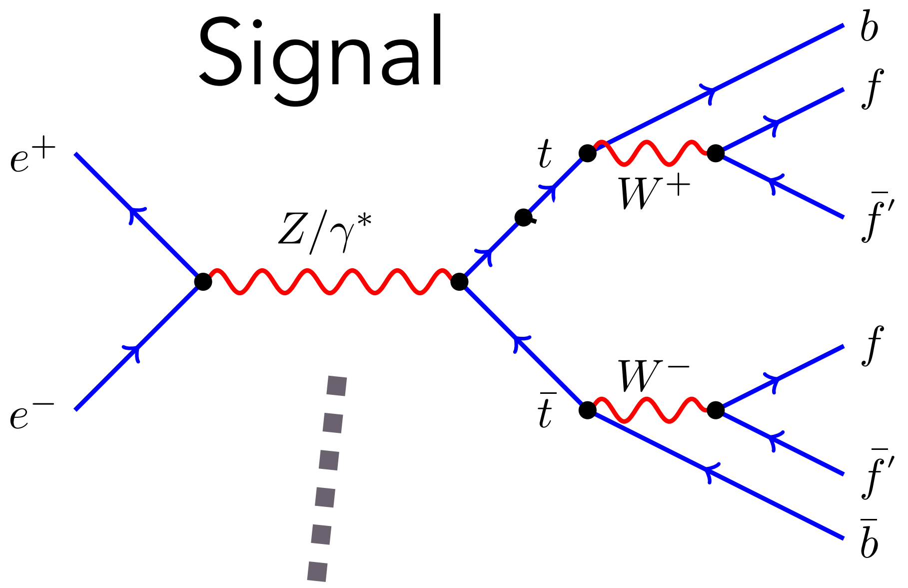
- Top physics at high-energy CLIC
- Forward-backward asymmetry
- Analysis strategy
- Top tagging
- Jet Trimming
- Top mass reconstruction
- Analysis
- Summary and Conclusion

Top Physics at High-Energy CLIC

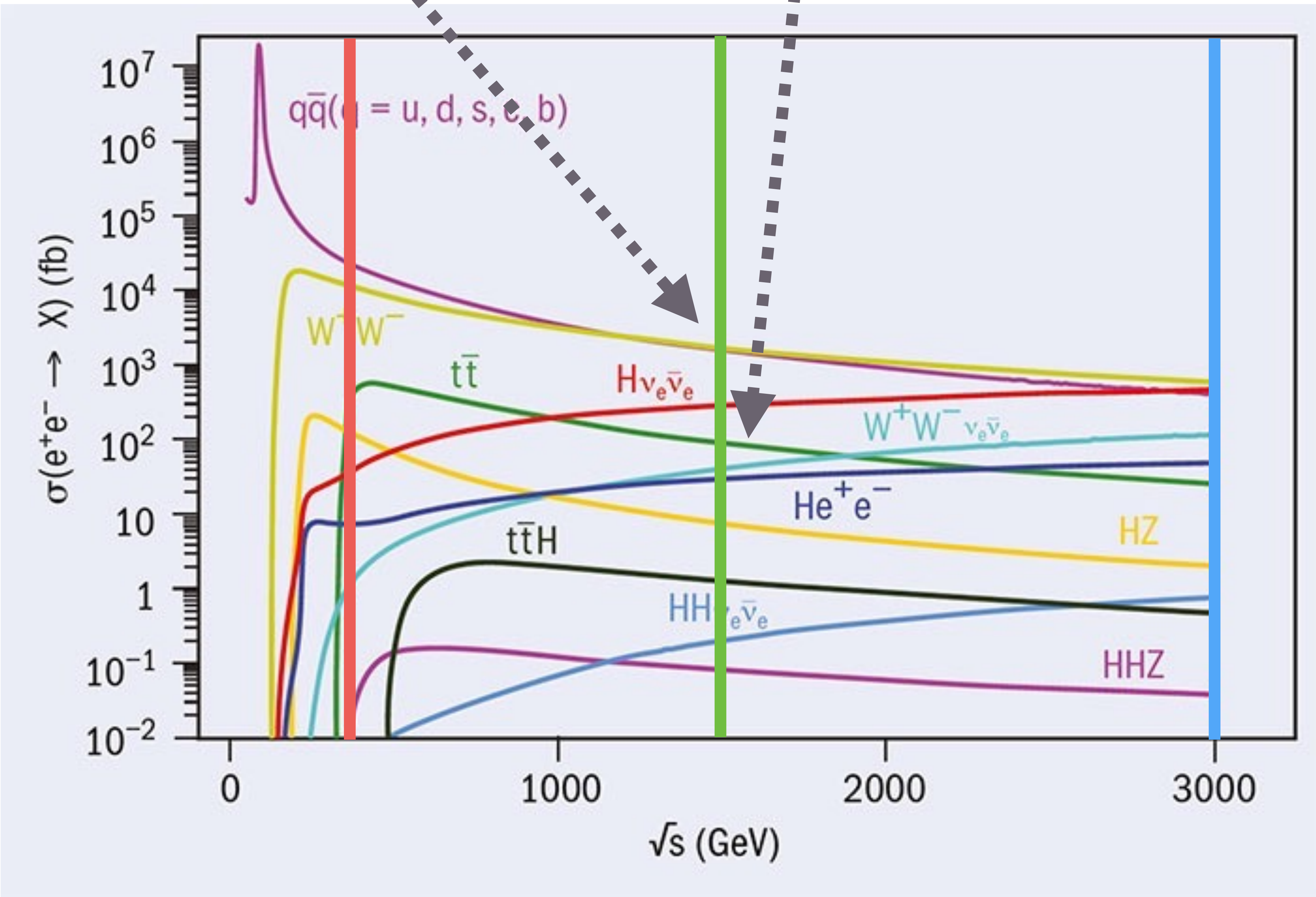
Backgrounds:

- qq, qqlv, qqqq, …

Signal



e^+e^- cross-section

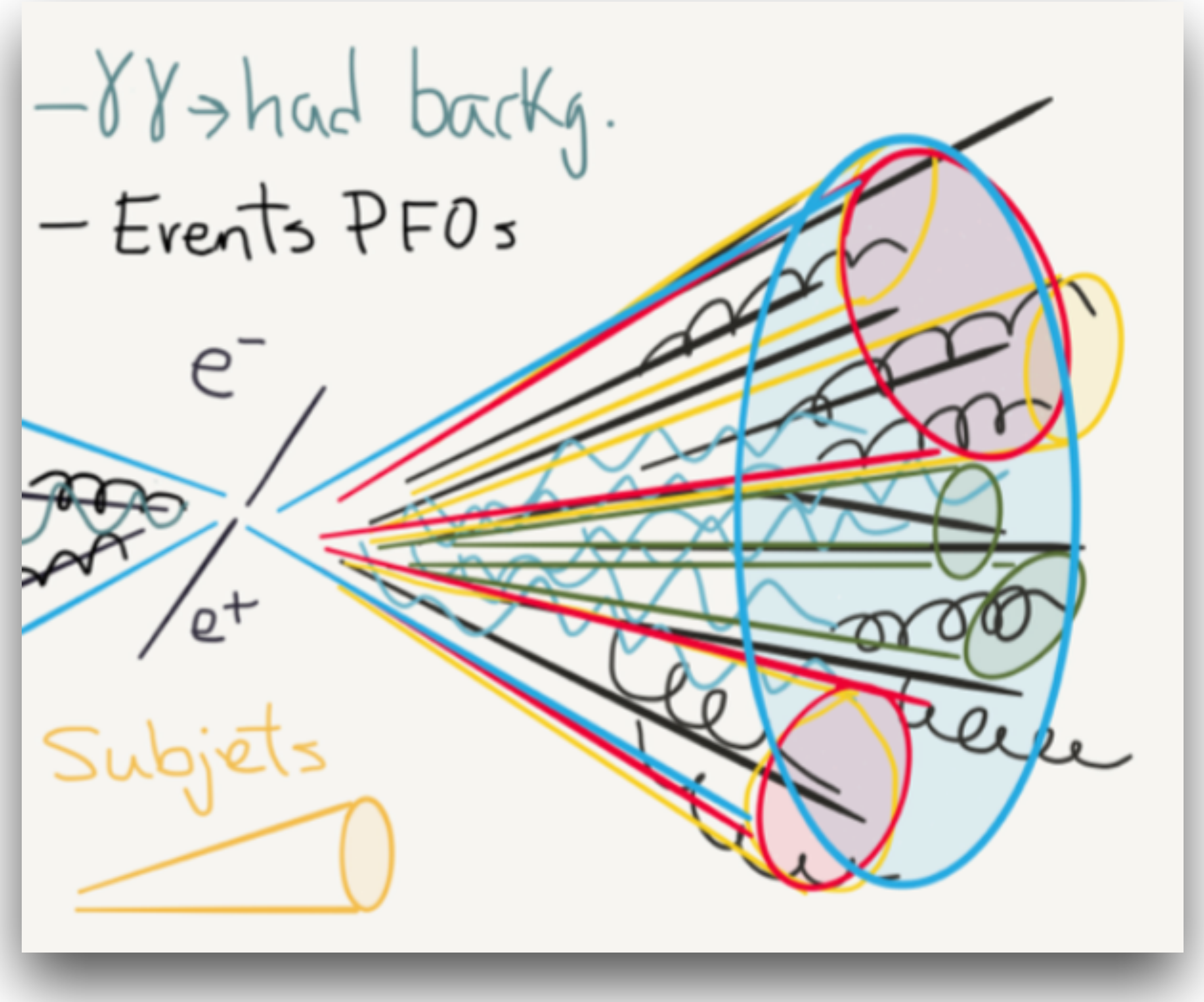


- To fully exploit physics case we need several energy stages going up to multi-TeV energies - defined by physics case w. considerations for technical constraints
- 380 GeV / 1.5 TeV / 3.0 TeV
- Incl. 100 fb^{-1} at 350 GeV for top mass threshold scan
- The top quark is of particular interest - couples strongly to the Higgs field, key to understanding EWSB and relation to SM gauge bosons
- Decays before hadronizing: the only naked quark - test ground for QCD - full advantage of the spin information
- Contributes via loops to processes that can be studied with high precision → Sensitive to BSM scenarios - may be first place a new particle shows up

Forward-Backward Asymmetry

- At high-energy CLIC operation, an increased boost leads to separation between the decay product of the two top quarks
- Benefit from software development at LHC dedicated to boosted events: reconstruction, tagging algorithms, etc.
- Top quark mass and the top quark couplings to Z and γ with high precision are among the main focuses of the initial stage of CLIC - plan to extend the top coupling study to high energy
- Determining top quark couplings through measurement of cross-sections and forward-backward asymmetries for different polarisations
- Sub-percent precision on anomalous electroweak couplings yields sensitivity to new physics at scales well beyond the direct reach
- Study of top quark couplings: form-factors or effective operators

Drawing by I. Garcia



See talk by M.Vos '*Top quark EW couplings*', LCWS2016, Tuesday 6 December 2016

Experimentally:

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

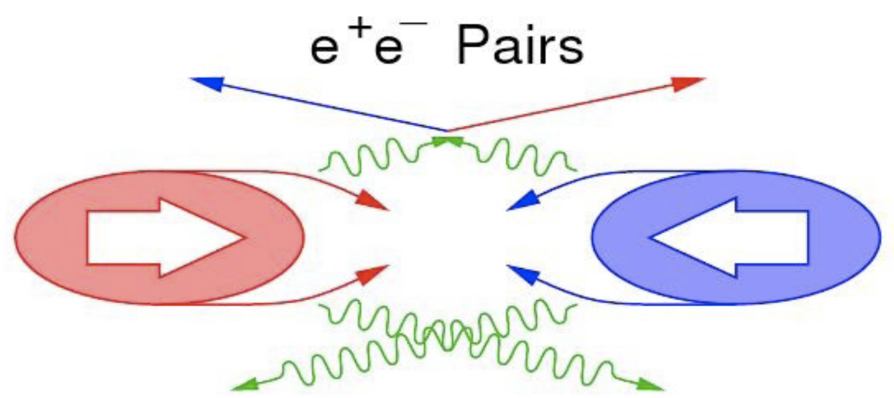
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

$$\Gamma^{t\bar{t}X}_{\mu}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu \left(\underline{F^X_{1V}}(k^2) + \gamma_5 \underline{F^X_{1A}}(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(i\underline{F^X_{2V}}(k^2) + \gamma_5 F^X_{2A}(k^2)\right)\right\}$$

CLIC Accelerator Environment

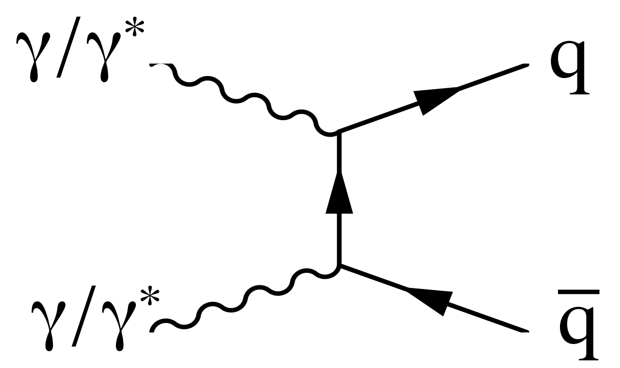
- The beam (and bunch) structure is rather distinct, with a bunch-to-bunch spacing of 0.5 ns
- Very small beam size at IP leads to very high EM-fields, i.e. interactions between colliding bunches, so-called Beamstrahlung

- Coherent e^+e^- pairs: 7 x 10^8 per BX, very forward
- Incoherent e^+e^- pairs: 3 x 10^5 per BX, rather forward, high occupancy, impact on detector design
- $\gamma\gamma \rightarrow$ hadrons: 3.2 events per BX at 3 TeV (1.3 at 1.4 TeV), main background in calorimeters and trackers, impact on physics
- Reduced to manageable level by combined p_T and timing cuts in the subdetectors

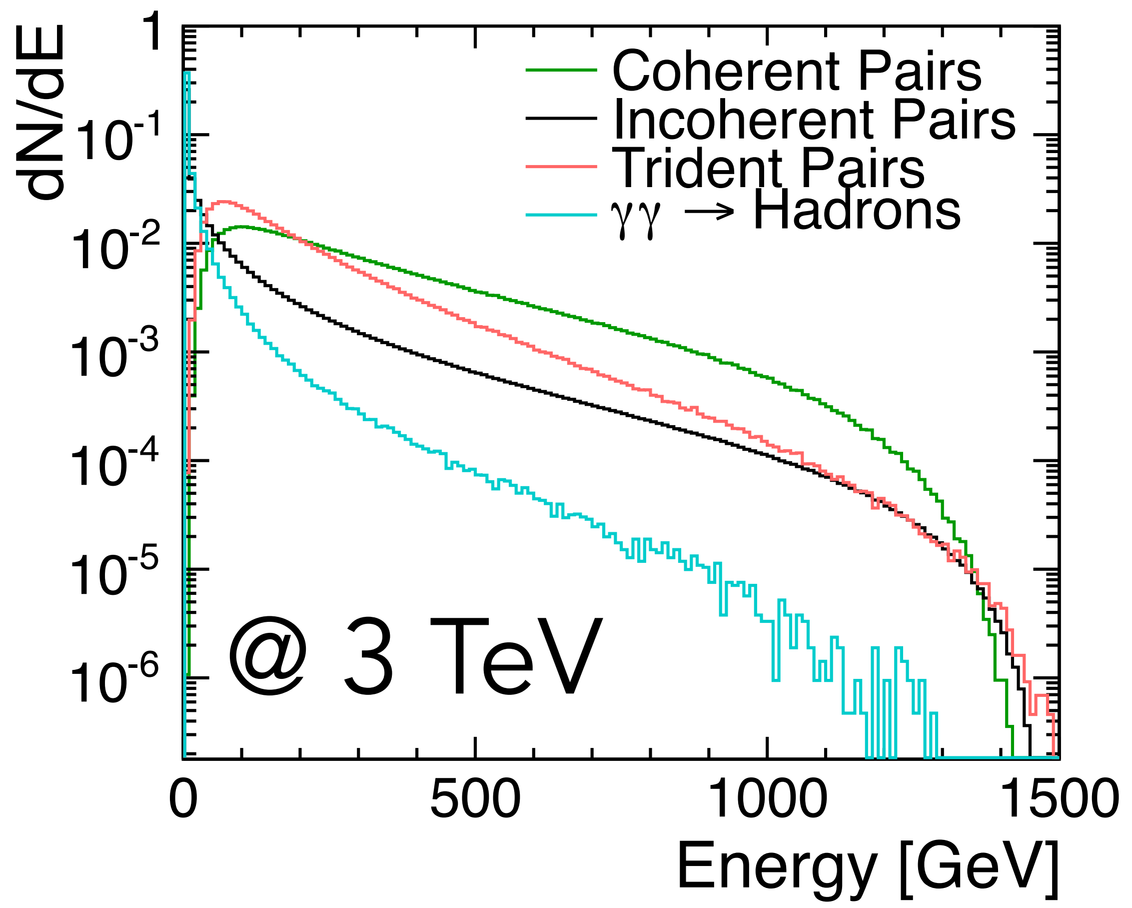


Beamstrahlung

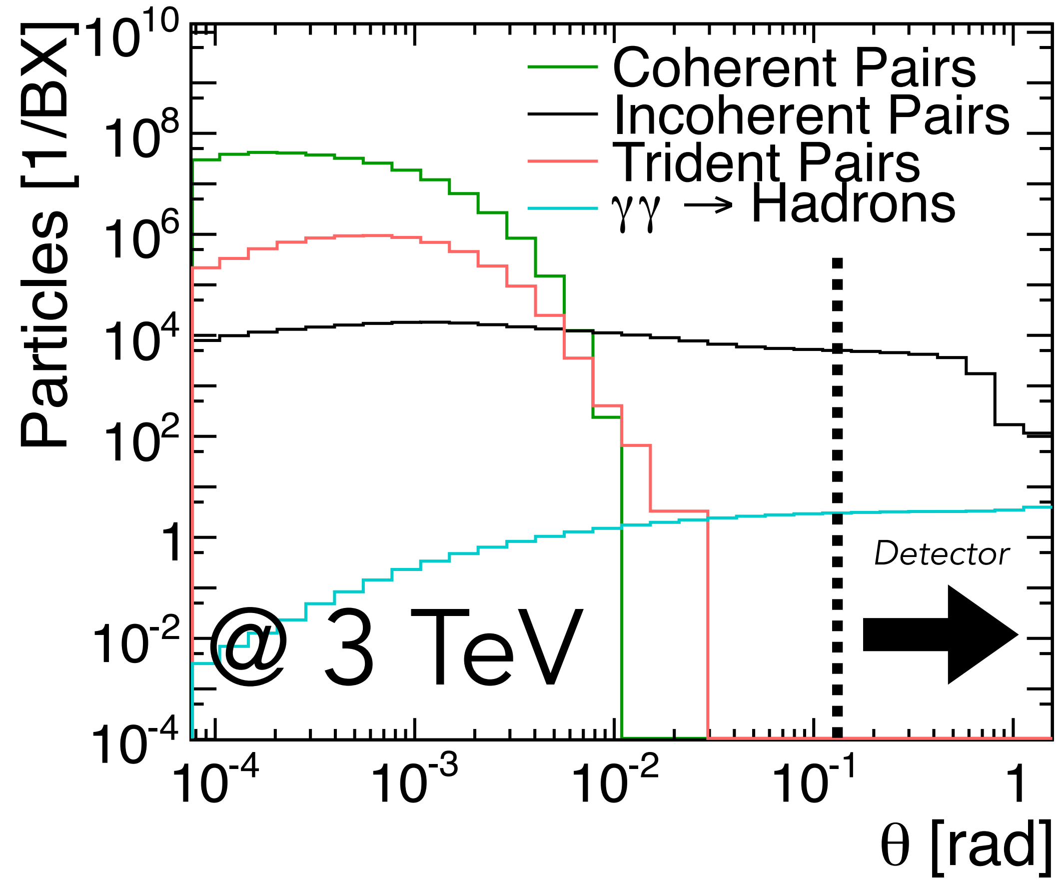
(synchrotron radiation)



Beam Background Energy



Beam Background Theta



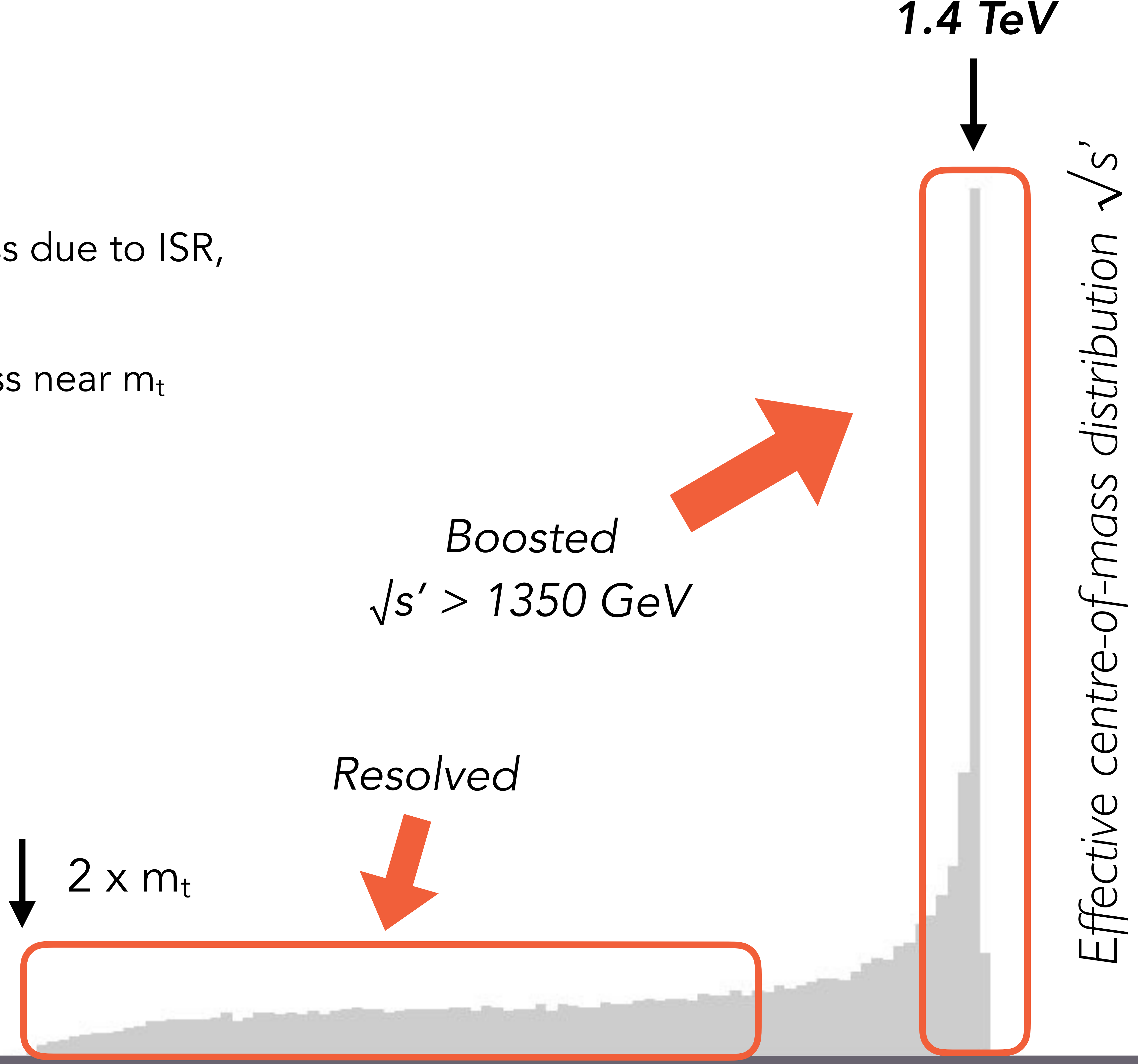
- Energy losses right at the interaction point leads to luminosity spectrum
- Most processes studied well above production threshold and profit from full luminosity
- E.g. full luminosity at 3 TeV: 5.9 x 10^{34} $cm^{-2}s^{-1}$ (1% most energetic 2.0 x 10^{34} $cm^{-2}s^{-1}$)

Analysis Strategy - 1.4 TeV

- Analysis concept studied at benchmark energy 1.4 TeV using the CLIC-ILD detector
- Using Default Selected Pandora PFO collection

- *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 products not isolated from each other or b-jet
  - Identify prongy structure that would be a signature of a top decay
  - Looking at $t \to W^{\pm}b$:
    - Fully hadronic decays $W^{\pm} \to qq$ (vertex charge challenging)
    - Semi-leptonic decays $W^{\pm} \to l\nu$



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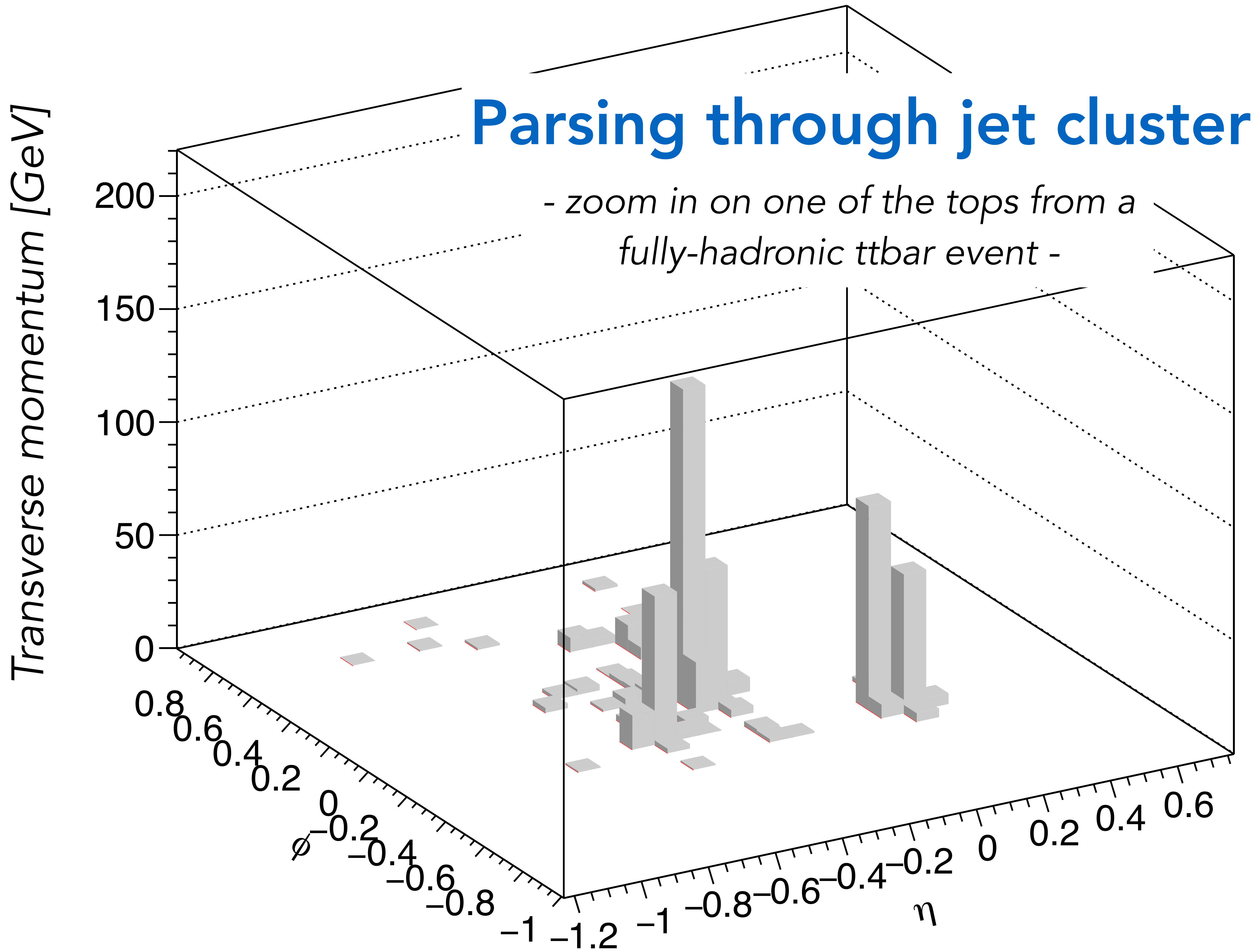
Top Tagging



Parsing through jet cluster

- zoom in on one of the tops from a fully-hadronic ttbar event -

- Top tagging is a powerful method to identity top quarks, in particular for boosted tops where the jet decay structure is complex (collimated collections of particles that look like single jets)
- Following the method from Kaplan et al.
  - **DOI: 10.1103/PhysRevLett.101.142001**
- First attempt at using a top tagging algorithm with CLIC
- Distinguish boosted top jets from light-quark and gluon jets using jet substructure:
  - Parsing jet cluster (Isolate events with three-four hard, nearby subjets)
  - Imposing kinematic constraints (exploit 3-body kinematics of top decay)

Top Tagging Algorithm

1) PFO objects are clustered into jets of size R (large jet) - any algorithm
   - Iteratively merge 4-vector pairs with closest $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ until $\Delta R < R$

2) Iteratively decluster each resulting jet (reversing each step in the jet clustering) to search for subjets
   - Split into two parts, reject softest if .... $\frac{p_T^{\mathrm{subjet}}}{p_T^{\mathrm{jet}}} < \delta_p$
   - Declustering <u>continues on the harder</u> object until:

Both subjets are harder than $p_T^{\mathrm{jet}} \cdot \delta_p$ ✓

Both subjets are too close $|\Delta\eta| + |\Delta\phi| < \delta_r$ ✗

Both subjets are softer than $p_T^{\mathrm{jet}} \cdot \delta_p$ ✗

3) If an original jet declusters into two subjets - step 2 is repeated on those subjets
   - Results in 1 (original jet), 2, 3, or 4 (additional soft gluon emission) subjets

1 ✗ →
2 ✗ →
3 ✓
4 ✓

Recover by other means?

4) Additional kinematic cuts

✗ = irreducible

Kinematic Cuts

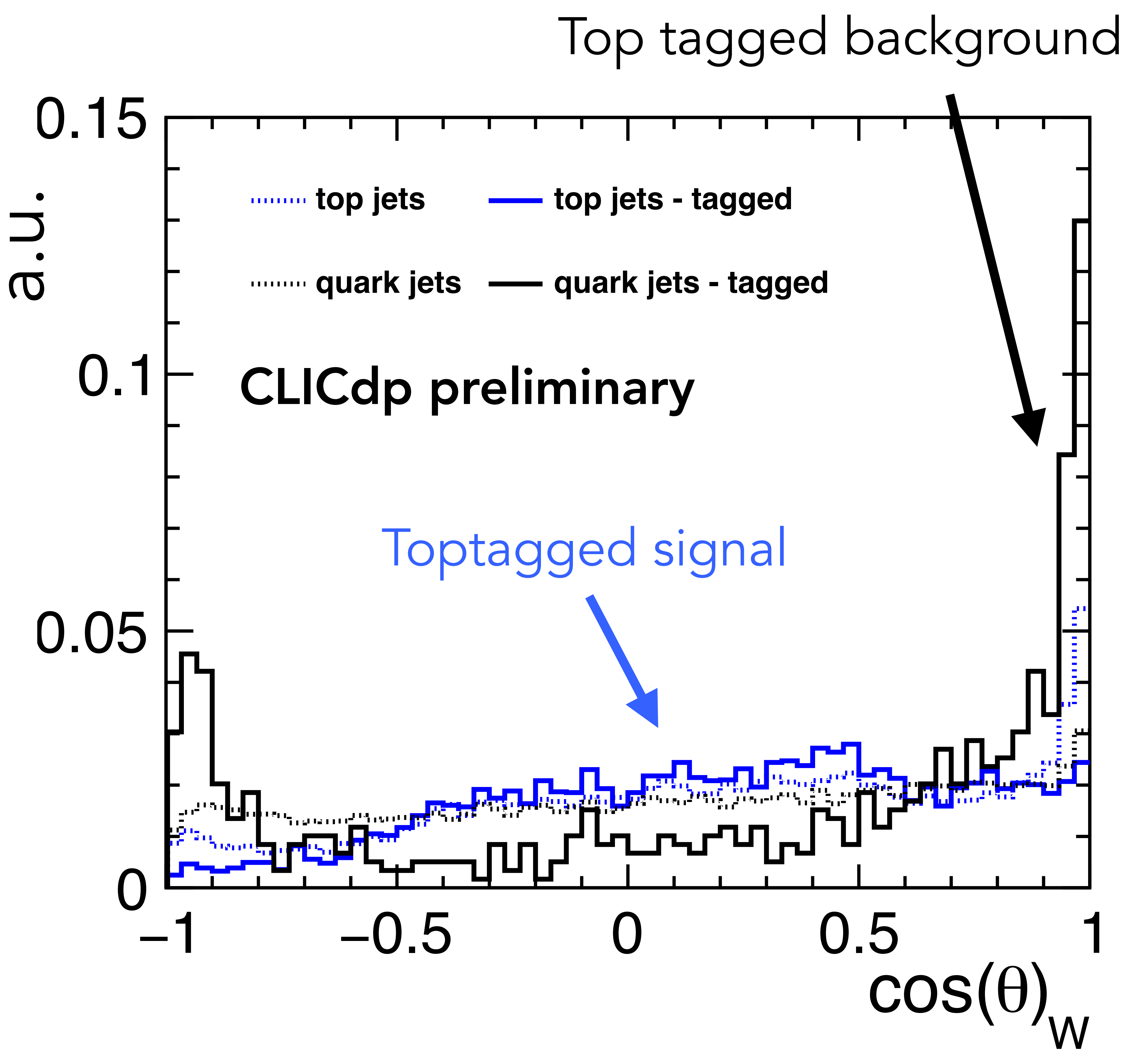
Purpose: make sure the resulting subjets are consistent with top mass, and that 2 are consistent with W mass

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, angle < 0.7

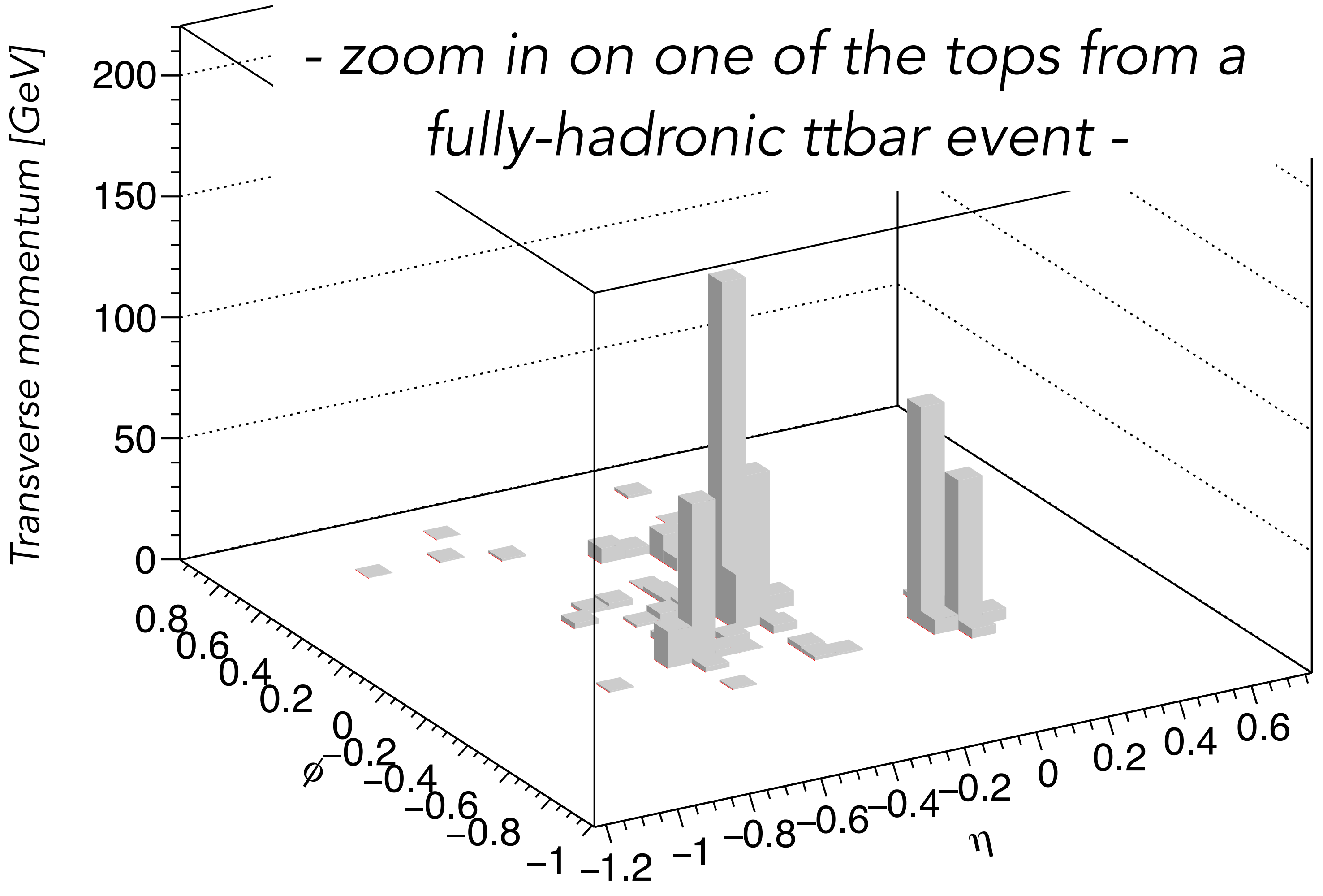
General:

- Boosted events: Effective centre-of-mass > 1350 GeV
- $|\eta| < 2.5$
- Top tagger parameter optimisation (R, δ_p , $|\Delta\eta| + |\Delta\phi| < \delta_r$)



Top Tagging Efficiency

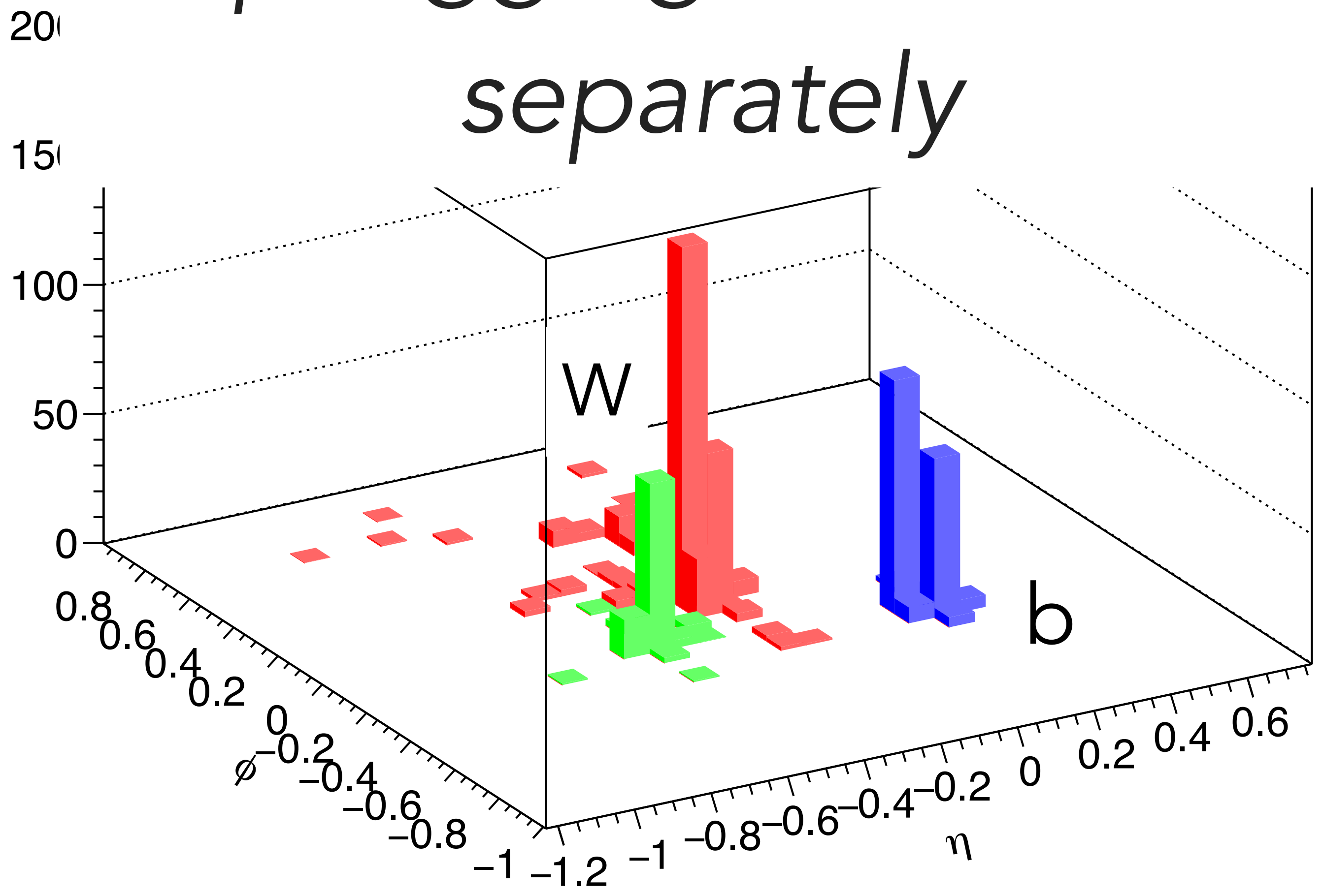
Parsing through jet cluster



- zoom in on one of the tops from a fully-hadronic ttbar event -

Top Tagging

The three subjets after top tagging are shaded separately



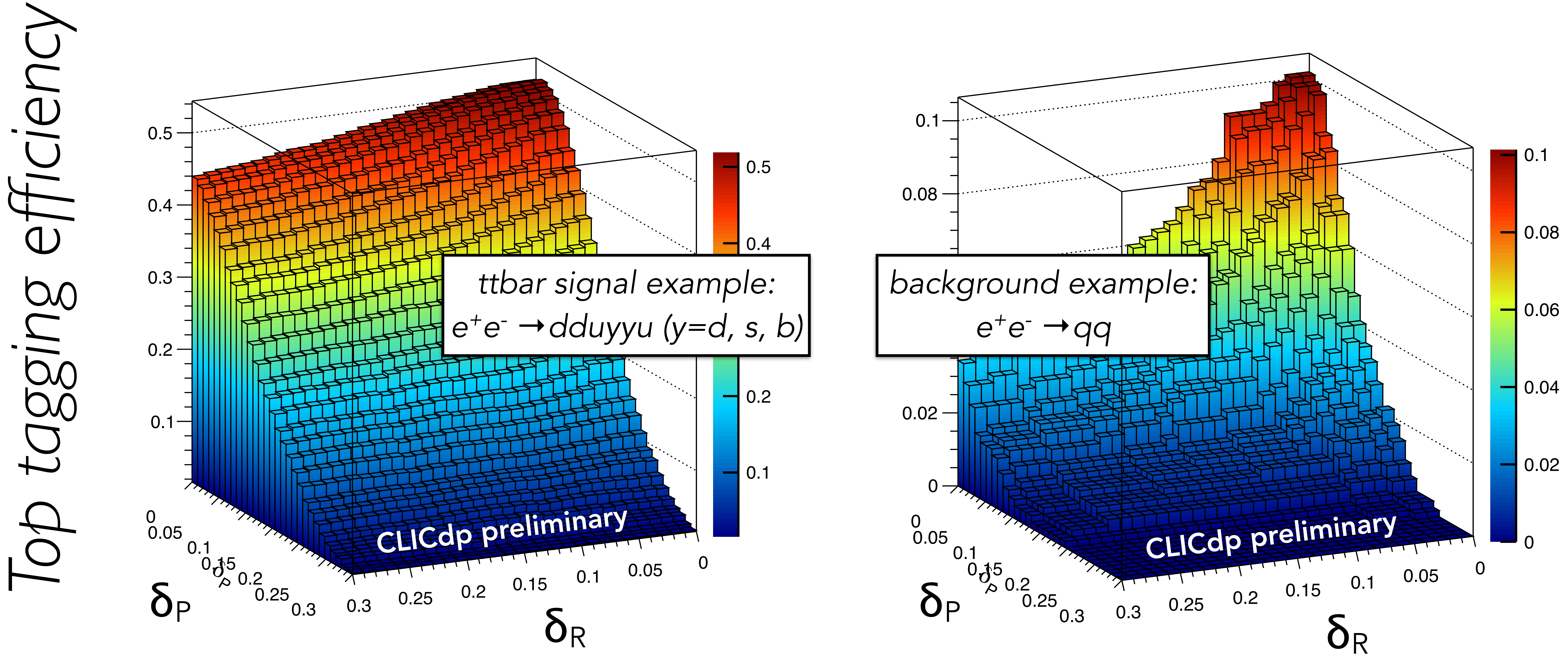
✔

CLICdp preliminary

	Top tagging efficiencies				"Easy" = Simple mass cut				Top mass reconstruction			
									Mass From Jet Reco		Mass From Tagging	
	Tagging Events Eff. (%)	Tagging Jets Eff. (%)	qq back. Events Eff. (%)	qq back. Jets Eff. (%)	Tagging Ev. Eff. Easy (%)	Tagg. Jets Eff. Easy (%)	qq back. Ev. Eff. Easy (%)	qq back. Jets Eff. Easy (%)	Mean (GeV)	Sigma (GeV)	Mean (GeV)	Sigma (GeV)
VLC R=1.5 beta=1 gamma=1	50.2	29.7	4	1.7	85.9	63.3	20.1	10.5	181.2	12.1	180.9	11.7
long. inv. kt R=1	52.6	31.2	2.6	1.2	86.3	63.6	13.3	6.9	182.8	12	182.5	11.8
Cambridge R=1 (2 most energetic jets)	56	33.7	1	0.5	88.9	67.7	11.4	5.9	176.1	9.5	171.4	7.8
VLC R=1 beta=1 gamma=1	56.6	34.2	2.2	1	87.9	66.1	12	6.2	177.5	10.2	177.5	9.9

Top Tagging Efficiency

VLC jet clustering algorithm (R=1.5, β=1, γ=1)



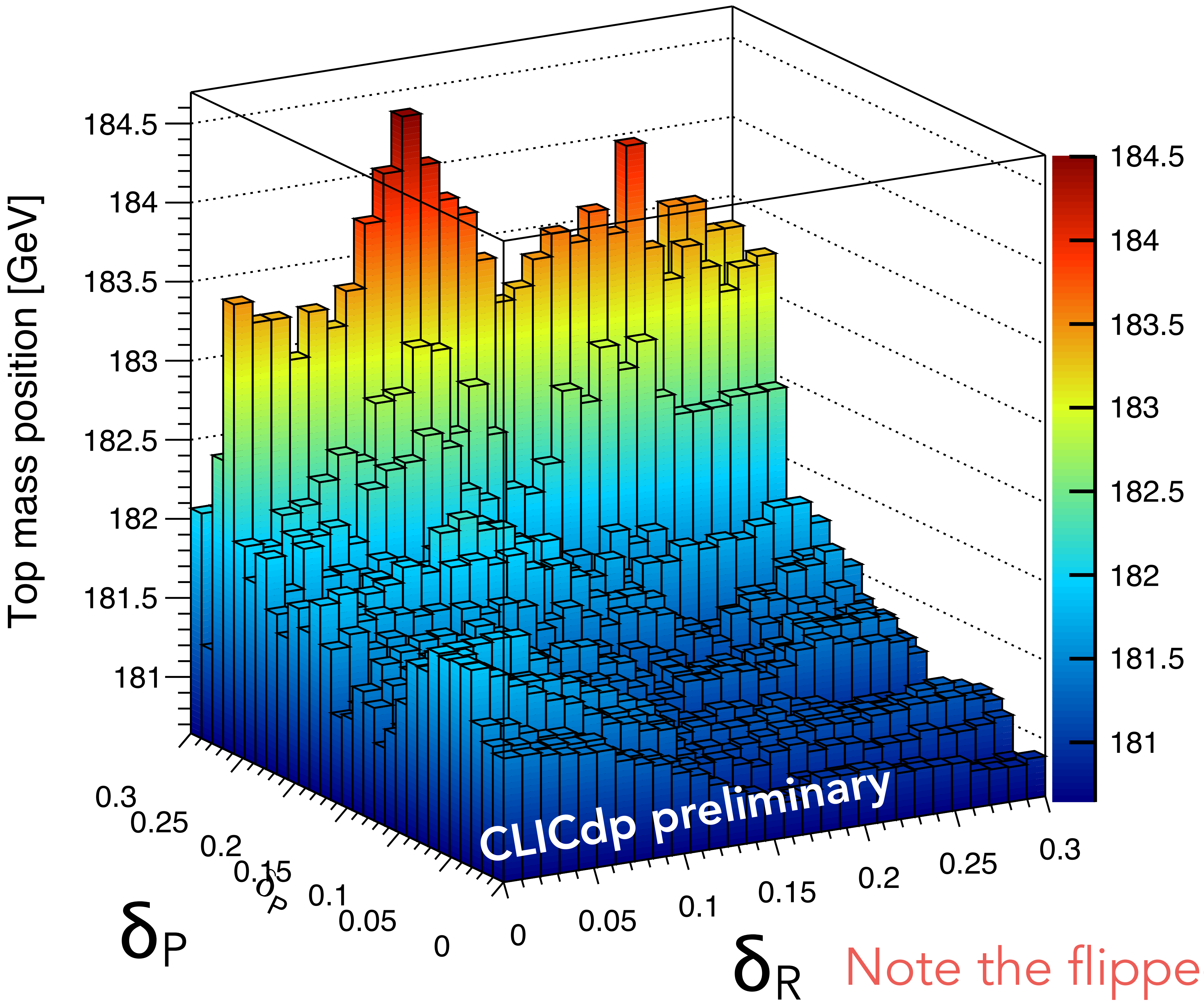
ttbar signal example:
$e^+e^- \rightarrow$ dduyyu (y=d, s, b)

background example:
$e^+e^- \rightarrow$ qq

Reconstruction after Top Tagging

Top reconstruction

VLC jet clustering algorithm (R=1.5, β=1, γ=1)



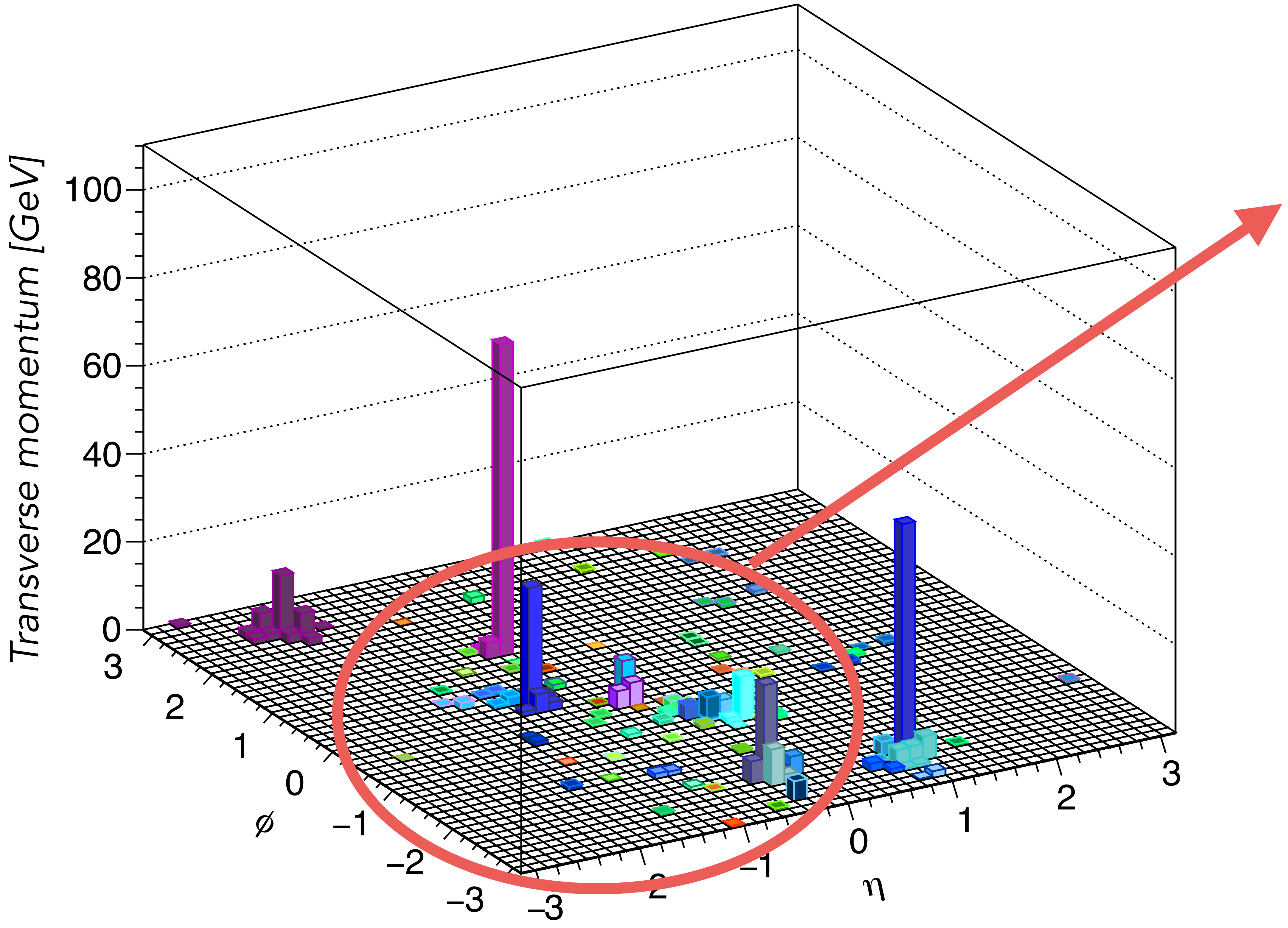
Note the flipped axis!

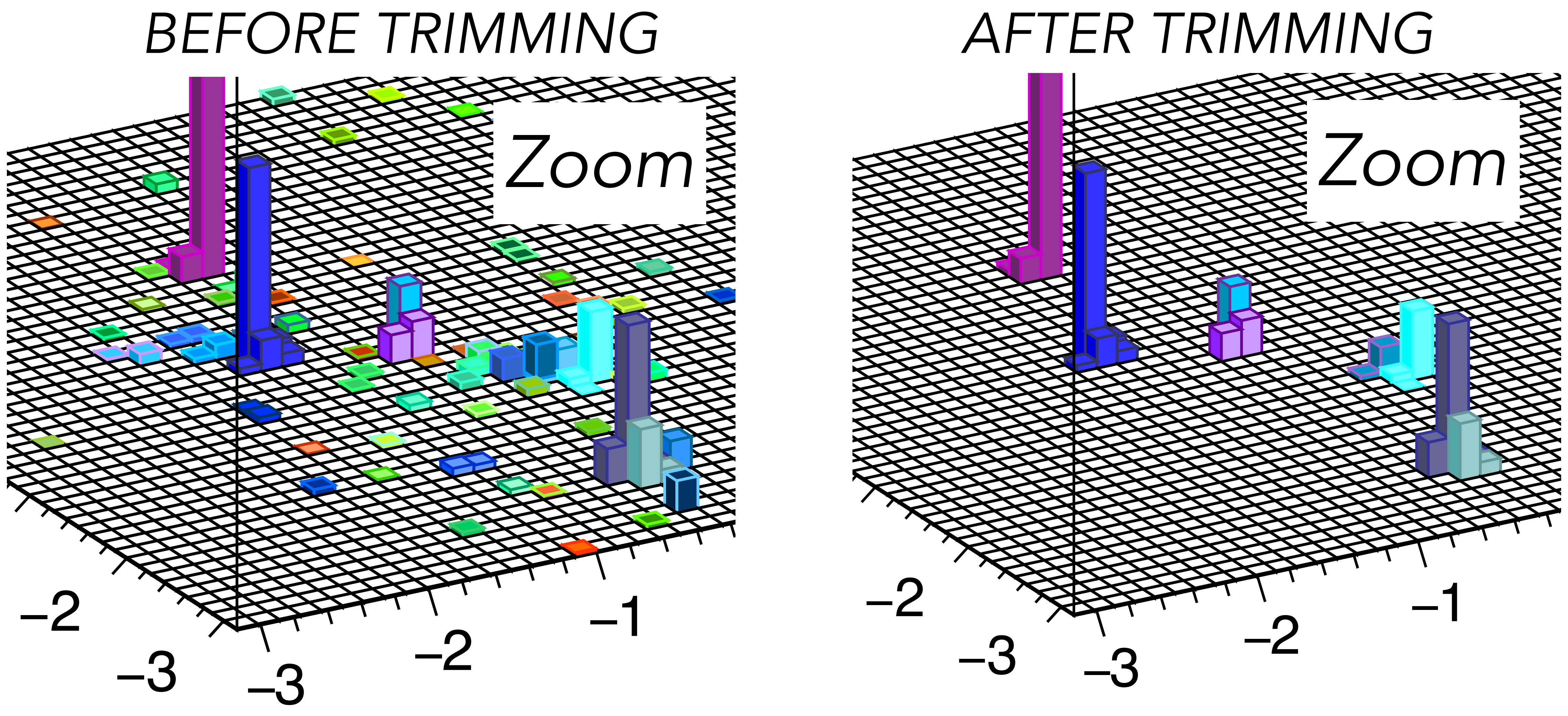
Reconstructed top mass position:

- Each point represents a gaussian fit to the reconstructed top mass (independent of the number of events)
- Using default (Selected) PFO collection gives a too high value of the top mass, can be overcome by by using tighter PFO selection or so-called jet trimming (next slide)

Jet Trimming

Full phi-eta space
fully-hadronic ttbar event





- Trimming of the jets is an alternative/complementary way to reduce the impact from the beamstrahlung background
- Pre-clustering into so-called microjets
- Inclusive pre-clustering of PFO objects into microjets
- Algorithm used: ee generalised kt
- Optimisation of:
  - Microjet energy threshold E_{th}
  - Jet radius R_{micro}

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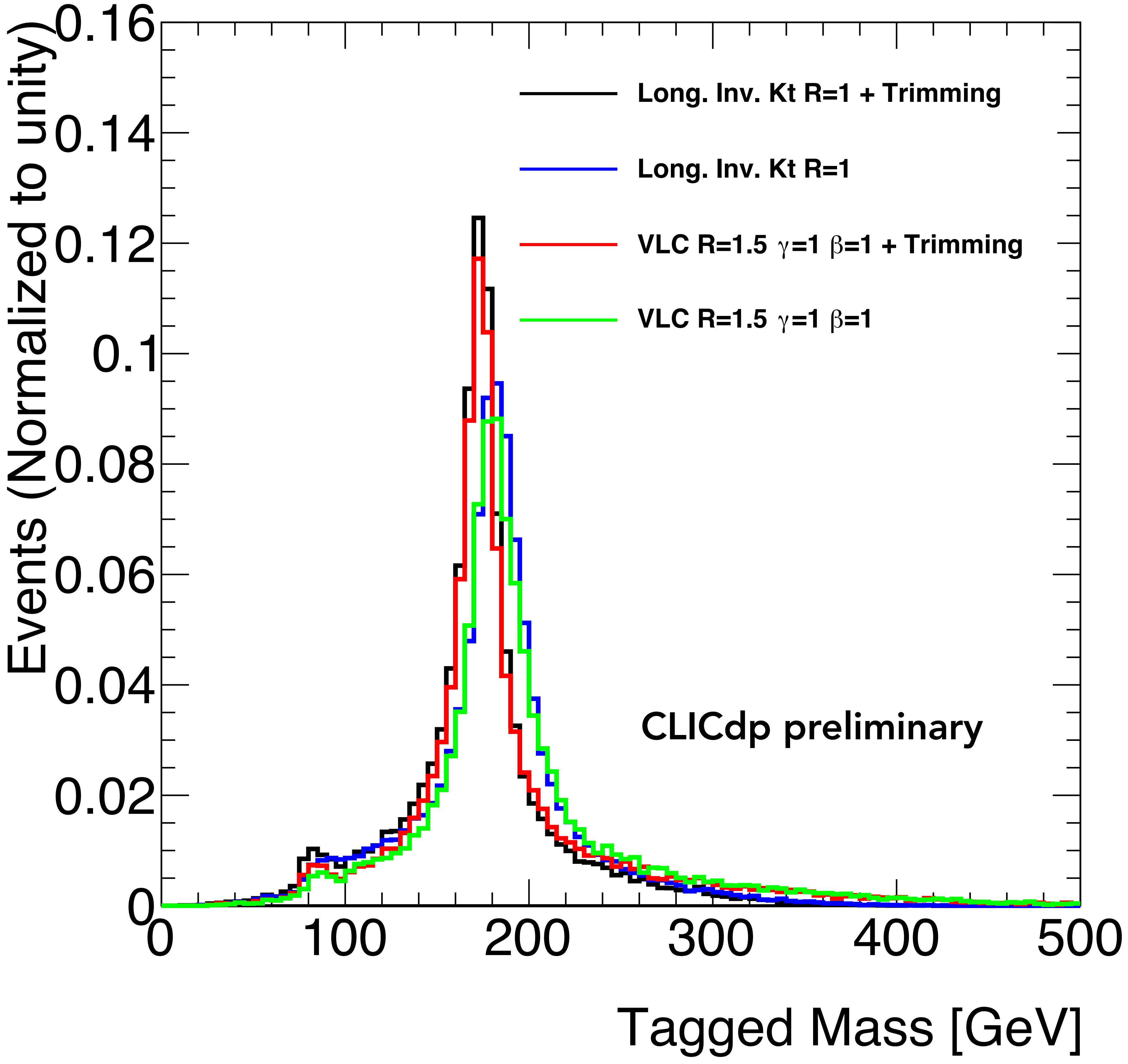
Jet Trimming Results



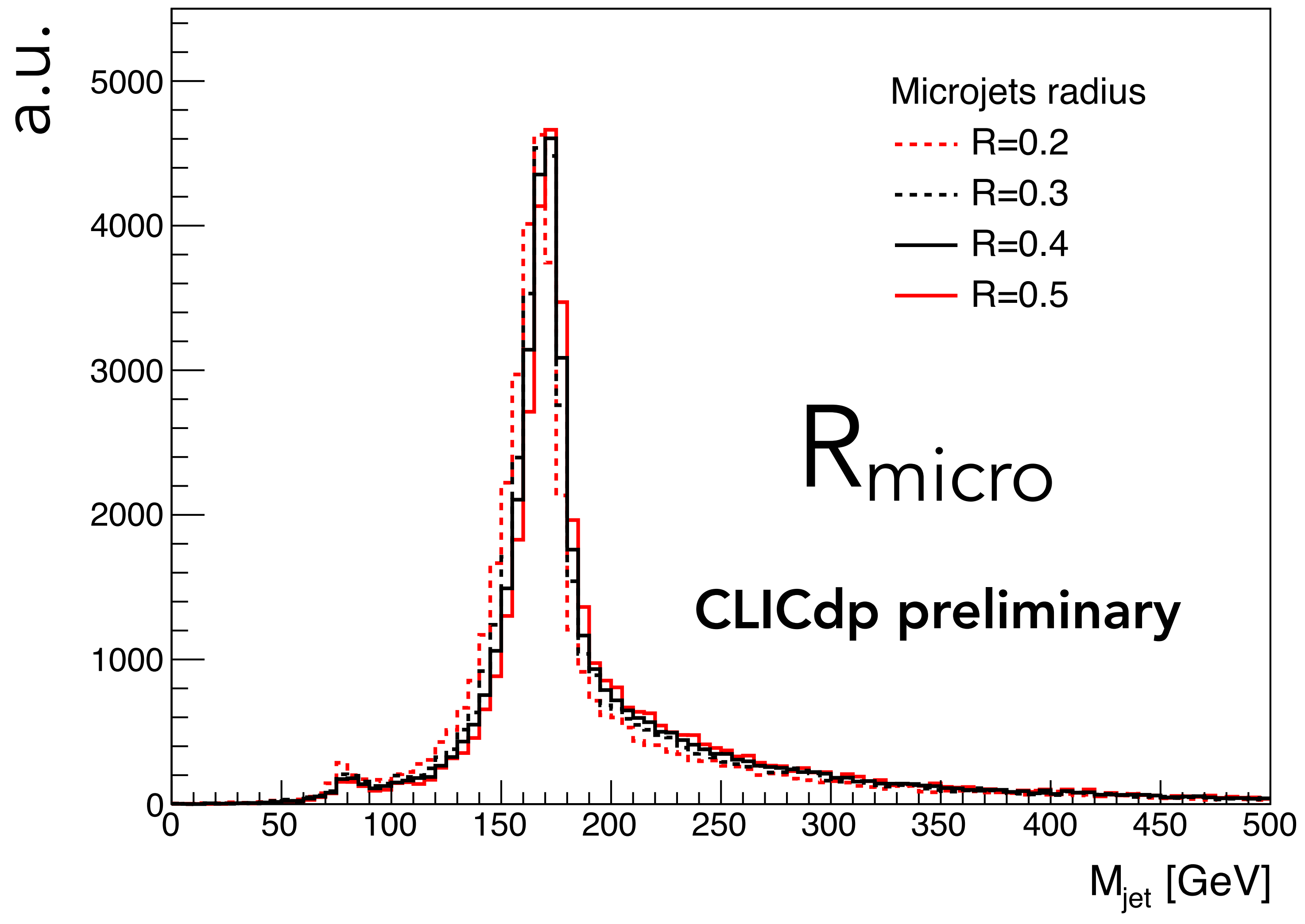
- Pushes the reconstructed mass towards m_t
- Additional Background rejection

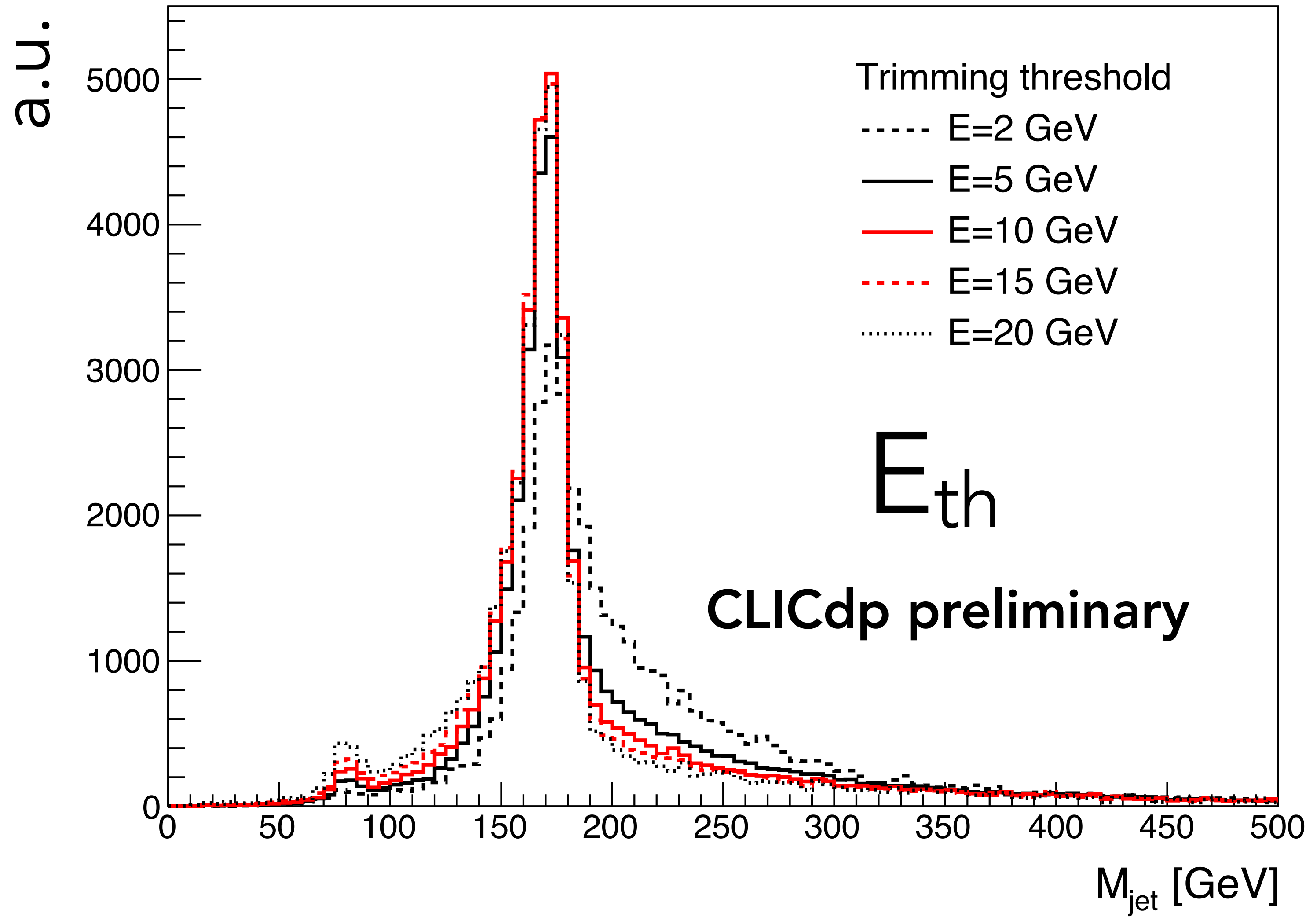
Trimming effect on top mass position

Optimisation of microjet parameters

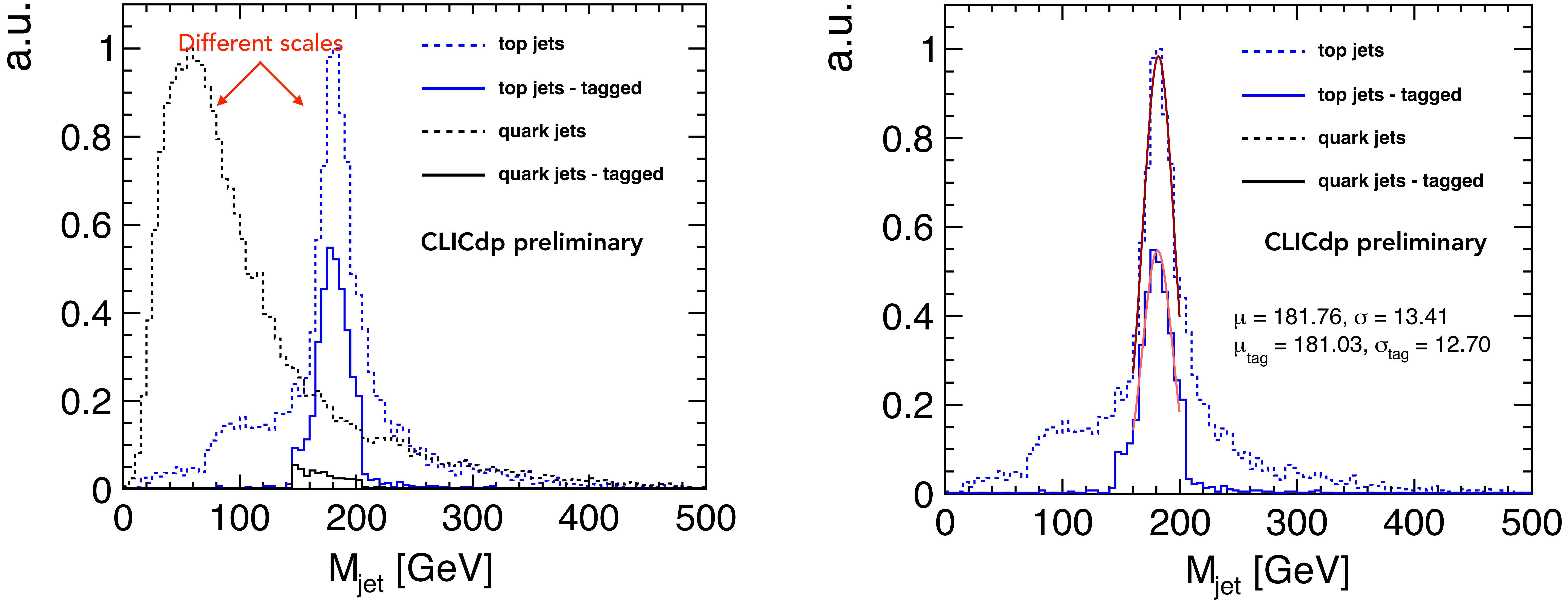
Optimal values:

- E_{th} = 5 GeV
- R_{micro} = 0.4





Top Mass Reconstruction



NOTE: 2 Excl. jets per event, i.e. 2 entries per event in histograms

- Mass resolution in the order of 7.5%
- Final optimisation still pending
- Incl. trimming (mass peak position shift to 173.7 GeV, mass resolution in the order of 5%)

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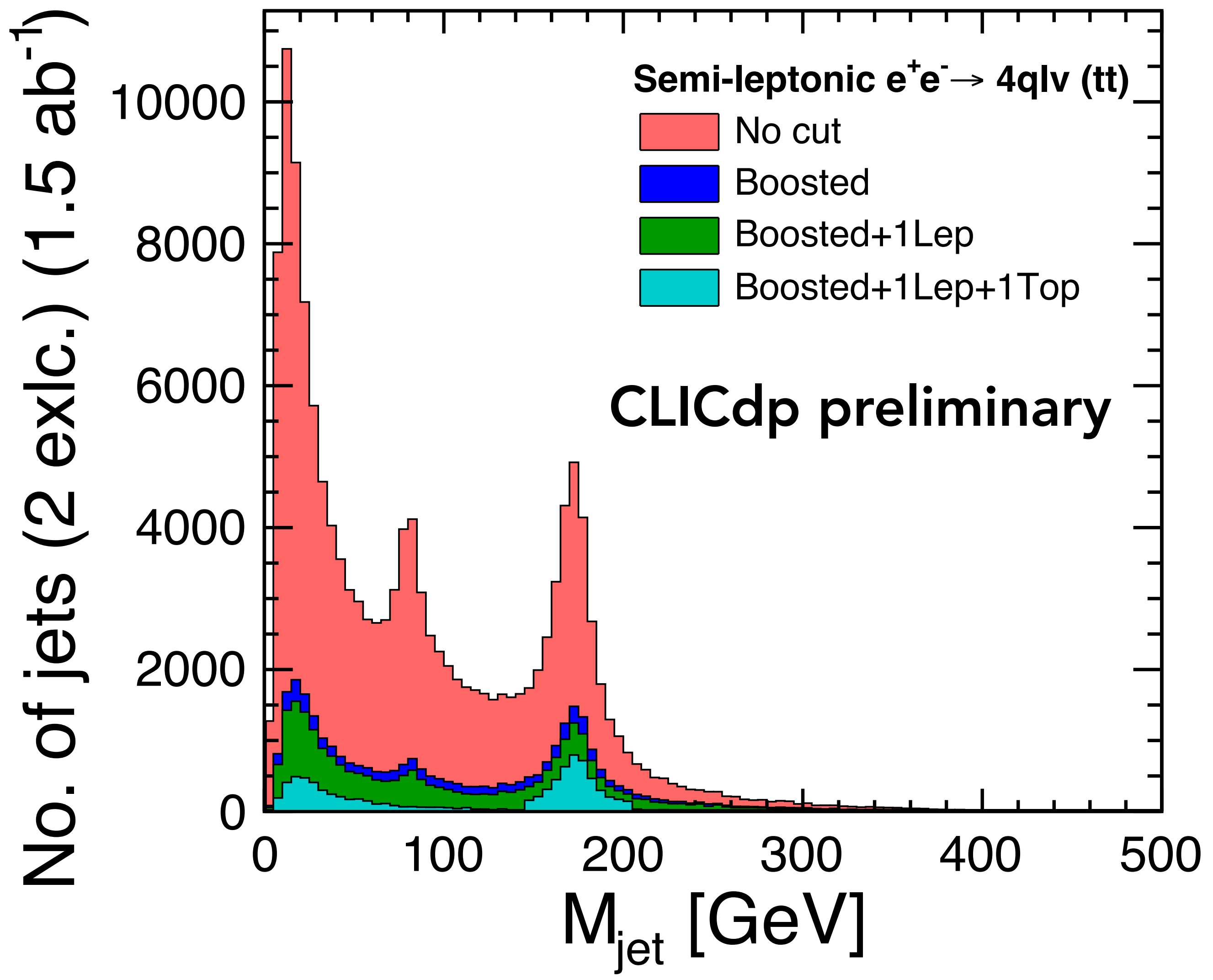
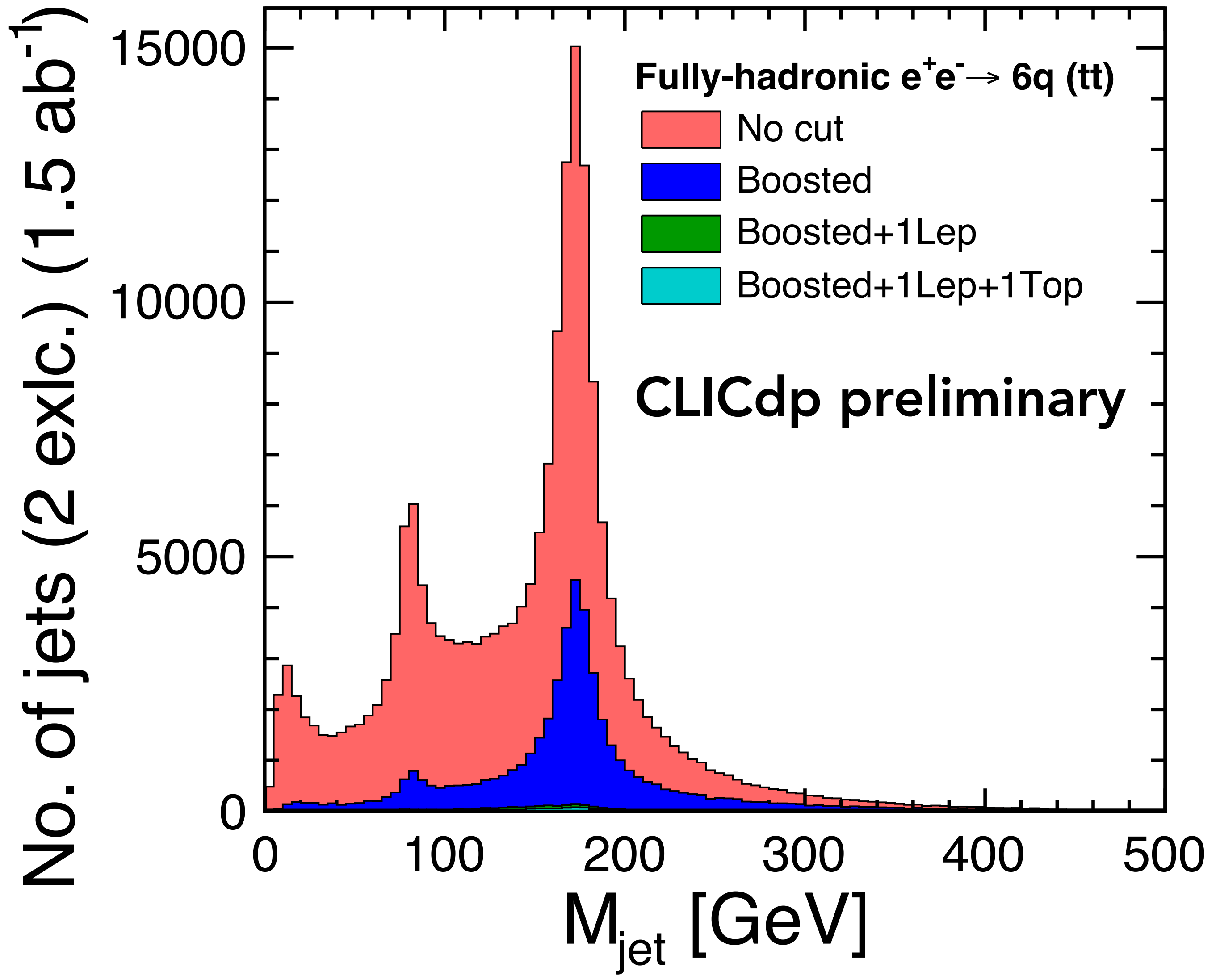
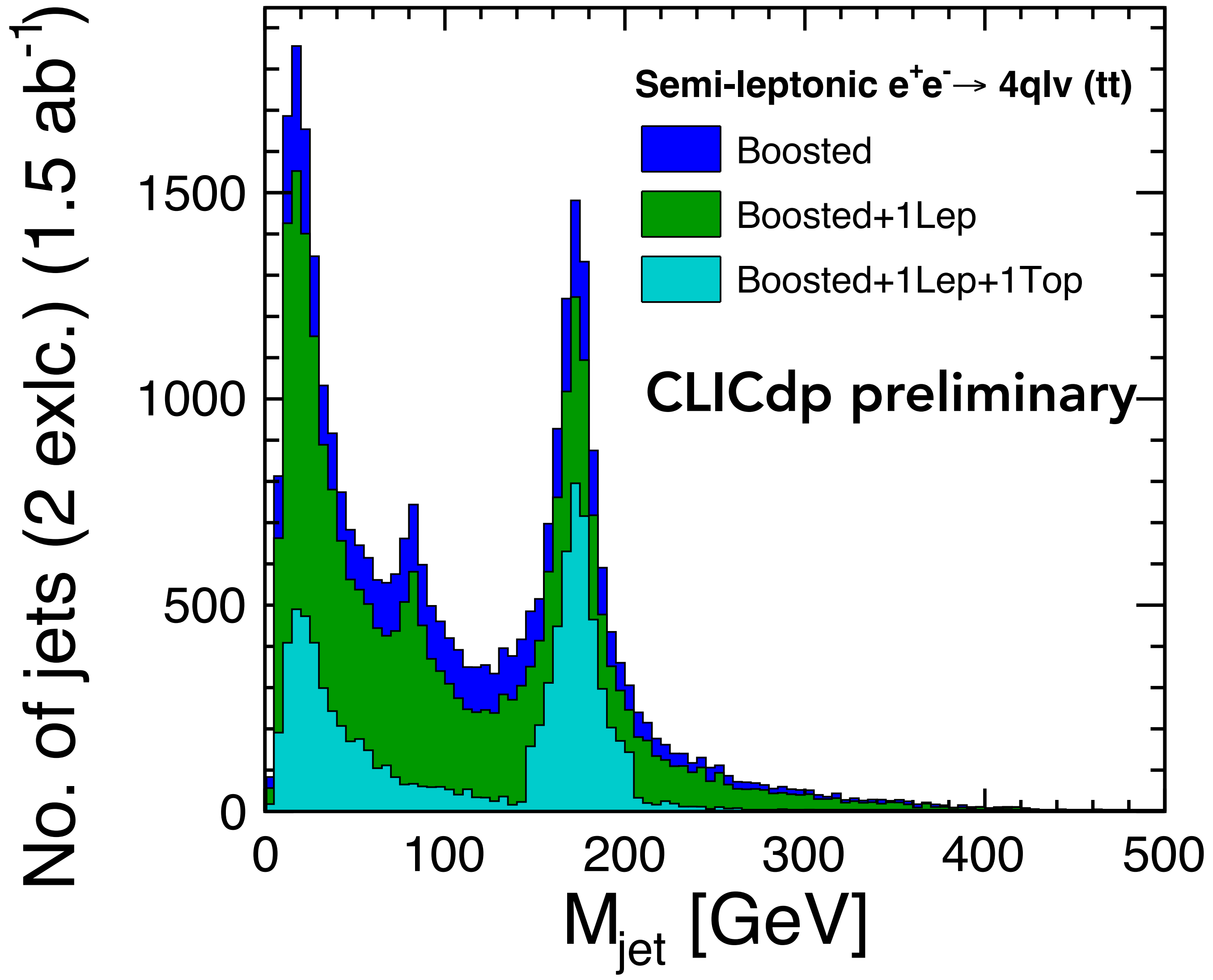
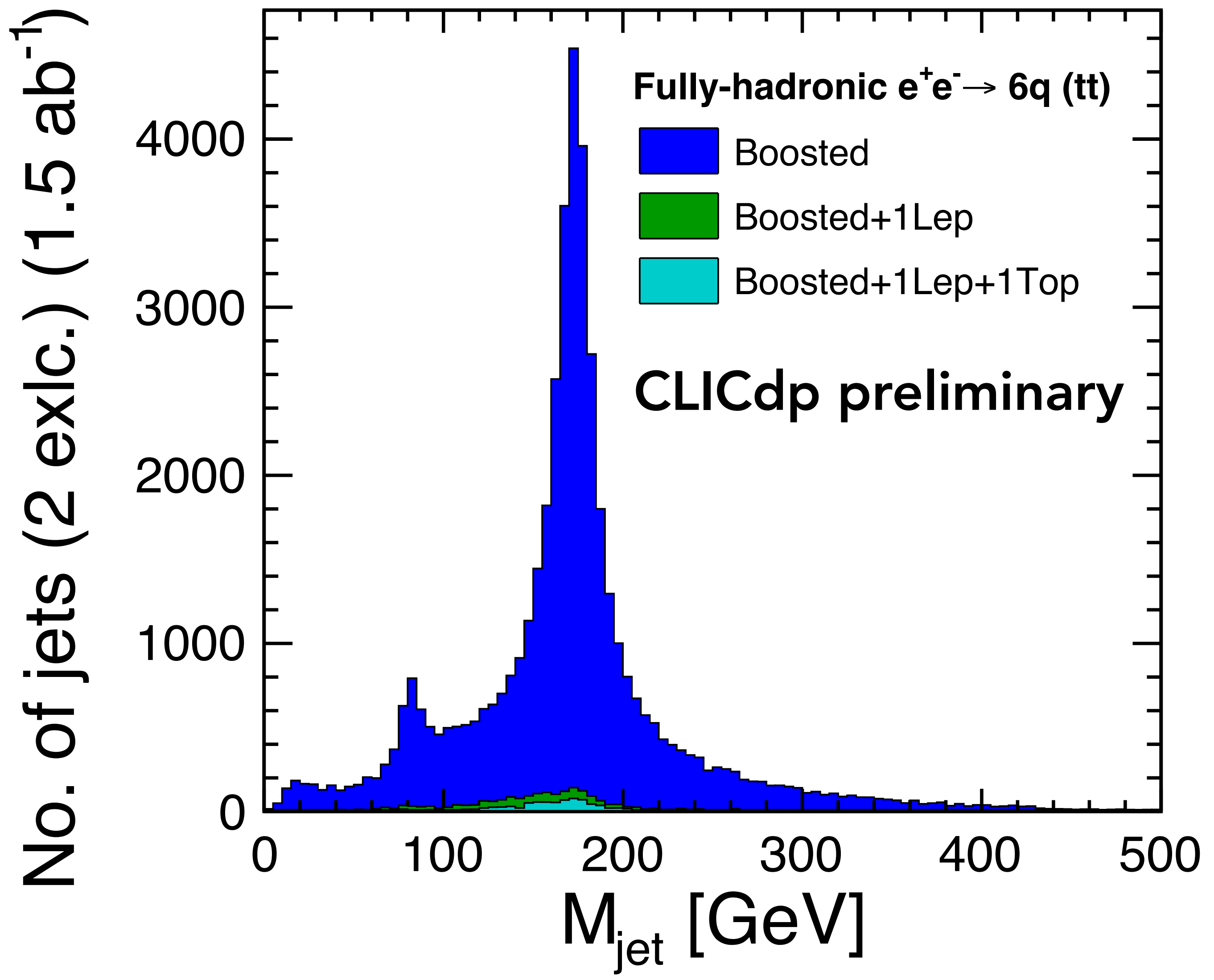
Analysis - Results for $P(e^-) = -80\%$









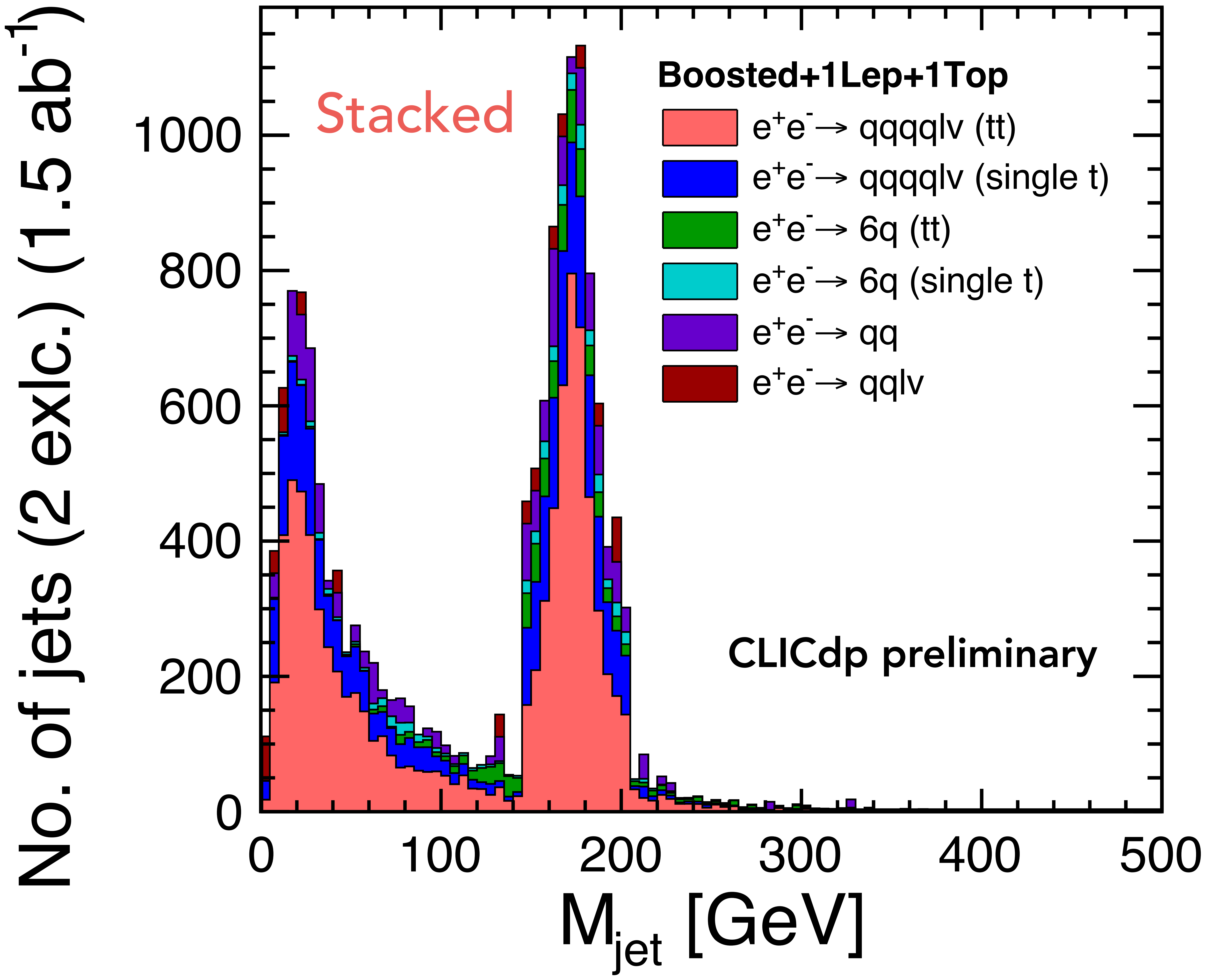
- *Technical cut: Boosted (√s'>1350 GeV)*
- *The following cuts are applied:*
  - 1 isolated lepton (electron or muon), incl. cuts on track energy, impact parameter, calorimeter information, and cone isolation
  - Jet clustering including trimming
  - 1 top tagged jet (VLC R=1.5, δ_r = 0.05, δ_p = 0.05), about 35 % signal efficiency
- Lepton charge can be used to reconstruct the charge of the top/anti-top

- Do same for P(e-) = +80%

Analysis - Results for $P(e^-)$ = -80%

- Plot shows e^+e^-→tt→qqqqvl signal (light red) and backgrounds, all shown after cuts on previous slide have been applied
- Not including all backgrounds yet, e.g. missing γe→qqqqe (forward)
- Further, event recovery possible
  - If top tagger failed
  - b-tagging
  - Electron channel (qqqqve) suffer from lower lepton isolation efficiency

	Signal [no. of events]	*Bkg [no. of events]*
No cut	140169	$2,42446\times10^7$
Boosted	32114	$5,12606\times10^6$
Boosted + 1Lep	25807	$1,59256\times10^6$
Boosted + 1Lep + 1 Top	**8942**	**7093**



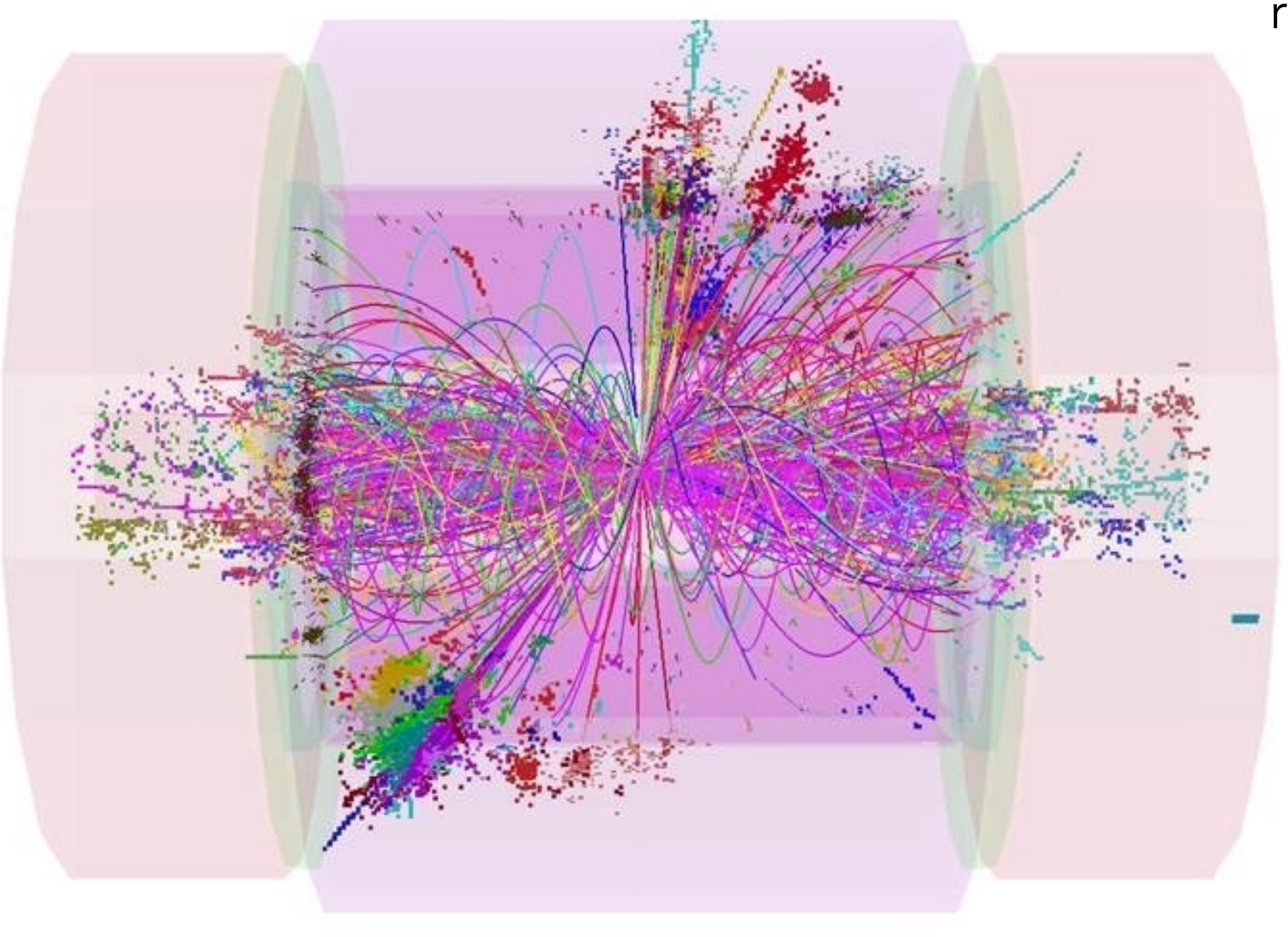
Conclusions and Summary

- The top precision physics programme at CLIC leads to strong requirements on the performance of the detector and the reconstruction software
- Following the method describe in Kaplan et al., we have implemented a Top Tagger including support for all jet algorithms implemented in Fastjet
- First time top tagger is used in CLIC
- The performance has been evaluated for boosted events and internal parameters were optimised with very promising results
- Jet trimming is a powerful way to correct the reconstructed top mass bias and show small improvement in top tagging efficiency compared to background
- Analysis based on this selection is underway, with preliminary results on forward-background asymmetry for the semi-leptonic ttbar decay channel to be expected soon!

Backup Slides

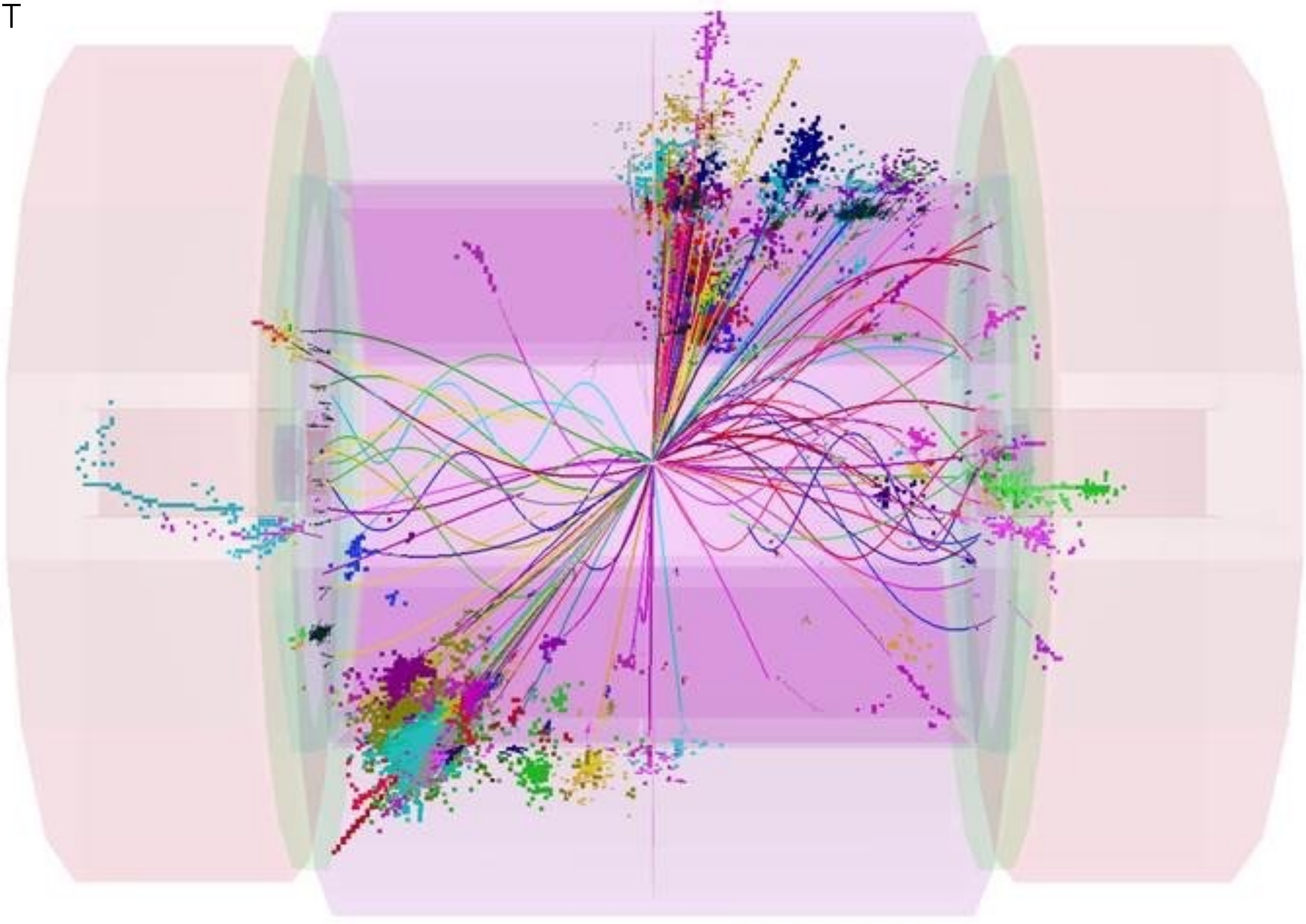
Combined p_T and Timing Cuts

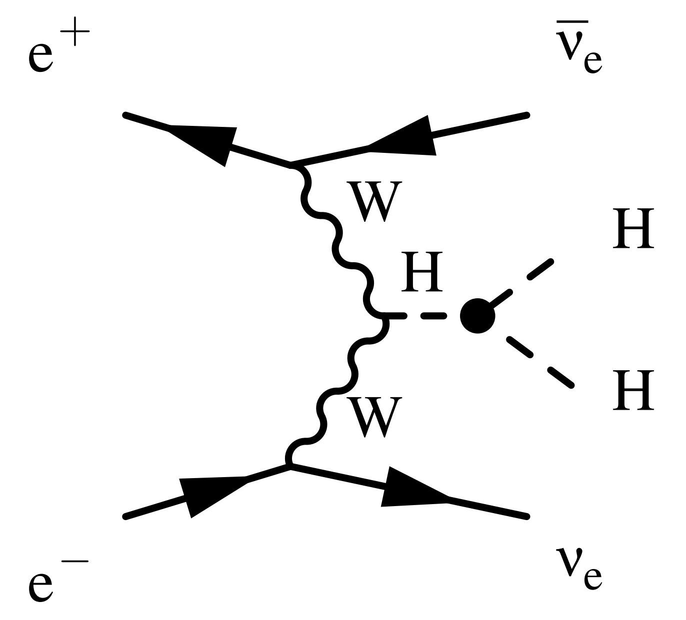
1.2 TeV background in reconstruction time window



Cuts depend on particle-type, p_T and detector region, protect high-p_T physics objects

85 GeV background after tight cuts





$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8\,\text{jets}$$