A new jet reconstruction algorithm for lepton colliders

Based on preprint arXiv:1404.4294

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Introduction

Jet reconstruction is a crucial step in many physics analyses at the LC

Future high-energy lepton colliders present an environment that **differs** in several important respects from that encountered **at the Z-pole**

Do we need to rethink jet reconstruction? Which algorithms are most suitable?

A brief history of sequential recombination algorithms

JADE 1980s

$$y_{ij} = \frac{E_i^2, E_j^2}{Q^2}(1 - \cos\theta_{ij})$$

Experience on e^+e^- data at Z-pole

Durham or e^+e^- k_t algorithm (LEP and SLC)

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

Adapt to hadron colliders

$$d_{ij} = min(p_{Ti}^{2n}, p_{Tj}^{2n})\Delta R_{ij}^{2n}/R^{2n}$$
$$d_{iB} = p_{Ti}^{2n}$$

n=0: Cambridge-Aachen
n=1: Longitudinally invariant k_t
n=-1: Anti-k_t (LHC default)

Feed back into e^+e^- algorithms

Generalised e^+e^- k_t algorithm

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

Moretti, Lonblad, Sjostrand, JHEP9808 (1998)
Catani, Dokshitzer, Webber, Phys.Lett. B285 (1992)
Catani, Dokshitzer, Seymour, Webber, Nucl.Phys. B406 (1994)
Ellis, Soper, Phys.Rev. D48 (1993)
All algorithms available in FastJet

Time to rethink e^+e^- algorithms!!

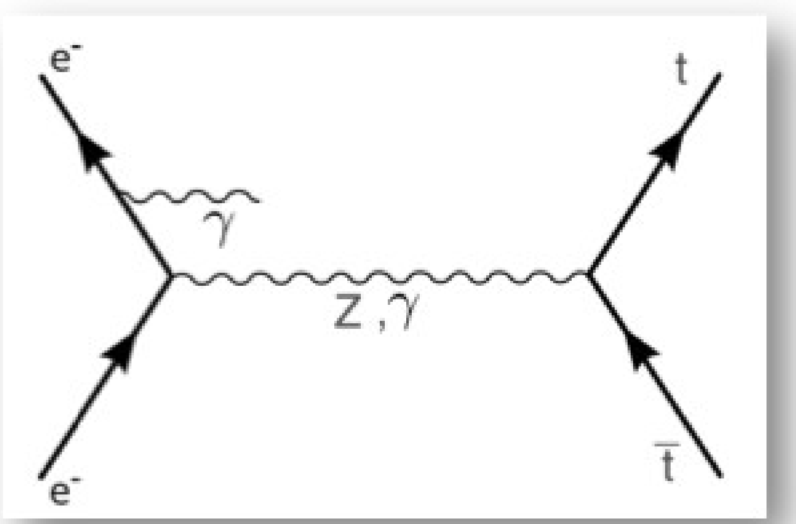
Boost invariance at hadron colliders

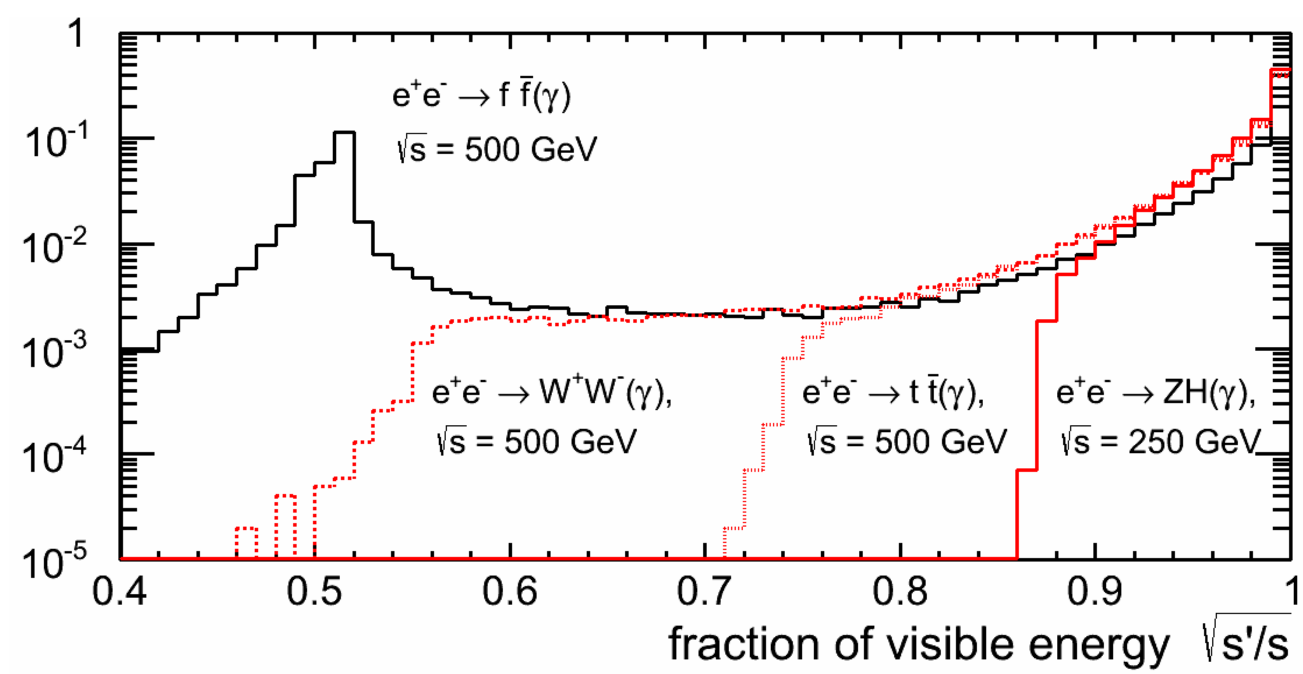
- At **hadron colliders the partons** that participate in the hard process generally **carry different fractions of the initial** hadron **energy.**
- The final state acquires a substantial **Lorentz boost** along the beam axis.
  - LHC di-jets: $\beta_z \sim 1$
  - LHC tt: $\beta_z \sim 0.5$
- Replace the [**energy, polar angle**] basis by

  [**transverse momentum, rapidity**]

Boost invariance at lepton colliders

- Photons emitted by the incoming beam particles (**Initial State Radiation**) can carry away a significant fractions of the nominal center-of-mass energy
- For $e^+e^- \rightarrow Z/\gamma^* \rightarrow f\bar{f}$ process, with $m_f < M_Z/2$ a large fraction of events ***returns*** to the **Z-pole**
- **In most interesting processes** at a future lepton collider ISR plays a much **less important role**
- At lepton colliders we must deal with minor boosts and the basis [E,θ] remains the most natural choice





Background levels at future LC

- The **pile-up** at the **LHC** is a serious challenge that has led to a large body of work on mitigation and correction methods
- **LEP** or **SLC presented effectively negligible background**
- The $\gamma\gamma \rightarrow$ **hadrons** background at **CLIC** has **strong** impact on jet reconstruction performance [CLIC CDR, Marshall & Thomson, arXiv:1308.4537]
- Less pronounced, but **non-negligible** impact on ILC physics [many studies, arXiv:1307.8102]
- Using hadron collider algorithms can reduce these problems [CLIC CDR]

The Valencia jet algorithm

A new clustering jet reconstruction algorithm that combines the good features of lepton collider algorithms, in particular the **Durham-like distance criterion;**

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

with the **robustness against background of** the longitudinally invariant **k_t algorithm**

$$d_{iB} = p_T^{2\beta}$$

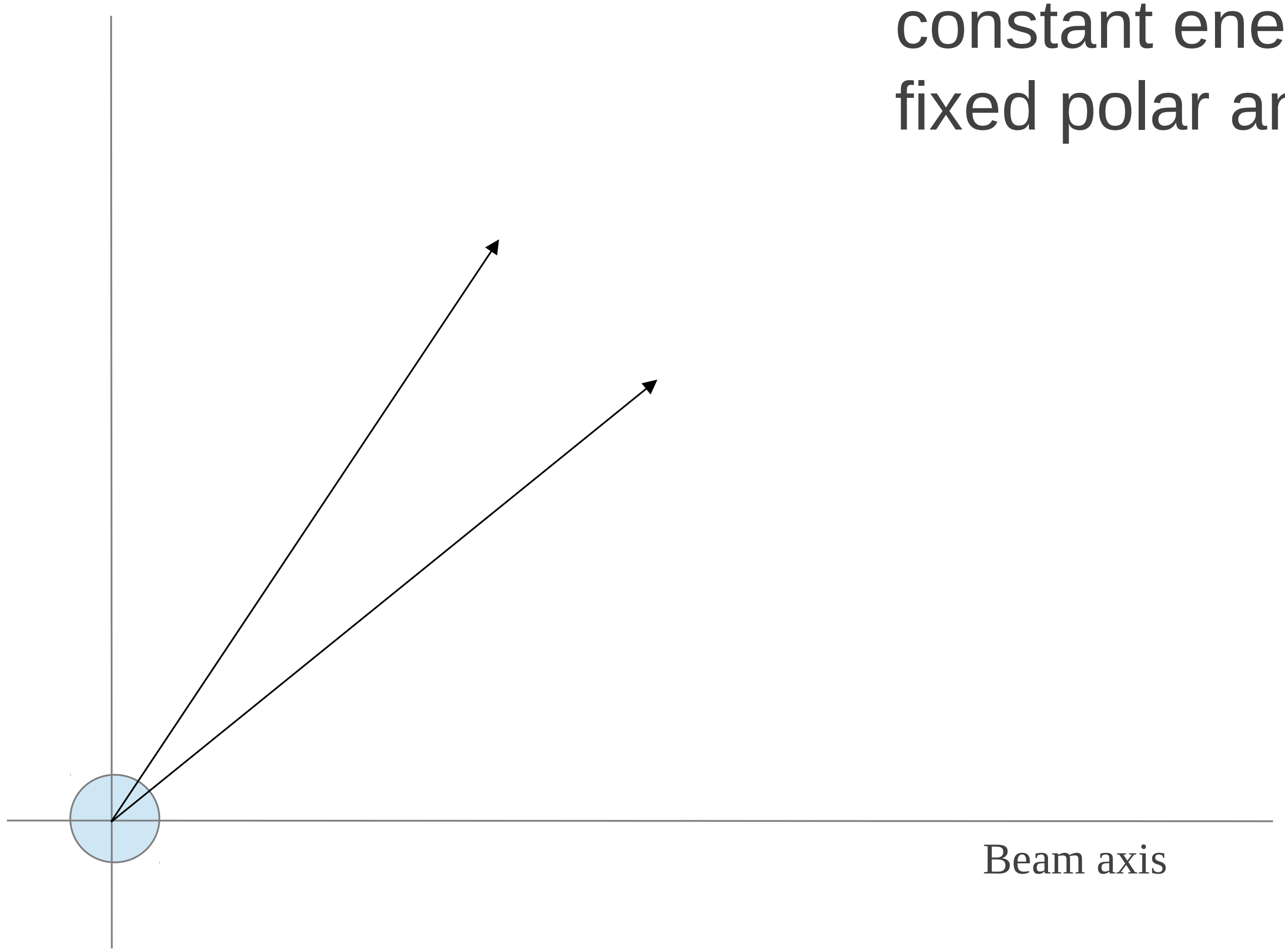
The exponent β allows to ***tune* the background rejection** level

The algorithm has been implemented as a **plugin for the *FastJet*** package and is available in fjcontrib

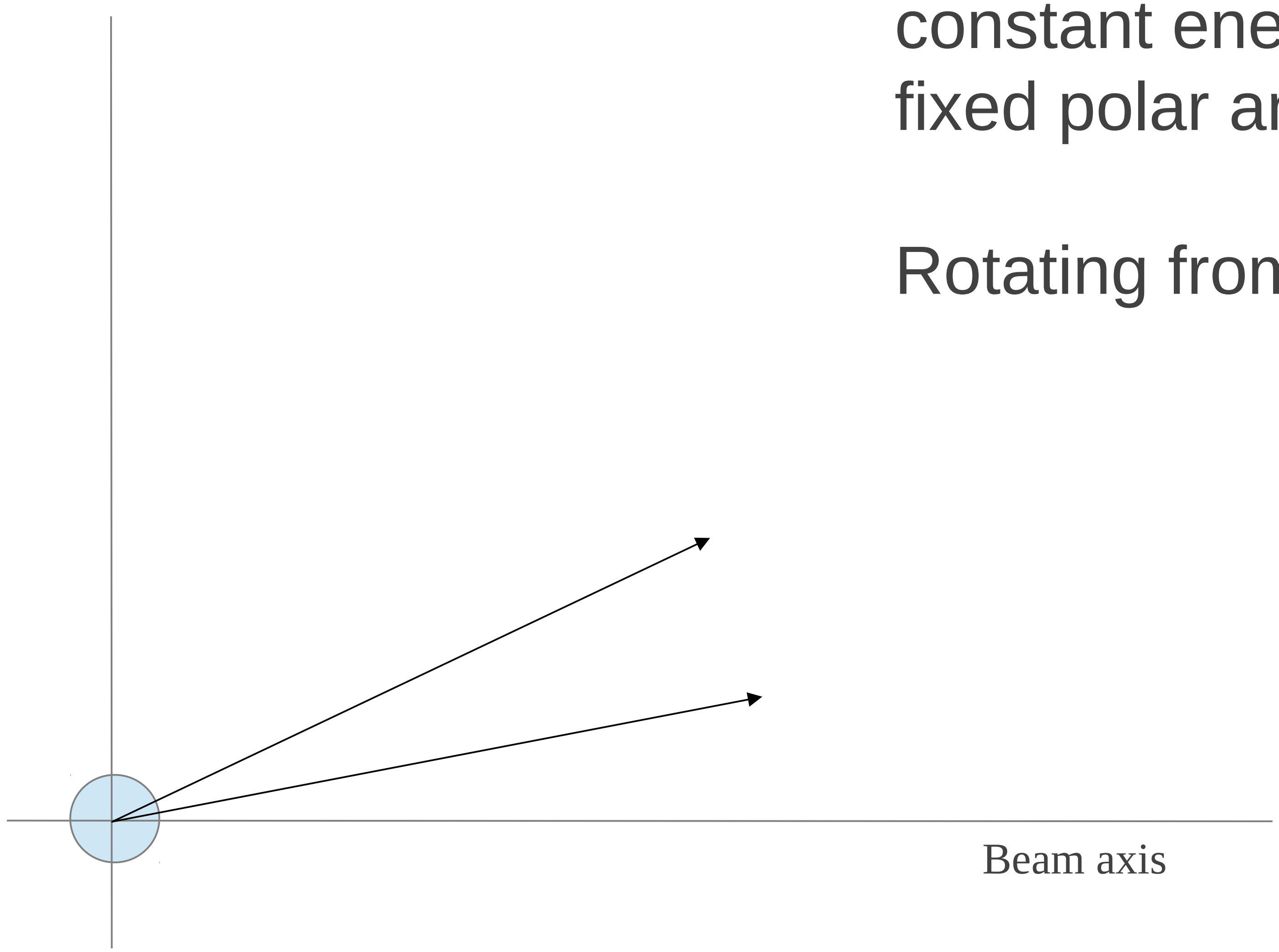
https://fastjet.hepforge.org/trac/browser/contrib/contribs/ValenciaJetAlgorithm

Comparison of the distance criteria

Two test particles with
constant energy (E = 1 GeV) and
fixed polar angle separation (100 mrad)



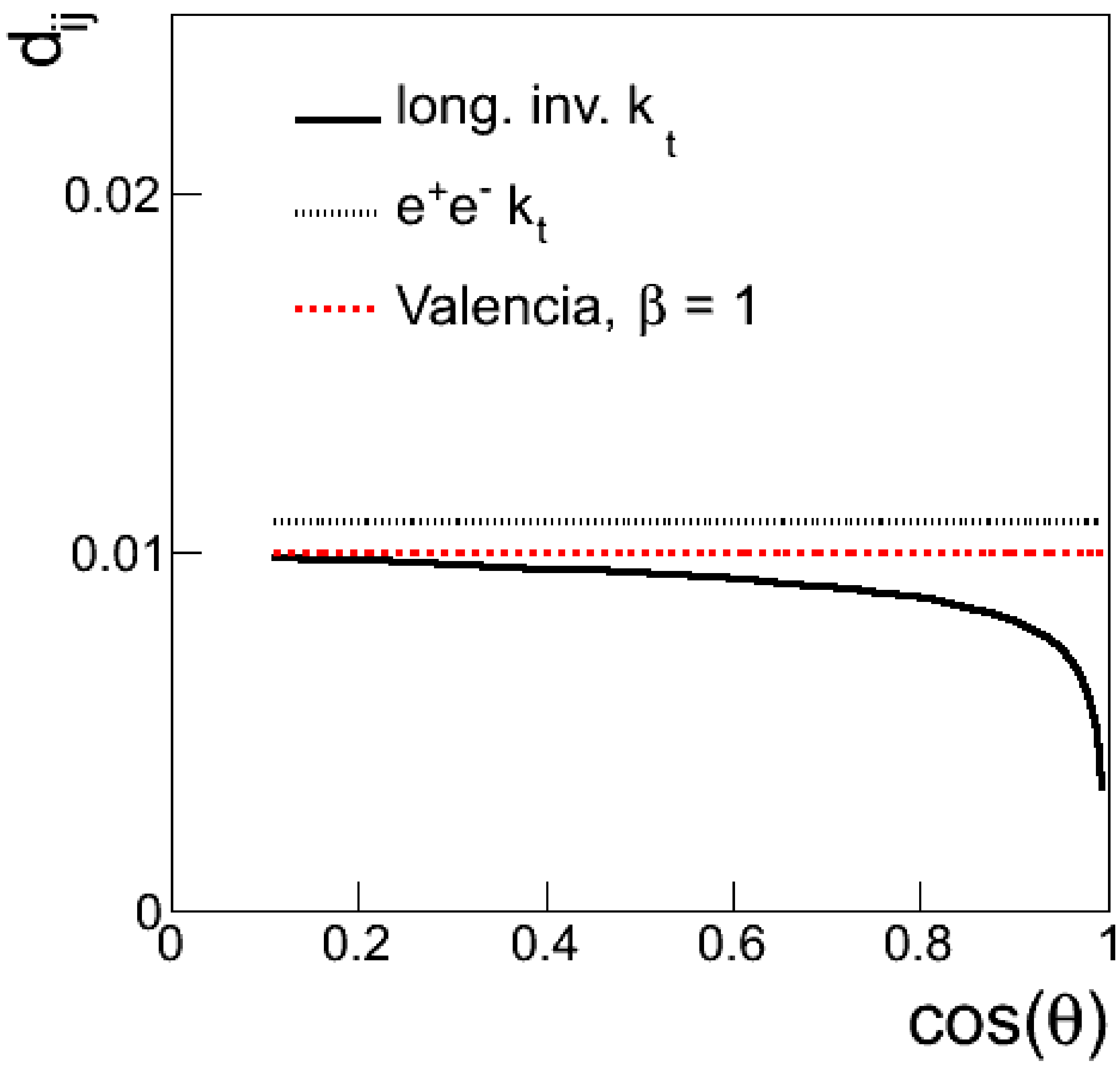
Comparison of the distance criteria



Two test particles with
constant energy (E = 1 GeV) and
fixed polar angle separation (100 mrad)

Rotating from central to forward region

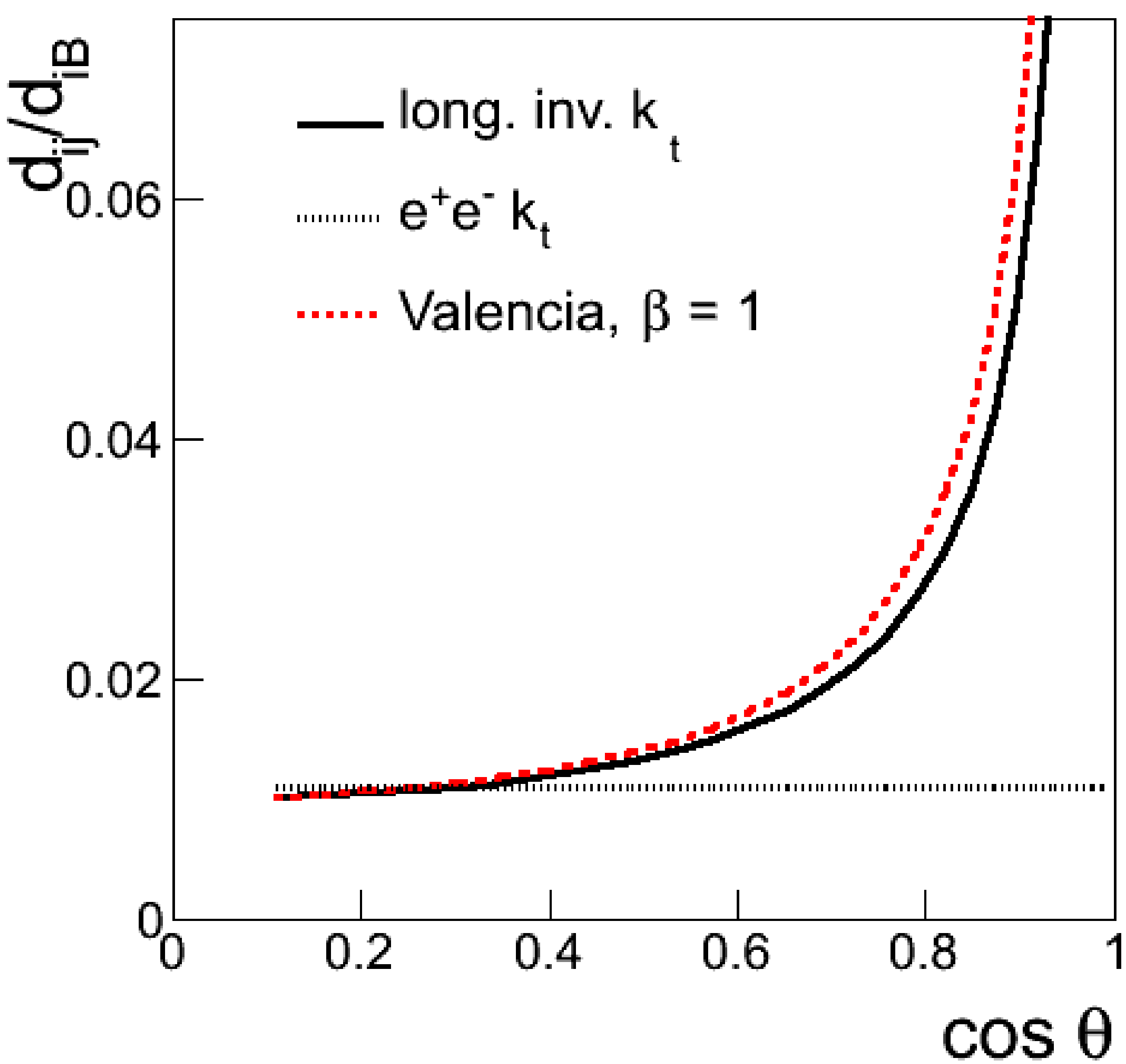
Comparison of the distance criteria



As the two-particle system rotates into the forward region, the distance d_{ij} of longitudinally invariant k_t decreases ($\Delta\eta$ increases, p_T decreases)

Traditional e^+e^- algorithms and Valencia have constant d_{ij}

Comparison of the distance criteria



The ratio of the inter-particle distance and the beam distance: d_{ij}/d_{iB} drives the robustness to (forward) background: the decision to assign the particle to final-state or beam jets depends on this ratio (and R)

Long. inv. k_t's robustness is indeed due to its increasing d_{ij}/d_{iB} ratio

Valencia with β=1 is similar (by design) to long. inv. k_t

Jet reconstruction performance

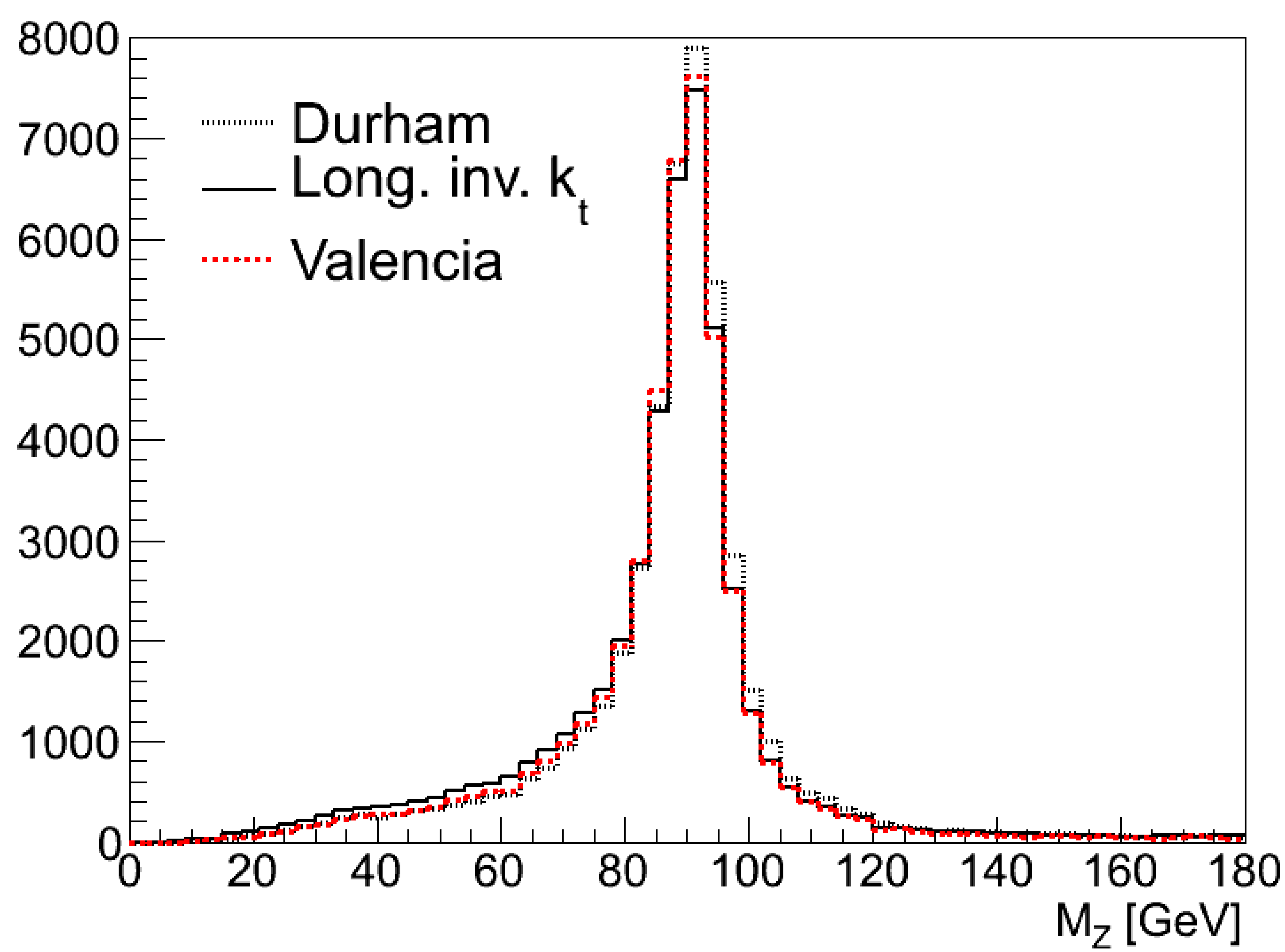
CLIC di-boson (ZZ) production @ 500 GeV

Reconstruct Particle Flow objects using PANDORA

Reconstruct jets (exclusive, n=4)

Form Z boson candidates, selecting best jet pairs

Chosen to facilitate comparison with Marshall&Thomson, CLIC CDR



No background: it doesn't really matter which algorithm you pick

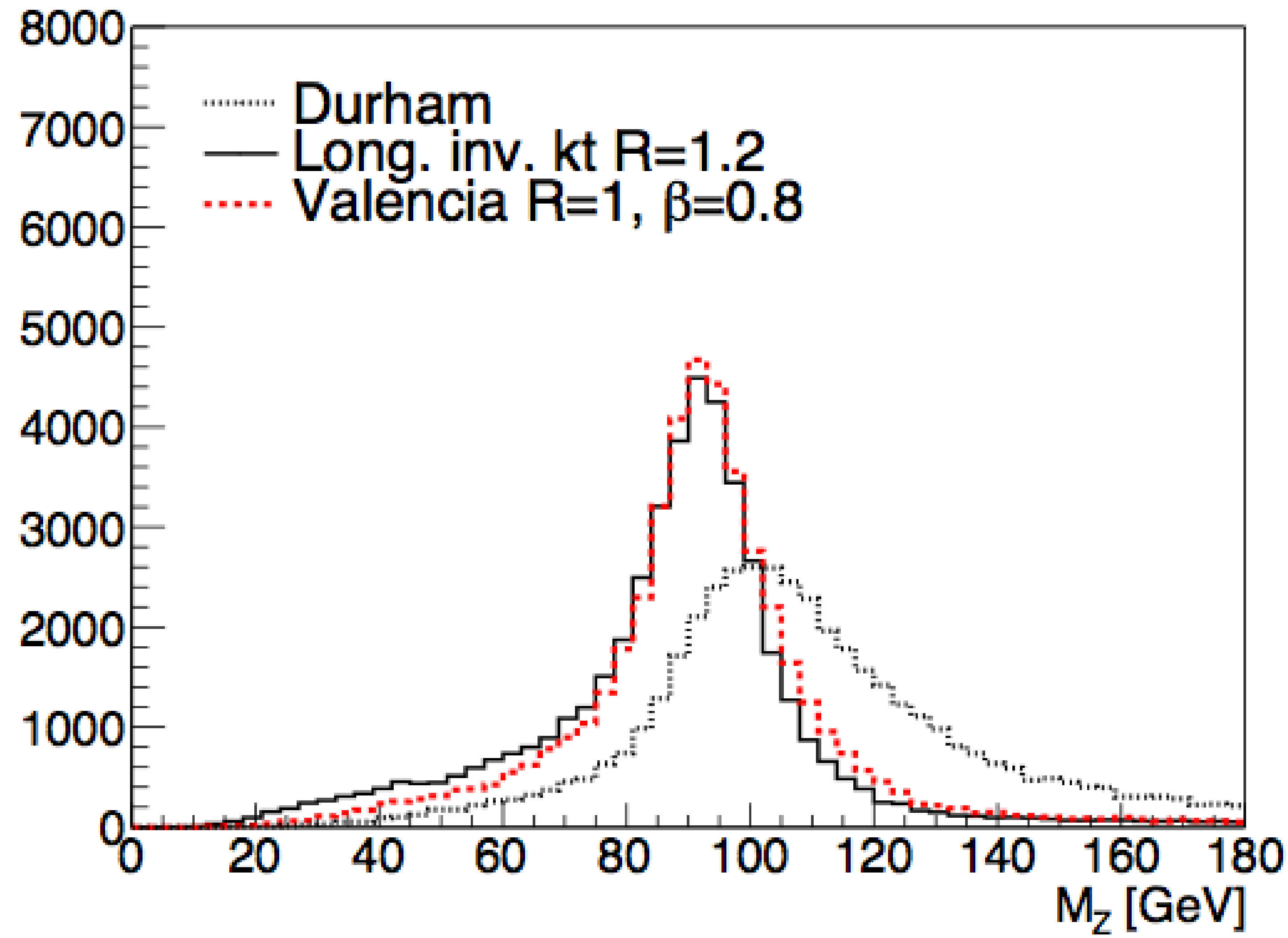
Jet reconstruction performance

CLIC di-boson (ZZ) production @ 500 GeV
+ 300 BX of γγ → hadrons

Reconstruct Particle Flow objects using PANDORA
+ quality and timing cuts

Reconstruct jets (exclusive, n=4)

Form Z boson candidates, selecting best jet pairs



Nominal background: Durham is severely affected, longitudinally invariant k_t and Valencia OK

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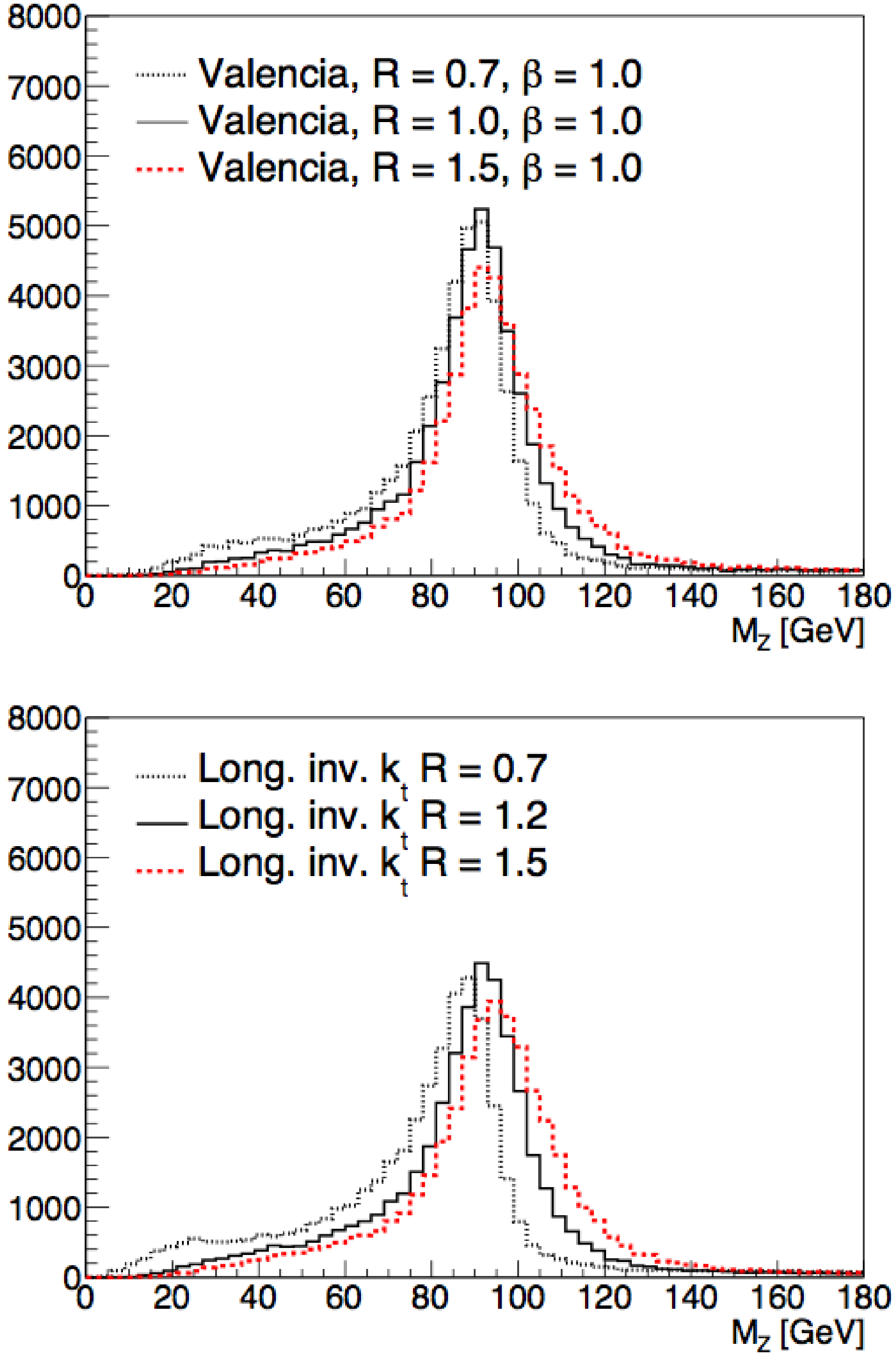
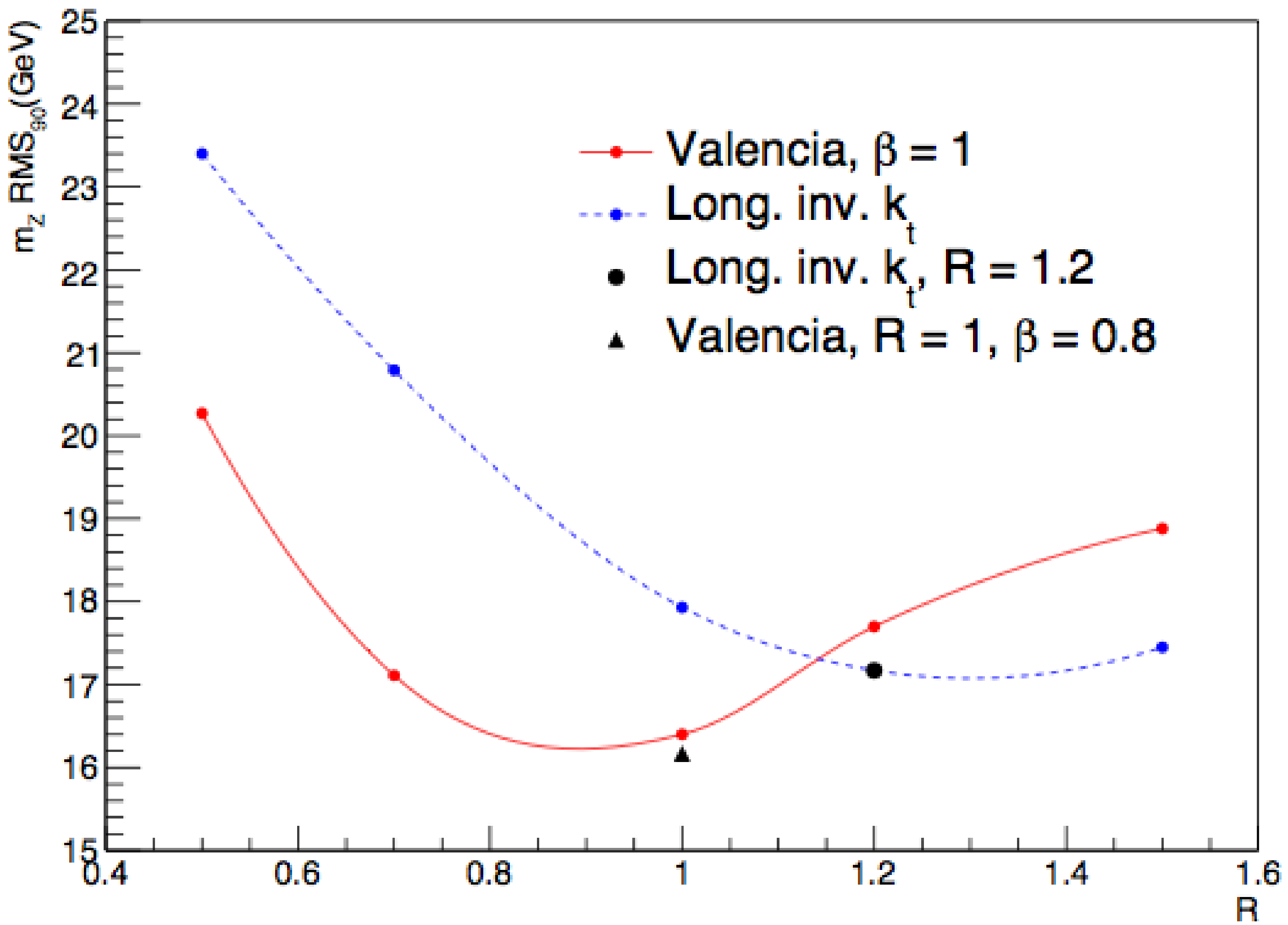
Parameter optimisation: R scan



The choice of parameters corresponds to the optimal setting determined in a scan over a broad range of parameters.



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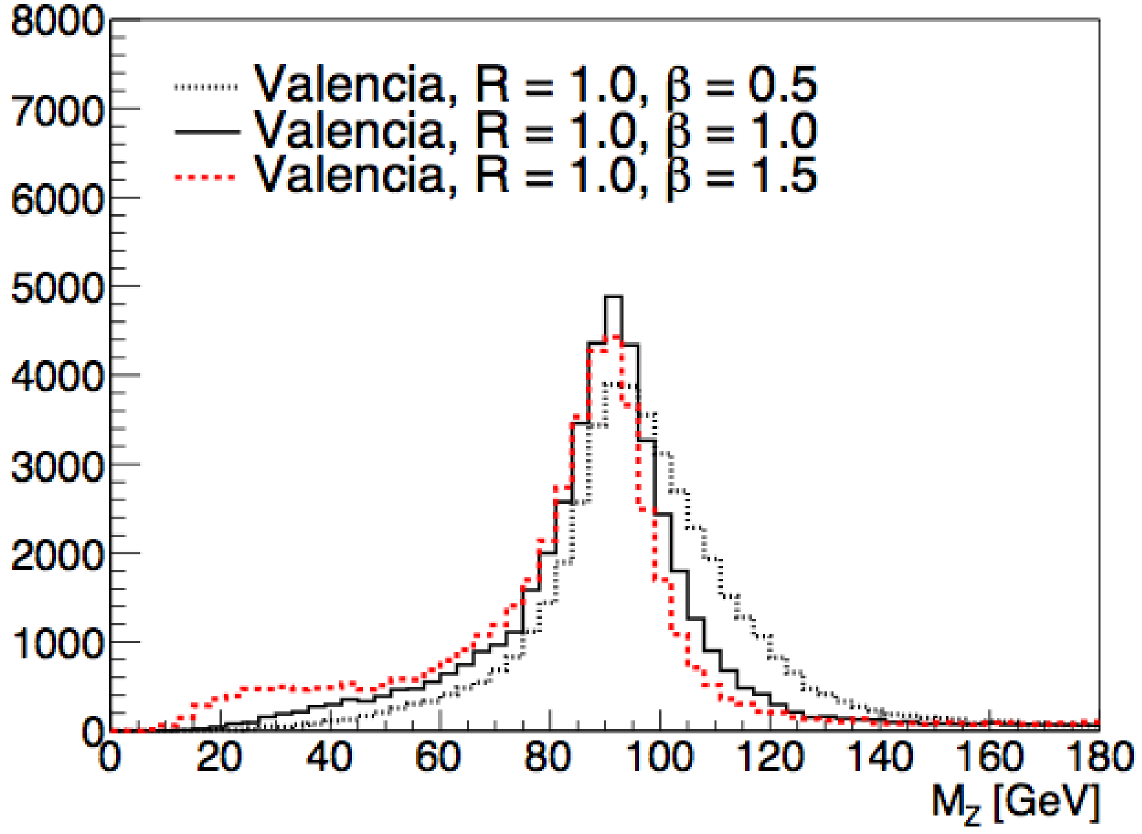
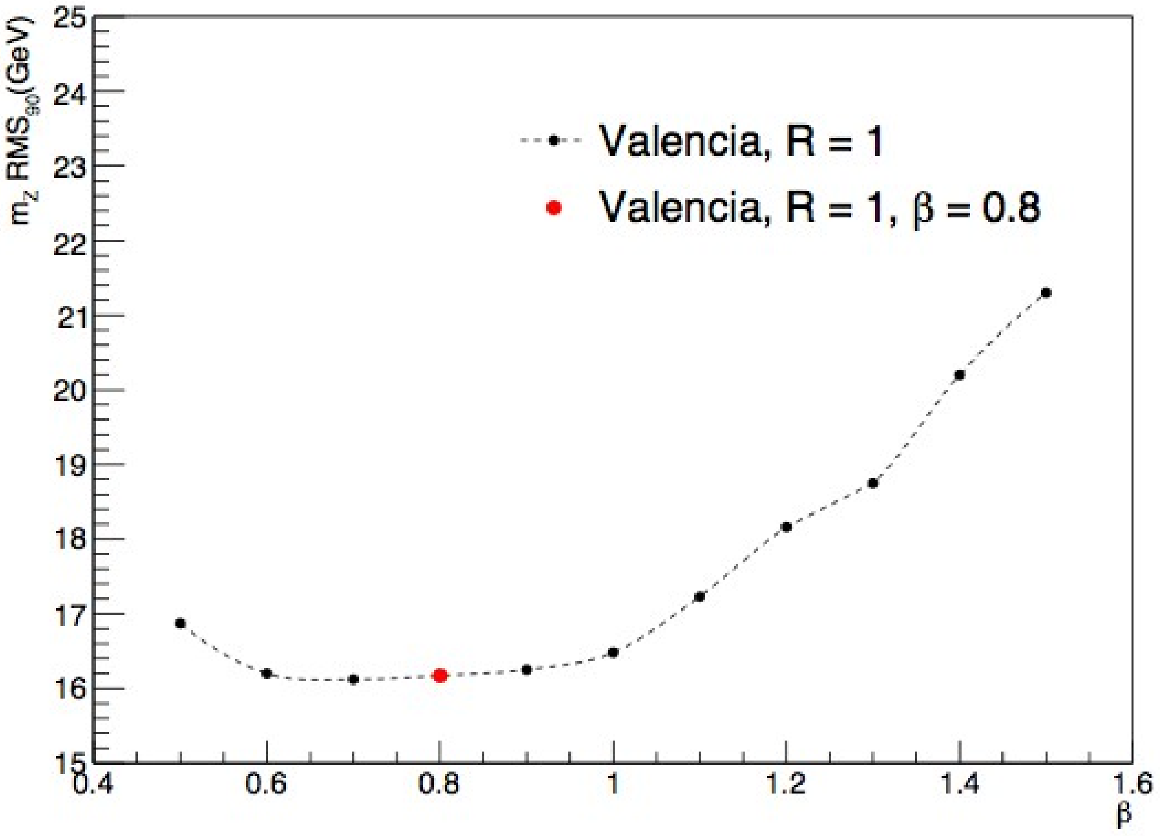
Parameter optimisation: β scan





Jet reconstruction performance

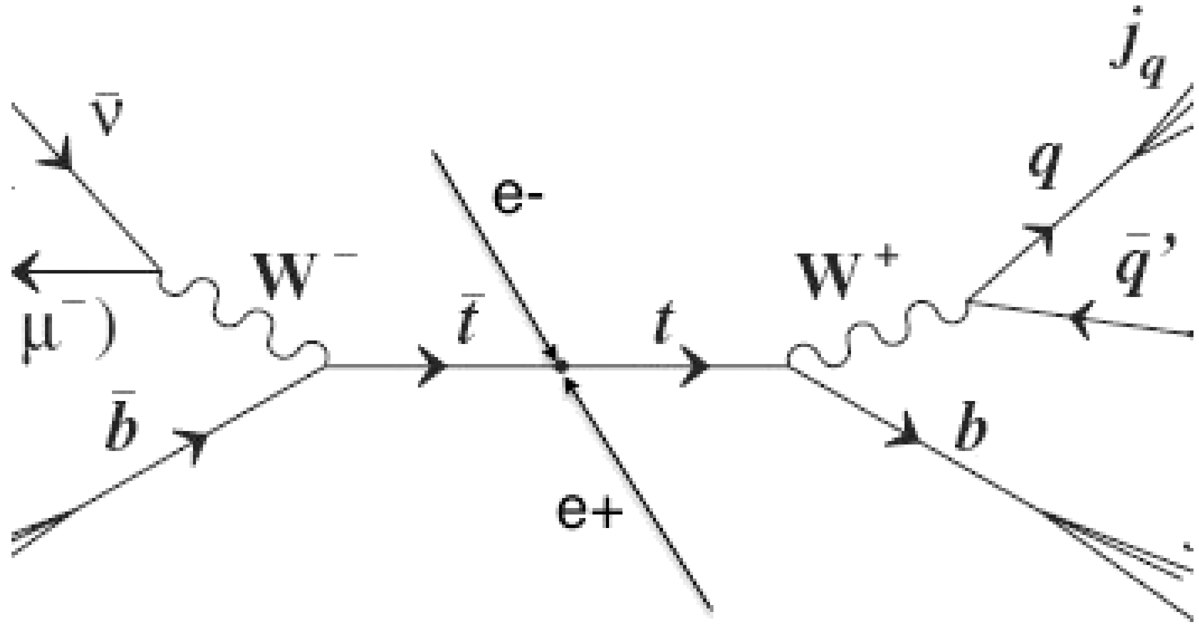
The previous results in numbers: central value, width of the Z-boson mass peak and RMS_{90}

$\sqrt{s} = 500$ GeV, no background overlay			
[GeV]	m_Z	σ_Z	RMS_{90}
Durham	90.6	5.4	13.8
long. inv. k_t	90.4	5.3	14.3
Valencia	90.3	5.2	12.5
$\sqrt{s} = 500$ GeV, 0.3 $\gamma\gamma \rightarrow$ *hadrons* events/BX			
[GeV]	m_Z	σ_Z	RMS_{90}
Durham	101.1	13.6	28.8
long. inv. k_t	92.0	9.0	17.2
Valencia	92.5	9.2	16.2

e^+e^- style algorithm can compete with hadron collider algorithm

Jet reconstruction performance

IFIC/LAL study of ILC lepton+jets tt @ 500 GeV, [arXiv:1307.8102]



DBD Samples

Event Generation
Whizard 1.95

Reconstruct Particle Flow objects using PANDORA

Reconstruct jets (exclusive, n=4)

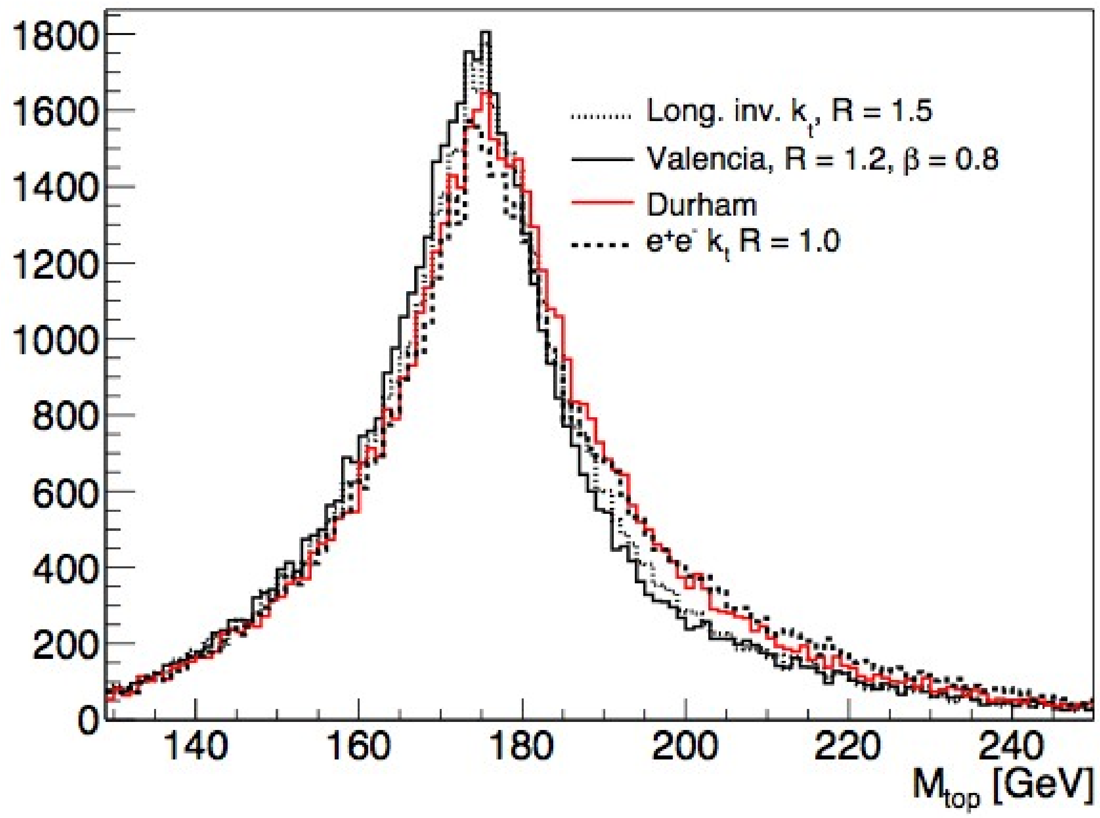
The signal is reconstructed by choosing the combination of *b* quark jet and W boson that minimises the following equation

$$d^2 = \left(\frac{m_{cand.} - m_t}{\sigma_{m_t}}\right)^2 + \left(\frac{E_{cand.} - E_{beam}}{\sigma_{E_{cand.}}}\right)^2 + \left(\frac{p_b^* - 68}{\sigma_{p_b^*}}\right)^2 + \left(\frac{cos\theta_{bW} - 0.23}{\sigma_{cos\theta_{bW}}}\right)^2$$

tt →(bjj)(blν)

We consider four jet reconstruction algorithms

- **Durham** algorithm
- **Generic e+e− k_t** algorithm with beam jets with R = 1
- **Longitudinally invariant k_t** algorithm with R = 1.5
- **Valencia** algorithm with R =1.2 and β = 0.8.



The choice of parameters corresponds to the optimal setting determined in a scan over a broad range of parameters.

Durham is affected by γγ -> hadrons, longitudinally invariant k_t and Valencia OK

Resolution on jets reconstruction

Degradation of all jet-related measurements due to **γγ → hadrons background**

RMS_{90} [GeV]	E_{4j}	E_W	m_W	E_t	m_t
Durham	23.2	19.6	20.3	19.5	21.4
e^+e^- k_t	25.6	20.8	21.6	20.5	22.8
long. inv. k_t	21.7	18.4	18.9	18.4	20.1
Valencia	21.4	18.0	18.8	18.2	20.0

Four-jet system

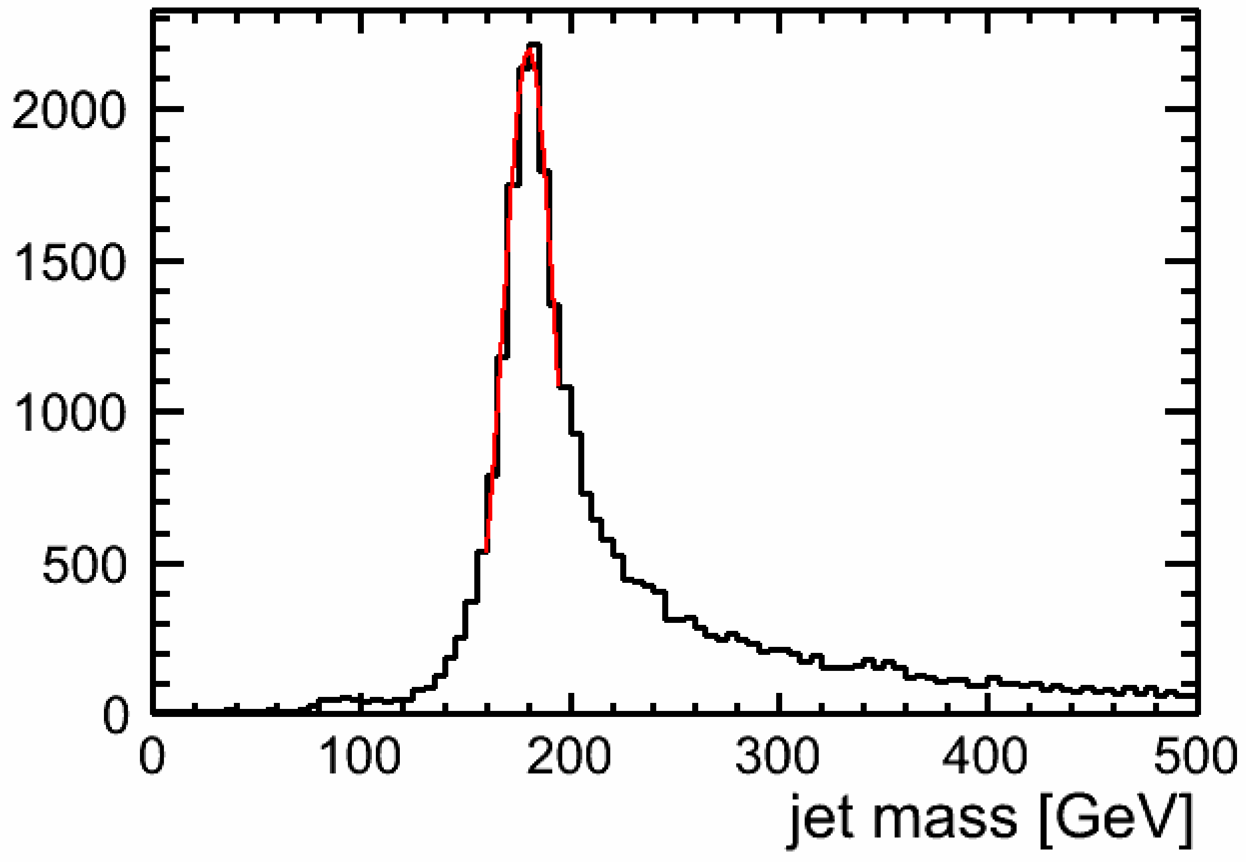
Hadronic top candidate

Hadronic W candidate

Durham and e+e- k_t significantly degraded.

Long. inv. k_t algorithm and Valencia offer better reconstruction for all hadronic observables

Multi-TeV operation



CLIC at 3 TeV, pairs of highly boosted top quarks

Reconstruct two jets!

A very narrow top mass peak (FWHM = 24 GeV)

Long tail due to radiation

Better performance than long. invariant kt and much better than Durham.

Studies with realistic background are ongoing

IR-safety

A key requirement to jet algorithms

From Salam & Soyez, JHEP 0705 (2007)
An infinitely soft particle cannot lead to a new (hard) [jet] being found...
...it makes no sense for the structure of multi-hundred GeV jets to change radically just because hadronisation, the underlying event or pileup threw a 1 GeV particle in between them.

The sequential recombination structure underlying the Valencia algorithm is generally thought to be intrinsically safe

A large number of **standard IR-safety tests** were performed on the FastJet plugin. **All succeeded.**

Conclusions

- $\gamma\gamma \rightarrow$ hadrons bkg. forces us to rethink jet reconstruction algorithms. The performance of classical e^+e^- algorithms is severally degraded
- **The Valencia** jet algorithm retains the natural inter-particle **distance criterion for e^+e^- collisions** and offers **robust performance** in the presence of the background levels expected at lepton colliders
- Shown to work on several benchmark analyses. Pre-print out on the arXiv since a few weeks: *Boronat, Garcia,Vos*, **A new jet reconstruction algorithm for lepton colliders, arXiv:1404.4294**
- Do try this at home! *https://fastjet.hepforge.org/trac/browser/contrib/contribs/ValenciaJetAlgorithm*
  And, please, contact us if you do: Ignacio.Garcia at ific.uv.es