

Helmholtz-Alliance Linear Collider Forum

29-30 April 2014 University of Bonn

Jet reconstruction at future linear e^+e^- colliders

I. García*, M. Vos
IFIC (CSIC/UVEG)
Valencia, Spain

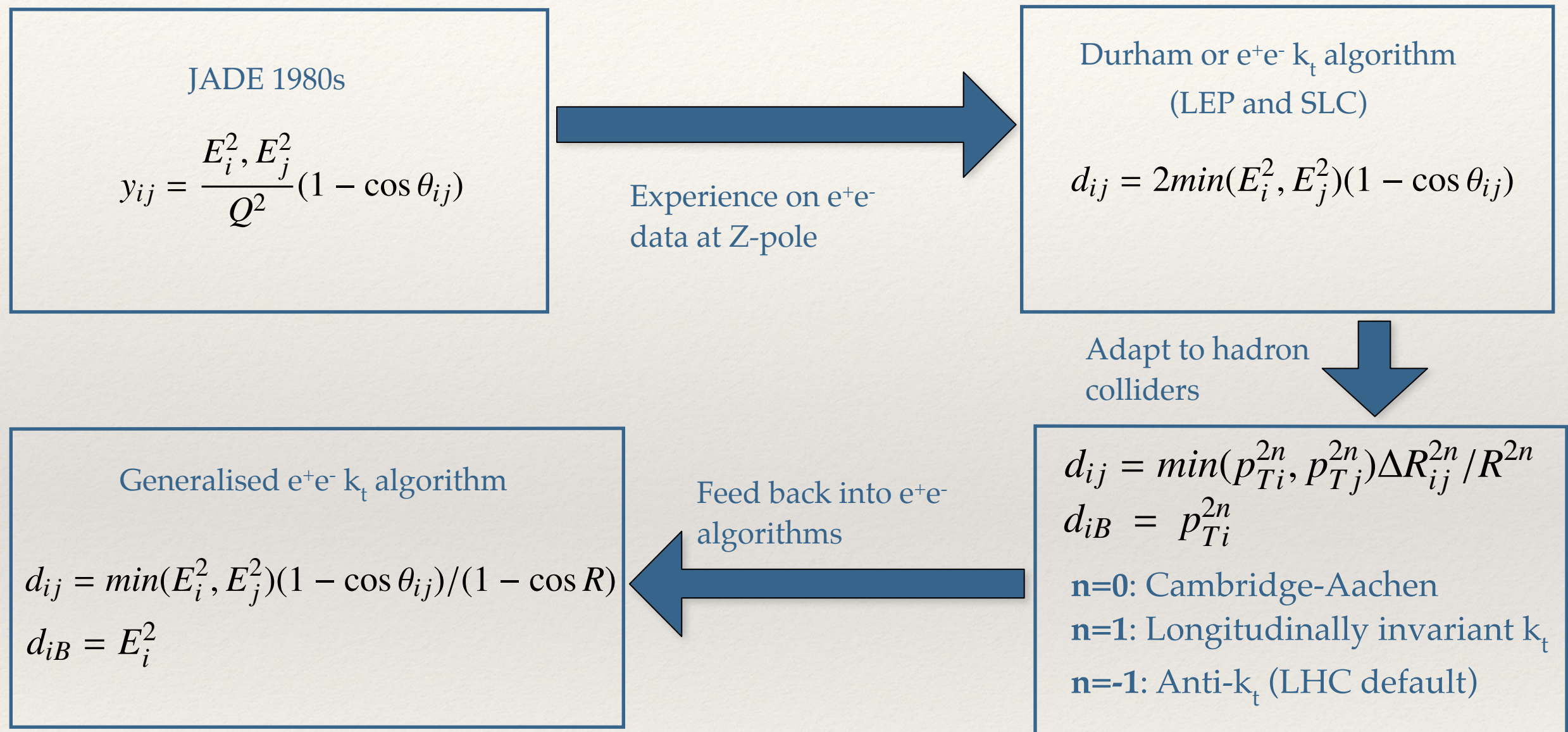
With help from Gavin Salam (CERN)



Introduction

- Jet reconstruction is a crucial step in the data analysis and it has to be adapted to the conditions of the machine
- **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



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

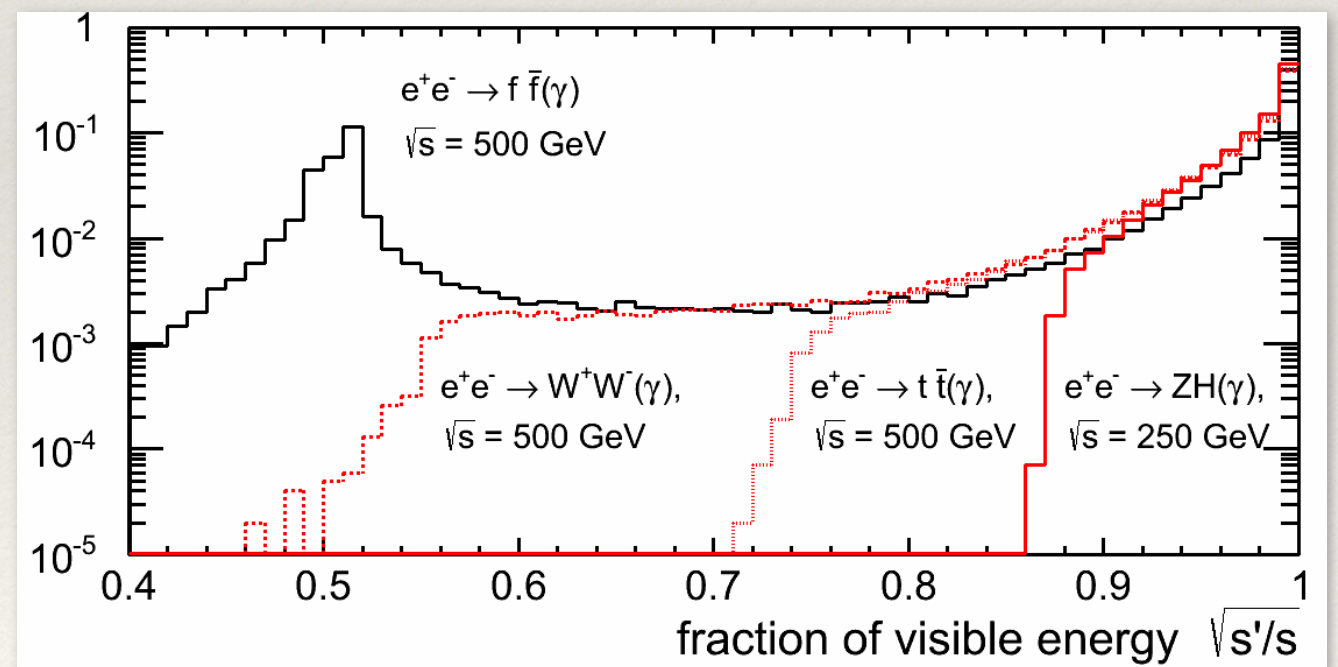
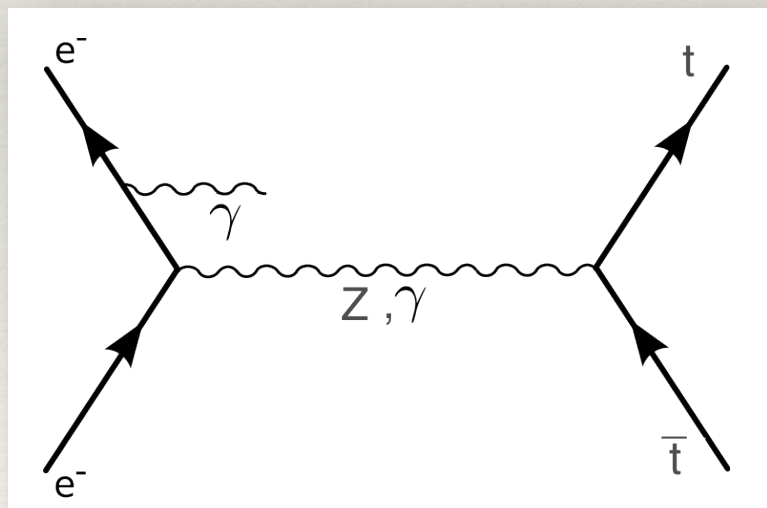
Time to rethink e⁺e⁻ algorithms!!

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 $m_f < M_Z/2 \rightarrow$ large fraction of events tends to *return* to the Z-pole
- However for **most interesting processes** at a future lepton collider ISR plays a much **less important role**
- At **lepton colliders** ISR leads to a **minor boost**
- The basis $[E, \theta]$ is 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**;

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

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

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

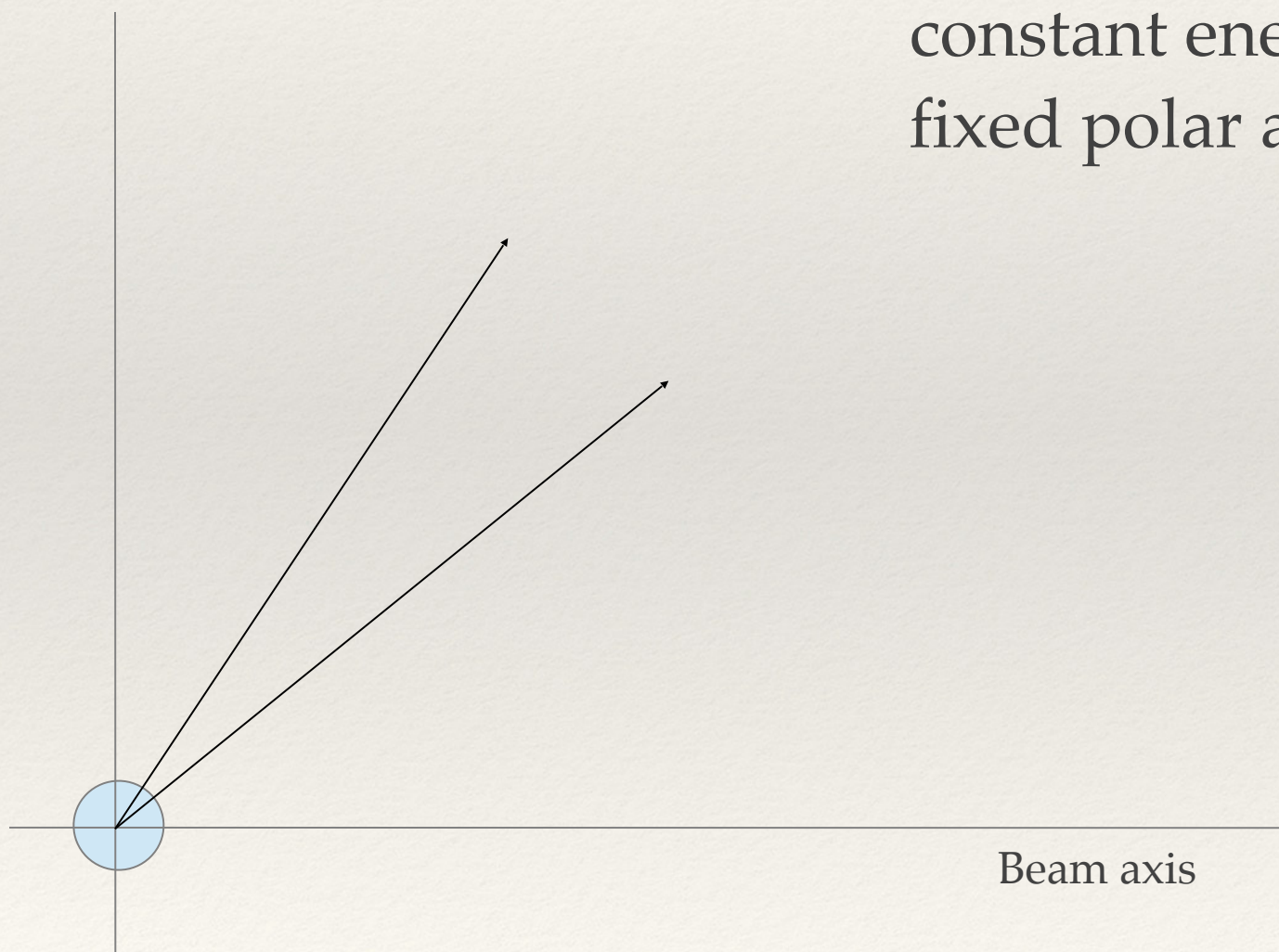
The exponent β allows to *tune* the **background rejection** level

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)**



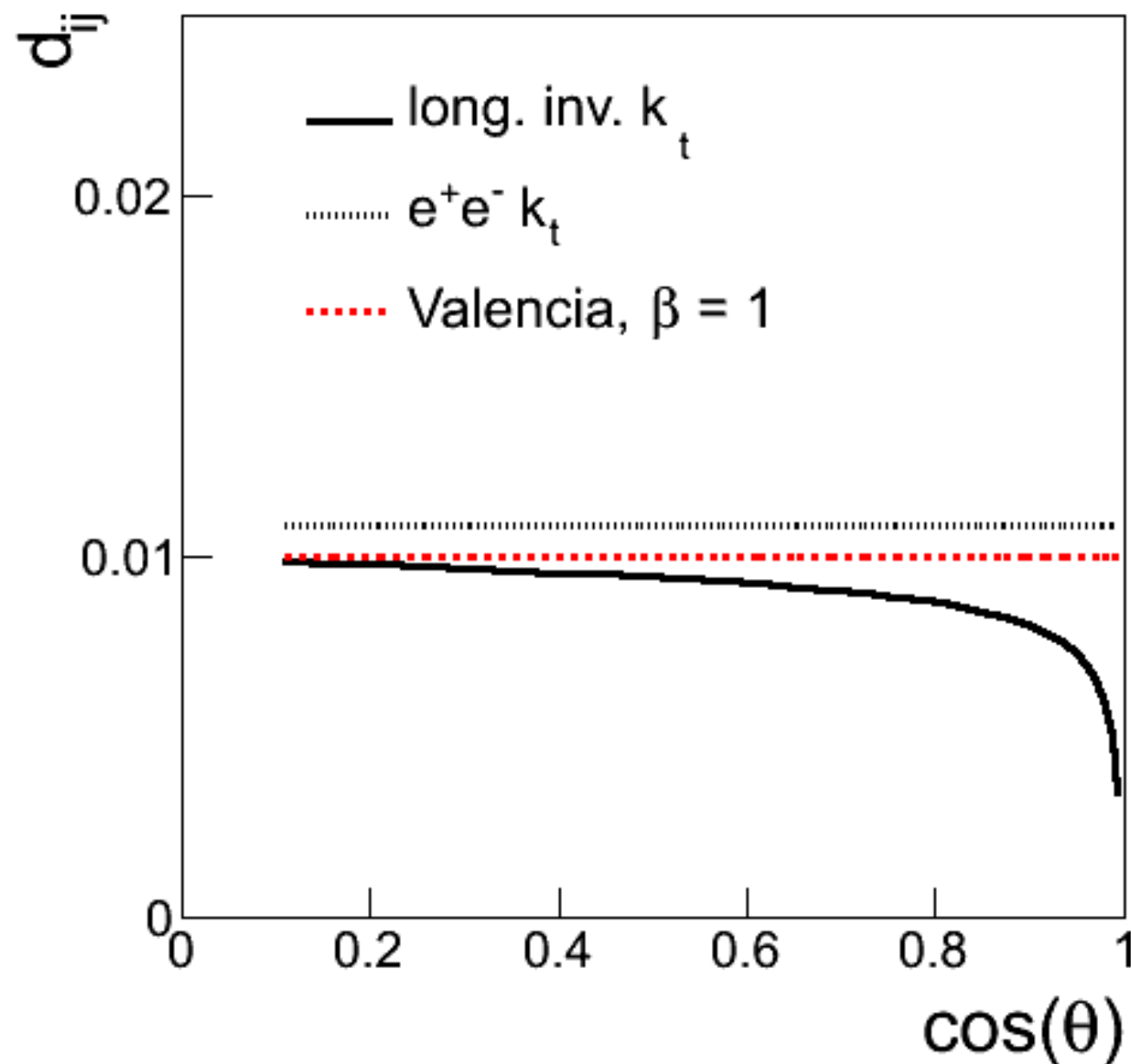
Comparison of the distance criteria

Two test particles with
constant energy ($E = 1 \text{ GeV}$) and
fixed polar angle separation (100 mrad)

Rotating from central to forward region



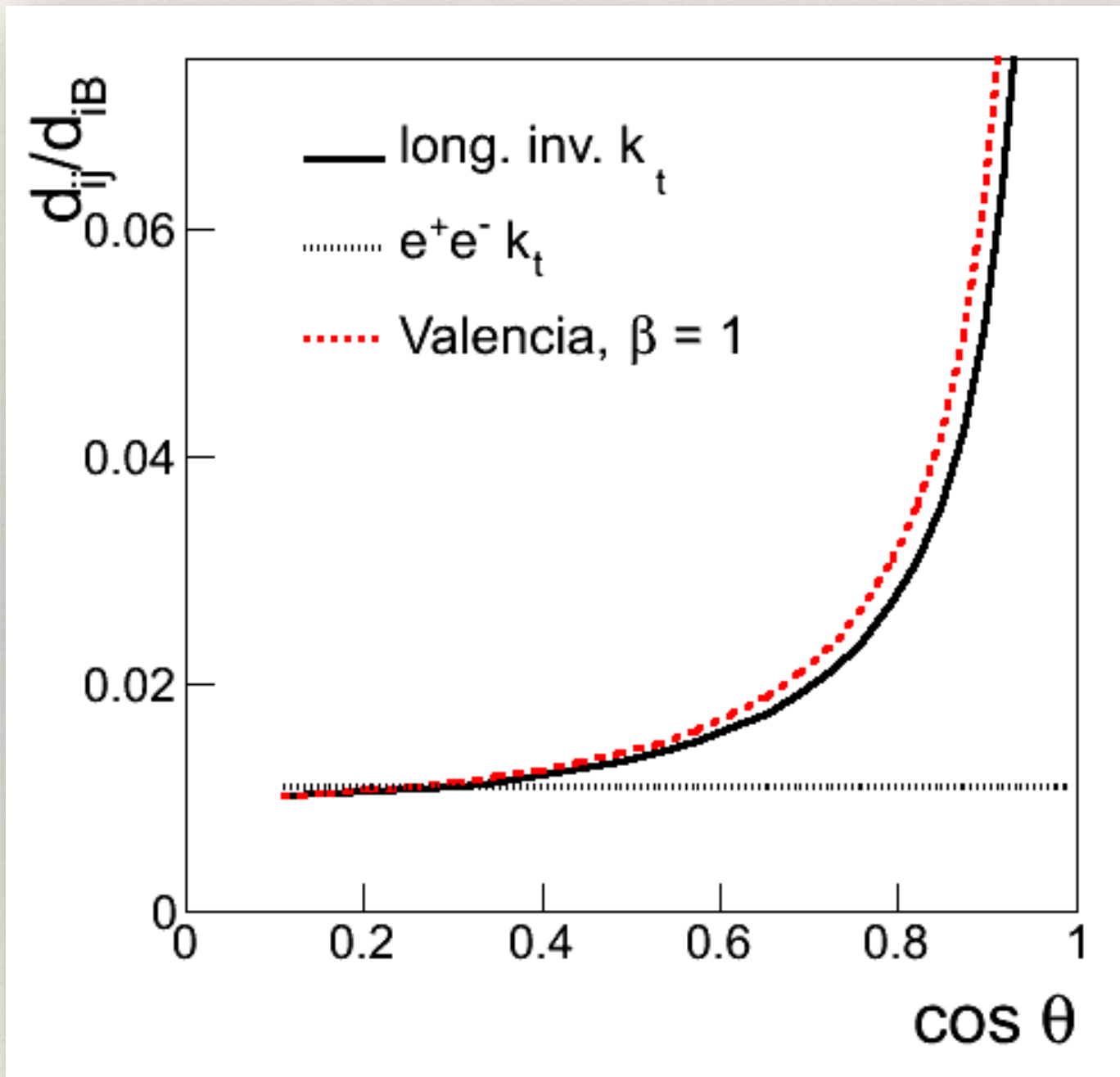
Comparison of the distance criteria



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 faster)

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 $\beta=1$ is similar (by design) to long. inv. k_t

Jet reconstruction performance

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

Event Generation

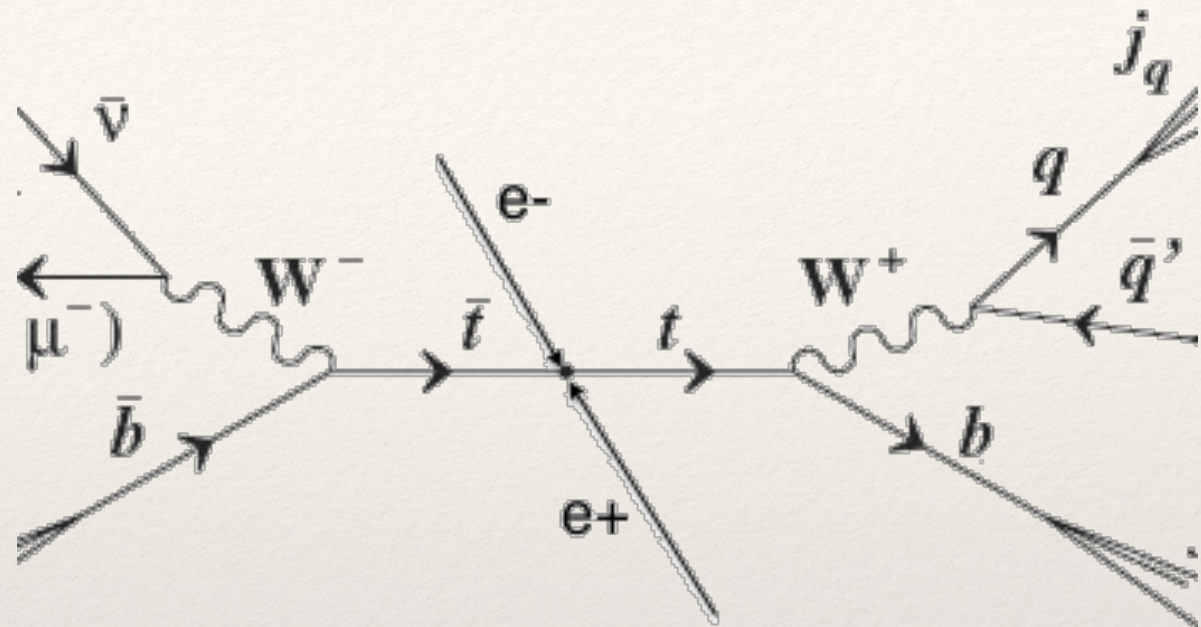
Whizard 1.95

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

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



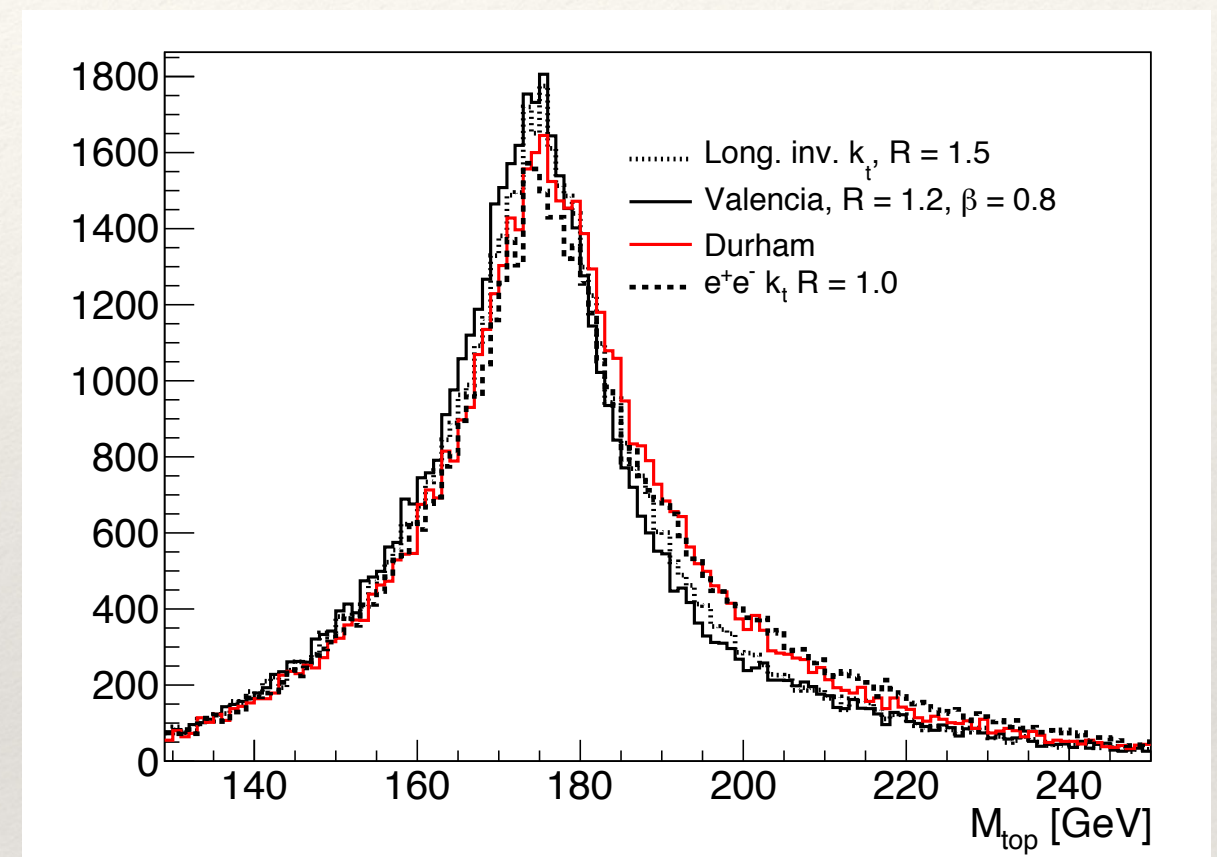
DBD Samples

$t\bar{t} \rightarrow (bjj)(b\bar{\nu})$

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 $\beta = 0.8$.

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



Durham is affected by $\gamma\gamma \rightarrow$ hadrons, longitudinally invariant k_t and Valencia OK

Resolution on jets reconstruction

Degradation of all jet-related measurements due to $\gamma\gamma \rightarrow$ 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 W candidate

Hadronic top candidate

Durham and $e^+e^- k_t$ significantly degraded.

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

Jet reconstruction performance

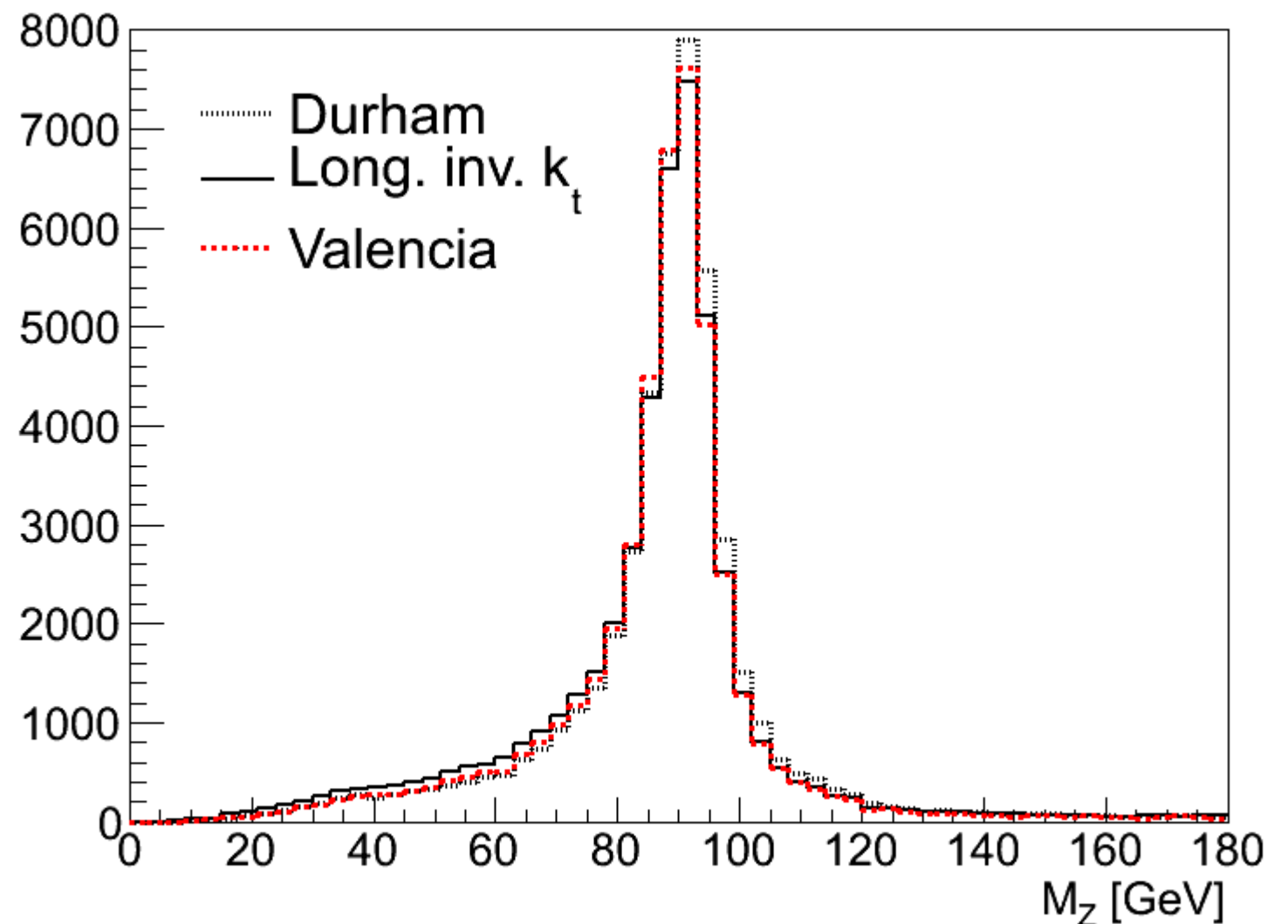
CLIC di-boson (ZZ)
production @ 500 GeV

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

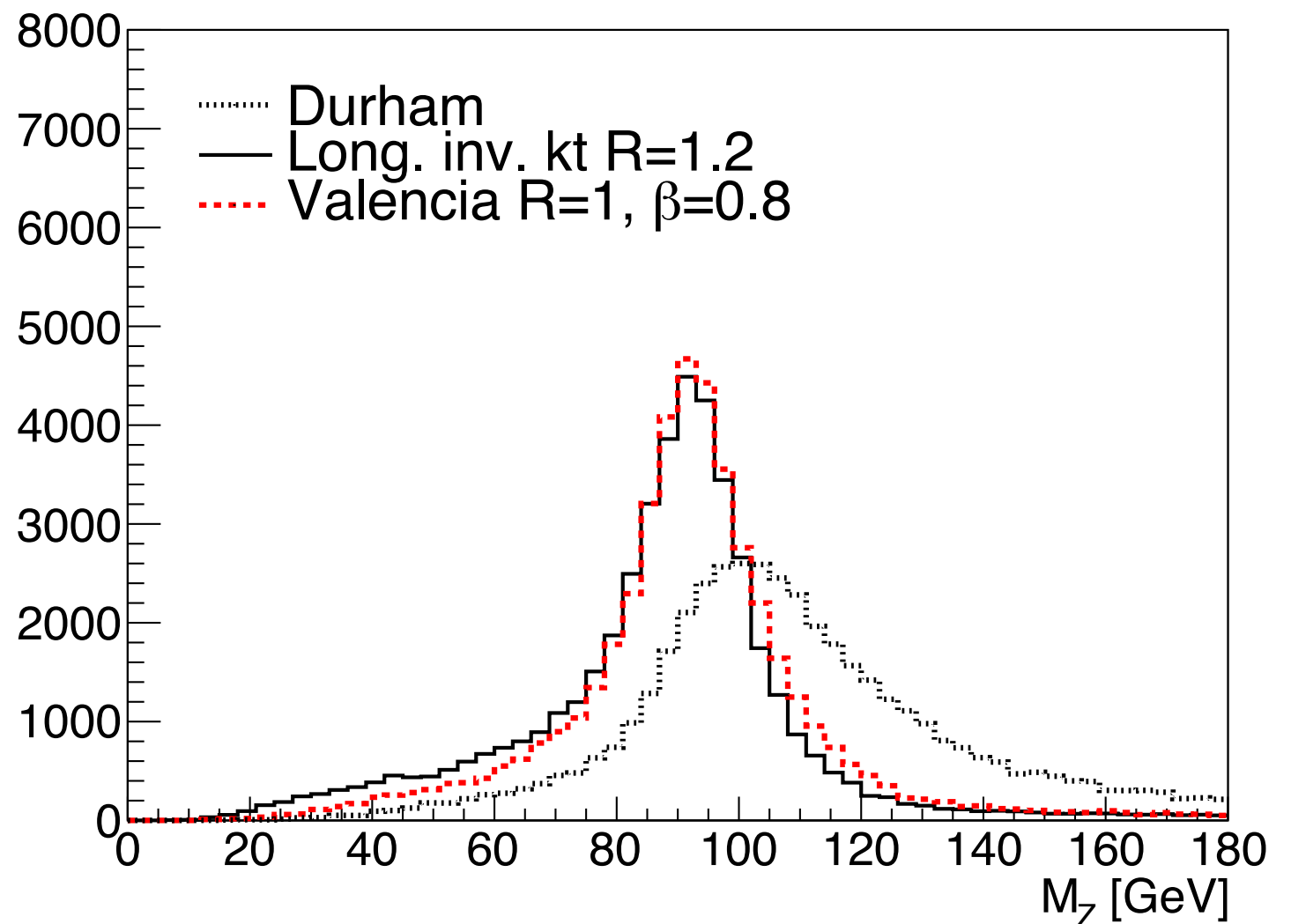
Jet reconstruction performance

CLIC di-boson (ZZ)
production @ 500 GeV
+ 300 BX of $\gamma\gamma \rightarrow \text{hadrons}$

Reconstruct Particle Flow
objects using PANDORA
+ quality and timing cuts

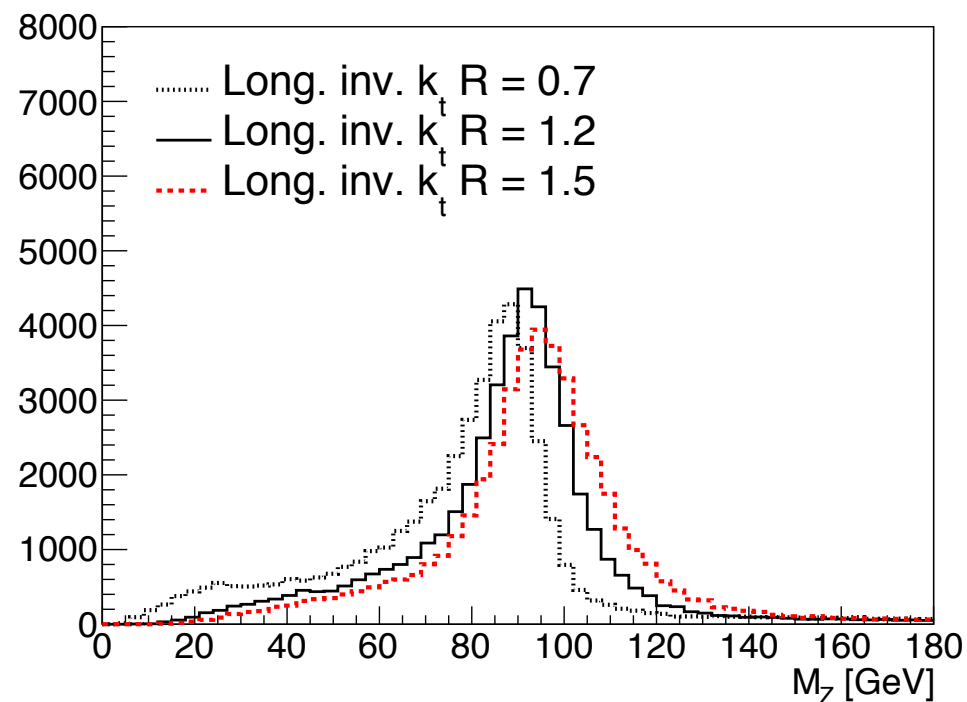
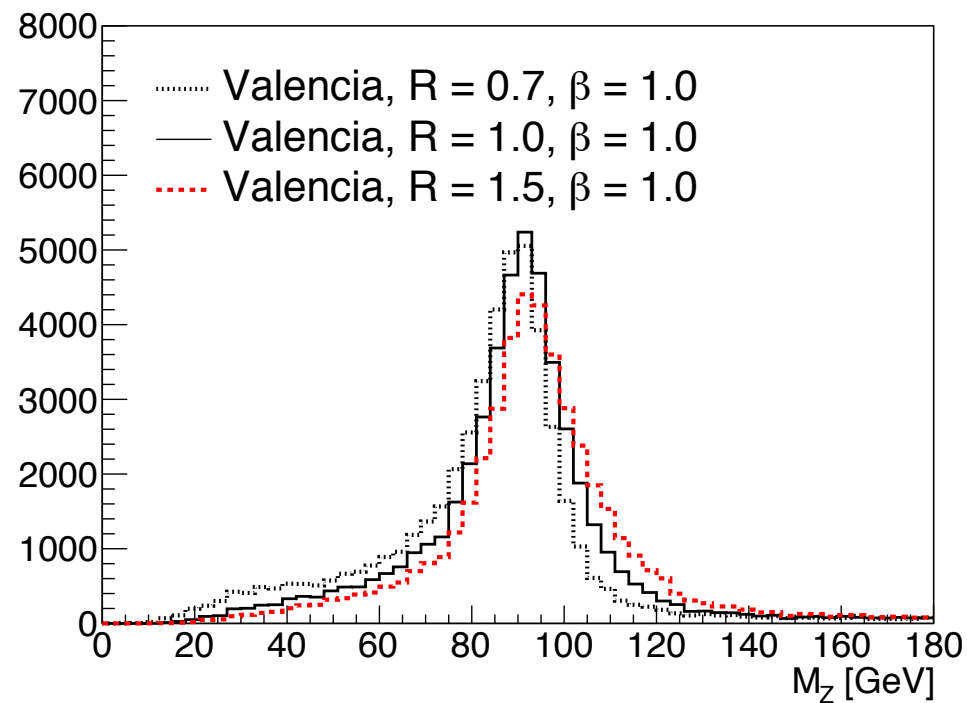
Reconstruct jets
(exclusive, $n=4$)

Form Z boson candidates,
selecting best jet pairs

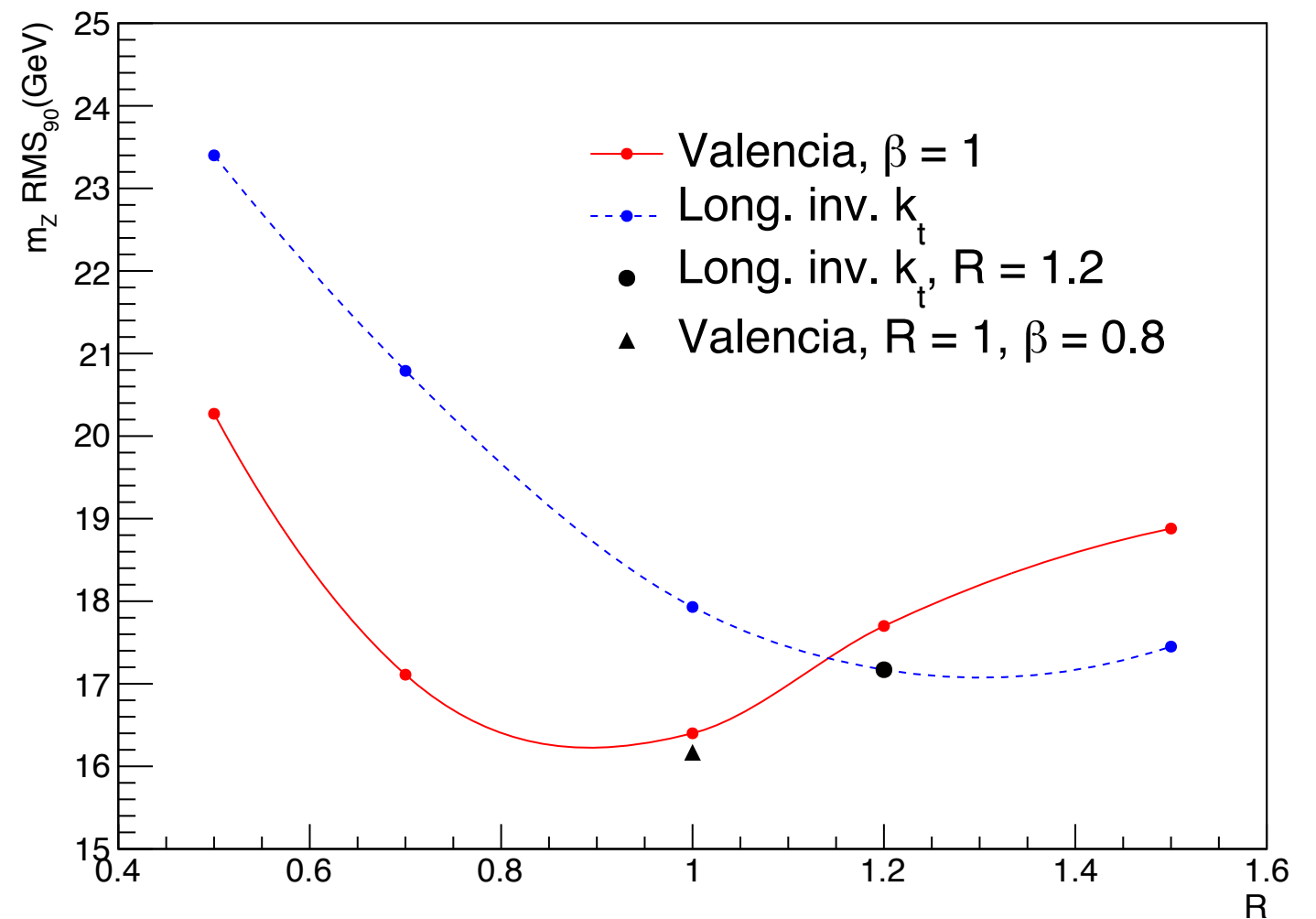


**Nominal background: Durham is severely affected,
longitudinally invariant k_t and Valencia OK**

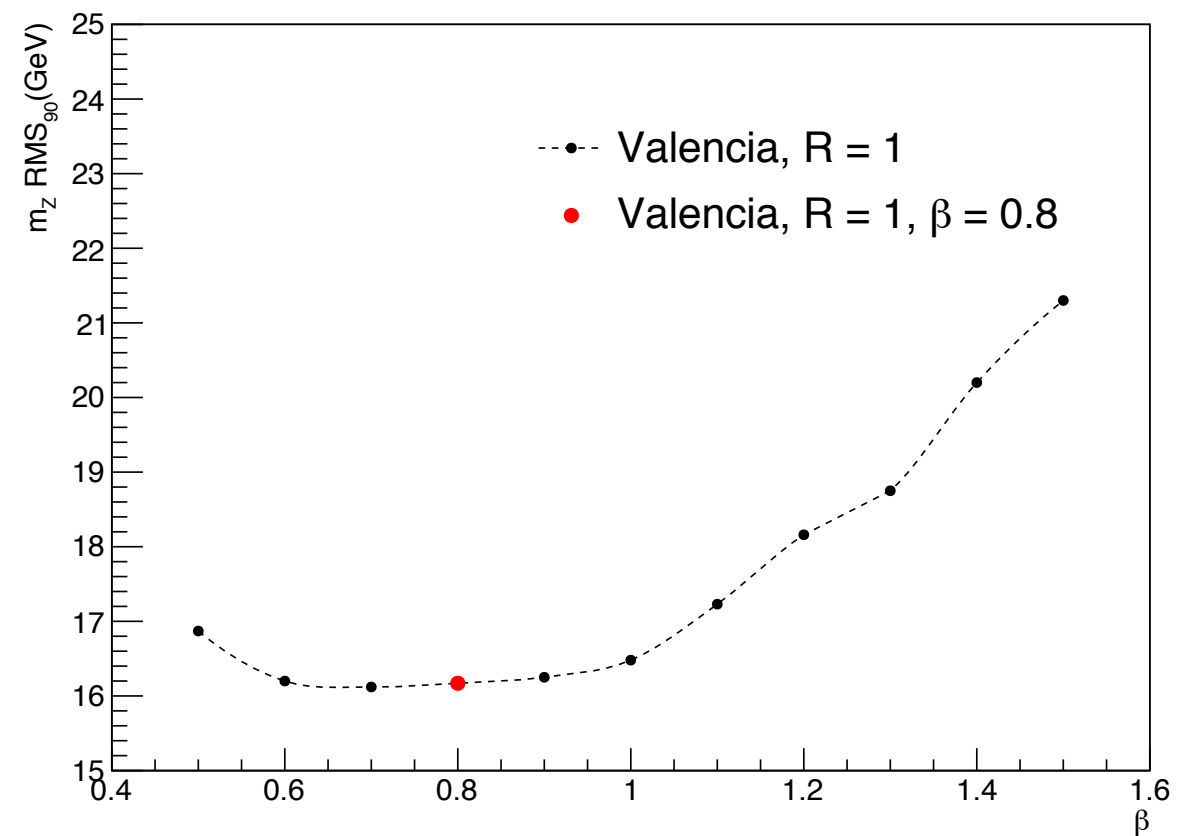
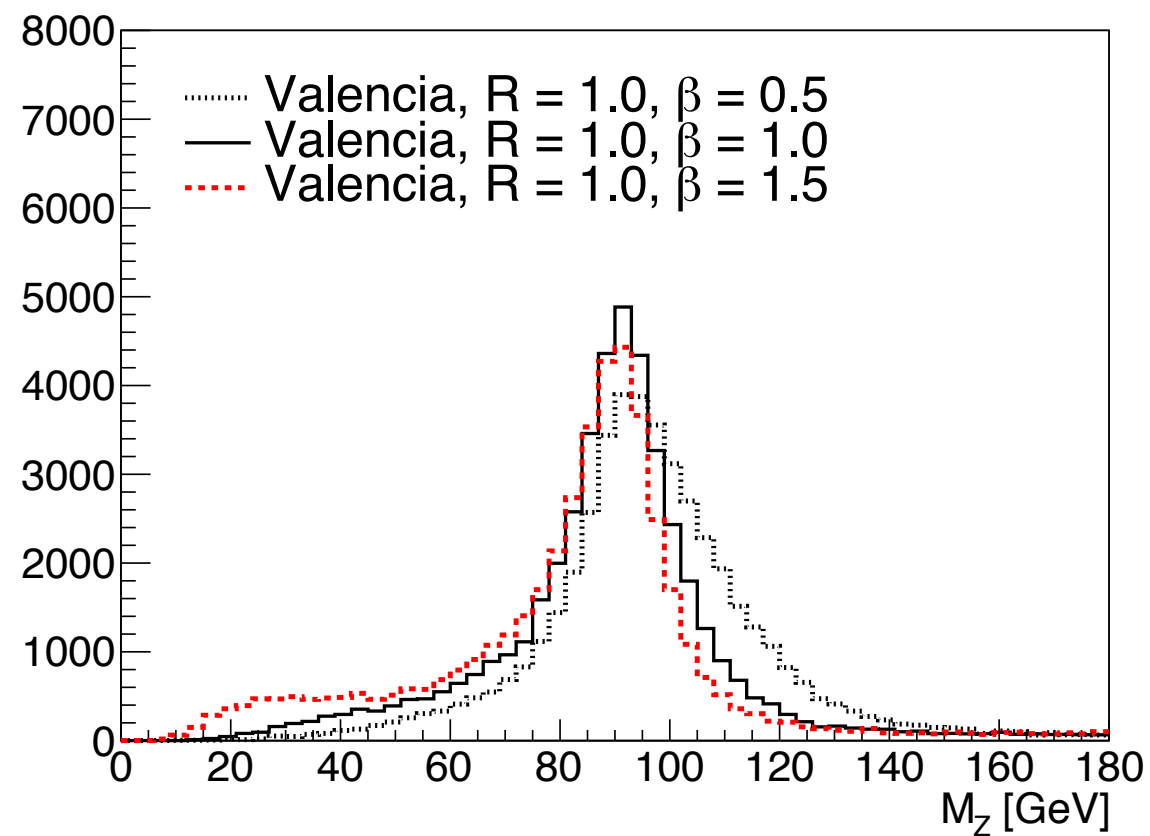
Algorithm parameters optimisation: R scan



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



Algorithm parameters optimisation: β scan



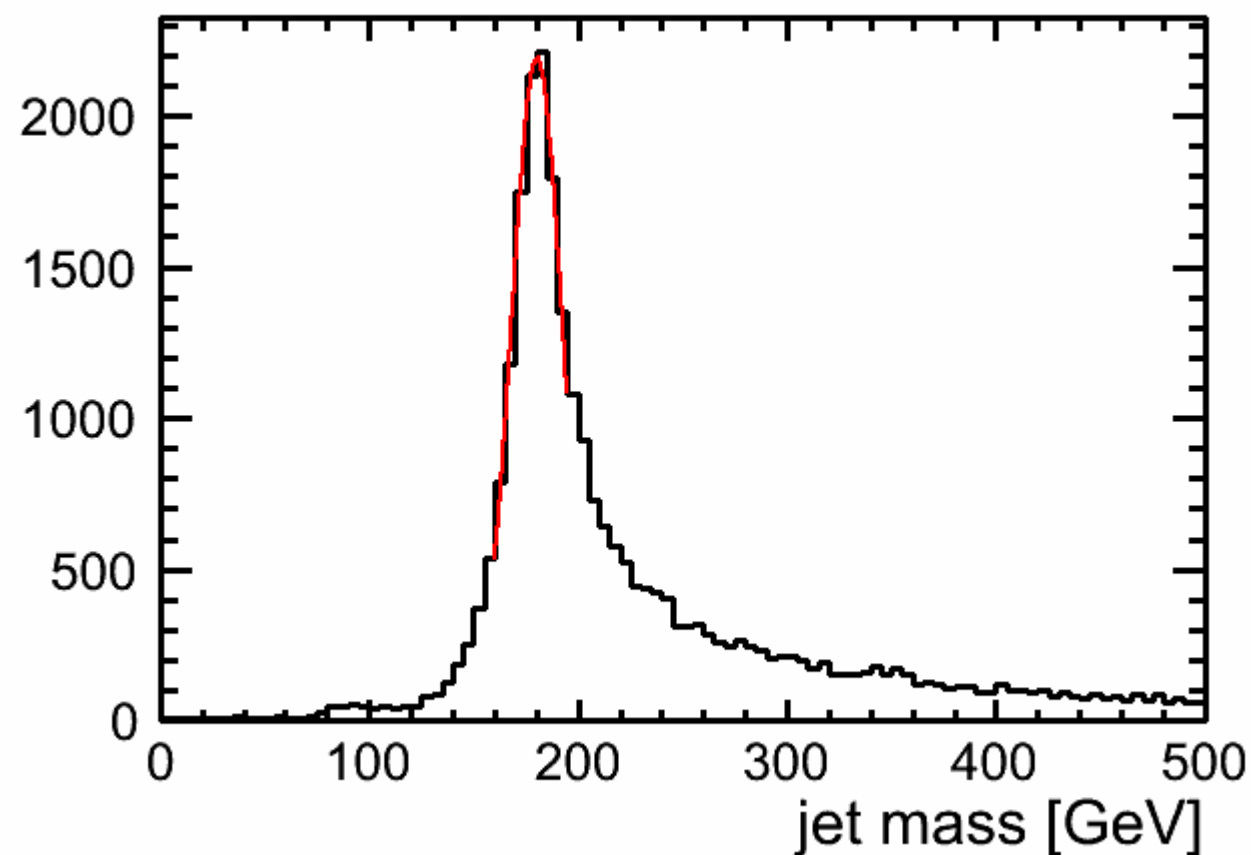
Jet reconstruction performance

The previous results in numbers: central value, width of the Z-boson mass peak and RMS₉₀

$\sqrt{s} = 500$ 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

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 k_t 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 e^+e^- algorithms because old e^+e^- algorithms are 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 $\gamma\gamma \rightarrow$ **hadrons background** levels expected at lepton colliders
- Shown to work on several benchmark analyses. Pre-print out on the arXiv since last week: *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>
- Contact me if help is needed: Ignacio.Garcia@ific.uv.es

THANK YOU FOR YOUR ATTENTION