

# A new jet reconstruction algorithm for lepton colliders

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# Introduction

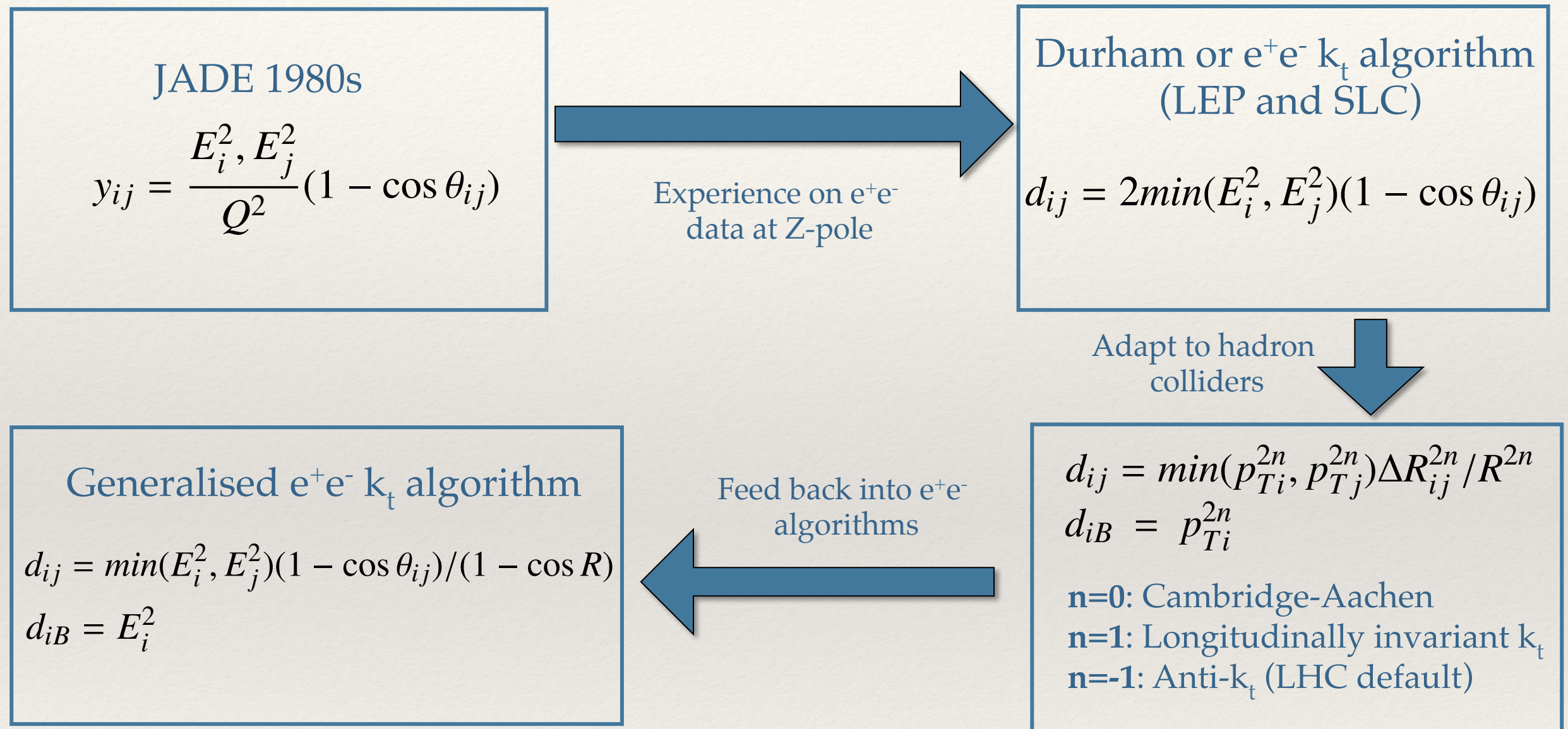
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**Jet algorithms must be:**

- ★ IR and collinear safe
  - observables are insensitive to soft or collinear emission
- ★ Simple to use in experiment and calculations
  - describe in a few lines
  - FastJet implementation
- ★ Subject to small hadronization corrections
  - Cambridge / Aachen at LEP
- ★ **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<sup>+</sup>e<sup>-</sup> algorithms!!**



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# Boost invariance

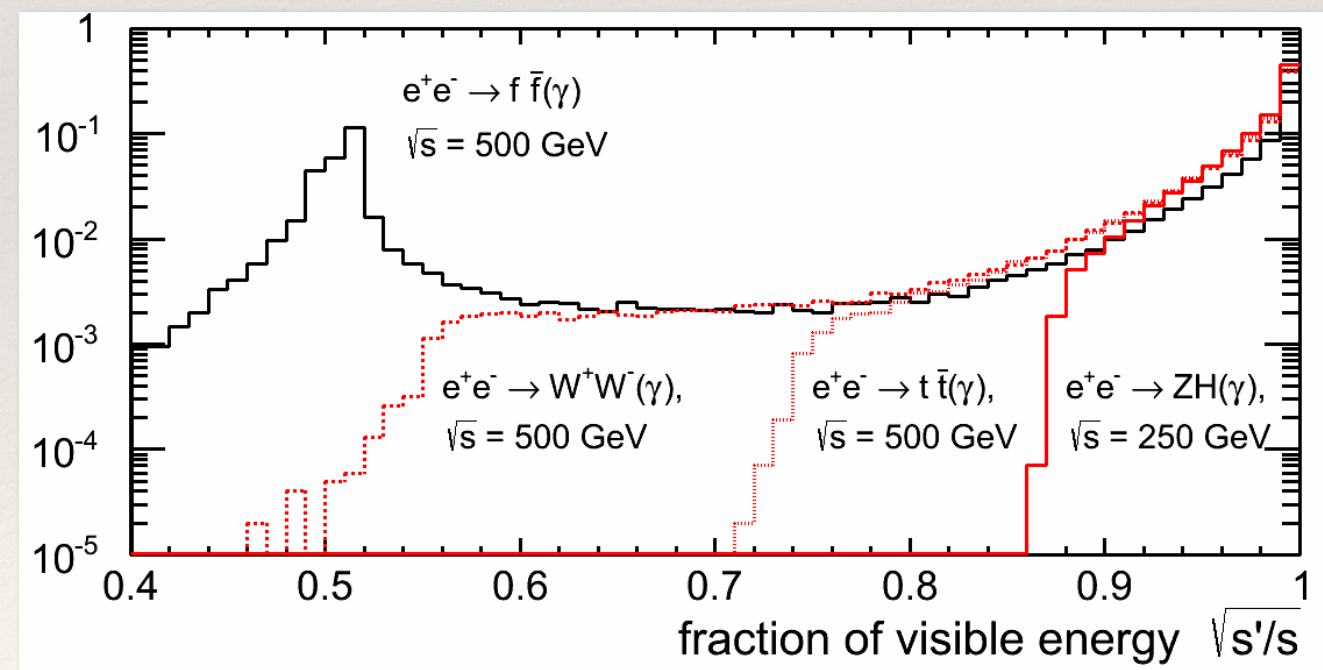
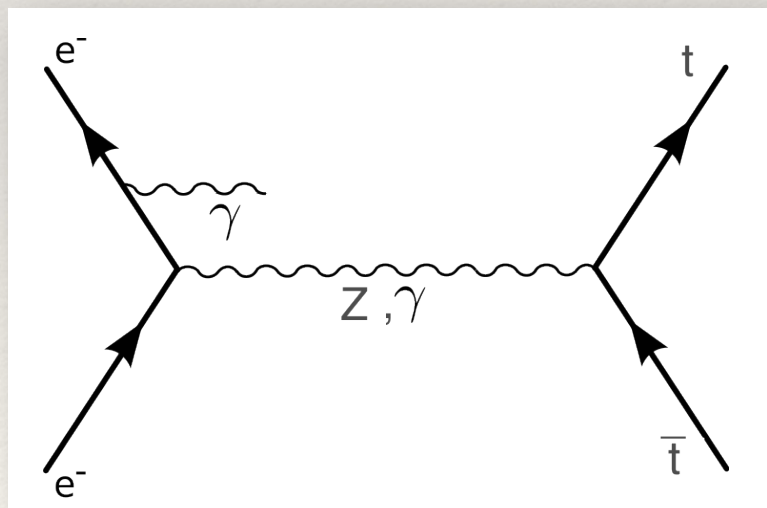
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- ★ At **hadron colliders** the **partons** that participate in the hard process generally **carry different fractions of the initial hadron energy**.
- ★ The final state acquires a substantial **Lorentz boost** along the beam axis.
  - LHC di-jets: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



# Boost invariance

- ★ Photons emitted by the incoming beam particles (**Initial State Radiation**) can carry away a significant fraction 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**





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# Background levels at future LC

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- ★ 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]



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# The Valencia jet algorithm

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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  $\beta$  allows to *tune* the **background rejection** level

The algorithm has been implemented as a plugin for the *FastJet* package and will be made available in the *fjcontrib* area

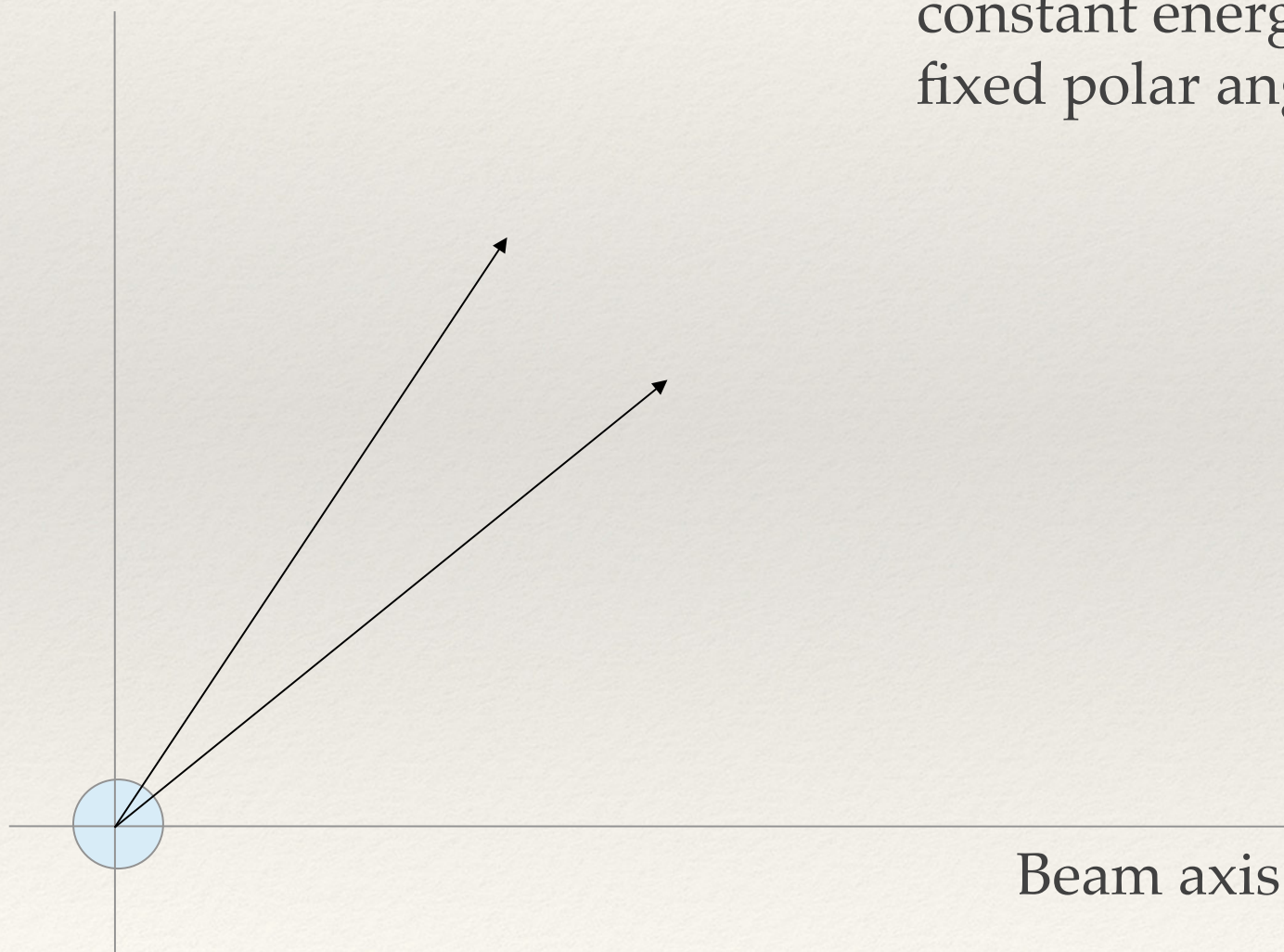


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# Comparison of the distance criteria

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





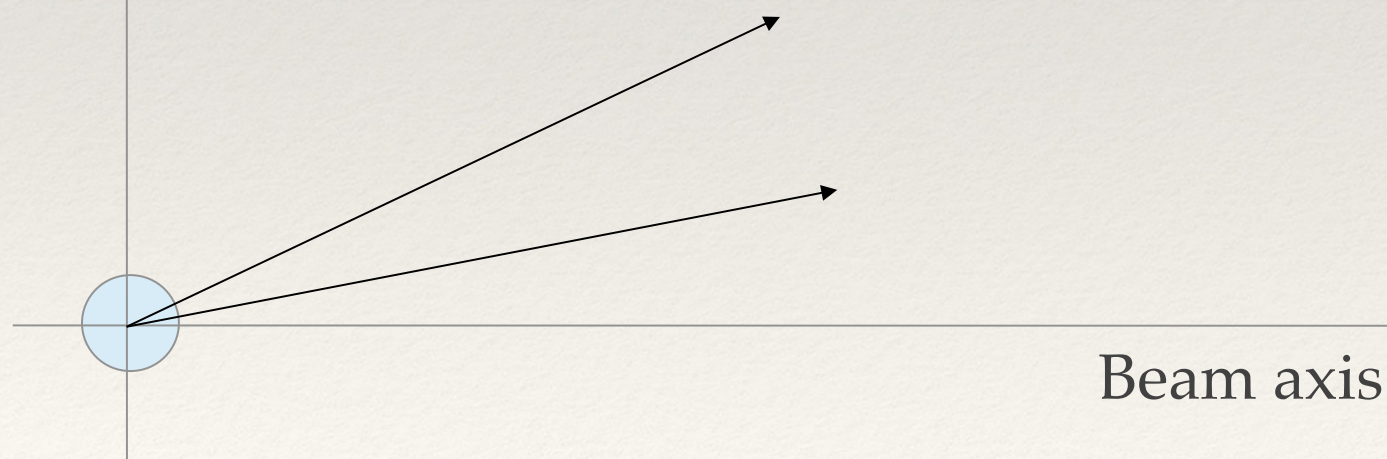
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# Comparison of the distance criteria

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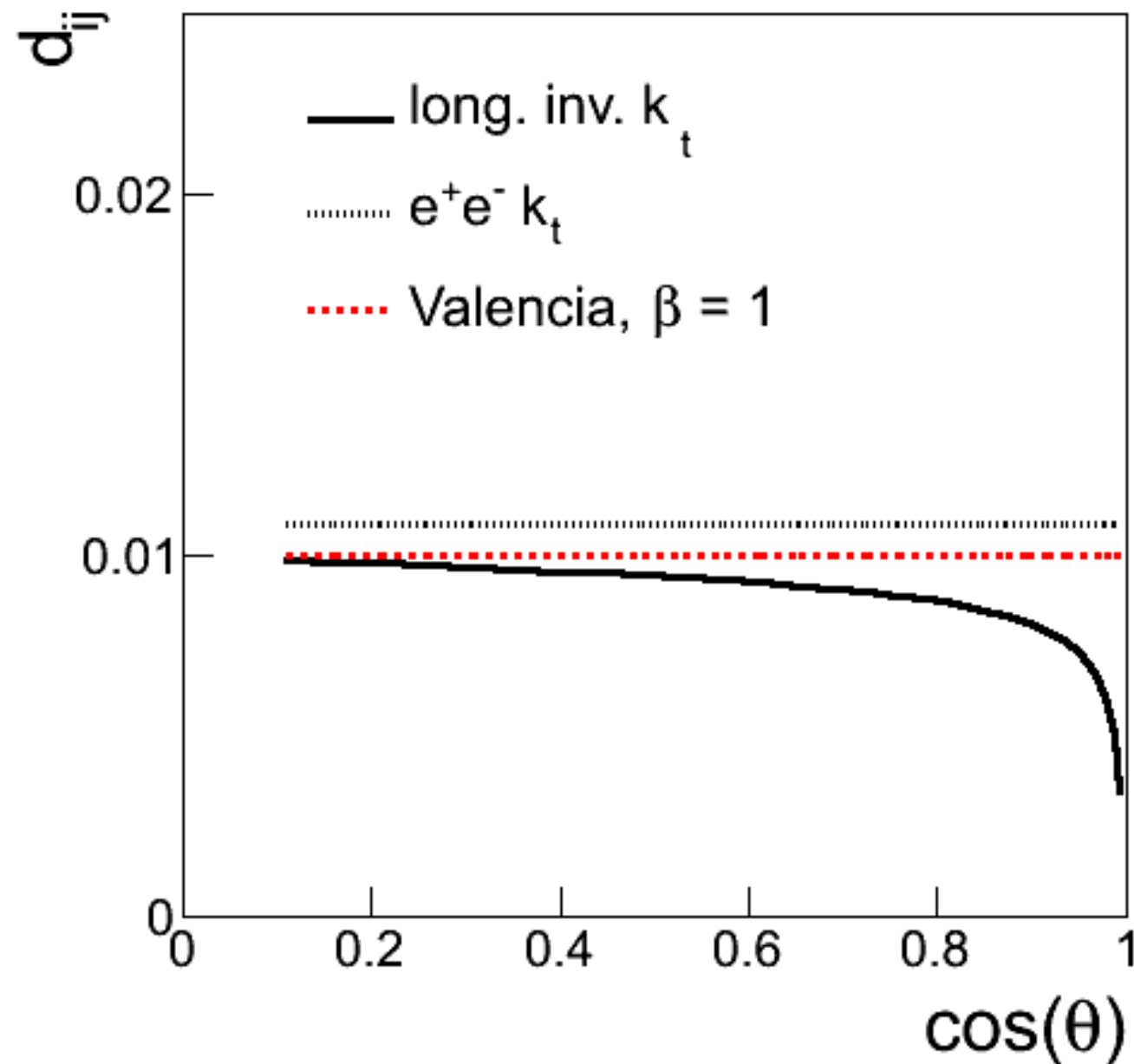
**Two test particles** with  
constant energy ( $E = 1 \text{ GeV}$ ) and  
fixed polar angle separation ( $100 \text{ mrad}$ )

Rotating from central to forward region





# Comparison of the distance criteria

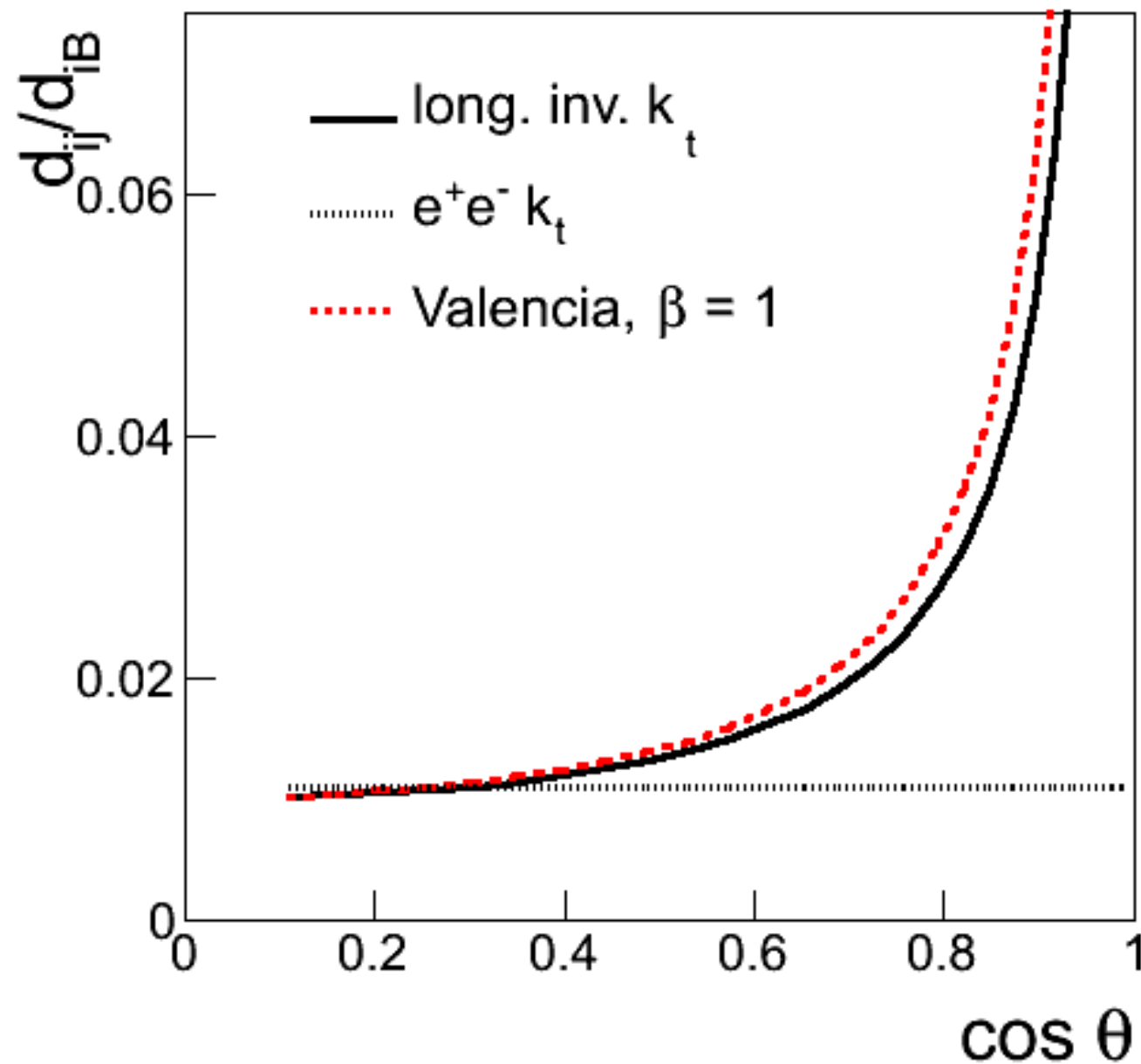


As the two-particle system rotates into the forward region, the distance  $d_{ij}$  of longitudinally invariant  $k_t$  decreases ( $\Delta\eta$  increases,  $p_T$  decreases faster)

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

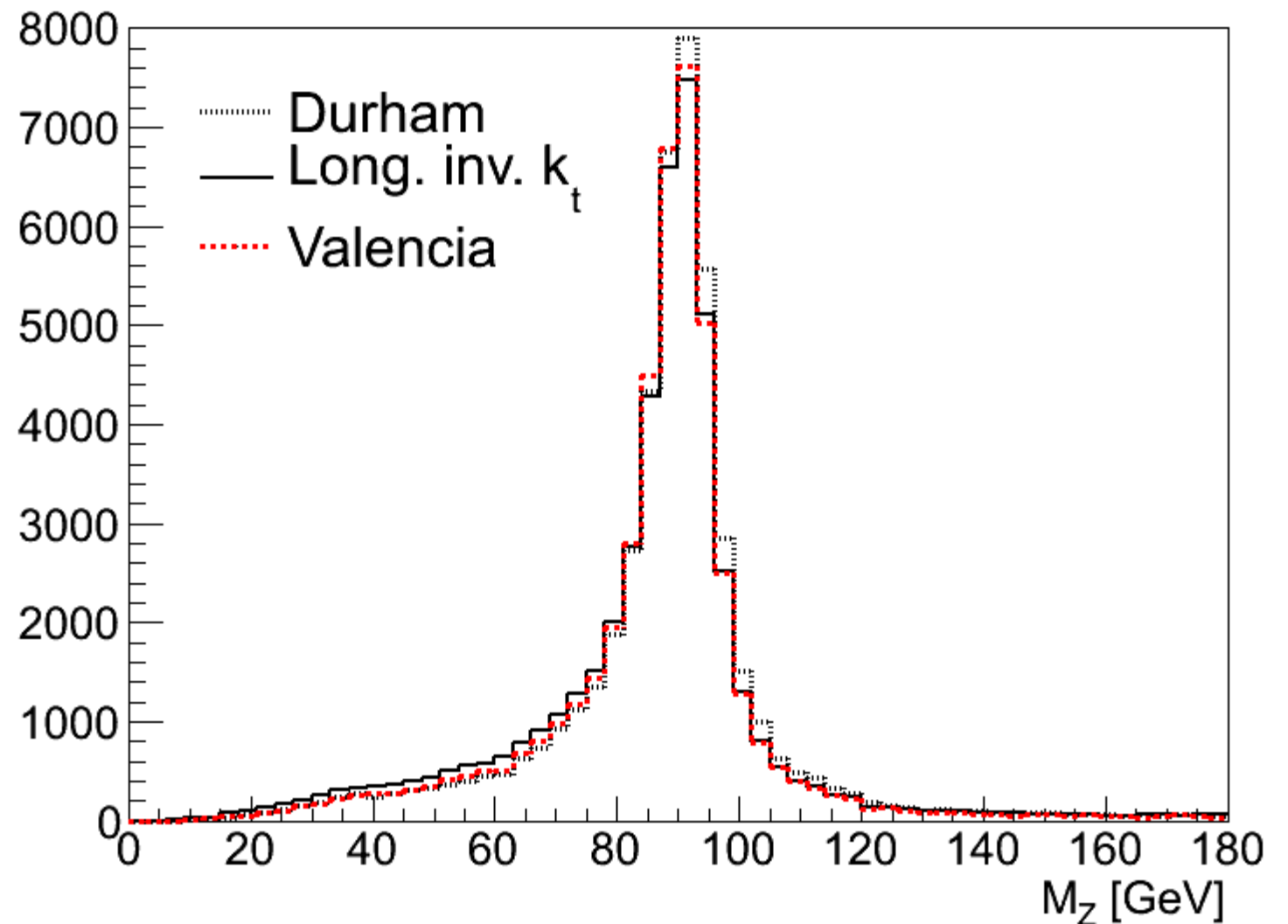
CLIC di-boson (ZZ)  
production @ 500 GeV

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**



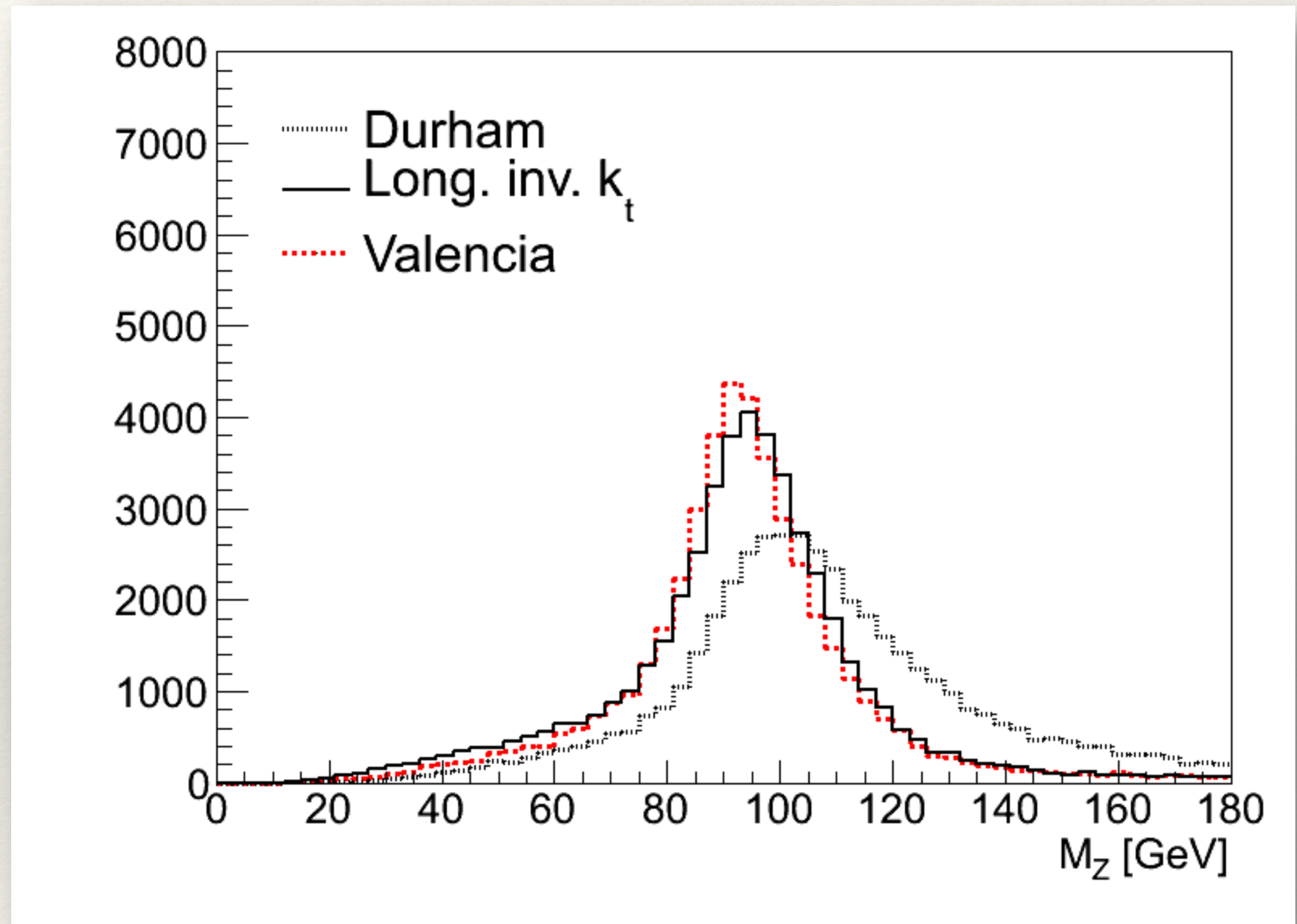
# Jet reconstruction performance

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**



# Jet reconstruction performance

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

$\sqrt{s} = 500 \text{ GeV}$ , no background overlay			
[ GeV ]	$m_Z$	$\sigma_Z$	RMS <sub>90</sub>
Durham	90.6	5.4	13.8
long. inv. $k_t$	90.4	5.3	14.3
Valencia	90.3	5.2	12.5
$\sqrt{s} = 500 \text{ GeV}$ , 0.3 $\gamma\gamma \rightarrow \text{hadrons}$ events/BX			
[ GeV ]	$m_Z$	$\sigma_Z$	RMS <sub>90</sub>
Durham	101.1	13.6	28.8
long. inv. $k_t$	95.1	10.9	17.9
Valencia	93.1	10.2	17.1

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



# What about the ILC?

At the ILC the situation is less critical, but action is nonetheless required:

Degradation of all jet-related measurements due to  $\gamma\gamma \rightarrow \text{hadrons}$  background, including vertex charge, observed in many studies

Follow example: IFIC/LAL study of lepton+jets  $t\bar{t}$  @ 500 GeV, [arXiv:1307.8102]

RMS <sub>90</sub> [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 significantly degraded.**  
**Hadron collider algorithm and Valencia offer better reconstruction for all hadronic observables**



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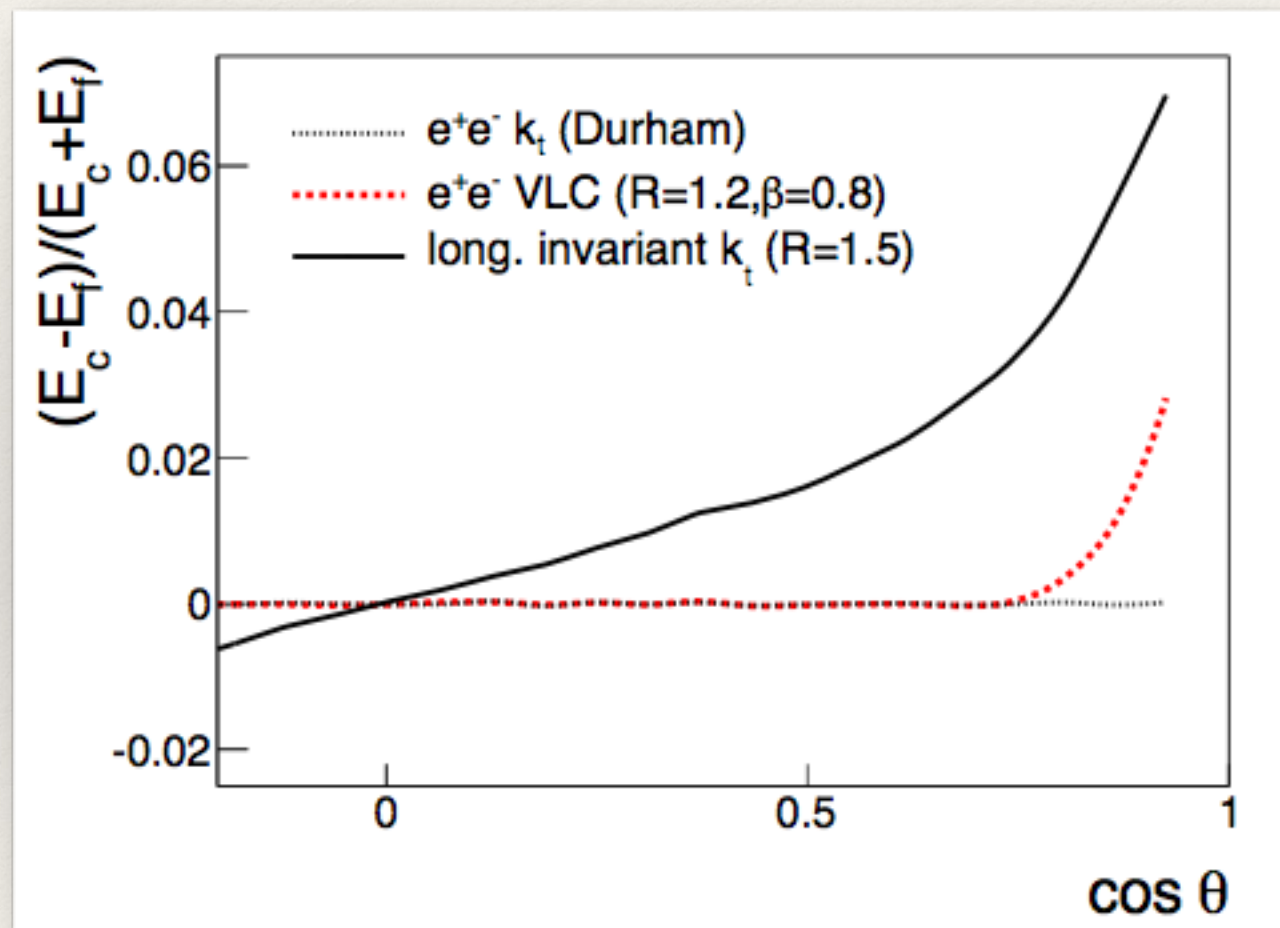
# Conclusions

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- ★  $\gamma\gamma \rightarrow$  hadrons bkg. forces us to rethink  $e^+e^-$  algorithms
- ★ The Valencia jet algorithm retains the natural inter-particle **distance criterion** for  $e^+e^-$  collisions and offers **robust performance** in the presence of the (mild) **background** levels expected at lepton colliders
- ★ It also allows to **tune the background rejection** for any machine and for the specific requirements of a given analysis
- ★ There is a paper to be submitted soon
- ★ Goes to show that, taking a break to rethink jet reconstruction, one can come up with new ideas (and better performance)



# Comparison of the distance criteria



Decreasing distance in forward region  
→ **bias in energy sharing**

Toy experiment with two jets with typical lateral development, separated by 1...

Pronounced bias for long. invariant  $k_t$

Effect of beam jets visible for very forward jets in Valencia algorithm