Jets at a future e^+e^- collider

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With thanks to Nacho García, Gavin Salam, André Sailer, Jesse Thaler

Scope of this talk

Jet reconstruction at the ILC is not simply an extension of the LEP/SLC experience

- higher energy, higher jet multiplicity, more background, better detectors

After introduction of $\gamma\gamma \rightarrow$ hadrons in full simulation, most LC physics studies now use hadron collider algorithms,

- is this the best we can do?

Time for a critical evaluation...

- understand impact of jet reconstruction on physics performance
- Rethink jet reconstruction algorithms

Can we benefit from recent progress in jet algorithms?

- Pile-up correction/mitigation?
- Jet substructure as a driver for detector design?
- Boosted objects?

Take advantage of “future projects” session of the BOOST workshop series

An Australian analogy

The pig-footed bandicoot had lived in Australia for millions of years, and was (according to mr. Darwin) very well adapted to its environment. Still it went extinct (almost without putting up a fight) soon after the arrival of Europeans.

The rabbit had adapted, over millions of generations, to its European habitat. It conquered Australia in a few years after its (unfortunate) introduction in the country.

Moral, so far:

yes, a hadron collider algorithm may work better...

But, is the rabbit the optimal animal for Australia?

An Australian analogy

But, is the rabbit the optimal animal for Australia?

Probably not... one ought to be able to design a better rabbit especially for Australia.

Moral: understand what makes longitudinally invariant jet finding work so well. And adapt the jet finding to make it even better for the purpose of high energy e^+e^- collisions.

Jets in e^+e^- colliders

Jet physics AND jet reconstruction performance are important at e^+e^- colliders

After a top (W, Z, Higgs) factory like the LHC, e^+e^- collider samples are relatively small:

→ 300.000 $t\bar{t}$ pairs at 500 GeV

Use hadronic final states (also in Higgsstrahlung analysis)

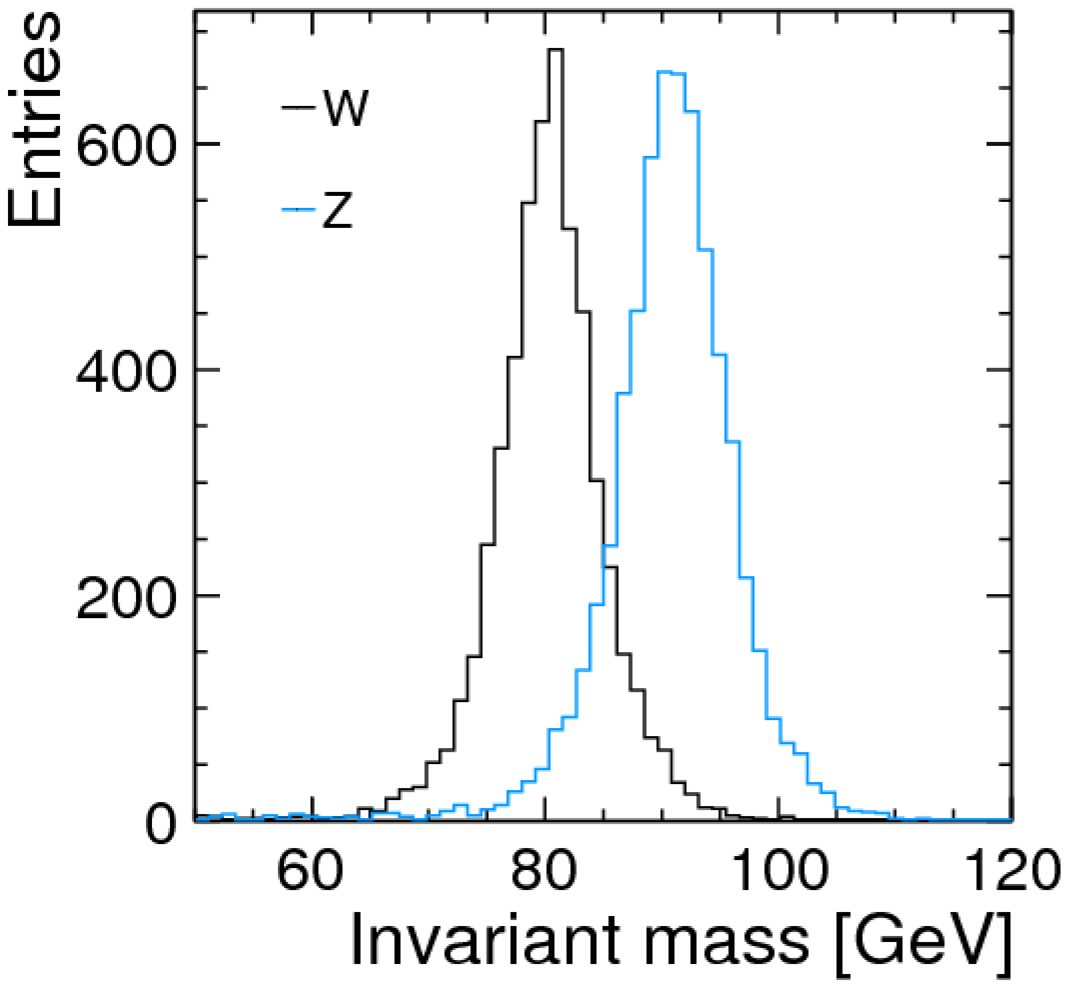
Distinguish hadronic W and Z decays

(the main calorimeter specification on energy resolution at low energy, a requirement on the jet mass resolution at high energy)

Jet multiplicity increases with center-of-mass energy

di-boson → 4 jets, Zh → 4 jets, $t\bar{t}$ → 6 jets, $t\bar{t}h$ → 8 jets

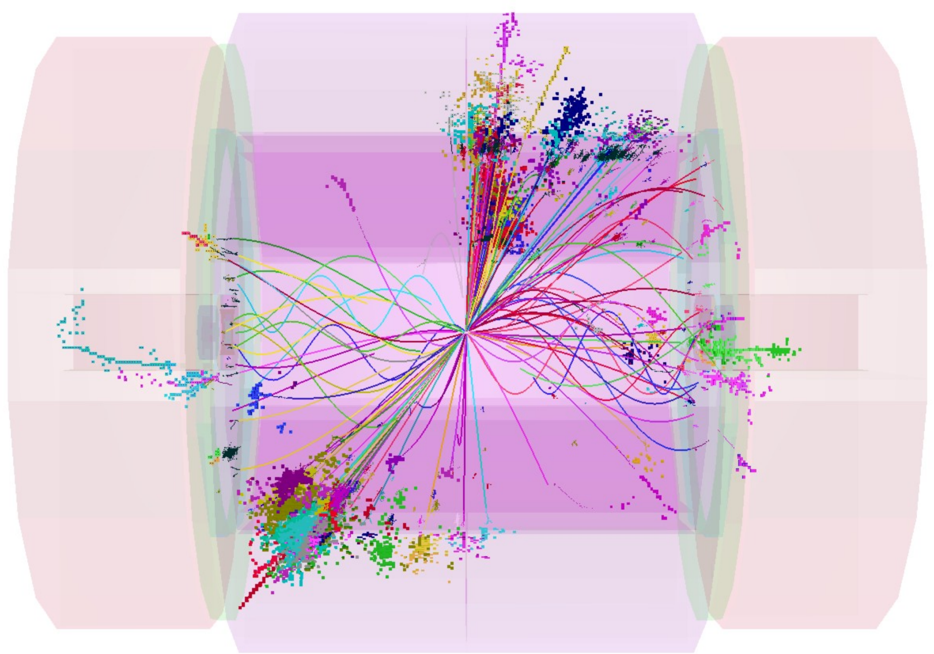
(jet reconstruction can spoil the energy measurement even if all particles are precisely measured)

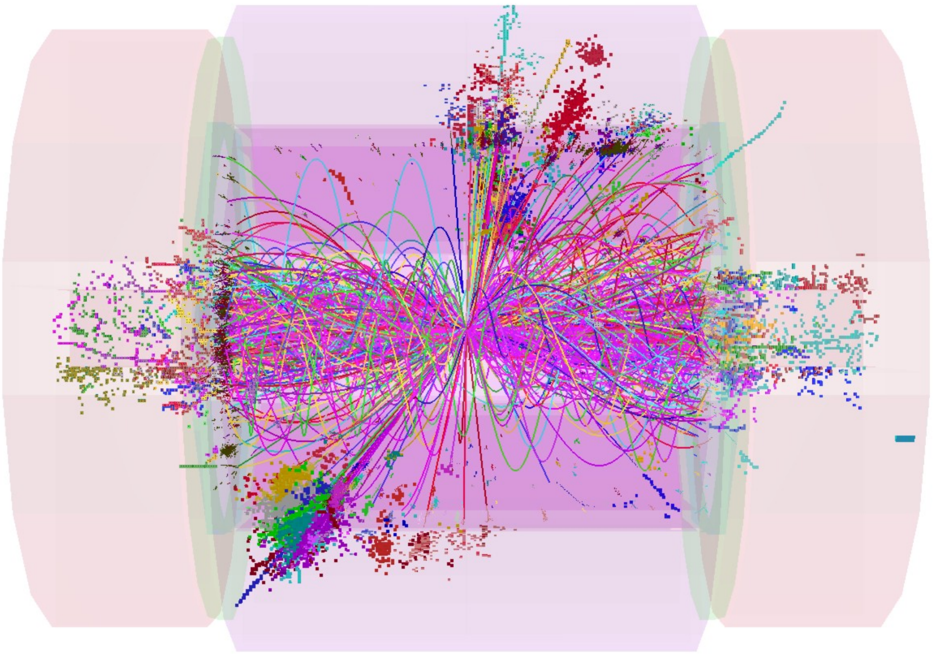


LC backgrounds

Lepton colliders offer a relatively clean environment (compared to the LHC), but not quite to the level that we can ignore backgrounds completely:

- Incoherent pair production
- $\gamma\gamma \rightarrow$ hadrons production





Example: a CLIC bunch train worth of $\gamma\gamma \rightarrow$ hadrons superposed on a physics event. If all CLIC3TeV detector systems integrate over 10 ns (=20BX), background deposits 1.2 TeV of energy in the calorimeter systems.

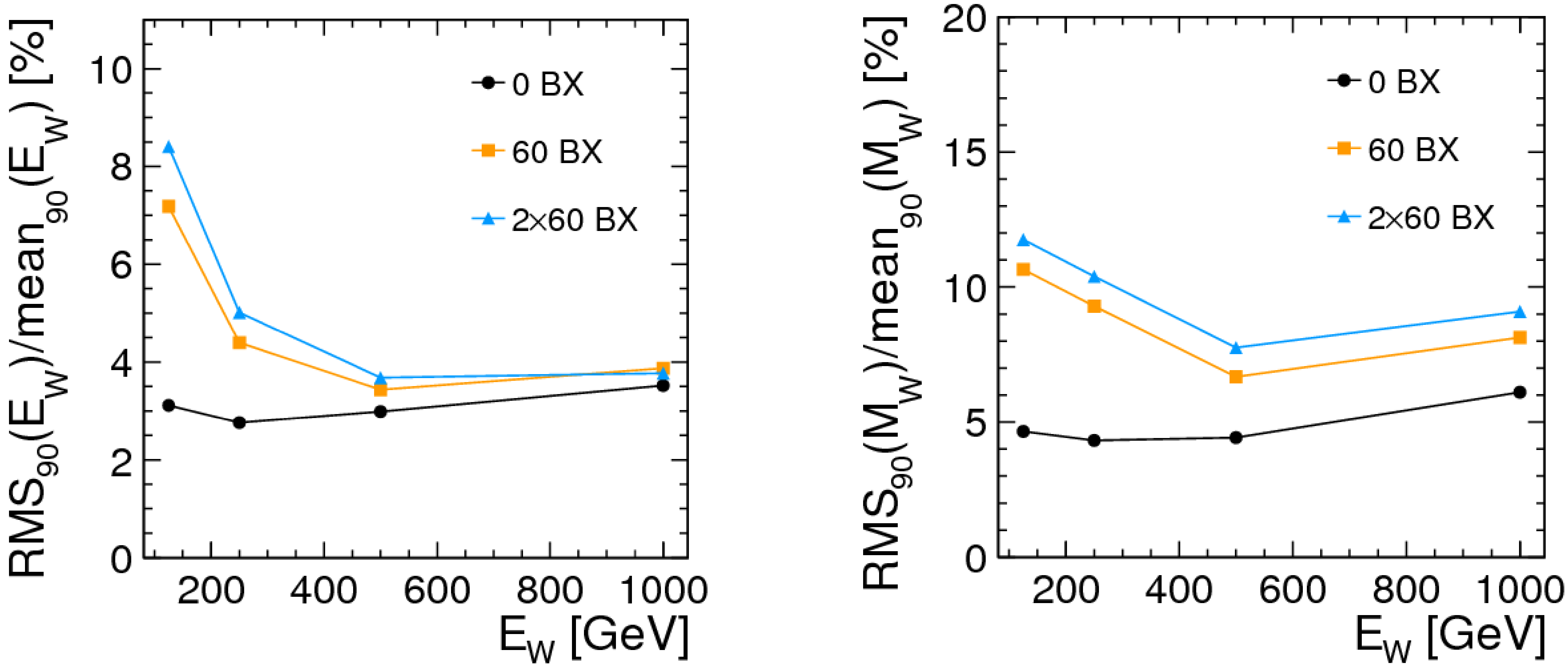
$\gamma\gamma \rightarrow$ hadrons

- Strongly peaked in the forward direction
- For a given machine, background level scales with instantaneous luminosity
  - → Much larger at 3 TeV than at 500 GeV (even with the same technology)
- Its impact depends on the bunch structure and detector read-out speed
  - → ILC, 1300 bunches spaced by 500 ns (typically single-BX read-out possible)
  - → CLIC, 312 bunches spaced by 0.5 ns

Use CLIC case as a stress test for jet reconstruction; if it works there, it's good for ILC too.

Impact of background

$e^+e^- \rightarrow W^+W^- \rightarrow l\nu\, q\bar{q}$ events at CLIC with W energies of 100, 250, 500 and 1000 GeV
Overlay 60 (120) BX worth of $\gamma\gamma \rightarrow$ hadrons, select in-time reconstructed particles, remove lepton
Reconstruct long. inv. k_t jets exclusively (N=2, R=0.7)



Energy resolution at high energy is not too badly affected,
mass resolution suffers everywhere

[CLIC CDR, Marshall, Münnich & Thomson, arXiv:1209.4039], non-negligible even for ILC physics [many studies, arXiv:1307.8102]

Jet energy resolution

Most of our jet studies analyze the power of Particle Flow and optimize detector designs

look at simple systems (i.e. di-jets)

minimize the dependence on the jet reconstruction algorithm (measure visible energy...)

For physics analyses we care about the W, Z and Higgs mass resolution in complex final states

may be considerably worse than expected from detector performance alone

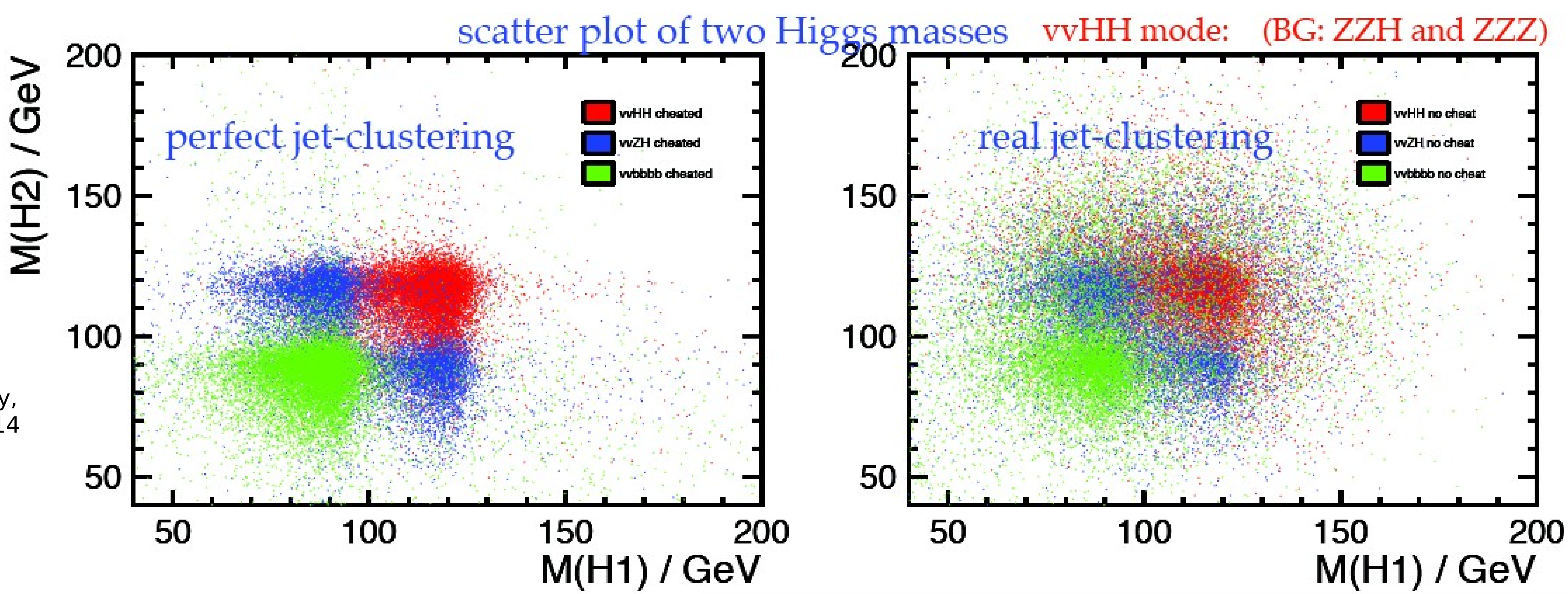
Define intermediate level: truth-particle jets constructed with the same algorithm

(for LCIO software, contact ignacio.garcia@ific.uv.es)

Detector level (Particle Flow objects) — Detector limitations...

Particle level (stable MC particles) — Inherent limitations of jet algorithms...

Parton level (W, Z, Higgs or top mass)



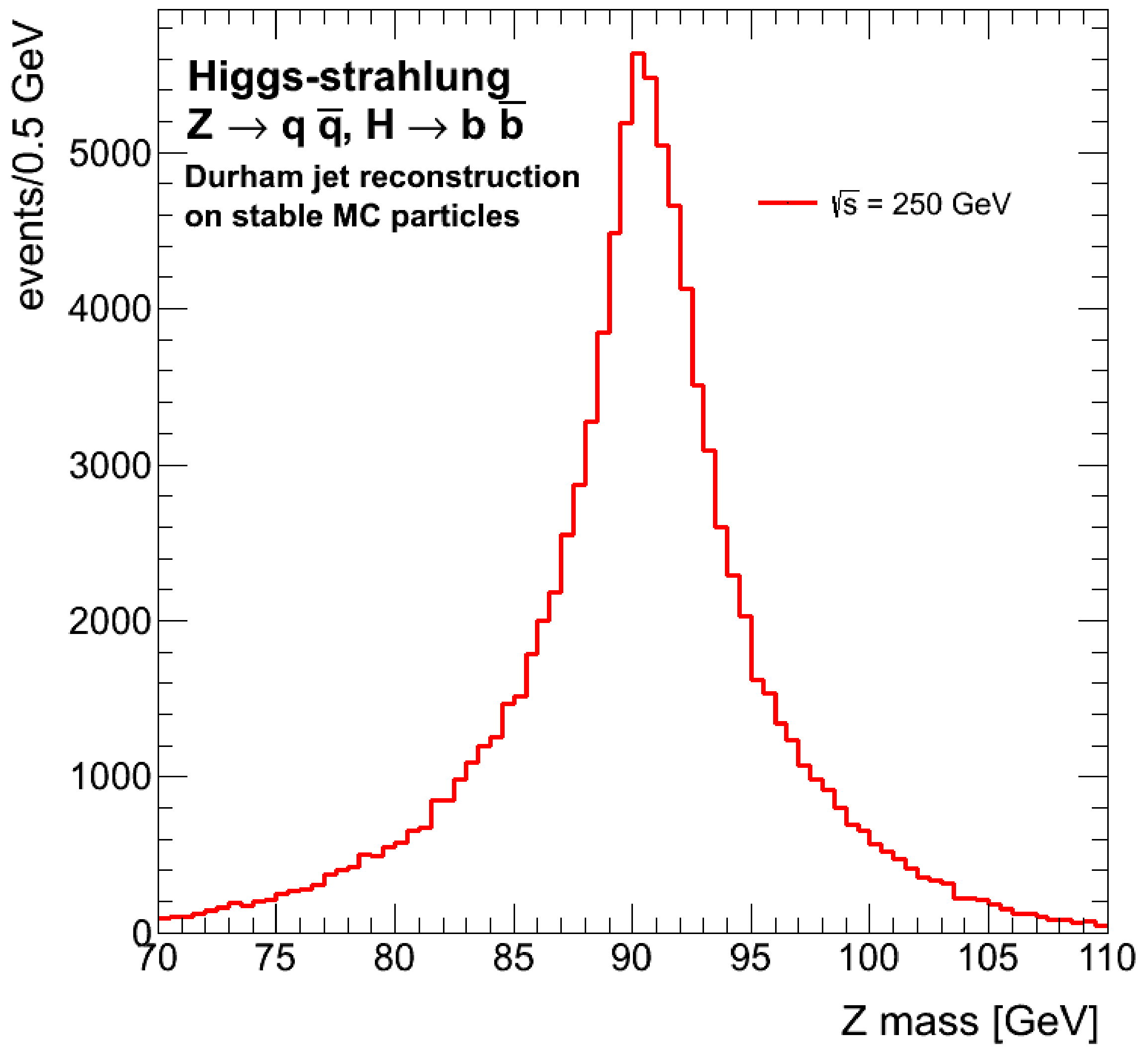
Junping Tian, ZHH study,
ILD meeting, Oshu, 2014

Toy setup

MadGraph 5 Matrix Element

Pythia8 parton shower

FastJet + fjcontrib



Z mass resolution for ZH production at 250 GeV RMS = 6 GeV due to "confusion" in jet algorithm alone

Very useful to try out new ideas:

- *can access FastJet plugins → sophisticated tool set*
- *isolate the effect of the algorithm → no noise from detector, ISR, bkg.*
- *not limited to benchmarks → study behaviour in a 18 TeV e+e- collider*
- *fast (no GRID) → turn-around time 5-10 minutes*

Jet algorithms

Lepton colliders:

Distance based on E, angle

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

Good old Durham (n=1, e^+e^- k_t) and Cambrige/Aachen (n=0)

Generalized lepton collider aglroithms:

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

Introduce beam jets → jet size R

A new kid on the block: the Valencia algorithm

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

Hadron colliders:

Hadron colliders:
longitudinally invariant
algorithms based on p_T, ΔR

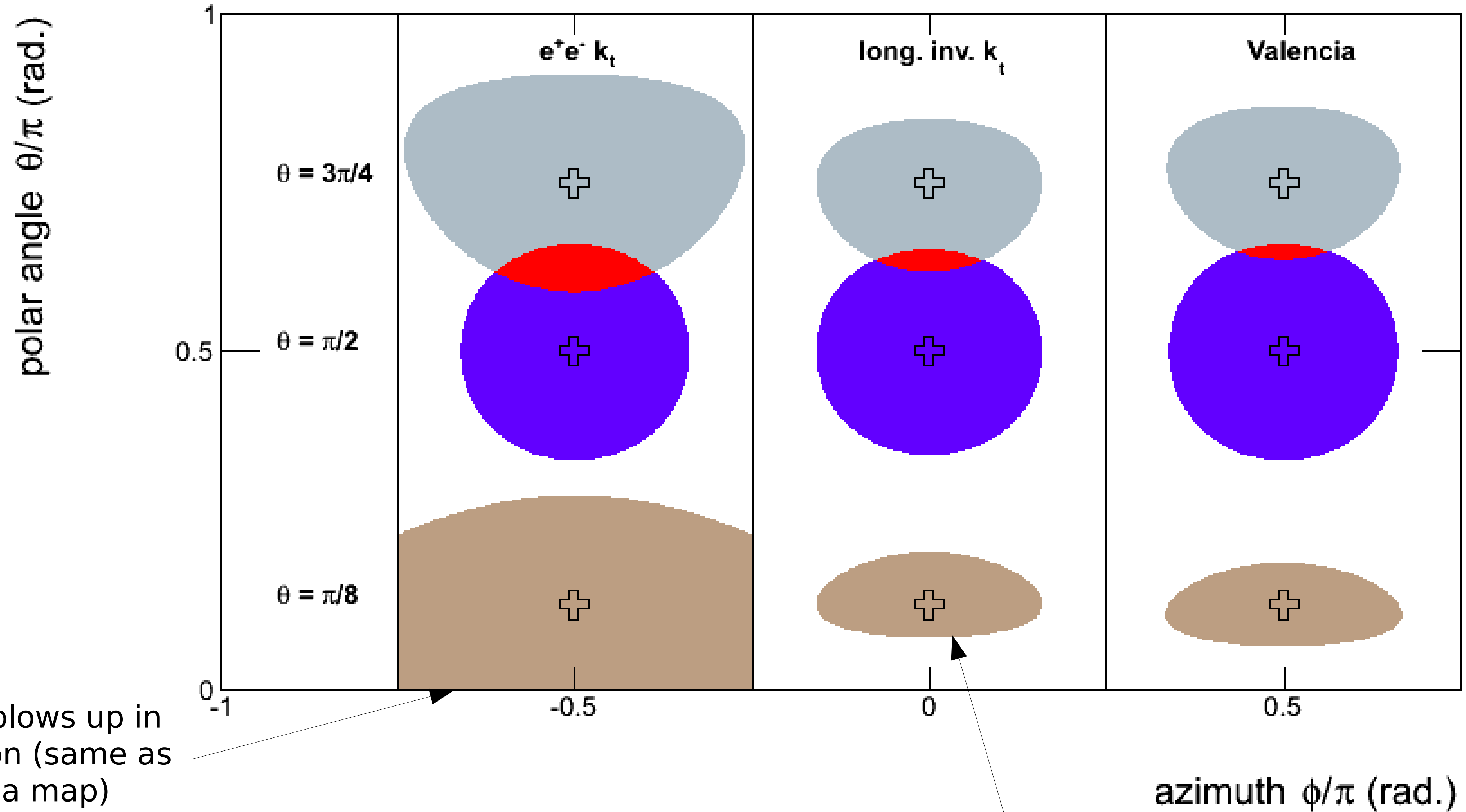
$$d_{ij} = min\left(p_{Ti}^{2n}, p_{Tj}^{2n}\right)\Delta R_{ij}^2/R^2$$
$$d_{iB} = p_{Ti}^{2n}$$

N=1, longitudinally invariant kt
N=0, Cambridge/Aachen
N=-1, anti-kt

Maintain energy and angle
Choose beam distance to increase robustness

Georgi's simple alternative (arXiv:1408.1161)

Jet sizes



φ extension blows up in this projection (same as Antartica on a map)

Circular jets in (y,φ) space asymmetric ellipses in (θ,φ)

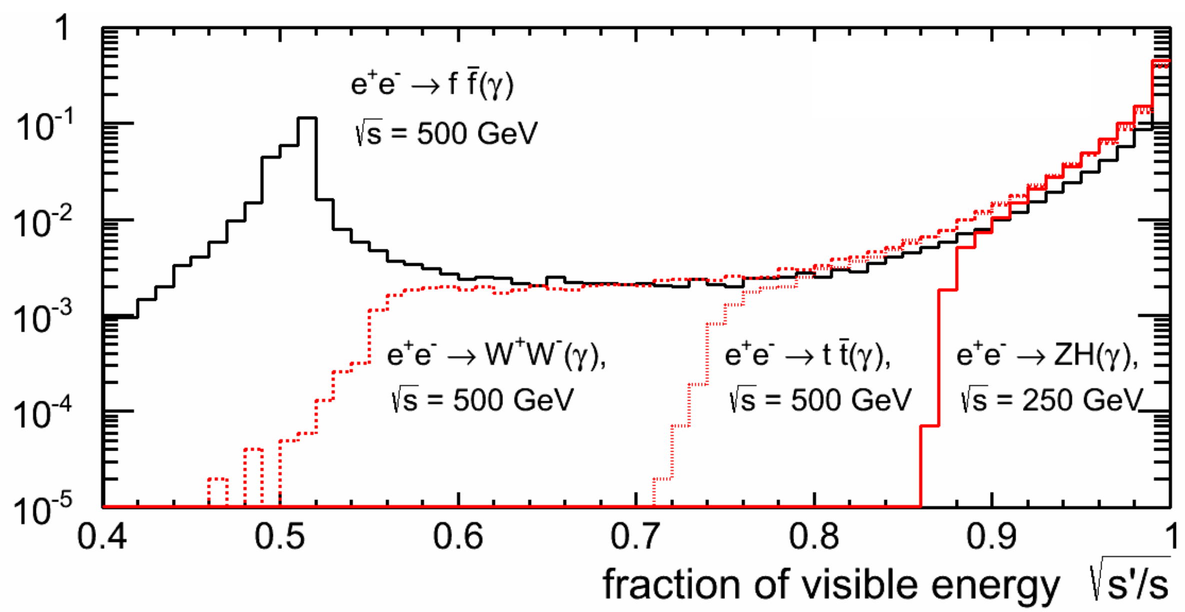
The footprint or area of jets depends on the jet algorithm
Three algorithms that yield a similar, circular area in the central detector produce very different jets in the forward region

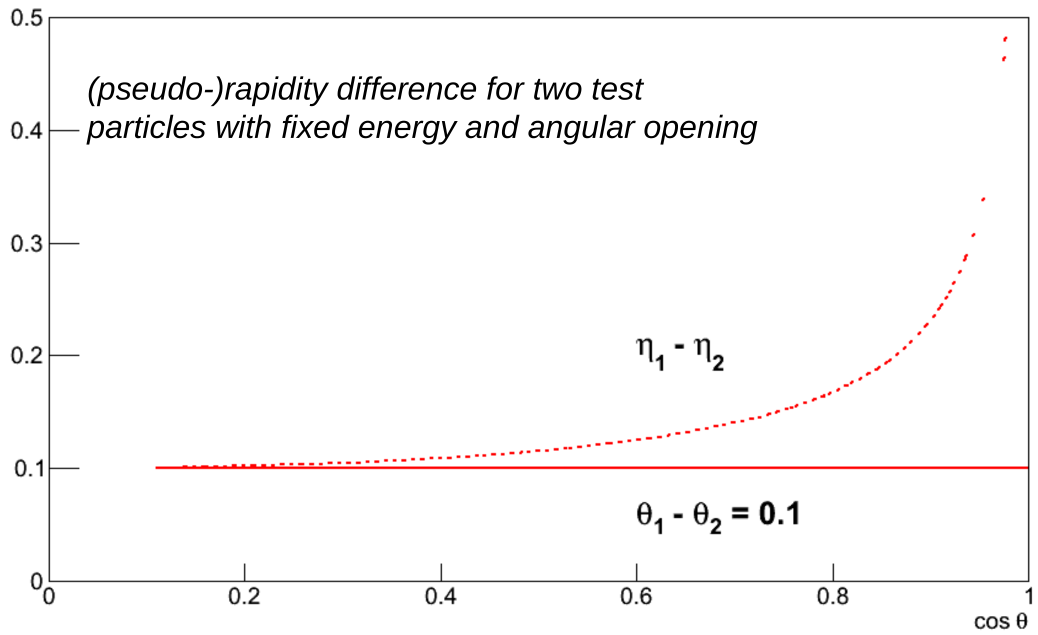
Jet reconstruction

Why does a hadron collider algorithm work better at at lepton collider than the equivalent lepton collider algorithm?

Do we need/want longitudinal invariance?

No. ISR and beamstrahlung lead to some boost, but in most interesting processes, it's very small.





No. It's potentially harmful. The rapidity difference is a poor measure of angular separation in collisions that are at rest in the laboratory.

Jet reconstruction

Why does a hadron collider algorithm work better at at lepton collider than the equivalent lepton collider algorithm?

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

vs.

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

Beam jets + shrinking footprint with polar angle yields increased robustness against forward-peaked γγ → hadrons!

The Valencia algorithm is an attempt to get the best of both worlds (with a twist):

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

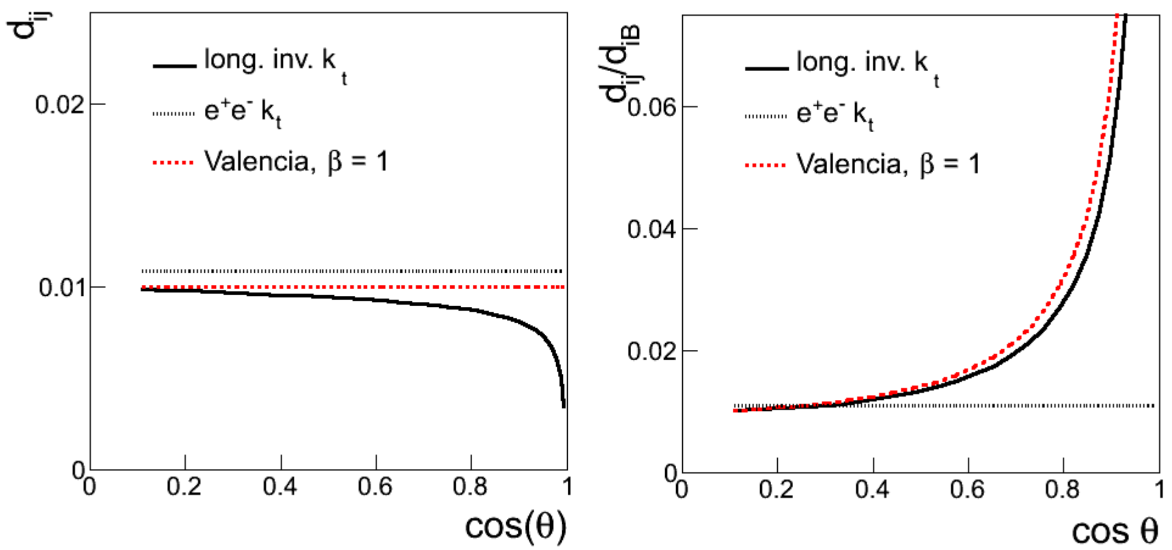
e^+e^- distance between particles

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

beam distance to mimic d_{ij}/d_{iB} behaviour

β to tweak background rejection

Boronat, Garcia, MV, arXiv:1404.4294, fjcontrib/trunk



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

Perturbative corrections

following Dasgupta, Magnea, Salam, Non-perturbative QCD effects in jets at hadron colliders, JHEP0802 (2008) 055

$e^+e^- \rightarrow q\bar{q}$ events at $\sqrt{s}$ = 250 GeV (toy setup)

Total energy correction: difference between jet energy and $\sqrt{s}/2$

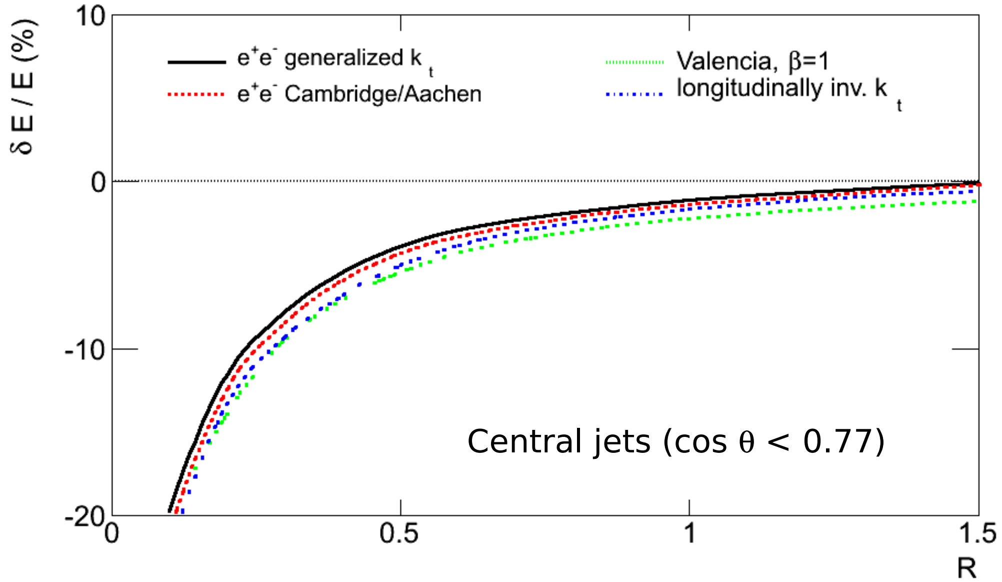
Dominated by perturbative corrections

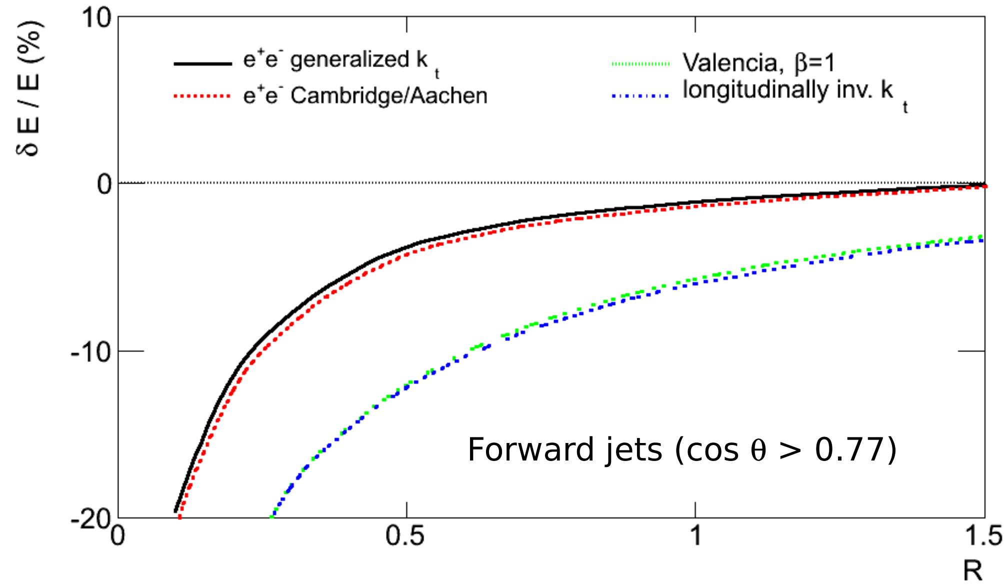
Corrections become large for R<0.5
Corrections tend to 0 for R>1

All algorithms are similar for central jets

Relative corrections are smaller for higher energy

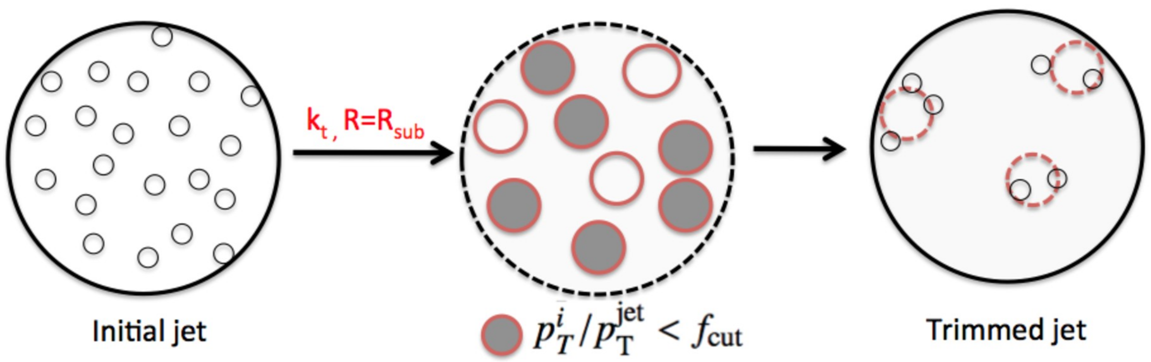
Corrections are much larger in forward detector for robust algorithms with shrinking footprint *(longitudinally invariant algorithms, Valencia)*





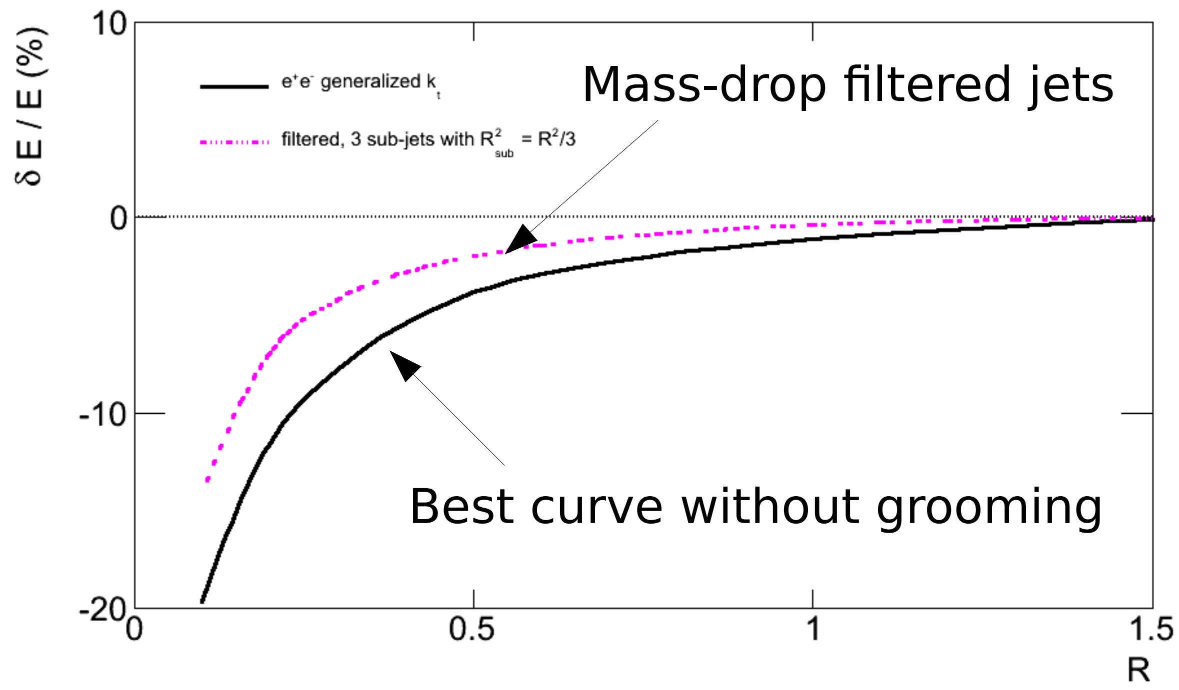
Jet grooming

Jet grooming
One of the main recipees at the LHC to deal with pile-up contamination of large-area jets



e⁺e⁻ grooming
Reconstruct exclusive Durham jets in $e^+e^- \rightarrow q\bar{q}$ (N=2),
break up into sub-jets with mass-drop filtering with $R = R_{sub}$,
Select 3 hardest sub-jets

For fair comparison, choose $R^2_{sub} = R^2/3$ so that area of 3 sub-jets adds up to same area



Grooming reduces perturbative corrections for a given jet area

→ better energy response
→ less exposure to background

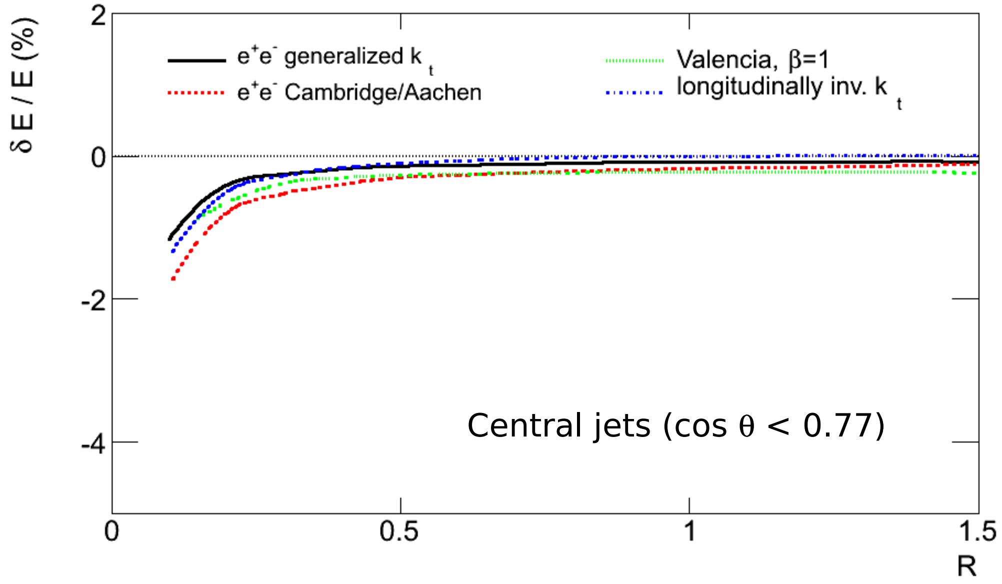
Large improvement! Deserves further study!

Non-perturbative corrections

following Dasgupta, Magnea, Salam, Non-perturbative QCD effects in jets at hadron colliders, JHEP0802 (2008) 055

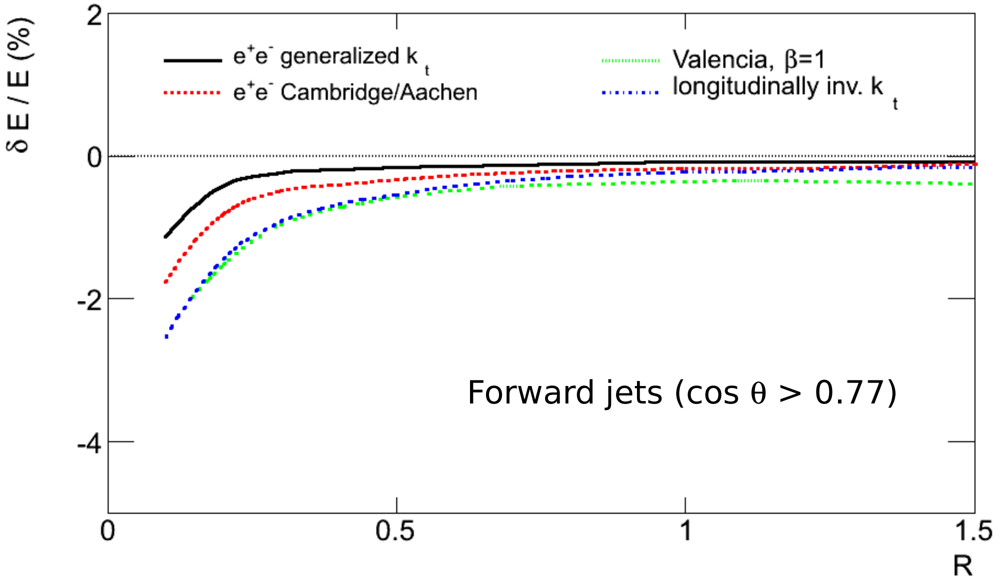
$e^+e^- \rightarrow q\bar{q}$ events at $\sqrt{s}$ = 250 GeV (toy setup)

Non-perturbative correction: difference between particle-level and parton-level jet energy (a.k.a. hadronization corrections)



Non-perturbative corrections (hadronization)
→ source of uncertainty in the Jet Energy Scale

Numerically much smaller
> 1% only for very small R



Shape similar to perturbative corrections

Interesting: fluctuations in correction are typically 10-20% smaller for round jets (anti-k_t) than for jets with more irregular shapes (k_t, C/A)

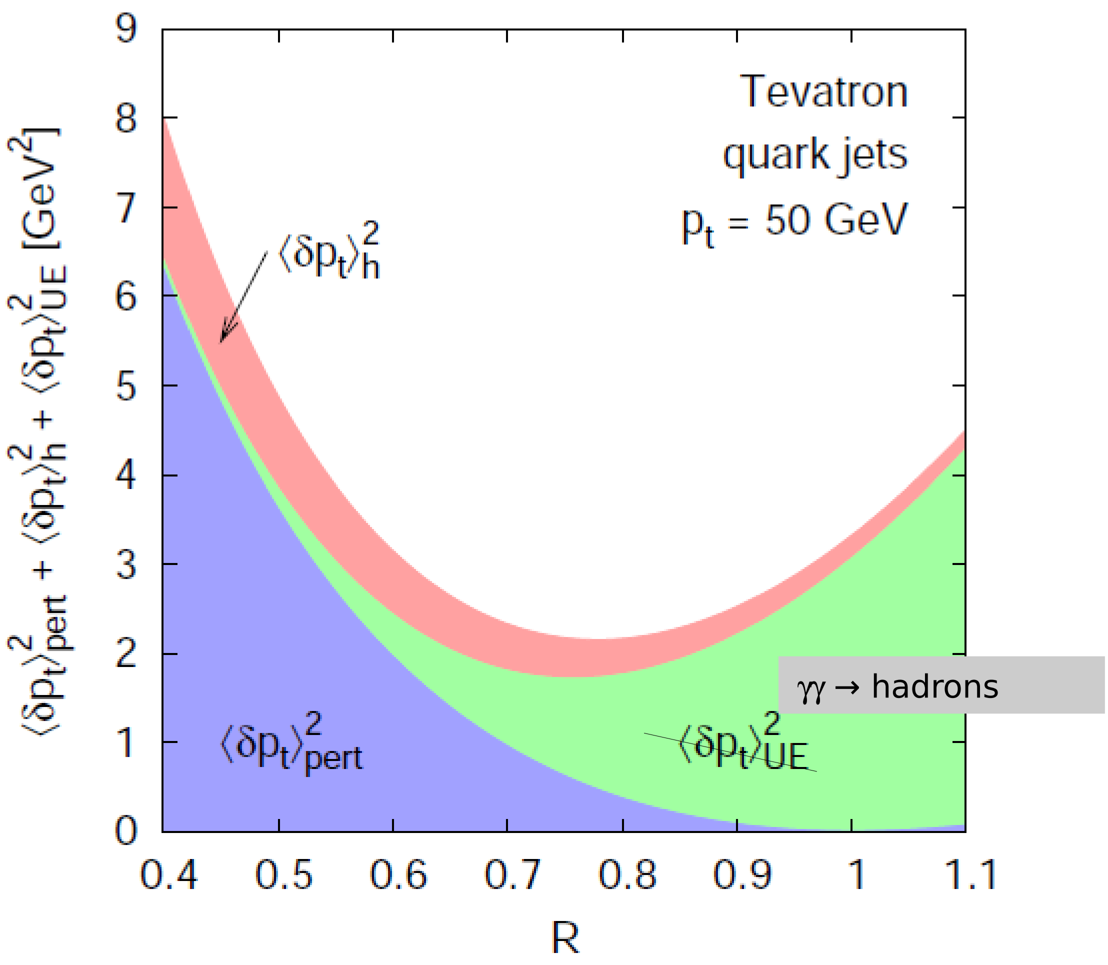
γγ → hadrons

Background contribution scales with R^2

Strongly dependent on center-of-mass energy

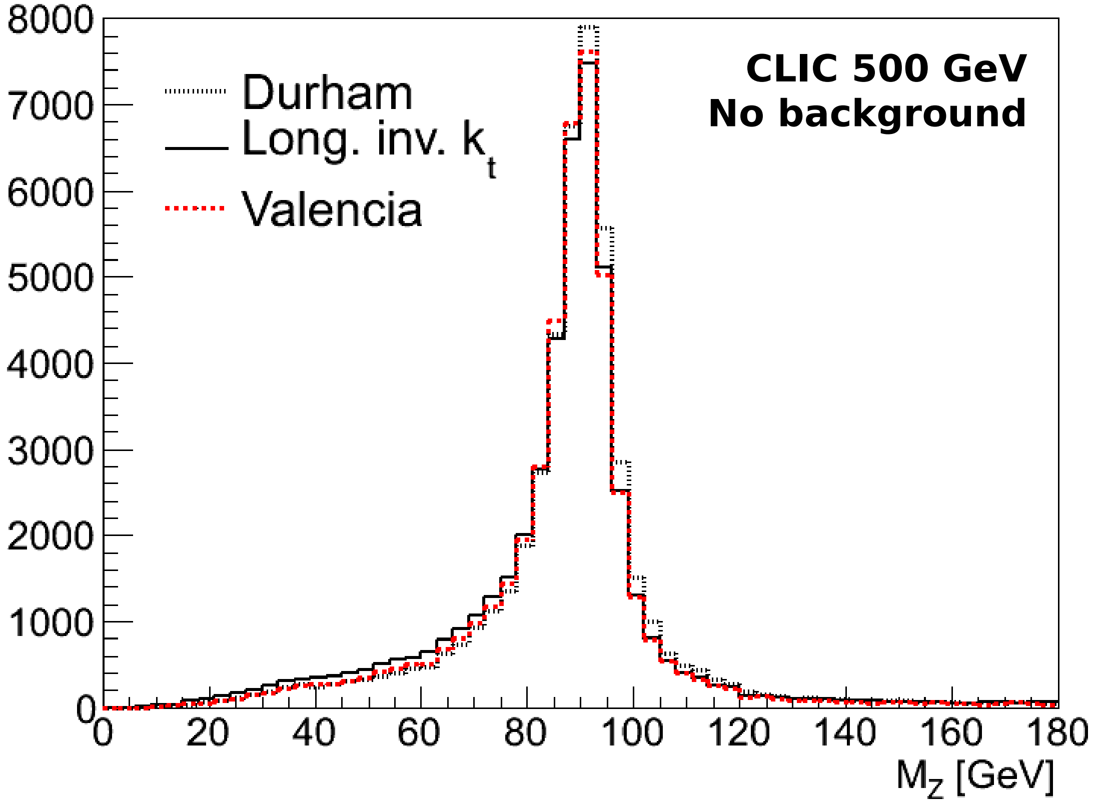
Much more important for forward jets than for central jets

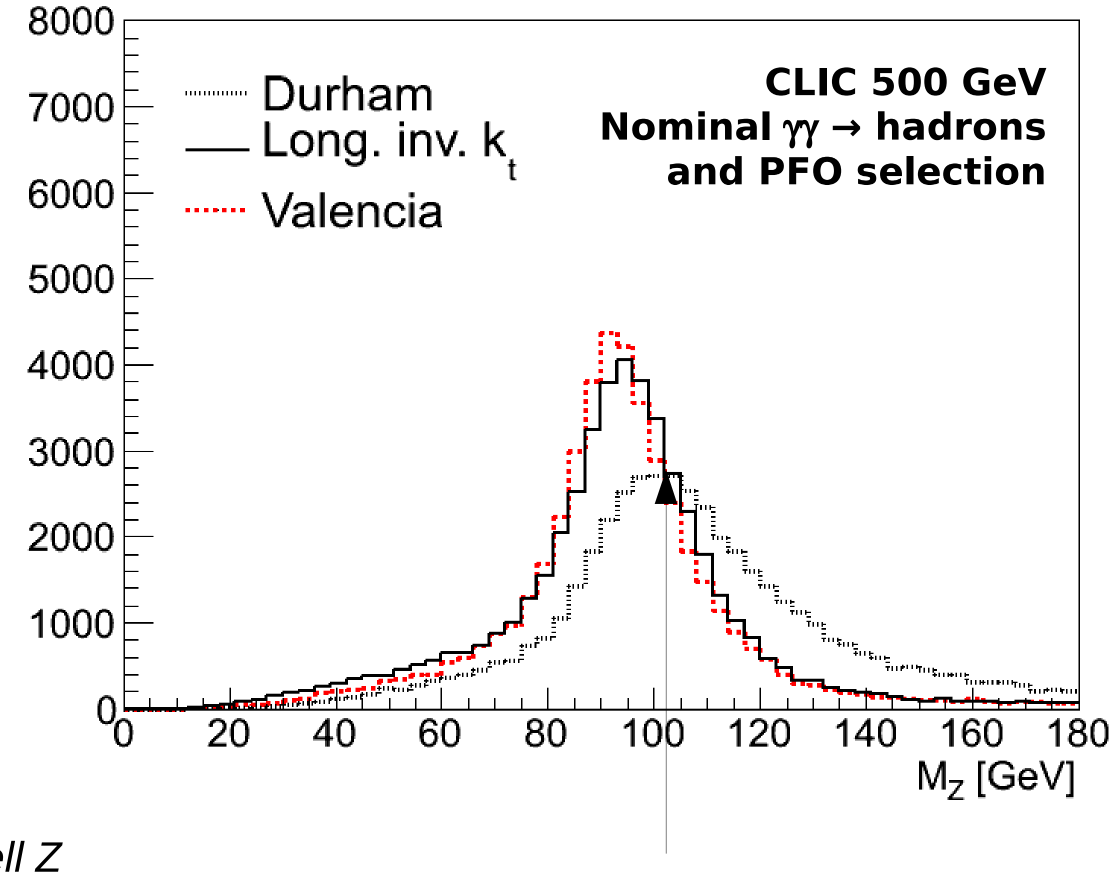
Reproduce a figure like this one from Dasgupta, Magnea, Salam, JHEP0802 (2008) 055 for several operation conditions: 250 GeV, 350 GeV, 500 GeV, 1 TeV, 1.4 TeV, 3 TeV



Realistic benchmark including background

Jet energy reconstruction with nominal background much less degraded with algorithms with shrinking footprint (long. Invariant algorithms, Valencia) than e^+e^- algorithms (CLIC, high energy)

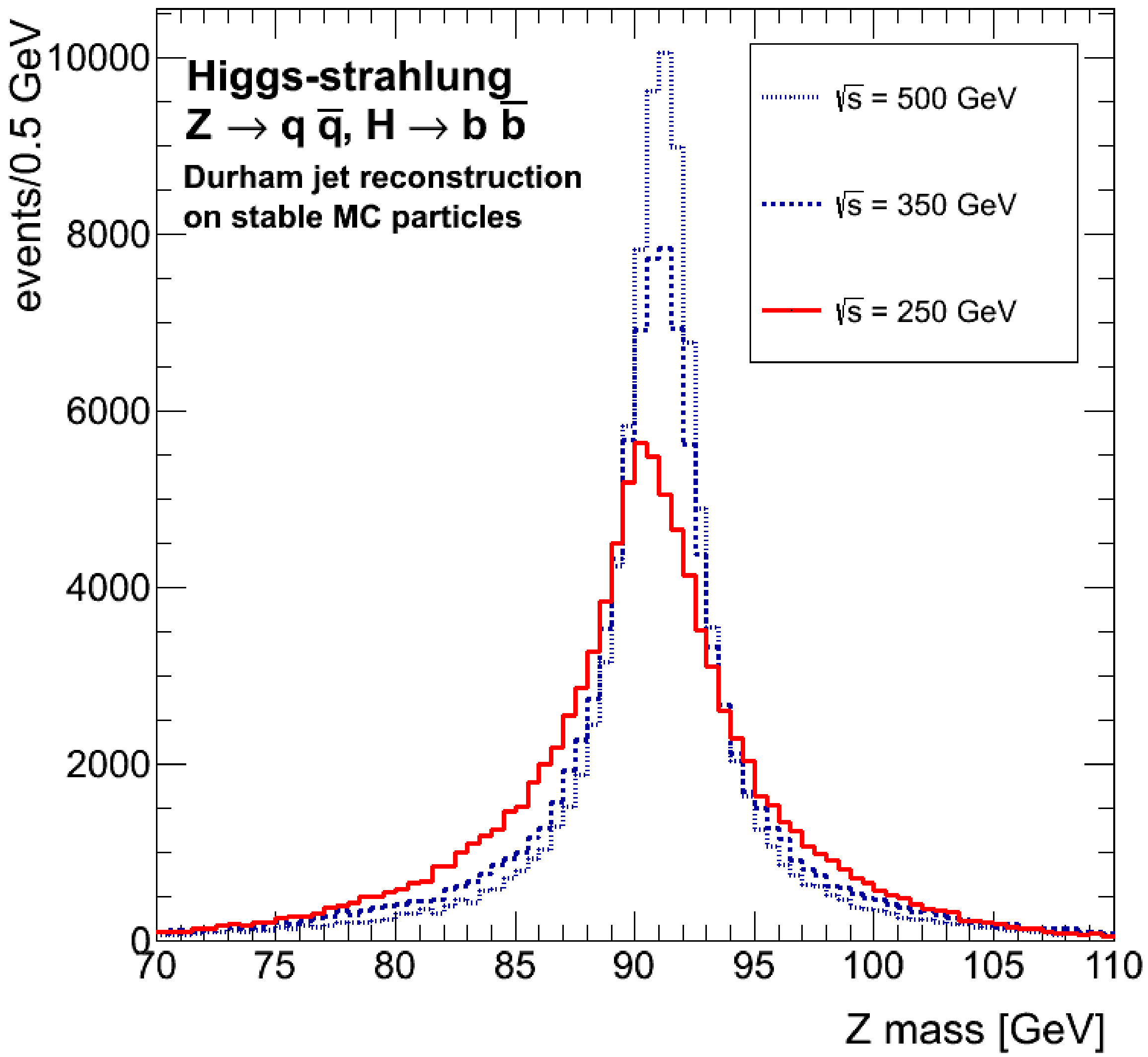




$ZZ \rightarrow q\bar{q}q\bar{q}$ events at CLIC with $\sqrt{s}$ = 500 GeV. Remove forward, or off-shell Z
Reconstruct exactly 4 jets, with optimized R (=1.2 for longitudinally invariant k_t, 1.0 for Valencia)
Find best pairs and report di-jet mass for background-free and nominal background

Here, Durham is clearly broken...

Confusion in multi-jet final states



$e^+e^- \rightarrow ZH$ production cross section peaks at ~250 GeV

The improved jet energy resolution and greater luminosity at 350 GeV may compensate

250 GeV → RMS_{90} = 4.2 GeV

350 GeV → RMS_{90} = 2.7 GeV

500 GeV → RMS_{90} = 1.3 GeV

Inclusive vs. exclusive

An easy example: top quark pair production

Exclusive clustering assumes that N hardest splits correspond to N final state partons

N=6 exclusive clustering works well at low energy

K_t distance between top quark decay products governed by t and W mass

→ $\sqrt{d_{qq}}$ roughly constant

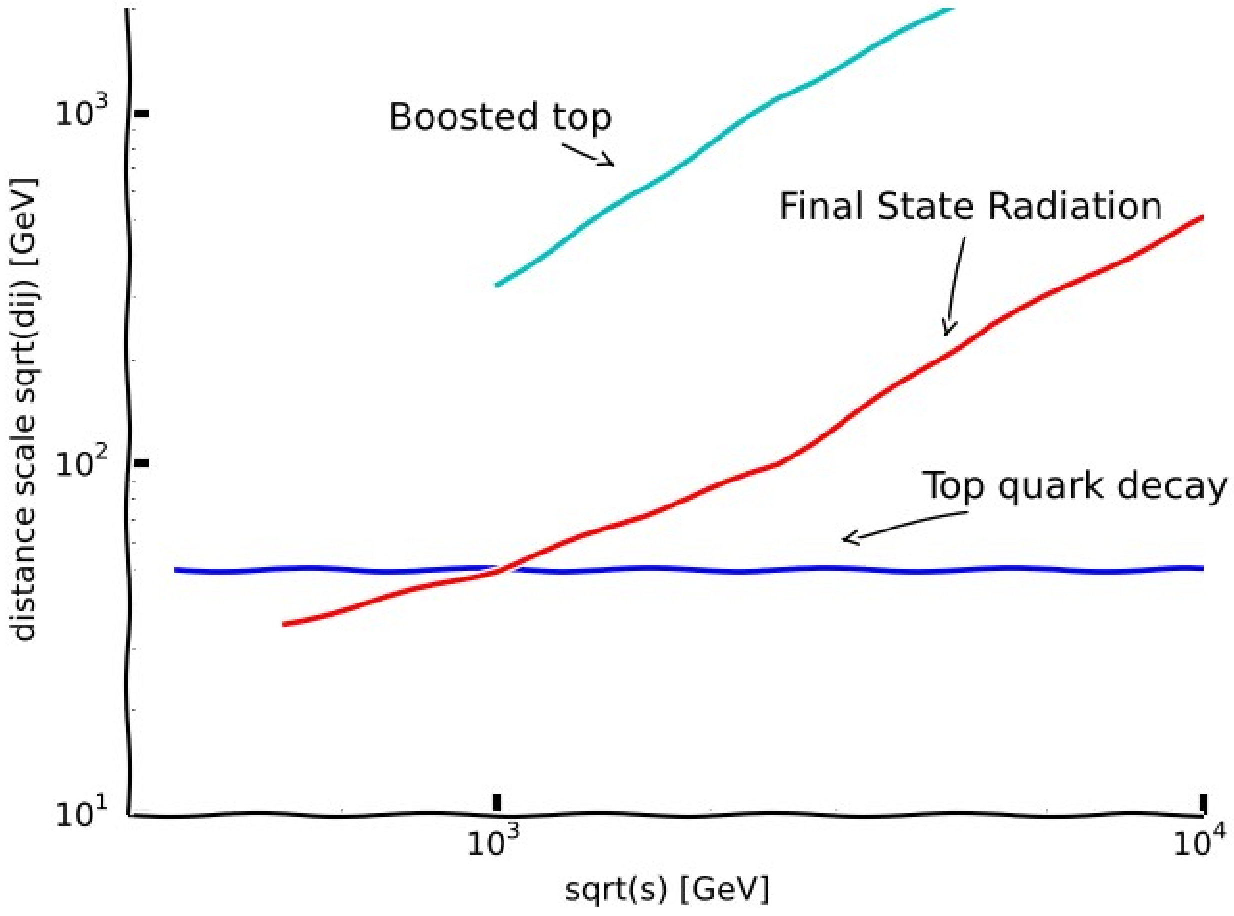
Distance of QCD final state radiation dqg increases with available phase space

→ $\sqrt{d_{qg}}$ proportional to $\alpha_s\sqrt{s}$

N=2 exclusive clustering at $\sqrt{s} \sim 1$

→ $\sqrt{d_{tg}}$ is approx. $\sqrt{s}/2$

Radiation from top quarks threatens N=6 exclusive clustering at high energy, but N=2 clustering takes over right in time



"Evolution of average distance scales"

Inclusive vs. exclusive

Not-so-easy: ZHH production

Hierarchy in energies increases with √s

When qg split is harder than Z → q$\bar{q}$ or H → b$\bar{b}$:

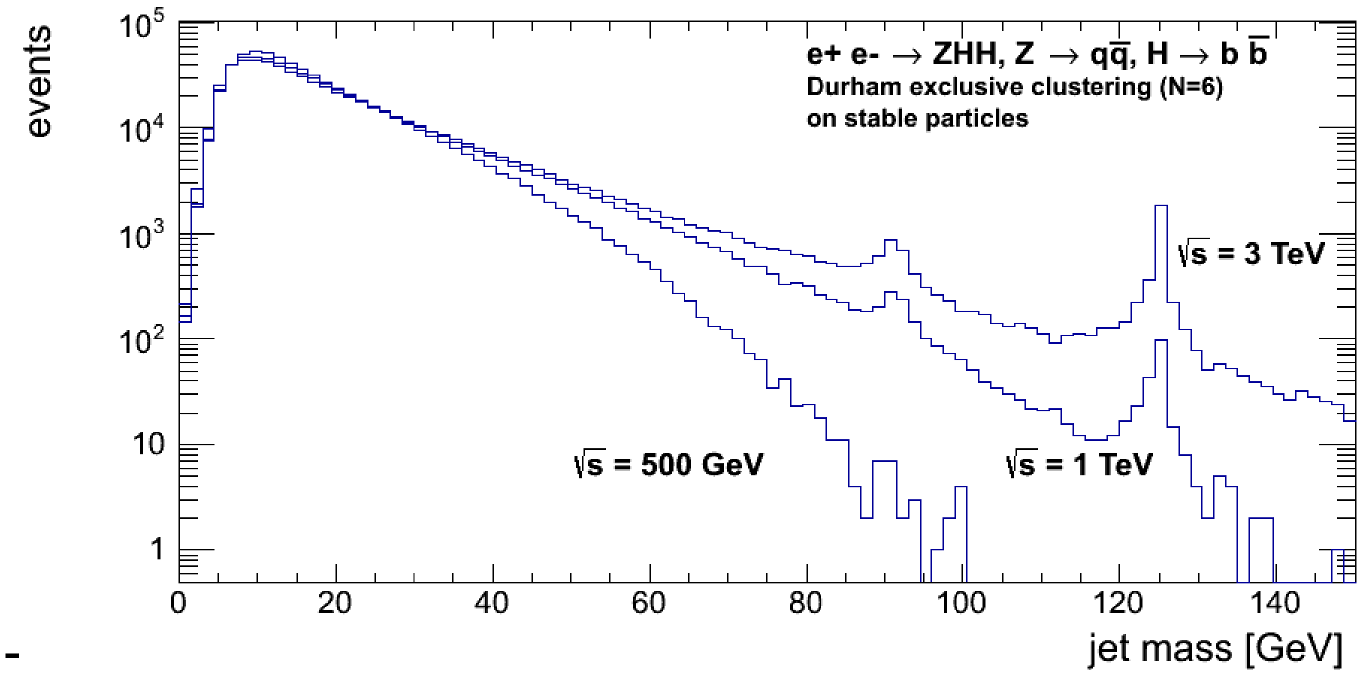
Z → q$\bar{q}$ or H → b$\bar{b}$ erroneously merged

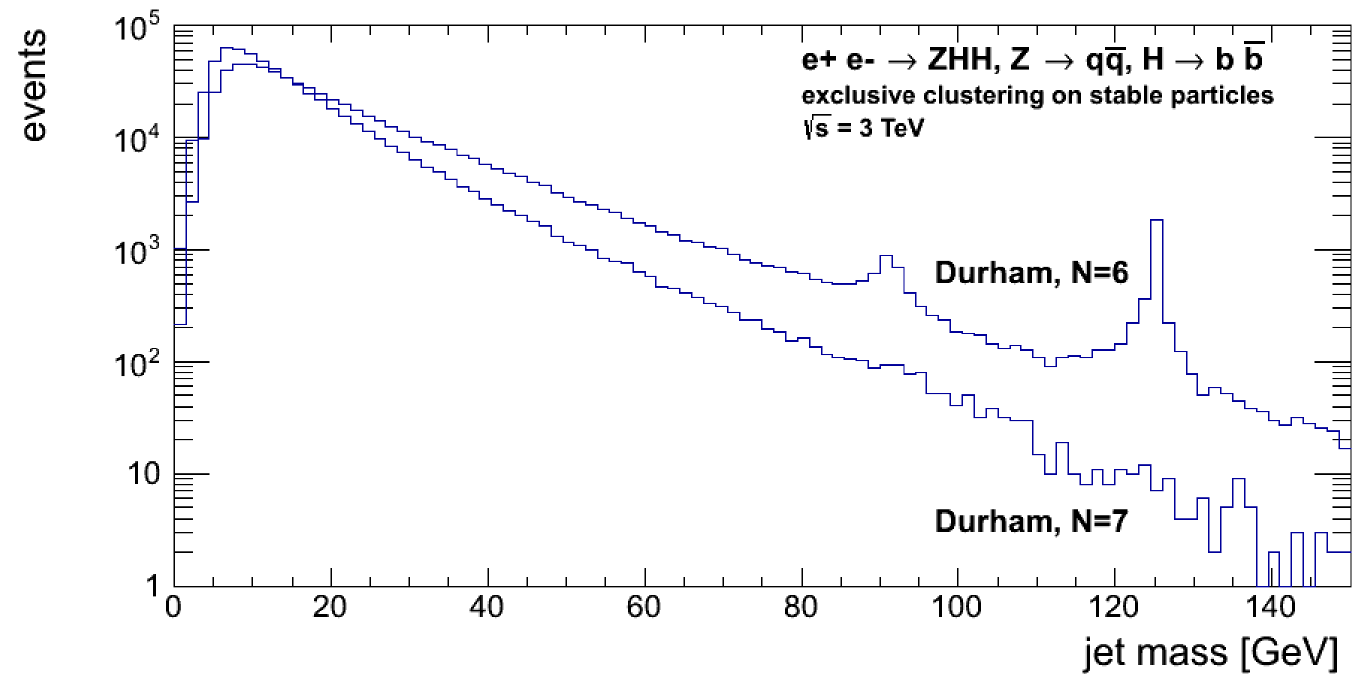
Failure mode is indeed observed in a small fraction (few %) of events at high energy (1-3 TeV)

Ironed out by allowing a seventh split (N=7).

Merge using extra information

N=3 not very satisfactory at relevant energy





Inclusive vs. exclusive

Exclusive: user specifies # jets or max. distance where clustering stops.

- Vast majority of lepton collider analyses

Inclusive: cluster until $d_{iB} > d_{ij}$ for all pseudo-jets

- Probably 100% of hadron collider analyses

Exclusive jet clustering is very powerful and versatile.

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FastJet WARNING: dcut and exclusive jets for jet-finders other
than kt should be interpreted with care.
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Exclusive clustering cannot be used (in a meaningful way) with jet algorithms with null or negative energy exponent (Cambridge-Aachen, anti-k_t)

Jet Energy Scale and Resolution

LHC: dominant detector-related uncertainty in nearly all analyses

(even if an analysis doesn't "use" jets, it suffers from jet-related uncertainties)

- Fragmentation, parton shower, hadronic shower model and dead material lead to large uncertainty in response
- JES constrained to approx 1% in γ + jet or Z + jet events; additional systematic for difference wrt calibration sample

(response differences between quark and gluon jets, dense/less dense environment, extrapolation to different energy range, pile-up)

LC: very good Particle Flow

Even the best PF cannot do much about neutrinos in jets (b/c-quark JES)

We need numbers for the difference in response for gluon and quark jets,

for 2-jet versus 4-jet versus 6-jet versus 8-jet events

LC: excellent in situ handles (Z-pole run (without background) $Z \rightarrow q\bar{q}$)

(response differences between quark and gluon jets, dense/less dense environment, extrapolation to different energy range, background)

Realistic energy uncertainty for ILC analyses:

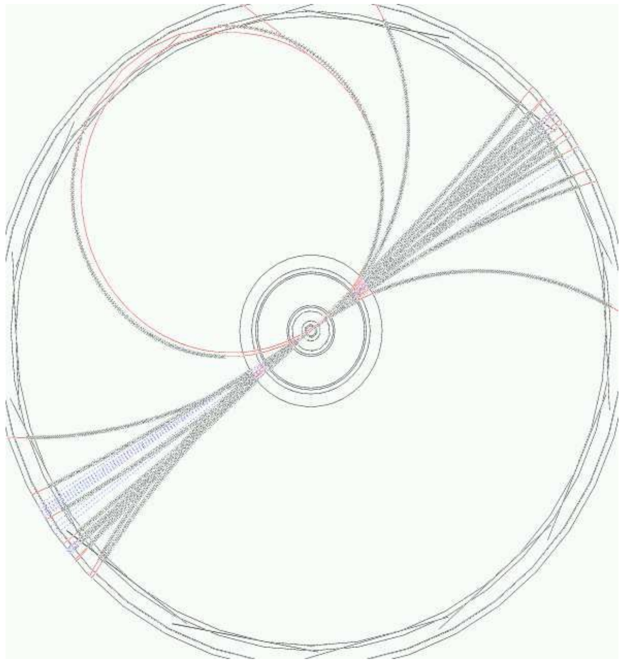
- can we define a one-uncertainty-fits-all-analyses number?
- is it 0.1%, 1%...? (any guess is better than assuming 0%; a newly formed team will provide realistic numbers)

For now, I'd recommend to simply run a simple check:

document how a 0.1%, 0.3%, 1% error in JES affect your result

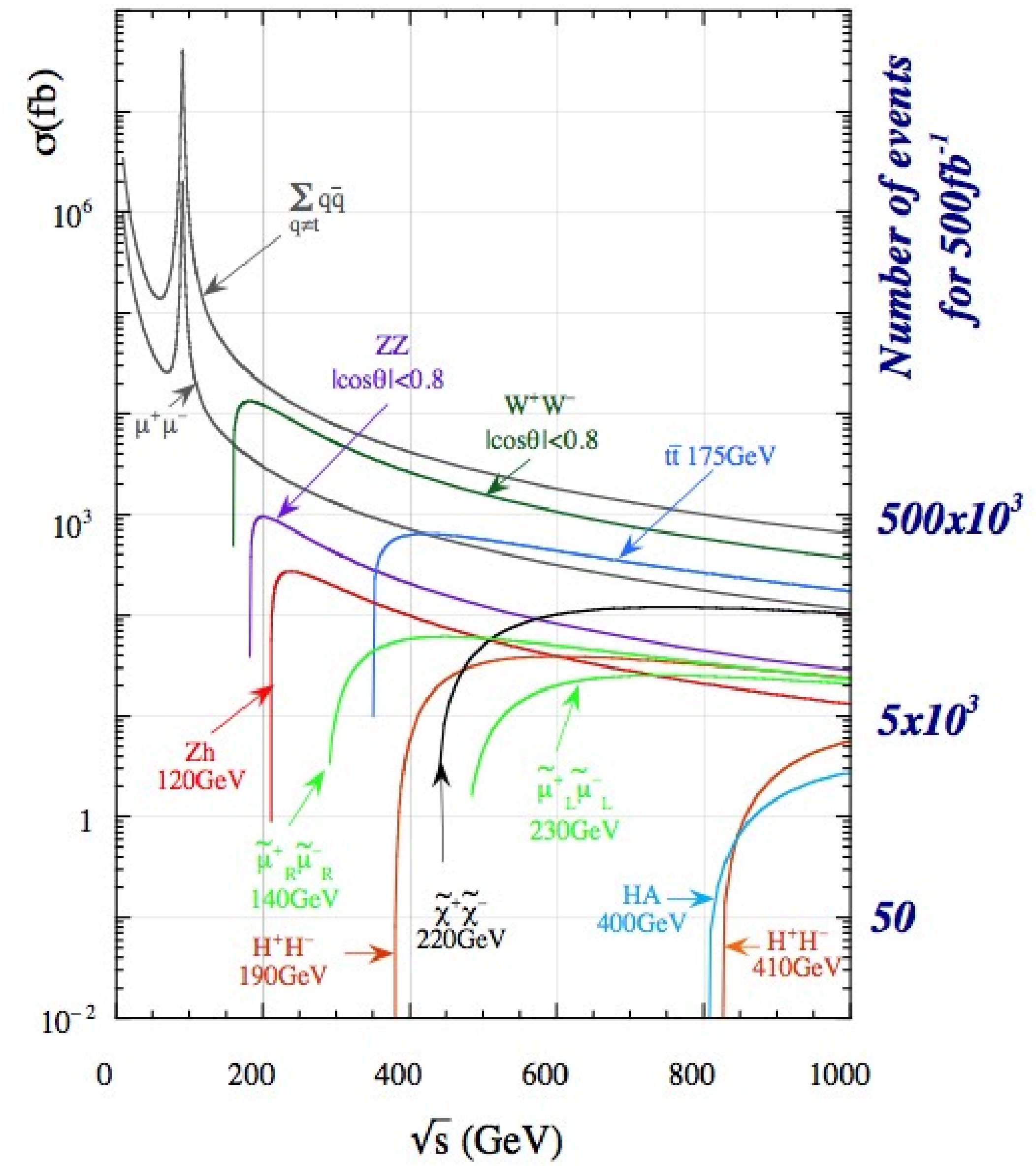
(you should probably be cautious if you find a 0.001% JES uncertainty ruins the result)

WW → $\bar{q}q\bar{q}q$ at 3 TeV
CLIC physics, hep/ph0412251



Boosted objects

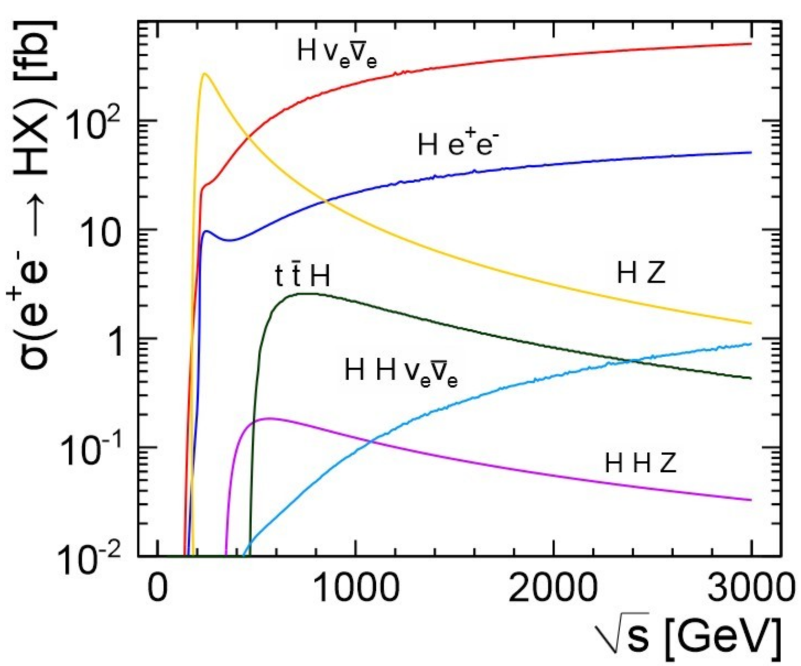
All objects (known so far) will be boosted in ILC upgrade (1 TeV)
And even more so during the CLIC high-energy stage (1.4, 3 TeV)



The role of boosted object tagging

In the continuum above $\sqrt{s} \gg m_Z$ the $e^+e^- \rightarrow q\bar{q}$ rate is of the same order as WW production, only one order of magnitude larger than $t\bar{t}$ production, and two orders above ZZ and Zh

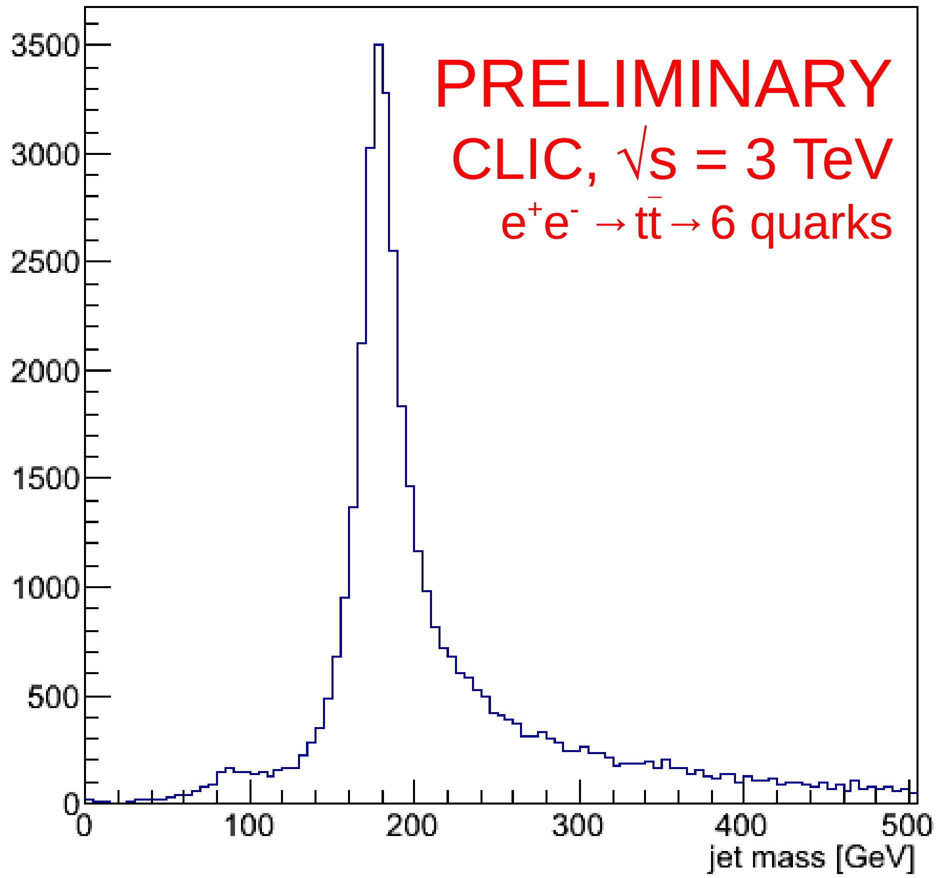
Relative to the LHC the role of boosted object tagging shifts from the “battle against QCD multi-jet production” to the more subtle art of separating W, Z, Higgs and top



Tag ZZ against WW
HHZ against WWZ

Boosted top quarks

Without $\gamma\gamma \rightarrow$ hadrons background



Detector performance for boosted hadronic top jets (E~1200 GeV)

- Energy resolution (RMS90) = 2.4%
- Jet mass resolution (RMS90) = 3.2% (WOW!)

Good selling point for ultra-granular calorimetry!

CLIC 3 TeV $e^+e^- \rightarrow t\bar{t}$

No background

CLIC-ILD detector simulation

PANDORA PFA

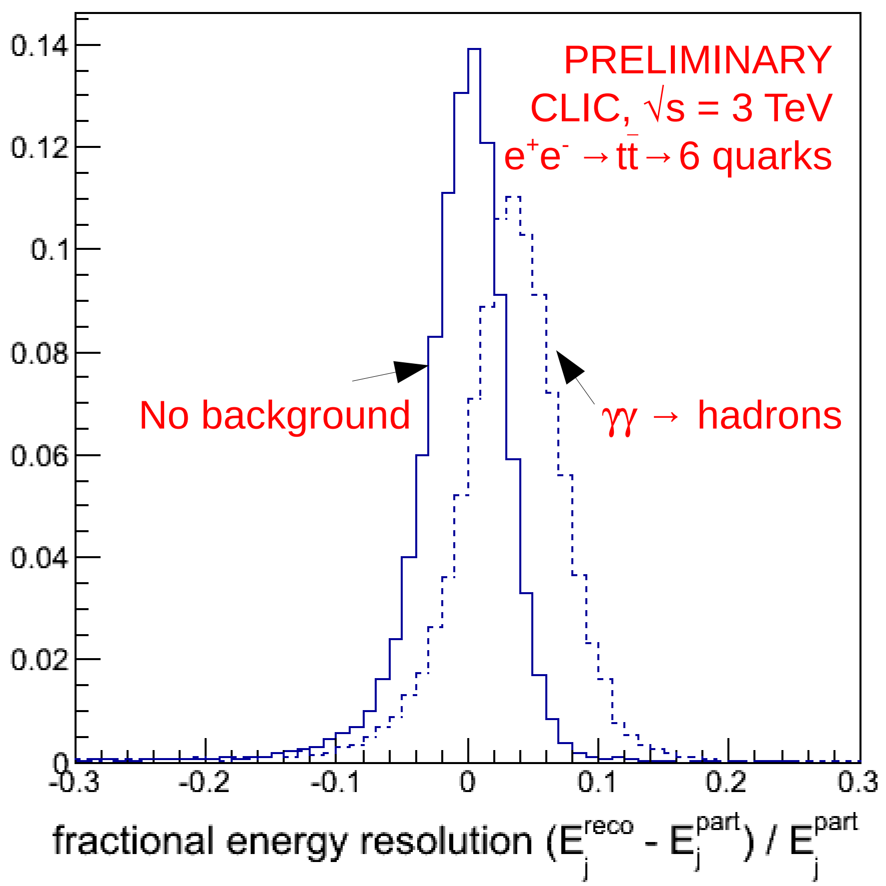
Valencia e^+e^- jet algorithm (N_j =2, R=1, β=1)

Could have picked long. inv. k_t with R=0.8-1.2

Note: resolution considers reconstructed energy versus stable particle jets; relative to the actual top parton the energy resolution is 5% and the width of the mass peak ~7%

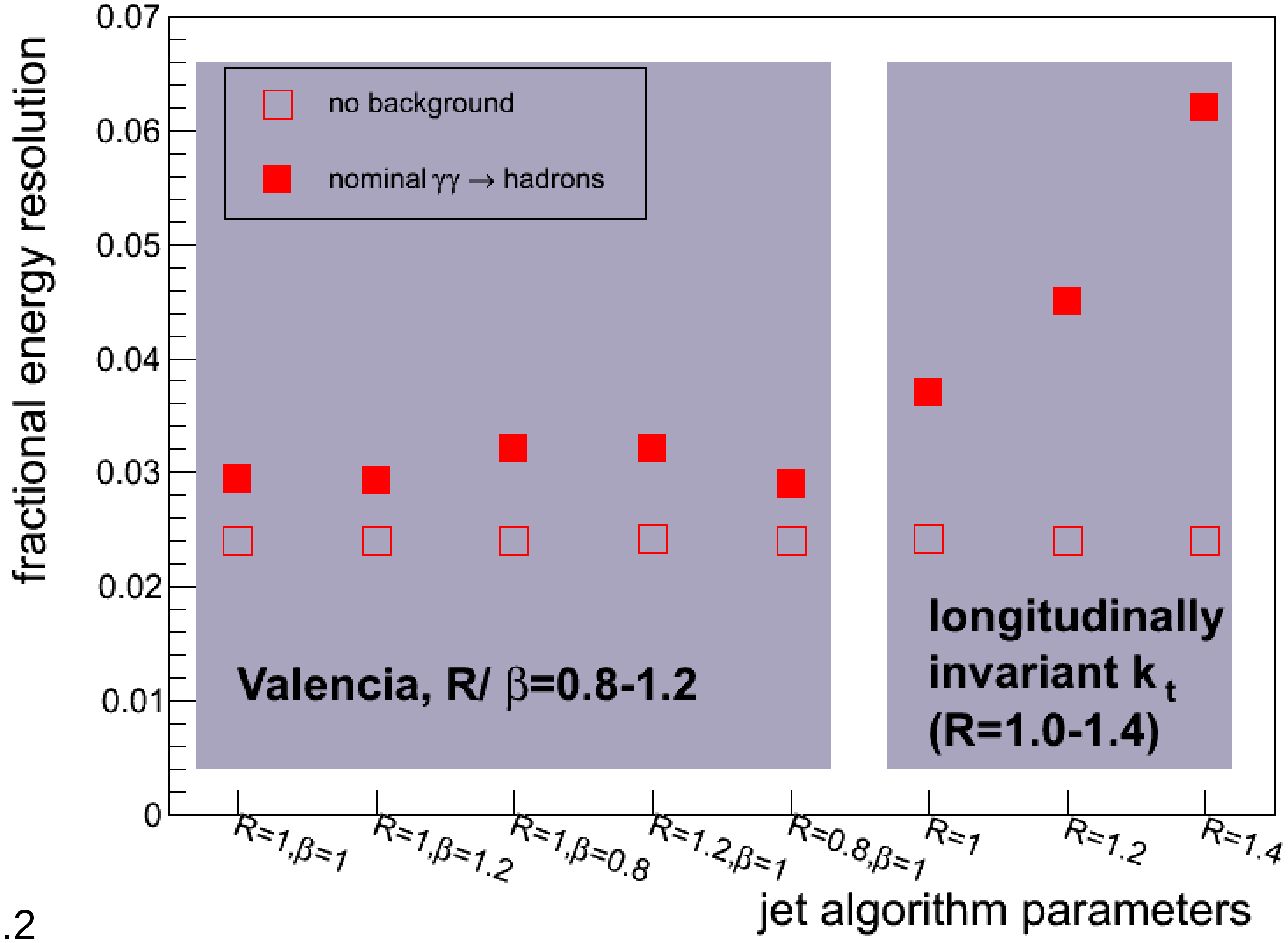
Boosted top quarks

With $\gamma\gamma \to$ hadrons background



Background has impact on fat jets:

Energy resolution degraded 2.4% → 2.9%



CLIC 3 TeV $e^+e^- \to t\bar{t}$

Adding $\gamma\gamma \to$ hadrons background

CLIC-ILD detector simulation

PANDORA PFA

Valencia e^+e^- jet algorithm (N_j =2, R=1, β=1.2)

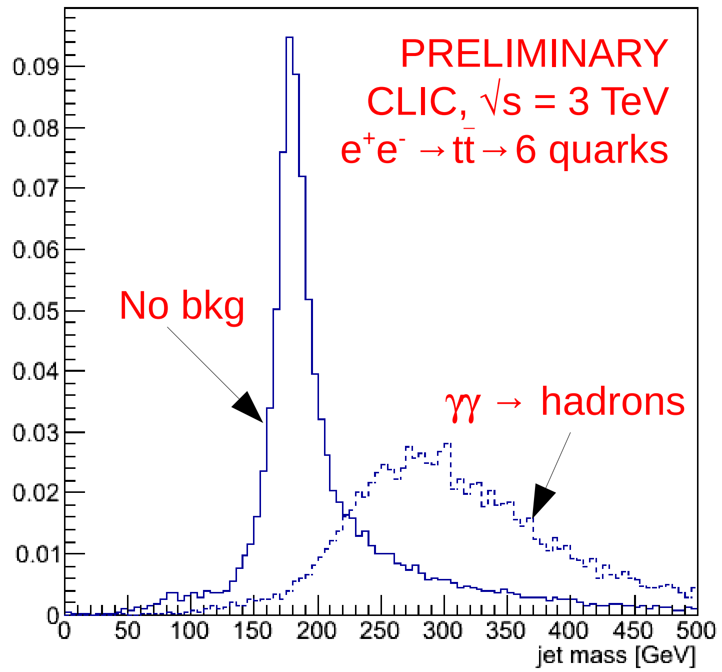
Significantly better now than long. inv. k_t with R=0.8-1.2

Note: particle jets used to determine resolution do not contain particles from $\gamma\gamma \to$ hadrons

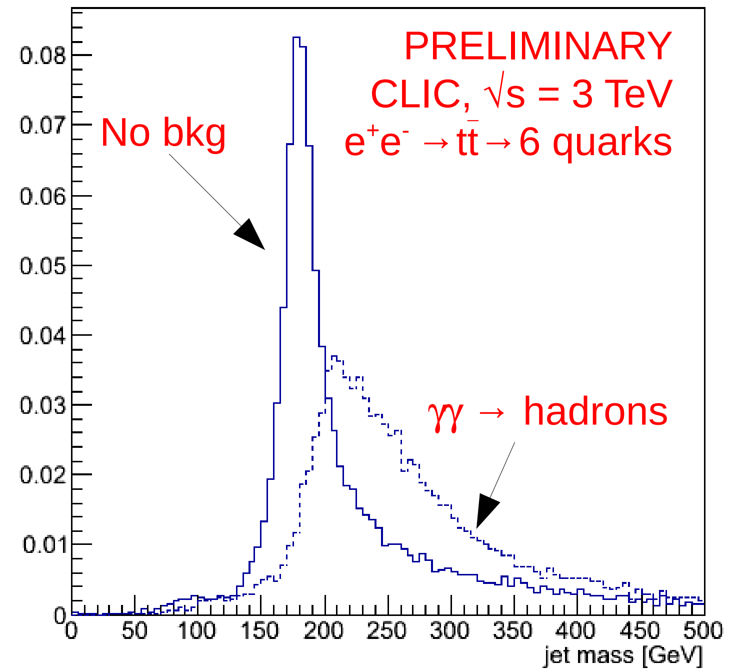
Boosted top quarks

With $\gamma\gamma \to$ hadrons background

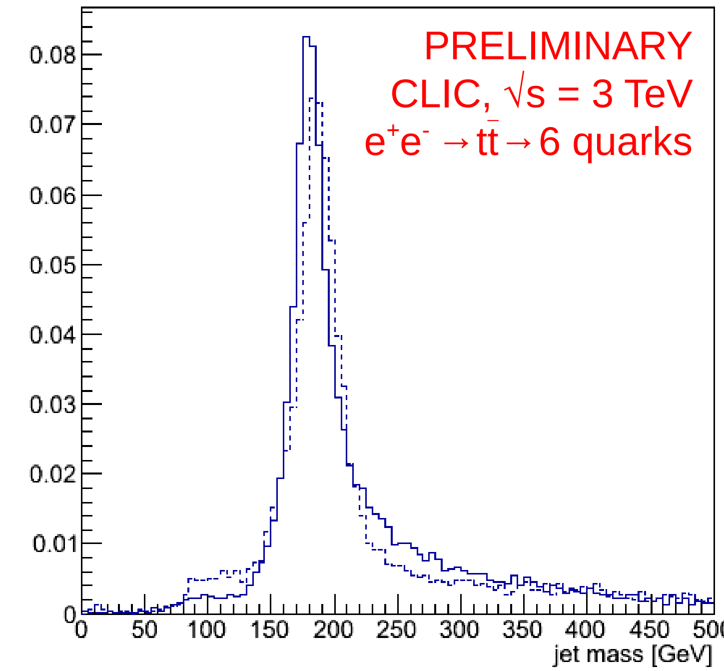
Longitudinally invariant k_t (R=1)



Valencia (R=1, β=1)



Valencia trimming

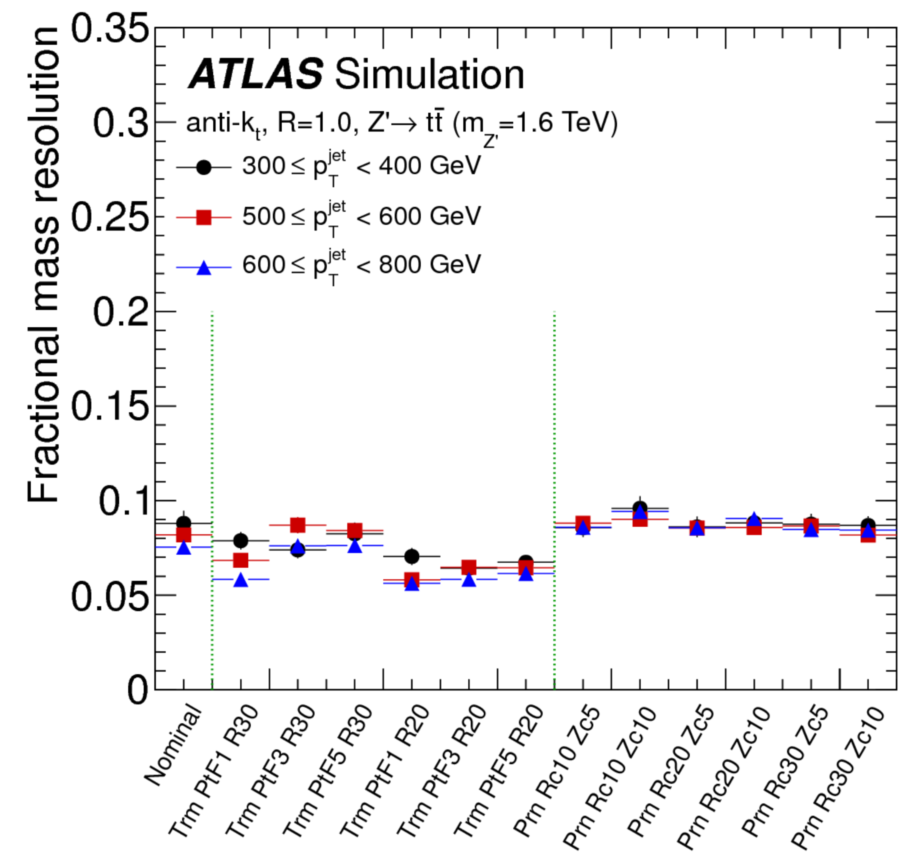


Background has a profound impact on fat jet substructure:

Raw jet mass resolution badly degraded
(from dream 3.2% to nightmare 16%)

Preliminary: grooming jets restores jet mass resolution to ~4%

Results correspond to a primitive e^+e^- variant of trimming based on 3+3 Valencia R=0.2 jets → optimisation needed



Summary

Particle flow detector concepts exist that measure stable particles very precisely:

$\Delta E/E \sim 3\%$ (weighted for relative abundance of particle species in jets)

Jet clustering is far from trivial in many-jet final states and with background overlay

- perturbative corrections
- non-perturbative (hadronization) corrections
- confusion due to multi-jet final states
- $\gamma\gamma \rightarrow$ hadrons background

LC is qualitatively different from LEP/SLC: a fresh look at e^+e^- jet reconstruction is needed

→ Back to basic: understand what you optimize

→ Isolate and quantify the impact on performance of above effects

a mild boost helps to sharpen the algorithm-related jet energy resolution

→ Adapt new tools from the LHC: groomed jets may yield better performance

Jet-related systematics are important

→ evaluate sensitivity of key analyses while we come up with estimates

Every EW-scale particle is a boosted object in a high energy (1-3 TeV) linear e^+e^- collider

Distinguish di-boson from $q\bar{q}$ production AND separate W, Z and Higgs

Highly granular particle flow calorimetry is great for substructure response

Background is a powerful enemy of fat jet substructure

Preliminary results indicate adapting existing tools (grooming) for pile-up mitigation is effective