Calorimeter Performance at CLIC

Matthias Weber (CERN)

Jet Reconstruction and Physics

Good jet energy reconstruction essential in many measurements
→ Larger cross-section in hadronic signatures, more challenging to reconstruct with high precision

Accurate jet energy measurement key point in distinguishing signatures → test case W and Z mass separation

Excellent Particle Flow identification (both type and energy) required for good jet performance
→good track reconstruction essential
→requires fine grained calorimeter for good cluster separation between close-by particles and matching of clusters and tracks

Jet Energy Resolution

Jet Energy resolution (JER): total Energy vs Jets

SO FAR: compare **total reconstructed energy** with **total energy sum of MC truth particle energies** in dijet events to quantify jet energy resolution → assumes energy distributed evenly in two jets, jet energy resolution related to total energy resolution by

$\Delta E_{jet}/E_{jet} = \sqrt{2}*\Delta E_{tot}/E_{tot}$

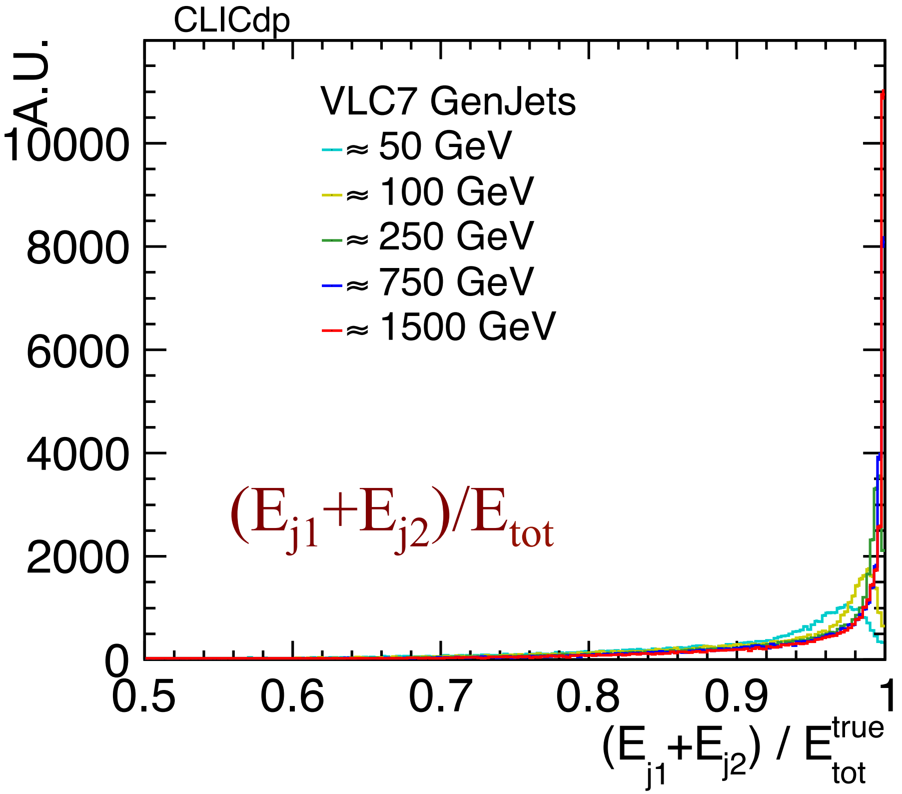
NOW: compare quantities of **reconstructed jets** with quantities of **MC truth jets clustering stable particles**

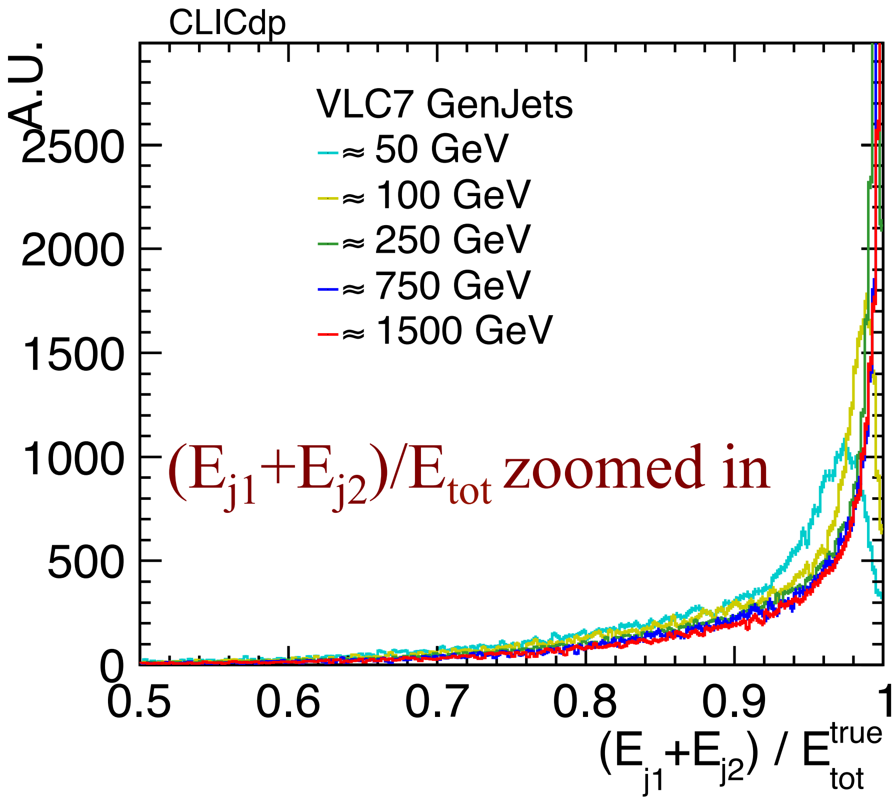
- Ignore neutrinos for MC particle jets
- Define reconstructed jets using as input
  - PandoraPFOs in events without background
  - TightSelectedPandoraPFOs in events with 3 TeV γγ→hadrons background
  - LE_LooseSelectedPandoraPFOs for 380 GeV γγ→hadrons
- Studied in Z→qq events, with q=u,d,s
- Jet algorithm: Valencia algorithm (VLC) γ=β=1.0, radius R=0.7, exclusive jet clustering of event in exactly two jets

Jet energies vs total event energy

MC truth jets, events with $\Delta\varphi(j1,j2)>2.8$

Compare energy sum of both jets vs total energy in event



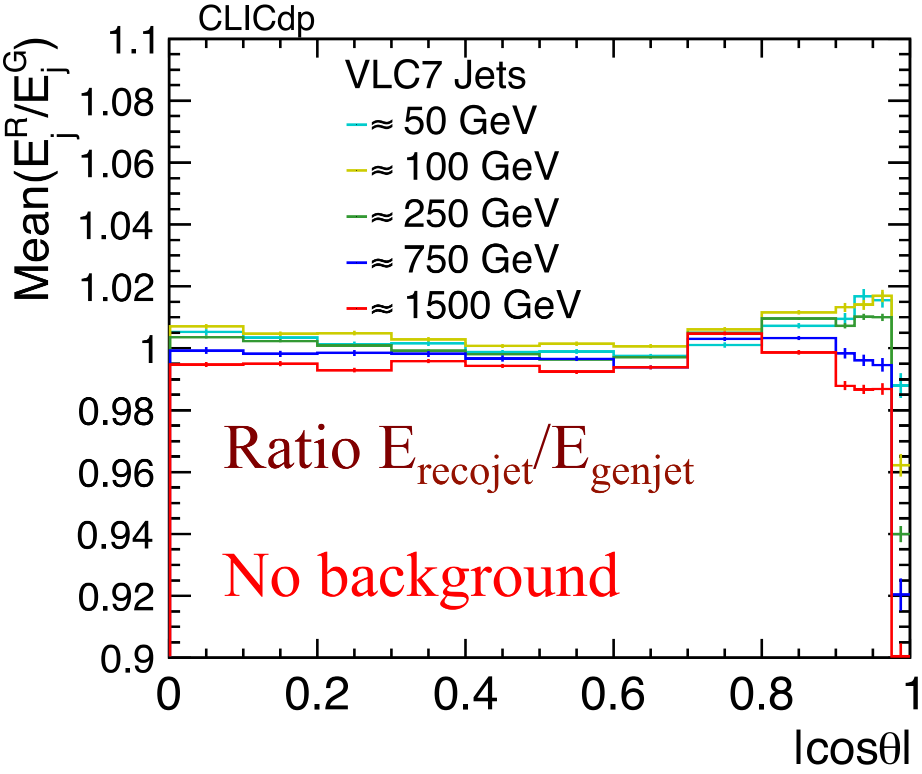


For most events in this preselection vast majority of total event energy contained in both jets, slightly larger tail to lower values for low energetic jets at 50 GeV →jet cone of R=0.7 well suited for study

Jet energy: particle level vs detector level

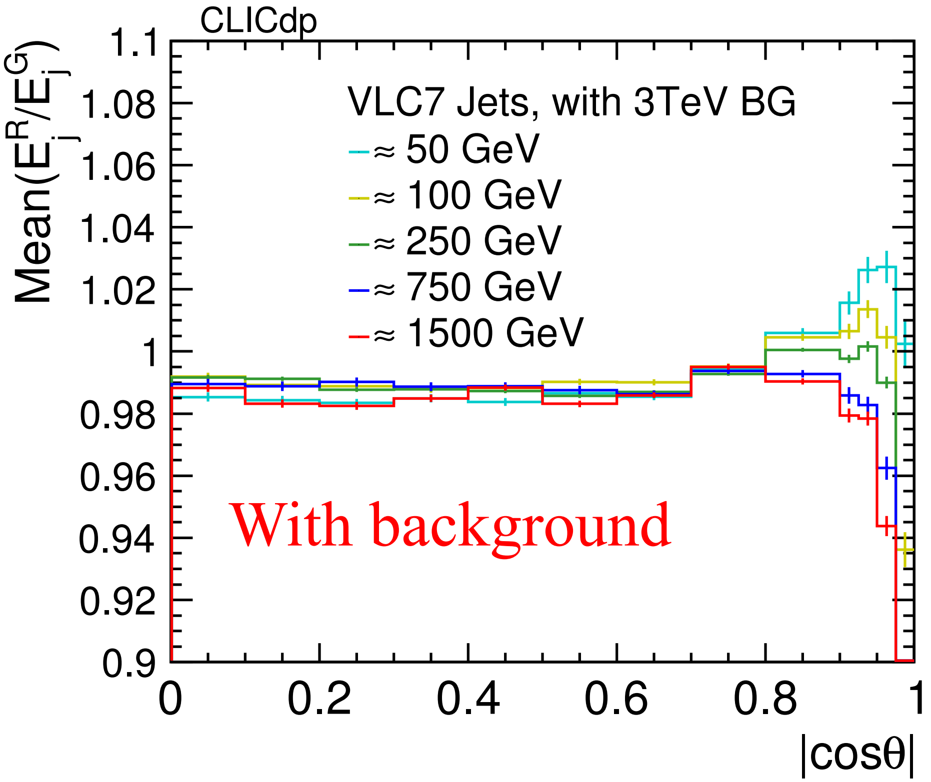
PandoraPFOs calibrated, no further calibration on jet energy

Check if γγ→hadrons background has large impact on energy collected in jet



Ratio $E_{recojet}/E_{genjet}$

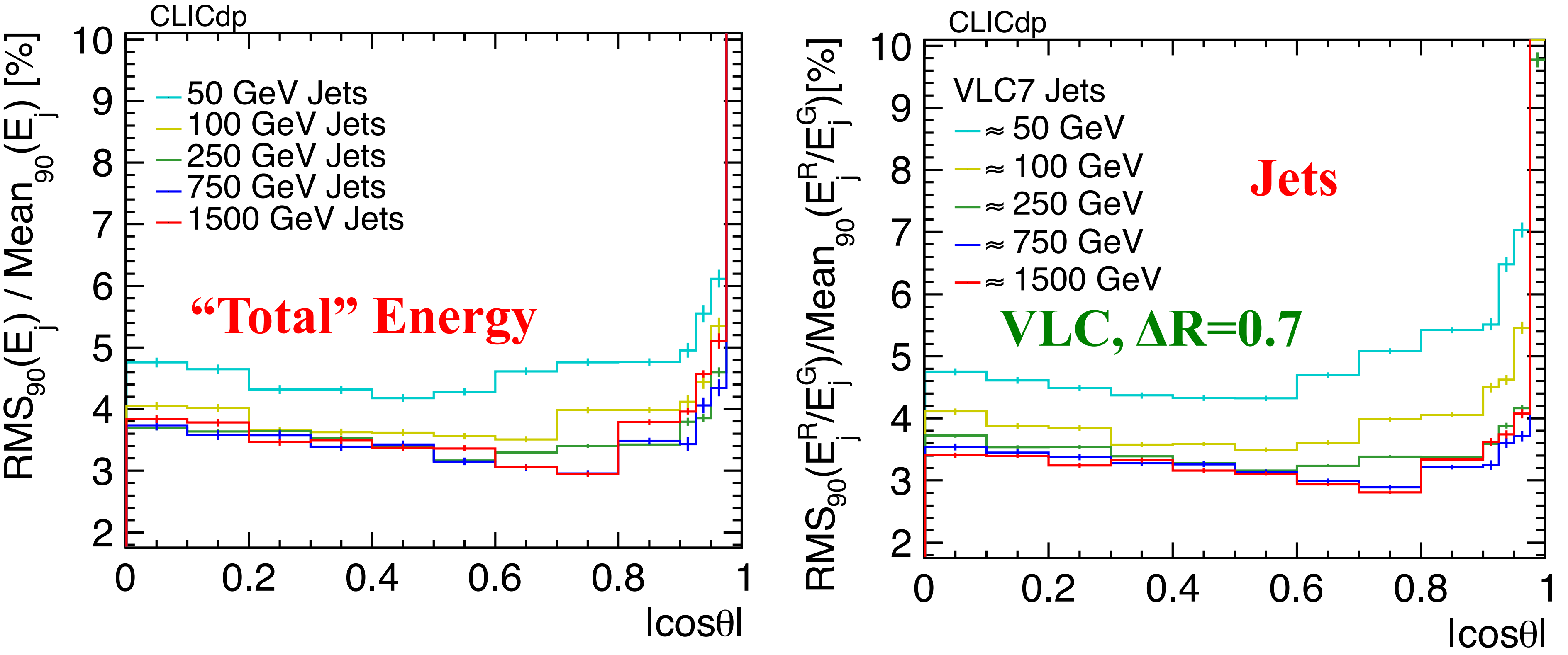
No background



With background

Angular matching requirement between detector level recojet and particle level genjet within 10°→ raw jet energy response close to unity for both cases, no large impact of background within jet cone

Jet Energy resolution (JER): total Energy vs Jets



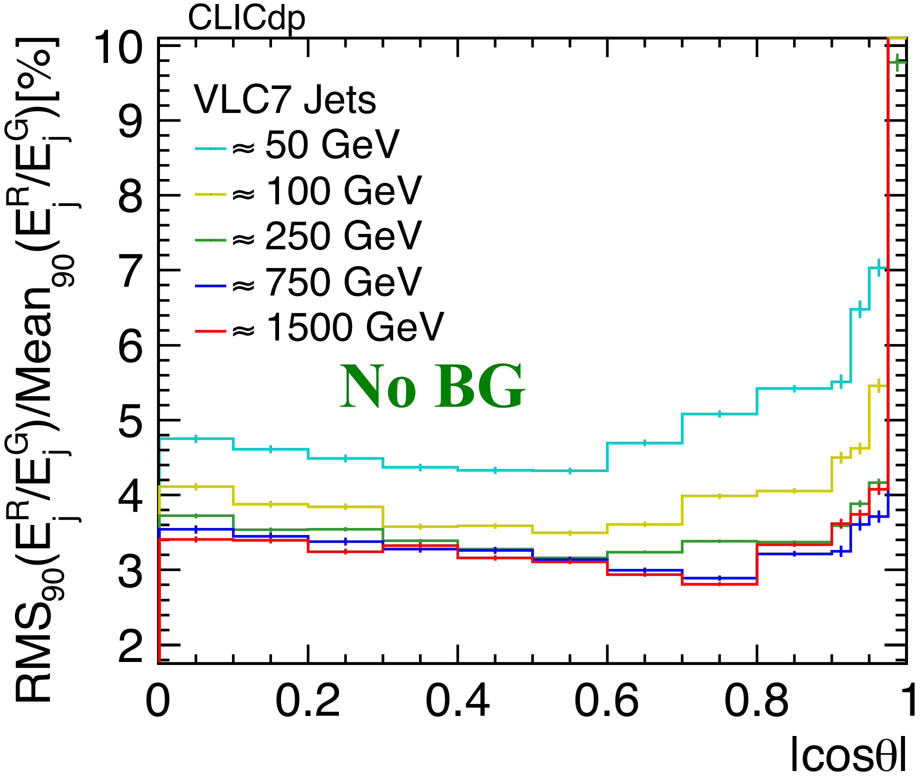
Jet Energy Resolution for several jet energies, as function of |cos θ| of quark

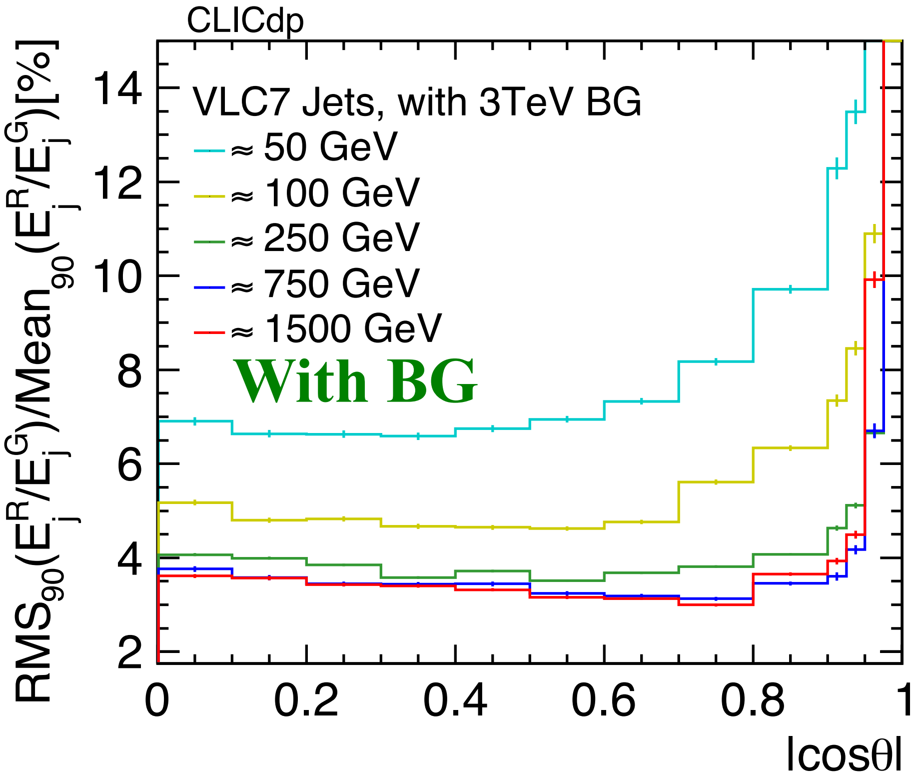
Compare reconstructed jets and particle jets, ΔR = 0.7

Angular matching between reconstructed and particle jet (<10 °)

→ Similar resolution values after jet clustering

JER vs cosTheta: with and without BG





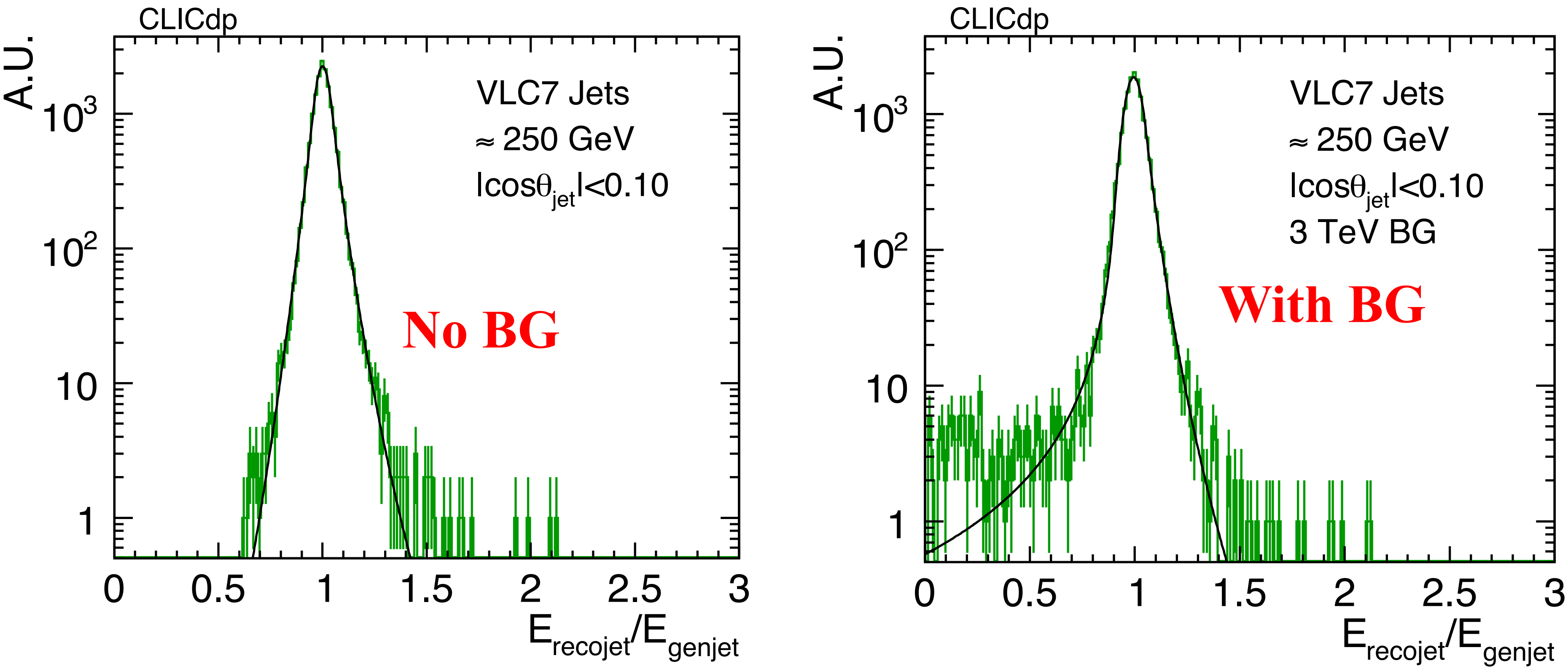
Compare resolution of reconstructed jets →3TeV conditions for overlay

→for 50 GeV jets increase from 4.5/5 % to 7 % in barrel

→for 100 GeV jets increase from 4 % from 5% in barrel, 6.5 % in endcap

At high jet energies mild increase, except for very forward jets

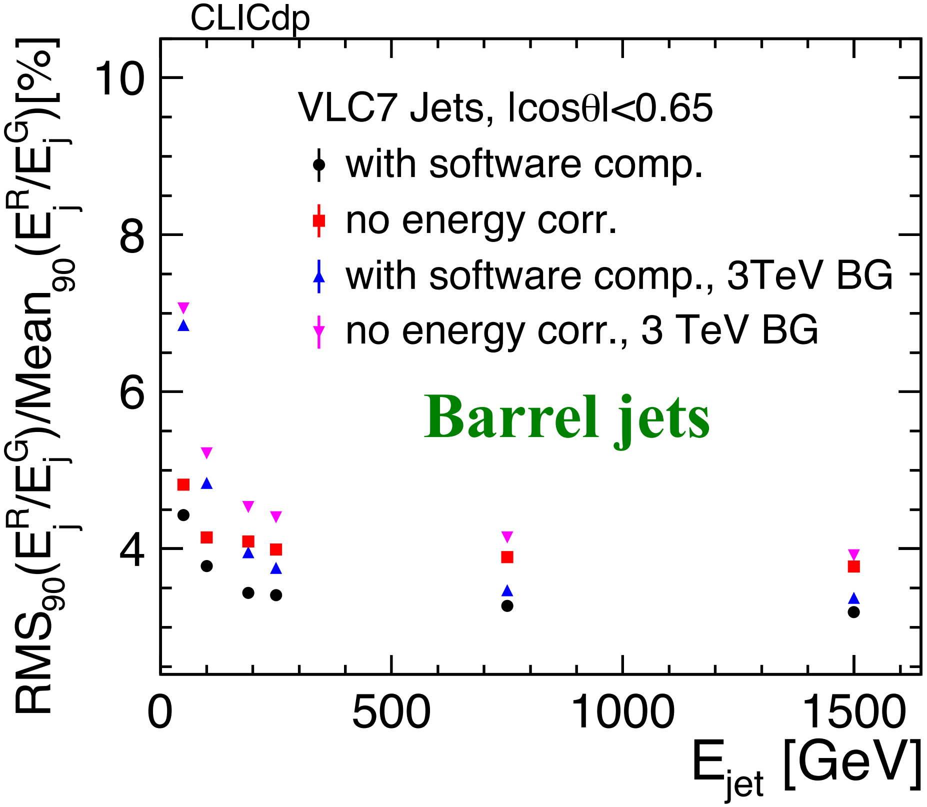
Jet Energy Resolution: Fit resolution curves

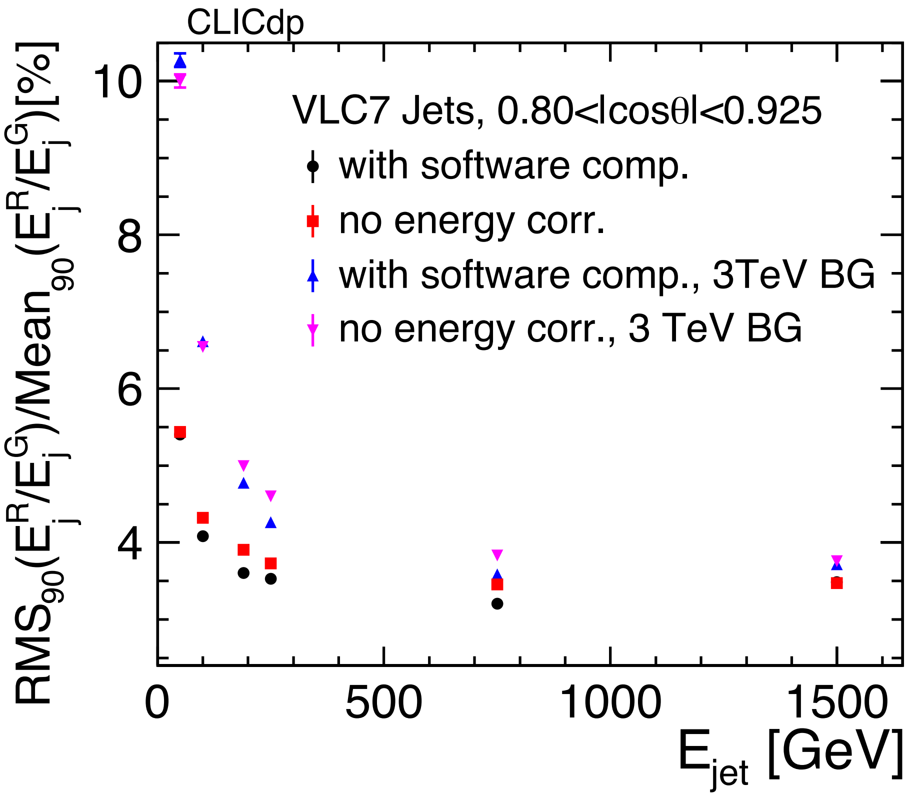


γγ → hadrons background leads to significant non gaussian tails in the jet energy resolution distribution, double sided crystal ball function (gaussian core and power law tails) fits most of the distribution for all detector regions

- Double sided crystal ball used by CMS
- Background creates a larger tail to lower resolution values

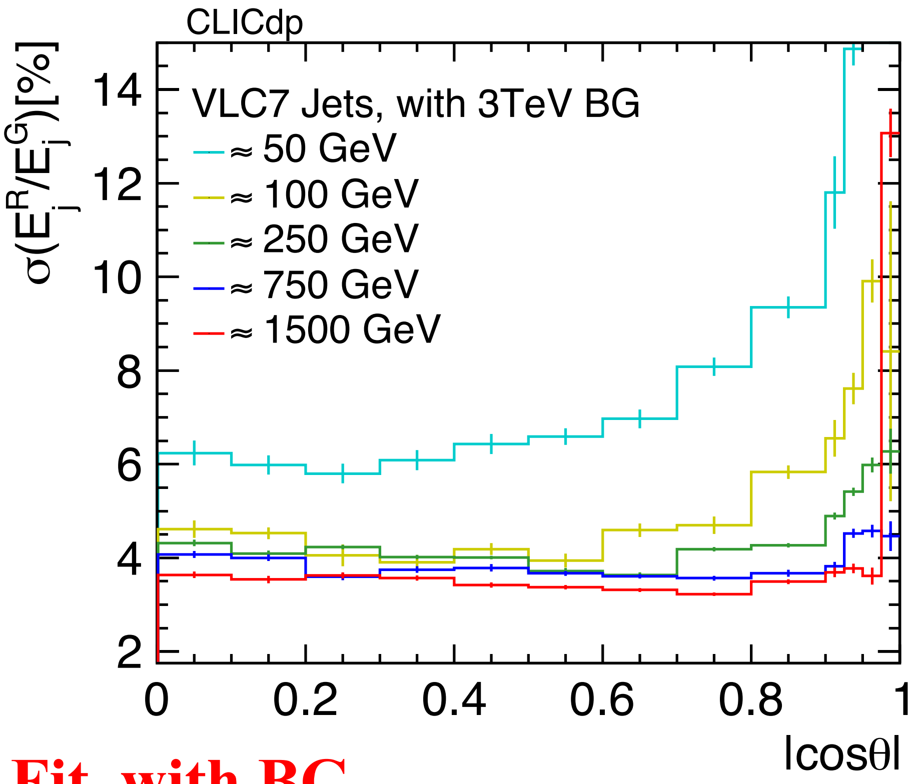
Software Compensation



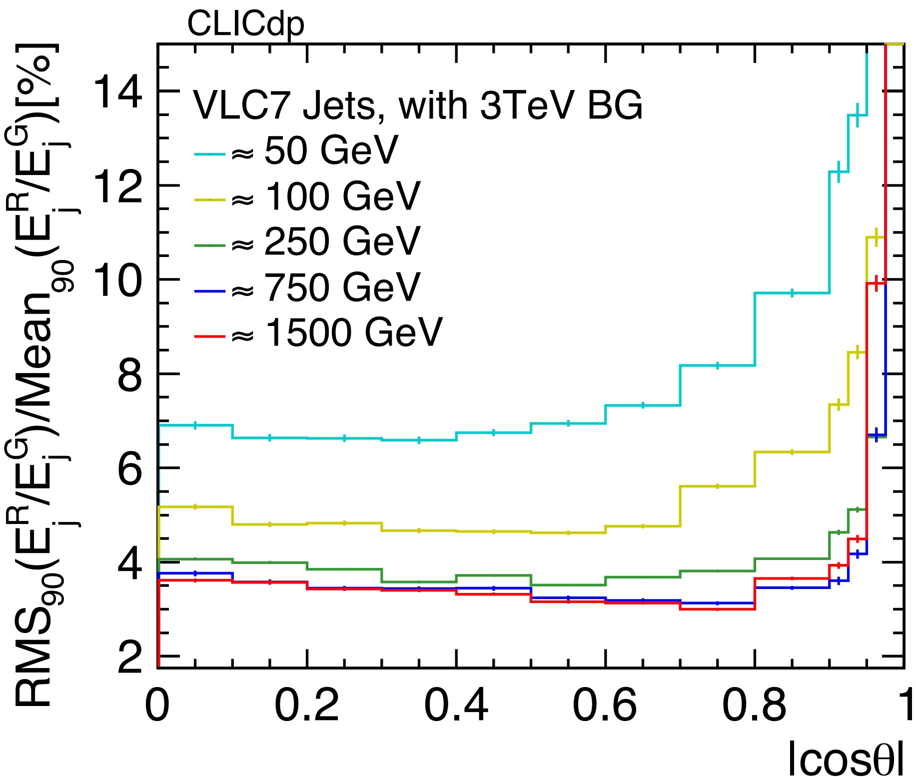


Software Compensation improvement similar without and with background (5-15 %), less improvement in endcap (5-10 %)

Jet Energy Resolution: CB fit σ vs RMS90



Fit, with BG

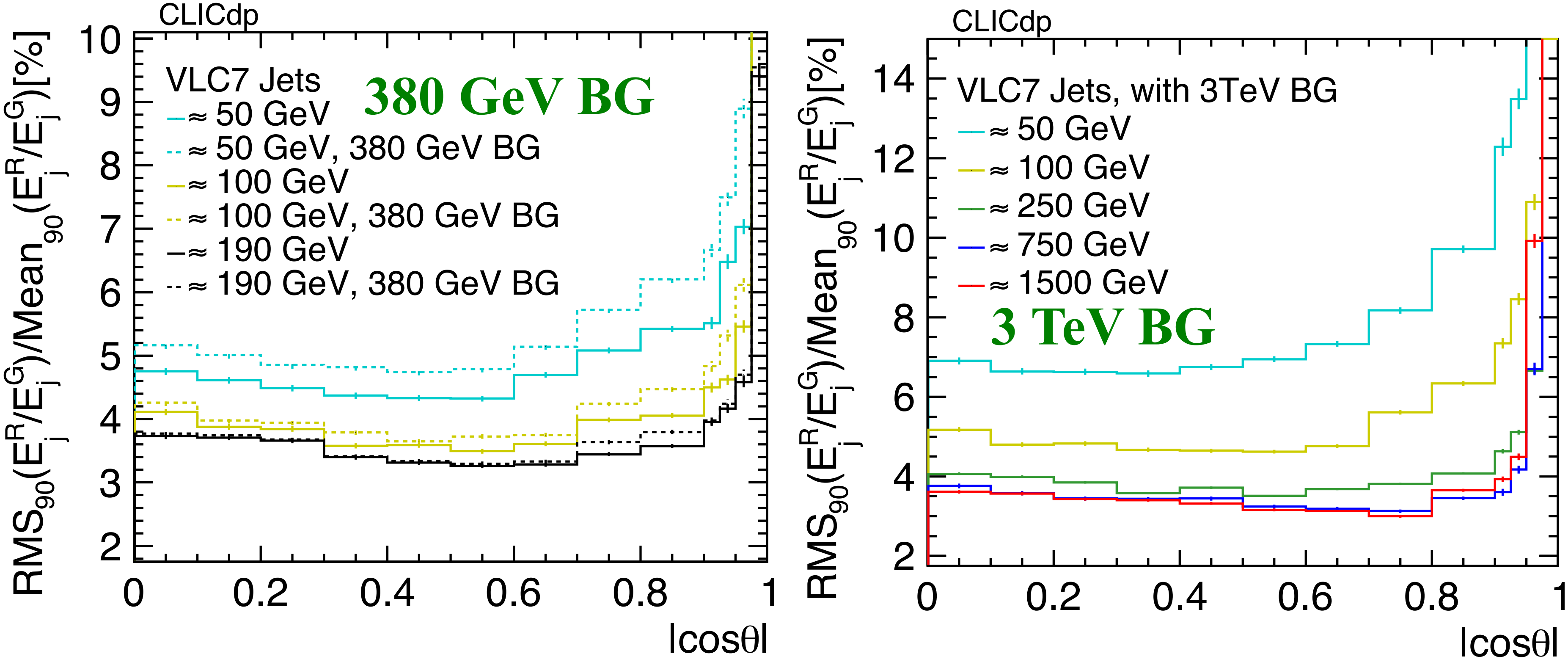


RMS 90, with BG

Fit jet energy response by double sided Crystal Ball function, use sigma of the Gaussian core as measure for jet energy resolution

For most energies resolution values of fit close to the RMS90 resolution measure, for high energies within 10-15 %

JER vs cosTheta: 380 and 3 TeV BG

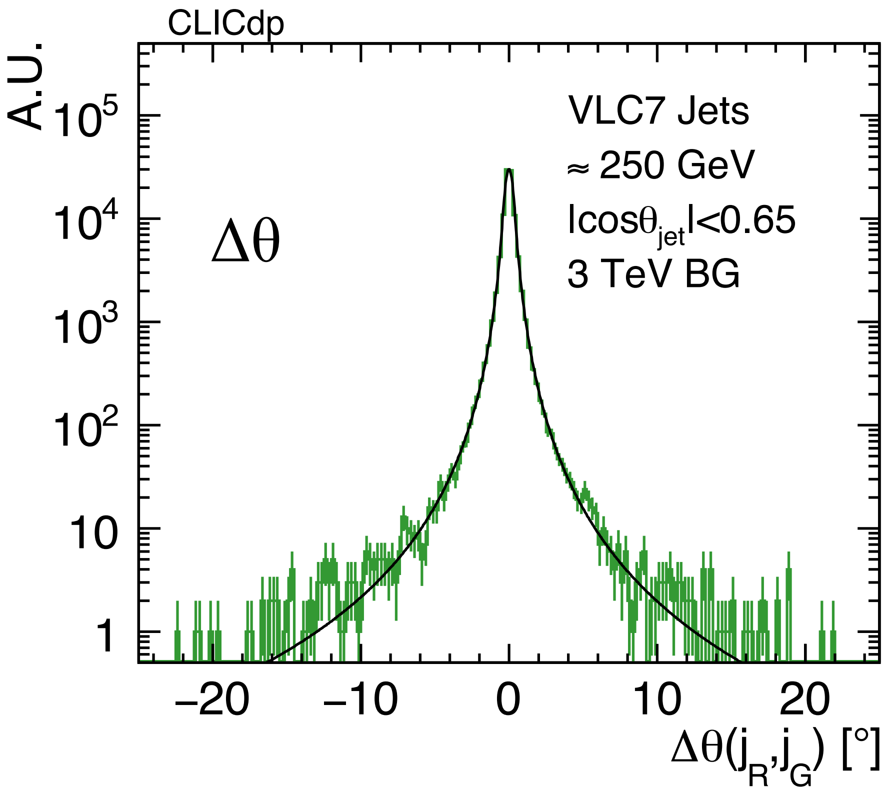


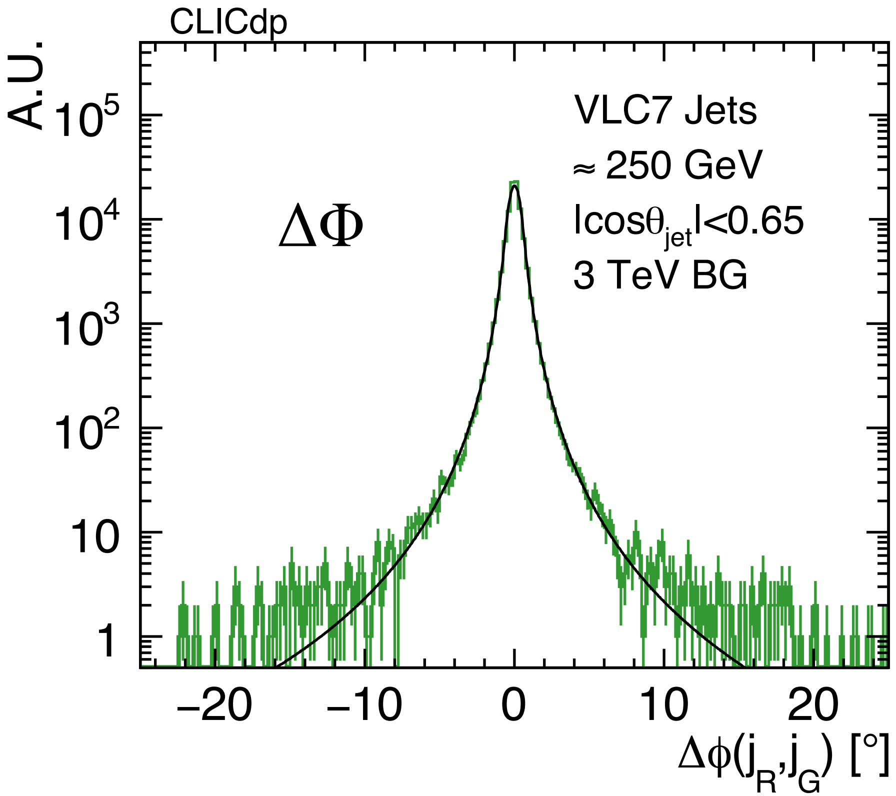
Compare background levels from γγ→hadrons of the 380 GeV machine to the 3 TeV machine

- Moderate increase in jet energy resolution for barrel jets even for 50 GeV jets, at 3 TeV machine increase from 5→7 %
- Almost no effect of background for barrel jets for energies >100 GeV

Jet Phi and Theta Resolution

Position Resolution: Fit resolution curves

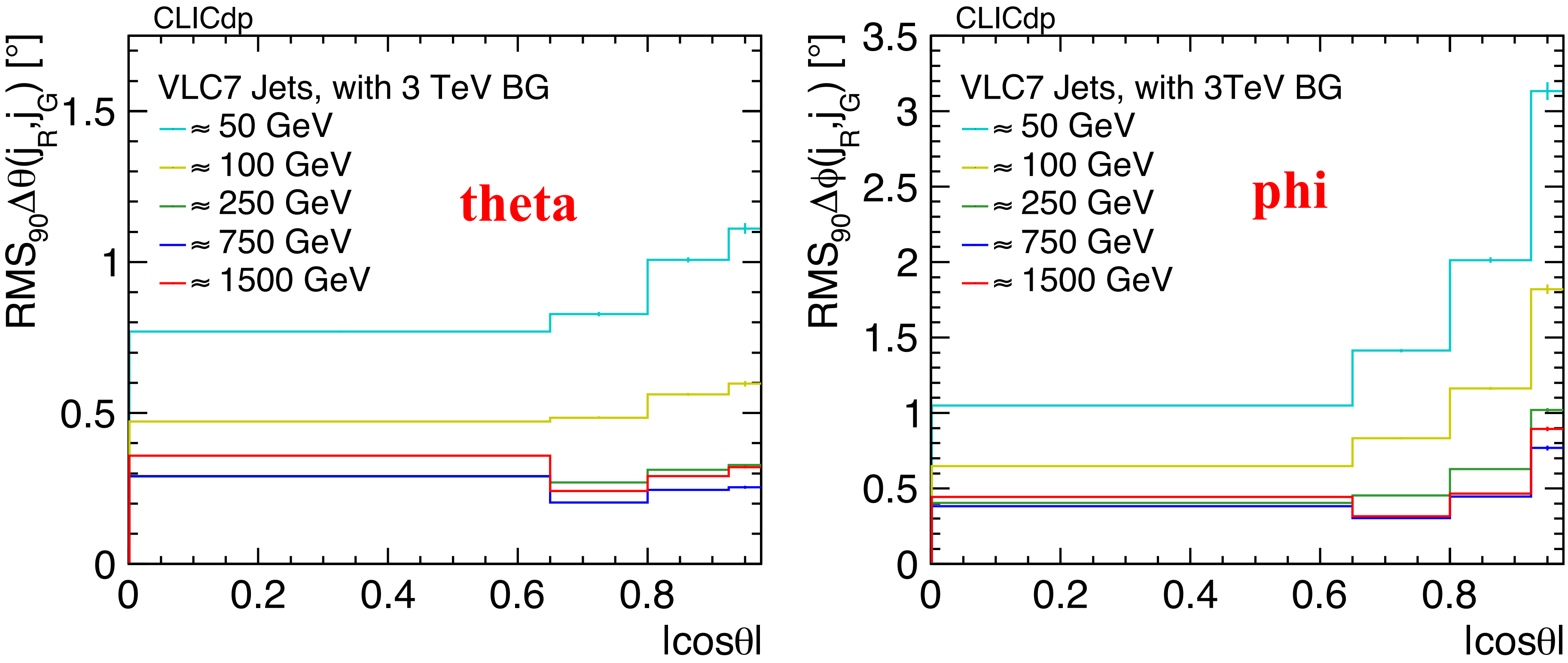




Δθ and ΔΦ distributions between reconstructed and closest MC truth jet

Fit with a double sided Crystal Ball function with a Gaussian core and two exponentials, fits most of the distribution well

Jet Phi and Theta Resolution with 3 TeV BG



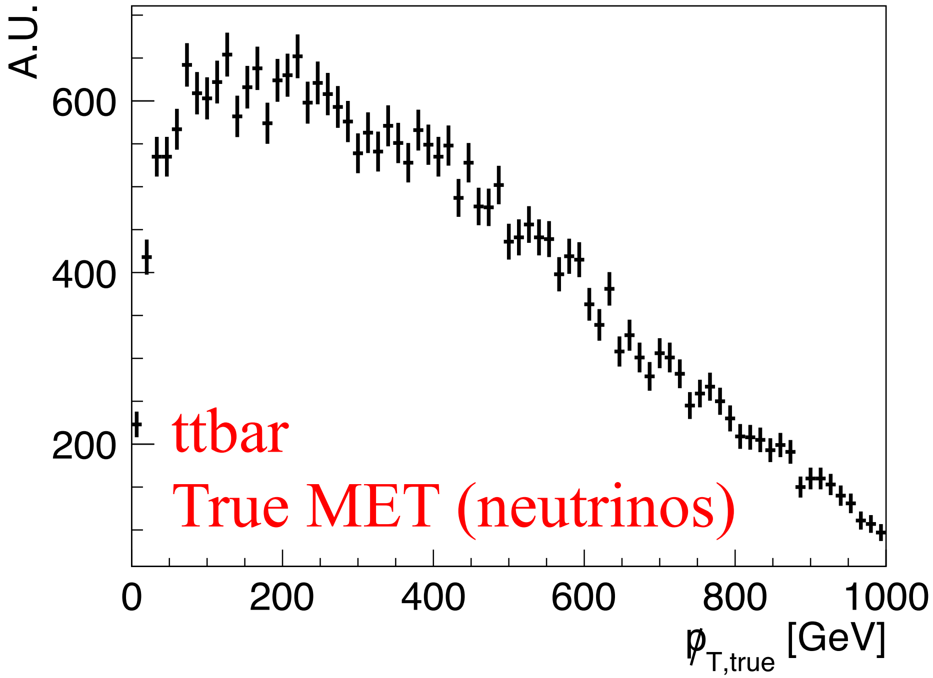
Theta/Phi resolutions below 1/1.5 degree for most detector regions for all jet energies, for forward region phi resolutions a bit larger for low energetic jets

MET Resolution

MET Resolution

Study two cases:
Events with fake MET: Z→qq (with q=u,d,s) at 3 TeV, investigate 3 TeV γγ→hadron backgrounds

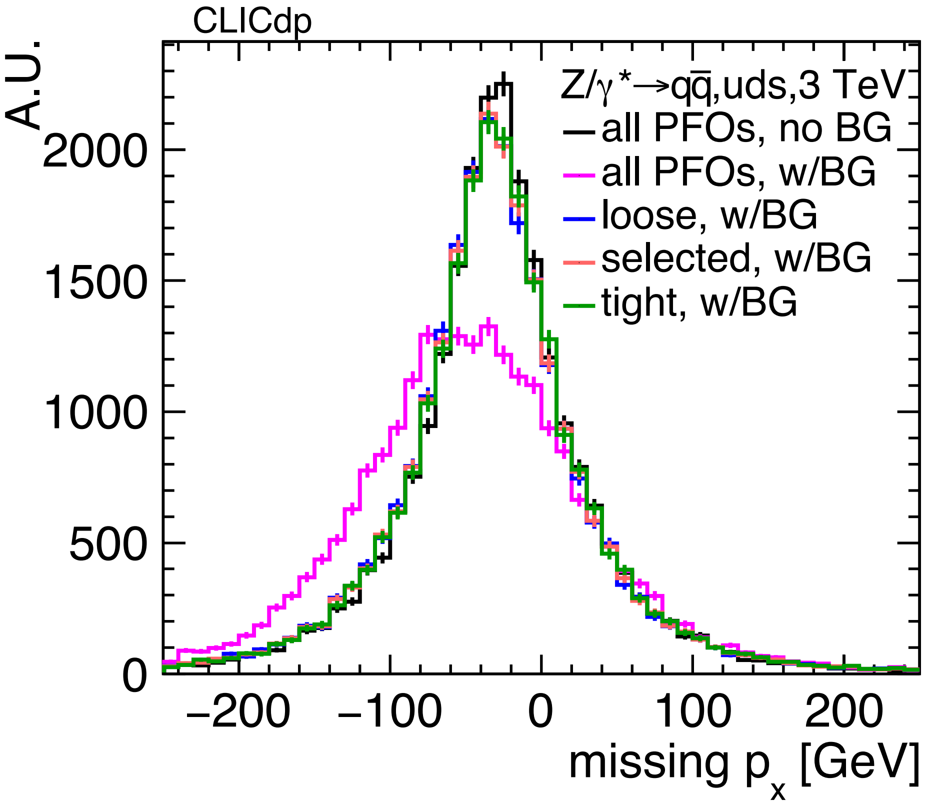
Events with genuine MET: semi- and di-leptonically ttbar events at 3 TeV, check background from γγ→hadrons at 3 TeV



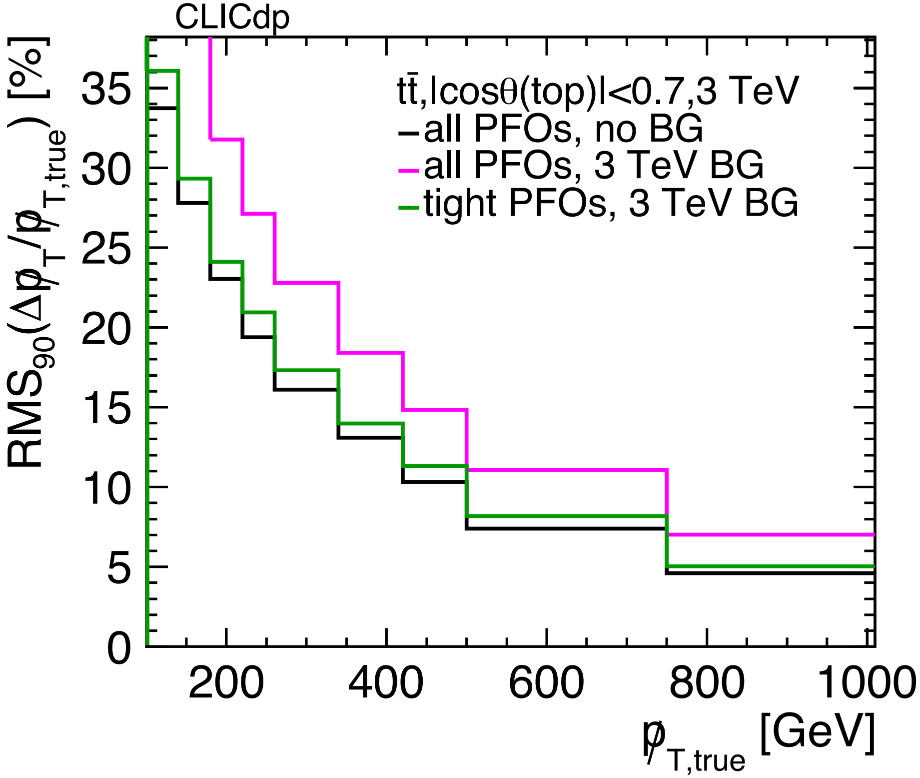
True missing transverse momentum from neutrinos in semi- & dileptonic ttbar → peaks around 100-250 GeV

MET Resolution

Z→qq @3TeV, fake MET



ttbar @3TeV, real MET



→using PFO selection cuts clearly improves resolution, tight selection cuts perform best

→ MET spectrum above 100 GeV, clearly improves with selection cuts, restrict range of tops to avoid a bias due to jets outside of detector acceptance

W and Z mass separation

W and Z mass with overlay

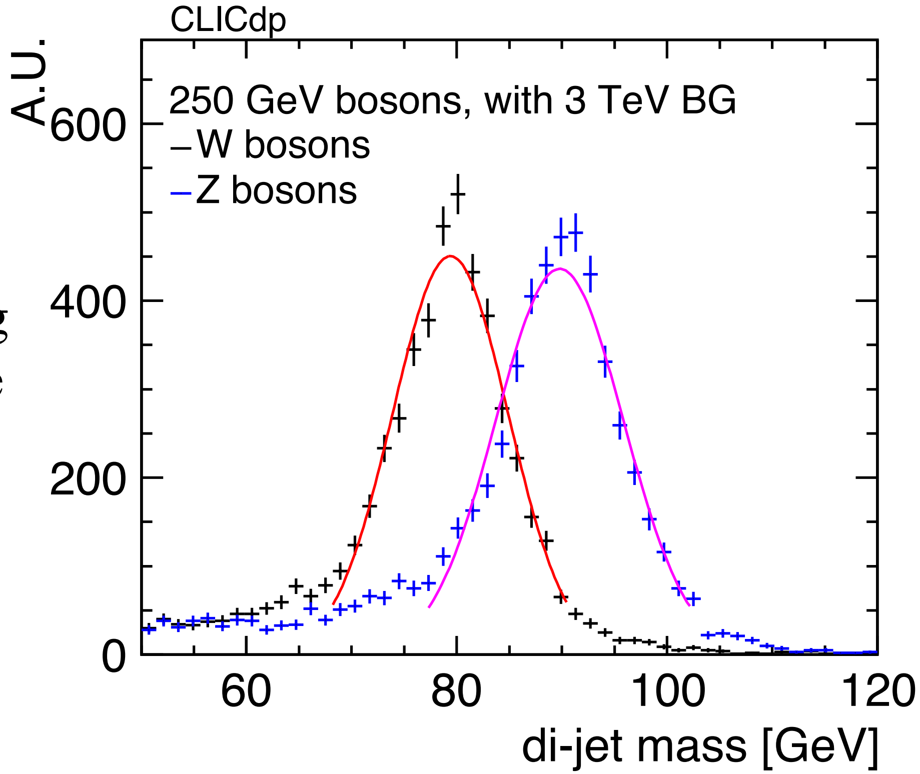
Study dijet mass reconstruction in WW→qq lν and ZZ→qq νν events

Impact of γγ→hadrons studied using 3 TeV beam conditions

Dijet mass peak separation quantified using the overlap fraction A_O and the corresponding selection efficiency ε (=1-A_O), defined by the gaussian fits (Integral normalised to 1)

$$A_O = \left(\int_{-500}^{X_{\text{int}}} gaussZ(x)dx + \int_{X_{\text{int}}}^{500} gaussW(x)dx \right) / 2$$

500 GeV c.m. WW and ZZ events, dijet mass



W and Z mass separation results

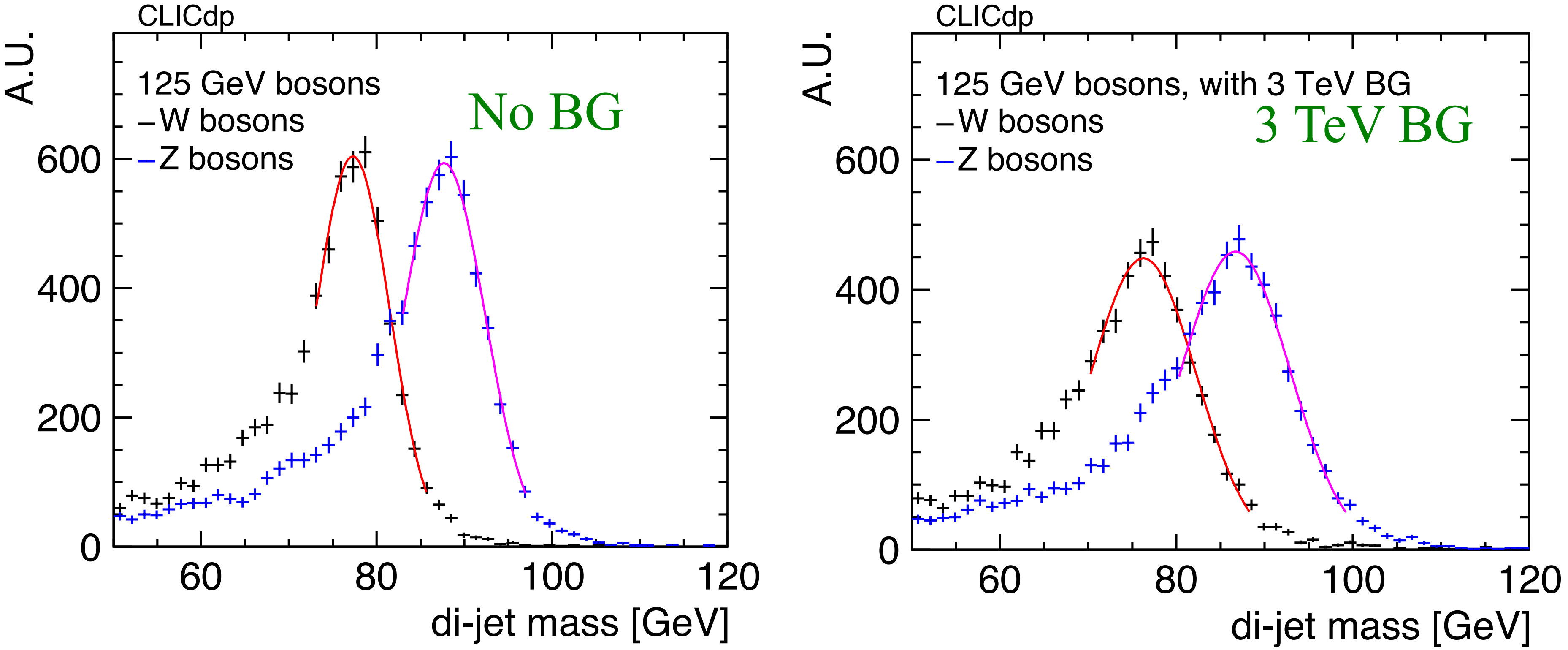
Background	$E_{W,Z}$ [GeV]	$\sigma_{m(W)}/m(W)$ [%]	$\sigma_{m(Z)}/m(Z)$ [%]	ε [%]	Separation [σ]
no BG	125	5.5	5.3	88	2.3
	250	5.3	5.4	88	2.3
	500	5.1	4.9	90	2.5
	1000	6.6	6.2	84	2.0
3 TeV BG	125	7.8	7.1	80	1.7
	250	6.9	6.8	82	1.8
	500	6.2	6.1	85	2.0
	1000	7.9	7.2	80	1.7
380 GeV BG	125	6.0	5.5	87	2.2

Without background overlap fraction between 10-16 %

Increase of overlap fraction to 15-20 % due to beam background effects (13% for 380 GeV backgrounds)

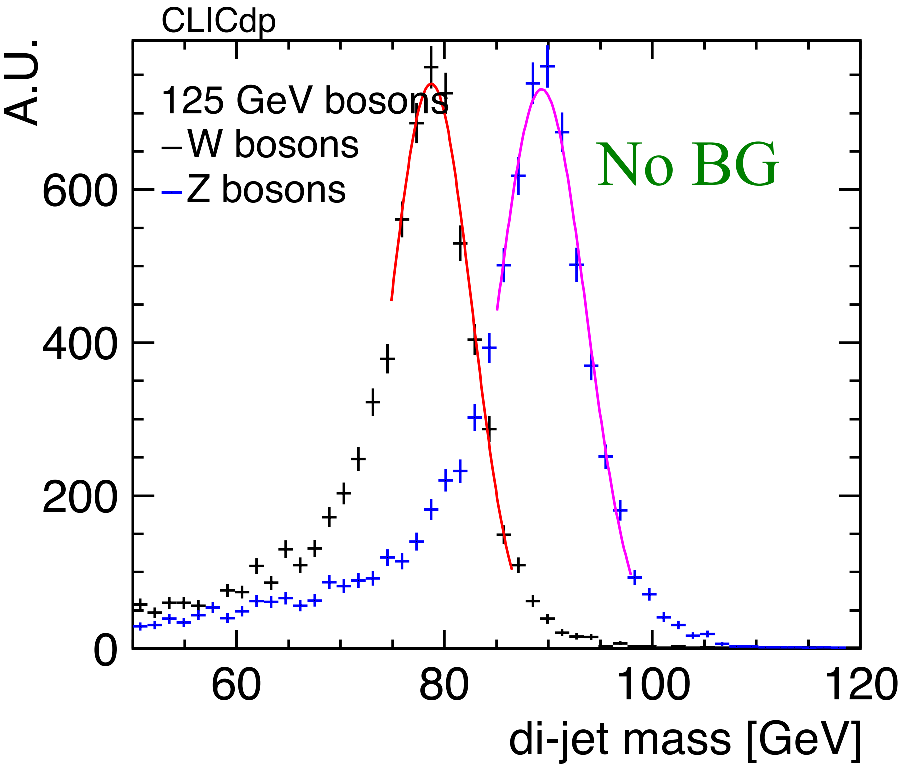
W and Z mass: VLC R=0.7 125 GeV bosons

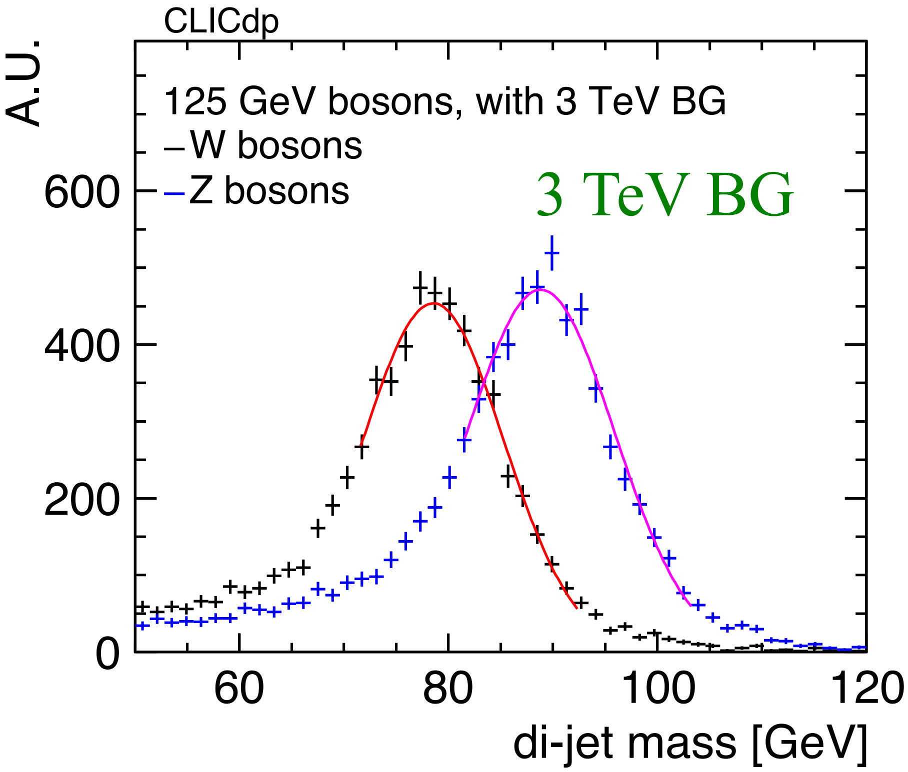
Dijet mass has long tail to lower masses



W and Z mass: VLC R=1.0 125 GeV bosons

Tail is indeed reduced
→what about other energies

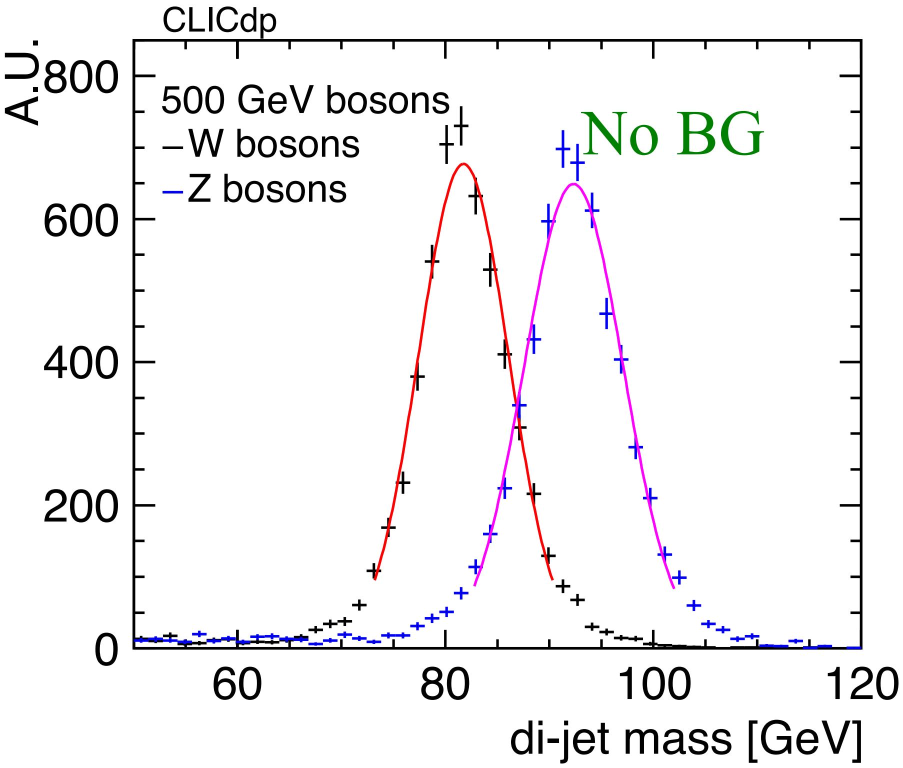




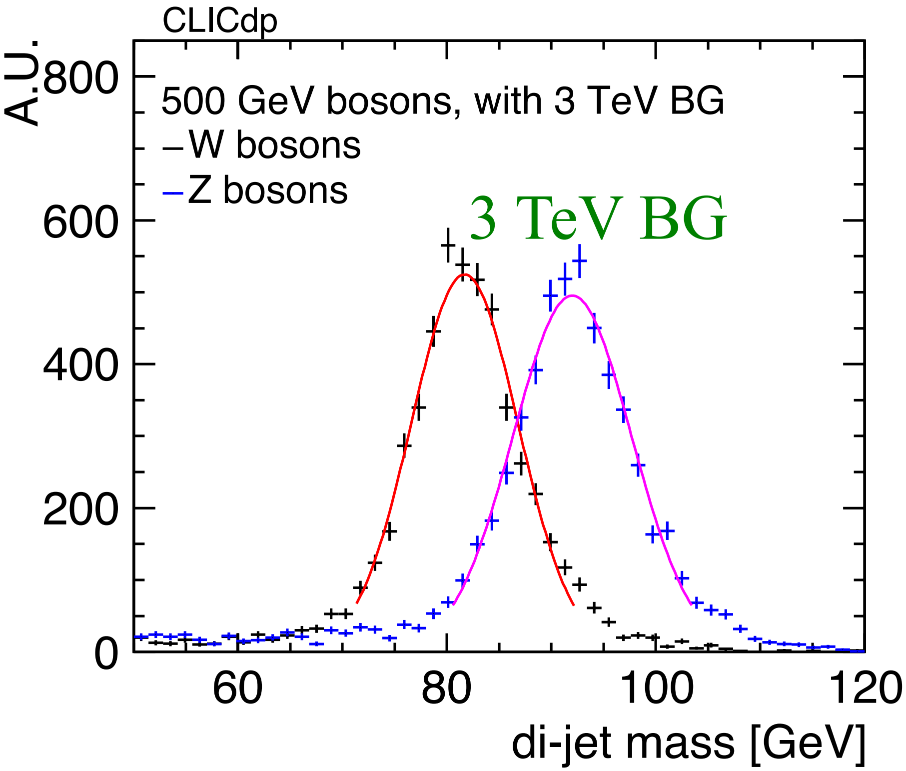
W and Z mass: VLC R=0.7 500 GeV bosons

Still nice di-jet mass peak, still symmetric

Symmetric di-jet mass distribution



No BG

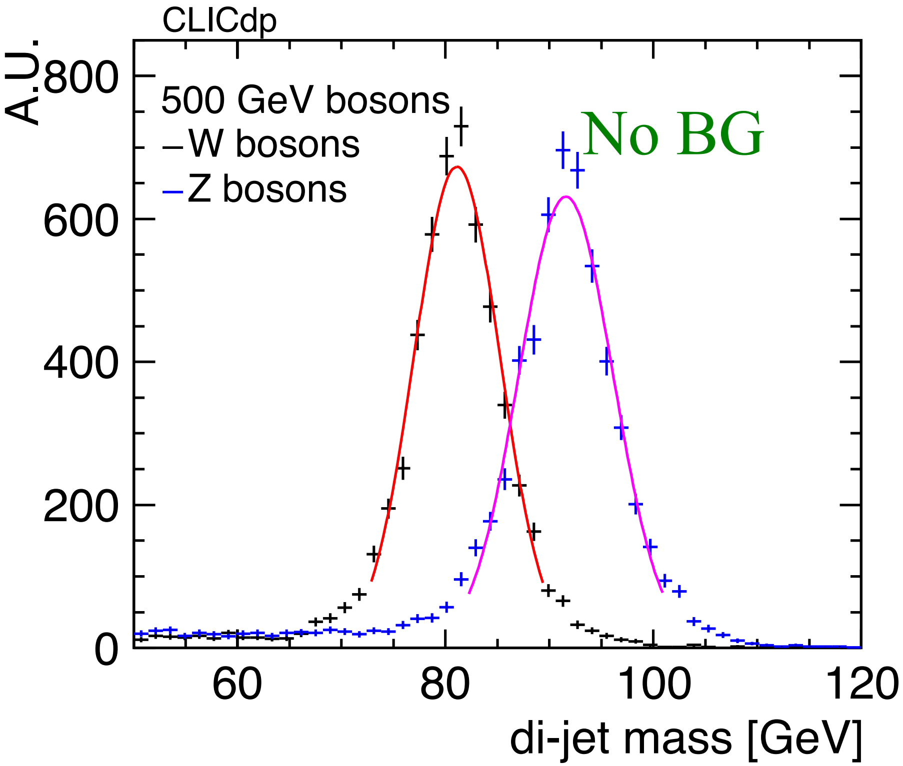


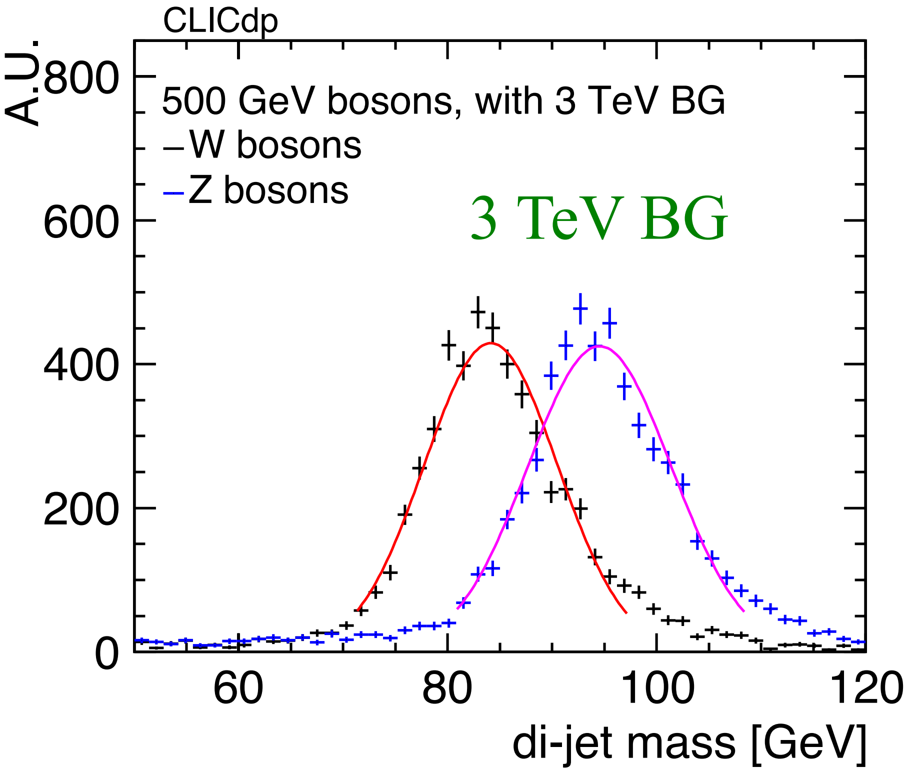
3 TeV BG

W and Z mass: VLC R=1.0 500 GeV bosons

Still nice di-jet mass peak, still symmetric

Tail to high di-jet masses starts to appear → more background is picked up





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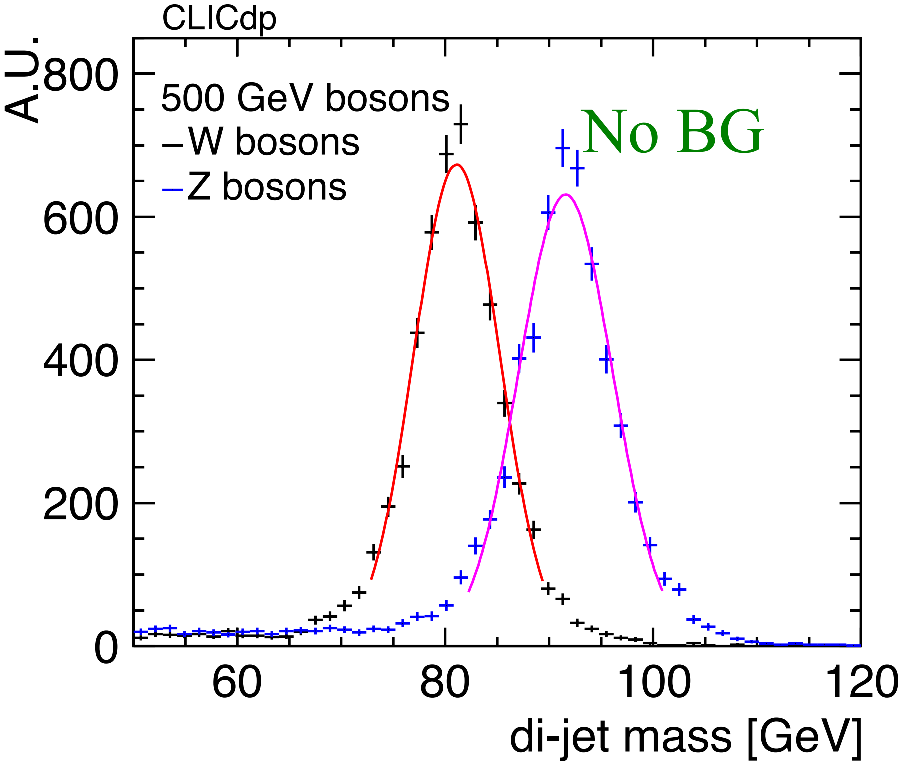
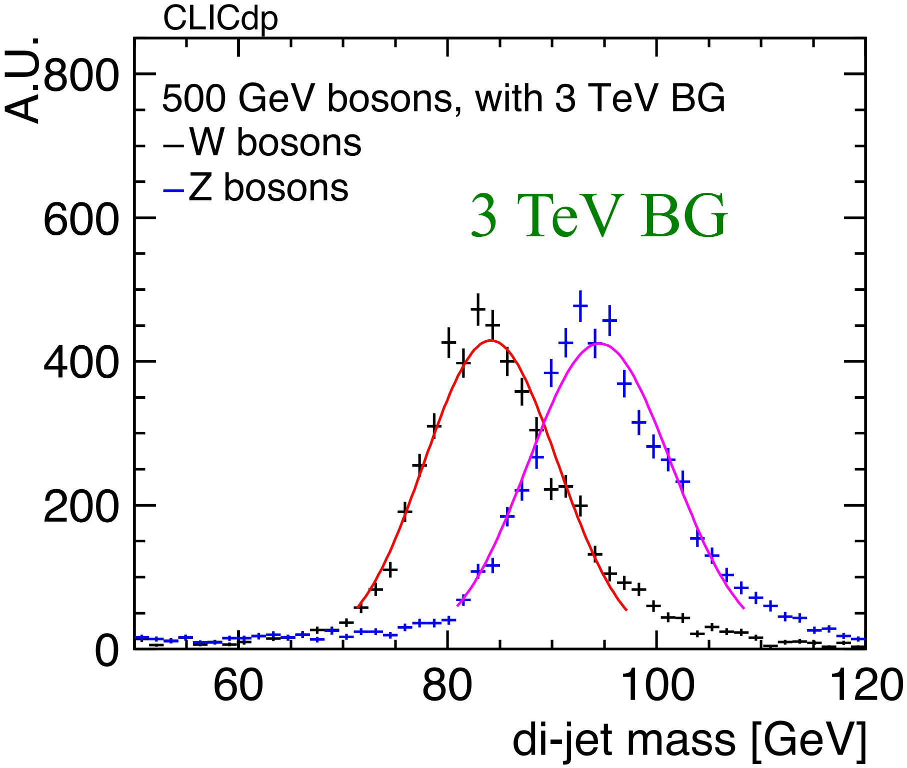




Conclusion

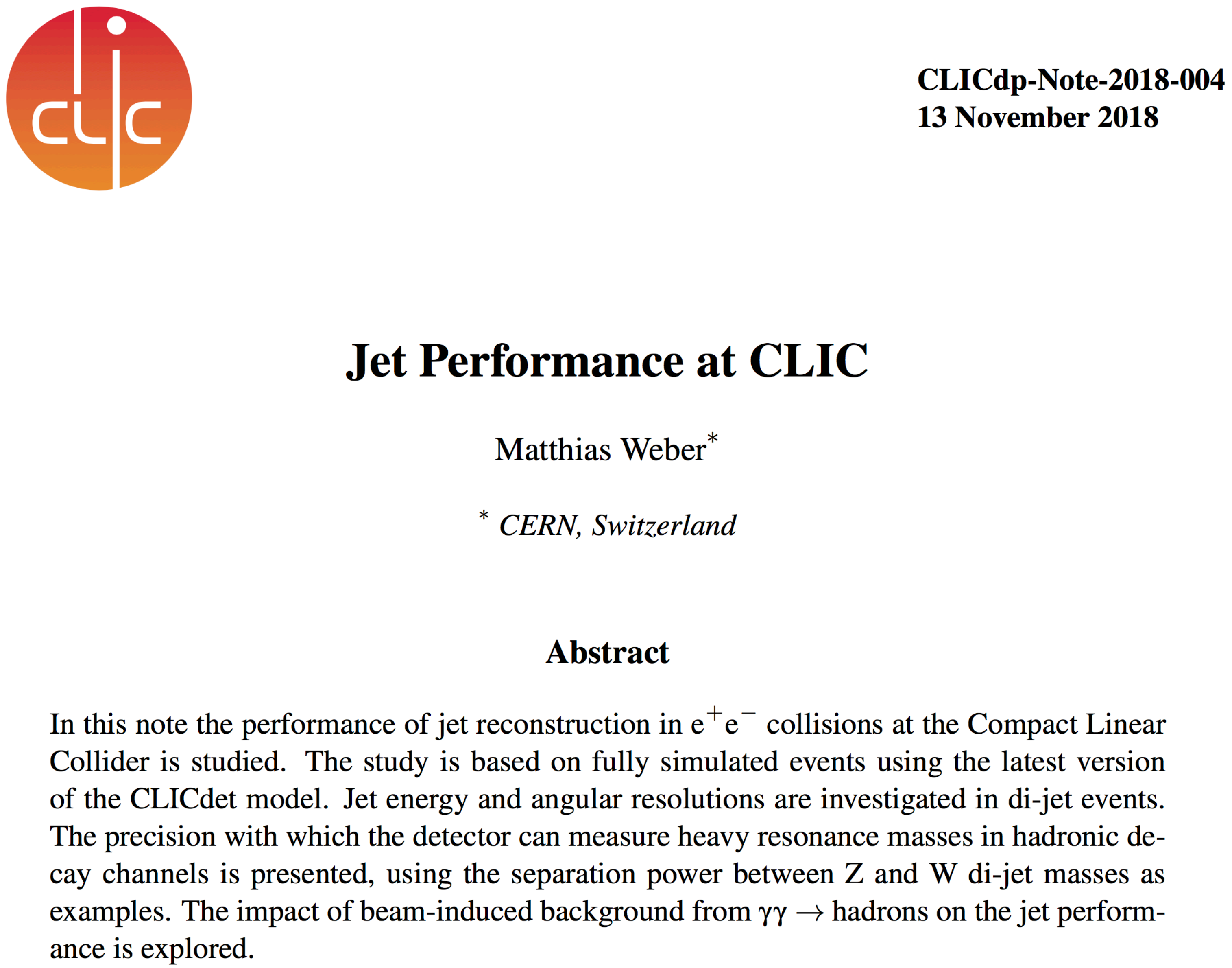
Jet energy resolution around 3-5% for all energies and all detector regions, up to 10 % for very forward jets
→RMS90 and sigma of double sided Crystal Ball fits lead to similar JER values

Beam backgrounds lead to an increase of the Jet Energy resolution to 7 % for 50 GeV jets, values below 5 % reached for jets energies above 100 GeV

Jet Phi resolutions below 2°, jet theta resolutions below 1° for energies from 50-1500 GeV jets with beam backgrounds overlaid

Achieve a W-Z dijet mass separation of 1.7-2.0 σ when including beam backgrounds
→cone of 0.7 works best for boson energies of 250 GeV and larger, for 125 GeV bosons larger cone preferred

→all Jet Studies documented in CLICdp-Note-2018-004 (CWR finished) and the DetectorPerformance Note



CLICdp-Note-2018-004
13 November 2018

Jet Performance at CLIC

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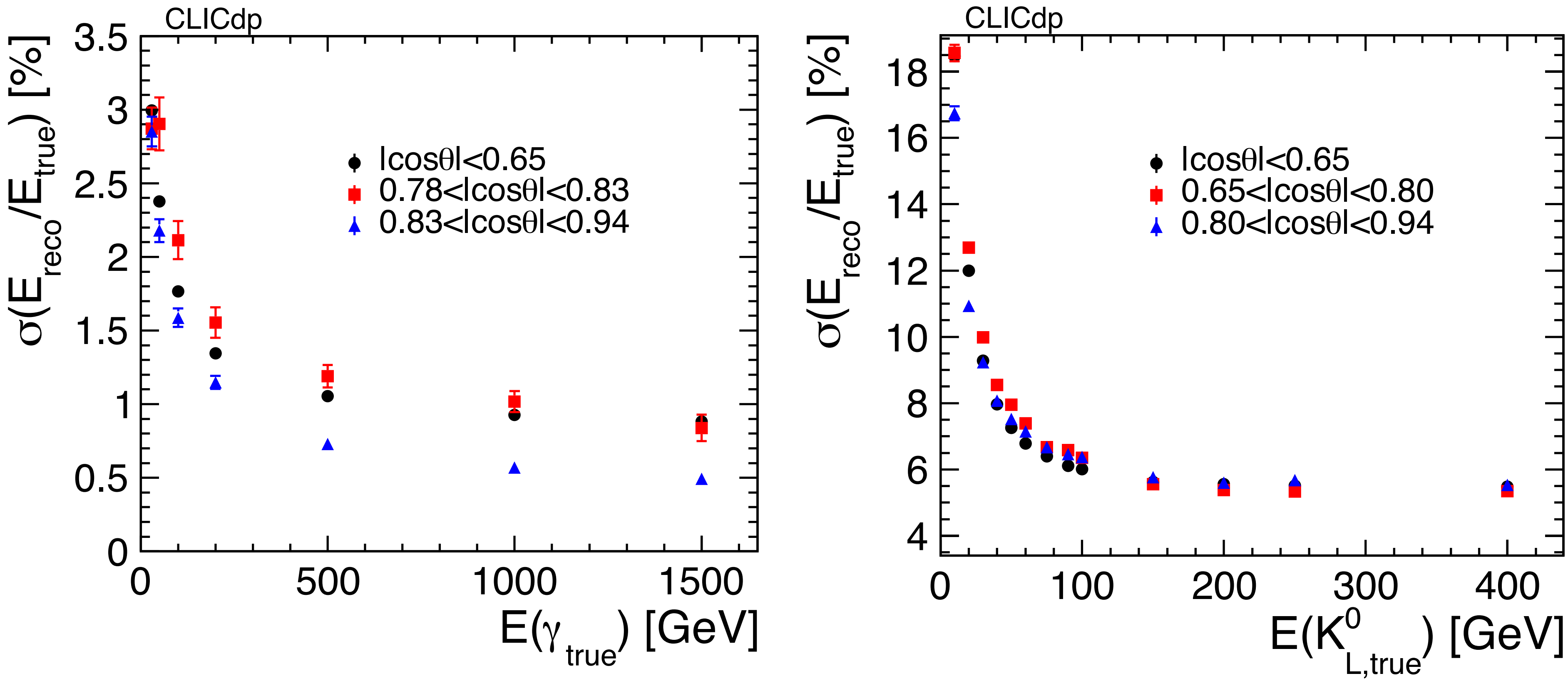
Abstract

In this note the performance of jet reconstruction in e^+e^- collisions at the Compact Linear Collider is studied. The study is based on fully simulated events using the latest version of the CLICdet model. Jet energy and angular resolutions are investigated in di-jet events. The precision with which the detector can measure heavy resonance masses in hadronic decay channels is presented, using the separation power between Z and W di-jet masses as examples. The impact of beam-induced background from $\gamma\gamma \rightarrow$ hadrons on the jet performance is explored.

BACKUP

Single Particle Performance

Photon and Kaon Energy Resolution

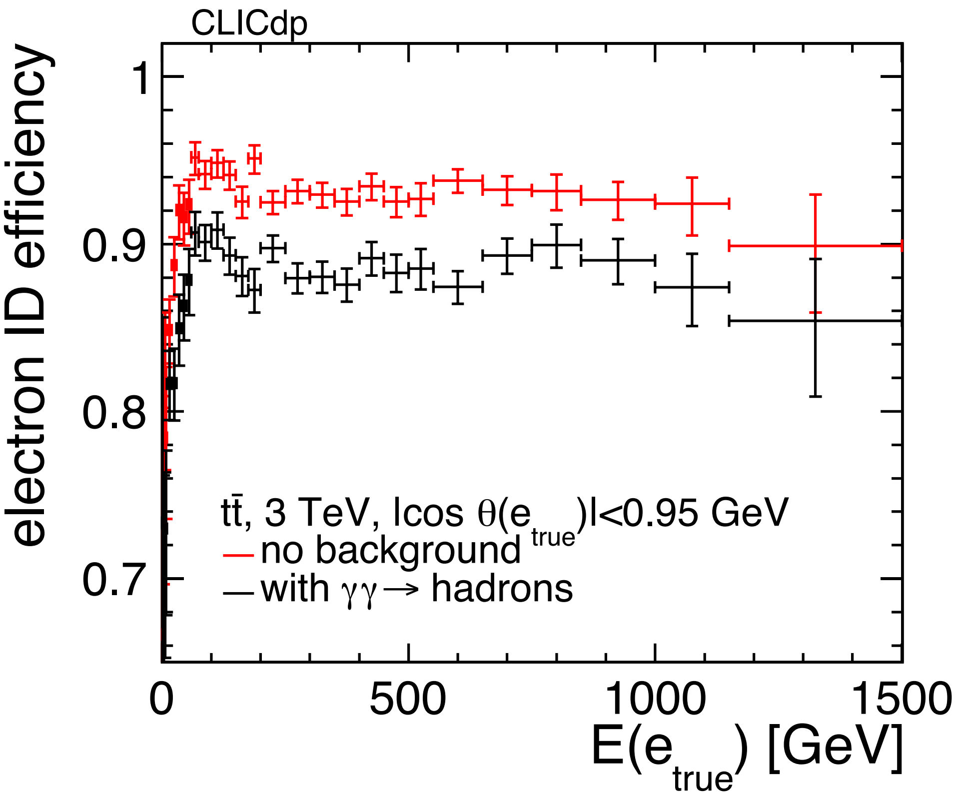


Photon energy resolution between 0.5-3 % from 30 to 1500 GeV

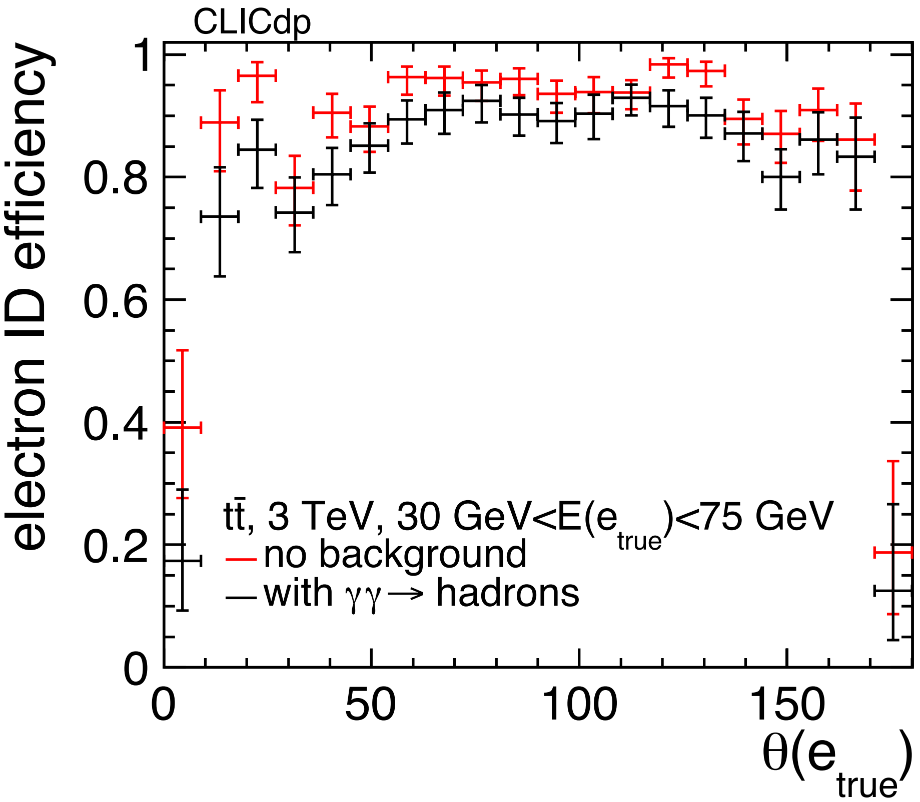
Kaon energy resolution between 5.5 and 18 % starting around 20 GeV

→Jet energy resolution distribution fitted with a Gaussian

Electron Efficiencies in ttbar @ 3 TeV

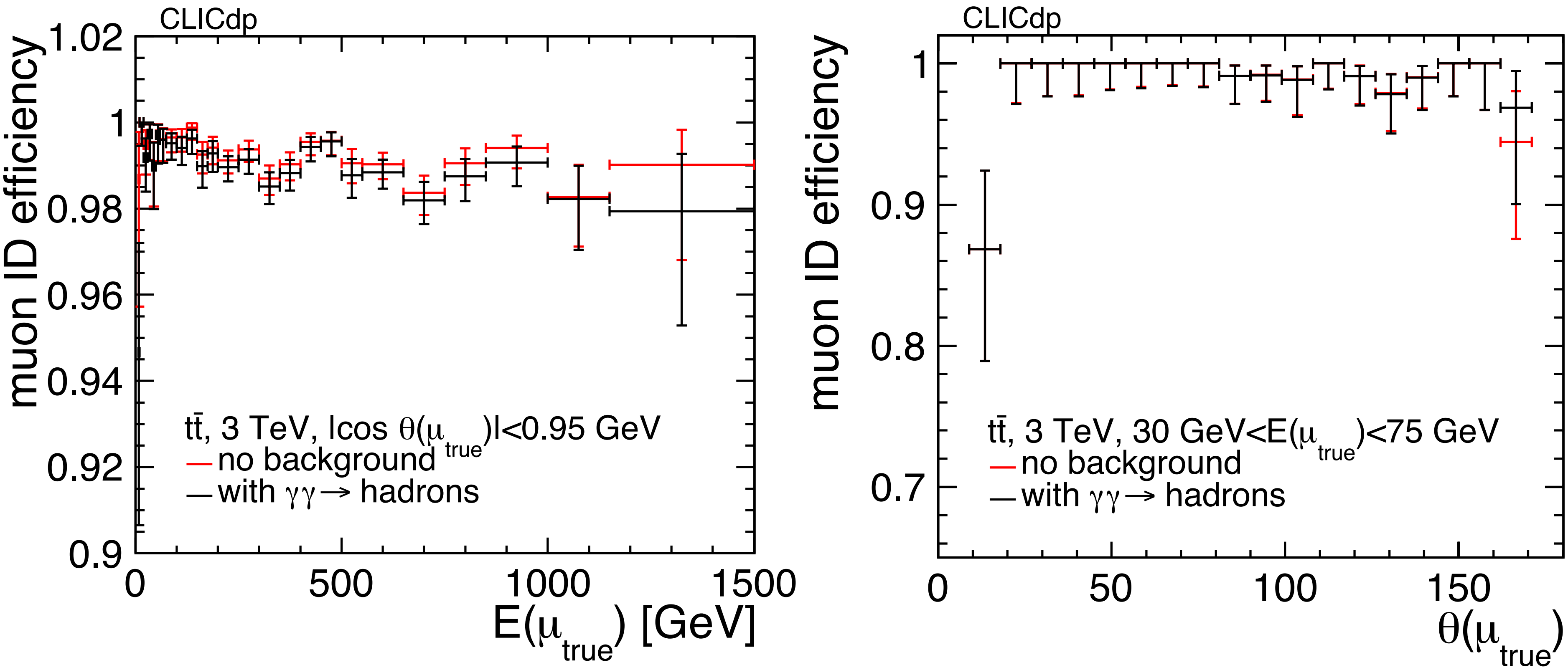


Electron efficiency vs electron energy
→ With background around 85-90 % starting at 25 GeV, 3-5 % difference to efficiency without background



Electron energy 30-75 GeV
Electron efficiency vs Theta
→ With background around 80 % in endcaps, around 90 % in barrel

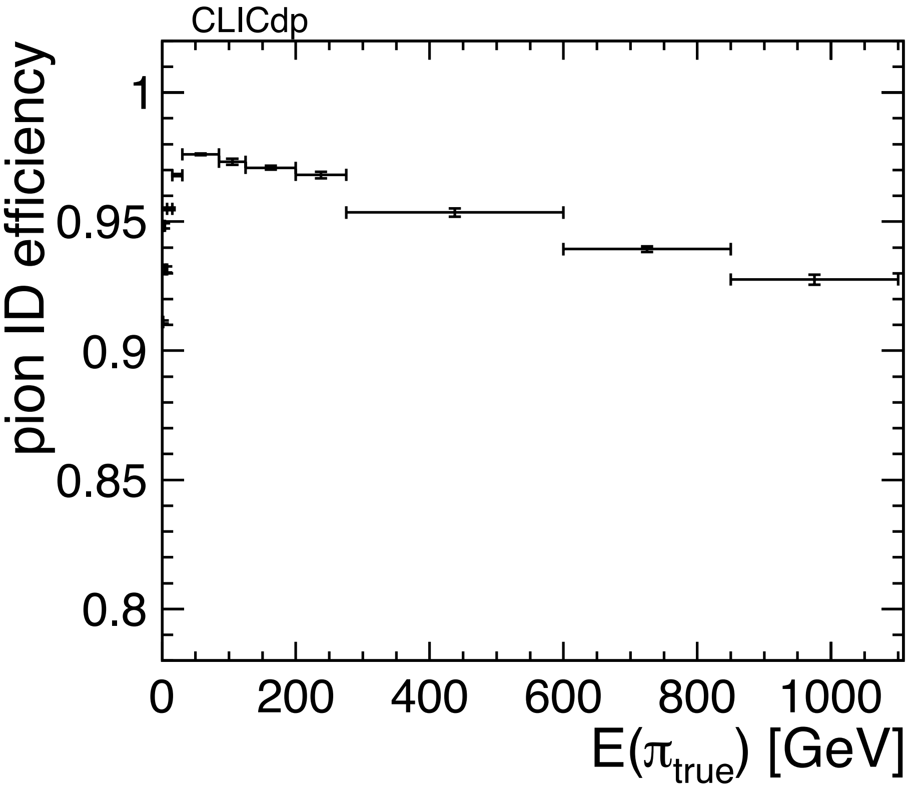
Muon Efficiencies in ttbar @ 3 TeV



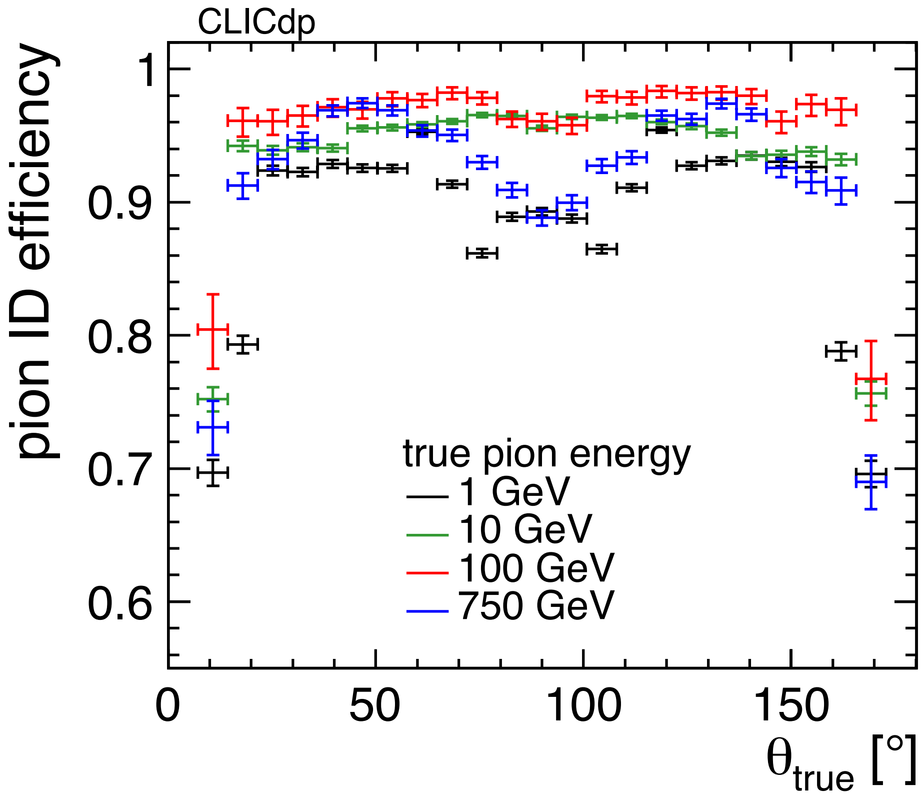
Electron efficiency vs electron energy
→ With background beyond 98%
starting at 5 GeV, less than 0.5 % effect
of background

Muon energy 30-75 GeV
Muon efficiency vs Theta pretty flat
around 98-99%

Pion Efficiencies

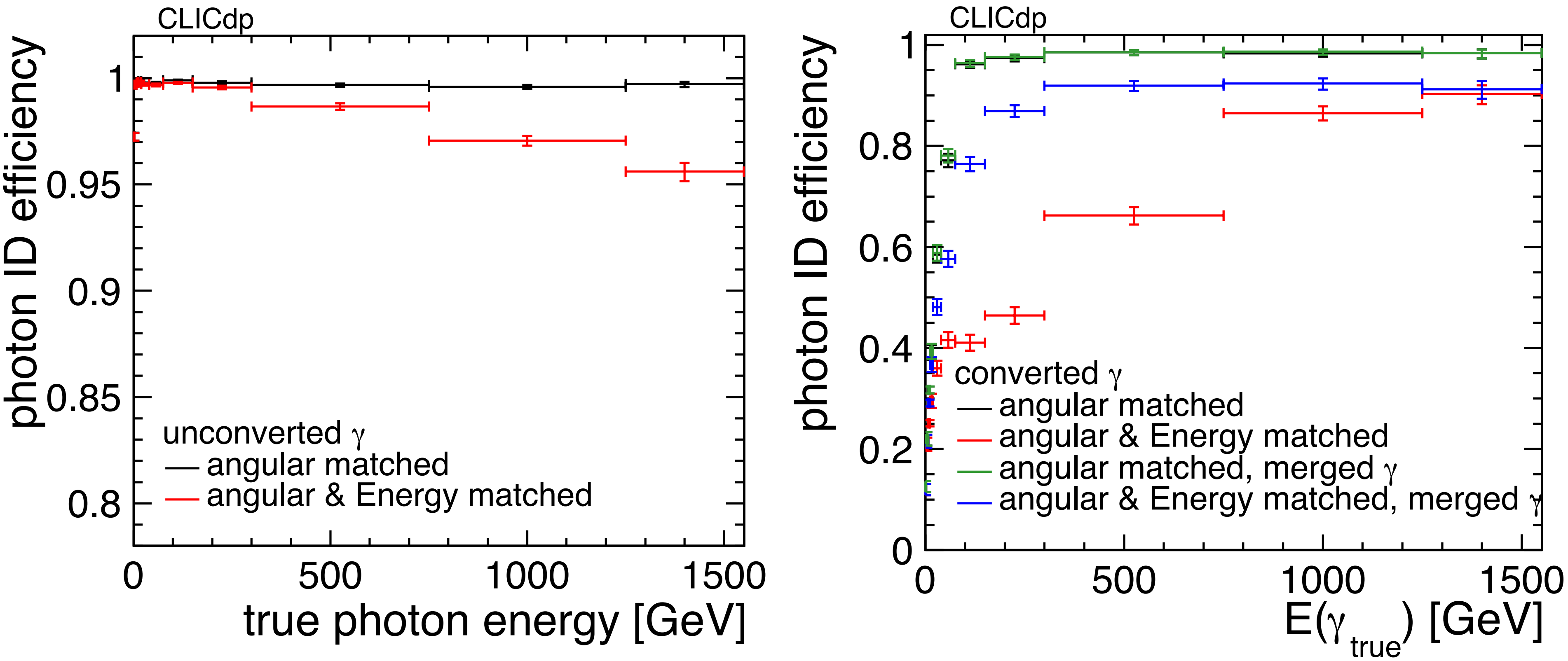


90-98% from 1-1000 GeV



Inefficiency at large energies in most central part of the detector

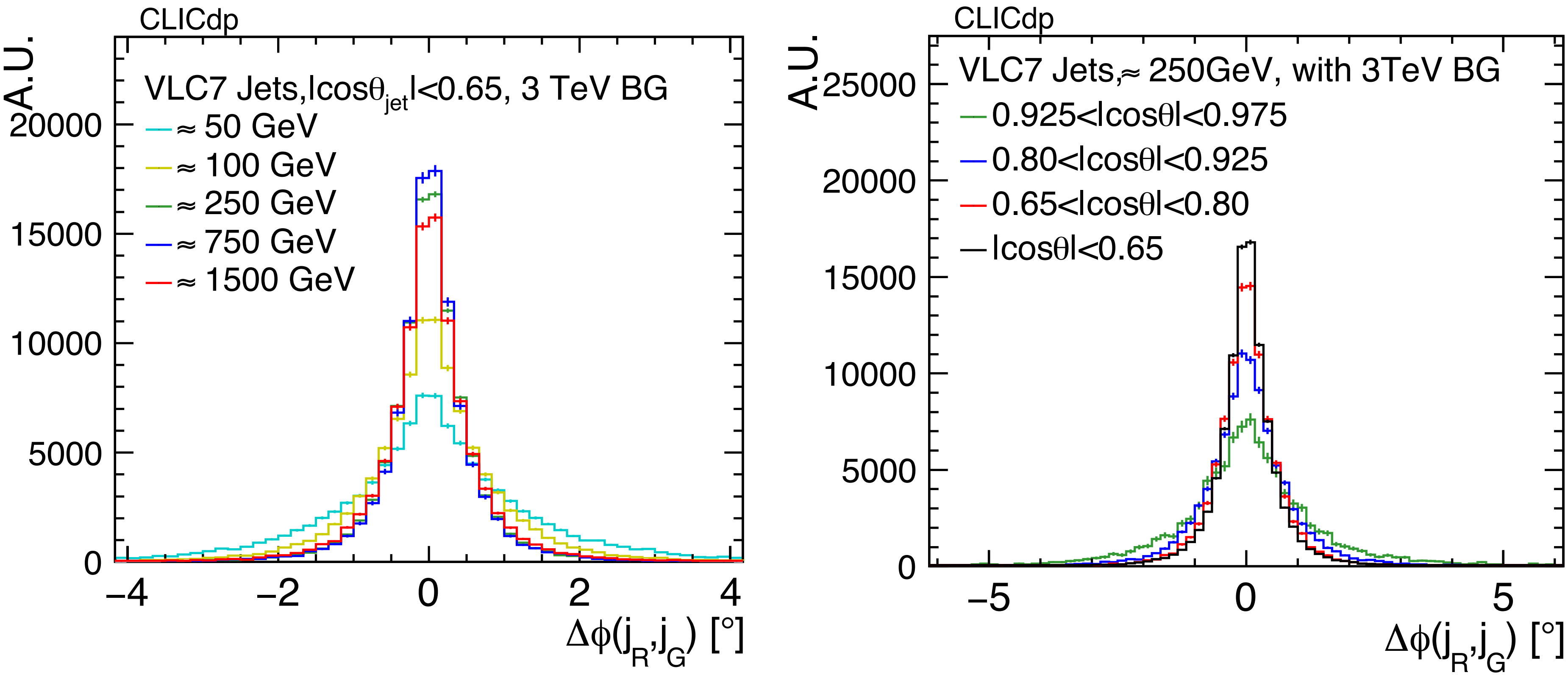
Photon Efficiencies



Over 98 % for unconverted photons

Unconverted photons (15 % of all photons): If photon clusters merged, then efficiencies beyond 95 % above 100 GeV, around 60 % for 25 GeV

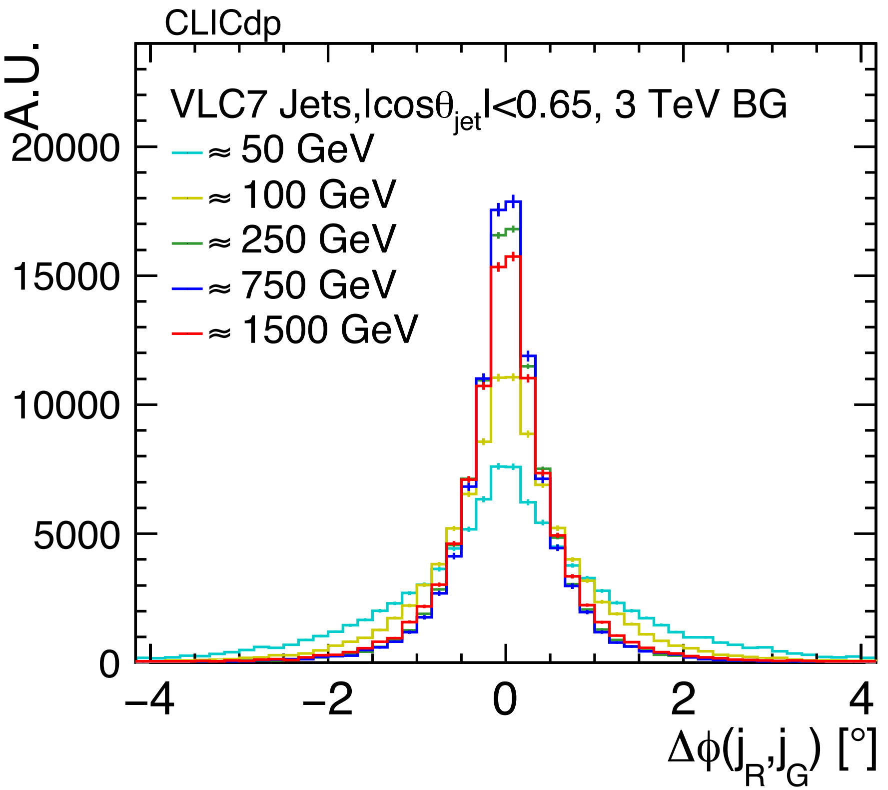
Photon and Kaon Energy Resolution

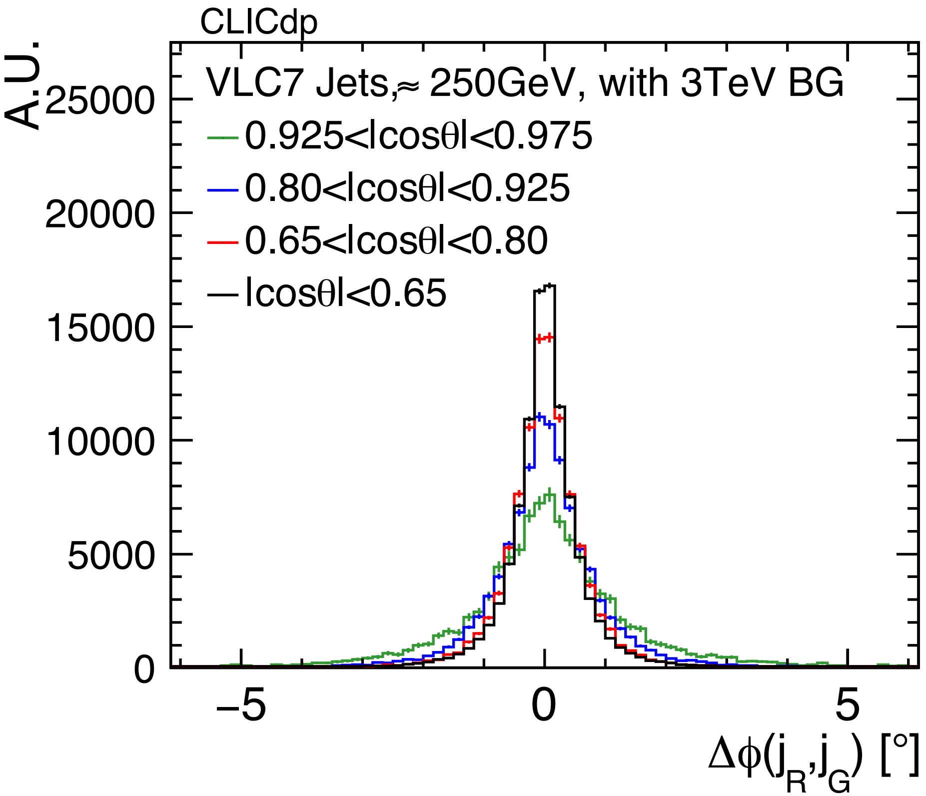


Phi Resolution increases for polar angles closer to the beamline

As function of jet energy with higher energies, jets are more collimated and jet phi resolution curve is less wide

ΔΦ Resolution vs jet Energy and polar angle





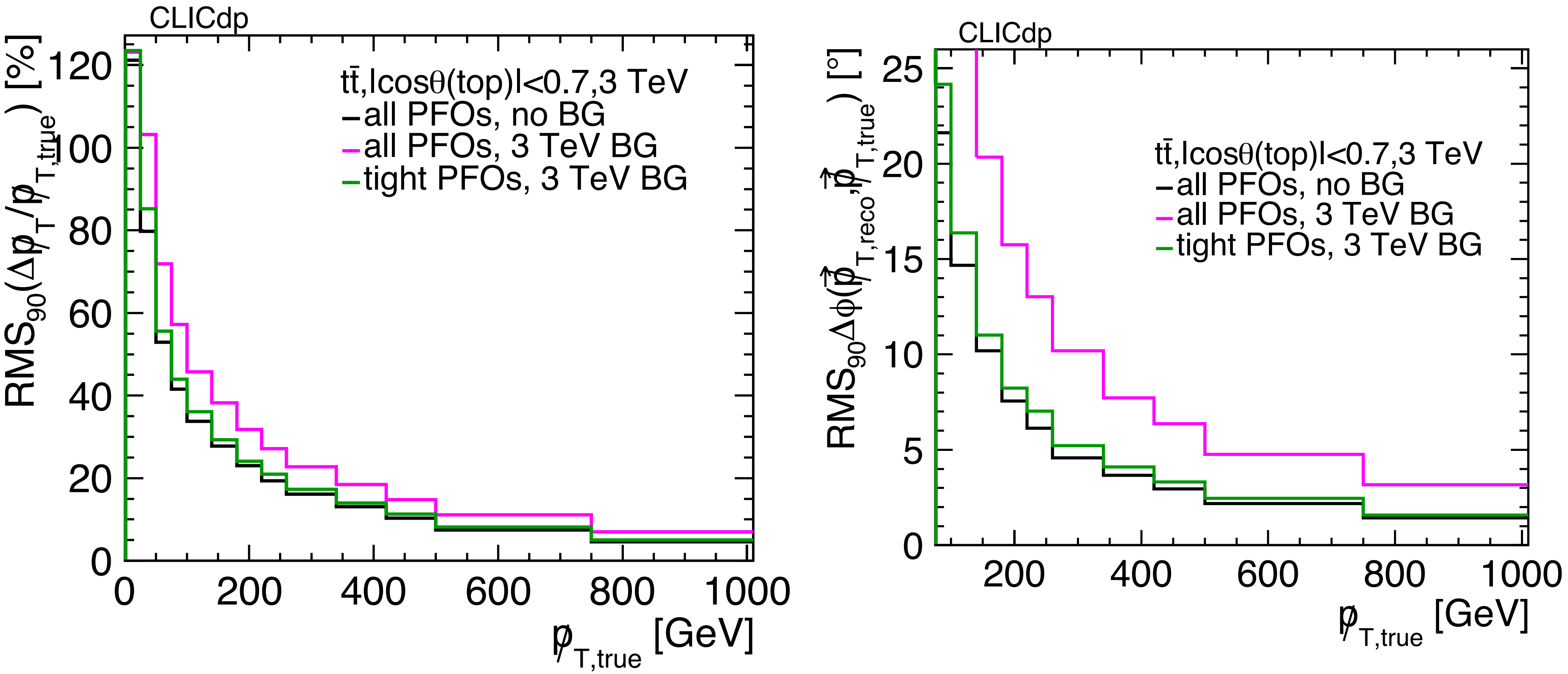
Phi Resolution increases for polar angles closer to the beamline

As function of jet energy with higher energies, jets are more collimated and jet phi resolution curve is less wide

MET Resolution

ttbar @3TeV, real MET, MET [GeV]

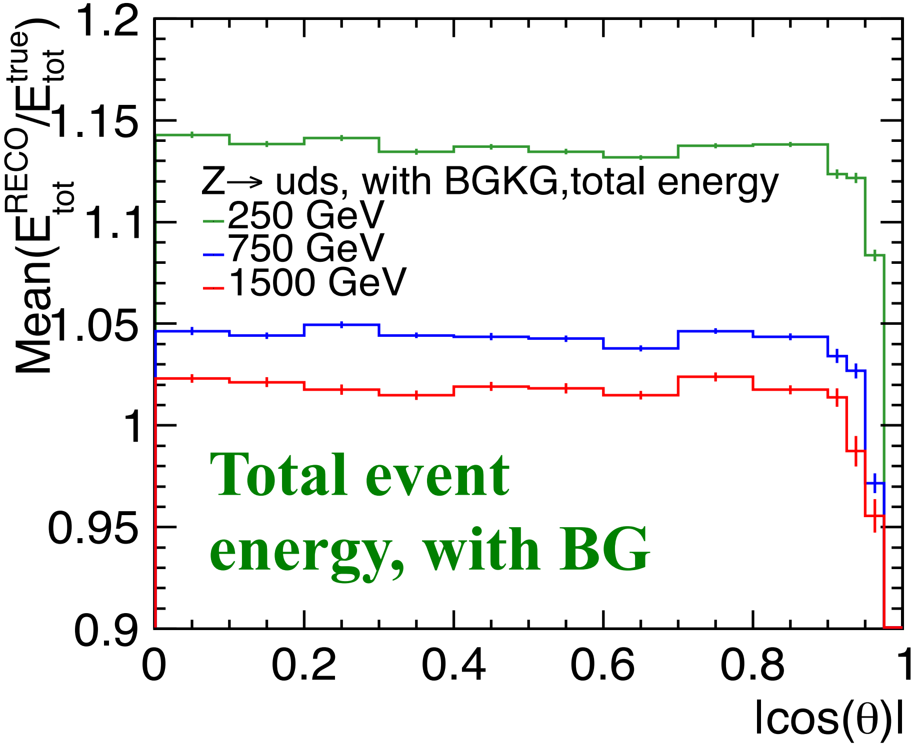
ttbar @3TeV, real MET, MET Phi

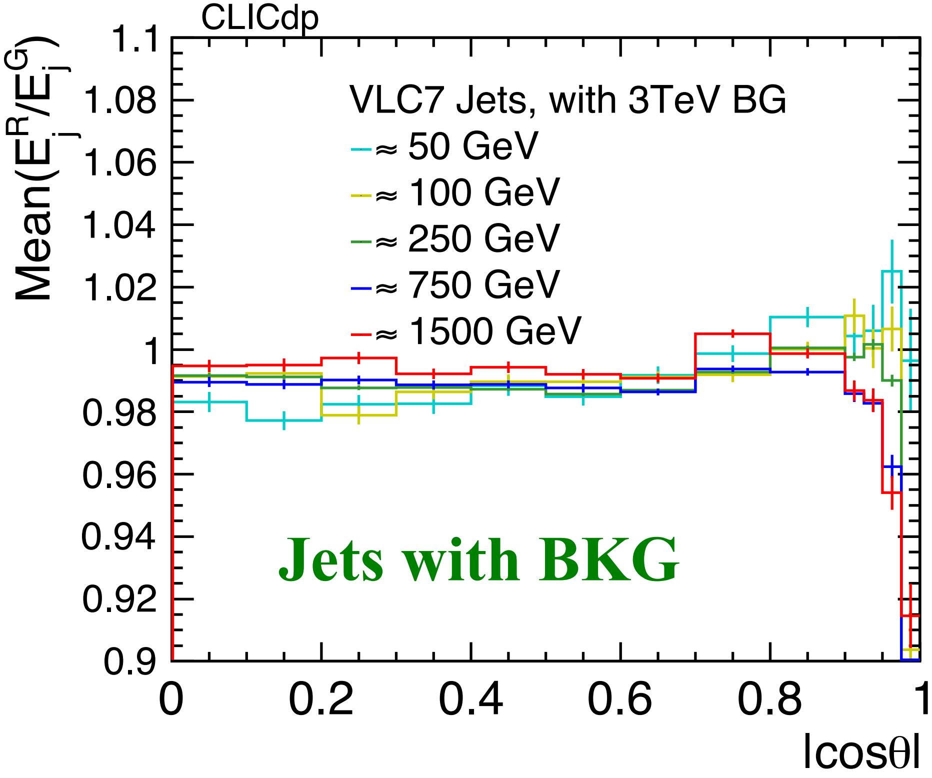


→using PFO selection cuts clearly improves resolution, tight selection cuts perform best, full MET spectrum

Angular resolution of MET vector, with selection cuts within 10 degrees of true vector above 150 GeV

Reconstructed jet energy vs MC particle jet energy





Overall event energy is increased by quite a bit after background is added (tight selection) → most of this additional energy is distributed in forward region, not all of this energy ends up in a jet cone

Reconstructed jet energies very close to particle jet energy

W and Z separation

Datasets WW→νμ qq and ZZ→νν qq, where q is a light quark
Veto for WW events where W is offshell, decaying into tb with t decaying leptonically, for Z keep offshell Z→νν (Z→qq always on shell)

- On MC truth: cluster all stable visible particles (status=1, excluding neutrinos), exclude lepton from W (and lepton daughters, e.g. FSR photons)

- On reconstructed level: use all pandora PFOs in events without background, use tightSelected PandoraPFOs when running on events with γγ→hadrons overlayed, remove PFOs around an angle of 25.8° (acos 0.9) of the isolated lepton from W's →with very high rate this removes reconstructed muons and FSR photons and very soft "additional" neutral hadrons

- Jet Algorithm: VLC Algorithm, R=0.7, β=γ=1.0, exclusive mode with 2 jets, cross-check with k_t algorithm, R=0.7 leads to very similar mass distributions

- W and Z mass calculated from dijet distributions

W and Z mass fits for different boson-energies

Dijet mass distributions have tail to lower mass values (including all events) for low energy sample, energy not sufficiently collected in two jets of ΔR=0.7

- Approach 1: fit first Gaussian over whole range, restrict upper boundary to three sigma (or upper limit of histogram) and 1 sigma to lower side, repeat fitting a gaussian until fitted sigma stable (variation within 2%)
- Approach 2: tail largely reduced if preselecting events where on MC truth 90 % of visible energy (for WW event minus isolated muon from second W) is clustered in the two particle jets → fit first Gaussian over total range, restrict upper boundary to three sigma (or upper limit of histogram) and 2 sigma to lower side, repeat fitting a gaussian until fitted sigma stable (variation within 2%)

→ Around 20 % removed for 125 GeV bosons, 7 % for 250 GeV bosons, below 1 % for higher energies

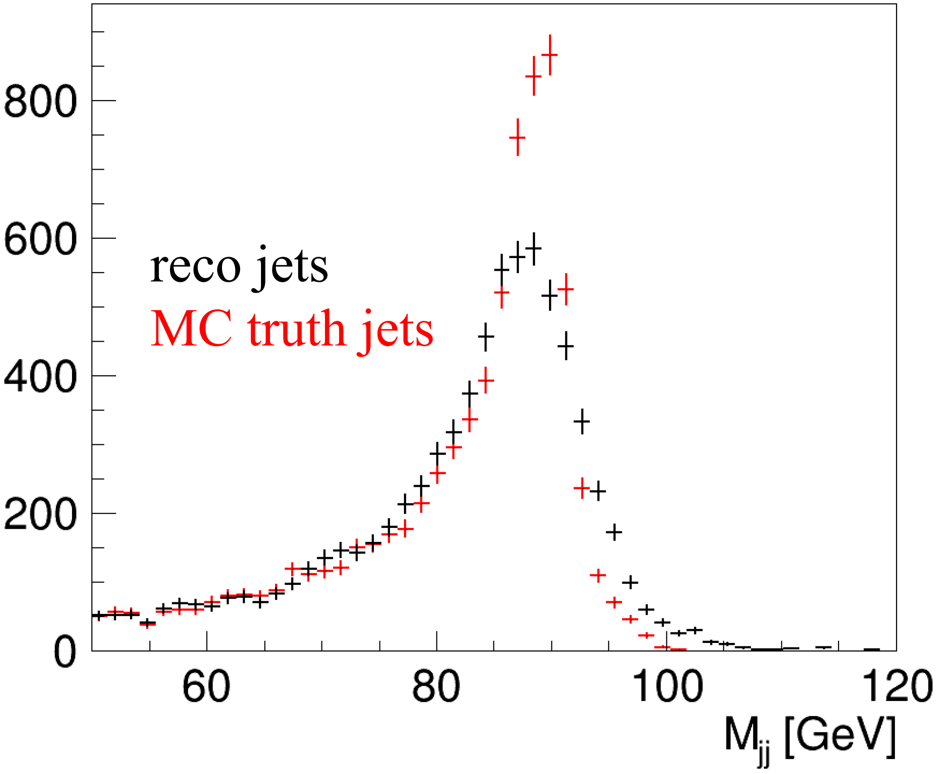
Fit peaks vary with energy → rescale Gaussian fits, so that mean of fit at W-mass (80.4 GeV) and Z-mass (91.2), fix ratio of sigma/mean while rescaling

→ Normalize rescaled Gaussian distributions (for same energy) to the same Integral

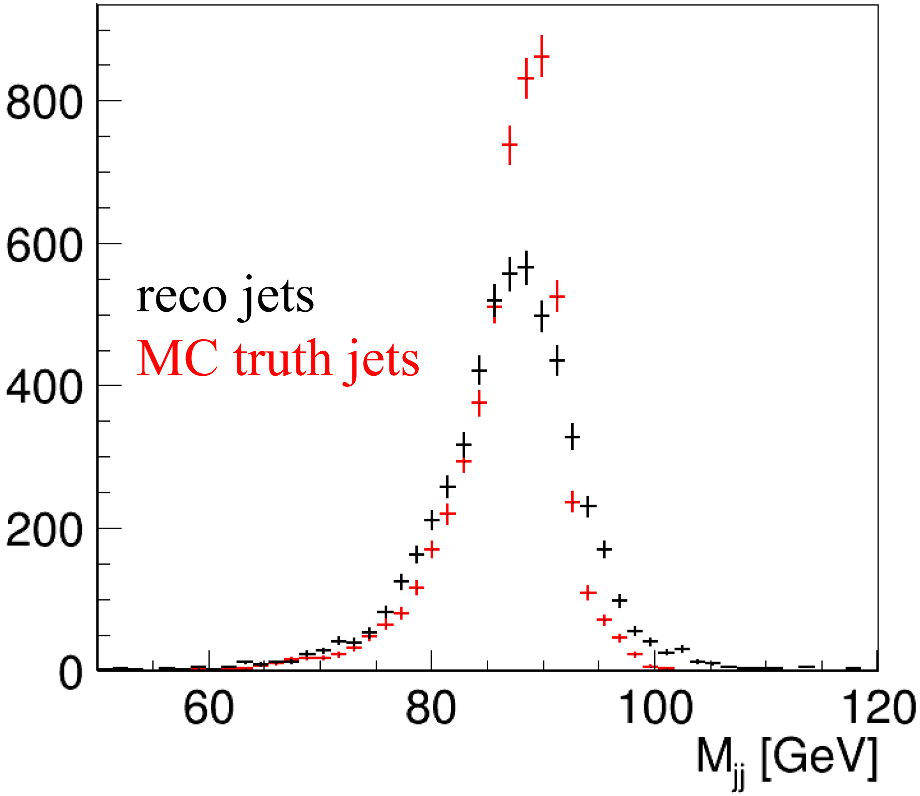
→ Calculate intersection point x_{int}

Z at 125 GeV

All events



Preselection on MC truth:
$(E_1^{true} + E_2^{true})/E_{tot}^{true} > 0.90$



Tail to lower dijet mass values already present on level of true particle jets

→ Largely reduced when cutting on ratio of clustered energy over total energy

→ Events in tail dominated by events with significant energy beyond those clustered in both jets (e.g. a hard third jet)

W and Z overlap fraction

Overlap fraction A_O:

$$A_o = \left(\int_{-500}^{X_{\text{int}}} gaussZ(x)\,dx + \int_{x_{\text{int}}}^{500} gaussW(x)\,dx \right) / 2$$

Efficiency: integral above/below intersection mass point divided by integral over the whole dijet mass range → average efficiency $E=1-A_O$

Ideal gaussian separation quantified by 2|ROOT::Math::normal_quantile (A_O,1)|

Same result for separation with different approach (seems more intuitive)

$\sigma = (Z_{mass}-W_{mass})/\sigma_{avg}$ with $\sigma_{avg} = (\sigma_Z+\sigma_W)/2$ the averaged σ of the rescaled Gaussian fits on the reconstructed Z and W dijet mass peaks for the different energies