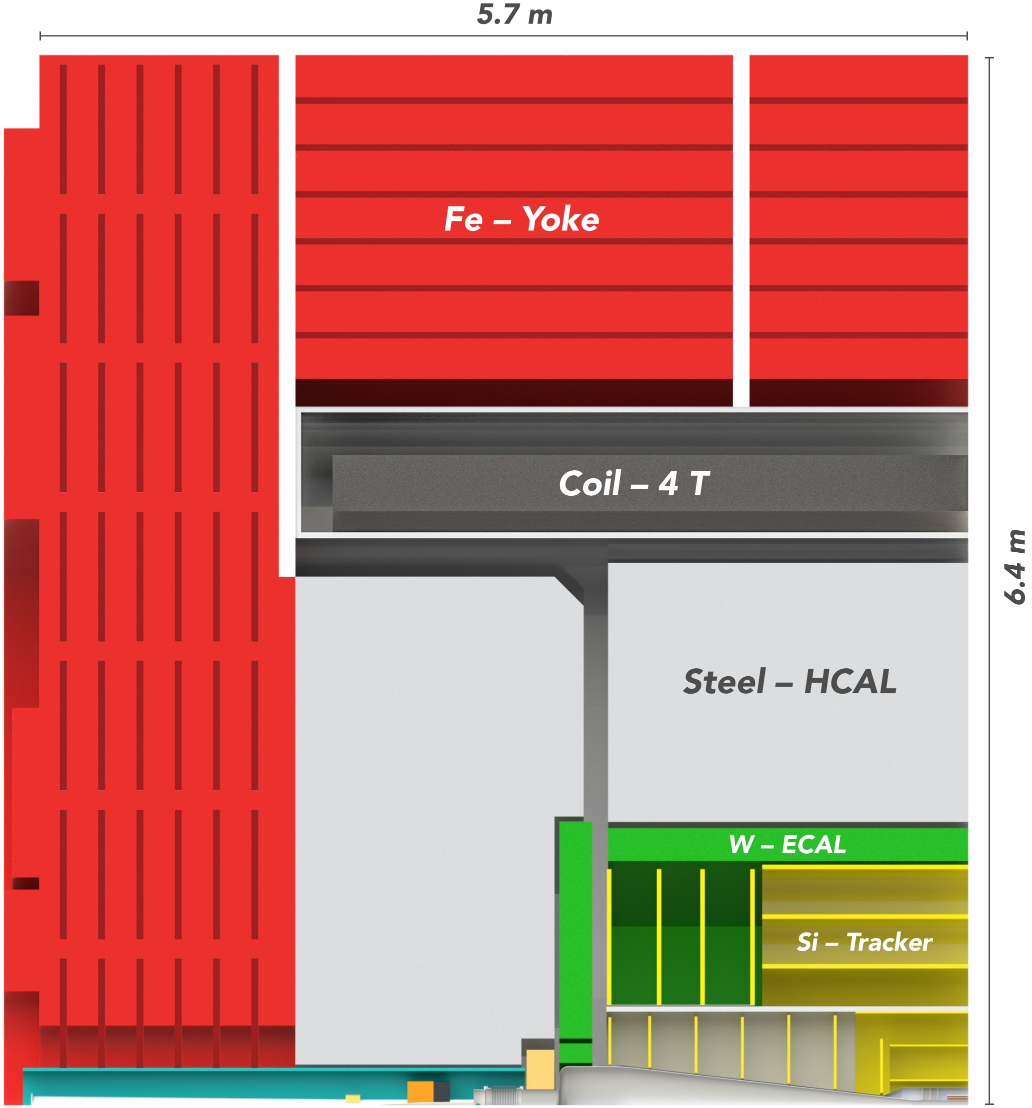
Detector Performance
At CLICdet

Matthias Weber (CERN)

CLICdet

postCDR detector model CLICdet, introduced in **CLICdp-Note-2017-001**

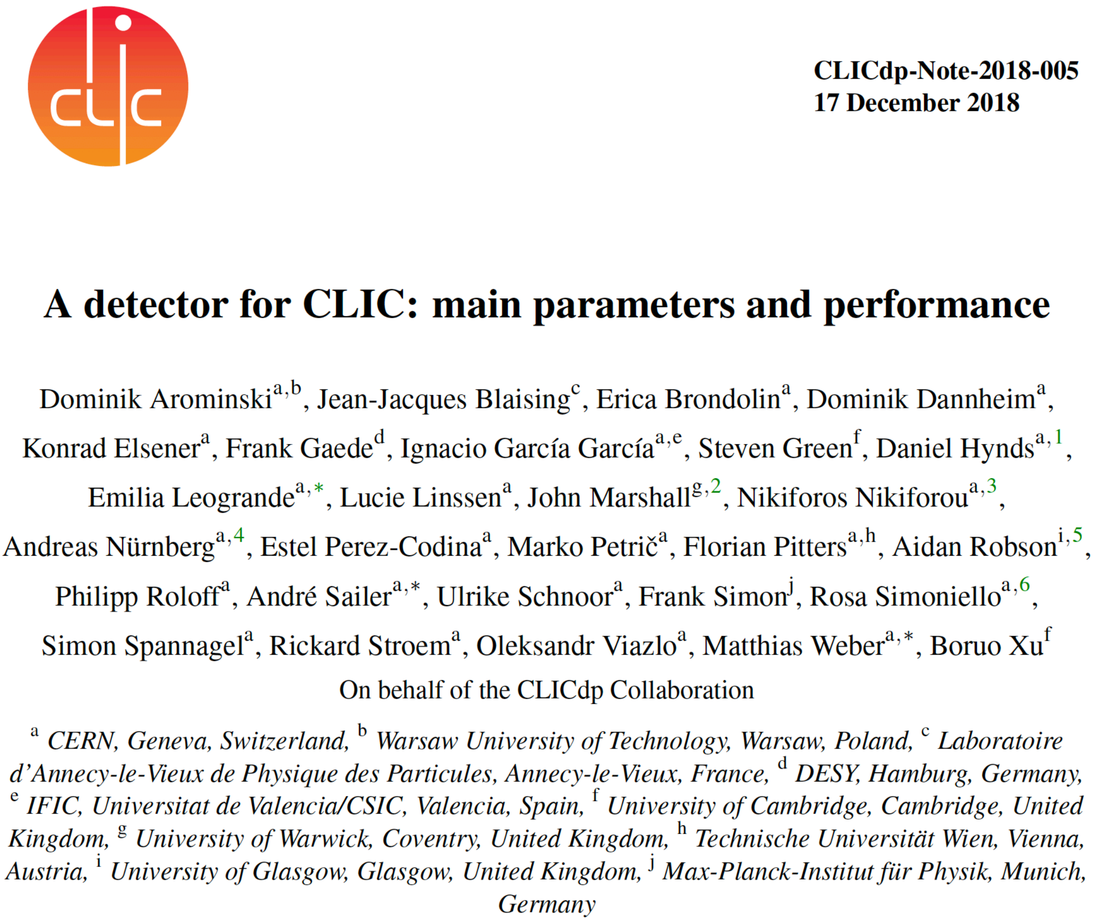


- 4 T solenoid outside of calorimetry
- Low mass all silicon tracking system
- 40 layer SiW ECAL → 22 X_0
- 60 layer Steel-SiPM Hcal → 7.5 λ
- RPCs for muon ID in Fe Yoke
- Very forward sampling electromagnetic calorimeters

→detector optimised for particle flow

CLIC Detector Performance

Detector performance studied in detail in **CLICdp-Note-2018-005**



CLICdp-Note-2018-005
17 December 2018

A detector for CLIC: main parameters and performance

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On behalf of the CLICdp Collaboration

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66 pages:
Experimental conditions and beam-induced backgrounds
→ Talk by Dominik Arominski

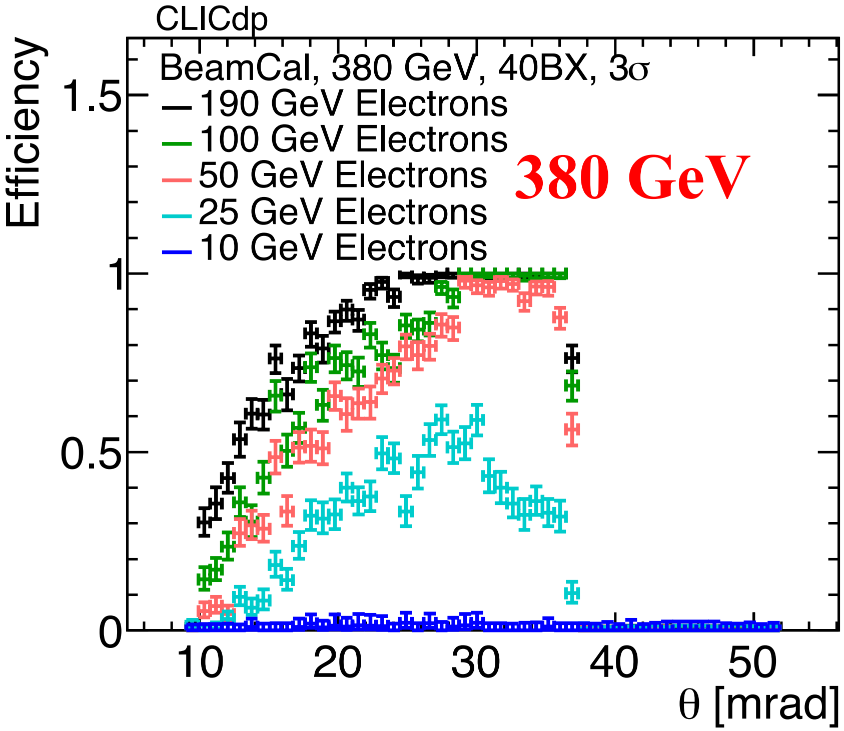
Physics Performance:

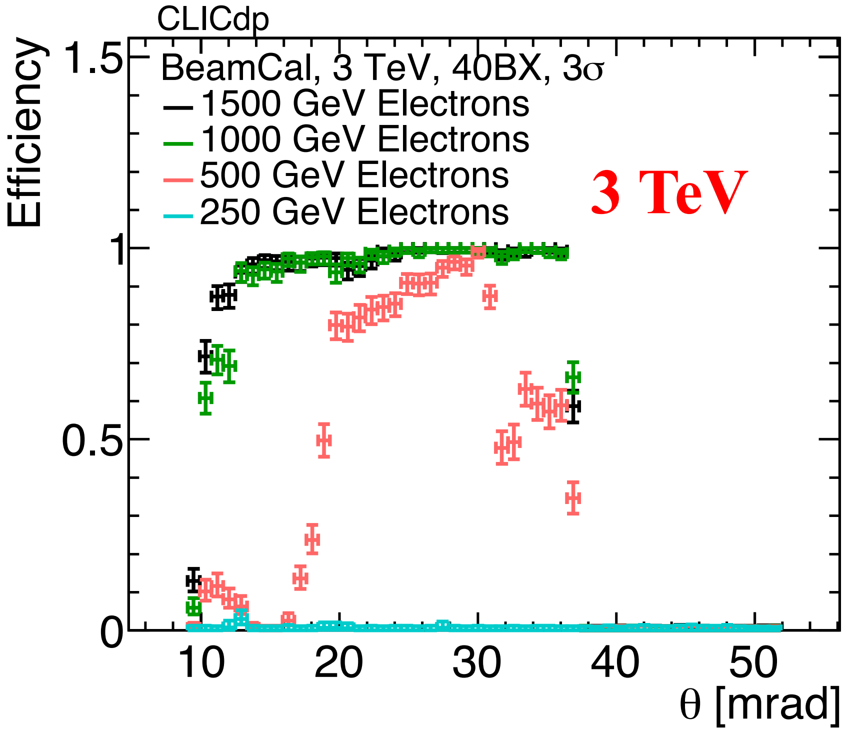
- Tracking in single particle events and more complex events e.g. ttbar
- Flavour Tagging
- Particle Flow identification in single particle events
- Jet and missing transverse energy performance, di-jet mass separation
- Very Forward Calorimetry

LumiCal and BeamCal

BeamCal Performance

Efficiency and fake rate in mono-energetic single electron events:
Overlay of incoherent pair background (40 BX), angular and energy matching between generated electron and reconstructed cluster



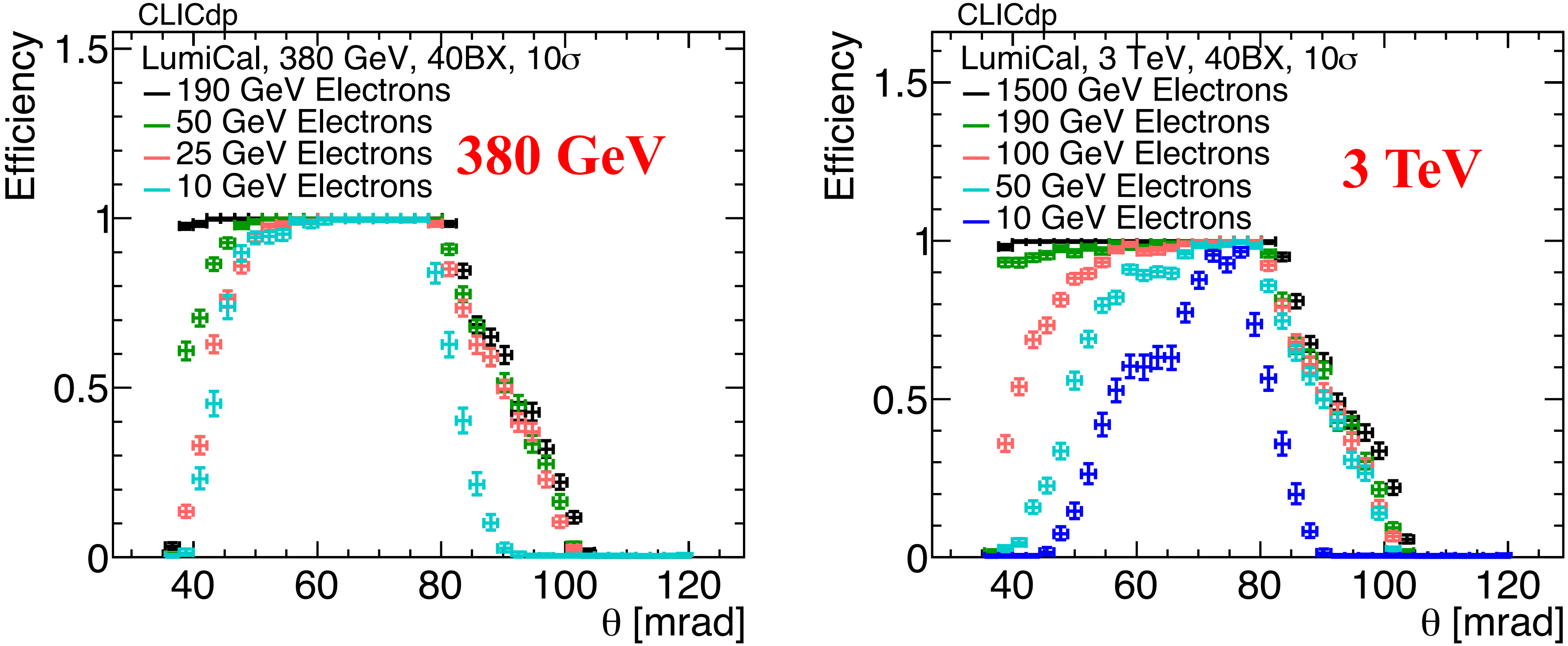


Energy resolution around 10% for whole energy range, fake rate below 10^{-4} for all electron energies studied

Flat θ resolution of 0.2 mrad for energies over 400 GeV (3 TeV BG)

LumiCal Performance

Efficiency and fake rate in mono-energetic single electron events:
Overlay of Incoherent pair background (40 BX), angular and energy matching between generated electron and reconstructed cluster



Energy resolution around 8% for low energies, decreasing to 2% for high energy electrons, fake rate below 1% for all electron energies studied
θ resolution of 20 μrad at 1.5 TeV

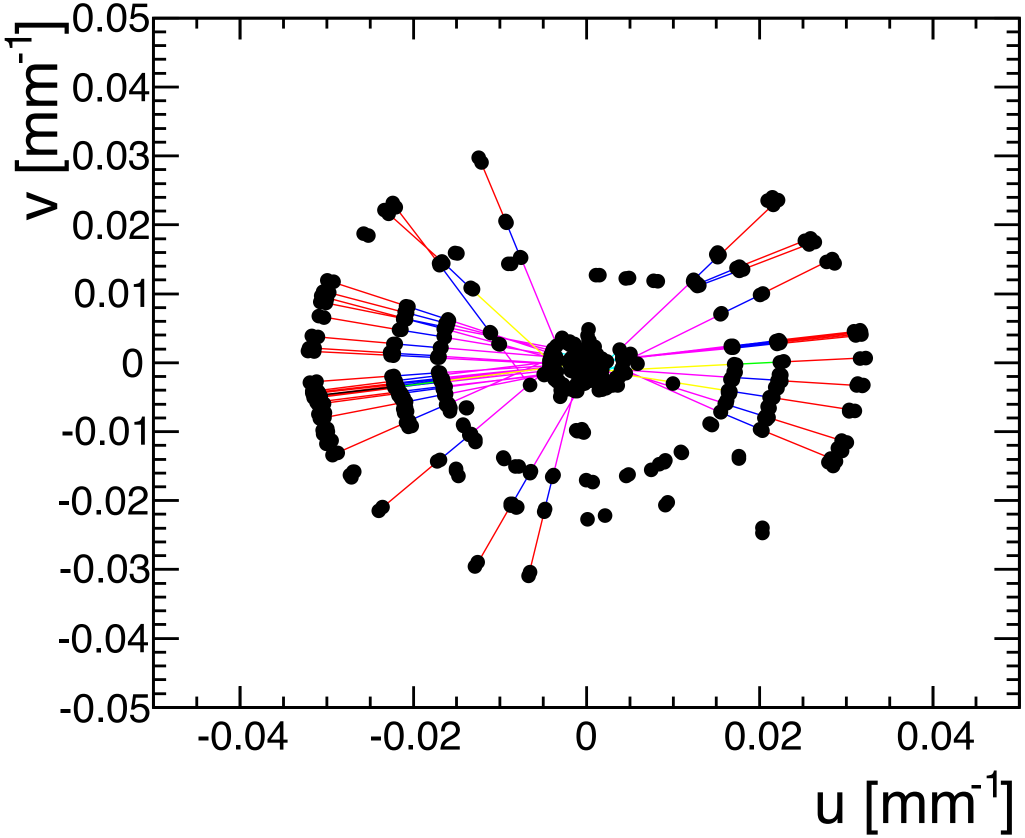
Track Reconstruction

Conformal tracking

Coordinate transformation from xy plane (perpendicular to the beam) to u-v co-ordinate system:

$$u = \frac{x}{x^2 + y^2} \qquad v = \frac{y}{x^2 + y^2}$$

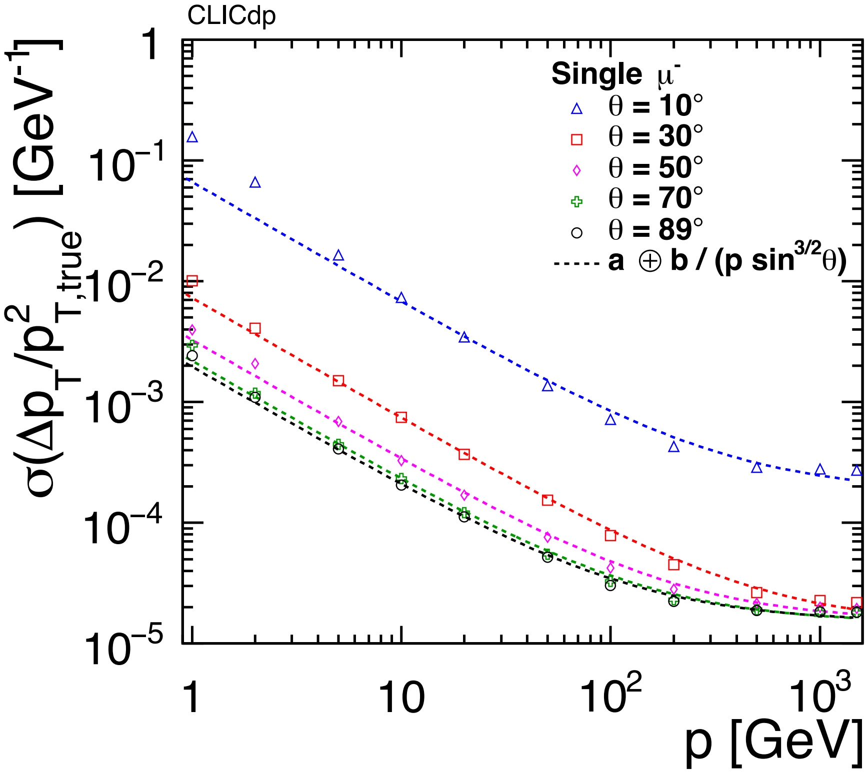
Perform straight line search in this 2D space:



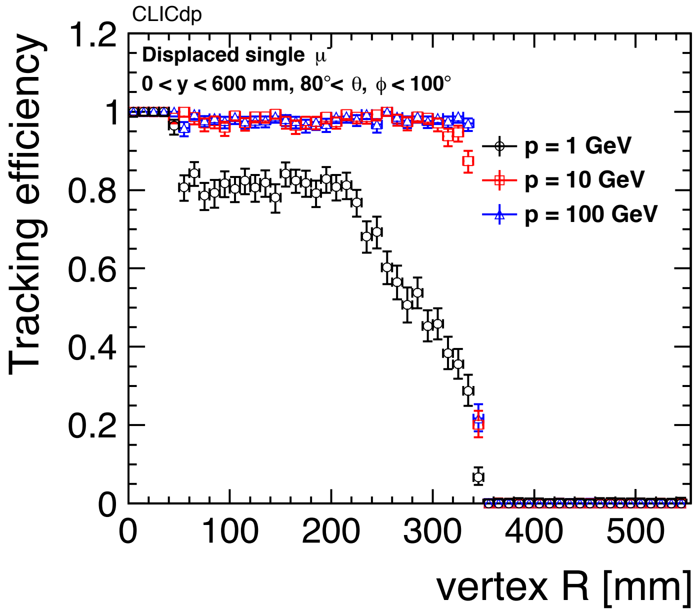
Tracking Performance

Prompt single particle tracks:
study of resolution (p_T, d_0, z_0, θ, φ)
Tracking efficiencies

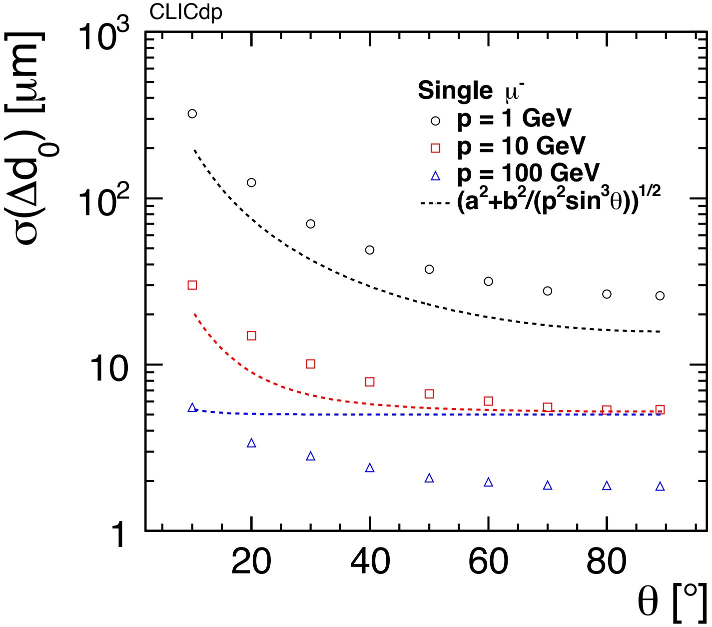
p_T resolution vs p



Displaced track eff. vs production vertex R

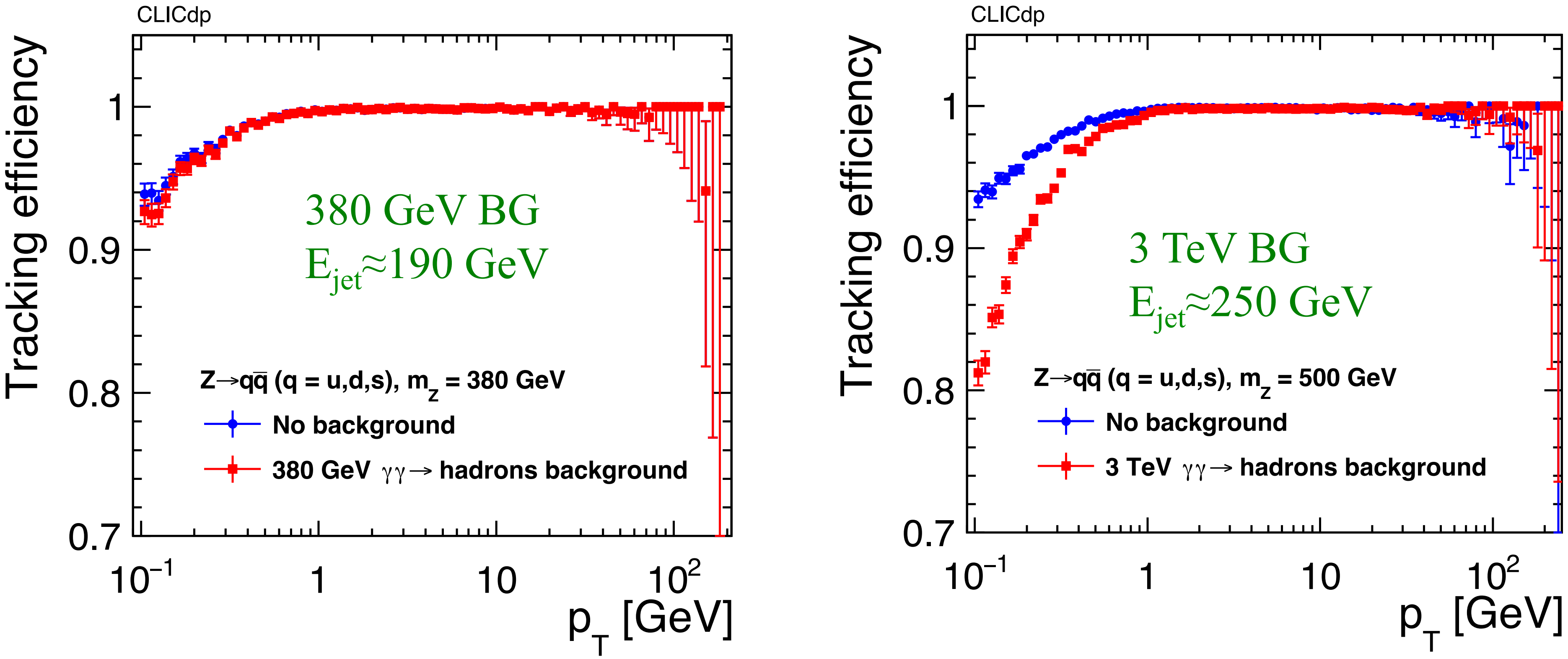


d_0 resolution vs polar angle θ



Complex events: impact of background

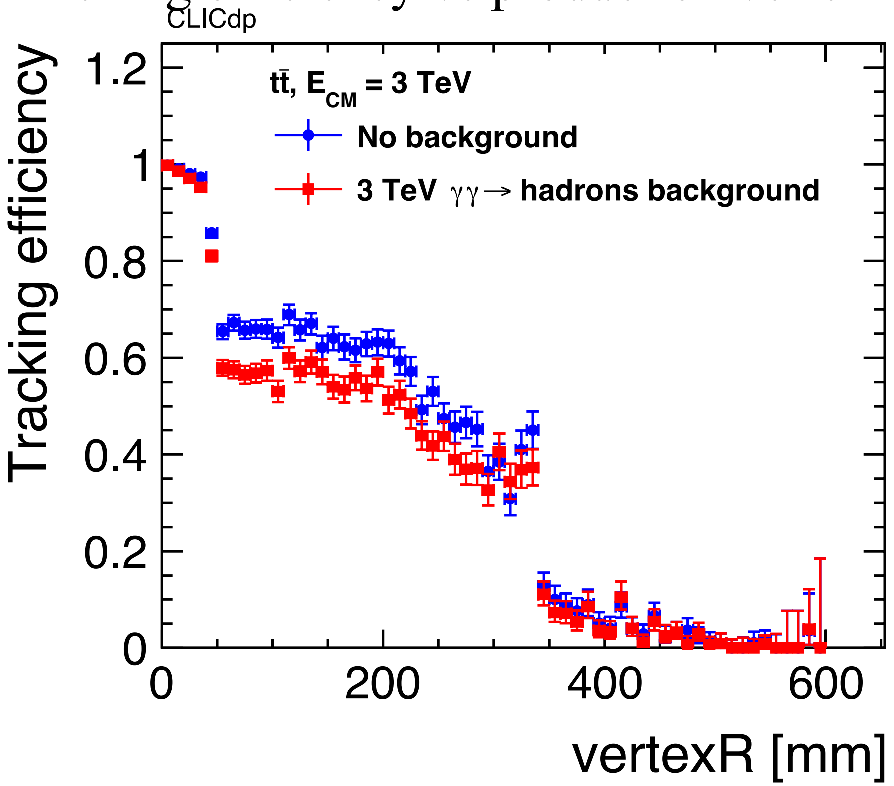
Di-jet events at various jet energies, study impact of beam-induced backgrounds from γγ→hadrons for 380 GeV and 3 TeV CLIC



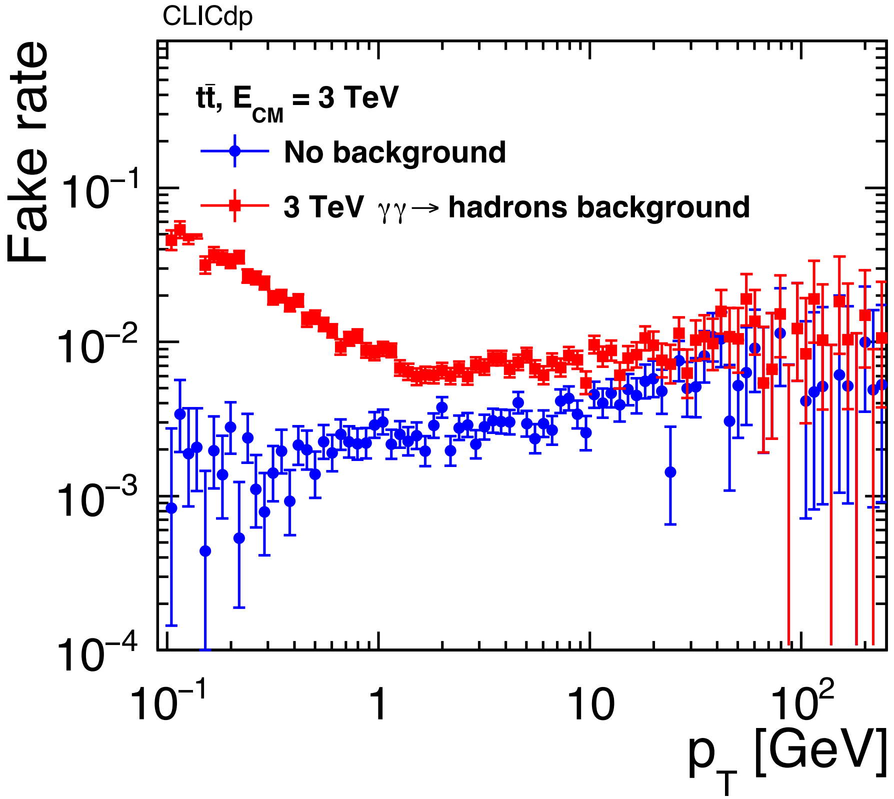
Even with 3 TeV background levels efficiency above p_T>1 GeV about 100 %,

ttbar events

Displaced tracks
Tracking efficiency vs production vertex R



Fake rate vs p_T



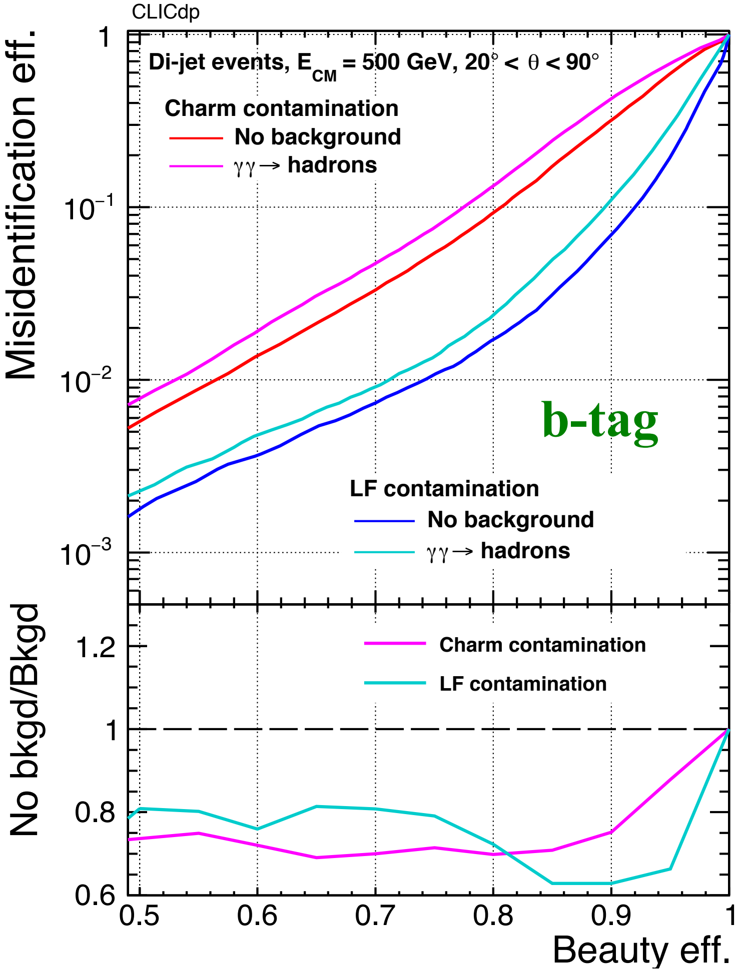
In 3 TeV background conditions around 60 % tracking efficiency for production radii up to 200 mm

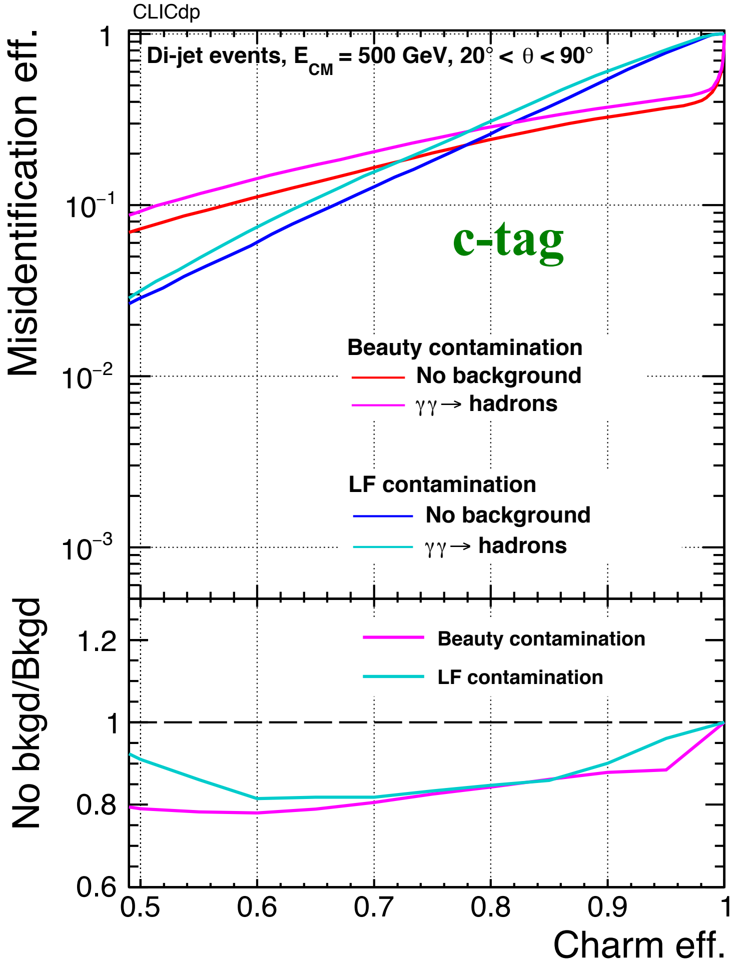
Below 4 % for all p_T, below 1 % above 1 GeV → ongoing effort to reduce fake rate

Flavour tagging

c and b tagging results

b and c tagging performed using LCFIPlus flavor tagging package: 250 GeV jets



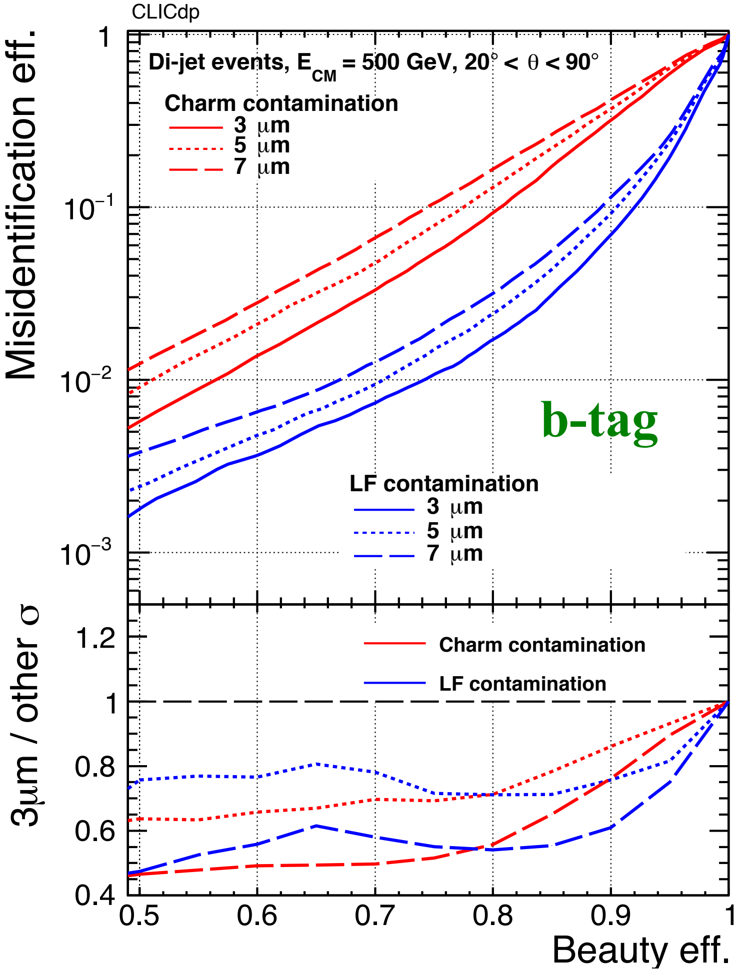


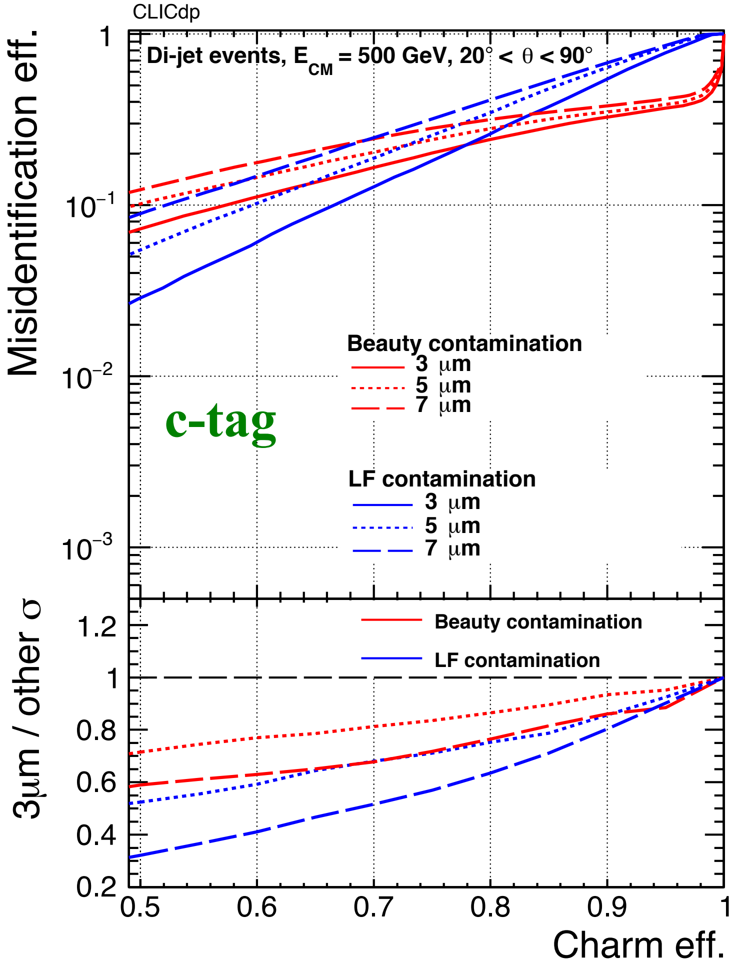
b-tagging: with 3 TeV beam BG at 80 % eff.: 13% missID for c and 2% light-flavor BG

c-tagging: with 3 TeV beam BG at 80 % eff.: 30% missID for b and light-flavor BG

c and b tagging: vertex single point resolution

Nominal parameter: 3 µm position resolution in vertex

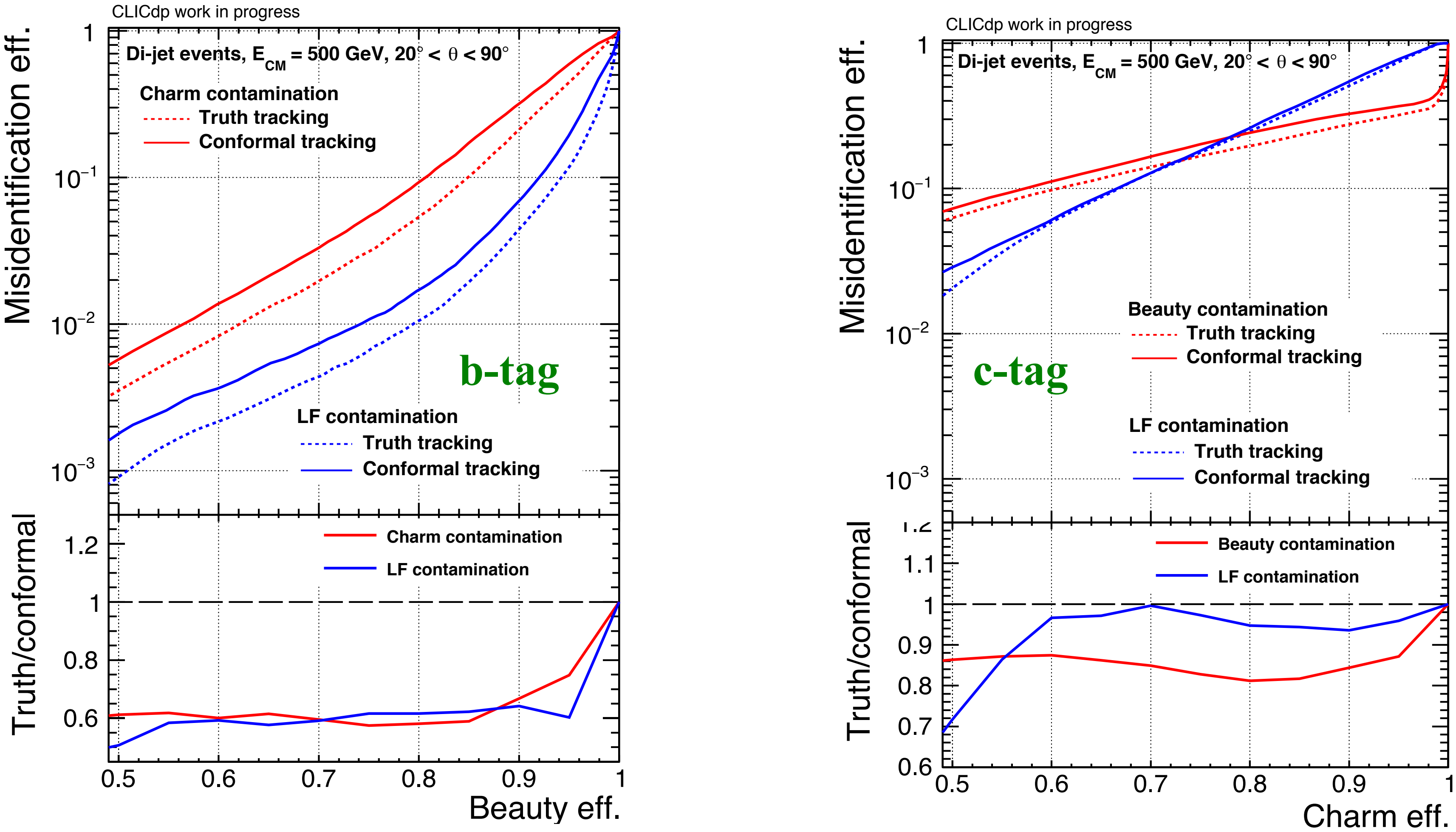




At 80 % b and c tagging efficiency miss-identification rate increases with worse single point resolution, by about 20 % (40%) with 5 µm (7 µm) position resolutions in vertex

c and b tagging: conformal vs truth tracking

True MC pattern recognition (truth tracking) as best possible tracking algorithm



Track reconstruction improvements in conformal tracking could lead to significantly improved miss-identification numbers → ongoing effort

Jet Performance

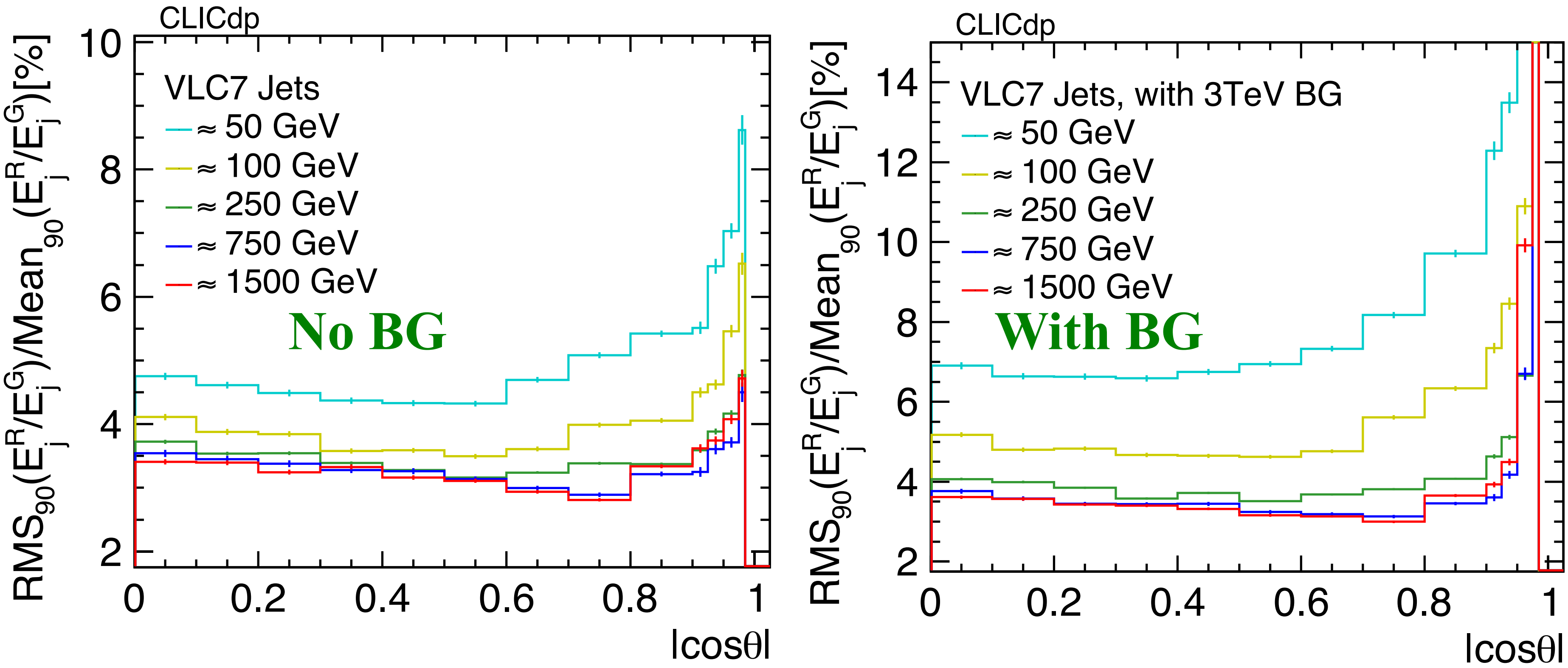
Jet Performance Studies

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

- Ignore neutrinos for MC particle jets
- Reconstructed jets use **particle flow objects** as input
  - PandoraPFOs in events without background
  - TightSelectedPandoraPFOs in events with 3 TeV $\gamma\gamma \rightarrow$hadrons background
  - LE_LooseSelectedPandoraPFOs for 380 GeV $\gamma\gamma \rightarrow$hadrons
- Studied in $Z/\gamma^* \rightarrow qq$ events, with q=u,d,s
- Jet algorithm: VLC algorithm, $\gamma=\beta=1.0$, radius R=0.7, exclusive jet clustering of event in exactly two jets

- Study resolutions of reconstructed jets angularly matched to particle level jets within 10°

Jet Energy Resolution vs cos θ: with and without BG



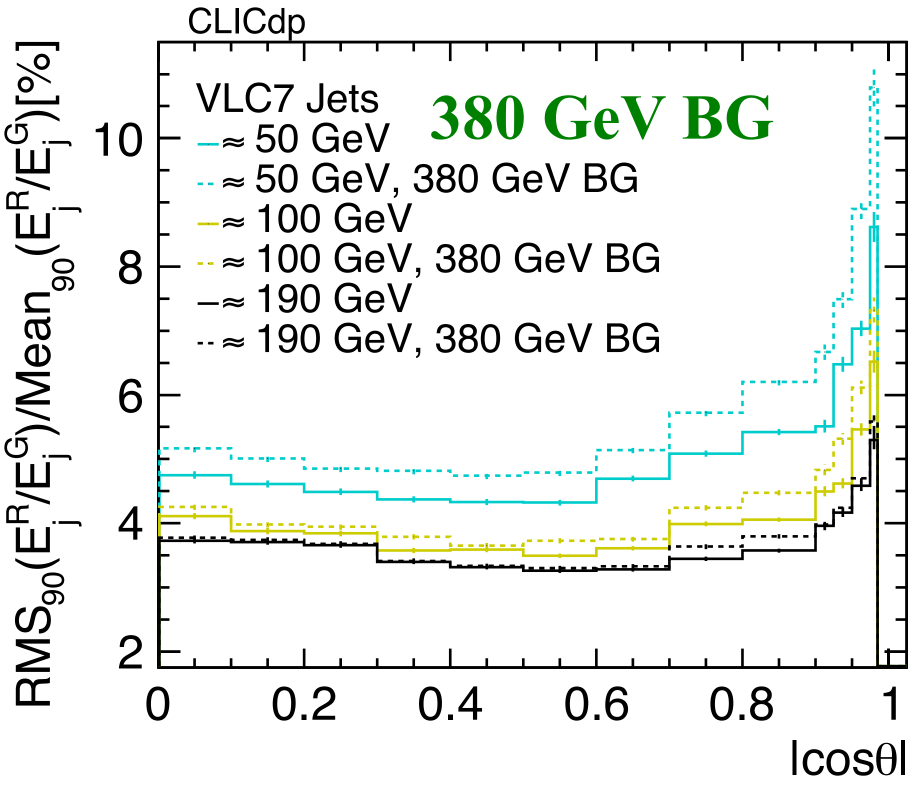
Compare resolution of reconstructed jets →3TeV conditions for overlay

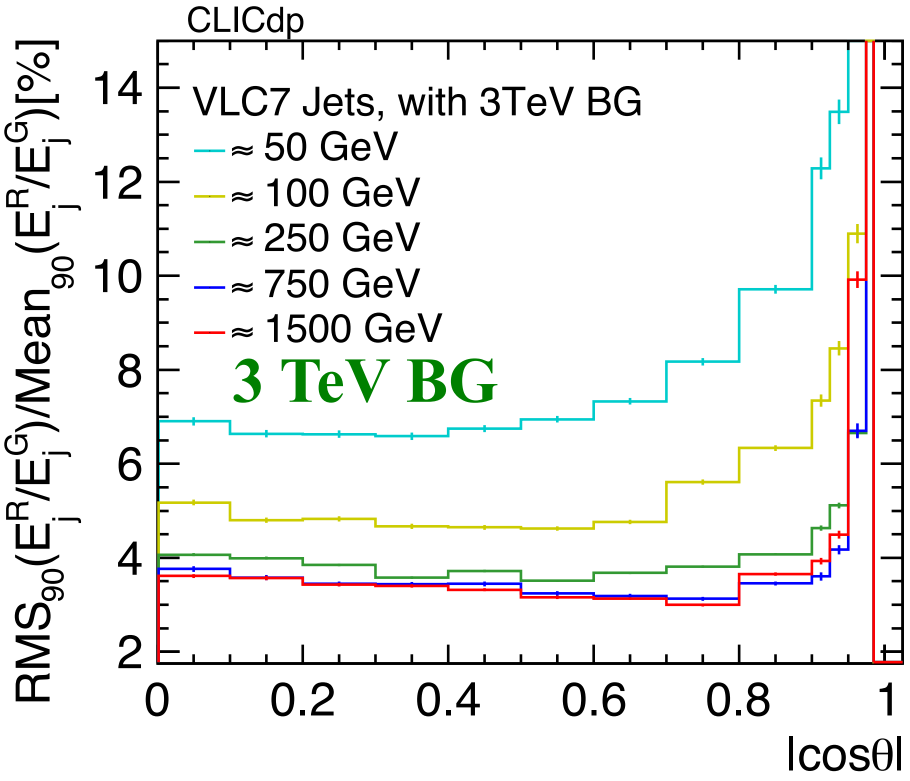
→for 50 GeV jets increase from 4.5/5 % to 7 % in barrel

→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

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, of additional 0.5 %, at 3 TeV machine increase from 5→7 %
- Almost no effect of background for barrel jets for energies >100 GeV

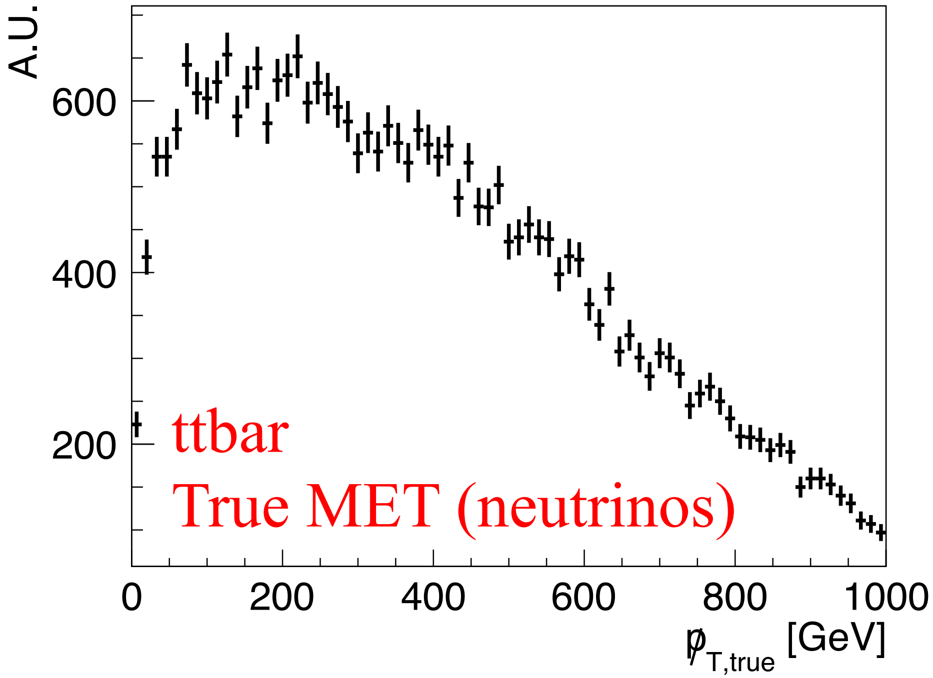
MET Resolution

Missing E_T (MET) Resolution

Study two cases:

Events with fake MET: $Z/\gamma^* \rightarrow qq$ (with q=u,d,s) at 3 TeV, investigate 3 TeV $\gamma\gamma \rightarrow$hadron backgrounds

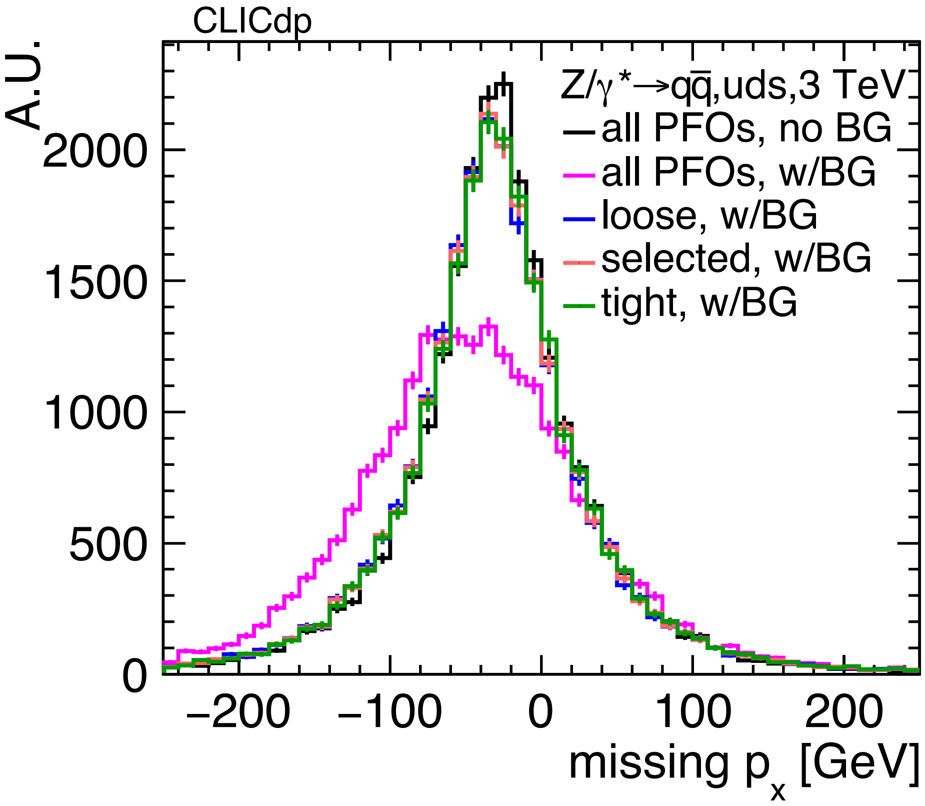
Events with genuine MET: semi- and di-leptonically ttbar events at 3 TeV, check background from $\gamma\gamma \rightarrow$hadrons at 3 TeV



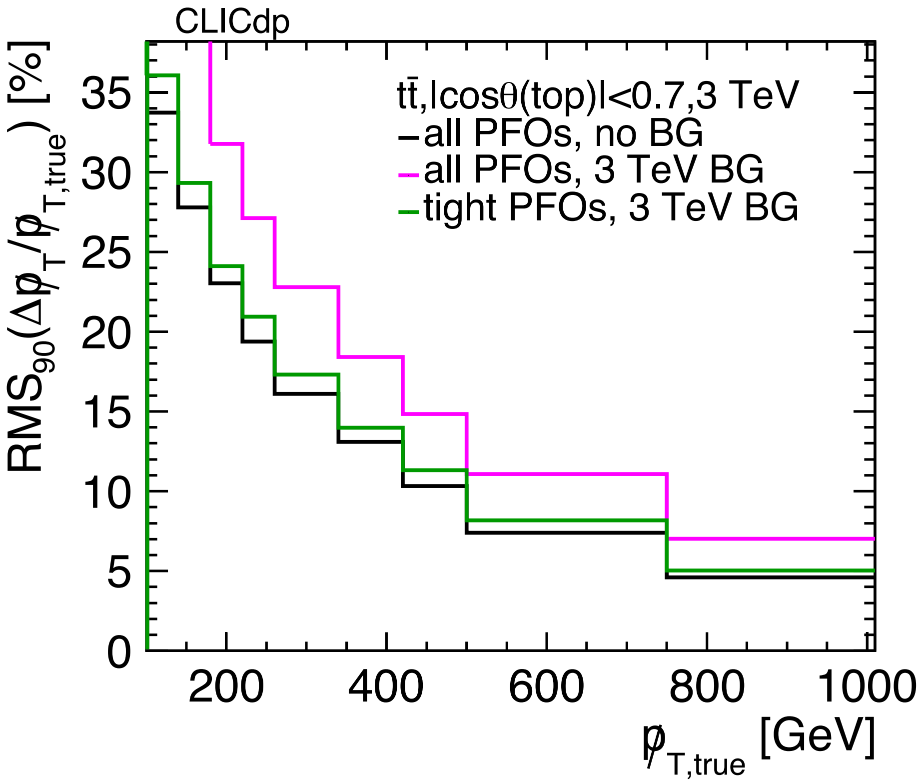
True missing transverse momentum from neutrinos in semi- & dileptonic ttbar → peaks around 100-250 GeV

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

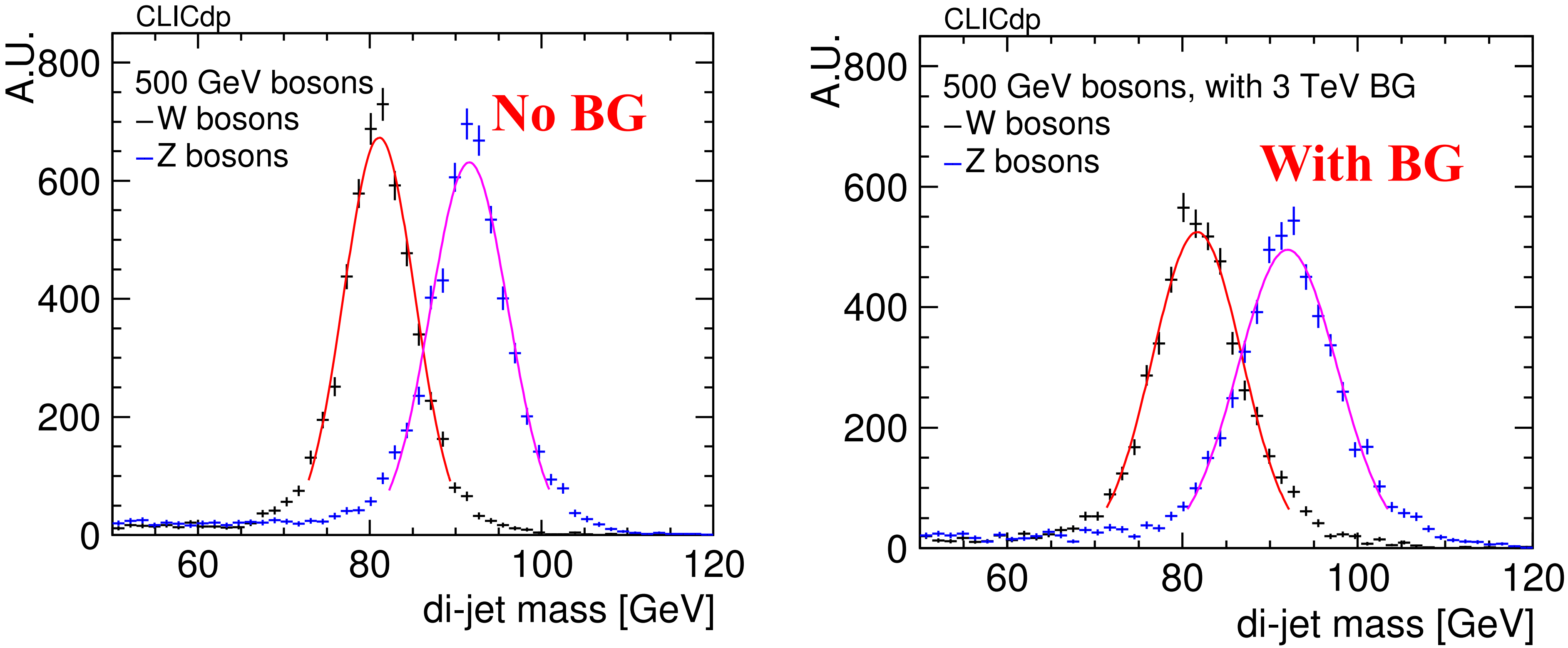
W and Z mass separation

W and Z di-jet mass with beam-induced background

Study di-jet mass reconstruction in WW→qq lν and ZZ→qq νν events

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)

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



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)

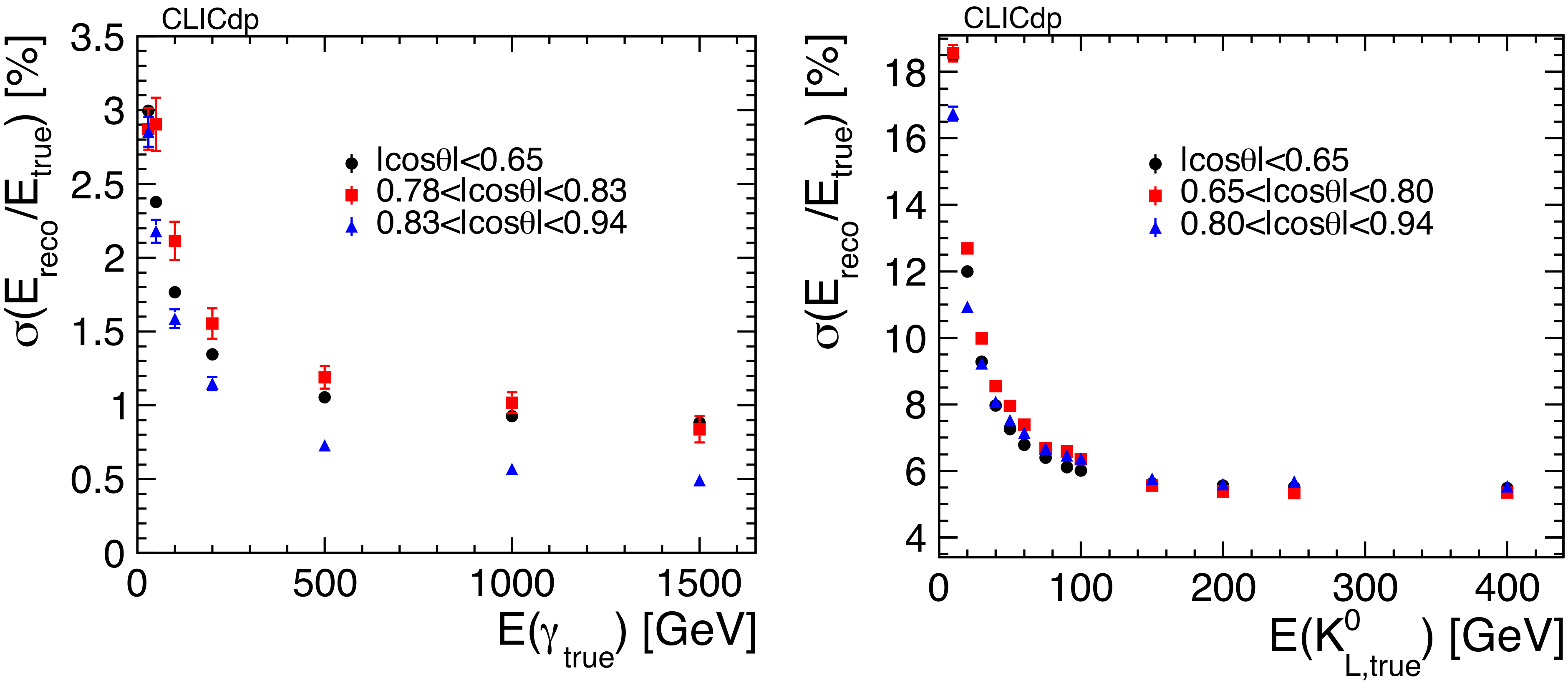
Conclusion

- Performance of post CDR detector model CLICdet studied in detail using full simulation
- Forward Calorimetry measures high energy electrons down to 20 mrad with high efficiency and low fake rates below sub % level
- Excellent d_0 resolution for high energetic isolated tracks (< 5 µm), tracking efficiency and performance studied for single prompt and displaced tracks, as well as busy event with and without simulation of beam-induced backgrounds from $\gamma\gamma \rightarrow$ hadrons
- b- and c-tagging has been studied in ttbar, cc, bb and light dijet events
- Jet energy resolution around 3-5% for all energies and all detector regions, up to 10 % for very forward jets
- Achieve a W-Z dijet mass separation of 1.7-2.0 σ when including beam backgrounds

BACKUP

Single Particle Performance

Photon and Kaon Energy Resolution



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

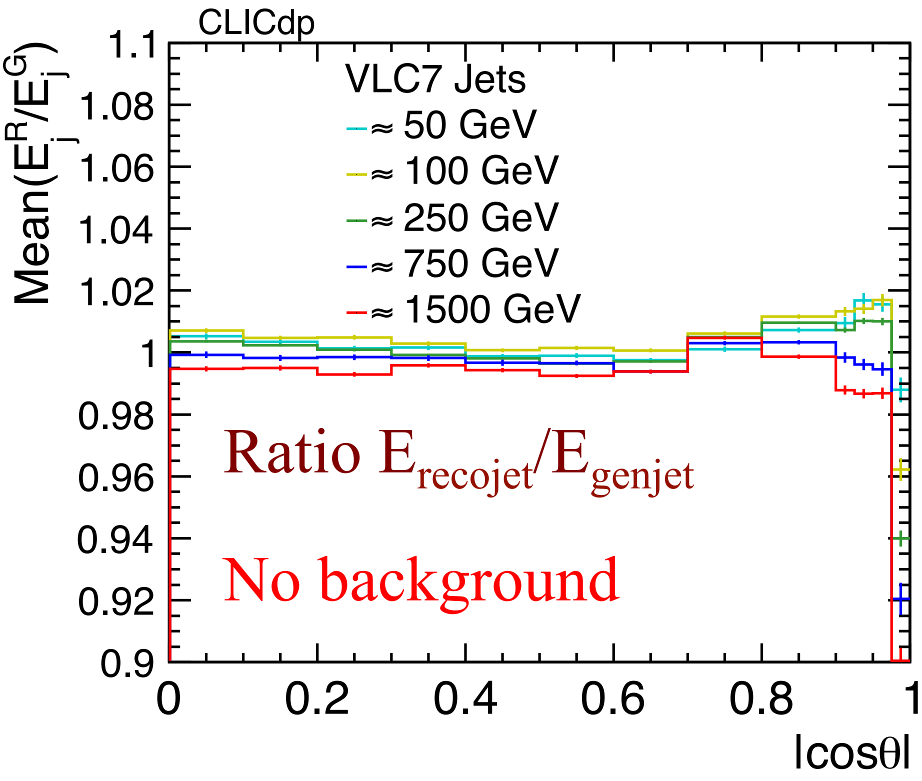
Kaon energy resolution between 5.5 and 18 % starting around 20 GeV

→Jet energy resolution distribution fitted with a Gaussian

Jet energy: particle level vs detector level

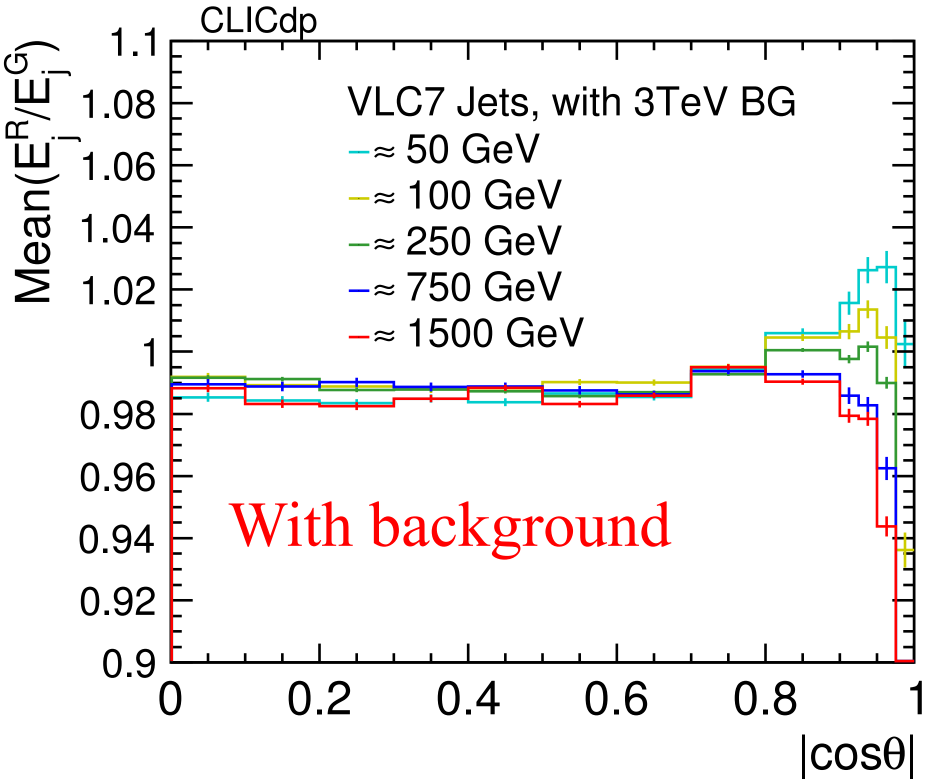
PandoraPFOs calibrated, no further calibration on jet energy

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



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

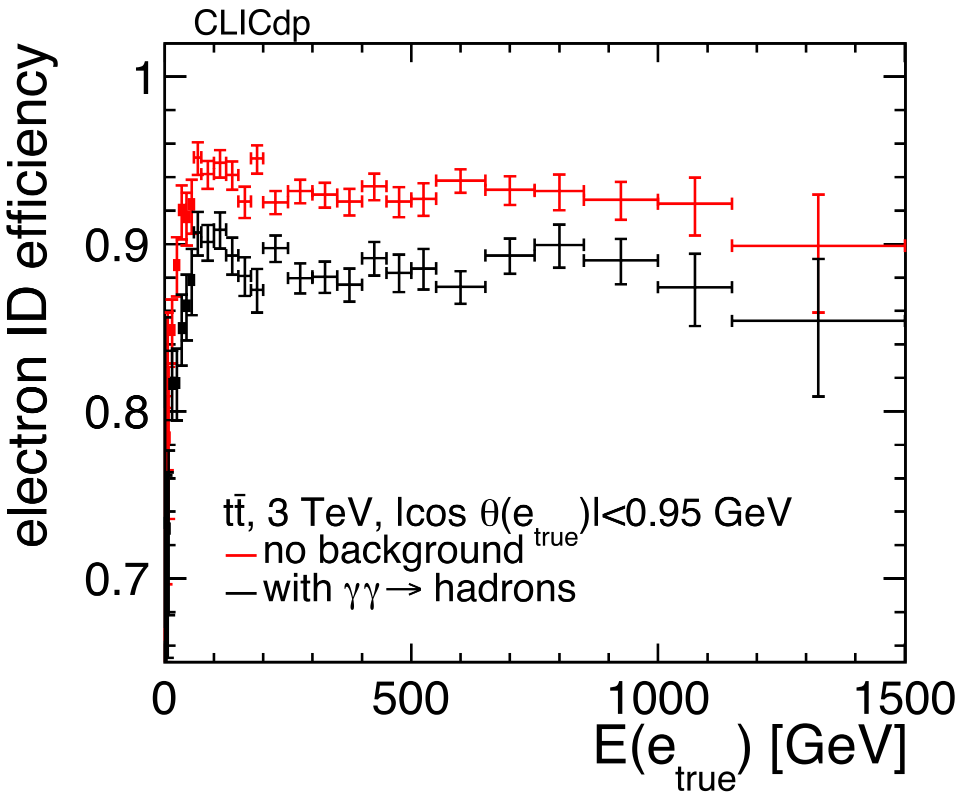
No background

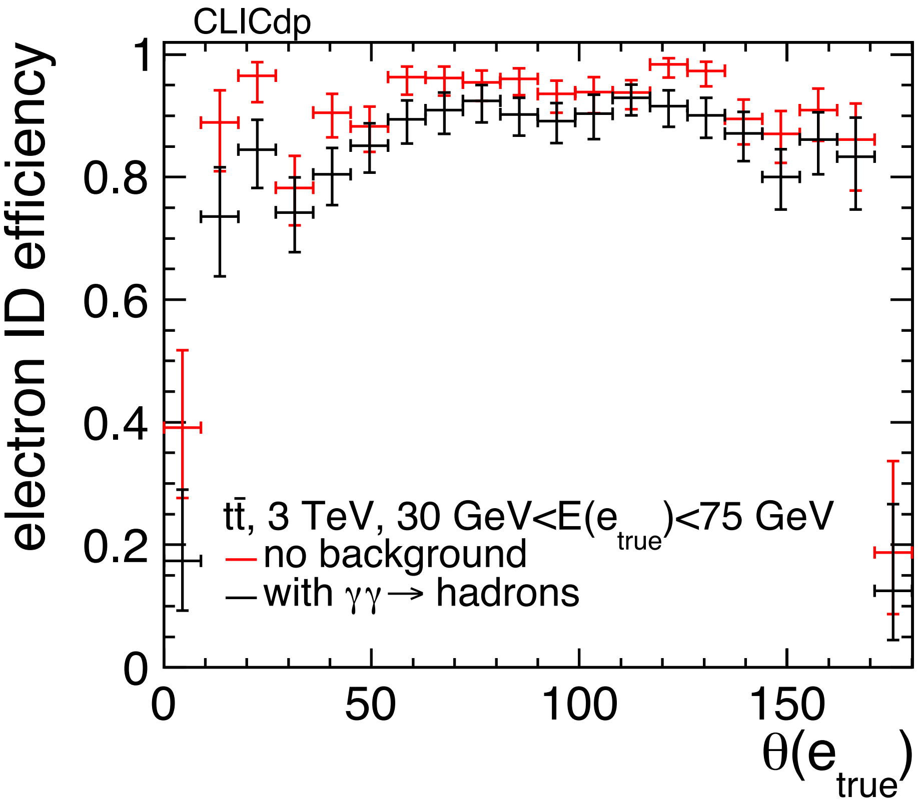


With background

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

Electron Efficiencies in ttbar @ 3 TeV

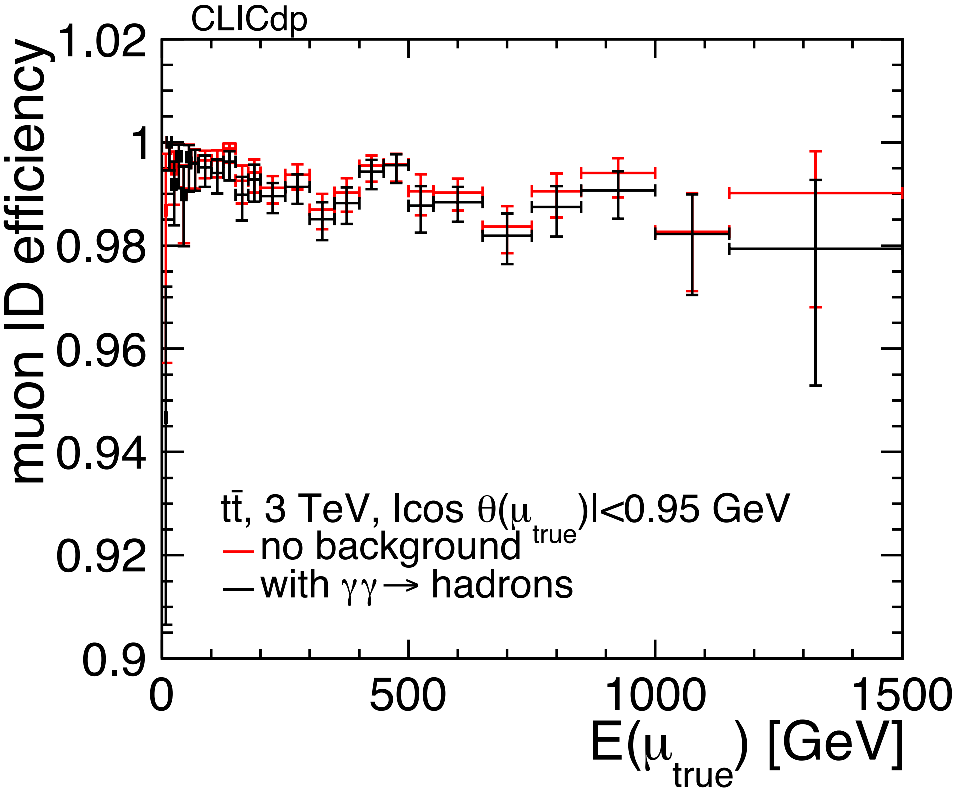


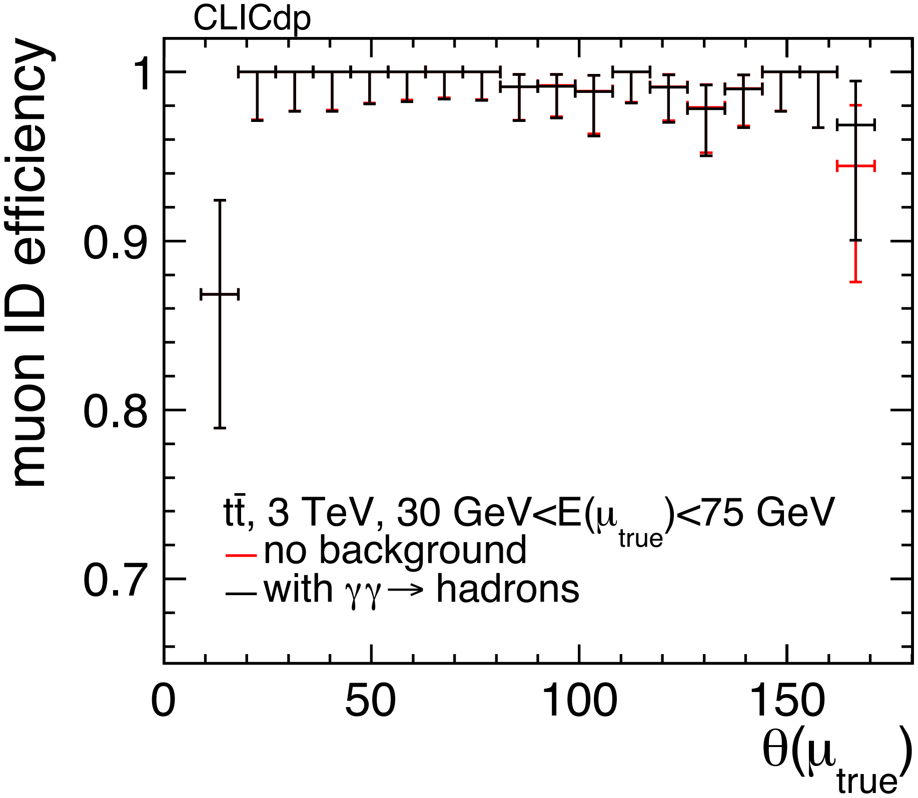


Electron efficiency vs electron energy
→ With background around 85-90 % starting at 25 GeV, 3-5 % difference to efficiency without background

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

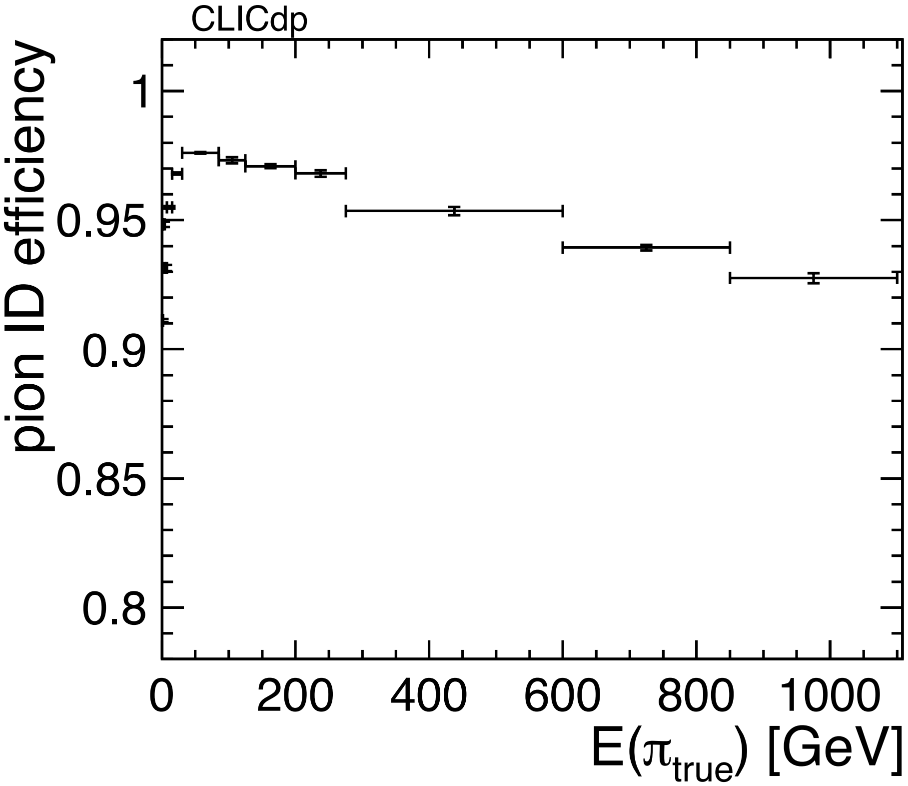


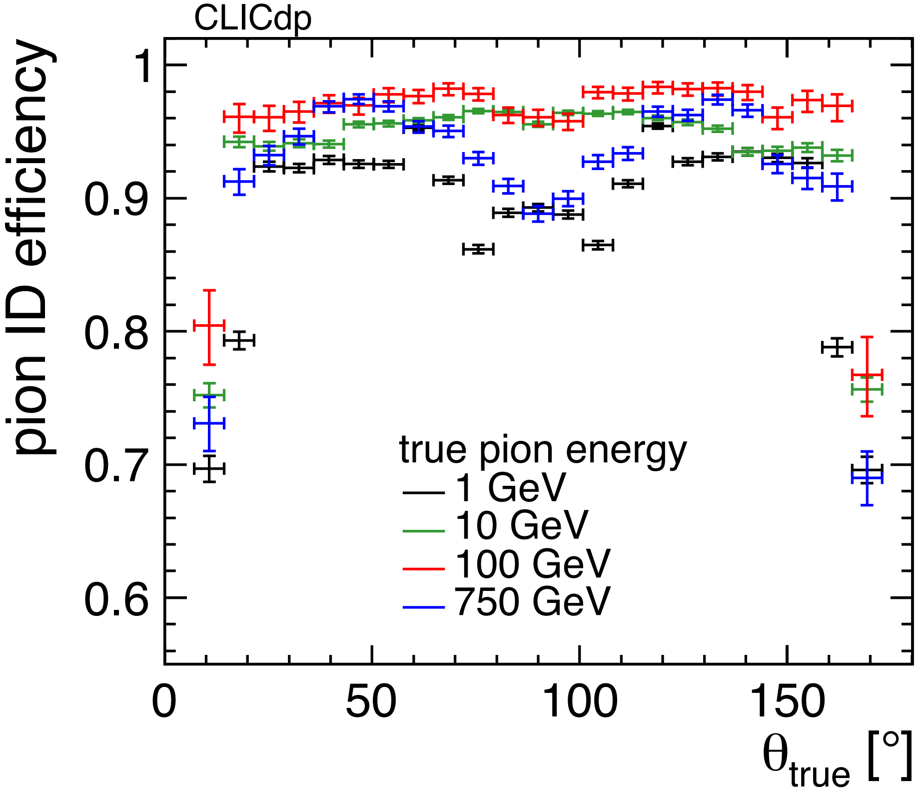


Electron efficiency vs electron energy
→ With background beyond 98% starting at 5 GeV, less than 0.5 % effect of background

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

Pion Efficiencies

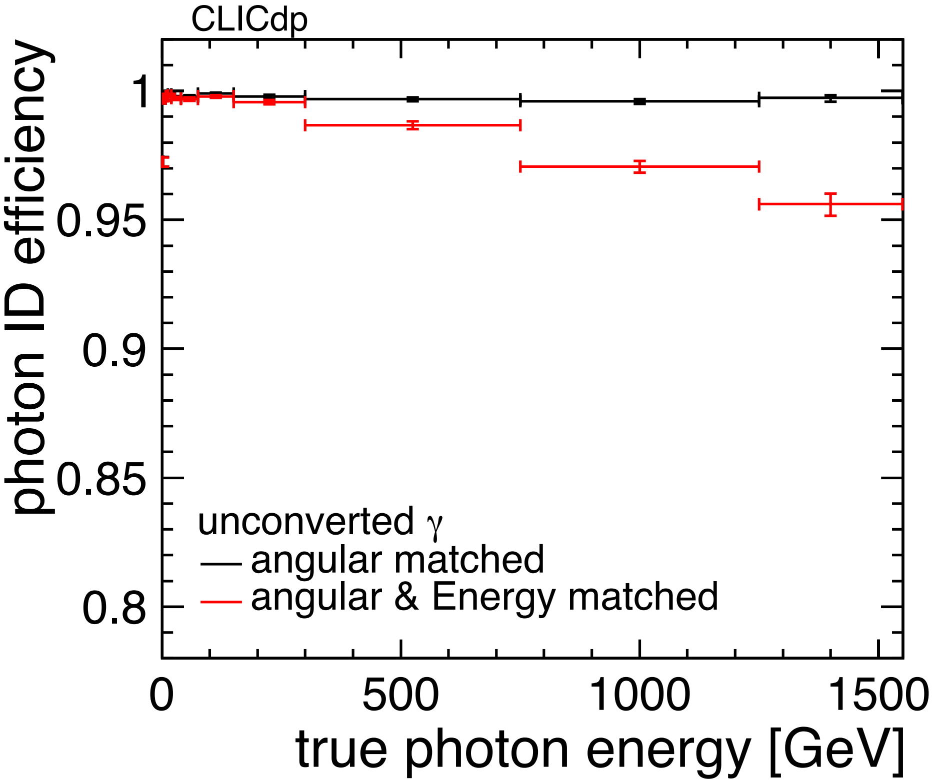




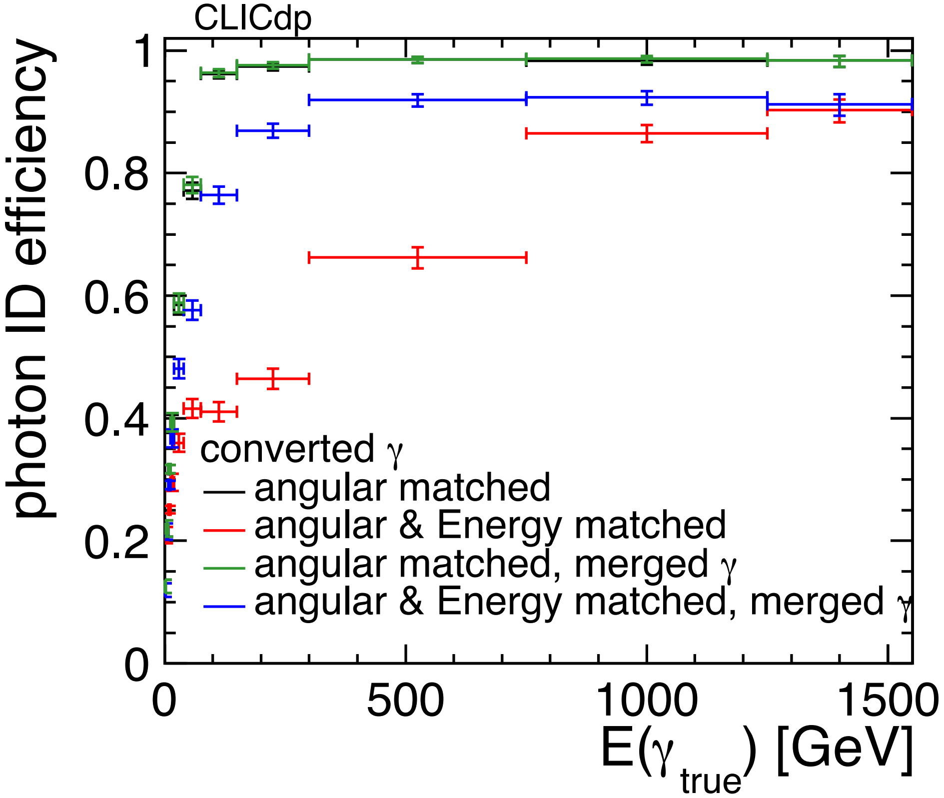
90-98% from 1-1000 GeV

Inefficiency at large energies in most central part of the detector

Photon Efficiencies



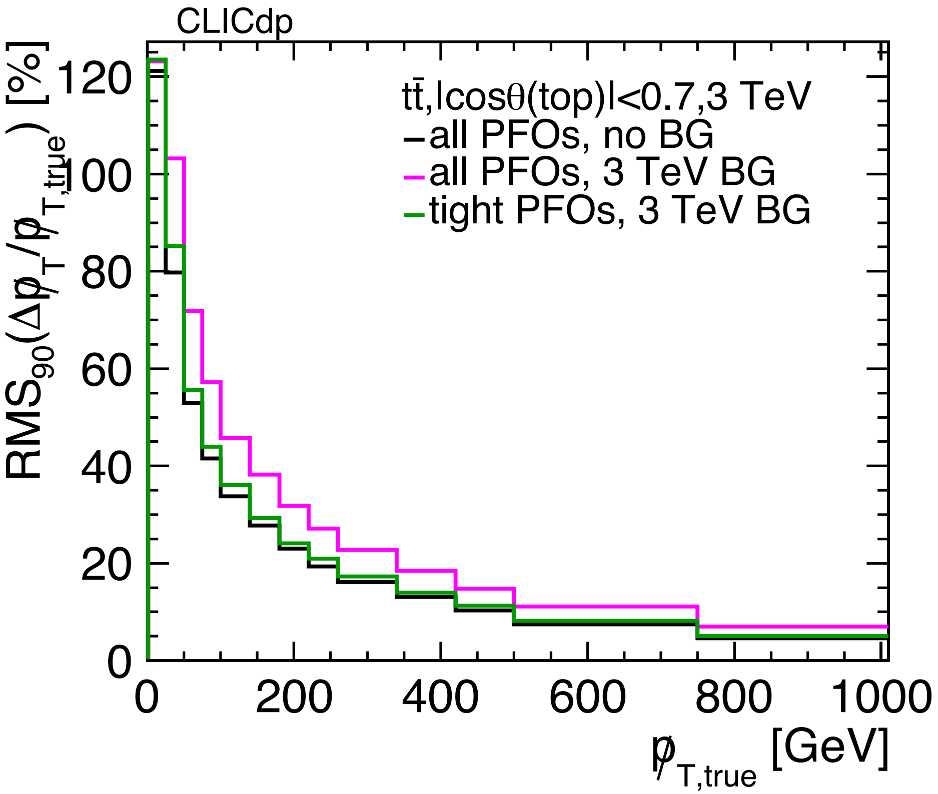
Over 98 % for unconverted photons



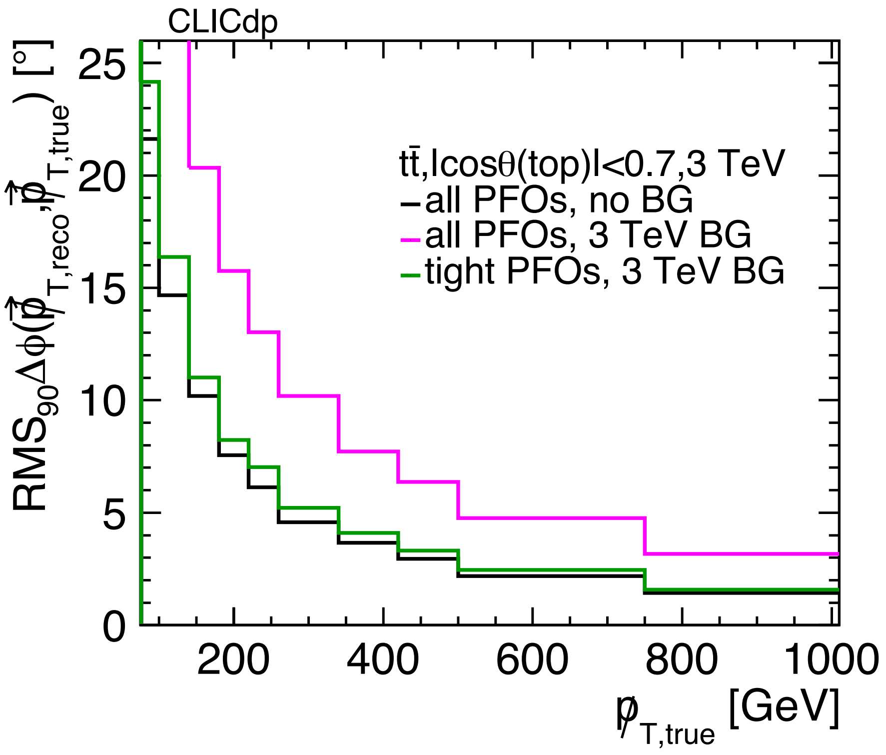
Unconverted photons (15 % of all photons): If photon clusters merged, then efficiencies beyond 95 % above 100 GeV, around 60 % for 25 GeV

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

Technical details

CLICdet model : CLIC_o3_v14

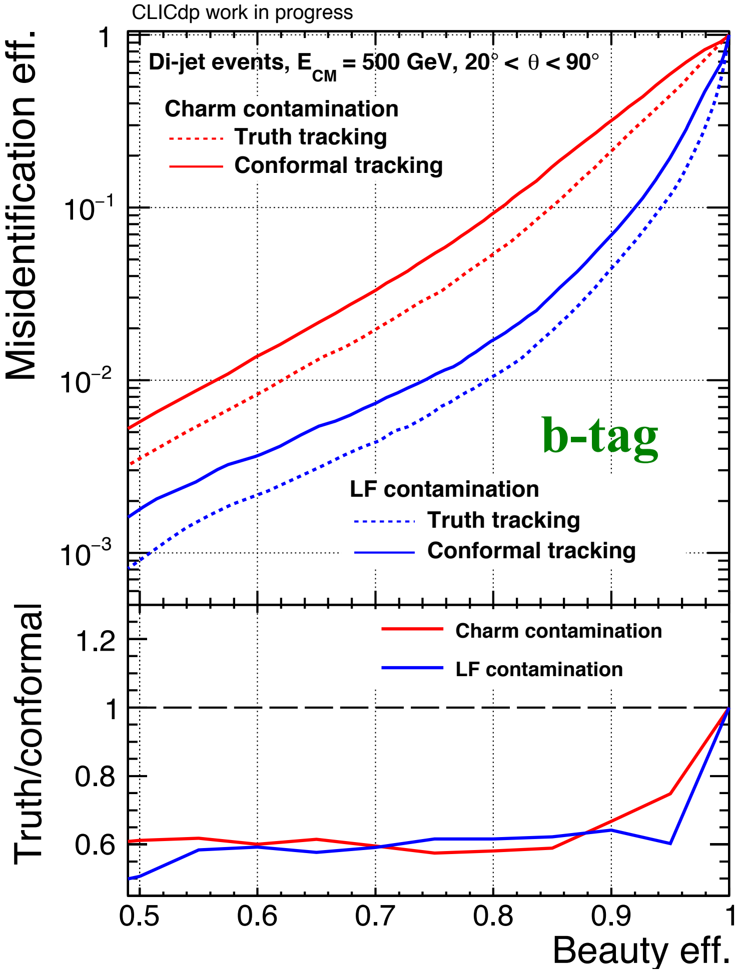
Tracking reconstruction: ConformalTracking

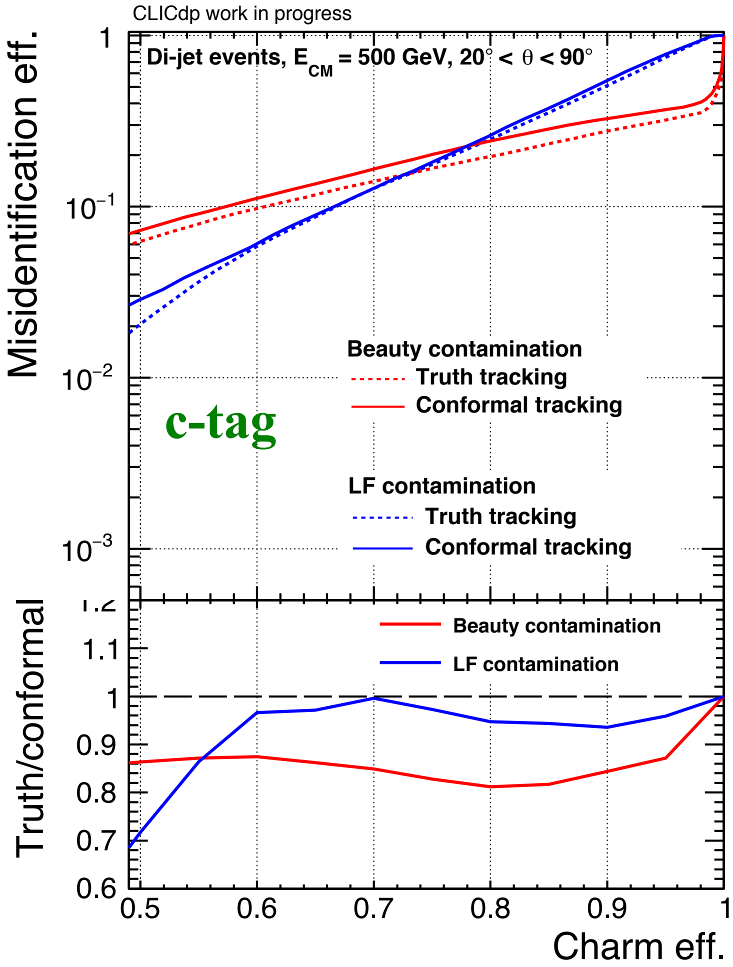
Software release: iLCSoft-18-10-11_gcc64

Software Compensation applied on HCAL clusters

c and b tagging: conformal vs truth tracking

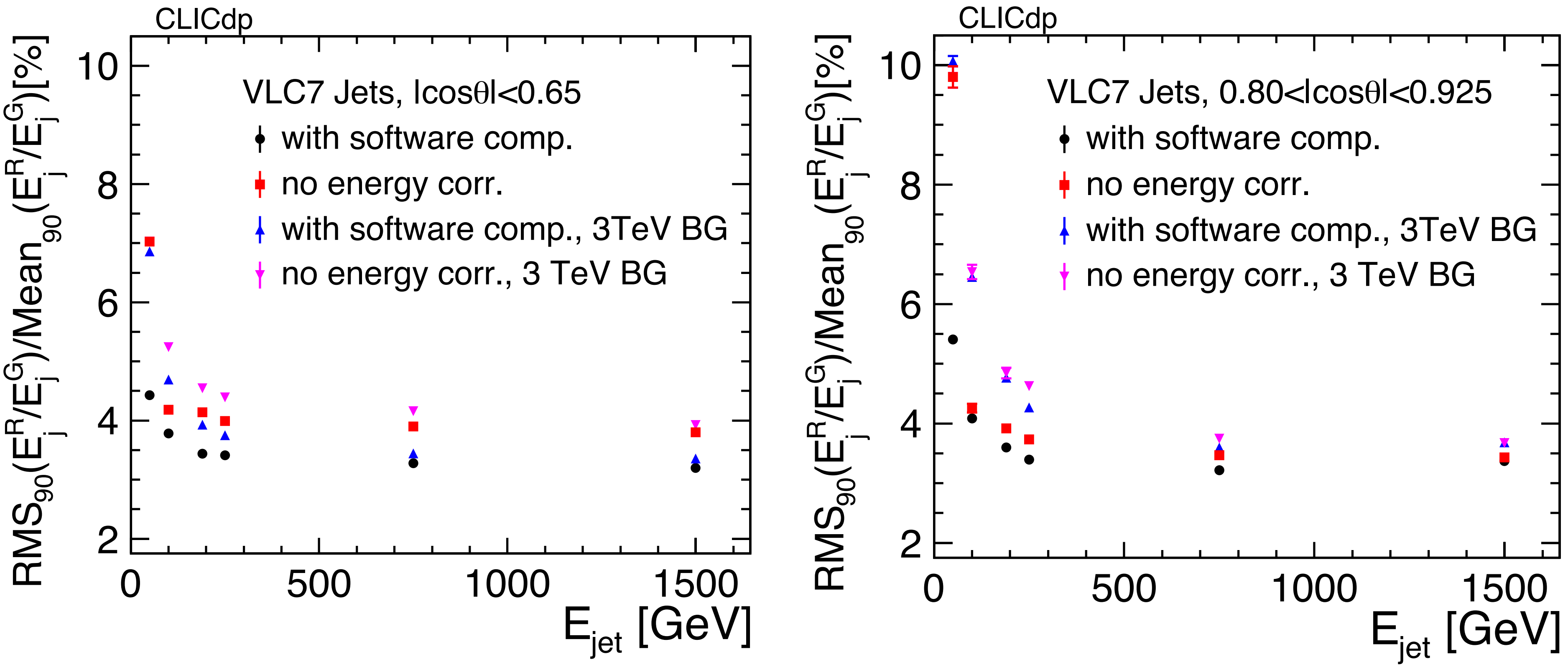
True MC pattern recognition (truth tracking) as best possible tracking algorithm





Track reconstruction improvements in conformal tracking can lead to significantly improved miss-identification numbers

Software Compensation in HCal



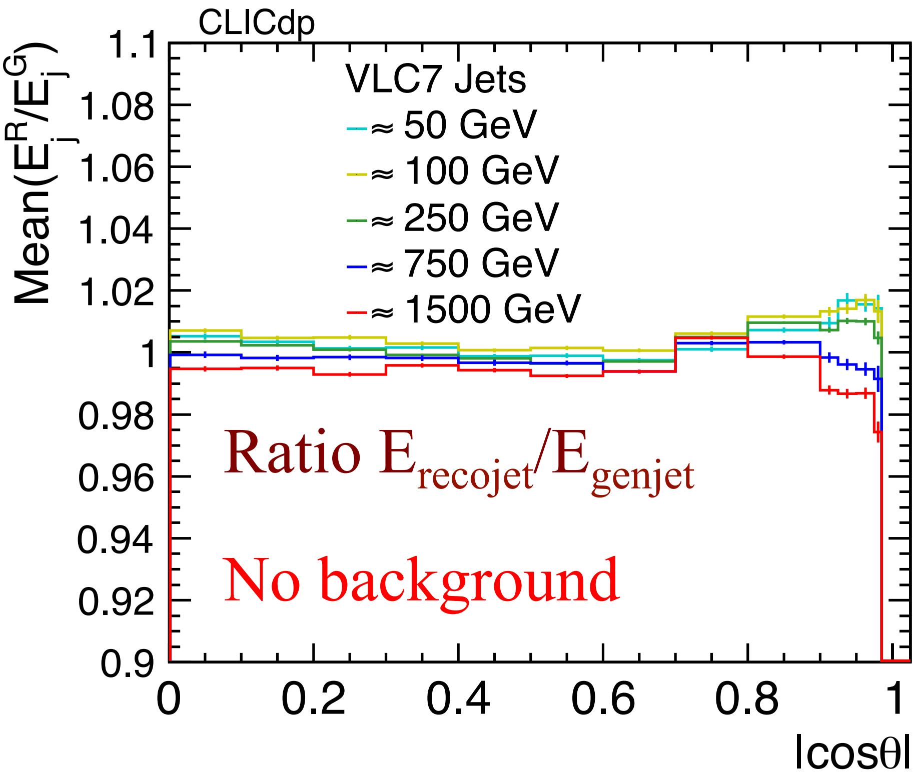
Tune using mono-energetic single K^0_L and neutron events produced flat in polar angle cos θ → improvement of energy response and energy resolution

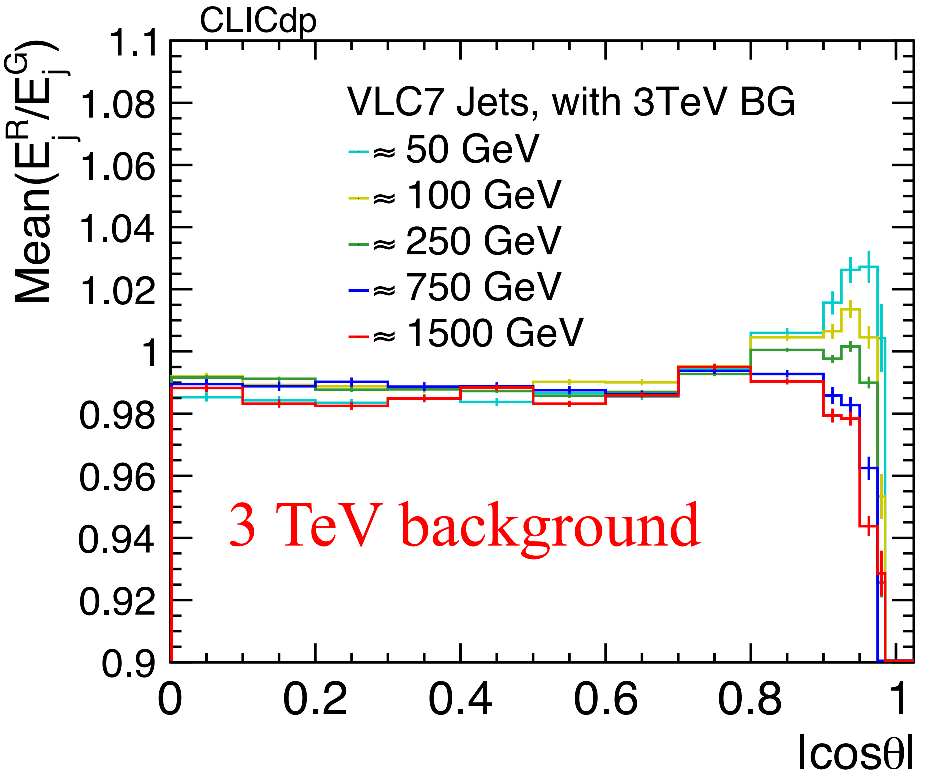
Both for events with and without beam-induced background, relative improvement of jet energy resolution of about 10 % in barrel, and 7.5-3 % in endcap

Jet energy: particle level vs detector level

PandoraPFOs calibrated, no further calibration on jet energy

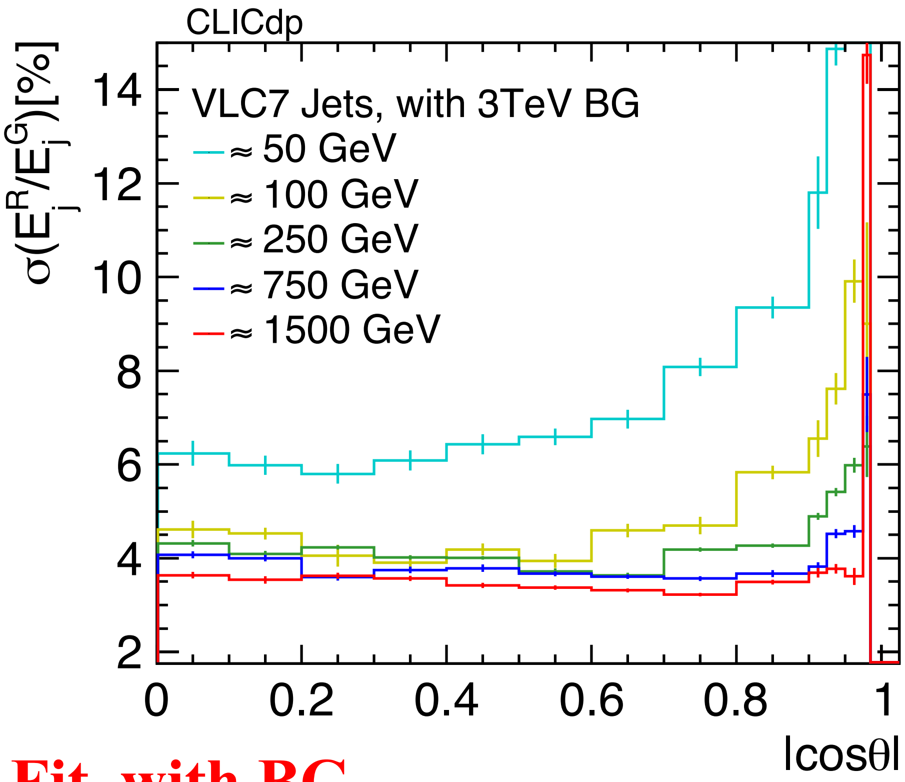
Check if γγ→hadrons background has large impact on energy collected in jet



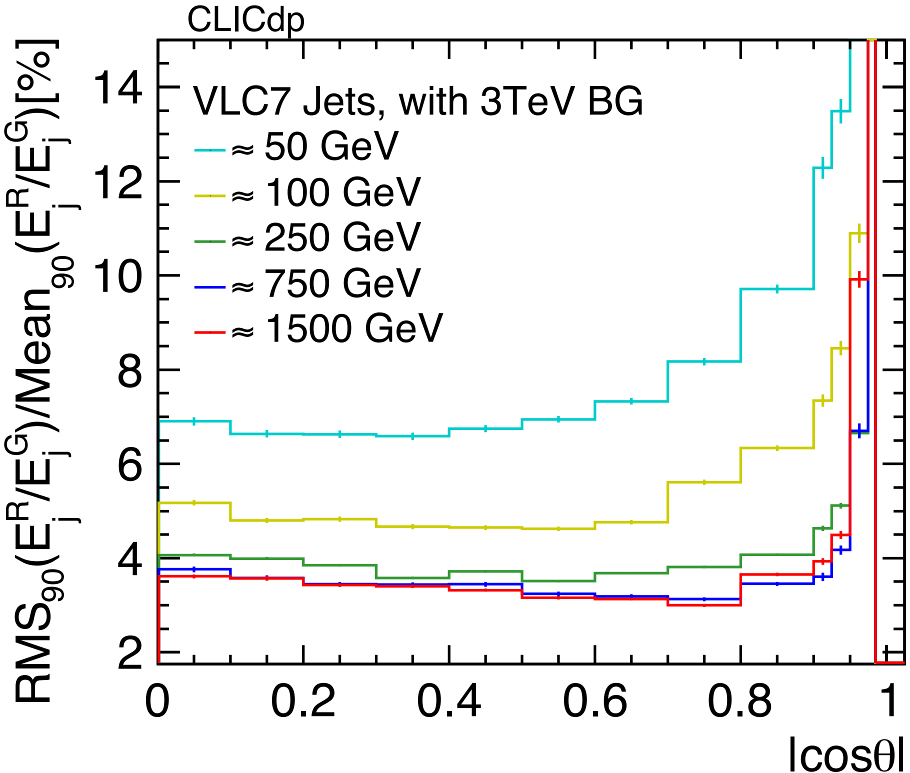


Angular matching requirement between detector level recojet and particle level genjet within 10°→ raw jet energy response close to unity for both cases, no large impact of background within jet cone

Jet Energy Resolution: CB fit σ vs RMS90



Fit, with BG

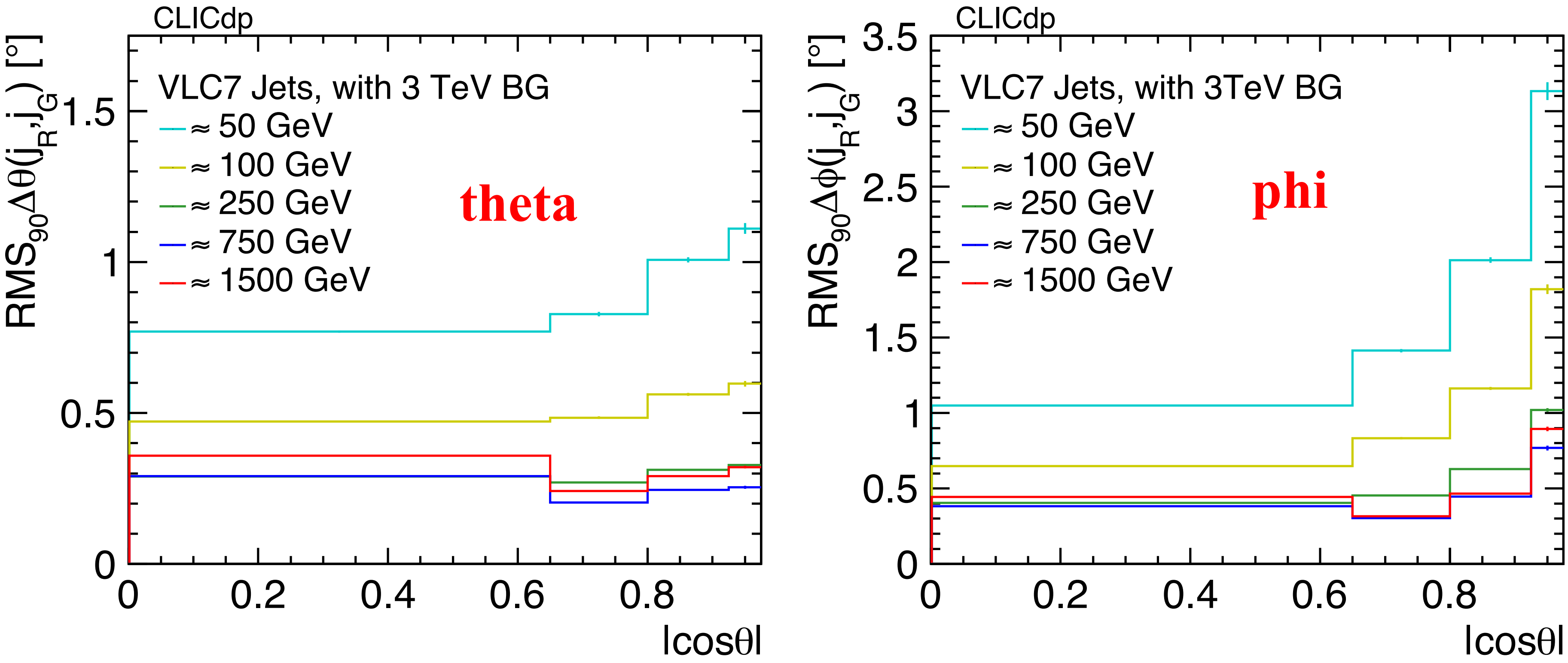


RMS 90, with BG

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 %

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

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

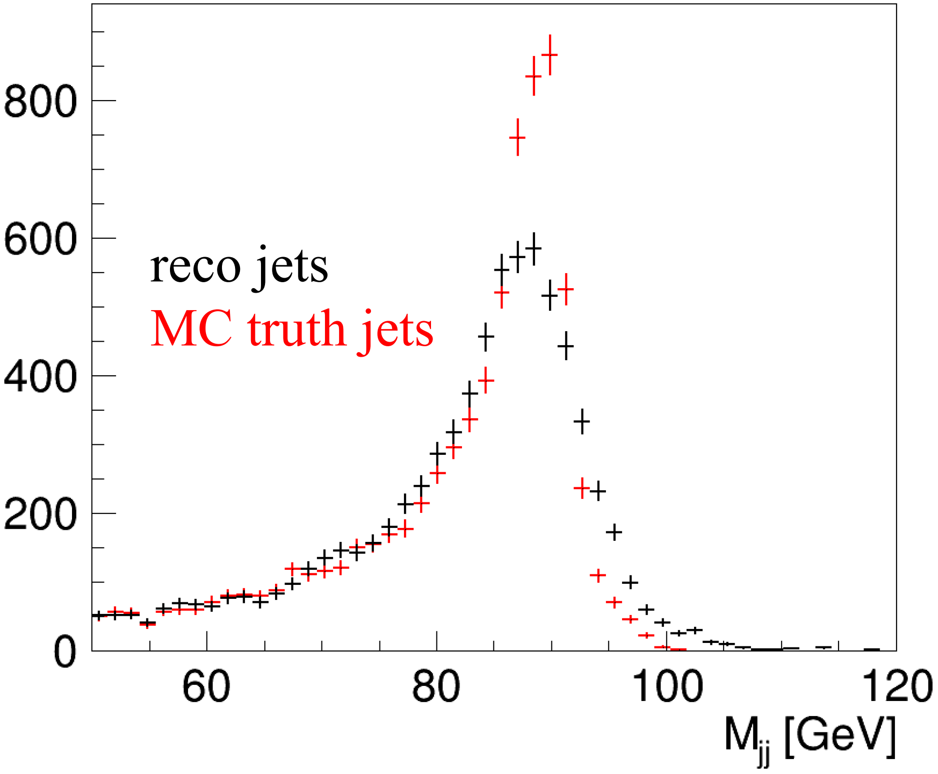
Fit peaks vary with energy → rescale Gaussian fits, so that mean of fit at W-mass (80.4 GeV) and Z-mass (91.2), fix ratio of sigma/mean while rescaling

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

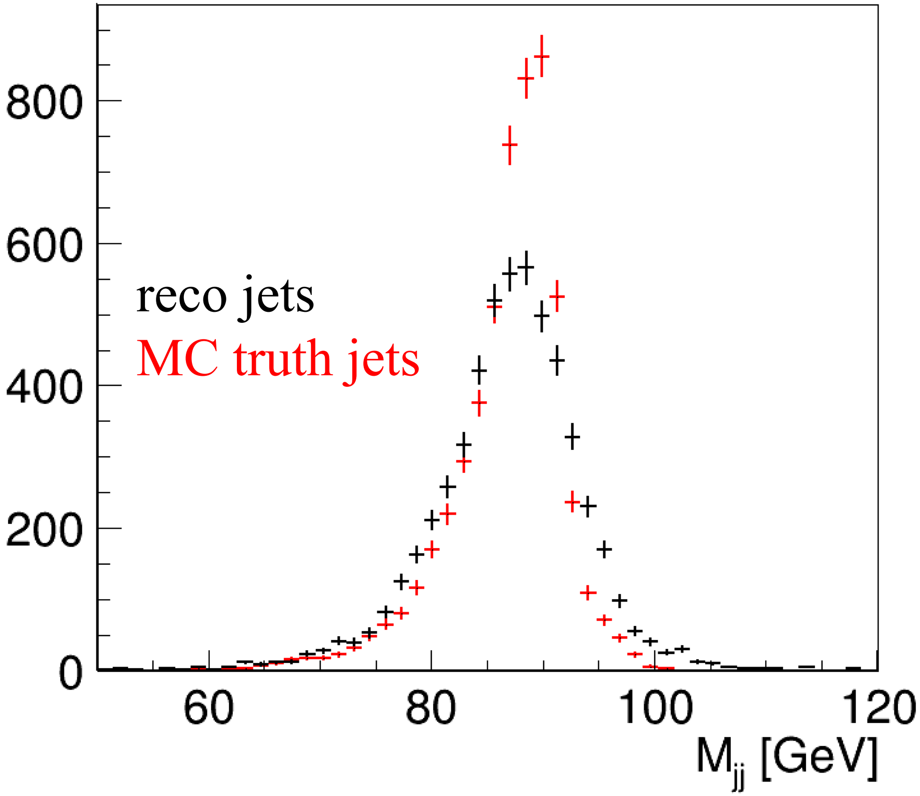
→ Calculate intersection point x_{int}

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