Anomalous Gauge Couplings and Vector Boson Scattering at CLIC 1.4TeV

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Effective Field Theory

- This analysis is based around an effective field theory where we assume the standard model is a low energy approximation of the full theory, which contains new physics.

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{\text{dimension } d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

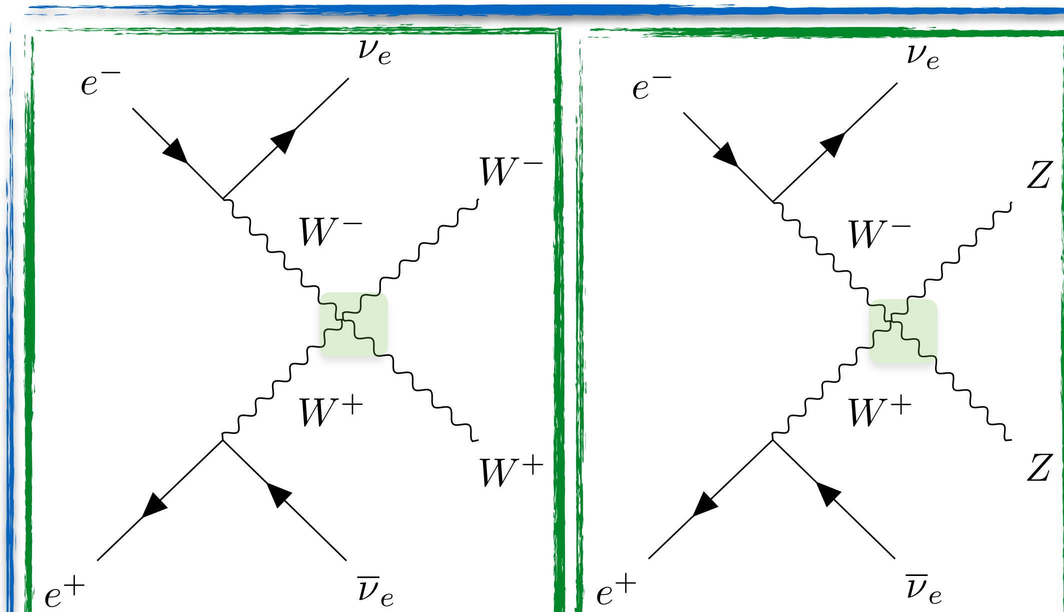
- An energy scale, Λ, is introduced that characterises the scale of the new physics. For $\Lambda >> \sqrt{s}$ the effective field theory is a good approximation.
- For this analysis consider the dimension 4 operators involving the anomalous couplings α_4 and α_5. (In SM α_4=α_5=0)
- These additional operators will change the magnitude of Feynman diagrams involving WWWW, WWZZ and ZZZZ vertices → CLIC will be sensitivity to these Feynman diagrams.
- I will be targeting vector bosons scattering with vvqqqq final state at 1.4 TeV in this analysis.

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i} c_i^{(4)} \mathcal{O}_i^{(4)}$$

$$\alpha_4 Tr[V^{\mu}V_{\mu}]^2 \qquad \alpha_5 Tr[V^{\nu}V_{\mu}]^2$$

$$V_{\mu} = -igW_{\mu} + ig'B_{\mu}$$

Gauge fields from SU(2)$_L$xU(1) symmetries in standard model.



Feynman diagrams relevant to CLIC, showing sensitivity to anomalous gauge couplings.

Sensitivity to α_4 and α_5

- To determine the sensitivity of CLIC to α_4 and α_5 it will be necessary to make a log likelihood distribution as a function of α_4 and α_5.
- There are two approaches which can be taken:
  - ✖ Generate new samples from generator level with different α_4 and α_5. These would have to then be processed through the full reconstruction chain. Very time consuming to get a well populated likelihood distribution…
  - ✔ Recalculate the matrix elements, for non-zero α_4 and α_5, at generator level, translate this to an event weight. Allows for a simple reweighting of events at the analysis stage. Only need to process one set of samples through reconstruction chain.

$$\text{Event Weight} = \frac{|M_{fi}(\alpha_4,\alpha_5)|^2}{|M_{fi}(\alpha_4=0,\alpha_5=0)|^2}$$

$$\sigma \propto |M_{fi}|^2$$

$$M_{fi} = \langle \phi_{final}|\hat{H}|\phi_{initial}\rangle \rightarrow \alpha_4 Tr[V^\mu V_\mu]^2 \quad \alpha_5 Tr[V^\nu V_\mu]^2$$

- Naively you may expect that the α_4 and α_5 weights should be quadratic, however, this neglects the effects of unitarisation.
- In whizard v1.95 K-matrix unitarisation is applied. For details please see http://arxiv.org/abs/arXiv:0806.4145.

$$M_{fi} \rightarrow M_{fi} + A\alpha_4 + B\alpha_5$$

$$|M_{fi}|^2 \rightarrow |M_{fi}|^2 + C\alpha_4 + D\alpha_5 + E\alpha_4^2 + F\alpha_4\alpha_5 + G\alpha_5^2$$

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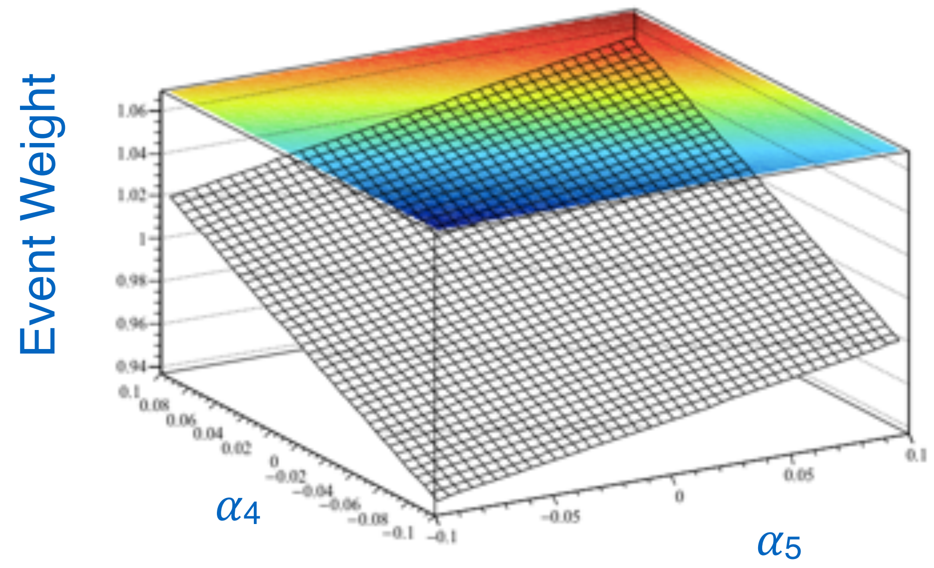
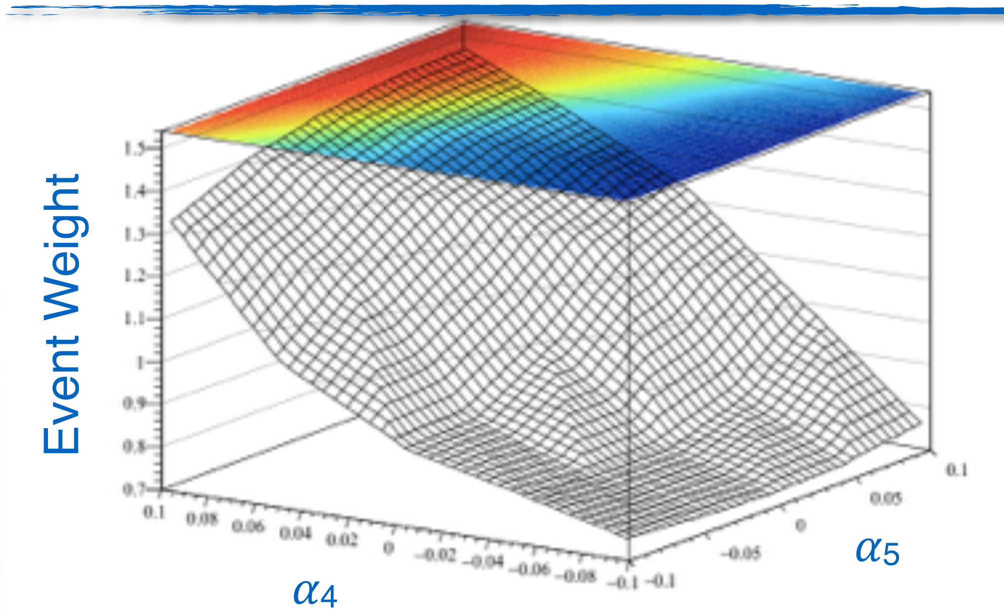
Example Event Weight

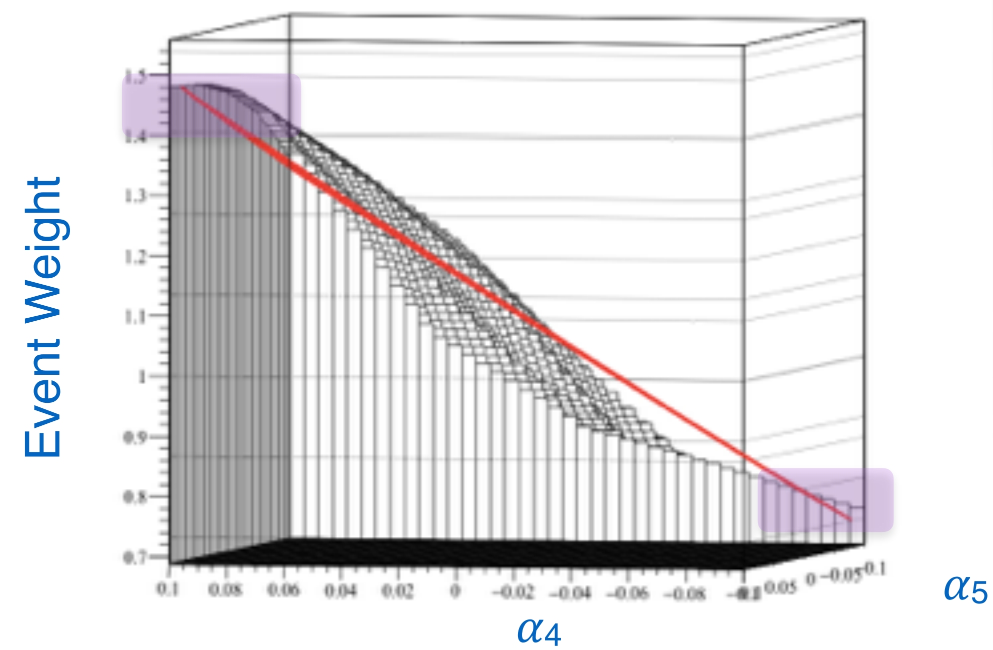


EVENT 1: No sign of K-matrix unitarisation taking effect here, but event weights are small so unlikely to violate unitarity.

- To make this plot I ran whizard using the reweighting mode taking a fixed number of steps in both the α_4 and α_5 parameter space.
- To allow me to reweight for any given set of α_4 and α_5 I applied bilinear interpolation between the points as this 2D function appears smooth.
- For particularly large event weights you can see a saturation in the event weight, which is most likely due to K-matrix unitarisation coming into play.
- ✓ So I now have the ability to access the weight information for the events and the weights themselves are behaving nicely, i.e. smoothly, even with a unitarisation scheme applied.



EVENT 2: Saturation effect appearing in event weight for larger event weights. Causes deviation from quadratic form.



Event Samples

- Important point to this analysis is that I cannot use the CLIC samples already in existence to get the event weights.
- Therefore, I have had to produce my own samples for this study for events which require reweighting.
- Any process in which non-zero α_4 and α_5 will significantly change the cross section will require reweighing. This includes the backgrounds qqqqlv, qqqqll and others…
- To begin with I have only remade the qqqqvv sample (350,000 events).
- It is my hope that only minimal numbers of backgrounds requiring reweighting will pass the selection cuts and so I can use the CLIC samples for those as the reweighting will have minimal impact on the study.

- Did I replicate the CLIC reconstruction chain correctly for the qqqqvv samples I have made?
  - I believe yes, see http://indico.cern.ch/event/539086/contributions/2274506/attachments/1323669/1986242/CLICdpAnalysis_Green_2016_8_16.pdf

- Reconstruction Chain Notes, all jobs run on the grid:
  - Generator - I used Whizard 1.97 for the unitarisation, CLIC samples used Whizard 1.95, but no major changes between the two. Beam spectrum files used are up to date. See backup for some more whizard setup details.
  - Simulation - clic-ild-cdr used. Mokka version 0706P08, which is a verified production version.
  - Reconstruction - Marlin version v0111Prod
  - Overlay - $\gamma\gamma \rightarrow$Had overlay applied using settings for 1.4 TeV jobs.

Samples

Process	Energy	#Events	σ [fb]	Normalised #Events
qqqqνν	1400	335300	24.7	37050
qqqqlν	1400	715200	115.3	172950
qqqqll	1400	1101100	71.7	107550
qqqq	1400	591800	1328.1	1992150
eγ→qqqqe - EPA	1400	129100	287.1	430650
eγ→qqqqe - BS	1400	126300	1160.7	1741050
γe→qqqqe - EPA	1400	137400	286.9	430350
γe→qqqqe - BS	1400	120200	1156.3	1734450
eγ→qqqqν - EPA	1400	180100	32.6	48900
eγ→qqqqν - BS	1400	175000	136.9	205350
γe→qqqqν - EPA	1400	177800	32.6	48900
γe→qqqqν - BS	1400	173800	136.4	204600
γγ→qqqq - Both EPA	1400	167300	753.0	1129500.0
γγ→qqqq - First EPA Second BS	1400	167900	4034.8	6052200
γγ→qqqq - First BS Second EPA	1400	170700	4018.7	6028050
γγ→qqqq - Both BS	1400	159800	21406.2	32109300
qqνν	1400	577200	933.9	1400850
qqlν	1400	2043200	4309.7	6464550
qqll	1400	2104400	2725.8	4088700
qq	1400	459000	4009.5	6014250

Signal samples I generated

4 jet events
+ 0, 1, 2 leptons events

4 jet events
from beam effects

The following table shows all the background samples I'm considering at the moment.

2 jet events
+ 0,1,2 leptons events

Analysis Chain

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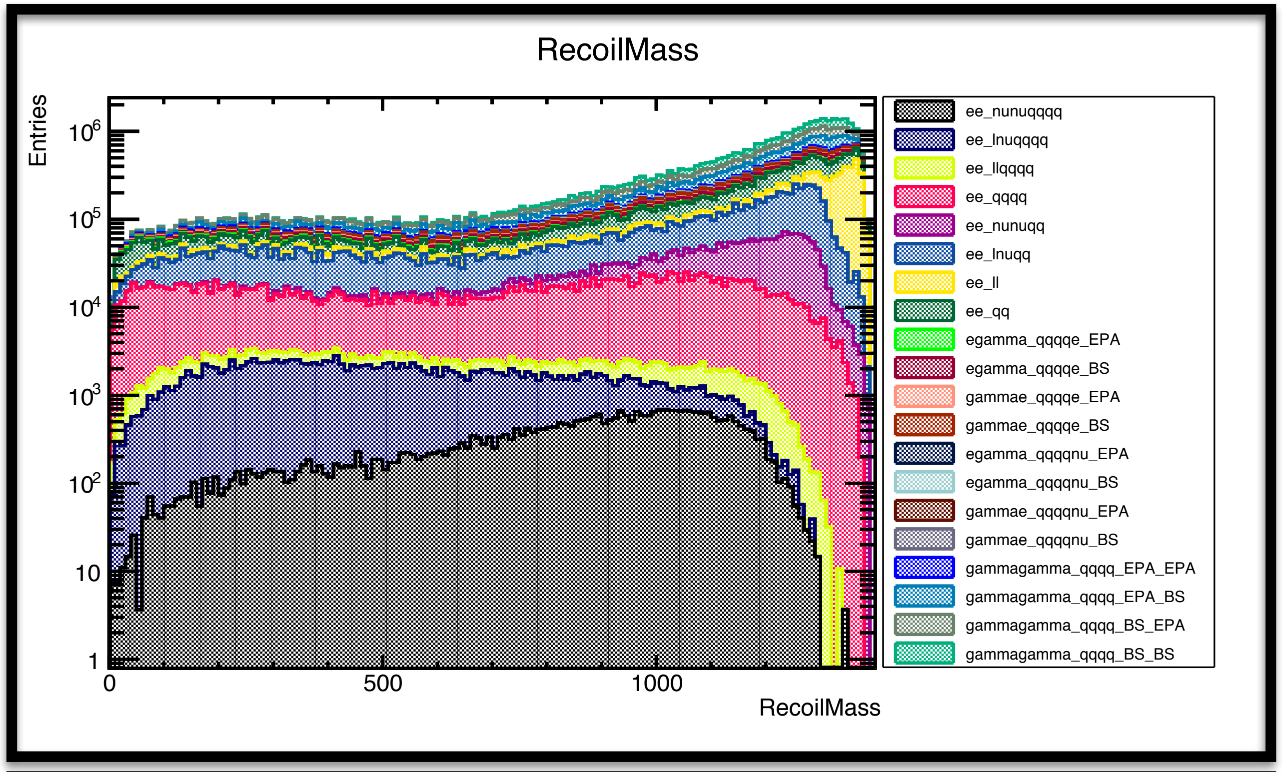
- To make the distributions of interest to compare the samples to FastJet was used to cluster the events into 4 jets:
  - KT Algorithm used with cone radius of 0.75.
  - ExclusiveNJet clustering mode applied.
- I then ran my own processor (on the SelectedCLICPFOs) to calculate the following variables:

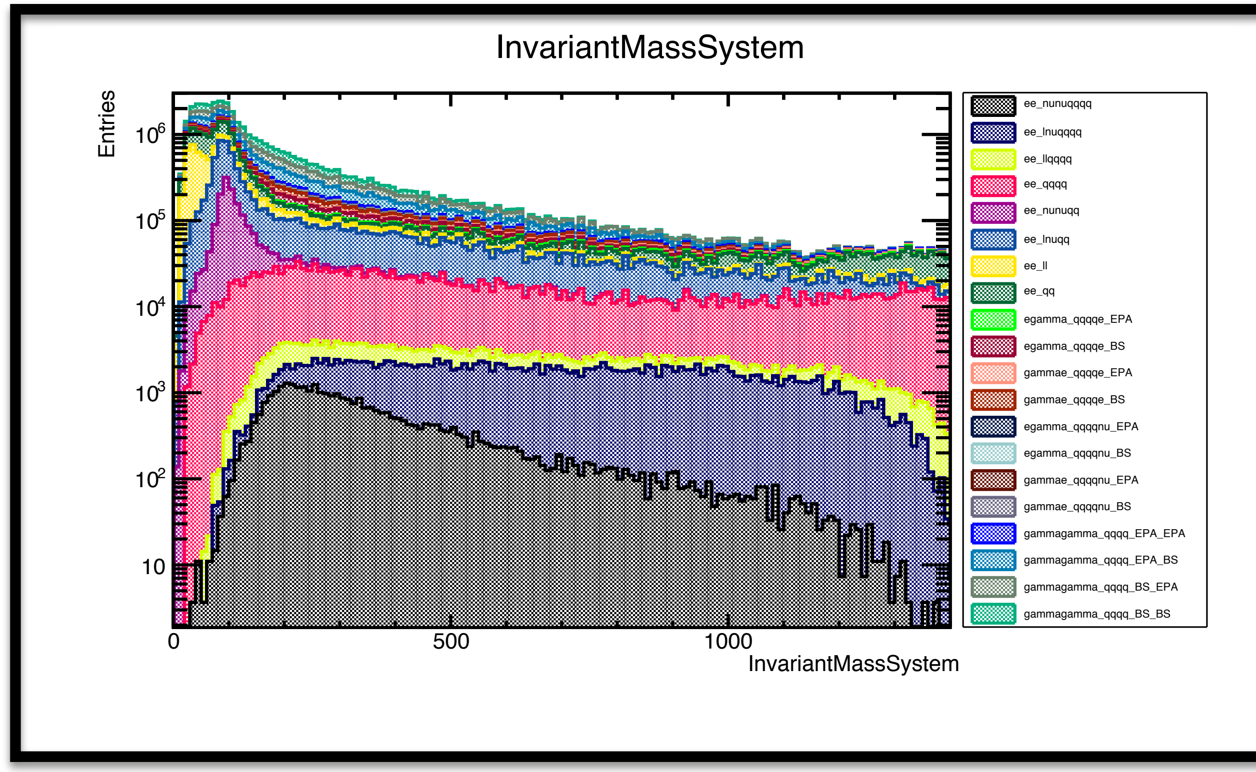
Variable	Description
M_{Recoil}	Recoil mass
P_t	Transverse Momentum
E_t	Transverse Energy
$\cos\theta_{Mis}$	Cosine theta of missing momentum
$\cos\theta_{Track}$	Cosine theta of highest energy track
Cone Energy	Energy in 10 degree cone around highest energy track
Y34	Jet clustering variable
NPartJets	Number of particles in jet
NChargedPartJet	Number of charged particles in jet
E_{Jet}	Energy of jets
W_{Mass}	Invariant mass of W boson using W pairing
Z_{Mass}	Invariant mass of Z boson using Z pairing
$\cos\theta_W^*$	Cosine theta of W in reference frame of WW (W pairing)
$\cos\theta_Z^*$	Cosine theta of Z in reference frame of ZZ (Z pairing)
$\cos\theta_{Jet}^*$	Cosine theta of jet in reference frame of W/Z

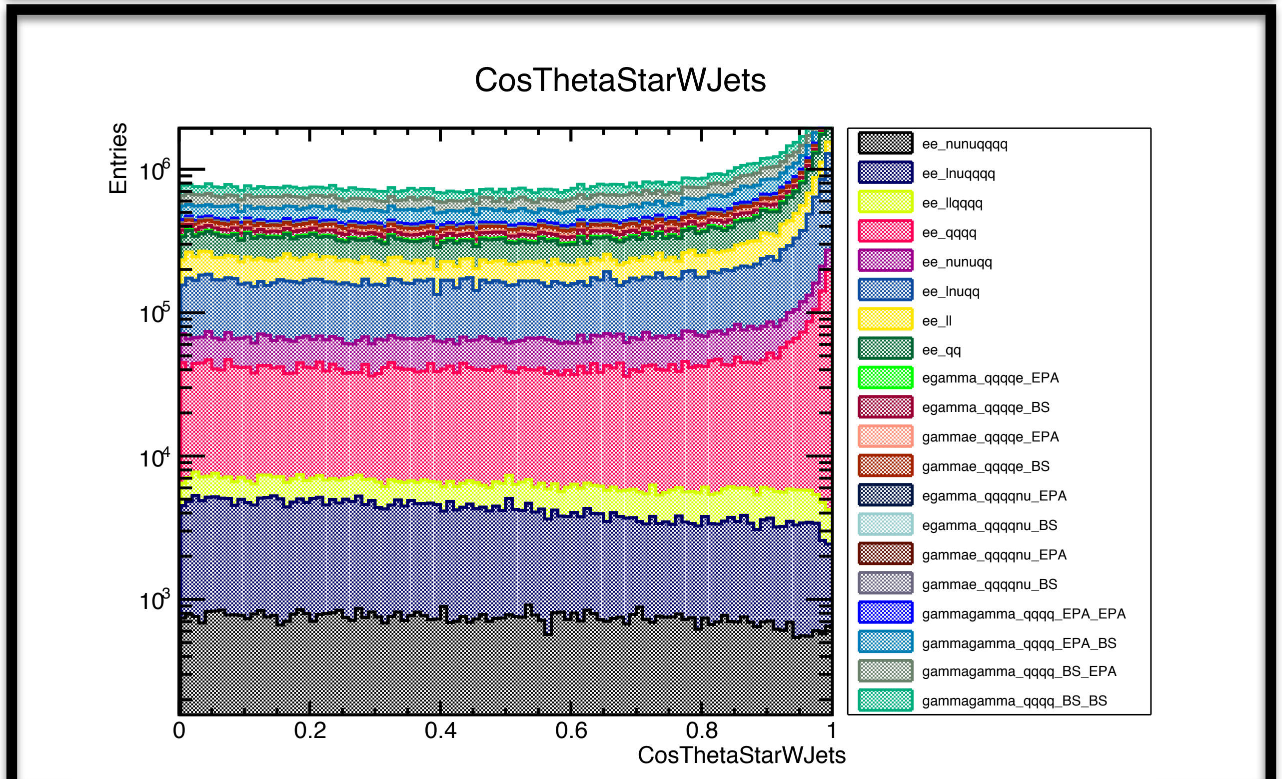
- W and Z pairing corresponds to finding the 2 pairs from the 4 of LCIO particles from FastJet that have the invariant masses closest to the W and Z true mass respectively.

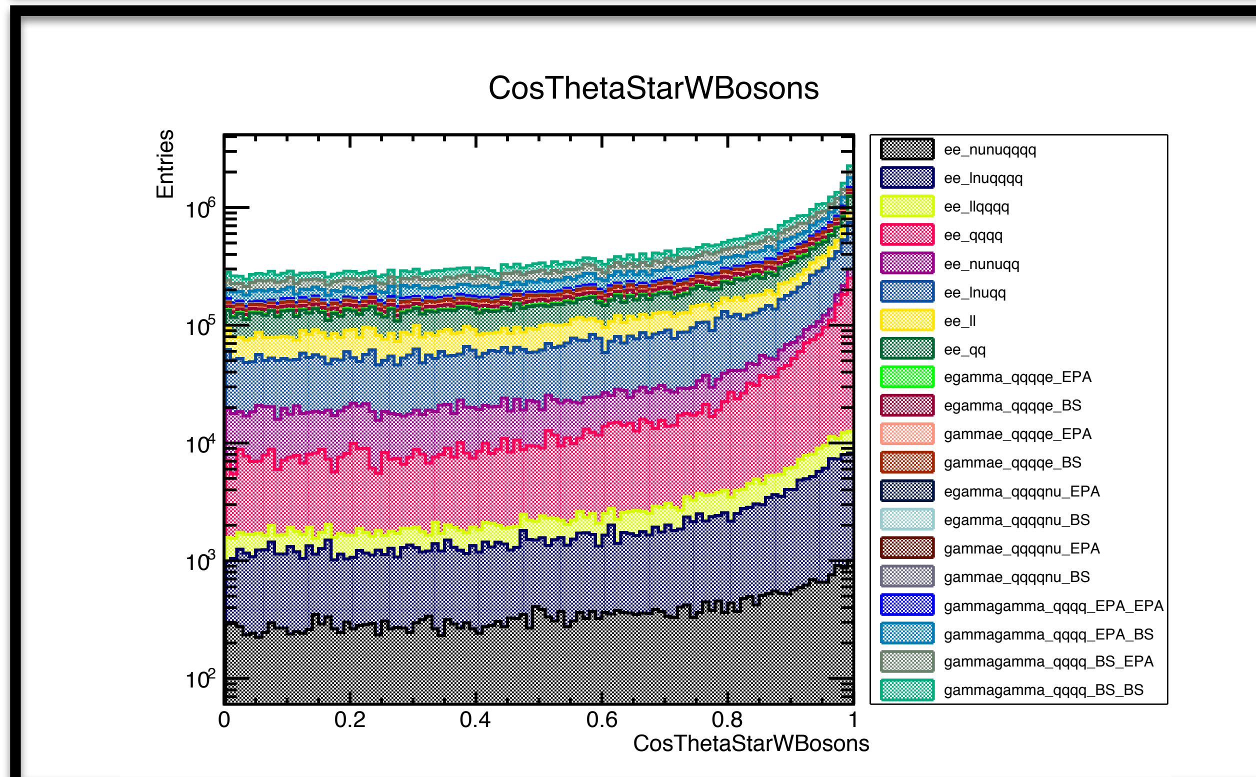
The jet clustering parameters may not be optimal, but it works well for a first run of the analysis.

Raw Distributions







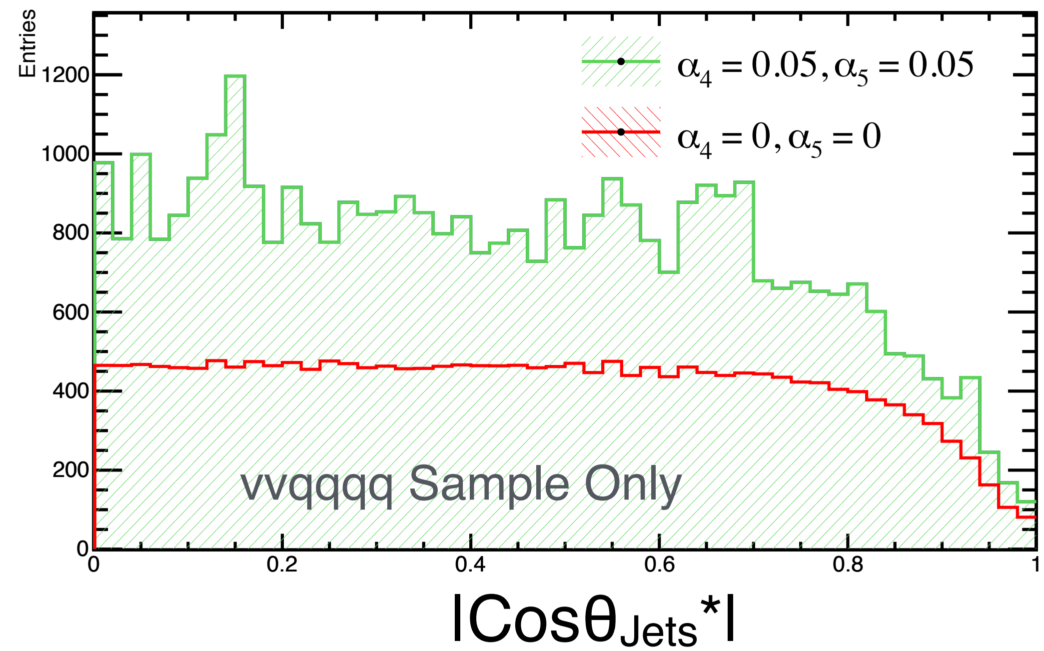


✔ Distributions seemed sensible, please see backup slides for full set.

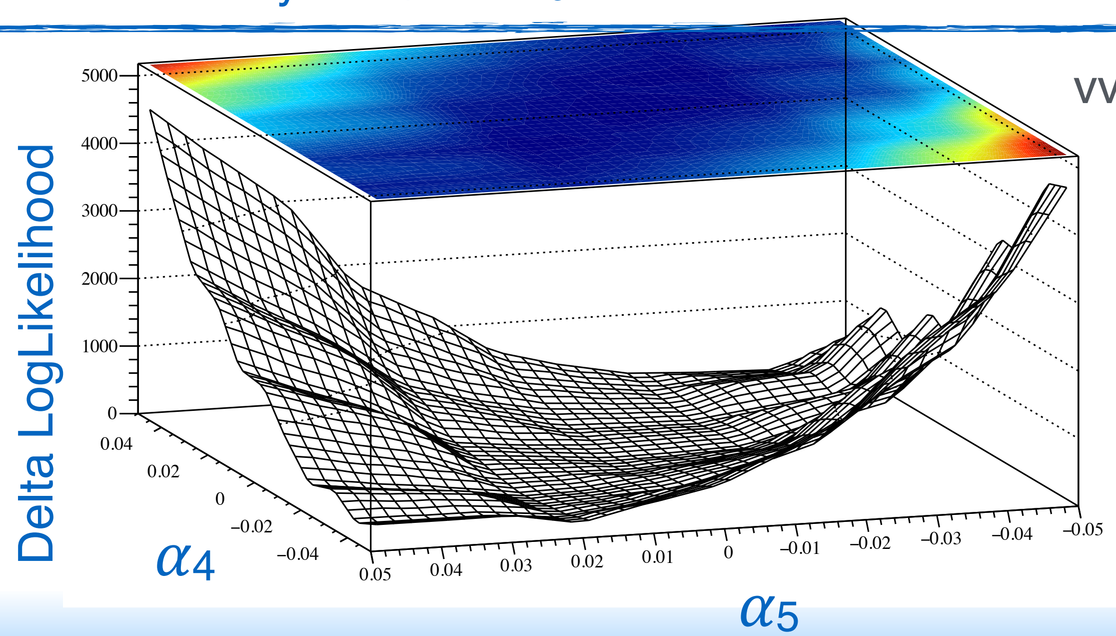
Analysis - Principle

- To determine the sensitivity of CLIC to the anomalous gauge couplings I will apply a log likelihood to distributions showing sensitivity to α_4 and α_5.
- As you can see the variable $\cos\theta_{Jets}^*$ shows sensitivity to the anomalous couplings and should provide a good basis for a likelihood fit.

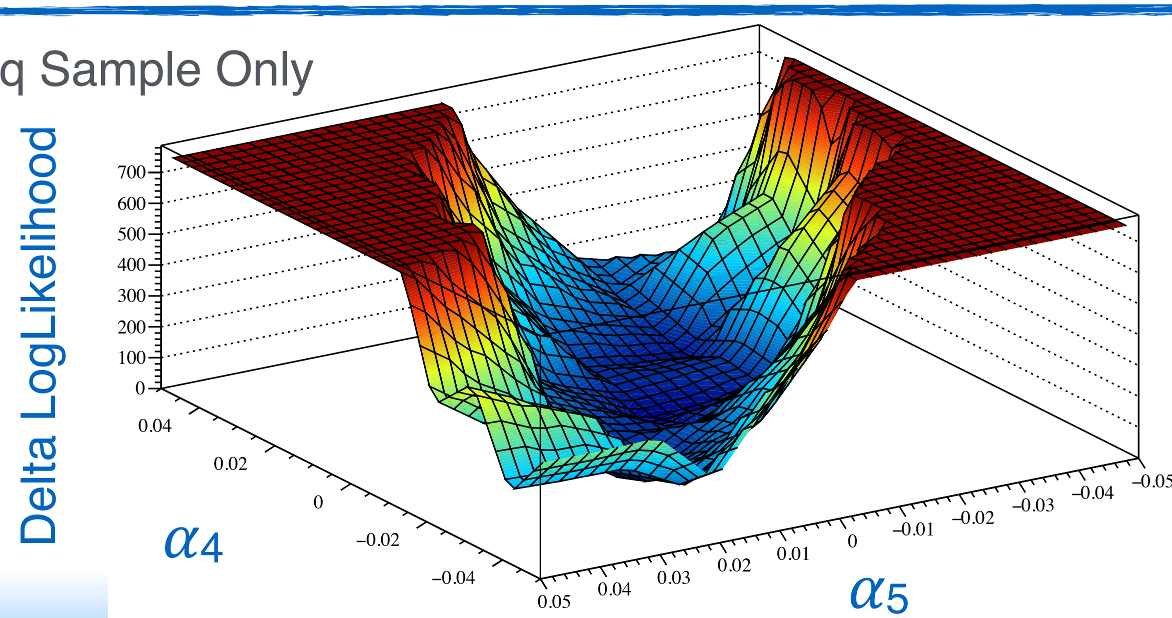
$\cos\theta_{Jet}^*$ Cosine theta of jet in reference frame of W/Z



- Fit each bin in the $|\cos\theta_{Jets}^*|$ distribution for a given α_4 and α_5 with a Poisson distribution and sum over all bins to calculate the negative log likelihood.
- Then plot this as a function of α_4 and α_5, then apply some careful interpretation to get some confidence limits on the CLIC sensitivity to α_4 and α_5.



vvqqqq Sample Only

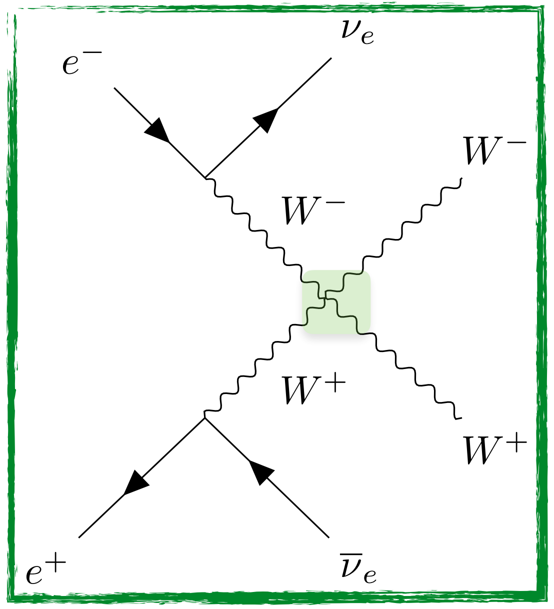


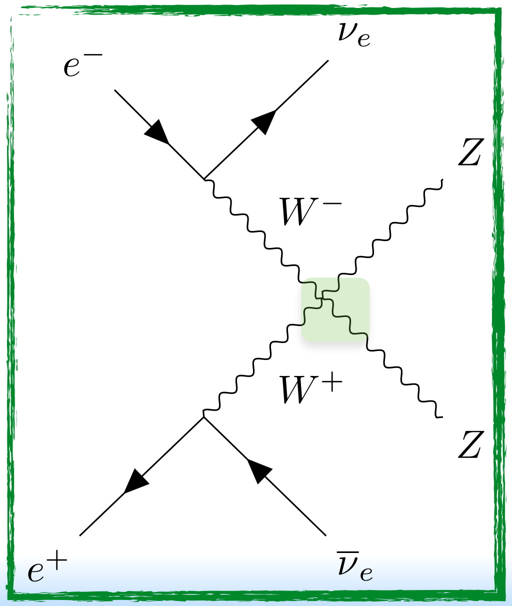
PreSelection Cuts

- To determine the true sensitivity of CLIC to α_4 and α_5 it is necessary to select the events that show sensitivity to α_4 and α_5.
- I will target the signal final state of vvqqqq with the qqqq coming from a pair of W or pair of Z bosons.
- As an initial step I applied the selection cuts used in a previous study performed in Cambridge in 2008 by Wenbiao Yan, for 1 TeV ILD.
- No guarantee that these are optimal, but yields sensible variables to look at for initial step.

Variable	Description	Cut
M_{Recoil}	Recoil mass	>=250 GeV
P_t	Transverse Momentum	>=40 GeV
E_t	Transverse Energy	>= 150 GeV
$Cos\theta_{Mis}$	Cosine theta of missing momentum	abs < 0.99
$Cos\theta_{Track}$	Cosine theta of highest energy track	abs < 0.99
Y34	Jet clustering variable	< 3.5
NPartJets	Number of particles in jet	>=3
NChargedPartJet	Number of charged particles in jet	>=2
E_{Jet}	Energy of jets	>10 GeV
W_{Mass}	Invariant mass of W boson using W pairing	60GeV < W_{Mass} < 88GeV
Z_{Mass}	Invariant mass of Z boson using Z pairing	85GeV < Z_{Mass} < 100GeV

Either or





Effect of Selected PreSelection Cuts

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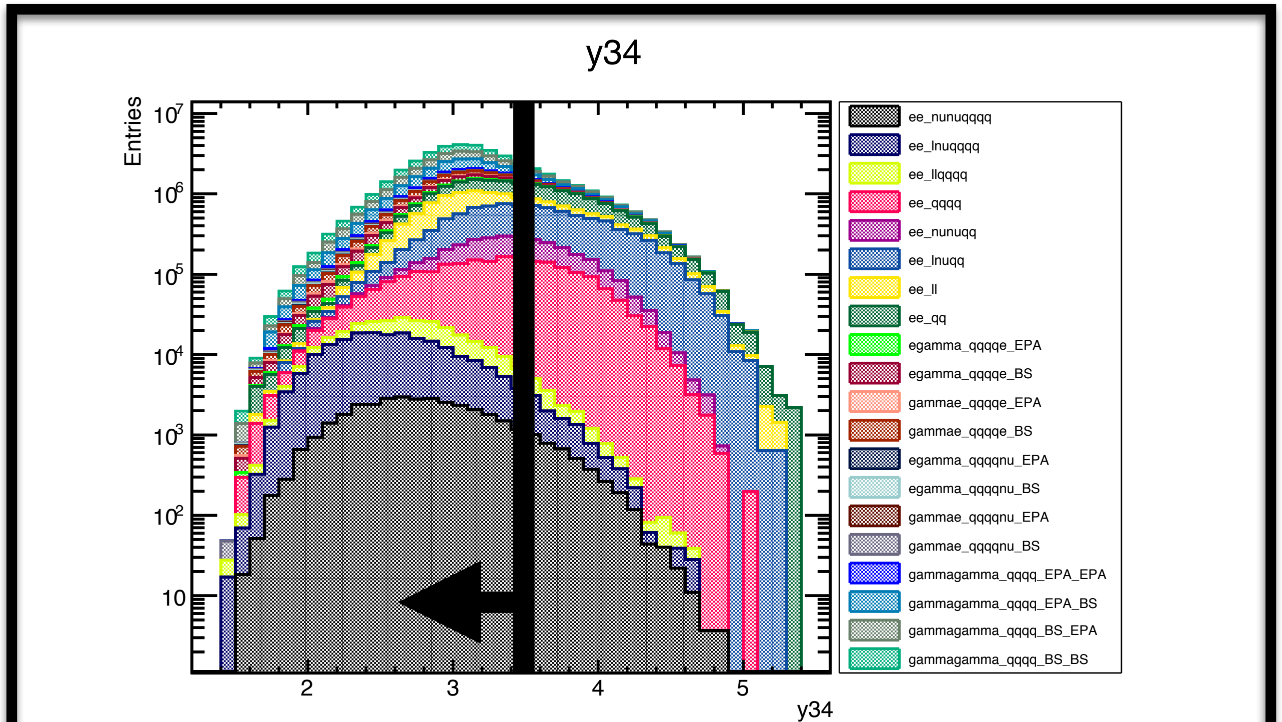
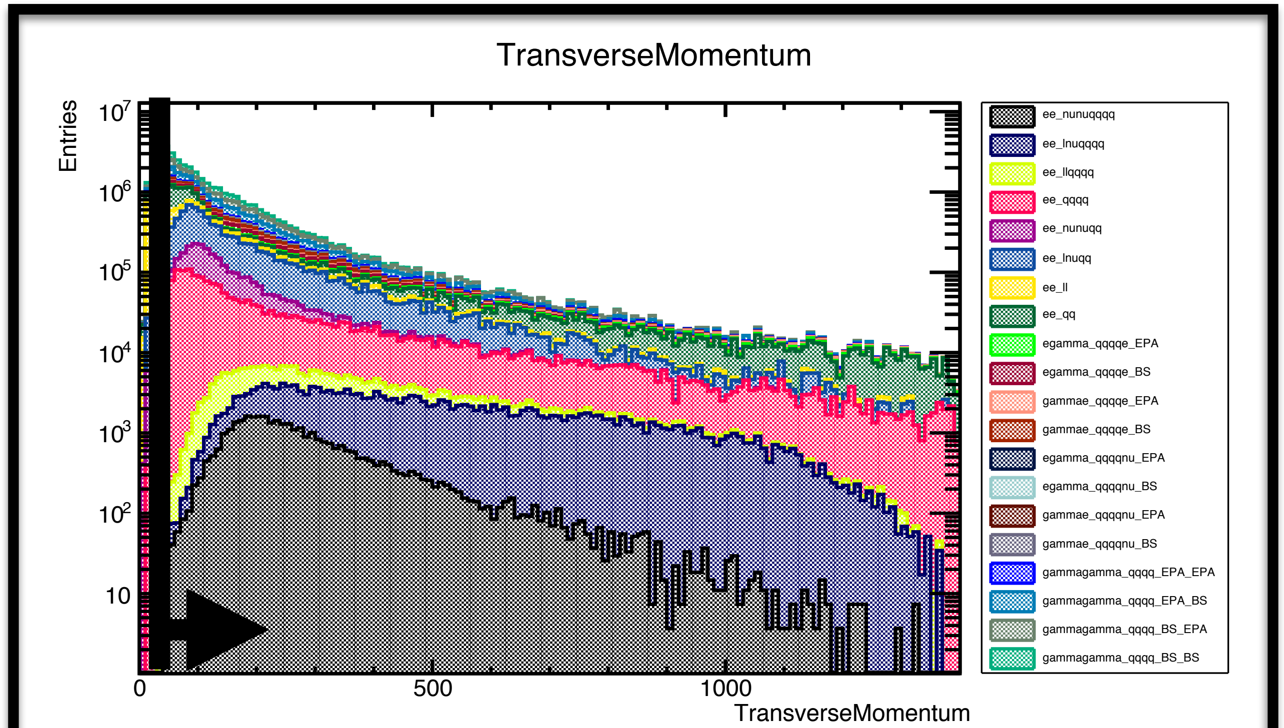
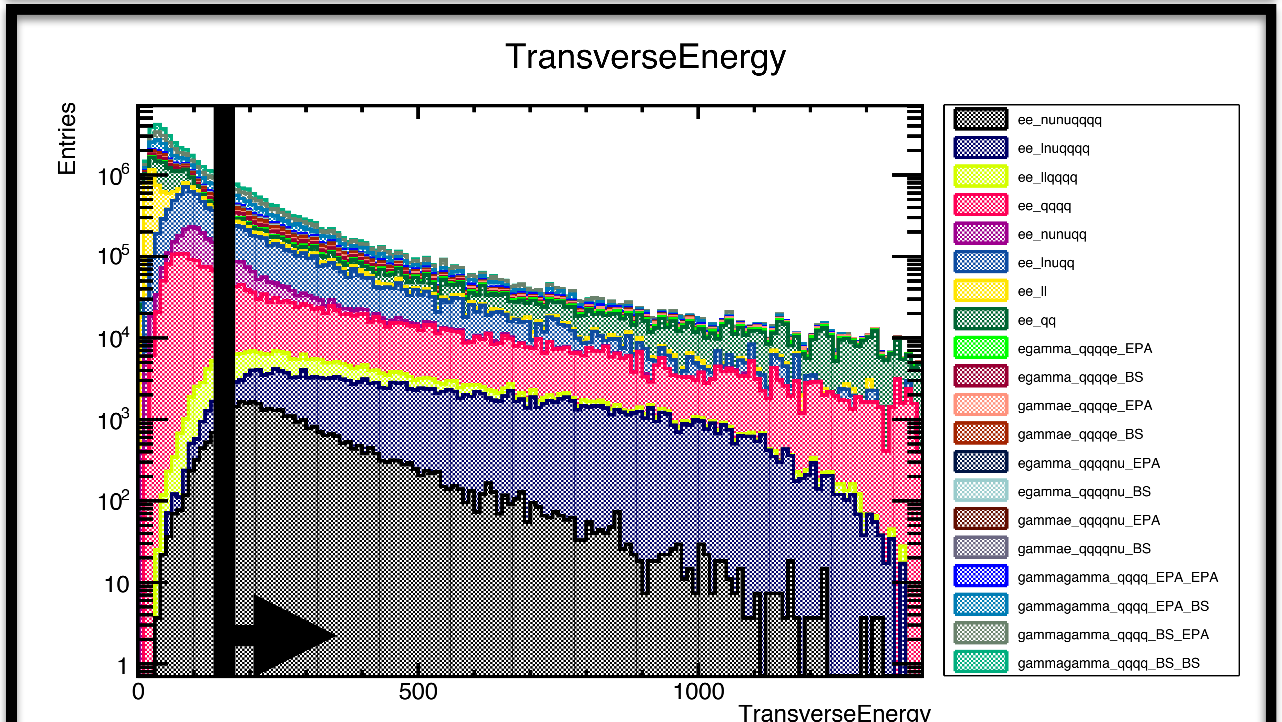


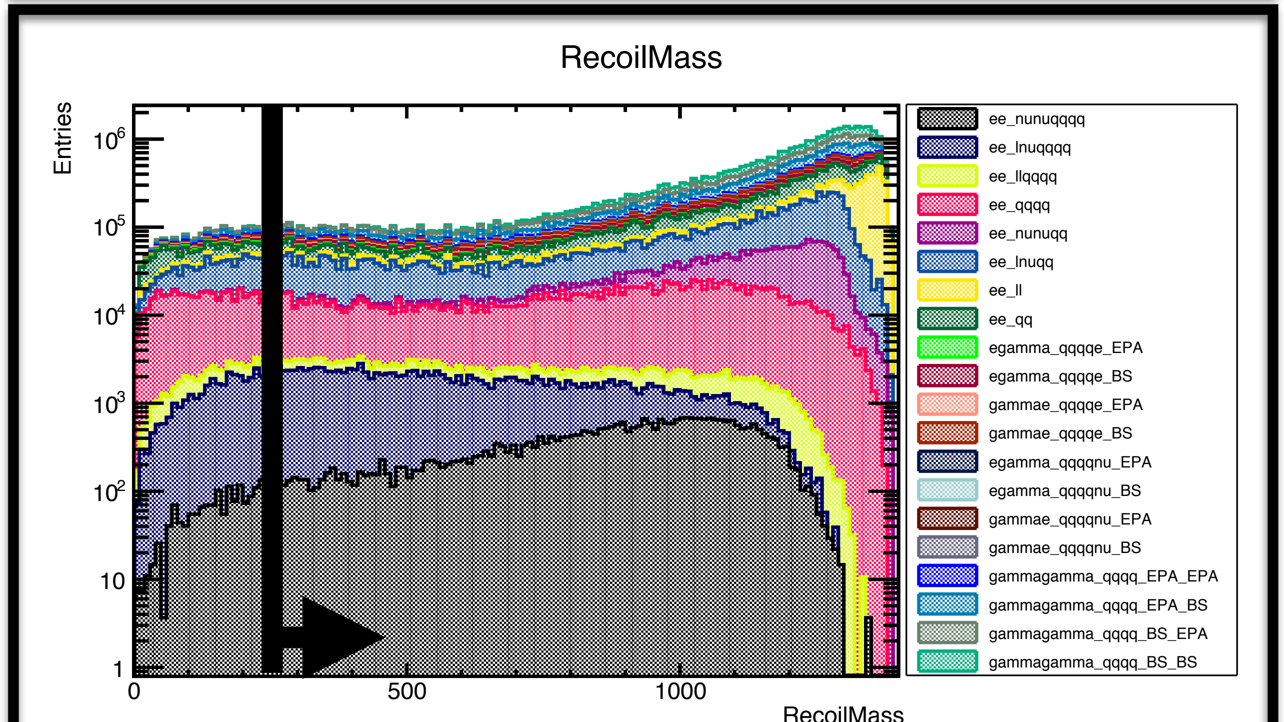
y34 < 3.5



p_T > 40 GeV

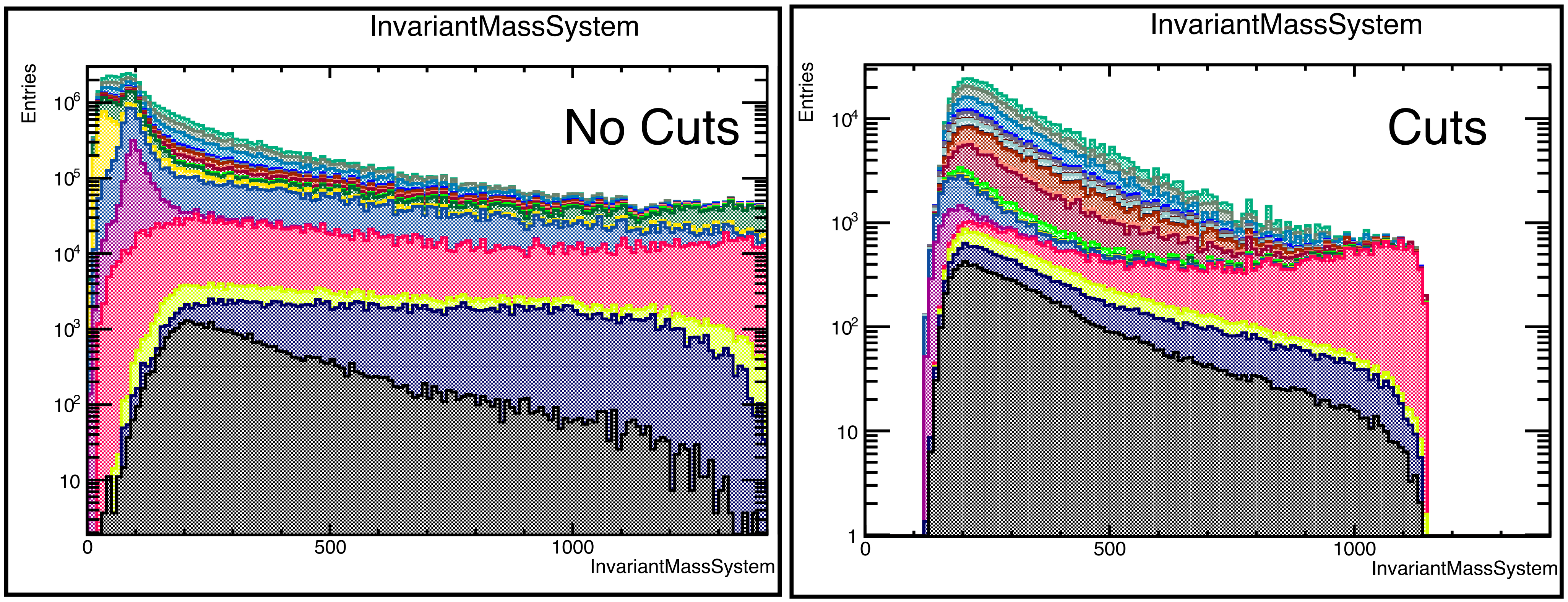


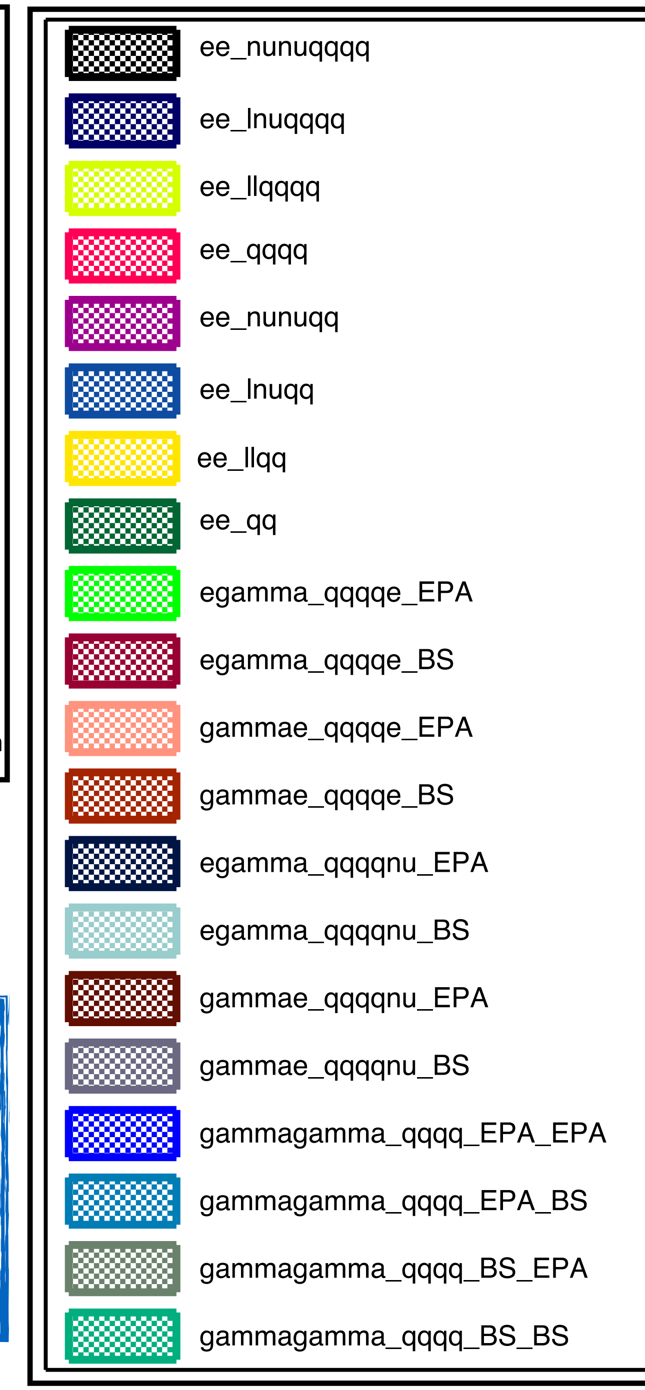
E_T > 150 GeV



M_{Recoil} > 250 GeV

Impact of PreSelection Cuts



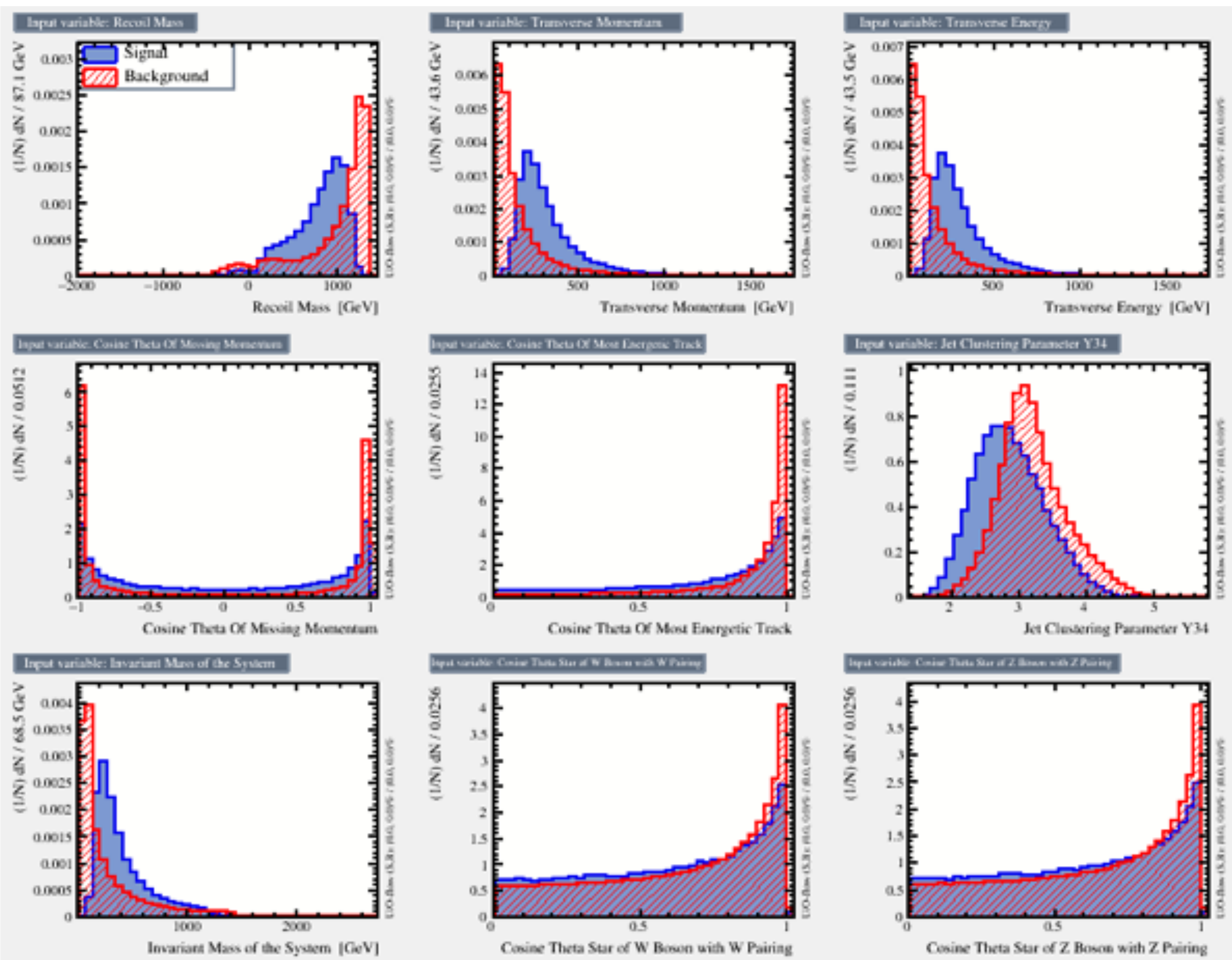


- The pre selection cuts look reasonable for an initial step.
  - Optimisation of these cuts and the inclusion of more is most on the todo list.
- However, due to the large number of remaining backgrounds it will be necessary to apply MVA.

TMVA First Look - Variable Choice

- I applied the BDT method in TMVA on the signal and backgrounds defined on slide 6.
- Initially I've trained using the variables defined in this table:
- Need to include the preselection cuts in training.

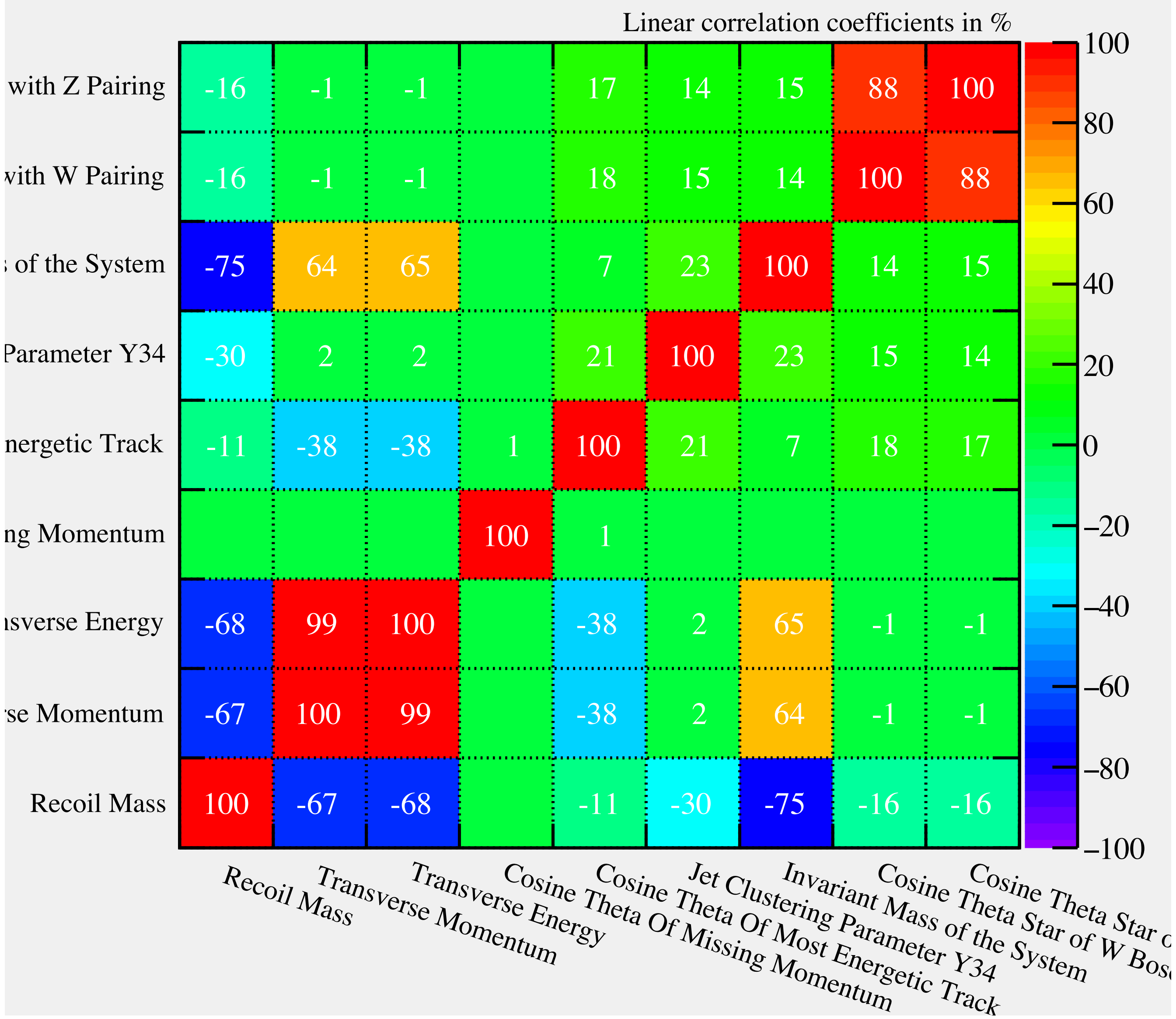
Variable	Description
M_{Recoil}	Recoil mass
P_t	Transverse Momentum
E_t	Transverse Energy
$Cos\theta_{Mis}$	Cosine theta of missing momentum
$Cos\theta_{Track}$	Cosine theta of highest energy track
Y34	Jet clustering variable
Invariant Mass	Invariant Mass of the System
$Cos\theta_W^*$	Cosine theta of W in reference frame of WW (W pairing)
$Cos\theta_Z^*$	Cosine theta of Z in reference frame of ZZ (Z pairing)



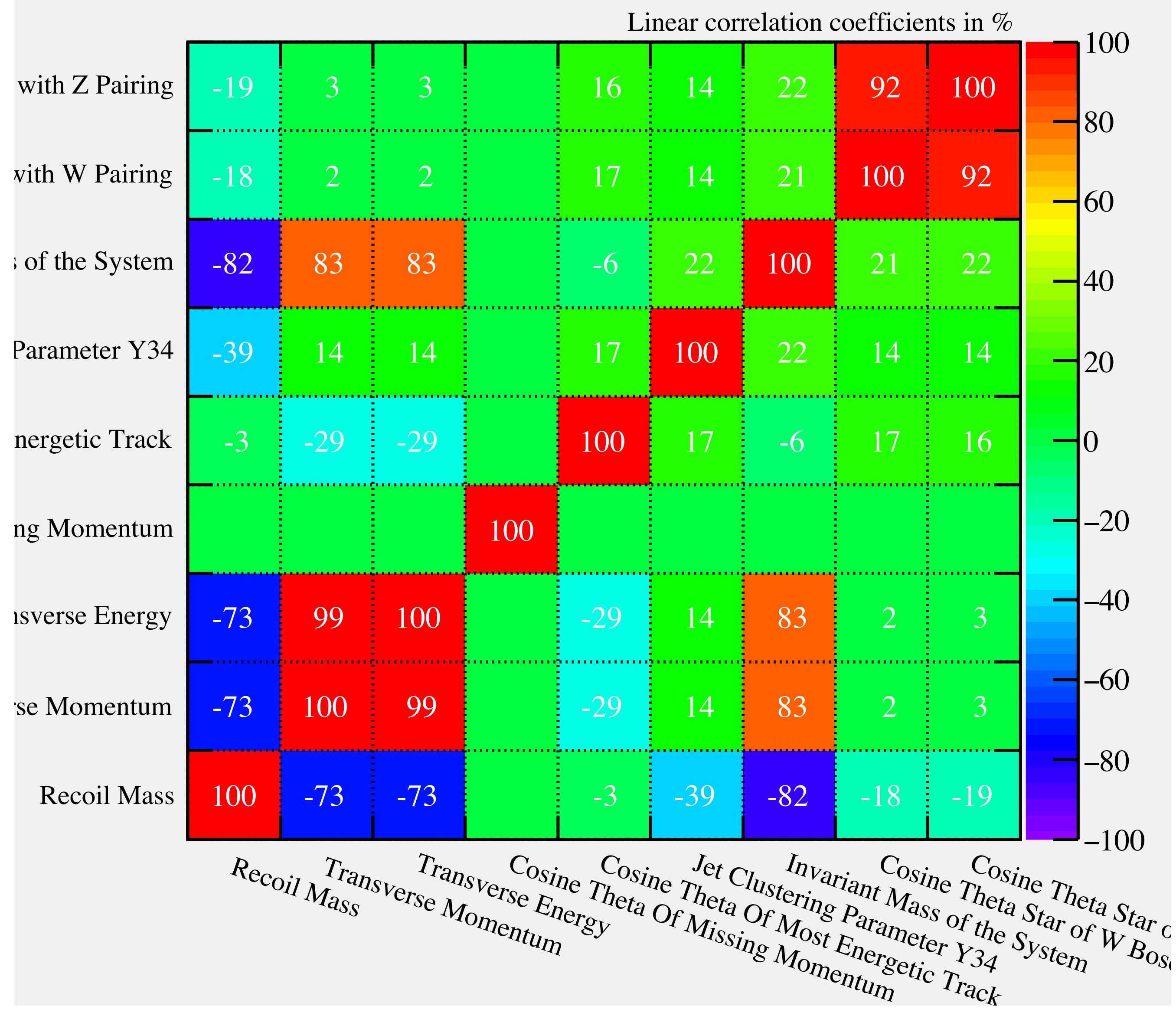
- Some don't have much distinguishing power.

TMVA First Look - Correlations and Significance

Correlation Matrix (signal)

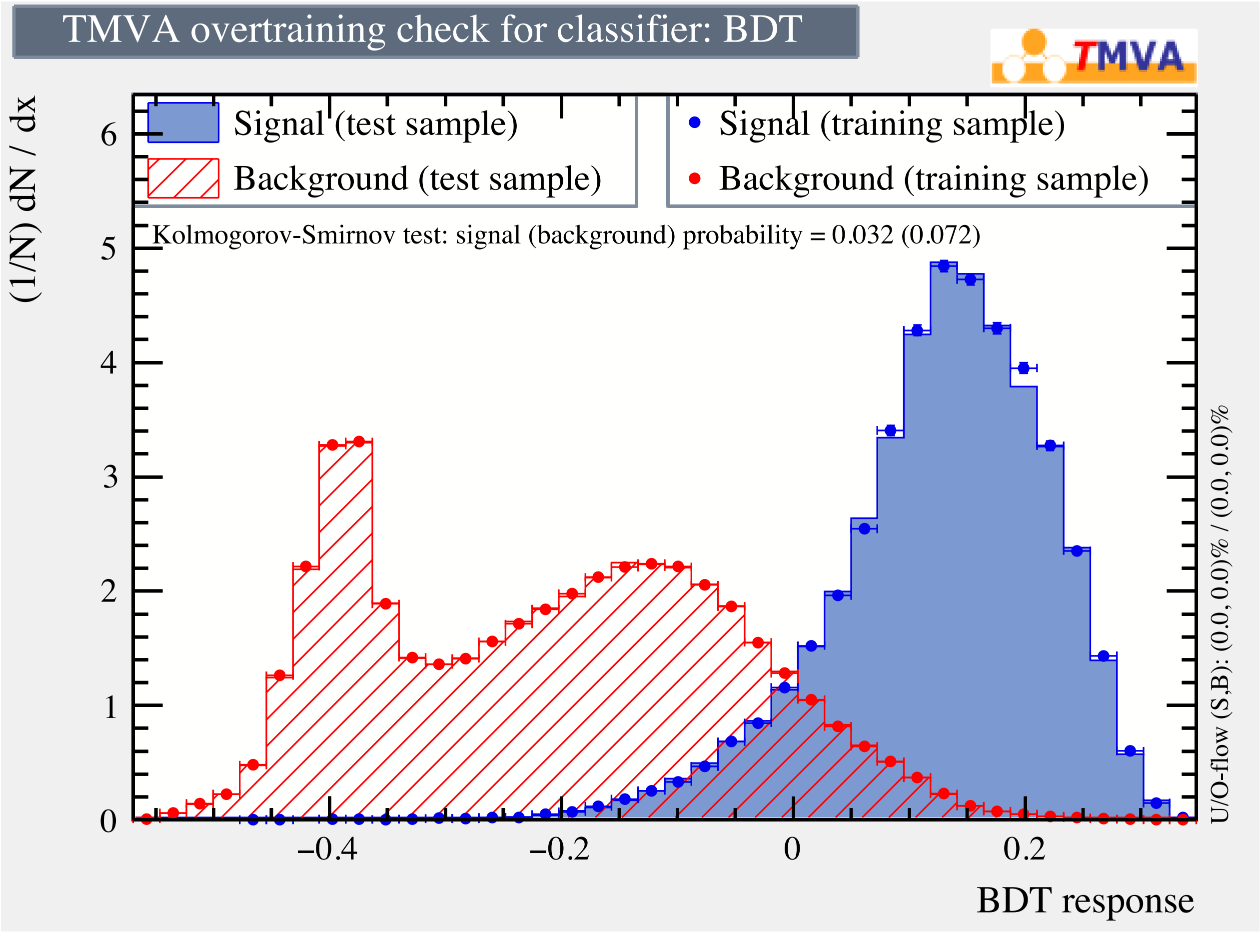


Correlation Matrix (background)

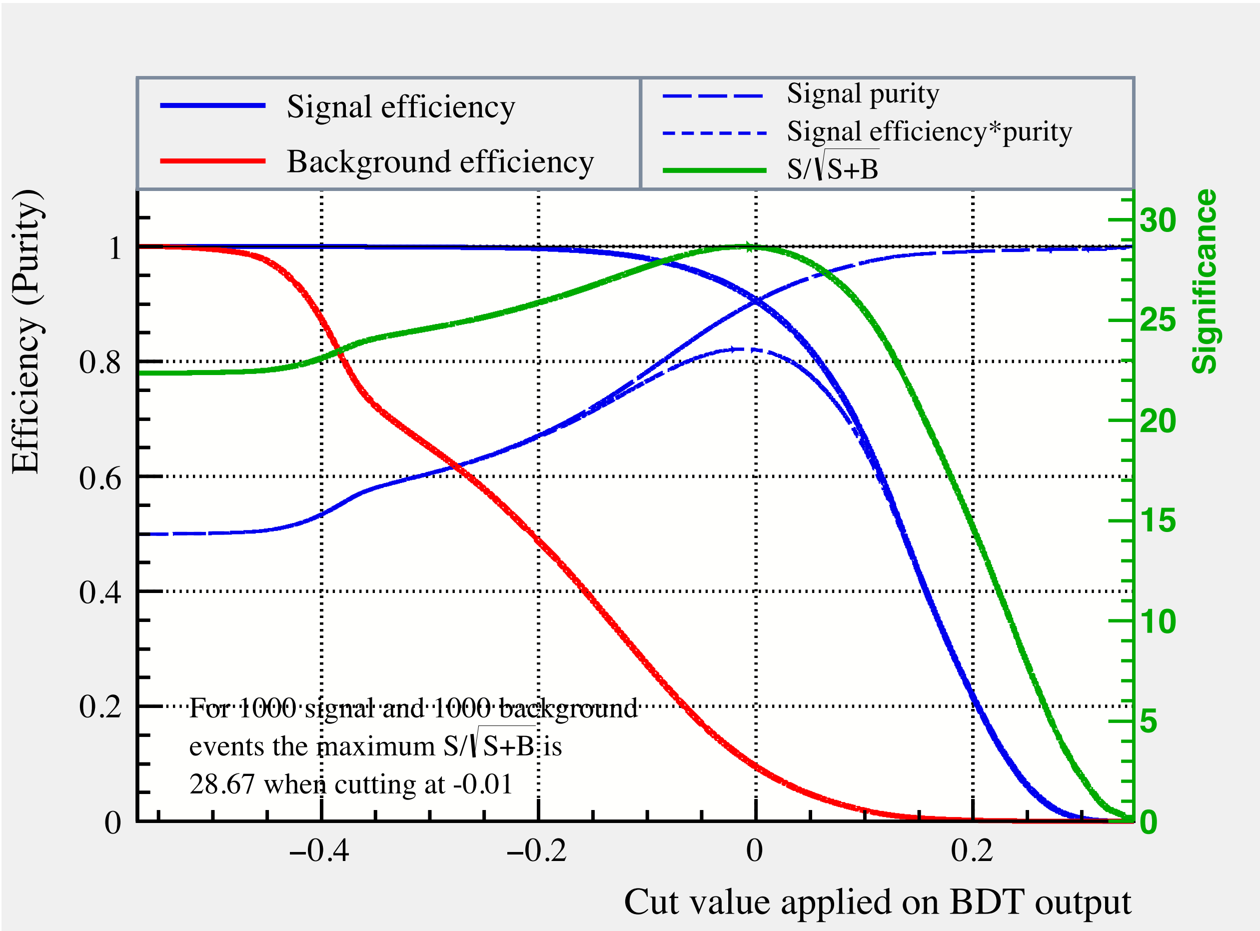


Some variables highly correlated so can remove some variables.

TMVA First Look - Significance



- On the positive side there appears to be no trouble with overtraining or lack of samples when training.



- There also appears a reasonable separation of signal and background even with these variables.
- However, this may be due to lack of preselection cuts.

Conclusions

- Samples of qqqqvv events where the event weight for non-zero anomalous couplings can be calculated have been generated and appear to be consistent with the existing CLIC samples.
- Event weights have been calculated for this qqqqvv sample and can be easily applied at the analysis stage.
- Background samples have been included in this study, but need
- There are still many areas where this analysis needs to be developed. Those on the todo list are:
  - Apply MVA results to likelihood fit.
  - Continue to develop selection cuts / TMVA approach.
  - Find other distributions sensitive to α_4 and α_5 to use in likelihood fit.
  - Jet clustering parameter optimisation.
  - PFO selection optimisation (loose, tight or selected).

Thank you for your attention!

Backup

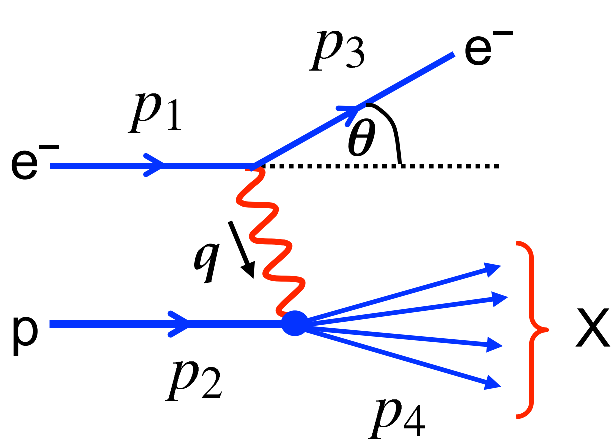
Whizard Setup Details

Whizard Setup

- α_s is set to 10^{-6} to stop radiation of gluons.
- Fragmentation/hadronisation parameters in pythia opal tuned. Hadronisation performed using PYTHIA (opposed to JETSET) interfaced to Tauola.
- 1.4 TeV to start with.
- Default cuts* see next slide
- Usual CLIC configuration otherwise:
  A. ISR on. ISR_m_in = 0.000511 (electron/positron mass). ISR_alpha = 0.0072993 (fine structure constant).
  B. User defined luminosity spectrum on and different ones for 1.4 TeV (19) and 3 TeV (11). Taken from /ilc/prod/software/beam_specta and using version 7 (latest and was recommended).
  C. Masses*

Default Cuts

- default_jet_cut : 10 GeV → "The default invariant mass cut in GeV applied to pairs of massless coloured particles."
- default_mass_cut : 4 GeV → "The default invariant mass cut in GeV applied to pair production of massless colourless charged particles and to photon emission."
- default_energy_cut : 10 GeV → "The default energy cut in GeV applied to photon and gluon emission."
- default_q_cut : 4 GeV → "The default Q cut in GeV applied to photon and gluon exchange."

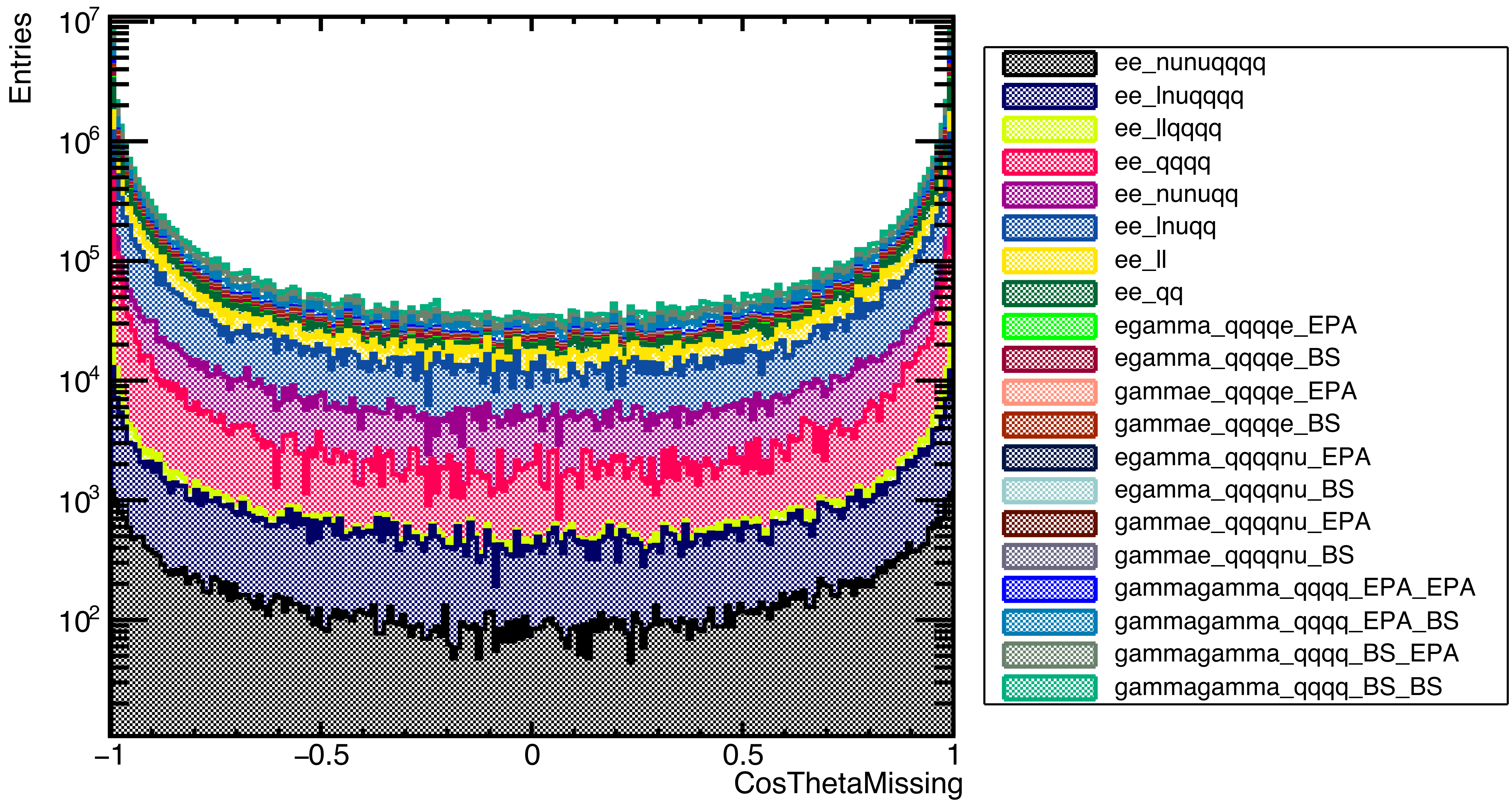


$$Q^2 \equiv -q^2$$

Raw Distributions of Signal + Background Samples

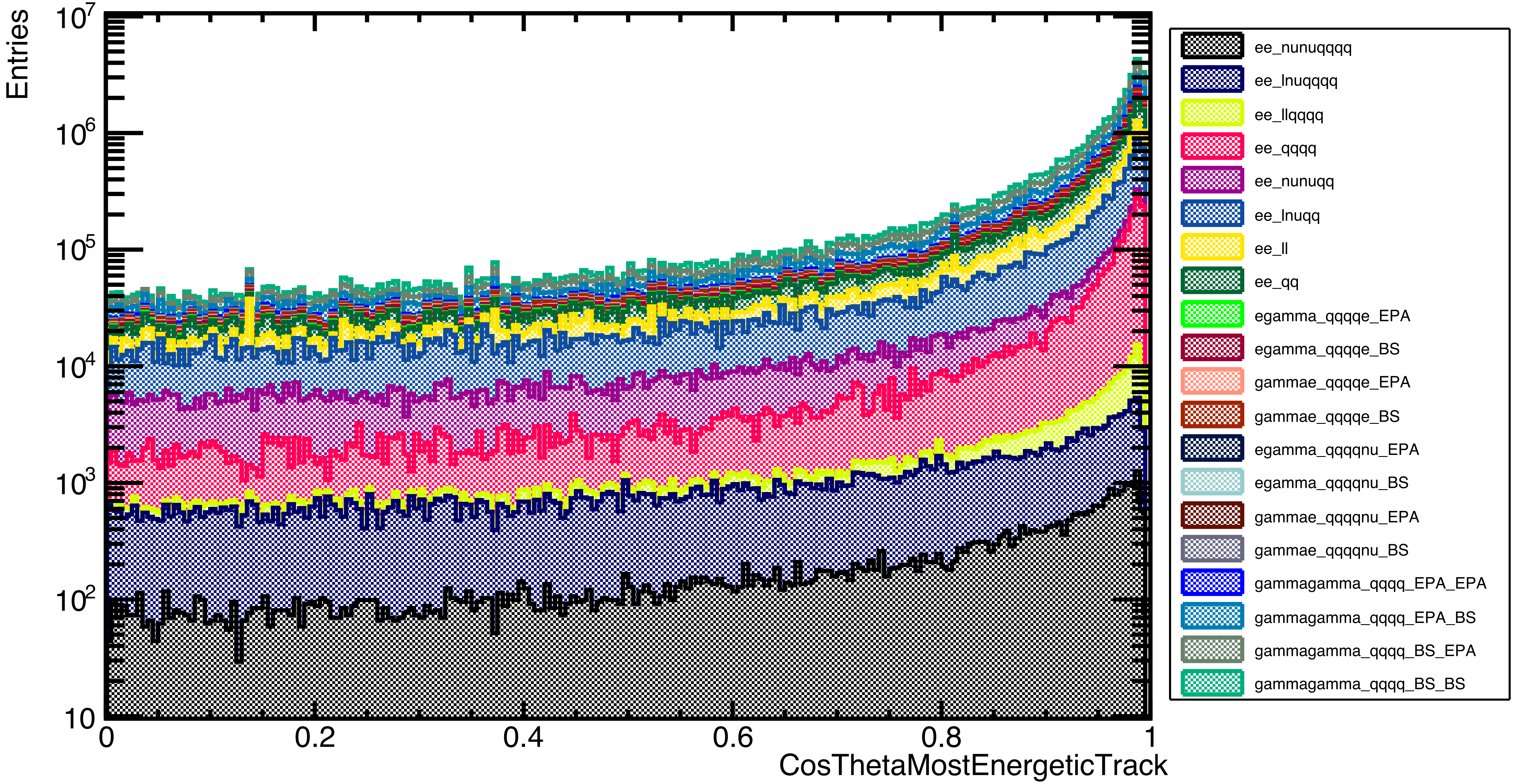
Please note: Samples labelled ee_ll in following slides are in fact ee_qqll!

CosThetaMissing



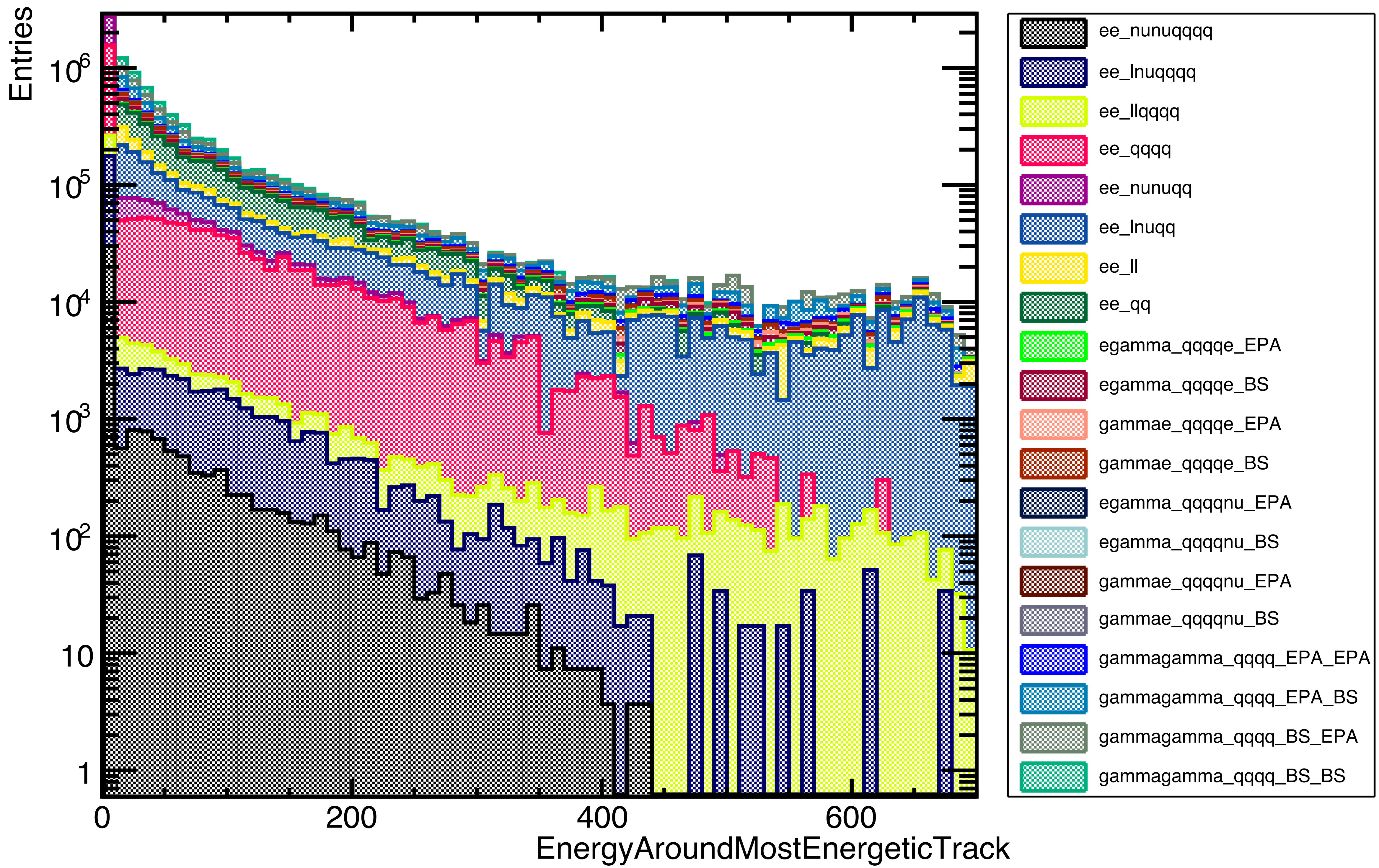
$\text{Abs}(\text{Cos}(\theta_{\text{Missing}})) < 0.99$

CosThetaMostEnergeticTrack



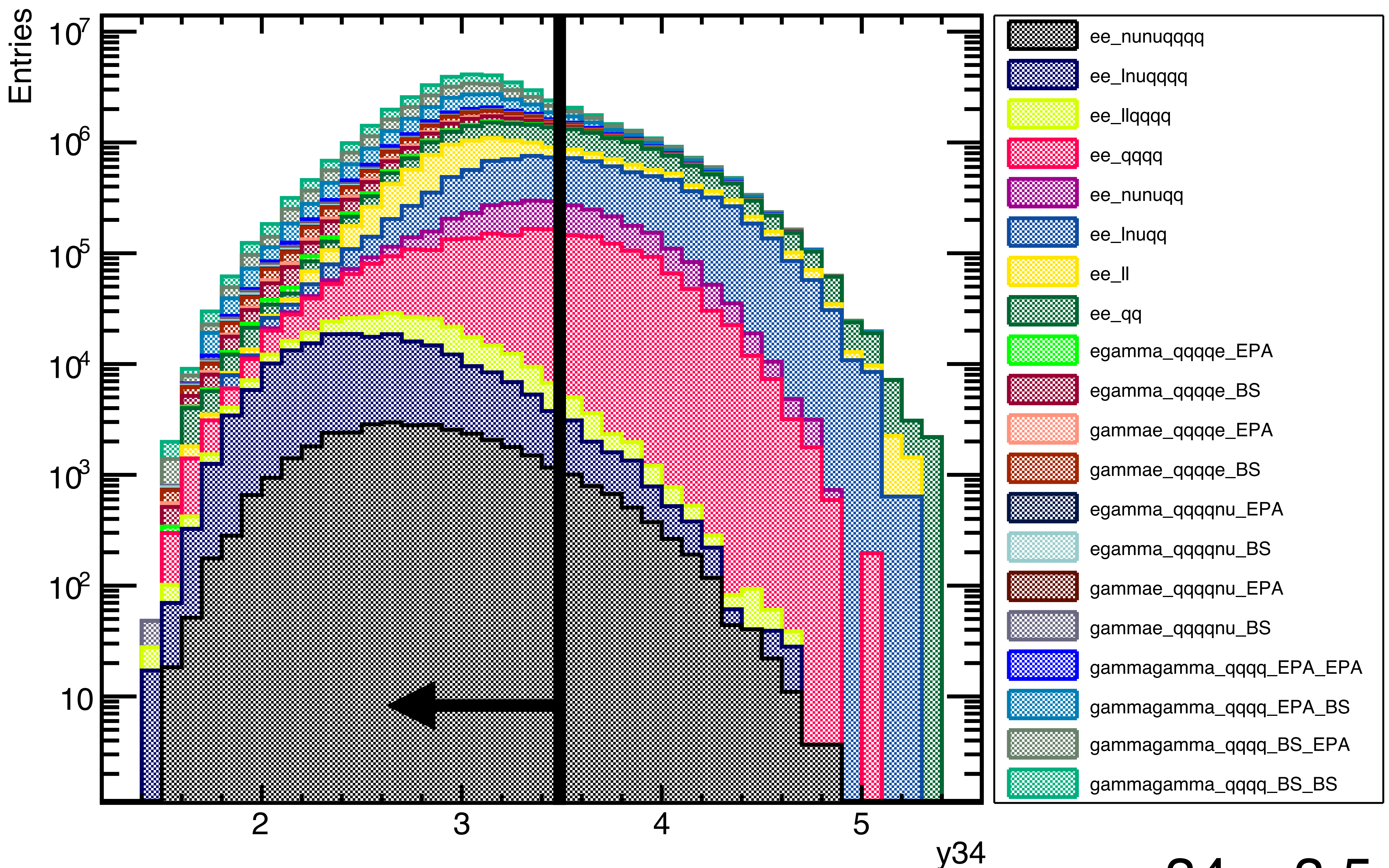
$$\text{Abs}(\text{Cos}(\theta_{\text{MostEnergeticTrack}})) < 0.99$$

EnergyAroundMostEnergeticTrack



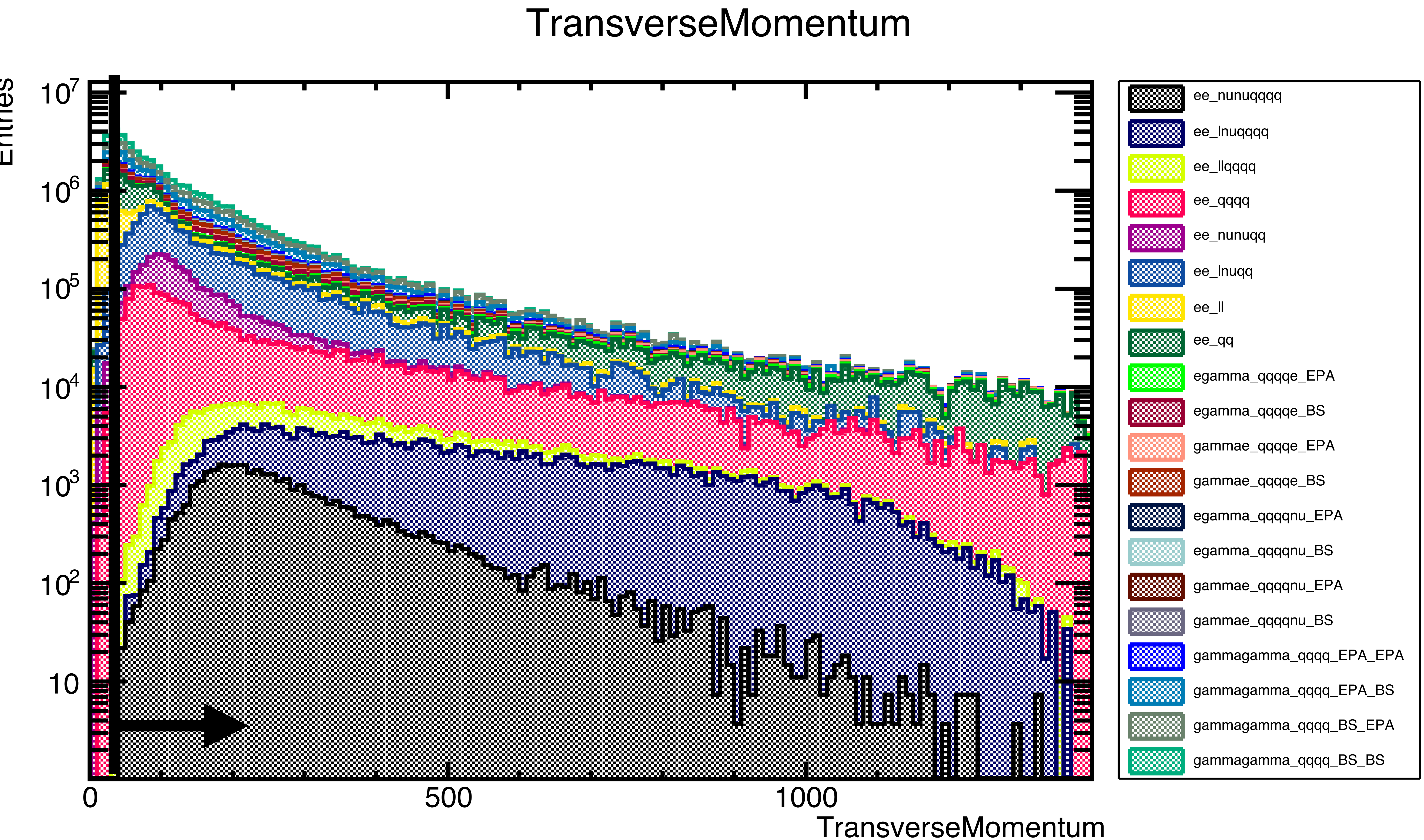
EnergyAroundMostEnergeticTack > 2 GeV

y34



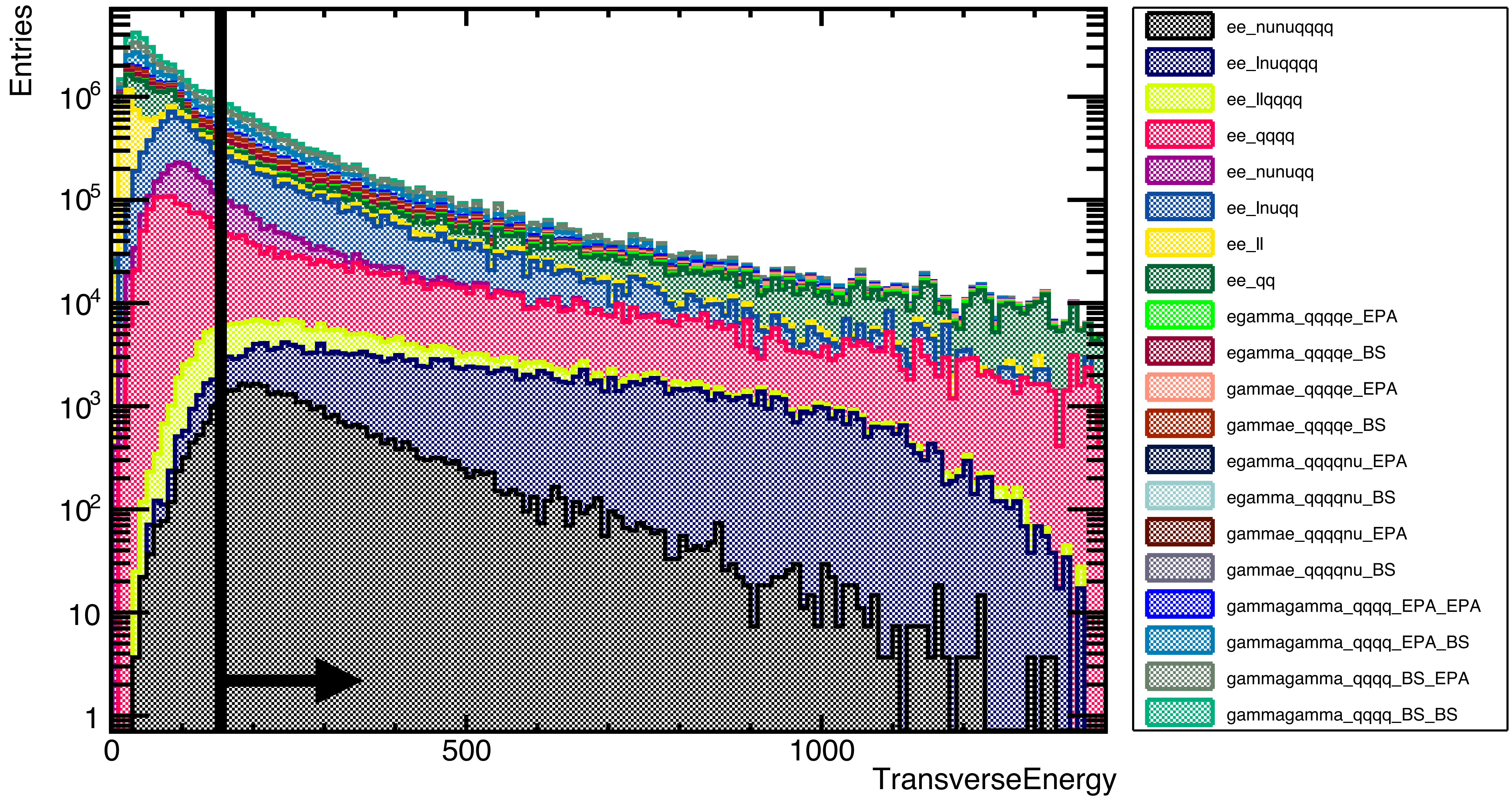
y34
Entries
10^7
10^6
10^5
10^4
10^3
10^2
10
2
3
4
5
y34
ee_nunuqqqq
ee_lnuqqqq
ee_llqqqq
ee_qqqq
ee_nunuqq
ee_lnuqq
ee_ll
ee_qq
egamma_qqqqe_EPA
egamma_qqqqe_BS
gammae_qqqqe_EPA
gammae_qqqqe_BS
egamma_qqqqnu_EPA
egamma_qqqqnu_BS
gammae_qqqqnu_EPA
gammae_qqqqnu_BS
gammagamma_qqqq_EPA_EPA
gammagamma_qqqq_EPA_BS
gammagamma_qqqq_BS_EPA
gammagamma_qqqq_BS_BS

y34 < 3.5

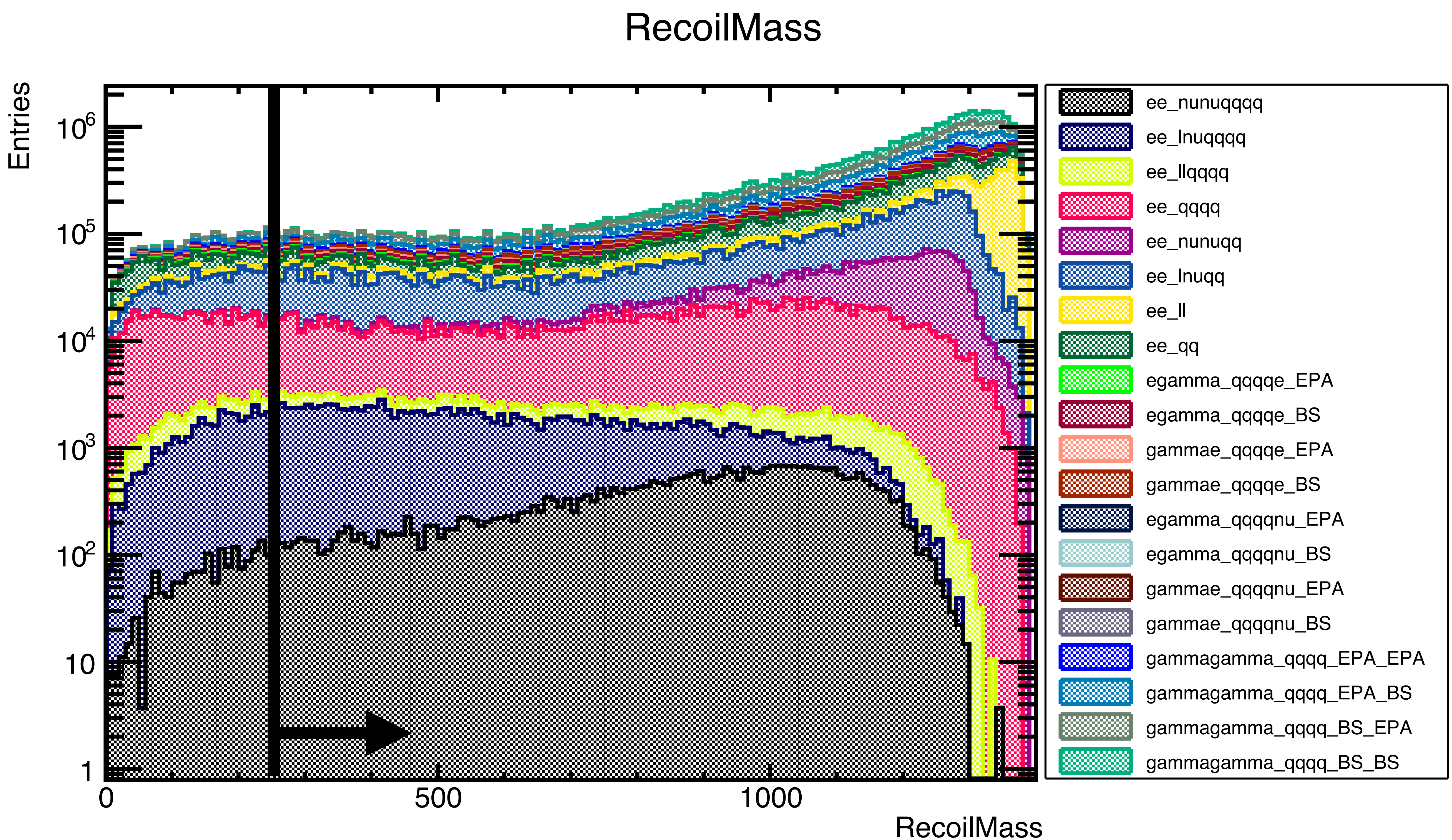


Transverse Momentum > 40 GeV

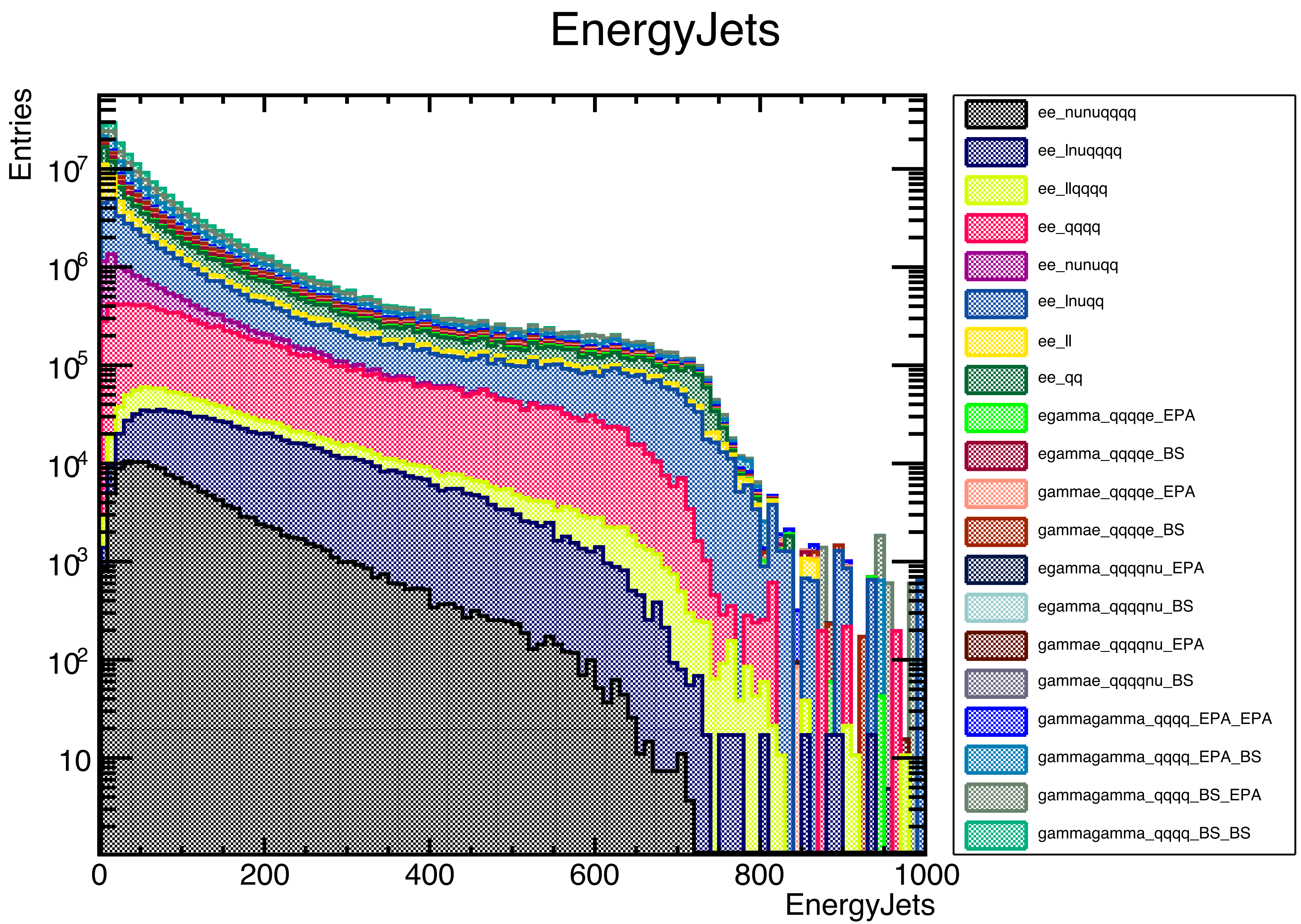
TransverseEnergy



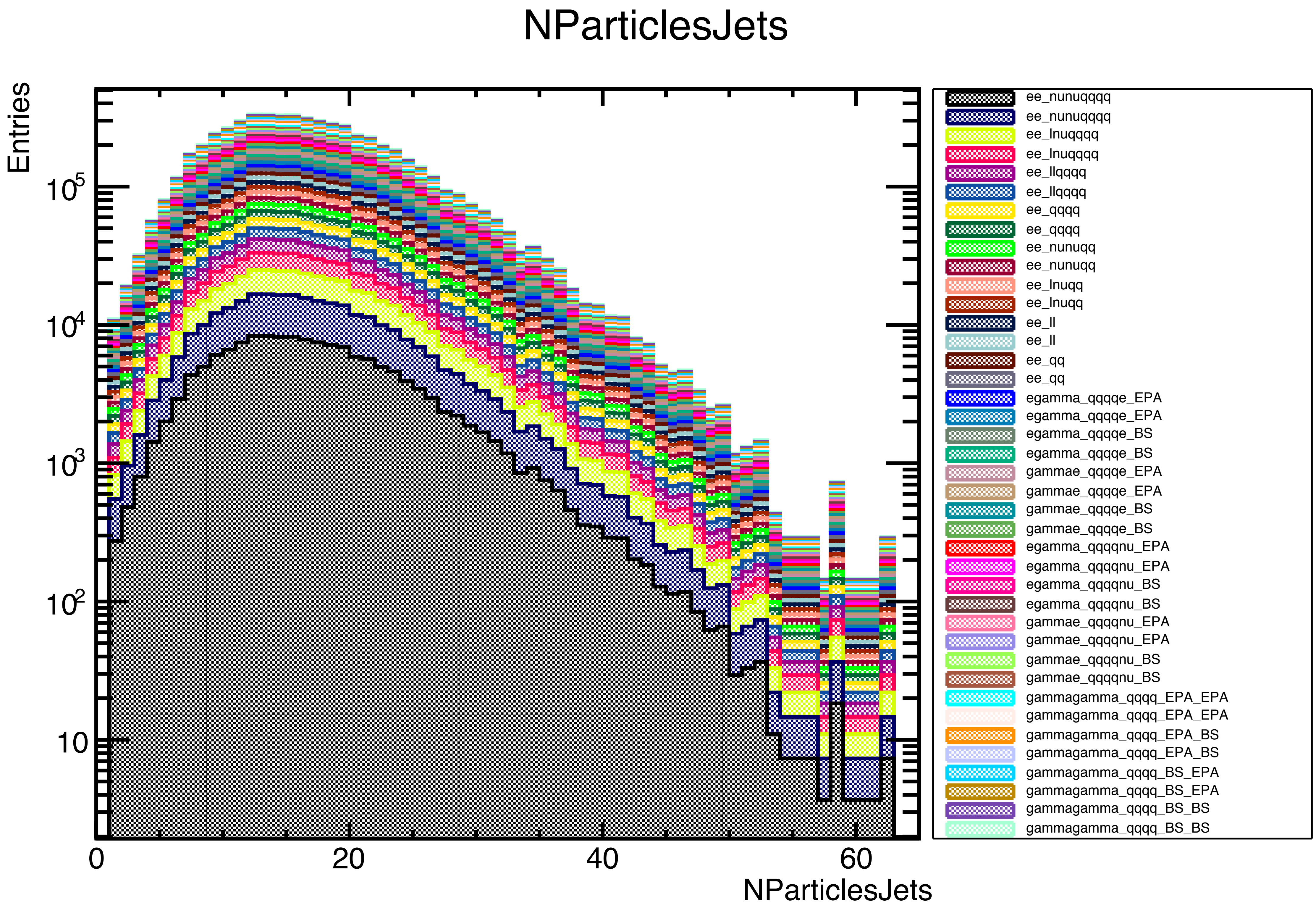
Transverse Energy > 150 GeV



Recoil Mass > 250 GeV



Energy in all jets in event > 10 GeV



Number of Particles in Any Jet > 3

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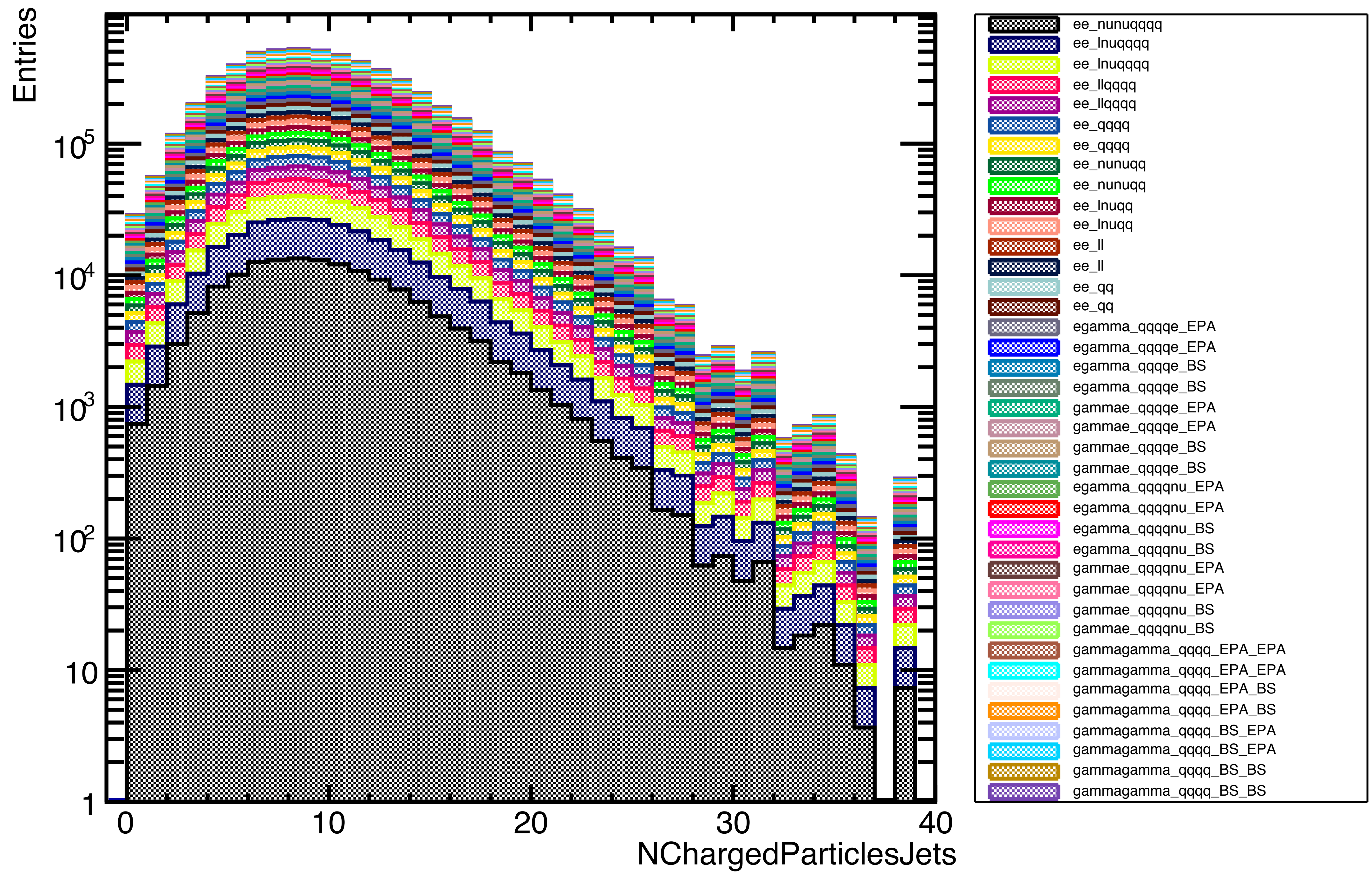
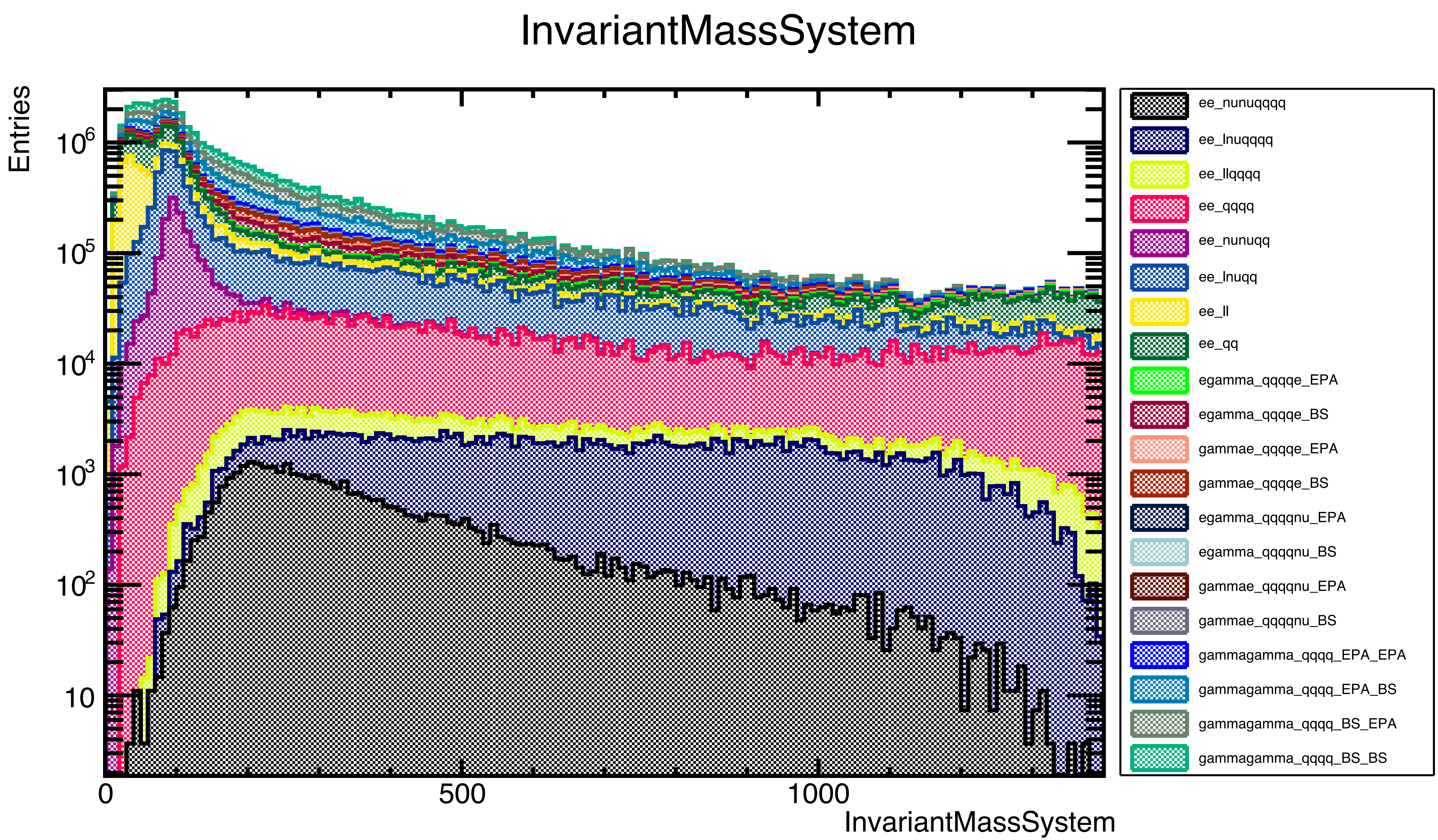
NChargedParticlesJets



Number of Charged Particle in Any Jet > 2


InvariantMassSystem
Entries
10^6
10^5
10^4
10^3
10^2
10
0
500
1000
InvariantMassSystem
ee_nunuqqqq
ee_lnuqqqq
ee_llqqqq
ee_qqqq
ee_nunuqq
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ee_qq
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gammae_qqqqe_EPA
gammae_qqqqe_BS
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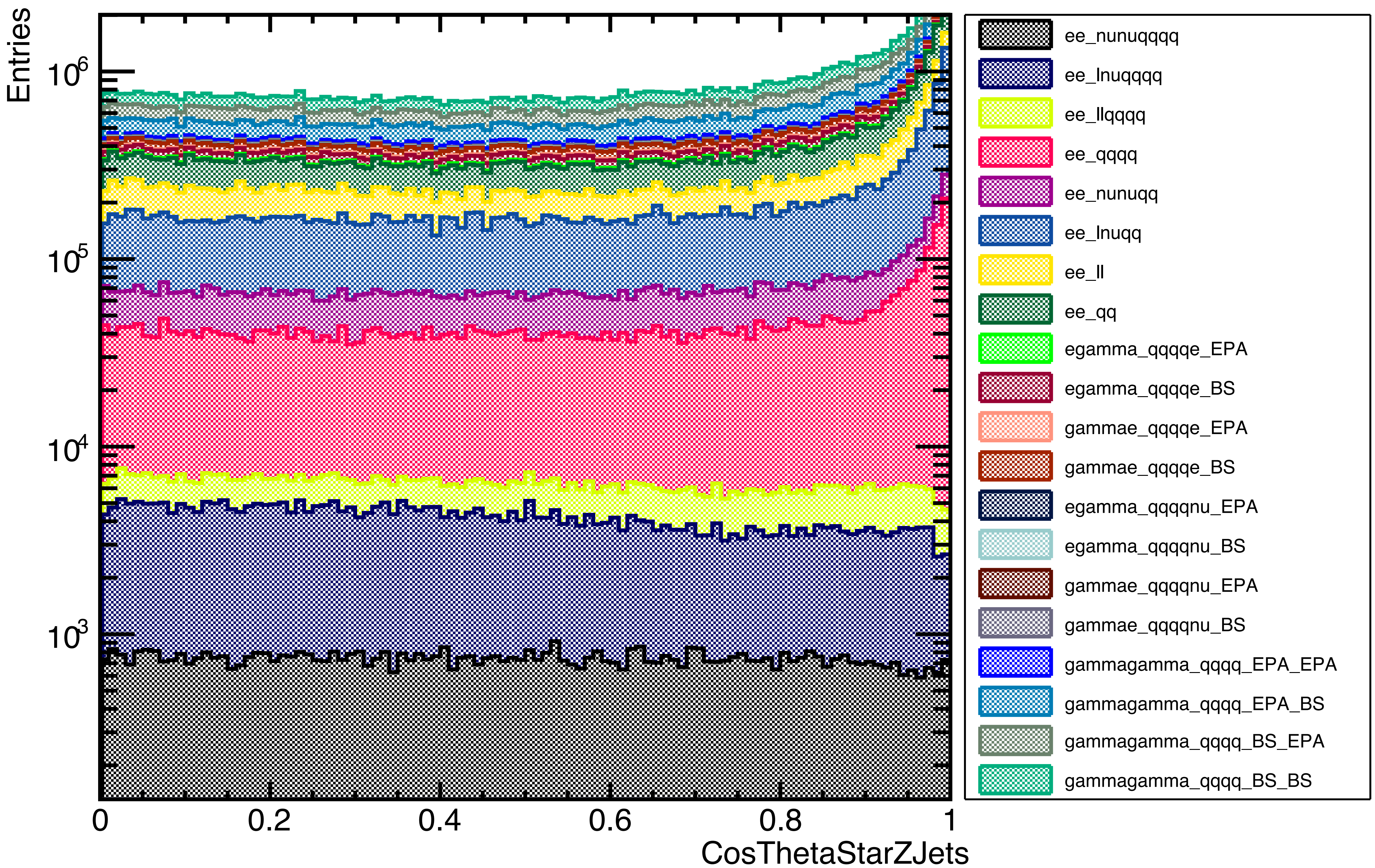
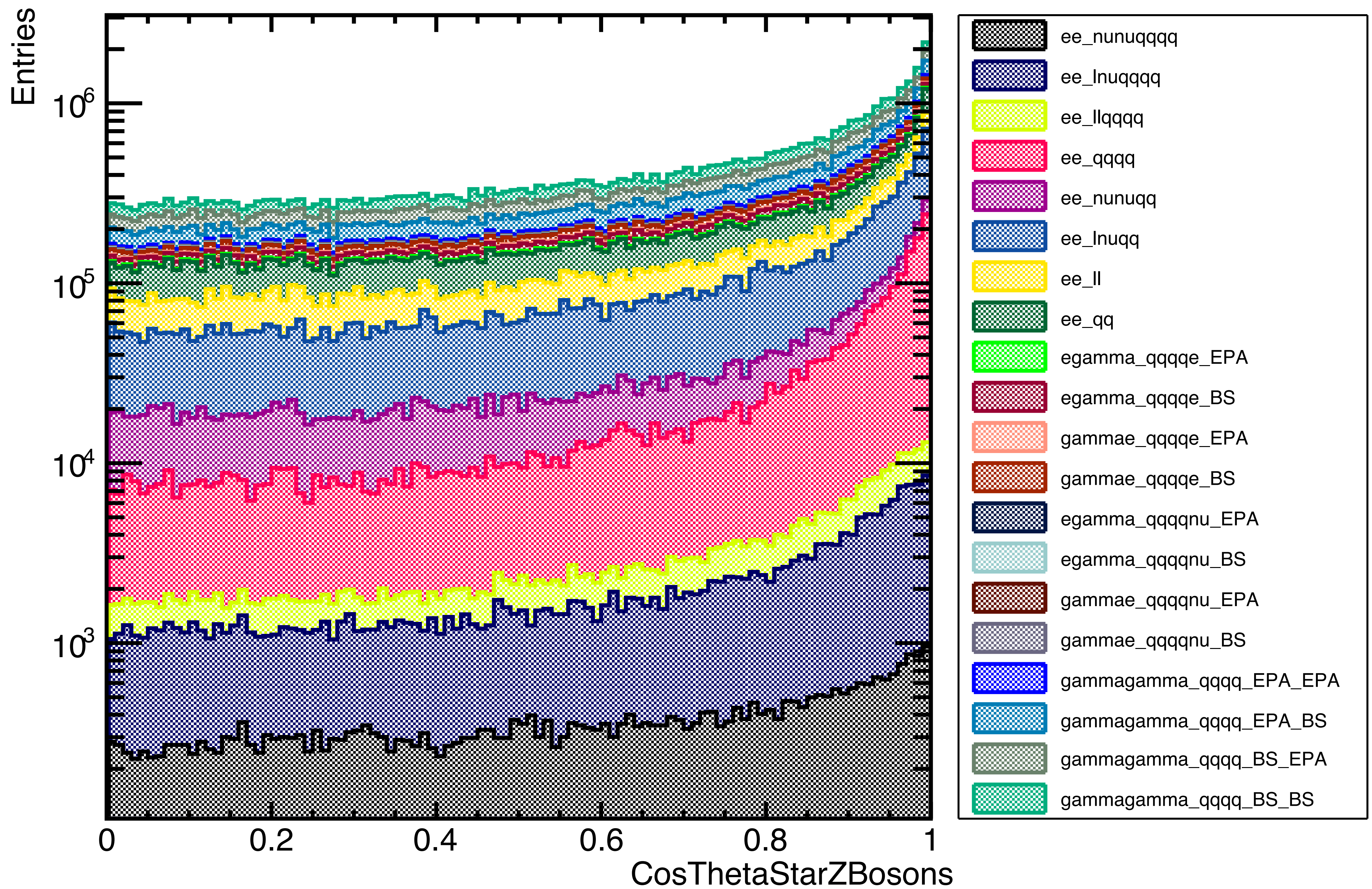
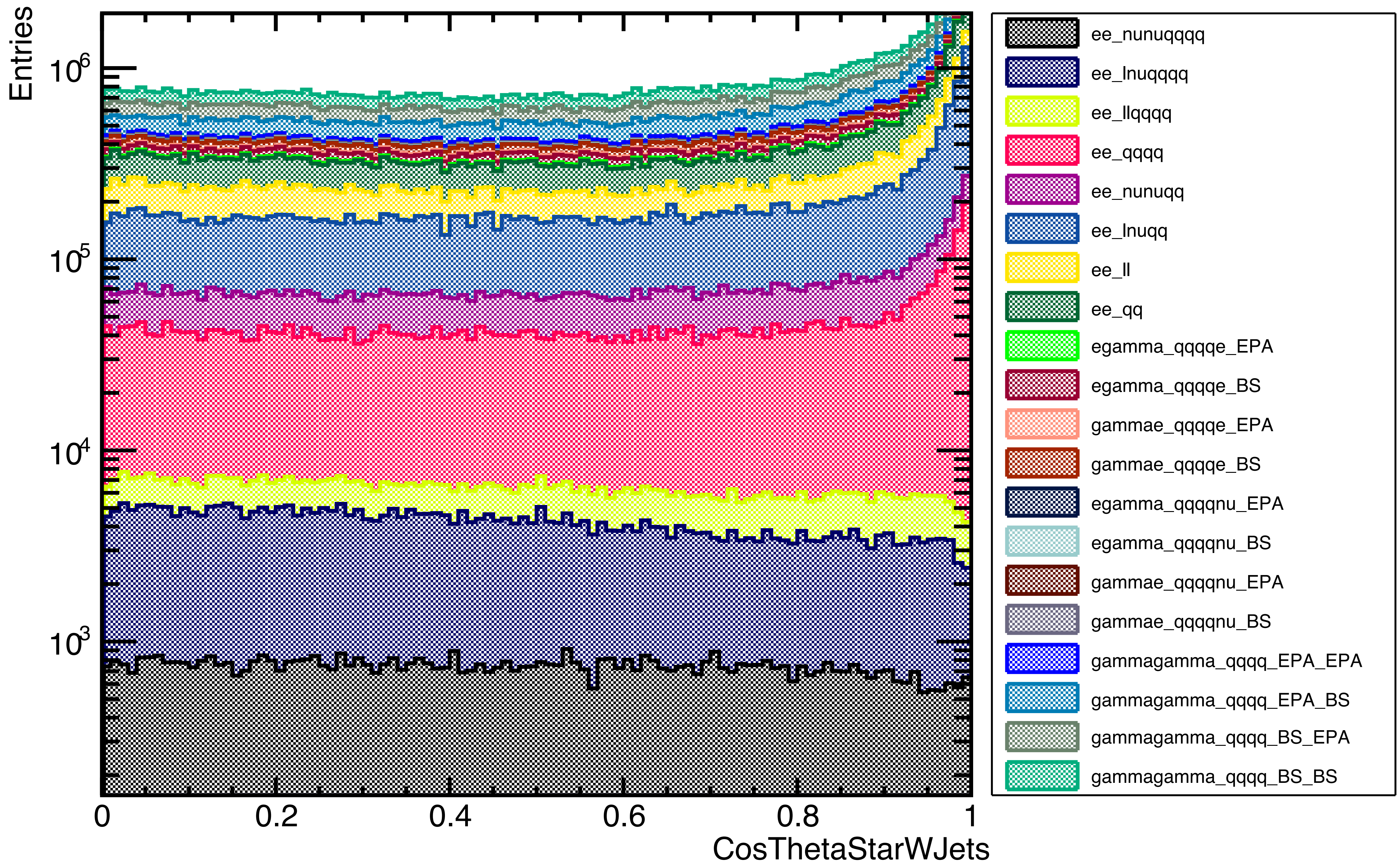
CosThetaStarZJets



CosThetaStarZBosons



CosThetaStarWJets



CosThetaStarWBosons