Separation of HH and HZ Final States Using Spin Correlations

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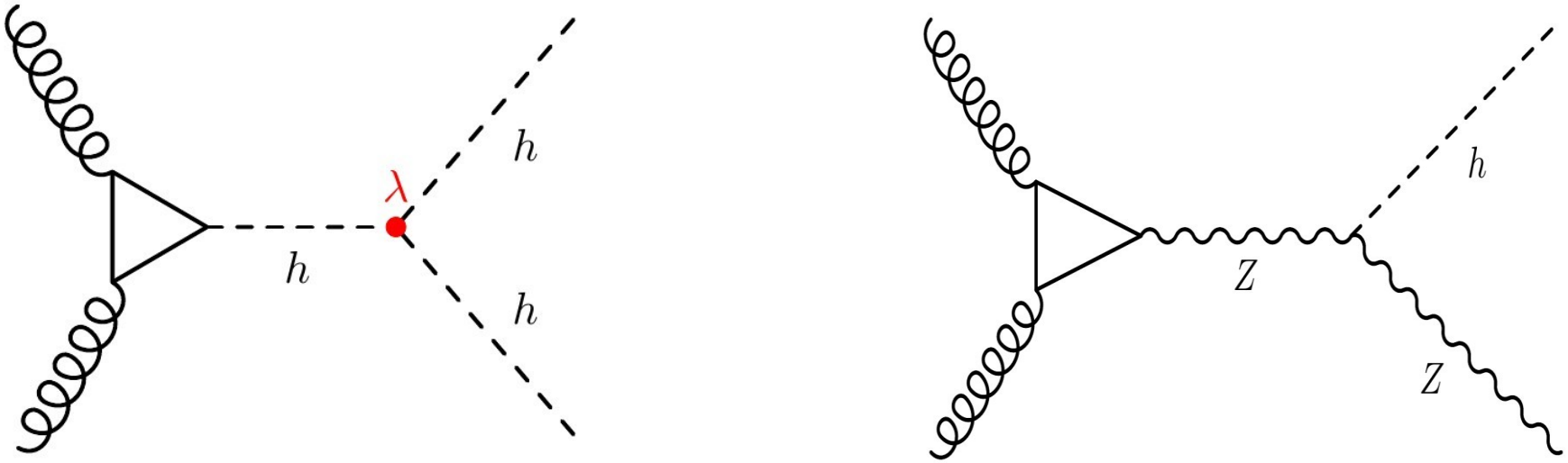
Background process

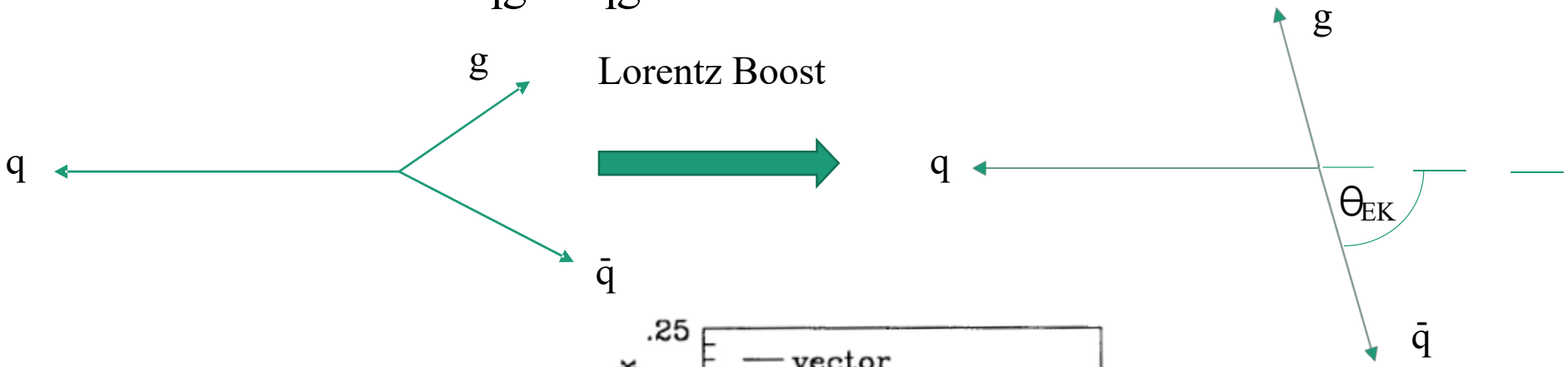


- HH and HZ kinematically very similar
- H is scalar particle: Spin 0
- Z has Spin 1
- Spin transfers to jets in final states

  ➡ correlation of angles

Ellis-Karliner Angle

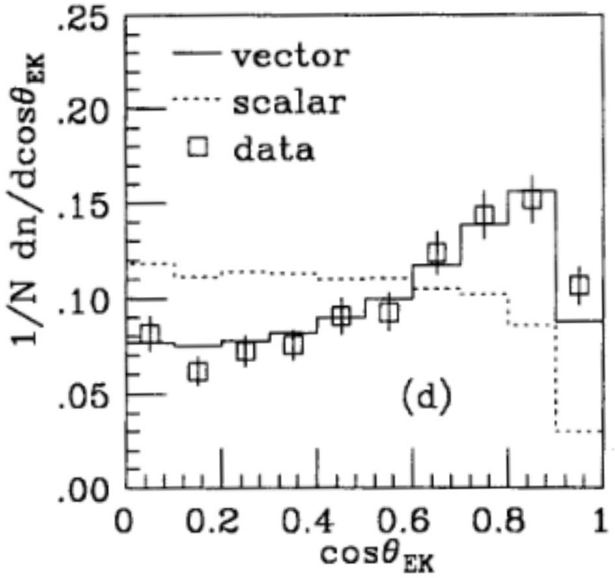
- An observable used for gluon spin: Ellis-Karliner Angle
- Angle between partons in $e^+e^- \rightarrow q\bar{q}g$ event
- Measured in restframe of $\bar{q}g$ or qg



- Formula for massless particles:

$$\cos\theta_{EK} = \frac{x_2 - x_3}{x_1} \quad \text{with}$$

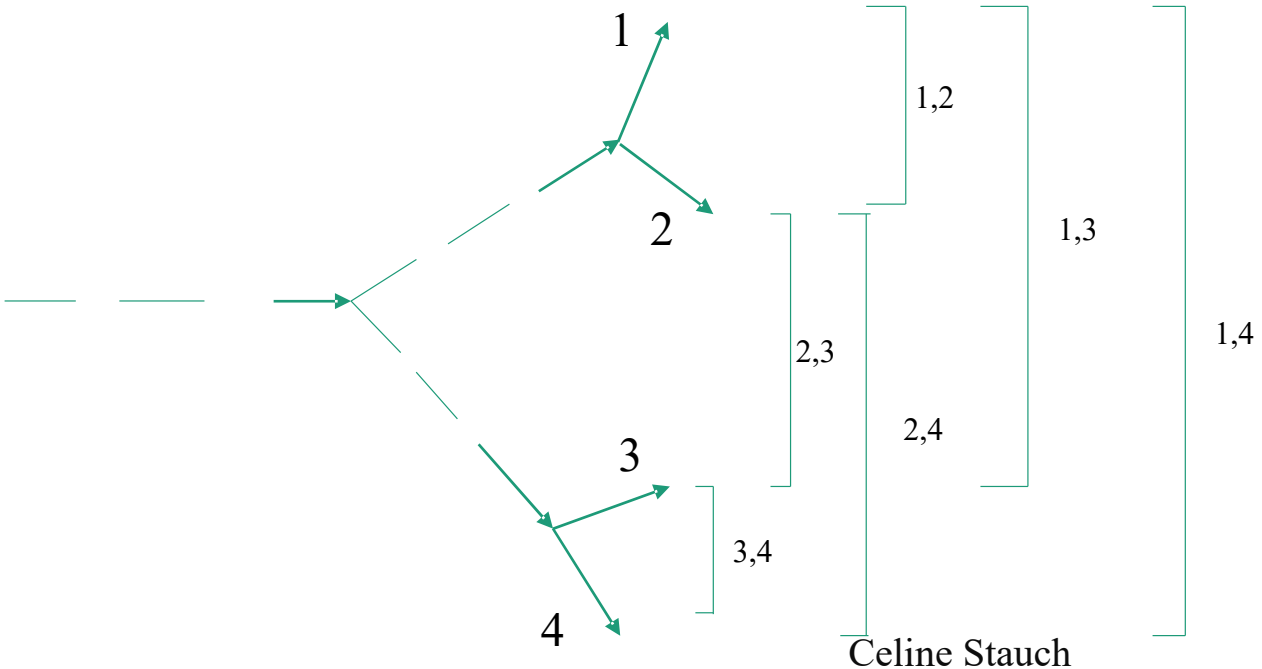
$$x_i = \frac{2E_i}{E_{cm}}$$



Ellis-Karliner Angle: Modification

➡ Use jets to represent partons in $\cos\theta_{EK}$

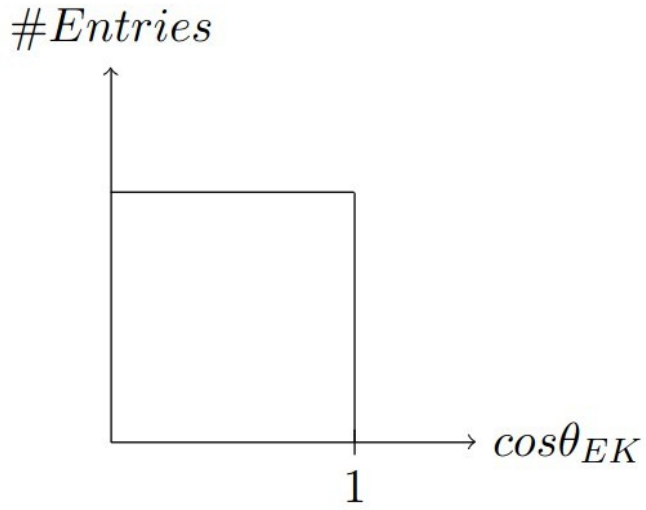
- Apply Lorentz transformation explicitly (ROOT EK)
  - ➢ Consider all possible combinations of two jets forming a H or Z
  - ➢ Choose option closest in mass to H or Z
  - ➢ Boost back to rest frame



Ellis-Karliner Angle: HZ processes - Expectations

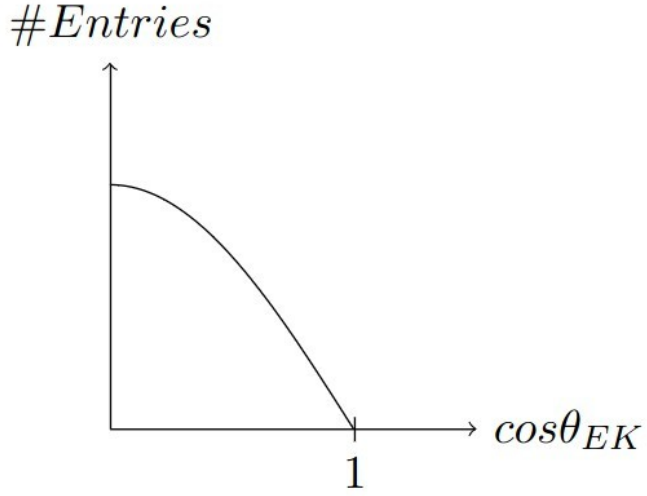
- Investigated using a generator level MC Simulation (ggHZ process in Powheg)
- Derive $\cos\theta_{EK}$ for jet pair which fits $H \rightarrow b\bar{b}$ or $Z \rightarrow b\bar{b}$ hypothesis best

Higgs Boson



→ expect box shaped distribution for scalar particle

Z Boson

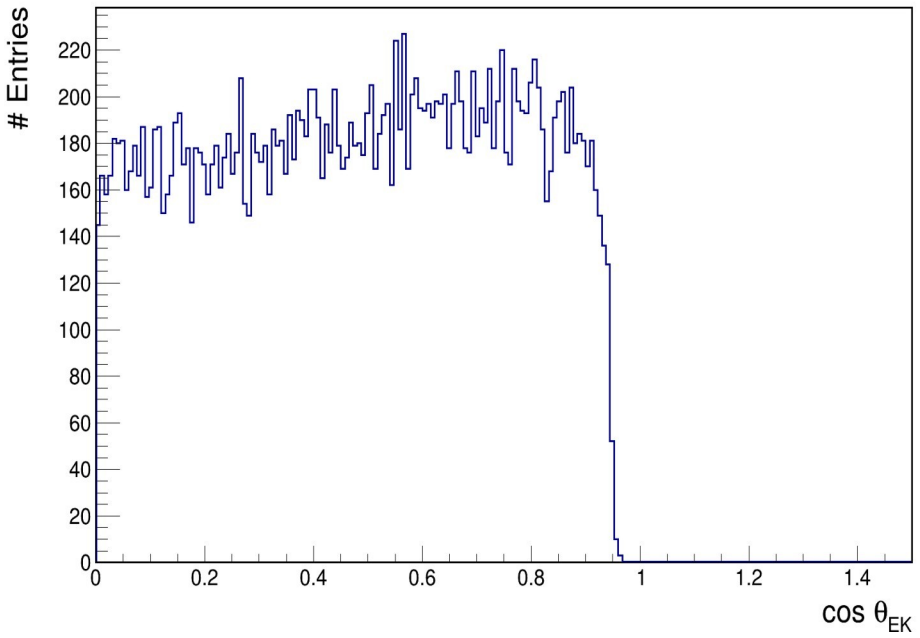


→ expect amount of entries to decrease towards end of phase space;
e.g. cosine shaped distribution

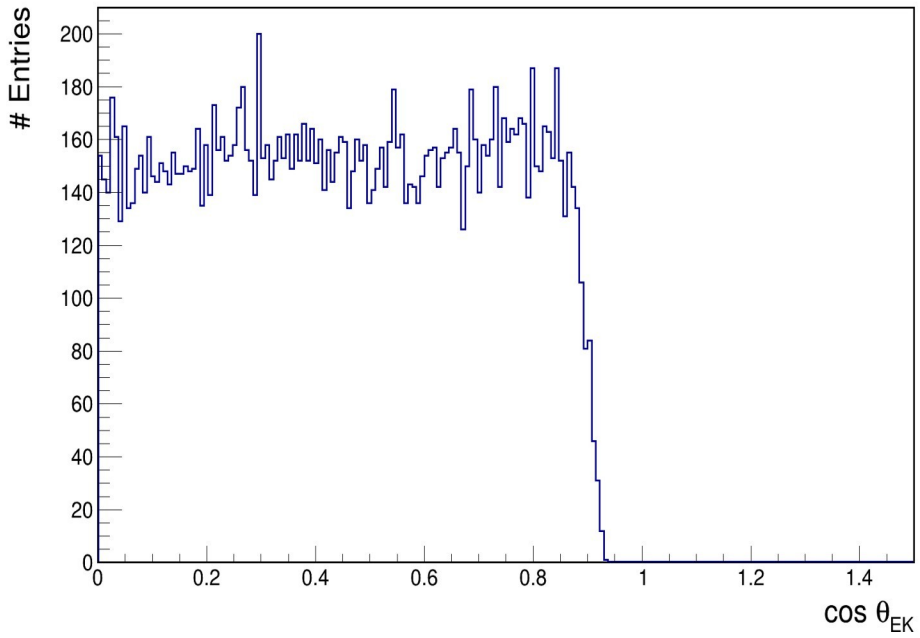
Ellis-Karliner Angle: HZ processes

➡ What are the results for a generator level MC Simulation?

Higgs Boson



Z Boson



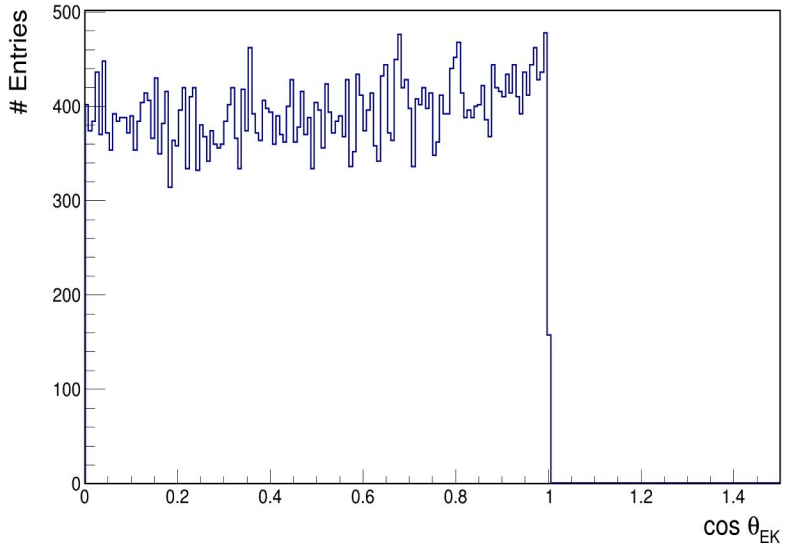
➡ Z Boson differs from expectations

Ellis-Karliner Angle: HZ processes on particle level

➡ Is the Information about spin correlation included in MC Simulation?

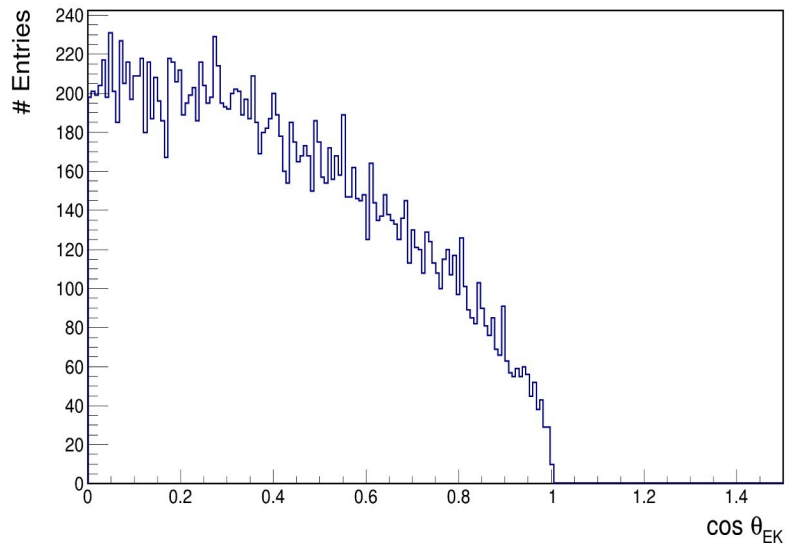
- Investigate $\cos\Theta_{EK}$ for first quark pair after decay of H and Z

Higgs Boson



➡ meets expectations of box shaped distribution for scalar particle

Z Boson



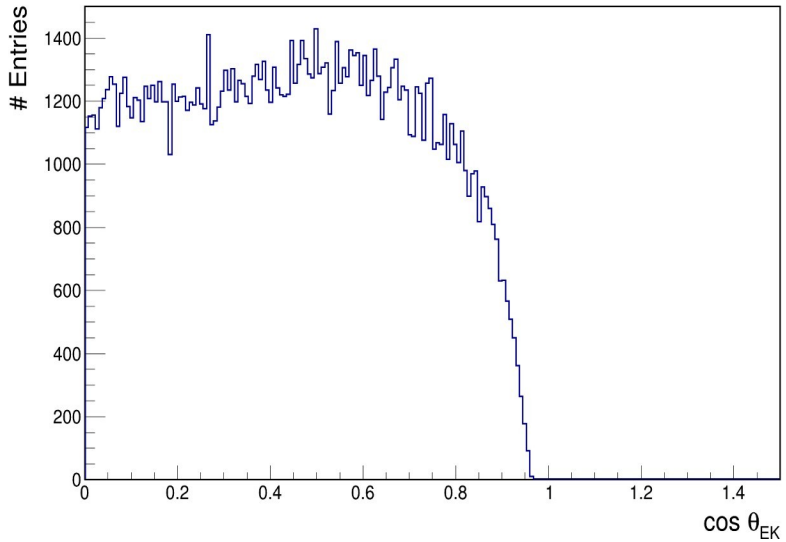
➡ meets expectations of decrease in entries towards end of phase space

➡ Spin information is encoded in decay particles of H and Z

Mimic b - tagging

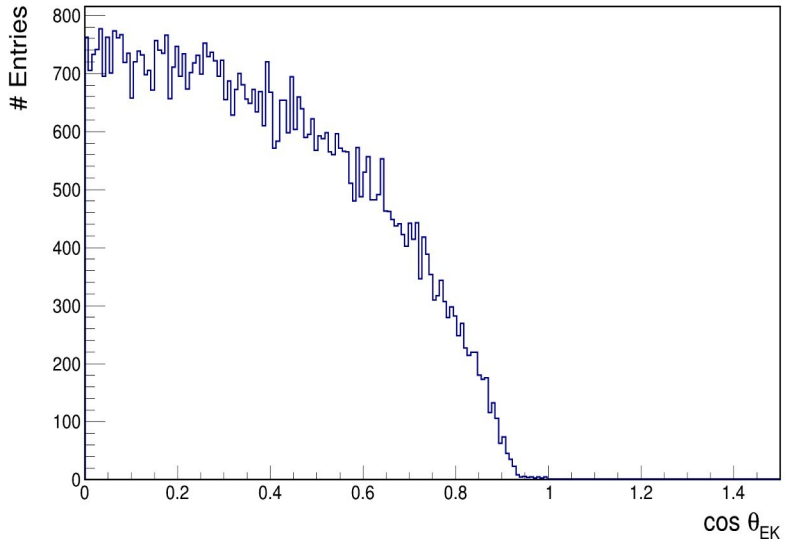
- Investigate spatial difference between jets and b quarks using $\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2}$
- Here: minimal spatial difference

Higgs Boson



→ meets expectations of box shaped distribution for scalar particle

Z Boson

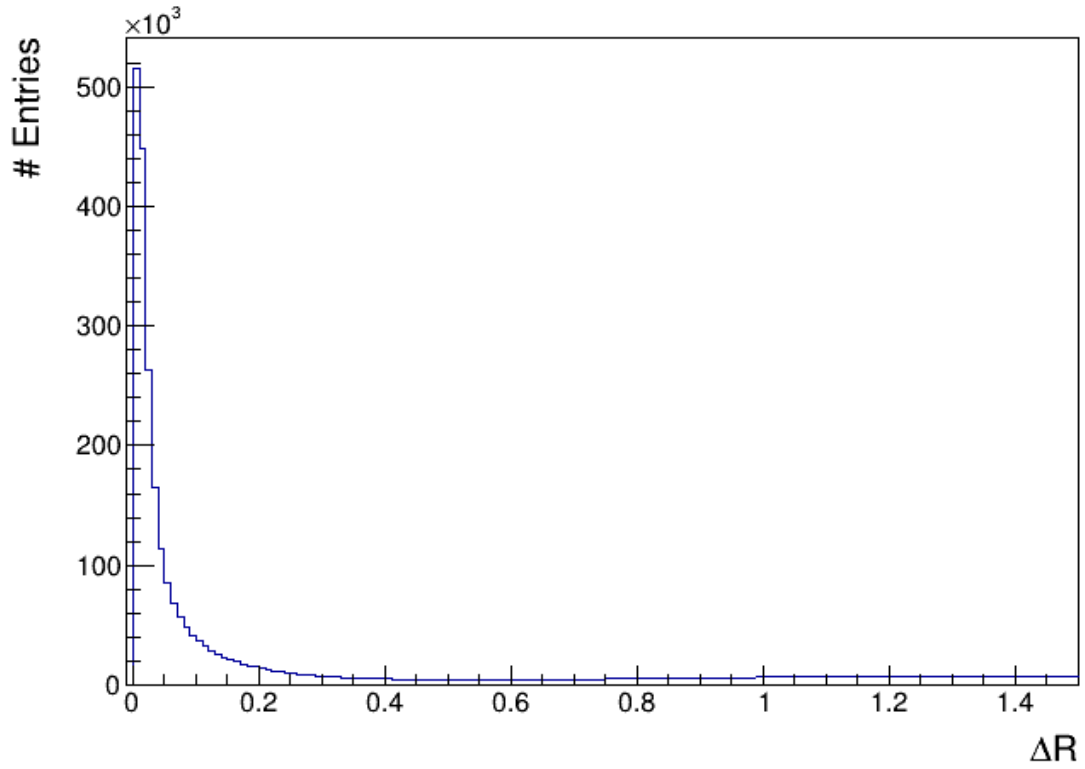


→ meets expectations of decrease towards end of phase space

→ More accurate jet selection improves resulting distributions

Threshold ΔR

- Find a threshold for ΔR
- Spatial difference needs to be below threshold;
  Here: ΔR = 0.5



→ Threshold will be used for jet selection

Pruning

→ Investigate jet substructure using Pruning

- Criteria on kinematic variables $z \equiv \frac{min(p_{T_i}, p_{T_j})}{p_{T_{i+j}}} < z_{cut}$

$$\Delta R_{ij} > D_{cut}$$

- Used on reconstructed jets
- Criteria tested at every recombination step
- If both cuts are passed → combination discarded
- Result: pruned jet
- Pruning impacts jet properties ; e.g. jet mass

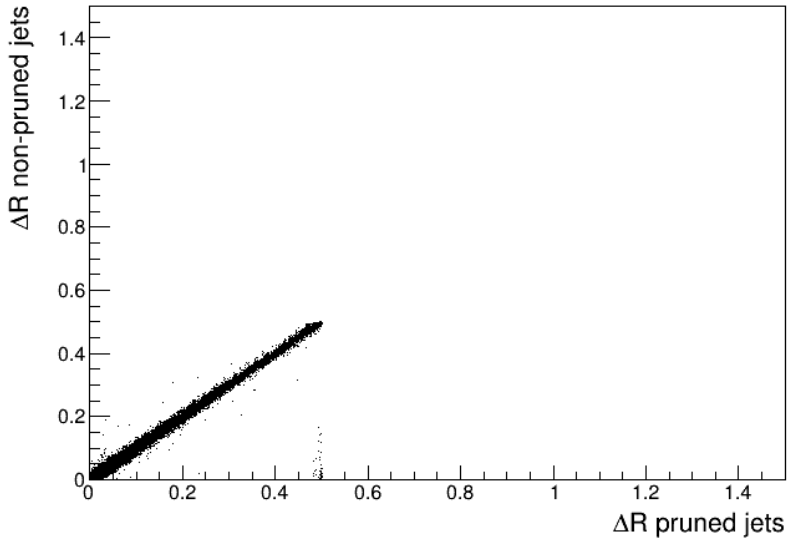
→ Pruning may improve jet selection

Impact of Pruning

➡ Investigate different strength of Pruning

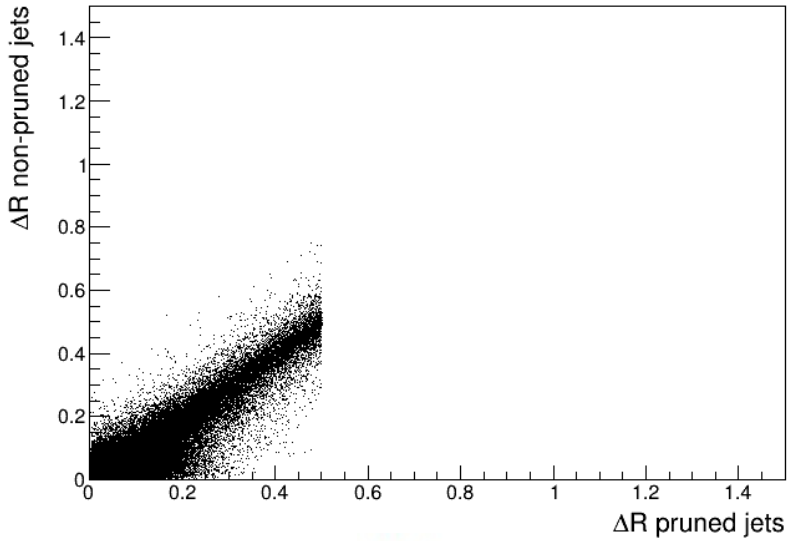
- Apply different criteria

$z_{cut} = 0.05$, $D_{cut} = 0.05$



➡ no significant clustering towards small ΔR

$z_{cut} = 0.7$, $D_{cut} = 0.05$



➡ large shift in ΔR and clustering towards smaller values

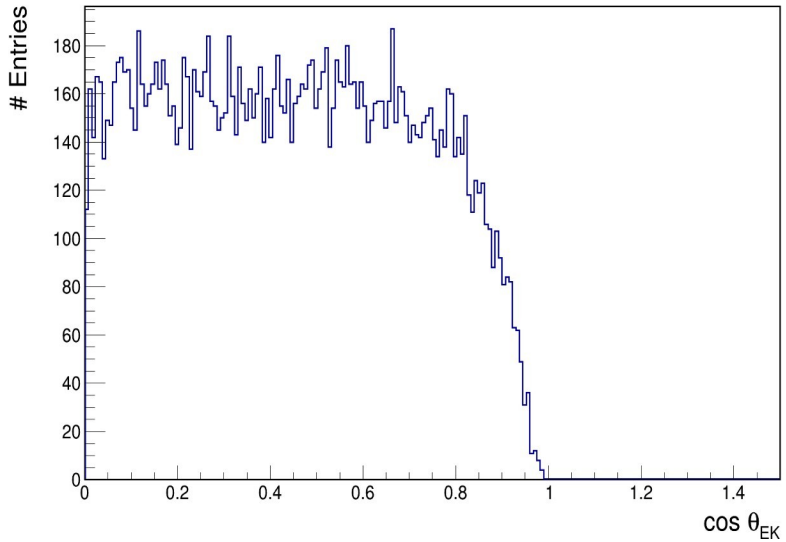
➡ Stronger pruning leads to smaller ΔR

Impact of Pruning

➡ How does pruning impact the distributions for $\cos\theta_{EK}$?

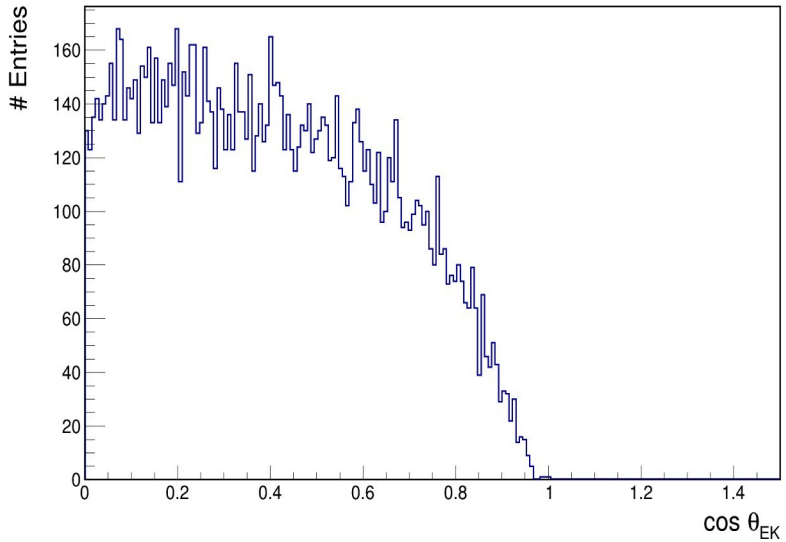
- Investigate $\cos\theta_{EK}$ for $z_{cut} = 0.7$ and $D_{cut} = 0.05$

Higgs Boson



➡meets expectations of box shaped distribution for scalar particle

Z Boson



➡meets expectations of decrease in entries towards end of phase space

➡Pruning improves jet selection

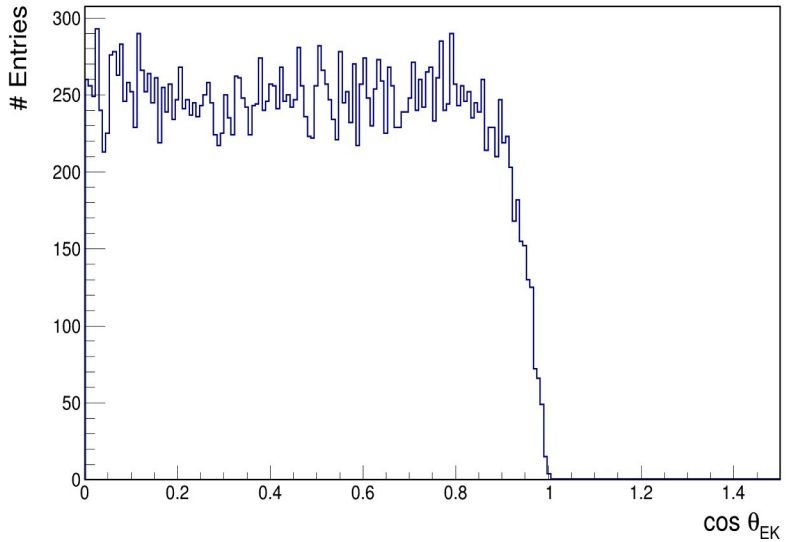
➡ Improves results for Z Boson

Mass scaling

➡ Pruning strongly shifts jet masses

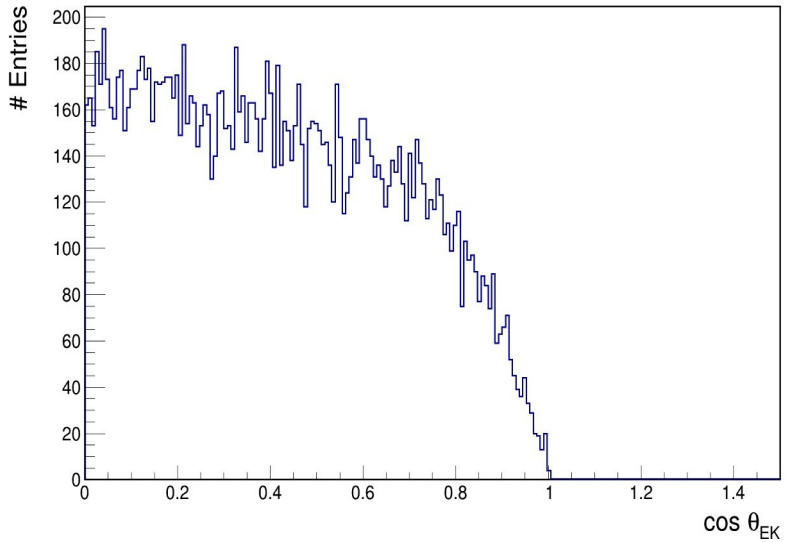
- Scale jet masses to the correct mass region after pruning
- Investigate $\cos\theta_{EK}$ for scaled jet masses

Higgs Boson



➡ meets expectations of box shaped distribution for scalar particle

Z Boson



➡ meets expectations of decrease in entries towards end of phase space

➡ Scaling the jet masses and pruning improves results for Z Boson

Summary: HZ processes

- To investigate the difference of the Z boson results to the expectation:
  - calculate Ellis-Karliner Angle for first daughter particles of H and Z
  - mimic b-tagging
  - investigate jet substructure using Pruning
  - scale jet masses

  → More accurate jet selection improves distributions for Z boson

- More approaches can be investigated to improve jet selection:
  e.g. using the jet constituent with the highest transverse momentum

Thank you for your attention!

Literature

[1]: Measurements of Gluon Spin-sensitive quantities at the Z0 resonance, The SLD Collaboration,
slac-pub-5975.pdf (stanford.edu)
[2]: SM Higgs Branching ratios and Total Decay Widths
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR
[3]: Status of Higgs Boson Physics, Particle Data Group
https://pdg.lbl.gov/2022/reviews/standard_model_and_related.html

Ellis-Karliner Angle: Modifications

- Derive a formula without neglecting masses (MOD EK)
  - Calculate Lorentz boost back to the rest frame based on reconstructed jets

$$\cos\theta_{EK} = \frac{x_2 - x_3}{x_1}$$

$$cos(\theta_{ek}) = \frac{-(-\frac{m_{12}^2}{m_{13}^2}\frac{\beta*E_2}{p_3}+\frac{m_{12}^2}{m_{13}^2}\frac{p_2}{p_3}+\frac{\beta*E_3}{p_3}+1)}{2*(-1-\frac{m_{12}^2}{m_{13}^2}\frac{p_2}{p_3})}$$

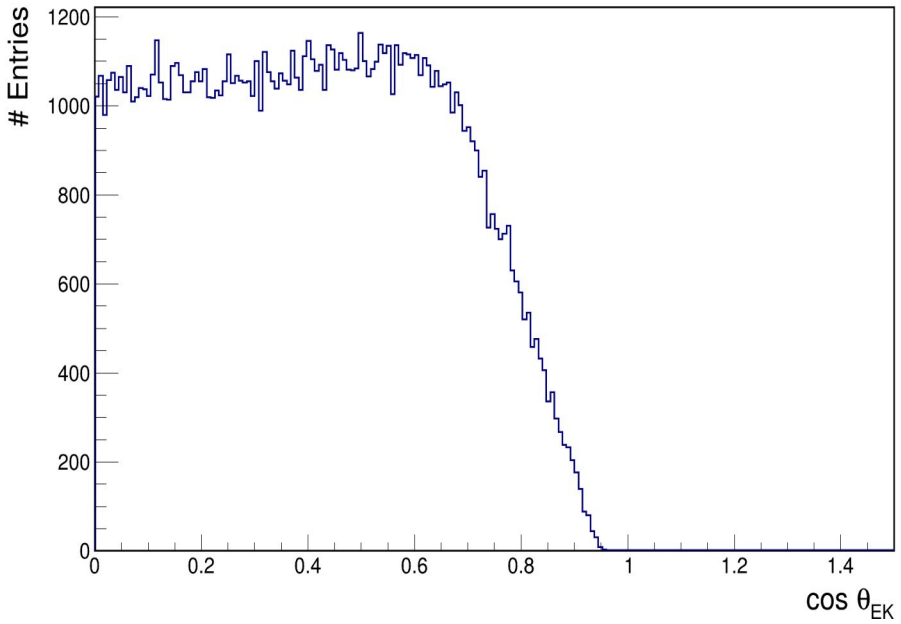
$$\frac{+sqrt((-\frac{m_{12}^2}{m_{13}^2}\frac{\beta*E_2}{p_3}+\frac{m_{12}^2}{m_{13}^2}\frac{p_2}{p_3}+\frac{\beta*E_3}{p_3}+1)^2}{2*(-1-\frac{m_{12}^2}{m_{13}^2}\frac{p_2}{p_3})}$$

$$\frac{+4*(1+\frac{m_{12}^2}{m_{13}^2}\frac{p_2}{p_3})*(\frac{m_{12}^2}{m_{13}^2}\frac{E_2}{\beta*p_3}+\frac{m_{12}^2}{m_{13}^2}*(\frac{m_3^2+m_1^2}{2\beta*\gamma*p_3*E_1})-(\frac{m_2^2+m_1^2}{2\beta*\gamma*p_3*E_1})-\frac{E_3}{\beta*p_3})}{2*(-1-\frac{m_{12}^2}{m_{13}^2}\frac{p_2}{p_3})}$$

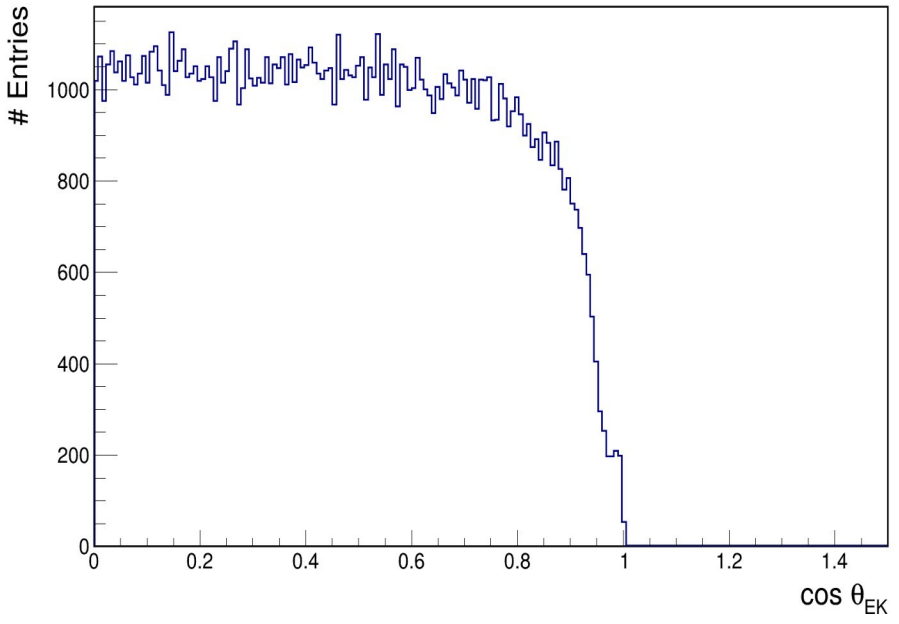
Ellis-Karliner Angle: HH processes

- Investigated using a generator level MC Simulation (ggHH process in Powheg)
  ⟶ expect box shaped distribution for scalar particle
- Derive $\cos\theta_{EK}$ for jet pair which fits $H \to b\bar{b}$ hypothesis best

MOD EK



ROOT EK

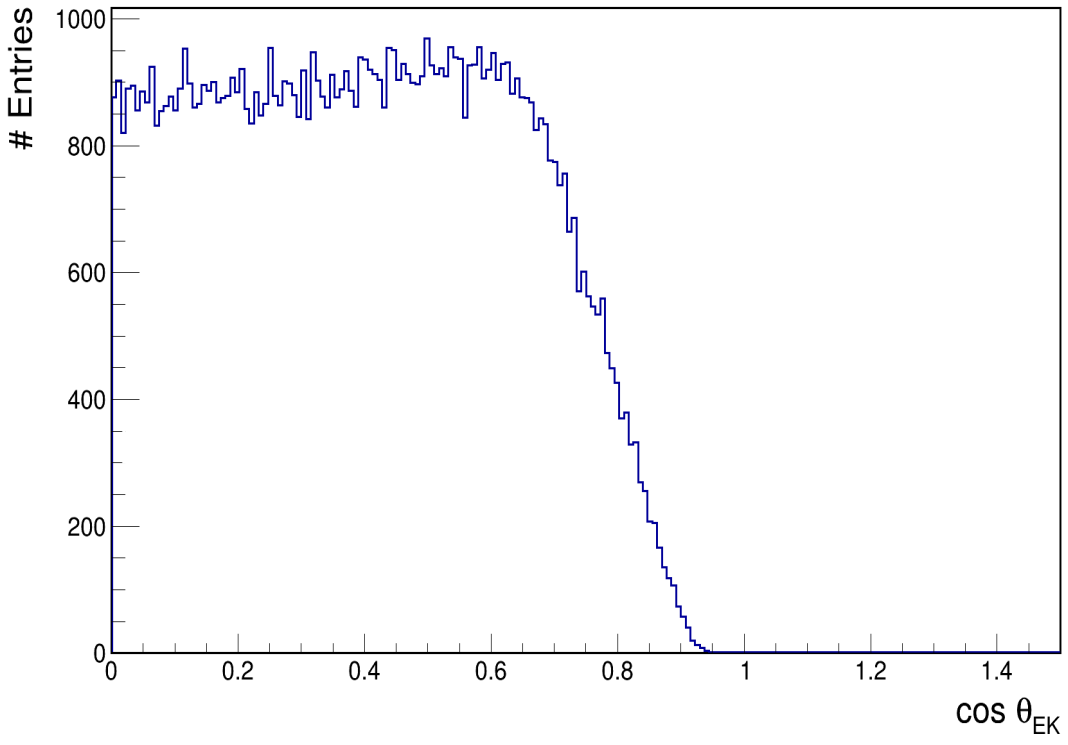


- Distribution from MOD EK differs from expectations toward end of phase space at $\cos\theta_{EK} \to 1$
  ⟶ Investigate subsets of phase space to find reason for difference

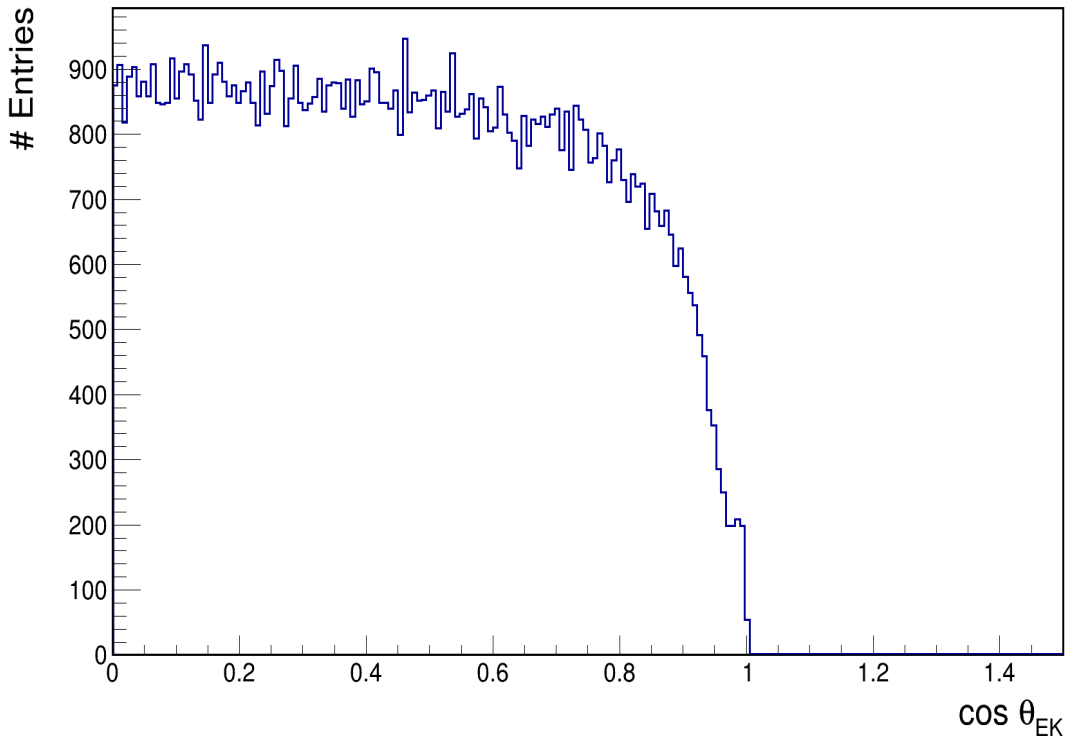
Appendix

HH MOD EK and ROOT EK for $\eta < 2.5$

MOD EK



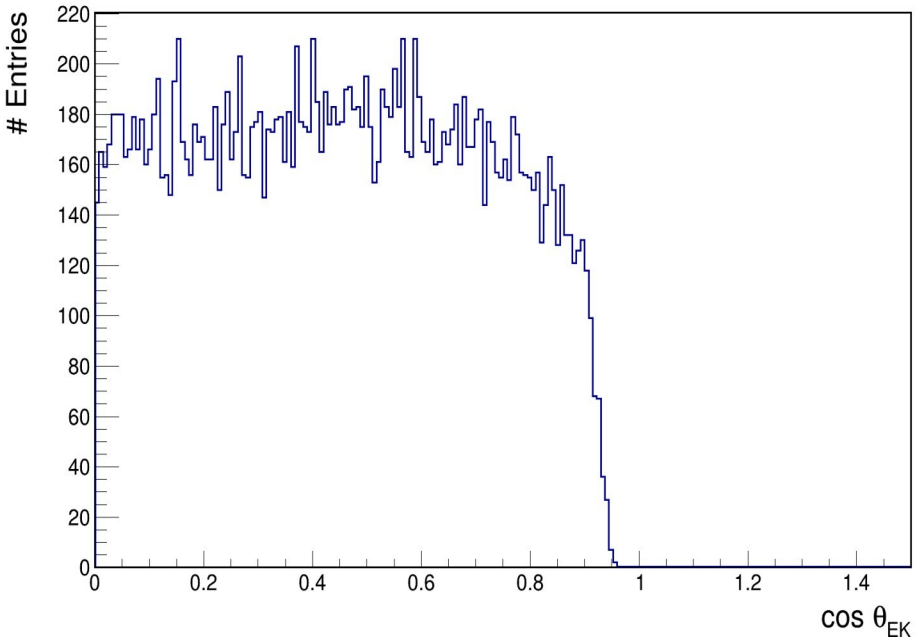
ROOT EK



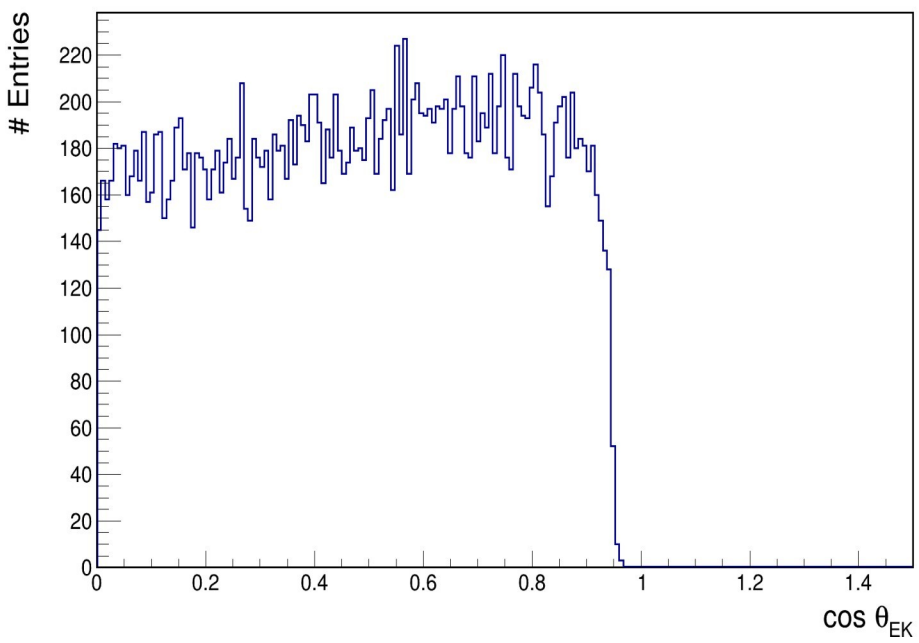
Pseudorapidity: HH processes - Results

Choose: $|\eta| > 2.5$

MOD EK



ROOT EK



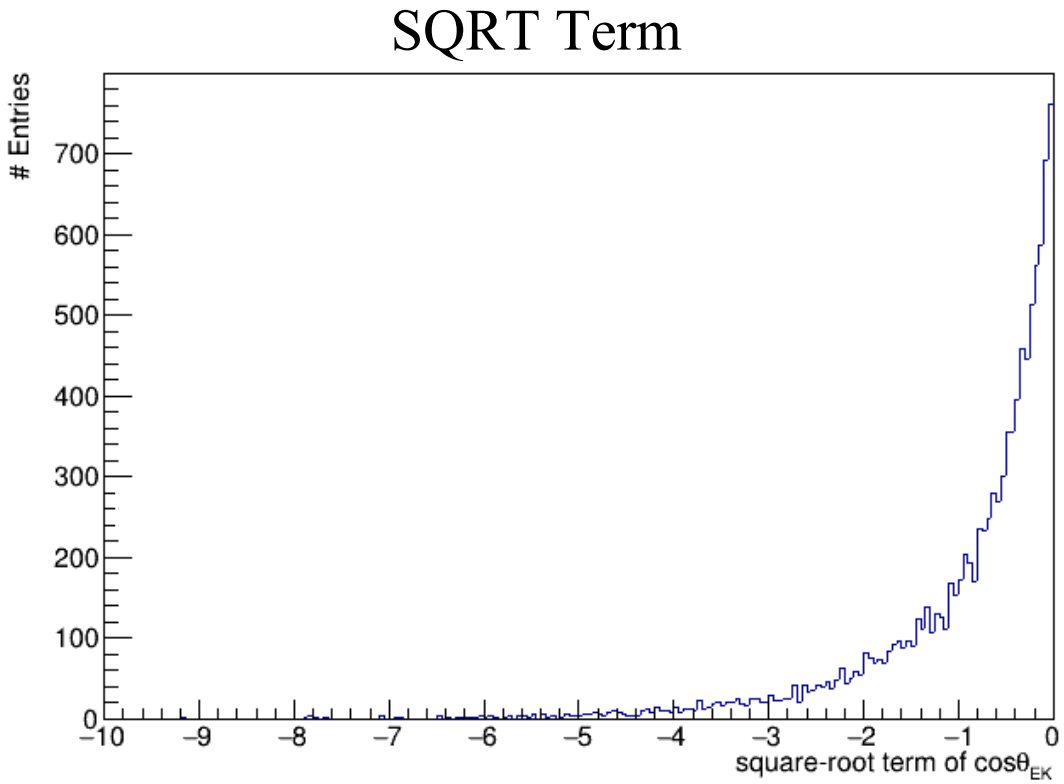
→ more forward events: distribution from MOD EK closer to expected box shape

Summary: HH processes

- Two methods of calculating Ellis-Karliner Angle
  ➡ MOD EK and ROOT EK
- To identify reason of difference of MOD EK checked:
  - subsets of phase space, e.g. using pseudorapidity η
  - input variables of both methods
    ➡ found better agreement in forward region, i.e $|\eta| >> 0$

    ➡ For remaining slides $|\eta| > 2.5$ and
    focus on ROOT EK

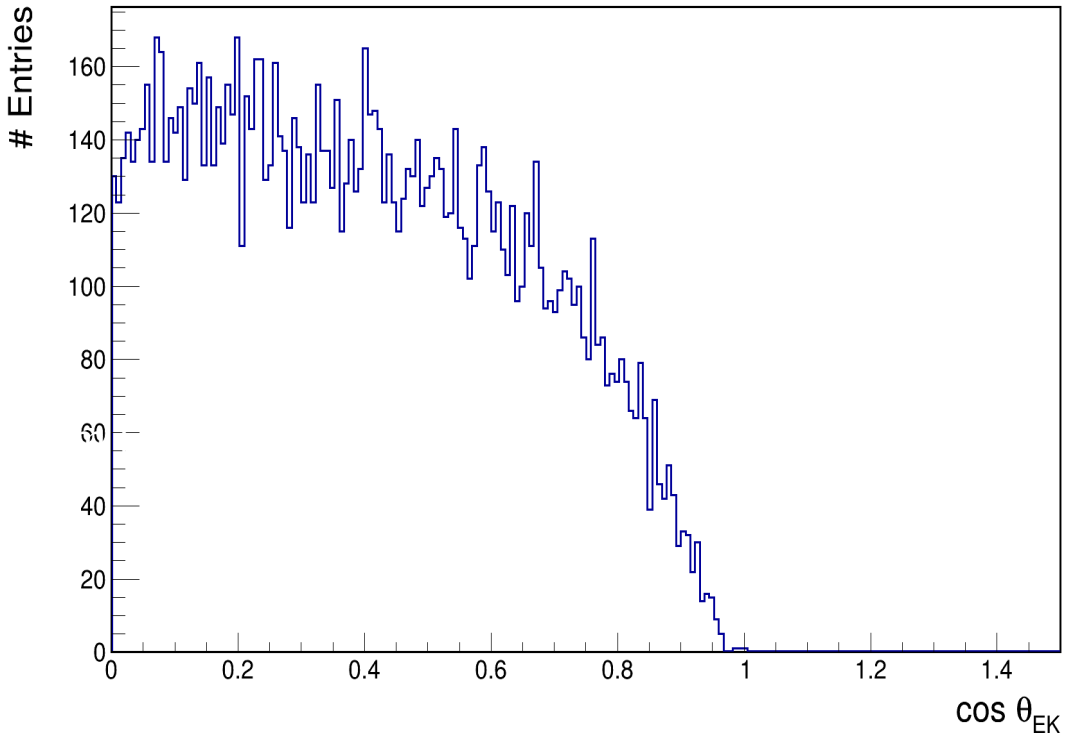
Appendix


SQRT Term
Entries
700
600
500
400
300
200
100
0
−10
−9
−8
−7
−6
−5
−4
−3
−2
−1
0
square-root term of cosθEK

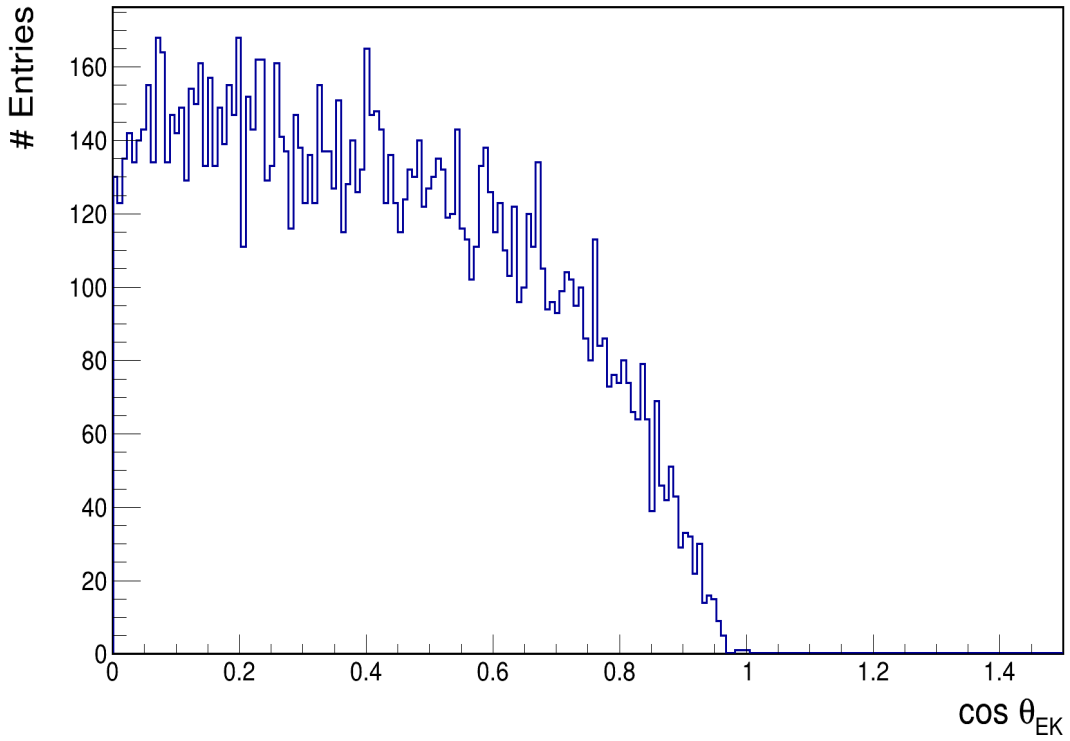
Appendix

Pruning using anti-k_T and C/A jet algorithms

anti-k_T



C/A



Appendix

Mass of jet pairs after Pruning