Lund Jet Plane studies at FCC-ee

FUTURE CIRCULAR COLLIDER

LPNHE PARIS

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Introduction and motivation

- **Analysis:** Prospects of QCD studies related to jet formation at FCC-ee using Lund Jet Plane (LJP) representation
  - motivated by the study of the sensitivity to α_s at FCC-ee, probing of α_s for different energies and tests of the renormalization group equation (RGE) in QCD
  - complementary to the 3/2 Jet cross-section ratio study for α_s
  - First study which looks at jet substructure at FCC-ee
- **Why at FCC-ee?**
  - provides a clean collision environment with high statistics for precise measurements
  - potential impact on detector parameters
- Use Delphes samples from Winter2023 campaign simulated for IDEA detector at $\sqrt{s}$ = 91 GeV
  - Use light jets from process: ee → Z → light jets (**p8_ee_Zud_ecm91)**

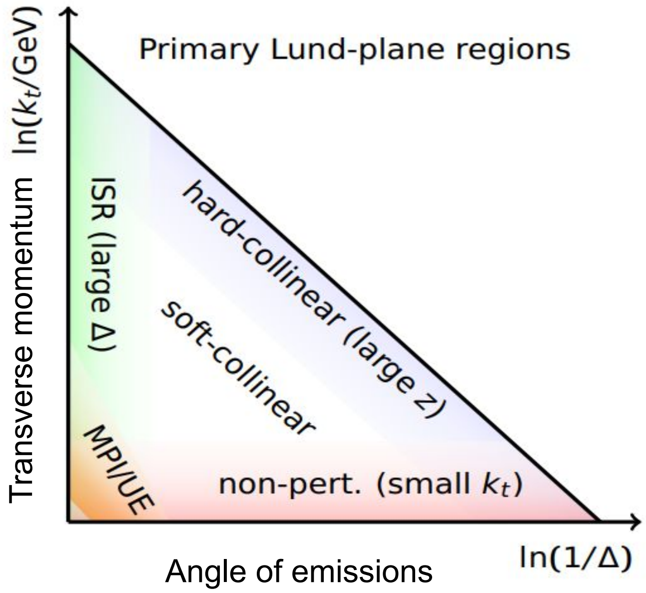
Introduction and motivation

Advantage of Lund Jet Plane method (LJP):

- QCD jet formation involves perturbative and non-perturbative effects; presence of these effects impact the precision of any measurement based on jets
- LJP works as a handle to separate these effects in a 2D representation using angle (Δ) and transverse momentum (k_t) of emissions within the jets and further opens a possibility to understand QCD behaviour separately for these perturbative and non-perturbative effects

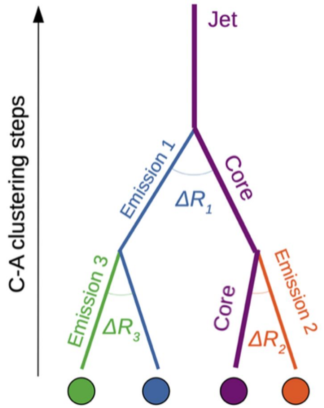
- **First let's understand LJP formation with more details**

(arXiv:1807.04758)



Introduction and motivation

- **Lund Jet plane (LJP)**



For "a" core and "b" emission branch

$$\Delta R = \Delta R_{ab} \;, \quad k_t \equiv p_{tb} \Delta R_{ab}$$

$$z \equiv p_{tb} / (p_{ta} + p_{tb})$$

- Start with a jet and cluster it again with Cambridge/Aachen (C/A) to have angular order information of emissions
- Decluster them in reverse (start with wide angle emission first)
- Within the iterative declustering, harder branch is always taken as core branch
- fill a triangle plane of two Lund variables from core and emission

ΔR_{ab} = angle of emission **b** wrt to core **a**

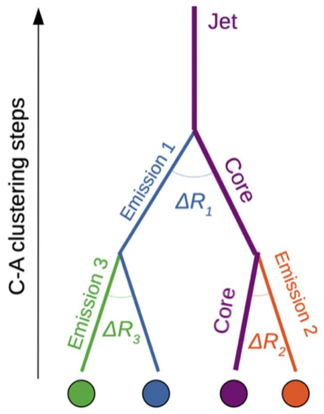
k_t = transverse momentum of **b** wrt **a**

(for $p_{tb} << p_{ta}$ and $\Delta << 1$)

z = momentum fraction taken by **b**

Introduction and motivation

- **Lund Jet plane (LJP)**



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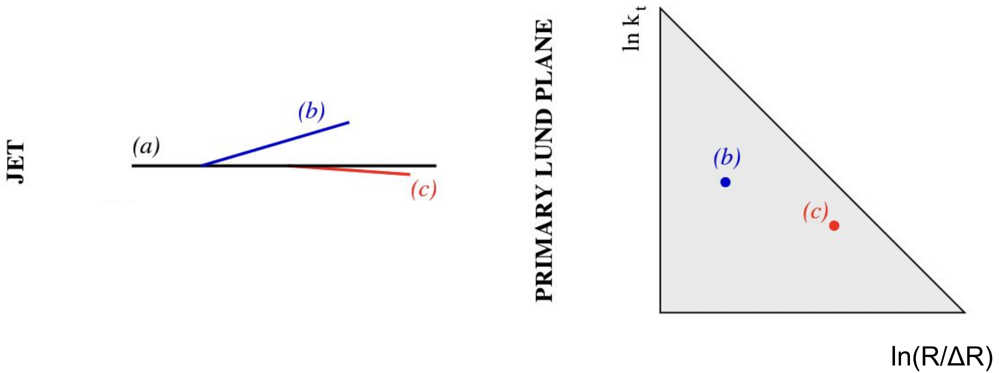
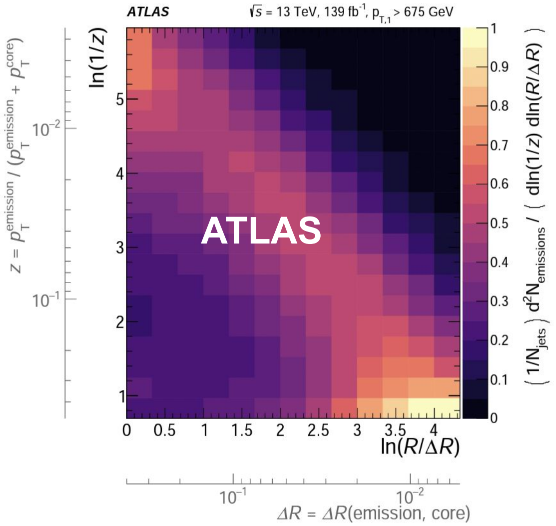


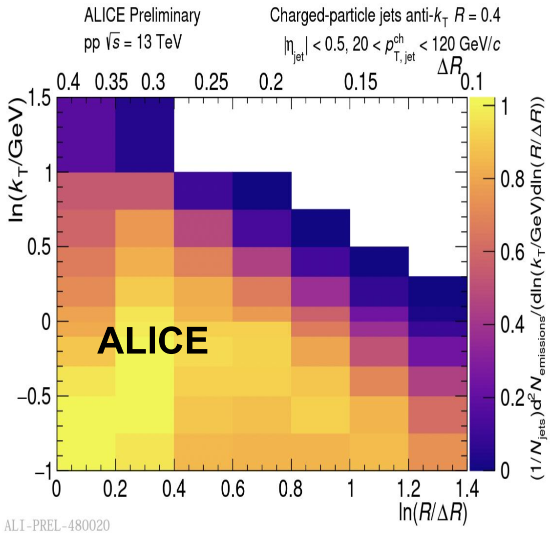
Recent Lund Jet Plane based measurements

- LJP studies at LHC √s = 13 TeV, following recent theoretical proposal (JHEP 12 (2018) 064)
- These studies measure the lund plane density for charged particles jets
- We are interested in following the same for FCC-ee environment

arXiv 2004.03540



arXiv 2111.00020



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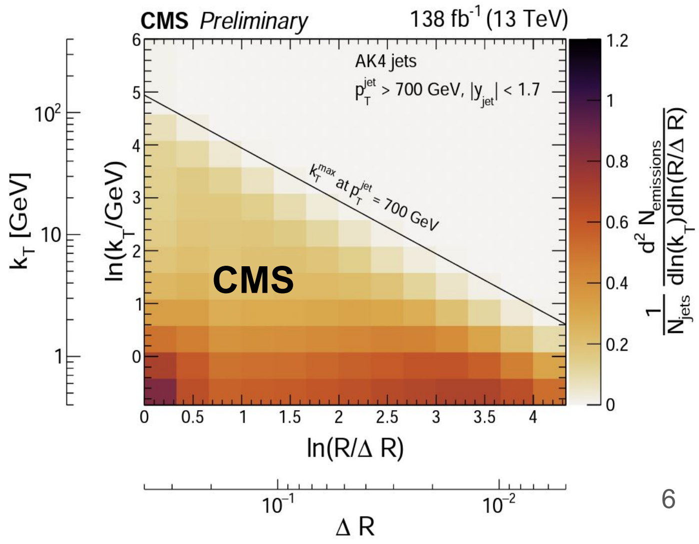


Methodology

1. Framework: HEP-FCC/FCCAnalyses
2. Jet Clustering:
   a. Input collection ReconstructedParticles (smeared reco particles)
   b. Definitions:

Valencia jets R = 1.5, beta = 1.0 inclusive clustering

Anti k_T jets R = 1.5, inclusive clustering

Valencia jet clustering

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

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

Anti-k_t and C/A jet clustering

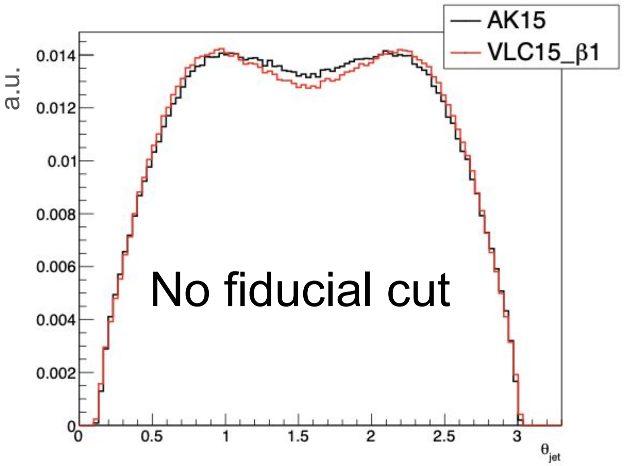
$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\frac{\Delta R_{ij}^2}{R^2}, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$

$$d_{iB} = p_{ti}^{2p},$$ for anti-k_t p = -1 and C/A p=0

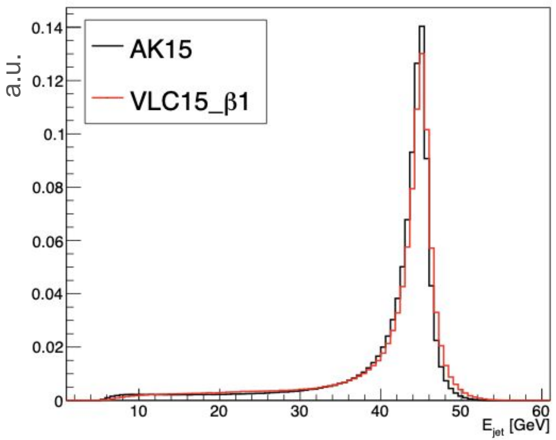
Note: cross-checks with different jet algorithms and different clustering configuration is in backup

Kinematic comparison for QCD jets: Valencia vs anti-k_T

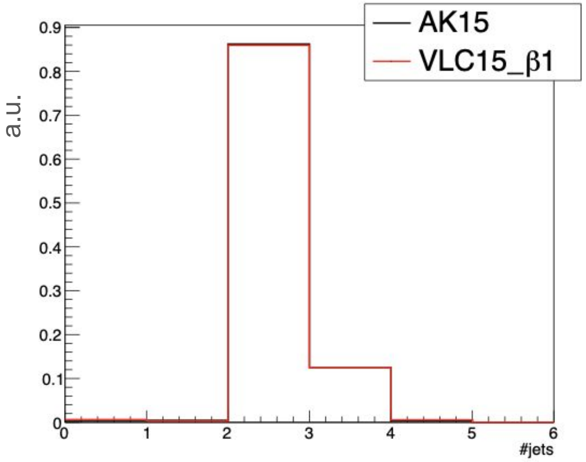
Process: ee_Zud_ecm91



θ_{jet}



E_{jet}>= 10 GeV



Njets > =2

Selections	Selection Efficiency
Jet energy >= 10 GeV	99.5%
Njets >=2	99.1%

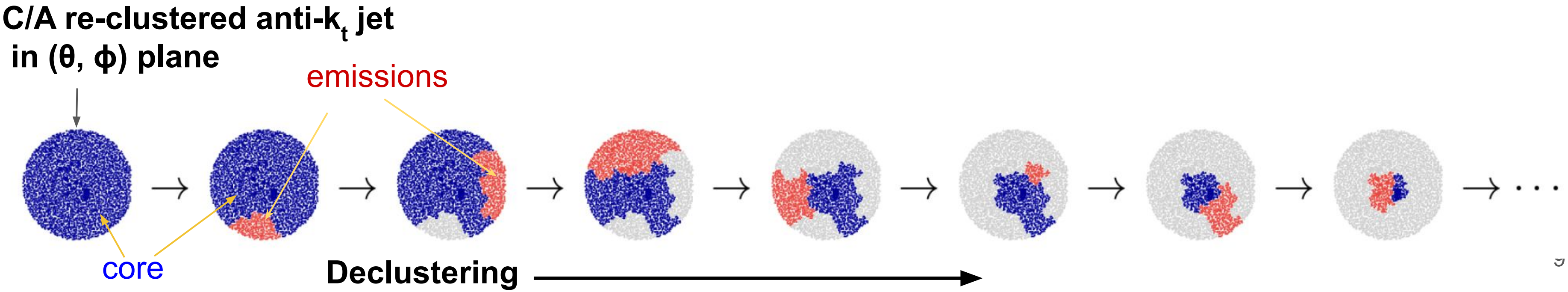
NOTE:
we use anti-k_T algorithm for preliminary studies

Methodology

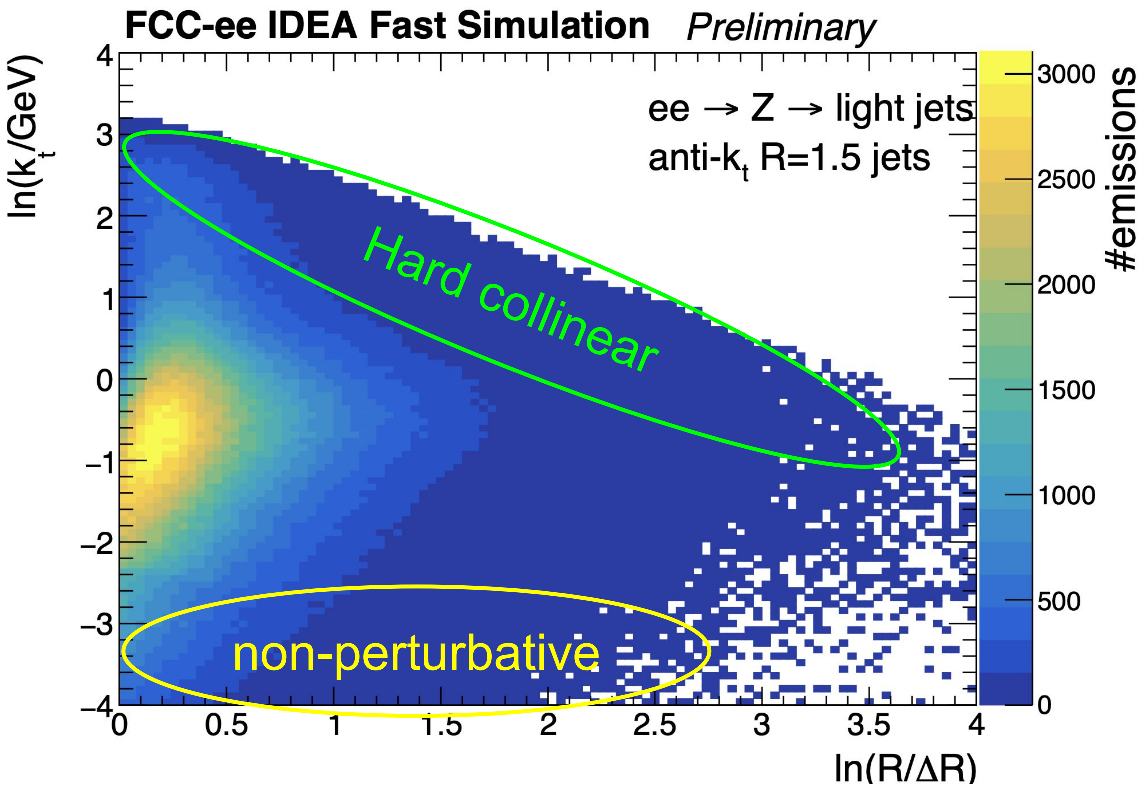
3. Once we have jet clustered, we save corresponding reco particle (smeared particles) constituents using "JetClusteringUtils::get_constituents"

4. Pick constituents of a jet

- The clustering information is not saved during jet reconstruction so first we recluster jet again with AK15 algorithm by saving the clustering subjet information using fastjet dedicated functions
- Afterwards, picking the same subjets, jet is clustered using C/A algorithm to follow angular-ordered clustering
- Now we go back and do declustering in angular order; start from wide angle first
- Calculate LJP variables using core and emission subjets iteratively and fill the LJP plane

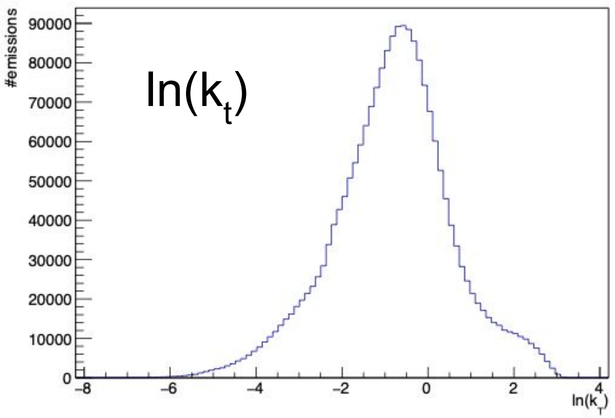


First look LJP representation (after event selection)

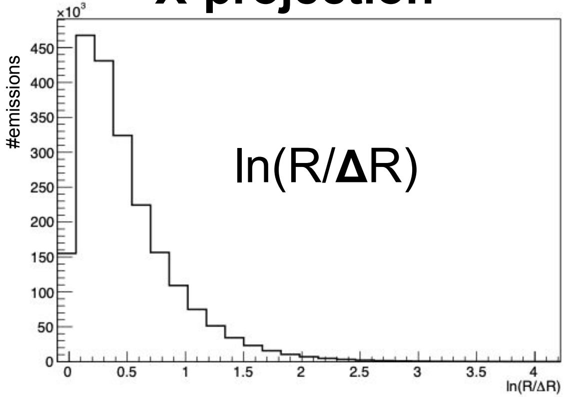


(LJP representation of jets using smeared particle constituents from fast simulation)

Y-projection



X-projection



Summary and other possibilities

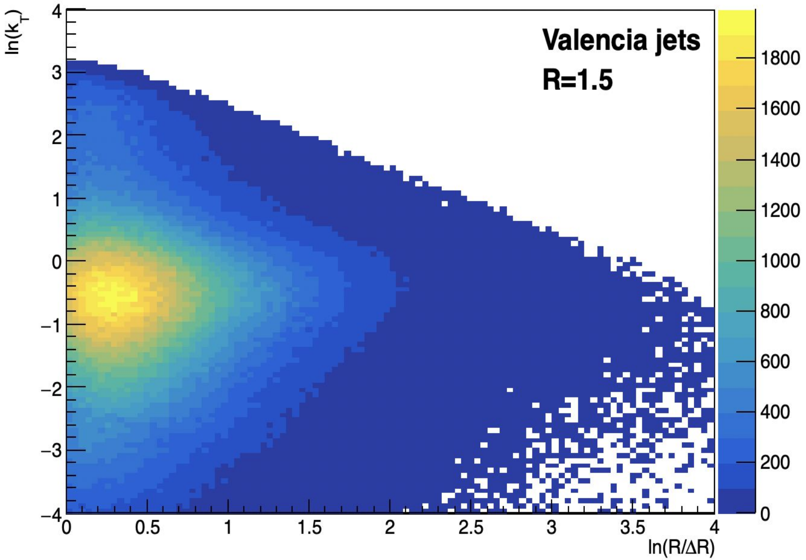
- First study which looks at jet substructure at FCC-ee
  - Motivated by the study of the sensitivity to α_s and test of RGE at FCC-ee
  - Present preliminary LJP representation for QCD jets (for AK15 inclusive jets) using delphes samples
  - explore sensitivity to detector parameters
- We need fullsim for a given α_s value to study the reconstruction of the LJP for different options of detector technologies.
- An α_s scan will be necessary to study the sensitivity of the reconstructed LJP to α_s
- **Other prospects:**
  - LJP tool can be used to develop tagging methods, e.g. heavy flavour jet tagging, EM objects tagging etc.

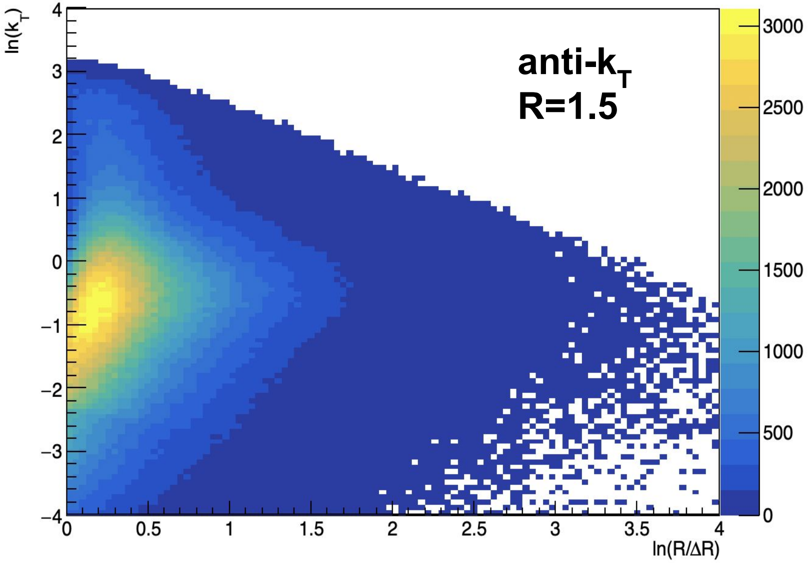
BACKUP

Technical questions

- In order to make progress further, we need recipe to reconstruct truth jets, currently I do not understand how to extract it from current samples

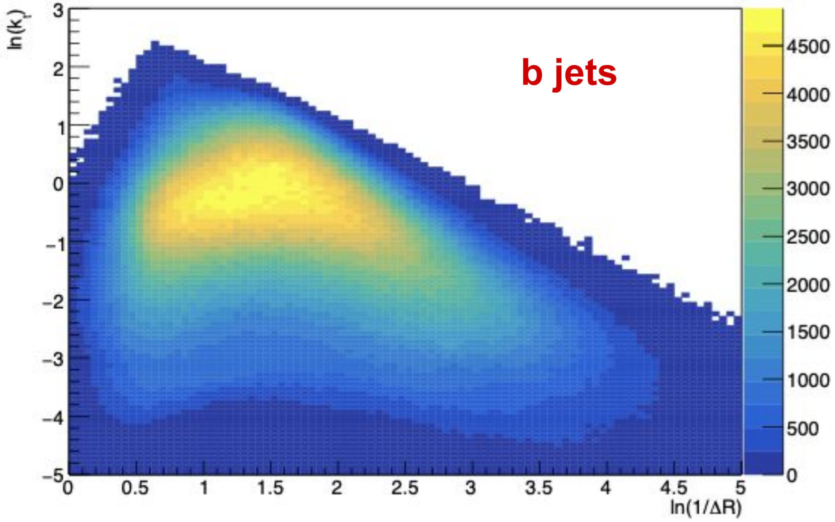
First look LJP representation for QCD light jets (after event selection)

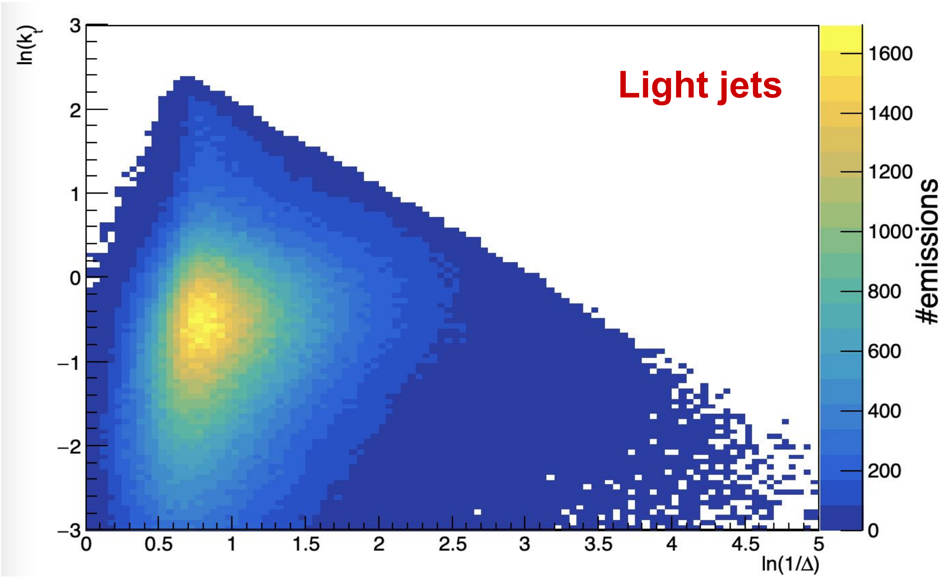




First look of LJP representation of valencia jets (R=0.5) at FCC-ee

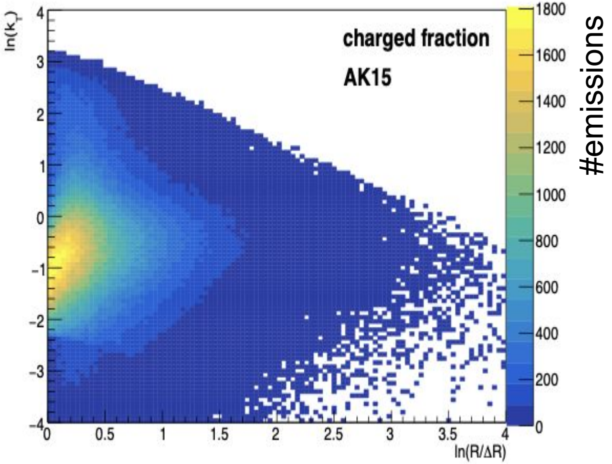
$\ln(k_t)$ vs $\ln(1/\Delta)$

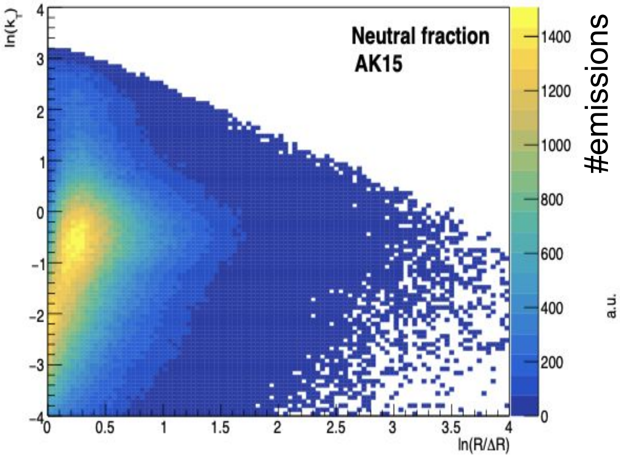


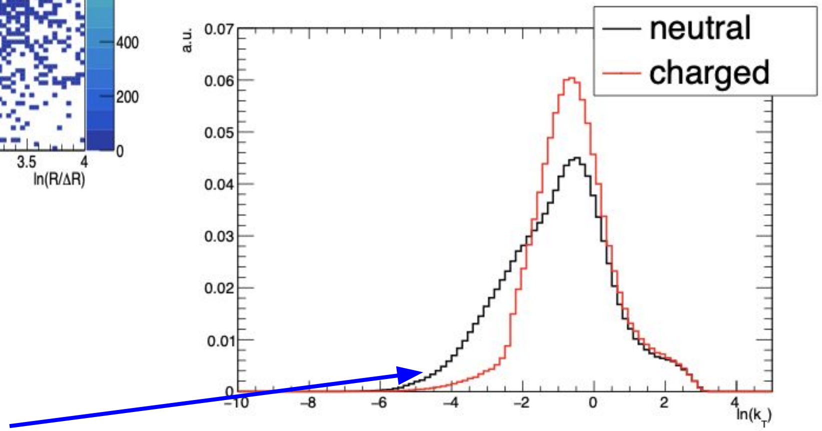


LJP for charged and neutral jet fraction (after event selection)

$\ln(k_t)$ vs $\ln(R/\Delta R)$



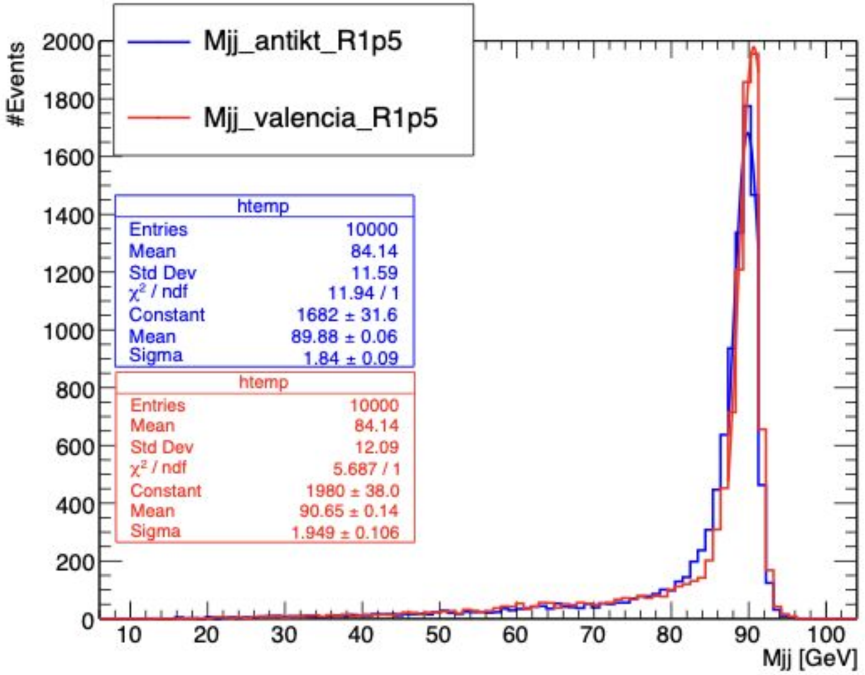




- tail distribution mostly contains neutral fraction
- Hard collinear region doesn't have much difference in both representation

Valencia vs anti-kt m_{jj} distribution for R=1.5

- Valencia jets has slight better mass resolution for reconstructed m_Z; but mass scale is same



Jet Clustering

Framework: HEP-FCC/FCCAnalyses

Jet Clustering: (according to examples given here)

- Input collection ReconstructedParticles

  .Define("pseudo_jets",   "JetClusteringUtils::set_pseudoJets_xyzm(RP_px, RP_py, RP_pz, RP_m)")
- Definitions: clustering_k_t, clustering_cambridge, clustering_valencia (with ß=1) (link)
- Configuration settings: **(R=0.5)**
  - **exclusive jet clustering:** upto exactly 4 jets

    .Define("FCCAnalysesJets_valencia", "JetClustering::clustering_valencia(0.5, **2, 4**, 0, 10, 1., 1.)(pseudo_jets)")

    .Define("FCCAnalysesJets_kt", "JetClustering::clustering_kt(0.5, **2, 4**, 0, 10)(pseudo_jets)")
    .Define("FCCAnalysesJets_cambridge", "JetClustering::clustering_cambridge(0.5, **2, 4**, 0, 10)(pseudo_jets)")

Jet Clustering

Framework: [HEP-FCC/FCCAnalyses]

Jet Clustering: (according to examples given [here])

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- Definitions: clustering_k_t, clustering_cambridge, clustering_valencia (with ß=1) ([link])
- Configuration settings: **(R=0.5)**
  - **exclusive jet clustering:** upto exactly 4 jets
  - **inclusive jet clustering**: with 5 GeV pT cut on jets

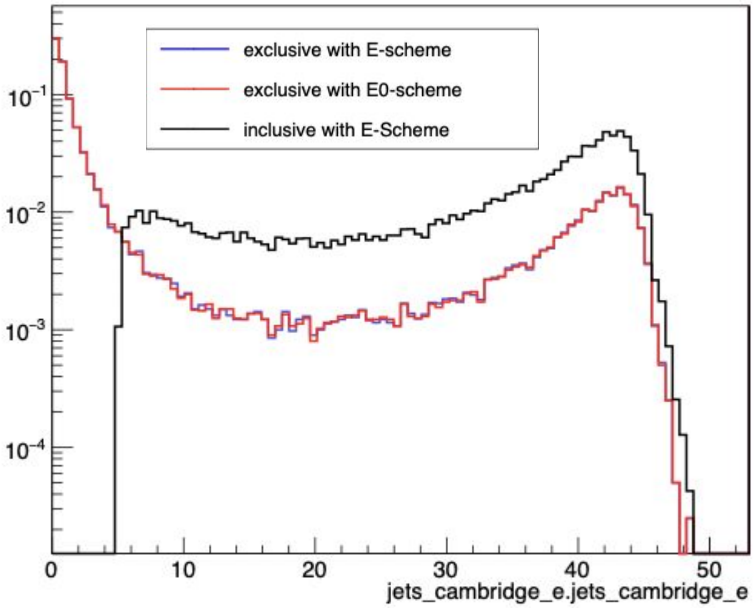
    .Define("FCCAnalysesJets_valencia", "JetClustering::clustering_valencia(0.5, **0, 5**, 0, 0, 1., 1.)(pseudo_jets)")

    .Define("FCCAnalysesJets_kt", "JetClustering::clustering_kt(0.5, **0, 5**, 0, 0)(pseudo_jets)")

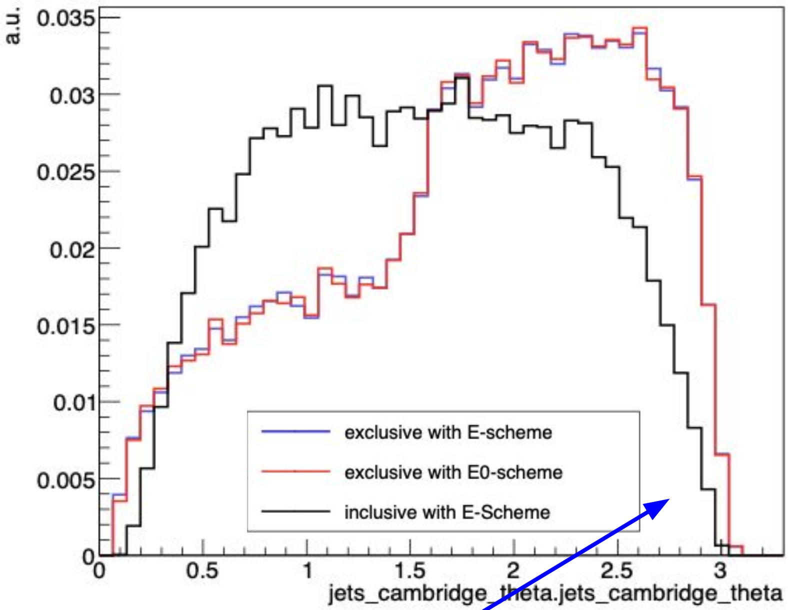
    .Define("FCCAnalysesJets_cambridge", "JetClustering::clustering_cambridge(0.5, **0, 5**, 0, 0)(pseudo_jets)")

Cambridge Jet Kinematic distributions

Jet E

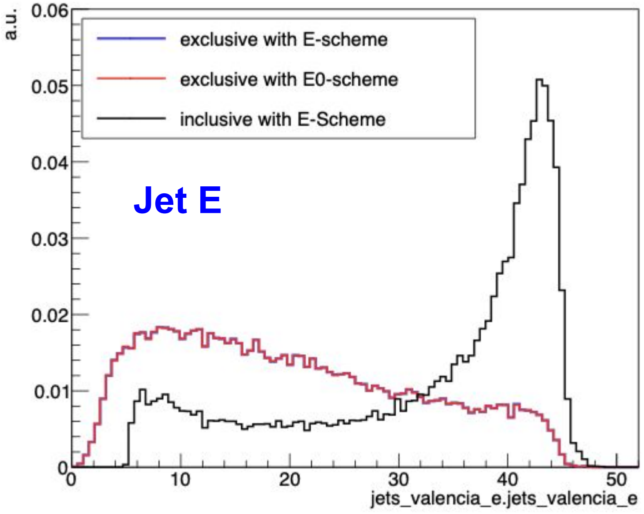


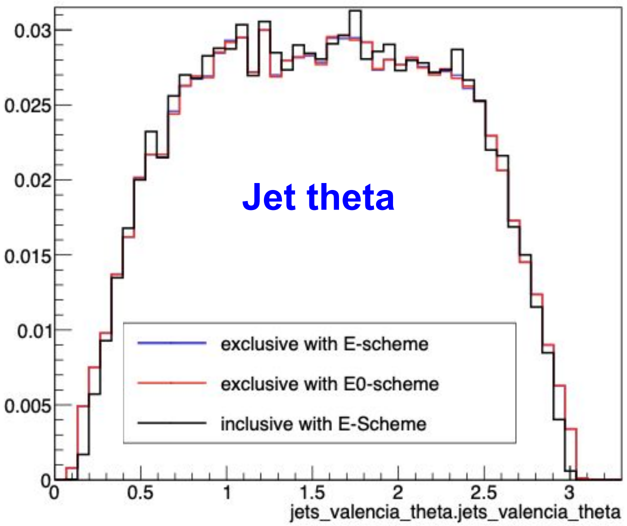
Jet theta

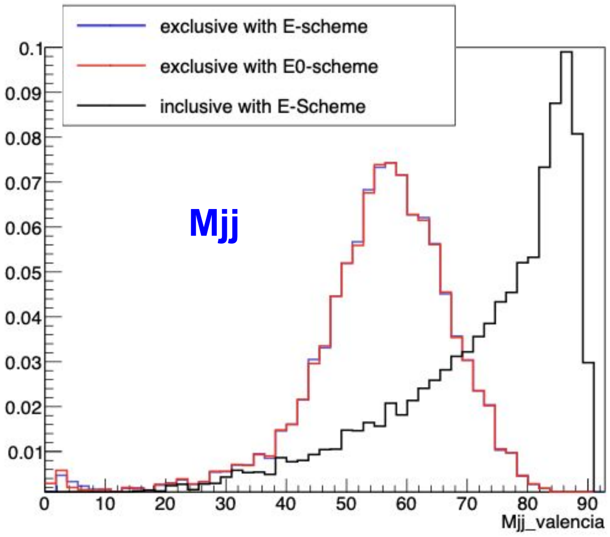


- With 5 GeV pT cut in inclusive clustering, jet theta distribution give symmetric distribution. But, in exclusive clustering, theta distribution becomes asymmetric⇒ clustering uses $\Delta\theta$ so the difference of p_T cut used in inclusive clustering does not explain this ⇒ points to some bug?
    - Inclusive clustering looks more reasonable. Checks with valencia algorithm is on next slide.

Valencia Jet Kinematic distributions

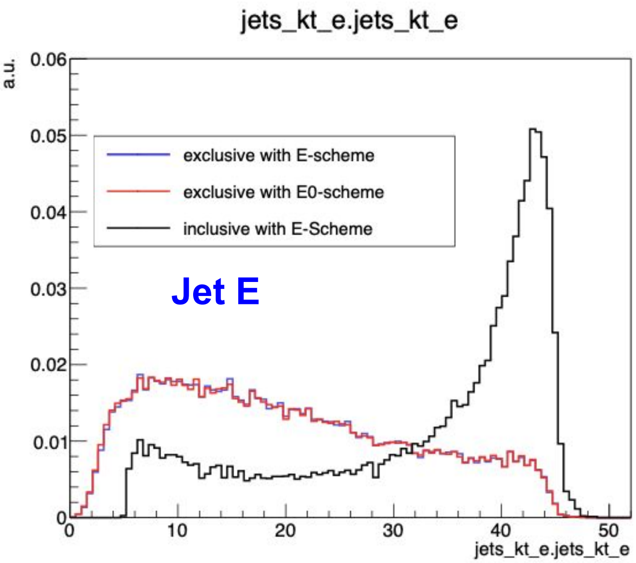


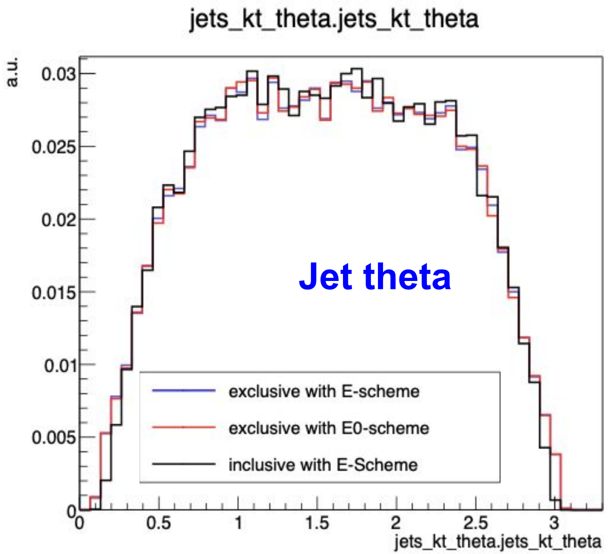


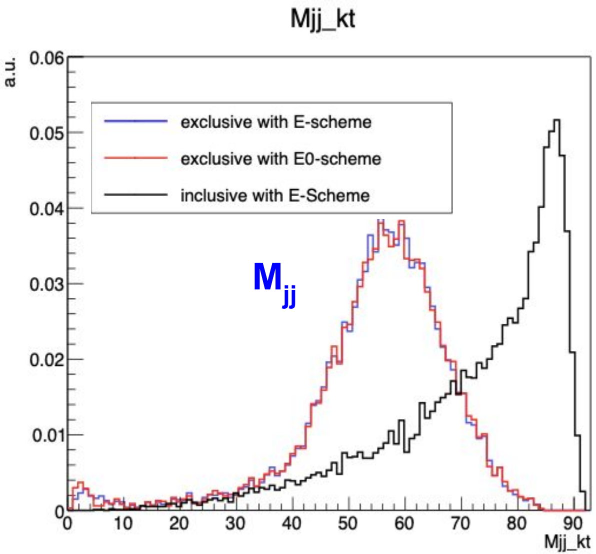


- Exclusive and inclusive clustering completely changes the valencia jet kinematics
  - **Jet energy**: peaks ~45 GeV for lights jets coming from Z-decay for inclusive; exclusive clustering loses the correlations with hard particles
  - **Jet theta**: looks more and less similar for inclusive and exclusive clusterings
  - **M_{jj}**: for inclusive, it peaks close to Z-mass, but, for exclusive this is not a case

k_t-Jet Kinematic distributions



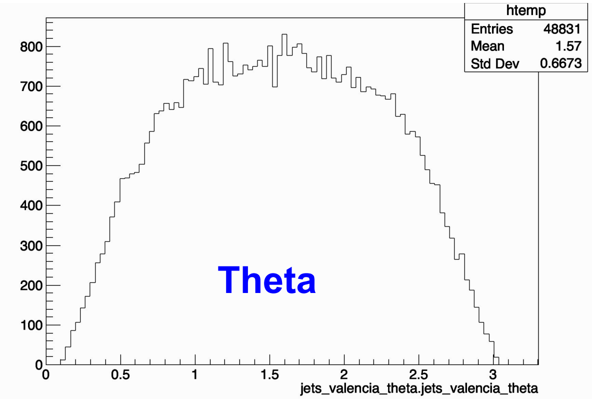


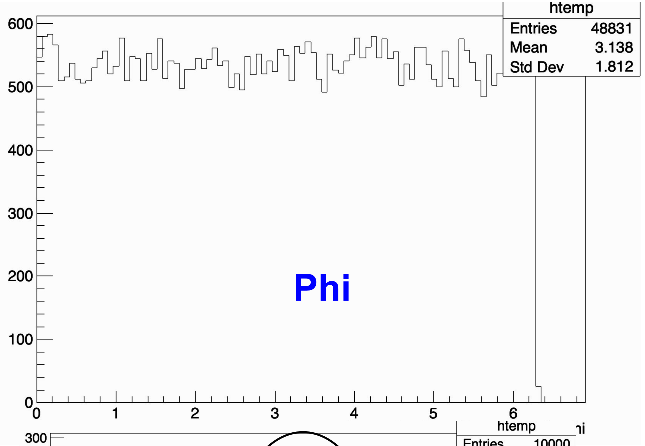


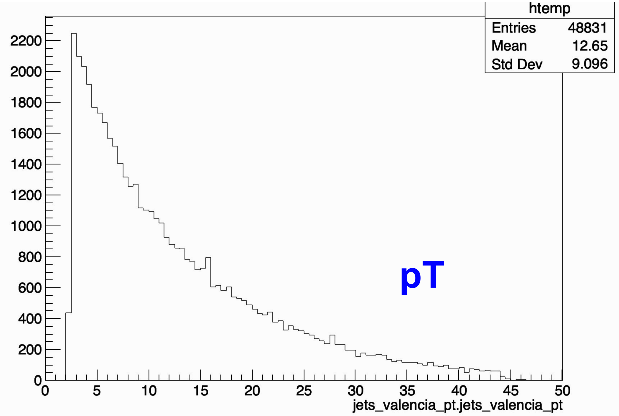
- k_t-clustering also shows same behaviour with inclusive and exclusive clustering
- The kinematics is very similar to valencia jets

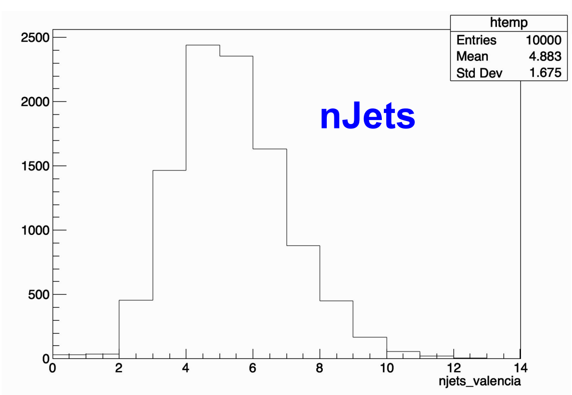
Other checks for exclusive clustering

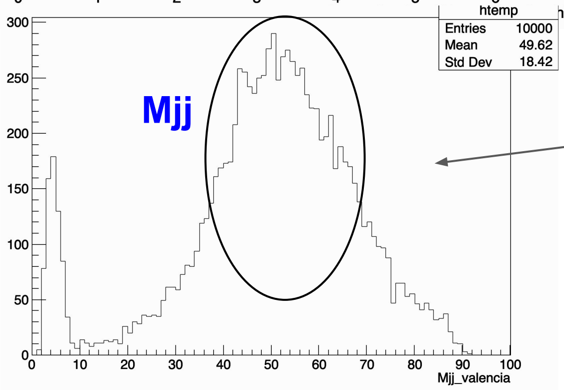
- Tried with one more exclusive configuration for valencia jets where there is selection on dcut (instead of njets)
  .Define("FCCAnalysesJets_valencia", "JetClustering::clustering_valencia(0.5, **1, 6**, 0, 0, 1., 1.)(pseudo_jets)")





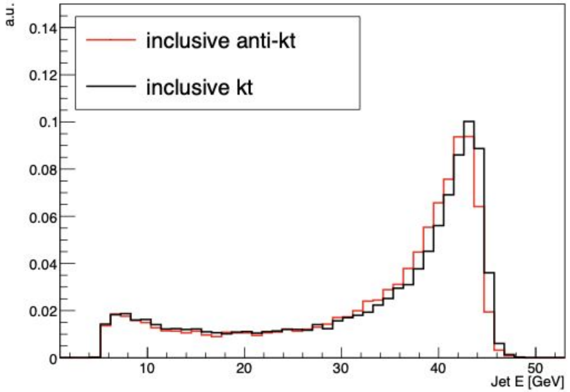


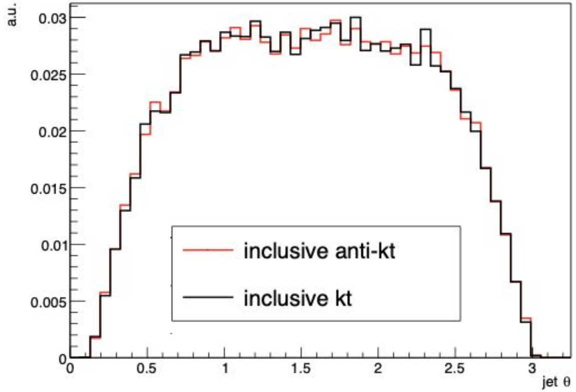




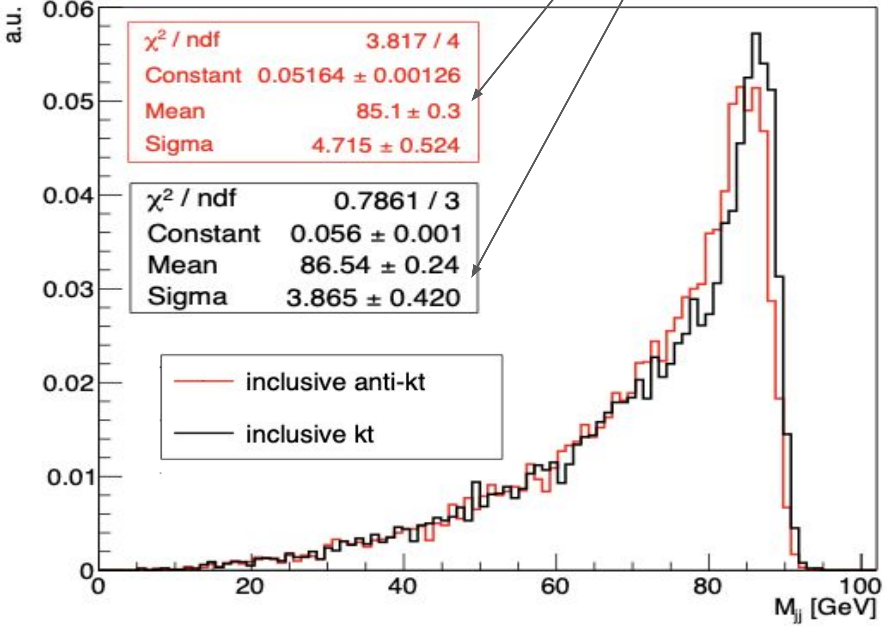
- Here also Mjj peaks around 50 GeV for jets coming from Z-decay
- Exclusive clustering does not allow to reproduce Z-mass well

k_t vs anti-k_t Jet Kinematic with inclusive clustering





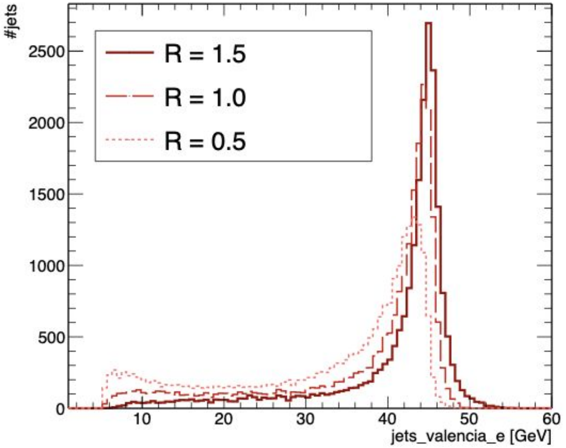
gaussian fit parameters after fitting Mjj peak

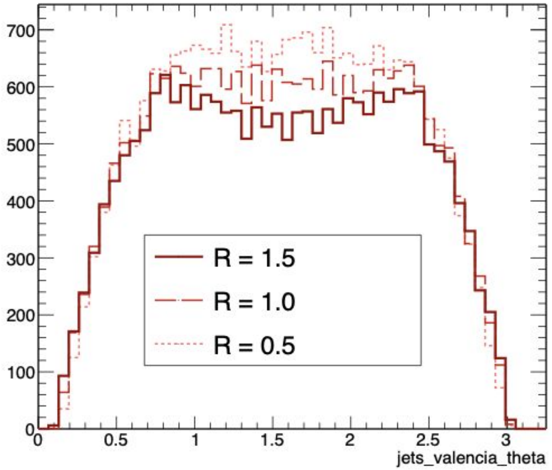


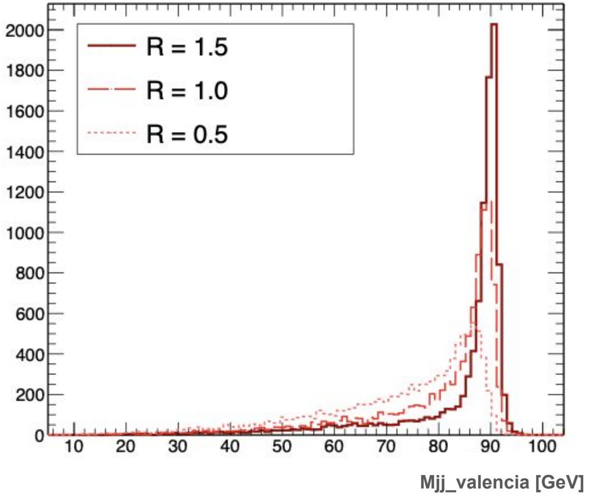
k_t and anti-k_t algorithms give a slight difference in jet kinematics which could be sensitive to choice of jet size. (this needs to be studied with jet sizes)

Note: Fastjet doesn't allow anti-kt algorithm with exclusive clustering

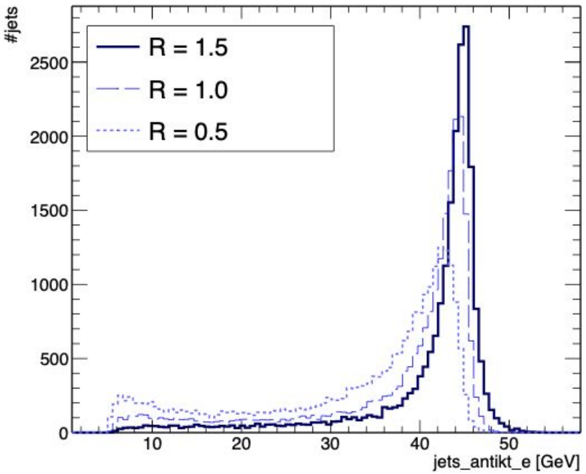
Inclusive Valencia Jet Kinematic distributions for different R

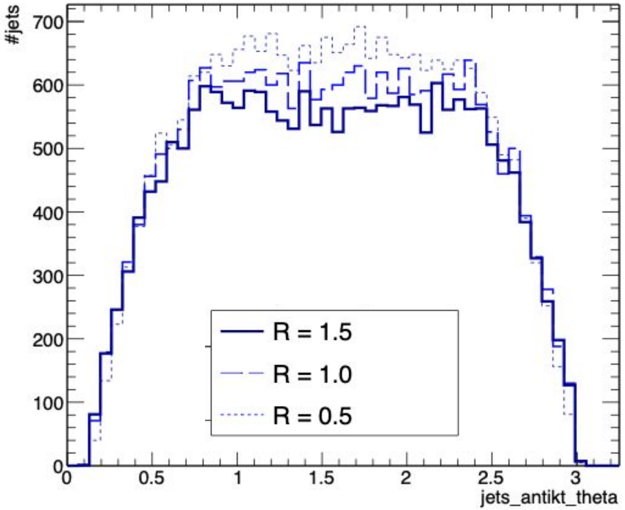


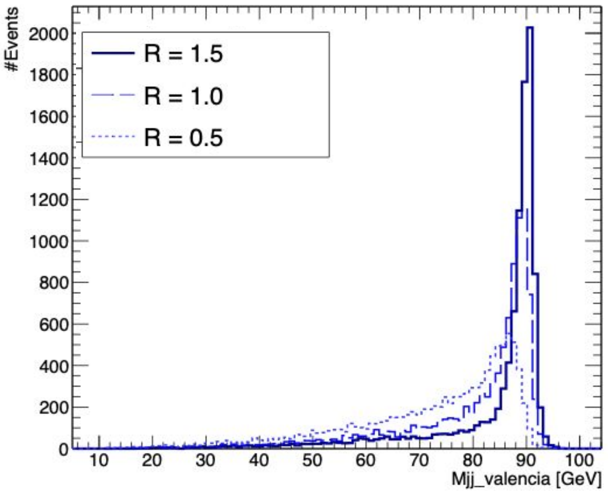




Inclusive anti-k_T Jet Kinematic distributions for different R







Ideas for next steps:

Binning of LJP variables (k_T, ΔR)

$\ln(k_T) = [-3, -2, -1, 0, 1]$
$\ln(R/\Delta R) = [0, 1, 2, 3]$
p_T binning = [10, 25, 35, 40, 45]

} Total 64 bins ⇒ LJP 2D distribution in every pT bins at reco level

Ideas for next steps:

- Try to create similar unfolding input as we have in ATLAS to run unfolding in one go, but…..

  KEY: TH1D h1_incl_unfolding_tjet_kt_DeltaR_pt_nominal;1
  KEY: TH2F h2_incl_unfolding_resp_kt_DeltaR_pt_nominal;1
  KEY: TH1F h1_incl_unfolding_rjet_kt_DeltaR_pt_nominal;1

- I do not see any recipe for truth jets from Delphes, it is not available in delphes samples also
- I only have mapping between truth and reco level particles
  - Make 2D LJP distributions for reco in every pT bin
  - Map truth particle with reco particle and fill truth level 2D map in reco pT bin