QCD & Lund Jet Plane studies at FCC-ee

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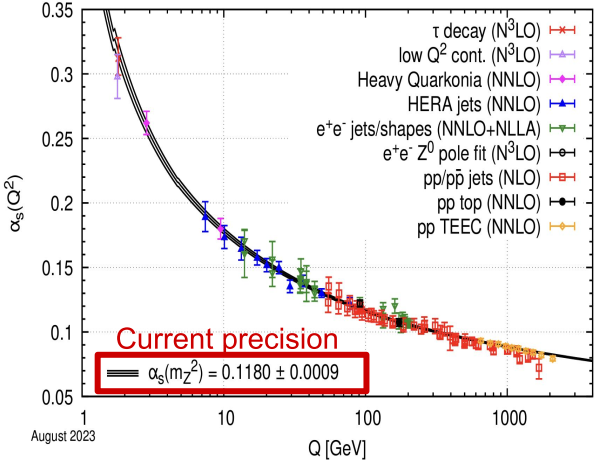
Introduction and motivation

- Analyse prospects of **QCD study@FCC-ee** using **3/2 Jet cross-section ($R_{3/2}$)** study and **Lund Jet Plane (LJP) representation**
- Aim to study the **sensitivity to α_s at FCC-ee**, to probe α_s for different energies (with $\sqrt{s}$ = 91, 240, 365 GeV) and test the Renormalization Group Equation (RGE) in QCD
  - α_s impacts both jet multiplicity and jet shape (emissions inside jet)
- Also look for the potential use of LJP for improving jet tagging (gluon jets, b jets) and impact for the optimization of detector parameters @FCC-ee

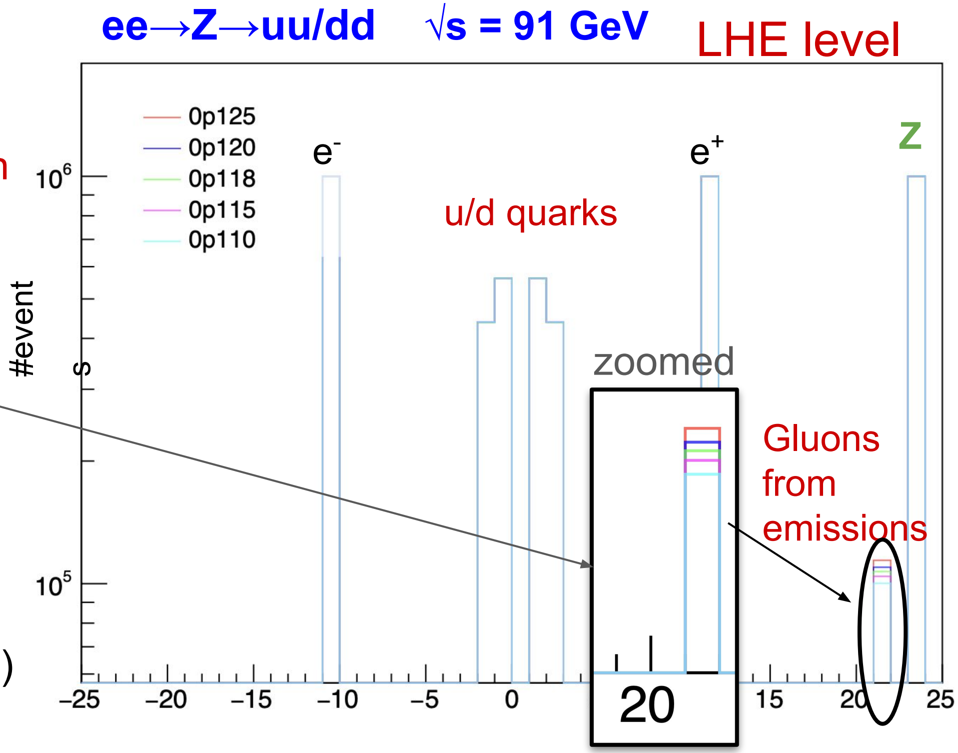


- **Why FCC-ee?**
  - Provides a clean collision environment with high statistics (10^6 X LEP Data at Z-pole); could bring significant improvement wrt to current α_s-precision
- Both analyses use **FCCAnalysis framework** along with centrally produced **Delphes samples**
- Recent LHC measurements focus on Lund Plane density measurement (See backup)

Samples

Use centrally produced Winter2023 Delphes samples for IDEA for both the analyses

- LHE level events are generated with Madgraph (MG5_aMC@NLO) for **ee→Z→ uu/dd** at **$\sqrt{s}$ = 91 GeV**
- Samples are generated with 5 different $\boldsymbol{\alpha_s}$ values: [0.110, 0.115, **0.118**, 0.120, 0.125]
- Emitted gluons multiplicity increases with α_s
- Events are further simulated with **Pythia and Delphes** generators (using IDEA detector card)
- #events = 1 M/sample



Other validation plots are in backup

Jet clustering algorithm

4.5 Generalised k_t algorithm for e^+e^- collisions

FastJet also provides native implementations of clustering algorithms in spherical coordinates (specifically for e^+e^- collisions) along the lines of the original k_t algorithms [24], but extended following the generalised pp algorithm of [14] and section 4.4. We define the two following distances:

$$d_{ij} = \min(E_i^{2p}, E_j^{2p}) \frac{(1 - \cos\theta_{ij})}{(1 - \cos R)}, \quad (9a)$$

$$d_{iB} = E_i^{2p}, \quad (9b)$$

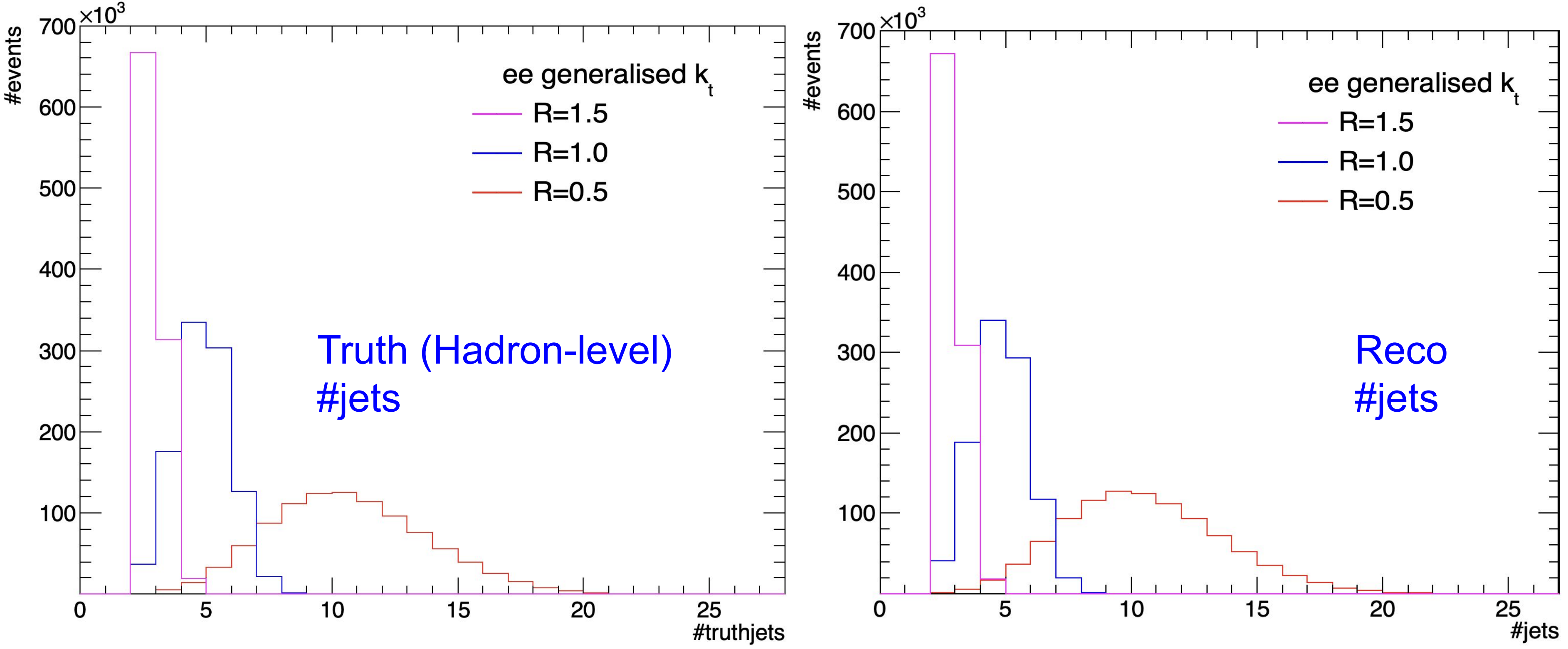
for a general value of p and R. At a given stage of the clustering sequence, if a d_{ij} is smallest then i and j are recombined, while if a d_{iB} is smallest then i is called an "inclusive jet".

For values of $R \leq \pi$ in eq. (9), the generalised e^+e^- k_t algorithm behaves in analogy with the pp algorithms: when an object is at an angle $\theta_{iX} > R$ from all other objects X then it forms an inclusive jet. With the choice $p = -1$ this provides a simple, infrared and collinear safe way of obtaining a cone-like algorithm for e^+e^- collisions, since hard well-separated jets have a circular profile on the 3D sphere, with opening half-angle R. To use this form of the algorithm, define

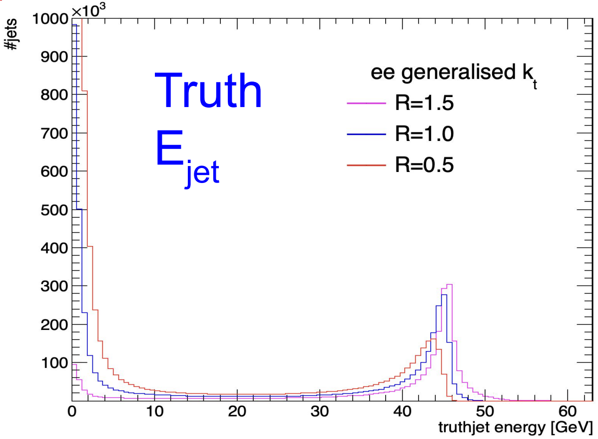
```
JetDefinition jet_def(ee_genkt_algorithm, R, p);
```

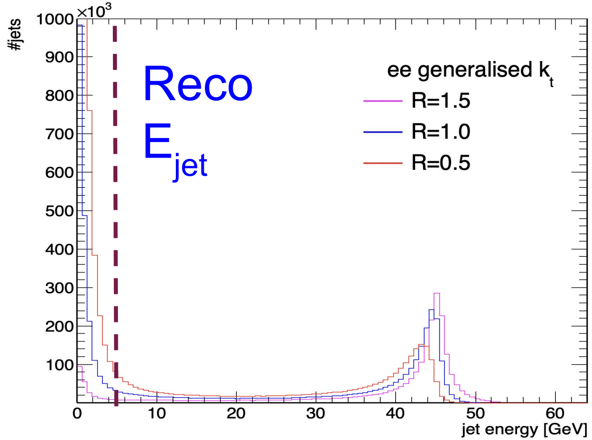
- Jet clustered with **ee Generalised k_t** (arXiv:1111.6097)
- **Input:** Jet constituents within **θ-region [0.3, π-0.3];** only include particles that are not close to beam
- For truth jet clustering:
  - Final stable particles are used
  - Neutrinos from hadronic decays inside jets are excluded from clustering for better comparison with RECO jets
- muons from pion decay are included

Jet multiplicity



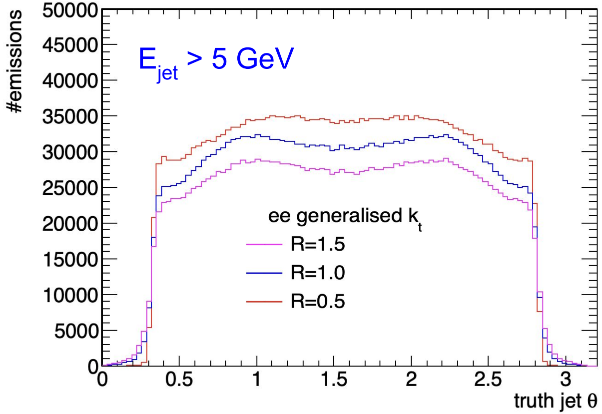
Jet reconstruction

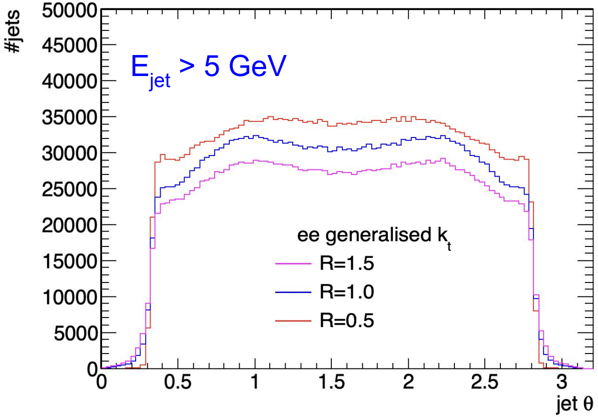




For analysis jets should further pass:

- E_{jet} > 5 GeV
- [0.3+R, π-0.3-R] angular acceptance
- #jets > 1





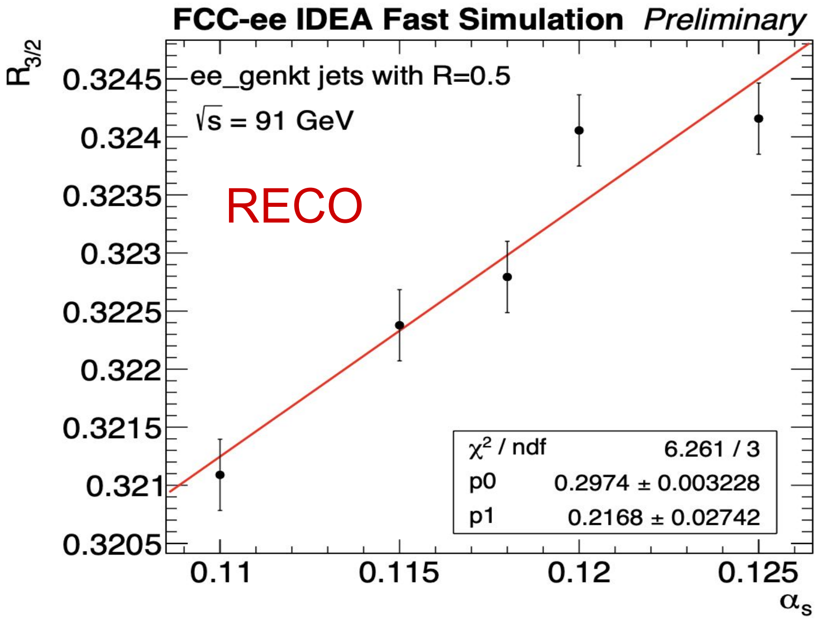
NOTE:

- For R=1.5 jet, **θ** cut is not possible
- Not much stats survive with **θ** cut for R=0.7, 0.8 and 1.0 jets; will request more stats.
- For now, use R=0.5 jets

Study I: $R_{3/2}$ studies

- Study jet cross section ratio between events with at least 3 jets vs 2 jets (α_s impacts jet multiplicity)
- Observe $R_{3/2}$ dependency on α_s

$$R_{3/2} = \frac{\text{The number of events with at least 3 jets}}{\text{The number of events with at least 2 jets}}$$

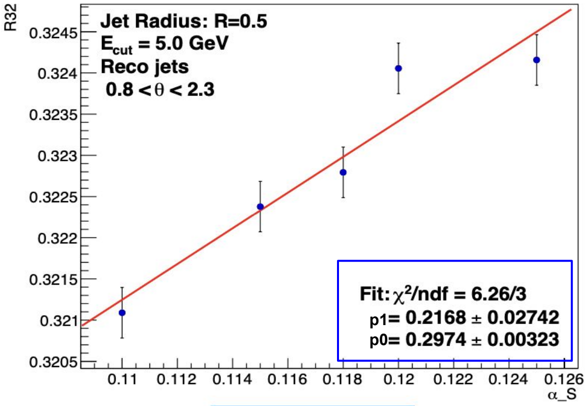


R=0.5 jets	Variation in $R_{3/2}$
Truth (Hadron-level)	$(0.21 \pm 0.03)\Delta\alpha_s$
Reco	$(0.22 \pm 0.03)\Delta\alpha_s$

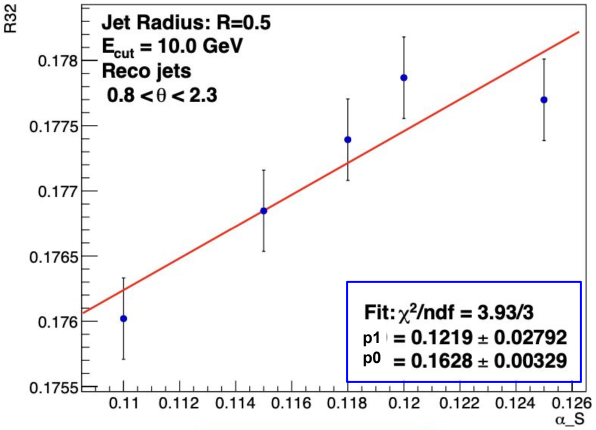
Note:

- Error bars represent stat. unc. Only
- See backup s20 for R=0.7,0.8,1.0 jets

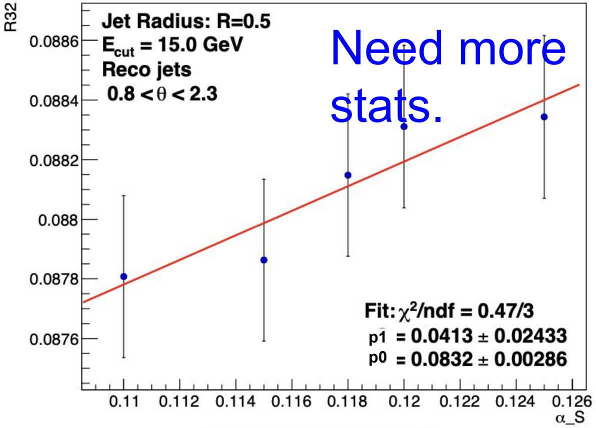
Study I: $R_{3/2}$ studies



Ecut=5GeV



Ecut=10GeV

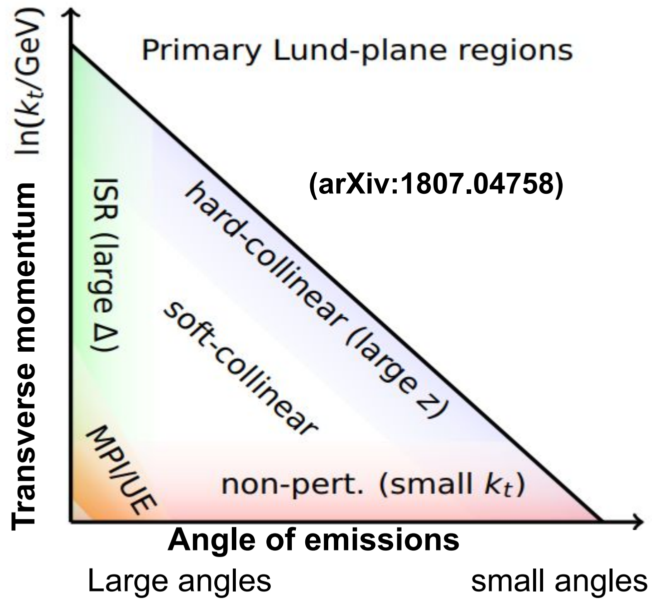


Ecut=15GeV

- **E_{jet} > 5 GeV** cut was used as the standard, though this cut impacts the jet multiplicity.
- Consequently, analyze the dependence of $R_{3/2}$ on this cut.
  - Dependence of $R_{3/2}$ on α_s decreases when comparing **E_{jet} > 10 GeV** with **E_{jet} > 5 GeV**.

Study II : Lund Jet Plane studies

- QCD jet formation involves perturbative and non-perturbative effects; presence of these effects impacts the precision of any measurement based on jets
- LJP works as a handle to separate these effects in a 2D representation using angle (ΔR) 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

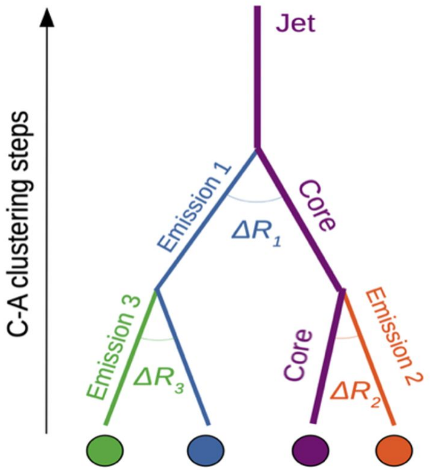


- α_s impacts jet shape (emissions within jets); Average density of emissions in LJP can be given as

$$\rho(k_T, \Delta R) \equiv \frac{1}{N_{\text{jets}}} \frac{d^2 N_{\text{emissions}}}{d\ln(k_T/\text{GeV})\, d\ln(R/\Delta R)} \approx \frac{2}{\pi} C_R \alpha_S(k_T)$$

Where C_R = color factor

How to build Lund Jet Plane?



- Start with a jet and cluster it again to have angular order information of emissions (*JHEP 12 (2018) 064*)
- Decluster them in reverse (start with wide angle emission first)
- Within the iterative declustering, harder branch is always taken as core branch
- Fill a triangular plane of two Lund variables (k_t and ΔR) from core and emission

NOTE:

- Angular ordered Cambridge/Aachen (C/A) declustering (following the theoretical proposal) depends on ΔR in (**y**, ϕ) plane used for LHC studies (given in backup)
- It is more accurate to perform ΔR-based declustering in the (**θ**, ϕ) plane for FCC-ee. Therefore, we use EECambridgePlugin algorithm

For "a" core and "b" emission branch

$$k_t \equiv p_{tb} \Delta R_{ab}$$

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

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

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

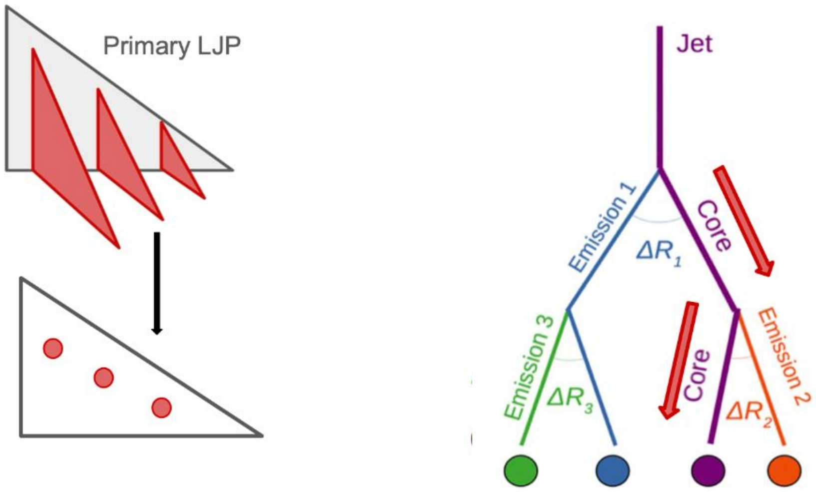
z = momentum fraction taken by **b**

Analysis studies for primary and secondary LJP

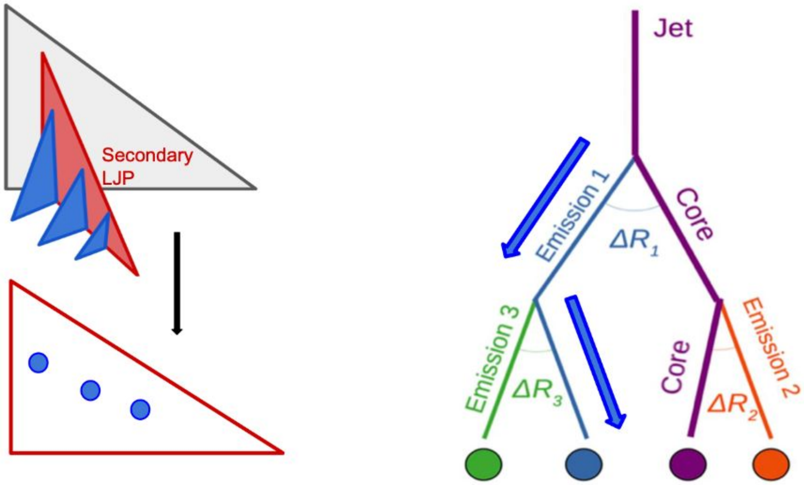
- Motivated from following the theoretical proposal [link] which show secondary LJP is mostly gluon induced

How to build Primary and Secondary Lund Jet Plane?

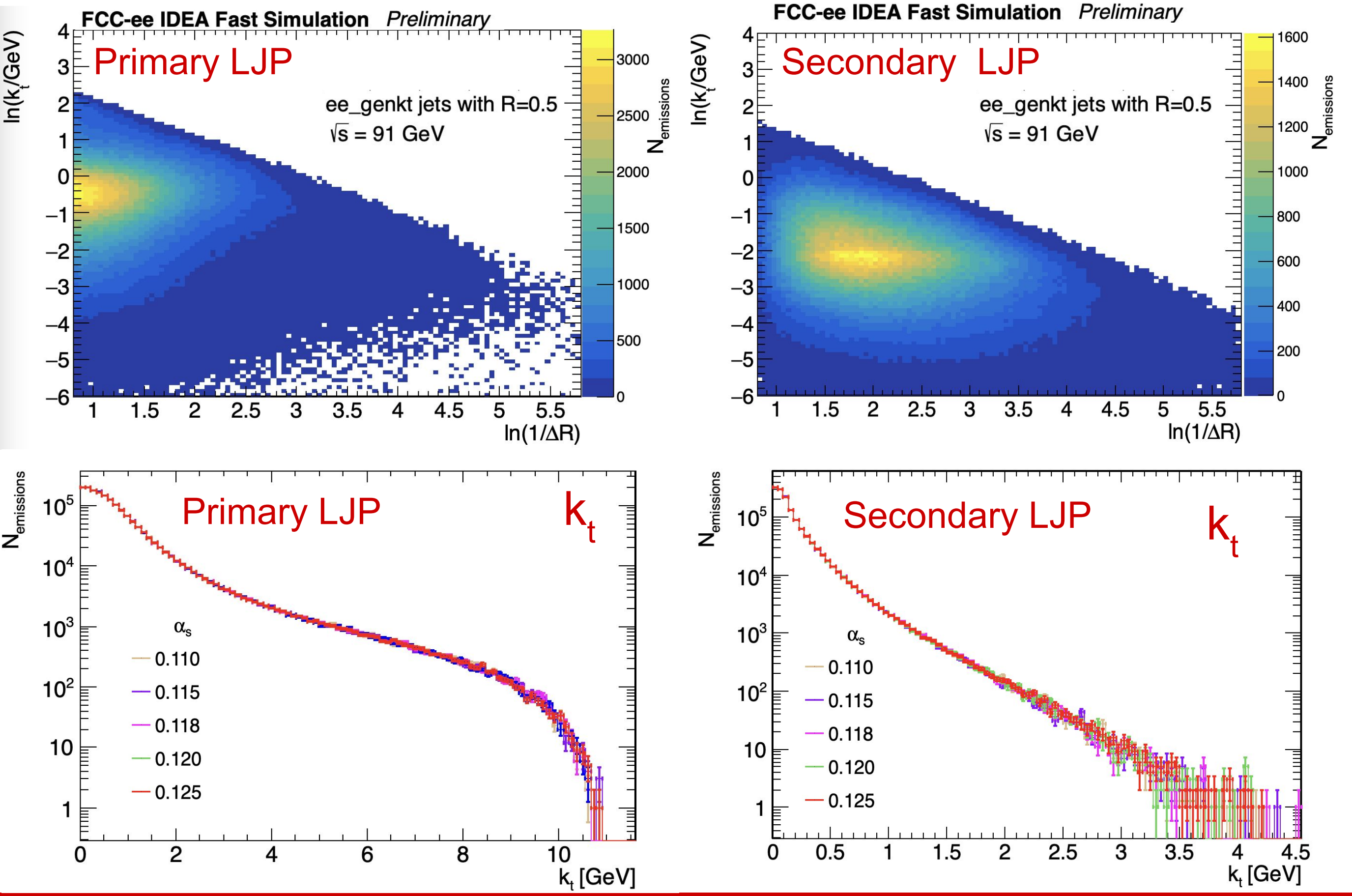
Primary LJP



Secondary LJP



Preliminary look at LJPs: Primary and Secondary LJP



Observe difference for primary and secondary LJPs

Secondary LJP corresponds mostly to gluon emission

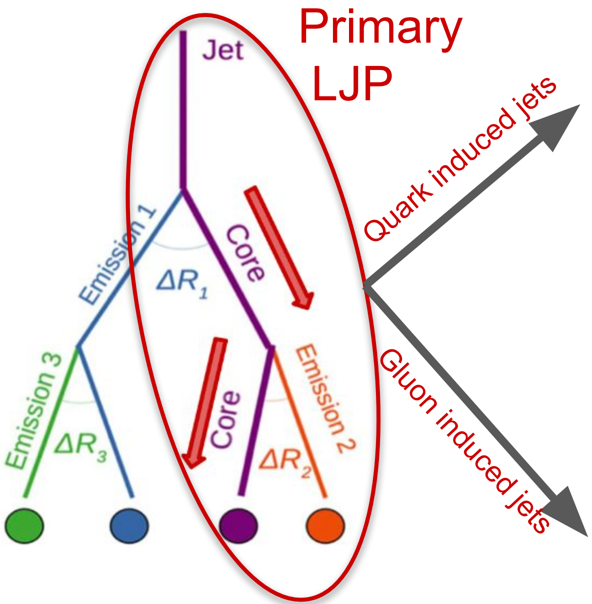
- leads towards developing jet tagging methods using LJP

Note:

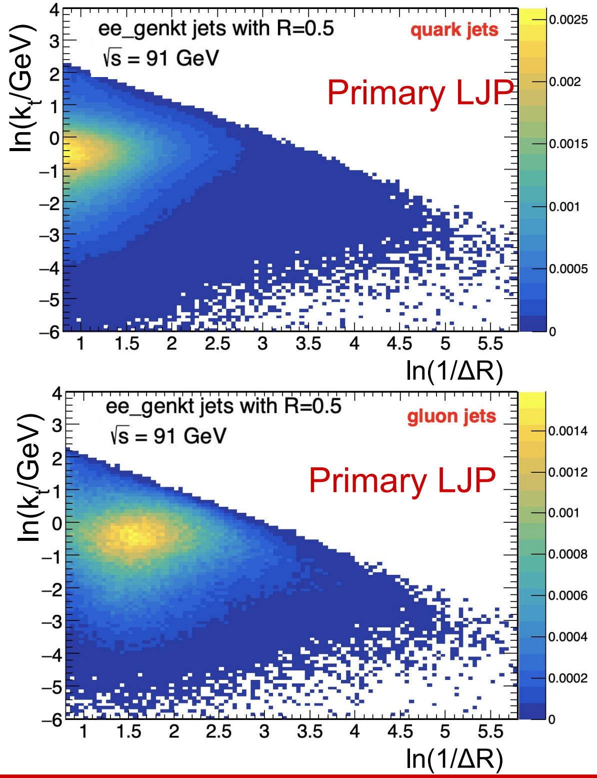
$\ln(k_t) = -3 \Rightarrow k_t \sim 50$ MeV
$\ln(k_t) = -2 \Rightarrow k_t \sim 135$ MeV
$\ln(k_t) = -1 \Rightarrow k_t \sim 360$ MeV
$\ln(k_t) = 1 \Rightarrow k_t \sim 3$ GeV
$\ln(k_t) = 3 \Rightarrow k_t \sim 20$ GeV

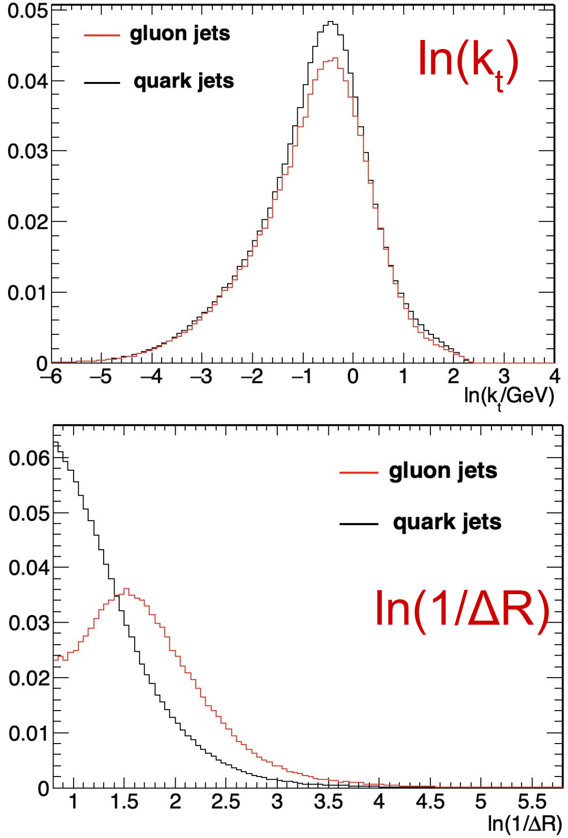
Potential of jet tagging using LJPs

- **Primary LJP for quark and gluon-induced jets**; will be extended to heavy (Z→bb) vs light flavor (H→gg) jets



ee→Z→uu/dd √s = 91 GeV



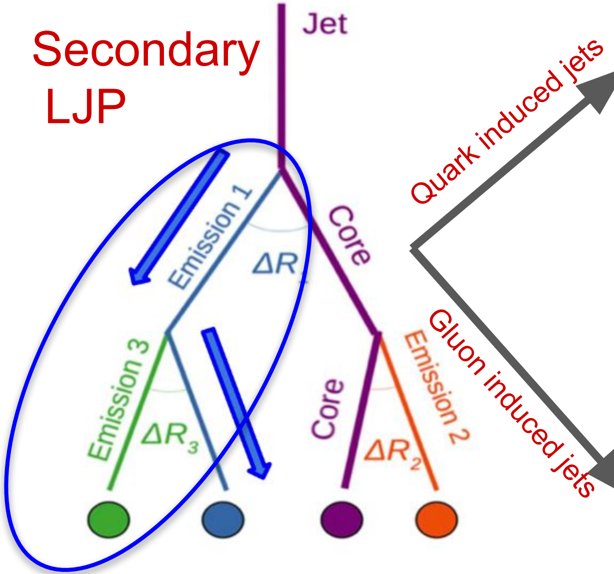


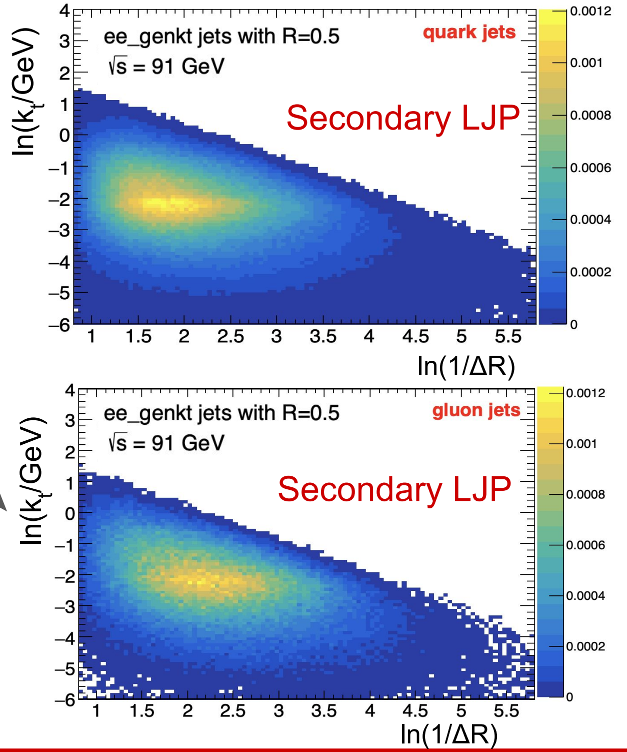
NOTE:
Gluons are emitted from quarks in ee→Z→ uu/dd process

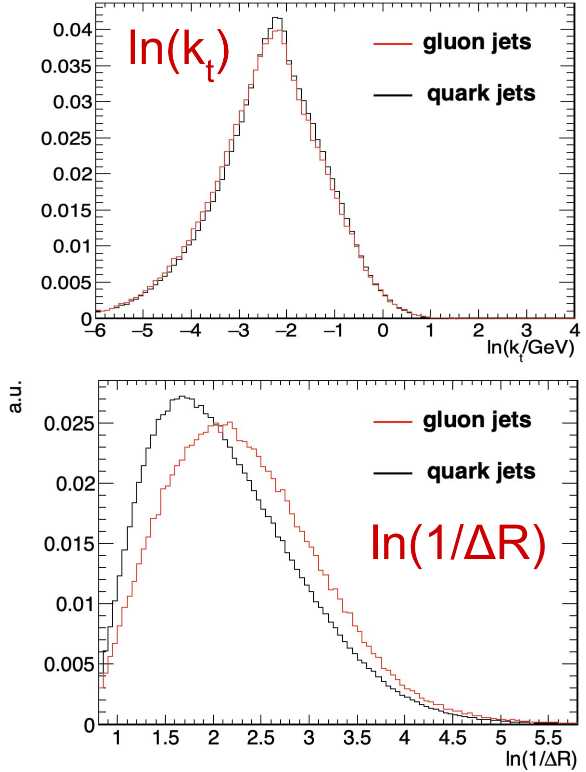
Potential of jet tagging using LJPs

- **LJP representation for first emission from quark- and gluon-induced jets**; observe similar pattern as expected since first emission corresponds mostly to gluons

ee→Z→uu/dd √s = 91 GeV







Summary and next steps

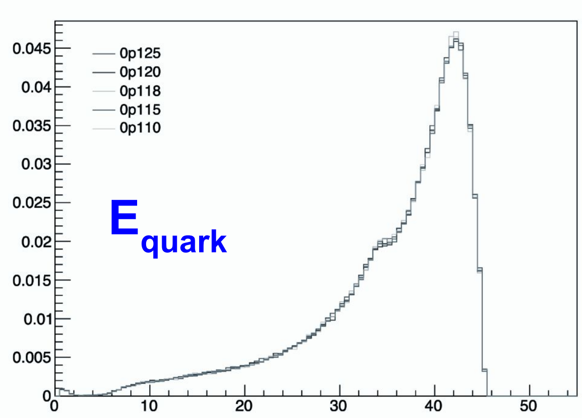
- Present updates of $R_{3/2}$ jet cross section study and Lund Jet Plane studies at FCC-ee
  - Motivated by the study of the sensitivity to α_s and test of RGE
- **$R_{3/2}$ study:**
  - Observe dependency of $R_{3/2}$ on variation of α_s; redo with more stats. to have conclusive results
  - Plan to study the same for with different targeted energies at FCC-ee
- **LJP Study:**
  - To our knowledge it is the first study that looks at jet substructure at FCC-ee
  - Switch to ee-dedicated algorithm for jet clustering/declustering
  - Plan to explore the sensitivity of the reconstructed LJP to:
    - α_s by doing α_s-scan
    - Optimization of the detector parameters
    - Also potential use for jet tagging methods at FCC-ee

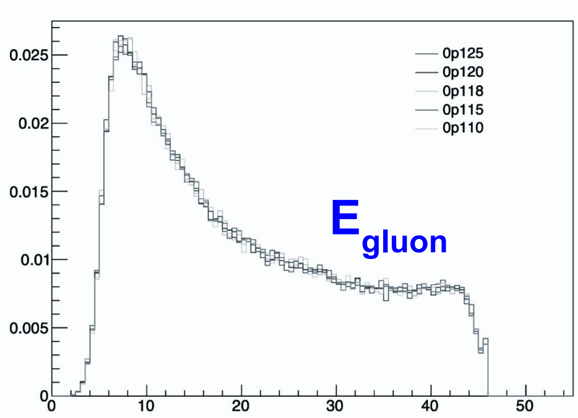
Thank you

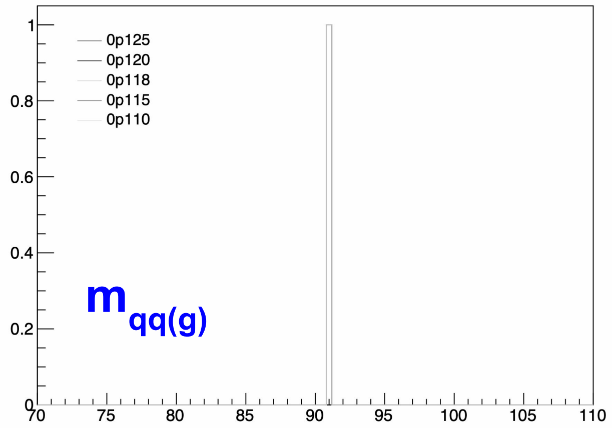
BACKUP

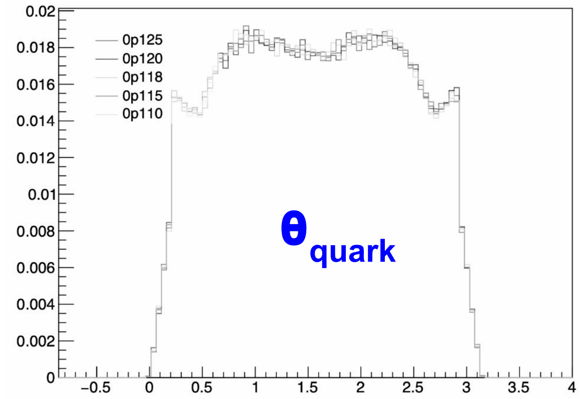
Validation studies:LHE level

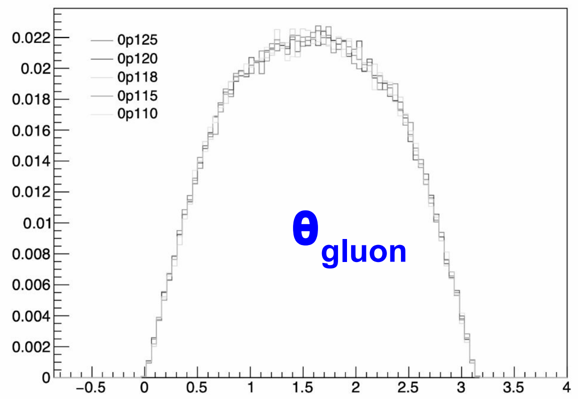
- Distributions are shown for different α_s values and are shape normalized
- No selection at generator level



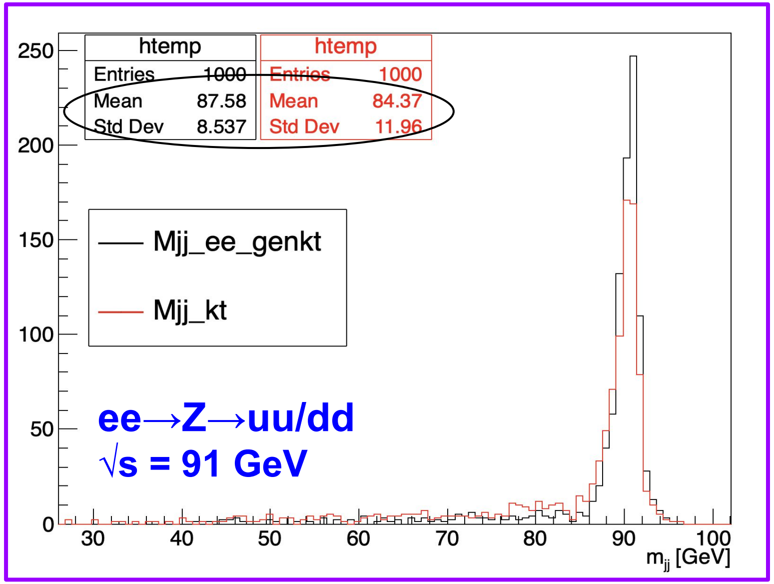








Jet reconstruction with Delphes samples



4.5 Generalised k_t algorithm for e^+e^- collisions arXiv:1111.6097

FastJet also provides native implementations of clustering algorithms in spherical coordinates (specifically for e^+e^- collisions) along the lines of the original k_t algorithms [24], but extended following the generalised pp algorithm of [14] and section 4.4. We define the two following distances:

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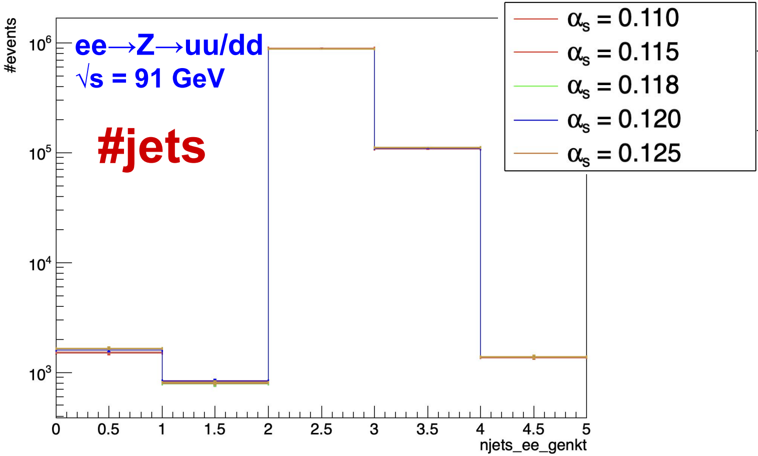
for a general value of p and R. At a given stage of the clustering sequence, if a d_{ij} is smallest then i and j are recombined, while if a d_{iB} is smallest then i is called an "inclusive jet".

For values of $R \leq \pi$ in eq. (9), the generalised e^+e^- k_t algorithm behaves in analogy with the pp algorithms: when an object is at an angle $\theta_{iX} > R$ from all other objects X then it forms an inclusive jet. With the choice $p = -1$ this provides a simple, infrared and collinear safe way of obtaining a cone-like algorithm for e^+e^- collisions, since hard well-separated jets have a circular profile on the 3D sphere, with opening half-angle R. To use this form of the algorithm, define

```
JetDefinition jet_def(ee_genkt_algorithm, R, p);
```



- Explored various jet reconstruction algorithms
- Better m_{jj} resolution with θ-based ee generalised k_t algorithms with R = 1.5 and p = -1 wrt $\Delta R(y,\phi)$-based k_t algorithms
- Jet kinematics distributions are in backup

Angular order-based jet declustering in (θ, ϕ) plane

- Use ee-dedicated Cambridge algorithm (**EECambridgePlugin**); Implemented in code with help from fastjet experts (link)
- Setup is in place

arXiv:1111.6097

5.4 Plugins for e^+e^- collisions

5.4.1 Cambridge algorithm

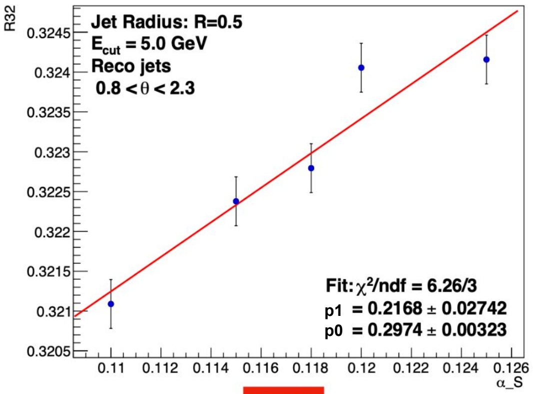
The original e^+e^- Cambridge [22] algorithm is provided as a plugin:

```
#include "fastjet/EECambridgePlugin.hh"
// ...
EECambridgePlugin (double ycut);
```

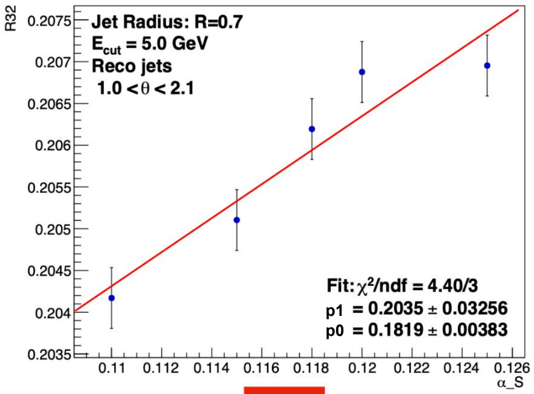
This algorithms performs sequential recombination of the pair of particles that is closest in angle, except when $y_{ij} = \frac{2\min(E_i^2, E_j^2)}{Q^2}(1 - \cos\theta) > y_{cut}$, in which case the less energetic of i and j is labelled a jet, and the other member of the pair remains free to cluster.

To access the jets, the user should use the `inclusive_jets()`, *i.e.* as they would for the majority of the *pp* algorithms.

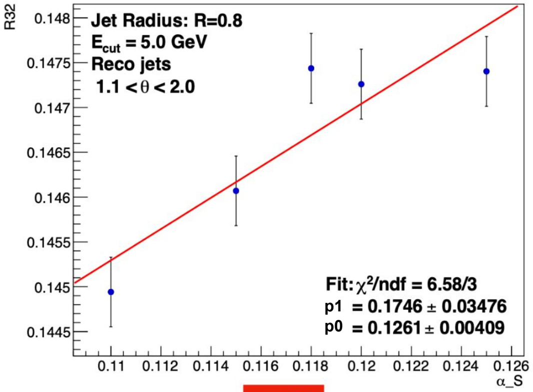
$R_{3/2}$ studies



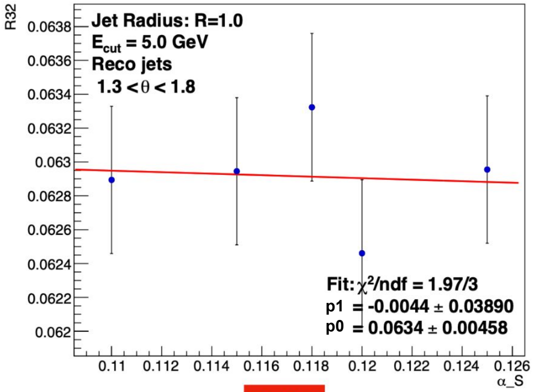
R=0.5



R=0.7



R=0.8

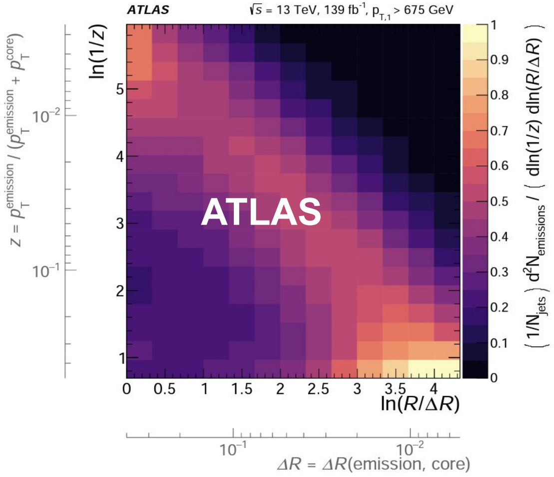


R=1.0

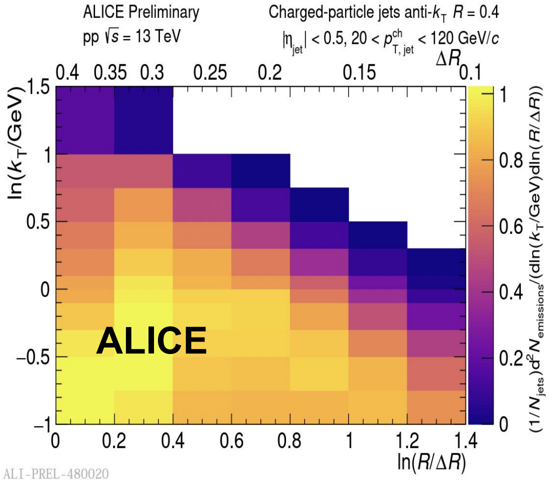
Recent Lund Jet Plane based measurements

- 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

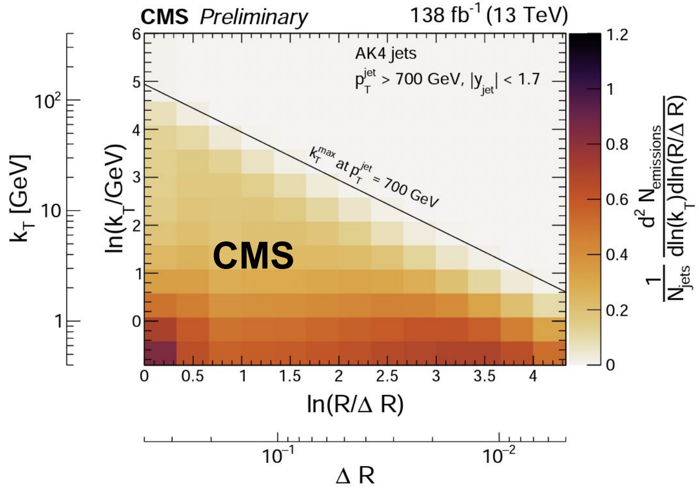
arXiv 2004.03540



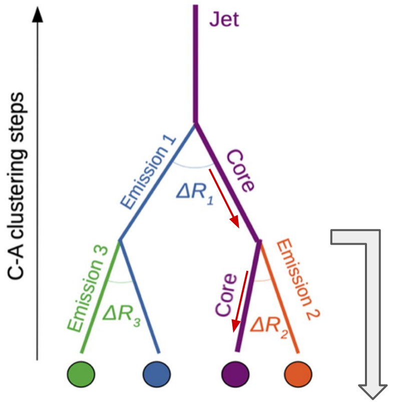
arXiv 2111.00020



CMS-PAS-SMP-22-007

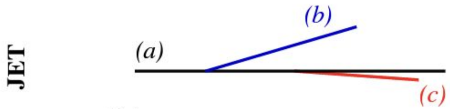


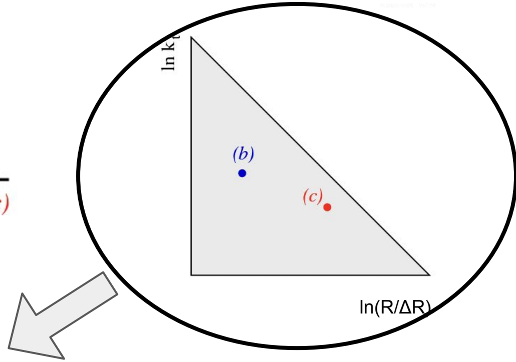
How to build Primary Lund Jet Plane?



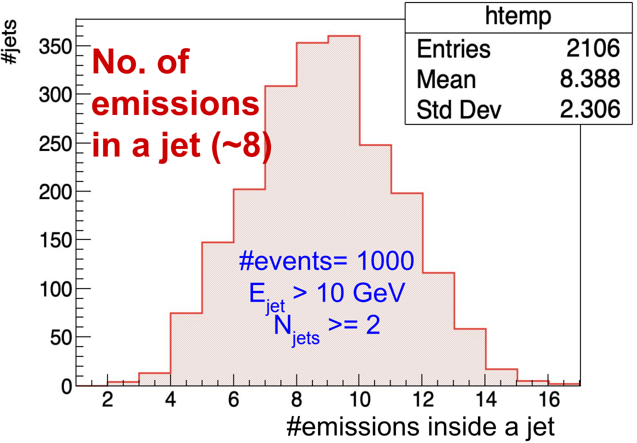
For R=1.5 jets clustered with k_t algorithm (Kt15)

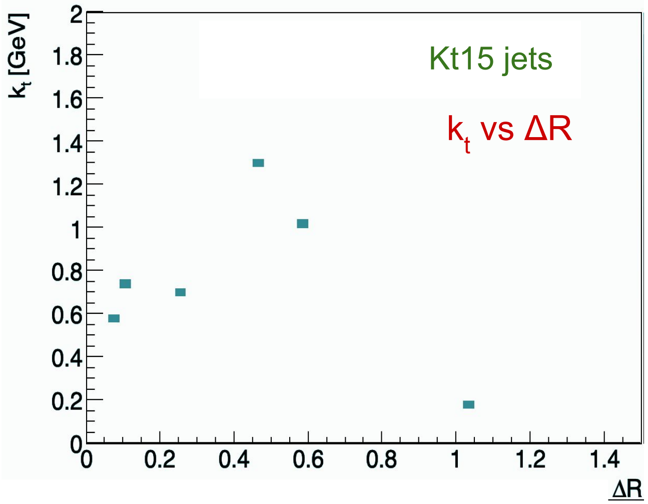
ee → Z→ uu/dd @91 GeV

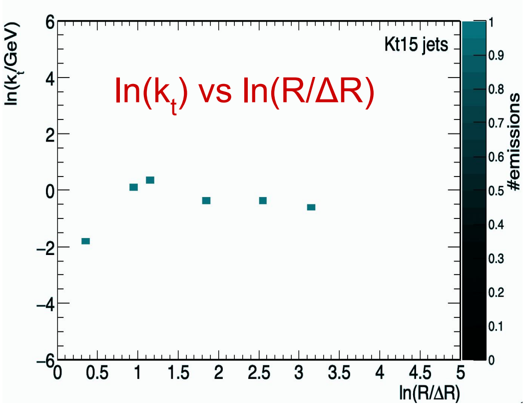




Emissions from the core branches







LJP representation for 1 jet of E_{jet} ~ 40 GeV

(both plots represent the same jet w/ and w/o log scale)