QCD & Lund Jet Plane studies at FCC-ee

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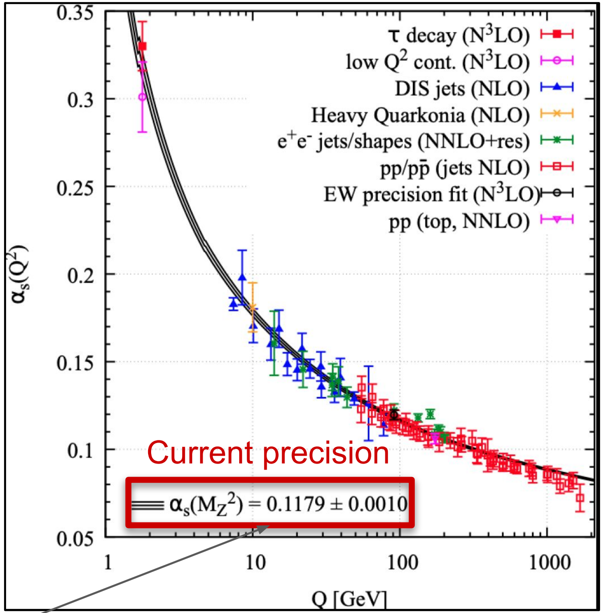
ECFA Early Career Researchers' Workshop

Introduction and motivation

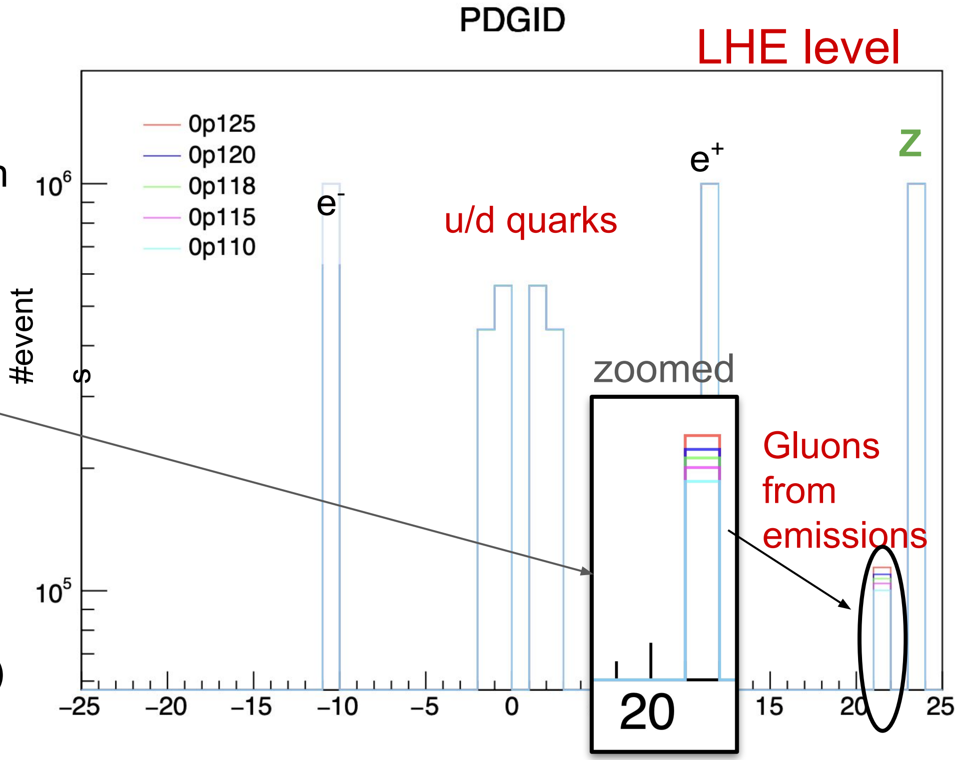
- Analyse prospects of **QCD study@FCC-ee** using **3/2 Jet cross-section ($R_{3/2}$)** study and **Lund Jet Plane (LJP) representation**
- Aim to study the **sensitivity to α_s at FCC-ee**, to probe α_s for different energies and test the Renormalization Group Equation (RGE) in QCD
  - α_s impacts both jet multiplicity and jet shape (emissions inside jet)
- Also look for the potential use of LJP for improving jet tagging 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)
  - Expect factor of 10 improvement with respect to the current α_s precision
- Both analyses use FCCAnalysis framework along with centrally produced Delphes samples



Samples

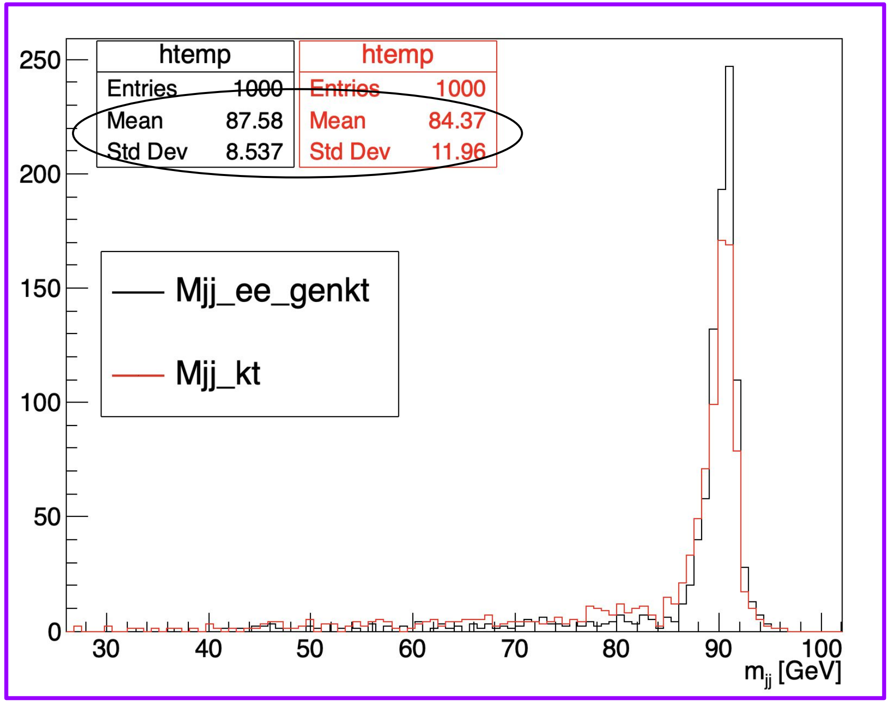
Use centrally produced Winter2023 Delphes samples for IDEA

- 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 LHE validation plots are in backup

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:

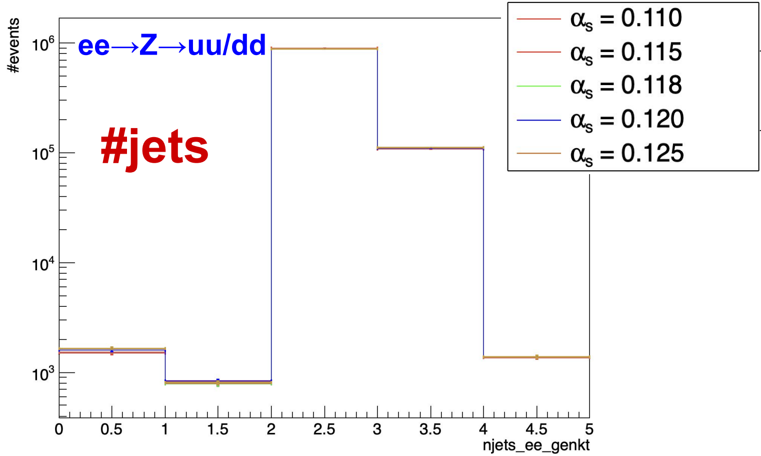
$$d_{ij} = \min(E_i^{2p}, E_j^{2p}) \frac{(1 - \cos\theta_{ij})}{(1 - \cos R)}, \quad (9a)$$

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

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".

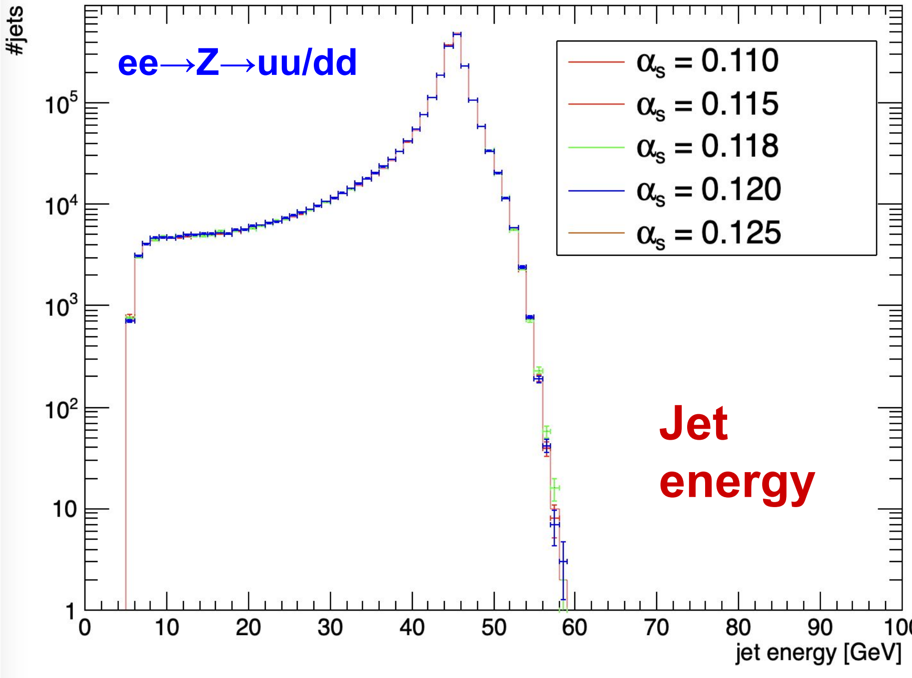
For values of $R \leq \pi$ in eq. (9), the generalised e^+e^- k_t algorithm behaves in analogy with the pp algorithms: when an object is at an angle $\theta_{iX} > R$ from all other objects X then it forms an inclusive jet. With the choice $p = -1$ this provides a simple, infrared and collinear safe 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

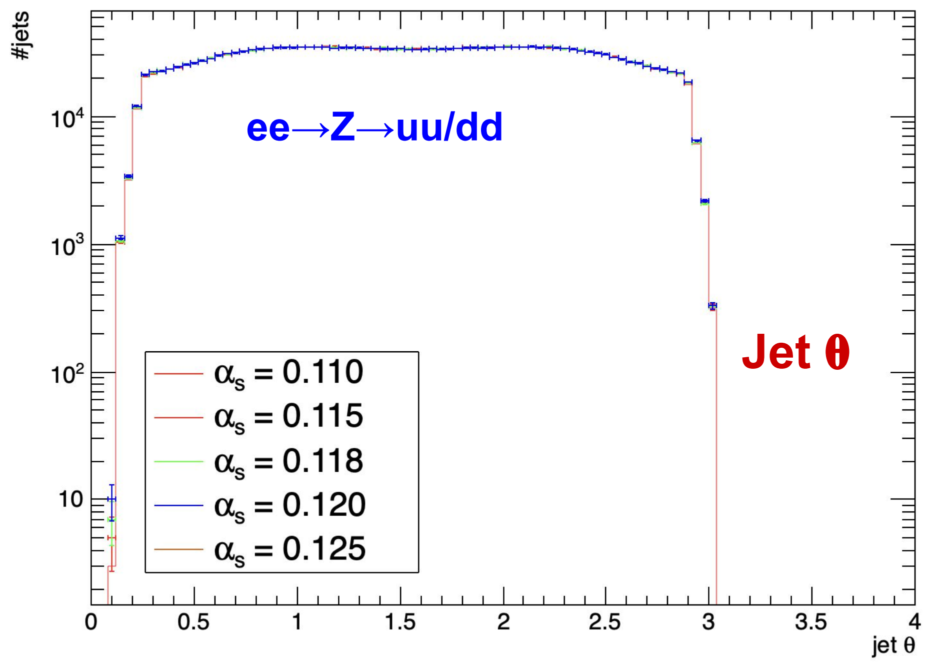
```
JetDefinition jet_def(ee_genkt_algorithm, R, p);
```



- Jet reconstruction with ee generalised k_t algorithm with R = 1.5 and p = -1
- Better m_{jj} resolution with θ-based k_t algorithms wrt $\Delta R(y, \phi)$-based k_t algorithms

Jet Kinematics





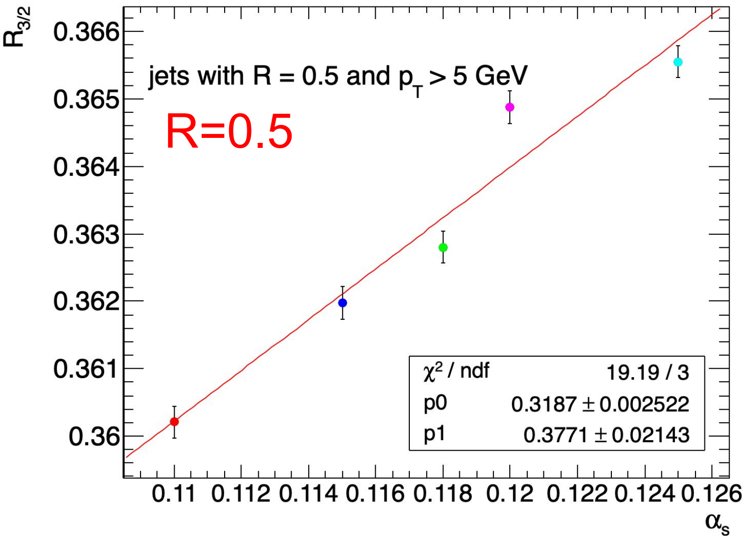
- Jet kinematics look as expected for Z→ uu/dd process

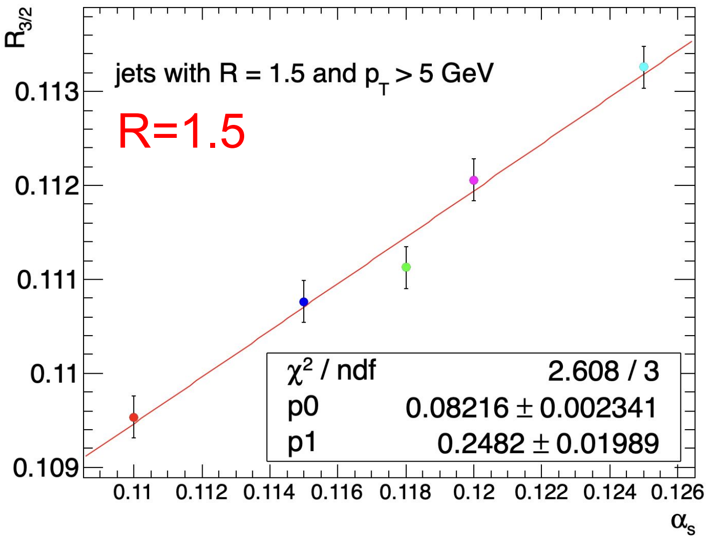
Study I: $R_{3/2}$ studies

- 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

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

Jets	Variation in $R_{3/2}$
R=0.5	0.38 ± 0.02 $\Delta\alpha_s$
R=1.5	0.25 ± 0.02 $\Delta\alpha_s$





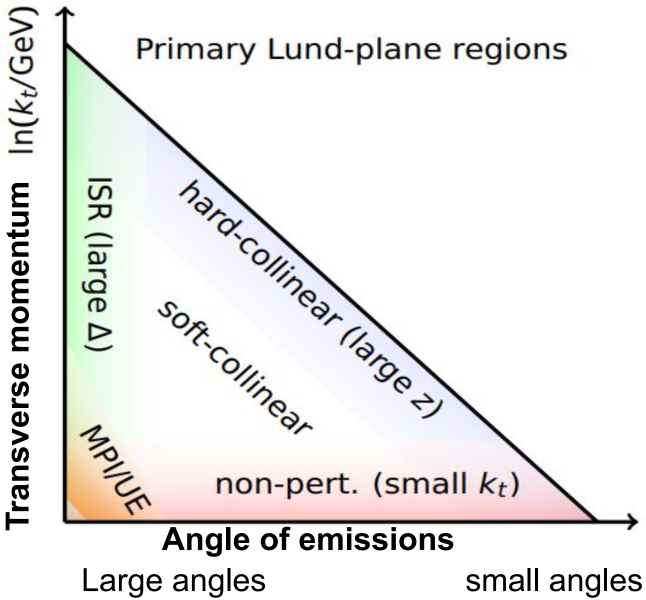
Next: Study ongoing with jets at hadron level

Study II : Lund Jet Plane studies

Benefits of Lund Jet Plane method (LJP):

- 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

(arXiv:1807.04758)



How to extract α_s ?

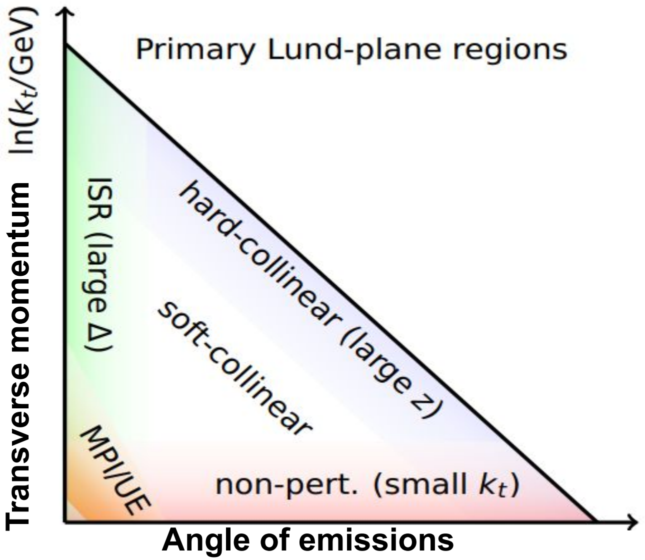
- QCD process behind jet formation is related to strong coupling constant α_s
  - Running constant which varies with different energies
  - Impacts jet shape (emissions within jets)

Average density of emissions in LJP can be given as:

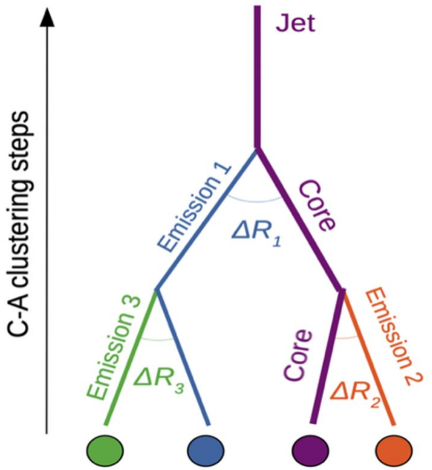
$$\rho(k_T, \Delta R) \equiv \frac{1}{N_{\text{jets}}} \frac{d^2 N_{\text{emissions}}}{d\ln(k_T/\,\text{GeV})\, d\ln(R/\Delta R)} \approx \frac{2}{\pi} C_R \alpha_S(k_T)$$

Where C_R = color factor

(arXiv:1807.04758)



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 triangle 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**

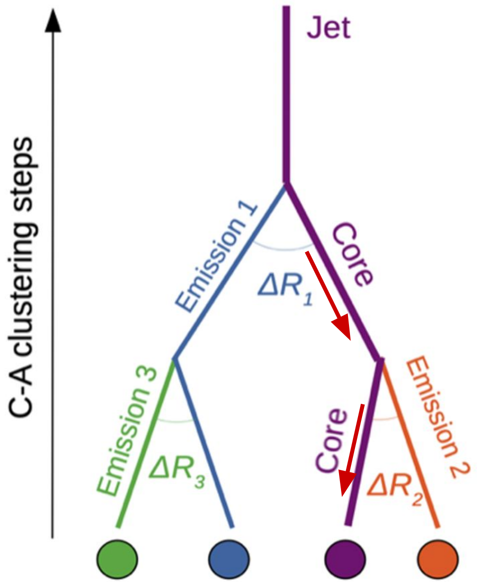
z = momentum fraction taken by **b**

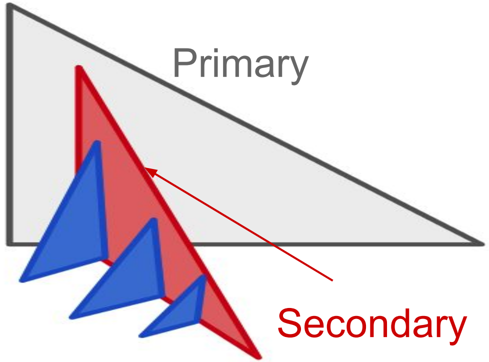
Analysis studies for primary and secondary LJP

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

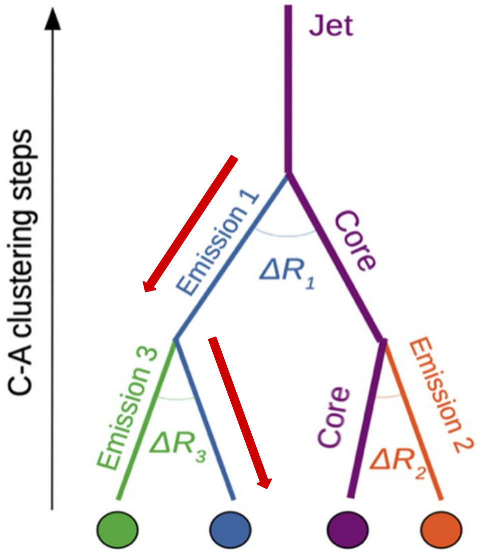
How to build Primary and Secondary Lund Jet Plane?

Primary LJP

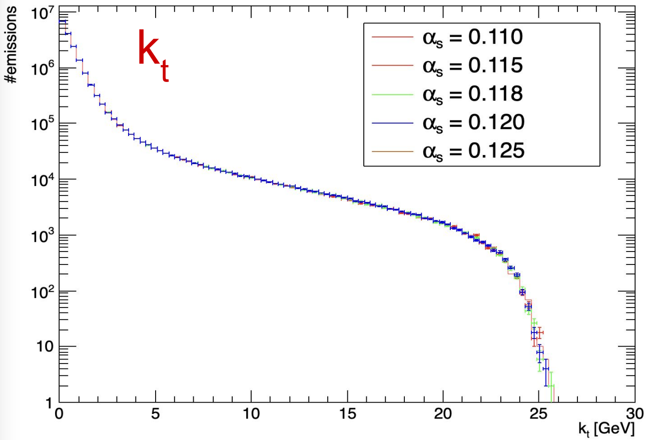


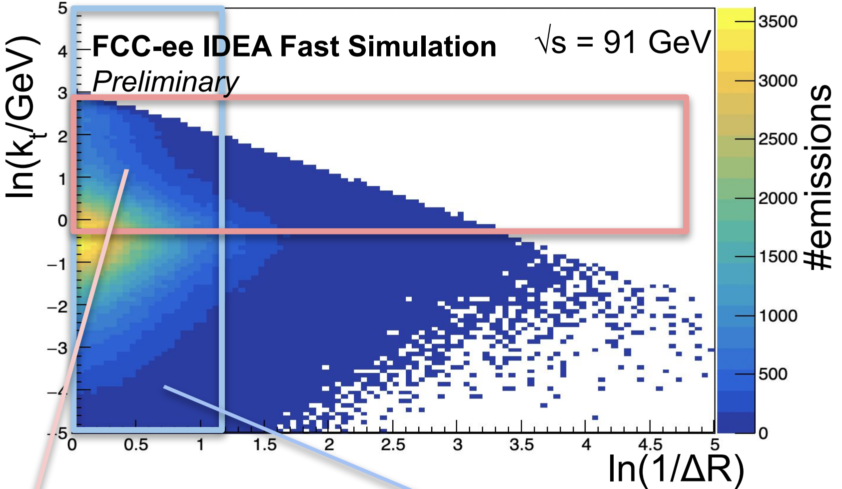


Secondary LJP



Preliminary look at LJPs: Primary LJP



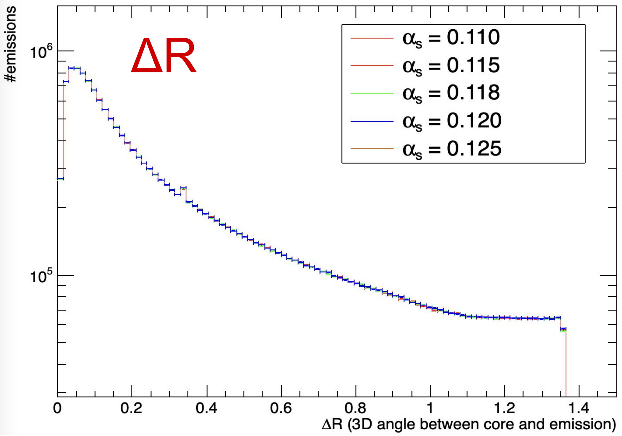


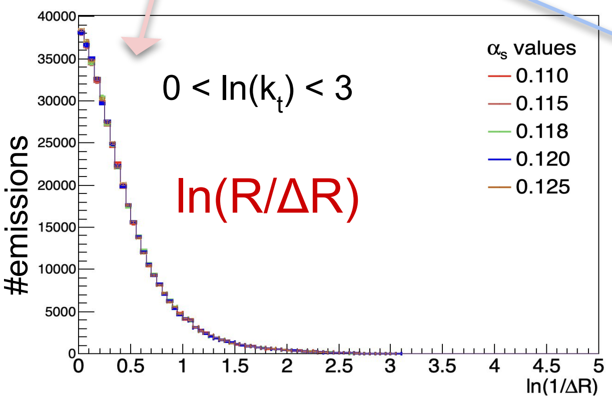
Selections:

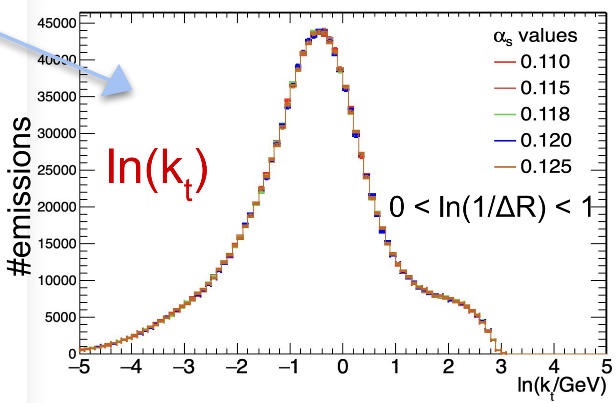
E_{jet} > 10 GeV

#jets > 1

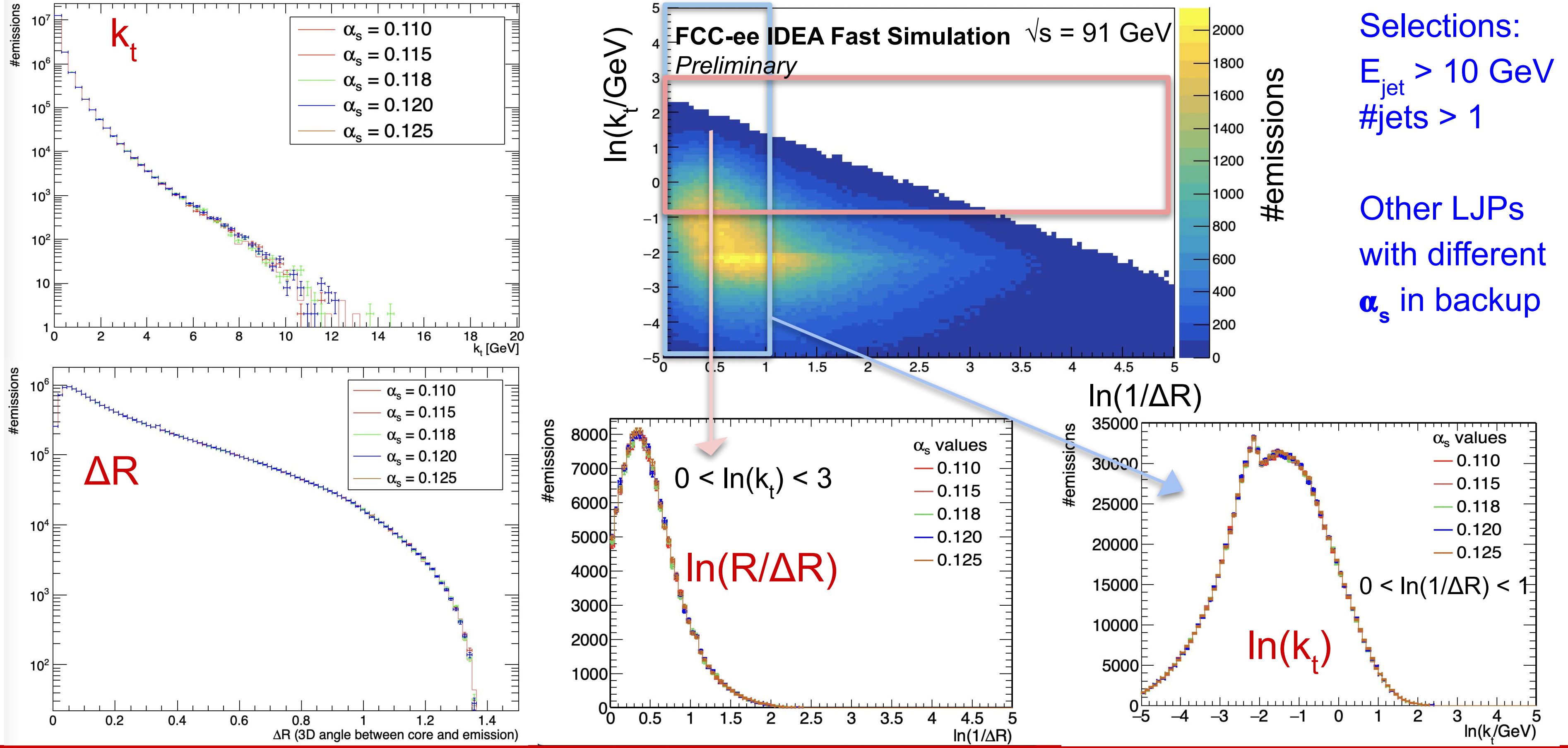
Other LJPs with different $\boldsymbol{\alpha_s}$ in backup







Preliminary look at LJPs: Secondary LJP



Selections:

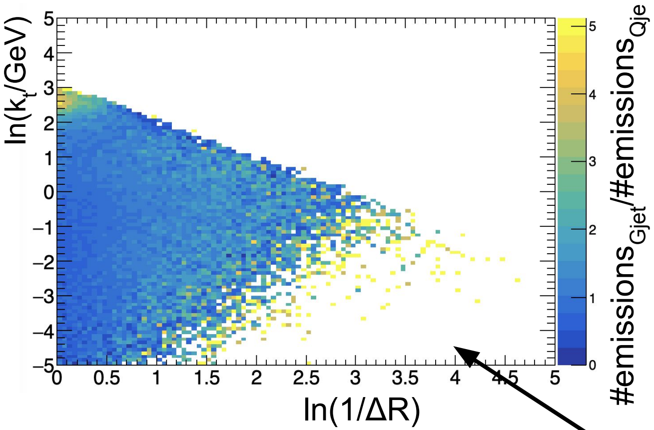
E_{jet} > 10 GeV

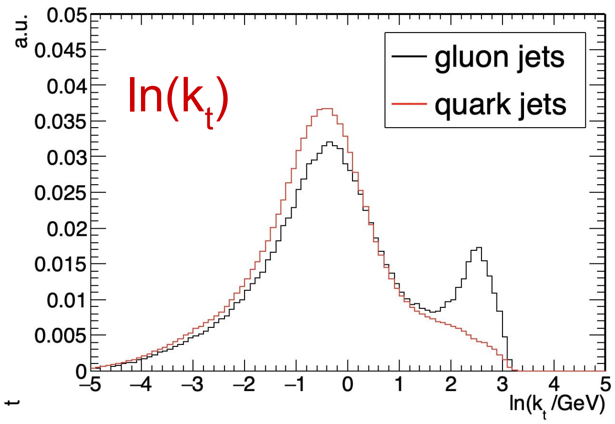
#jets > 1

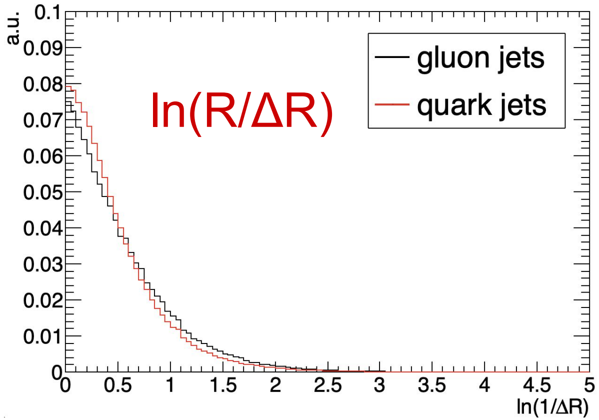
Other LJPs with different α_s in backup

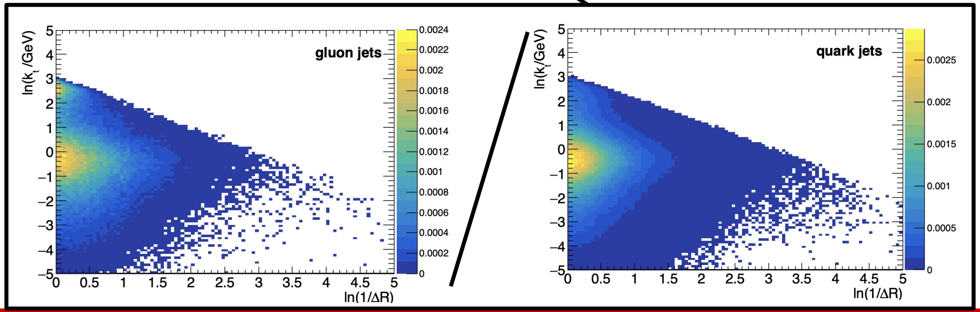
Other efforts and interests

- Our team is also working to study the potential of LJP for jet tagging methods
  - For now study is ongoing for quark and gluon jets; will be extended to heavy (Z→bb) vs light flavor (H→gluglu) jets









I am also taking responsibility as MC contact for FCC SM subgroup

Summary and next steps

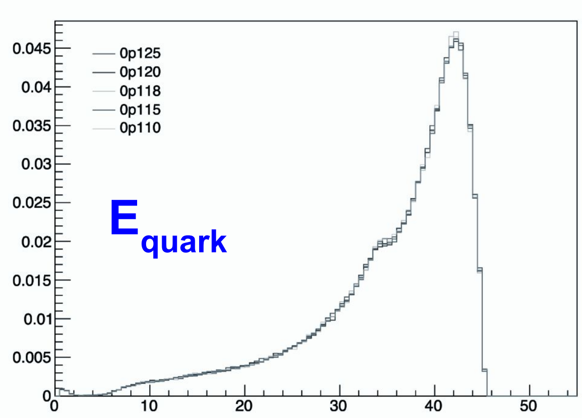
- Present updates of $R_{3/2}$ jet cross section study and Lund Jet Plane studies at FCC-ee
  - Motivated by the study of the sensitivity to α_s and test of RGE
- **$R_{3/2}$ study:**
  - Observe dependency of $R_{3/2}$ on variation of α_s
  - Study ongoing with jets at hadron level
- **LJP Study:**
  - To our knowledge it is first study which 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; (explore both Primary and Secondary LJP)
    - Optimization of the detector parameters
    - Also potential use for jet tagging methods at FCC-ee

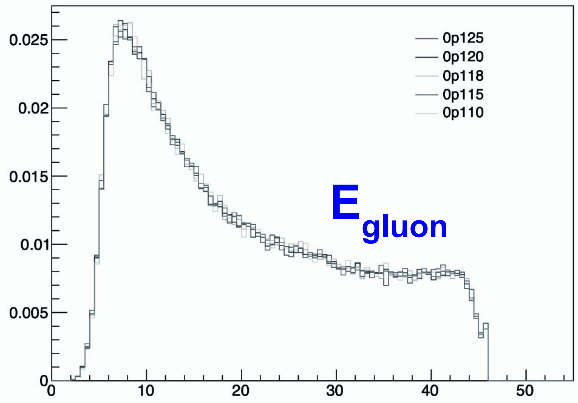
Thank you

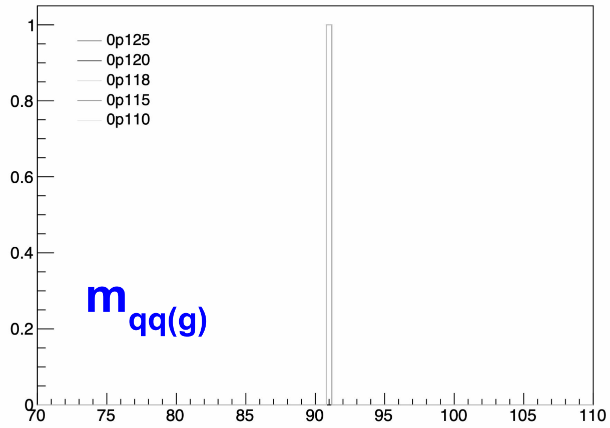
BACKUP

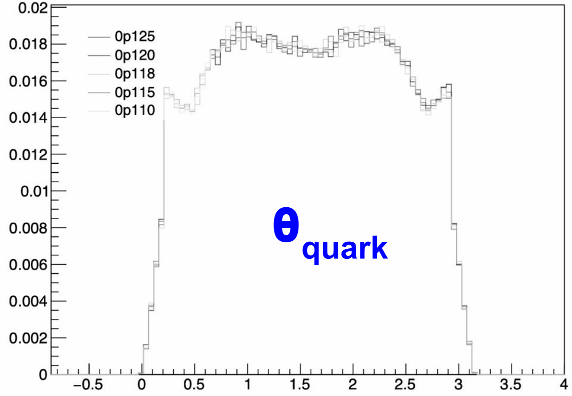
Validation studies:LHE level

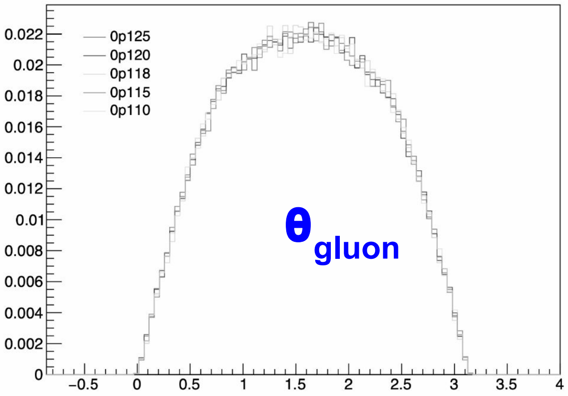
- Distributions are shown for different α_s values and are shape normalized
- No selection at generator level



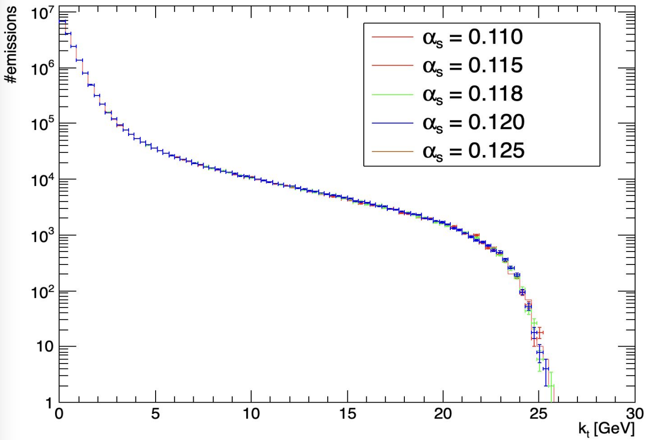


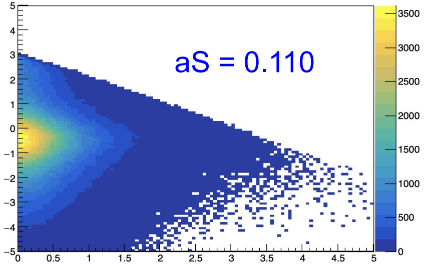


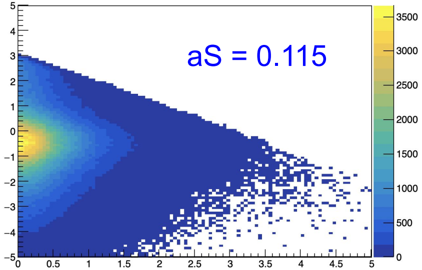


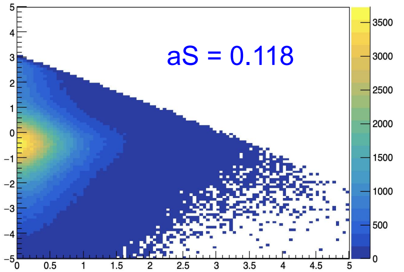


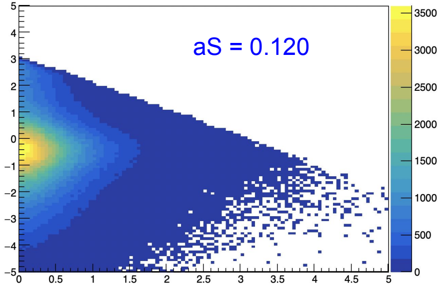
Preliminary look at LJPs: Primary LJP

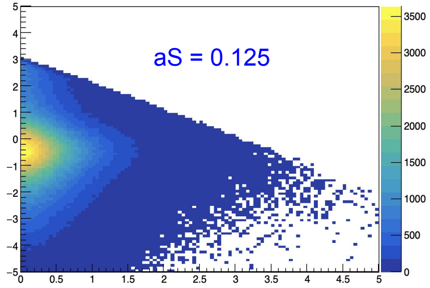


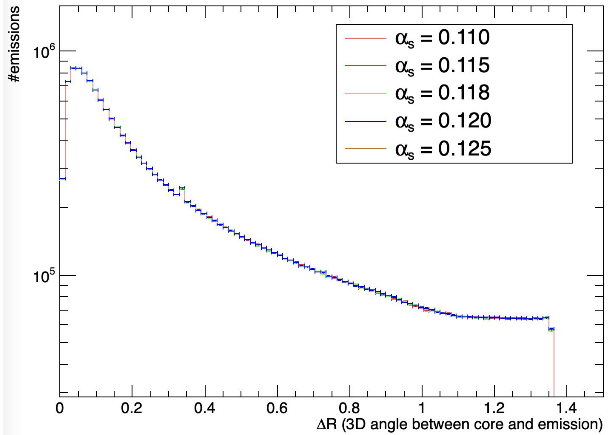




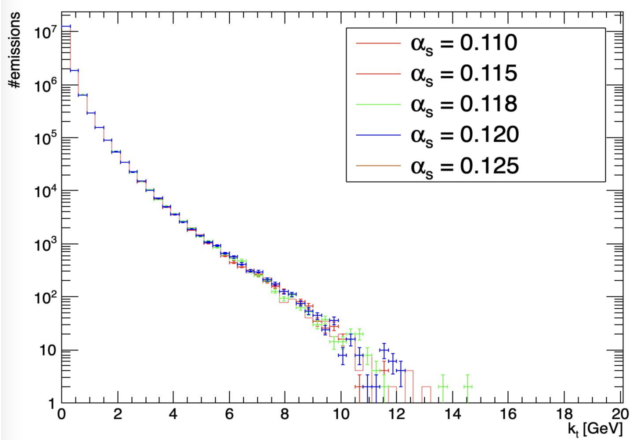


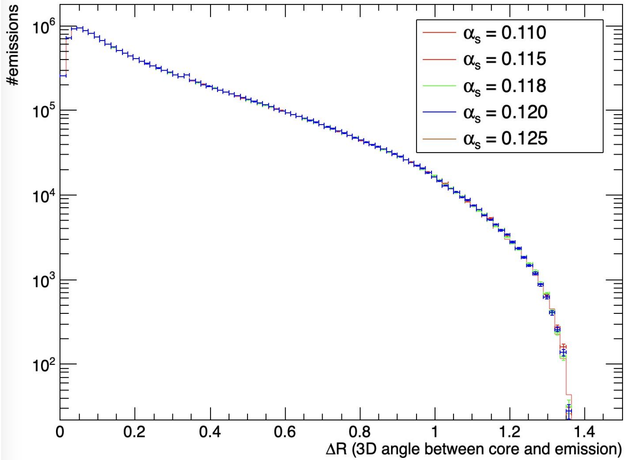


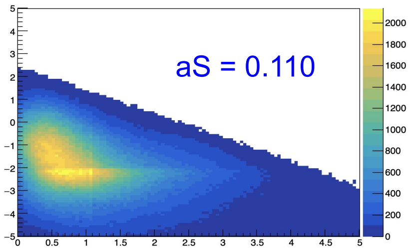


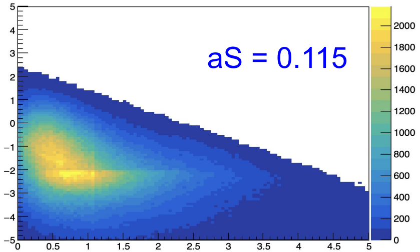


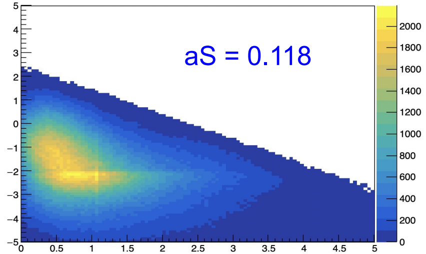
Preliminary look at LJPs: Secondary LJP

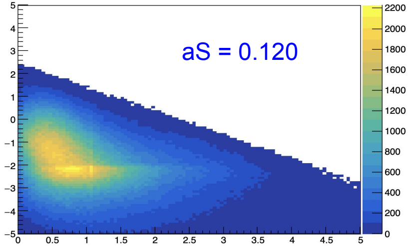


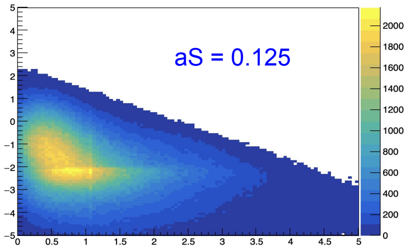












Angular order-based jet declustering in (θ, ϕ) plane

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

5.4 Plugins for e^+e^- collisions

arXiv:1111.6097

5.4.1 Cambridge algorithm

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

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

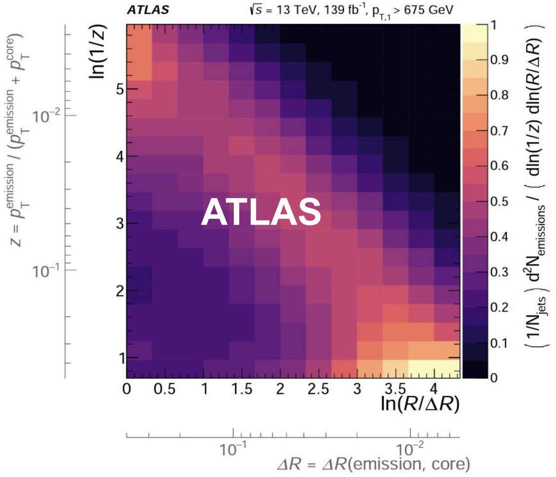
This algorithms performs sequential recombination of the pair of particles that is closest in angle, except when $y_{ij} = \frac{2\min(E_i^2,E_j^2)}{Q^2}(1-\cos\theta) > y_{cut}$, in which case the less energetic of i and j is labelled a jet, and the other member of the pair remains free to cluster.

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

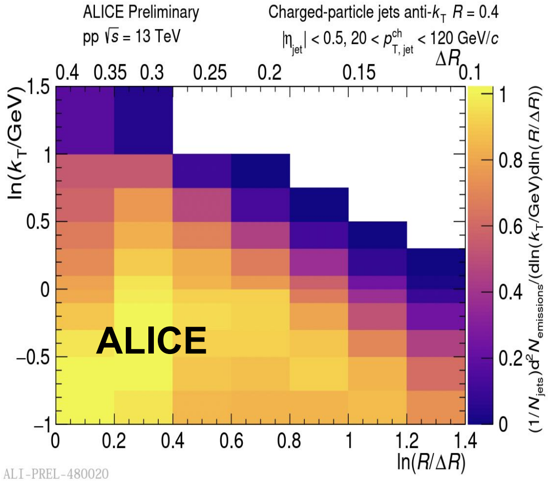
Recent Lund Jet Plane based measurements

- 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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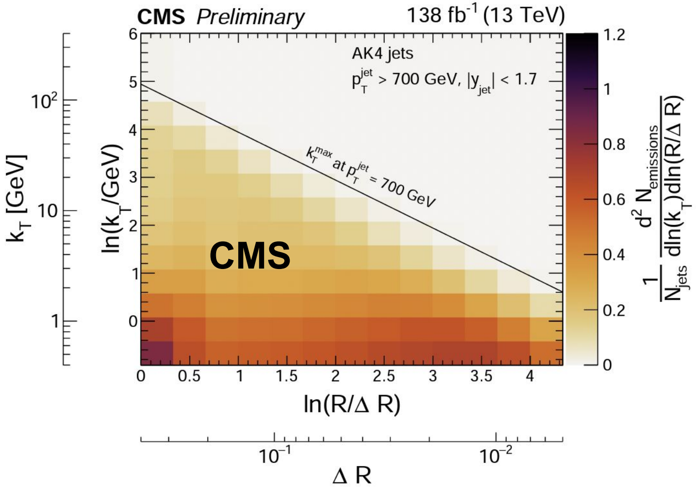
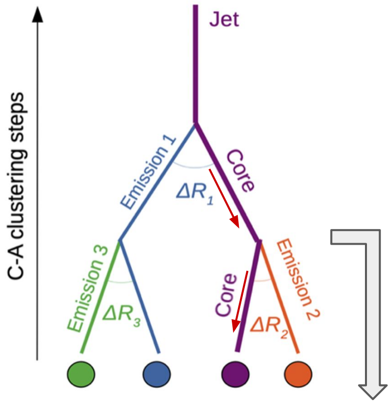


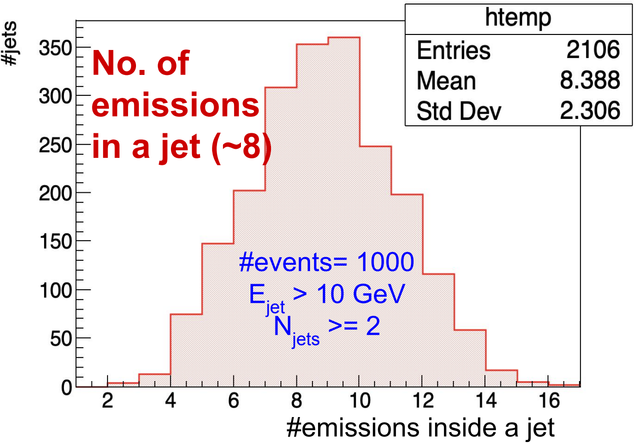
How to build Primary Lund Jet Plane?



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

ee → Z→ uu/dd @91 GeV

Emissions from the core branches



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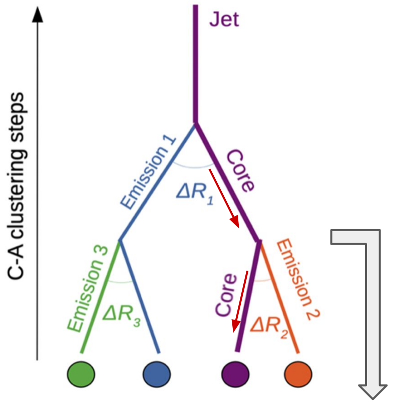

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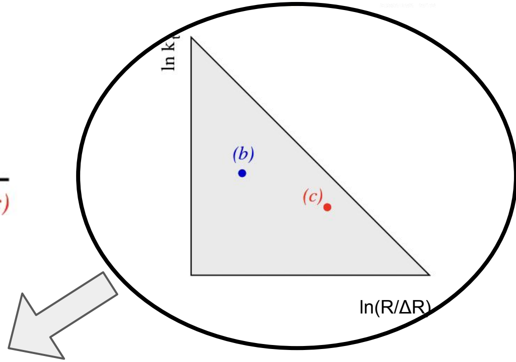
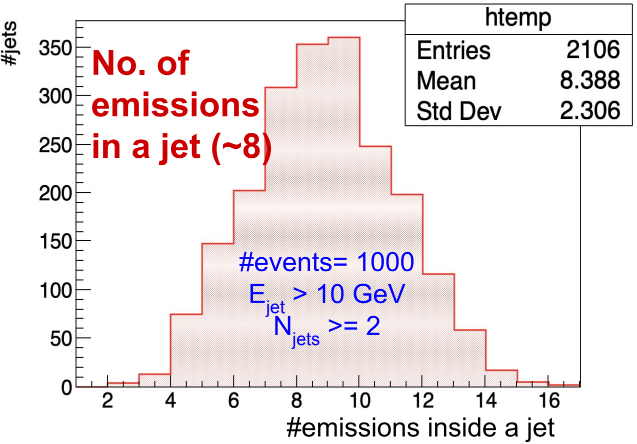
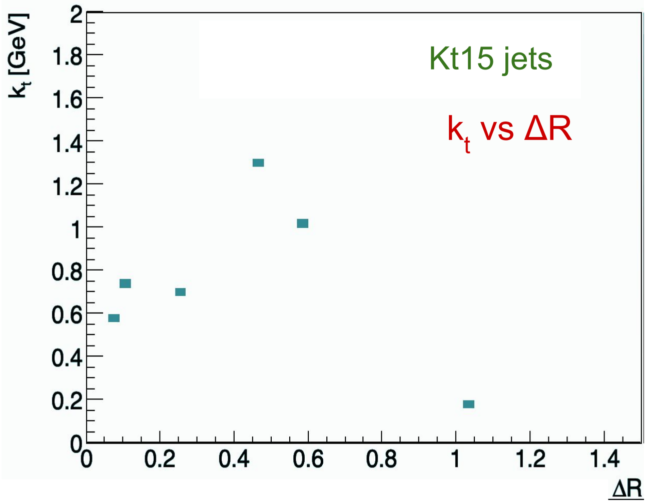
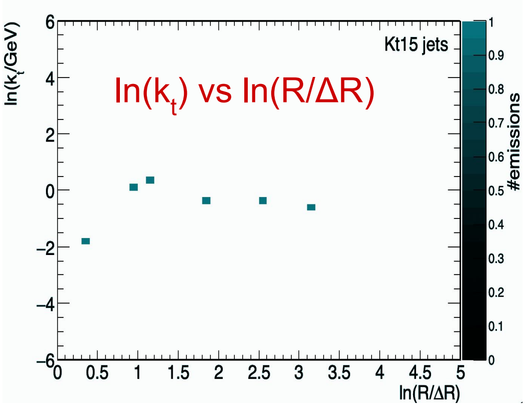


Emissions from the core branches



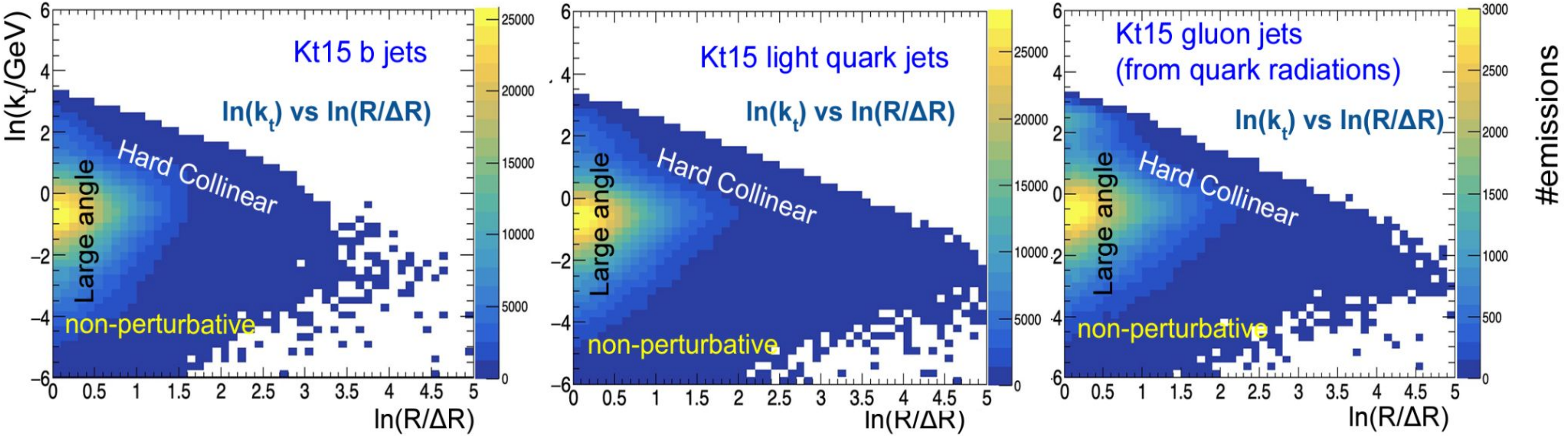




LJP representation for 1 jet of E_{jet} ~ 40 GeV

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

LJP representation for light and heavy flavor jets at higher energy



- For process ee→ Z→bb and ee→Z→uu/dd (+ gluons from quark radiation) @91 GeV ; #events = 1 M
- Selection: E_{jet} > 10 GeV, N_{jets} >= 2; selection efficiency > 99%; use two leading p_T jets
- Difference in the large ln(R/ΔR) region shows that light jets are more collimated than heavy flavour jets; working on further understanding in more detail