FUTURE CIRCULAR COLLIDER

QCD with jets at FCC-ee

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Line Delagrange, Lata Panwar, Reina Camacho Toro, Bogdan Malaescu

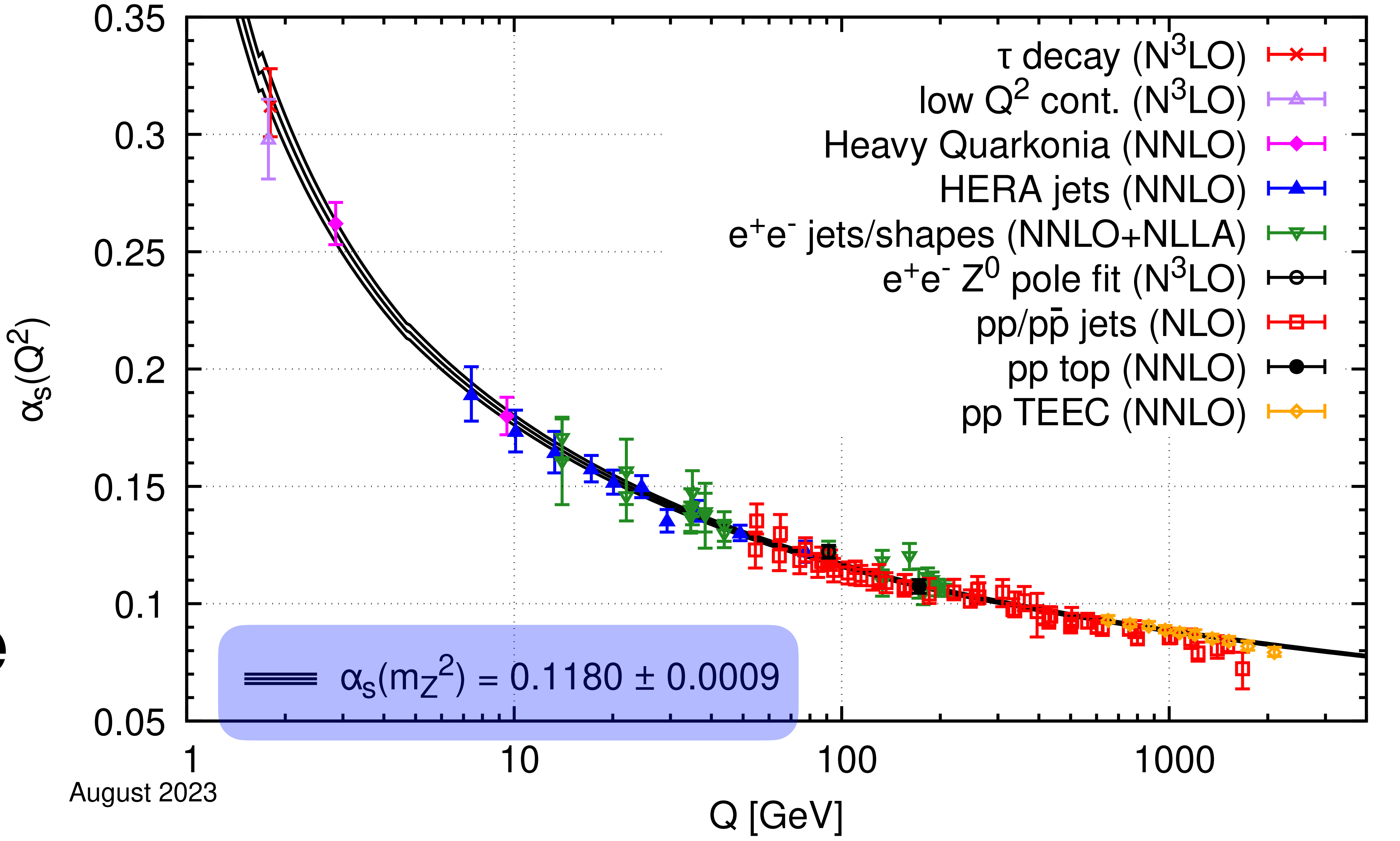
The slides are largerly inspired from Lata's talk at the 2nd Italy & France workshop

Motivations

- Goal: study of **sensitivity to** α_S and evolution as a function of the **RGE** at FCC-ee

- α_S impacts both **jet multiplicity** and **jet shape** $\rightarrow R_{3/2} = \sigma_{\geq 3j}/\sigma_{\geq 2j}$, **Lund Jet Plane**

- FCC-ee will provide **very high luminosity** and **clean collision environment**:
  - $10^6 \times$ LEP Data at Z-pole
  - Kinematically constrained initial and final states (no PDF & MPI; uncoloured initial state)
  - QCD radiations only in final state, well separated jets



Current precision: $\Delta\alpha_S$~1%

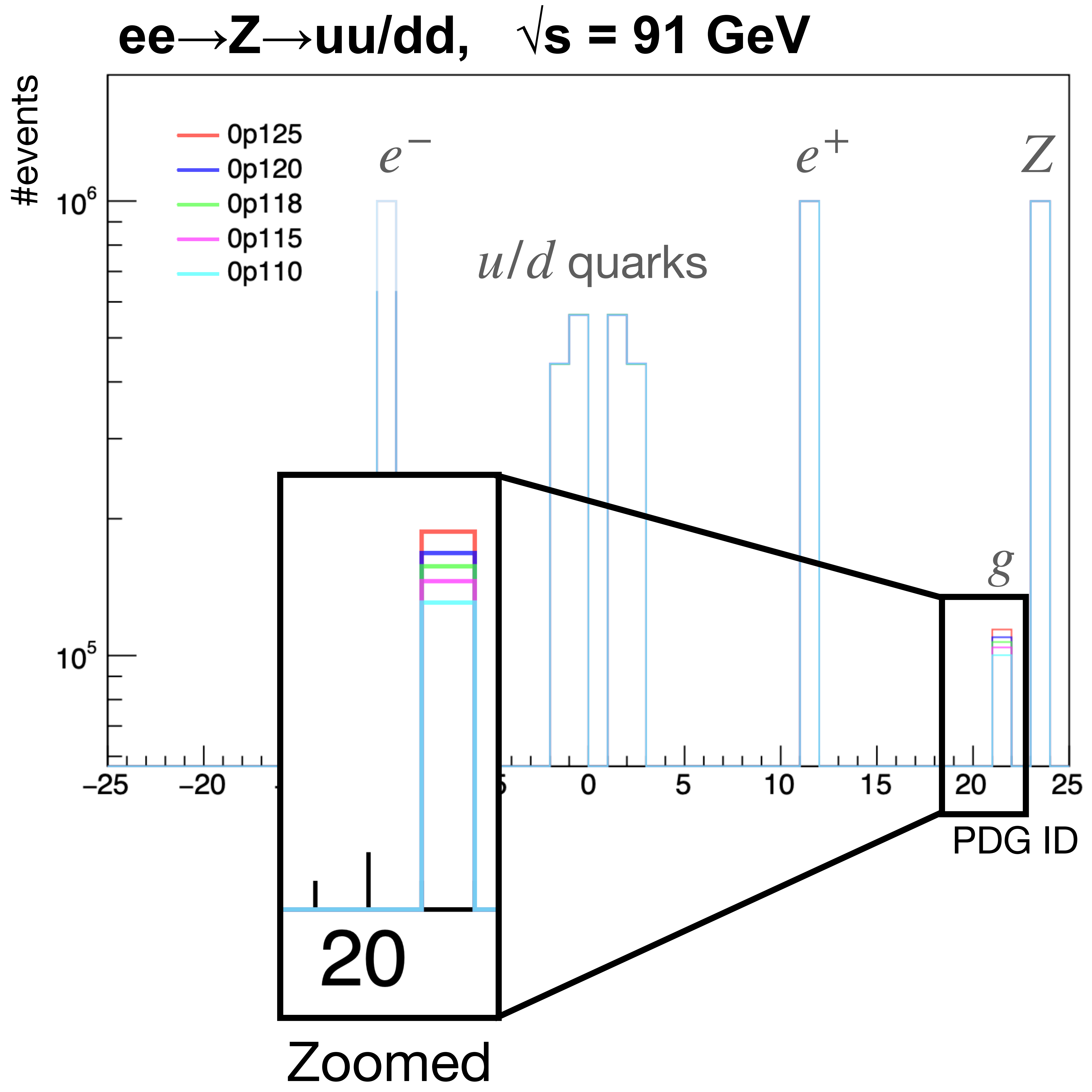
Samples

- Generating 10M $e^+e^- \to Z \to q\bar{q}$ *(q=u or d)* events with **Madgraph** (MG5_aMC@NLO)

- for 5 different $\alpha_S(M_Z)$ values: [0.110, 0.115, **0.118**, 0.120, 0.125]

- Events are further simulated with **Pythia and Delphes,** using **IDEA detector** card

- Emitted gluons multiplicity increases with $\alpha_S(M_Z)$



Jet clustering

- Using **ee generalised k_T algorithm** (1111.6097)
- **Inputs:** Jet constituents within **θ-region** $[0.3,\ \pi - 0.3]$ (excluding particles that are 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

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:

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

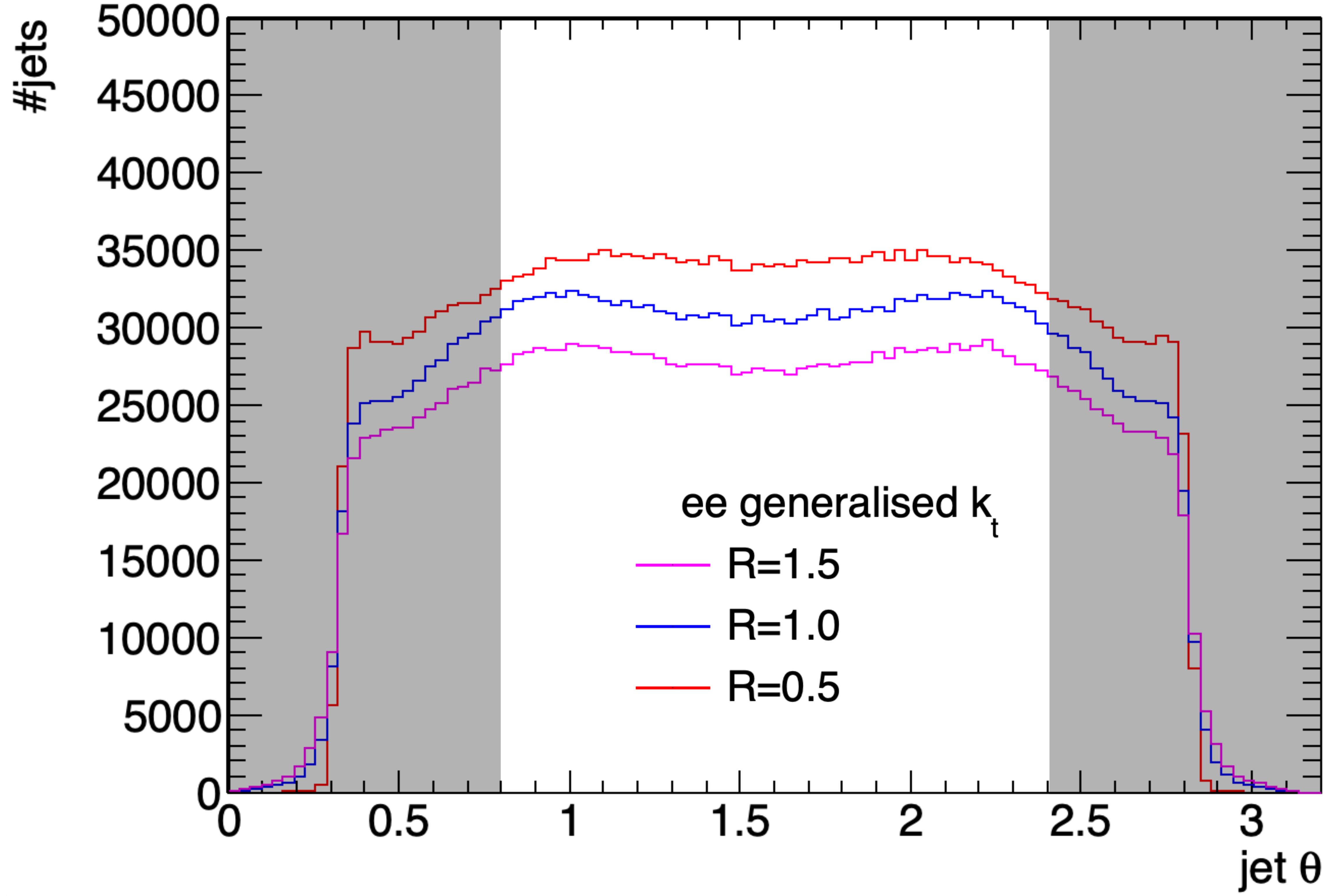
$$d_{iB} = E_i^{2p}\,, \qquad (9b)$$

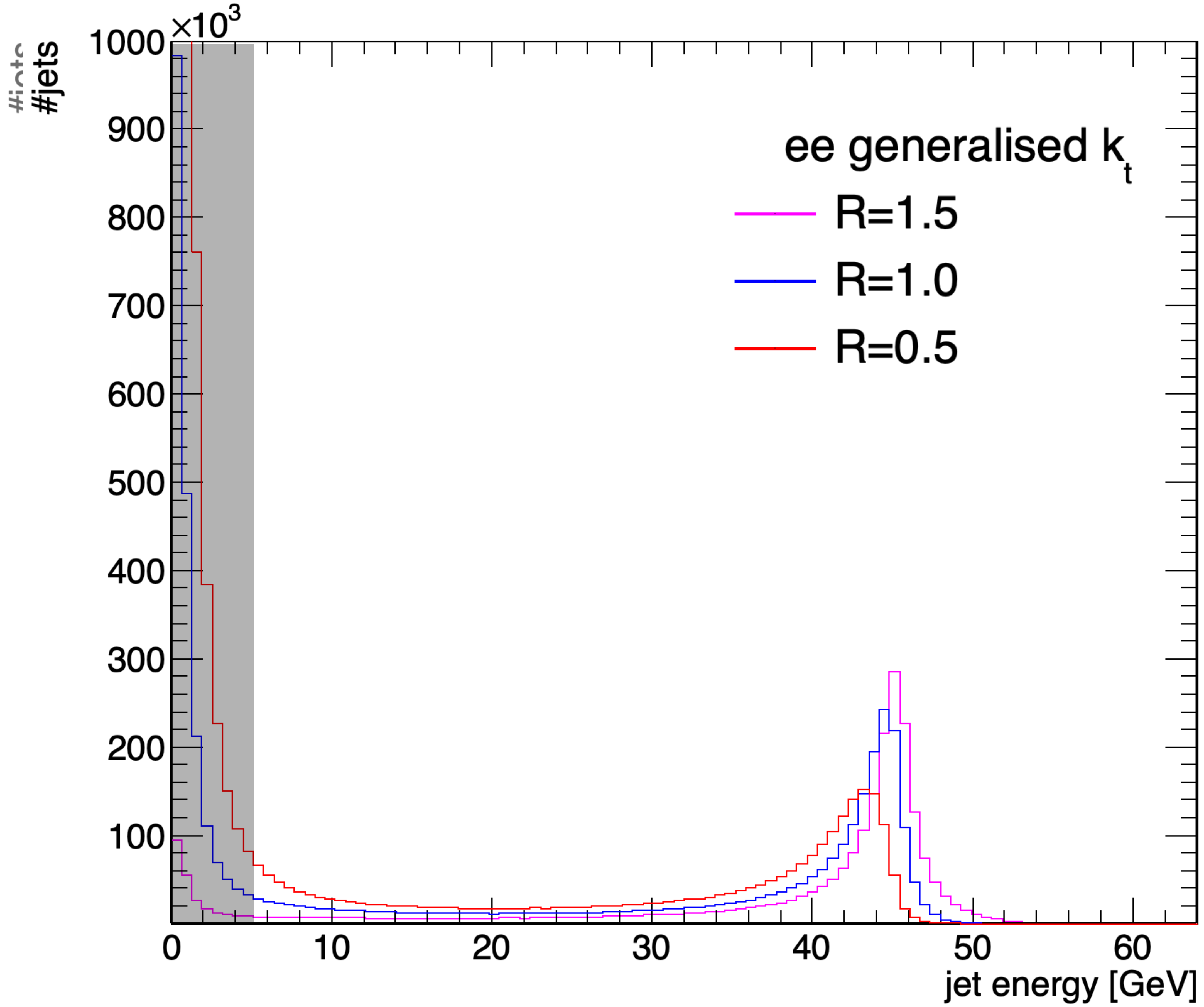
for a general value of p and R. At a given stage of the clustering sequence, if a d_{ij} is smallest then i and j are recombined, while if a d_{iB} is smallest then i is called an "inclusive jet".

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);
```

Reco jet selection



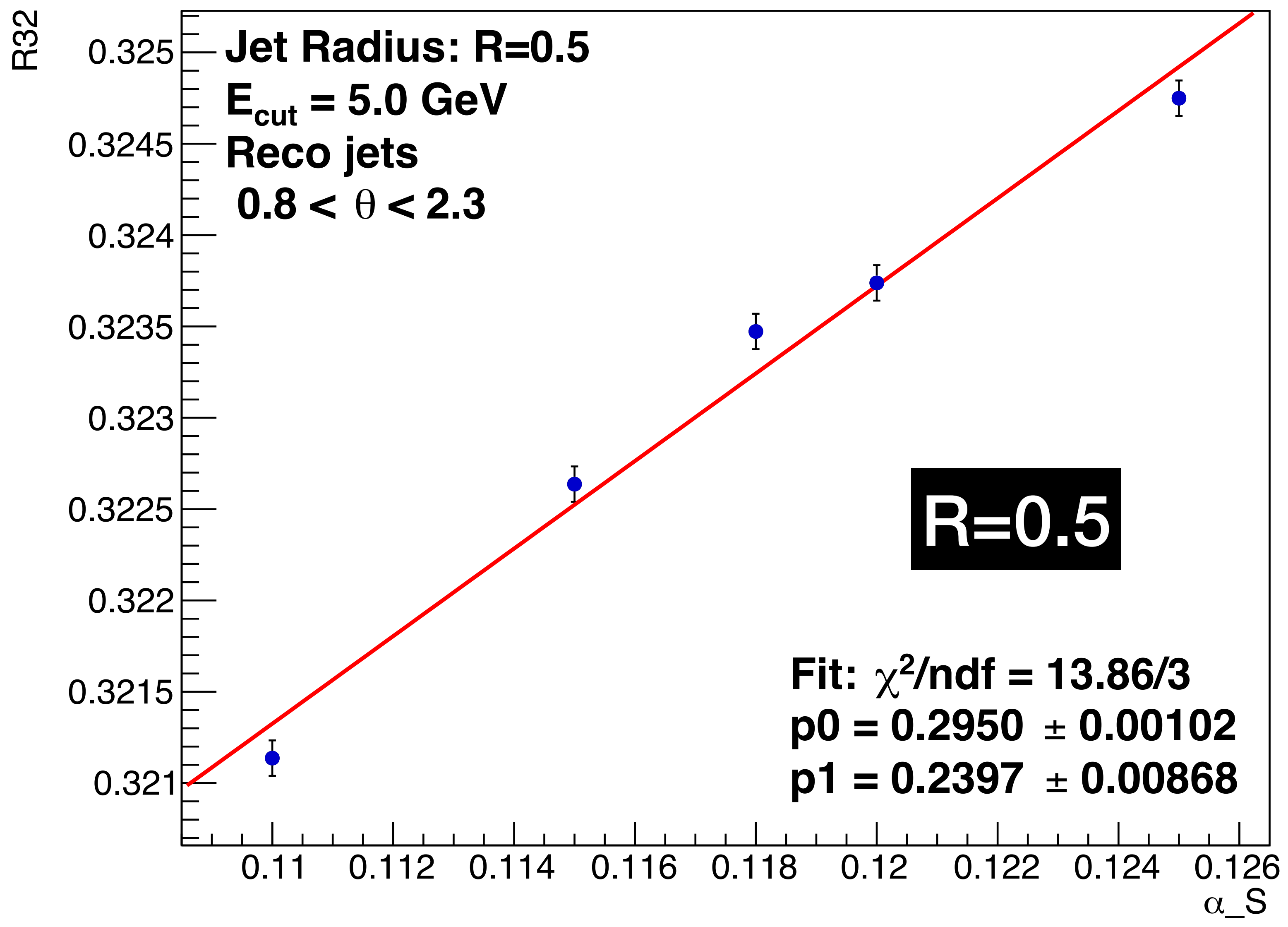


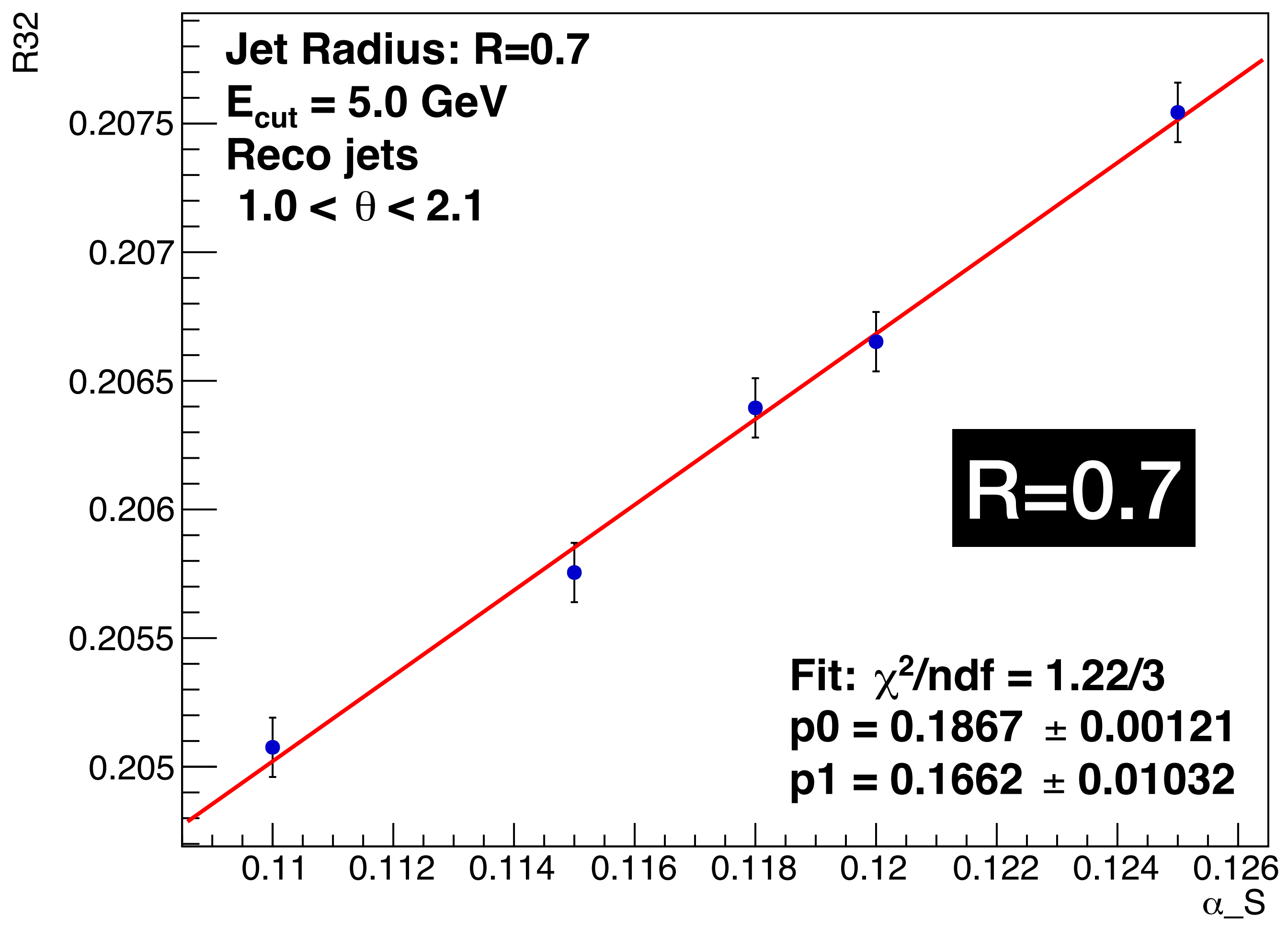
Selection cuts for R=0.5

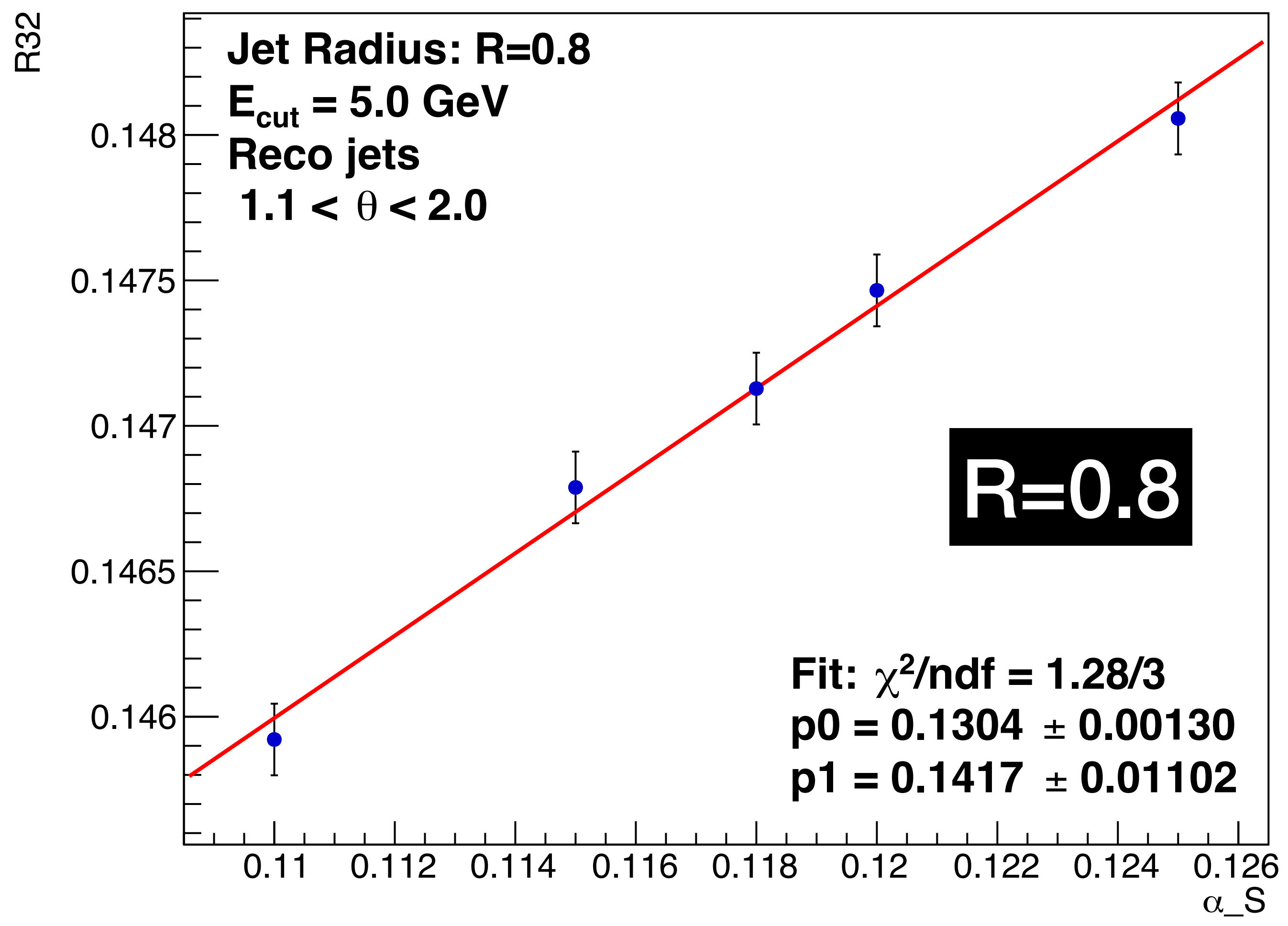
$E_{jet} > 5$ GeV, $[0.3 + R,\ \pi - 0.3 - R]$ angular acceptance, #jets > 1

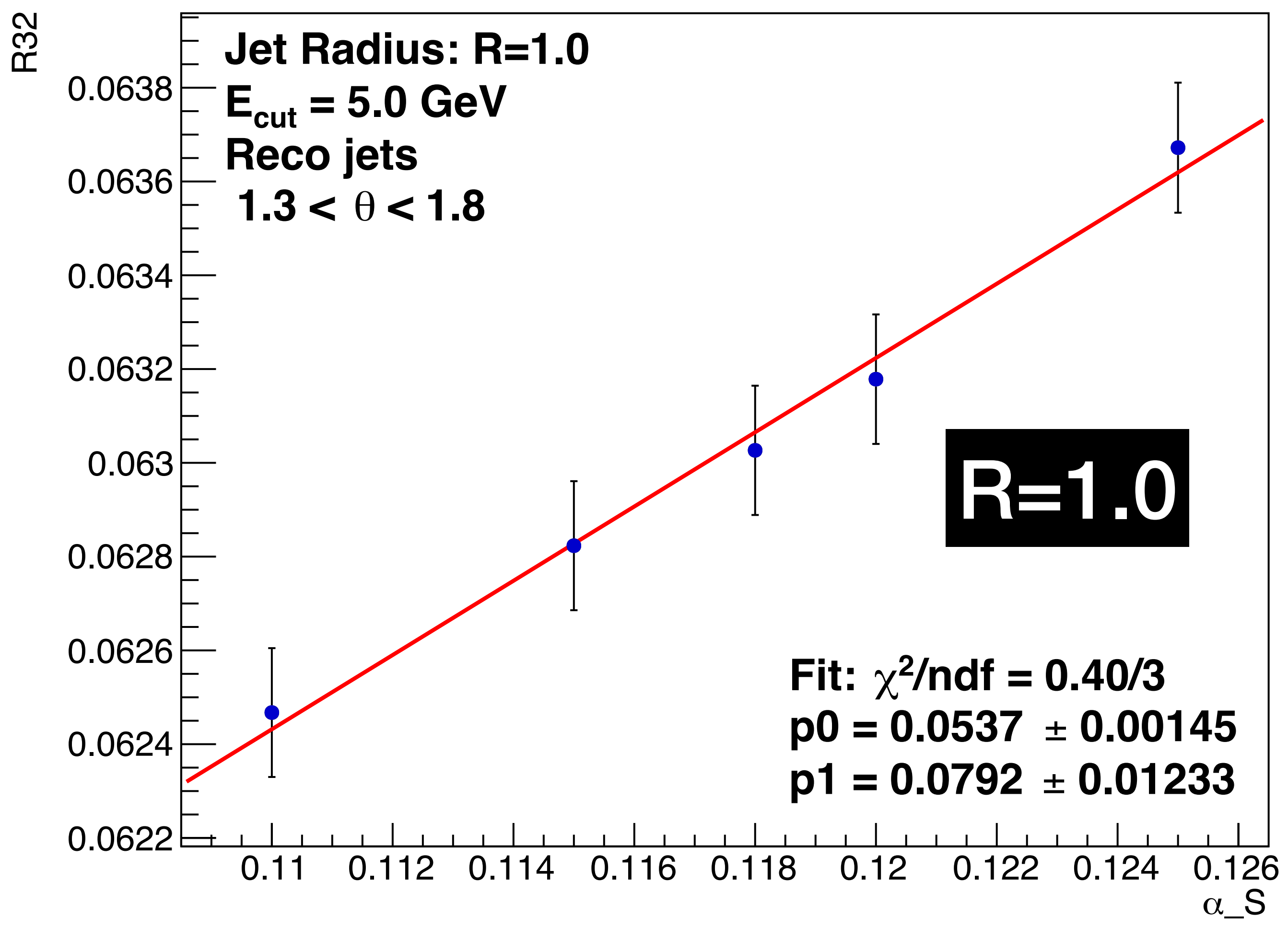
$R_{3/2}$ study

- Jet cross section ratio between events with at least 3 jets over at least 2 jets
- Linear $R_{3/2}$ dependency on $\alpha_S(M_Z)$
- Study of impact of R: sensitivity decrease with R



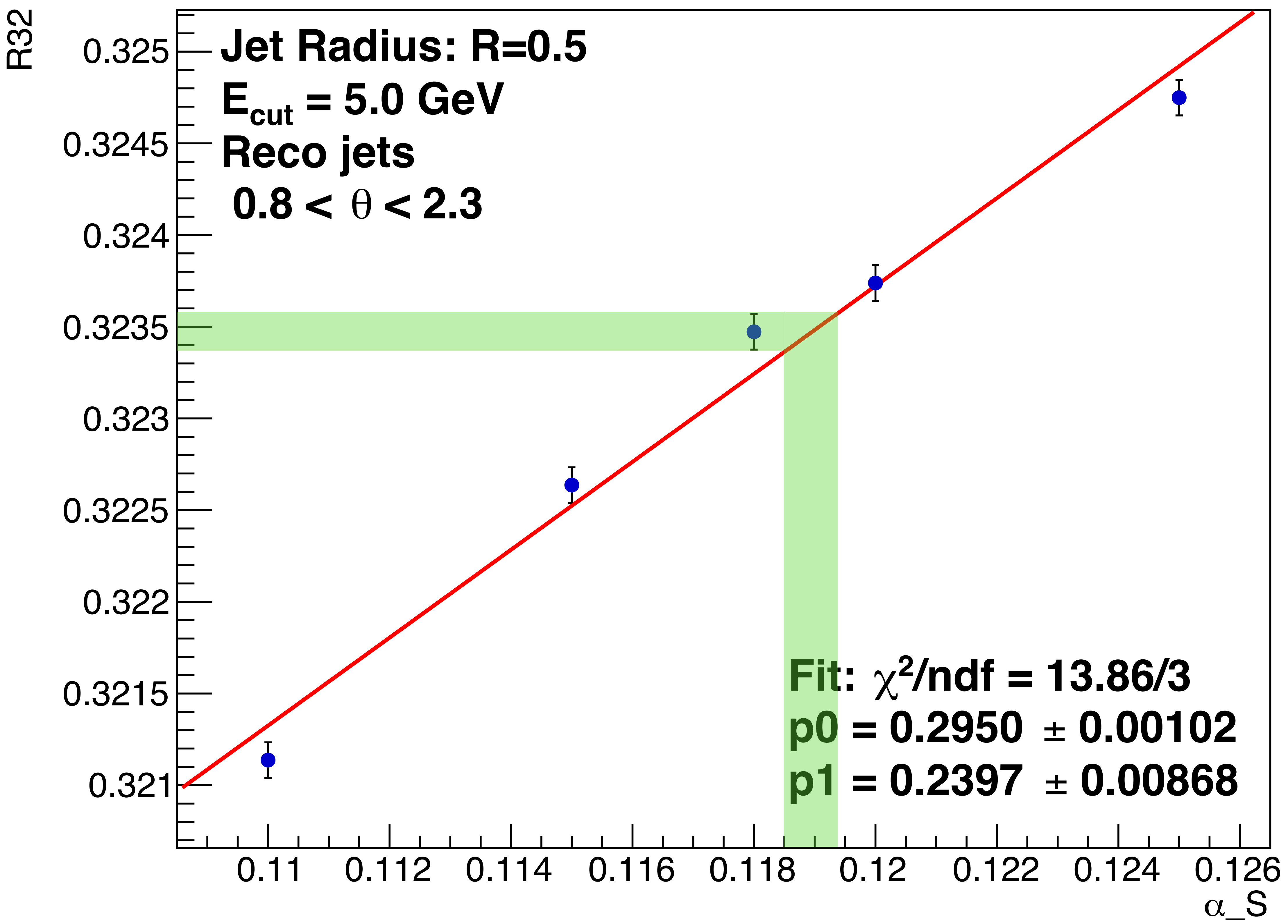






$R_{3/2}$ study

- Error bars represent stat. unc. only
- With 10^7 events generated, for $\alpha_S(M_Z) = 0.118$: $\Delta R_{3/2}^{stat} = 0.03\ \%$
- At the Z pole of FCC-ee, 10^{13} Z produced, ~3×10^{12} of them decaying to light quarks
- Expected statistical sensitivity to α_S
  $\Delta\alpha_S^{stat} = 0.0002\ \%$
  → challenge for experimental and theoretical uncertainties



$$\delta R_{3/2} = (0.240 \pm 0.009)\delta\alpha_S$$

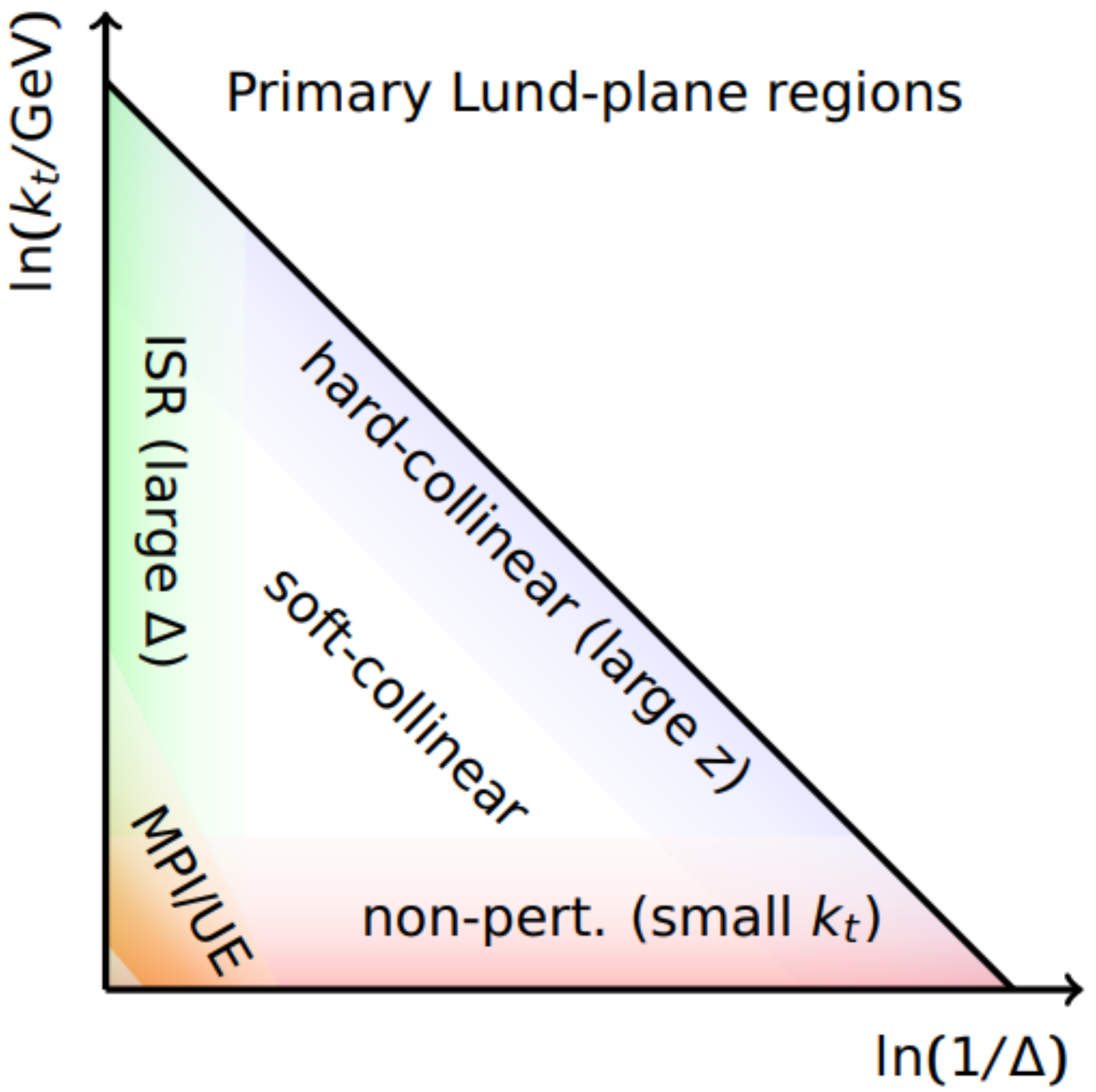
The Lund Jet Plane

- LJP organises the emissions within a jet in terms of their **transverse momentum** and **angular separation**
- Widely used for jet modelling studies and jet tagging
- QCD processes behind jet formation are related to α_S

  → LJP density + normalisation **sensitive to α_S**

$$\rho(k_t, \Delta R) = \frac{1}{\mathrm{N_{jets}}} \frac{d^2(\#\text{emissions})}{d\ \ln(k_T/\text{GeV})\ d\ \ln(R/\Delta R)} \approx \frac{2\mathrm{C_F}\alpha_S(k_T)}{\pi}$$

  → Broad range of scale covered to **test the running of α_S** with coherent analysis of uncertainties



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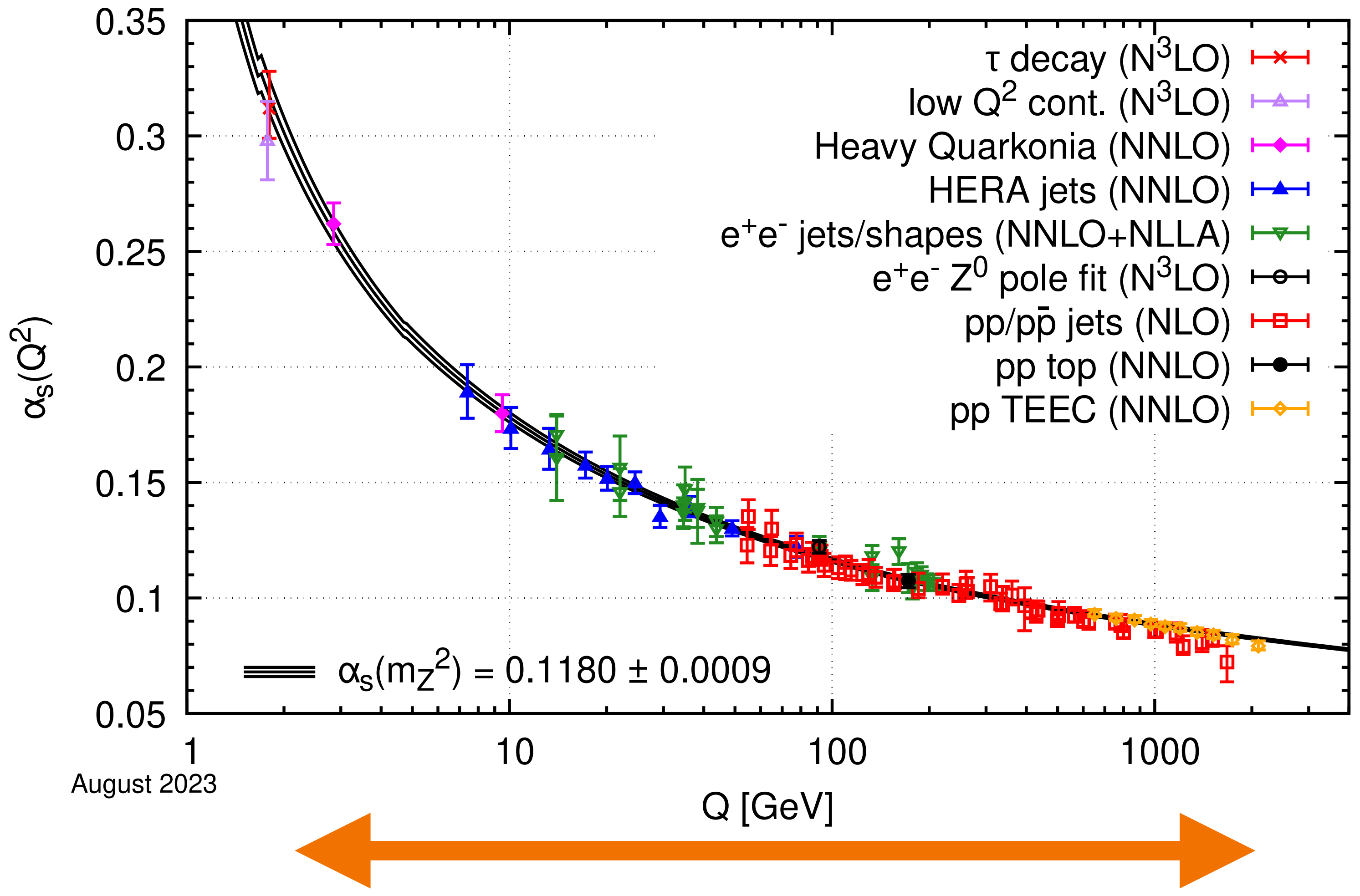
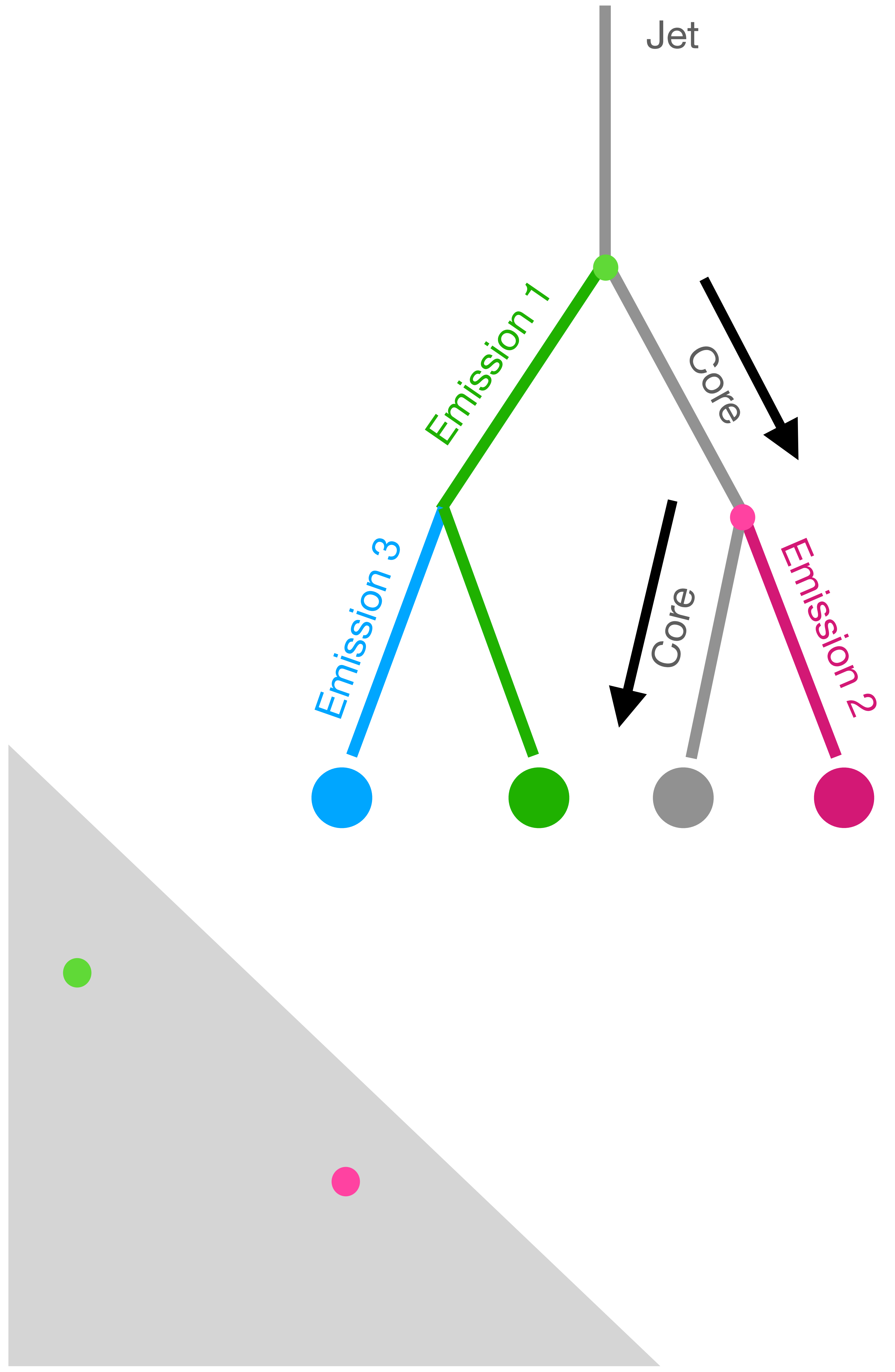


LJP construction

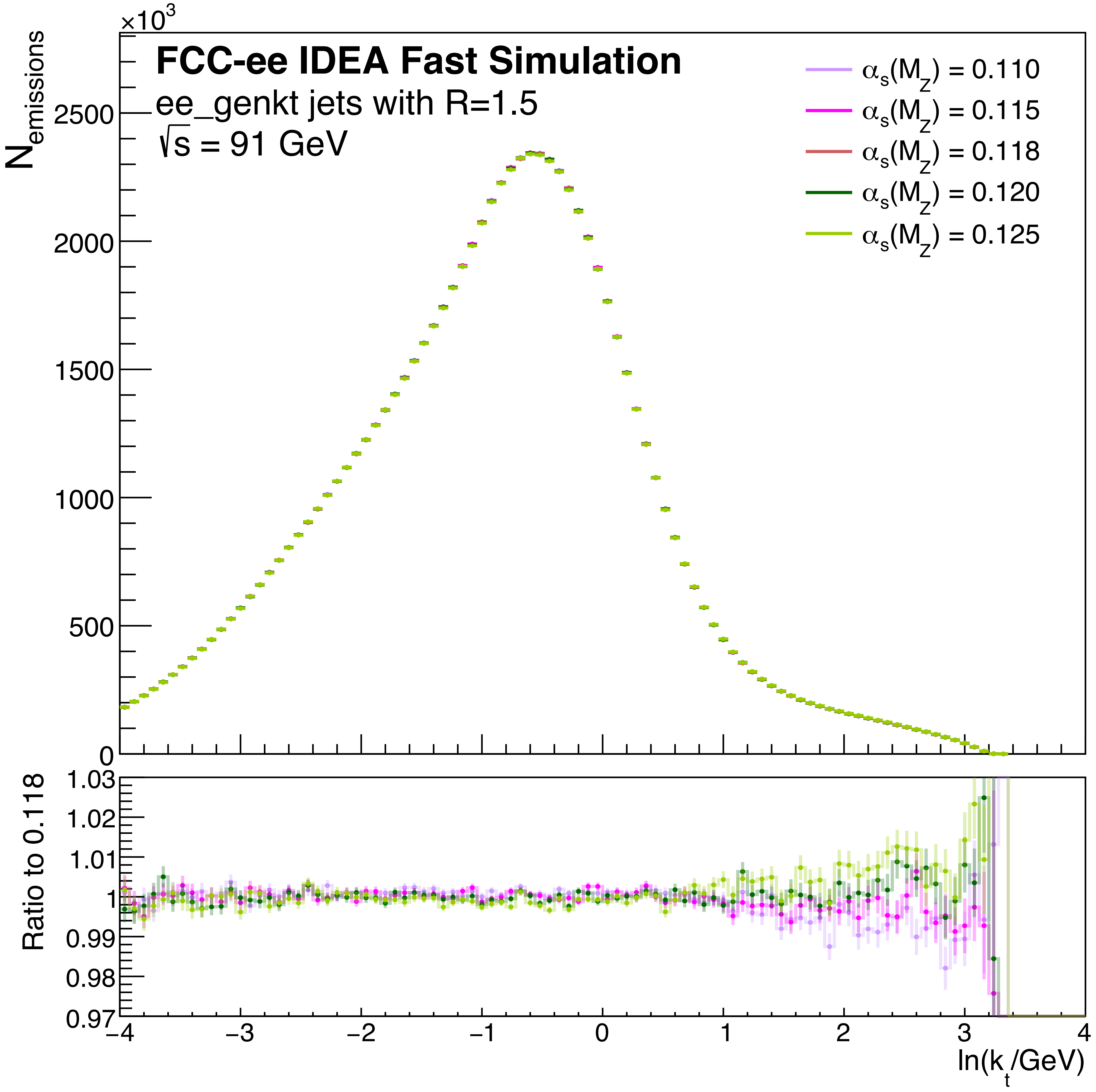
- <u>Construction</u>:
  - Clustering jet with **ee generalised-k_T algorithm**
  - Reclustering the tracks inside the jets using **Cambridge-Aachen algorithm** (angular-ordered, adapted for ee study by parametrising ΔR with θ rather than y)
  - Declustering it and at each step compute ΔR (angle between emission and emitter) and k_T (relative transverse momentum of the emission)
- Considering **Primary LJP** and **Secondary LJP** (built following first emission)



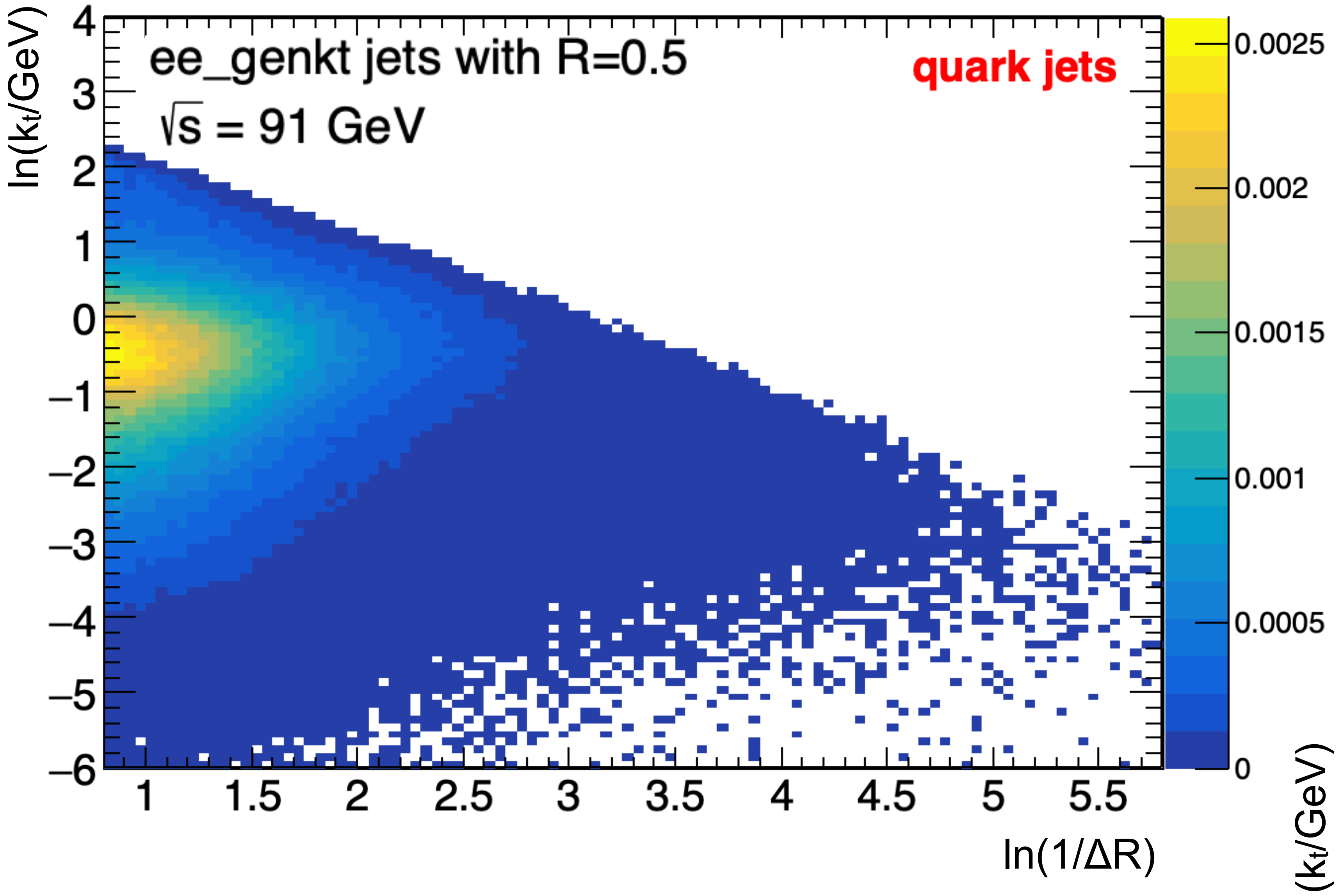
Primary LJP

Sensitivity to $\alpha_S(M_Z)$

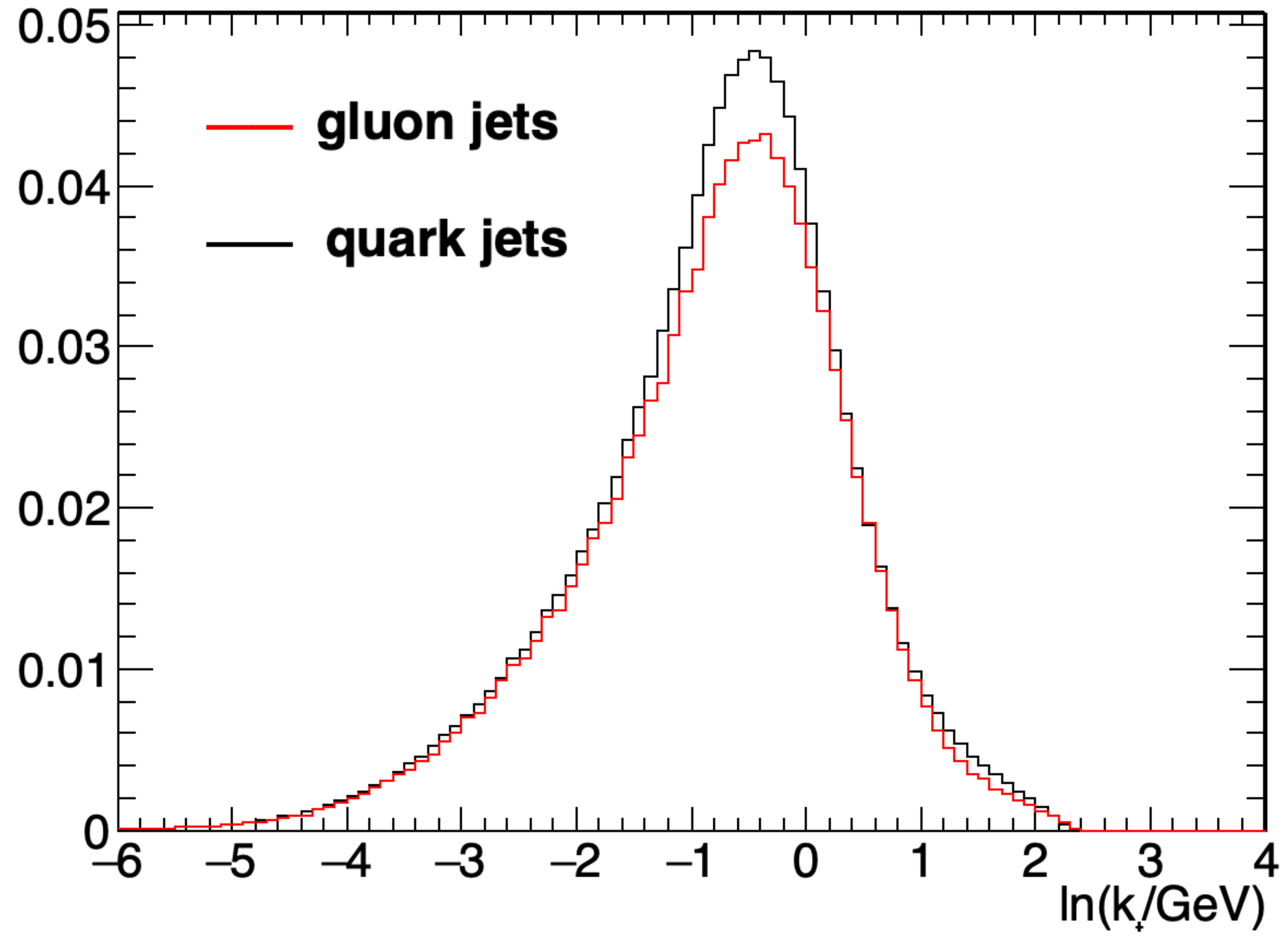
- Prospective studies of the **Lund Jet Plane** in an FCC-ee environment with MC simulations (same samples as for the $R_{3/2}$ study)
- Using large-R jets (R=1.5), scan in $\alpha_S(M_Z)$
- Hint of **sensitivity to $\alpha_S(M_Z)$** in LJP shape with increase of harder emissions with $\alpha_S(M_Z)$
- Strong requirements on energy and angular resolution for the detectors, tracking and reconstruction algorithms (would need full simulations)

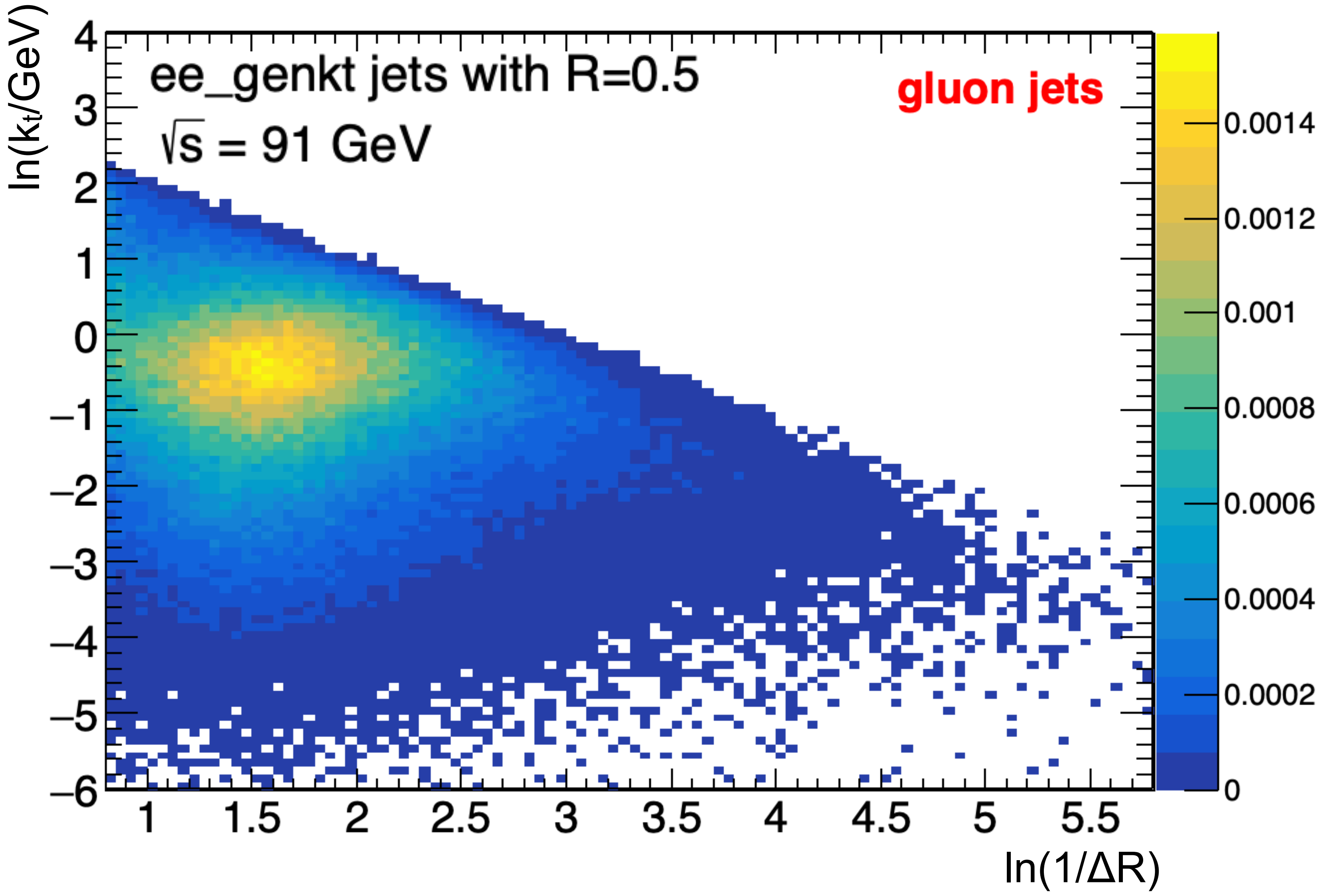


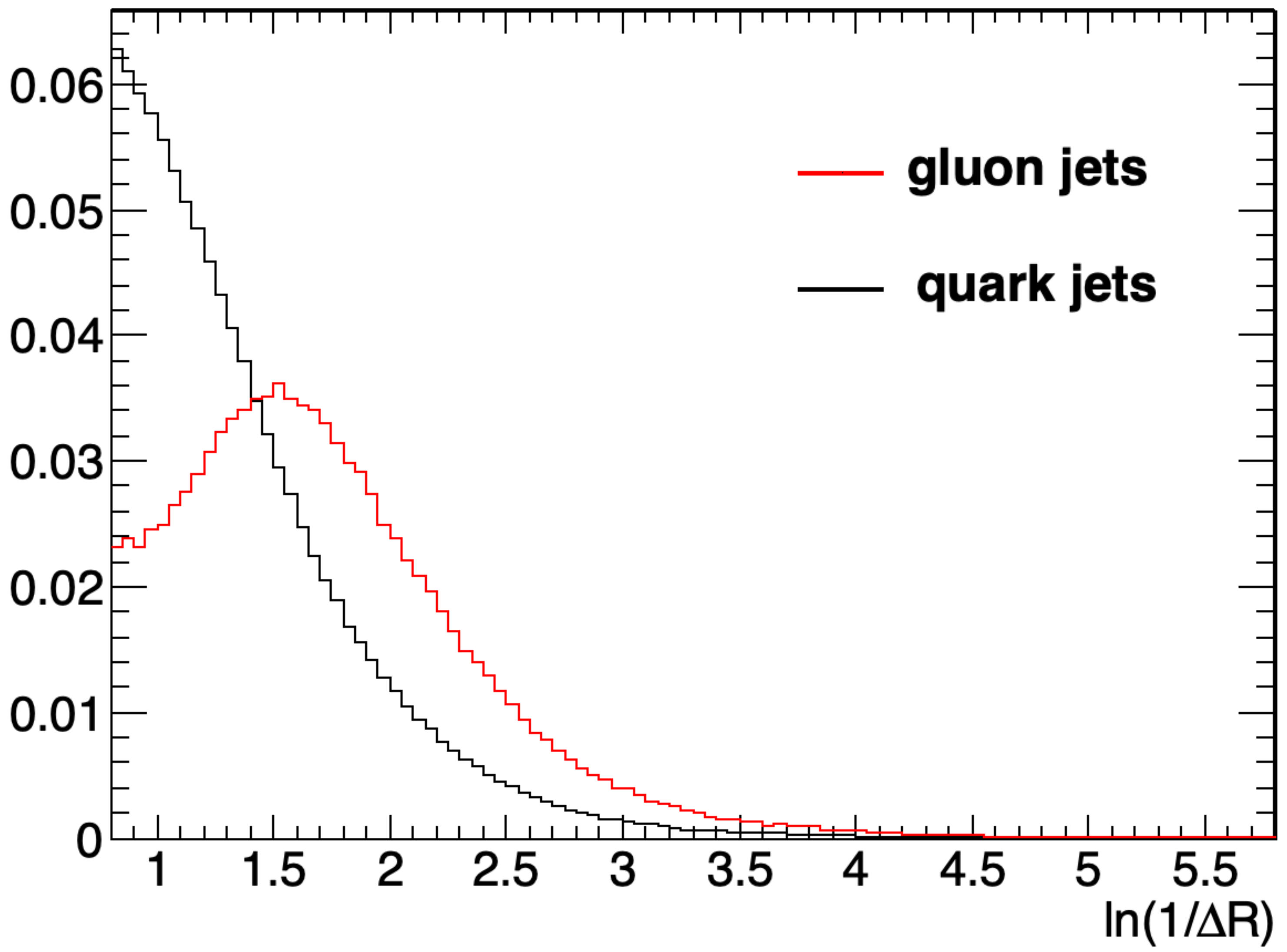
Jet tagging potential



Primary LJP for quark and gluon-induced jets; can be extended to heavy ($Z \to bb$) vs light flavor ($H \to gg$) jets

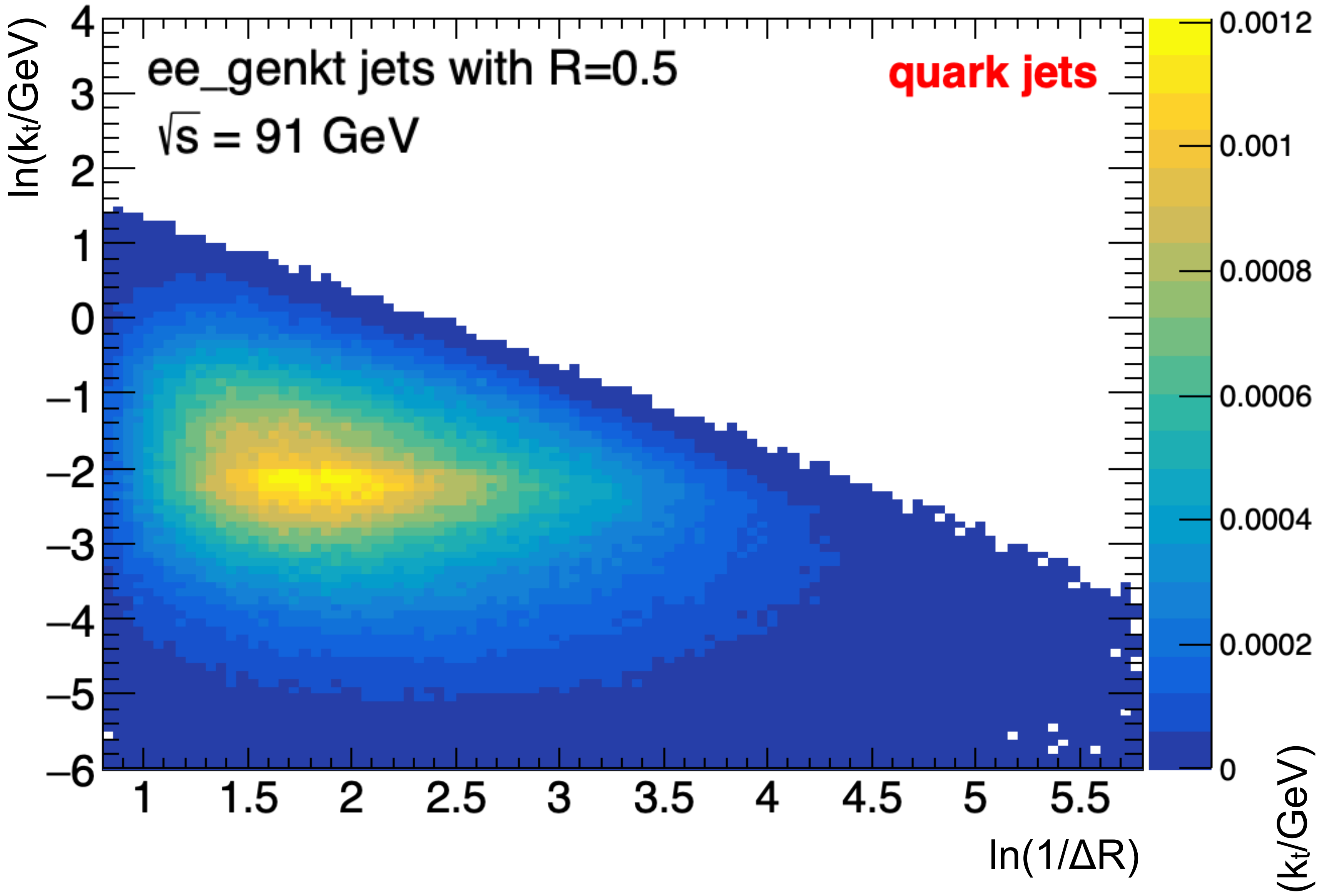




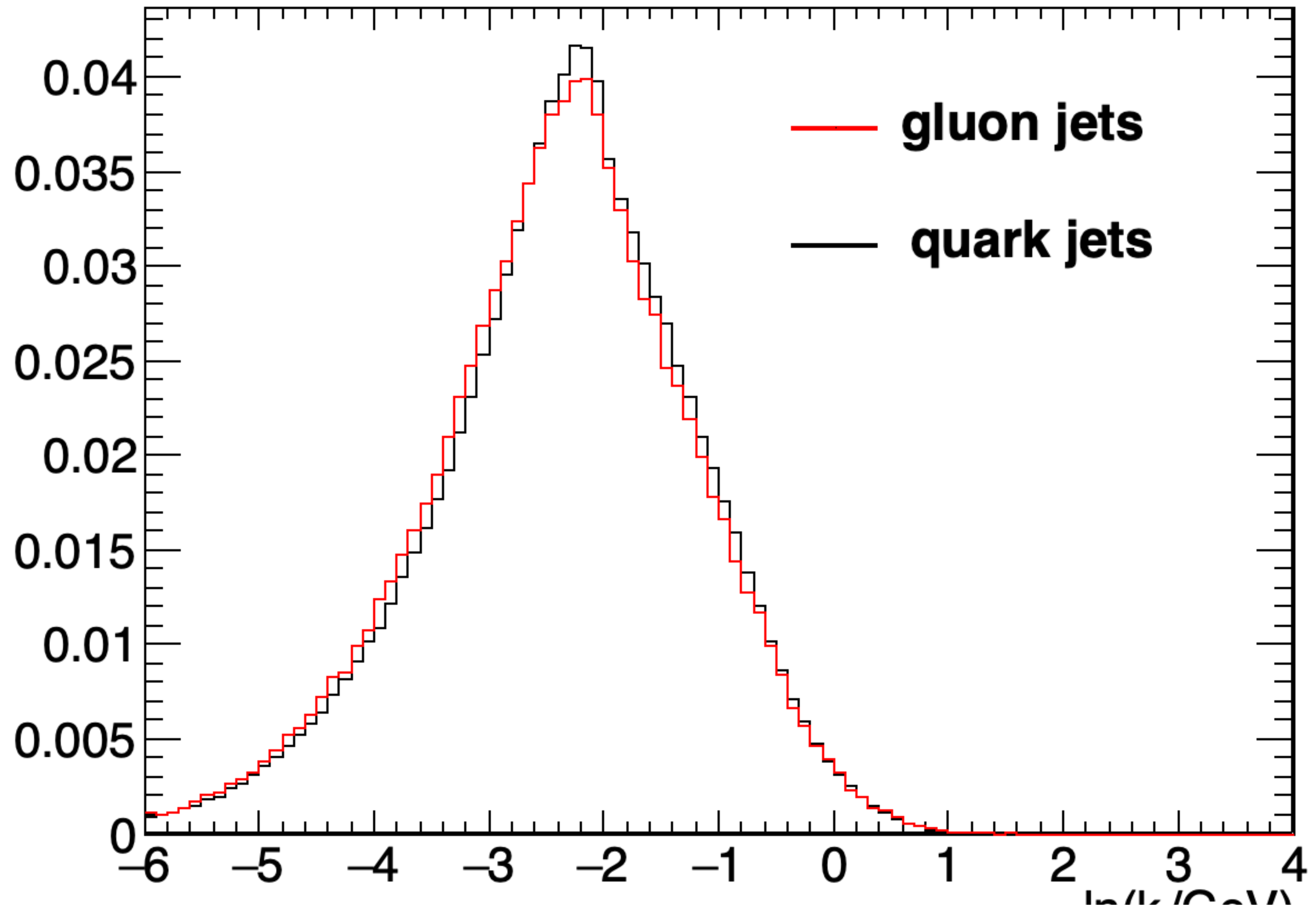


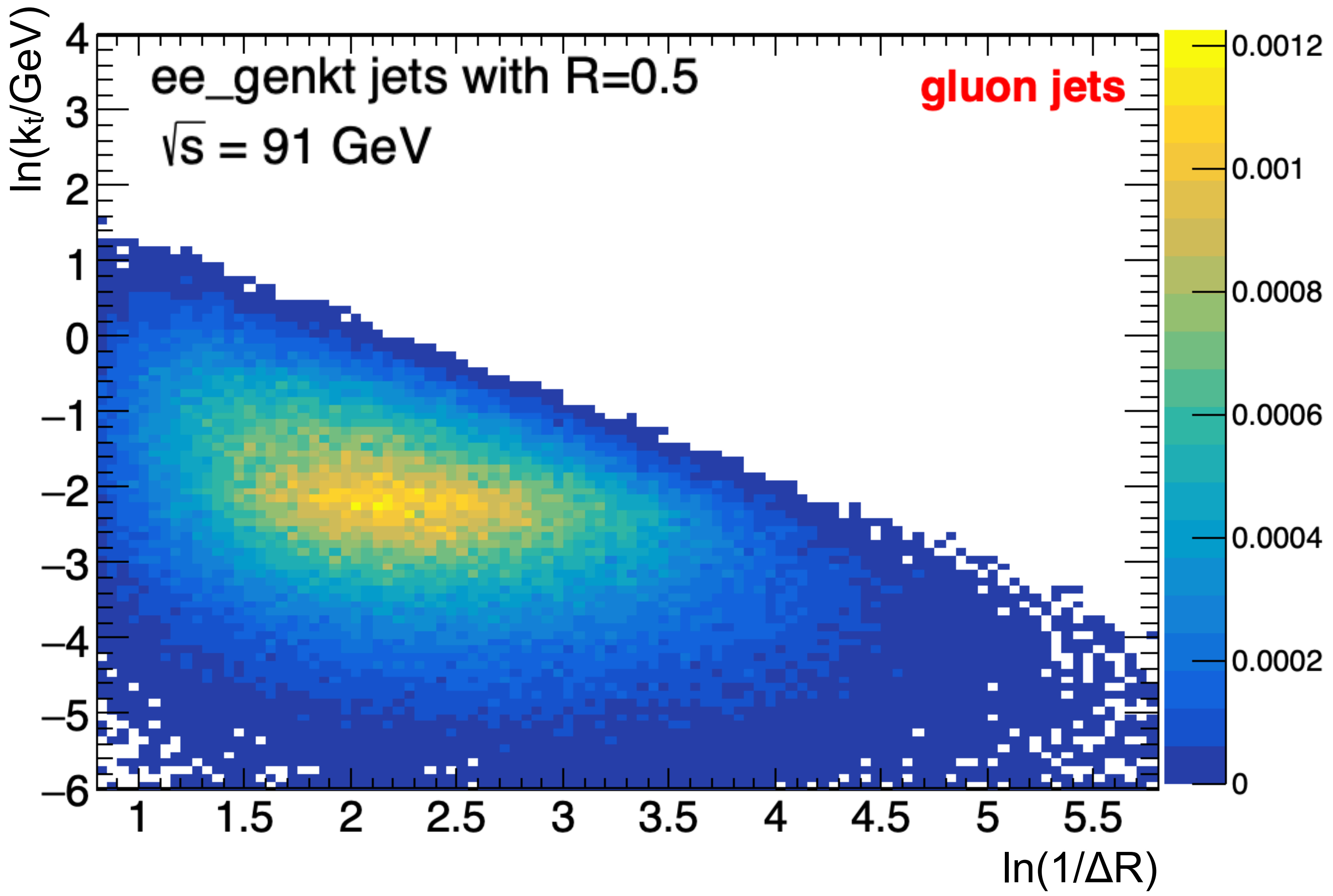
Note: Gluons are emitted from quarks in $e^+e^- \to Z \to u\bar{u}/d\bar{d}$ process

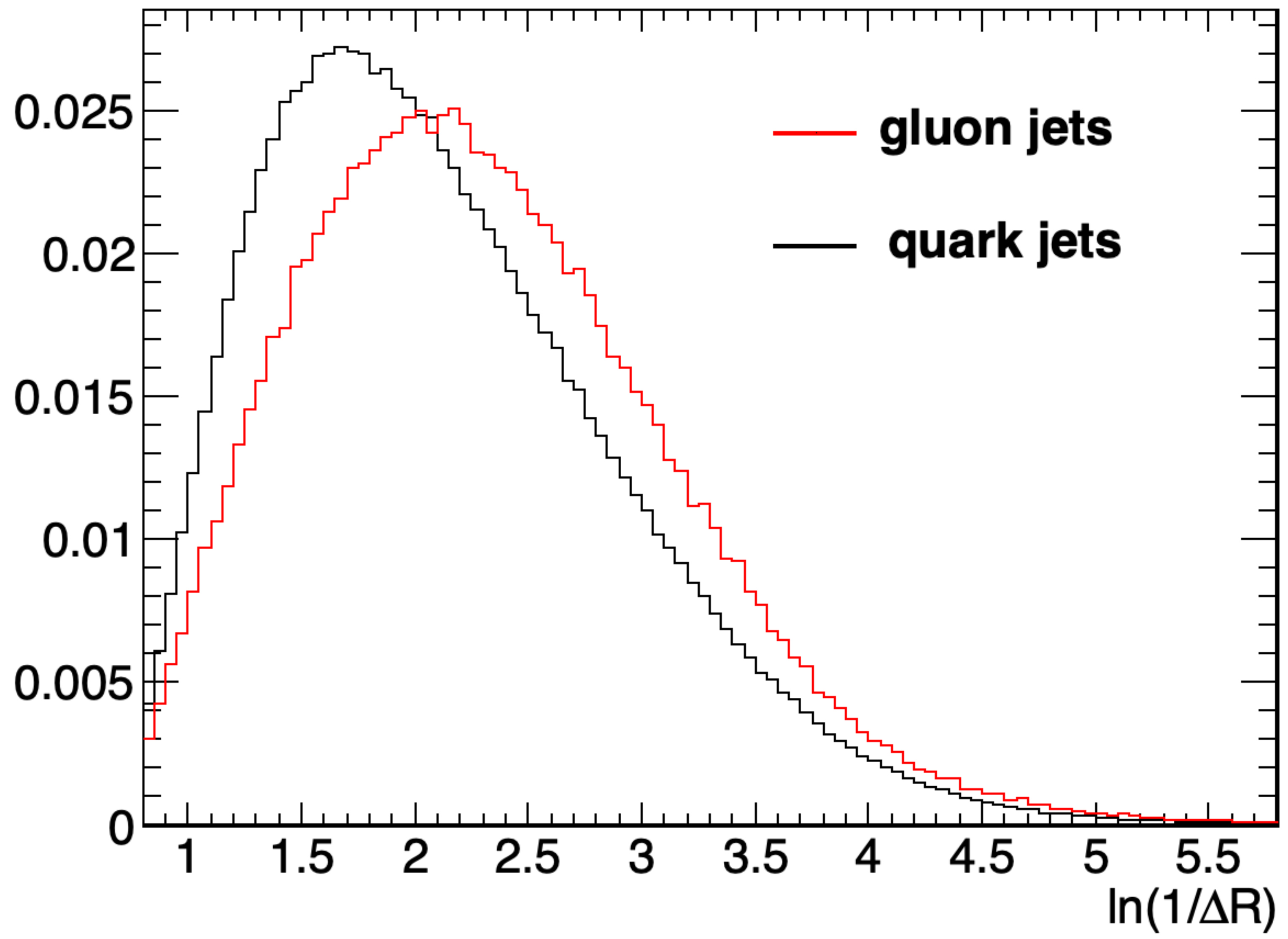
Jet tagging potential



Secondary LJP for quark and gluon-induced jets







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Conclusion

- Jet studies at FCC-ee motivated by the sensitivity to $\alpha_S(M_Z)$ and test of the RGE
- $R_{3/2}$ study shows great sensitivity to $\alpha_S(M_Z)$ at FCC-ee, with expected statistical sensitivity to α_S of the order of $\Delta\alpha_S = 0.0002\,\%$
- **Lund Jet Plane** study shows hint of sensitivity to $\alpha_S(M_Z)$
  - Sensitivity to its running not explored
  - Potential for jet tagging
- Both study benefit from large statistics available at FCC-ee
  → stringent demand on detector design and theoretical predictions to control systematics

Backup

High-precision gluon & quark jet studies

- Poorly known gluon radiation and fragmentation leads to **large discrepancy between MC generators** for gluon jets (Existing MC tuning relies mostly on **quark-enriched samples**)

- FCC-ee exploited as a **pure gluon factory**:
  - $H \to gg$ (8% BR, 120k extra-clean di-gluon events) vs $Z \to qq$ (10^{10} events)
  - $Z \to bbg$ (g in one hemisphere recoiling against 2 b-jets in the other)

- Multiple high-precision analyses:
  - **q/g discrimination** (training on pure samples)
  - **Non-pQCD** (gluon fragmentation, colour reconnection…)
  - **pQCD** (NNLL PS tuning, *jet substructure*)