quark gluon separation at LHC

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quark gluon separation Motivation

- at LHC collisions →quark, gluon →jet: most of present analysis assume they cannot be distinguished.
- If it is possible...
  - discriminate New physics
    - gluino/squark decay to LSP → hard quark
    - ISR from SUSY production →gluon rich
    - QCD process → gluon rich EW process→hard quark
  - Energy calibration (fake Wjj peak..)
- They have different nature and may be distinguished.

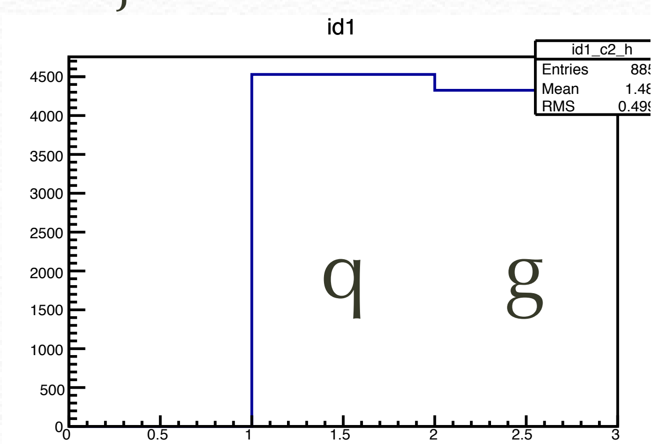
Example: degenerate SUSY

(Mukohopadhyay, Nojiri, Yanagida JHEP10(2014)012)

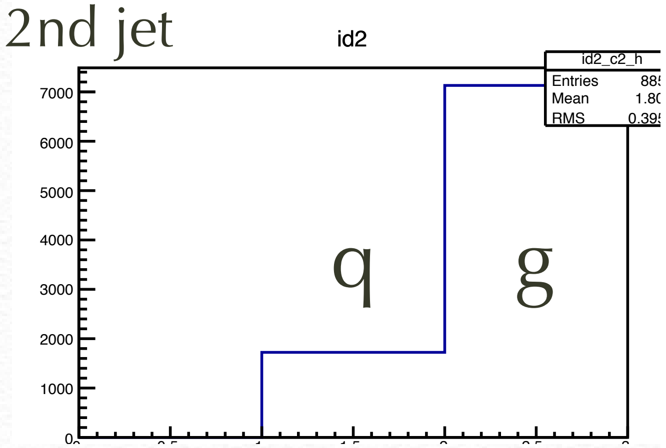
- Background: Z+ jets. The leading jet must originate from quark.
- ISR of gluino: leading process is gg→ gluino gluino. ISR tend to be gluon.
- PT(q) i>PT(gl). If Kinematical cut is applied, fraction if quark increases.

gluino production

1st jet

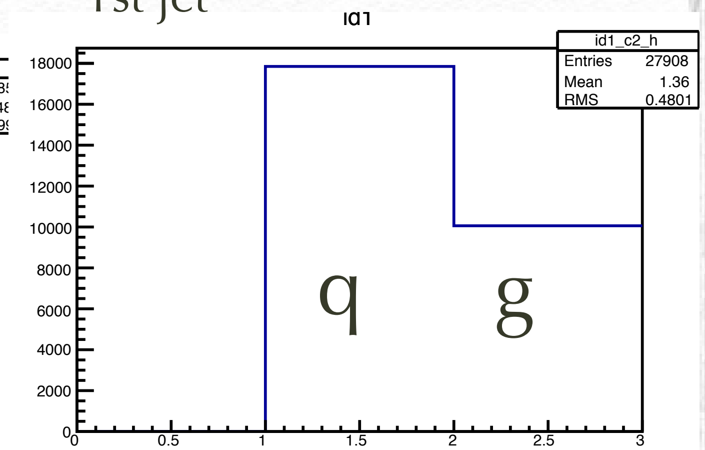


2nd jet

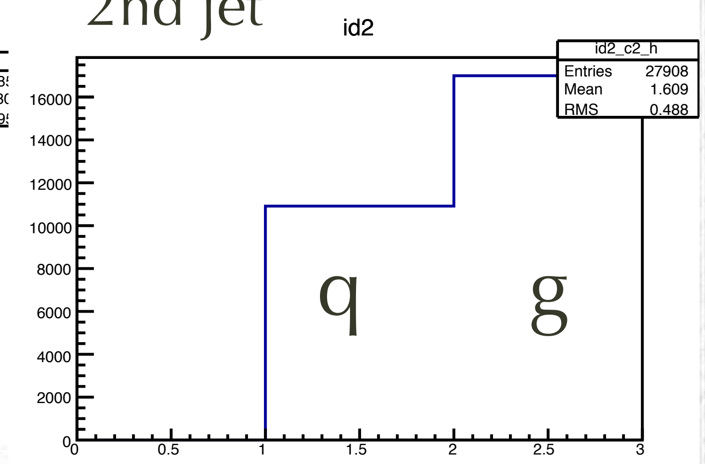


z+3j

1st jet



2nd jet



contents of this talk

- quantity that has been proposed to improve quark gluon separation
  - **nch :number of charged tracks**
  - **jet shape (jet width -> C1)**
  - **jet mass**
- **new variable: number of associated jets**
- MC simulations   improvement and MC dependence

quark and gluon jet separation studies

- Number of partons at Q^2(had) → number of particles
  →**number of charged particles** (non-perturbative physics)

- **Jet shape** (broadness of the jet, and mass)

Girth : $$g = \sum_{i \in \mathrm{jet}} \frac{p_T^i}{p_T^{jet}} r_i \,.$$ jet mass

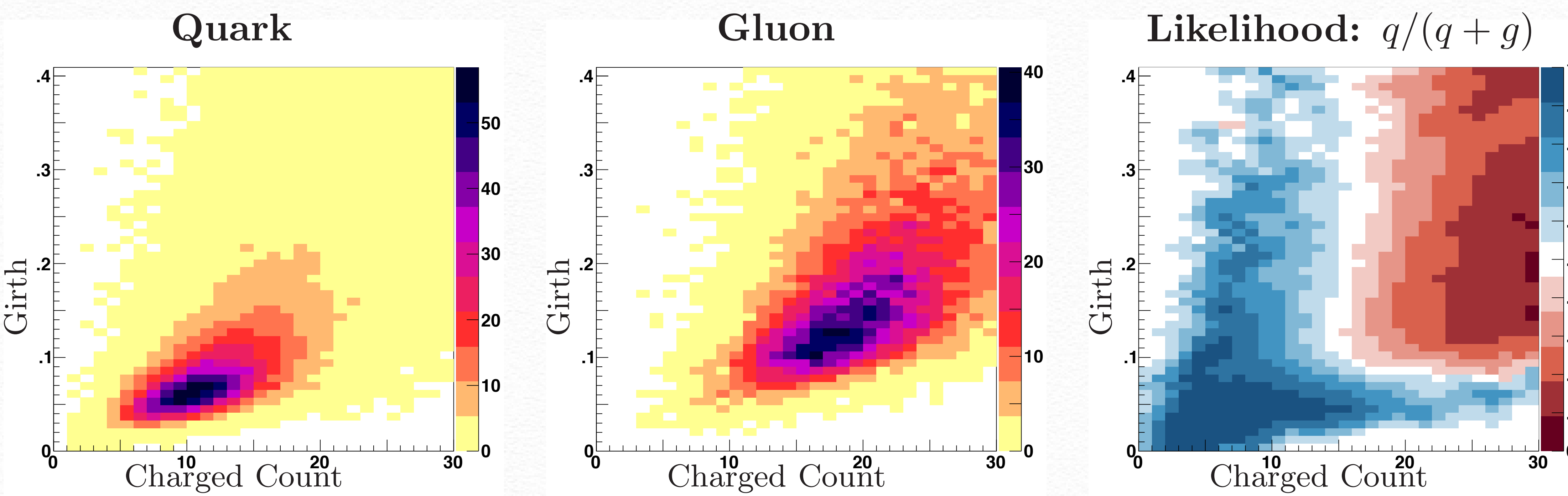
$$C_1^{(\beta)} = \sum_{i<j \in J} p_{Ti}\, p_{Tj} (\Delta R_{ij})^{\beta}$$ Larkoski et al JHEP 1306.108(2013)

Infrared safe and calculable “in principle”

Monte Carlo (Pythia, Herwig++, Shelpa)
parton shower(soft collinear) + hadronization modeling (NP)

Using all possible parameter to increase the separation

"gluon jet" : more charged tracks and broader than "quark jet"



arXive 1211.7038 Gallicchio and Schwartz

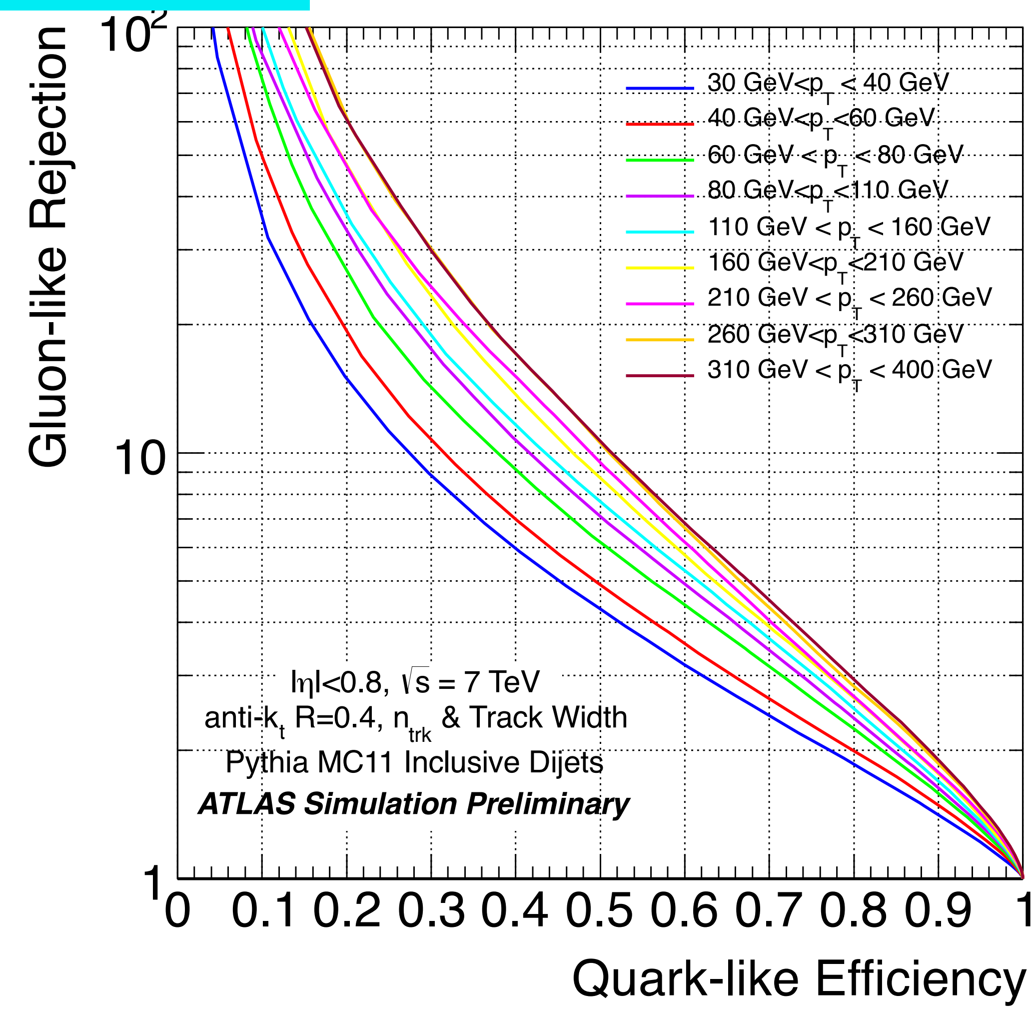
This earlier study has shown very good separation between quark and gluon based on pythia6

quark and gluon comparisons

ATLAS-CONF-2012-138

Nhan Tran (FNAL) for Lepton Photon

- Quark- and gluon-initiated jets have different properties
- Many search applications for distinguishing quarks and gluon jets
  - Hadronically decaying vector bosons
  - monojet, dijet searches
  - SUSY searches with high quark jet multiplicity
- **Jet width and number of charged tracks** provide good discrimination

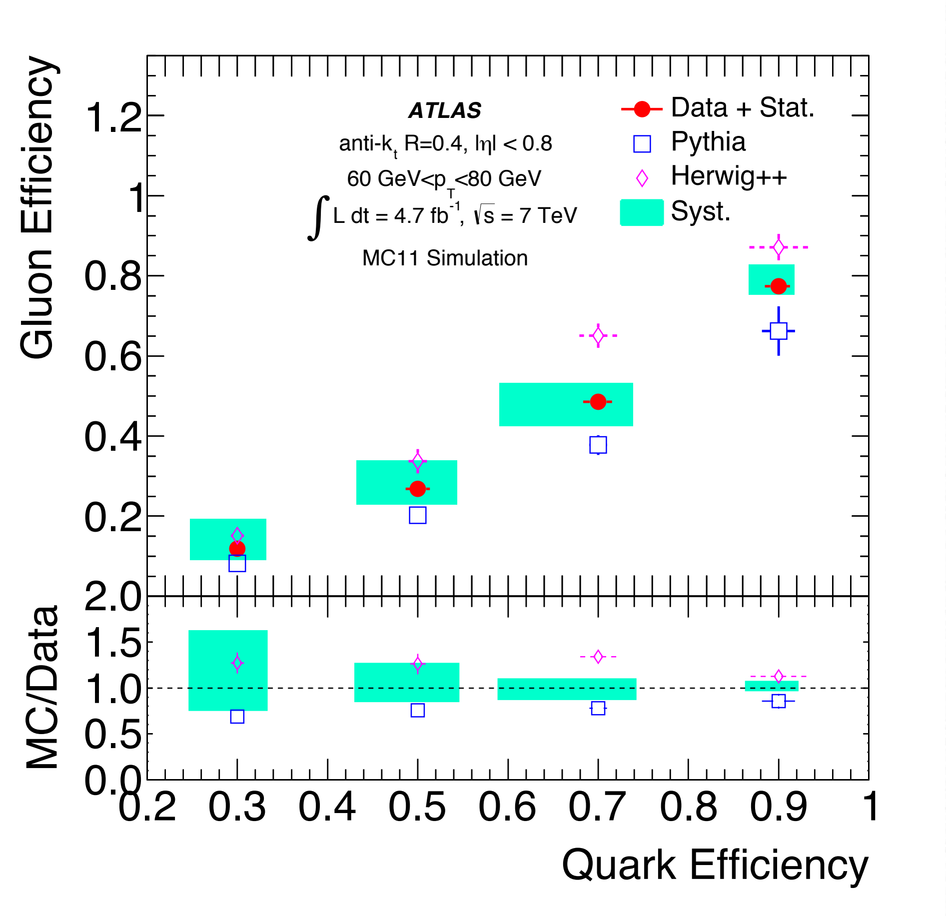


Example: for 50% quark jet efficiency, we can reject 90% gluon jets

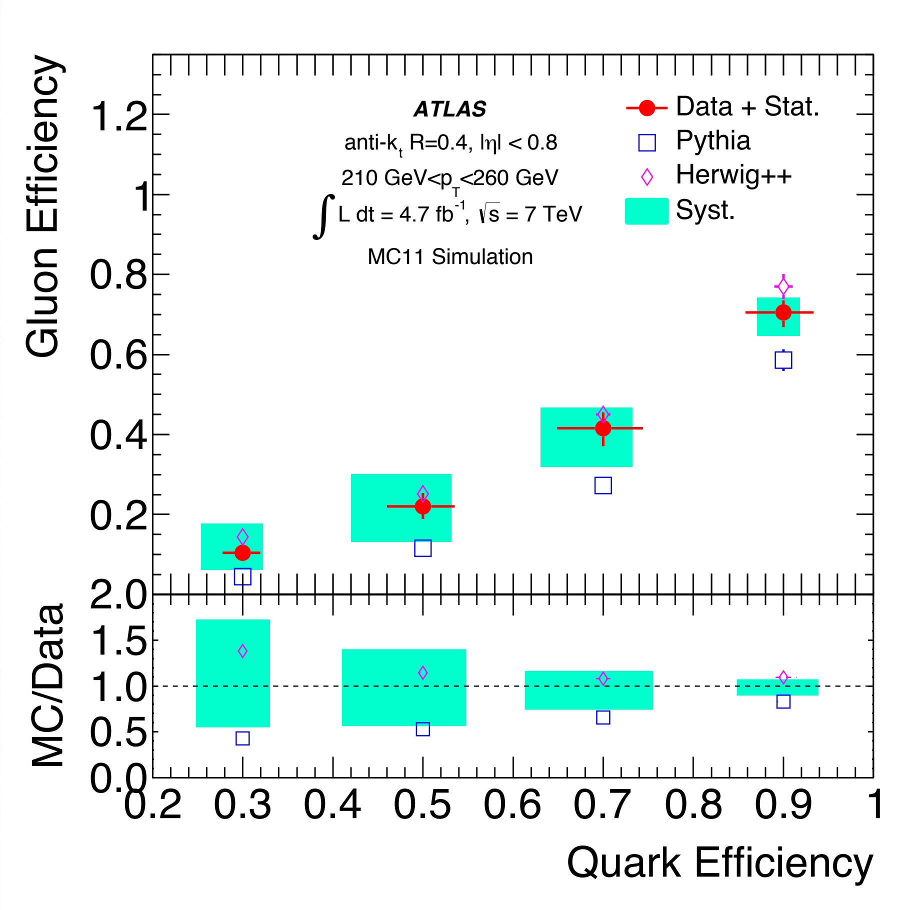
More discriminant at higher pTs

need careful validation of the data

Recent ATLAS analysis (CERN-PH-EP-2014-058)



(a)



(b)

cannot use MC because they disagree each other.

Data driven, use 2j, γ j, isolate jets…

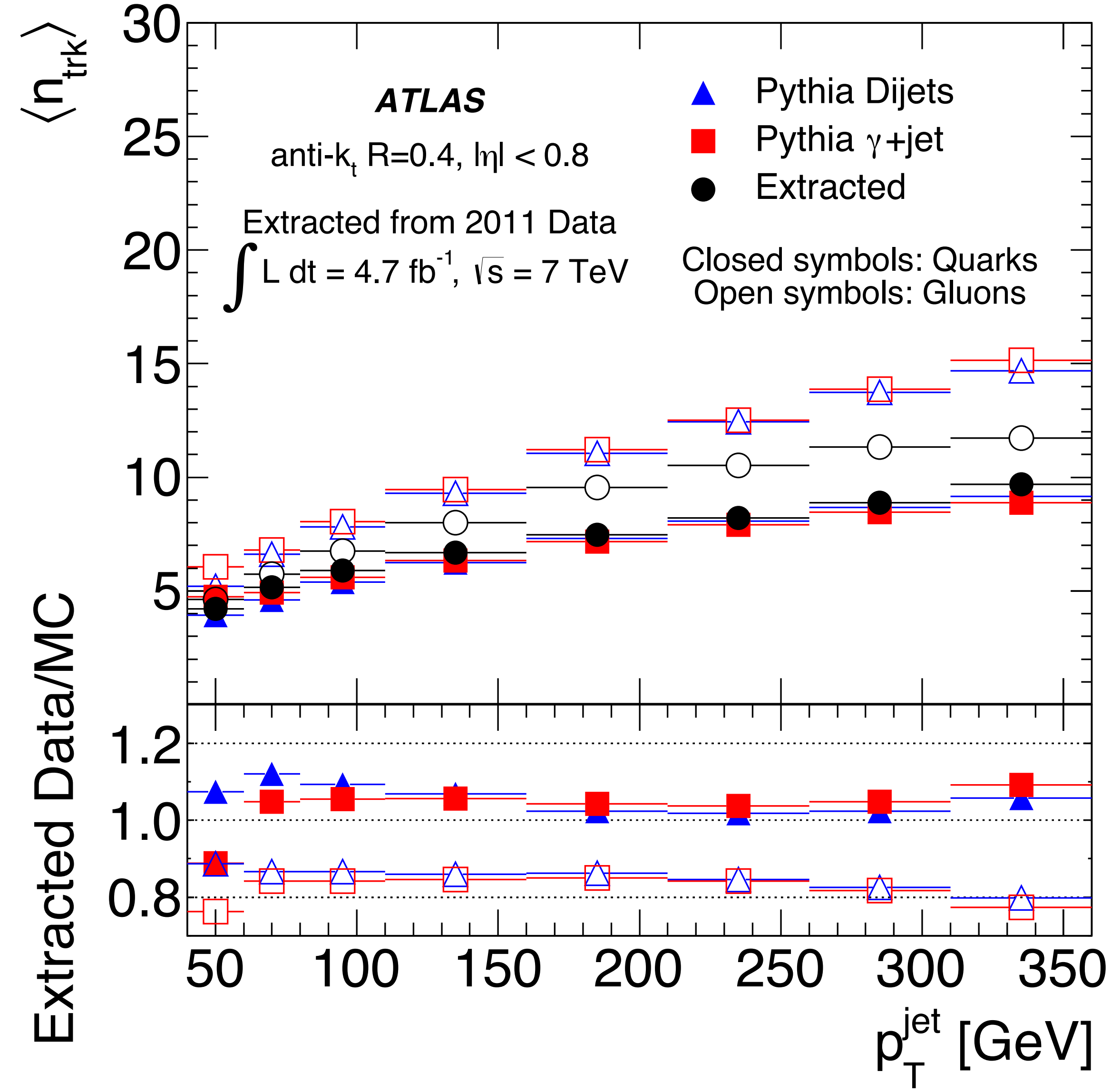
large MC dependence: good (bad) separation with Pythia6(Herwig)

Nature becomes closer to Herwig++ at High pT

not as good as expected, why? any improvement

q vs g :Number of tracks

- Parton shower:Number of partons at Q^2(had) → number of particles →**number of charged particles**
- Infrared non-safe, non-perturbative physics:
  ratio still can be calculated
- rejection rate is determined by tail regions.

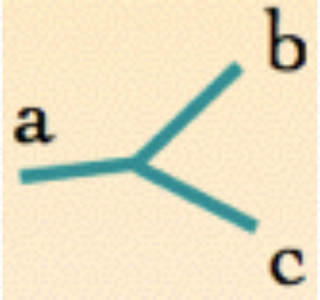


even after tuning by low energy data
number of particles of high pt jets has some uncertainty

Infrared safe quantities (width, mass etc..)

- Better understanding / theory and MC comparison
- calculation proceeds with
  - splitting function

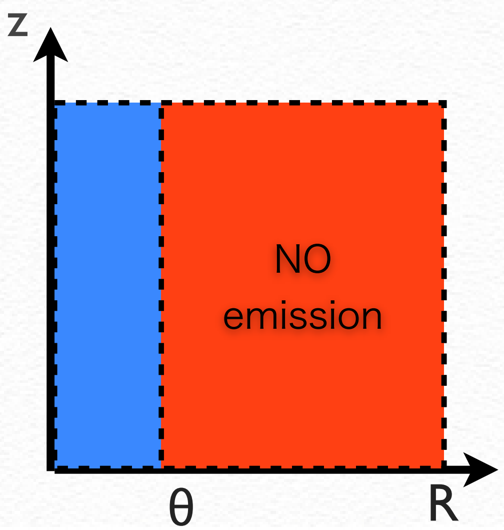
$$dp(\theta) = \frac{d\theta}{\theta} \int dz \frac{\alpha_S}{\pi} P(z)$$



  - Sudakov factor (probability of non-emitting)

$$\Delta(R \to \theta) = \prod_{\theta_k \in [\theta, R]} [1 - dp(\theta_k)] = \exp\left[- \int dp(\theta') \right]$$

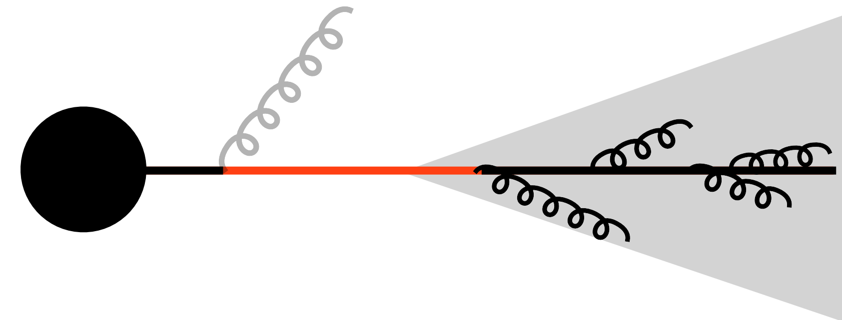
  - resolution



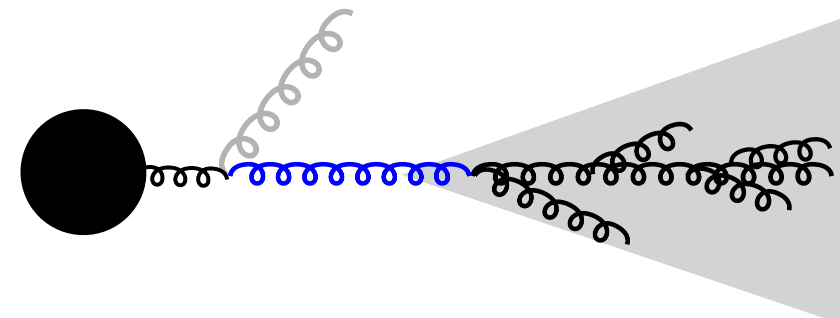
Jet mass : Quarks vs Gluons

- Signal effeciency

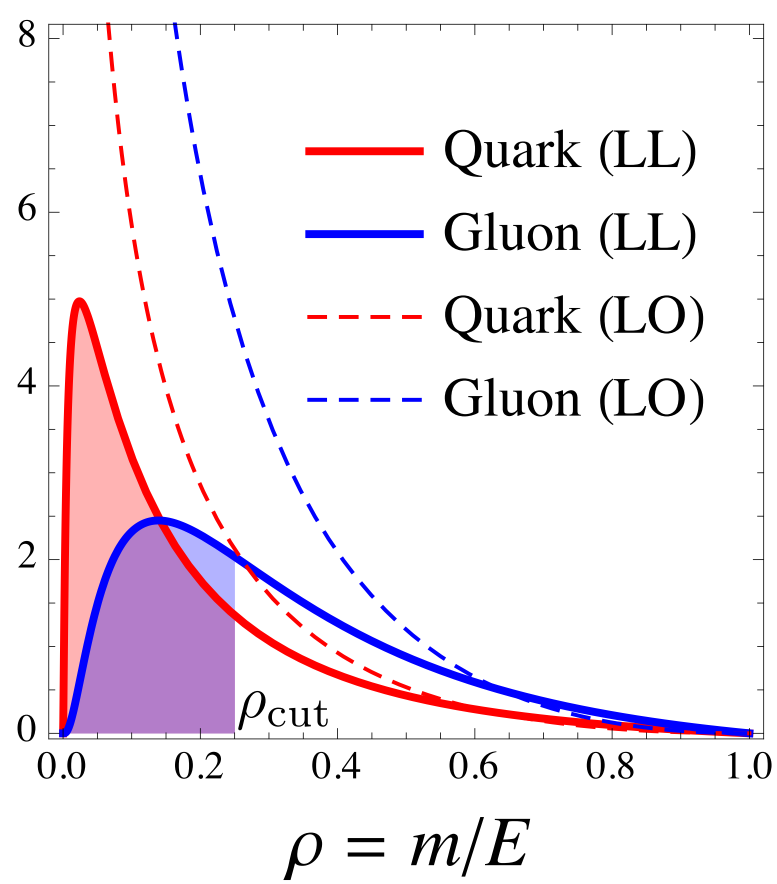
$$\epsilon_Q = \mathrm{Prob}_Q(\rho < \rho_{\rm cut}) = \exp[-C_F \frac{2\alpha_S}{\pi} \ln^2 \rho_{\rm cut}]$$



$$\epsilon_G = \mathrm{Prob}_G(\rho < \rho_{\rm cut}) = \exp[-C_A \frac{2\alpha_S}{\pi} \ln^2 \rho_{\rm cut}]$$



$$\frac{d\epsilon_i}{d\rho} = \frac{1}{\sigma_i}\frac{d\sigma_i}{d\rho}$$



- Gluon mass is greater than Quarks
- Efficiency ratio from QCD prediction at LL order is

$$\frac{\ln \epsilon_G}{\ln \epsilon_Q} = \frac{C_A}{C_F} = \frac{9}{4}$$

Observable, C_1

A. Larkoski, G. Salam, J. Thaler, JHEP06(2013)108

$$C_1^{(\beta)} = \frac{\sum_{i<j} p_{T,i} p_{T,j} \Delta R_{ij}^{\beta}}{(\sum_i p_{T,i})^2}$$

$$\beta > 0$$

Larger value means better separation

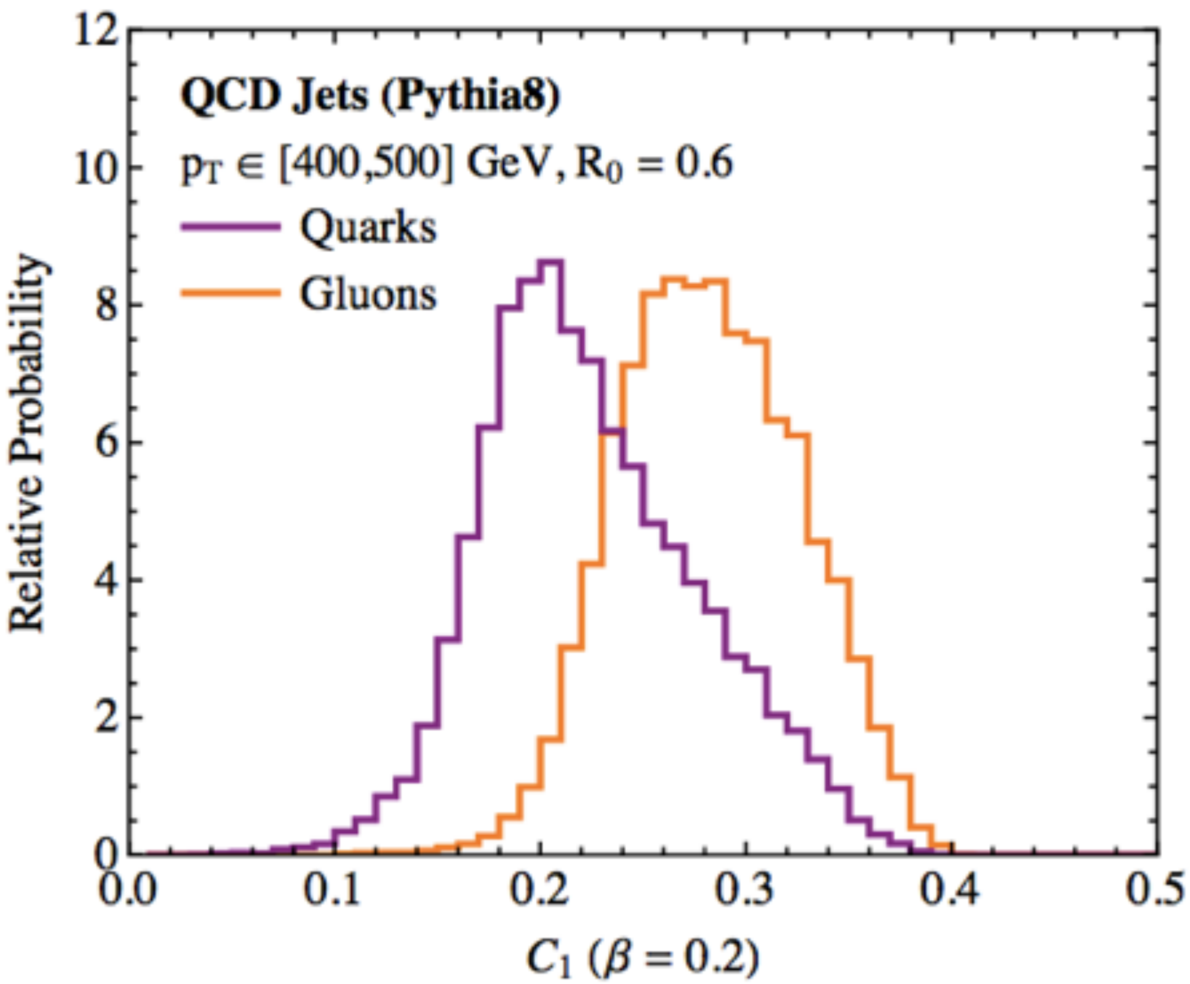
- Efficiency ratio at NLL order

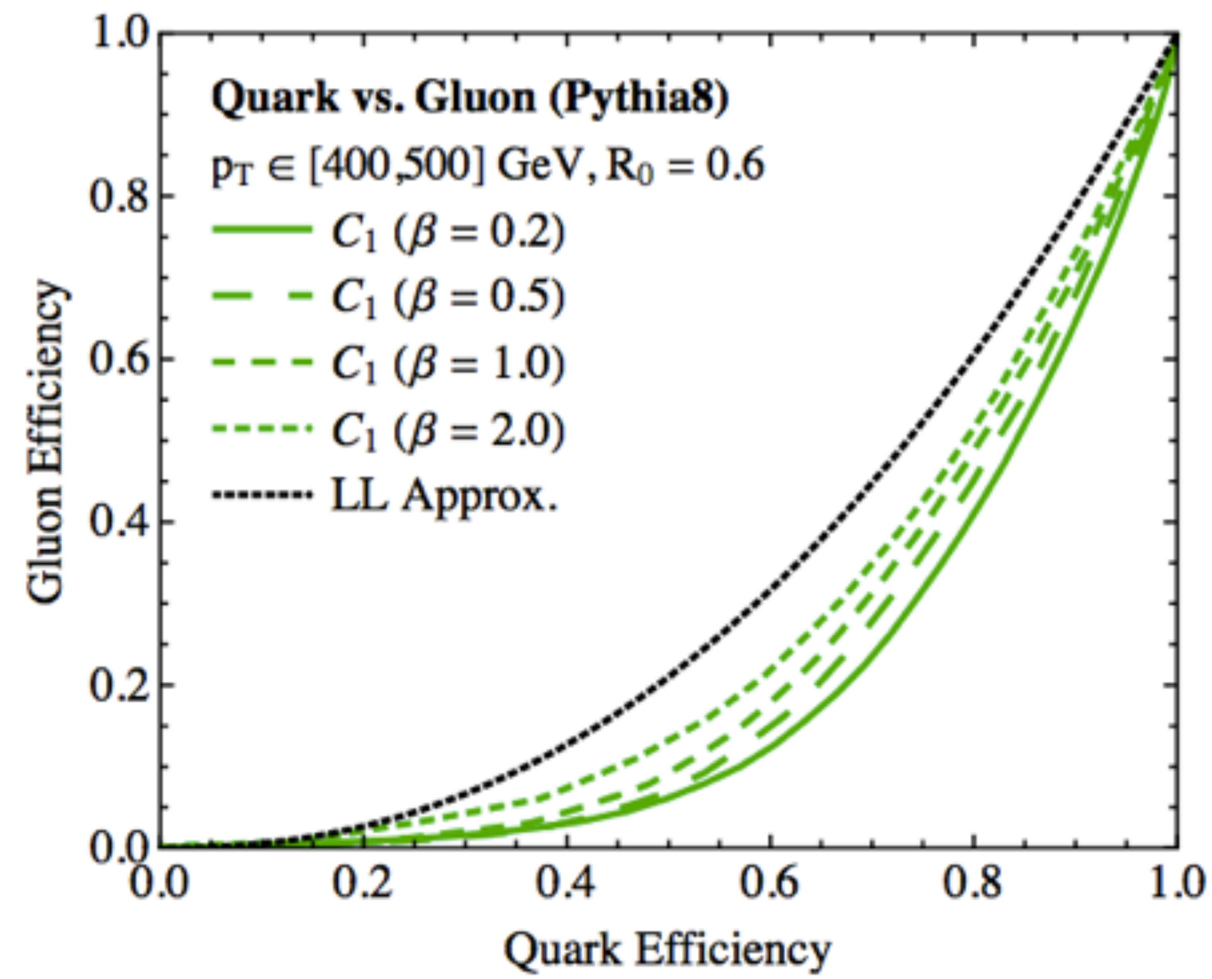
$$\frac{\ln \epsilon_G}{\ln \epsilon_Q} = \frac{C_A}{C_F}\Bigg[1 + \underbrace{\frac{n_F - C_A}{3C_A}\sqrt{\frac{\alpha_S C_F}{\pi\beta \ln 1/\Sigma_Q}}}_{\text{subleading terms in the splitting functions}} + \underbrace{\frac{\alpha_S \pi}{3}\frac{n_F - C_A}{\beta}}_{\text{multiple emission}} + \underbrace{\frac{n_F - C_A}{C_A}\frac{\alpha_S}{36\pi}\frac{b_0}{\beta}(2-\beta)}_{\text{running of } \alpha_s} - \underbrace{\frac{17}{36}\frac{\alpha_S}{\pi}\frac{C_F}{C_A}\frac{n_F - C_A}{\beta \ln 1/\Sigma_Q}}_{\text{matrix element correction}}\Bigg]$$

- Small β lead to better Quark-Gluon separation
- Contribution from 2nd-term (√ αs term) looks most important
- Actually, 3rd term is most significant numerically

MC study

- C_1 with β=0 is collinear-unsafe observable
- Authors recommend β=0.2





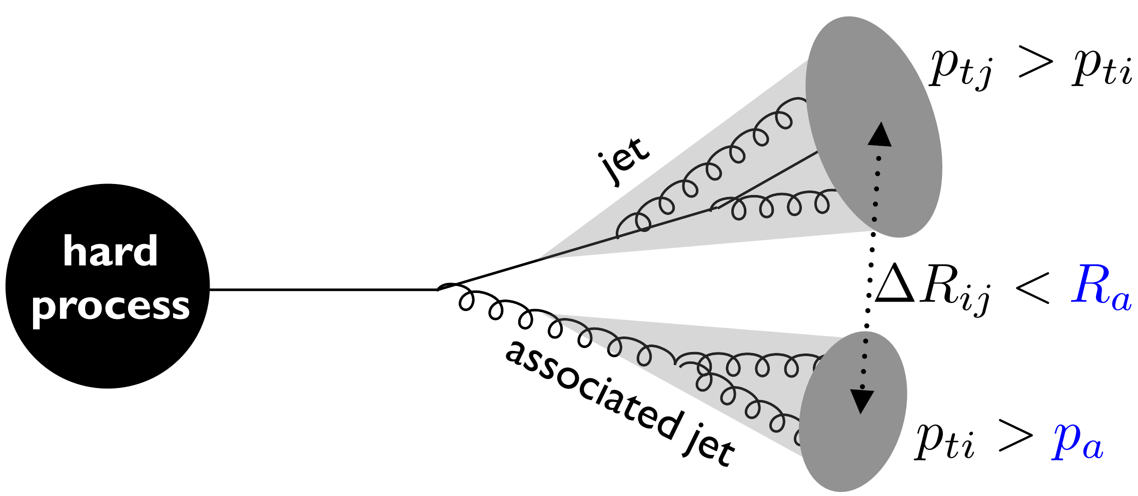
A. Larkoski, G. Salam, J. Thaler, JHEP06(2013)108

Further improvement
Number of associated jet

gluon jet is broader and many particles spill
outside jet cone (additional jets)

1.Jet clustering anti-K_T R=0.4

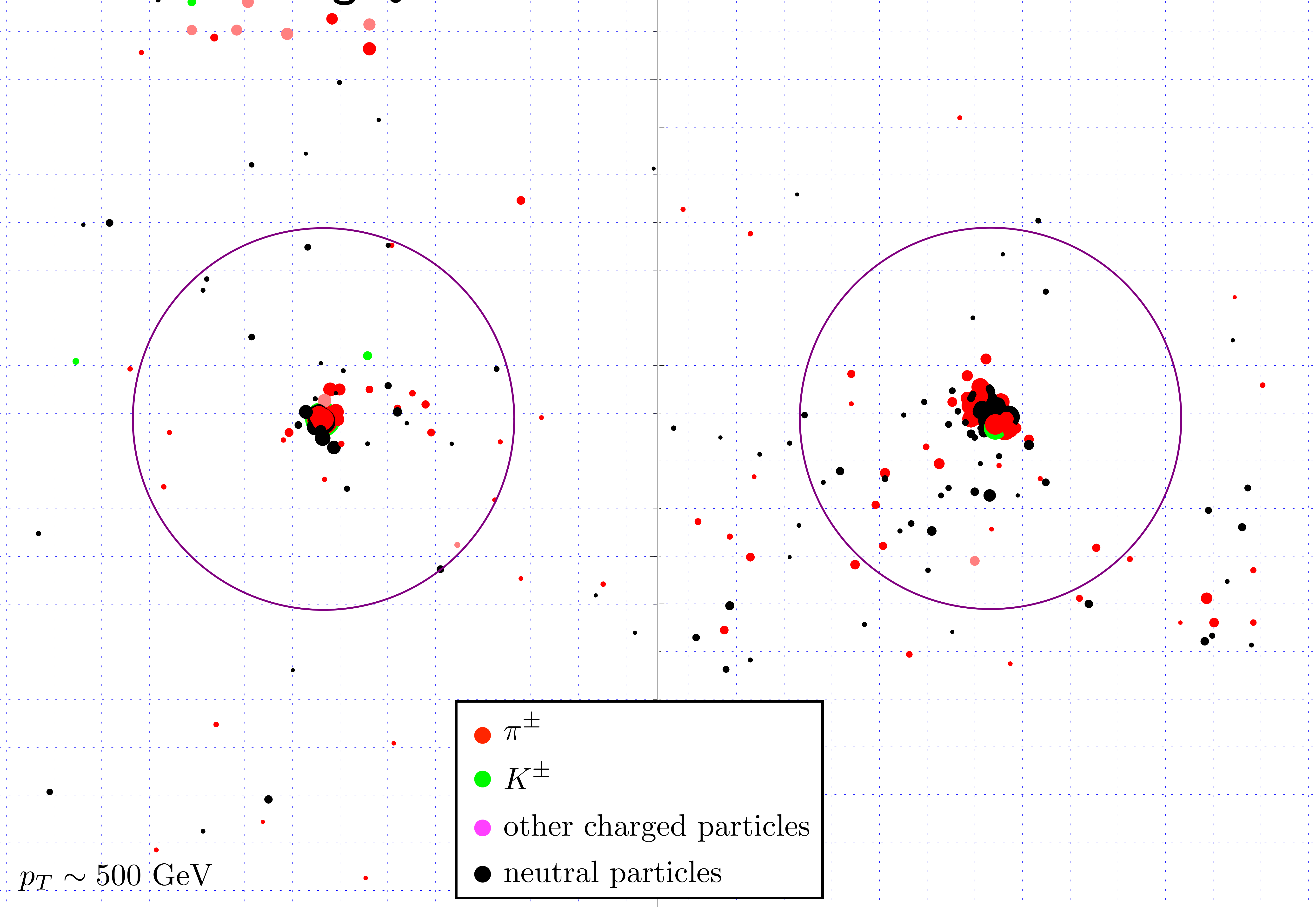
2. Count number of jets in ΔR<0.8
but ΔR (p_{Ta}/p_{Tj})<0.4
(avoid counting accidental hard objects)



QCD :gluon emits nearby jets P(g)/P(q)~2

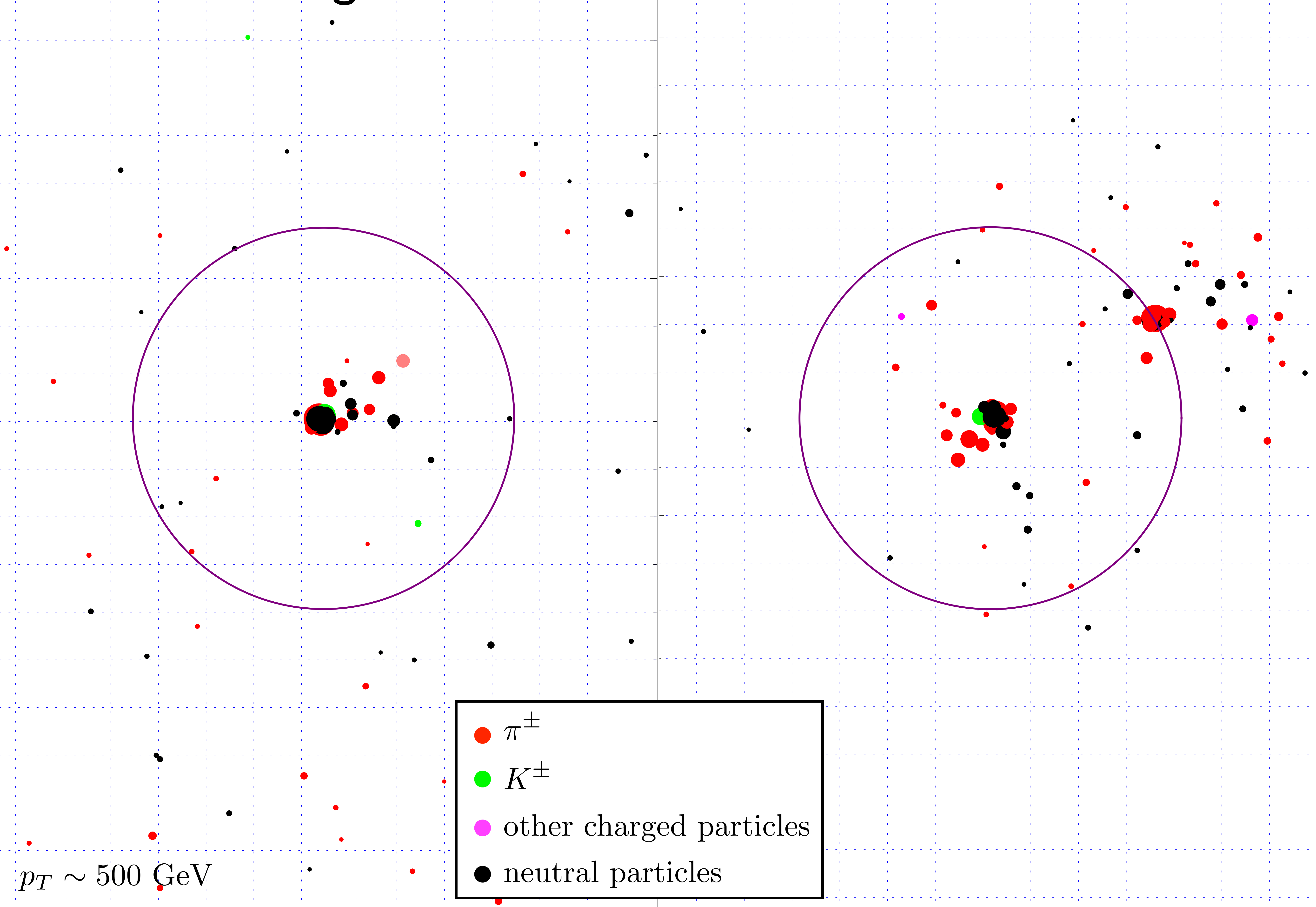
Can we distinguish Quarks from Gluons?

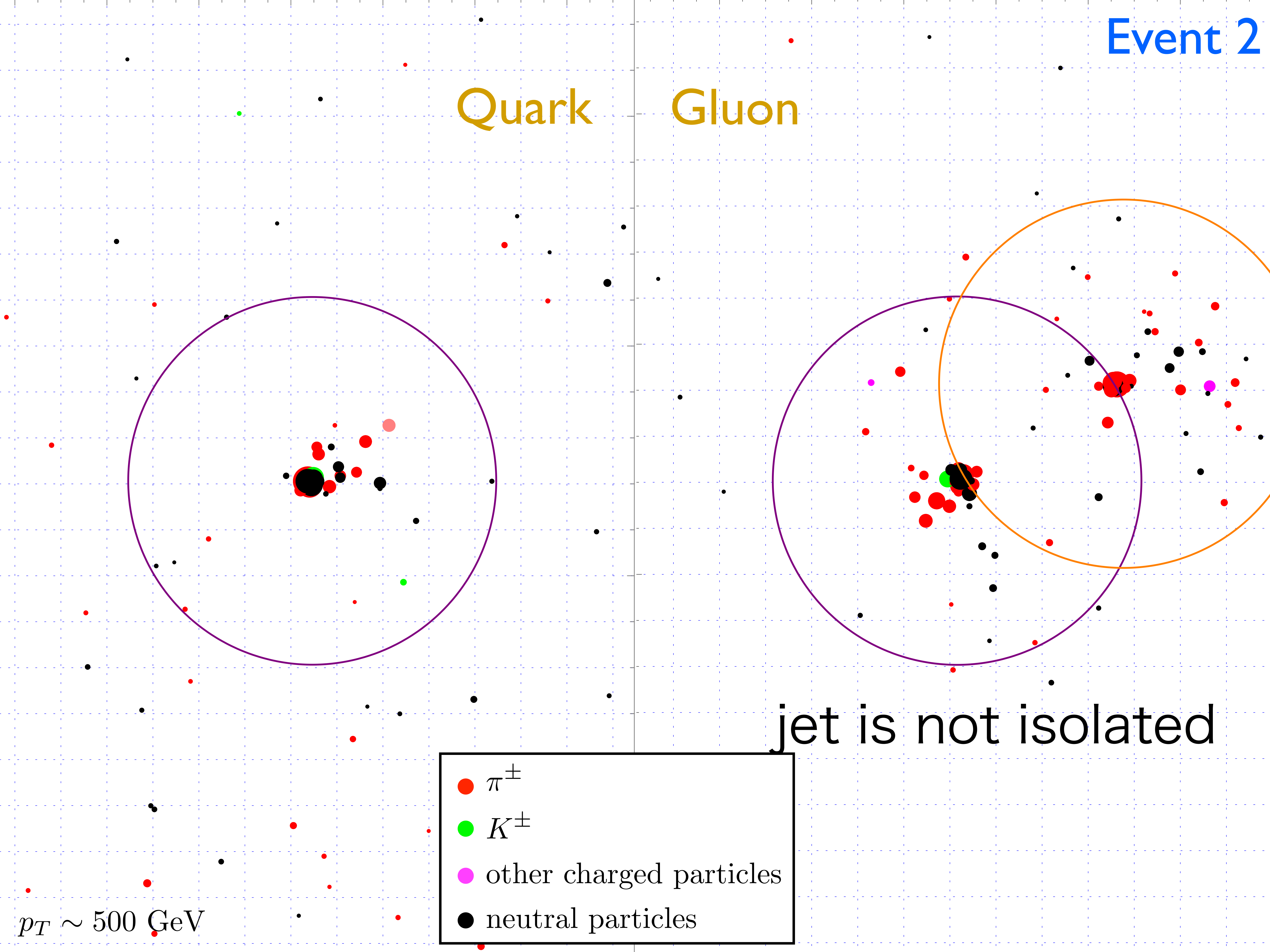
Event 1



Can we distinguish Quarks from Gluons?

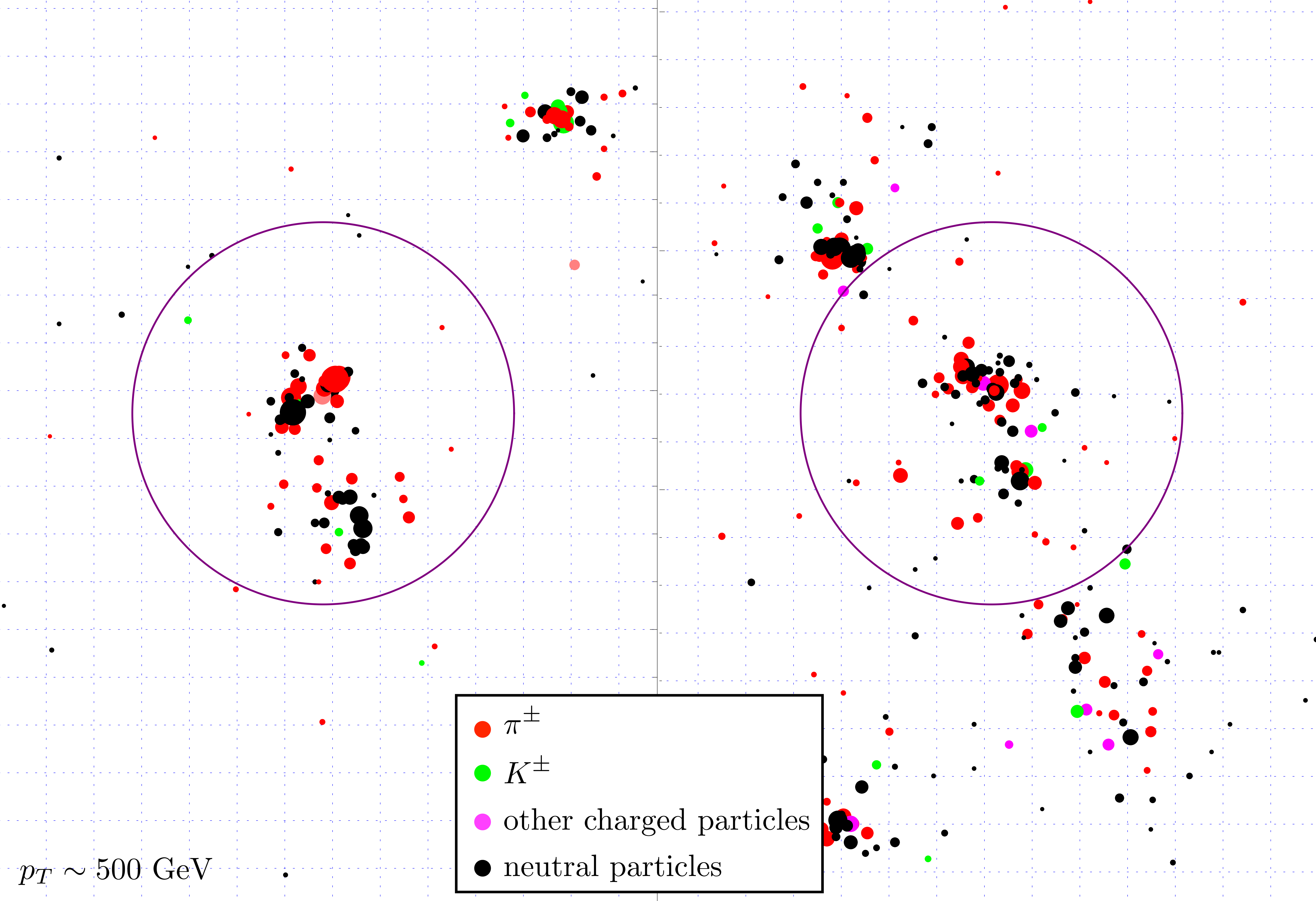
Event 2



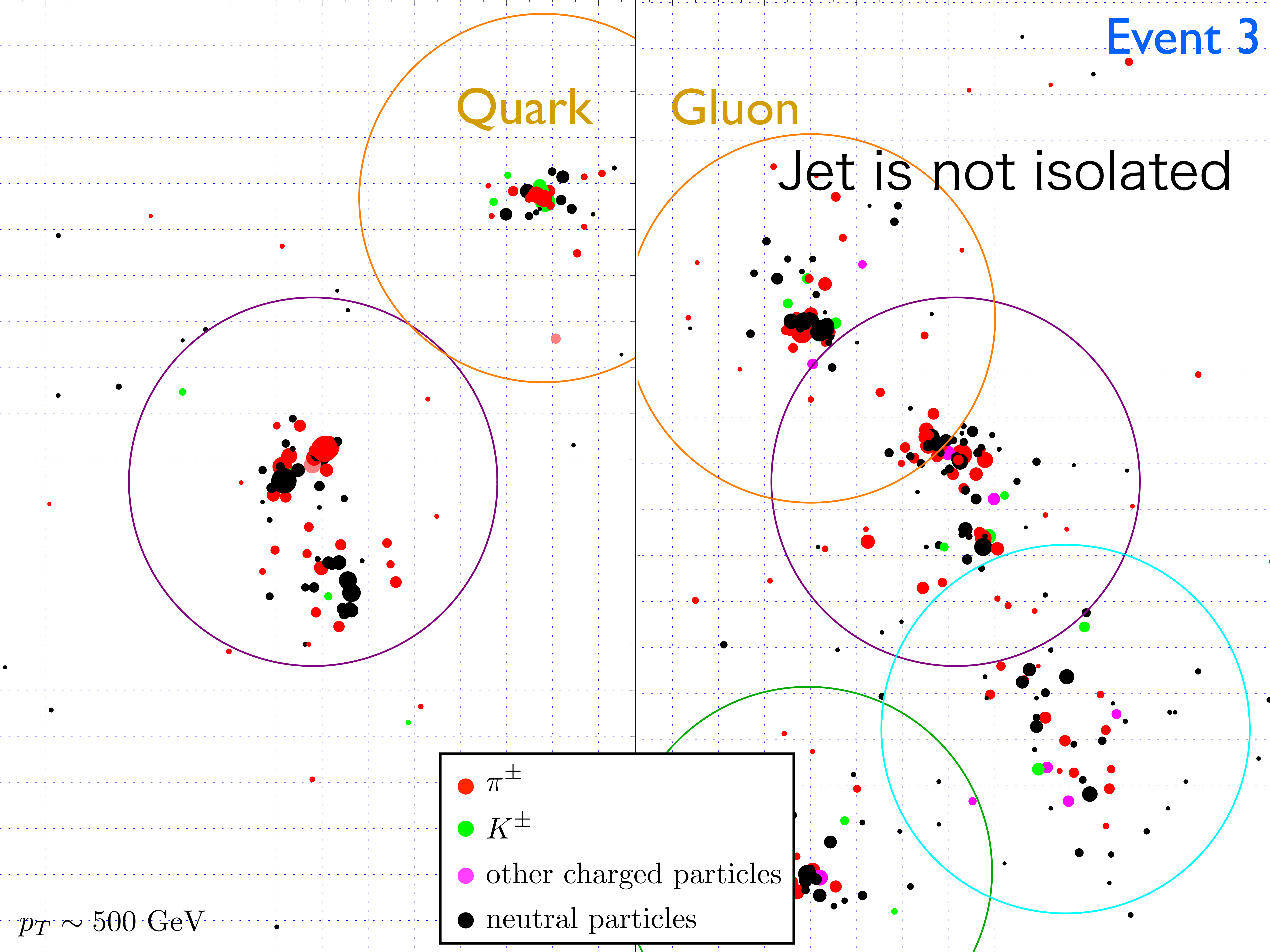

Event 2
Quark
Gluon
jet is not isolated
$\pi^{\pm}$
$K^{\pm}$
other charged particles
neutral particles
$p_T \sim 500$ GeV

Can we distinguish Quarks from Gluons?

Event 3

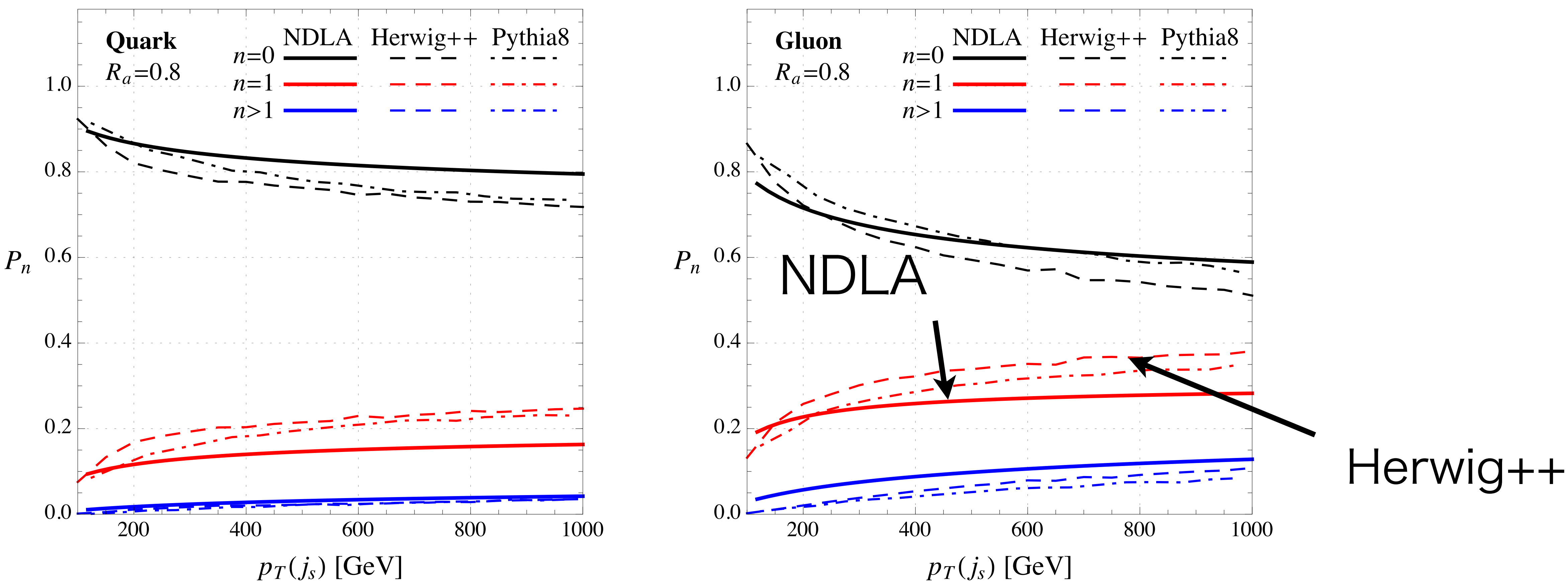


$p_T \sim 500$ GeV


Event 3
Quark
Gluon
Jet is not isolated
$\pi^{\pm}$
$K^{\pm}$
other charged particles
neutral particles
$p_T \sim 500$ GeV

jets with associated jet is more likely to be gluon

DLLA predicts P1(gluon)~2P1(quark) agree with Herwig++
Pythia P1(gluon)~P1(quark)



quark gluon

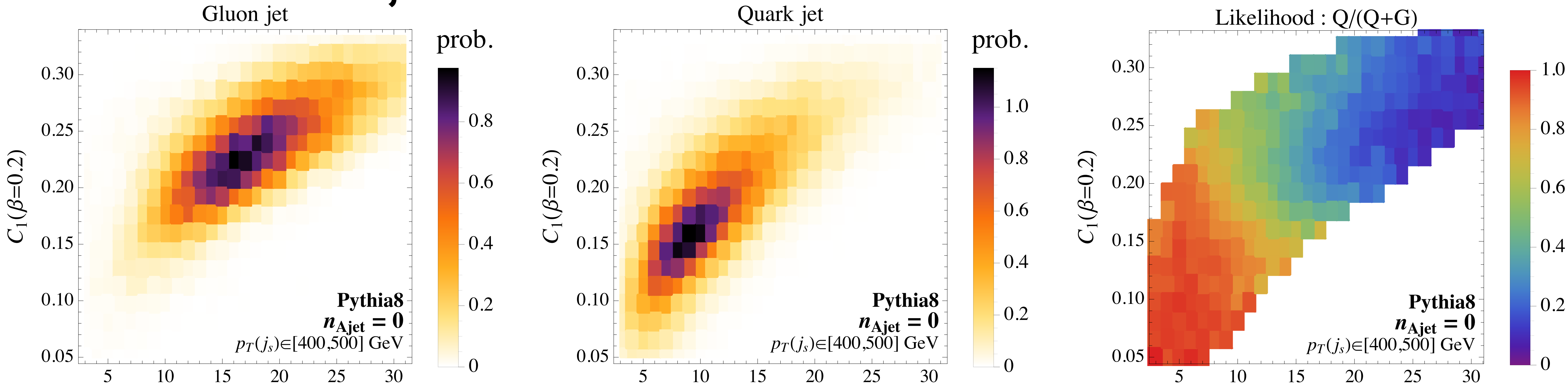
NDLA vs Herwig++ & Pythia8

my previous claims in some talk on large disagreement was due to pythia 6.4.26 bug (latest is 6.4.28) ported from pythia-pgs of MadGraph. (use most latest one always and check consistency even if you have generated lots of events already)

Multivariate analysis(MVA) with # of associated jet categories

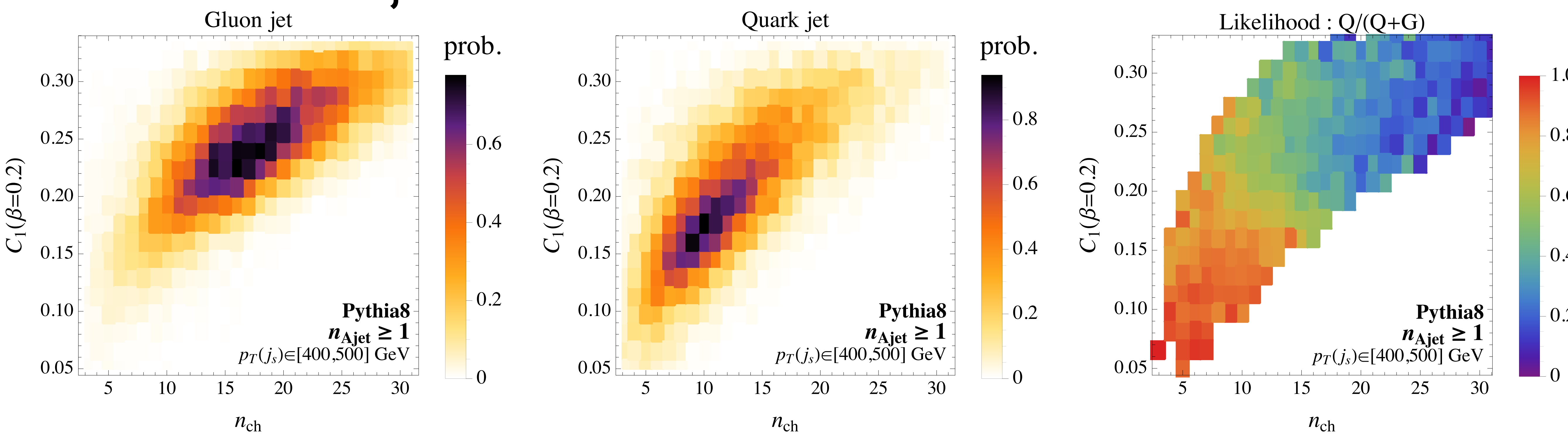
Delphes with track pT cuts, UE, MI etc

- # of associated jet = 0

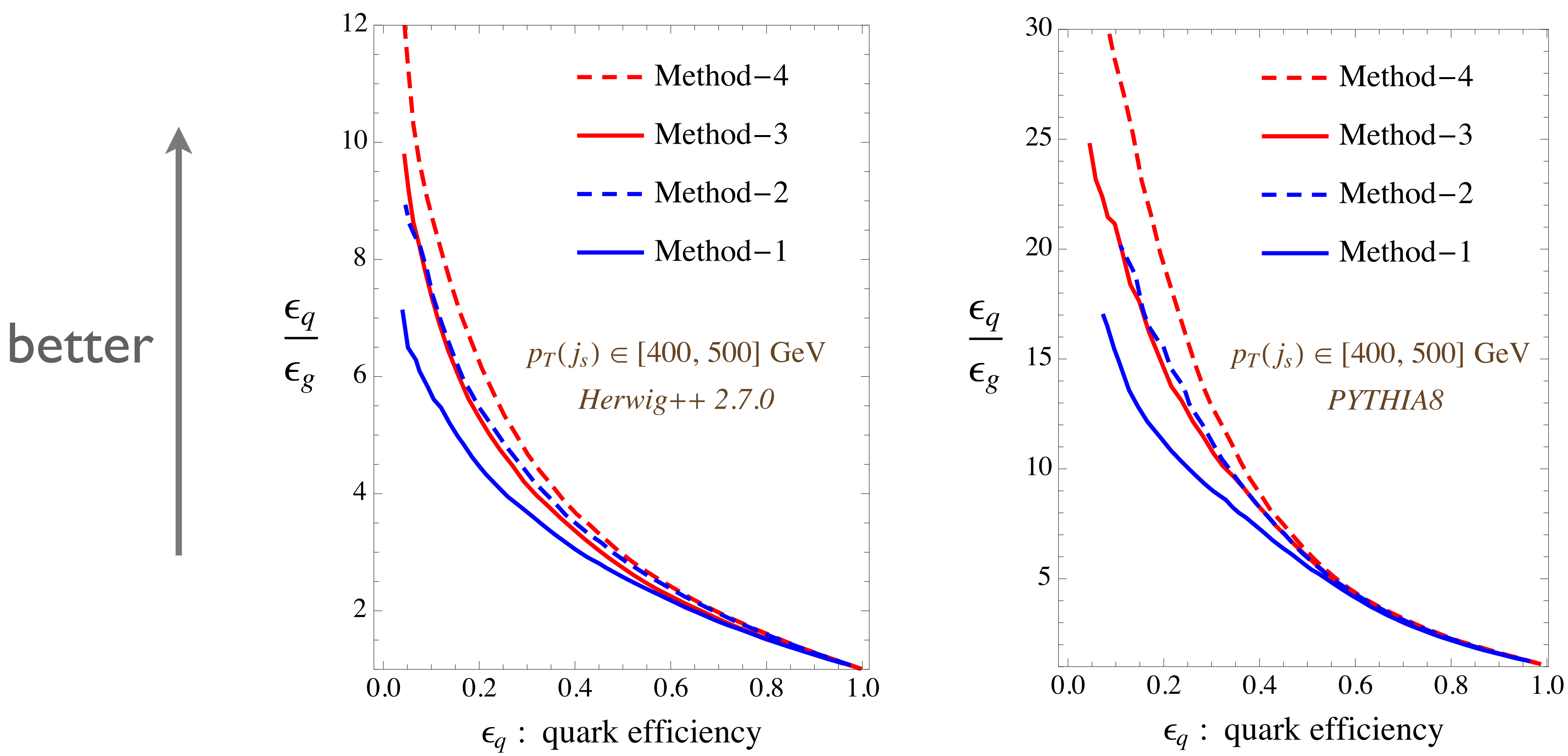


n_{ch} ← (# of charged particles in jet)

- # of associated jet ≧ 1



- Method-1: MVA(n_{ch} + C_1)
- Method-2: MVA(n_{ch} + C_1) + associated jet information
- Method-3: MVA(n_{ch} + C_1 + m/p_T)
- Method-4: MVA(n_{ch} + C_1 + m/p_T) + associated jet information



Associated jets bring information outside a leading jet, and improve the performance of Quark-Gluon separation!

Associate jet variable

- Covers finite(large) angle emission, somewhat related with mass or C1 of the jet.
- “ glooming” with wider R (jet pT cut on associated jet.)
- number of associated jet distribution is “consistent” with NDLL accuracy calc. large Ra/R and pa/p and $\alpha^n \log^{2n}$ and $\alpha^n \log^{2n-1}$.
- No need to change LHC “jet analysis” anti-KT, fixed cone etc

for application

- Experimental studies using "isolated jets" : bias killing gluon jet. It is not practical because high PT jets have associated jets with high probability
- generators do not agree on number of nearby jets. They are different in shower, color connection .. -> quantity to tune MC models.
- take only $p_a/p_j << 1$ "soft collinear activity" (but not hard substructure
- Underlying events could be a problem, though our simulations show it is not big.