quark gluon separation at LHC

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quark gluon separation
Motivation

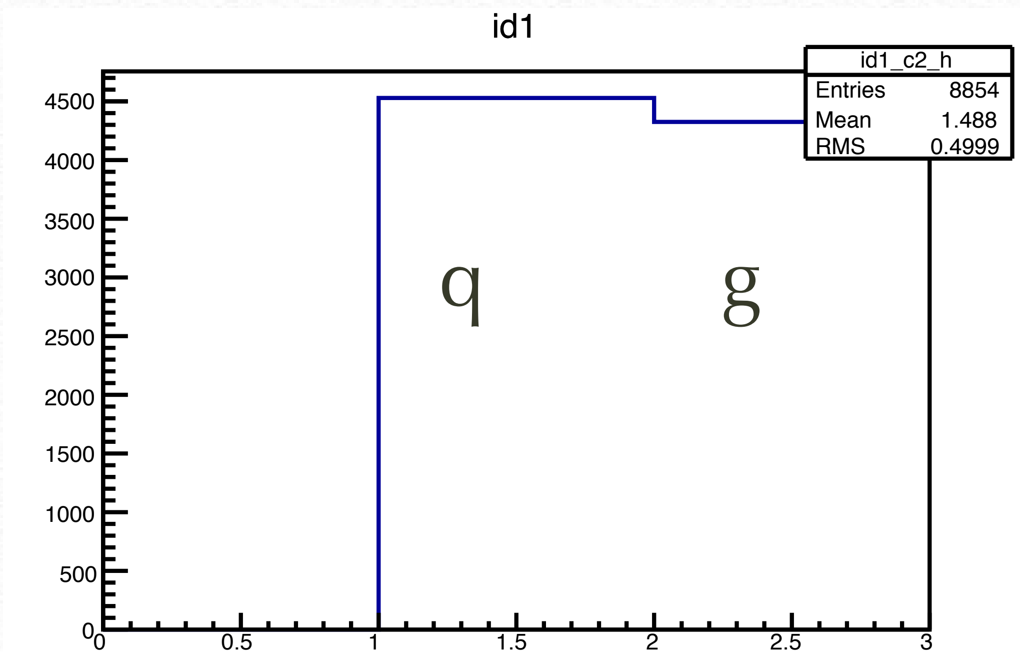
- quark, gluon →jet: most of present analysis assume they cannot be distinguished.
- However…
  - gluino/squark decay to LSP → hard quark
  - ISR from SUSY production →gluon rich
  - QCD process → gluon rich /EW process→hard quark
- quark gluon separation -> discriminate New physics
- Energy calibration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

Example: degenerate SUSY

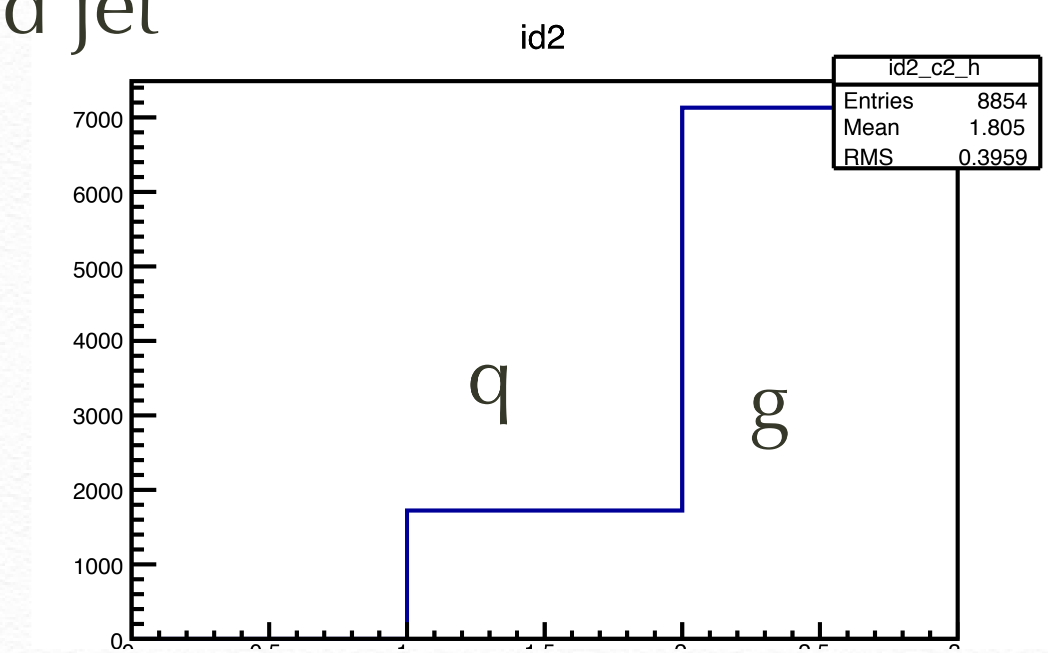
(Mukohopadhyay, Nojiri, Yanagida JHEP10(2014)012)

gluino production

1st jet

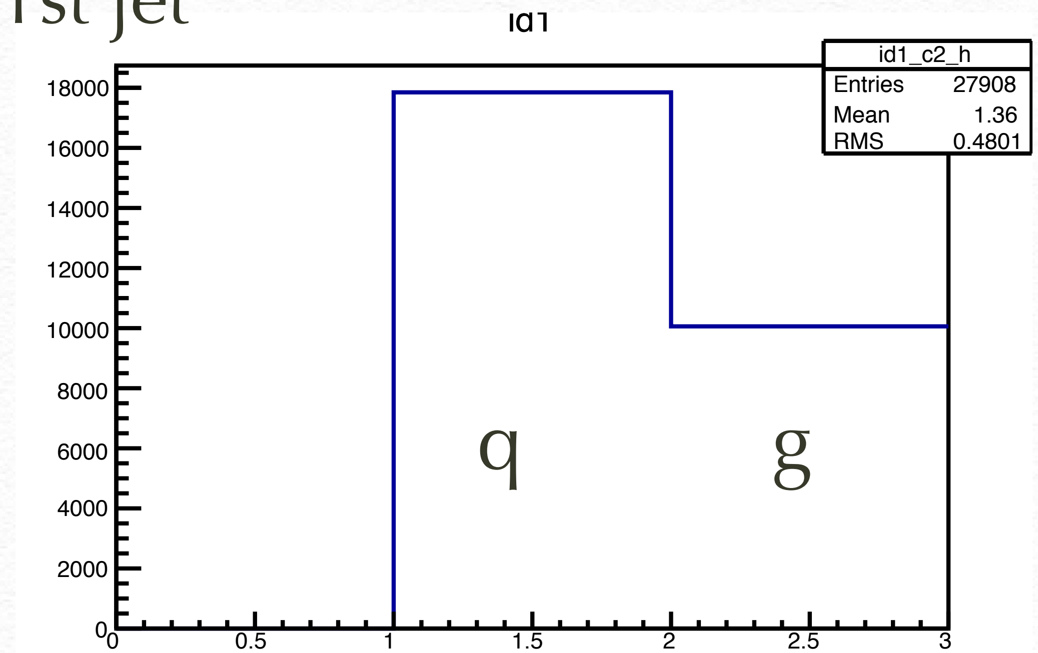


2nd jet

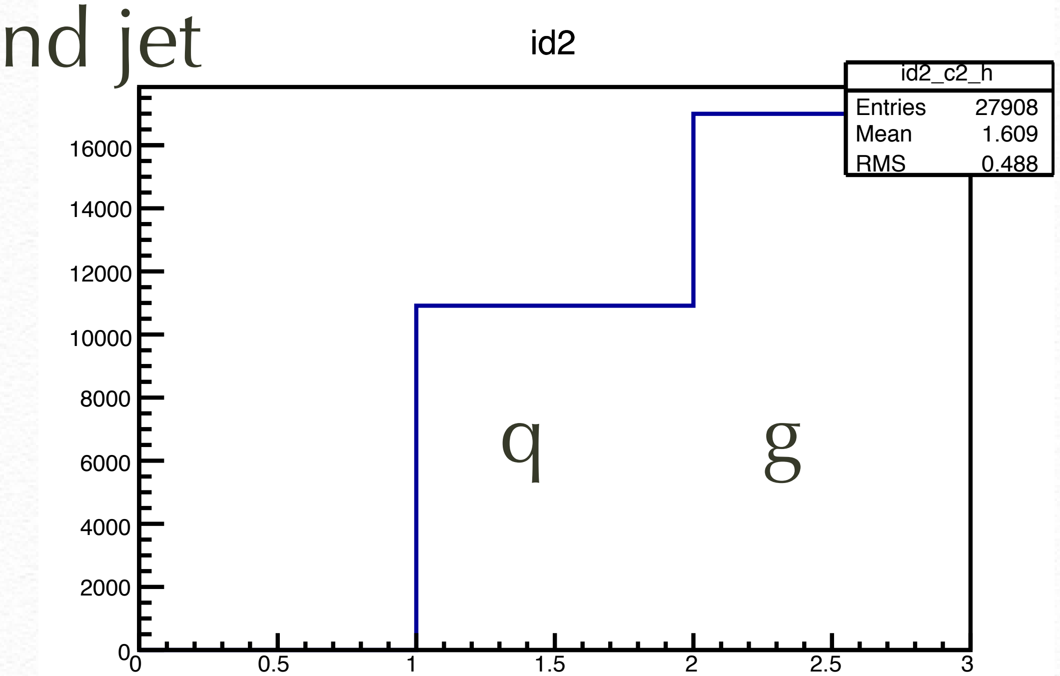


z+3j

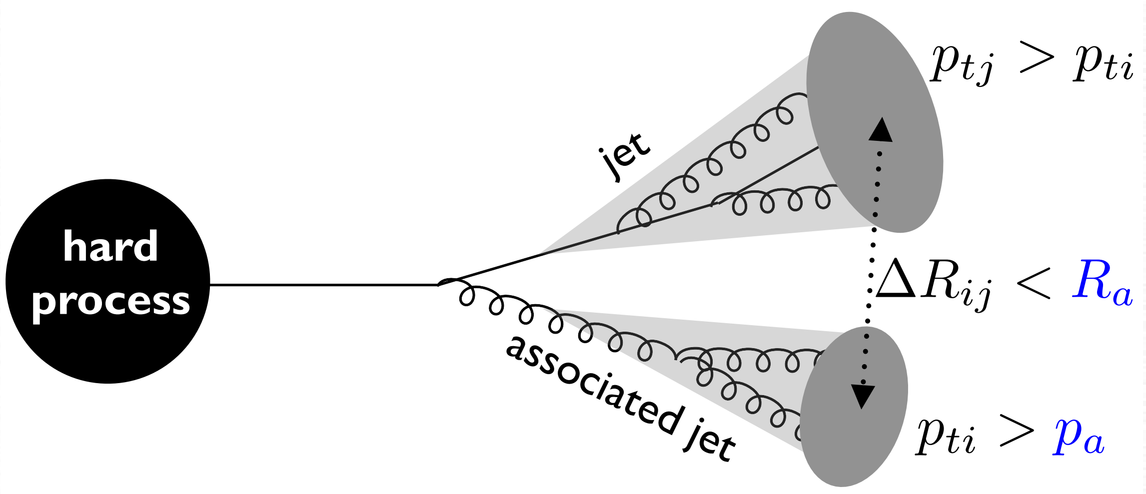
1st jet



2nd jet



- quantity that has been proposed for quark gluon separation
  - **nch :number of charged tracks**
  - **jet shape (jet width -> C1)**
  - **jet mass**
- In this talk **new variable: number of associated jet**



- **MC dependence, comparison with QCD**

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

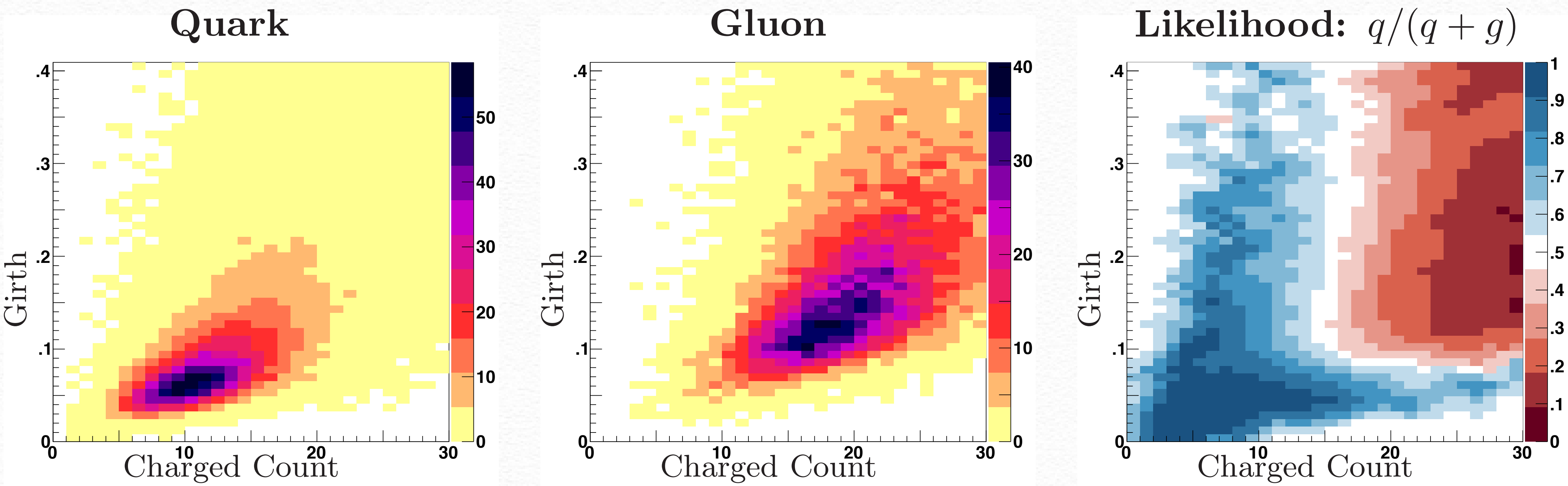
$$C_1^{(\beta)} = \sum_{i<j\in J} p_{Ti}\, p_{Tj} (\Delta R_{ij})^\beta$$ Larkoski et al JHEP 1306.108(2013)

Infrared safe and calculable "in principle"

Monte Carlo (Pythia, Herwig++)
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

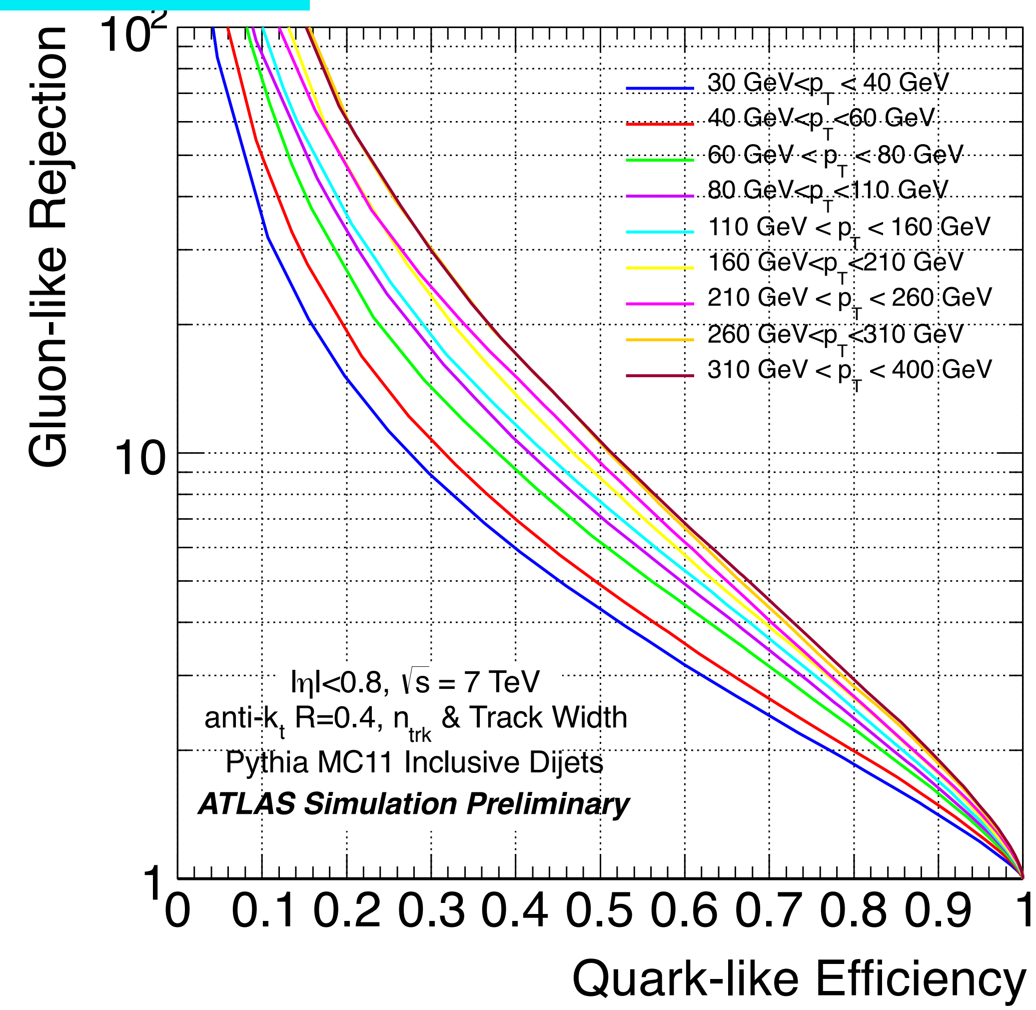
This earlier study has shown very good separation between quark and gluon based on pythia 6

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

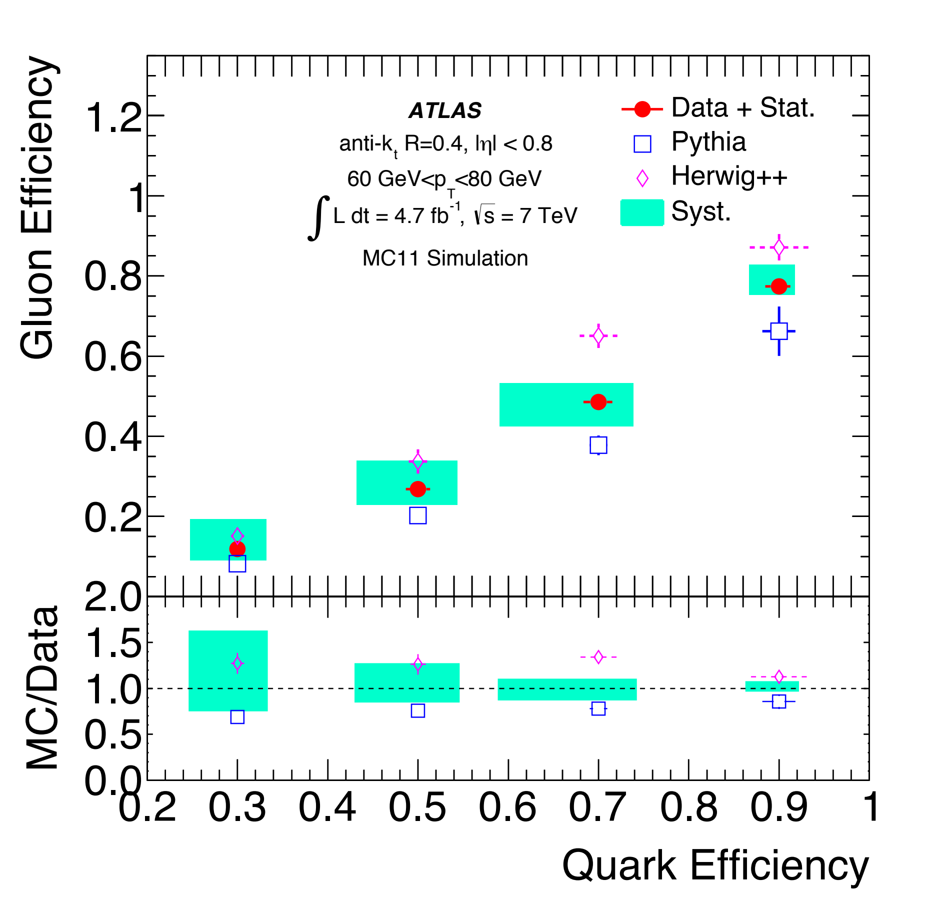


Example: for 50% quark jet efficiency, we can reject 90% gluon jets

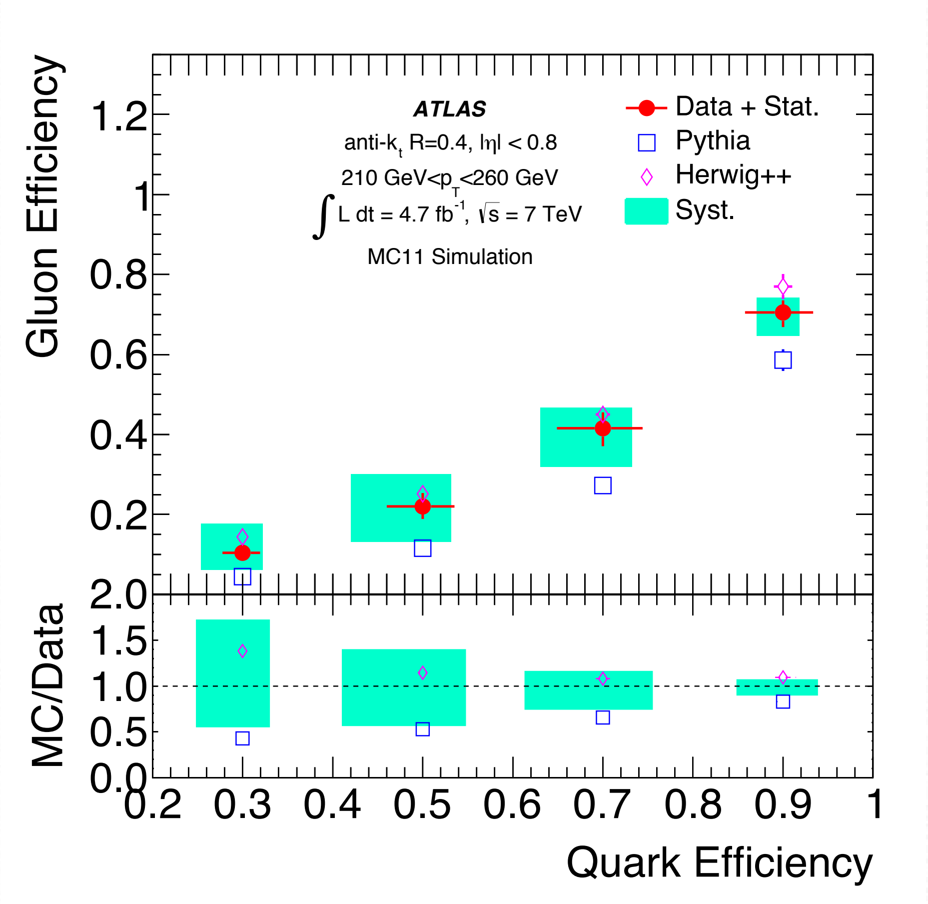
More discriminant at higher pTs

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, γj, isolate jets…

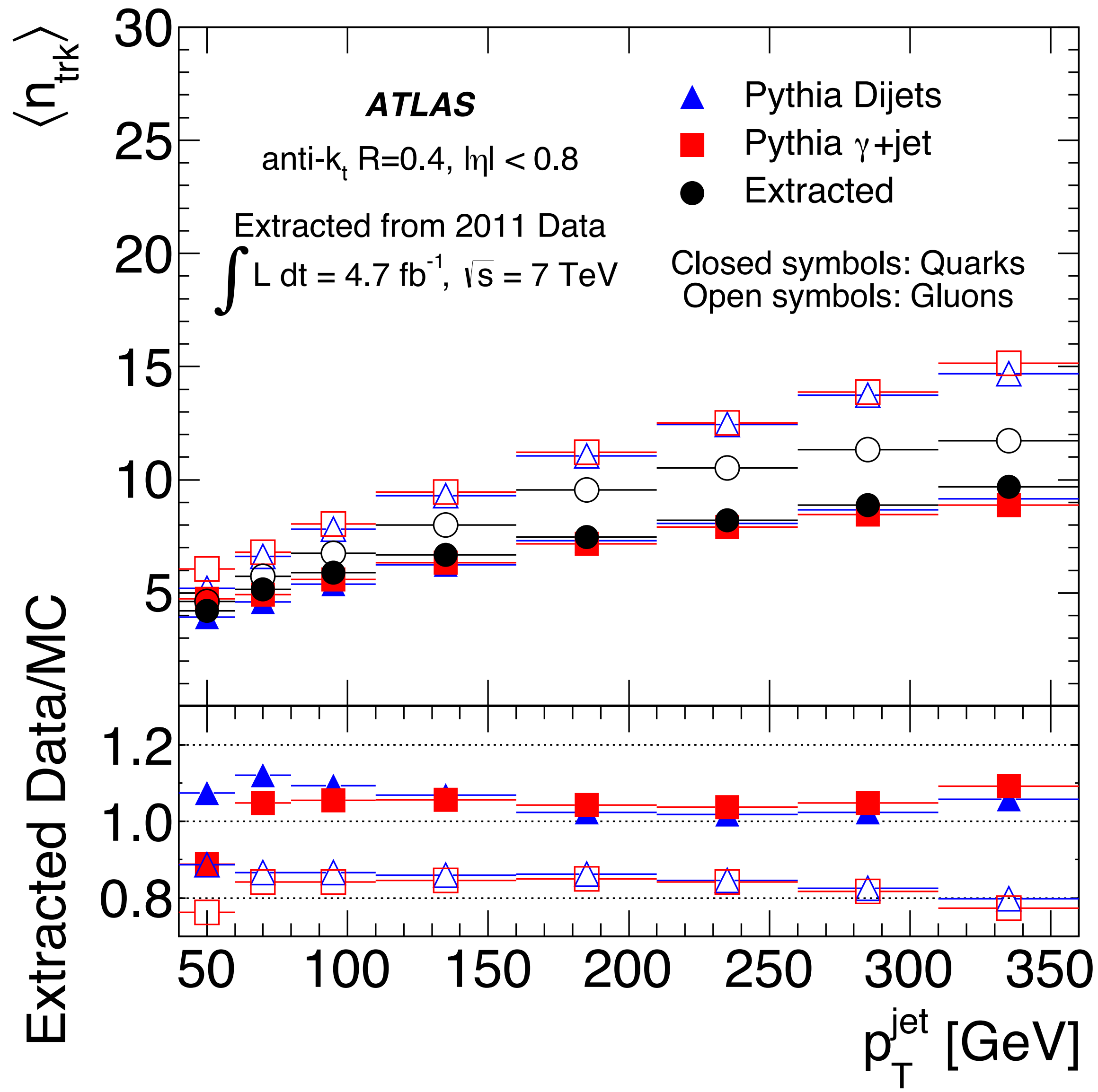
large MC dependence: good (bad) separation with Pythia6(Herwig)

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. → uncertainty remains



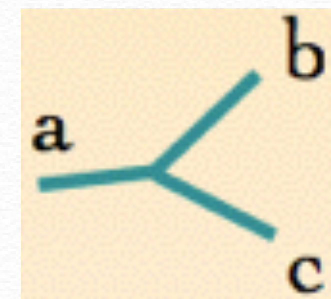
go for

Infrared safe quantities are relatively safe

Infrared safe quantities (width, mass etc..)

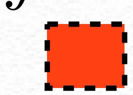
- Better understanding / theory and MC comparison
- calculation proceeds with
  - splitting function

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

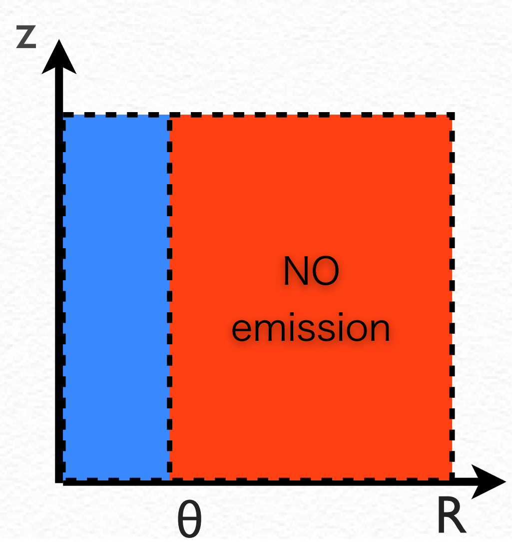


  - Sudakov factor (probability of non-emitting)

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



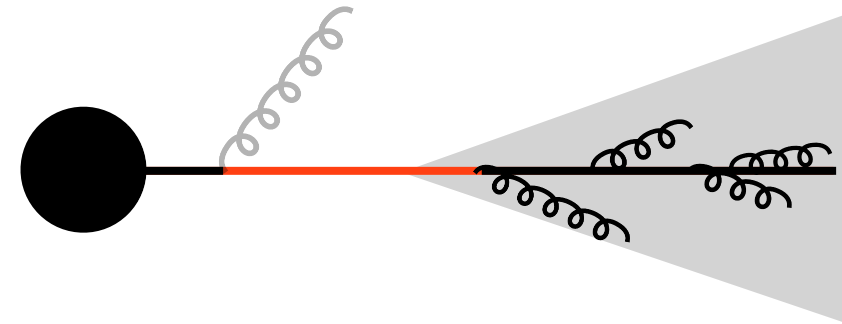
  - resolution



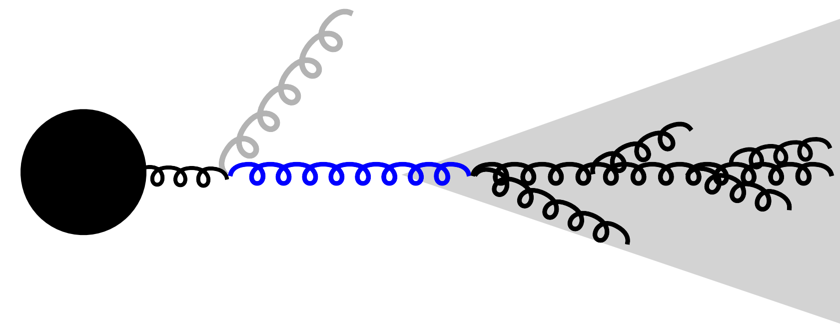
Jet mass : Quarks vs Gluons

- Signal effeciency

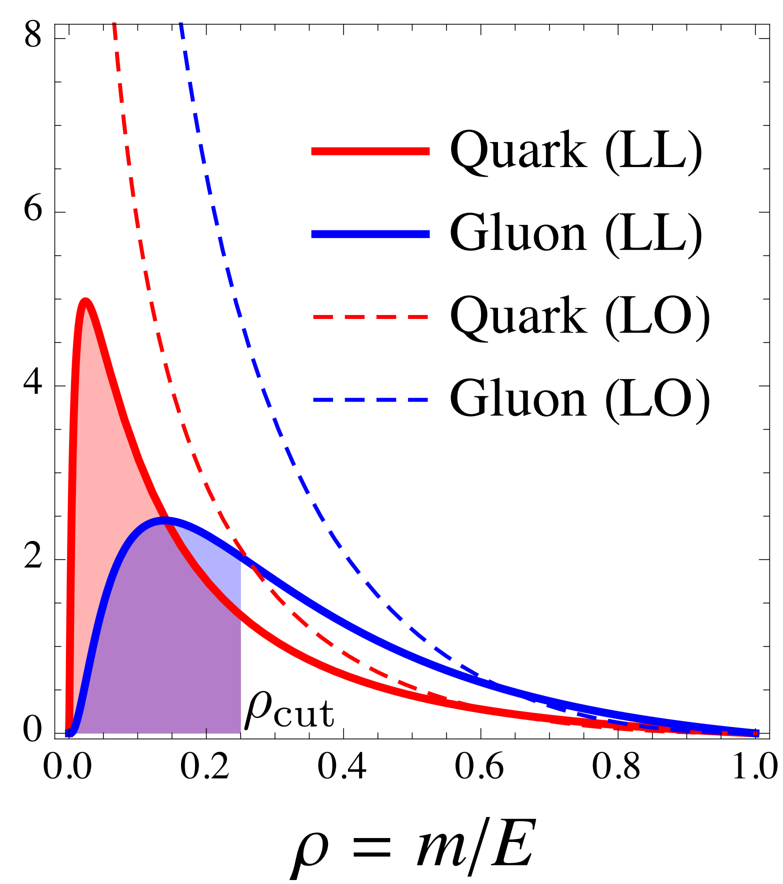
$$\epsilon_Q = \mathrm{Prob}_Q(\rho < \rho_{\mathrm{cut}}) = \exp[-C_F \frac{2\alpha_S}{\pi} \ln^2 \rho_{\mathrm{cut}}]$$



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



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



- 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

subleading terms in the splitting functions — multiple emission

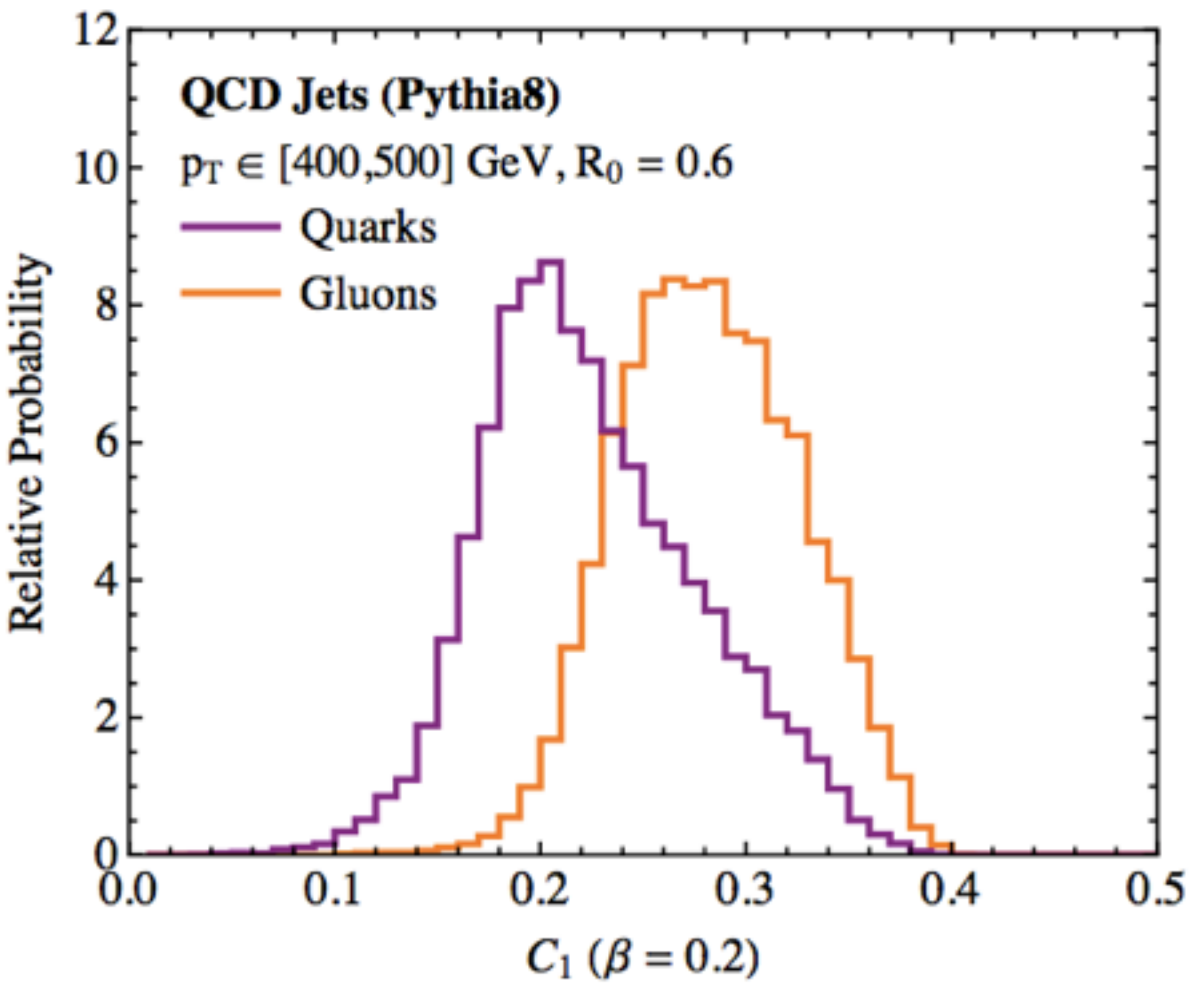
$$\frac{\ln \epsilon_G}{\ln \epsilon_Q} = \frac{C_A}{C_F}\left[1 + \frac{n_F - C_A}{3C_A}\sqrt{\frac{\alpha_S C_F}{\pi\beta \ln 1/\Sigma_Q}} + \frac{\alpha_S \pi}{3}\frac{n_F - C_A}{\beta} + \frac{n_F - C_A}{C_A}\frac{\alpha_S}{36\pi}\frac{b_0}{\beta}(2-\beta) - \frac{17}{36}\frac{\alpha_S}{\pi}\frac{C_F}{C_A}\frac{n_F - C_A}{\beta \ln 1/\Sigma_Q}\right]$$

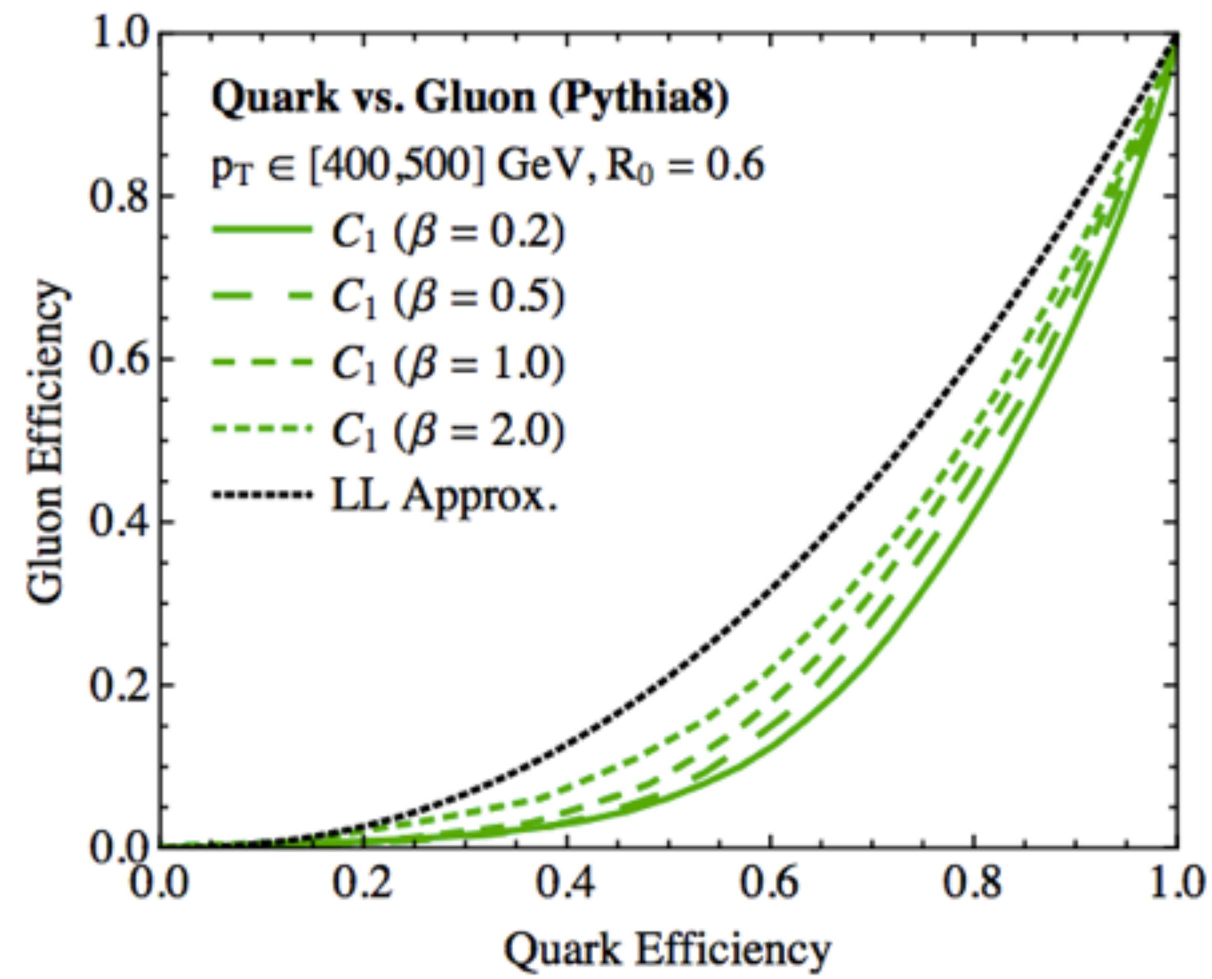
running of αs — matrix element correction

- 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

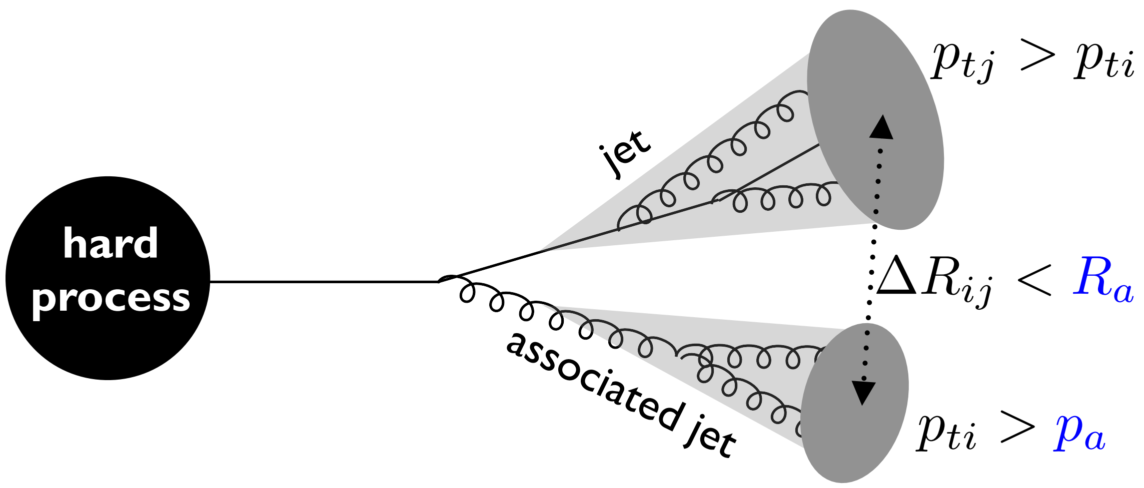
Further improvement
Number of associated jet

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

1.Jet clustering anti-K_T R=0.4

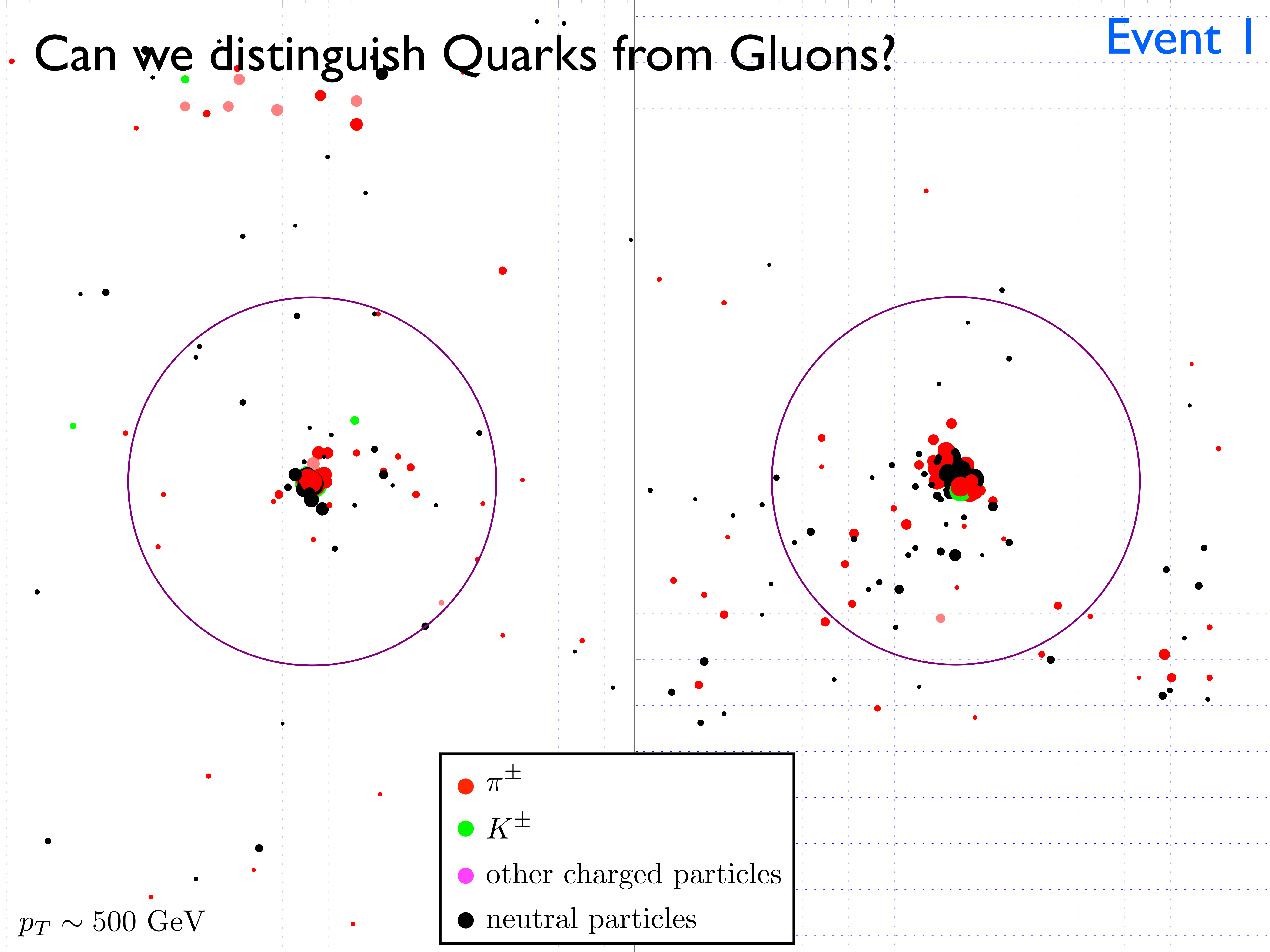
2. Count number of jets in $\Delta R<0.8$ but $\Delta R\ (p_{Ta}/p_{Tj})<0.4$
(avoid counting accidental hard objects)

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



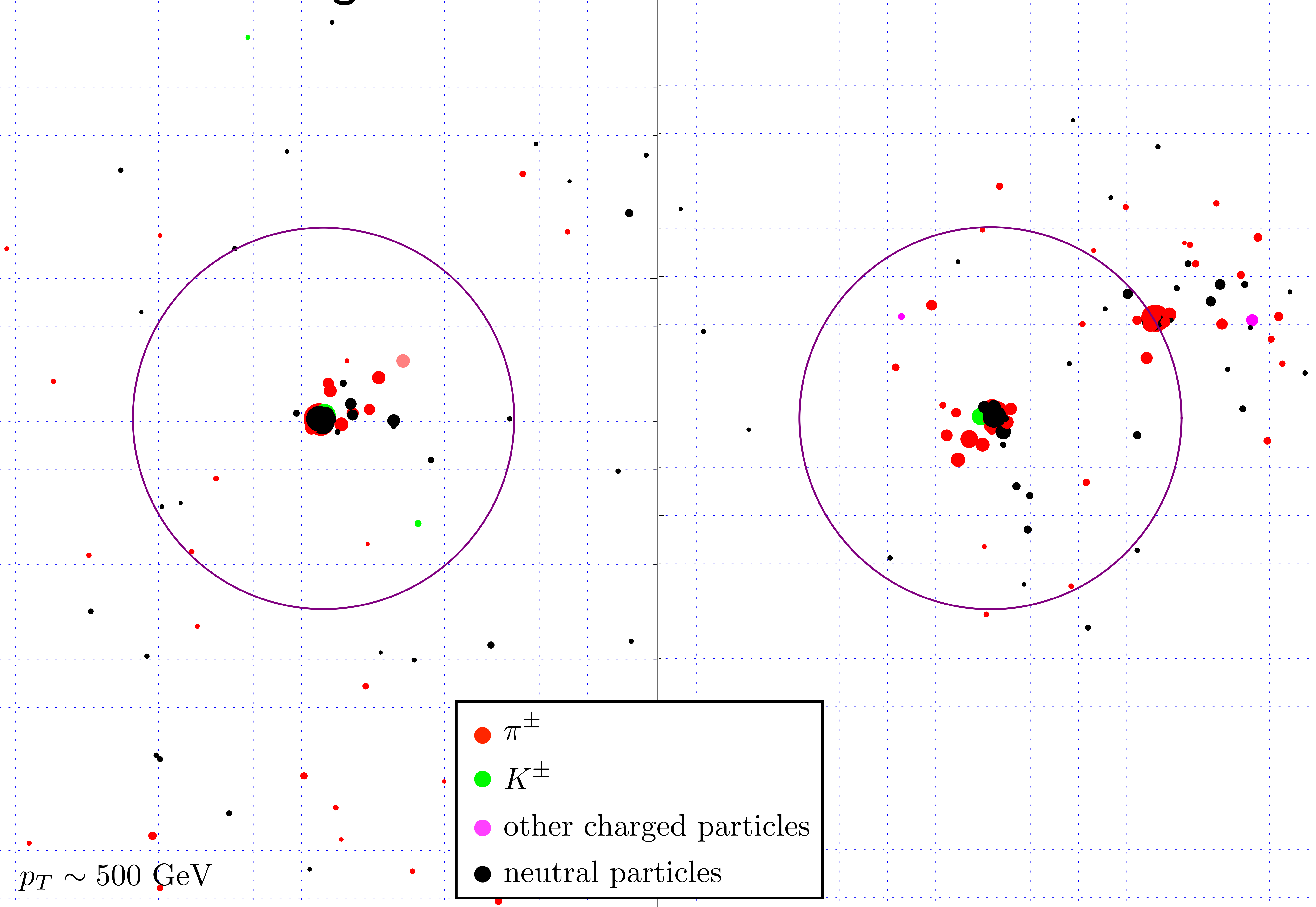
Can we distinguish Quarks from Gluons?

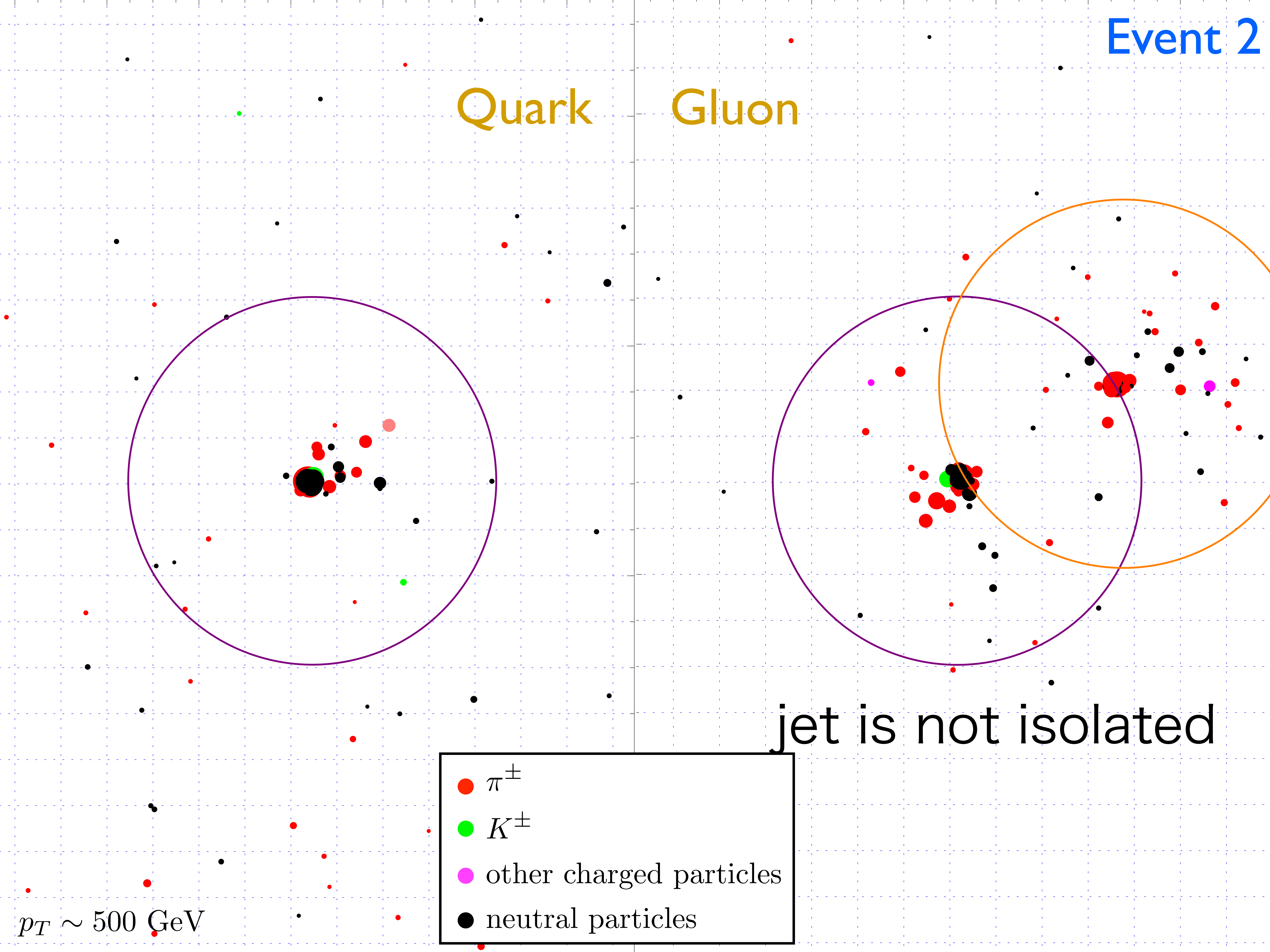
Event 1



Can we distinguish Quarks from Gluons?

Event 2

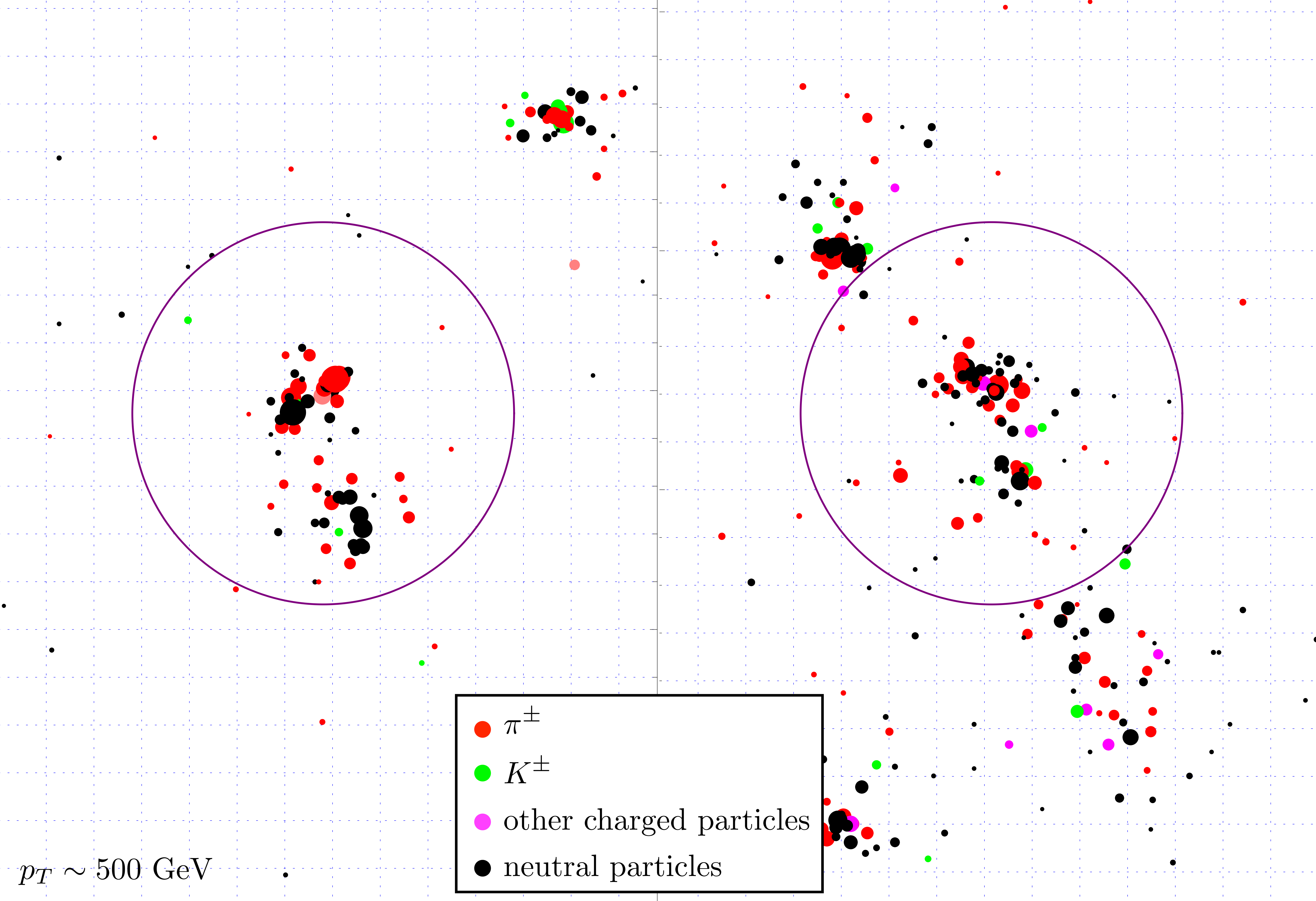


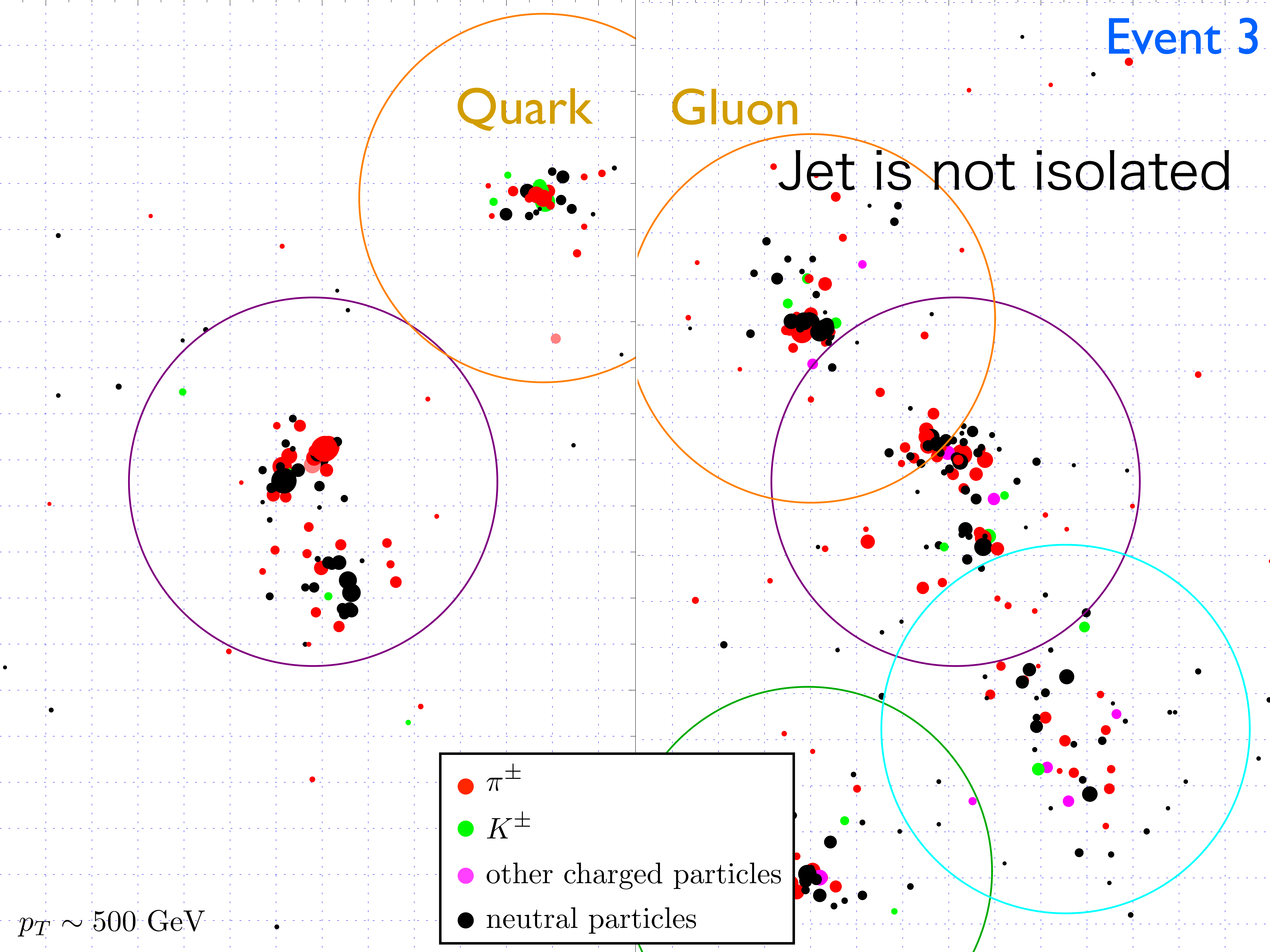


Event 2
Quark
Gluon
jet is not isolated
$\pi^{\pm}$
$K^{\pm}$
other charged particles
neutral particles
$p_T \sim 500$ GeV

Can we distinguish Quarks from Gluons?

Event 3





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

comparison with QCD

generating function

$$\Phi_i(u) = \sum_n R_n^i u^n .$$

jet rate $R_n^i = R_n^i(p_j, \xi)$

$$\xi = \Delta R^2/2$$

recursive equation

$$\Phi_q(u,p_j,\xi) = u + \int_{\xi_j}^{\xi} \frac{d\xi'}{\xi'} \int_{p_a/p_j}^{1} dz \frac{\alpha_S(k_t^2)}{2\pi} P_{gq}(z) \Phi_q(u,p_j,\xi') \left[\Phi_g(u,zp_j,\xi') - 1\right] ,$$

$$\Phi_g(u,p_j,\xi) = u + \int_{\xi_j}^{\xi} \frac{d\xi'}{\xi'} \int_{p_a/p_j}^{1} dz \frac{\alpha_S(k_t^2)}{2\pi} \left\{ P_{gg}(z) \Phi_g(u,p_j,\xi') \left[\Phi_g(u,zp_j,\xi') - 1\right] + P_{qg}(z) \left[\{\Phi_q(u,p_j,\xi')\}^2 - \Phi_g(u,p_j,\xi') \right] \right\} . \quad (2.5)$$

solution⋯

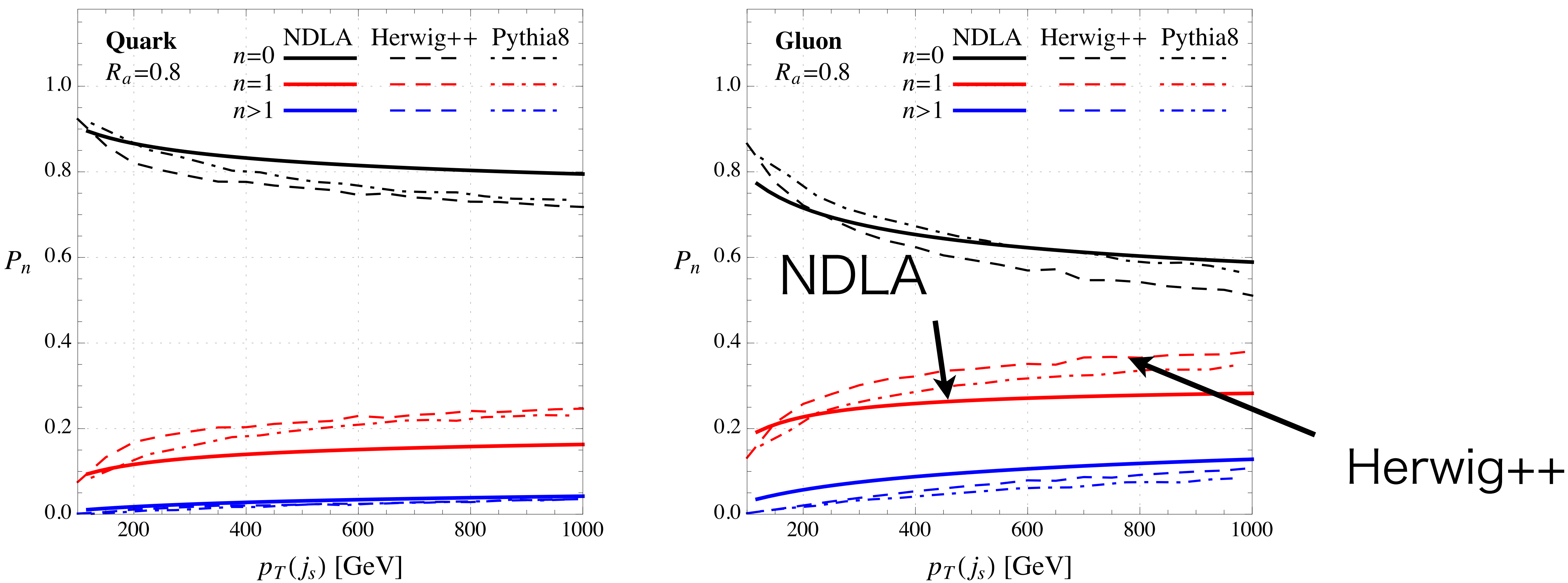
$$\Phi_q(u,\kappa,\lambda) = u \exp\left\{ \int_0^{\lambda} d\lambda' \int_0^{\kappa} d\kappa' \, \Gamma_q(\kappa',\lambda',\kappa,\lambda) \left[\Phi_g(u,\kappa',\lambda') - 1\right] \right\}$$

$$\kappa = \ln(p_j/p_a) , \quad \kappa' = \ln(zp_j/p_a) ,$$

$$\lambda = \ln(\xi_a/\xi_j) = 2\ln(R_a/R) , \quad \lambda' = \ln(\xi'/\xi_j) .$$

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

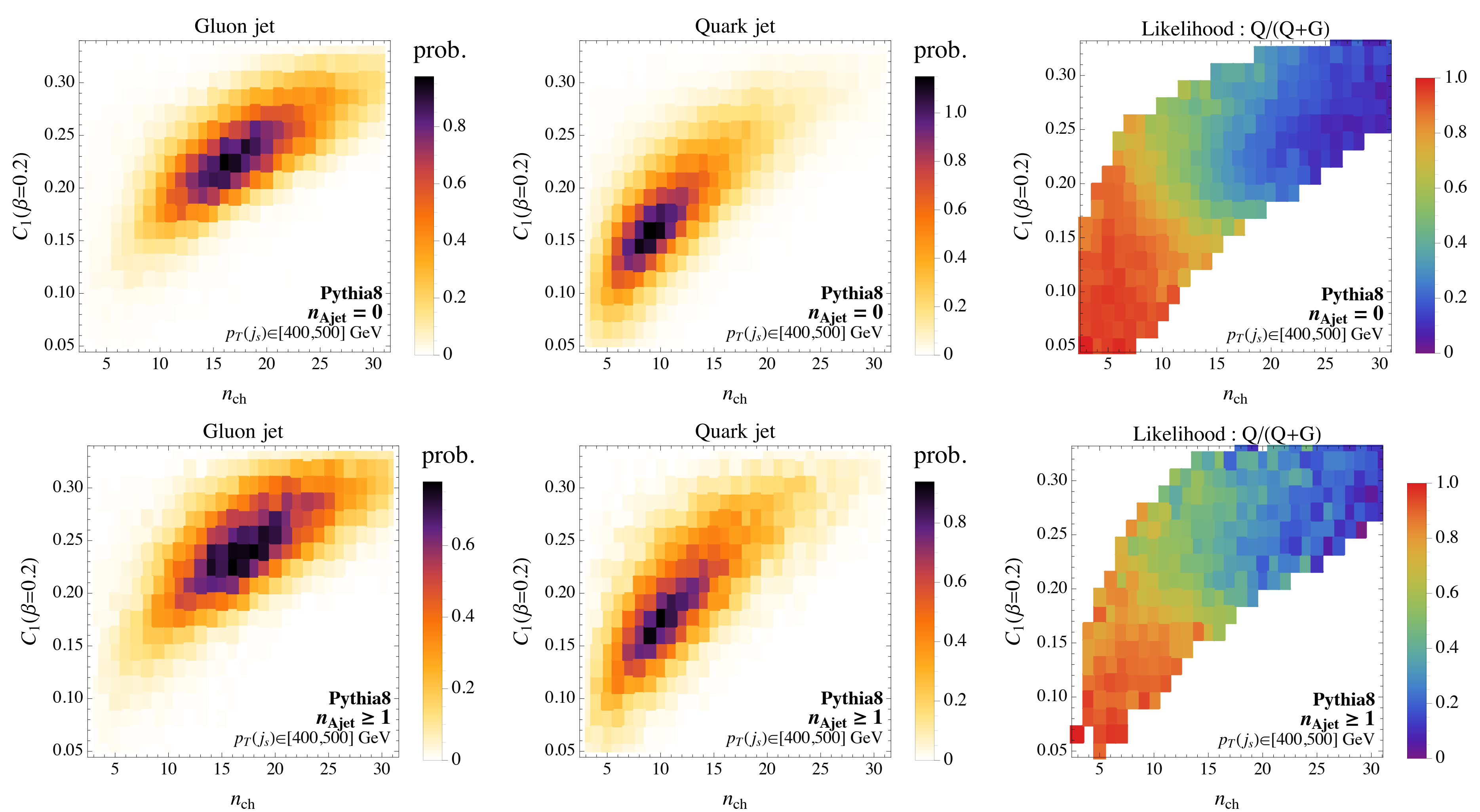
Associate jet variable

- Covers finite(large) angle emission, some correlation with jet mass or C1 of the 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
- ⇆" glooming" for wider R clustering (jet pT cut on associated jet.)

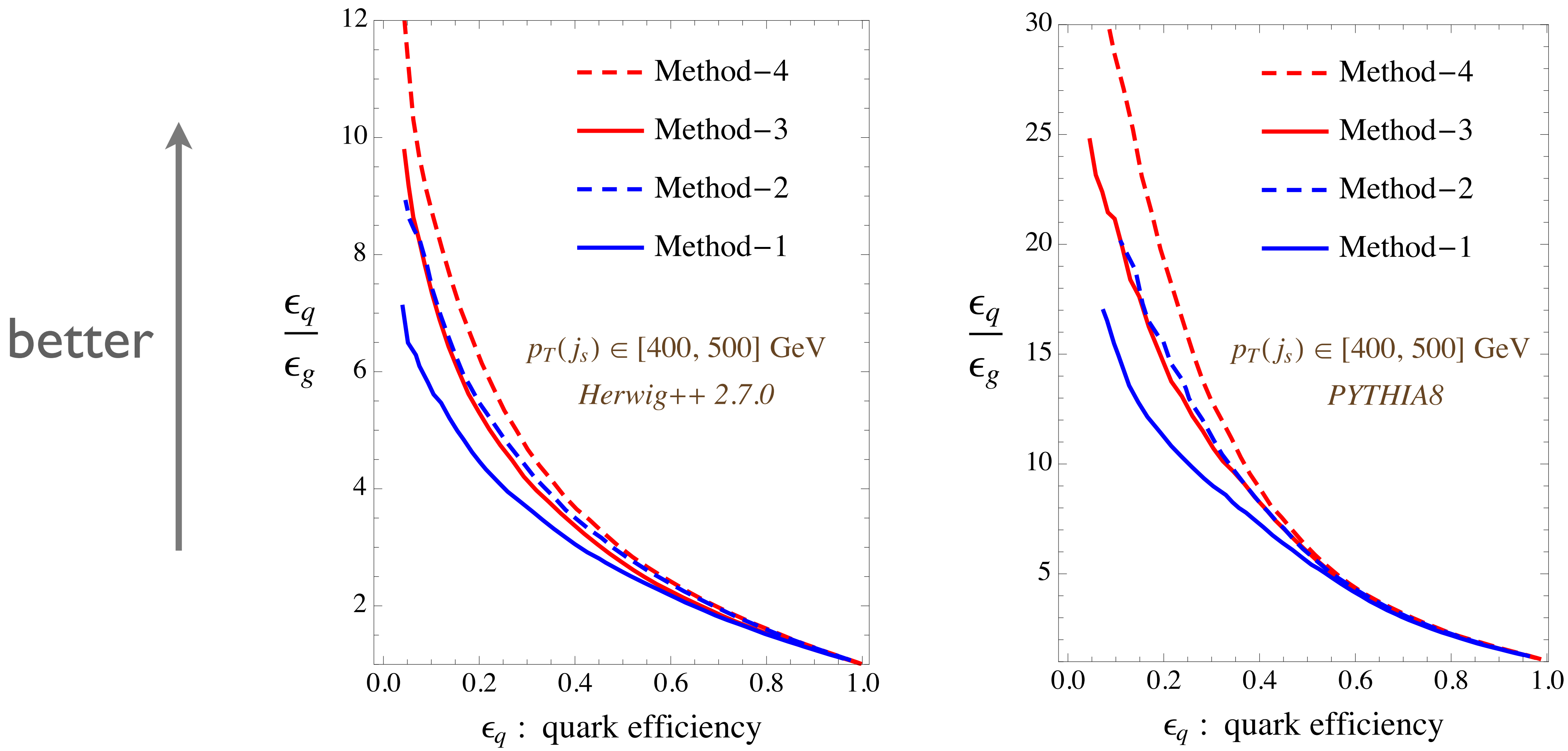
MVA with associated jet

- Tell MVA if jet has associated jets or not
- separate training with and without associated jet using m/pjet, C1, nch
- Alternatively you can use m(pjet+pa)/pTjet, giving roughly same quark gluon separation.

- # of assoc jet = 0
- # of assoc. jet ≧ 1

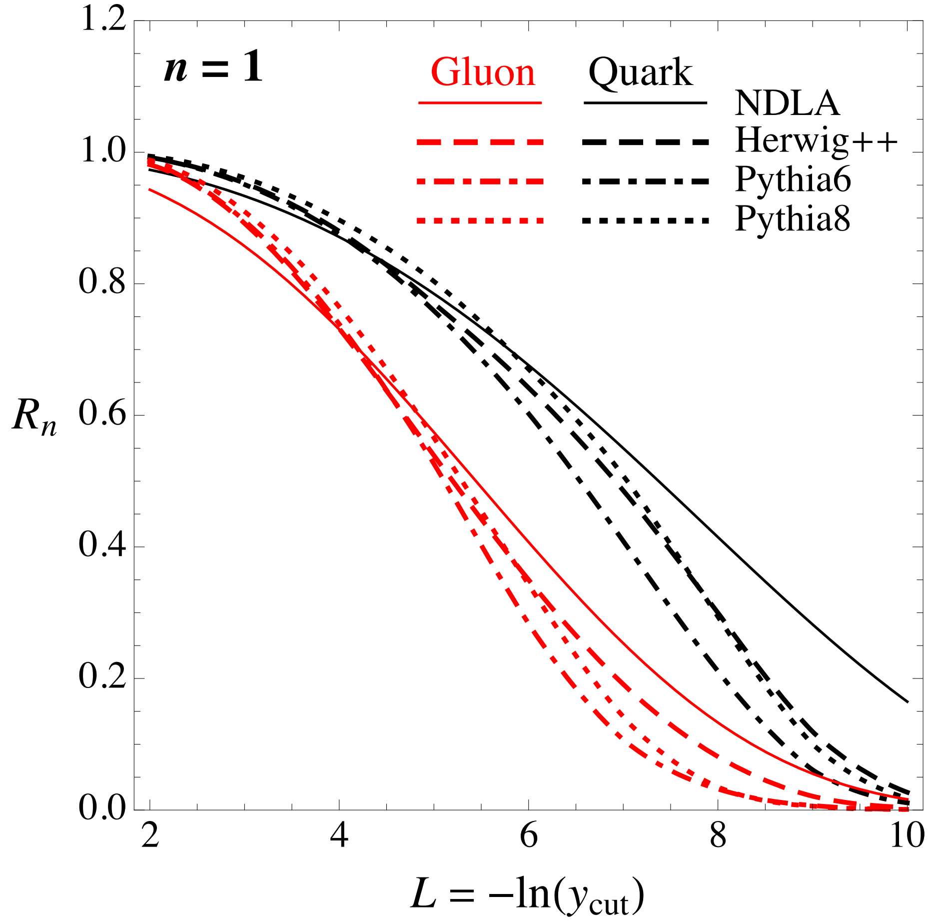


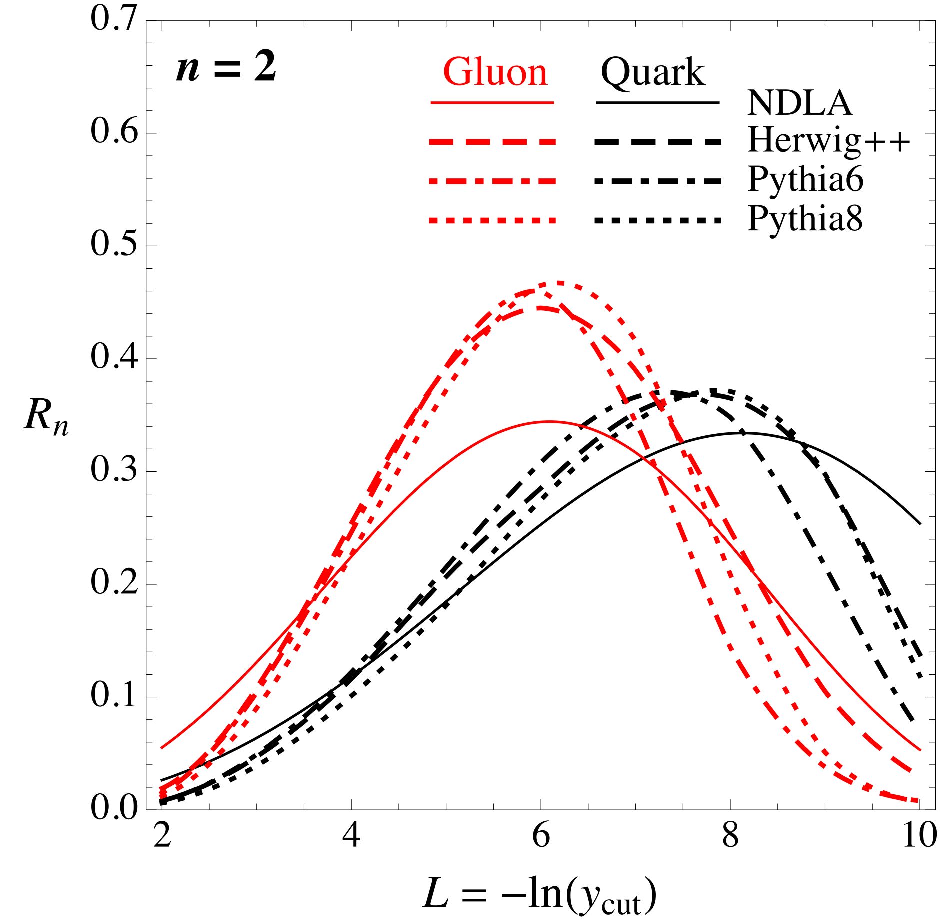
- Method-1: MVA(n_{ch} + C_1)
- Method-2: MVA(n_{ch} + C_1) + associated jet information
- Method-3: MVA(n_{ch} + C_1 + m/p_T)
- Method-4: MVA(n_{ch} + C_1 + m/p_T) + associated jet information



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

inside jet:subjet rate





cluster jet → re-cluster jet by kt

→ stop at cut

$y_{ik} = \min\{p_{ti}^2, p_{tk}^2\}\frac{\Delta R_{ik}^2}{R^2 p_j^2}$, < ycut

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 model
- Underlying events could be a problem, though our simulations show it is not big.