Fragmentation of Gluon and Quark jets at CDF

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Motivation

- **Jets as a subject of studies:**

  → jet fragmentation/structure is driven by very soft QCD

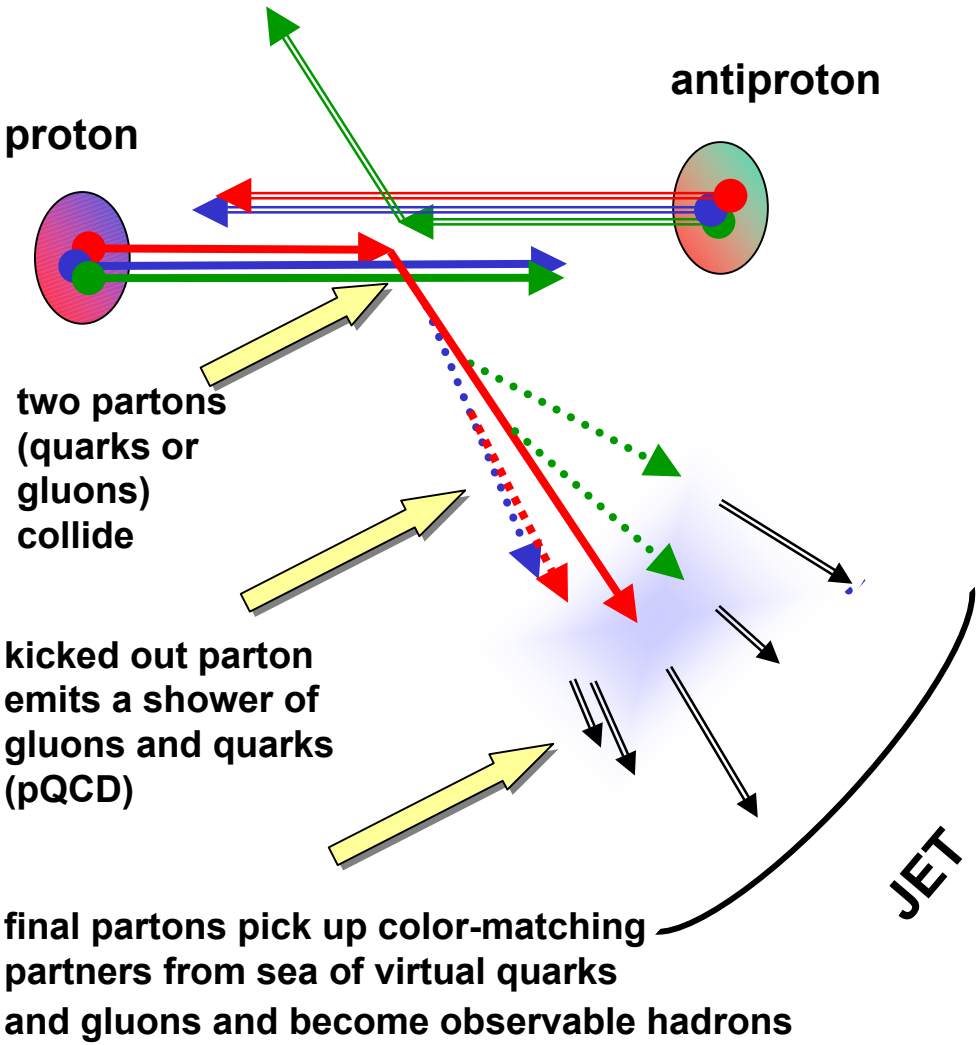
  * **borderline between pQCD and non-pQCD (which domain defines jet properties?)**
  * **data from Tevatron complement e^+e^- and *ep* measurements (test of universality of jets)**

- **Jets as a tool in high P_T physics:**

  → better understanding of jet fragmentation is important for many analyses

  * $t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}qqqq$ **(signal: q-jets, background: lots of g-jets)**
  * $t\bar{t}$ **production mechanisms:** $gg \rightarrow t\bar{t}$ **vs** $q\bar{q} \rightarrow t\bar{t}$
  * **MC based jet energy corrections (verification of MC is important)**

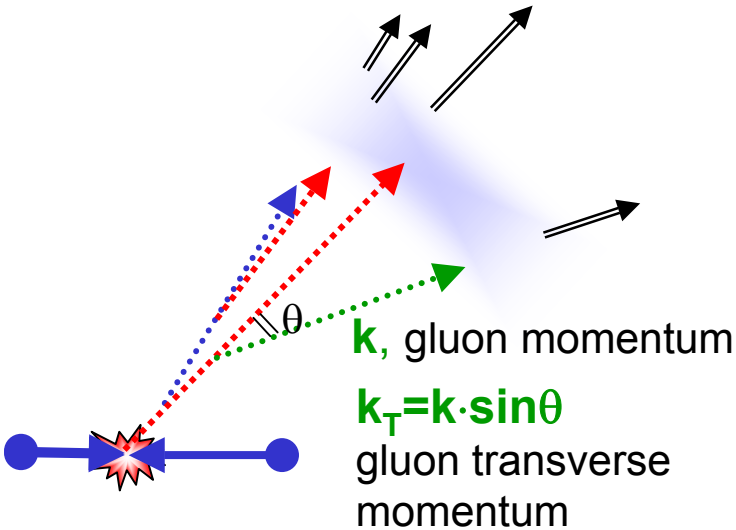
Jet formation: three steps

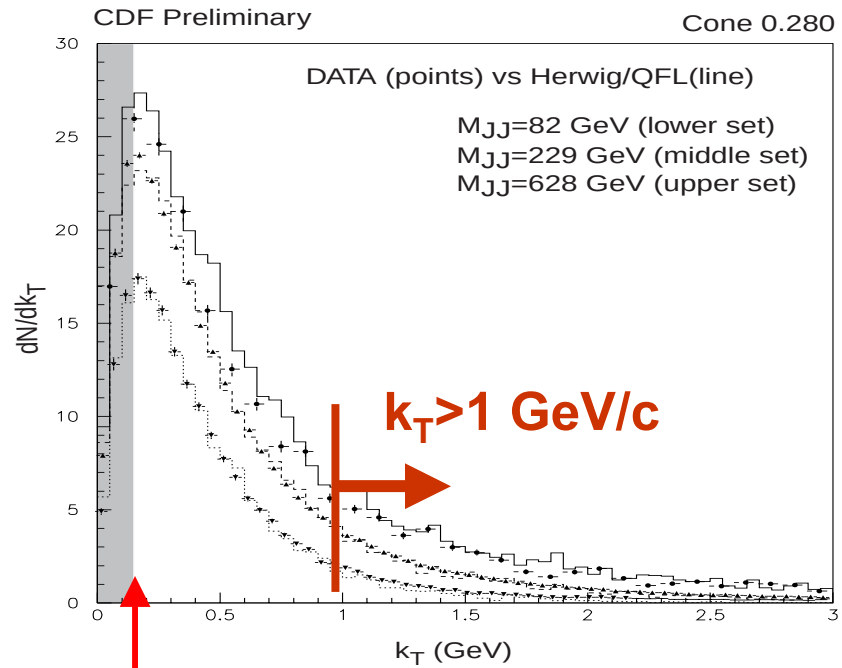


- **Step 1**
  - Hard scattering
- **Step 2**
  - Parton shower (pQCD)
- **Step 3**
  - Hadronization (non-pQCD)

Jet fragmentation

Parton shower: Theory portrait 1

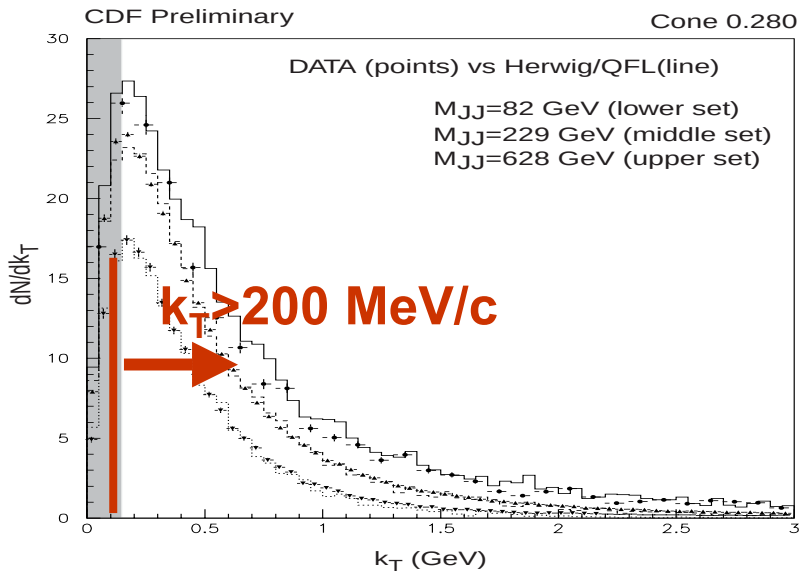




Can we push Q_{cutoff} down to ~200 MeV?

- **Theory**
  - — Jet fragmentation is driven by soft gluon emission
  - — $\omega \sim \alpha_S \ln^2(E/k_T) > 1$ at $k_T < 1$ GeV
  - — Need to set comfortably high cutoff $Q_{cutoff} \sim 1$ GeV
- **Data**
  - — $k_T < 1$ GeV for most particles

Parton showering: Theory portrait 2 (MLLA)



MLLA (or NLLA), Modified (Next-to-) Leading Log Approximation

Mueller (1983); Dokshitzer, Troyan (1984); Malaza, Webber (1984)

- **set comfortably large cutoff scale Q_{cutoff} ($k_T > Q_{cutoff}$)**
- **emission diagrams with leading-log & sub-leading-log precision in all orders**

$$\alpha_s^n \ln^{2n}\left(E_{jet}\right) \qquad \alpha_s^n \ln^{2n-1}\left(E_{jet}\right)$$

- **interference between diagrams of the same order in α_S via angular ordering**
- **re-sum diagrams in all orders**

  → **final analytical results are infrared stable—cutoff scale can be set as low as Λ_{QCD}: $Q_{cutoff}=\Lambda_{QCD}$ (~200 MeV), and it is called Q_{eff}**

Phenomenological hadronization: LPHD

Local Parton Hadron Duality hypothesis (LPHD)

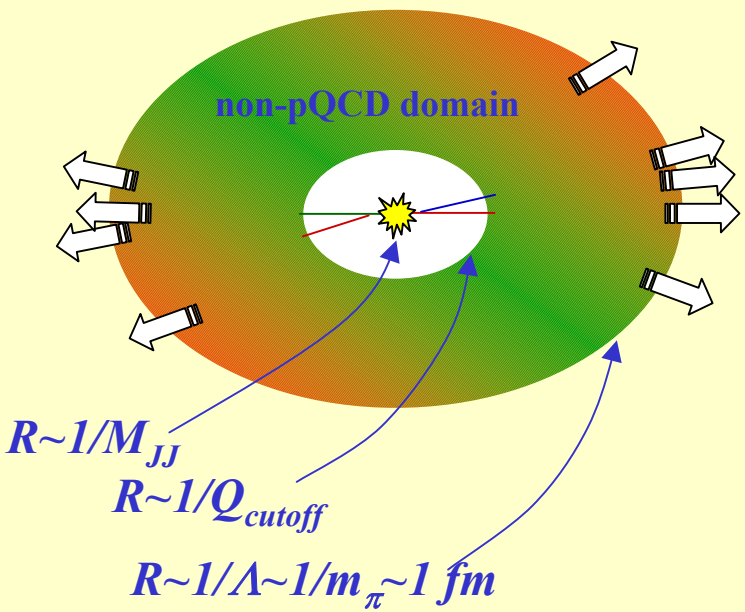
Azimov, Dokshitzer, Khoze, Troyan (1985)

- Link between partons (theory) and hadrons (experiment)
- assumes that hadronization occurs locally and hadron distributions closely resemble parton ones: e.g., $N_{hadrons}=K_{LPHD}N_{partons}$
- Naïve interpretation of LPHD
  - → each parton picks up a color-matching partner from the sea of virtual quarks and gluons and becomes a hadron
  - → if all hadrons are accounted for, $K_{LPHD} \sim 1$
  - → if only charged particles are observed, $1/2 < K_{LPHD(\pm)} < 2/3$ (isospin symmetry)
  - →fraction of energy carried by charged particles is ~0.6 ⇒ one may expect $K_{LPHD(\pm)} \sim 0.6$

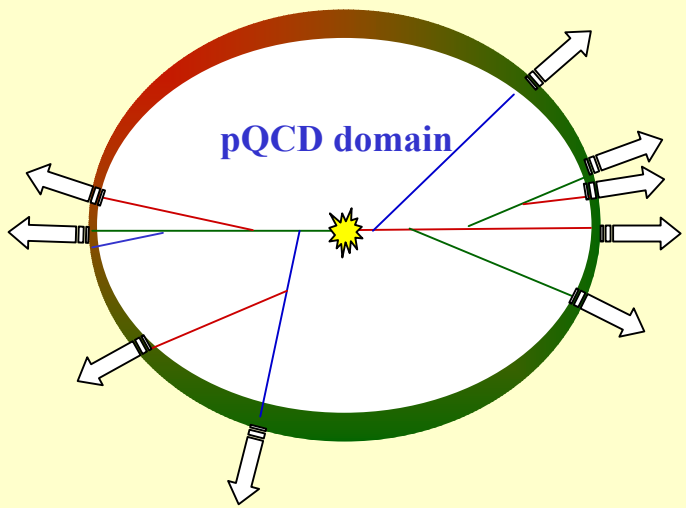
CDF: $K_{LPHD(\pm)}=0.58\pm0.05\pm0.08$ PRL87,211804,2001

Studying jet fragmentation…

What is the domain of pQCD?



or



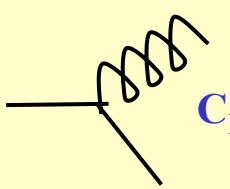
$Q_{cutoff} \sim 1$ GeV

$Q_{cutoff} \approx \Lambda_{QCD}$(~200 Mev)

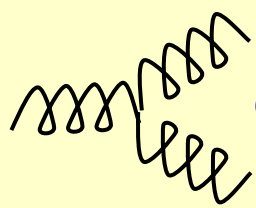
Difference between quark & gluon jets

- **Nature of the difference between quark & gluon jets**

  → gluon color charge > quark color charge ⇒ **gluon jets should be more active than quark jets**



$C_F=4/3$



$C_A=3$

Ratio of relative probabilities of soft gluon emission out of gluon & quark is the ratio of their color charges: $C_A / C_F=9/4$

- **Observation of quark & gluon jet fragmentation differences**

  → **mean multiplicities of particles in jets, N_g and N_q (this talk)**

  → shape of multiplicity distributions

  → **shape of momentum distributions (this talk)**

  → jet shapes (particle and energy flows)

  → correlation of particles in jets

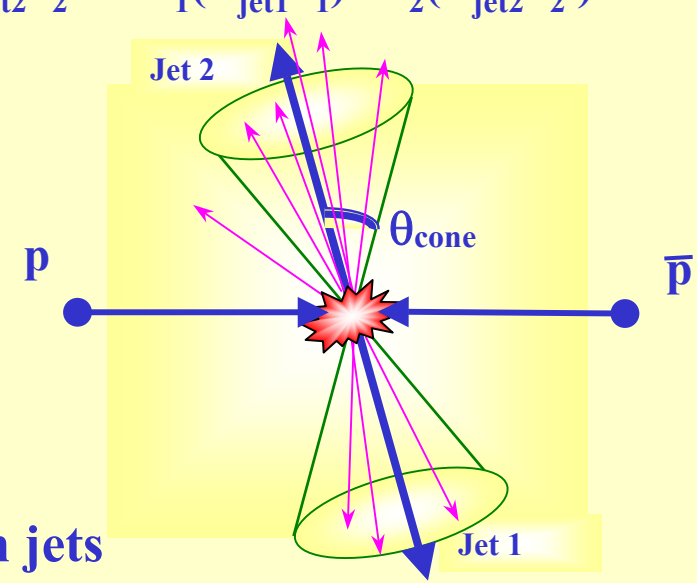
Multiplicity in quark and gluon jets: *theory*

MLLA(or NLLA) and its extensions: *multiplicity of partons in jets*

Gluon Jets:
–Multiplicity: $N_g(Y)$
–Momentum distribution: $dN_g(\xi,Y)/d\xi$
where $\xi=\log(1/x_p)$, $x_p=p/E_{jet}$

Quark Jets are different by a factor of 1/r :
–Multiplicity: $N_q(Y)=N_g(Y)/r(Y)$
–Momentum distribution: $dN_q/d\xi = 1/r(\xi)\, dN_g/d\xi$

- **Scaling variable:** $Y=\ln(Q/Q_{eff})$, cutoff $Q_{eff} \sim \Lambda_{QCD}$, energy scale $Q = 2E_{jet}\tan(\theta/2) \approx E_{jet}\theta$
  → **Everything depends on** $Y = \ln(E_{jet}\theta/Q_{eff})$ → $E_{jet}\theta$ **scaling, where** θ **is small**
  → $E_{jet}\theta$ **scaling:** $E_{jet1} \neq E_{jet2}$ and $\theta_1 \neq \theta_2$, but $E_{jet1}\theta_1 = E_{jet2}\theta_2 \Rightarrow N_1(E_{jet1}\theta_1) = N_2(E_{jet2}\theta_2)$

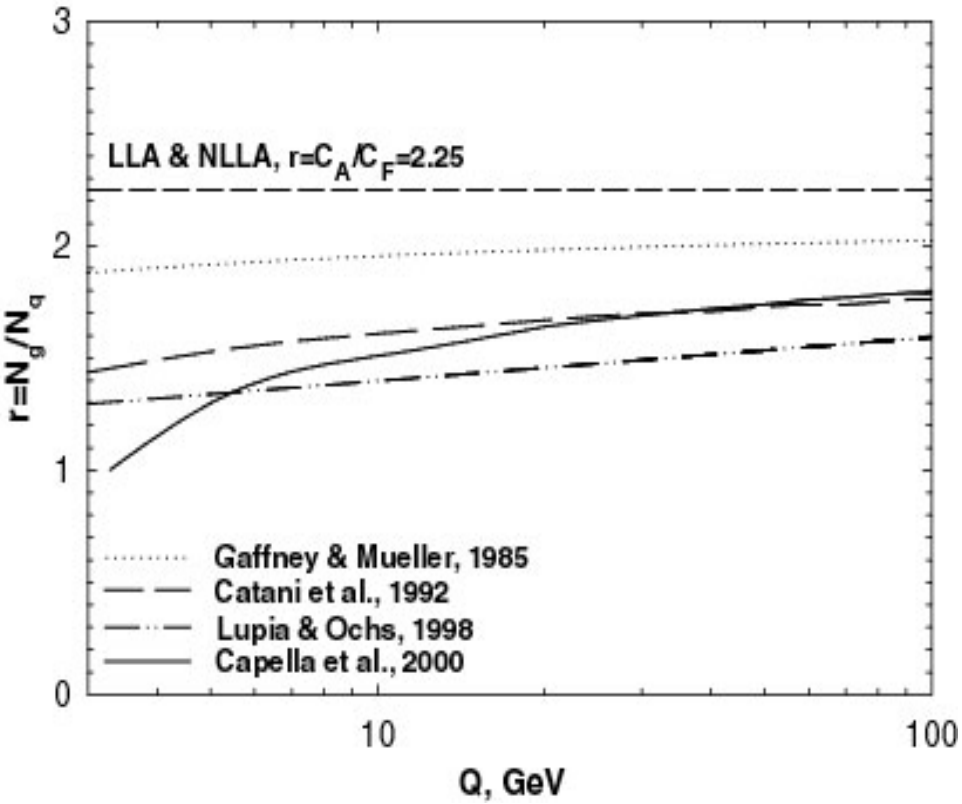


LPHD: *link between partons and hadrons*

$N_{\pm hadrons} = K_{LPHD(\pm)}\, N_{partons}$

$K_{LPHD(\pm)}$ **assumed to be the same for quark & gluon jets**

Theoretical predictions for ratio $r=N_g/N_q$



Theory: $r=N_g/N_q$ =1.4-1.8, Q=10-100 GeV

LLA & NLLA: $r=C_A/C_F=9/4$

full phase space (all particles), $E_{jet}\rightarrow\infty$

Brodsky & Gunion, PRL37(1976) 402;
Konishi *et.al.*, Nucl.Phys. B157(1979) 45

limited phase space (only soft particles), $E_{particle}<<E_{jet}$, E_{jet}=finite

Khoze, Lupia & Ochs, EPJ C5(1998) 77

Full phase space, Q≈10-100 GeV

- **α_S corrections up to NNLO: r≈1.9-2.0**

  Gaffney & Mueller, Nucl.Phys. B250(1985)109

- **Energy conservation up to NNLO: r≈1.5-1.8**

  Catani *et.al.*, Nucl.Phys. B377(1992)445

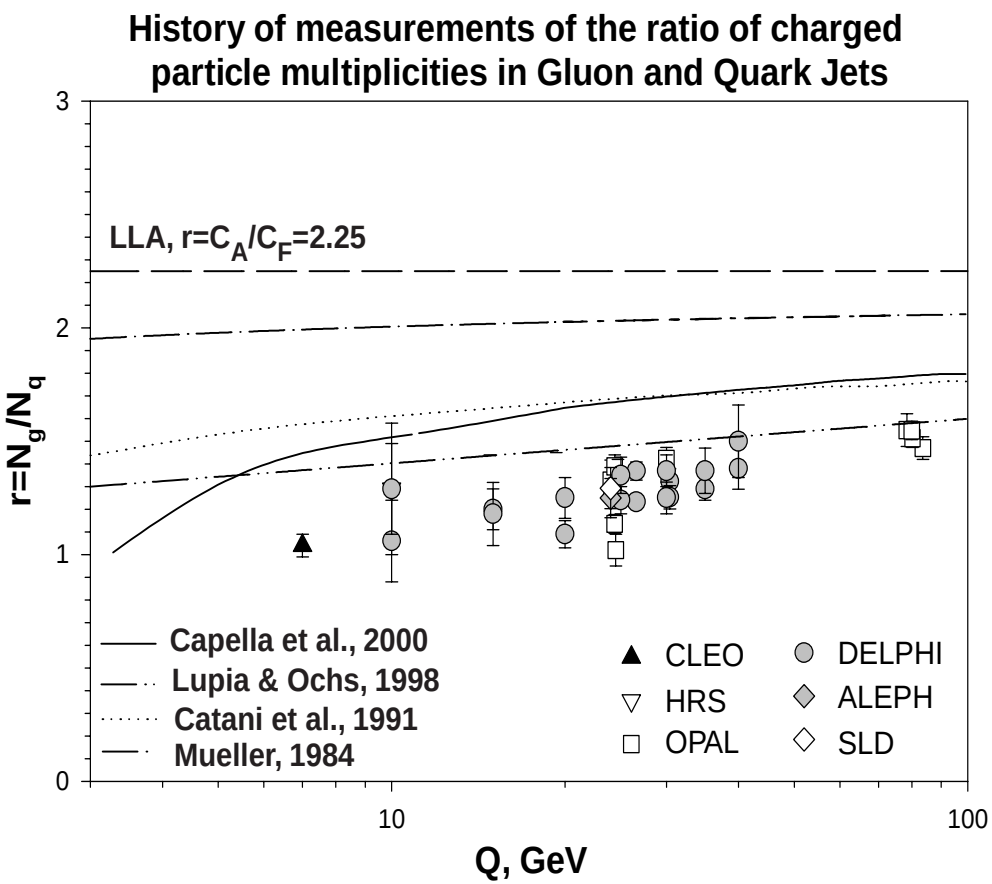
- **Numerical solutions: r≈1.3-1.6**

  Lupia & Ochs, PL B418(1998)214

- **Energy conservation & corrections up to 3NLO: r≈1.4-1.8**

  Capella *et.al.*, PRD61(2000) 074009

Ratio of multiplicities in quark & gluon jets: History of measurements



e^+e^- results—long standing problem

1991: r = 1.02±0.07 (OPAL)

1993: r = 1.27±0.07 (OPAL)

1995: r = 1.10±0.03 (OPAL)

r = 1.25±0.04 (OPAL)

r = 1.22±0.03 (ALEPH)

<r> = 1.26±0.07 (SLD)

1996: r = 1.24±0.03 (DELPHI)

r = 1.55±0.07 (OPAL)

1998: r = 1.47±0.05 (OPAL)

1999: <r> = 1.37±0.02 (DELPHI)

1999: r = 1.51±0.04 (OPAL)

2001: r = 1.42±0.05 (OPAL)

What's wrong with measurements of $r=N_g/N_q$ at e^+e^- colliders?

- Results have drifted over 10 years from 1.0 to 1.5

Concerns:

- 3-jet events → non-trivial event topology → not so many well identified gluon jets
- Different jet finding algorithms give inconsistent results (k_T, cone)
- Particles assigned to jets by jet algorithm (ambiguity in assignment of particles by k_T algorithm)
- Heavy dependence on Monte-Carlo jet fragmentation
- Model-depended analyses
- Quark and gluon jets from different event topologies are compared

Problems of comparison with theory:

- Energy scale confusion (in general, there is no unique energy scale which describes jet properties in 3-jet events)

  Eden, Gustafson, Khoze, EPJ C11(1991)345

- Quark jets of heavy flavors are included in some studies

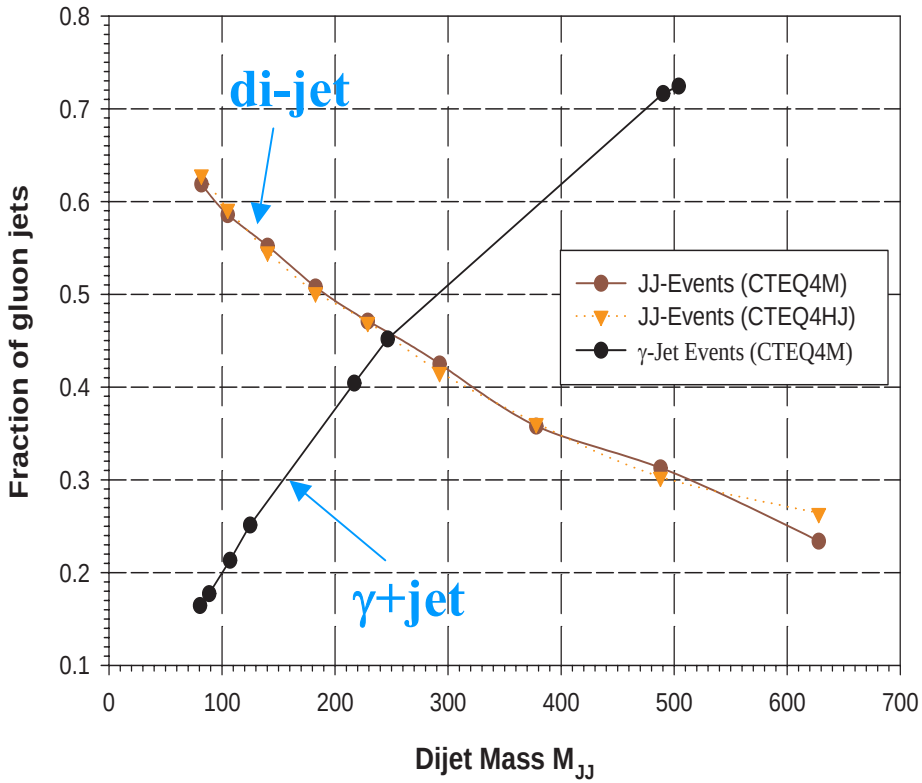
Shopping list for gluon jets…

- So far there is only one model-independent measurement with gluon jets at well defined scale!

Measurements	Jet energy range	
	"Quarks"	"Gluon"
Mean multiplicity	5-104 GeV	10, 40 GeV
Multiplicity distributions	5-104 GeV	40 GeV
Momentum distributions	5-104 GeV	40 GeV
Fragmentation functions	5-104 GeV	40 GeV
Jet shapes	5-104 GeV	No
Correlation of particles in jets	45.6 GeV	No

How can one study Quark & Gluon jets at Tevatron?

- **Gluon jets are produced in plenty at Tevatron:**
  - advantage of trivial event topology of di-jet and V+jet events
- **Comparing data samples with very different fractions of gluon jets:**
  - di-jet vs. γ+jet (this analysis)
  - di-jet vs. W+jet (have to deal with ν)
  - di-jet vs. Z+jet (clean, but small statistics)



$$dijet: \; gg \to gg, \quad qg \to qg, \quad qq \to qq$$

$$\gamma + jet: \quad qg \to q\gamma, \quad q\bar{q} \to g\gamma$$

Analysis strategy at CDF

- **Multiplicity per jet, N, is a weighted sum of multiplicities in quark, N_q, and gluon, N_g, jets:**

$$N = n_g N_g + n_q N_q$$

- **Two equations for two samples:**

$$N_{jj} = n_g^{jj} N_g + (1 - n_g^{jj}) N_q$$
$$N_{\gamma j} = n_g^{\gamma j} N_g + (1 - n_g^{\gamma j}) N_q$$

- **Provided one knows n_g^{jj} and $n_g^{\gamma j}$, the ratio $N_{jj}/N_{\gamma j}$ allows to extract the ratio of multiplicities in gluon and quark jets $r = N_g/N_q$**

$$r = 1 + \frac{1 - \frac{N_{\gamma j}}{N_{jj}}}{n_g^{jj} \frac{N_{\gamma j}}{N_{jj}} - n_g^{\gamma j}}$$

- **Caveat: gamma-jet events have a fraction of fake gammas, i.e. they have a fraction ε of jet-jet events (where stiff π^0 from a regular jet is faking a photon):**

$$N_{\gamma j} = (1-\varepsilon)(n_g^{\gamma j} N_g + (1 - n_g^{\gamma j}) N_q) + \varepsilon N_{fake}$$

Final Formula for ratio $r=N_g/N_q$

$$r = 1 + \frac{\alpha - \varepsilon_\gamma(\alpha - 1) - \dfrac{N_{\gamma j}}{N_{jj}}}{n_g^{jj}\dfrac{N_{\gamma j}}{N_{jj}} - \varepsilon_\gamma\, n_g^{real\,\gamma j} - (1-\varepsilon_\gamma)\alpha\, n_g^{jj}}$$

$N_{\gamma j}$	- multiplicity in "photon"-jet sample(including fakes)
N_{jj}	- multiplicity in jet-jet sample
ε_γ	- fraction of real photons in photon-jet sample
n_g^{jj}	- gluon fraction in jet-jet sample
$n_g^{real\gamma j}$	- gluon fraction in 100% pure γ-jet sample
α	- correction factor due to fakes(ratio of multiplicities of a jet opposite to fake and a regular jet from dijet event)

Final formulae for multiplicities in Gluon and Quark jets

- **The same set of equations allows to measure the charged particle multiplicities in gluon and quark jets:**

$$N_{jj} = n_g^{jj} N_g + (1 - n_g^{jj}) N_q$$

$$N_{\gamma j} = (1-\varepsilon)(n_g^{\gamma j} N_g + (1 - n_g^{\gamma j}) N_q) + \varepsilon N_{fake}$$

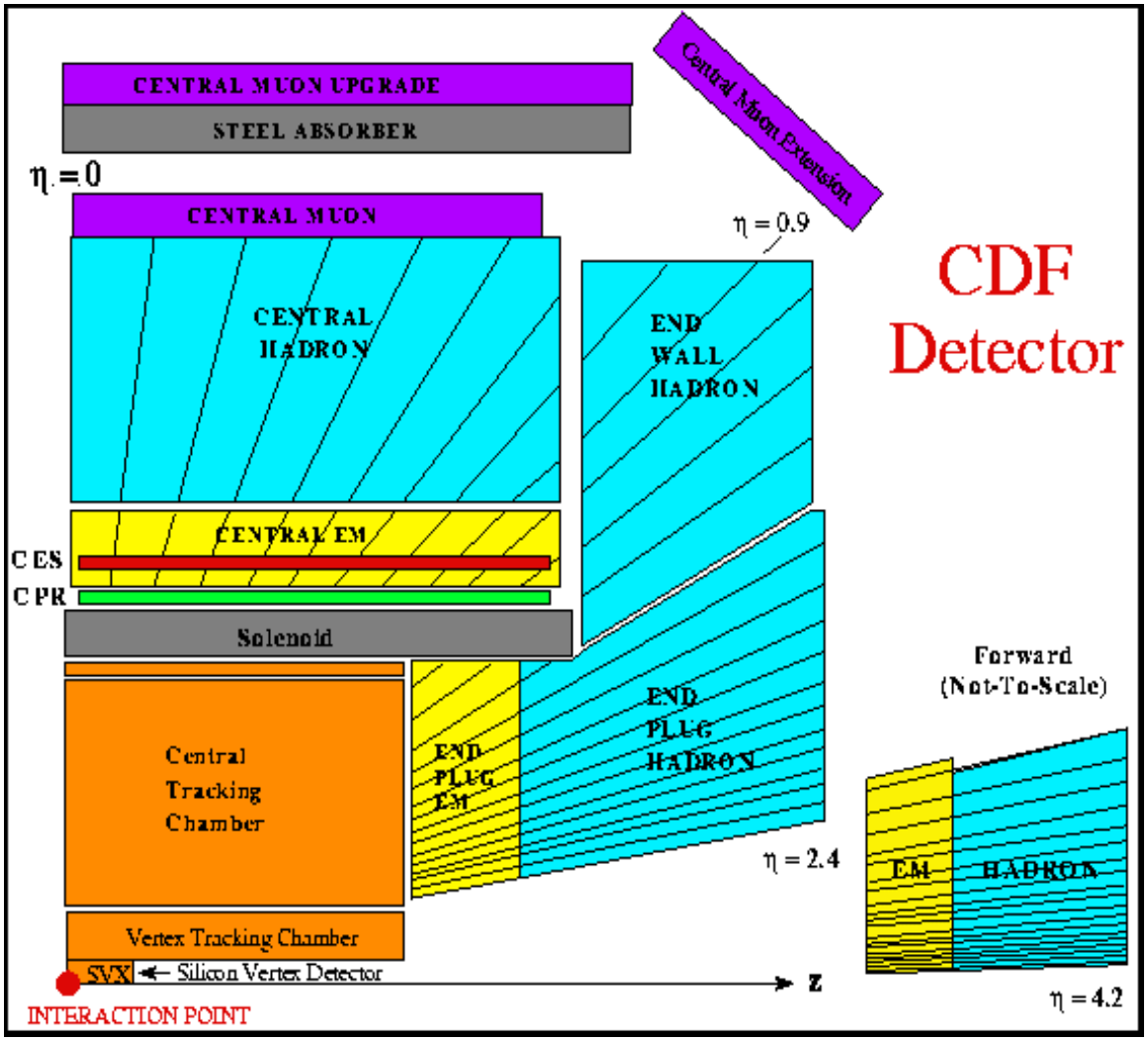
Multiplicity in gluon jet:

$$N_g = \frac{r N_{jj}}{n_g^{jj}(r-1)+1}$$

Multiplicity in quark jet:

$$N_q = \frac{N_{jj}}{n_g^{jj}(r-1)+1}$$

Overview of the CDF detector



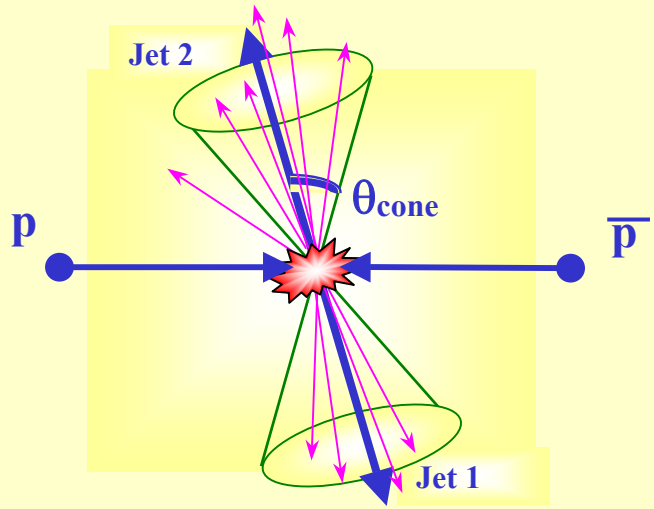
- **Sub-detectors used in the analysis:**
  - **VTX:**
    vertex reconstruction
  - **CTC:**
    tracks
  - **CPR & CES:**
    photon identification
  - **Calorimeter (central & end wall hadron):**
    photons & jets

Data selection

- **Run1B data**
- **Cone jet finder (R=0.7), energy corrected to parton level**
- **Central di-jet & γ+jet events with M_{jj} or $M_{\gamma j}$ ~72-120 GeV**
- **di-jet or γ+jet center of mass frame: E_{jet}=1/2M ($\langle E_{jet} \rangle$=41 and 53 GeV)**
- **Fraction of gluon jets: <u>di-jet events</u> — ~60%, <u>γ+jet events</u> — ~20%**
  - $\rightarrow$ **extracted using CTEQ4M+Herwig 5.6 (cross-checks: Pythia, CTEQ4A2, & CTEQ4A4)**
- **Photon sample purity: 75%—90%**
- **Energy scale $Q = 2E_{jet}\tan(\theta/2) \approx E_{jet}\theta_C$ (~10-25 GeV)**
- **Assume that gluon and quark jet properties are the same in two samples**

Multiplicity measurement

- Dijet center of mass frame
- Tracks are counted in cones with opening angle θ_C=0.28, 0.36, & 0.47 around jet direction



- Things to deal with:
  - Backgrounds not correlated with jet direction:
    secondary interactions, underlying event, and accelerator induced backgrounds
  - Backgrounds correlated with jet direction:
    γ-conversions, charged particles from K°_{S} and Λ decays
  - CTC track reconstruction inefficiency

Multiplicity in Gluon & Quark jets

- **CDF data, comparison to:**
  - — **e^+e^- data:** model-independent results
  - — **theory:** 3NLLA expressions (PRD61 (2000) 074009)

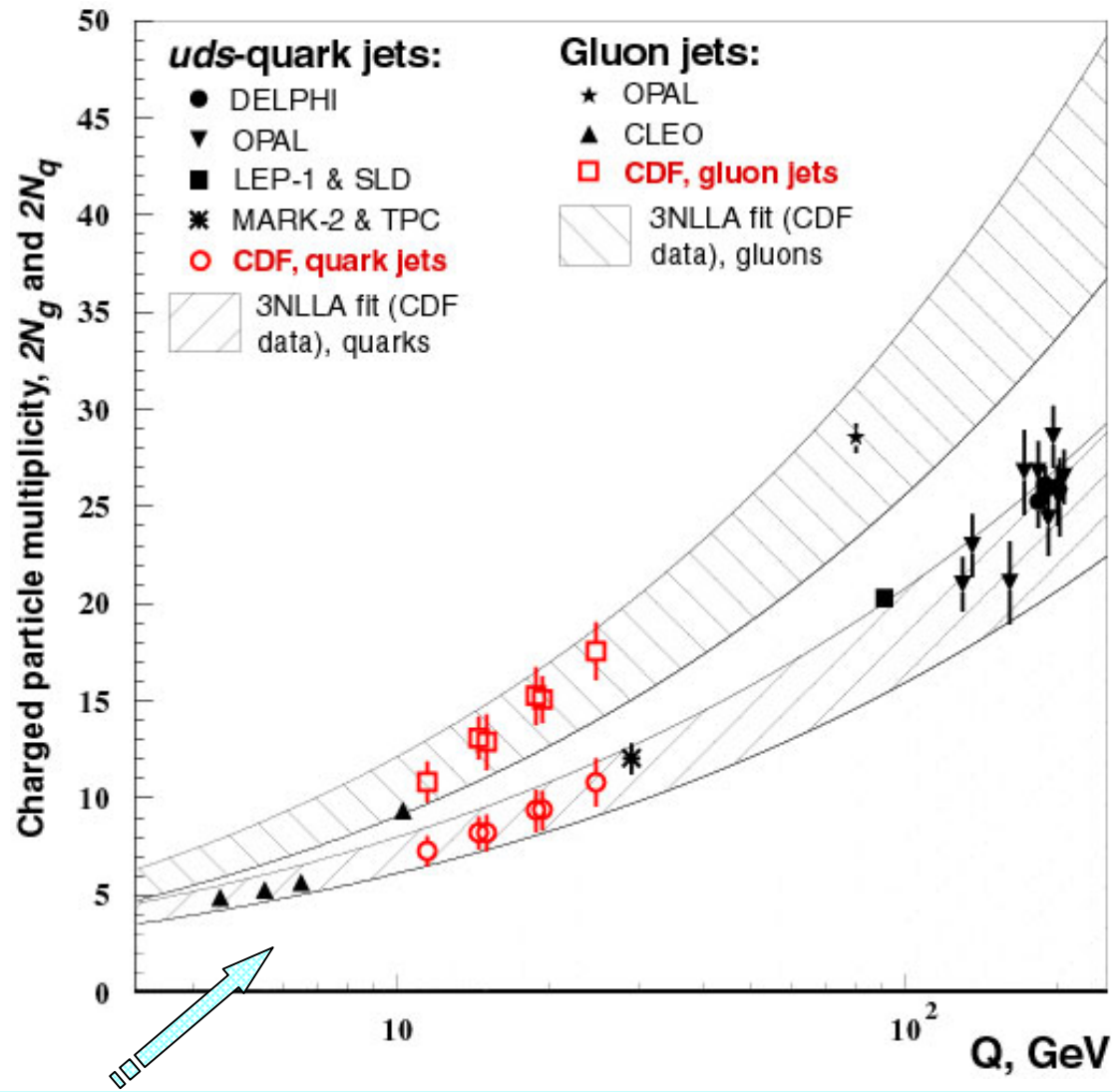
✓ **CDF and e^+e^- data agree** (except for CLEO at <7 GeV)

✓ **CDF and e^+e^- data follow 3NLLA trends**

(except for CLEO at <7 GeV)

✓ **CDF data confirm $Q \approx E_{jet}\theta_C$ scaling**

→ $E_{jet1} \neq E_{jet2}$ and $\theta_1 \neq \theta_2$, but $E_{jet1}\theta_1 = E_{jet2}\theta_2 \Rightarrow$ $N_1(E_{jet1}\theta_1) = N_2(E_{jet2}\theta_2)$

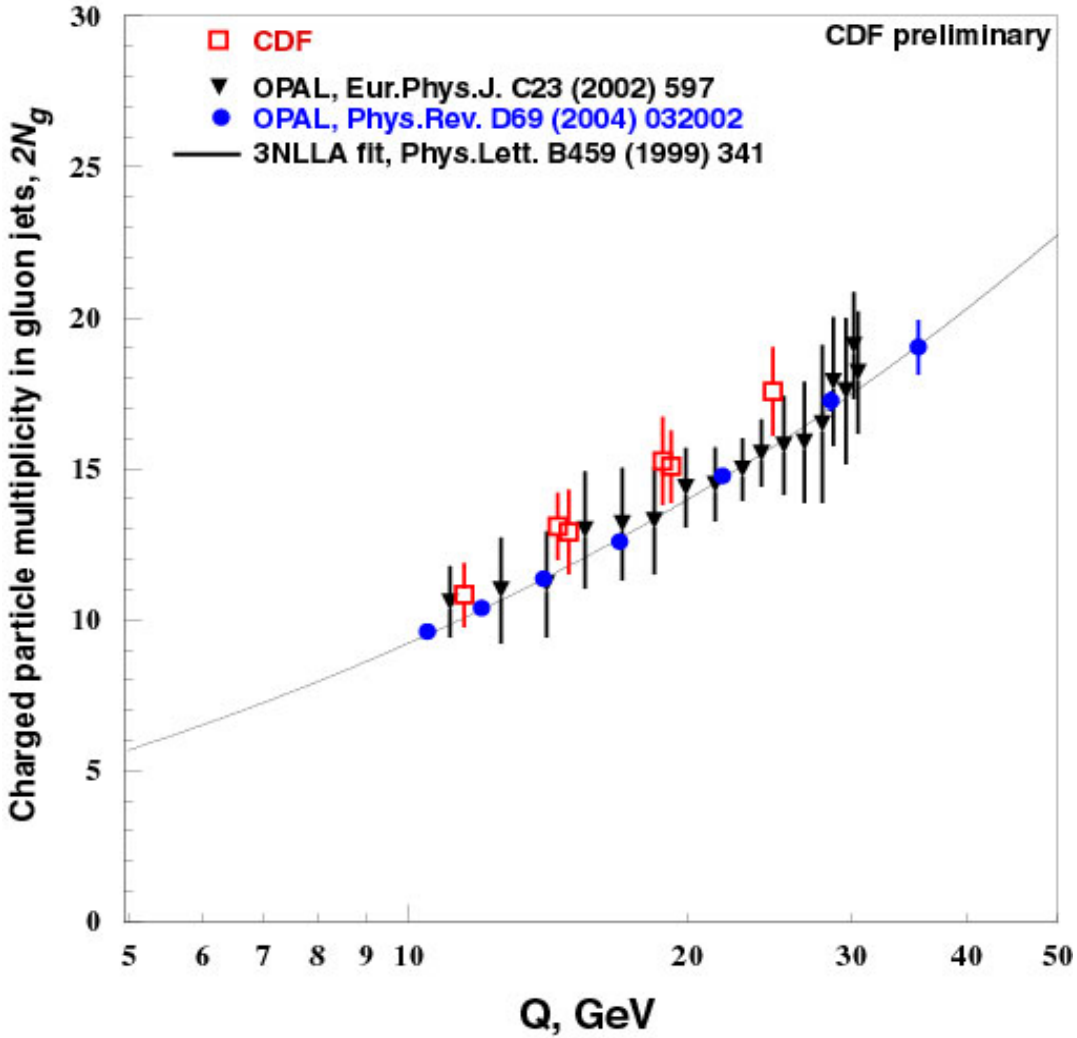


3NLLA curves: use Q_{eff}=230 MeV from previous CDF study, with normalization fitted to CDF gluon & quark data separately; width of band corresponds to uncertainties in normalization

Multiplicities in Gluon jets

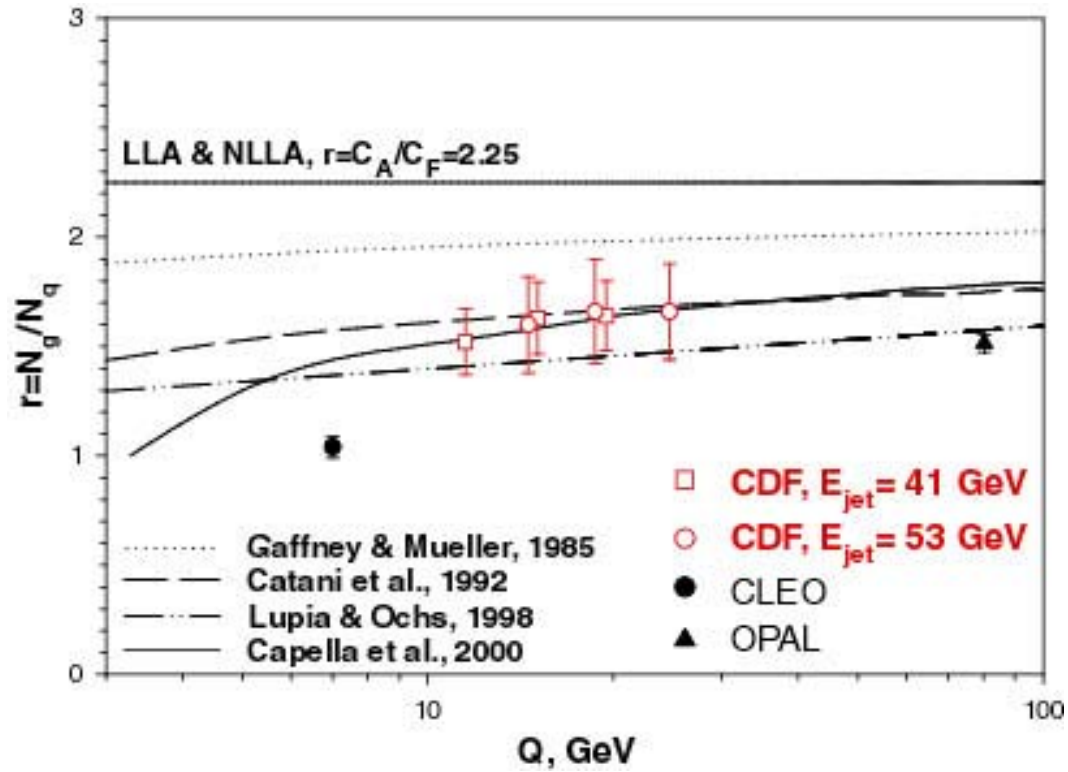
- ✓ CDF <u>model-independent</u> results vs. recent e^+e^- <u>model-dependent</u> data:

  → good agreement



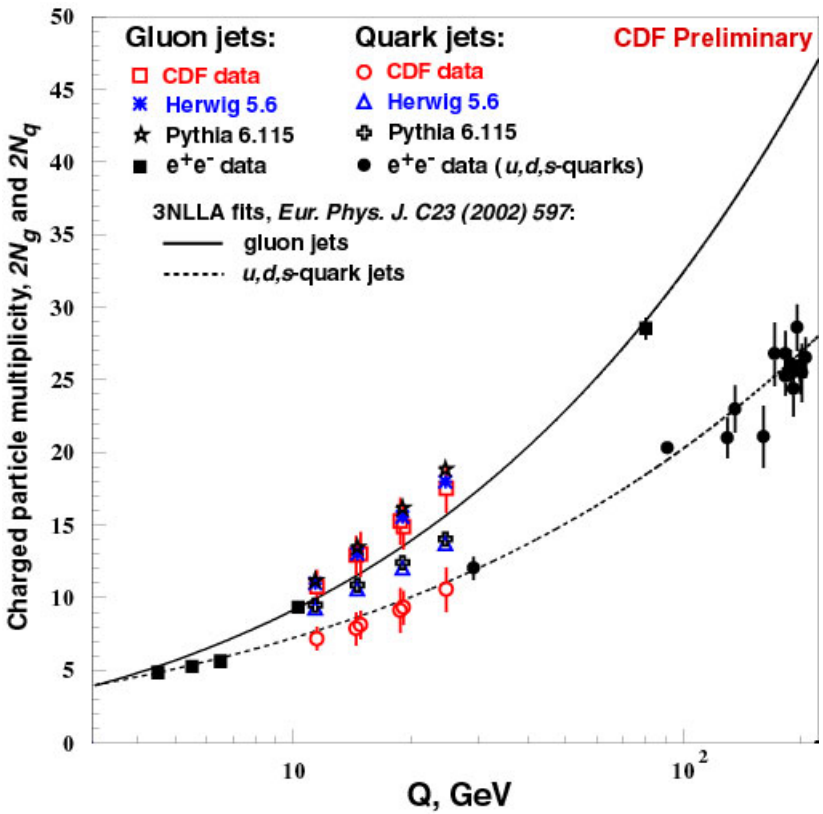
Ratio of multiplicities in Gluon & Quark jets

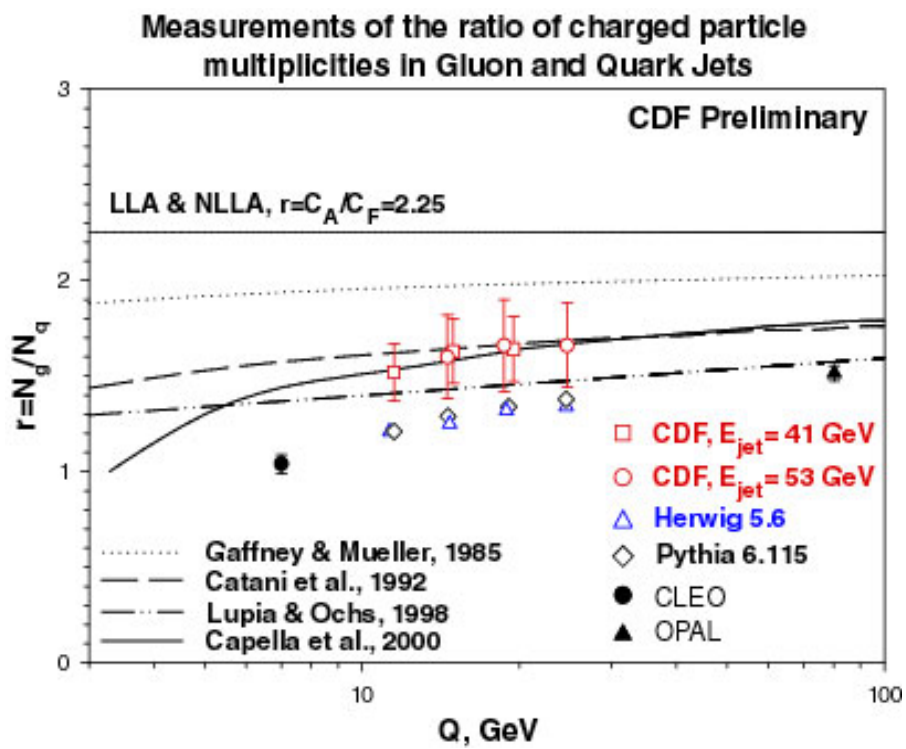
- ✓ **CDF result: r=1.64±0.17 at Q=19 GeV**
- ✓ **CDF and OPAL data agree (r=1.51±0.04 at Q=80 GeV)**
- ✓ **CDF data follow trends of the recent NLLA extensions:**
  - → Q_1=41 GeV * 0.47 rad =19.2 GeV
  - → Q_2=41 GeV * 0.28 rad =11.5 GeV
  - → $\Delta r = r(Q_1) - r(Q_2) = 0.12 \pm 0.02 \pm 0.05$
- ✓ **CLEO point at Q~7 GeV fall out…**



e^+e^- data: only model-independent results are presented on the plot

CDF results: comparison with Monte Carlo





- **Herwig 5.6 & Pythia 6.115 reproduce gluon jets fairly well**
- **<u>Herwig 5.6 & Pythia 6.115 over-estimate multiplicity in quark jets by ~30%</u>**
- **Pythia gives ~3-4% higher multiplicity than does Herwig**

- **Herwig & Pythia are <u>below</u> CDF data**
- **Herwig & Pythia are <u>smaller</u> than NLLA predictions**

Results on multiplicities in Gluon & Quark jets, and their ratio

✓ **CDF results confirm $Q \approx E_{jet}\theta_C$ scaling**

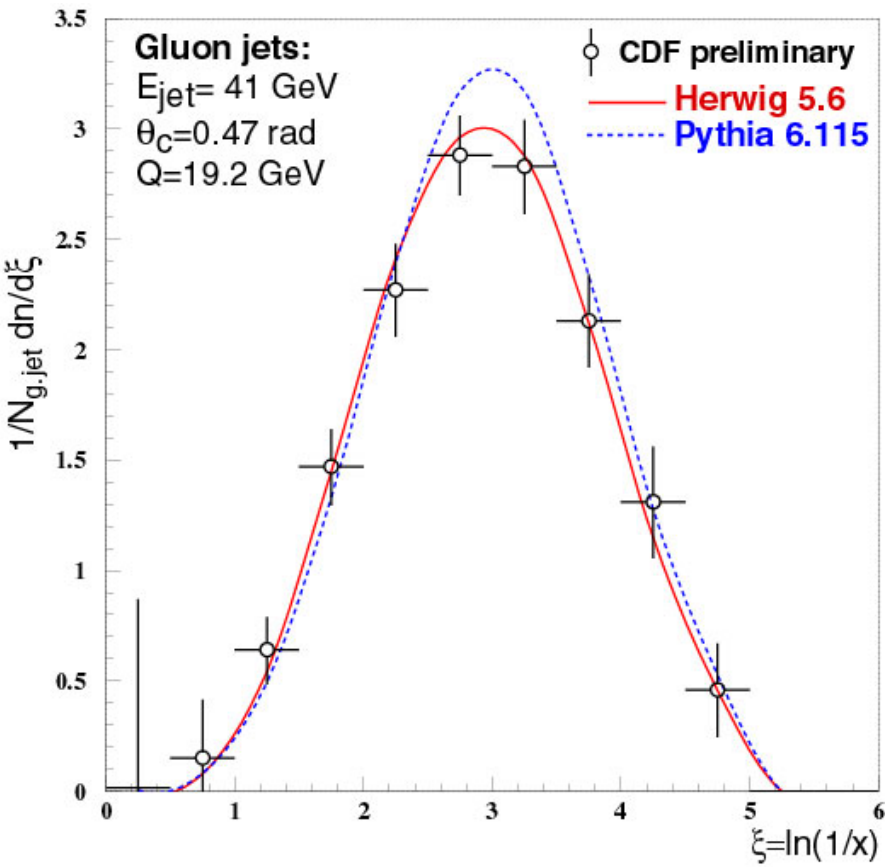
$\rightarrow$ $E_{jet1} \neq E_{jet2}$ and $\theta_1 \neq \theta_2$, but $E_{jet1}\theta_1 = E_{jet2}\theta_2 \Rightarrow N_1(E_{jet1}\theta_1) = N_2(E_{jet2}\theta_2)$ (same colors in table)

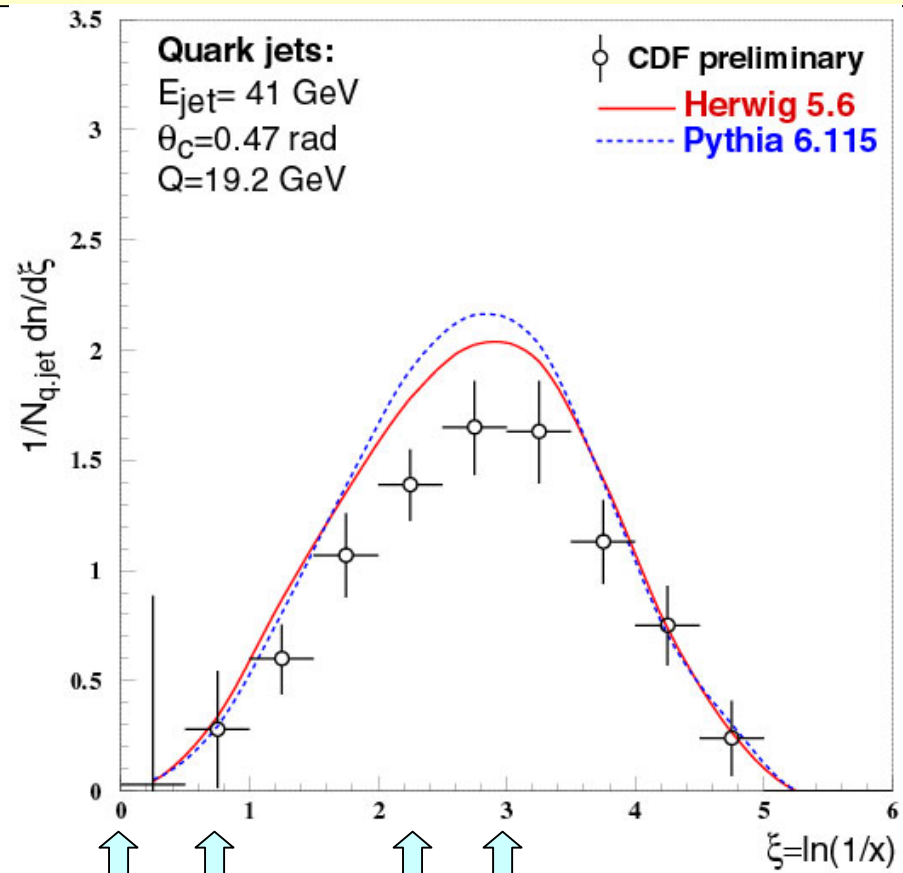
Cone size, θ_C		0.28 rad	0.36 rad	0.47 rad
Energy scale, $Q=2E_{jet}\tan(\theta_C/2) \approx E_{jet}\theta_C$		**11.5 GeV**	**14.7 GeV**	**19.2 GeV**
E_{jet}=41GeV	N_g	**4.98±0.07±0.52**	**6.02±0.08±0.55**	**6.94±0.08±0.58**
	N_q	**3.28±0.04±0.37**	**3.70±0.11±0.40**	**4.23±0.12±0.47**
	$r= N_g/N_q$	**1.52±0.08±0.13**	**1.63±0.09±0.14**	**1.64±0.09±0.14**
$Q=2E_{jet}\tan(\theta_C/2) \approx E_{jet}\theta_C$		**14.7 GeV**	**18.9 GeV**	**24.7 GeV**
E_{jet}=52.5GeV	N_g	**5.94±0.12±0.69**	**7.02±0.13±0.72**	**8.08±0.14±0.72**
	N_q	**3.70±0.17±0.43**	**4.22±0.18±0.49**	**4.86±0.19±0.57**
	$r= N_g/N_q$	**1.60±0.12±0.19**	**1.66±0.13±0.20**	**1.66±0.13±0.18**

Momentum distribution of charged particles in Gluon & Quark jets

Gluon jets: Herwig and Pythia are in reasonable agreement with data

Quark jets: Herwig and Pythia <u>disagree</u> with data





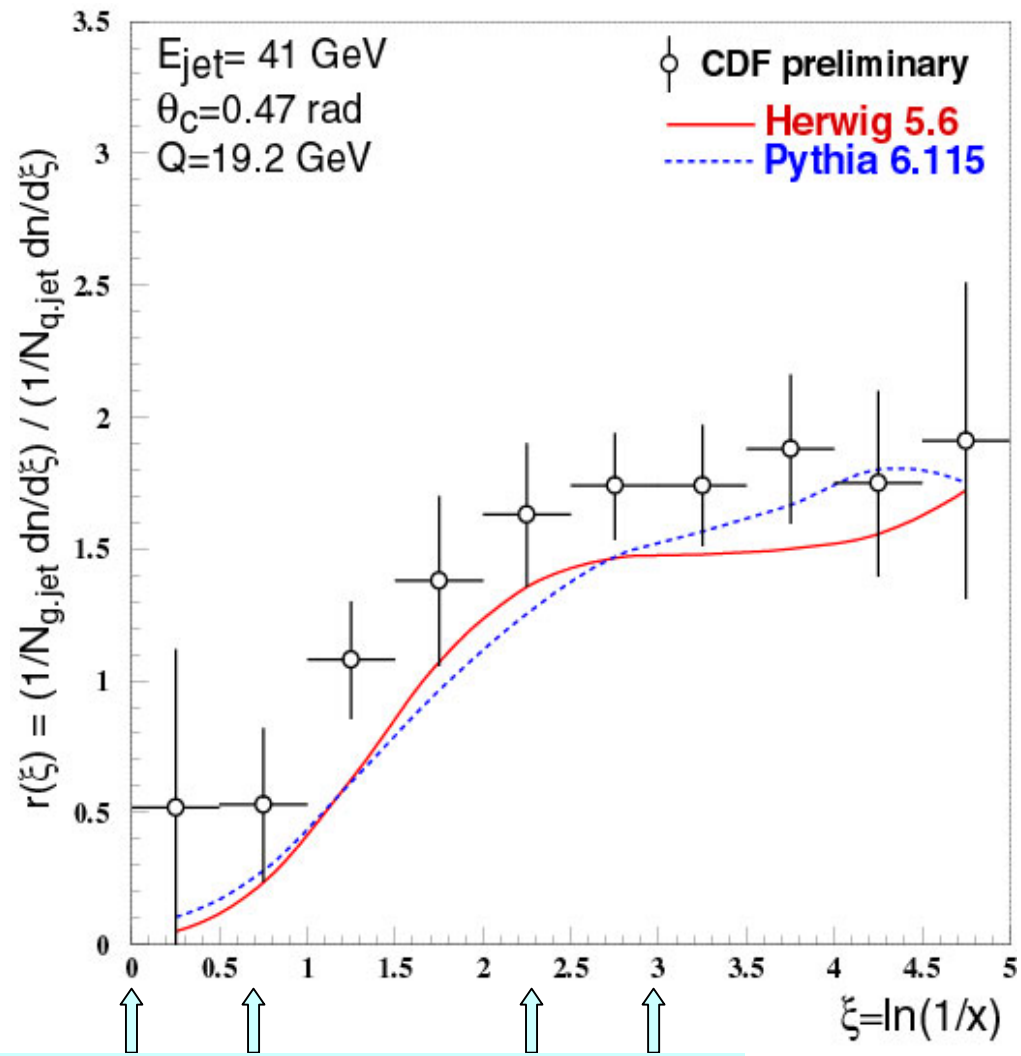
$x = p/E_{jet} = 1$ 0.5 0.1 0.05

Ratio of momentum distribution of charged particles in Gluon & Quark jets

CDF data vs. MC:

→ Monte Carlos qualitatively reproduce the shape of r(ξ)

→ Monte Carlos predict lower ratio r(ξ)



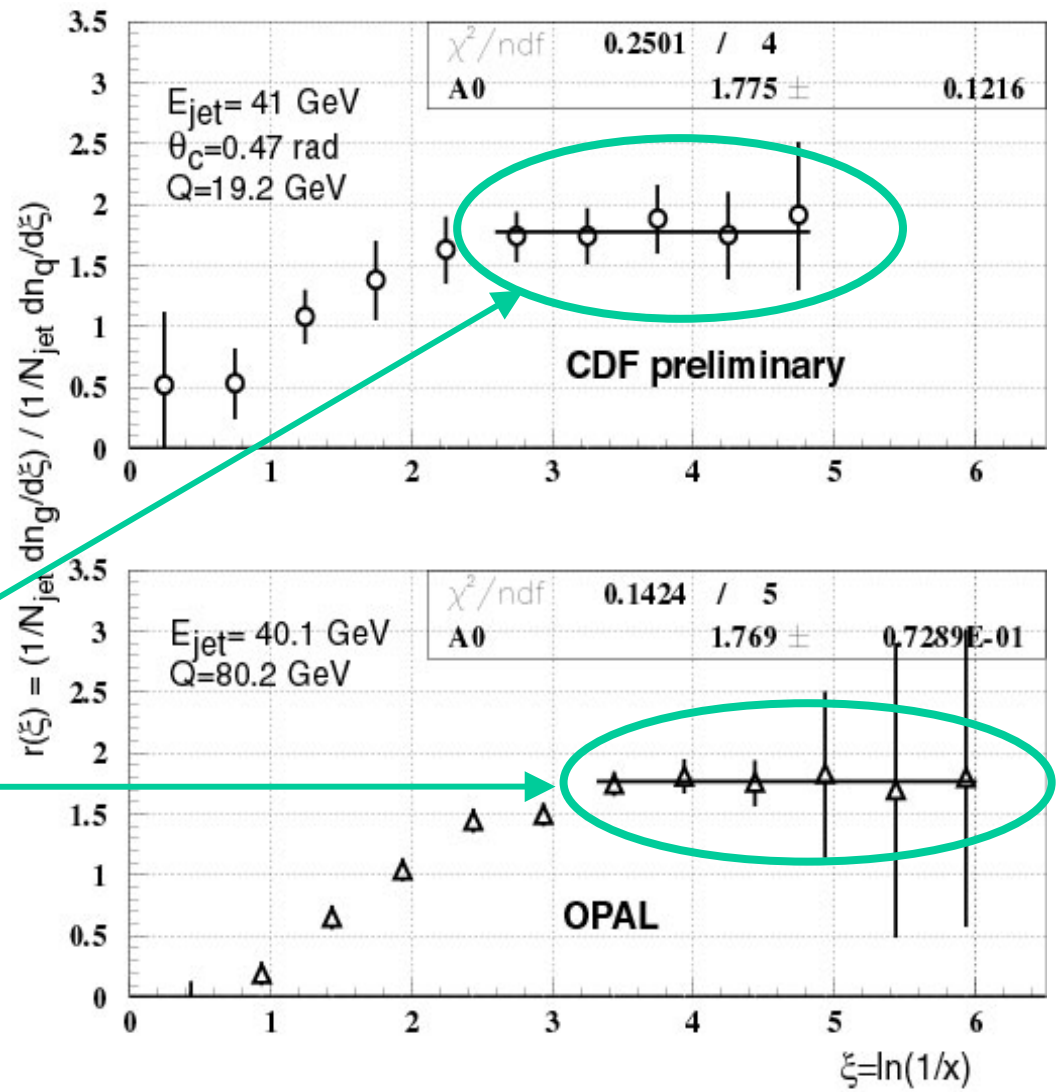
$x = p/E_{jet} =$ 1 0.5 0.1 0.05

Ratio of momentum distribution of charged particles in Gluon & Quark jets, cont.

CDF vs. OPAL:

→ **Both CDF and OPAL see a constant ratio, $r(\xi_{soft})\approx 1.8$, in the soft part of the spectrum, as expected from theory**

Khoze, Lupia & Ochs, EPJ C5(1998)77



soft particles

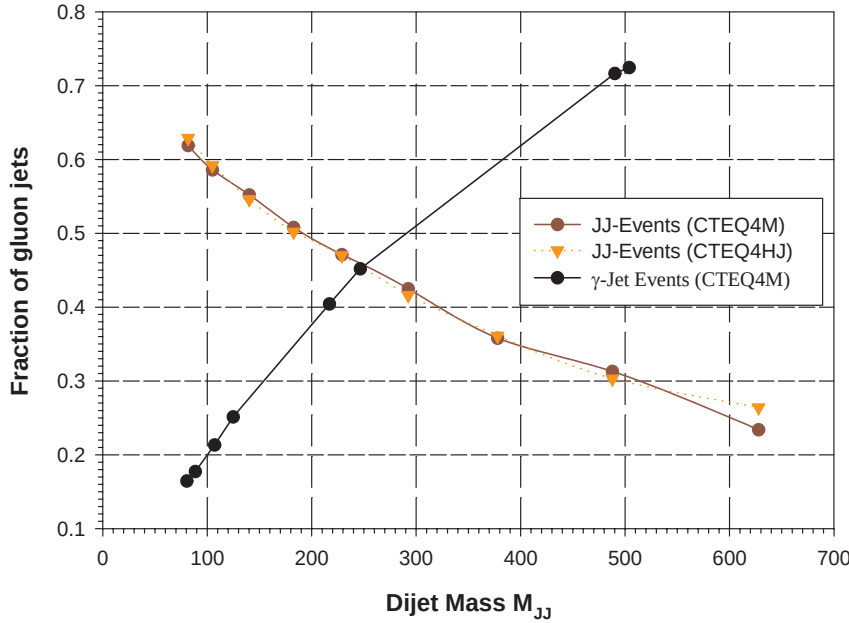
Summary

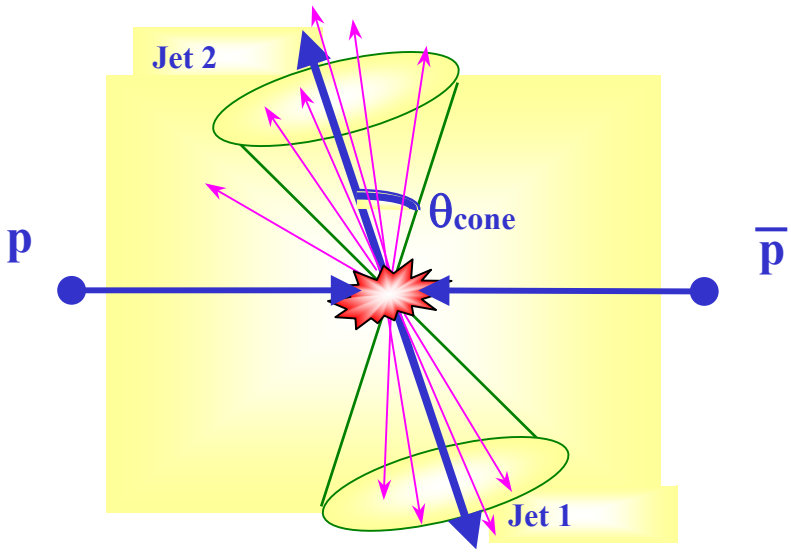
- ✓ **First model-independent analysis of Gluon and Quark jet differences using charged particles at hadron colliders**
  - → Results submitted for publication in PRL
- ✓ **Multiplicities and ratio follow predictions of recent extensions to Next-to-Leading Log Approximation**
  - → Most of jet fragmentation can be successfully described by pQCD calculations
- ✓ **Good agreement with e^+e^- results**
  - → Suggests universality of jets
- ✓ **$r=N_g/N_q=1.64\pm0.17$ at Q=19 GeV**
  - → Difference can be potentially used to better differentiate between signal and background (mostly gluon jets) in measurements involving jets from *b*-quarks, $W\rightarrow q`q``$, and $Z\rightarrow qqbar$
- ✓ **Herwig 5.6 and Pythia 6.115 reproduce gluon jets fairly well, but systematically over-estimate multiplicity in quark jets by ~30%**
  - → More detailed studies are needed to trace the origin of disagreement

Backup slides

Analysis at CDF

- **gluon jets are produced in plenty:**
  no need to look on 3-jet events
- **compare data samples with very different fractions of gluon jets:**
  dijet vs. γ+jet
- **do analysis in dijet or γ+jet center of mass frame:**
  unambiguous assignment of tracks to jets
- **count particles in cone θ_C<<1:**
  as prescribed by theory
- **energy scale $Q=2E_{jet}\tan(\theta_C/2) \approx E_{jet}\theta_C$**
- **assume that gluon and quark jet properties are the same in two samples**
- **using fractions of gluon jets in two samples, unfold algebraically to obtain N_g and N_q**





Data selection cuts

- Run1B data
- Jets are reconstructed by JetClu with R=0.7
- Jet energy is corrected to the parton level

Event cuts (dijet & γ+jet events):

- only two well-balanced jets (or γ & jet):

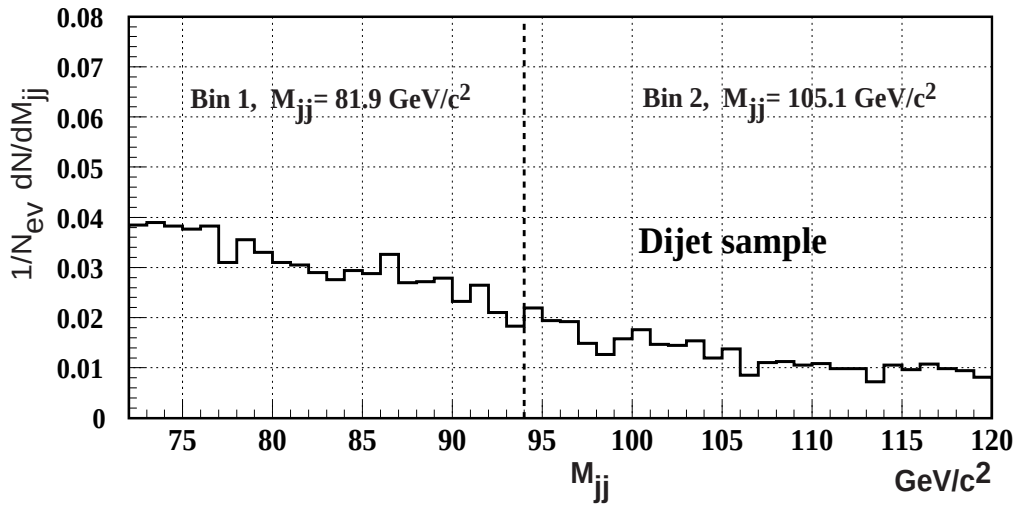
$$\frac{\left|\vec{P}_{T1}+\vec{P}_{T2}\right|}{\left(P_{T1}+P_{T2}\right)} \leq 0.15$$

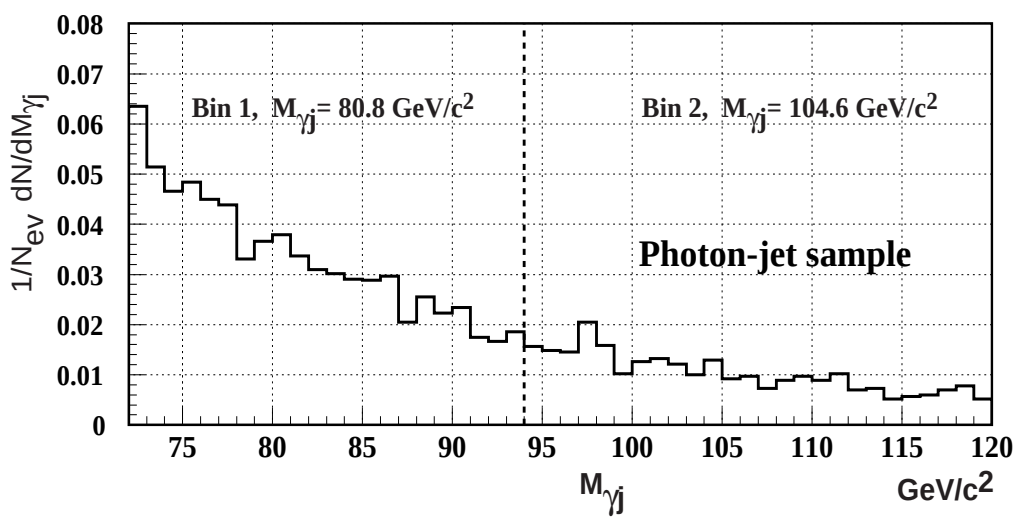
- both jets (or γ & jet) in the central region: $|\eta|<0.9$
- 1 or 2 well reconstructed vertices
- z-position of the primary vertex: $|z|<60$ cm, and $|z_{vx1}-z_{vx2}|>12$ cm if two vertices

Photon ID cuts:

- one photon with $E_T>20$GeV
- $HAD/EM_{total}<0.125$
- photon isolation: <1 GeV in R=0.4
- no track pointing to photon cluster
- shape of shower profile consistent with one photon

Data selection continued…





- **Events are subdivided into two bins according to the invariant mass:**

  → uniform log-scale width **$\ln(M_2/M_1)$=0.3**, always wider than calorimeter invariant mass resolution **$\delta M_{jj}/M_{jj}$≈10%-15%**
- **Bin 1: M_{jj}~72-94 GeV/c^2; $|E_{jet}|$≈41 GeV**
- **Bin 2: M_{jj}~94-120 GeV/c^2; $|E_{jet}|$≈53 GeV**

	Dijet	"pho"+jet
Bin1	3,602	2,526
Bin 2	1,768	910

Data selection: systematics & cross-checks

- **Systematics:**
  - **jet energy scale:**
    varied scale by +/-5%
  - **jet energy balance:**
    use 0.15 for dijets & 0.125 for γ+jet events (motivated by MC studies)
  - **jet algorithm bias:**
    compare properties of MC jets reconstructed by JetClu R=0.4 & R=1.0
  - **small difference in invariant mass:**
    apply correction & compare results
- **Cross-checks:**
  - **studied multiplicity dependence on η_{jet}:**
    no significant dependence observed
  - **compared multiplicity in jets from events with 1 & 2 vertices:**
    no significant difference observed

Gluon fractions

$$r = 1 + \frac{\alpha - \varepsilon_\gamma(\alpha - 1) - \frac{N_{\gamma j}}{N_{jj}}}{n_g^{jj}\frac{N_{\gamma j}}{N_{jj}} - \varepsilon_\gamma\, n_g^{real\,\gamma j} - (1 - \varepsilon_\gamma)\alpha\, n_g^{jj}}$$

n_g^{jj} — gluon fraction in dijet events

$n_g^{real\gamma j}$ — gluon fraction in 100% pure γ-jet events

	Dijet	100% pure γ+jet
E_{jet}=41GeV	0.615±0.006	0.216±0.009
E_{jet}=53GeV	0.588±0.008	0.256±0.015

- **Gluon fractions are extracted by using Herwig5.6+CTEQ4M PDF set (default)**
  - **Systematics uncertainty: Herwig+CTEQ4A2, Herwig+CTEQ4A4, & Pythia+CTEQ4M**

    → systematic uncertainty on gluon fractions is ~2%

Fraction of real photons

$$r = 1 + \frac{\alpha - \varepsilon_\gamma(\alpha - 1) - \frac{N_{\gamma j}}{N_{jj}}}{n_g^{jj}\frac{N_{\gamma j}}{N_{jj}} - \varepsilon_\gamma\, n_g^{real\ \gamma j} - (1 - \varepsilon_\gamma)\alpha\, n_g^{jj}}$$

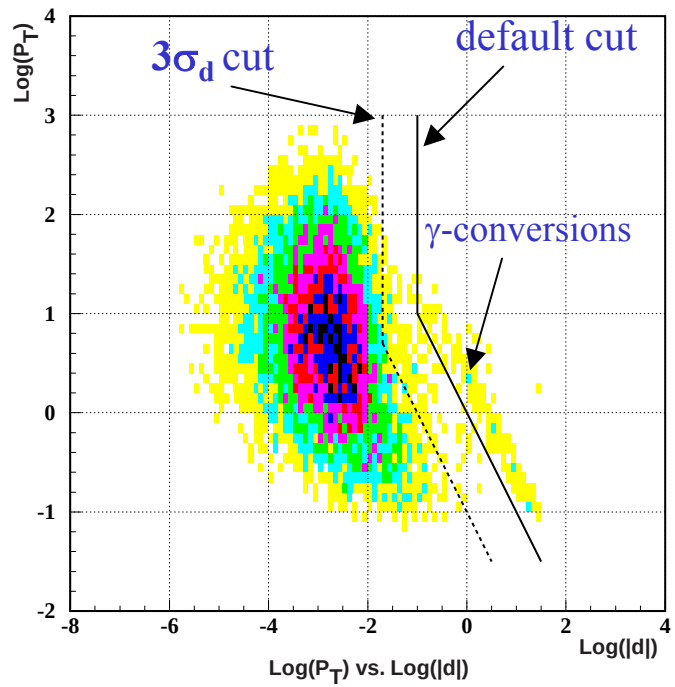
ε_γ **- fraction of real photons**

- **Estimation of ε_γ is based on measurement of the number of photon conversions in the material in front of CPR**
  - **Probability of conversion for:**
    - →**real photon: $\mu_\gamma = 1 - e^{-7/9X}$** (X is the amount of material in radiation lengths)
    - →**background $\pi^0 \to \gamma\gamma$: $\mu_B = 2\mu_\gamma - \mu_\gamma^2$**
  - **Systematics:** considered underlying event CPR hit rate, shower back-scattering, η/π^0 and K_S/π^0 rates

	Fraction of real photons
E_{jet}=41GeV	0.75±0.04(stat)±0.04(syst)
E_{jet}=53GeV	0.90±0.07(stat) ±0.05(syst)

Multiplicity measurement, slide2

- **Vertex cuts on impact parameter, d_0, and $\Delta z=|z_{vertex}-z_{track}|=6$ cm**
  - — **remove secondary interactions, γ-conversions, K_S and Λ decays, etc.**
  - — **systematics: try tighter cuts ($3\sigma_d$ & $\Delta z=4$ cm)**
- **Correction for remaining γ-conversions & products of K_S and Λ decays (based on MC). Typical values are 3.5% & 4%, respectively**
  - — **systematics: no corrections**



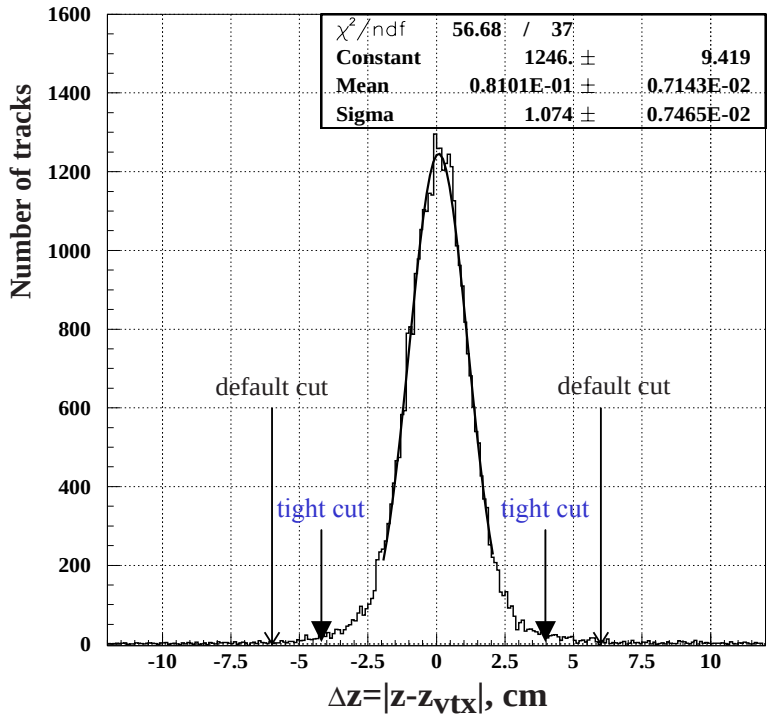


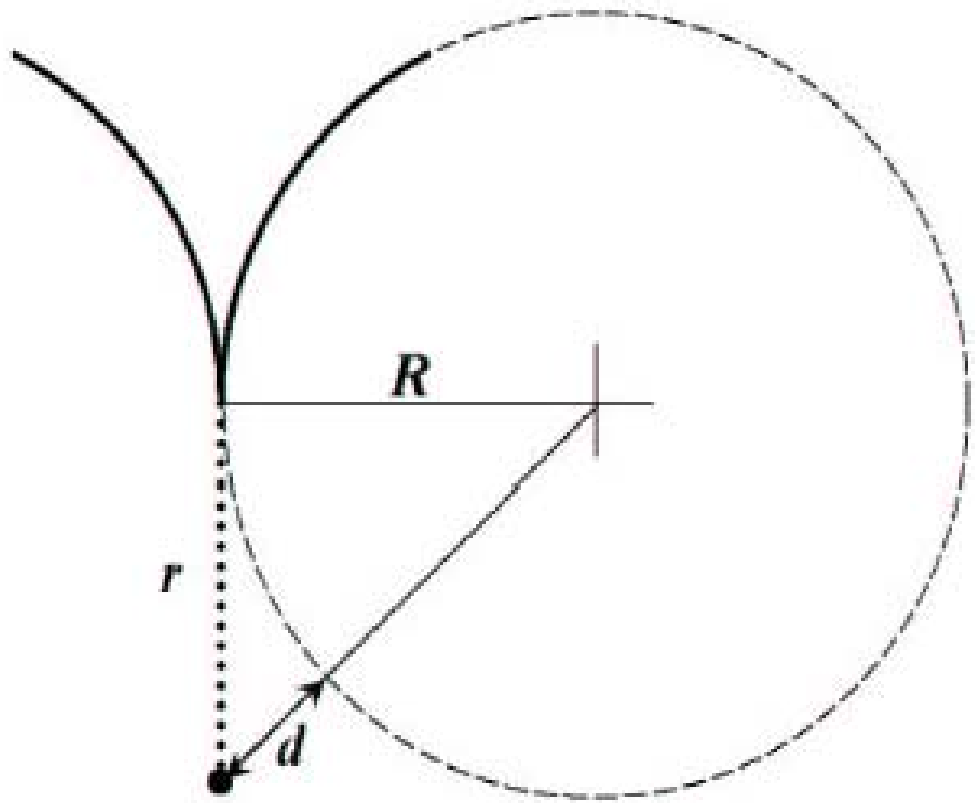
Illustration of impact parameter for γ-conversions

- **Impact parameter, d0, and track P_T are strongly correlated for electrons and positrons from γ-conversions occurred at distance R from the primary interaction point.**

$$R = p / eB$$

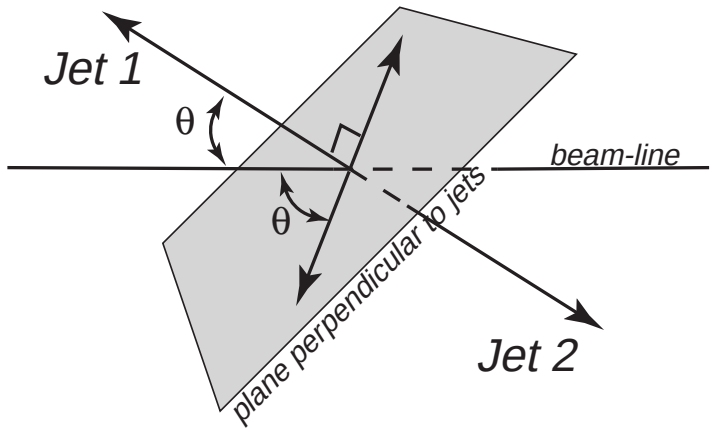
$$d = \sqrt{R^2 + r^2} - R \approx R\left(1 + \frac{1}{2}\frac{r^2}{R^2}\right) - R = \frac{r^2}{2R} = \frac{eBr^2}{2p}$$

$$\log d = \log\left(\frac{eBr^2}{2}\right) - \log p$$

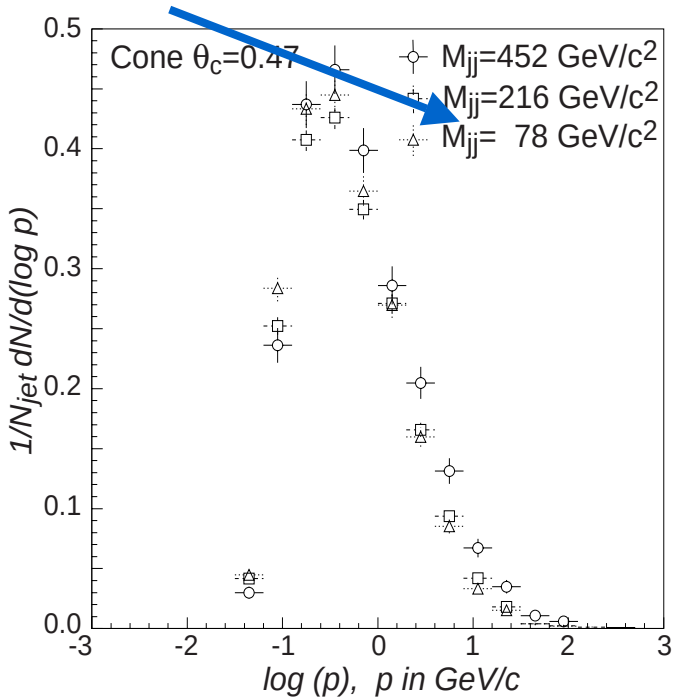


Multiplicity measurement, slide3

- **Complementary cone subtraction:**
  - — underlying event, secondary interactions (with unresolved vertex)
    - → 0.2 to 0.5 tracks per cone (θ_C=0.28-0.47 rad)
  - — systematics:
    - → study dependence of multiplicity in complementary cone on jet energy & multiplicity in jet cone (effect is small: ~0.1 track for θ_C= 0.47)
- **CTC inefficiency correction**
  - — based on embedding tracks from one jet into the other and re-running reconstruction
    - → correction size is ~6-8%, depending on jet energy & cone size
  - — systematics: tighter matching criteria
- **Correction for loss of tracks with P_T<0.3 GeV:**
  - — MC based, typical value is <2%
  - — systematics: no correction



almost independent of jet energy



Multiplicity measurement, slide4

$$r = 1 + \frac{\alpha - \varepsilon_\gamma(\alpha - 1) - \frac{N_{\gamma j}}{N_{jj}}}{n_g^{jj}\frac{N_{\gamma j}}{N_{jj}} - \varepsilon_\gamma\, n_g^{real\ \gamma j} - (1 - \varepsilon_\gamma)\alpha\, n_g^{jj}}$$

Multiplicity in jets from dijet & photon+jet events:

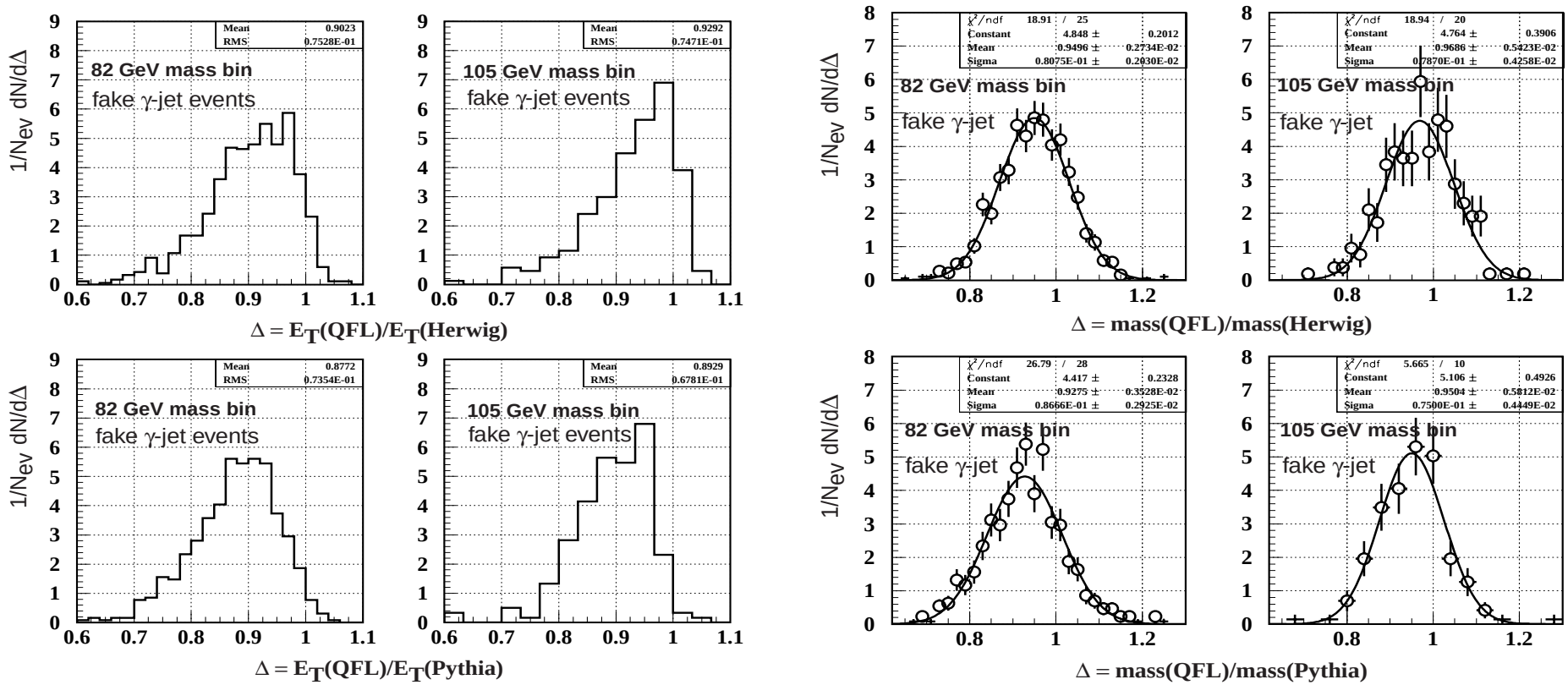
		θ_C=0.28	θ_C=0.36	θ_C=0.47
E_{jet}=41GeV	N_{jj}	4.476±0.025	5.287±0.027	6.052±0.029
	$N_{\gamma j}$	4.01±0.04	4.64±0.04	5.31±0.05
E_{jet}=53GeV	N_{jj}	5.19±0.04	6.05±0.04	6.94±0.04
	$N_{\gamma j}$	4.53±0.07	5.23±0.08	6.00±0.08

Comment:

errors are statistical only; N_{jj} & $N_{\gamma j}$ do not include corrections for remaining products of K_S and Λ decays and losses of low P_T tracks (these are applied to N_g & N_q directly)

MC study of "*Fake photon+jet*" events

- Fakes are usually energetic π^0 or η from regular jets
- Fake, on average, carries only ~90% of the original jet energy
- The measured invariant mass of fake-jet event is less than actual by ~5%



Multiplicity in the jet opposite to fake photon

$$r = 1 + \frac{\alpha - \varepsilon_\gamma(\alpha - 1) - \frac{N_{\gamma j}}{N_{jj}}}{n_g^{jj}\frac{N_{\gamma j}}{N_{jj}} - \varepsilon_\gamma\, n_g^{real\ \gamma j} - (1 - \varepsilon_\gamma)\alpha\, n_g^{jj}}$$

α = N(jet opposite to fake photon) / N(jet from dijet events)

- **invariant mass of fake+jet events is mis-measured by 5%**
- **same mass bins are actually populated by events of higher true $M_{\gamma j}$ values than for the case of dijet events $\Rightarrow$ leads to α >1.0**
- **three methods to estimate α:**
  Herwig, Pythia and "shifted" dijet data (energy of one of the jets is shifted down by 10%) . The average of all three methods is taken as default value.
- **systematics due dependence on MC fragmentation model:**
  compare Herwig & Pythia based results $\rightarrow$ effect is small (~2%)

	θ_C=0.28	θ_C=0.36	θ_C=0.47
E_{jet}=41GeV	1.040±0.016	1.035±0.014	1.041±0.015
E_{jet}=53GeV	1.032±0.012	1.036±0.011	1.034±0.011

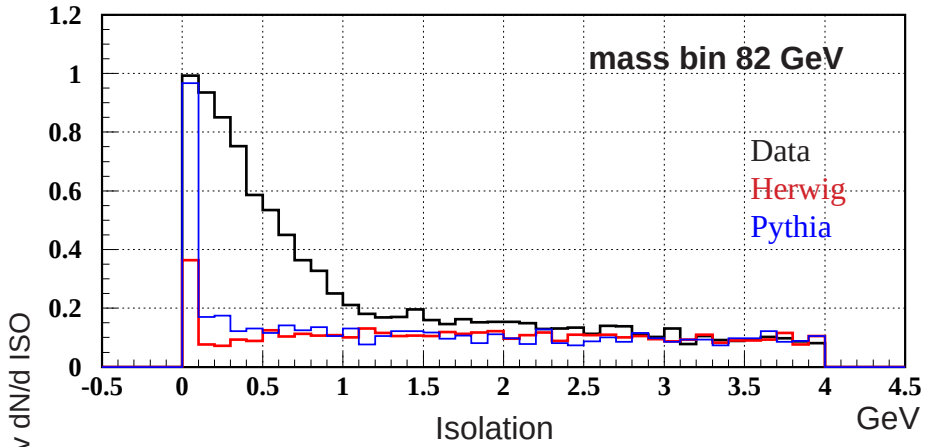
Summary of systematic uncertainties

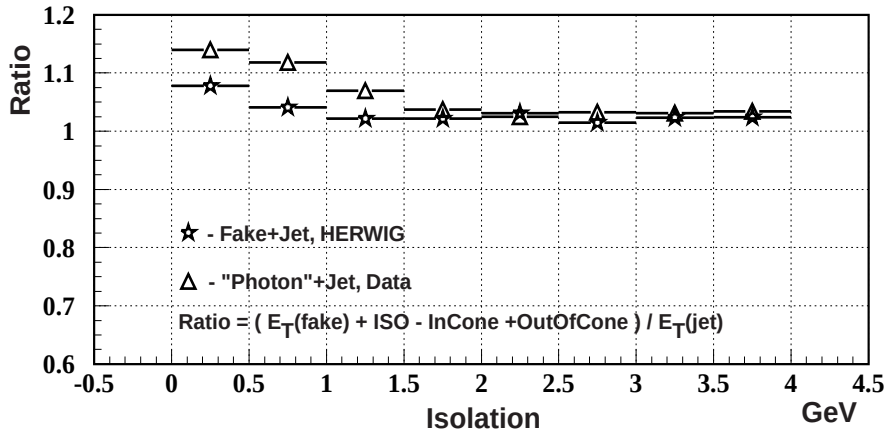
- **The systematic uncertainties due to particular source vary with cone size, θ_C, and jet energy**

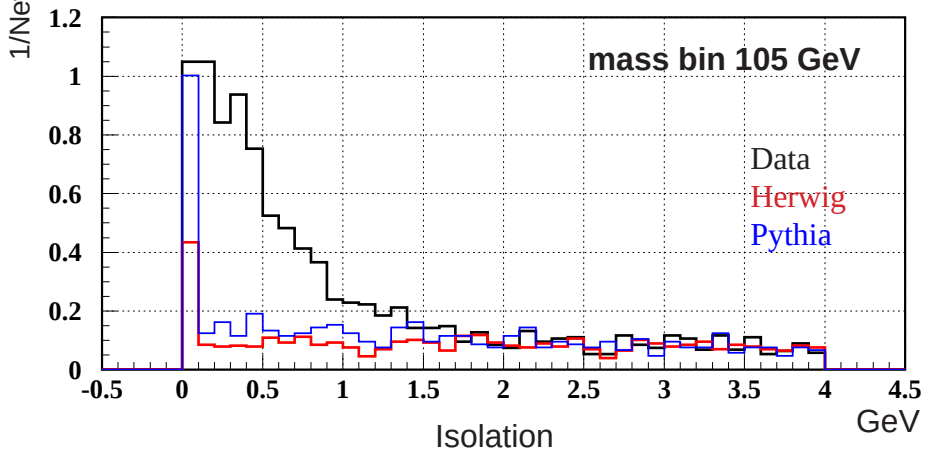
- **The individual systematic uncertainties for results with the same jet energy but different cone size, θ_C, are strongly correlated**

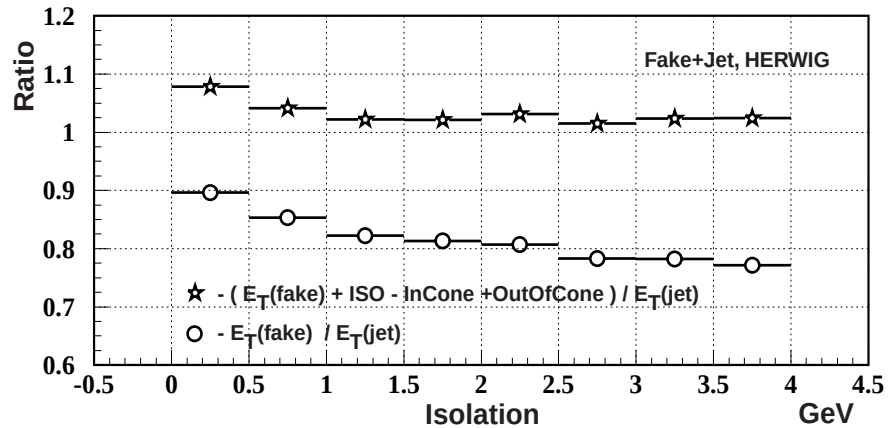
- **Major systematics in multiplicities, N_g and N_q**
  - **background track removal: 7-10%**
  - **jet algorithm bias: 1-7%, depending on θ_C**
  - **jet energy scale: 2-5%**
  - **photon sample purity: 1-4%**
- **Major systematics in the ratio, $r=N_g/N_q$**
  - **jet energy scale: 4-9%**
  - **photon sample purity: 4-6%**
  - **background track removal: 3-6%**
  - **energy balance: 1-5%**

Photon (& Fake) Isolation energy



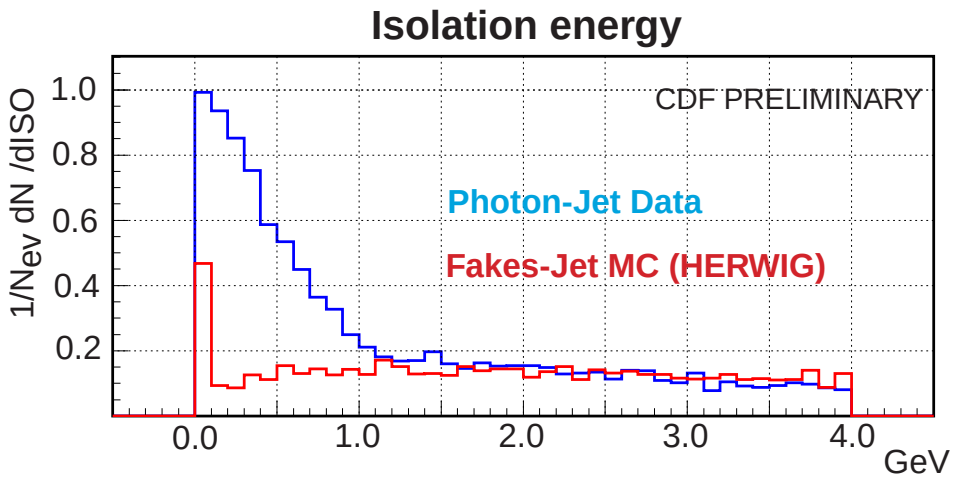


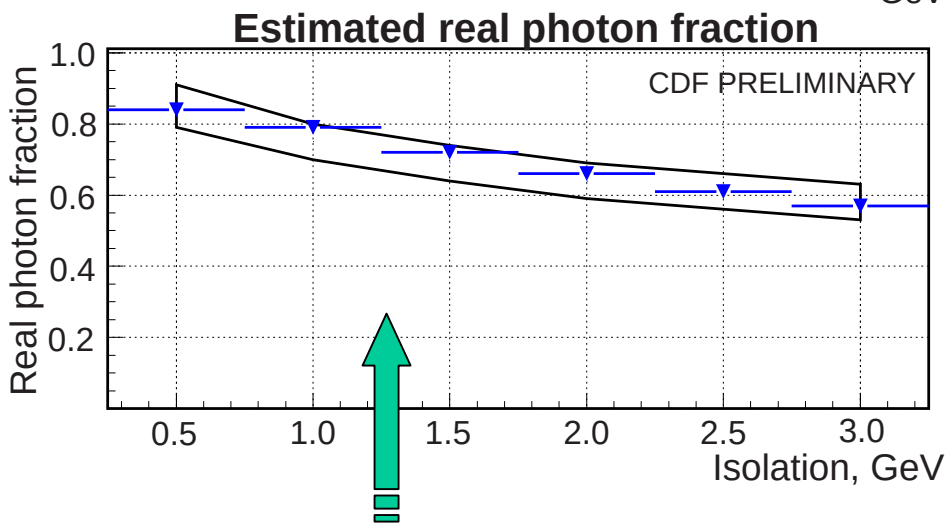




Fraction of real photons: cross-check

- **As a cross-check, we estimated the real photon fraction by comparing the isolation energy distribution in data and MC fakes. The results of both methods are in agreement.**



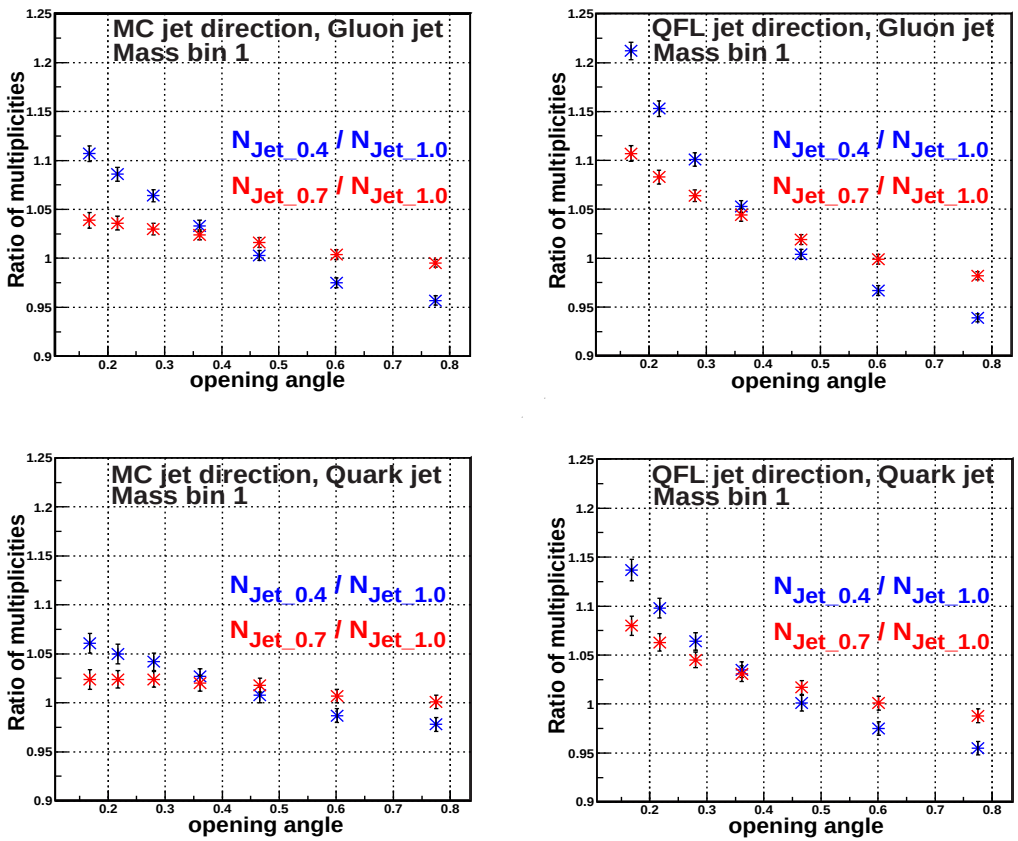


Points: alternative method
Band: CPR method (stat.&syst. uncertainties)

Bias due to jet finding algorithm

- Ideal (for our studies) algorithm should always give two jets per event.
- In reality, the number of jets depend on the clustering cone.
- Method to estimate the systematic error:

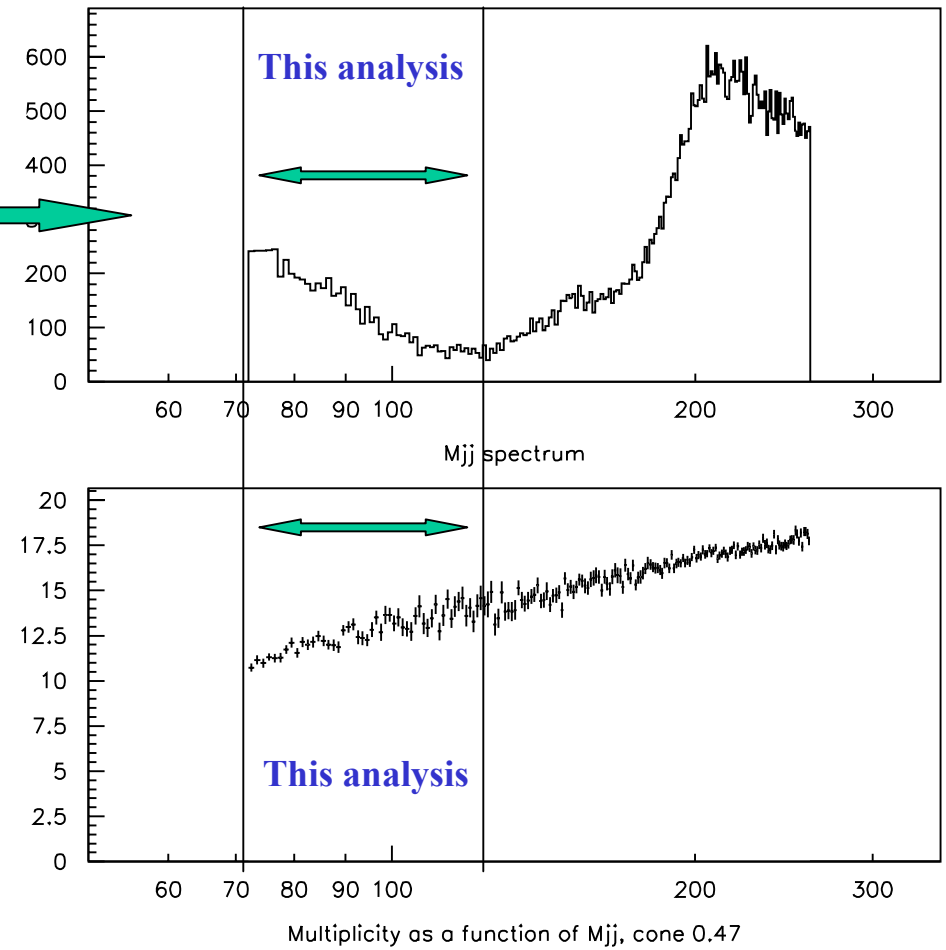
1) **Run Monte Carlo with JETCLU(R=0.4), JETCLU(R=0.7) and JETCLU(R=1.0)**
2) **Compare multiplicities in various cones for jets reconstructed with different clustering cones.**



Data selection: effect of trigger

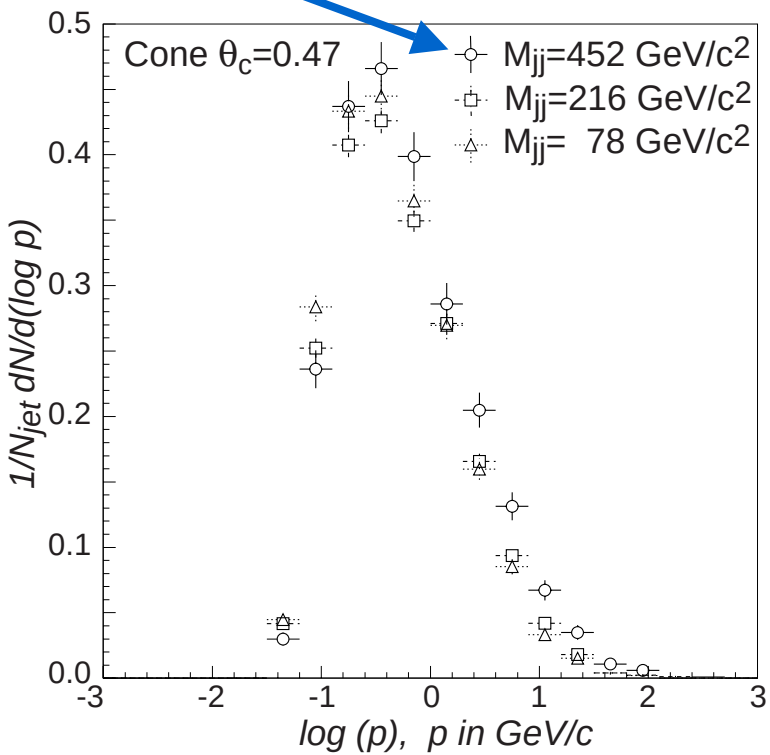
- Dijets: **Jet20 trigger, threshold is E_T>20 GeV, pre-scaled by 1000**
  → Any trigger bias?

- Photon+jet: **photon trigger thresholds are 23 & 50 GeV**
  → Jet is not a trigger object
  → no bias in jet properties

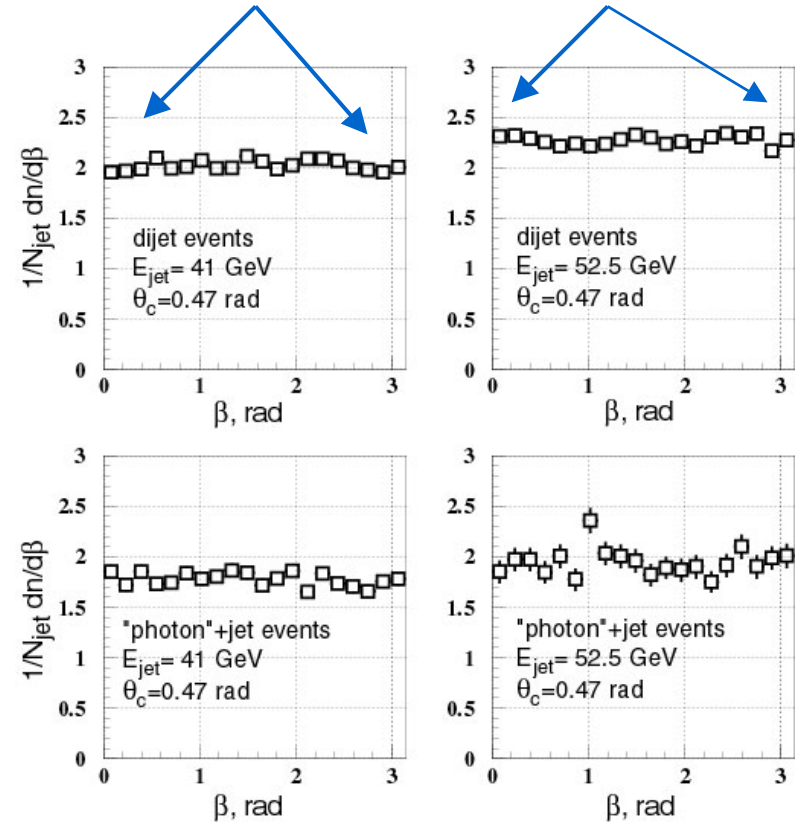


CDF analysis: multiplicity measurement

independent of jet energy



no visible sings of enhancement



Uncorrelated background subtraction

→ sources: **underlying event, accelerator induced background, secondary interactions with unresolved vertex**

→ method: **complementary cones**

Any signs of initial-to-final-state color coherence?

→ **sensitive observable:** polar angle β in (η,φ)-plane

→ **signature:** enhancement in "preferred" direction