Measurement of charged particle multiplicities in gluon and quark jets.

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Measurement at CDF

- At CDF, we always deal with a mixture of quark and gluon jets:

  $N = n_g N_g + n_q N_q$, where N is <u>multiplicity per jet</u>

- Dijet and photon-jet events have different fractions of gluon jets **:**

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

- 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 $r = N_g/N_q$.

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

- Caveat: gamma-jet events have a fraction of fake gammas, i.e. they have a fraction ε of jet-jet events:

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

Final Formula

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

$N_{\gamma j}$ - 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(CTEQ4M)

$n_g^{real\,\gamma j}$ - gluon fraction in 100% pure γ-jet sample (CTEQ4M)

α - correction factor due to fakes(ratio of multiplicities of a jet opposite to fake and a regular jet)

Multiplicity in gluon and quark jets

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

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

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

Gluon jet multiplicity:

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

Quark jet multiplicity:

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

What has changed since the last blessing?

- Event selection: new energy balance cut for "photon"+jet events
- All systematic errors are carefully revised
- Herwig & Pythia fakes → better understanding of effect
- Estimate of multiplicities in gluon and quark jets

	Old blessed results	New results
E_{jet}=40 GeV	r=1.61±0.11±0.28	r=1.61±0.08±0.16
		N_g=7.02±0.08±0.80
		N_q=4.36±0.12±0.57
E_{jet}=53 GeV	r=1.65±0.13±0.20	r=1.67±0.13±0.26
		N_g=8.25±0.14±0.93
		N_q=4.95±0.19±0.79

Data selection cuts

Event cuts (for both dijet & γ+jet events):

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

$$\frac{\Delta E_t}{(E_{t1}+E_{t2})} \leq 0.15$$

- Only events with both jets (or γ & jet) in the central region of the detector: $|\eta|<0.9$
- Only events with 1 or 2 well reconstructed vertices
- z-position of the primary vertex: $|z|<60cm$, and $|z_1-z_2|>12cm$ if there are two vertices

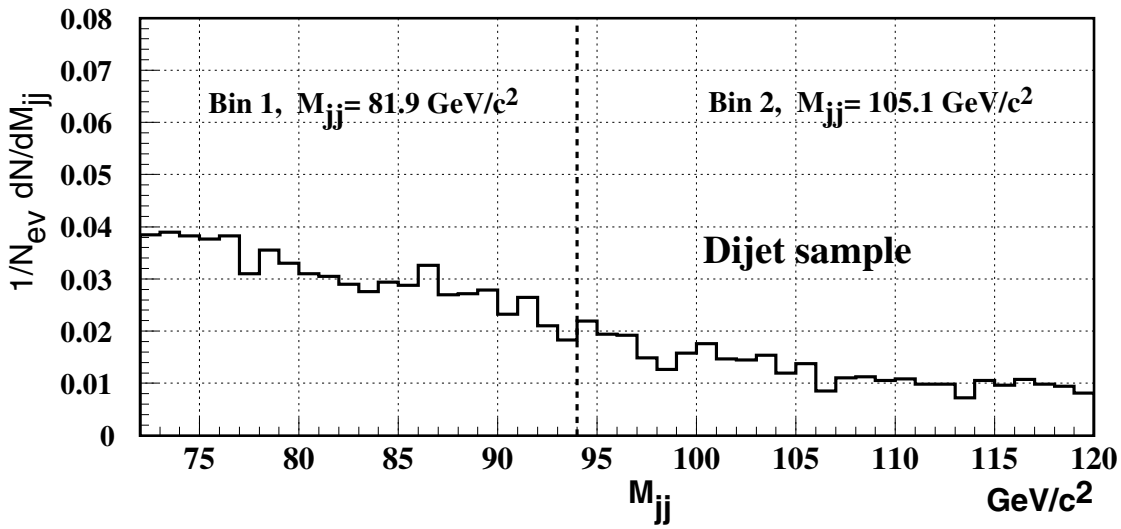
Photon cuts:

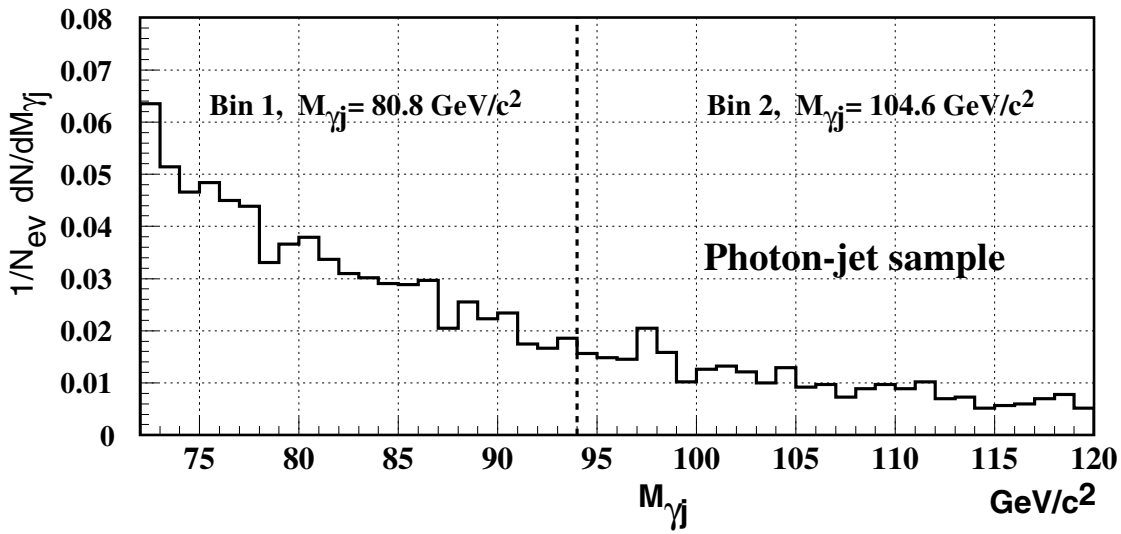
- $HA/EM_{total}<0.125$
- One photon candidate with $E_T>20GeV$
- $|X_{CES}|<17.5cm$, $14cm<|Z_{CES}|<217cm$
- Photon isolation of *1 GeV* in cone0.4
- no 3D CTC reconstructed tracks pointing to a cluster with a photon candidate
- Energy in the second CES cluster (if present) $<1GeV$
- Only events with CES shower profile fit $\chi^2 < 20$

- Old photon+jet energy balance:

$$\Delta E_t \leq \frac{0.15}{\sqrt{2}} * (E_{t1}+E_{t2})$$

Data selection continued…

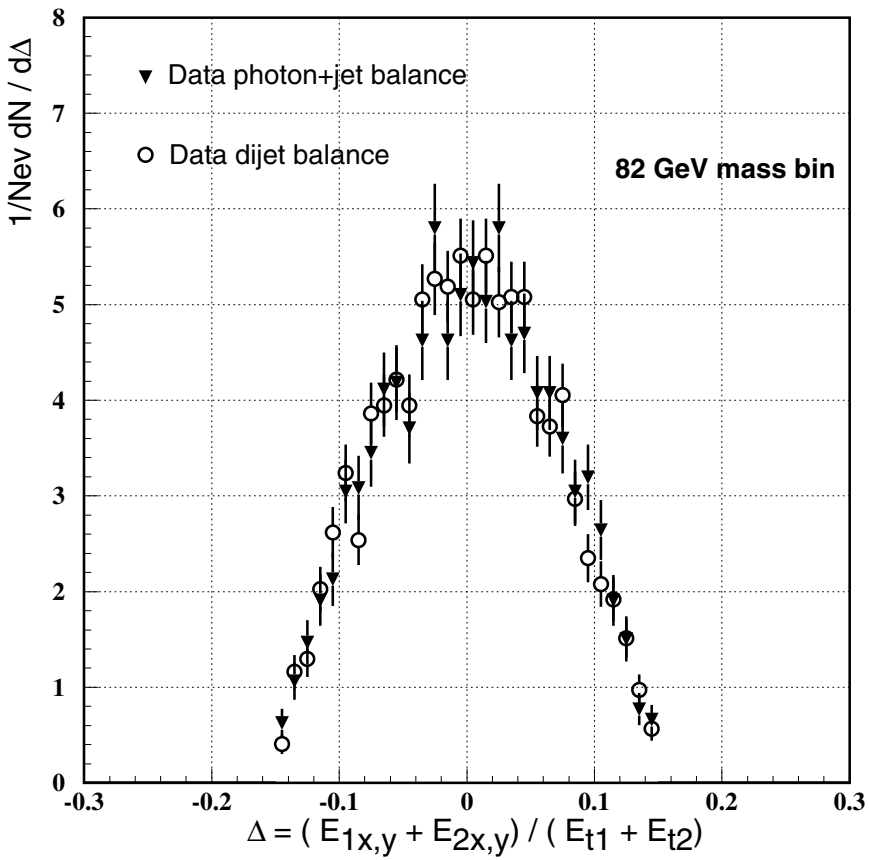


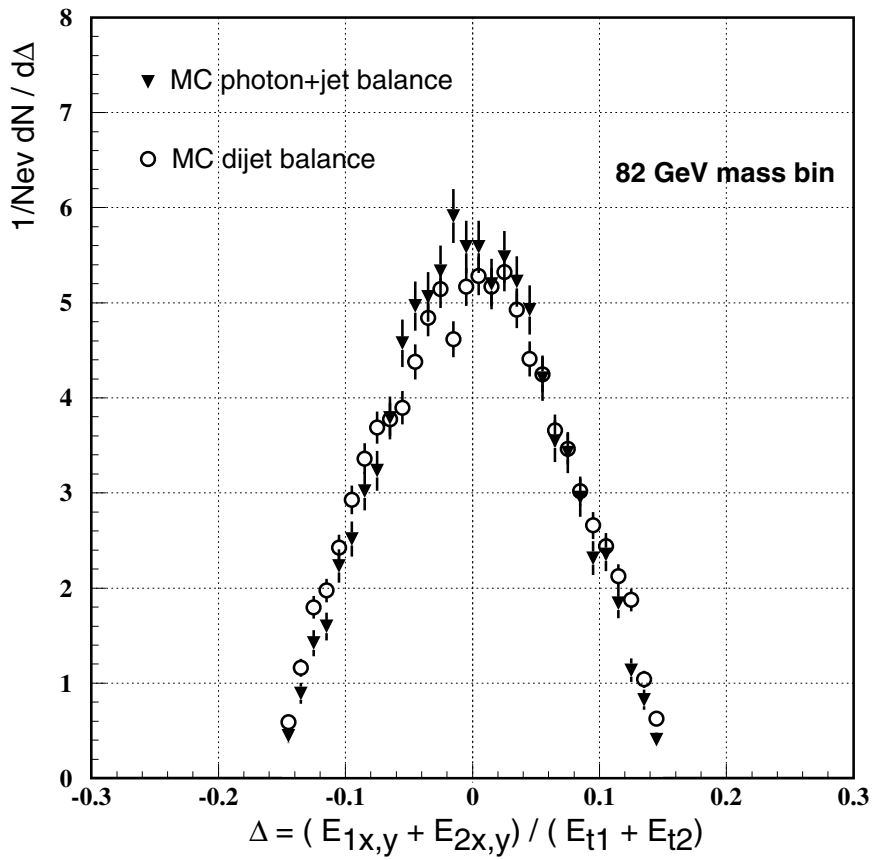


- After the selection cuts, events were further subdivided into two bins according to the dijet mass energy.
- Dijet mass range for Bin 1 is 72-94 GeV/c^2
- Dijet mass range for Bin 2 is 94-120 GeV/c^2

Dijet and Photon+Jet energy balance

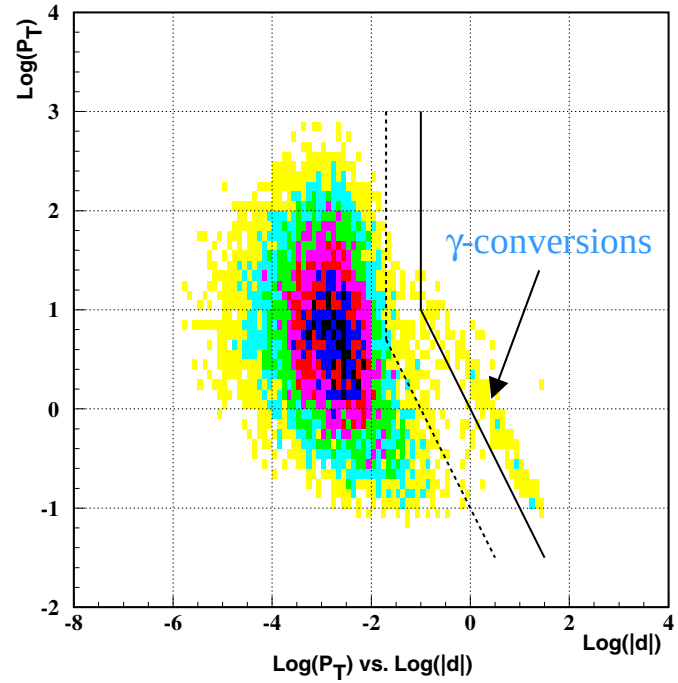
- The balance width is almost the same for dijets and photon+jet events.
- There is a good agreement between data and MC



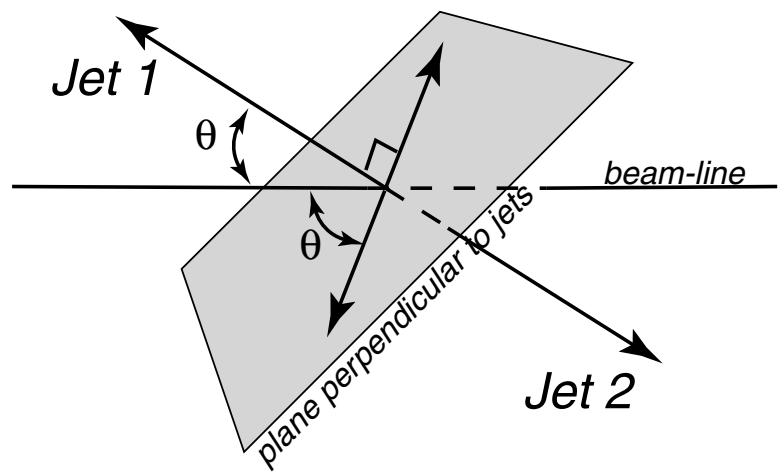


Multiplicity measurement

- Dijet center of mass frame
- Tracks are counted in the cone θ_C=0.47 around jet direction
- Vertex cut on impact parameter $\mathbf{d_0}$ (to remove γ-conversions)
- Vertex cut on **Δz** (to remove tracks due to secondary interactions)**: | Δz |<*6cm***
- Correction for remaining γ-conversions (based on MC)
- Uncorrelated background subtraction (complimentary cones)
- CTC efficiency correction



	Dijet	"photon"+jet
E_{jet}=***40GeV***	5.99±0.03	5.28±0.04
E_{jet}=***53GeV***	6.88±0.04	5.92±0.08



Gluon fractions

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

n_g^{jj} - gluon fraction in jet-jet sample (CTEQ4M+Herwig)

$n_g^{real\,\gamma j}$ - gluon fraction in 100% pure γ-jet sample (CTEQ4M+Herwig)

- Gluon fraction is extracted from HERWIG5.6 with CTEQ4M PDF set (default)

	Dijet	100% pure γ+jet
E_{jet}=***40GeV***	0.612±0.006	0.216±0.009
E_{jet}=***53GeV***	0.585±0.008	0.256±0.015

Fraction of real photons

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

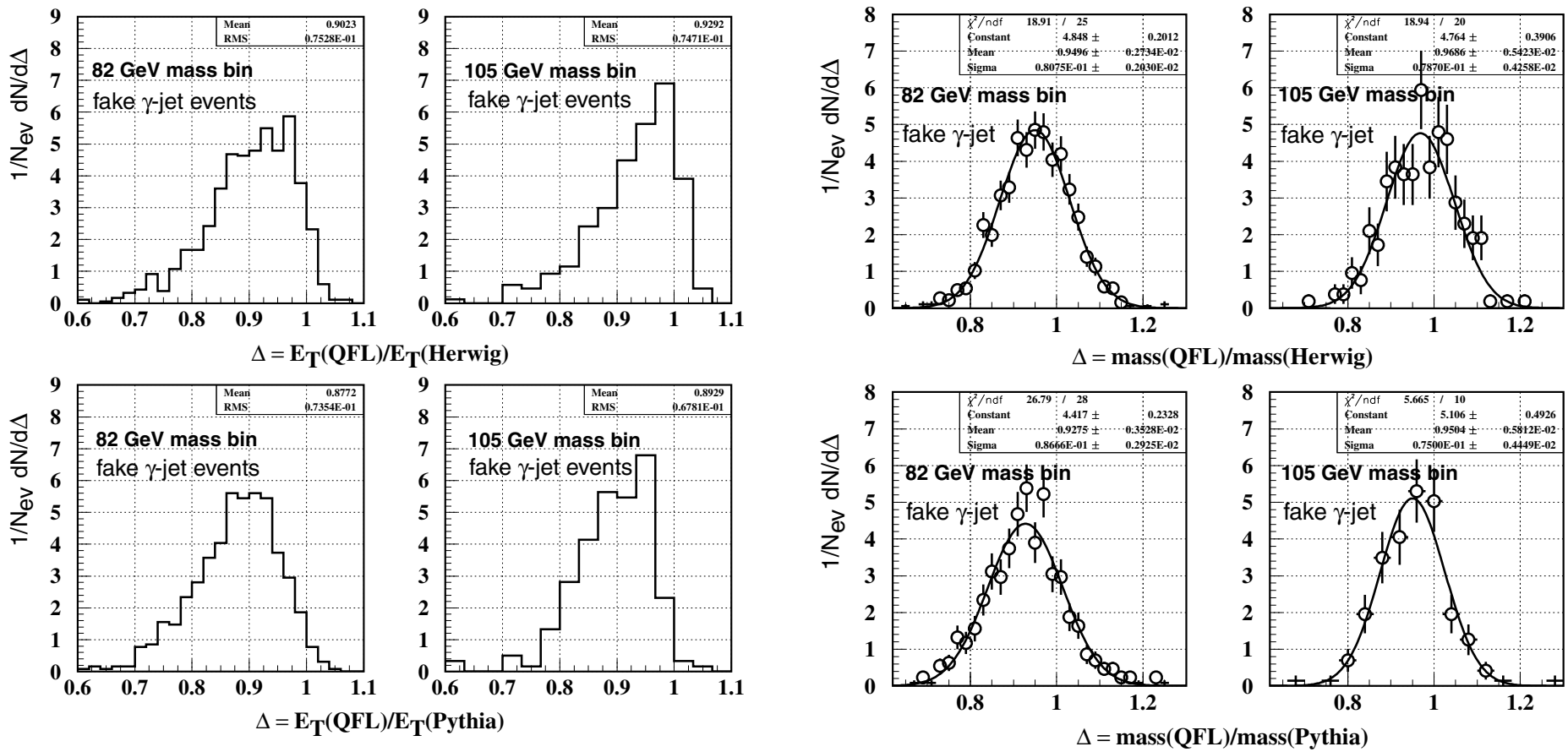
ε_γ - fraction of real photons in "photon"-jet sample

	Fraction of real photons
E_{jet}=***40GeV***	0.74±0.04
E_{jet}=***53GeV***	0.90±0.07

- Fraction of real photon-jet events. Based on CPR weights, obtained with **GetCPRWeight. CDF** routine (statistical errors only).
- We explored the possibility to estimate the real photon fraction by comparing the isolation energy distribution in data and MC fakes. The results of both methods are in agreement.

Fake photon+jet events

- Fake, in average, carries only about 90% of energy of the original jet (plots on the left).
- The measured invariant mass of fake-jet event is less than actual by around 5% (plots on the right).



Multiplicity in the jet opposite to a fake photon

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

- *same mass bins are actually populated with events of higher true $M_{\gamma j}$ values than for the case of dijet events à leads to* **α >1.0**
- *since we require gamma-jet E_T balance, we will tend to pick up events where energy measurement of the jet opposite to the fake fluctuated down à due to the known anti-correlation between energy measurement error and multiplicity in a jet, the jets opposite to fake will tend to have slightly higher multiplicity à leads to* **α >1.0**

ü We use three methods to estimate **α:** Herwig, Pythia and "Shifted" dijet data (one of jets is shifted down by 10%) **.** The average of all three methods is taken as default value.

	Herwig	Pythia	"Shifted" dijets
E_{jet}=***40GeV***	1.027±0.015	1.082±0.016	1.030±0.009
E_{jet}=***53GeV***	0.996±0.026	1.053±0.027	1.037±0.012

Final results

- The errors due to all sources of systematic uncertainties are added in quadratures. **CDF PRELIMINARY**

Jet Energy	**40 GeV**	**53 GeV**
Jet multiplicity in dijet events, N_{jj}	5.99±0.03	6.88±0.04
Jet multiplicity in "photon"+jet events, $N_{\gamma j}$	5.28±0.04	5.92±0.08
Fraction of gluon jets in dijet events, n_g^{jj}	0.612±0.006	0.585±0.008
Fraction of gluon jets in pure γ-jet events, $n_g^{\gamma j}$	0.216±0.009	0.256±0.015
Fraction of real photons in "photon"+jet events, ε_γ	0.74±0.04	0.90±0.07
α-correction, $\alpha = N_{fake\text{-}jet} / N_{jj}$	1.046±0.013	1.029±0.022
Multiplicity in gluon jets, N_g	***7.02±0.08±0.80***	***8.25±0.14±0.93***
Multiplicity in quark jets, N_q	***4.36±0.12±0.57***	***4.95±0.19±0.79***
Ratio of multiplicities, $r = N_g / N_q$	***1.61±0.08±0.16***	***1.67±0.13±0.26***

Sources of systematic errors

- **Event Selection:**
  - Cut on $|\eta|$
  - Number of vertices
  - Jet energy scale
  - E_T balance
  - Photon id (isolation cut)
  - Correction due to difference in invariant mass spectrums
  - Jet algorithm effects
- **Multiplicity measurement:**
  - Impact parameter cut
  - Vertex cut on Δz
  - Remaining γ-conversion correction
  - Uncorrelated background (complimentary cones)
  - CTC efficiency corrections
  - Losses of low P_T tracks
- **Gluon jet fractions in both samples**
- **Fraction of real photons in "photon"-jet sample**
- **Influence of fragmentation model (Herwig, Pythia) on estimate of α-corr.**

New sources of systematic errors considered after the last blessing are highlighted with blue.

Systematic uncertainties due to event selection cuts

- **We varied the event selection cuts to study the related systematic effects. <u>The maximum deviations from default values in each case were taken as an estimate of corresponding systematic error</u>.**

Default cuts	**Systematic error evaluation method**
$\|\eta_{jet1,2}\|<0.9$	$\|\eta_{jet1,2}\|>0.1$ $\|\eta_{jet1,2}\|<0.7$
Energy balance: $\Delta E_T/(E_{T1}+E_{T2})<0.15$	**<0.125** (both samples) **<0.125** ("photon"-jet only)
Number of primary vertices of class 12: **Nvx12≤2**	**Nvx12=1**
Photon isolation: **ISO<1 GeV**	**ISO<1.5 GeV**

Systematic uncertainties due to event selection cuts: *Jet energy scale*

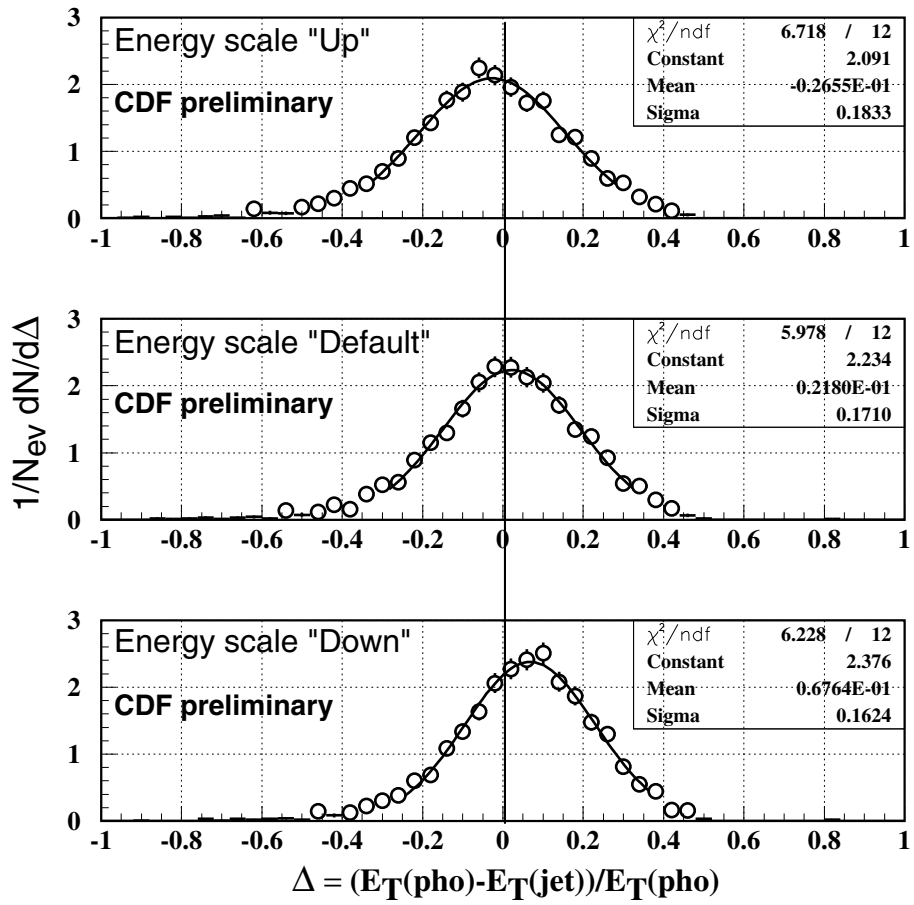
- We shifted jet energy by ±5% to study the systematics due to imprecise knowledge of jet

  absolute energy scale (options "MD" and "PD" in JTC96X).

  → ***"photon"-jet balance*** *is moving by the same ±5% while* ***dijet balance*** *remains unchanged*

  → *"photon"-jet balance cut was allowed to "move" along with Gaussian peak*

- We also varied relative jet energy scale (options "DM" and "DP" in JTC96X) leaving central scale unchanged.
- <u>Maximum deviation is taken as systematics estimate.</u>



Systematic uncertainties due to event selection cuts: *Jet algorithm effects and mass spectrum corrections.*

- **Jet algorithm effects.**

The default cone size is 0.7

→ *contains most of the jet activity (good!)*

→ *two closely spaced jets can be resolved as one (bad!).*

Method to estimate the systematic error:

1) Re-run data and Monte Carlo selecting only events where **N_{jet}(cone 0.7)=N_{jet}(cone 0.4).** Jet energy is still reconstructed with cone 0.7 → it helps to avoid bias due to possible difference in energy scales for cone 0.4 and 0.7 jets.

1) Repeat all measurements and compare to default values.

- **Mass spectrum corrections (not applied for default case).**

To account possible difference in unsmeared distributions, dijet and "photon"-jet invariant mass spectrums were unsmeared and weighted to be the same → effect turns out to be negligible.

Systematic uncertainties due to event selection cuts: summary

Systematics source	E_{jet}=40 GeV			E_{jet}=53 GeV		
	ΔN_g	ΔN_q	Δr	ΔN_g	ΔN_q	Δr
η cut	0.15	-0.10	0.07	0.13	-0.14	0.08
Nvx12 cut	0.09	0.10	-0.02	-0.10	0.26	-0.10
Balance cut	-0.06	0.09	-0.05	0.15	-0.16	0.09
Jet energy scale	0.32	-0.11	0.09	-0.40	0.23	-0.15
Photon isolation	0.06	-0.09	0.05	-0.01	0.01	-0.01
Jet algorithm	0.03	-0.04	0.02	0.09	-0.13	0.06
Mass spec. correction	-0.01	0.0	0.0	0.0	0.0	0.0

Systematic uncertainties in multiplicity measurements

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

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

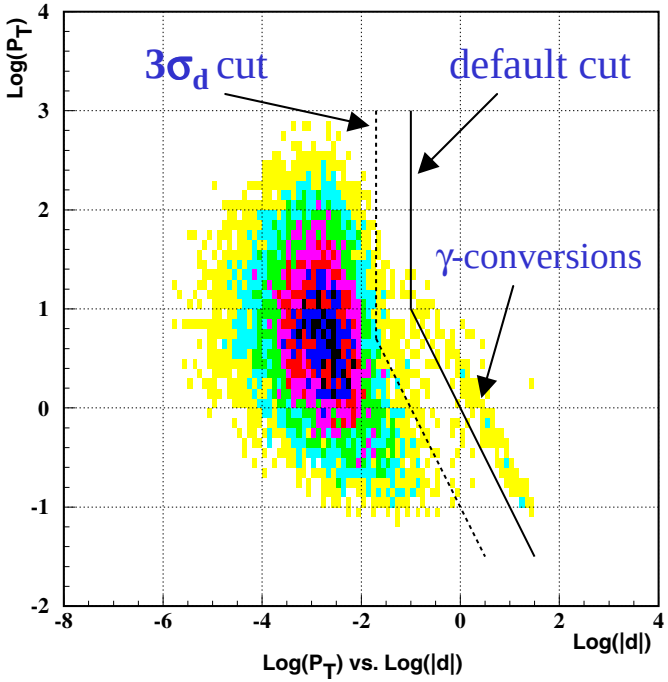
$$N_q = \frac{N_{jj}}{n_g^{jj}(r-1)+1}$$

$N_{\gamma j}$ - multiplicity in "photon"-jet sample(including fakes)

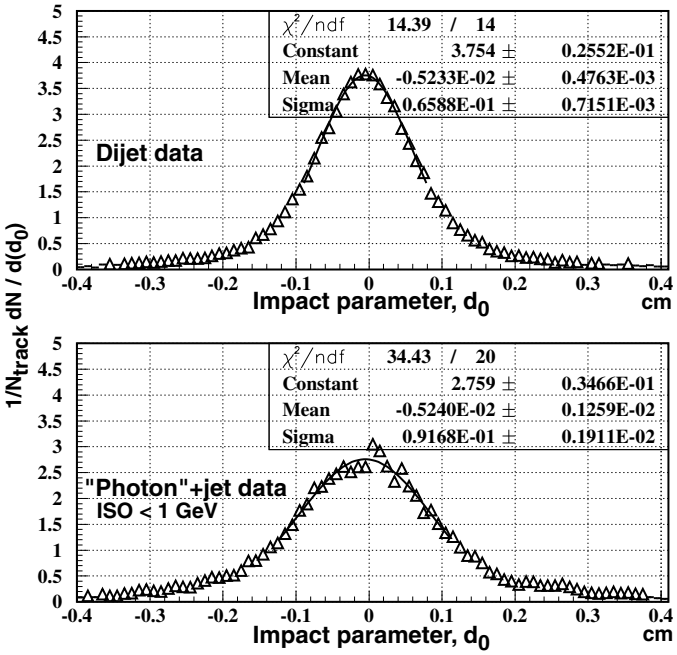
N_{jj} - multiplicity in jet-jet sample

- **Notice, that N_{jj} and $N_{\gamma j}$ appear only as a ratio in the formula for $r=N_g/N_q$ → CTC efficiency correction and correction for remaining γ-conversions will have almost no effect on $r=N_g/N_q$.**
- No CTC correction was applied to estimate sytematics (default correction was 6.3% and 7.5% for events from two mass bins).
- No remaining γ-conversions removal to estimate systematics (default correction was –3.5%)
- Measurements were repeated with cut $P_T(track) > 0.5\ GeV$ to estimate the effect of low P_T track losses.

Systematic uncertainties in multiplicity measurements (part 2)

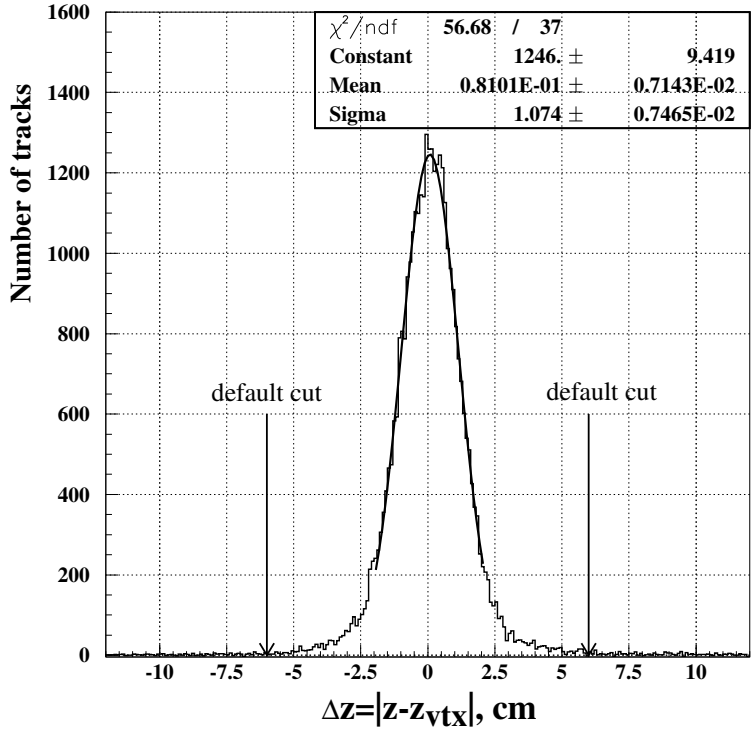


Dijet: σ_d = 0.066
"Photon"-jet: σ_d =0.092



- We varied impact parameter cut to study systematics.
- The ***default cut*** is the same for dijet and "photon"-jet samples. Its value is determined by position of γ-conversions on (log(|d|), log(P_T))-plane.
- The ***deviated cut*** removes tracks outside $3\sigma_d$ region, where σ_d is the impact parameter resolution (the impact resolution is different for tracks from dijet and "photon"-jet samples).

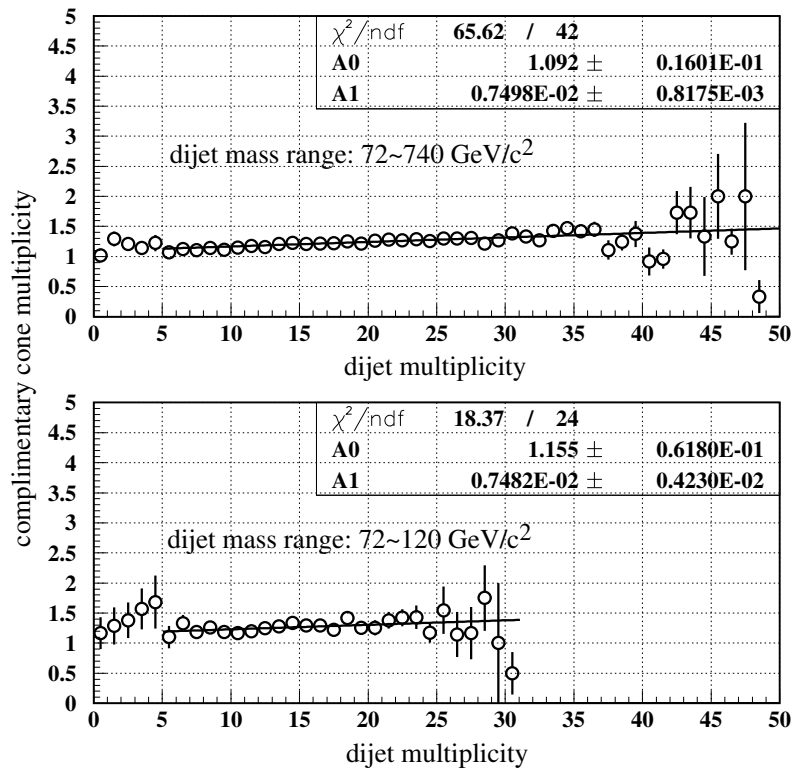
Systematic uncertainties in multiplicity measurements (part 3)



- **Systematics due to Δz cut**

— default cut: **| Δz |<6.0 cm**

— deviated cut: **| Δz |<4.0 cm ,** which is three less than distance between vertices



- **Systematics due to complimentary cone subtraction.**

Correlation of complimentary cone and jet multiplicities

→ linear fit → extrapolation to zero is taken as ***default*** underlying event contribution (0.55 track per cone).

Raw complimentary cone multiplicity (0.63 track per cone) is taken as ***systematics estimate***.

Systematic uncertainties in multiplicity measurements: summary

- The effects of systematic uncertainties in multiplicity measurements are summarized in table below.

Systematics source	E_{jet}=40 GeV			E_{jet}=53 GeV		
	ΔN_g	ΔN_q	Δr	ΔN_g	ΔN_q	Δr
Impact param. cut	-0.47	-0.37	0.03	-0.49	-0.45	0.06
Δz cut	-0.13	-0.10	0.01	-0.14	-0.15	0.02
remaining γ-conv.	0.23	0.15	0.0	0.28	0.17	0.0
complimentary cones	-0.07	-0.08	0.01	-0.15	-0.01	-0.04
CTC efficiency corr.	-0.43	-0.26	0.0	-0.59	-0.37	0.01
losses of low P_T tracks	-0.01	0.02	-0.01	0.09	0.12	0.06

Systematics due to PDF set choice

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

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

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

n_g^{jj} - gluon fraction in jet-jet sample, $n_g^{real\gamma j}$ - gluon fraction in pure γ-jet sample

- We considered different PDF sets to determine the systematic uncertainty due to fraction of gluon jets (CTEQ4M is default). The effect of PDF sets is shown in table.

PDF set	***E_{jet}=40 GeV***			***E_{jet}=53 GeV***		
	ΔN_g	**ΔN_q**	**Δr**	**ΔN_g**	**ΔN_q**	**Δr**
CTEQ4A2	**-0.04**	**0.0**	**-0.01**	**-0.05**	**0.03**	**-0.02**
CTEQ4A4	**0.01**	**-0.01**	**0.01**	**0.12**	**-0.07**	**0.05**

Systematics due to fraction of real photons in "photon"+jet sample

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

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

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

ε_γ - fraction of real photons in "photon"-jet sample

- GETCPRWEIGHT.CDF routine provides means to determine the systematic uncertainties of a real photon fraction. The effect is shown in table.

Source of CPR systematics	E_{jet}=40 GeV			E_{jet}=53 GeV		
	ΔN_g	ΔN_q	Δr	ΔN_g	ΔN_q	Δr
CPR hit rate	-0.06	0.09	-0.05	-0.06	0.09	-0.04
Back-scattering	0.07	-0.12	0.06	0.11	-0.15	0.07
η/π^0 rate	0.02	-0.03	0.01	0.01	-0.01	0.0
K_S/π^0 rate	-0.02	0.03	-0.01	-0.01	0.01	0.0

Influence of MC fragmentation model on estimates of ***α-correction*** and ***gluon fractions***

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

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

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

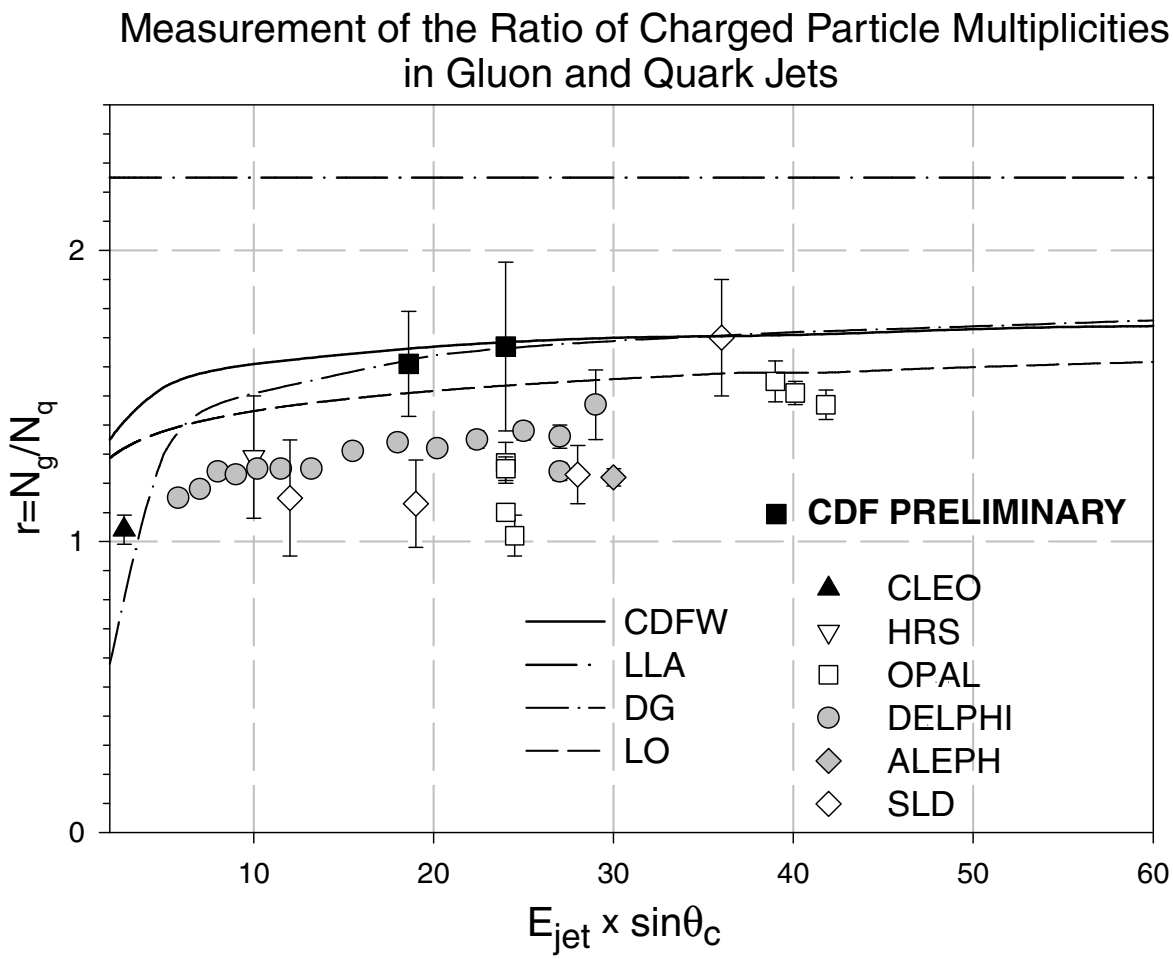
α - correction factor due to fakes(ratio of multiplicities of a jet opposite to fake and a regular jet)

- We rely on Monte Carlo in estimates of α and ***fractions of gluon jets*** in data samples. To find the systematic error due to MC fragmentation model, we compared the results based on Herwig and Pythia predictions.

Method of estimates	***E_{jet}=40 GeV***			***E_{jet}=53 GeV***		
	ΔN_g	**ΔN_q**	**Δr**	**ΔN_g**	**ΔN_q**	**Δr**
Difference between Herwig & Pythia	**0.01**	**-0.09**	**0.03**	**-0.06**	**-0.01**	**-0.01**

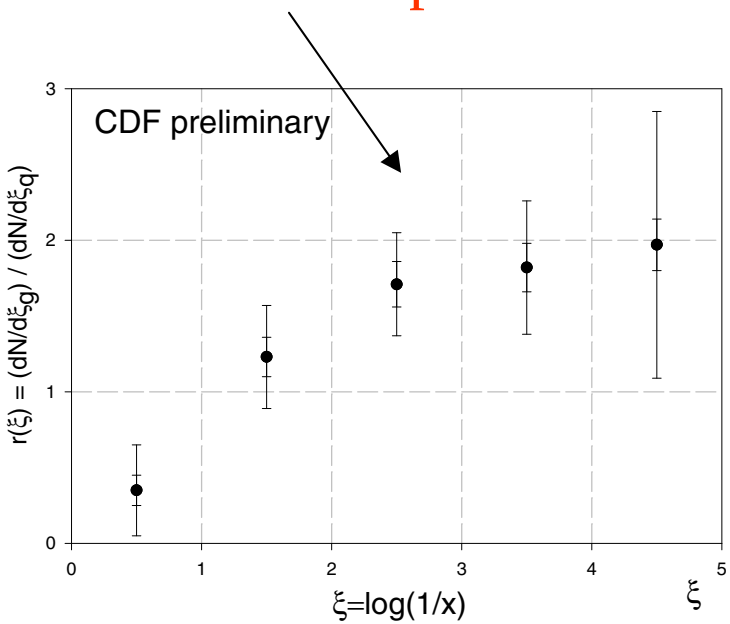
CDF results in comparison to earlier experimental results and theoretical predictions

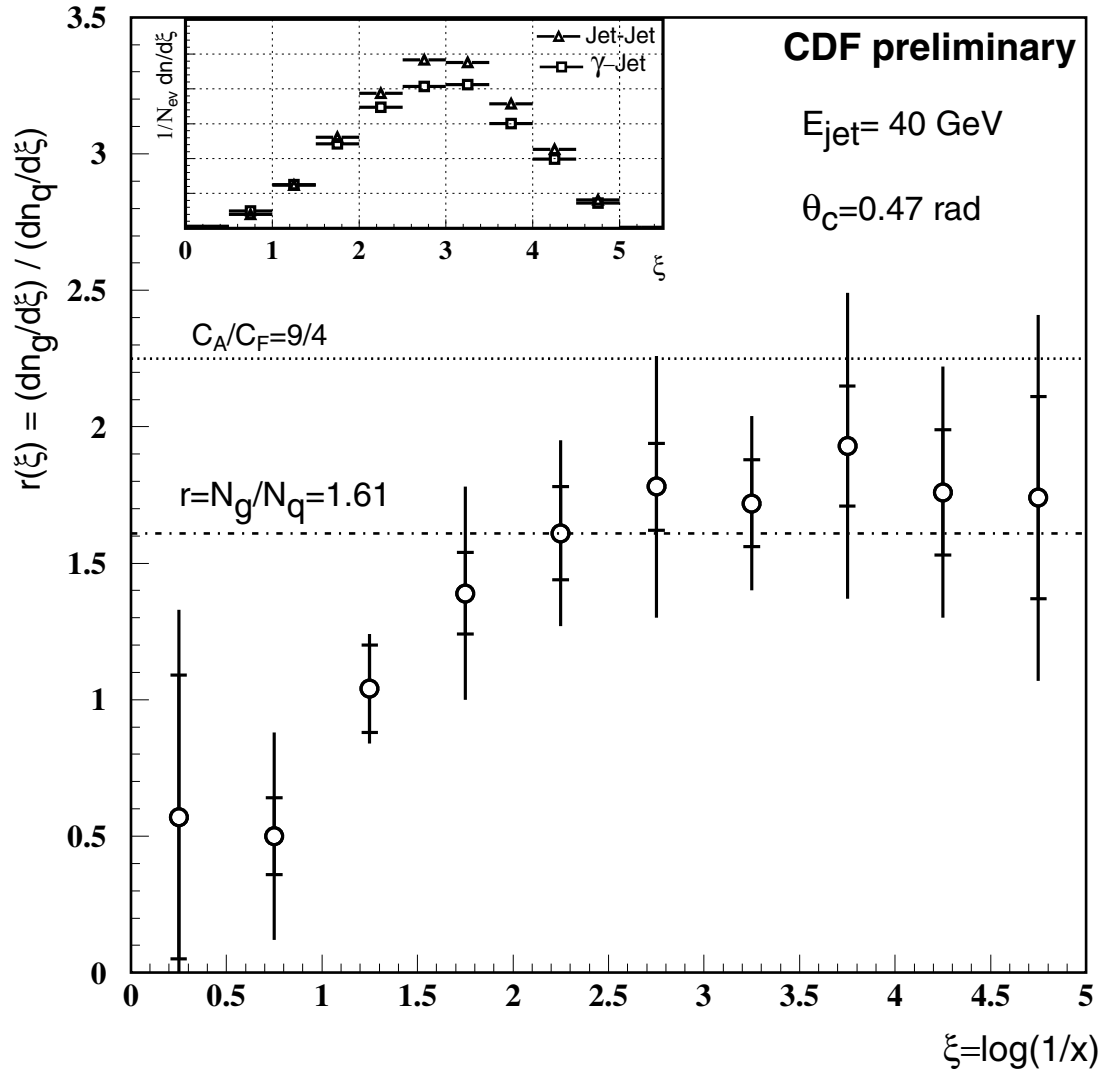
- Measurement of the ratio of charged particle multiplicities in gluon and quark jets.
- θ_C is the opening angle or cone around the jet direction.



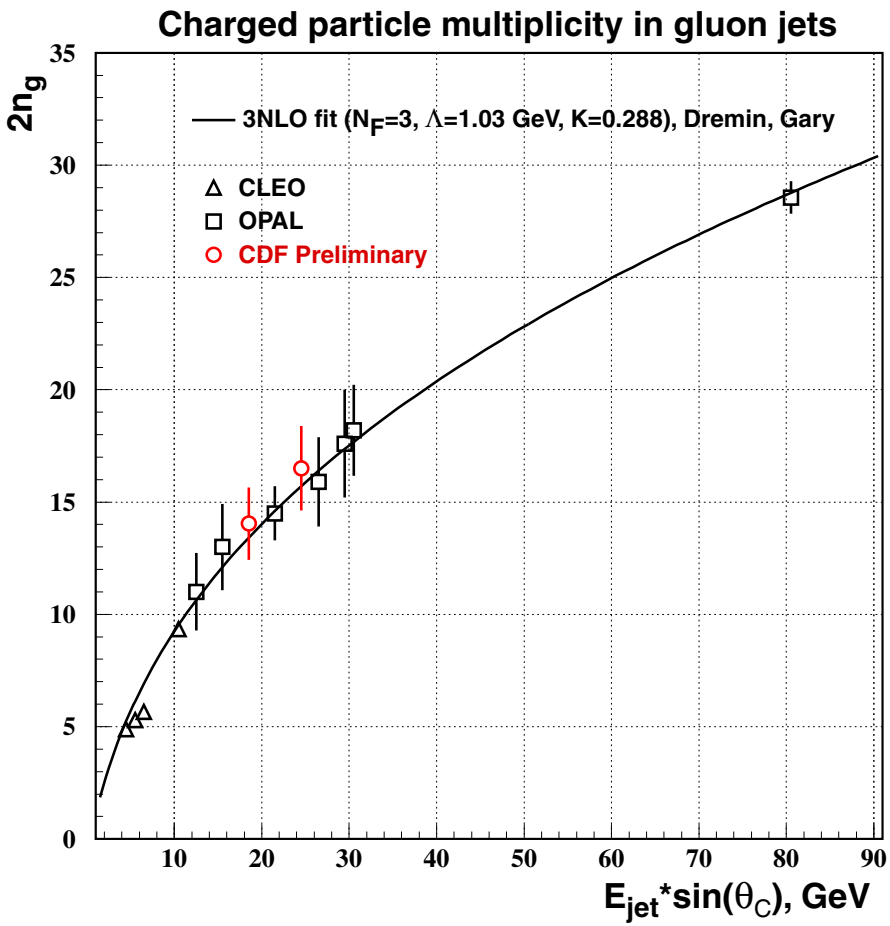
Momentum dependent ratio

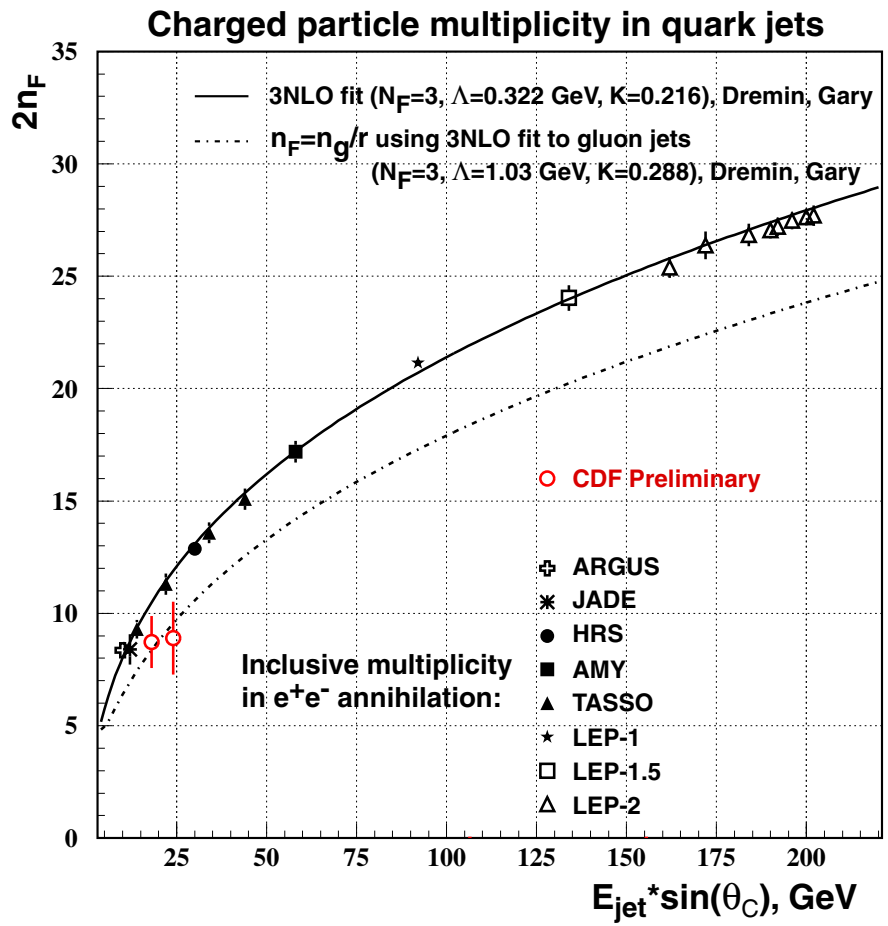
- The ratio of momentum spectra of charged particles from gluon and quark jets.
- Old blessed plot





Charged particle multiplicities in gluon and quark jets





Comparison to Monte-Carlo

- We considered ***quark-quark*** and ***gluon-gluon*** events to find the multiplicity in gluon and quark jets and their ratio.

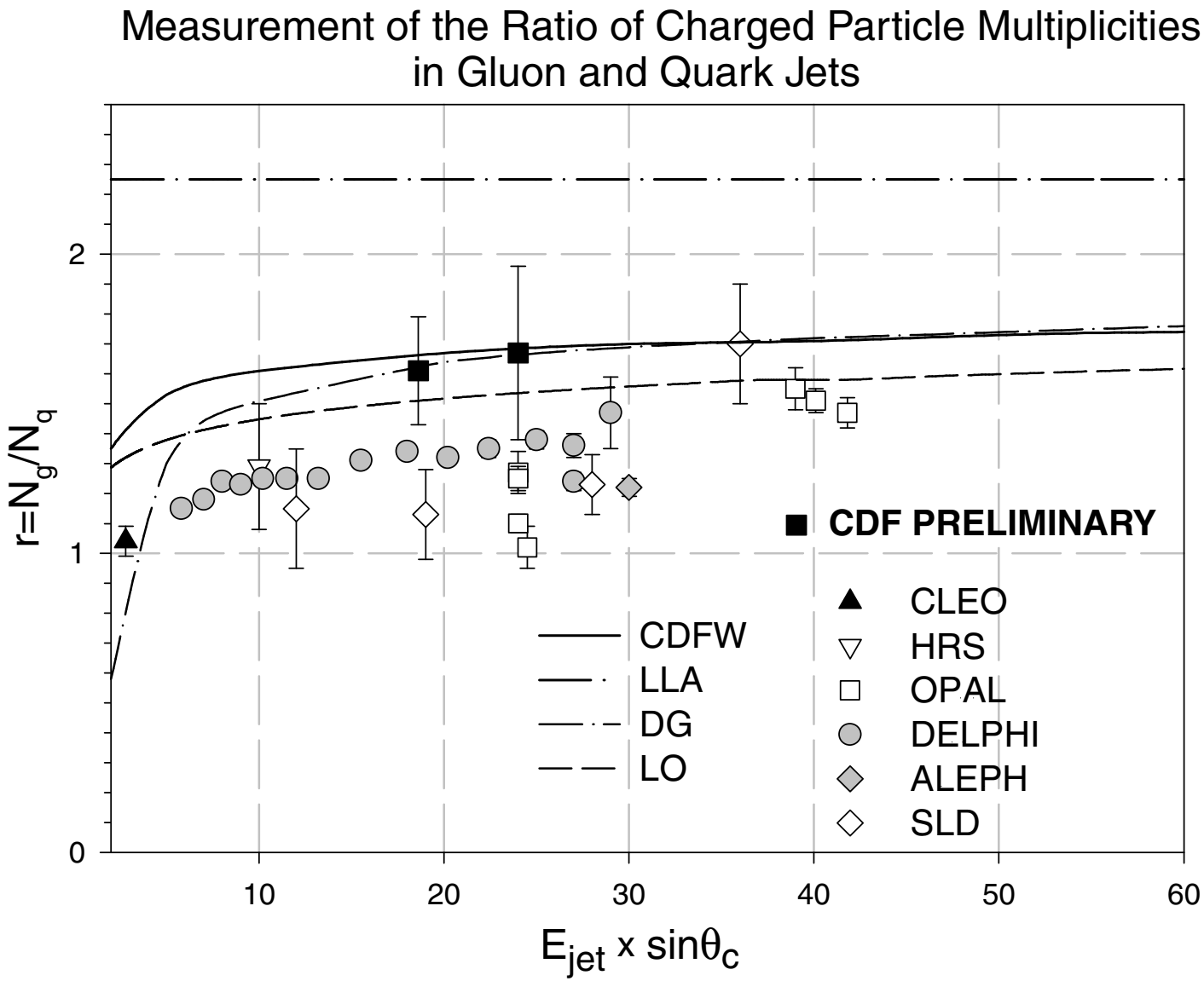
	Data CDF PRELIMINARY		Herwig 5.6		Pythia 6.115	
	E_{jet}=*40GeV*	E_{jet}=*53GeV*	E_{jet}=*40GeV*	E_{jet}=*53GeV*	E_{jet}=*40GeV*	E_{jet}=*53GeV*
N_g	**7.02±0.08 ±0.80**	**8.25±0.14 ±0.93**	**7.84±0.03**	**8.96±0.04**	**8.33±0.03**	**9.46±0.04**
N_q	**4.36±0.12 ±0.57**	**4.95±0.19 ±0.79**	**6.30±0.04**	**6.96±0.05**	**6.41±0.04**	**7.14±0.05**
$r=N_g/N_q$	**1.61±0.08 ±0.16**	**1.67±0.13 ±0.26**	**1.24±0.01**	**1.29±0.01**	**1.30±0.01**	**1.33±0.01**

Results for pre-blessing

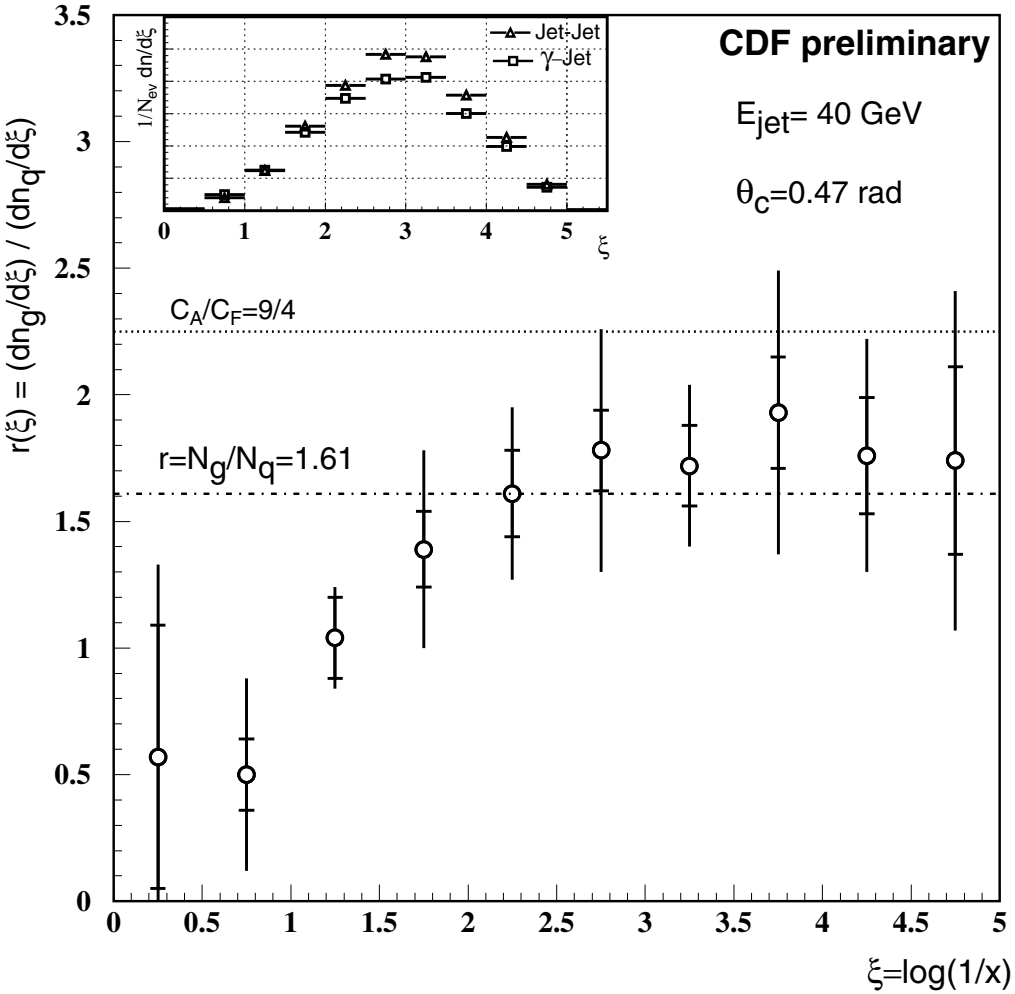
CDF PRELIMINARY

Jet Energy	40 GeV	53 GeV
Jet multiplicity in dijet events, N_{jj}	5.99±0.03	6.88±0.04
Jet multiplicity in "photon"+jet events, $N_{\gamma j}$	5.28±0.04	5.92±0.08
Fraction of gluon jets in dijet events, n_g^{jj}	0.612±0.006	0.585±0.008
Fraction of gluon jets in pure γ-jet events, $n_g^{\gamma j}$	0.216±0.009	0.256±0.015
Fraction of real photons in "photon"+jet events, ε_γ	0.74±0.04	0.90±0.07
α-correction, $\alpha = N_{fake\text{-}jet} / N_{jj}$	1.046±0.013	1.029±0.022
Multiplicity in gluon jets, N_g	***7.02±0.08±0.80***	***8.25±0.14±0.93***
Multiplicity in quark jets, N_q	***4.36±0.12±0.57***	***4.95±0.19±0.79***
Ratio of multiplicities, $r = N_g / N_q$	***1.61±0.08±0.16***	***1.67±0.13±0.26***

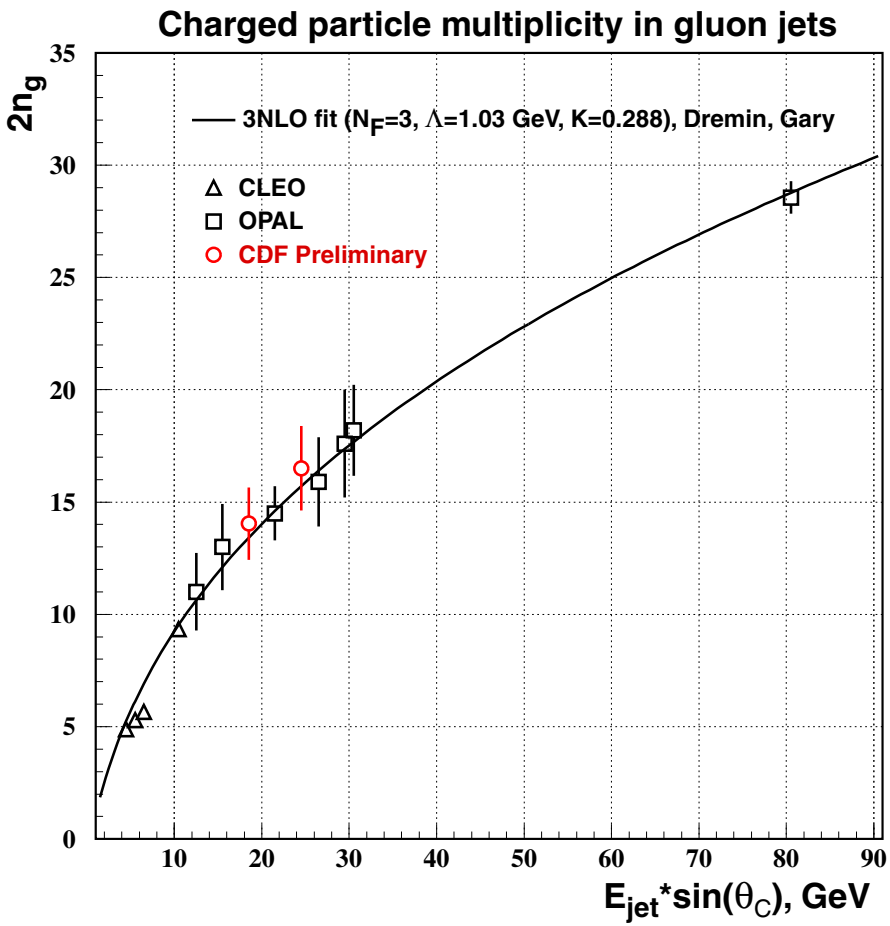
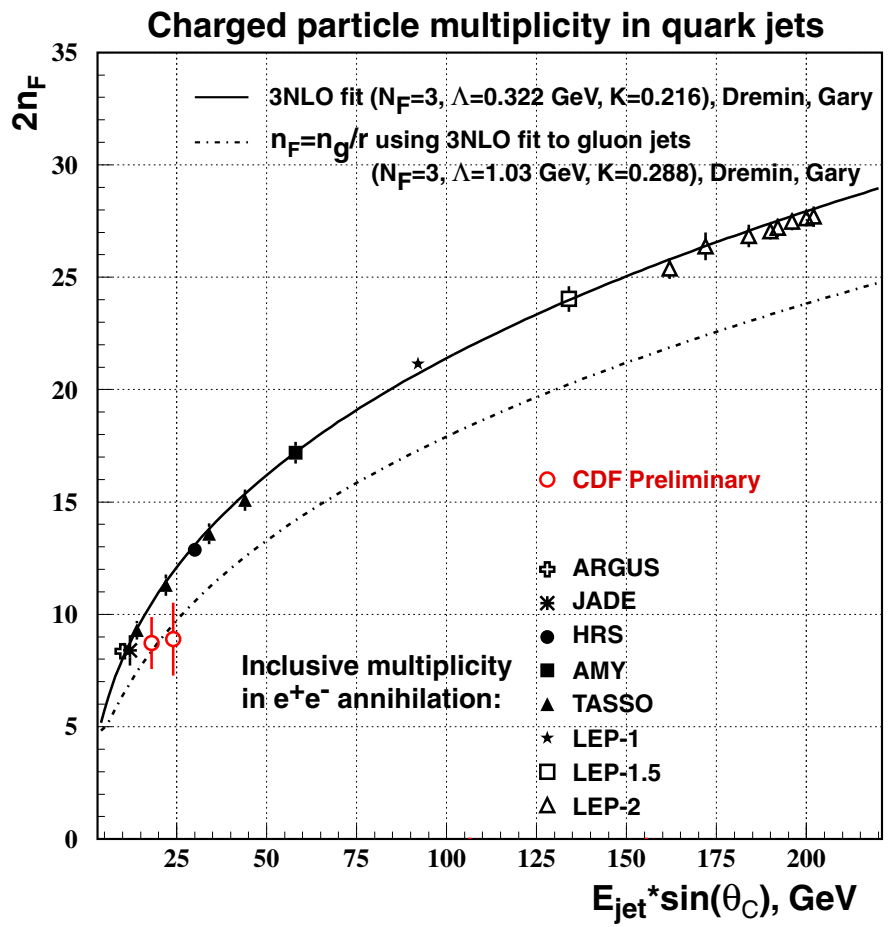
Results for pre-blessing



Results for pre-blessing



CDF PRELIMINARY

ξ	$r(\xi)$	Stat. error	Syst. error
0.25	0.57	0.52	0.55
0.75	0.50	0.14	0.35
1.25	1.04	0.16	0.12
1.75	1.39	0.15	0.36
2.25	1.61	0.17	0.30
2.75	1.78	0.16	0.45
3.25	1.72	0.16	0.28
3.75	1.93	0.22	0.54
4.25	1.76	0.23	0.40
4.75	1.74	0.37	0.56

Results for pre-blessing