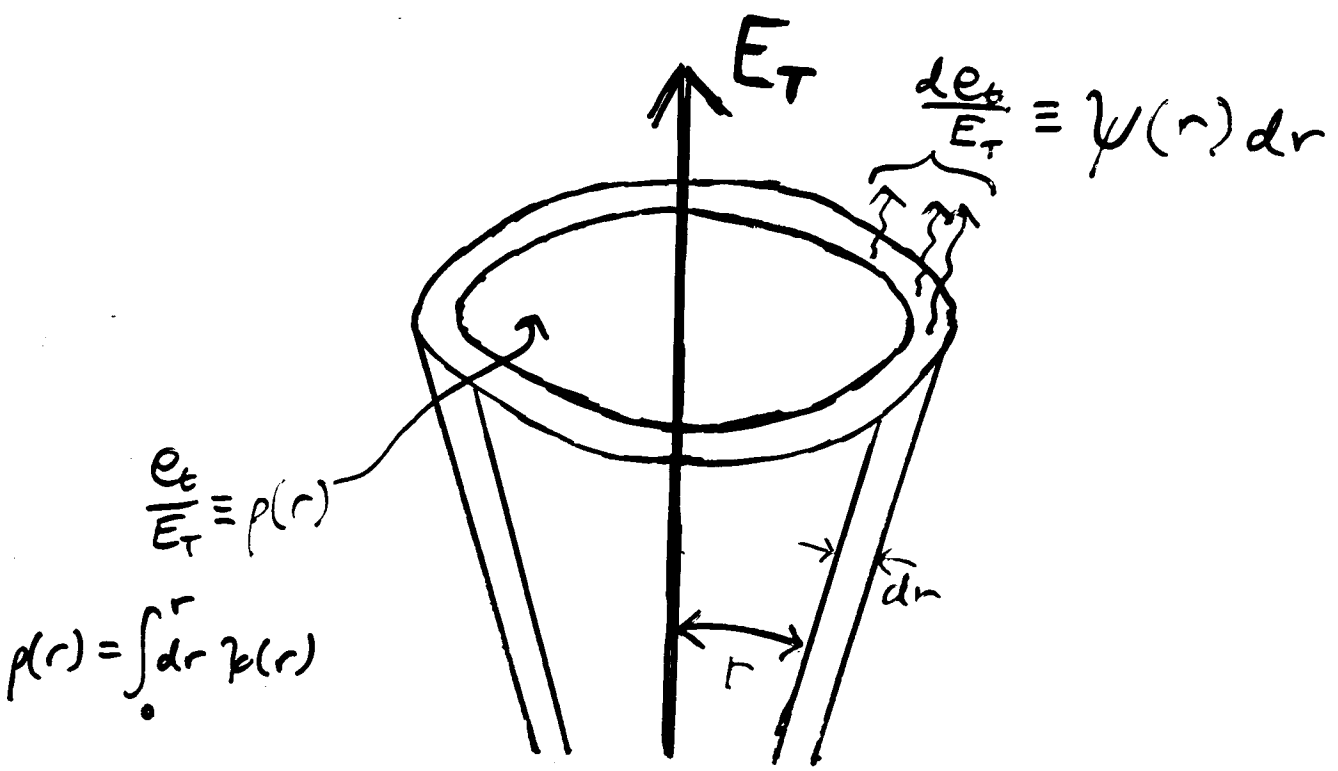
JET ENERGY PROFILES

- NLO calculations vs Monte Carlo models

Mike Seymour
CERN & RAL



Terry Heuring, La Thuile '06.

HERWIG seems too narrow

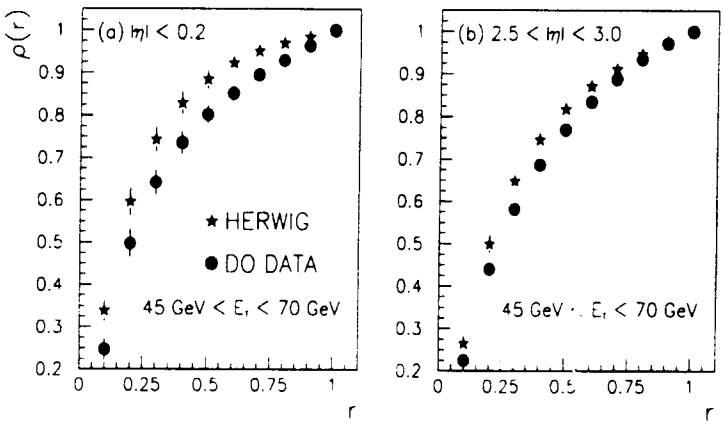


Figure 1: The average integrated E_T fraction versus the subcone radius is plotted for the data and HERWIG Monte Carlo, before calorimetric effects are removed, for the E_T range 45-70 GeV for (a) $|\eta| \leq 0.2$ and (b) $2.5 \leq |\eta| \leq 3.0$.

So does NLO calculation (strong scale dependence)

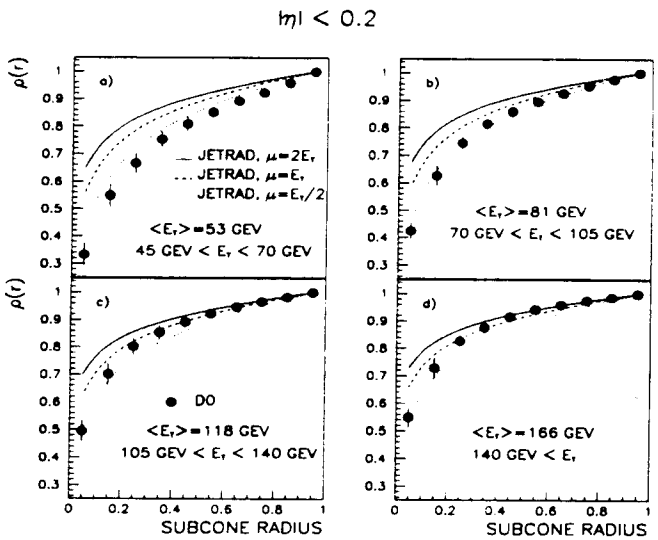


Figure 2: The measured jet shapes, with calorimetric effects removed, compared to NLO predictions (JETRAD) with three renormalization scales for $|\eta| \leq 0.2$ for the jet E_T range (a) 45-70 GeV, (b) 70-105 GeV, (c) 105-140 GeV, (d) greater than 140 GeV.

Terry Heuring, La Thuile '96

CDF & DO in good agreement

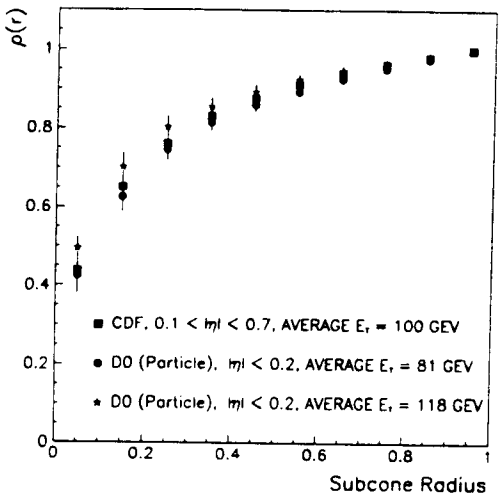


Figure 3: A comparison of the DØ and CDF jet shapes. The CDF measurement was made using charged tracks only for $0.1 < |\eta| < 0.7$ and average $E_T = 100$ GeV. The two DØ measurements ($|\eta| \leq 0.2$), with detector effects removed, were made at E_T's above and below that of CDF. Good agreement is seen.

strong jet definition dependence (esp. in the Calculation)

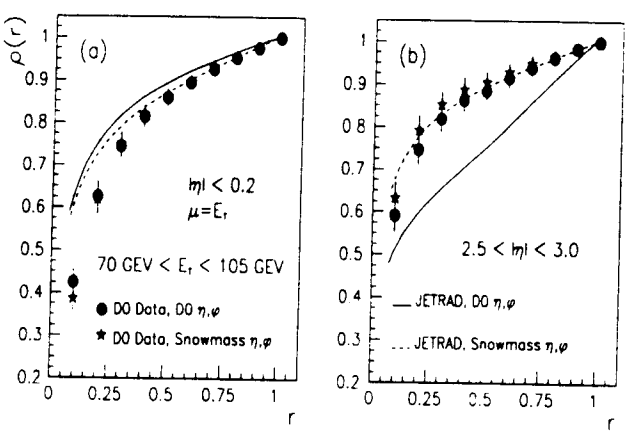


Figure 4: Comparisons of jet shapes from data and NLO predictions using different jet direction definitions for jets with $70 < E_T < 105$ and for (a) $|\eta| \leq 0.2$ and (b) $2.5 \leq |\eta| \leq 3.0$.

JET DEFINITIONS

Analytical calculations: only 2 partons per jet

$\Rightarrow$ all algorithms are like $E_T S$:

naive: $R_{sep} = 2R$

$E_T S$: $R_{sep} = 1.3R$

$k_\perp$: $R_{sep} = R$

Monte Carlo: $k_\perp$ unambiguous

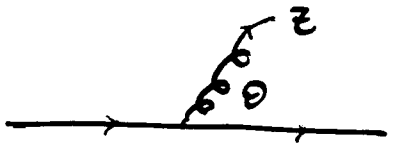
cone? Use $E_T S$:

1/ Iterative cone

2/ Reiterate using midpoint of every pair

3/ Resolve overlaps à la CDF.

Parton shower based on SOFT and COLINEAR limits: HOW GOOD IS THE PARTON SHOWER APPROXIMATION?

Final state: 

$$dP = \frac{d\theta^2}{\theta^2}\, dz\, P(z)\, \frac{d\phi}{2\pi}\, \frac{\alpha_s}{2\pi}$$

quark jet: $P(z) = C_F \frac{1+(1-z)^2}{z}$

gluon jet: $P(z) = C_A \frac{z^4 + 1 + (1-z)^4}{z} + T_R N_f \left(z^2 + (1-z)^2\right)$

Easy to integrate analytically:

quark jet: $\left[2 C_F \log \frac{R}{r} - \frac{3}{2} C_F\right] \frac{1}{r}$ small r

$2 C_F \left(1 - \frac{r}{R_{sep}}\right) \frac{1}{r}$ large r

gluon jet: $\left[2 C_A \log \frac{R}{r} - \frac{11}{6} C_A + \frac{2}{3} N_f T_R\right] \frac{1}{r}$ small

$2 C_A \left(1 - \frac{r}{R_{sep}}\right) \frac{1}{r}$ large

Dominated by soft gluons for both small and large r $\Rightarrow$ good approximation?

Initial state: $dP \sim 4C\,d\eta\,\frac{de_t}{e_t}\,\frac{d\phi}{2\pi}\,\frac{\alpha_s}{2\pi}$

Use soft limit only

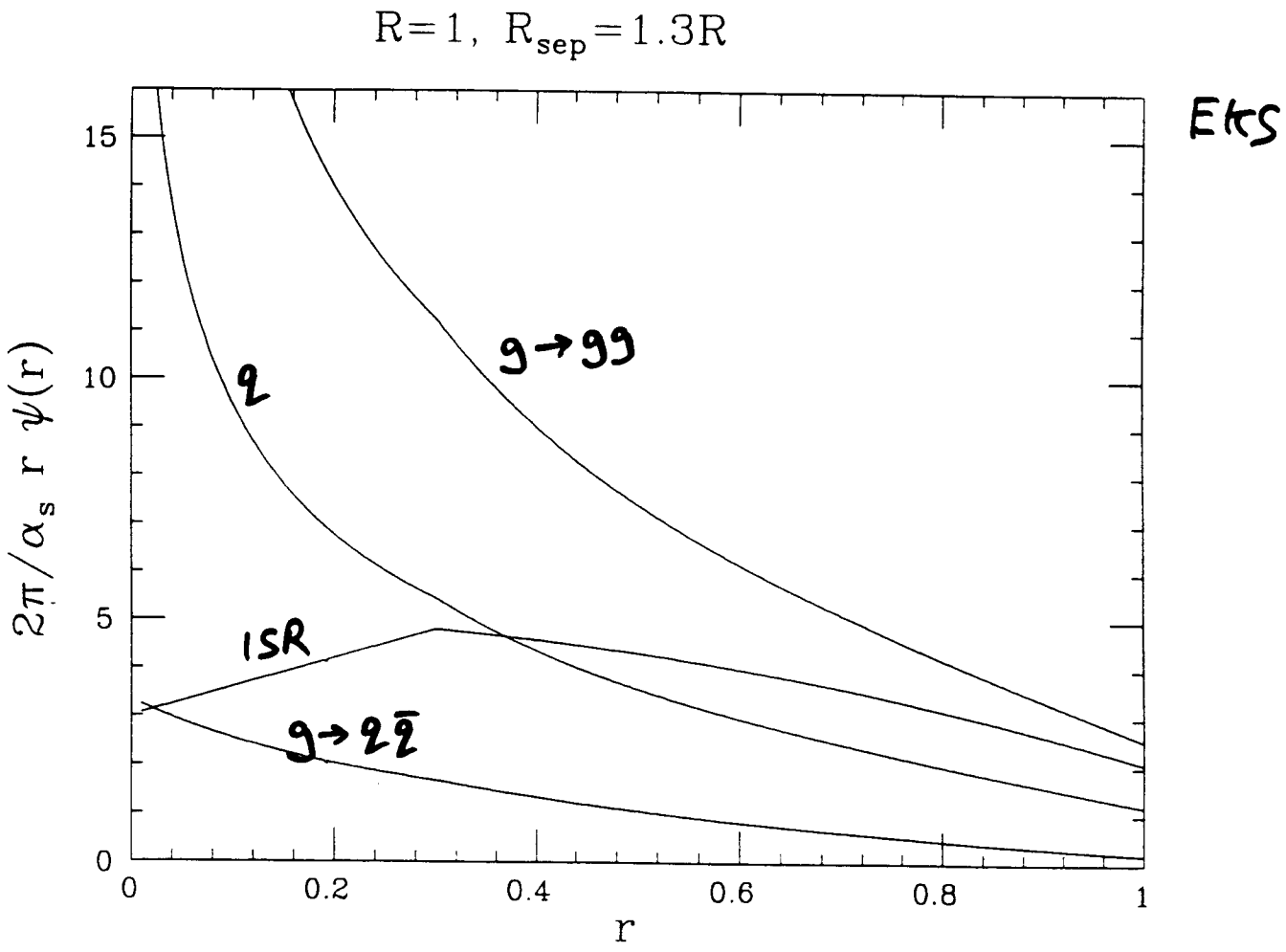
'Colour factor' function of dynamics of hard scattering

Large N_c limit + dominant singularities

$\Rightarrow \quad C \sim \frac{1}{2}C_A \sim C_F$

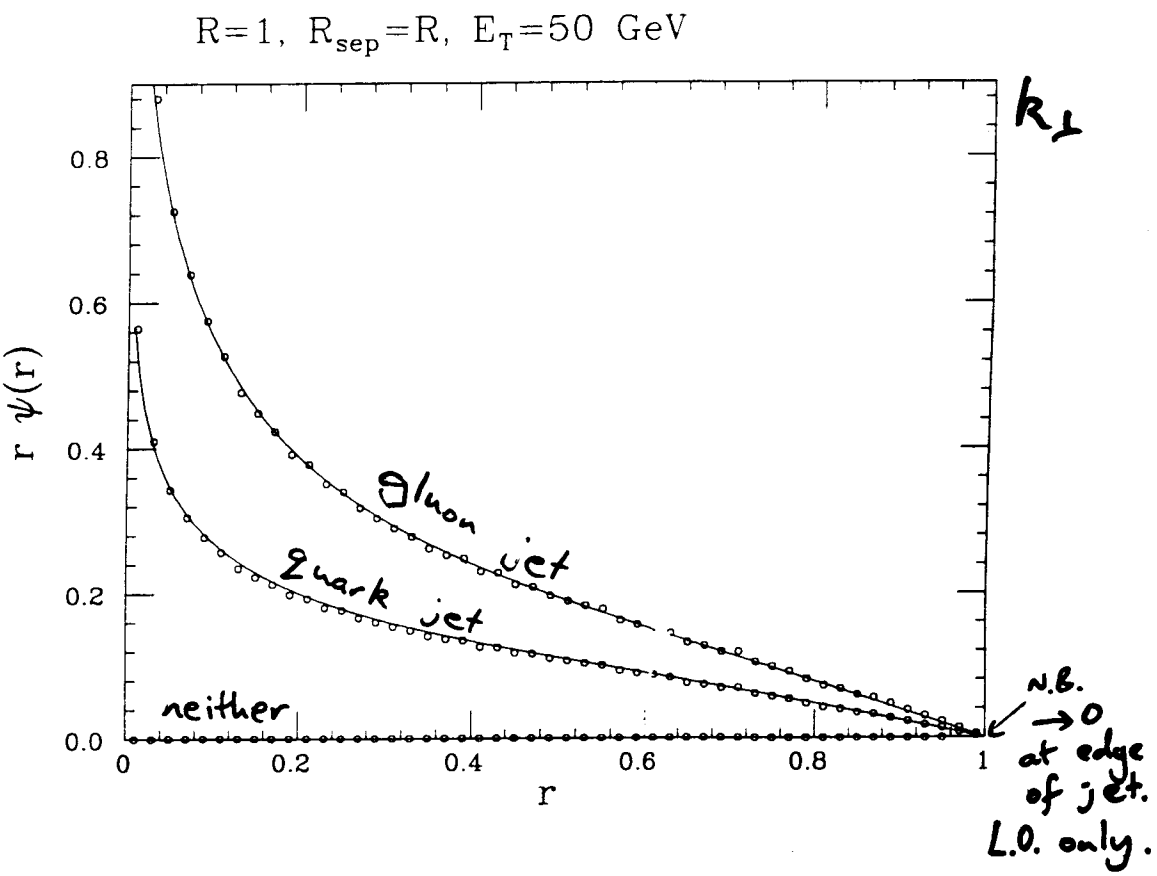
for both quark and gluon jets

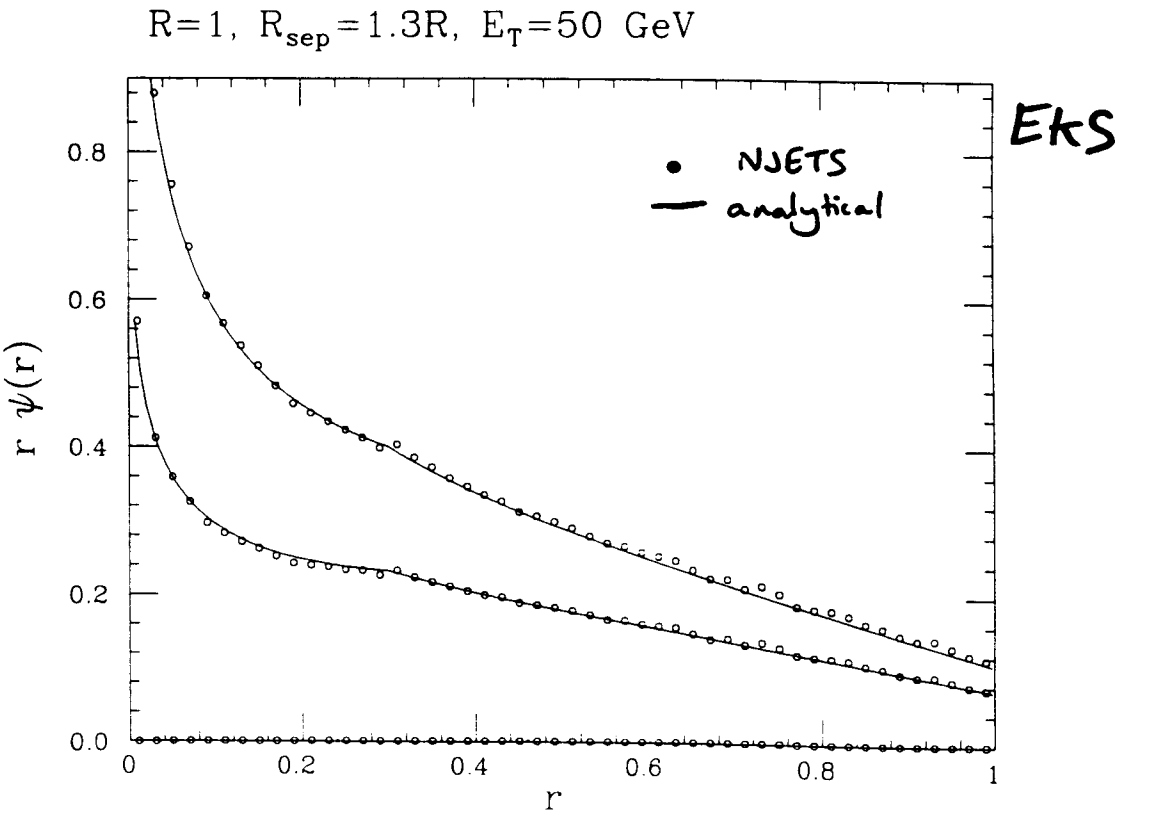
Coefficient functions :



EKS

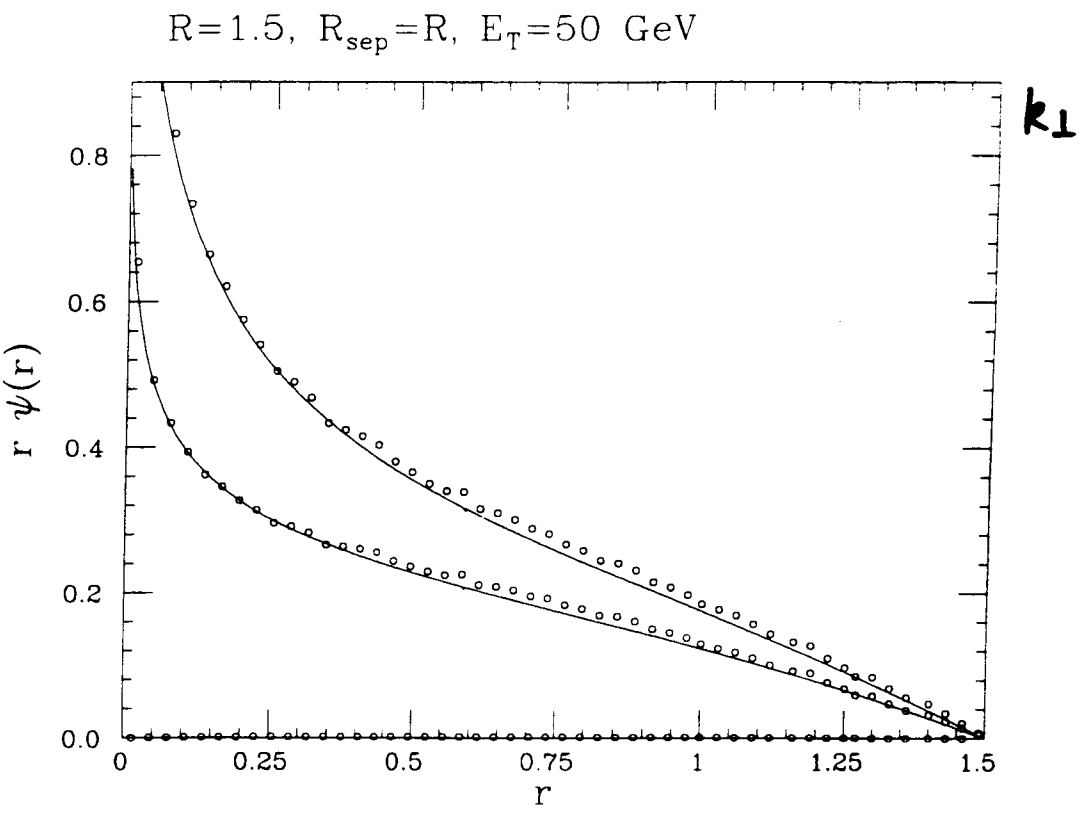
Comparison of analytical calculation with NJETS:

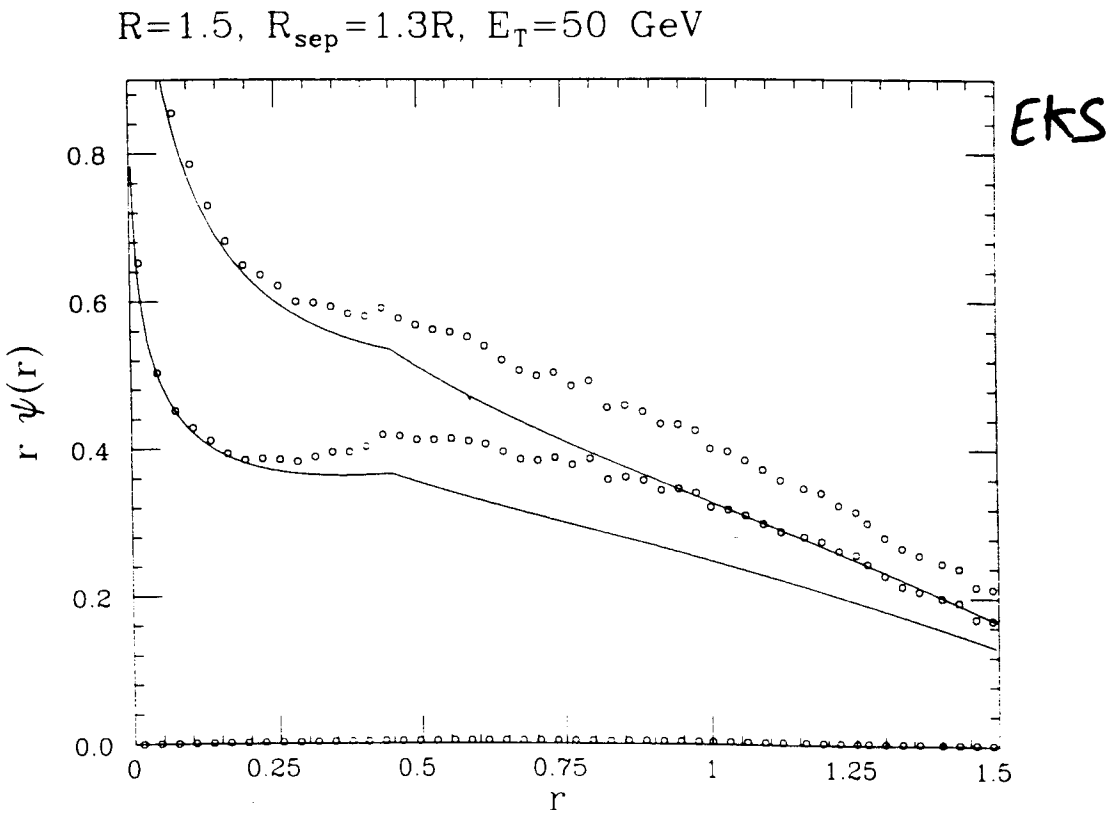




The parton shower is a pretty good approximation!

...except for very large R...

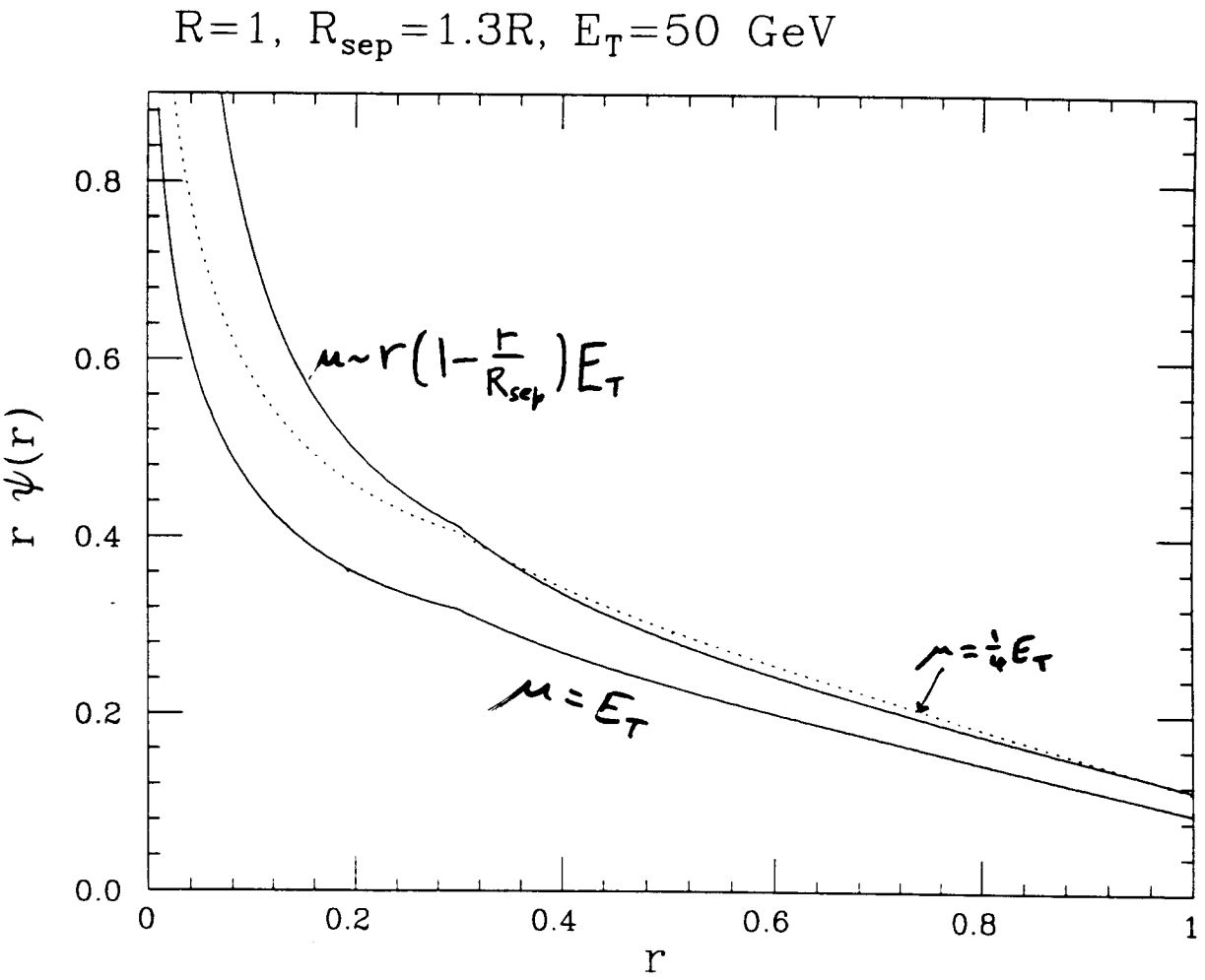




How far can we take the one-gluon result...?

Running coupling: 'best' scale is upper limit for gluon transverse momenta:

$$\mu \sim r\left(1-\frac{r}{R_{sep}}\right)E_T$$



Similar to $\mu \sim \frac{1}{4}E_T$ at large r.

...as found by EKS:

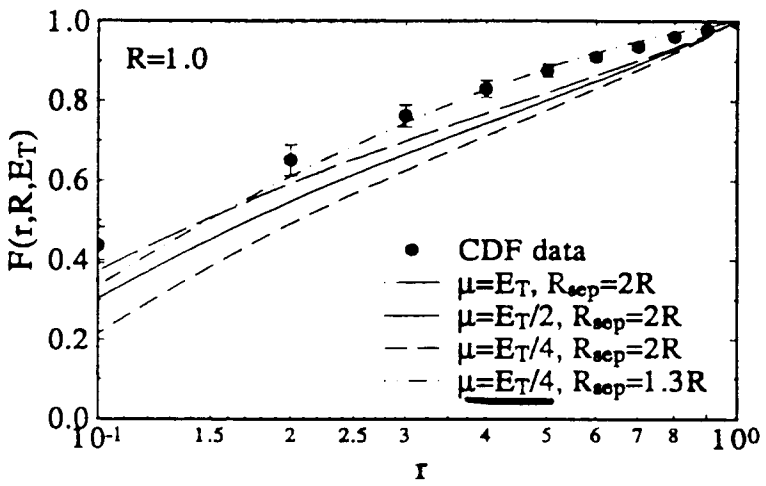


FIG. 3. The energy profile of a 100 GeV jet, taken from (5).

Power Corrections

Can go one step further by including running coupling inside phase space integrals:

$$\psi(r) \sim \frac{1}{rE_T}\int_0^{rE_T} dq_t\ \alpha_s(q_t)$$

integral runs down to zero momenta = over Landau pole → renormalon ambiguity

Introduce infrared-finite coupling as an arbitrary parameter:

$$\bar{\alpha}_0(Q_0) \equiv \frac{1}{Q_0}\int_0^{Q_0} dq\ \alpha_s(q)$$

where Q_0 is a completely arbitrary scale ~ few GeV.

Gives power correction:

$$\psi(r) \sim \alpha_s(rE_T) + \left(\frac{Q_0}{rE_T}\right)\left[\bar{\alpha}_0(Q_0) - \alpha_s(rE_T)\right]$$

$\bar{\alpha}_0(Q_0)$: ~0.52 $Q_0=2$; ~0.42 $Q_0=3$

Dokshitzer & Webber Phys Lett 352B (1995) 451.

Gives excellent fit to e^+e^- data...

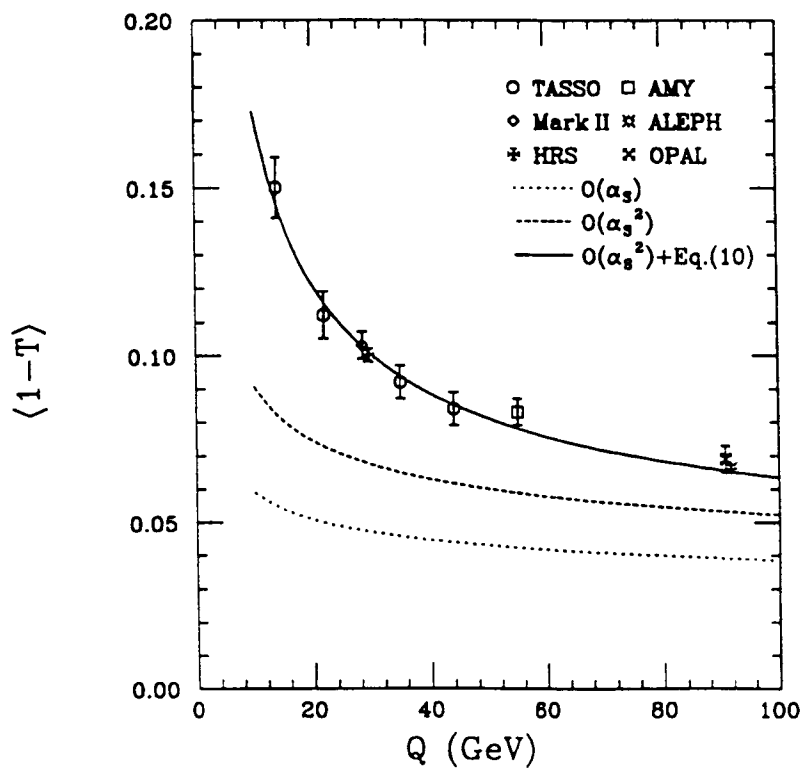
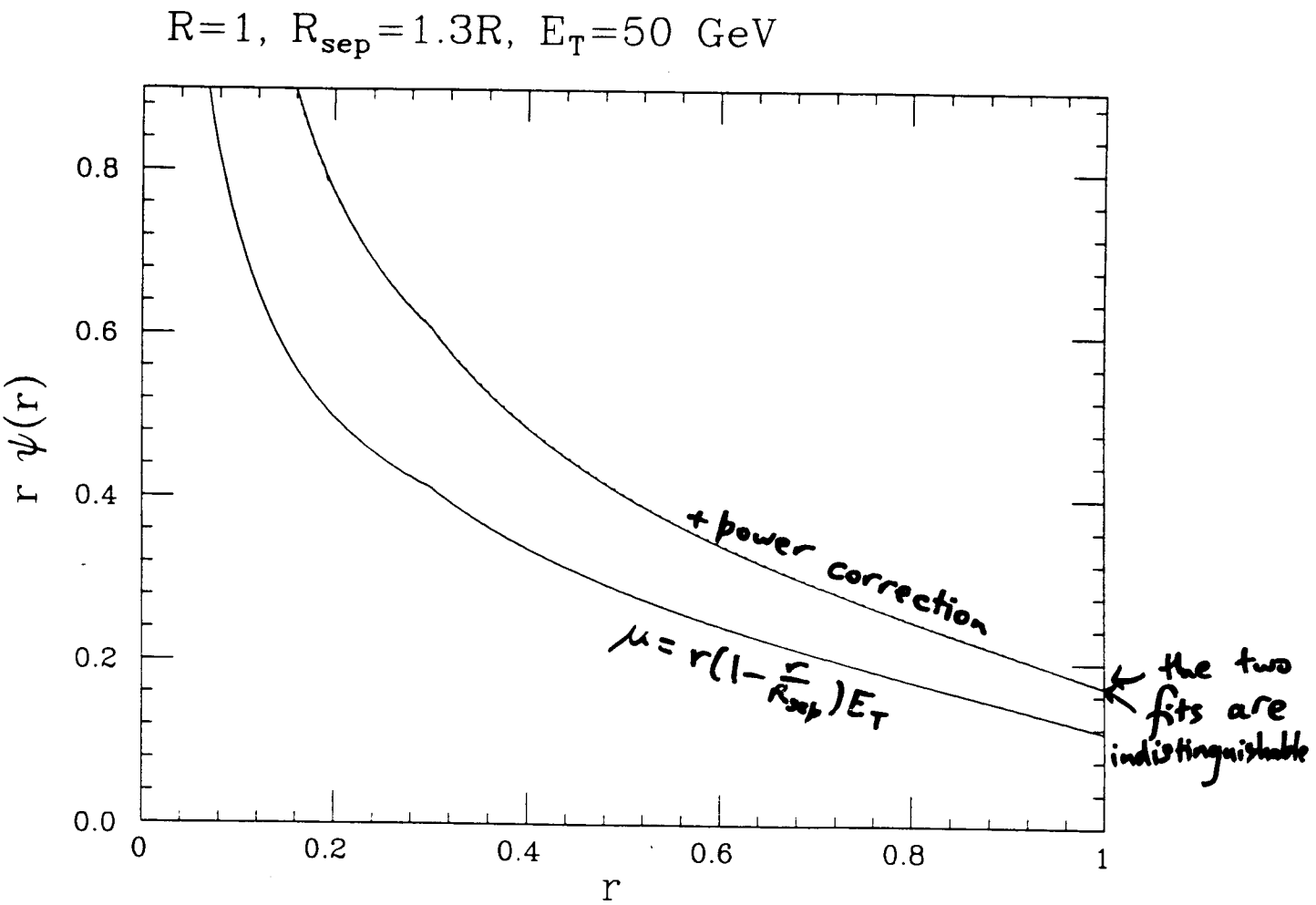


Figure 1: Mean value of $1 - T$, where T is the thrust.

We also obtain good fits for other values of the arbitrary infrared matching parameter μ_I. At $\mu_I = 3$ GeV, for example, we find

Fits to e^+e^- give ~unique prediction:



Sudakov Resummation

At small r:

$$\rho(r) \sim 1 + \alpha_s \log^2 \frac{1}{r} + \alpha_s^2 \log^4 \frac{1}{r} + \dots$$

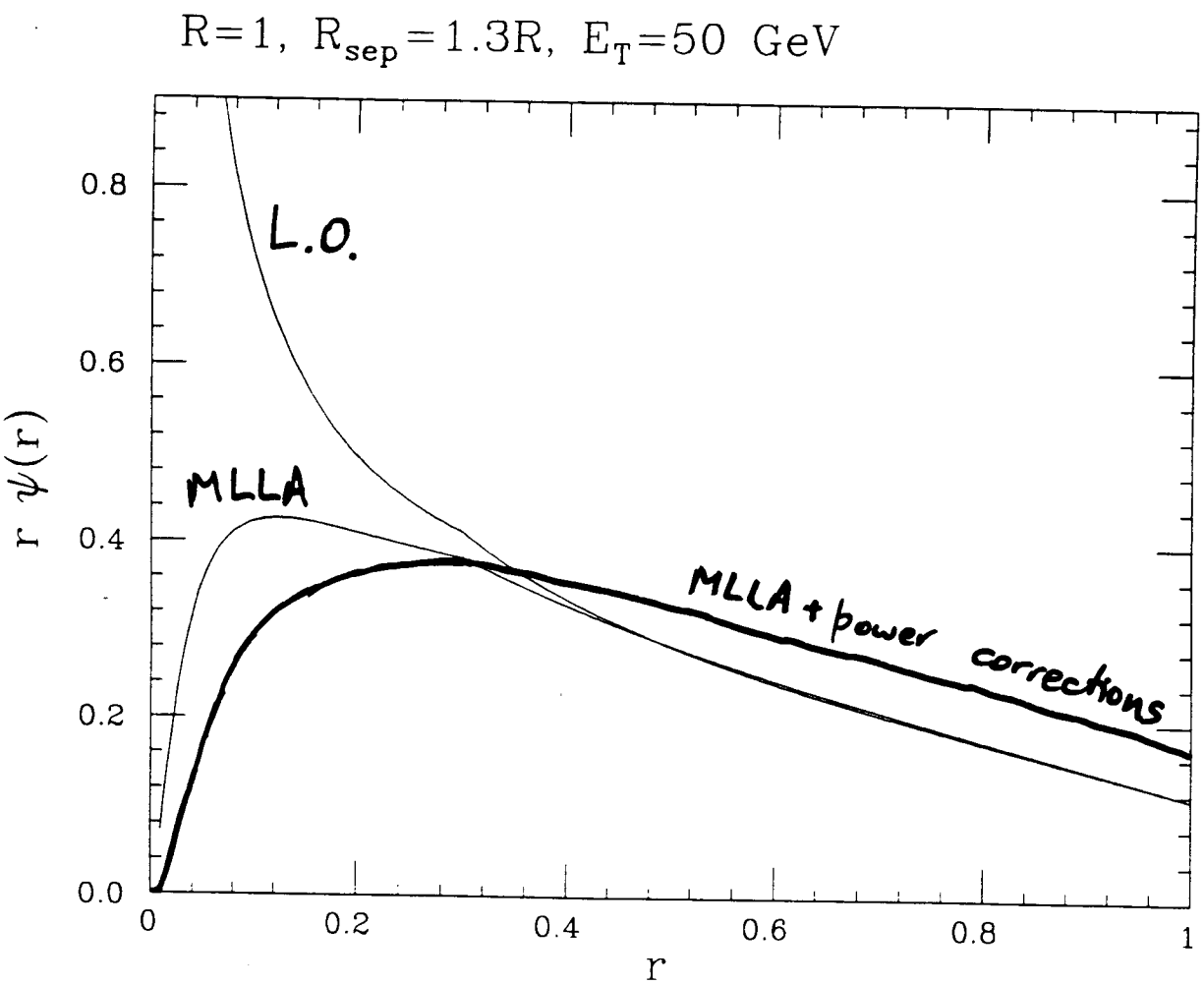
Straightforward to sum these terms to all orders in α_s and at least MLLA

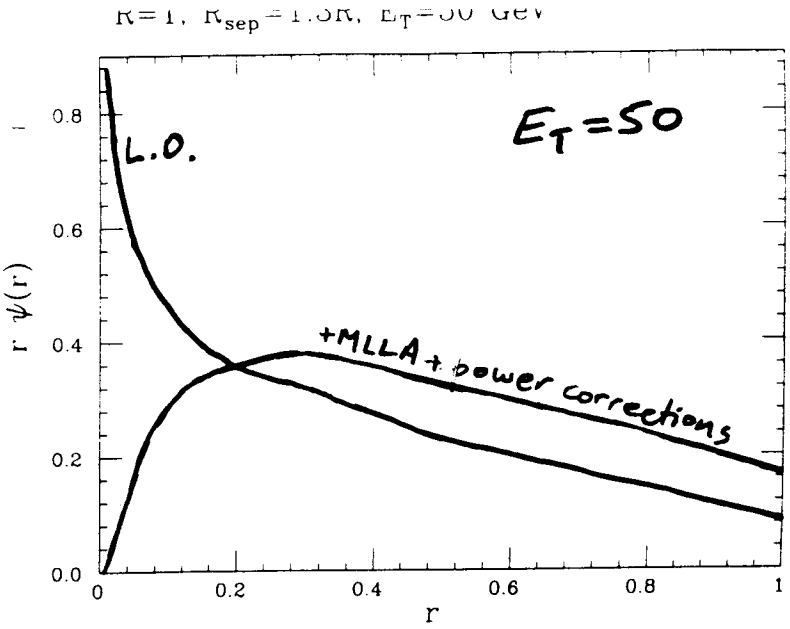
LLA: $\alpha_s^n \log^{2n} \frac{1}{r}$

MLLA: $+ \alpha_s^n \log^{2n-1} \frac{1}{r}$

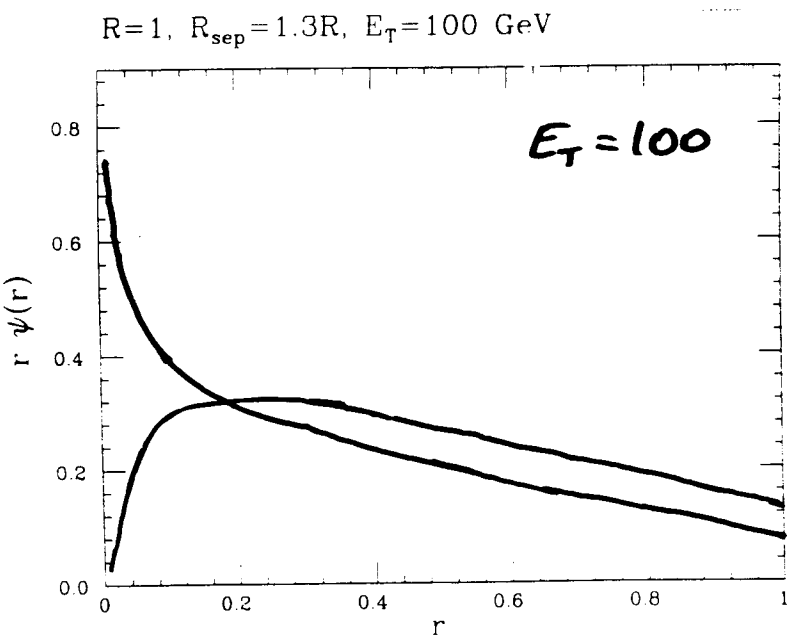
$\vdots$

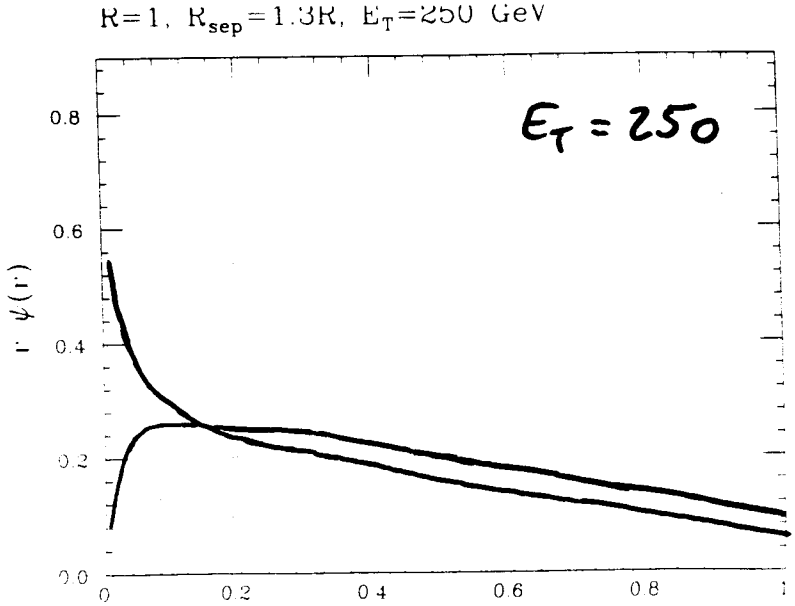
NLLA: $+ \alpha_s^n \log^n \frac{1}{r}$


R=1, R_{sep}=1.3R, E_T=50 GeV
L.O.
MLLA
MLLA + power corrections
r ψ(r)
r
0.0
0.2
0.4
0.6
0.8
1



} total correction ~ factor 2





Still ~50% even at high E_T

Comparison With Parton Shower Monte Carlos

Three steps:

1/ Parton shower

All above effects included:

- running coupling
- small x resummation (MLLA)

Plus:
- soft gluon coherence (angular ordering)
- exact multiparton kinematics

2/ Hadronization

Similar to power corrections:

- parton shower cut off at $Q_0 \sim 1$ GeV
- hadrons produced near but between soft gluons

Same for quarks and gluons except for overall factor: 2 colour strings for gluon, 1 for quark.

$\Rightarrow$ Well constrained by e^+e^- data (except ...)

3/ Underlying event

Parton shower does not use up all of hadrons' energy.

→ Remnants undergo soft collision

→ Extra source of E_T flow

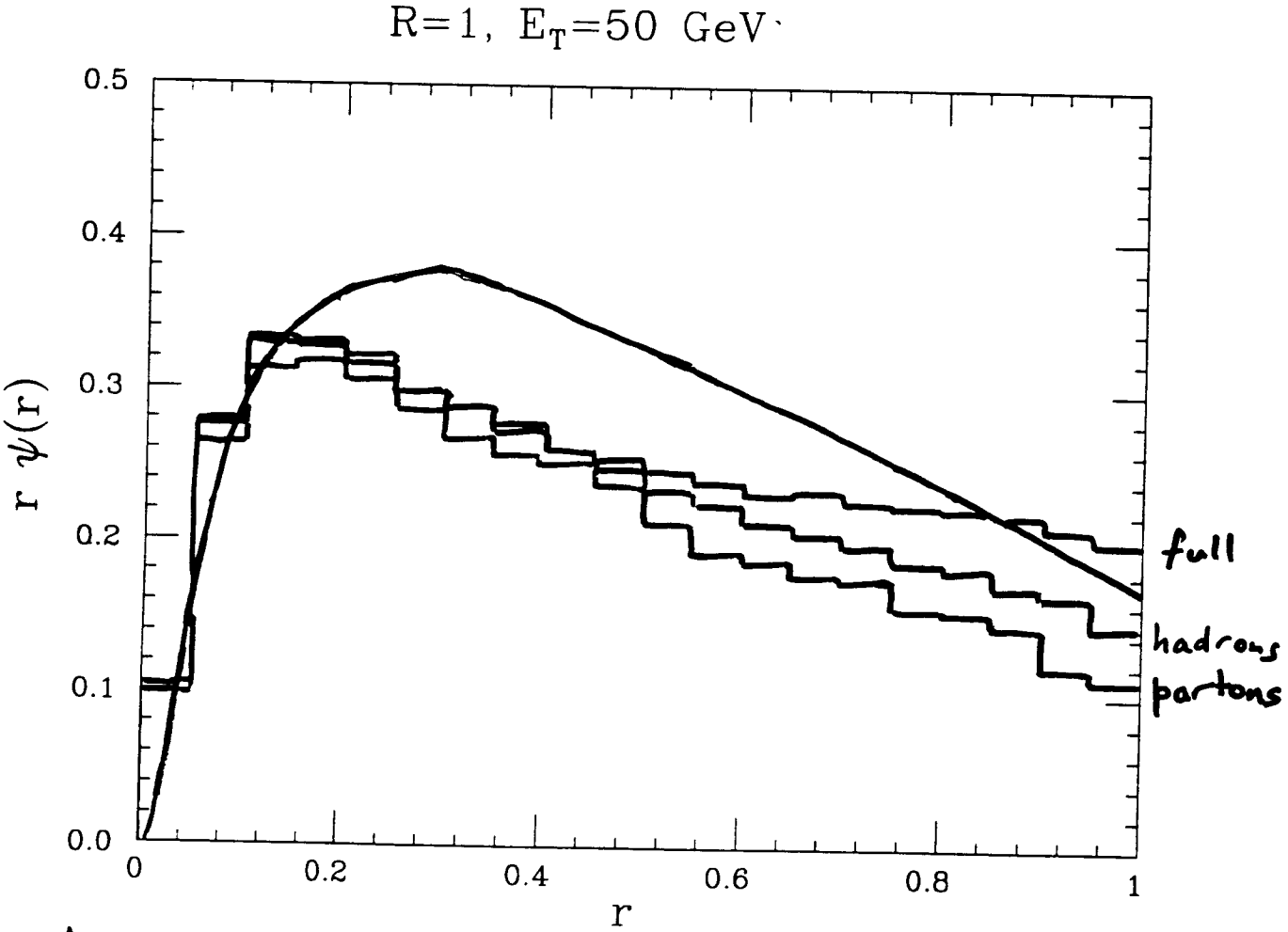
Very poorly understood:

HERWIG = parametrization of soft hadron-hadron collision data. Uncorrelated with hard process

PYTHIA = multiparton scattering → many parameters, fitted to soft hadron-hadron collision data. Mild correlation with hard process.

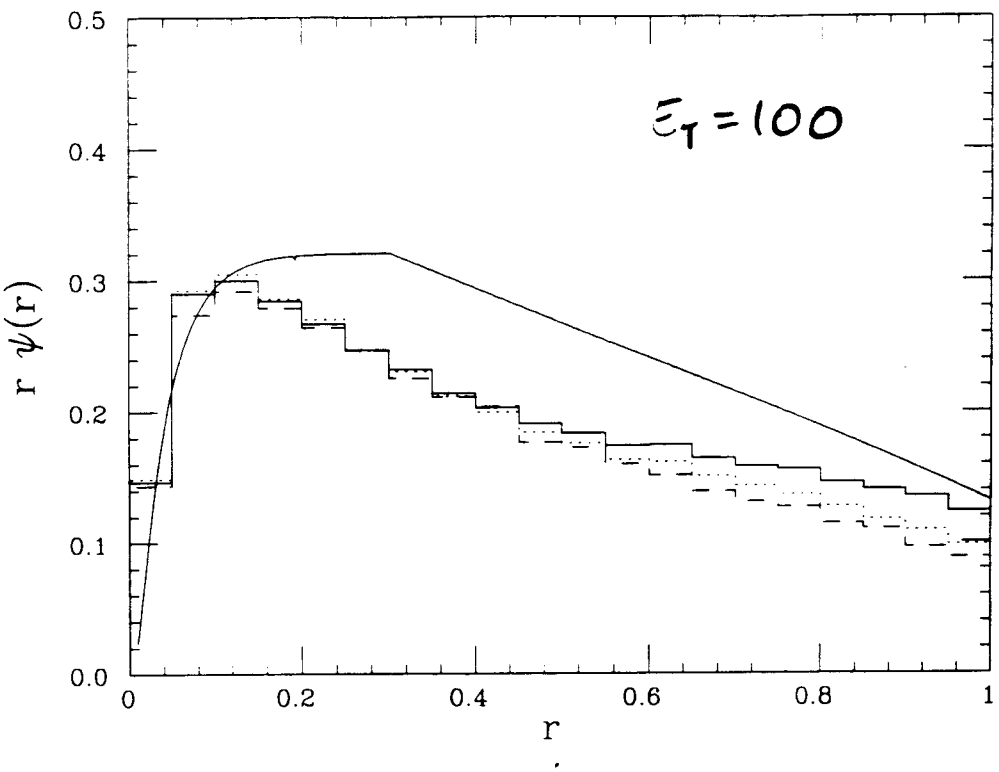
If you are sensitive to S.U.E., you are in trouble.....

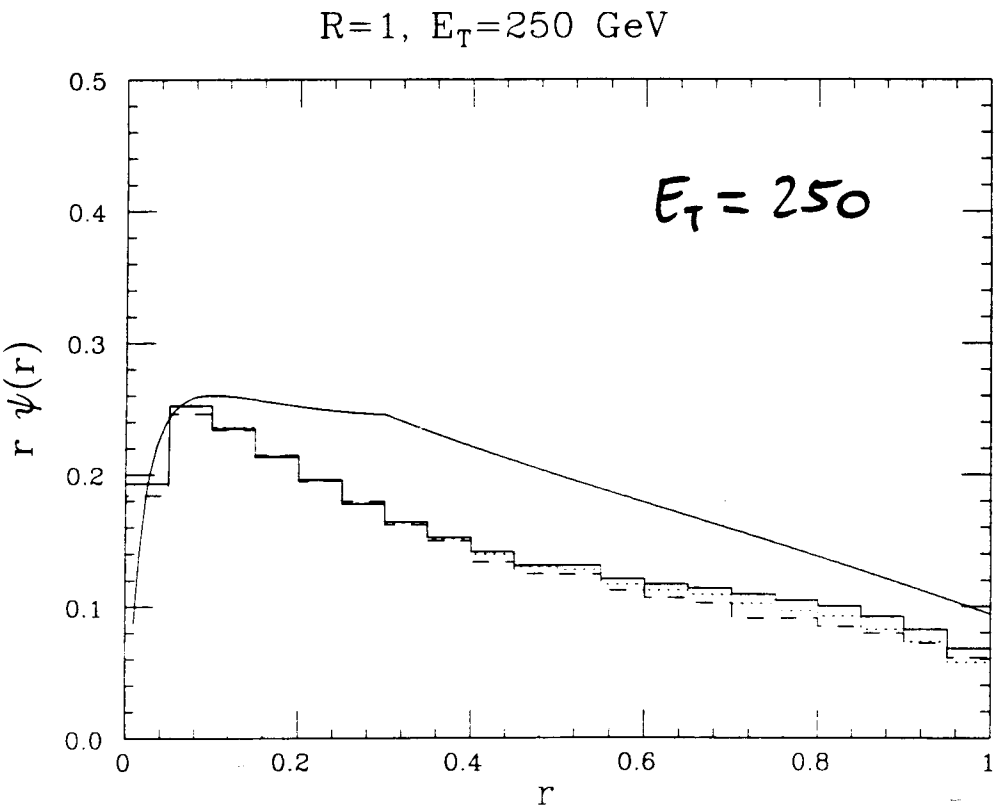
c.f. Marchesini & Webber, PRD 38(1988) 3419



Analytical results not much like HERWIG.

Much broader.


R=1, E_T=100 GeV
E_T=100
r ψ(r)
r
0.0
0.1
0.2
0.3
0.4
0.5
0
0.2
0.4
0.6
0.8
1


R=1, E_T=250 GeV
E_T=250
r ψ(r)
r
0.0
0.1
0.2
0.3
0.4
0.5
0
0.2
0.4
0.6
0.8
1

K. Astur $\bar{p}p$ '93.

Resolving subjets first solves most problems.

Good agreement with data, small corrections.

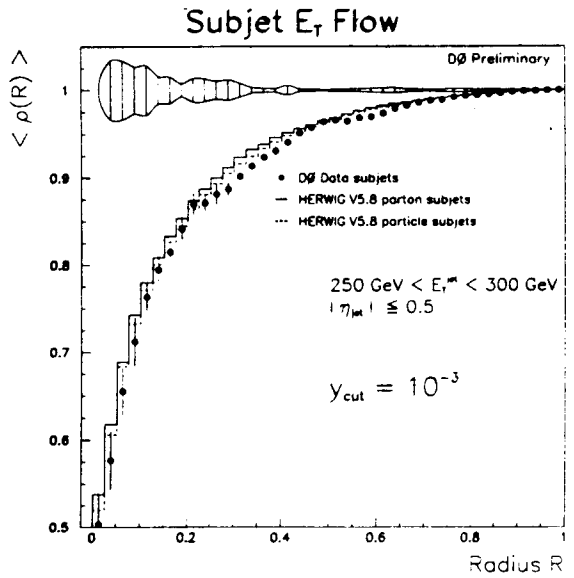


FIG. 5. $\rho(r)$ using subjets found with $y = 0.001$. Errors on the points are statistical while the size of the systematic errors are described by the band at the top.

CONCLUSIONS

- Energy profile should be understandable from simple effects. cf EEC in e^+e^-
- Preliminary results disagree with parton shower
- Jet definition very important is there a good one?
- Monte Carlo models should beat L.O. calculation hands down!