HARD SCATTERING IN HIGH ENERGY QCD(*)

(∼100 papers submitted)

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3. Studies of jet shapes in e^+e^- and ep (∼8 papers)
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   - Inclusive jets at 1800 GeV
   - Cross section ratios at 630/1800 GeV
6. Multi-Jet production at LEP/HERA (∼10 papers)
7. Heavy quark production (∼25 papers)
   - $g \to Q\bar{Q}$ studies in e^+e^-
   - c and b production at HERA
   - b and t production at the Tevatron

(*) http://home.cern.ch/~mlm/talks/eps99.ps.gz

INTRODUCTION

- Interesting to focus on few specific problems, where progress is either taking place at a quick pace (e.g. the study of power corrections and jet shapes), or where theoretical progress is still required to make full use of the rich and accurate new sets of experimental data available

- It is equally important to acknowledge the immense richness of the submitted contributions, and to provide a comprehensive review of the multitude of tests and measurements available today

- I will be forced to leave out topics which are not (or not yet) directly related to the regime of *HARD* QCD:
  - "Soft" QCD (e.g. detection and study of resonances inside jets)
  - BE correlations, FD correlations
  - Multiparticle production
  - etc.

THANKS to the (QCD) physics coordinators of all experiments, for the prompt submission of draft papers, and for replying to my enquiries!

SOFT FRAGMENTATION, MULTIPARTICLE PRDCTN, ...

[1_186] SLD: Charged $\pi^{\pm}$, $\mathbf{K}^{\pm}$ and p/$\bar{\mathbf{p}}$ in $\mathbf{Z^0}$ Decays

[1_394] ALEPH: Inclusive production of π^0, η, η', K_S, and Λ in two- and three-jet Z^0 decays

[1_397] ALEPH: Inclusive ρ^0, $f_0(980)$ and $f_2(1270)$ production in Z decays

[1_389] ALEPH: FD correlations in $\Lambda\Lambda$ and $\overline{\Lambda\Lambda}$ pairs in Z^0 decays

[3_143] DELPHI: FD effects for p pairs at the Z^0

[3_146] DELPHI: Identified Resonances in q/g Jets

[3_147] DELPHI: $\Lambda(1520)$ Production in Hadronic Z^0 Decays

[1_221] DELPHI: 2-D Analysis of BE Correlations at the Z^0

[1_222] DELPHI: Multiplicity Fluctuations in 1- and 2-Dimensional Angular Intervals vs Analytic QCD Calculations

[1_229] DELPHI: Charged and Identified Particles from the hadronic decay of W bosons and in $e^+e^-\to q\bar{q}$

[1_276] L3: Moments of the N_{ch} distribution in Z^0 Decays

[3_277] L3: Measurement of BE Correlations for Charged and Neutral Pions in Z^0 Decays

[3_280] L3: Elongation of the Pion Source in Z^0 Decays

[1_89] OPAL: Leading Particle Production in Light Flavour Jets

[1_23] OPAL: Intermittency and Correlations in Z^0 Decays

[3_64] OPAL: Transverse and Longitudinal BE Correlations in Z^0 Decays

[3_63] OPAL: Spin Alignment of $\rho^{\pm}(770)$ and $\omega(782)$ in Z^0 Decays

[3_65] OPAL: BE Correlations in $K^{\pm}K^{\pm}$ from $Z^0\to jj$

[3_66] OPAL: N_{ch} in Z decays into u, d, and s quarks

THEORETICAL TOOLS:

- New techniques for evaluation of LO multiparticle amplitudes (Draggiotis, Kleiss, Papadopoulos, 1_652)
- NLO, NNLO calculations available for a large class of processes. Recent developments include: new techniques for the evaluation of collinear/soft limits at NNLO (Kosower&Uwer, 1_129), NLO for BFKL (see P.Marage's talk), NLO for 4 jets in e^+e^-, $\mathcal{O}(\alpha_s^3, m_b^4)$ corrections to $R_{\rm had}$ (Chetyrkin, Harlander, Kühn 1_444)
- Resummation of large Logs at the edge of phase-space (event shapes, γ production, W/Z p_T spectra, heavy-quark production and fragmentation, DY)
- Analitical understanding of power corrections (Sterman 1_712), and explorations of the PT-nonPT transition region in QCD (Eden 1_206)

EXPERIMENTAL INPUTS:

- Jet production $(p\bar{p}, e^+e^-, ep, \gamma\gamma)$
- W/Z production (impact on W width measurement)
- Heavy quark production
- Properties of final states (shapes, multiplicities, frag functions, heavy-quark fractions). These have impact on perturbative QCD studies, as well as on the study of power corrections and non-perturbative physics, and on the extraction of $\alpha_S(M_Z)$

SANITY CHECKS OF QCD

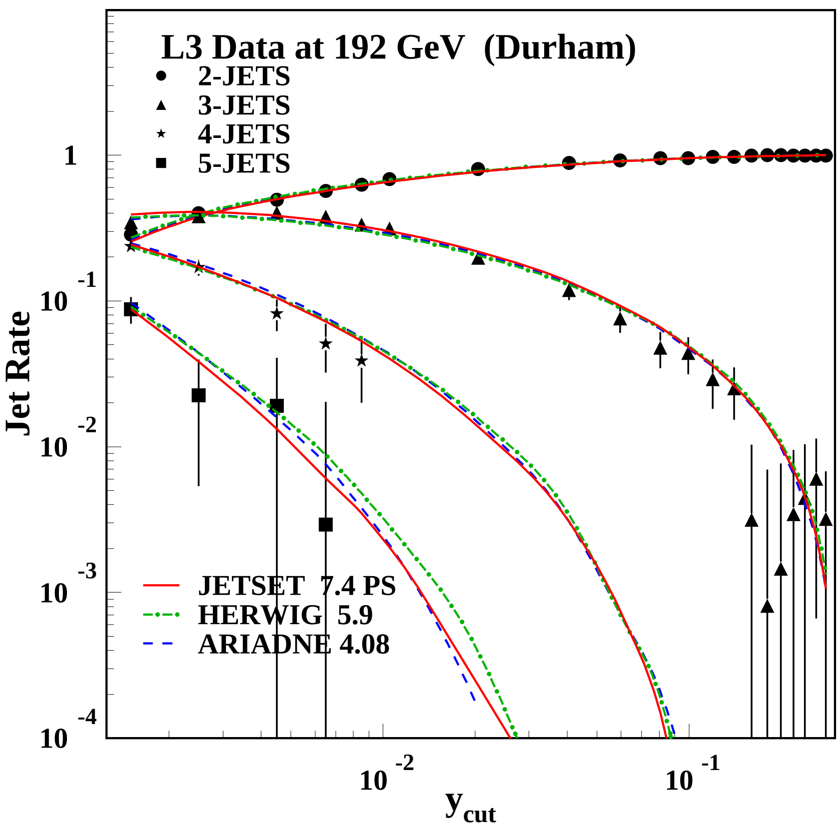
- Tests of QCD and QFT, with no direct impact on specific measurements (or not yet!):
  - not yet sufficiently accurate to change our knowledge of fundamental parameters (e.g. m_b)
  - qualitative in nature (e.g. tests of colour coherence)
  - explore hard-wired fundamental features of QCD (e.g. flavour independence of α_S, $N_c = 3$, ...)
- Testify the increased sophistication of experimental techniques
- Prepare the terrain for possible future applications, e.g.:
  - background removal in searches for New Physics
  - use of q/g discrimination
  - use of colour-coherence patterns to separate production of colour-singlet objects from multi-jet backgrounds

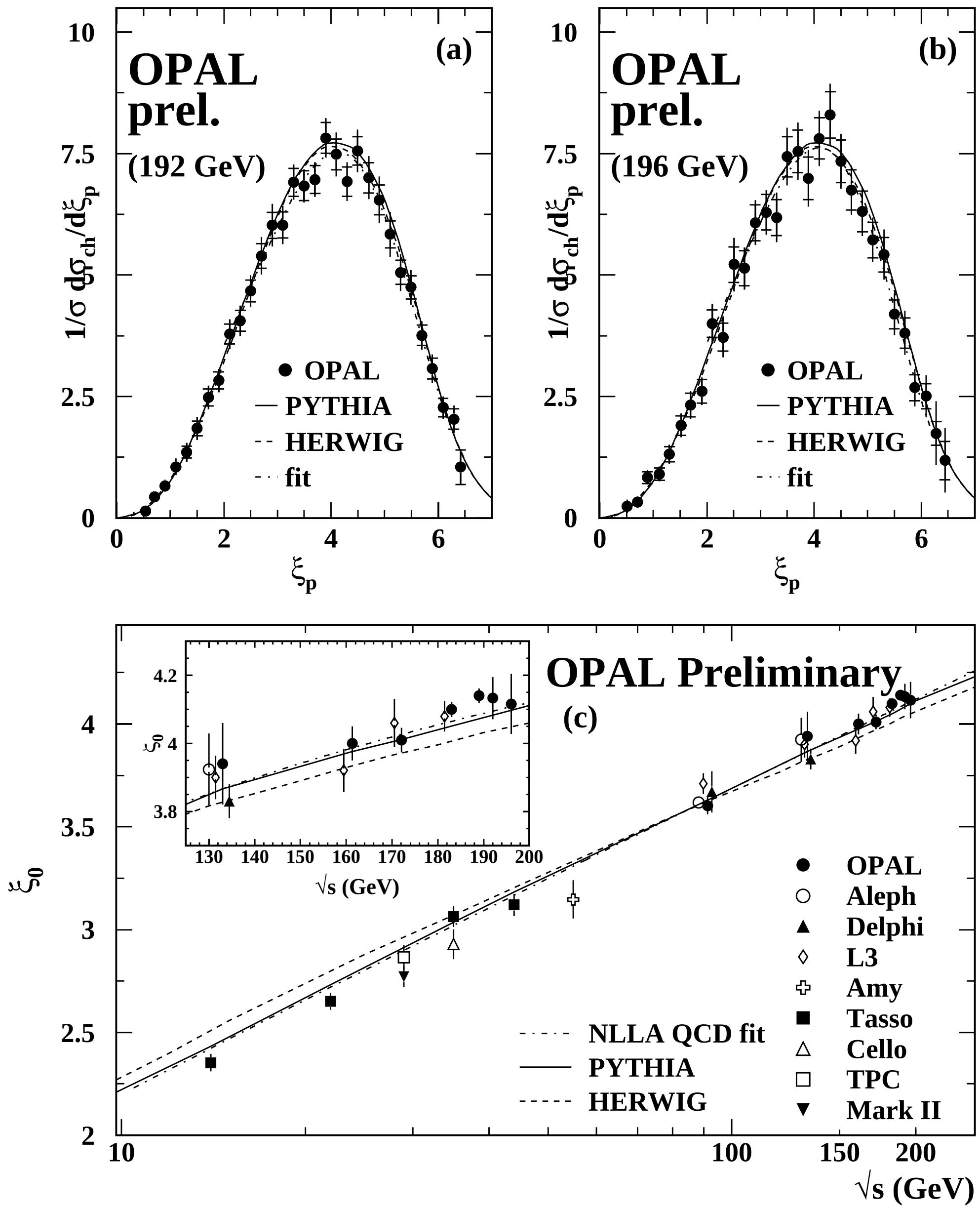
SANITY CHECKS: EVOLUTION WITH $\sqrt{S}$, up to 196 GeV

..392] ALEPH: QCD studies at 192 and 96 GeV

..232] L3: QCD studies at 192 and 96 GeV

..80] OPAL: QCD studies at 192 and 96 GeV





SANITY CHECKS: QUARK-MASS EFFECTS I

Measurement of the b-quark mass at M_{Z^0} (using 3-jet rates, shapes, etc.)

[1_3] OPAL:

$$m_b(M_Z)/GeV =$$

[1_384] ALEPH:

$$m_b(M_Z)/GeV = \begin{array}{ll} 3.04 \pm 0.92 & \text{3-jet fraction} \\ 3.78 \pm 0.27 & B_{W_2} \end{array}$$

$$m_b^{\overline{\mathrm{MS}}}(m_b)/GeV = \begin{array}{ll} 4.16 \pm 1.10 & \text{3-jet fraction} \\ 5.04 \pm 0.32 & B_{W_2} \end{array}$$

[1_223] DELPHI:

$$m_b(M_Z)/GeV = 2.61 \pm .18_{st} \begin{array}{c} +.45 \\ -.49 \end{array}_{frag} \pm .04_{tag} \pm .07_{th}$$

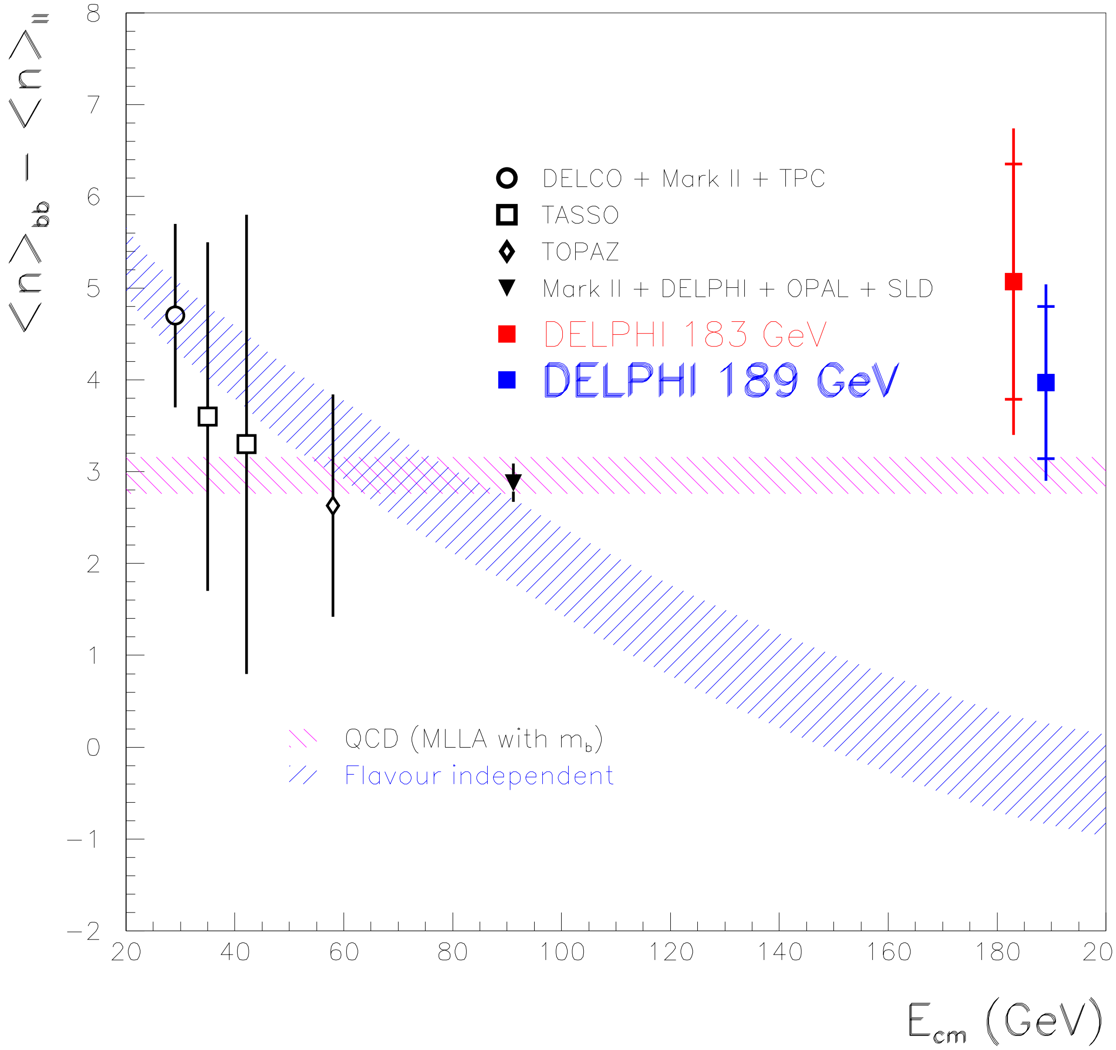
[1_449] A. Brandenburg et al, SLD:

$$m_b(M_Z)/GeV = 2.52 \pm .27_{st} \begin{array}{c} +.33 \\ -.47 \end{array}_{sys} \begin{array}{c} +.28 \\ -1.39 \end{array}_{had} \pm .48_{th}$$

Compare w. $m_b^{\overline{\mathrm{MS}}}(m_b) = 4.20(8)$ from QCD SR and NNLO in $\Upsilon(1S)$ (Beneke/Signer, Hoang, Melnikov/Yelkhovsky '99)

SANITY CHECKS: QUARK MASS EFFECTS II

[1_220] DELPHI: Hadronization Properties of b vs (u, d, s) at $\sqrt{s}$ = 183-189 GeV:



Verified QCD prediction of constant

$$\delta_{bl} \equiv \langle n \rangle_{bb} - \langle n \rangle_{ll} \, ,$$

with

$$\delta_{bl} = \begin{array}{ll} 5.07 \pm 1.28_{stat} \pm 1.07_{syst} & \sqrt{S} = 183 \\ 3.97 \pm 0.83_{stat} \pm 0.68_{syst} & \sqrt{S} = 189 \end{array}$$

Shaded band normalised to LEP1 data: $\delta_{bl} = 2.96 \pm 0.20$

SANITY CHECKS: COLOUR COHERENCE

[1_163e] D0: Evidence of Color Coherence in $W + Jets$ Events in $p\bar{p}$ at $\sqrt{s} = 1.8$ TeV

[1_145] DELPHI: A Test of QCD Coherence and LPHD using Symmetric 3-Jet Events

[1_510] DELPHI: Testing of the New Parton Final State Reconstruction Method Using $Z^0 \rightarrow b\bar{b}g$ Mercedes Events

SANITY CHECKS: FLAVOUR INDEP. OF α_s

[1_25] OPAL:

$$\frac{\alpha_s^b}{\alpha_s^f} = 0.997 \pm 0.050$$

$$\frac{\alpha_s^c}{\alpha_s^f} = 0.993 \pm 0.015$$

[1_223] DELPHI:

$$\frac{\alpha_s^b}{\alpha_s^f} = 1.005 \pm 0.012$$

SANITY CHECKS: b COUPLINGS:

[1_182] SLD: An Improved Study of the Structure of $\mathbf{b\bar{b}g}$ Events Using $\mathbf{Z^0}$ Decays:

$$\Delta\mathcal{L} = \frac{\kappa}{4m_b} g_s \, \bar{b}\sigma_{\mu\nu} b \, G_{\mu\nu} \rightarrow -0.11 < \kappa < 0.08$$

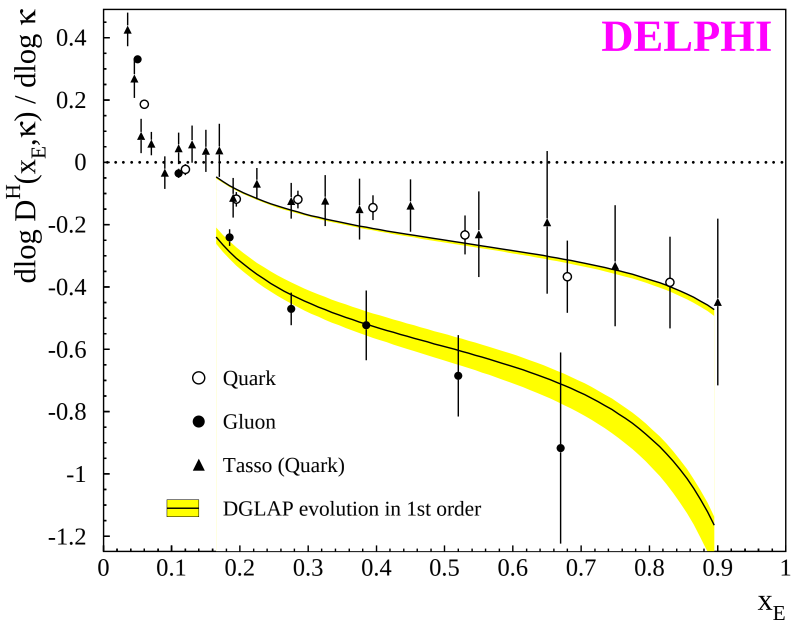
[1_183] SLD: Symmetry Tests in Polarized $\mathbf{Z^0}$ Decays to $\mathrm{b}\bar{\mathbf{b}}\mathrm{g}$:

no evidence for T-odd CP-even or
T-odd CP-odd asymmetries

SANITY CHECKS: C_A/C_F from N_{ch} and $F(z)$ in q/g jets

[1_571] DELPHI: $F_g(z)$ and scaling violations in q/g jets:

$$\frac{C_A}{C_F} = 2.23(9)(6)$$



[1_383] DELPHI: Scale Dependence of N_{ch} in q and g Jets:

$$\frac{C_A}{C_F} = 2.246 \pm 0.062_{stat} \pm 0.080_{sys} \pm 0.095_{th}$$

[1_4] OPAL: N_{ch}, N_{π^0} and N_η comparison between q and g jets.

[1_6] OPAL: A simultaneous measurement of α_S and QCD colour factors

[1_24] OPAL: Experimental properties of gluon and quark jets from a point source

$$\frac{C_A}{C_F} = 2.29 \pm 0.09_{\rm stat} \pm 0.15_{\rm syst}$$

Test of color reconnection: Ariadne MC disfavored by data.

EVENT SHAPES IN e^+e^- and ep

[1_113] Movilla Fernández et al, Tests of Power Corrections to Event Shape Distributions from e^+e^- Annihilation

[1_224] DELPHI: Consistent Measurements of α_s from Precise Oriented Event Shape Distributions

[1_144] DELPHI: QCD Results from the Measurements of Event Shape Distributions between 48 and 189 GeV

[1_279] L3: QCD studies and α_S using event structures from 30 to 189 GeV.

[1_410] ALEPH: QCD studies at 189 GeV.

[1_2] OPAL: QCD studies at 172-189 GeV.

[1_5] OPAL: Jet measurements at 35 (JADE) and 189 GeV.

[1_157k] H1: Study of Event Shapes in DIS

EVENT SHAPES IN e^+e^- and ep

- Infrared and collinear safe observables
- Sensitive to properties of QCD radiation $\Rightarrow$ allow measurement of α_S
- QCD predictions available at NNLO fixed order plus resummation of NLL logarithms for e^+e^-. Lower accuracy for ep.
- Sensitive to non-perturbative power-suppressed (i.e. $\propto 1/Q$) effects $\Rightarrow$ allow study of the hadronization phase

Extractions of α_S in the past have used a description of non-PT corrections to event-shapes based on the hadronization models of shower MC's (Herwig, Jetset). With the recent progress in the theoretical understanding of the structure of power corrections (Dokshitser, Marchesini, Salam, Webber), the effect of hadronization corrections can be included, with simple analytical expressions, dependent on a single parameter.

Non-PT corrections described by calculable observable-dependent functions, parametrised by a single, universal phenomenological parameter, the average of $\alpha_S(Q)$ at low scale: (usually $\mu_0 = 2$ GeV)

$$\alpha_0(\mu_0) = \frac{1}{\mu_0} \int_0^{\mu_0} \mathrm{d}q \; \alpha_S(q)$$

It is common to use either *moments* of shape variables, or *distributions*. The use of distributions allows to *fit* the best choice of renormalization scale μ, thereby reducing the theoretical uncertainties.

In the case of 1^{st} moments:

$$\langle \mathcal{F} \rangle = \langle \mathcal{F}_{PT} \rangle + \langle \mathcal{F}_{non-PT} \rangle$$

with (Dokshitser et al.):

$$\langle \mathcal{F}_{non-PT} \rangle = c_F \; \mathcal{P}$$

$\mathcal{F} =$	$1-T$	M_H^2	B_T	B_W	C
$c_F =$	2	2	1	1/2	3π

and ($\mathcal{M} = 1.795$, "Milan" factor)

$$\mathcal{P} = \frac{4C_F}{\pi^2}\,\mathcal{M}\,\frac{\mu}{\sqrt{S}}\;\left[\alpha_0(\mu) - \alpha_S(\sqrt{s}) + \mathcal{O}(\alpha_S^2)\right]$$

In the case of distributions, the effect of power corrections is to shift the value of the observable in the PT QCD prediction:

$$\frac{d\sigma}{d\mathcal{F}}(\mathcal{F}) = \frac{d\sigma^{PT}}{d\mathcal{F}}(\mathcal{F} - \mathcal{P}\,D_{\mathcal{F}})$$

where $\mathcal{P}$ is the same as for the 1st moment, and $D_{\mathcal{F}}$ can be calculated for each observable. It can be a constant:

$$D_{\mathcal{F}} = \begin{cases} 2 & \mathcal{F} = 1 - T \\ 3\pi & \mathcal{F} = C \end{cases}$$

or a function:

$$D_{\mathcal{F}} = \frac{1}{2}\log\frac{1}{\mathcal{F}} + B_{\mathcal{F}}(\mathcal{F}, \alpha_S(\mathcal{F}\sqrt{s})) \quad \mathcal{F} = B_T,\, B_W$$

Let us begin with $\alpha_S(M_Z)$ determinations obtained from QCD fits, with non-PT effects described via MC programs.

NEW MEASUREMENTS:

ALEPH [1_410] :

$$\begin{aligned}\alpha_S(189) &= 0.1119(15)_{stat}(11)_{sys}(30)_{th}\\ \alpha_S(M_Z) &= 0.1249(44)\\ \alpha_S(M_Z)_{[LEP1+LEP2]} &= 0.1216(39)\end{aligned}$$

DELPHI [1_144] :

$$\begin{aligned}\alpha_S(189) &= 0.1116(24)_{stat}(\quad)_{sys}(\quad)_{th}\\ \alpha_S(M_Z) &= 0.1246(30)_{stat}(\quad)_{sys}(\quad)_{th}\end{aligned}$$

L3 [1_279]:

$$\begin{aligned}\alpha_S(189) &= 0.1101(18)_{exp}(56)_{th}\\ \alpha_S(M_Z) &= 0.1227(22)_{exp}(69)_{th}\\ \alpha_S(M_Z)_{[30-189\ \mathrm{GeV}]} &= 0.1220(62)\end{aligned}$$

OPAL [1_5] :

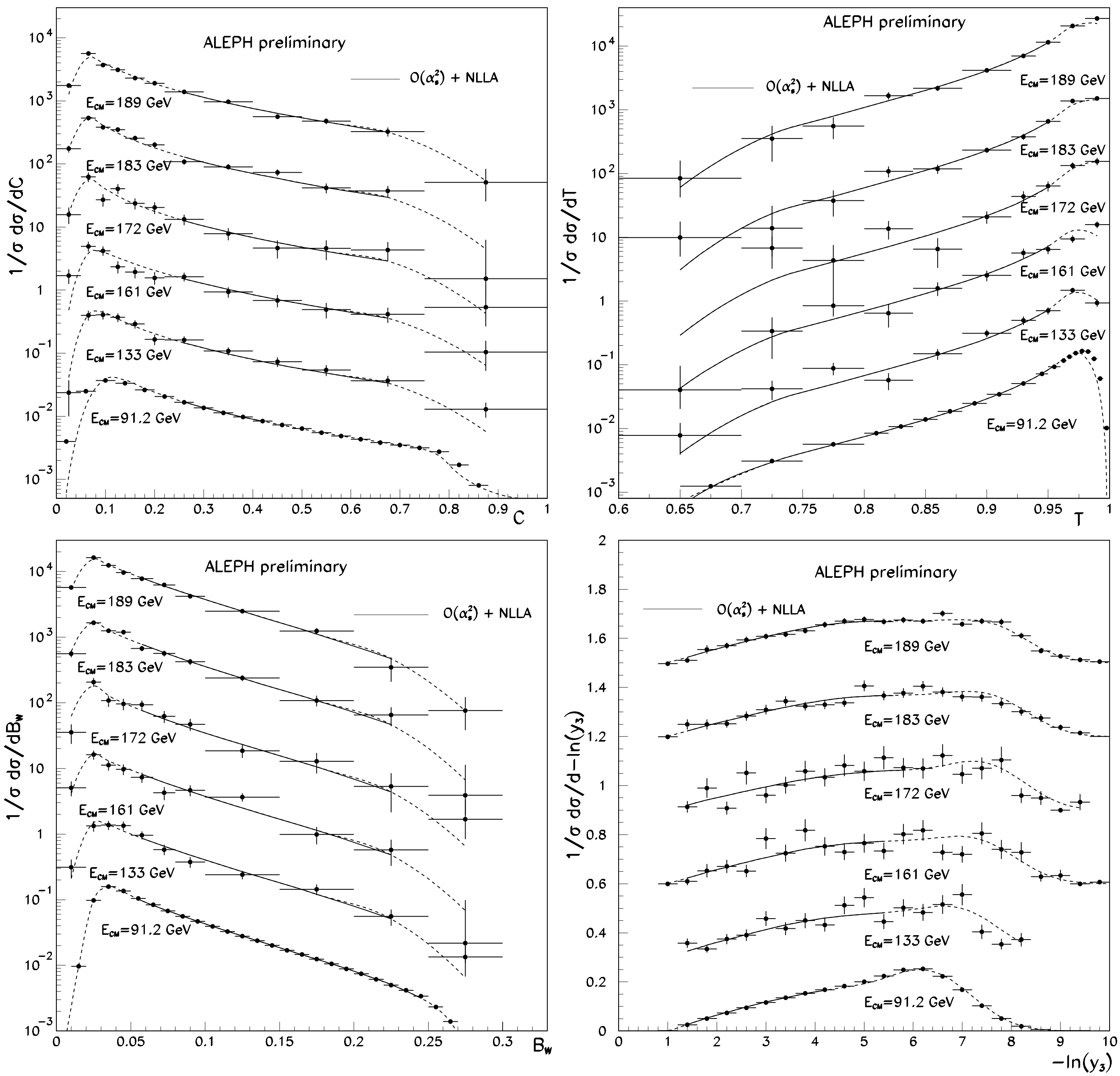
$$\begin{aligned}\alpha_S(189) &= 0.1085(15)_{stat}(27)_{sys}(20)_{had}\left({}^{+22}_{-3}\right)_{scale}\\ \alpha_S(M_Z) &= 0.1206\left({}^{+54}_{-46}\right)\\ \alpha_S(M_Z)^{(*)}_{[35-189]} &= 0.1199\left({}^{+38}_{-25}\right)\end{aligned}$$

$^{(*)}$ Uses data from JADE, in addition to OPAL LEP1 and LEP2

My 189 GeV average:

$\alpha_S(189) = 0.1105(4)$ $\alpha_S(M_Z) = 0.1232(5)$

ALEPH $\mathcal{O}(\alpha_S^2)$+NNL shape fits



SHAPE VARIABLES: RESULTS II

$\alpha_S(M_Z)$ determinations obtained from QCD fits, with non-PT effects described by analytic power corrections. New measurements:

FROM 1^{st} MOMENTS:

DELPHI [1_144] (Fig ⇒):

$$\begin{aligned} \alpha_0(2\,\mathrm{GeV}) &= 0.5(1) \\ \alpha_S(189) &= 0.1102(23)_{stat}(18)_{sys}(24)_{th} \\ \alpha_S(M_Z) &= 0.1229(28)_{stat}(22)_{sys}(31)_{th} \end{aligned}$$

H1 [1_157k] (Fig ⇒):

$$\begin{aligned} \alpha_0(2\,\mathrm{GeV}) &= 0.50(5) \\ \alpha_S(M_Z) &= 0.12(1) \end{aligned}$$

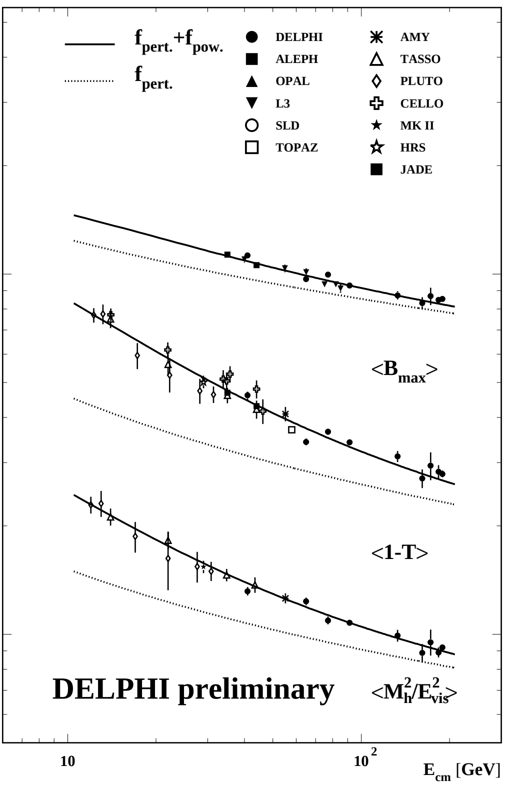
FROM SHAPE DISTRIBUTIONS:

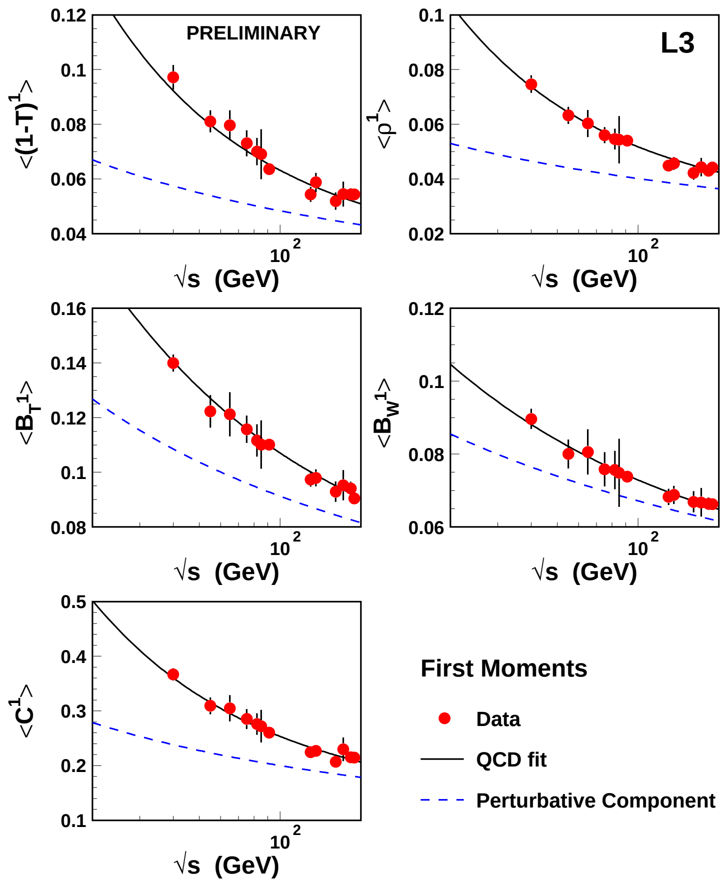
L3 [1_279] (Fig ⇒):

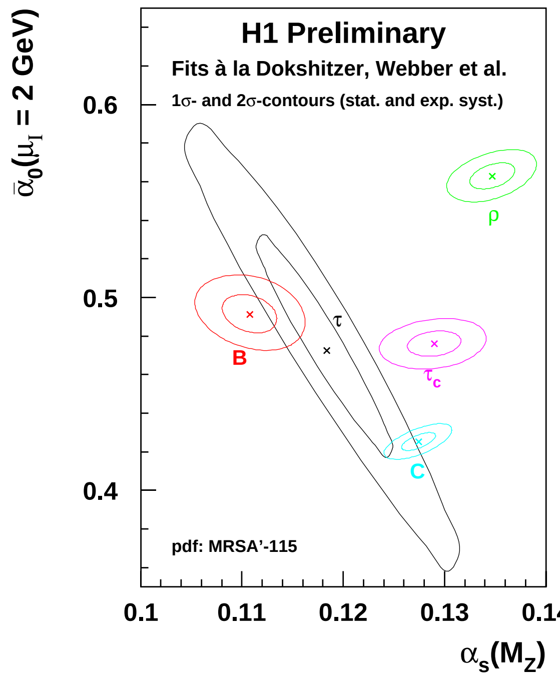
$$\begin{aligned} \alpha_0(2\,\mathrm{GeV}) &= 0.490(46)_{avg} \\ \alpha_S(M_Z) &= 0.1106(36)_{exp}(40)_{th} \end{aligned}$$

Movilla Fernández et al, [1_113] JADE, LEP (Fig ⇒):

$$\begin{aligned} \alpha_0(2\,\mathrm{GeV}) &= 0.50\,^{+.9}_{-.6} \\ \alpha_S(M_Z) &= 0.1068 \pm .0011_{stat}\,{}^{+.0033}_{-0.043}\,{}_{sys}\,{}^{+.0043}_{-0.029}\,{}_{th} \\ \alpha_S(M_Z) &= 0.1141 \pm .0012_{stat}\,{}^{+.0034}_{-0.024}\,{}_{sys}\,{}^{+.0055}_{-0.041}\,{}_{th} \quad \text{(no } B_W\text{)} \end{aligned}$$







Dokshitzer, Marchesini, Salam:

(solid: dist's; dashes: moments):

lovilla Fernández

iebel

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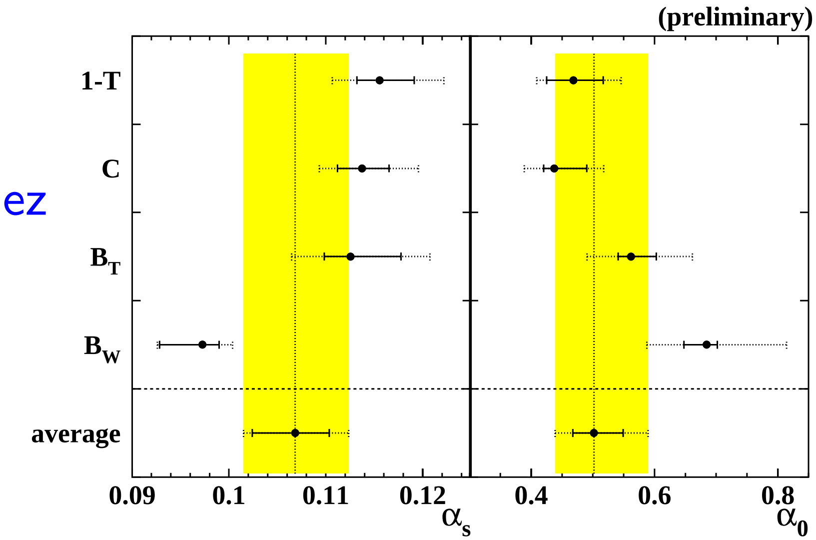
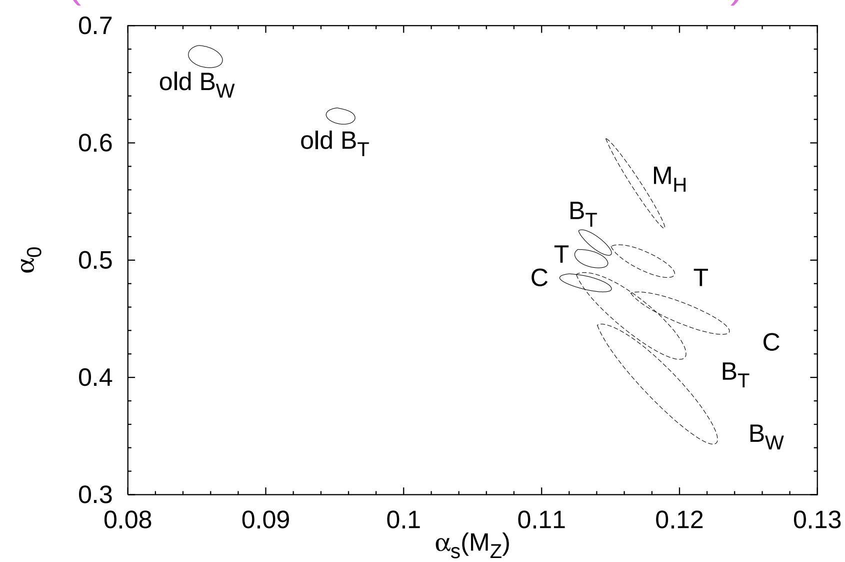




- Good consistency in the extraction of $\alpha_S(M_Z)$ from QCD+hadronization corrections, and from 1^{st} moments using analytic power corrections
- Larger uncertainties at HERA, due to lack of NNLO calculations and NLL resummations
- Significant differences in $\alpha_S(M_Z)$ when fitting shape distributions with power corrections
- Indication of *insufficient squeezing* in the theoretical predictions for the shift of some observables (in particular B_W and B_T) due to power corrections. Supported by comparison with hadronization corrections predicted by MC's
- We are moving in the right direction for a phenomenological understanding of power corrections, but more work is necessary before extractions of α_S can be improved.

OTHER NEW $\alpha_S(M_Z)$ MEASUREMENTS

[1_157] H1: Fit the Inclusive Jet Rate $\mathrm{d}^2\sigma/\mathrm{d}E_T\mathrm{d}Q^2$:

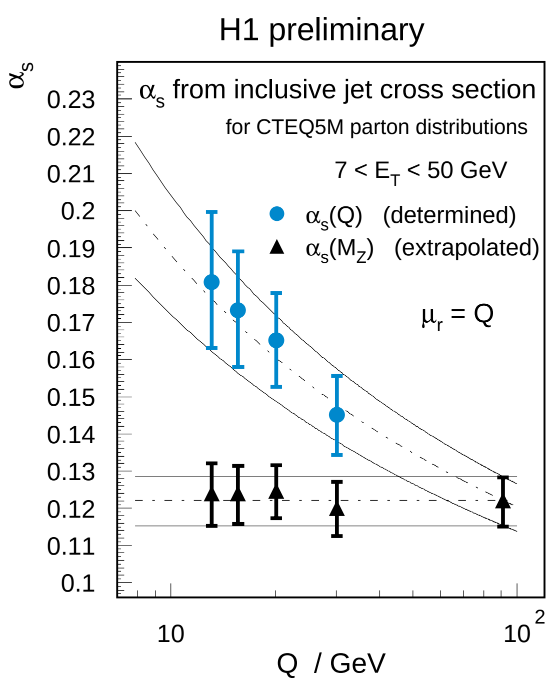
$$\alpha_S(M_Z) = \begin{array}{ll} 0.1181(30)_{exp}\binom{+39}{-46}_{th}\binom{+36}{-15}_{PDF} & \mu_R = E_T \\ 0.1221(34)_{exp}\binom{+54}{-59}_{th}\binom{+33}{-16}_{PDF} & \mu_R = Q \end{array}$$

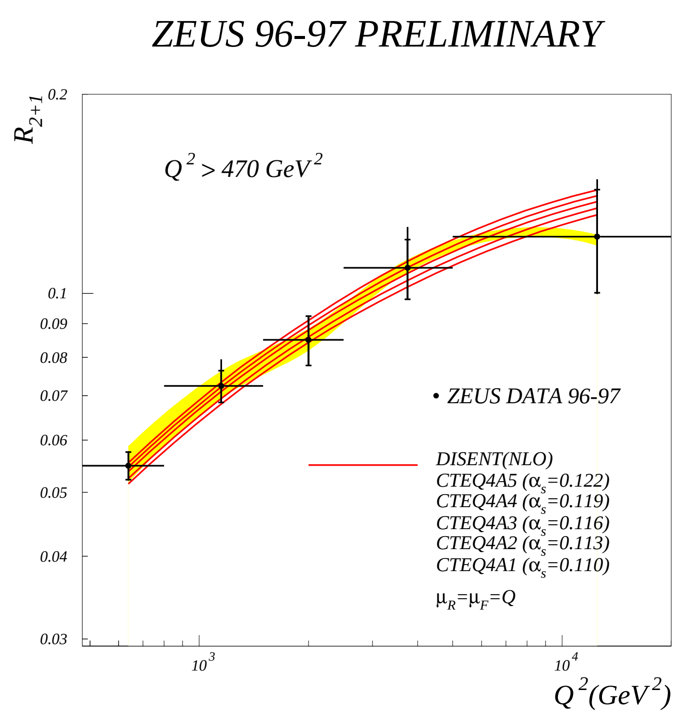
[1_157y] H1: Fit the Dijet Rate $\mathrm{d}n_{\mathrm{dijet}}/\mathrm{d}y_2$:

$$\alpha_S(M_Z) = \begin{array}{ll} 0.1189\binom{+64}{-81}_{exp}\binom{+59}{-46}_{th}\binom{+13}{-55}_{PDF} & k_\perp^{DIS} \text{ alg. Breit Frame} \\ 0.1143\binom{+75}{-89}_{exp}\binom{+74}{-64}_{th}\binom{+8}{-54}_{PDF} & \text{Durham alg. Lab Frame} \end{array}$$

[1_543] ZEUS: Fit the Dijet fraction vs Q^2:

$$\alpha_S(M_Z) = 0.120(3)_{stat}\binom{+5}{-6}_{exp}\binom{+3}{-2}_{th}$$





[1_392] ALEPH: QCD studies at 192 and 196 GeV:

$$\alpha_S(192) =$$
$$\alpha_S(M_Z) =$$

[1_232] L3: QCD studies at 192 and 196 GeV:

$$\alpha_S(192) = 0.1108(35)_{exp}(56)_{theory}$$
$$\alpha_S(M_Z) = 0.1220(15)_{exp}(60)_{theory}$$

[1_80] OPAL: QCD studies at 192 and 196 GeV:

$$\alpha_S(192) = 0.1025(38)_{stat}(54)_{syst}$$
$$\alpha_S(M_Z)_{[30-192\ \mathrm{GeV}]} = 0.1135(47)_{stat}(67)_{syst}$$

[1_2] OPAL: QCD studies at 172-189 GeV:

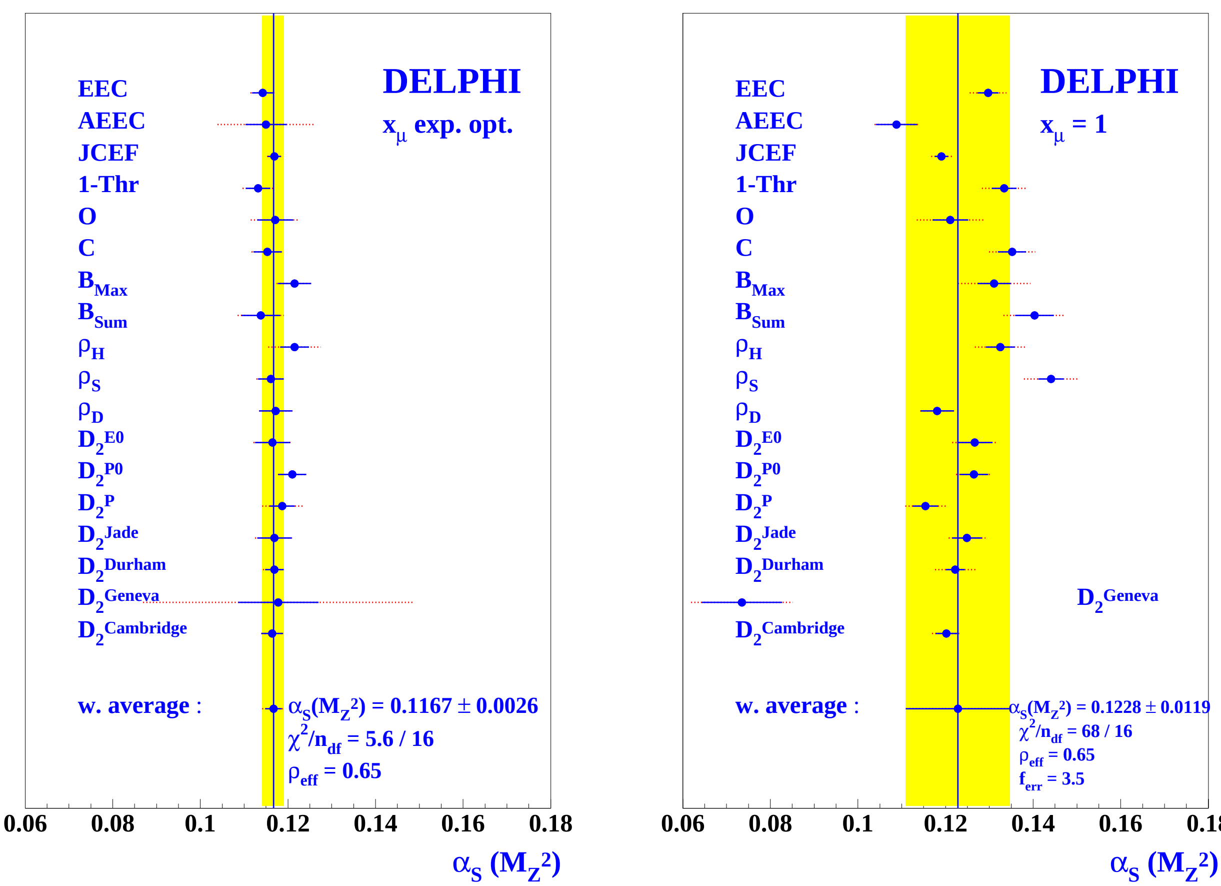
$$\alpha_S(187) = 0.106(1)_{stat}(4)_{syst}$$
$$\alpha_S(M_Z)_{[172-189\ \mathrm{GeV}]} = 0.117(5)$$

[1_157y] DELPHI: Fits to oriented shape variables at 91.2 GeV: scales "optimised" by fitting shapes for each variable. (⇒ Fig)

$$\alpha_S(M_Z) = \begin{array}{ll} 0.1173 \pm 0.0023 & \text{18 shape variables} \\ 0.1180 \pm 0.0018 & \text{Jet cone E fraction} \end{array}$$

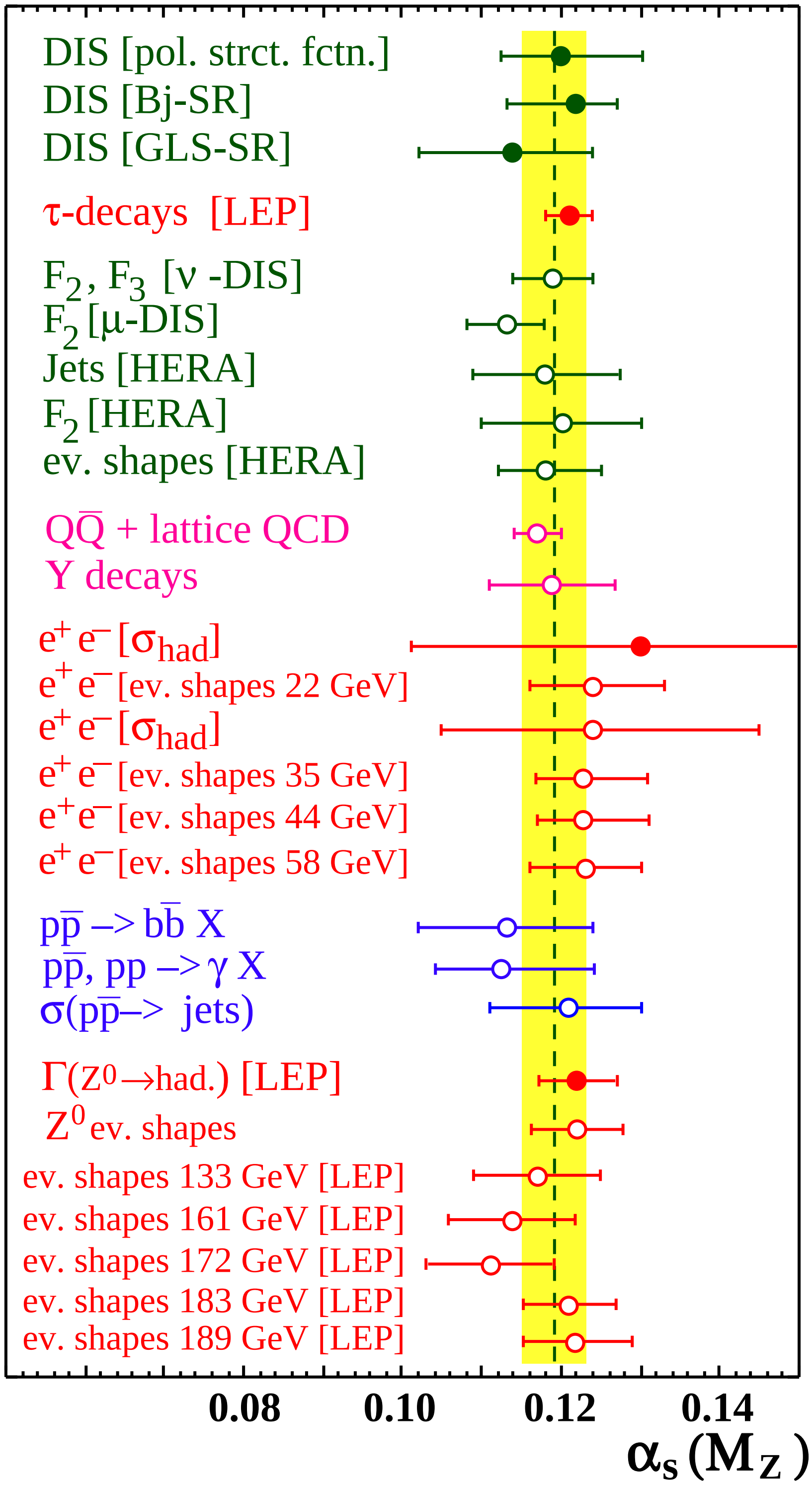
This optimization procedure has no theoretical basis. Although the consistency of the extracted values of α_S for all 18 variables is tantalising, I do not consider these error estimates theoretically solid. Nevertheless, I have no precise understanding of which bias could cause such an amazing convergence in the values of α_S!

Obs	Fit Range	x_μ	χ^2/n_{df}	n_{df}
EEC	$28.8^\circ - 151.2^\circ$	0.0112 ± 0.0006	1.02	236
AEEC	$25.2^\circ - 64.8^\circ$	0.0066 ± 0.0018	0.98	75
JCEF	$104.4^\circ - 169.2^\circ$	0.0820 ± 0.0046	1.05	124
$1 - T$	0.05 - 0.30	0.0033 ± 0.0002	1.24	89
O	0.24 - 0.44	2.30 ± 0.40	0.90	33
C	0.24 - 0.72	0.0068 ± 0.0006	1.02	82
B_{Max}	0.10 - 0.24	0.0204 ± 0.0090	0.89	47
B_{Sum}	0.12 - 0.24	0.0092 ± 0.0022	1.19	40
ρ_H	0.03 - 0.14	0.0036 ± 0.0004	0.63	54
ρ_S	0.10 - 0.30	0.0027 ± 0.0019	0.82	16
ρ_D	0.05 - 0.30	2.21 ± 0.38	1.02	68
D_2^{E0}	0.07 - 0.25	0.048 ± 0.020	0.85	68
D_2^{P0}	0.05 - 0.18	0.112 ± 0.048	1.02	68
D_2^{P}	0.10 - 0.25	0.0044 ± 0.0004	1.00	47
D_2^{Jade}	0.06 - 0.25	0.126 ± 0.049	1.05	75
D_2^{Durham}	0.015 - 0.16	0.0126 ± 0.0015	0.92	96
D_2^{Geneva}	0.015 - 0.03	7.10 ± 0.28	0.84	19
$D_2^{Cambridge}$	0.011 - 0.18	0.066 ± 0.019	0.98	145



$\alpha_S(M_Z)$ WORLD AVERAGE

From S. Bethke, hep-ex/9812026



Using measurements with $\Delta\alpha_S < 0.008$ only:

$$\alpha_S(M_Z) = 0.119 \pm 0.004$$

If Lattice is left out $\rightarrow \alpha_S(M_Z) = 0.120 \pm 0.005$

$\alpha_S(M_Z)$ measurements

I don't dare stealing from S.Bethke the pleasure to produce the new World Average for $\alpha_S(M_Z)$!! Proper averaging of the new LEP results requires detailed knowledge of the correlation matrices for the various experiments, and will be done soon, I expect, by the QCD LEP Working Group.

However, I don't see indications that the most recent updates on the value of α_S submitted to this Conference will change significantly the central value and the determination of the error on $\alpha_S(M_Z)$.

The most recent extractions of α_S from the fits to jet shapes at 189 GeV support a slightly larger value of $\alpha_S(M_Z)$ relative to the pre-EPS World average of 0.119 ± 0.004. So my best bet for the next WA is

$$\alpha_S(M_Z) = 0.121 \pm 0.004.$$

Progress in the analytic, phenomenological understanding of power corrections, needed to extract α_S from jet shapes, is remarkable. However, the current results should be taken in my view more as an indication that the direction of these theoretical developments is correct, than as a strong input for a reduction of the theoretical error on α_S.

Even more interestingly, they set the stage for future progress in the area of jet physics in hadronic collisions, where large statistics and huge lever arms in energy will lead to minuscule statistical uncertainties on α_S in the future years.

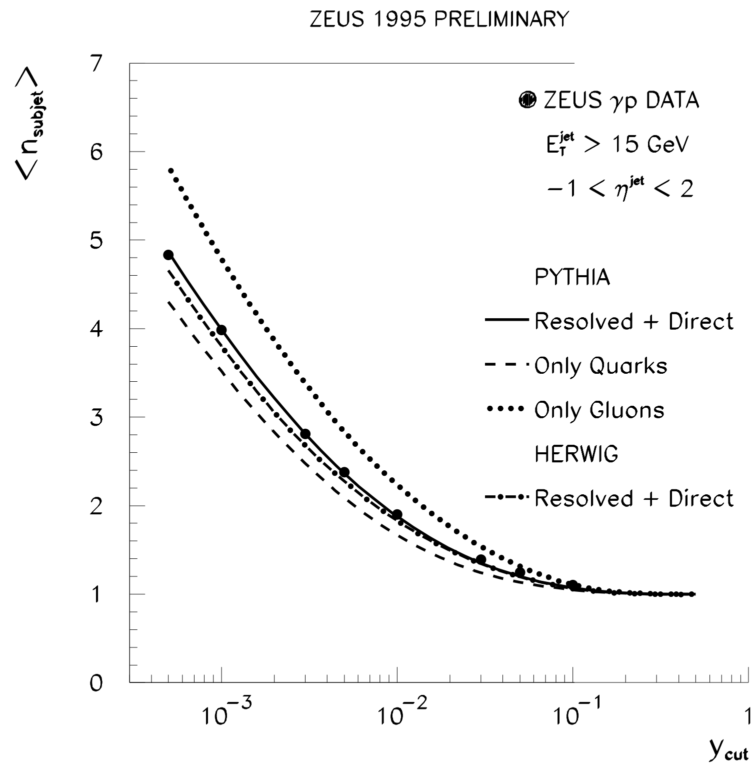
JET STRUCTURES IN $\bar{p}p$ and ep

[1_163d] DO: Subjet multiplicity at $\sqrt{S} = 630$ and 1800 GeV

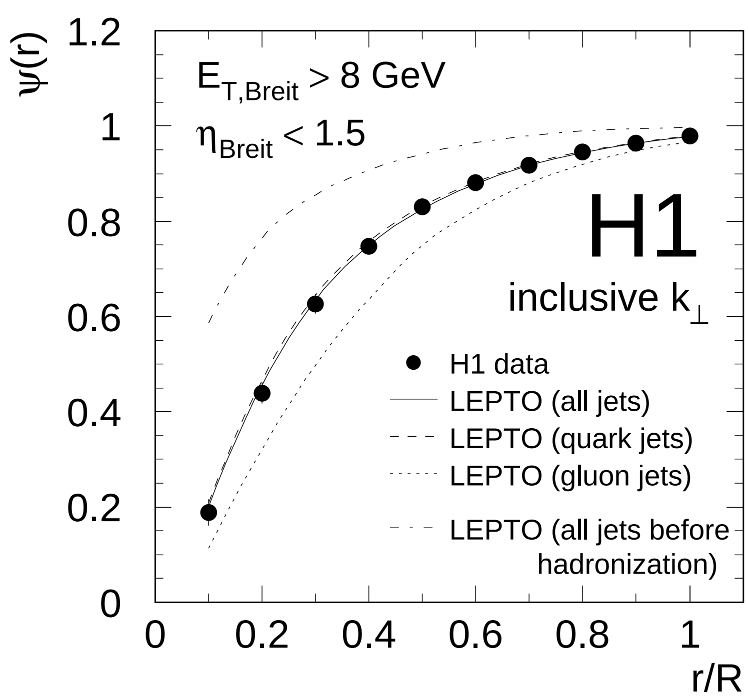
[1_600] CDF: Jet fragmentation studies at the Tevatron:

excellent agreement with MDLA!

[1_530] ZEUS: Jet substructure in γp:



[1_157x] H1: Jet substructure in Dijet DIS:



JETS AT THE TEVATRON

1_163c D0 – Inclusive Jet Production in $p\bar{p}$ Collisions at $\sqrt{s} =$ 1800 GeV and 630 GeV at D0

1_593 CDF – Measurement of the Inclusive Jet Cross Section at 1800 GeV

1_594 CDF – Measurement of Inclusive Jet Cross Section at 630 GeV

1_163a D0 – The Triple Differential Dijet Cross Section at D0

1_595 CDF – Two Jet Differential Cross Section from CDF

1_596 CDF – The Fully Corrected Dijet Invariant Mass Distribution from CDF

1_163d D0 – Subjet Multiplicity at $\sqrt{s} = 1800$ and 630 GeV

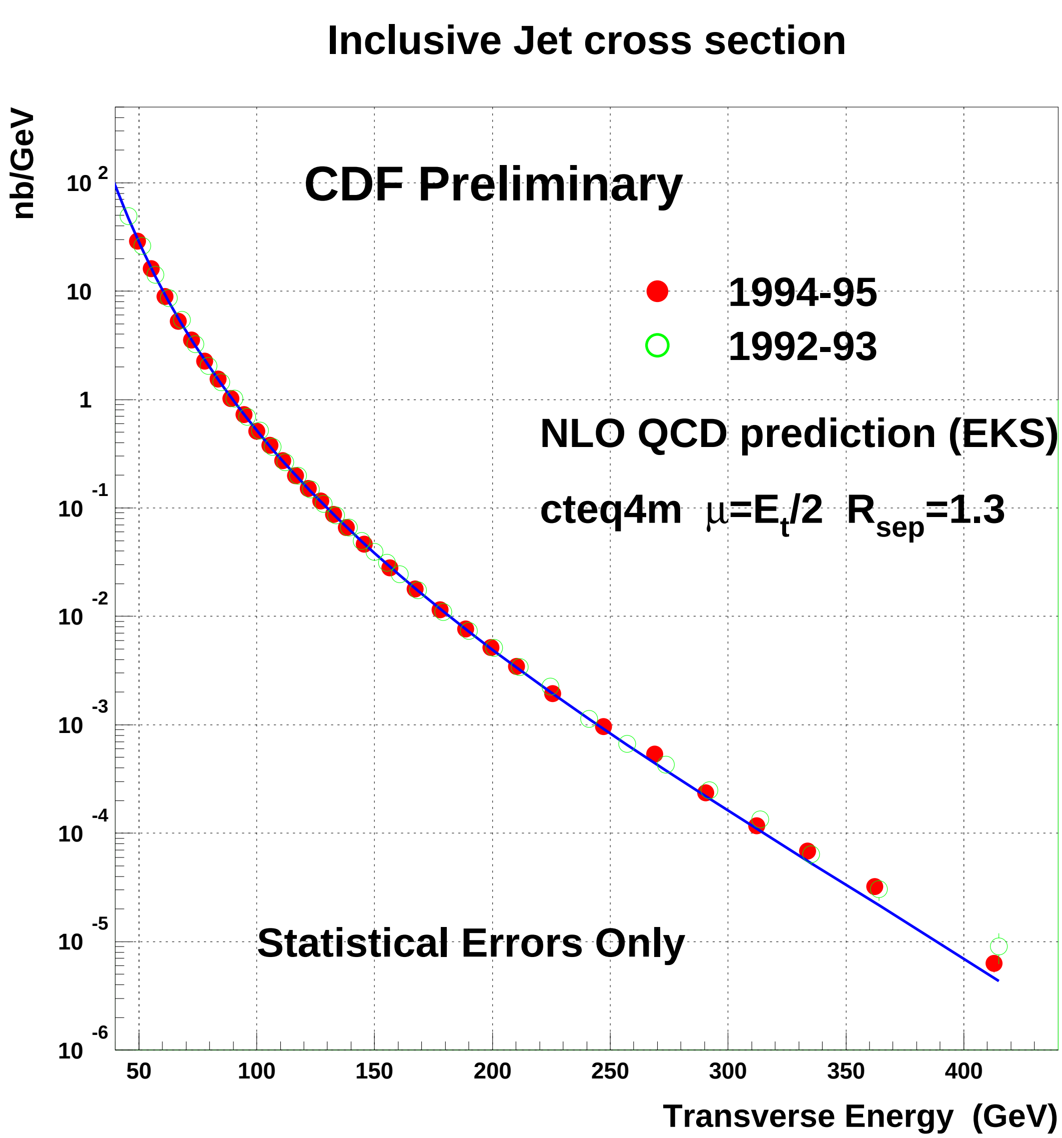
1_600 CDF – Jet Fragmentation Studies at the Tevatron

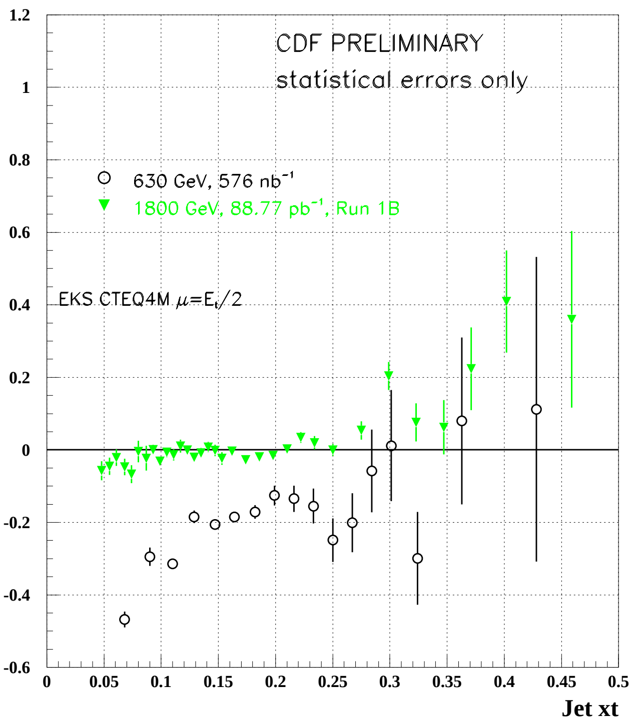
Jet production at the Tevatron

Goals:

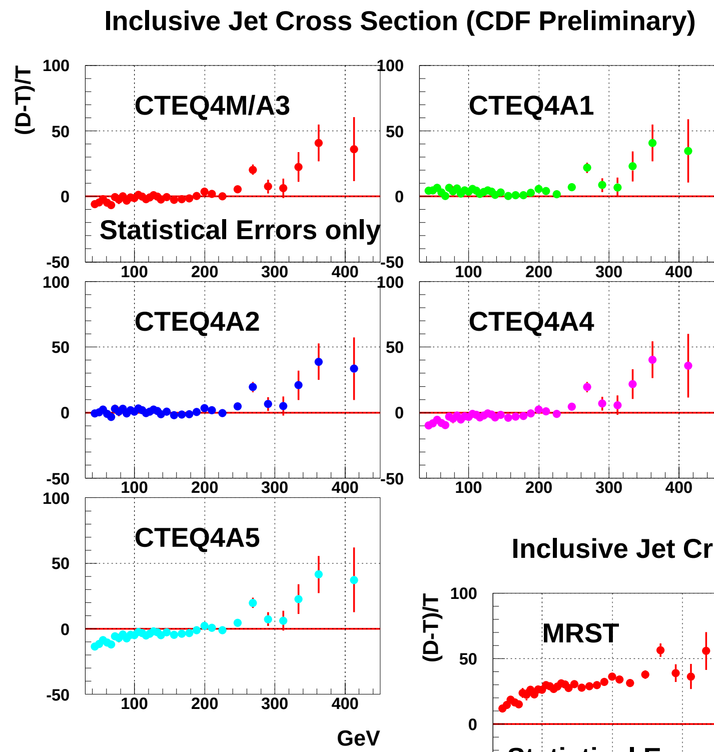
- Test QCD: calculations available at NLO
- Extract information on $f_{q,g}(x, Q^2)$ at large Q^2
- Measure α_S over a huge range of Q^2
- Look for deviations from QCD, explore quark structure at small distances
- Look for resonances in the mass spectrum

CDF results:

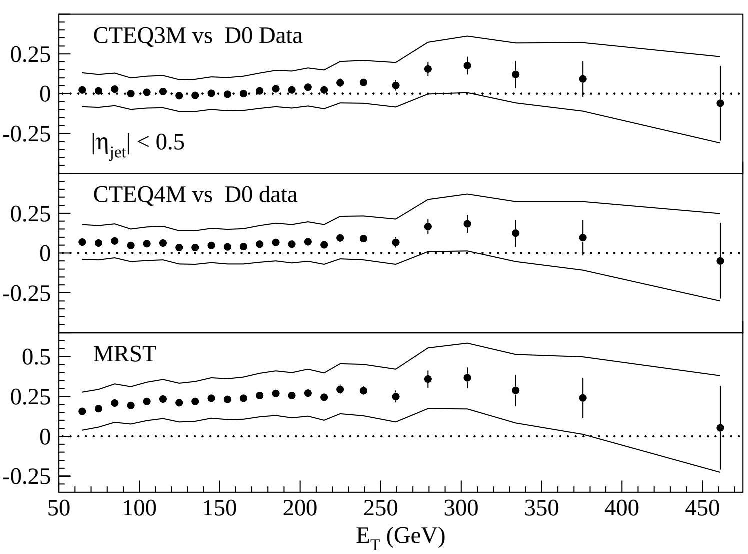




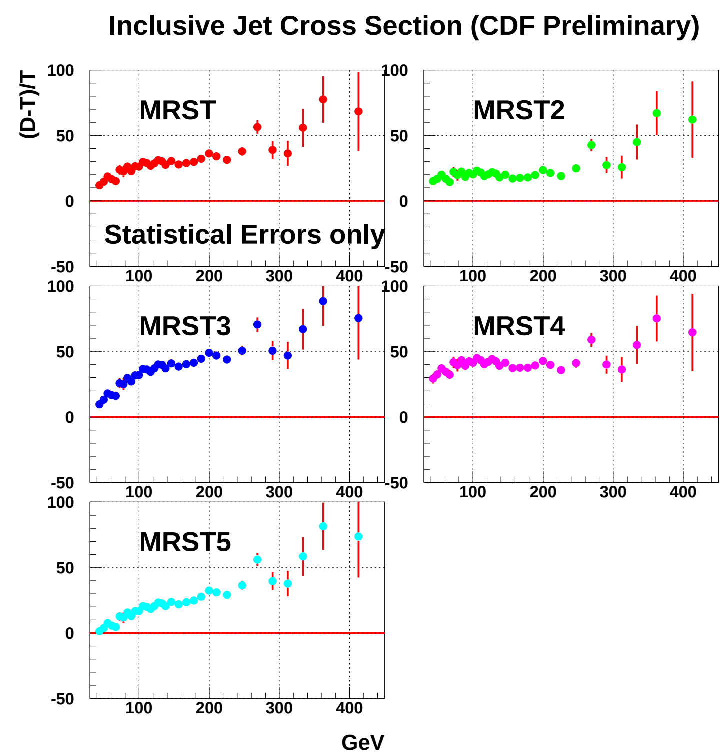
CDF PRELIMINARY
statistical errors only
630 GeV, 576 nb^{-1}
1800 GeV, 88.77 pb^{-1}, Run 1B
EKS CTEQ4M μ=E$_t$/2
Jet xt



Inclusive Jet Cross Section (CDF Preliminary)
(D-T)/T
CTEQ4M/A3
Statistical Errors only
CTEQ4A1
CTEQ4A2
CTEQ4A4
CTEQ4A5
GeV



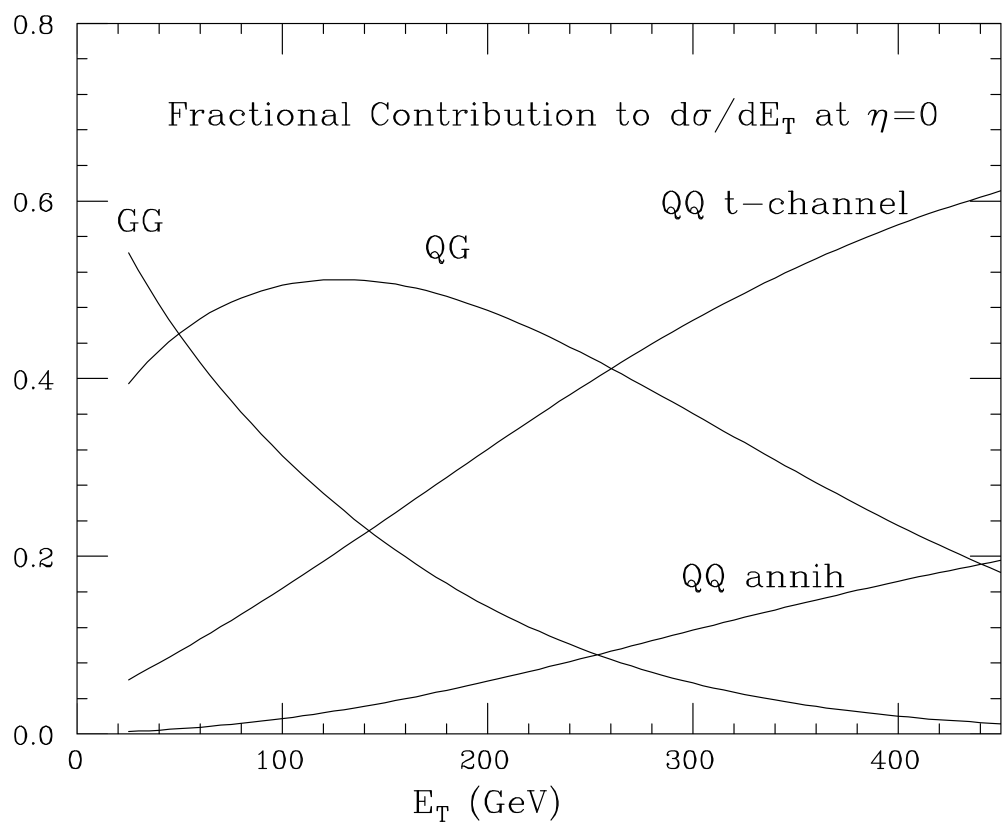
CTEQ3M vs D0 Data
$|\eta_{jet}| < 0.5$
CTEQ4M vs D0 data
MRST
E_T (GeV)



Inclusive Jet Cross Section (CDF Preliminary)
(D-T)/T
MRST
Statistical Errors only
MRST2
MRST3
MRST4
MRST5
GeV

What is the true uncertainty from PDF's at large x?

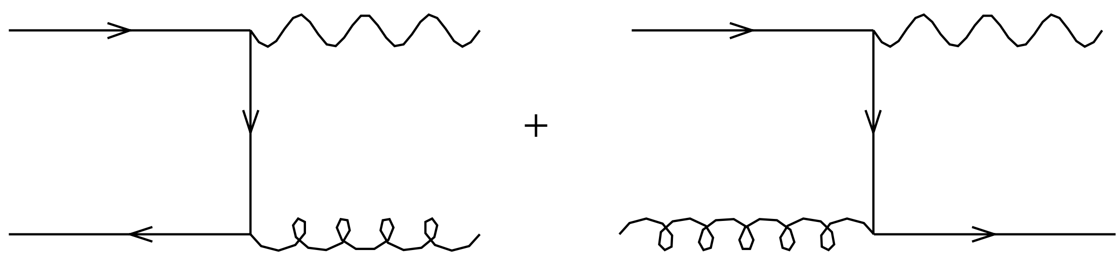
- Large-x quarks are constrained by DIS data to within few %.
- The CDF anomaly requires changes in the large-x gluon density by factors of $\mathcal{O}(2)$:



Is such a dramatic change in $f_g(x, Q^2)$ consistent with data from other processes?

Only other independent constraint on $f_g(x, Q^2)$ comes from

Prompt photons in fixed-target:



In pN collisions $g(x) \gg \bar{q}(x)$, and

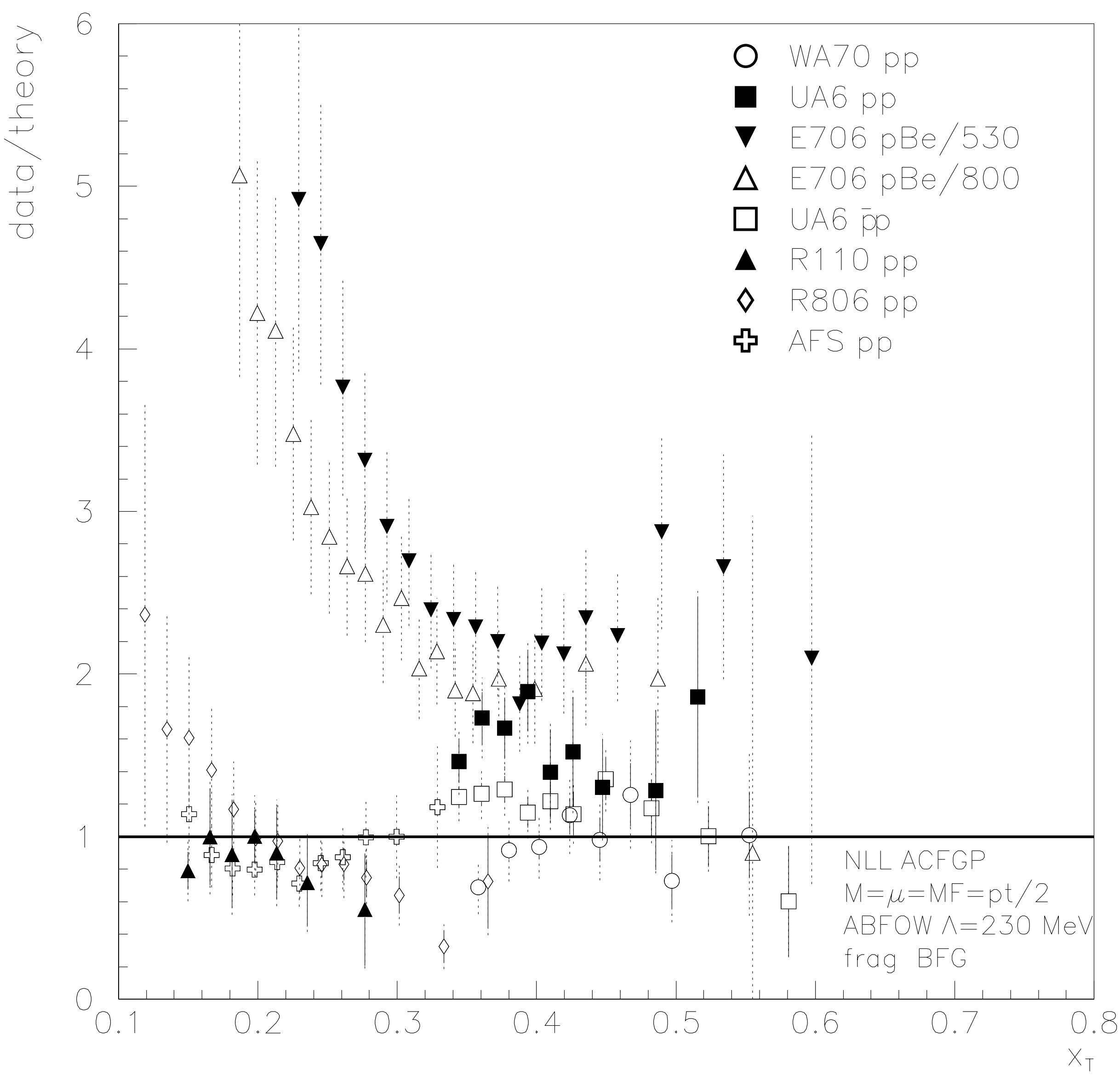
$$\frac{d\sigma}{dE_T}(qg \to q\gamma) \gg \frac{d\sigma}{dE_T}(q\bar{q} \to g\gamma)$$

Data from FNAL and CERN fxd target experiments are usually used to extract $f_g(x, Q^2)$ at large x.

- How reliable are these extractions?
- How reliable is the theory of prompt-γ production?

A comparison of data and NLO theory shows inconsistencies at small E_T between the various experiments:

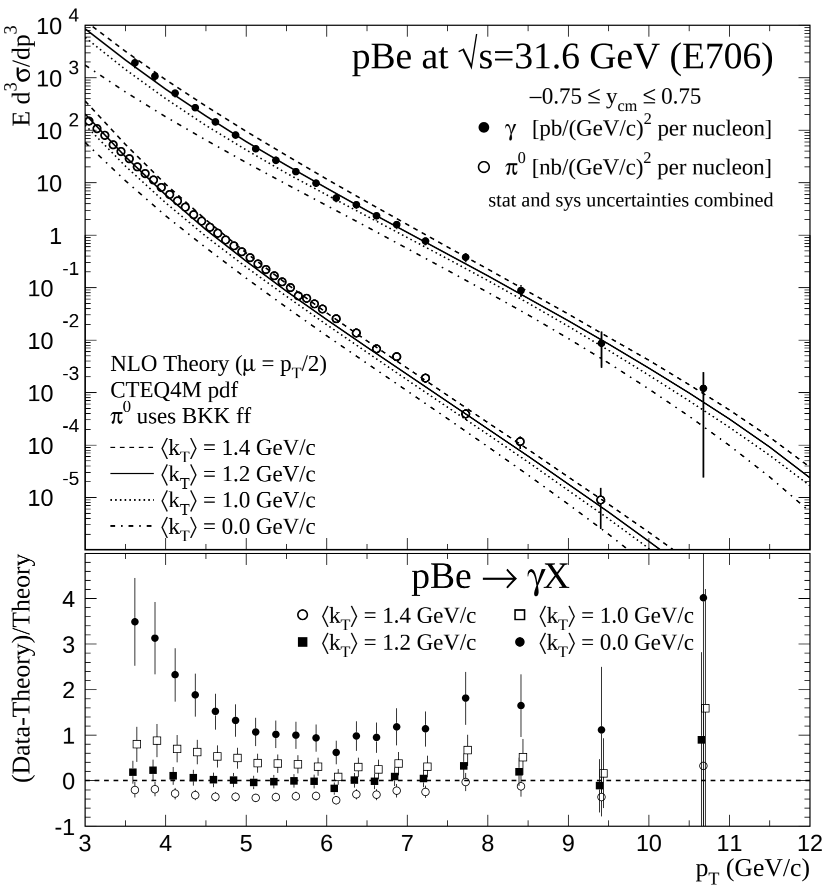
[1_635] Aurenche, Fontannaz, Guillet, Kniehl, Pilon, Werlen '99:

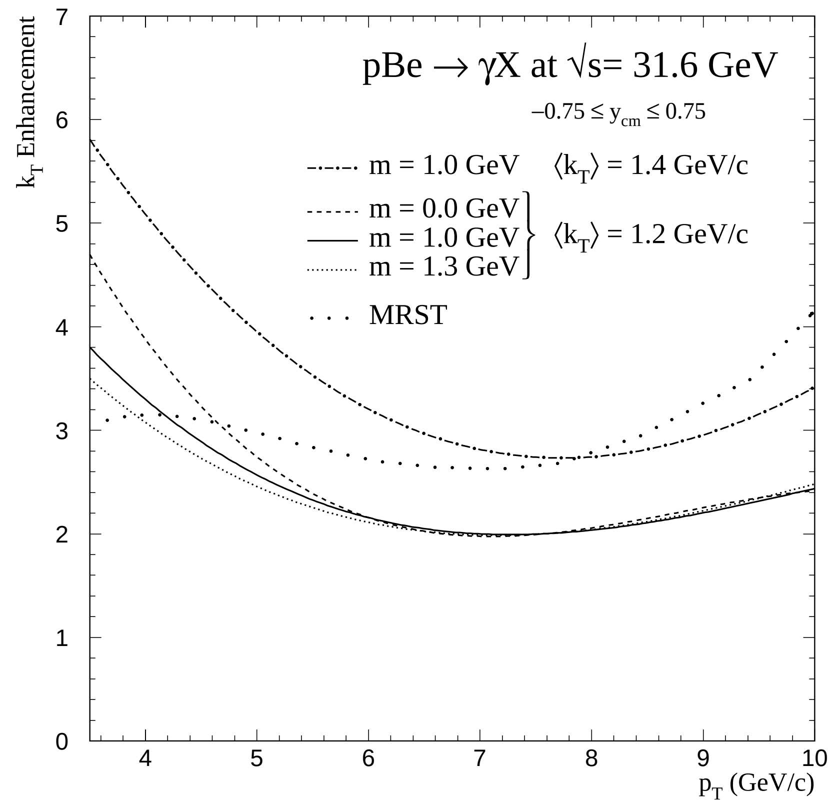


Problem # 1:

s it turns out, prompt-γ data at small E_T ($x \sim 0.3$) cannot be fitted with-ut inclusion of a large non-perturbative ontribution, from the intrinsic k_T of artons inside the nucleon: CTEQ, MRST

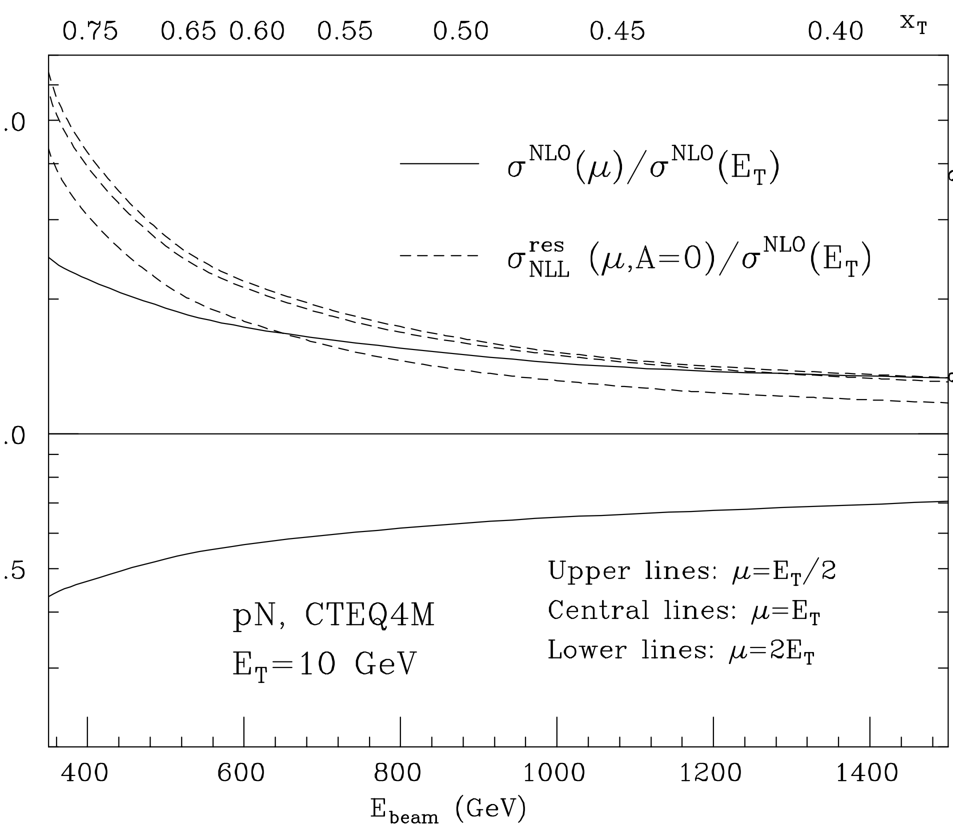
Inclusion of these effects, however, has large model dependence, and has a big impact also on the rate at large E_T (i.e. $x \sim 0.6$):





Problem # 2:

s $x \to 1$, large Sudakov effects become impor-
ant, and fixed-order perturbation theory is in-
ufficient to accurately calculate the rates. A
esummation of $\left[\alpha_s \ln^2(1-x)\right]^n$ corrections
o all orders of PT is necessary
Kidonakis [1_164]):
atani,Oleari,Mangano,Nason,Vogelsang '99



The corrections induced by the Sudakov resummation are very large at large E_T, and should be included in the fits to the data. No significant effect, as expected, is however found at low E_T, and the problem with the intrinsic k_T remains to be solved:

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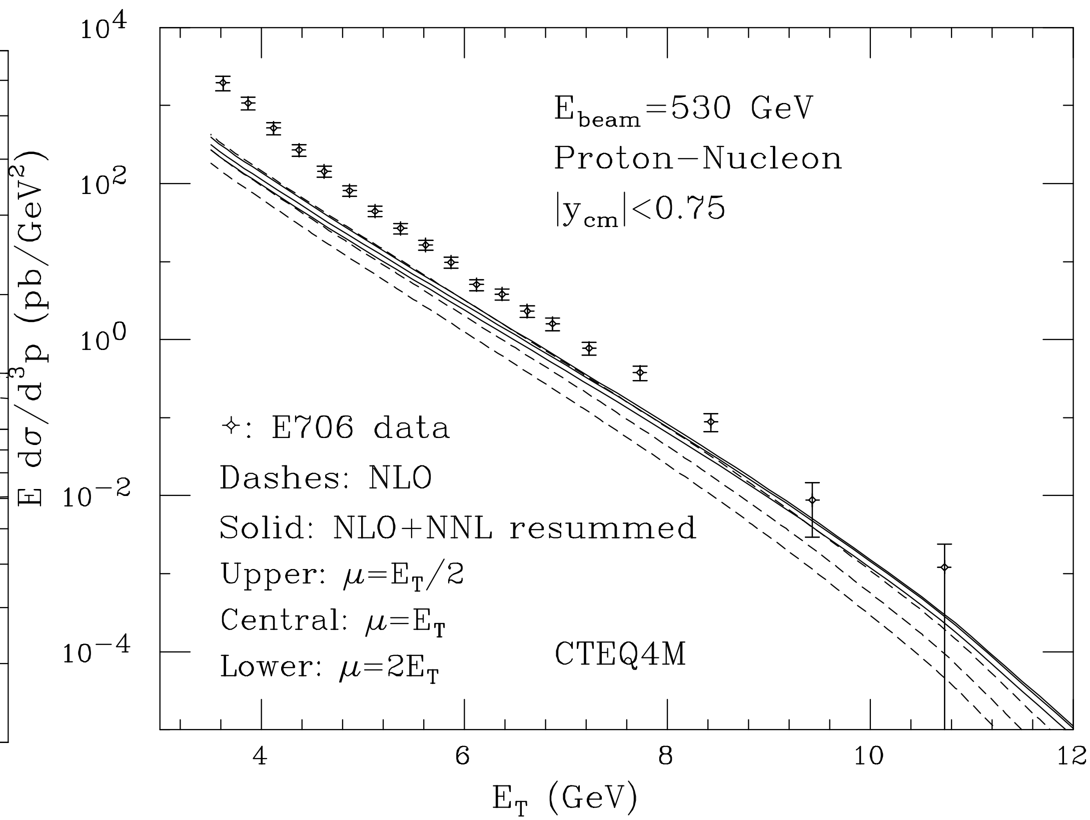
Catani,Oleari,Mangano,Nason,Vogelsang '99



CONCLUSIONS:

- The issue of the large-x behaviour of $f_g(x)$ remains an open problem
- Given the large size of resummation corrections at large E_T, it is unlikely that the fixed-target data will be consistent with the large $f_g(x)$ required to explain the CDF data

The problem of the high-E_T jet data will hopefully be solved using the data from the upcoming run of the Tevatron (due to start in the Summer 2000), thanks to an increase energy ($\sqrt{S} \to 2$ TeV, 10% increase):

- if the discrepancy is due to f_g then
  the discrepancy will arise at E_T values 10% larger
- if the discrepancy is due to new physics then
  the discrepancy will arise at same E_T

630/1800 GeV X-section ratios

It is expected that a large fraction of theoretical and experimental systematics will cancel when taking the ratio:

$$R(x_T = \frac{2E_T}{\sqrt{S}}) \; = \; \frac{[E_T^3 \, ds/dE_T]_{\sqrt{S}=630}}{[E_T^3 \, ds/dE_T]_{\sqrt{S}=1800}}$$

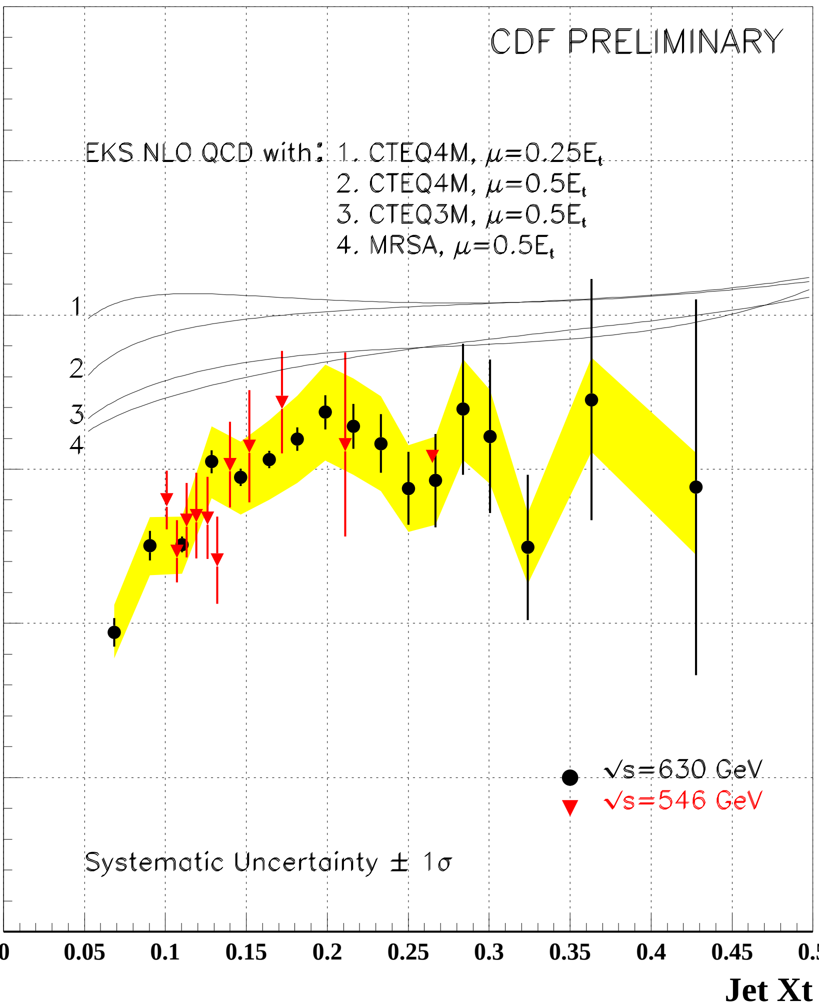
In the exact scaling limit $R(x_T) = 1$. Deviations from 1 arise from scaling violations in α_S and in the parton densities. The NLO theoretical uncertainity on this ratio is better than 10%.

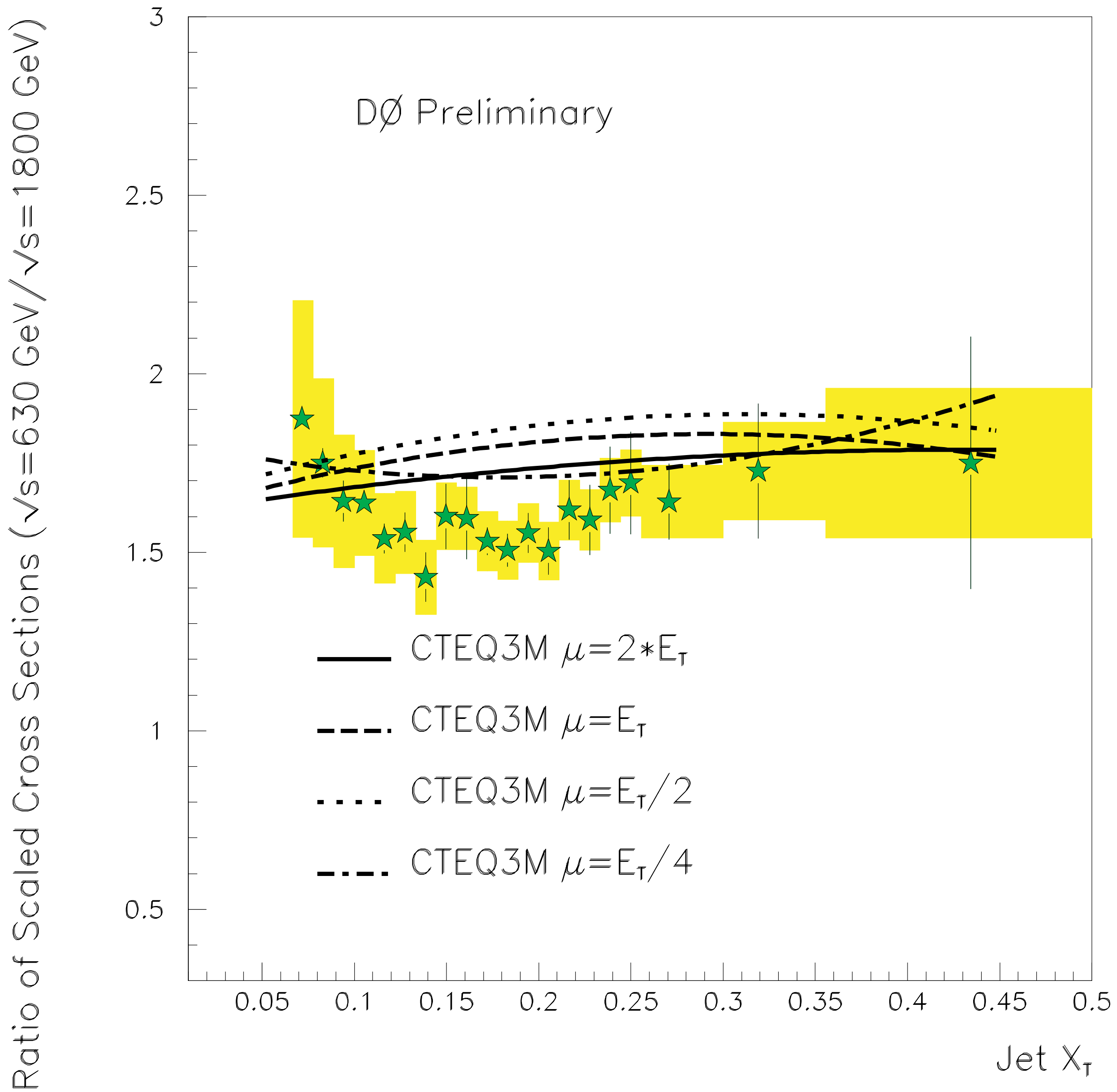
CDF and D0 observe serious deviations from theory at $x_T \lesssim 0.15$ ($E_T^{630} \lesssim 50$ GeV) ($\Rightarrow$ Figure).

What's more, the pattern of deviations is inconsistent between the two experiments. I feel this is a clear indication of the contamination of the PT results from power-suppressed effects.

(For previous studies of power-suppressed effects in the jet cross-sections and ratios, see e.g. D.Soper, `he-ph/9706320`, as well as work in progress by Huston et al)

CROSS-SECTION RATIOS FROM CDF (left) and D0 (right)





A PEDESTRIAN'S EVALUATION OF x_T RATIOS AND POWER CORRECTIONS

Let us approximate the inclusive jet cross-section with the value of the differential cross-section at $y = 0$ for both jets. In this case, at LO, one gets:

$$R(x_T) \; = \; \Sigma(x_T, \; 630 \text{ GeV})/\Sigma(x_T, \; 1800 \text{ GeV})$$

with

$$\Sigma(x_T, \sqrt{S}) \; = \; \alpha_S^2(\mu) \; F^2(x_T, \mu), \quad \mu = x_T \sqrt{S}/2$$

and

$$F(x) = G(x) + \frac{4}{9} \sum_{q,\bar{q}} \left[Q(x) + \bar{Q}(x) \right]$$

It turns out that this is indeed a very good approximation to the exact result, and in any case Σ does embody most of the scaling violations expected of the exact cross-section.

Power-suppressed corrections can be included by including a factor:

$$\Sigma(x_T, \sqrt{S}) \rightarrow \Sigma(x_T, \sqrt{S}) \times \left(1 \; + \; \frac{A}{E_T}\right) \; ,$$

What is the possible origin of A, and what is its right order of magnitude?

- Energy lost outside the jet cone ($A < 0$)
- Energy from the underlying event inside the jet cone ($A > 0$)
- Intrinsic k_T effects ($A > 0$)

PT contributions to the energy gain/loss can be evaluated and removed. However this can be done at LO only, since they are effects of $\mathcal{O}(\alpha_S^3)$ in PT.

Some energy changes induced by non-PT effects can be extracted from data and corrected for. E.g. the energy deposited in the cone by at least a part of the Minimum Bias underlying event.

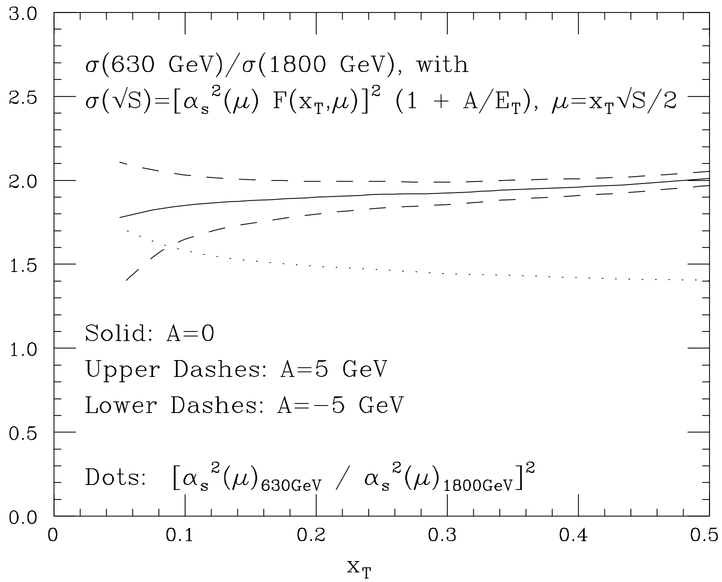
Correcting for these effects may leave with A or arbitrary sign, depending on whether one under- or over-corrects.

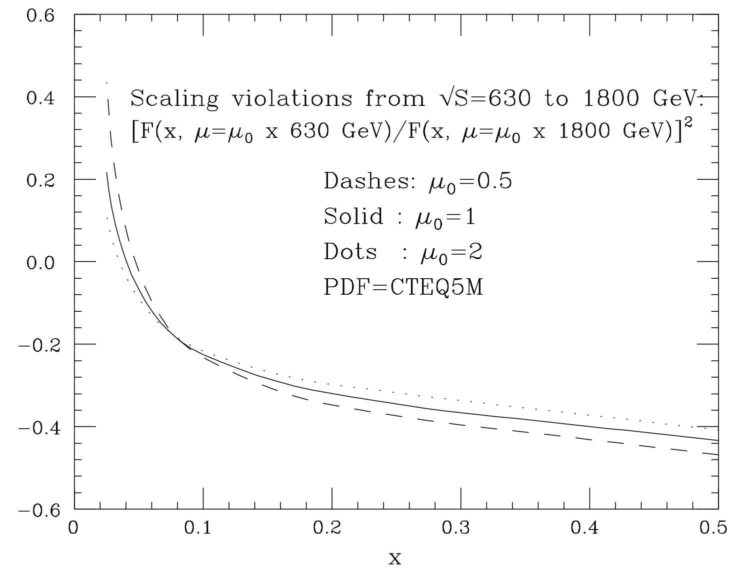
Finally, there is class of non-PT (e.g. parton recombinations with the beam fragments and with nearby jets) which are out of control.

The scale for all these effects is $\Lambda \sim \mathcal{O}(1 \text{ GeV})$. Assuming a $1/E_T^n$ fall-off of the cross-section, ones gets $A \sim n\Lambda$.

Values of $A \sim 5$ GeV should therefore NOT be surprising.

or $A \sim \pm 5$ GeV the effects are large, and can be consistent with the deviations bserved by CDF and D0:

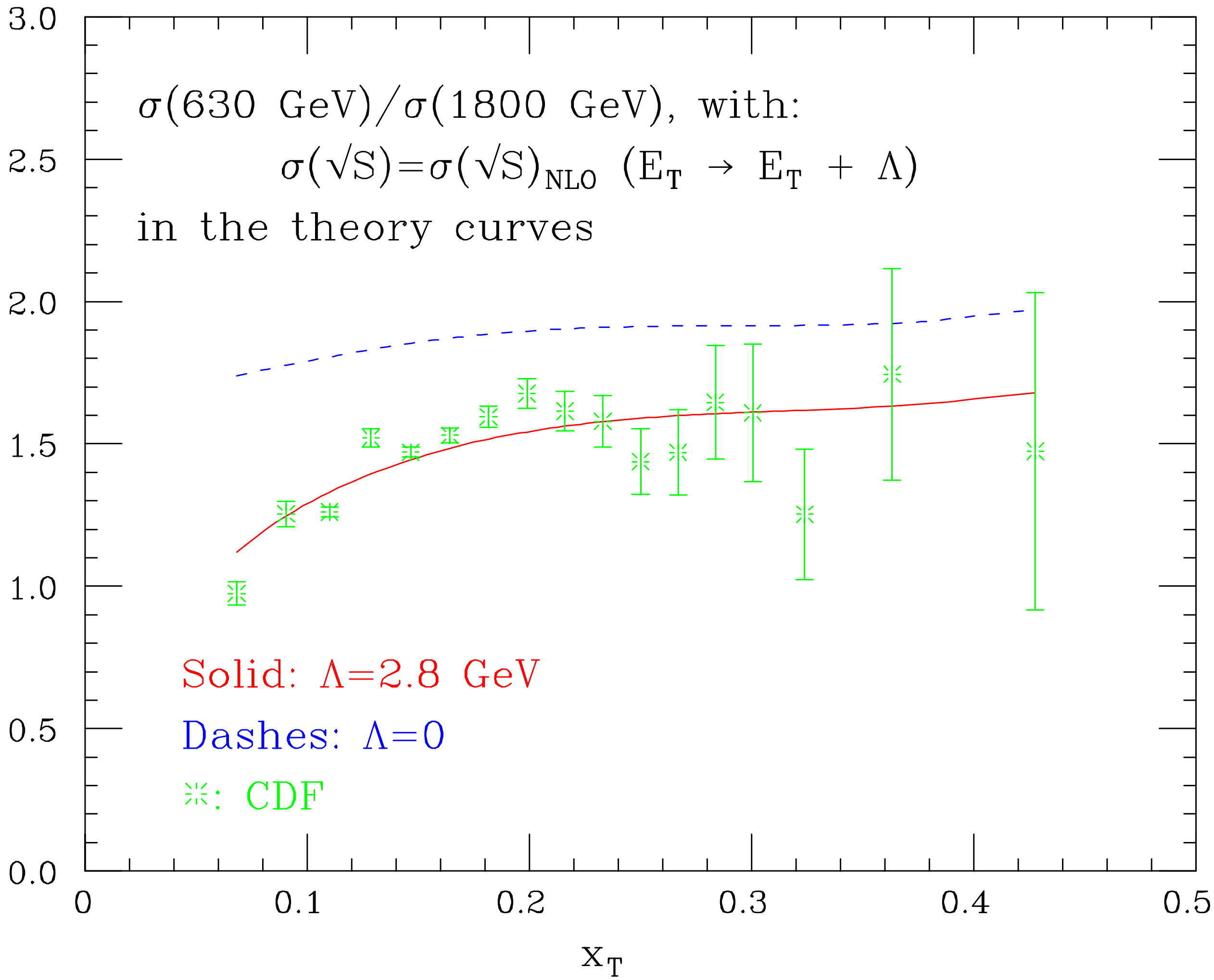




lotice that at $x_T \sim 0.05$ all scaling violations are due to the running of α_S, since this is n approximate fixed point for the evolution of the partonic luminosity $F(x_T)^2$. This is solid result, independent of the PDF set chosen, since in this range of x_T structure unctions are known with great accuracy. As a result, we don't expect that an anomaly n the 630/1800 ratio can be explained by playing with PDF's.

s the results above show, the case is in my view compelling for an explanation in terms f (acceptably sized) power-like corrections.

Using the exact NLO jet cross-section (CTEQ3M, $\mu = E_T/2$):



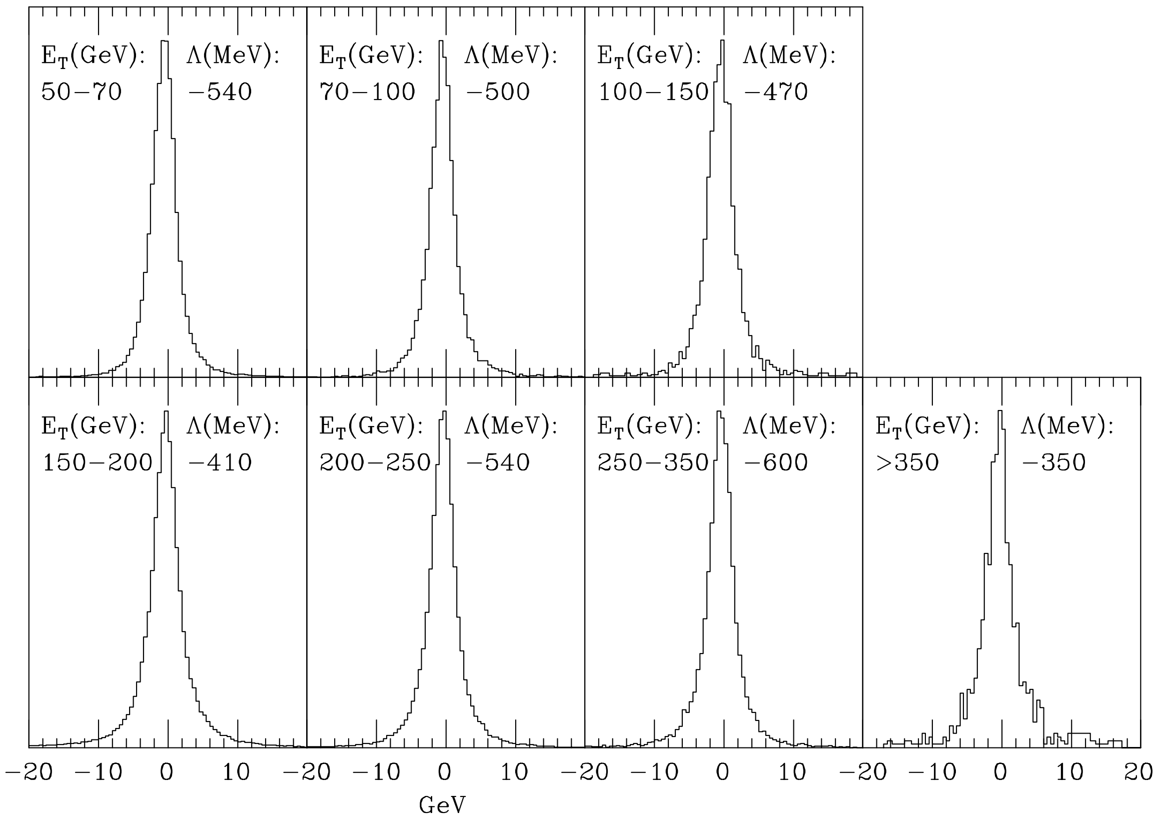
A shift in parton-level jet energy of -2.8 GeV provides a good fit to the CDF data.

Is such a shift acceptable?

Notice that the effect is large even at large x_T.

Herwig predictions for

$$E_{T,jet}^{\text{hadron-level}} - E_{T,jet}^{\text{parton-level}}$$



Each inset corresponds to jet in the indicated range of E_T. The value of Λ indicated (in MeV) corresponds to the average energy shift induced by hadronization corrections.

- Corrections of order 500 MeV
- Corrections $\sim$ independent of E_T for $50 < E_T < 500$ GeV
- Corrections are a non-negligible fraction of the effect necessary to explain the discrepancies between CDF/D0 data and NLO theory.

Conclusions on jet production at the Tevatron

- There is no evidence in my view for departures from QCD
- Current discrepancies (E_T spectrum at CDF, x_T ratios 630/1800 at both CDF and D0) are within theoretical and experimental uncertainties once proper account is taken of:
  - true uncertainties on the extraction of the gluon density
  - power corrections
  - limitations of the cone algorithm
- In view of this, it is premature in my view to use jets for accurate measurements, such as the extraction of $\alpha_S(Q^2)$
- However, better use can be made in the future of the large statistics, high E_T reach, and powerful control of the experimental systematics, if progress on the theory side can achieve:
  - firmer understanding of the intrinsic k_T effects in fixed-target γ production
  - NLL resummations for jet shape variables, á la LEP/SLD
  - control (even at the phenomenological level) of the power corrections
- New ideas are needed for observables which can help disentangling the various components of the theoretical uncertainties

MULTIJET PHENOMENA IN e^+e^- and ep

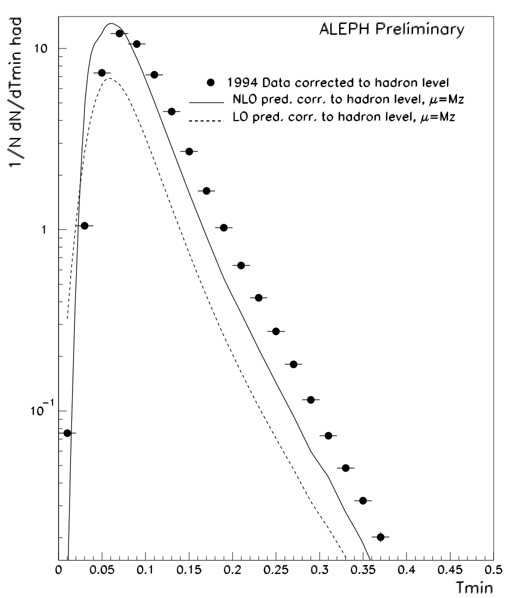
[1_544] ZEUS: Three-jet distributions in γp,
$M_{3j} > 50$ GeV. OK with LO QCD

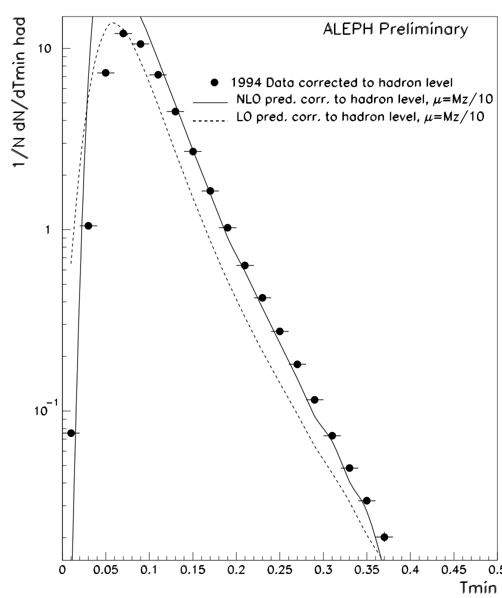
[1_553] ZEUS: High-mass dijet X-sections in γp,
$47 < M_{jj} < 140$ GeV. OK with NLO QCD

[1_531] ZEUS: Dijet X-sections in DIS.

[1_] H1:First measurement of 3-jet production in DIS:
OK with LO QCD

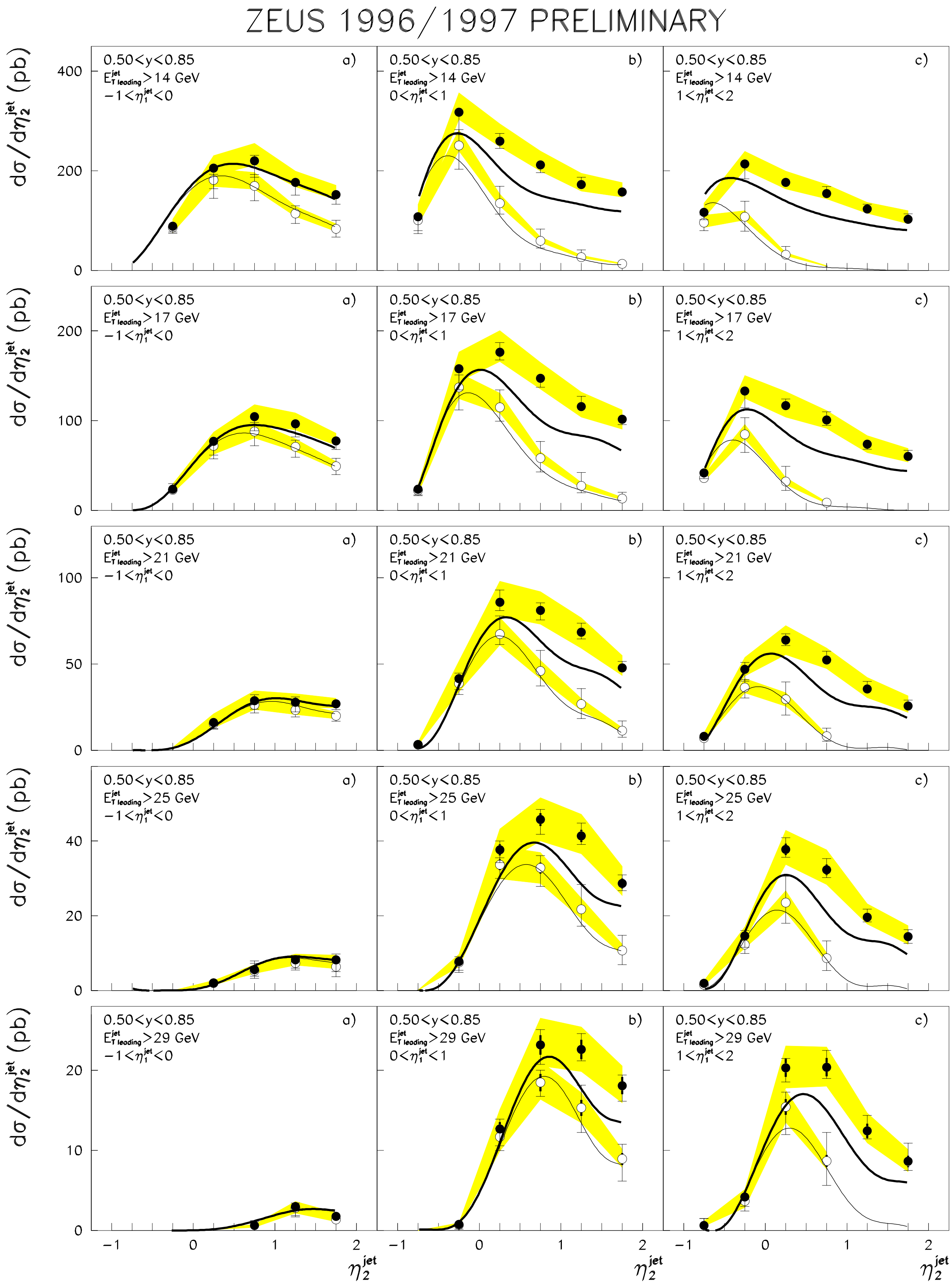
[1_386] ALEPH: NLO tests for 4-jet observables in Z^0
decays: good agreement, but $\mu = M_Z/10$!:





$\Rightarrow$ still no stringent limits on the absence of a light gluino from these data.

[1_540] ZEUS: Dijet X-sections in γp: not enough resolved-γ contribution from $x_\gamma \sim 0.5$: (relative to AFG-HO f_q^γ):



PHOTONS AND GAUGE BOSON PRODUCTION PROPERTIES AT THE TEVATRON AND HERA

[1_599] CDF: Measurement of the Isolated Photon Cross Section

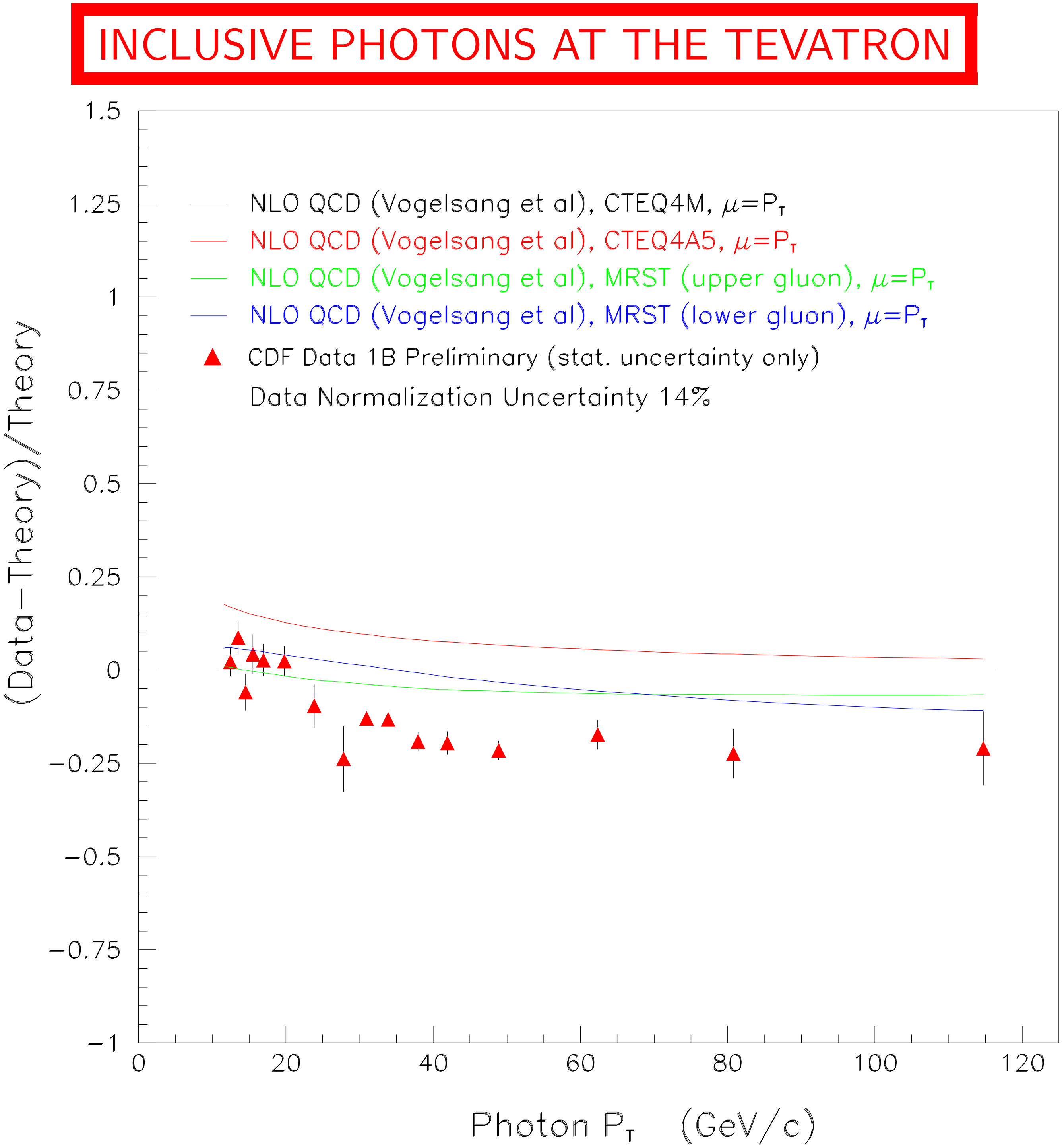
[1_598] CDF: Diphoton Production

[1_601] CDF: Measurement of W Production with Associated Jets in $p\overline{p}$ Collisions at 1.8 TeV

[1_71b] D0: Measurement of the Angular Distribution of Electrons from $W \rightarrow e\nu$ Decays Observed in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

[1_71d] D0: Measurement of the Transverse Momentum Distribution of W and Z Bosons Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

[1_531] ZEUS: Prompt Photon Processes in Photoproduction



INCLUSIVE PHOTONS AT THE TEVATRON
NLO QCD (Vogelsang et al), CTEQ4M, μ=P_T
NLO QCD (Vogelsang et al), CTEQ4A5, μ=P_T
NLO QCD (Vogelsang et al), MRST (upper gluon), μ=P_T
NLO QCD (Vogelsang et al), MRST (lower gluon), μ=P_T
CDF Data 1B Preliminary (stat. uncertainty only)
Data Normalization Uncertainty 14%
(Data−Theory)/Theory
Photon P_T (GeV/c)
1.5
1.25
1
0.75
0.5
0.25
0
−0.25
−0.5
−0.75
−1
0
20
40
60
80
100
120

HVQ's in $\gamma\gamma$ collisions at LEP2

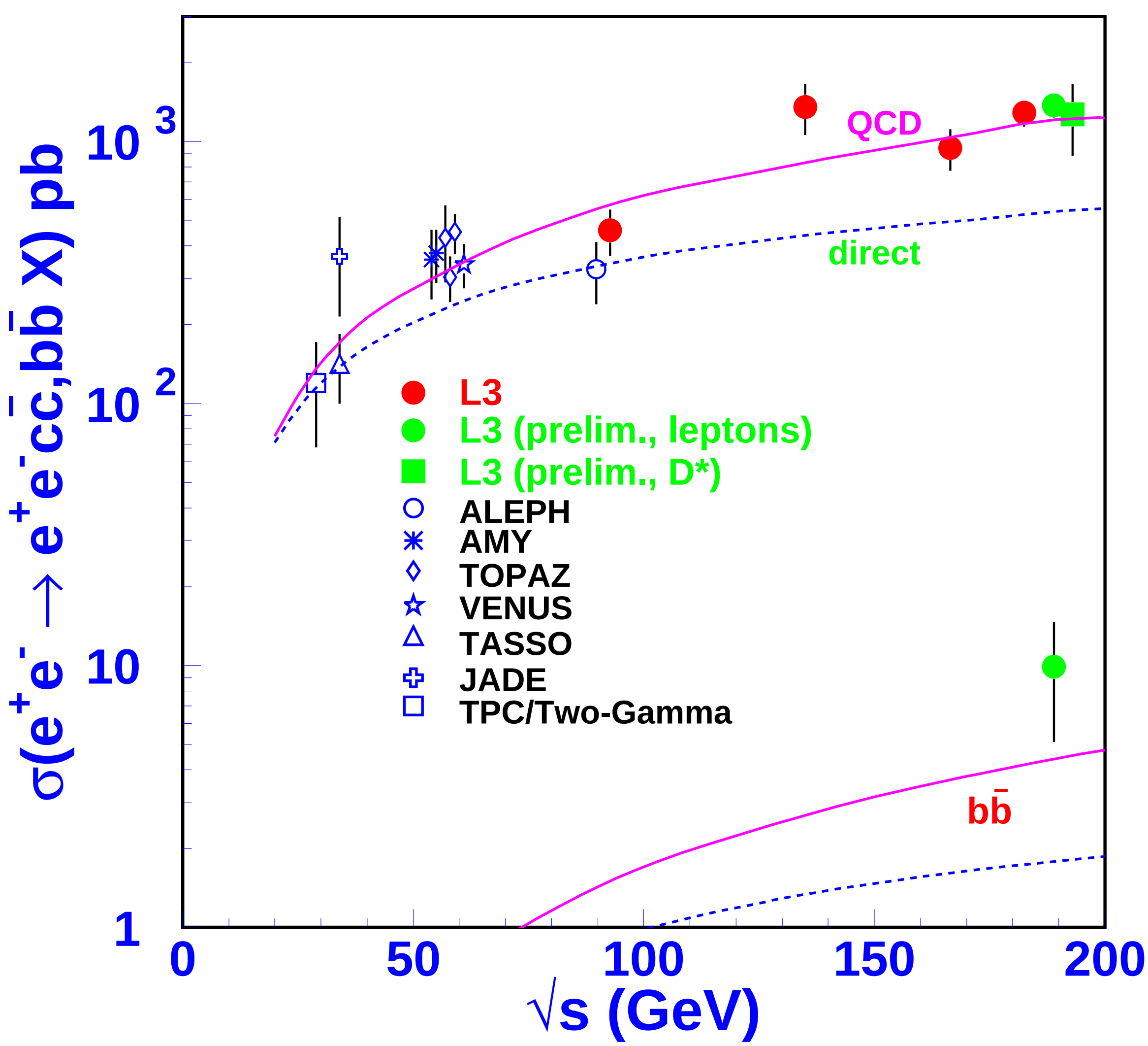
Beautiful results! First measurements of $b\bar{b}$ production.

[1_265] L3: $c\bar{c}$ and $b\bar{b}$ production in $\gamma\gamma$ at 91-189 GeV

[1_275] L3: D^* production and p_T spectra in $\gamma\gamma$ at 183-189 GeV

[1_23] OPAL: D^* production and p_T spectra in $\gamma\gamma$ at 183-189 GeV

All papers share the same conclusions: good agreement with QCD, provided resolved component of the γ is included



$g \to c\bar{c}$, $b\bar{b}$ SPLITTING FRACTIONS IN Z^0 DECAYS

- Largest single source of error on R_b!
- QCD (Seymour '95, up-to-date α_S):

$$n_{Z^0}(g \to c\bar{c})\rangle = 2.2\% \quad n_{Z^0}(g \to b\bar{b})\rangle = 0.2\%$$

- Not to be used as *universal* gluon-splitting probabilities: they reflect the spectrum of gluons in $Z \to$ jets.

[1_9, 1_10] OPAL: $g \to b\bar{b}$, $g \to c\bar{c}$, in 4-jet events:

$$\begin{aligned} \langle n_{Z^0}(g \to c\bar{c})\rangle &= 3.20(21)(38) \cdot 10^{-2} \\ \langle n_{Z^0}(g \to b\bar{b})\rangle &= 2.15(43)(80) \cdot 10^{-3} \end{aligned}$$

[1_281] L3:

$$\langle n_{Z^0}(g \to c\bar{c})\rangle = [2.45(35)(45) - 3.74(n_{b\bar{b}} - 0.26)] \cdot 10^{-2}$$

[1_226] DELPHI:

$$\langle n_{Z^0}(g \to b\bar{b})\rangle = 3.3 \pm 1.0 \pm 0.7 \cdot 10^{-3}$$

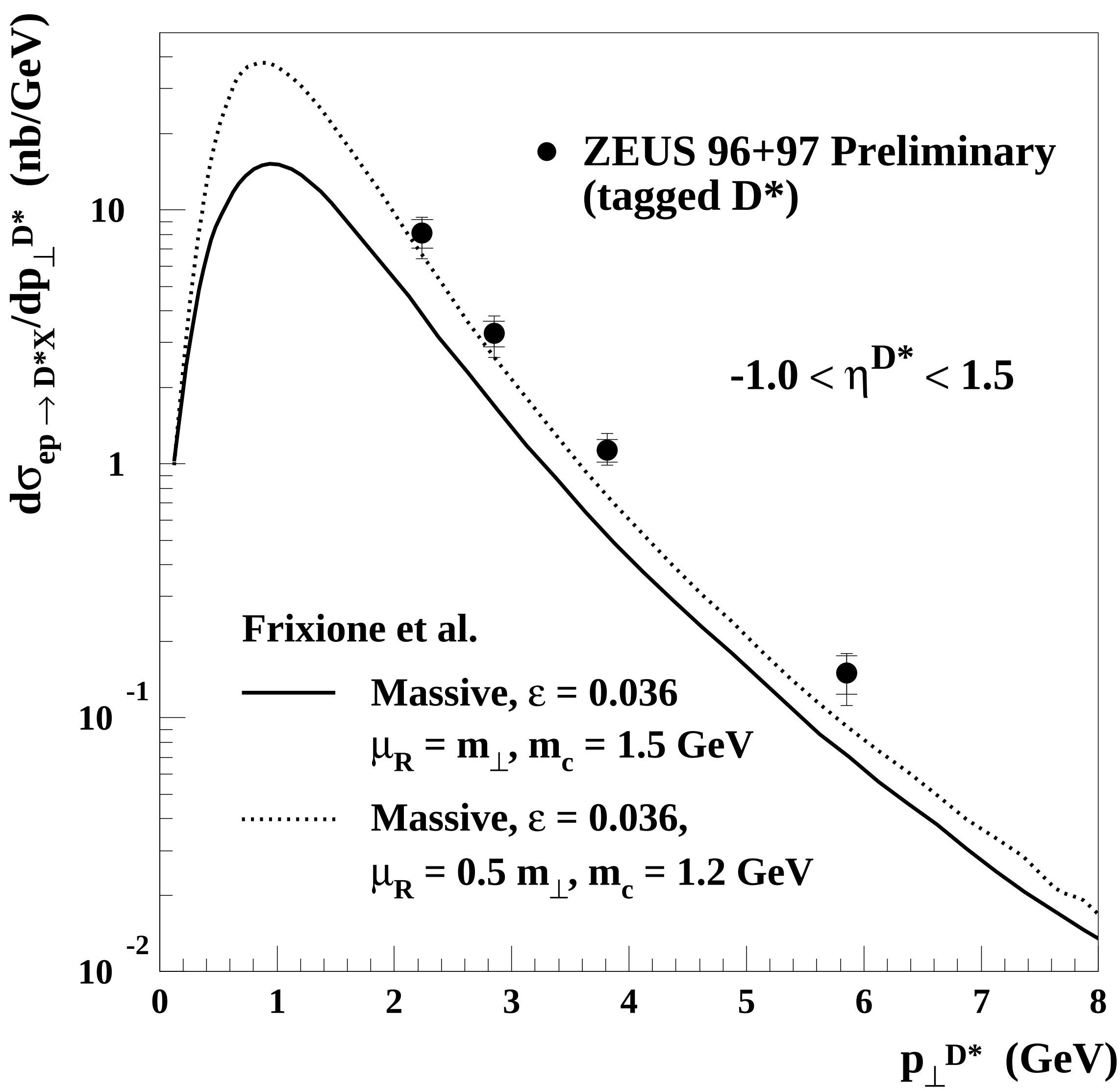
[1_184] SLD:

$$\langle n_{Z^0}(g \to b\bar{b})\rangle = 3.07(71)(66) \cdot 10^{-3}$$

NB: Detection efficiencies $\sim$ few % $\Rightarrow$ large theoretical extrapolation to full rate! Marginal agreement between resummed QCD and shower MC's (Miller/Seymour '98) $\Rightarrow$ systematics larger than quoted?

c, b QUARK PRODUCTION AT HERA

[1_525] ZEUS: $D_s^{\pm}$, $D^{*\pm}$ production in γp



[1_528] ZEUS: $D^{*\pm}$ production in jets

[1_498] ZEUS: b production in γp, w. $b \to \ell X$
[5_157v] H1: b production in γp, w. $b \to \ell X$:

H1 single lepton:

$$\sigma^{vis}_{b\bar{b}}(\mathrm{nb}) = \begin{array}{ll} 0.93 \pm 0.08_{stat}\,{}^{+0.21}_{-0.12}{}_{syst} & \text{H1 Data} \\ 0.19 & \text{LO Aroma MC} \end{array}$$

H1 dimuons:

$$\sigma^{vis}_{b\bar{b}}(\mathrm{pb}) = \begin{array}{ll} 55 \pm 30_{stat} \pm 7_{syst} & \text{H1 Data} \\ 17 & \text{LO Aroma MC} \end{array}$$

ZEUS single lepton:

$$\sigma^{vis}_{b\bar{b}}(\mathrm{pb}) = \begin{array}{ll} 39 \pm 11_{stat}\,{}^{+0.23}_{-16}{}_{syst} & \text{ZEUS Data} \\ 10 & \text{LO Herwig} \end{array}$$

$$\boxed{\sigma(b\bar{b}) \sim 4 \times \text{QCD.}}$$

VERY difficult to accept, since QCD describes well charm production at HERA! More work is clearly needed to compare data and theory.

BOTTOM QUARK PRODUCTION AT THE TEVATRON

Sore point for NLO QCD:

- very large (~ 2) scale uncertainty
- dependence on the knowledge of non-PT $b \rightarrow B$ fragmentation function

However, within the theoretical uncertainties, the agreement with data is acceptable ($\Rightarrow$ Figure)

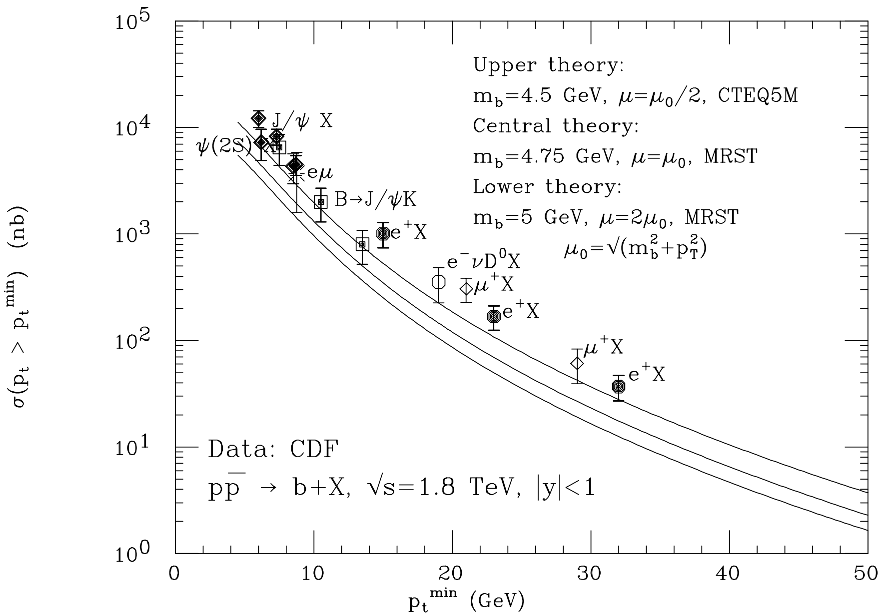
The theory provides a good description of the shapes of $b\bar{b}$ correlations in the azimuthal plane and in rapidity (CDF 1_123, D0). All results$^{(*)}$ indicate that

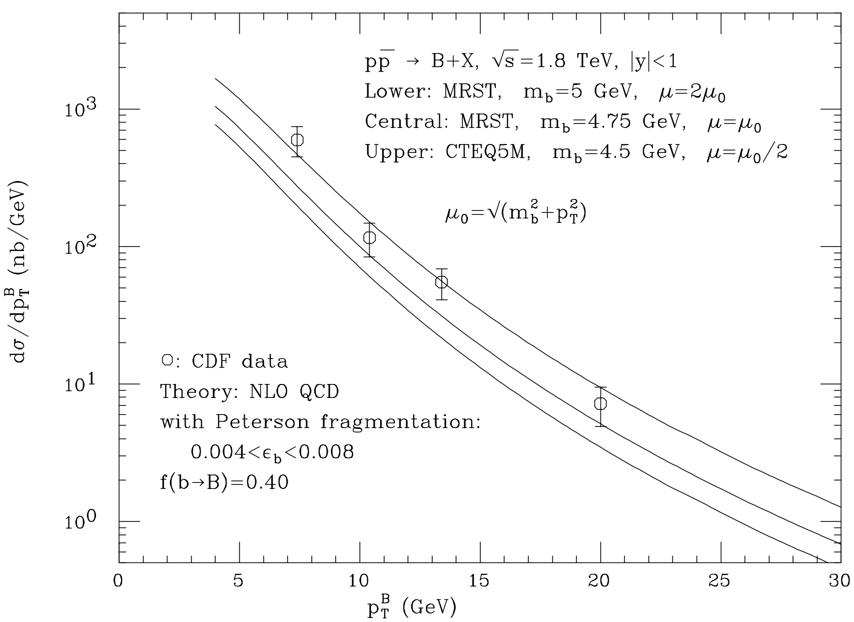
- one-particle inclusive distributions
- azimuthal and rapidity correlations
- $\sqrt{S}$ evolution of cross-sections

are well described in shape by NLO QCD, and only the absolute normalization, affected by large scale-dependence uncertainties, needs to be stretched to the extreme range of theoretical systematics to be accomodated.

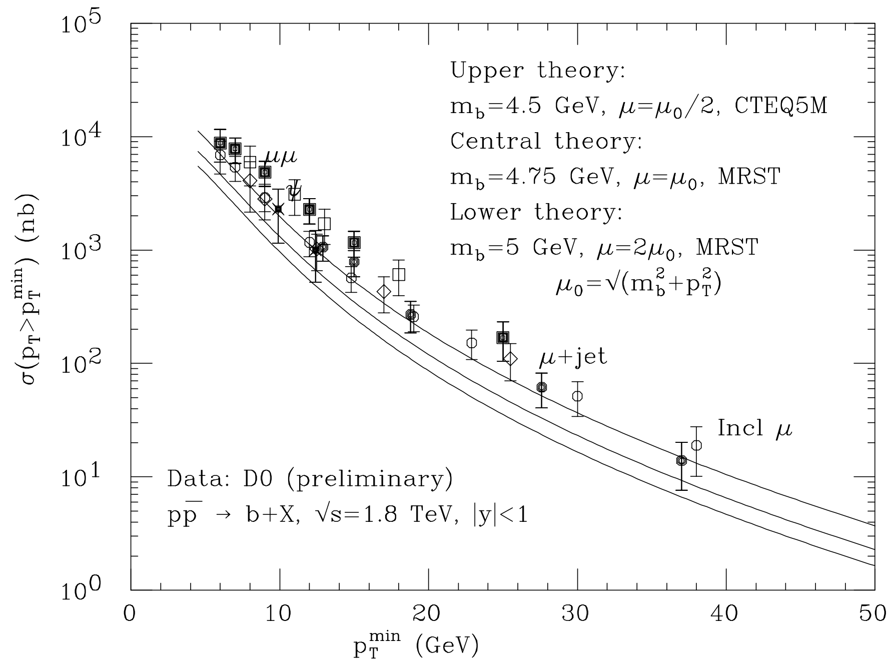
$^{(*)}$ With the exception of a 1995 (but yet unpublished) preliminary measurement by D0, supporting an anomalous production of b quarks at large rapidities.

New data from CDF [1_37]:





New data from D0:

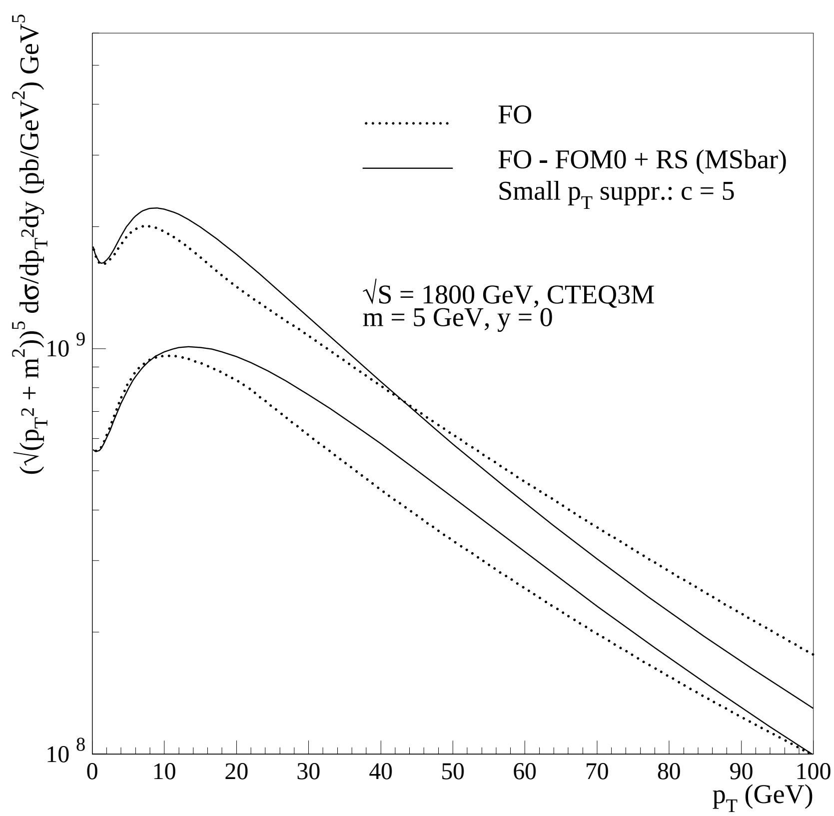


Recent progress in theory:

- resummation of large $\log(p_T/m_b)$ (Olness, Tung, Scalise; Cacciari, Greco, Nason):
  - improved scale dependence at large p_T
  - resummed rate $\gtrsim$ NLO rate with $\mu = \mu_0/2$

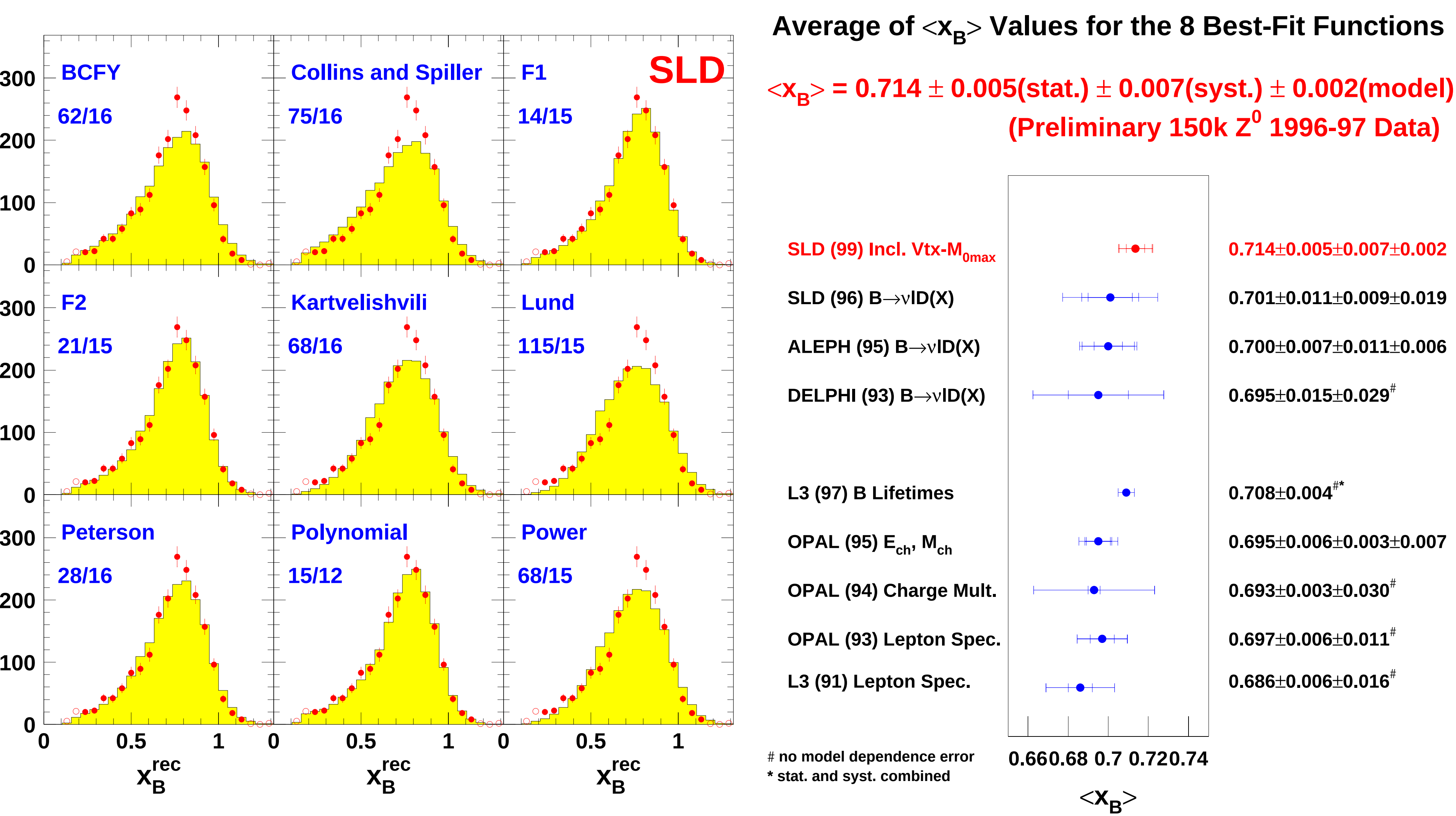
$\Rightarrow$ going in the right direction to agree with CDF/D0 data.

Cacciari
Greco
Nason



- $\mathcal{O}(\alpha_S^2)$+NLL studies of fragmentation functions in e^+e^- (Nason, Oleari), with new accurate experimental results from LEP and SLD ($\Rightarrow$ Fig.)

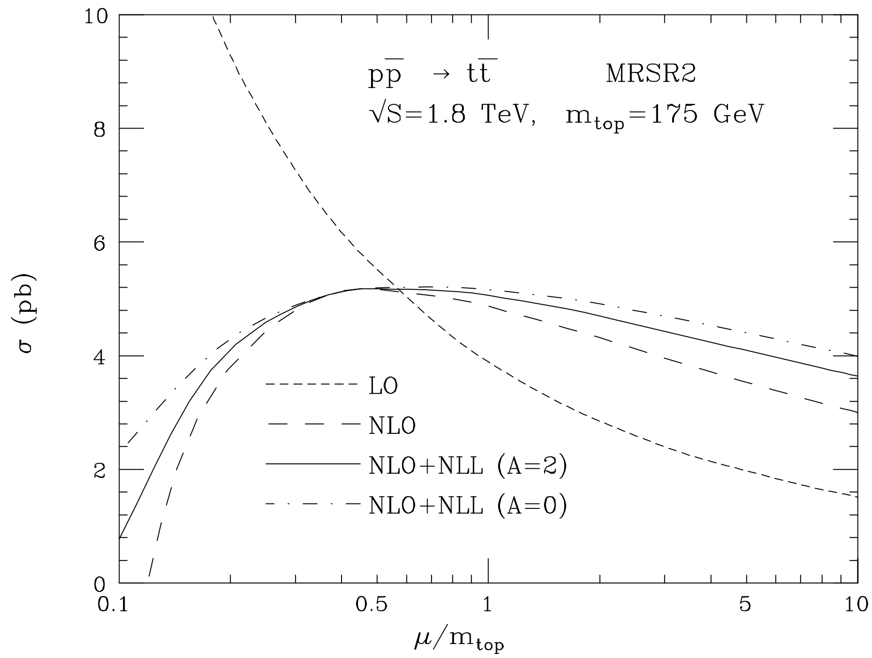
lew measurement of b fragmentation function by SLD [1_182]:



TOP QUARK PRODUCTION AT THE TEVATRON

Theoretical status: NLL resummation of Sudakov threshold effects has been carried out. (Sterman, Laenen, Kidonakis; Bonciani, Catani, Mangano, Nason).

Results indicate good reduction in scale uncertainty, to the level of $\pm 5\%$ (Bonciani et al.):



There is in addition a $\pm 7\%$ uncertainty due to the choice of PDF's: (Bonciani et al.):

PDF	$\mu = m_{top}/2$	$\mu = m_{top}$	$\mu = 2m_{top}$
MRST	5.04	4.92	4.57
MRST$g\uparrow$	5.22	5.09	4.72
MRST$g\downarrow$	4.90	4.79	4.45
MRST$\alpha_S\downarrow$	4.84	4.74	4.42
MRST$\alpha_S\uparrow$	5.20	5.07	4.68
CTEQ5M	5.41	5.30	4.91
CTEQ5HJ	5.61	5.50	5.10

TOP QUARK CROSS SECTIONS

New determination of the top cross section from CDF:
1σ reduction relative to the old result, BETTER AGREEMENT with QCD.

Systematically lower value for the "best" measurements, higher values for the lower-statistics, higher-systematics channels.

Results, in pb, for $m_{top} = 175$ GeV:

CDF	D0	BCMN	BC	K
6.5 ± 1.5	5.4 ± 1.5	5.0 ± 0.6	$5.57\,^{+0.07}_{-0.42}$	7

- CDF: EPS # 5_455
- D0: PRD60(1999)012001, rescaled from 172.1 to 175 GeV.
- BCMN: Bonciani, Catani, MLM, Nason, NLL, Mellin inversion, NPB529(1998)424. Unc. range given by scale and PDF variations.
- BC: Berger, Contopanagos, LLog, CTEQ3M, PRD57(1998)253
- K: Kidonakis, NLL, cutoff resummation, hep-ph/9904507

CONCLUSIONS

- After 25 years, QCD is still a *very rich an exciting field*, with progress both in the experimental techniques and in the theoretical understanding

- *Measurements are becoming more and more sophisticated*, and the challenge for theorists is becoming harder and harder

- The accuracy in the *extraction of α_S is reaching its limits.* New theoretical developments will be necessary to take advantage of the future ep and $p\bar{p}$ (as well as LHC) data.

- A consistent *phenomenological picture of the impact of the hadronization phase* on the structure of final states is emerging. Tests in e^+e^- collisions are becoming very compelling, and the universality of the description of power corrections has been tested even in ep collisions.

- Application of these ideas to *hadronic collisions will require more work.* The new frontier is the evaluation of NNLO cross-sections and NNL resummations. Attention should go to the use of appropriate jet algorithms, and to the identification of appropriate observables.

- *Extraction of the gluon density* from photon and jet data has also *reached the limit of theoretical accuracy.* Progress on the above points will be necessary before further improvements can be achieved.