Tests of Perturbative QCD and Jet Physics

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XIX International Symposium on Lepton and Photon Interactions at High Energies

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http://d0server1.fnal.gov/users/womersley/LeptonPhoton99.ppt

Topics in QCD

- **A vast domain:**
  - in the past 12 months, 473 papers with "QCD" in the title were submitted to the hep-ph archive
    (admittedly, this does include "Cosmological QCD Phase Transition and Dark Matter")
  - 93 abstracts submitted to EPS '99

- **Hence I shall have to be selective: focus on**
  - final states: jets, photons, weak bosons and heavy flavour
  - measurements of α_s (fundamental parameter of the theory)

- Pleasant to be able to speak purely on my own behalf rather than trying to represent the "party line" of all the experiments — please therefore excuse any biases from my background as a Tevatron experimentalist.

- Thanks to everyone who helped me put this presentation together, and apologies to all those whose work had to be omitted or brutally summarized.

Jets

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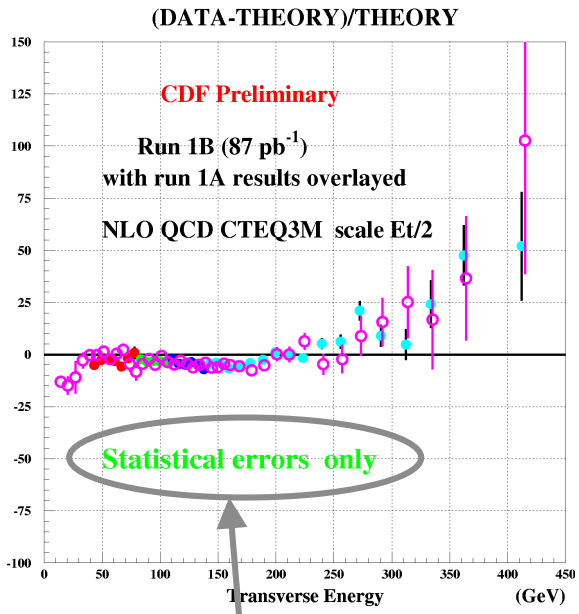
Jet cross sections at $\sqrt{s}$ = 1.8 TeV

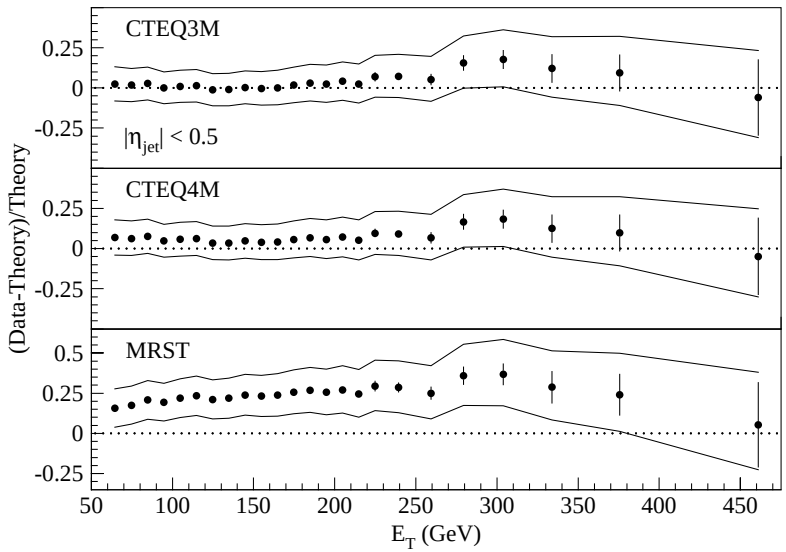
- **So much has been said about the high-E_T behaviour of the cross section that it is hard to know what can usefully be added**

CDF



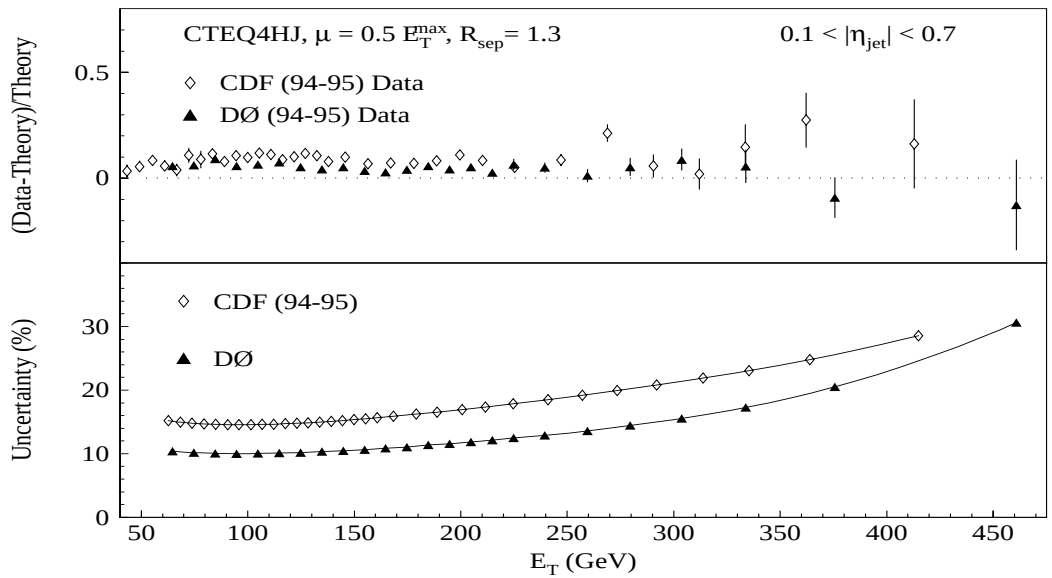
NB Systematic errors not plotted

DØ



The DØ and CDF data agree

- **DØ analyzed 0.1 < |η| < 0.7 to compare with CDF**
  - Blazey and Flaugher, hep-ex/9903058 Ann. Rev. article



- **Studies (e.g. CTEQ4HJ distributions shown above) show that one can boost the gluon distribution at high-x without violating experimental constraints*; results are more compatible with CDF data points**

  *except maybe fixed-target photons, which require big k_T corrections before they can be made to agree with QCD (see later)

What have we learned?

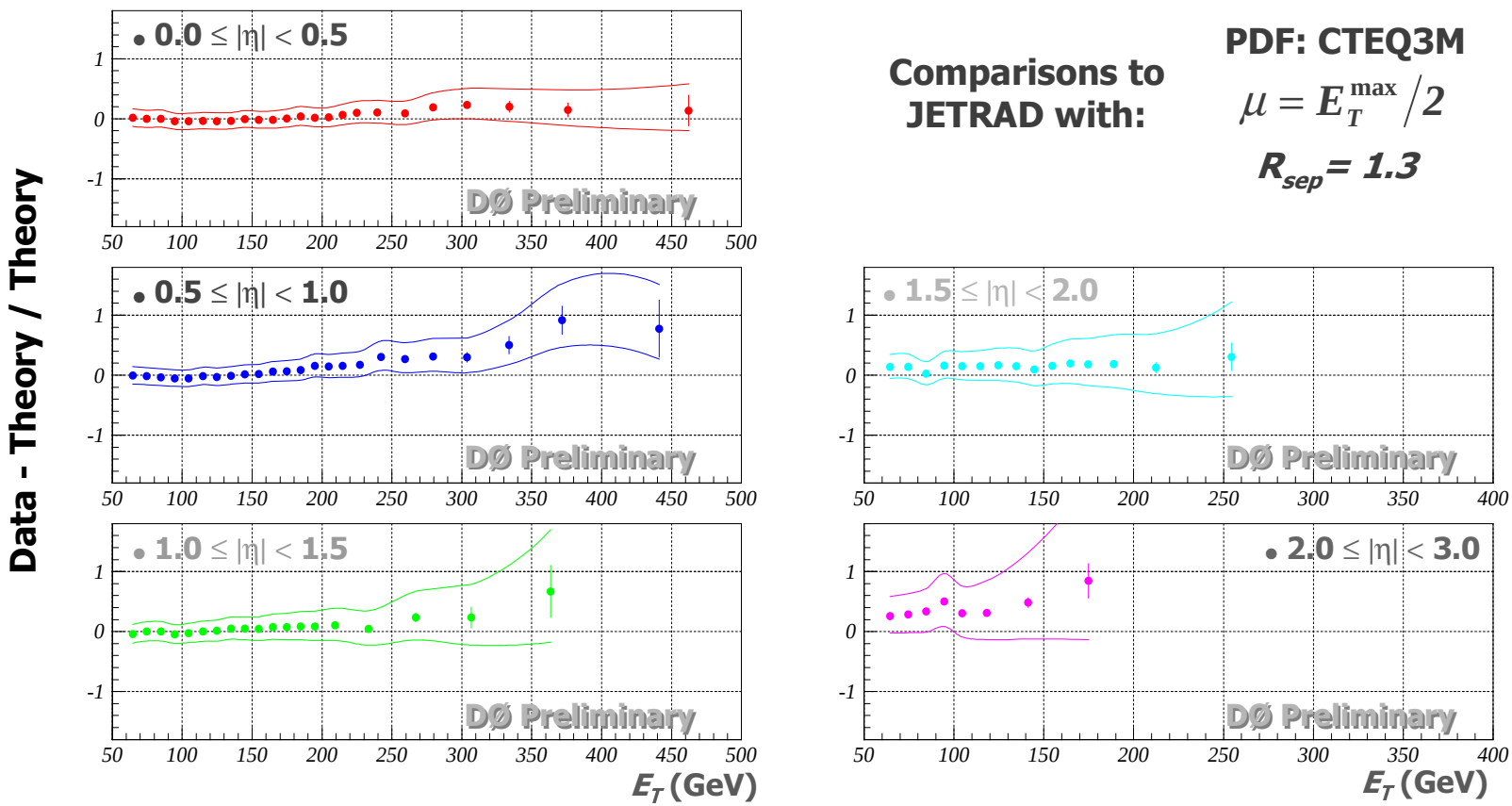
- **Whether the CDF data show a real or just a "visual" excess at high E_T depends critically on understanding the systematic errors and their correlations as a function of E_T**

- **Whether nature has actually exploited the "freedom" to enhance gluon distributions at large x will only be clear with the addition of more data**
  - factor 20 more data in Run II, starting summer 2000, will extend the reach to higher E_T and should make the asymptotic behaviour clearer

- **whatever the Run II data show, this has been a useful lesson:**
  - parton distributions have uncertainties, whether made explicit or not
  - a full understanding of experimental systematics and their correlations is a good thing

Forward Jets

- **DØ inclusive cross sections up to $|\eta|$ = 3.0**



Comparisons to JETRAD with:

PDF: CTEQ3M

$\mu = E_T^{\max}/2$

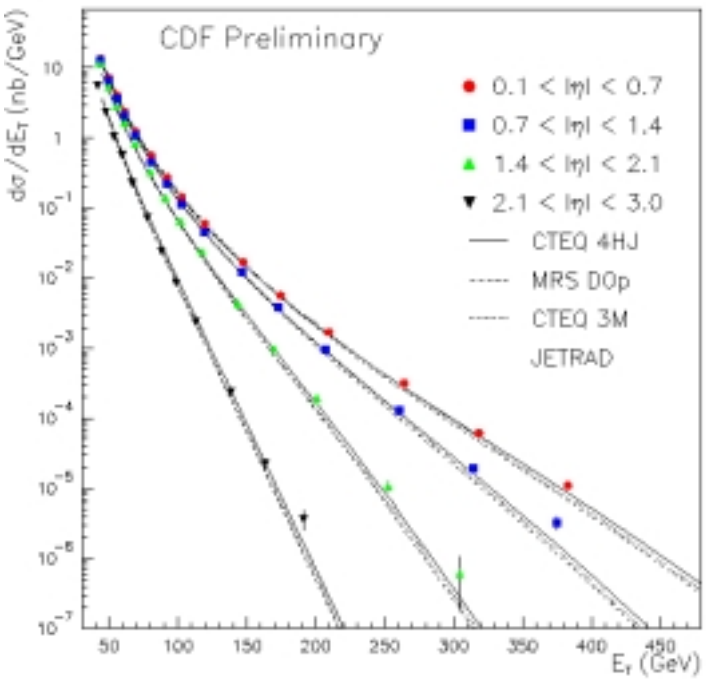
R_{sep} = 1.3

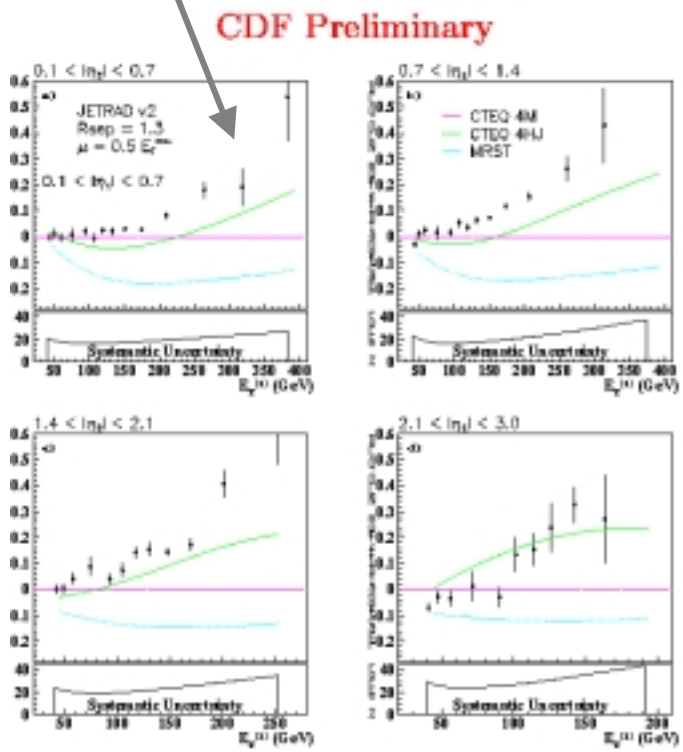
Triple differential dijet cross sections

Triple differential cross sections can be used to extract or constrain PDF's

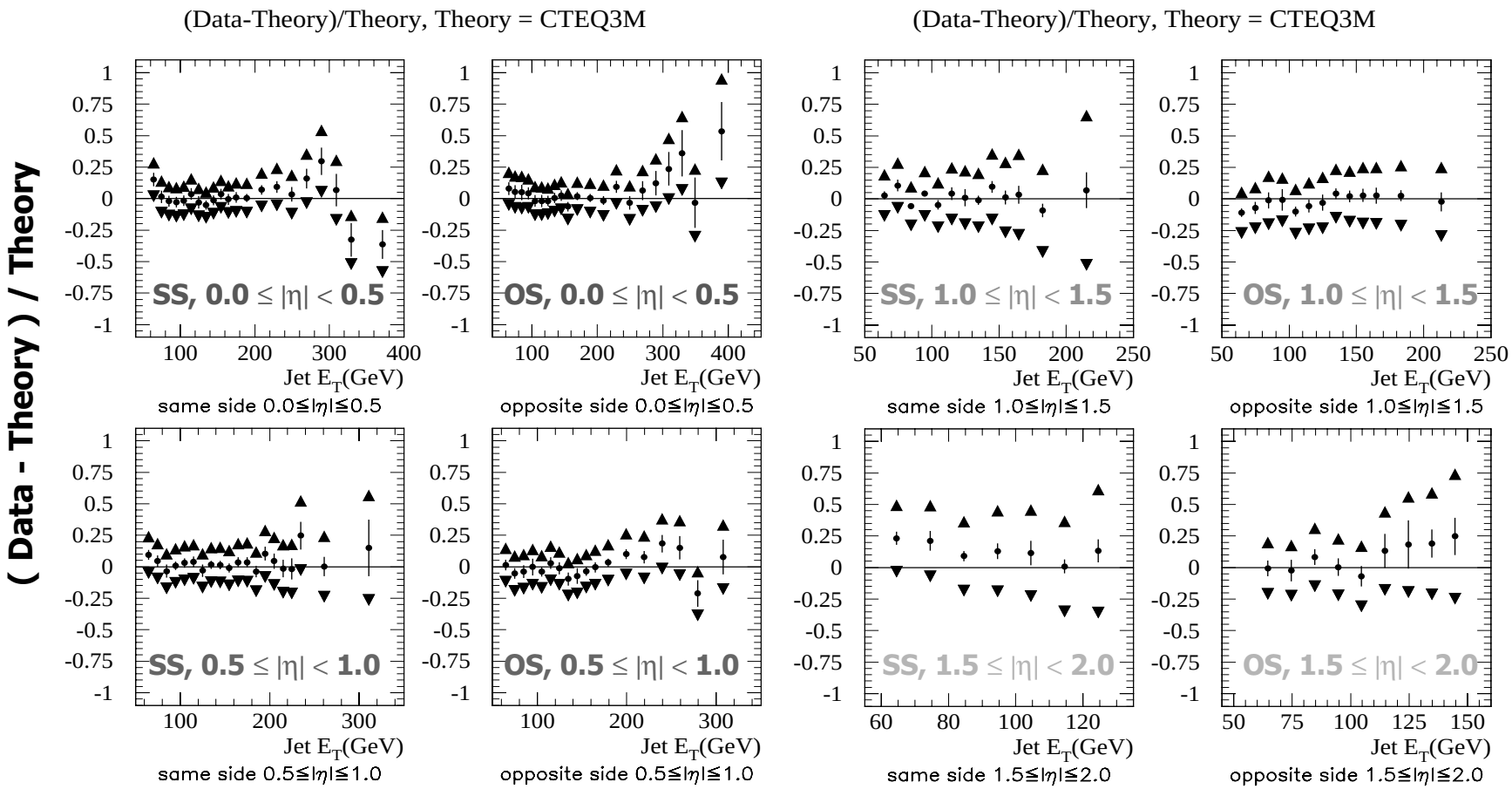
- **CDF: one jet central ($0.1 < |\eta_1| < 0.7$), the other allowed up to $|\eta_2| = 3.0$**

At high E_T, the same behaviour as the inclusive cross section, presumably because the same events



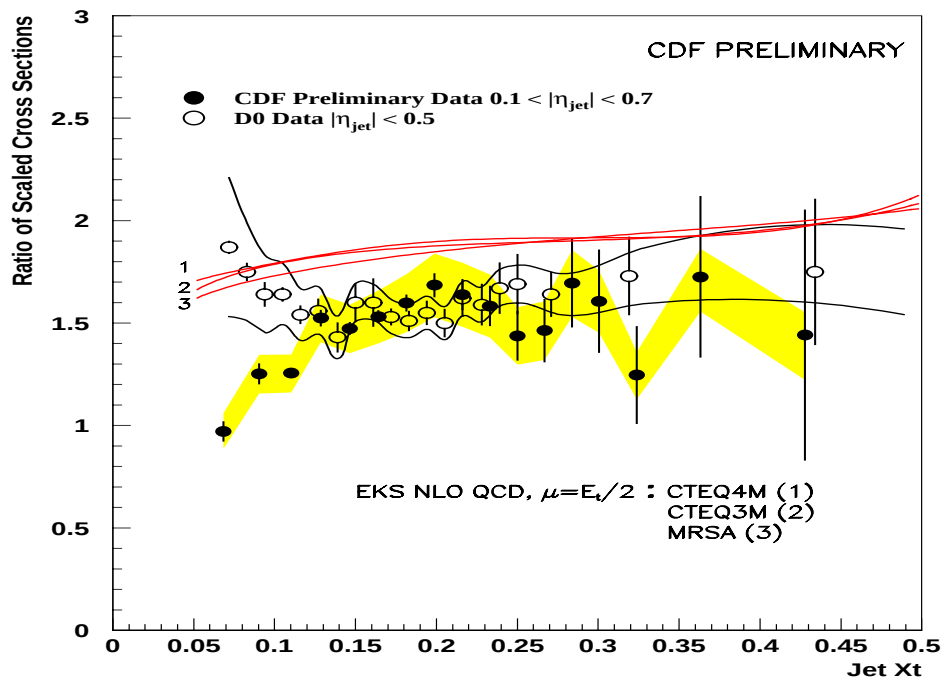


- **DØ: same side ($\eta_1 \sim \eta_2$) and opposite side ($\eta_1 \sim -\eta_2$) topologies measured up to $|\eta| = 2.0$**



Jet cross sections at $\sqrt{s}$ = 630 GeV

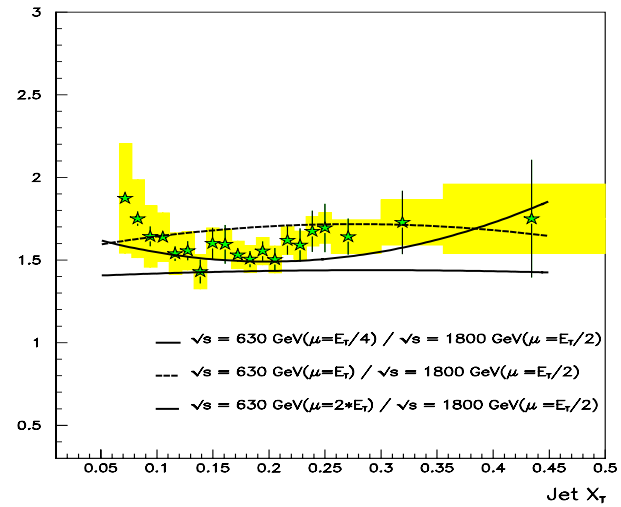
- **DØ and CDF both measure a preliminary ratio of cross sections 630/1800 GeV**



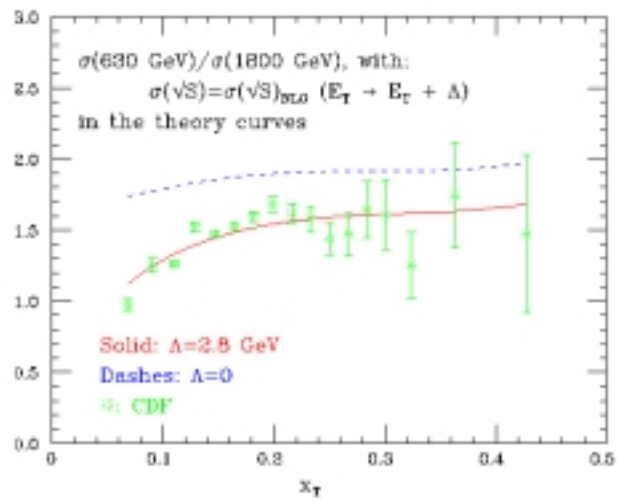
- **Not obviously consistent with each other (especially at low x_T) or with NLO QCD (at any x_T)**

Suggested explanations

- **Different renormalization scales at the two energies**
  - OK, so it's allowed, but . . .



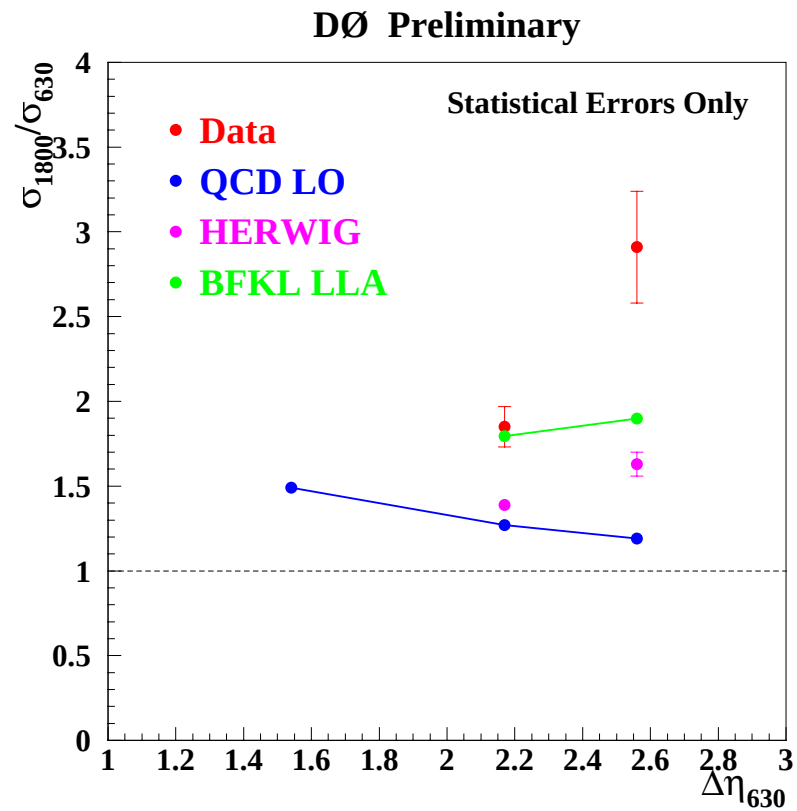
- **Mangano proposes an O(3 GeV) non-perturbative shift in jet energy**
  - losses out of cone
  - underlying event
  - intrinsic k_T
  - could be under or overcorrecting the data (or even different between the experiments — DØ?)



BFKL

- **Another attempt to find an observable which displays BFKL behaviour**

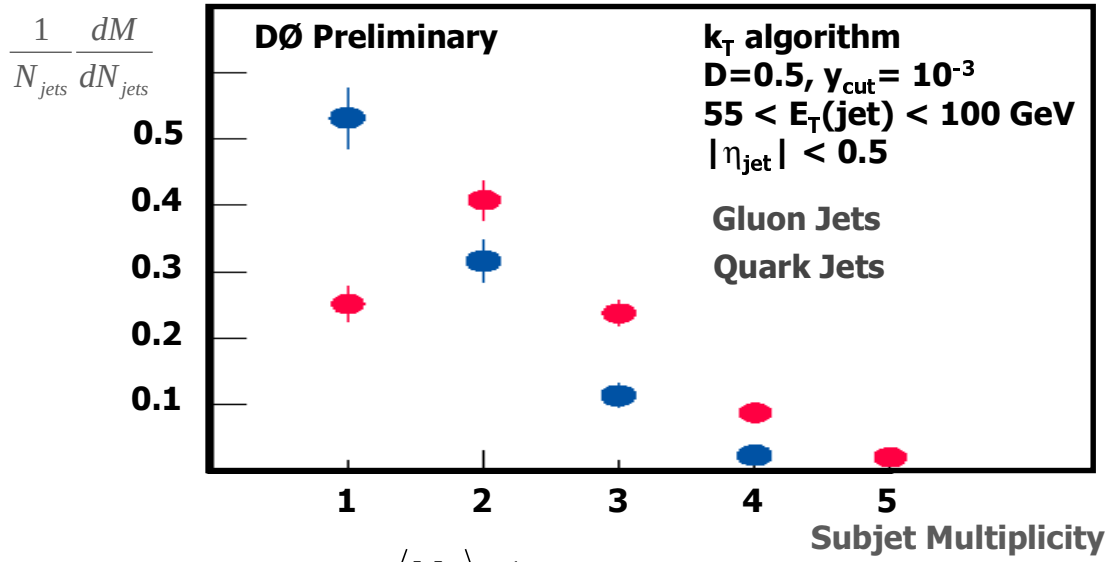
- **DØ measurement of 630/1800 GeV cross section ratio at large rapidity separations**
  - use bins such that x and Q^2 are the same in the two datasets (but different $\Delta\eta$)



- **What's going on here?**
  - data behave qualitatively like BFKL (but also like HERWIG)
  - given that we can't predict the 630/1800 GeV ratio of inclusive cross sections, how much can we really infer?

Jet Structure at the Tevatron

- **Subjets inside jets: perturbative part of fragmentation**
- **DØ compares 630 to 1800 GeV data at same E_T and η, and infers q and g jet differences**



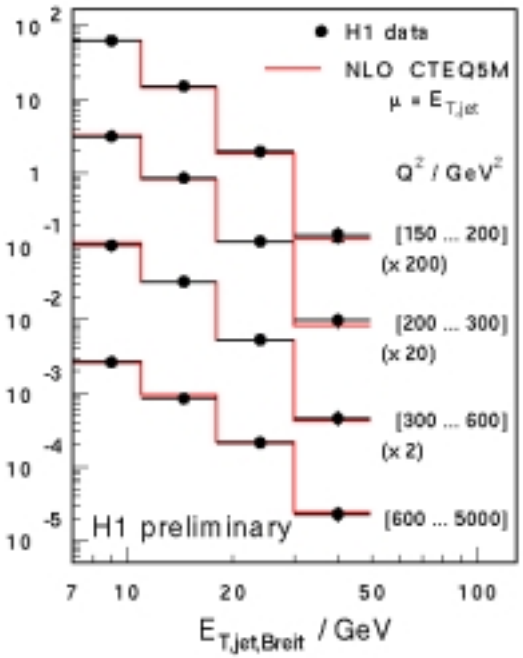
DØ Data $$R = \frac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1} = 1.91 \pm 0.04$$

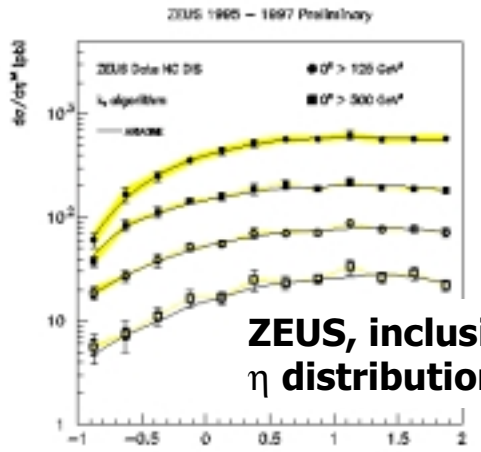
HERWIG 5.9 $$R = 1.86 \pm 0.04$$

Jet production at HERA

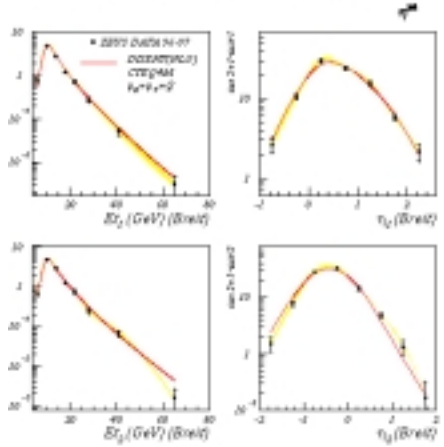
- **Inclusive jets, 2-jet and 3-jet cross sections at HERA - good agreement with QCD**

H1, inclusive jets

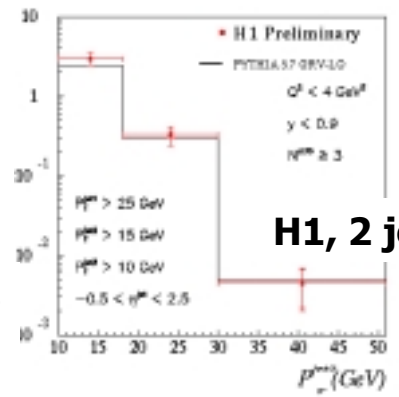




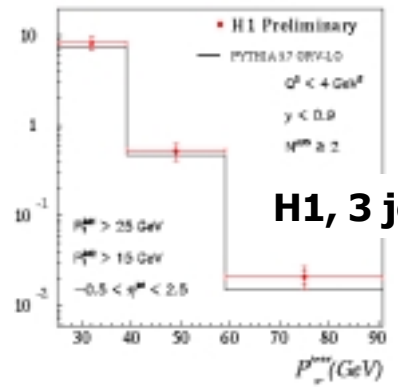
ZEUS, inclusive jets η distribution



ZEUS, 2 jets



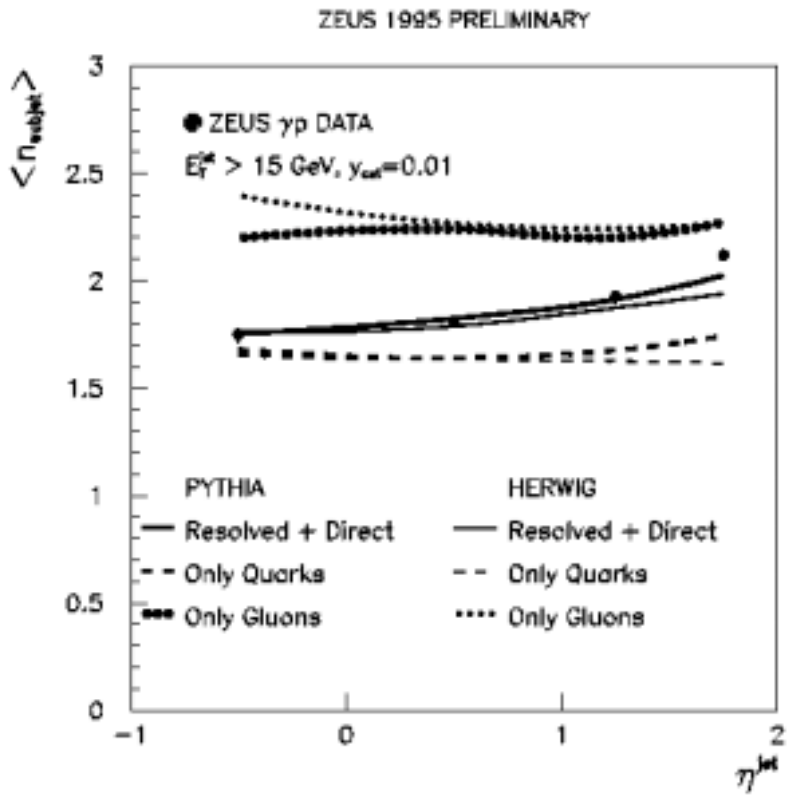
H1, 2 jets



H1, 3 jets

Jet structure at HERA

- **ZEUS: subjet multiplicity rises as jets become more forward**
- **Consistent with expectations (more gluons) and HERWIG**



Jets: final remarks

- **More data will settle the high-E_T issue**
  - "the horse is dead"

- **Running the Tevatron at 630 GeV was surprisingly productive; allowed well-controlled tests of QCD using ratios**
  - politically difficult to get running time when one is searching for new physics, but we may want to do it again

Photons

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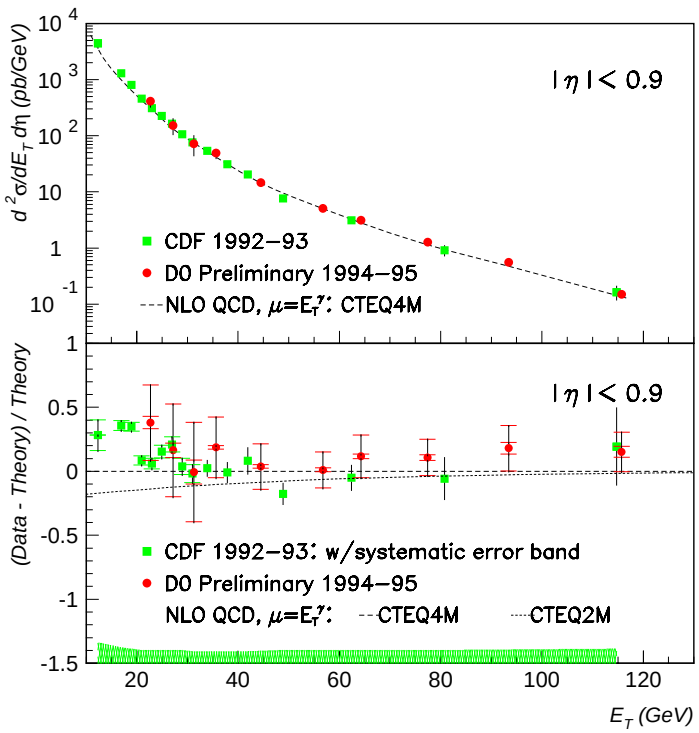
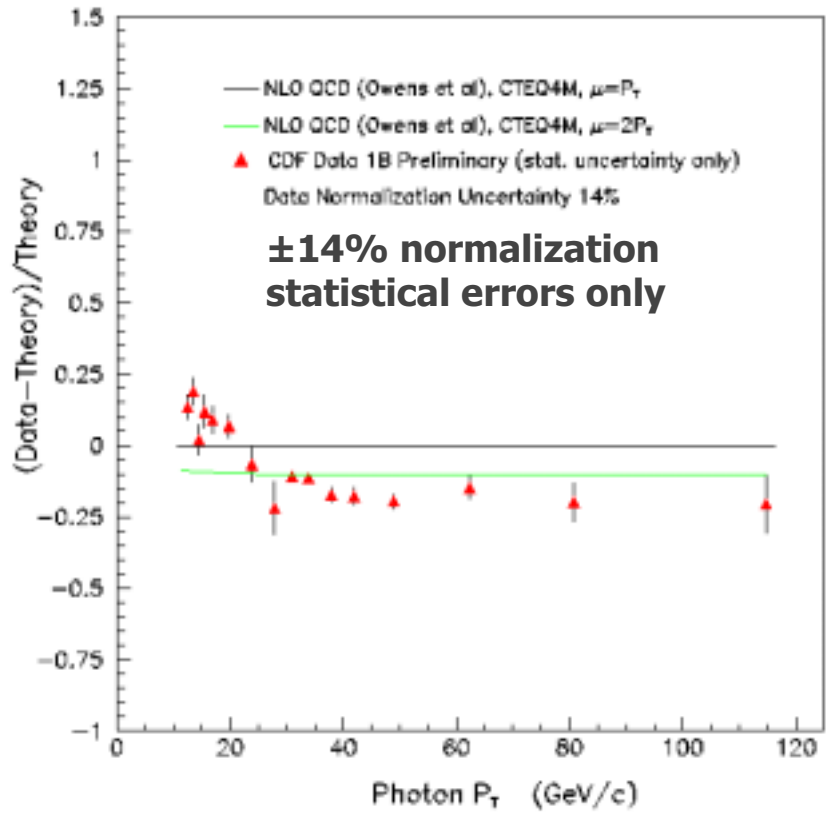
Photon cross section at the Tevatron

- **CDF and DØ**



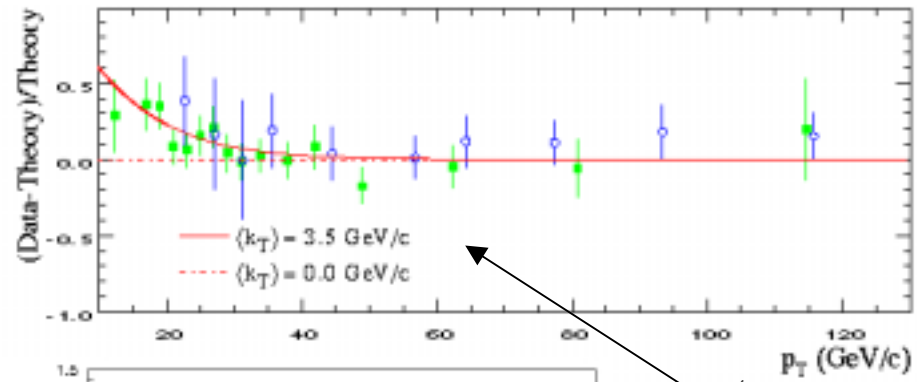
- **New CDF Preliminary**

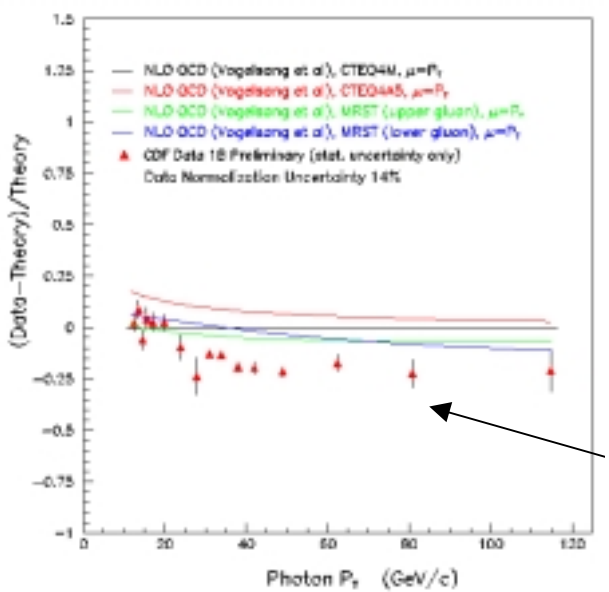


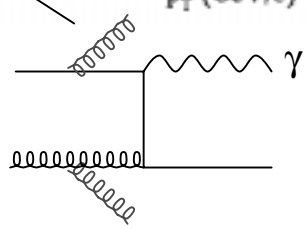
QCD prediction is NLO Owens et al.
Note: E_T range probed with photons is lower than with jets

k_T at low E_T?

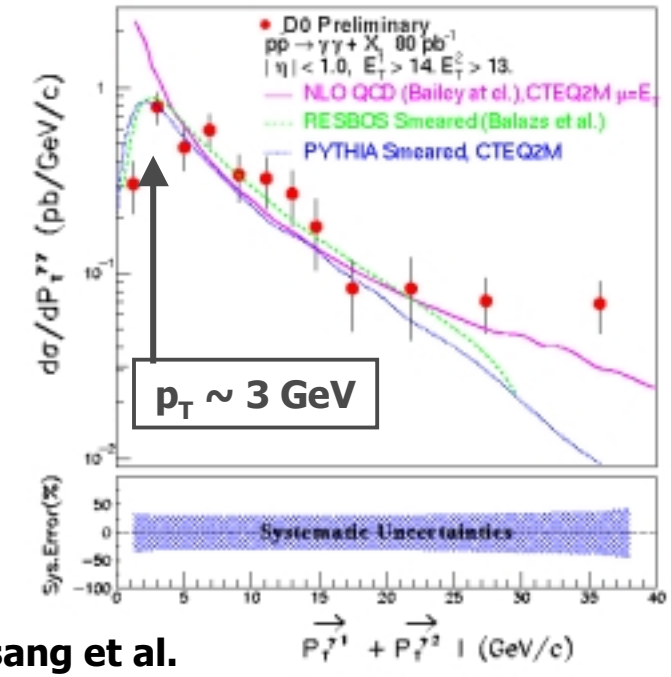
- **Gaussian smearing of the transverse momenta by a few GeV can model the rise of cross section at low E_T (hep-ph/9808467)**







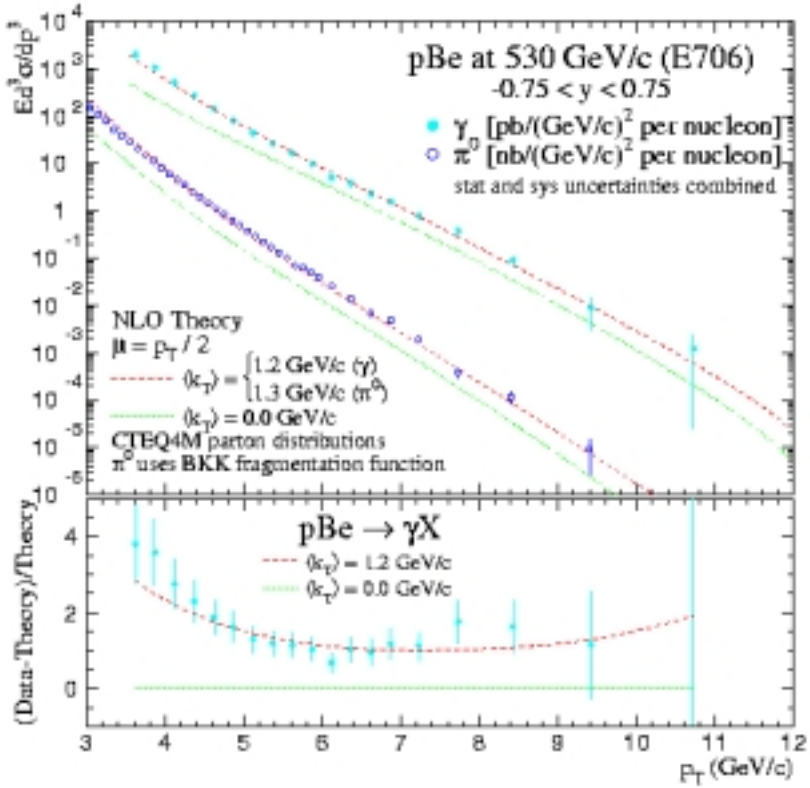
Motivated by observed $p_T(\gamma\gamma)$

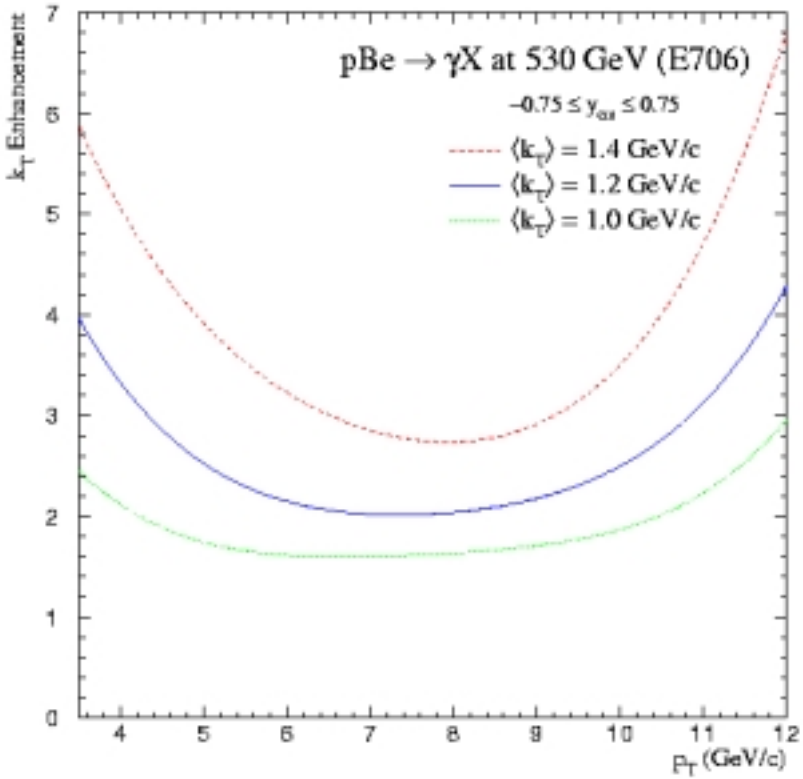


But note: Vogelsang et al. get closer to the observed shape than the Owens prediction with no extra k_T (NLO fragmentation and $\mu_R \neq \mu_F$)

Fixed target photon production

- **Even larger deviations from QCD observed in fixed target (E706)**

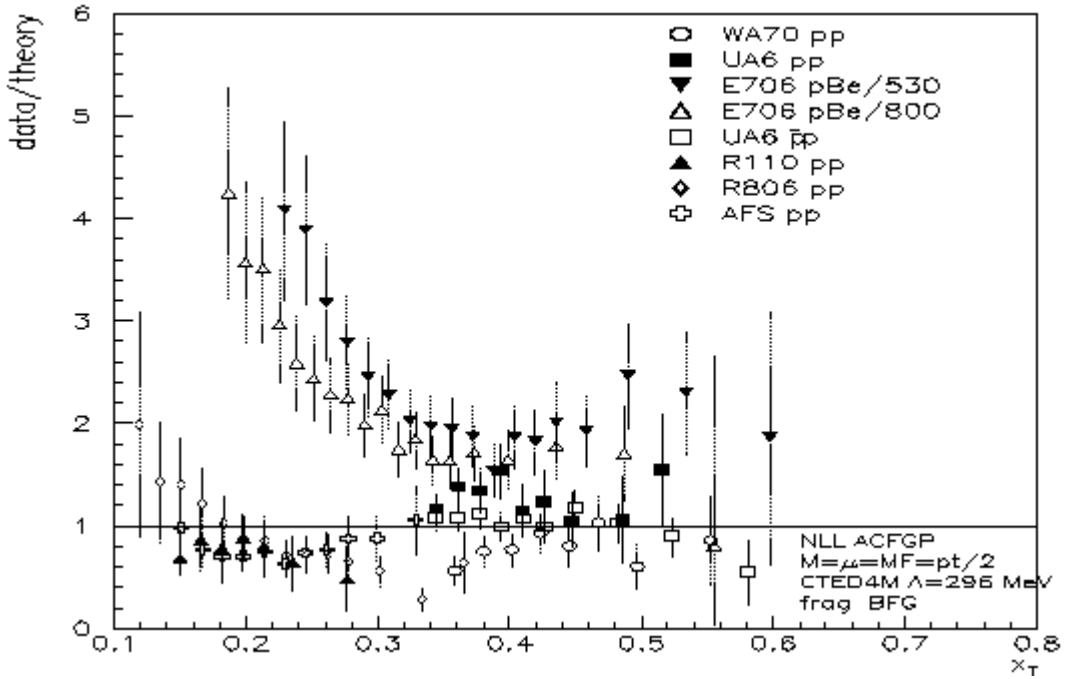




- **again, Gaussian smearing (~1.2 GeV here) can account for the data**

A contrary view

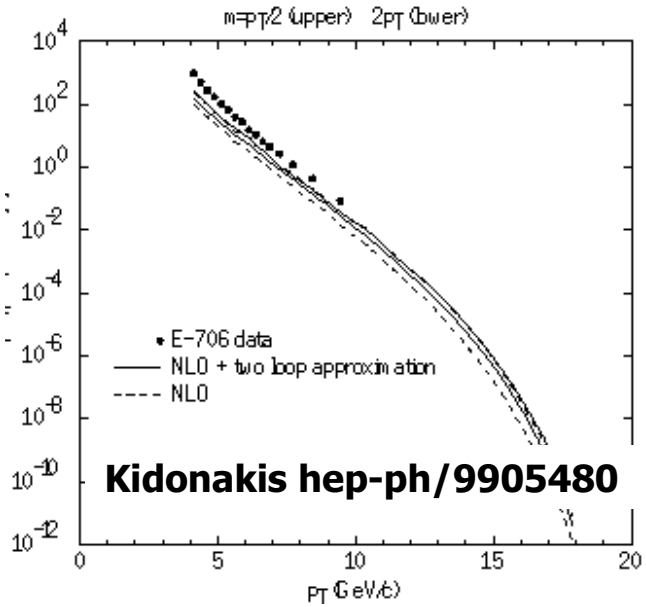
- **Aurenche et al., hep-ph/9811382**



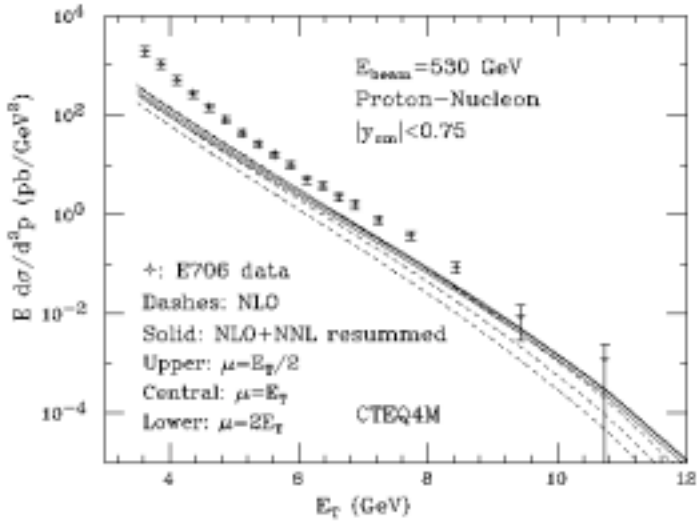
- **NLO QCD (sans k_T) can fit all data with the sole exception of E706**
  - "does not appear very instructive to hide this problem by introducing an extra parameter fitted to the data at each energy"

Resummation

- **Gaussian smearing has told us pretty much all that it can — its predictive power is small (e.g. what happens to forward photons?)**
- **The "right way" to do this should be resummation of soft gluons**
  - works nicely for $\gamma\gamma$ and W/Z p_T



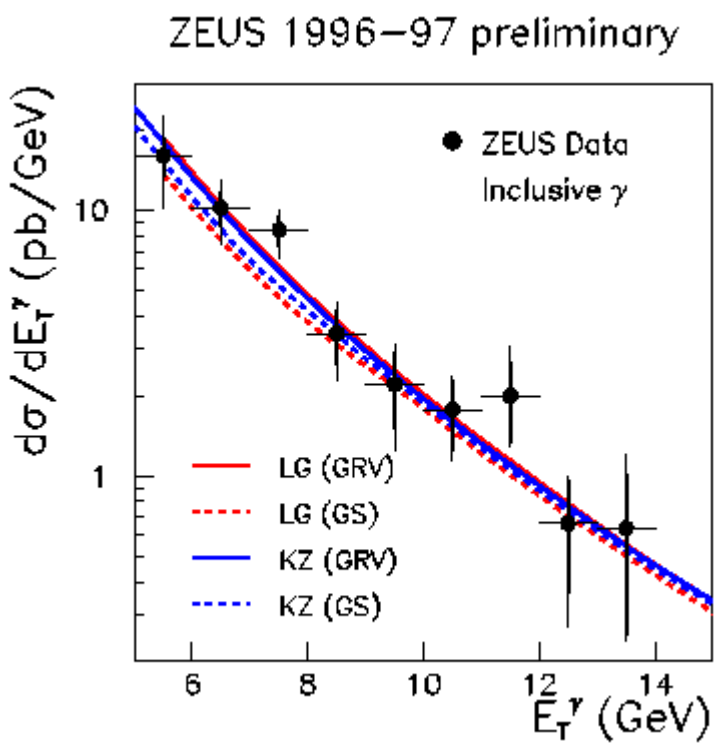
Catani et al. hep-ph/9903436

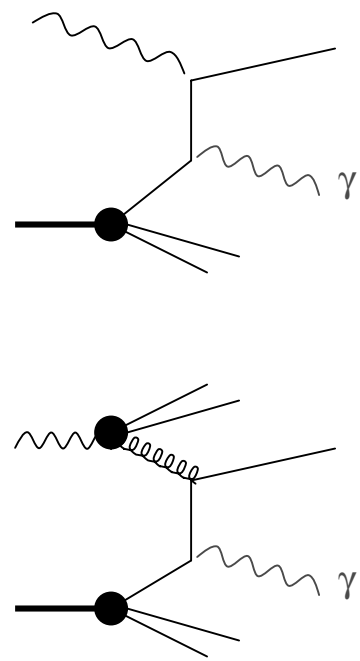


- **This approach does not seem to model E706 data**
  - are there other terms to resum? Or is the whole idea, that soft gluons are responsible for this discrepancy, mistaken?

Direct Photons at HERA

- **ZEUS data agrees well with NLO QCD (DIS 99)**
  - similar E_T range to E706
  - no need for k_T





Weak Bosons

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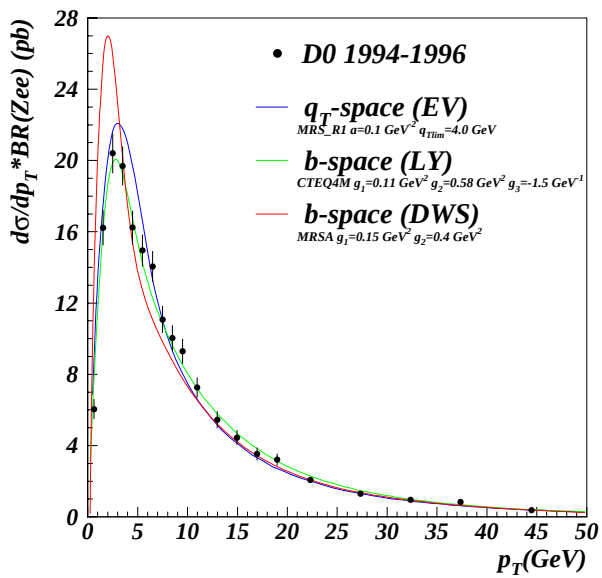
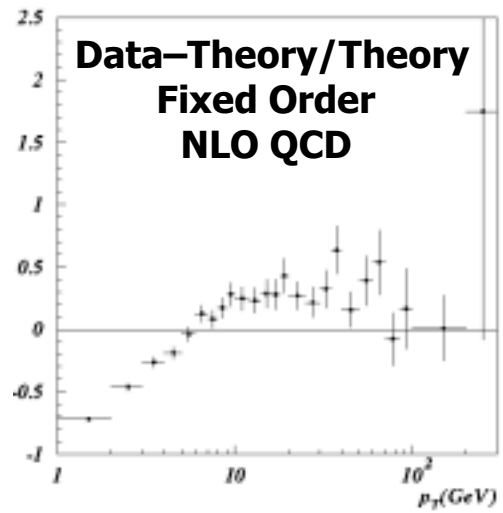
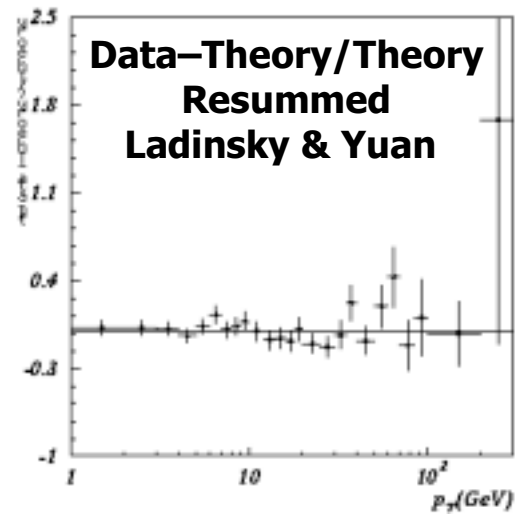
Z transverse momentum

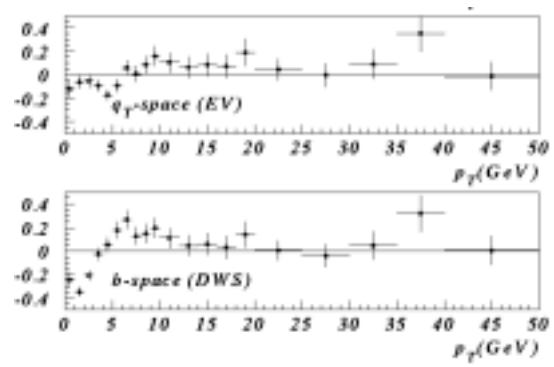
- **New DØ results hep-ex/9907009**



Data







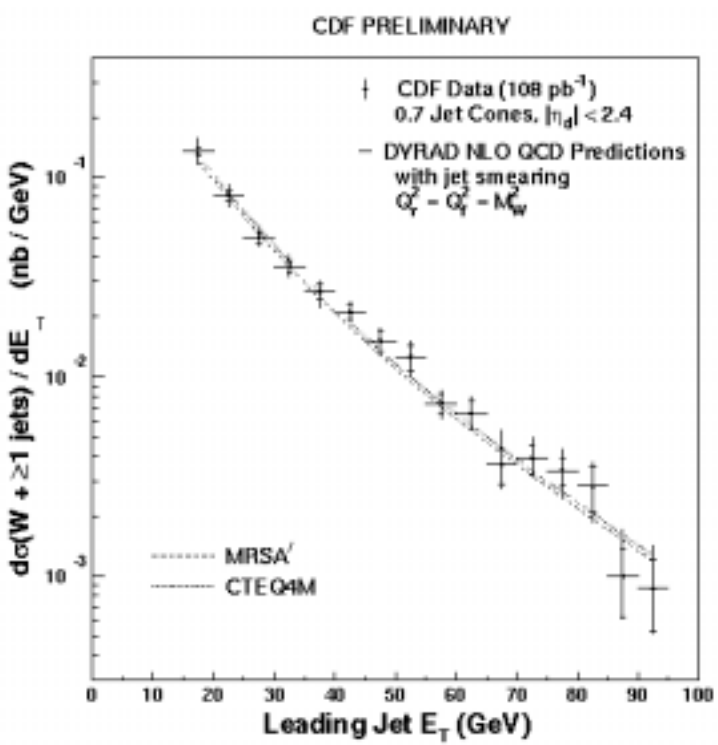
Ellis & Veseli and Davies, Webber & Stirling (Resummed)

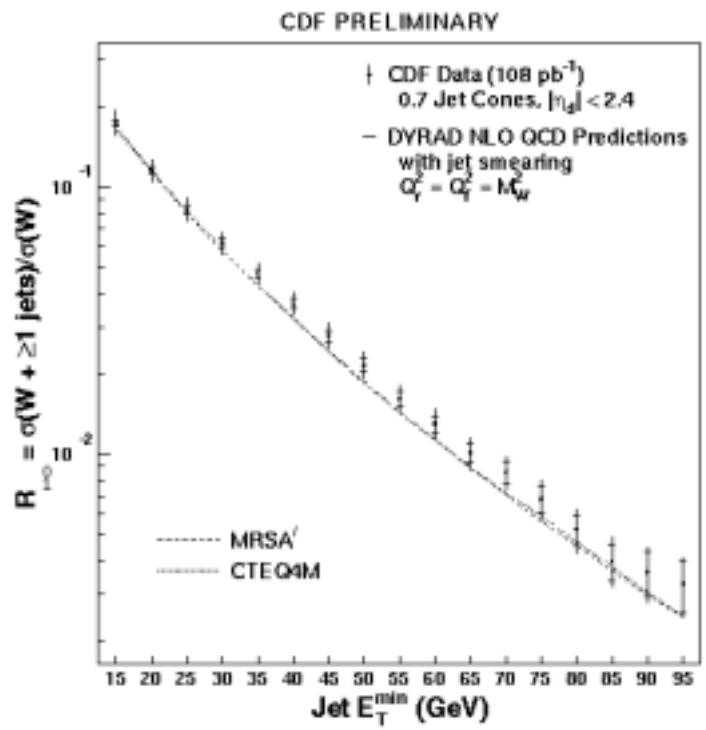
not quite as good a description of the data

W + jets

- **DØ used to show a W+1jet/W+0jet ratio badly in disagreement with QCD. This is no longer shown (the data were basically correct, but there was a bug in the DØ version of the DYRAD theory program).**

- **CDF measurement of W+jets cross section agrees well with QCD:**





Heavy Flavour Production

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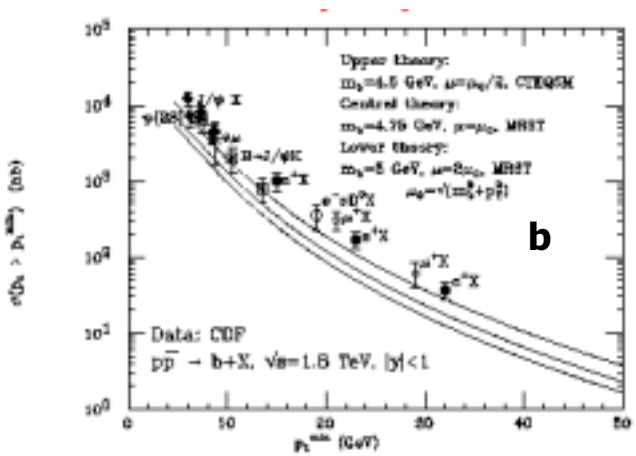
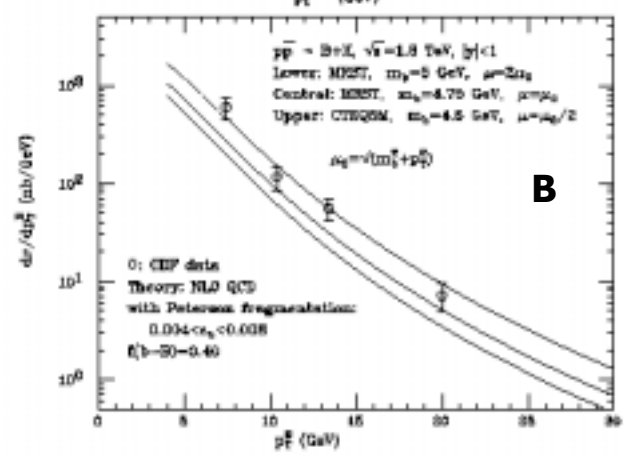
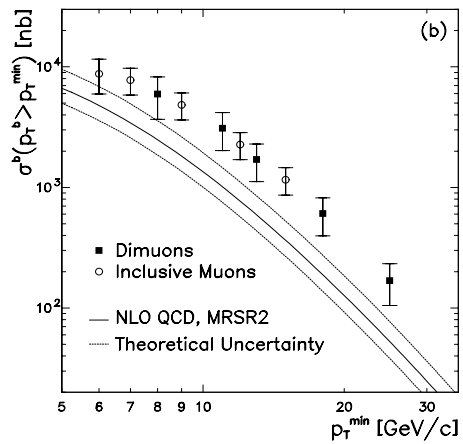
b production at the Tevatron

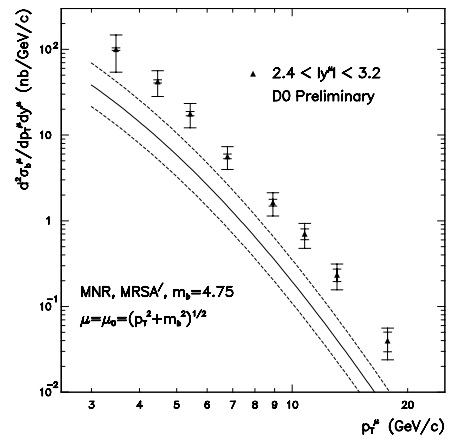
- **b cross section at CDF and at DØ**

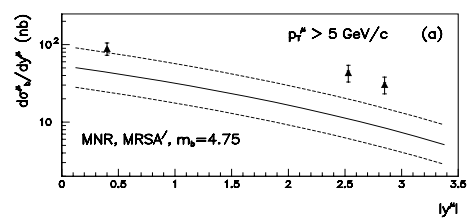




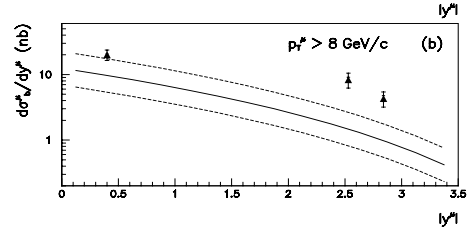
central **forward**







Cross section vs. |y|
$p_T > 5$ GeV/c

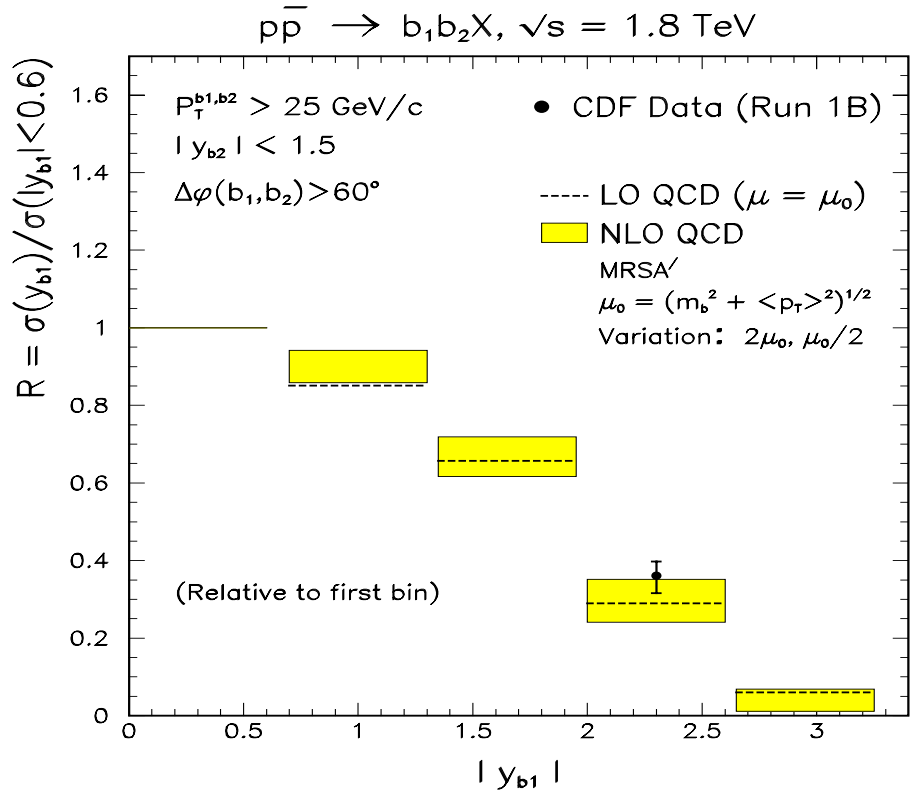


$p_T > 8$ GeV/c

- **Data continue to lie ~ 2 × central band of theory**

b rapidity correlations

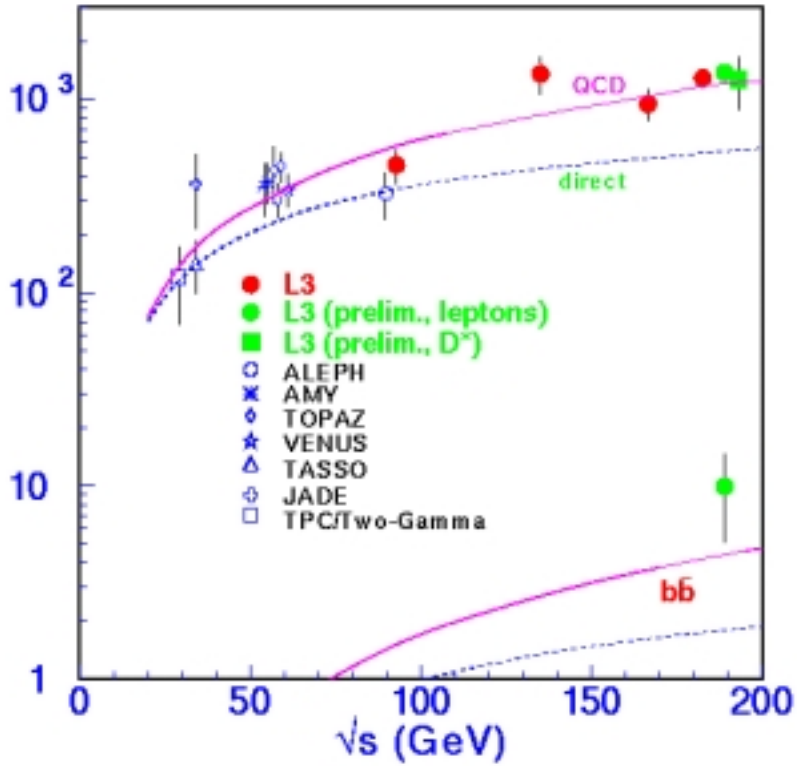
- **CDF** Fermilab-Pub-98/392-E

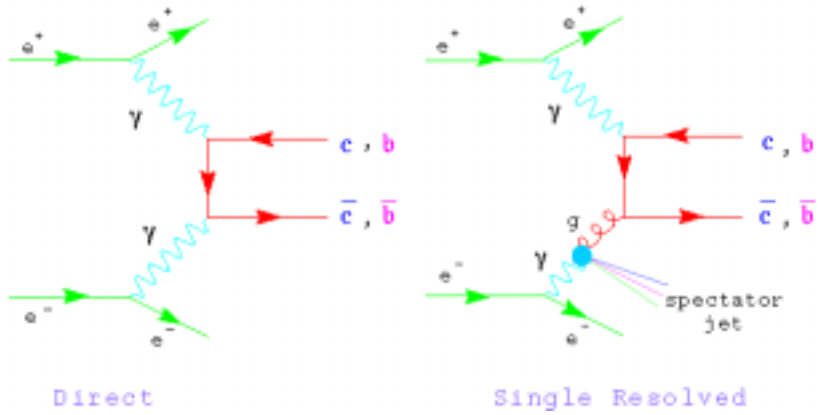


- **QCD does a good job of predicting both inclusive distributions and correlations, hence it's unlikely that any exotic new production mechanism is responsible for the higher than expected cross section**

Heavy quark production at LEP

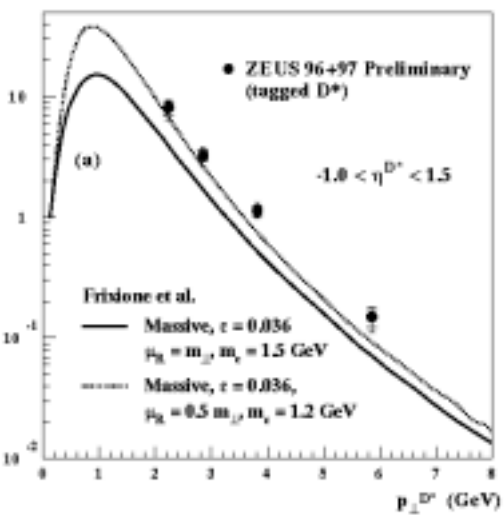
- $\gamma\gamma \rightarrow$ **QQ at LEP (L3-2421, L3-2427, OPAL-PN390)**
  - first observation of bb ($\sim$ 2-3 $\times$ QCD)
  - reasonable agreement with NLO QCD provided hadronic component of gamma included

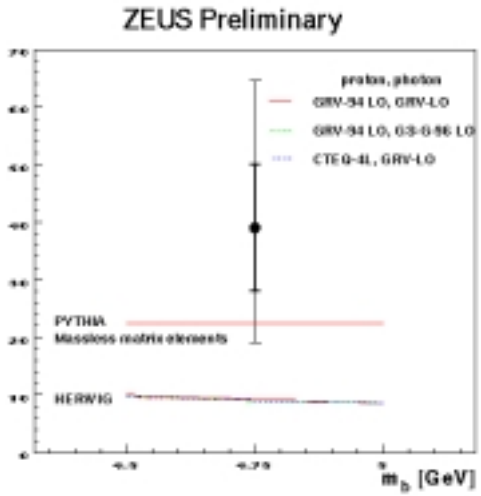


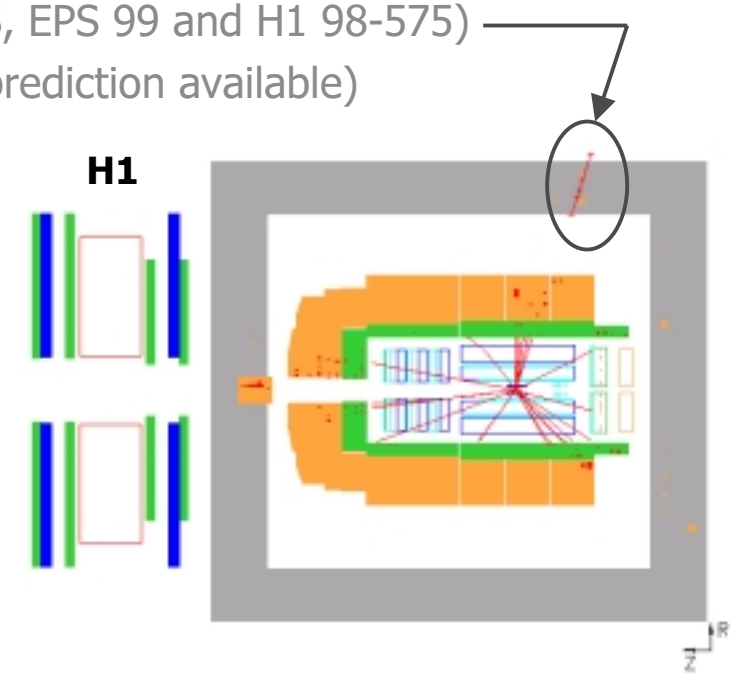


Heavy quark production at HERA

- **Charm**
  - $D_s^{\pm}$, $D^{*\pm}$ production in γp (ZEUS, EPS 99)
  - Cross section ~2 × QCD (maybe OK if charm mass assumed = 0)
- **Bottom**
  - b production in γp with b → lepton (ZEUS, EPS 99 and H1 98-575)
  - Cross section ~ 3-5 x QCD (but only LO prediction available)

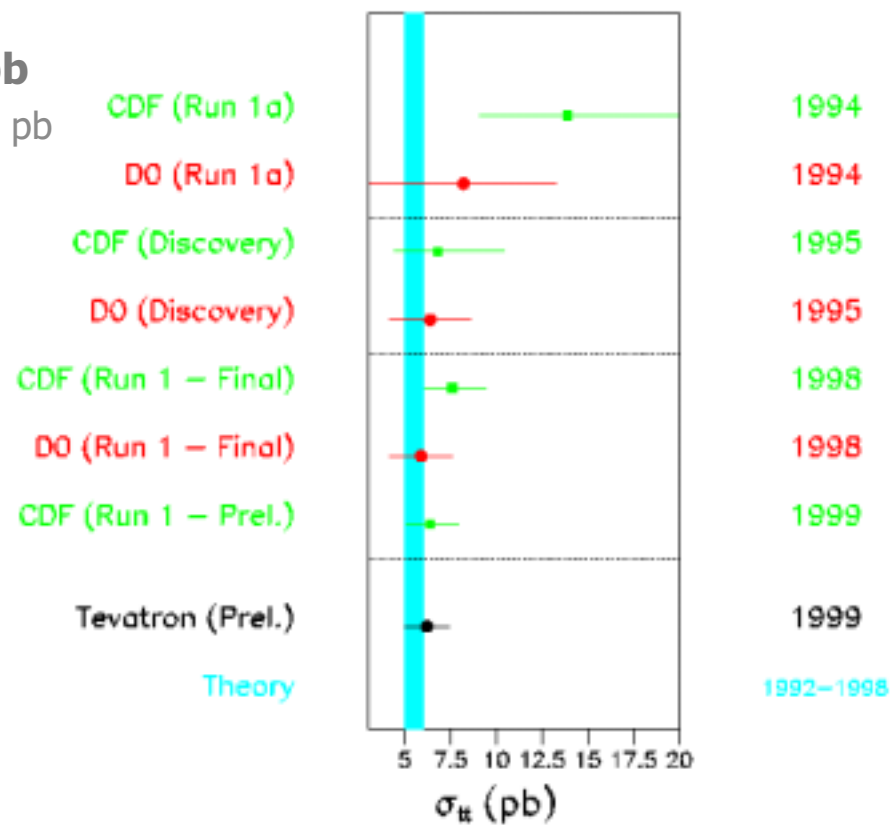






t production at the Tevatron

- **New CDF result**
  - **σ(175 GeV) = 6.5 +1.7 –1.4 pb**
  - cf. PRL 80 (1998) 2773: 7.6 +1.8 –1.5 pb
- **DØ PRD 60 (1999) 012001**
  - **σ(172 GeV) = 5.9 ± 1.7 pb**
- **Theoretical predictions**
  - Bonciani et al., NP B529 (1998) 424
    - **5.0 ± 0.6 pb**
  - Berger & Contopanagos, PRD 57(1998) 253
    - **5.6 +0.1 –0.4 pb**
  - Kidonakis hep-ph/9904507
    - **7.0 pb**



- **Excellent agreement between data and theory**
  - let no one say that we can't calculate heavy quark production (provided the quark is heavy enough!)

α_s

New α_s from LEP 1

- **LEP EWWG Summer 1999 (G. Quast at EPS99)**
  - α_s from $\Gamma_{hadrons}/\Gamma_{leptons}$ at m_Z: $\alpha_s(M_Z) = 0.123 \pm 0.004 \pm {}^{0.003}_{0.}\ (m_H)$
  - α_s from full SM fit: $\alpha_s(M_Z) = 0.119 \pm 0.003$

New α_s from DIS at NNLO

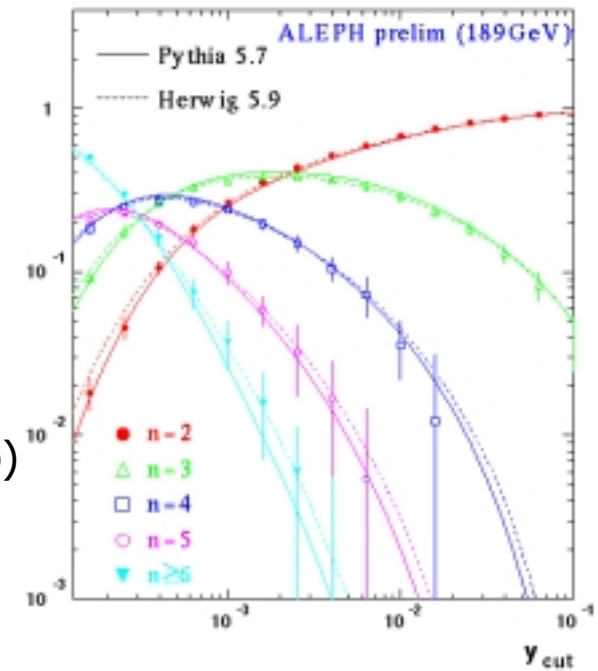
- **Santiago and Ynduráin (hep-ph/9904344)**
  - extracted α_s from F_2 measured in DIS (SLAC, BCDMS, E665 and HERA)
  - $\alpha_s(M_Z) = 0.1163 \pm 0.0023$

- **Kataev, Parente and Sidorov (hep-ph/9905310)**
  - extracted α_s from xF_3 measured in CCFR
  - $\alpha_s(M_Z) = 0.118 \pm 0.006$

α_s from 189 GeV data at LEP 2

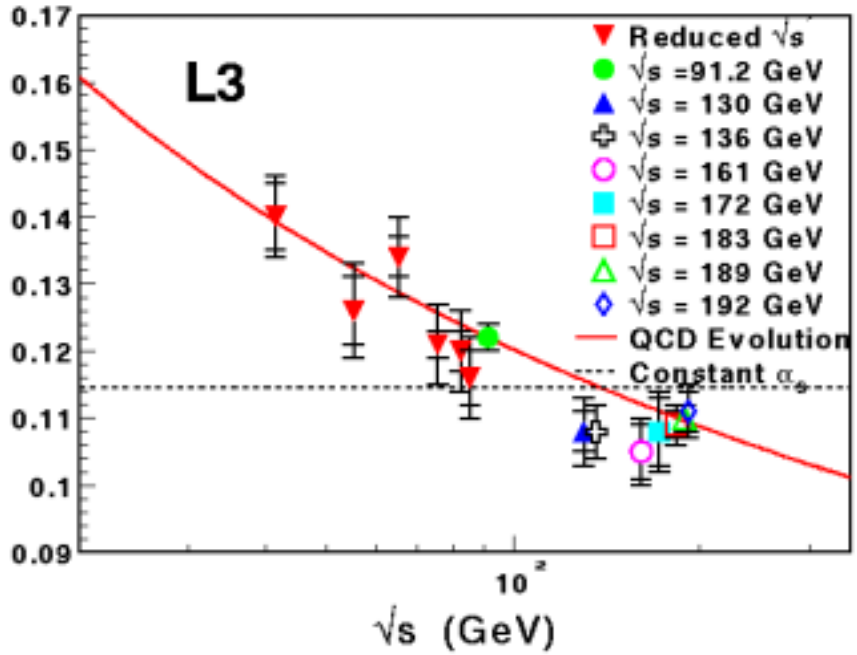
Event shapes, charged particle and jet multiplicities
Non-perturbative effects modelled with MC programs

- **ALEPH (99-023)**
  - $\alpha_s(189) = 0.1119 \pm 0.0015(\text{stat}) \pm 0.0011(\text{sys}) \pm 0.0030(\text{theo})$
  - $\boldsymbol{\alpha_s(M_Z) = 0.1216 \pm 0.0039}$ LEP 1 + LEP 2
- **DELPHI (99-114)**
  - $\alpha_s(189) = 0.1116 \pm 0.0024(\text{stat})$
- **L3 (L3-2414)**
  - $\alpha_s(189) = 0.1101 \pm 0.0018(\text{exp}) \pm 0.0056(\text{theo})$
  - $\boldsymbol{\alpha_s(M_Z) = 0.1220 \pm 0.0062}$ 30–189 GeV
- **OPAL (PN-403)**
  - $\alpha_s(189) = 0.1085 \pm 0.0015(\text{stat}) \pm 0.0027(\text{sys}) \pm 0.0020(\text{had}) \pm^{0.0022}_{0.0003}(\text{scale})$
  - $\boldsymbol{\alpha_s(M_Z) = 0.1199 \pm^{0.0038}_{0.0025}}$ 35–189 GeV including JADE data



α_s from 192-196 GeV data at LEP 2

- **L3 QCD studies at 192 GeV (L3-2440)**
  - $\alpha_s(M_Z) = 0.1220 \pm 0.0015(exp) \pm 0.0060(theo)$



- **OPAL QCD studies at 192 and 196 GeV (PN-415) new for LP99**
  - $\alpha_s(M_Z) = 0.113 \pm 0.006$

α_s from H1

- **Fit to inclusive jet rate $d^2\sigma/dE_T dQ^2$ (EPS 99)**

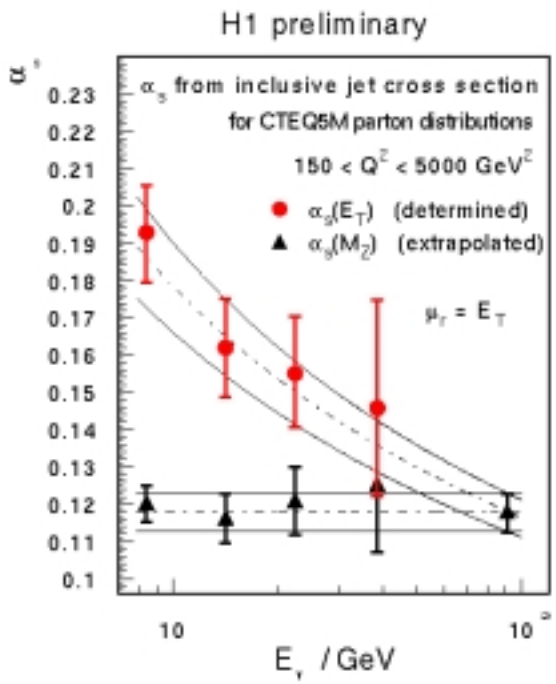
$$\alpha_s(M_Z) = 0.1181 \pm 0.0030(\text{exp}) \pm^{0.0039}_{0.0046}(\text{th}) \pm^{0.0036}_{0.0015}(\text{PDF}) \quad \mu_R = E_T$$

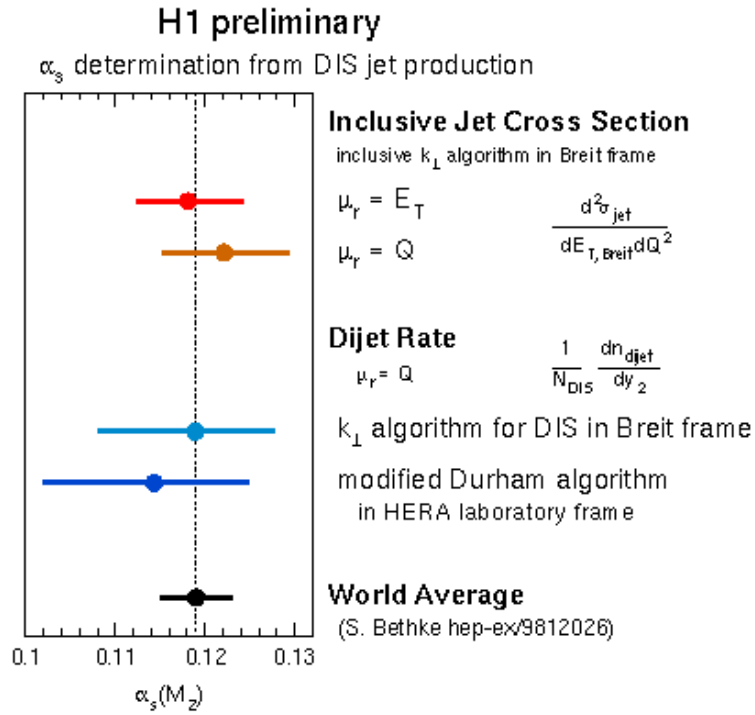
$$\alpha_s(M_Z) = 0.1221 \pm 0.0034(\text{exp}) \pm^{0.0054}_{0.0059}(\text{th}) \pm^{0.0033}_{0.0016}(\text{PDF}) \quad \mu_R = Q$$

- **Fit to dijet rate (EPS 99)**

$$\alpha_s(M_Z) = 0.1189 \pm^{0.0064}_{0.0081}(\text{exp}) \pm^{0.0059}_{0.0046}(\text{th}) \pm^{0.0013}_{0.0055}(\text{PDF}) \quad k_T^{DIS}\text{, Breit frame}$$

$$\alpha_s(M_Z) = 0.1143 \pm^{0.0075}_{0.0089}(\text{exp}) \pm^{0.0074}_{0.0064}(\text{th}) \pm^{0.0008}_{0.0054}(\text{PDF}) \quad \text{Durham, lab frame}$$

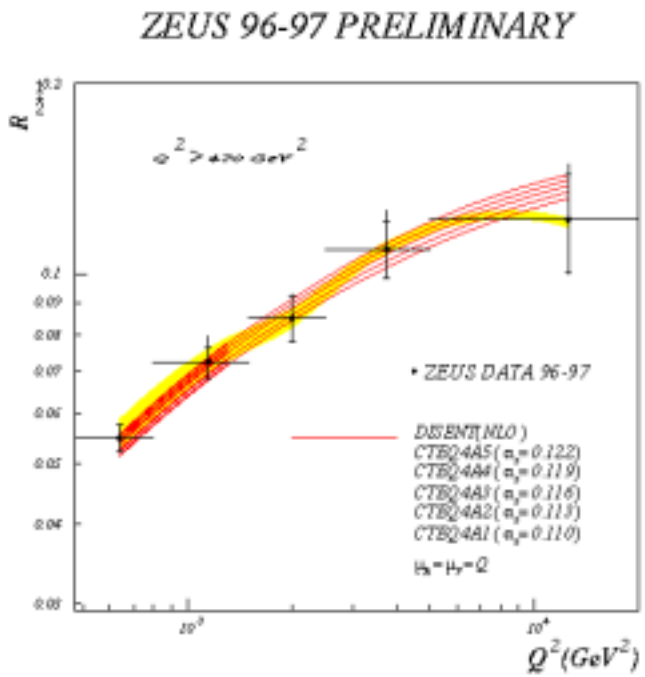




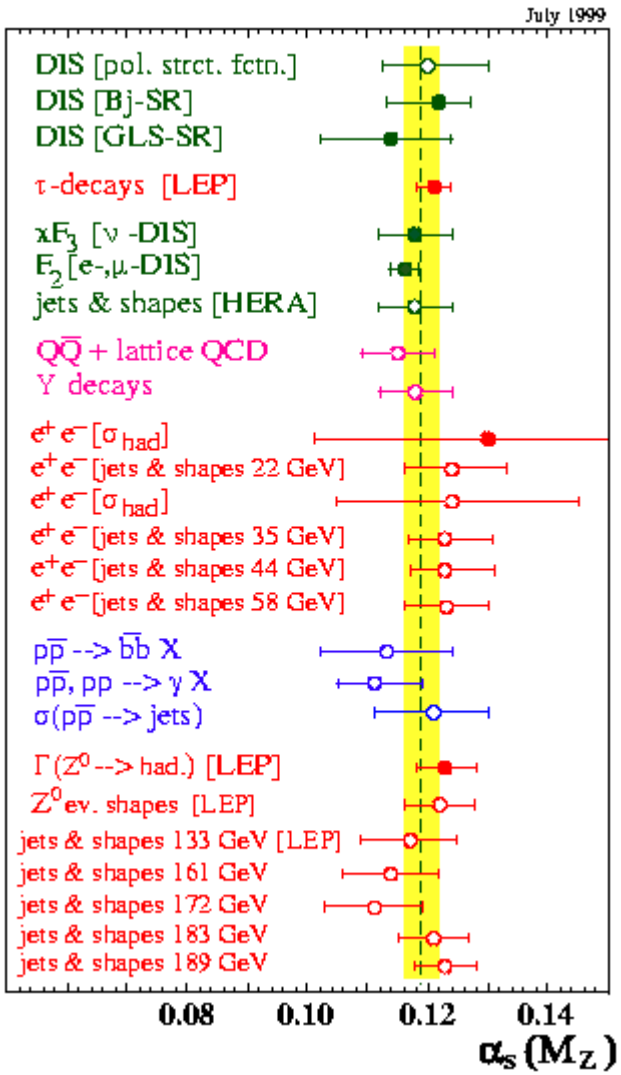
α_s from ZEUS

- **ZEUS fit to dijet fraction vs. Q^2 (EPS 99)**

$$\alpha_s(M_Z) = 0.120 \pm 0.003(\text{stat}) \pm^{0.005}_{0.006}(\text{exp}) \pm^{0.003}_{0.002}(\text{theo})$$



Summer 1999 world average α_s



- **From S. Bethke (private communication) average of all 25**

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

- **average based only on complete NNLO QCD results (filled circles in plot)**

$$\alpha_s(M_Z) = 0.119 \pm 0.003$$

- **excellent consistency between low and high energy, DIS, $\bar{p}p$ and e^+e^-, etc.**

- **Minimal change from previous world average (hep-ex/9812026)**
  - $\alpha_s(M_Z) = 0.119 \pm 0.004$ or
  - $\alpha_s(M_Z) = 0.120 \pm 0.005$ excluding lattice

α_s consistency tests

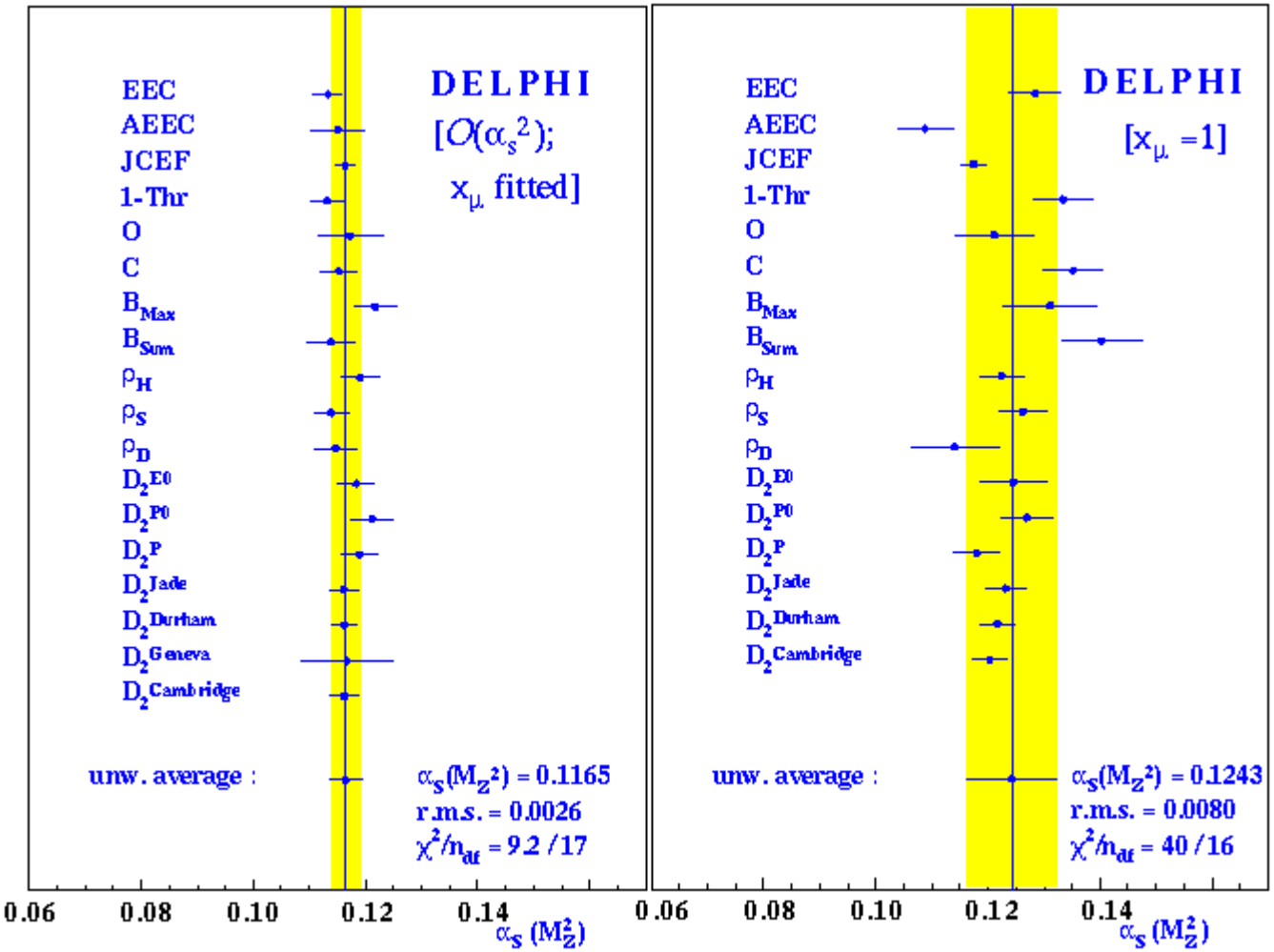
- **We know α_s very well — are any predictions limited by its precision?**

- **At this stage the interesting measurements, to me, are more tests of self-consistency in our understanding of how to calculate QCD rather than actual measurements of α_s**
  - DELPHI oriented event shape variables w/ optmized scale
  - event shape variables using power corrections (see Bryan Webber's talk)
  - α_s extraction from CDF jet cross section

α_s from DELPHI

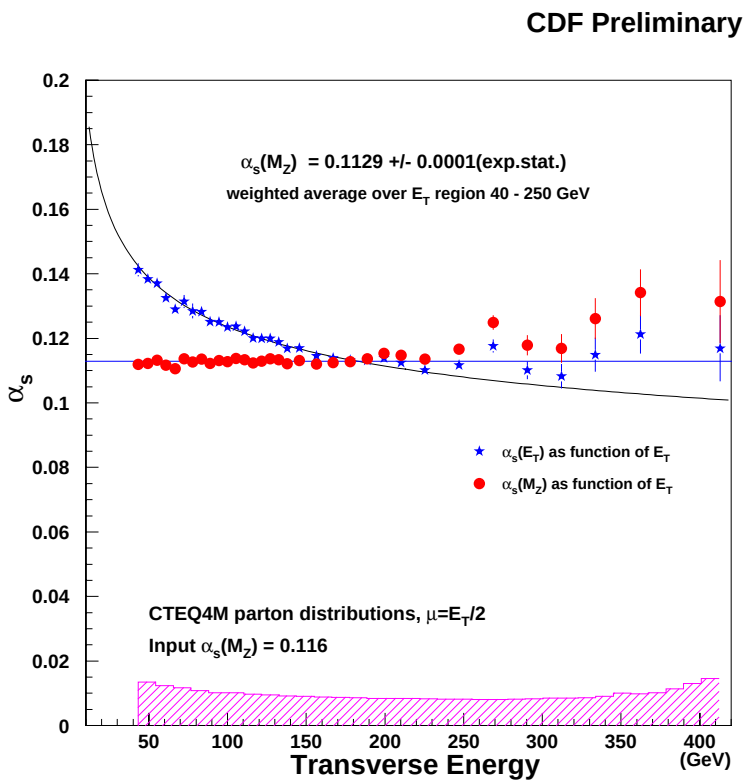
- **DELPHI fits to oriented shape variables at M_Z (99-122)**
  - $\alpha_s(M_Z) = 0.1173 \pm 0.0023$ 18 shape variables
  - $\alpha_s(M_Z) = 0.1180 \pm 0.0018$ Jet cone energy fraction
- **this extraction relies on "optimization" of the renormalization scale for each variable**
  - simultaneous fit of α_s and $x_\mu = \mu^2/Q^2$
  - resulting scales range from $\mu = (0.003Q)^2$ to $(7Q)^2$!
- **procedure is theoretically unjustified (so I am told by theorists) but consistency of results is interesting**
- **errors should probably be taken with a grain of salt**

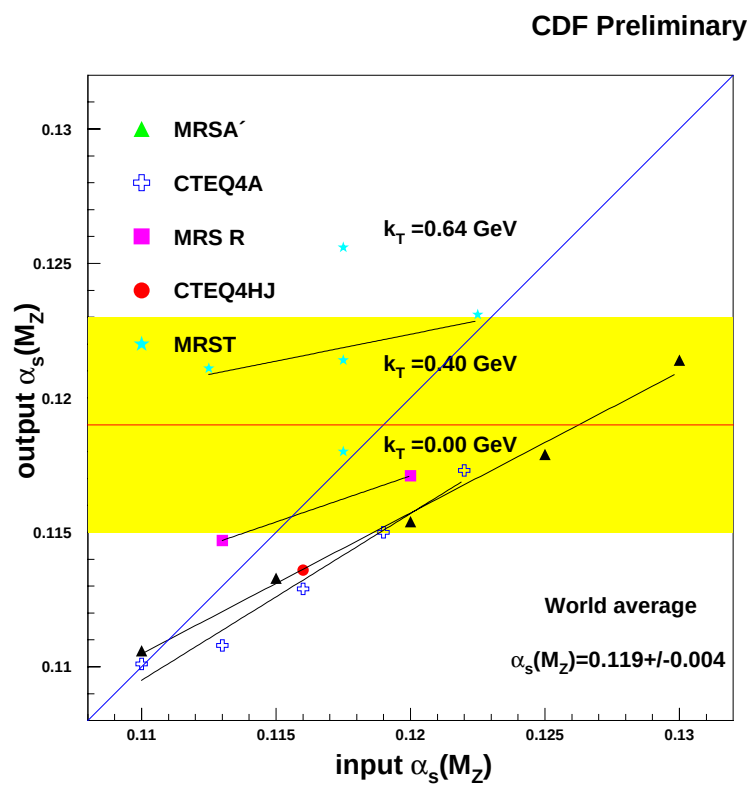
I suspect that this is telling us something about QCD
— though maybe not (or not just) the value of α_s


DELPHI
[$O(\alpha_s^2)$; x_μ fitted]
EEC
AEEC
JCEF
1-Thr
O
C
B_{Max}
B_{Sum}
ρ_H
ρ_S
ρ_D
D_2^{E0}
D_2^{P0}
D_2^{P}
D_2^{Jade}
D_2^{Durham}
D_2^{Geneva}
$D_2^{Cambridge}$
unw. average :
$\alpha_s(M_Z^2) = 0.1165$
r.m.s. = 0.0026
$\chi^2/n_{df} = 9.2/17$
0.06
0.08
0.10
0.12
0.14
$\alpha_s(M_Z^2)$
DELPHI
[$x_\mu = 1$]
EEC
AEEC
JCEF
1-Thr
O
C
B_{Max}
B_{Sum}
ρ_H
ρ_S
ρ_D
D_2^{E0}
D_2^{P0}
D_2^{P}
D_2^{Jade}
D_2^{Durham}
$D_2^{Cambridge}$
unw. average :
$\alpha_s(M_Z^2) = 0.1243$
r.m.s. = 0.0080
$\chi^2/n_{df} = 40/16$
0.06
0.08
0.10
0.12
0.14
$\alpha_s(M_Z^2)$

α_s from CDF jet cross section

- **Nice demonstration of the evolution of α_s;** $\alpha_s(M_Z) = 0.113 \pm {}^{0.008}_{0.009}$
  - but large sensitivity to PDF's, input α_s and whether one assumes any k_T





Some final remarks

I have not had time to discuss

Lots of cute measurements

- **dijet mass and angular distributions**
- **color coherence**
  - of third jet direction, of energy flow between jets, of subjets inside jets
- **flavor independence of α_s**
- **chromomagnetic coupling of b (SLD)**
- **jet final states at LEP**
- **C_A/C_F**
- **q/g jet differences**

etc etc.

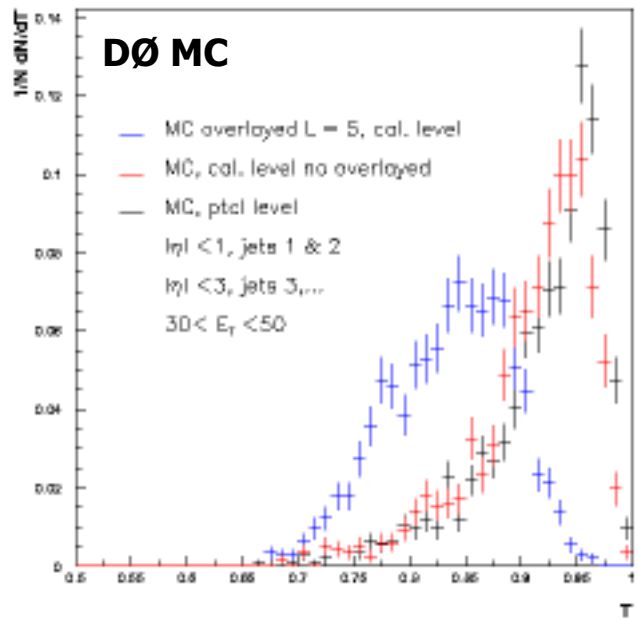
What I would like for Christmas

- **PDF's with uncertainties, or technique for propagation of PDF uncertainties as proposed by Giele**
  - so we don't get excited unnecessarily by things like the high E_T jet "excess"

- **Theoretical and experimental effort to understand the underlying event**
  - don't subtract it out from jet energies
    - it's an inconsistent treatment of the event
    - the 1800/630 GeV jet data may indicate problems with our usual assumption that the underlying event is ~ a minbias event
  - would also allow a consistent treatment of double parton scattering

Jet Algorithms

- **Fermilab Run II/ Les Houches workshops**
- **Various species of k_T**
- **Can the cone algorithm be made acceptable?**
- **Theoretical desires**
  - "infrared safety is not a joke!"
  - avoid ad hoc parameters like R_{sep}
- **Experimental desires**
  - sensitivity to noise, pileup, negative energies

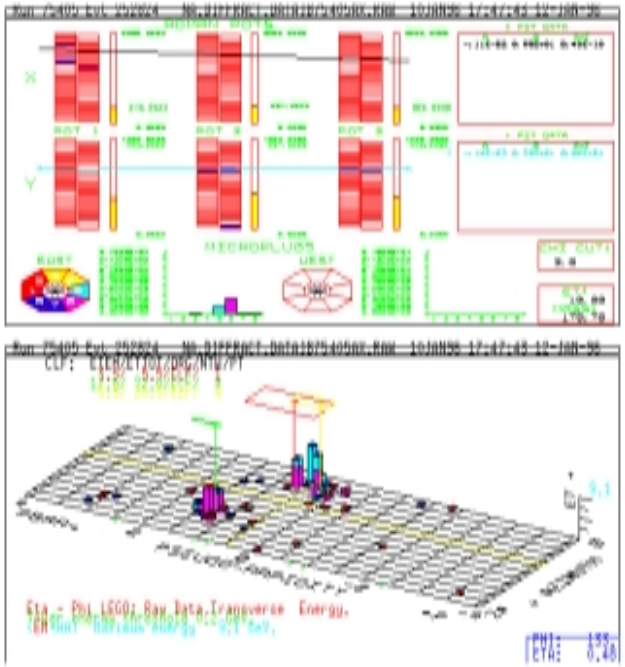


Effect of pileup on Thrust
k_T algorithm jets, E_T > 30 GeV

Something we have failed to describe

- **Here is dijet production at the Tevatron — a perturbative process, which I have told you is well modelled by NLO QCD**
- **Except for one detail: in a substantial fraction (a few %?) of these events one of the protons doesn't break up**
- **What's going on?**
  - Pomeron exchange?
  - I would rather think in terms of parton correlations inside the proton

CDF dijet event with Roman Pot track



Diffractive processes like this do not form part of a consistent picture, and my hunch is that we won't understand them properly as long as we think of them as inherently alien to perturbative QCD

Conclusions

Testing QCD typically means testing our ability to calculate within QCD

- **Our calculational tools are working well, especially at moderate to high scales**
  - the state of the art is NNLO calculations, NLL resummations
- **Some interesting things (challenges!) are happening as we approach scales of order 5 GeV**
  - problems calculating b cross sections
  - problems with low p_T direct photon production (k_T?)
  - indications of few GeV jet energy effects?
- **Other challenges for the future**
  - identification of appropriate jet algorithms
  - underlying event in hadron-hadron collisions
  - understanding parton distribution uncertainties
  - consistent understanding of hard diffractive processes

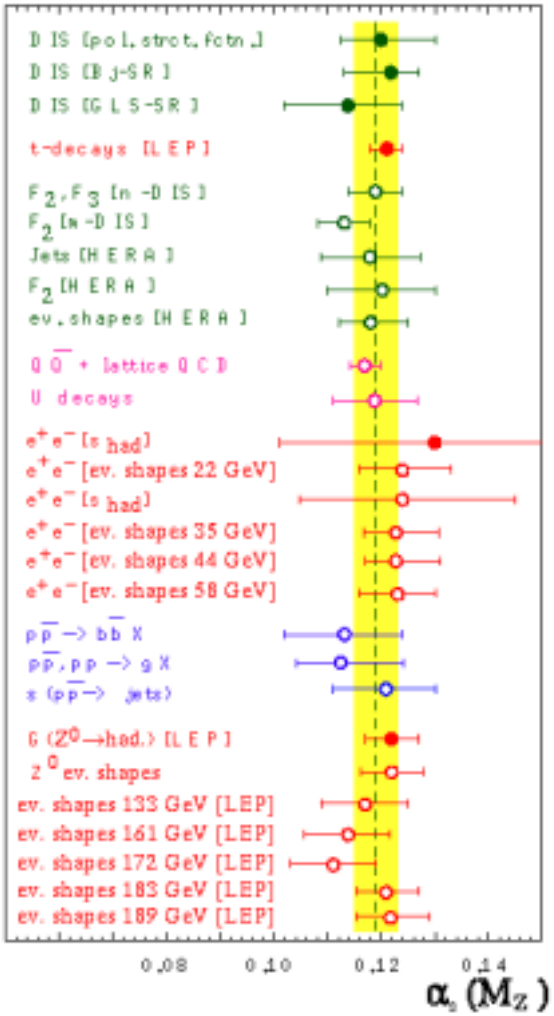
Backup slides

1998 α_s world average

- **From S. Bethke hep-ex/9812026**
  - $\alpha_s(M_Z) = 0.119 \pm 0.004$ or
  - $\alpha_s(M_Z) = 0.120 \pm 0.005$ excluding lattice

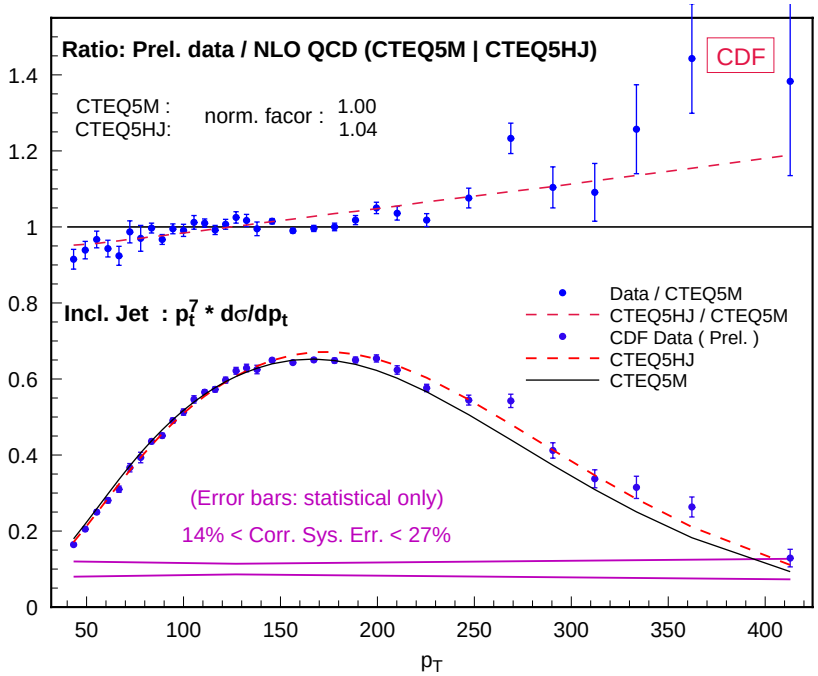
- **errors subject to discussion:**
  - most are dominated by theoretical uncertainties
  - correlations between results
  - rms of measurements ~ 4 x naïve error estimate assuming no correlations
  - errors go up as more measurements included
  - "if alpha s were used to build bridges. . ."

- **nonetheless, excellent consistency between low and high energy, DIS, $\bar{p}p$ and e^+e^-, etc.**

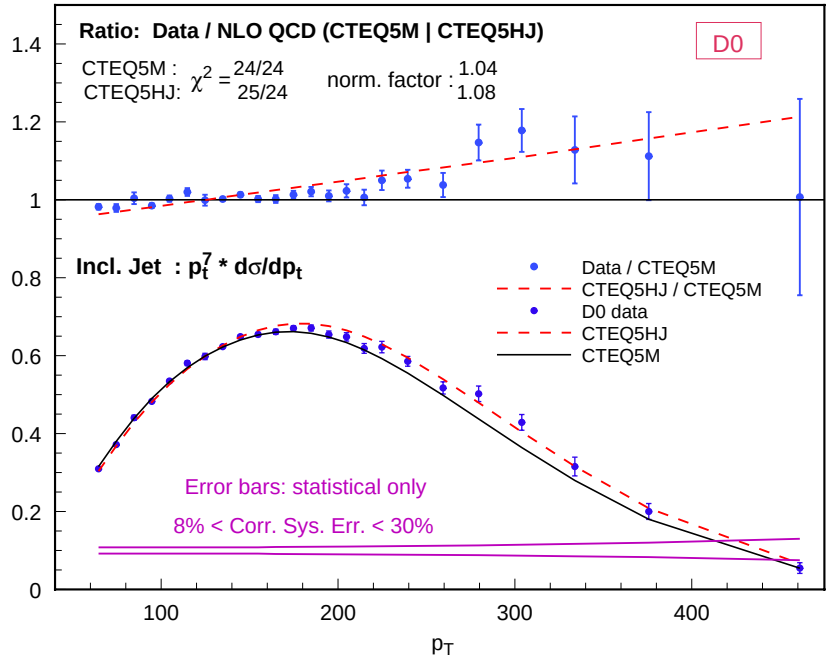


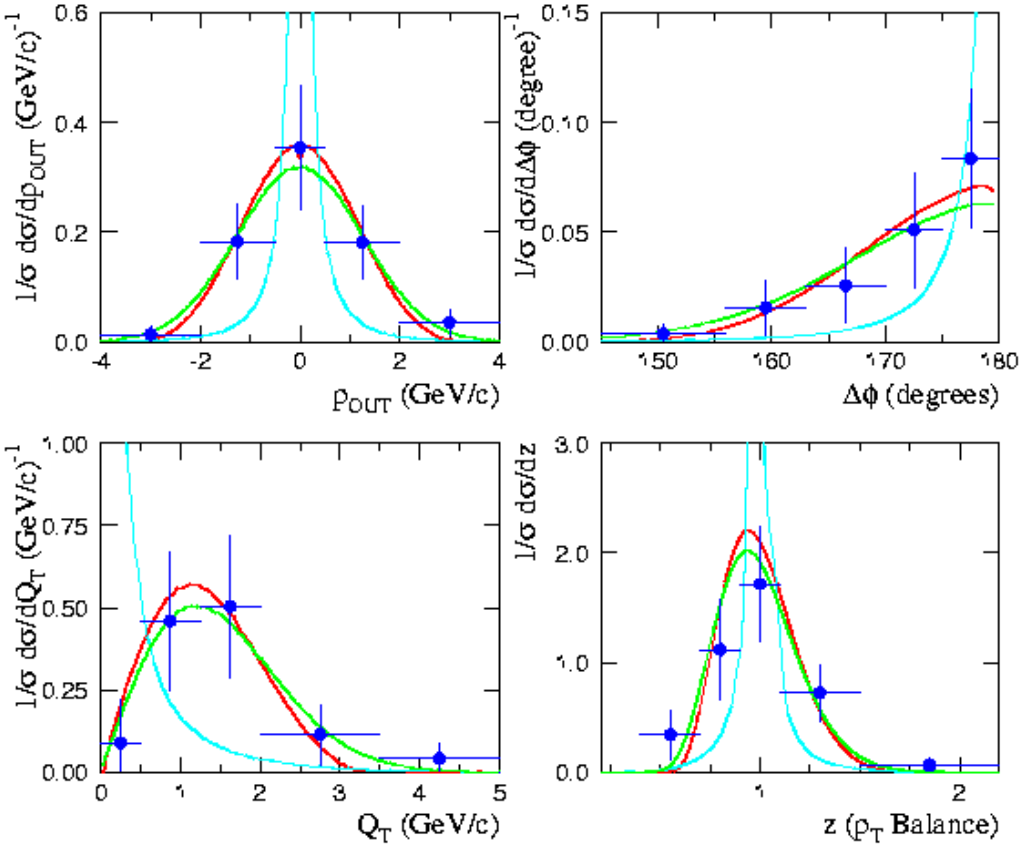
Jet data with CTEQ5 PDF's

- **CDF data**



- **DØ data**





$\pi^- Be \rightarrow \gamma\gamma X$ at 515 GeV/c

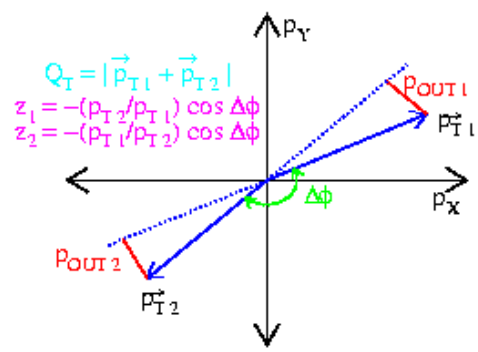
$p_T^\gamma > 4.0$ GeV/c

$-0.80 < y^\gamma < 0.80$

$\Delta\phi > 105°$

$M > 10$ GeV/c^2

Resummed (RESBOS)

NLO (Bailey et al.)

PYTHIA ($\langle k_T \rangle = 1.1$ GeV/c)