Beauty Production in Hadronic Collisions

Michelangelo Mangano
Theory Division, Physics Department
CERN

Topical Workshop on Hadron Collider Physics
Michigan State University, East Lansing, MI
June 14-18 2004

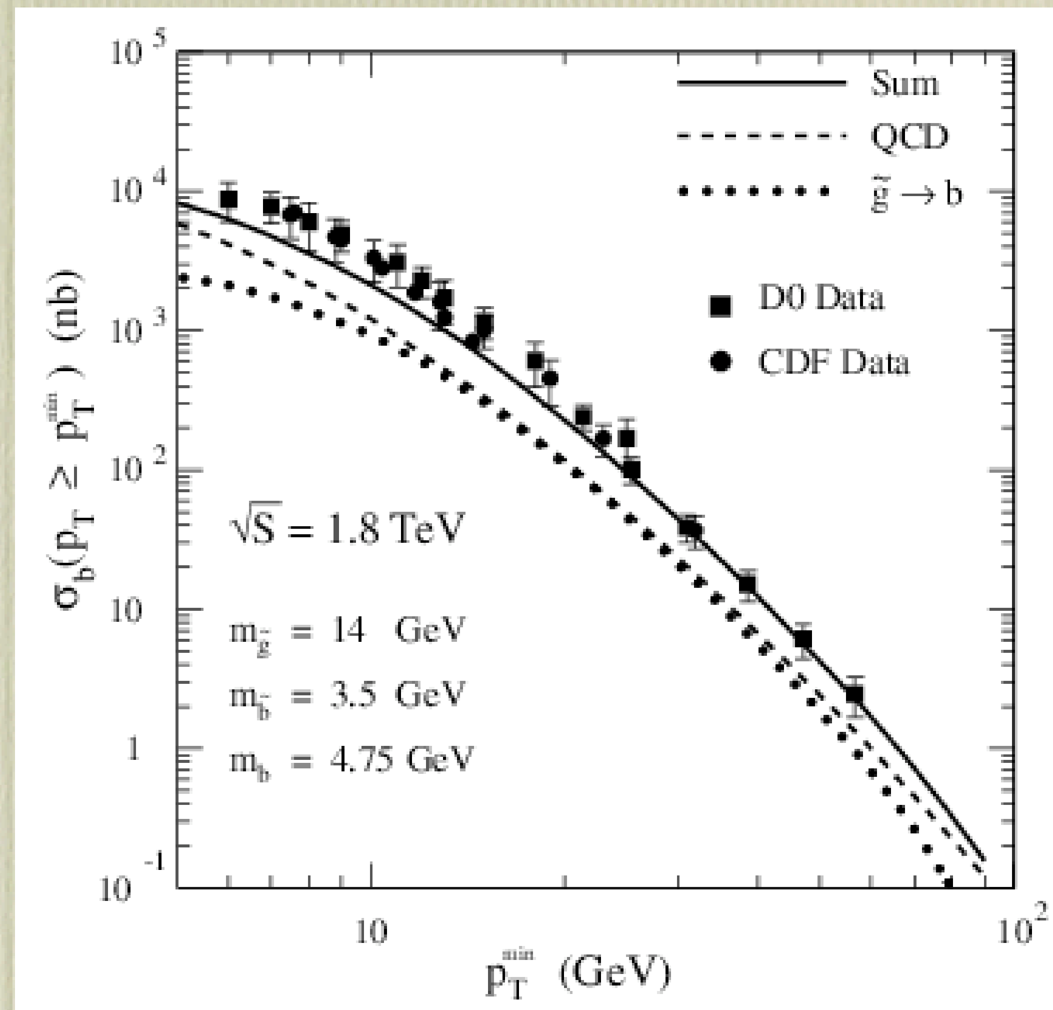
- The study of events with b quarks has led to some of the most important Tevatron results:
  - discovery and study of the top quark
  - appreciation of the colour-octet-mediated quarkonium production mechanisms
  - B physics in general (spectroscopy, lifetimes, sin 2β, etc)
- These results have been obtained while both CDF and D0 were reporting **"factor of 3 discrepancies"** between observed and predicted b-hadron cross-sections
- To claim that we "need" to understand b production in order to make new discoveries is therefore a bit exagerated: important discoveries should be able to stand on their feet without appealing to the prediction of a QCD calculation

Nevertheless, lack of confidence in the ability to describe the properties of events containing b quarks, in addition to raising doubts over the general applicability of pQCD in hadronic collisions, does limit our potential for the discovery of possibly subtle and unexpected new phenomena

Example:

Berger, Harris, Kaplan, Sullivan, Tait, Wagner, PRL 86 (2001) 4231

dard model (MSSM) [3]. We postulate the existence of a relatively light gluino $\tilde{g}$ (mass $\simeq$ 12–16 GeV) that decays into a bottom quark and a light bottom squark $\tilde{b}$ (mass $\simeq$ 2–5.5 GeV). The $\tilde{g}$ and the $\tilde{b}$ are the spin-1/2 and spin-0 supersymmetric partners of the gluon (g) and bottom quark (b). In our scenario the $\tilde{b}$ is either long-lived or decays hadronically. We obtain good agreement with hadron collider rates of bottom-quark production. Several



In some cases, existing measurements challenge the theory in ways which go beyond simple overall normalization issues, pointing at effects which are apparently well beyond reasonable theoretical systematics

CDF: Study of the heavy flavor content of jets produced in association with W bosons in ppbar collisions at √S=1.8 TeV, PRD65, 052007

We present a detailed examination of the heavy flavor content of the $W+$jet data sample collected with the Collider Detector at Fermilab during the 1992–1995 collider run at the Fermilab Tevatron. Jets containing heavy flavor quarks are selected via the identification of secondary vertices or semileptonic decays of b and c quarks. There is generally good agreement between the rates of secondary vertices and soft leptons in the data and in the standard model simulation including single and pair production of top quarks. An exception is the number of events in which a single jet has both a soft lepton and a secondary vertex tag. In $W+2,3$ jet data, we find 13 such events where we expected 4.4 ± 0.6 events. The kinematic properties of this small sample of events are statistically difficult to reconcile with the simulation of standard model processes.

CDF: Heavy flavour properties of jets produced in ppbar interactions at √S=1.8 TeV, PRD69, 072004

Finally, with these calibrations we find that away-jets have a 30–50% excess of soft lepton tags as compared with the simulation, corresponding to $(2.5–3.5)\sigma$, depending on the selection of the away-jets; the selections include (a) all away-jets, (b) a subset with SECVTX tags, and (c) another subset with JPB tags (the three results are highly correlated and should not be combined). The size of this excess is consistent with the differences between the NLO prediction and the $b\bar{b}$ cross section measurements at the Tevatron that are based upon the detection of one and two leptons from b-quark decays. A possible interpretation of this excess, the one that motivated this study, is the pair production of light scalar quarks with a 100% semileptonic branching ratio. Due

It cannot be contested, therefore, that the study of b production properties should be one of the main priorities for Run II

Starting from the situation as it developed during Run I, I will review here the progress in the theoretical developments

More details on the historical evolution of X-sect measurements in:
http://mlm.home.cern.ch/mlm/talks/Bcrosssection.pdf

I will then present the implications of the first preliminary results from Run II.

The theoretical analysis of the 1.96 TeV data is contained in:
M.Cacciari, S.Frixione, MLM, P.Nason and G.Ridolfi, arXiv:hep-ph/0312132.

I will conclude by calling for more aggressive engagement of the experimental community in these measurements

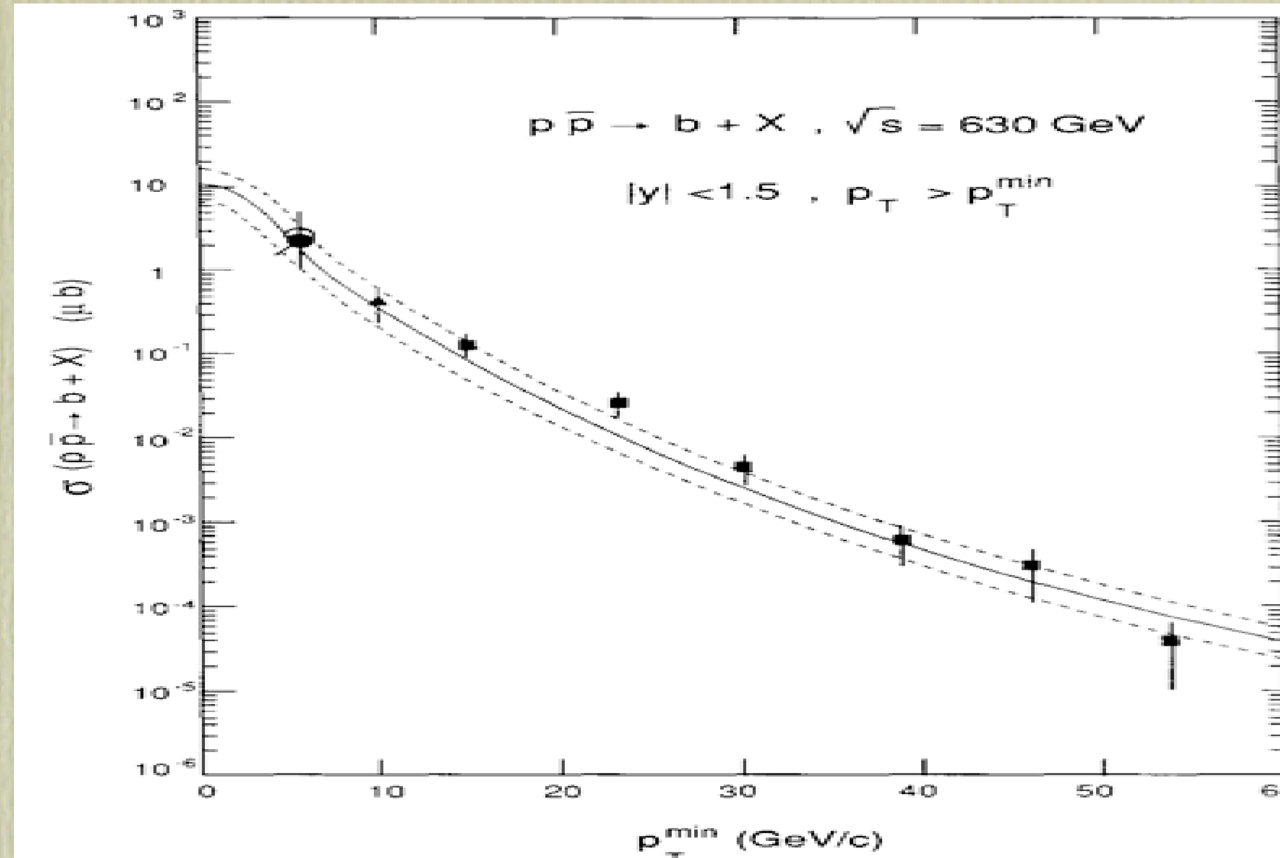
1988-1991:

UA1, PL B213 (1988) 405

UA1, PL B256 (1991) 121

Inclusive muons,
muons in jets, J/ψ

UA1/QCD ~ **1**



June 1992: *CDF, PRL 68 (1992) 3403*

Exclusive $B^{\pm} \to \psi K^{\pm}$, 14±4 events from run O, '88-89

$$\sigma(\bar{p}p \to B^- X;\, P_T > 9.0\ \mathrm{GeV}/c,\ |y| < 1.0) = 2.8 \pm 0.9(\mathrm{stat}) \pm 1.1(\mathrm{syst})\ \mu\mathrm{b}\,.$$

σ(pp→bX; PT>11.5 GeV, |y|<1):

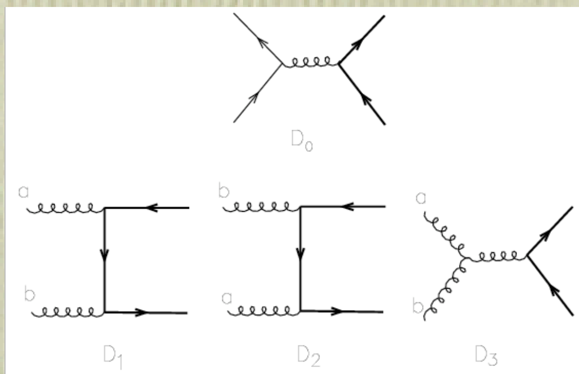
CDF = 6.1±1.9±2.4 μb

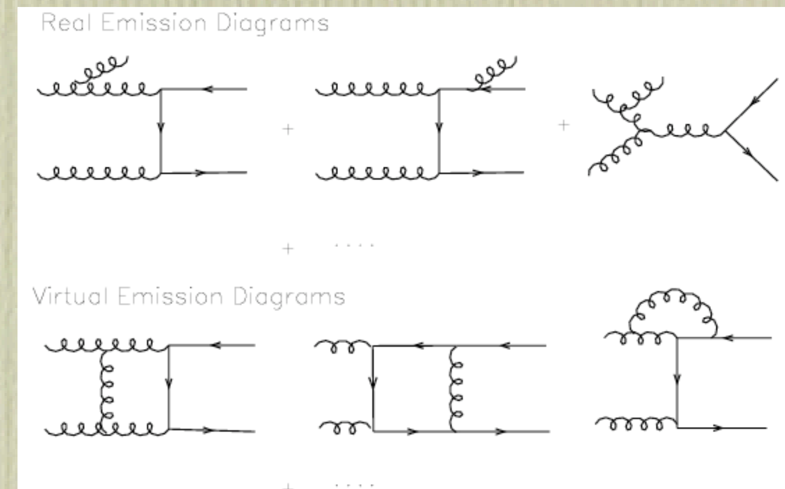
theory = 1.1±0.5 μb

CDF/QCD ~ **5** (but Δ = 1.6σ only)

What did we mean then by "QCD theory"?

Full, massive, NLO evaluation of the b quark inclusive spectrum: $\frac{d^2\sigma}{dp_T\,dy}$



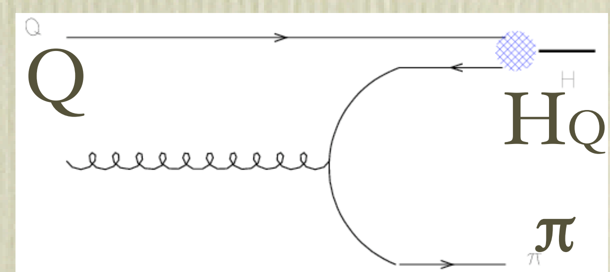


Nason, Dawson, Ellis:
NPB327 (1989) 49 (total rate)
NPB303 (1988) 607 (spectrum)

Beenakker, van Neerven, Meng, Schuler, Smith,
NP B351 (1991) 507 (spectrum)

Convolution with a b→B non-perturbative fragmentation function:

$$\frac{d\sigma(B)}{dp_T} = \int \frac{dz}{z}\,\frac{d\sigma(b)}{d\hat{p}_T}\, f(b \to B; z)\,, \qquad \hat{p}_T = p_T/z$$



usually modeled a la Peterson et al:

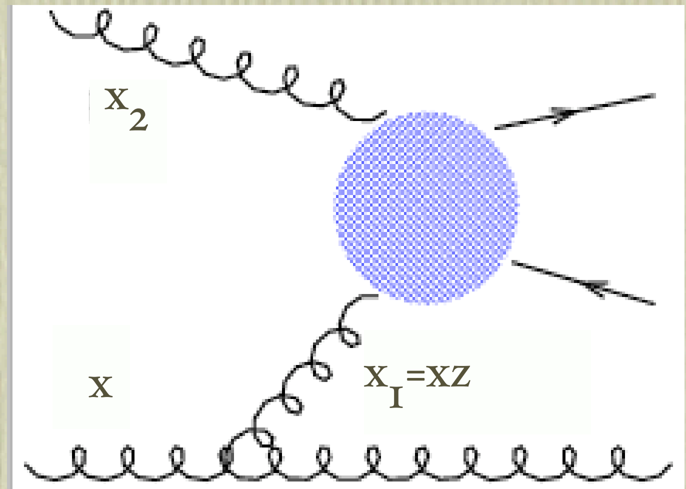
Peterson, Schlatter, Schmitt Zerwas: PRD27 (1983) 105

$$f(Q \to H_Q, z) \sim \frac{1}{z\,[1 - 1/z - \varepsilon_Q/(1-x)]^2} \quad \text{with} \quad \varepsilon_Q \sim \frac{\Lambda^2}{m_Q^2} \quad \text{and} \quad \langle 1 - z \rangle \sim \sqrt{\varepsilon_Q}$$

PDF's extracted from global NLO fits (DFLM, MT, MRS, CTEQ) and ϵ_Q extracted from LO fits of e+e- → cc data, using then $\epsilon_b = m_c^2/m_b^2\, \epsilon_c$

Chrin, Z.Phys C36 (1987) 163

Small-x effects?



$$\sigma(Q\bar{Q}g) \sim \int_{x_1}^{1} dx\, f(x)\, dz\, P_{gg}(z)\, \delta(x_1 - xz) \int dx_2\, f(x_2) \hat{\sigma}(Q\bar{Q}, x_1 x_2 S)$$

$$\sim \int_{x_1}^{1} \frac{dx}{x} f(x) \frac{2C_A \alpha_s}{x_1/x} \int dx_2\, f(x_2) \hat{\sigma}(Q\bar{Q}, x_1 x_2 S)$$

As a result: $\frac{\hat{\sigma}_{NLO}(gg \to Q\overline{Q}g)}{\hat{\sigma}_{LO}(gg \to Q\overline{Q})} \overset{\hat{s}\to\infty}{\to} \alpha_s \frac{\hat{s}}{m^2}$ Assuming $f(x) \sim \frac{A}{x^{1+\delta}}$

we get:

$$\frac{\sigma_{\rm NLO}(p\bar{p} \to Q\overline{Q})}{\sigma_{\rm LO}(p\bar{p} \to Q\overline{Q})} \sim \begin{cases} \alpha_s \log \frac{S}{4m^2} & \text{if } \delta \log \frac{S}{4m^2} \ll 1 \\ \alpha_s \frac{1+\delta}{\delta} & \text{if } \delta \log \frac{S}{4m^2} \gg 1 \end{cases}$$

These logs will appear at all orders of PT : need for resummation!

Notice however that they are quenched when the input PDF is already steeper than 1/x

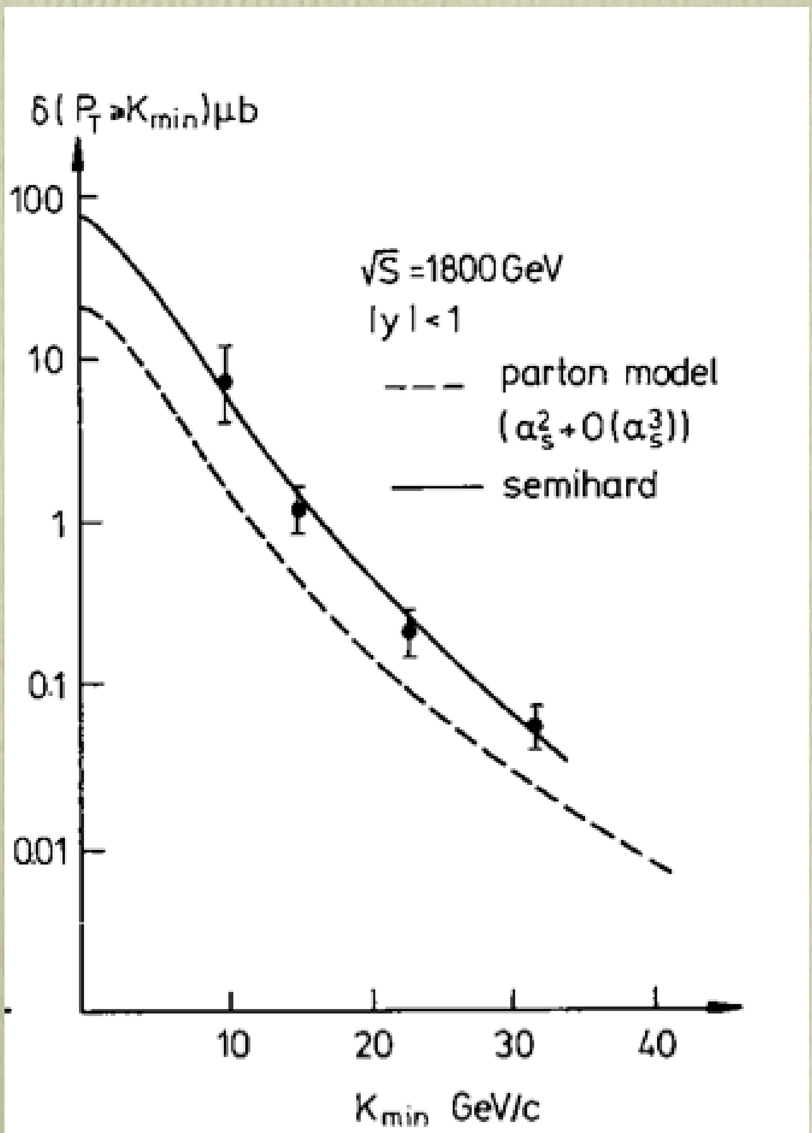
Formalism:

Collins&Ellis, Nucl.Phys.B360:3-30,1991

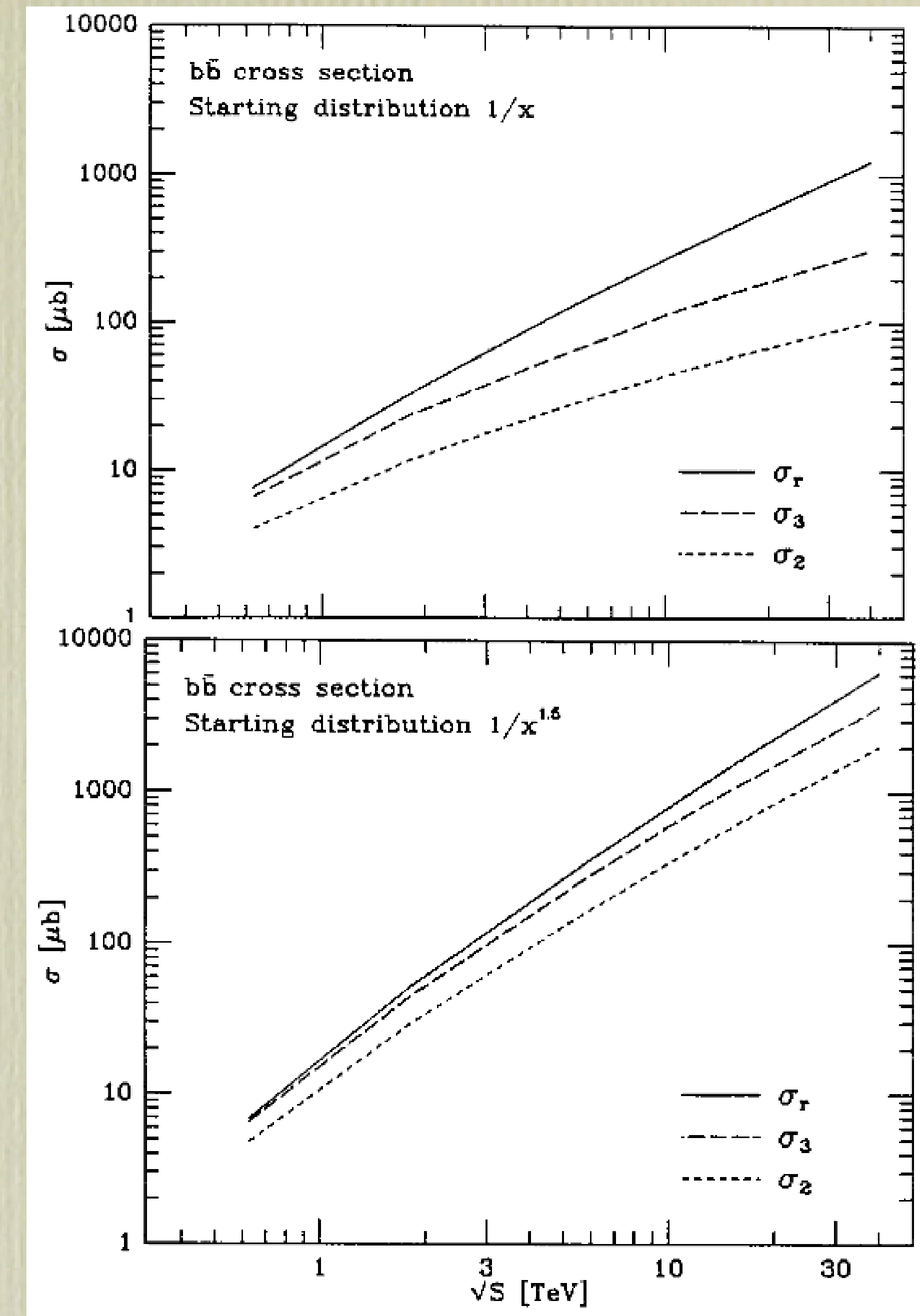
Catani, Ciafaloni&Hautmann, Nucl.Phys.B366:135-188,1991

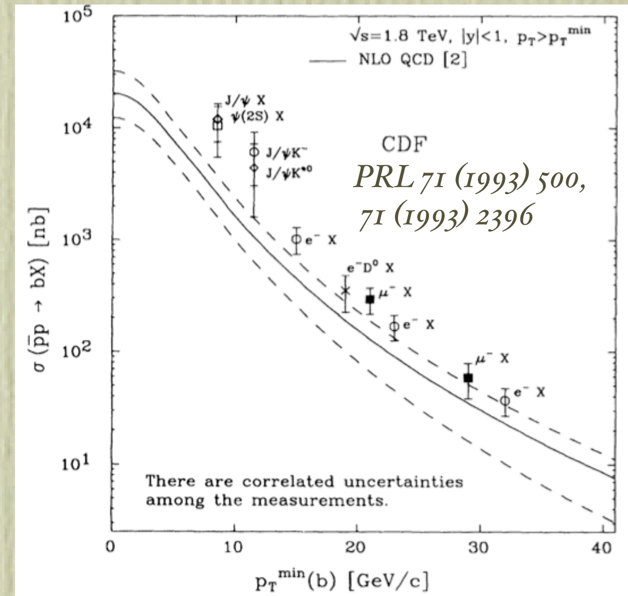
Collins&Ellis

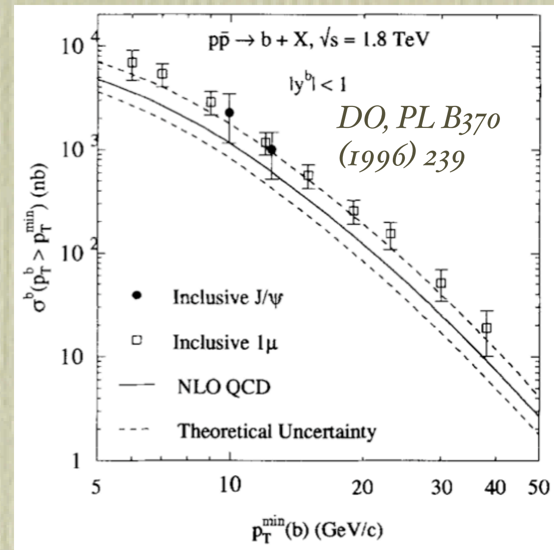
a	σ2(μb)	σ3(μb)	σres(μb)
1	12	23	33
1.5	29	44	51

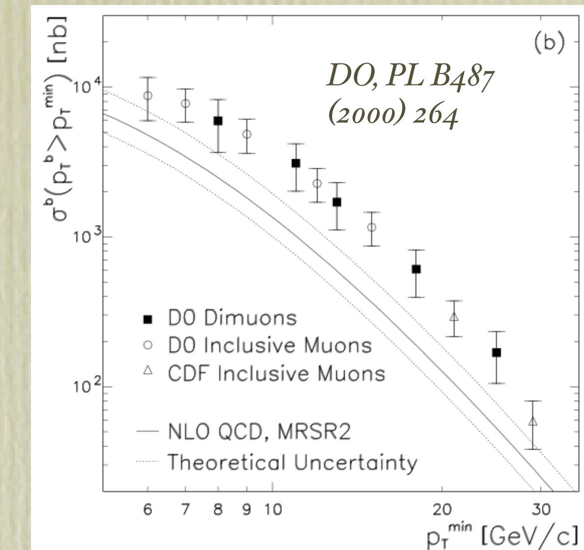


Levin, Ryskin, Shabelski, Phys.Lett.B260:429-432,1991, Sov.J.Nucl.Phys.53:657,1991

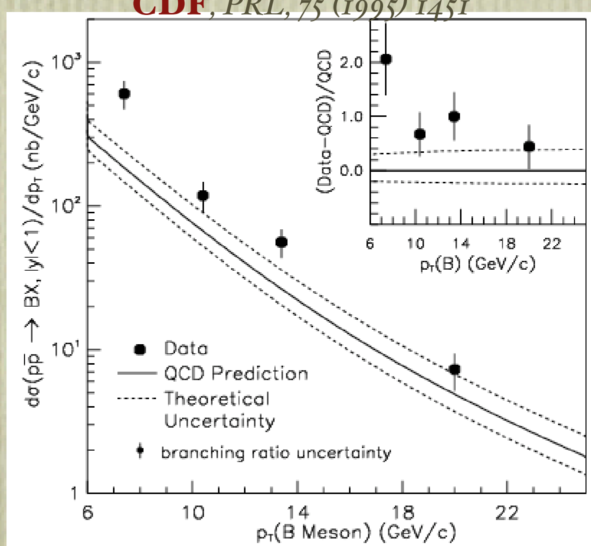


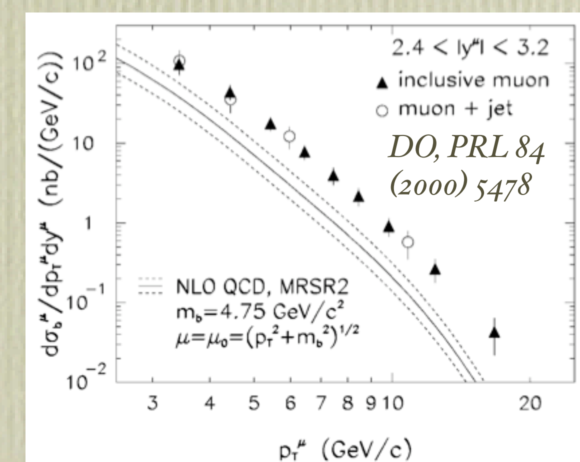


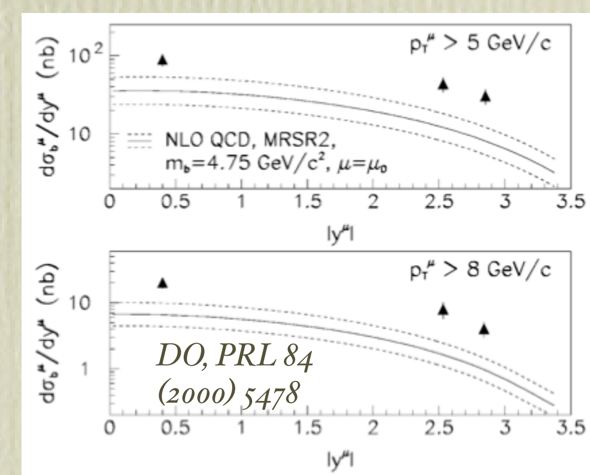




CDF, *PRL, 75 (1995) 1451*





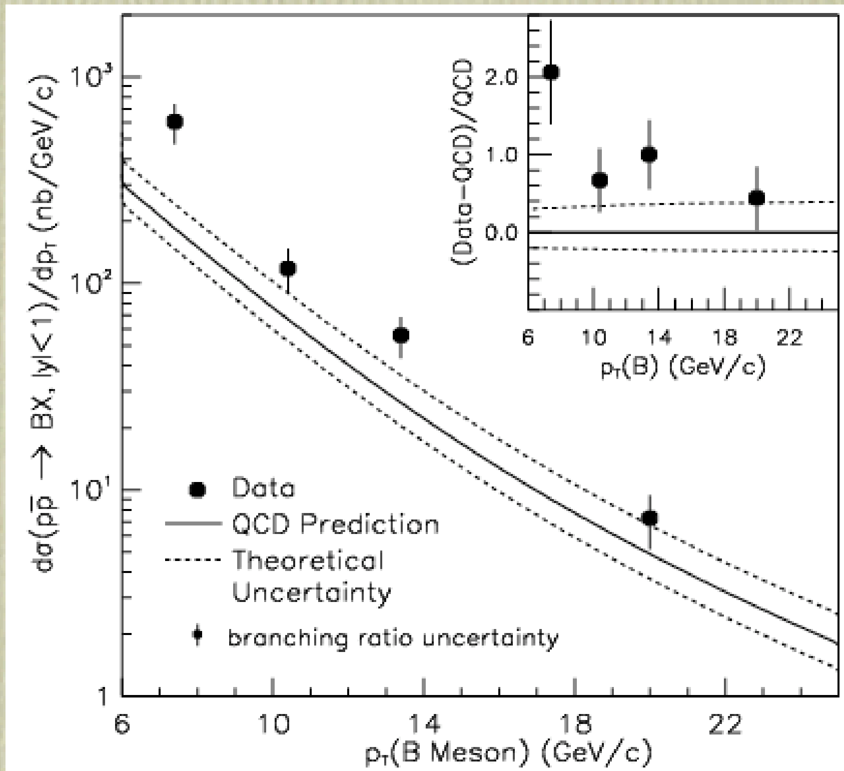


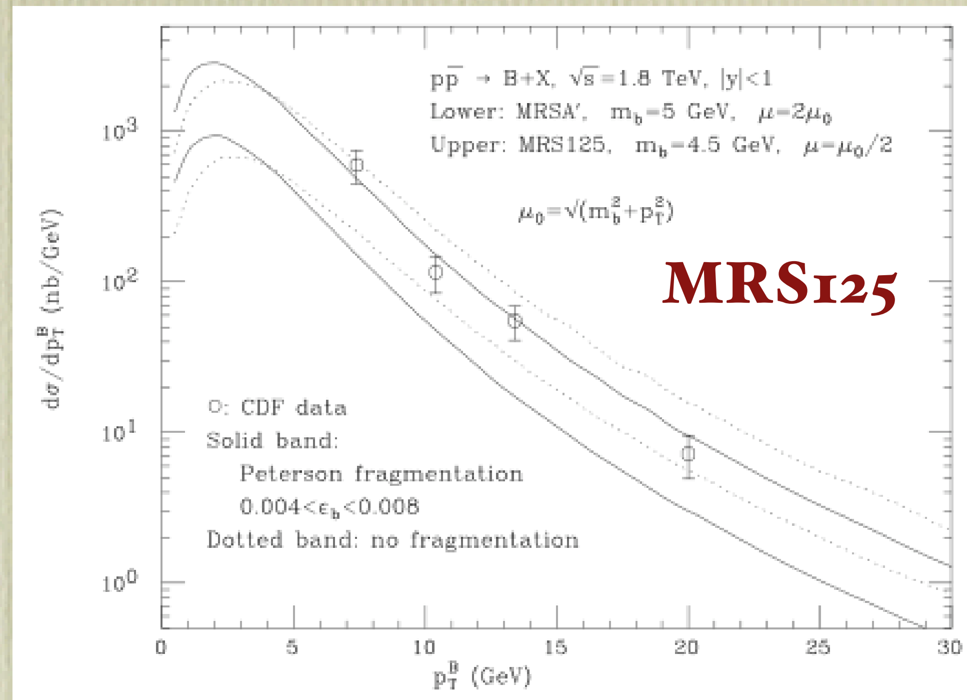
More details on the historical evolution of X-sect measurements in:
http://mlm.home.cern.ch/mlm/talks/Bcrosssection.pdf

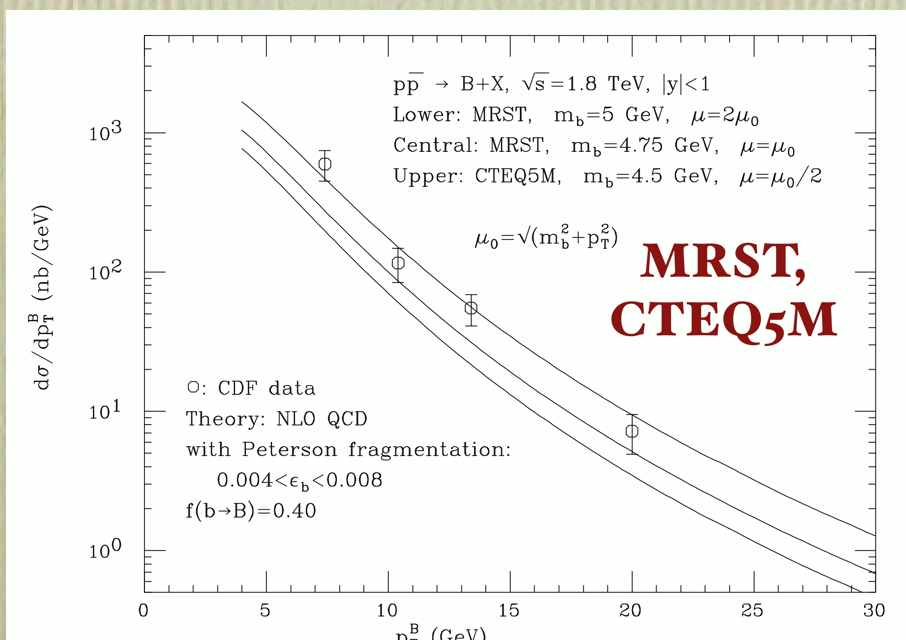
Time dependence - PDF fits evolve:

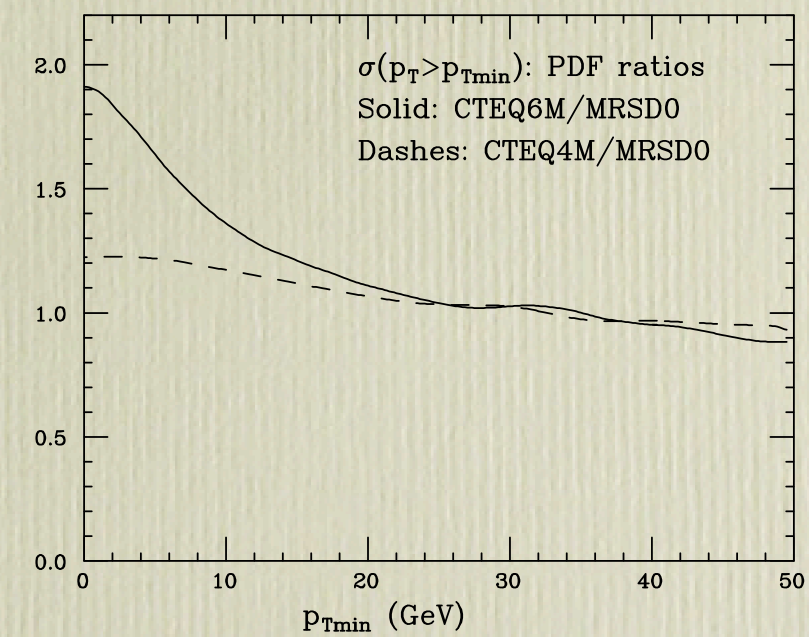
CDF 1995:

Frixione, MLM, Nason, Ridolfi, hep-ph/9702287









Fragmentation function systematics

Around 1997 we started convincing ourselves that the systematics related to the non-perturbative fragmentation function was being seriously underestimated. **MLM, 2 Lectures on HQ production, hep-ph/9711337**

$$\frac{d\sigma(B)}{dp_T} = \int \frac{dz}{z} \frac{d\sigma(b)}{d\hat{p}_T} f(b \to B; z) \, , \qquad \hat{p}_T = p_T/z$$

known from PT

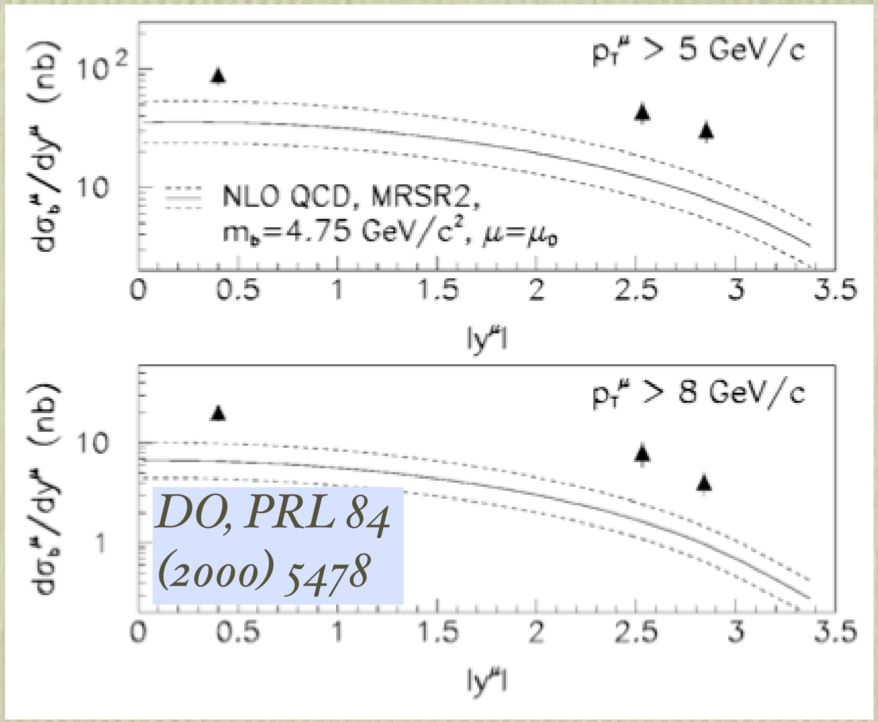
fit to e+e- data, under the assumption of factorization and universality.

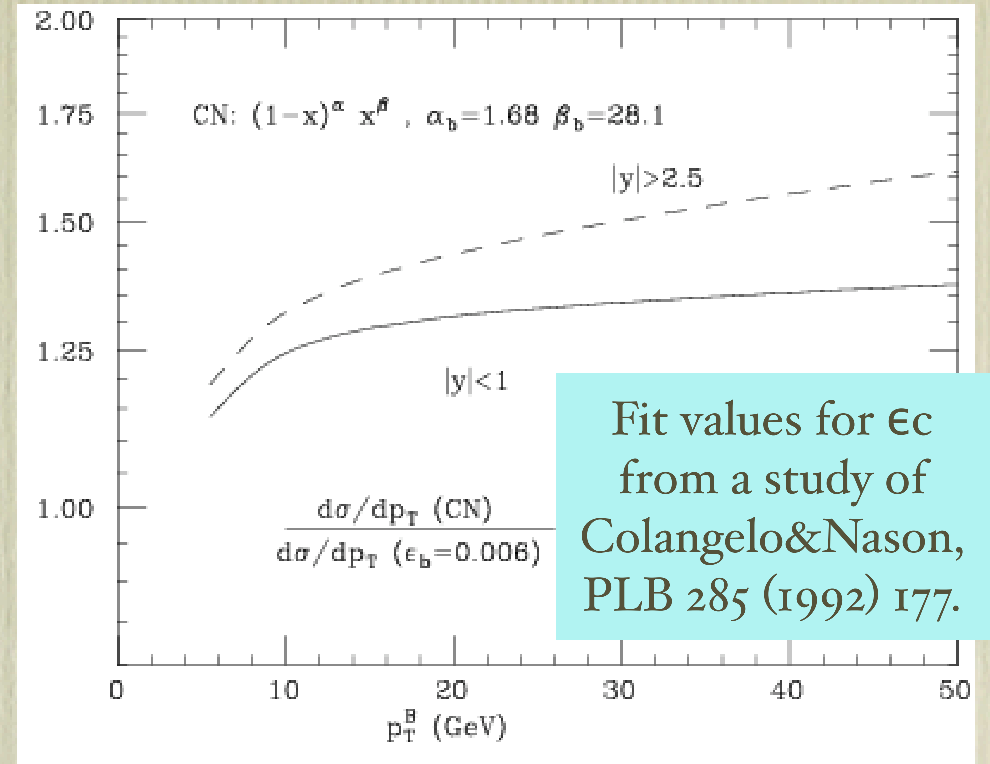
Assuming $\frac{d\sigma}{d\hat{p}_T} \sim \frac{1}{\hat{p}_T^N}$ we easily get: $\frac{d\sigma}{dp_T} \sim \int \frac{dz}{z} (\frac{z}{\hat{p}_T})^N f(z) = f_N \frac{d\sigma}{d\hat{p}_T}$

Due to the steeply falling slope, the spectrum in hadronic collisions is sensitive to a large moment of the FF. On the contrary, in e+e- we are directly sensitive to <z>, which is the first moment. Fits to e+e- data are therefore not very sensitive to what really matters for pp, and higher accuracy in the data (and in the theory used for the fit) is required to extract meaningful results for pp.

Different parameterizations, giving similar fits to e+e- data, could lead to very different results when used in hadronic b production

The effects will vary as a function of rapidity, since at larger rapidities the slope of $d\sigma/dp_T$ steepens (N grows), going in the direction of DO findings at large eta (MLM, hep-ph/9711337)





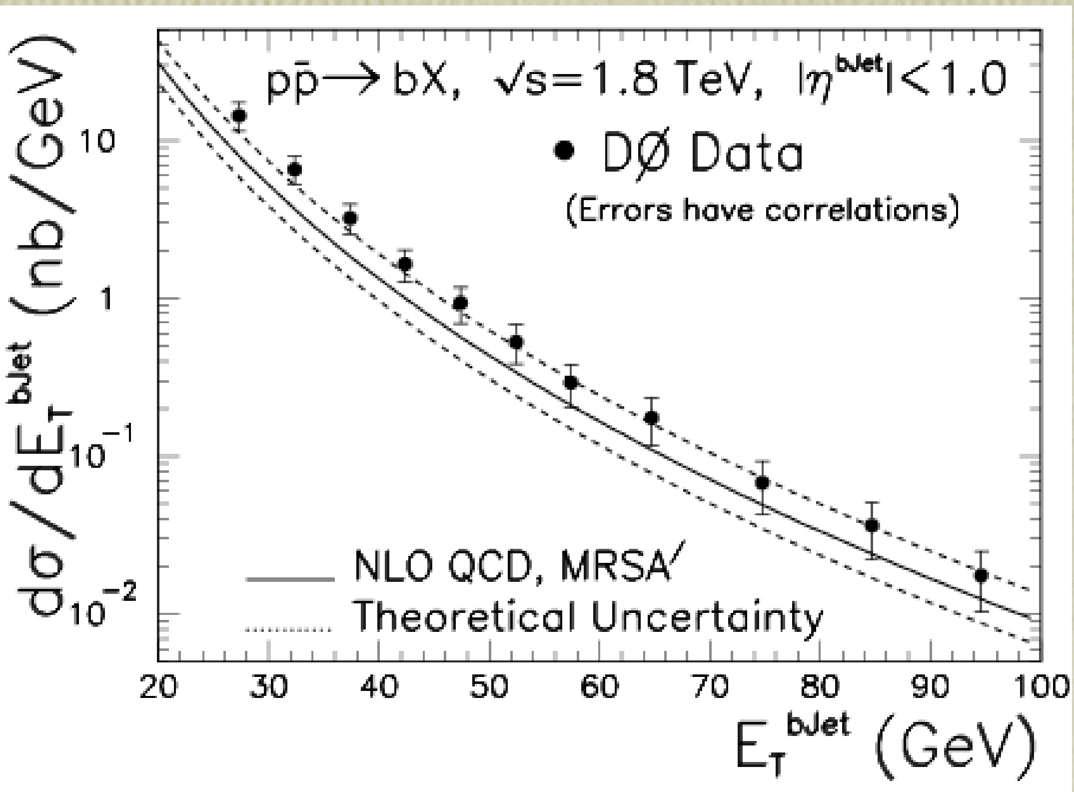
It then became obvious that one should try to select observables with the least possible dependence on the fragmentation properties of b quarks. This demands small dependence on the precise value of pT(B). The best choice seemed to be looking at the **spectrum of b-jets,** namely jets including a b quark, regardless of the energy fraction carried by the b itself. We expected this to lead to reduced dependence on large collinear logarithms and on the fragmentation function

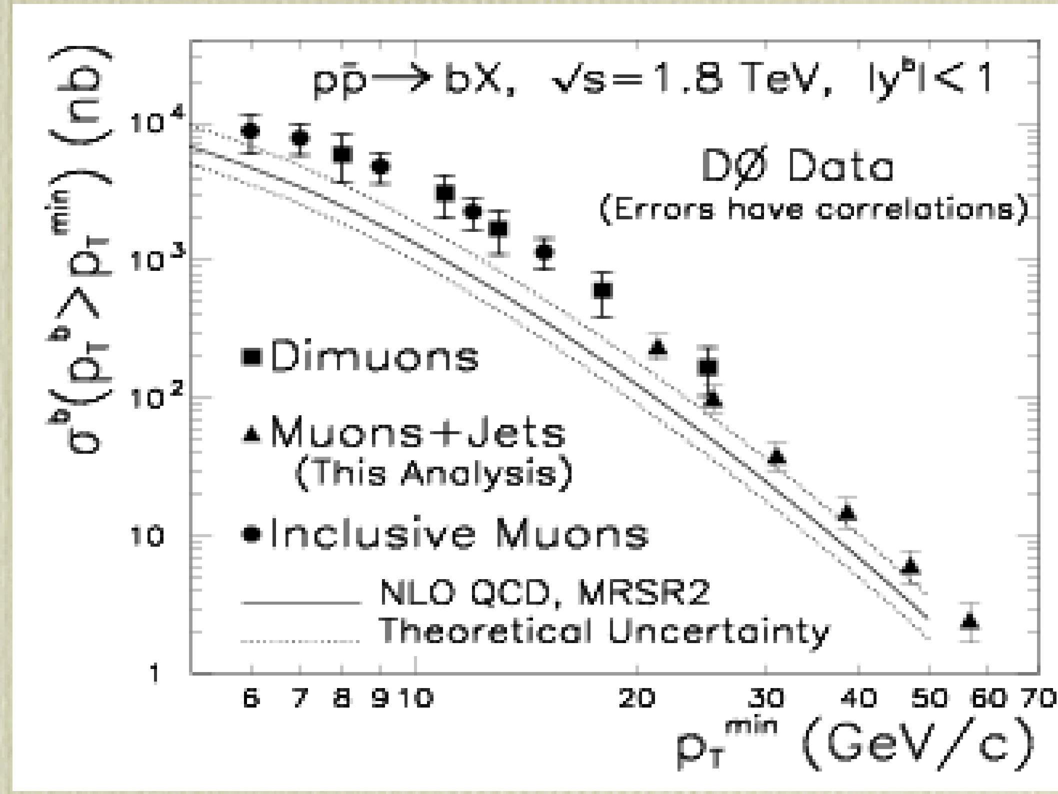
Frixione & MLM, *Nucl Phys B483 (1997) 321*

Aug 2000:

DO, PRL, 85 (2000) 5068

b-jet cross-section





Better agreement with QCD than for measurements on b-hadrons: we are going in the right direction!

Time had come for a new full appraisal of fragmentation functions

- consistent level of accuracies in the calculations for e^+e^- and hadronic production
  - available by 1998 with the work of Cacciari, Greco Nason (⇒)

JHEP 9805:007,1998

- good data to allow accurate fits
  - avoid passing through the charm, fit directly Z-> b fragmentation data
  - data finally available in 2001

The formalism: Cacciari, Greco, Nason, JHEP 9805:007,1998; see also Olness Scalise Tung, PRD59 014506 (1998)

Fixed order (**FO**):

$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + O(\alpha_s^4) \qquad B(m) = \beta(m) + \gamma(m)\log(\mu/m)$$

Fixed order, 0-mass (**FOmo**):

$$\frac{d\sigma}{dp_T} = A(0)\,\alpha_s^2 + [\beta(0) + \gamma(0)\log(\mu/m)]\,\alpha_s^3$$

NLL resummed (**RS**):

$$\frac{d\sigma}{dp_T} = \alpha_s^2 \sum_{i=0}^{\infty} a_i\,[\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=0}^{\infty} b_i\,[\alpha_s \log(\mu/m)]^i$$

$$+ O(\alpha_s^4(\alpha_s \log \mu/m)^i) + O(\alpha_s^2 \times \mathrm{PST}) \qquad \mathrm{PST} = O(m^2/p_T^2)$$

Fixed order + NLL resummation (**FONLL**):

FONLL=FO + [RS-FOm0] x G(m,pT)

$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + G(m,p_T)\left[\alpha_s^2 \sum_{i=2}^{\infty} a_i\,[\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=1}^{\infty} b_i\,[\alpha_s \log(\mu/m)]^i\right]$$

A factor G(m,pT) is introduced to suppress the higher-order logs in the low-pT region, where their dominance and their resummation is not justified:

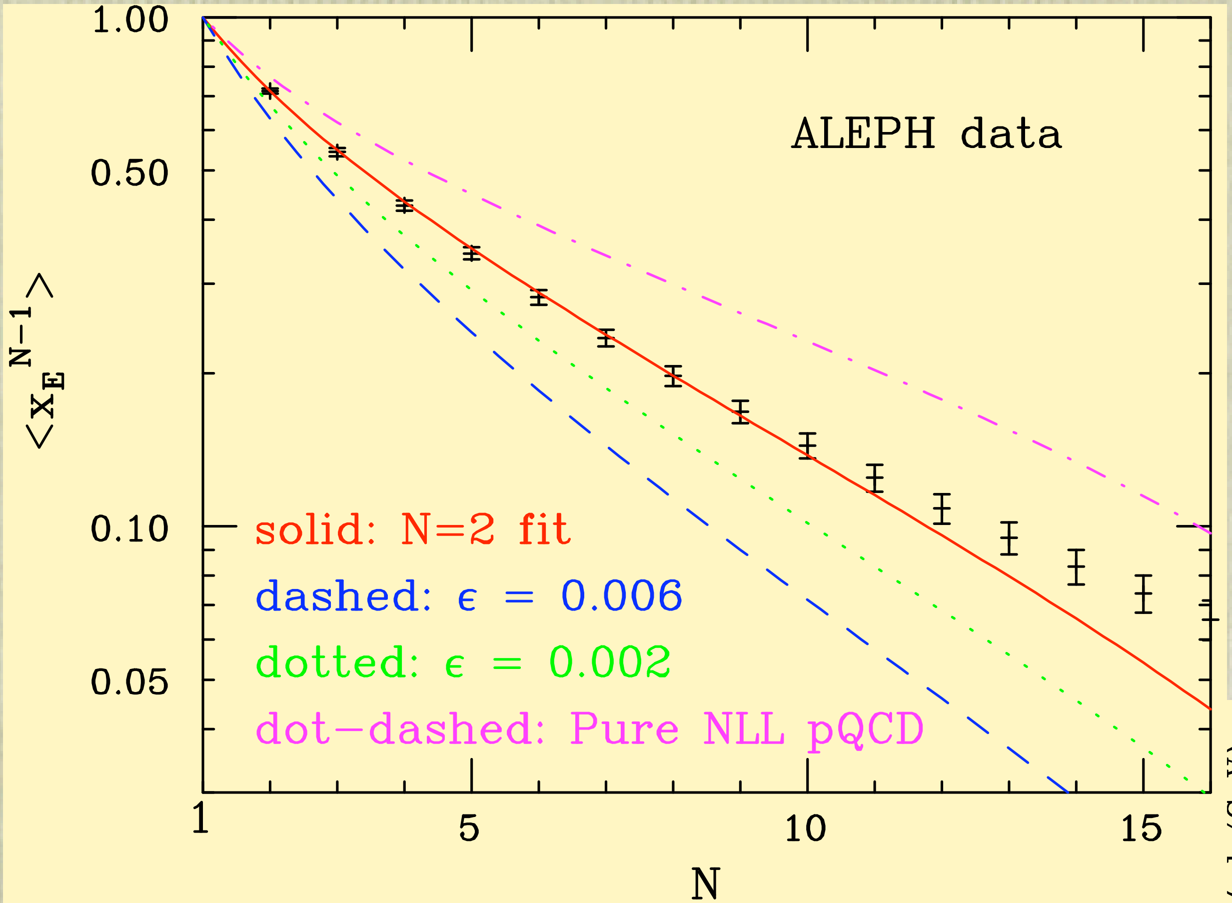
$$G(m,p_T) \to 1 \text{ for } p_T >> m$$

In practice, the following interpolating function is used, with c=5:

$$G(m,p_T) = \frac{p_T^2}{p_T^2 + c^2 m^2}$$

Better fits, and a new assessment of the B cross-section:

P. Nason and M.Cacciari, Phys.Rev.Lett.89:122003,2002

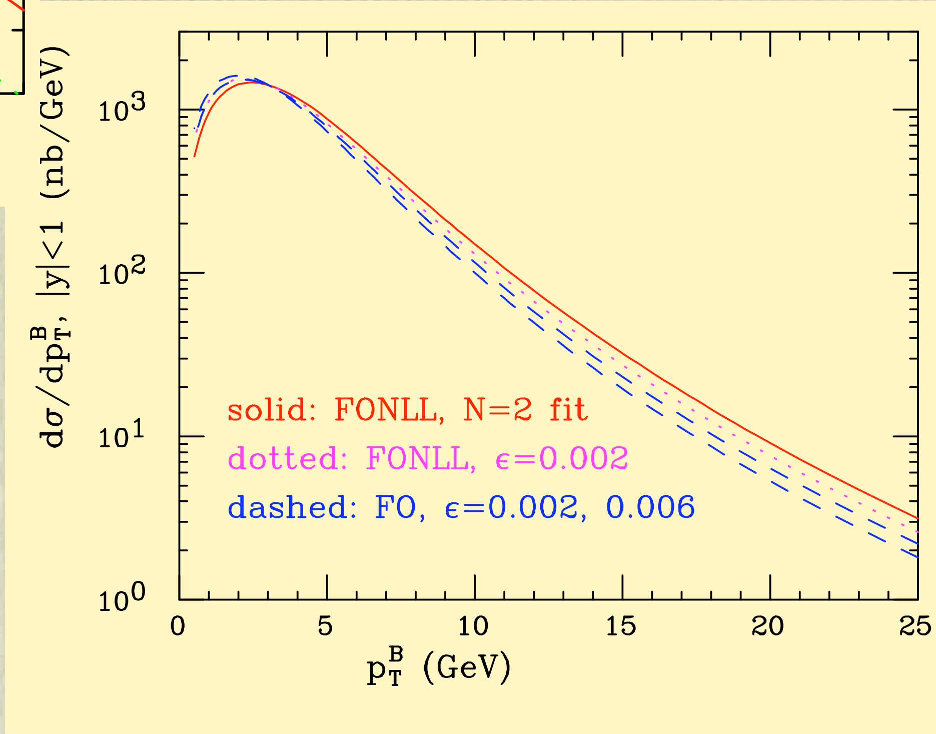


"N=2 fit":

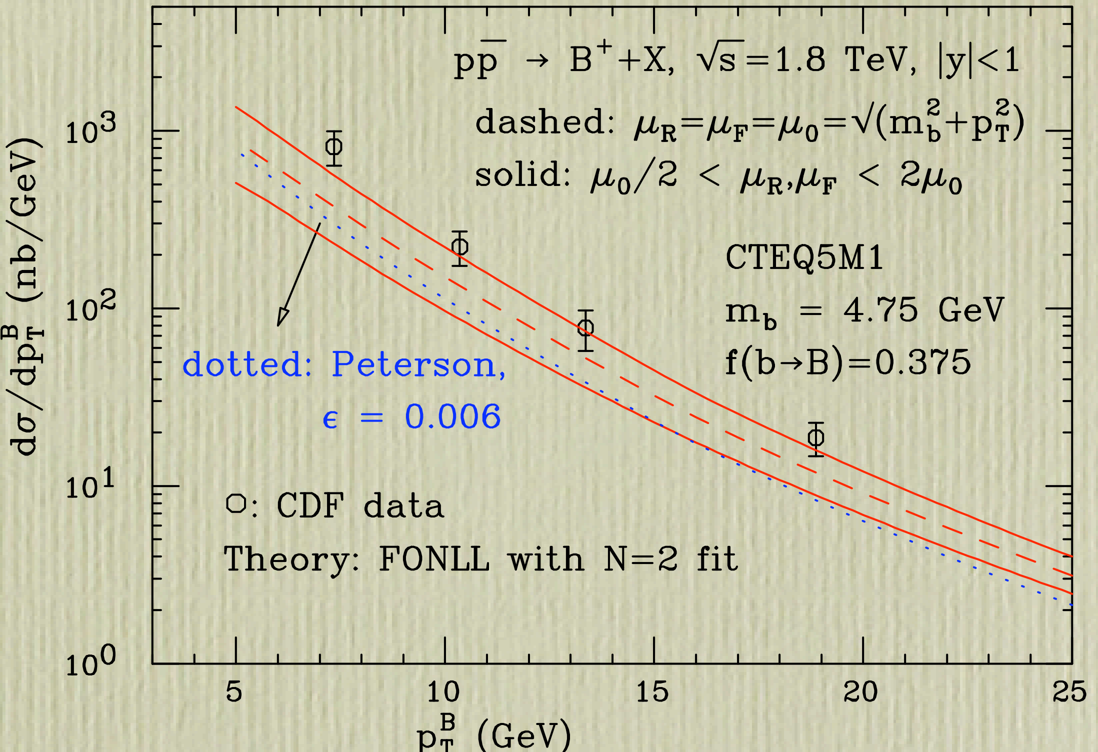
Fit of the second moment of the FF, using the Kartelishvili form:

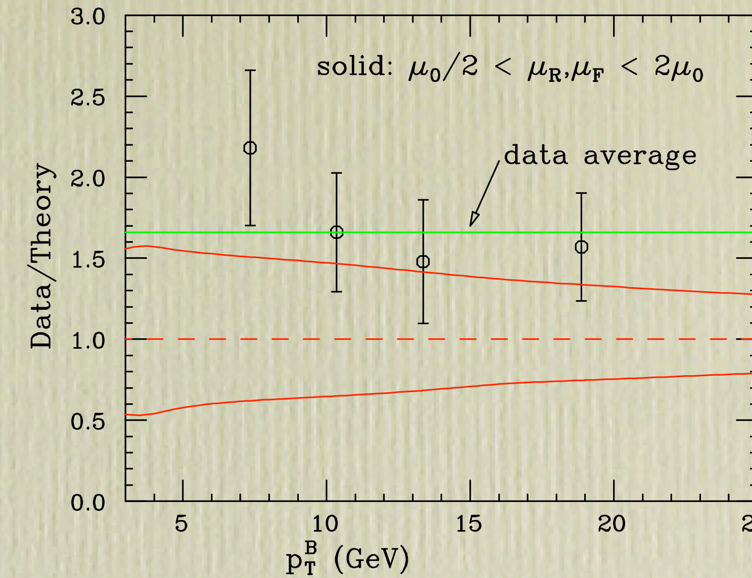
$$F(z,\alpha) = (\alpha+1)(\alpha+2)\, z^{\alpha}\, (1-z)$$

Kartvelishvili, Likhoded, Petrov, PL B78 (1978) 615



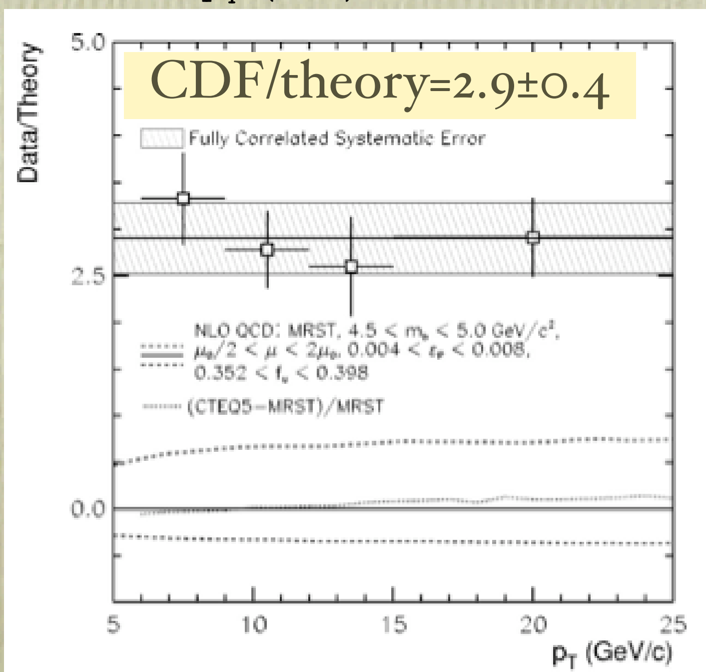
Results P. Nason and M.Cacciari, Phys.Rev.Lett.89:122003,2002





1.7 ± 0.5 (theory) ± 0.5 (expt)

cfr the comparison with theory published by CDF



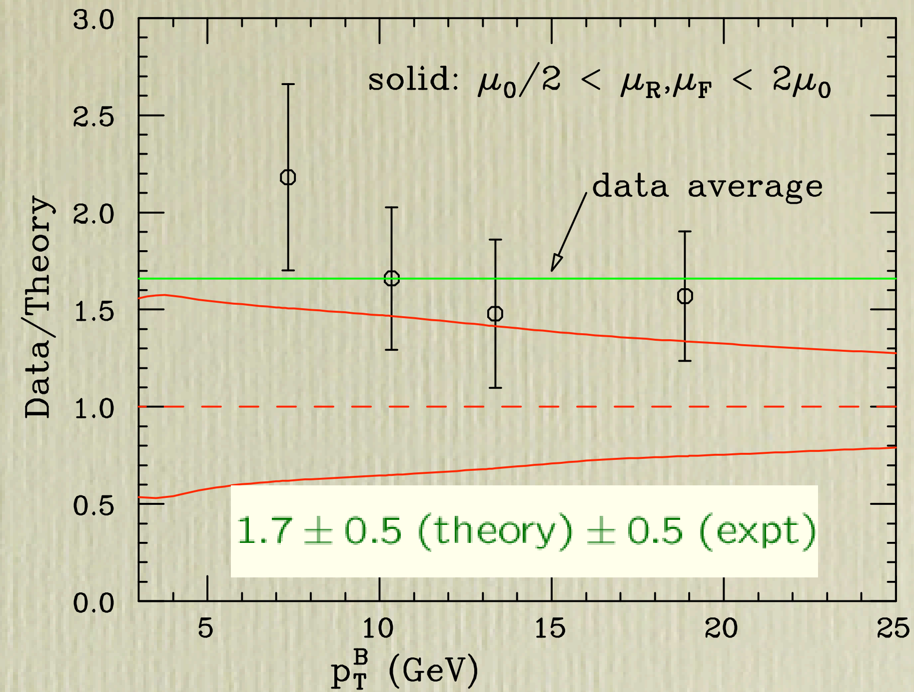
Reduction in the discrepancy is due to four basic points:

1. FONLL calculation brings about a 20% increase in the intermediate p_T region.
2. The fragmentation step for going from a "perturbative" b quark to a B hadron seems to be too strong at small p_T in the CDF implementation. We get a 20% increase in the small p_T region.
3. A Peterson fragmentation function with $\epsilon = 0.006$ is too soft (present e^+e^- data favour values around 0.002); this is a 20% effect.
4. A more accurate use of e^+e^- input data on the fragmentation function brings about another 20% effect.

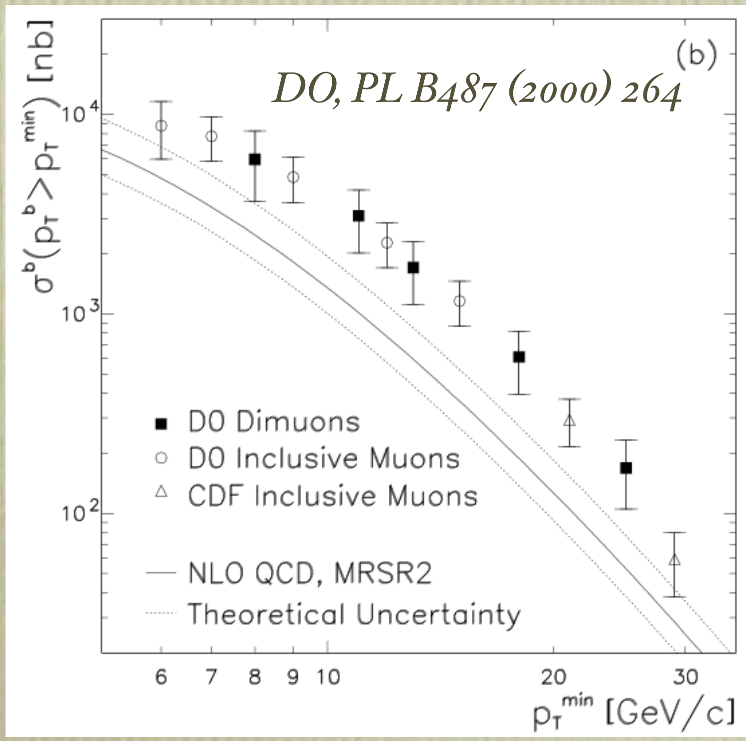
The net effect is $1.2^3 = 1.7$ and $2.9/1.7 = 1.7$, so that the 2.9 CDF discrepancy becomes our 1.7.

At the end of Run I, the situation could be summarised as follows:

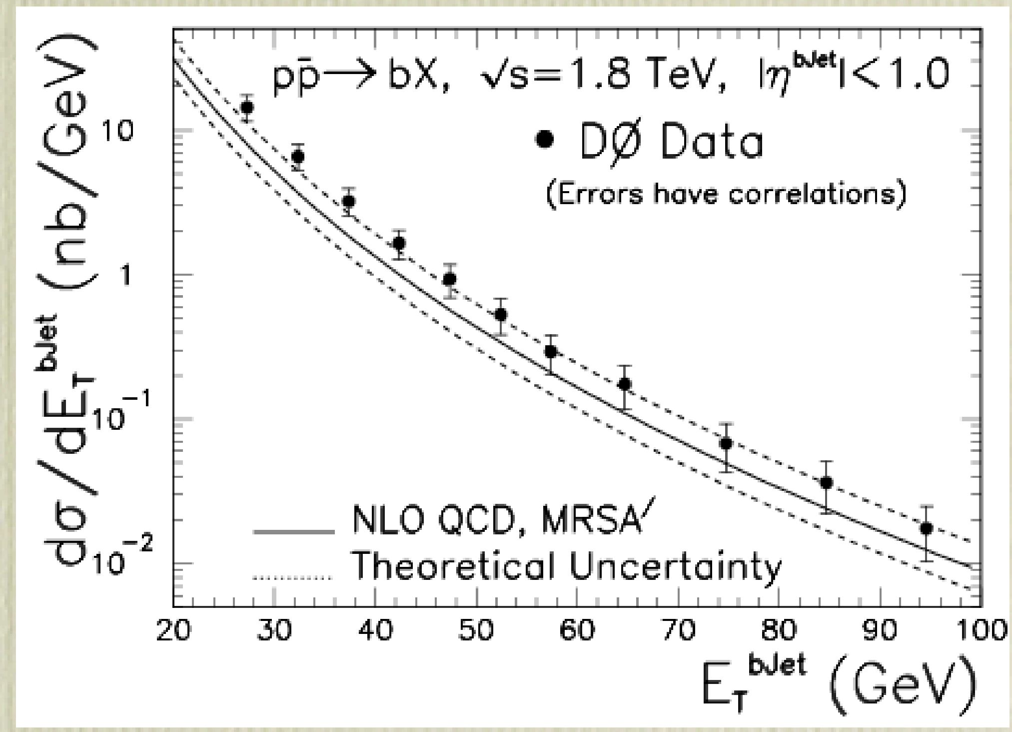
low-pt, exclusive B-meson production:



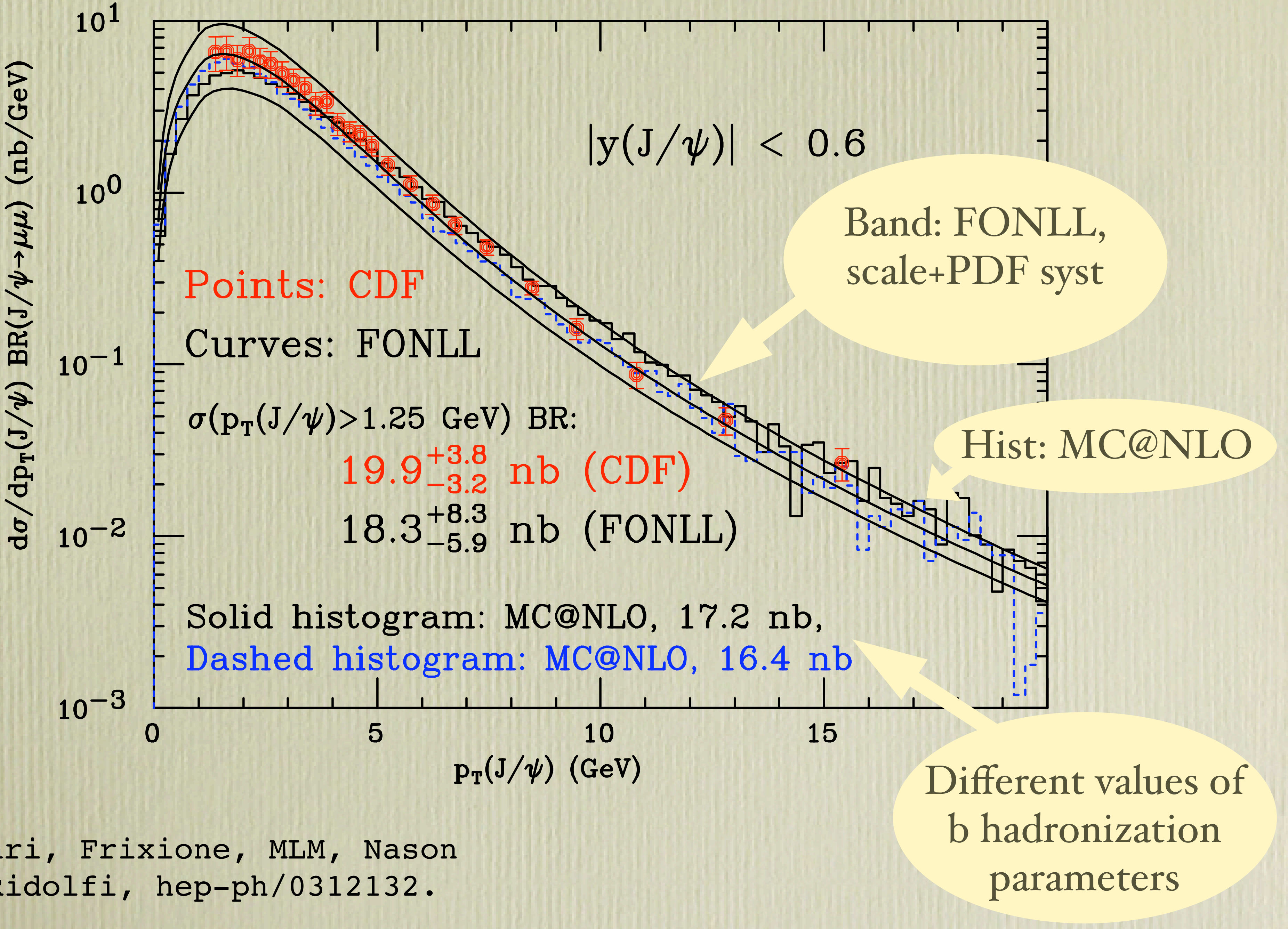
mid-pt, incl. b semileptonic decays



high-Et, inclusive b-production in jets:



December 2003: first data from Run II analysis released by CDF (M.Bishai, Wine&Cheese at FNAL)

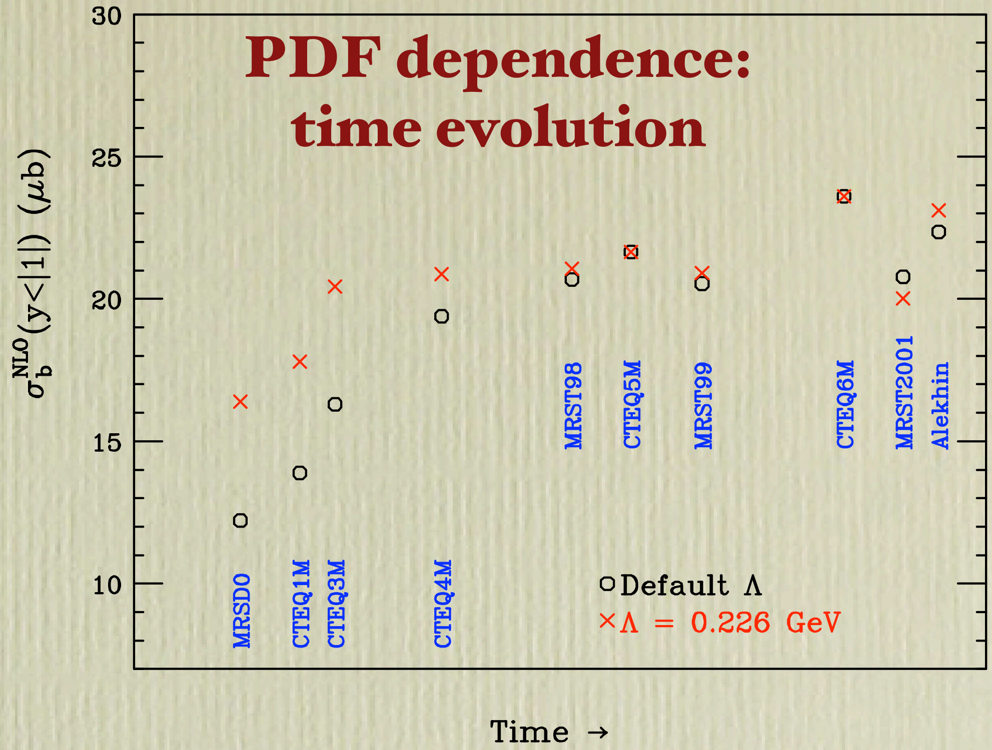


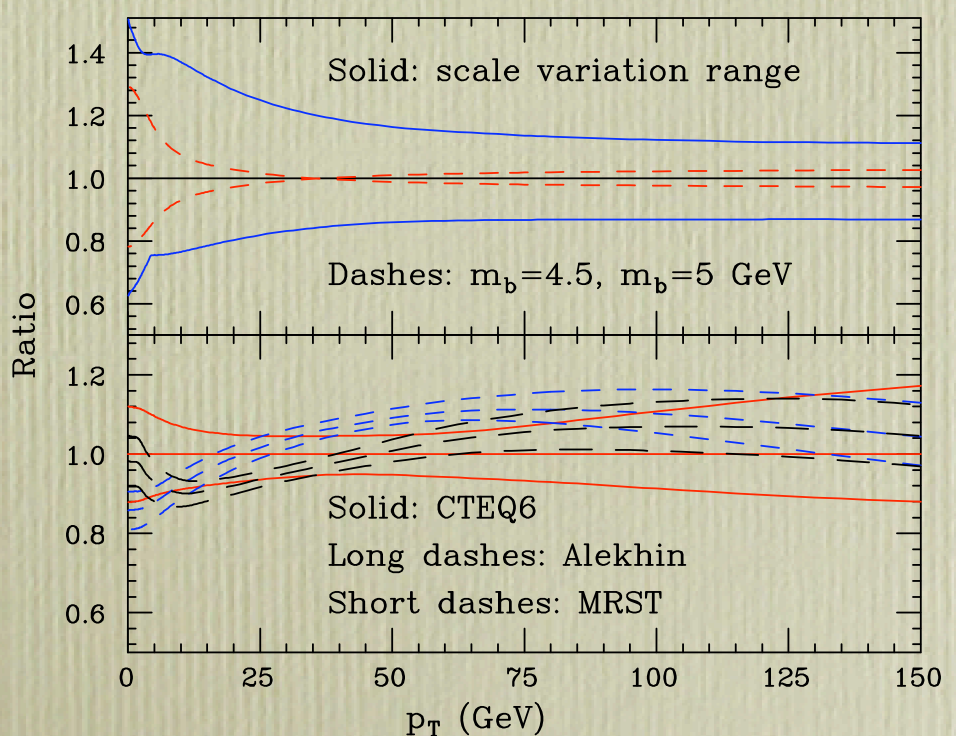
Cacciari, Frixione, MLM, Nason and Ridolfi, hep-ph/0312132.

PDF and scale systematics, 2004

The evolution of the extraction of α_s in PDF fits changed the rate by almost a factor of **two** in the last 10 yrs: this absorbed a good fraction of the early discrepancies!

PDF dependence: time evolution



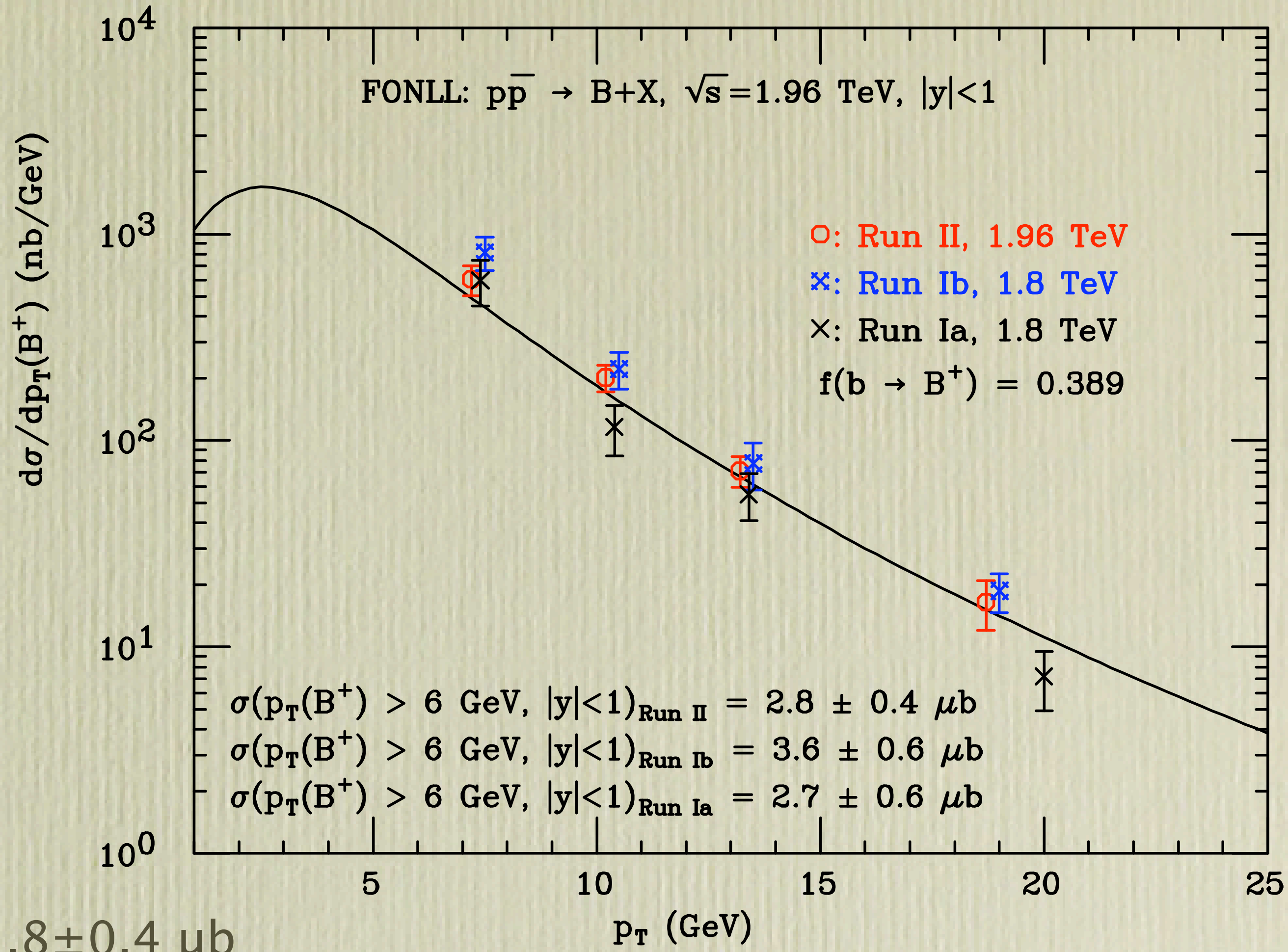


Scale uncertainty obtained by varying μ_R and μ_F independently within the range $\mu_0/2 < \mu_{R,F} < 2\mu_0$ with the constraint

$$1/2 < \mu_R \times \mu_F / \mu^2_0 < 2$$

Current uncertainty from PDF estimated at ±15%, with some inconsistency however between the PDF error bands provided by different groups

Comparing run II and run Ia/Ib data



Run II data should be about 10% higher than run I. They are instead 25% lower w.r.t. Ib. Not inconsistent with exp uncertainties, but clearly moves in the right direction

$\sigma(pp \to B^+; P_T > 6, |y| < 1)_{\text{run II}}$: 2.8±0.4 μb

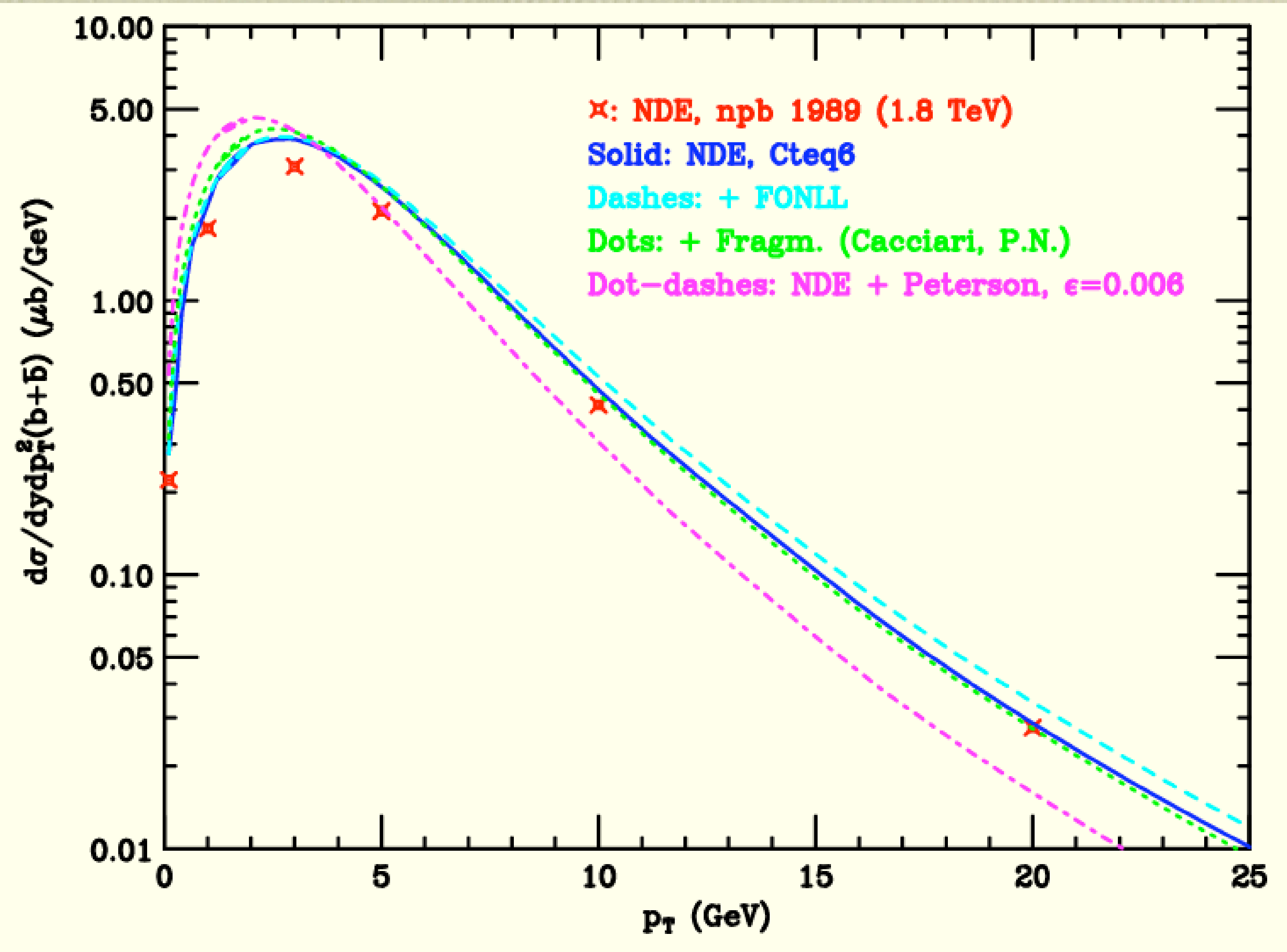
$\sigma(pp \to B^+; P_T > 6, |y| < 1)_{\text{run Ib}}$: 3.6±0.6 μb

$\sigma(pp \to B^+; P_T > 6, |y| < 1)_{\text{run Ia}}$: 2.7±0.6 μb

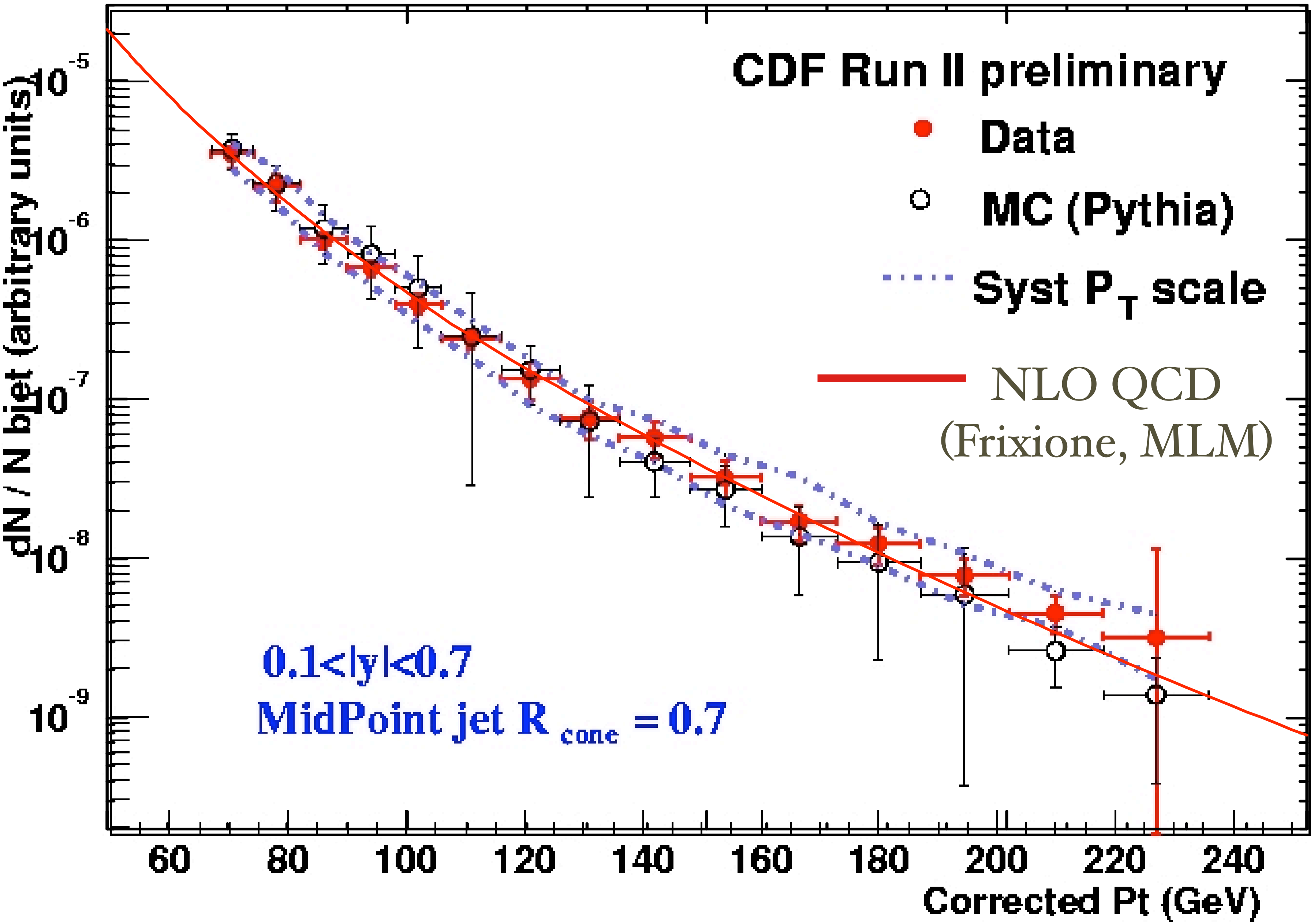
In addition to this, in the 1.96 TeV comparison we gain another 20%:

- +10% due to new PDFs (CTEQ6M vs 5M)
- + 7% due to Fb=0.375 ->0.4

Time evolution of the pQCD spectra

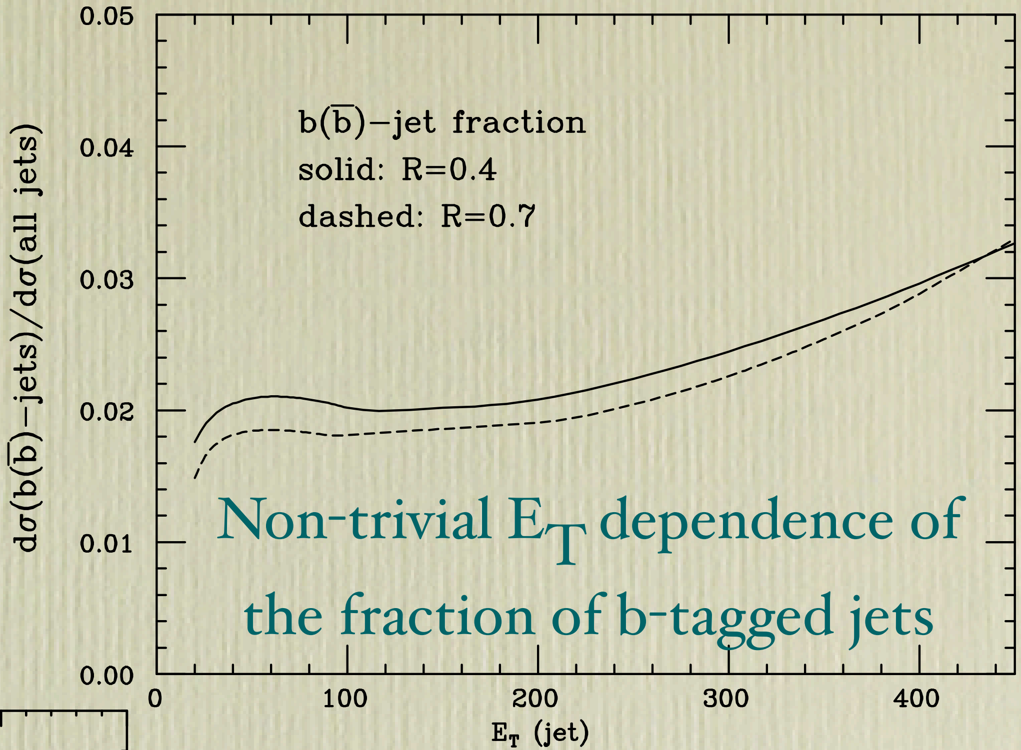


New: CDF b-jets in Run II

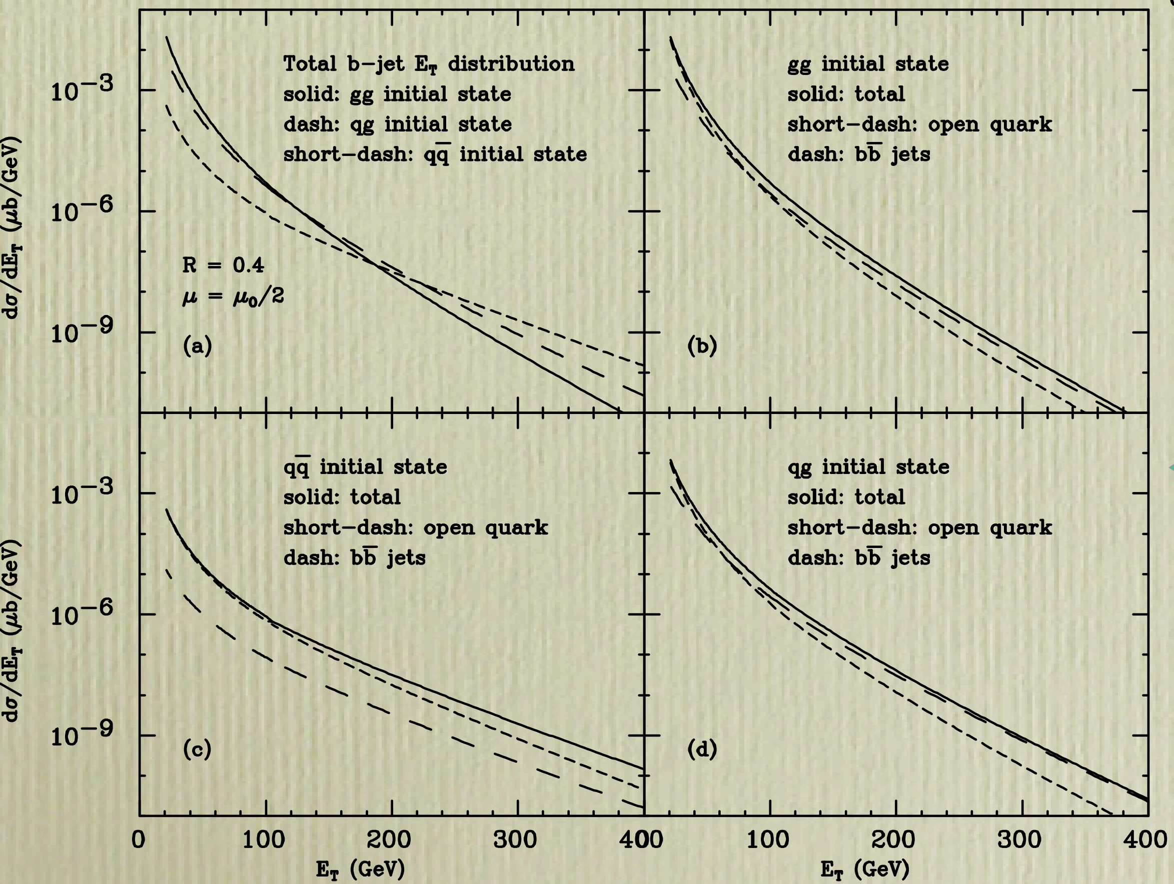


Interesting b-jet observables for run II analyses :

Frixione & MLM, *Nucl Phys B483 (1997) 321*



Non-trivial E_T dependence of the fraction of b-tagged jets



Non-trivial E_T dependence of the fraction of double-tag vs single-tag events (varying fraction of g-splitting vs back-to-back components)

Conclusions

- **Within the current uncertainties, the 1.96 TeV CDF data in the range 0<pt<20 GeV are correctly described by:**
  - **perturbative QCD at the NLO+NLL level, supplemented with non-PT fragmentation functions extracted from LEP/SLD data,**
  - **MC@NLO**
- The still large theory systematics, however, cannot rule out effects at the level of ±30-40% due to small-x logarithms or to new physics.
- The confirmation of these data by CDF itself, and by D0, is crucial.
- The analyses should be extended to larger pt, where scale dependence is reduced to ±20%, using the various alternative observables:
  - exclusive and semileptonic decays (up to and above 100 GeV)
  - b jets (up to the multi-100 gev domain)
- Final states defined by more complex selection criteria (e.g. combined SVX and lepton tags, correlations between b and bbar, etc) should be explored and compared to predictions based on MC@NLO.
- **With better analysis tools becoming available (MC@NLO) a reconsideration of the anomalies observed by CDF in Run I is mandatory, and should be performed by both experiments.**
- **Full exploration of the b production dynamics should be taken very seriously by CDF and DO. Huge statistics and much improved detectors should be fully expoited!**