Les Rencontres de Physique de la Vallée d'Aoste
La Thuile - March 2004

Twenty Years of Bottom Production

(and Charm, and Top)

vs. QCD

Matteo Cacciari
LPTHE
Université Pierre et Marie Curie (Paris 6)

A success story, a few glitches left, and some good lessons

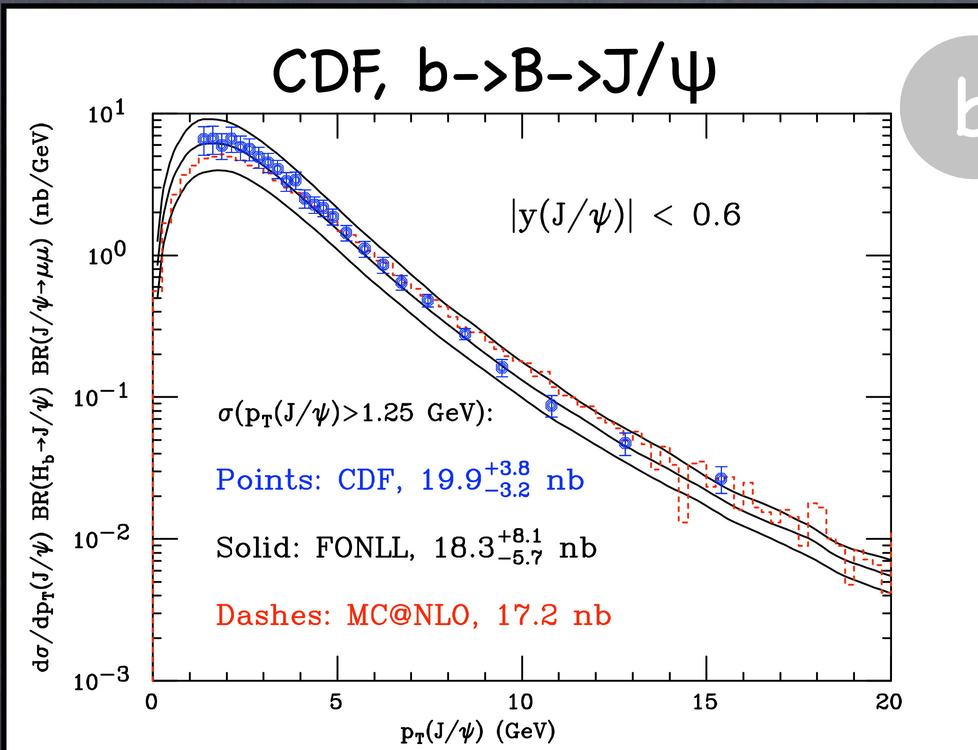
What shall we mean by "success"?

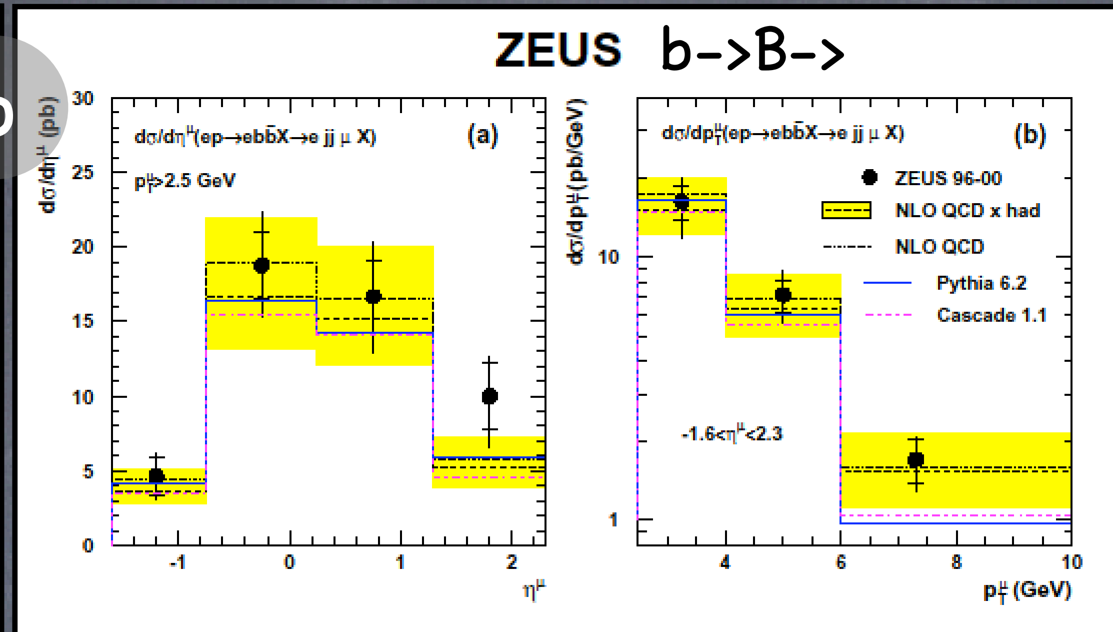
Take massive Next-to-Leading Order perturbative QCD (+ NLL resummation, where needed) as a reference, and ask for its ability to:

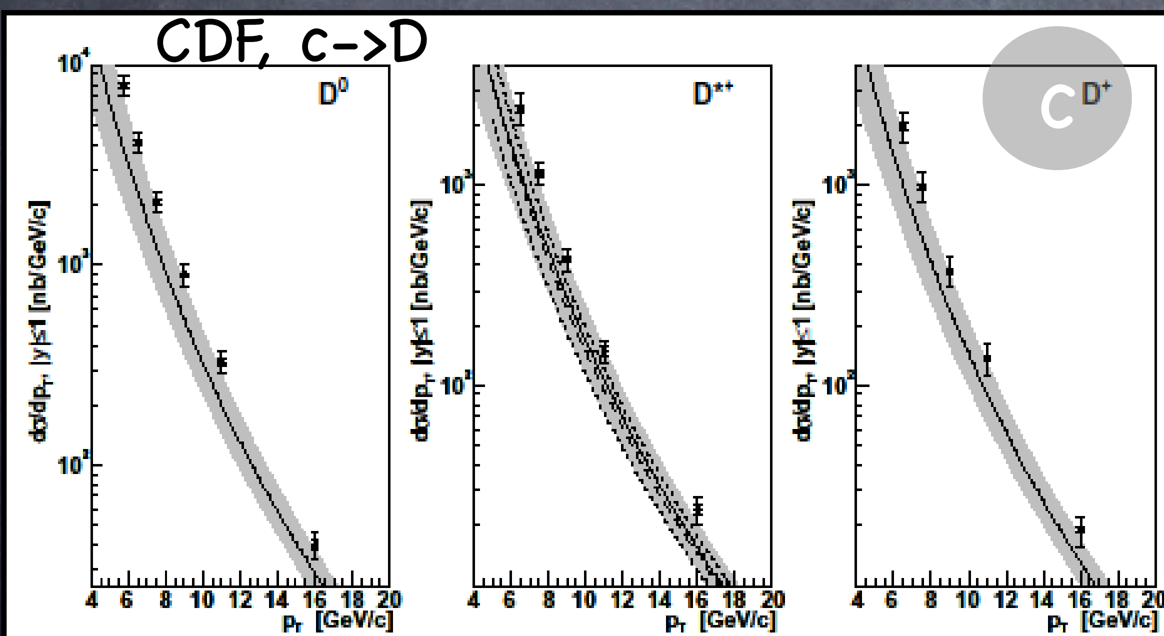
- predict total rates for charm, bottom and top production
- describe differential distributions with the addition of a minimal, self-consistent, and possibly universal set of non-perturbative inputs

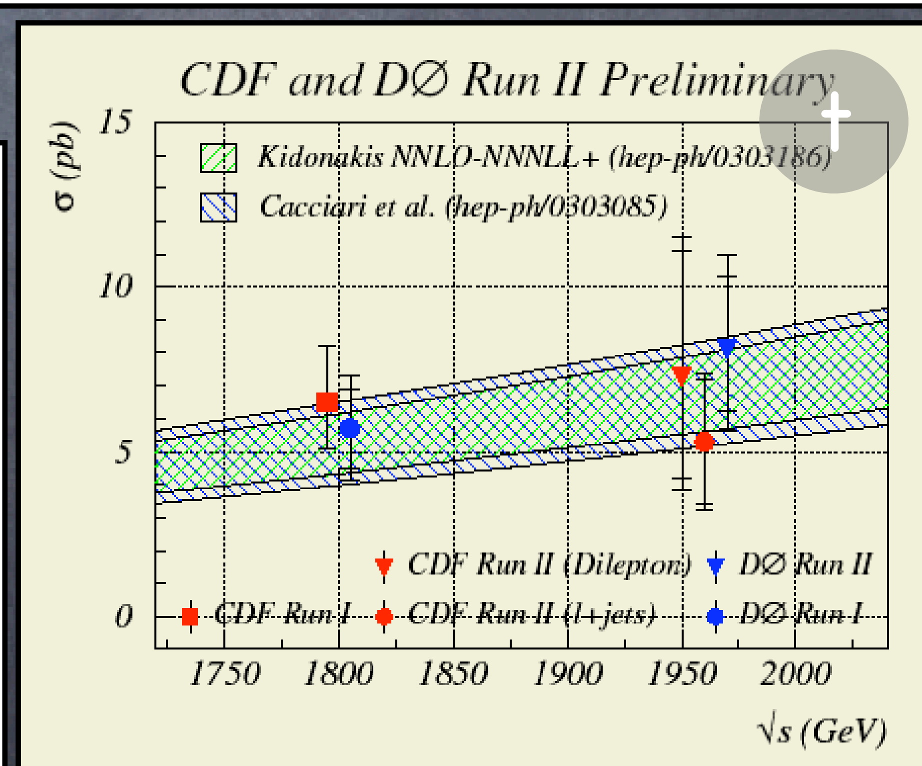
A successful comparison will be an agreement between possibly real measurements (i.e. little or no extrapolations/deconvolutions) and QCD predictions, within both experimental and theoretical uncertainties (ren./fact. scales, quark masses, strong coupling, PDFs and FFs, ...)

Heavy Quark Production vs. NLO(++) QCD









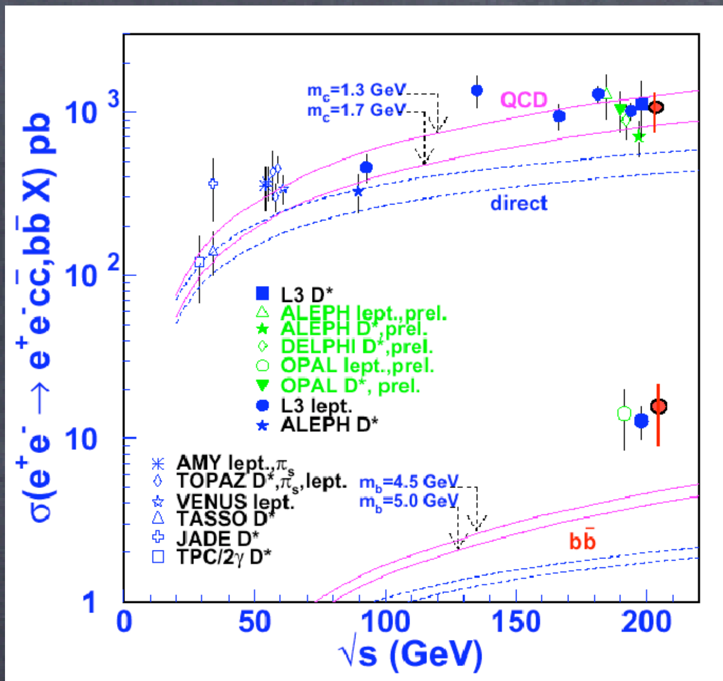
These examples qualify for the 'successfulness' test:

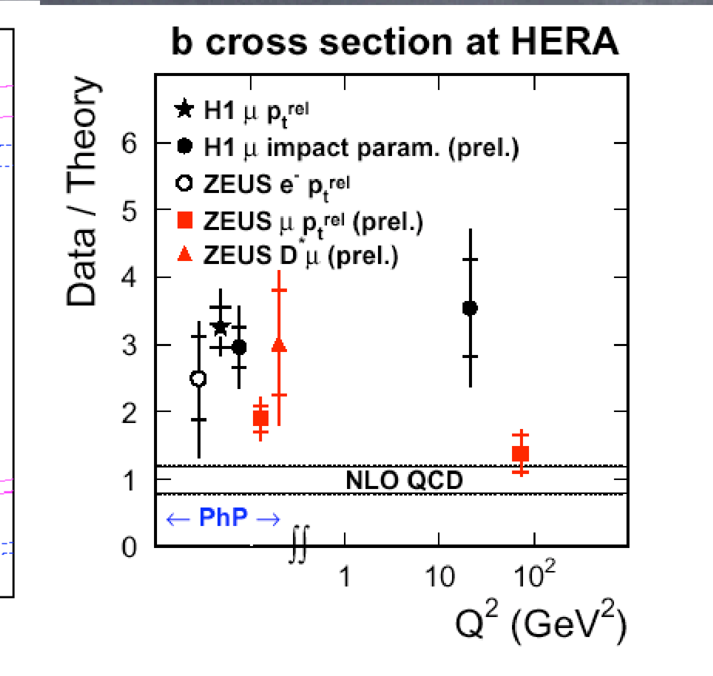
- the measurements contain little or no MonteCarlo extrapolation or deconvolution, at least compared to the final expt. error. This should avoid the possibility of biasing an experimental measurement with a theoretical prejudice (e.g. a MC calculation)
- the calculations are all massive and accurate at least to NLO
- the inclusion of non-perturbative information (where needed) has been performed in a minimal and self-consistent way
- the theoretical uncertainties have been explored in a reasonably exaustive manner

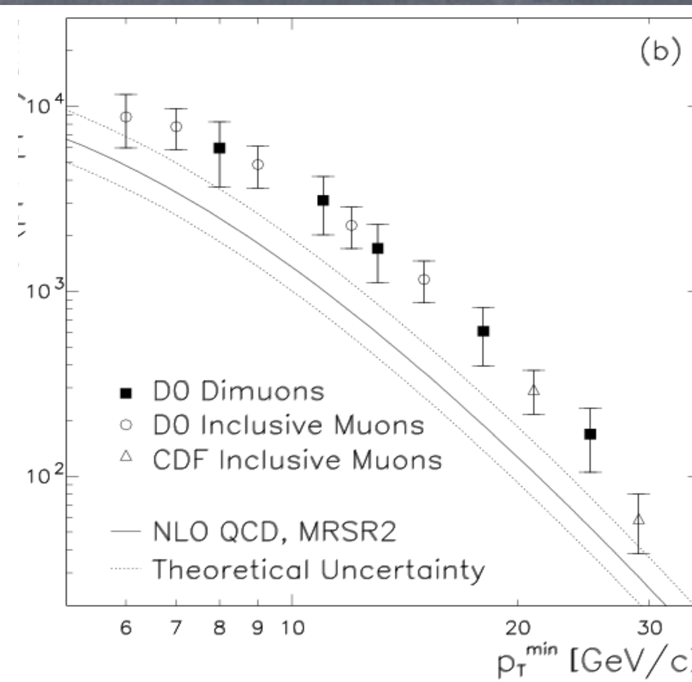
OK, so, the Standard Model is in agreement with the data......

What's the big deal?!?

Until recently, a much bleaker picture was being presented







While for charm (large th. unc.) and for top (large expt. unc.) agreement was found, for bottom production discrepancies of '<u>a factor of three</u>' or so were typically quoted in γγ, γp and pp

Let's look at these comparisons in detail

NB: the hadroproduction part of this talk draws generously from a seminar that M.L. Mangano gave at Fermilab in January. His full talk, with many more details, can be found at http://cern.ch/~mlm/talks/Bcrosssection.pdf

It's worth remembering that most of the perturbative QCD ingredients have been available for some time now:

Hadroproduction

Nason, Dawson, Ellis, NP B327 (1989) 49, NP B303 (1988) 607

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

Photoproduction

Nason, Ellis, NP B312 (1989) 551

Smith, van Neerven, NP B374 (1992) 36

$\gamma\gamma$

Drees, Kraemer, Zunft, Zerwas, PL B306 (1993) 371

→ NLO (massive)

Collinear resummation

Mele, Nason, NP B361 (1991) 626

MC, Greco, NP B421 (1994) 530

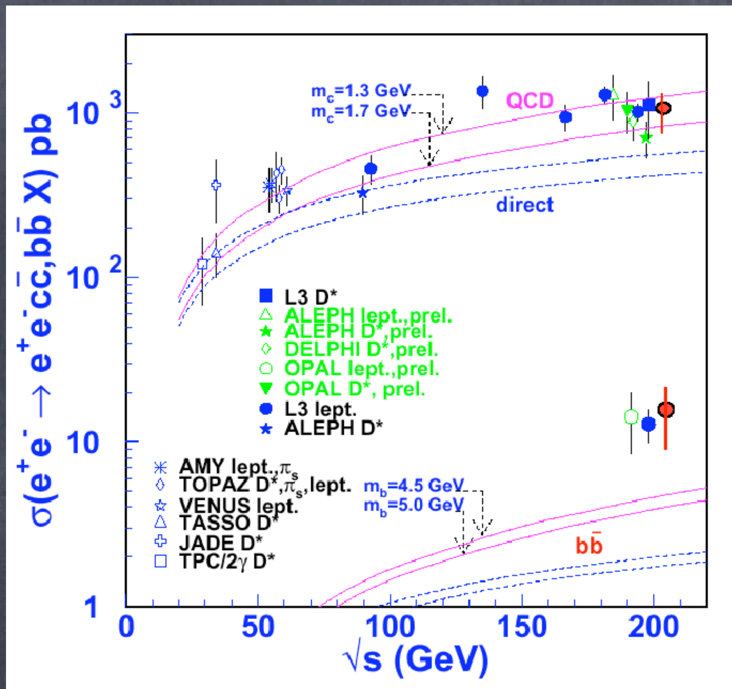
Threshold resummation

Bonciani, Catani, Mangano, Nason, NP B529 (1998) 424

→ NLL

+ surely many others. Apologies to those I forgot.

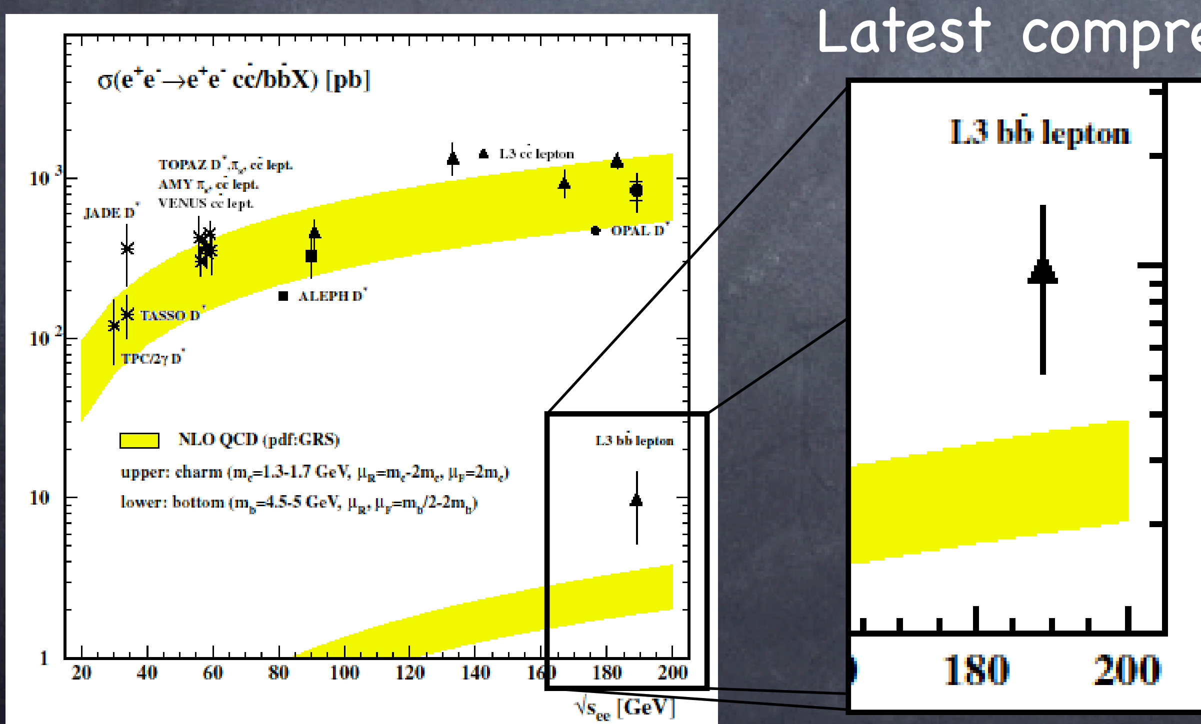
□□ $\to Q\bar{Q}$ @ LEP2



Good agreement for charm

Large apparent discrepancy for bottom

L3, OPAL and DELPHI report a factor of three excess over NLO QCD predictions



Latest comprehensive theoretical review

S. Frixione, M. Krämer and E. Laenen
[J. Phys. G: Nucl. Part. Phys. 26 (2000) 723]

4 pb

2 pb

Full estimate of theoretical uncertainty slightly larger than shown on experimental plots

NH ELSEVIER
22 March 2001
PHYSICS LETTERS B
Physics Letters B 503 (2001) 10–20
www.elsevier.nl/locate/npe

Measurements of the cross sections for open charm and beauty production in $\gamma\gamma$ collisions at $\sqrt{s} = 189$–202 GeV

L3 Collaboration

L3 1999-2001

[Phys. Lett. B503 (2001) 10]

Abstract:

measured and compared to next-to-leading order perturbative QCD calculations. The cross section of b production is measured in $\gamma\gamma$ collisions for the first time. It is in excess of the QCD prediction by a factor of three. © 2001 Published by Elsevier

Expt.

$$\sigma(e^+e^- \to e^+e^- b\bar{b}X)_{\text{combined}}$$
$$= 13.1 \pm 2.0(\text{stat}) \pm 2.4(\text{syst})\ \text{pb}.$$

Recent update:

$$\sigma(e^+e^- \to e^+e^- b\bar{b}X)_{\text{combined}} = 12.8 \pm 1.7\ (\text{stat}) \pm 2.3\ (\text{syst})\ \text{pb}$$

Theory

open beauty threshold energy is set to 10.6 GeV. For $\langle\sqrt{s}\rangle = 194$ GeV and a b quark mass of 4.5 GeV, this cross section is 4.4 pb. The $b\bar{b}$ cross section is

Theoretical uncertainties?

Conclusions:

this cross section is 4.4 pb. The $b\bar{b}$ cross section is measured in $\gamma\gamma$ collisions for the first time and is a factor of 3 and about 4 statistical uncertainty standard deviations higher than expected.

All in all, data and theory are fairly compatible at the 3-sigma level. Claiming a "factor of three excess" in the abstract is perhaps a little premature....

Rumours of my death have been greatly exaggerated. --Mark Twain

OPAL 2000 [OPAL-Note PN 455 (2000)]

Expt.

$\sigma(e^+e^- \to e^+e^- b\bar{b}) =$
$14.2 \pm 2.5\ (\text{stat})\ ^{-4.8}_{+5.3}\ (\text{sys})\ \text{pb}.$

Theory

massive b quarks [5], with the direct contribution shown separately. The prediction of the NLO calculation for the total cross-section at $\sqrt{s_{ee}} = 200$ GeV is 3.88 pb and 2.34 pb for a b quark mass of 4.5 GeV and 5.2 GeV, respectively, significantly lower than both measurements. A recent measurement of the open beauty cross-

---

DELPHI 2002

$\sigma_{b\bar{b}} = 14.9\ \pm 3.3\,(\text{stat}) \pm 3.4\,(\text{syst})\ \text{pb}$ (Muon p_T-rel.)

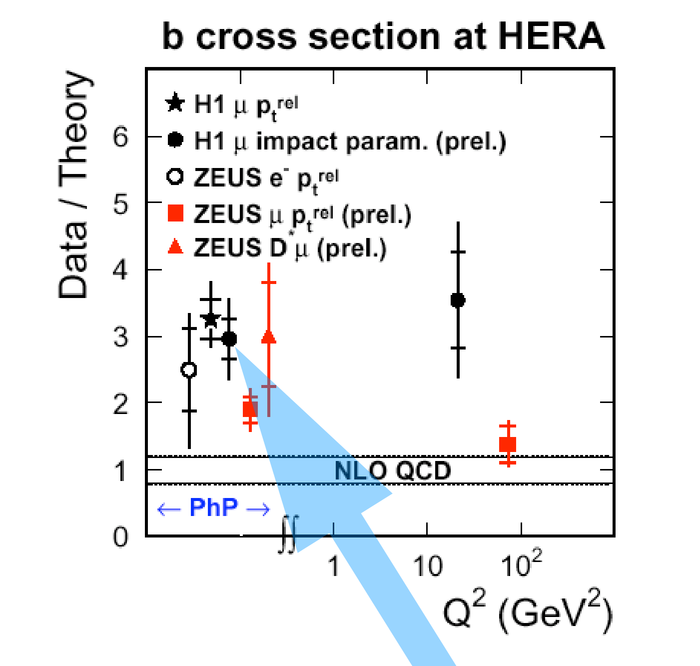
$\sigma^{b\bar{b}} = 11.4 \pm 4.5\,\text{pb}$ (Muon p_T-rel. + K-lepton charge corr.)

Results from L3, DELPHI and OPAL fully compatible.
Unfortunately, only L3 has published its analysis in final form.

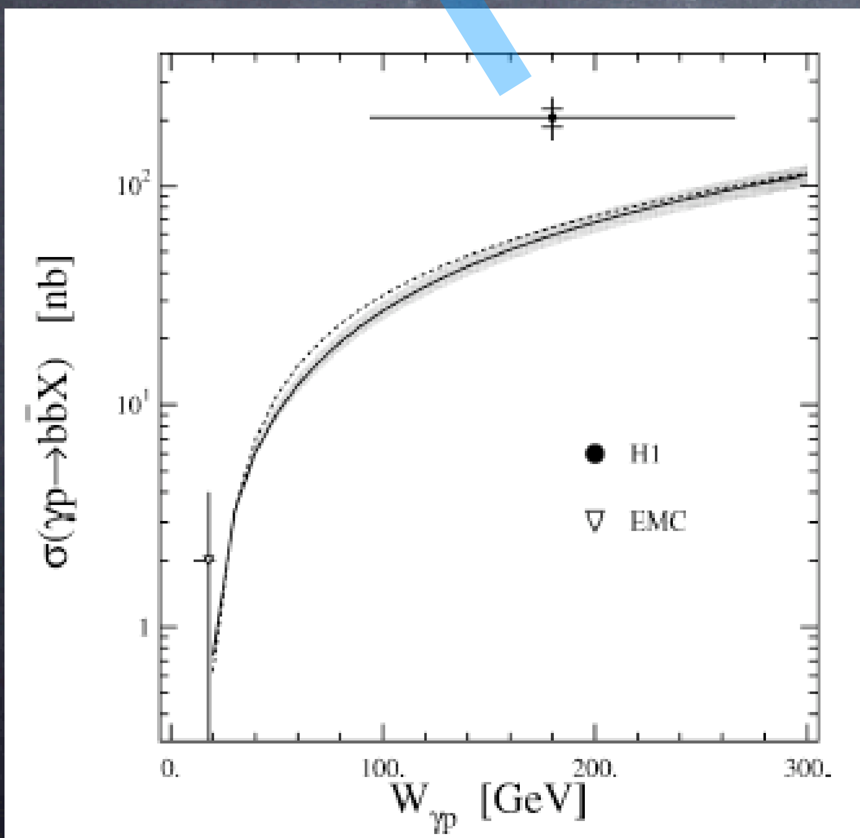
NB: all three collaborations used PYTHIA for extracting the b signal (with the same technique) and also for extrapolating from the cuts to the full space.
The three measurements are therefore strongly correlated.

Plea: could ALEPH do it? In a different way? Publishing visible cross sections?

Bottom Photoproduction



First measurements at HERA apparently showed fairly large discrepancies



H1 1999 [Phys. Lett. B467 (1999) 156]

ELSEVIER
11 November 1999
PHYSICS LETTERS B
Physics Letters B 467 (1999) 156–164

Measurement of open beauty production at HERA

H1 Collaboration

180 GeV, respectively. The measured cross sections are higher than the expectation based on a NLO QCD calculation.

ZEUS 2001 [Eur. Phys. J. C18 (2001) 625]

Eur. Phys. J. C 18, 625–637 (2001)
Digital Object Identifier (DOI) 10.1007/s100520100571

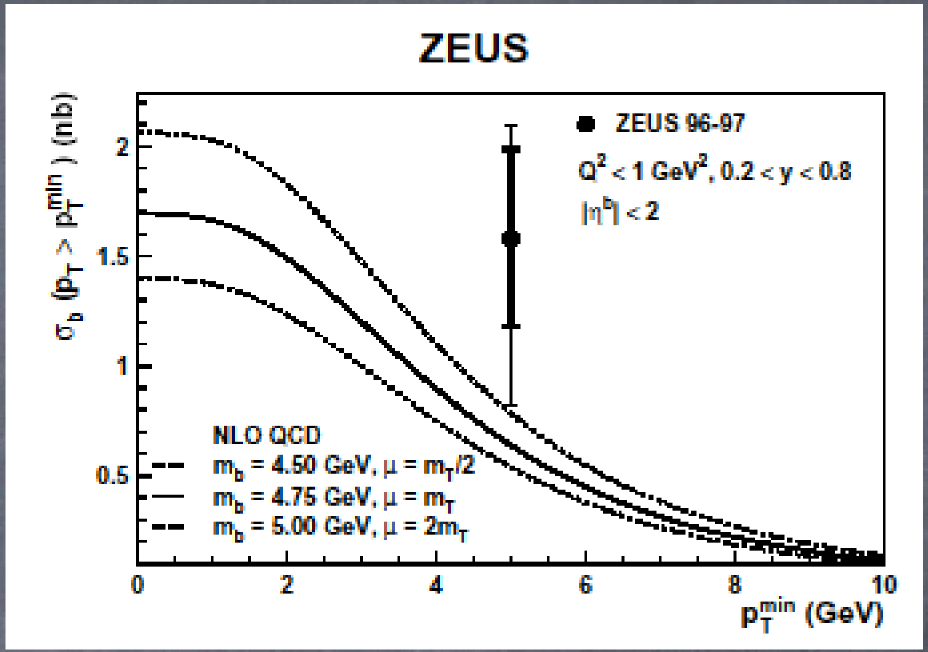
THE EUROPEAN PHYSICAL JOURNAL C

Measurement of open beauty production in photoproduction at HERA

The ZEUS Collaboration

The extrapolated cross section lies somewhat above the central NLO prediction, consistent with the general observation that NLO QCD calculations underestimate beauty production both in hadroproduction [4–6] and photoproduction at HERA [3].

H1 1999



ZEUS 2003 [hep-ex/0312057]

DESY-03-212
December 2003

Beauty photoproduction measured using decays into muons in dijet events in ep collisions at $\sqrt{s} = 318$ GeV

ZEUS Collaboration

Introduction

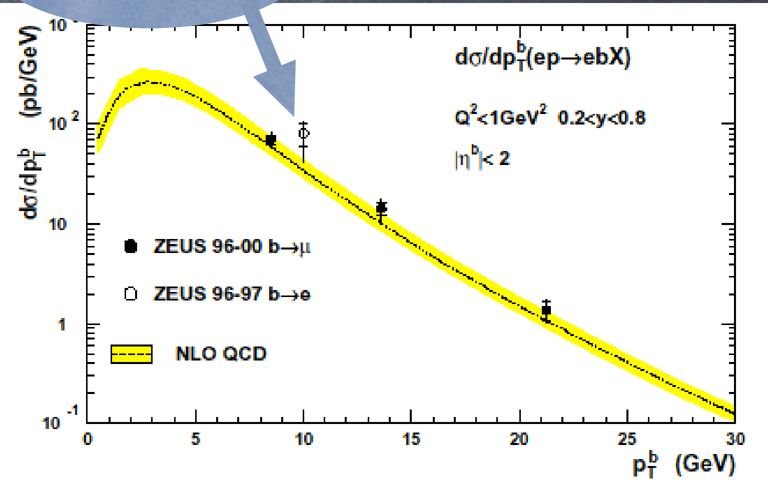
ZEUS 2001

...ction cross section has been measured in $p\bar{p}$ collisions at the ISR [2], $Sp\bar{p}S$ [3] and Tevatron colliders [4], in $\gamma\gamma$ interactions at LEP [5] and in fixed-target πN [6] and pN [7] experiments. Apart from the $Sp\bar{p}S$ data and the fixed-target experiments, the results were significantly above the NLO QCD prediction. The H1 measurement in ep interactions at HERA [8] found a cross section significantly larger than the prediction. The previous ZEUS measurement [9] was above, but consistent with, the prediction.

Conclusions

The large excess of the first measurement of beauty photoproduction over NLO QCD, reported by the H1 collaboration [8], is not confirmed. The present result is consistent with the previous ZEUS measurement using semi-leptonic B decays into electrons [9]. Beauty photoproduction in ep collisions is reasonably well described both by NLO QCD and by a MC model that includes a substantial flavour excitation component.

ZEUS 2001



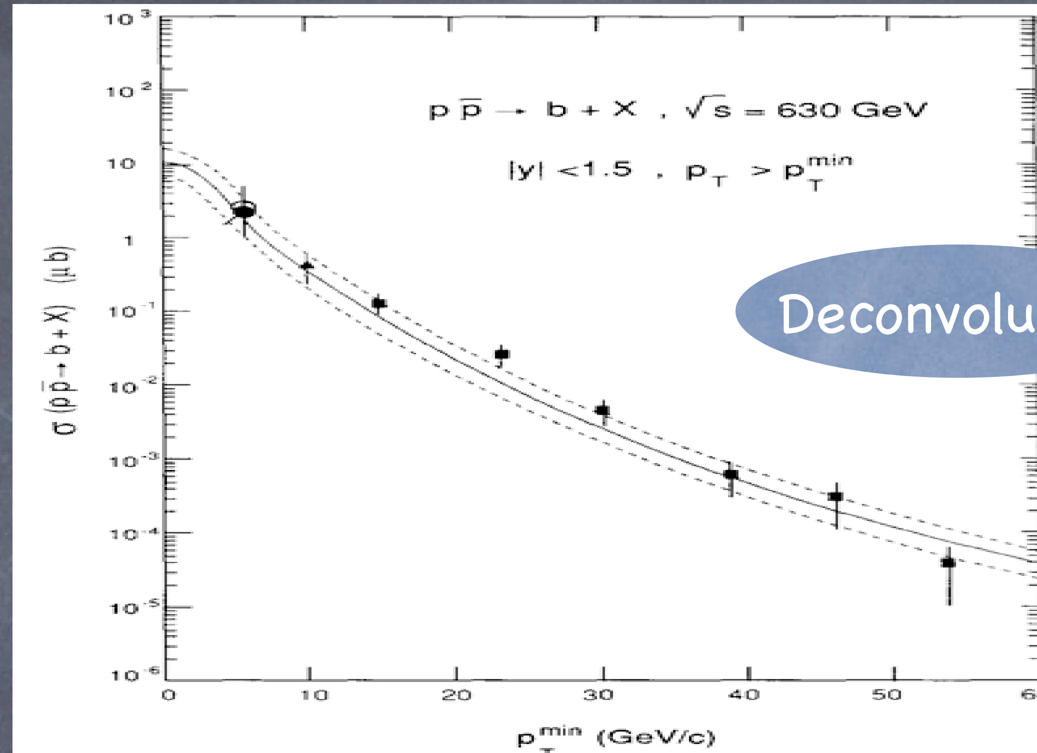
Bottom production in $p\bar{p}$ collisions

UA1 1988-1991

UA1, PL B213 (1988) 405

UA1, PL B256 (1991) 121

UA1/QCD ~ 1



Deconvoluted!

CDF 1992

PRL 68 (1992) 3403

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

Deconvoluted!

σ(pp→bX; PT>11.5 GeV, |y|<1): CDF = 6.1 ± 1.9 ± 2.4 b

theory = 1.1 ± 0.5 b

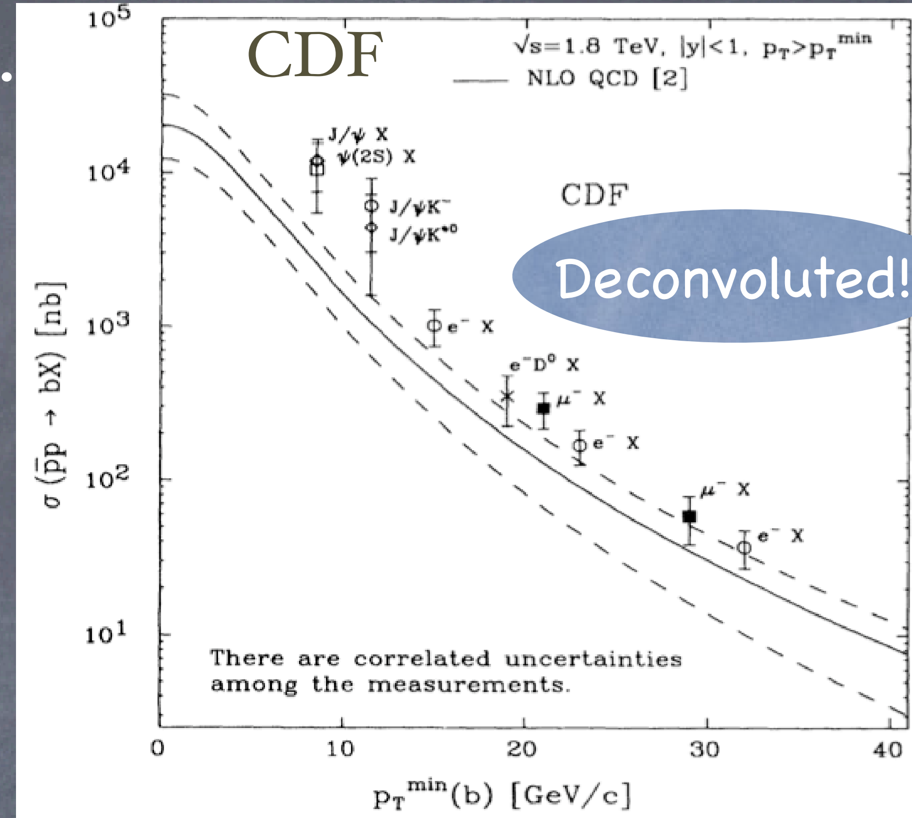
tion. Our measurement is approximately 1.6 standard deviations above the theoretical calculation.

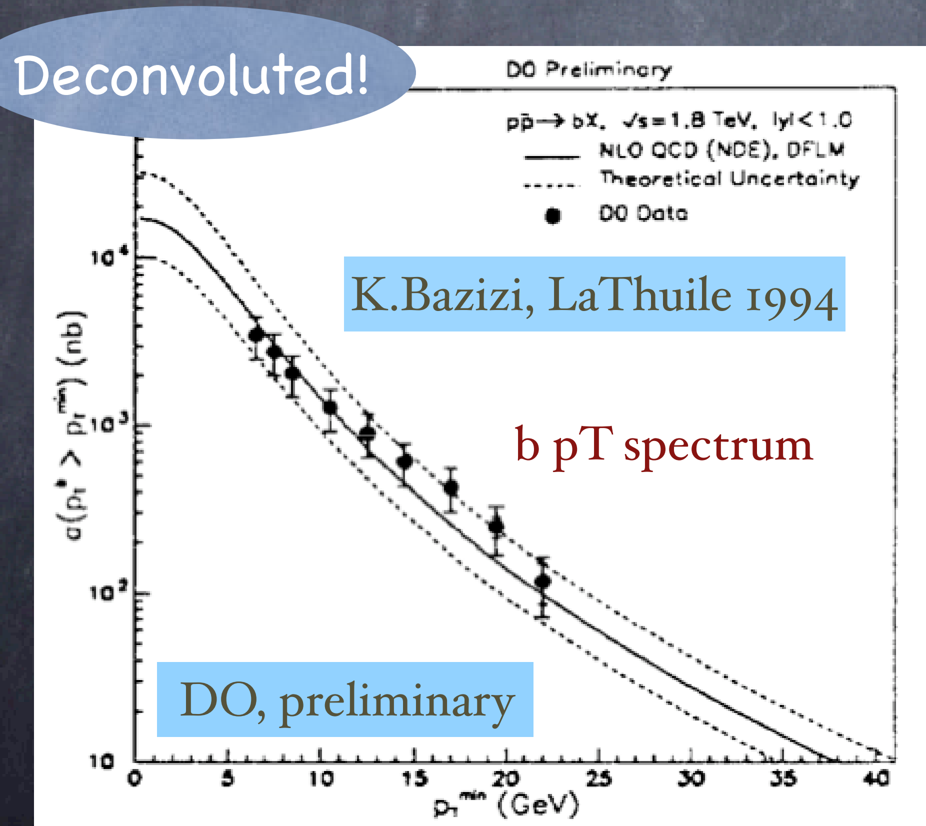
The 'usual' plot enters the stage....

CDF 1993

PRL 71 (1993) 500, PRL 71 (1993) 2396

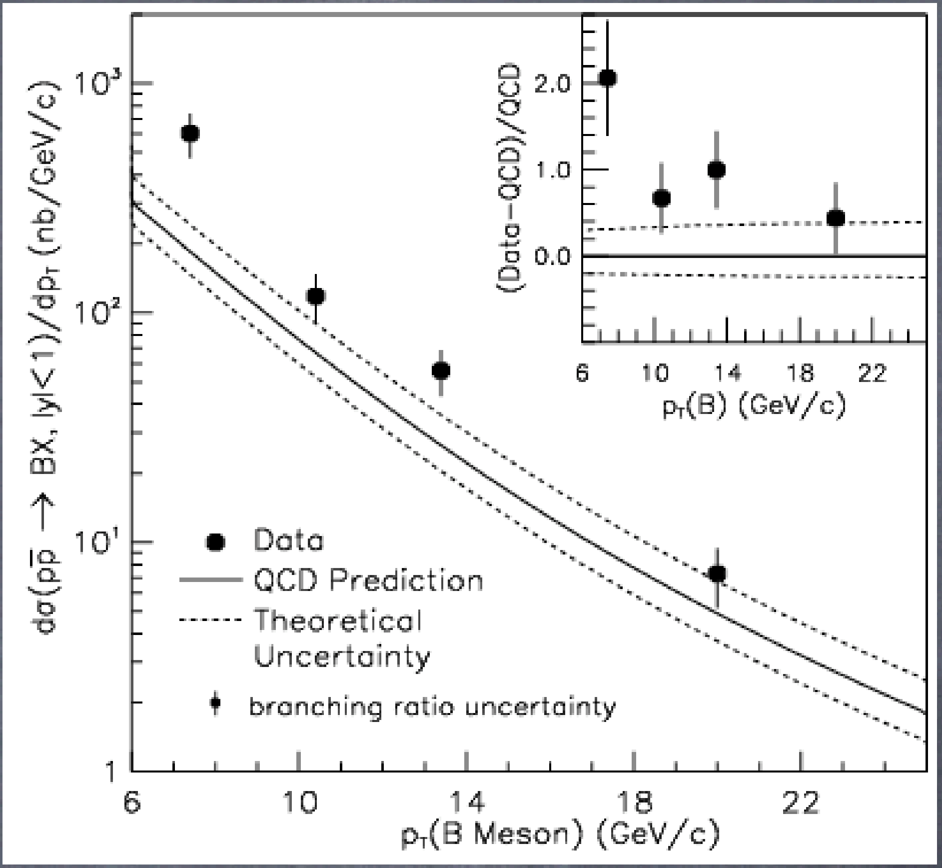
agreement within the experimental errors. This result supports the conclusion of previous CDF analyses that the next-to-leading order QCD calculation tends to underestimate the inclusive b-quark cross section.





DO finds however no excess at this stage: consistent with QCD, barely consistent with CDF

“Real” observables are also measured:



CDF 1995

PRL 75 (1995) 1451

B mesons, NOT deconvoluted to b quark level

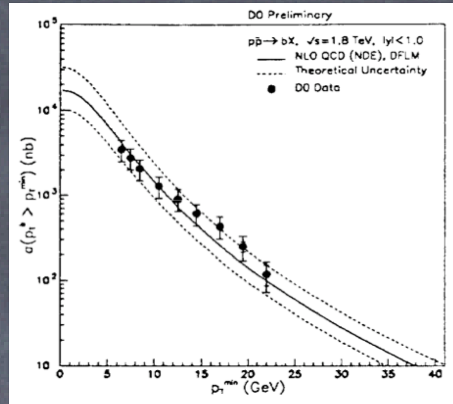
However, how is the theoretical predictions for B mesons calculated?

Fig. 2. To determine the level of agreement between the data and the theoretical prediction, the predicted cross section is fitted to the measurements, holding the shape constant and varying the magnitude. The fit yields an overall scale factor of $1.9 \pm 0.2 \pm 0.2$, with a confidence level of 20%. In conclusion, we find that the shape of the B meson differential cross section presented here is adequately described by next-to-leading order QCD, while the absolute rate is at the limits of that predicted by typical variations in the theoretical parameters. It will be interesting

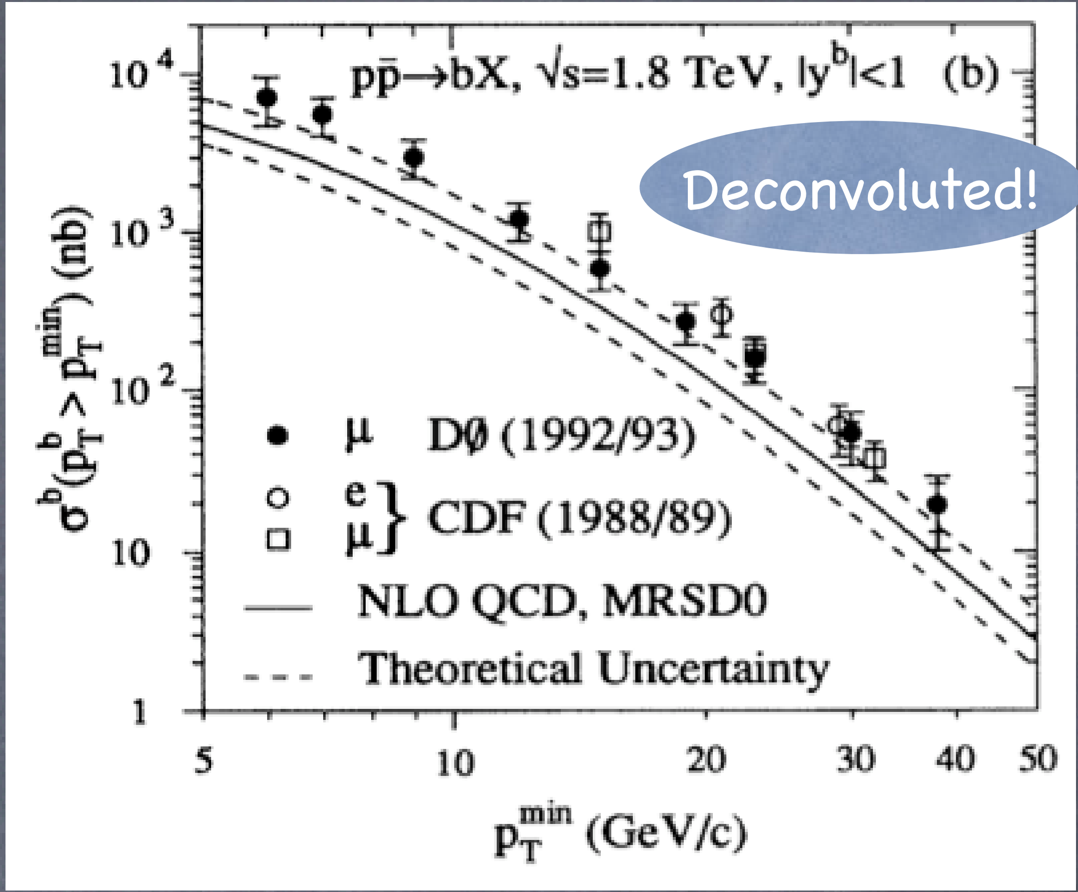
The possible ‘disagreement’ between data and theory is quantified for the first time

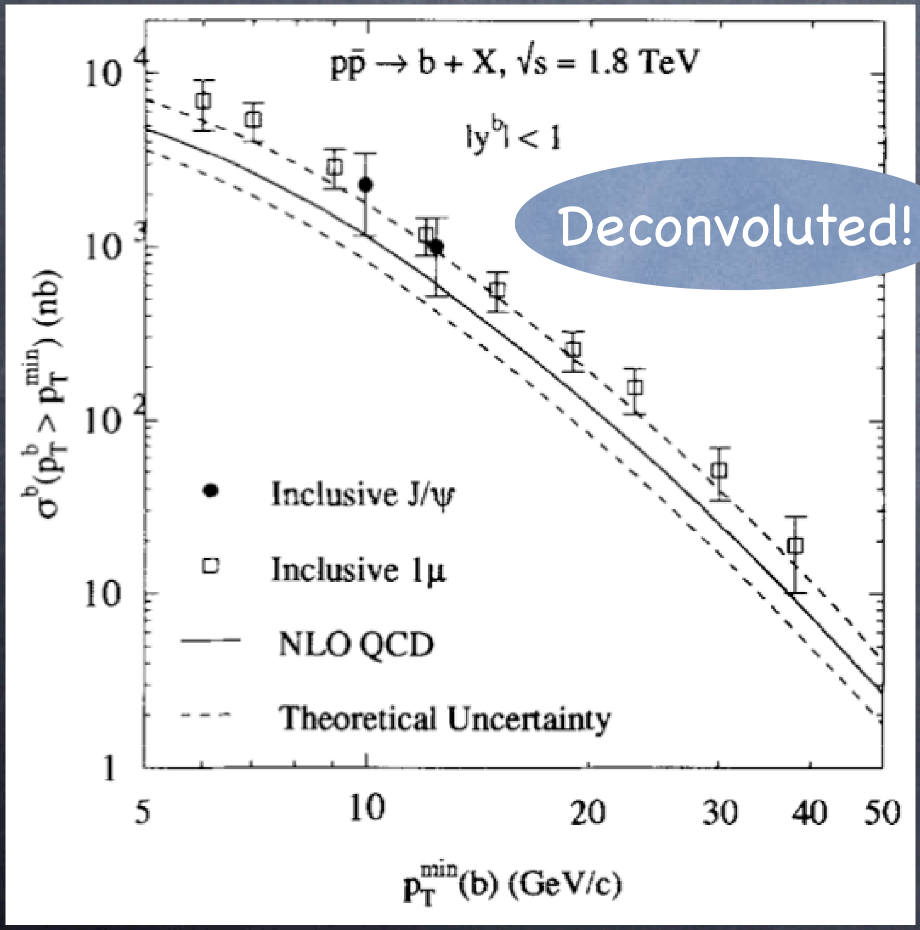
D0 1995-1996

PRL 74 (1995) 3548
PL B370 (1996) 239



The final D0 data become more CDF-like. However, they are still compatible with NLO QCD





Conclusions:

tion. Our measurement indicates that, within theoretical uncertainties, the NLO QCD description [1] of heavy flavor production in $p\bar{p}$ at $\sqrt{s}$ = 1.8 TeV is adequate for the kinematic range $|y^b| < 1.0$ and $p_T^b > 6$ GeV/c.

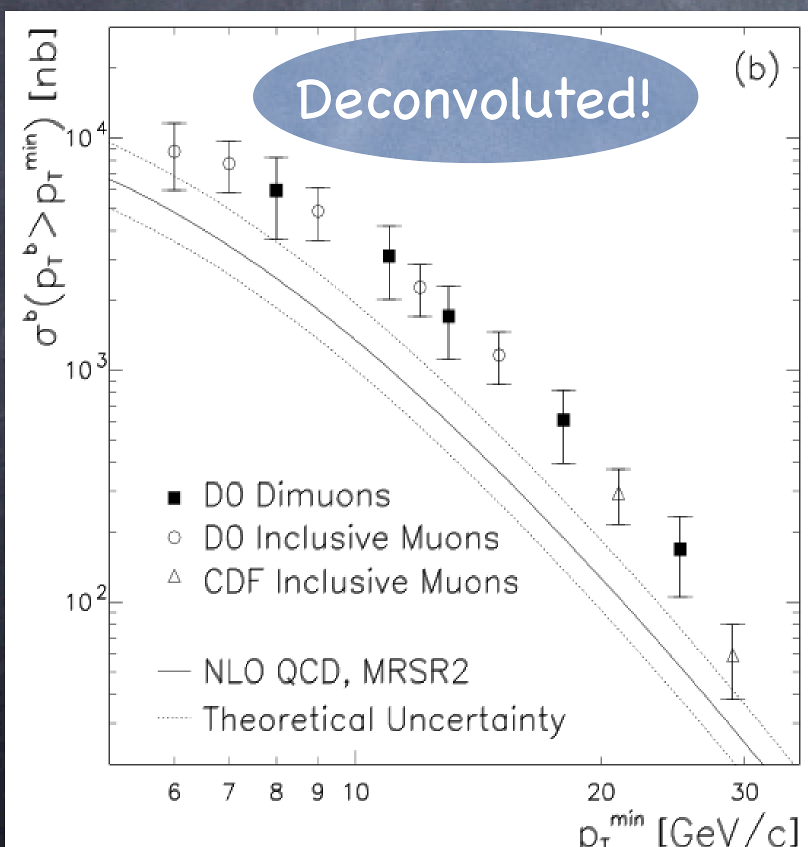
A few years later, the data (or the attitude?) change....

Despite the conclusions of the previous paper ("adequate description"), the previously measured b cross section is now considered "systematically larger" in the Introduction:

D0 1999-2000

PL B487 (2000) 264

Measurements of the b quark production cross section and $b\bar{b}$ correlations in $p\bar{p}$ collisions provide an important test of perturbative quantum chromodynamics (QCD) at next-to-leading order (NLO). The measured b quark production cross section at $\sqrt{s} = 1.8$ TeV [1–4] is systematically larger than the central values of the NLO QCD predictions [5,6].



This, of course, helps accepting the conclusion that the new data show now a considerable excess:

Conclusions

as described above and is dominated by the variation of the scales. The ratio of the data to the central NLO QCD prediction is approximately three over the entire p_T^{min} range covered.

approximately three

D0 2000

PRL 84 (2000) 5478

Forward muons from b decay

Not quite: TH systematics not included

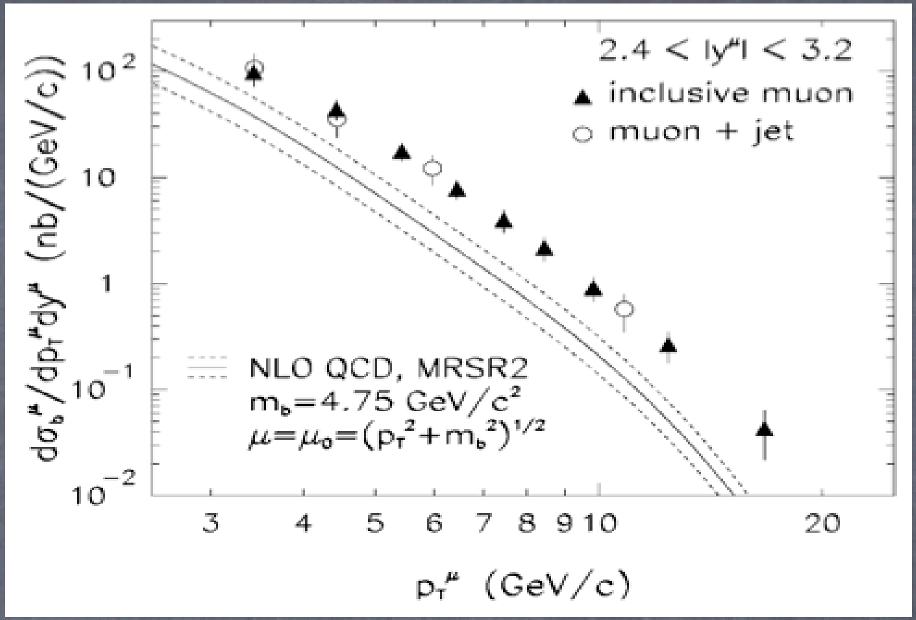


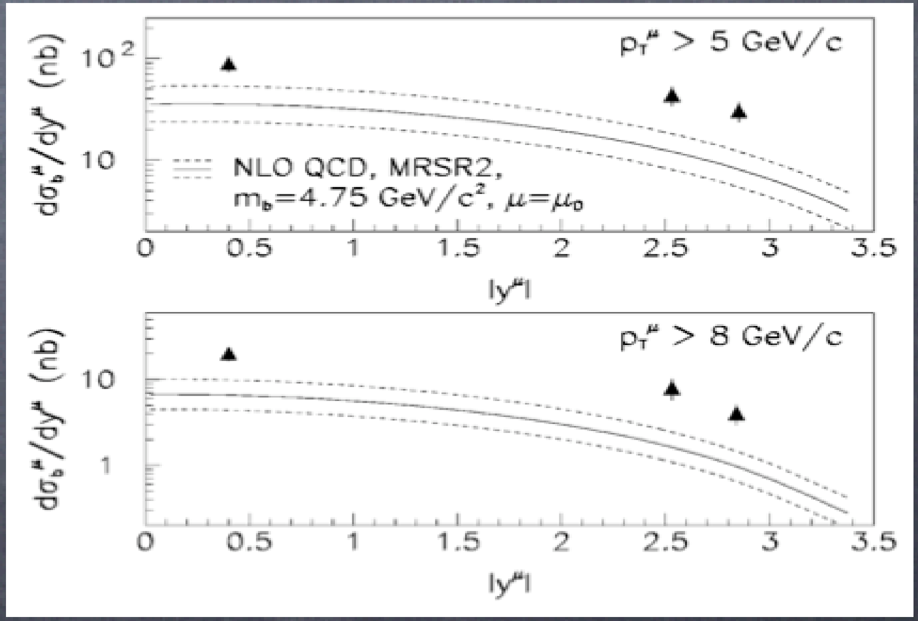
TABLE II. The cross section of muons from b-quark decay compared to NLO QCD. Errors are statistical and systematic added in quadrature.

$p_T^\mu > 5$ GeV/c

Rapidity	$\langle y \rangle$	Measured σ_b^μ (nb)	Theory σ_b^μ (nb)	Ratio
0.00–0.80	0.40	89 ± 16	36	2.5 ± 0.4
2.40–2.65	2.53	43.5 ± 9.4	12	3.6 ± 0.8
2.65–3.20	2.85	30.5 ± 6.6	8.4	3.6 ± 0.8

$p_T^\mu > 8$ GeV/c

Rapidity	$\langle y \rangle$	Measured σ_b^μ (nb)	Theory σ_b^μ (nb)	Ratio
0.00–0.80	0.40	20.1 ± 3.7	6.6	3.0 ± 0.6
2.40–2.65	2.53	7.9 ± 2.2	1.6	4.8 ± 1.3
2.65–3.20	2.84	4.1 ± 1.1	0.99	4.0 ± 1.1

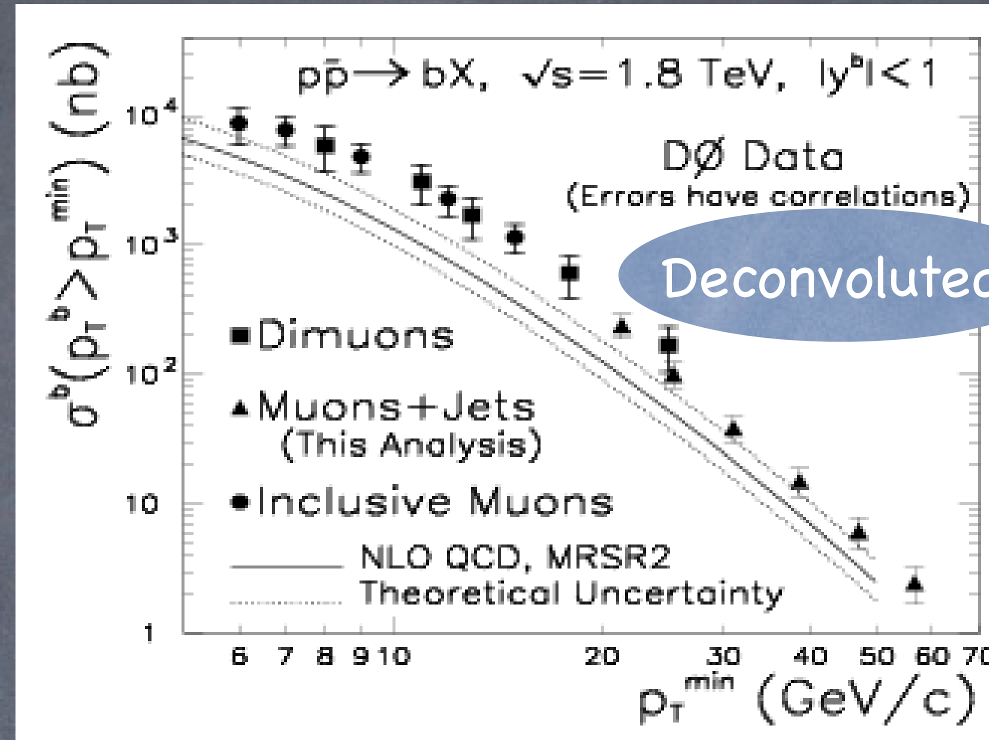


Abstract & Conclusions:

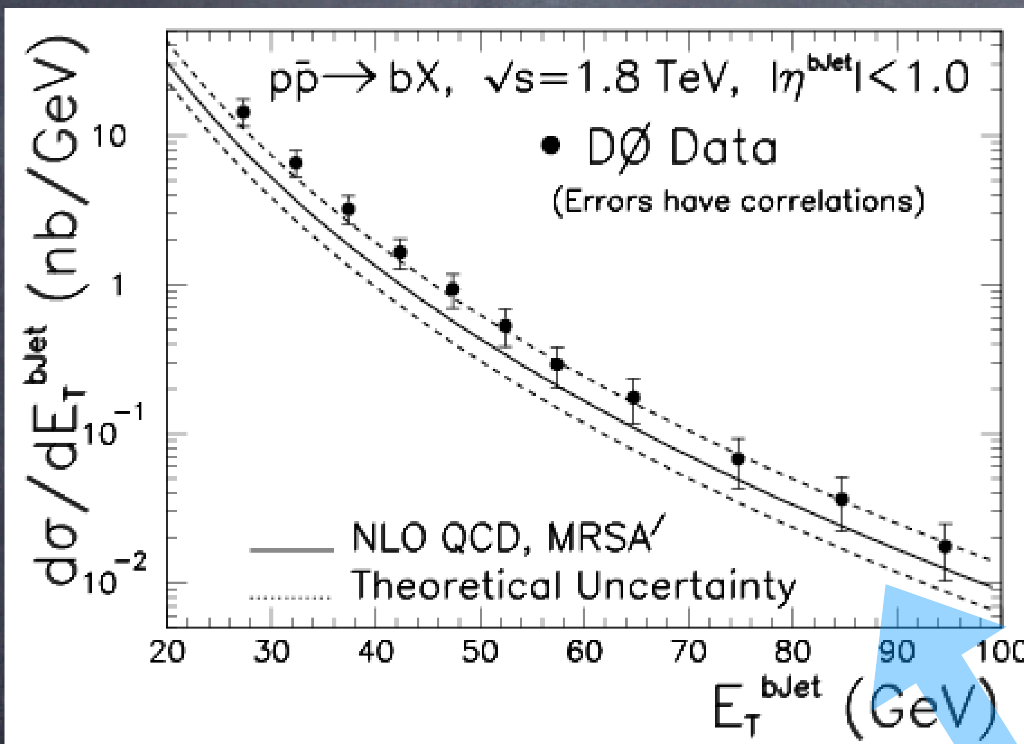
analysis were collected by the D0 experiment at the Fermilab Tevatron. We find that next-to-leading-order QCD calculations underestimate b-quark production by a factor of 4 in the forward rapidity region.

D0 2000

PRL 85 (2000) 5068



Most recent D0 results: b-jets and large p_T b-quarks



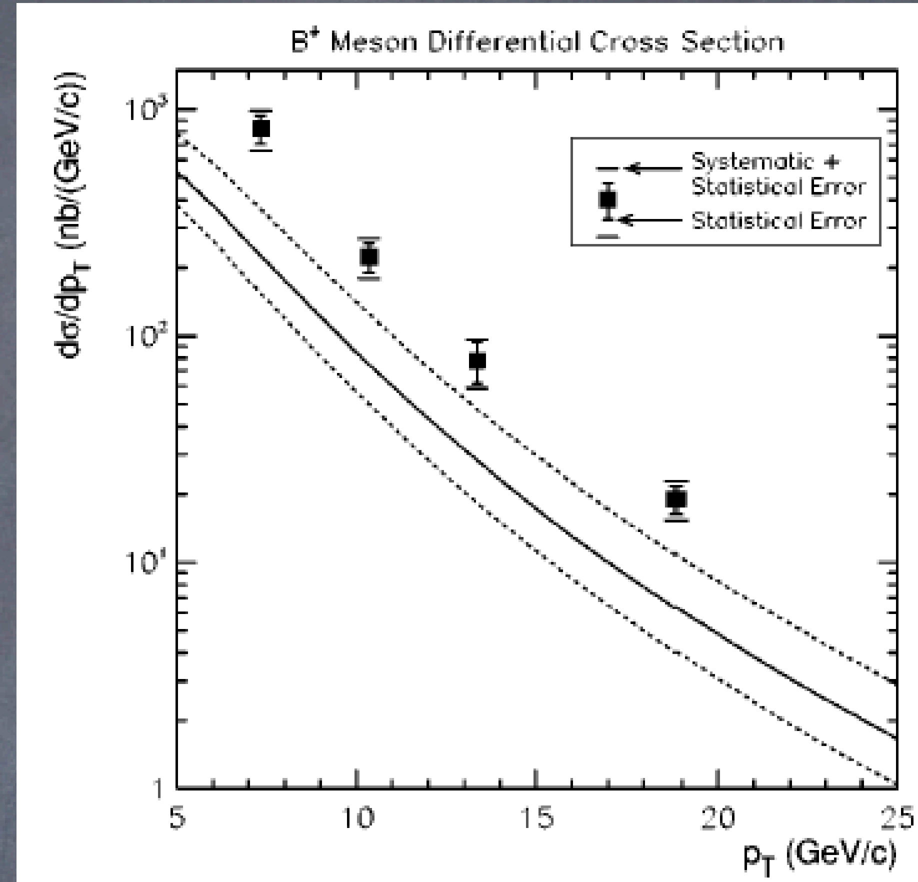
b-jets are observable quantities:
no need for a deconvolution

Figure 2 displays the same general pattern of past *b* production measurements [4–11], with data lying above the central values of the prediction, but comparatively less so in the present case, where general agreement between measurement and the upper band of the theoretical uncertainty is observed.

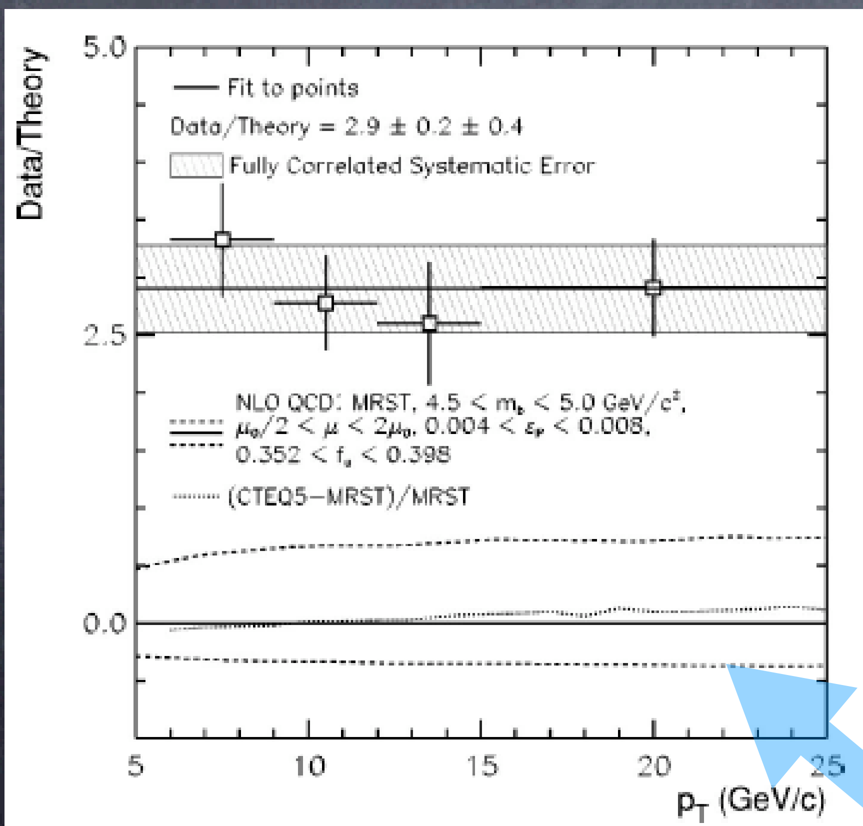
CDF 1998-2002

PRL 85 (2002) 5068

Last CDF Run I result:
B mesons, superseding 1995 result



Data/Theory ratio

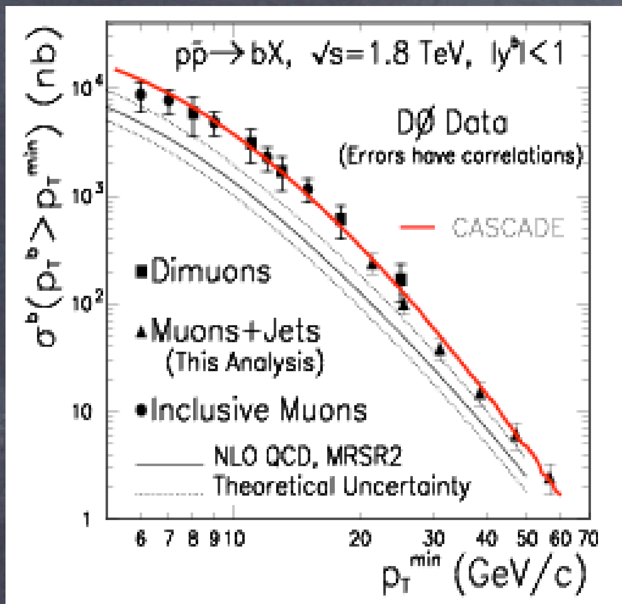


tainties. The differential cross section is measured to be 2.9 ± 0.2 (stat$\oplus$syst$_{p_T}$)± 0.4 (syst$_{fc}$) times higher than the NLO QCD predictions with agreement in shape. The first

However, once more, the theoretical uncertainty is not included in the error on the ratio

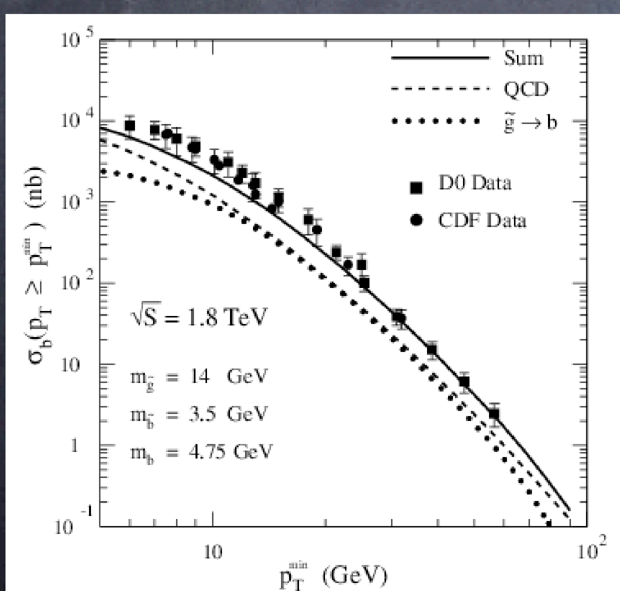
BTW: being the data points a ratio, shouldn't this band better be around 1 and not 0 ?!?

By the years 2001-2002, lots of discrepant data.
Proposed explanations range from the semi-conventional....



H. Jung, CASCADE, [Phys. Rev. D65 (2002) 034015]
MC implementation of small-x dynamics, following CCFM
Main criticism: lack of control of NLO effects

....to the very exotic ones:



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

Theoretical ingredients of a VCE
(Very Conventional Explanation)

The prediction for the distribution of a 'real particle' (J/ψ or muon) can be obtained by convoluting:

1) the NLO (+ NLL = FONLL) calculation for b quarks
2) the fragmentation of the b quark into a B meson, f(b->B)
3) the decay of the B meson into the J/ψ or the muon

$$\frac{d\sigma(B)}{dp_T} = \frac{d\sigma(b)}{d\hat{p}_T} \otimes f(b \to B) \otimes g(B \to J/\psi)$$

For f(b->B) the Peterson et al. form with ϵ_b = 0.006 is used in most experimental papers, following a determination by Chrin made in 1987 (sic) using charm data, $\epsilon_b = m_c / m_b \; \epsilon_c$ rescaling, and LO Montecarlo calculations

Not being the b quark a physical particle, f(b->B) cannot be a physical observable: its details depend on the perturbative calculation it is interfaced with. A single fragmentation function cannot do for all calculations

Around 1997 [MC, M. Greco, PRD 55 (1997) 7134, M.L. Mangano, lectures on HQ production, hep-ph/9711337] we started arguing that systematics related to fragmentation risked being underestimated, and called for a stricter consistency between HQ FF determination from e+e- data and their use elsewhere:

For one thing, ϵ_b fitted within a NLO description is smaller than the usual 0.006 value. Hence, a harder Peterson will give a larger cross section in the $p_T > m_b$ region

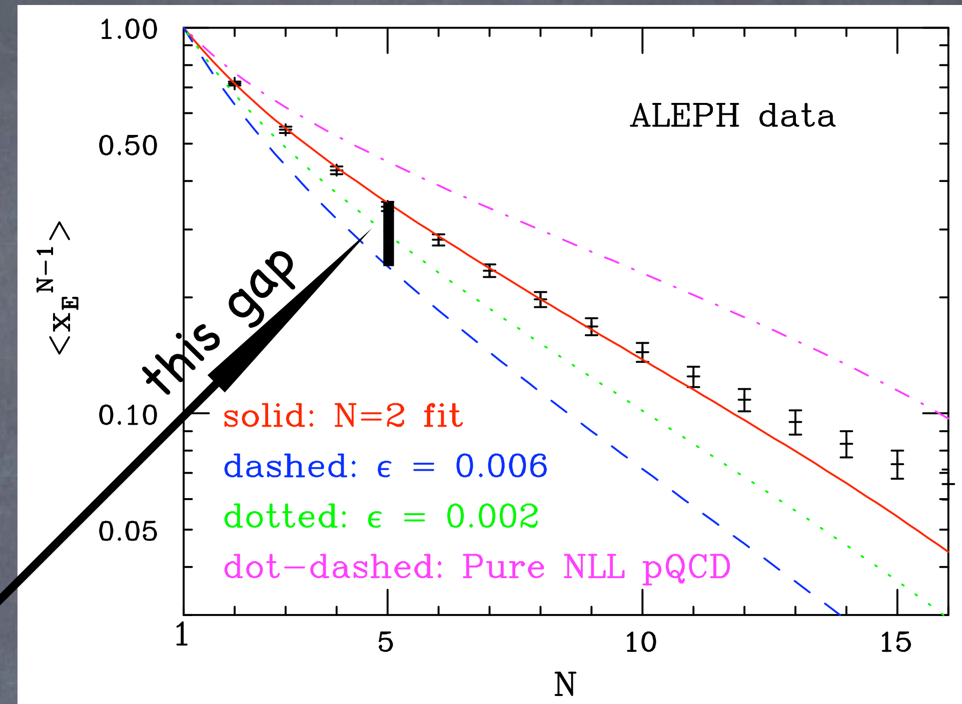
It was also noted that, due to the steeply falling spectrum of the partonic cross section, the transverse momentum distribution in hadronic collisions is sensitive to large moments of the FF, while it is the second moment, <z>, which is mainly determined from e+e- data

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

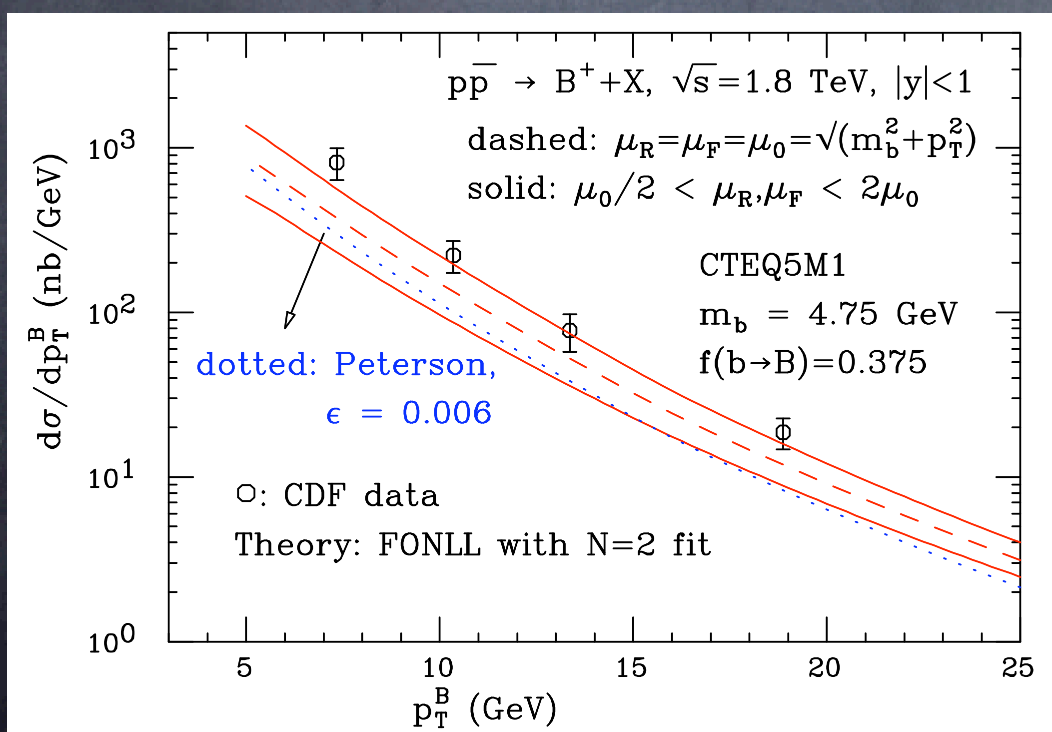
In proton-(anti)proton collisions N is of order 5. Therefore, a proper extraction of moments around this one from e+e- collisions is more important than a good description of the spectrum

From the year ~ 2000 accurate enough data on B fragmentation were finally available from LEP, allowing good fits up to N=10 or so.

NB. NLL resummed pQCD calculation needed
[B. Mele and P. Nason, Nucl. Phys. B361 (1991) 626]



Note that Peterson with ϵ_b = 0.006 underestimates the moments around N=5. Its use will consequently underestimate the B cross section



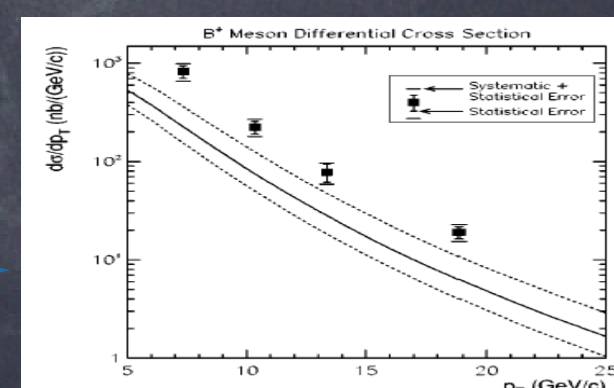
MC and P. Nason, Phys. Rev. Lett. 89 (2002) 122003

With these ingredientes, a much better description of the B meson CDF data can be given:

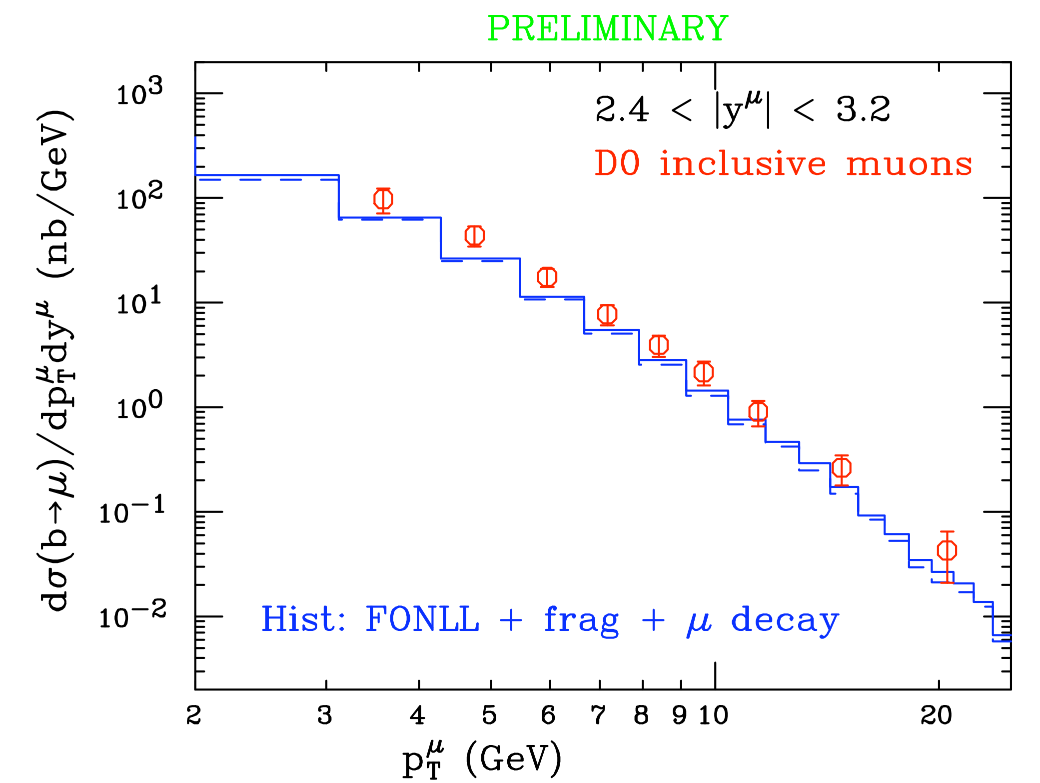
Data/Theory = 1.7 ± 0.5 (expt.) ± 0.5 (th.)

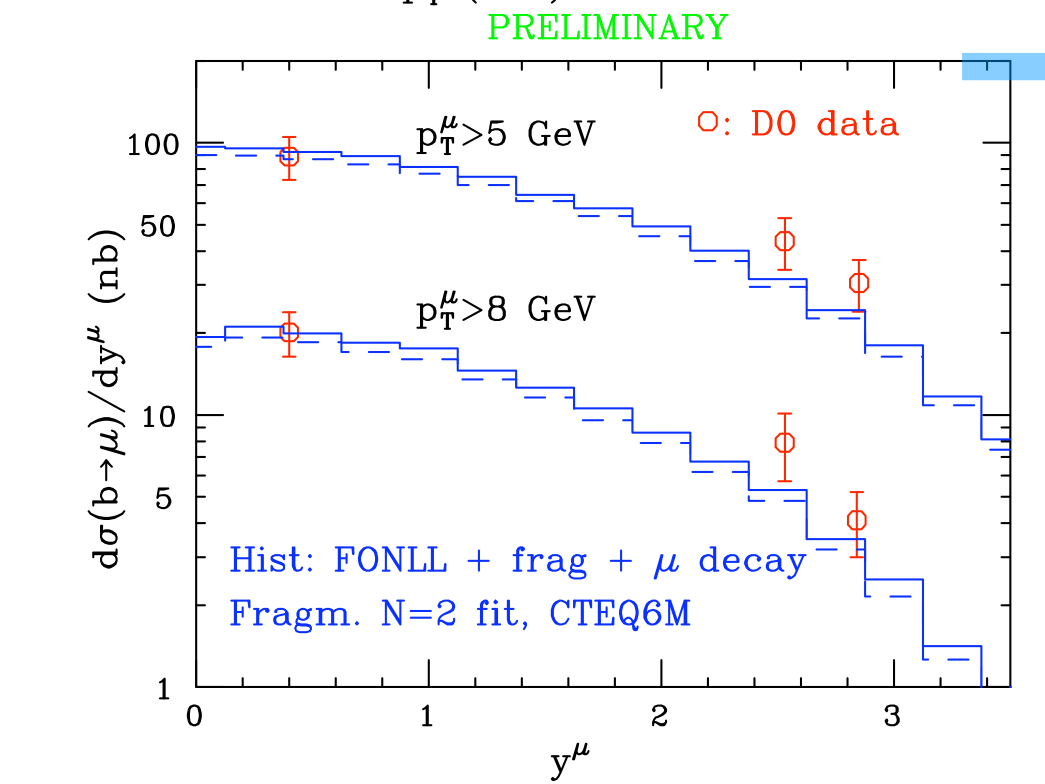
i.e. no significant discrepancy

compare

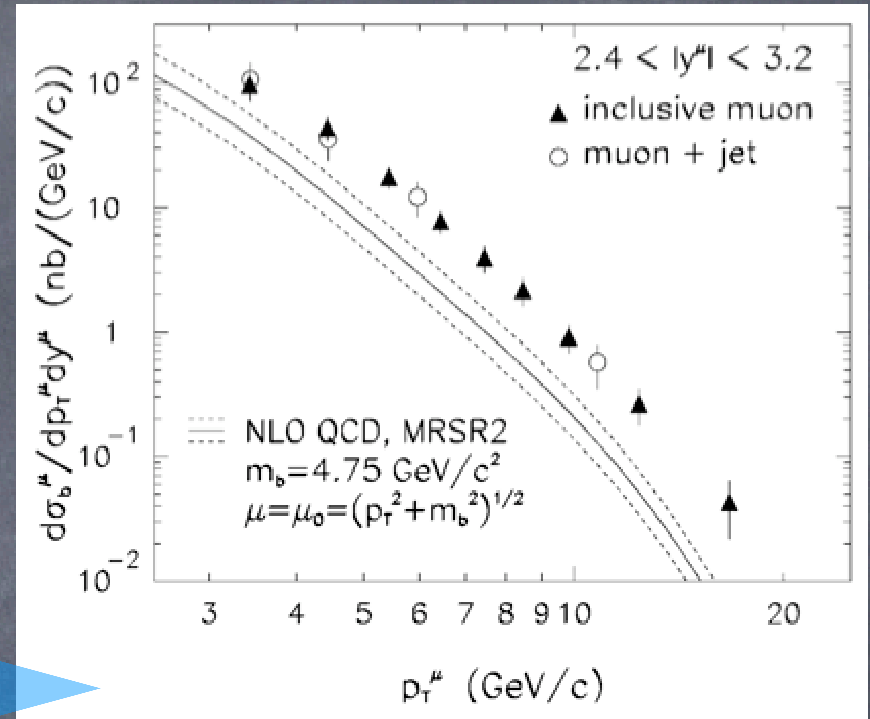


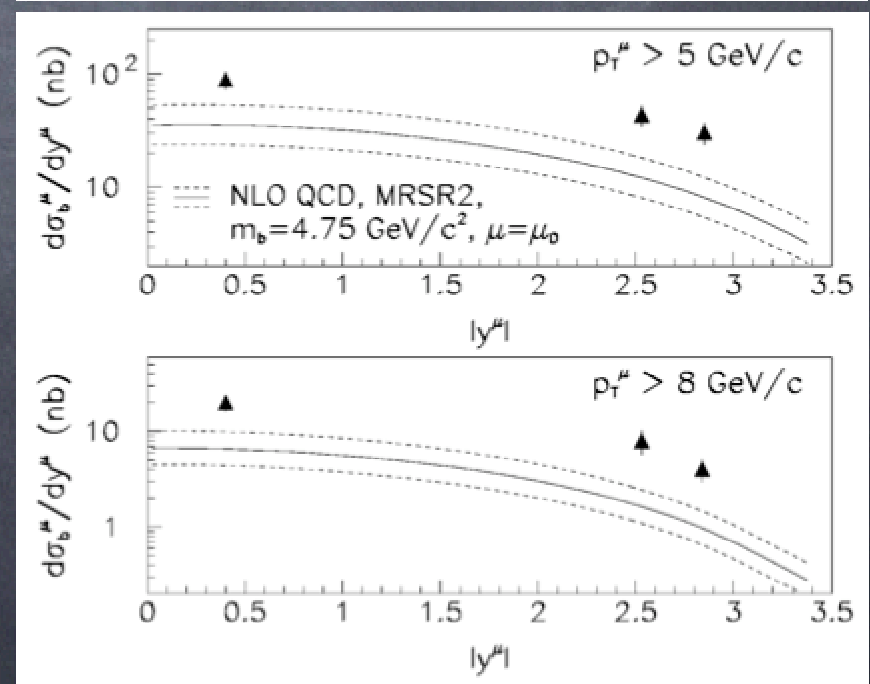
D0 'forward muons from b' data are also now better described



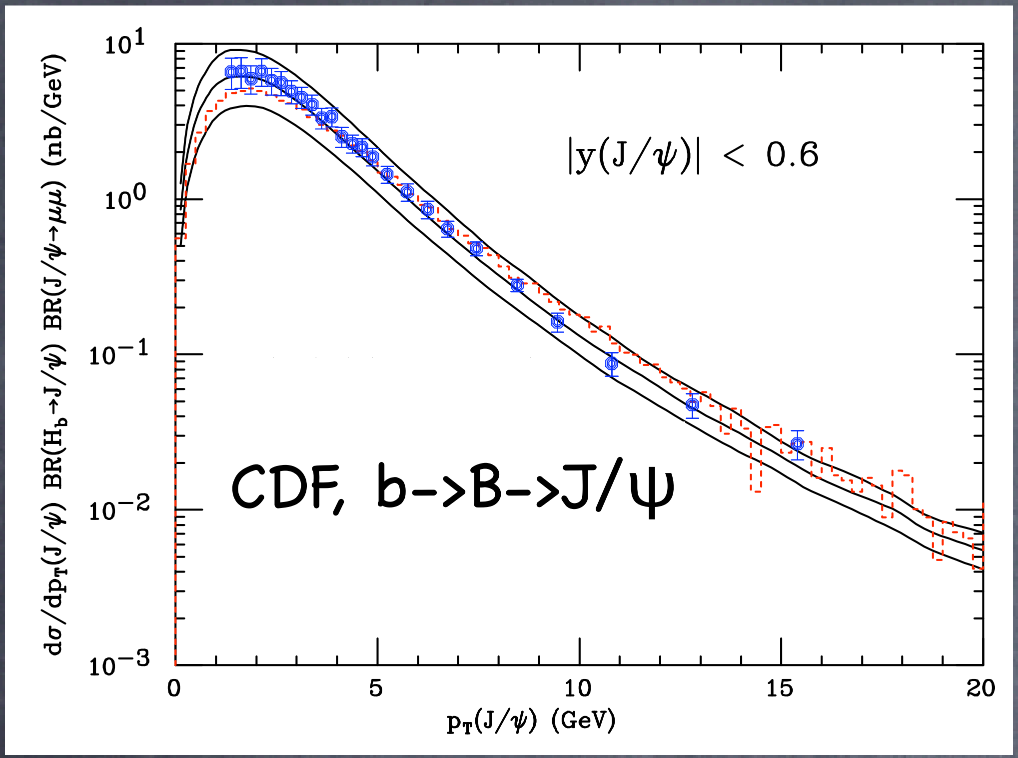


compare





2003: CDF Run II preliminary data at 1.96 TeV



MC, Frixione, Mangano, Nason, Ridolfi, hep-ph/0312132

$\sigma(pp \to H_b \to \psi;\ P_{T\psi} > 1.25,\ |y| < 0.6)$

$$\sigma^{CDF}_{J/\psi} = 19.9 \ {}^{+3.8}_{-3.2\,stat+syst}\ \text{nb} \qquad \sigma^{FONLL}_{J/\psi} = 19.0 \ {}^{+8.4}_{-6.0}\ \text{nb}$$

$\sigma(pp \to H_b X;\ P_T > 0,\ |y| < 0.6) \times B(H_b \to \psi)$

$$\sigma^{CDF}_{H_b} = 24.5 \ {}^{+4.7}_{-3.9\,stat+syst}\ \text{nb} \qquad \sigma^{FONLL}_{H_b} = 22.9 \ {}^{+9.5}_{-6.8}\ \text{nb}$$

$\sigma(pp \to bX;\ P_T > 0,\ |y| < 1)$

$$\sigma^{CDF}_b(|y| < 1) = 29.4 \ {}^{+6.2}_{-5.4\,stat+syst}\ \mu\text{b}$$

$$\sigma^{NLO}_b(|y| < 1) = 23.6 \ {}^{+11.9}_{-7.6}\ \mu\text{b}$$

Theory-Data agreement now almost embarassing. Fully compatible within errors.

Central values move slightly apart as we go to more ‘artificial’ cross sections. Indication of uncertainties and systematics related to deconvolution procedures.

So, what happened?

How did we go from 'factor of three' excesses to full agreement?

A combination of various factors:

- the real distance between data and theory was actually never this large, once ALL uncertainties were taken into account
- new measurements without corrections to unphysical particles (ZEUS, CDF) may have minimized the risk of biasing the data
- both the data and the theory have moved, often within the errors (which might have been larger than previously thought)
- new experimental input (and better use of some of them, e.g. bottom FF) allowed producing more reliable theoretical predictions

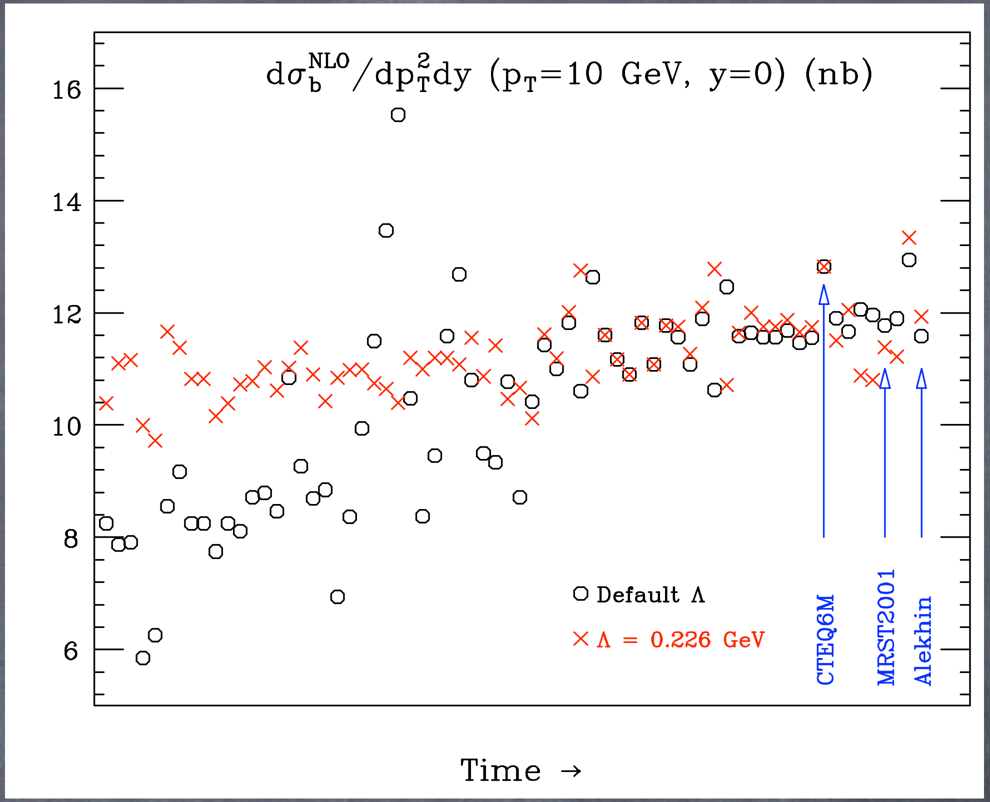
Examples ->

PDFs

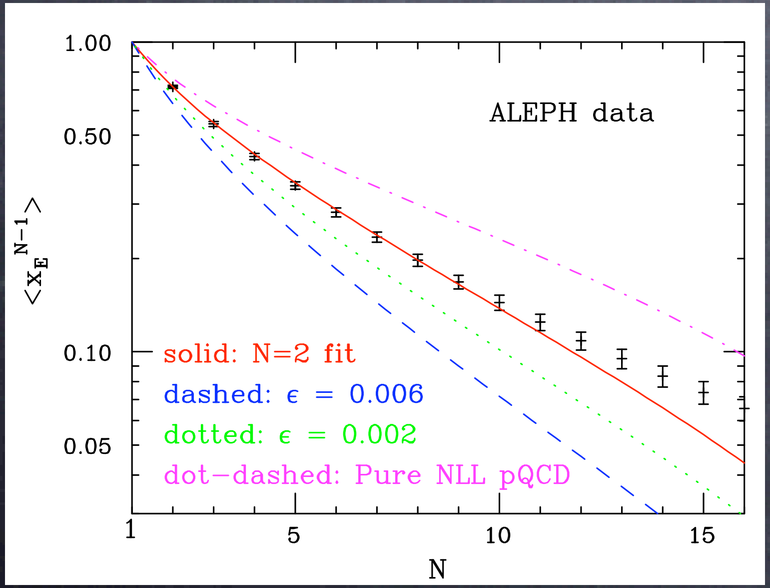
Exercise: calculate the b hadroproduction cross section with every PDF set which has ever been published

RESULT: even a factor of two from early sets to modern ones.

NB. a very large part of this discrepancy is due to the evolution of the value for α_s



FFs



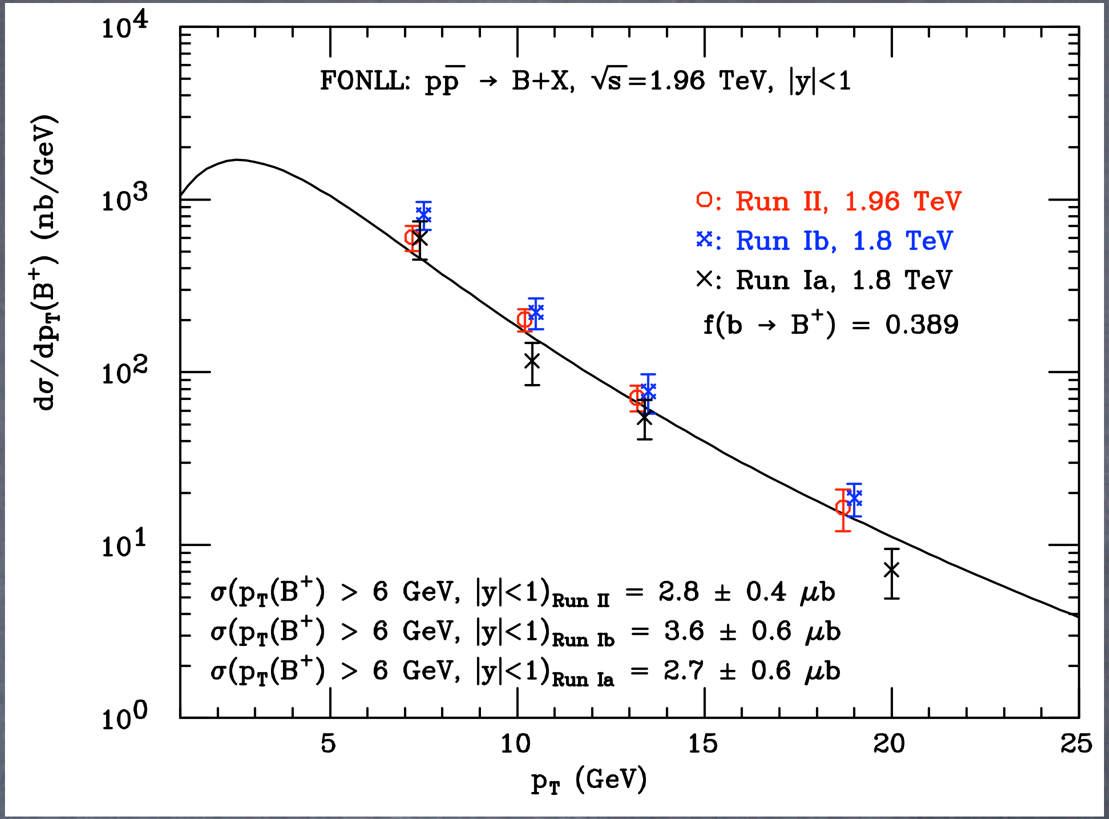
Switching from the usual Peterson with ϵ_b = 0.006 to a FF fitted in moment space increases the large-p_T cross section by 40%.

This is the single most significant increase, and the one not simply due to improved experimental input.

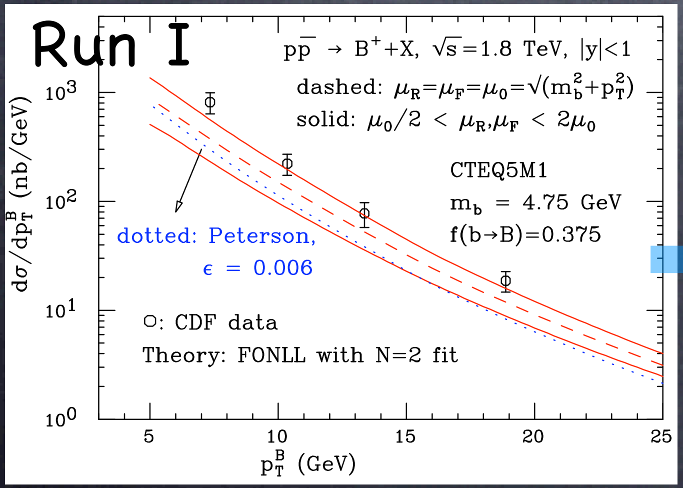
Data

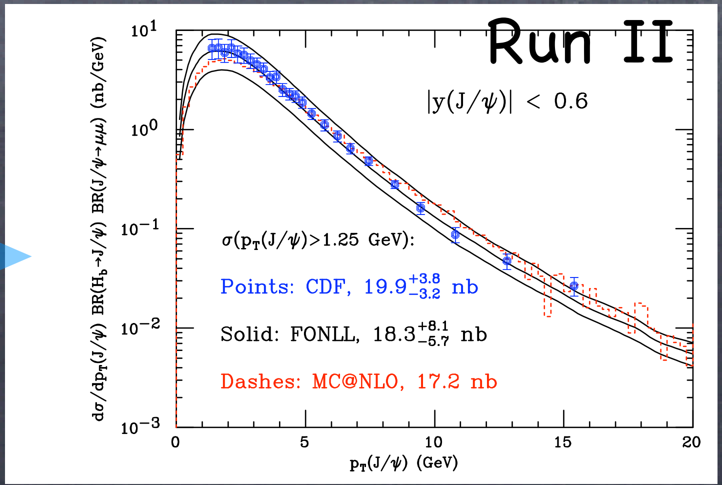
If the input from PDFs and the measurements and extraction of HQ FFs pushed the theory up, the data ‘helped’ coming down a little:

Compare Run II data to Run I ones: should be 10% higher, they are instead about 25% lower



This is the main reason why the same calculation which predicted a CENTRAL VALUE a factor of 1.7 lower than the CENTRAL VALUE of the data, is now in perfect agreement with Run II data





A furter 15-20% is given by updates in the PDFs (CTEQ5M1 -> CTEQ6M)

Summarizing....

- the description of b production cross section by pQCD is not as bad as it appeared. Actually, it's pretty good.
- in part, the changes are due to theoretical improvements and to legitimate movements of experimental data/inputs within errors
- in part, the discrepancy was never as large and significant as said/written. Plotting 1-sigma erros only and discussing central value ratios forgetting errors altogether might lead to a distorted perception of reality

"Only astronomers use 1-sigma errors" (Licia Verde, yesterday's talk)
Well......

When a particle physicists has to be reminded by a cosmologist how to properly treat errors, you know that something is wrong...

Conclusions

- NLO (+NLL) QCD does a good job in predicting real and unbiased observables. Part of the success is due to the possibility of controlling the whole chain from parton to hadron, carefully matching perturbative and non-perturbative contributions. Experiments should avoid publishing only deconvoluted/ extrapolated quantities, which might include strong biases from MC
- New physics is not needed to explain most of the recent bottom production data, but there is still some room for it within the uncertainties
- Higher order calculations (years away anyway) or further resummations should not change the picture, but may help in reducing the theoretical uncertainties (e.g. small-x effects for total b cross section at the Tevatron)