Orsay - IPN
22 avril 2005

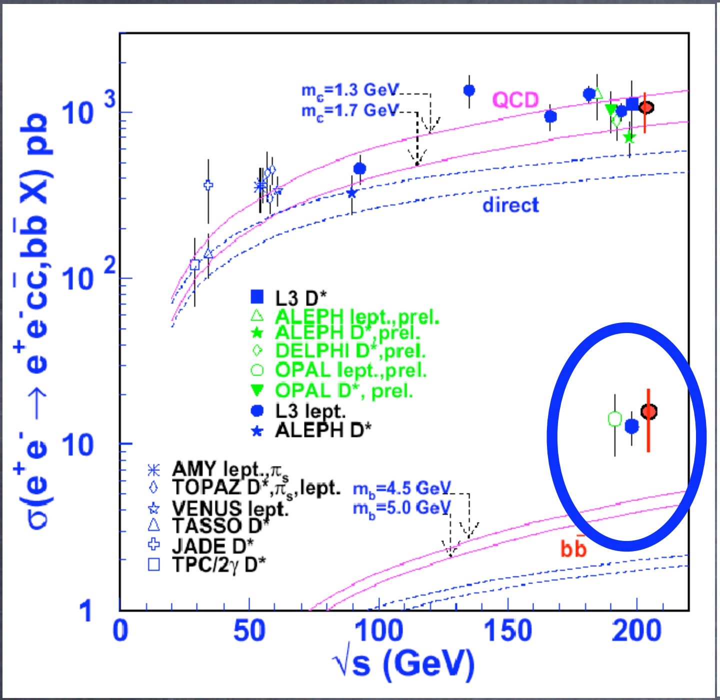
Heavy Quarks in p(anti-)p Collisions

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

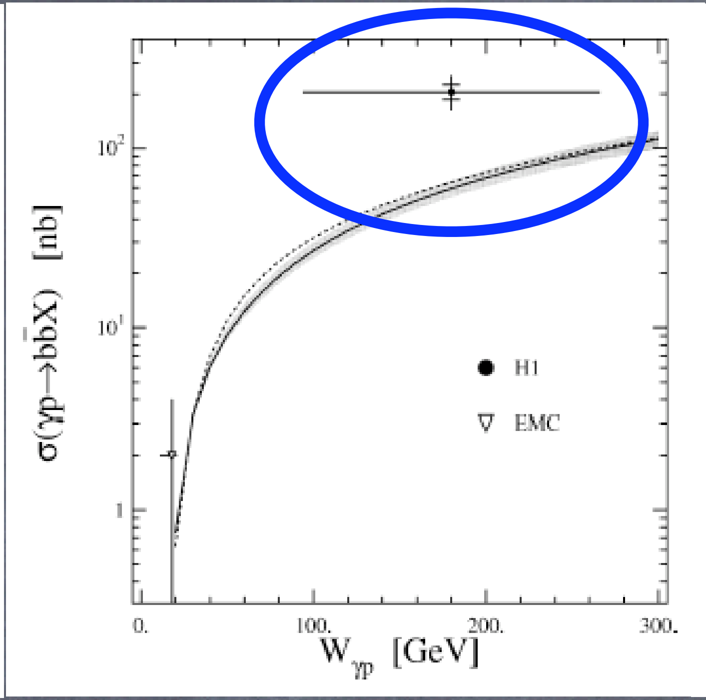
- Review of bottom production
- charm and bottom at RHIC

Bottom: What's going on?!?

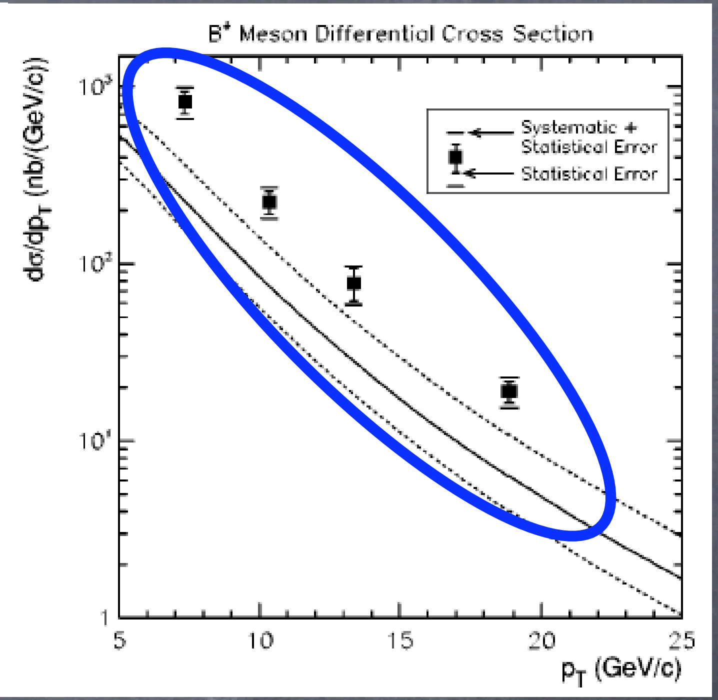
$\gamma\gamma \longrightarrow b\bar{b}$



$\gamma p \longrightarrow b\bar{b}$



$p\bar{p} \longrightarrow BX$



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 hadronic production in detail

NB: the hadroproduction part of this talk draws generously from a seminar that M.L. Mangano gave at Fermilab in January 2004. His full talk, with many more details, can be found at http://cern.ch/~mlm/talks/Bcrosssection.pdf and hep-ph/0411020

The theory benchmark for comparisons

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, ...)

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

YY

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.

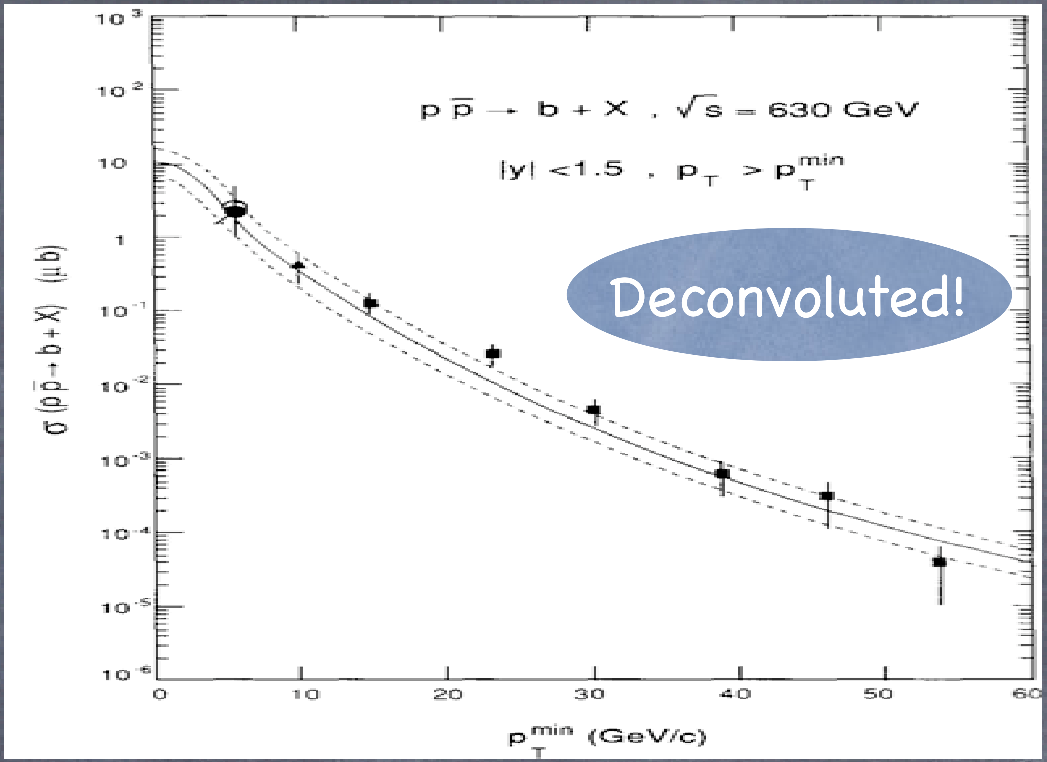
Bottom production in $p\bar{p}$ collisions

UA1 1988-1991

PL B213 (1988) 405

PL B256 (1991) 121

UA1/QCD ~ 1



Deconvoluted!

NB. UA1 also published data for physical particles, B mesons and muons. At that time, they could however not easily be compared to theoretical predictions

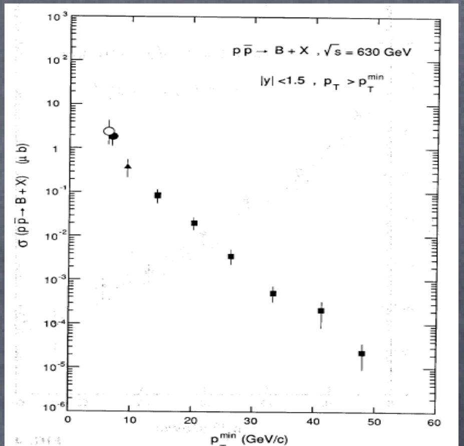


FIG. 5

CDF 1992

PRL 68 (1992) 3403

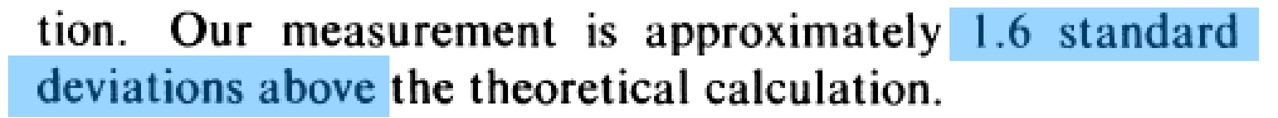
$$\sigma(\bar{p}p \to B^-X;\, P_T > 9.0\ \mathrm{GeV}/c,\, |y| < 1.0) = 2.8 \pm 0.9(\mathrm{stat}) \pm 1.1(\mathrm{syst})\ \mu\mathrm{b}.$$

Deconvoluted!

$\sigma(pp \to bX;\ p_T > 11.5$ GeV, $|y| < 1)$:

CDF = 6.1 ± 1.9 ± 2.4 μb

theory = 1.1 ± 0.5 μb

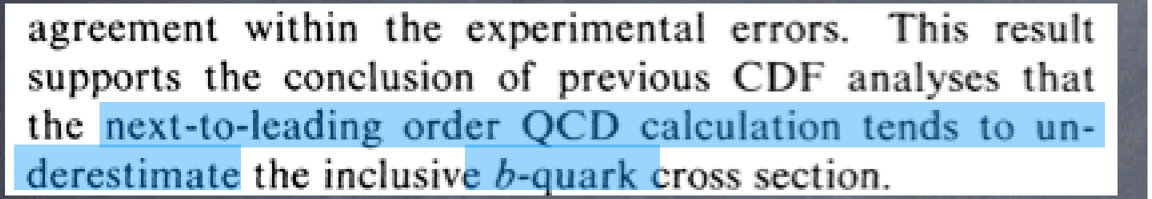


tion. Our measurement is approximately 1.6 standard deviations above the theoretical calculation.

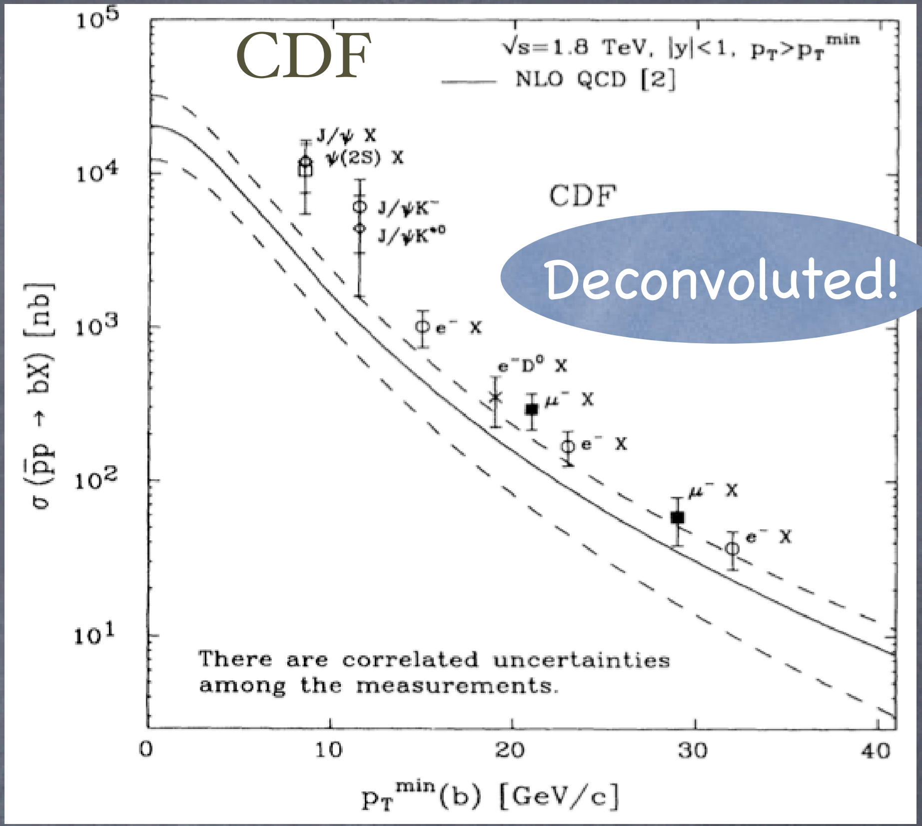
The ‘usual’ plot enters the stage....

CDF 1993

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

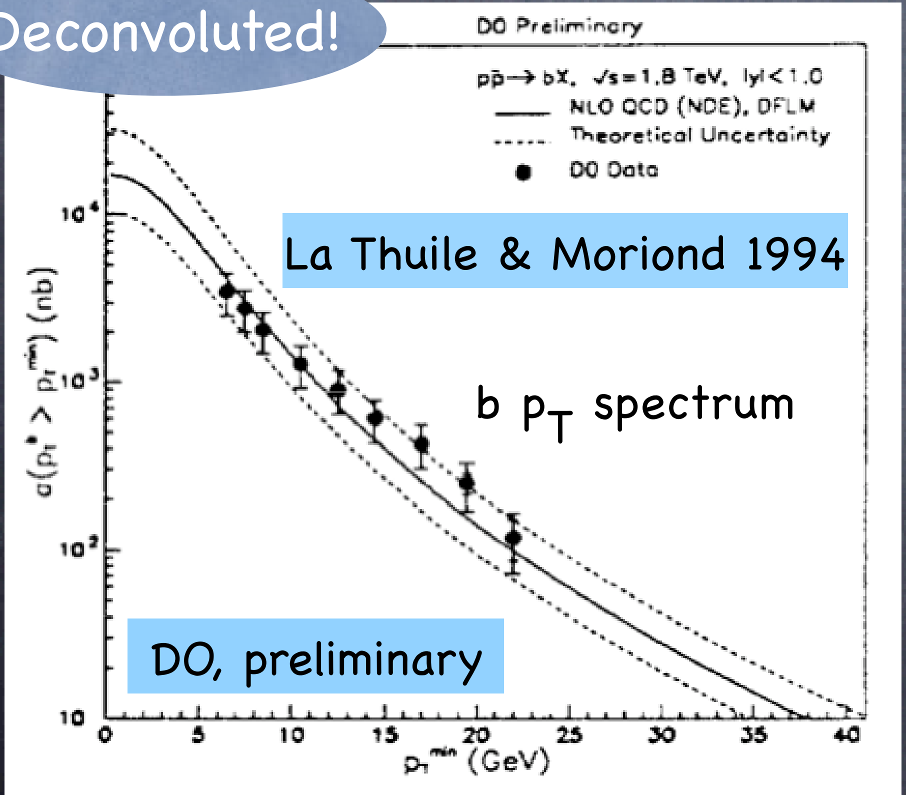


agreement within the experimental errors. This result supports the conclusion of previous CDF analyses that the next-to-leading order QCD calculation tends to underestimate the inclusive *b*-quark cross section.



Deconvoluted!

Deconvoluted!



La Thuile & Moriond 1994

b p_T spectrum

D0, preliminary

D0 finds however no excess at this stage: consistent with QCD, barely consistent with CDF

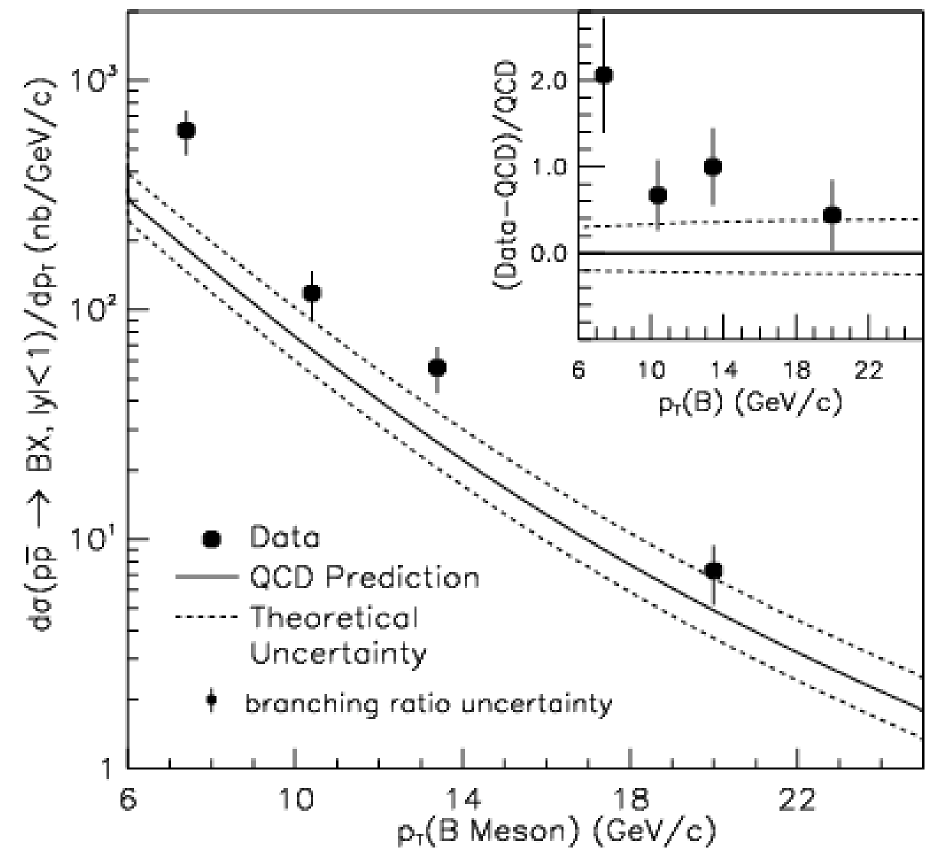
“Real” observables are also measured:

CDF 1995

PRL 75 (1995) 1451

B mesons, NOT deconvoluted
to b quark level

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



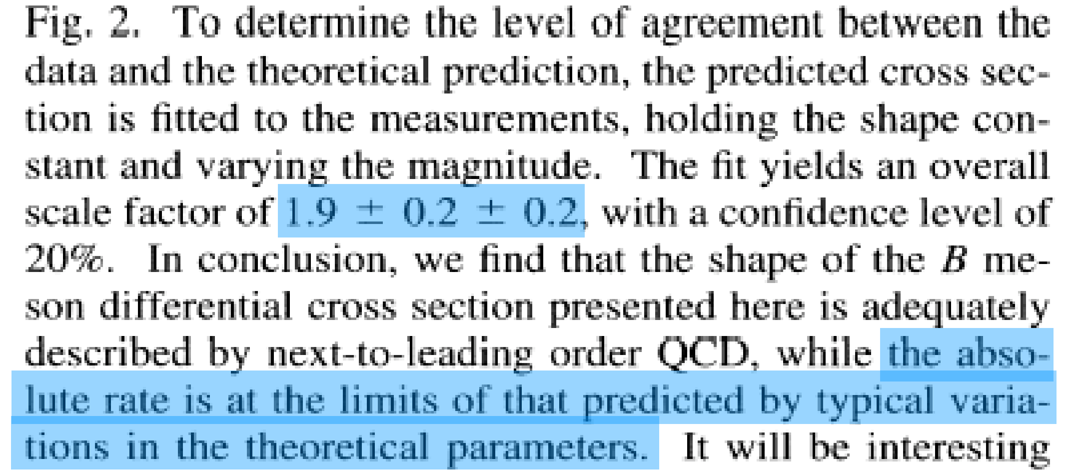


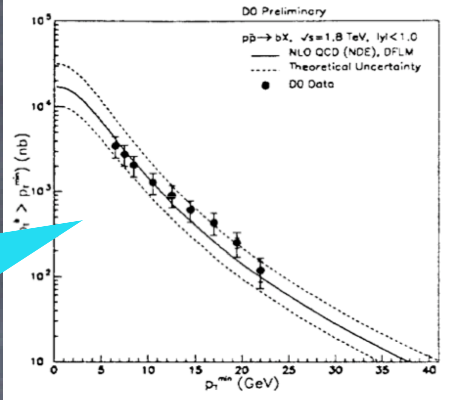
Fig. 2. To determine the level of agreement between the data and the theoretical prediction, the predicted cross section is fitted to the measurements, holding the shape constant and varying the magnitude. The fit yields an overall scale factor of 1.9 ± 0.2 ± 0.2, with a confidence level of 20%. In conclusion, 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

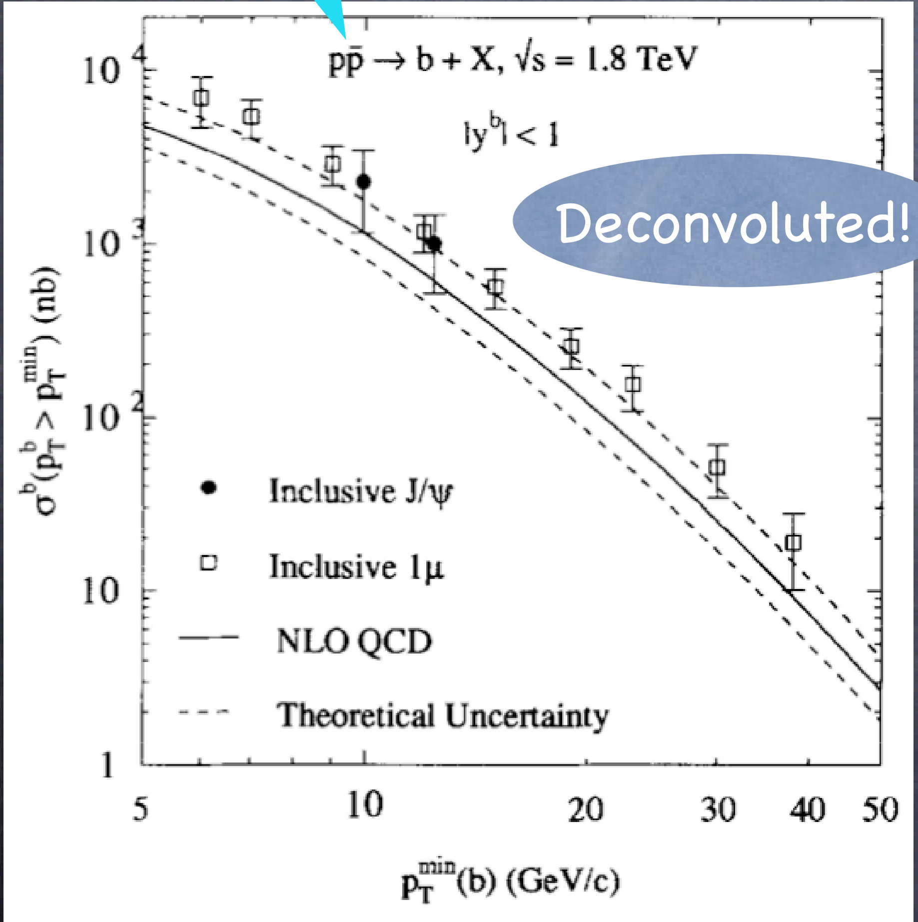
PRL 74 (1995) 3548
PL B370 (1996) 239

Preliminary

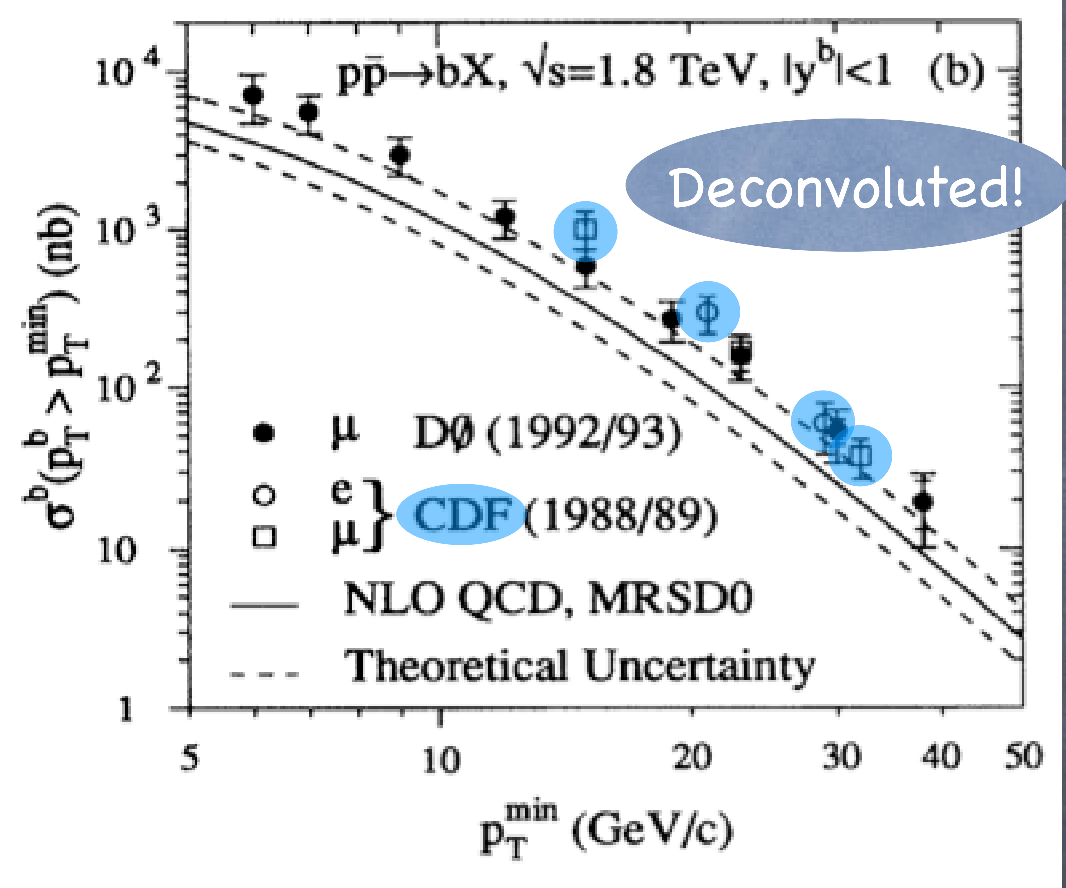


Final

The final D0 data become more CDF-like.



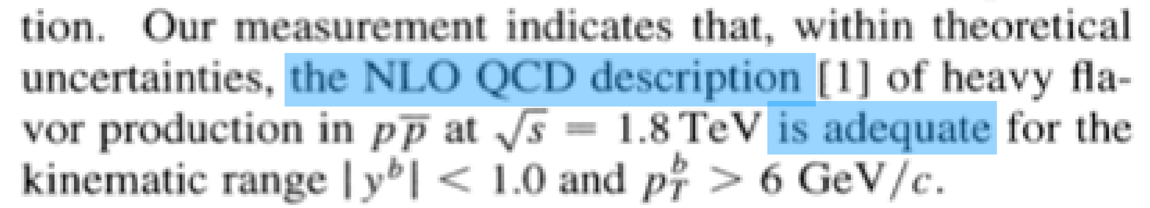
Deconvoluted!



Deconvoluted!

However, they are still compatible with QCD:

Conclusions



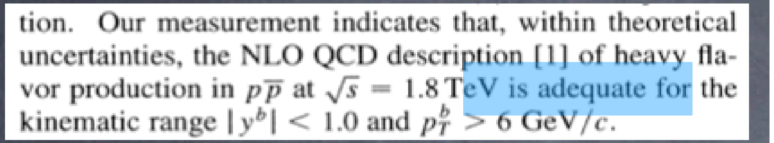
tion. Our measurement indicates that, within theoretical uncertainties, the NLO QCD description [1] of heavy flavor production in $p\bar{p}$ at $\sqrt{s} = 1.8$ TeV is adequate for the kinematic range $|y^b| < 1.0$ and $p_T^b > 6$ GeV$/c$.

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

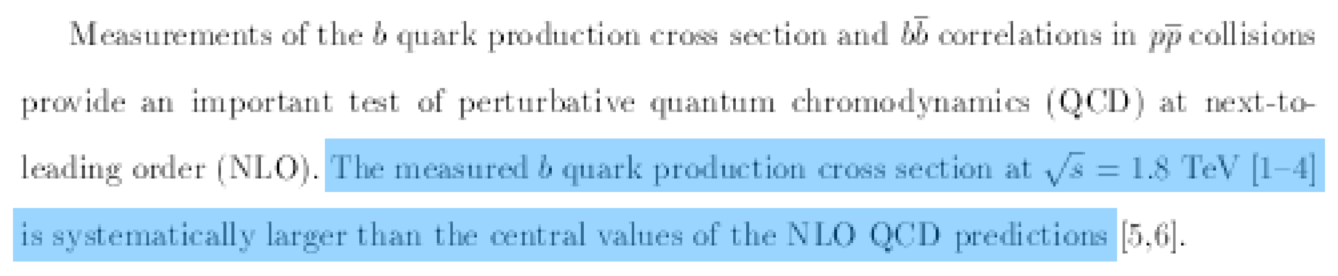
D0 1999-2000

PL B487 (2000) 264

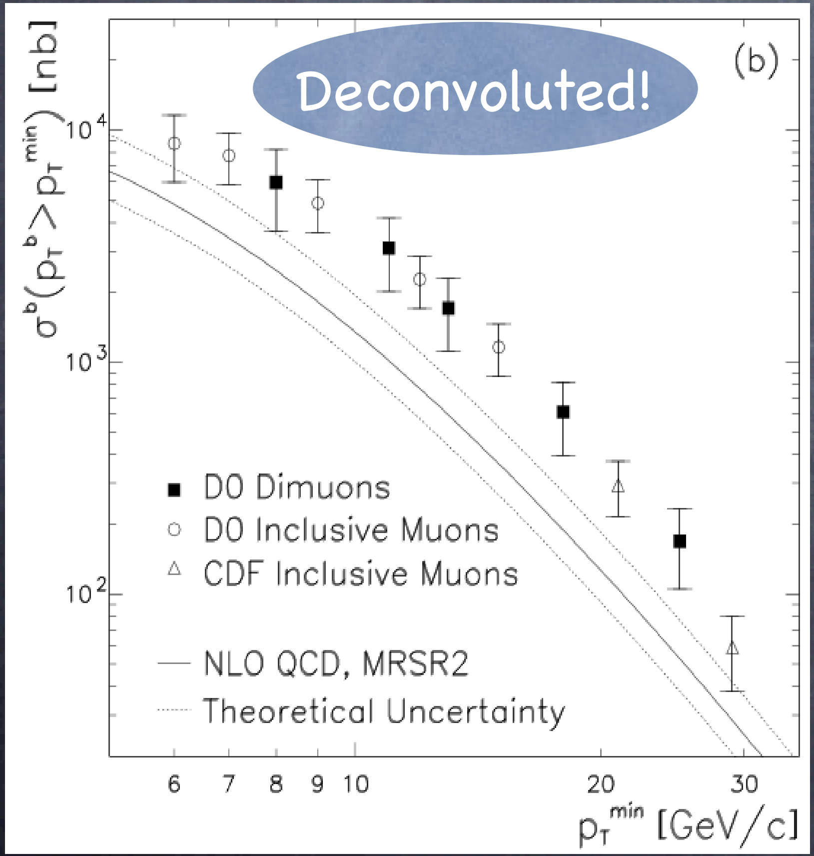
Despite the conclusions of the previous paper ("adequate description"), the previously measured b cross section is now described as being "systematically larger" in the Introduction:



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

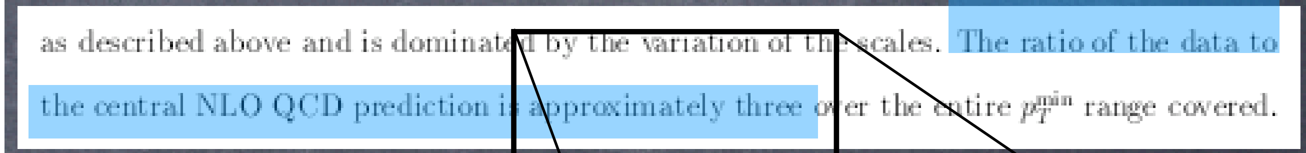


Measurements of the b quark production cross section and $b\bar{b}$ correlations in $p\bar{p}$ collisions provide an important test of perturbative quantum chromodynamics (QCD) at next-to-leading order (NLO). The measured b quark production cross section at $\sqrt{s}$ = 1.8 TeV [1–4] is systematically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

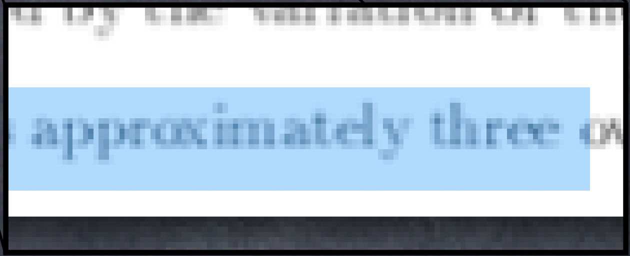


This, of course, helps accepting the conclusion that the new data show now a considerable excess:

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.

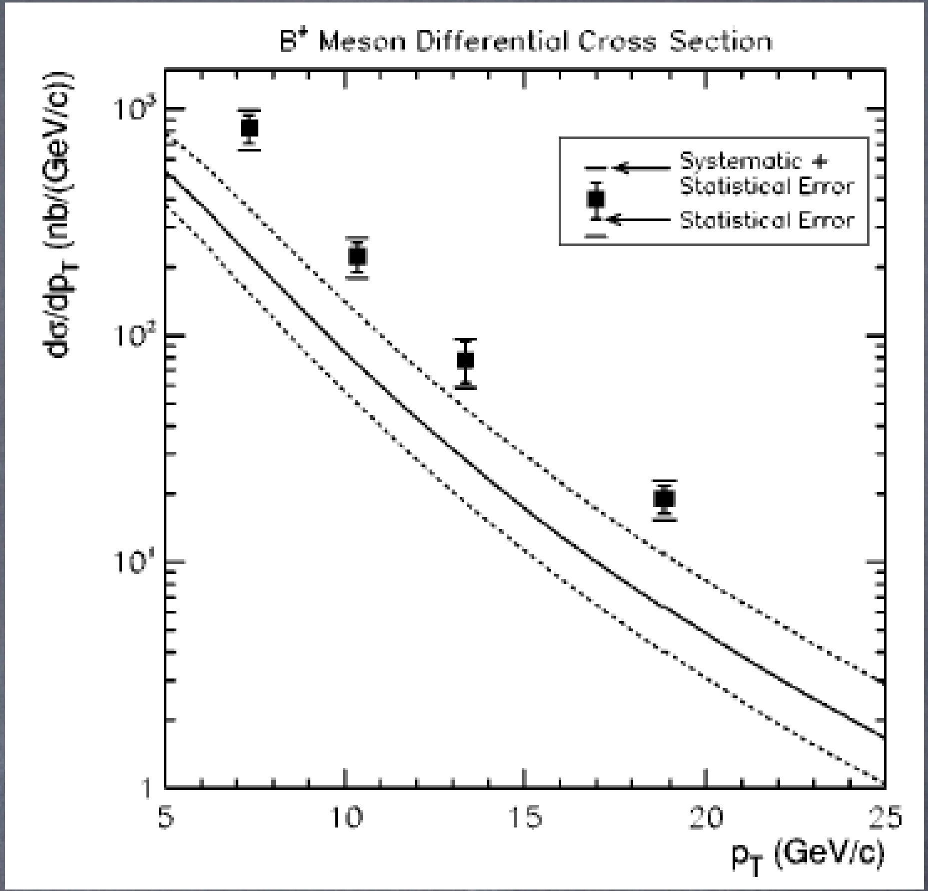


approximately three

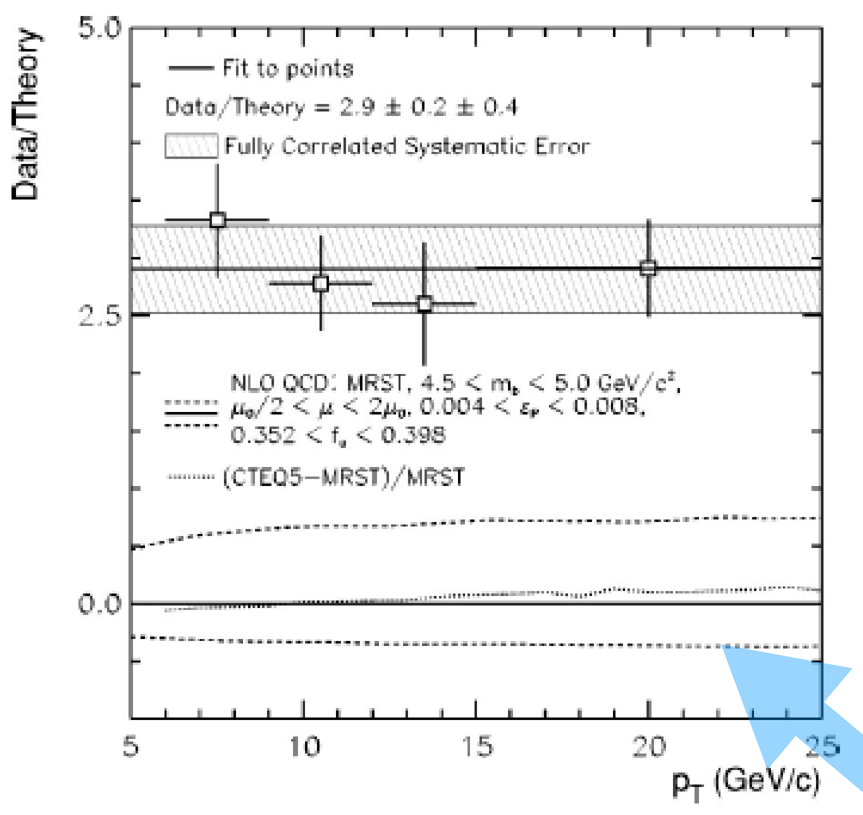
CDF 1998-2002

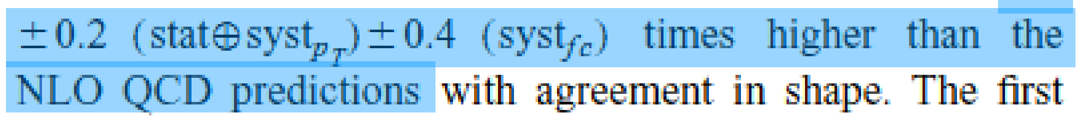
PRD 65 (2002) 052005

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$_{f_c}$) 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 ?!?

Theoretical ingredients of a VCE

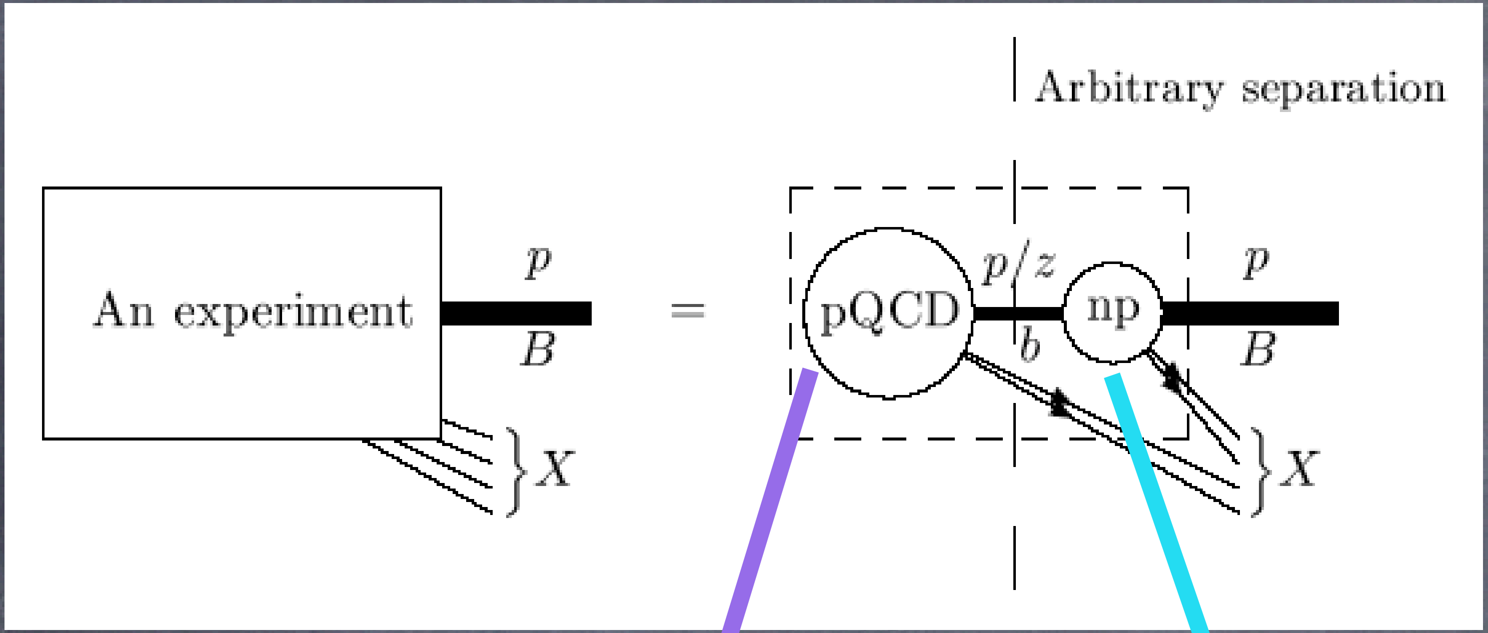
(Very Conventional Explanation)

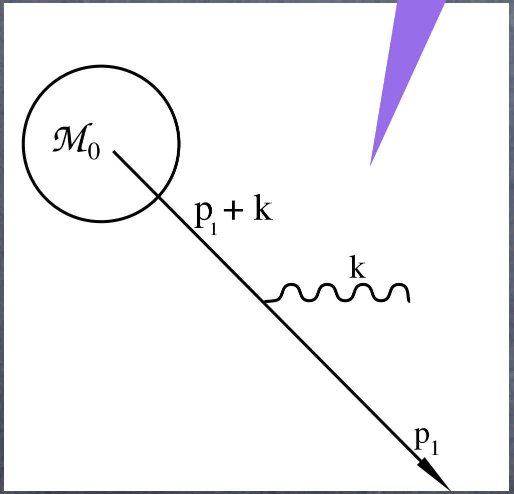
The prediction for the distribution of a 'real particle' (J/ψ or muon) can be obtained by convoluting:

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

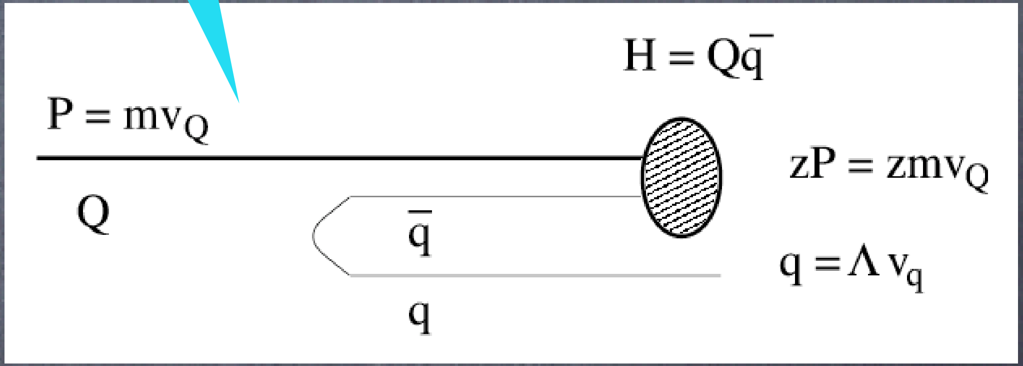
$$\frac{d\sigma(b \to B \to J/\psi)}{dp_T} = \frac{d\sigma(b)}{d\hat{p}_T} \otimes f(b \to B) \otimes g(B \to J/\psi)$$

For f(b->B) the Peterson, Schlatter, Schmitt, Zerwas form with $\epsilon_b = 0.006$ is used in most experimental papers, following a determination by Chrin made in 1987 (sic) using charm data, $\epsilon_b = m_c^2/m_b^2\ \epsilon_c$ rescaling, and LO Montecarlo calculations





Perturbative: gluon radiation



Non-perturbative: hadronization

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

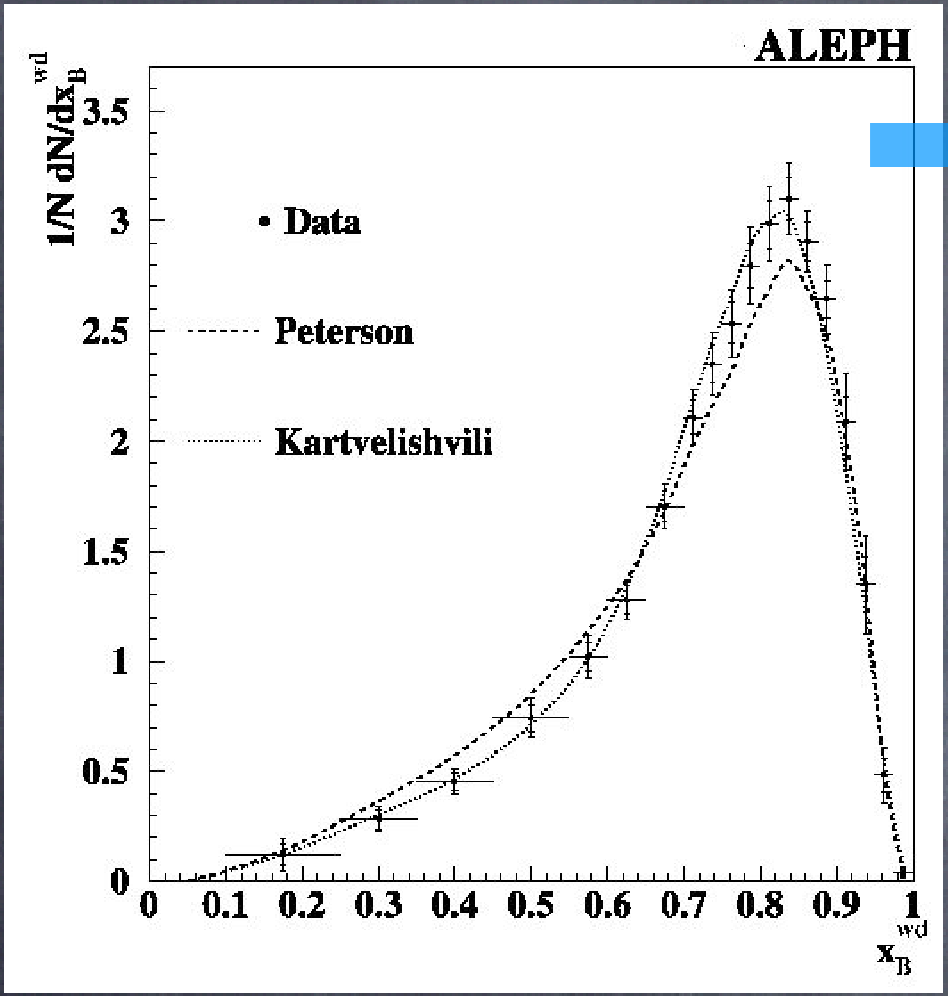
Assuming $\frac{d\sigma}{d\hat{p}_T} \sim \frac{1}{\hat{p}_T^N}$ we get $\frac{d\sigma}{dp_T} \sim \int \frac{dz}{z} (\frac{z}{\hat{p}_T})^N f(z) = f_N \frac{d\sigma}{d\hat{p}_T}$

In proton-(anti)proton collisions N is of order 5 for $p_T \sim$ 10-20 GeV. Therefore,

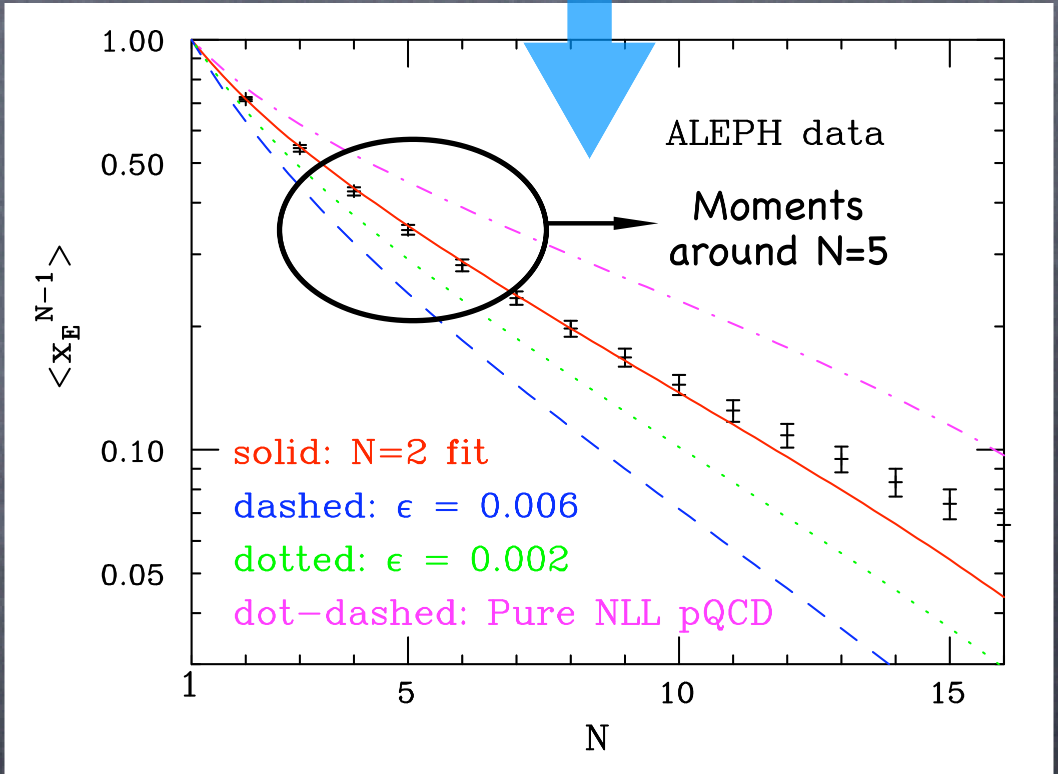
a proper extraction of moments around this one from e+e- collisions is more important than a good description of the spectrum

x_E space

Moments space



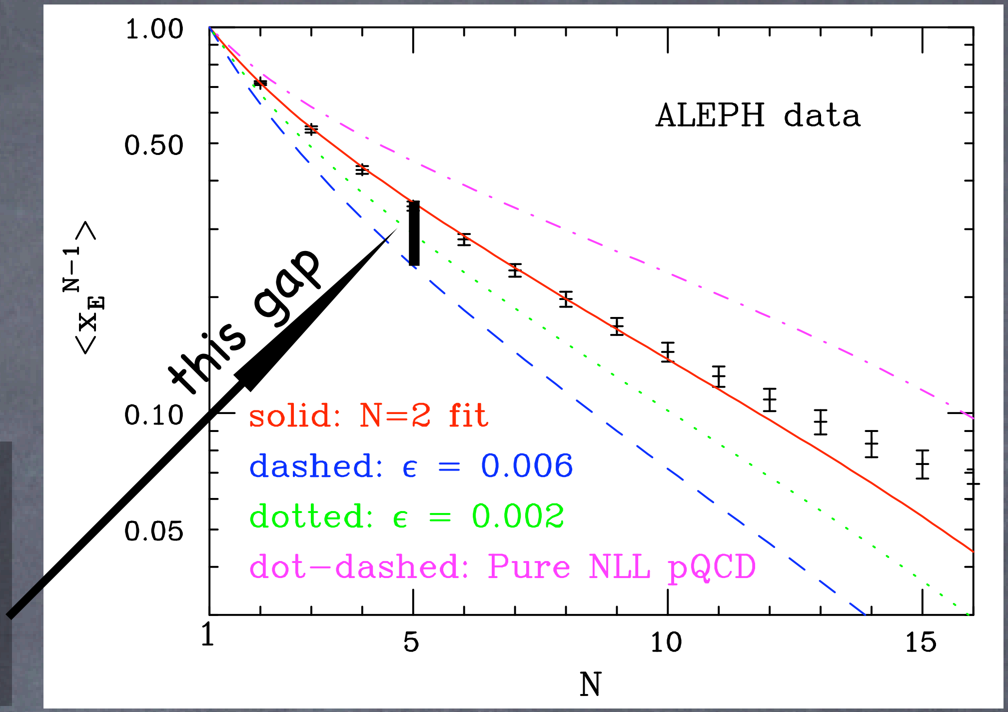
$$\langle x_E^{N-1}\rangle = \int_0^1 x_E^{N-1} f(x_E)\,dx_E$$



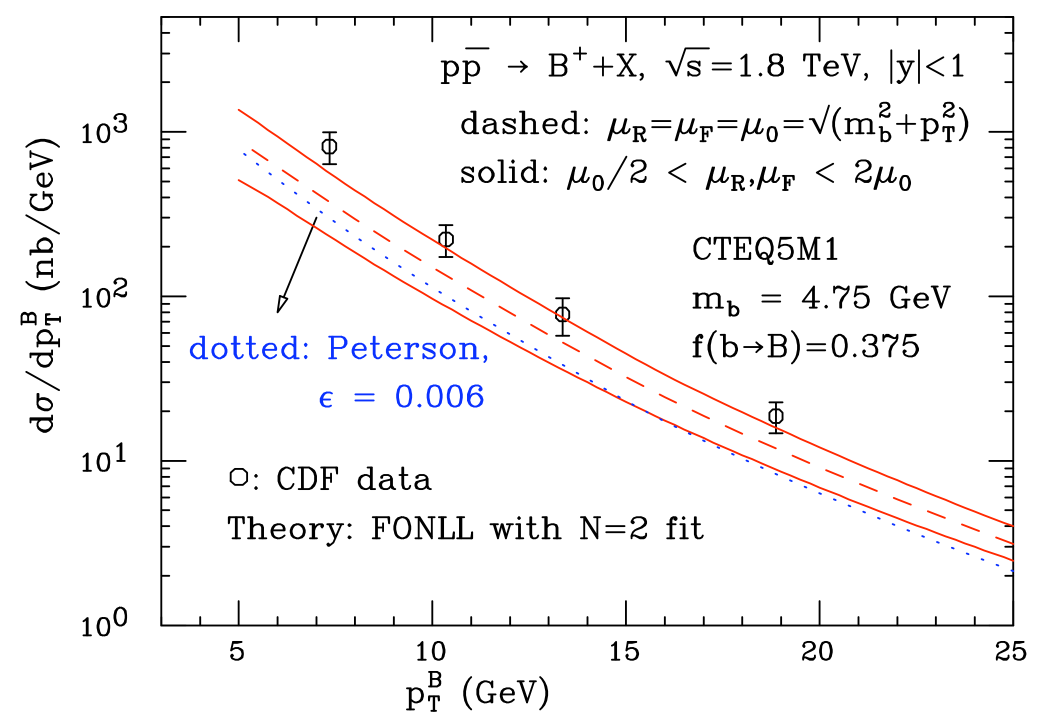
We don't fit this......

...but rather this.

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



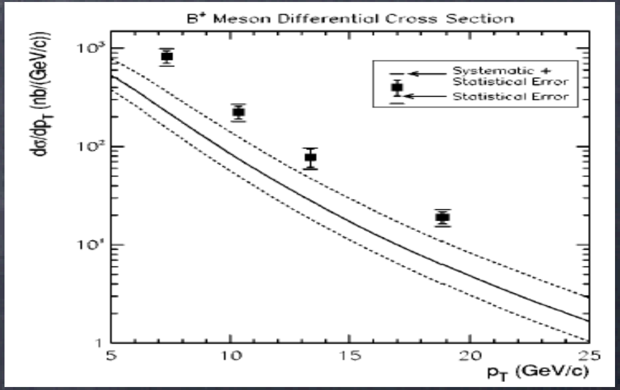
MC and P. Nason, Phys. Rev. Lett. 89 (2002) 122003

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.)

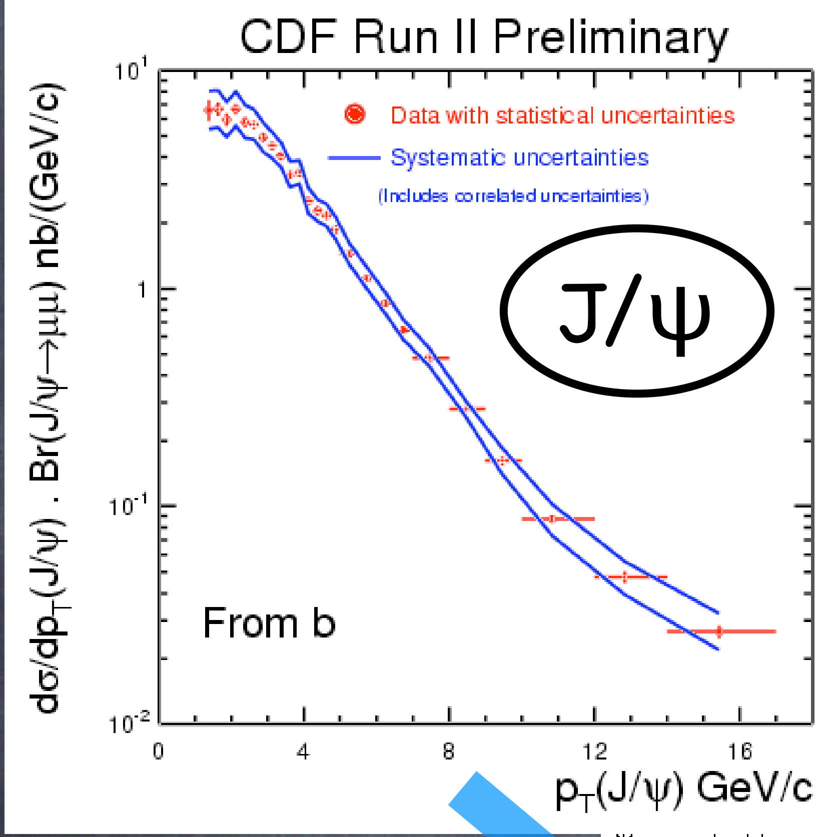
i.e. no significant discrepancy

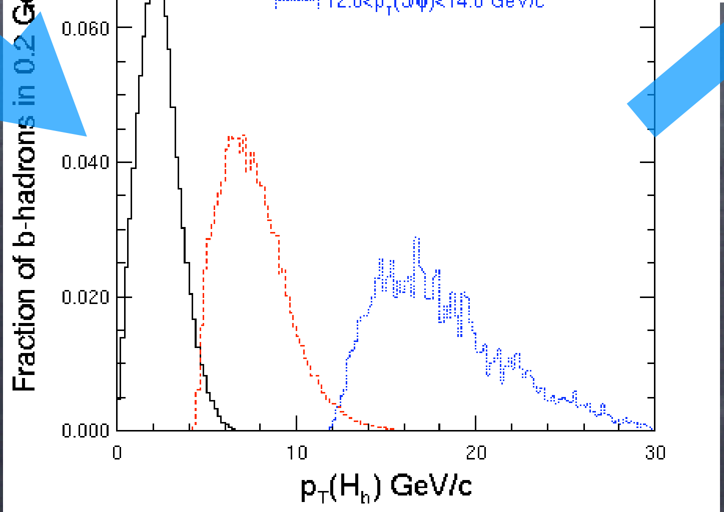
compare

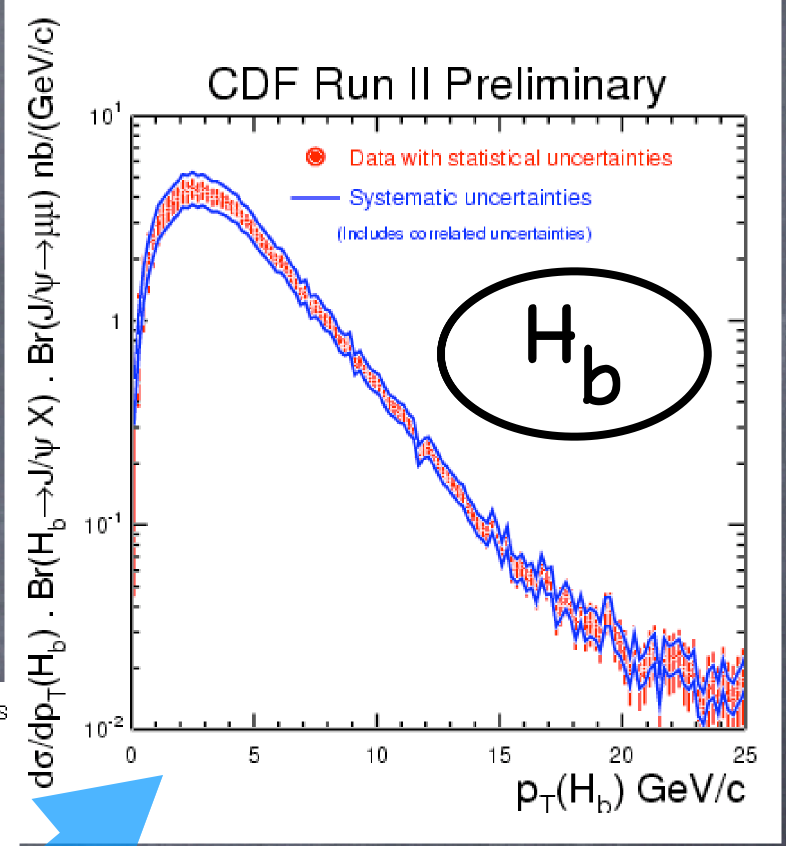


The Tevatron Run II data

A few months ago, CDF published the first preliminary bottom results from Run II data (CDF Note 6285)







Simulation of B hadron momentum distribution as a function of the J/ψ momentum

Insofar as QCD effects are concerned, both B hadrons and J/ψ are physical observables

Ingredients of the theoretical prediction

Perturbative items:

- NLO massive calculations
- NLL resummations

$\}$ FONLL (for LEP + Tevatron)

Inputs: bottom mass (4.5 - 5 GeV) and α_s (Λ = 0.226 GeV)

- Uncertainties: ren/fact scale variations

Non-perturbative items:

- gluon and light quarks PDFs
- b quark to B meson fragmentation

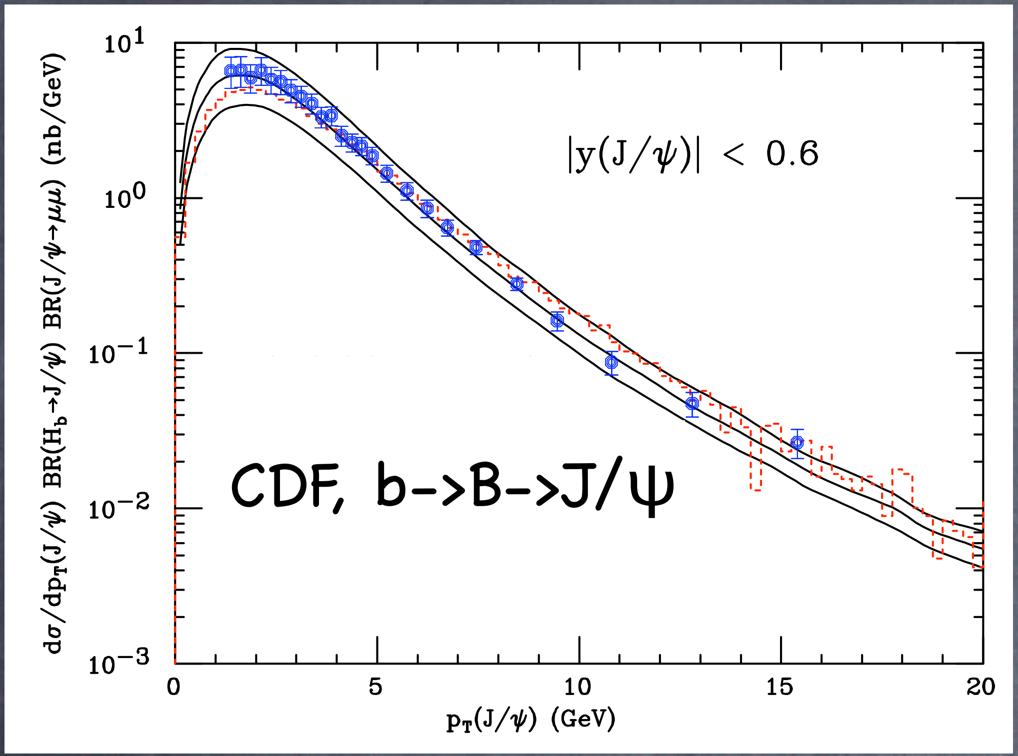
Input: NLL fit to LEP data (only some moments are important)

- B meson to J/ψ decay spectrum

Inputs: BR from PDG (1.15 ± 0.06 %)
Spectrum from CLEO or BABAR
(detailed knowledge irrelevant due to boost)

- B meson mass (5.3 GeV)

2003: CDF Run II preliminary data at 1.96 TeV



MC, Frixione, Mangano, Nason, Ridolfi, JHEP 0407 (2004) 033

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

$$\sigma^{CDF}_{J/\psi} = 19.9\ {}^{+3.8}_{-3.2\,stat+syst}\ \mathrm{nb}$$

$$\sigma^{FONLL}_{J/\psi} = 18.3\ {}^{+8.1}_{-5.7}\ \mathrm{nb}$$

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

$$\sigma^{CDF}_{H_b} = 24.5\ {}^{+4.7}_{-3.9\,stat+syst}\ \mathrm{nb}$$

$$\sigma^{FONLL}_{H_b} = 22.9\ {}^{+9.5}_{-6.8}\ \mathrm{nb}$$

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

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

$$\sigma^{FONLL}_{b}(|y_b| < 1) = 25.0\ {}^{+12.6}_{-8.1}\ \mu\mathrm{b}$$

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.

NB. Data finally published in hep-ex/0412071. No significant changes -->

CDF, hep-ex/0412071

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

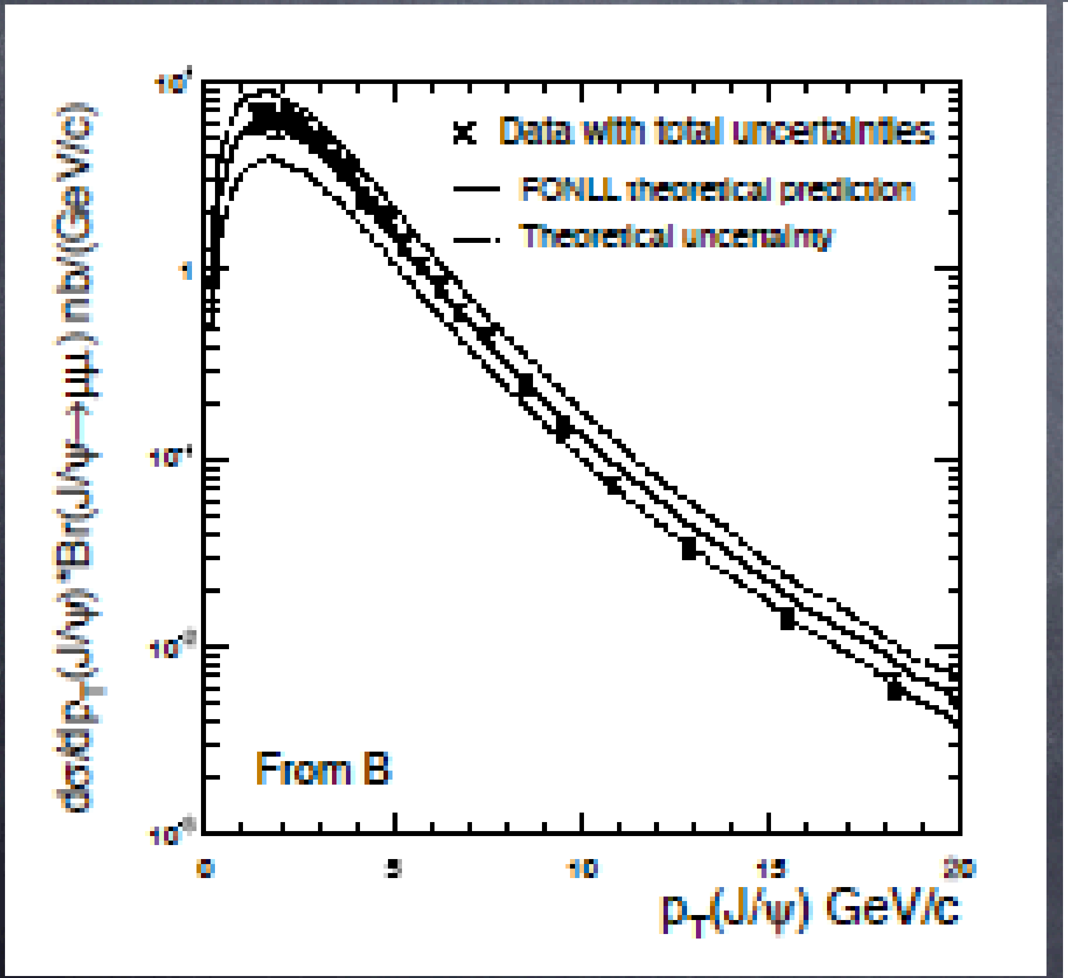
$$\sigma(p\bar{p} \rightarrow H_b,\ H_b \rightarrow J/\psi, p_T(J/\psi) > 1.25\ \ \mathrm{GeV}/c, |y(J/\psi)| < 0.6)$$
$$= 0.330 \pm 0.005(stat)^{+0.036}_{-0.033}(syst)\ \mu\mathrm{b}.$$

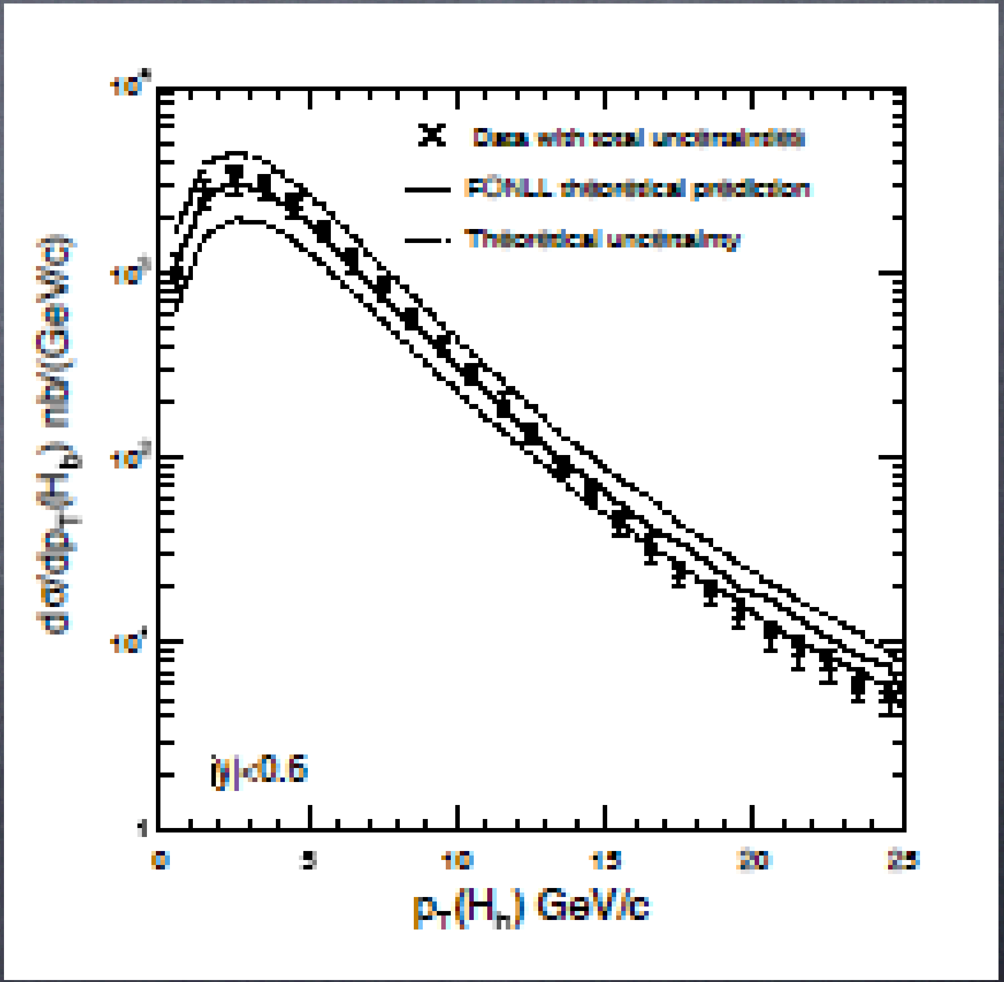
$$\sigma^{FONLL}_{J/\psi} = 0.31^{+0.14}_{-0.10}\ \mu b$$

$\sigma(pp \rightarrow H_b X;\ P_T > 0,\ |y| < 0.6)$

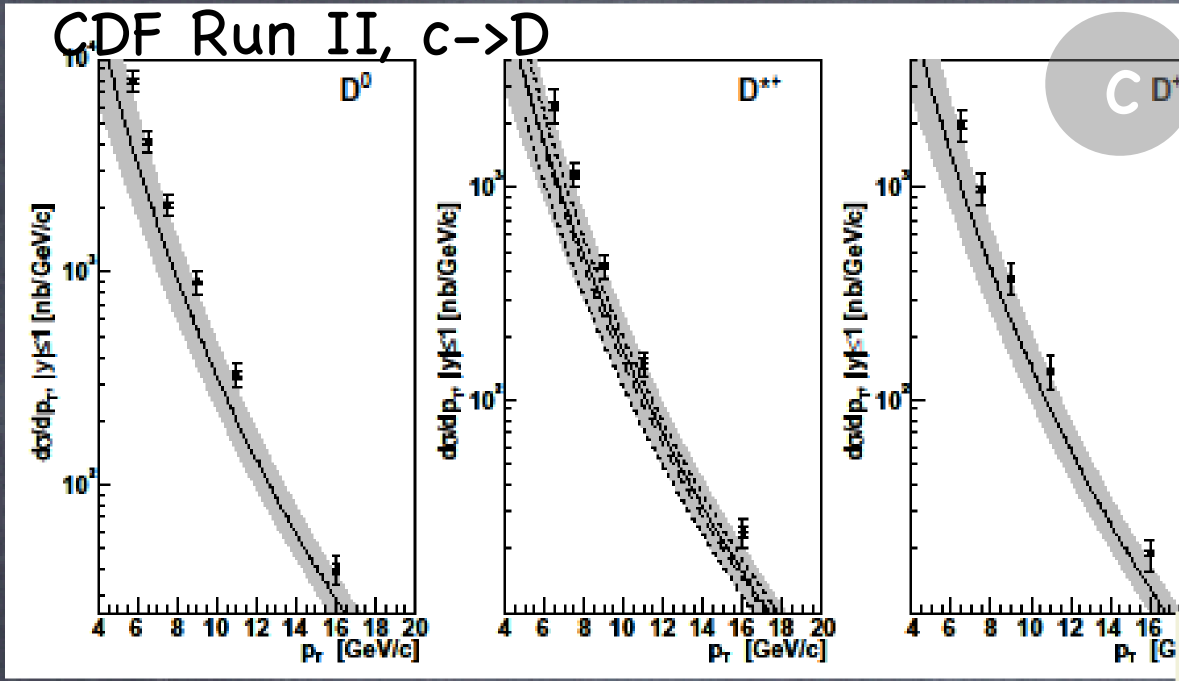
$$\sigma(p\bar{p} \rightarrow H_b X, |y| < 0.6) = 17.6 \pm 0.4(stat)^{+2.5}_{-2.3}(syst)\ \mu\mathrm{b}.$$

$$\sigma^{FONLL}_{(|y|<0.6)} = 16.8^{+7.0}_{-5.0}\ \mu\mathrm{b}$$





Charm and top also look OK

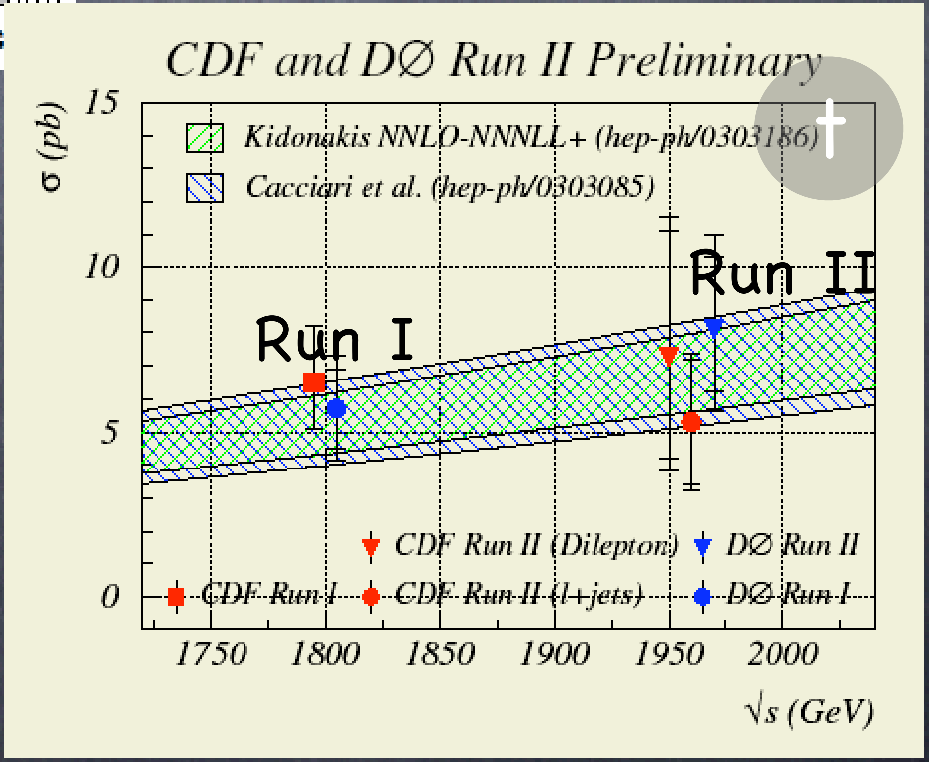


CDF Run II, c->D

c

P$_T$ distributions of charmed mesons

(same framework as for bottom)



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Run I

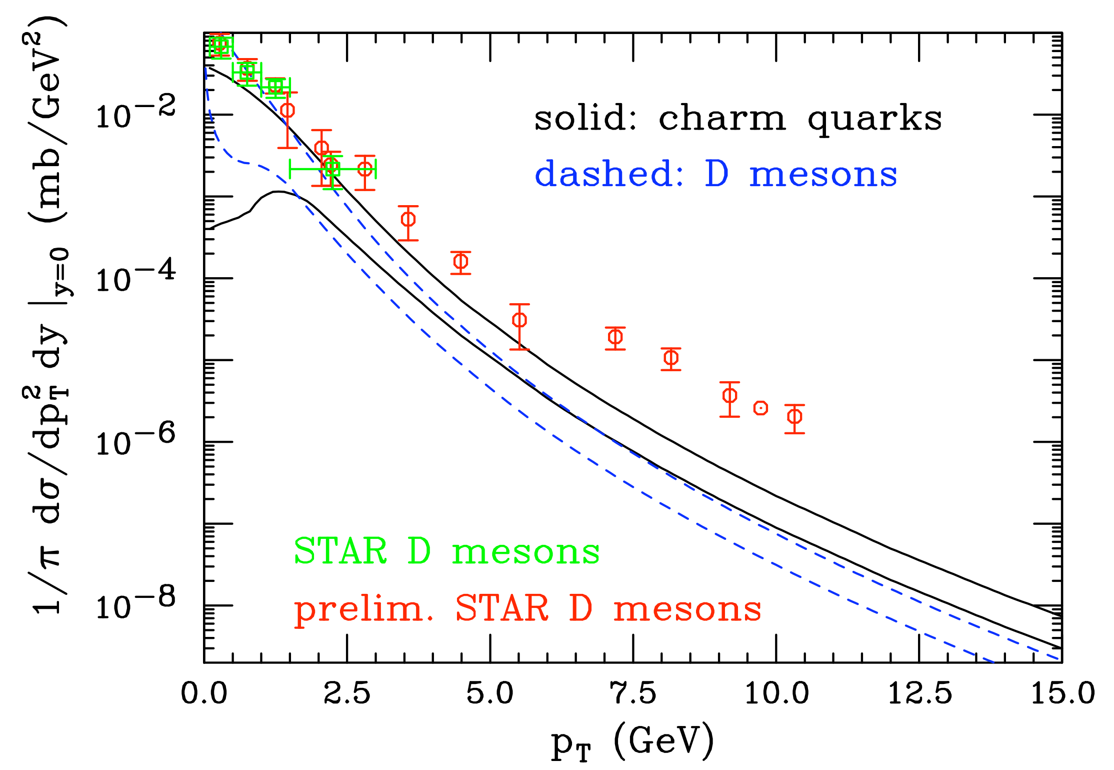
Run II

Top total cross section

The RHIC data

Charm and bottom @ RHIC

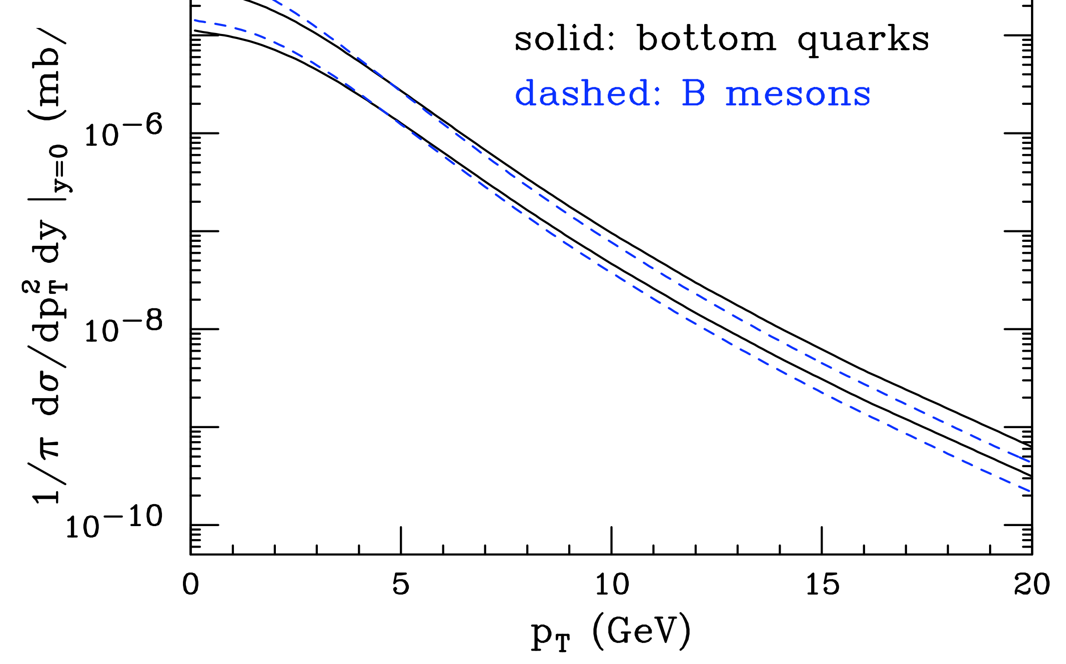
[MC, P. Nason, R. Vogt, hep-ph/0502203]



Charm and D mesons

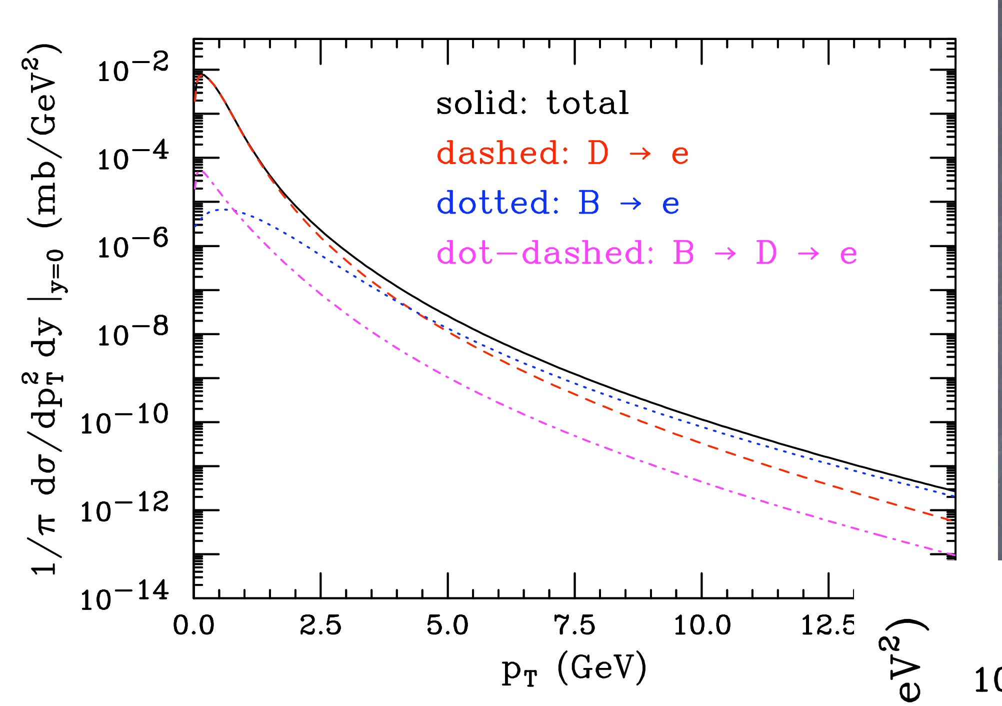
NB. No `nuclear' effects in predictions.
Just a `perturbative QCD' benchmark

Bottom and B mesons

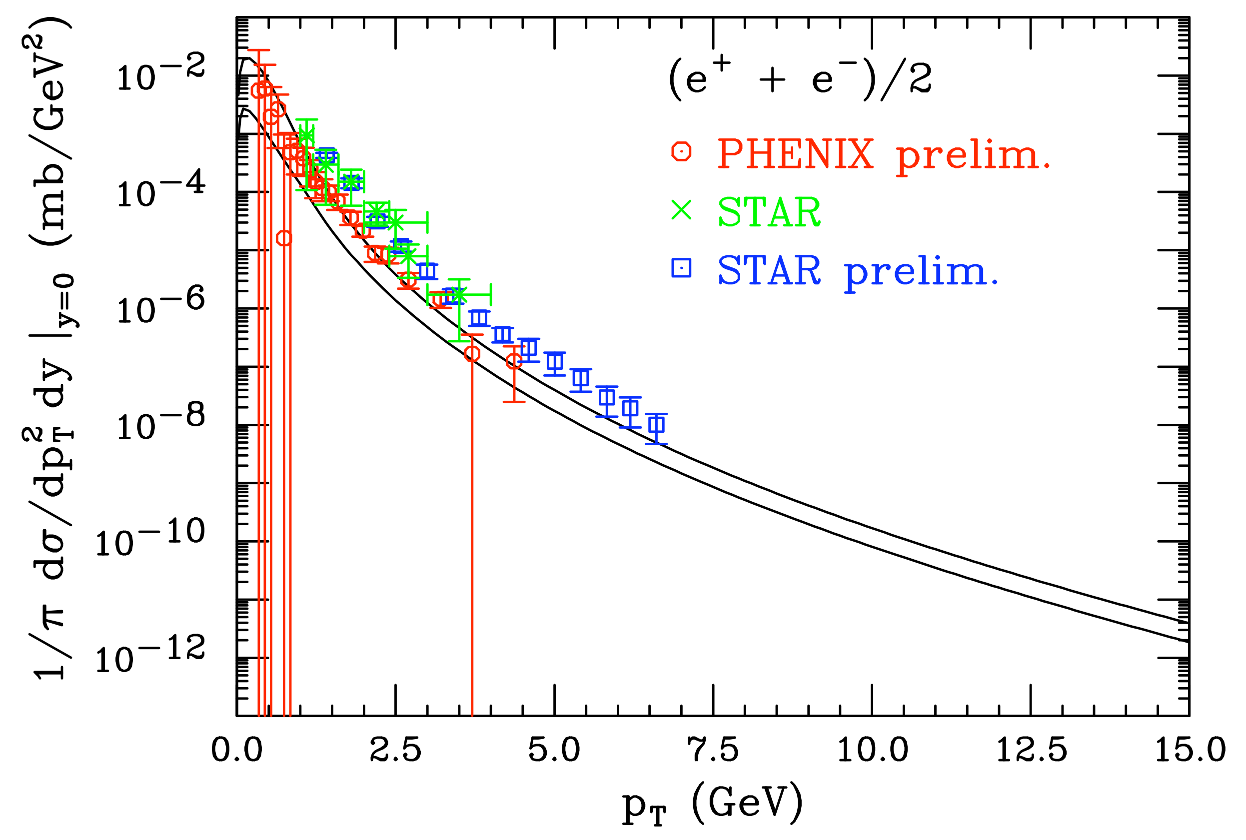


Electrons from Heavy Quarks @ RHIC

[MC, P. Nason, R. Vogt, hep-ph/0502203]



$$pp \xrightarrow{pQCD} Q \xrightarrow{NP\,fragm.} H_Q \xrightarrow{decay} e$$



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. Plotting 1-σ errors only and discussing central value ratios forgetting errors altogether might have lead to a distorted perception of reality (`*When people quote systematic uncertainties, they usually mean it*'. -- *M.L. Mangano*)
- both the data and the theory have moved, often legitimately within the uncertainties (which might have been larger than previously thought)
- new measurements without corrections to unphysical particles (ZEUS, CDF) may have minimized the risk of biasing the data. Whatever the reason, they are now in good agreement
- new experimental input (and better use of some of them, e.g. bottom FF) allowed producing more reliable theoretical predictions

Conclusions

NLO (+NLL) QCD does a good job in predicting real and unbiased bottom (and charm) hadroproduction data.

Part of the success is due to the possibility of controlling, from the theory side, 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 MonteCarlo:

"Thou shalt not publish only results for unphysical objects"