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Heavy flavours in pQCD: theory vs data

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Foreword

- One of the most daunting tasks the heavy ion community faces is that of understanding heavy flavour physics in nuclear collisions
- Headaches are not new in the field: b physics has been a major problem in QCD for 15 years
- The situation has recently much improved, at least for open heavy flavours. I'll review the case of c and b production in non-nuclear collisions, showing that cross sections to be used as benchmarks are now under an unprecedented level of control, and that of quarkonium

Production of open heavy flavours

By saying that a quark is heavy, we simply mean:

$$m_Q \gg \Lambda_{QCD}$$

If one is interested in the production dynamics, this allows one to compute perturbatively the open-Q cross section (as opposed to the open-u cross section, which diverges)

c, b, and t production can formally be treated in the same manner

However, phenomenological implications are very different:

$$m_t/\Lambda_{QCD} \simeq 800 \quad \Longrightarrow \quad \alpha_S(m_t) \simeq 0.1$$

$$m_b/\Lambda_{QCD} \simeq 15 \quad \Longrightarrow \quad \alpha_S(m_b) \simeq 0.21$$

$$m_c/\Lambda_{QCD} \simeq 4 \quad \Longrightarrow \quad \alpha_S(m_c) \simeq 0.33$$

Furthermore, the larger this ratio, the more important the impact of long-distance physics (such as hadronization)

Basics

Heavy flavour production in hadronic collisions is written in terms of the usual factorization formulae

$$d\sigma_{H_1 H_2 \to Q\overline{Q}}(S) = \sum_{ij} \int dx_1 dx_2 f_i^{(H_1)}(x_1) f_j^{(H_2)}(x_2) d\hat{\sigma}_{ij \to Q\overline{Q}}(\hat{s} = x_1 x_2 S)$$

- PDFs $f_i^{(H)}$ cannot be computed in perturbation theory (long-distance physics)
- Short distance cross sections $d\hat{\sigma}_{ij \to Q\overline{Q}}$ are computable in perturbation theory

$$d\hat{\sigma} = \sum_{i=2}^{\infty} a_i \alpha_S^i \;=\; a_2 \alpha_S^2 + a_3 \alpha_S^3 + a_4 \alpha_S^4 + \quad \ldots\ldots\ldots$$

LO NLO NNLO $\mathrm{N}^k\mathrm{LO}$

The computation of a_2 is trivial, that of a_3 *very* difficult, that of a_4 almost impossible
$\Longrightarrow$ we have to live with NLO for a long while

This may be troublesome, since at the NLO there is still a large scale dependence
$\Longrightarrow$ NNLO may not be small

But there are more serious troubles...

Troubles

1) Large logs appear in the perturbative coefficients

$$a_i = \sum_{k=0}^{i-2} a_i^{(i-2-k)} \log^{i-2-k} \mathcal{Q}$$

where $\mathcal{Q}$ "large" means $\alpha_S \log^2 \mathcal{Q} \gtrsim 1$. $\mathcal{Q}$ *may or may not* depend on the observable. If $\mathcal{Q}$ is large, the logs *must be resummed* (i.e., the expansion is rearranged)

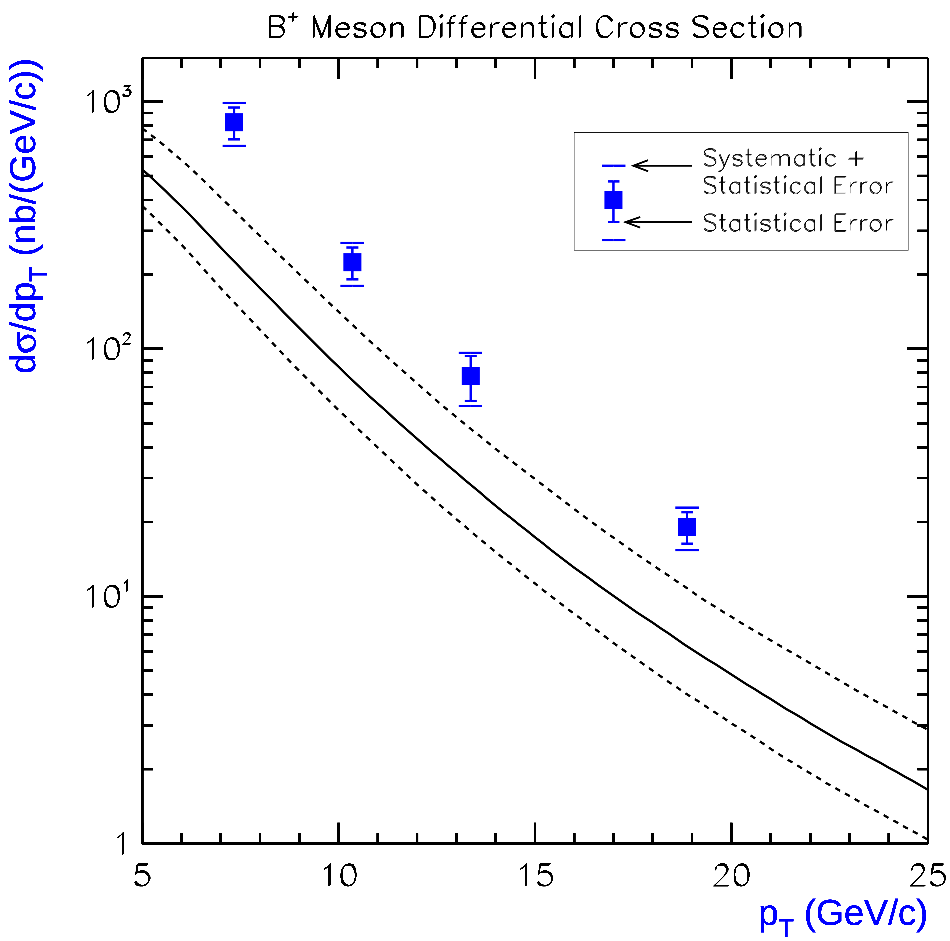
2) The quarks, although heavy, cannot be observed. Need to describe the quark-to-hadron transition (fragmentation), which always involves a quantity not computable in perturbation theory. Example (single-inclusive spectrum)

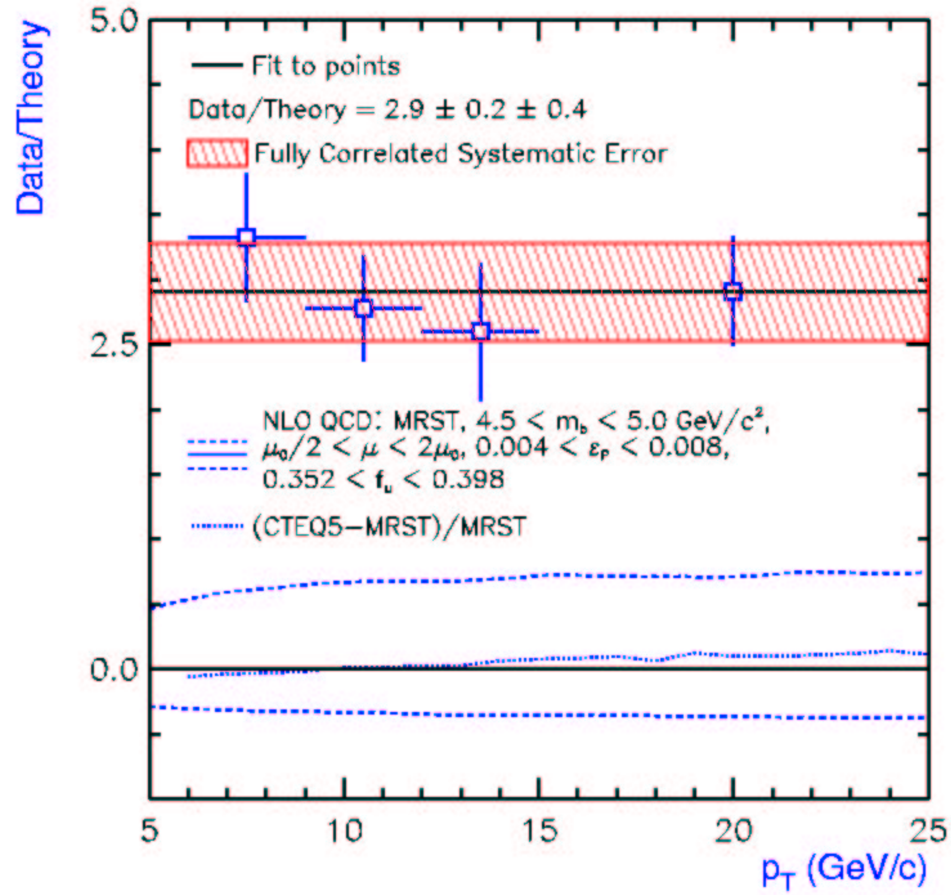
$$\frac{d\hat{\sigma}(H_Q)}{dp_T} = \int \frac{dz}{z} D^{Q \to H_Q}(z, \epsilon) \frac{d\hat{\sigma}(Q)}{d\hat{p}_T}, \qquad p_T = z\hat{p}_T$$

- $D^{Q \to H_Q}$ is a long-distance physics effect

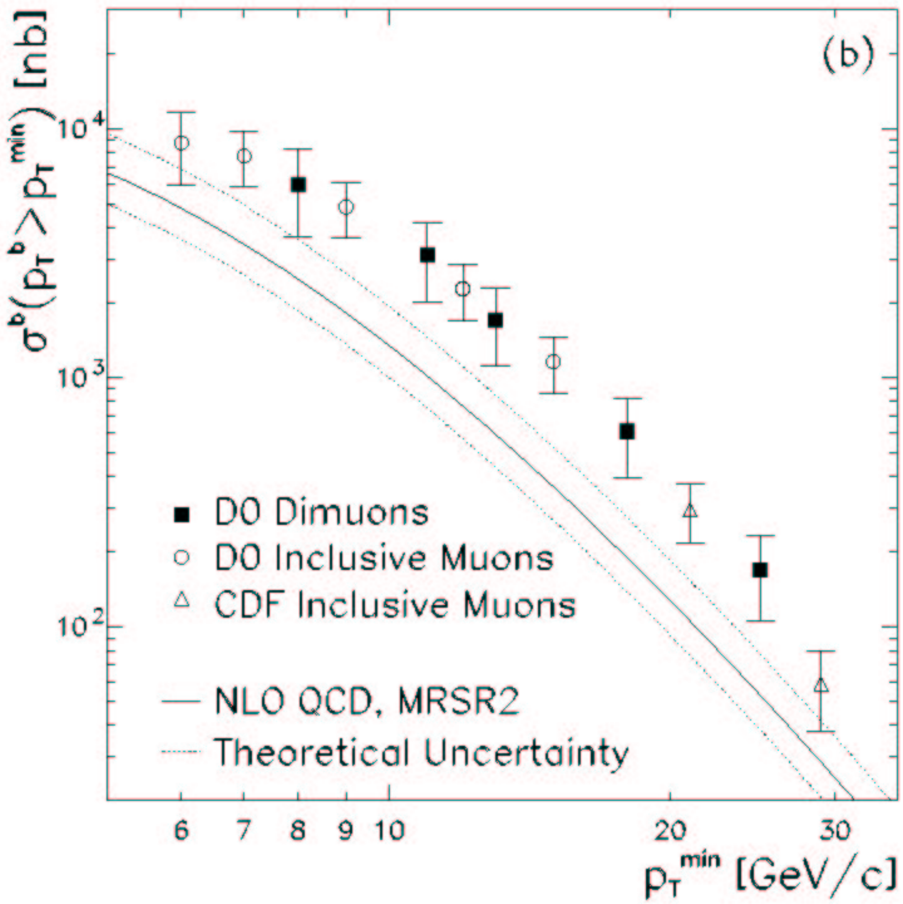
However, let's pretend there are no large logs, and compare predictions with (a fairly random selection of) data $\longrightarrow$

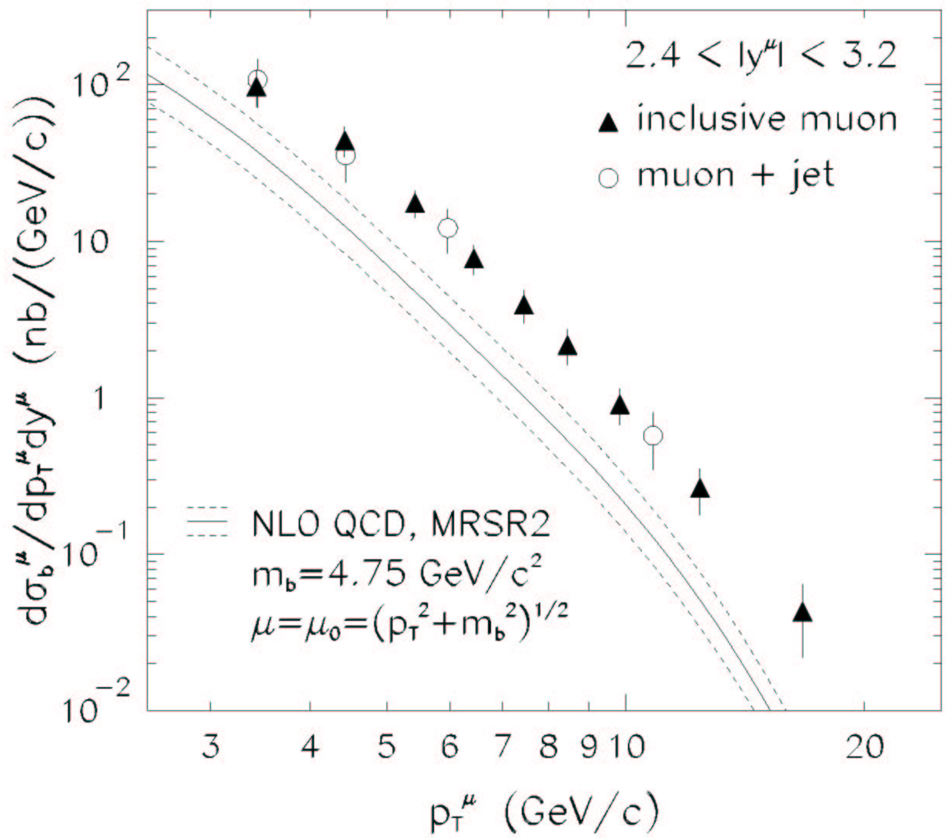
B^+ data, CDF 2001



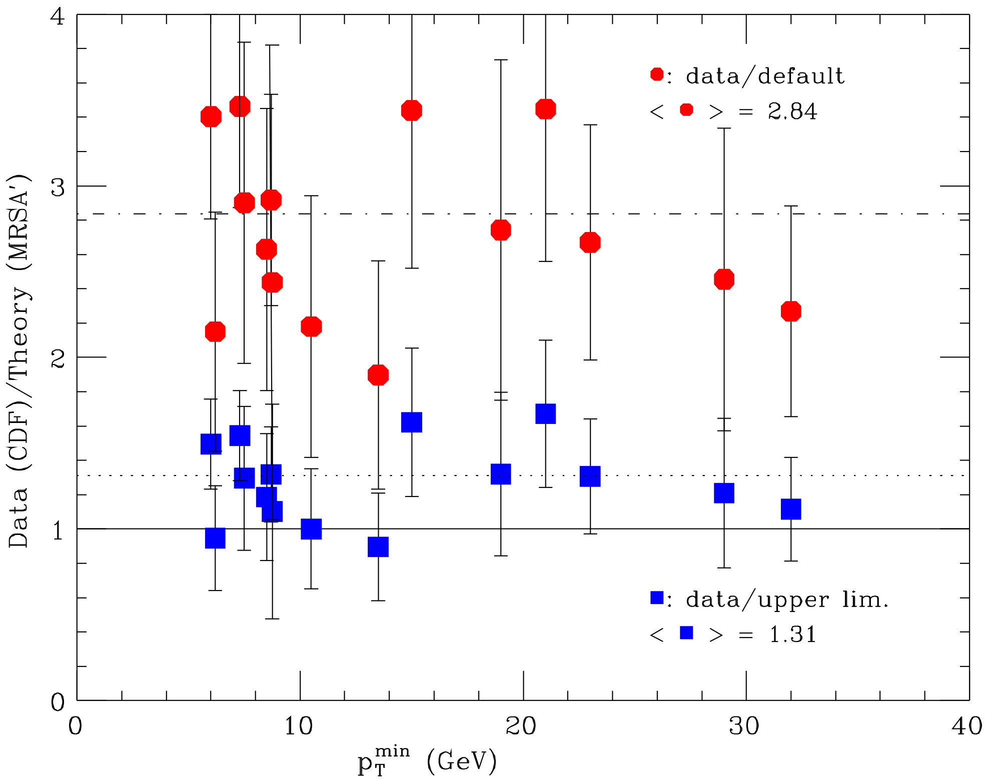


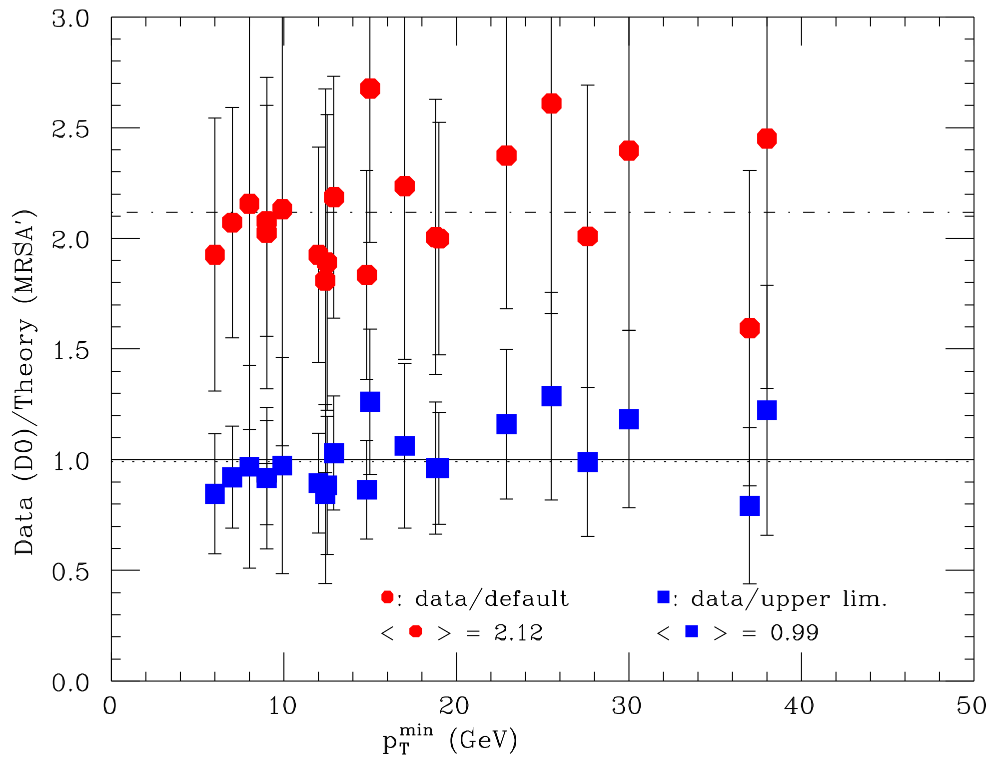
b-quark data, D0 2000





Tevatron data before 2000





- Shapes generally OK, normalization way off, with CDF worse than D0
- Theory predictions can be stretched to get agreement (very extreme parameter choices, involving m_b, μ, Λ_{QCD})
- The vast majority of these data are relevant to b-quarks (deconvolution performed by experiments)

Is there a serious problem?

Since the mass sets the scale of the perturbative expansion $(\alpha_S = \alpha_S(m_Q))$, we expect the situation for charm to be even worse

Apparently, this is a naive expectation $\longrightarrow$

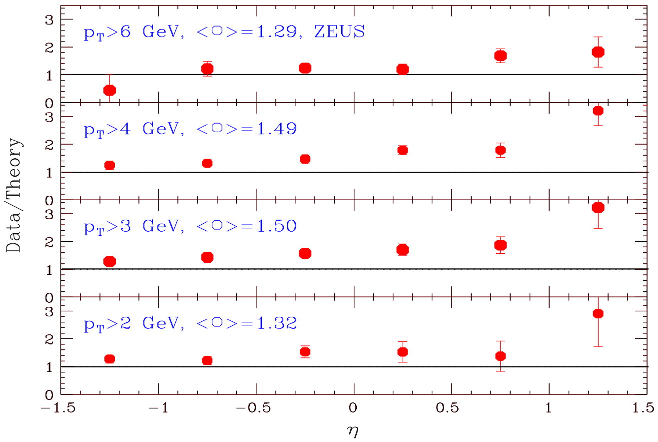
So, we have to look for an explanation for the b production excess

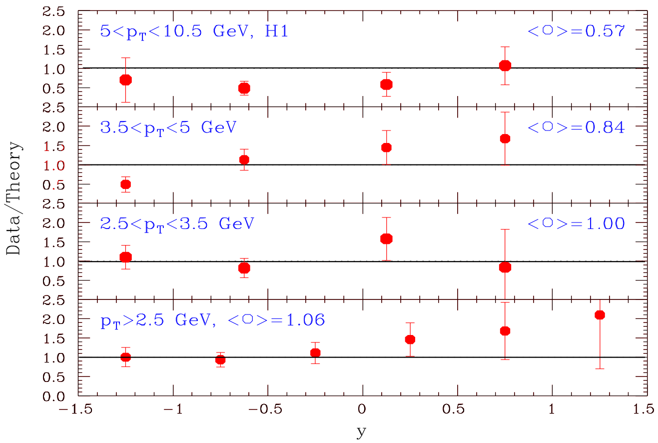
1) New physics
   The HEP community would warmly welcome such a solution
   Most recent proposal ($\tilde{g} \to \tilde{b}b$, Berger *et al*, hep-ph/0012001) appears ruled out by LEP data (Janot, hep-ph/0403157)

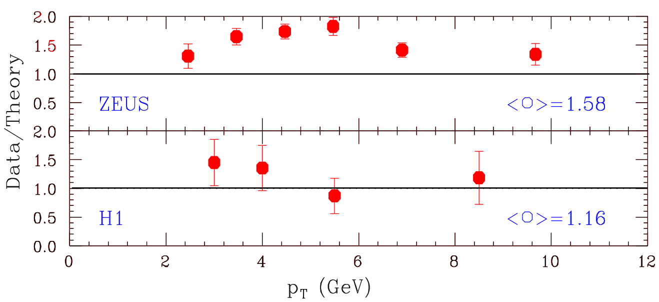
2) NLO QCD is not sufficient to describe the data
   - Do large logs spoil the convergence of the series?
   - Is the fragmentation description not appropriate?
   - Need yet higher orders?

3) To which extent do the data depend on theoretical assumptions?

A compilation of charm data







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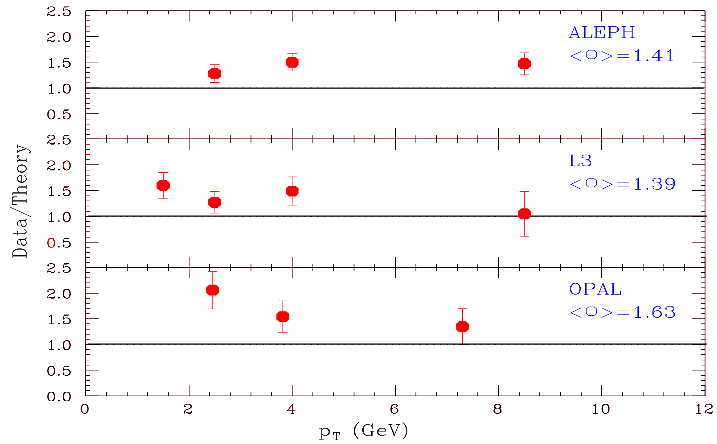
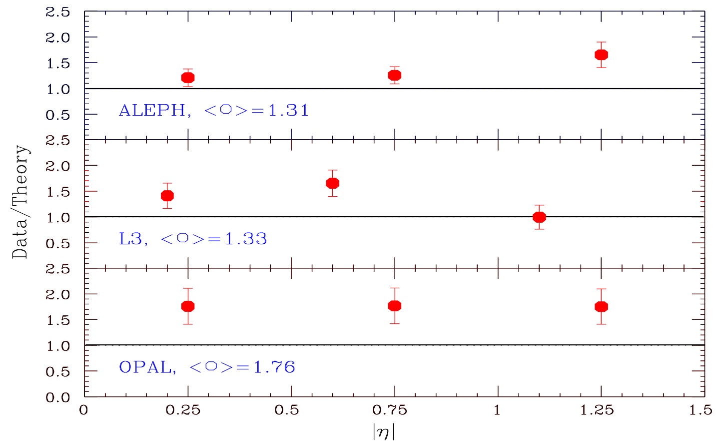


LEP: shapes OK, norm on the upper side of QCD



HERA: H1 OK, ZEUS so-and-so (harder p_T, excess at $\eta > 0$). DIS OK

Fixed-target data are too numerous to summarize (studies of $c\bar{c}$ correlations by E791 and E831). Agreement can be obtained by supplementing NLO with k_T-kick effects

There are glitches, but QCD does generally well

Observable-dependent logarithms

These logs depend strictly on the kinematics of the final state (including cuts)

$$\mathcal{Q} = \frac{p_T(Q)}{m_Q}, \qquad p_T(Q) \gg m_Q$$

$$\mathcal{Q} = \frac{p_T(Q\overline{Q})}{m_Q}, \qquad p_T(Q\overline{Q}) \simeq 0$$

$$\mathcal{Q} = 1 - \frac{\Delta\phi(Q\overline{Q})}{\pi}, \qquad \Delta\phi(Q\overline{Q}) \simeq \pi$$

- Analytic resummations are observable-dependent and technically fairly involved; unavailable except for a few simple cases
- Must be matched to fixed-order results to be relevant to phenomenology
- Monte Carlo and numerical approaches will play an important role in the future

For single-inclusive p_T distributions, FONLL (Cacciari, Greco & Nason), an NLL resummation matched to NLO, is available. A matched result for *any observable* in b physics can be obtained with MC@NLO (SF, Nason, Webber), which resums logs through HERWIG showers, and thus is not restricted to single-inclusive spectra

Observable-independent logs

- Threshold logs: $\mathcal{Q} = 1 - 4m_Q^2/\hat{s}$ $\quad (\longrightarrow \ \hat{s} \simeq 4m_Q^2)$

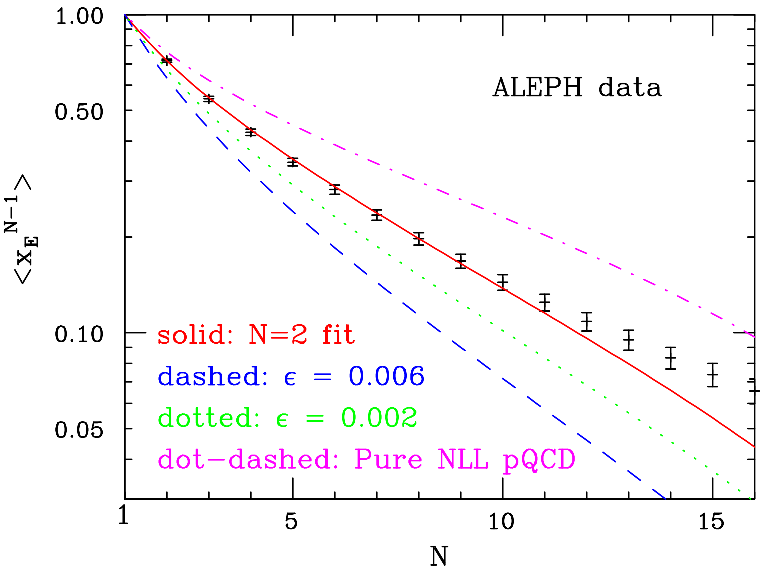
  Techniques to resum these logs are rather well established; they are rather marginal in c and b physics, except for b production at HERA-B

- Small-x logs: $\mathcal{Q} = m_Q^2/\hat{s}$ $\quad (\longrightarrow \ \hat{s} \gg m_Q^2)$

  Theoretically challenging and intriguing, with the necessity of going beyond standard Altarelli-Parisi equations (Collins & Ellis, CCFM), introducing in the process unintegrated (in k_T) PDFs

  - What is NLO and what is pure small-x?
  - Extraction of unintegrated PDFs needs much more work
  - MC implementation (CASCADE) somewhat sensitive to non-small-x contributions

How about the fragmentation function?



- The p_T spectrum is power-like

$$\frac{d\sigma_b}{d\hat{p}_T} \simeq \frac{C}{\hat{p}_T^N} \quad \Longrightarrow \quad \frac{d\sigma_B}{dp_T} = \frac{C}{p_T^N} D_N^{b\to B}$$

$$D_N^{b\to B} = \int dz z^{N-1} D^{b\to B}(z;\epsilon)$$

This approximates $d\sigma_B$ fairly well

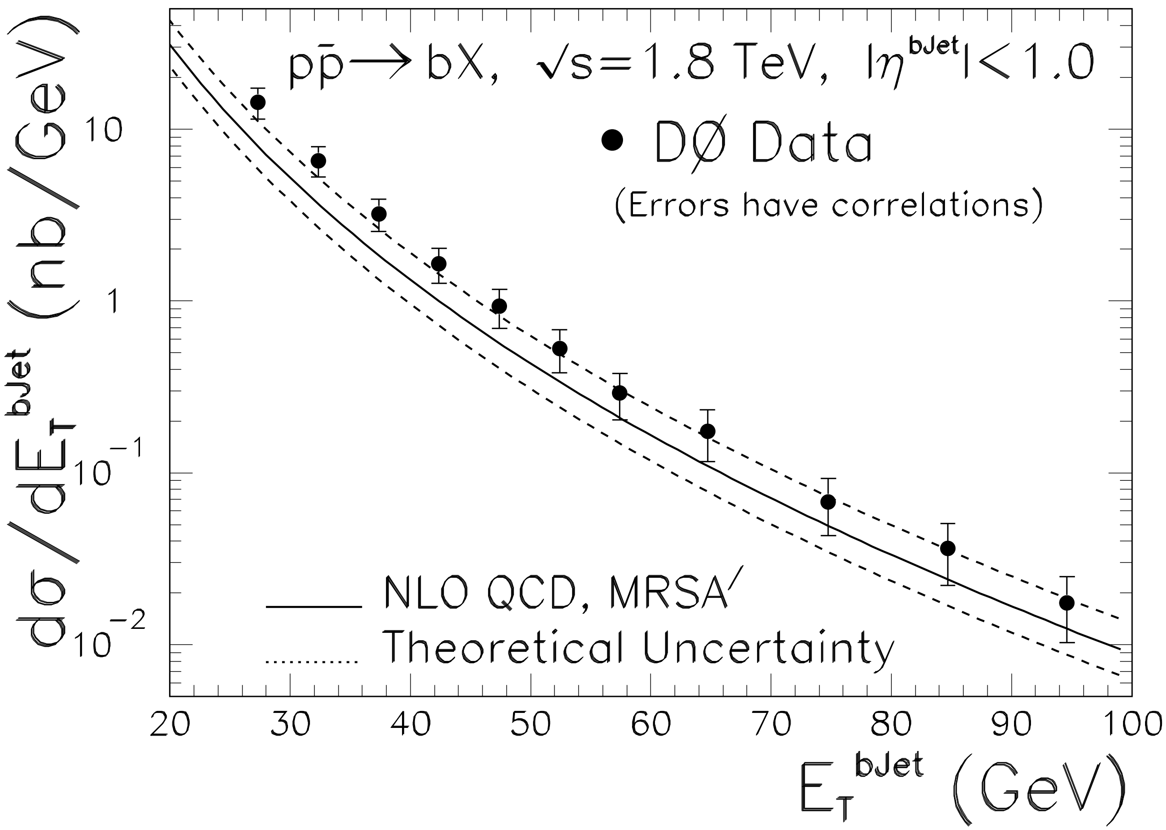
- Fitted $D^{b\to B}(z;\epsilon)$ must agree with data for the relevant Mellin moments

This is not true at present, in spite of the fact that z-space fit at LEP is excellent. One thus fits directly in N space (Cacciari&Nason), getting $\epsilon_{N-space} = 0.0003$ instead of $\epsilon_{z-space} = 0.002$. At the Tevatron, $N \sim 5$

For the purpose of comparing single-inclusive spectra, fit the Mellin moments

b physics without fragmentation

A different approach consists in getting rid of the fragmentation function altogether, by looking at jets containing b quarks (i.e., any b-hadron species) rather than at a specific b-hadron species



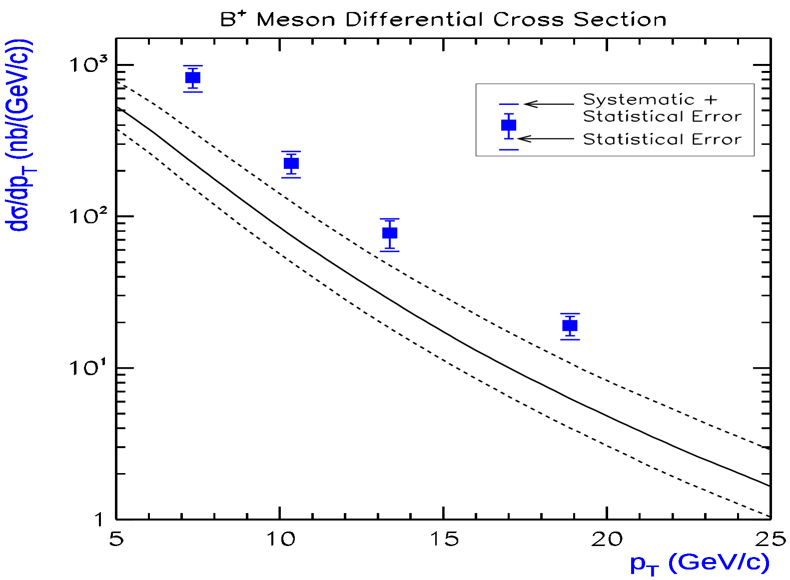
Data: D0 2000

Theory: SF & Mangano

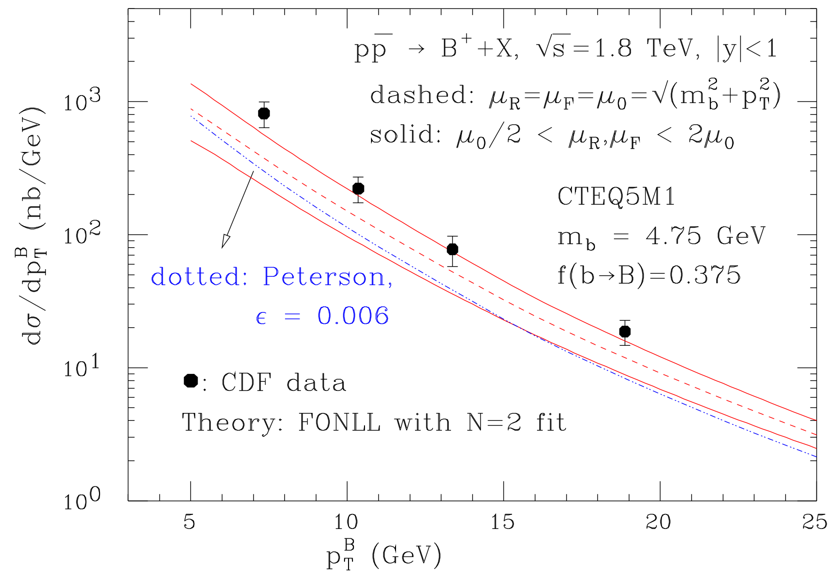
We are on the right track!

NLO theoretical predictions are also less prone to develop large p_T logs, since the p_T of the b doesn't enter the definition of the observable

Let's check CDF B^+ data



FONLL &
N-space fit



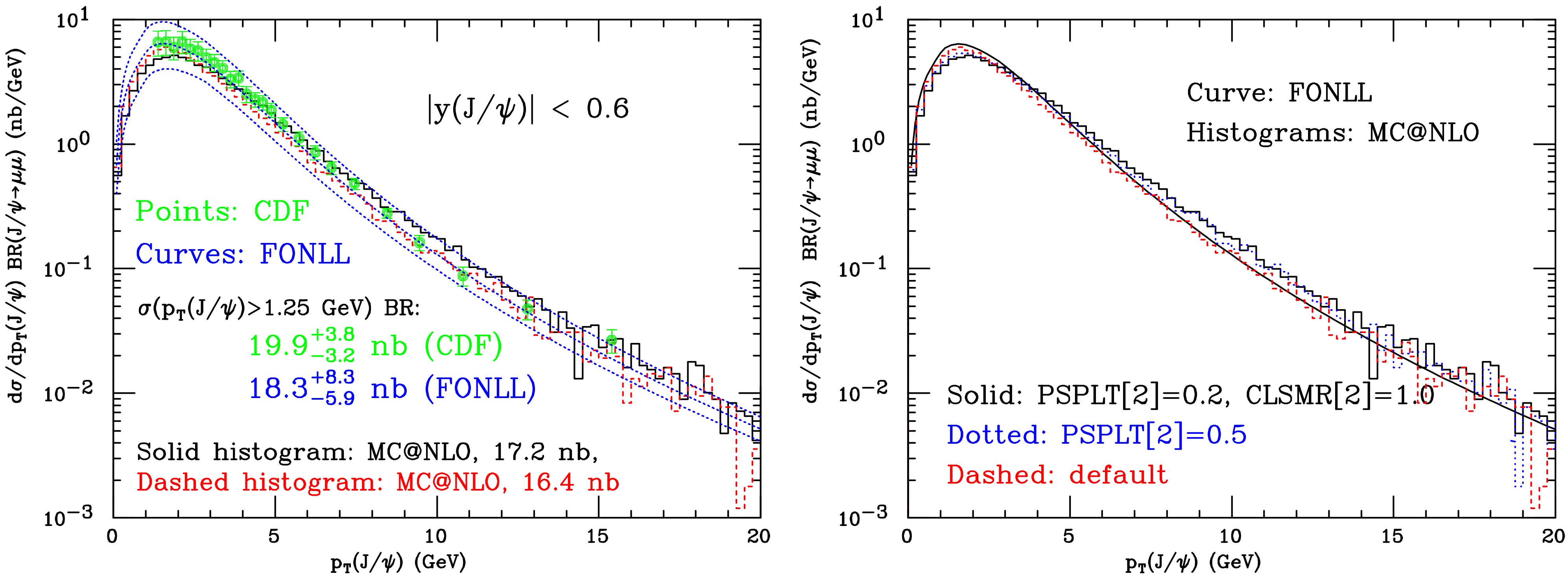
Data/Theory$=2.9 \pm 0.2 \pm 0.4$

Data/Theory$=1.7 \pm 0.5 \pm 0.5$

- Improvement due to NLO $\rightarrow$ FONLL (20%), and to the correct treatment of the fragmentation (45%). Data are consistent with the upper end of the QCD band
- This is the *same* pattern as for b-jets

■ Warning: older b data are typically presented in terms of b quarks $\Longrightarrow$ it is wise to reconsider former $B \rightarrow b$ deconvolutions

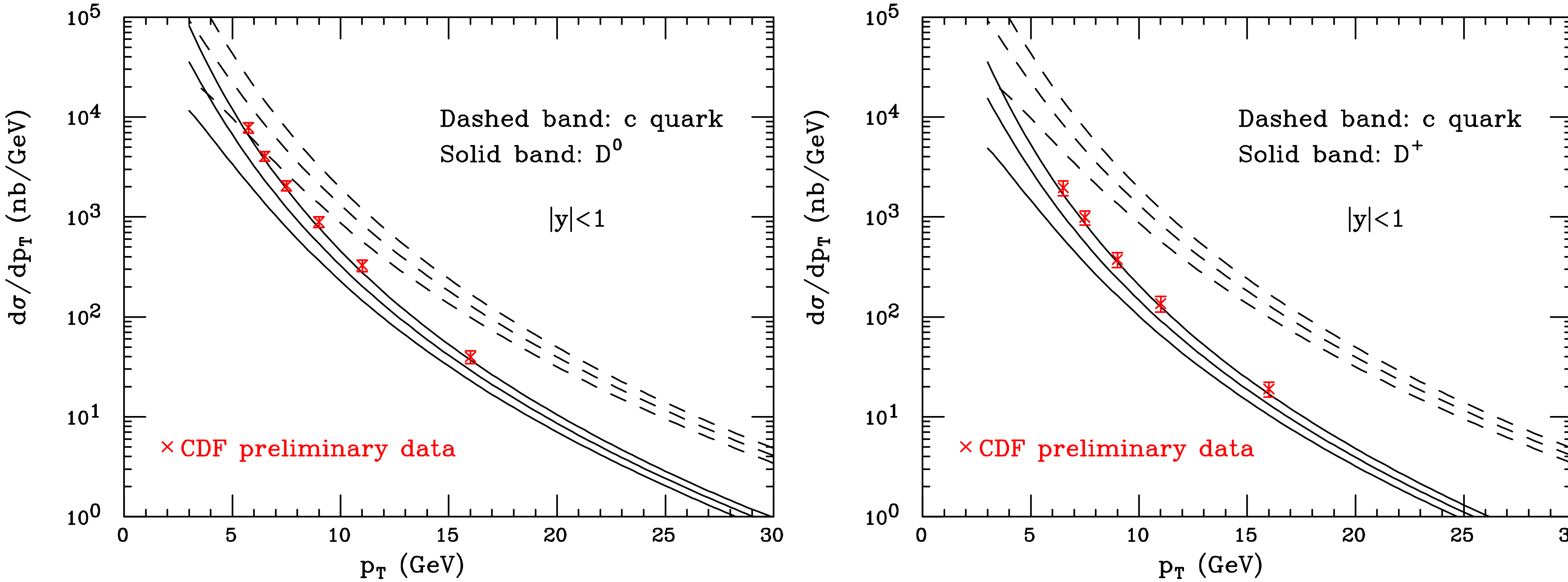
Run II data $(B \to J/\psi \to \mu^+\mu^-)$



Best ever agreement with data

- Very involved theoretical prediction, down to previously unprobed p_T values
- Old approach would have implied quoting b rates by unfolding $b \to B \to J/\psi$
- Excellent agreement between MC@NLO and FONLL, if the large dependence (at small p_T) on the hadronization scheme of the latter is taken into account

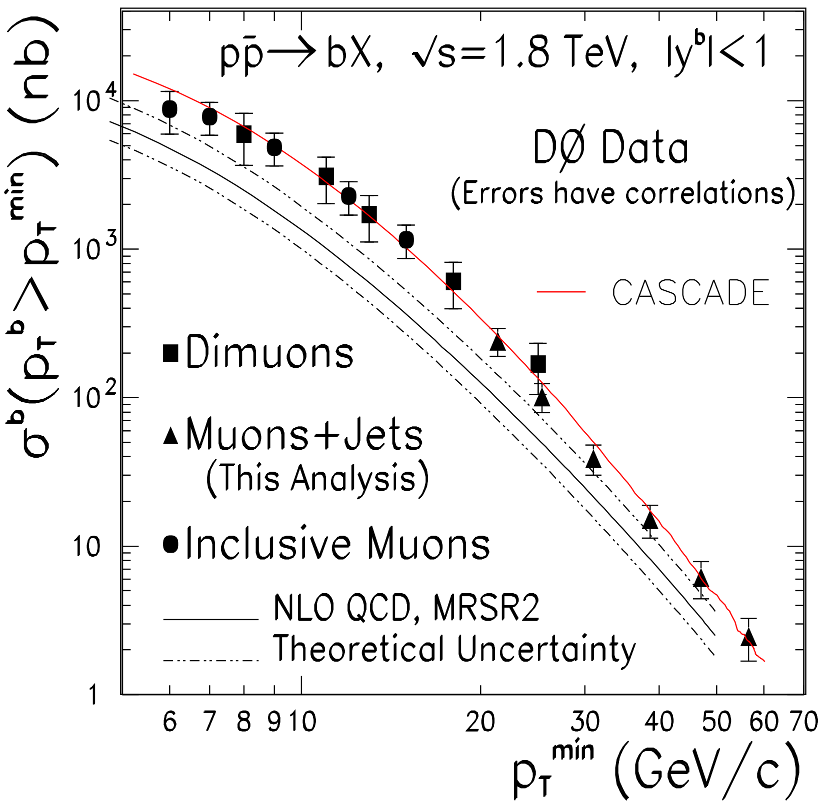
Run II data (D^0 and D^+)



Plots: Cacciari and Nason

- These data are now approved (CDF, hep-ph/0307080)
- This is *very* good news: tests N-space fit to fragmentation function, and resummation in a region equivalent to $p_T^{(b)} \simeq 50$ GeV
- A fully consistent picture is now emerging from c and b measurements

Is b production small-x physics?



According to Collins and Ellis ($\sim$ 30% increase), one would say no. CASCADE (Jung) does well, but leaves a few questions open

- Why is the $B \rightarrow b$ deconvolution not a problem here?
- Is it the small-x evolution that drives the prediction, or the k_T of the incoming partons?
- How precisely are the unintegrated PDFs (especially the gluon) determined from HERA data?
- Why is CASCADE doing slightly worse for c than for b (hep-ph/0311249)?

I don't think Q production at the Tevatron is small-x physics. These results however hint that CASCADE is a viable tool for studying reactions where small x's must be a factor (low-p_T charm at LHC). It would be important to clarify the role of higher-order QCD corrections. Systematic determination of PDFs should also be addressed

Open-b production: what to take home

The backbone of *all* the theoretical computations (in collinear factorization) are the NLO results of Nason, Dawson & Ellis and vNeerven *etal* (1987–1989!)

So, why has the picture changed?

Substantially, *it has not*

- A careful reconsideration of systematics errors leads to the conclusion that most of the (large) discrepancies were at the 2σ level at most (Mangano)
- By far, the most significant changes in the theoretical predictions are due to the non-computable inputs (Λ_{QCD}, PDFs), and to the understanding of their extraction from data (fragmentation)
- NLO corrections are essential. The matching with the resummed results, as done in MC@NLO and FONLL, further improves the agreement with data, and reduces the scale uncertainty
- Experiments started to quote quantities as close as possible to raw data (no $B \to b$ deconvolutions, no extrapolations from visible regions)

Open-Q perspectives for LHC

The theoretical tools which allow a fairly satisfactory description of today data are expected to perform well at LHC too (where uncertainties will however be larger). Differences between c and b production will be more evident there

- Small-p_T c production is promising for small-x studies. Probing a large p_T range (say, 0–40 GeV?) may allow to *see* the transition to the small-x regime in a largely model-independent way
- Extrapolations $\sqrt{S} = 14 \longrightarrow 5.5$ TeV are accurate to some %, and give reliable benchmarks. However, control pp and pA runs would allow one to check universality and cleanly disentagle new long-distance effects
- The study of Q-$\overline{Q}$ correlations should be performed systematically

On the theoretical side, it is reasonable to expect that MC@NLO will be made available for charm too (the code is ready; it's the smallness of the charm mass that causes problems, such as numerical instabilities, which need be addressed). Progress on numerical resummations possible. It's unlikely that NNLO results will appear soon

Quarkonium production

A factorization formula (Bodwin, Braaten & Lepage) holds again (NRQCD)

$$d\sigma_{H_1 H_2 \to H}(S) = \sum_{ij} \int dx_1 dx_2 f_i^{(H_1)}(x_1) f_j^{(H_2)}(x_2) d\hat{\sigma}_{ij\to H}(\hat{s} = x_1 x_2 S)$$

$$d\hat{\sigma}_{ij\to H} = \sum_n d\hat{\sigma}(ij \to Q\overline{Q}[n]) \langle \mathcal{O}^H[n] \rangle \qquad n = \{c = (1,8); {}^{2S+1}L_J\}$$

NRQCD (Caswell & Lepage), a rigorous consequence of QCD ($\Lambda_{QCD}/m_Q \to 0$), is an effective field theory in which Q and $\overline{Q}$ are treated as non-relativistic

- NRQCD matrix elements $\langle \mathcal{O}^H[n] \rangle$ are analogous to PDFs and FFs: they cannot be computed in perturbation theory, and are universal

$$\langle \mathcal{O}^H[n] \rangle \sim \mathrm{Prob}(Q\overline{Q}[n] \longrightarrow H)$$

- Short distance cross sections $d\hat{\sigma}(ij \to Q\overline{Q}[n])$ can be computed in pQCD

■ If pQCD can describe open-Q data, we expect that NRQCD does a good job too

Computations in NRQCD

Armed with faith, we thus proceed to computing cross sections....

$$d\hat{\sigma}_{ij\to H} = \sum_n d\hat{\sigma}(ij \to Q\overline{Q}[n])\langle \mathcal{O}^H[n]\rangle$$

This in an infinite sum, which contains an infinite numbers of long-distance parameters which must be measured $\longrightarrow$ lack of predictivity. However:

$$\langle \mathcal{O}^H[n]\rangle \propto v^{f(n,H)} \qquad v^2 \simeq 0.3, 0.1 \quad \text{for} \quad c\bar{c}, b\bar{b}$$

$$\Longrightarrow \qquad d\hat{\sigma}_{ij\to H} = \sum_{m,k} s_{m,k}\alpha_S^m v^k$$

+ The systematic expansion in α_S and v provides a computational framework similar to that for open-Q

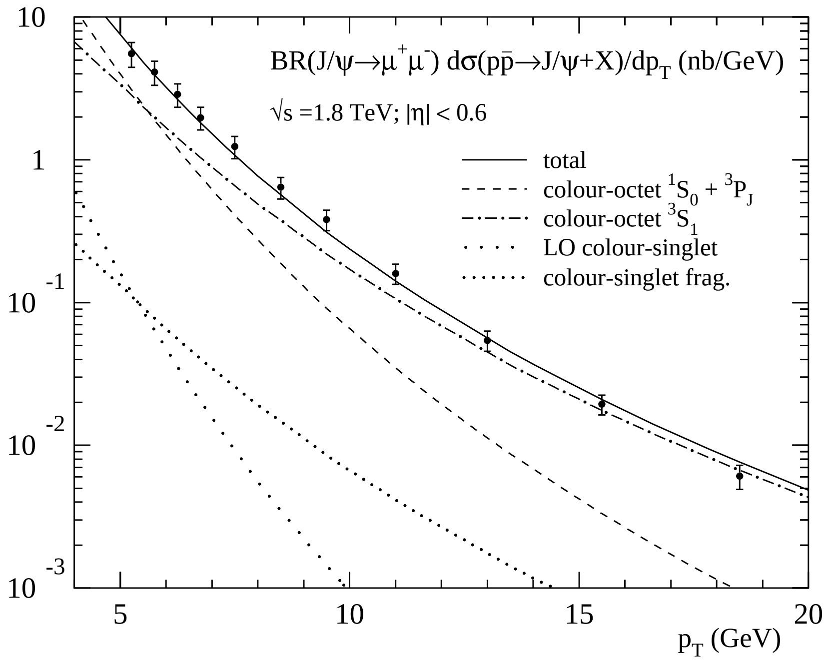
+ Heavy quark spin symmetry and vacuum saturation approximation reduce the number of independent $\langle \mathcal{O}^H[n]\rangle$'s

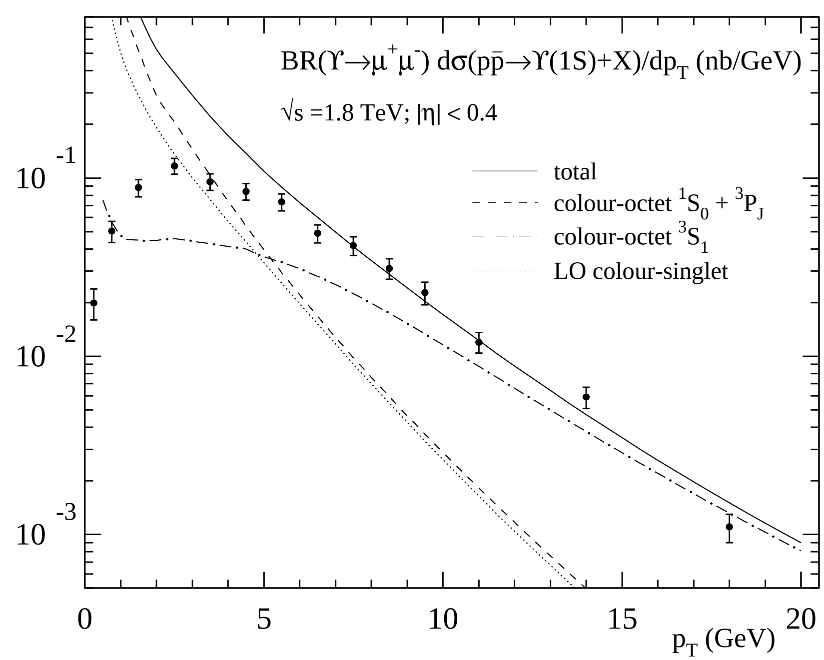
− Factorization is so far unproven (as in many other cases)

− The double series is slowly "convergent", particularly so for charm

− As for open Q's, short distance cross sections can be plagued by large logs

J/ψ and Υ at run I



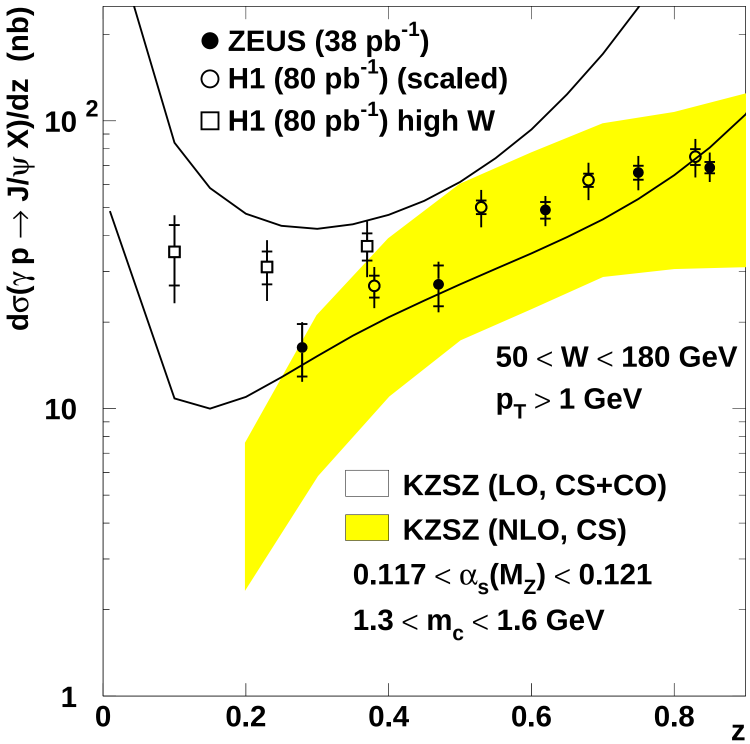


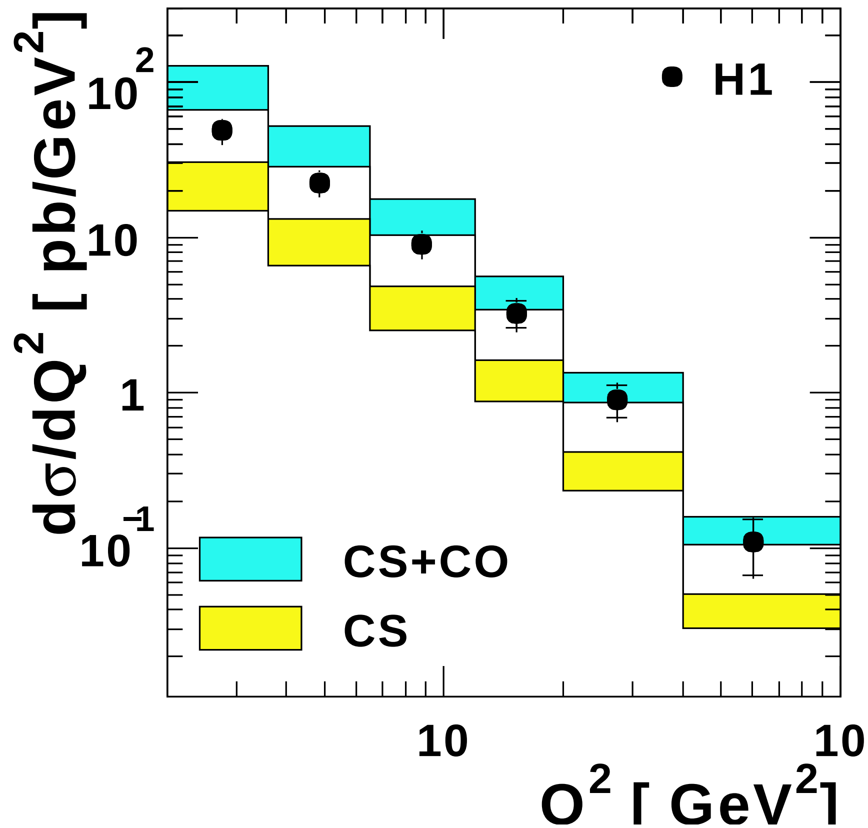
- Matrix elements respect scaling rules within the (*very* large) uncertainties. Fit to data at colliders introduce a dependence on PDFs in $\langle \mathcal{O}^H[n] \rangle$. CS matrix elements obtained from potential-model computations

- Measurements down to $p_T = 0$ expose the problem of higher orders; the shape can be reproduced by b-space resummation (hep-ph/0404158). New run II data also for $p_T(J/\psi) \to 0$

Most important check on matrix elements: universality $\longrightarrow$ see HERA data

J/ψ at HERA





- γp data consistent with NLO CS (see also p_T – low z dominated by resolved γ)
- At $z \to 1$ logs appear, and v expansion breaks down; resummation in v appears to improve the agreement in shape for large z. Very low p_T's dominate
- DIS generally OK, except for z (z has a non-trivial experimental definition)

Ambiguous results. CSM ruled out 10 years ago at Tevatron. The "convergence" of the α_S and v series is problematic

Colour Evaporation Model

Uses the results for open-Q production to get quarkonium

$$d\hat{\sigma}^{(\mathrm{CEM})}_{ij\to H} = F_H \int_{4m_Q^2}^{4m_M^2} dm^2_{Q\overline{Q}} \frac{d\hat{\sigma}(ij \to Q\overline{Q})}{dm^2_{Q\overline{Q}}}$$

CEM can also be formally written in the same form as NRQCD, with

$$\mathcal{O}^H[n] = \chi^* \kappa_n \psi \left(\sum_X |H + X\rangle\langle H + X| \right) \psi^* \kappa'_n \chi \qquad \longrightarrow$$

$$F_H \sum_n \chi^* \kappa_n \psi \left(\sum_X |Q\overline{Q}(m^2_{Q\overline{Q}} < 4m_M^2) + X\rangle\langle Q\overline{Q}(m^2_{Q\overline{Q}} < 4m_M^2) + X| \right) \psi^* \kappa'_n \chi$$

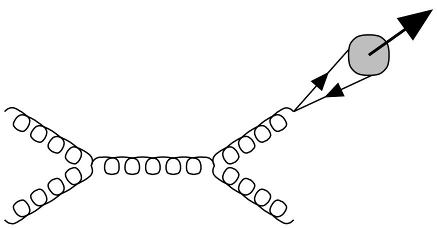
- Changes scaling rules: $v^{f(n,H)} \to v^{2L}$
- Reproduces J/ψ and Υ data at the Tevatron (with a k_T-kick – non universal?)
- A problem: $(\sigma(\chi_c)/\sigma(J/\psi))_{HH} \neq (\sigma(\chi_c)/\sigma(J/\psi))_{\gamma p}$ at fixed target. Evidence of a weak dependence on p_T of the J/ψ decay fractions (especially $\psi(2S)$)
- Ruled out by polarization in prompt production and B decays $\Longrightarrow$ just apply it to spin-averaged cases

Speaking of polarization...

J/ψ and Υ polarizations are one of the most solid NRQCD predictions

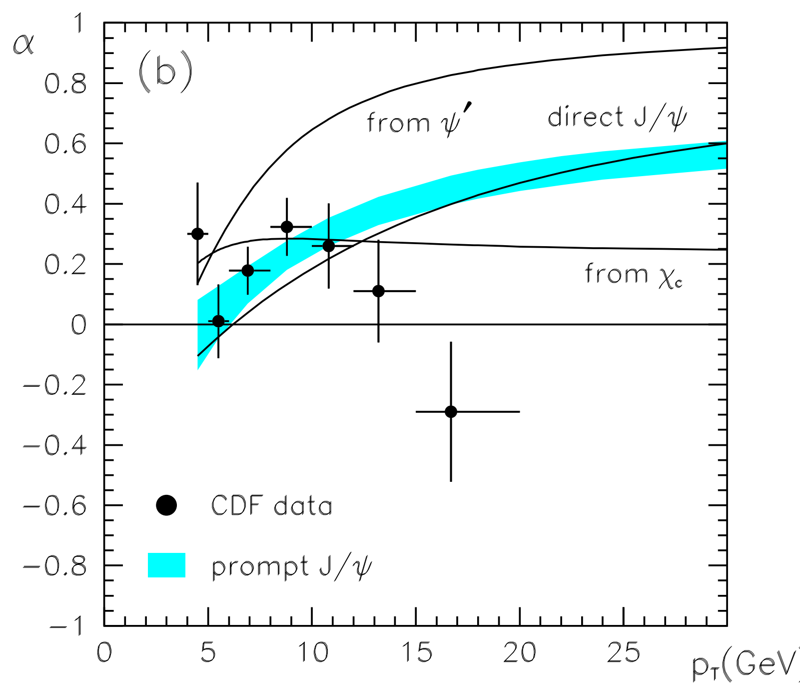
$$\frac{d\sigma_{H\to\mu^+\mu^-}}{d\cos\theta} \propto 1 + \alpha\cos^2\theta, \qquad \alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}, \qquad \theta = \angle(p_{\mu^+}, p_H^{(boost)})$$

At large p_T the colour-octet ${}^3S_1$ fragmentation contribution is expected to be dominant



which is confirmed by prompt-J/ψ and -Υ production data. Large p_T $\Rightarrow$ gluon on-shell $\Rightarrow$ transversely polarized $\Rightarrow$ polarization transferred to H $\Rightarrow$ $\alpha = 1$

- Higher-orders in α_S and v, feeddown, spin-flip corrections ($\mathcal{O}(v^2)$) dilute the polarization
- Very large spin-flip corrections may be the solution (not supported by lattice so far (Bodwin))
- Large $\mathcal{O}(v^2)$ corrections to $g \to H$ absorbed into matrix elements: but is convergence spoiled?
- Are scaling rules appropriate for charmonium?
- Study hadronic activity around H?



Summary on quarkonium

NRQCD appears to be a solid theory derived from QCD, with a well defined computational framework. There are however a couple of serious problems

1) Polarization predictions (dominated by CO) don't reproduce data

2) NLO CS (i.e., without CO) does reproduce photoproduction data

Both issues question the role of CO, which is however essential for theoretical consistency (NLO corrections to non-S waves). The picture of 2) is blurred by the many sources of higher-order corrections not yet considered. We should also remind the

3) Anomalous double-$c\bar{c}$ production at Belle ($J/\psi\,\eta_c$ and $J/\psi\,c\bar{c}$)

This is so large that it seems hard to get it by whatever means in pQCD, let alone NRQCD. Needs further experimental studies

- Polarization measurements at run II a priority: $\psi(2S)$?
- Photoproduction measurements at larger p_T's less prone to factorization-breaking corrections. Is statistics sufficient?
- Can lattice computations help to understand scaling rules? Resummations and higher-order corrections to be pursued systematically (fundamental in open-Q)

Conclusions

Perturbative QCD and NRQCD are two well established computing frameworks for obtaining predictions for open-Q and quarkonium observables

- Open-Q data are fairly well reproduced by pQCD. Higher orders, resummations, and their matchings are essential to get the picture right
- We'd like very much NRQCD to be right; but a few problems remain, the most significant being the failure to reproduce J/ψ polarization data. Theoretical computations are *not* at the same level of accuracy as in pQCD

The LHC may or may not discover BSM physics (mind the desert); but it will surely shed further light on heavy quark physics, which will be of invaluable help in the AA program

- ♦ Open-Q data *should* be in agreement with what pQCD predicts. Measurements will tell a lot on PDFs, FFs, and possibly the first evidence of small-x behaviour will emerge
- ♦ LHC is the machine that will confront NRQCD with its responsibilities: Υ polarization *must* come out right. The most interesting scenario: J/ψ still wrong: $\Longrightarrow$ different scaling rules? Theory needs to improve

Backup slides

Logs in single-inclusive spectra

The fixed-order prediction is

$$\frac{d\sigma}{dp_T^2} = \sum_{i=2}^{\infty} a_i \alpha_S^i \;=\; a_2\alpha_S^2 + a_3\alpha_S^3 + a_4\alpha_S^4 + \quad \ldots\ldots$$

LO NLO NNLO N^{k}LO

If either the b or the $\bar{b}$ is tagged, and its p_T is used to fill a histogram, then:

$$a_i = \sum_{k=0}^{i-2} a_i^{(i-2-k)} \log^{i-2-k} \frac{p_T^2}{m^2} \quad \Longrightarrow \quad a_3 = a_3^{(0)} + a_3^{(1)} \log \frac{p_T^2}{m^2}$$

The coefficients a_i^{i-2-k} have a non-trivial p_T dependence, such that:

- When $p_T \to 0$, the coefficients a_i tend to a constant $\longrightarrow a_k\alpha_S^k \gg a_{k+1}\alpha_S^{k+1}$
- When $p_T \gg m$, the logs dominate in $a_i \longrightarrow a_k\alpha_S^k \simeq a_{k+1}\alpha_S^{k+1}$

When $p_T \gg m$, N^{k}LO computations are useless

The large-p_T regime

Just keep the log terms: they are easy to compute to any order! (*resummation*)

$$\frac{d\sigma}{dp_T^2} = \alpha_S^2 \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} r_i^{(j)} \alpha_S^j \left(\alpha_S \log \frac{p_T^2}{m^2}\right)^i = \alpha_S^2 \sum_{i=0}^{\infty} r_i^{(0)} \left(\alpha_S \log \frac{p_T^2}{m^2}\right)^i \qquad \text{LL}$$

$$+ \ \alpha_S^3 \sum_{i=0}^{\infty} r_i^{(1)} \left(\alpha_S \log \frac{p_T^2}{m^2}\right)^i \qquad \text{NLL}$$

$$+ \ \ldots\ldots\ldots\ldots\ldots\ldots \qquad \text{N}^k\text{LL} + \text{PST}$$

The difficulties of the N^{k}LO computations are hidden in the PST $\equiv (m/p_T)^a$ terms, which are irrelevant for $p_T \gg m$, but crucial for $p_T \lesssim m$. So the key question is:

What does $p_T \gg m$ mean? (i.e., which are the p_T values involved?)

Roughly speaking, the neglected terms are of $\mathcal{O}(m/p_T)$

- In my opinion, resummed computations are needed only for $p_T^{(B)} \gtrsim 50$ GeV at the Tevatron (for charm at HERA, $p_T^{(D)} \gtrsim 10$ GeV)

My opinion is as good as anyone else's, since a quantitative statement is *impossible*

The way out

Match the resummed computation with the fixed-order one, in such a way that either of them dominates in the relevant p_T region

♦ Example: FONLL (Cacciari, Greco & Nason)

$$\frac{d\sigma}{dp_T^2} = a_2\alpha_S^2 + a_3\alpha_S^3 + \alpha_S^2 \sum_{i=2}^{\infty} r_i^{(0)} \left(\alpha_S \log \frac{p_T^2}{m^2}\right)^i + \alpha_S^3 \sum_{i=1}^{\infty} r_i^{(1)} \left(\alpha_S \log \frac{p_T^2}{m^2}\right)^i$$

Features:

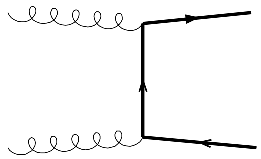
- Better than NLO computations
- Better than resummed computations
- Introduces a matching uncertainty

Similar work (at LL) in VFNS *à la* ACOT

Agreement between resummed computations and data up to intermediate p_T values is typically accidental. Always use matched computations when in doubt about what "intermediate" means

Why standard MC's fail at small p_T's

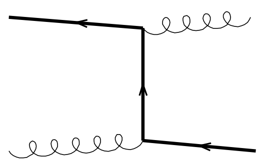
MC rule: if we aim to study any physical system, we start by producing it in the hard process $\Longrightarrow$



Flavour CReation

This is going to underestimate the rate by a factor of 4 (which is not so important), and to miss key kinematic features (which is crucial – see R. Field)

So break the rule and add other hard processes



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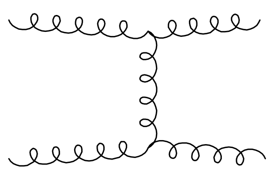


Gluon SPlitting

- In FEX, the missing Q or $\overline{Q}$ results from initial-state radiation. A cutoff PTMIN avoids divergences in the matrix element
- In GSP, the Q and $\overline{Q}$ result from final-state gluon splitting. PTMIN is again necessary to obtain finite results

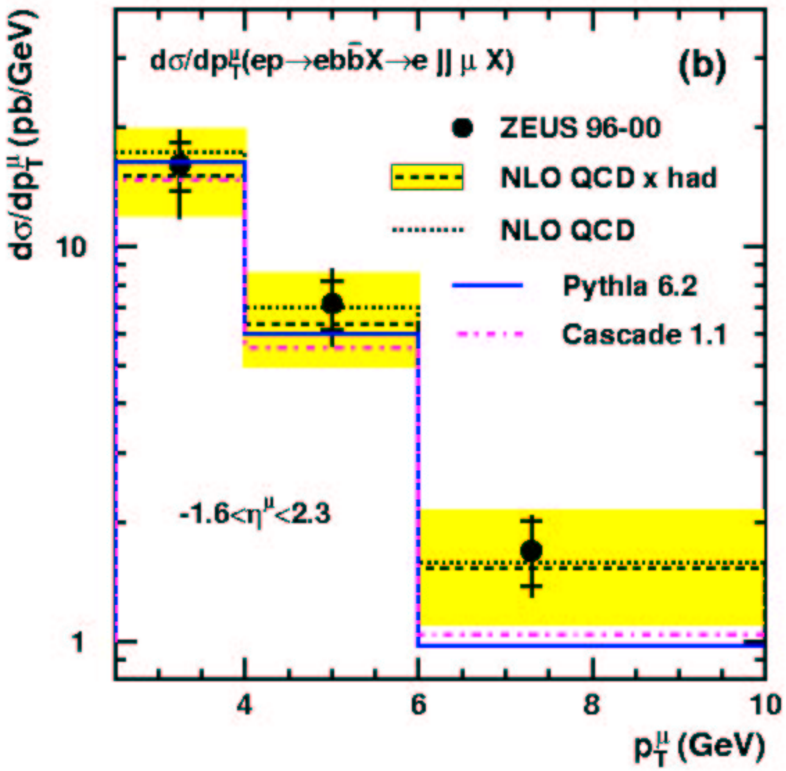
The solution *is* available

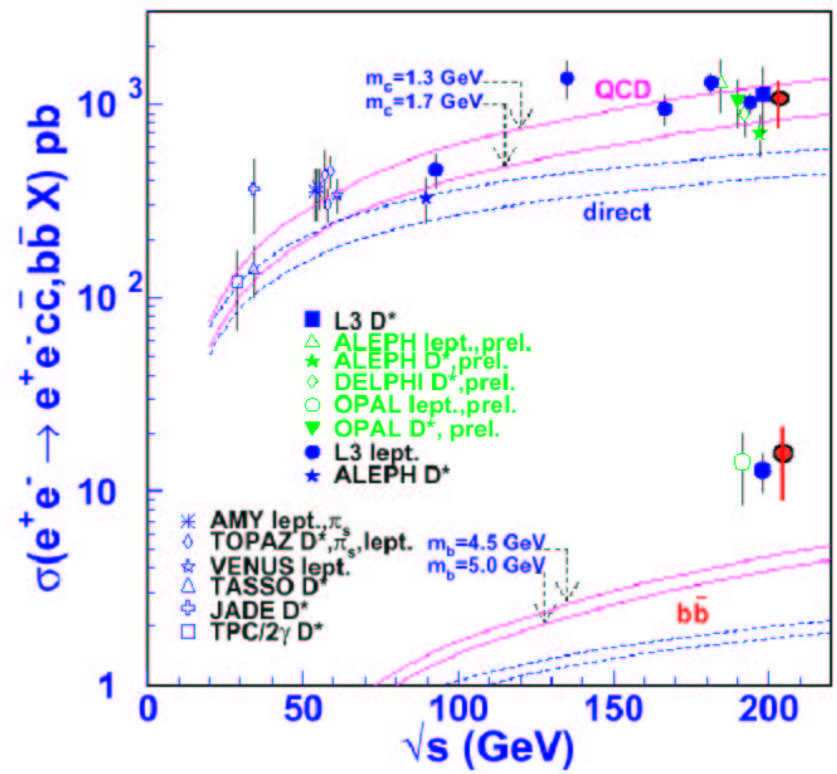
By adding NLO corrections to the MC as done in MC@NLO (SF, Nason & Webber) there are no matrix element divergences left

- MC@NLO vs standard MC's
  - + No PTMIN dependence, no separate generation of FCR, FEX, and GSP
  - + Reliable prediction of hard emission, and for $p_T \to 0$
  - − Misses some of the higher logs in GSP
- MC@NLO vs FONLL
  - + Fully realistic final state, hadronization, and decay
  - + Works for any observable
  - − *Formally* less accurate in terms of logs

MC@NLO can be used to obtain state-of-the-art theoretical predictions, and/or to treat raw data

On theoretical prejudices





The agreement between pQCD and HERA results is constantly improving: data are now presented in the visible cross section. At LEP:

- Experiments use the same technique ($p_T^{(rel)}$)
- Experiments use the same Monte Carlo for extrapolating a very narrow visible region (at low p_T) to the full phase space

I don't think LEP data, presented in this form, are currently a problem for QCD