La Thuile
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Open Problems in Heavy Quark Production

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"Simple" talk: no fancy stuff about resummations or hard higher order calculations!! Rather, a lot of phenomenology and brick-and-mortar comparisons between theory and experiments:

- a few details about the state-of-the-art of theoretical calculations
- recent (and less recent) experimental results: $p\bar{p}$ (Tevatron), ep (HERA), e^+e^-, $\gamma\gamma$ (LEP)

“Open Problems”

means

“Is There a Significant Excess in Heavy Quark Production?”

Actually, “excess” could be

a problem, a nuisance, or an opportunity

according to your own taste or hope.

Key feature of heavy quarks: $m \gg \Lambda_{QCD}$. Hence, fixed order perturbation theory is finite, since collinear singularities are cut off $\rightarrow$ no need for factorization $\rightarrow$ total heavy quark production rates are calculable. NLO results are presently available.

However, this is not the and of the story: both higher order resummations and non-perturbative physics play an important role:

- Large coefficients in the perturbative expansion can appear: "collinear" $\log(p_T/m)$ or "Sudakov" $\log(1-x)/(1-x)$ terms need to be resummed to all orders.
- charm and bottom (not top!) hadronize before decaying $\rightarrow$ some form of parametrization for momentum degradation needs to be included when studying differential cross sections

General framework for heavy quark calculations

You will usually have:

- a fixed order perturbative calculation = FO
- a resummed calculation to logarithmic accuracy = RES

FO is best where the logs are small. RES is best where the logs are large.....

....does this suggest you anything....?

YES, of course: MERGE them!

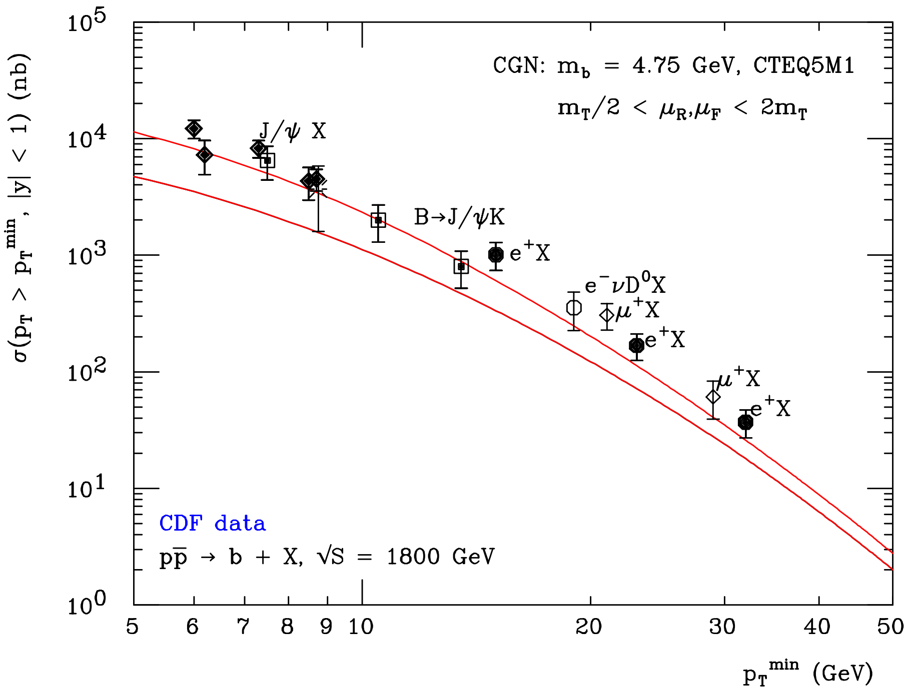
Matched results = exact finite order terms (up to some order in α_s) + logarithmic resummation:

$$\text{FORES} = \text{FO} + \text{RES} - \text{overlapping terms}$$

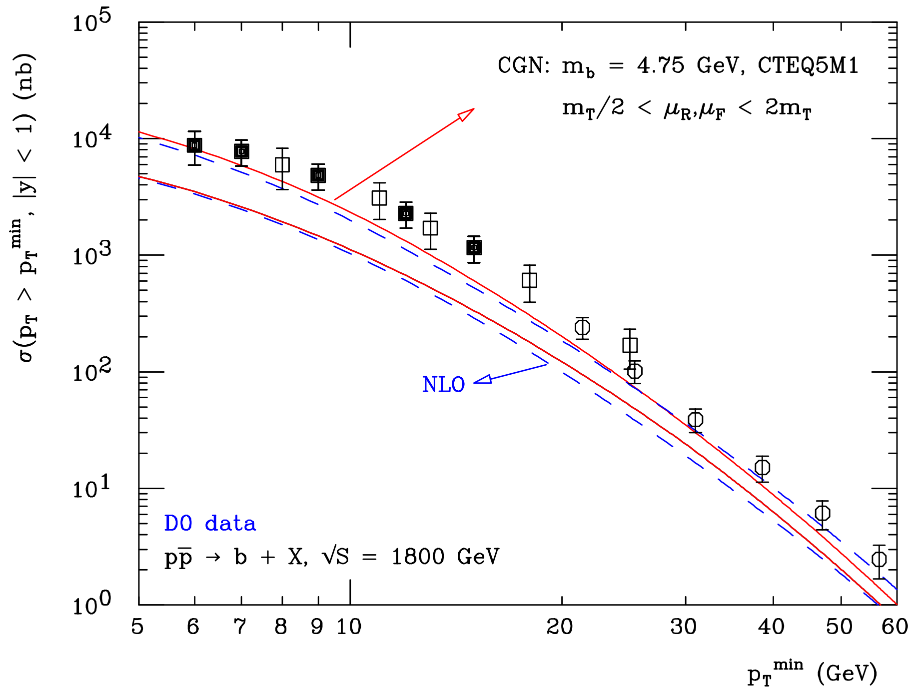
Eventually, if needed, you might convolute the final result FORES with some non-perturbative fragmentation function (e.g. to describe quark $\rightarrow$ hadron transitions).

b quarks @ Tevatron

CDF



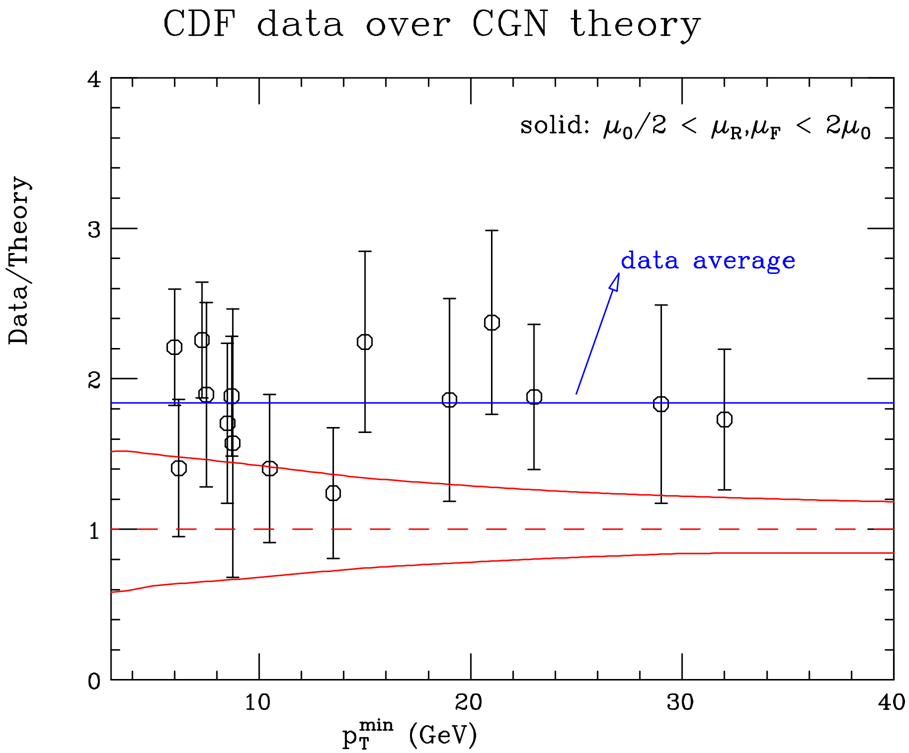
DO

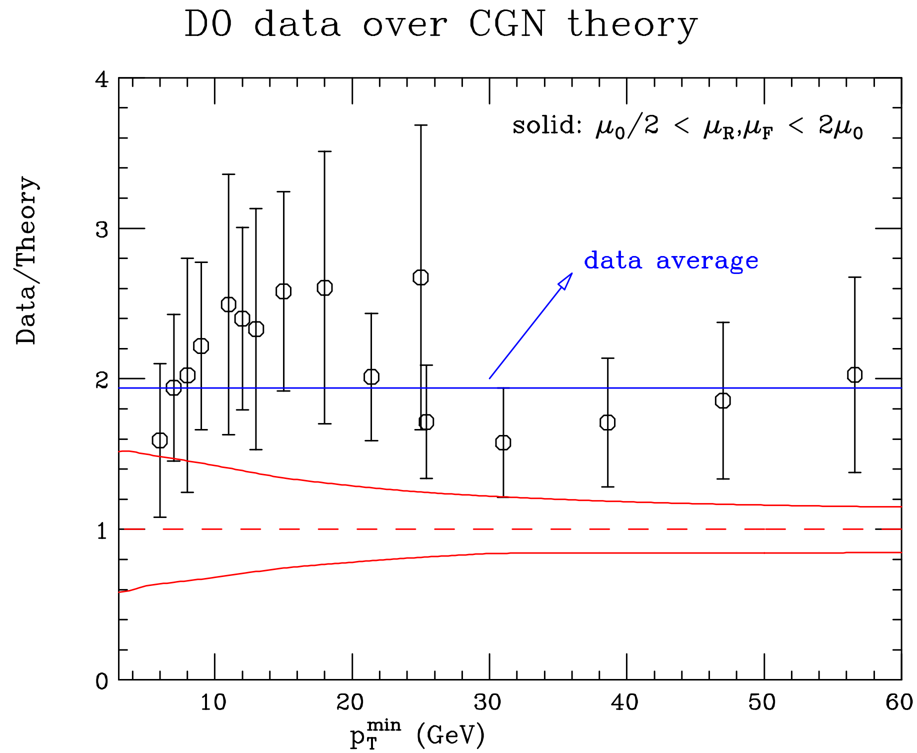


Theory: MC, Greco, Nason [JHEP **05** (1998) 007] (full NLO + NLL collinear resummation)

Data from D0 and CDF fairly compatible. Within errors (both theoretical and experimental), borderline agreement with theory too.
NB: no parameter (mass, QCD coupling, scales, etc....) has been pushed to its limits in producing this plot).

b quarks @ Tevatron

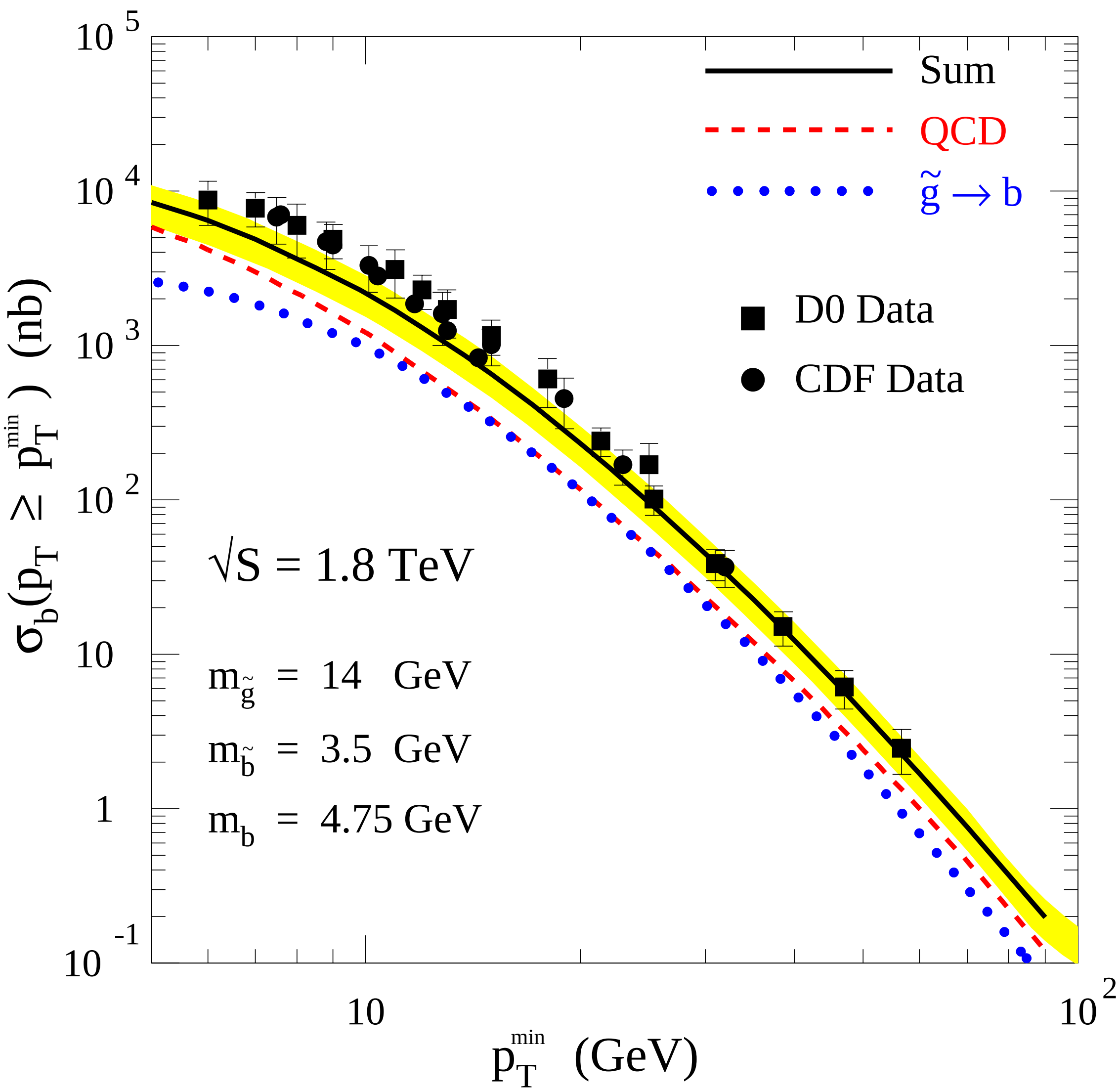




Data/Theory $\simeq$ 1.8 - 2

New physics in heavy quark production?

The discrepancy has been around long enough that a SUSY-based solution has been proposed: light gluino and bottom squark production [Berger, Harris, Kaplan, Sullivan, Tait, Wagner, PRL **86**, 4231 (2001)]



Production of light gluinos followed by their decay into bottom and bottom squark:

$$p\bar{p} \rightarrow \tilde{g}\tilde{g} \text{ and } \tilde{g} \rightarrow b\tilde{b}$$

$g \to b\bar{b}$ splitting at LEP and SLC

$$g_{bb} \equiv \frac{\Gamma(Z^0 \to q\bar{q}g,\, g \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})}$$

Experimental Results:	g_{bb} (%)
World Average	0.25 ± 0.051

Theoretical Results:	g_{bb} (%)
Leading Order (α_s^2)	0.110
LO + NLL (Seymour)	0.207
LO + NLL (Miller, Seymour)	0.175
HERWIG	0.25
PYTHIA	0.16 - 0.28 (0.46)

Data/Theory ratio $\simeq$ 1.2 - 1.6

Data and theory fairly compatible within uncertainties.

D^* photoproduction @ HERA

Data for D^* mesons are available from both H1 and ZEUS.

The theoretical prediction are built as for the Tevatron b data:

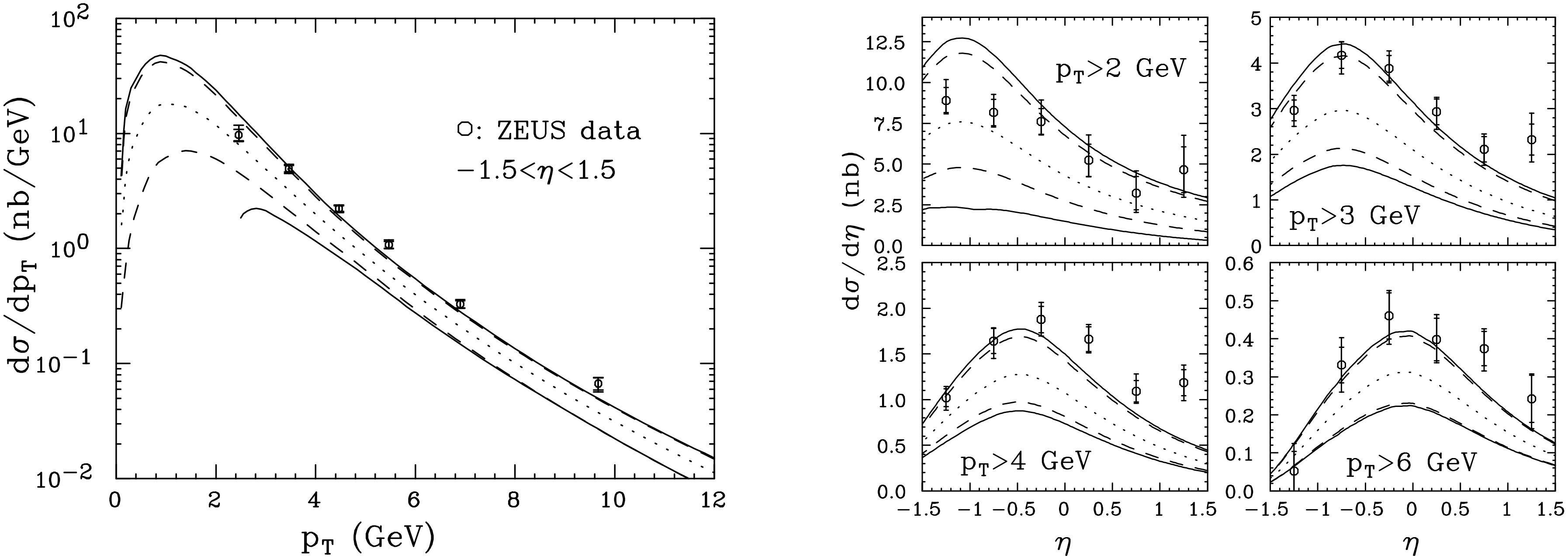
collinearly resummed calculation merged with a fixed order result

This has to be done for both the direct (γp) and the resolved (parton from γ-proton) processes $\rightarrow$ NB. SIX terms involved!

On top of this, you need to convolute with a Weizsäcker-Williams

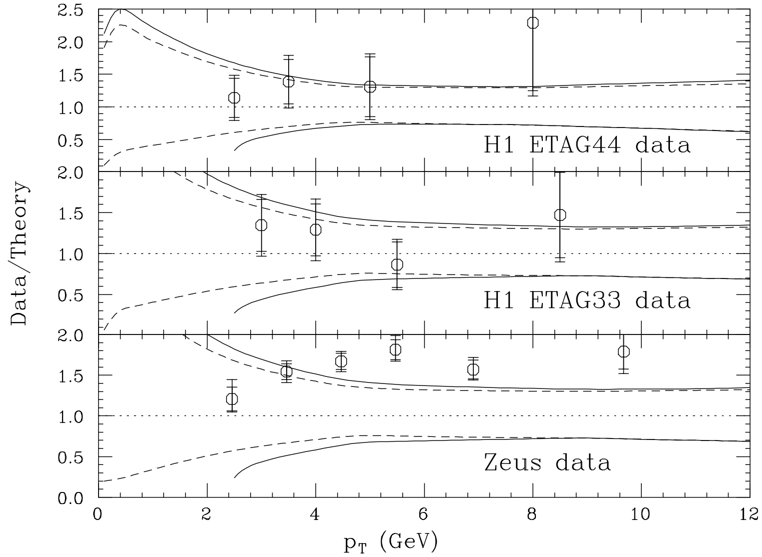
Then, the resulting charm quark p_T spectrum is convoluted with a non-perturbative fragmentation function, describing the charm $\rightarrow$ D^* meson hadronization transition.

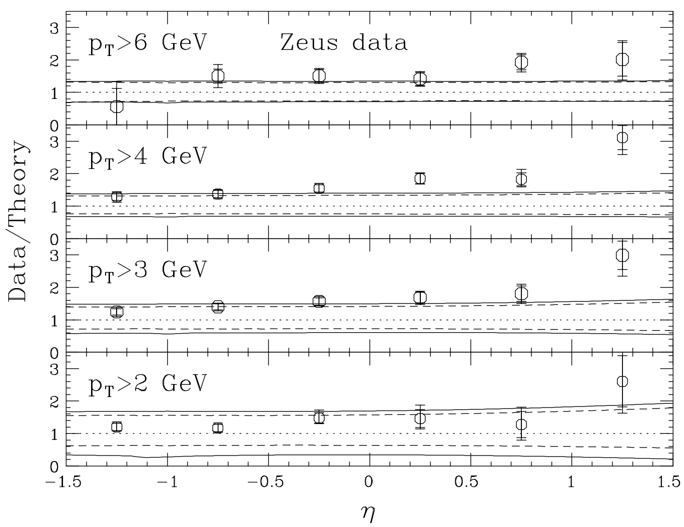
D^* photoproduction data @ HERA

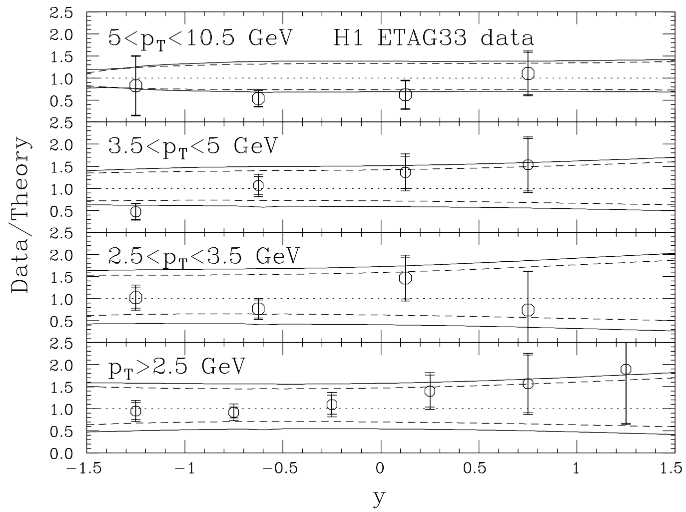


(S. Frixione and P. Nason, hep-ph/0201281, NLO + NLL)

D^* photoproduction data @ HERA



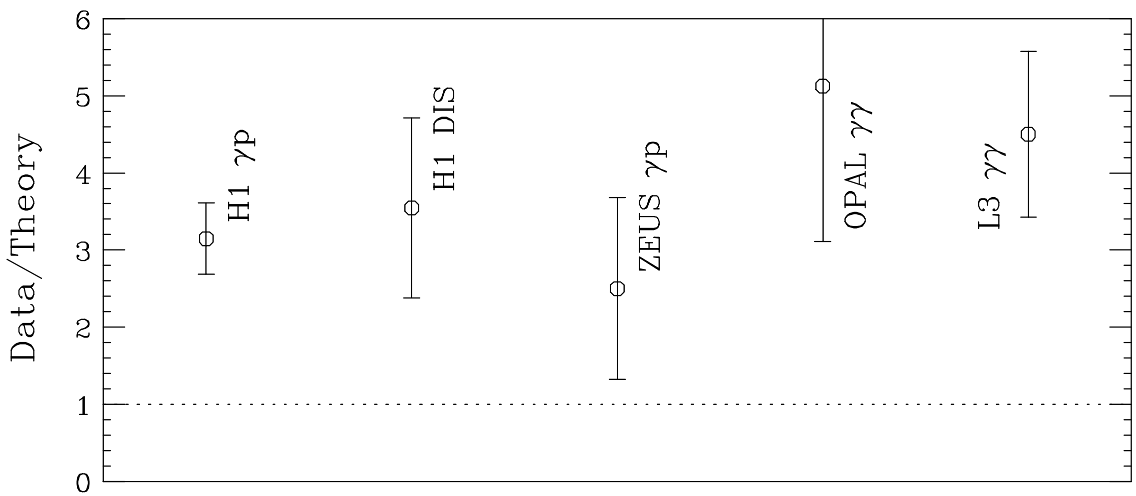




(S. Frixione and P. Nason, hep-ph/0201281)

Data/Theory ratios $\simeq$ 1 - 2

Bottom photoproduction at HERA and LEP

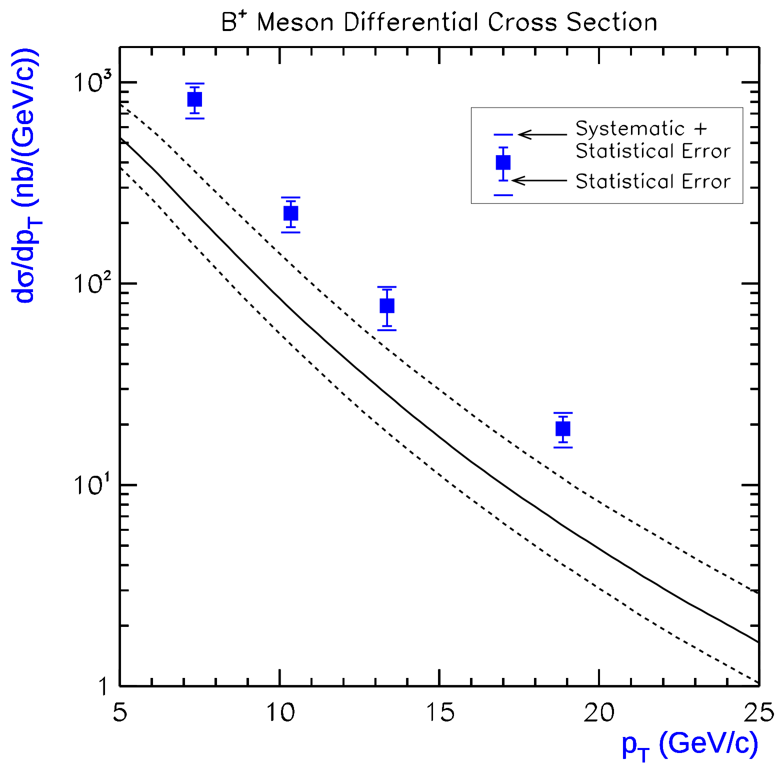


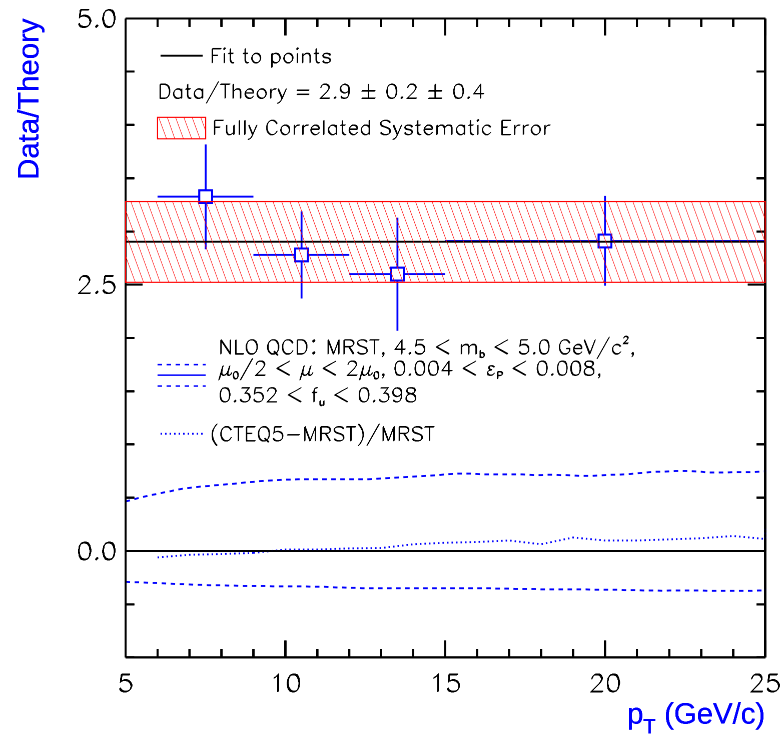
(S. Frixione, hep-ph/0111368)

Data/Theory ratios $\simeq$ 3 - 4 or more. Even larger than for charm production in the same experiment. However, bottom should be better behaved than charm from a perturbative point of view!

No explanation for these experimental results readily available.

CDF data: B mesons (hep-ph/0111359)





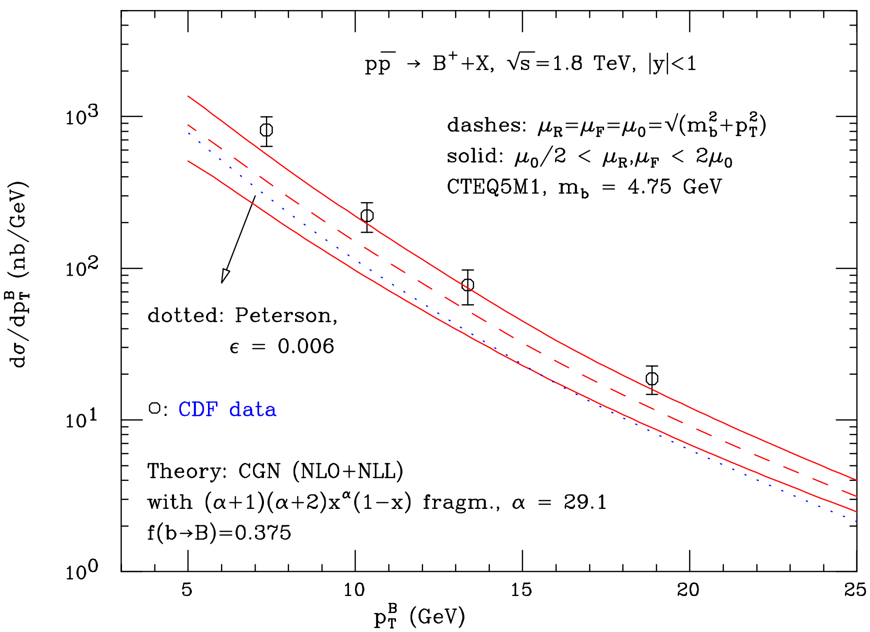
$$\frac{d\sigma^{B}}{dp_T} = \frac{d\sigma^{b}}{dp_T} \otimes D^{b\to B}(z)$$

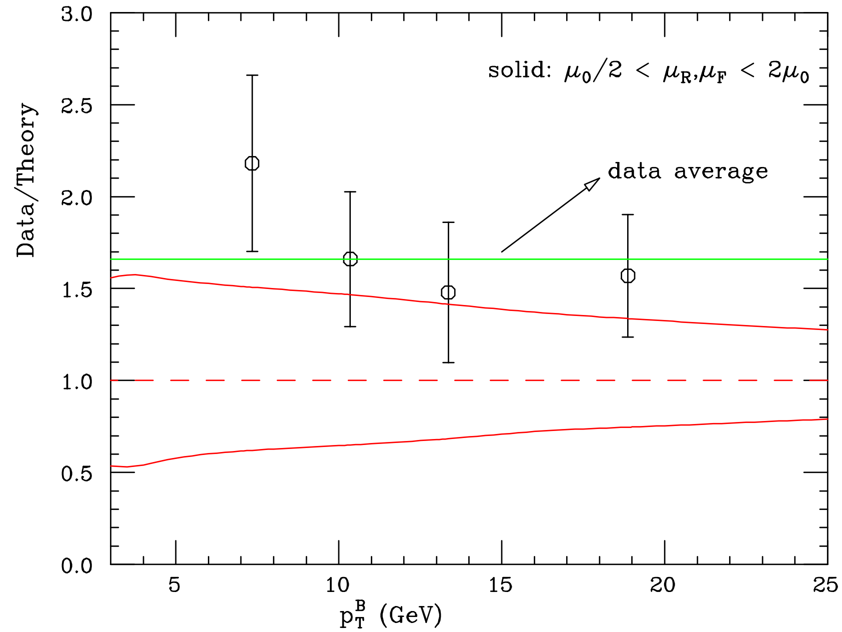
$$D^{b\to B}(z) = \text{Peterson et al. form}, \ \epsilon = 0.006$$

$$\text{Data/Theory} = 2.9 \pm 0.2 \ (\text{stat} \oplus \text{syst}_{p_T}) \ \pm 0.4 \ (\text{syst}_{\text{fc}})$$

CDF data: B mesons

Updated plots:





- CGN NLO + NLL b quark spectrum instead of NLO
- non-perturbative fragmentation function determined from moments space e^+e^- data

Data/Theory $\simeq$ 1.7

(MC, P. Nason, preliminary results)

Theoretical approach to B mesons hadroproduction

Not the whole spectrum of the non-perturbative fragmentation function is important in hadron collisions.

Mellin moments definition:

$$D_N{}^{b\to B} \equiv \int_0^1 dz\; z^{N-1} D^{b\to B}(z)$$

If $\sigma^b(p_T) \simeq A/p_T^5$ then (Mangano, Nason, Ridolfi):

$$\sigma^B(p_T) = \sigma^b(p_T) \otimes D^{b\to B}(z) \simeq \frac{A}{p_T^5} \int dz\; z^4\; D^{b\to B}(z)$$

Therefore, only the moments of the non-perturbative fragmentation function around $N \simeq 5$ are important! Actually, they are much more important than the perfect knowledge of the whole spectrum!

Hence, watch out what you fit in e^+e^- and what non-perturbative fragmentation function you use.

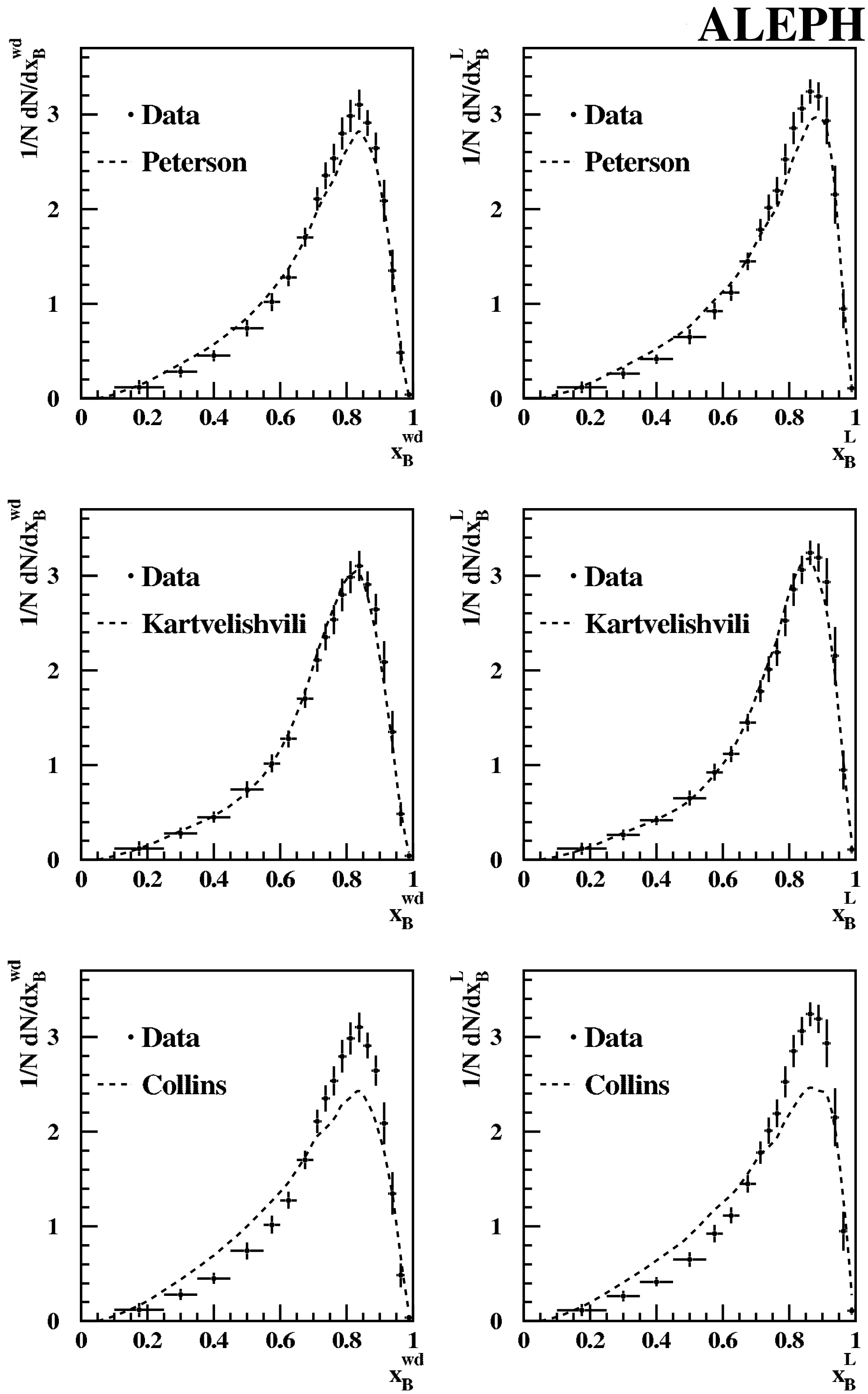


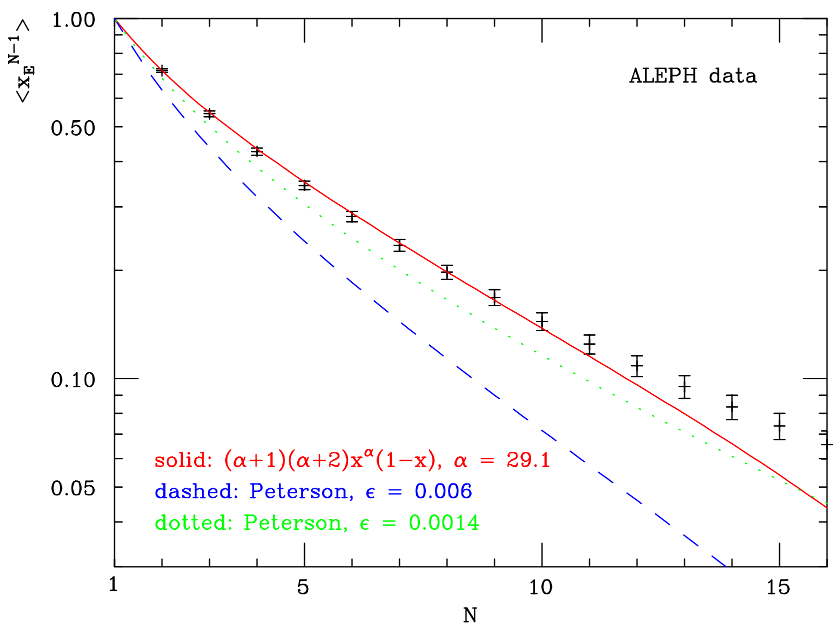
Figure 4: Scaled energy of the leading and weakly-decaying B meson, as reconstructed from data. The best-fit distributions for the Peterson model, the Kartvelishvili model, and the Collins model are superimposed. For the data, the bin-to-bin errors are highly correlated, as shown in the error matrices in the Appendix.

B meson production in e^+e^- collisions

$$\frac{1}{\sigma}\frac{d\sigma}{dx_E} = D^{\rm pt}(x; Q, m; \Lambda_{QCD}) \otimes D^{\rm np}(x; \epsilon_1 ... \epsilon_n)$$

pt = perturbative QCD (state of the art: (N)NLO + NLL collinear + NLL Sudakov) [Mele, Nason (1991); MC, Catani (2001)]

np = non-perturbative contribution, assumed process independent. Phenomenological parameters $(\epsilon_1 ... \epsilon_n)$ fitted to data. NOT UNIQUE (depends on details and parameters of perturbative part) [MC, Greco (1997)]



$Q = 91.2$ GeV
$m_b = 4.75$ GeV
$\Lambda^{(5)} = 0.226$ GeV

Conclusions

Theoretical tools are available for calculating heavy quark cross sections in many different reactions, also resumming potentially large collinear and Sudakov logs.

If you believe in the universality of a non-perturbative fragmentation function, you can also predict D or B meson cross section.

No single heavy quark cross-section is lower than theory! However:

D^* cross sections at HERA and inclusive bottom from gluon splitting at LEP appear fairly compatible with theoretical predictions. Theoretical uncertainties are large.

B meson production at the Tevatron could become compatible using a different approach for the non-perturbative fragmentation function extraction in e^+e^- collisions

b quark at the Tevatron appears a little higher ($\sim$ factor of 2). Is the experimental result possibly affected by uncertainties in describing the $b \to B$ transitions? (See also b-jets D0 data)

So far, I should say : "No significant excess"

However, b quark rates at HERA and in $\gamma\gamma$ collisions really puzzling: actually even less well behaved than charm in the same experiments!! Unlikely behaviour in a perturbative context. $\to$?