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Heavy flavour production

DIS05, Madison, 27/4/2005

Plan

- One of the best studied topics in particle physics, with a huge amount of data for basically all possible observables $\Longrightarrow$ Too many things to review

- I'll not discuss final-state properties, only production dynamics

- I'll mainly concentrate on top and open-b physics

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 formula

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

- 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 N^{k}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 (single-log in what follows)

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

where $\mathcal{Q}$ "large" means $\alpha_S \log \mathcal{Q} \gtrsim 1$, i.e. $a_k \alpha_S^k \simeq a_{k+1} \alpha_S^{k+1}$.

If $\mathcal{Q}$ is large, the logs *must be resummed*

(This is equivalent to a rearrangement of the perturbative expansion)

2) Bottom and charm, although heavy, hadronize before decay. 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: must be extracted from data

The ubiquitous logarithms

1) Observable-dependent logs: depend strictly on the kinematics of the final state (including cuts). Occur in specific regions of the phase space

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

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

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

2) Observable-independent logs

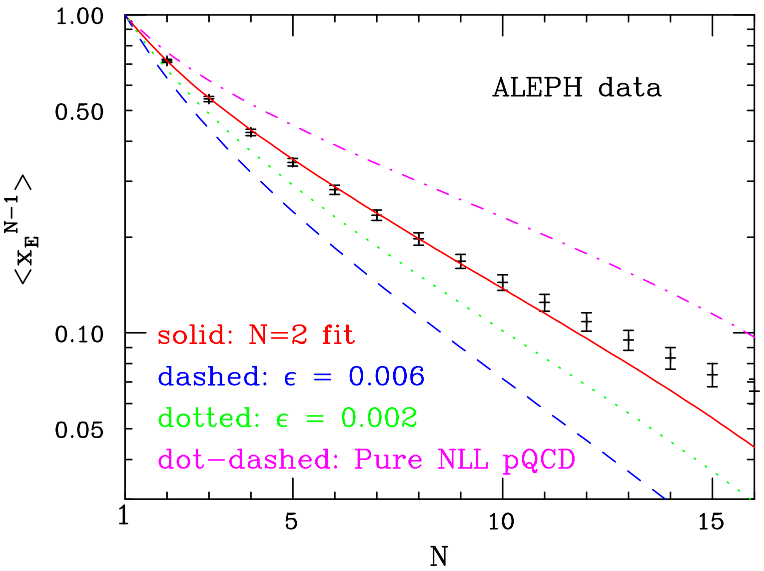
Threshold logs: occur when the c.m. energy is small

$$\mathcal{Q} = 1 - \frac{4m_Q^2}{\hat{s}}, \qquad \hat{s} \simeq 4m_Q^2$$

Small-x logs: occur when the c.m. energy is large

$$\mathcal{Q} = \frac{m_Q^2}{\hat{s}}, \qquad \hat{s} \gg m_Q^2$$

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.
  At LEP, Tevatron, and LHC, $2 \le N \le 7 \Longrightarrow$ Fit $N=2$ (Cacciari&Nason)

Standard and $N=2$ fits are not equivalent: beyond-LO cross sections are negative at large z's, and this region is not included in standard fits. Unfortunately, the large-z region gives important contributions to the normalization (old FONLL fits with $d\sigma/dz > 0$ gave $\epsilon \simeq \epsilon_{N=2}$! (Nason&Oleari))

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

Top production: theoretical ingredients

Top is an excellent testing ground for QCD predictions: no hadronization, and moderate K factors; at the Tevatron, only threshold logs are relevant

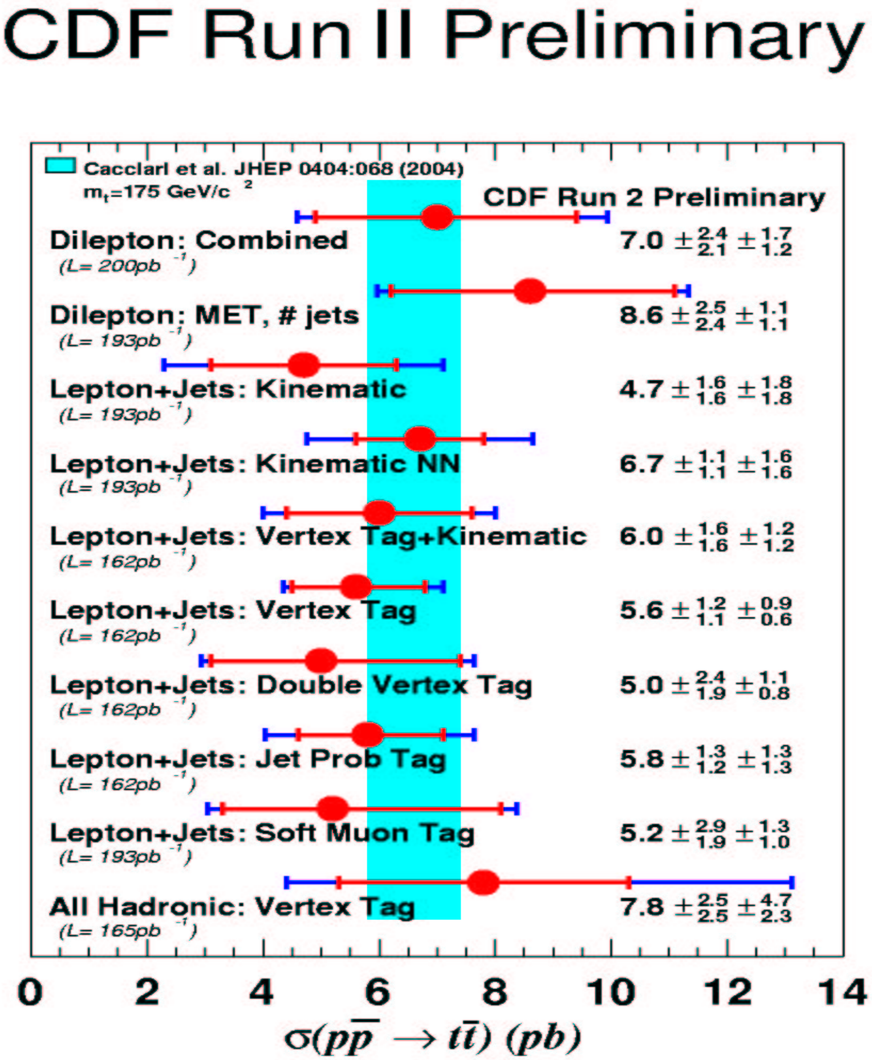
- Rates computed to NLO accuracy: Nason, Dawson, Ellis (1988); Beenakker, vNeerven, Meng, Schuler, Smith (1991)

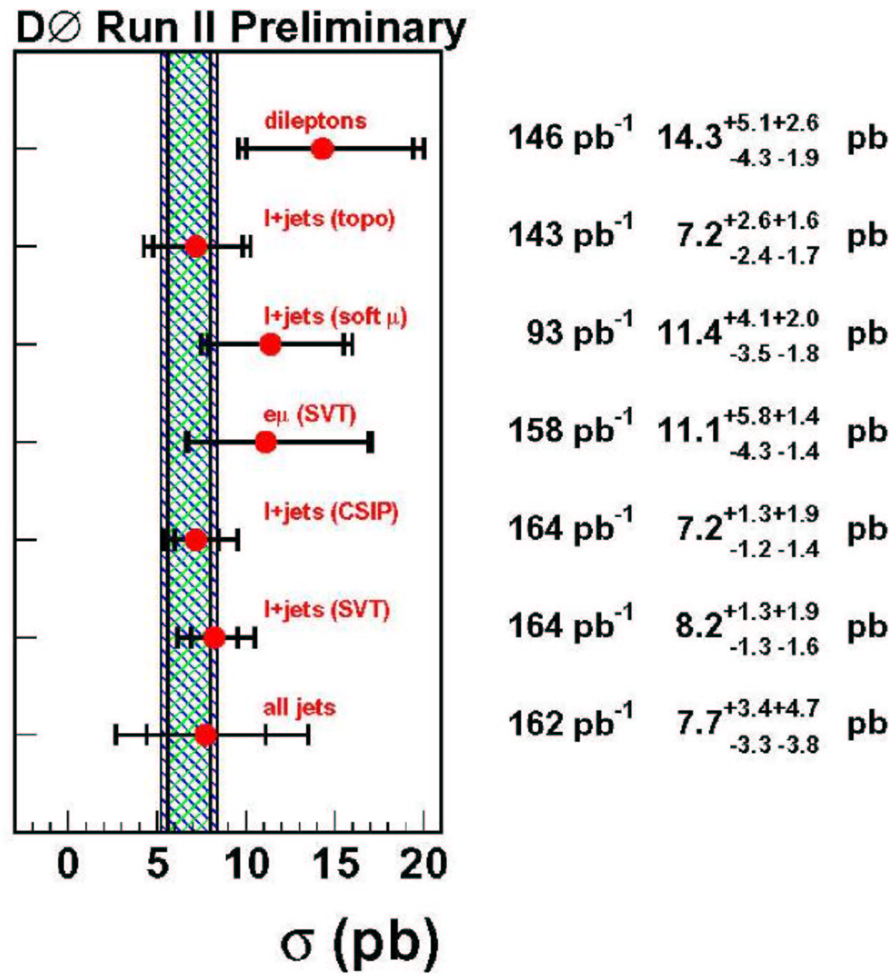
- Resummation of threshold logs available up to NLL: Sterman, Laenen, Contopanagos, Kidonakis, Oderda (1996–1998); Bonciani, Catani, Mangano, Nason (1997–1998). Rates don't change much, scale dependence reduced by a factor of two

Technical note: the notation used by Kidonakis, Laenen, Moch & Vogt of N^{k}LL refers to logs after the expansion of the exponent. The so-called NNNLL-NNLO results (Kidonakis & Vogt) differ from the "standard" NLO+NLL computations by *some* higher-order terms; other terms of the same order are not included. In particular, no proper NNLO computation is available for heavy flavour production

Top production at the Tevatron

Run I results are in good agreement with QCD predictions

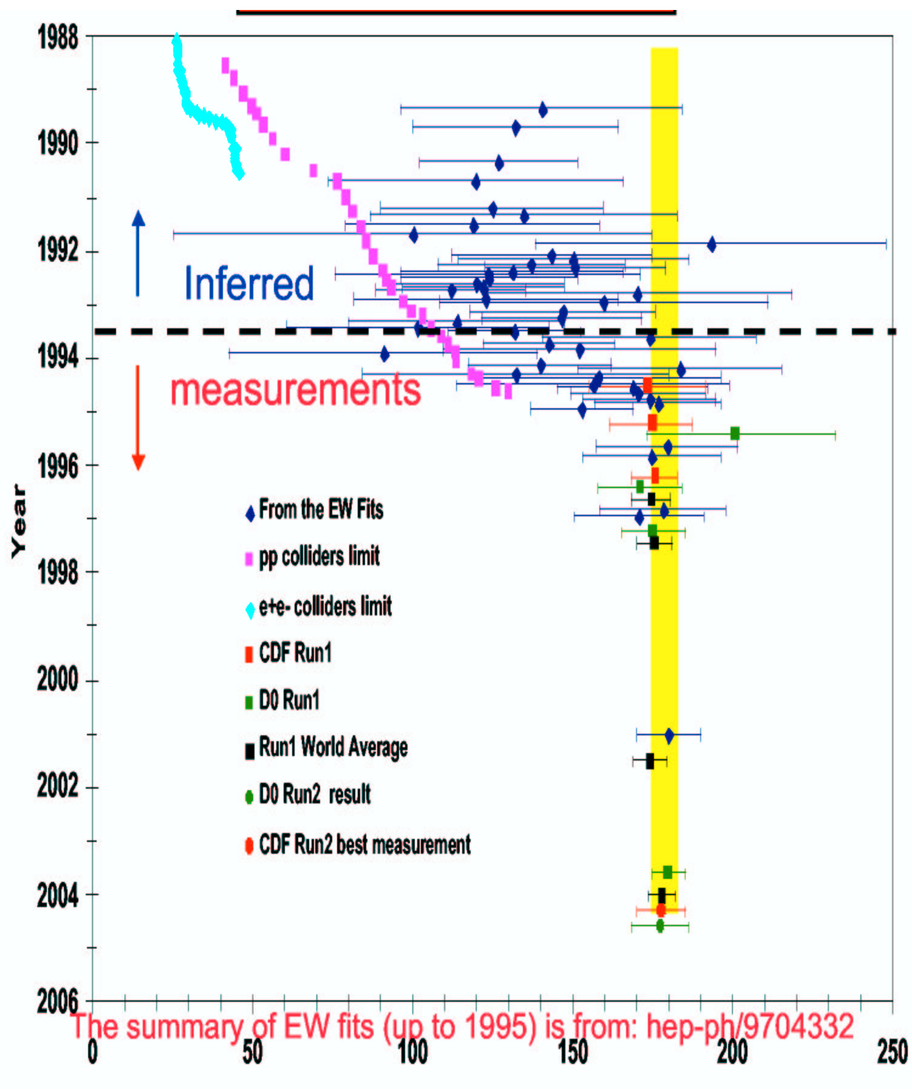




Data: winter conferences 2005; Theory: NLO+NLL, Cacciari, SF, Mangano, Nason, Ridolfi

- What is the value of the top mass?

Top mass is a key parameter of the SM



Top mass measurements are very precise

$$m_{top} = 174.3 \pm 5.1 \xrightarrow{\text{D0}} 178.0 \pm 4.3 \text{ GeV}$$

$$m_{top} = 173.5^{+4.1}_{-4.0} \text{ GeV (CDF Run II)}$$

$$\sigma_{NLO+NLL}(m_{top} = 175) = 6.70^{+0.71}_{-0.88} \text{ pb}$$

$$\sigma_{NLO+NLL}(m_{top} = 180) = 5.75^{+0.59}_{-0.75} \text{ pb}$$

Either mass value will results in σ predicted by QCD in agreement with data

Not so easy for EW global fits

$$(\Delta\sigma/\sigma)_{scales} \simeq \pm 5\%$$

$$(\Delta\sigma/\sigma)_{PDF} \simeq \pm 7\%$$

$$\sigma_{NLO} = 6.47 \xrightarrow{+NLL} 6.70 \text{ pb } (+3.5\%)$$

- Marginal theoretical improvements possible with better understanding of ΔPDFs
- More stringent tests from QCD viewpoint will have to wait for the LHC

Bottom and charm production: theoretical ingredients

This is a severe testing ground for QCD predictions: hadronization effects are important, K factors are large (~ 2), large logs affect many observables

- Rates computed to NLO accuracy (same as for top)
- Updated fragmentation functions (i.e. as for PDFs)
- Resummation of threshold logs up to NLL (same as for top)
- Resummation of observable-dependent logs up to NLL (with many caveats $\longrightarrow$)
- Resummation of small-x logs: this is a theoretically challenging and intriguing problem, which entails the necessity of going beyond standard Altarelli-Parisi equations (Collins & Ellis; Catani, Ciafaloni, Fiorani, Marchesini), introducing in the process unintegrated (in k_T) PDFs
  Analytic implementations difficult (Ball, Ellis), Monte Carlo methods a viable alternative: CASCADE (Jung, Salam)

Resummation of observable-dependent logs

All resummed computations must be matched to fixed-order ones (a double-counting problem), to be phenomenologically sensible

The standard (analytic) approach has some drawbacks: is observable-specific, technically involved, prone to mistakes. Above all, it has been systematically studied to NLL only for single-inclusive p_T spectra

- p_T/m: state of the art is FONLL (Cacciari, Greco, Nason; SF, Cacciari, Nason). Similar strategy followed by Olness, Scalise, Tung, building upon Aivazis, Collins, Olness, Tung; some NLL terms are missing here

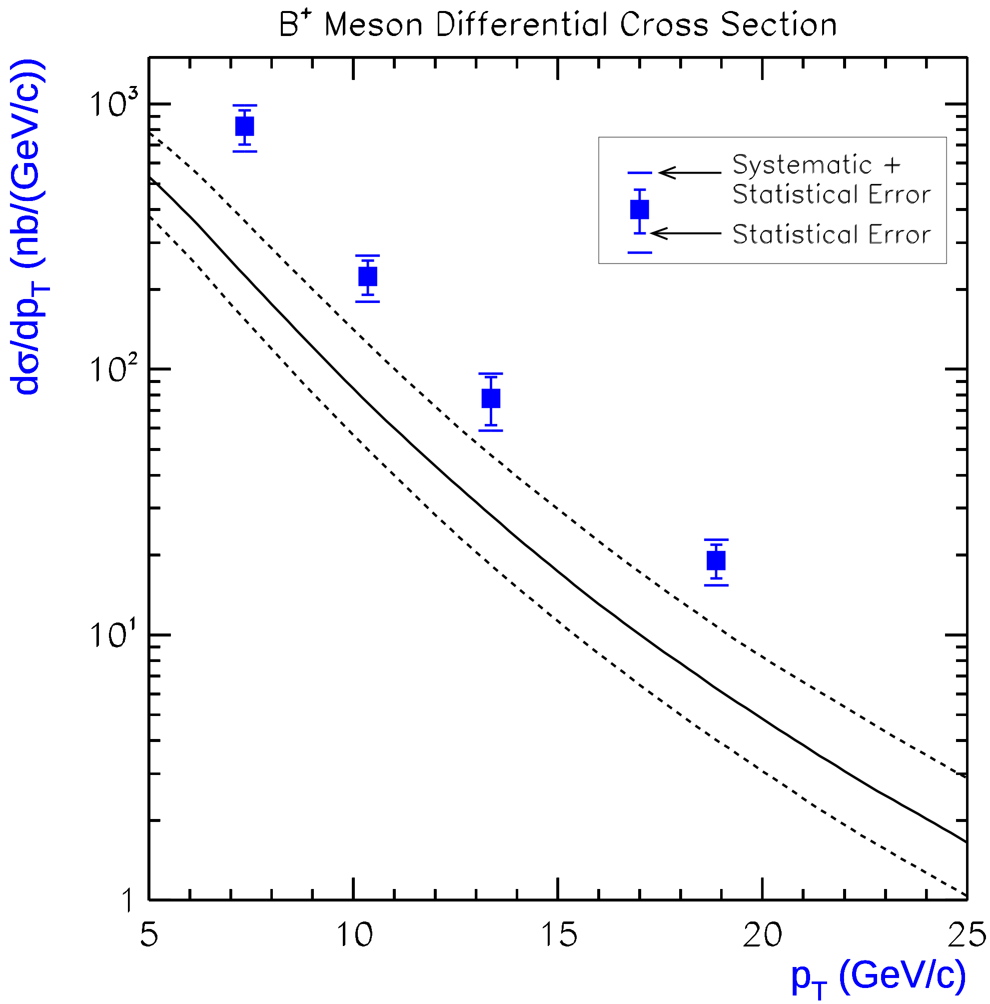
More flexible methods have recently become available, which will allow the study of more involved observables

- MC@NLO (SF, Webber; SF, Nason, Webber) NLO matrix elements are included in a parton shower Monte Carlo, that performs the resummation
- CAESAR (Banfi, Salam, Zanderighi) "Standard" type of resummation, but performed numerically rather than analytically. Not applied to heavy flavour, not matched to fixed-order results yet

A long-standing problem: b at colliders

For about 15 years single-inclusive b p_T spectrum data have been a factor 2–3 higher than NLO QCD predictions

An *example*: last $B^{\pm}$ CDF Run I data

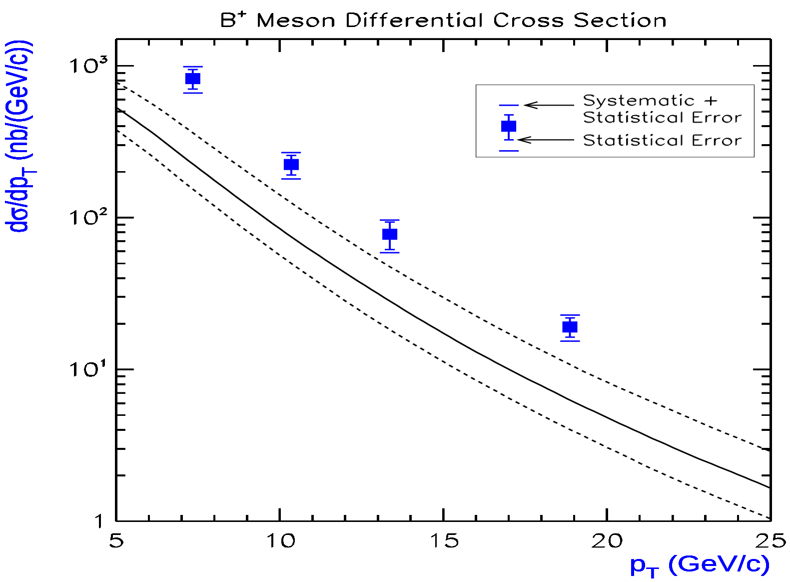


Data/Theory$=2.9 \pm 0.2 \pm 0.4$

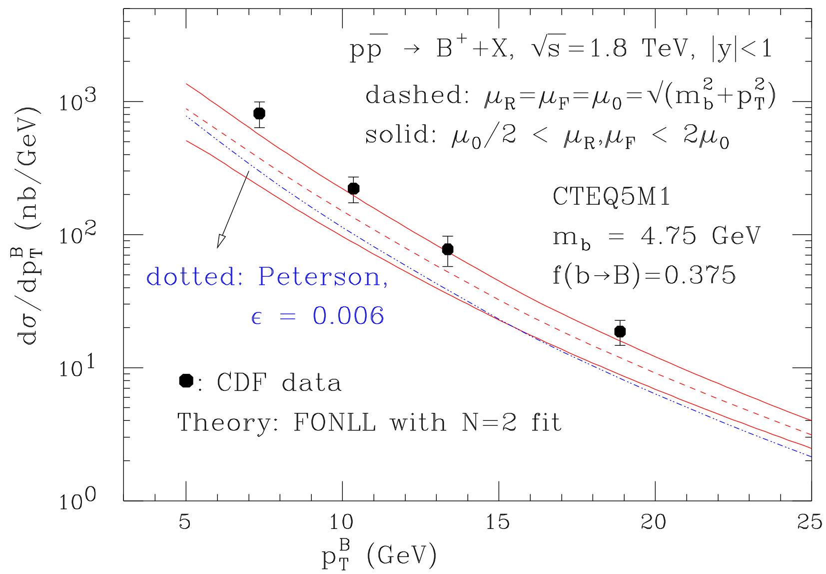
- Many speculations on new physics, which did not survive the test of LEP
- Most of the old data presented in terms of b quarks. Information of the $B \to b$ deconvolutions lost in the details of the analysis
- QCD predictions for B hadrons did not use the appropriate fragmentation functions
- Resummation never included

$\Longrightarrow$ Repeat the comparison with matched computations and modern fragmentation functions and for B-hadron data

Let's check CDF B^+ data



FONLL & N-space fit



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

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

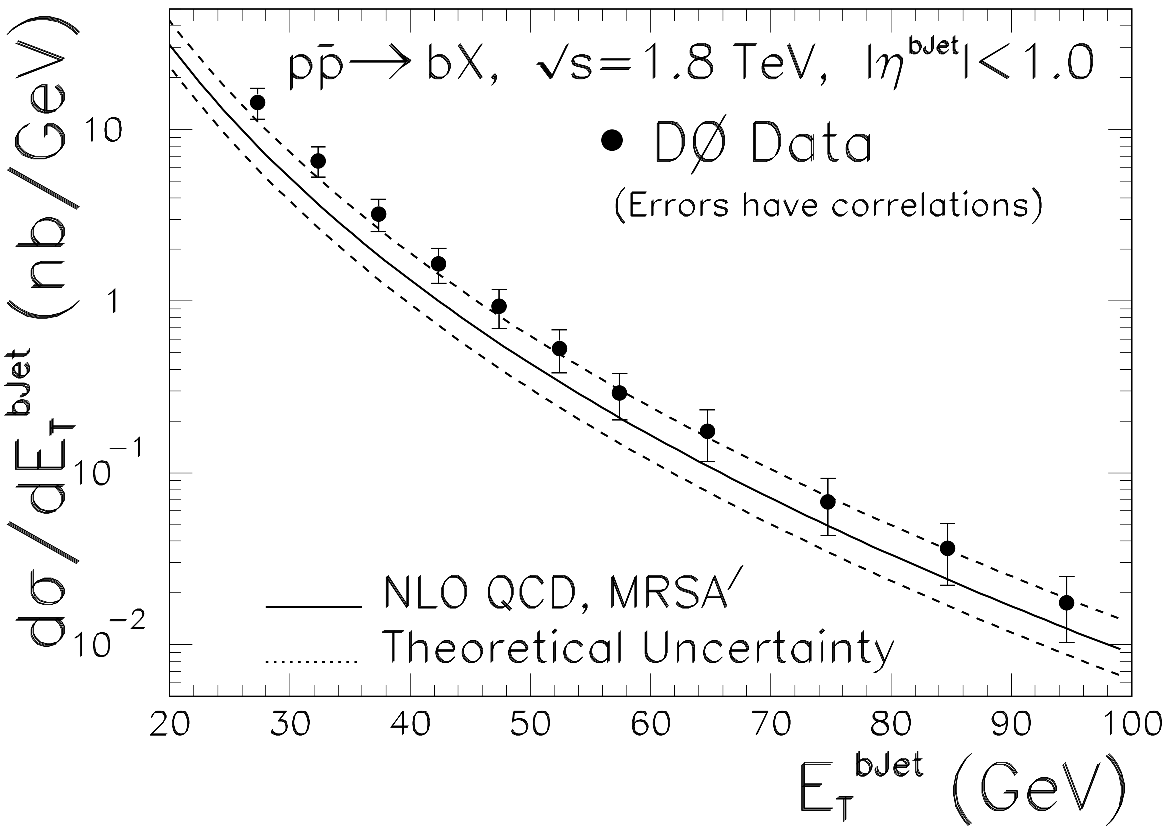
Cacciari & Nason

- 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

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



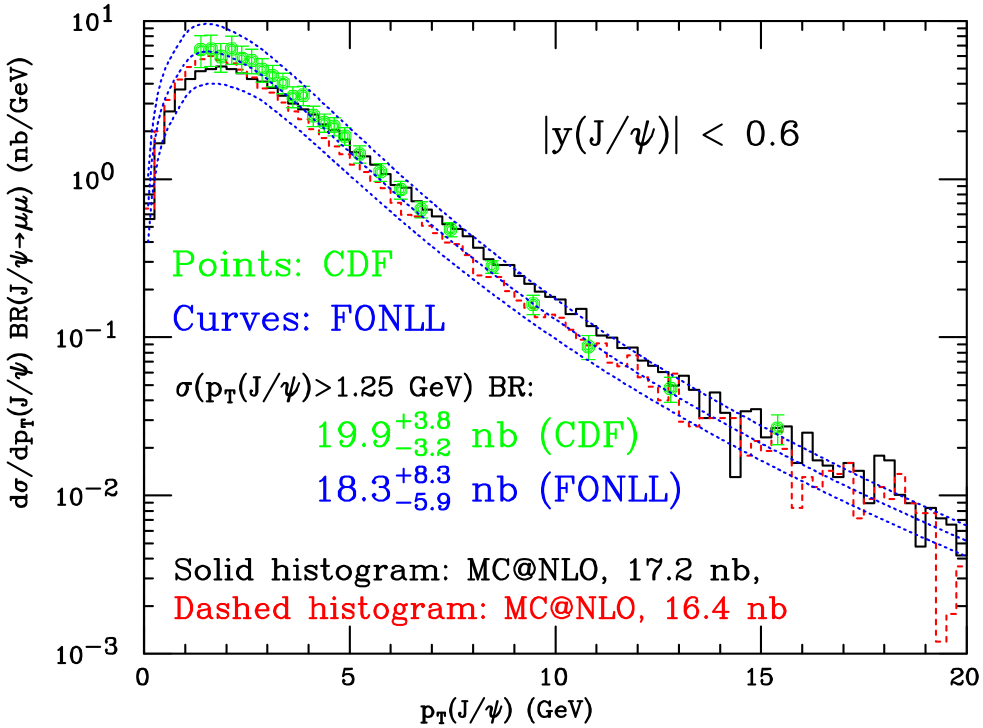
Data: D0 2000

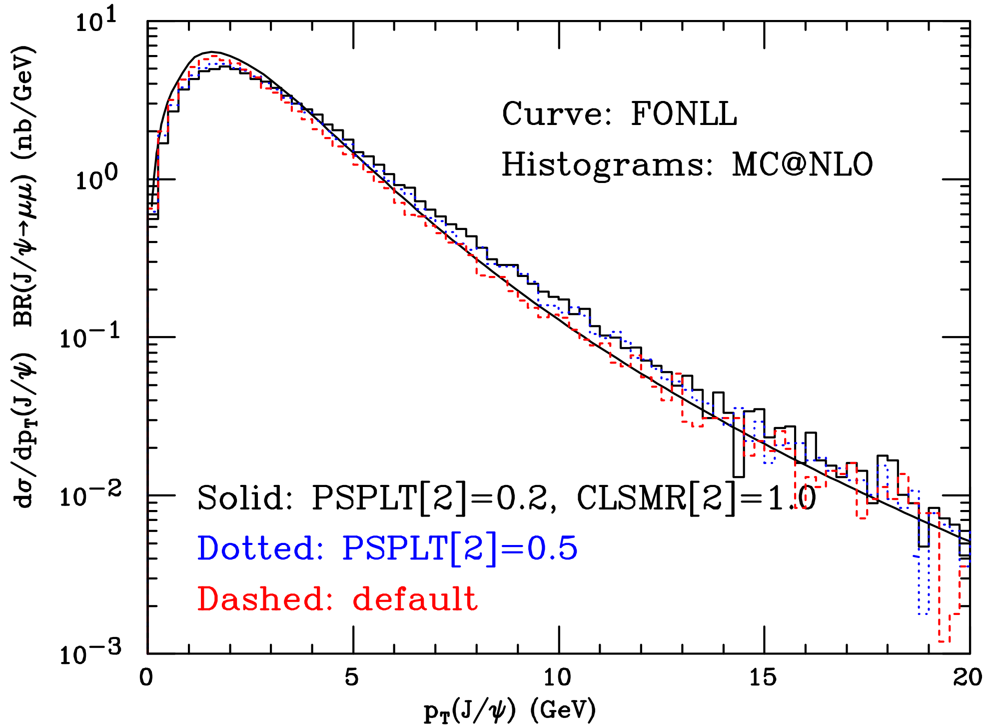
Theory: SF, Mangano

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

$\longrightarrow$ More tests in Run II, with an extended p_T range

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



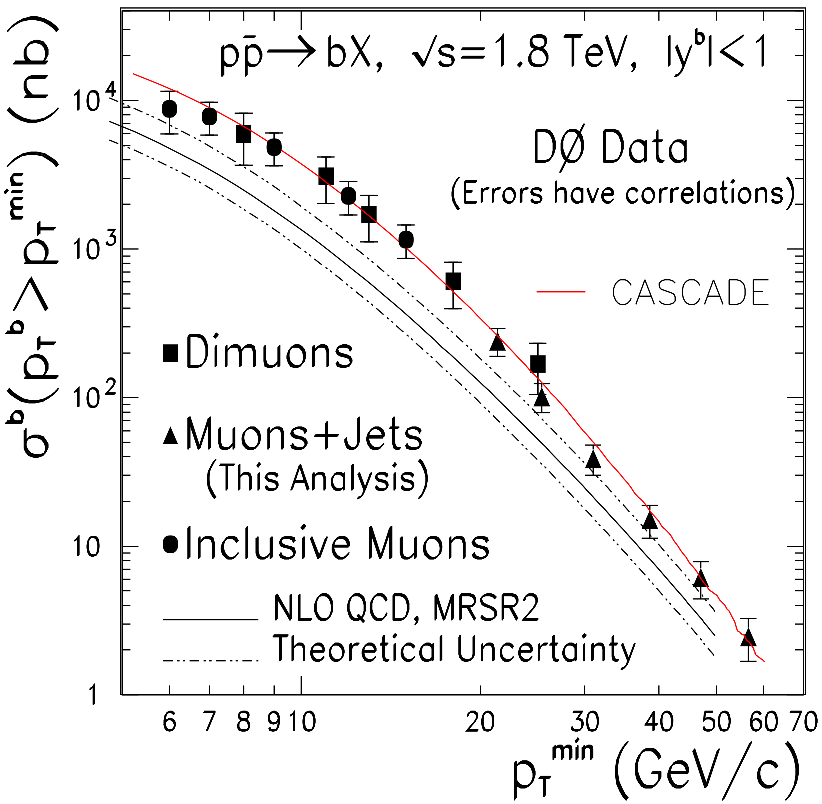


Theory: CFMNR

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

Is b production small-x physics?



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

- Why is the $B \to b$ 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

Problem gone?

I think it's gone. Data for b quarks are probably beyond recovery, which weakens the claim, but Run II will surely tell. It's worth recalling that the backbone of *all* the computations (in collinear factorization) are the NLO results of the late 80's!

So, why has the picture changed?

Substantially, *it has not*

- A careful reconsideration of systematics errors leads to the conclusion that most of the *discrepancies were at the 2σ level or smaller* (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*)

b at HERA

The first HERA data on b (photoproduction) appeared in 1999-2000 and caused some excitement, since they appeared to follow the trend then seen at the Tevatron

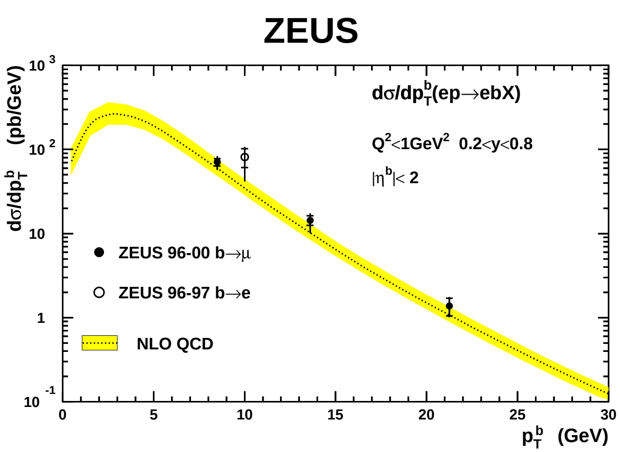
$$\sigma(\text{data})/\sigma(\text{NLO QCD}) = 3.26 \pm 0.74\,, \qquad \text{H1}\,, \quad \texttt{hep-ex/9909029}$$
$$\sigma(\text{data})/\sigma(\text{NLO QCD}) = 2.50 \pm 1.18\,, \qquad \text{ZEUS}\,, \quad \texttt{hep-ex/0011081}$$

The result of H1 is 3 σ away from 1, while that of ZEUS is only 1.3 σ

Preliminary results at EPS01, ICHEP02, EPS03 seemed to confirm these results. Blessed results are now available:

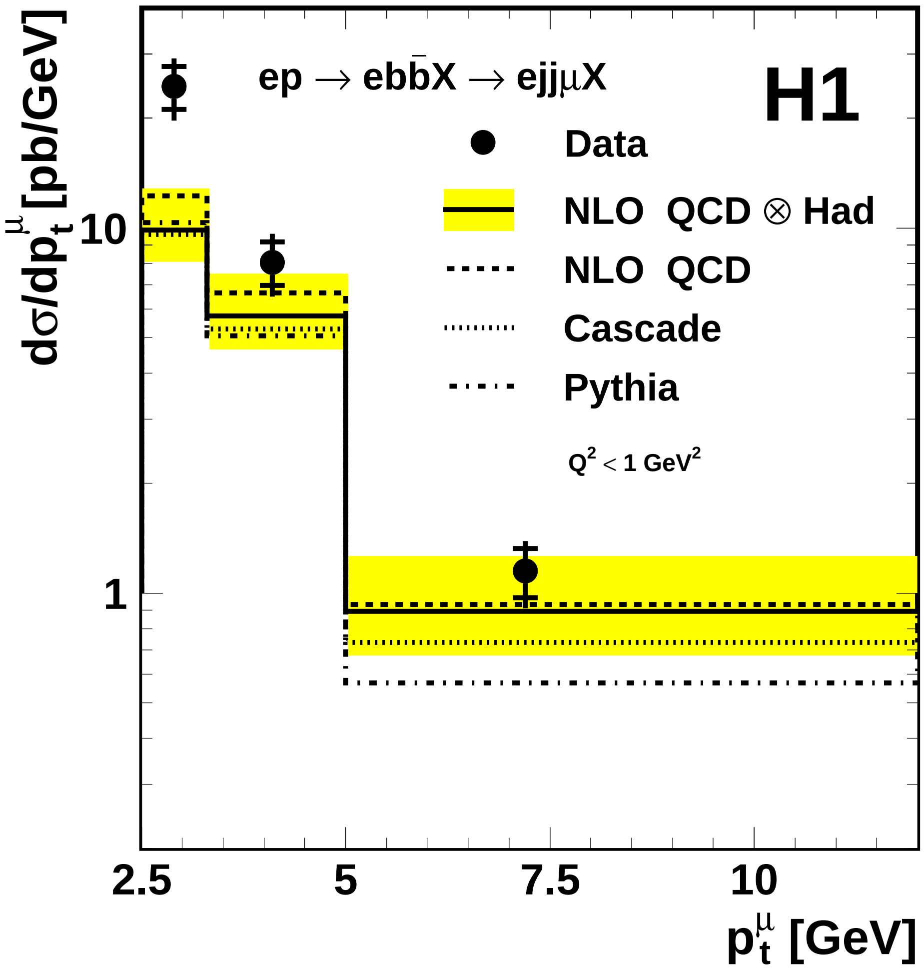
$$\sigma(\text{data})/\sigma(\text{NLO QCD}) = 1.61 \pm 0.51\,, \qquad \text{H1}\,, \quad \texttt{hep-ex/0502010}$$
$$\sigma(\text{data})/\sigma(\text{NLO QCD}) = 1.99 \pm 0.47\,, \qquad \text{H1}\,, \quad \texttt{hep-ex/9909029}^{\star}$$

*re-analysis of hep-ex/9909029 performed in hep-ex/0502010

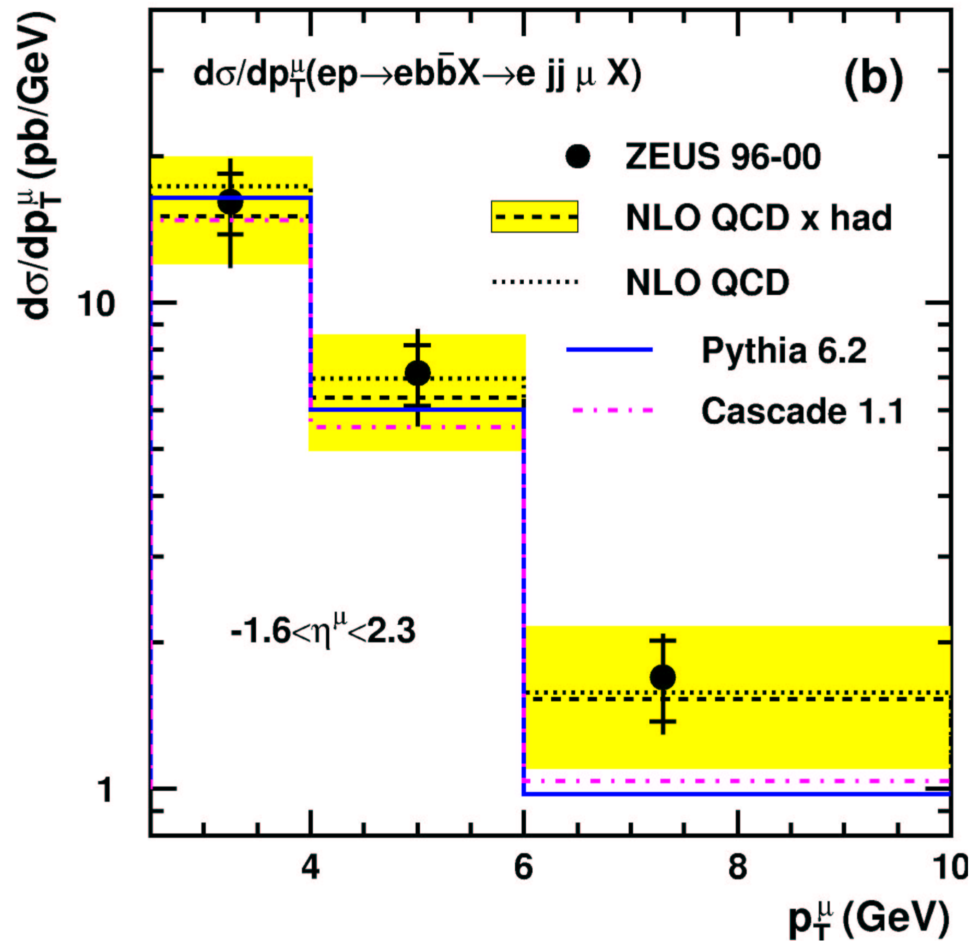


- Experiments understand much better these very complicated analyses
- Vertexing techniques started to be used, smaller number of extrapolations involved: data are less dependent on MC truth

b at HERA: photoproduction



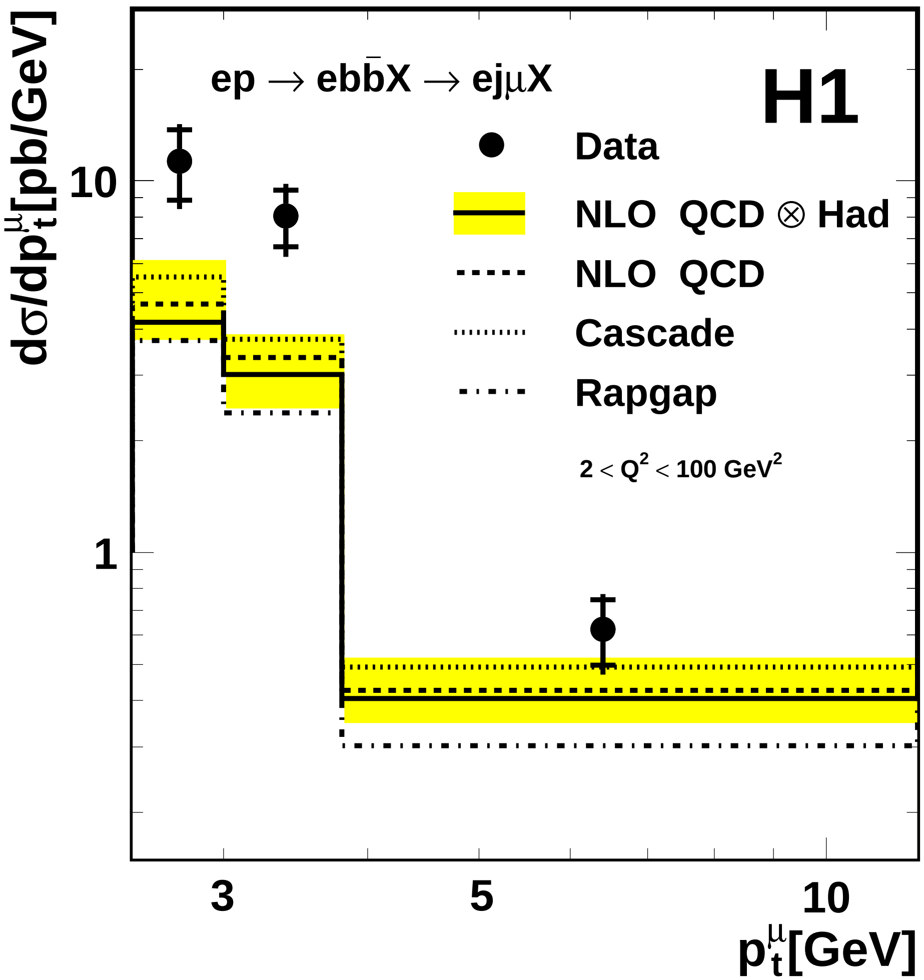
H1, hep-ex/0502010

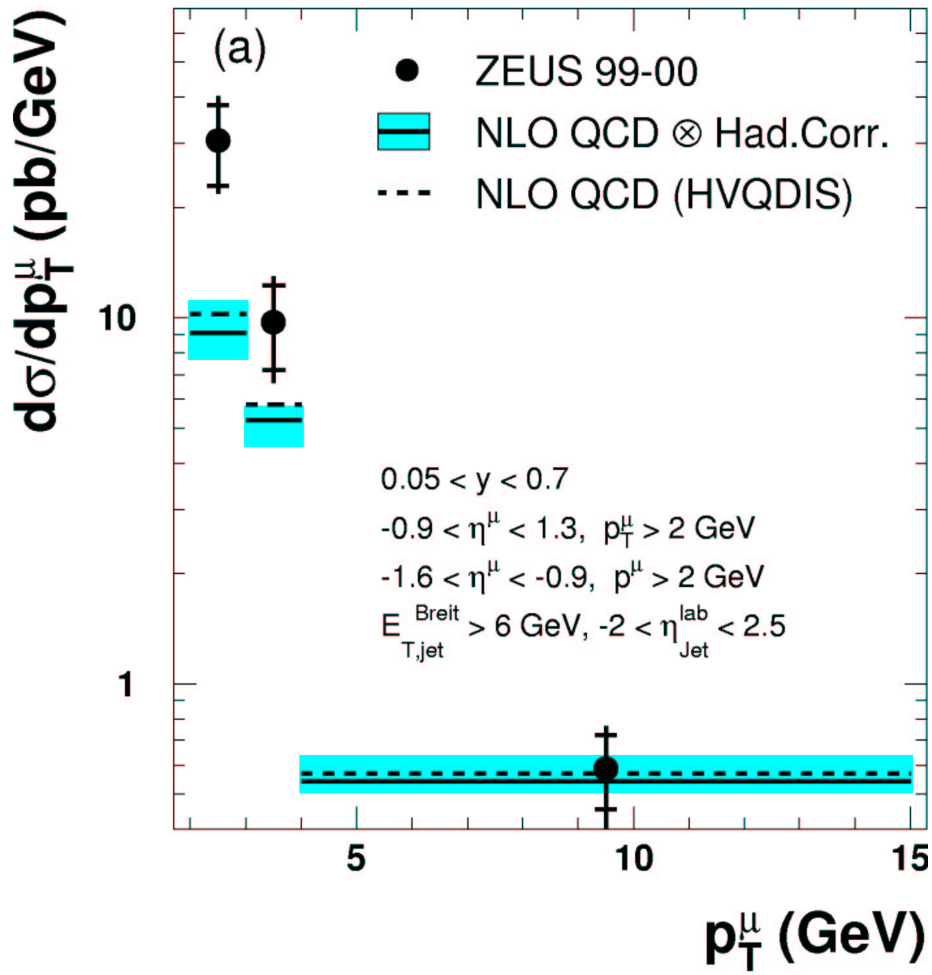


ZEUS, hep-ex/0312057

Theory: FMNR

b at HERA: DIS



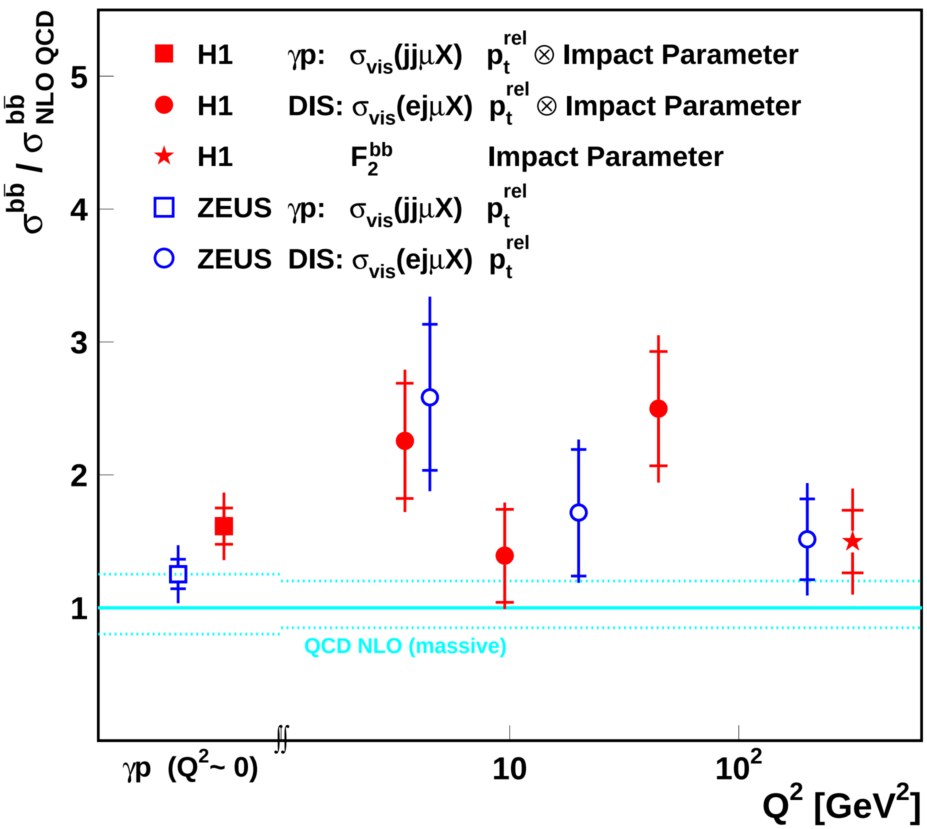


H1, hep-ex/0502010

ZEUS, hep-ex/0405069

Theory: Harris & Smith

b at HERA: summary



Although data are still on the high side, there is a general agreement with QCD predictions. A systematic excess seems to be present:

- At low p_T's
- At intermediate Q^2 in DIS

The computations appear to be solid in these regions. Low-p_T measurements will greatly benefit from improving vertexing performances

HERA II data will be needed for either of the discrepancies above to become compelling

What we have learned

- Understanding PDFs and fragmentation functions is mandatory
- It is essential to match NLO (or higher) results to resummed results (not yet done at HERA, but much less relevant than at Tevatron)
- Data must be as independent as possible of MC truth (tricky in $D^*\mu$ correlations, at low p_T's at HERA)

Charm physics

Open charm data have been compared to QCD predictions for a while, and no spectacular disagreement has been found

HERA measurements follow this trend, although a few glitches remain

- Basically all predictions fail to describe D^* data at $\eta > 0$
- H1 D^* p_T spectrum is softer than FONLL predictions, ZEUS is harder

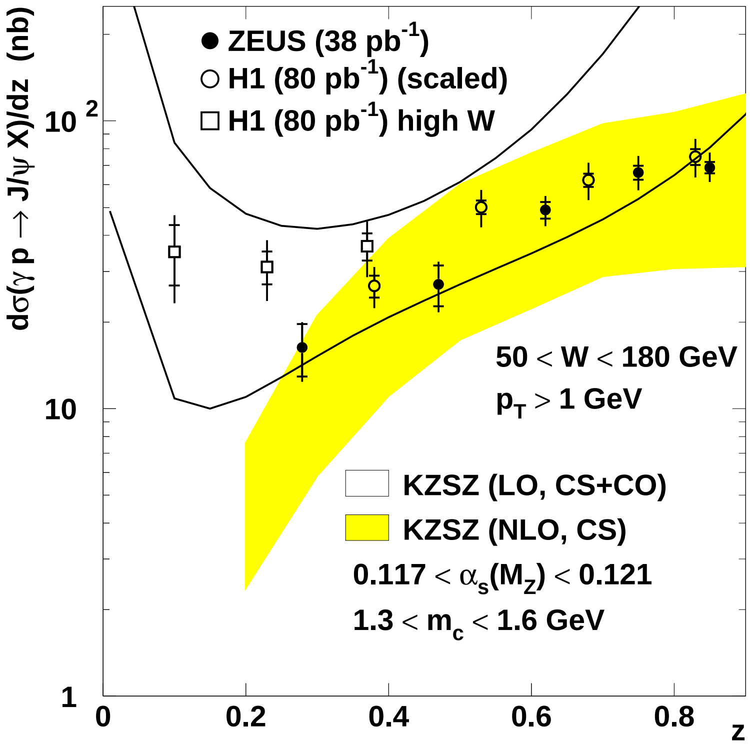
Possibly more problems will soon emerge. There is a tremendous amount of work being done on this at HERA, with a lot of data still only on conference papers. However:

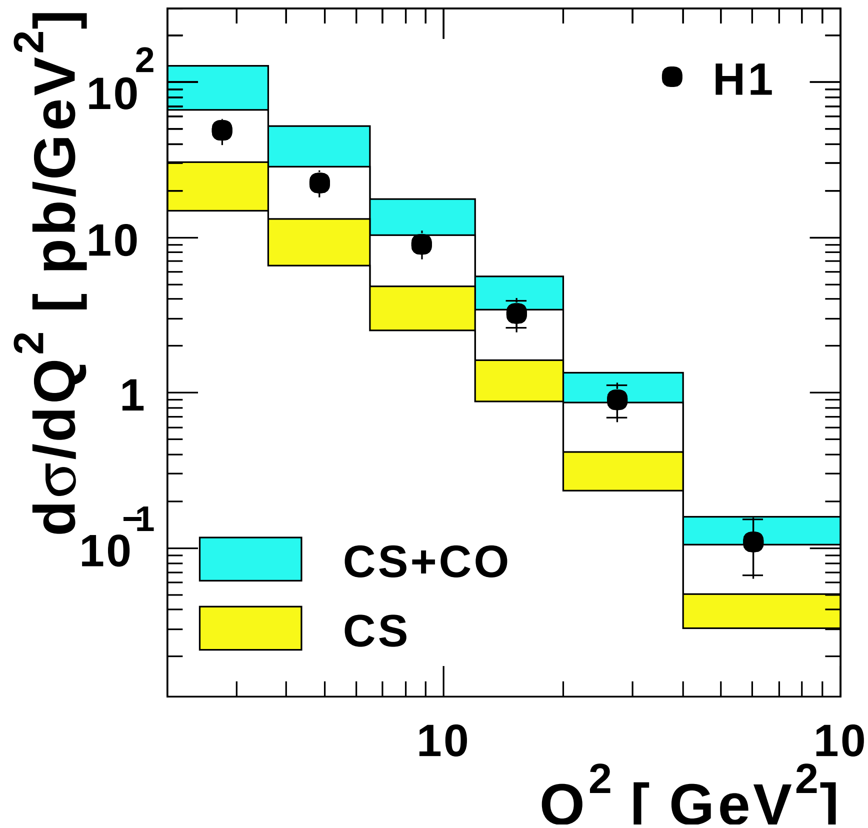
I can't see open charm as a major source of problems
for QCD in the near future

On the other hand, the theoretical understanding of quarkonium production is not on the same footing as that of open quark production

- **Very challenging problems in J/ψ physics**

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)

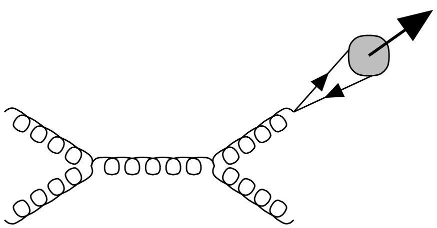
Ambiguous results. CSM ruled out 10 years ago at Tevatron.
Must sort this out. NRQCD inconsistent without CO

J/ψ at hadron colliders

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

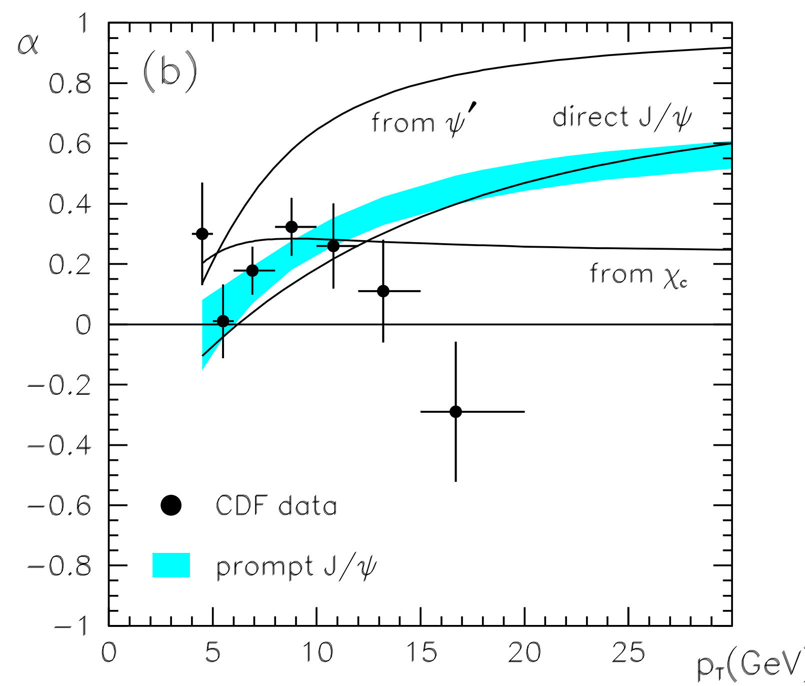
$$\frac{d\sigma_{H\to\mu^+\mu^-}}{d\cos\theta} \propto 1 + \alpha\cos^2\theta, \qquad \alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}, \qquad \theta = \angle(p_{\mu^+}, p_H^{(boost)})$$

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))
- Are scaling rules appropriate for charmonium?
- The *perturbative* computation of Khoze, Martin, Ryskin, Stirling predicts longitudinal polarization



Outlook

QCD is nowadays fairly successful in reproducing heavy flavour data *(yes, including b)*, as the result of long years of understanding long- and short-distance physics, and of very complicated measurements

The theory frontier:

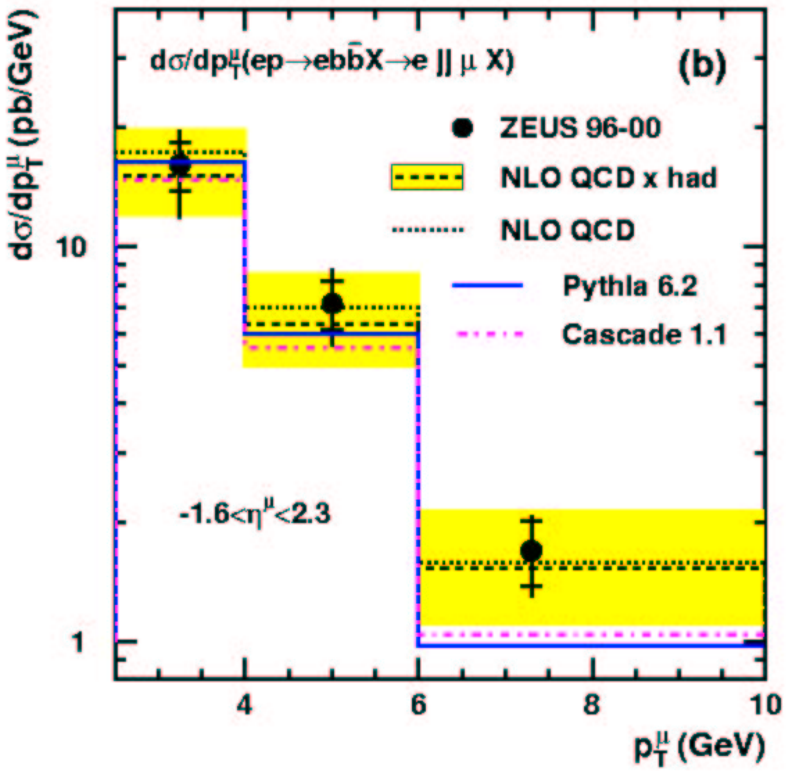
- NNLO results for open-Q cross sections, small-x physics
- Improved computations of photoproduction processes in NRQCD

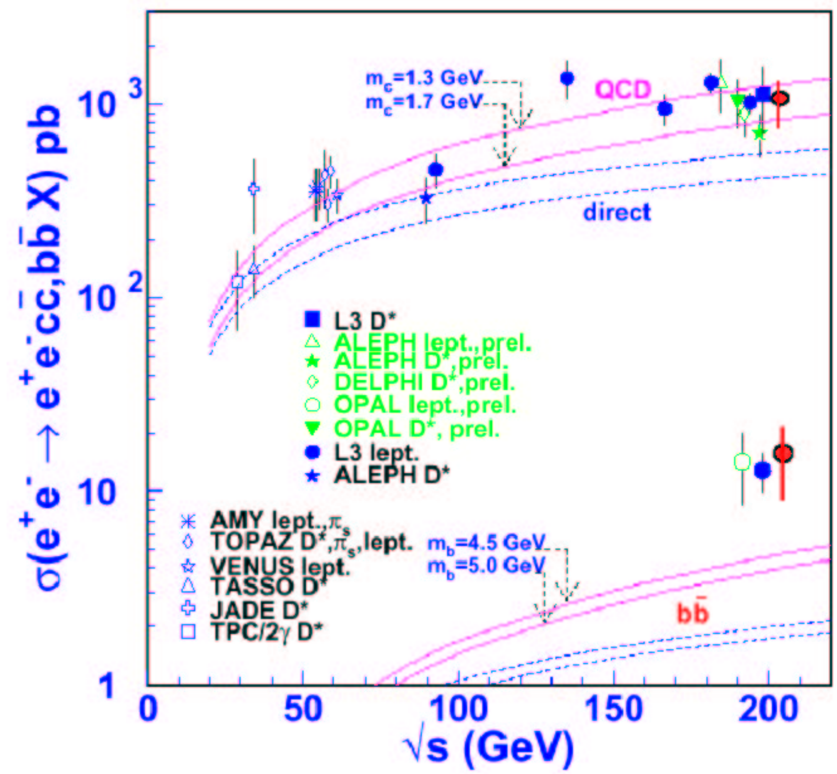
The exciting experimental program ahead:

- LHC: a top factory, and a new energy regime
  - $t\bar{t}$ kinematics, single-t measurements
  - Υ polarization, possibly the cleanest test for NRQCD
  - small-x physics with c data?
- Tevatron: larger p_T range, $b\bar{b}$ correlations
- HERA: more b data, J/ψ measurements

BACKUP SLIDES

On extrapolations and MC truth



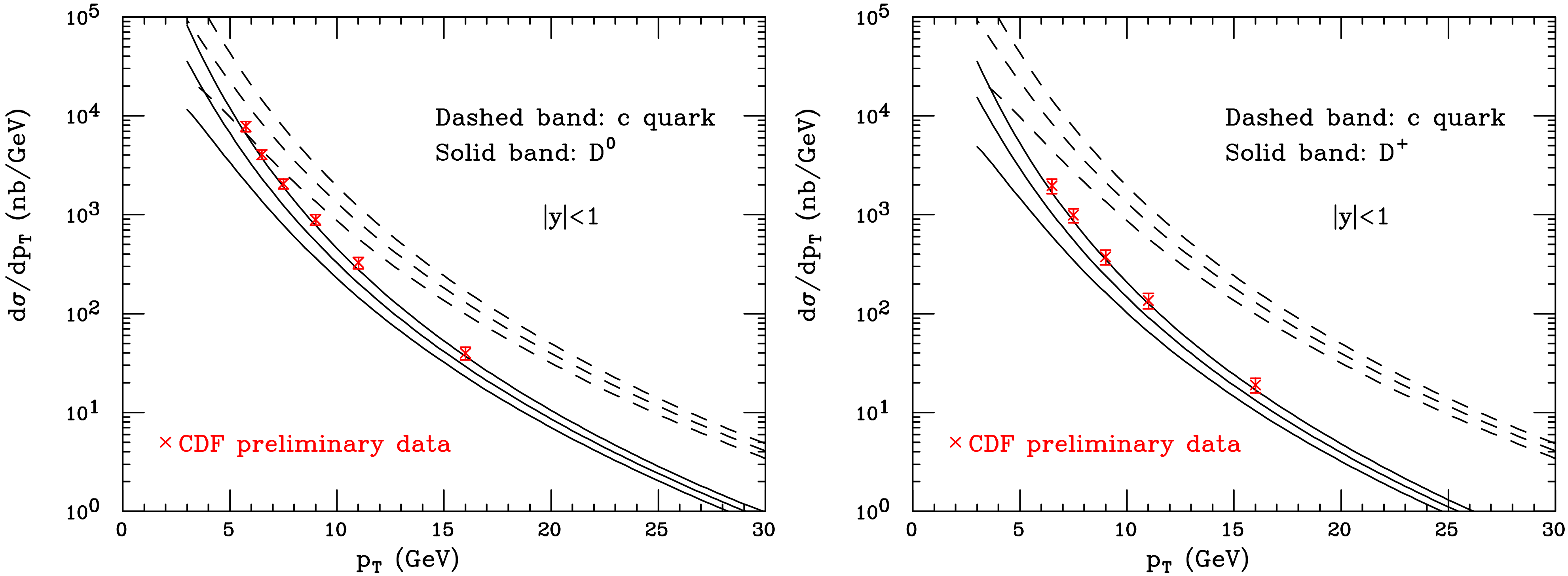


The agreement between pQCD and HERA results is constantly improving: data are now routinely presented in the visible region. At LEP ($\gamma\gamma$ collisions):

- 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

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

Quarkonium production

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

$$d\sigma_{H_1H_2\to H}(S) = \sum_{ij}\int dx_1 dx_2 f_i^{(H_1)}(x_1) f_j^{(H_2)}(x_2) d\hat{\sigma}_{ij\to H}(\hat{s} = x_1x_2S)$$

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

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

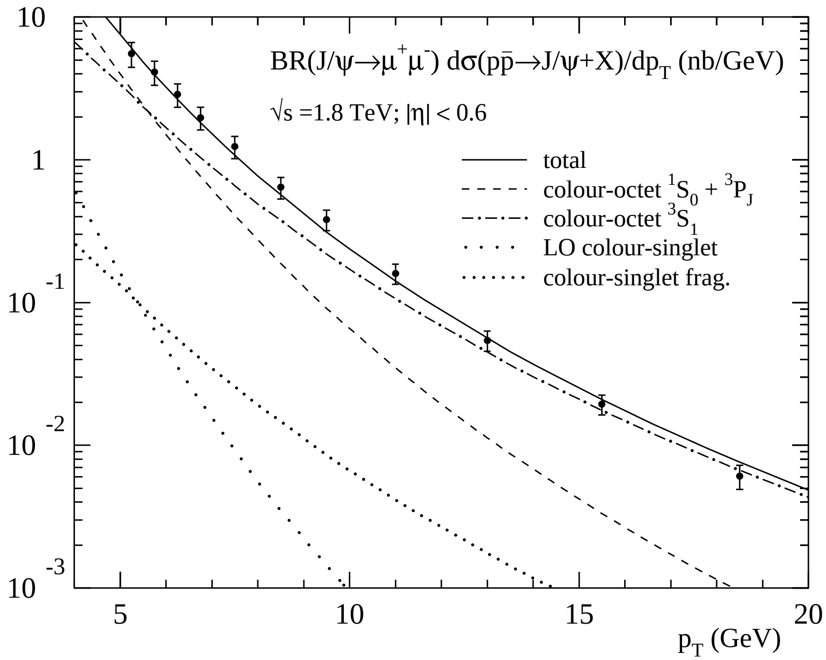
+ Heavy quark spin symmetry and vacuum saturation approximation reduce the number of independent $\langle \mathcal{O}^H[n]\rangle$'s

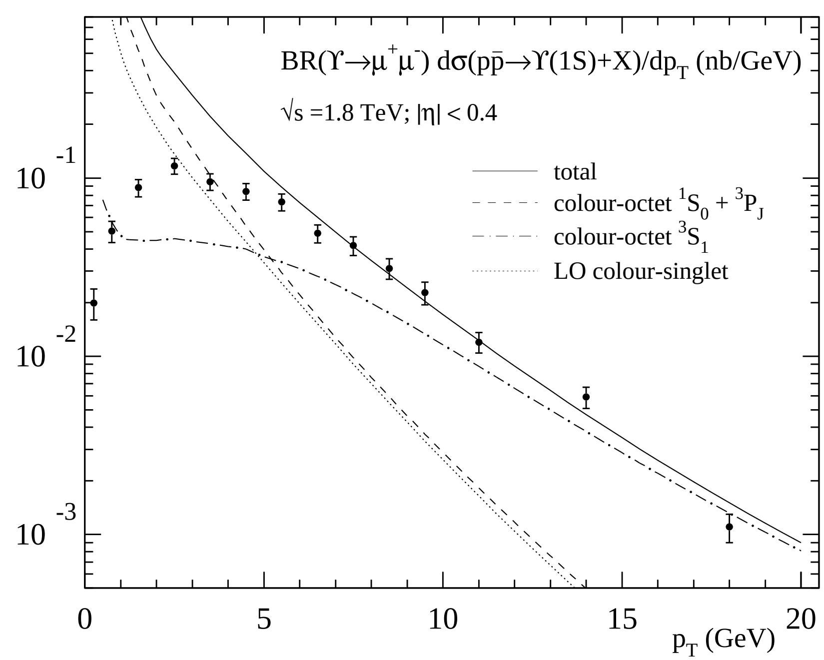
− Factorization is so far unproven (as in many other cases)

− 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

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