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Heavy Quark Production

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- Tools for predictions
  - One-particle distributions (FONLL)
  - Exclusive tools
  - Recent developments towards NNLO
- Recent measurements
  - $\gamma\gamma \to b\bar{b}$ by ALEPH
  - $p\bar{p} \to H_b X$ and correlations by CDF
- Data/theory comparisons

A generic heavy quark production process

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

A generic final state observable

This part is QCD.
How accurately can we predict it?
What ingredients do we need?

Disclaimer

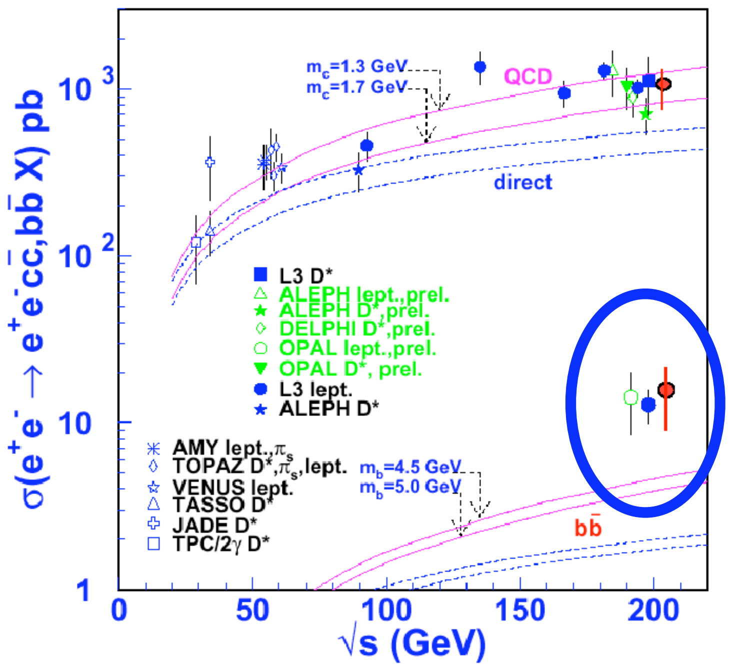
Not a ‘multiparticle dynamics’ talk

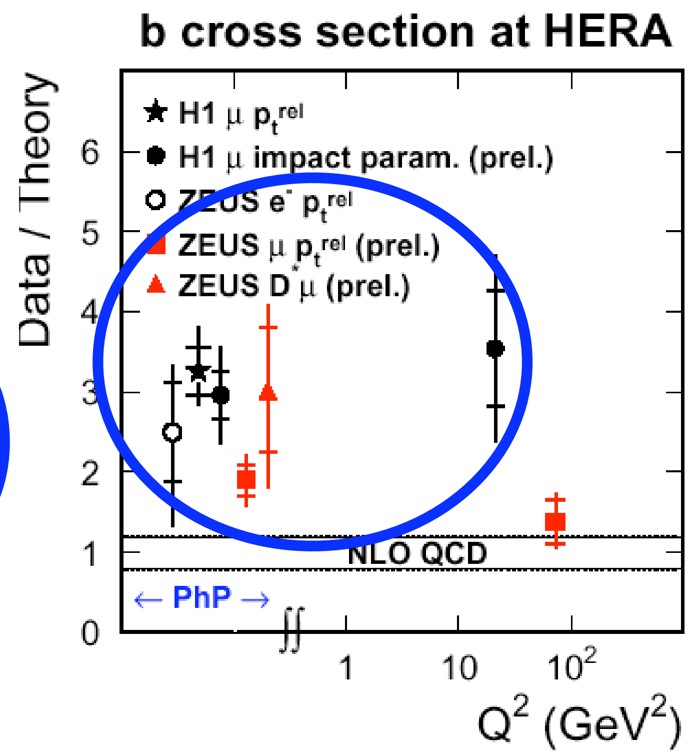
Only hadron-hadron collisions and leading twist perturbative QCD predictions will be considered

The purpose is to establish to what extent QCD is successful in describing heavy quark production in this simple case, before moving on to more complex environments

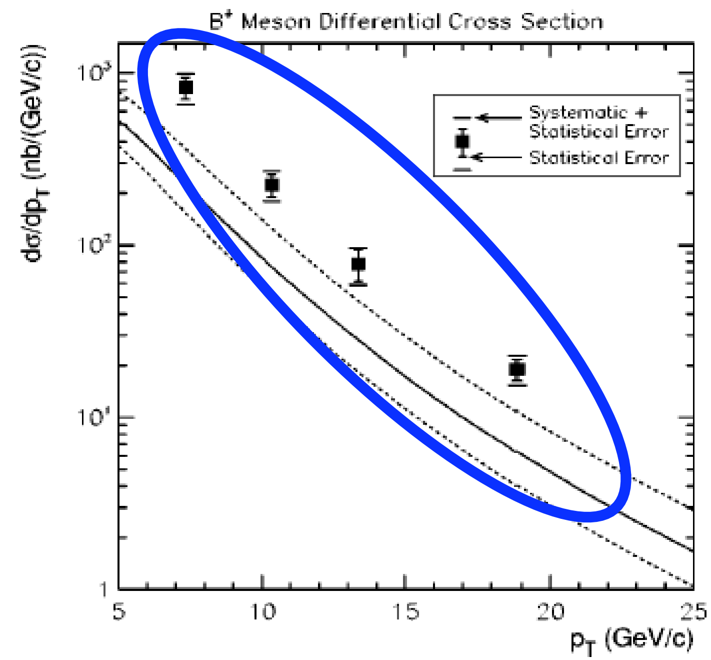
The recent past (< 2002)

LEP





Tevatron



Apparent generalised discrepancy:

factor ~ 3 excess for **bottom** production

A successful comparison

- predict correctly total rates
- predict correctly differential distributions by only adding a <u>minimal</u>, <u>self-consistent</u> and <u>universal</u> set of <u>non-perturbative inputs</u>

NB. A successful comparison will be all the more so if it is an agreement between possibly real measurements (i.e. little or no extrapolations/deconvolutions) and QCD predictions, **<u>within</u> <u>both experimental and theoretical uncertainties</u>** (ren./fact. scales, quark masses, strong coupling, PDFs and FFs, ...)

This means that theorists should try to build flexible and 'exclusive' tools

A generic heavy quark production process

NLO QCD
+ resummations

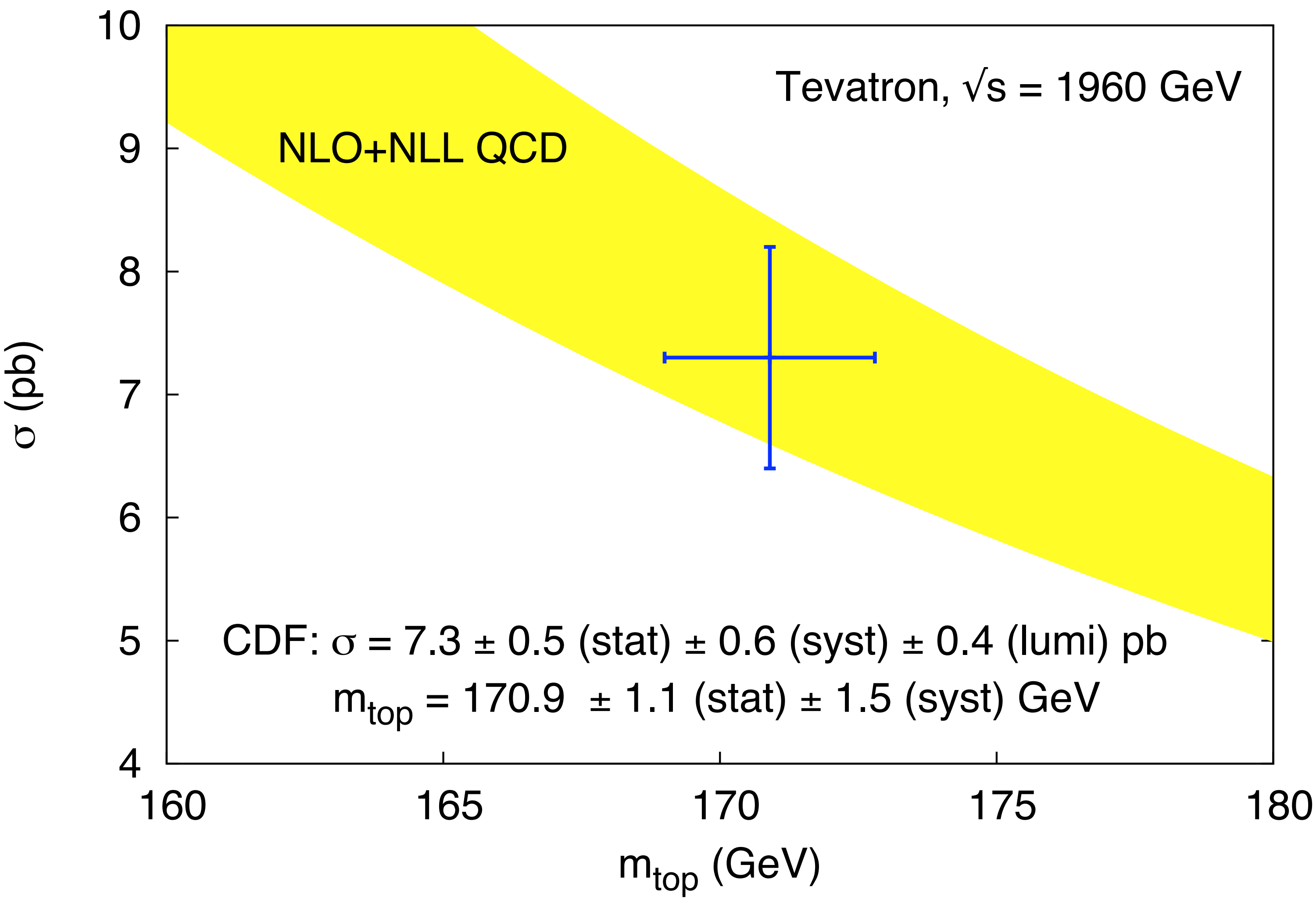
minimal &
properly extracted
NP fragm.

simulation
(usually MC)
of decay

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

For predicting total cross
sections one can stop here

Top total cross section



Good agreement with QCD predictions

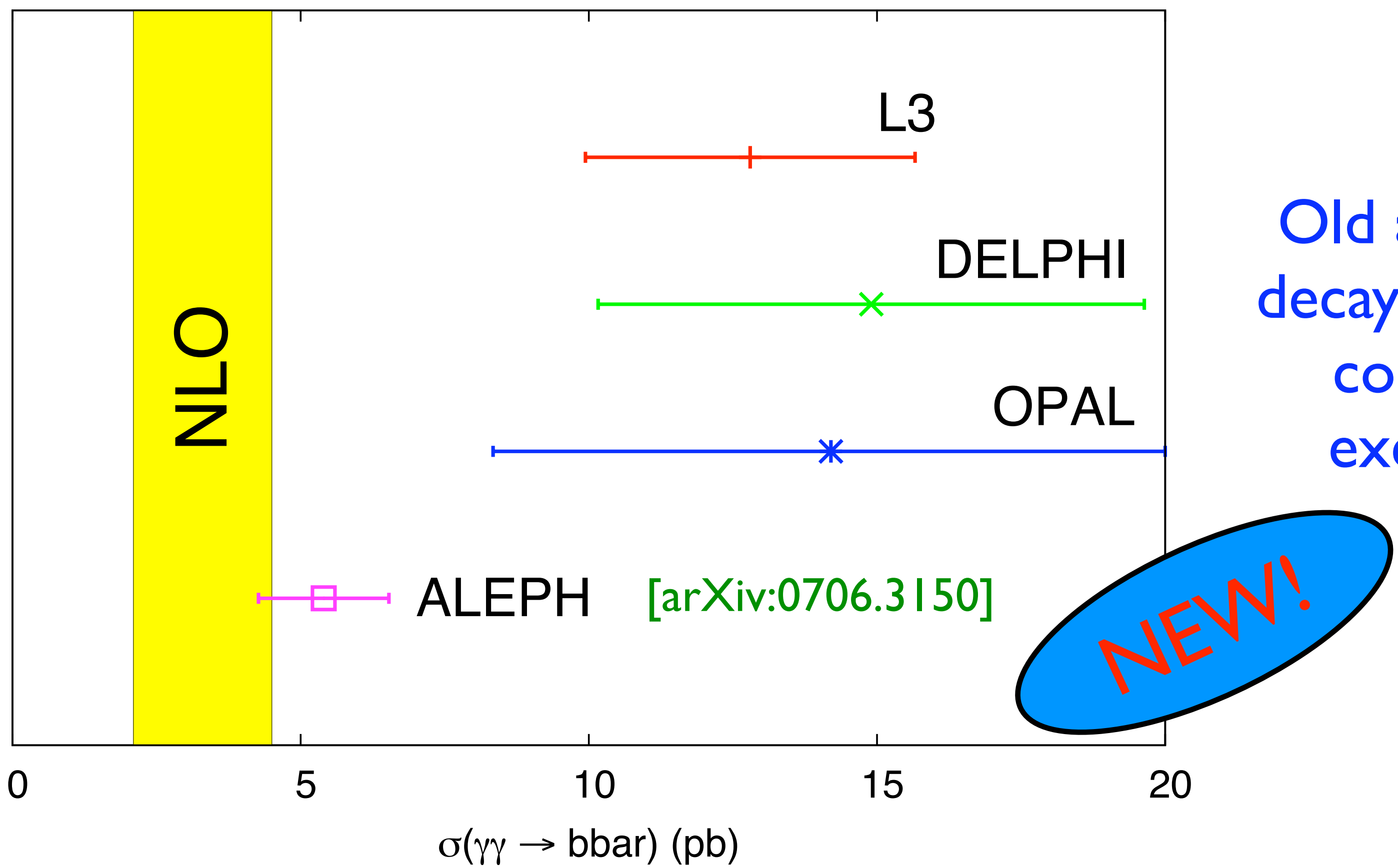
NB: cross section data and theory almost good enough to extract mass from comparison

Not yet competitive with direct measurement, but getting there
Bonus: this would be a NLO pole mass (i.e. better defined than LO PYTHIA mass)

A bottom total cross section measurement

(Beware: you never know where your extrapolation tool might have been)

$$\gamma\gamma \to b\bar{b}$$



Old analyses, all based on B decay into muons, seemed to consistently indicate an excess, albeit with large uncertainties

A recent ALEPH measurement, which uses instead lifetime tagging, is in good agreement with the NLO prediction

[For details see e.g. Alex Finch's talk at PHOTON 2007]

Let's get differential

Total cross sections are rarely really measured.

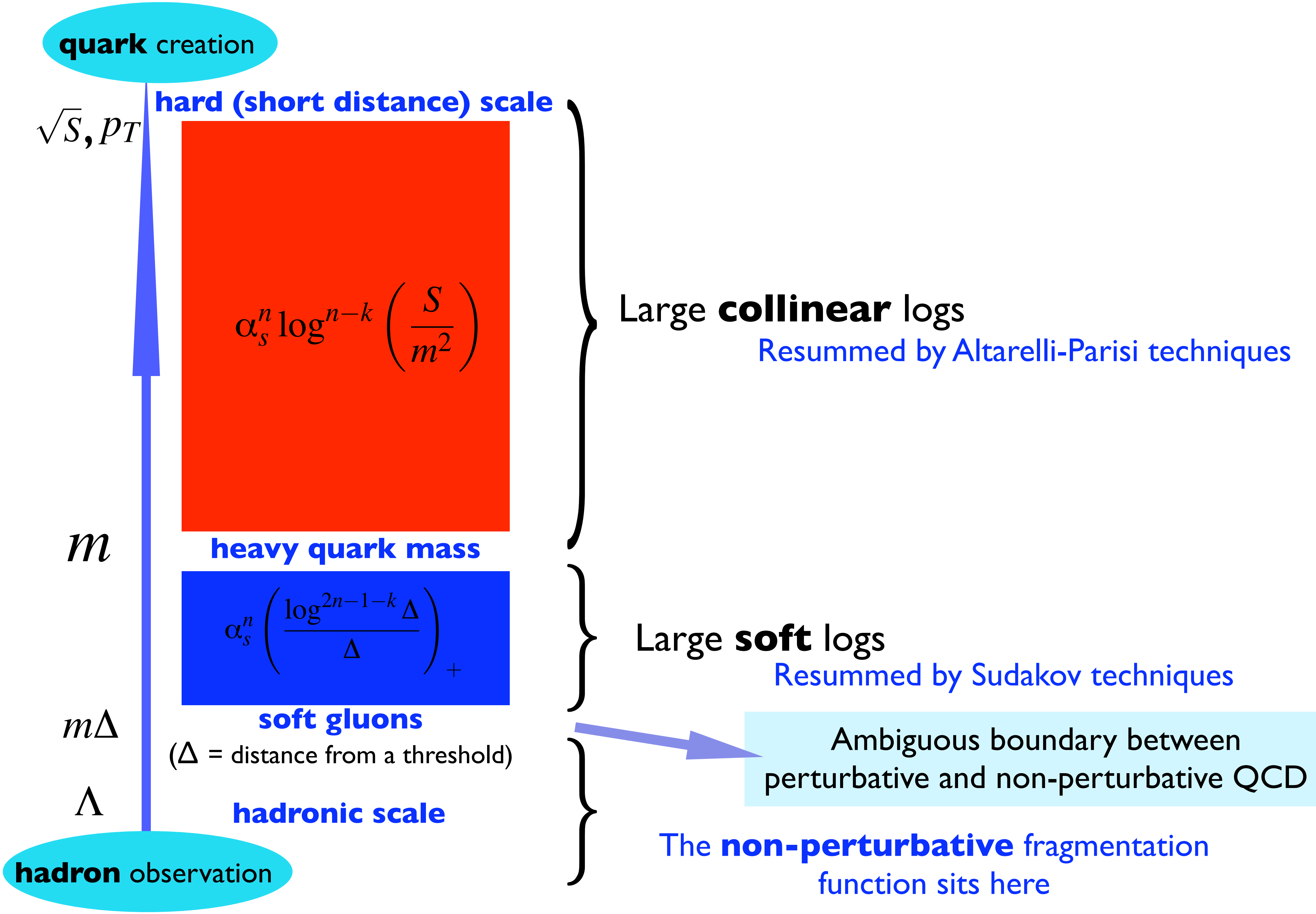
Usually they are obtained by deconvoluting and/or extrapolating the real measurement
This introduces a potential bias from theoretical prejudice that we'd like to avoid

Alternative: **differential** cross section

However, predictions for differential distributions are **harder**:

- Any multi-scale quantity in QCD will display possibly **large logarithms** in the perturbative expansion. These logs will tend to spoil the convergence of the series. Hence, **resummations** will be needed
- Eventually, resummations will not be enough, and genuinely **non-perturbative** contributions will need to be added. They should be included in a correct and minimal way, so as not to spoil the predictivity of pQCD

The many scales in heavy quark production



Phenomenological implementation

$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D^{np}$$

measured cross section

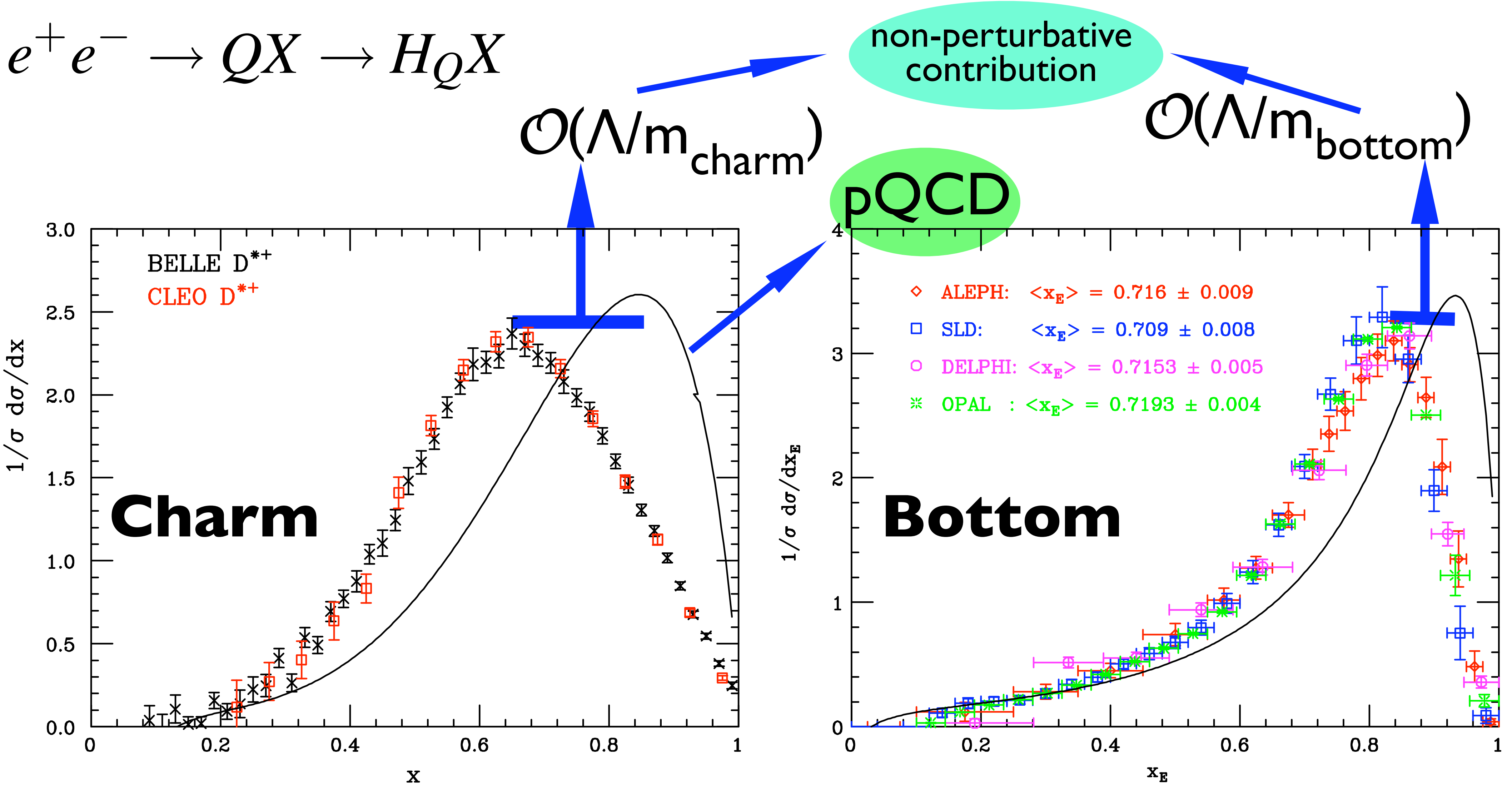
NLO (+NLL) calculation

non-perturbative fragmentation
(usually extracted from e+e- data)

The first bits of a NNLO calculation (2-loop massive diagrams in small mass limit) have very recently appeared [Czakon, Mitov, Moch], but a full calculation and its phenomenological implementation are still far away

NEW!

Non-perturbative fragmentation



- non-perturbative contribution limited in size and compatible with expectations
- high-accuracy expt. data allow it to be precisely determined

Non-perturbative fragmentation

$\langle x^{N-1} \rangle$ moments can give a more quantitative picture:

N	2
c @ 10.58 GeV	0.7359
c @ 91.2 GeV (NS)	0.5858
c @ 91.2 GeV (full)	0.5954
b @ 91.2 GeV	0.7634
BELLE $D^{*+} \to D^0$ (ISR corr.)	0.6418 ± 0.0042
ALEPH D^{*+} (ISR corr.)	0.4920 ± 0.0152
ALEPH B	0.7163 ± 0.0085
CLEO D^{*+}	$0.877^{+0.009}_{-0.010}$
BELLE $D^{*+} \to D^0$	$0.872^{+0.005}_{-0.006}$
ALEPH D^{*+}	$0.840^{+0.022}_{-0.031}$
Tab. 2 and eq. (4.2)	0.868
ALEPH B	$0.938^{+0.009}_{-0.014}$
SLD B	$0.931^{+0.016}_{-0.030}$

N=2 moments (i.e. $\langle x \rangle$)

pQCD

data

$$D^{np} = \frac{\text{data}}{\text{pQCD}}$$

charm ~ 1 - 0.16

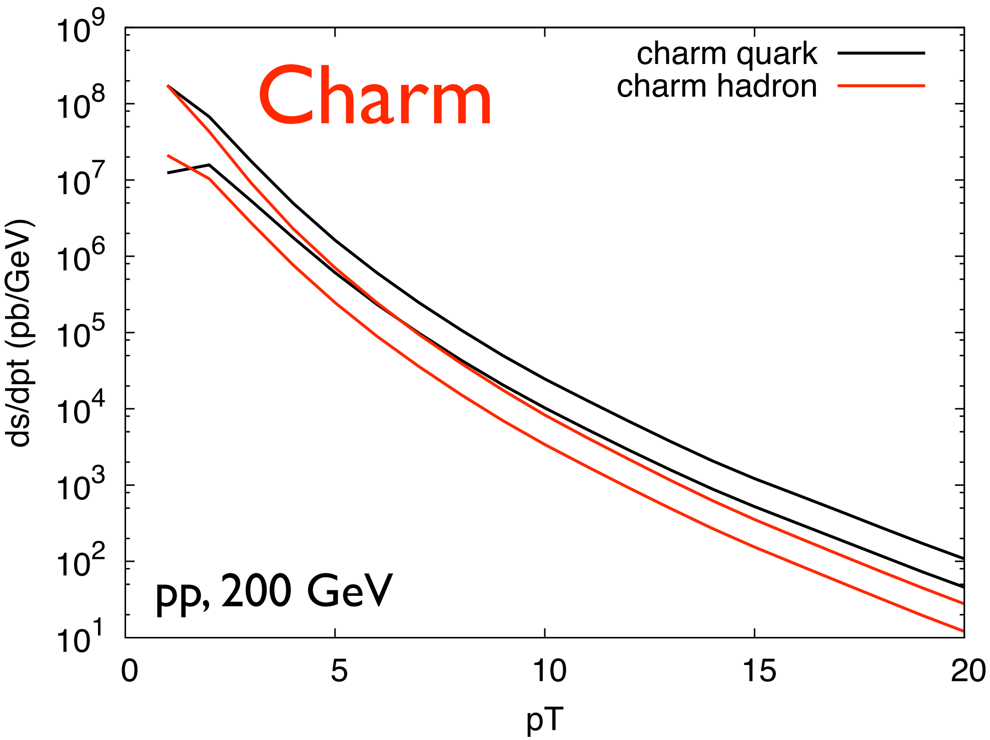
bottom ~ 1 - 0.06

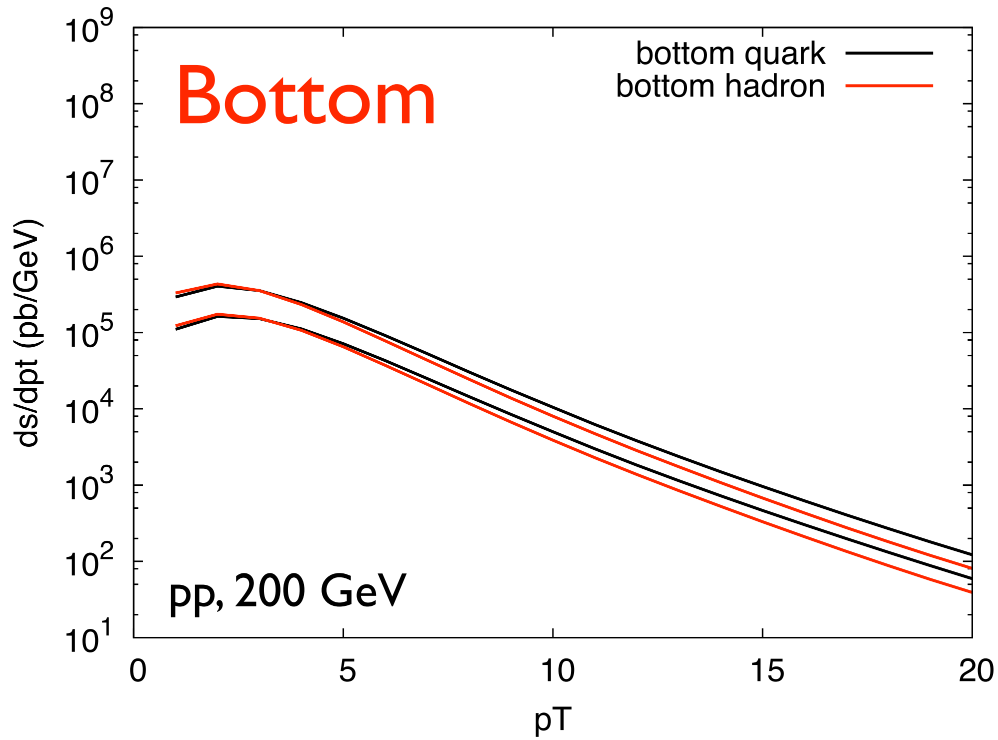
Compatible with $D_N^{np} = 1 - \frac{(N-1)\Lambda}{m} + \cdots$ and $\Lambda \simeq 0.25$ GeV

Heavy quark cross sections

Heavy quarks are special:
their **total number** (and that of **heavy hadrons)**
is a **genuine prediction of pQCD**

Not so for **differential** distributions: hadrons and quarks differ





However, the non-perturbative correction is expected
(and observed) to be **parametrically small,** $\mathcal{O}(\Lambda/m)$
(Still, at large p_T the effect can be large)

More exclusive tools

To describe correlations one needs exclusive control over both heavy quarks and, for a realistic prediction, over they hadronisation and decay products

- **Shower MonteCarlos** [e.g. PYTHIA, HERWIG, ...]

  Leading order matrix elements, parton shower, detailed hadronisation and decay models

- **NLO + fragmentation + decay**

  Next-to-leading order matrix elements, no parton shower, very simple minded hadronisation and decay

  + PYTHIA [Geiser, Nuncio Quiroz] (photoproduction)

  Better description of hadronisation and decays, but no shower

  NEW!

- **MC@NLO** [Frixione, Webber]

  Proper matching of NLO matrix elements and parton shower, interfaced to HERWIG for proper hadronisation and decays models, but a lot of negative weights

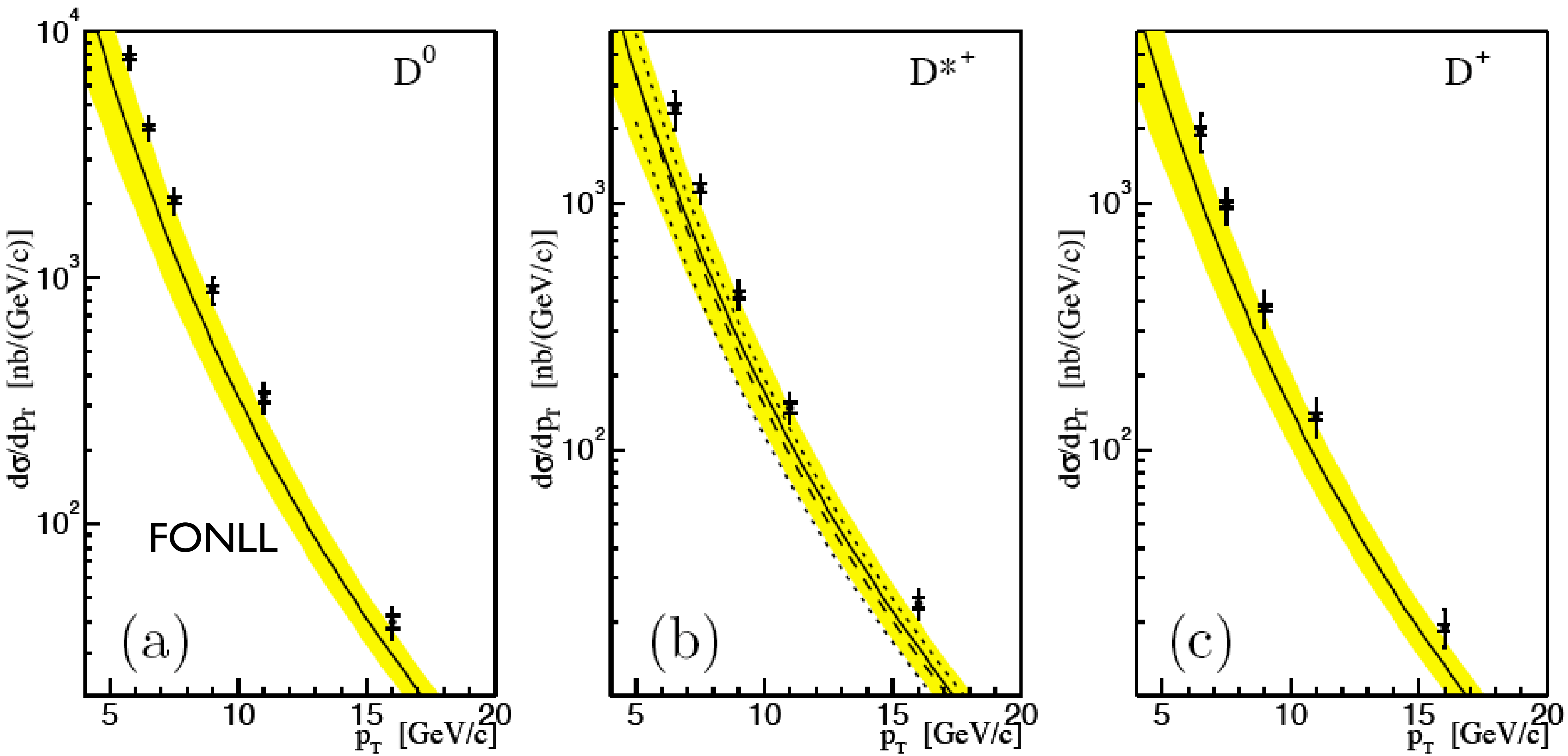
- **POWHEG** [Nason]

  Like MC@NLO, but positive weights only. Can be interfaced to any shower MonteCarlo

  NEW!

Charm production @ Tevatron Run II

CDF Run II   c → D data   [PRL 91:241804,2003]



The non-perturbative charm fragmentation needed to describe the c → D hadronization has been extracted from moments of ALEPH data at LEP.

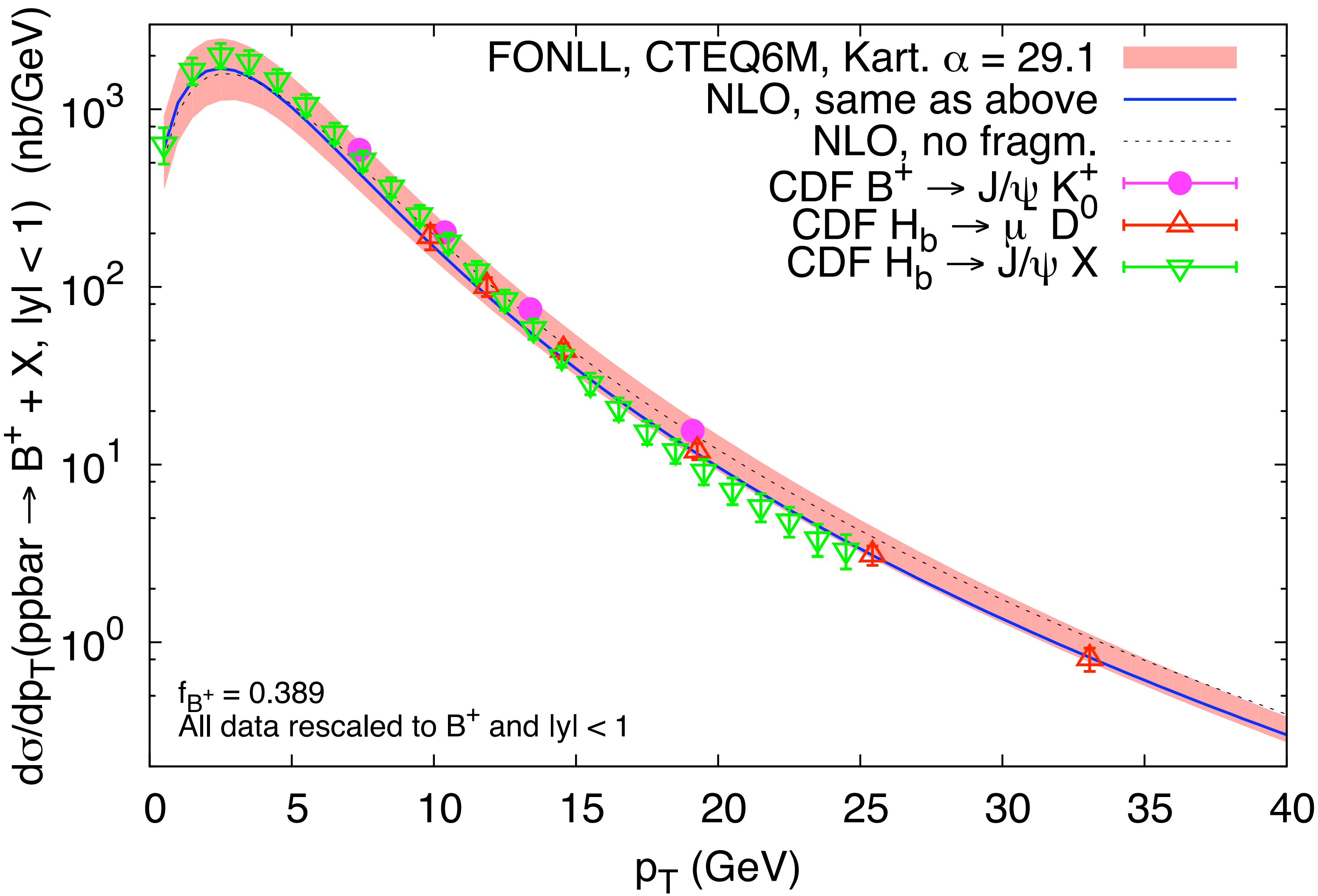
Bottom integrated cross sections @ Tevatron

CDF	THEORY (FONLL)
$H_b \to J/\Psi\ X$	
$\sigma(H_b, p_T > 0, \lvert y\rvert < 0.6) = 17.6 \pm 0.4^{+2.5}_{-2.3}\quad \mu b$	$15.3^{+6.7}_{-4.4}\quad \mu b$
$B^+ \to J/\Psi\ K^+$	
$\sigma(B^+, p_T > 6\ \mathrm{GeV}, \lvert y\rvert < 1) = 2.78 \pm 0.24\quad \mu b$	$2.28^{+0.88}_{-0.58}\quad \mu b$
$H_b \to \mu^-\ D^0$	
$\sigma(H_b, p_T > 9\ \mathrm{GeV}, \lvert y\rvert < 0.6) = 1.34 \pm 0.08^{+0.13}_{-0.14} \pm 0.07\quad \mu b$	$1.38^{+0.48}_{-0.32}\quad \mu b$

NEW!

- Good agreement between experiments and theoretical prediction
- Expt. errors smaller than theoretical ones

Bottom differential cross sections @ Tevatron

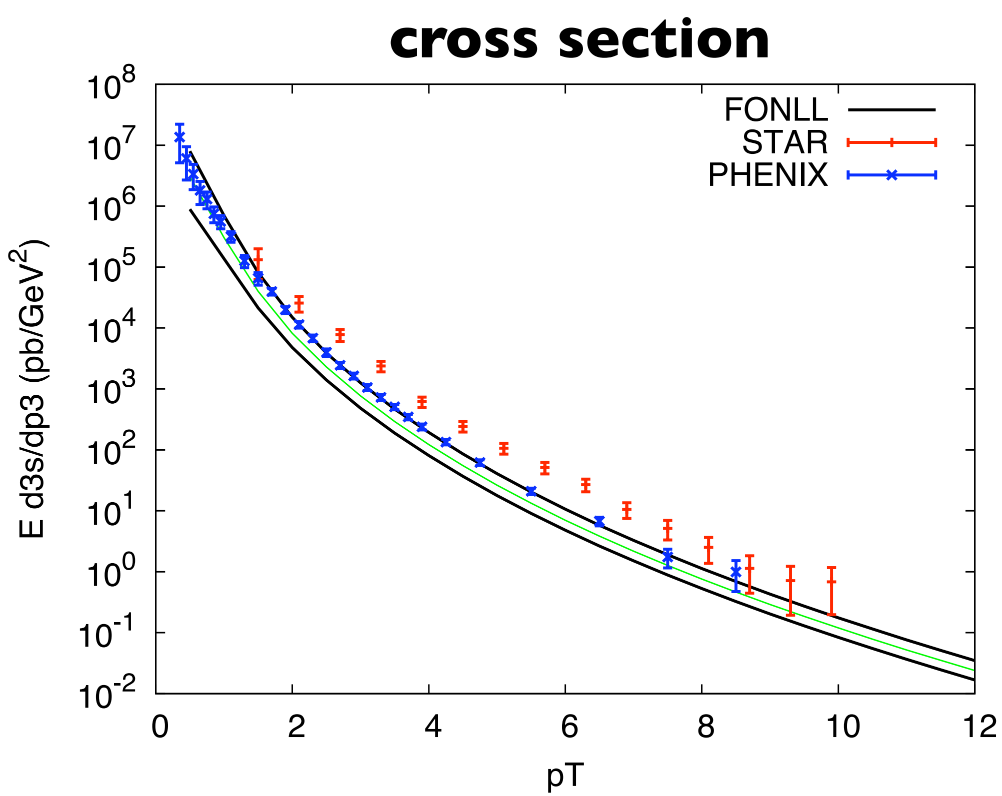


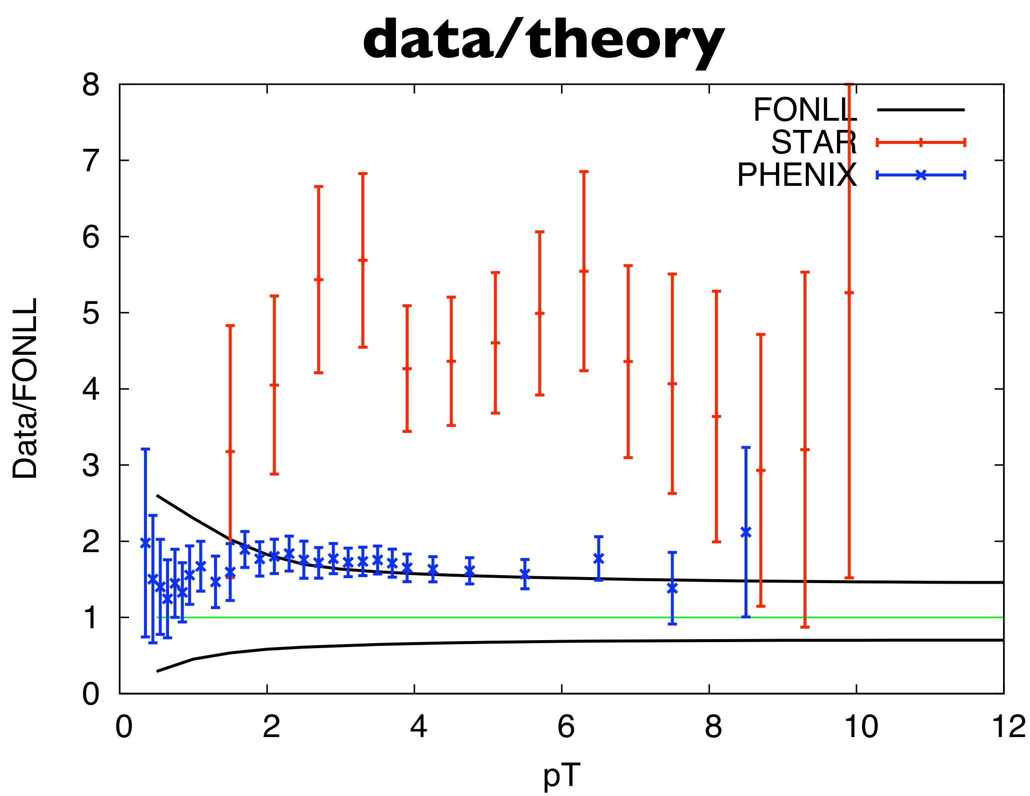
Good agreement, with minimal non-perturbative correction

NLO is sufficient for correct total rate prediction

Charm and bottom production @ RHIC

Non-photonic electrons from charm and bottom



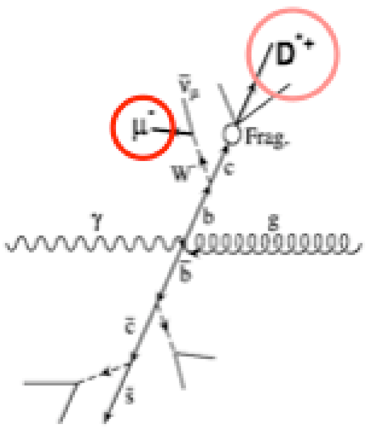


STAR non-photonic electron data show a sizable excess, while PHENIX (and other comparisons) seem to agree with theoretical predictions

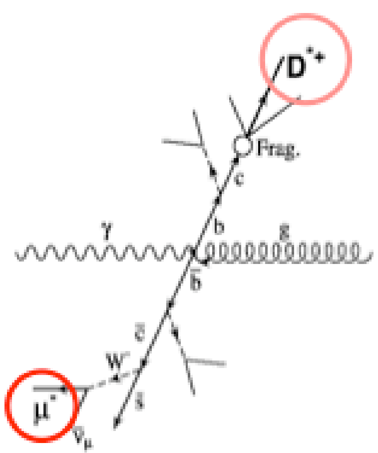
Applications

Eur.Phys.J.C50:299-314,2007 hep-ex/0609050

Visible Beauty Cross sections from $ep \rightarrow b\bar{b}X \rightarrow D^* \mu X'$



$p_T(D^*) > 1.9$ GeV, $-1.5 < \eta(D^*) < 1.5$, $p_T(\mu) > 1.4$ GeV, $-1.75 < \eta(\mu) < 1.3$	data/NLO
ZEUS $\sigma_{vis} = 160 \pm 37(\text{stat})\ ^{+30}_{-57}$ (syst.) pb **FMNR⊗PYTHIA $\sigma_{vis} = 67\ ^{+20}_{-11}$ (NLO) $^{+13}_{-9}$ (frag+br) pb**	$2.4\ ^{+0.9}_{-1.3}$
Photoproduction only: $Q^2<1$ GeV^2, $0.05<y<0.85$ ZEUS $\sigma_{vis} = 115 \pm 29(\text{stat})\ ^{+21}_{-27}$ (syst.) pb **FMNR⊗PYTHIA $\sigma_{vis} = 54\ ^{+15}_{-10}$ (NLO) $^{+10}_{-7}$ (frag+br) pb**	$2.1\ ^{+0.8}_{-1.0}$



Extrapolated to b level using PYTHIA **$y_{rap}(b) < 1$, $Q^2 < 1$ GeV^2, $0.05<y<0.85$,**

σ (ep –> b or b X) = 11.9 ± 2.9 (stat) $^{+1.8}_{-3.3}$ (sys) nb

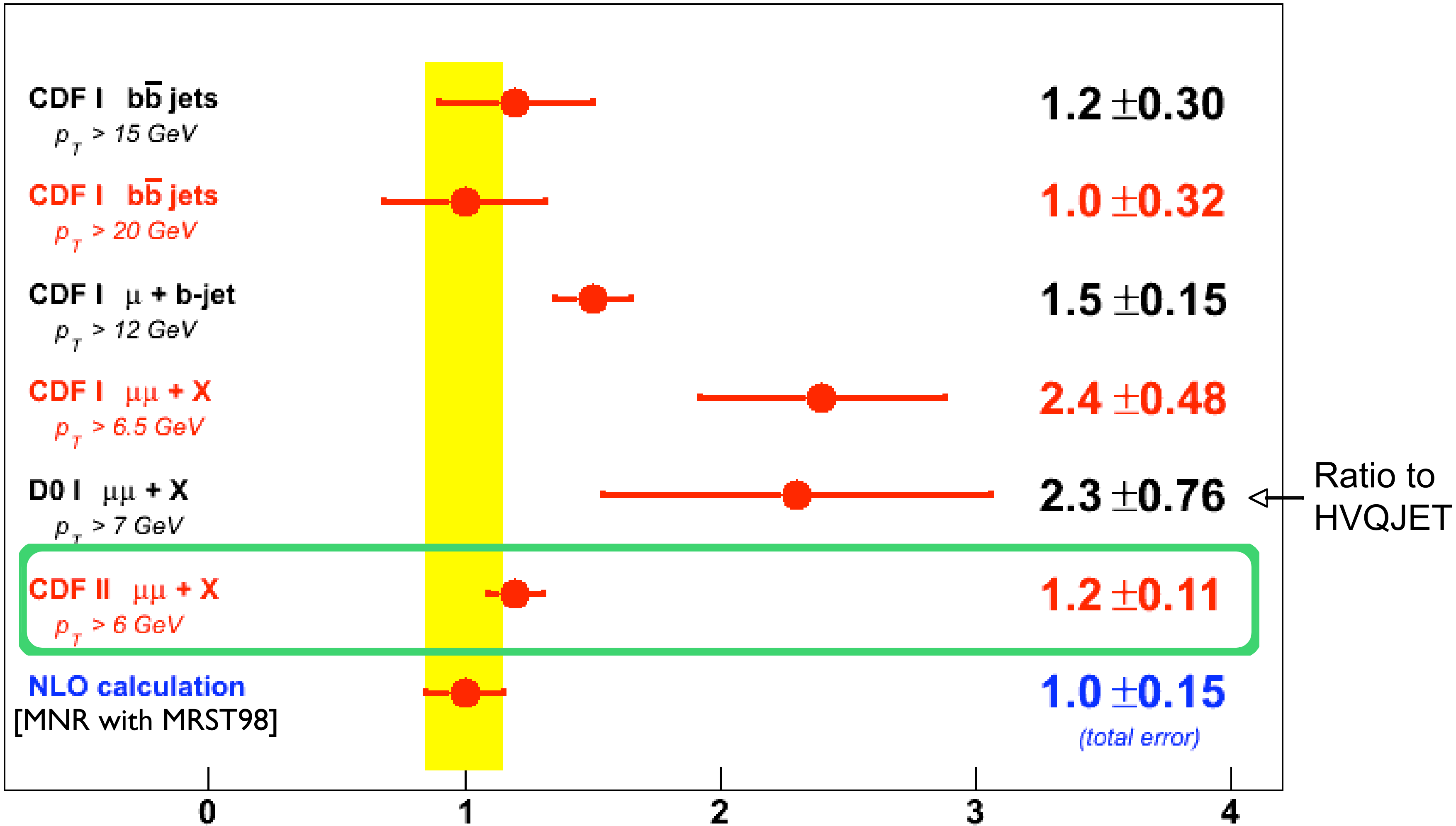
NLO QCD (FMNR) = $5.8\ ^{+2.1}_{-1.3}$ nb

data/NLO $2.0\ ^{+0.8}_{-1.1}$

- Data and theory still compatible
- Comparisons at b quark and visible level yield the same data/NLO ratio
- Therefore the extrapolation was reliable
- Consistent with similar analysis by H1 (see backup slides)

$b\bar{b}$ correlations

A. Annovi, EPS 2007



$< R_{2b} > = \sigma(\text{data})/\sigma(\text{NLO})$

Some earlier measurements showed a **suspicious pattern** (the more muons, the larger the disagreement), but the most recent measurement is in perfect agreement with a NLO-based prediction

Conclusions

- Heavy quark phenomenology is mature and has the tools to produce predictions in many **realistic** situations. These predictions can include all the available knowledge for calculating heavy quark production in QCD. Since they are implemented in a rigorous framework, it is usually possible to also provide a (more or less reliable) estimate of the **theoretical uncertainty**

- Most predictions seem to agree well with Tevatron and HERA data for charm and bottom production. The STAR excess looks a little puzzling, given the better agreement of many other measurements

- Final note: given the size of intrinsic pQCD uncertainties, it is very unlikely that effects of the order of a few (tens of) percent will ever be visible just by comparing to the absolute value of the cross sections. This might (might!) only be doable with a NNLO calculation

Backup slides

Factorization 'theorem' for heavy quark hadroproduction

Collins, Soper, Sterman, Nucl. Phys. B263 (1986) 37

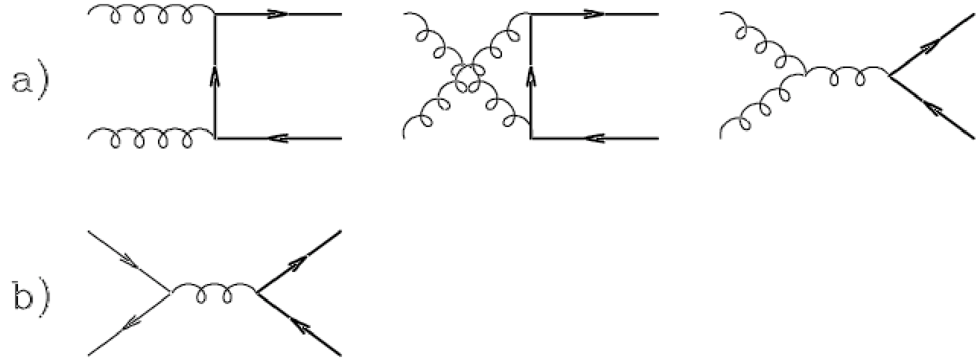
$$\sigma_Q(S,m^2) = \sum_{i,j\in L} \int dx_1 dx_2 \hat{\sigma}_{ij\to QX}(x_1x_2S, m^2; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) F_{i/A}(x_1,\mu_F) F_{j/B}(x_2,\mu_F) + O\left(\frac{\Lambda}{m}\right)^p$$

Light flavours only

contribute most of the total cross section. The hard scattering function is perturbatively calculable in an expansion in powers of $\alpha_s(M)$: potential singularities in H have been factorized into the parton distribution functions. Corrections to this formula are suppressed by powers of (hadron mass scale/M).

We have by no means proved this result in this paper, but we believe that the analysis given here should make the result plausible. We are arguing that heavy

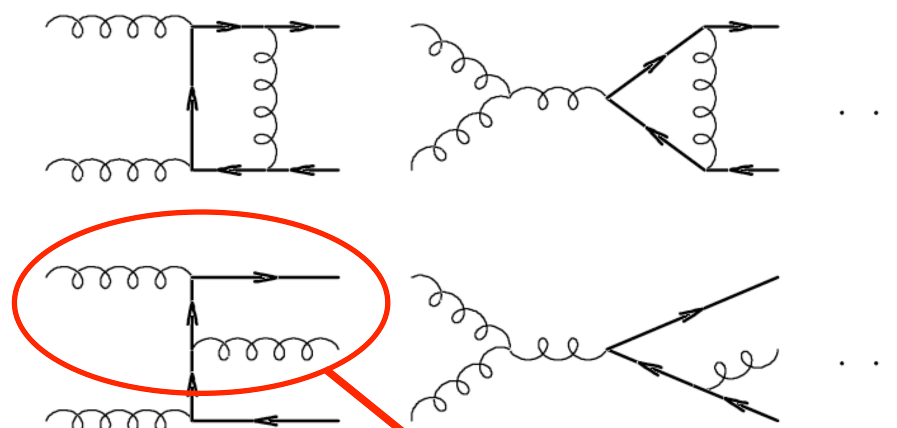
NLO implementation of factorization theorem



Leading order diagrams

(Some of the) Next-to-Leading order diagrams

Nason, Dawson, Ellis, NP B327 (1989) 49, NP B303 (1988) 607
Beenakker, van Neerven, Meng, Schuler, Smith, NP B351 (1991) 507



'flavour excitation'

No need to have, e.g., charm in the proton

This is still the state of the art for fixed order perturbative calculations, and should be the building block of all phenomenological predictions:

- it incorporates in a rigorous manner production "channels" like flavour excitation and gluon splitting which Monte Carlo or 'improved' leading order calculations have to include by hand (beware MC tunes and recipes!!)
- it allows a **rough estimate of the theoretical uncertainty**

Extraction of the non-perturbative component

Three issues are important:

1. The perturbative description (and its parameters) used in extracting the FF must match the one used in calculating predictions using the FF

2. Try to extract an as universal as possible non-perturbative FFs. Resumming the perturbative collinear logarithms (large at LEP: log(√S/m)) helps doing precisely this

3. Because of the steep slope of transverse momentum distributions in hadron-hadron collisions, higher Mellin moments of the FF are actually more important than its x-space shape:

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

Heavy **quark** spectrum, N typically ~ 4,5

Heavy **meson** spectrum

Mellin **moment** of the fragmentation function

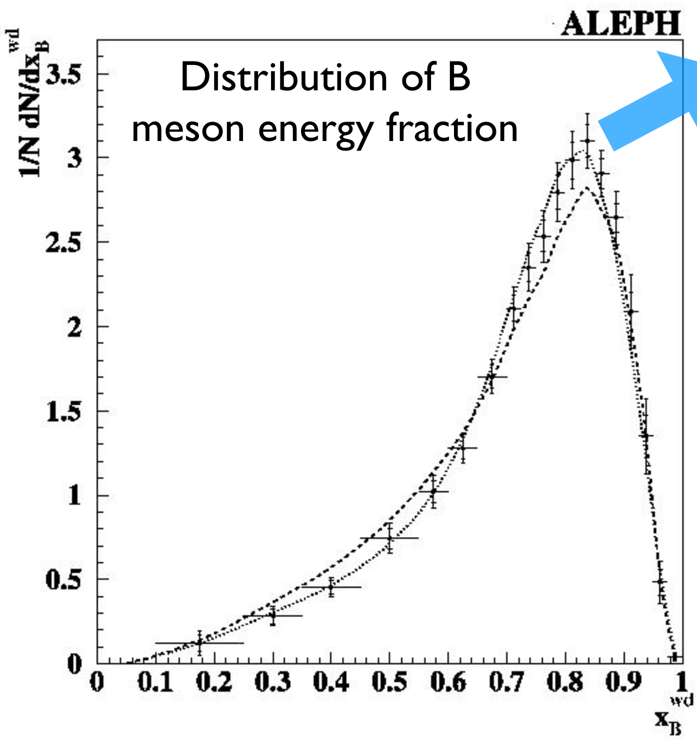
Heavy **quark** spectrum

Fitting well the proper moments (N ~ 4-5) is therefore more important then describing the whole fragmentation spectrum in e+e- collisions, if the fragmentation function is then to be used for making predictions in hadronic collisions

[This third step, is a bit exotheric, but numerically fairly important. It's the one which explaines why the usual Peterson FF in conjunction with a NLO calculation does not give a good description of heavy quark fragmentation: FF's extracted from moments are quite harder!]

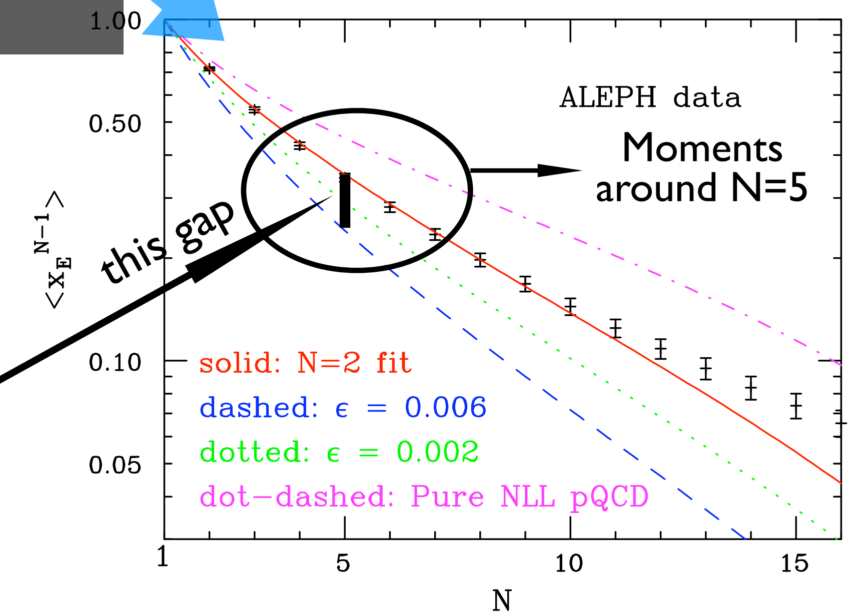
Extraction of the non-perturbative component for FONLL

Fit **moments** of LEP fragmentation data:



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

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



Don't fit this...... **...but rather this**

The extracted fragmentation functions are specific to the FONLL framework

For a comparison, they **roughly** correspond to Peterson et al. FF's with $\boldsymbol{\epsilon_c \approx 0.005}$ and $\boldsymbol{\epsilon_b \approx 0.0005}$

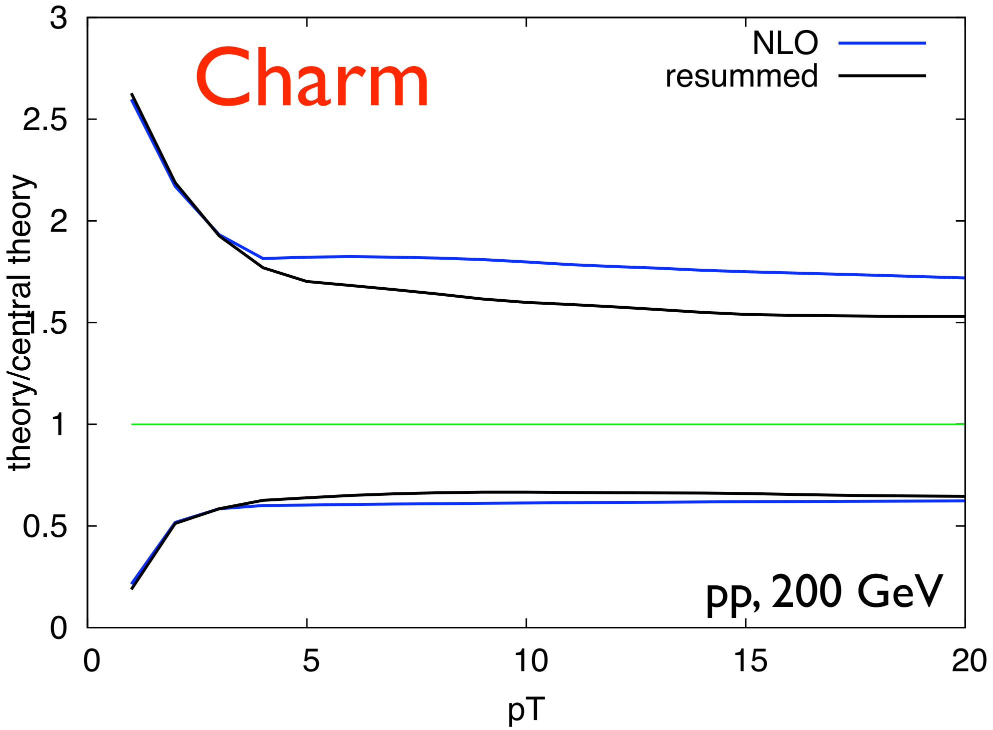
$\Rightarrow$ quite harder than 'usual' values $\epsilon_c \approx 0.06$ and $\epsilon_b \approx 0.006$

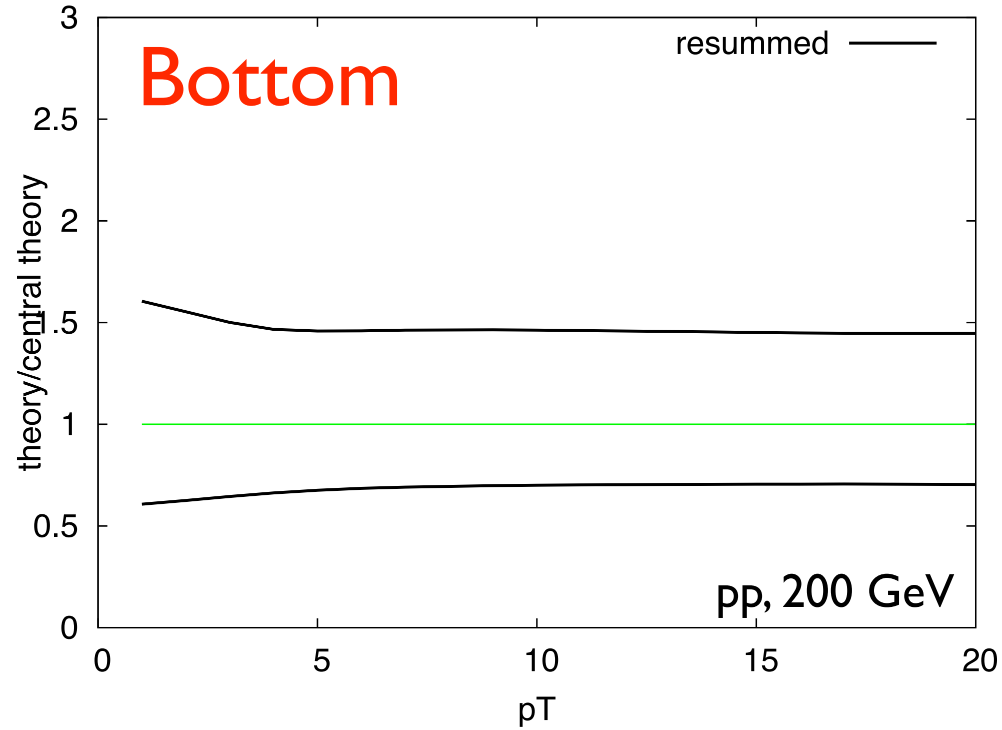
$\Rightarrow$hadronic cross sections will be larger

Perturbative uncertainties

$$\frac{\textbf{max} \text{ and } \textbf{min} \text{ of theory}}{\textbf{central} \text{ theory}}$$

Vary scales independently, vary mass, sum in quadrature, take max and min





No big effect of resummation in this region. But its big contribution lies in the accurate determination of the non-perturbative component from e+e- data

Non-perturbative uncertainties

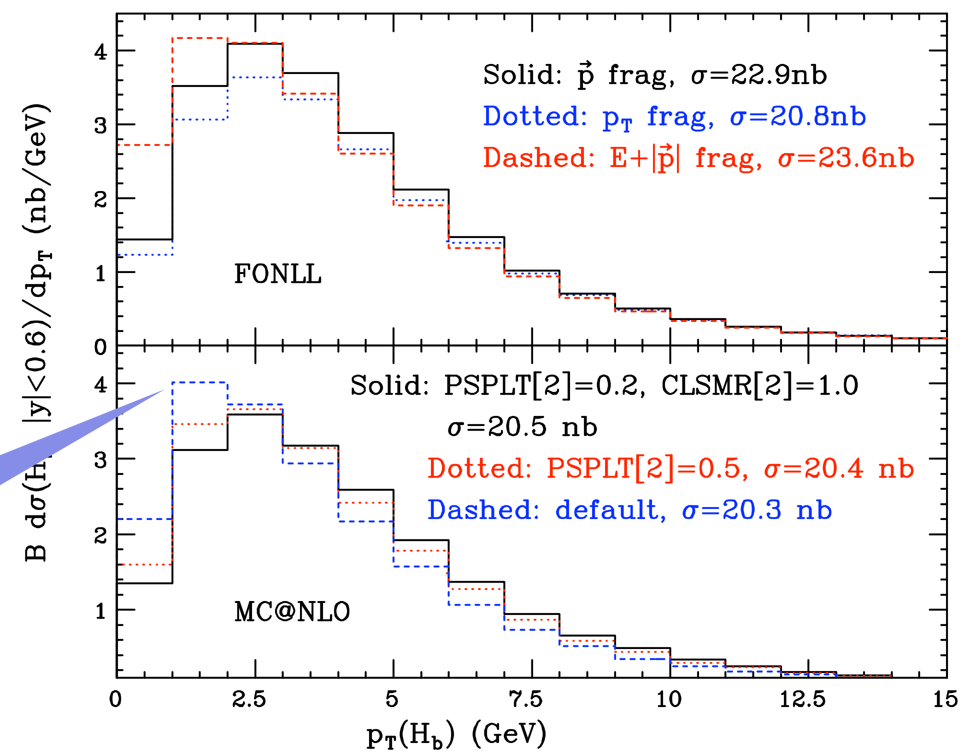
The non-perturbative FF is usually employed in hadronic collisions by writing

$$E_H \frac{d^3\sigma_H(p_H)}{dp_H^3} = E_Q \frac{d^3\sigma_Q(p_Q)}{dp_Q^3} \otimes D^{np}_{Q\to H}$$

Besides the uncertainties in its extraction from data (usually small with modern data), bear in mind that when the transverse momentum is small two things happen:

1. The "independent fragmentation" picture fails, as factorization-breaking higher twists grow large. So, whatever the result of the convolution above, there will be further uncertainties looming over it

2. Scaling a massive particle's 4-momentum is an ambiguous operation. One can scale the transverse momentum at constant rapidity, the 3-momentum at constant angle in a given frame, etc.



Different fragmentation choices