HERA and the LHC Workshop
WG3 – Heavy Quarks
Summary

Part 1. Theory (M.Cacciari)

Part 2. Benchmark cross sections and small-x (A.Dainese)

Part 3. Outlook on HVQ physics at HERA-II (A.Geiser)

WG3 Conveners:

M.Cacciari, M.Corradi, A.Dainese,
A.Meyer, M.Smizanska, U.Uwer,C.Weiser

Disclaimer

Two parts:

1 - Global summary: not just this meeting, but also references to previous ones. In some instances, summary of summaries

Not a point-by-point summary. Rather, will give a personal selection of issues/presentations/outcomes (apologies to those overlooked or misinterpreted)

Explicit references to authors/speakers will be random and/or incomplete. Again, preemptive apologies to those whose name is missing. Please refer to agendas where talks and transparencies are posted

2 - Massimo Corradi's summary on HQ fragmentation studies

Main issues: ‘test’ theory, see if HERA can constrain approaches/parameters for LHC

Open Heavy Quark production:

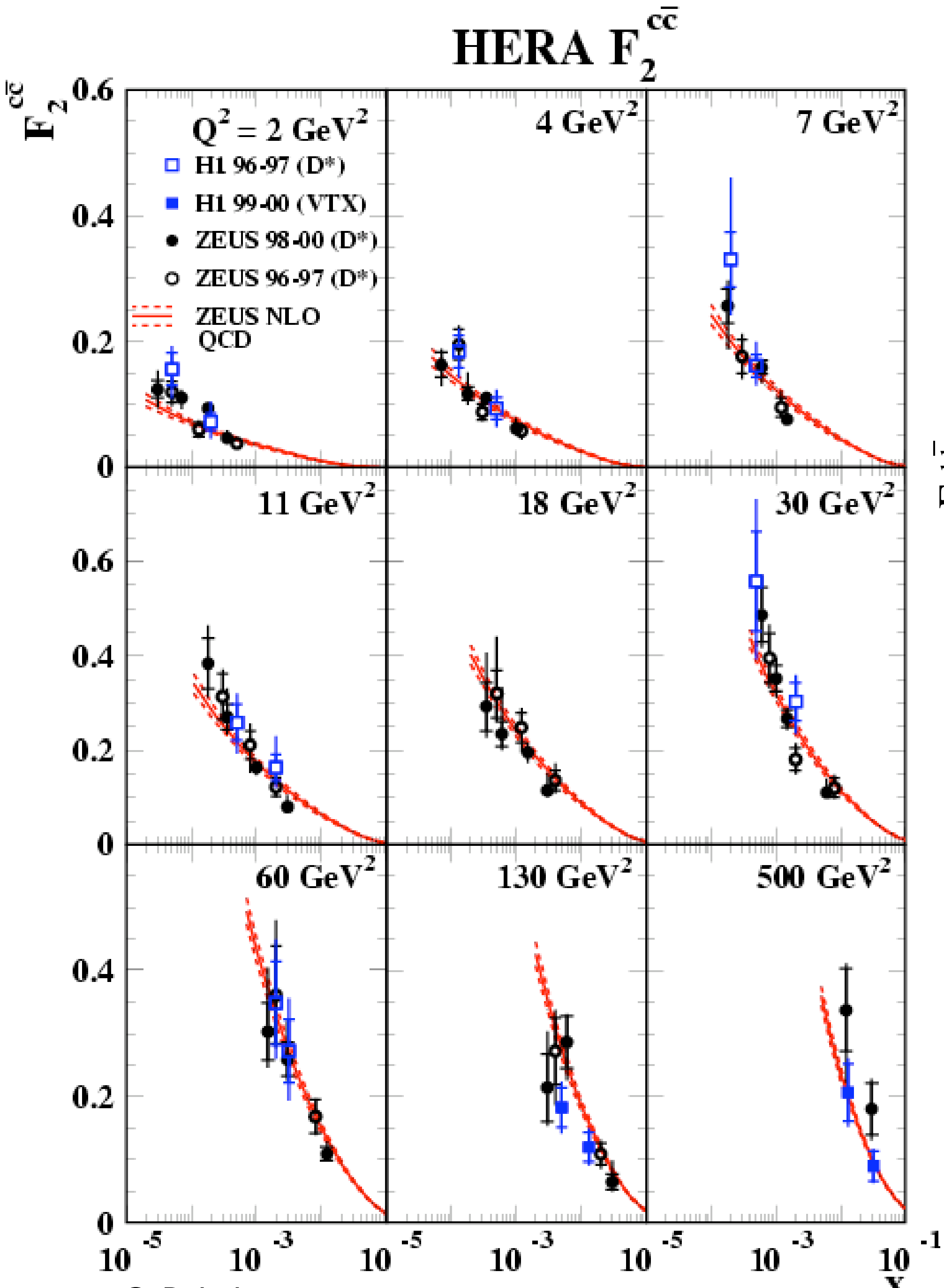
- fixed order calculations
- resummed calculations (Laenen, Kniehl, Schienbein, Kretzer,....)
- kT-factorization (Zotov, Baranov, A. Lipatov, ...)
- small-x (Jung, Peters, Kolhinen, Kutak, ...)
- exclusive production (Piskounova, ...)
- Montecarlo/MC@NLO
- ....

Quarkonium production:

- NRQCD
- kT-factorization
- summary from the Quarkonium Working Group (A. Meyer)

Not pursued in the workshop

Open Heavy Quark production

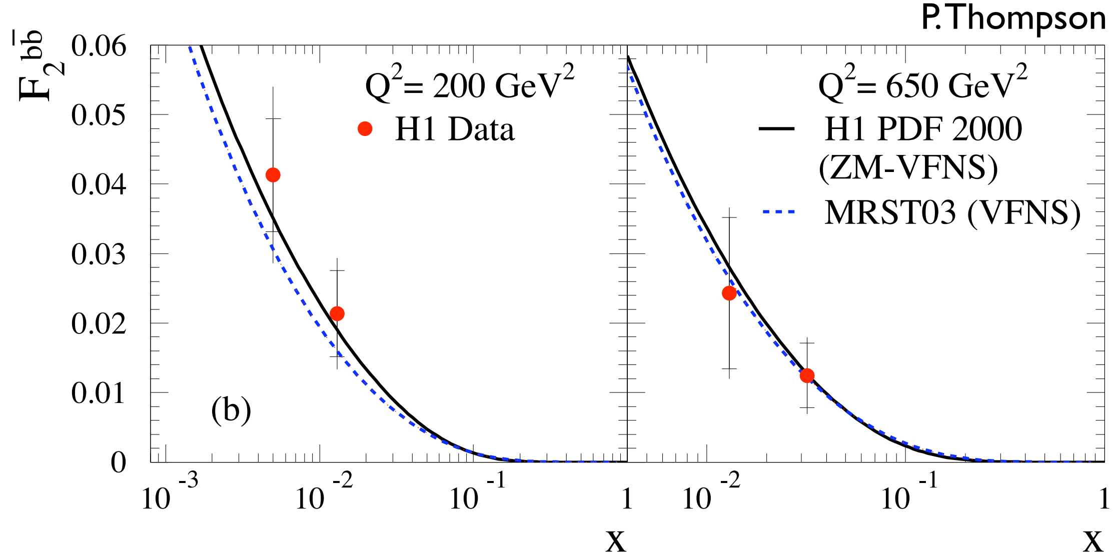


O. Behnke

In HERA parlance:

photoproduction, F_2^c and F_2^b

P. Thompson



Open Heavy Quark production

Many approaches are possible:

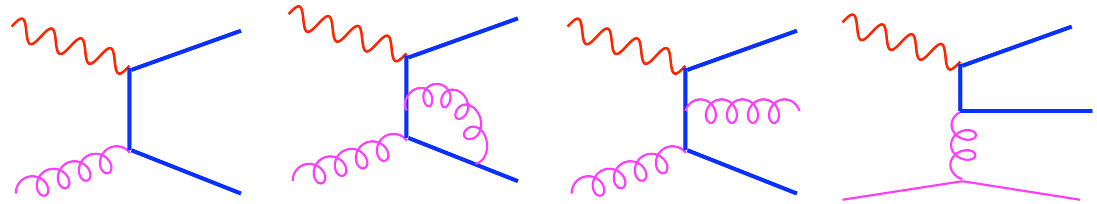
Fixed order: NLO, NNLO
FONLL/`massless`/ACOT/VFNS/....
K_T-factorization
CASCADE
PYTHIA
MC@NLO
....

We are providing **benchmarks** for HERA/LHC observables in order to gauge strengths/weaknesses, similarities and differences of the various approaches.

See Andrea Dainese's summary later for results and plots

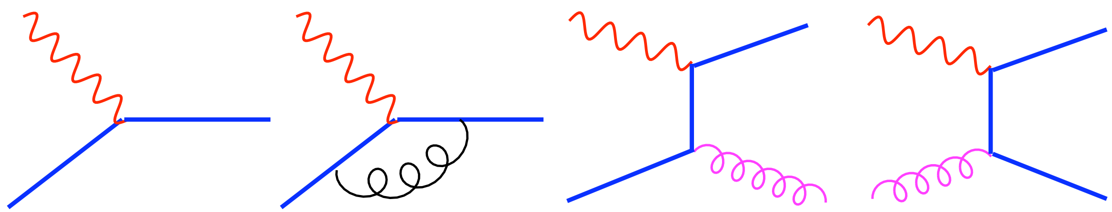
F_2^c and F_2^b

massive



$$F_2^h \sim \sum_{\text{light partons}} f_i(\mu) \otimes C_i^{\overline{MS}}(Q,m,\mu)$$

'massless'



$$F_2^h \sim \sum_{\text{all partons}} f_i(\mu) \otimes C_i^{\overline{MS}}(Q,\mu)$$

‘Massless’ is actually a somewhat unfortunate name choice

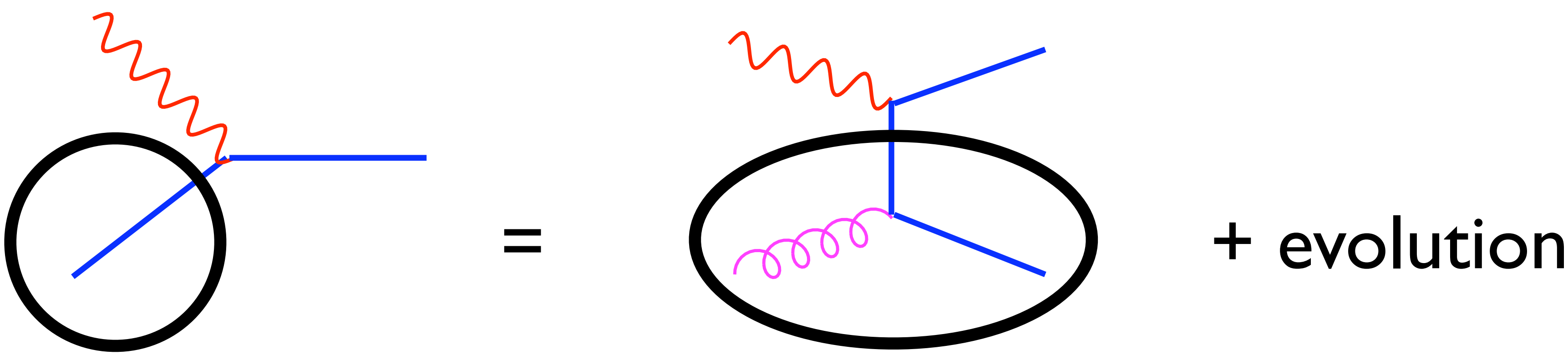
In fact, the mass of the heavy quark is fully present in the important logarithmic terms, via the HQ PDF initial condition and successive evolution. In MSbar scheme:

$$f_h(m_h) = 0 \qquad + \text{ AP} \qquad \frac{d f_h(\mu)}{d\log\mu^2} = \frac{\alpha_S(\mu)}{2\pi} f_g \otimes P_{qg} + \cdots$$

giving

$$f_h(\mu) = \frac{\alpha_S(\mu)}{2\pi} \log\frac{\mu^2}{m_h^2} f_g \otimes P_{qg} + \cdots$$

This is, of course, the same **mass log** found in fixed order calculations, but it is **resummed to all orders** by the evolution of the PDFs:



So, the heavy quark mass is included in the **dynamics**. It’s the **kinematics** which is massless.
Of course, this becomes important close to the threshold

‘Resummed’ is more accurate than ‘massless’

So, a resummed structure function is closely connected to a heavy quark PDF

However, which heavy quark PDF?

What do you get as a PDF *user?*

First of all, *acronyms:*

- *ACOT* (CTEQn, n<6)
- *ACOT(χ)* (CTEQ6HQ)
- S(implified)-*ACOT*
- Thorne & Roberts (MRST)
- FOPT (GRV)
- (Bouza, Chuvakin, Matounine, Smith, and van Neerven: partial NNLO VFNS)

Need a manual to choose? Choose at all?

S. Kretzer

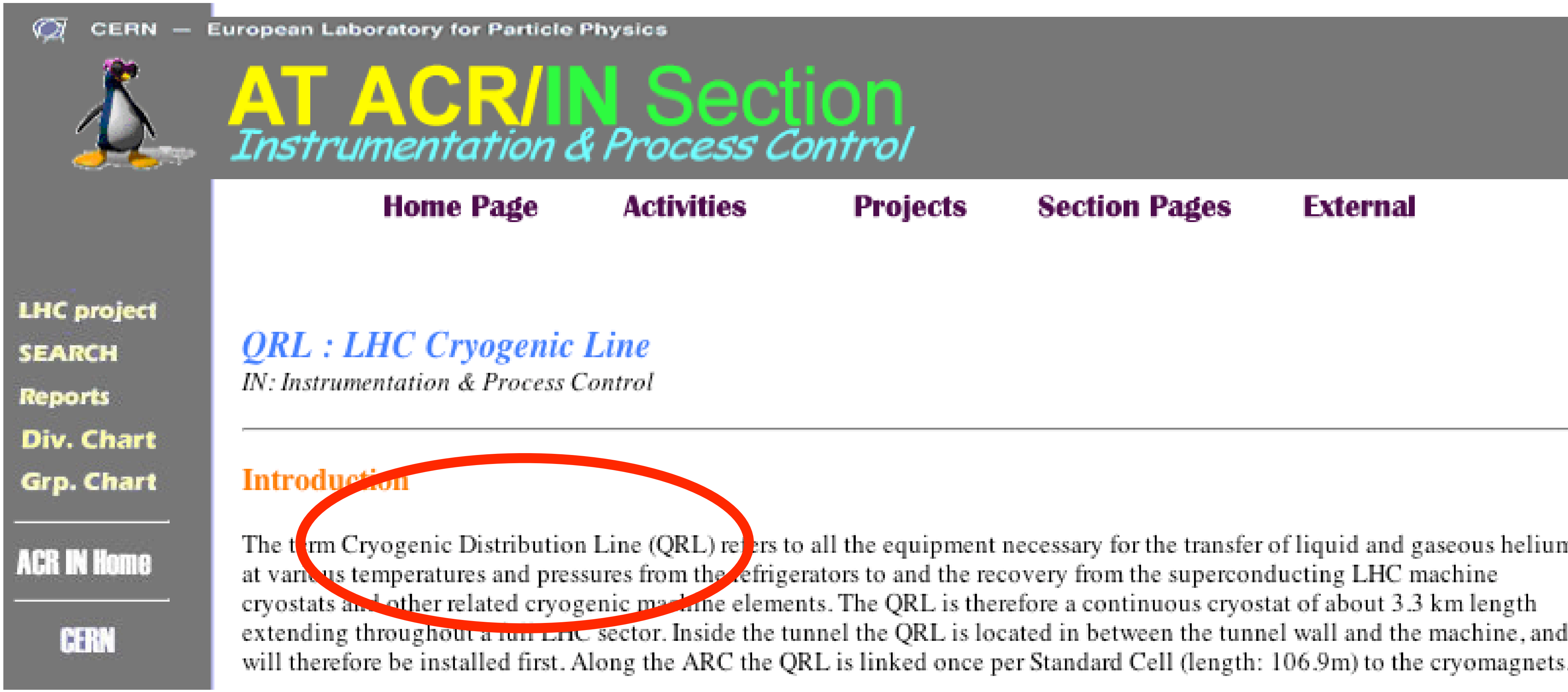
In order to clarify the situation, I'll...... add one more acronym!

All the `massless' calculations are actually

Resummed Mass Logarithms approaches

The quest for the acronym

Today's most prominent CERN department is surely the Accelerators one.
I decided therefore to try to be inspired by their logic:



C → Q		+14: R → F	
D → R	Non trivial mapping	+14: M → A	**F**inally **A**bove **L**eading!!
L → L		0 : L → L	

In order to clarify the situation, I'll...... add one more acronym!

All the `massless' calculations are actually

Resummed Mass Logarithms approaches **RML**

RML + scheme choice = all acronyms

This `common ingredient' (i.e. RML) is of course present not only in heavy quark structure functions calculations, but also for resummed calculations in photon-hadron and hadron-hadron collisions:

RML + scheme choice = (FONLL, massless, GM-VFNS, ...)

NB: while for a final result (a cross section) one can (must) live with a scheme uncertainty, the situation is more delicate for ingredients like PDFs.

Ideal situation: the PDF should be as simple as possible (MSbar and ZM-VFNS?) and only contain dynamics. Is it possible to avoid fitting in the threshold regions altogether?

The kinematical effects related to thresholds can then be provided by the users via the proper coefficient functions (of course, numerical problems are easily foreseen...)

Bottom quark PDF at LHC

The bottom quark can enter, in the form of a PDF, a number of interesting processes:

Process	Interest	Accuracy
single-top t-channel	SM, top EW couplings and polarization, V_{tb}. Anomalous couplings.	NLO
single-top + W		NLO
Wbj	SM, bkg to single top	(NLO)
gamma+b	SM, SUSY bkg, b-pdf	NLO
Z+b		NLO
inclusive h,A	SUSY discovery/ measurements at large tan(beta)	NNLO
h,A+b		NLO
$H^+ + t$	SUSY discovery, couplings	NLO

A. Tonazzo Study in ATLAS. (← Z+b)

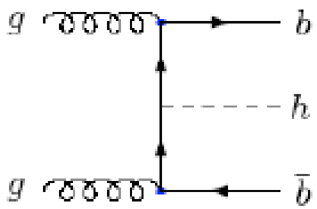
Standard processes

Searches (discoveries?)

F. Maltoni

Single out Higgs production with bottom quarks

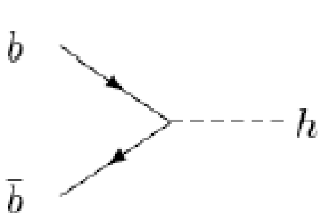
One way:

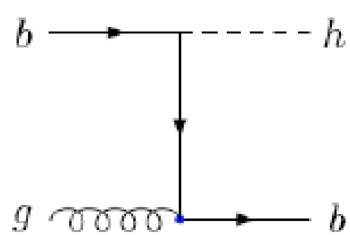


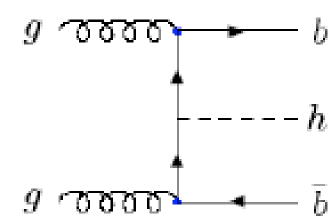
Keep the b massive and use the gg process for all three studies. The b mass acts as an infrared cutoff and there are no divergences. This is the 4 Flavour Scheme (4FS)

or the other:

The "leading-order process" depends on how INCLUSIVE is the measurement to be performed:







FULLY INCLUSIVE | 1 b at high p_T | 2 b's at high p_T

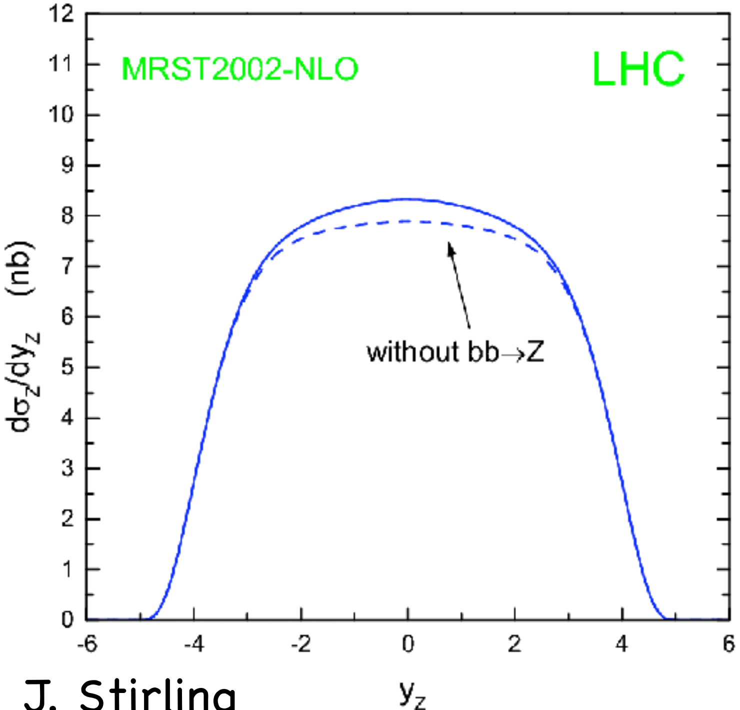
In so doing the large logs $\alpha_S \ln\left(\frac{m_h^2}{m_b^2}\right)$ are resummed into the b distribution function $b(x, m_h^2)$

This is the 5 flavour scheme.

F. Maltoni

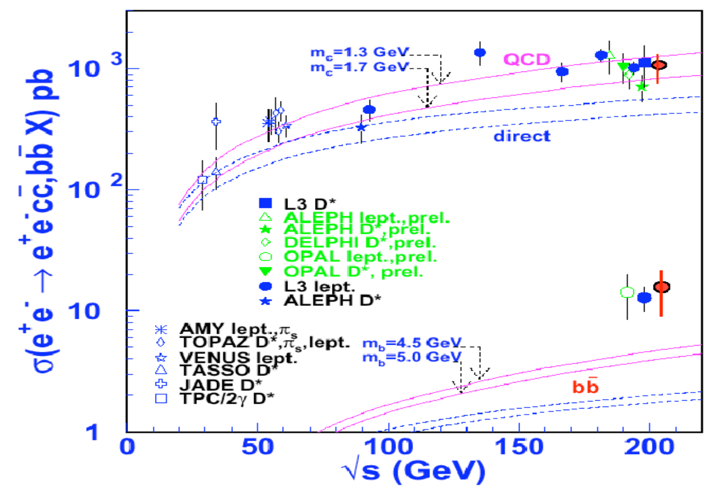
No further phenomenological input in b-quark PDF, but rather resummation of logs and therefore improvement of theoretical prediction

pp -> Z

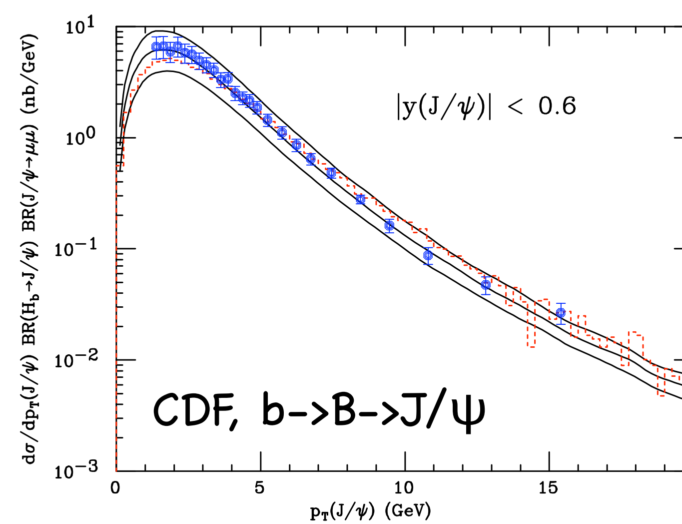


J. Stirling

Besides entering NNLO calculations for Higgs production, b-quark PDF also make up 5% of the total Z production at LHC. If we aim at a 1% accurate hadronic physics, we must make sure we control the b PDF at the 20% level



Recalling that the b PDF is nothing but a "chunk" of the NLO calculations in b productions, and given some recent scares (though the situation now looks better) we might wonder if we are really confident we control the b PDF



Importance of fragmentation.
See M. Corradi's summary

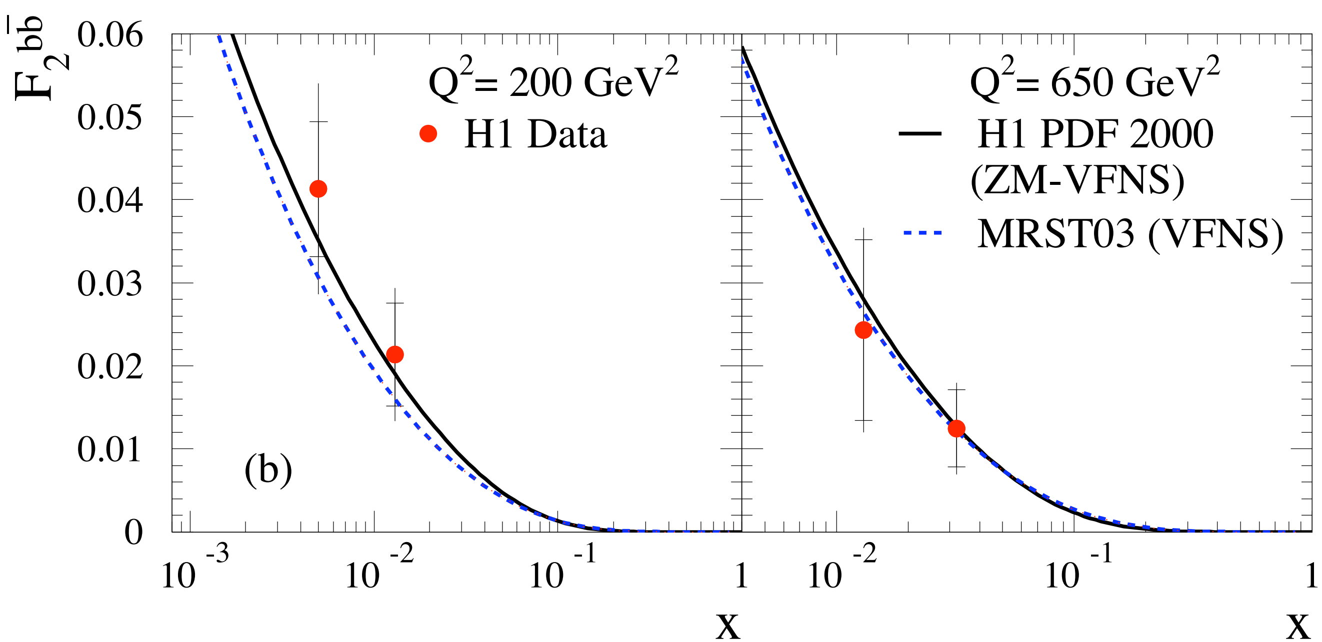
How well can HERA measure the heavy quark structure functions at large Q^2 ? To what extent can the resummed charm and bottom PDFs be tested?

The intrinsic accuracy of the evolved heavy quark PDF will of course be no better than that of the corrisponding gluon density.

To this we should add the typical perturbative uncertainties due to scale variations if calculating a cross section like a structure function

Estimate: ~ 10% (PDF) + 15% (pQCD)

Present HERA data unfortunately still have a larger uncertainty:



P.Thompson

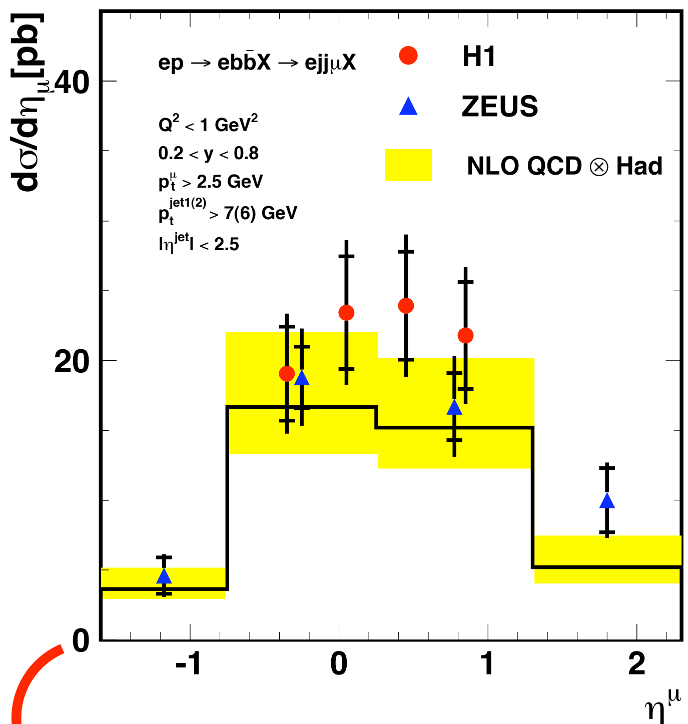
Error ~ 50%. Not enough to really 'test' the HQ PDF, unless very large discrepancies were found

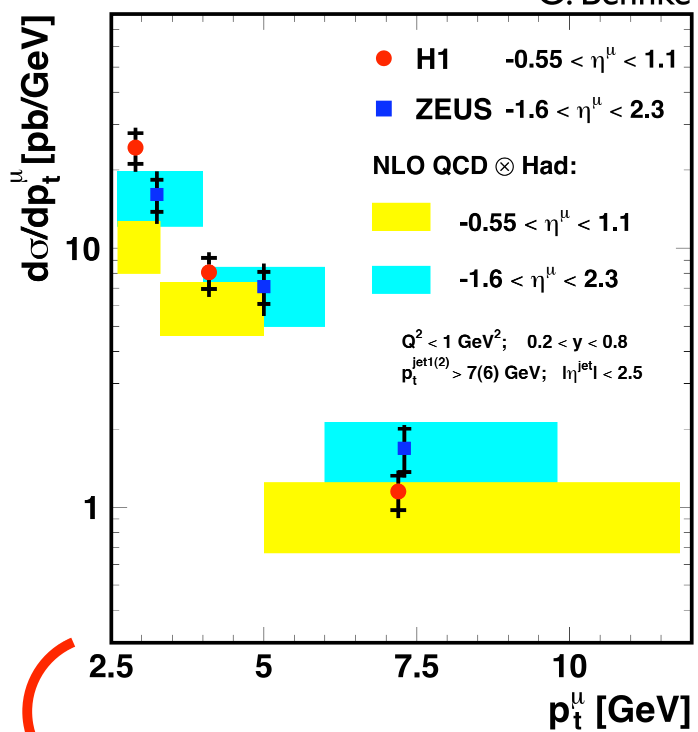
What prospects/hopes for HERA II?

So far, an ideal world, where structure functions (i.e. total cross sections) are measured.

In real life, one measures exclusive final state within specific phase space regions. Hence, in order to compare to predictions, one must either extrapolate (possibly by small factors) to full phase space or (better!) calculate prediction for the same exclusive observable (Of course, the two options require the same degree of theoretical knowledge)

O. Behnke





Good agreement H1 vs ZEUS

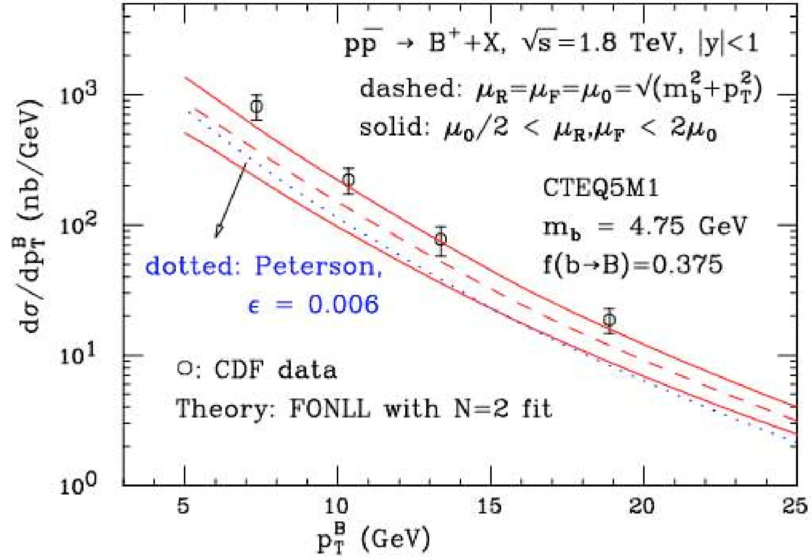
ZEUS: No excess at low p_t^μ

Non-perturbative components like heavy quark to heavy hadron fragmentation must be know in order to evaluate such predictions. What kind of accuracy and amount of knowledge is it necessary?

Heavy hadron p_T distributions

.

$$\frac{d\sigma}{dp_T^H}(p_T^H) = \int \frac{dx}{x}\, D^{\rm np}(x)\, \frac{d\sigma^{\rm pert}}{dp_T^Q}\left(\frac{p_T^H}{x}\right)$$



- $\frac{d\sigma^{\rm pert}}{dp_T^Q}$ = perturbative diff. cross section

- $D^{\rm np}(x)$ = non-perturbative Fragmentation Function (FF)

Needs to be taken from data

Tevatorn beauty excess was partly due to the use of not appropriate $D^{\rm np}(x)$ ...

Only $\langle x \rangle^{\text{np}}$ matters

- Even if not calculable,
  we know something about $D^{\text{np}}(x)$:

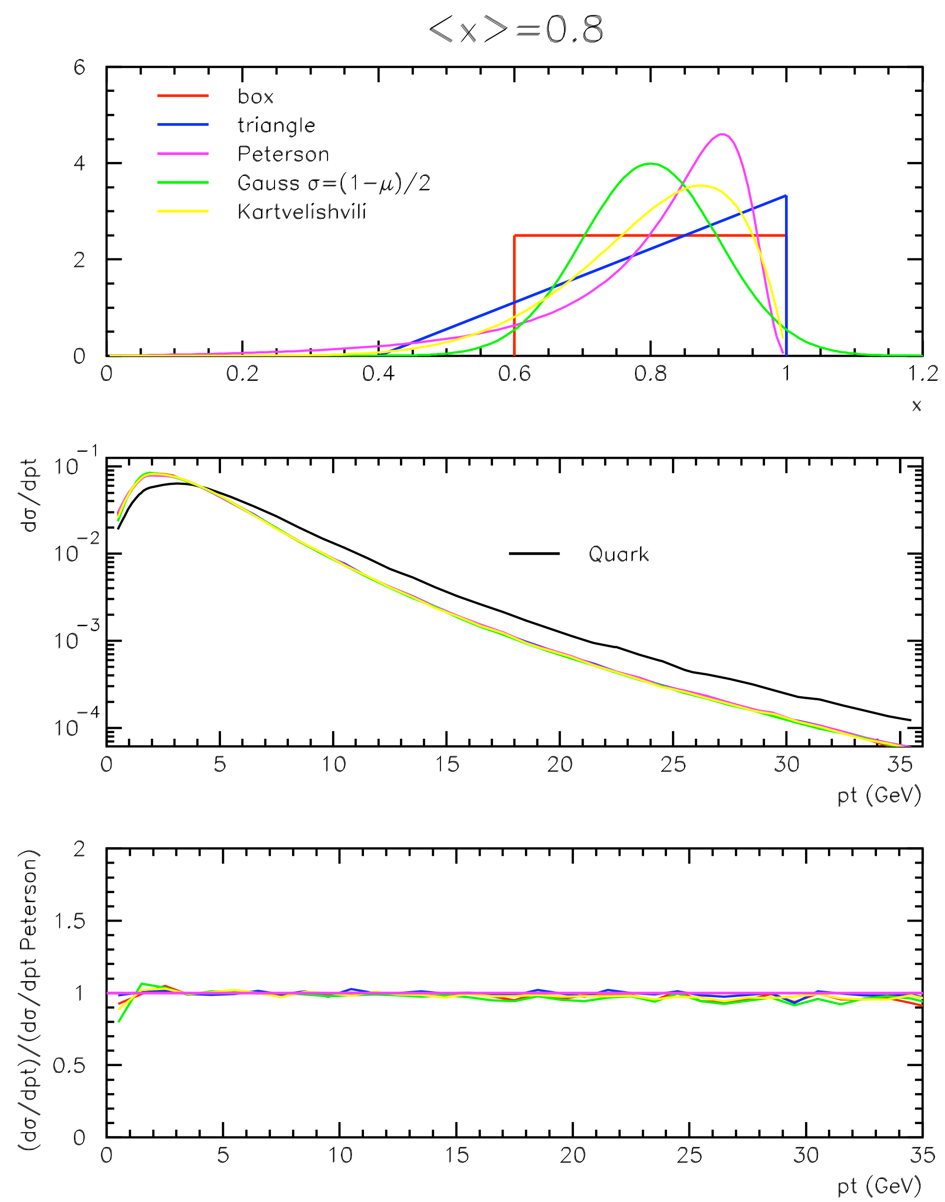
$$\langle x \rangle = 1 - O(\epsilon) \text{ where } \epsilon = \frac{\Lambda_{\text{QCD}}}{m_Q} \ll 1$$

- For $\frac{d\sigma^{\text{pert}}}{dp_T} \sim p_T^{-N}$

$$\frac{d\sigma}{dp_T^H}(p_T) = \frac{d\sigma^{\text{pert}}}{dp_T^Q}(p_T)\ (\langle x \rangle^{\text{np}})^{N-1} + O(\epsilon^2)$$

  what is important is the mean of $D(x)$
  not the shape !

- For reasonable shapes of FF, $\langle x \rangle^{\text{np}}$ is the only relevant parameter for heavy hadron spectra in pp (ep) $\Longrightarrow$



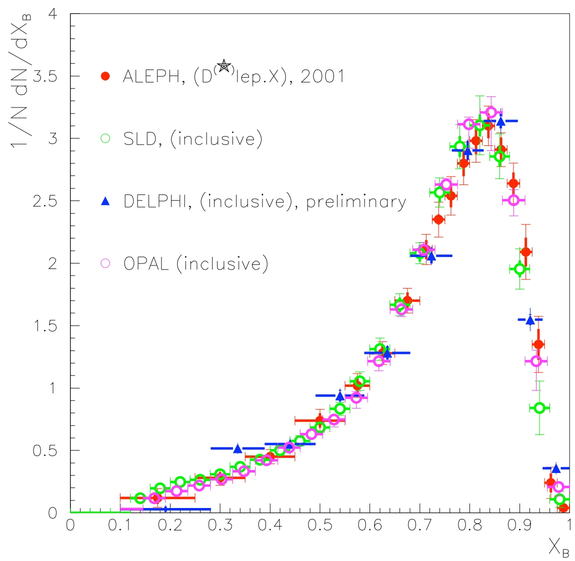
$\langle x \rangle^{\rm np}$ from e^+e^- data

Obsevable at e^+e^-: scaled energy distribution of the B hadron: $f(x_B)$, $x_B = \frac{2E_B}{Q}$

$$\langle x_B \rangle = \langle x \rangle^{\rm np} \langle x \rangle^{\rm pert}$$

Two ingredients are needed to extract $\langle x \rangle^{\rm np}$:

$\langle x_B \rangle$
from direct measurements:



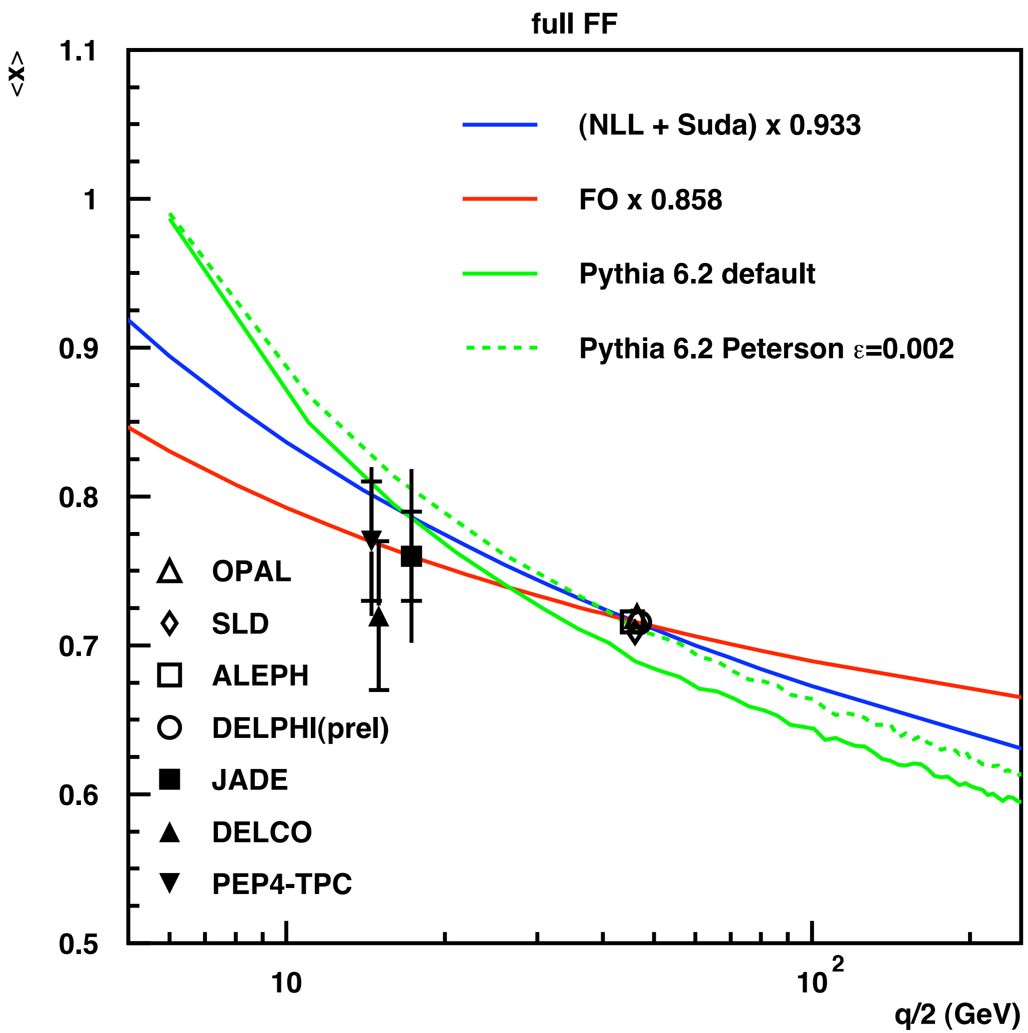
$\langle x_B \rangle = 0.713 \pm 0.03$ (raw average)

$\langle x \rangle^{\rm pert}$
from the particular perturbative theory considered:

- FO + NLL resummation of FFs (FONLL), Theor. uncertainty at $Q = M_Z \sim 2\%$
- FO, Theor. uncertainty at $\sim 5\%$
- MC+PS (Pythia)

.

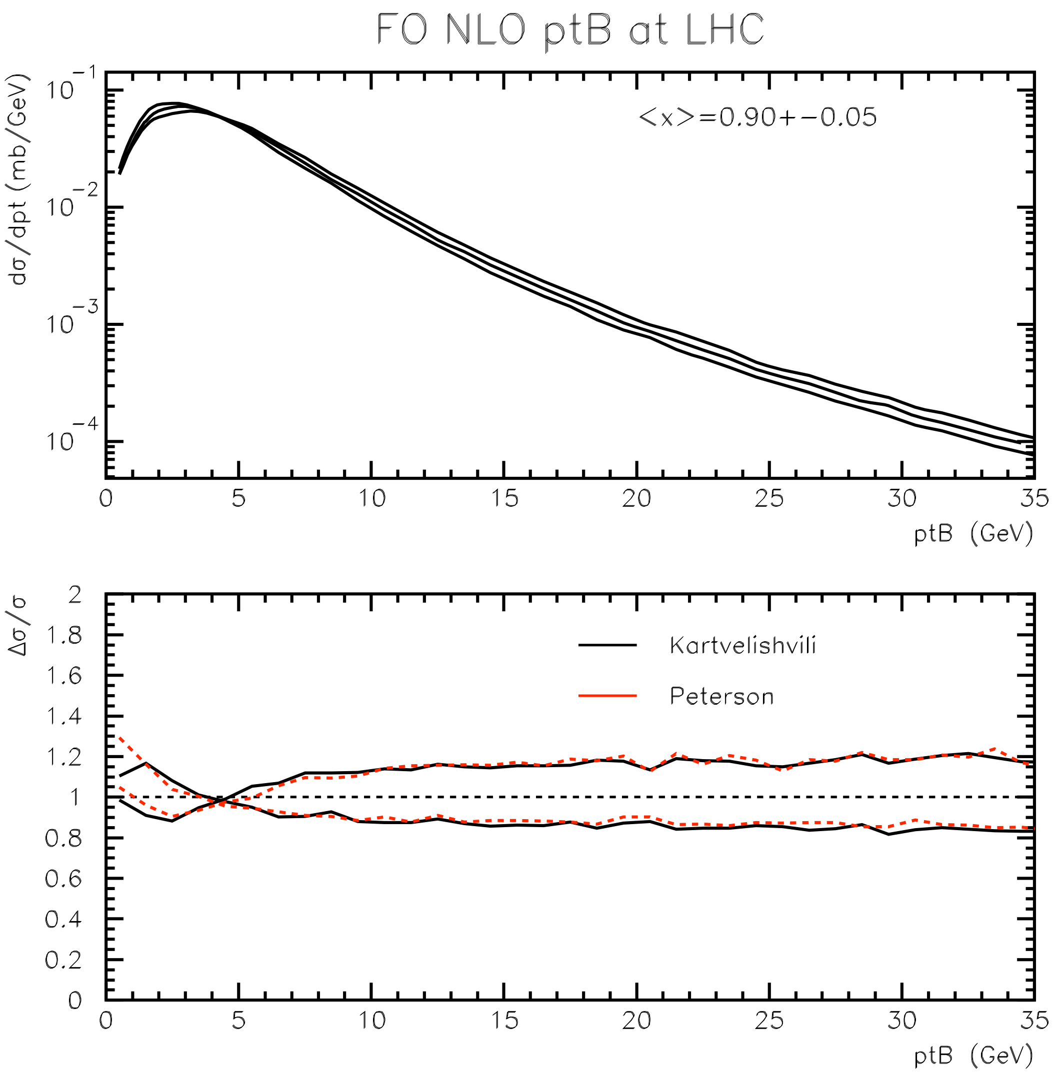
Results on $\langle x \rangle^{\rm np}$



- NLL: $\langle x \rangle^{\rm np,NLL} = 0.93 \pm 0.02$
  uncertainty dominated by scale variations
  Peterson $\epsilon = 0.0004$ $(0.0002 - 0.0008)$
- FO: $\langle x \rangle^{\rm np,FO} = 0.90 \pm 0.05$
  uncertainty from difference with NLL
  Peterson $\epsilon = 0.0011$ $(0.0002 - 0.0039)$
- Pythia 6.2:
  Default (Lund-Bowler) too soft

  Reasonable agreement with data with Peterson with $\epsilon = 0.002$

Effect on p_T^B spectrum at LHC



Predictions for LHC:

$\Longleftarrow$ FO NLO p_T distribution at LHC (MNR) smeared with $\langle x\rangle^{\text{np}} = 0.90 \pm 0.05$

- FO:
  $$\frac{\Delta\langle x\rangle^{\text{np}}}{\langle x\rangle^{\text{np}}} = 5.5\% \Longrightarrow \frac{\Delta(\sigma)}{\sigma} = 22\%$$

- NLL:
  $$\frac{\Delta\langle x\rangle^{\text{np}}}{\langle x\rangle^{\text{np}}} = 2\% \Longrightarrow \frac{\Delta(\sigma)}{\sigma} = 7\%$$

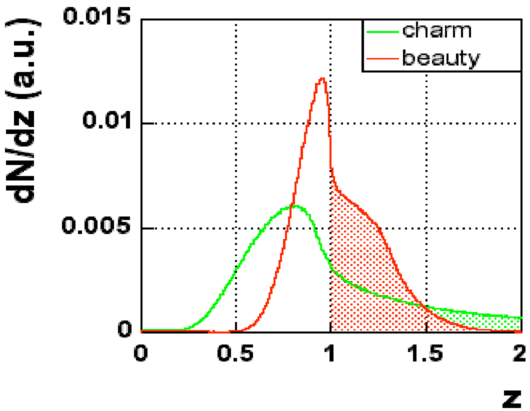
All this work assuming that the factorization of $D^{np}(x)$ works, but

- Factorization holds for $p_T/m_Q \gg 1$
  how large are deviations at small-moderate p_T?

- Do FF fitted to e^+e^- apply to ep, pp ?

  MC hadronization models predict sizeable effects, e.g. Beam-drag effects in Pythia

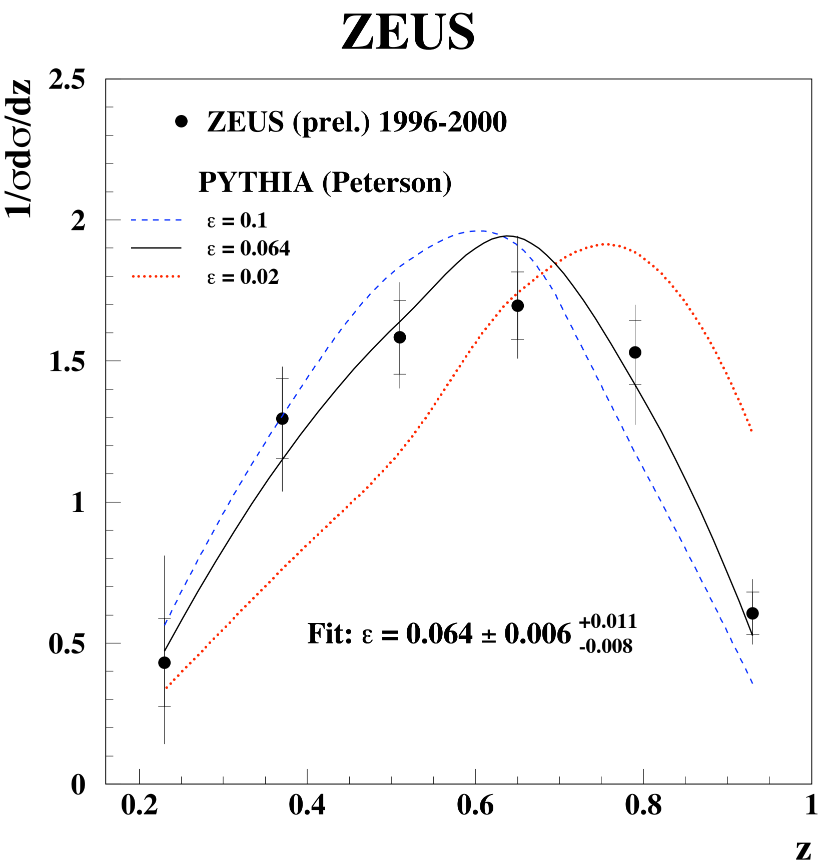
  Alice
  $2.5 < y < 4.5$
  $p_T^l > 2$ GeV
  (R. Guernane)



- Need to test factorization and measure FF in an hadronic enviroment:

  ZEUS(prel.) result on charm $\Longrightarrow$

  more FF measurements from HERA to come...



$(E+P_{\|})_{D^*}/(E+P_Z)_{\text{Jet}}$

Summary (of first two parts of summary)

1 - HERA can help in testing/constraining the heavy quark PDFs, provided experimental accuracies of order 20% should be achieved

2 - Non-perturbative heavy quark fragmentation can be predictive (at large pT) after proper extraction from experiment of a very limited number of parameters (one?). However, its limitations in hadronic environment and small pT should be carefully checked.

3 - Might somebody please tell me what QRL stands for.....?