2^{nd} HERA-LHC Workshop

(Working Group 3)

Heavy Quarks

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Conveners
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Review of the 1^{st} workshop (theory)
including some news from DIS2006

1^{st} HERA-LHC Workshop

(Start-up meeting: March 2004, final presentation: March 2005)

Theory aspects:

- **Production: Benchmark cross sections**
  Schemes: fixed-order / resummed; Monte Carlo
- **Fragmentation**
- **Soft-gluon resummation**
- **k_{T} factorization**
  (correlations in $Q\bar{Q}$ production, quarkonium production, associated Higgs + jet production)
- **Λ / $\bar{\Lambda}$ asymmetries in the QGSM**

Experimental aspects:

- **Overview of HERA results**
  (open charm, open beauty, quarkonium, F_2^c, F_2^b, $Q\bar{Q}$ correlations, $c \to H_c$ fragmentation)
- **Detection: Trigger and Reconstruction at the LHC experiments**

Heavy Quarks as a Test of QCD

- **Basic formulae:**

$$d\sigma_Q = \int dx_1 dx_2 \int dz$$
$$f_{a/h_1}(x_1,\mu_F) f_{b/h_2}(x_2,\mu_F)$$ **PDFs for partons a, b**
$$\times d\hat{\sigma}(a+b \to Q+X)$$ $\times$ **hard scattering, produce heavy quark** $Q = c, b$
$$d\sigma_H = \int dz\, d\sigma_Q \times D_{H/Q}(z,\mu_F)$$ $\times$ **fragmentation into hadron** H

$+$ **power corrections**

- **Schemes:**

massive scheme (FFNS): $m_Q \neq 0$, **initial state:** $a, b = g, q, \bar{q}$, **final state:** $Q, \bar{Q}$
threshold region OK, large logs: $\ln(p_T^2/m_Q^2)$

massless scheme (ZM-VFNS): $m_Q = 0$, **initial state:** $a, b = g, q, \bar{q}, Q, \bar{Q}$
improvement at large p_T**: resums large logs in heavy quark PDFs**

- **Matching:** **transition region ?** $\to$ **FONLL, GM-VFNS**

Heavy Quark PDFs

- **CTeQ: simplified ACOT (SACOT$_\chi$) a general-mass (GM) scheme**

  more natural parton kinematics:

$$\chi = x\left(1 + \frac{(\Sigma M)^2_{\text{final}}}{Q^2}\right)$$

→ **smooth and physical threshold behavior ($F_2,\ F_L$)**

→ **simplicity**

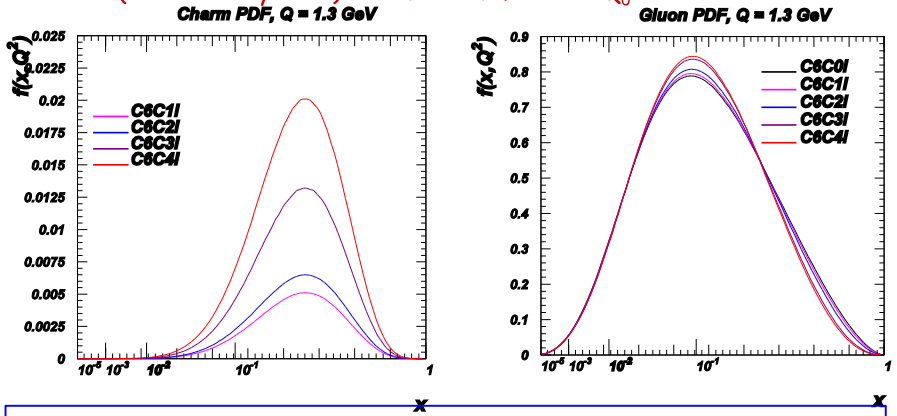
- **Is there a non-perturbative charm component in the nucleon?**

→ **preliminary results shown at DIS2006**

→ **await more accurate data from HERA II impact on phenomenology at LHC**

Charm and Gluon Distributions at Q = 1.3 GeV

Varying amounts of input lightcone charm components
(à la Brodsky etal.) : Momentum frac. at Q_0 = 0 — 0.02.

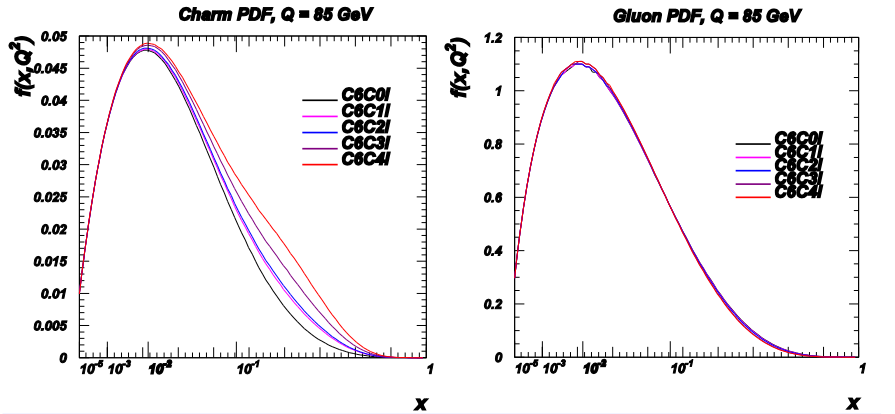


Horizontal axis is scaled in $x^{1/3}$—inbetween linear and log—in order to exhibit the behavior at both large and small x.

Charm and Gluon Distributions at $Q^2 = (85\ \text{GeV})^2$

W.K.Tung DIS2006

Varying amounts of input lightcone charm components
(à la Brodsky etal.) : Momentum frac. at Q0 = 0 — 0.02.



* Very substantial amount of charm, over the radiatively generated component (C6C0I), still persists at this very large scale ➔ there can be interesting phenomenological consequences even at LHC.

Heavy Quark PDFs: NNLO ?

W K Tung: NNLO not urgent: out-weighed by other sources of uncertainties, like parametrizations, power-law corrections

Roberts, Thorne: detailed prescription for DIS structure function at NNLO

ZM-VFNS not feasible at NNLO: discontinuities in F_2^c !

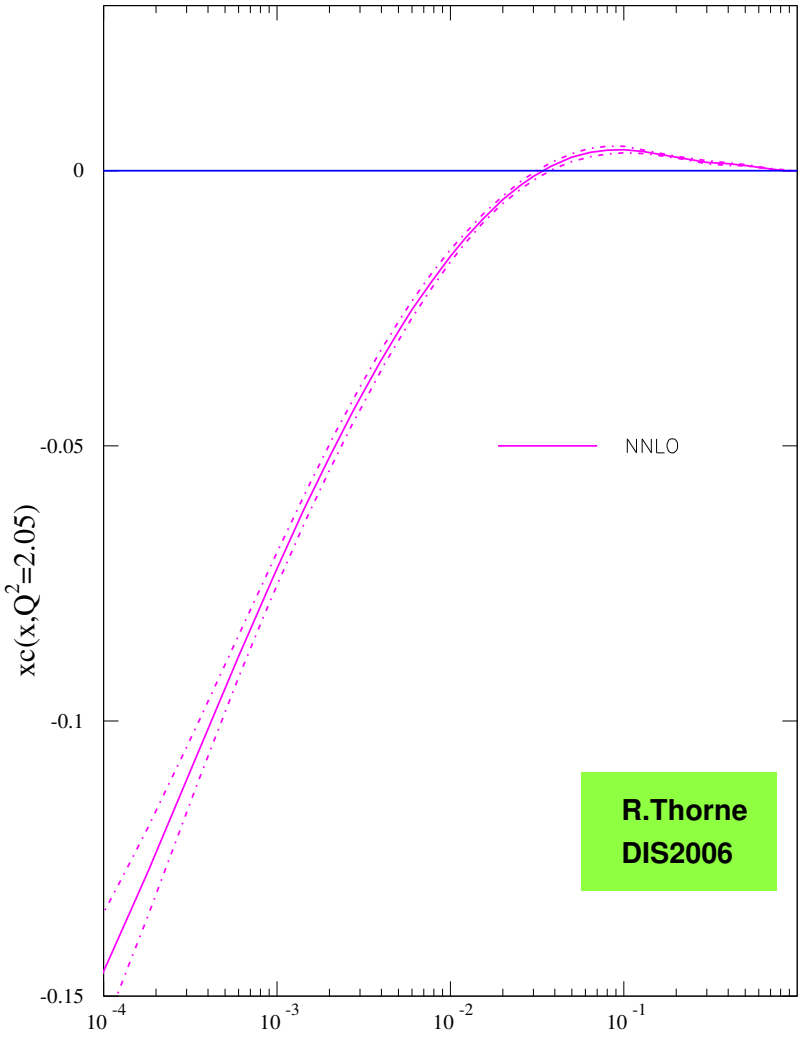
TR-VFNS: shift m^2/Q^2 terms between coefficient functions imposing constraints (smoothness of $dF_2/d\ln Q^2$, freeze higher-order α_s terms when going through threshold $Q^2 = m_c^2$)

$\rightarrow$ continuous F_2, but discontinuous and negative PDFs

F_2^c not well-defined at NNLO: not IR-safe

sophisticated and complicated

unclear how this works for other processes



Heavy Quark Fragmentation

up to now: FFs for $g, q, \bar{q}, Q, \bar{Q} \to H$ fitted to phenomenological forms, HQ contribution "switched on" at threshold

but

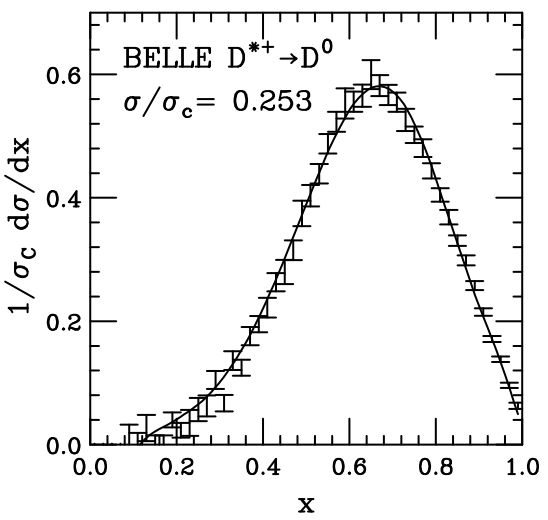
FFs have thresholds like PDFs, need matching across threshold (Cacciari, Nason, Oleari, see DIS2006)

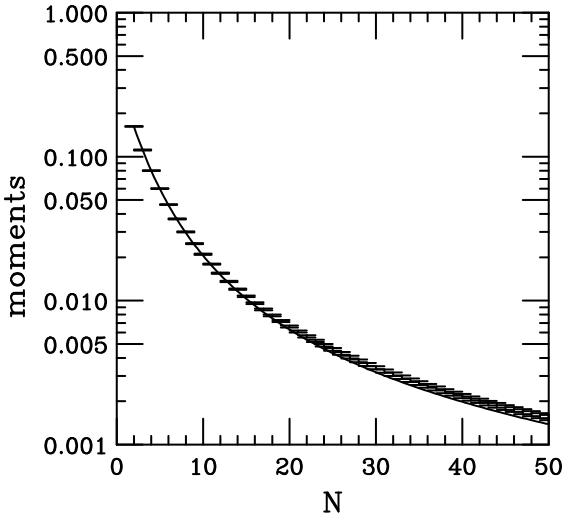
now available: time-like equivalent of Collins-Tung relations for PDFs: parametrize light partons ($g, q, \bar{q}$), generate HQ FFs radiatively

$\to$ allow **global fits**

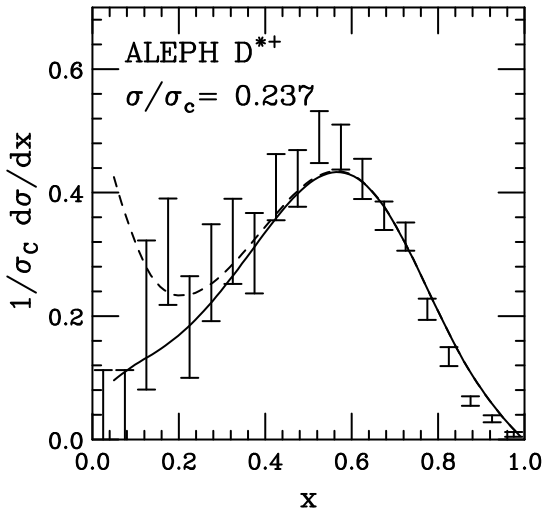
Oleari (DIS2006): fit to BELLE, CLEO and ALEPH data

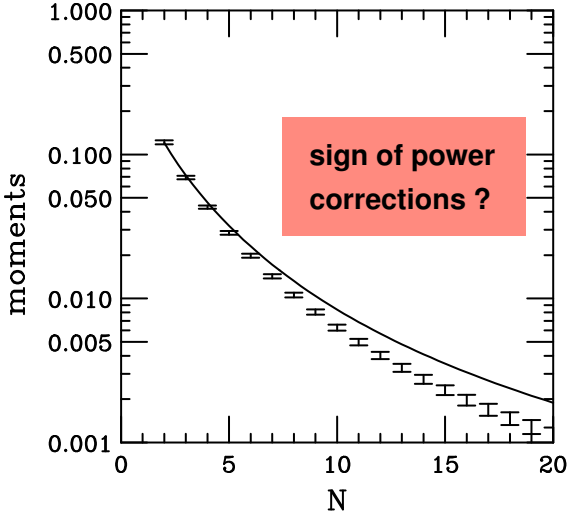
include Tevatron and **HERA II** data





C.Oleari DIS2006





Benchmark Cross Sections

Different theoretical approaches, for single-inclusive HQ production:

- **(F)MNR: fixed-order at NLO (for γp and pp)**
- **HVQDIS: fixed-order at NLO (for DIS)**
- **FONLL: NLO + leading log's resummed**
- **GM-VFNS: NLO + leading log's resummed**
- **CASCADE: MC, k_{T} factorization**
- **RAPGAP: MC, LO $\gamma^* g \to Q\bar{Q}$**

same input (as far as possible: α_s, m_c, m_b, PDF)
uncertainty bands – mainly from scale variation: $\frac{1}{2}\mu_0 < \mu_F, \mu_R < 2\mu_0$ with $\mu_0 = m_{\mathrm{T}} = \sqrt{m_Q^2 + p_{\mathrm{T}}^2}$ or $\sqrt{4m_Q^2 + Q^2}$ (for DIS)

To be improved:

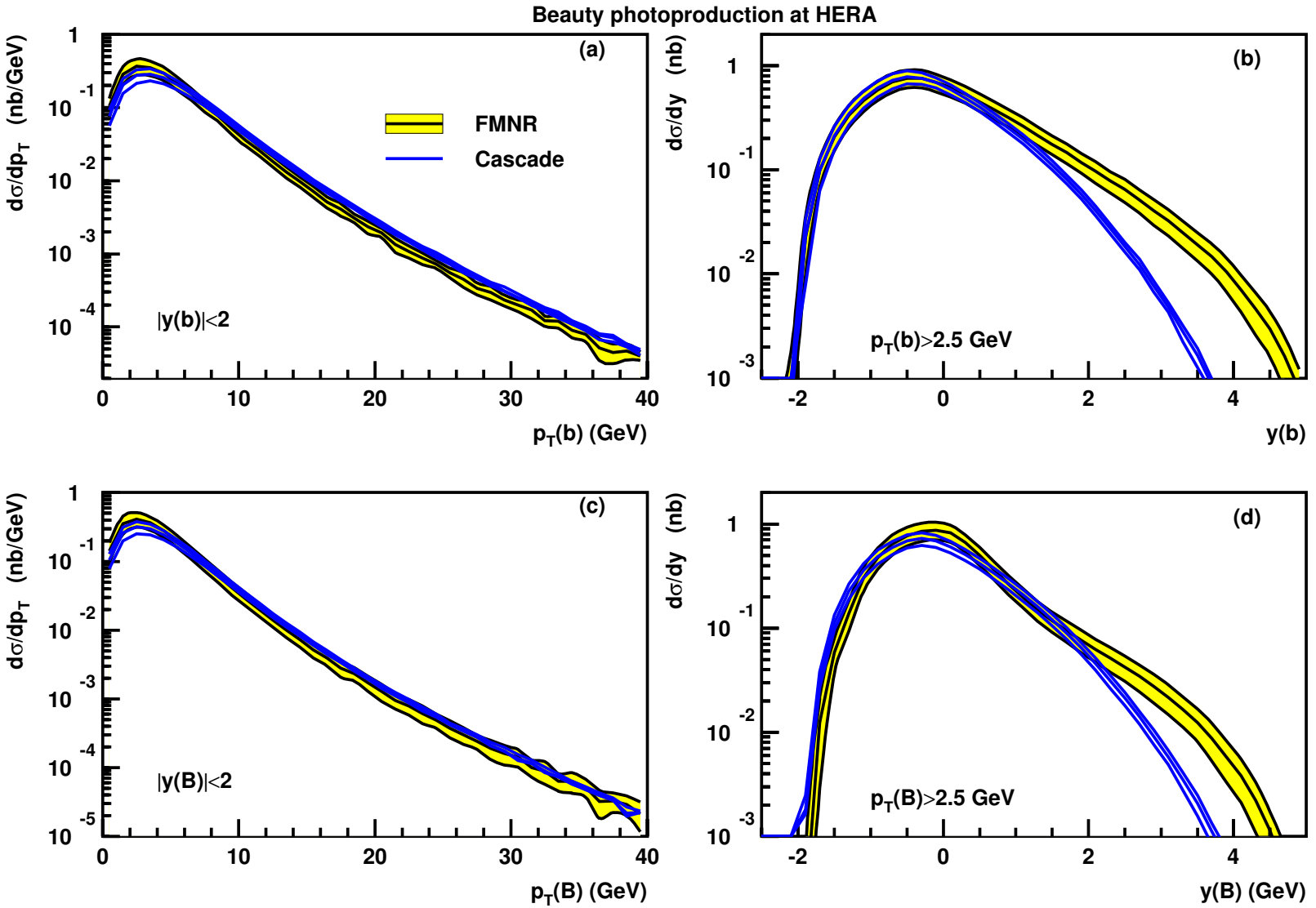
- **dependence on PDF**
- **dependence on fragmentation**
- **MC implementation**

Example: Beauty Photoproduction

Predictions from

- **FMNR**
- **CASCADE**

Need improvement at high y

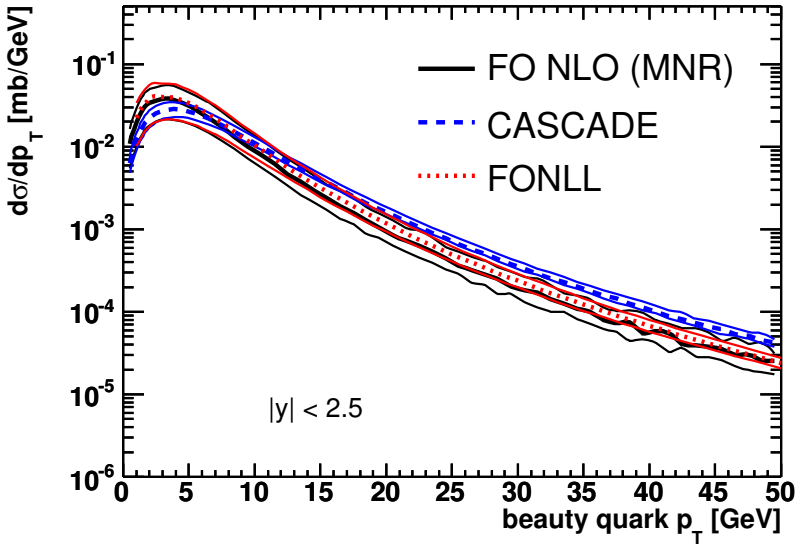


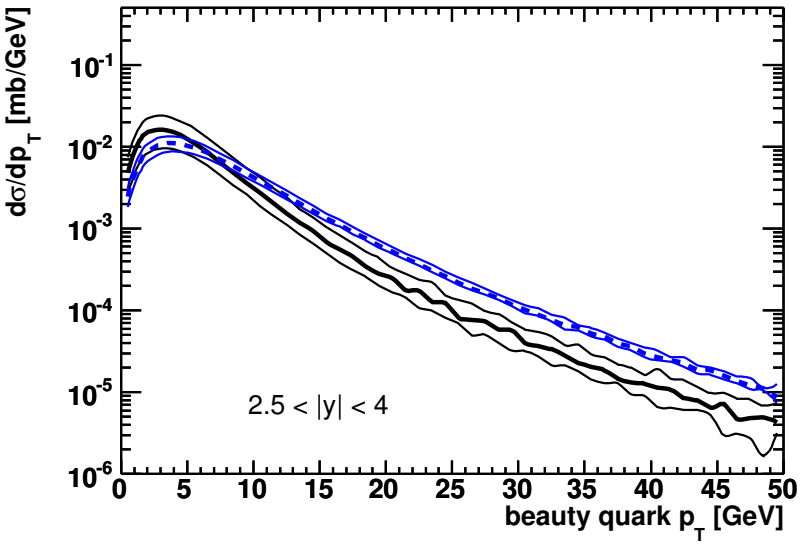
Example: Beauty Production at the LHC

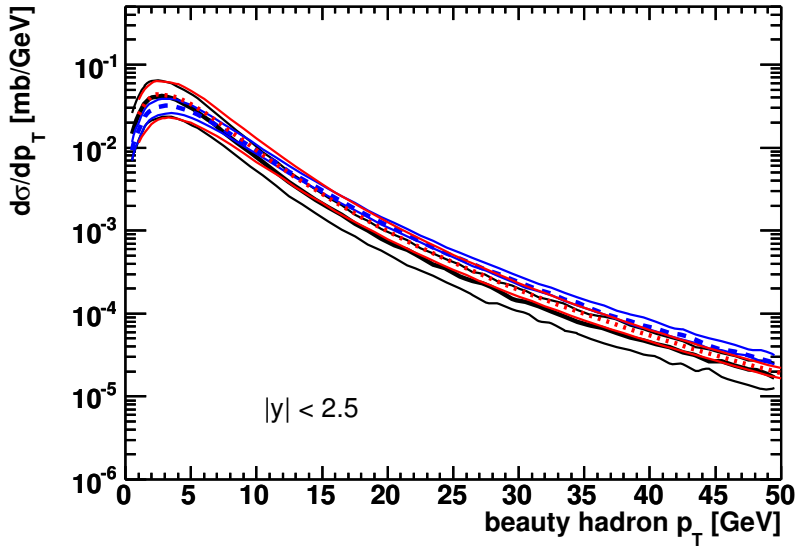
Predictions from

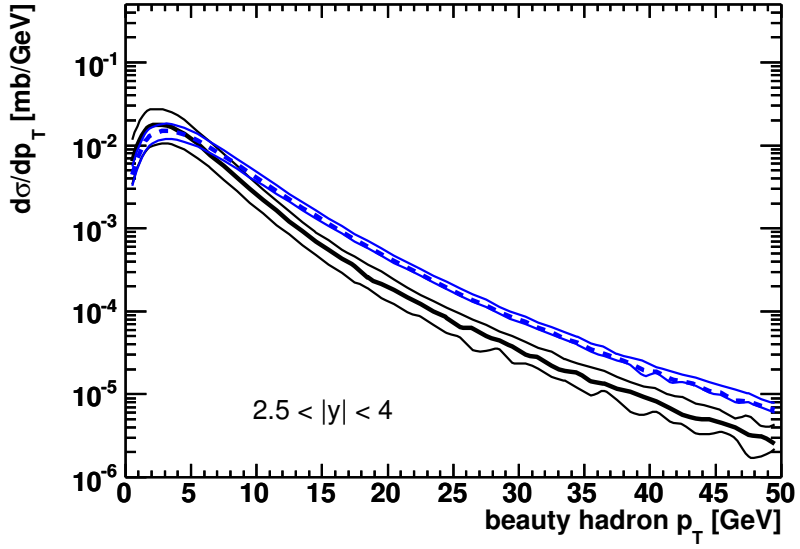
- **MNR**
- **FONLL**
- **CASCADE**

Factor of up to 5 uncertainty at high p_T, y









Soft-Gluon Resummation

Remnants of long-distance dynamics → logarithmic terms, singular near edges of phase space.

Threshold resummation

perturbative result for observable ω

$$\omega = 1 + \alpha_s \left(L^2 + L + 1\right) + \alpha_s^2 \left(L^4 + L^3 + L^2 + L + 1\right) + \ldots$$

resummed:

$$\omega = \exp\left\{L g_1(\alpha_s L) + g_2(\alpha_s L) + \ldots\right\} + \text{suppressed terms}$$

for the differential structure function $d^2F_2^Q/dT\,dU$ (Eynck, Laenen, Moch):

$$g_1(\lambda) = \frac{C_F}{\pi b_0 \lambda}\left(\lambda + (1-\lambda)\ln(1-\lambda)\right)$$

with $\lambda = b_0 \alpha_s \ln N$ and $L^i = \left(\frac{\ln^{i-1}(\rho)}{\rho}\right)_+$, $\rho = \frac{s_4}{m_Q^2}$, $M_{X'}^2 = m_Q^2 + s_4$

→ reduced scale dependence

Other observables ? e.g. heavy quark + jet

Small-x Effects

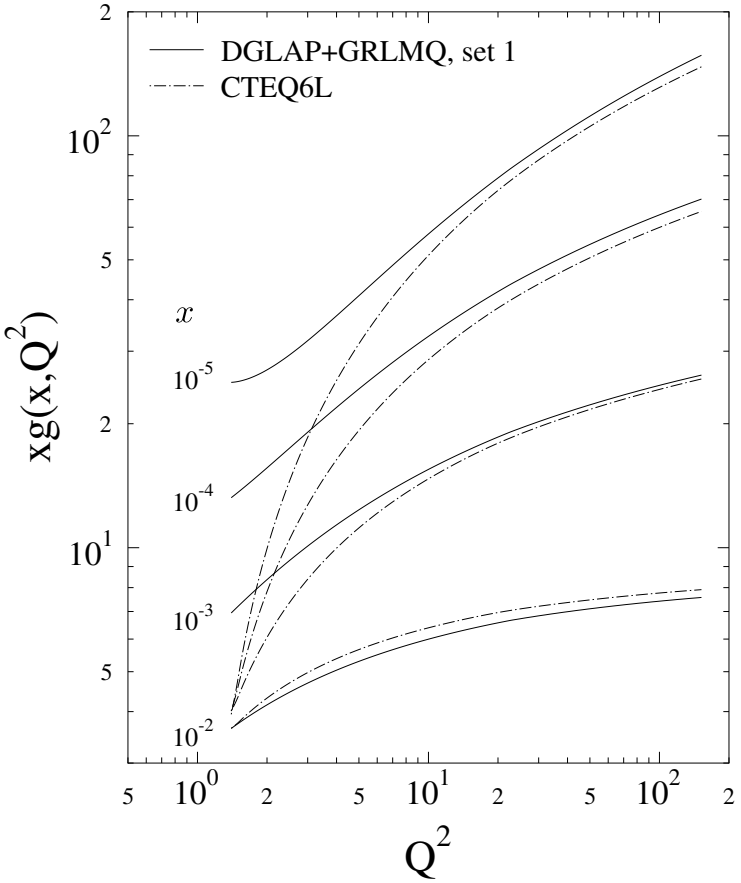
($x < 10^{-4}$, Q^2 in perturbative regime)

GLRMQ

DGLAP + non-linear g recombination

→ **enhanced gluon**

→ **enhanced b production at LHC**



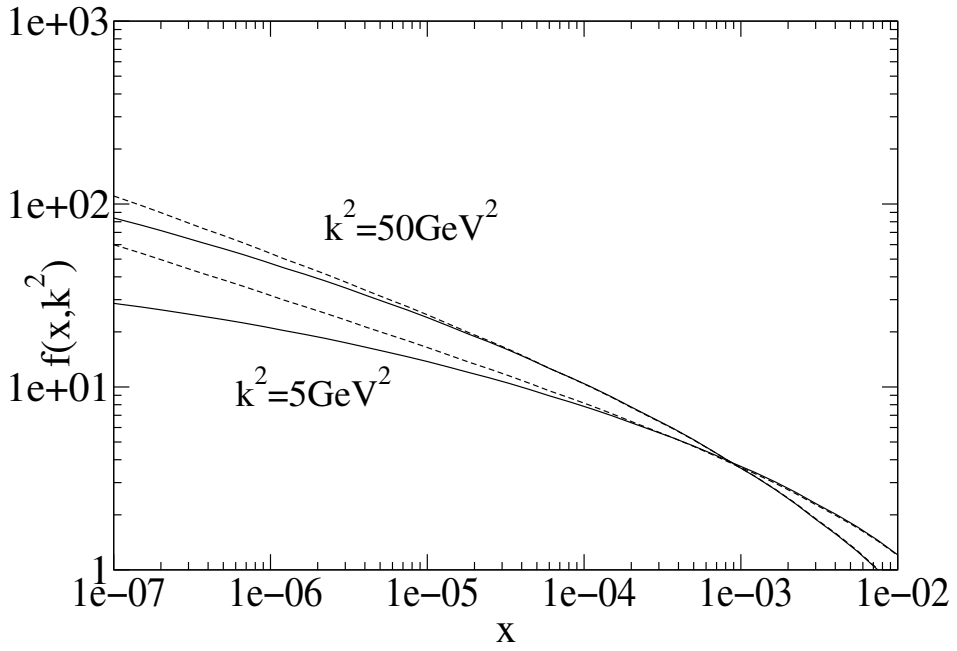
KKMS

DGLAP + BK saturation effects

k_T-factorization (unintegrated PDF)

→ **suppressed gluon**

→ **suppressed b production at LHC ?**



Small-x Effects

GLRMQ

(Eskola, Kolhinen, Vogt)

- **based on LO evolution**

$\rightarrow$ **include NLO corrections !**

KKMS*

(Jung, Kutak, Peters, Motyka)

- **comprises:**
  - **+ BFKL with subleading $\ln 1/x$ terms**
  - **+ non-singular parts of DGLAP**
  - **+ quark singlet from DGLAP**
  - **+ non-linear terms from BK**
  - **+ choice of scale in α_s**

  $\rightarrow$ **unified prescription?**
- **no significant effect within ALICE/ CMS acceptance (Peters DIS2006)**

Let $pp \rightarrow c + X$ at the LHC decide?

* Kutak, Kwiecinski, Martin, Stasto

Conclusion for Heavy Quarks at the LHC

- **PDFs: input comes from HERA I/II**
  compare TR-VFNS and SACOT$_\chi$! Do we need NNLO ?
- **FFs: global fits ? Include Tevatron and HERA II data !**
- **Benchmark cross sections: source of discrepancies (FF?), improve MC implementation and test at HERA II !**
- **HQ schemes: work out also for signal processes ($b + \bar{b} \to H$, $c + s \to H^+$, but also $W/Z/\gamma+$ tagged HQ) !**
- **k_T factorization: use HERA II data to determine unintegrated PDFs $\to$ work out predictions for LHC !**