# CERN-DESY Workshop

## HERA and the LHC

A workshop on the implications of
HERA for LHC physics

June 6-9, 2006 at CERN

WG1: pdf
WG2: multi-jet final states, energy flows
WG3: Heavy quarks ← convened by
WG4: Diffraction
WG5: MC tools

M. Cacciari
H. Spiesberger
A. Dainese
A. Geiser

see http://www.desy.de/~heralhc/

DIS 2006
Tsukuba JAPAN

# Summary of the Heavy Flavour Working Group

Uri Karshon (Weizmann)
Ingo Schienbein (SMU Dallas)
Paul Thompson (Birmingham)

DIS 2006, April 24, 2006

# Heavy Flavour WG: theory talks

Ingo Schienbein (SMU Dallas)

- Heavy flavour schemes
    - Inclusive (Thorne, Tung)
    - 1-particle inclusive (Kniehl)
    - Evolution of FFs with heavy quark thresholds (Cacciari)
- Heavy quark fragmentation (Oleari)
- Heavy quark production at RHIC (Cacciari)
- Heavy quarks and kT-factorization (Zotov, Peters)
- Charmonium production: CEM vs. NRQCD (Lee)

# Heavy flavour schemes

Heavy Flavour Physics -- FFNS and VFNS

Thorne

hep-ph/0603143
hep-ph/0601245

**limited**

- Heavy Flavour Schemes: FFN, ~~ZM-VFN~~, GM-VFN, FONLL
- MRST FFNS PDFs at LO/NLO
  - Up to date FFNS PDFs needed!
  - MRST'04 PDFs at Q_0 = 1 GeV, evolved with n_f = 3

    Important: use $\alpha_s(n_f=3)$

**mandatory for
fully global
analysis**

- Proposal for a GM-VFNS at NNLO
  - Used in global analysis at NNLO!

Interpolation between FFN and ZM-VFN **at hadron level.** Overlap subtracted, thus similar to GM-VFN (but different in spirit).

# A GM-VFNS at NNLO

Robert Thorne

hep-ph/0601245

The only existing detailed proposal for a GM-VFN at NNLO
Again: GM-VFN mandatory for fully global PDF analysis!

1.) Matching conditions (ZM-VFN or GM-VFN):

$$f_i^{n+1}(\mu) = A_{ik}(\mu) \otimes f_k^n(\mu); \mathrm{NNLO} : A_{ik}(\mu = m) \neq 0$$

2.)Def. of GM-VFN: require for Observable

$$O[S^n](\mu) = O[S^{n+1}](\mu)$$

3.)Exploit **freedom to reshuffle m^2/Q^2 terms** between coefficients to ensure **continous and smooth** behaviour.
Along with ordering of the series below and above threshold

Pretty complicated!!! (sophisticated **and** complicated)

How to compute hard scattering cross sections
for other processes???

# Heavy flavour schemes

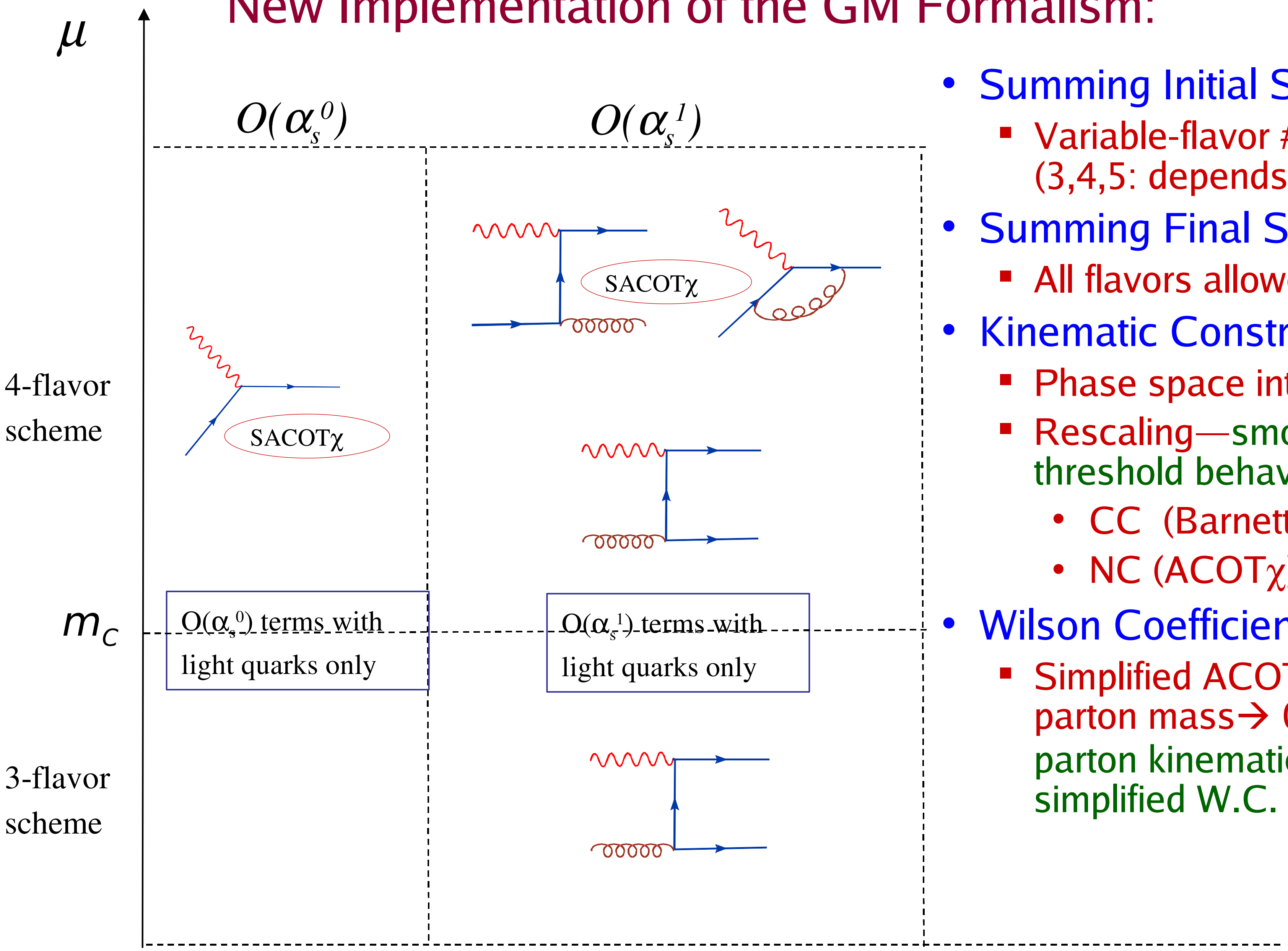
Heavy Quark Mass Effects and
Heavy Flavor Parton Distributions

Tung,Belyaev,Pumplin,
Stump,Yuan

- General Mass (GM) formalism (Collins)
  NLO-implementation: S-ACOT$_\chi$
- GM global analysis vs HERA I charm production
- Phenom. study of charm in the nucleon:
  - Usually assumed that charm produced purely radiatively by gluon splitting. Important to test and quantify!

# New Implementation of the GM Formalism:

$F^{tot}$



$\mu$

$O(\alpha_s^0)$

$O(\alpha_s^1)$

4-flavor
scheme

SACOTχ

SACOTχ

$m_c$

$O(\alpha_s^0)$ terms with
light quarks only

$O(\alpha_s^1)$ terms with
light quarks only

3-flavor
scheme

- Summing Initial S. partons
  - Variable-flavor # schemes (3,4,5: depends on Q)
- Summing Final S. partons
  - All flavors allowed by P.S.
- Kinematic Constraints:
  - Phase space integration limits;
  - Rescaling—smooth and physical threshold behavior
    - CC (Barnett)
    - NC (ACOTχ)
- Wilson Coefficients:
  - Simplified ACOT (initial state parton mass→ 0)—more natural parton kinematics and greatly simplified W.C.

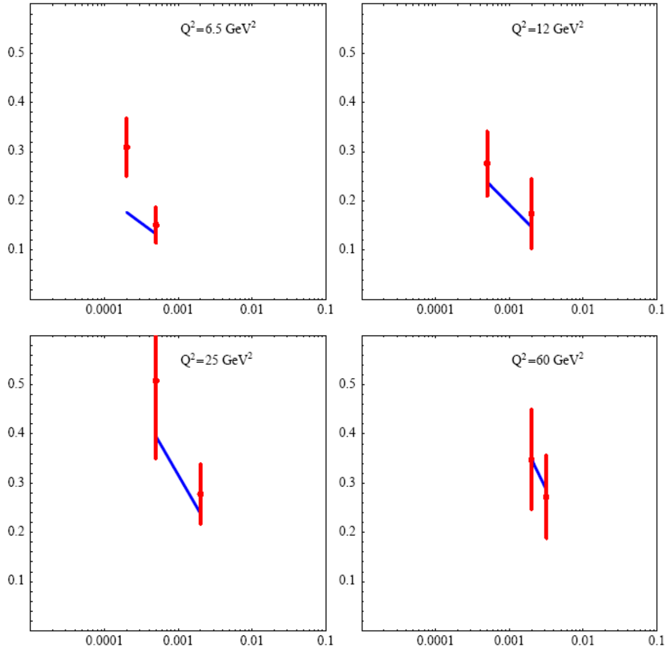
Some fine prints:

- Subtraction terms to rem
- Slightly different treatme

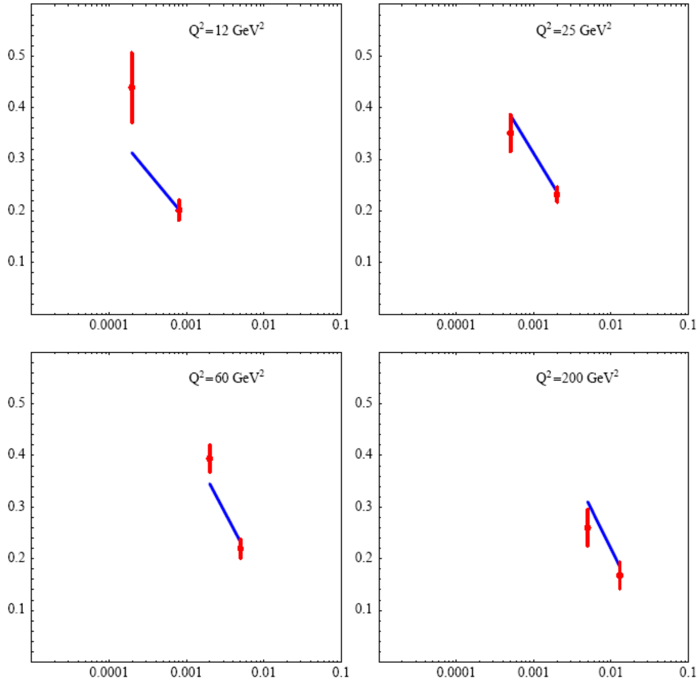
$$\sum_a \int \frac{d\xi}{\xi}\, f_N^a(\xi,\mu)\, \widehat{\omega}_{Ba}^{\lambda}\left(\frac{x}{\xi}, \frac{\hat{s}}{\mu}, \frac{m_Q}{\mu}, \alpha_s(\mu)\right)$$

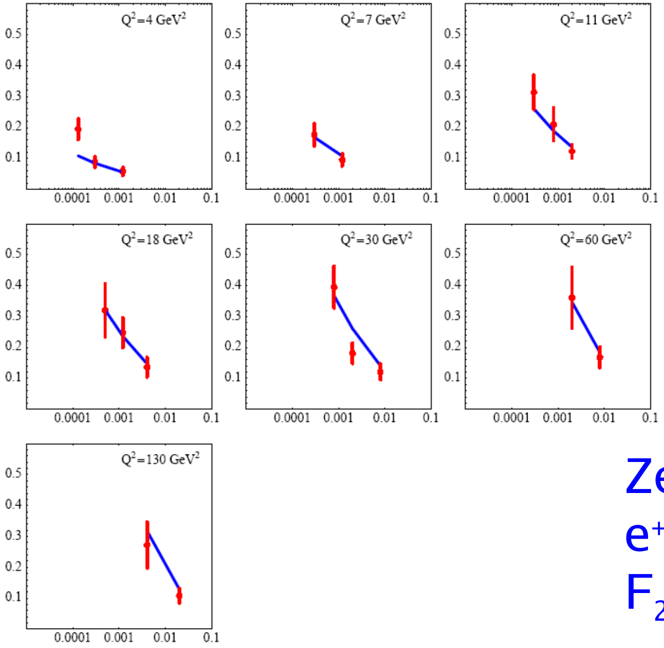
# GM global analysis and HERA I Charm Production data

H1 NC
$e^+p$ 96-97
$F_2^c$

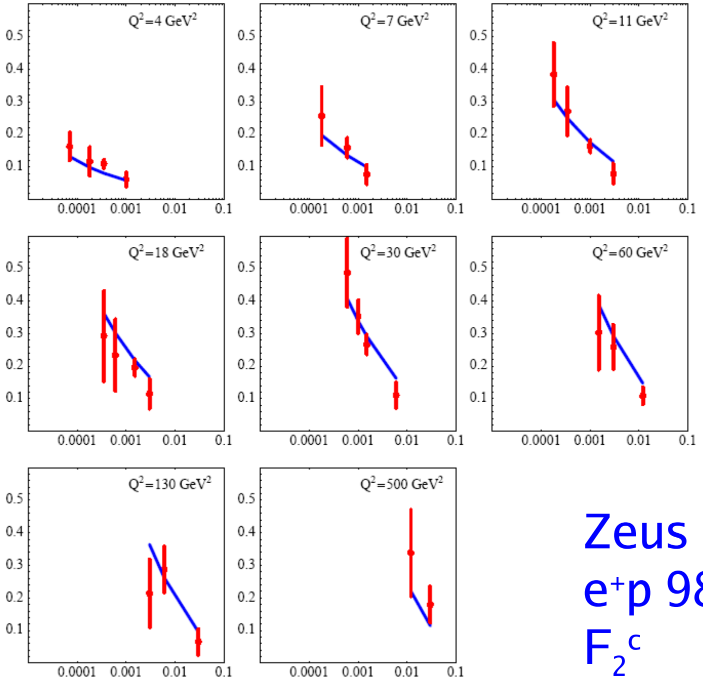


H1 NC
$e^+p$ 99-00
X



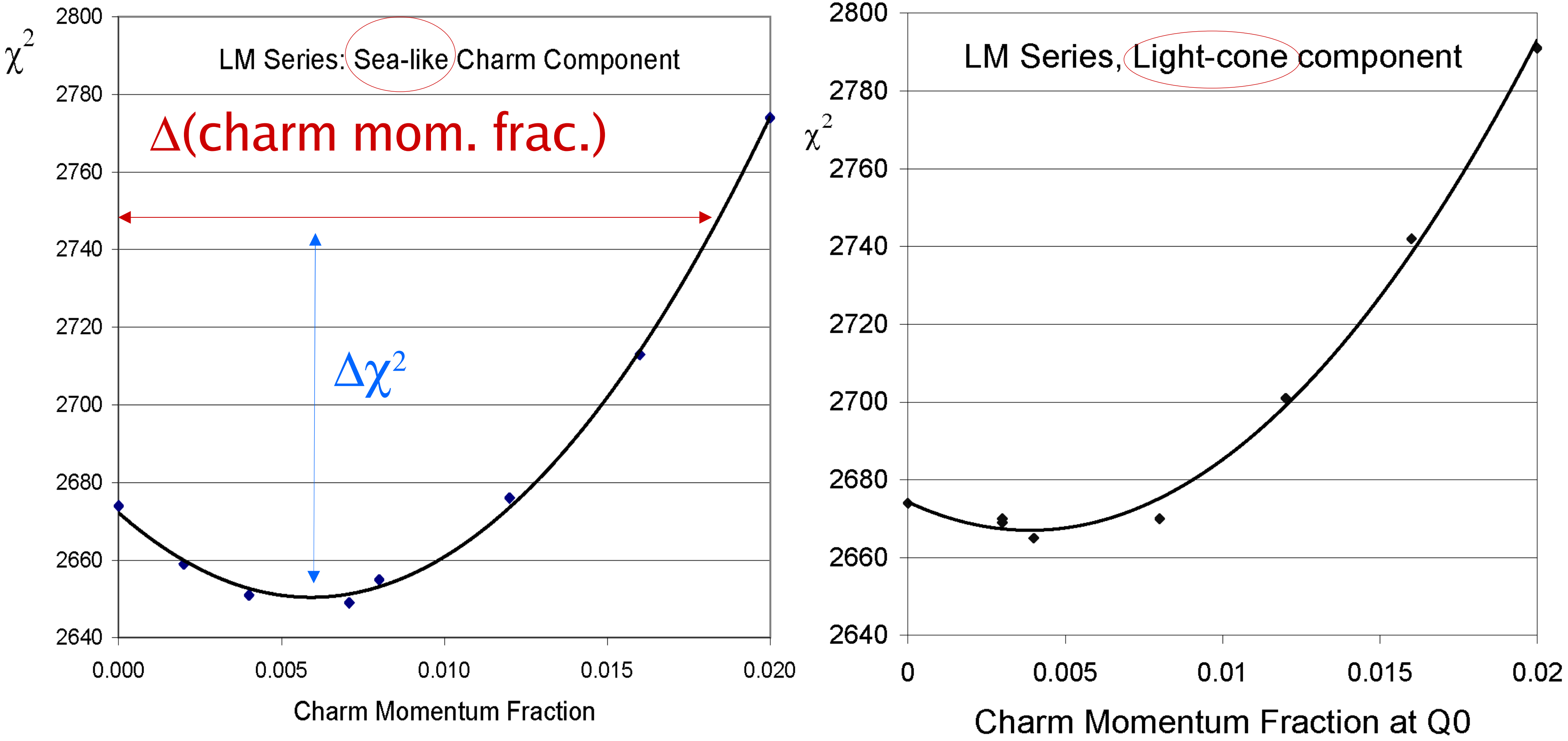


Zeus NC
$e^+p$ 96-97
$F_2^c$



Zeus NC
$e^+p$ 98-00
$F_2^c$

# Goodness-of-fit vs. input non-perturbative Charm momentum fraction

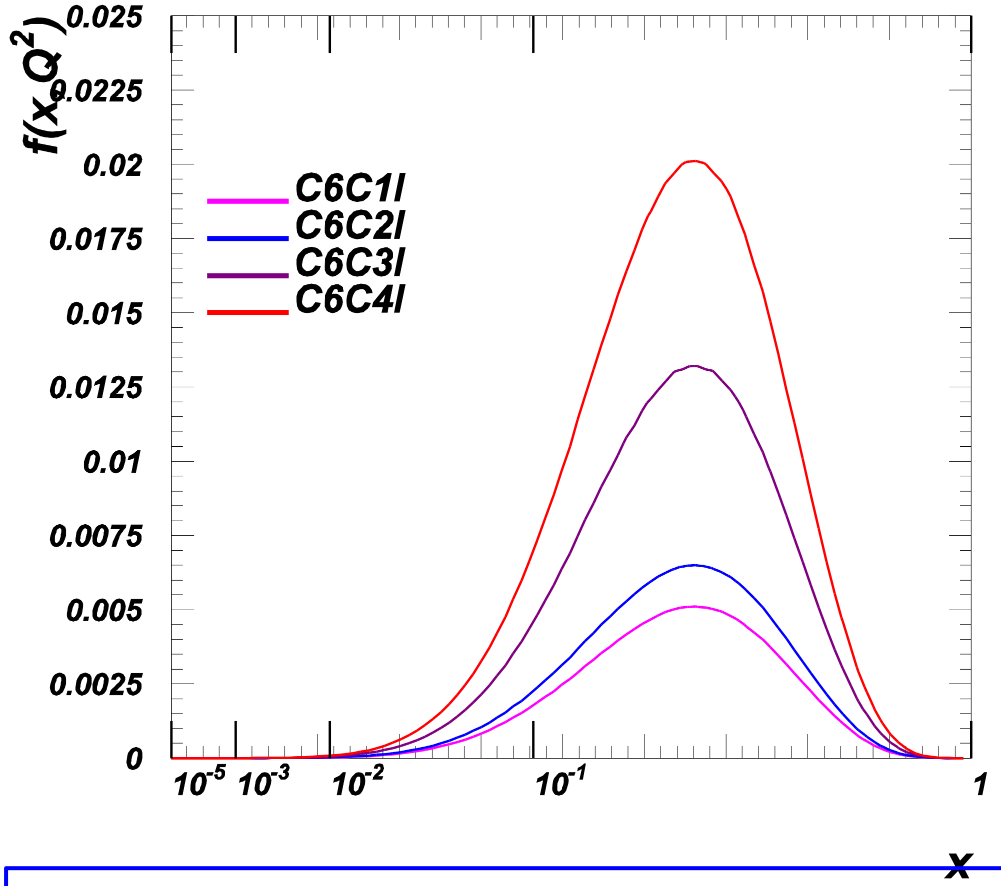


The appropriate value for $\Delta\chi^2$ in the current global analysis environment has not yet been investigated. Hence, the value for the allowed charm mom. frac. should be taken as indicative only.

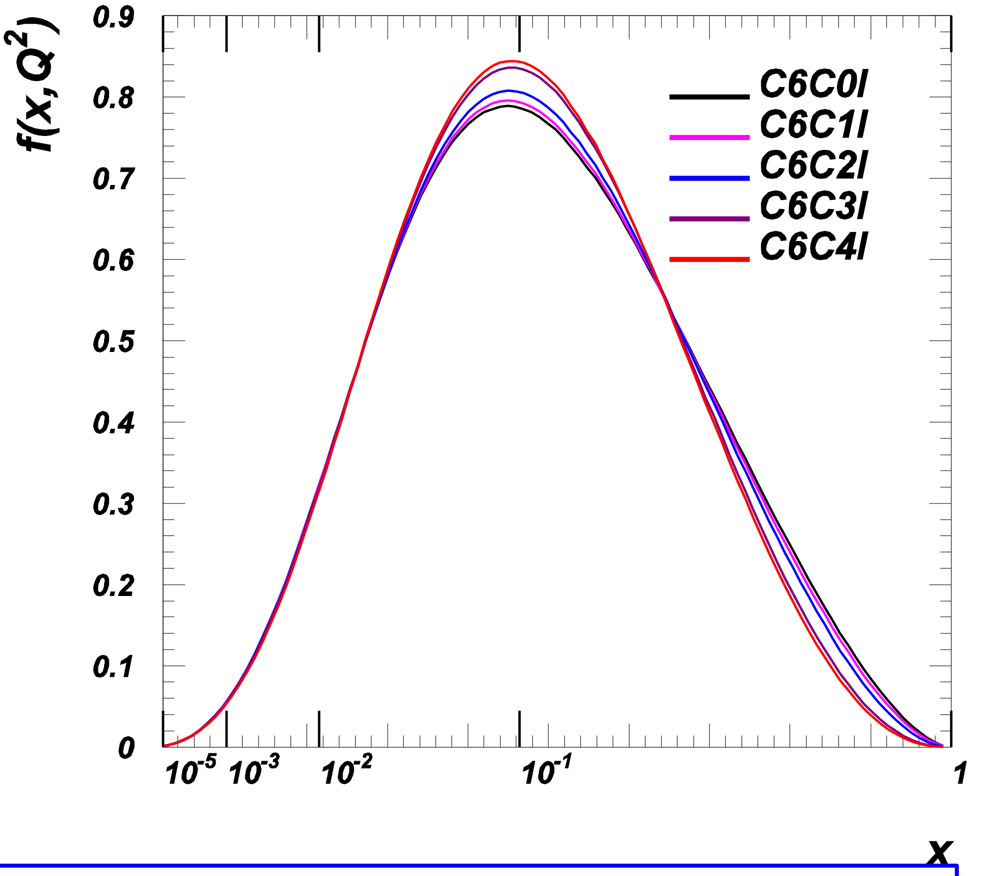
# Charm and Gluon Distributions at Q = 1.3 GeV

Varying amounts of input lightcone charm components

(à la Brodsky etal.) : Momentum frac. at $Q_0$ = 0 — 0.02.



Charm PDF, Q = 1.3 GeV

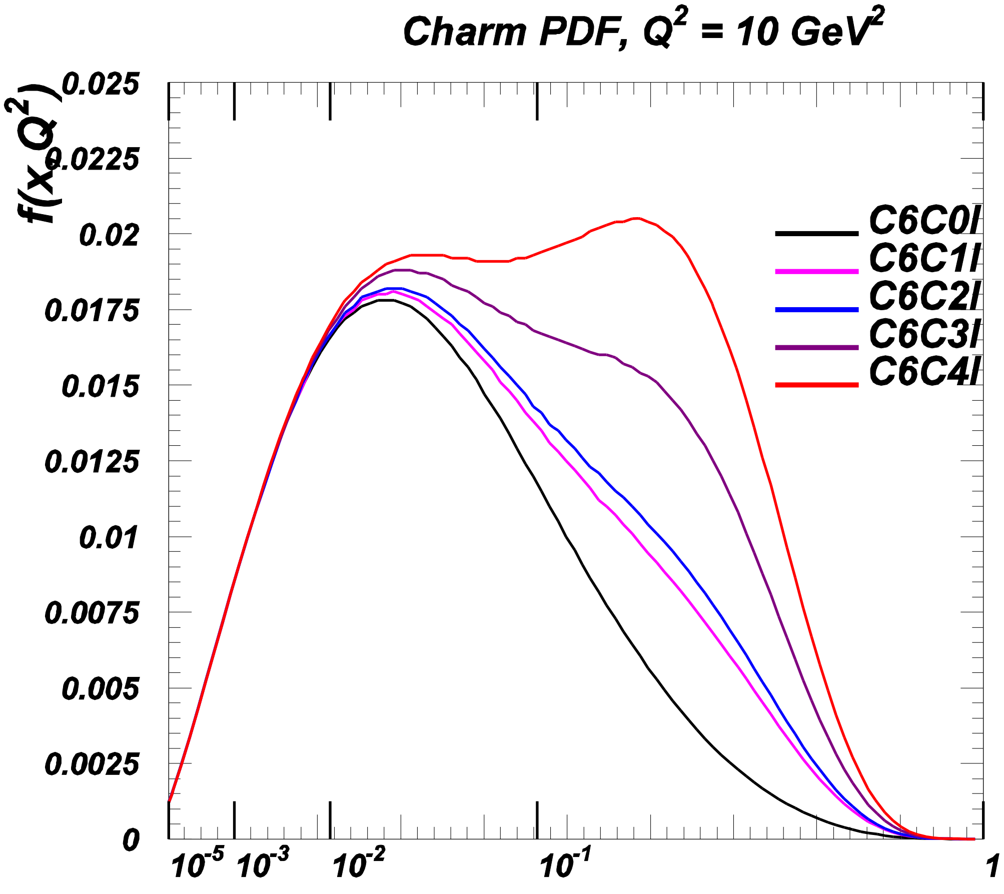


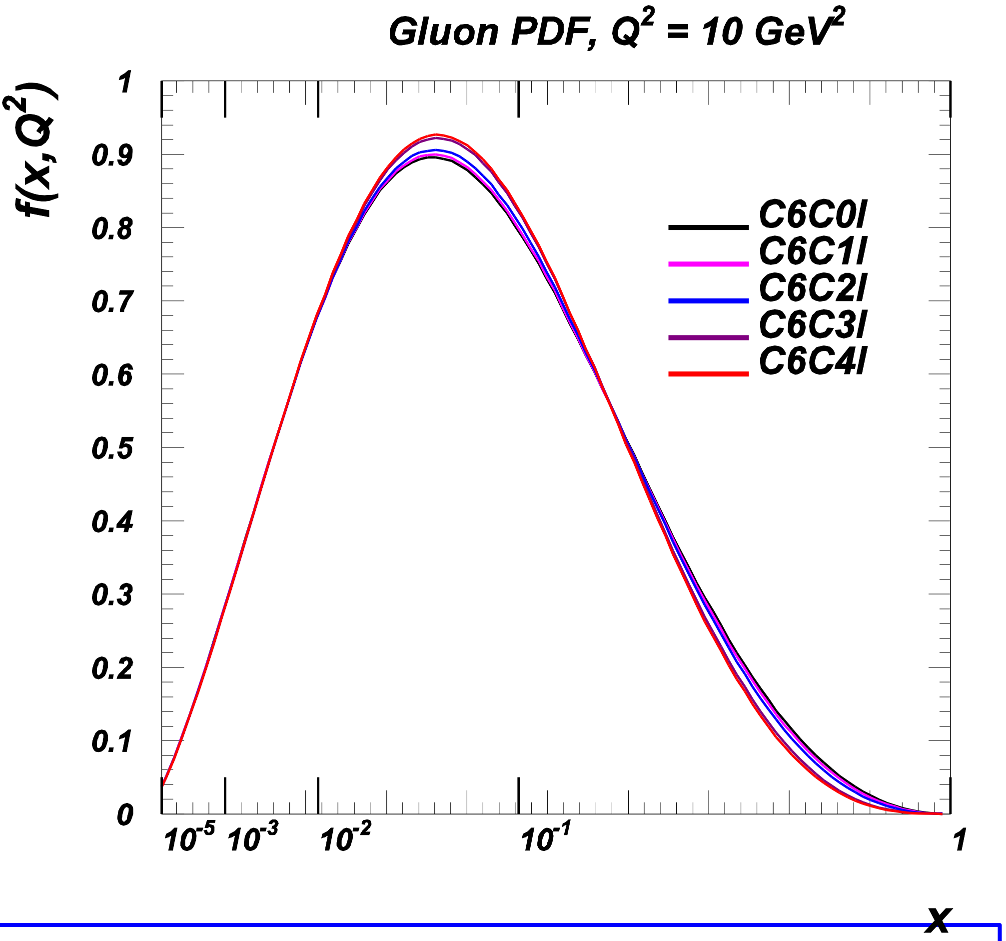
Gluon PDF, Q = 1.3 GeV

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 $Q^2 = 10\ \mathrm{GeV}^2$

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

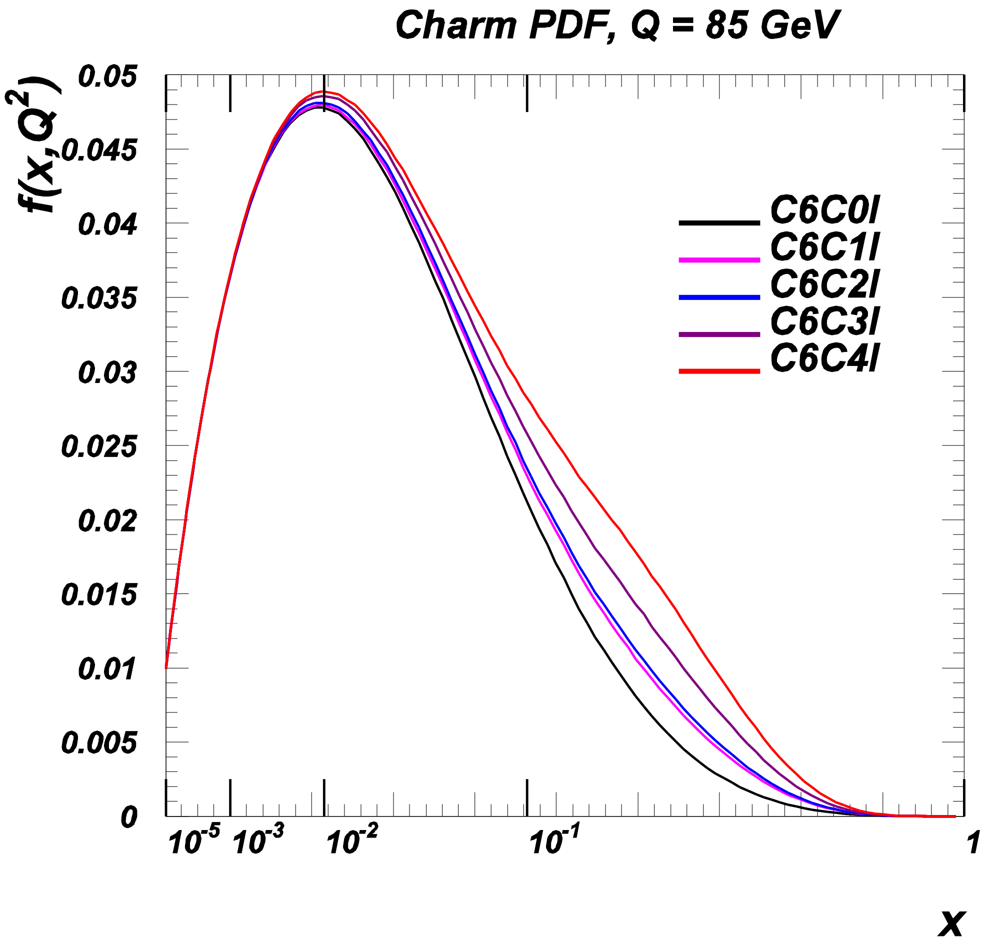

Charm PDF, $Q^2 = 10\ \mathrm{GeV}^2$

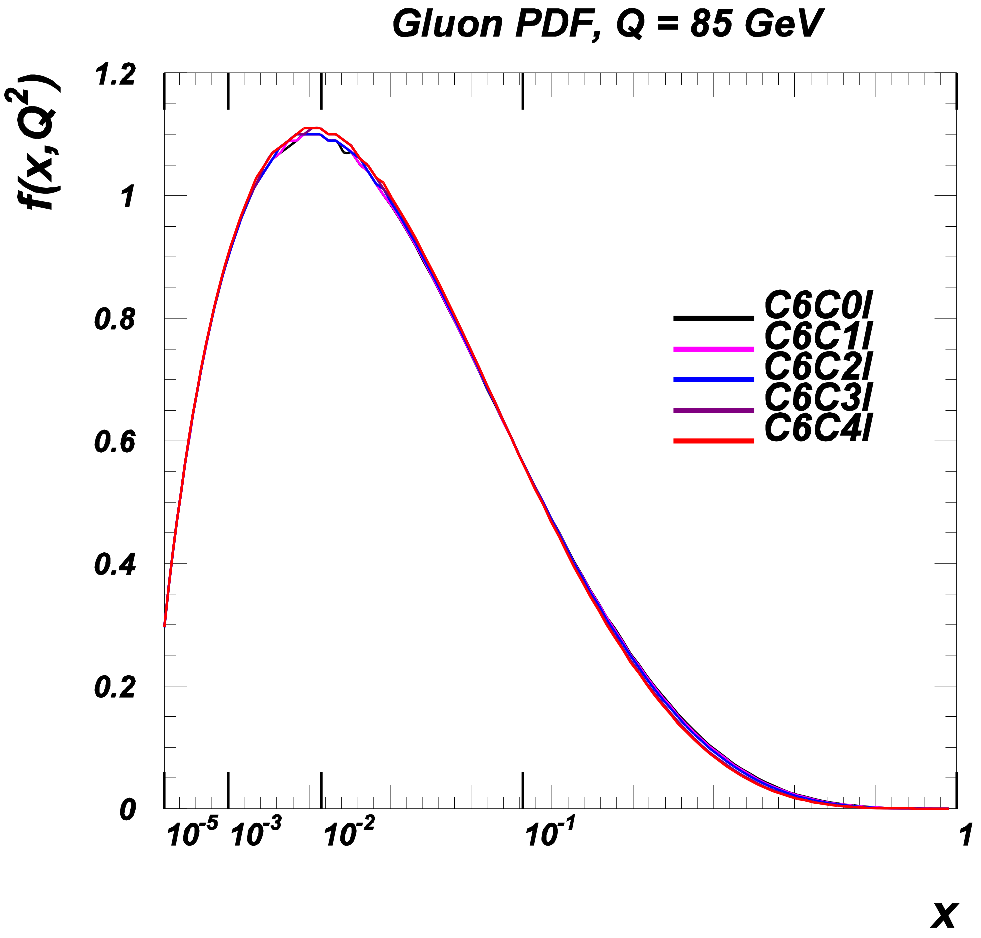

Gluon PDF, $Q^2 = 10\ \mathrm{GeV}^2$

* Two-component charm distr. is apparent! (The radiatively generated component is represented by C6C0l (black) curve.

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

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


Charm PDF, Q = 85 GeV


Gluon PDF, Q = 85 GeV

* Very substantial amount of charm, over the radiatively generated component (C6C0l), still persists at this very large scale ➔ there can be interesting phenomenological consequences even at LHC.

# Heavy flavour schemes: One-particle inclusive case

Kniehl,Kramer,
IJS,Spiesberger

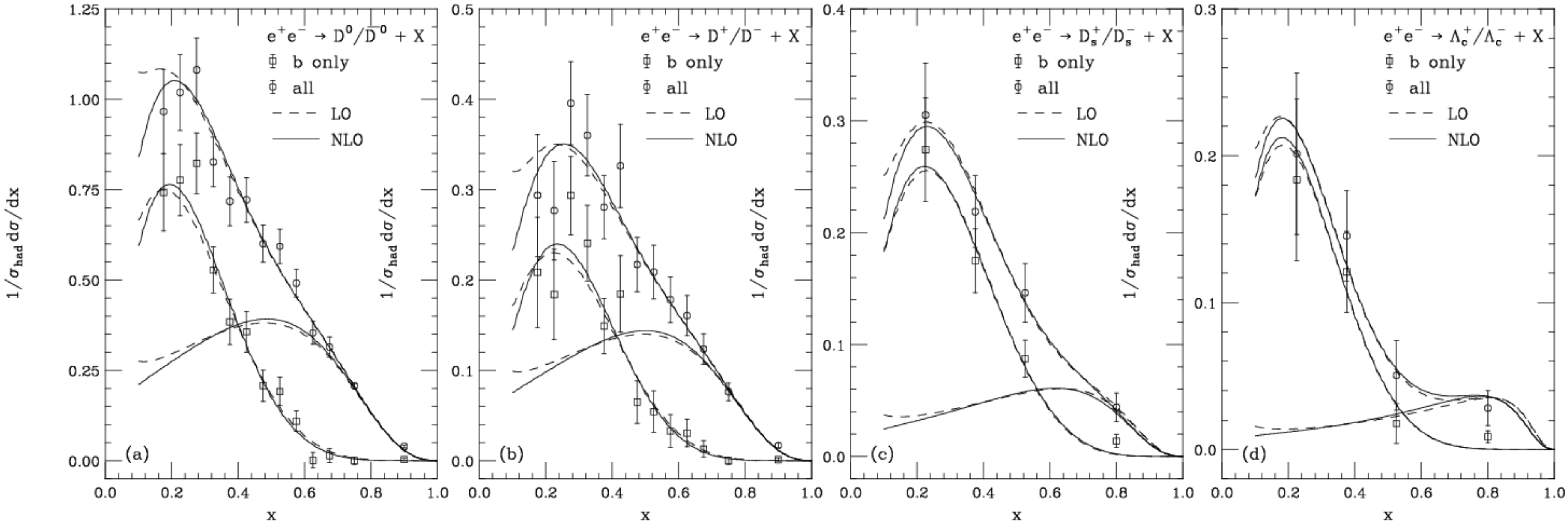
D meson production in a GM-VFN

hep-ph/0508129

- For the same reasons as in the inclusive case it is important to have a GM-VFNS for one-particle inclusive production of heavy quarks/hadrons
- GM-VFN predictions are now available for a number of processes!
- FFs from fits to LEP data

# EXTRACTION OF $D^0$, $D^+$, $D_s^+$, AND $\Lambda_c^+$ FFS FROM LEP1 [1]

- $(1/\sigma_{\mathrm{tot}})d\sigma/dx$, ZM-VFNS
- $\mu_R, \mu'_F = \sqrt{S}$
- Fit to LEP1 data from OPAL [2]



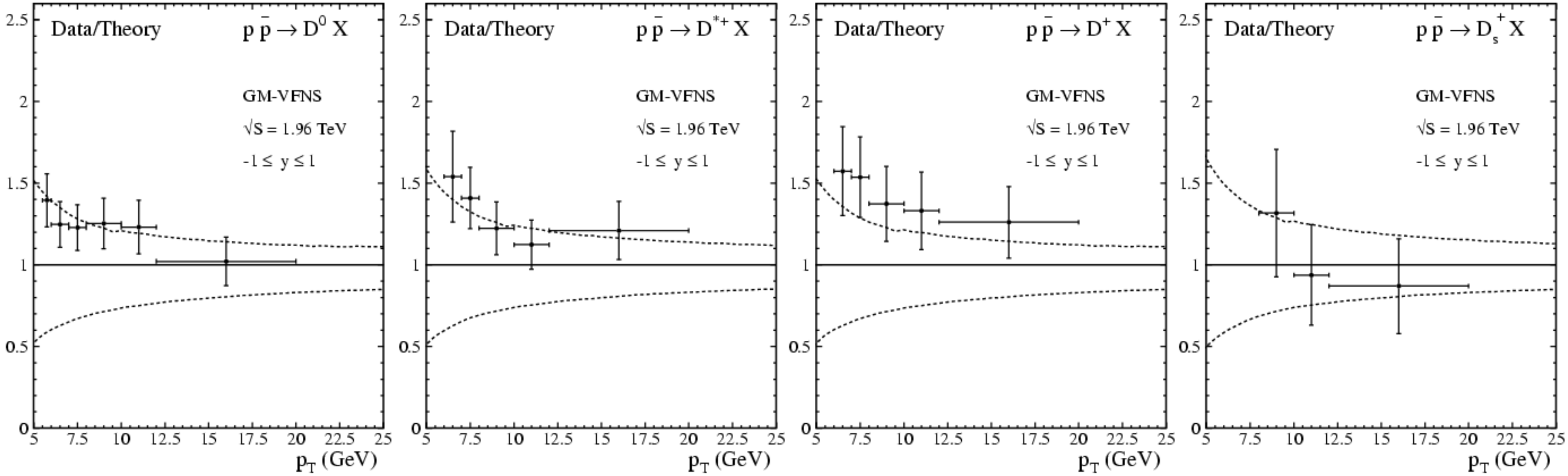
---

[1] B.K., Kramer, PRD71(2005)094013

[2] Alexander et al, ZPC72(1996)1

# COMPARISON WITH CDF II DATA FOR $p\bar{p} \to (D^0, D^{\star +}, D^+, D_s^+)X$ [1]

- $d\sigma/dp_T$ (nb/GeV), $|y| \leq 1$, GM-VFNS
- Uncertainty band: independent variation of $\mu_R, \mu_F, \mu'_F = \xi m_T$, $\xi \in [1/2, 2]$



- Prompt charm data (no secondary charm from $B$ decay) from CDF in run II
- Data and Theory compatible within errors
- Central values: Data/Theory $\simeq 1.5 - 1.2$

---

[1] Kniehl,Kramer,I.S.,Spiesberger,hep-ph/0508129; [2] Acosta et al, PRL91(2003)241804

# Heavy flavour schemes

Fragmentation functions with heavy quark thresholds

Cacciari,Nason,Oleari

hep-ph/0504192

Fragmentation functions do change when a quark threshold is crossed, pretty much like parton distribution functions do: 4-flavour FF's evolve differently from 5-flavour ones (not to mention the existence of the fifth FF!)

The problem has however been pretty much ignored so far in fits to light hadron fragmentation functions:

- Data usually only span an energy range between ~30 and 90 GeV, void of heavy quark thresholds
- **All** flavours are parametrized by phenomenological forms, with charm and bottom being treated like light flavours
- When fitted initial conditions are given at a very low scale [O(1 GeV)] heavy quark contributions are simply "switched on" at the mass thresholds, i.e. mimicking the Collins-Tung space-like threshold condition, $F_h(x,m) = 0$

# All the threshold conditions

Summarizing:

At NLO

$$
\begin{aligned}
D_h^{(n)}(x,\mu) = D_{\bar{h}}^{(n)}(x,\mu) = \\
\int_x^1 \frac{dy}{y}\, D_g(x/y,\mu)\, \frac{\alpha_\mathrm{S}}{2\pi}\, C_\mathrm{F}\, \frac{1+(1-y)^2}{y} \left[\log\frac{\mu^2}{m^2} - 1 - 2\log y\right]
\end{aligned}
$$

$$
\begin{aligned}
D_g^{(n)}(x,\mu) &= D_g^{(n_\mathrm{L})}(x,\mu)\left(1 - \frac{T_\mathrm{F}\alpha_\mathrm{S}}{3\pi}\log\frac{\mu^2}{m^2}\right) \\
D_{i/\bar{i}}^{(n)}(x,\mu) &= D_{i/\bar{i}}^{(n_\mathrm{L})}(x,\mu) \qquad \text{for } i = q_1,\ldots,q_{n_\mathrm{L}}\ .
\end{aligned}
$$

Time-like equivalent of Collins-Tung relations for parton distribution functions

# Outlook: light hadron FF's fit

Analogously to the parton distribution functions case, evolving through a threshold allows to **dynamically generate** the heavy quark fragmentation functions

Recall:

$$D_h^{(n)}(x,\mu) = D_{\bar{h}}^{(n)}(x,\mu) = \int_x^1 \frac{dy}{y} D_g(x/y,\mu) \frac{\alpha_S}{2\pi} C_F \frac{1+(1-y)^2}{y} \left[\log\frac{\mu^2}{m^2} - 1 - 2\log y\right]$$

This will allow to perform fits to light hadron fragmentation data parametrizing only the **three light** quarks and the gluon FF's. The **charm** and **bottom** ones will be **radiatively generated**

Eventually, a comparison with the `five light flavours' sets available today will be possible

Kretzer, '00
Kniehl, Kramer, Poetter, '00
Bouhris, Fontannaz, Guillet, Werlen, '01
....

Work in progress

# Heavy quark fragmentation

QCD analysis of D and B meson FFs

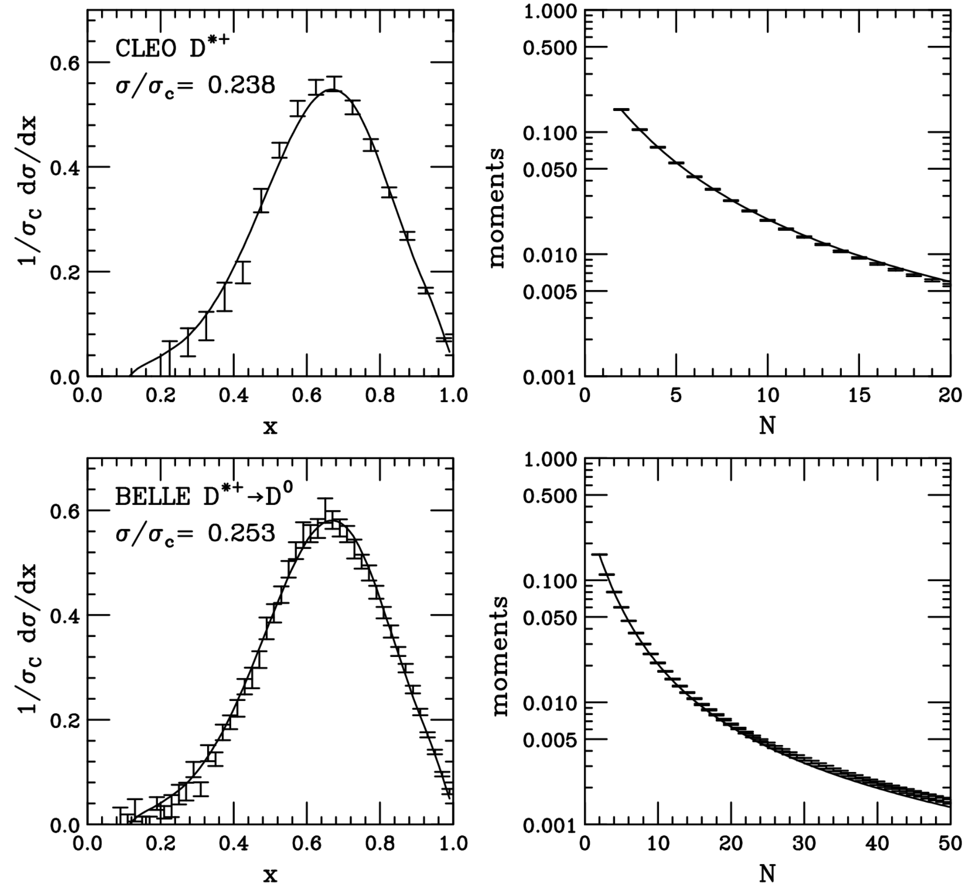
Oleari,Cacciari,Nason

hep-ph/0510032

Sophisticated QCD analysis:

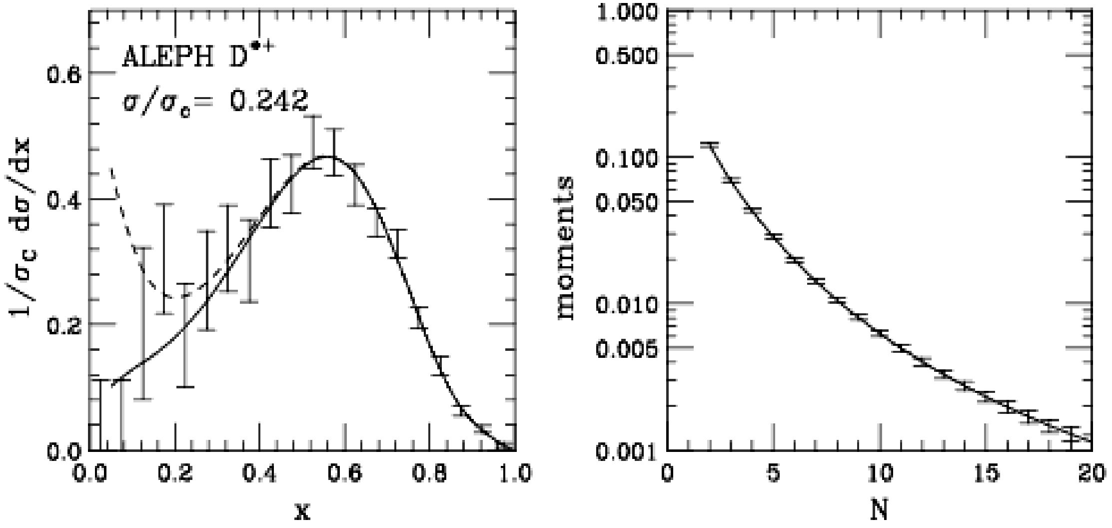
- NLO QCD: initial conditions, evolution, coefficient functions
- NLL soft gluon resummation
- Evolution with proper matching at bottom threshold (see above)
- Data corrected for ISR

# CLEO and BELLE $D^*$ fits



- ✓ $D$ mesons data fits near the $\Upsilon(4S)$ mass (10.6 GeV)
- ✓ Very good fit in the whole $x$ range
- ✓ More fits in [Cacciari, Nason and C.O.], where $D^* \to D\,X$ have been modeled from decay chains and branching ratios
- ✓ $B$ mesons data fits near the $Z^0$ mass (91.2 GeV)

# ALEPH $D^*$ fits at LEP



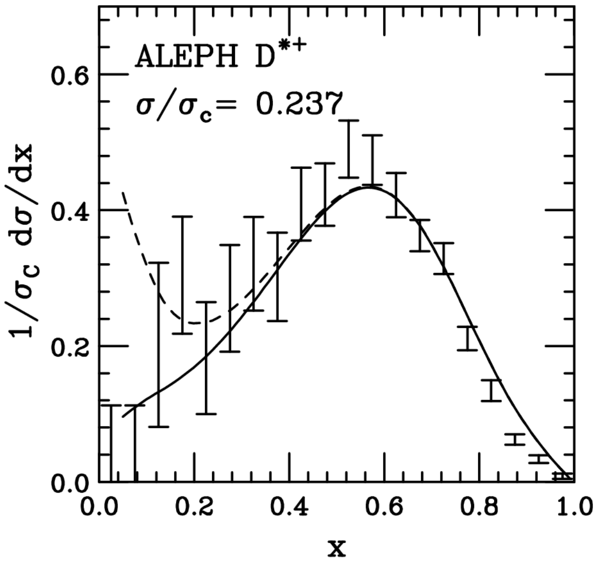
- ✗ very few useful points
- ✗ large error bars

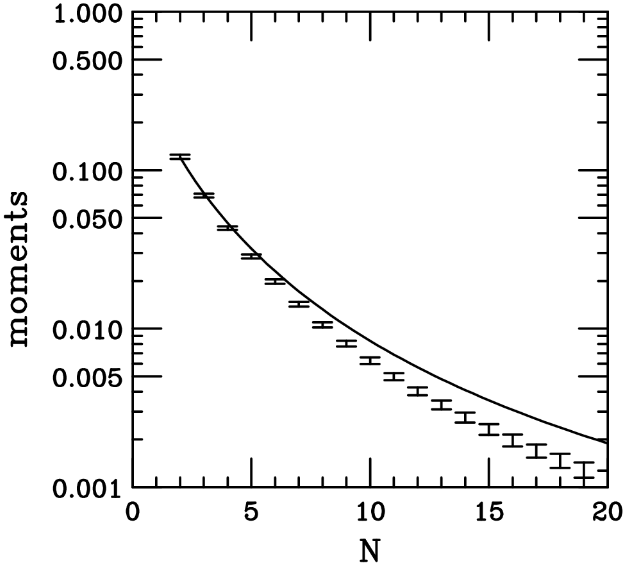
$$D_{\mathrm{NP}}(x) = \mathrm{Norm.} \times \left[ \delta(1-x) + c\,\frac{(1-x)^a x^b}{N_{a,b}} \right]$$

| | | | |
|---|---|---|---|
| ALEPH | $a = 2.4 \pm 1.2\,,$ | $b = 13.9 \pm 5.7$ | $c = 5.9 \pm 1.7$ |
| CLEO/BELLE | $a = 1.8 \pm 0.2\,,$ | $b = 11.3 \pm 0.6$ | $c = 2.46 \pm 0.07$ |

What about the supposed universality of the non-perturbative fragmentation function?

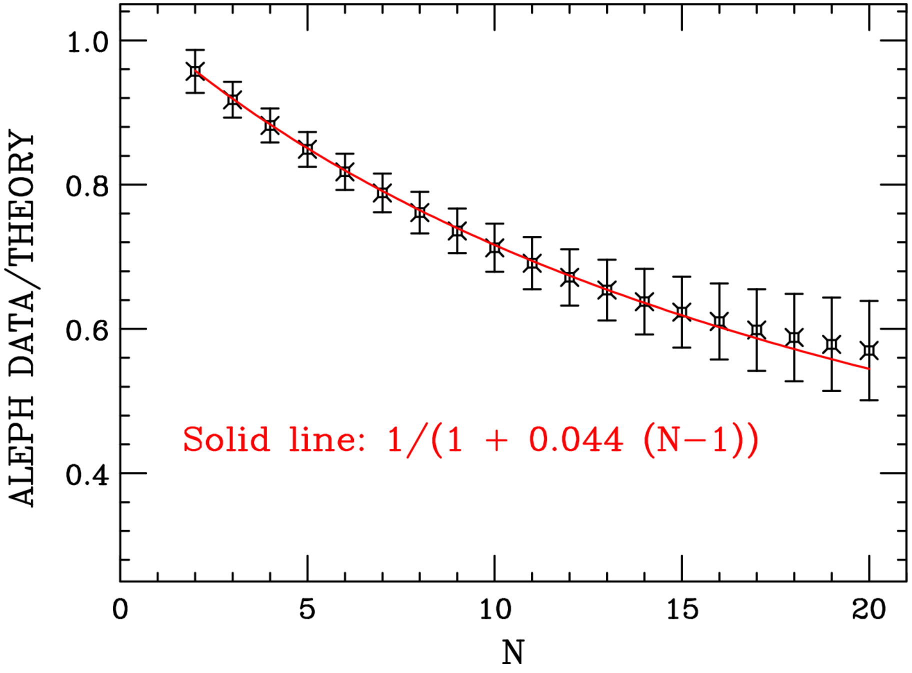
# ALEPH with CLEO/BELLE parameters





- ✗ Discrepancy in the large-$x$ (large-$N$) region
- ✗ The ratio data/theory well modeled by

$$\frac{1}{1+0.044\,(N-1)}$$



# Possible explanation

We can only speculate about the possible origin of the discrepancy.
If this were due to a non-perturbative correction to the coefficient function of the form

- $1 + \frac{C(N-1)}{q^2}$ this would lead to the extra factor

$$\frac{1+\frac{C(N-1)}{M_Z^2}}{1+\frac{C(N-1)}{M_\Upsilon^2}} \quad \Longrightarrow \quad \sim \frac{1}{1+0.044\,(N-1)} \quad \text{if} \quad C \sim 5\,\mathrm{GeV}^2 \qquad \text{large value!!}$$

- $1 + \frac{C(N-1)}{E}$ with $E = \sqrt{q^2}/2$ then $C \sim 0.52$ GeV, a much more acceptable value.

Demonstrating the absence (or the existence) of $1/E$ corrections in fragmentation functions would be a very interesting result, since it would help to validate or disprove renormalon-based predictions.

# Heavy quark production at RHIC

Cacciari et al

Charm and bottom production at RHIC

hep-ph/0502203,
hep-ph/0511257

- Provide solid QCD benchmark predictions based on FONLL (not 'just another model') including theoretical uncertainties
  - Fair agreement with pp and dAu RHIC data
- The calculation of the quenching ratio for electrons coming from heavy quarks depends critically on the charm/bottom yield. Need for an accurate prediction of their relative production cross sections

For details see Matteo's talk

# Heavy quarks and kT-factorization

New test for the kT-factorization:
beauty quark production at HERA

Zotov,Lipatov

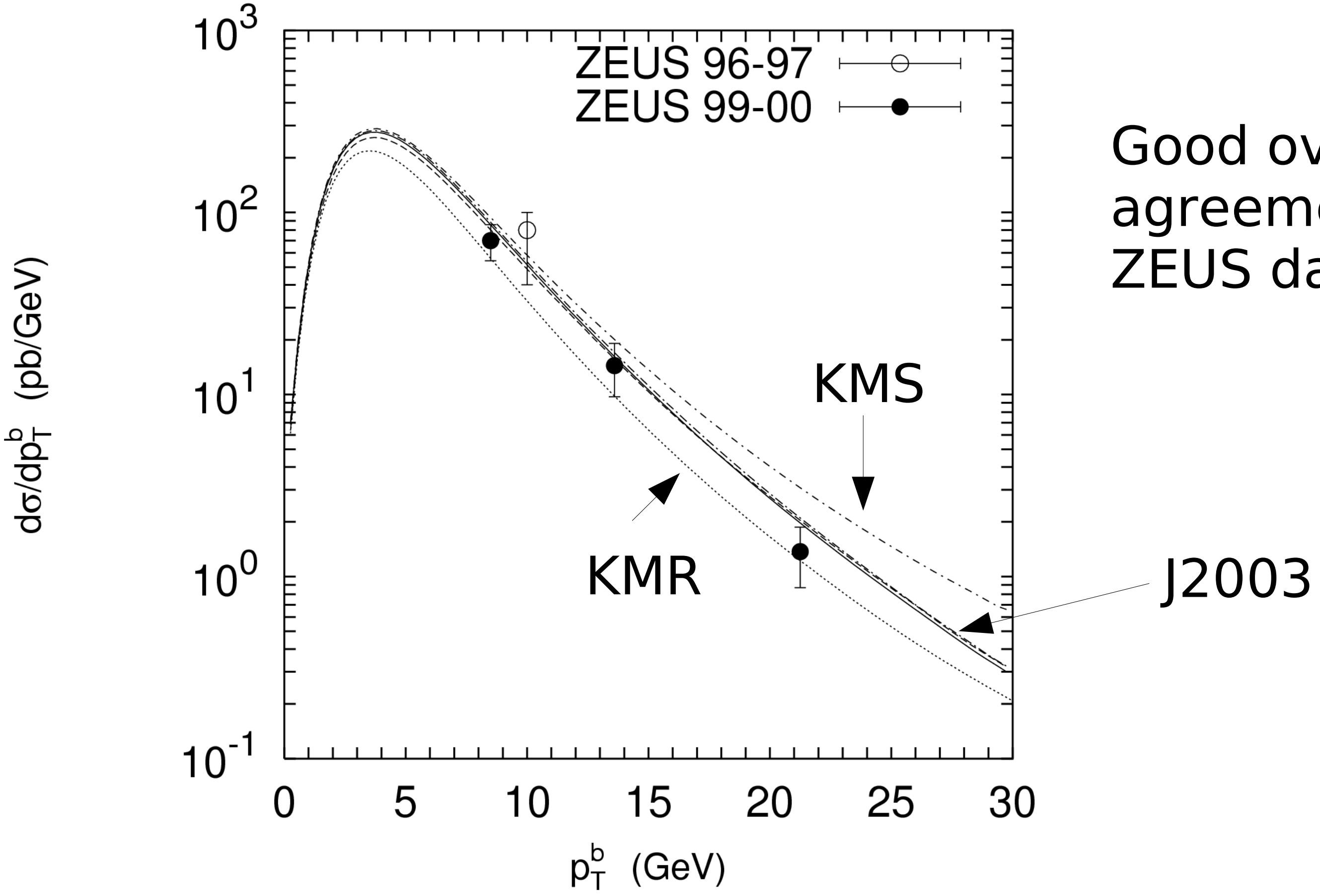
hep-ph/0601240 $\gamma p$
hep-ph/0603017 DIS

- Detailed comparison with differential cross sections
- Predictions also for charm production at LEP and HERA

(Important: Test same approach with several processes)

# Heavy quarks and kT-factorization

Zotov

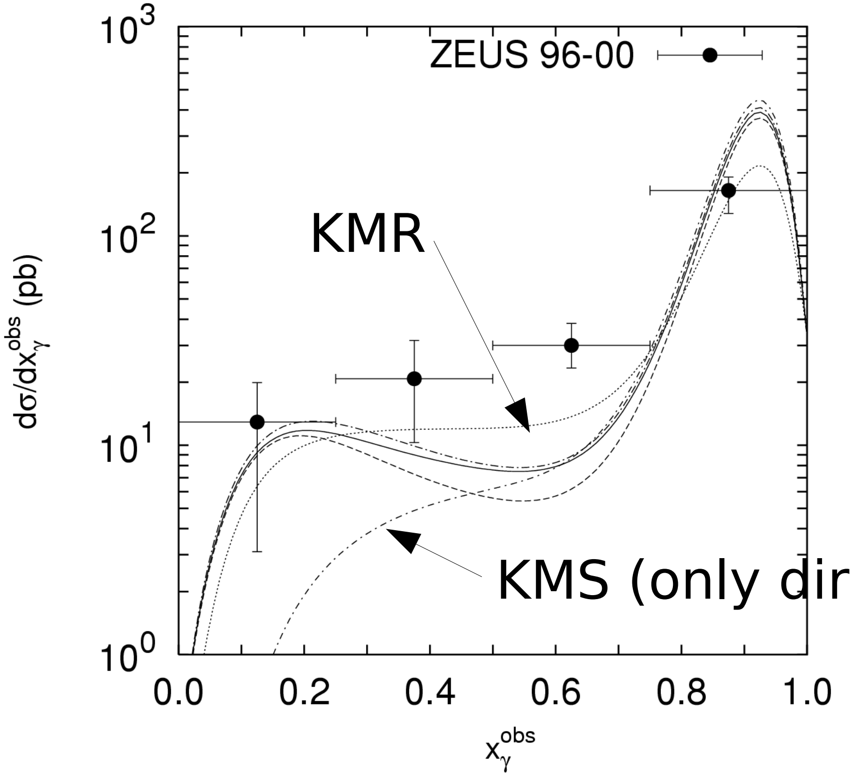


Good overall agreement with ZEUS data

**Figure 2:** *The differential c.s.* $d\sigma/dp_T^b$ *of inclusive beauty photoproduction at* $|\eta^b| < 2, Q^2 < 1$ $GeV^2$ *and* $0.2 < y < 0.8$. *All curves are the same as in Fig. 1.*

# Heavy quarks and kT-factorization

Zotov



KMR

KMS (only direct contribution)

Resolved contribution important

Strong dependence on UGD at low $x_\gamma^{obs}$

All in all, reasonable agreement with data

**Figure 13:** *The differential c.s.* $d\sigma/dx_\gamma^{obs}$ *of dijets with associated muon from b-decay at* $-1.6 < \eta^\mu < 2.3, p_T^\mu > 2.5$ $GeV$, $Q^2 < 1$ $GeV^2, 0.2 < y < 0.8, p_T^{jet_1} > 7, p_T^{jet_2} > 6$ $GeV$ *and* $|\eta^{jet}| < 2.5$. *The curves are obtained with account of resolved photon contribution.*

# Heavy quarks and kT-factorization

Non-linear Gluon Evolution and Heavy Quark Production at the LHC

Peters,Jung,
Kutak,Motyka

- Test non-linear effects in evolution of unintegrated PDFs
  - Gluon UPDF from HERA F2 data
  - Compute HQ production at HERA,Tevatron and LHC
  - Tiny effects observed; no significant differences between linear and non-linear evolution

# Evolution formalism

Peters

- Gluon evolution in the framework of unintegrated gluon density and $k_t$-factorization
- Kwiecinski et al: Unified BFKL and DGLAP description including saturation effects (KKMS)

- Improvement of BFKL equation by adding non-singular part of DGLAP gluon splitting function
- Resummation of both, leading ln $Q^2$ and ln $1/x$ terms
- Including dominant sub-leading ln $1/x$ effects via consistency constraint and running $\alpha_s$

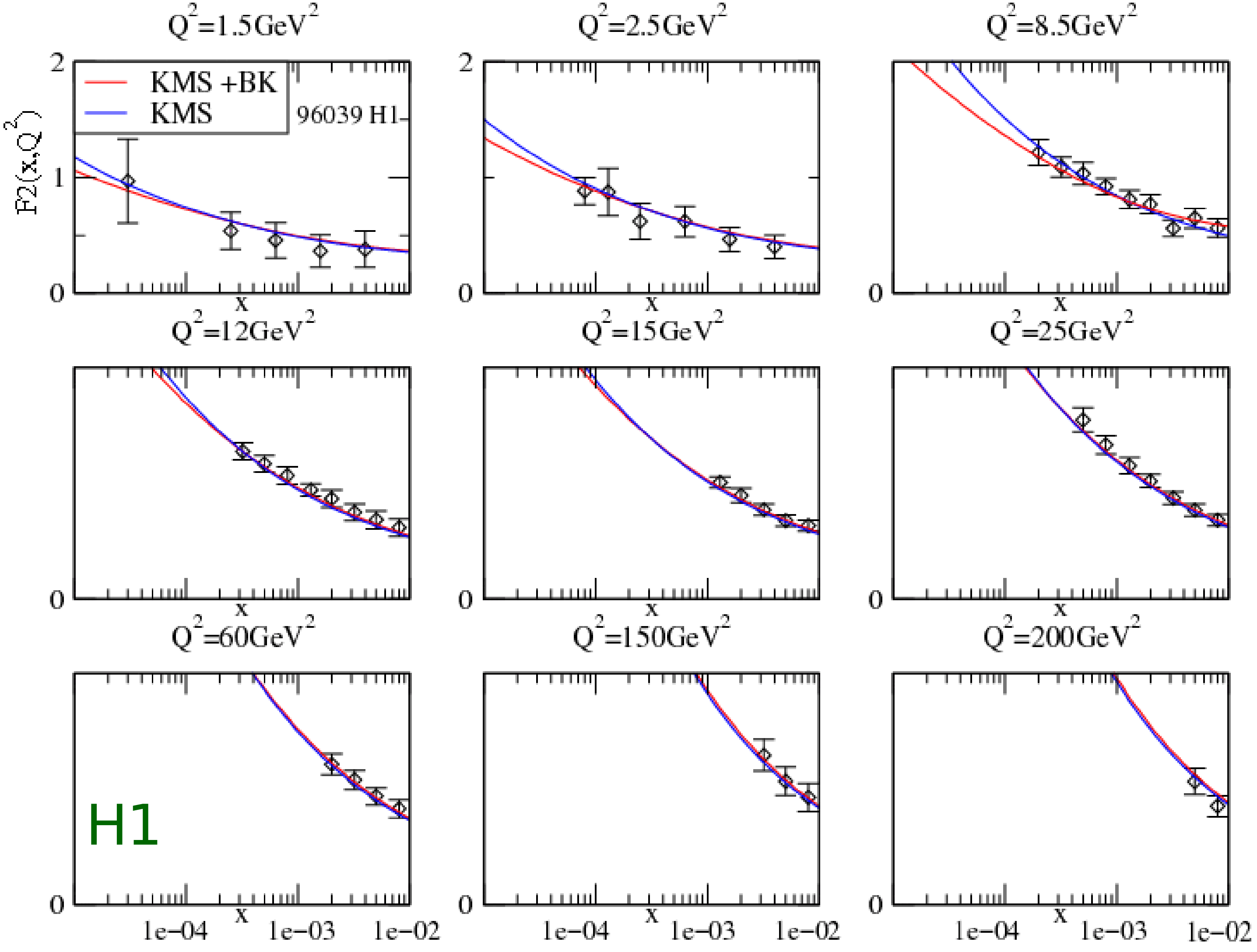
[Kwiecinski, Martin, Stasto, PRD **56** (1997), 3991]

- Non-linear part from BK equation to account for gluon recombination

[Kutak, Kwiecinski, EPJ **C29** (2003), 521]

# Constraints by HERA *F2*

Peters



Linear vs

non-linear with

$R$ = 2.8 GeV$^{-1}$

↑

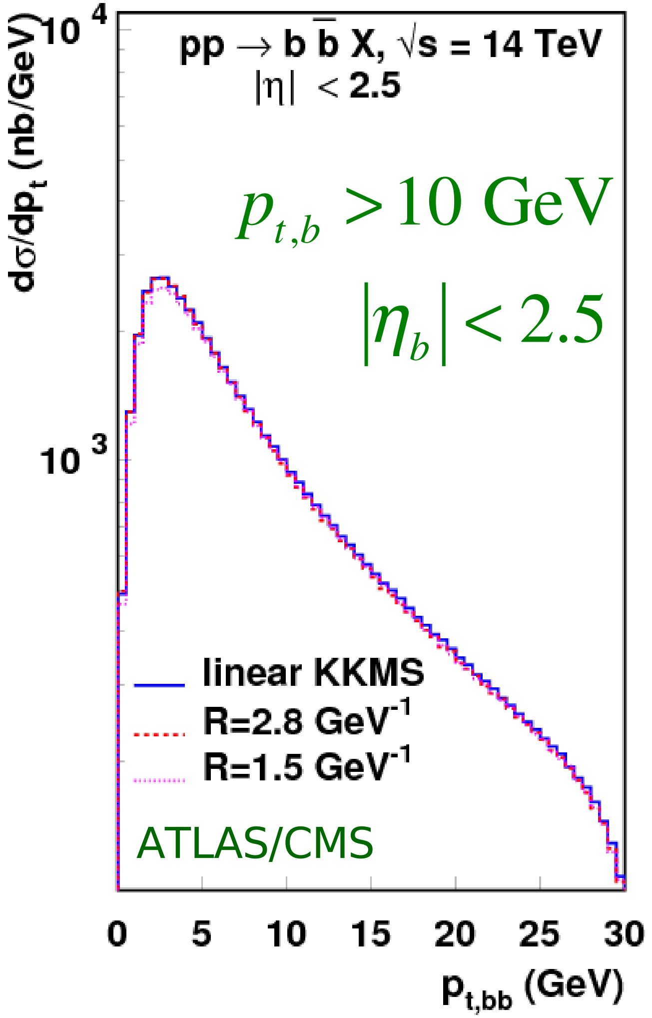
Radius of dense gluon system

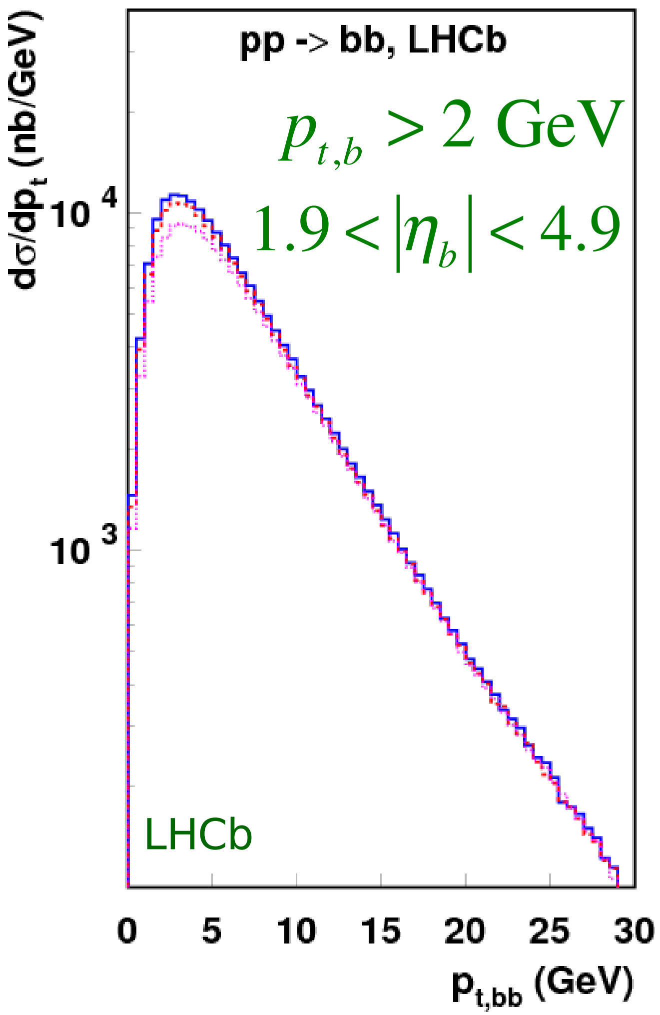
$$xg(x,k_0^2)$$

$$= N(1-x)^\rho$$

- Evolution formalism describes the data well, no significant difference between linear and non-linear evolution

# $b\bar{b}$ production at *ATLAS/CMS* and *LHCb* Peters





- Within the ATLAS/CMS acceptance cuts no saturation effects observable
- Linear evolution and $k_t$-factorization can be safely applied

# Charmonium production

CEM vs. NRQCD
in Charmonium Production

<u>Lee</u>,Bodwin,Braaten

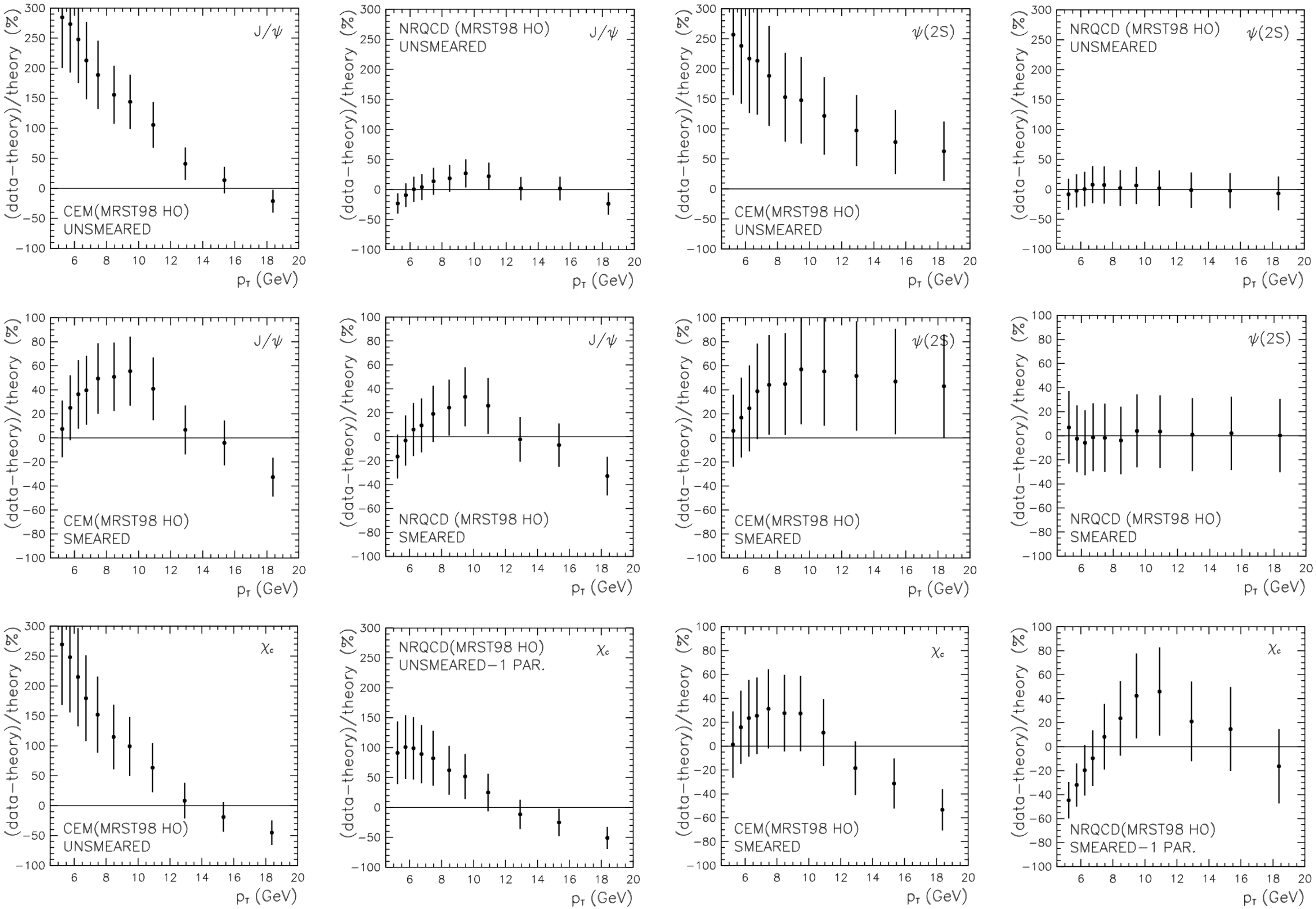
hep-ph/0504014

# CEM vs. NRQCD in charmonium production

Jungil Lee

hep-ph/0504014

- We compared CEM and NRQCD predictions for charmonium production with the CDF data.
  - NLO $2 \to 1$ parton processes are included.
  - Multiple gluon emission effect is included using $k_T$-smearing.
- CEM
  - not satisfactory in both normalization and slope.
  - $k_T$ smearing improves CEM prediction but still unsatisfactory.
- NRQCD
  - NRQCD factorization has more free parameters than the CEM, but it gives a satisfactory fit to the data.
  - In the $P$-wave case, which is constrained by decay data, $k_T$ smearing is essential to obtain a satisfactory fit.
- Proper inclusion of effects of multiple soft-gluon emission could provide a stringent test of NRQCD factorization in the $P$-wave case.


(data−theory)/theory (%)
p_T (GeV)
J/ψ
CEM(MRST98 HO)
UNSMEARED
NRQCD (MRST98 HO)
UNSMEARED
J/ψ
ψ(2S)
CEM(MRST98 HO)
UNSMEARED
NRQCD (MRST98 HO)
UNSMEARED
ψ(2S)
J/ψ
CEM(MRST98 HO)
SMEARED
J/ψ
NRQCD (MRST98 HO)
SMEARED
ψ(2S)
CEM(MRST98 HO)
SMEARED
ψ(2S)
NRQCD (MRST98 HO)
SMEARED
χc
CEM(MRST98 HO)
UNSMEARED
NRQCD(MRST98 HO)
UNSMEARED−1 PAR.
χc
χc
CEM(MRST98 HO)
SMEARED
χc
NRQCD(MRST98 HO)
SMEARED−1 PAR.