Inclusive D- and B-Meson Production at the LHC

Seminar Universitaet Muenster, May 7, 2012

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based on work in collaboration with

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- Theoretical framework:

  the General-Mass Variable-Flavor-Number Scheme for
  1-particle inclusive heavy-meson production
  measure p_T and η of observed heavy meson

- Numerical results for D- and B-meson production:
  $p + p \to D + X$, $(D = D^{\pm}, D^0, D^{*\pm}, D_s^{\pm})$,
  $p + p \to B + X$, $(B = B^{\pm}, B^0, B_s)$

  for comparison with LHC data from ATLAS, ALICE, LHCb, CMS

- At the LHC: expect higher statistics, higher transverse momentum
  ➜ more reliable test of QCD,
  ➜ better understanding of background for new physics searches

Massive or Massless Heavy Quarks?

1-particle inclusive heavy-meson production: two scales, m and p_T

$m \neq 0 \longrightarrow$

- correct threshold behavior
  no collinear divergences from $Q \to Q + g$
  ($Q =$ charm, bottom)
  but terms $\propto \log(p_T/m)$
- large corrections at large μ

$m = 0 \longrightarrow$

- mass singularities ($1/\epsilon$-poles instead of $\log m^2$-terms)
  absorbed in PDFs and FFs
- QCD prediction: DGLAP (RG) evolution resums
  large logarithms $\log(p_T/m)$
- more reliable at large p_T
- not reliable at heavy quark threshold

Two basic approaches:

- Fixed Order Perturbation Theory (FFNS)
- Parton Model (ZM-VFNS)

(FFNS: Fixed Flavour Number Scheme, VFNS: Variable Flavour Number Scheme, ZM: Zero Mass)

- Fixed-Flavor-Number Scheme (FFNS):
  only light partons in the initial state
  heavy quark produced in the final state
  available at fixed order: $O(\alpha_s)$
- Zero-Mass Variable Flavor-Number Scheme (ZM-VFNS):
  heavy quark is a parton: PDFs, FFs
  resum large logarithms (DGLAP, RG)
  heavy quark treated as massless

Interpolating scheme:

- Parton Model with quark masses: GM-VFNS
  tailored for DIS (F_2^c, F_L^c): ACOT, S-ACOT$_\chi$

➜ General-Mass Variable Flavor-Number Scheme (GM-VFNS):

- Combine massive (low scale) and massless (high scale) calculations: exploit freedom to choose an appropriate factorization scheme (Collins 1998)
- Conventionally, PDFs and FFs are defined in the $\overline{\mathrm{MS}}$ scheme and $\overline{\mathrm{MS}}$ scheme is based on a massless calculation (massless and massive calculations contain different singularities)
- ➜ Match massless and massive calculations:

$$d\sigma_{\mathrm{sub}} = \lim_{m\to 0} d\tilde{\sigma}(m) - d\hat{\sigma}_{\overline{\mathrm{MS}}}$$

The subtracted cross section (in a massive calculation)

$$d\hat{\sigma}(m) = d\tilde{\sigma}(m) - d\sigma_{\mathrm{sub}}$$

can be used with universal $\overline{\mathrm{MS}}$ parton distribution and fragmentation functions

- Collinear logs: $\log(p_T^2/m^2) = \log(p_T^2/\mu^2) + \log(\mu^2/m^2)$, terms with $\log(\mu^2/m^2)$:
  subtracted from hard part and
  absorbed in parton distribution and fragmentation functions
  resummed by DGLAP evolution equations

➜ Parton distribution functions for g, u, d, s, and c, (and b), heavy quark is a parton: $f_Q \neq 0$

for 1-particle inclusive heavy-quark production: fragmentation functions

➜ Not only for $Q \to H$, $H = D, B$: $D_Q^H(z, \mu_{F'}^2)$, but every parton can fragment into the observed heavy hadron

- VFNS: PDF for heavy quark, $f_Q = 0$ below, $f_Q \neq 0$ above threshold;
  $\longrightarrow$ GM-VFNS with $m \neq 0$
- Fragmentation functions, with non-perturbative input and perturbative RG evolution
- Large collinear logarithms $\ln(\mu^2/m^2)$ resummed in evolved $f_c(x, \mu^2)$
  and $D_Q^D(x, \mu^2)$
  (set $\mu = p_T$, eventually)

- Subprocesses
  - at LO: $g + g \to Q + \bar{Q}$, $q + \bar{q} \to Q + \bar{Q}$ (hadroproduction, for photoproduction, DIS: $\gamma^* + g \to c + \bar{c}$)
  - at NLO: 1-loop diagrams, gluon bremsstrahlung $g + g \to Q + \bar{Q} + g$
  - also $g + q \to Q + \bar{Q} + q$ and
  - heavy-quark-initiated processes: e.g., $g + Q \to g + Q$ (treated as a massless parton)

➜ Every parton can fragment to the heavy meson:

  - fragmentation functions for $c \to D$, $g \to D$, $q \to D$ and $b \to B$, $g \to B$, $q \to B$, including $c \to B$

Applications available for

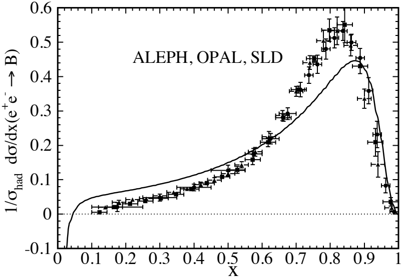
- $\gamma + \gamma \to D^{*\pm} + X$
  direct and resolved contributions — EPJC22, EPJC28
- $\gamma^* + p \to D^{*\pm} + X$
  photoproduction — EPJC38, EPJC62, PLB679
  for HERA and LHeC
- $p + \bar{p} \to (D^0, D^{*\pm}, D^\pm, D_s^\pm, \Lambda_c^\pm) + X$
  good description of Tevatron data
  intrinsic charm — PRD71, PRL96, PRD79
- $p + \bar{p} \to B + X$
  works for Tevatron data at large p_T — PRD77
- for the LHC (this talk):
  $p + p \to B + X$ — PRD84
  $p + p \to D + X$ — arXiv:1202.0439

Input

- PFD from CTEQ6.6
- FF from fits to e^+e^- data:
  for D^0, $D^\pm$, D^*: Kneesch, Kniehl, Kramer, Schienbein, 2008
  for D_s, Λ_c: Kniehl, Kramer, 2006
  for B-mesons: Kniehl, Kramer, Schienbein, Spiesberger, 2008
- Results always for average with charge-conjugated states
- Kinematic range following measurements of the LHC collaborations
- Scale parameters
  for factorization: initial-state, PDF: μ_I, final-state, FF: μ_F,
  and renormalization: μ_R
  $\mu_i = \xi_i \sqrt{m^2 + p_T^2}$
  varied by factors 2 up and down
- Charm mass $m_c = 1.5$ GeV, bottom mass $m_b = 4.5$ GeV

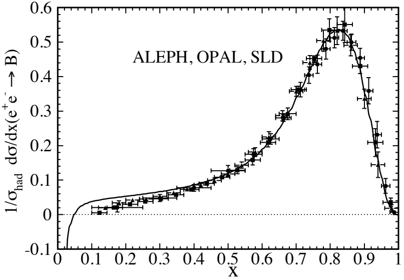
$$p + p \rightarrow B + X \quad \text{with} \quad B = B^{\pm}, B^{0}, B_s$$

Phys. Rev. D84 (2011) 094026



FF for $b \to B$
from fitting to e^+e^- data
(ALEPH, OPAL, SLD, $\mu = M_Z$)

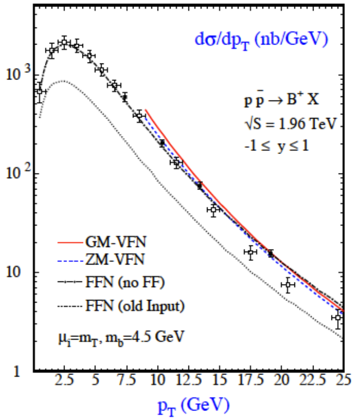
very poor fit from Peterson:
$D(x, \mu_0^2) = N \frac{x(1-x)^2}{[(1-x)^2+\epsilon x]^2}$

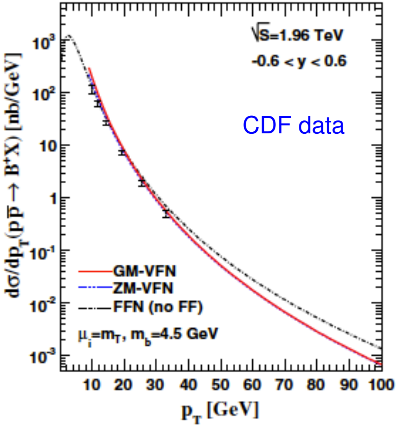


➜ use Kartvelishvili-Likhoded:
$D(x, \mu_0^2) = N x^\alpha (1-x)^\beta$
starting scale $\mu_0 = m_b = 4.5$ GeV

same shape for all B^0, B^+, B_s
valid for average of $B^+ + B^-$ etc.

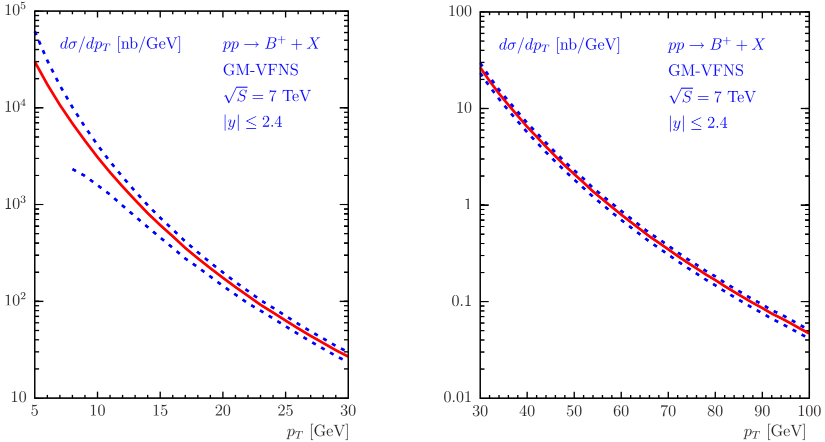
Kniehl, G. K., Schienbein, Spiesberger
PRD77





open symbols: J/Ψ CDF 2005
solid symbols: $J/\Psi K^+$ CDF 2007
FFN (old input): obsolete PDFs,
α_s too low

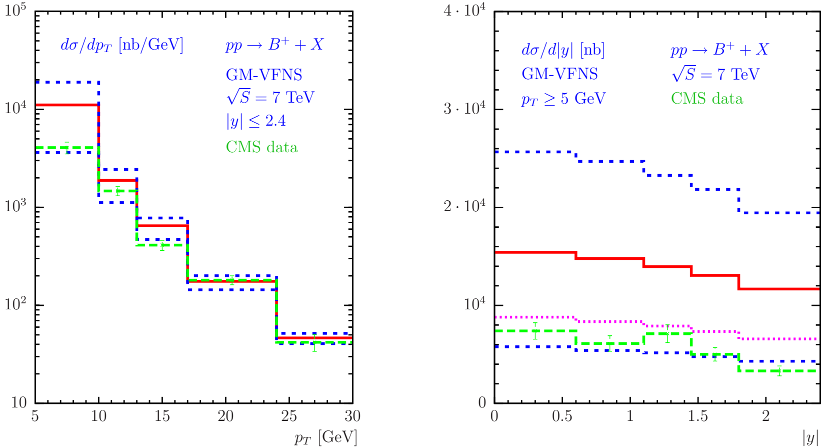
$p_T \gg m_b$: GM-VFNS merges
with ZM-FVNS,
FFN breaks down



LHC at $\sqrt{s} = 7$ TeV ➜ reach to larger p_T

with much larger cross sections and reduced scale uncertainties

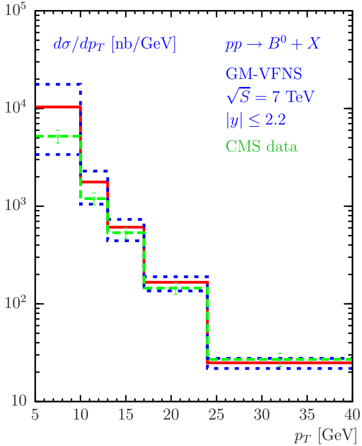
(red: central values, blue: scale variation by factors 2 up and down)

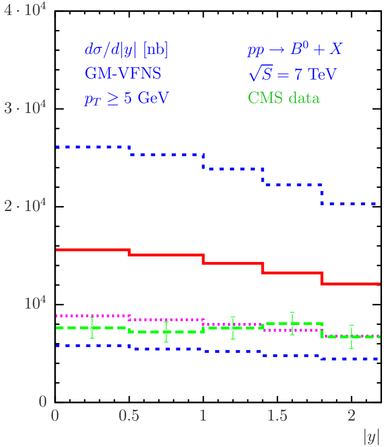


present data from CMS for $(B^+ + B^-)/2$

p_T up to 30 GeV

dotted line: $\xi_I = \xi_F = 0.7$

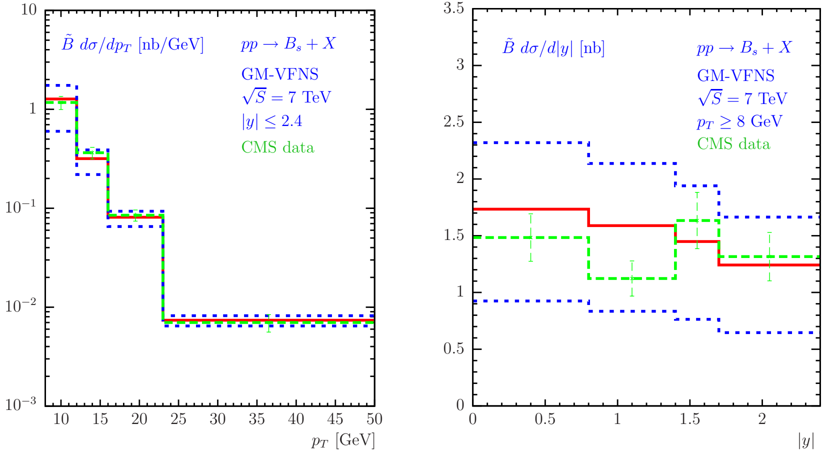




present data from CMS for $(B^0 + \bar{B}^0)/2$

p_T up to 40 GeV

dotted line: $\xi_I = \xi_F = 0.7$

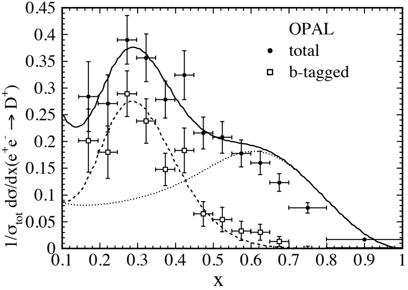


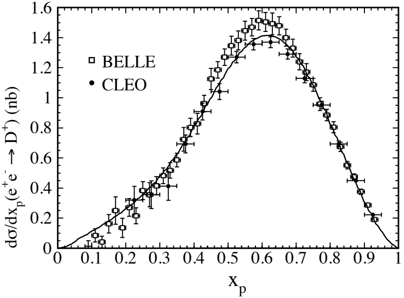
…and for $(B_s + \bar{B}_s)/2$: p_T up to 50 GeV

➜ with good agreement between data and theory

$p + p \rightarrow D + X$ with $D = D^0, D^{\pm}, D^{*\pm}, D_s$

arXiv:1202.0439





FF for $c \to D^+$
from fitting to e^+e^- data

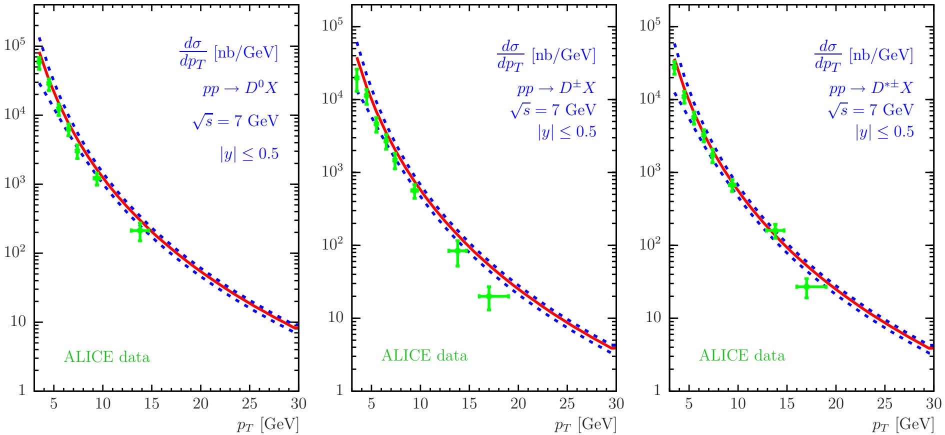
2008 analysis based on GM-VFNS
$\mu_0 = m = 1.5$ GeV
Bowler parametrization

global fit: data from
ALEPH, OPAL, BELLE, CLEO

also available: BELLE/CLEO fit

KKKS: Kneesch, Kramer, Kniehl, Schienbein, NPB799 (2008)

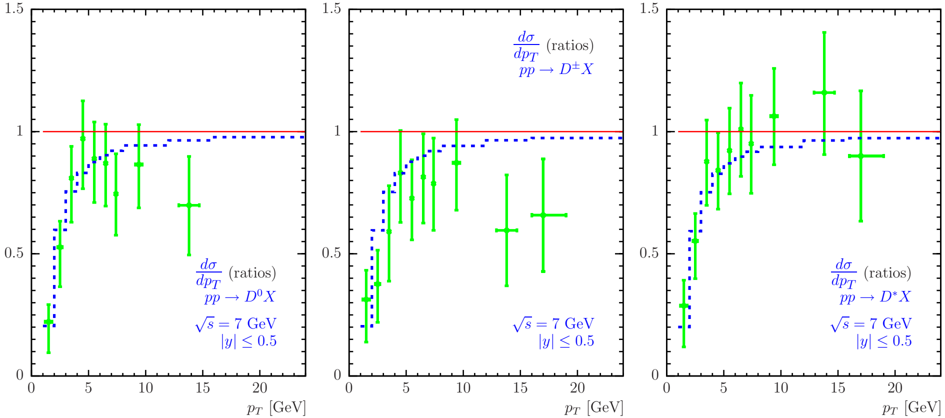
tension between low and high energy data sets $\to$ speculations about non-perturbative (power-suppressed) terms



D^0, $D^{\pm}$, D^*: ALICE data

➜ with good agreement between data and theory

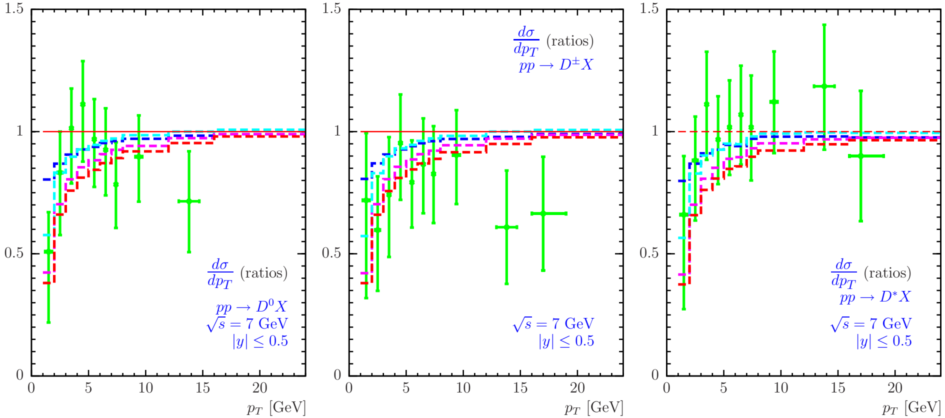
ALICE $\sqrt{s} = 7$ GeV, $\xi = 0.8$ and MSTW2008-NLO



Choose proper value for scale parameters: $\xi_I = \xi_F = 0.8$, $\xi_R = 1$

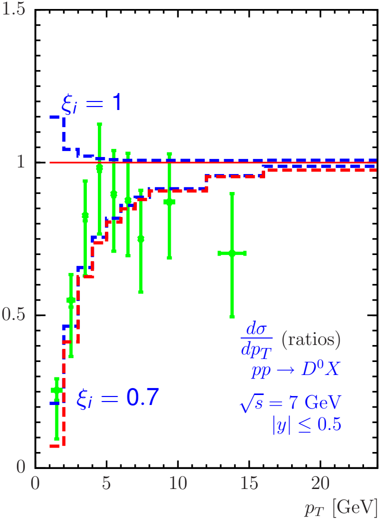
and MSTW2008-NLO: value of $m_c = 1.5$ GeV consistent with FF and PDF

histogram and data normalized to predictions with $\xi_I = \xi_F = \xi_R = 1$



(all results normalized to prediction with $\xi_I = \xi_F = 0.7$, $\xi_R = 1$, CTEQ6.6)

dashed: PDFs from CT10, HERAPDF 1.5 (NLO), MSTW08-NLO, NNPDF 2.1

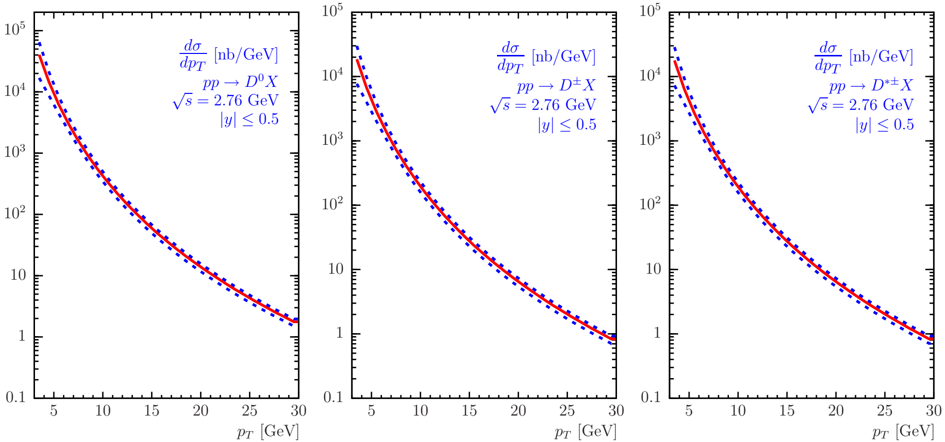


Uncertainties due to the value of the charm mass ?

$m_c = 1.5 \to 1.4$ GeV

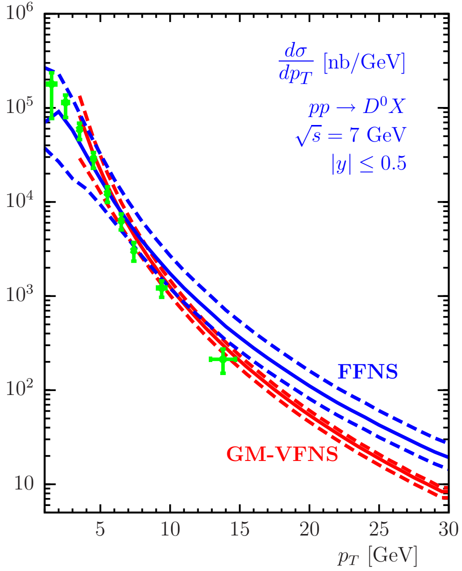
➜ small increase at low p_T

(MSTW2008-NLO)



CERN-PH-EP-ALICE-2012-069

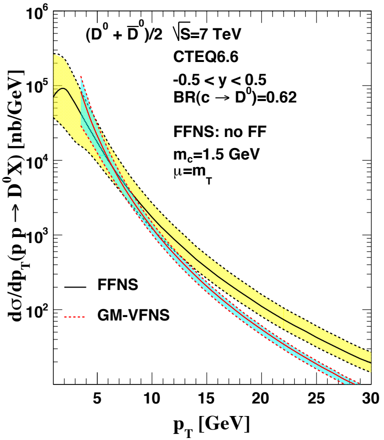
➜ used to determine suppression in Pb-Pb collisions



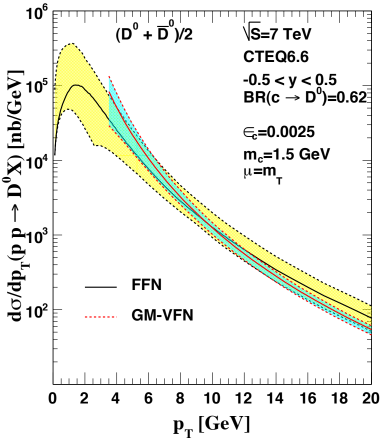
FFNS:
describes turnover at low p_T,
but too high at high p_T

GM-VFNS:
reduced scale uncertainty
due to resummed large logs

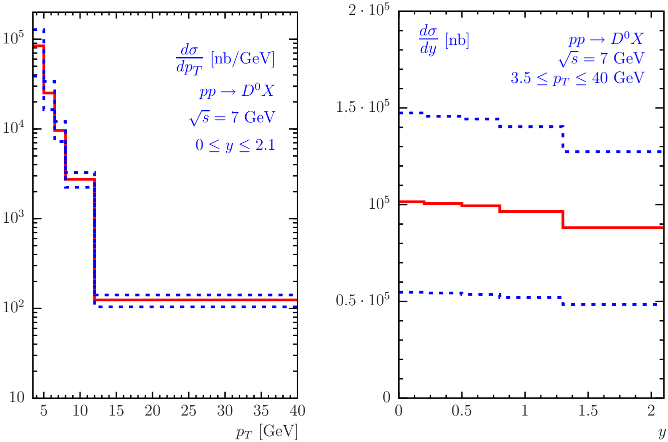
for FFNS:
no FF, $BR(c \to D^0) = 0.62$



no evolved fragmentation function



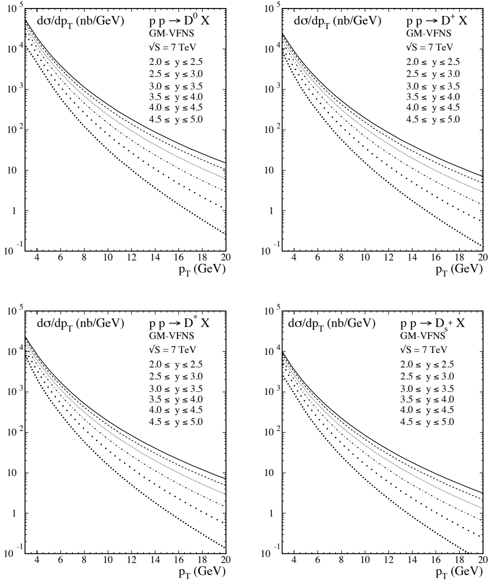
Peterson FF: FFNS closer to GM-VFNS, but still too steep



D^0, similar for $D^{\pm}$, D^*: to be compared with ATLAS data

➜ good agreement between data and theory

D-MESONS AT LHCB



D^0, $D^\pm$, D^*, D_s,

for a comparison with data LHCb data:

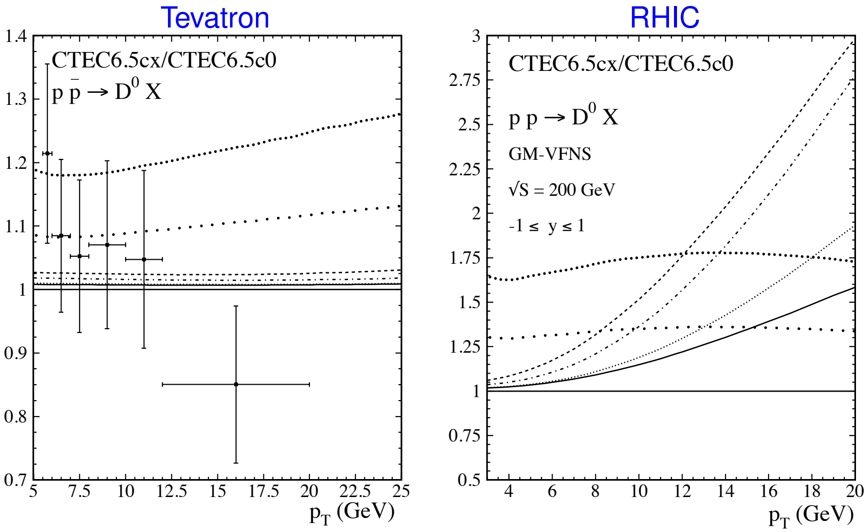
LHCb-CONF-2010-013

good agreement

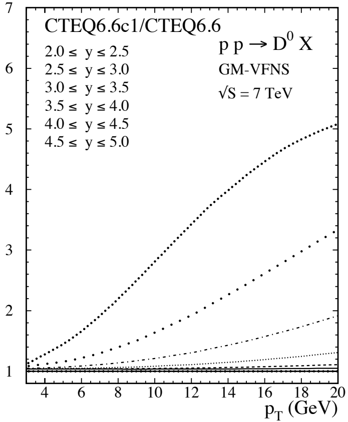
Intrinsic charm:
$c(x, \mu_0) \neq 0$ at initial scale $\mu_0 = m_c$

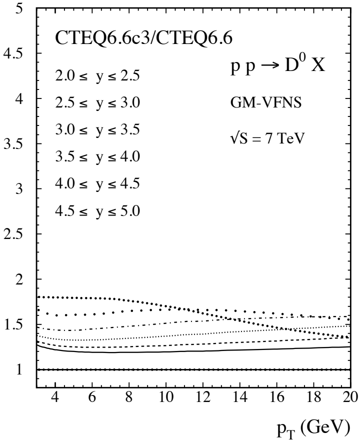
Models implemented in CTEQ 6.5C (PRD75, 2007)
global fit allows average momentum $\langle x \rangle_{c+\bar{c}}$ or order 1 %

1. Light-cone Fock-space picture (Brodsky et al.), concentrated at large x
   $\langle x \rangle_{c+\bar{c}} = 0.57, 2.0\,\%$
2. Meson-cloud model (Navarra et al.)
   $\langle x \rangle_{c+\bar{c}} = 0.96, 1.8\,\%$
3. Phenomenological model: sea-like charm, broad in x
   $\langle x \rangle_{c+\bar{c}} = 1.1, 2.4\,\%$


Tevatron
CTEC6.5cx/CTEC6.5c0
p p̄ → D^0 X
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
5
7.5
10
12.5
15
17.5
20
22.5
25
p_T (GeV)
RHIC
CTEC6.5cx/CTEC6.5c0
p p → D^0 X
GM-VFNS
√S = 200 GeV
-1 ≤ y ≤ 1
3
2.75
2.5
2.25
2
1.75
1.5
1.25
1
0.75
0.5
4
6
8
10
12
14
16
18
20
p_T (GeV)

PRD79, 2009





CTEQ6.6 updated:

BHPS, 3.5 % ($c + \bar{c}$) at $\mu = 1.3$ GeV

high-strength sea-like charm

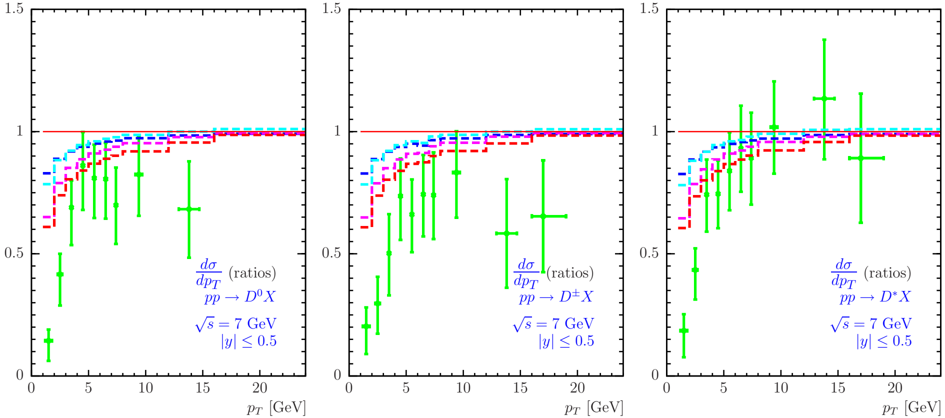
➜ large effects expected at large rapidities

SUMMARY

- The General-Mass Variable-Flavor-Number Scheme:
  - Rigorous theoretical framework for one-particle inclusive heavy quark production
  - Framework for global analysis
  - including full mass dependence
  - including resummed large logarithms in universal PDFs and FFs
  - no ad-hoc weight functions
- Many new numerical results for
  - $pp \to D + X$
  - $pp \to B + X$
- Predictions for *D*- and *B*-meson production in good agreement, First comparisons with LHC data are promising
- Mass effects moderate
- From future LHC data expect tight constraints for *D* and *B* FFs

Backup Slides

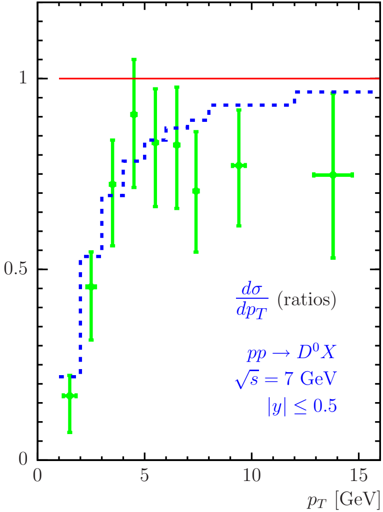
ALICE $\sqrt{s} = 7$ GeV, PDF uncertainty, $\xi = 1$



(all results normalized to default prediction with $\xi_I = \xi_F = 1$, $\xi_R = 1$, CTEQ6.6)

dashed: PDFs from CT10, HERAPDF 1.5 (NLO), MSTW08-NLO, NNPDF 2.1

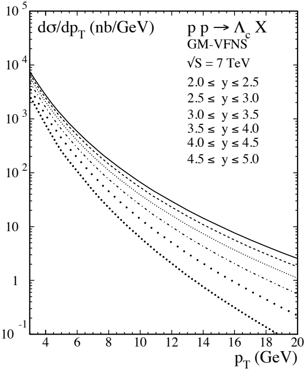
ALICE $\sqrt{s} = 7$ GeV, $\xi = 0.7$



Choose proper value for scale parameters:

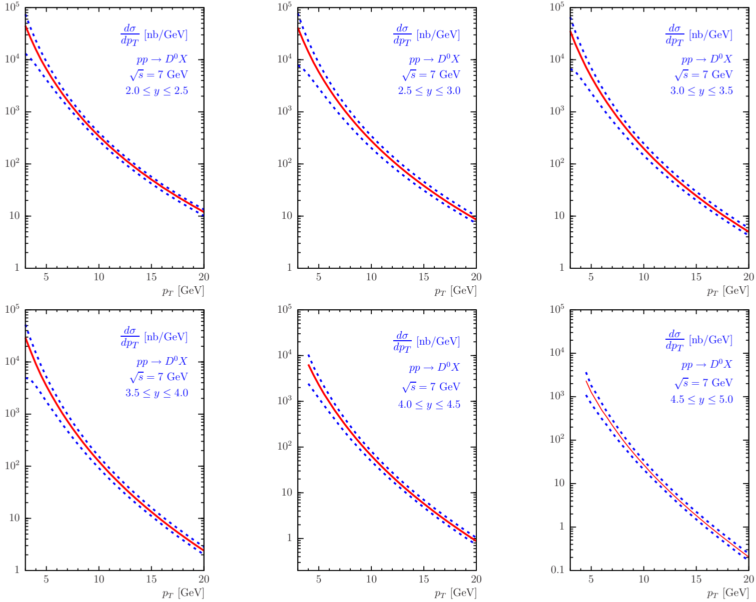
$\xi_I = \xi_F = 0.7, \quad \xi_R = 1$

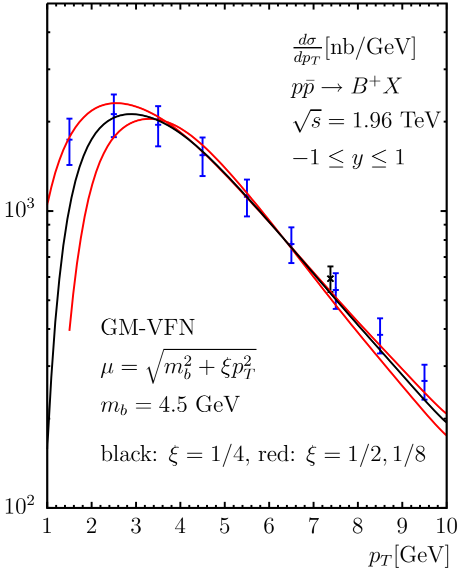
(histogram and data normalized to default prediction with $\xi_I = \xi_F = \xi_R = 1$)



Λ_c:
to be compared with LHCb

LHCB: SCALE UNCERTAINTIES





- evaluate *b*-quark initiated part at LO to match subtraction terms
- evaluate subtraction terms including m_b dependence
- impose threshold condition $\hat{s} > 4m_b^2$
- choose $\mu_F^2 = m_b^2 + \xi p_T^2$ so that $\mu_F \longrightarrow m_b$ for $p_T \longrightarrow 0$