INCLUSIVE $D$- AND $B$-MESON PRODUCTION AT THE LHC

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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 $\eta$ of observed heavy meson

• Numerical results for $D$- and $B$-meson production:

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

$p + p \rightarrow B + X$, $(B = B^\pm, B^0, B_s)$

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 $p_T$

$m \neq 0 \rightarrow$
- 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 $\mu$

$m = 0 \rightarrow$
- 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
**HEAVY FLAVOUR SCHEMES**

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
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 $\overline{\text{MS}}$ scheme and $\overline{\text{MS}}$ scheme is based on a massless calculation (massless and massive calculations contain different singularities)

- Match massless and massive calculations:

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

The subtracted cross section (in a massive calculation)

\[ d\hat{\sigma}(m) = d\tilde{\sigma}(m) - d\sigma_{\text{sub}} \]

can be used with universal $\overline{\text{MS}}$ parton distribution and fragmentation functions
Massive VFNS (GM-VFNS)

- 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 $Q \rightarrow H, H = D, B$: $D^H_Q(z, \mu_F^2)$, 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; $\rightarrow$ 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: \( g + g \rightarrow Q + \bar{Q}, \ q + \bar{q} \rightarrow Q + \bar{Q} \)  
  (hadroproduction, for photoproduction, DIS: \( \gamma^* + g \rightarrow c + \bar{c} \))  
- at NLO: 1-loop diagrams, 
gluon bremsstrahlung \( g + g \rightarrow Q + \bar{Q} + g \)  
- also \( g + q \rightarrow Q + \bar{Q} + q \) and  
- heavy-quark-initiated processes:  
e.g., \( g + Q \rightarrow g + Q \)  
  (treated as a massless parton)

→ Every parton can fragment to the heavy meson:
  - fragmentation functions for \( c \rightarrow D, \ g \rightarrow D, \ q \rightarrow D \)  
  and \( b \rightarrow B, \ g \rightarrow B, \ q \rightarrow B \), including \( c \rightarrow B \)
Applications available for

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

Input

- PFD from CTEQ6.6
- FF from fits to $e^+e^-$ data:
  - for $D^0$, $D^\pm$, $D^*$: Kneesch, Kniehl, Kramer, Schienbein, 2008
  - for $D_s$, $\Lambda_c$: 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: $\mu_i$, final-state, FF: $\mu_F$, and renormalization: $\mu_R$
  - $\mu_i = \xi_i \sqrt{m^2 + p_T^2}$
  - varied by factors 2 up and down
- Charm mass $m_c = 1.5$ GeV, bottom mass $m_b = 4.5$ GeV
$\rho + \rho \rightarrow B + X \quad \text{with} \quad B = B^\pm, B^0, B_s$

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**FRAGMENTATION FUNCTIONS FOR B MESONS**

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:

\[
D(x, \mu_0^2) = Nx^\alpha (1 - x)^\beta
\]

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.

Kramer, Kniehl, Schienbein, HS, PRD77
**B at the Tevatron**

Open symbols: \( J/\psi \) CDF 2005

Solid symbols: \( J/\psi K^+ \) CDF 2007

FFN (old input): obsolete PDFs, \( \alpha_s \) too low

\( p_T \gg m_b \): GM-VFNS merges with ZM-FVNS, FFN breaks down
LHC at $\sqrt{s} = 7$ TeV \( \rightarrow \) 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: \(\xi_l = \xi_F = 0.7\)

see talk by Wolfram Erdmann
present data from CMS for \((B^0 + \bar{B}^0)/2\)

\(p_T\) up to 40 GeV

dotted line: \(\xi_I = \xi_F = 0.7\)
\( B_s \) AT CMS

\[
\tilde{B} \frac{d\sigma}{dp_T} \text{ [nb/GeV]} \quad pp \to B_s + X
\]

GM-VFNS
\( \sqrt{S} = 7 \text{ TeV} \)
\( |y| \leq 2.4 \)

CMS data

\[
p_T \geq 8 \text{ GeV}
\]

\( \sqrt{S} = 7 \text{ TeV} \)
GM-VFNS
\( pp \to B_s + X \)

\( \tilde{B} \frac{d\sigma}{d|y|} \text{ [nb]} \)

\( p_T \geq 8 \text{ GeV} \)
CMS data

\[
\tilde{B} \frac{d\sigma}{dp_T} \text{ [nb/GeV]} \quad pp \to B_s + X
\]

GM-VFNS
\( \sqrt{S} = 7 \text{ TeV} \)
\( |y| \leq 2.4 \)

CMS data

\( p_T \geq 8 \text{ GeV} \)
CMS data

\[ \text{... and for } (B_s + \bar{B}_s)/2: \ p_T \text{ up to 50 GeV} \]

\[ \rightarrow \text{with good agreement between data and theory} \]
$p + p \rightarrow D + X$ with $D = D^0, D^\pm, D^{*\pm}, D_s$

arXiv:1202.0439
**Fragmentation Functions for Charmed Mesons**

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

2008 analysis based on GM-VFNS

$\mu_0 = m = 1.5 \text{ GeV}$

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 $\rightarrow$ speculations about non-perturbative (power-suppressed) terms
\( \text{ALICE } \sqrt{s} = 7 \text{ GeV} \)

\[
\frac{d\sigma}{dp_T} \text{ [nb/GeV] } \quad pp \rightarrow D^0 X \quad \sqrt{s} = 7 \text{ GeV} \quad |y| \leq 0.5
\]

\[
\frac{d\sigma}{dp_T} \text{ [nb/GeV] } \quad pp \rightarrow D^\pm X \quad \sqrt{s} = 7 \text{ GeV} \quad |y| \leq 0.5
\]

\[
\frac{d\sigma}{dp_T} \text{ [nb/GeV] } \quad pp \rightarrow D^{*\pm} X \quad \sqrt{s} = 7 \text{ GeV} \quad |y| \leq 0.5
\]

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

\( \rightarrow \) with good agreement between data and theory

see talk by Rosa Romita
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 $\xi_I = \xi_F = \xi_R = 1$
ALICE $\sqrt{s} = 7$ GeV, PDF UNCERTAINTY

(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
ALICE $\sqrt{s} = 7$ GeV, CHARM MASS

Uncertainties due to the value of the charm mass?

$m_c = 1.5 \rightarrow 1.4$ GeV

→ small increase at low $p_T$

(MSTW2008-NLO)
ALICE $\sqrt{s} = 2.76$ GeV

$\frac{d\sigma}{dp_T}$ [nb/GeV] $pp \to D^0 X$
$\sqrt{s} = 2.76$ GeV $|y| \leq 0.5$

$\frac{d\sigma}{dp_T}$ [nb/GeV] $pp \to D^\pm X$
$\sqrt{s} = 2.76$ GeV $|y| \leq 0.5$

$\frac{d\sigma}{dp_T}$ [nb/GeV] $pp \to D^{*\pm} X$
$\sqrt{s} = 2.76$ GeV $|y| \leq 0.5$

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, $BR(c \rightarrow D^0) = 0.62$
no evolved fragmentation function

Peterson FF: FFNS closer to GM-VFNS, but still too steep
$D$-MESONS AT ATLAS

$0 \leq y \leq 2.1$  
$\sqrt{s} = 7 \text{ GeV}$  
$pp \rightarrow D^0 X$

$\frac{d\sigma}{dp_T} \ [\text{nb/GeV}]$

$p_T \ [\text{GeV}]$

$40 \ 35 \ 30 \ 25 \ 20 \ 15 \ 10 \ 5 \ 0$

$3.5 \leq p_T \leq 40 \text{ GeV}$

$\sqrt{s} = 7 \text{ GeV}$

$pp \rightarrow D^0 X$

$\frac{d\sigma}{dy} \ [\text{nb}]$

$y$

$2 \cdot 10^5$

$1.5 \cdot 10^5$

$10^5$

$0.5 \cdot 10^5$

$0$

$3.5 \leq p_T \leq 40 \text{ GeV}$

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

→ good agreement between data and theory

see talk by Adam Edward Barton
$D$-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**

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 \( x \)**
   \[ \langle x \rangle_{c+\bar{c}} = 1.1, 2.4 \% \]
**Intrinsic Charm: Tevatron and RHIC**

### Tevatron

CTEC6.5\textsubscript{cx}/CTEC6.5\textsubscript{c0}  
\( p \bar{p} \rightarrow D^0 X \)

### RHIC

CTEC6.5\textsubscript{cx}/CTEC6.5\textsubscript{c0}  
\( p p \rightarrow D^0 X \)

- GM-VFNS
- \( \sqrt{S} = 200 \text{ GeV} \)
- \(-1 \leq y \leq 1\)

PRD\textsubscript{79}, 2009
CTEQ6.6 updated:

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

high-strength sea-like charm

\(\rightarrow\) large effects expected at large rapidities
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
- \( pp \rightarrow D + X \)
- \( pp \rightarrow B + X \)

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

Choose proper value for scale parameters:

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

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

$\Lambda_c$: to be compared with LHCb

\begin{align*}
\frac{d\sigma}{dp_T} \text{ (nb/GeV)} & \quad p p \rightarrow \Lambda_c X \\
\text{GM-VFNS} & \\
\sqrt{S} = 7 \text{ TeV} & \\
2.0 \leq y \leq 2.5 & \\
2.5 \leq y \leq 3.0 & \\
3.0 \leq y \leq 3.5 & \\
3.5 \leq y \leq 4.0 & \\
4.0 \leq y \leq 4.5 & \\
4.5 \leq y \leq 5.0 &
\end{align*}
LHCb: scale uncertainties

\[
\frac{d\sigma}{dp_T} \quad [\text{nb/GeV}]
\]

- \( pp \to D^0X \)
- \( \sqrt{s} = 7 \text{ GeV} \)

\( 2.0 \leq y \leq 2.5 \)

\( 2.5 \leq y \leq 3.0 \)

\( 3.0 \leq y \leq 3.5 \)

\( 3.5 \leq y \leq 4.0 \)

\( 4.0 \leq y \leq 4.5 \)

\( 4.5 \leq y \leq 5.0 \)
\[
\frac{d\sigma}{dp_T}[\text{nb/GeV}] \\
p\bar{p} \to B^+ X \\
\sqrt{s} = 1.96 \text{ TeV} \\
-1 \leq y \leq 1
\]

- 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 \( \mu_F \to m_b \) for \( p_T \to 0 \)

\( m_b = 4.5 \text{ GeV} \)

black: \( \xi = 1/4 \), red: \( \xi = 1/2, 1/8 \)