Heavy quarks production measurements with the LHCb experiment

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Winter Workshop on Recent QCD Advances at the LHC
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Outline

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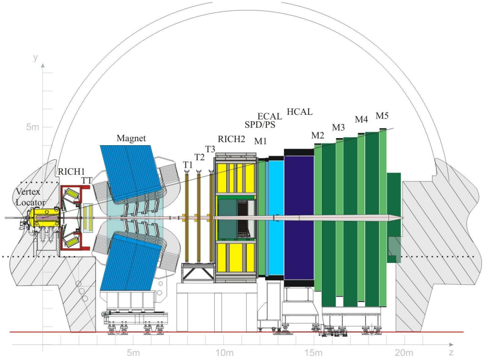
The LHCb detector



optimized for *b*-physics

excellent also for charm physics

unique kinematic range: $2 < \eta < 5$, down to $p_T \approx 0$

- excellent vertex resolution (VELO)
- particle identification (RICH: $\pi/K/p$, ECAL: e/γ, MUON)
- trigger: L0 (HCAL,ECAL,MUON: high p_T e/γ/hadron/μ)
  HLT1 (s/w: L0 confirmation + impact parameter cuts)
  HLT2 (software: global event reconstr. & selection)

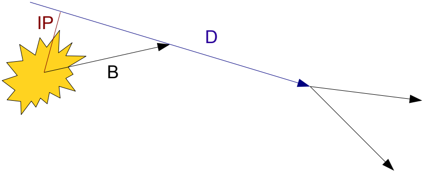
LHCb and heavy quark physics

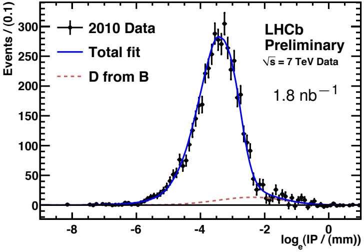
- LHCb physics program:
  precise measurements of *CP* violation and rare decays
- with first data measure for charm & beauty:
  - first *CP* violation and rare decay measurements
  - cross sections and polarizations
  - fragmentation fractions
  - look for/confirm new resonances
  - tune MC generators
- this talk covers these subjects

Outline

Open charm cross sections

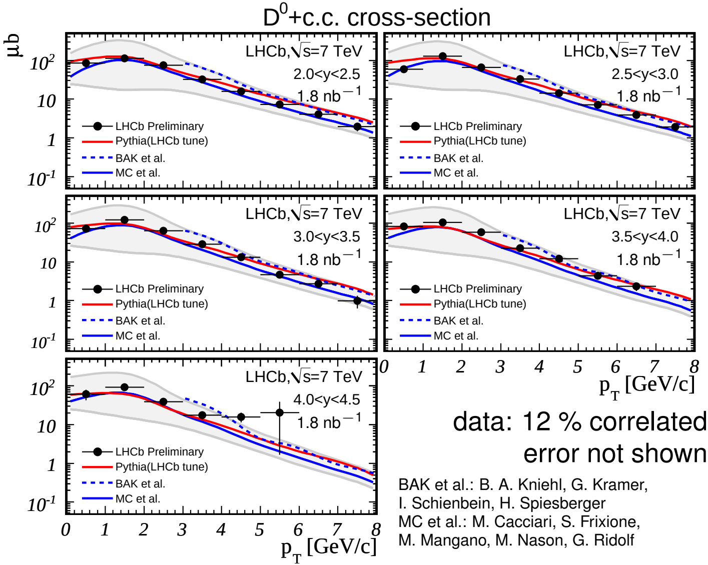
- prompt[1] open charm production in bins of transverse momentum $p_T < 8$ GeV/c, rapidity $2 < y < 4.5$
- 1.8 nb^{-1}, micro bias trigger (VELO track segment, 100 % efficient)
- secondary charm: *D* from decay of long-lived particles
- secondary fraction from D impact parameter (*IP*) distribution





[1] direct and via non-weak decays

Results for $D^0 \to K^-\pi^+$ + cc

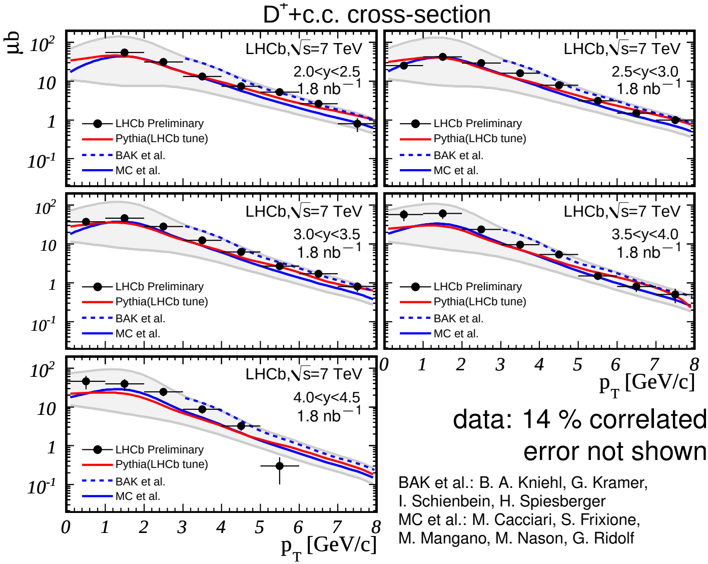


data: 12 % correlated error not shown

BAK et al.: B. A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger

MC et al.: M. Cacciari, S. Frixione, M. Mangano, M. Nason, G. Ridolf

Results for $D^+ \to K^- \pi^+ \pi^+$ + cc

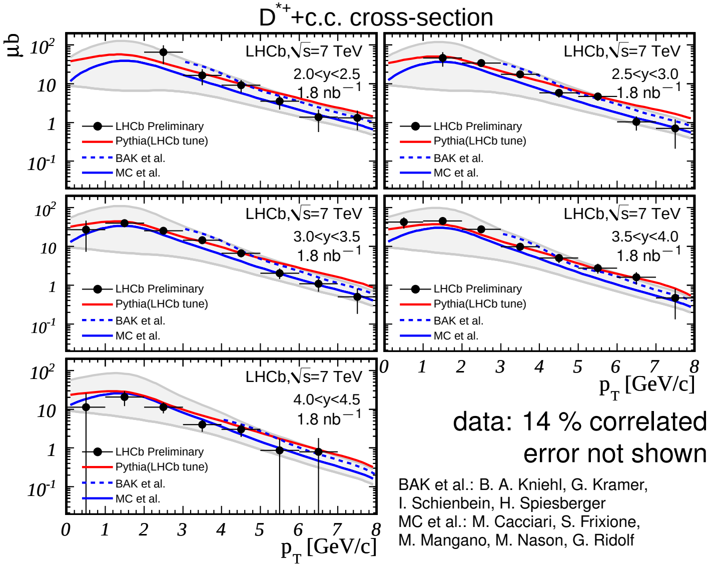


data: 14 % correlated error not shown

BAK et al.: B. A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger

MC et al.: M. Cacciari, S. Frixione, M. Mangano, M. Nason, G. Ridolf

Results for $D^{*+} \to \pi^+ D^0(K^- \pi^+)$ + cc



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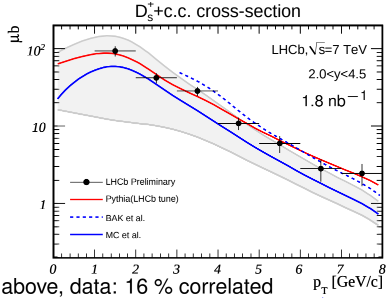
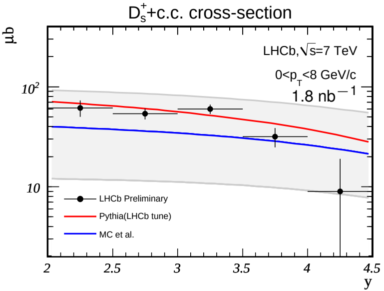
BAK et al.: B. A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger

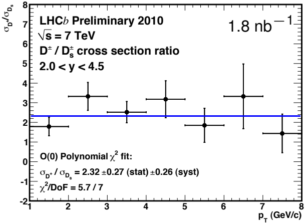
MC et al.: M. Cacciari, S. Frixione, M. Mangano, M. Nason, G. Ridolf

Results for $D_s^+ \to \phi(K^- K^+)\pi^+$ + cc





above, data: 16 % correlated error not shown



$$\frac{\sigma(D^+)}{\sigma(D_s^+)} = 2.32 \pm 0.27 \pm 0.26$$

consistent with (PDG):

$$\frac{f(c\to D^+)}{f(c\to D_s^+)} = 3.08 \pm 0.70$$

combining all modes:

$p_T < 8$ GeV/c, $2 < y < 4.5$:

$\sigma(pp \to H_c)_y = 1234 \pm 189\mu$b

extrap.: $\sigma(pp \to c\bar{c})_{4\pi} = 6100 \pm 934\mu$b

Outline

Quarkonia: $\psi(2S)$, X(3872)

Heavy quarks at LHCb

Markward Britsch

Introduction

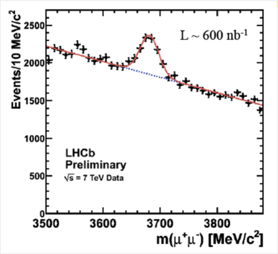
Open charm

Quarkonia

Beauty

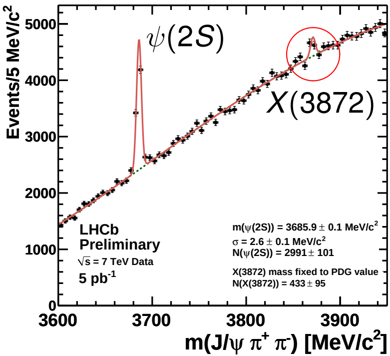
Summary

$\psi(2S) \to \mu^+\mu^-$



- $\psi(2S)$ yields 2 % of $J/\psi(1S)$ (Stefano De Capua's talk)
- but: easier to interpret (direct production dominates)
- measure differential cross section, polarization

prompt $J/\psi(1S)\pi^+\pi^-$

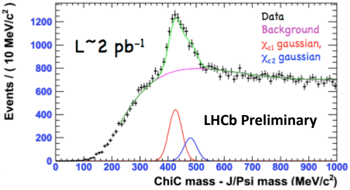


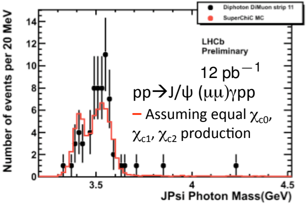
- measure $X(3872)$ mass
- cross section relative to $\psi(2S)$

Quarkonia: χ_c

- sensitivity to $\chi_{c1}(1P)$ and $\chi_{c2}(2P)$, if mass res. fixed
- cross section ratio to $J/\psi(1S)$ and $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ in bins of J/ψ p_T (prompt and from b)
- $\rightarrow$ important to interprete inclusive $J/\psi(1S)$ correctly

$\chi_c \rightarrow J/\psi(1S)\gamma$



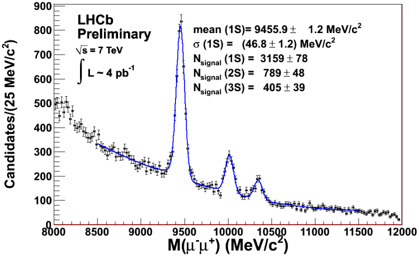


exclusive quarkonia production:

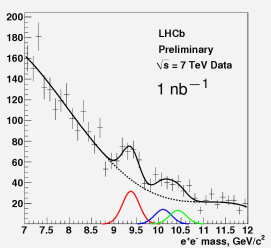
- we see: $J/\psi(1S)$ – photon pomeron fusion
- we see: $\chi_c \rightarrow J/\psi(1S)\gamma$ – double pomeron fusion

Quarkonia: Υ

$\Upsilon \to \mu^+\mu^-$, 4 nb^{-1}



$\Upsilon \to e^+e^-$, 1 nb^{-1}

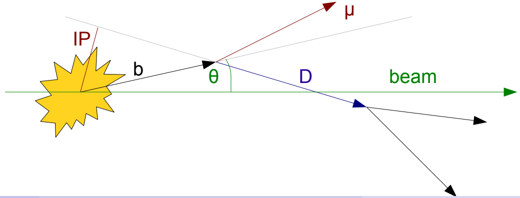


- measure
  - cross section times $\mathcal{B}(\Upsilon \to \mu^+\mu^-)$ in p_{T} and/or y
  - ratio of cross section between different Υ states
  - polarization

Outline

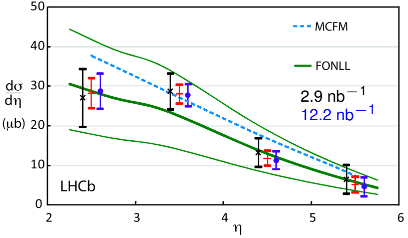
b cross section

- using detached $J/\psi(1S)$ (see Stefano's talk)
- in the following: using inclusive semileptonic decays: $b \to D^0 X \mu^- \bar{\nu}$, $(D^0 \to K^- \pi^+)$ and charge conjugate (cc)
- estimate background **prompt** D separated by its IP
- estimate long lived background from wrong sign events $D^0 \mu^+$ and cc
- measure cross section as function of pseudo rapidity $\eta = -\ln(\tan\frac{\theta}{2})$
- using 15 nb^{-1}: **Phys. Letters B 694 (2010) 209**
- similar: using $B^0 \to D^{\star -} \mu^+ \nu X$ (LHCb-CONF-2010-012)



b cross section, $b \to D^0 X \mu^- \bar{\nu}$, $(D^0 \to K^- \pi^+)$

data (stat. error only):
micro bias triggered ($\times$) 2.9 nb^{-1}
μ-triggered ($\bullet$) 12.2 nb^{-1}
average (+)



- comparison with:
  - MCFM: NLO with a PDF MSTW8NL (`http://mcfm.fnal.gov/`)
  - FONLL: CTEQ6.5 PDF, NLO with next to leading log correction, includes b-hadronization (Cacciari et al.)
- integrated cross section:
  - $\sigma(pp \to H_b)_\eta = (75.3 \pm 5.4 \pm 13.0)\mu$b in $2 < \eta < 6$ agrees with other results
  - $\sigma(pp \to b\bar{b})_{4\pi} = (284 \pm 20 \pm 49)\mu$b in 4π
  - LEP fragmentation fractions used (+19 % if Tevatron f_b)

b-hadronization fractions

- fragmentation fractions are important, see above
- to measure absolute branching fractions of B_s, use normalization by $\overline{B}^0 + B^-$ decays $\rightarrow$ need $\frac{f_s}{f_u+f_d}$
- method similar to above, now using final states $D^0 X\mu^-\bar{\nu}$, $D^+ X\mu^-\bar{\nu}$, $D_s^+ X\mu^-\bar{\nu}$
- using **dominant** semileptonic decay modes, *e.g.*: $\overline{B}_s^0 \rightarrow D_s^+ \ldots$, $\overline{B}^0 \rightarrow D^0 \ldots$, correct for cross feeds, *e.g.*, $\overline{B}^0 \rightarrow D_s^+ \ldots$, $\overline{B}_s^0 \rightarrow D^0 \ldots$
- correct for D & B branching ratios ($\Gamma_{\rm SL}(B_s) = \Gamma_{\rm SL}(B_{u/d})$)
- use 3 pb^{-1}, μ-trigger

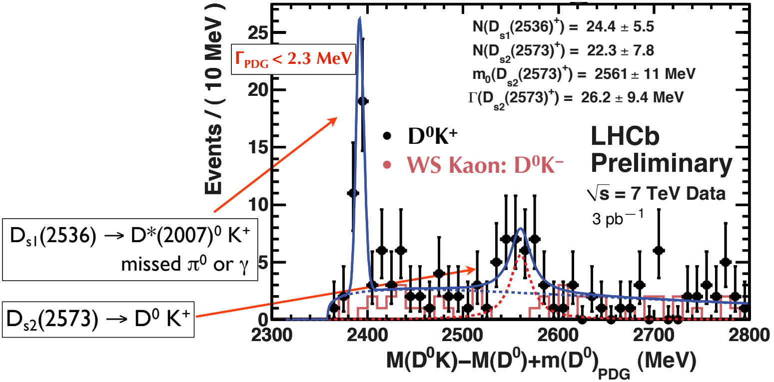
$$\frac{f_s}{f_u+f_d} = \frac{N(\overline{B}_s^0)}{N(\overline{B}^0 + B^-)} = \frac{n(\overline{B}_s^0 \rightarrow DX\mu^-\bar{\nu})}{n(B_{d/u} \rightarrow DX\mu^-\bar{\nu})} \underbrace{\frac{\tau_{B^-} + \tau_{\overline{B}^0}}{2\tau_{\overline{B}_s^0}}}_{B \text{ branching ratio correction}}$$

http://indico.cern.ch/getFile.py/access?contribId=4&sessionId=0&resId=3&materialId=slides&confId=111524

$\overline{B}_s^0 \to D^0 K^+ X \mu^- \bar{\nu}$, 3 pb^{-1}

Cross feed for $\overline{B}^0 \to D^0 X \mu^- \bar{\nu}$:

$\overline{B}_s^0 \to D^0 X \mu^- \bar{\nu}$ through $\overline{B}_s^0 \to D_{sJ} X \mu^- \bar{\nu}$, $D_{sJ} \to D^0 K^+ X$



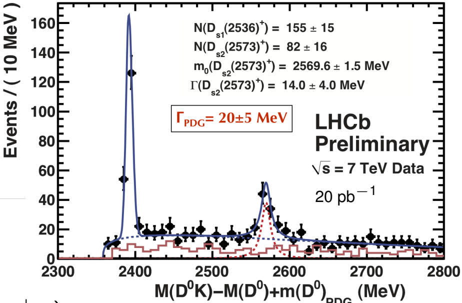
DØ observed $B_s \to D_{s1}(2536)^+ \mu^+ \bar{\nu}$, $D_{s1}(2536)^+ \to D^{*+} K^0$

(PRL 102 051801)

$B_s \to D_{s2}(2573)^+ \mu^+ \bar{\nu}$ unseen before, confirm w/ more data

$\overline{B}_s^0 \to D^0 K^+ X \mu^- \bar{\nu}$, 20 pb^{-1}

using 20 pb^{-1}
8.3σ significance for
$B_s \to D_{s2}(2573)^+ X \mu^+ \bar{\nu}$
Discovery!
arXiv:1102.0348,
submitted to
Phys. Lett. B



$$\frac{\mathcal{B}(B_s \to D_{s2}^{*+} X \mu^+ \bar{\nu})}{\mathcal{B}(B_s \to D_{s1}^{+} X \mu^+ \bar{\nu})} = 0.61 \pm 0.14 \pm 0.05$$

and together with yield from 3 pb^{-1}:

$$\frac{\mathcal{B}(B_s \to D_{s1}^{+} X \mu^+ \bar{\nu})}{\mathcal{B}(B_s \to X \mu^+ \bar{\nu})} = (5.3 \pm 1.2 \pm 0.4)\ \%, \quad (\text{DØ: } = (9.8 \pm 3.0)\ \%)$$

(PRL 102 051801)

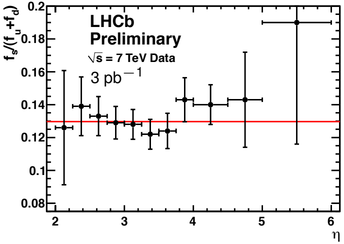
$$\frac{\mathcal{B}(B_s \to D_{s2}^{*+} X \mu^+ \bar{\nu})}{\mathcal{B}(B_s \to X \mu^+ \bar{\nu})} = (3.2 \pm 1.0 \pm 0.4)\ \%$$

Result on $\frac{f_s}{f_u+f_d}$

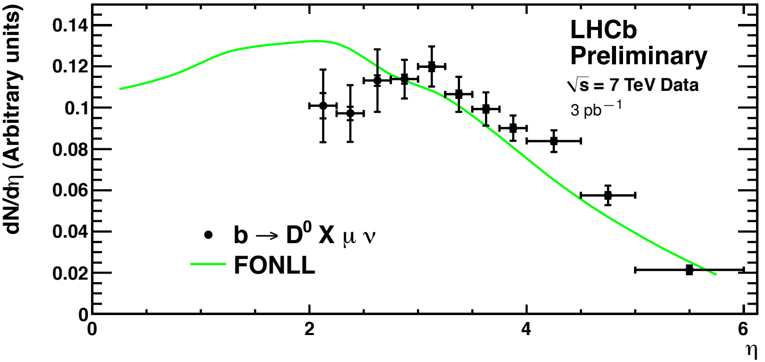
$\frac{f_s}{f_u+f_d} = 0.130 \pm 0.004 \pm 0.013$
LEP: 0.129 ± 0.012
Tevatron: 0.18 ± 0.03 (higher p_T threshold, different cross feed treatment)

- $\overline{B}_s^0 \to D^0 K^+ X \mu^- \bar{\nu}$ most important correction
- largest systematics: due to this correction and charm branching ratios' error
- most systematics cancel in ratio

within statistical errors
$\frac{f_s}{f_u+f_d}$ constant in η



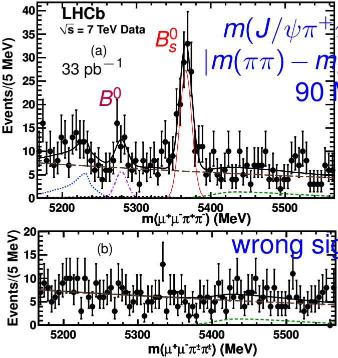
$b \to D^0 X \mu^- \bar{\nu}$, $\frac{dN}{d\eta}$



- background subtracted
- errors: statistical and uncorrelated systematics (correlated errors not negligible)

Observation of the decay $B_s^0 \to J/\psi f_0(980)$

arXiv:1102.0206, Submitted to Physics Letters B

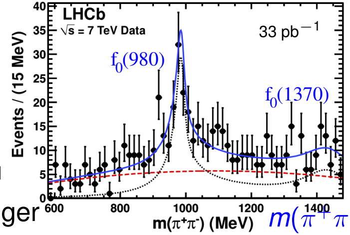


$m(J/\psi\pi^+\pi^-)$, $|m(\pi\pi) - m_{f_0}| <$ 90 MeV

wrong sign

33 pb^{-1}

di-μ trigger



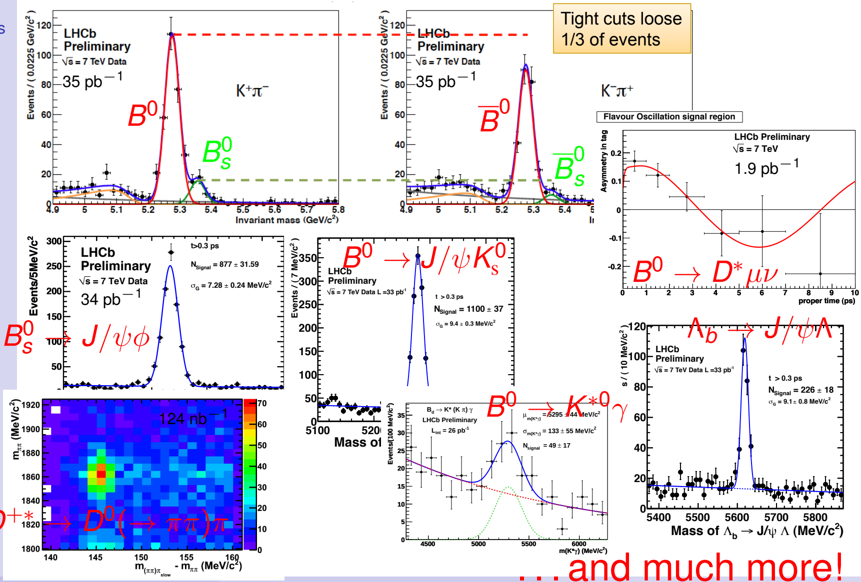
$m(\pi^+\pi^-)$, $|m(J/\psi\pi\pi) - m_{B_s}| <$ 30 MeV

significance: *CP* violation analysis on $B_s \to J/\psi\phi$ needs angular analysis

$$R_{f_0/\phi} = \frac{\Gamma(B_s \to J/\psi f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\psi\phi, \phi \to K^+K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033}$$

- predictions between 0.07 and 0.5 [arXiv:1009.4939]
- *CP* analysis w/o angular analysis seems possible

. . . and more heavy quark physics . . .



. . . and much more!

Outline

Summary and outlook

- many analyses on heavy flavor ongoing at LHCb
- heavy flavor cross sections agree with predictions
- $\sigma(pp \to c\bar{c})_{4\pi} = (6100 \pm 934)\mu\text{b}$
- $\sigma(pp \to b\bar{b})_{4\pi} = (284 \pm 20 \pm 49)\mu\text{b}$
- $\frac{f_s}{f_u+f_d} = 0.130 \pm 0.004 \pm 0.013$
- discovered and measured relative $\mathcal{B}$: $B_s \to D_{s2}^{*+} X \mu^+ \bar{\nu}$
- discovered and measured $R_{f_0/\phi}$: $B_s \to J/\psi f_0(980)$

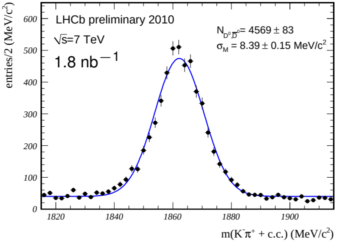
Ongoing work:

- open charm update using 14 nb^{-1}, including Λ_c
- quarkonia analyses
- use semileptonics to measure $\frac{f_{\Lambda_b}}{f_u+f_d}$
- beauty and charm *CP* violation & rare decays analyses

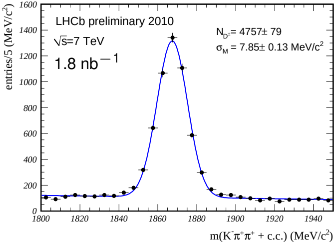
Outline

6 backup slides

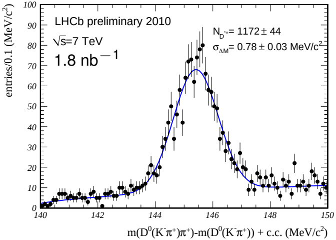
Open charm cross sections: raw yields



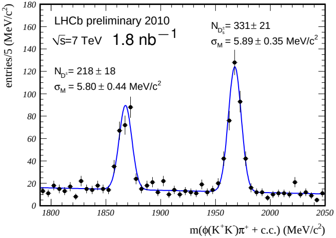
$D^0 \rightarrow K^-\pi^+$ + cc



$D^+ \rightarrow K^-\pi^+\pi^+$ + cc



$D^{*+} \rightarrow \pi^+ D^0(K^-\pi^+)$ + cc



$D_s^+ \rightarrow K^-K^+\pi^+$ + cc

Open charm: Systematic errors – varying with analysis

Correlated systematic errors:

- luminosity determination: 10 %
- tracking efficiency: correlated 3 % per track
- branching ratio error: 1.3 to 5.8 %
- peaking background: 0 to 1.6 %

Uncorrelated systematic errors:

- cut efficiency correction: 3.4 to 5.4 %
- MC statistics: 1 to 10% (high value only at edges)
- PID efficiency correction: 1 to 10 %
- prompt secondary subtraction: 2 to 4.1 %
- fit procedure: 1 to 4.5 %

Open charm: theory

- BAK et al.: B. A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger
  - `CTEQ 6.5c0` PDFs
  - quark to hadron transition probabilities: [T.Ketsch et al., Nucl. Phys. B799 (2008) 34–59]
- MC et al.: M. Cacciari, S. Frixione, M. Mangano, M. Nason, G. Ridolf
  - `CTEQ 6.6` PDFs
  - estimated error due to charm quark mass and renormalization and factorization scale
  - we included: quark to hadron transition probabilities as quoted by DPG from e^+e^- colliders close to $\Upsilon(4S)$

Example: $b \to D^0 X \mu^- \bar{\nu}$

$\ln \frac{IP}{\mathrm{mm}}$ $\qquad$ $m(K^-\pi^+)$

RS

Signal=28474±190

Prompt=773±44

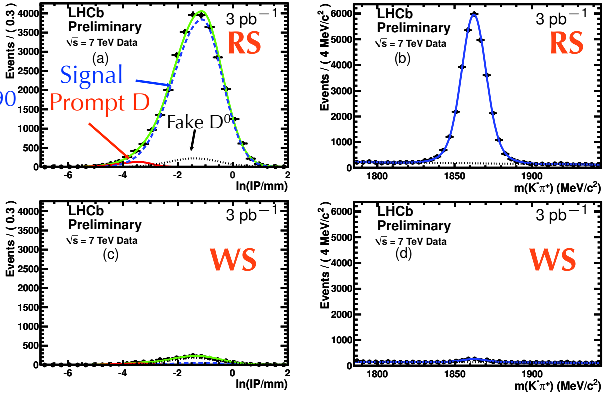
Sideb.=1776±33

WS

Signal=422±43

Prompt=204±19

Sideb.=1410±21



Semileptonic *b*: comparison data – MC

Heavy quarks at LHCb

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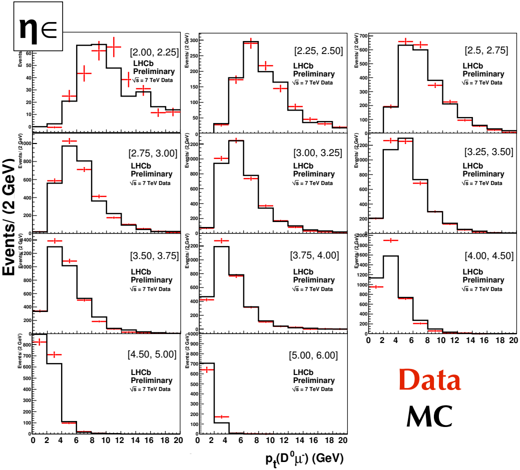
backup slides

- η dependence, D^0 mode: compare shape w/ theory
- few events at low p_T, low $\eta \to \mu$ trigger threshold
- extrapolation error for η bins with 0 efficiency is included



Heavy quarks at LHCb

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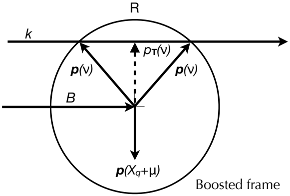
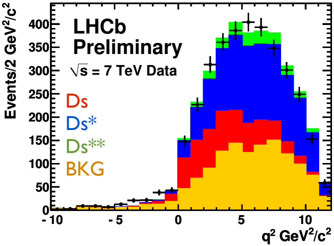
backup slides

$B_s \to D_s X \mu^- \bar{\nu}$: q^2 fit

- relative $\mathcal{B}$ of $D_s/D_s^*/D_s^{**}$ needed to constrain D_s mode efficiency
- use ν reconstruction
- D_s^*/D_s ratio well predicted, but D^{**} fraction highly uncertain





$$\frac{\mathcal{B}(\overline{B}_s^0 \to D_s^{**} X \mu\nu)}{\mathcal{B}(\overline{B}_s^0 \to D_s^{*,**} X \mu\nu)} = (11^{+22}_{-11})\ \%$$

error (eff.($B_s \to D_s X \mu^- \bar{\nu}$)) $= 3\ \%$