b Production Cross Sections and Fragmentation Fractions at LHCb

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on behalf of the LHCb collaboration

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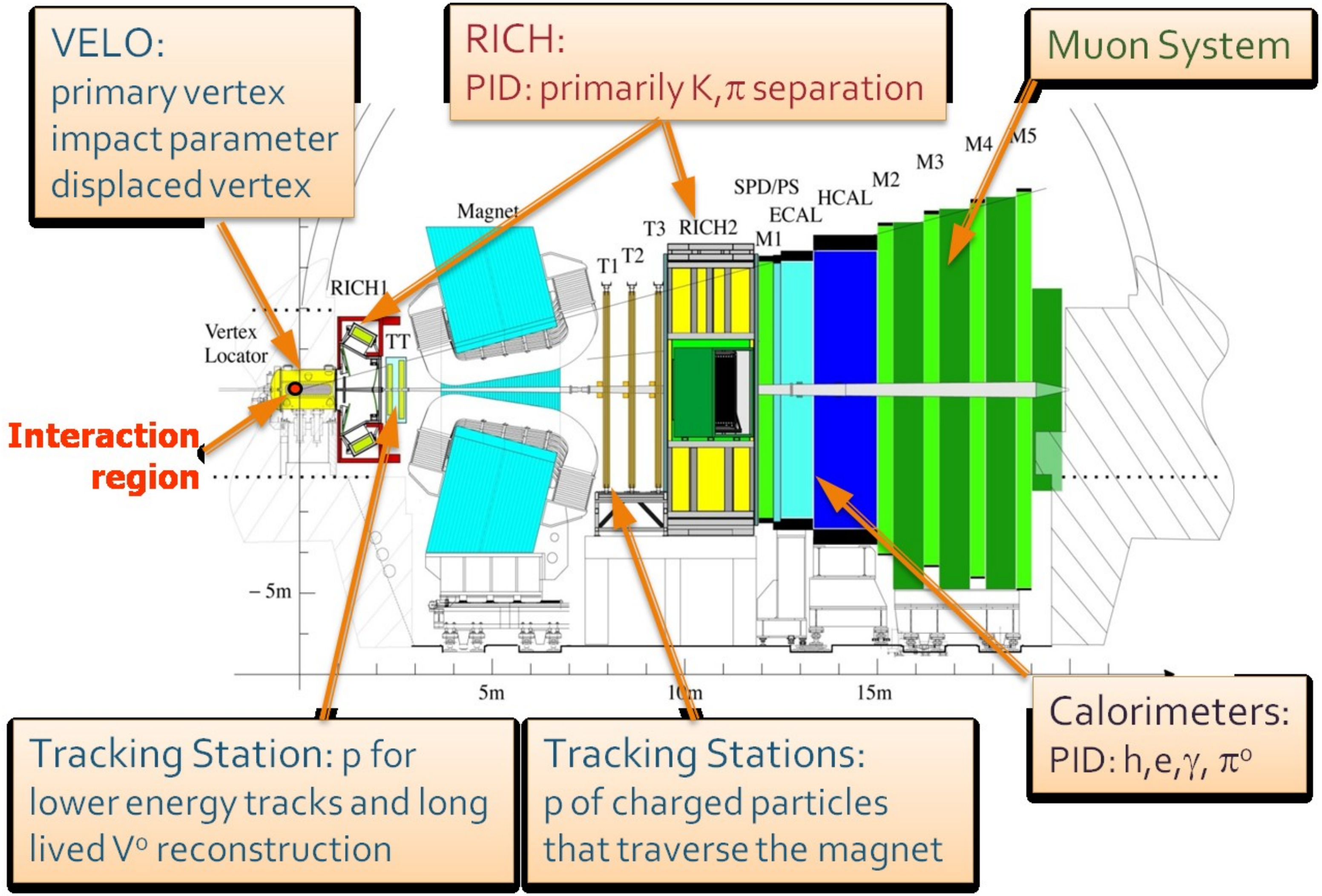
Overview

- Beauty production cross section in $\sqrt{s}$ = 7 TeV *pp* collisions can be compared to QCD predictions
  - also needed to estimate sensitivity to New Physics in *B* decays
- Will present two measurements of $\sigma(pp \to b\bar{b}X)$
  - using $b \to D^0 X \mu \nu$ and using $b \to J/\psi X$
- Ratio of fragmentation fractions f_s/f_d needed for precise measurement of B_s branching fractions, e.g. $B_s \to \mu\mu$
- Long-standing disagreement in fragmentation fractions $f_{\Lambda b}/(f_u+f_d)$ measured at LEP and at TeVatron
- Will present measurements of f_s/f_d and $f_{\Lambda b}/(f_u+f_d)$ using semileptonic modes, and of f_s/f_d using hadronic modes

The LHCb Experiment

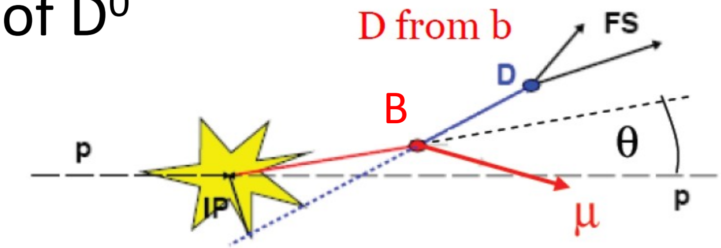
Single forward arm spectrometer covering 2.0 < η < 5.5 (η= -ln[tan(θ/2)])



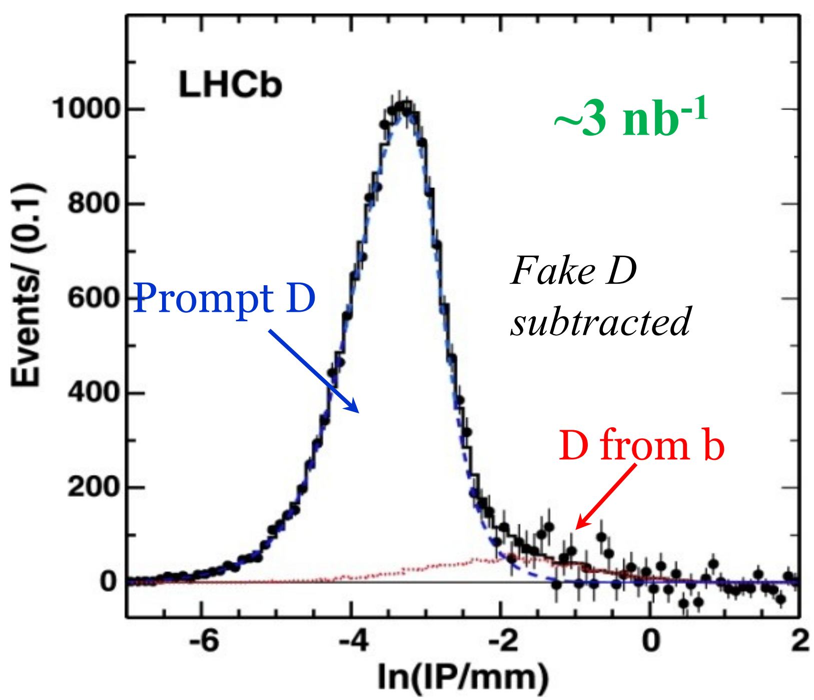
b Cross Section using $b \to D^0 X \mu \nu$

Vertex $D^0(\to K\pi)$ with right-sign μ, cut on Impact Parameter (IP) of μ then distinguish prompt D^0 and D^0 from B using IP of D^0

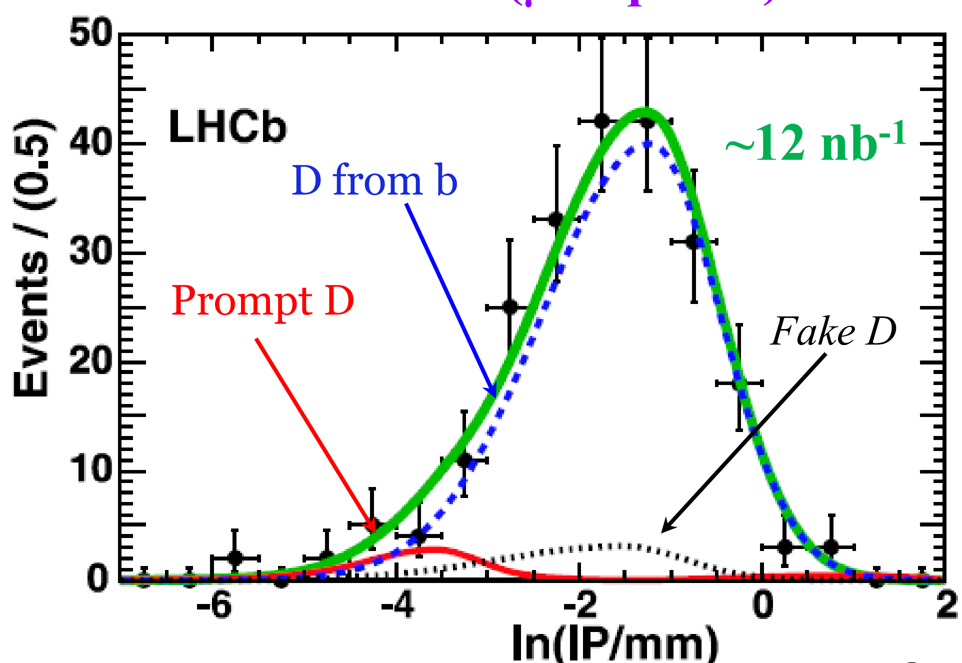
Two independent samples used: $3 nb^{-1}$ taken with unbiased trigger, and $12 nb^{-1}$ requiring single muon trigger



IP D^0 (NO μ requirement)



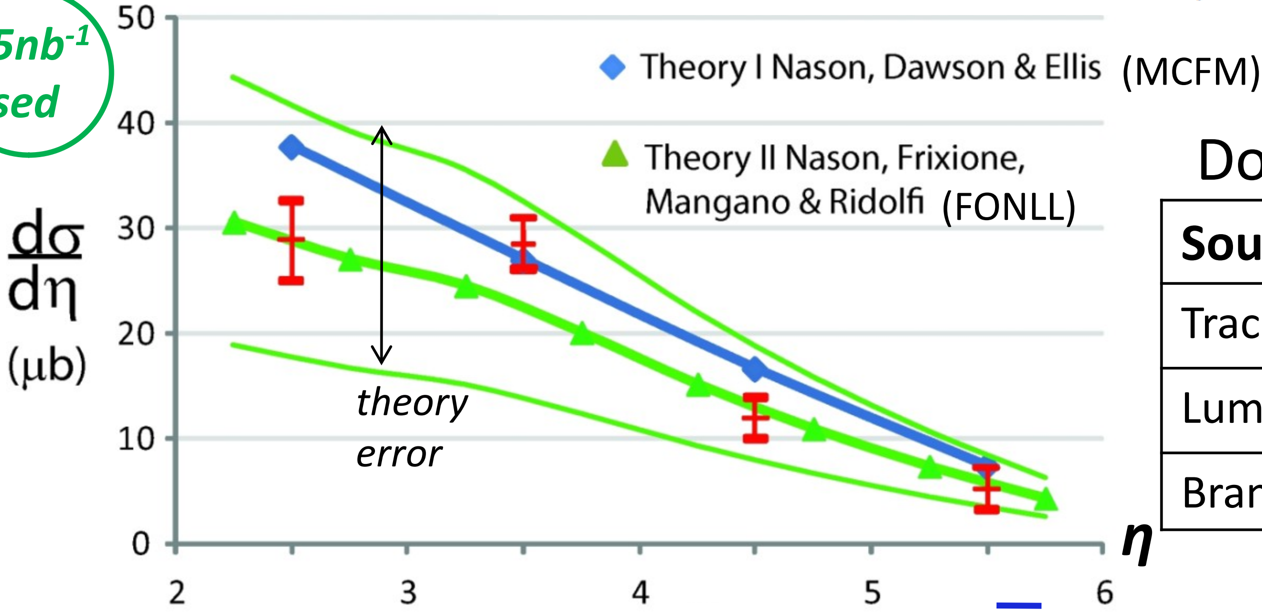
IP of D^0 (μ required)



b Cross Section using $b \rightarrow D^0 X \mu \nu$

Use: $$\sigma(pp \rightarrow H_b X) = \frac{\#\text{ of detected } D^0\mu^- \text{ and } \overline{D}^0\mu^+ \text{ events}}{2\mathcal{L} \times \text{efficiency} \times \mathcal{B}(b \rightarrow D^0 X \mu^- \overline{\nu})\mathcal{B}(D^0 \rightarrow K^-\pi^+)}$$

15nb^{-1} used



Dominant systematics

Source	**Size**
Tracking efficiency	10%
Luminosity	10%
Branching/frag. fractions	8%

For $2 < \eta < 6$ (measured): $\sigma(pp \rightarrow b\overline{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$ (stat) (syst)

Extrapolate to 4π *(using Pythia)*: $\boxed{\sigma(pp \rightarrow b\overline{b}X) = (284 \pm 20 \pm 49)\ \mu b}$

Using TeVatron (instead of LEP) fragmentation fractions gives: $\boxed{\sigma(pp \rightarrow b\overline{b}X) = (338 \pm 24 \pm 58)\ \mu b}$

(increase of 19%)

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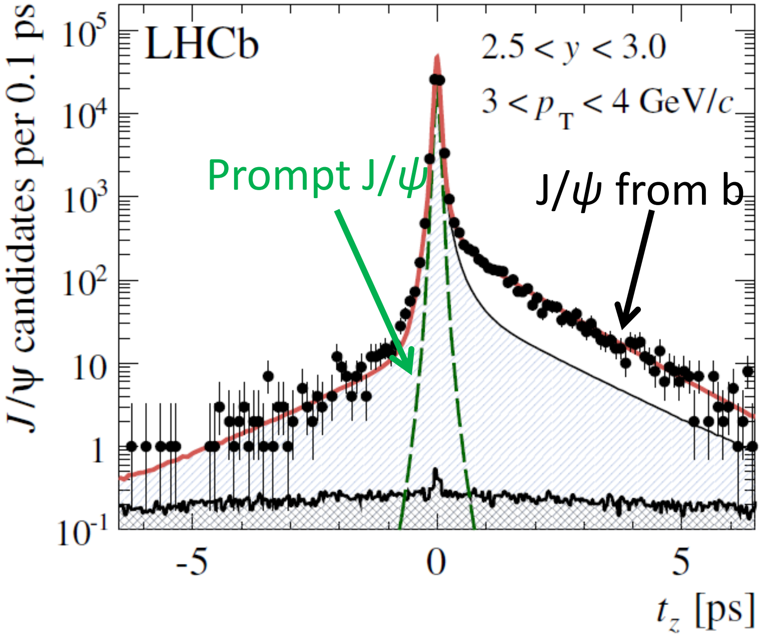
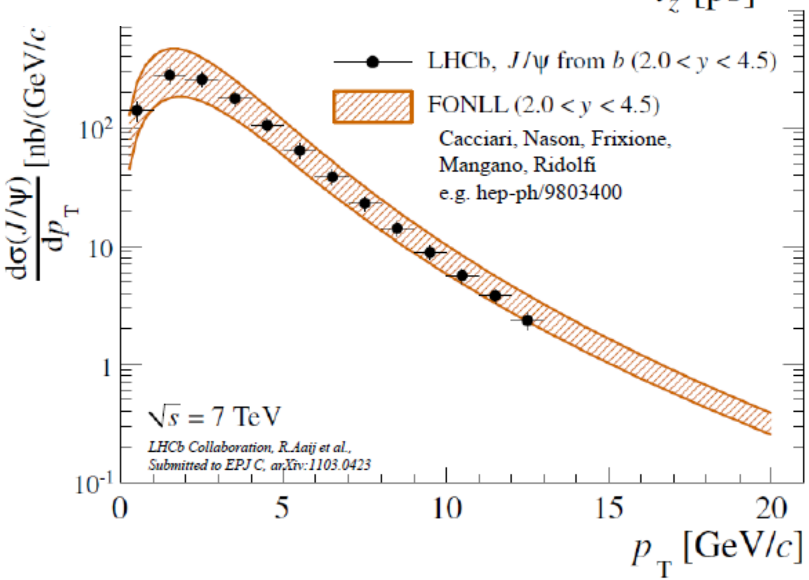
b Cross Section using $b \to J/\psi X$





Reconstruct $J/\psi \to \mu\mu$, using both single muon and dimuon triggers

Fit to pseudo-proper time, $t_z \equiv (z_{J/\psi} - z_{PV}) \times M_{J/\psi} / p_z$ in bins of p_T and y

Dominant systematics:

Source	**Size**
Tracking efficiency	8%
Luminosity	10%
B.R.($b \to J/\psi X$)	9%

5.2pb^{-1} used

$\boxed{\sigma(pp \to b\bar{b}X) = (288 \pm 4 \pm 48)\ \mu b}$

(with LEP fragmentation fractions, 2% change when using TeVatron fractions is included in syst. error)

*Submitted to Eur. Phys. J **C***

Preprint: hep-ex/1103.0423

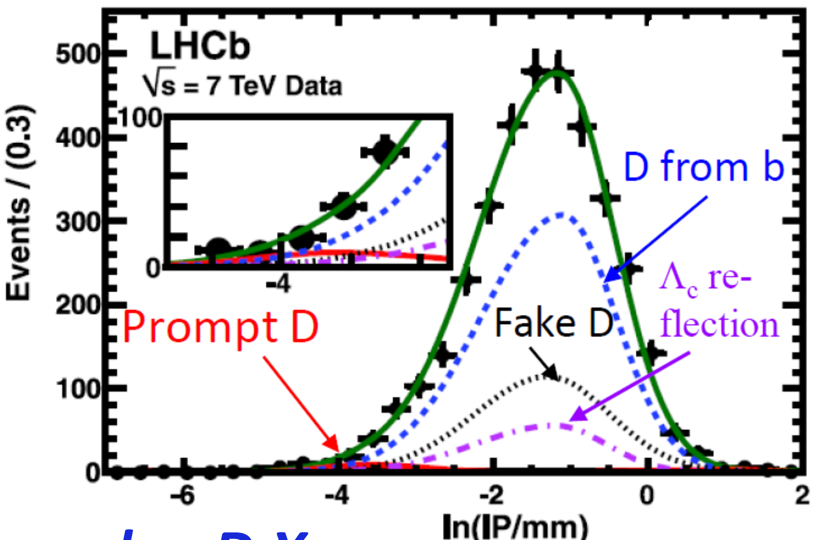
(also prompt J/ψ cross section)

Fragmentation Fractions using Semileptonic Decays

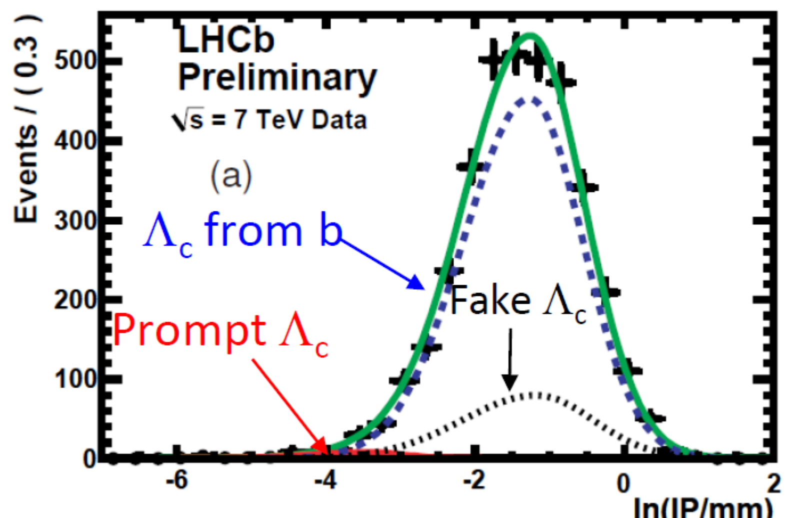
Can measure $f_s/(f_u+f_d)$ and $f_{\Lambda_b}/(f_u+f_d)$ using $D^0X\mu\nu$, $D^+X\mu\nu$, $D_sX\mu\nu$, $\Lambda_cX\mu\nu$

Similar strategy to x-sec measurement, but must correct for cross-feeds from such decays as $B_s \to D_{s1,2}(\to D^0K)X\mu\nu$, $B^{0/+} \to D_sKX\mu\nu$, and $\Lambda_b \to D^0pX\mu\nu$

Use $\Gamma_{SL}(B^+) = \Gamma_{SL}(B^0) = \Gamma_{SL}(B_s)$ (known to hold within 1% from e.g. HQET) and $\Gamma_{SL}(\Lambda_b)/\Gamma_{SL}(B^0) = 1.04 \pm 0.02$



$b \to D_sX\mu\nu$



$b \to \Lambda_cX\mu\nu$

3pb^{-1} used

First observation of $B_s \rightarrow D_{s2}^{*+} X \mu^- \bar{\nu}$

Evidence for resonance seen whilst checking $b \rightarrow D^0 K X \mu \nu$ mass spectrum

Confirmed in larger data sample, with significance of ≈8σ

$$\frac{\mathcal{B}(\overline{B}{}^0_s \rightarrow D_{s2}^{*+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}{}^0_s \rightarrow D_{s1}^{+} X \mu^- \overline{\nu})} = 0.61 \pm 0.14 \pm 0.05$$

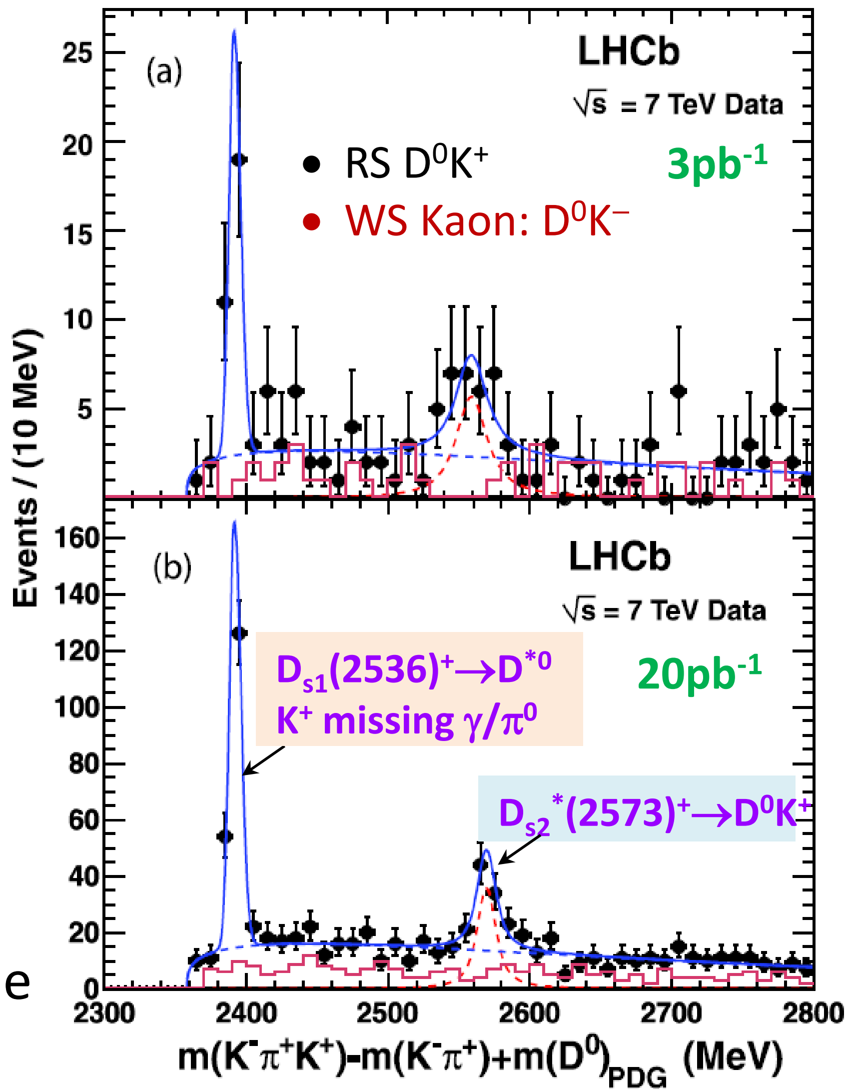
$$\frac{\mathcal{B}(\overline{B}{}^0_s \rightarrow D_{s1}^{+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}{}^0_s \rightarrow X \mu^- \overline{\nu})} = (5.4 \pm 1.2 \pm 0.5)\%$$

$$\frac{\mathcal{B}(\overline{B}{}^0_s \rightarrow D_{s2}^{*+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}{}^0_s \rightarrow X \mu^- \overline{\nu})} = (3.3 \pm 1.0 \pm 0.4)\%$$

Also: measured mass and width of D_{s2}^{*+}

confirmed DØ observation of D_{s1} mode

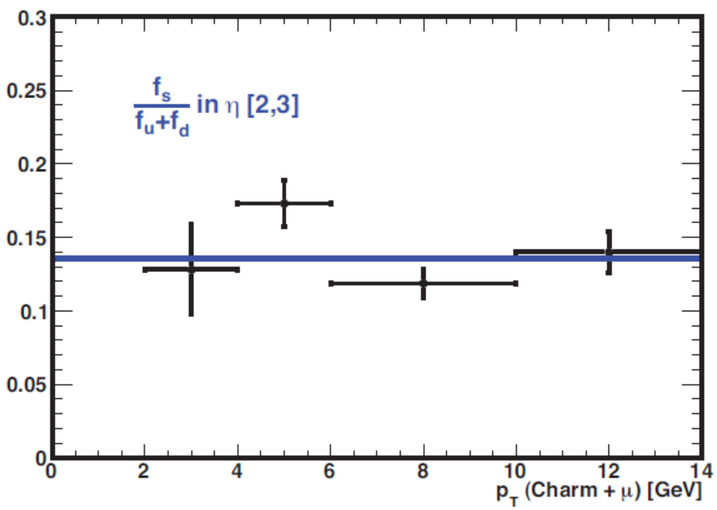
*Published in Phys. Lett. **B 698**, 14 (2011)*

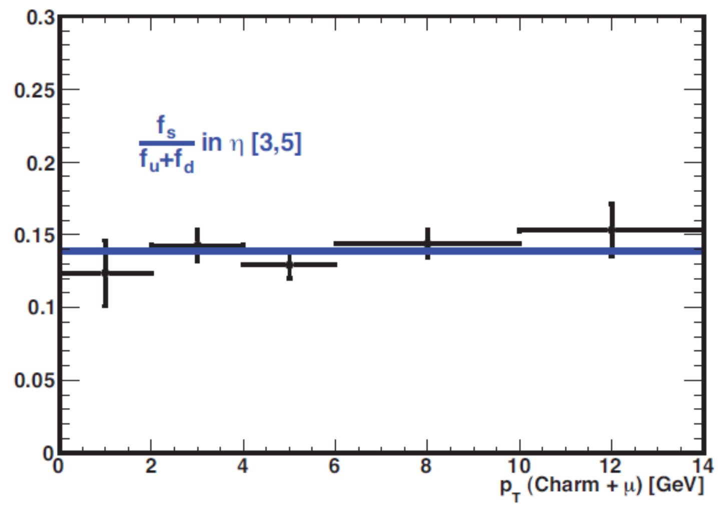


Semileptonic $f_s/(f_u + f_d)$ Result

$$f_s/(f_u + f_d) = 0.130 \pm 0.004\ (\text{stat})^{+0.012}_{-0.011}(\text{syst})$$

cf. LEP: 0.128 ± 0.012 (HFAG), and TeVatron: 0.135 ± 0.016 (CDF semilep.)





3pb^{-1} used

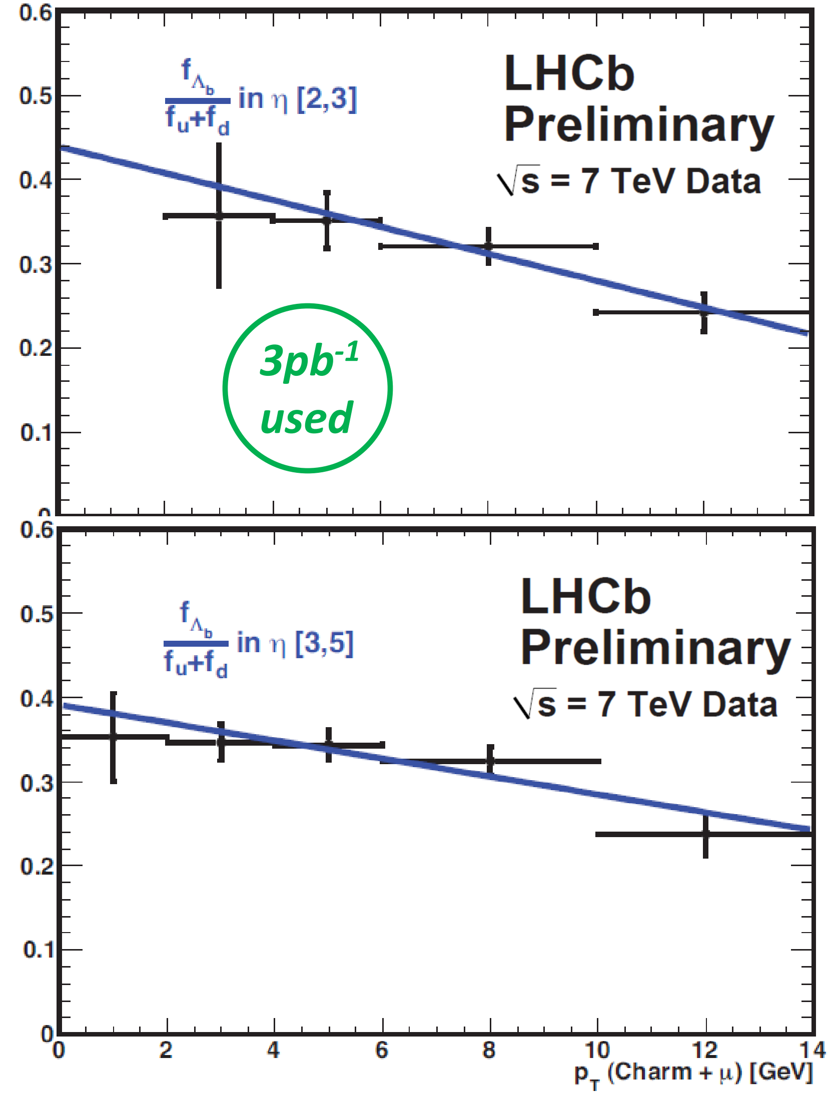
Dominant systematics

Source	**Size**
Branching fractions of charm hadrons	±5.5%
Subtraction of $B_s \to D^0 K X \mu\nu$ bkg	+4.1% -1.1%

No evidence for dependence of $f_s/(f_u + f_d)$ on either η or p_T

Good agreement with LEP and TeVatron values

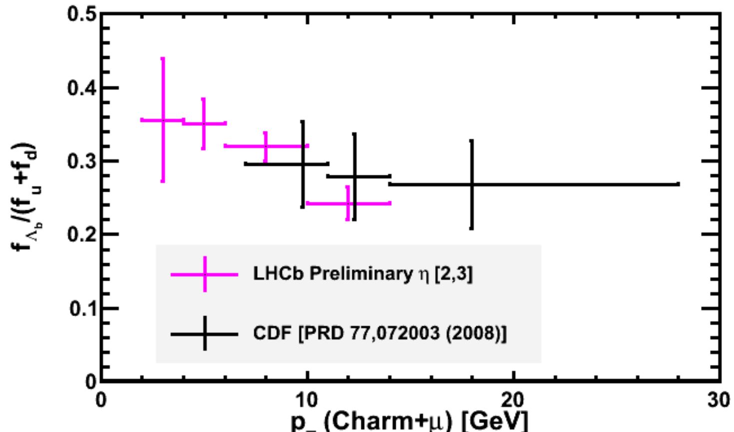
Semileptonic $f_{\Lambda_b}/(f_u + f_d)$ Result



Slope with p_T ***not*** consistent with zero.

Parameterising with straight line gives:

$f_{\Lambda_b}/(f_u+f_d) = (0.401 \pm 0.019 \pm 0.106) - (0.0120 \pm 0.0025 \pm 0.0012) * p_T/\text{GeV}$, for $p_T < 14$ GeV



26% uncertainty on BR($\Lambda_c \rightarrow pK\pi$) completely dominates the systematics

cf. LEP: 0.112 ± 0.031 (< p_T >≈40 GeV),

CDF: $0.281 \pm 0.012^{+0.129}_{-0.103}$ (< p_T >≈14 GeV)

f_s/f_d using Hadronic Decays

Decays $B_d \to D^- K^+$ and $B_s \to D_s^- \pi^+$ involve only tree level diagrams, hence ratio of branching fractions is theoretically calculable

$$\mathrm{BR}(\bar{B}_q^0 \to D_q^+ P^-) = \frac{G_F^2 (m_{B_q}^2 - m_{D_q}^2)^2 |\vec{q}| \tau_{B_q}}{16\pi m_{B_q}^2} \times |V_q^* V_{cb}|^2 \left[f_P F_0^{(q)}(m_P^2) \right]^2 |a_1(D_q P)|^2$$

form factor

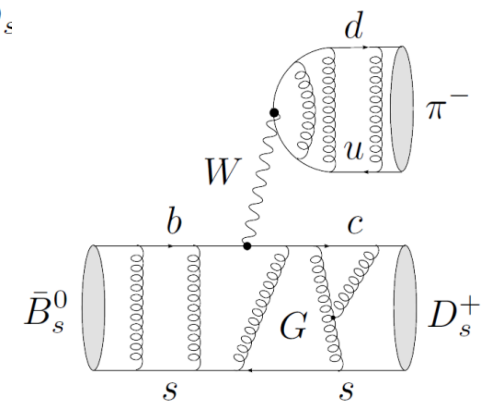
deviation from factorisation

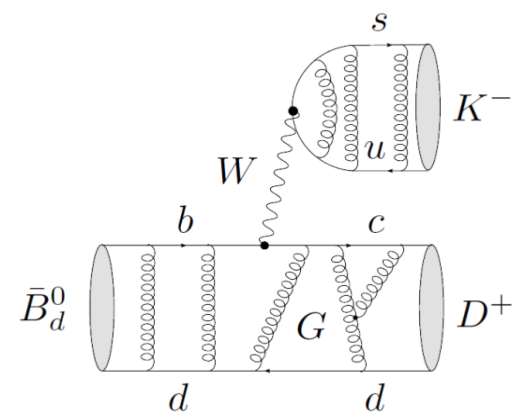
$$\frac{f_d}{f_s} = 13.45 \times \frac{\tau_{B_s}}{\tau_{B_d}} \times \left[\mathcal{N}_a \mathcal{N}_F \frac{\epsilon_{D_s\pi}}{\epsilon_{DK}} \frac{N_{DK}}{N_{D_s}} \right]$$

Phys. Rev. D 82, 034038 (2010)

$$\mathcal{N}_a \equiv \left| \frac{a_1(D_s^- \pi^+)}{a_1(D^- K^+)} \right|^2 = 1.00 \pm 0.02$$

$$\mathcal{N}_F \equiv \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)} \right]^2 = 1.24 \pm 0.08$$





Similar situation for $B_d \to D^- \pi^+$ and $B_s \to D_s^- \pi^+$, but with exchange diagram

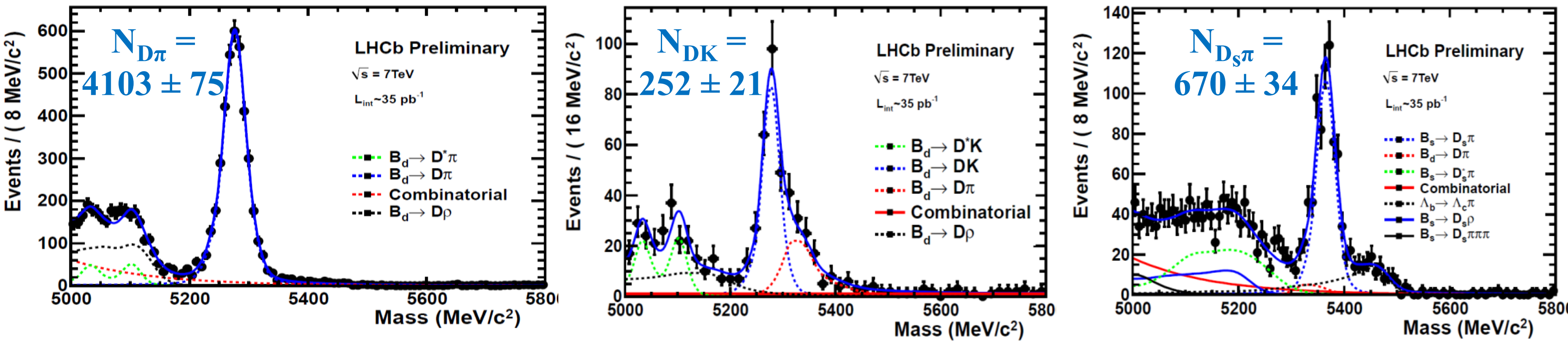
$$\frac{f_d}{f_s} = 1.018 \frac{\tau_{B_s}}{\tau_{B_d}} \left[\tilde{\mathcal{N}}_a \mathcal{N}_F \mathcal{N}_E \frac{\epsilon_{D_s\pi}}{\epsilon_{D_d\pi}} \frac{N_{D_d\pi}}{N_{D_s\pi}} \right]$$

$$\mathcal{N}_E = 0.966 \pm 0.075$$

Phys. Rev. D 83, 014017 (2011)

f_s/f_d using Hadronic Decays

Multivariate selection designed to minimise efficiency differences between modes. Effect of PID cuts evaluated using *D** control samples.



From $B_s \to D_s^-\pi^+$ and $B_d \to D^-K^+$: $f_s/f_d = 0.250 \pm 0.024 \pm 0.018 \pm 0.017$
(stat) (syst) (theory)

From $B_s \to D_s^-\pi^+$ and $B_d \to D^-\pi^+$: $f_s/f_d = 0.256 \pm 0.014 \pm 0.018 \pm 0.026$

Combine, accounting for correlated uncertainties: $f_s/f_d = 0.253 \pm 0.017 \pm 0.018 \pm 0.020$

LHCb-CONF-2011-013

35pb^{-1} used

Agrees well with semileptonic result

Also: extract World's best BR($B_d \to D^-K^+$) *(see talk of M. Whitehead)*

Conclusions

LHCb has measured the *b* cross section in √*s* = 7 TeV *pp* collisions:

$\sigma(pp \to b\bar{b}X) = (284 \pm 20 \pm 49)\ \mu b$ *(LEP fractions)*

$\sigma(pp \to b\bar{b}X) = (338 \pm 24 \pm 58)\ \mu b$ *(TeVatron fractions)*

($b \to D^0 X \mu\nu$, 15nb^{-1})

$\sigma(pp \to b\bar{b}X) = (288 \pm 4 \pm 48)\ \mu b$ *($b \to J/\psi X$, 5.2pb^{-1})*

In agreement with (and more precise than) QCD predictions

LHCb has measured the ratios of fragmentation fractions:

$f_s/f_d = 0.272 \pm 0.008 \pm 0.024$ *(semileptonic, 3pb^{-1})*

$f_{\Lambda_b}/(f_u+f_d) = (0.401 \pm 0.019 \pm 0.106) - (0.0120 \pm 0.0025 \pm 0.0012)*p_T/\text{GeV}$, for $p_T < 14$ GeV *(semileptonic, 3pb^{-1})*

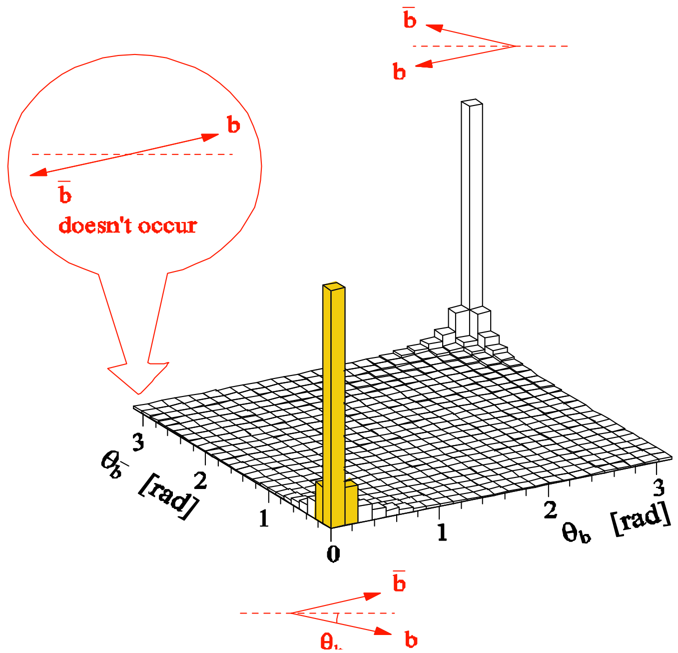
$f_s/f_d = 0.253 \pm 0.017 \pm 0.018 \pm 0.020$ *(hadronic, 35pb^{-1})*

f_s/f_d *in good agreement with LEP and TeVatron; p_T dependence of* $f_{\Lambda_b}/(f_u+f_d)$ *may reconcile different measurements*

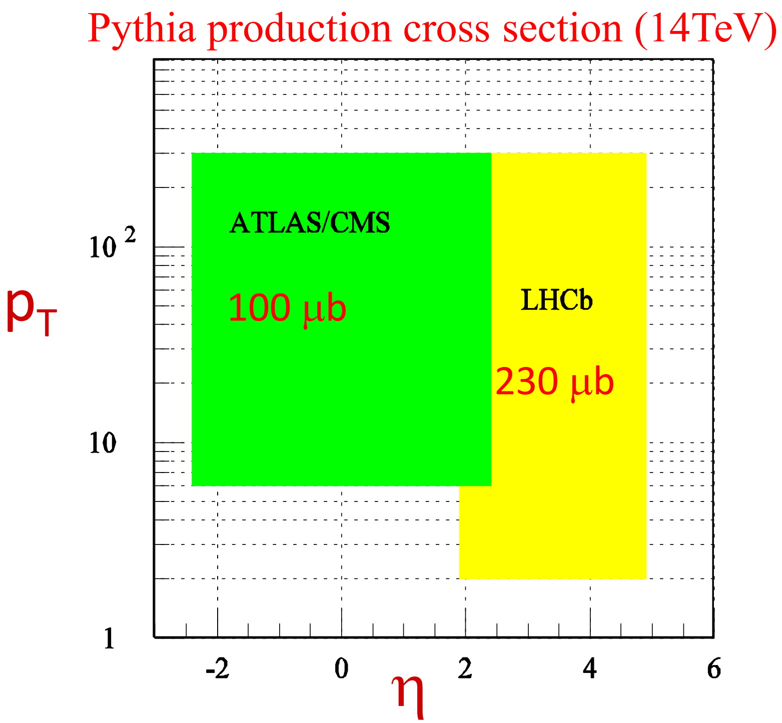
Also: first observation of $B_s \to D_{s2}^{*+} X \mu^- \bar{\nu}$, and World's best BR($B_d \to D^- K^+$)

Backup

LHCb Acceptance



b's are produced at low angles, and in the same hemisphere



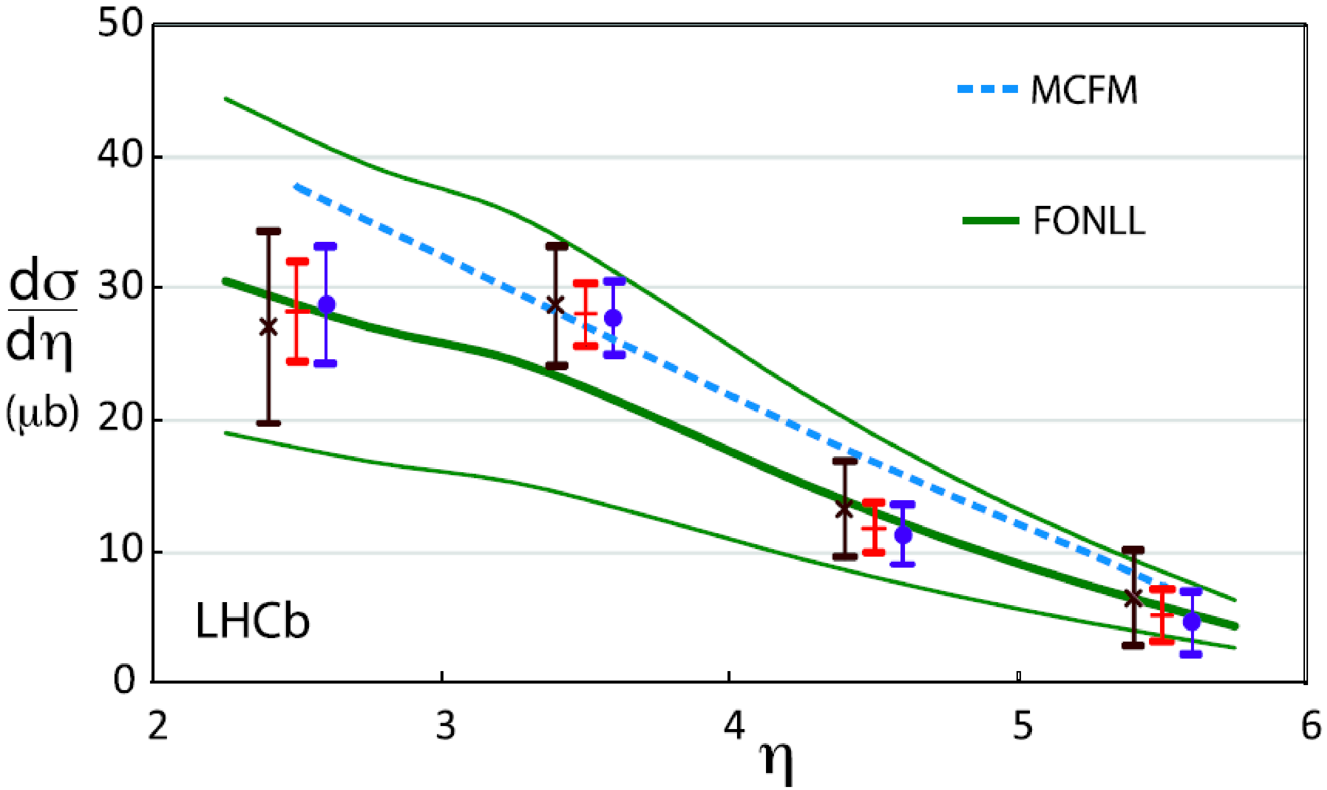
Nice overlap of acceptance with GPDs

Systematics for $b \rightarrow D^0 X \mu \nu$

Table 2: Systematic uncertainties.

Source	Error (%)	Source	Error (%)
Luminosity	10.0	Prompt & Dfb shapes	1.4
Tracking efficiency	10.0	$\mathcal{B}\,(D^0 \to K^-\pi^+)$	1.3
$\mathcal{B}(b \to D^0 X \mu^- \overline{\nu})$	5.1	$D^0\mu^-$ vertex χ^2 cut	1.2
Assumed branching fractions	4.4	Kaon identification	1.2
LEP fragmentation fractions	4.2	Muon fakes	1.0
Generated b p_{T} distribution	3.0	D^0 mass cut	1.0
Muon identification	2.5	D^0 vertex χ^2 cut	0.6
χ^2_{IP} cut	2.5	D^0 flight distance cut	0.4
MC statistics	1.5	Pion identification	0.3
Total		17.3%	

Combination for $b \to D^0 X \mu \nu$

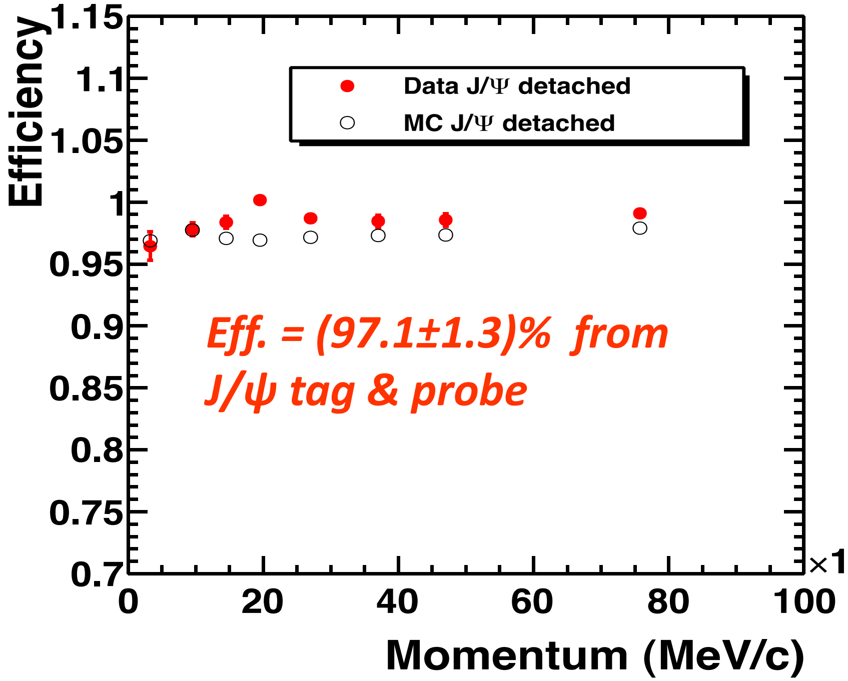


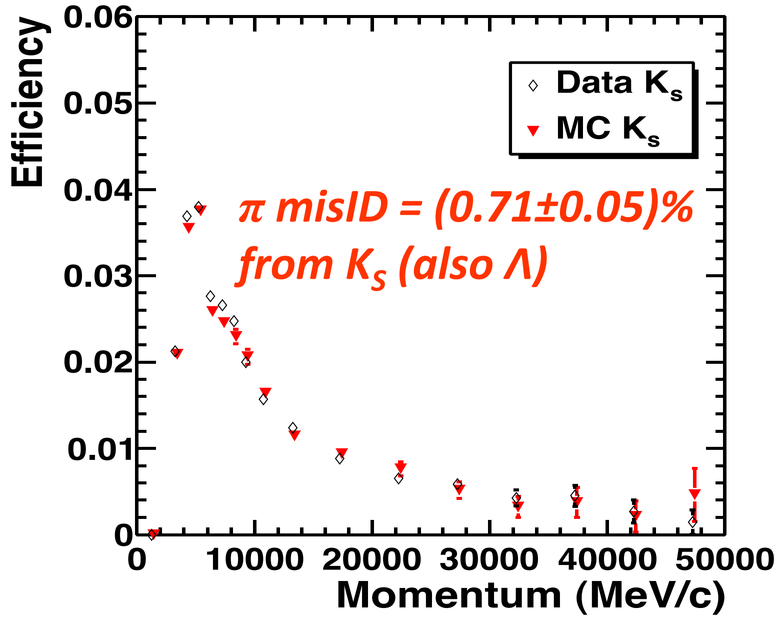
Unbiased trigger, $3 nb^{-1}$

Single muon trigger, $12 nb^{-1}$

Combination

Muon Identification





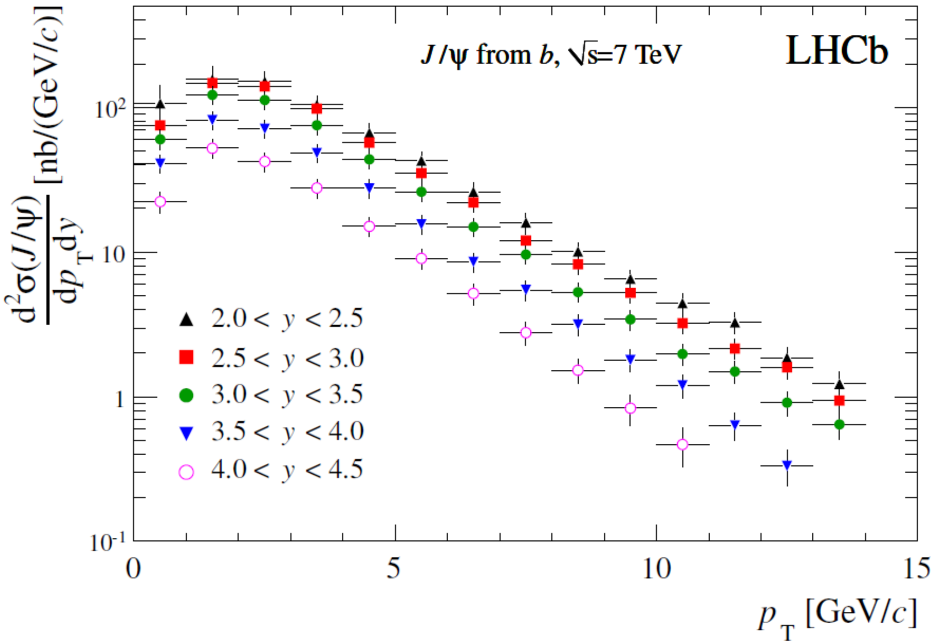
Most misID is due to π→μ decays in flight

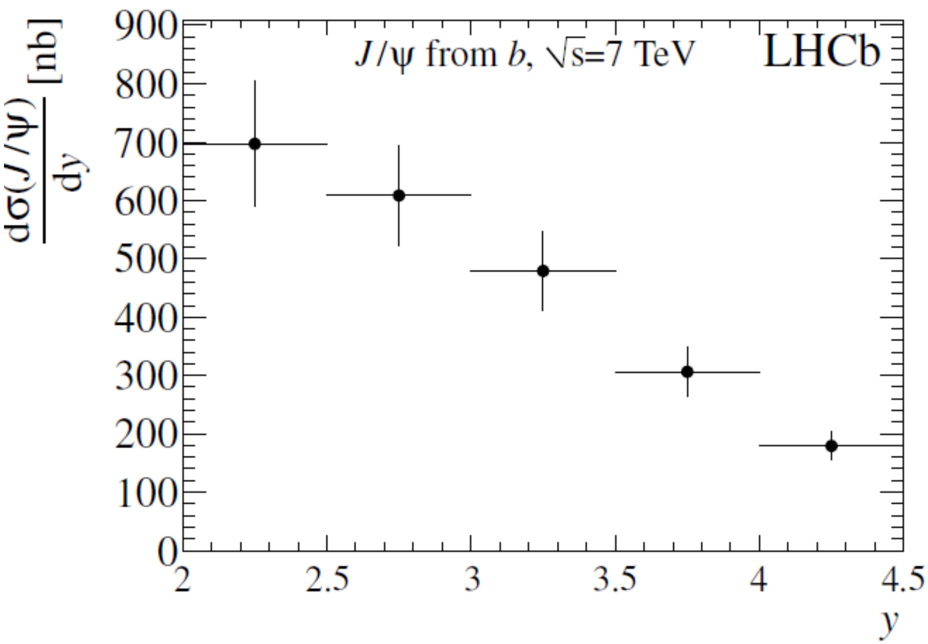
Systematics for $b \to J/\psi X$

Table 1: Summary of systematic uncertainties.

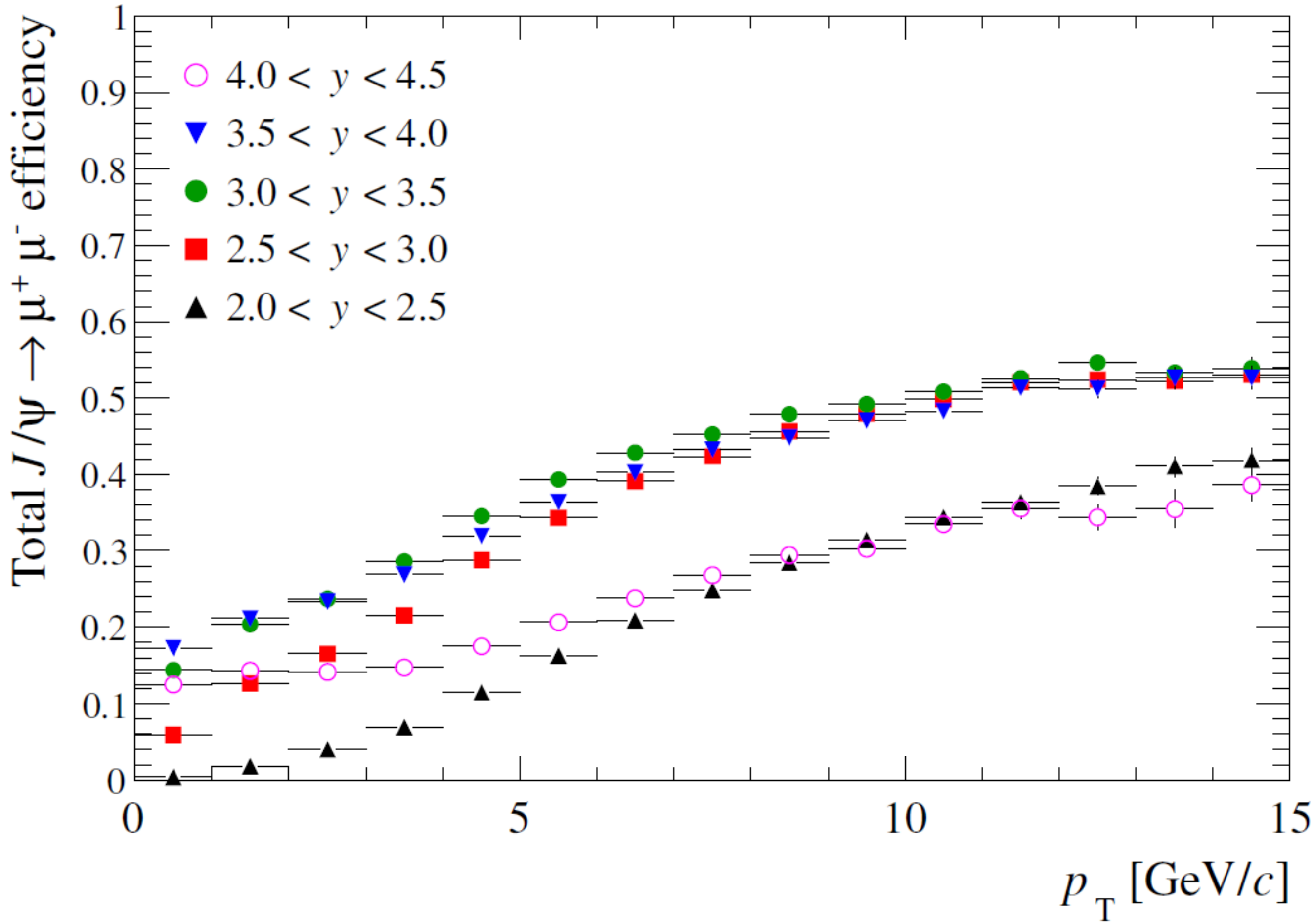
Source	Systematic uncertainty (%)
Correlated between bins	
Inter-bin cross-feed	0.5
Mass fits	1.0
Radiative tail	1.0
Muon identification	1.1
Tracking efficiency	8.0
Track χ^2	1.0
Vertexing	0.8
GEC	2.0
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	1.0
Luminosity	10.0
Uncorrelated between bins	
Bin size	0.1 to 15.0
Trigger	1.7 to 4.5
Applied only to J/ψ from b cross-sections, correlated between bins	
GEC efficiency on B events	2.0
t_z fits	3.6
Applied only to the extrapolation of the $b\bar{b}$ cross-section	
b hadronisation fractions	2.0
$\mathcal{B}(b \to J/\psi X)$	9.0

$b \to J/\psi X$ dependence on y



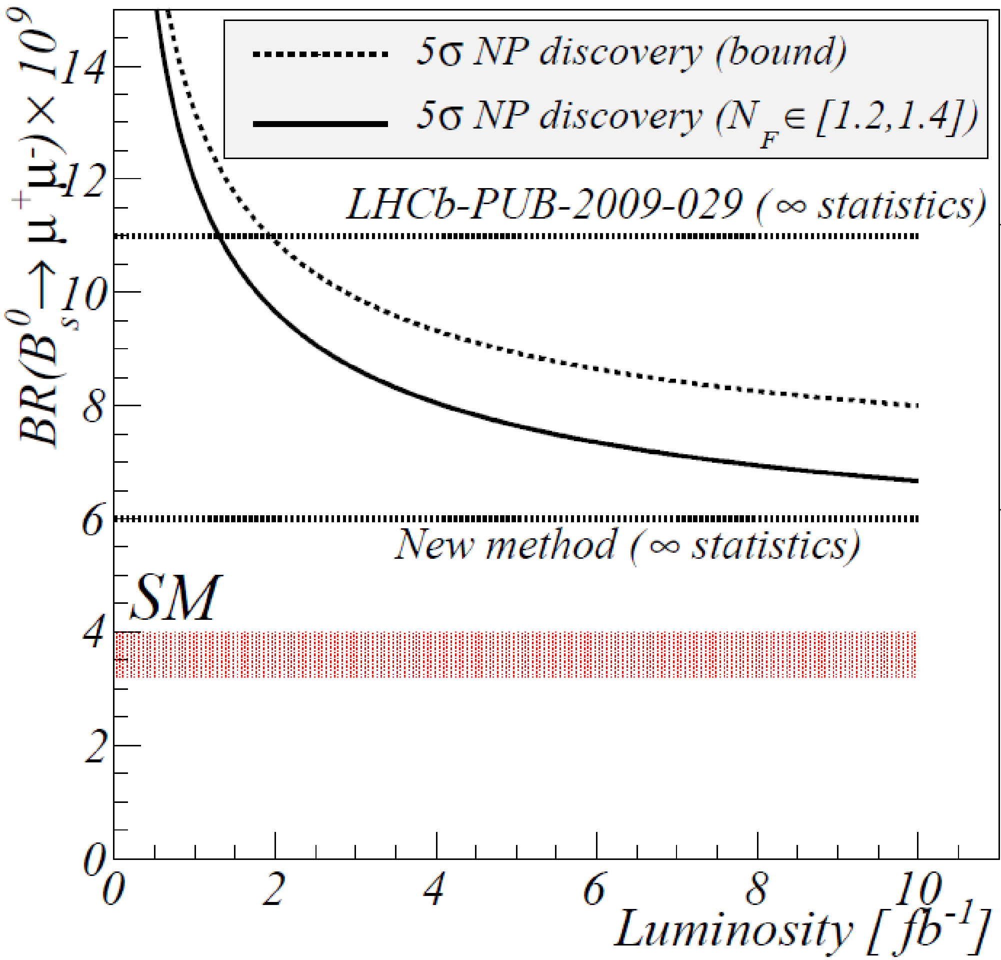


$b \to J/\psi X$ efficiencies from MC



Efficiencies for prompt J/ψ and for J/ψ from b assumed equal (no cuts on impact parameter or decay length)

f_s/f_d for $B_s \to \mu\mu$



Reach with $\sigma(f_s/f_d)$ = 13% (current PDG)

Reach with $\sigma(f_s/f_d)$ = 7% (our ambition!)

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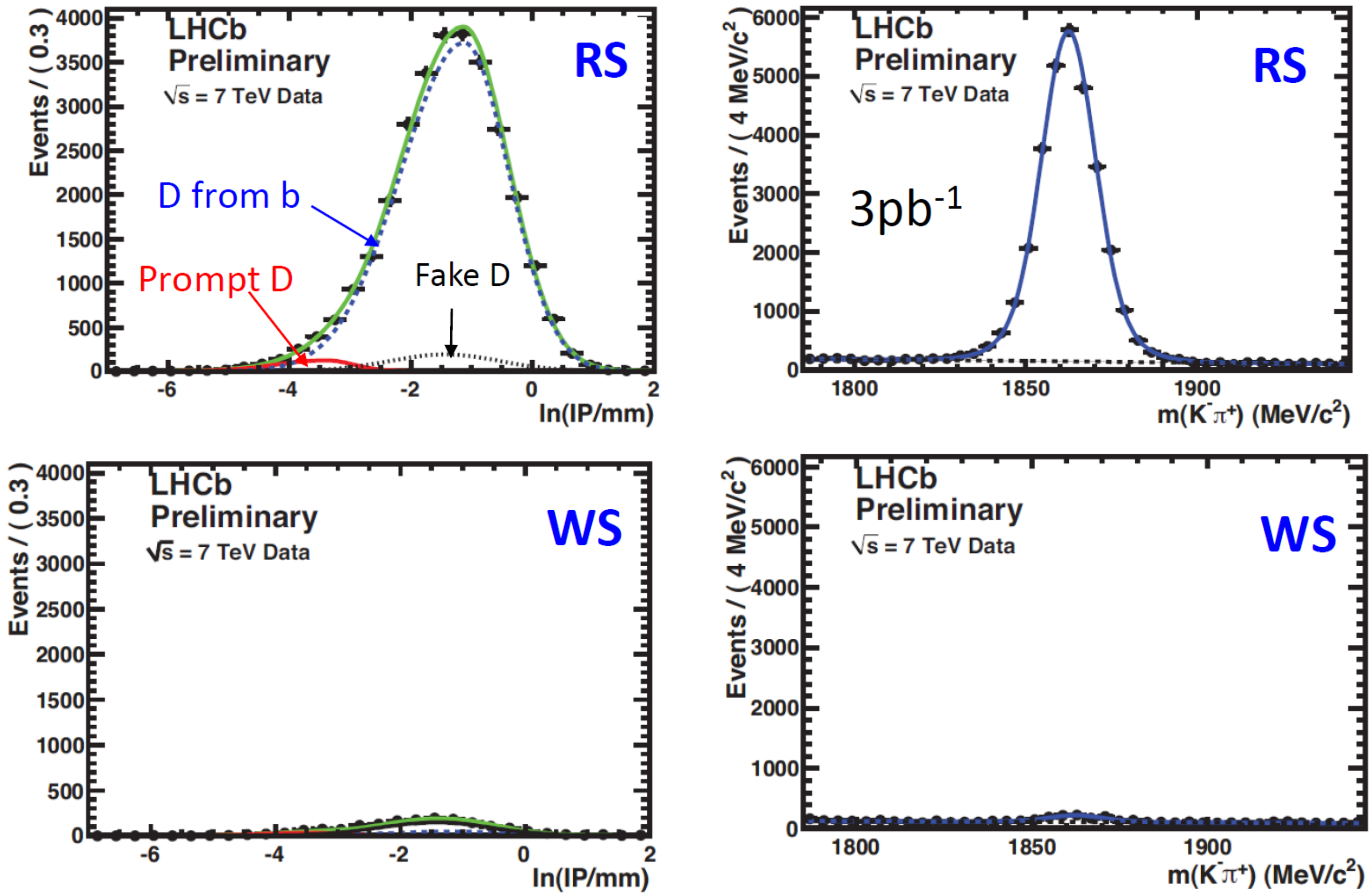
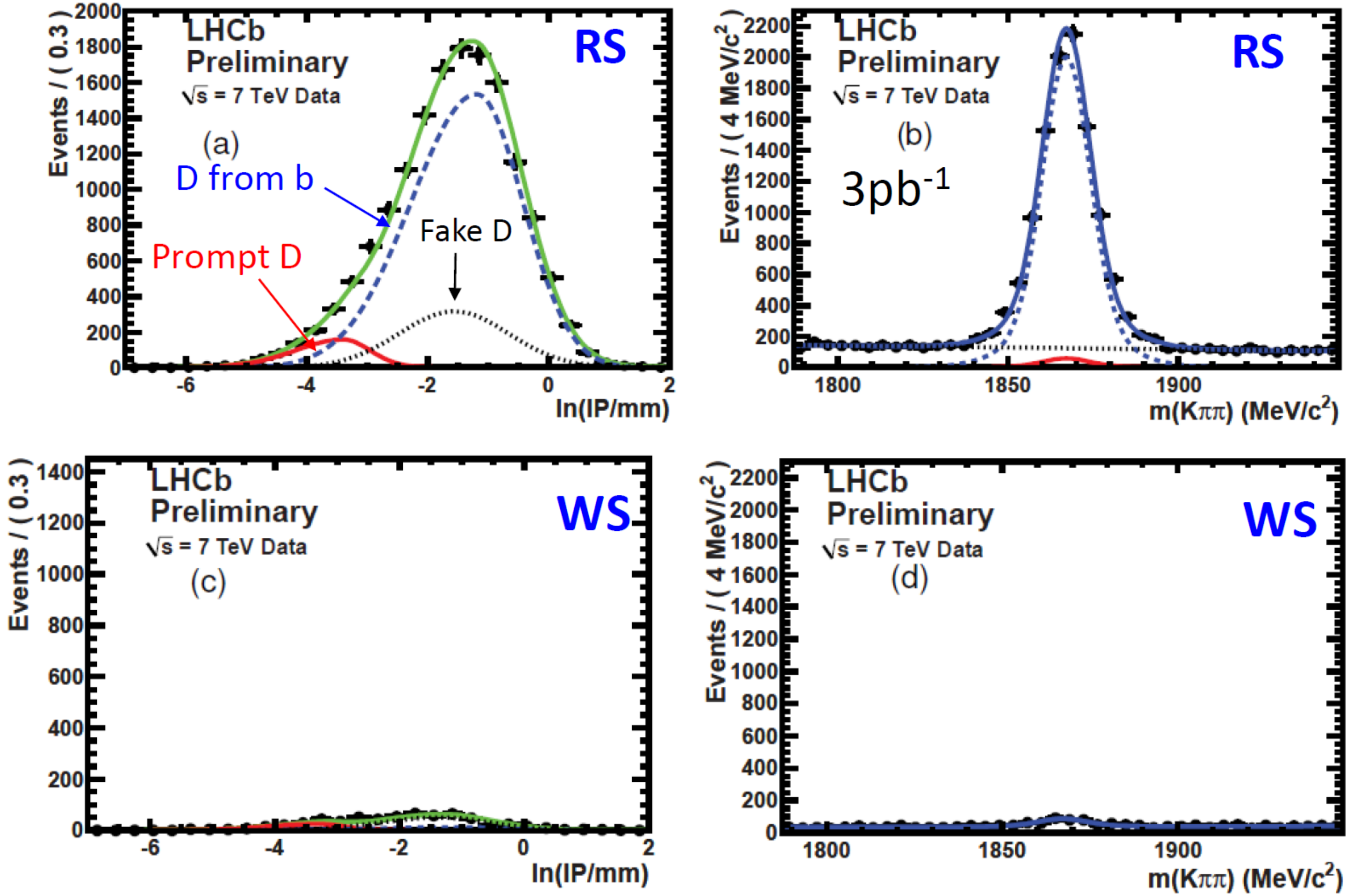
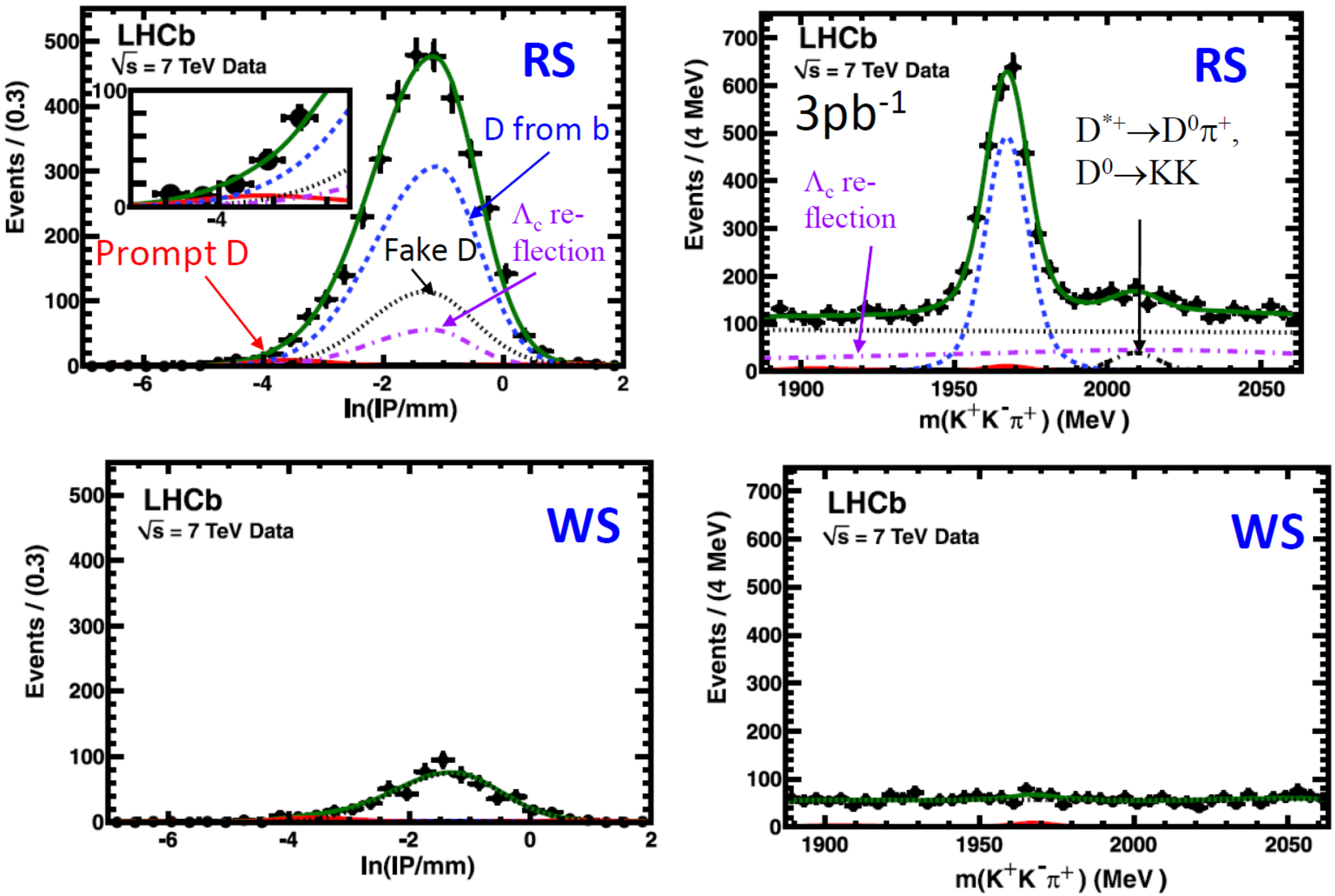
Semileptonics: $b \to D^0 X \mu \nu$



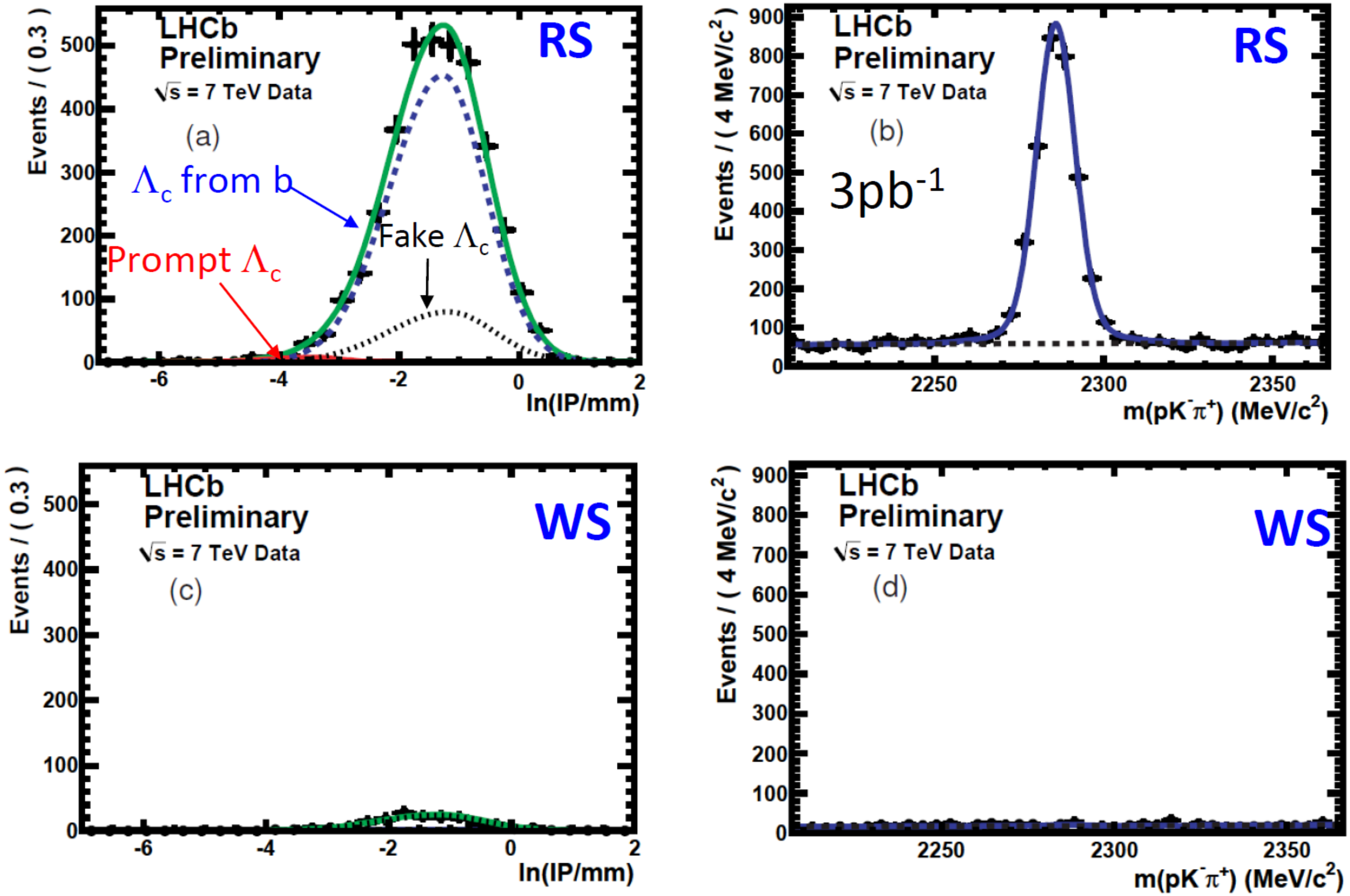
Semileptonics: $b \rightarrow D^{+} X \mu \nu$



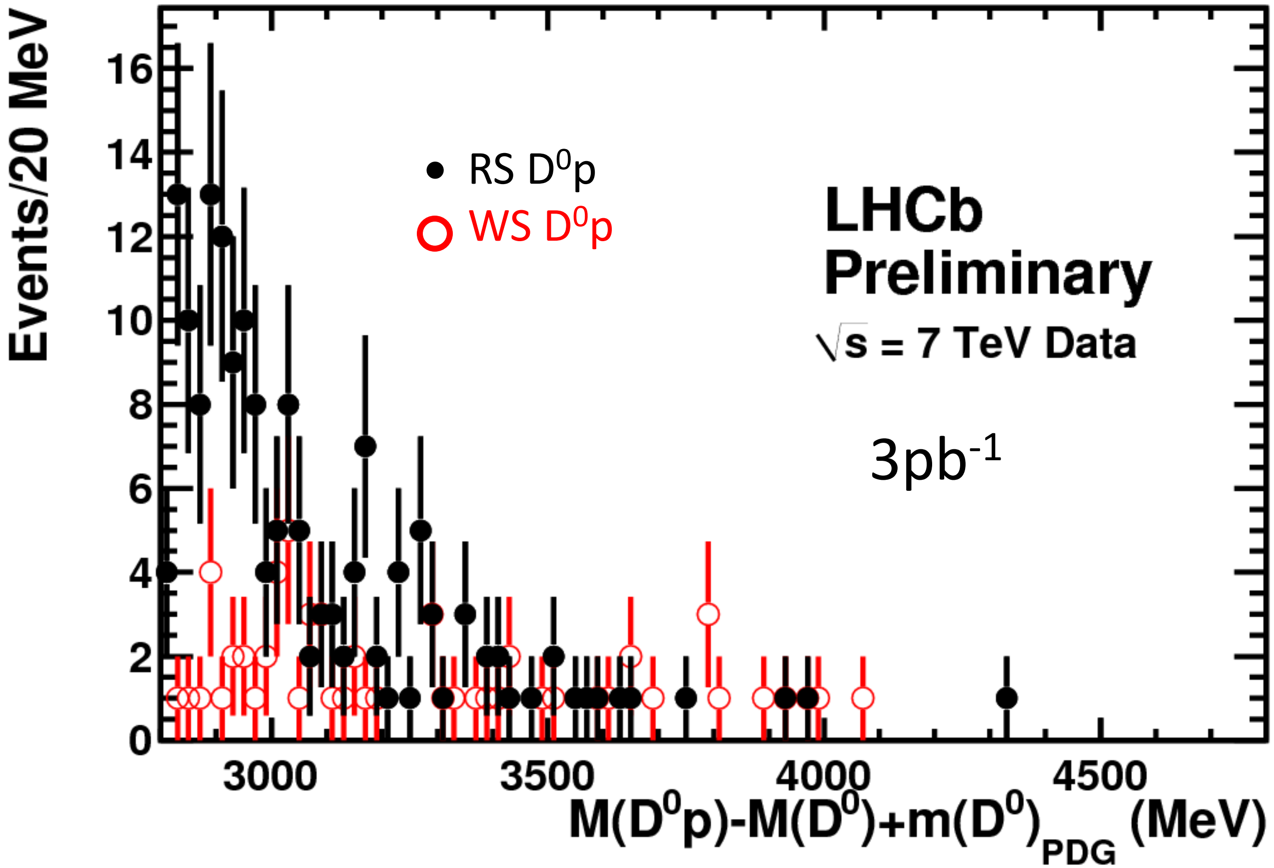
Semileptonics: $b \to D_s X \mu \nu$



Semileptonics: $b \rightarrow \Lambda_c X \mu \nu$

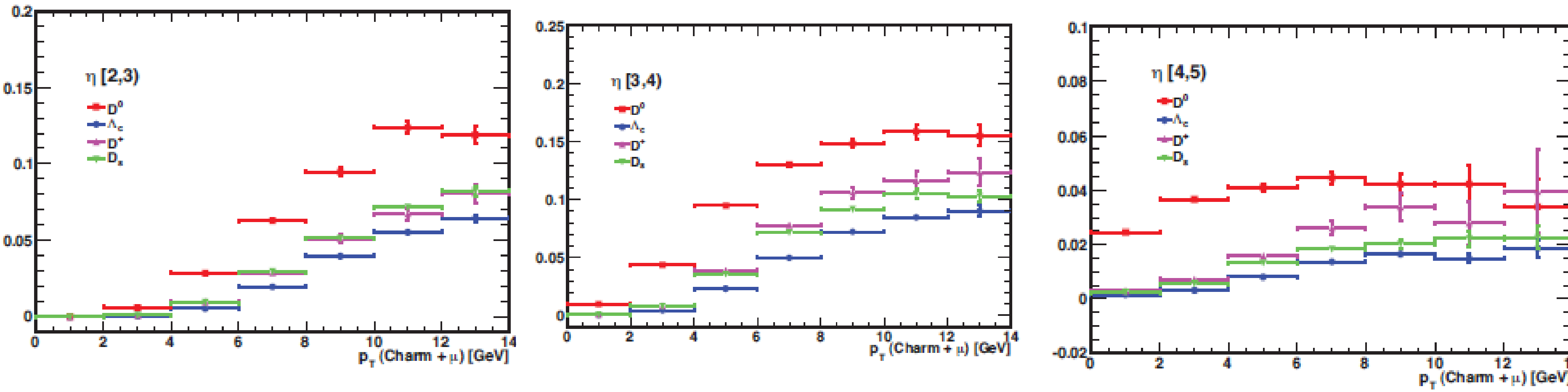


Semileptonics: $b \to D^0 p X \mu \nu$

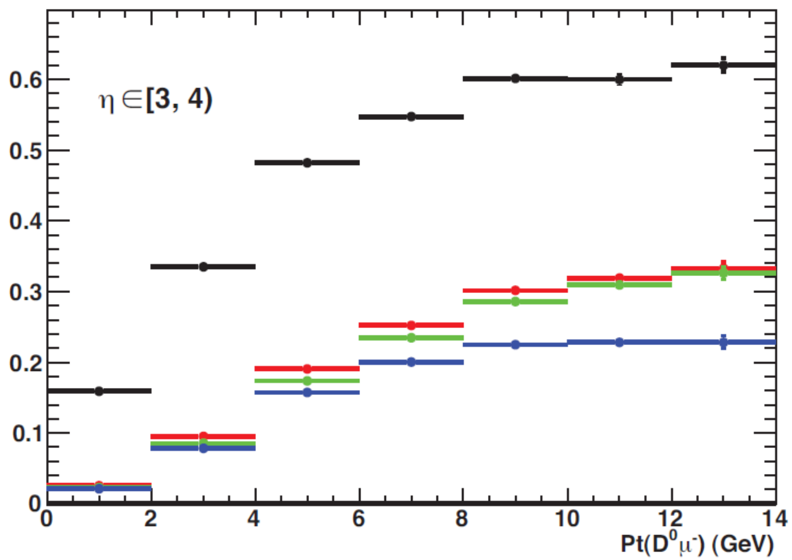


Possible contributions from $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$, both of which can decay into $D^0 p$

Semileptonics: Efficiencies



Efficiency breakdown for $D^0\mu$



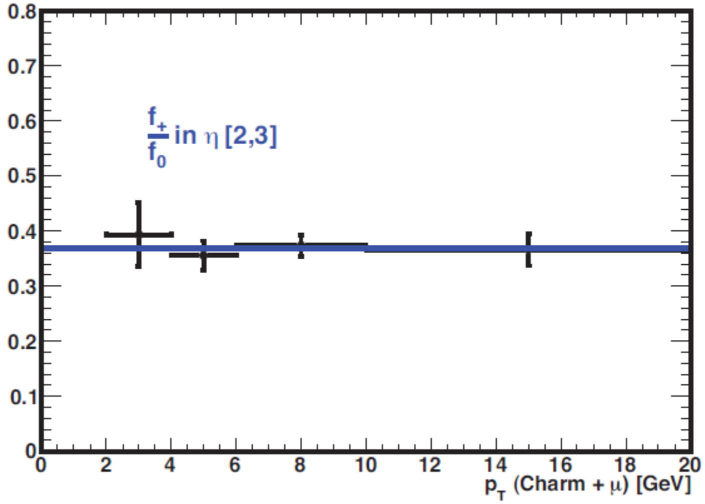
Track acceptance and reconstruction

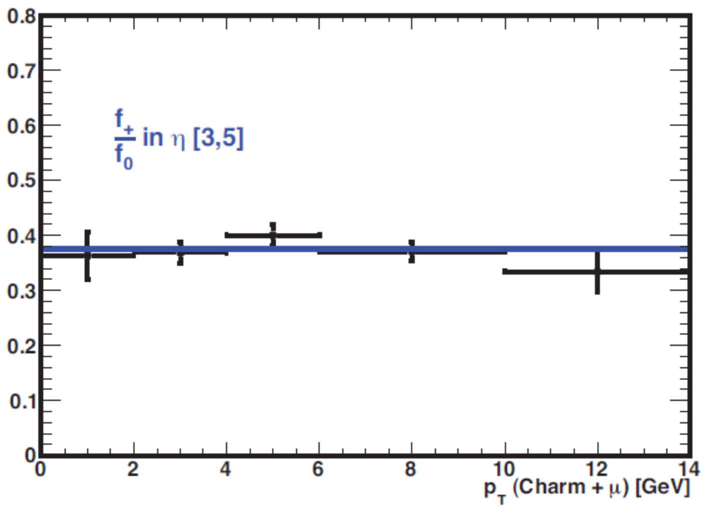
Muon selection & trigger

K and π p_T cuts

PID cuts

Semileptonics: Cross-check





$$\frac{f_+}{f_0} \equiv \frac{N(B_{u,d} \to D^+ X \mu \nu)}{N(B_{u,d} \to D^0 X \mu \nu)}$$

$$\left.\frac{f_+}{f_0}\right|_{meas} = 0.373 \pm 0.006(\text{stat}) \pm 0.007(\text{eff}) \pm 0.014$$

$$\left.\frac{f_+}{f_0}\right|_{pred} = 0.375 \pm 0.023$$

Systematics for Semileptonic $f_s/(f_u + f_d)$

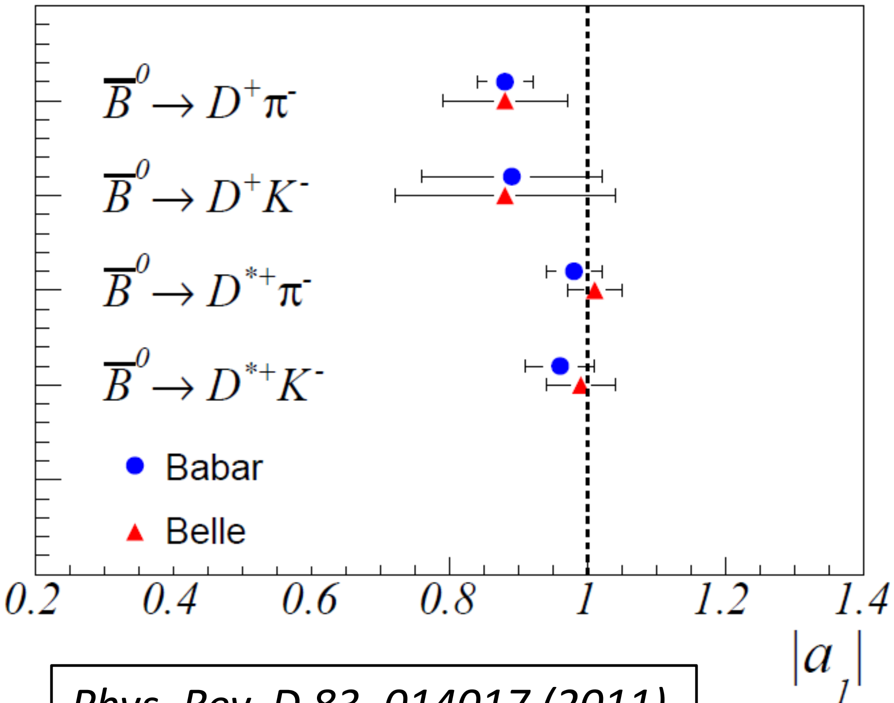
Source	Error (%)
Bin by bin efficiency correction	1.0
Charm hadron branching fractions	5.5
$Bs \rightarrow DK\mu\nu X$	+4.1 -1.1
MC modeling	3.0
$B \rightarrow DsK\mu\nu X$	2.0
Background Modeling	2.0
Tracking efficiency	2.0
Lifetime ratio	1.8
PID efficiency	1.4
Trigger Efficiency	1.4
Total	+8.9 -7.8

Deviations from Factorisation

$$\frac{\mathrm{BR}(\bar{B}_d^0 \to D^{(*)+} P^-)}{d\Gamma(\bar{B}_d^0 \to D^{(*)+} \ell^- \bar{\nu}_\ell)/dq^2|_{q^2=m_P^2}} = 6\pi^2 \tau_{B_d} |V_P|^2 f_P^2 |a_1(D_q P)|^2 \underline{X_P}$$

$X_P \approx 1$ within <1%
(X_V is exactly 1)

Can use *B* Factory results to obtain:



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$$\mathcal{N}_a \equiv \left| \frac{a_1(D_s^- \pi^+)}{a_1(D^- K^+)} \right|^2$$

No evidence for deviation of ratio of any $|a_1|$'s from 1.
Use of LHCb measurements can improve value for $B_d \to D^- K^+$

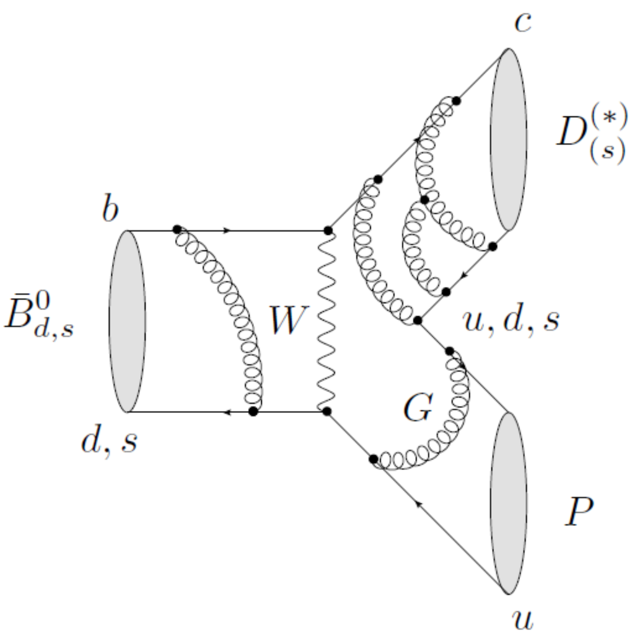
Exchange diagram in $B_d \to D^- \pi^+$

Can be constrained using $\frac{\mathrm{BR}(\bar{B}_d^0 \to D^{*+} K^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^{*+} \pi^-)} = (7.76 \pm 0.34 \pm 0.29)\%$

Babar, *PRL* ***96*** *011803 (2006)*

Ratio of tree amplitudes is

$$\left| \frac{T'^{(*)}}{T^{(*)}} \right|_{\text{fact}} = \left| \frac{V_{us}}{V_{ud}} \right| \frac{f_K}{f_\pi} \frac{F^{B \to D^{(*)}}(m_K^2)}{F^{B \to D^{(*)}}(m_\pi^2)}$$



Hence extract

$$\left| \frac{T^*}{T^* + E^*} \right| = 0.983 \pm 0.028$$

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Use this to estimate

$$\mathcal{N}_E \equiv \left| \frac{T}{T + E} \right|^2 = 0.966 \pm 0.056 \pm 0.05$$
$$= 0.966 \pm 0.075$$

To allow for differences between *D* and *D** cases

Systematics for Hadronic f_d/f_s

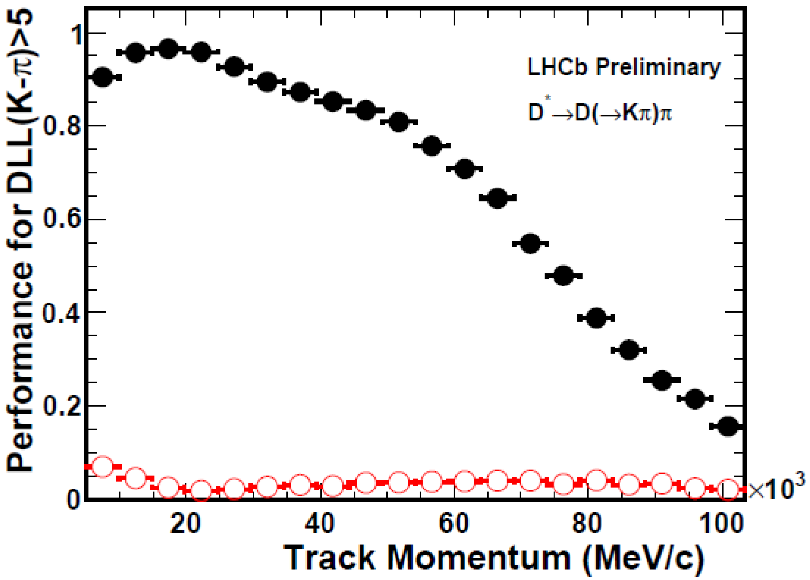

TABLE I. Systematic uncertainties for the $\mathcal{B}\left(B^0 \to D^- K^+\right)$ and f_s/f_d measurements.

PID calibration	1.5%
Fit model	3%
Trigger simulation	2%
$\mathcal{B}(B^0 \to D^- \pi^+)$	4.9%
$\mathcal{B}(D_s^\pm \to KK\pi)$	5%
$\mathcal{B}(D^\pm \to K\pi\pi)$	2%
τ_{B_s}/τ_{B_d}	1.5%

Efficiency and misID of tight Kaon ID cut used to select $B_d \to D^- K^+$