Studies of open heavy flavour production at LHCb

Liming Zhang

(Syracuse University)

on behalf of the LHCb Collaboration

DIS 2011

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- b cross-section
  - Semi-leptonic (SL) $b \to D^0 X \mu \nu$
  - $b \to J/\psi\ X$
- B fragmentation fractions
  - Semi-leptonic (SL)
  - Hadronic $B_s \to D_s^- \pi^+$ and $B^0 \to D^- \pi^+ / K^+$
- Open charm cross-section

Motivation

Cross section measurements:

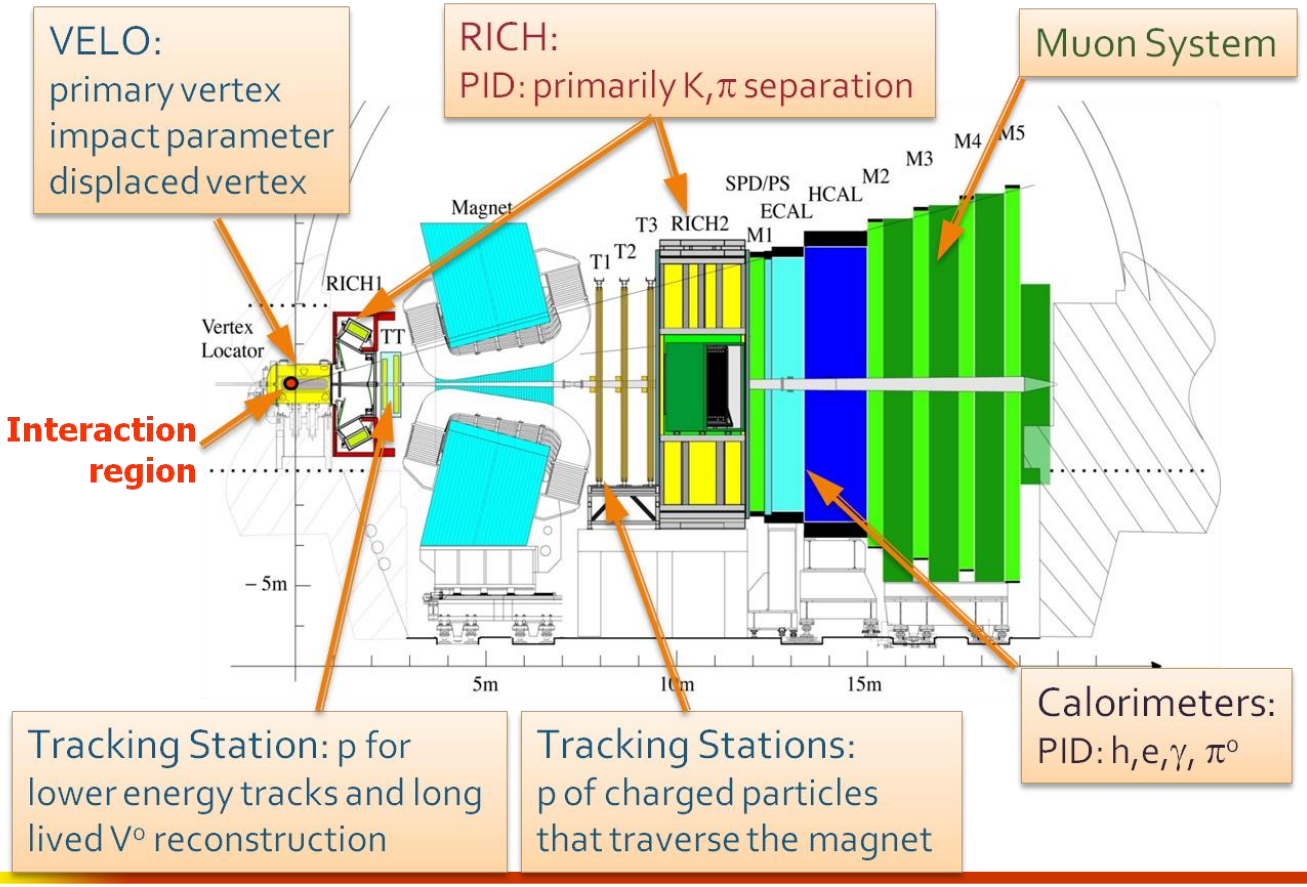
- Comparison to QCD predictions

Fragmentation fractions:

- Input to inclusive b cross section measurement
- f_s needed for all B_s^0 branching ratios measurement
- $f_{\Lambda b}$ is also interesting
  - CDF's value is substantial larger than LEP's.
  - Explained by CDF: it's because of difference of $<p_T(B)>$

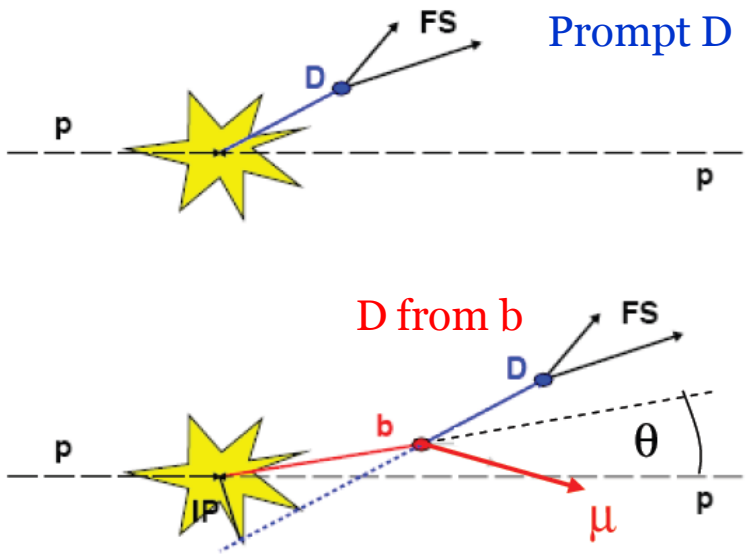
LHCb Experiment

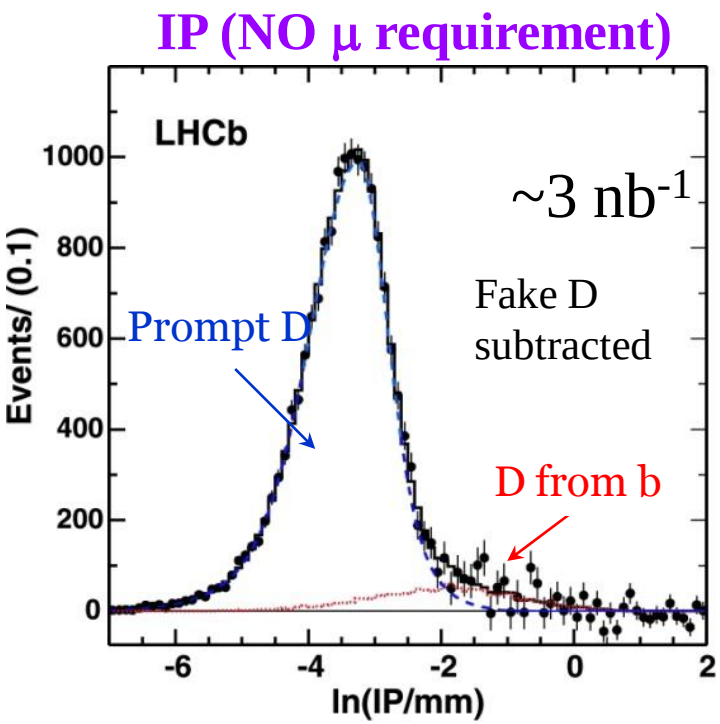
- The LHCb detector is a single arm forward spectrometer
- Unique regime: $1.9<\eta<4.9$, down to $p_T \sim 0$ for production studies, where pseudorapidity $\eta=-\ln[\tan(\theta/2)]$



b cross section: semi-leptonic

- Measure right-sign, vertexed, $D^0(\rightarrow K^-\pi^+)\mu^-$ combinations with tracks not pointing at primary vertex
- Background from "Prompt" D separated from signal (D from b) using impact parameter (IP)





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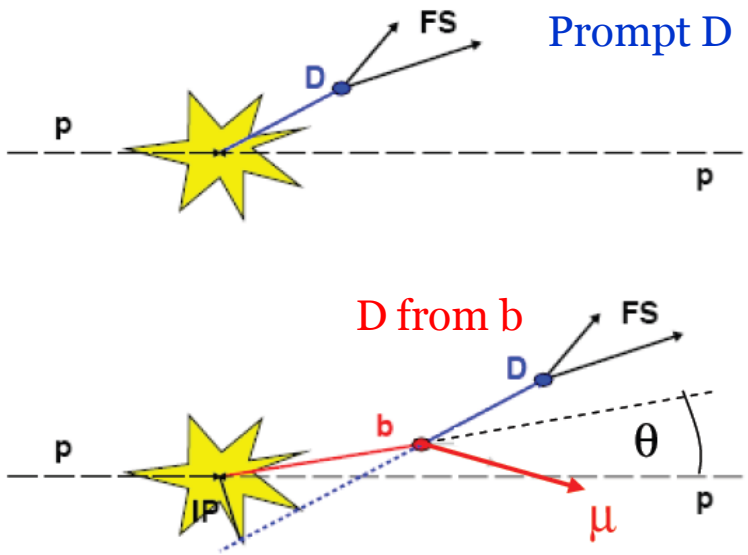
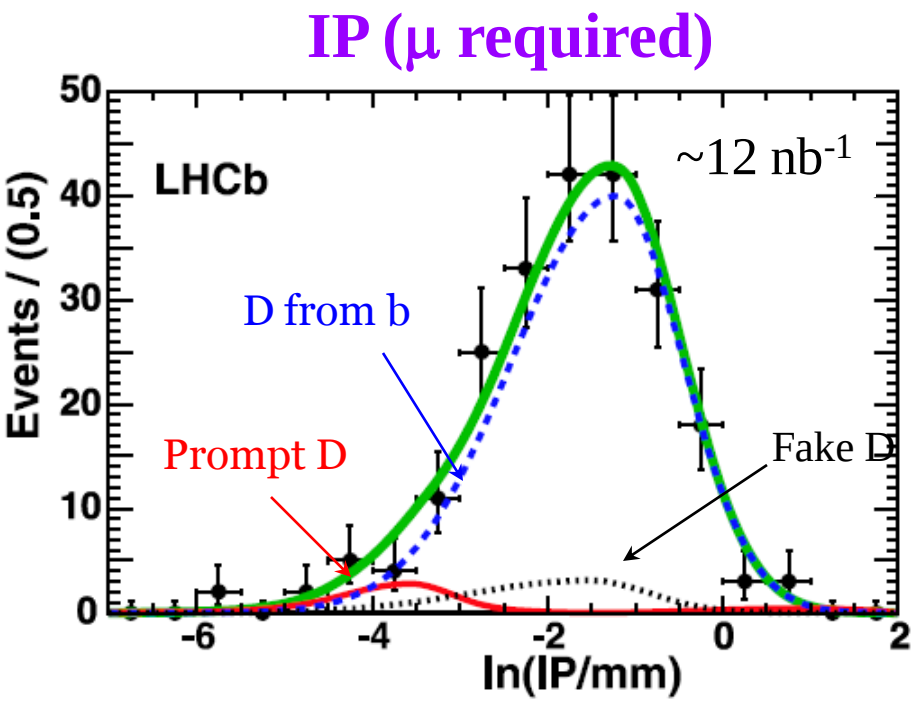
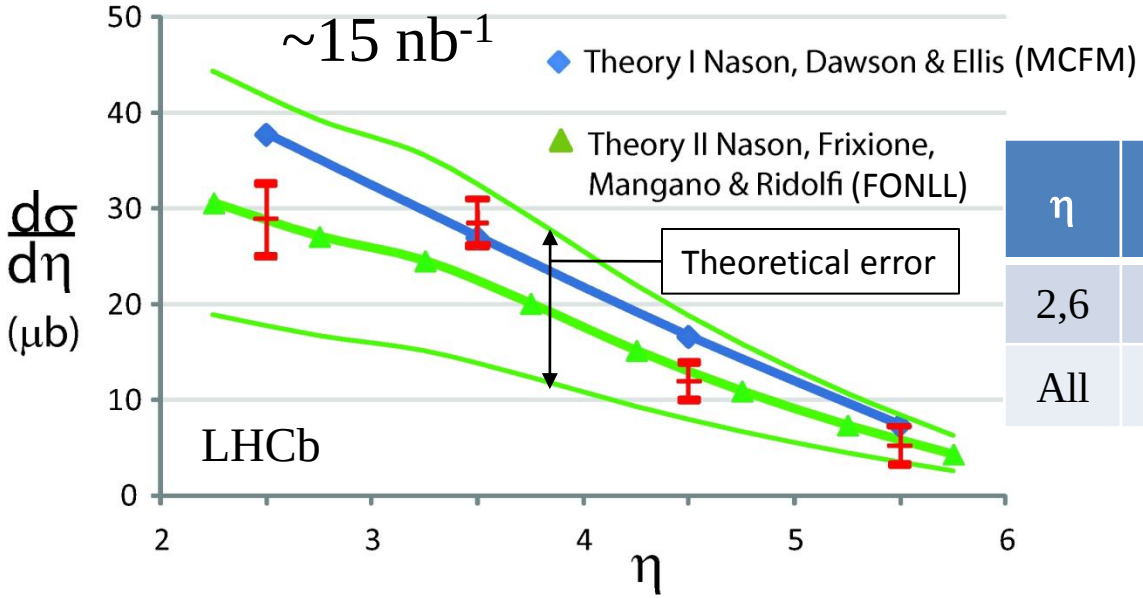




b cross section: semi-leptonic

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



σ (μb)

η	Theory I	Theory II	Measurement
2,6	89.0	70.2^{+39}_{-44}	75.3 ± 5.4 ± 13.0
All	332	253^{+114}_{-96}	284 ± 20 ± 49

Main Systematics:

Luminosity 10% (known in last year), tracking 10%

σ increases by 19% if using Tevatron's B fragmentation fractions other than LEP's due to b-baryon percentage rising from (9.1±1.5)% (LEP) to (21.4±6.8)% (Tevatron)

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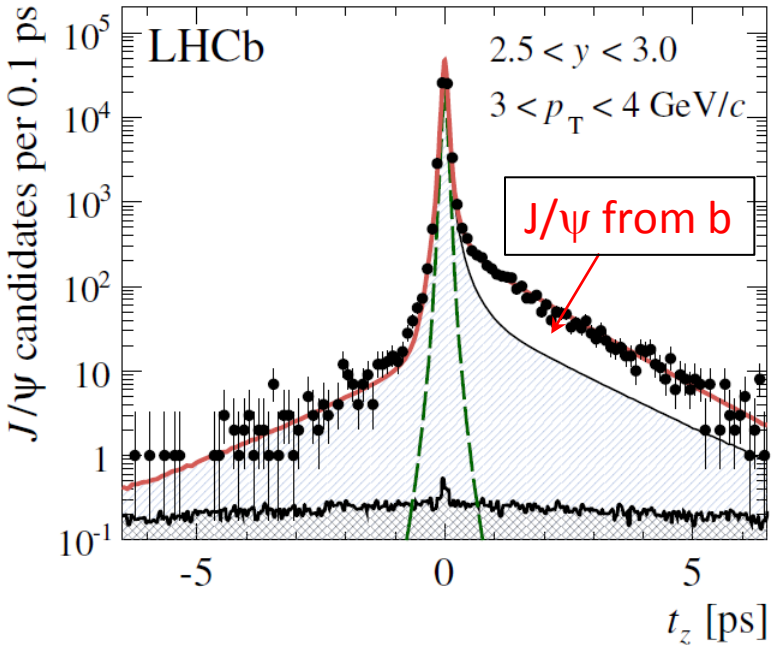
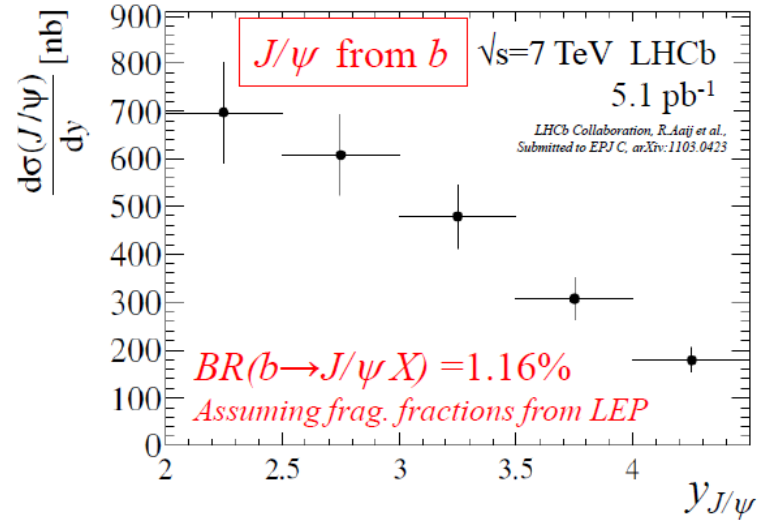
b cross section from b→J/ψX

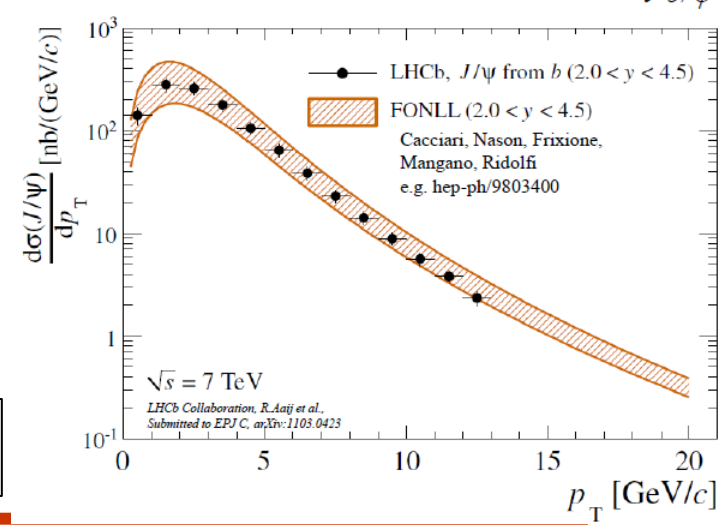


$$\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\ \mu b$$



Pseudo lifetime $t_z = \dfrac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$

Used to separate prompt and J/ψ from b



Submitted to EPJC. Arxiv:1103.0423

b-hadron fractions from Semi-Leptonic

- Measure $f_s/(f_u+f_d)$ & $f_{\Lambda b}/(f_u+f_d)$
- Use $D^0X\mu^-\bar{\nu}$, $D^+X\mu^-\bar{\nu}$, $D_S^+X\mu^-\bar{\nu}$ and $\Lambda_c^+X\mu^-\bar{\nu}$
  - Cross feed between channels must be taken into account, for example $\bar{B}_s \to (D_s^{**} \to D^0K)X\mu^-\bar{\nu}$ and $\bar{B}^{0/-} \to D_sKX\mu^-\bar{\nu}$
  - We measure $D^0K^+X\mu^-\bar{\nu}$ and $D^0pX\mu^-\bar{\nu}$ in our data

$$\frac{f_s}{f_u+f_d} = \frac{N(\overline{B}_s^0)}{N(\overline{B}^0+B^-)} = \frac{n_{\rm corr}(\overline{B}_s^0 \to DX\mu^-\overline{\nu})}{n_{\rm corr}(B \to D^0X\mu^-\overline{\nu}) + n_{\rm corr}(B \to D^+X\mu^-\overline{\nu})} \frac{\tau_{B^-}+\tau_{\overline{B}^0}}{2\tau_{\overline{B}_s^0}}$$

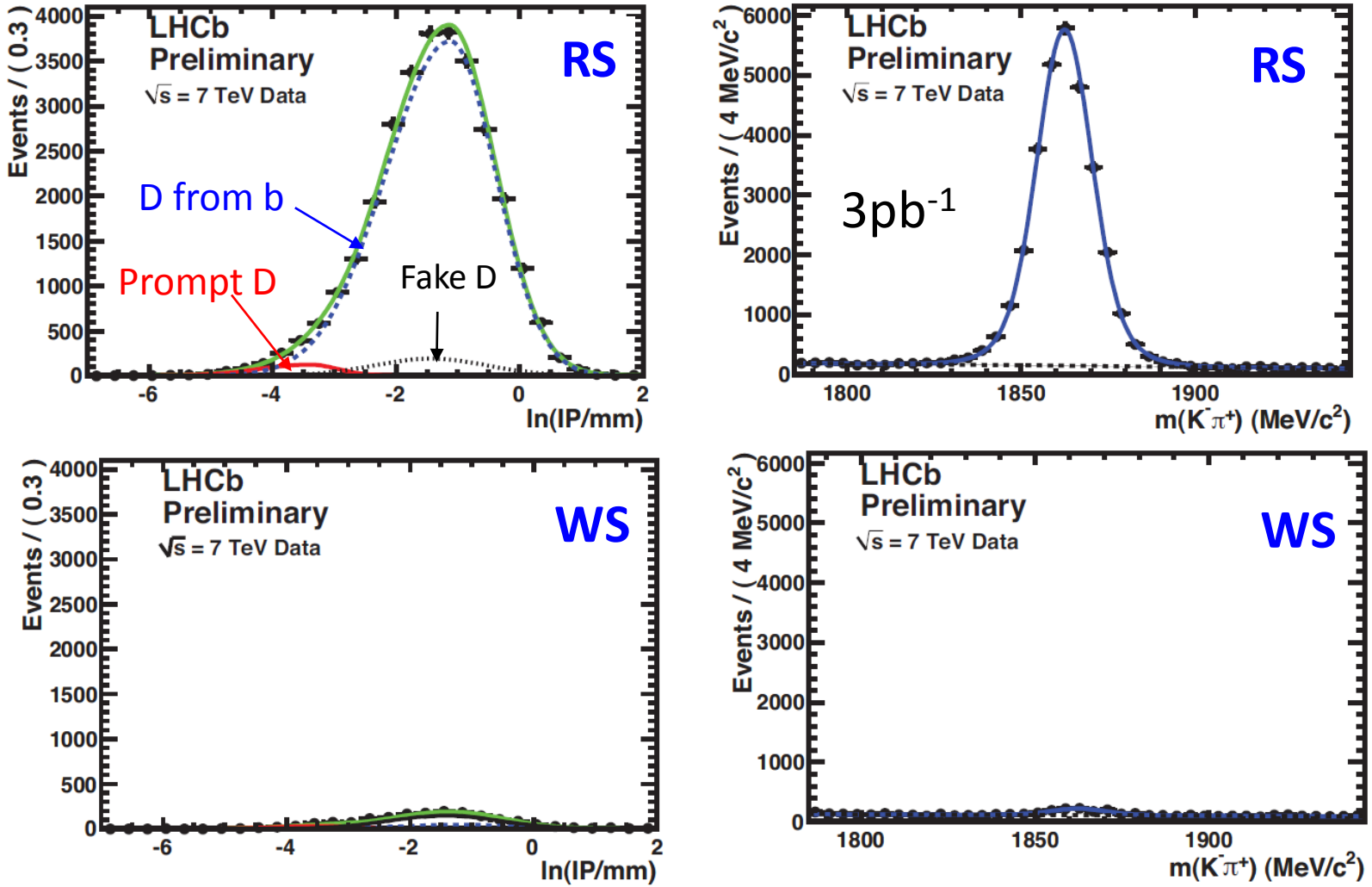
n_{corr}: efficiency, branching fraction and cross-feed corrected yield

Using $\Gamma_{SL}(B_s) = \Gamma_{SL}(B_d) = \Gamma_{SL}(B_u)$, known from theory to <1%

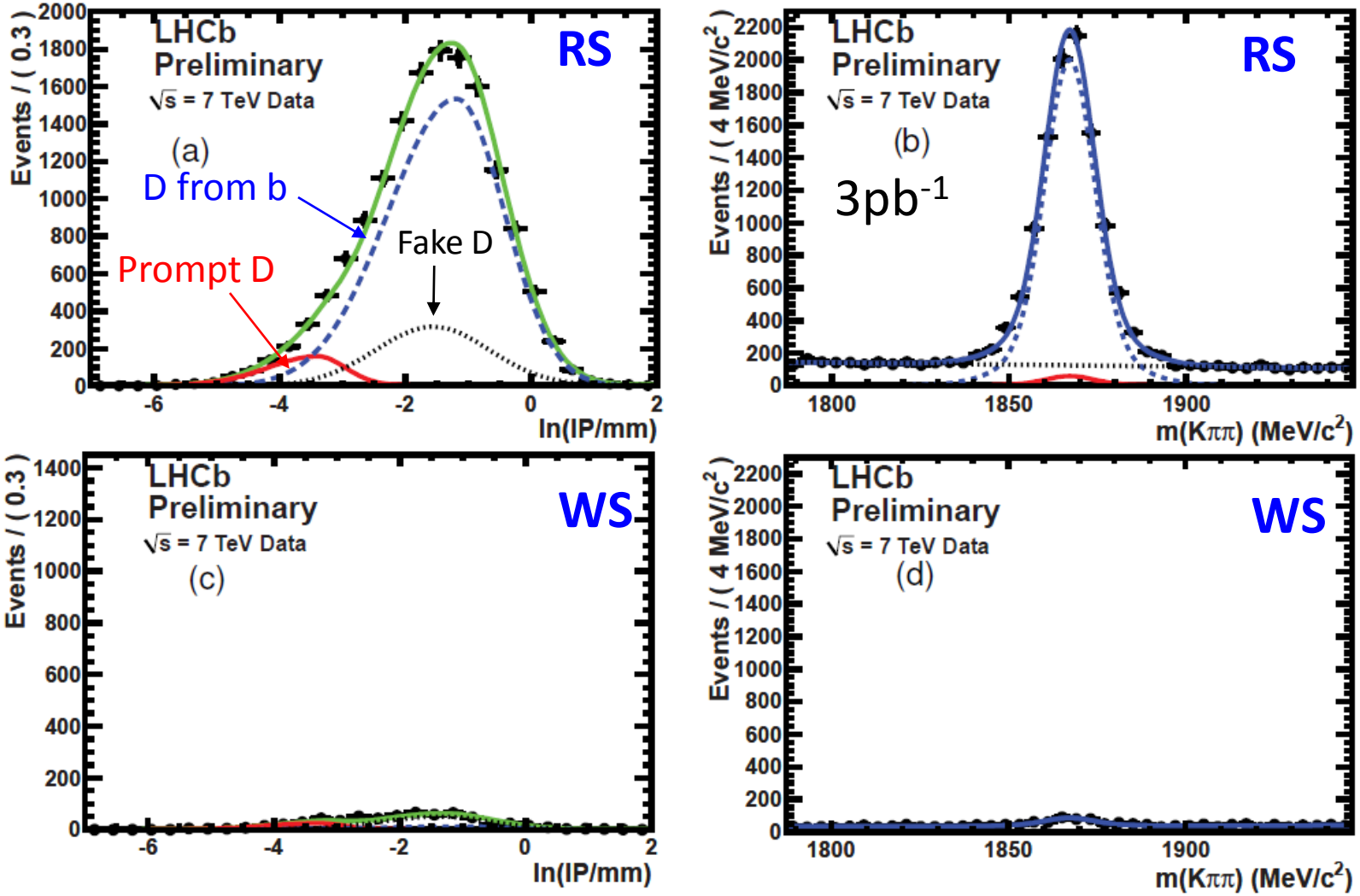
$\Gamma_{SL}(B_d)/\Gamma_{SL}(\Lambda_b) = 1.04 \pm 0.02$

- Measure the ratio as functions of η and p_T(charm+μ)

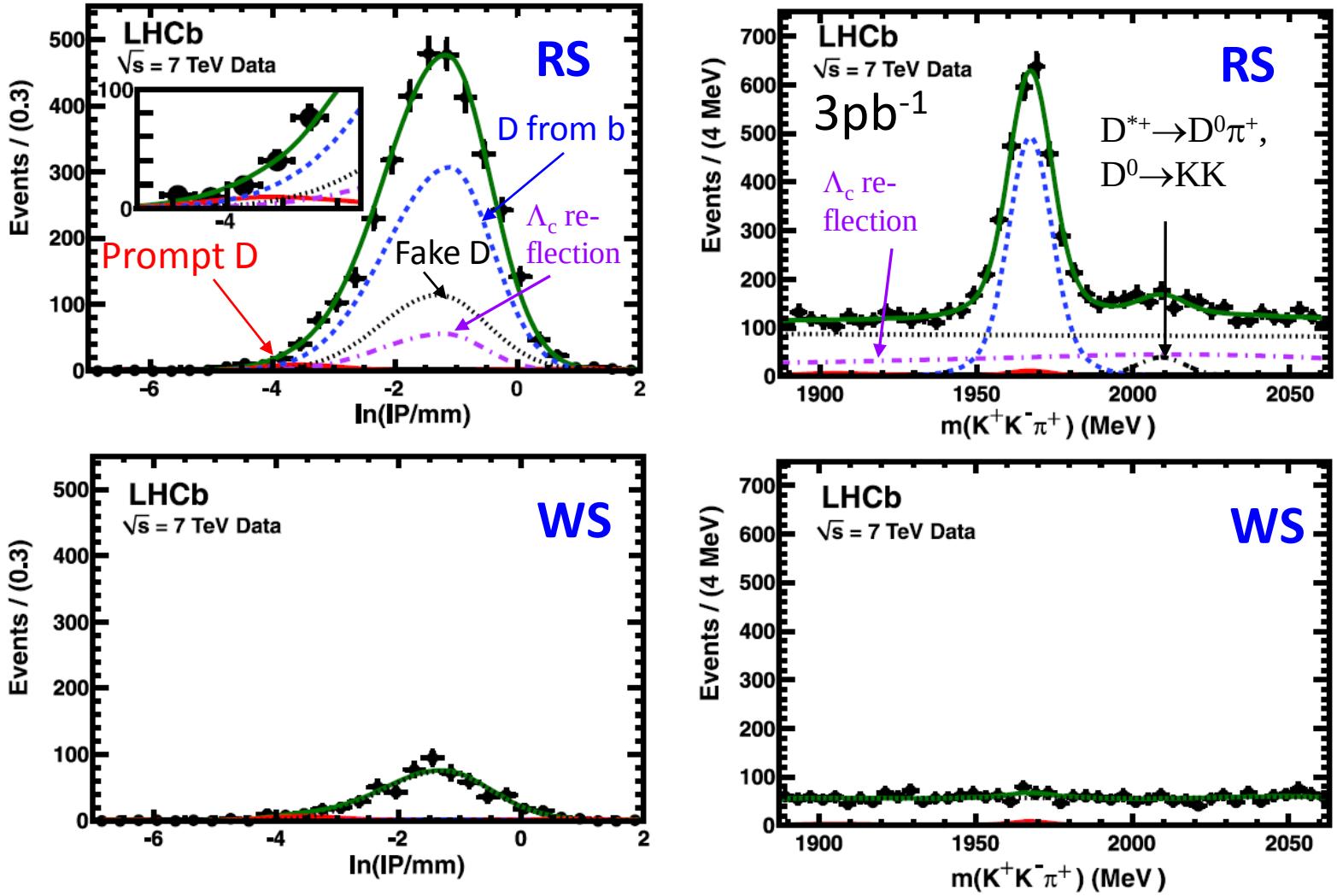
$b \to D^0 X \mu \bar{\nu}$



$b \to D^+ X \mu \bar{\nu}$



$b \to D_s^+ X \mu \bar{\nu}$



$\overline{B}_s \to D^0 K^+ X \mu^- \overline{\nu}$

- First observation of $\overline{B}_s \to D_{s2}^{*+} X \mu^- \overline{\nu}$
- Also measured the mass & width of D_{s2}^{*+}

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

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

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

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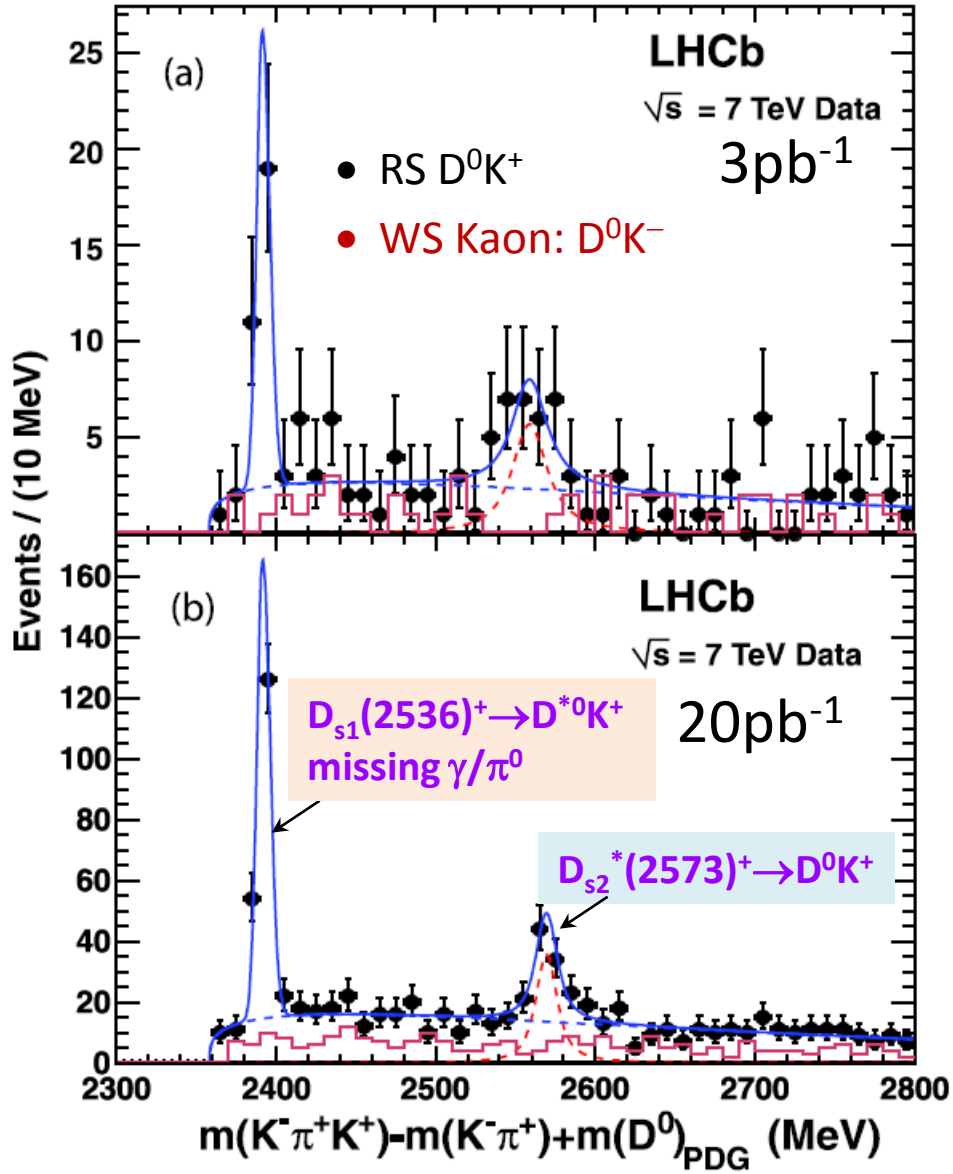
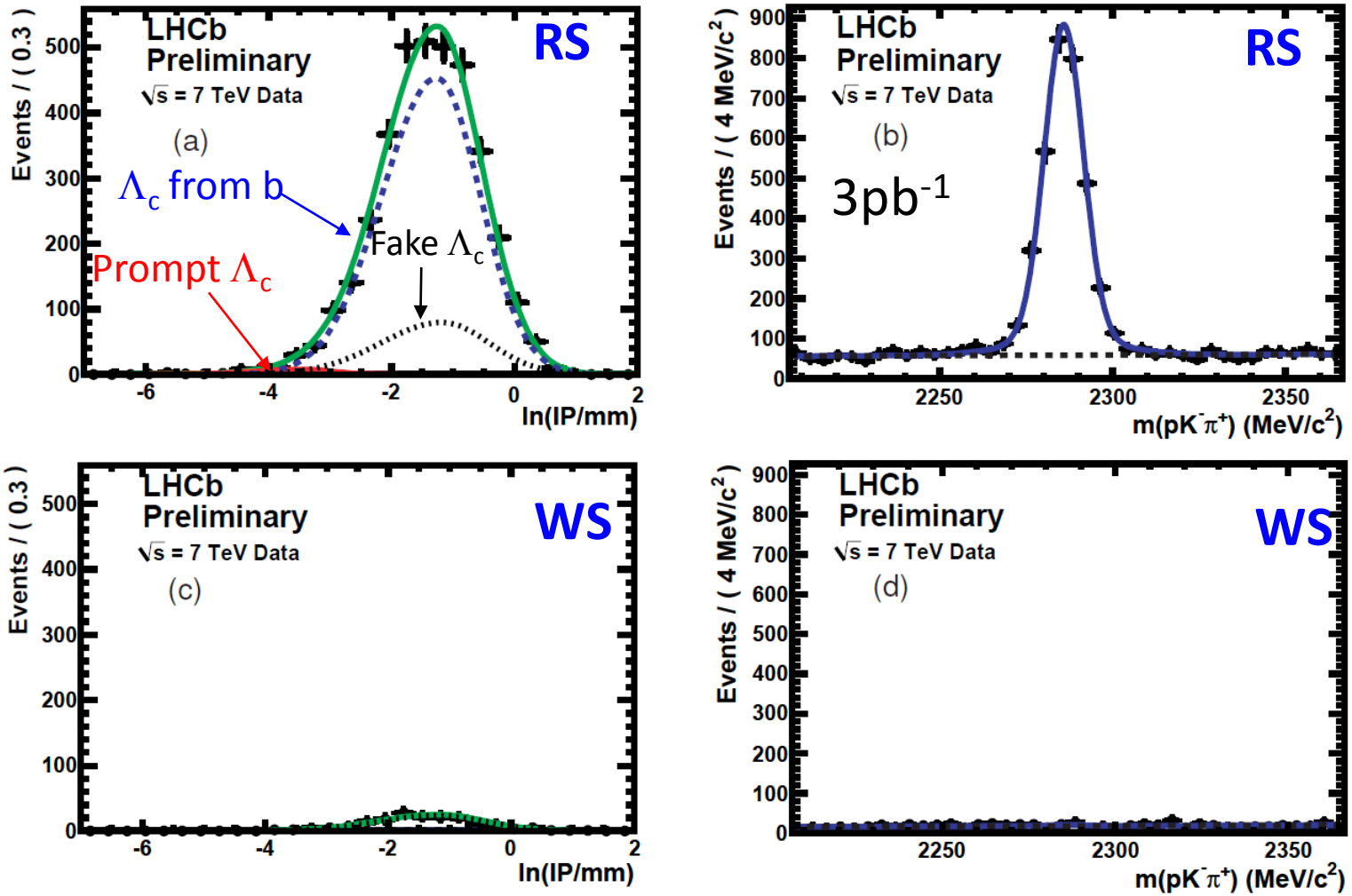


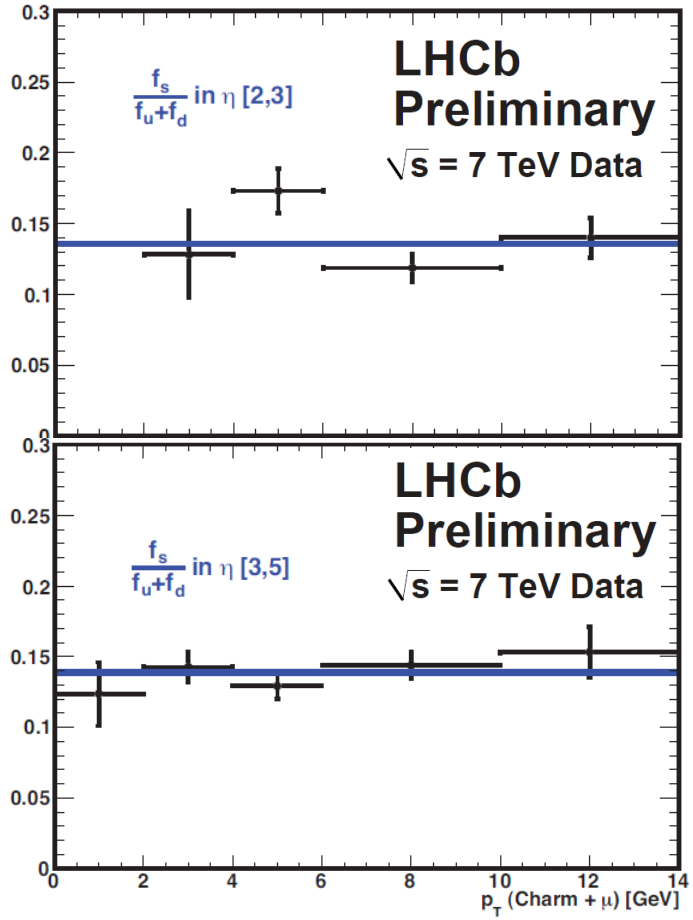
$b \to \Lambda_c^+ X \mu \nu$



$f_s/(f_u+f_d)$ from Semi-leptonic B decays

$$f_s/(f_u+f_d) = 0.136 \pm 0.004(\text{stat.})\ ^{+0.012}_{-0.011}\ (\text{sys.})$$ *preliminary*

3pb^{-1}



LEP: 0.128 ± 0.012 (HFAG)

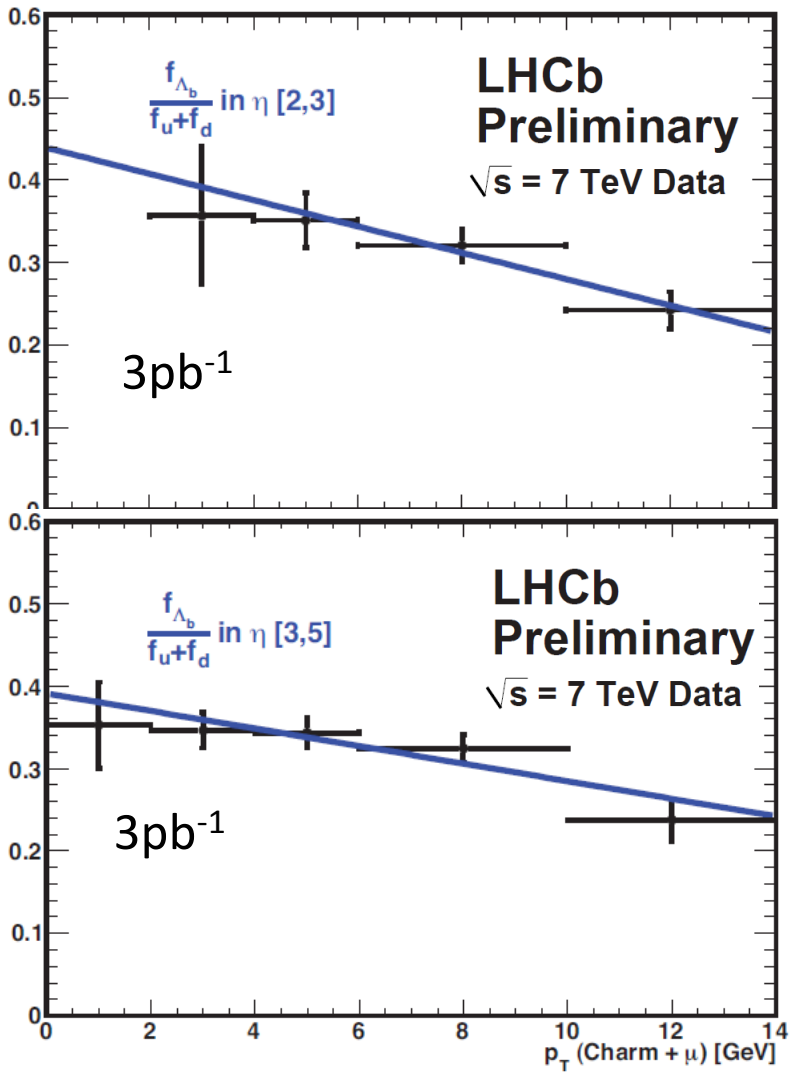
Tevatron: 0.135 ± 0.016 (CDF semi-lep)

Systematic uncertainties

Source	Error (%)
Bin by bin efficiency correction	1.0
Charm hadron branching fractions	5.5
Bs→DKμνX	+4.1 -1.1
MC modeling	3.0
B→DsKμνX	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

$f_s/(f_u+f_d)$ doesn't depend on η or p_T(charm+μ)

$f_{\Lambda b}/(f_u+f_d)$



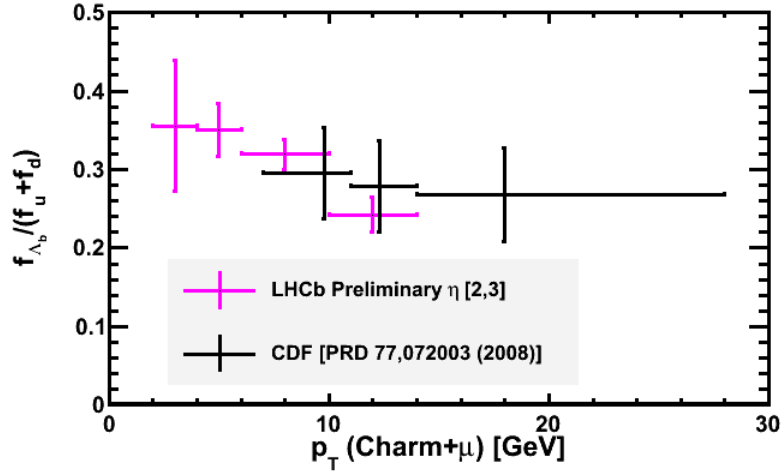
$f_{\Lambda b}/(f_u+f_d)$ not consistent with being flat over p_T

If fit with straight line, we get for $p_T < 14$ GeV

$$\frac{f_{\Lambda_b}}{f_u+f_d} = (0.401 \pm 0.019 \pm 0.106) - (0.0120 \pm 0.0025 \pm 0.0012) \times p_T / \mathrm{GeV}$$

Systematic error:

26% from $\mathcal{B}(\Lambda_c \to pK\pi)$, total 26.5%



CDF value $(0.281 \pm 0.012^{+0.011}_{-0.056}{}^{+0.128}_{-0.086})$ $\langle p_T \rangle_{CDF} \approx 14.1$ GeV

LEP value 0.112±0.031 $\langle p_T \rangle_{LEP} \approx 40$ GeV

f_s/f_d from hadronic decays

- $B^0 \to D^- K^+$ and $B_s^0 \to D_s^- \pi^+$ only have tree-diagram process, the ratio of their branching ratios is theoretically calculable [PRD 82, 034038 (2010)].
- Similar situation for $B^0 \to D^- \pi^+$ except additional W exchange process.
- We measure yield ratios to compute f_s/f_d

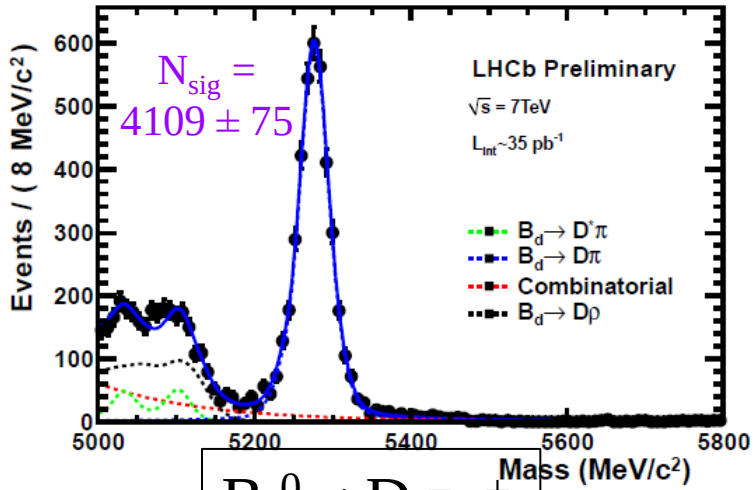
$$\frac{N(D_s^- \pi^+)}{N(D^- K^+)} = \frac{f_s}{f_d} \frac{\varepsilon(D_s^- \pi^+)}{\varepsilon(D^- K^+)} \frac{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}{\mathcal{B}(B^0 \to D^- K^+)}$$

$$\frac{N(D_s^- \pi^+)}{N(D^- \pi^+)} = \frac{f_s}{f_d} \frac{\varepsilon(D_s^- \pi^+)}{\varepsilon(D^- \pi^+)} \frac{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+)}$$

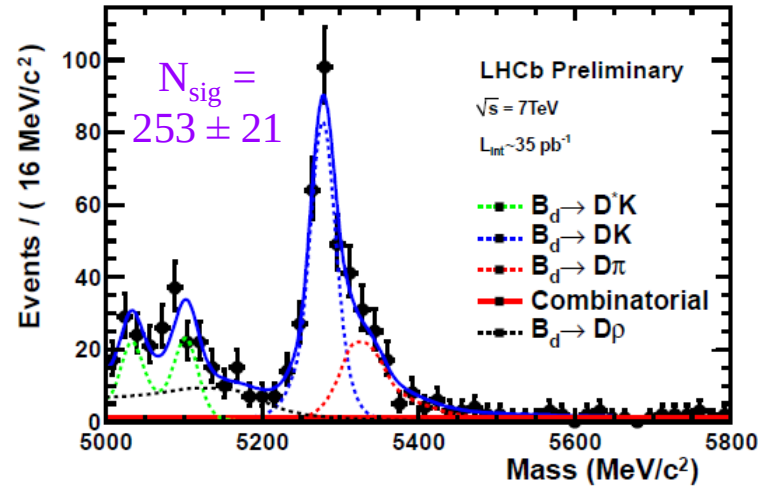
- The theoretical errors on $\mathcal{B}$'s are 6–10%

f_s/f_d from hadronic decays

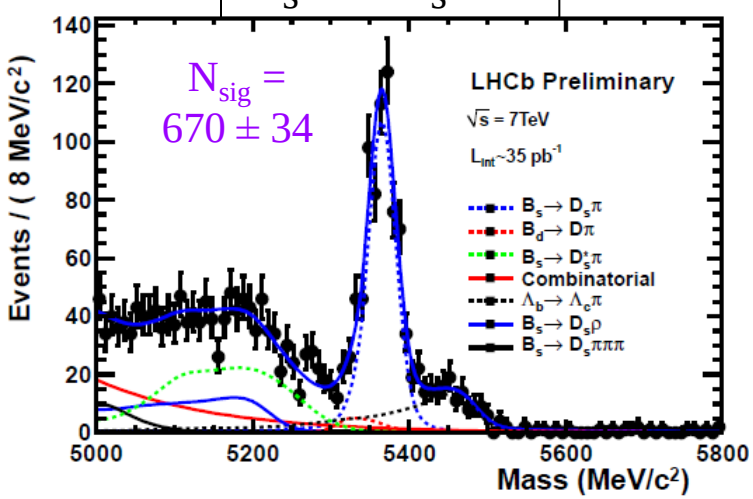
$B^0 \to D^- \pi^+$



$B^0 \to D^- K^+$



$B_s^0 \to D_s^- \pi^+$



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$$\frac{f_s}{f_d} = 0.242 \pm 0.024 \pm 0.018 \pm 0.016 \quad [D^-\pi^+]$$

$$= 0.249 \pm 0.013 \pm 0.020 \pm 0.025 \quad [D^-K^+]$$

$$= 0.245 \pm 0.017 \pm 0.018 \pm 0.018 \quad \text{[Average]}$$

(stat.) (syst.) (theo.)

World best: *preliminary*

$$\mathcal{B}(B^0 \to D^- K^+) = (2.02 \pm 0.17 \pm 0.12) \times 10^{-4}$$

Open Charm Production

- Cross sections of D^0, $D^*(2010)^+$, D^+ and D_S^+ in bins of p_T and y from $0<p_T<8$ GeV and $2<y<4.5$
  - Preliminary results on 1.8 nb^{-1}

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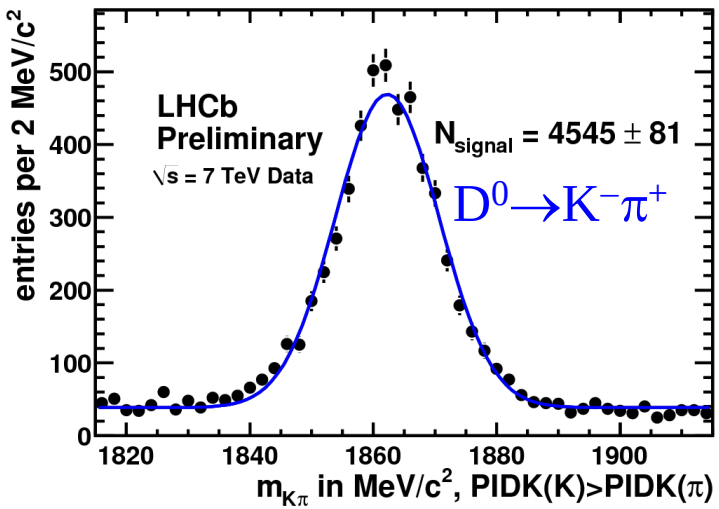
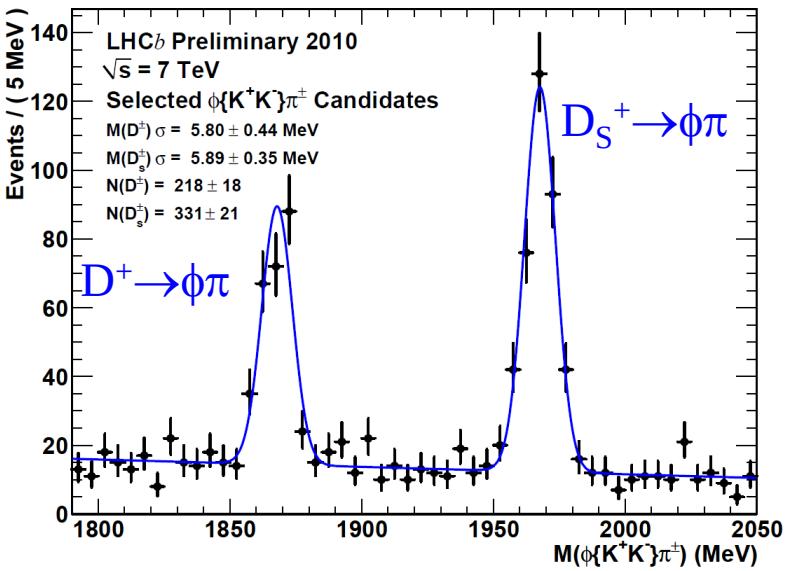
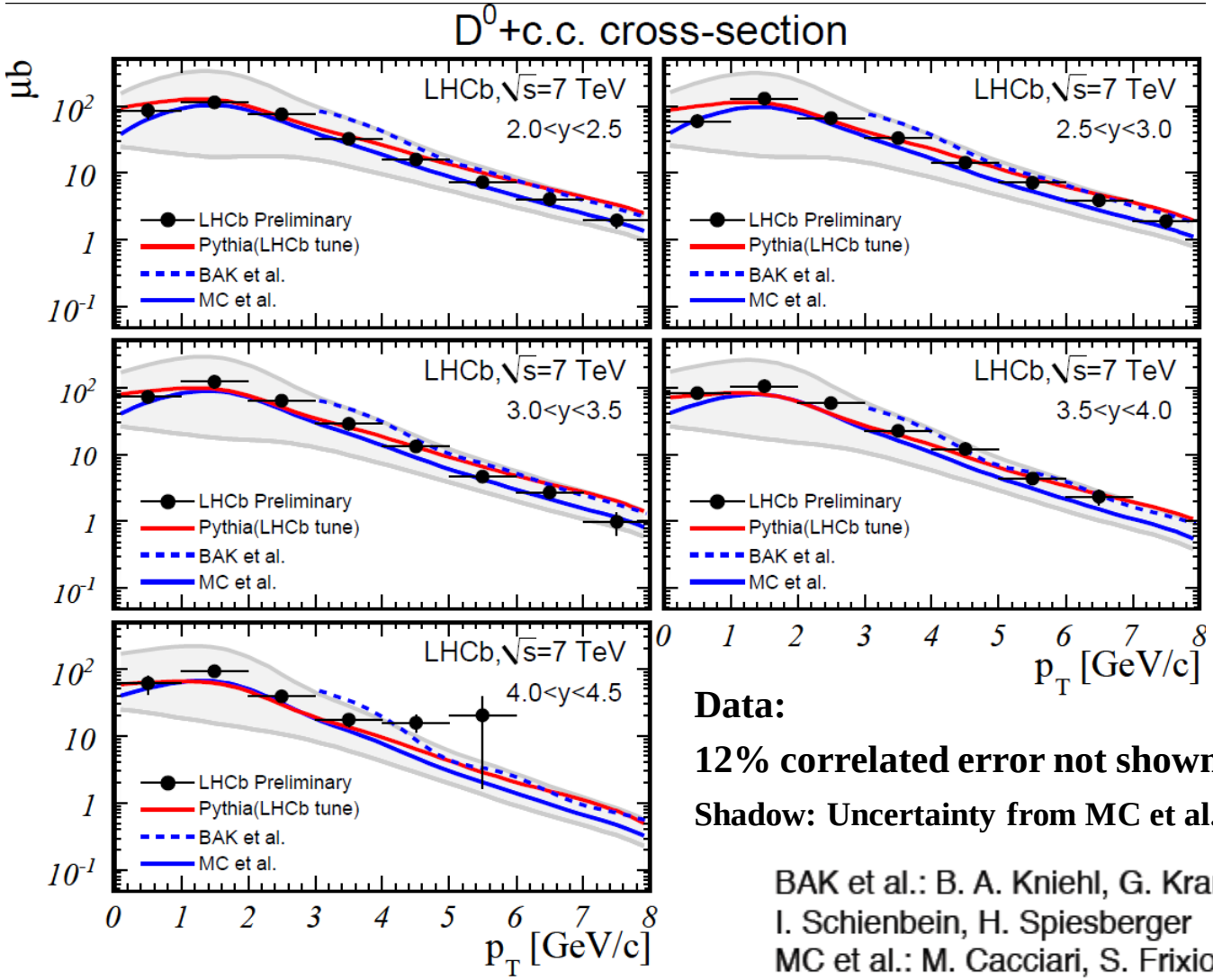
- Same approach as b-cross section analysis
  - Mass distributions determine fake D background and ln(IP) used to separate the background due to B decay.





D^0 cross section (1.8 nb^{-1})



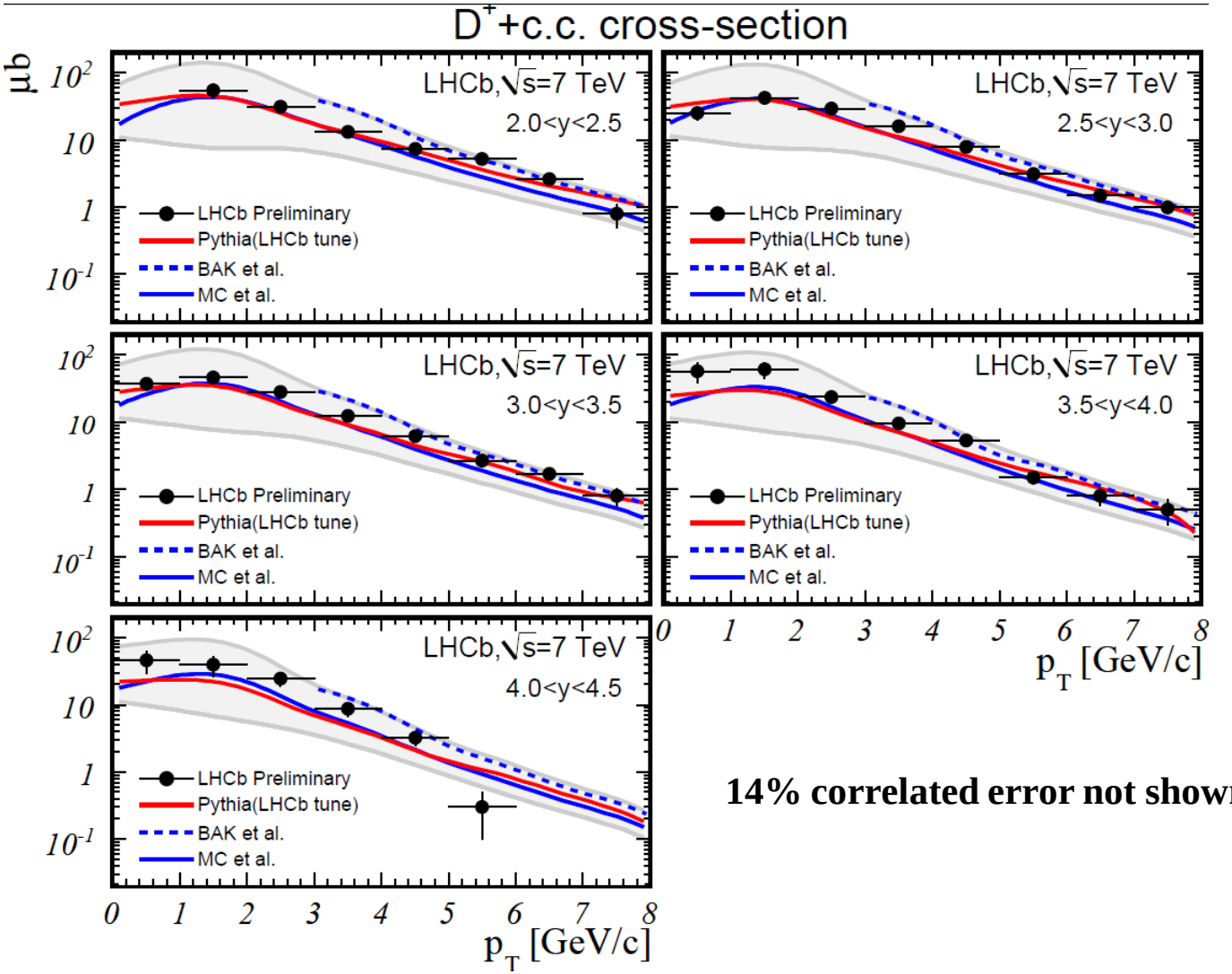
Data:

12% correlated error not shown

Shadow: Uncertainty from MC et al.

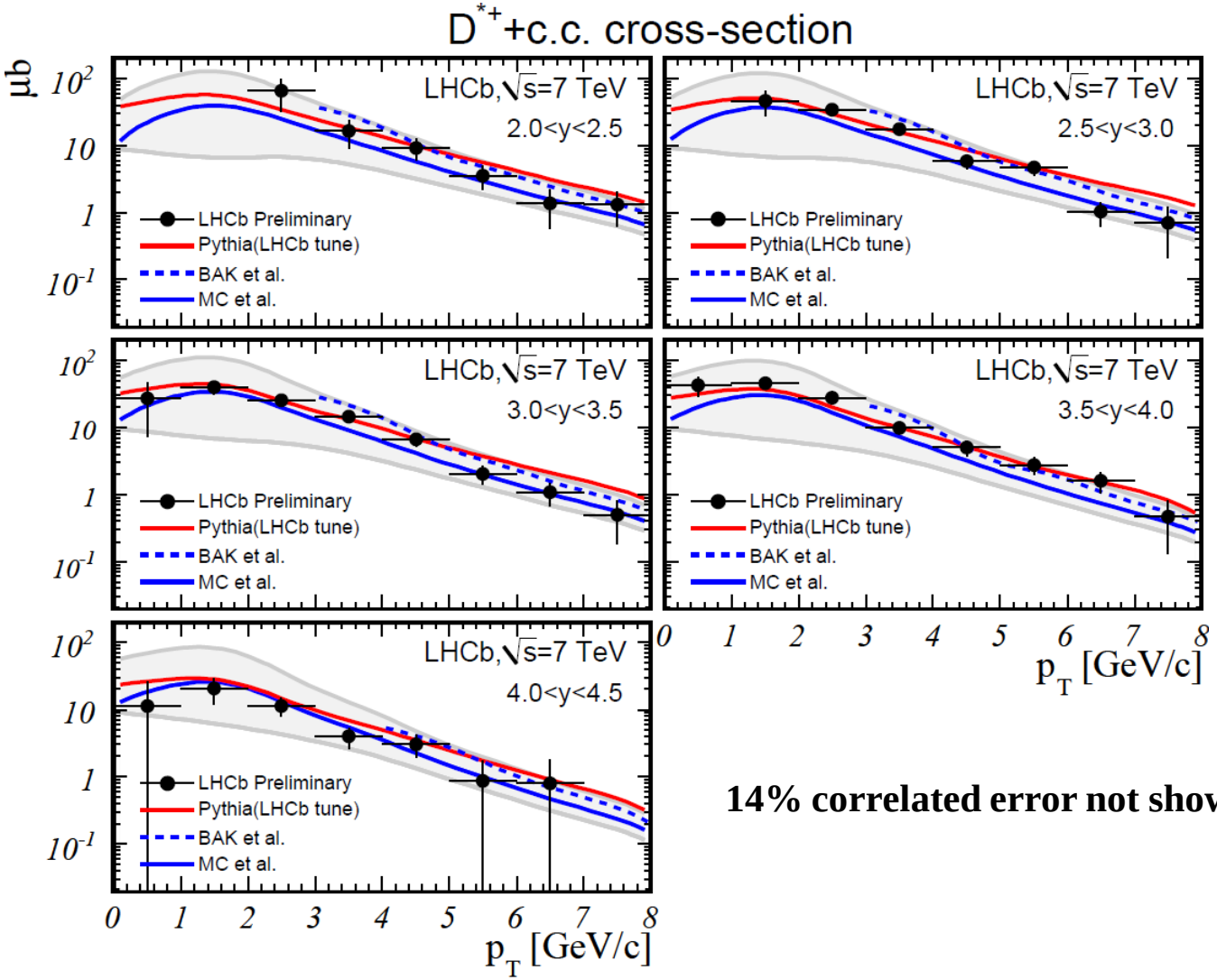
BAK et al.: B. A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger
MC et al.: M. Cacciari, S. Frixione, M. Mangano, P. Nason, G. Ridolfi.

D^+ cross section (1.8 nb^{-1})



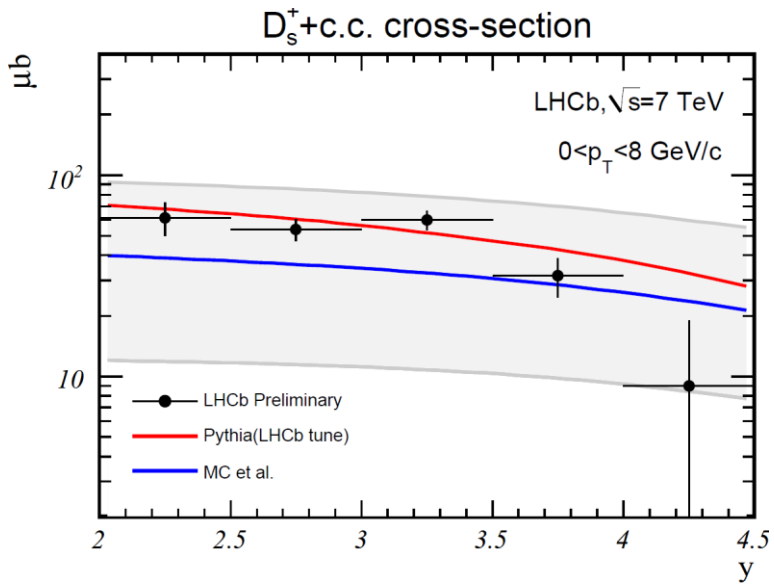
14% correlated error not shown

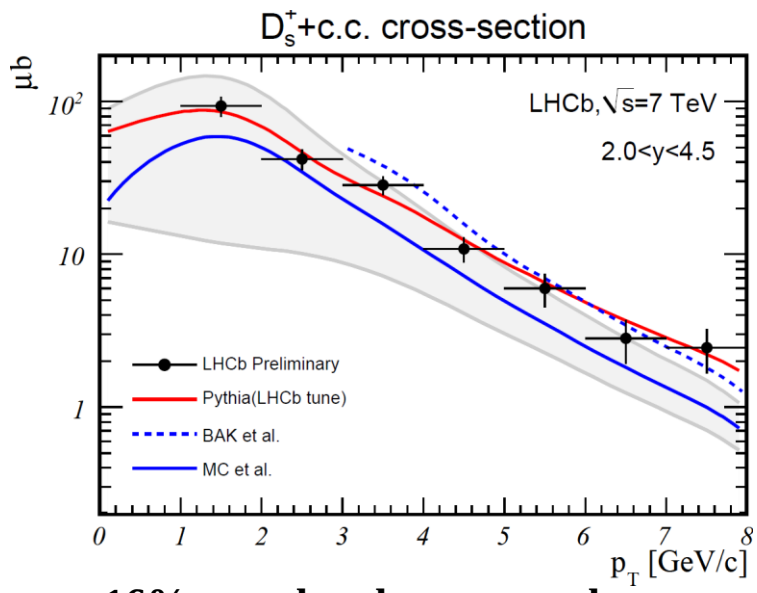
D^{*+} cross section (1.8 nb^{-1})



14% correlated error not shown

D_S^+ cross section (1.8 nb^{-1})





16% correlated error not shown

- The shape and absolute normalization are in good agreement with theoretical predictions
- Combining all *preliminary*

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$\sigma(pp \to c\bar{c}X) = 1.23 \pm 0.19$ mb (p_T<8 GeV, 2<y<4.5)

$\sigma(pp \to c\bar{c}X) = 6.10 \pm 0.93$ mb (full p_T and y with Pythia extrapolation)

Summary

- b cross section:
  - $\sigma(pp \to b\bar{b}X) = 284 \pm 20 \pm 49\ \mu b$ $\boxed{b \to D^0 X \mu^- \bar{\nu}}$ $15nb^{-1}$
  - $\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\ \mu b$ $\boxed{b \to J/\psi X}$ $5.1pb^{-1}$

The values increase by 19% if using Tevatron's B fractions

- Extra:
  - First observation $\bar{B}_s^0 \to D_{s2}^{*+} X \mu^- \bar{\nu}$
  - World best $\mathcal{B}(B^0 \to D^- K^+)$ *preliminary*
- Fragmentation fractions: *preliminary*

$$\frac{f_s}{f_d} = 0.272 \pm 0.008 \pm 0.024 \quad \text{[semi-leptonic]} \quad 3pb^{-1}$$

$$= 0.245 \pm 0.017 \pm 0.018 \pm 0.018 \quad \text{[hadronic]} \quad 35pb^{-1}$$

(stat.) (syst.) (theo.)

$$\frac{f_{\Lambda_b}}{f_u + f_d} = (0.401 \pm 0.019 \pm 0.106) - (0.0120 \pm 0.0025 \pm 0.0012) \times p_T / \text{GeV}$$

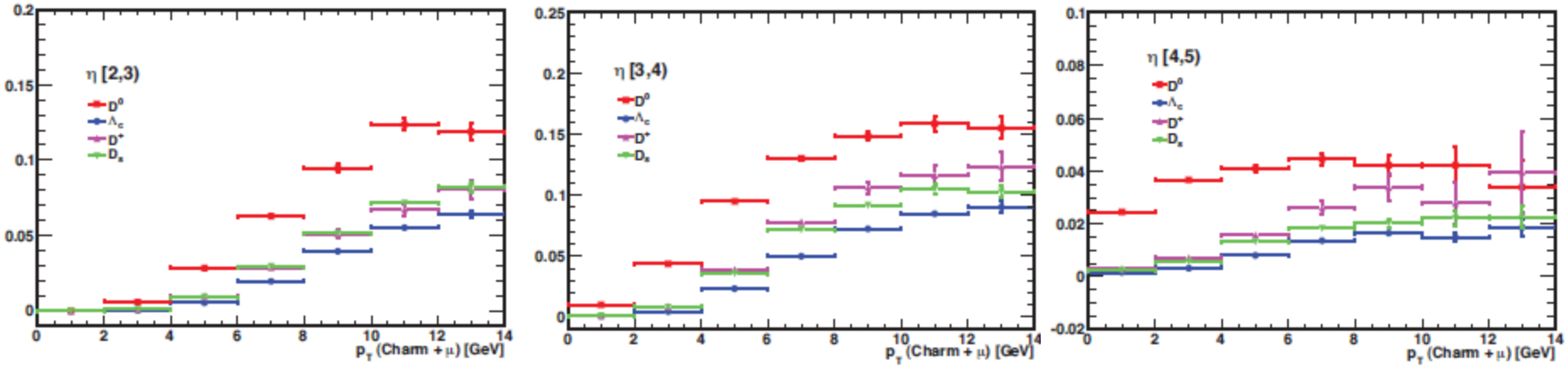
for $p_T < 14$ GeV $3pb^{-1}$

- Open charm cross section: *preliminary*
  - $\sigma(pp \to c\bar{c}X) = 6.10 \pm 0.93$ mb ~20× of b σ $1.8nb^{-1}$

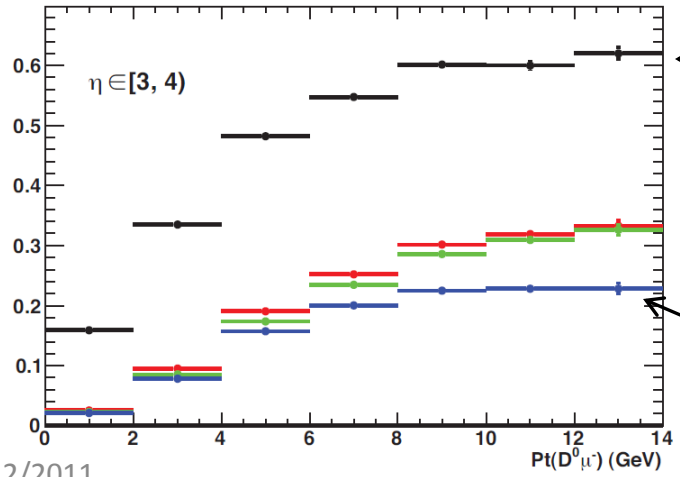
Backup

b fraction from Semi-Leptonic

- Efficiency



- Individual Efficiency ($D^0\mu^-$ as an example)



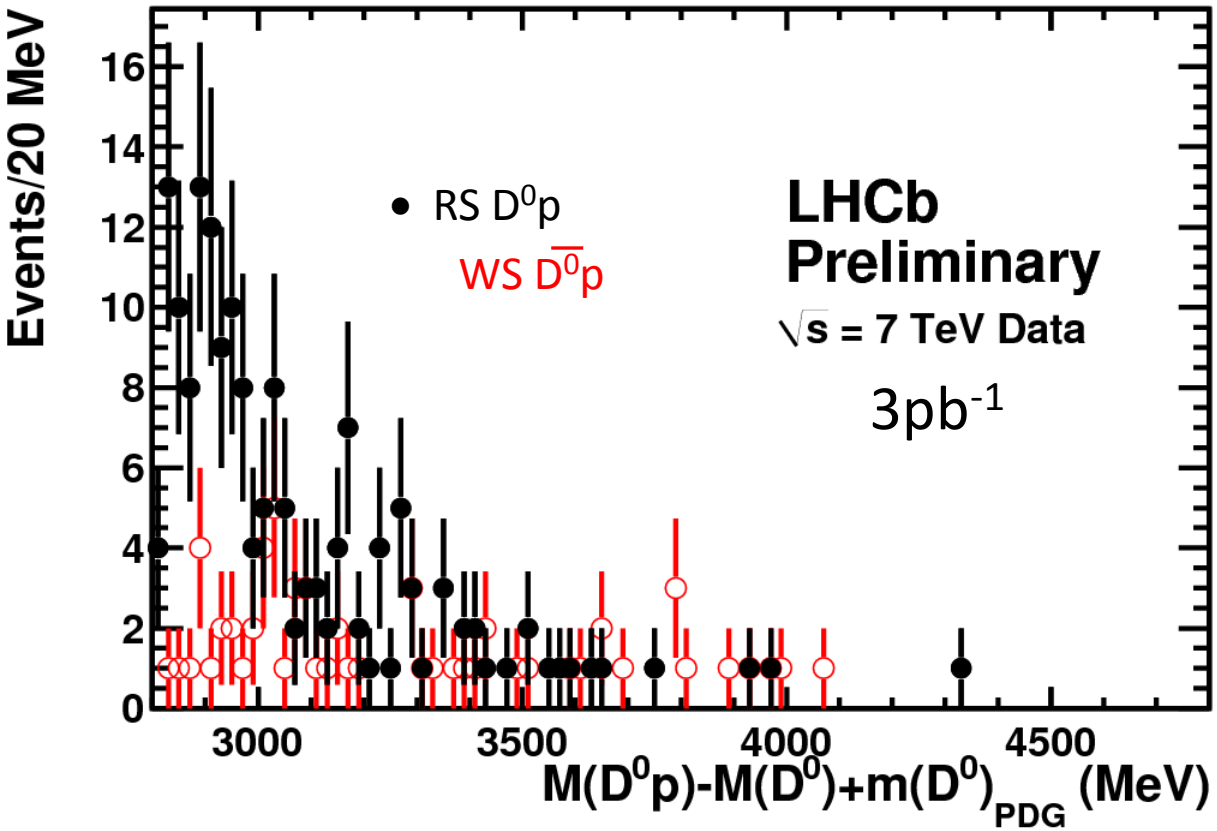
Acceptance + long track reconstruction

Muon Selection + Muon trigger

K and π p_T cuts

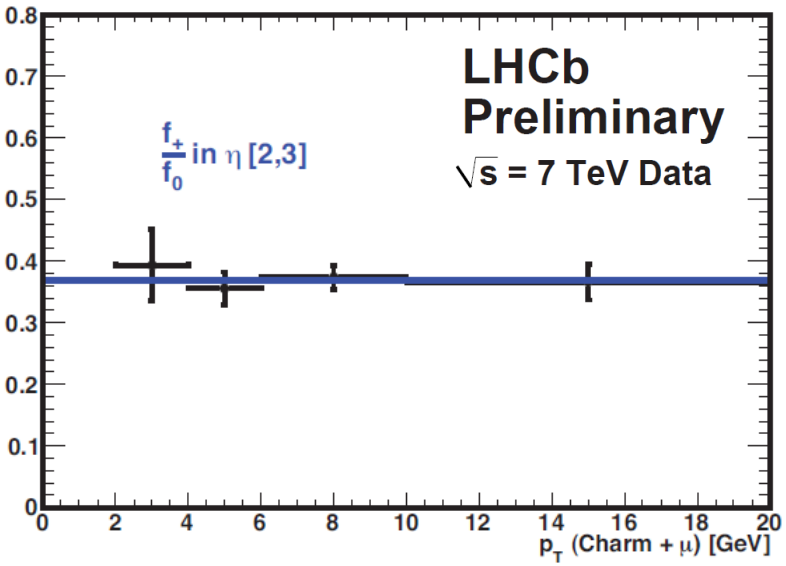
PID cuts

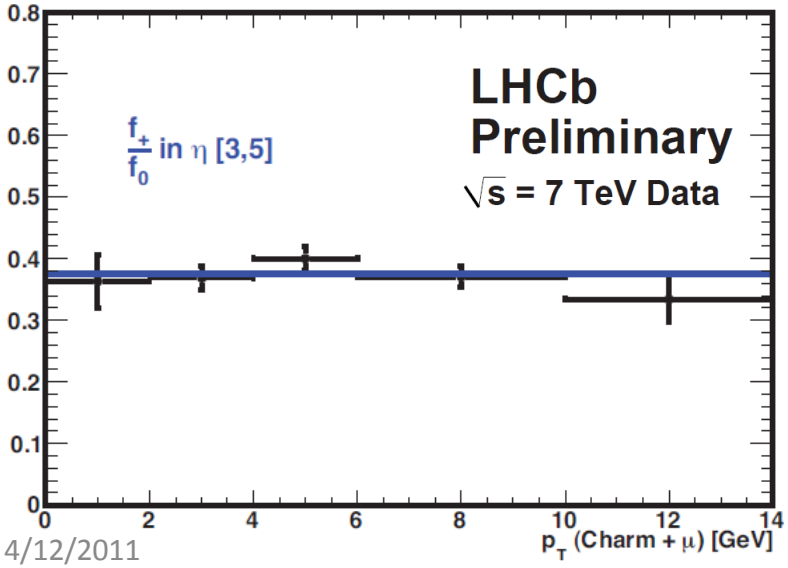
$\Lambda_b \rightarrow D0pX\mu^-\bar{\nu}$



Signal: 76 ± 17 ± 11

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



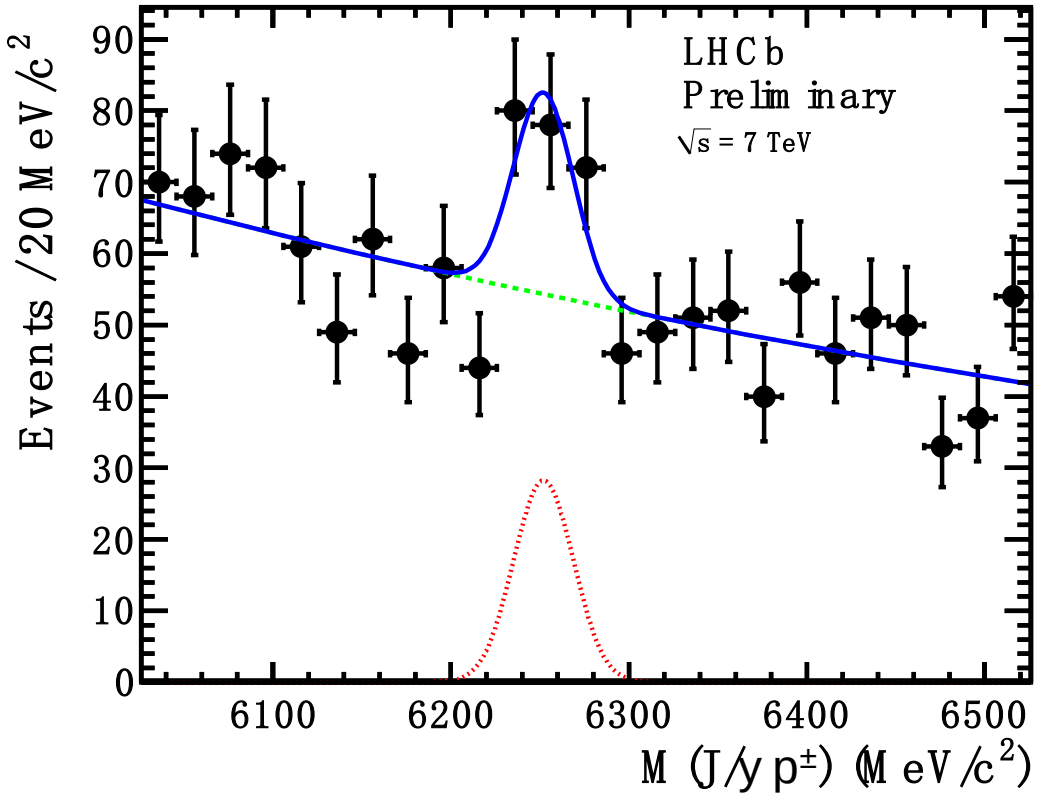


$$\frac{f_+}{f_0} = 0.373 \pm 0.006(\text{stat})$$

$$\pm 0.007(\text{eff}) \pm 0.014$$

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

$B_c \to J/\psi\ \pi^+$



N_{sig}=59±18

4.1σ

Main Systematics:

B_c lifetime 6.0%

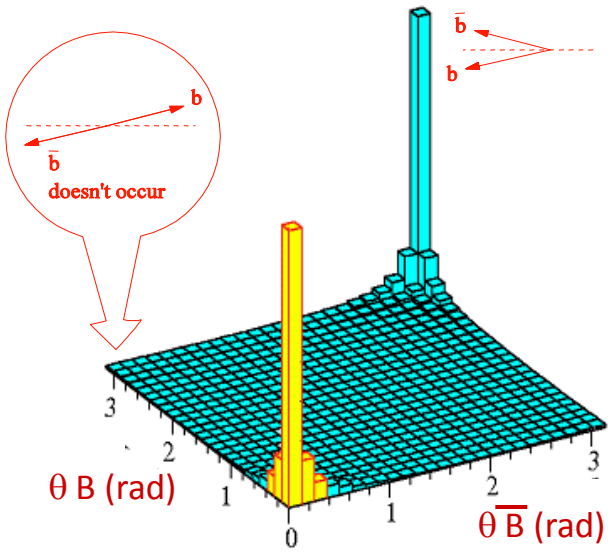
Total 7.9%

$$R_{c+} = \frac{\sigma(B_c^+) \times \mathscr{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+) \times \mathscr{B}(B^+ \to J/\psi K^+)} = (2.2 \pm 0.8 \pm 0.2)\%$$

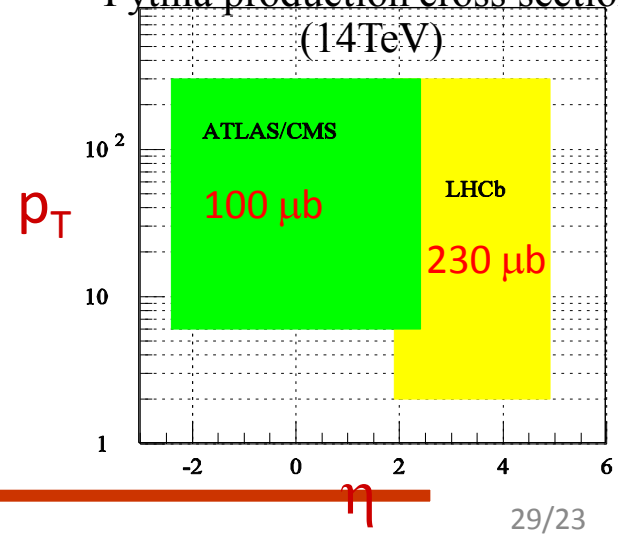
The LHCb Experiment

- LHCb is a dedicated B physics experiment at LHC
  - High beauty cross section expected: 200-500 μb @ 7-14 TeV
  - Access to all b-hadrons: B^+, B^0, B_s, B_c, b-baryons
- Luminosity limited to ~ $2x10^{32}$ to limit multiple interactions per bunch crossing
  - Expect to reach this in 2010
  - Expect ~ $2fb^{-1}$ and ~10^{12} bb pairs per nominal year @ 14 TeV (10^7 secs)
  - ~200 pb^{-1} in 2010 and $1fb^{-1}$ in 2011 @ 7 TeV
- LHCb acceptance optimised for forward $b\bar{b}$ production: Forward single arm spectrometer $1.9<\eta<4.9$
  - b-hadrons produced at low angle
  - Correlated $b\bar{b}$-production in same hemisphere

Production ∠ of B vs $\bar{B}$

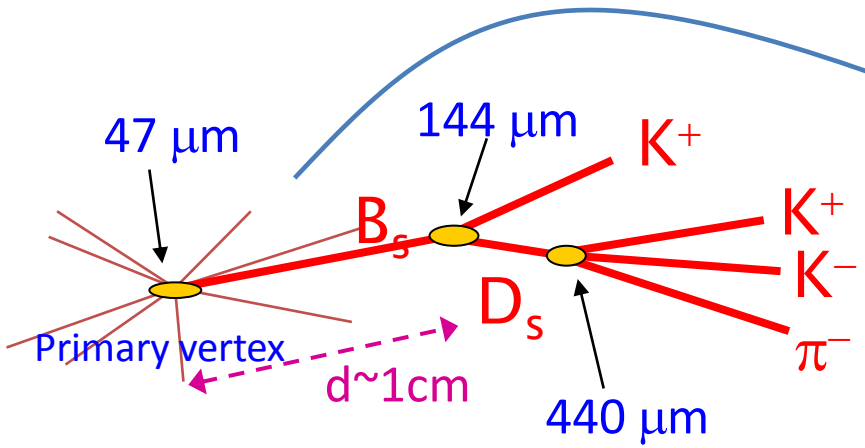


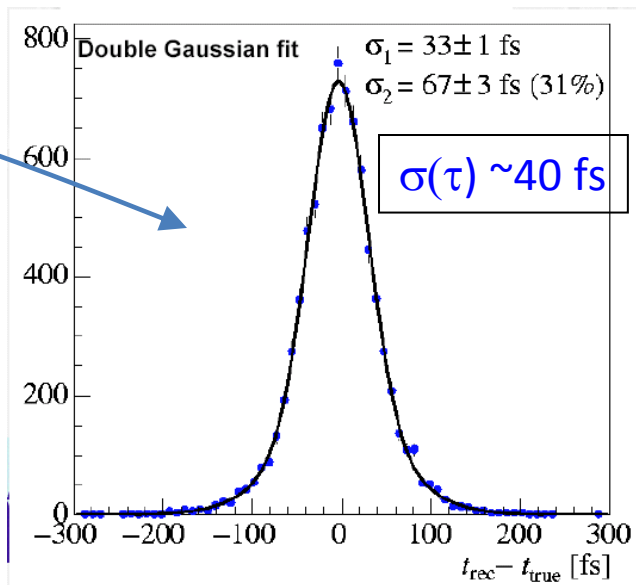
Pythia production cross section (14TeV)



B-Vertex Measurement

Example: $B_s \rightarrow D_s K$ (MC simulation)





Decay time resolution = 40 fs

Vertex Locator (Velo)

Silicon strip detector with

~ 5 μm hit resolution

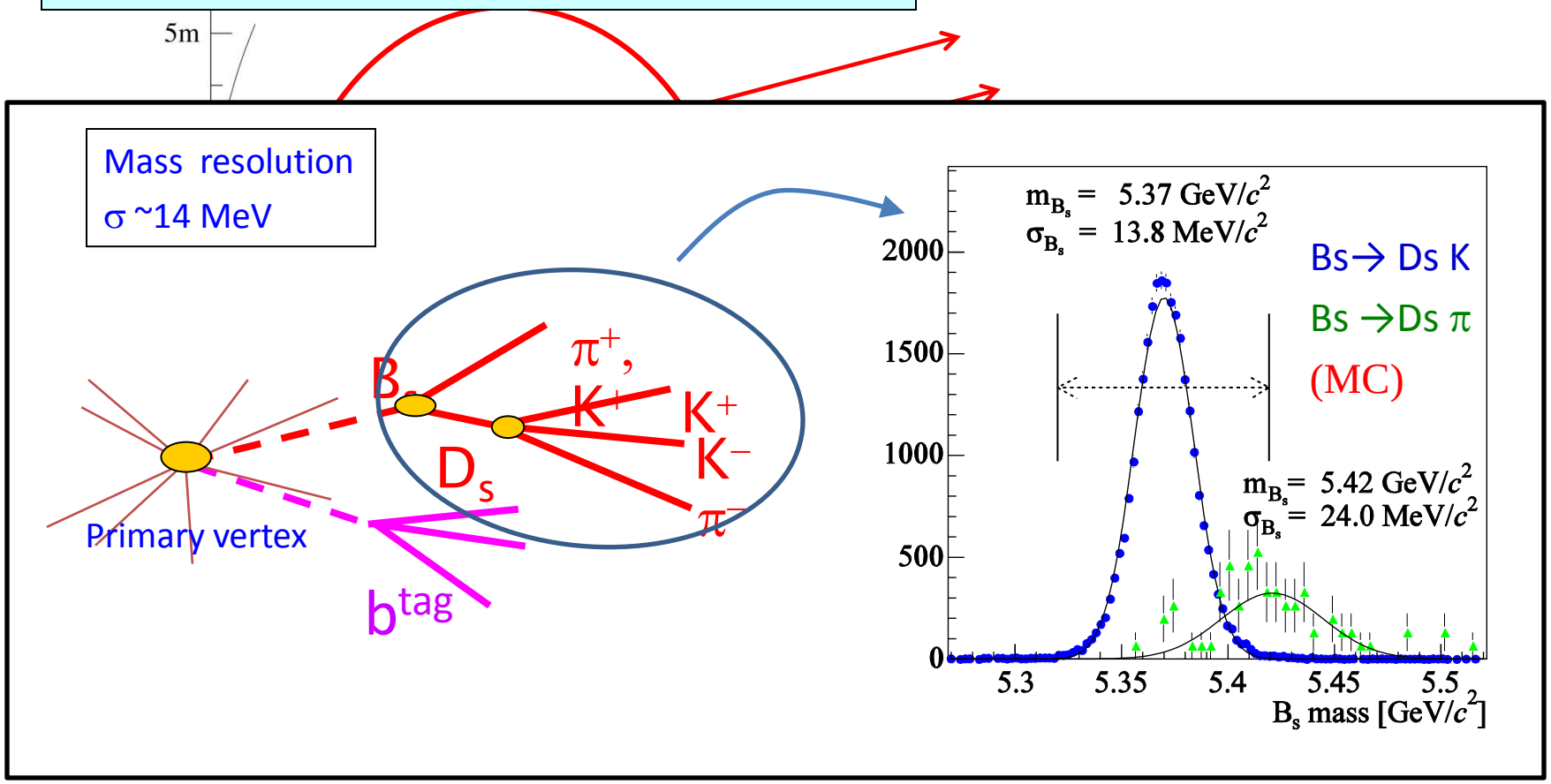
→ 30 μm IP resolution

Vertexing:

- trigger on impact parameter
- measurement of decay distance (time)

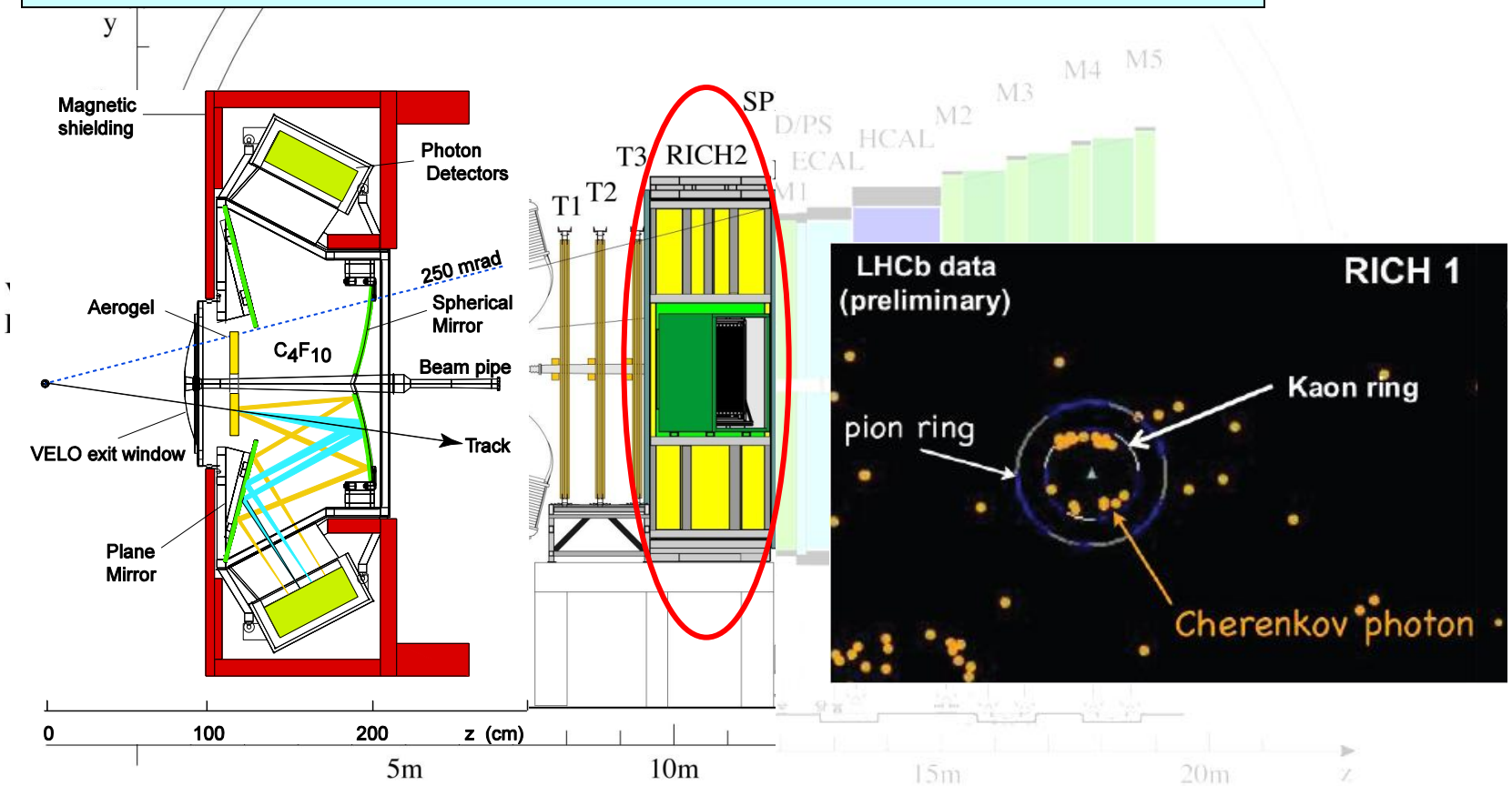
Momentum and Mass measurement

Momentum meas. + direction (VELO):
Mass resolution for background suppression



Hadron Identification

RICH: K/π identification using Cherenkov light emission angle

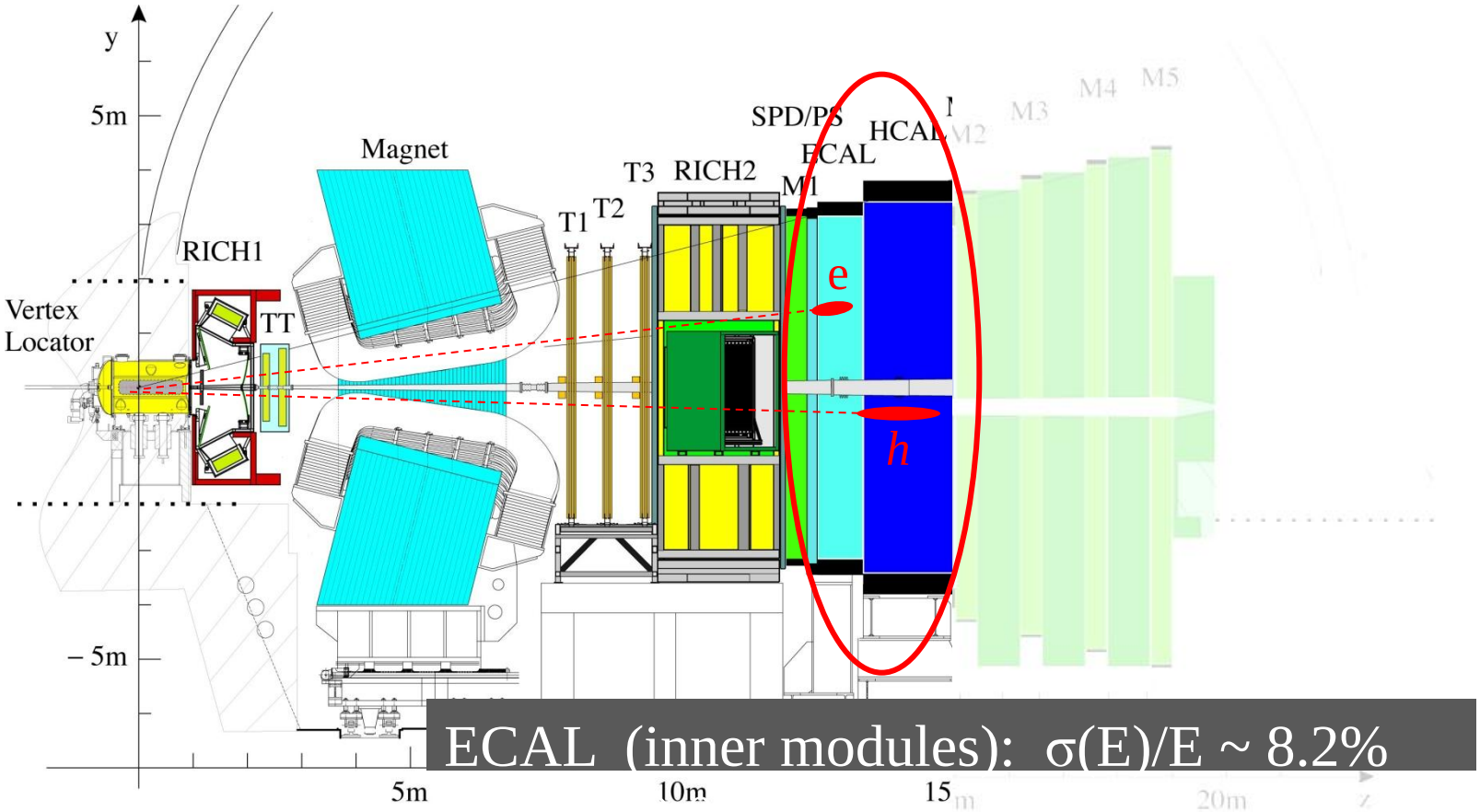


RICH1: 5 cm aerogel n=1.03

4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m3 CF_4 n=1.0005

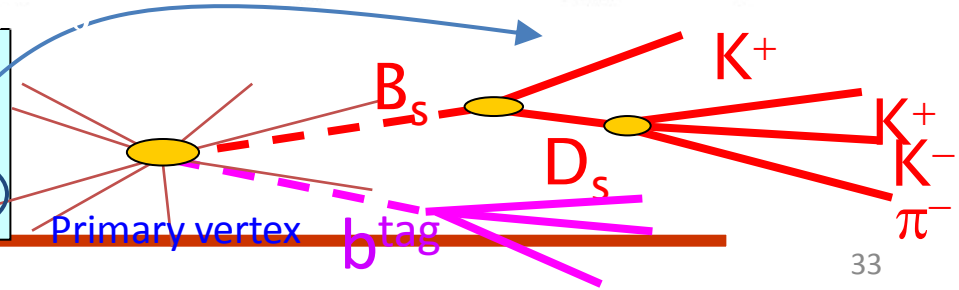
Particle identification and L0 trigger



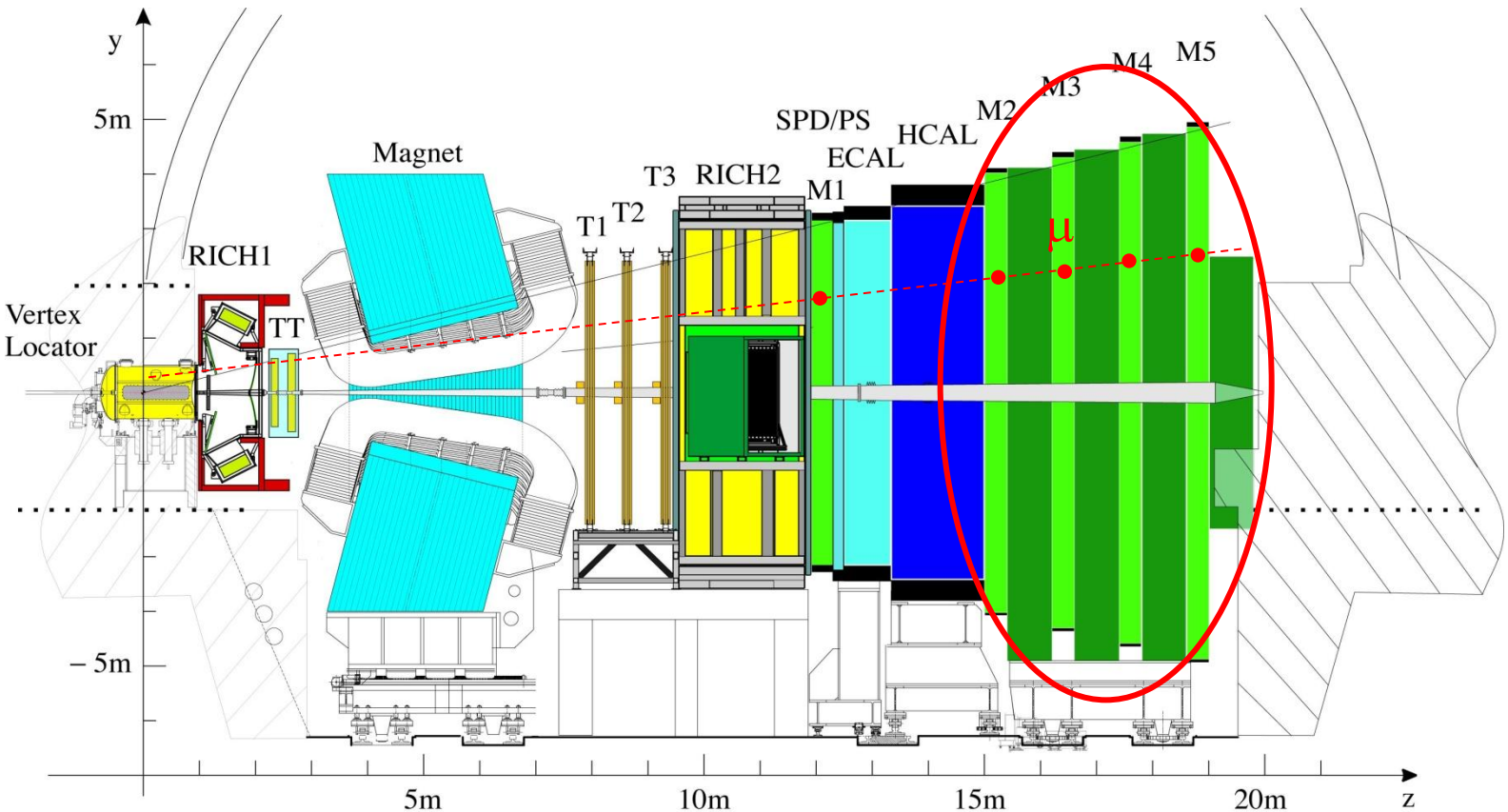
ECAL (inner modules): $\sigma(E)/E \sim 8.2\%$

Calorimeter system :

- Identify electrons, hadrons, π^0 ,γ
- Level 0 trigger: high E_T electron and hadron



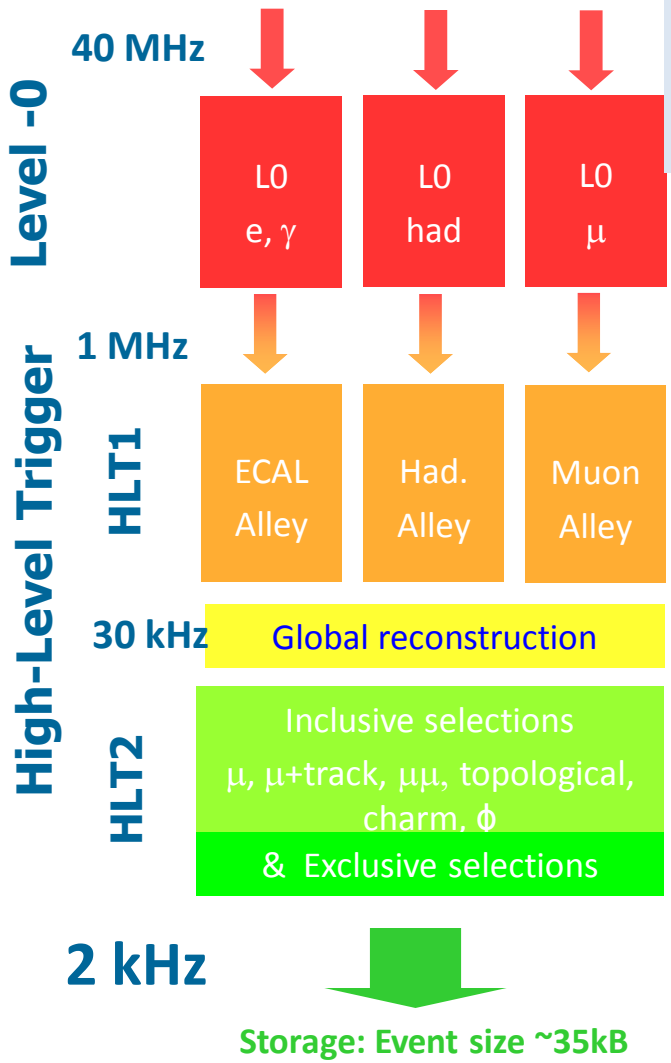
Muon System



- Physics: $B_s \to J/\psi\ \phi$, $B_s \to \mu^+\mu^-$, etc.
- Level 0 trigger: fast information from high P_t muons
- OS flavour tagging

Trigger

Trigger is crucial as $\sigma_{b\bar{b}}$ is less than 1% of total inelastic cross section and B decays of interest typically have $B < 10^{-5}$



- **Hardware level (L0)**

  Search for high-p_T μ, e, γ and hadron candidates

- **Software level (High Level Trigger, HLT)**

  Farm with $\mathcal{O}$(2000) multi-core processors

  HLT1: Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts

  HLT2: B reconstruction + selections

	ε(L0)	ε(HLT1)	ε(HLT2)
Electromagnetic	70 %	> ~80 %	> ~90 %
Hadronic	50 %		
Muon	90 %		

Very high efficiency

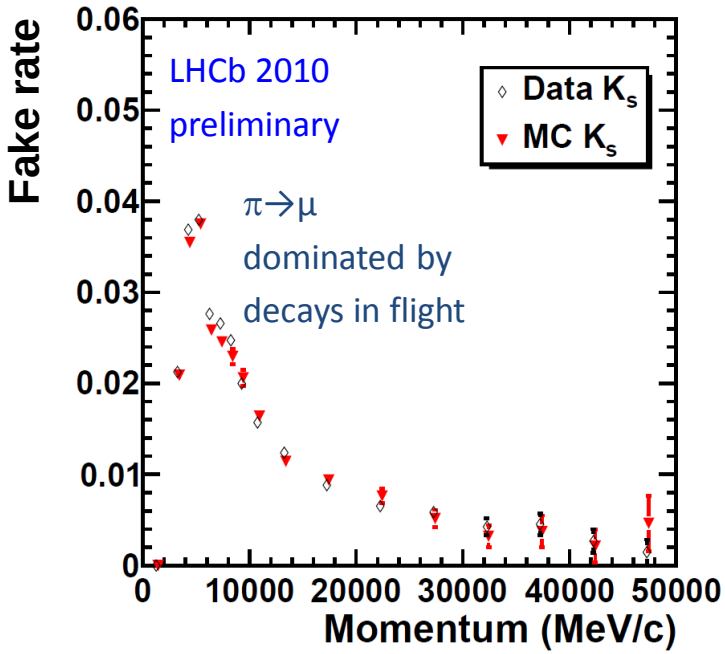
Muon identification studies

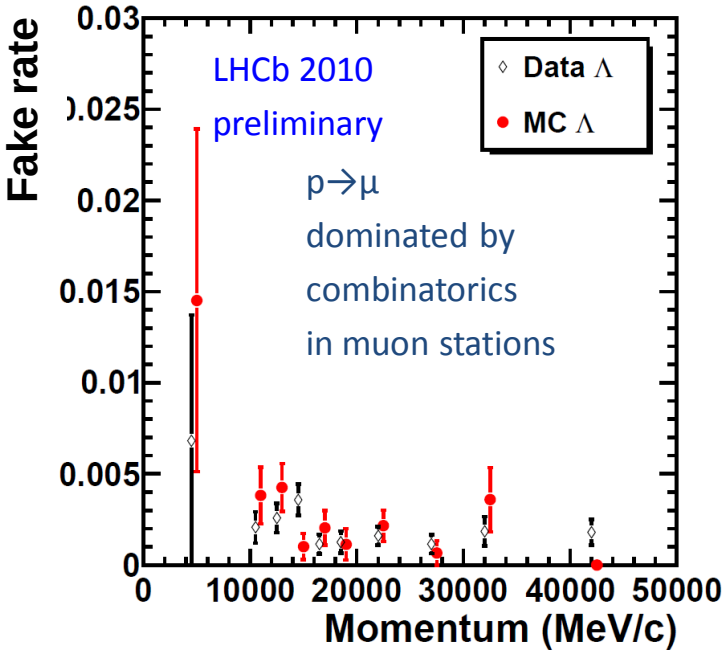
Plan to use $J/\psi \rightarrow \mu^+\mu^-$ to measure muon ID efficiency

Muon ID efficiency: ~94% (MC)

Do not have enough J/ψ yet.

Fake Rate of $\pi \rightarrow \mu$ and $p \rightarrow \mu$





Diagrams of B→DP

$$\mathrm{BR}(\bar{B}_q^0 \to D_q^+ P^-) = \frac{G_F^2 (m_{B_q}^2 - m_{D_q}^2)^2 |\vec{q}| \tau_{B_q}}{16\pi m_{B_q}^2}$$

$$\times |V_q^* V_{cb}|^2 \left[f_P F_0^{(q)}(m_P^2) \right]^2 |a_1(D_q P)|^2$$

PRD 82, 034038 (2010)

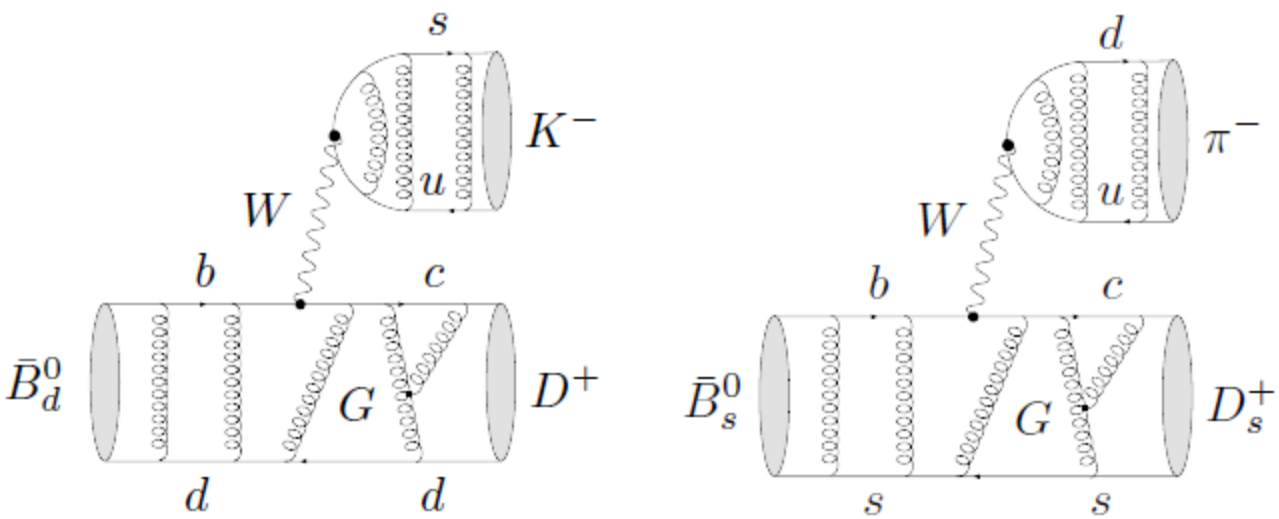


FIG. 1: The $\bar{B}_d^0 \to D^+ K^-$ and $\bar{B}_s^0 \to D_s^+ \pi^-$ decay topologies.

Inputs for f_s/f_d in hadronic

$B_d \to DK$ / $B_s \to D_s\pi$:

- Same 4 particles in the final state
- At present theoretical error of order 7%

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

$B_d \to D\pi$ / $B_s \to D_s\pi$:

- Similar final state
- Theoretical error of order 9% (extra contribution from *exchange diagram)*

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

Ratio of non-factorizable effects

$$\mathcal{N}_a \equiv \left|\frac{a_1(D_s\pi)}{a_1(DK)}\right|^2 = 1.00 \pm 0.02,$$

PhysRevD.83.014017,2011

Ratio of form factors

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

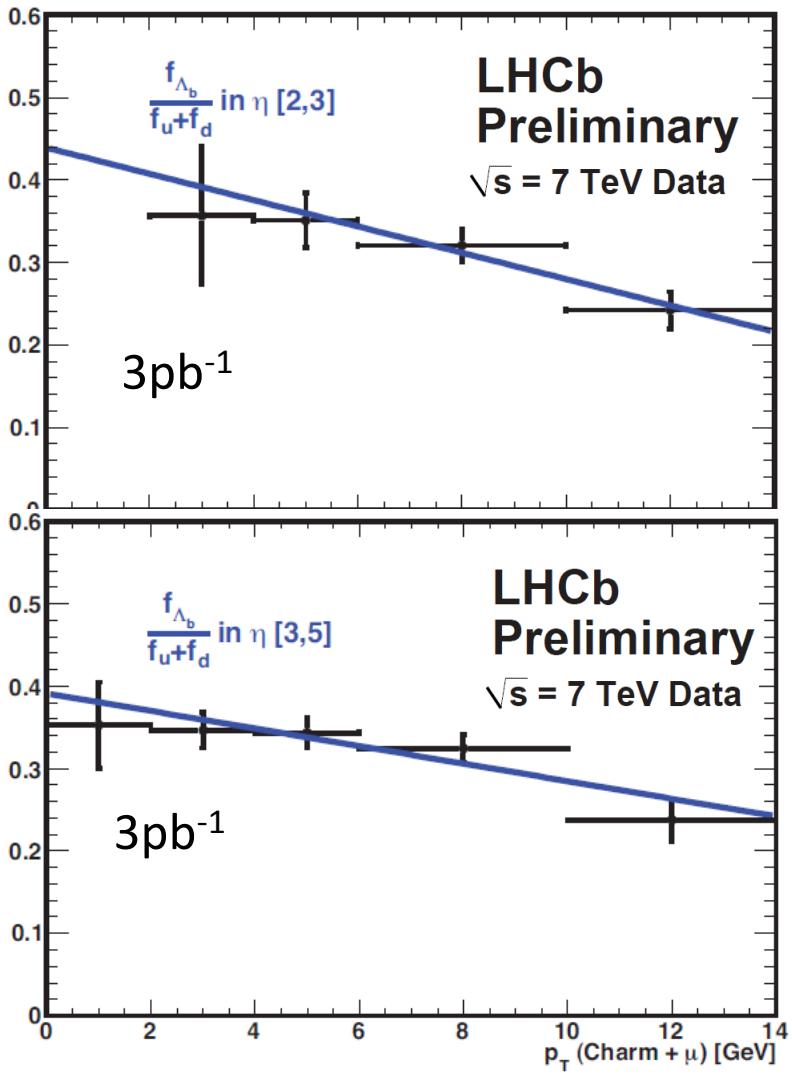
Phys. Rev., D49:238–246, 1994.

(hope for more accurate lattice result this year)

Extra correction from the exchange diagram

$$\mathcal{N}_E = 0.966 \pm 0.056$$

$f_{\Lambda b}/(f_u+f_d)$



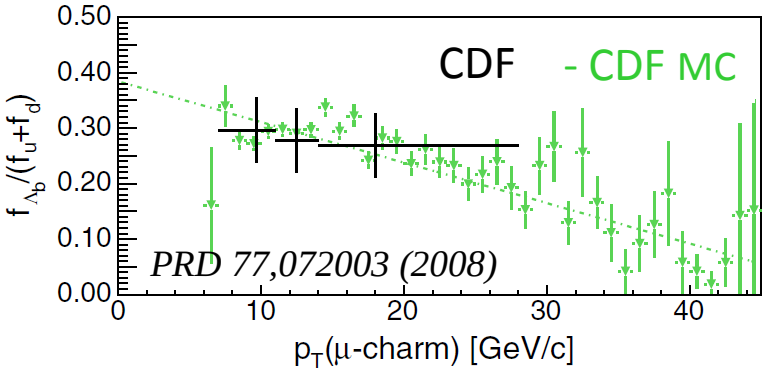
$f_{\Lambda b}/(f_u+f_d)$ not consistent with being flat over p_T

If we fit with straight lines, we get

$$\frac{f_{\Lambda_b}}{f_u+f_d} = (0.401 \pm 0.019 \pm 0.106) - (0.0120 \pm 0.0025 \pm 0.0012) \times p_T / \text{GeV}$$

Systematic error:

26% from $\mathcal{B}(\Lambda_c \to pK\pi)$, total 26.5%



CDF value $(0.281 \pm 0.012^{+0.011}_{-0.056}{}^{+0.128}_{-0.086})$ $\langle p_T \rangle_{CDF} \approx 14.1\,\text{GeV}$

LEP value 0.112±0.031 $\langle p_T \rangle_{LEP} \approx 40\,\text{GeV}$