# Measurement of the Ratio $\mathcal{B}(\Lambda_b \to \Lambda_c \mu \upsilon)/\mathcal{B}(\Lambda_b \to \Lambda_c \pi)$ at CDF

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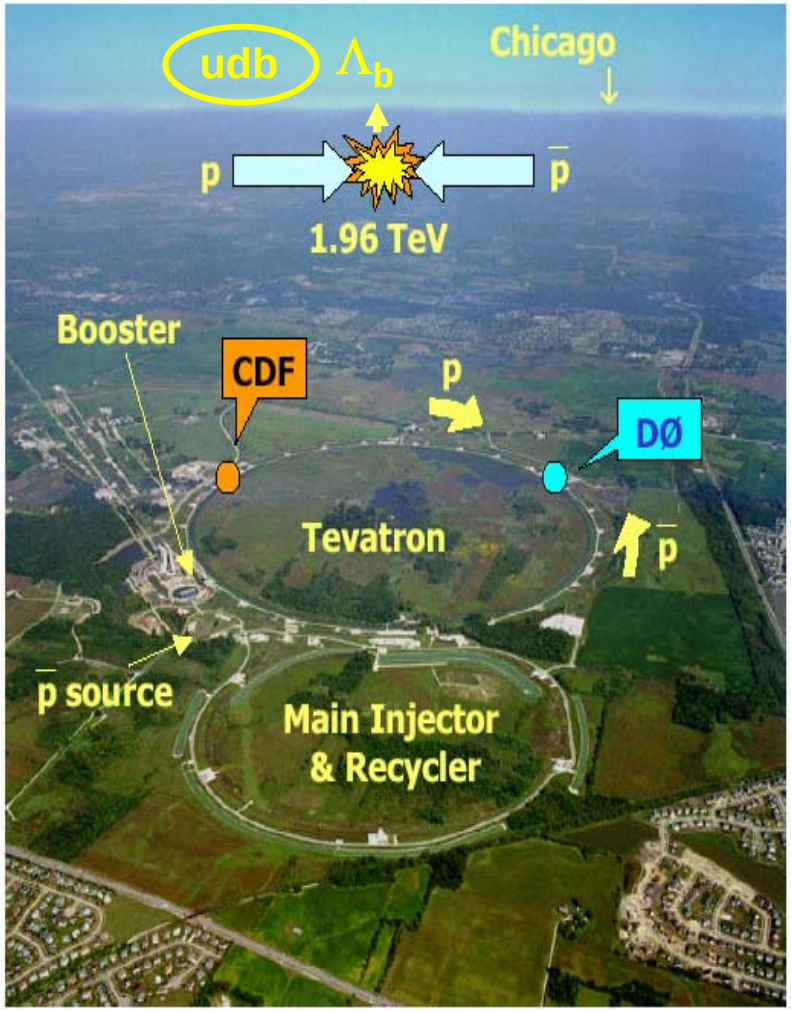
**Fermi National Laboratory Seminar, June 28th, 2005**

# Outline

- Why $\Lambda_b$
- CDF Detector, Trigger
- $\Lambda_b$ Relative Branching Fractions



# Big Picture : Why $\Lambda_b$ Baryon?

$\Lambda_b^0$ u d b $I(J^P) = 0(\frac{1}{2}^+)$

$I(J^P)$ not yet measured; $0(\frac{1}{2}^+)$ is the quark model prediction.

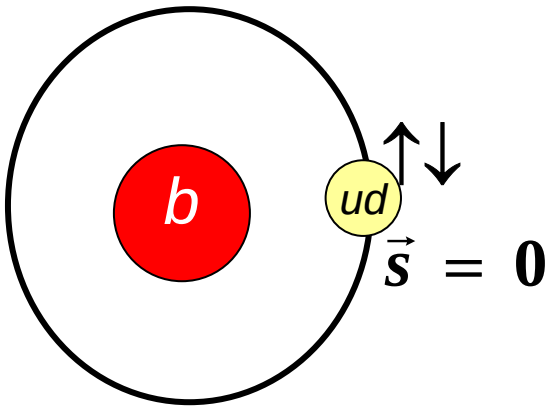
Mass $m = 5624 \pm 9$ MeV (S = 1.8)

Mean life $\tau = (1.229 \pm 0.080) \times 10^{-12}$ s

$c\tau = 368\ \mu$m

| $\Lambda_b^0$ DECAY MODES | Fraction $(\Gamma_i/\Gamma)$ |
|---|---|
| $J/\psi(1S)\Lambda$ | $(4.7 \pm 2.8) \times 10^{-4}$ |
| $\Lambda_c^+ \pi^-$ | seen |
| $\Lambda_c^+ a_1(1260)^-$ | seen |
| $\Lambda_c^+ \ell^- \bar{\nu}_\ell$ anything | [t] $(9.2 \pm 2.1)$ % |
| $p\pi^-$ | $< 5.0 \times 10^{-5}$ |
| $pK^-$ | $< 5.0 \times 10^{-5}$ |
| $\Lambda\gamma$ | $< 1.3 \times 10^{-3}$ |

- Heavy Quark Effective Theory (HQET) simplifies the calculation of b-hadron BR
  - Assuming $m_b >> \Lambda_{QCD}$
  - Corrections expressed in the power of $1/m_b$ and $\alpha_s(m_b)$
- Spin of light degrees of freedom = 0, sub-leading order corrections are simpler than those of b- mesons.



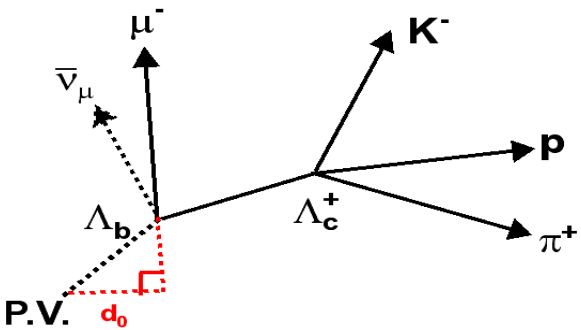

$$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu})^{theory} = 6.6\ \%$$

$$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)^{theory} = 0.45\%$$

# Experiment $\mathcal{B}(\Lambda_b \to \Lambda_c \mu \upsilon)/\mathcal{B}(\Lambda_b \to \Lambda_c \pi)$ ?

- Four charged tracks in the final state
- Data come from the same trigger, most systematics cancel.
- Control samples: similar decays in the B meson system

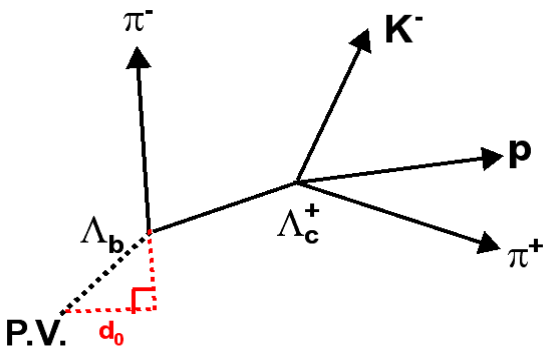
$$\frac{\mathcal{B}(\overline{B}^0 \to D^+ \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}^0 \to D^+ \pi^-)} \quad \text{and} \quad \frac{\mathcal{B}(\overline{B}^0 \to D^{*+} \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}^0 \to D^{*+} \pi^-)}$$




$\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu}_\mu$
$\to pK^-\pi^+$

- Relative BR is the yield ratio corrected for the efficiency, e.g:

$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu})}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)} = \frac{N_{\Lambda_b \to \Lambda_c \mu \overline{\nu}} \times \varepsilon_{\Lambda_b \to \Lambda_c \pi}}{N_{\Lambda_b \to \Lambda_c \pi} \times \varepsilon_{\Lambda_b \to \Lambda_c \mu \overline{\nu}}}$$



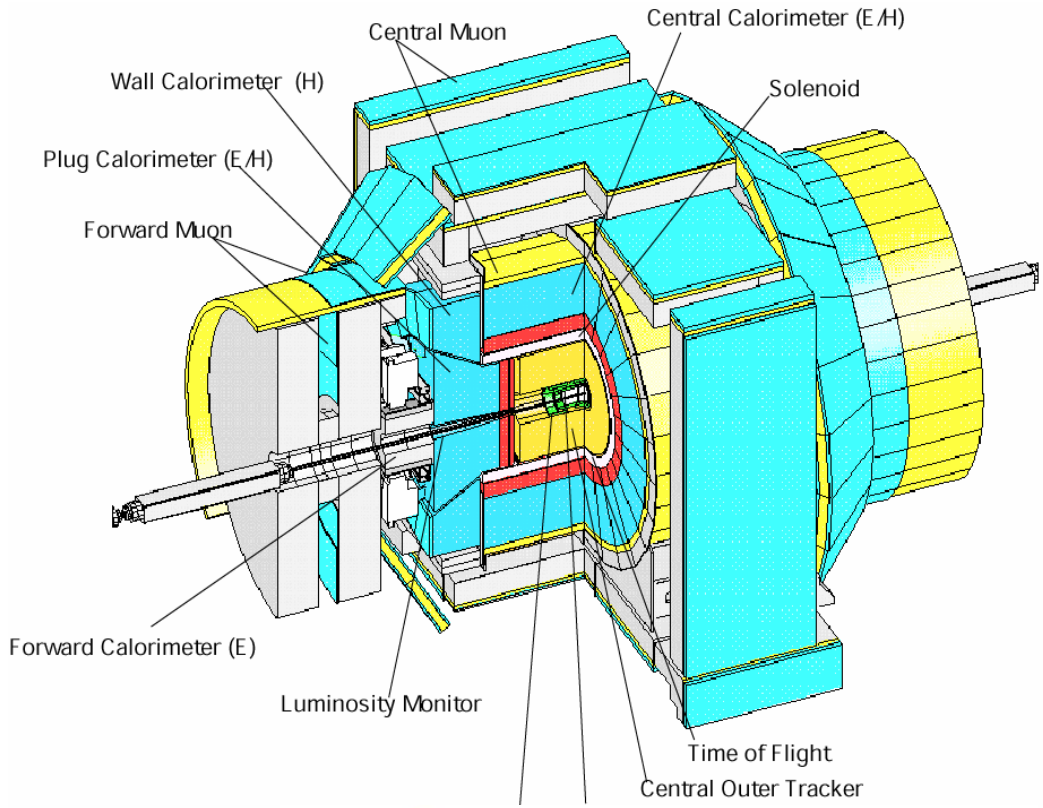

$\Lambda_b \to \Lambda_c^+ \pi^-$
$\to pK^-\pi^+$

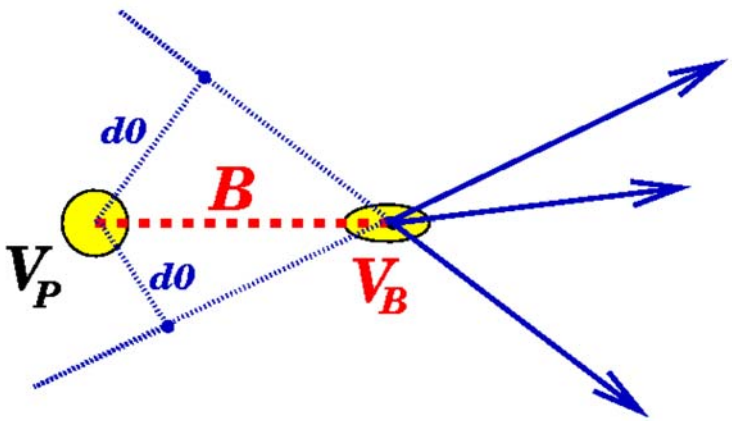
But since we can not reconstruct neutrinos, several backgrounds can fake our semileptonic signals in the data ….

$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu})}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)} = \frac{(N_{B_{mix} \to \Lambda_c \mu X} - N_{bg}) \times \varepsilon_{\Lambda_b \to \Lambda_c \pi}}{N_{\Lambda_b \to \Lambda_c \pi} \times \varepsilon_{\Lambda_b \to \Lambda_c \mu \overline{\nu}}}$$

# CDF Detector & Trigger

- Silicon Tracker
  - $|\eta| < 2$
  - $\sigma_{vertex} \sim 30\ \mu m$
- Central Outer Tracker (COT)
  - 96 layers drift chamber, up to $|\eta| \sim 1$
  - $\sigma_{P_T}/P_T \sim 0.15\%\ P_T$
- Muon chamber
  - 4 layers drift chamber outside the calorimeter
  - $|\eta| < 0.6$
- Two displaced-track trigger
  - $p_T > 2$ GeV/c, $120\ \mu m \le d_0 \le 1$ mm, $L_{xy} > 200\ \mu m$, $\Sigma\ p_T > 5.5$ GeV/c
  - 150 M events analyzed for this measurement



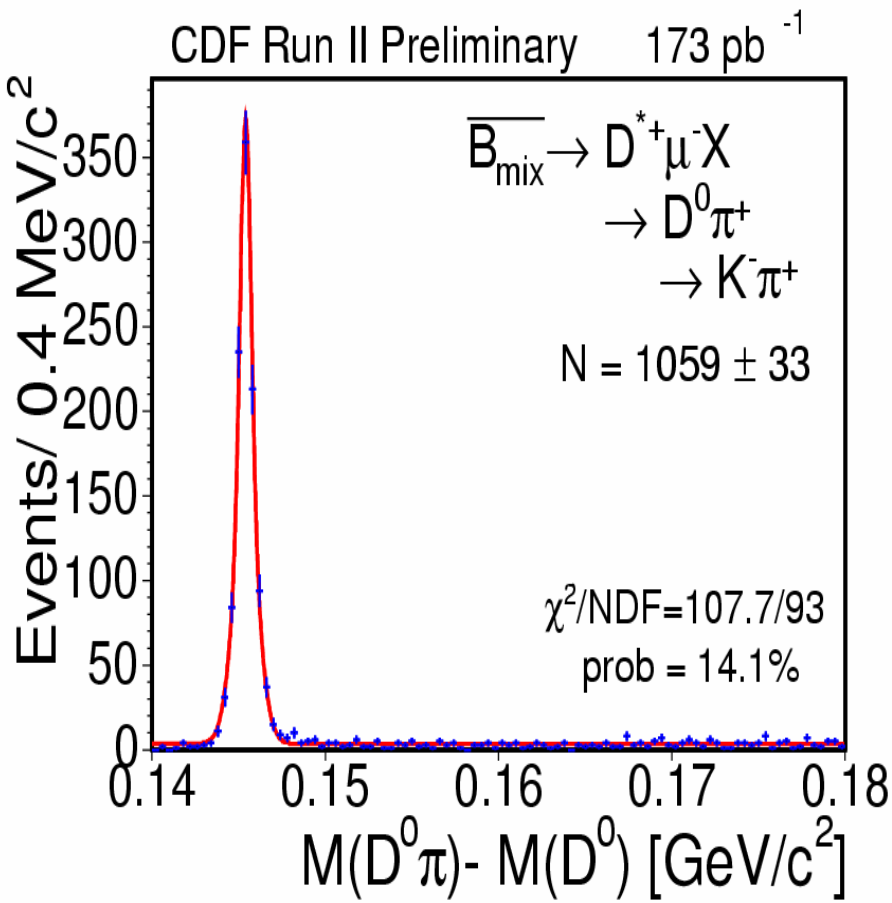



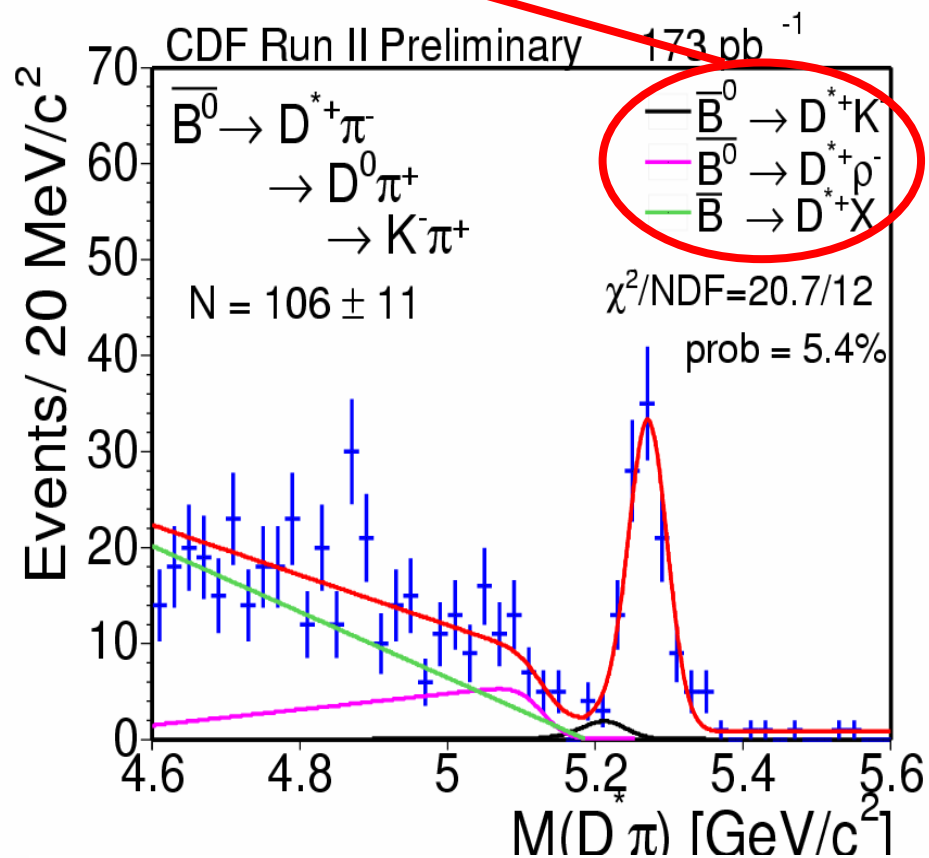
# Control Sample $B^0 \rightarrow D^*X$, $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^-\pi^+$

Inclusive Semileptonic Signal

Hadronic Signal

Background shapes come from MC



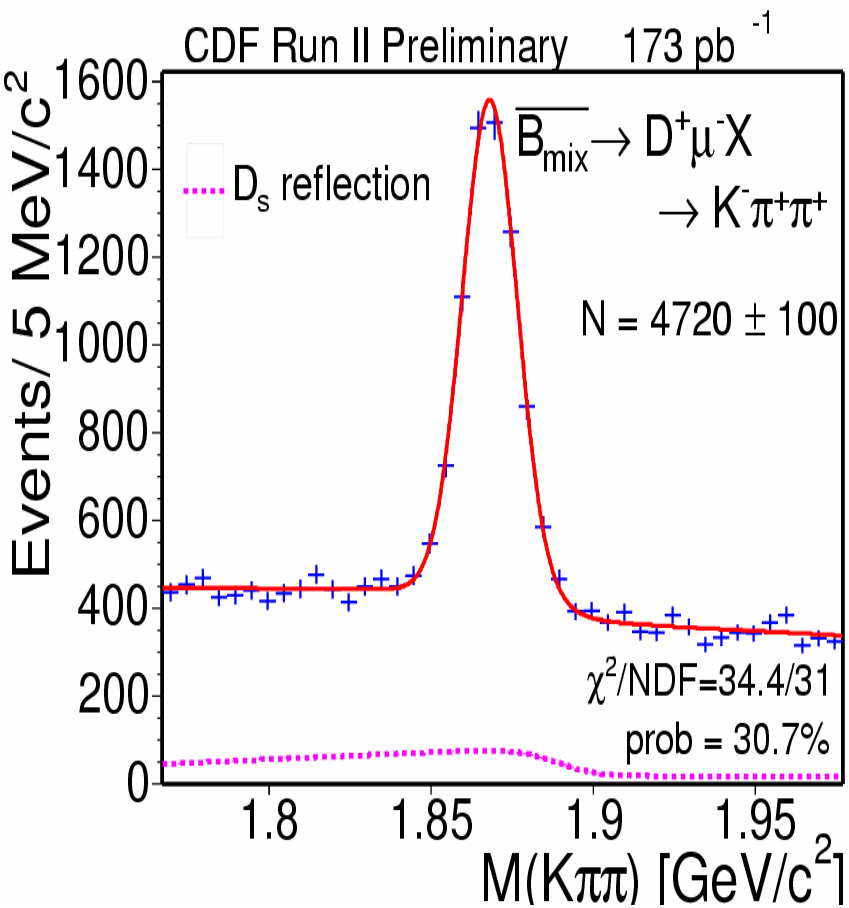



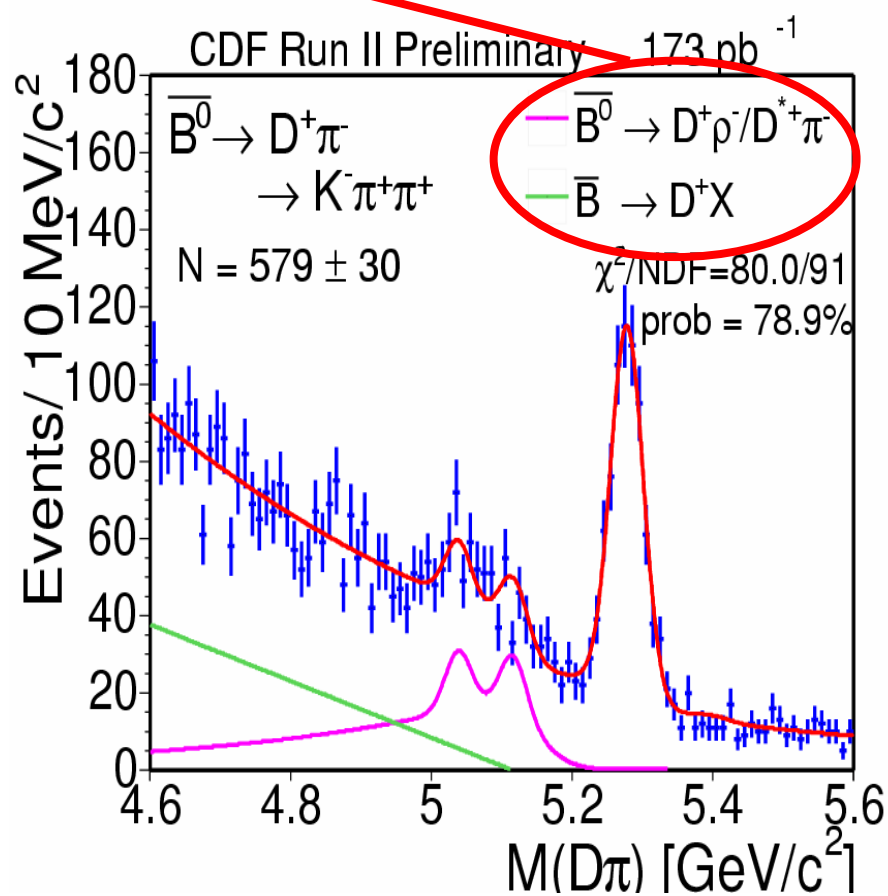
# Control Sample $B^0 \rightarrow DX$, $D^+ \rightarrow K^-\pi^+\pi^+$

Inclusive Semileptonic Signal

Hadronic Signal

Background shapes come from MC



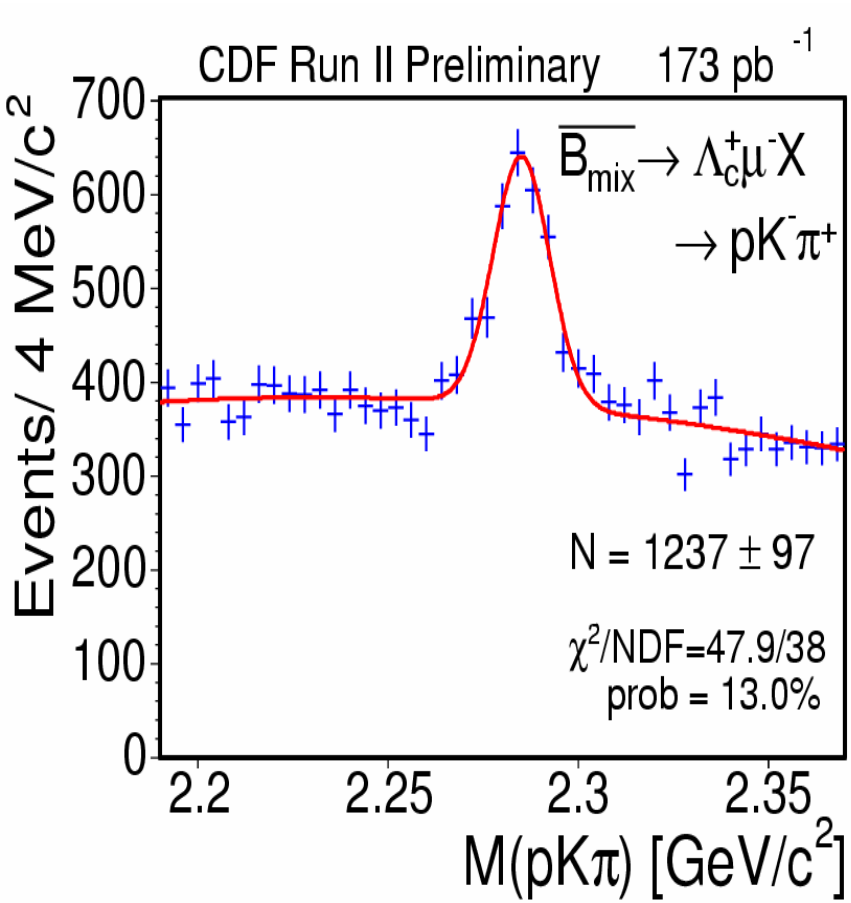



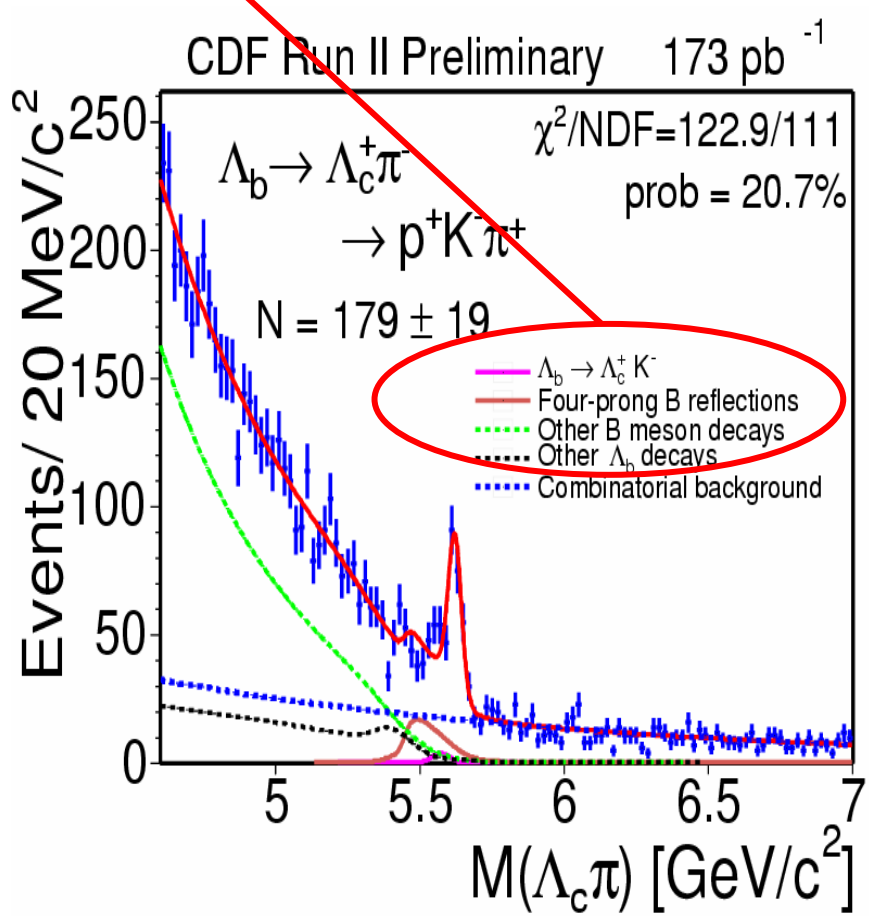
# Signal Sample $\Lambda_b \rightarrow \Lambda_c X$ $\Lambda_c \rightarrow p^+ K^- \pi^+$

Inclusive Semileptonic Signal

Hadronic Signal

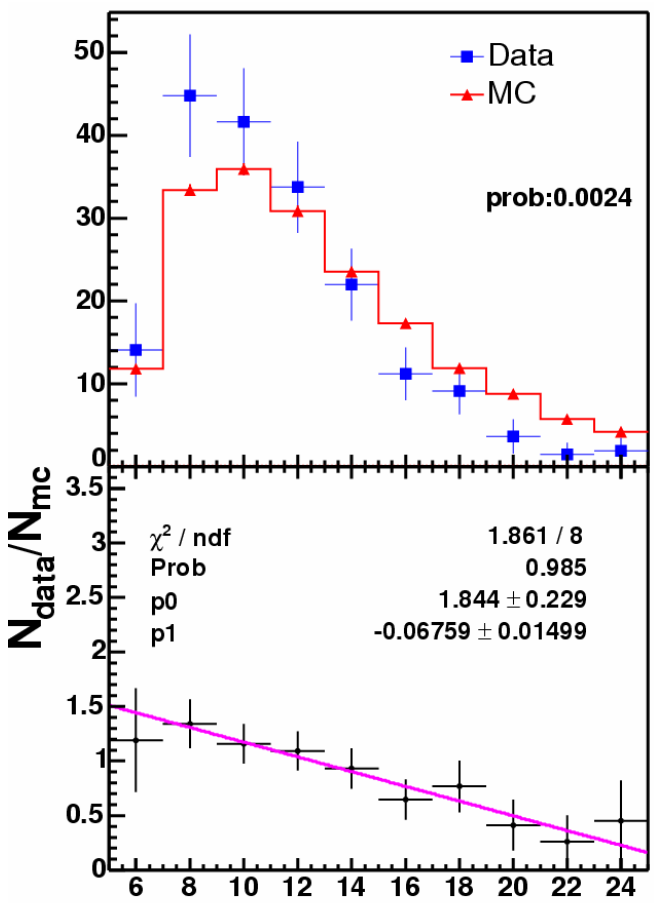
Background shapes come from MC



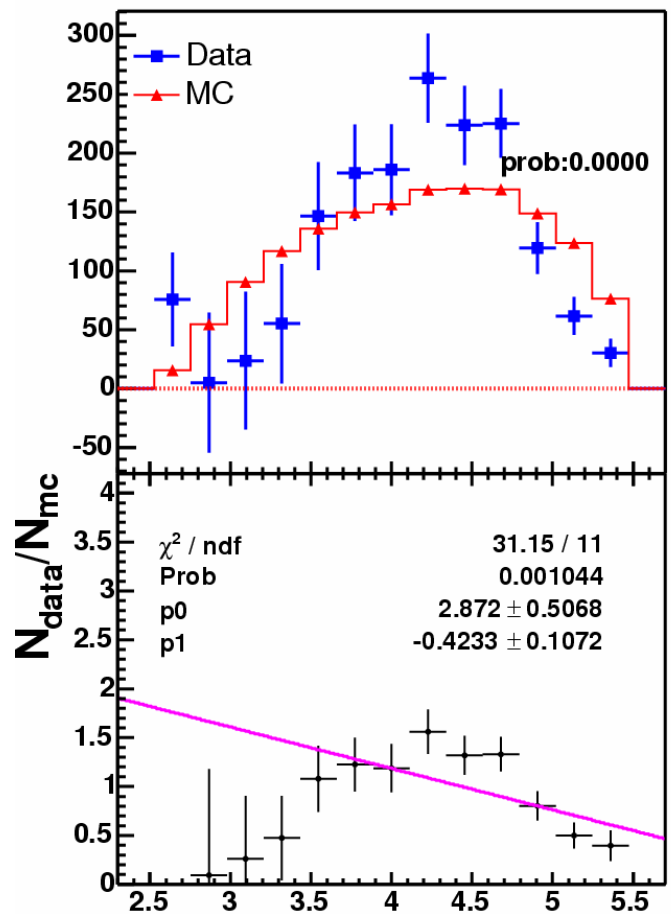



# MC and Data Comparison: Before

- We used MC to obtain relative efficiencies of signals and backgrounds.
- Compare MC and background subtracted signal distribution in the data.
- Tune our MC if MC and data disagree, e.g: $P_T(\Lambda_b)$, $M(\Lambda_c\mu)$

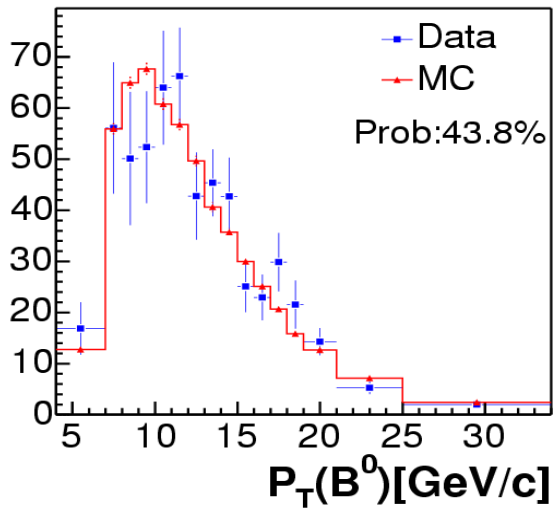


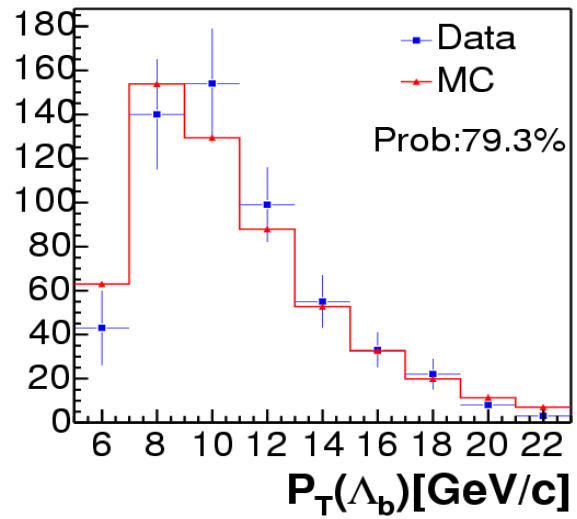

$P_T(\Lambda_b)$[GeV/c]

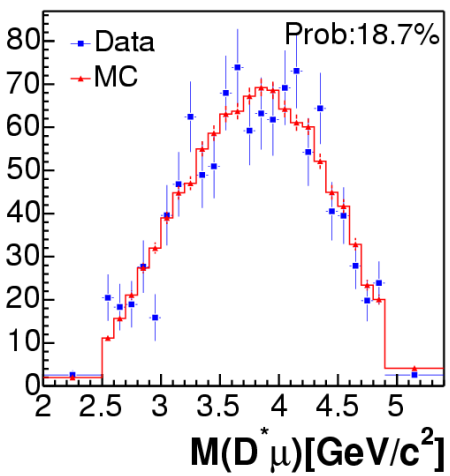


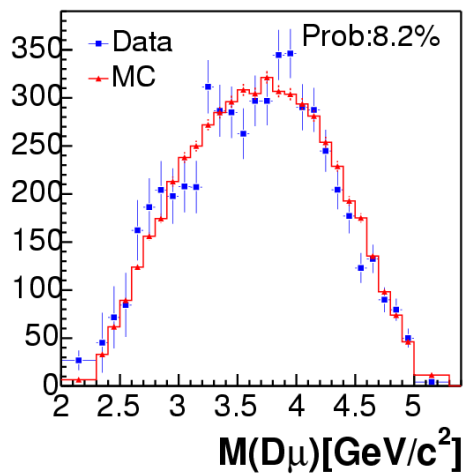

$M(\Lambda_c\mu)$[GeV/$c^2$]

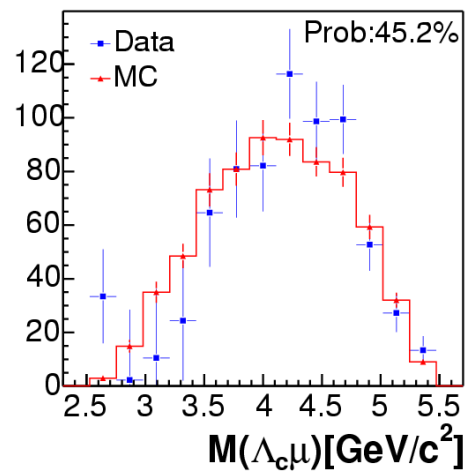
# MC and Data Comparison : After



# Where Are the Semileptonic Backgrounds from?

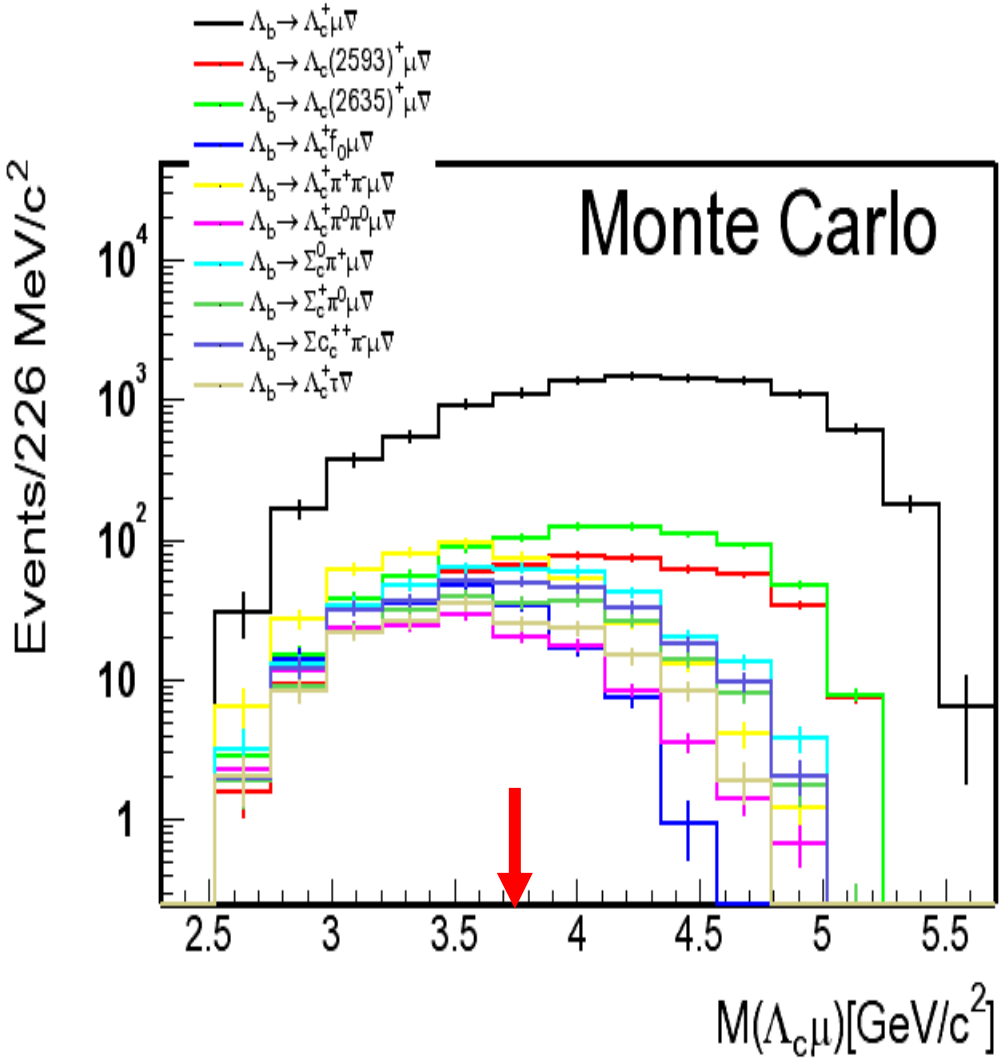
- Physics Background
  - b-hadron decays into a charm, a $\mu$ and additional particles, e.g:

$$\Lambda_b \rightarrow \Lambda_c^+(2593)\mu\bar{\nu}$$
$$\rightarrow \Lambda_c^+\pi^+\pi^-$$

  - Reduced by the $M(\Lambda_c\mu)$ cut
  - Normalize the amount to the measured hadronic signal

$$\frac{N_{\text{physics}}}{N_{\text{hadronic}}} = \frac{\sum_i \mathcal{B}_{\text{physics}} \times \varepsilon_{\text{physics}}}{\mathcal{B}_{\text{hadronic}} \times \varepsilon_{\text{hadronic}}}$$

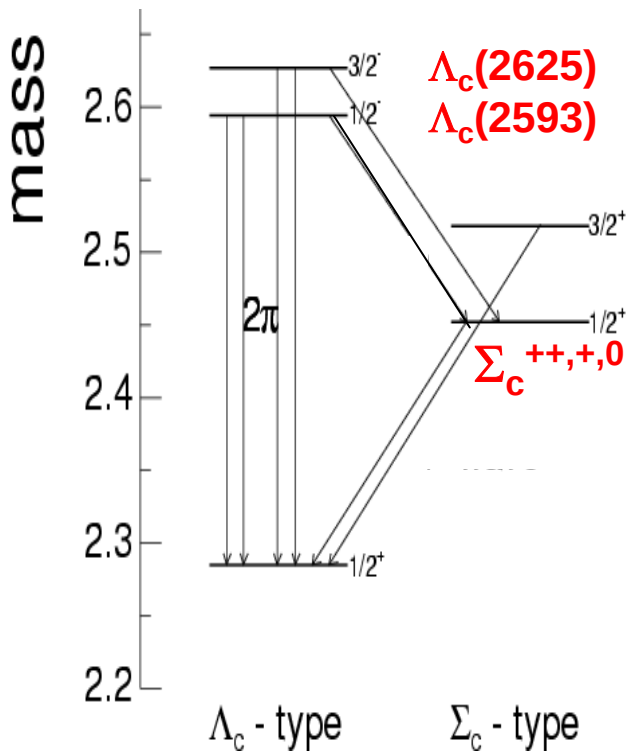
  - BRs come from PDG, theoretical estimate and preliminary measurements



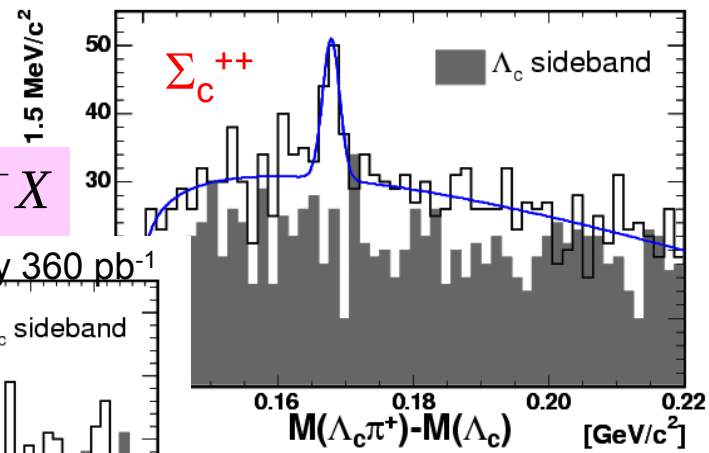

- ~10% contribution

# First Observation of $\Lambda_b$ Semileptonic Background

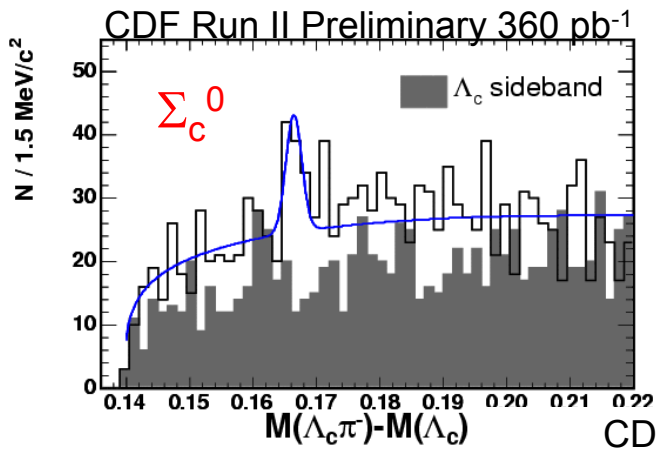
- Estimated the BR based on the observation



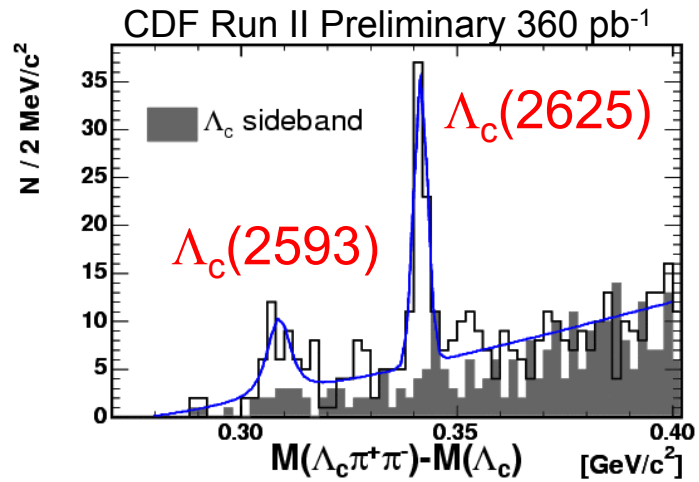

$$\Lambda_b \to \Sigma_c^{++}\pi^-\mu^- X$$




$$\Lambda_b \to \Sigma_c^{0}\pi^+\mu^- X$$




$$\Lambda_b \to \Lambda_c^{*+}\mu^- X$$



# How to Obtain $\mathcal{B}(\Lambda_b \to \Lambda_c \pi)$?

- Make use of previous CDF measurements

$$\text{CDF RunII}\ \frac{\sigma_{\Lambda_b}(P_T > 6\,GeV/c)}{\sigma_{B^0}(P_T > 6\,GeV/c)} \times \frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)}{\mathcal{B}(\bar{B}^0 \to D^- \pi^-)} = 0.82 \pm 0.08(\text{stat}) \pm 0.11(syst) \pm 0.22\ (\Lambda_c\ \text{BR})$$

$$\frac{\sigma_b \cdot f_{\Lambda_b}}{\sigma_b \cdot f_d}$$

$$\text{CDF Run I}\ \frac{f_{\Lambda_b}}{f_d} = 0.236 \pm 0.084$$

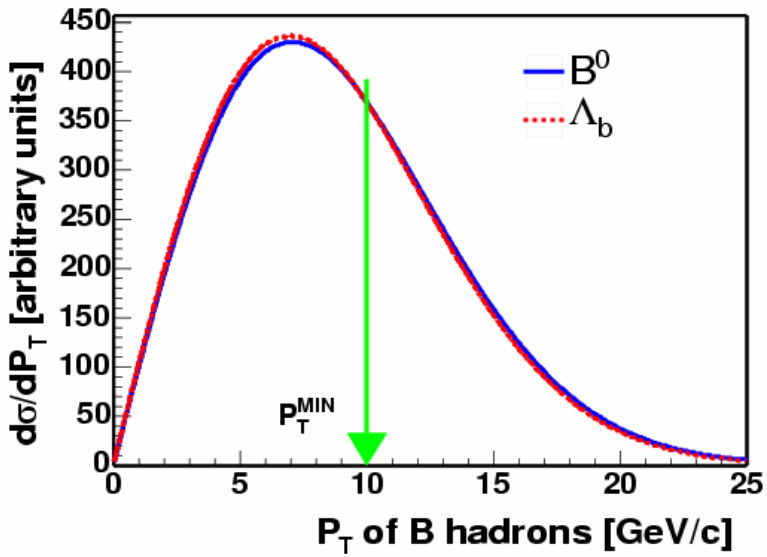
- $\Lambda_b$ MC $P_T$ spectrum using fully reconstructed decay was not available for CDF I
  - Correct the CDF I $f_{lambdab}/f_d$ using measured $P_T$ spectrum
    - Acceptance correction
    - Different $P_T$ thresholds affect the ratio 10 GeV/c vs. 6 GeV/c

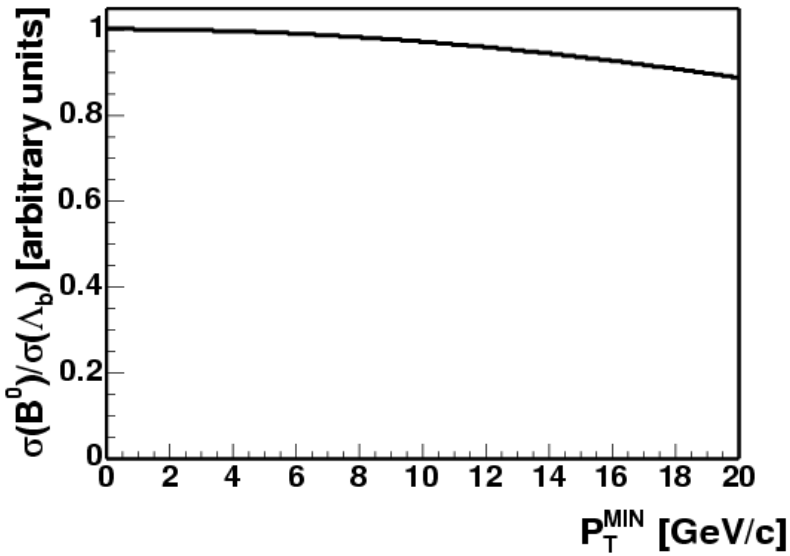
$$\frac{\sigma_{\Lambda_b}(P_T > 6\,\text{GeV/c})}{\sigma_{B^0}(P_T > 6\,\text{GeV/c})} = 0.56 \pm 0.20(\text{stat} + syst)\ ^{+0.19}_{-0.11}\ (pT)$$

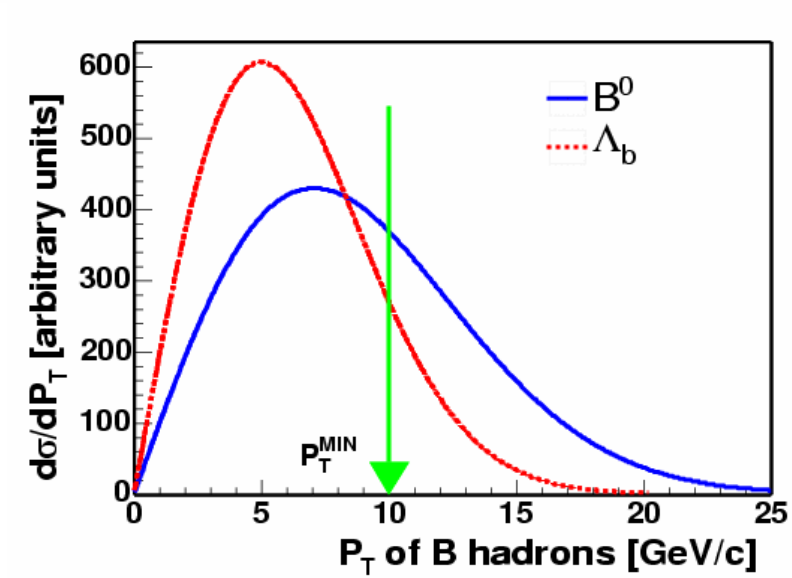
$$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-) = \left( 0.41 \pm 0.19(\text{stat} + syst)\ ^{+0.06}_{-0.08}\ (pT) \right)\%$$

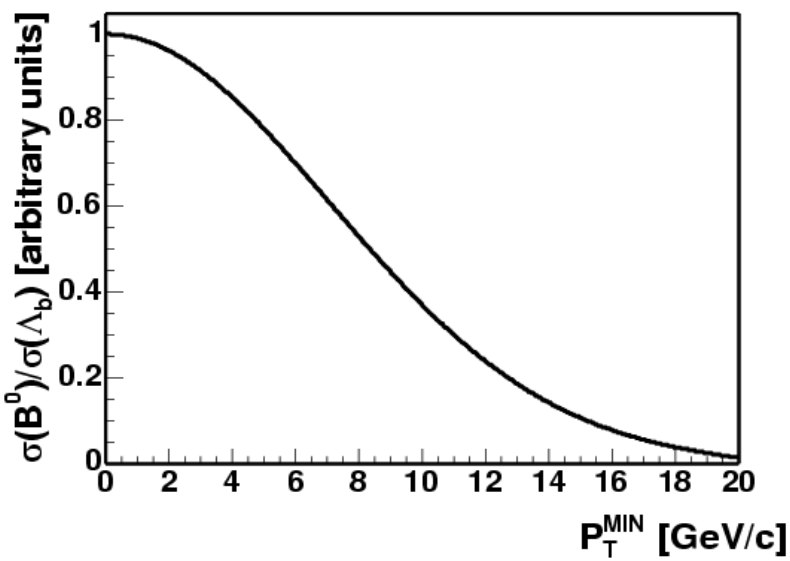
*Consistent with the prediction 0.45% (**Phys. Lett. B586, 337**)*

# How to Obtain $\mathcal{B}(\Lambda_b \to \Lambda_c \pi)$?



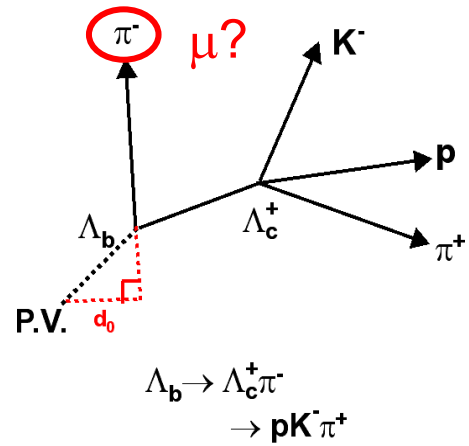



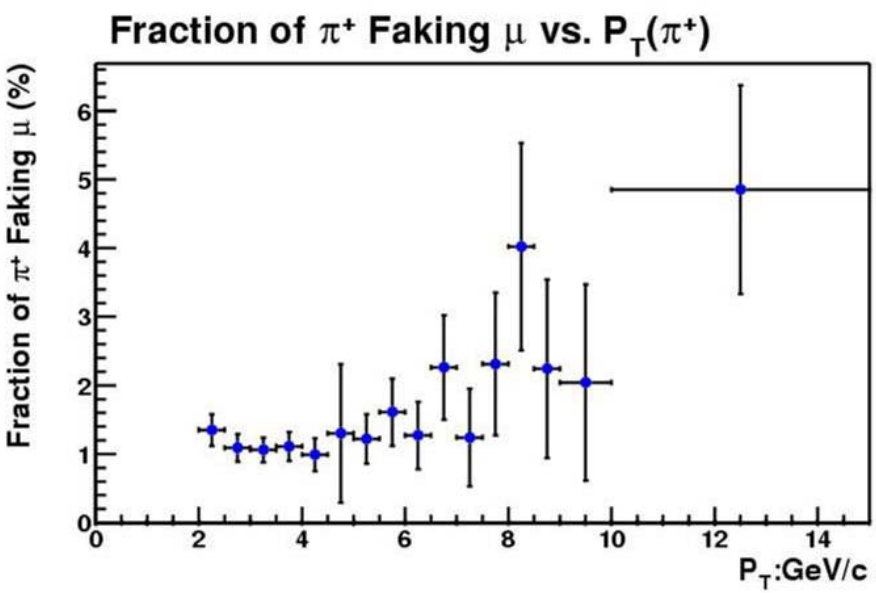



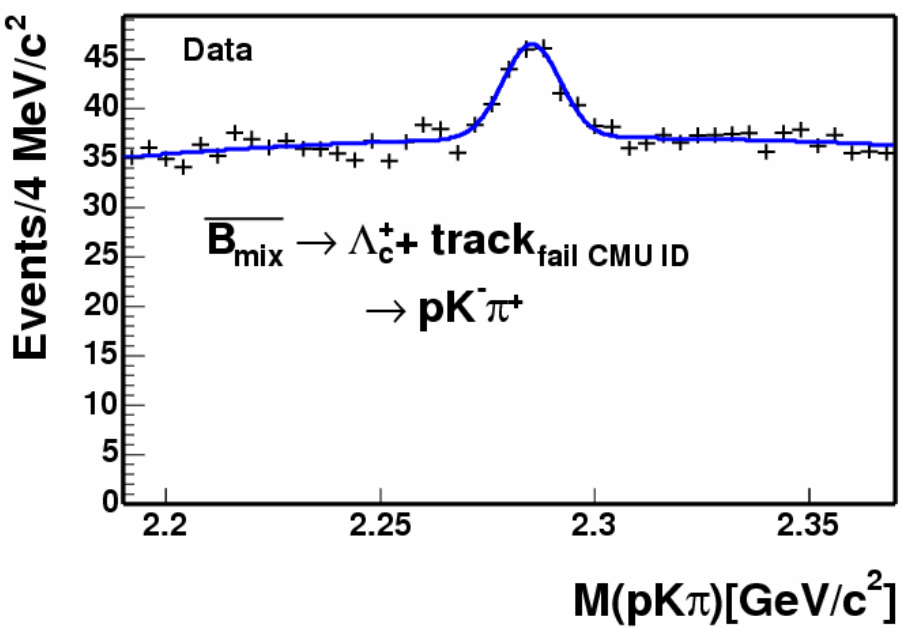



# Where Are the Semileptonic Backgrounds from?

- Muon Fakes
  - p, K, $\pi$ fake muons
  - $c\tau$ and muon $d_0$ cuts suppress prompt fakes
  - Our fakes mostly come from b decays
  - Weight "$\Lambda_c$+TRK$_{fail\mu}$" events with the $\mathcal{P}_{fake}$
  - p, K, $\pi$ fractions from the inclusive B MC
  - ~5% contribution

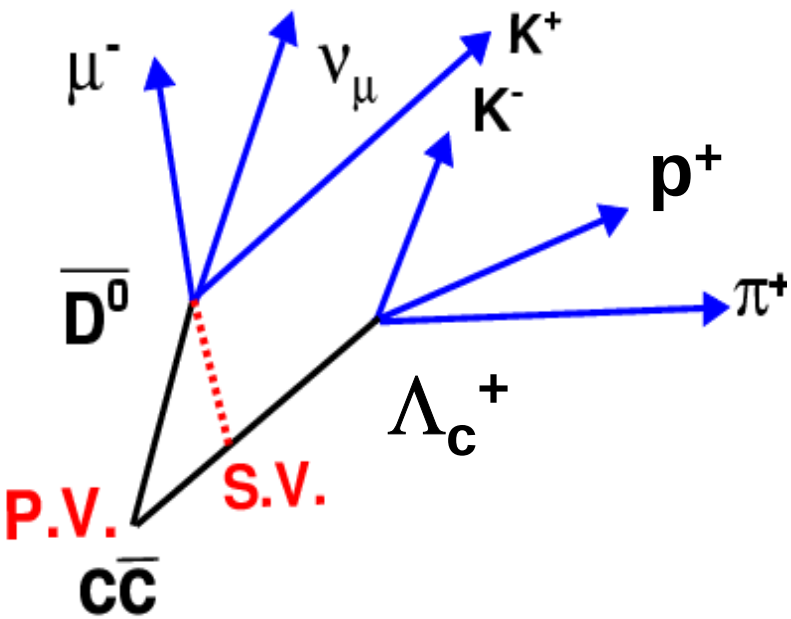


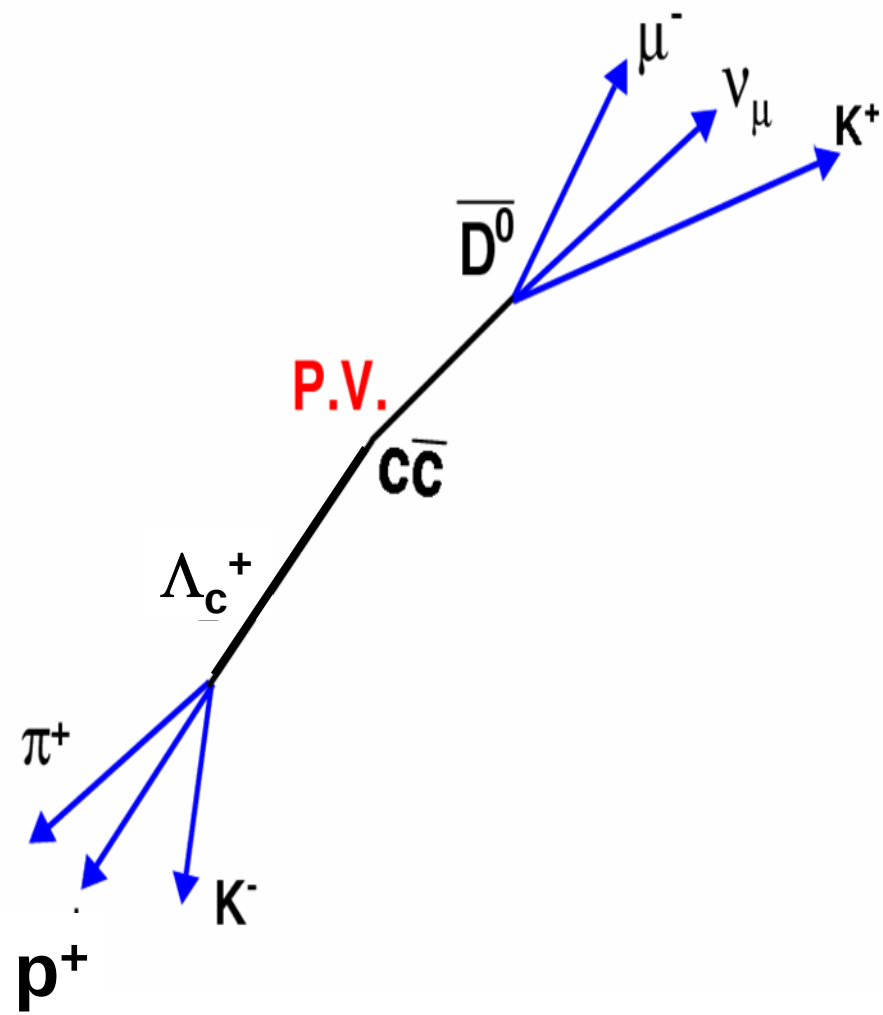



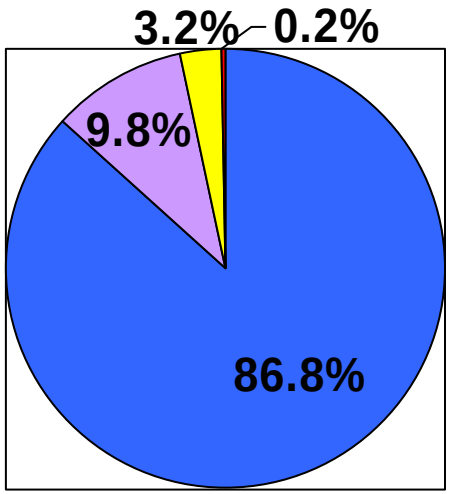
# Where Are the Semileptonic Backgrounds from?

- QCD $b\bar{b}, c\bar{c}$ Pair Production:
  - charm and $\mu$ from different b- or charmed hadrons
  - Suppressed due to the $c\tau$ and $P_T(\mu)$ cuts
  - Rely on Pythia MC
  - Most sensitive to gluon splitting
  - ~0.2% contribution

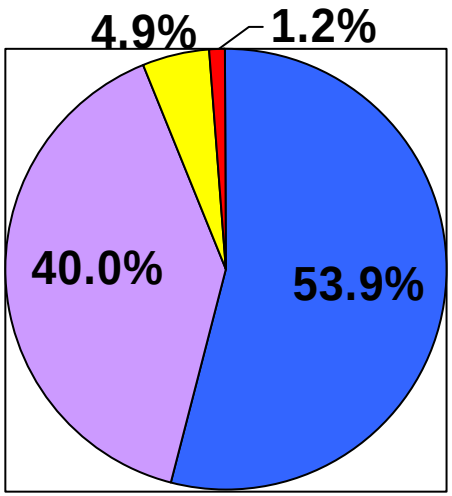


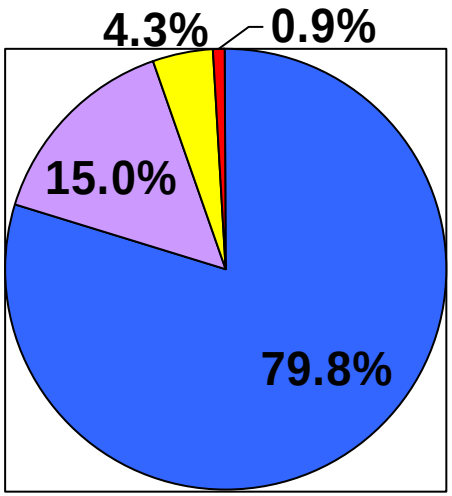
# Inclusive Semileptonic Sample Composition




$$B_{\mathrm{mix}} \to \Lambda_c \mu X$$



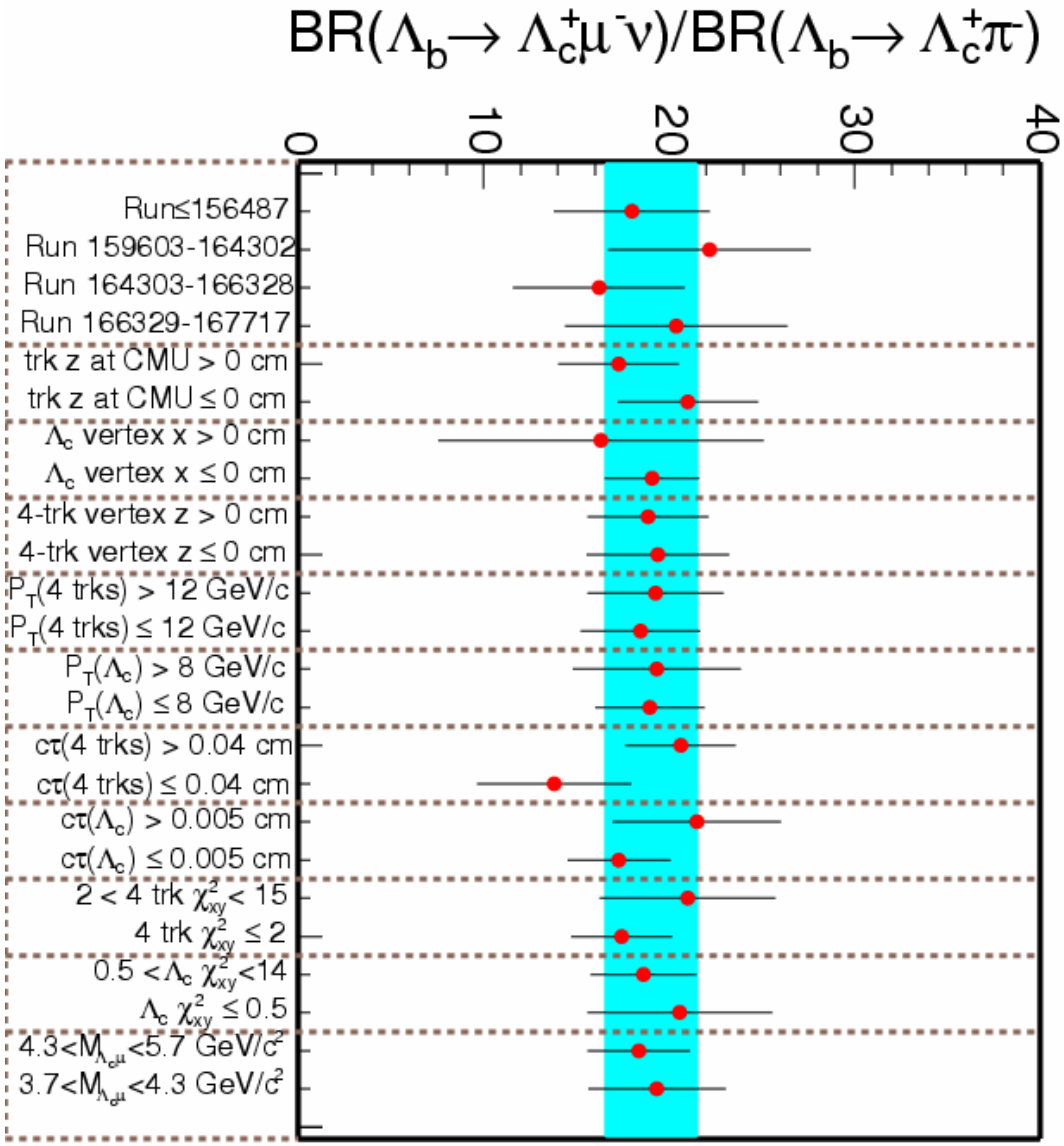

$$B_{\mathrm{mix}} \to D^{+} \mu X$$




$$B_{\mathrm{mix}} \to D^{*+} \mu X$$

Signal | Physics | Fake mu | ccbar,bbbar

# Consistency Check



# Dominant Systematics

- Physics background and hadronic signal branching fractions
  - Measured: from PDG
  - Estimated or Unmeasured
    - **multiply the BR by 2 or 0**

- Mass fitting model
  - Vary the constant parameters in the fit
  - Several background shapes come from inclusive MC
    - **vary BR of the dominant decays**

- MC modeling of acceptance and efficiency
  - pT spectrum
    - **affect the efficiency and $\mathcal{B}(\Lambda_b \to \Lambda_c \pi)$**
  - $\Lambda_c$ and $\Lambda_b$ polarizations
    - **reweight the angular distribution according to the polarization states**
  - $\Lambda_b$ semileptonic decay model
    - **size of the independent MC for reweighting the phase space distribution**
    - **uncertainty on the predicted slope parameters for the Isgur-Wise function**

# Uncertainty Summary

Physics background and hadronic signal branching fractions

MC modeling of efficiency and acceptance

| | fractional uncertainty (%) | | |
|---|---|---|---|
| | $\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu})}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)}$ | $\frac{\mathcal{B}(\bar{B}^0 \to D^+ \mu^- \bar{\nu})}{\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)}$ | $\frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu})}{\mathcal{B}(\bar{B}^0 \to D^{*+} \pi^-)}$ |
| Measured BR | **+3.5 -10.5** | **± 8.2** | **± 2.3** |
| Estimated BR | **± 2.5** | **± 9.2** | **± 6.2** |
| CDF Internal | | | |
| Mass fitting | ± 3.2 | ± 4.1 | < 0.1 |
| Muon fake | ± 0.9 | ± 0.7 | ± 0.4 |
| Pt spectrum | +1.4-2.5 | ± 3.2 | ± 2.2 |
| CDF material | ± 1.1 | ± 1.7 | ± 1.3 |
| $\varepsilon$ scaling | ± 0.4 | ± 0.5 | ± 0.4 |
| $b\bar{b}, c\bar{c}$ | ± 0.2 | ± 2.2 | ± 1.3 |
| $\Lambda_{b,c}$ polarizations | ± 1.9 | -- | -- |
| $\Lambda_c$ Dalitz | ± 0.4 | -- | -- |
| $\Lambda_b$ lifetime | ± 1.1 | -- | -- |
| $\Lambda_b$ decay model | ± 2.9 | -- | -- |
| | **± 6.0** | **± 6.1** | **± 3.4** |
| Statistical | **± 15.0** | **± 10.2** | **± 13.0** |

# Control Sample Result

$$\frac{\mathcal{B}(\overline{B}^0 \to D^+\mu^-\overline{\nu})}{\mathcal{B}(\overline{B}^0 \to D^+\pi^-)} = 9.8 \pm 1.0\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.8\,(\text{BR}) \pm 0.9\,(\text{UBR})$$

**Consistent with the 2004 world average** `7.8 ± 1.0 at the 1σ` **level**

**New world average ratio 8.3 ± 0.9**

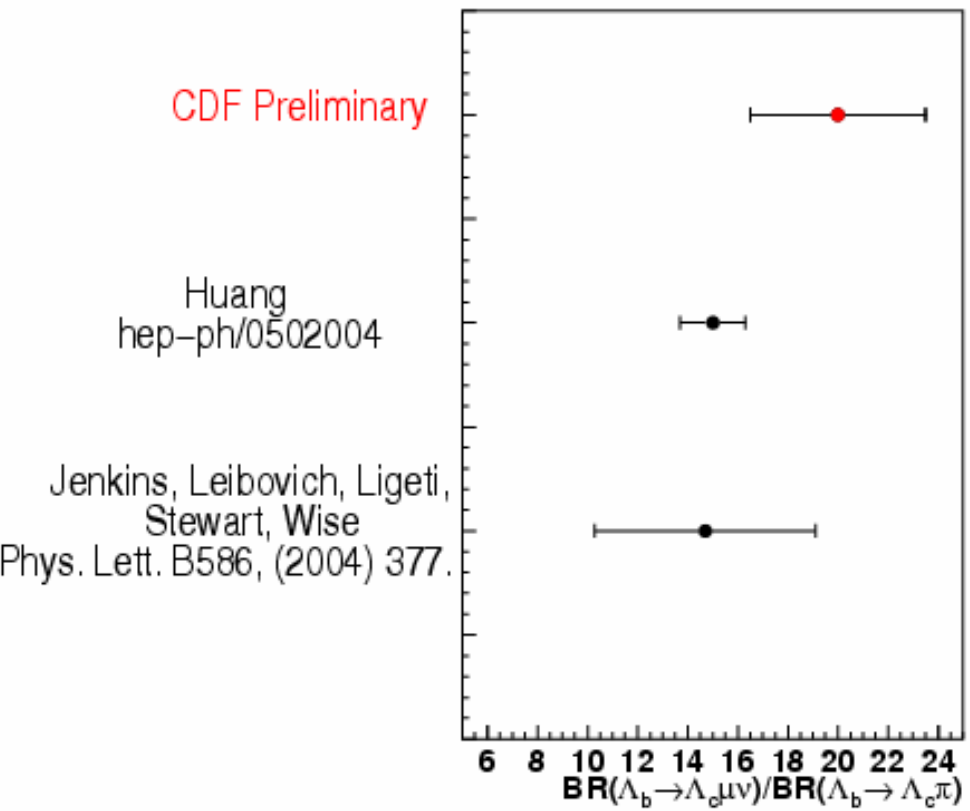
$$\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu})}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-)} = 17.7 \pm 2.3\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{BR}) \pm 1.1\,(\text{UBR})$$

**Consistent with the 2004 world average** `19.7 ± 1.7 at the 0.7σ` **level**

**New world average ratio 19.1 ± 1.4**

# Signal Sample Result

$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu})}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)} = 20.0 \pm 3.0\,(\text{stat}) \pm 1.2(syst)\,{}^{+0.7}_{-2.1}\,(\text{BR}) \pm 0.5\,(\text{UBR})$$




- Experimental Uncertainties dominated by:
  - Data sample size
  - $\mathcal{B}(\Lambda_b \to \Lambda_c \pi)$
    - CDF Run I $f_{baryon}/fd$
    - $\mathcal{B}(\Lambda_c \to pK\pi)$

# $\mathcal{B}(\Lambda_b \to \Lambda_c \mu \upsilon)$?

Combined the ratio of BR and $\mathcal{B}(\Lambda_b \to \Lambda_c \pi)$, we have

$$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}) = \left( 8.1 \pm 1.2\,(\mathrm{stat})^{+1.1}_{-1.6}\,(syst) \pm 4.3\ (\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)) \right)\%$$

Consistent with DELPHI result (Phys. Lett. B585, 63)

$$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu})^{\mathrm{DELPHI}} = \left( 5.0^{+1.1}_{-0.9}\,(\mathrm{stat})^{+1.6}_{-1.2}\,(syst) \right)\%$$

Weighted average

$$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu})^{\mathrm{WORLD}} = \left( 5.5 \pm 1.8\,(stat + syst) \right)\%$$

Also in agreement with the theoretical prediction 6.6% ***(Phys. Lett. B586, 337)***

## $|V_{cb}|$ Exercise

$$\frac{d\Gamma(\Lambda_b \to \Lambda_c \mu \bar{\nu})}{dq^2} = G \cdot |V_{cb}|^2 \cdot \kappa(q^2) \cdot \mathcal{F}^2(q^2)$$

- Plug in the weighted average and the theoretical slope parameter of the ISGW function into the formula for $\mathcal{B}(\Lambda_b \to \Lambda_c \mu \upsilon)$

$$\Lambda_b \quad |V_{cb}| = 0.038 \pm 0.006\,(\text{exp}) \pm (0.002 \sim 0.006)\,(\text{theory})$$

Consistent with the $|V_{cb}|$ from HFAG 2004 measured with B->D*lυ decays ***(hep-ex/0412073)***

$$B \text{ meson} \quad |V_{cb}| = 0.0414 \pm 0.0010\,(\text{exp}) \pm (0.0018)\,(\text{theory})$$

# What Do We Know about $\Lambda_b$ Now?

Mass $m = 5624 \pm 9$ MeV $(S = 1.8)$

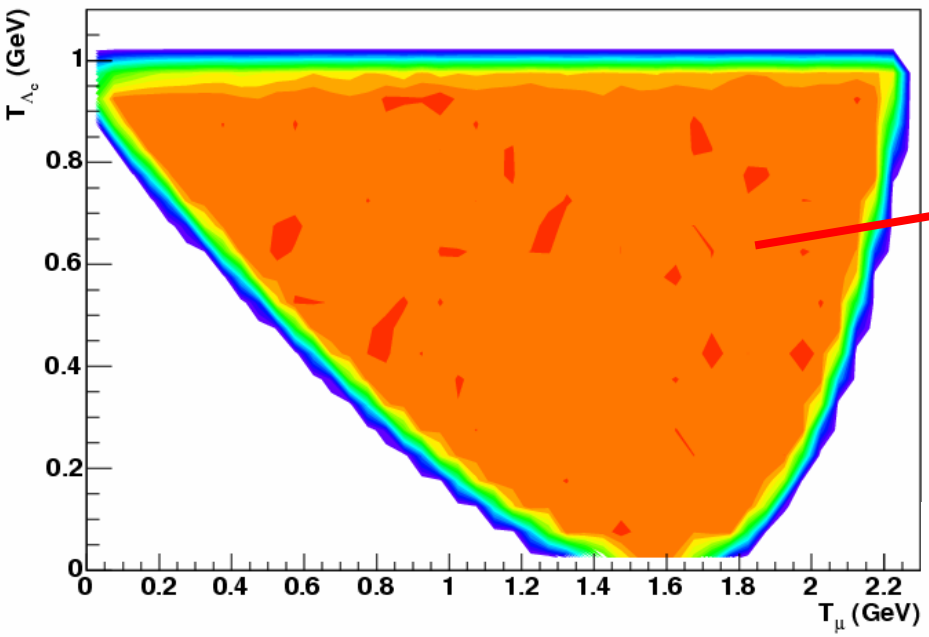
Mean life $\tau = (1.229 \pm 0.080) \times 10^{-12}$ s

$c\tau = 368\ \mu$m

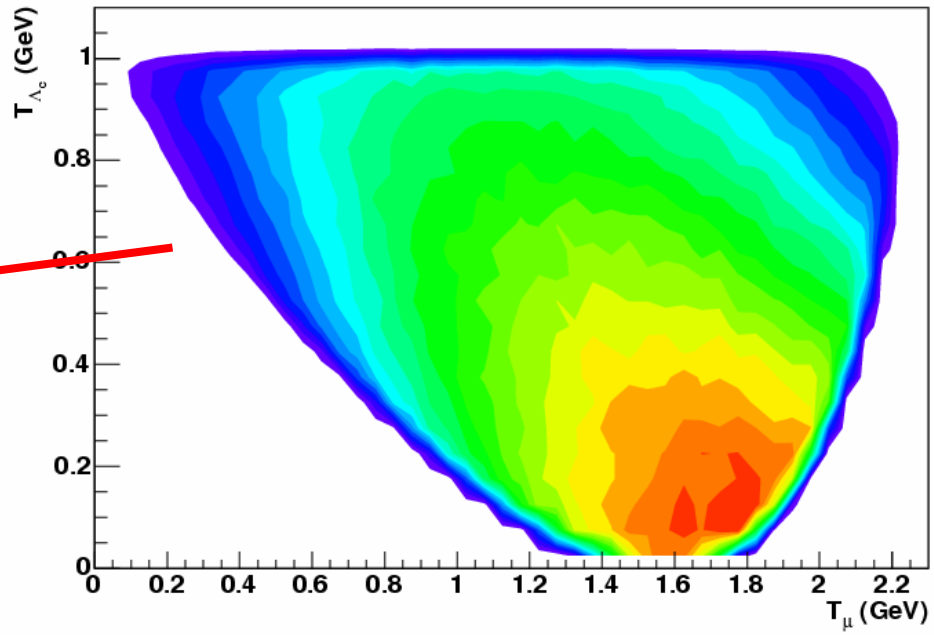
| $\Lambda_b^0$ DECAY MODES | Fraction $(\Gamma_i/\Gamma)$ |
|---|---|
| $J/\psi(1S)\Lambda$ | $(4.7 \pm 2.8) \times 10^{-4}$ |
| $\Lambda_c^+ \pi^-$ | $(4.1 \pm 2.0) \times 10^{-3}$ |
| $\Lambda_c^+ a_1(1260)^-$ | seen |
| $\Lambda_c \ell \upsilon$ | $(5.5 \pm 1.8)$ % |
| $p \pi^-$ | $< 5.0 \times 10^{-5}$ |
| $p K^-$ | $< 5.0 \times 10^{-5}$ |
| $\Lambda \gamma$ | $< 1.3 \times 10^{-3}$ |
| $\Lambda_c(2593)^+ \ell \upsilon$ | seen |
| $\Lambda_c(2625)^+ \ell \upsilon$ | seen |
| $\Sigma_c^{++} \pi^- \ell \upsilon$ | seen |
| $\Sigma_c^0 \pi^+ \ell \upsilon$ | seen |

# Back Up Slides

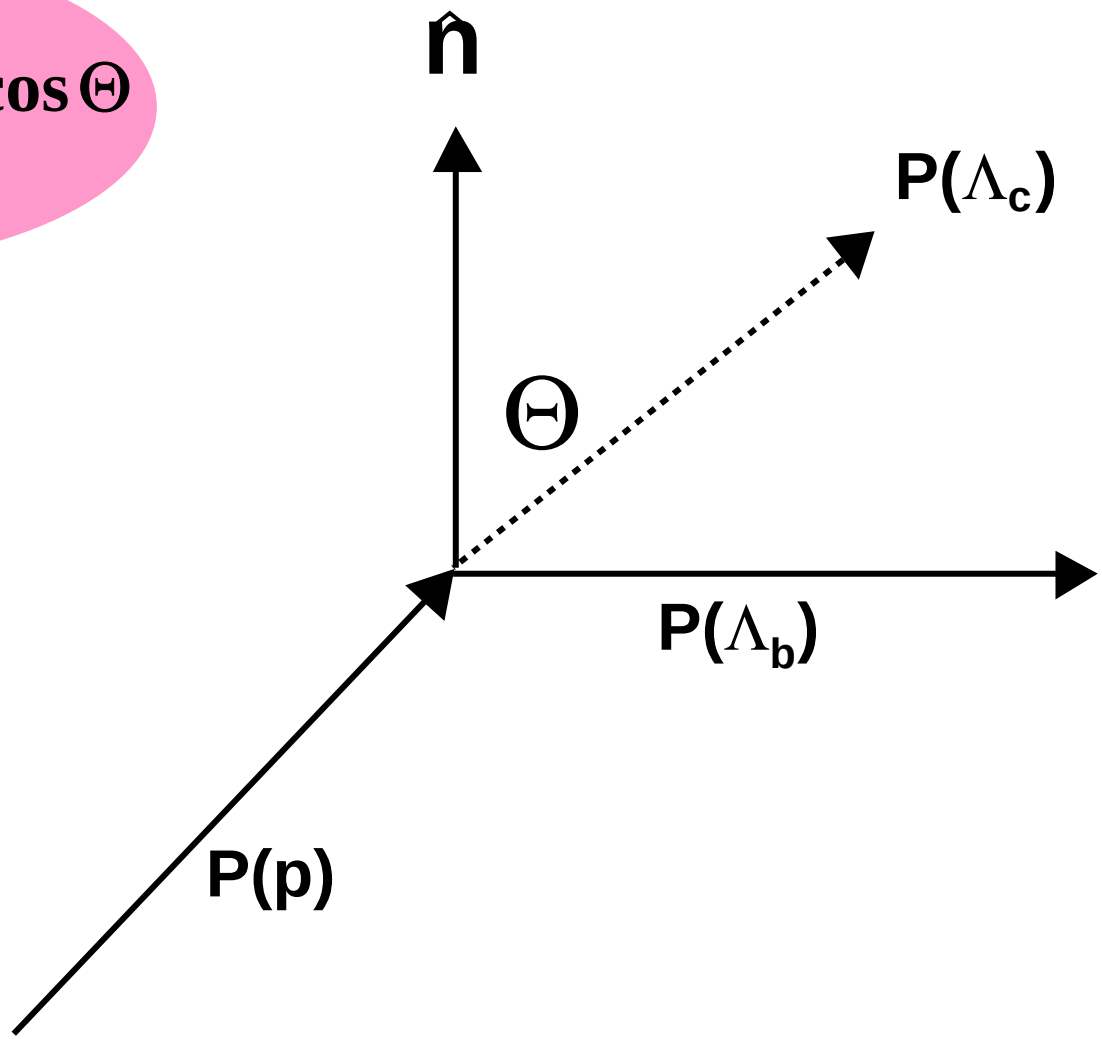
# MC Tuning




Flat phase space




Form factor weighted

# $\Lambda_b$ Polarization

$$\frac{dN}{d\cos\Theta} \propto 1 + P_{\Lambda_b} \cos\Theta$$