Measurement of the production fraction times branching fraction
\[ f(b \rightarrow \Lambda_b) \cdot B(\Lambda_b \rightarrow J/\psi \Lambda) \]

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**Introduction**

**Motivation**

\( \Lambda_b^0 \) baryon: Experimental Status

- \( \Lambda_b^0(udb) \) is the lightest \( b \) baryon.
- Only a few decay channels studied and \( BR \) uncertainties are large \( \sim 30 - 60\% \).
- A measurement of the \( \Lambda_b^0 \rightarrow J/\psi \Lambda^0 \) \( BR \) establishes the methods to study \( b \rightarrow s \) (FCNC) decays such as \( \Lambda_b \rightarrow \mu^+ \mu^- \Lambda \) (where \( \Lambda_b^0 \rightarrow J/\psi \Lambda^0 \) can be used as a normalization channel).
- From PDG (2010):
  - \( f(b \rightarrow \Lambda_b) \cdot \mathcal{B}(\Lambda_b \rightarrow J/\psi \Lambda) = (4.7 \pm 2.3) \times 10^{-5} \).
  - Roughly \( f(b \rightarrow \Lambda_b) \sim f(b \rightarrow b_{\text{baryon}}) \sim 0.1 \) \(^1\)
  - \( \mathcal{B}(\Lambda_b \rightarrow J/\psi \Lambda) \sim 5 \times 10^{-4} \).

\(^1 f(b \rightarrow b_{\text{baryon}}) = (8.5 \pm 2.2) \times 10^{-2} \)
\( \Lambda_b^0 \rightarrow J/\psi \Lambda^0 \) branching fraction predictions

- PQCD\(^2\): \( \mathcal{B}(\Lambda_b \rightarrow J/\psi \Lambda) \sim (1.7 - 5.3) \times 10^{-4} \).
- Factorization\(^3\): several (quark) models predict \( \mathcal{B}(\Lambda_b \rightarrow J/\psi \Lambda) \sim (1.1 - 6.1) \times 10^{-4} \).

\(^2\)PRD 65, 074030 (2002).

**Figure 1**: Factorization ansatz introduces an effective color number to take account of the non-factorizable terms in the decay amplitude [PRD 58, 014016 (1998), figure from LHCb-2008-005 Public Note]
Tevatron and the DØ Detector

**Tevatron**
- $\sqrt{s} = 1.96$ TeV.
- 396 ns bunch spacing
- $L_{\text{peak}} \sim 4 \times 10^{32}/cm^2/s$

**DØ Detector**
- Excellent muon detector, $|\eta| < 2.2$.
- Silicon Microstrip Tracker and Central Fiber Tracker in a 2T solenoid allows accurate vertex and track reconstruction.
Data for this analysis is recorded using single muon and dimuon triggers.
$\Lambda_b^0$ reconstruction

- $p_T(\mu) > 2$ GeV/c
- $p_T(\mu^+\mu^-) > 3$ GeV/c
- $p_T(\Lambda) > 1.6$ GeV/c,
- $\Lambda^0$ decay length ($L_{xy}/\sigma_{L_{xy}} > 4$),
- ($\Lambda^0$ decay vertex to $J/\psi$ vertex) pointing angle ($< 2.5^\circ$),

Due to $\Lambda^0$ large lifetime ($c\tau \sim 8$ cm), the $p$ and $\pi$ are required to have large impact parameter.

DØ can not distinguish between protons and pions. From Monte-Carlo, $p_T(p) > p_T(\pi)$. Then assume $p$ is leading.
$B^0_d$ reconstruction

- Similar conditions to reconstruct $K^0_S \rightarrow \pi^+\pi^-$. 
- We use $B^0_d \rightarrow J/\psi K^0_S$ as normalization channel for $\Lambda^0_b \rightarrow J/\psi \Lambda^0$.  
- Track pairs simultaneously identified as both $\Lambda^0$ and $K^0_S$ due to different mass assignments to the same tracks are removed.
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Armeteros-Podolanski plots after removing track pair ambiguities.
Measurement of $f(b \rightarrow \Lambda_b) \cdot B(\Lambda_b \rightarrow J/\psi \Lambda)$

Event Reconstruction

$\Lambda^0_b$ and $B^0_d$ reconstruction and yields

- $\Lambda^0_b$ ($B^0_d$) are reconstructed by performing a constrained fit to a common vertex for the $\Lambda^0$ ($K^0_S$) and two muon tracks.
- Minimum transverse proper decay length ($>2$) to reduce ($J/\psi$) prompt background.

![Graphs showing invariant mass distributions for $\Lambda_b$ and $B^0$ decay products.](image)
**Λ^0_b → J/ψΛ^0** Branching Fraction measurement: method

\[ N_{\text{obs}} [\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)] = N_{\text{prod}} [\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)] \times \epsilon_R [\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)] \]

where the number of decays produced in collisions is:

\[ N_{\text{prod}} [\Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)] = \mathcal{L}\sigma(p\bar{p} \rightarrow b\bar{b}) f(b \rightarrow \Lambda_b) \times Br (\Lambda_b \rightarrow J/\psi\Lambda^0) \times Br (J/\psi \rightarrow \mu^+\mu^-) \times Br (\Lambda^0 \rightarrow p\pi^-) \]

The efficiency \( \epsilon_R \) (acceptance + detector + reconstruction) can be obtained from simulations. **Similar expressions for \( B^0_d \rightarrow J/\psi K^0_S \).**
\( \Lambda_b^0 \rightarrow J/\psi \Lambda^0 \) Branching Fraction measurement: method

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N_{\text{obs}} [\Lambda_b \rightarrow J/\psi (\mu^+ \mu^-) \Lambda^0 (p\pi^-)] = N_{\text{prod}} [\Lambda_b \rightarrow J/\psi (\mu^+ \mu^-) \Lambda^0 (p\pi^-)] \\
\times \epsilon_R [\Lambda_b \rightarrow J/\psi (\mu^+ \mu^-) \Lambda^0 (p\pi^-)]
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N_{\text{prod}} [\Lambda_b \rightarrow J/\psi (\mu^+ \mu^-) \Lambda^0 (p\pi^-)] = \mathcal{L} \sigma(p\overline{p} \rightarrow b\overline{b}) f(b \rightarrow \Lambda_b) \\
\times Br (\Lambda_b \rightarrow J/\psi \Lambda^0) Br (J/\psi \rightarrow \mu^+ \mu^-) Br (\Lambda^0 \rightarrow p\pi^-)
\]

The efficiency \( \epsilon_R \) (acceptance+detector+reconstruction) can be obtained from simulations. Similar expressions for \( B_d^0 \rightarrow J/\psi K_S^0 \). Then:

\[
\sigma_{\text{rel}} = \frac{f(b \rightarrow \Lambda_b) \cdot B(\Lambda_b \rightarrow J/\psi \Lambda)}{f(b \rightarrow B^0) \cdot B(B^0 \rightarrow J/\psi K_S^0)} = \frac{N_{\Lambda_b \rightarrow J/\psi \Lambda}}{N_{B^0 \rightarrow J/\psi K_S^0}} \cdot \frac{B(K_S^0 \rightarrow \pi^+ \pi^-)}{B(\Lambda \rightarrow p\pi^-)} \cdot \epsilon.
\]

\[
\epsilon \equiv \frac{\epsilon_R[B^0 \rightarrow J/\psi K_S^0]}{\epsilon_R[\Lambda_b \rightarrow J/\psi \Lambda]}
\]

(Most systematic errors cancel in this ratio)
The relative efficiency $\epsilon$ is determined from MC simulation:
- Pythia (production) + EvtGen$^4$ (decay) + GEANT (detector).
- Same reconstruction algorithm as in data.

Data and Monte Carlo distributions are found to be in good agreement. Below an example.

We found $\epsilon = 2.37 \pm 0.05$. 

Dominant systematic unc.:
- Unknown $\Lambda_b^0$ polarization, impacts evaluation of $\epsilon$.
- $\Lambda_b^0$ initially polarized was implemented in EvtGen, assigning the correct spin density matrix. $\Lambda_b \to J/\psi\Lambda$ is described completely in terms of 5 (helicity) angles.
- Polarization is observed (mainly) through $\theta$:

$$I(\theta) = \frac{1}{2} (1 + \alpha_{\Lambda_b} P_{\Lambda_b} \cos \theta) \quad (1)$$

($\alpha_{\Lambda_b}$ and $P_{\Lambda_b}$ are the $\Lambda_b^0$ (weak PV) asymmetry parameter and polarization.)
$\Lambda_0^b \rightarrow J/\psi \Lambda^0$ Branching Ratio measurement: results

\[
\frac{f(b \rightarrow \Lambda_b) \cdot B(\Lambda_b \rightarrow J/\psi \Lambda)}{f(b \rightarrow B^0) \cdot B(B^0 \rightarrow J/\psi K_s^0)} = 0.345 \pm 0.034 \text{ (stat.)} \\
\pm 0.033 \text{ (syst.)} \pm 0.003 \text{ (PDG)}
\]

- From the PDG, $f(b \rightarrow B^0) \cdot B(B^0 \rightarrow J/\psi K_s^0) = (1.74 \pm 0.08) \times 10^{-4}$.

Then:

\[
f(b \rightarrow \Lambda_b) \cdot B(\Lambda_b \rightarrow J/\psi \Lambda) \quad [\times 10^{-5}] = \\
6.01 \pm 0.60 \text{ (stat.)} \pm 0.58 \text{ (syst.)} \pm 0.28 \text{ (PDG)} = \\
6.01 \pm 0.88
\]

[PDG 2010: $(4.7 \pm 2.3) \times 10^{-5}$]

- arXiv:1105.0690. Accepted in PRD-RC.
Final comments: $\Lambda^0_b \rightarrow \mu^+ \mu^- \Lambda^0$

- We can use $\Lambda_b \rightarrow J/\psi + \Lambda$ to normalize $\Lambda_b \rightarrow \mu^+ \mu^- + \Lambda$:
  
  $BR[\Lambda_b \rightarrow \mu^+ \mu^- + \Lambda] = \frac{BR[\Lambda_b \rightarrow J/\psi + \Lambda] \times BR[J/\psi \rightarrow \mu^+ \mu^-]}{\varepsilon_{b \rightarrow W \rightarrow s} \times \frac{N_{\text{obs}}[\Lambda_b \rightarrow \mu^+ \mu^- + \Lambda_{[\pi p]}]}{N_{\text{obs}}[\Lambda_b \rightarrow J/\psi_{[\mu \mu]} + \Lambda_{[\pi p]}]}}$

- The BR of this rare decay ($\sim 2 - 5 \times 10^{-6}$ in SM) can be enhanced by new physics effects ($\times 10$ in SUSY models).

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5 PRD 64, 074001 (2001); PRD 81, 056006 (2010); arXiv:0808.2113.
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- The BR of this rare decay ($\sim 2 - 5 \times 10^{-6}$ in SM) can be enhanced by new physics effects ($\times 10$ in SUSY models).\(^5\)

- CDF reported the observation of this decay a few days ago (arXiv:1107.3753v1): using our measurement they found $\mathcal{B}(\Lambda_b \rightarrow \mu^+ \mu^- \Lambda) = 1.73 \pm 0.42 \text{ (stat)} \pm 0.55 \text{ (syst.)}$ and no significant deviation from the SM.

\(^5\) PRD 64, 074001,(2001); PRD 81,056006 (2010); arXiv:0808.2113.
Conclusions

- A new measurement of $f(b \rightarrow \Lambda_b) \cdot B(\Lambda_b \rightarrow J/\psi \Lambda)$ has been performed and is found to be:

  $$(6.01 \pm 0.60 \text{ (stat.)} \pm 0.58 \text{ (syst.)} \pm 0.28 \text{ (PDG)}) \times 10^{-5}$$

- This result represents a reduction by a factor of $\sim 3$ of the uncertainty with respect to the previous measurement.

- Important measurements such as the branching ratio of FCNC decays ($\Lambda_b \rightarrow \mu^+\mu^-\Lambda$) or the $\Lambda_b$ polarization can be performed with the tools developed in this analysis.

  Stay tuned, we are working on that!
Final comments: How can we extract \( \mathcal{B}(\Lambda_b \to J/\psi \Lambda) \)?

- We need an external measurement of \( f(b \to \Lambda_b) \). We are not aware of any direct measurement of this quantity.
- \( f(b \to b_{baryon}) \neq f(b \to \Lambda_b) \). Tevatron has observed \( \Xi^-_b, \Sigma_b, \Omega_b \), and recently \( \Xi^0_b \).
- To first approximation,
  \[
  f(b \to b_{baryon}) \approx f(b \to \Lambda_b) + f(b \to \Xi^-_b) + f(b \to \Xi^0_b).
  \]
  - Assume isospin invariance. Then \( f(b \to \Xi^-_b) \approx f(b \to \Xi^0_b) \).
  - It's also observed that
    \[
    \frac{f(b \to B_s)}{f(b \to B_d)} \approx \frac{f(b \to \Xi^-_b)}{f(b \to \Lambda_b)}.
    \]
  - Then: \( \mathcal{B}(\Lambda_b \to J/\psi \Lambda) \approx (11.08 \pm 1.09 \text{ (stat)} \pm 1.06 \text{ (syst)} \pm 3.13 \text{ (PDG)}) \times 10^{-4} = (11.08 \pm 3.48) \times 10^{-4} \).
  - Same assumptions to the W.A would lead to \( (8.67 \pm 4.84) \times 10^{-4} \).

- Experimental results favors models which predict a larger value for this branching ratio.

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6 arXiv:1010.1589v2