b polarization as a probe of new physics

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Work in progress, with

Mario Galanti, Andrea Giammanco (experiment)

Yuval Grossman, Emmanuel Stamou, Jure Zupan (theory)

Motivation

Polarization of decay products contains valuable information.

- Example: (SUSY) LH vs. RH stop/sbottom decaying to b's

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- **Evidence** observed at **LEP** in $Z \to b\bar{b}$.

ALEPH: PLB 365, 437 (1996); OPAL: PLB 444, 539 (1998); DELPHI: PLB 474, 205 (2000)

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- How to measure b polarization at the **LHC**?
- Can we **calibrate** the measurement on Standard Model samples?
- Can we use it for discovering / characterizing **new physics**?

b spin in a hadron

b quark is heavy $m_b \gg \Lambda_{\mathrm{QCD}}$

chromomagnetic moment $\mu_b \propto \dfrac{1}{m_b}$

b spin is **preserved** in hadronization

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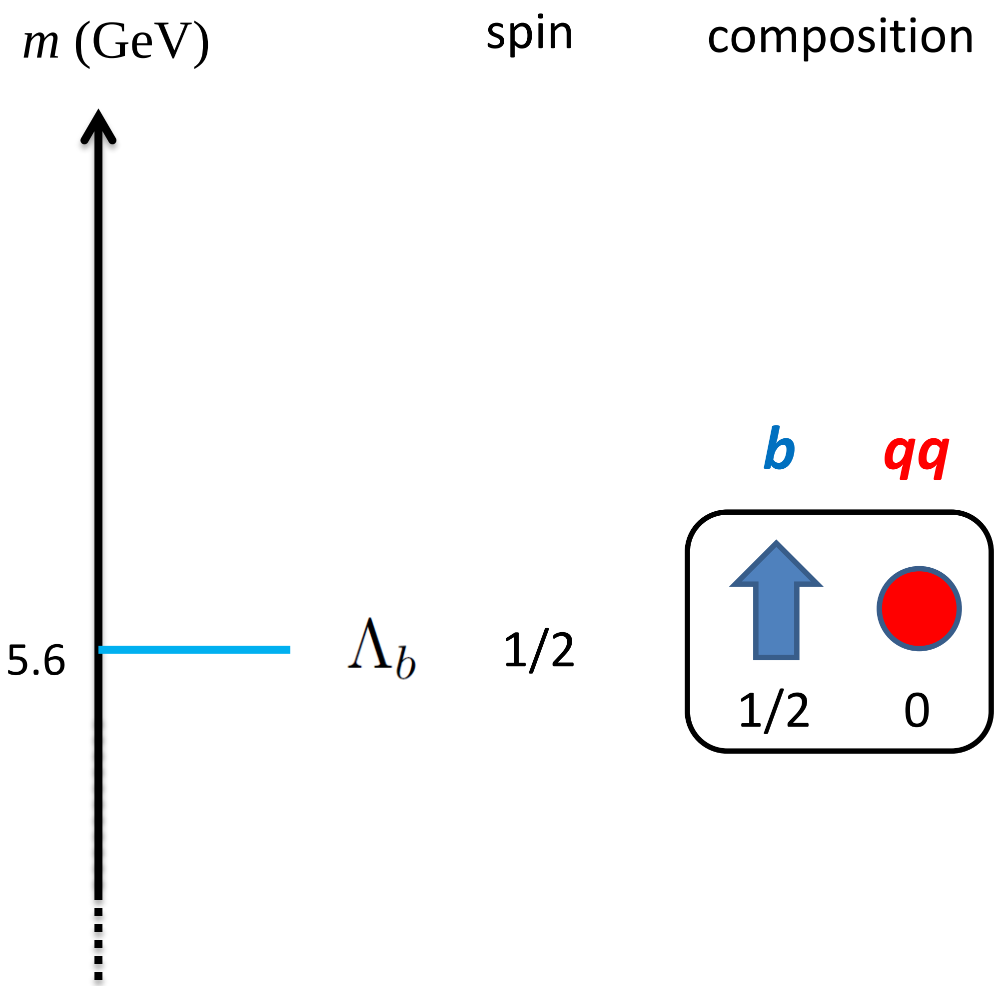
Mesons (≈ 90%): useless b/c decay as scalars

Baryons (≈ 10%): much more interesting!

b spin in a baryon



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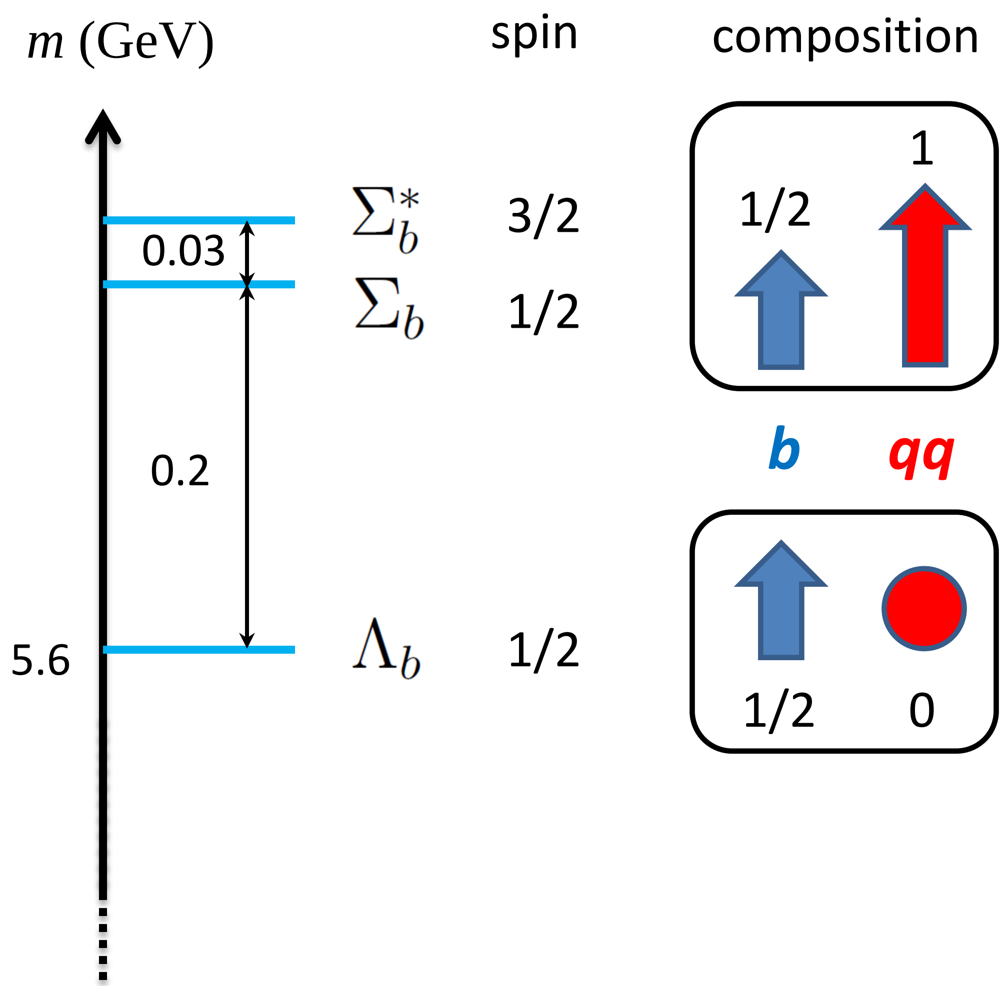

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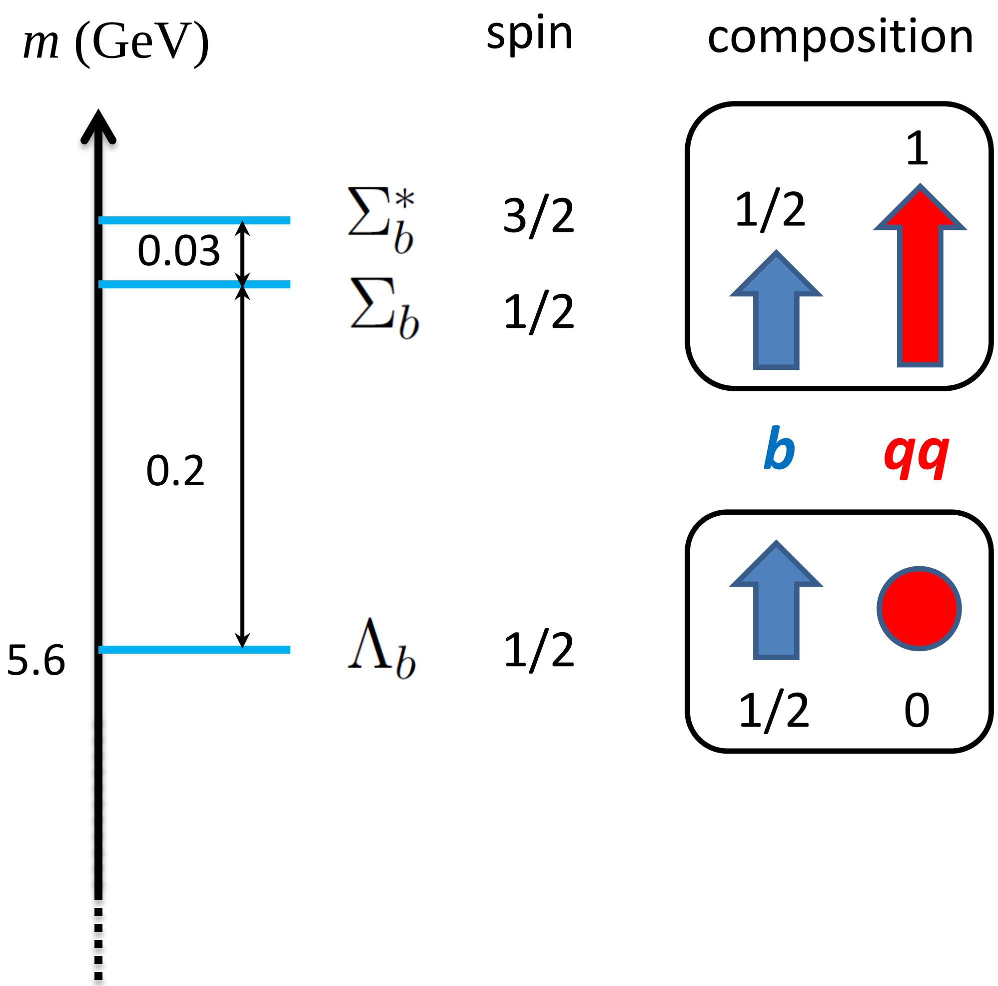

b spin **oscillates** due to chromomagnetic moment interaction.

Then decay to Λ_b:

$$\Sigma_b^{(*)} \to \Lambda_b \pi$$

b spin is **preserved**

Polarization retention

For interpreting polarization measurement, need to know

$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)}$$

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Polarization loss due to Λ_b's from $\Sigma_b^{(*)}$ decays:

Produced in *b* spin basis, but decay in $\Sigma_b^{(*)}$ mass basis

diquarks

S spin-0 isosinglet

T spin-1 isotriplet

$$|\Lambda_{b,+\frac{1}{2}}\rangle = |b_{+\frac{1}{2}}\rangle|S_0\rangle$$

$$|\Sigma_{b,+\frac{1}{2}}\rangle = -\sqrt{\tfrac{1}{3}}\,|b_{+\frac{1}{2}}\rangle|T_0\rangle + \sqrt{\tfrac{2}{3}}\,|b_{-\frac{1}{2}}\rangle|T_{+1}\rangle$$

$$|\Sigma^*_{b,+\frac{1}{2}}\rangle = \sqrt{\tfrac{2}{3}}\,|b_{+\frac{1}{2}}\rangle|T_0\rangle + \sqrt{\tfrac{1}{3}}\,|b_{-\frac{1}{2}}\rangle|T_{+1}\rangle$$

$$|\Sigma^*_{b,+\frac{3}{2}}\rangle = |b_{+\frac{1}{2}}\rangle|T_{+1}\rangle$$

Example: $|b_{+\frac{1}{2}}\rangle|T_0\rangle = -\sqrt{\tfrac{1}{3}}\,|\Sigma_{b,+\frac{1}{2}}\rangle + \sqrt{\tfrac{2}{3}}\,|\Sigma^*_{b,+\frac{1}{2}}\rangle$

Polarization retention

For interpreting polarization measurement, need to know

$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)}$$

Result:

$$r = \frac{1 + (1 + 4w_1)A/9}{1 + A}$$

depends on two hadronization parameters:

$$A = \frac{\mathrm{prob}(\Sigma_b^{(*)})}{\mathrm{prob}\,(\Lambda_b)} = 9\,\frac{\mathrm{prob}(T)}{\mathrm{prob}(S)} \qquad\qquad w_1 = \frac{\mathrm{prob}\,(T_{\pm 1})}{\mathrm{prob}\,(T)}$$

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More precisely, account for $\Sigma_b{}^{(*)}$ widths (interference):

$$|E\rangle \propto \int d\cos\theta\, d\phi \sum_{J,M} \langle J, M \,|\, \tfrac{1}{2}, +\tfrac{1}{2};\, 1, m\rangle \,\frac{p_\pi(E)}{E - m_J + i\Gamma(E)/2} \times$$

$$\times \sum_{s} \langle \tfrac{1}{2}, s;\, 1, M-s \,|\, J, M\rangle\, Y_1^{M-s}(\theta,\phi)\, |\theta,\phi\rangle\, |s\rangle$$

pion momentum

Λ_b spin

$$\rho(E) \propto \mathrm{Tr}_{\theta,\phi}\, |E\rangle\, \langle E|$$

$$\rho \propto \int_{m_{\Lambda_b}+m_\pi}^{\infty} dE\, p_\pi(E)\, \exp\left(-E/T\right) \rho(E)$$

Result:

$$r \approx \frac{1 + (0.23 + 0.38 w_1)\, A}{1 + A}$$

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No direct measurement of A yet.

Statistical hadronization model: $A \approx 2.4$

Pythia tunes (from light hadron data): $0.24 \lesssim A \lesssim 0.45$

DELPHI: $w_1 = -0.36 \pm 0.30 \pm 0.30$ CLEO: $w_1 = 0.71 \pm 0.13$

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Stati

It would be useful to measure *r* directly.

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Extracting A and w_1 from anisotropy of r

$$w_1 = \frac{\mathrm{prob}\,(T_{\pm 1})}{\mathrm{prob}\,(T)}$$ applies along the fragmentation axis

If b is polarized transversely, r is different.

$$r_L \approx \frac{1 + (0.23 + 0.38 w_1)\, A}{1 + A}$$

$$r_T \approx \frac{1 + (0.62 - 0.19 w_1)\, A}{1 + A}$$

Measuring both r_L and r_T would allow determining A and w_1.

Λ_b decay modes

Choose semileptonic mode, **inclusive** in charm hadrons (large BR, no hadronic uncertainties).

	Mode		Fraction (Γ_i/Γ)
Γ_1	$J/\psi(1S)\Lambda \times$ B$(b \to \Lambda_b^0)$		$(5.8 \pm 0.8) \times 10^{-5}$
Γ_2	$p D^0 \pi^-$		$(5.9 {}^{+4.0}_{-3.2}) \times 10^{-4}$
Γ_3	$p D^0 K^-$		$(4.3 {}^{+3.0}_{-2.4}) \times 10^{-5}$
Γ_4	$\Lambda_c^+ \pi^-$		$(5.7 {}^{+4.0}_{-2.6}) \times 10^{-3}$
Γ_5	$\Lambda_c^+ K^-$		$(4.2 {}^{+2.6}_{-1.9}) \times 10^{-4}$
Γ_6	$\Lambda_c^+ a_1(1260)^-$		seen
Γ_7	$\Lambda_c^+ \pi^+ \pi^- \pi^-$		$(8 {}^{+5}_{-4}) \times 10^{-3}$
Γ_8	$\Lambda_c(2595)^+ \pi^-$, $\Lambda_c(2595)^+ \to \Lambda_c^+ \pi^+ \pi^-$		$(3.7 {}^{+2.8}_{-2.3}) \times 10^{-4}$
Γ_9	$\Lambda_c(2625)^+ \pi^-$, $\Lambda_c(2625)^+ \to \Lambda_c^+ \pi^+ \pi^-$		$(3.6 {}^{+2.7}_{-2.1}) \times 10^{-4}$
Γ_{10}	$\Sigma_c(2455)^0 \pi^+ \pi^-$, $\Sigma_c^0 \to \Lambda_c^+ \pi^-$		$(6 {}^{+5}_{-4}) \times 10^{-4}$
Γ_{11}	$\Sigma_c(2455)^{++} \pi^- \pi^-$, $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$		$(3.5 {}^{+2.8}_{-2.3}) \times 10^{-4}$
Γ_{12}	$\Lambda K^0 2\pi^+ 2\pi^-$		
Γ_{13}	$\Lambda_c^+ \ell^- \overline{\nu}_\ell$ anything	[a]	(9.9 ± 2.2) %
Γ_{14}	$\Lambda_c^+ \ell^- \overline{\nu}_\ell$		$(6.5 {}^{+3.2}_{-2.5})$ %
Γ_{15}	$\Lambda_c^+ \pi^+ \pi^- \ell^- \overline{\nu}_\ell$		(5.6 ± 3.1) %
Γ_{16}	$\Lambda_c(2595)^+ \ell^- \overline{\nu}_\ell$		$(8 \pm 5) \times 10^{-3}$
Γ_{17}	$\Lambda_c(2625)^+ \ell^- \overline{\nu}_\ell$		$(1.4 {}^{+0.9}_{-0.7})$ %
Γ_{18}	$\Sigma_c(2455)^0 \pi^+ \ell^- \overline{\nu}_\ell$		
Γ_{19}	$\Sigma_c(2455)^{++} \pi^- \ell^- \overline{\nu}_\ell$		
Γ_{20}	$p h^-$	[b]	$< 2.3 \times 10^{-5}$
Γ_{21}	$p \pi^-$		$(4.1 \pm 0.8) \times 10^{-6}$
Γ_{22}	$p K^-$		$(4.9 \pm 0.9) \times 10^{-6}$
Γ_{23}	$\Lambda \mu^+ \mu^-$		$(1.08 \pm 0.28) \times 10^{-6}$
Γ_{24}	$\Lambda \gamma$		$< 1.3 \times 10^{-3}$

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Γ_{11}	$\Sigma_c(2455)^{++}\pi^-\pi^-$, $\Sigma_c^{++}\to\Lambda_c^+\pi^+$		$(3.5\ ^{+2.8}_{-2.3}) \times 10^{-4}$
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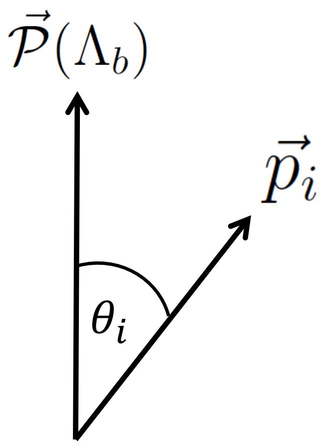
Choose semileptonic mode, **inclusive** in charm hadrons (large BR, no hadronic uncertainties).

Also:

$\Lambda_b \to p\, D^0\, \ell^- \bar{\nu}_\ell$ expect very small

Semileptonic Λ_b decays

$$\Lambda_b \to X_c \ell^- \bar{\nu}$$



$$\frac{1}{\Gamma_{\Lambda_b}} \frac{d\Gamma_{\Lambda_b}}{d\cos\theta_i} = \frac{1}{2}\left(1 + \alpha_i\, \mathcal{P}\left(\Lambda_b\right)\cos\theta_i\right)$$

$$\alpha_\ell = \frac{-\frac{1}{6} + 2\rho + 6\rho^2 - \frac{22}{3}\rho^3 - \frac{1}{2}\rho^4 + 6\rho^2\log\rho + 4\rho^3\log\rho}{\frac{1}{2}\left(1 - 8\rho + 8\rho^3 - \rho^4 - 12\rho^2\log\rho\right)} \approx -0.26$$

$$\alpha_\nu = 1 \qquad\qquad \rho = \frac{m_c^2}{m_b^2}$$

$\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b)$ corrections are absent, and α_s corrections are few %.

Manohar, Wise
PRD 49, 1310 (1994)

Czarnecki, Jezabek, Korner, Kuhn, PRL 73, 384 (1994)
Czarnecki, Jezabek, NPB 427, 3 (1994)

Polarization measurement

- Demand a **muon** (with IP and $p_{\mathrm{T,rel}}$) inside a jet.

- **Reconstruct** the neutrino (up to 2-fold ambiguity) by using:
  - Λ_b mass constraint
  - Line from primary to secondary vertex as Λ_b direction of motion

Dambach, Langenegger, Starodumov, NIMA 569, 824 (2006) [hep-ph/0607294]

- Measure neutrino $\boldsymbol{A}_{\mathbf{FB}}$ in Λ_b rest frame

$$A_{\mathrm{FB}} \equiv \frac{N_+ - N_-}{N_+ + N_-} = f_{\Lambda_b} \frac{\alpha}{2} \mathcal{P}(\Lambda_b)$$

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Λ_b fragmentation fraction (≈ 8%)

i.e., semileptonic B-meson "background" (isotropic) dilutes A_{FB}.

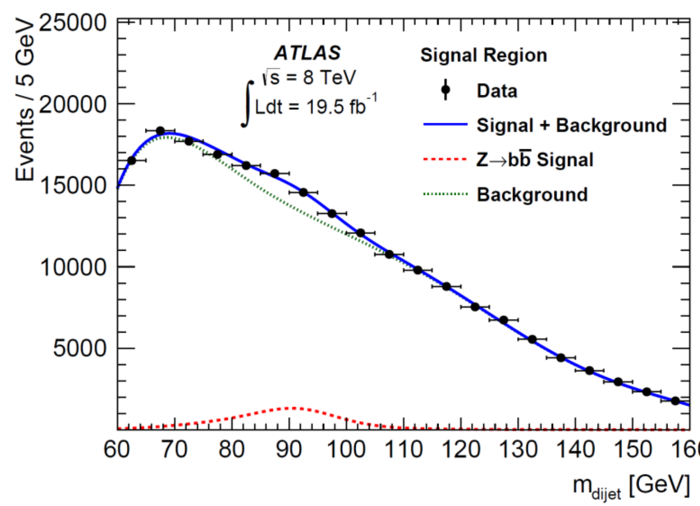
- (optional) To eliminate the B mesons, demand the presence of $\Lambda \to p\pi^-$ in the jet (see backup slides).

Where to measure

- **Top pair production**
  + Maximal polarization (≈ 1)
  + Large cross section
  + Easy to select a clean sample
  > 3σ significance possible at ATLAS/CMS (lepton + jets channel) with existing 8 TeV data, even for *r* = 0.5 (preliminary estimate).

- **Z production**
  + Large polarization (≈ 0.94)
  + Large cross section
  – Large QCD background (S/B ≈ 1/15) contributes statistical fluctuations.
  Likely not measurable anytime soon.

arXiv:1404.7042



LEP

$$\mathcal{P}(\Lambda_b) = -0.23^{+0.24}_{-0.20}{}^{+0.08}_{-0.07} \quad \text{(ALEPH)}$$

$$\mathcal{P}(\Lambda_b) = -0.49^{+0.32}_{-0.30} \pm 0.17 \quad \text{(DELPHI)}$$

$$\mathcal{P}(\Lambda_b) = -0.56^{+0.20}_{-0.13} \pm 0.09 \quad \text{(OPAL)}$$

Where to measure

- **QCD production**
  + Large cross section
  – Unpolarized at leading order
  + *Transverse* polarization at NLO
  = Strong dependence on kinematics
  – Significant only at low momenta

$$\mathcal{P}(b) \sim \alpha_s m_b / p_b$$

Relevant for LHCb

Dharmaratna, Goldstein
PRD 53, 1073 (1996)

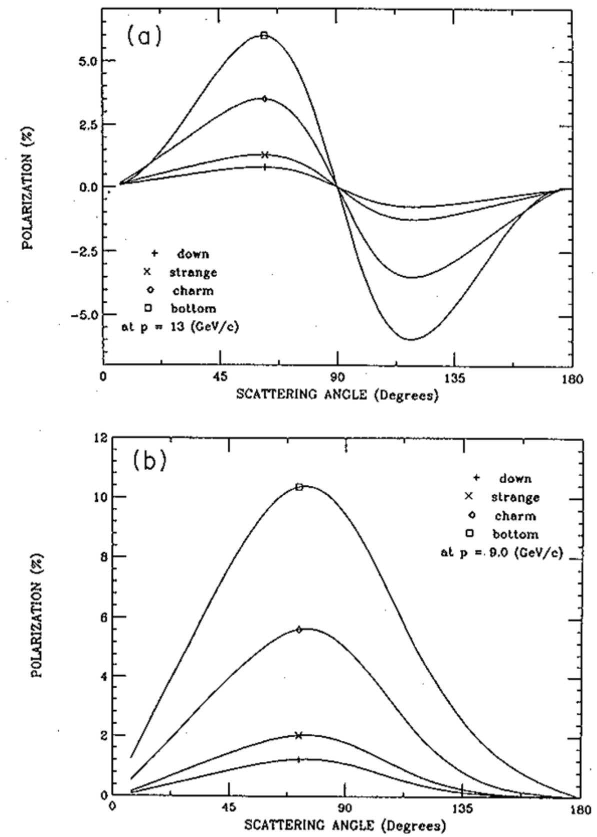


FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.

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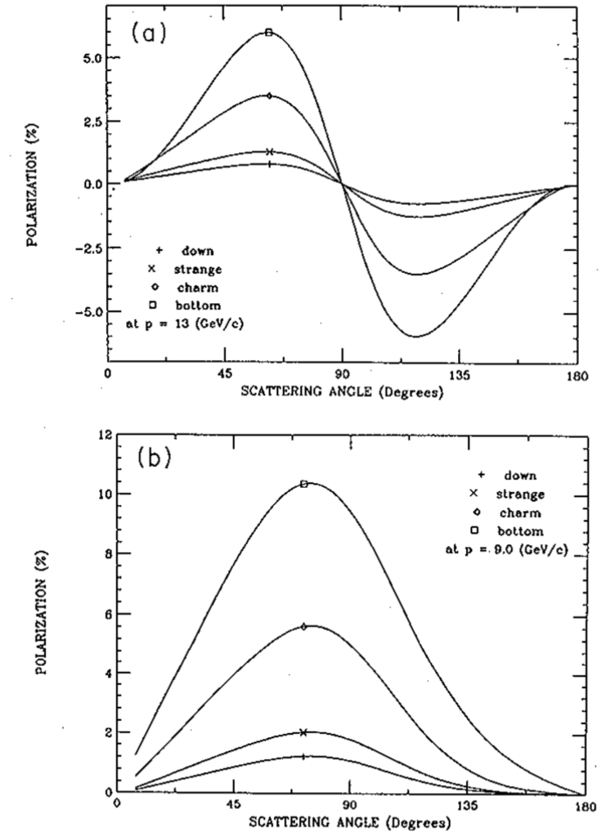


FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.

LHCb has already measured:

Measurements of the $\Lambda_b^0 \to J/\psi\,\Lambda$ decay amplitudes and the Λ_b^0 polarisation in pp collisions at $\sqrt{s} = 7$ TeV

PLB 724, 27 (2013)
[arXiv:1302.5578]

$$\mathcal{P}(\Lambda_b) = 0.06 \pm 0.07 \pm 0.02$$

Far from optimal because the dependence on kinematics was ignored.

b's from new physics

Example: b's from pair produced **sbottoms or stops** (2 b's per event)

Assumptions about a future analysis:

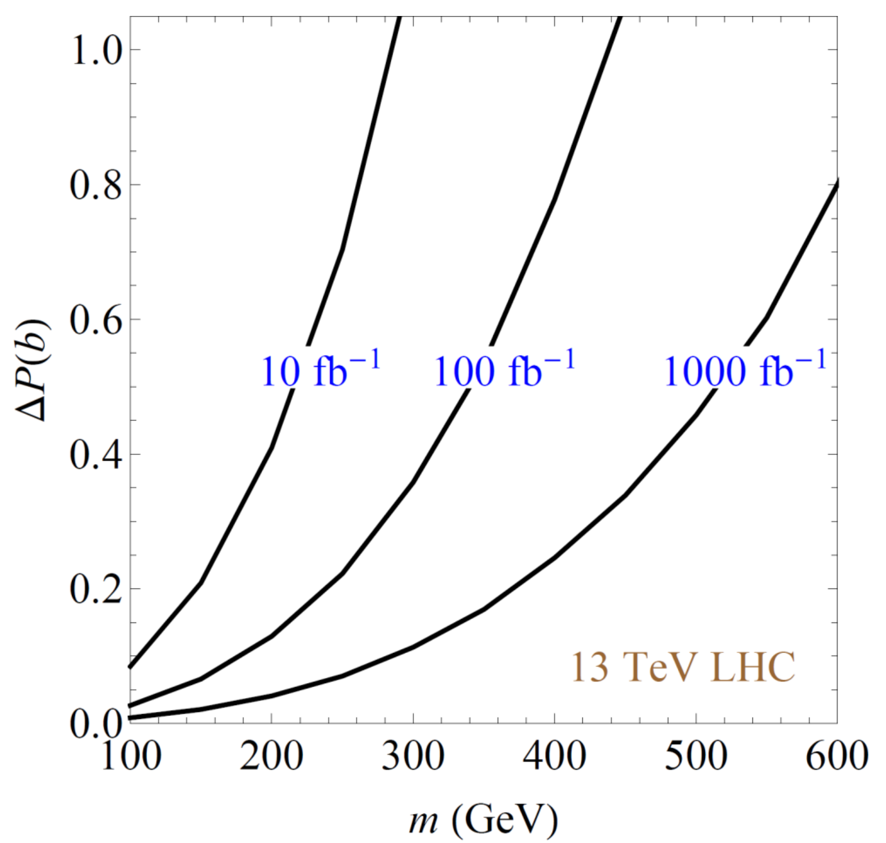
- $S/B \gtrsim 1$
- signal efficiency $\epsilon_S = 0.1$
- muon BR x efficiency $\epsilon_{b\to\mu} = 0.06$
- Using neutrino A_{FB}, i.e., $\alpha = 1$
- Not requiring a Λ
- Statistical uncertainty dominates

$$\Delta\mathcal{P}(b) = \frac{\sqrt{2}\,(1 + B/S)}{\alpha\, r\, f_{\Lambda_b}\sqrt{\epsilon_{b\to\mu}\,\epsilon_S\,\mathcal{L}\,\sigma_S}} \approx \frac{330}{\sqrt{\mathcal{L}\,\sigma_S}}$$

$r = 0.7$

$$-1 < \mathcal{P}(b) < 1$$

$\tilde{t}\tilde{t}^*$ or $\tilde{b}\tilde{b}^*$



b's from new physics

Example: b's from pair produced **gluinos** (2 b's per event)

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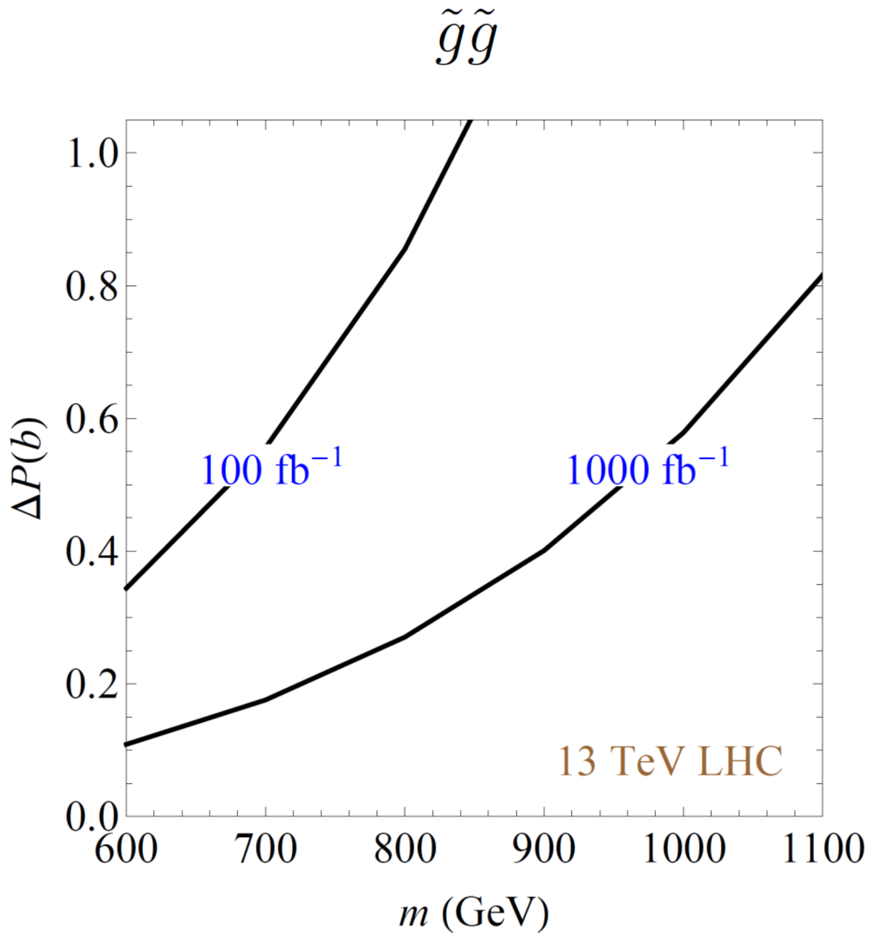


Measuring c polarization with Λ_c

- Same formalism ensures $\mathcal{O}(1)$ polarization retention.
- $\mathcal{O}(\Lambda_{\rm QCD}/m_c)$ corrections less negligible than $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$ but we propose to determine r experimentally anyway.
- Fragmentation fraction: $f_{\Lambda_c} \approx 8\%$
- Potentially promising decay mode: $\Lambda_c^+ \to pK^-\pi^+$
  - 5% BR (vs. 2% for semileptonic).
  - Automatic reduction of D-meson background.

  Decay product most sensitive to polarization can be determined experimentally.
- Calibration sample: $t\bar{t}$ with $W^+ \to c\bar{s}$

b polarization as a probe of new physics

Yevgeny Kats
Weizmann Institute of Science

Work in progress, with
Mario Galanti, Andrea Giammanco (experiment)
Yuval Grossman, Emmanuel Stamou, Jure Zupan (theory)

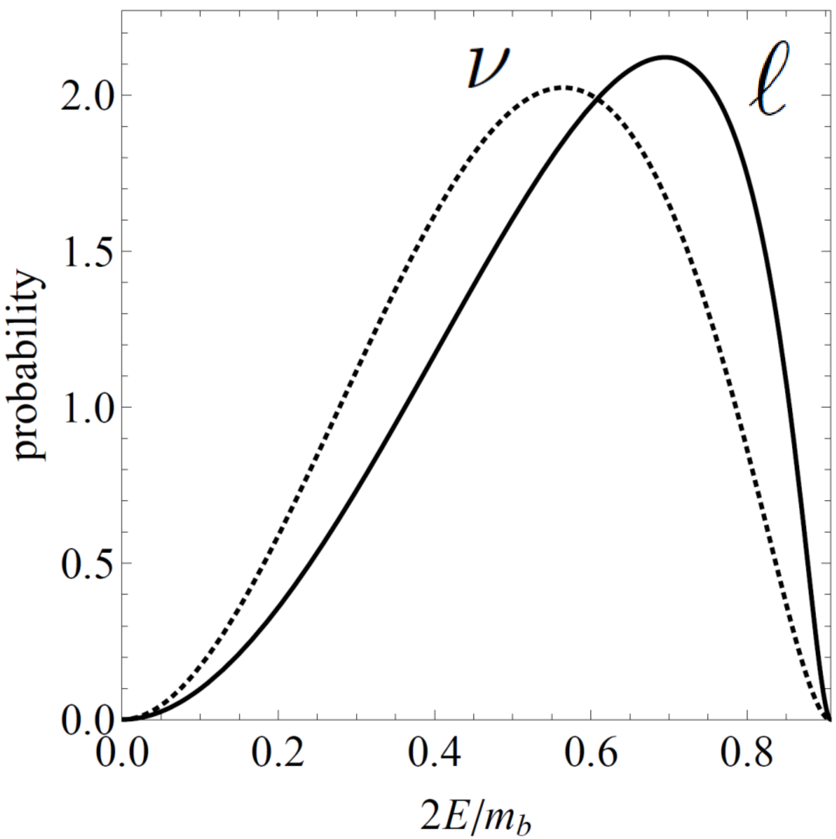
Thank You!

Backup slides

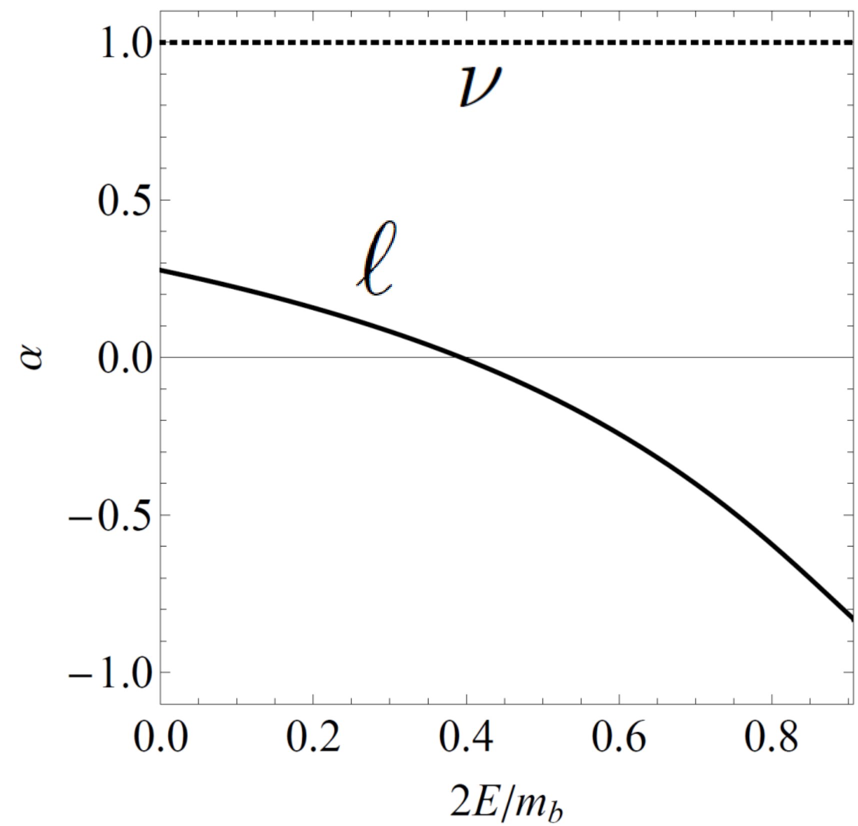
Energy dependence in Λ_b decay

$$\Lambda_b \to X_c \ell^- \bar{\nu}$$

energy distribution



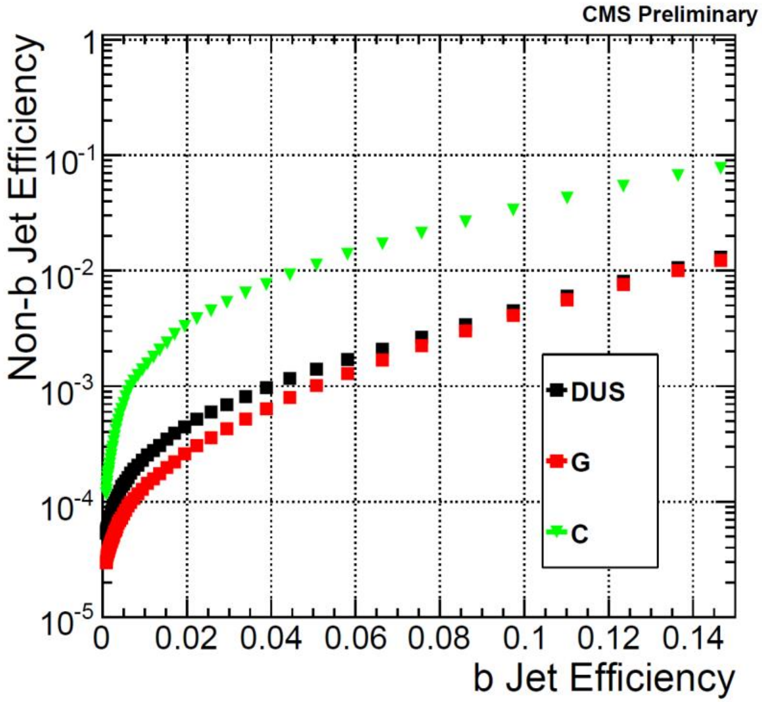
A_{FB} vs. energy



Soft muon *b*-tagging

CMS PAS BTV-09-001

MC @ 10 TeV



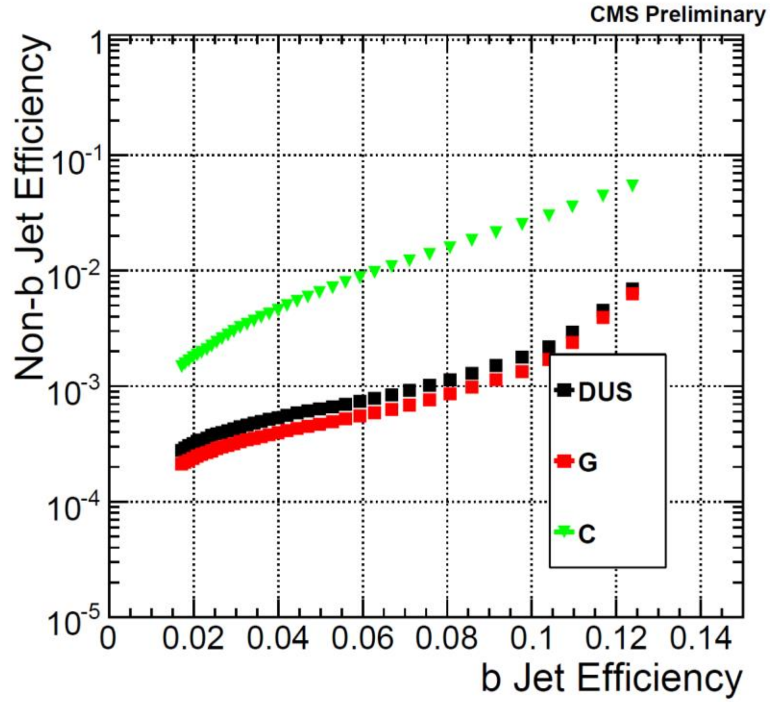


Figure 9: Mistag rate versus efficiency for the "soft muon by $p_{T_{rel}}$" (left) and "soft muon by IP" (right) taggers.

Λ requirement

Λ_c decay modes

Inclusive modes

Γ_{67}	e^+ anything	$(4.5 \pm 1.7)\,\%$
Γ_{68}	$p e^+$ anything	$(1.8 \pm 0.9)\,\%$
Γ_{69}	Λe^+ anything	
Γ_{70}	p anything	$(50 \pm 16)\,\%$
Γ_{71}	p anything (no Λ)	$(12 \pm 19)\,\%$
Γ_{72}	p hadrons	
Γ_{73}	n anything	$(50 \pm 16)\,\%$
Γ_{74}	n anything (no Λ)	$(29 \pm 17)\,\%$
$\boxed{\Gamma_{75}}$	$\boxed{\Lambda \text{ anything}}$	$\boxed{(35 \pm 11)\,\%}$
Γ_{76}	$\Sigma^\pm$ anything	$(10 \pm 5)\,\%$
Γ_{77}	3prongs	$(24 \pm 8)\,\%$

Semileptonic modes

~~Γ_{64}~~	~~$\Lambda \ell^+ \nu_\ell$~~	~~$(2.0 \pm 0.6)\,\%$~~
~~Γ_{65}~~	~~$\Lambda e^+ \nu_e$~~	~~$(2.1 \pm 0.6)\,\%$~~
~~Γ_{66}~~	~~$\Lambda \mu^+ \nu_\mu$~~	~~$(2.0 \pm 0.7)\,\%$~~

Λ decay modes

$\boxed{\Gamma_1}$	$\boxed{p\pi^-}$	$\boxed{(63.9 \pm 0.5)\,\%}$
Γ_2	$n\pi^0$	$(35.8 \pm 0.5)\,\%$
Γ_3	$n\gamma$	$(1.75 \pm 0.15) \times 10^{-3}$
Γ_4	$p\pi^-\gamma$	$(8.4 \pm 1.4) \times 10^{-4}$
Γ_5	$p e^- \overline{\nu}_e$	$(8.32 \pm 0.14) \times 10^{-4}$
Γ_6	$p \mu^- \overline{\nu}_\mu$	$(1.57 \pm 0.35) \times 10^{-4}$

Overall BR ≈ 20%. Need $\Lambda \to p\pi^-$ reconstruction efficiency > 50% to have statistical advantage. Will be possible with upgraded detectors (?)