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Baryons as polarimeters for ATLAS and CMS

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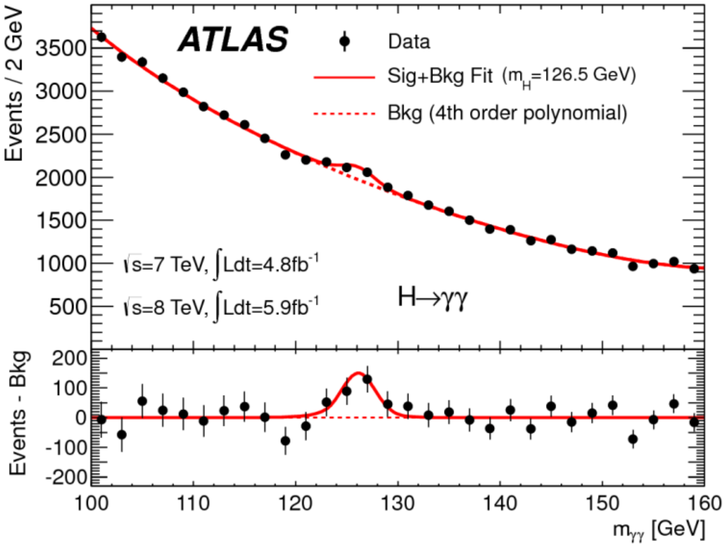
arXiv:1505.02771 (for heavy quarks)
in collaboration with:
Mario Galanti, Andrea Giammanco (experiment)
Yuval Grossman, Emmanuel Stamou, Jure Zupan (theory)

arXiv:1505.06731 (for light quarks)

Motivation

Information about new physics
is encoded in the Standard Model
particles produced in the event.



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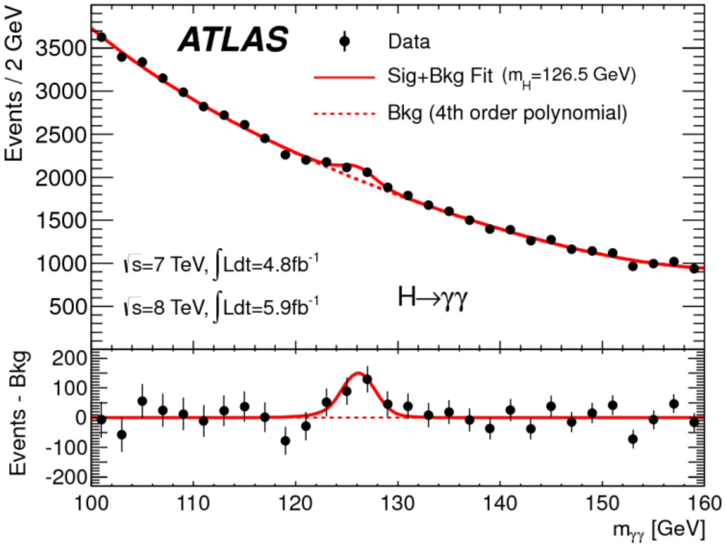
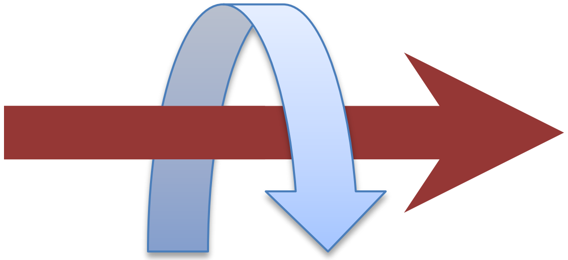


1968: SLAC u up quark	1974: Brookhaven & SLAC c charm quark	1995: Fermilab t top quark	1979: DESY g gluon
1968: SLAC d down quark	1947: Manchester University s strange quark	1977: Fermilab b bottom quark	1923: Washington University* γ photon
1956: Savannah River Plant ν_e electron neutrino	1962: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W W boson
1897: Cavendish Laboratory e electron	1937 : Caltech and Harvard μ muon	1976: SLAC τ tau	1983: CERN Z Z boson



Each particle carries **momentum** and **spin**.

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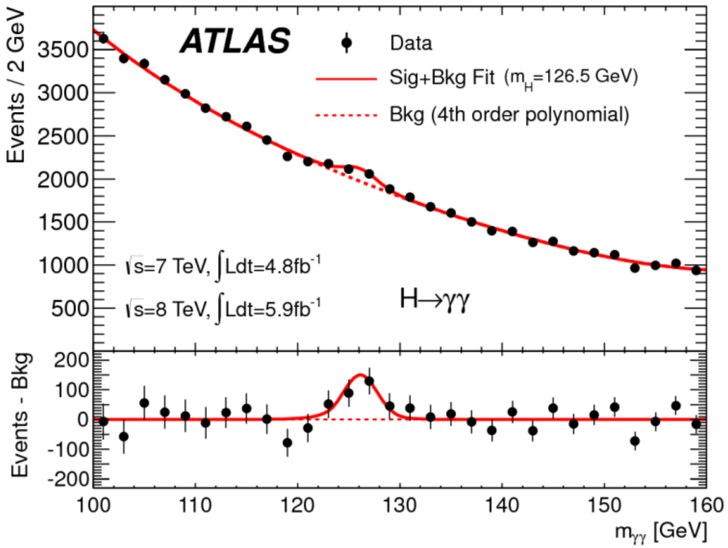
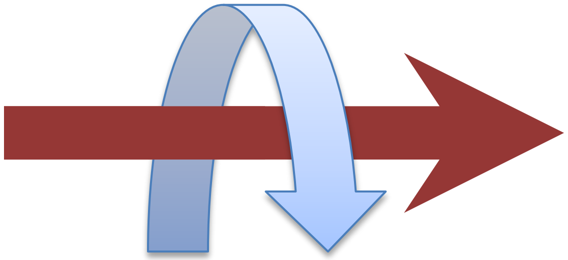




Each particle carries **momentum** and **spin**.

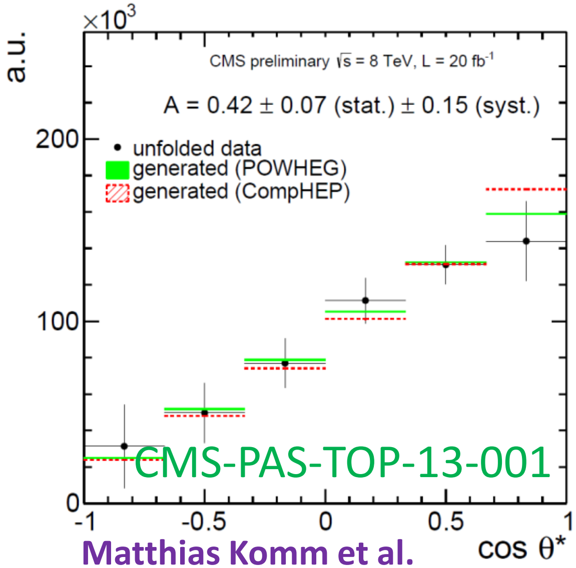
For **quarks**, momentum is easily reconstructed.

Is it possible to measure also their spin state (polarization)?

Motivation

Top quark polarization measurements are now standard.

single top production



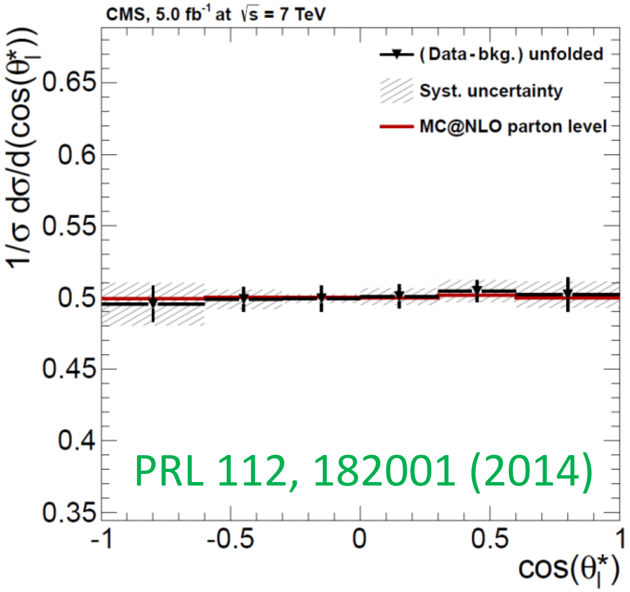
CMS-PAS-TOP-13-001

Matthias Komm et al.

$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.)$$

EW process → polarized

top pair production



PRL 112, 182001 (2014)

QCD process → unpolarized

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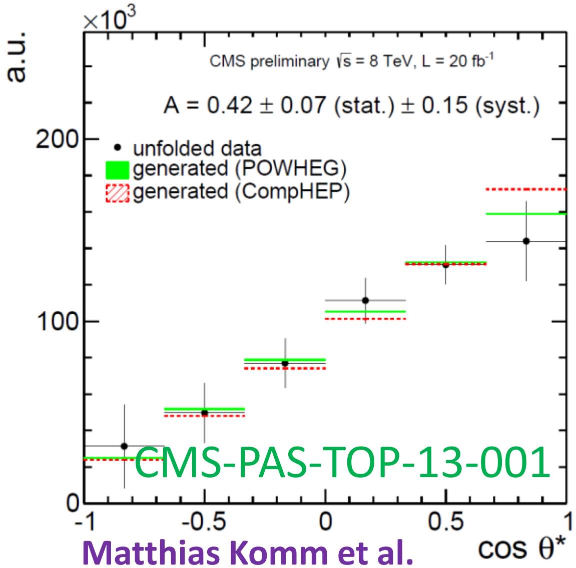

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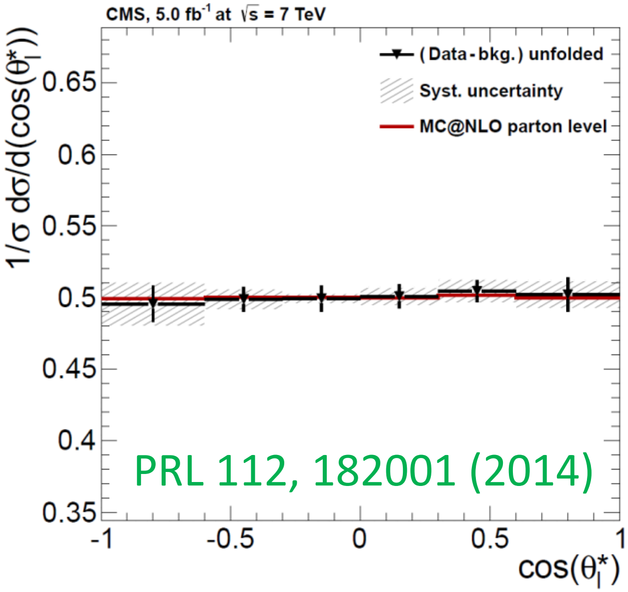

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Polarization of tops from **new physics** processes will teach us about their production mechanism!

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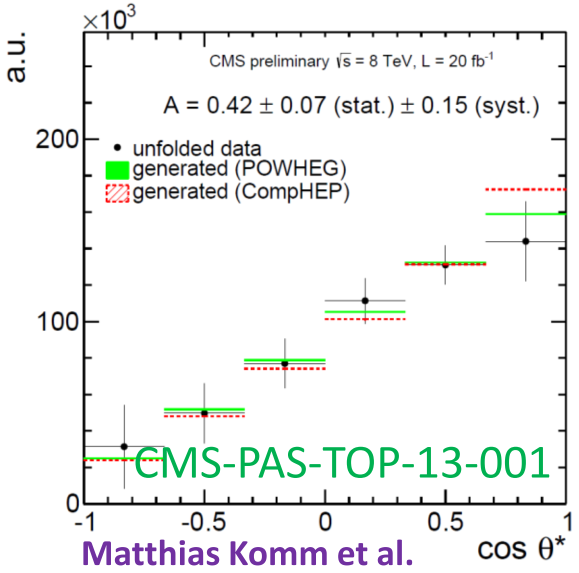

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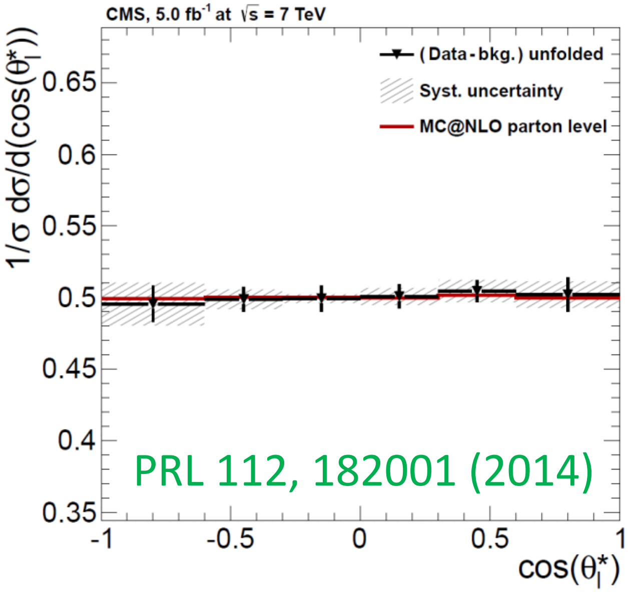

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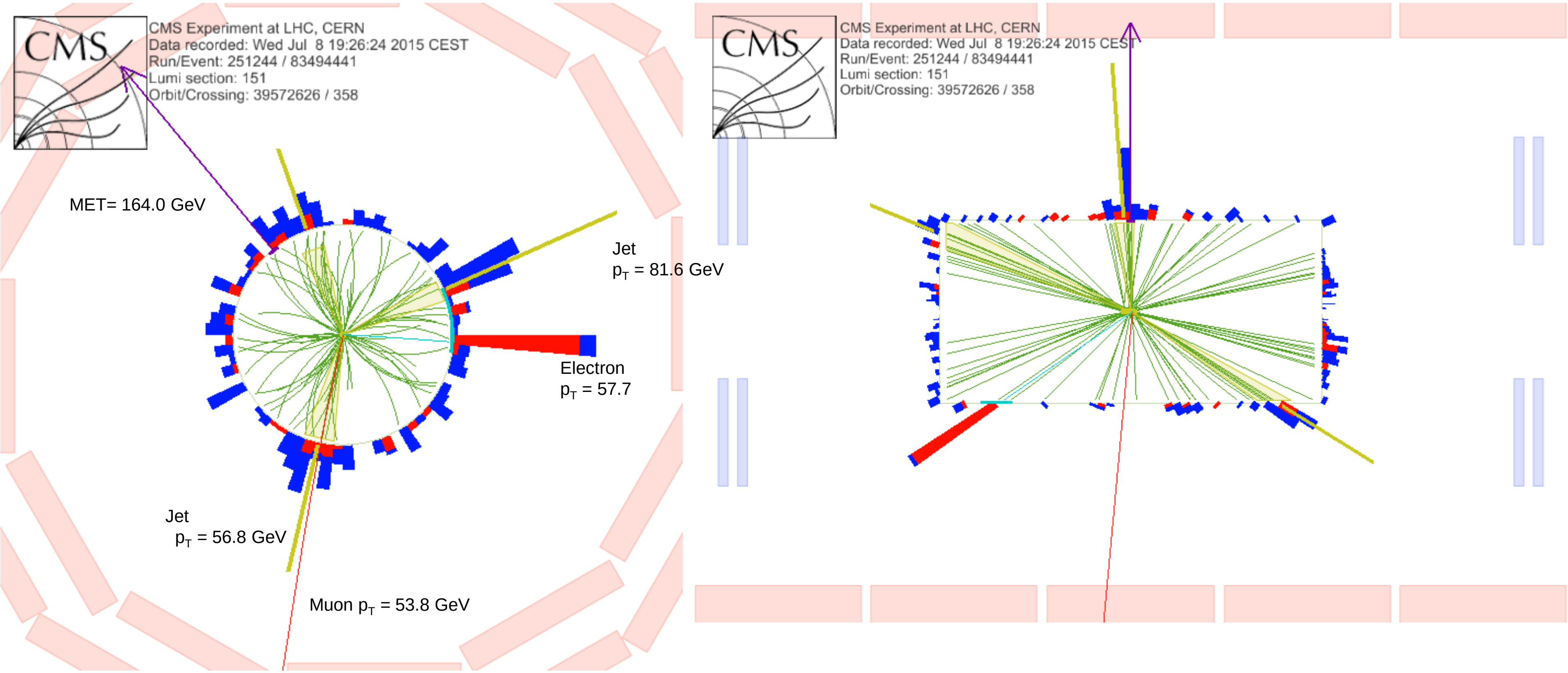
EW process → polarized

QCD process → unpolarized

Polarization of tops from **new physics** processes will teach us about their production mechanism!

Can we do analogous measurements for the **other quarks**?

Motivation



Quarks produce jets of hadrons.

Quark’s **momentum** reconstructed from tracks, calorimeter deposits.

How can one reconstruct quark’s **spin state (polarization)**?

Motivation

Hadronization is complicated (non-perturbative QCD).

Does the polarization survive the hadronization and the subsequent decays? Which hadron carries it?

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For heavy quarks (b, c):

- The jet contains an energetic heavy-flavored hadron.
- When it is a **baryon**, part of the polarization is expected to be retained. Falk and Peskin, PRD 49, 3320 (1994) [hep-ph/9308241]

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Evidence observed at **LEP** via Λ_b ($\approx bud$) baryons in $Z \to b\bar{b}$.

$\mathcal{P}(\Lambda_b) = -0.23^{+0.24}_{-0.20}{}^{+0.08}_{-0.07}$ (ALEPH) PLB 365, 437 (1996)

$\mathcal{P}(\Lambda_b) = -0.49^{+0.32}_{-0.30} \pm 0.17$ (DELPHI) PLB 474, 205 (2000)

$\mathcal{P}(\Lambda_b) = -0.56^{+0.20}_{-0.13} \pm 0.09$ (OPAL) PLB 444, 539 (1998) [hep-ex/9808006]

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- Can the **LHC** measure b polarization? c polarization?
  What about light quark polarizations (u, d, s)?
- Can we **calibrate** the measurements on Standard Model samples?
- Can we use them for discovering / characterizing **new physics**?

Source of polarized quarks: $t\bar{t}$ samples

- $t \rightarrow W^{+}b$ produces polarized $\boldsymbol{b}$ quarks.

  $W^{+} \rightarrow c\bar{s}, u\bar{d}$ produces polarized $\boldsymbol{c}$, $\boldsymbol{s}$, $\boldsymbol{u}$, $\boldsymbol{d}$ quarks.

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  Charm tagging, charge tagging (leptonic W) make it possible to study the different quarks separately.

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- Statistics in Run 2 is as large as in Z decays at LEP.

b-quark polarization retention

chromomagnetic moment

$$\mu_b \propto \frac{1}{m_b}$$

$$m_b \gg \Lambda_{\mathrm{QCD}}$$

b spin **preserved** during hadronization

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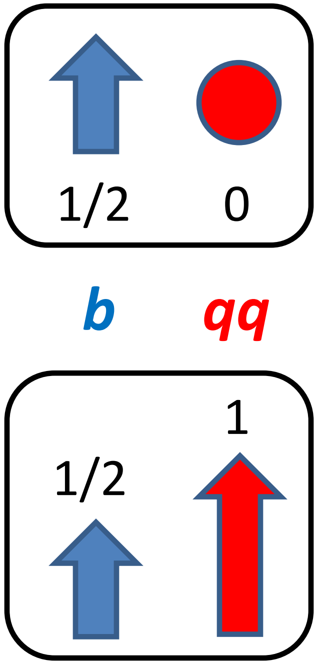

Λ_b

b spin **preserved** during lifetime

Σ_b

Σ_b^*

b spin **oscillates** during lifetime

Λ_b sample contaminated by $\Sigma_b^{(*)} \to \Lambda_b \pi$

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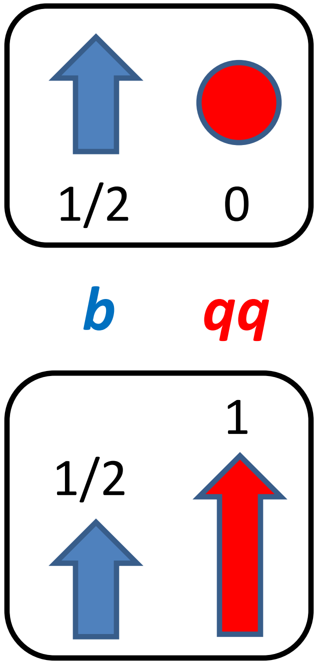

$$\Lambda_b$$

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$$\Sigma_b$$

$$\Sigma_b^*$$

b spin **oscillates** during lifetime

Λ_b sample contaminated by $\Sigma_b^{(*)} \to \Lambda_b \pi$

Fragmentation fraction into baryons ≈ 8%

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To what extent is the polarization preserved?

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

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

diquarks

S

spin-0
isosinglet

T

spin-1
isotriplet

$$\boxed{\begin{aligned}
&|\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 \\
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To what extent is the polarization preserved?

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

diquarks

S	T
spin-0 isosinglet	spin-1 isotriplet

$$A = \frac{\mathrm{prob}(\Sigma_b^{(*)})}{\mathrm{prob}\ (\Lambda_b)} = 9\ \frac{\mathrm{prob}(T)}{\mathrm{prob}(S)}$$

$$w_1 = \frac{\mathrm{prob}\ (T_{\pm 1})}{\mathrm{prob}\ (T)}$$

Falk and Peskin
PRD 49, 3320 (1994)

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Production as a b spin eigenstate.

Decay as a Σ_b or Σ_b^* mass eigenstate.

e.g. $|b_{+\frac{1}{2}}\rangle|T_0\rangle = -\sqrt{\frac{1}{3}}\;|\Sigma_{b,+\frac{1}{2}}\rangle + \sqrt{\frac{2}{3}}\;|\Sigma^*_{b,+\frac{1}{2}}\rangle$

b-quark polarization retention

To what extent is the polarization preserved?

$$\boxed{r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} \approx \frac{1+(1+4w_1)\,A/9}{1+A}}$$

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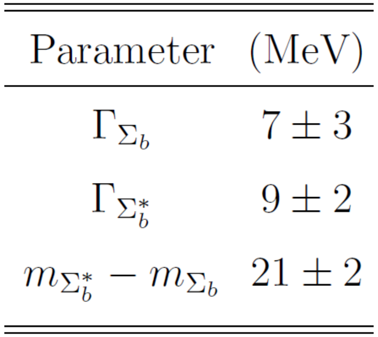
Production as a *b* spin eigenstate.

Decay as a Σ_b or Σ_b^* mass eigenstate.

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

b-quark polarization retention

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



Parameter	(MeV)
Γ_{Σ_b}	7 ± 3
$\Gamma_{\Sigma_b^*}$	9 ± 2
$m_{\Sigma_b^*} - m_{\Sigma_b}$	21 ± 2

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

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

pion momentum

Λ_b spin

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

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

phase space

statistical hadronization model ($T \approx 165$ MeV)

review: PLB 678, 350 (2009) [arXiv:0904.1368]

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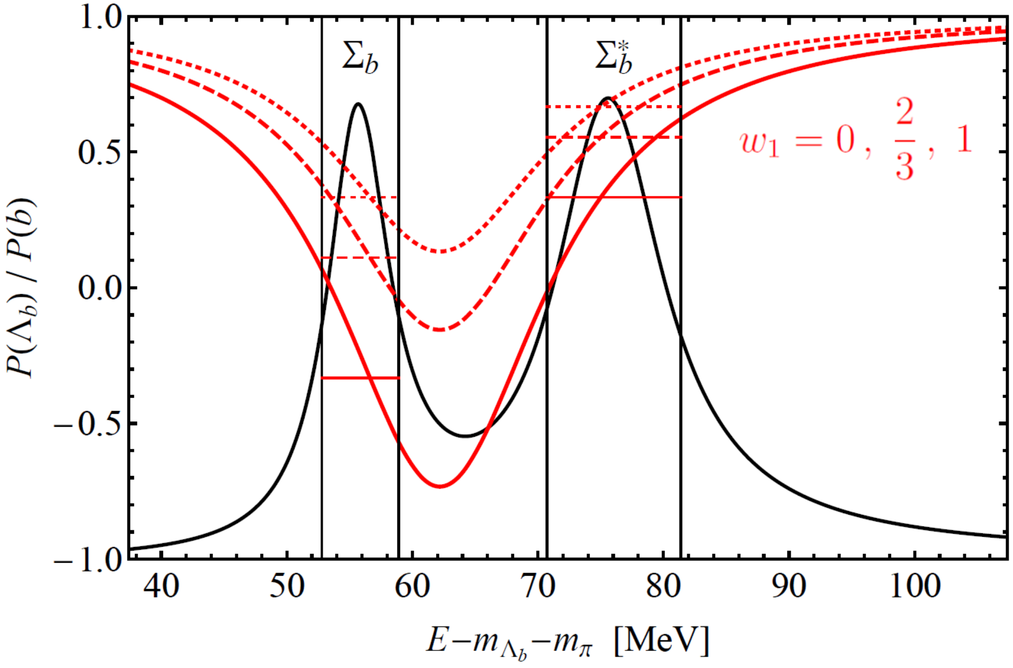
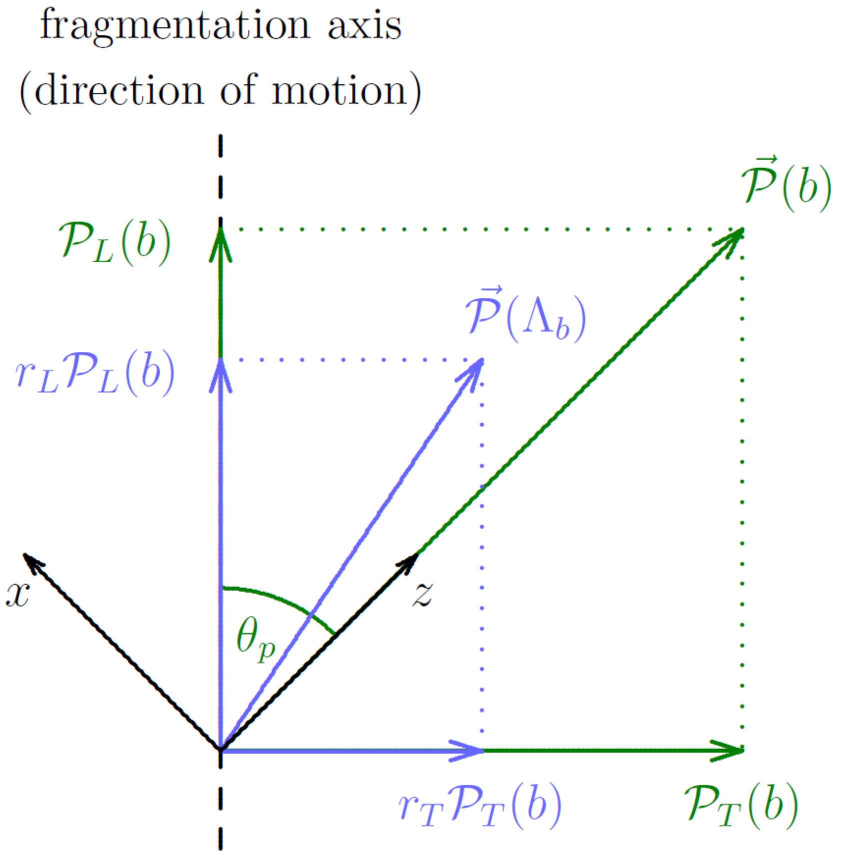


$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} \approx \frac{1 + (0.23 + 0.38 w_1)\, A}{1 + A}$$

b-quark polarization retention

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

If the b is polarized transversely, r is different.



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

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

b-quark polarization retention

Polarization retention factors are given by:

$$r_L \approx \frac{1 + (0.23 + 0.38 w_1)\, A}{1 + A} \qquad r_T \approx \frac{1 + (0.62 - 0.19 w_1)\, A}{1 + A}$$

where

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

What is known about A and w_1?

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- LEP $1 \lesssim A \lesssim 10$ $w_1 = -0.36 \pm 0.30 \pm 0.30$

  DELPHI-95-107

- Pheno. model $A \approx 6$ $w_1 \approx 0.41$

  Adamov, Goldstein, PRD 64, 014021 (2001) [hep-ph/0009300]

- Statistical had. model $A \approx 2.6$

  review: PLB 678, 350 (2009) [arXiv:0904.1368]

- Pythia tunes $0.24 \lesssim A \lesssim 0.45$

  based on light hadron data!

- CESR (charm)

  CLEO, PRL 78, 2304 (1997)

  $w_1 = 0.71 \pm 0.13$

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What is known about A and w_1?

Overall, $A \sim \mathcal{O}(1)$, $0 \leq w_1 \leq 1$ ⇨ $r_L, r_T \sim \mathcal{O}(1)$

consistent with polarization
measurements from LEP

A and w_1 can be measured:

– Measure samples with known b-quark polarization

– Study $\Sigma_b^{(*)} \to \Lambda_b \pi$ decays (even in unpolarized samples)

c-quark polarization retention

- Similar to the b-quark case, heavy-quark limit suggests $\mathcal{O}(1)$ polarization retention in the Λ_c.

  $\mathcal{O}(\Lambda_{\rm QCD}/m_c)$ corrections less negligible than $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$ but we propose to determine r experimentally anyway.

- Fragmentation fraction:

$$f_{\Lambda_c} = (5.7 \pm 0.7)\,\%$$

Gladilin
EPJC 75, 19 (2015)
[arXiv:1404.3888]

s-quark polarization retention

- Cannot argue for polarization retention using heavy-quark limit.

  Cannot argue for polarization loss either!

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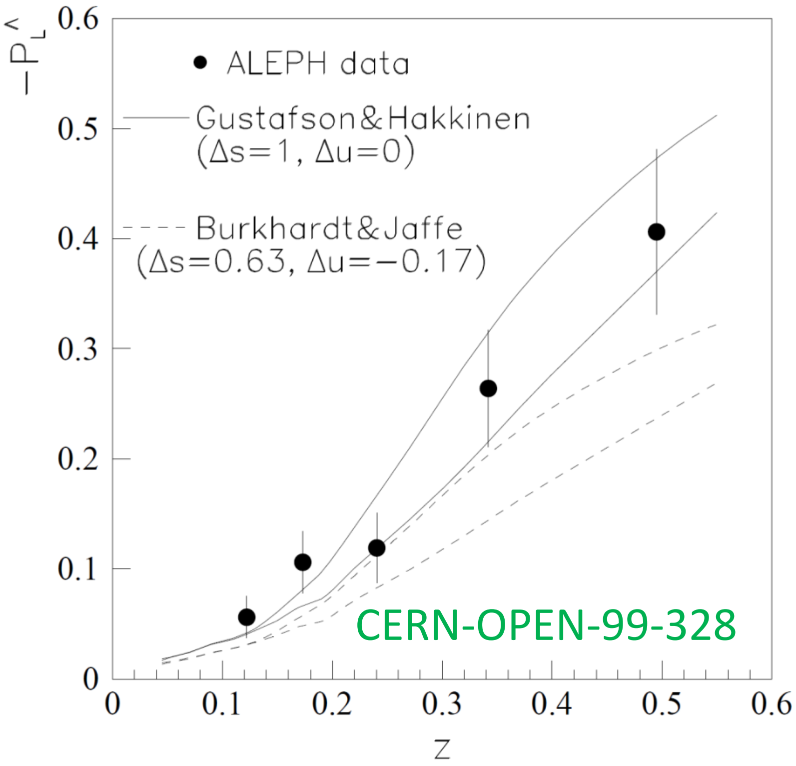
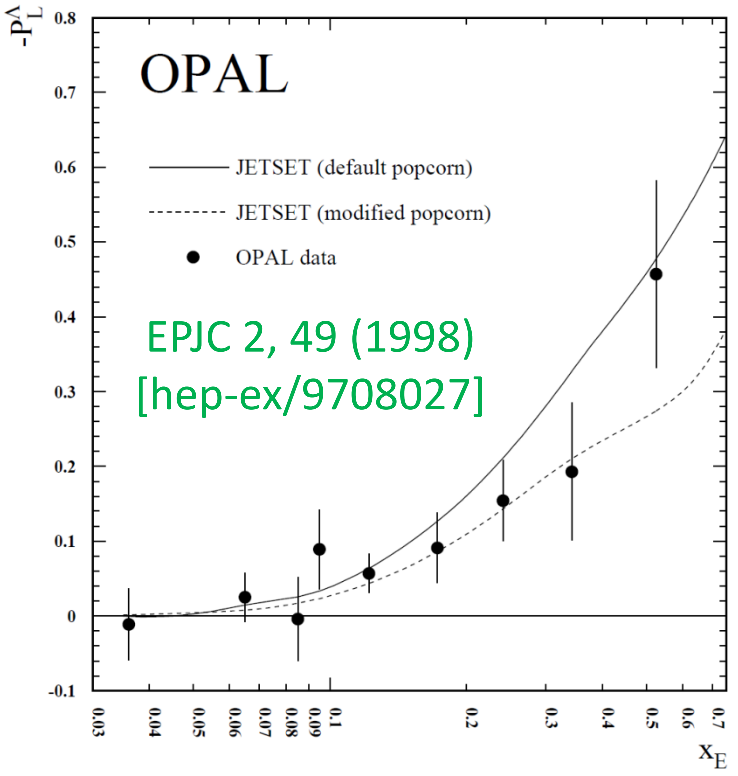
- Λ polarization studies were already done at LEP, in Z decays.



CERN-OPEN-99-328



EPJC 2, 49 (1998)
[hep-ex/9708027]

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  Cannot argue for polarization loss either!

- Λ polarization studies were already done at LEP, in Z decays.

  For $z > 0.3$:

  $\mathcal{P}(\Lambda) = -0.31 \pm 0.05$ **ALEPH**, CERN-OPEN-99-328

  $\mathcal{P}(\Lambda) = -0.33 \pm 0.08$ **OPAL**, EPJC 2, 49 (1998) [hep-ex/9708027]

  Contributions from all quark flavors are included.

  For strange quarks only (non-negligible modeling uncertainty):

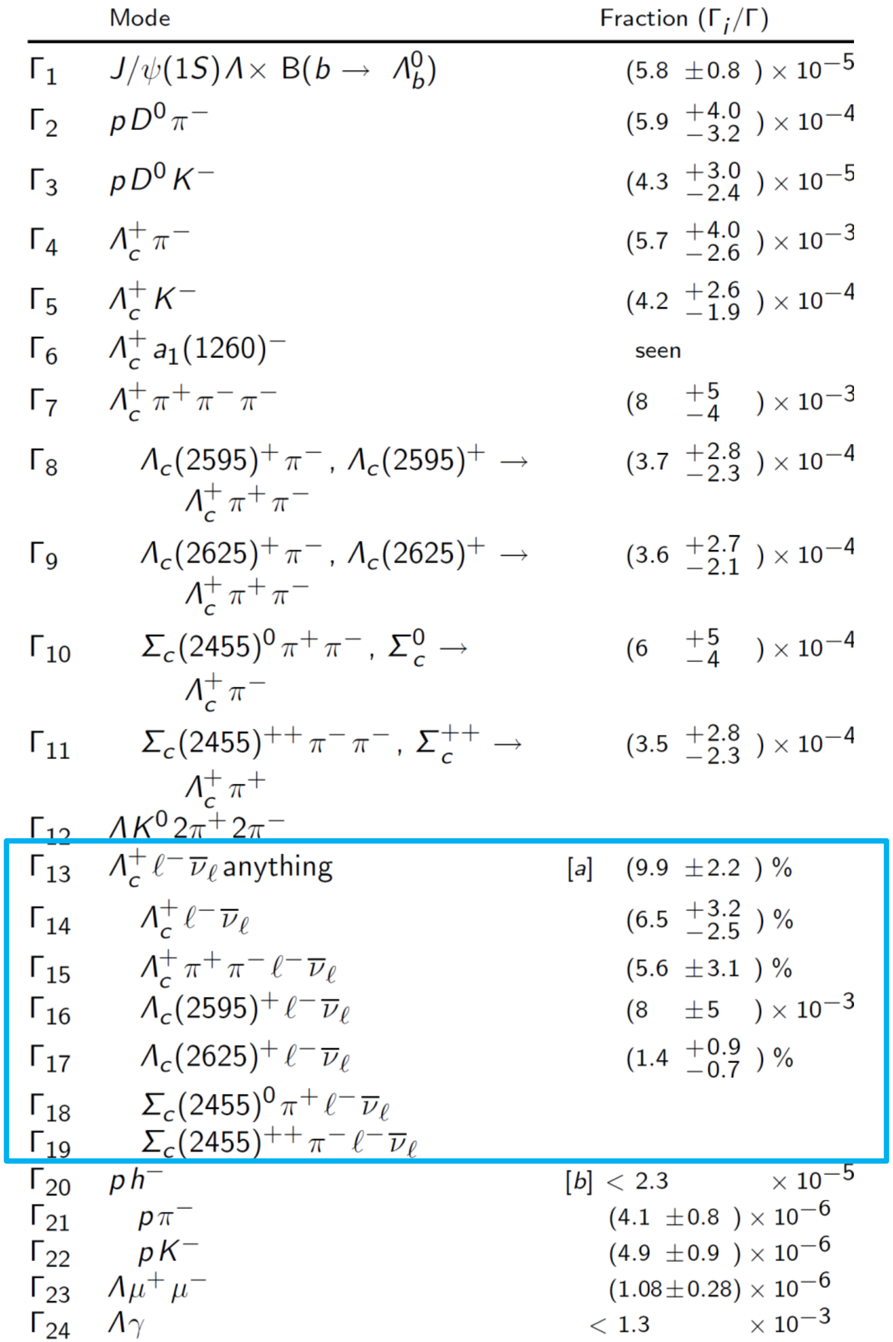
  $$-0.65 \lesssim \mathcal{P}(\Lambda) \lesssim -0.49$$

  Sizable polarization retention!

Λ_b polarization measurement

Which Λ_b decay to use?

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($b\to\Lambda_b^0$)		$(5.8\ \pm0.8\ )\times10^{-5}$
Γ_2	$pD^0\pi^-$		$(5.9\ ^{+4.0}_{-3.2}\ )\times10^{-4}$
Γ_3	pD^0K^-		$(4.3\ ^{+3.0}_{-2.4}\ )\times10^{-5}$
Γ_4	$\Lambda_c^+\pi^-$		$(5.7\ ^{+4.0}_{-2.6}\ )\times10^{-3}$
Γ_5	$\Lambda_c^+K^-$		$(4.2\ ^{+2.6}_{-1.9}\ )\times10^{-4}$
Γ_6	$\Lambda_c^+a_1(1260)^-$		seen
Γ_7	$\Lambda_c^+\pi^+\pi^-\pi^-$		$(8\ ^{+5}_{-4}\ )\times10^{-3}$
Γ_8	$\Lambda_c(2595)^+\pi^-$, $\Lambda_c(2595)^+\to\Lambda_c^+\pi^+\pi^-$		$(3.7\ ^{+2.8}_{-2.3}\ )\times10^{-4}$
Γ_9	$\Lambda_c(2625)^+\pi^-$, $\Lambda_c(2625)^+\to\Lambda_c^+\pi^+\pi^-$		$(3.6\ ^{+2.7}_{-2.1}\ )\times10^{-4}$
Γ_{10}	$\Sigma_c(2455)^0\pi^+\pi^-$, $\Sigma_c^0\to\Lambda_c^+\pi^-$		$(6\ ^{+5}_{-4}\ )\times10^{-4}$
Γ_{11}	$\Sigma_c(2455)^{++}\pi^-\pi^-$, $\Sigma_c^{++}\to\Lambda_c^+\pi^+$		$(3.5\ ^{+2.8}_{-2.3}\ )\times10^{-4}$
Γ_{12}	$\Lambda K^0 2\pi^+ 2\pi^-$		
Γ_{13}	$\Lambda_c^+\ell^-\overline{\nu}_\ell$ anything	[a]	$(9.9\ \pm2.2\ )$ %
Γ_{14}	$\Lambda_c^+\ell^-\overline{\nu}_\ell$		$(6.5\ ^{+3.2}_{-2.5}\ )$ %
Γ_{15}	$\Lambda_c^+\pi^+\pi^-\ell^-\overline{\nu}_\ell$		$(5.6\ \pm3.1\ )$ %
Γ_{16}	$\Lambda_c(2595)^+\ell^-\overline{\nu}_\ell$		$(8\ \pm5\ )\times10^{-3}$
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}	ph^-	[b]	$<2.3\ \times10^{-5}$
Γ_{21}	$p\pi^-$		$(4.1\ \pm0.8\ )\times10^{-6}$
Γ_{22}	pK^-		$(4.9\ \pm0.9\ )\times10^{-6}$
Γ_{23}	$\Lambda\mu^+\mu^-$		$(1.08\pm0.28)\times10^{-6}$
Γ_{24}	$\Lambda\gamma$		$<1.3\ \times10^{-3}$

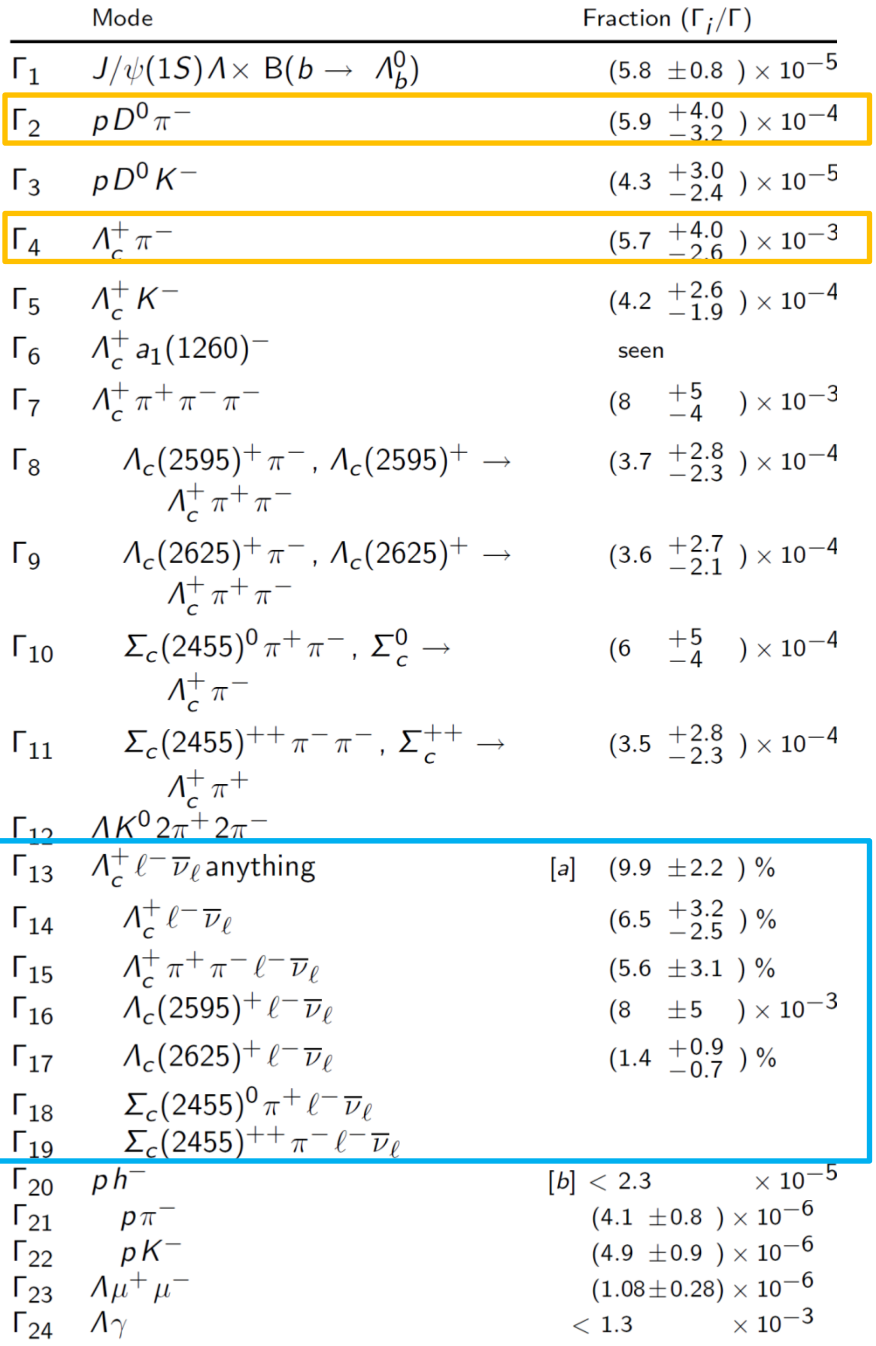
Λ_b polarization measurement

Which Λ_b decay to use?

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

Includes also:

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



	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}	$\Lambda \gamma$		$< 1.3 \times 10^{-3}$

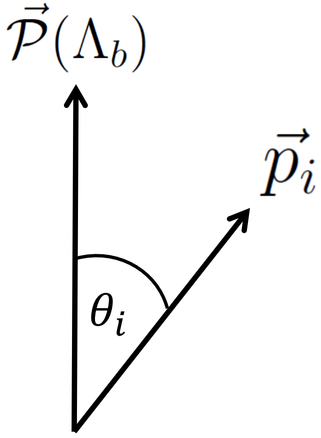
Λ_b polarization measurement

For the inclusive semileptonic decays

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

Λ_b polarization is encoded in the angular distributions

$$\frac{1}{\Gamma_{\Lambda_b}} \frac{d\Gamma_{\Lambda_b}}{d\cos\theta_i} = \frac{1}{2}\left(1 + \alpha_i \mathcal{P}\left(\Lambda_b\right)\cos\theta_i\right) \qquad i = \ell \text{ or } \nu$$



Λ_b polarization measurement

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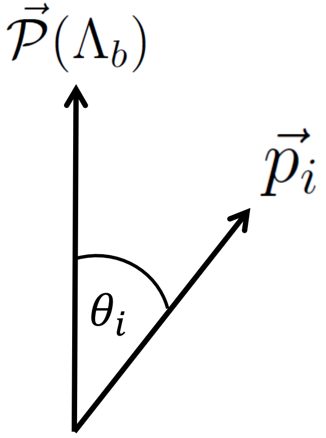

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$$\frac{1}{\Gamma_{\Lambda_b}} \frac{d\Gamma_{\Lambda_b}}{d\cos\theta_i} = \frac{1}{2}\left(1 + \alpha_i \, \mathcal{P}\left(\Lambda_b\right) \cos\theta_i\right) \qquad i = \ell \text{ or } \nu$$

where

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

$$\uparrow$$

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

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

Manohar, Wise
PRD 49, 1310 (1994)
[arXiv:hep-ph/9308246]

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

Λ_b polarization measurement

Inclusive approach

- Demand a **muon** (with IP and $p_{\mathrm{T,rel}}$) inside a jet, like in soft-muon b tagging. e.g. CMS-PAS-BTV-09-001

Λ_b polarization measurement

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

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

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- Measure neutrino A_{FB} in the Λ_b rest frame

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

Λ_b polarization measurement

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Λ_b fragmentation fraction (≈ 7%)

Semileptonic B-meson background (isotropic) dilutes the A_{FB}.

Inclusive approach: live with it → high efficiency

Λ_b polarization measurement

Semi-inclusive approach

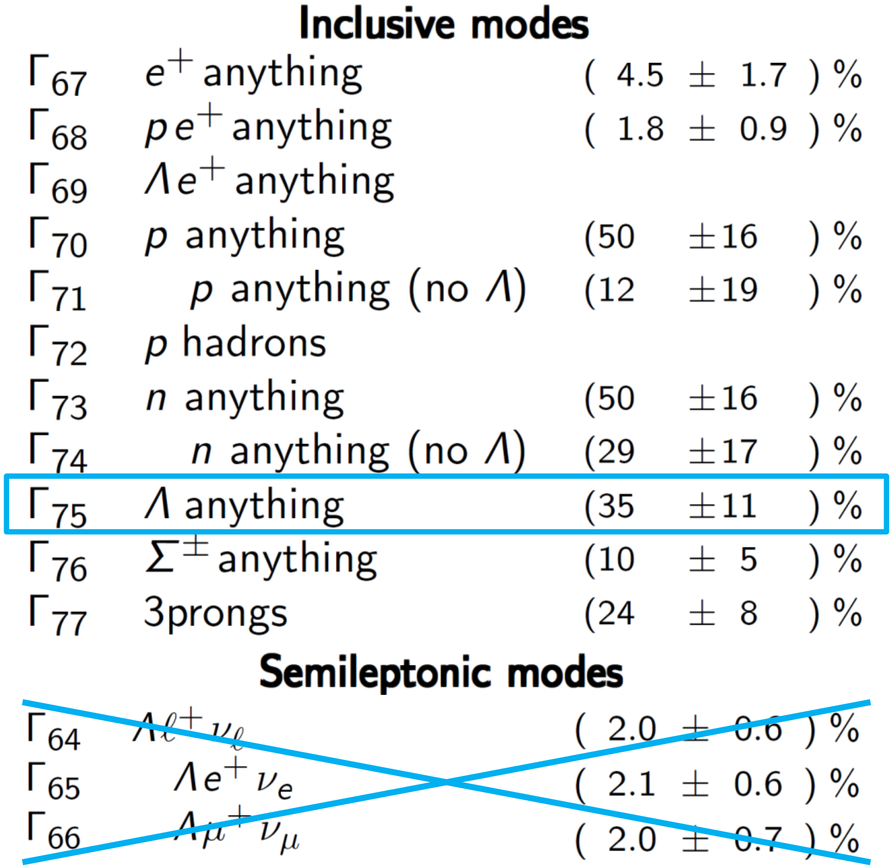
- In addition, demand the presence of $\Lambda \to p\pi^-$ in the jet.

Λ_b polarization measurement

Semi-inclusive approach

- In addition, demand the presence of $\Lambda \to p\pi^-$ in the jet.

Λ_c decay modes



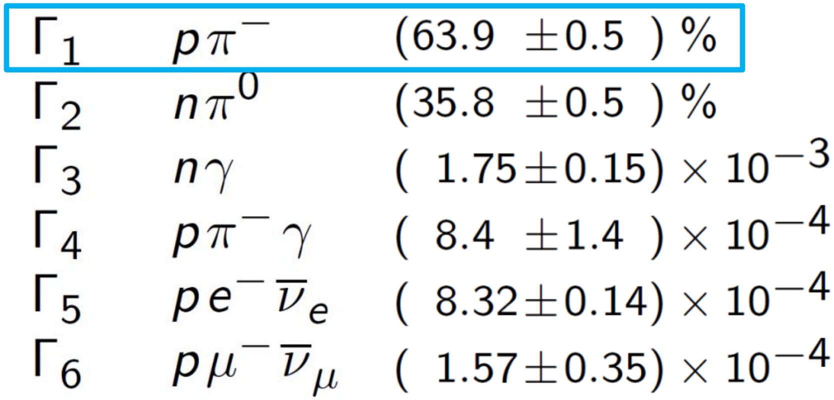
Inclusive modes

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

Semileptonic modes

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

Λ decay modes



Γ_1	$p\pi^-$	(63.9 ±0.5) %
Γ_2	$n\pi^0$	(35.8 ±0.5) %
Γ_3	$n\gamma$	(1.75±0.15) × 10^{-3}
Γ_4	$p\pi^-\gamma$	(8.4 ±1.4) × 10^{-4}
Γ_5	$p e^- \overline{\nu}_e$	(8.32±0.14) × 10^{-4}
Γ_6	$p \mu^- \overline{\nu}_\mu$	(1.57±0.35) × 10^{-4}

Overall branching fraction ≈ 20%.

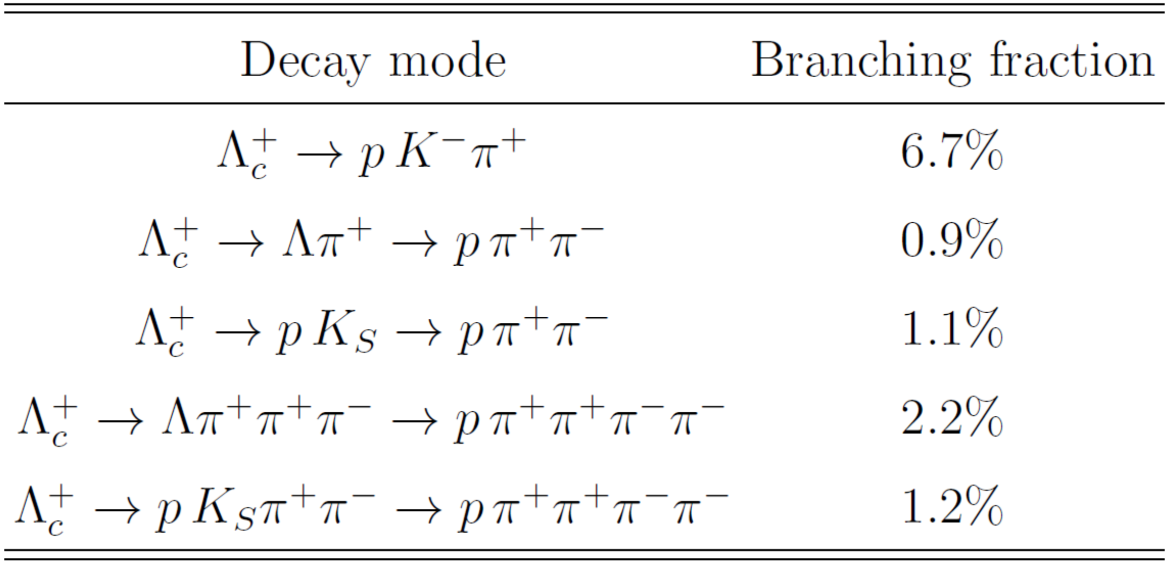
Additional losses due to $\Lambda \to p\pi^-$ reconstruction efficiency.

Will likely improve when tracking detectors are upgraded.

Λ_b polarization measurement

Exclusive approach

- Use several fully-reconstructible modes of Λ_c



Decay mode	Branching fraction
$\Lambda_c^+ \to p\, K^- \pi^+$	6.7%
$\Lambda_c^+ \to \Lambda \pi^+ \to p\, \pi^+ \pi^-$	0.9%
$\Lambda_c^+ \to p\, K_S \to p\, \pi^+ \pi^-$	1.1%
$\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^- \to p\, \pi^+ \pi^+ \pi^- \pi^-$	2.2%
$\Lambda_c^+ \to p\, K_S \pi^+ \pi^- \to p\, \pi^+ \pi^+ \pi^- \pi^-$	1.2%

Higher purity, better reconstruction,
but lower efficiency.

Λ_c polarization measurement

$$\Lambda_c^+ \to pK^-\pi^+$$ (BR ≈ 6.7%)

- Three tracks reconstructing the Λ_c mass.

- Spin analyzing powers α_i seem to be large for K^-, small for p and π^+.

NA32: Jezabek, Rybicki, Rylko, PLB 286, 175 (1992)

Precise values not essential if SM calibration samples are available for measuring $\alpha_i r$.

Λ_c polarization measurement

Intrinsic backgrounds to $\Lambda_c^+ \to pK^-\pi^+$ due to:

- Other Λ_c decays, e.g. $\Lambda_c^+ \to pK^-\pi^+\pi^0,\ \Sigma^+\pi^-\pi^+,\ \pi^+\pi^-\pi^+\Lambda$

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- D-meson decays, e.g. $D^+ \to \pi^+K^-\pi^+,\ \pi^+K^-\pi^+\pi^0$

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

  $D_s^+ \to K^+K^-\pi^+,\ K^+K^-\pi^+\pi^0$

Λ_c polarization measurement

Intrinsic backgrounds to $\Lambda_c^+ \to pK^-\pi^+$ due to:

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- D-meson decays, e.g.

$$\begin{aligned} D^+ &\to \pi^+K^-\pi^+,\ \pi^+K^-\pi^+\pi^0 \\ D^0 &\to \pi^+K^-\pi^+\pi^- \\ D_s^+ &\to K^+K^-\pi^+,\ K^+K^-\pi^+\pi^0 \end{aligned}$$

Handles for suppressing them:

❖ **Typical momentum hierarchy in the lab frame:** $p > K^- > \pi^+$

Λ_c polarization measurement

Intrinsic backgrounds to $\Lambda_c^+ \to pK^-\pi^+$ due to:

- ➢ Other Λ_c decays, e.g. $\Lambda_c^+ \to pK^-\pi^+\pi^0, \boxed{\Sigma^+\pi^-\pi^+,\ \pi^+\pi^-\pi^+\Lambda}$
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- **Veto on a 4th track consistent with the Λ_c vertex**

Λ_c polarization measurement

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Handles for suppressing them:

- Typical momentum hierarchy in the lab frame: $p > K^- > \pi^+$
- Veto on additional further-displaced vertices/kinks
- Veto on a 4th track consistent with the Λ_c vertex
- **Lifetime differences:** $\tau(\Lambda_c^+, D^0, D_s^+, D^+) \simeq (2, 4, 5, 10) \times 10^{-13}\ \mathrm{s}$

Λ_c polarization measurement

Intrinsic backgrounds to $\Lambda_c^+ \to pK^-\pi^+$ due to:

- Other Λ_c decays, e.g. $\Lambda_c^+ \to pK^-\pi^+\pi^0,\, \Sigma^+\pi^-\pi^+,\, \pi^+\pi^-\pi^+\Lambda$
- D-meson decays, e.g. $D^+ \to \boxed{\pi^+K^-\pi^+},\, \pi^+K^-\pi^+\pi^0$

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

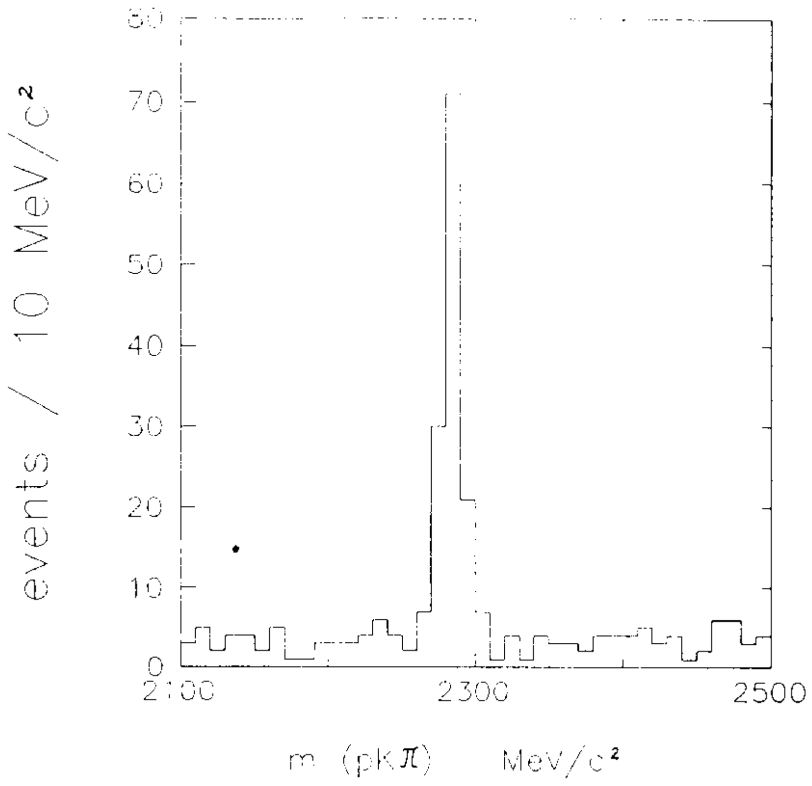
$$D_s^+ \to \boxed{K^+K^-\pi^+},\, K^+K^-\pi^+\pi^0$$

Handles for suppressing them:

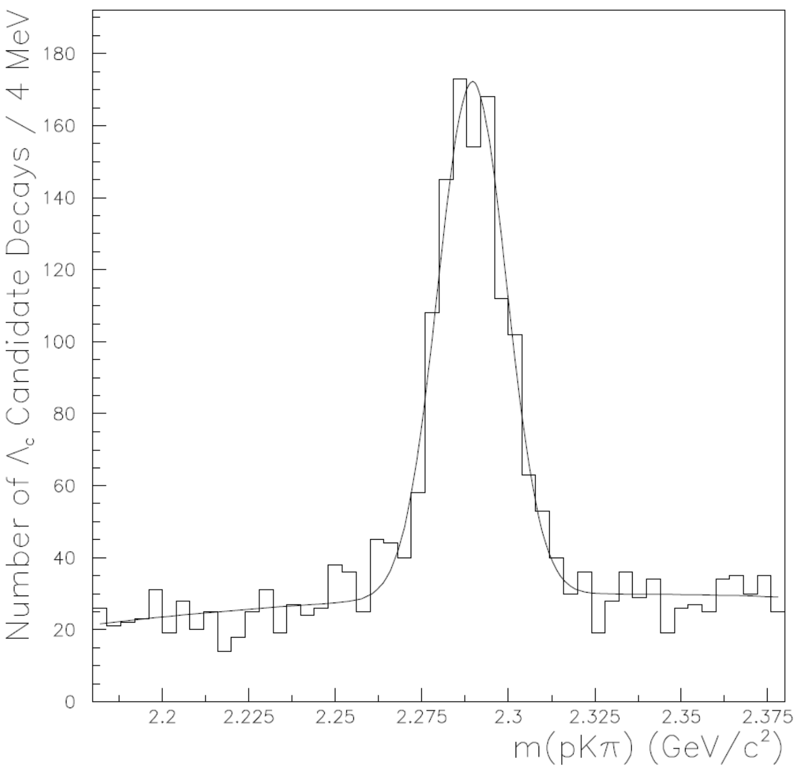
- Typical momentum hierarchy in the lab frame: $p > K^- > \pi^+$
- Veto on additional further-displaced vertices/kinks
- Veto on a 4th track consistent with the Λ_c vertex
- Lifetime differences: $\tau(\Lambda_c^+, D^0, D_s^+, D^+) \simeq (2, 4, 5, 10) \times 10^{-13}$ s
- **Target particular 3-prong backgrounds by vetoing on consistency with their corresponding interpretations.**

Λ_c polarization measurement

Two fixed-target experiments reconstructed this decay in the past.



NA32: Jezabek, Rybicki, Rylko
PLB 286, 175 (1992)

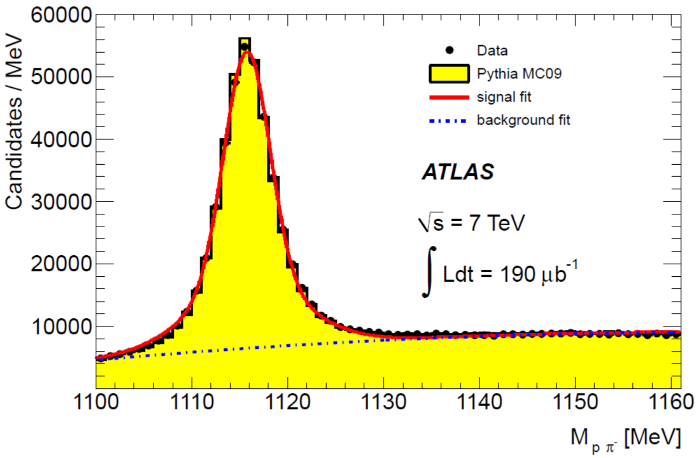


E791: PLB 471, 449 (2000)
[arXiv:hep-ex/9912003]

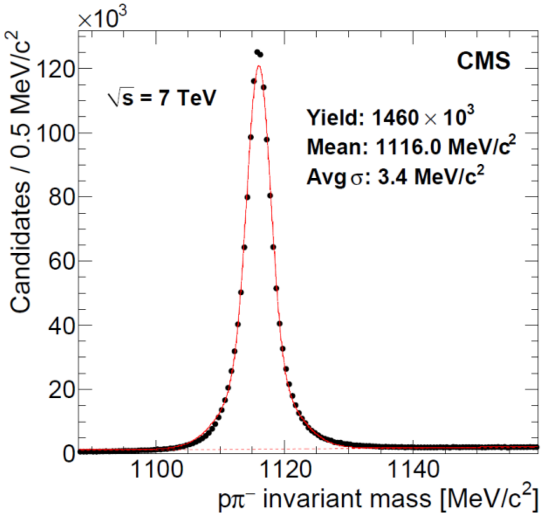
Λ polarization measurement

$$\Lambda \to p\,\pi^- \qquad \text{(BR} \approx 64\%)$$

- Pair of tracks from a highly displaced vertex reconstructing the Λ mass.
- Spin analyzing power $\alpha \approx 0.64$
- ATLAS and CMS already have experience with Λ's

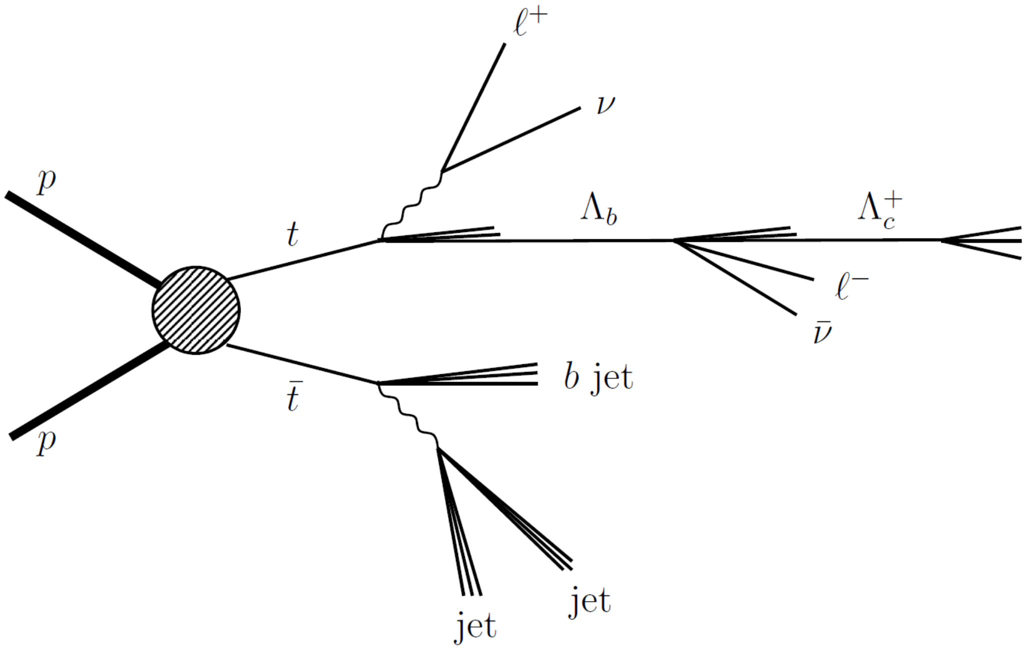


PRD 85, 012001 (2012)
[arXiv:1111.1297]



JHEP 05, 064 (2011) [arXiv:1102.4282]

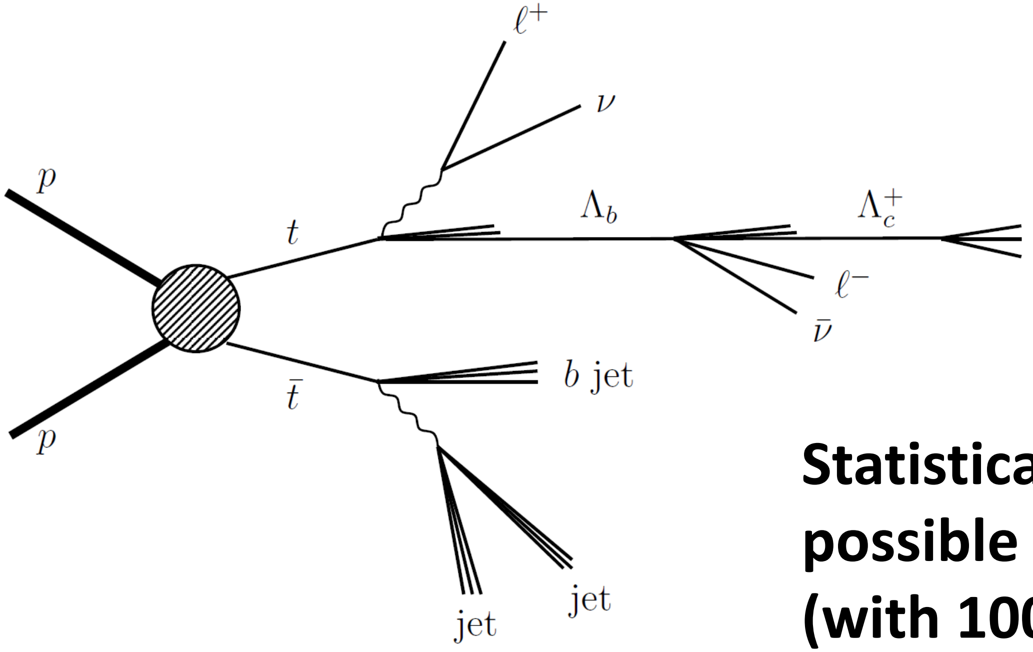
Measurement of b polarization in $t\bar{t}$



Main ingredients of the analysis:

- Typical single-lepton $t\bar{t}$ selection (w/soft-muon b tag)
- Typical kinematic reconstruction and global event interpretation
- Λ_b reconstruction (using inclusive, semi-inclusive or exclusive approach) and polarization measurement

Measurement of b polarization in $t\bar{t}$



Statistical precision of about 10% possible at ATLAS/CMS in Run 2 (with 100/fb of data)

Selection	Expected events		
Baseline	$3\times10^6\ t\bar{t}+\mathcal{O}(10^6)$ bkg		
Soft-muon b tagging	$5\times10^5\ t\bar{t}+\mathcal{O}(10^4)$ bkg		$r_L = 0.6$
Signal events ($t\to b\to\Lambda_b\to\mu\nu X_c$)		Purity (example)	$\Delta\mathcal{A}_{FB}/\mathcal{A}_{FB}$
Inclusive	34 400	$\mathcal{O}(f_{\text{baryon}})$ (e.g., 7%)	±7%
Semi-inclusive	$2300\times(\epsilon_\Lambda/30\%)$	70%	±8%
Exclusive	$1040\times(\epsilon_{\Lambda_c}/25\%)$	30%	±19%
		100%	±10%

Measurement of b polarization in Z decays

Z production: $pp \to Z \to b\bar{b}$

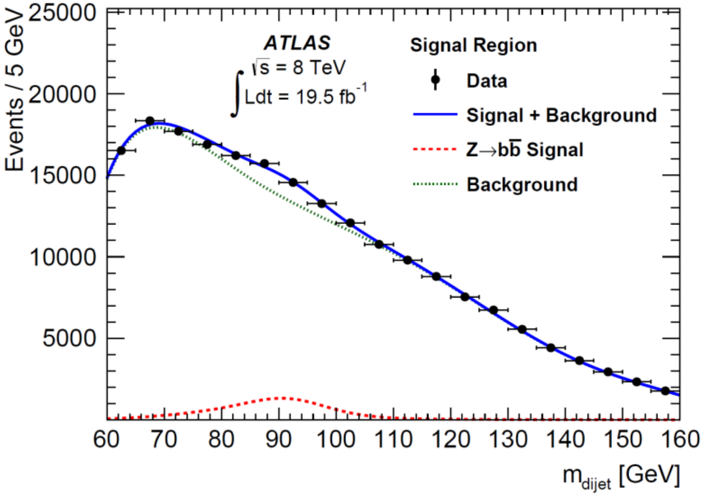
- Longitudinally polarized b quarks (similar to $t\bar{t}$)
- Large cross section

$$\frac{\sigma(pp \to Z \to b\bar{b})}{\sigma(pp \to t\bar{t} \to W^+W^-b\bar{b})} \sim 10$$

- Large QCD background (at 8 TeV, S/B ≈ 1/15 even for p_T^Z > 200 GeV) dilutes the asymmetry.

Probably less effective than $t\bar{t}$.

→



PLB 738, 25 (2014)
[arXiv:1404.7042]

Measurement of b polarization in QCD events

QCD production: $pp \to b\bar{b} + X$

- 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 (primarily) for LHCb

Dharmaratna and Goldstein
PRD 53, 1073 (1996)

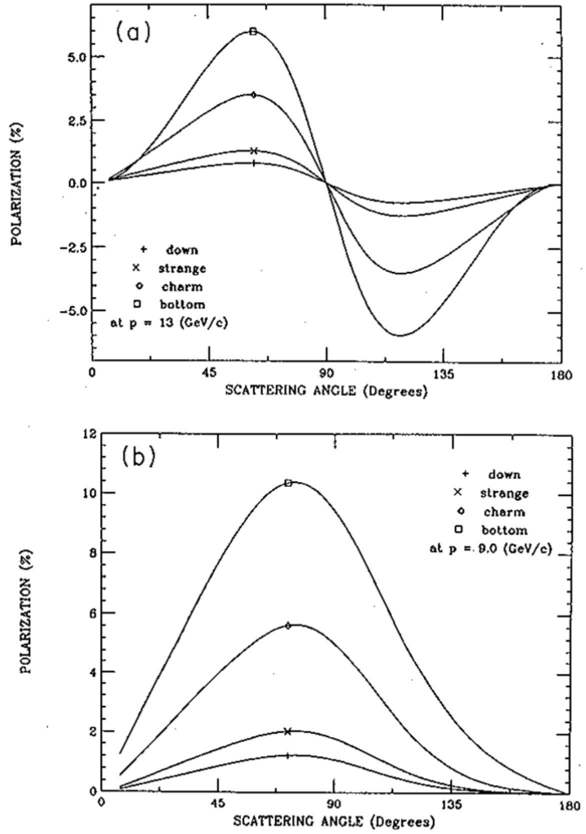


FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.

Measurement of b polarization in QCD events

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PRD 53, 1073 (1996)

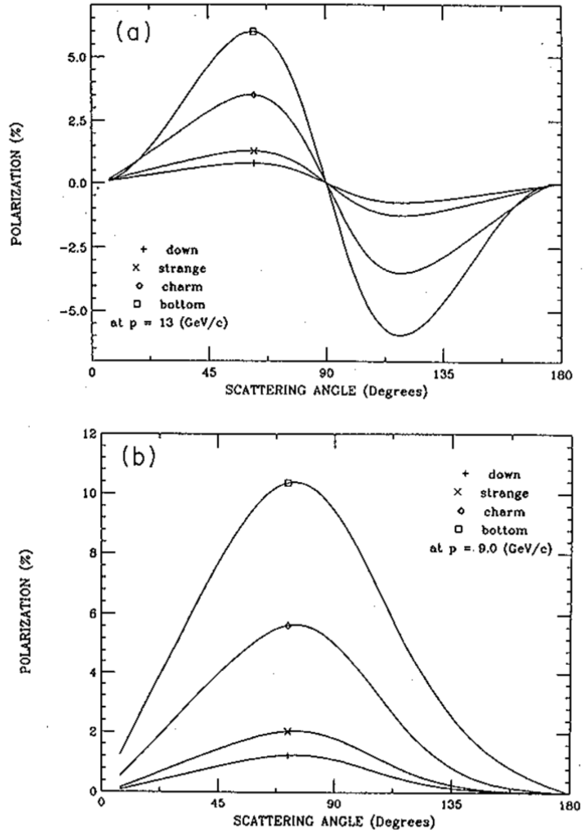
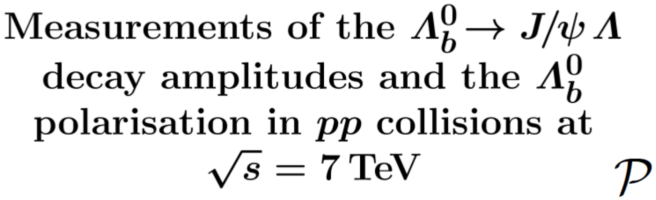


FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.

Existing LHCb analysis:



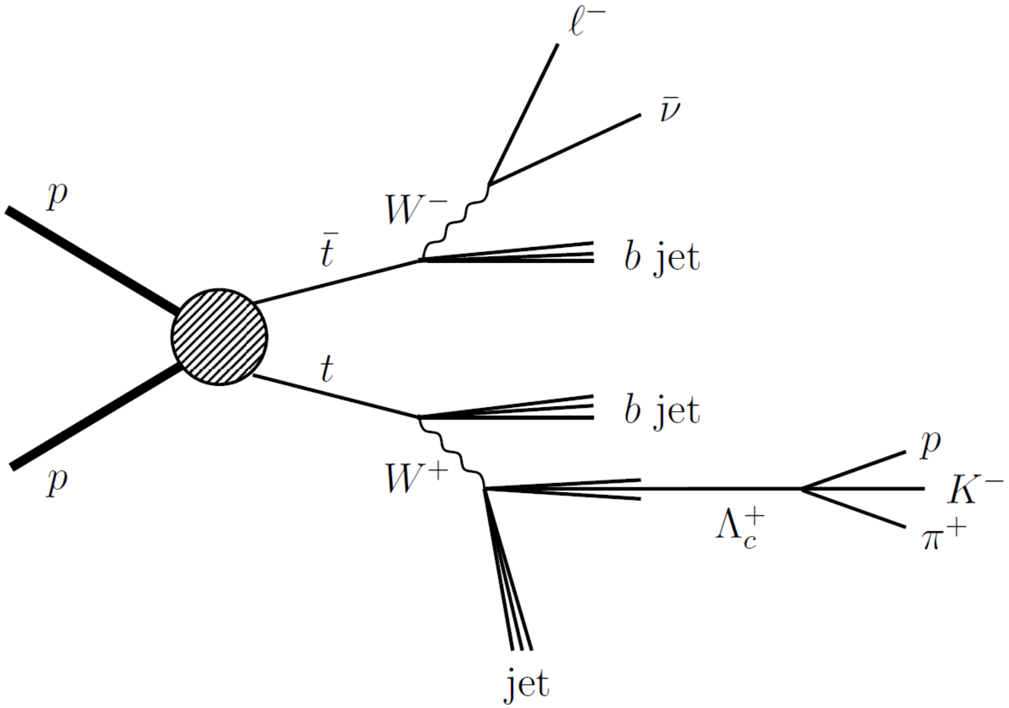
Measurements of the $\Lambda_b^0 \to J/\psi\,\Lambda$ decay amplitudes and the Λ_b^0 polarisation in pp collisions at $\sqrt{s} = 7$ TeV

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

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

Suboptimal because the dependence on kinematics is ignored.

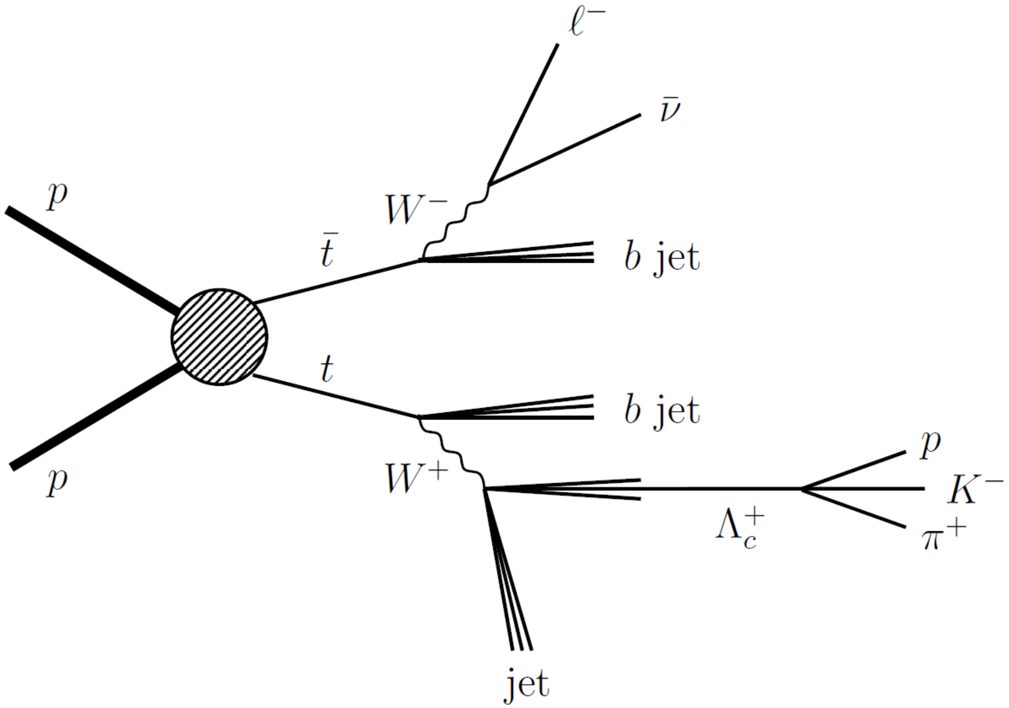
Measurement of c polarization in $t\bar{t}$



Main ingredients of the analysis:

- Typical single-lepton $t\bar{t}$ selection
- Typical kinematic reconstruction and global event interpretation
- Λ_c reconstruction and polarization measurement

Measurement of c polarization in $t\bar{t}$

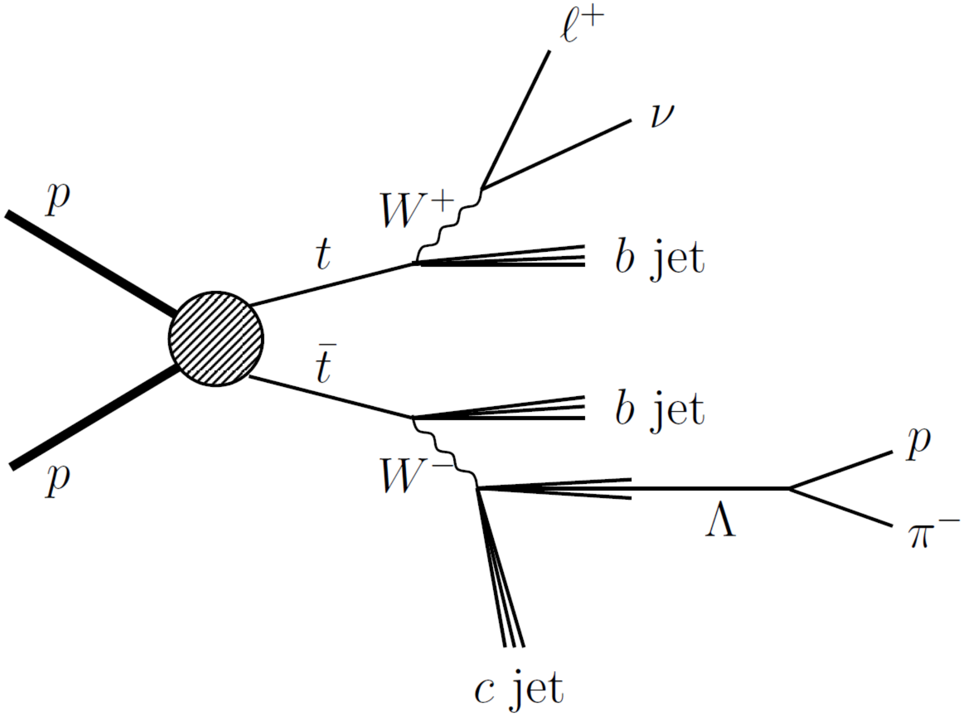


Statistical precision of order 10% possible at ATLAS/CMS in Run 2 (with 100/fb of data)

$\alpha_i r_L = 0.6$

Selection	Expected events	Purity (example)	$\Delta\mathcal{A}_{FB}/\mathcal{A}_{FB}$
Baseline	$1.7\times10^6\ t\bar{t} + \mathcal{O}(10^5)$ bkg		
$\Lambda_c^+ \to pK^-\pi^+$	$810\times(\epsilon_{\Lambda_c}/25\%)$	20% 100%	26% 11%

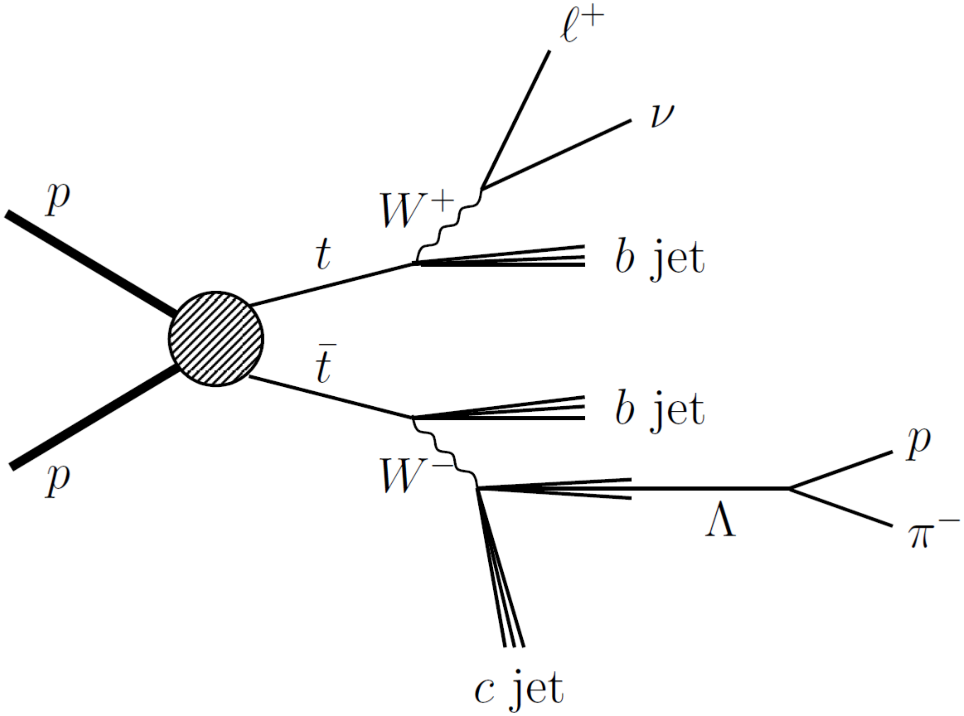
Measurement of s polarization in $t\bar{t}$



Main ingredients of the analysis:

- Typical single-lepton $t\bar{t}$ selection
- Typical kinematic reconstruction and global event interpretation
- Charm tagging
- Λ reconstruction and polarization measurement

Measurement of s polarization in $t\bar{t}$



Statistical precision of roughly 16% possible at ATLAS/CMS in Run 2 (with 100/fb of data)

Measuring A directly

A is simply the ratio of the $\Sigma_b^{(*)}$ and Λ_b yields, independent of the b polarization:

$$A = \frac{\mathrm{prob}(\Sigma_b^{(*)})}{\mathrm{prob}\,(\Lambda_b)} = 9\,\frac{\mathrm{prob}(T)}{\mathrm{prob}(S)}$$

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Can be measured by any experiment that can see $\Sigma_b^{(*)} \to \Lambda_b \pi$: LHCb, ATLAS, CMS, maybe even re-analysis of Tevatron data.

CDF, PRL 99, 202001 (2007) [arXiv:0706.3868]

CDF, PRD 85, 092011 (2012) [arXiv:1112.2808]

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CDF, PRL 99, 202001 (2007) [arXiv:0706.3868]

CDF, PRD 85, 092011 (2012) [arXiv:1112.2808]

Same for $\Sigma_c^{(*)}$ and Λ_c , where Belle and BaBar can also help.

Belle, arXiv:1404.5389

Measuring w_1 directly

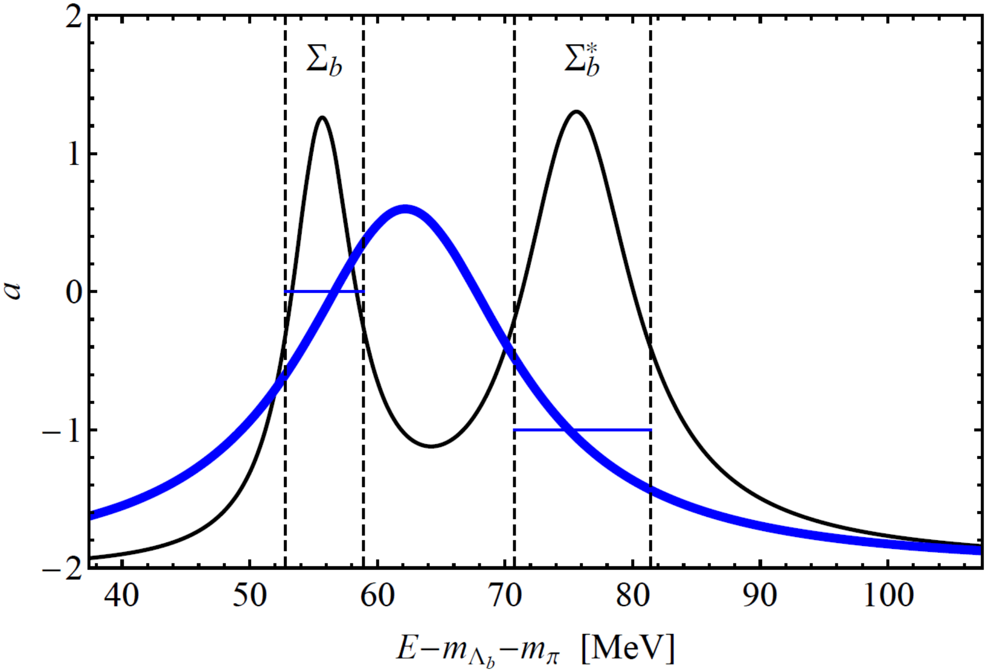
The angular distribution of $\Sigma_b^{(*)} \to \Lambda_b \pi$ is sensitive to w_1, independent of the b polarization:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2} + \frac{9}{8}\,a\left(w_1 - \frac{2}{3}\right)\left(\cos^2\theta - \frac{1}{3}\right)$$

where a is given in the plot.

Can be measured by any experiment that can reconstruct these decays (see previous slide).

Same for $\Sigma_c^{(*)}$ and Λ_c.

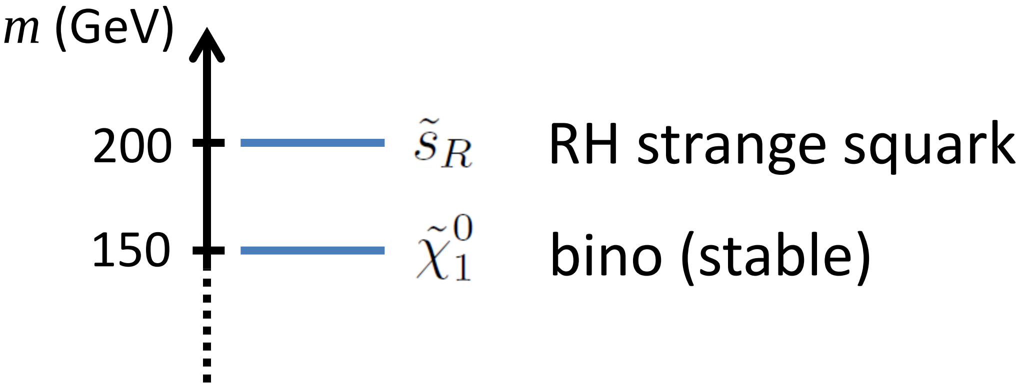


New physics example

Suppose a jets + MET excess is being attributed to:

$$pp \to \tilde{s}_R \tilde{s}_R^*$$

$$\tilde{s}_R \to s\, \tilde{\chi}_1^0$$



m (GeV)

200 — $\tilde{s}_R$ RH strange squark

150 — $\tilde{\chi}_1^0$ bino (stable)

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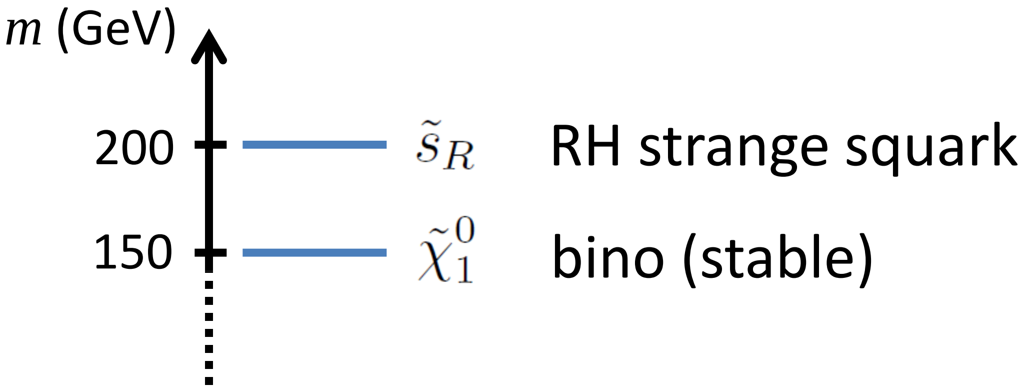
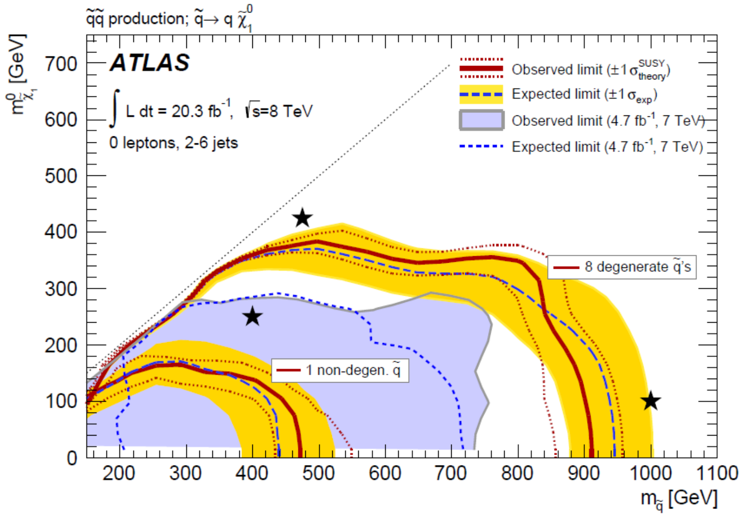
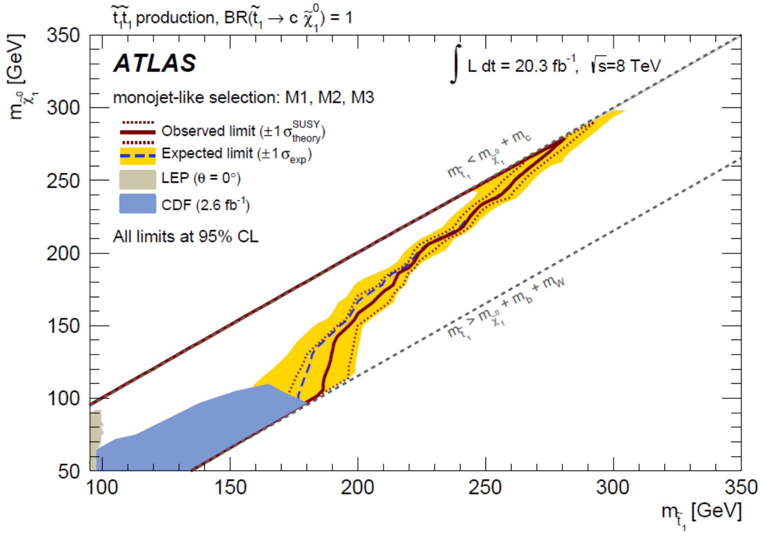


This scenario was barely beyond the reach of Run 1.



JHEP 09, 176 (2014) [arXiv:1405.7875]



PRD 90, 052008 (2014) [arXiv:1407.0608]

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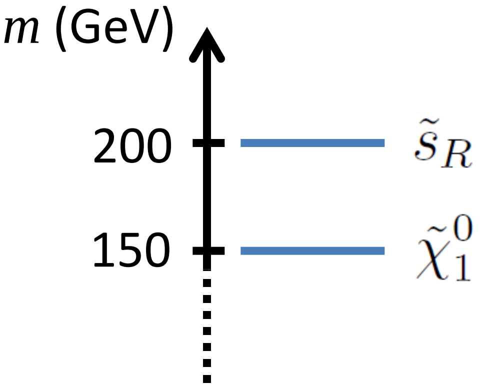

RH strange squark

bino (stable)

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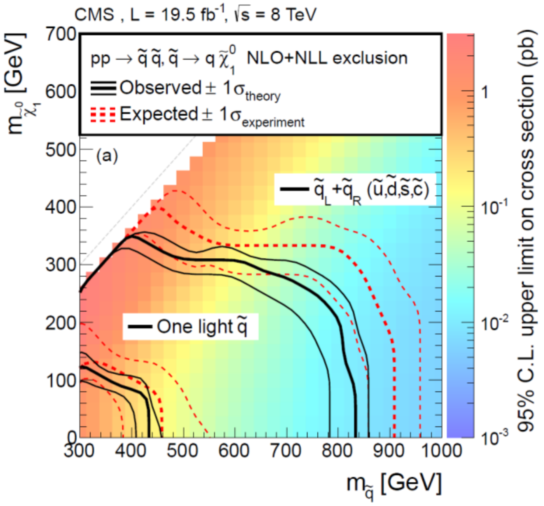
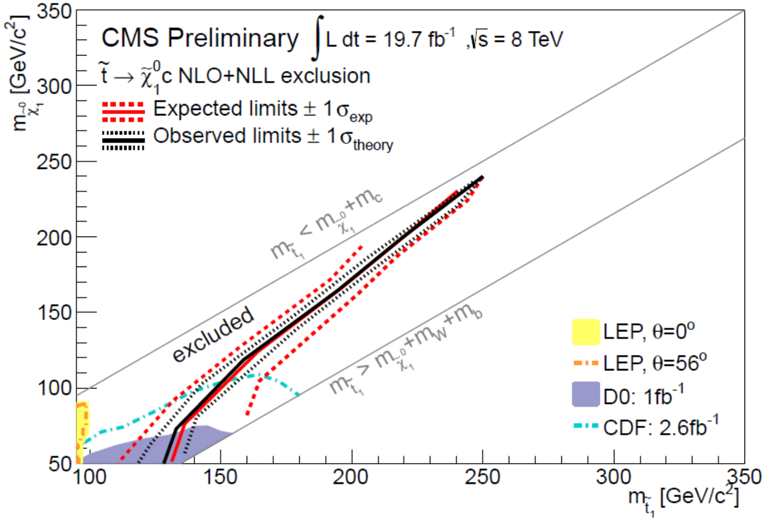


*The masses of interest are unfortunately not shown.

JHEP 06, 055 (2014) [arXiv:1402.4770]



CMS-PAS-SUS-13-009

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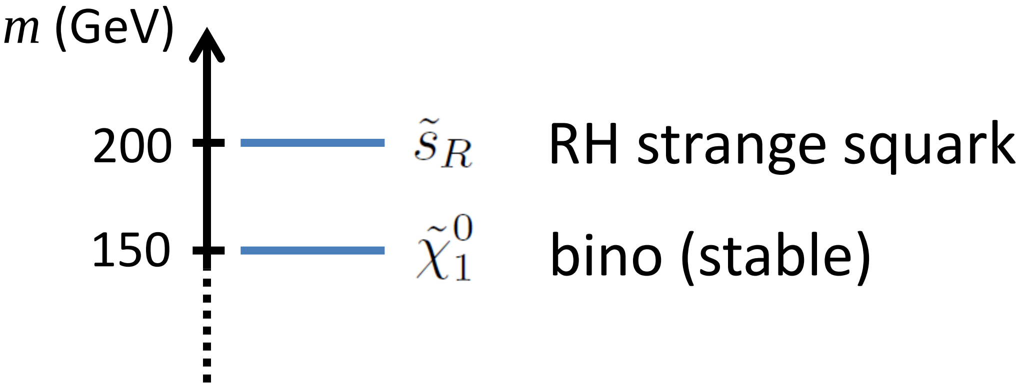

Test this interpretation by measuring the s-quark polarization.

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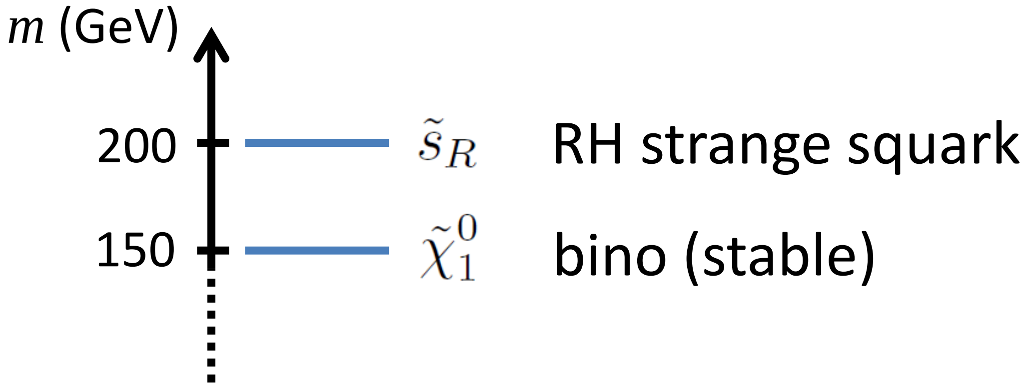

Test this interpretation by measuring the s-quark polarization.

Rough estimate (see paper for details):

for 3 ab^{-1} of 14 TeV data: statistical precision of 30%

(even without optimization of selection cuts, without accounting for the expected detector upgrades, and without combining ATLAS and CMS)

u, d polarizations

Cannot use decays of protons or neutrons,

but can again consider the Λ ($\approx sud$).

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Burkardt and Jaffe, PRL 70, 2537 (1993) [arXiv:hep-ph/9302232]
Jaffe, PRD 54, 6581 (1996) [arXiv:hep-ph/9605456]

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Information can also be obtained (although not yet) from:

- Polarized DIS and polarized pp collisions

  e.g., COMPASS, EPJC 64, 171 (2009)
  Deng (STAR), Phys.Part.Nucl. 45, 73 (2014)

- Lattice QCD simulations

  QCDSF, PLB 545, 112 (2002) [arXiv:hep-lat/0208017]
  CSSM and QCDSF/UKQCD, PRD 90, 014510 (2014) [arXiv:1405.3019]
  Chambers et al., arXiv:1508.06856

u, d polarizations

Studying u and d jets from $W^+ \rightarrow u\bar{d}$ decays in $t\bar{t}$ samples is in principle possible, but requires much more statistics than c and s because:

- No u or d tagging; c-tag veto is only partially effective (Can define separate u and d samples, contaminated by c and s respectively, using W_{leptonic} charge.)
- Fragmentation fractions $u, d \rightarrow \Lambda$ smaller than $s \rightarrow \Lambda$
- Polarization transfer is smaller

Overview

- SM $t\bar{t}$ production
  - Source of polarized b, c, s, d, u quarks
  - Statistics in Run 2 as large as in Z decays at LEP
  - Event reconstruction, charm tagging, charge tagging

  make it possible to study the different quarks separately

- Valuable information about QCD will be obtained.

  Interplay with LHCb, LEP, polarized DIS, polarized pp collisions, phenomenological models of QCD, lattice QCD.

- After calibrated on SM samples, measurements can be applied to new physics.

Supplementary Slides

Mass splittings and widths

bottom system

$$m_{\Lambda_b} = 5619.5 \pm 0.4 \text{ MeV}$$

Parameter	(MeV)
$m_{\Sigma_b} - m_{\Lambda_b}$	194 ± 2
$m_{\Sigma_b^*} - m_{\Lambda_b}$	214 ± 2
$\Delta \equiv m_{\Sigma_b^*} - m_{\Sigma_b}$	21 ± 2
Γ_{Σ_b}	7 ± 3
$\Gamma_{\Sigma_b^*}$	9 ± 2

charm system

$$m_{\Lambda_c} = 2286.5 \pm 0.2 \text{ MeV}$$

Parameter	(MeV)
$m_{\Sigma_c} - m_{\Lambda_c}$	167.4 ± 0.1
$m_{\Sigma_c^*} - m_{\Lambda_c}$	231.9 ± 0.4
$\Delta \equiv m_{\Sigma_c^*} - m_{\Sigma_c}$	64.5 ± 0.5
Γ_{Σ_c}	2.2 ± 0.2
$\Gamma_{\Sigma_c^*}$	15 ± 1

Soft muon b tagging

CMS PAS BTV-09-001

MC @ 10 TeV

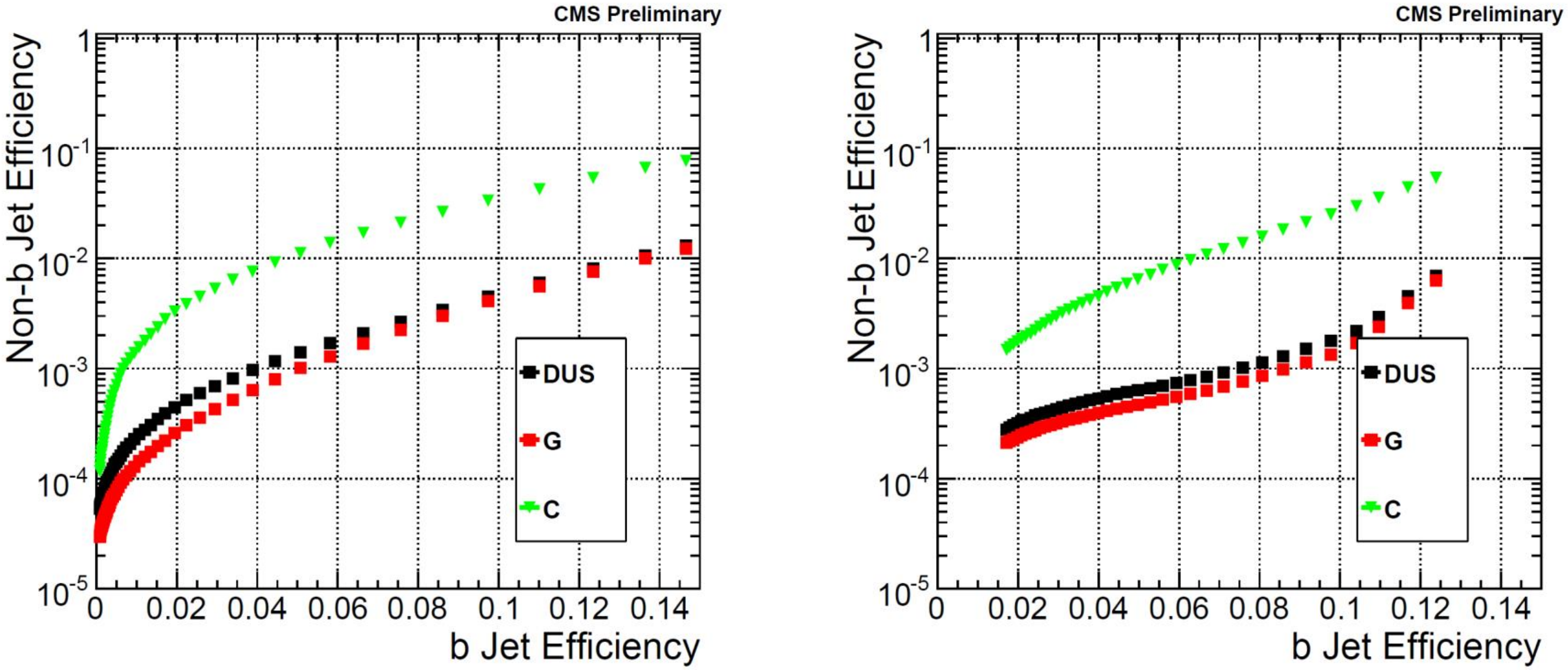

Figure 9: Mistag rate versus efficiency for the "soft muon by $p_{\mathrm{T}_{rel}}$" (left) and "soft muon by IP" (right) taggers.