8th International Workshop on Top Quark Physics
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Measuring polarizations of bottom, charm, strange, up and down quarks in top decays

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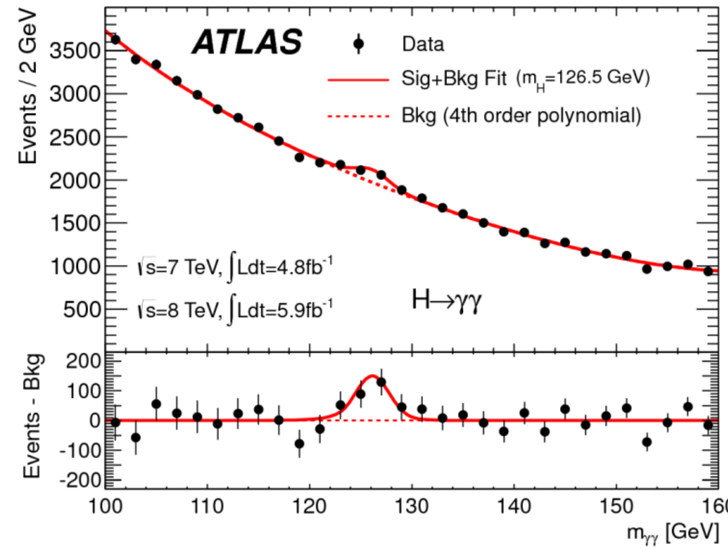
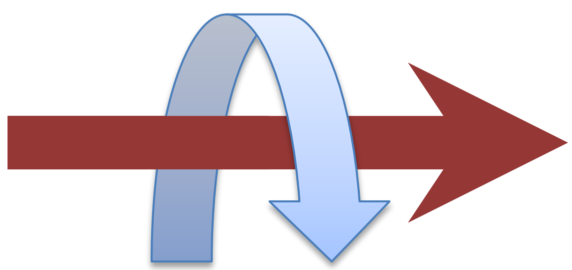
arXiv:1505.02771 (for heavy quarks)
in collaboration with:
Mario Galanti, Andrea Giammanco (experiment)
Yuval Grossman, Emmanuel Stamou, Jure Zupan (theory)

arXiv:1505.06731 (for light quarks)

Motivation

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





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

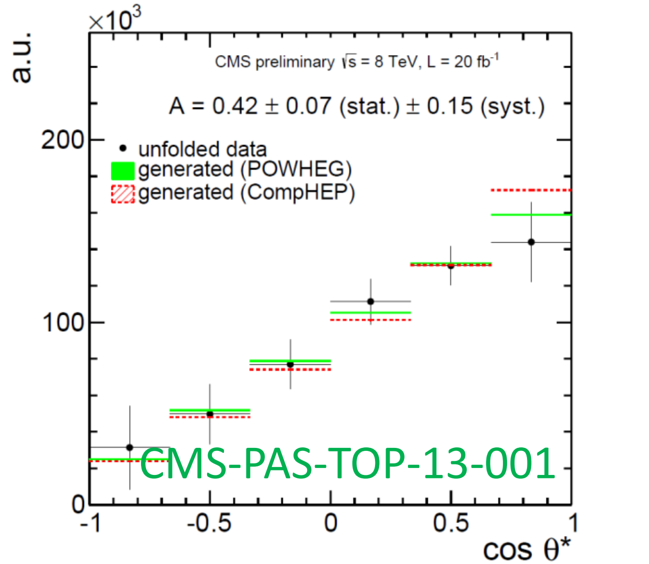
For **quarks**, momentum is easily reconstructed.

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

Motivation

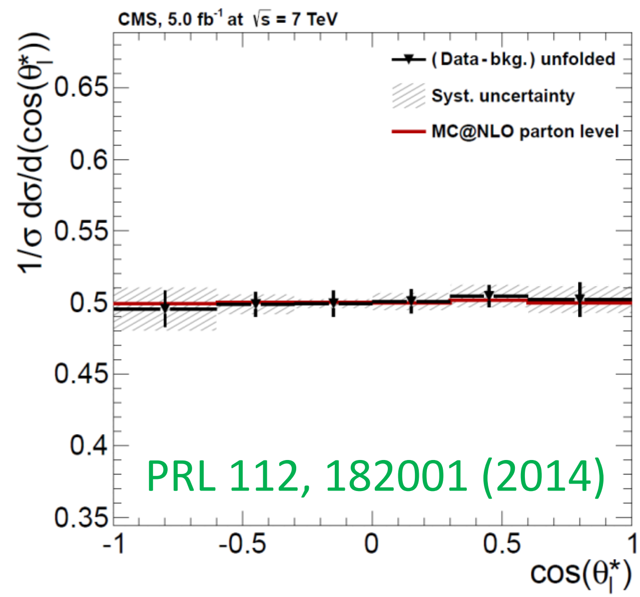
Top quark polarization measurements are now standard.

single top production



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

top pair production



EW process → polarized

QCD process → unpolarized

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

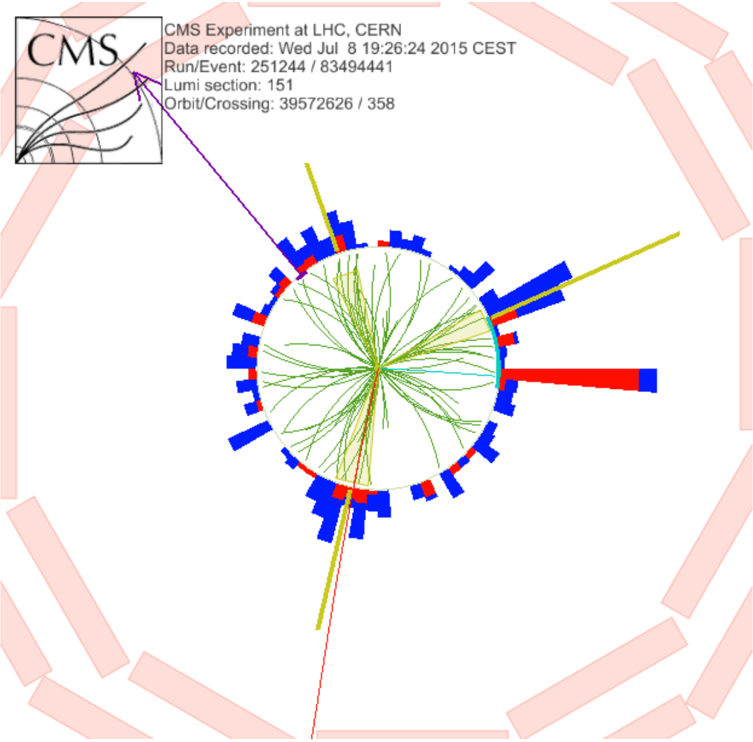
Can we do analogous measurements for the **other quarks**?

Motivation

Quarks produce jets of hadrons.

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

?



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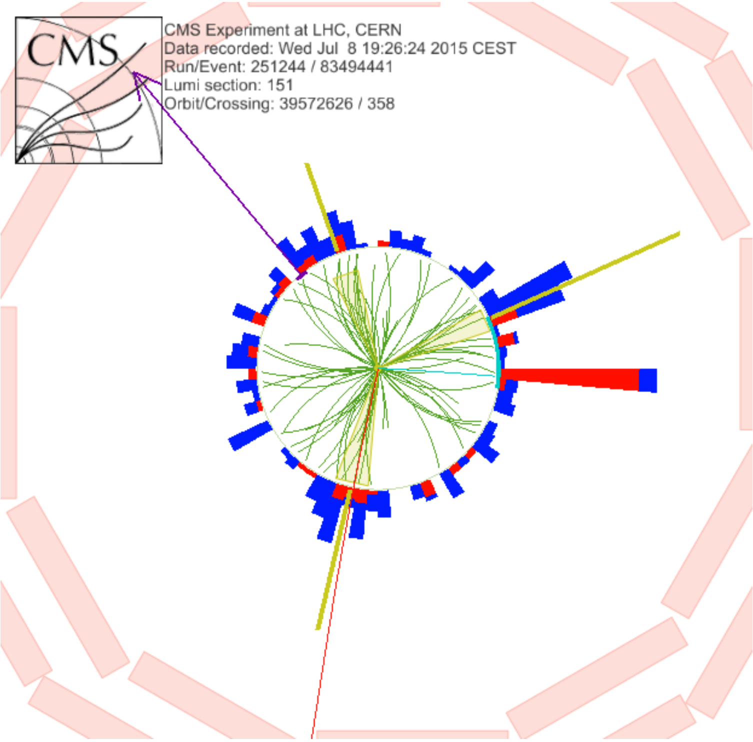

→ **Additional motivation, independent of new physics:** Measurements in Standard Model samples with known quark polarization will teach us about QCD.

Motivation

Quarks produce jets of hadrons.

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

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]

(See Supplementary Slides for details.)

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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]

Motivation

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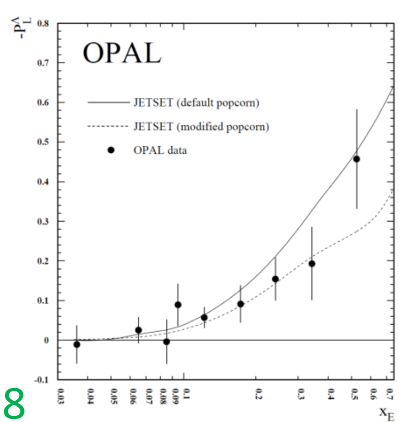
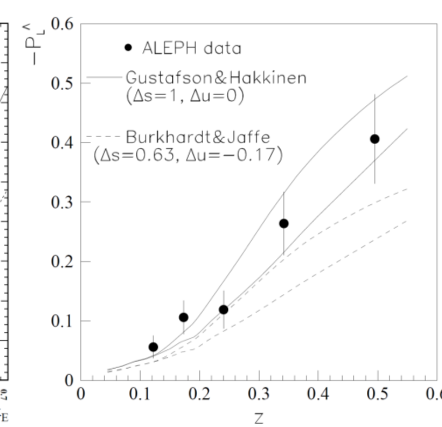
Sizable polarization observed at LEP also for Λ ($\approx sud$) baryons in $Z \to q\bar{q}$.

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

ALEPH: PLB 374, 319 (1996); CERN-OPEN-99-328





Great source of polarized quarks: Standard Model $t\bar{t}$ samples

- $t \to W^+ b$ produces polarized $\boldsymbol{b}$ quarks.
  $W^+ \to c\bar{s}, u\bar{d}$ produces polarized $\boldsymbol{c}$, $\boldsymbol{s}$, $\boldsymbol{u}$, $\boldsymbol{d}$ quarks.
- Easy to select a clean $t\bar{t}$ sample (e.g., in lepton + jets)
- Event reconstruction and charm tagging make it possible to study the different quark flavors separately.
- Statistics in Run 2 is as large as in Z decays at LEP.

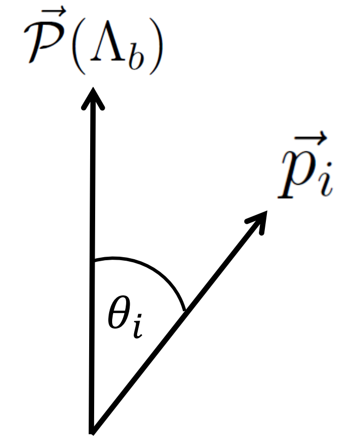
Λ_b polarization measurement

Can use the inclusive semileptonic decays

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

Λ_b polarization is encoded in the angular distributions

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



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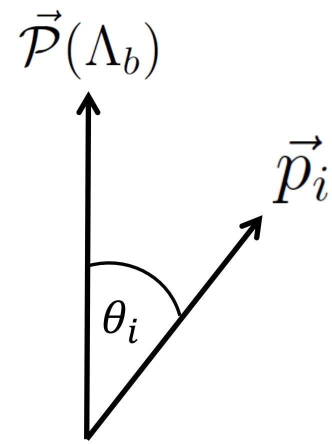

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where

$$\alpha_\ell = \frac{-\frac{1}{3} + 4x_c + 12x_c^2 - \frac{44}{3}x_c^3 - x_c^4 + 12x_c^2\log x_c + 8x_c^3\log x_c}{1 - 8x_c + 8x_c^3 - x_c^4 - 12x_c^2\log x_c} \approx -0.26$$

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

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

$$\Lambda_b \rightarrow X_c \ell^- \bar{\nu} \quad \text{(BR} \approx \text{10\% per flavor)}$$

- Soft-muon b tagging — e.g. CMS-PAS-BTV-09-001
- Neutrino reconstruction using…
  - Λ_b mass constraint
  - Λ_b flight direction

  Dambach, Langenegger, Starodumov
  NIMA 569, 824 (2006) [hep-ph/0607294]
- Neutrino A_{FB} measurement (in the Λ_b rest frame)
- Approaches regarding semileptonic B-meson background:

Inclusive	keep it
Semi-inclusive	demand $\Lambda \rightarrow p\pi^-$ among decay products
Exclusive	demand a fully-reconstructible Λ_c decay

See paper for many additional details…

Λ_c polarization measurement

$$\Lambda_c^+ \to pK^-\pi^+ \quad \text{(BR} \approx 6.7\%)$$

- Three tracks reconstructing the Λ_c mass.
- Backgrounds under the mass peak can be suppressed in various ways (see Supplementary Slides).
- Spin analyzing powers α_i seem to be large for K^-, small for p and π^+.

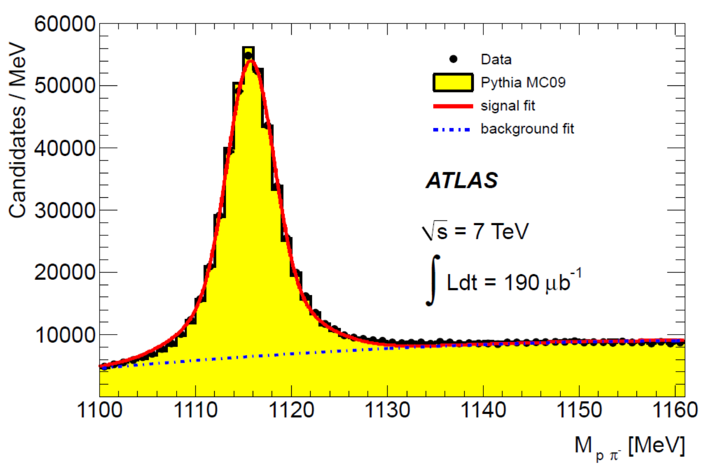
  NA32: Jezabek, Rybicki, Rylko, PLB 286, 175 (1992)

  Precise values not essential if SM calibration samples are available.

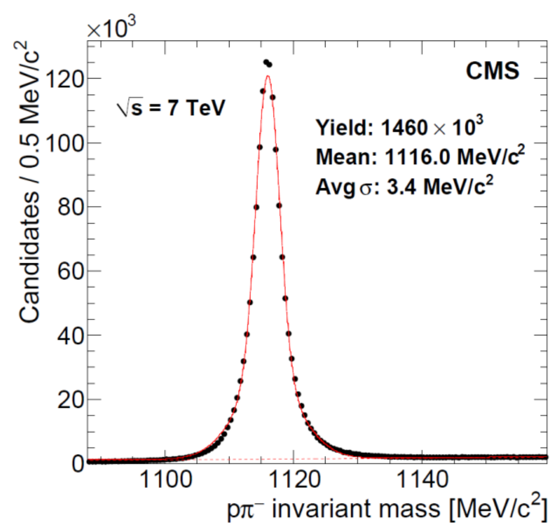
Λ polarization measurement

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

- 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

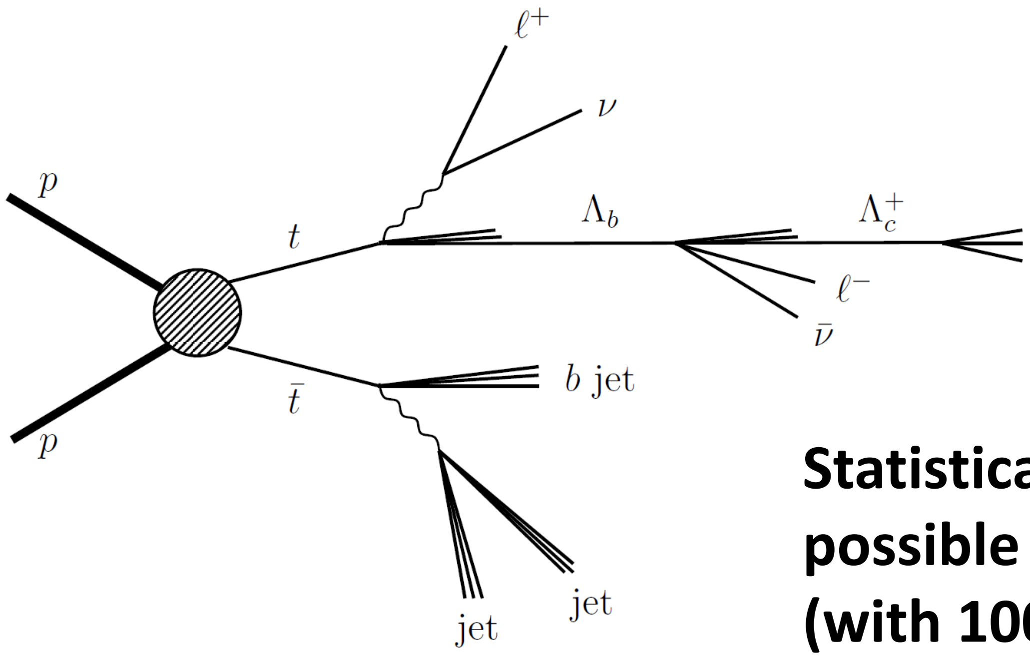


PRD 85, 012001 (2012) [arXiv:1111.1297]



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

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



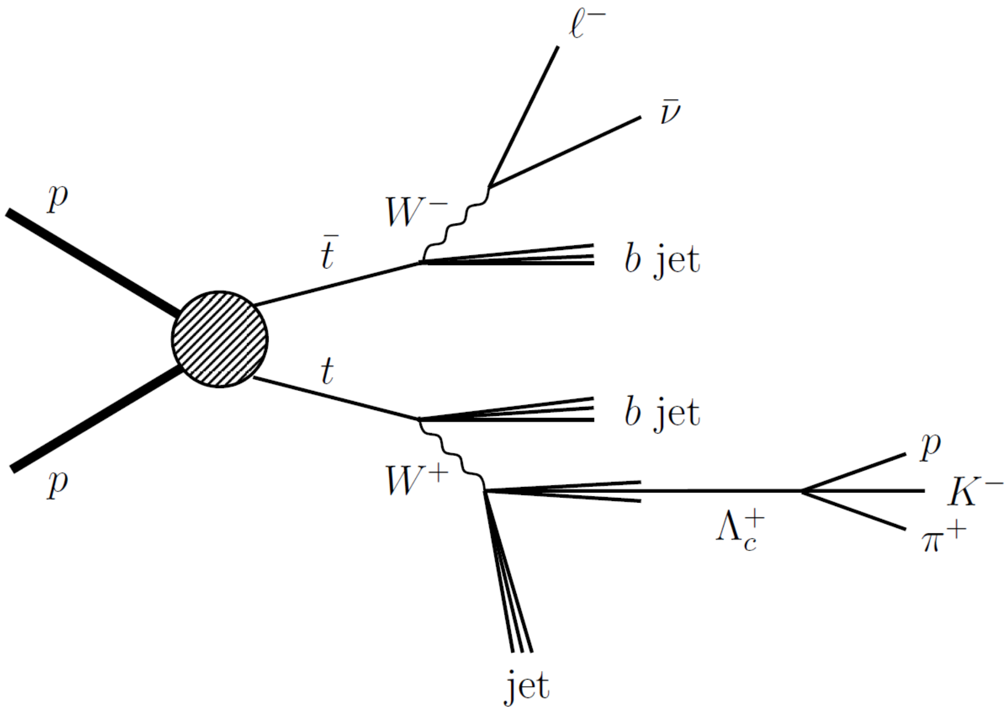
Statistical precision of about 10% possible at ATLAS/CMS in Run 2 (with 100/fb of data)

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 c polarization in $t\bar{t}$

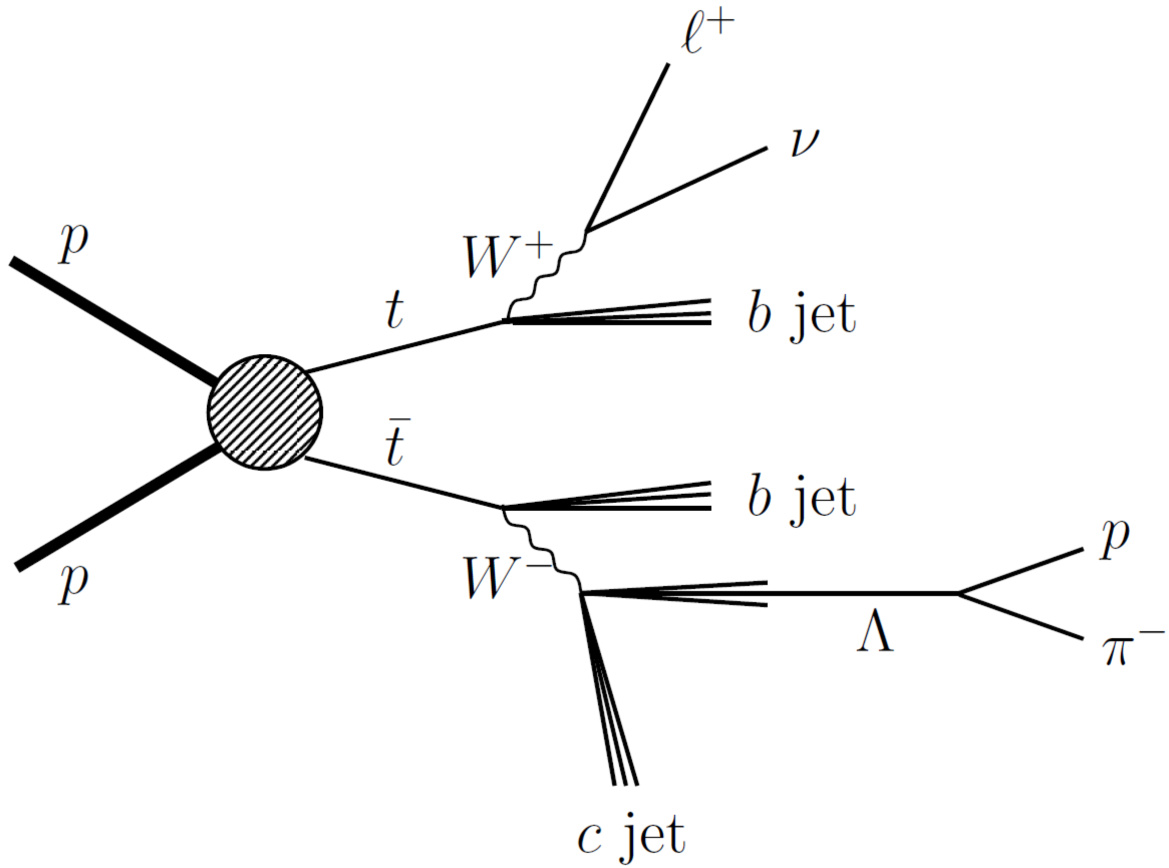


Statistical precision of order 10% possible at ATLAS/CMS in Run 2 (with 100/fb of data)

$\alpha_i r_L = 0.6$

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%	26%
		100%	11%

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)

u, d polarizations

Cannot use decays of protons or neutrons, but can again consider the Λ (≈ sud).

Naïve quark model: all the Λ spin is on the s ☹

Nucleon DIS + flavor SU(3): u and d carry about –20% each ☺

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

Further inputs possible in the future from:

- Polarized DIS and polarized pp collisions

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

- Lattice QCD

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

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Studies of u, d jets in $t\bar{t}$ samples will require **much more statistics** than s, also because:

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

Overview

- SM $t\bar{t}$ production
  - Clean source of polarized b, c, s, d, u quarks
  - Flavor separation via event reconstruction, charm tagging
  - Statistics in Run 2 as large as in Z decays at LEP
  - Measurements of b, c, s polarizations already in Run 2

- Valuable information about QCD will be obtained.
  Interplay with HQET, models of QCD, lattice QCD,
  LEP, LHCb, polarized DIS, polarized pp collisions.

- After calibration on $t\bar{t}$, measurements can be applied
  to new physics (example in Supplementary Slides).

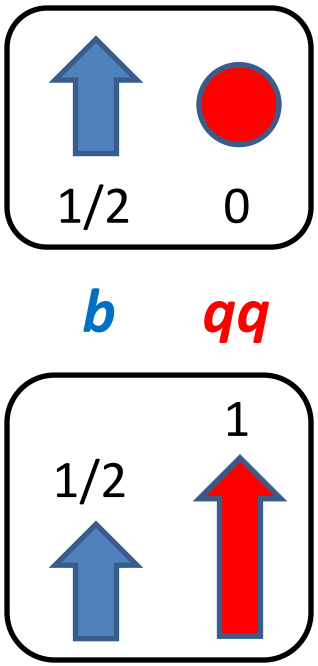
Supplementary Slides

b-quark polarization retention

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

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

b spin **preserved** during hadronization



Λ_b — *b* spin **preserved** during lifetime

Σ_b, Σ_b^* — *b* spin **oscillates** during lifetime

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

Fragmentation fraction into baryons ≈ 8%

b-quark polarization retention

To what extent is the polarization preserved?

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

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

diquarks

S	T
spin-0 isosinglet	spin-1 isotriplet

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

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

Falk and Peskin
PRD 49, 3320 (1994)

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

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

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

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

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?

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

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

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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

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

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

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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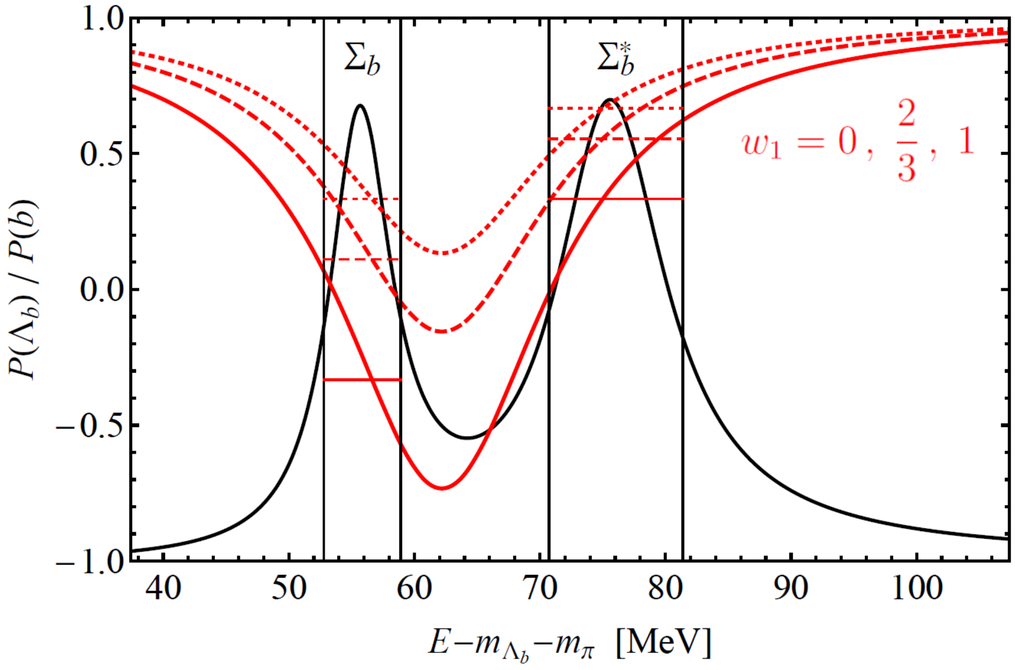
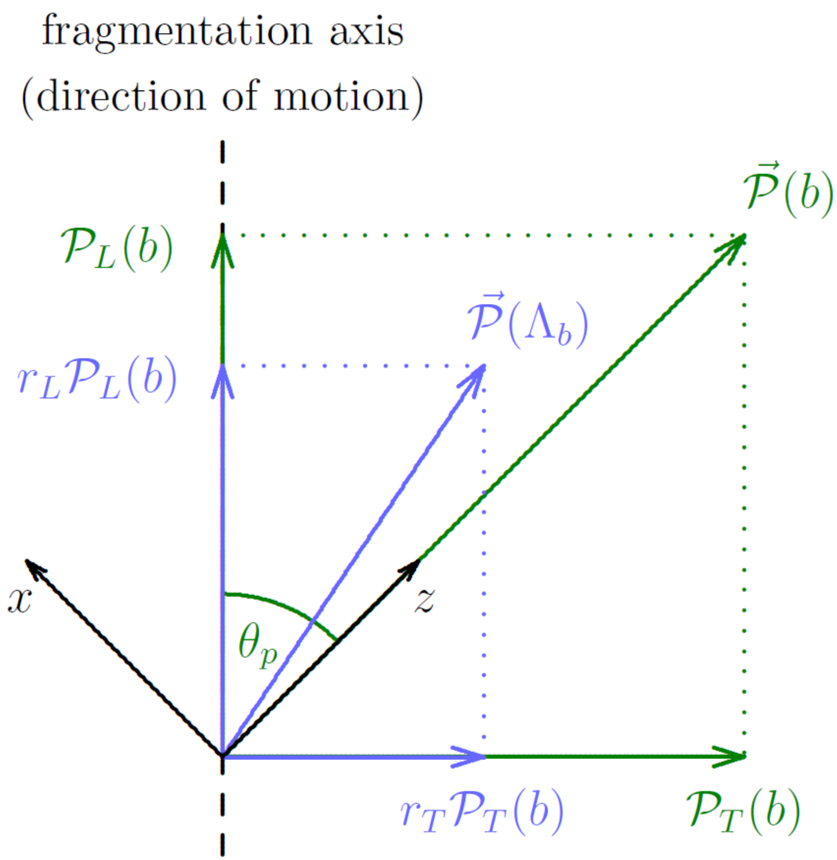


$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} \approx \frac{1 + (0.23 + 0.38 w_1)\, A}{1 + A}$$

b-quark polarization retention

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

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

What is known about A and w_1?

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

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

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

  DELPHI-95-107
- Pheno. model $\quad A \approx 6 \quad w_1 \approx 0.41$

  Adamov, Goldstein, PRD 64, 014021 (2001) [hep-ph/0009300]
- Statistical had. model $\quad A \approx 2.6$

  review: PLB 678, 350 (2009) [arXiv:0904.1368]
- Pythia tunes $\quad 0.24 \lesssim A \lesssim 0.45$

  based on light hadron data!

- CESR (charm)

  CLEO, PRL 78, 2304 (1997)

  $w_1 = 0.71 \pm 0.13$

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

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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]

bottom system

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

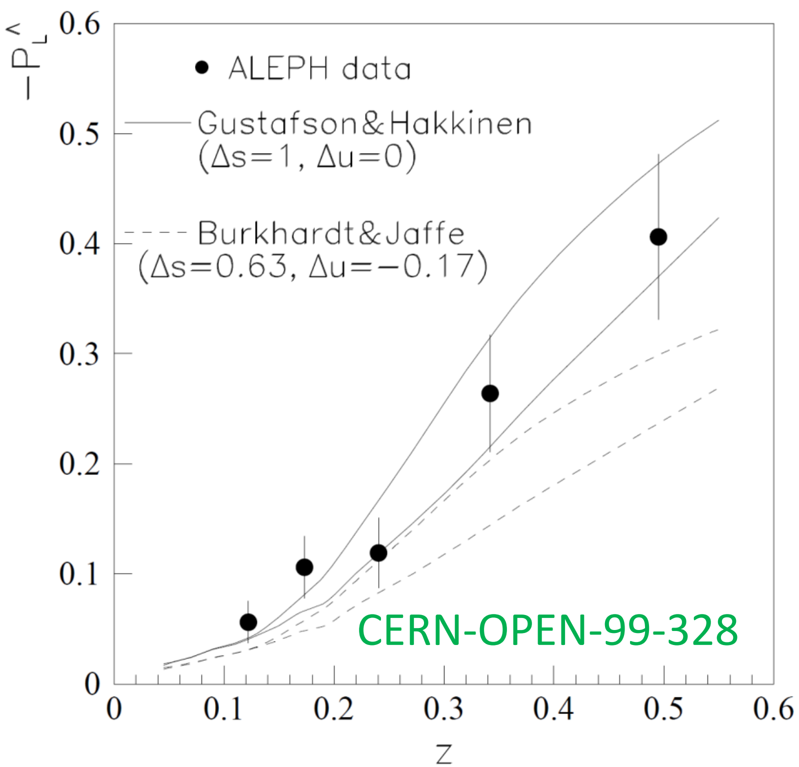
$m_{\Lambda_c} = 2286.5 \pm 0.2$ MeV

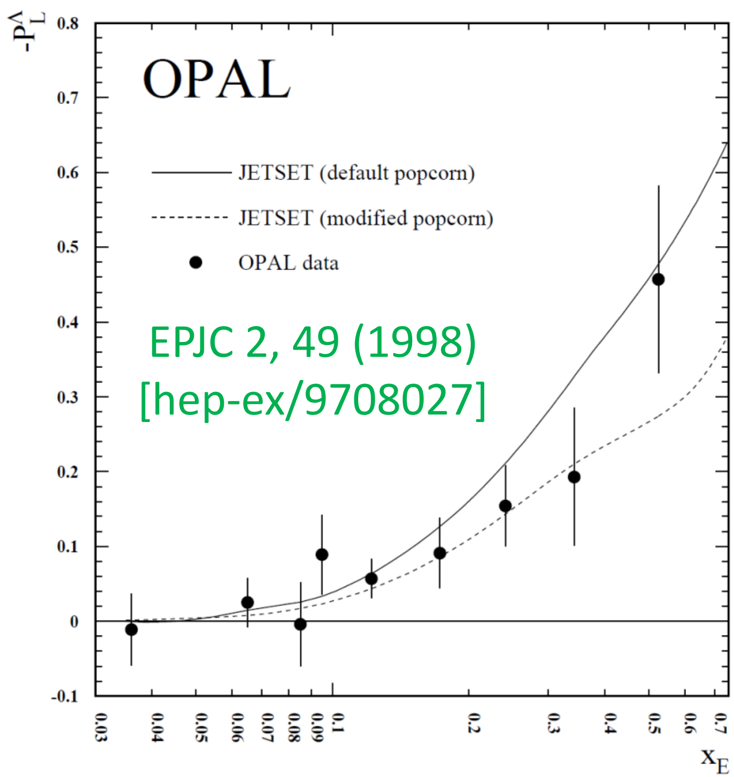
Parameter	(MeV)
$m_{\Sigma_c} - m_{\Lambda_c}$	167.4 ± 0.1
$m_{\Sigma_c^*} - m_{\Lambda_c}$	231.9 ± 0.4
$\Delta \equiv m_{\Sigma_c^*} - m_{\Sigma_c}$	64.5 ± 0.5
Γ_{Σ_c}	2.2 ± 0.2
$\Gamma_{\Sigma_c^*}$	15 ± 1

s-quark polarization retention

- Cannot argue for polarization retention using heavy-quark limit. Cannot argue for polarization loss either!

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





s-quark polarization retention

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

Which decay mode(s) to use for measuring the polarization?

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

Λ_b decay modes

Which decay mode(s) to use for measuring the polarization?

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$(b \to \Lambda_b^0)$		$(5.8 \pm 0.8) \times 10^{-5}$
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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}	$\Lambda_c^+ \ell^- \bar{\nu}_\ell$ anything	[a]	(9.9 ± 2.2) %
Γ_{14}	$\Lambda_c^+ \ell^- \bar{\nu}_\ell$		$(6.5 {}^{+3.2}_{-2.5})$ %
Γ_{15}	$\Lambda_c^+ \pi^+ \pi^- \ell^- \bar{\nu}_\ell$		(5.6 ± 3.1) %
Γ_{16}	$\Lambda_c(2595)^+ \ell^- \bar{\nu}_\ell$		$(8 \pm 5) \times 10^{-3}$
Γ_{17}	$\Lambda_c(2625)^+ \ell^- \bar{\nu}_\ell$		$(1.4 {}^{+0.9}_{-0.7})$ %
Γ_{18}	$\Sigma_c(2455)^0 \pi^+ \ell^- \bar{\nu}_\ell$		
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Γ_{20}	$p h^-$	[b]	$< 2.3 \times 10^{-5}$
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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

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

- **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]

- 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 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_c decay modes

Inclusive modes

Γ_{67}	e^+ anything	(4.5 ± 1.7) %
Γ_{68}	pe^+ 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	$n\gamma$	$(1.75 \pm 0.15) \times 10^{-3}$
Γ_4	$p\pi^-\gamma$	$(8.4 \pm 1.4) \times 10^{-4}$
Γ_5	$pe^-\overline{\nu}_e$	$(8.32 \pm 0.14) \times 10^{-4}$
Γ_6	$p\mu^-\overline{\nu}_\mu$	$(1.57 \pm 0.35) \times 10^{-4}$

Overall 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.

Soft muon b tagging

CMS PAS BTV-09-001

MC @ 10 TeV

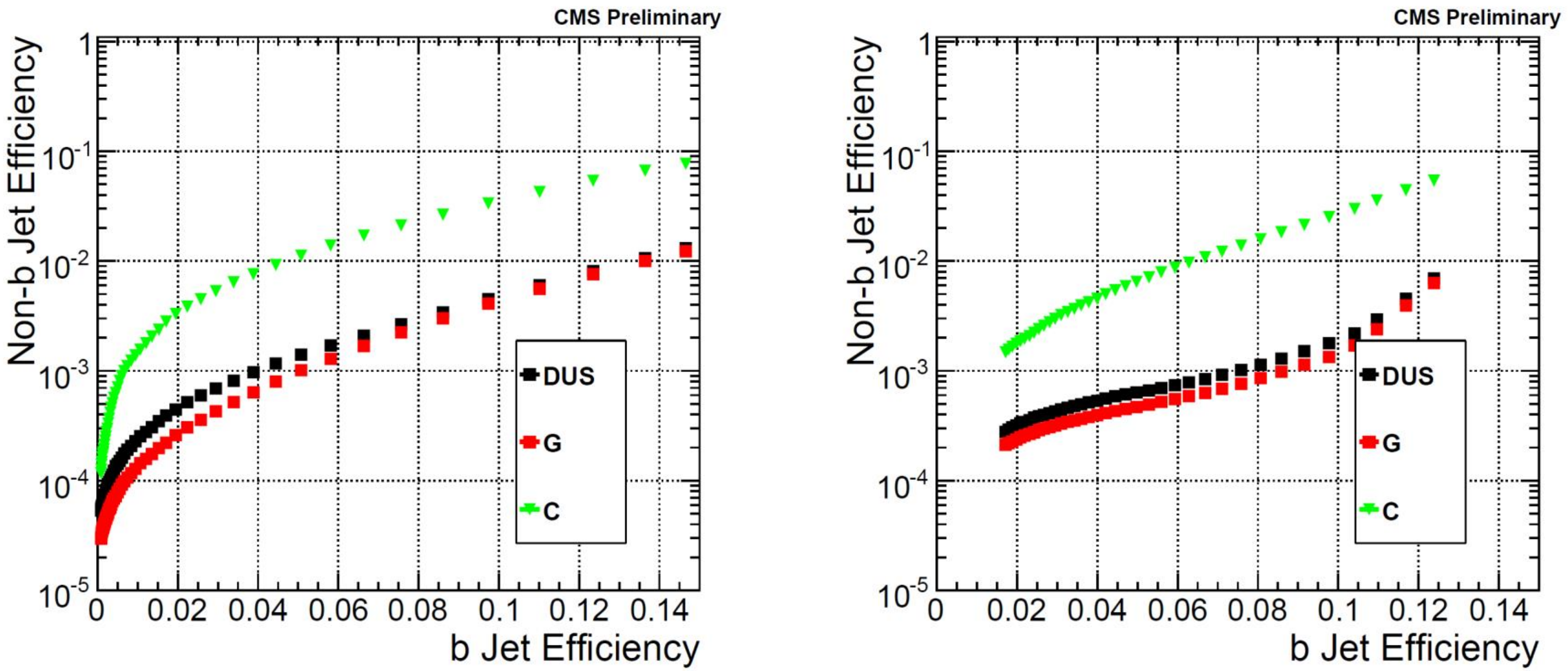


Figure 9: Mistag rate versus efficiency for the "soft muon by $p_{\mathrm{T}rel}$" (left) and "soft muon by IP" (right) taggers.

Λ_b polarization in QCD production

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)

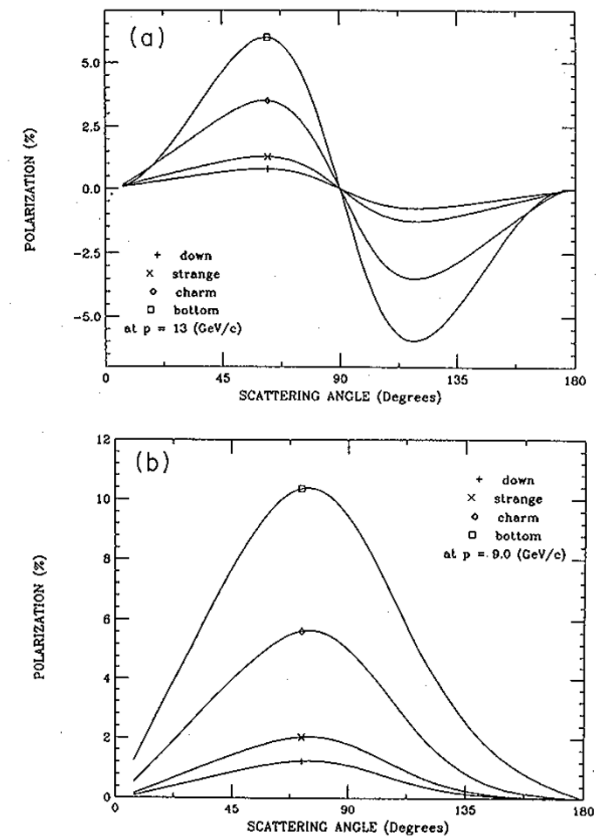


FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.

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.

Λ_b polarization in Z decays

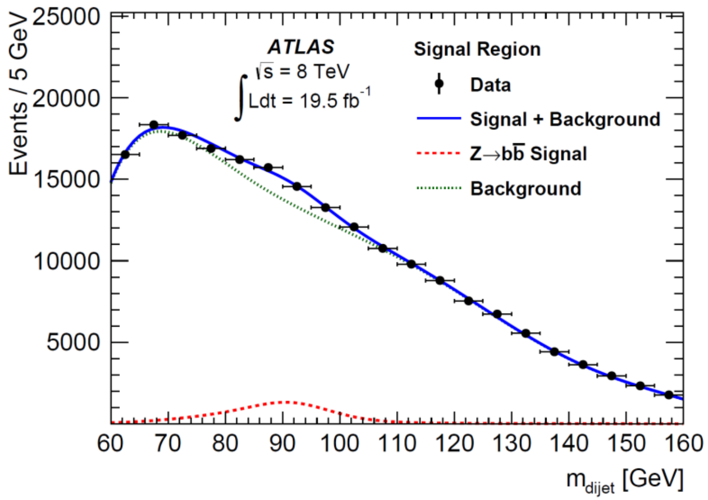
Z production: $pp \to Z \to b\bar{b}$

- Longitudinally polarized b quarks
- 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. →

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



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

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

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

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

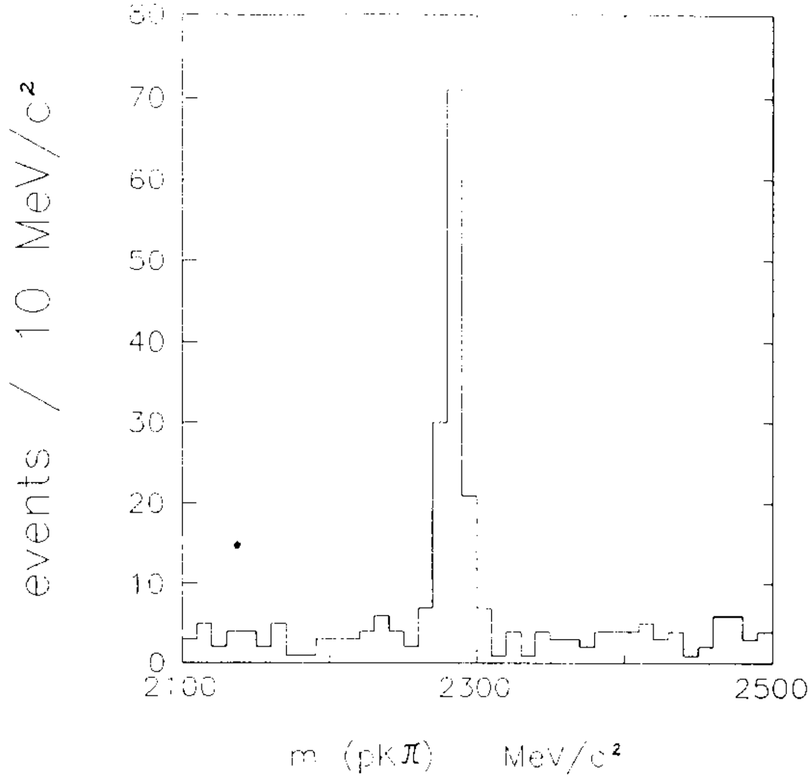
  $D_s^+ \to K^+K^-\pi^+,\ K^+K^-\pi^+\pi^0$

Handles for suppressing them:

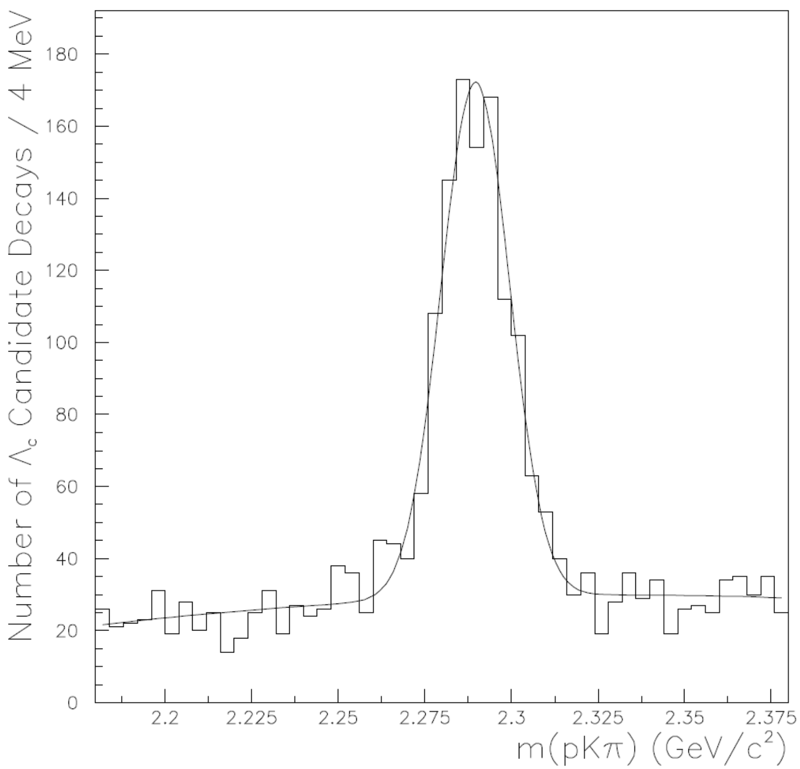
- Typical momentum hierarchy in the lab frame: $p > K^- > \pi^+$
- Veto on additional further-displaced vertices/kinks
- Veto on a 4th track consistent with the Λ_c vertex
- Lifetime differences: $\tau(\Lambda_c^+, D^0, D_s^+, D^+) \simeq (2, 4, 5, 10) \times 10^{-13}$ s
- Target particular 3-prong backgrounds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

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

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



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



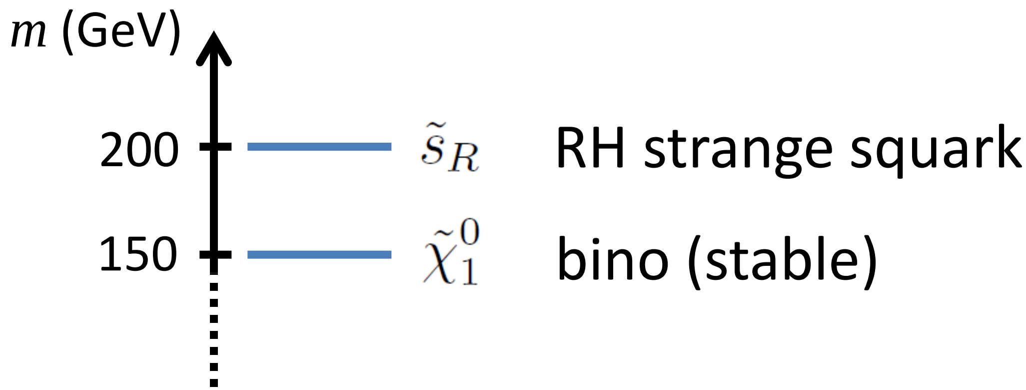
E791: PLB 471, 449 (2000)
[arXiv:hep-ex/9912003]

New physics example

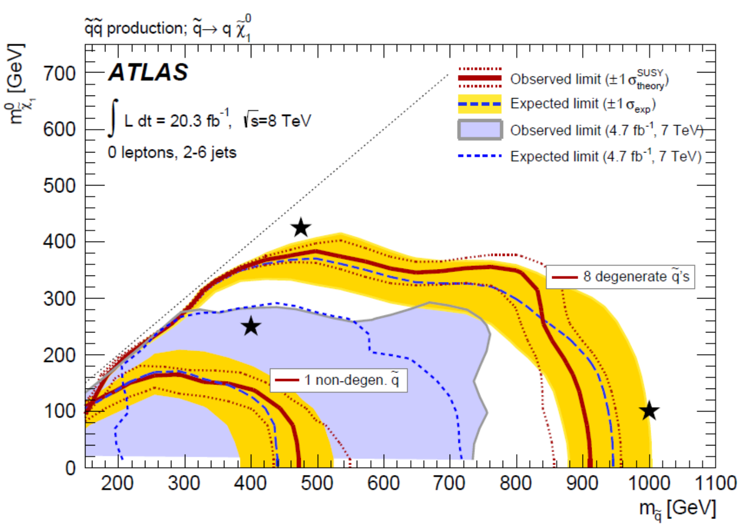
Suppose a jets + MET excess is being attributed to:

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

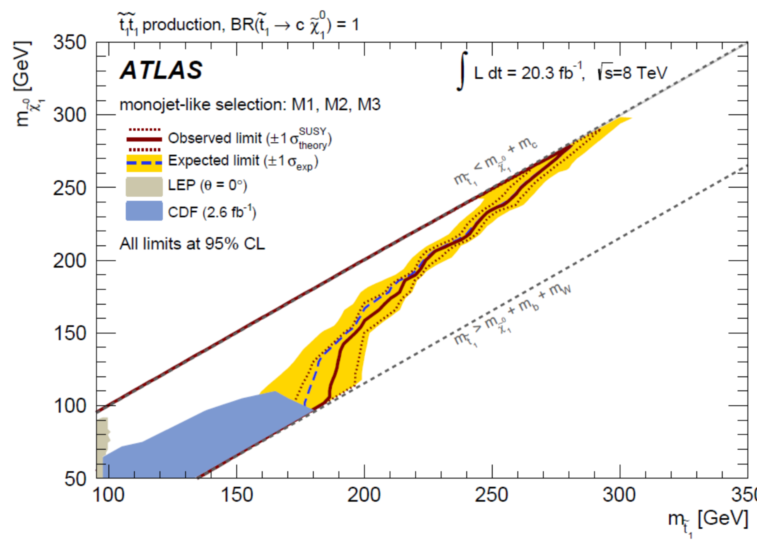
$$\tilde{s}_R \to s\, \tilde{\chi}_1^0$$



This scenario was barely beyond the reach of Run 1.



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



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

New physics example

Suppose a jets + MET excess is being attributed to:

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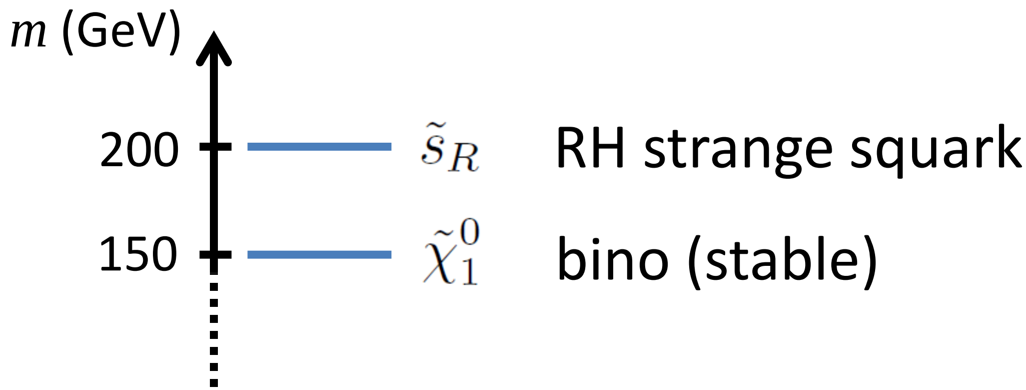
$$\tilde{s}_R \rightarrow s\, \tilde{\chi}_1^0$$



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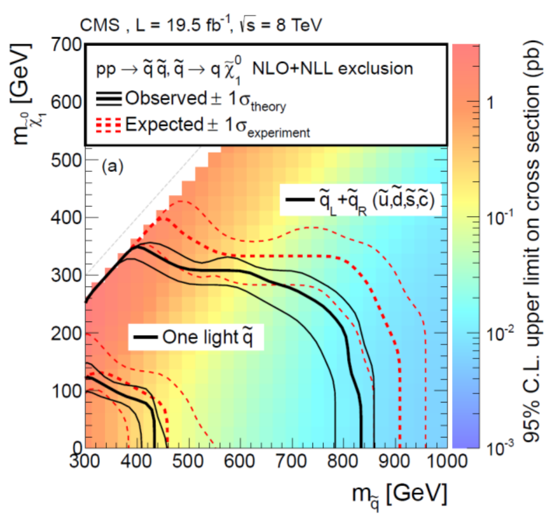
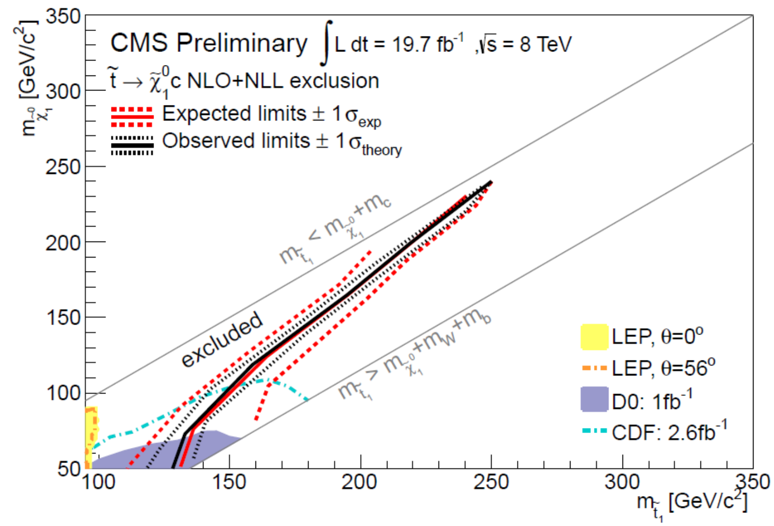


*The masses of interest are unfortunately not shown.

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



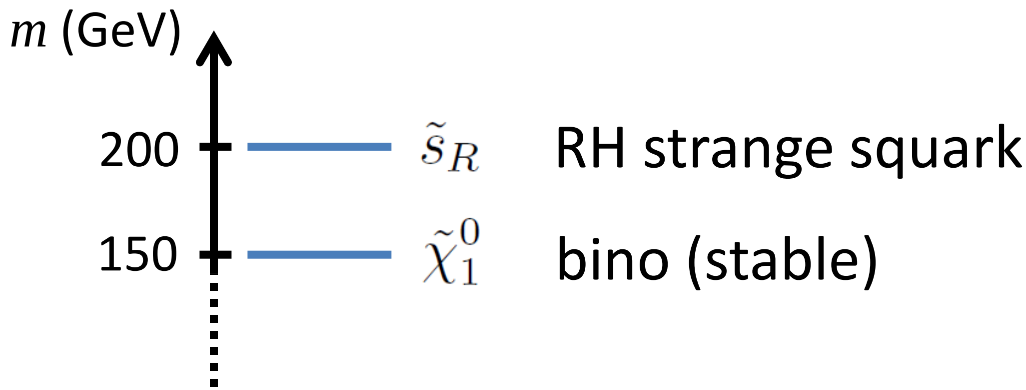
CMS-PAS-SUS-13-009

New physics example

Suppose a jets + MET excess is being attributed to:

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

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



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)