LFC17: Old and New Strong Interactions from LHC to Future Colliders *ECT* 14.9.2017*

Measuring quark polarizations at ATLAS and CMS

Yevgeny Kats

Based on:

JHEP 11 (2015) 067 [arXiv:1505.02771]
with Galanti, Giammanco, Grossman, Stamou, Zupan

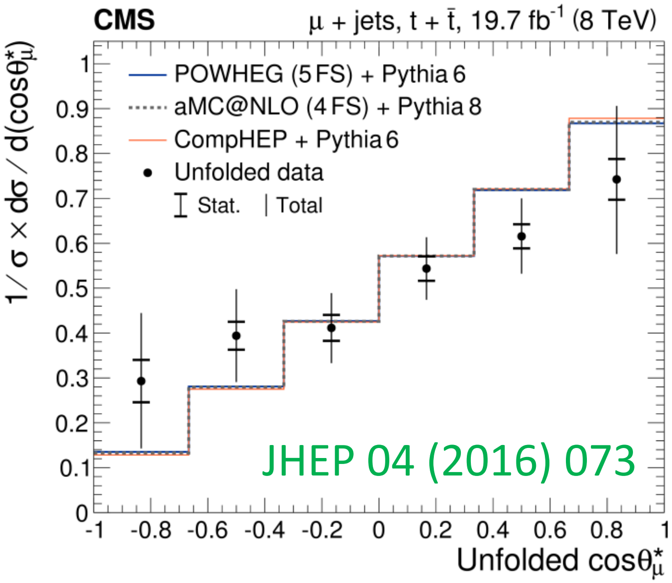
Phys. Rev. D 92, 071503 (2015) [arXiv:1505.06731]

JHEP 11 (2016) 011 [arXiv:1512.00438]

Motivation

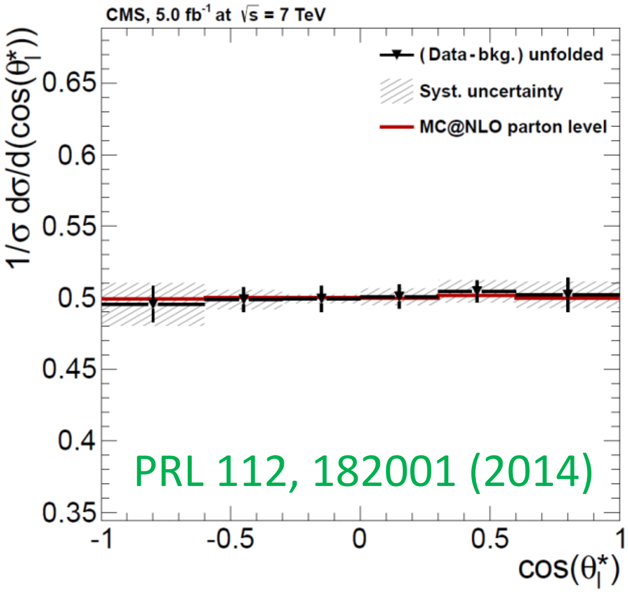
ATLAS and CMS already measure **top quark** polarization.

single top production



JHEP 04 (2016) 073

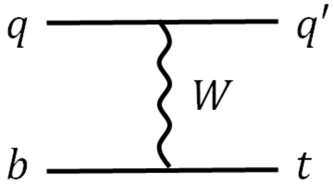
top pair production

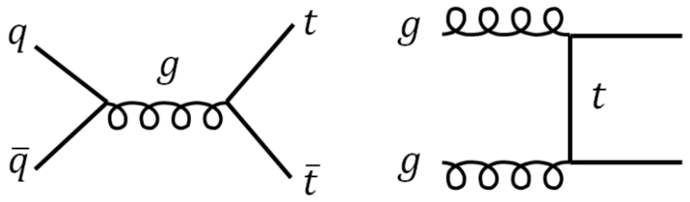


PRL 112, 182001 (2014)

EW process → polarized

QCD process → unpolarized





etc.

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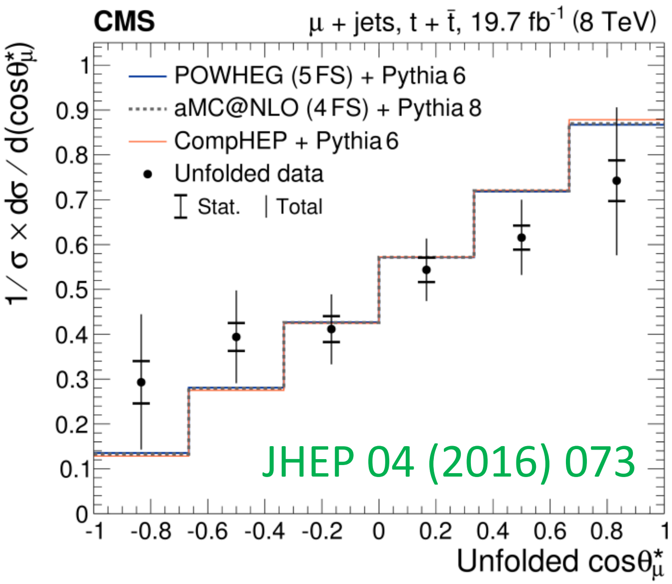

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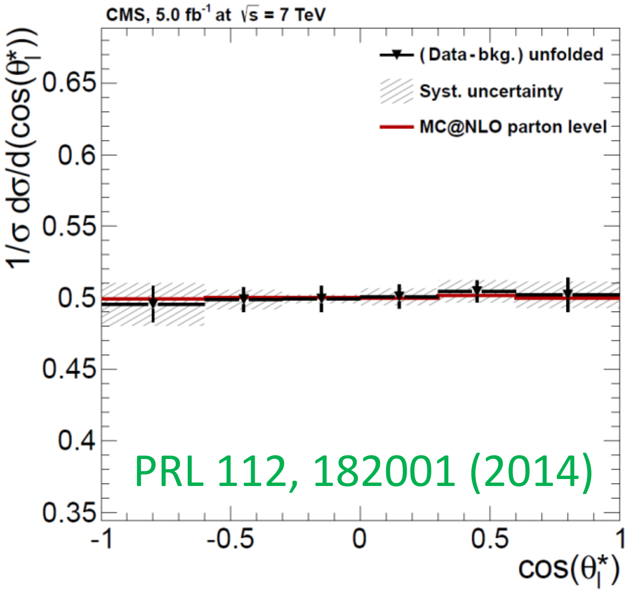

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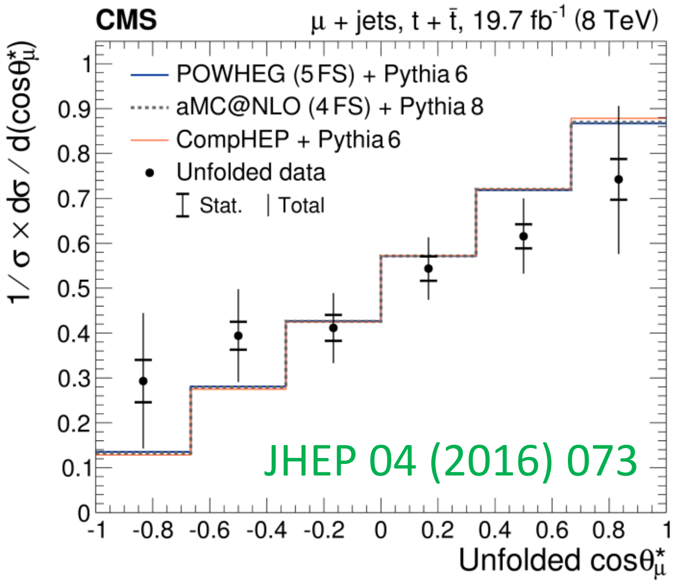

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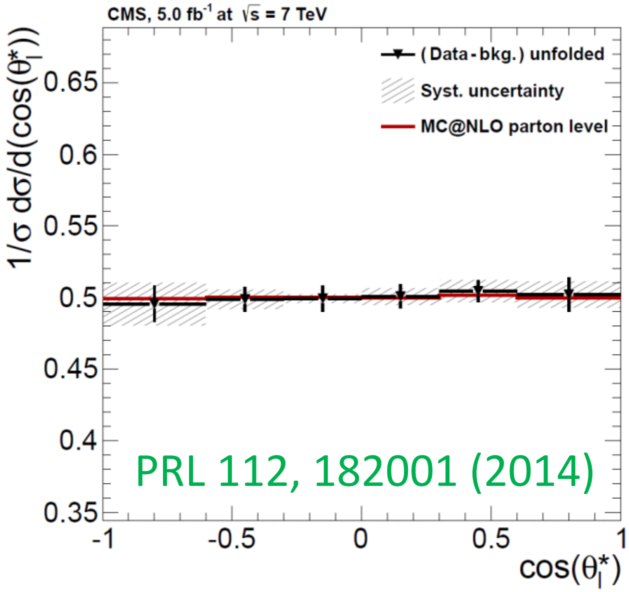

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QCD process → unpolarized

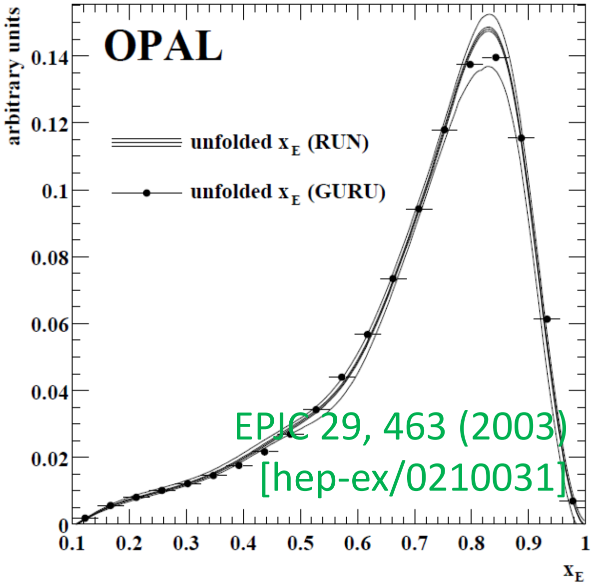
Polarization of tops from **new physics** processes will teach us about their production mechanism.

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

Heavy quarks (b, c)

For heavy quarks, $m_q \gg \Lambda_{\mathrm{QCD}}$

- The quark is carried by a **very energetic** heavy-flavored hadron.



EPJC 29, 463 (2003)
[hep-ex/0210031]

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- When it is a **baryon**, $\mathcal{O}(1)$ fraction of the polarization is expected to be retained.

  Mannel and Schuler, PLB 279, 194 (1992)

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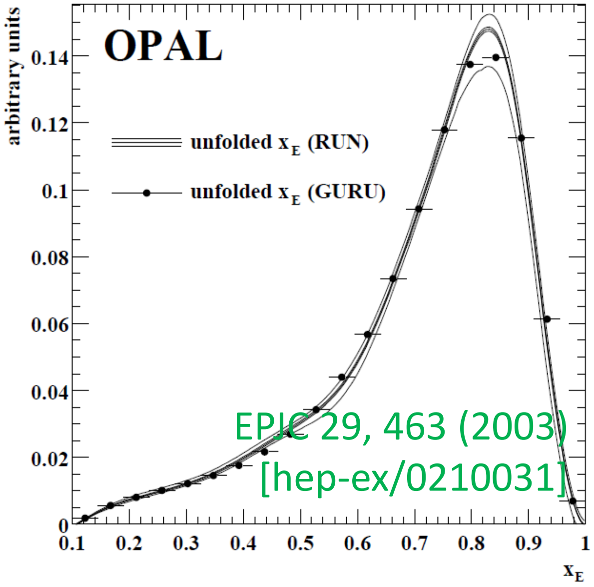

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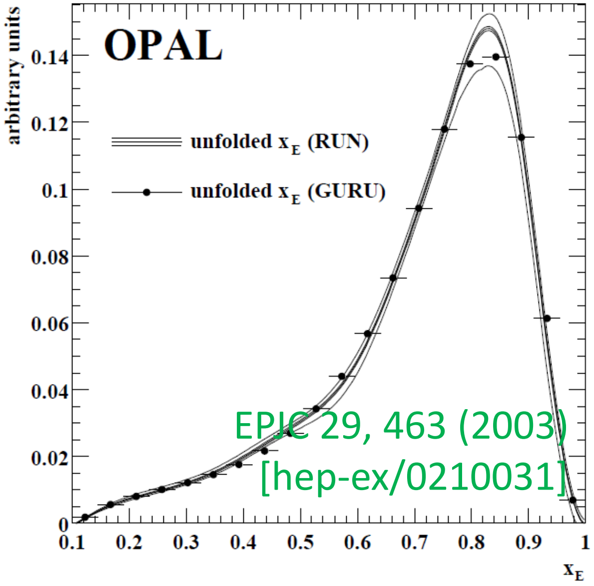

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Evidence observed at **LEP** via Λ_b ($\approx bud$) baryons in $Z \to b\bar{b}$.

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

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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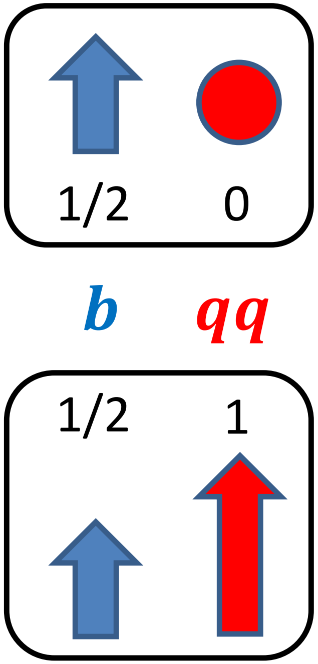


Λ_b

b spin **preserved** also during lifetime

Σ_b, Σ_b^*

b spin **oscillates** during lifetime

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

fragmentation fraction $f\,(b \to \text{baryons}) \approx 8\%$

c-quark polarization retention

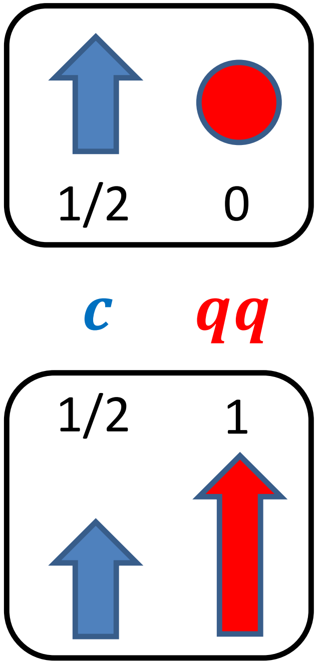
chromomagnetic moment

$$\mu_c \propto \frac{1}{m_c}$$

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

as a rough approximation

c spin **preserved** during hadronization



Λ_c

c spin **preserved** also during lifetime

$\Sigma_c(2455)$

Σ_c, Σ_c^*

$\Sigma_c(2520)$

c spin **oscillates** during lifetime

Λ_c sample contaminated by $\Sigma_c^{(*)} \to \Lambda_c \pi$

fragmentation fraction $f(c \to \text{baryons}) \approx 6\%$

b-quark polarization retention

Dominant polarization loss effect

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

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

b-quark polarization retention

Dominant polarization loss effect

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

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

$$\left|\Lambda_{b,+1/2}\right\rangle = \left|b_{+1/2}\right\rangle \left|S_0\right\rangle$$

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

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

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

“diquarks”

S	T
spin-0 isosinglet	spin-1 isotriplet

Production as a b spin eigenstate.

Decay as a Σ_b or Σ_b^* mass eigenstate.

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

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"diquarks"

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

$$w_1 = \frac{\text{prob}(T_{\pm 1})}{\text{prob}(T)}$$ along axis of fragmentation

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Falk and Peskin
PRD 49, 3320 (1994)
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e.g. $$\left|b_{+1/2}\right\rangle \left|T_0\right\rangle = -\sqrt{\tfrac{1}{3}}\left|\Sigma_{b,+1/2}\right\rangle + \sqrt{\tfrac{2}{3}}\left|\Sigma^*_{b,+1/2}\right\rangle$$

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

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

Can do it by considering $\Sigma_b^{(*)}$ propagation:

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

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

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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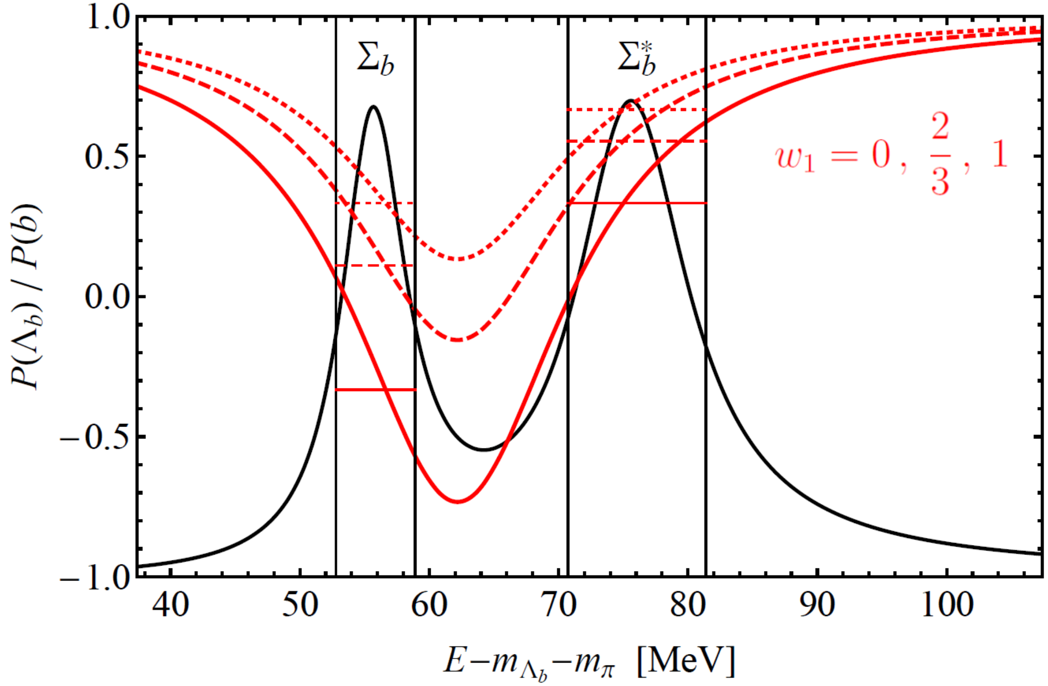


$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} \approx \frac{1 + (0.23 + 0.38 w_1) A}{1 + A}$$

b-quark polarization retention

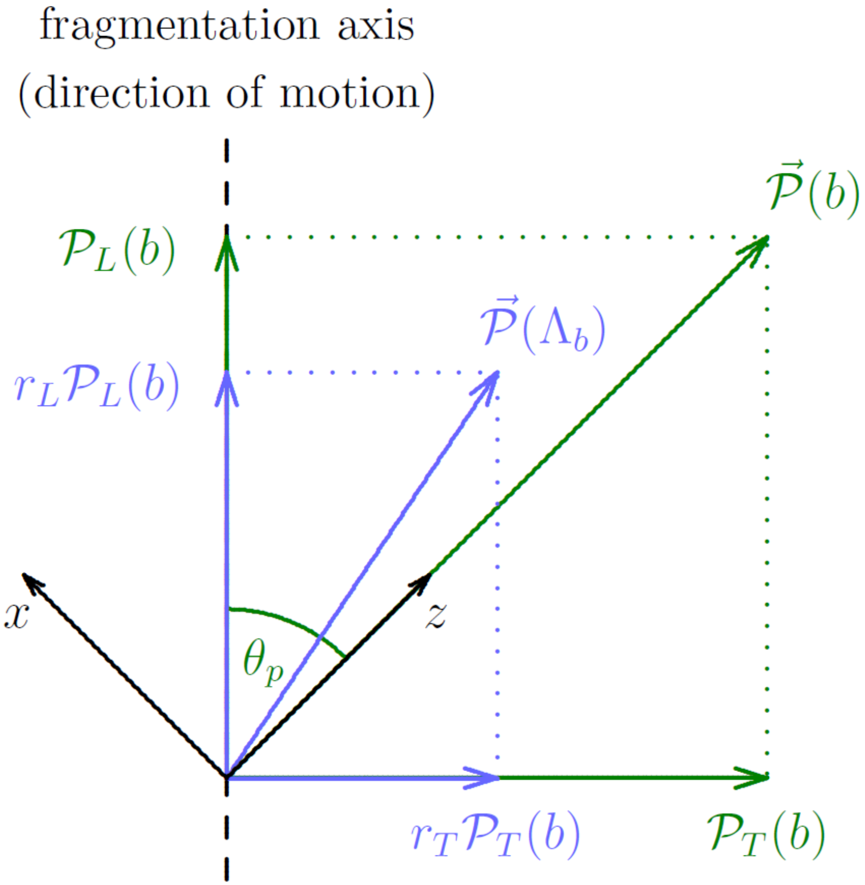
$$r_L \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A}$$

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

Directional dependence, since

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

holds along the fragmentation axis.



Heavy quark polarization retention

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What is known about A and w_1 (for both b and c quarks)?

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What is known about A and w_1 (for both b and c quarks)?

Pythia tunes $0.24 \lesssim A \lesssim 0.45$ (based on light hadron data)

DELPHI (LEP) $1 \lesssim A \lesssim 10\ (b)$ $w_1 = -0.36 \pm 0.30 \pm 0.30\ (b)$

DELPHI-95-107

E791 $A \approx 1.1\ (c)$

PLB 379, 292 (1996)

CLEO (CESR) $w_1 = 0.71 \pm 0.13\ (c)$

PRL 78, 2304 (1997)

Statistical hadronization $A \approx 2.6$ (b and c)

review: PLB 678, 350 (2009)

Adamov & Goldstein $A \approx 6$ (b and c) $w_1 \approx 0.41\ (b),\ 0.39\ (c)$

PRD 64, 014021 (2001)

Heavy quark polarization retention

$$r_L \approx \frac{1 + (0.23 + 0.38 w_1)A}{1 + A} \qquad A = \frac{\text{prob}\left(\Sigma_b^{(*)}\right)}{\text{prob}\left(\Lambda_b\right)} = 9\ \frac{\text{prob}(T)}{\text{prob}(S)}$$

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What is known about A and w_1 (for both b and c quarks)?

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

r_L consistent with Λ_b

results from LEP

s-quark polarization retention?

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

  Cannot argue for polarization loss either!

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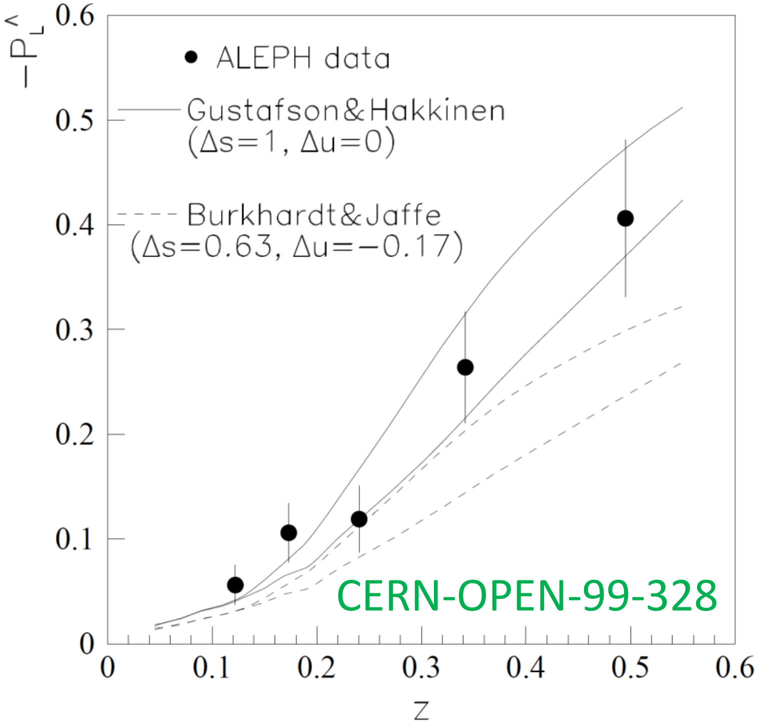
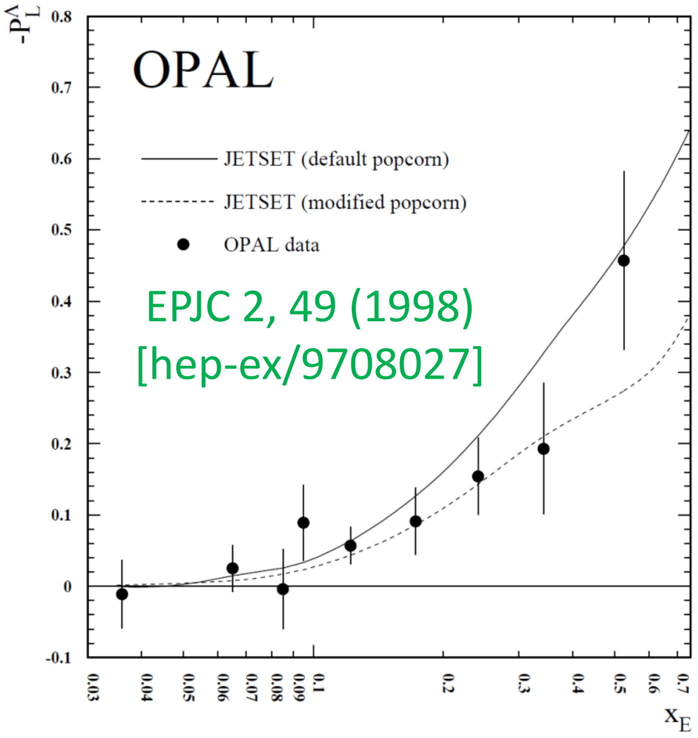


CERN-OPEN-99-328



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

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  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!

Nice sources of polarized quarks

Top pair production $pp \to t\bar{t}$

- $t \to W^+ b$ produces polarized $\boldsymbol{b}$ quarks.
  - $\hookrightarrow c\bar{s}, u\bar{d}$ 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).
- Kinematic reconstruction and charm tagging enable studying the different quark flavors separately.
- Statistics in Run 2 is as large as in Z decays at LEP.

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***W*+*c* production** $pp \to W^- c$

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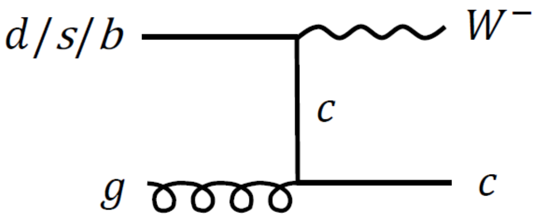

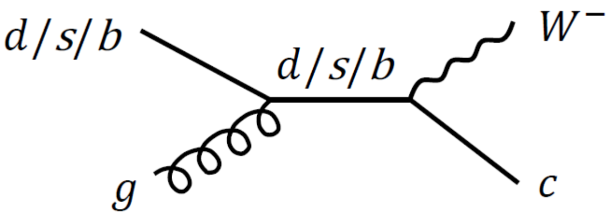

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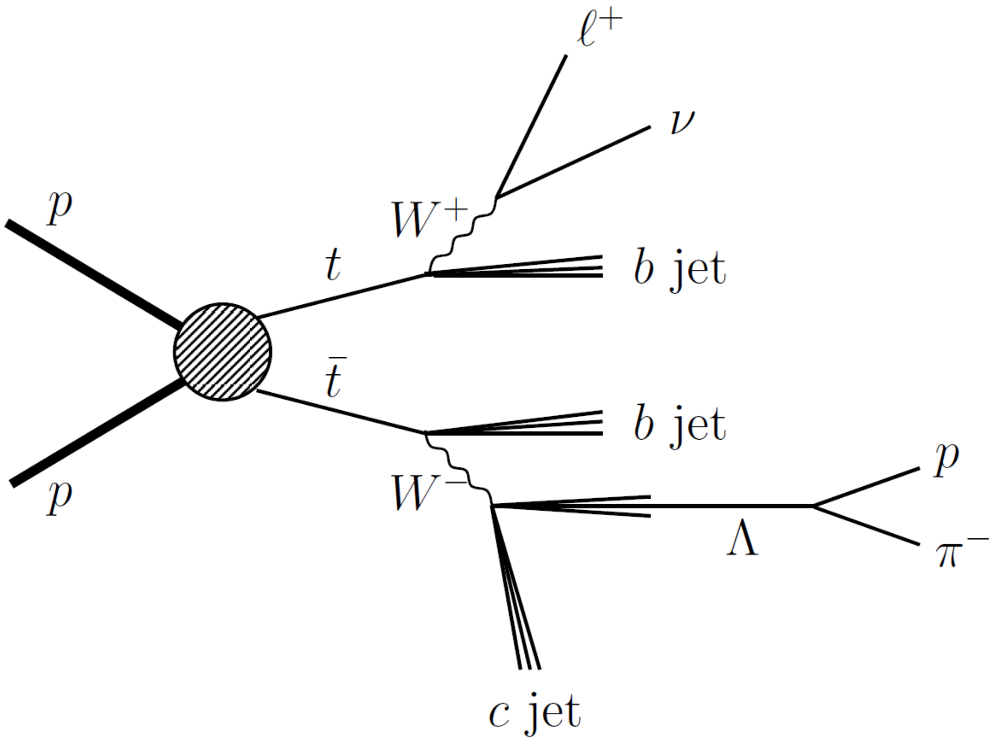
$\boldsymbol{W}$+$\boldsymbol{c}$ production $pp \to W^- c$

- Polarized $\boldsymbol{c}$ quarks.
- Order-of-magnitude higher statistics than $t\bar{t}$, although backgrounds are higher too.

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



Main steps:

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

Λ polarization measurement

In the Λ rest frame, the decay

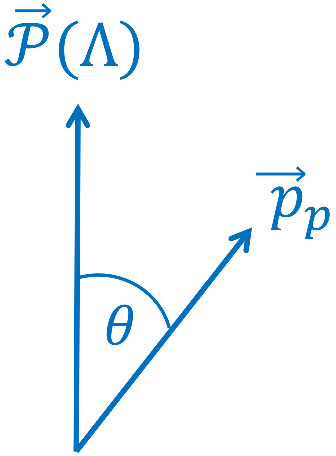
$$\Lambda \rightarrow p\,\pi^-$$

has the angular distribution

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}\left(1 + \alpha\,\mathcal{P}(\Lambda)\cos\theta\right)$$

where

$$\alpha = 0.642 \pm 0.013$$



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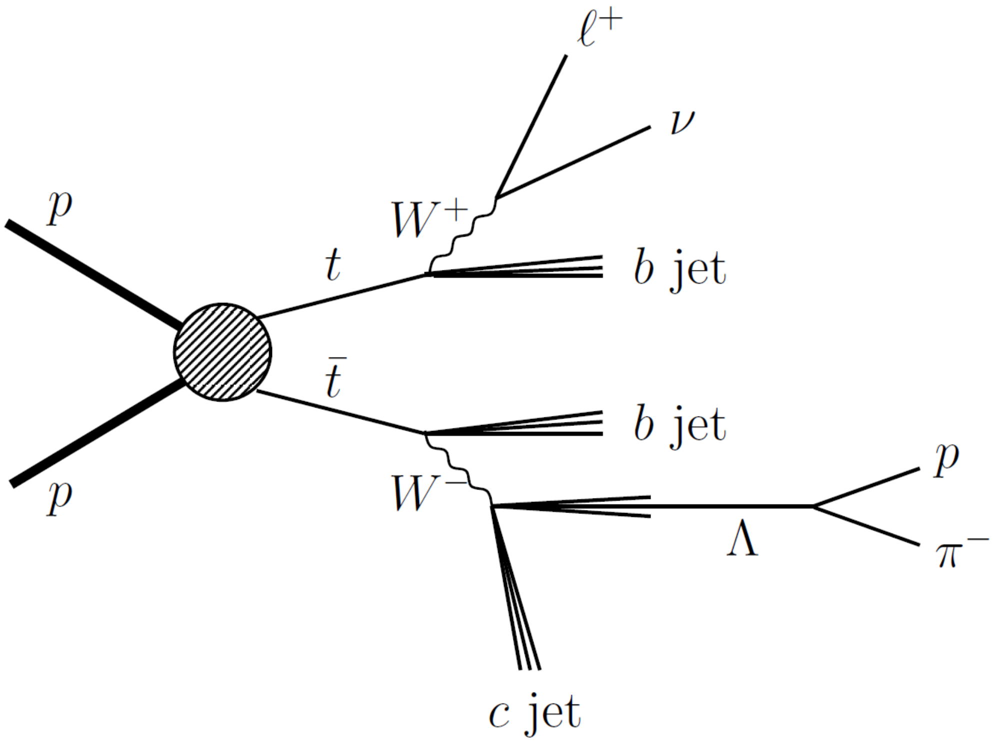
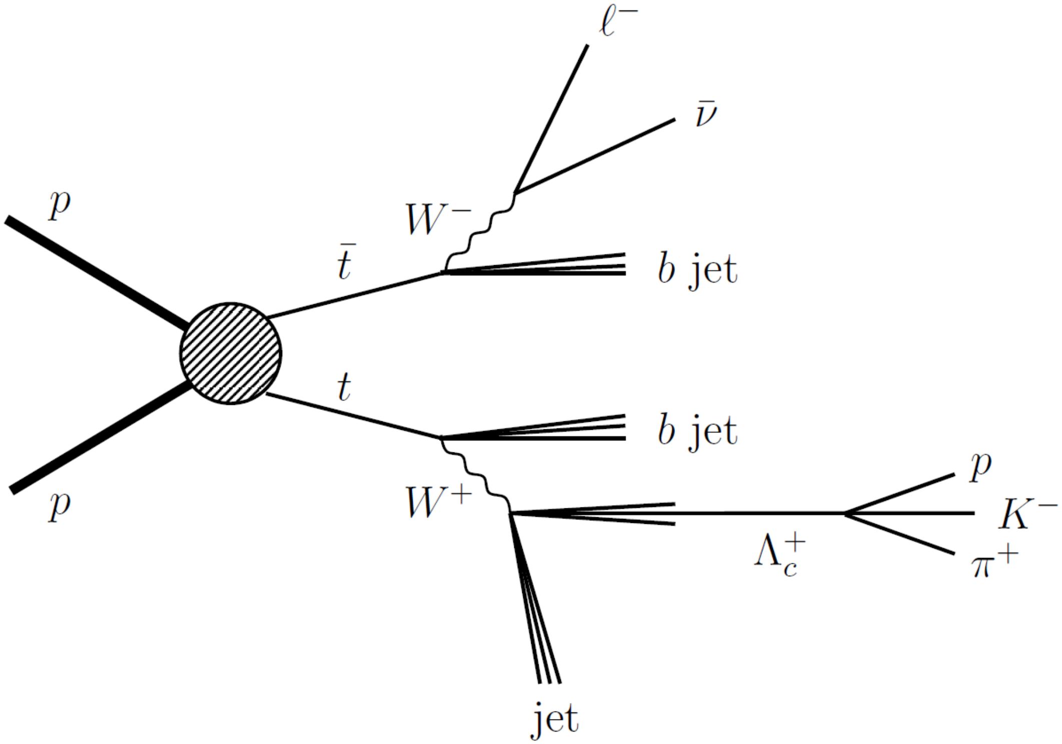


Statistical precision of roughly 16% possible at ATLAS/CMS in Run 2 (with 100 fb^{-1} of data).

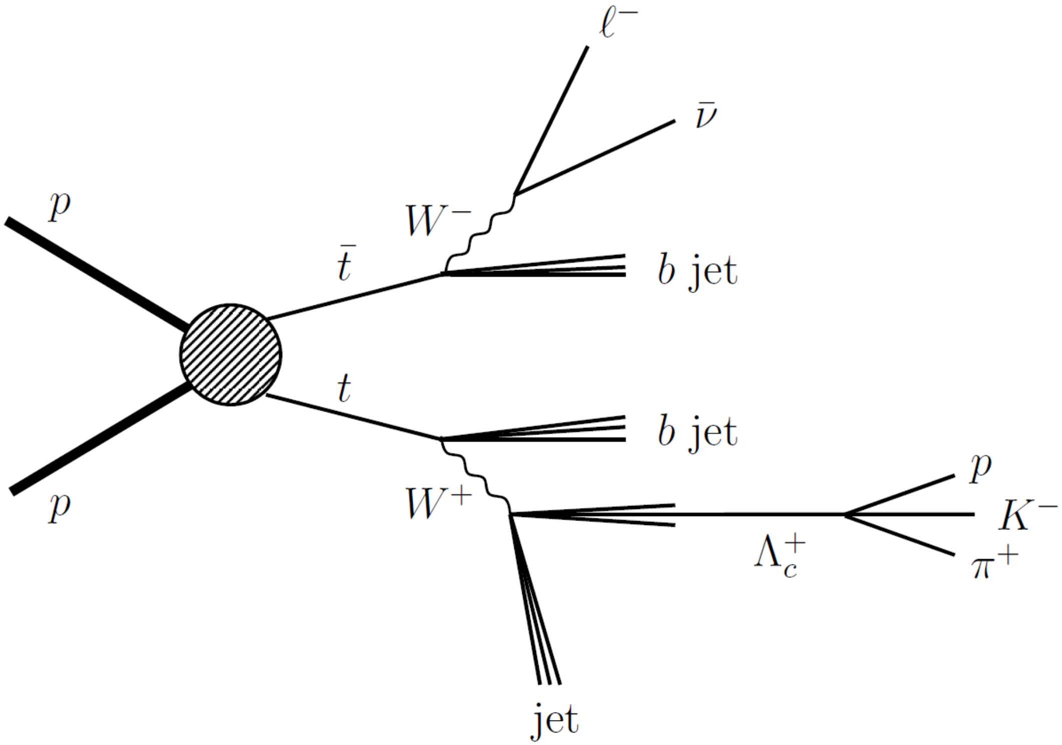
Measurement of c polarization in $t\bar{t}$



Main steps:

- 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 $t\bar{t}$

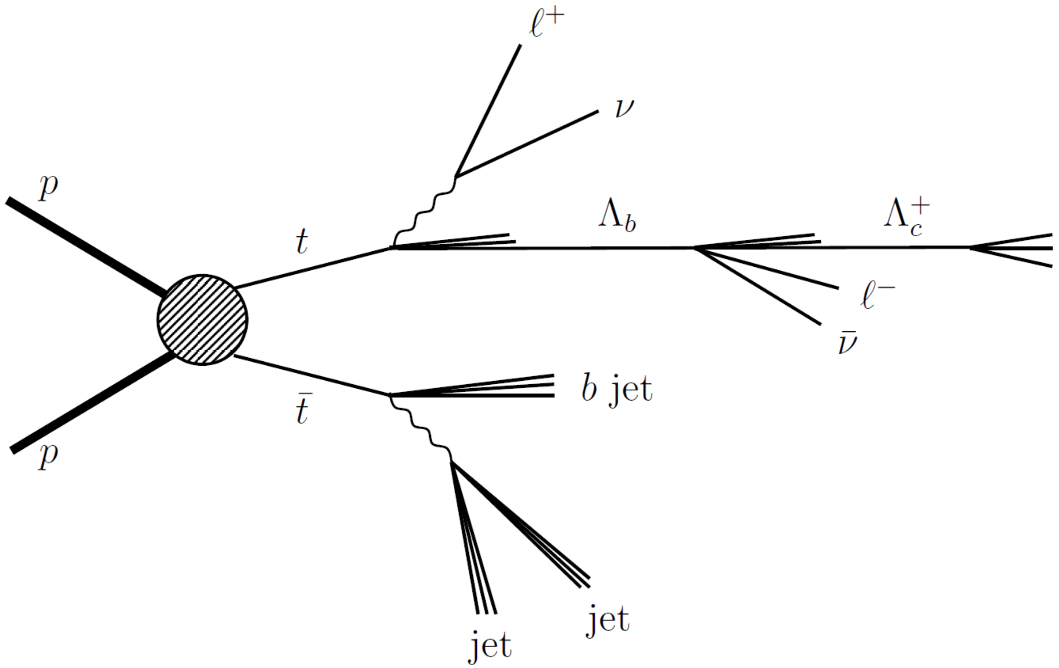


$\alpha_i r_L = 0.6$

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

Statistical precision of order 10% possible
at ATLAS/CMS in Run 2 (with 100 fb^{-1} of data).

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



Main steps:

- 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

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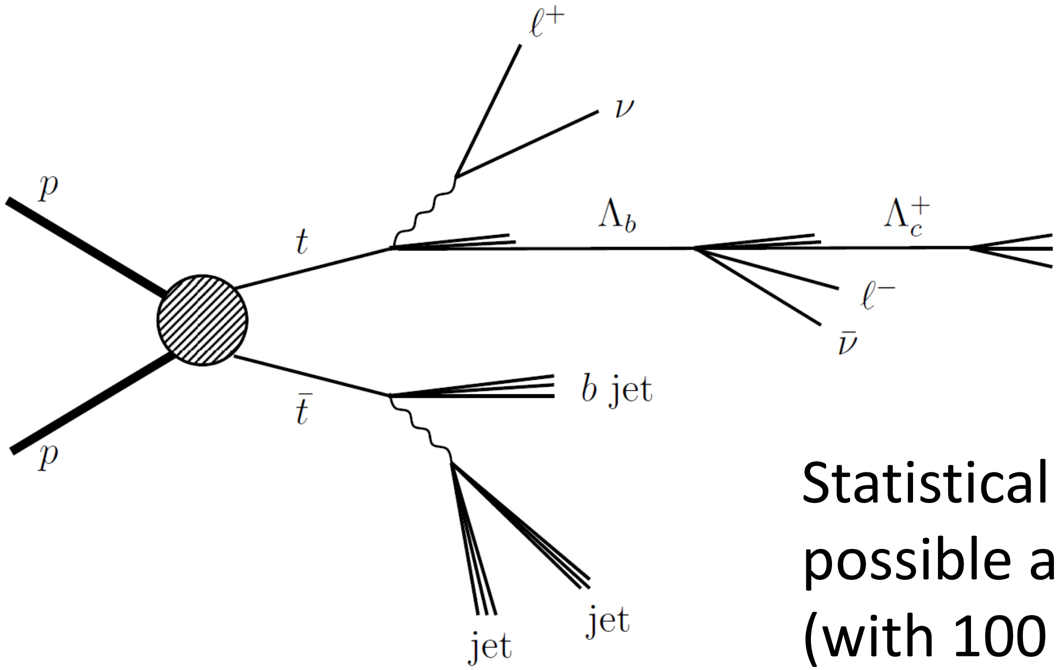
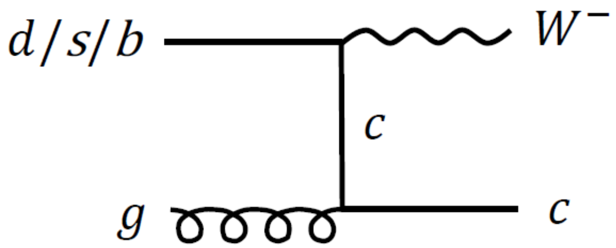
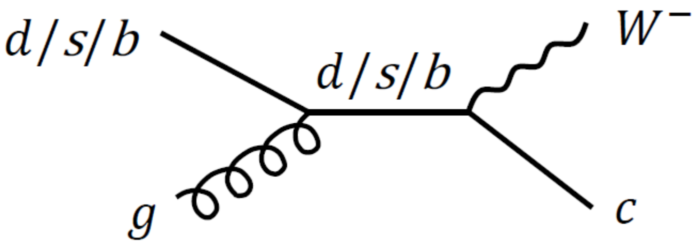


Statistical precision of about 10% possible at ATLAS/CMS in Run 2 (with 100 fb^{-1} of data)

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 W+c





ATLAS and CMS measured W+c cross section at 7 TeV

ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]

CMS, JHEP 1402, 013 (2014) [arXiv:1310.1138]

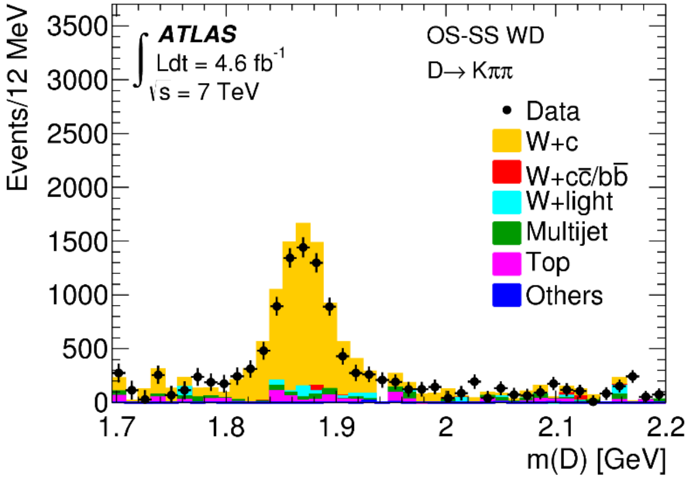
in particular by relying on the decays

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

Similar to our decay of interest

$$\Lambda_c^+ \to p K^- \pi^+$$

(See backup slides for more details.)



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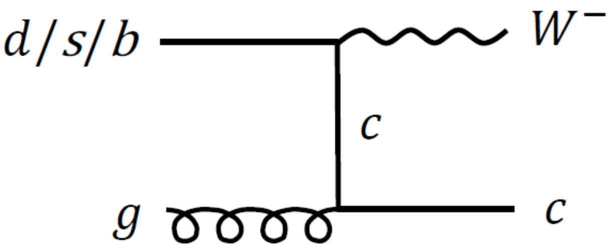

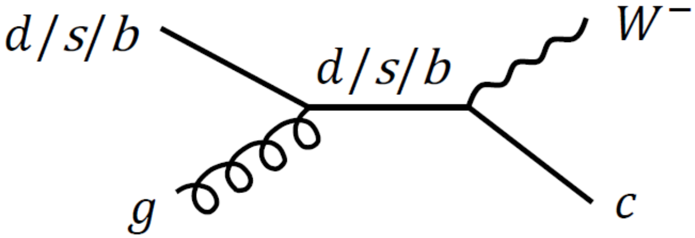

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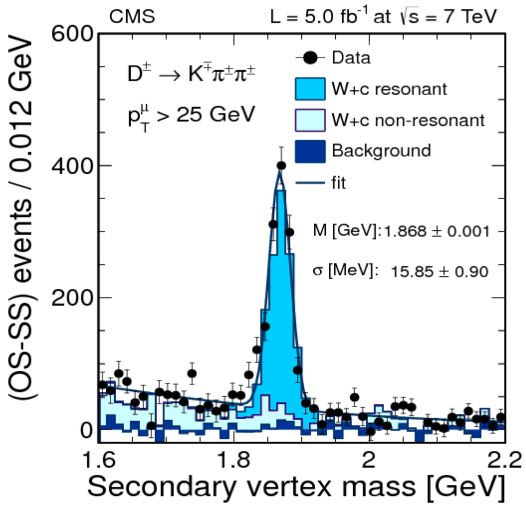

Measurement of b polarization in QCD events

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

- Enormous cross section, but **unpolarized** at the leading order.

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- At NLO → **transverse** polarization (an opportunity to measure r_T)

→ strong kinematic dependence

→ suppressed at high momenta $\mathcal{P}(b) \sim \alpha_s \frac{m_b}{p_b}$

Bernreuther, Brandenburg, Uwer, PLB 368, 153 (1996)

Dharmaratna and Goldstein, PRD 53, 1073 (1996)

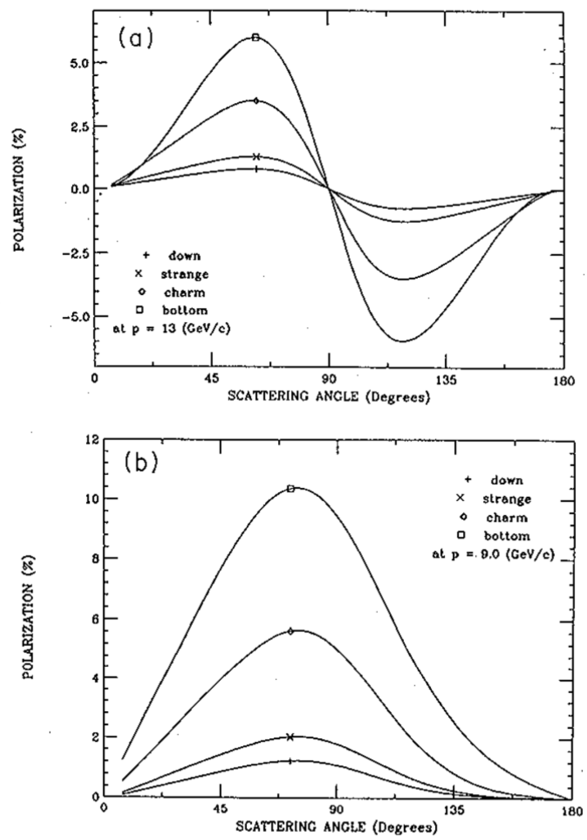

FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.

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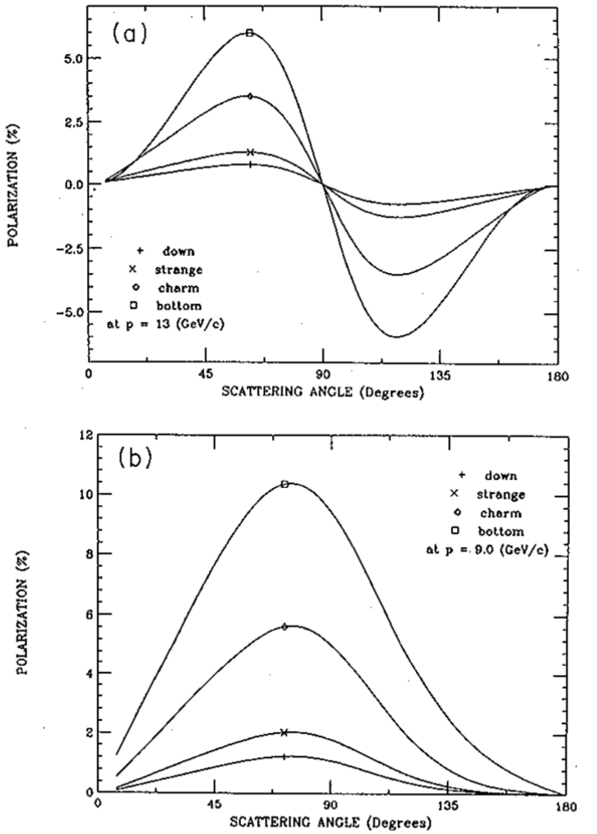

FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.

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 $\sqrt{s} = 7\,\mathrm{TeV}$

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

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

Suboptimal due to inclusiveness over the kinematics.

Measuring A directly

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

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

Can be measured by any experiment that can reconstruct

$$\Sigma_b^{(*)\pm,0} \rightarrow \Lambda_b\,\pi^{\pm,0}$$

In particular, LHCb, ATLAS, CMS in inclusive QCD samples.

Could have been done even at the Tevatron.

CDF, PRL 99, 202001 (2007) [arXiv:0706.3868]
CDF, PRD 85, 092011 (2012) [arXiv:1112.2808]

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$$\Sigma_b^{(*)\pm,0} \;\to\; \Lambda_b\, \pi^{\pm,0}$$

In particular, LHCb, ATLAS, CMS in inclusive QCD samples.

Same holds for

$$\Sigma_c^{(*)++,+,0} \;\to\; \Lambda_c^+\, \pi^{\pm,0}$$

where B factories can also help.

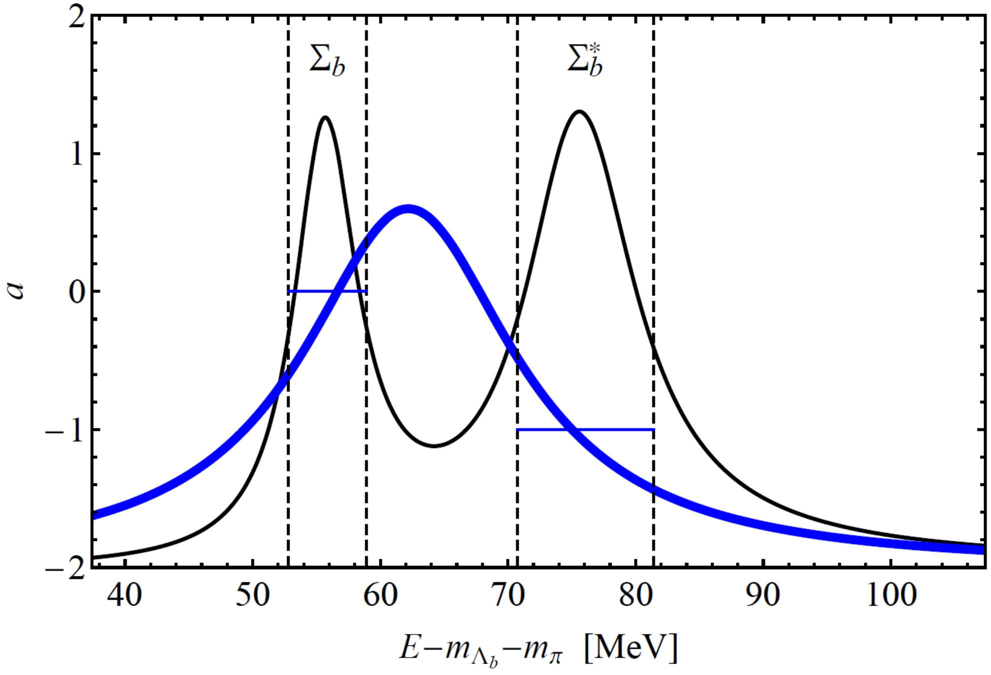
Belle, PRD 89, 091102 (2014) [arXiv:1404.5389]

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 (e.g., LHCb, ATLAS, CMS).

Same holds for $\Sigma_c^{(*)}$ and Λ_c.

Summary: motivated measurements

In $t\bar{t}$ production (ATLAS, CMS)

- Longitudinal Λ_b polarization in b jets → r_L for bottom
- Longitudinal Λ_c polarization in c jets → r_L for charm
- Longitudinal Λ polarization in s jets → long. pol. FF for strange
- (far future) Longitudinal Λ polarization in u, d jets → long. pol. FFs for up, down

In W+c production (ATLAS, CMS, maybe LHCb)

- Longitudinal Λ_c polarization → r_L for charm
  (Esp. LHCb may also try separating out the $\Sigma_c^{(*)}$ contributions.)

In QCD production (LHCb, ATLAS, CMS)

- Transverse Λ_b (and Λ_c?) polarization
  as a function of the event kinematics → r_T for bottom (charm?)

Summary: motivated measurements

In QCD production (LHCb, ATLAS, CMS)

- $\Sigma_b^{(*)}$ yields (relative to direct Λ_b) → A
  and pion angular distribution → w_1
  for bottom
- $\Sigma_c^{(*)}$ yields (relative to direct Λ_c) → A
  and pion angular distribution → w_1
  for charm

In new-physics samples, once discovered (ATLAS, CMS)

- Measure quark polarizations → learn about the new physics
  (Statistics will likely be a severe limitation.)

In $t\bar{t}$ and W+c production in the long term (ATLAS, CMS, LHCb)

- Measurements of polarized fragmentation functions.

Thank You!

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

Measurement of b polarization in Z decays

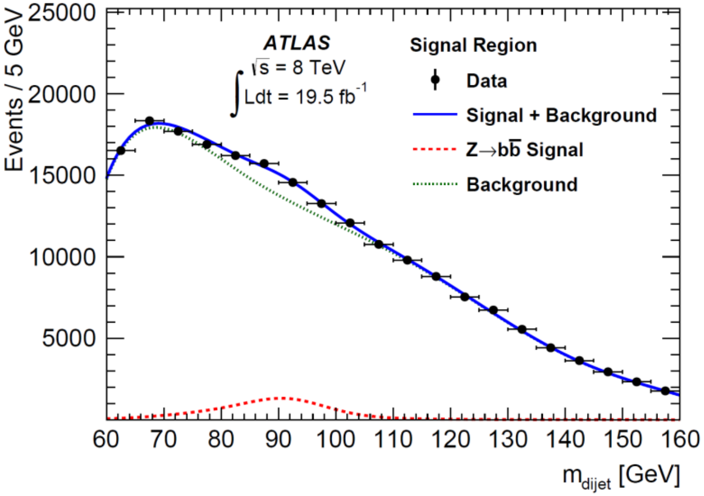
Z production: $pp \to Z \to b\bar{b}$

- 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.

→



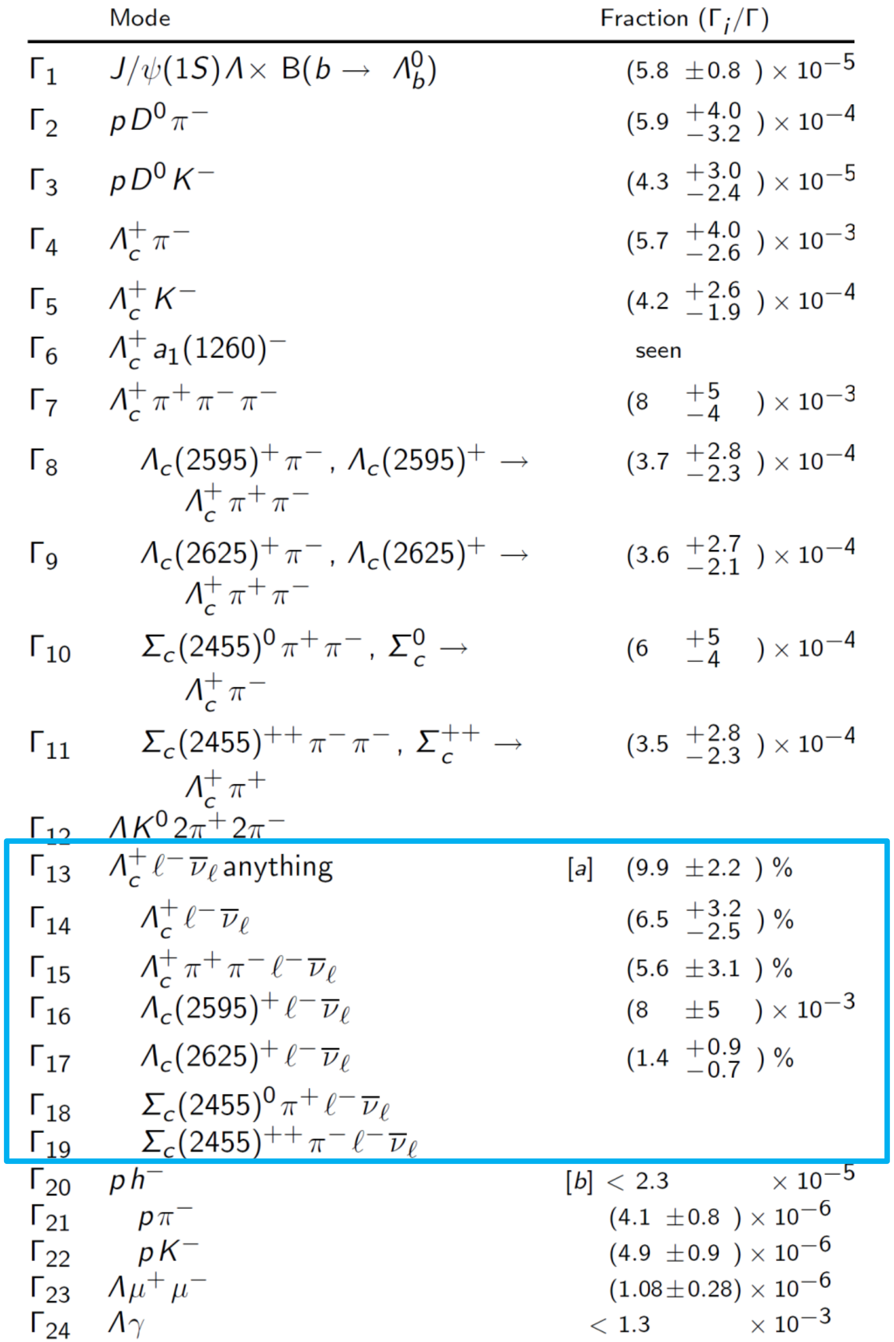
PLB 738, 25 (2014)
[arXiv:1404.7042]

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

Λ_b polarization measurement

Which Λ_b decay to use?

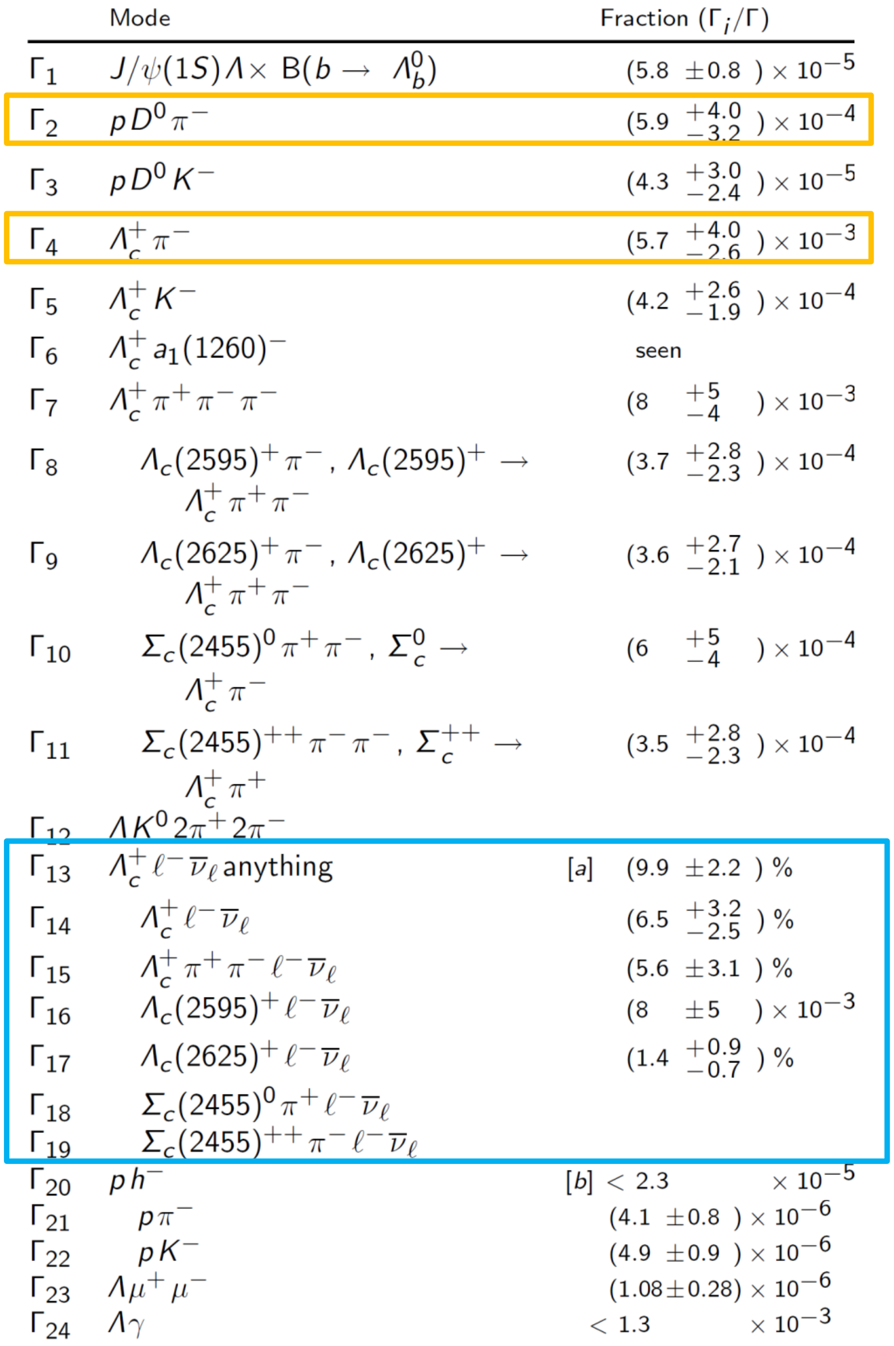
We picked **semileptonic** mode **inclusive** in charm hadrons (large BR, no hadronic uncertainties).



	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 ± 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}	$\Lambda_c(2595)^+\ell^-\overline{\nu}_\ell$		$(8\pm5)\times10^{-3}$
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?



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Γ_6	$\Lambda_c^+ a_1(1260)^-$		seen
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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}	$\Lambda_c^+ \ell^- \overline{\nu}_\ell$ 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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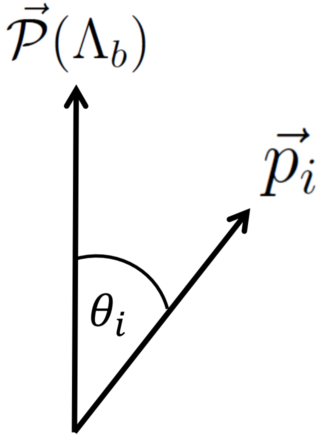
Includes also:

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

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

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

where

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

$$\uparrow$$

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

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

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

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

Λ_b polarization measurement

$\Lambda_b \to X_c \ell^- \bar{\nu}$ (BR ≈ 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 $\Lambda \to p\pi^-$ among decay products
Exclusive	demand a fully-reconstructible Λ_c decay

See paper for many additional details…

Λ_c polarization measurement

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

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

NA32: Jeżabek, Rybicki, Ryłko, PLB 286, 175 (1992)

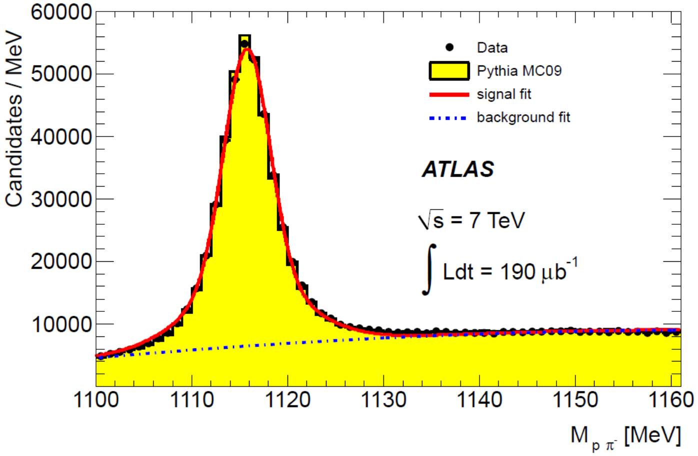
Precise values not essential for new physics samples if SM calibration samples are available.

Also, α_i can be determined (e.g., in LHCb) from a sample of **Λ_c's produced from inclusive b-hadron decays** by calibrating on $\Lambda_c^+ \rightarrow \Lambda\,\pi^+$ (where $\alpha_\Lambda = -0.91 \pm 0.15$).

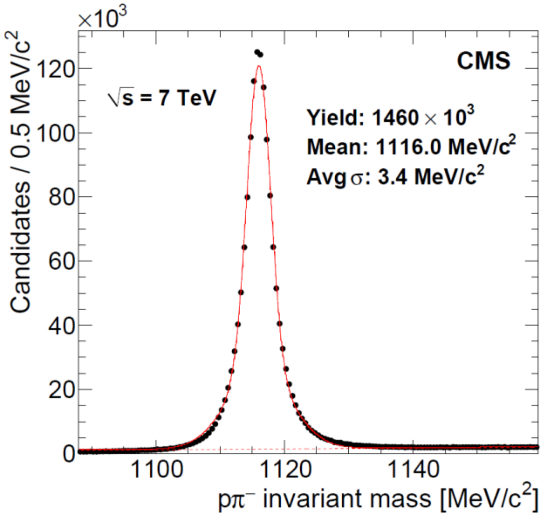
Λ polarization measurement

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

- 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

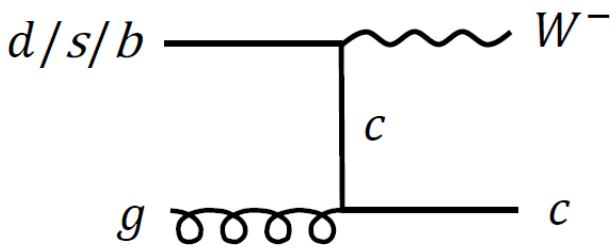


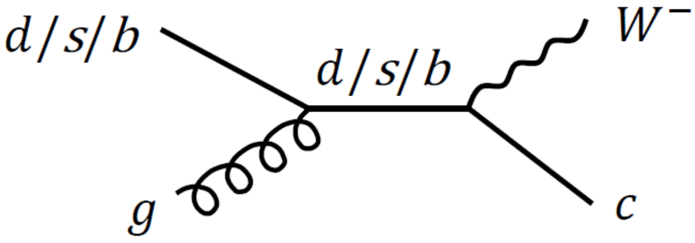
PRD 85, 012001 (2012)
[arXiv:1111.1297]



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

Measurement of c polarization in W+c





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Similar to our decay of interest

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Example: $D^+ \to K^-\pi^+\pi^+$ in ATLAS

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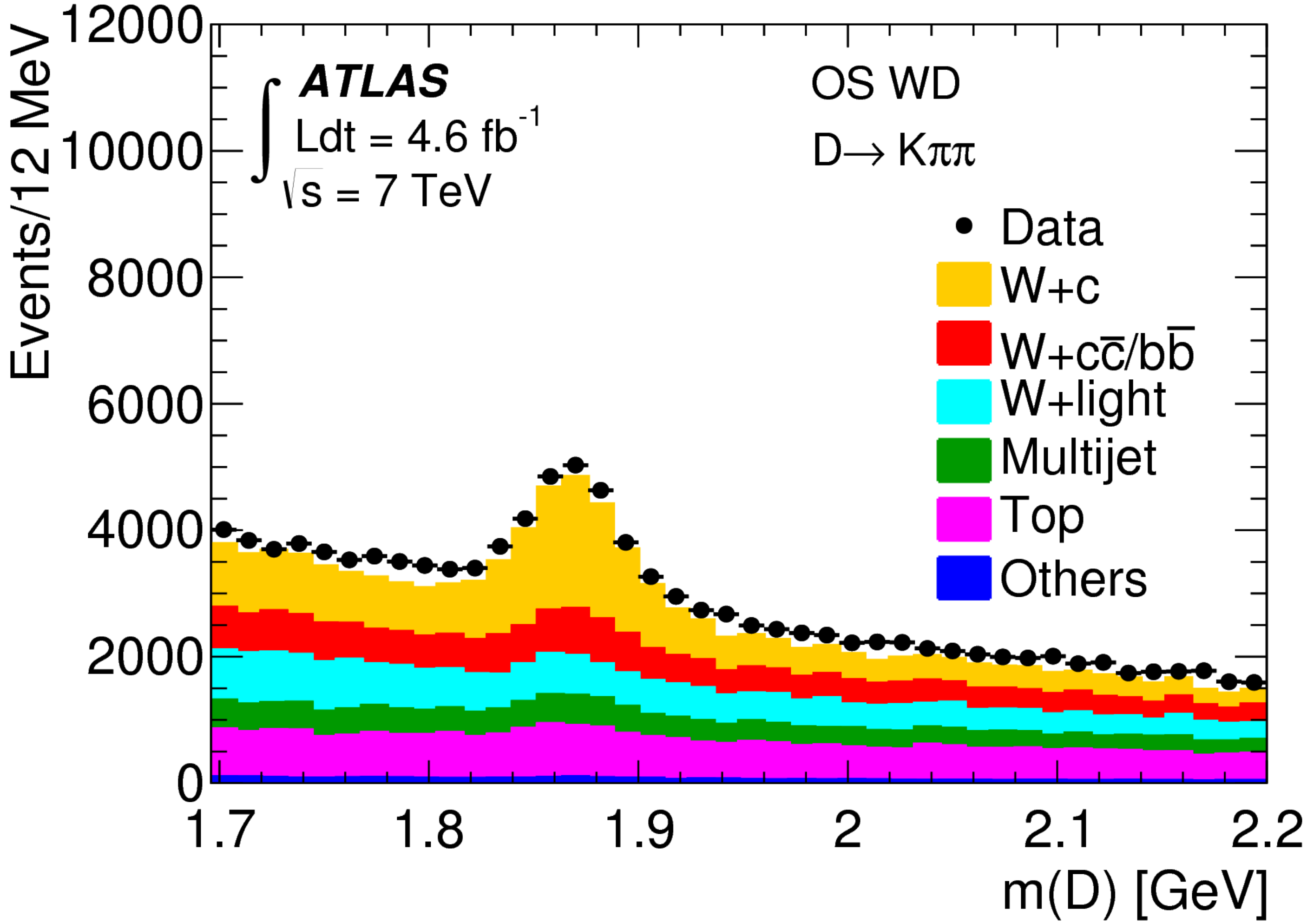

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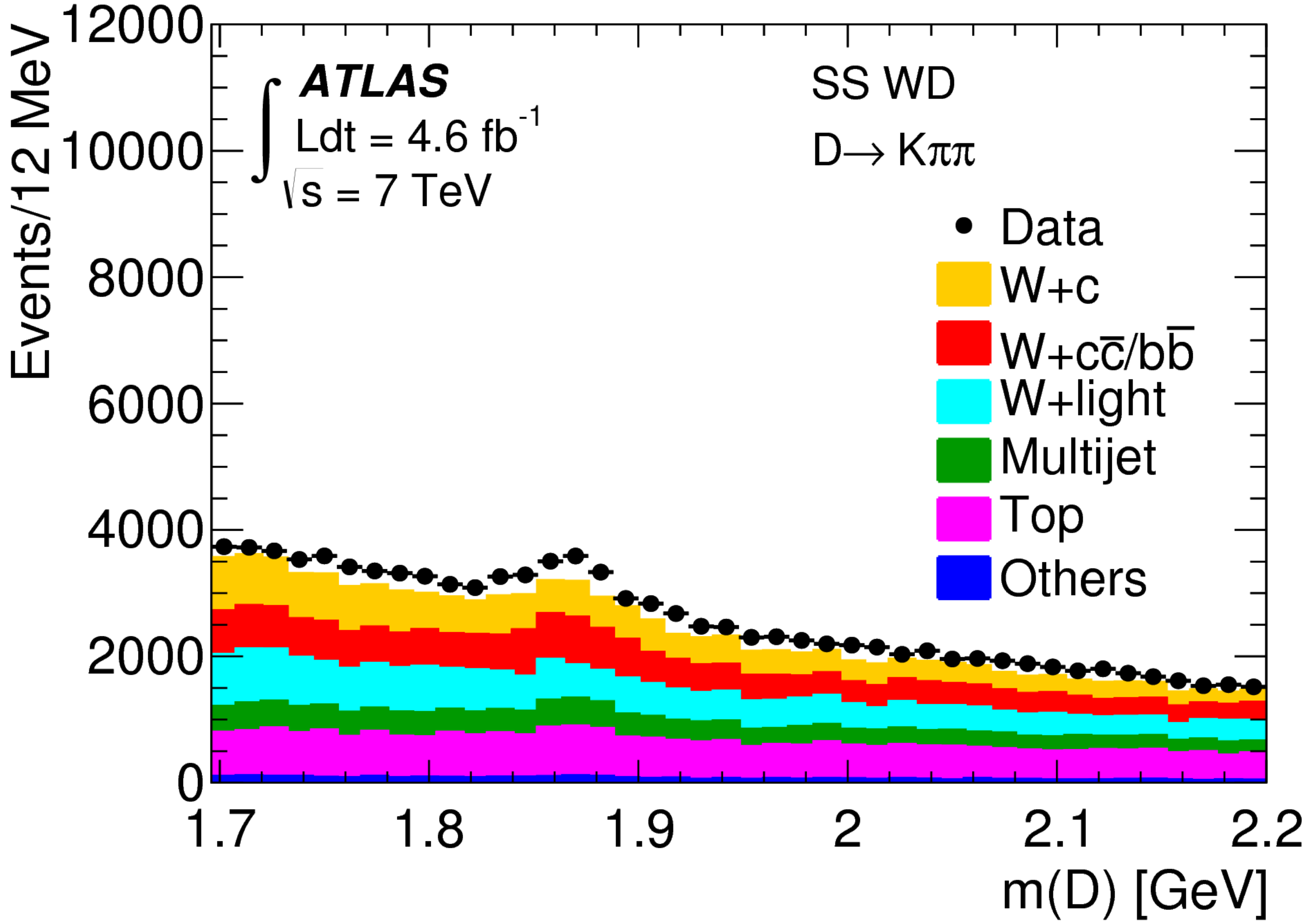

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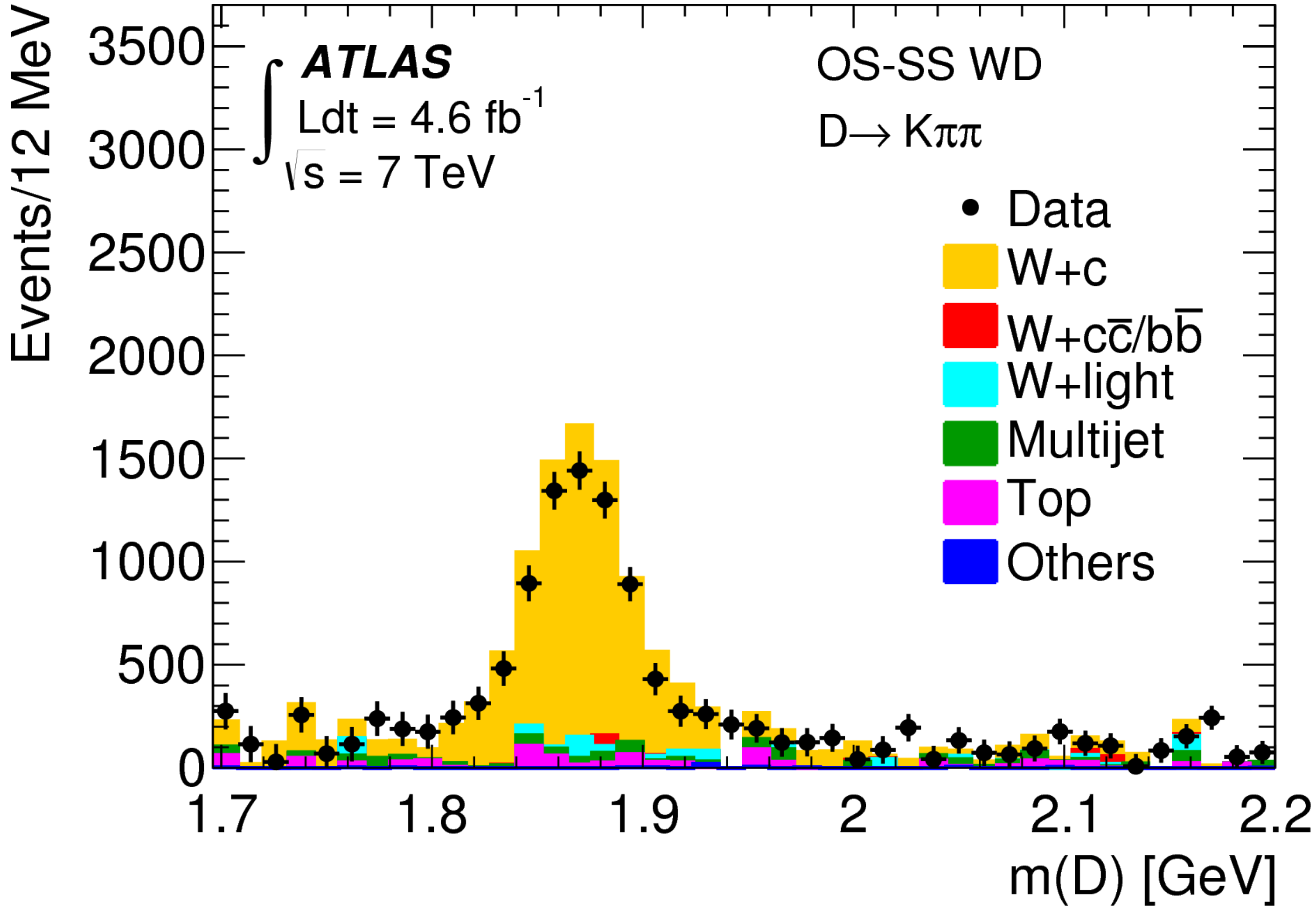
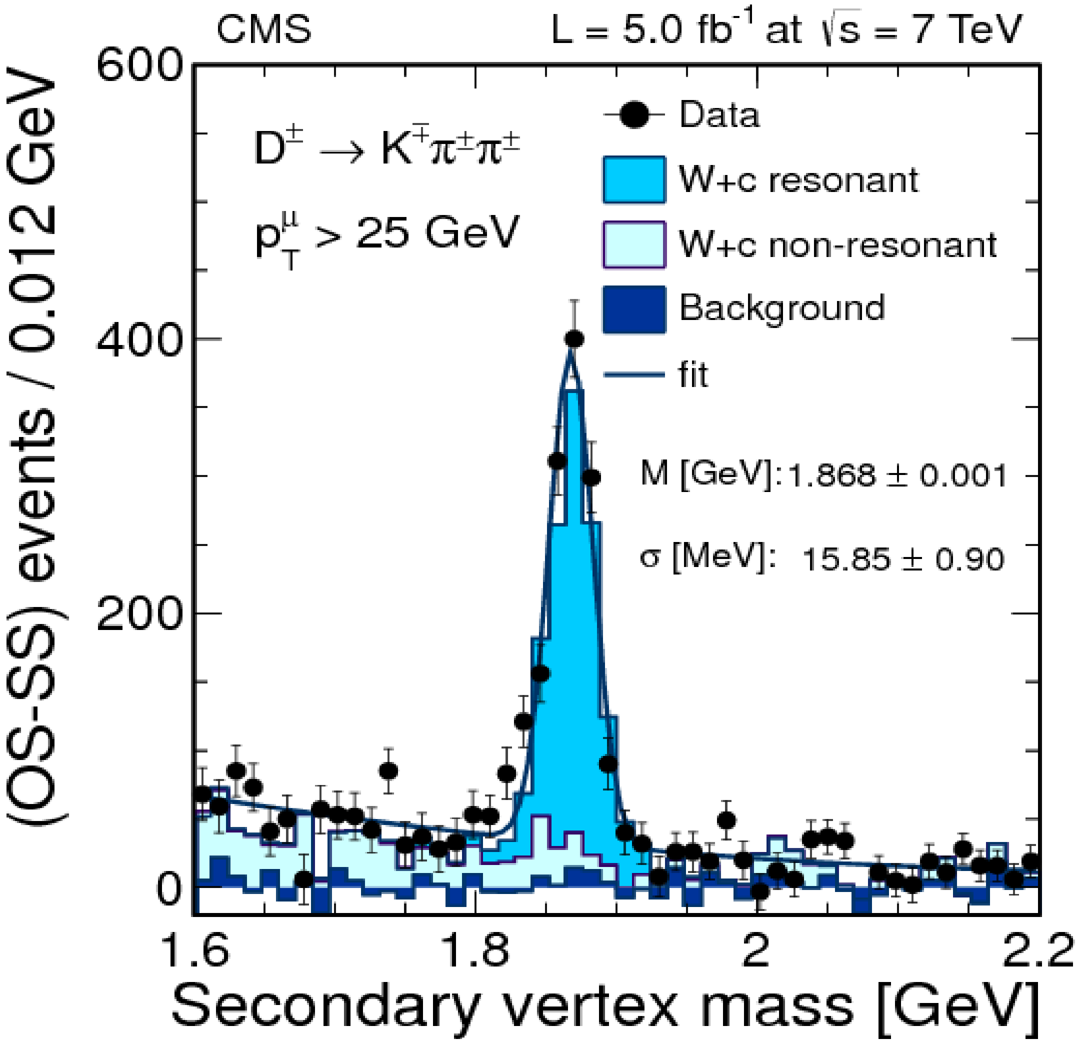


Example: $D^+ \rightarrow K^-\pi^+\pi^+$ in CMS

CMS, JHEP 1402, 013 (2014) [arXiv:1310.1138]



$\Lambda_c^+ \to pK^-\pi^+$ vs. $D^+ \to K^-\pi^+\pi^+$

Same signature (3-prong displaced vertex, mass peak), but:

- The $\Lambda_c^+ \to pK^-\pi^+$ signal peak is smaller:

$$\frac{f(c \to D^+)\,\mathcal{B}(D^+ \to K^-\pi^+\pi^+)}{f(c \to \Lambda_c^+)\,\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} \approx 5.3$$

while background is roughly the same.

Ambiguity resolution: in the lab frame, $|\vec{p}(p)| > |\vec{p}(\pi^+)|$.

- The Λ_c^+ vertex is less displaced:

$$\tau_{\Lambda_c^+} \approx \frac{\tau_{D^0}}{2} \approx \frac{\tau_{D_s^+}}{2.5} \approx \frac{\tau_{D^+}}{5}$$

e.g., in CMS analysis, < 20% of events had a good secondary vertex

(events contain about 61% D^0, 24% D^+, 8% D_s^+, 6% Λ_c^+)

Improvements for W+c in Run 2

- **Statistics x 60** (cross section x 3, luminosity x 20)

  (S/B remains similar because cross sections increase by similar factors.)

- **Upgrades to ATLAS and CMS pixel detectors**

  ATLAS: installed IBL

  Innermost layer at: **3.3 cm (vs. 5.0 cm in Run 1)**

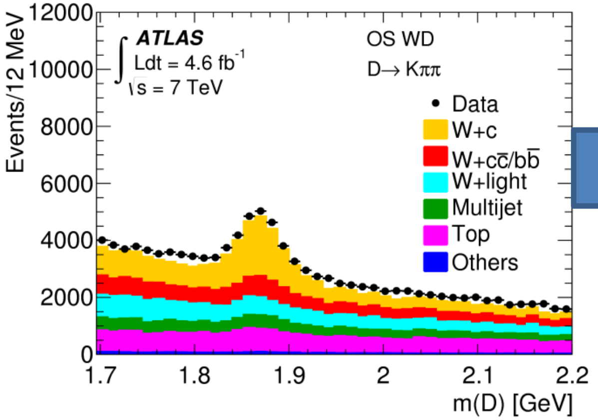
  Smaller pixel size: **50 x 250 (vs. 50 x 400) μm^2**

  CMS: pixel detector upgrade in winter 2016-2017

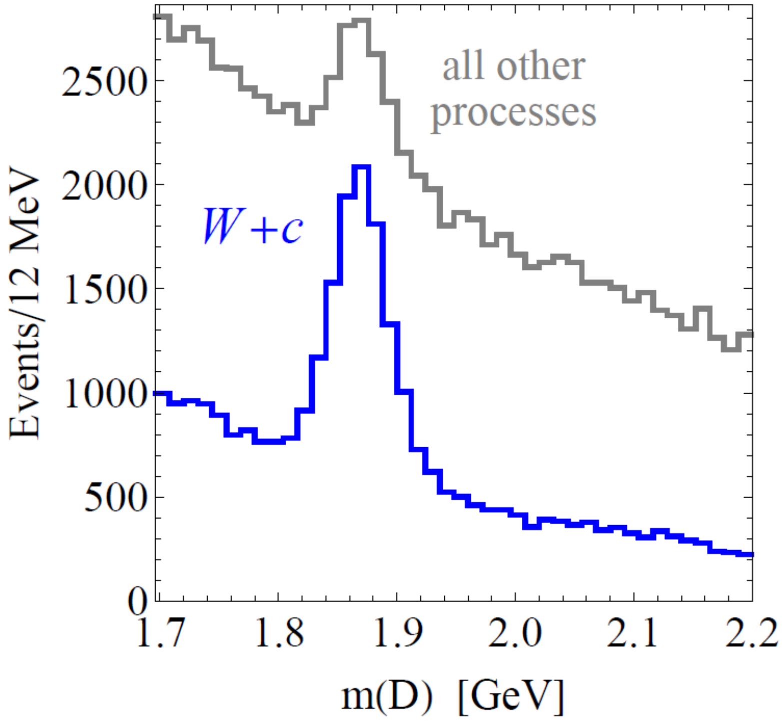
  Innermost layer at: **3.0 cm (vs. 4.4 cm now)**

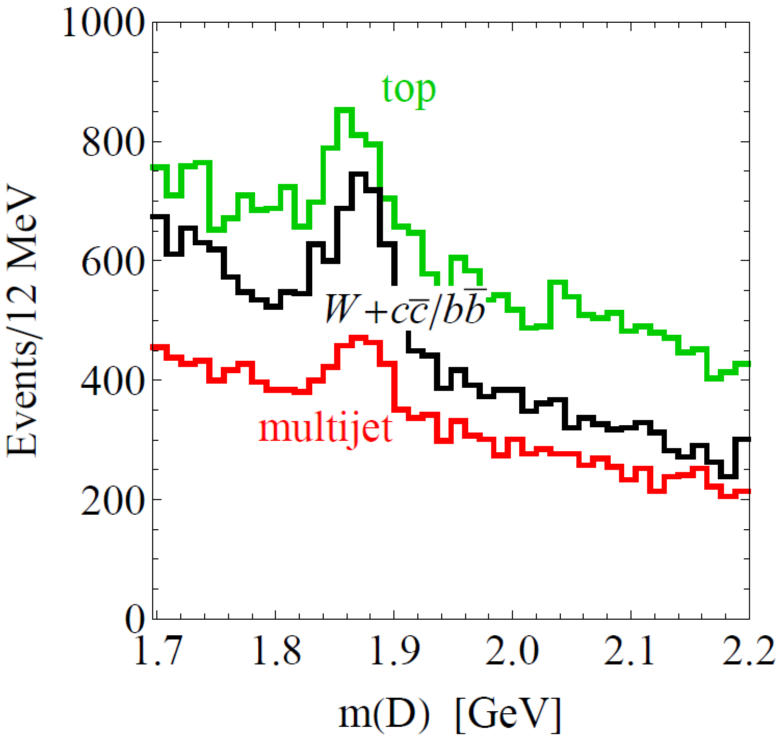
  Pixel size unchanged: **100 x 150 μm^2**

Backgrounds: ATLAS D^+ example



ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]





Λ_c polarization backgrounds in W+c

PEAKING COMPONENTS (REAL Λ_c)

- **c's in multijet:** unpolarized
- $W^+ \to c\bar{s}$ in **top:** polarized like the signal
- **b's** in **top, W+$b\bar{b}$, multijet:** polarization due to

  electroweak $b \to \Lambda_c, \Sigma_c^{(*)}$

  Control region with highly-displaced Λ_c's ($\tau_b \approx 7\tau_{\Lambda_c}$).
- **W+$c\bar{c}$**: can be estimated from the wrong-sign sample

SMOOTH COMPONENTS (FAKE Λ_c)

At the very least, can be extrapolated from sidebands
(up to a certain systematic uncertainty).

Statistical precision for W+c in Run 2

A variable sensitive to the polarization:

$$A_{\mathrm{FB}} = \frac{N(\cos\theta_{K^-} > 0) - N(\cos\theta_{K^-} < 0)}{N}$$

Statistical uncertainty:

$$\sigma(A_{\mathrm{FB}}) = \sqrt{\frac{1 - {A_{\mathrm{FB}}}^2}{N}} \approx \frac{1}{\sqrt{N}}$$

The signal contribution:

$$A_{\mathrm{FB,S}} = \frac{\alpha_{K^-}\mathcal{P}(\Lambda_c)\,S}{2N}$$

Significance of observing non-zero $\mathcal{P}(c)$:

$$\frac{|A_{\mathrm{FB,S}}|}{\sigma(A_{\mathrm{FB}})} = \frac{|\alpha_{K^-}\mathcal{P}(\Lambda_c)|}{2}\frac{S}{\sqrt{N}}$$

Statistical precision for W+c in Run 2

A ballpark figure

- Start with the ATLAS D^+ peak.
- Account for the difference between the $D^+ \to K^-\pi^+\pi^+$ and $\mathit{\Lambda}_c^+ \to pK^-\pi^+$ rates.
- Assume Run 2 statistics (100 fb^{-1})

Without the displacement issue, $S/\sqrt{N} \approx 47$.

For, e.g., $|\alpha_K$–$\mathcal{P}(\Lambda_c)| = 0.4$, this gives 11% precision.

Suppose that relaxed displacement requirements

increase N by a factor of 2 while still losing 1/2 of S.

Still, 3σ significance for observing non-zero $\mathcal{P}(c)$.

u, d polarizations

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

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., PRD 92, 114517 (2015) [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:

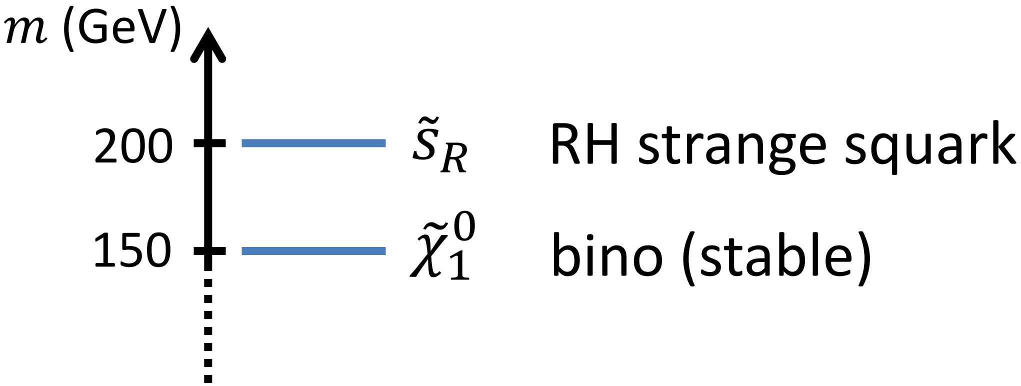
- No u or d tagging; c-tag veto only partially effective
  (Can define separate u and d samples, contaminated by c and s respectively, using W_{leptonic} charge.)
- Fragmentation fractions of $u, d \to \Lambda$ smaller than $s \to \Lambda$

New physics example

Suppose a jets + MET excess is being attributed to:

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

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



New physics example

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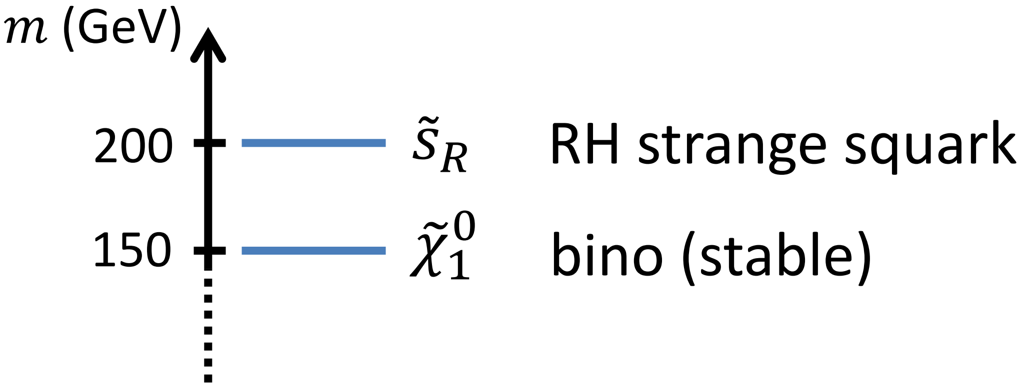
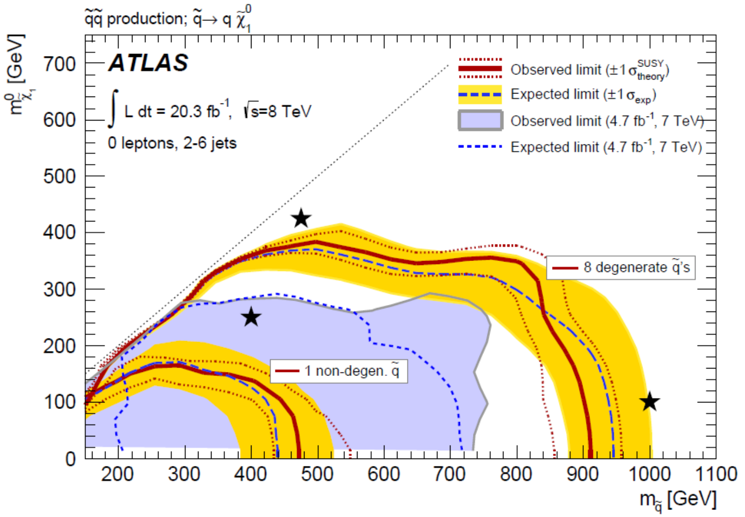
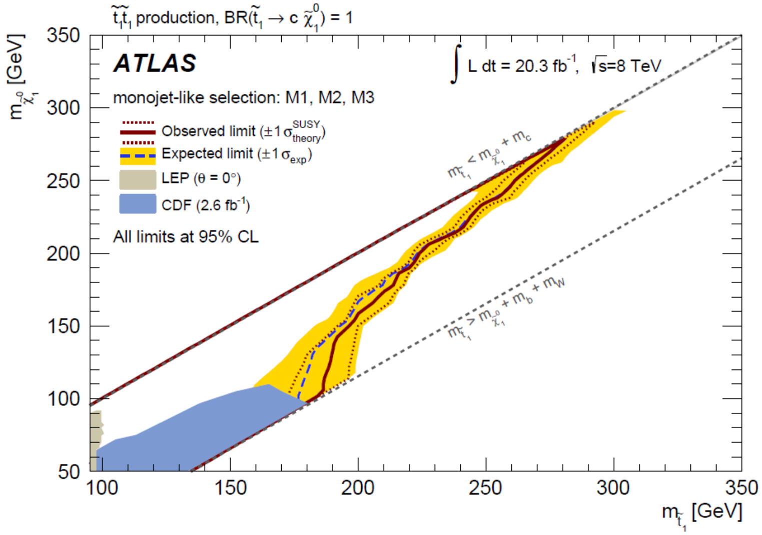


This scenario was barely beyond the reach of Run 1.



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



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

New physics example

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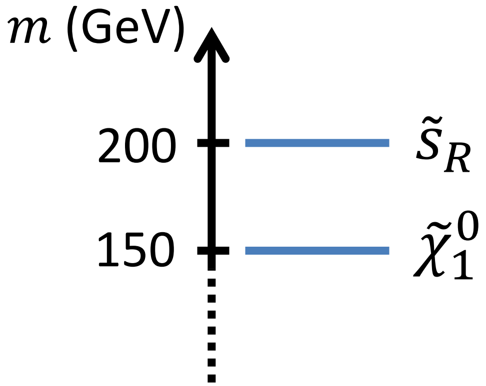
$pp \to \tilde{s}_R \tilde{s}_R^*$

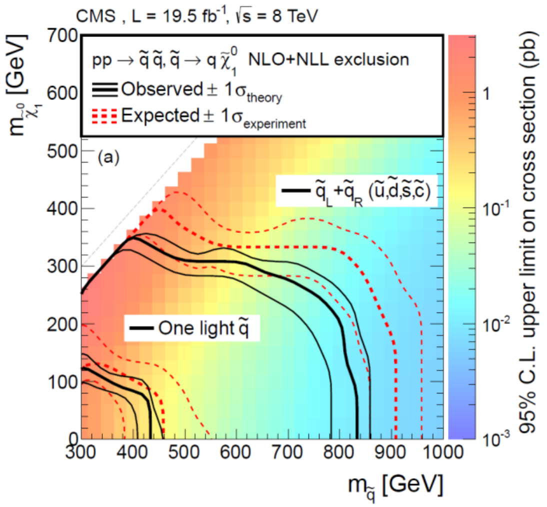
$\tilde{s}_R \to s \tilde{\chi}_1^0$



$\tilde{s}_R$ RH strange squark

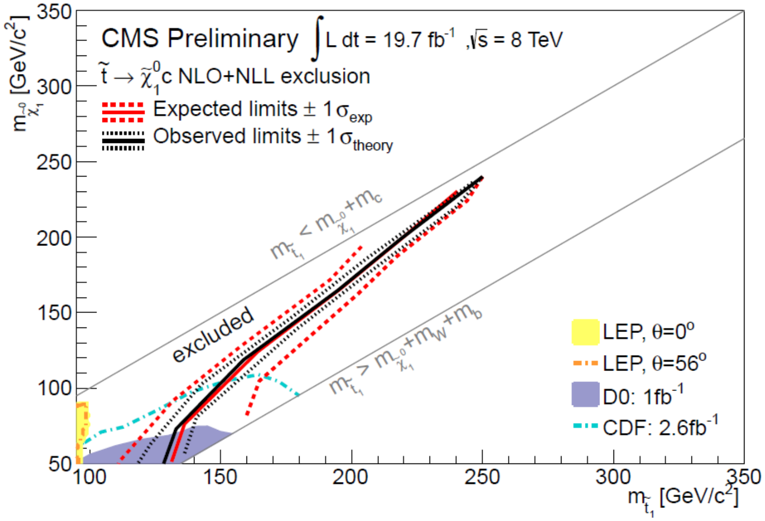
$\tilde{\chi}_1^0$ bino (stable)

This scenario was barely beyond the reach of Run 1.



*The masses of interest are unfortunately not shown.

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



CMS-PAS-SUS-13-009

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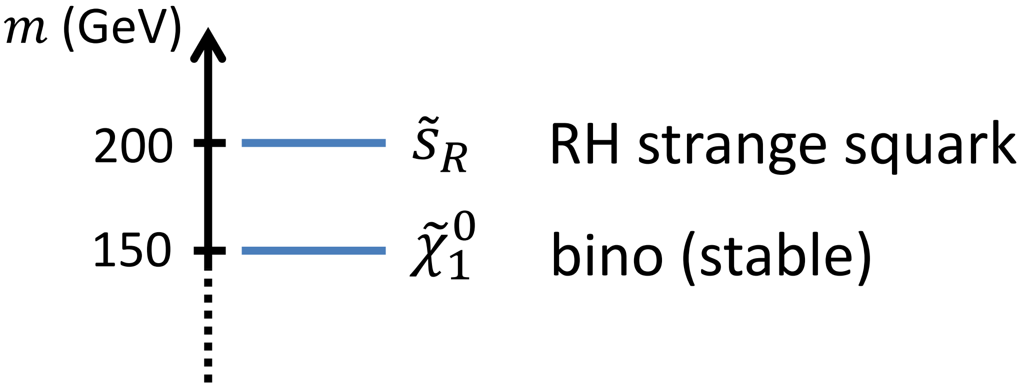

Test this interpretation by measuring the s-quark polarization.

Rough estimate (see paper for details):

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

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