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Probing spin correlations, entanglement, and Bell nonlocality in bottom quark pairs at the LHC

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Based on:

Kats, Uzan, JHEP 03 (2024) 063 [arXiv:2311.08226]

Afik, Kats, Muñoz de Nova, Soffer, Uzan, PRD 111 (2025) L111902 [arXiv:2406.04402]

Motivation

ATLAS and CMS already measure spin correlations in $pp \to t\bar{t}$.

Density matrix for the t and $\bar{t}$ spins:

$$\rho = \frac{1}{4}\left(\mathbb{1} \otimes \mathbb{1} + \tilde{B}_i^+ \, \sigma^i \otimes \mathbb{1} + \tilde{B}_i^- \, \mathbb{1} \otimes \sigma^i + \tilde{C}_{ij} \, \sigma^i \otimes \sigma^j\right)$$

Angular distributions of leptons from top decays:

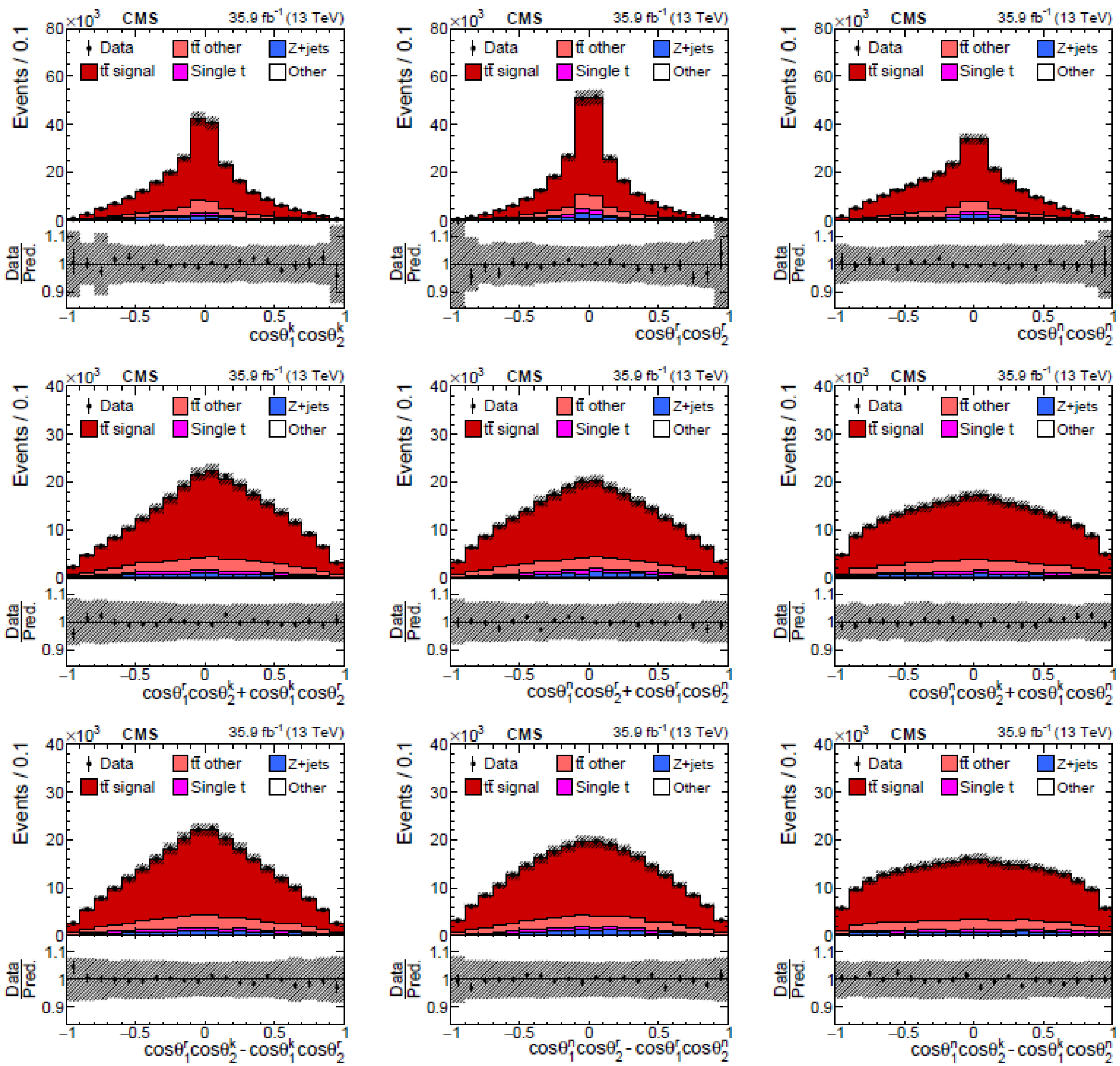
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_1^i} = \frac{1}{2}\left(1 + B_1^i \cos\theta_1^i\right)$$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_1^i \cos\theta_2^j} = \frac{1}{2}\left(1 - C_{ij}\cos\theta_1^i \cos\theta_2^j\right)\ln\left(\frac{1}{|\cos\theta_1^i \cos\theta_2^j|}\right)$$

$B = \alpha\tilde{B}$, $C = \alpha^2\tilde{C}$, $\alpha \simeq 1$ (spin analyzing power)

Motivation

ATLAS and CMS already measure spin correlations in $pp \to t\bar{t}$.



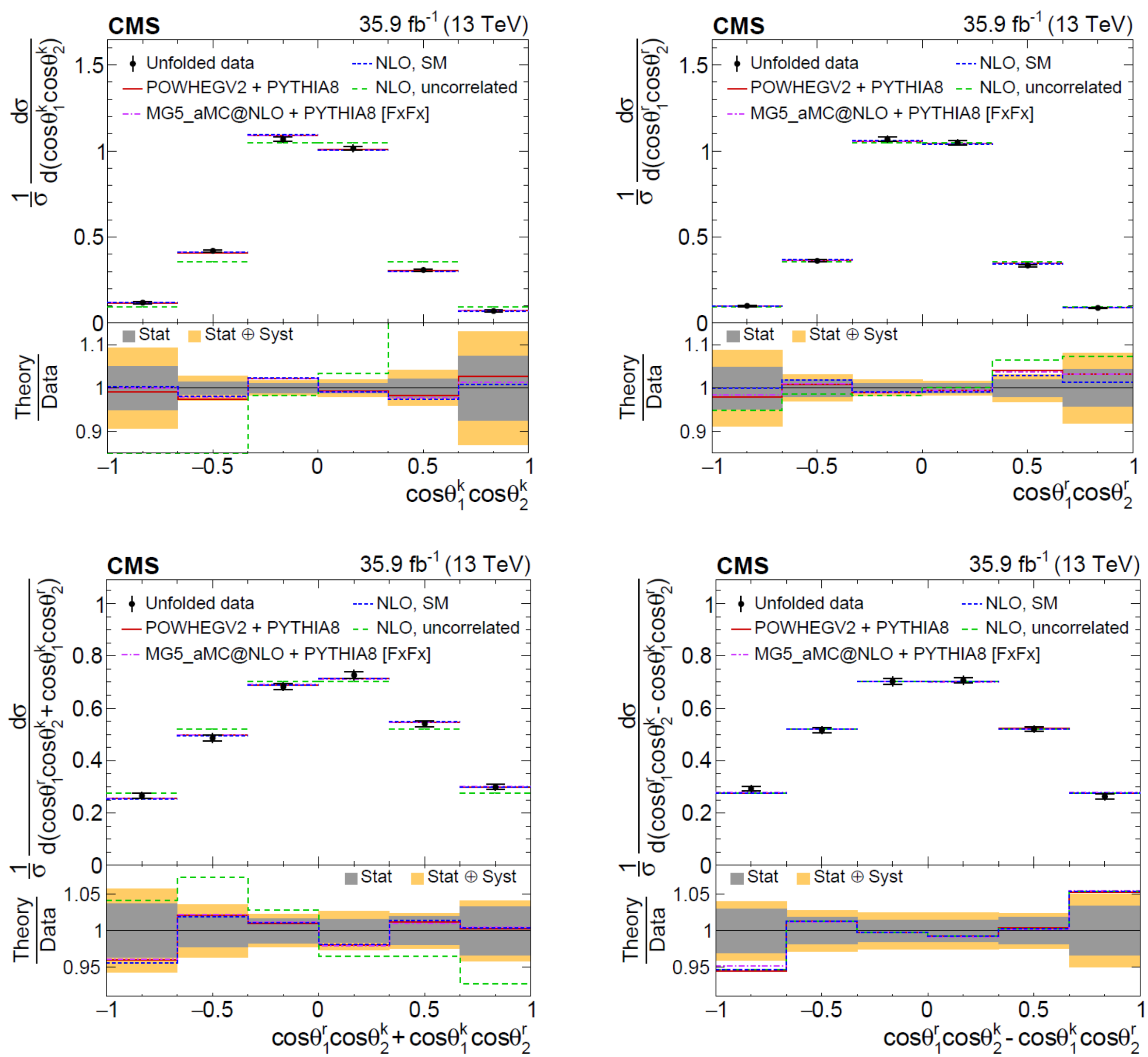
CMS Collaboration

PRD 100, 072002 (2019)

[arXiv:1907.03729]

Motivation

ATLAS and CMS already measure spin correlations in $pp \to t\bar{t}$.

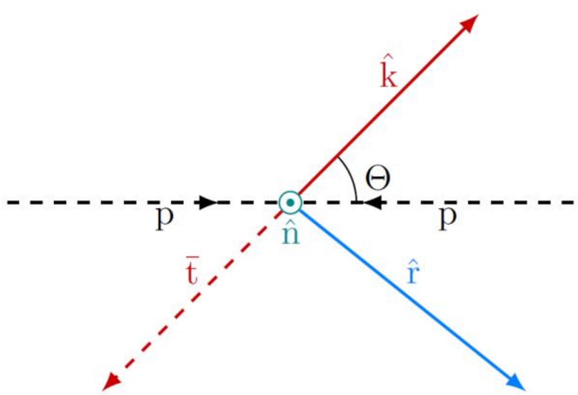


CMS Collaboration
PRD 100, 072002 (2019)
[arXiv:1907.03729]

Motivation: QCD

ATLAS and CMS already measure spin correlations in $pp \to t\bar{t}$.

Coefficient	Measured	POWHEGv2	MG5_aMC@NLO	NLO calculation
C_{kk}	0.300 ± 0.038	$0.314\,^{+0.005}_{-0.004}$	$0.325\,^{+0.011}_{-0.006}$	$0.331\,^{+0.002}_{-0.002}$
C_{rr}	0.081 ± 0.032	$0.048\,^{+0.007}_{-0.006}$	$0.052\,^{+0.007}_{-0.005}$	$0.071\,^{+0.008}_{-0.006}$
C_{nn}	0.329 ± 0.020	$0.317\,^{+0.001}_{-0.001}$	$0.324\,^{+0.002}_{-0.002}$	$0.326\,^{+0.002}_{-0.002}$
$C_{rk} + C_{kr}$	-0.193 ± 0.064	$-0.201\,^{+0.004}_{-0.003}$	$-0.198\,^{+0.004}_{-0.005}$	$-0.206\,^{+0.002}_{-0.002}$
$C_{rk} - C_{kr}$	0.057 ± 0.046	$-0.001\,^{+0.002}_{-0.002}$	$0.004\,^{+0.002}_{-0.002}$	0
$C_{nr} + C_{rn}$	-0.004 ± 0.037	$-0.003\,^{+0.002}_{-0.002}$	$0.001\,^{+0.002}_{-0.002}$	$1.06\,^{+0.01}_{-0.01} \times 10^{-3}$
$C_{nr} - C_{rn}$	-0.001 ± 0.038	$0.002\,^{+0.002}_{-0.002}$	$0.001\,^{+0.003}_{-0.002}$	0
$C_{nk} + C_{kn}$	-0.043 ± 0.041	$-0.002\,^{+0.002}_{-0.002}$	$0.003\,^{+0.002}_{-0.002}$	$2.15\,^{+0.04}_{-0.07} \times 10^{-3}$
$C_{nk} - C_{kn}$	0.040 ± 0.029	$-0.001\,^{+0.002}_{-0.002}$	$-0.001\,^{+0.002}_{-0.002}$	0



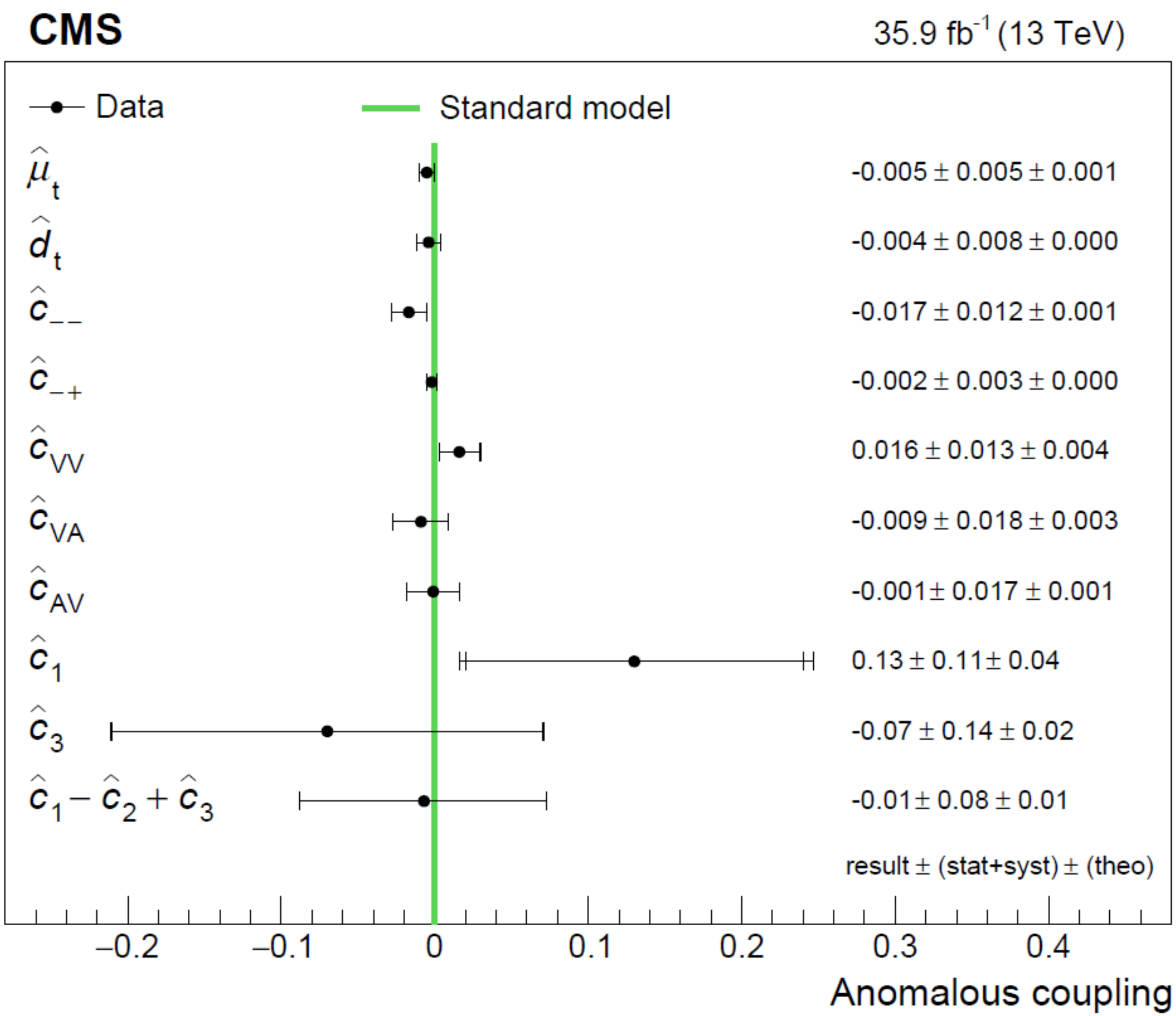
CMS Collaboration

PRD 100, 072002 (2019)

[arXiv:1907.03729]

Motivation: BSM searches

ATLAS and CMS already measure spin correlations in $pp \to t\bar{t}$.



CMS Collaboration
PRD 100, 072002 (2019)
[arXiv:1907.03729]

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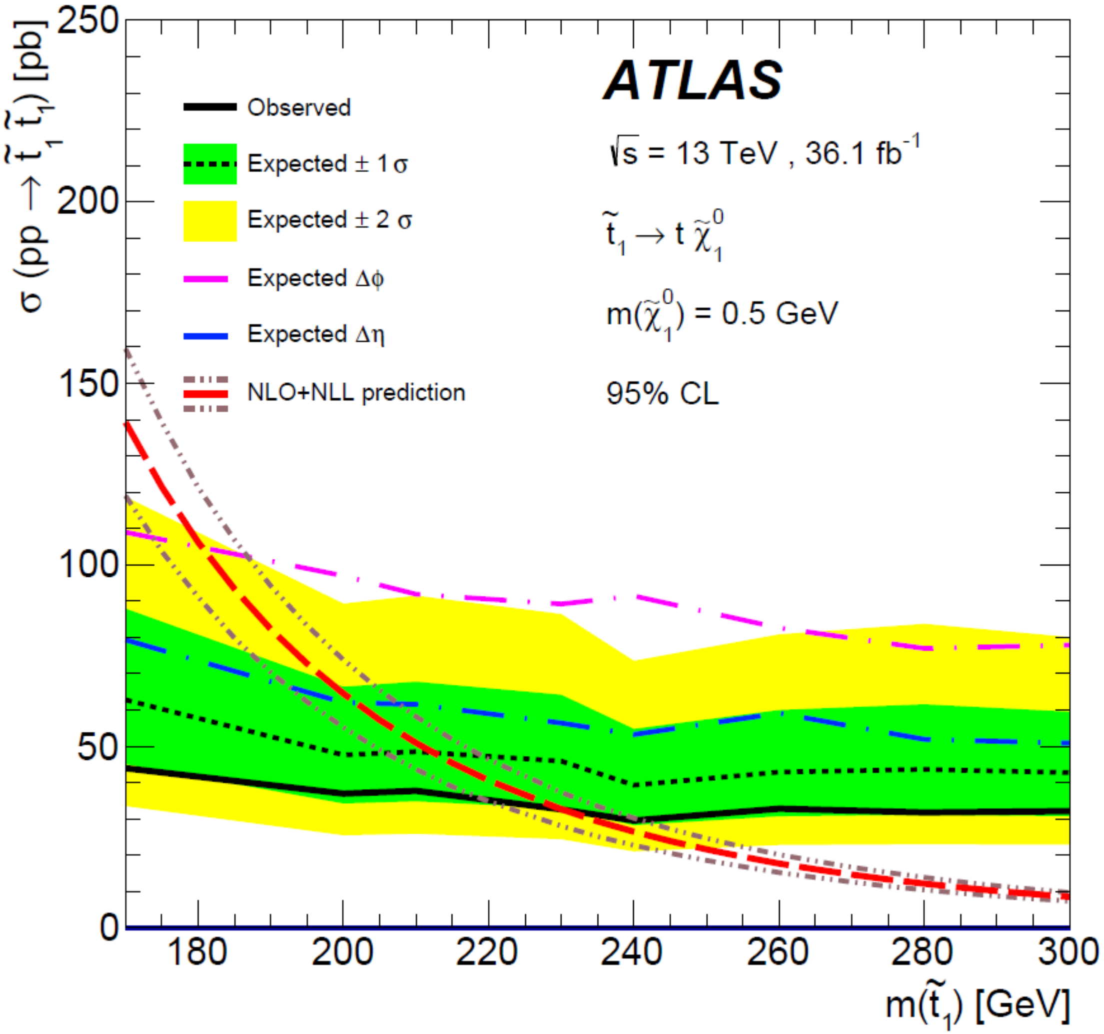

ATLAS Collaboration
EPJC 80 (2020) 754
[arXiv:1903.07570]

Motivation: quantum properties

ATLAS and CMS already measure entanglement in $pp \to t\bar{t}$.

ATLAS Collaboration, Nature 633 (2024) 542 [arXiv:2311.07288]

Article

Observation of quantum entanglement with top quarks at the ATLAS detector

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The ATLAS Collaboration*✉

Entanglement is a key feature of quantum mechanics[1–3], with applications in fields such as metrology, cryptography, quantum information and quantum computation[4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic[9–13] to the macroscopic[14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision dataset with a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 inverse femtobarns $(\text{fb})^{-1}$ recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, at which the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from the limitations of the Monte Carlo event generators and the parton shower model in modelling top-quark pair production. The entanglement marker is measured to be $D = -0.537 \pm 0.002\,(\text{stat.}) \pm 0.019\,(\text{syst.})$ for 340 GeV $< m_{t\bar{t}} <$ 380 GeV. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.

Motivation

ATLAS and CMS already measure spin correlations in $pp \to t\bar{t}$.

Do similar opportunities exist for

$$pp \to b\bar{b}$$

$$pp \to c\bar{c}$$

$$pp \to s\bar{s}$$

…

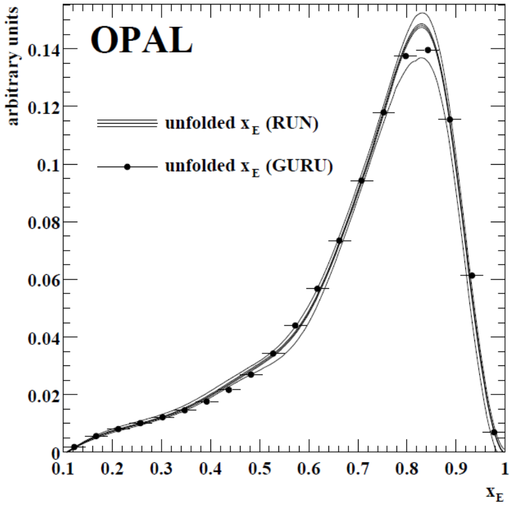
?

Nontrivial because the quarks hadronize and produce jets.

But nevertheless possible!

b-quark polarization retention

The b quark is carried by an **energetic** hadron with a **displaced** decay.



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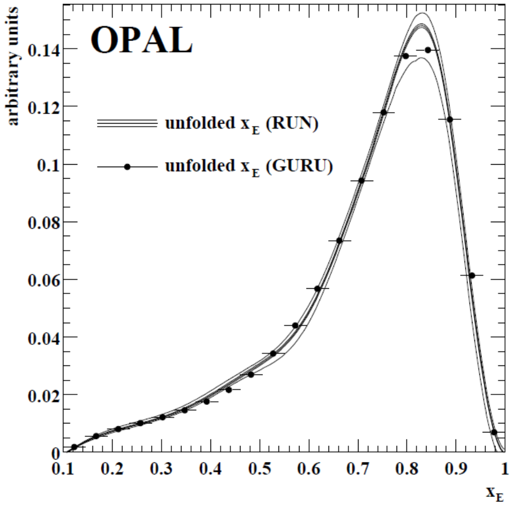

chromomagnetic moment

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

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

b spin **preserved** during hadronization

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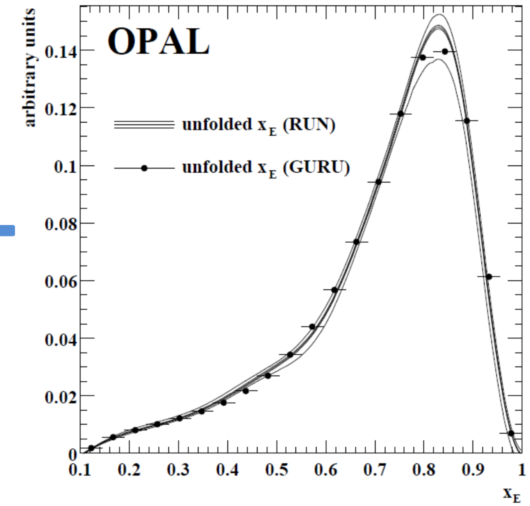

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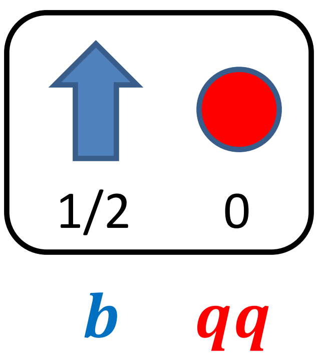


Λ_b

b spin also **preserved** during lifetime

Mannel and Schuler, PLB 279, 194 (1992)

Close, Körner, Phillips, Summers, J. Phys. G 18, 1703 (1992)

Falk and Peskin, PRD 49, 3320 (1994) [hep-ph/9308241]

b-quark polarization retention

Evidence of Λ_b polarization was observed at **LEP**

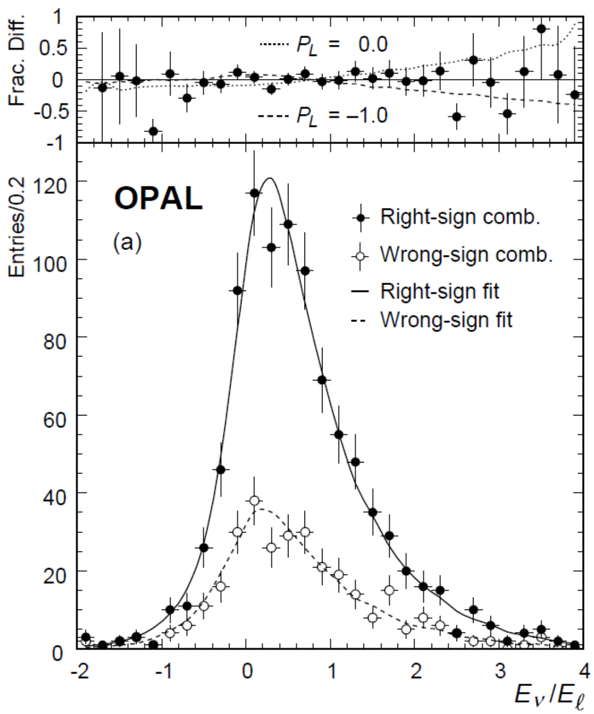
in $Z \to b\bar{b}$, where $\mathcal{P}(b) \simeq -0.94$:

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

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

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

stat. syst.



ALEPH Collaboration, PLB 365, 437 (1996)

DELPHI Collaboration, PLB 474, 205 (2000)

OPAL Collaboration, PLB 444, 539 (1998)

Some polarization loss due to contamination from $\Sigma_b^{(*)} \to \Lambda_b \pi$.

LEP → **longitudinal polarization retention factor** $r_L = 0.47 \pm 0.14$

For transverse polarization, possibly different, r_T

Galanti, Giammanco, Grossman, Kats, Stamou, Zupan, JHEP 11 (2015) 067 [1505.02771]

b-quark polarization retention

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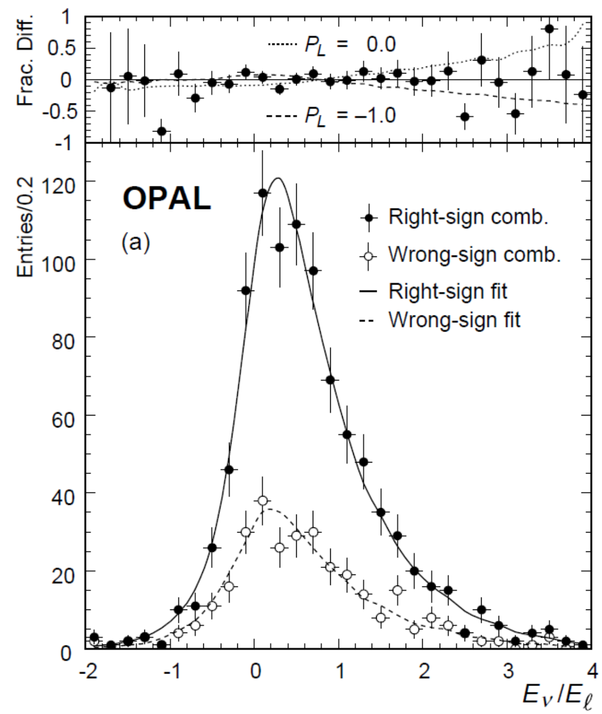

Some polarization loss due to contamination from $\Sigma_b^{(*)} \to \Lambda_b \pi$.

LEP → **longitudinal polarization retention factor** $r_L = 0.47 \pm 0.14$

Can also be measured using $t\bar{t}$ samples at the LHC (see backup slides)!

Galanti, Giammanco, Grossman, Kats, Stamou, Zupan, JHEP 11 (2015) 067 [1505.02771]

Spin correlations in $b\bar{b}$ and $c\bar{c}$

$$\tilde{\mathbf{C}} = \begin{pmatrix} c_{kk} & c_{kn} + c_r & c_{rk} - c_n \\ c_{kn} - c_r & c_{nn} & c_{nr} + c_k \\ c_{rk} + c_n & c_{nr} - c_k & c_{rr} \end{pmatrix}$$

	$t\bar{t}$, no cuts
c_{kk}	0.324 ± 0.006
c_{rr}	0.009 ± 0.006
c_{nn}	0.333 ± 0.006
$2c_{rk}$	-0.211 ± 0.008

MadGraph + MadSpin, LO QCD, $\sqrt{s} = 13$ TeV

Spin correlations in $b\bar{b}$ and $c\bar{c}$

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	$t\bar{t}$, no cuts	$b\bar{b}$, no cuts	$c\bar{c}$, no cuts
c_{kk}	0.324 ± 0.006	0.296 ± 0.004	0.284 ± 0.004
c_{rr}	0.009 ± 0.006	0.004 ± 0.004	-0.006 ± 0.004
c_{nn}	0.333 ± 0.006	0.299 ± 0.004	0.298 ± 0.004
$2c_{rk}$	-0.211 ± 0.008	-0.197 ± 0.006	-0.188 ± 0.006

MadGraph + MadSpin, LO QCD, $\sqrt{s} = 13$ TeV

Spin correlations in $b\bar{b}$ and $c\bar{c}$

$$\tilde{\mathbf{C}} = \begin{pmatrix} c_{kk} & c_{kn} + c_r & c_{rk} - c_n \\ c_{kn} - c_r & c_{nn} & c_{nr} + c_k \\ c_{rk} + c_n & c_{nr} - c_k & c_{rr} \end{pmatrix}$$

	$t\bar{t}$, no cuts	$b\bar{b}$, no cuts	$c\bar{c}$, no cuts	$b\bar{b}$ with cuts	$c\bar{c}$ with cuts
c_{kk}	0.324 ± 0.006	0.296 ± 0.004	0.284 ± 0.004	-0.987 ± 0.004	-0.984 ± 0.006
c_{rr}	0.009 ± 0.006	0.004 ± 0.004	-0.006 ± 0.004	-0.603 ± 0.004	-0.609 ± 0.006
c_{nn}	0.333 ± 0.006	0.299 ± 0.004	0.298 ± 0.004	0.591 ± 0.004	0.603 ± 0.006
$2c_{rk}$	-0.211 ± 0.008	-0.197 ± 0.006	-0.188 ± 0.006	-0.038 ± 0.006	-0.008 ± 0.009

MadGraph + MadSpin, LO QCD, $\sqrt{s} = 13$ TeV

Baryon decay angular distributions

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i^{\pm}} = \frac{1}{2}\left(1 + B_i^{\pm}\cos\theta_i^{\pm}\right)$$

$$B_i^{\pm} = \alpha_{\pm}\, r_i\, f\, \tilde{B}_i^{\pm}$$

spin analyzing power

polarization retention factor (r_L or r_T)

$$f = \frac{N_{\rm sig}}{N_{\rm bg} + N_{\rm sig}}$$

sample purity

$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta_i^{+}\cos\theta_j^{-})} = \frac{1}{2}\left(1 - C_{ij}\cos\theta_i^{+}\cos\theta_j^{-}\right)\ln\left(\frac{1}{|\cos\theta_i^{+}\cos\theta_j^{-}|}\right)$$

$$C_{ij} = \alpha_{+}\alpha_{-}\, r_i\, r_j\, f\, \tilde{C}_{ij}$$

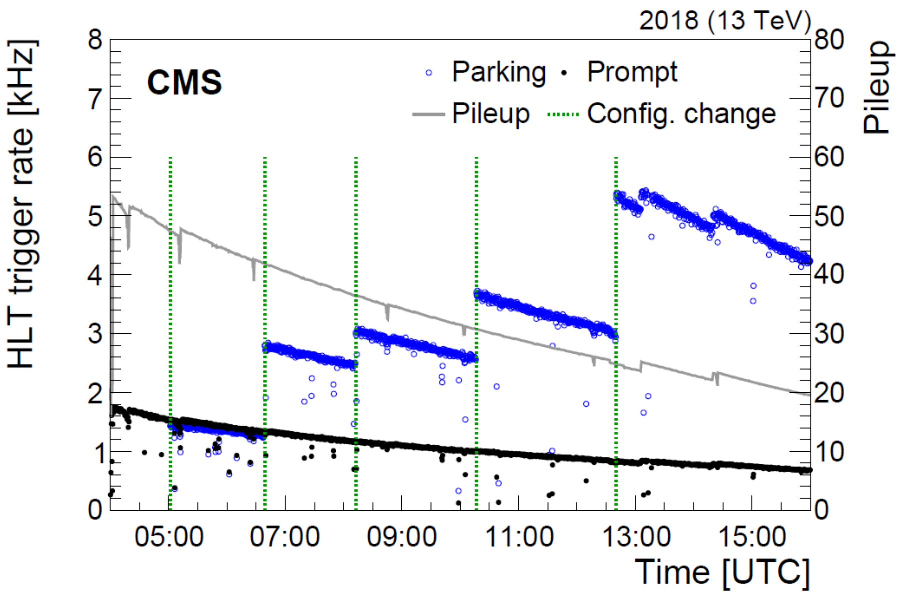
Standard datasets

	ATLAS		CMS	
	Run 2	HL-LHC	Run 2	HL-LHC
Collider energy $\sqrt{s}$ [TeV]	13	14	13	14
Integrated luminosity $\mathcal{L}$ [fb^{-1}]	140	3000	140	3000
Trigger-motivated cuts:				
Jet p_T cut [GeV]	460	400	500	520
Double muon p_T cut (without isolation) [GeV]	15	10	37, 27	37, 27
Single muon p_T cut (with isolation) [GeV]	27	20	24	24
Double electron p_T cut (without isolation) [GeV]	18	10	25	25
Single electron p_T cut (with isolation) [GeV]	27	22	28	32 or 26
Jet $\|\eta\|$ cut	2.4	3.8	2.4	4.0
Muon $\|\eta\|$ cut	2.4	2.5	2.4	2.4
Electron $\|\eta\|$ cut	2.4	2.5	2.4	2.4

Special dataset: CMS parked data

CMS Collaboration, Phys. Rept. 1115 (2025) 678 [arXiv:2403.16134]

- **Data parking:** record the data when bandwidth allows and process it later.
- **Trigger:** muon with a low p_T threshold (varying between 7 and 12 GeV) and impact parameter significance.
- Operated during part of Run 2 ($\sim 42\ \mathrm{fb}^{-1}$)
- Original motivation: measurements of LFU violation (R_K etc.)
  ***"B* parking" dataset**



$b\bar{b}$ analysis selection for $\Lambda_b \to X_c \mu^- \bar{\nu}_\mu$

- Pair of opposite-sign muons (inside jets) satisfying the offline trigger cuts and each carrying $> 20\%$ of the jet momentum.
- At least one of the jets is "b tagged" (with assumed efficiency of 80%), e.g. by muon impact parameter.

Dominant remaining background:

semileptonic B-meson decays

Possible approaches to dealing with it:

Inclusive keep it (to keep the signal efficiency high)

Semi-inclusive demand $\Lambda \to p\pi^-$ coming from the b decay vertex
(costly in efficiency because the Λ decays far)

Exclusive demand a fully reconstructed Λ_c decay

Mixed (one choice for one jet, another choice for the second)

$b\bar{b}$ analysis selection for $\Lambda_b \to X_c\mu^- \bar{\nu}_\mu$

Selection	Decay Modes	Branching Ratio
Inclusive	$\Lambda_b \to X_c\mu^-\bar{\nu}_\mu$	11%
Semi-inclusive	$\Lambda_c^+ \to \Lambda X$	38%
	$\Lambda \to p\pi^-$	64%
Exclusive	$\Lambda_c^+ \to pK^-\pi^+$	6.3%
	$\Lambda_c^+ \to \Lambda\pi^+ \to p\pi^-\pi^+$	0.8%
	$\Lambda_c^+ \to pK_S \to p\pi^-\pi^+$	1.1%
	$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^- \to p\pi^+\pi^+\pi^-\pi^-$	2.3%
	$\Lambda_c^+ \to pK_S\pi^+\pi^- \to p\pi^+\pi^+\pi^-\pi^-$	1.1%
	$\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$	4.5%
	$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$	1.9%
	total	18%

Run 2 precision for $b\bar{b}$

channel →	inclusive	inclusive/inclusive		inclusive/exclusive	
trigger	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
standard	0.003	0.14	0.10	0.11	0.079
parked	0.0003	0.039	0.027	0.031	0.022

channel →	semi-inclusive	semi-inclusive/semi-inclusive		semi-inclusive/inclusive	
trigger	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
standard	0.005	0.36	0.25	0.16	0.11
parked	0.0004	0.050	0.035	0.031	0.022

channel →	exclusive	exclusive/exclusive		exclusive/semi-inclusive	
trigger	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
standard	0.003	0.18	0.11	0.18	0.13
parked	0.0004	0.049	0.034	0.034	0.024

Note: Since the performance of the different channels is comparable, sensitivity can be improved by combining channels.

Run 2 precision for $b\bar{b}$

channel →	inclusive	inclusive/inclusive		inclusive/exclusive	
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standard	0.005	0.36	0.25	0.16	0.11
parked	0.0004	0.050	0.035	0.031	0.022

channel →	exclusive	exclusive/exclusive		exclusive/semi-inclusive	
trigger	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
standard	0.003	0.18	0.11	0.18	0.13
parked	0.0004	0.049	0.034	0.034	0.024

Note: Since the performance of the different channels is comparable, sensitivity can be improved by combining channels.

HL-LHC precision for $b\bar{b}$

channel →	inclusive	inclusive/inclusive		inclusive/exclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.0004	0.015	0.011	0.012	0.0086
300	0.0022	0.13	0.091	0.10	0.071

channel →	semi-inclusive	semi-inclusive/semi-inclusive		semi-inclusive/inclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.0004	0.018	0.013	0.012	0.0084
300	0.0027	0.21	0.15	0.12	0.082

channel →	exclusive	exclusive/exclusive		exclusive/semi-inclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.0004	0.019	0.013	0.013	0.0093
300	0.0025	0.16	0.11	0.13	0.091

Note: Since the performance of the different channels is comparable, sensitivity can be improved by combining channels.

Quantum properties in $b\bar{b}$ spins

- **Entanglement:** density matrix cannot be written in a separable form

$$\rho = \sum_n p_n \rho_n^b \otimes \rho_n^{\bar{b}}$$

Sufficient condition:

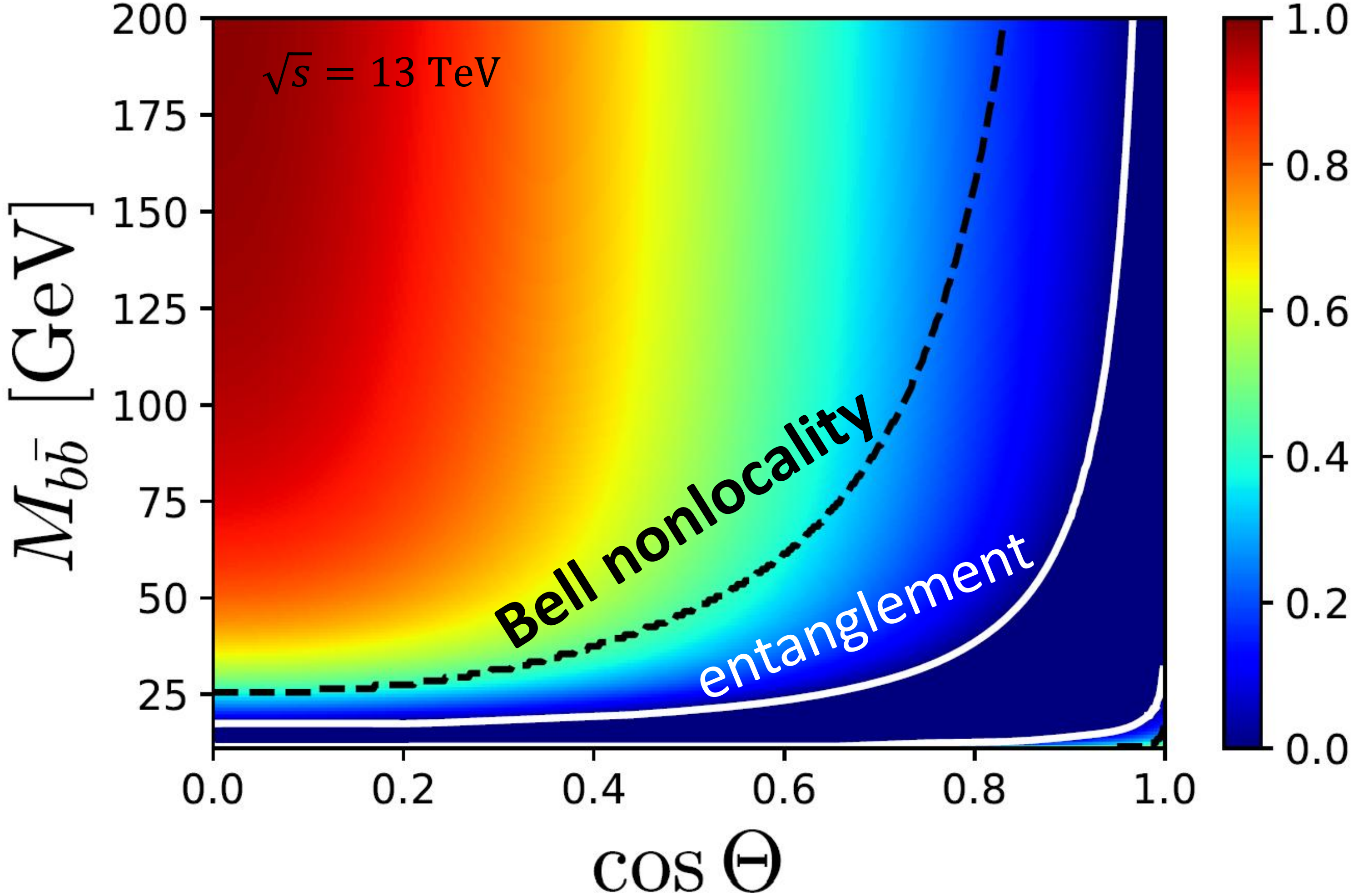
$$\Delta \equiv \frac{-C_{nn} + |C_{kk} + C_{rr}| - 1}{2} > 0$$

- **Bell nonlocality:** the state can violate Bell inequalities, i.e. QM cannot be replaced with local hidden variables.

Sufficient condition:

$$\mathcal{V} \equiv C_{kk}^2 + C_{rr}^2 - 1 > 0$$

Quantum properties in $b\bar{b}$ spins



Quantum properties in $b\bar{b}$ spins

	$\sigma\epsilon_{\mu\mu}$ [pb]	$\mathcal{L}$ [fb^{-1}]	N	C_{kk}	C_{rr}	C_{nn}	Δ	$\mathcal{V}$	r_L	$\sigma_\Delta^{\rm stat}$	$\sigma_\mathcal{V}^{\rm stat}$	$\frac{\Delta}{\sigma_\Delta^{\rm stat}}$	$\frac{\mathcal{V}}{\sigma_\mathcal{V}^{\rm stat}}$
	Run 2, $\sqrt{s} = 13$ TeV												
ATLAS	1.9×10^4	140	2.7×10^4	0.94	0.57	-0.56	0.54	0.21	0.75	0.14	0.33	3.9	0.6
									0.45	0.23	0.78	2.3	0.3
LHCb	3.9×10^6	5.7	1.8×10^4	0.55	0.67	-0.56	0.39	-0.24	0.75	0.17	0.34	2.2	-0.7
									0.45	0.29	0.62	1.3	-0.4
CMS B parking	7.9×10^5	41.6	1.8×10^5	0.76	0.63	-0.59	0.49	-0.03	0.75	0.055	0.120	8.9	-0.3
									0.45	0.092	0.256	5.3	-0.1
	HL-LHC, $\sqrt{s} = 14$ TeV												
ATLAS	9.9×10^4	3000	1.0×10^6	0.91	0.85	-0.83	0.79	0.55	0.75	0.02	0.06	> 10	8.7
									0.45	0.04	0.13	> 10	4.3
LHCb	4.3×10^6	300	8.2×10^4	0.79	0.88	-0.81	0.74	0.43	0.75	0.080	0.215	9.2	2.0
									0.45	0.135	0.406	5.5	1.0

$r_T = 0.7$

For LHCb: a trigger requiring a muon with $p_T > 1.8$ GeV, displaced SV, at least one charged particle with $p_T > 1.6$ GeV inconsistent with PV.

Conclusions and outlook

- $b\bar{b}$ spin correlation measurements may be possible even with Run 2 datasets, especially with the CMS parked data.
- $c\bar{c}$ spin correlation measurements may become possible at the HL-LHC.
- Can measure the polarization retention factors r_L and r_T (more refined: the polarized fragmentation functions):

$$r_L^2 = \frac{C_{kk}}{c_{kk}\alpha_+\alpha_- f}\,, \quad r_T^2 = \frac{C_{nn}}{c_{nn}\alpha_+\alpha_- f}\,, \quad r_T^2 = \frac{C_{rr}}{c_{rr}\alpha_+\alpha_- f}$$

- Measuring r_L via the polarized b and c quarks in $t\bar{t}$ samples could be a simpler first step. JHEP 11 (2015) 067 [arXiv:1505.02771]
- Can $b\bar{b}$ and $c\bar{c}$ spin correlations be useful for discovering or characterizing new physics? Work in progress with David Uzan.
- Measurements of entanglement (Run 2) and Bell nonlocality (HL-LHC) are feasible in $b\bar{b}$, similar to $t\bar{t}$.

Supplemental Slides

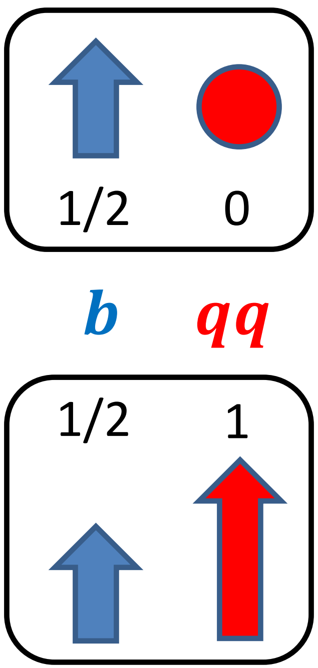
b-quark polarization retention

chromomagnetic moment

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

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

b spin **preserved** during hadronization



Λ_b

b spin also **preserved** during lifetime

Σ_b, Σ_b^*

b spin **oscillates** during lifetime

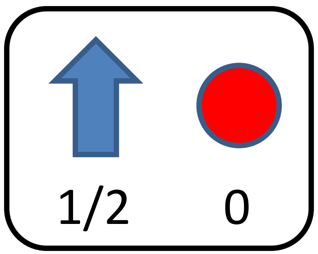
Λ_b sample contaminated by $\Sigma_b^{(*)} \to \Lambda_b \pi$

c-quark polarization retention

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

$m_c \gg \Lambda_{\mathrm{QCD}}$ as a rough approximation

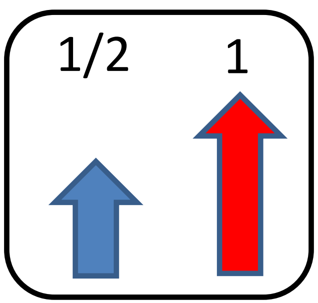
c spin **preserved** during hadronization



Λ_c

c spin also **preserved** during lifetime

c qq



$\Sigma_c(2455)$ → Σ_c, Σ_c^* ← $\Sigma_c(2520)$

c spin **oscillates** during lifetime

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

b-quark polarization retention

Dominant polarization loss effect

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

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

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

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

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

Production as a b spin eigenstate.

Decay as a Σ_b or Σ_b^* mass eigenstate.

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

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

"diquarks"

S	T
spin-0 isosinglet	spin-1 isotriplet

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

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

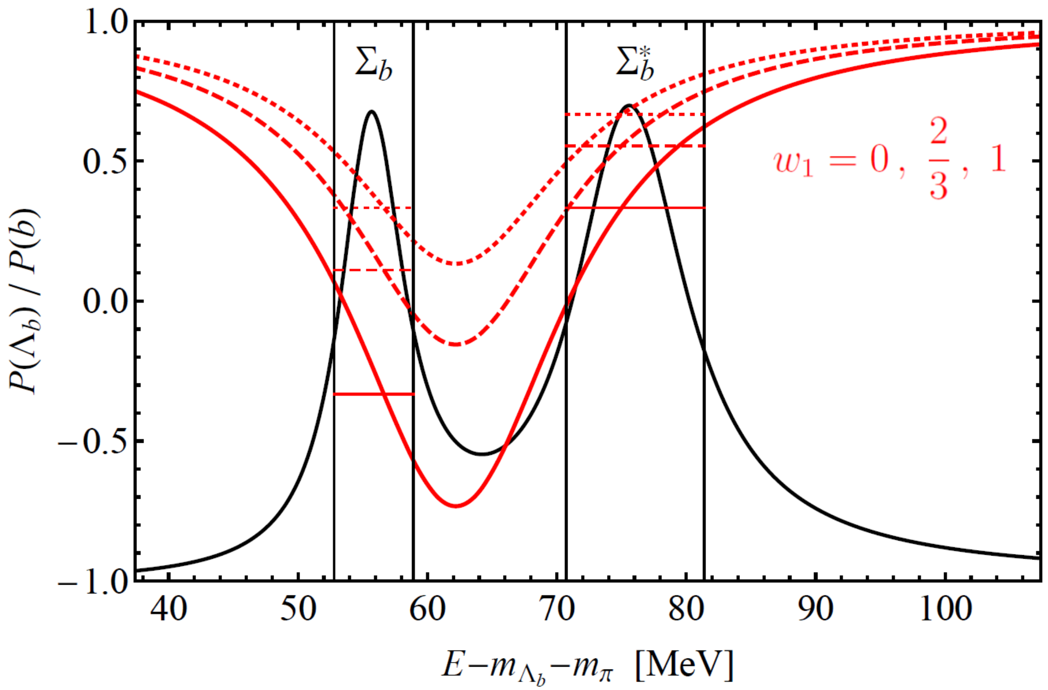
$$r \approx \frac{1 + (1 + 4w_1)A/9}{1 + A}$$

Falk and Peskin, PRD 49, 3320 (1994) [hep-ph/9308241]

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



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

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

b-quark polarization retention

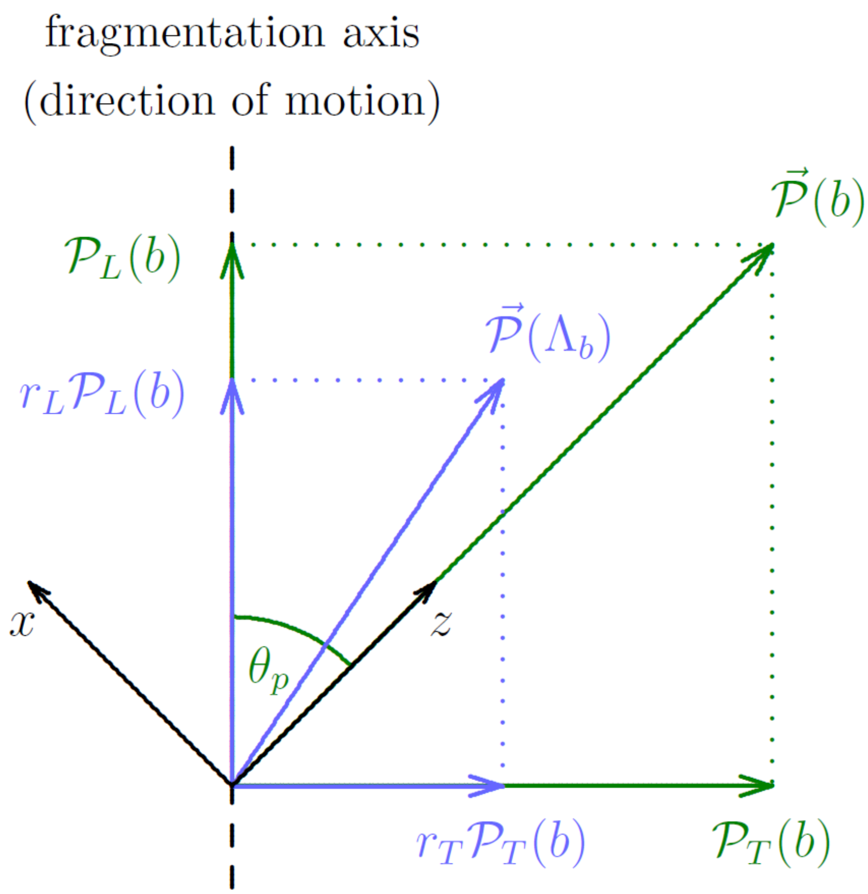
$$r_L \approx \frac{1 + (0.23 + 0.38 w_1) A}{1 + A}$$

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

Directional dependence, since

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

holds along the fragmentation axis.



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

Heavy quark polarization retention

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

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

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

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

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

Pythia tunes $0.24 \lesssim A \lesssim 0.45$ (but 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

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

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

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

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

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?

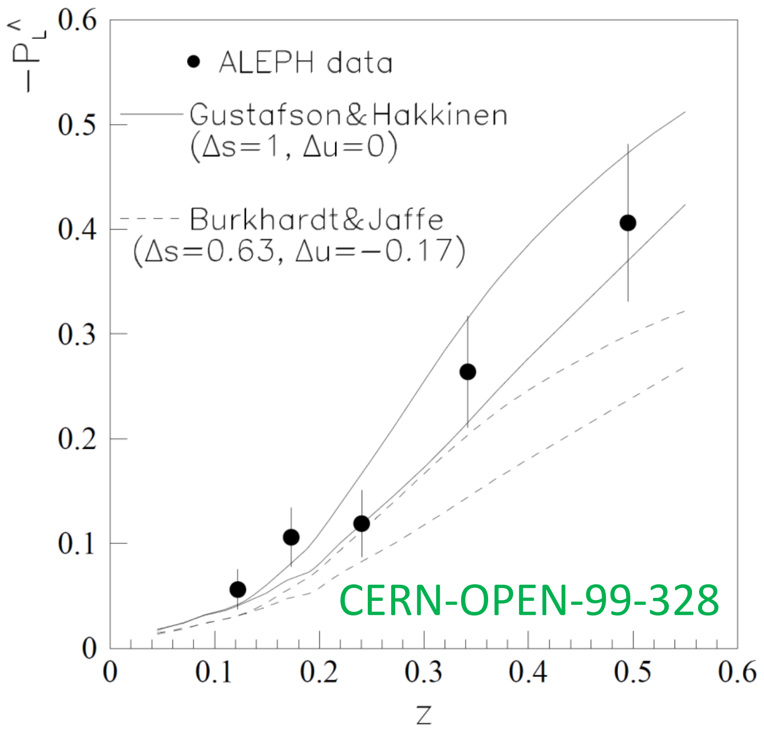
- Cannot argue for polarization retention using heavy-quark limit.

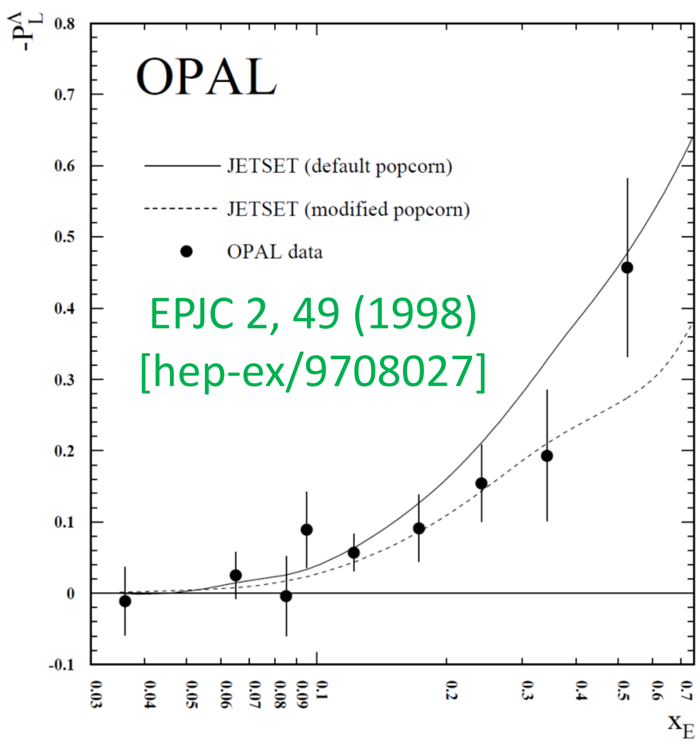
  Cannot argue for polarization loss either!

s-quark polarization retention!

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

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





s-quark polarization retention!

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

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

Baryon decays of interest

Fragmentation Fraction		Decay Scheme	BR	Spin analyzing power
$b \to \Lambda_b$	7.0%	$\Lambda_b \to X_c \mu^- \bar{\nu}_\mu$	11%	$\alpha_{\mu^-} \approx -0.26$, $\alpha_{\bar{\nu}_\mu} \approx 1$
		with $\Lambda \to p\pi^-$	2.7%	
		with Λ_c^+ reco.	2.0%	
$c \to \Lambda_c$	6.4%	$\Lambda_c^+ \to pK^-\pi^+$	6.3%	$\alpha_{\text{eff}} \approx 0.662$
		$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$	3.5%	$\alpha_{\mu^+} \approx 1$
		with $\Lambda \to p\pi^-$	2.2%	

Baryon decays of interest

Fragmentation Fraction		Decay Scheme	BR	Spin analyzing power
$b \to \Lambda_b$	7.0%	$\Lambda_b \to X_c \mu^- \bar{\nu}_\mu$	11%	← inclusive
		with $\Lambda \to p\pi^-$	2.7%	← semi-inclusive
		with Λ_c^+ reco.	2.0%	← exclusive
$c \to \Lambda_c$	6.4%	$\Lambda_c^+ \to pK^-\pi^+$	6.3%	← hadronic
		$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$	3.5%	← semileptonic
		with $\Lambda \to p\pi^-$	2.2%	

+ mixed channels with one selection on one side and another on the other

Measuring r_L via ATLAS/CMS $t\bar{t}$ samples

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

- $t \to W^+ b$ produces polarized b quarks.
  - $\hookrightarrow c\bar{s}$ produces polarized c and s quarks.
- Easy to select a clean $t\bar{t}$ sample (e.g., in lepton + jets).
- Kinematic reconstruction along with b and c tagging enable obtaining high-purity samples of b, c and s jets.
- Statistics in Run 2 is as large as in Z decays at LEP.
- Run 2 data allows measuring r_L with $\mathcal{O}(10\%)$ precision for b, c, s.

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

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

Event counts for $b\bar{b}$ analysis

Run 2

m_{jj} cut [GeV]	$N_{b\bar{b}}^{ii}$	$N_{b\bar{b}}^{ss}$	$N_{b\bar{b}}^{ee}$	$N_{b\bar{b}}^{is}$	$N_{b\bar{b}}^{ie}$	$N_{b\bar{b}}^{se}$
no cut	8.0×10^4	200	640	8.1×10^3	1.4×10^4	730
100	4.7×10^4	121	380	4.8×10^3	8.5×10^3	430
300	2.7×10^3	5.0	21	230	490	20
500	360		2.9	20	65	1.8
parked data	1.1×10^6	1.1×10^4	8700	2.2×10^5	1.9×10^5	2.0×10^4
purity f [%]	0.55	32	44	4.2	4.9	38

HL-LHC

m_{jj} cut [GeV]	$N_{b\bar{b}}^{ii}$	$N_{b\bar{b}}^{ss}$	$N_{b\bar{b}}^{ee}$	$N_{b\bar{b}}^{is}$	$N_{b\bar{b}}^{ie}$	$N_{b\bar{b}}^{se}$
no cut	6.7×10^6	8.1×10^4	5.4×10^4	1.5×10^6	1.2×10^6	1.3×10^5
100	2.6×10^6	3.1×10^4	2.1×10^4	5.7×10^5	4.7×10^5	5.1×10^4
300	9.6×10^4	610	780	1.5×10^4	1.7×10^4	1.4×10^3
500	1.2×10^4	35	98	1.3×10^3	2.2×10^3	120
750	2.0×10^3	3.0	16	150	360	13
1000	460		3.7	27	82	2.5
purity f [%]	0.55	32	44	4.2	4.9	38

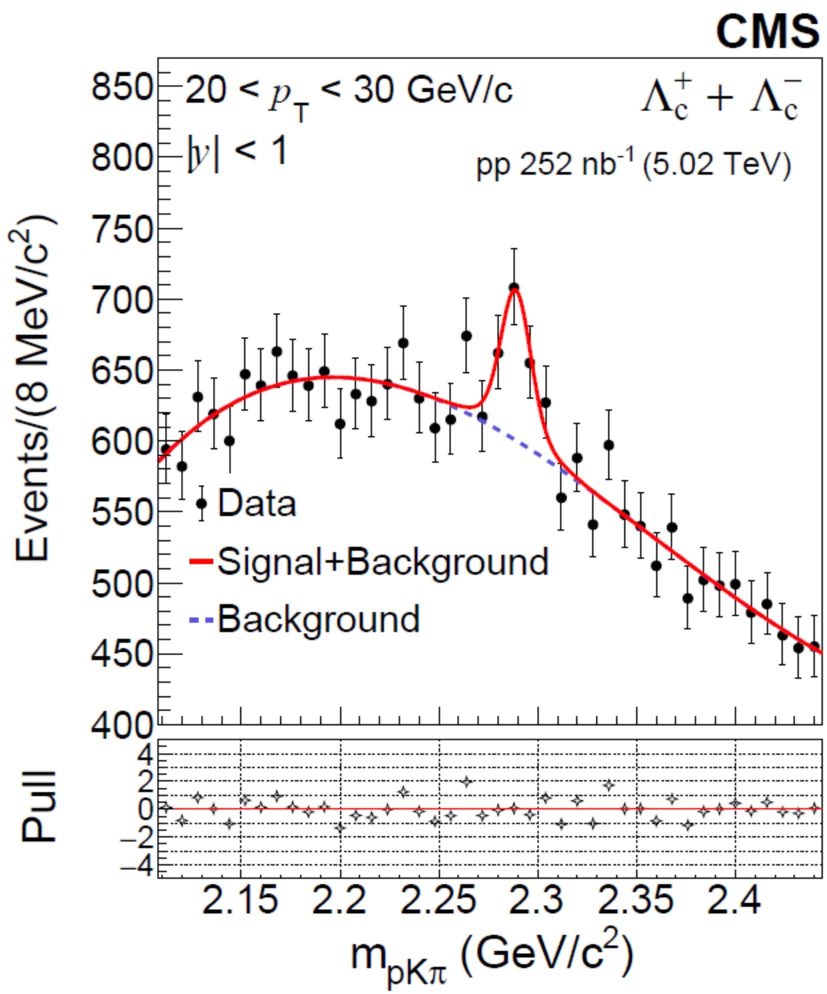
Hadronic selection for $c\bar{c}$ analysis

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

- Three hadron tracks consistent with a common vertex and the Λ_c^+ mass hypothesis.
- Backgrounds:
  - Other charmed hadron decays, e.g., $D^+ \to \pi^+K^-\pi^+(\pi^0)$.
  - Charmed hadrons from b jets.
  - Combinatorial background due to random track combinations.

Hadronic selection for $c\bar{c}$ analysis

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



CMS Collaboration
JHEP 01 (2024) 128
[arXiv:2307.11186]

Semileptonic selection for $c\bar{c}$ analysis

- Pair of opposite-sign muons (inside jets) satisfying the offline trigger cuts.
- $\Lambda \to p\pi^-$ decay in each jet (will help reconstruct the Λ_c^+ and eliminate the D-meson background).
- The inferred Λ trajectory should form a displaced vertex with the muon, or the Λ should carry a significant fraction of the jet momentum (to ensure that the Λ originates from the Λ_c^+ decay).
- Charm tagging against b jets with 40% signal efficiency (which likely makes the background from b jets negligible; see paper for more details).

Event counts and precision for $c\bar{c}$ analysis

HL-LHC

channel	$N_{c\bar{c}}$	f [%]	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
hadronic	24		—	—
semileptonic	2.4×10^3	100	0.060	0.042
mixed	3.9×10^3	100 – 14	0.072 – 0.19	0.050 – 0.13

Challenges for $s\bar{s}$ analyses

- ATLAS/CMS jet triggers require $p_T \gtrsim 400\ \mathrm{GeV}$, limiting the statistics.

- Only about 3% of the energetic Λ baryons decay sufficiently early inside the tracker, again limiting the statistics.

- Large backgrounds from other dijet processes (no "s tagging" algorithms) lead to low sample purity ($\sim 1\%$).

Spin correlations opportunities summary

Quark	Channel	Run 2 standard	Run 2 parked	HL-LHC
c	hadronic			
	semileptonic			✓
	mixed			✓
b	inclusive/inclusive	(✓✗)	(✓)	(✓)
	semi-inclusive/semi-inclusive	✓✗	✓	✓
	exclusive/exclusive	✓✗	✓	✓
	inclusive/exclusive	(✓✗)	(✓)	(✓)
	inclusive/semi-inclusive	(✓✗)	(✓)	(✓)
	exclusive/semi-inclusive	✓✗	✓	✓

✓ promising   ✓✗ borderline   (✓) purity < 10%

Statistical uncertainties

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i^{\pm}} = \frac{1}{2}\left(1 + B_i^{\pm}\cos\theta_i^{\pm}\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta_i^{+}\cos\theta_j^{-})} = \frac{1}{2}\left(1 - C_{ij}\cos\theta_i^{+}\cos\theta_j^{-}\right)\ln\left(\frac{1}{|\cos\theta_i^{+}\cos\theta_j^{-}|}\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dX_{\pm}} = \frac{1}{2}\left(1 - \frac{C_{ij}^{\pm}}{2}X_{\pm}\right)\cos^{-1}(|X_{\pm}|)$$

$$C_{ij}^{\pm} = C_{ij} \pm C_{ji} \qquad X_{\pm} = \cos\theta_i^{+}\cos\theta_j^{-} \pm \cos\theta_j^{+}\cos\theta_i^{-}$$

Uncertainties from fitting to statistically fluctuated data:

$$\Delta B_i^{\pm} \simeq \frac{\sqrt{3}}{\sqrt{N}}\,, \quad \Delta C_{ij} \simeq \frac{3}{\sqrt{N}}\,, \quad \Delta C_{ij}^{\pm} \simeq \frac{3\sqrt{2}}{\sqrt{N}}$$

Statistical uncertainties

$$B_i^{\pm} = \alpha_{\pm} r_i f b_i^{\pm} \qquad C_{ii} = \alpha_+ \alpha_- r_i^2 f c_{ii}$$

$$C_{ij}^{+} = 2\alpha_+ \alpha_- r_i r_j f c_{ij} \qquad C_{ij}^{-} = 2\alpha_+ \alpha_- r_i r_j f c_{\ell}$$

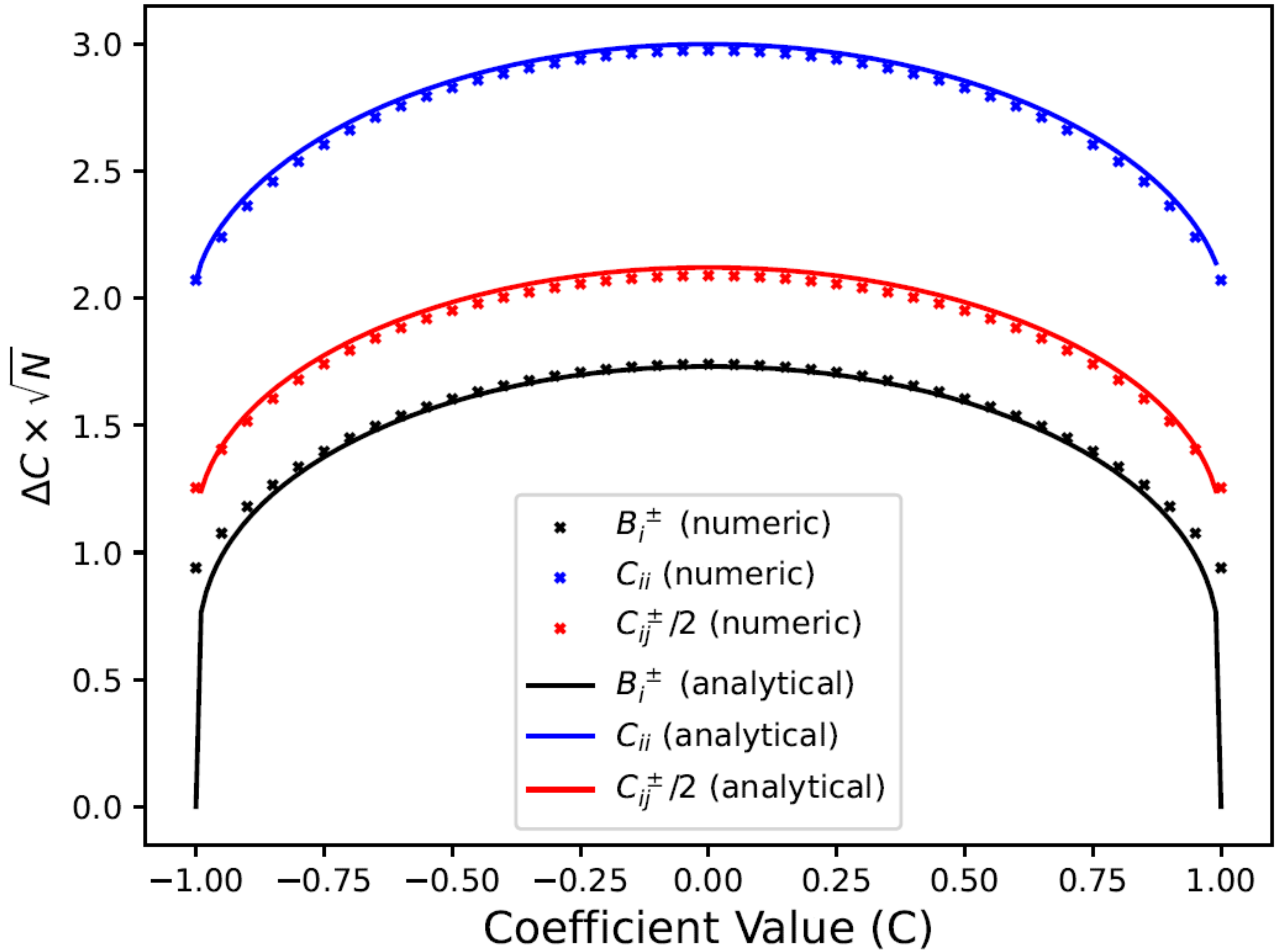
$$\Delta b_i^{\pm} \simeq \frac{\sqrt{3}}{|r_i \alpha_{\pm}| \sqrt{f N_{\rm sig}}} \,,$$

$$\Delta c_{ii} \simeq \frac{3}{r_i^2 |\alpha_+ \alpha_-| \sqrt{f N_{\rm sig}}} \,,$$

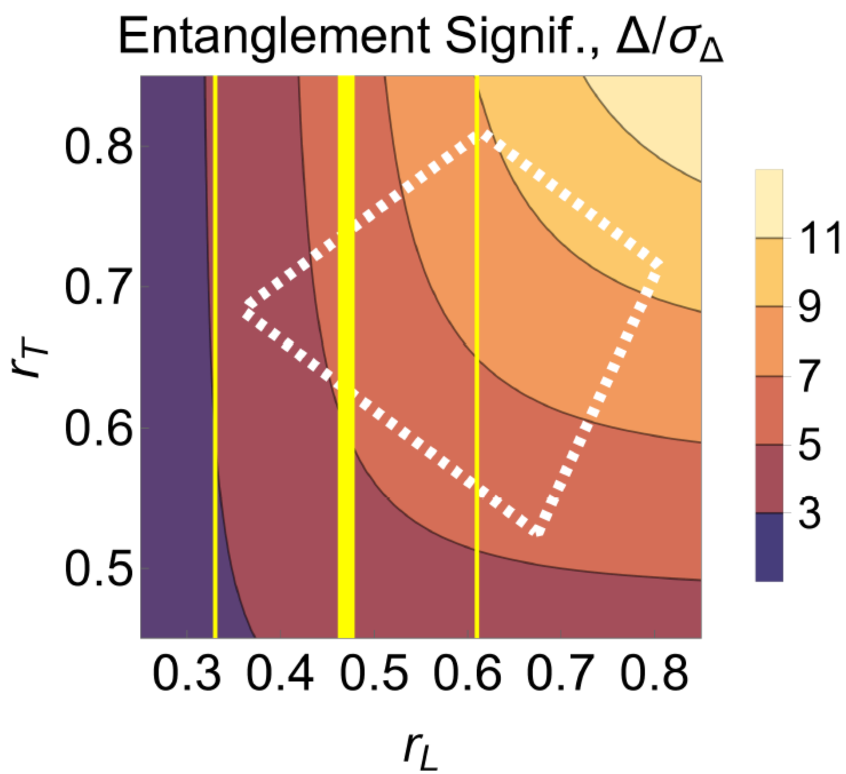
$$\Delta c_{ij(\ell)} \simeq \frac{3}{\sqrt{2}\, |r_i r_j \alpha_+ \alpha_-| \sqrt{f N_{\rm sig}}}$$

Statistical uncertainties

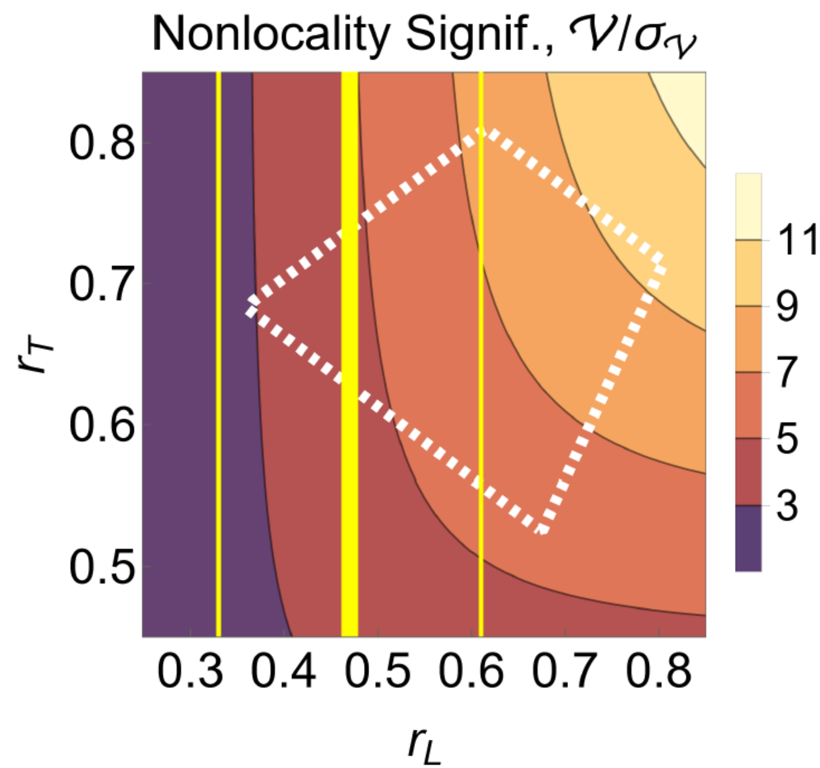
Dependence on the value of the coefficient:



Quantum properties in $b\bar{b}$ spins



CMS B parking
$\mathcal{L} \approx 42\ \mathrm{fb}^{-1}$



HL-LHC ATLAS
$\mathcal{L} \approx 3000\ \mathrm{fb}^{-1}$