

New Physics Directions in the LHC era and beyond (MPIK, Heidelberg)
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Spin correlations of bottom and charm quark pairs at the LHC for SM and BSM physics

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

Motivation

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

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:

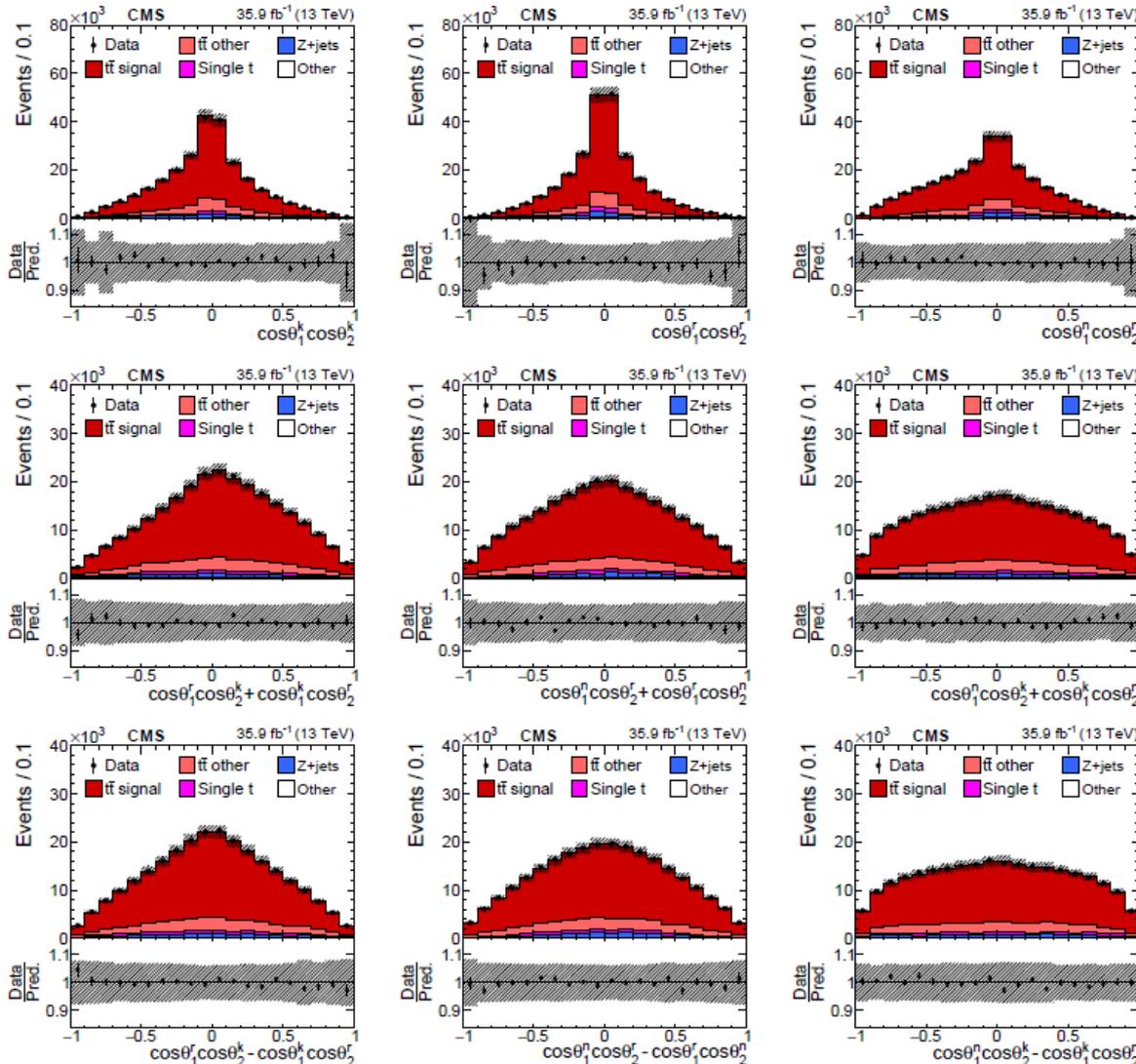
$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_1^i} = \frac{1}{2} \left(1 + B_1^i \cos \theta_1^i \right)$$

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

Motivation

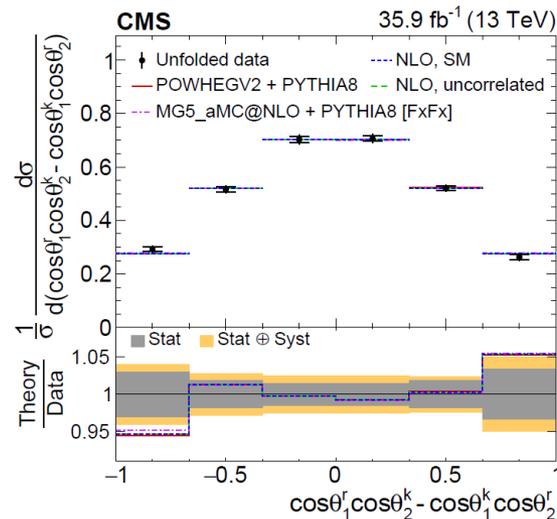
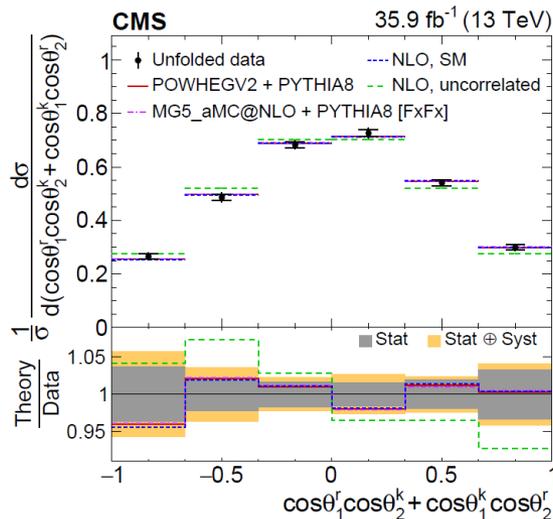
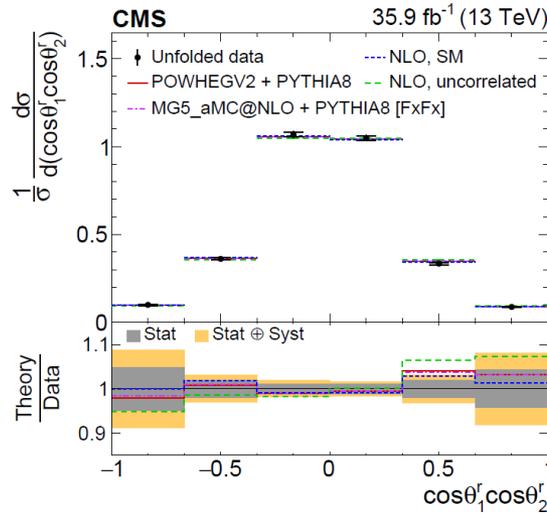
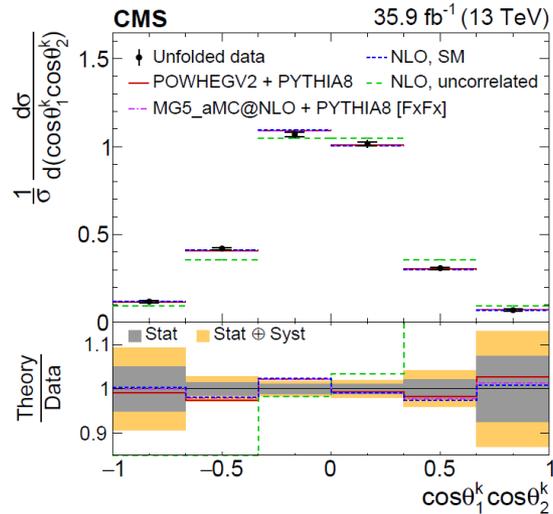
ATLAS and CMS already measure spin correlations in $pp \rightarrow t\bar{t}$.

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



Motivation

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

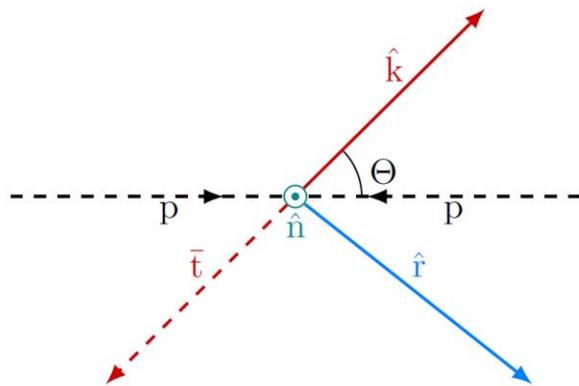


CMS Collaboration
PRD 100, 072002 (2019)
[arXiv:1907.03729]

Motivation

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

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]

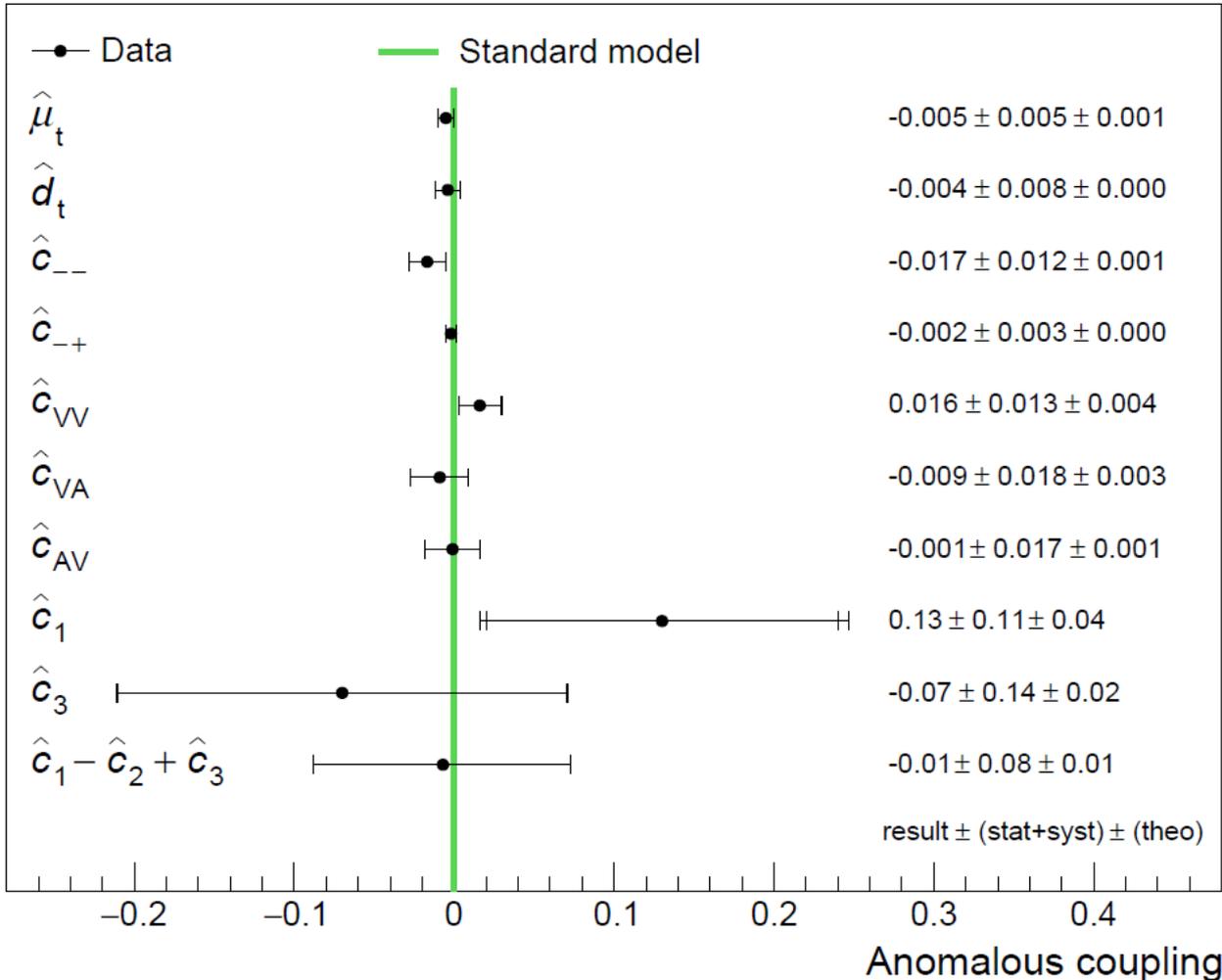
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ATLAS and CMS already measure spin correlations in $pp \rightarrow t\bar{t}$.

CMS

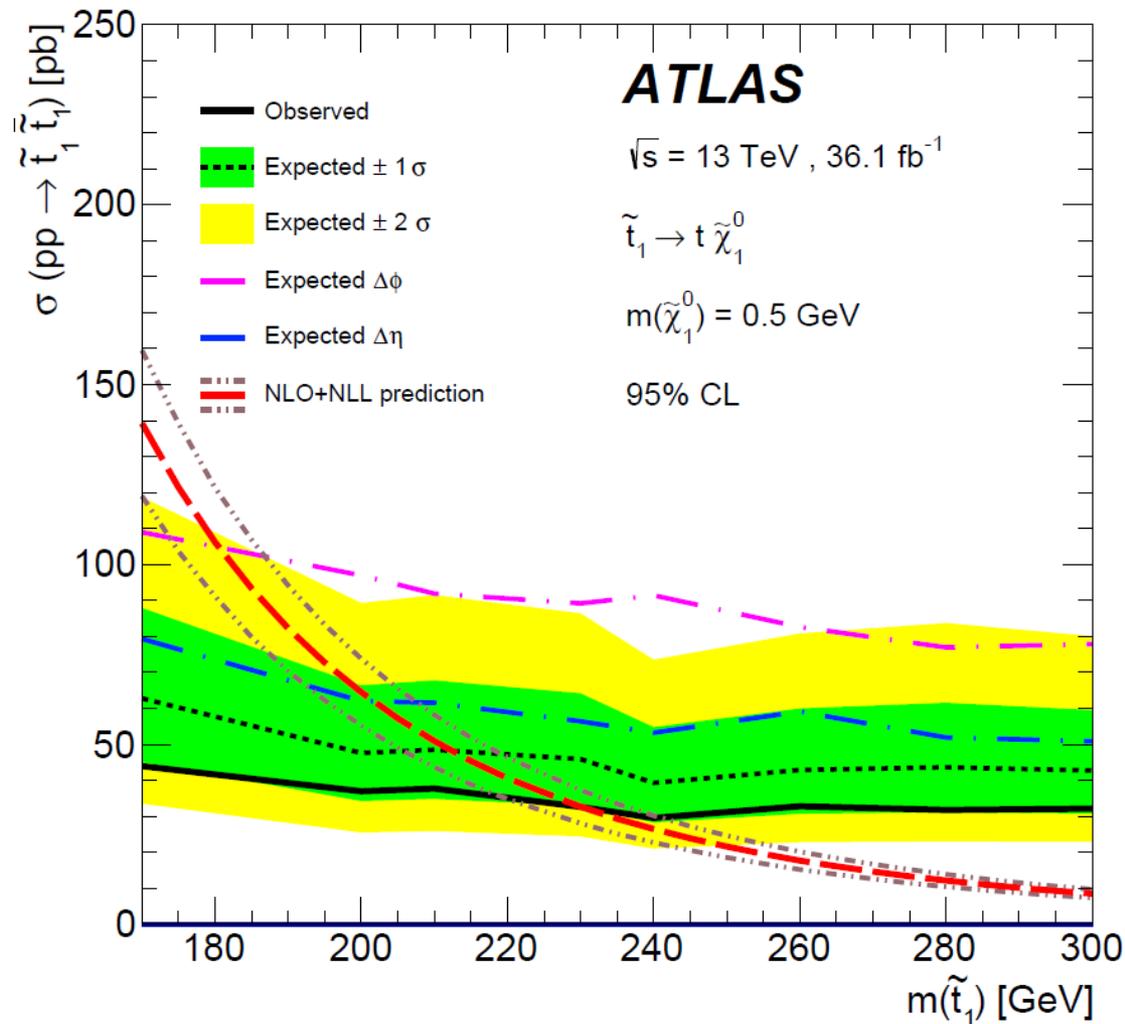
35.9 fb⁻¹ (13 TeV)

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



Motivation

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



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

Motivation

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

Can we do something similar with

$$pp \rightarrow b\bar{b}$$

$$pp \rightarrow c\bar{c}$$

$$pp \rightarrow s\bar{s}$$

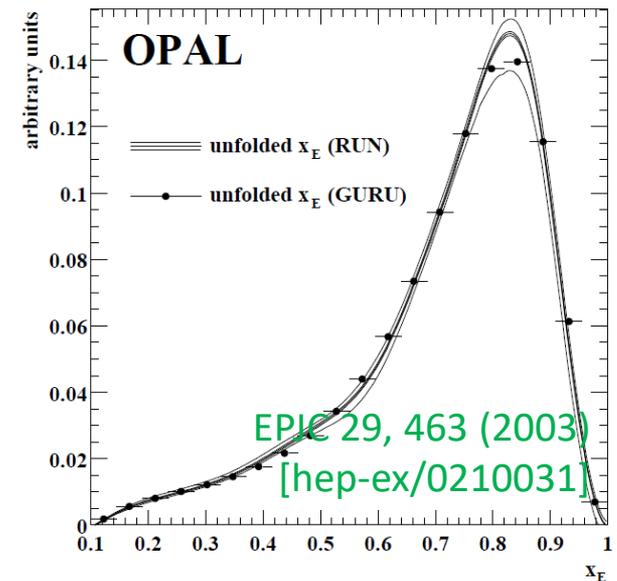
...

?

Heavy quarks (b, c)

For heavy quarks ($m_q \gg \Lambda_{\text{QCD}}$):

- The quark is carried by a very energetic heavy-flavored hadron with a displaced decay.
- When it is a **baryon**, $\mathcal{O}(1)$ fraction of the polarization is expected to be retained.



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

chromomagnetic
moment

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

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

b spin **preserved**
during hadronization

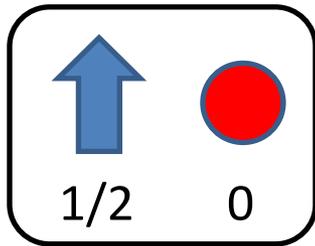
b-quark polarization retention

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

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

b spin **preserved**
during hadronization



b *qq*

$$\Lambda_b$$

b spin **preserved**
also during lifetime

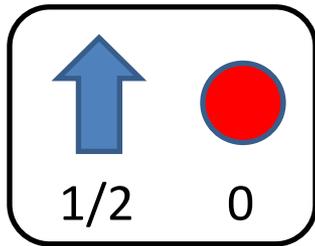
b -quark polarization retention

chromomagnetic
moment

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

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

b spin **preserved**
during hadronization



Λ_b

b spin **preserved**
also during lifetime

b qq

Evidence observed at **LEP** in $Z \rightarrow b\bar{b}$, where $\mathcal{P}(b) \simeq -0.94$.

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

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

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

stat. syst.

Degree of polarization retention

polarization
retention factor

$$r \equiv \frac{\mathcal{P}(\Lambda_q)}{\mathcal{P}(q)} = ?$$

- From a theoretical model:

$$r_L, r_T \sim 0.5$$

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

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

- From combination of LEP measurements of Λ_b in Z decays:

$$r_L = 0.47 \pm 0.14$$

ALEPH Collab., PLB 365, 437 (1996)
DELPHI Collab., PLB 474, 205 (2000)
OPAL Collab., PLB 444, 539 (1998) [hep-ex/9808006]

- Analogous measurements for the b and c quarks can be done in ATLAS/CMS $t\bar{t}$ samples, where these quarks are highly polarized.

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 $c\bar{c}$

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

	$t\bar{t}$, no cuts	$b\bar{b}$, no cuts	$c\bar{c}$, no cuts
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 decays of interest

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

Baryon decays of interest

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

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

Baryon decay angular distributions

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

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

spin analyzing
power
polarization
retention factor
(r_L or r_T)
 $f = \frac{N_{\text{sig}}}{N_{\text{bg}} + N_{\text{sig}}}$
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

- **Data parking:** record the data when bandwidth allows and process it later.
- **Trigger:** muon with a low p_T threshold (7 and 12 GeV) and impact parameter significance.
- Operated during part of Run 2 ($\sim 42 \text{ fb}^{-1}$)
- First papers using this dataset appeared just recently:

Aram Hayrapetyan *et al.* (CMS), “Test of lepton flavor universality in $B^\pm \rightarrow K^\pm \mu^+ \mu^-$ and $B^\pm \rightarrow K^\pm e^+ e^-$ decays in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$,” (2024), [arXiv:2401.07090 \[hep-ex\]](https://arxiv.org/abs/2401.07090).

Aram Hayrapetyan *et al.* (CMS), “Search for long-lived heavy neutrinos in the decays of B mesons produced in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$,” (2024), [arXiv:2403.04584 \[hep-ex\]](https://arxiv.org/abs/2403.04584).

Spin correlations opportunities summary

Quark	Channel	Run 2		HL-LHC
		standard	parked	
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%

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 \[arXiv:1505.02771\]](#)
- Measurements of entanglement and Bell inequalities violation, similar to $t\bar{t}$. [Work in progress with Afik, Muñoz de Nova, Soffer, Uzan.](#)
- Can spin correlations be useful for discovering or characterizing new physics? [Work in progress with Uzan.](#)

Supplemental Slides

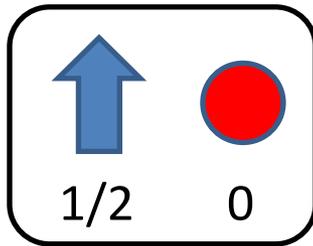
b-quark polarization retention

chromomagnetic
moment

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

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

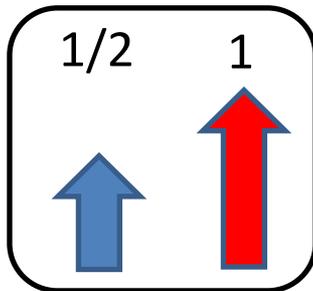
b spin **preserved**
during hadronization



b *qq*

Λ_b

b spin **preserved**
also during lifetime



Σ_b, Σ_b^*

b spin **oscillates**
during lifetime

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

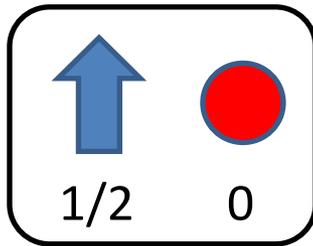
c-quark polarization retention

chromomagnetic
moment

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

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

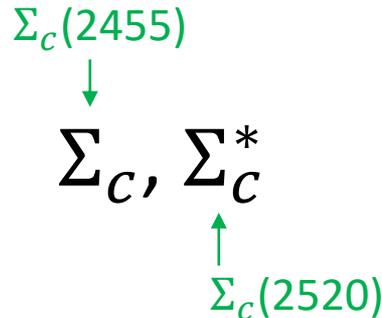
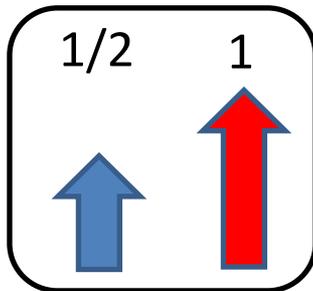
c spin **preserved**
during hadronization



Λ_c

c spin **preserved**
also during lifetime

c *qq*



c spin **oscillates**
during lifetime

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

b -quark polarization retention

Dominant polarization loss effect

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

$$\begin{aligned} |\Lambda_{b,+1/2}\rangle &= |b_{+1/2}\rangle |S_0\rangle \\ |\Sigma_{b,+1/2}\rangle &= -\sqrt{\frac{1}{3}} |b_{+1/2}\rangle |T_0\rangle + \sqrt{\frac{2}{3}} |b_{-1/2}\rangle |T_{+1}\rangle \\ |\Sigma_{b,+1/2}^*\rangle &= \sqrt{\frac{2}{3}} |b_{+1/2}\rangle |T_0\rangle + \sqrt{\frac{1}{3}} |b_{-1/2}\rangle |T_{+1}\rangle \\ |\Sigma_{b,+3/2}^*\rangle &= |b_{+1/2}\rangle |T_{+1}\rangle \end{aligned}$$

Production as a b spin eigenstate.

Decay as a Σ_b or Σ_b^* mass eigenstate.

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

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

“diquarks”

S	T
spin-0	spin-1
isosinglet	isotriplet

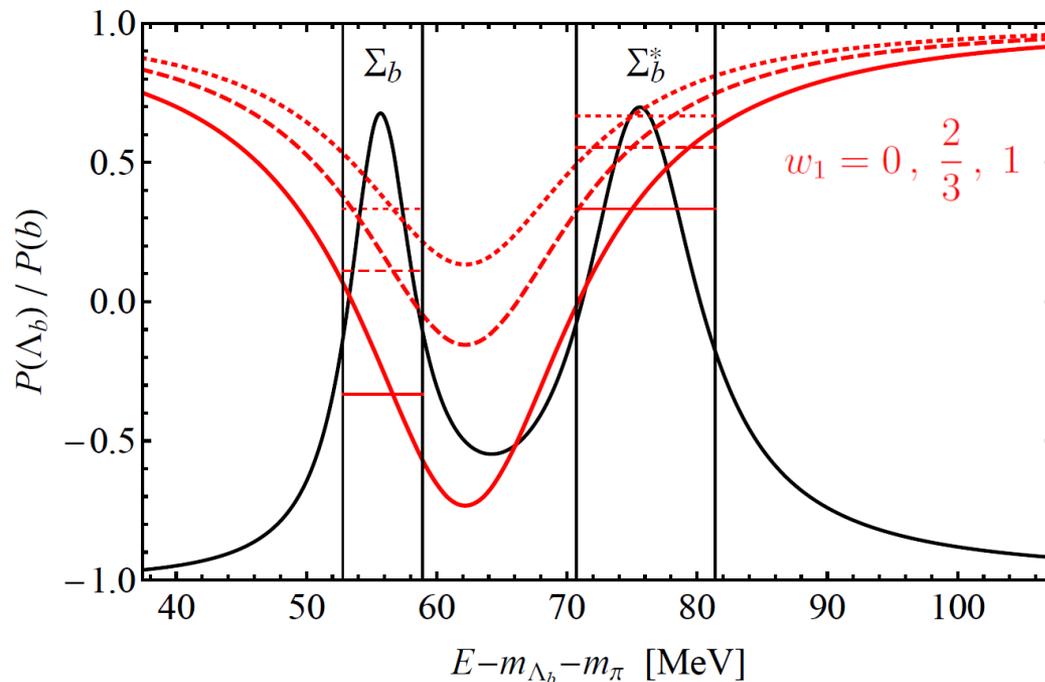
$$A = \frac{\text{prob}(\Sigma_b^{(*)})}{\text{prob}(\Lambda_b)} = 9 \frac{\text{prob}(T)}{\text{prob}(S)}$$

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

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

b -quark polarization retention

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



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

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

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

b -quark polarization retention

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

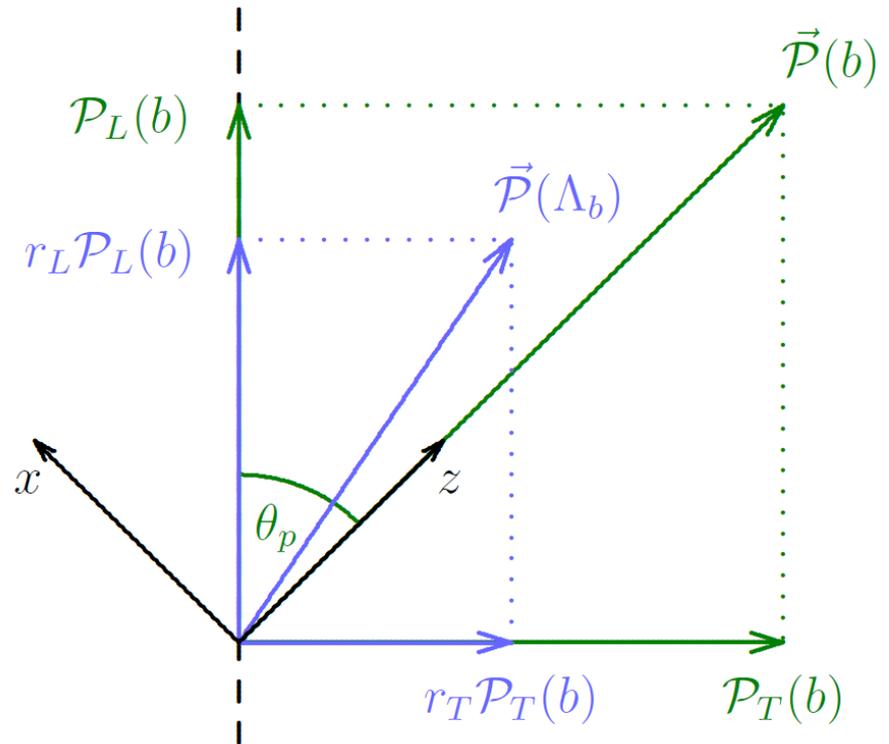
$$r_T \approx \frac{1 + (0.62 - 0.19w_1)A}{1 + A}$$

Directional dependence, since

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

holds along the fragmentation axis.

fragmentation axis
(direction of motion)



Heavy quark polarization retention

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

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

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

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

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

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) **CLEO (CESR)** $w_1 = 0.71 \pm 0.13$ (c)
PLB 379, 292 (1996) 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

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

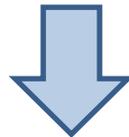
$$A = \frac{\text{prob}(\Sigma_b^{(*)})}{\text{prob}(\Lambda_b)} = 9 \frac{\text{prob}(T)}{\text{prob}(S)}$$

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

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

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

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

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

- $t \rightarrow W^+ b$ produces polarized b quarks.
 $\hookrightarrow c\bar{s}$ produces polarized c 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 and c jets.
- Statistics in Run 2 is as large as in Z decays at LEP.
- Run 2 data allows measuring r_L with $O(10\%)$ precision for both b and c .

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

Selection for $b\bar{b}$ analysis

- ❑ Pair of opposite-sign muons (inside jets) satisfying the offline trigger cuts and carrying $> 20\%$ of the jet momentum.
- ❑ At least one of the jets is “ b tagged” (with assumed efficiency 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 $\Lambda \rightarrow p\pi^-$ coming from the b vertex
(significant cost in efficiency because the Λ decays far)

Exclusive demand a fully-reconstructible Λ_c decay

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

Selection for $b\bar{b}$ analysis

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

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

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

channel \rightarrow	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 \rightarrow	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 \rightarrow	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
trigger	$r_i \Delta b_i^\pm$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
standard	0.003	0.14	0.10
parked	0.0003	0.039	0.027

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

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

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

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

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

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

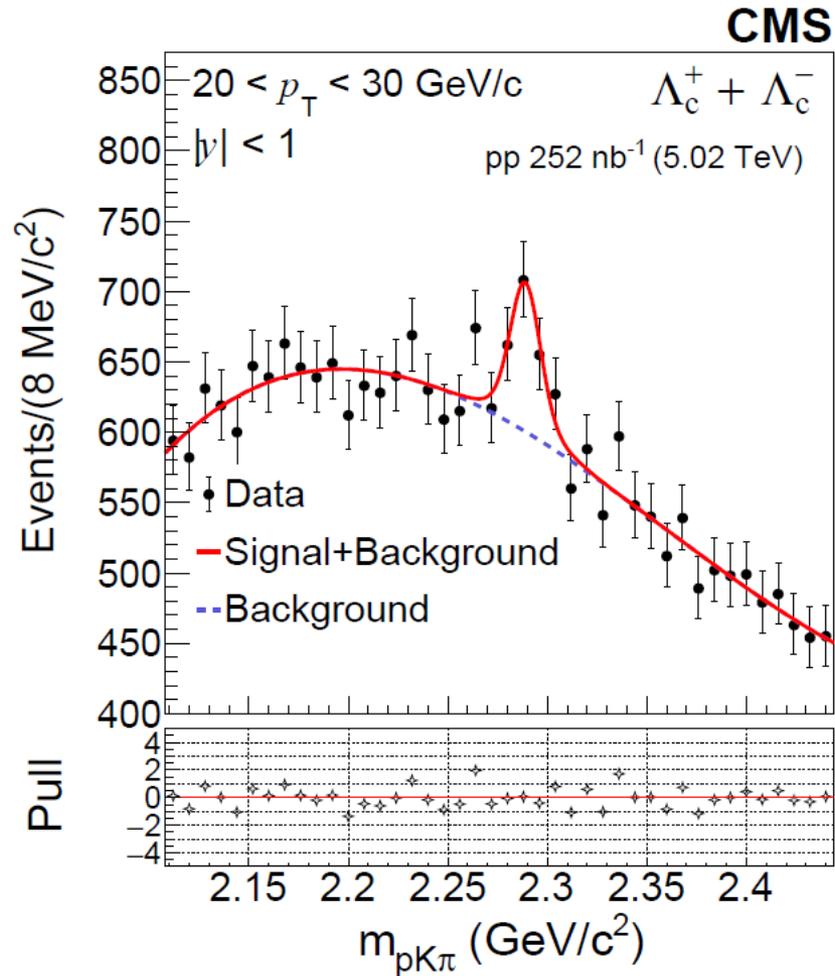
Hadronic selection for $c\bar{c}$ analysis

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

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

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

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



CMS Collaboration
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[arXiv:2307.11186]

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

- ❑ Pair of opposite-sign muons (inside jets) satisfying the offline trigger cuts.
- ❑ $\Lambda \rightarrow p\pi^-$ 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

Statistical uncertainties

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

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

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

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

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

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

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

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

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

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

Statistical uncertainties

Dependence on the value of the coefficient:

