Ben-Gurion University
of the Negev

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Prospects for Measuring Quark Polarization and Spin Correlations in $b\bar{b}$ and $c\bar{c}$ samples at the LHC

David Uzan & Yevgeny Kats

arXiv:2311.08226, JHEP03(2024)063

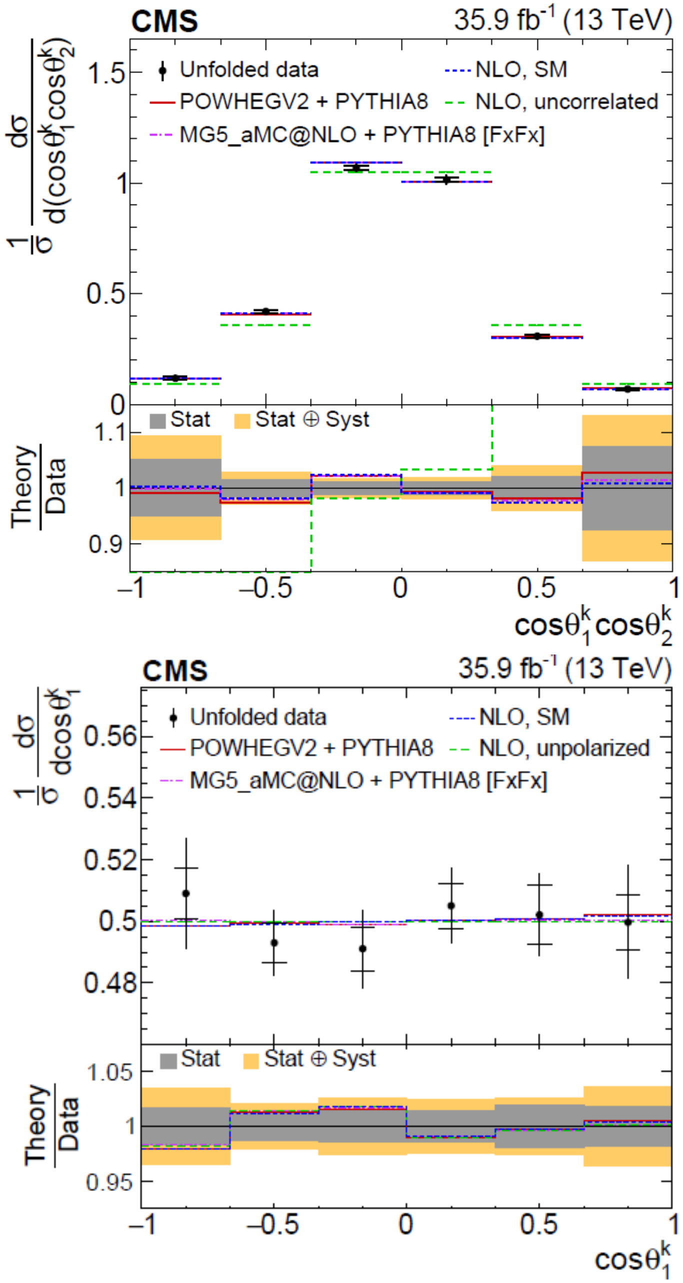
Motivation

CMS and ATLAS measured the polarization and spin correlations in top pair production $pp \rightarrow t\bar{t}$.

The spin density matrix for t and $\bar{t}$:

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

Can we conduct similar measurements for the **other quarks**?



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

Simulated Quark Spin Correlations

MadGraph and MadSpin simulation of t, b and c.

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

$\{\hat{k}, \hat{n}, \hat{r}\}$ set of orthonormal axes defined in the $q\bar{q}$ CM frame.

	$t\bar{t}$, 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

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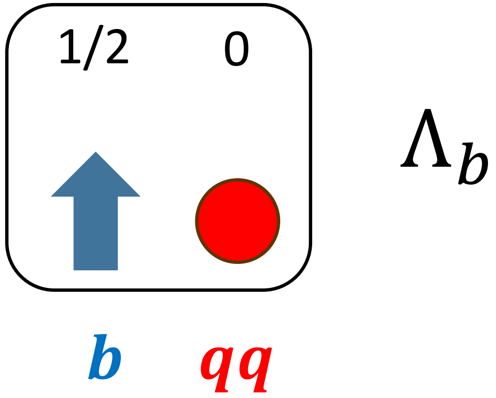
$\{\hat{k}, \hat{n}, \hat{r}\}$ set of orthonormal axes defined in the $q\bar{q}$ CM frame.

	$t\bar{t}$, 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

Measuring Polarization and Spin Correlations

For non-top quarks, we use baryons (Λ_q).

$$\mu_q \propto \frac{1}{m_q}, \qquad m_q \gg \Lambda_{\text{QCD}}$$



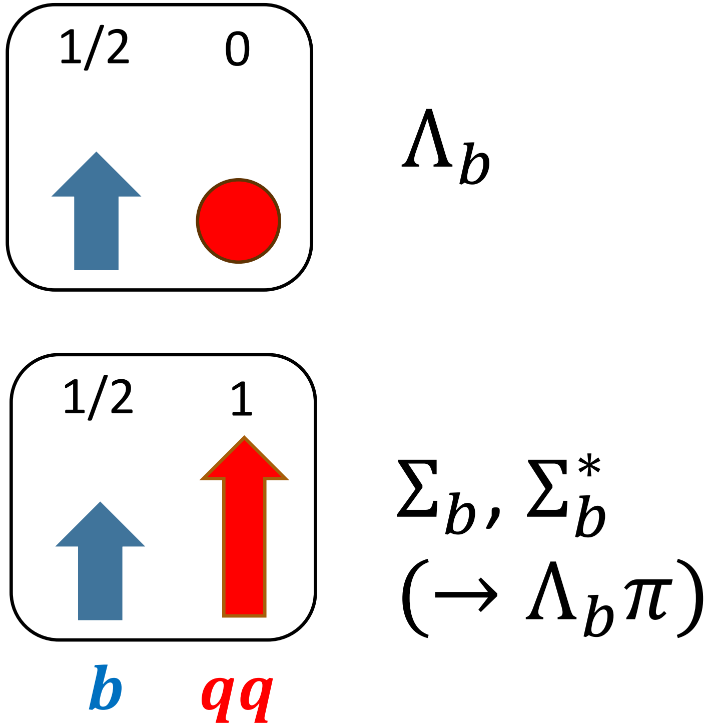
Measuring Polarization and Spin Correlations

For non-top quarks, we use baryons (Λ_q).

$$\mu_q \propto \frac{1}{m_q}, \qquad m_q \gg \Lambda_{\text{QCD}}$$

Some loss during hadronization:

$$r_{T/L} = \frac{\mathcal{P}_{T/L}(\Lambda_q)}{\mathcal{P}_{T/L}(q)} \sim 0.5$$



Polarization retention factor. Depends on the direction (transverse or longitudinal).

Falk and Peskin, PRD 49 , 3320 (1994) [hep-ph/9308241]
Galanti, Giammanco, Grossman, Kats, Stamou, Zupan, JHEP 11 (2015) 067 [1505.02771]

Baryon Decay Angular Distributions

Using θ_i, the decay product angle in relation to one of the axes $\{\hat{k}, \hat{n}, \hat{r}\}$:

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

$$B_i^\pm = \alpha_\pm \; r_i \; f b_i^\pm$$

Spin analyzing power

Polarization retention factor (r_T or r_L)

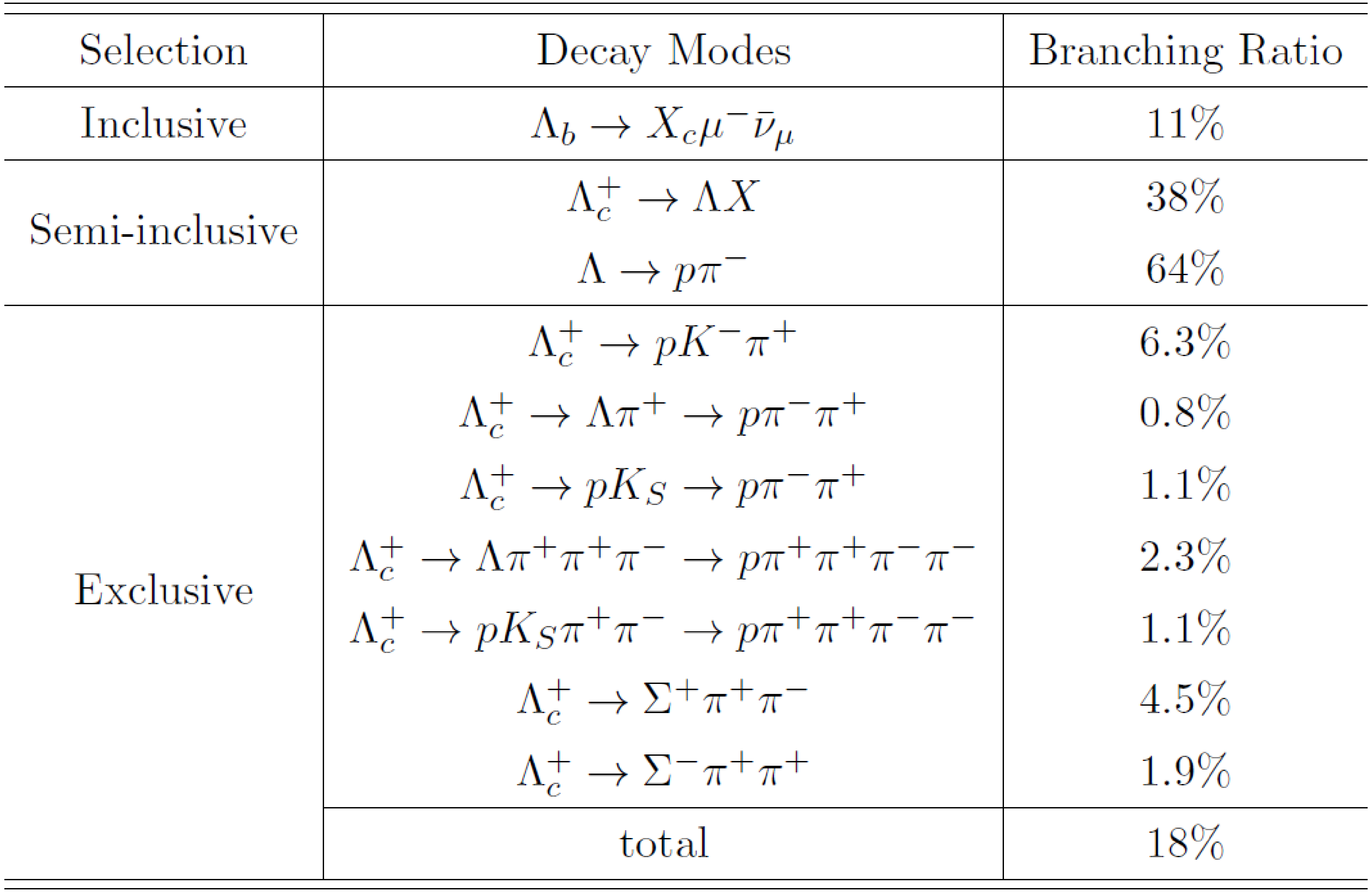
$$f = \frac{N_{sig}}{N_{sig} + N_{bg}}$$

Sample Purity

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

$$C_{ij} = \alpha_+ \alpha_- r_i r_j f c_{ij}$$

Bottom Channel $\Lambda_b \to \mu^- \bar{\nu}_\nu X_c$



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%

Trigger Motivated Cuts

ATLAS Dimuon Triggers:

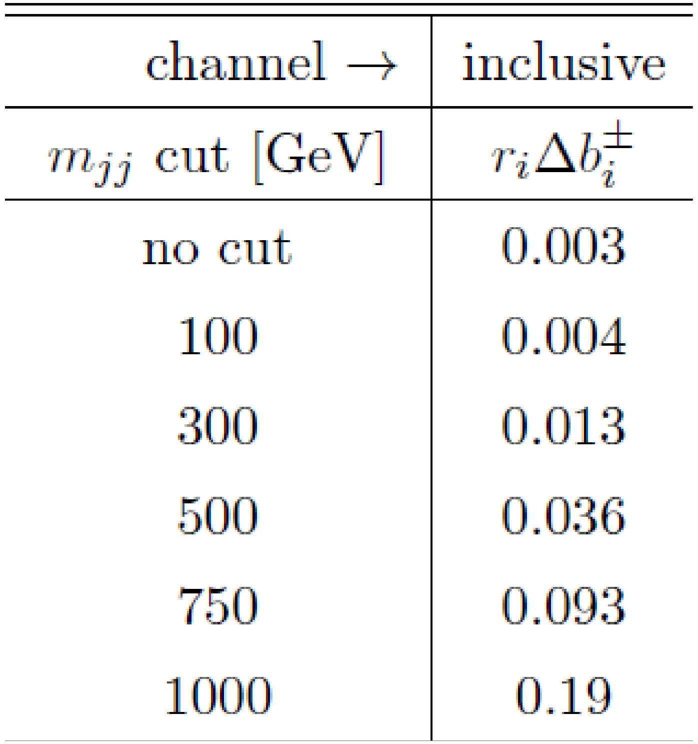
Dimuon trigger motivated cuts: $p_T^\mu > 15$ GeV without isolation and $|\eta| < 2.4$.

CMS Parked Data:

Recorded CMS data during Run 2 ($\sim$ 42 fb^{-1}) to be processed later.
CMS collaboration, arXiv:2403.16134

- Single muon trigger.
- Lower specialized trigger p_T cuts, between 7 and 12 GeV.
- Transverse impact parameter significance cut.

Expected Statistical Uncertainties for Run 2 Data

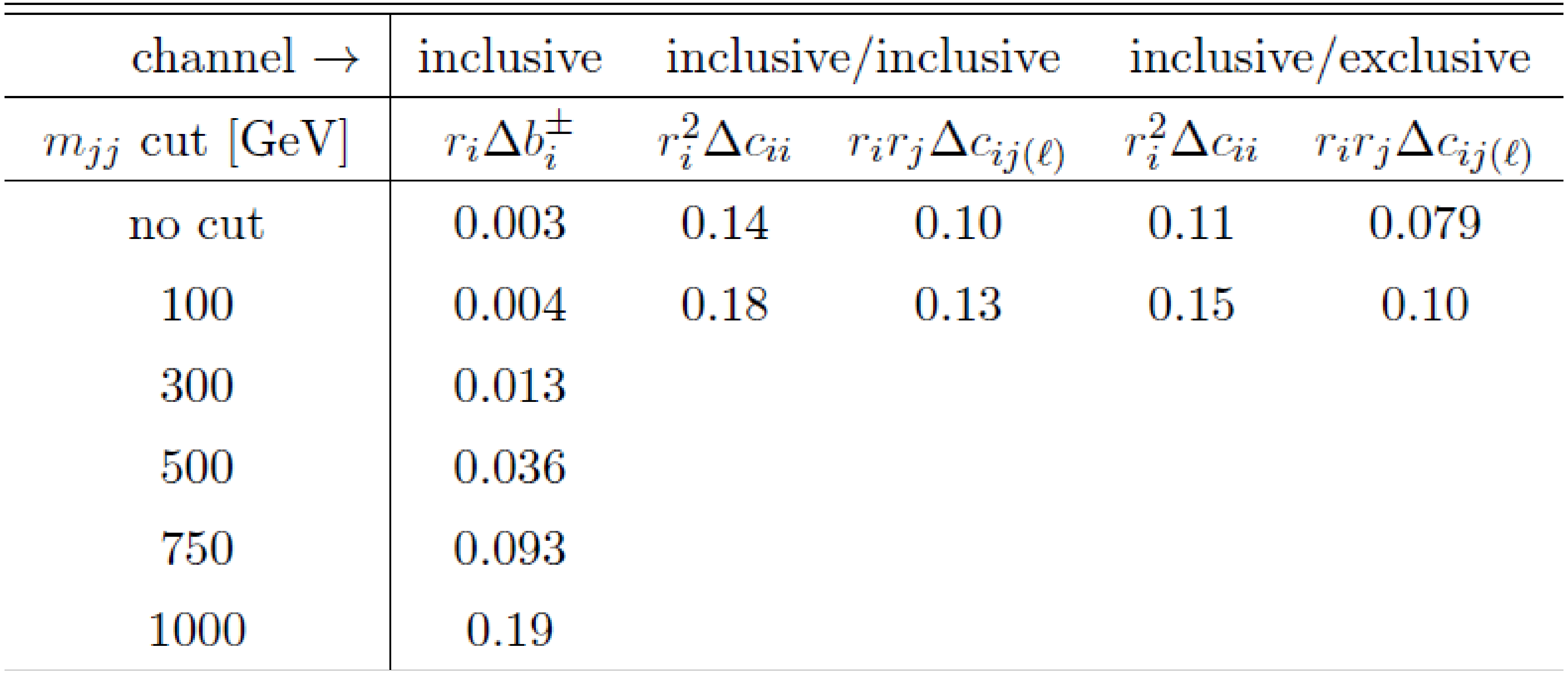


channel →	inclusive
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$
no cut	0.003
100	0.004
300	0.013
500	0.036
750	0.093
1000	0.19

Polarization and spin correlations range: $[-1,1]$.

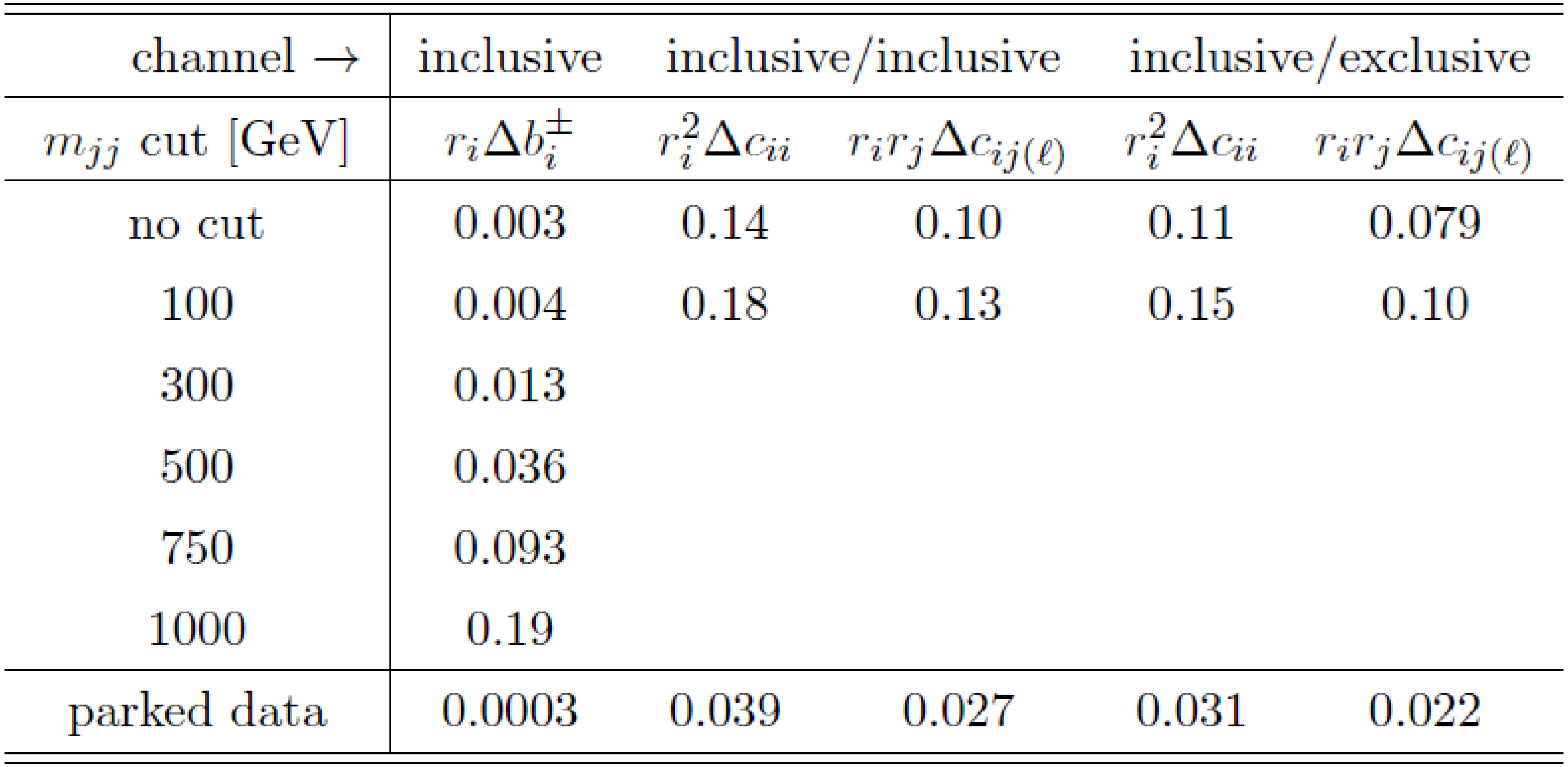
Simulated using Pythia8 + MadGraph.

Expected Statistical Uncertainties for Run 2 Data



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	0.003	0.14	0.10	0.11	0.079
100	0.004	0.18	0.13	0.15	0.10
300	0.013				
500	0.036				
750	0.093				
1000	0.19				

Expected Statistical Uncertainties for Run 2 Data

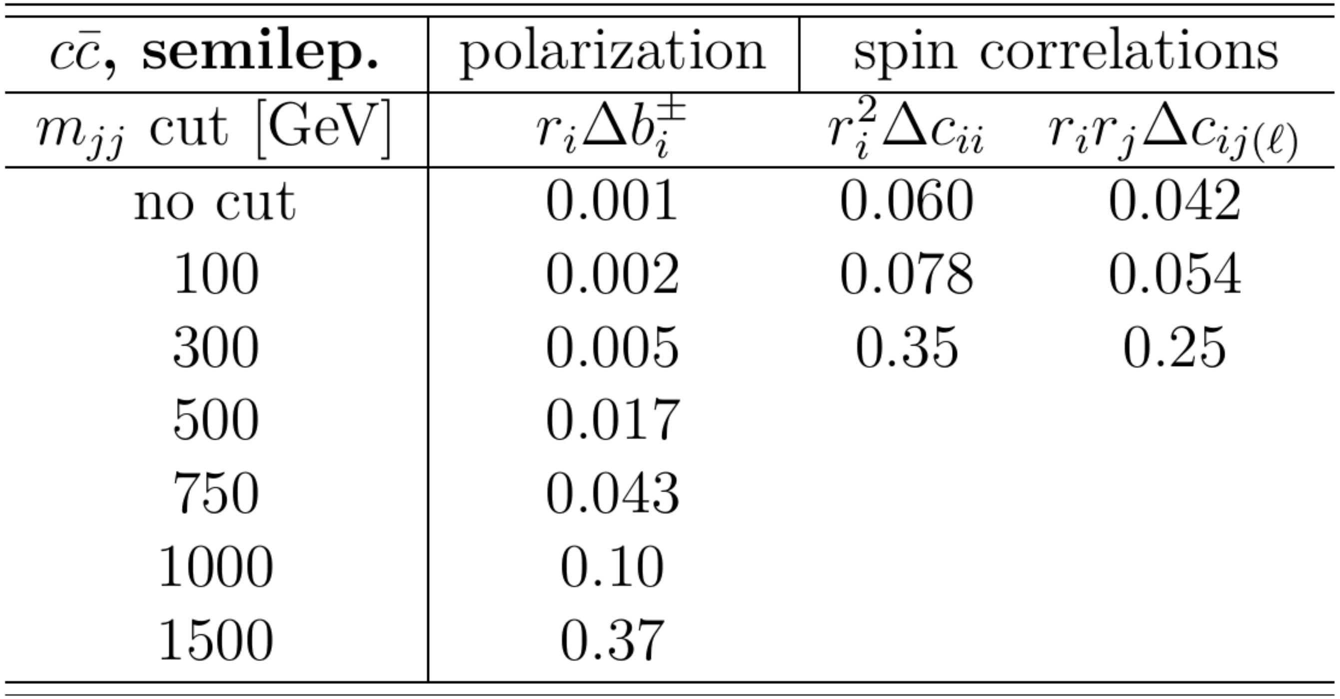


channel →	inclusive	inclusive/inclusive		inclusive/exclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.003	0.14	0.10	0.11	0.079
100	0.004	0.18	0.13	0.15	0.10
300	0.013				
500	0.036				
750	0.093				
1000	0.19				
parked data	0.0003	0.039	0.027	0.031	0.022

Spin correlations can be measured in Run 2.

Charm Channel $\Lambda_c^+ \to \mu^+\nu_\mu\Lambda(\to p\pi^-)$

HL-LHC (3000 fb^{-1}) results:



$c\bar{c}$, **semilep.**	polarization	spin correlations	
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	0.001	0.060	0.042
100	0.002	0.078	0.054
300	0.005	0.35	0.25
500	0.017		
750	0.043		
1000	0.10		
1500	0.37		

Spin correlations will be measurable at the HL-LHC.

Polarization Retention Factor Measurement

Using the measured values ($B_i,\ C_{ij}$) and the partonic predictions ($b_i,\ c_{ij}$):

$$r_i = \frac{B_i}{b_i \alpha f}$$

$$r_i^2 = \frac{C_{ii}}{c_{ii}\alpha^2 f}, \qquad r_i r_j = \frac{C_{ij} \pm C_{ji}}{2c_{k(ij)}\alpha_+ \alpha_- f}$$

Can lead to information on QCD polarization transfer in fragmentation.

Entanglement and Bell's Inequality, $\boldsymbol{pp \to b\bar{b}}$

$$\Delta = \frac{-C_{nn} + |C_{kk} + C_{rr}| - 1}{2}$$

$$\mathcal{V} = C_{kk}^2 + C_{rr}^2 - 1$$

Entanglement measurement is possible in Run 2 (ATLAS, CMS and LHCb).

Bell's inequality will be possible at the HL-LHC.

Afik, Kats, Muñoz de Nova, Soffer, Uzan, arXiv:2406.04402

Conclusions & Future work

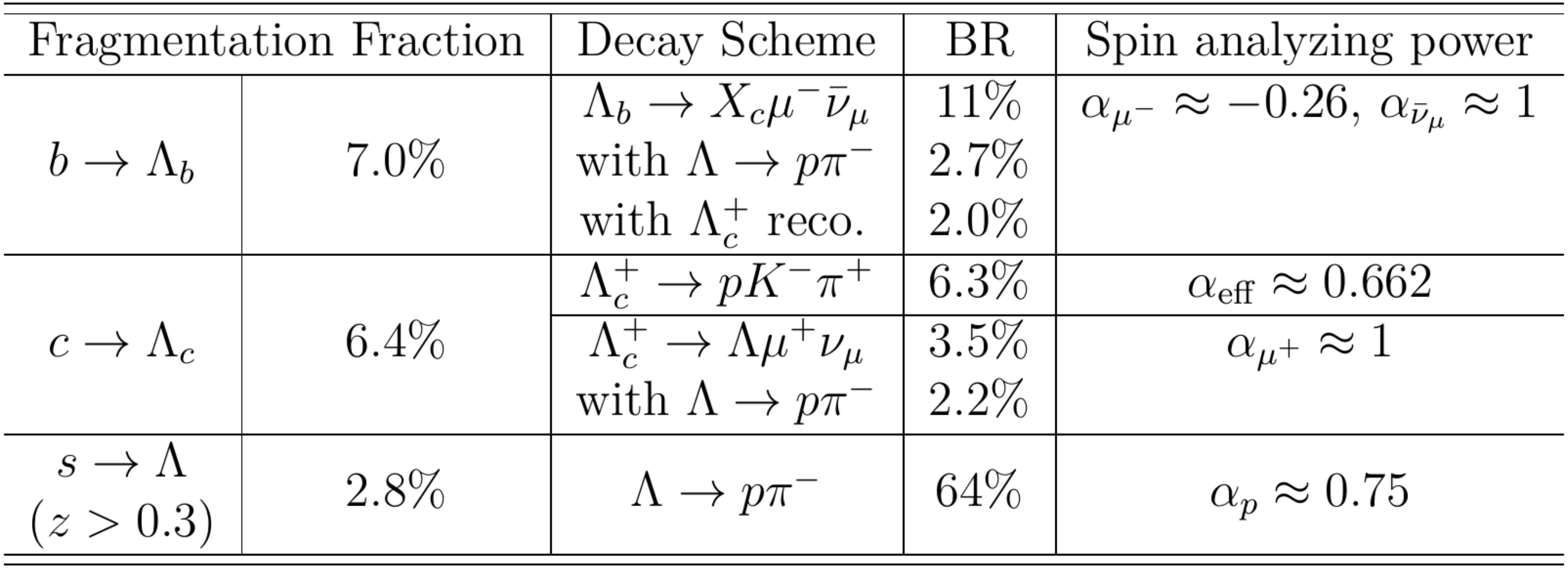
- We showed that there is merit to measuring polarization and spin correlations in di-jet events for the heavy quarks.
- There is enough statistics already in Run 2 for polarization measurements in b and c.
- We can measure spin correlations in Run 2 using parked data for b.
- We will be able to measure spin correlations of c with HL-LHC.
- We proposed that using the measured spin correlations we can extract $r_{T/L}$.
- The spin correlations can be used as a probe for entanglement (**arxiv:2406.04402**) and BSM physics.

Thank you!

Supplemental Material

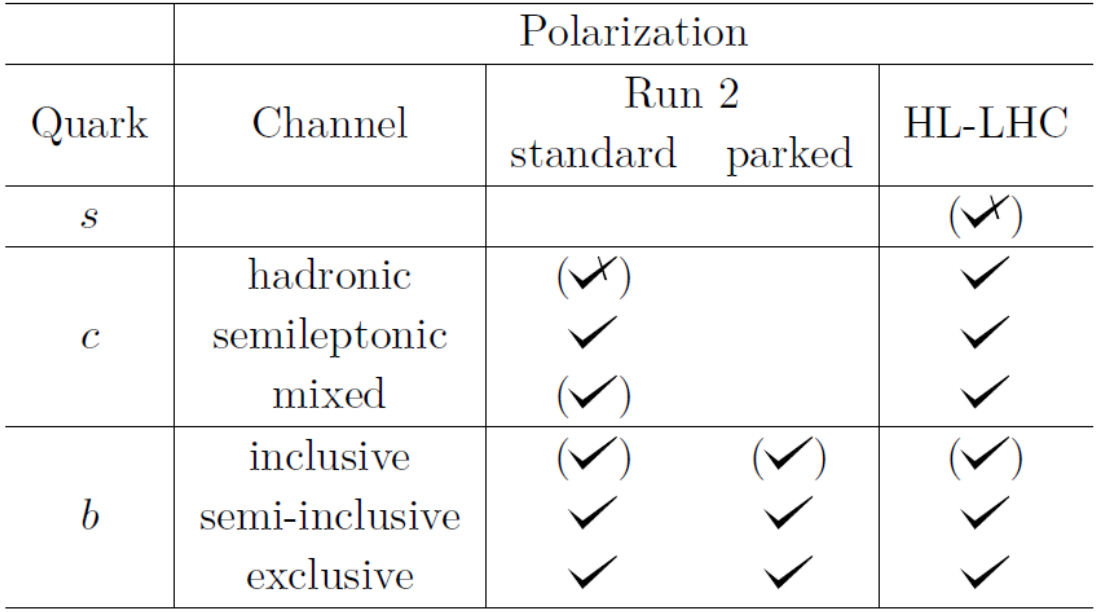
Heavy Quark Decay Chain

We decided to look into four decay chains:

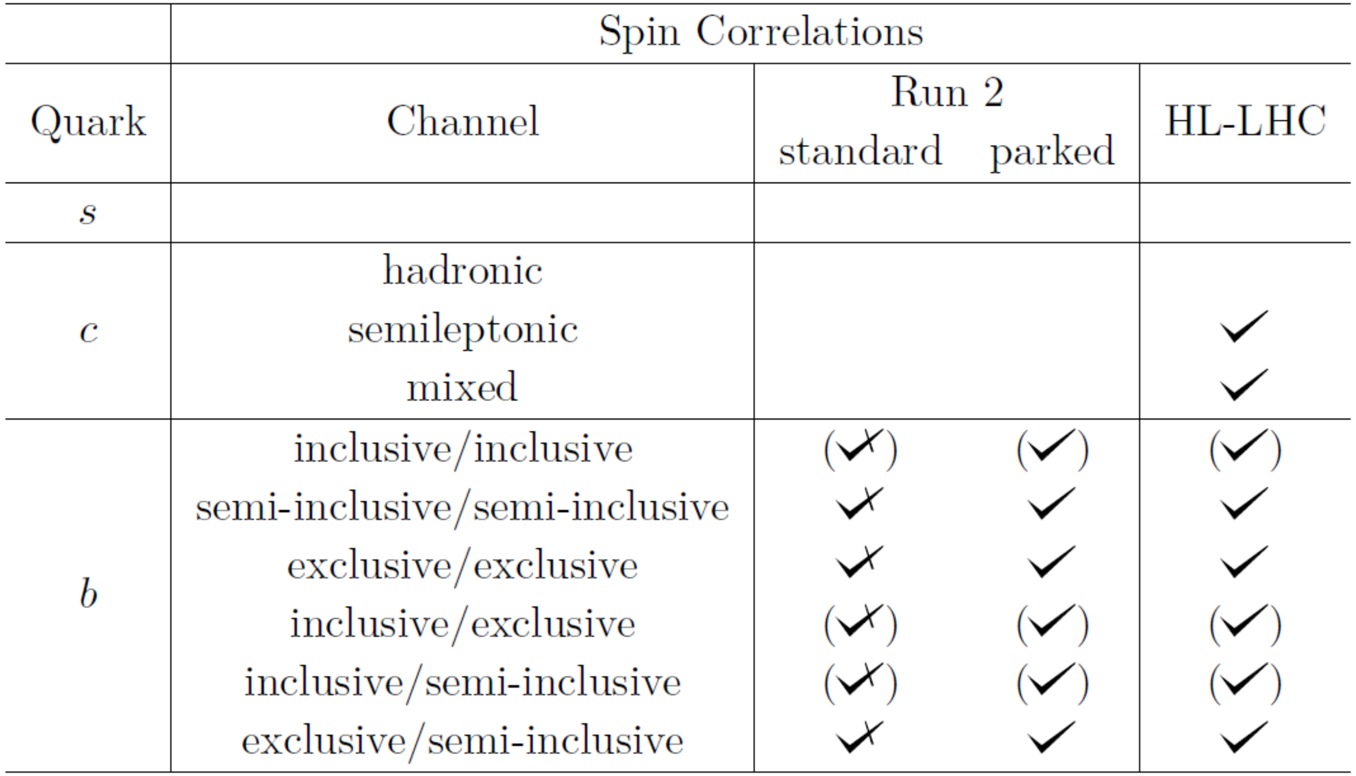


Fragmentation Fraction		Decay Scheme	BR	Spin analyzing power
$b \to \Lambda_b$	7.0%	$\Lambda_b \to X_c \mu^- \bar{\nu}_\mu$	11%	$\alpha_{\mu^-} \approx -0.26,\ \alpha_{\bar{\nu}_\mu} \approx 1$
		with $\Lambda \to p\pi^-$	2.7%	
		with Λ_c^+ reco.	2.0%	
$c \to \Lambda_c$	6.4%	$\Lambda_c^+ \to pK^-\pi^+$	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%	
$s \to \Lambda$ $(z > 0.3)$	2.8%	$\Lambda \to p\pi^-$	64%	$\alpha_p \approx 0.75$

Prospects for All Channels Examined



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



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

Density Matrix

The most general case for spin-1/2:

$$R \propto \tilde{A}\mathbb{1} \otimes \mathbb{1} + \tilde{B}_i^{+}\sigma^i \otimes \mathbb{1} + \tilde{B}_i^{-}\mathbb{1} \otimes \sigma^i + \tilde{C}_{ij}\sigma^i \otimes \sigma^j$$

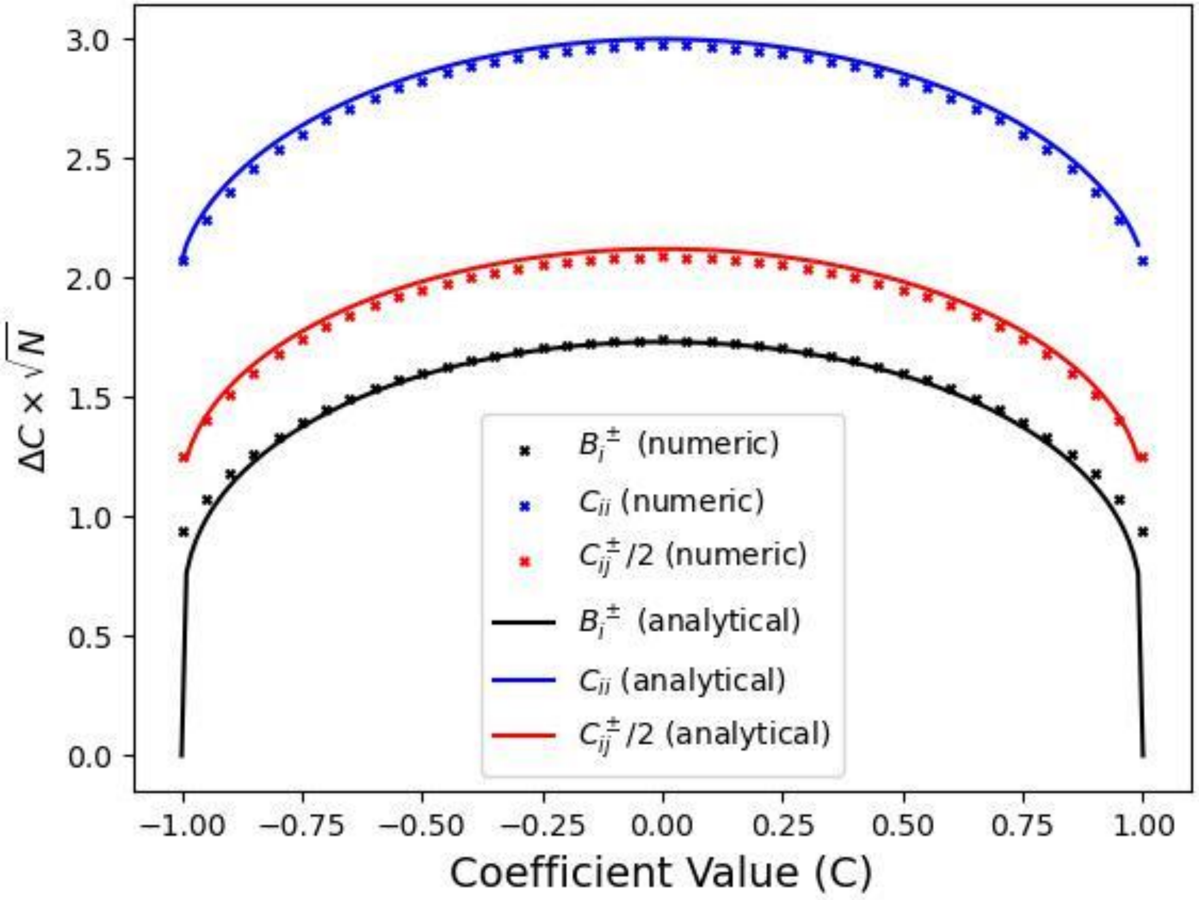
where $\tilde{A}$ determines the total cross section and kinematics, $\widetilde{\boldsymbol{B}}^{\pm}$ are three-dimensional vectors characterizing the polarization, and $\widetilde{\boldsymbol{C}}$ is a 3×3 matrix characterizing the spin correlations.

Statitical Uncertainty of Polarization and Spin Correlations

$$\Delta b_i = \frac{A_B}{r_i \alpha \sqrt{f N_{sig}}}$$

$$\Delta c_{ii} = \frac{A_{c_{ii}}}{r_i^2 \alpha^2 \sqrt{f N_{sig}}}$$

$$\Delta c_{k(ij)} = \frac{A_{c_{ij}}}{r_i r_j \alpha^2 \sqrt{f N_{sig}}}$$



Spin Measurement through Mesons

Mesons can’t be used for spin measurements.

$$|\downarrow\rangle_b|\downarrow\rangle_{\bar{q}}, \qquad |\downarrow\rangle_b|\uparrow\rangle_{\bar{q}}$$

For B^* meson, where $\frac{1}{2}\otimes\frac{1}{2}=0\oplus 1=\mathrm{B}\oplus\mathrm{B}^*$:

$$P\left(\bar{B}^*(-1)\right)=\frac{1}{2}, \qquad P\left(\bar{B}^*(0)\right)=\frac{1}{4}, \qquad P\left(\bar{B}^*(1)\right)=0, \qquad P\left(B(0)\right)=\frac{1}{4}$$

$$B^*\to B\gamma$$

We get uniform angular distribution, no information of the spin of the b quark.

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

Spin Measurement through Baryons

For the baryons the spin is retained:

$$|\downarrow\rangle_b|\downarrow\rangle_q|\downarrow\rangle_{q'}, \qquad |\downarrow\rangle_b|\downarrow\rangle_q|\uparrow\rangle_{q'}, \qquad |\downarrow\rangle_b|\uparrow\rangle_q|\downarrow\rangle_{q'}, \qquad |\downarrow\rangle_b|\uparrow\rangle_q|\uparrow\rangle_{q'}$$

$$\left(\frac{1}{2}\right)_b \otimes \left(\frac{1}{2}\right)_q \otimes \left(\frac{1}{2}\right)_{q'} = \frac{1}{2} \otimes (1 \oplus 0) = \underset{\boldsymbol{\Lambda_b}}{\frac{1}{2}} \oplus \underset{\boldsymbol{\Sigma_b}}{\frac{1}{2}} \oplus \underset{\boldsymbol{\Sigma_b^*}}{\frac{3}{2}}$$

We lose polarization information in hadronization through indirect Λ_b production:

$$b \rightarrow \Sigma_b, \Sigma_b^*, \Lambda_b, \qquad \Sigma_b^{(*)} \rightarrow \Lambda_b \pi$$

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

Energy and Momentum Reconstruction

Energy and momentum reconstruction in the b channel:

$$E_{\Lambda_b} = \langle z \rangle E_b = E_{X_c\mu} + \mathrm{E}_\nu$$

The term E'_{jet} is the jet energy with subtraction from all tracks originating in the primary vertex:

$$E_{X_c\mu} = \frac{3\langle z \rangle E'_{jet} - (1 - \langle z \rangle)E_\nu}{1 + 2\langle z \rangle} \approx \frac{3\langle z \rangle}{2\langle z \rangle + 1} E'_{jet}$$

The second term in the numerator is an order of magnitude lower than that of the jet.

Energy and Momentum Reconstruction

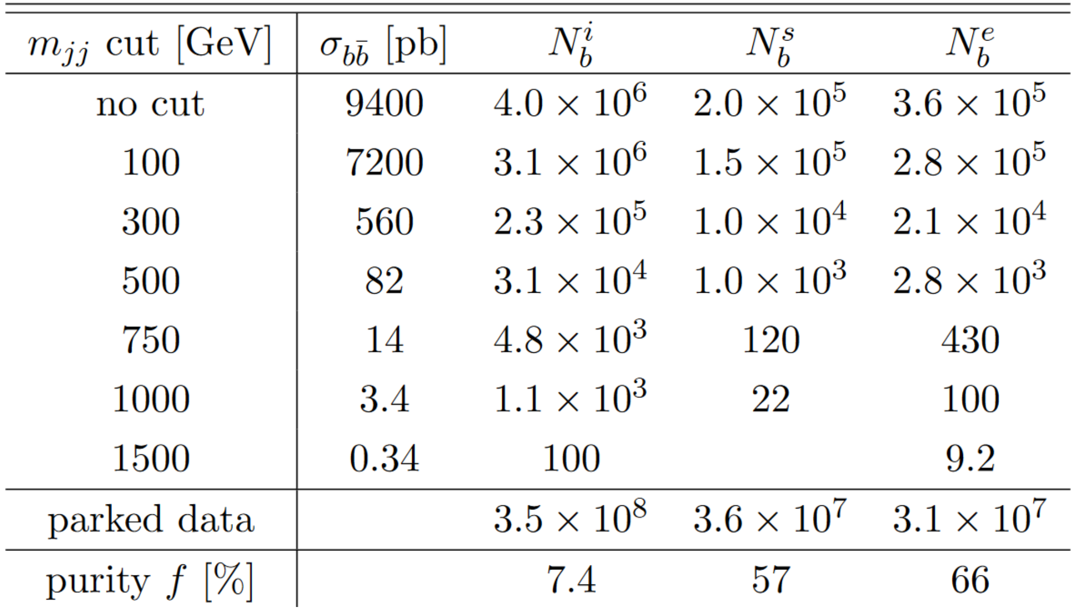
We can get the momentum of the neutrino through:

$$P_\nu^\perp = -P_\perp, \qquad P_\nu^\parallel = -a \pm \sqrt{b}$$

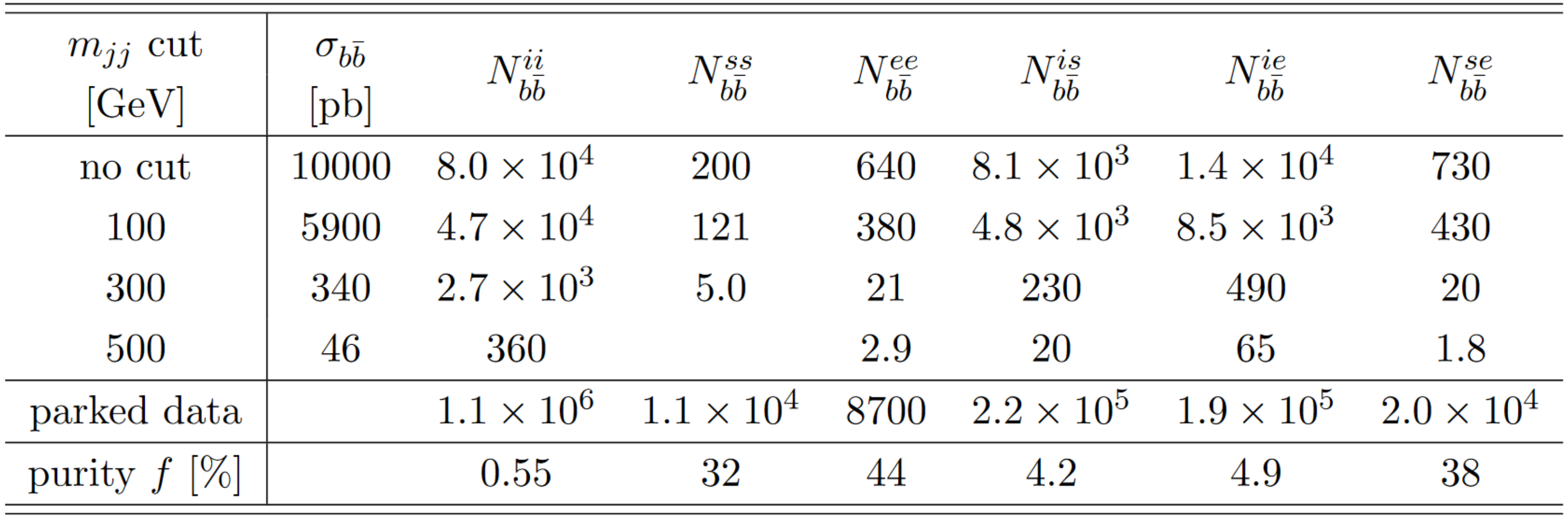
where:

$$a = \frac{\left(m_{\Lambda_b}^2 - m^2 - 2P_\perp^2\right)P_\parallel}{2(P_\parallel^2 - E^2)}, \qquad b = \frac{\left(m_{\Lambda_b}^2 - m^2 - 2P_\perp^2\right)E^2}{4(P_\parallel^2 - E^2)} + \frac{E^2 P_\perp^2}{P_\parallel^2 - E^2}$$

Expected Number of Events for $b\bar{b}$ in Run 2

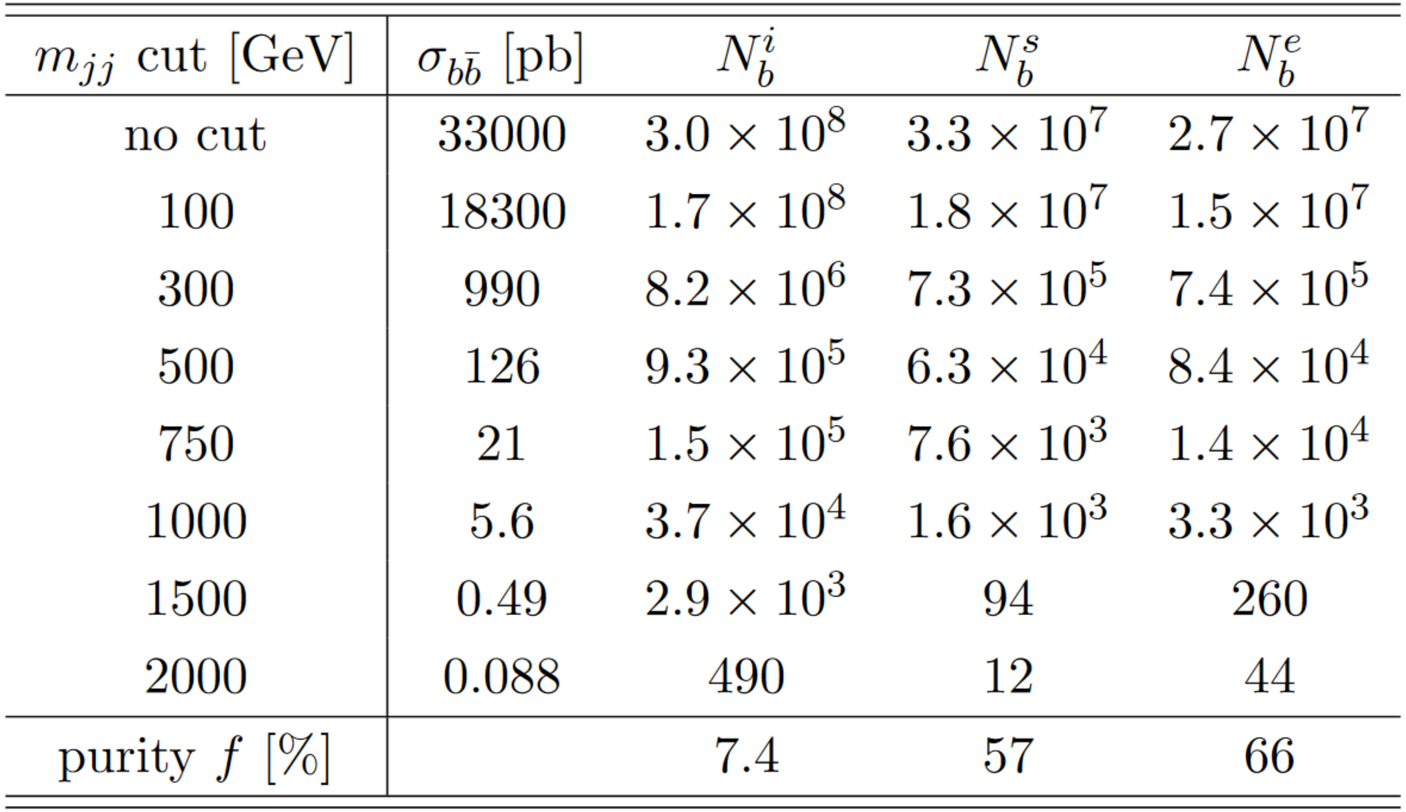


m_{jj} cut [GeV]	$\sigma_{b\bar{b}}$ [pb]	N_b^i	N_b^s	N_b^e
no cut	9400	4.0×10^6	2.0×10^5	3.6×10^5
100	7200	3.1×10^6	1.5×10^5	2.8×10^5
300	560	2.3×10^5	1.0×10^4	2.1×10^4
500	82	3.1×10^4	1.0×10^3	2.8×10^3
750	14	4.8×10^3	120	430
1000	3.4	1.1×10^3	22	100
1500	0.34	100		9.2
parked data		3.5×10^8	3.6×10^7	3.1×10^7
purity f [%]		7.4	57	66



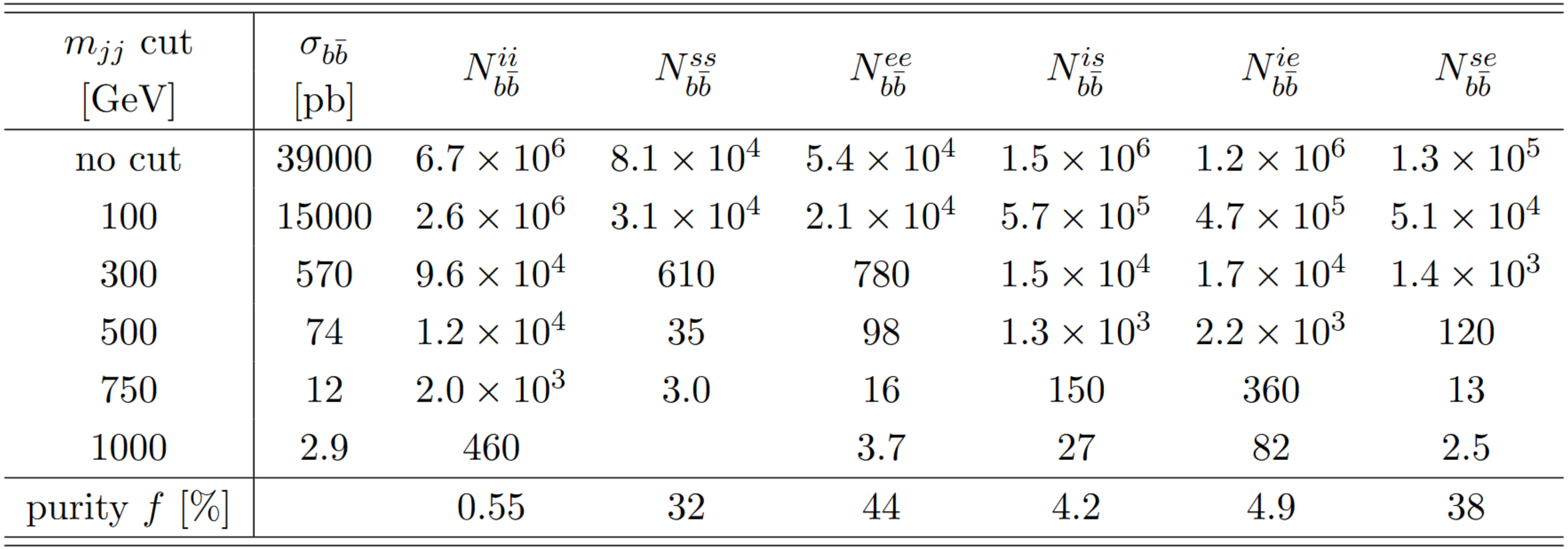
m_{jj} cut [GeV]	$\sigma_{b\bar{b}}$ [pb]	$N_{b\bar{b}}^{ii}$	$N_{b\bar{b}}^{ss}$	$N_{b\bar{b}}^{ee}$	$N_{b\bar{b}}^{is}$	$N_{b\bar{b}}^{ie}$	$N_{b\bar{b}}^{se}$
no cut	10000	8.0×10^4	200	640	8.1×10^3	1.4×10^4	730
100	5900	4.7×10^4	121	380	4.8×10^3	8.5×10^3	430
300	340	2.7×10^3	5.0	21	230	490	20
500	46	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

Expected Number of Polarization Events for $b\bar{b}$ in HL-LHC



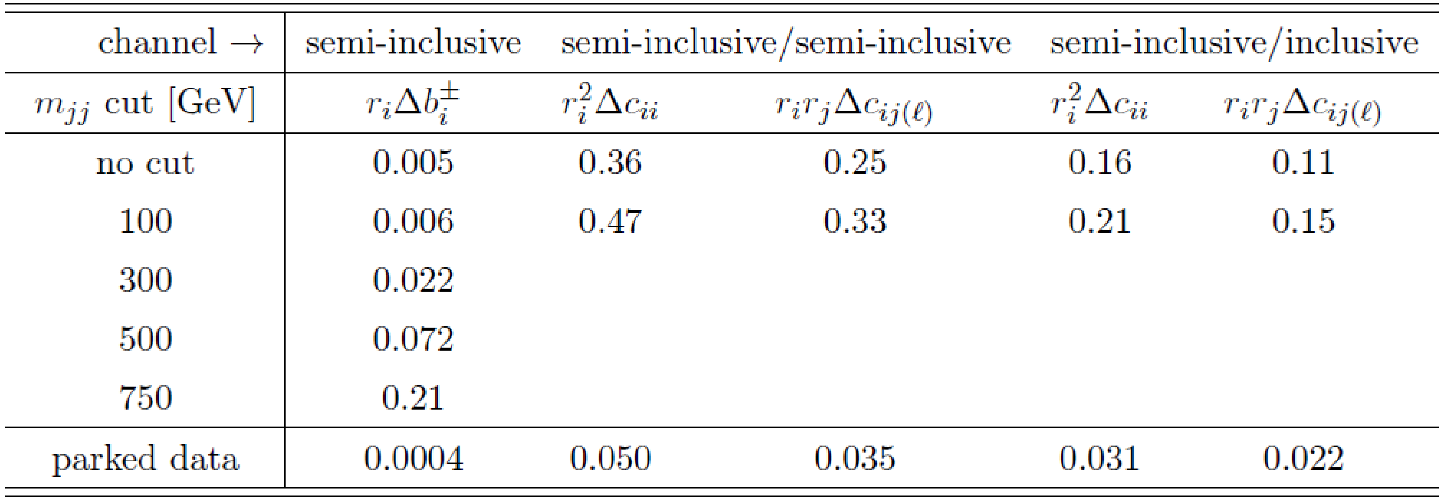
m_{jj} cut [GeV]	$\sigma_{b\bar{b}}$ [pb]	N_b^i	N_b^s	N_b^e
no cut	33000	3.0×10^8	3.3×10^7	2.7×10^7
100	18300	1.7×10^8	1.8×10^7	1.5×10^7
300	990	8.2×10^6	7.3×10^5	7.4×10^5
500	126	9.3×10^5	6.3×10^4	8.4×10^4
750	21	1.5×10^5	7.6×10^3	1.4×10^4
1000	5.6	3.7×10^4	1.6×10^3	3.3×10^3
1500	0.49	2.9×10^3	94	260
2000	0.088	490	12	44
purity f [%]		7.4	57	66

Expected Number of Spin Correlations Events for $b\bar{b}$ in HL-LHC

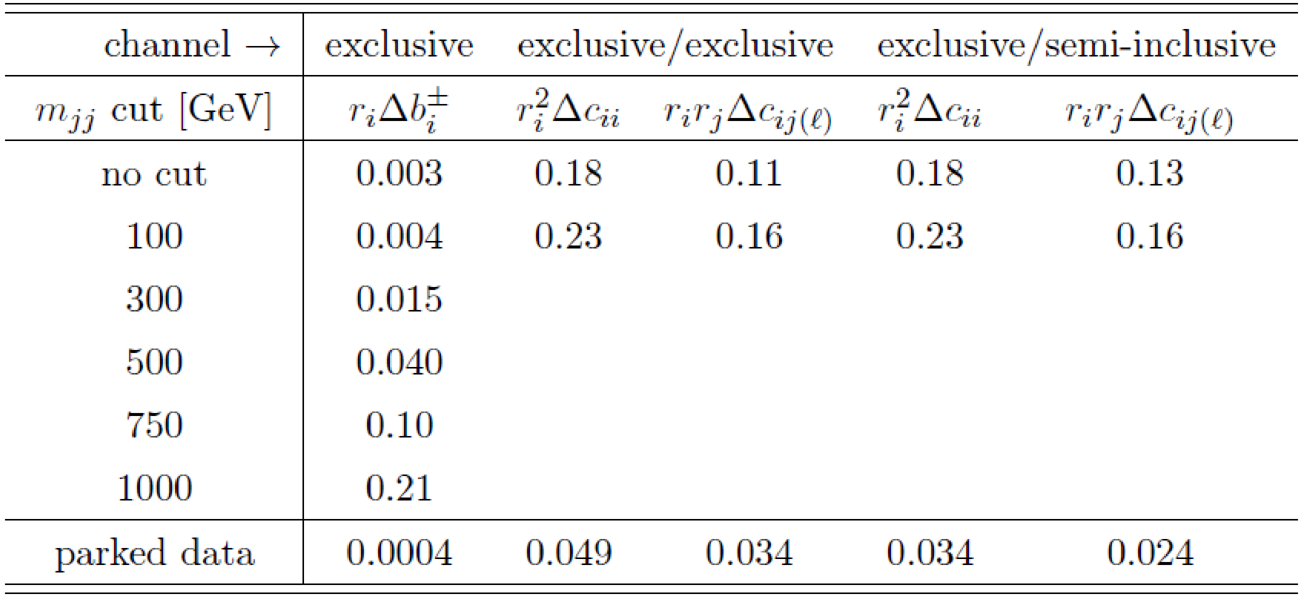


m_{jj} cut [GeV]	$\sigma_{b\bar{b}}$ [pb]	$N^{ii}_{b\bar{b}}$	$N^{ss}_{b\bar{b}}$	$N^{ee}_{b\bar{b}}$	$N^{is}_{b\bar{b}}$	$N^{ie}_{b\bar{b}}$	$N^{se}_{b\bar{b}}$
no cut	39000	6.7×10^6	8.1×10^4	5.4×10^4	1.5×10^6	1.2×10^6	1.3×10^5
100	15000	2.6×10^6	3.1×10^4	2.1×10^4	5.7×10^5	4.7×10^5	5.1×10^4
300	570	9.6×10^4	610	780	1.5×10^4	1.7×10^4	1.4×10^3
500	74	1.2×10^4	35	98	1.3×10^3	2.2×10^3	120
750	12	2.0×10^3	3.0	16	150	360	13
1000	2.9	460		3.7	27	82	2.5
purity f [%]		0.55	32	44	4.2	4.9	38

Expected Statistical Uncertainty for $b\bar{b}$ in Run 2

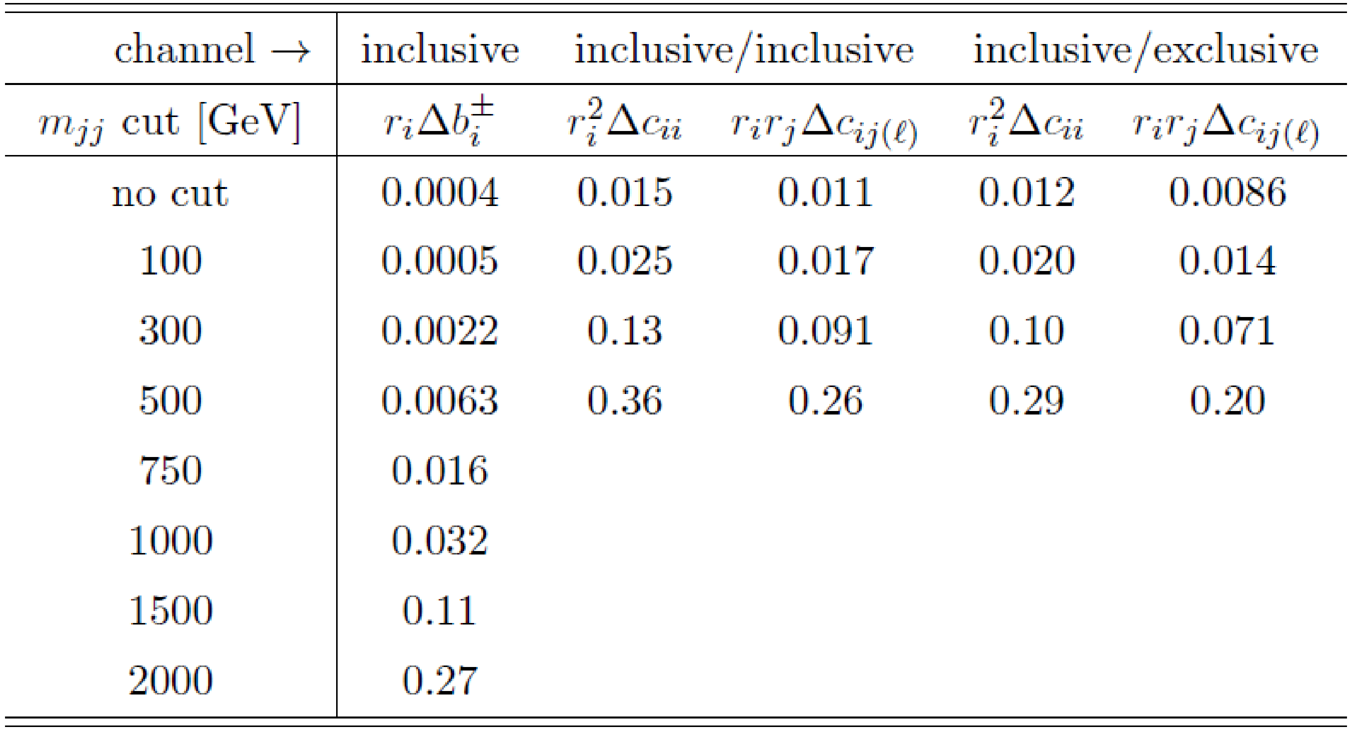


channel →	semi-inclusive	semi-inclusive/semi-inclusive		semi-inclusive/inclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.005	0.36	0.25	0.16	0.11
100	0.006	0.47	0.33	0.21	0.15
300	0.022				
500	0.072				
750	0.21				
parked data	0.0004	0.050	0.035	0.031	0.022



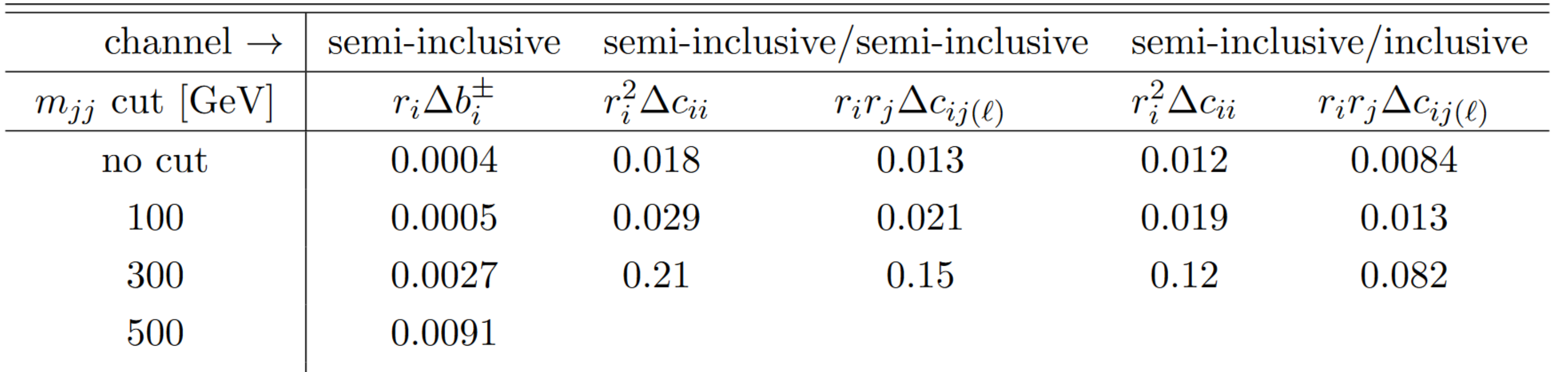
channel →	exclusive	exclusive/exclusive		exclusive/semi-inclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.003	0.18	0.11	0.18	0.13
100	0.004	0.23	0.16	0.23	0.16
300	0.015				
500	0.040				
750	0.10				
1000	0.21				
parked data	0.0004	0.049	0.034	0.034	0.024

Expected Statistical Uncertainty for $b\bar{b}$ in HL-LHC

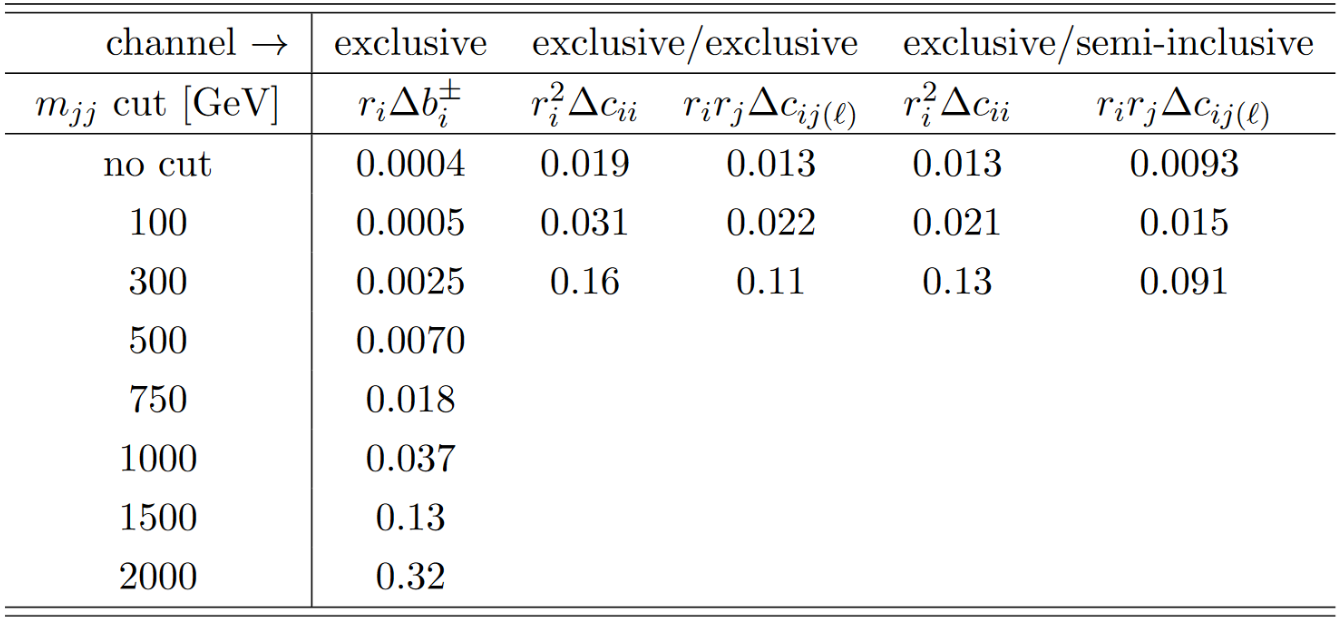


channel →	inclusive	inclusive/inclusive		inclusive/exclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.0004	0.015	0.011	0.012	0.0086
100	0.0005	0.025	0.017	0.020	0.014
300	0.0022	0.13	0.091	0.10	0.071
500	0.0063	0.36	0.26	0.29	0.20
750	0.016				
1000	0.032				
1500	0.11				
2000	0.27				

Expected Statistical Uncertainty for $b\bar{b}$ in HL-LHC

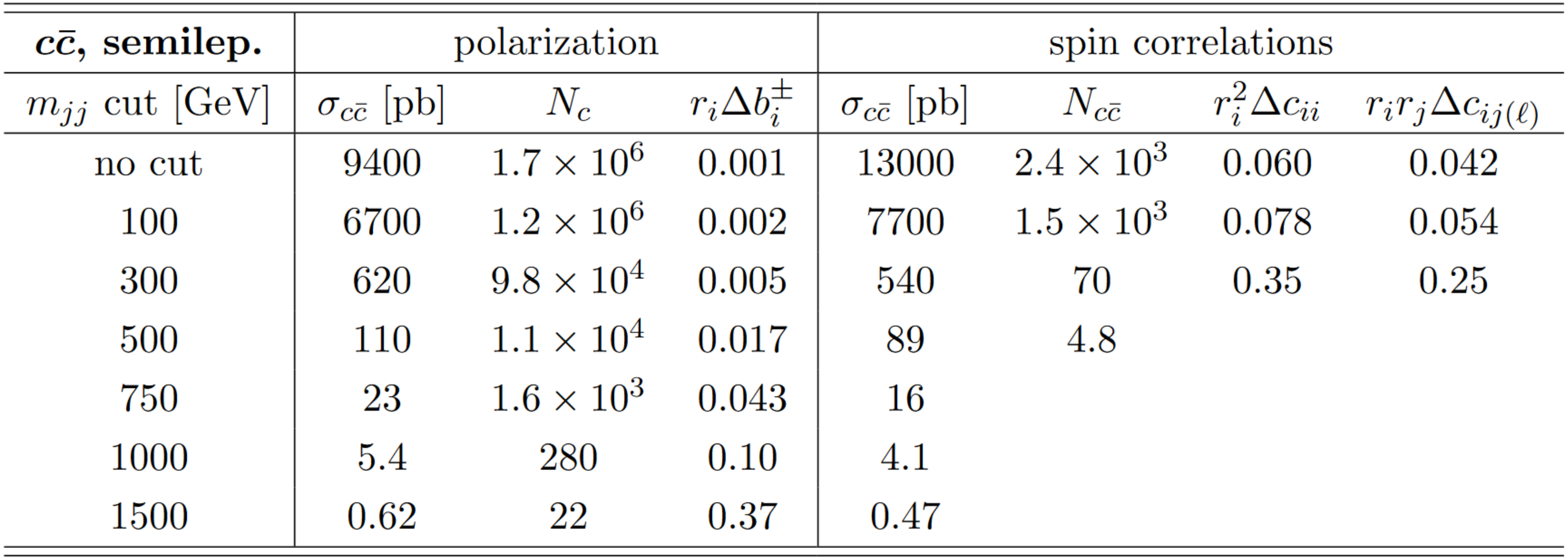


channel →	semi-inclusive	semi-inclusive/semi-inclusive		semi-inclusive/inclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.0004	0.018	0.013	0.012	0.0084
100	0.0005	0.029	0.021	0.019	0.013
300	0.0027	0.21	0.15	0.12	0.082
500	0.0091				
750	0.026				
1000	0.058				
1500	0.24				



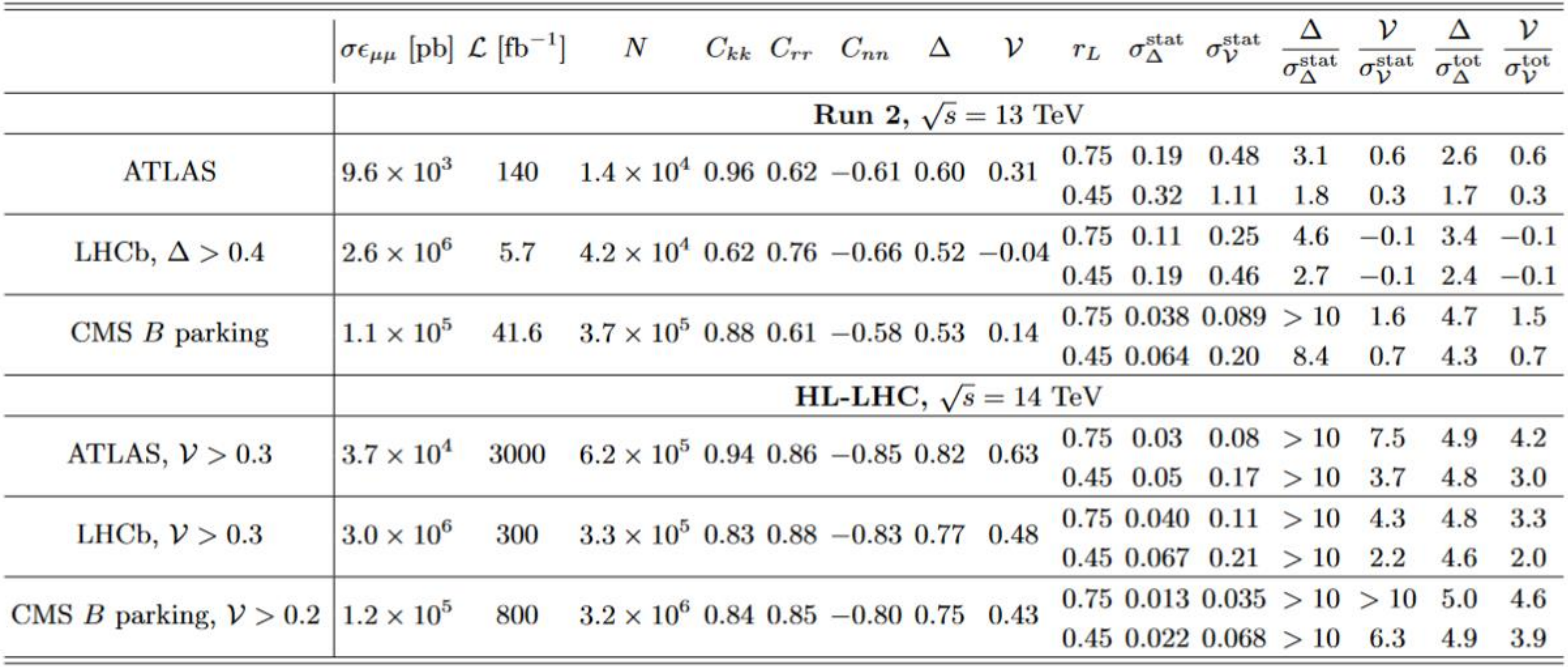
channel →	exclusive	exclusive/exclusive		exclusive/semi-inclusive	
m_{jj} cut [GeV]	$r_i \Delta b_i^{\pm}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	0.0004	0.019	0.013	0.013	0.0093
100	0.0005	0.031	0.022	0.021	0.015
300	0.0025	0.16	0.11	0.13	0.091
500	0.0070				
750	0.018				
1000	0.037				
1500	0.13				
2000	0.32				

Expected Statistical Uncertainty and Number of Events for $c\bar{c}$ in HL-LHC



$c\bar{c}$, semilep.	polarization			spin correlations			
m_{jj} cut [GeV]	$\sigma_{c\bar{c}}$ [pb]	N_c	$r_i \Delta b_i^{\pm}$	$\sigma_{c\bar{c}}$ [pb]	$N_{c\bar{c}}$	$r_i^2 \Delta c_{ii}$	$r_i r_j \Delta c_{ij(\ell)}$
no cut	9400	1.7×10^6	0.001	13000	2.4×10^3	0.060	0.042
100	6700	1.2×10^6	0.002	7700	1.5×10^3	0.078	0.054
300	620	9.8×10^4	0.005	540	70	0.35	0.25
500	110	1.1×10^4	0.017	89	4.8		
750	23	1.6×10^3	0.043	16			
1000	5.4	280	0.10	4.1			
1500	0.62	22	0.37	0.47			

Entanglement and Bell's Inequality, $pp \to b\bar{b}$



	$\sigma\epsilon_{\mu\mu}$ [pb]	$\mathcal{L}$ [fb^{-1}]	N	C_{kk}	C_{rr}	C_{nn}	Δ	$\mathcal{V}$	r_L	$\sigma_\Delta^{\text{stat}}$	$\sigma_\mathcal{V}^{\text{stat}}$	$\frac{\Delta}{\sigma_\Delta^{\text{stat}}}$	$\frac{\mathcal{V}}{\sigma_\mathcal{V}^{\text{stat}}}$	$\frac{\Delta}{\sigma_\Delta^{\text{tot}}}$	$\frac{\mathcal{V}}{\sigma_\mathcal{V}^{\text{tot}}}$
	Run 2, $\sqrt{s} = 13$ TeV														
ATLAS	9.6×10^3	140	1.4×10^4	0.96	0.62	-0.61	0.60	0.31	0.75	0.19	0.48	3.1	0.6	2.6	0.6
									0.45	0.32	1.11	1.8	0.3	1.7	0.3
LHCb, $\Delta > 0.4$	2.6×10^6	5.7	4.2×10^4	0.62	0.76	-0.66	0.52	-0.04	0.75	0.11	0.25	4.6	-0.1	3.4	-0.1
									0.45	0.19	0.46	2.7	-0.1	2.4	-0.1
CMS B parking	1.1×10^5	41.6	3.7×10^5	0.88	0.61	-0.58	0.53	0.14	0.75	0.038	0.089	> 10	1.6	4.7	1.5
									0.45	0.064	0.20	8.4	0.7	4.3	0.7
	HL-LHC, $\sqrt{s} = 14$ TeV														
ATLAS, $\mathcal{V} > 0.3$	3.7×10^4	3000	6.2×10^5	0.94	0.86	-0.85	0.82	0.63	0.75	0.03	0.08	> 10	7.5	4.9	4.2
									0.45	0.05	0.17	> 10	3.7	4.8	3.0
LHCb, $\mathcal{V} > 0.3$	3.0×10^6	300	3.3×10^5	0.83	0.88	-0.83	0.77	0.48	0.75	0.040	0.11	> 10	4.3	4.8	3.3
									0.45	0.067	0.21	> 10	2.2	4.6	2.0
CMS B parking, $\mathcal{V} > 0.2$	1.2×10^5	800	3.2×10^6	0.84	0.85	-0.80	0.75	0.43	0.75	0.013	0.035	> 10	> 10	5.0	4.6
									0.45	0.022	0.068	> 10	6.3	4.9	3.9