How to measure transverse polarization on a symmetric collider

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1. Motivations

Polarization of baryons: important application

Parity violation

Eisler et al., PRD108(1957)1353

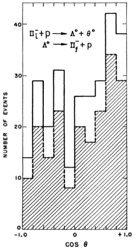
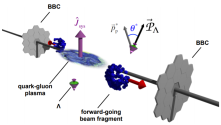


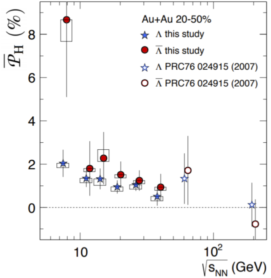
Fig. 1. Distribution in cosθ for process (1). The shaded area represents events for production angles in the center-of-mass range 30°–150°.

$$Dis = 1 + P_\omega \alpha \cos\theta$$

QGP verticity

STAR, Nature548(2017),62





top and New Physics

- charged lepton asymmetry
- top polarization
- $t\bar{t}$ spin correlation

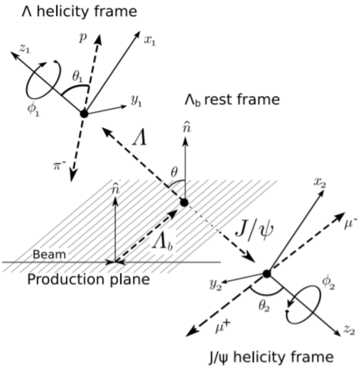
Extra observables in decays of polarized baryons.

polarization measurements of Λ_b

$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega),$$

TABLE I. The coefficients f_{1i}, f_{2i} and F_i of the probability density function in Eq. (3) [15].

i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
1	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	P	$\cos\theta$
2	$a_+a_+^* - a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\cos\theta_1$
3	$a_+a_+^* + a_-a_-^* - b_+b_+^* - b_-b_-^*$	$P\,\alpha_\Lambda$	$\cos\theta\,\cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
5	$-a_+a_+^* + a_-a_-^* + \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	P	$\frac{1}{2}(3\cos^2\theta_2 - 1)\,\cos\theta$
6	$-a_+a_+^* + a_-a_-^* - \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\,\cos\theta_1$
7	$-a_+a_+^* - a_-a_-^* - \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	$P\,\alpha_\Lambda$	$\frac{1}{2}(3\cos^2\theta_2 - 1)\,\cos\theta\cos\theta_1$
8	$-3\mathrm{Re}(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\cos\phi_1$
9	$3\mathrm{Im}(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\sin\phi_1$
10	$-\frac{3}{2}\mathrm{Re}(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\cos(\phi_1 + 2\,\phi_2)$
11	$\frac{3}{2}\mathrm{Im}(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\sin(\phi_1 + 2\,\phi_2)$
12	$-\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\cos\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos\phi_2$
13	$\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\cos\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin\phi_2$
14	$-\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\,\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos(\phi_1 + \phi_2)$
15	$\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\,\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin(\phi_1 + \phi_2)$
16	$\frac{3}{\sqrt{2}}\mathrm{Re}(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\,\sin\theta_2\,\cos\theta_2\,\cos\phi_2$
17	$-\frac{3}{\sqrt{2}}\mathrm{Im}(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\,\sin\theta_2\,\cos\theta_2\,\sin\phi_2$
18	$\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos(\phi_1 + \phi_2)$
19	$-\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin(\phi_1 + \phi_2)$



polarization measurements of Λ_b: $\Lambda_b \to J\psi(\mu^+\mu^-)\Lambda(p\pi^+)$

Transverse polarization of Λ_b (through $\Lambda_b \to J/\psi\Lambda$)

$P_{\Lambda_b}^{\mathrm{LHCb}} = 0.06 \pm 0.07 \pm 0.02$ PLB724(2013),27

$P_{\Lambda_b}^{\mathrm{CMS}} = 0.00 \pm 0.06 \pm 0.06$ PRD97(2018),072010

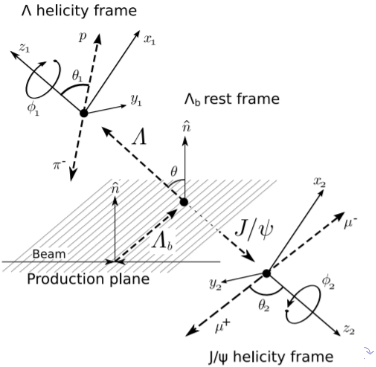
world average

$$P_{\Lambda_b}^{\mathrm{HFLAV}} = 0.03 \pm 0.06$$

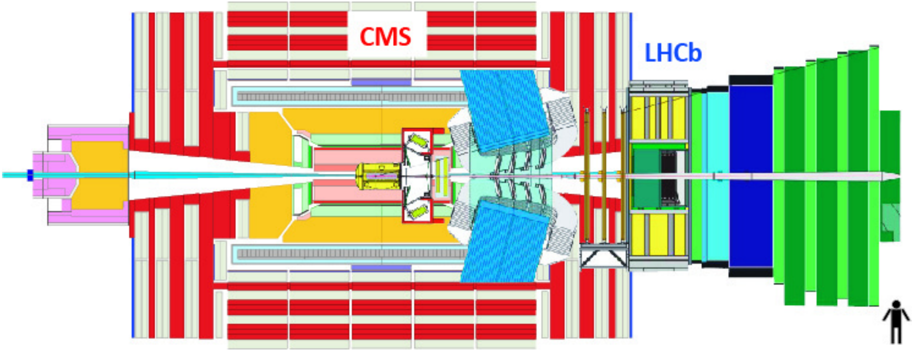
theoretical prediction

at the 10% level

P_Λ is large, P_{Λ_b} is small.

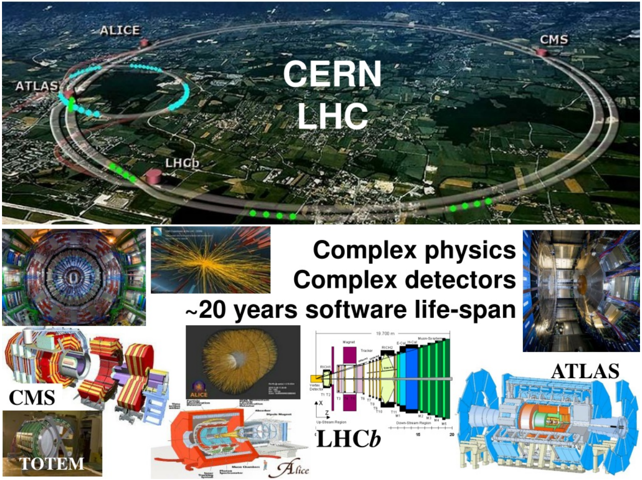


$P_{\Lambda_b}^{\mathrm{LHCb}}$ and $P_{\Lambda_b}^{\mathrm{CMS}}$ are two different things.



2 Transverse Polarization of Λ_b

detectors on LHC



symmetric detector (CMS ATLAS)

- Parity $\mathbb{P}$
- rotation of π: $\mathbb{R}_z(\pi)$

asymmetric detector (LHCb)

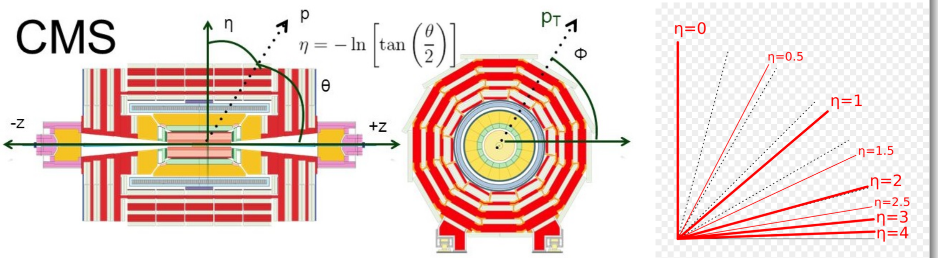
$\mathbb{R}_z(\pi)\mathbb{P}$

anti-symmetric detector (BESIII)

$\mathbb{R}_z(\pi)\mathbb{P}$

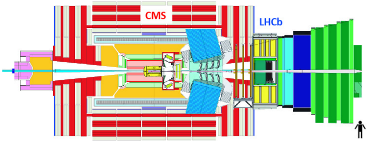
Pseudorapidity, Pseudorapidity-dependence of detectors

Pseudorapidity



Pseudorapidity coverage

- LHCb: $2 \sim 5$
- CMS and ATLAS: $-2.5 \sim 2.5$
- ALICE: $-3.4 \sim 5.0$



Pseudorapidity-dependence of P_{Λ_b}

definition of transverse unite vector(s) $\hat{n}$

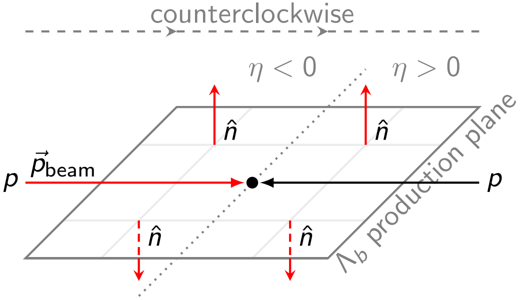


Figure: definition of $\hat{n}$: $\hat{n} = \frac{\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda_b}}{|\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda_b}|}$.

Pseudorapidity-dependence of P_{Λ_b}

$P_{\hat{n}}(\eta, p_T) = \vec{P}_{\Lambda_b} \cdot \hat{n}$ can be nonzero, and odd on pseudorapidity η

$$P_{\hat{n}}(\eta, p_T) = -P_{\hat{n}}(-\eta, p_T) \tag{1}$$

Proof of eq. (1)

definition of transverse polarization of Λ_b

Up to an irrelevant overall factor, the transverse polarization of Λ_b for a given pseudorapidity η is defined as

$$P_{\hat{n}}(\eta, p_T) \equiv \sum_{\lambda, X} \lambda \left| \langle \Lambda_b(\vec{p}_{\Lambda_b}, \lambda) X | \mathcal{T} | p(\vec{p}_{\text{beam}}) p(-\vec{p}_{\text{beam}}) \rangle \right|^2$$

$$P_{\hat{n}}(-\eta, p_T) \equiv \sum_{\lambda, X} \lambda \left| \langle \Lambda_b(-\vec{p}_{\Lambda_b}, \lambda) X | \mathcal{T} | p(\vec{p}_{\text{beam}}) p(-\vec{p}_{\text{beam}}) \rangle \right|^2$$

λ: the spin quantization of Λ_b along the $\hat{n}$ direction, $\vec{S} \cdot \hat{n}$.

Proof of eq. (1): adopt symmetry of $R_z(\pi)$

$$P_{\hat{n}}(-\eta, p_T) = \sum_{\lambda,X} \lambda \left| \langle \Lambda_b(-\vec{p}_{\Lambda_b}, \lambda) X | \mathbb{R}_z^\dagger(\pi) \mathbb{R}_z(\pi) \mathcal{T} | p(\vec{p}_{\text{beam}}) p(-\vec{p}_{\text{beam}}) \rangle \right|^2$$

$$= \sum_{\lambda,X} \lambda \left| \langle \Lambda_b(\vec{p}_{\Lambda_b}, -\lambda) X^{\mathbb{R}} | \mathbb{R}_z(\pi) \mathcal{T} | p(\vec{p}_{\text{beam}}) p(-\vec{p}_{\text{beam}}) \rangle \right|^2$$

$$= \sum_{\lambda} \lambda \sum_{X} \left| \left\langle \Lambda_b(\vec{p}_{\Lambda_b}, -\lambda) X^{\mathbb{R}_z(\pi)} | \mathcal{T} \mathbb{R}_z(\pi) | p(\vec{p}_{\text{beam}}) p(-\vec{p}_{\text{beam}}) \right\rangle \right|^2$$

$$= \sum_{\lambda,X} \lambda \left| \langle \Lambda_b(\vec{p}_{\Lambda_b}, -\lambda) X | \mathcal{T} | p(-\vec{p}_{\text{beam}}) p(\vec{p}_{\text{beam}}) \rangle \right|^2$$

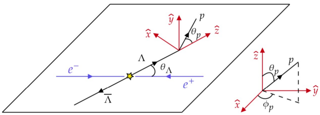
$$= -\sum_{\lambda,X} \lambda \left| \langle \Lambda_b(\vec{p}_{\Lambda_b}, \lambda) X | \mathcal{T} | p(\vec{p}_{\text{beam}}) p(-\vec{p}_{\text{beam}}) \rangle \right|^2$$

$$= -P_{\hat{n}}(\eta, p_T)$$

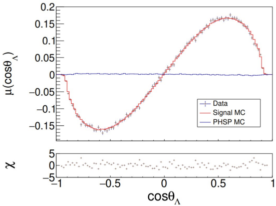
Important! Eq. (1) always holds, regardless the Λ_b production mechanism.

Comparison of symmetric and anti-symmetric colliders

- symmetric colliders: Eq. (1) always holds, regardless that Λ_b is produced though strong or weak interactions.
- pair-production on anti-symmetric colliders: $(e^+e^- \to \Lambda\bar{\Lambda})$ Eq. (1) holds, if the hadrons are produced through strong/EM interactions.



BESIII, PRL129(2022),131801



$$\mu[\cos(\theta_\Lambda)] = (m/N)\sum_{i=1}^{N_k}(n_{1,y}^{(i)} - n_{2,y}^{(i)})$$

$$\mu(\cos\theta_\Lambda) = \frac{\alpha_- - \alpha_+}{2}\frac{1+\alpha_{J/\psi}\cos^2\theta_\Lambda}{3+\alpha_{J/\psi}}P_y(\theta_\Lambda)$$

$$P_y(\cos\theta_\Lambda) = \frac{\sqrt{1-\alpha_{J/\psi}^2}\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_{J/\psi}\cos^2\theta_\Lambda}.$$

Comparison of $P^{\text{CMS}}_{\Lambda_b}$ and $P^{\text{LHCb}}_{\Lambda_b}$

$$P^{\text{LHCb}}_{\Lambda_b} = \langle P_{\hat{n}} \rangle^{\eta \in (+2,+5)} = \frac{\int_{+2}^{+5} P_{\hat{n}}(\eta) N(\eta) d\eta}{\int_{+2}^{+5} N(\eta) d\eta} \neq 0$$

$$P^{\text{CMS}}_{\Lambda_b} = \langle P_{\hat{n}} \rangle^{\eta \in (-2.5,+2.5)} \equiv \frac{\int_{-\infty}^{+\infty} P_{\hat{n}}(\eta) N(\eta) d\eta}{\int_{-\infty}^{+\infty} N(\eta) d\eta} = 0$$

What if $P_{\Lambda_b}^{\text{CMS}}$ nozero?

$$P_{\Lambda_b}^{\text{CMS}} = 0.00 \pm 0.06 \pm 0.06$$

Measuring $P_{\Lambda_b}^{\text{forward}}$ on CMS and ATLAS

Avoid cancellation: transverse pol. of the forward region

$$P_{\Lambda_b}^{\text{forward}} = \frac{\int_0^{+\infty} P_{\hat{n}}(\eta) N(\eta) d\eta}{\int_0^{+\infty} N(\eta) d\eta}$$

adopting all the data

$$P_{\Lambda_b}^{\text{forward}} = \frac{\int_{-\infty}^{+\infty} \text{sign}(\eta) P_{\hat{n}}(\eta) N(\eta) d\eta}{\int_{-\infty}^{+\infty} N(\eta) d\eta}$$

Measuring $P_{\Lambda_b}^{\text{forward}}$ on CMS and ATLAS

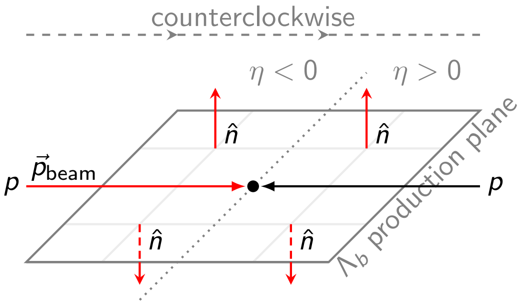


Figure: definition of $\hat{n}$: $\hat{n} = \frac{\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda_b}}{|\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda_b}|}$.

$$P_{\hat{n}}(\eta) = -P_{\hat{n}}(-\eta)$$

$$P_{\Lambda_b}^{\text{forward}} = \frac{\int_{-\infty}^{+\infty} \text{sign}(\eta) P_{\hat{n}}(\eta) N(\eta)}{\int_{-\infty}^{+\infty} N(\eta) d\eta}$$

Measuring $P_{\Lambda_b}^{\text{forward}}$ on CMS and ATLAS

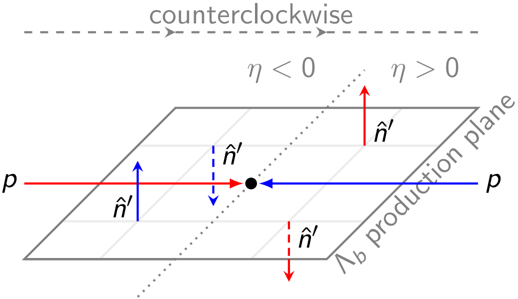


Figure: Definition of $\hat{n}'$: $\vec{n}' \equiv \frac{\vec{p}\,'_{\text{beam}} \times \vec{p}_{\Lambda_b}}{|\vec{p}\,'_{\text{beam}} \times \vec{p}_{\Lambda_b}|}$

$$P_{\hat{n}'}(\eta) = P_{\hat{n}'}(-\eta)$$

$$P_{\Lambda_b}^{\text{forward}} = \frac{\int_{-\infty}^{+\infty} P_{\hat{n}'}(\eta) N(\eta) d\eta}{\int_{-\infty}^{+\infty} N(\eta) d\eta}$$

Looking forward to the updated Λ_b polarization measurements

$$P_{\Lambda_b}^{\text{LHCb}}(2013) = 0.06 \pm 0.07 \pm 0.02$$

~~$P_{\Lambda_b}^{\text{CMS}}(2018) = 0.00 \pm 0.06 \pm 0.06$~~

~~$P_{\Lambda_b}^{\text{HFLAV}} = 0.03 \pm 0.06$~~

- $P_{\Lambda_b}^{\text{LHCb}}(2024) = ?$, with data five times larger: 0.✠✠ $\pm\, 0.03$
- $P_{\Lambda_b}^{\text{CMS,ATLAS,forward}} = ?$ in 2025?

3 Summary and outlook

- the previous measurement of the Λ_b polarization by CMS collaboration should be exactly equal to zero.
- The updated LHCb Λ_b transverse polarization measurement is undergo.
- strongly suggest CMS and ATLAS to perform the measurement of the Λ_b transverse polarization in the forward region of the pseudorapidity.

Thanks for your attention!