QCD and Baryon Polarization

Lecture 6:

Hyperon and Heavy Flavor Baryon Polarization II

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How to measure polarization of unstable baryons—basic concepts

- Look at *angular distribution* of weak decay products
- Angular distribution of the decay products depends on *both* the original baryon polarization *and* the parity-violating decay asymmetry for the particular decay channel
- $\Lambda^0 \to p\pi^-$ two-body decay has 64% branching fraction and large decay asymmetry parameter $\alpha = 0.750 \pm 0.009 \pm 0.004$ from PDG 2019
  - Was $\alpha = 0.642 \pm 0.013$ in PDG 2018! New measurements by BES III and CLAS have shifted the value significantly! In principle would change values of extracted Λ^0 polarization in earlier publications
  - Possible to go back and re-evaluate, e.g. 1976 discovery paper used $\alpha = 0.647 \pm 0.013$

How to measure polarization of unstable baryons—basic concepts

- Two-body decay of Λ^0: In the rest frame of the Λ^0, the proton angular distribution is

$$\frac{dN}{d\Omega} \propto (1 + \alpha P \cos\theta)$$

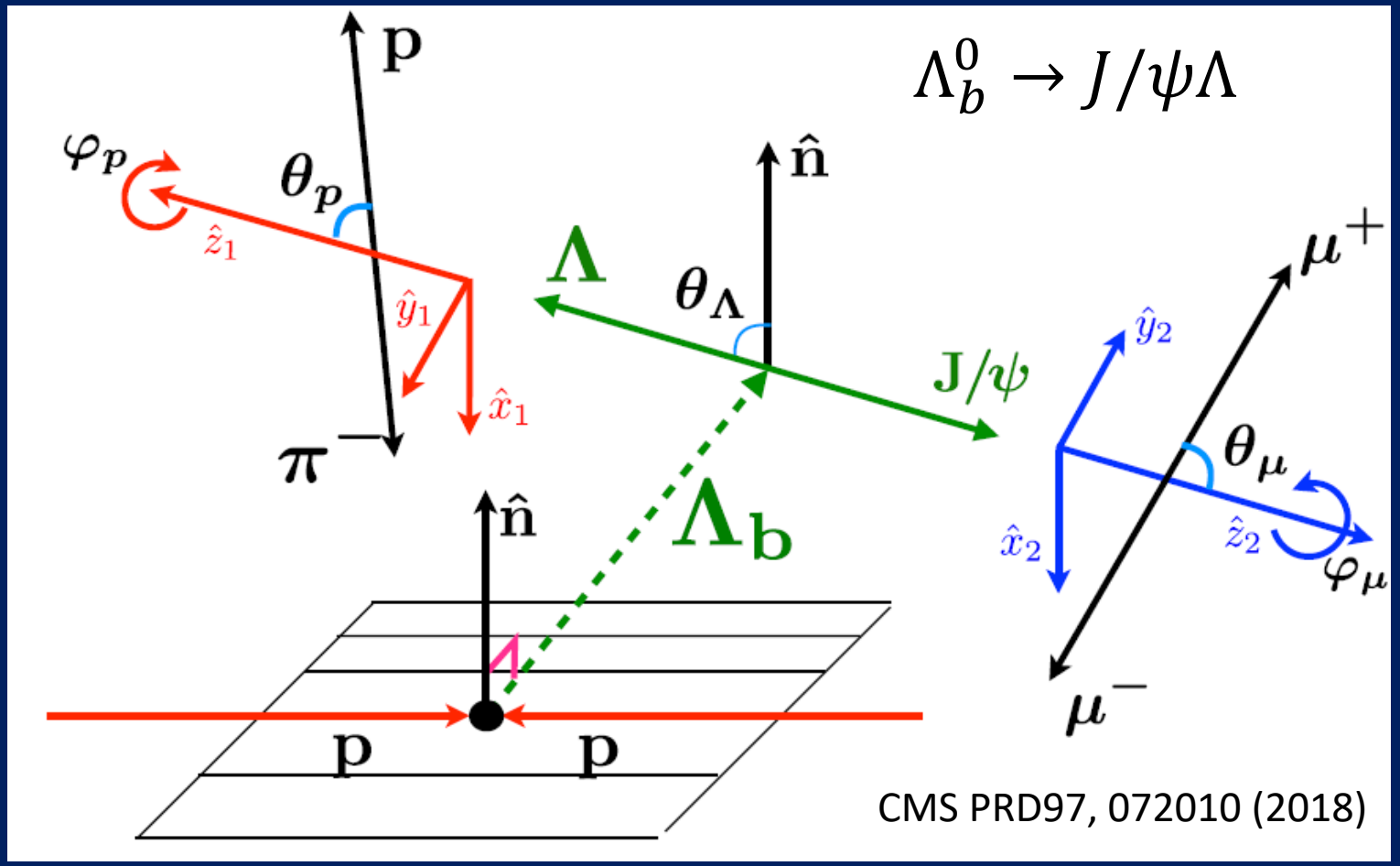
where θ is the angle between the proton momentum and the Λ^0 spin

The more particles in the final state, the more complicated the angular analysis!

- "The kinematics of the $\Lambda_b^0 \to J/\psi\Lambda$ decay, including the subsequent decays of the J/ψ meson and the Λ baryon, can be parameterized by five decay angles and a unit vector in the direction transverse to the production plane, $\hat{n}$, against which the polarization is measured." (LHCb, arXiv:2004.10563)
  - See also Blake and Kreps, "Angular distribution of polarized Λ_b^0 baryons decaying to $\Lambda l^+ l^-$," JHEP 11, 138 (2017)
- Need to consider each decay mode separately!

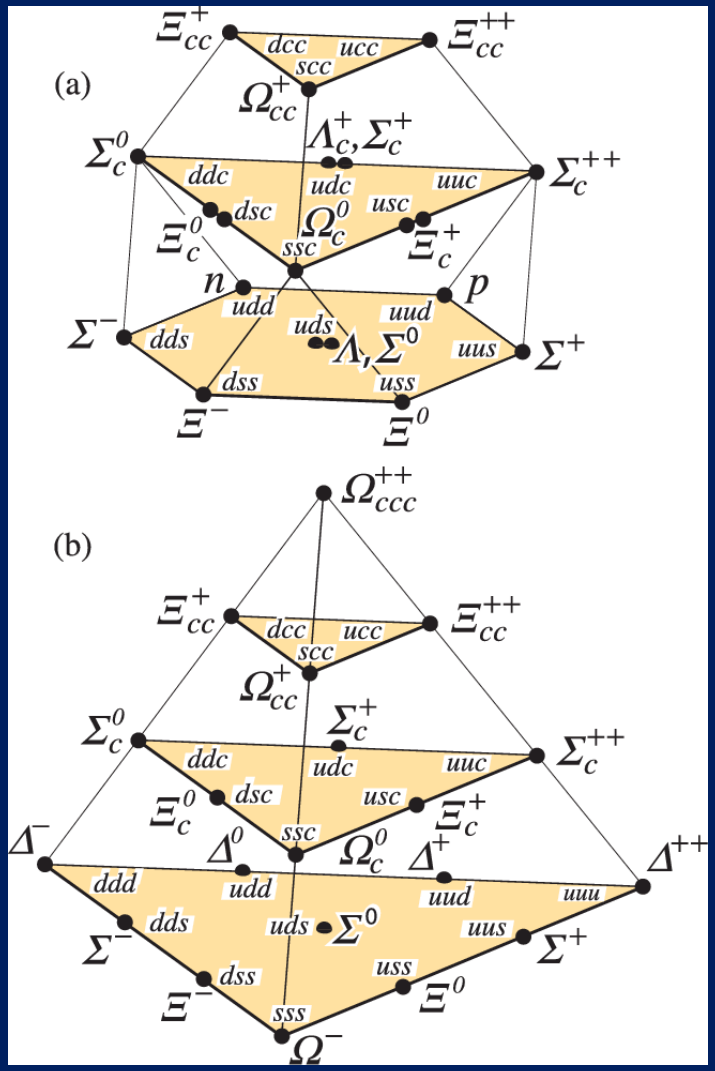
$$\hat{n} = \frac{\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda_b}}{|\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda_b}|}$$

The more particles in the final state, the more complicated the angular analysis!



CMS PRD97, 072010 (2018)

Charmed baryons

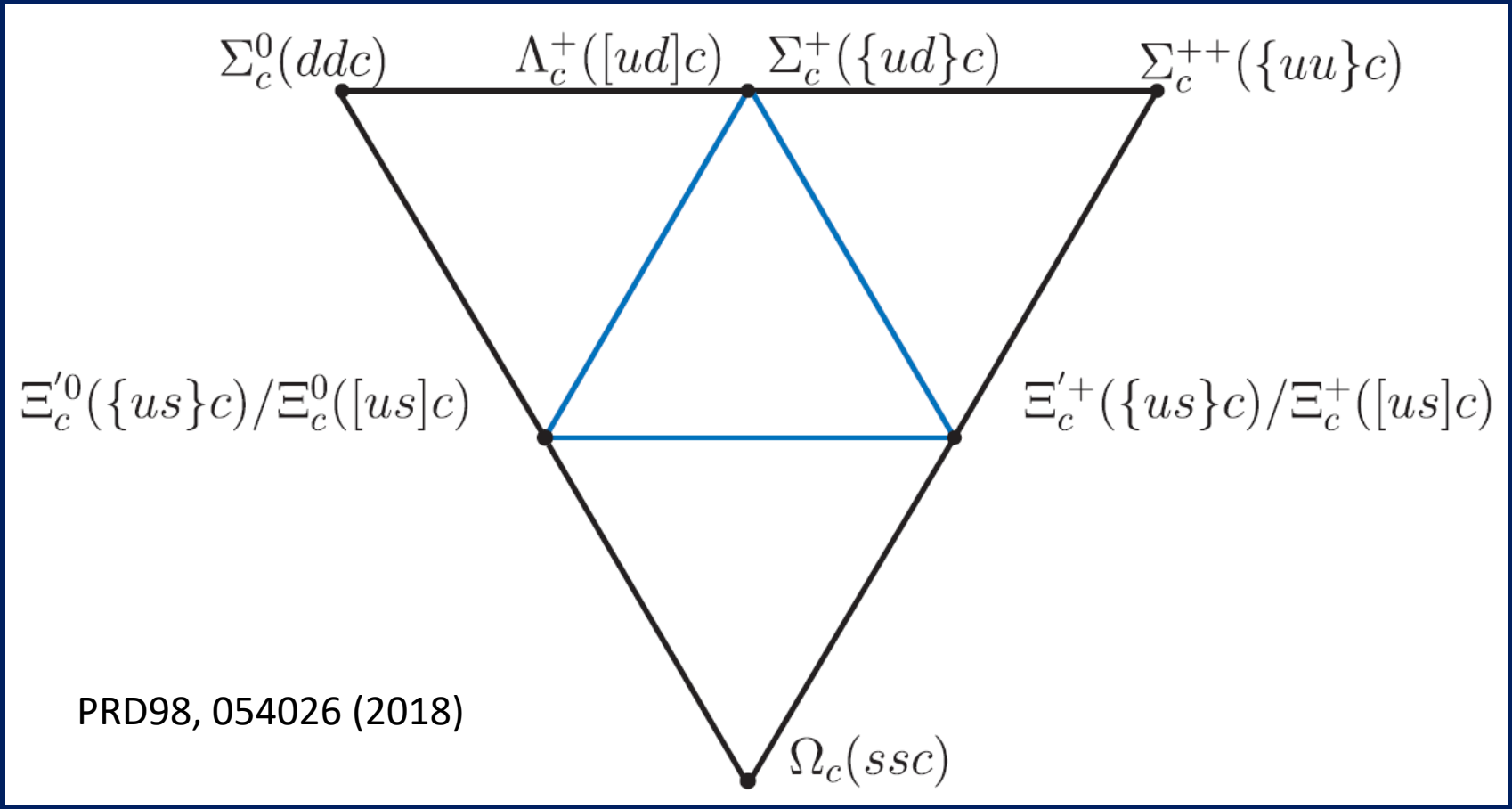


Nomenclature:

- 1c plus 2u, ud, or 2d - Λ_c^+ (isospin 0) or charmed Sigmas (isospin 1)
- 1c, 1s plus 1u or 1d – charmed Xis (isospin ½)
- 1c, 2s - Ω_c^0 (isospin 0)
- Also have double charmed Xis and Omega, triple charmed Omega

SU(4) baryons (can contain u,d,s,c)
J. Phys. G46, 065014 (2019),
adapted from PDG

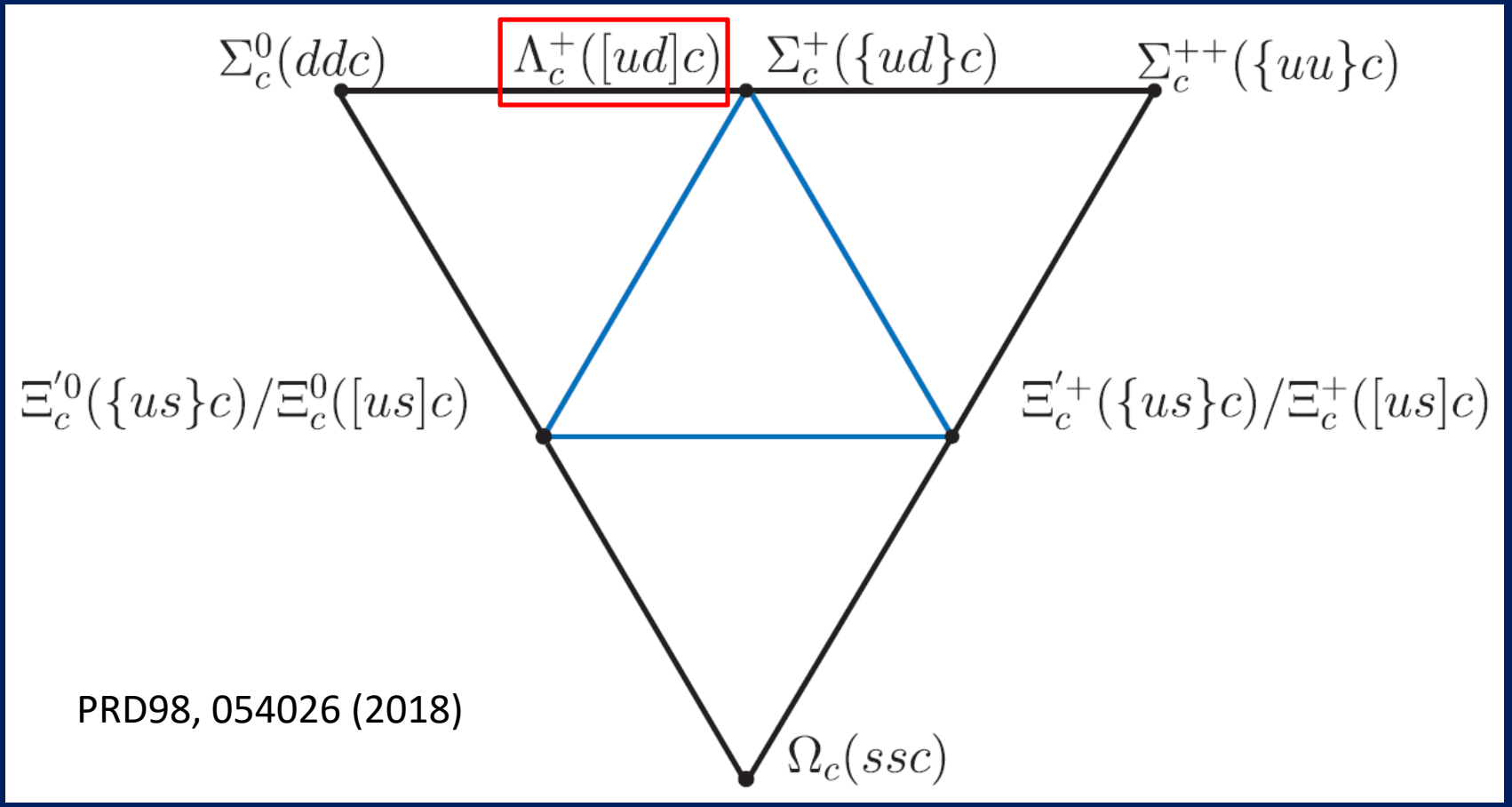
Charmed baryons



PRD98, 054026 (2018)

FIG. 1. The blue and black triangles denote the heavy baryons in the $\bar{3}_f$ and the 6_f flavor representations, respectively. [...] and {...} denotes the two light quarks are antisymmetric and symmetric in the flavor space, respectively.

Charmed baryons



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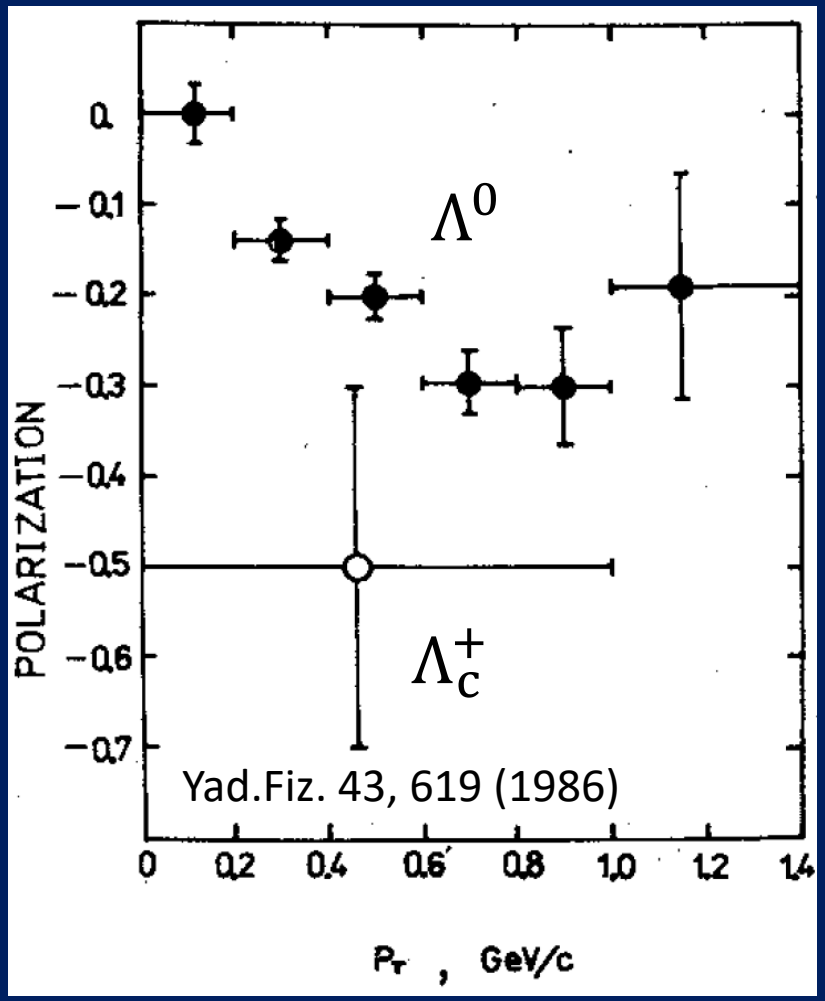
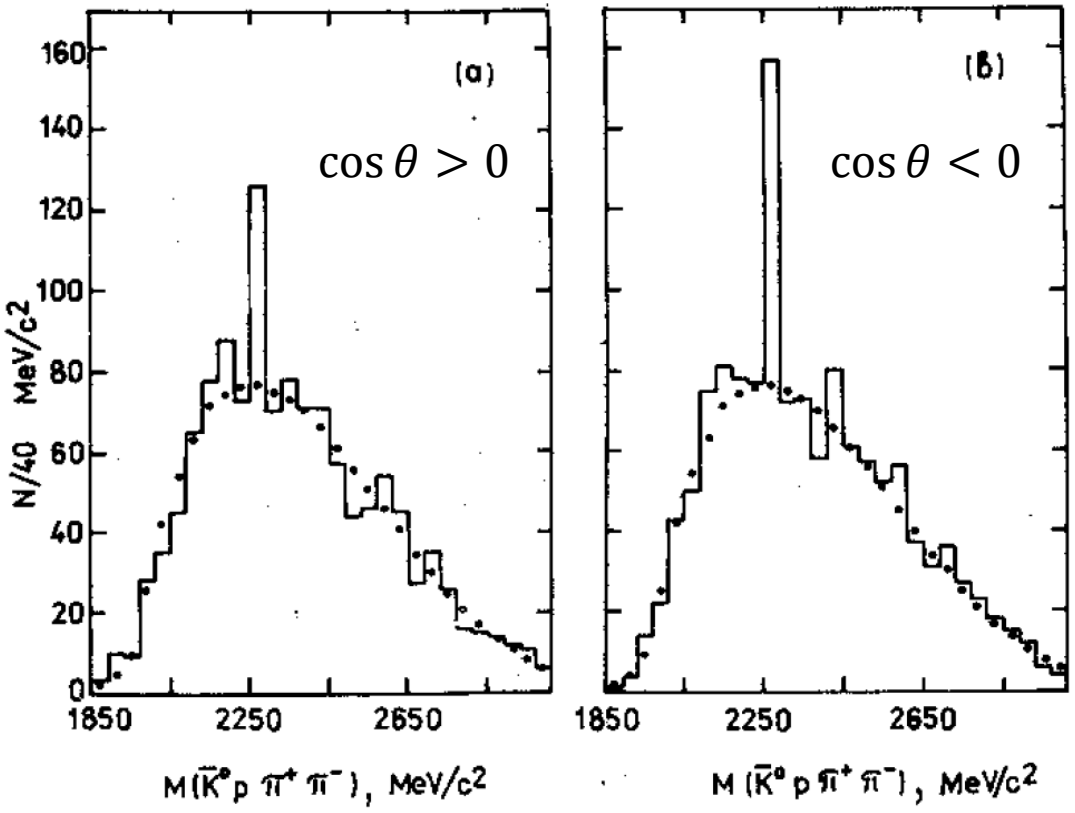
Λ_c^+ *polarization measurements*



- BIS-2 experiment at Serpukhov
  - 40-70 GeV neutron beam on carbon
  - 57 $\Lambda_c^+ \to \Lambda^0\pi^+\pi^+\pi^-$
  - 130 $\Lambda_c^+ \to \bar{K}^0 p\pi^+\pi^-$ ($\bar{K}^0$ should be K_s^0??)
- Found 0.5 +- 0.2 transverse polarization, same sign as for Λ^0 polarization

$\Lambda_c^+ \to \bar{K}^0 p \pi^+ \pi^-$: *Proton direction*



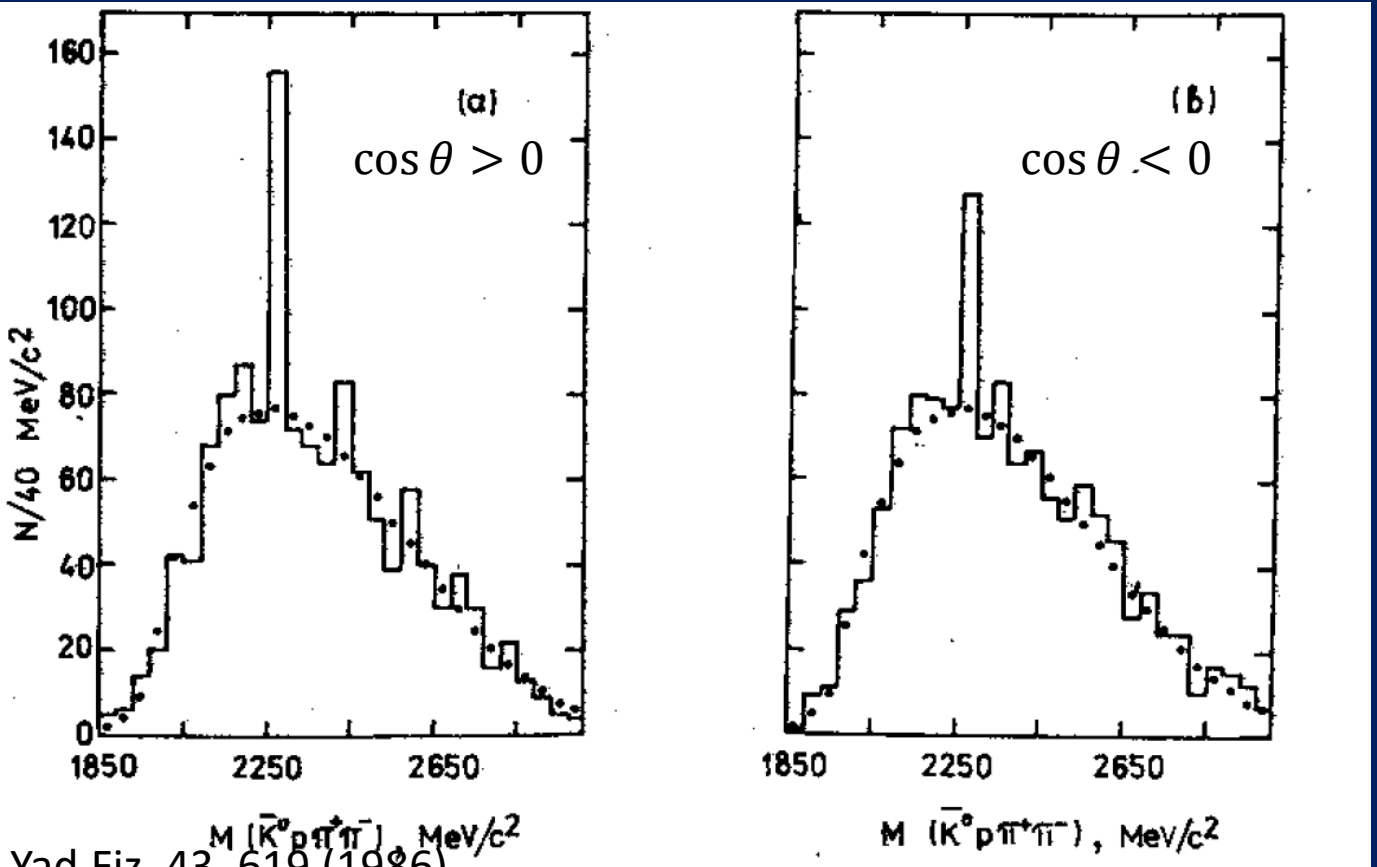
Yad.Fiz. 43, 619 (1986)

Fig. 1. The invariant $\bar{K}^0 p \pi^+ \pi^-$ mass spectra obtained for events with the proton emitted in the "up" (a) and "down" (b) directions. The dotted curves represent the fit to the spectra by the background function.

BIS-2 experiment, neutron beam.

More protons go "down"

$\Lambda_c^+ \to \bar{K}^0 p\pi^+\pi^-$: Kaon direction



Yad.Fiz. 43, 619 (1986)

Fig. 2. The invariant $\bar{K}^0 p\pi^+\pi^-$ mass spectra obtained for events with the $\bar{K}^0$ emitted in the "up" (a) and "down" (b) directions. The dotted curves represent the fit to the spectra by the background function.

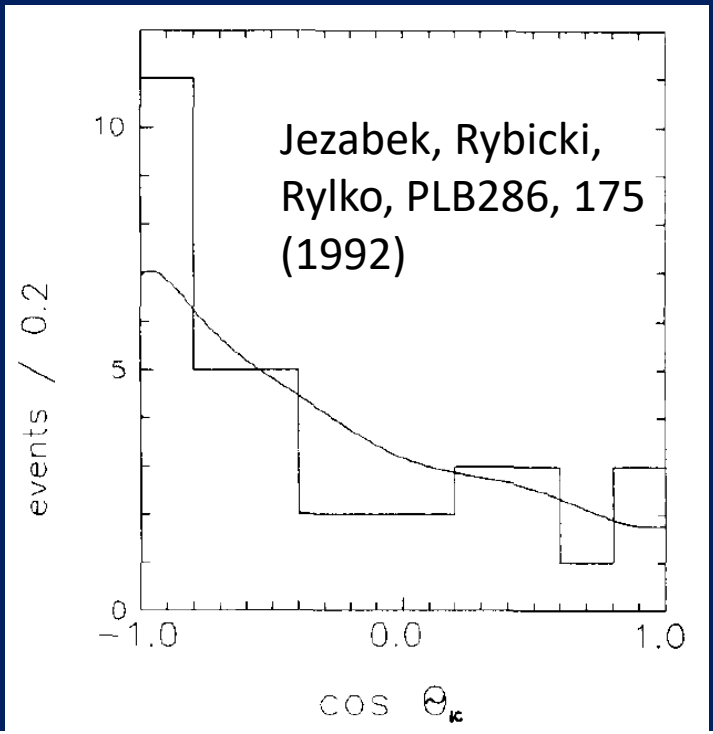
BIS-2 experiment, neutron beam

More kaons go "up"

Λ_c^+ polarization measurements

- CERN NA32 (ACCOR) data
  - 230 GeV π^- beam on Cu
  - 160 $\Lambda_c^+ \to pK^-\pi^+$
- Claimed first observation of Λ_c^+ polarization in hadroproduction!
  - Disconnect between physics in Soviet Union and Europe…(?)
- Kaon preferentially emitted in direction opposite to normal of production plane
- Transverse production polarization of Λ_c^+ observed
  - Larger magnitude with larger p_T

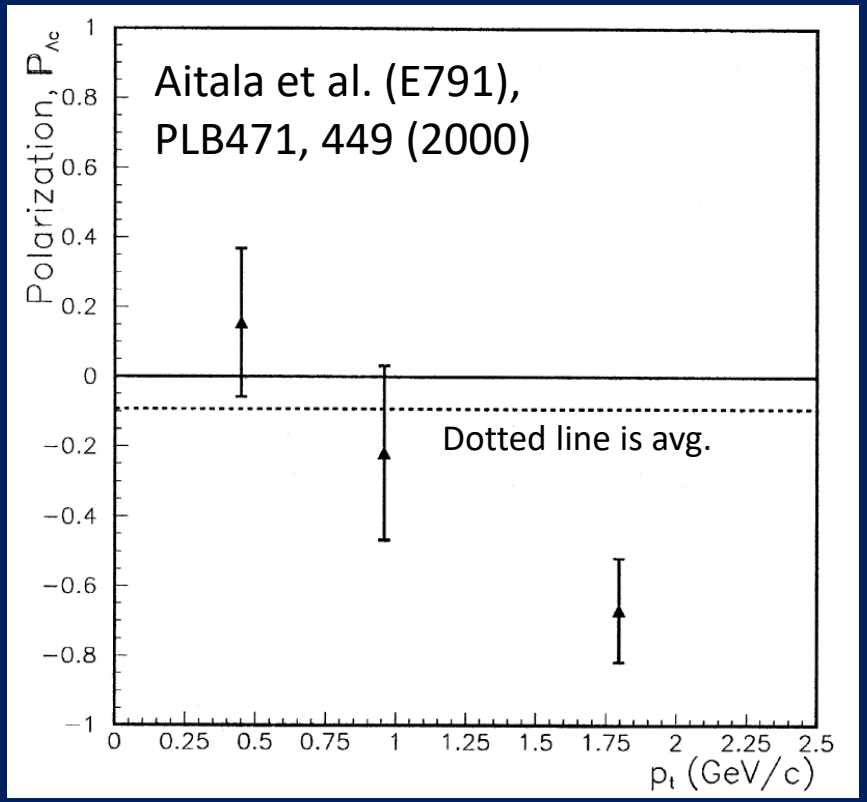
Product of (negative) decay asymmetry parameter and polarization. (Opposite sign convention from others)



p_T cut (GeV/c)	$\langle p_T \rangle$ (GeV/c)	Number of events	d_1 moment ($\cos\theta_K$ distribution)	χ^2
all p_T	0.90	121	-0.22 ± 0.15	9.8
$p_T < 0.7$	0.44	51	$0.04 \pm^{0.27}_{0.26}$	9.5
$p_T > 0.7$	1.24	70	$-0.36 \pm^{0.18}_{0.17}$	5.9
$p_T < 1.1$	0.62	84	0.08 ± 0.20	15.9
$p_T > 1.1$	1.54	37	$-0.65 \pm^{0.22}_{0.18}$	6.3

Λ_c^+ polarization measurements

- Fermilab E791
  - 500 GeV π^- beam on Pt and C
  - 946 $\Lambda_c^+ \to pK^-\pi^+$
- First 5-D resonant amplitude analysis
  - However, incorrect amplitude model employed! D. Marangotto, arXiv:2004.12318
- Measured transverse polarization
  - Sign in agreement with NA32 analysis and model by G. Goldstein
  - But some concern about reliability of results given incorrect amplitude model…



Λ_c^+ *polarization measurements*

- Fermilab E831
  - ~180 GeV γ beam on BeO – photon beam!
  - $\Lambda_c^+ \to pK_s^0$ and $\Lambda_c^+ \to \Lambda^0\pi^+$ and corresponding $\overline{\Lambda}_c^+$ modes
- Polarization consistent with zero, but almost 2σ positive for $\overline{\Lambda}_c^+$
- Product of $\alpha_{\Lambda_c} P$ given for both decay modes, but P only extracted for $\Lambda_c^+ \to \Lambda^0\pi^+$ because need more study of decay asymmetry parameter for other mode
- Only preliminary results in conference proceedings: Carrillo, Castromonte, Oropeza, AIP Conf. Proc. 1026, 303 (2008)

Λ_c^+ *polarization measurements*

- Fermilab E831 – Photon beam!
- AIP Conf. Proc. 1026, 303 (2008)

TABLE 1. Preliminary $\alpha_{\Lambda_c} P$ values for both decay modes.

	$\alpha_{\Lambda_c} P$-Particles	$\alpha_{\Lambda_c} P$-Antiparticles
$\Lambda_0 \pi$	0.030 ± 0.131	0.278 ± 0.139
$K_s p$	0.061 ± 0.096	0.276 ± 0.099

TABLE 2. Preliminary results for $\Lambda_c \rightarrow \Lambda_0 \pi$ polarization.

		P_{Λ_c}-Particles	P_{Λ_c}-Antiparticles
α^+_{PDG}	$= -0.98 \pm 0.19$	-0.0308 ± 0.1339	0.2839 ± 0.1521
α^+_{FOCUS}	$= -0.78 \pm 0.16 \pm 0.19$	$-0.0386 \pm 0.1679 \pm 0.1106$	$0.3566 \pm 0.1926 \pm 0.1485$

Λ_c^+ *polarization: Status*

- Λ_c^+ polarization measured in four independent experiments:
  - Serpukhov BIS-2 (neutron beam)
  - CERN NA 32 (π^- beam)
  - Fermilab E791 (π^- beam)
  - Fermilab E831 (photon beam)
- All results suggest negative polarization, but with relatively large uncertainties
- Need new measurements!

Λ_b^0 *polarization measurements*

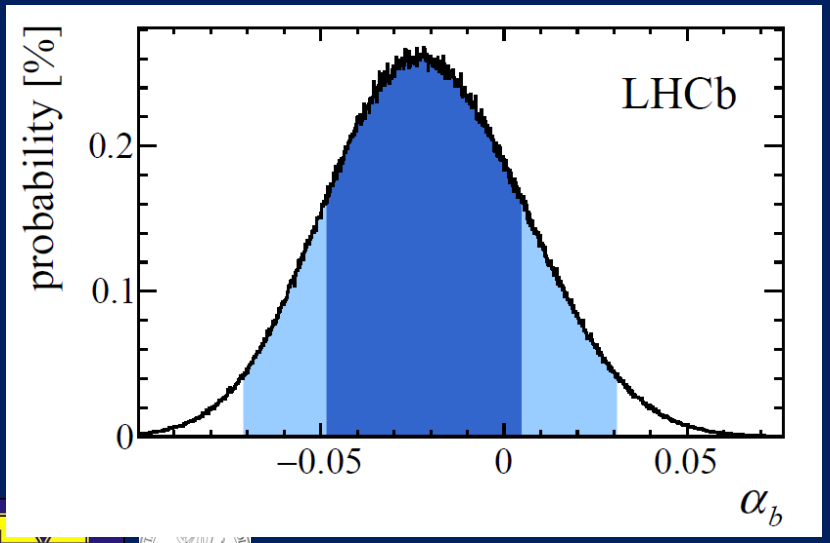
- LHCb 7 TeV p+p measured transverse production polarization of 7200 $\Lambda_b^0 \to J/\psi\Lambda$ consistent with zero ($x_F \approx 0.02$):
  $P_b = 0.06 \pm 0.07 \pm 0.02; \quad \alpha = 0.05 \pm 0.17 \pm 0.07$
  - PLB724, 27 (2013)

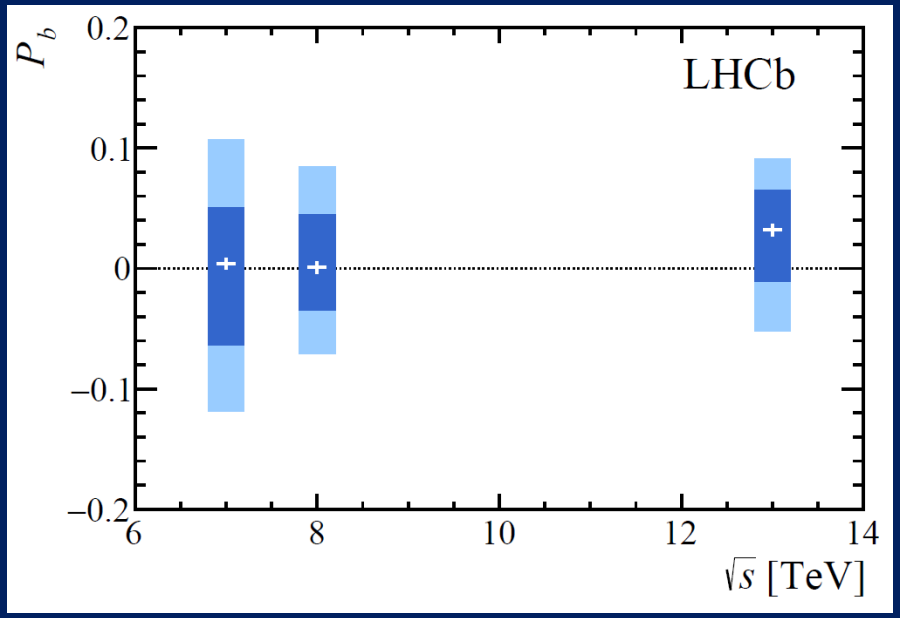
- ATLAS *assumed* zero Λ_b^0 polarization and extracted $\alpha = 0.30 \pm 0.16 \pm 0.06$ for $\Lambda_b^0 \to J/\psi\Lambda$
  - PRD 89, 092009 (2014)

- CMS 7 and 8 TeV p+p: $\Lambda_b^0 \to J/\psi\Lambda$:
  $P_b = 0.00 \pm 0.06 \pm 0.06; \quad \alpha = 0.14 \pm 0.14 \pm 0.10$
  - PRD97, 072010 (2018)

Λ_b^0 *polarization measurements*

- New! LHCb 7, 8, 13 TeV p+p $\Lambda_b^0 \to J/\psi\Lambda$, 1-20 GeV p_T. Best measurement of decay asymmetry parameter, and new measurements of polarization (consistent w/zero).
  - arXiv:2004.10563





Theoretical ideas regarding heavy baryon production

- Heavy quark fragmentation into a heavy hadron has been studied using a variety of techniques
  - Operator Product Expansion techniques
  - Light cone quantization
  - QCD perturbation theory (especially for multi-heavy hadrons)
  - Heavy-quark effective theory
  - . . .

Heavy-Quark Effective Theory (HQET)

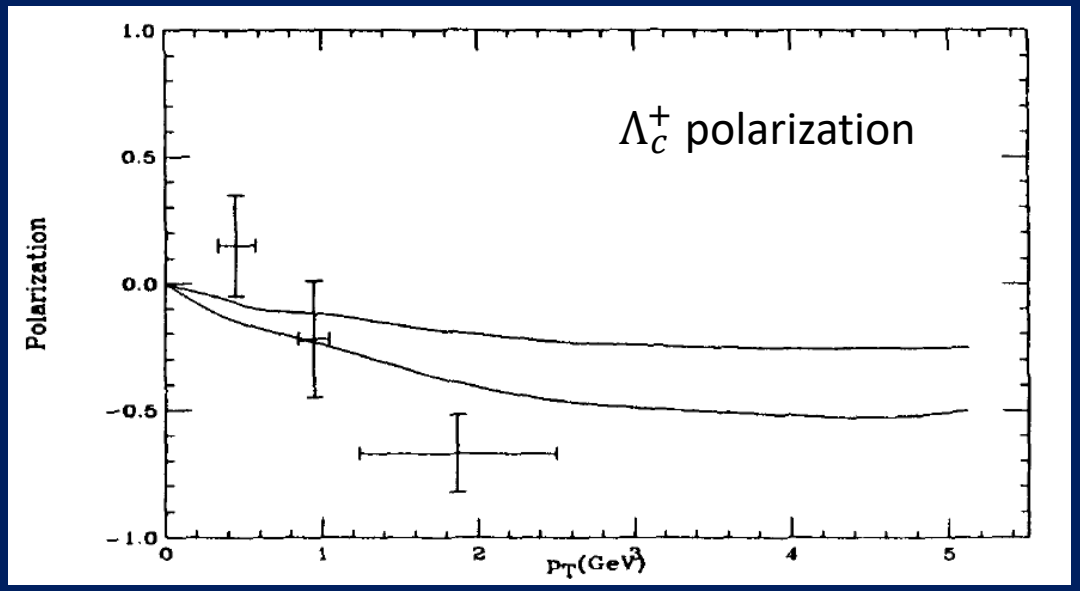
- Effective theories in QCD – typically limit yourself to a particular (approximate) regime where certain things simplify with respect to full QCD
- HQET: Because $m_Q \gg \Lambda_{QCD}$, take limit as $m_Q \to \infty$
  - An approximation, but *model-independent*!
  - Radiative and nonperturbative corrections to the $m_Q \to \infty$ limit can be systematically investigated

Heavy-Quark Effective Theory (HQET)

- HQET predicts that heavy baryons coming from energetic heavy quarks retain a large fraction of the heavy quark polarization
  - See e.g. Mannel and Schuler, PLB279, 194 (1992); Falk and Peskin, PRD49, 3320 (1994)

- Supported by LEP e+e- annihilation data using $Z \rightarrow \bar{b}b$ decays with observed Λ_b^0 baryons
  - In Standard Model, decay of Z produces b quarks with large average *longitudinal* polarization of -0.94
  - E.g. OPAL measured nonzero *longitudinal* polarization of Λ_b^0 from Z decay: $-0.56 + 0.20 - 0.13 \pm 0.09$
    - PLB444, 539 (1998)

Heavy flavor baryon phenomenology



G. Goldstein, Spin Praha proceedings 2001.
Two curves are range of calculation.

- So far little phenomenology!
- Comparison to E791 Λ_c^+ polarization measurement by Gary Goldstein.
- Uses a hybrid model with perturbatively generated c quark polarization in the hard scattering process, followed by hadronization via recombination with a (ud) diquark system
- Polarization of the c quark retained by the baryon

Summary: Lecture 6

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- A wealth of measurements exist showing large "spontaneous" transverse hyperon polarization, based on angular distributions of decay products
  - The more particles in the final state, the more complex the angular analysis!
  - Need both nonzero polarization and nonzero decay asymmetry parameter for the particular decay channel in order to perform such measurements

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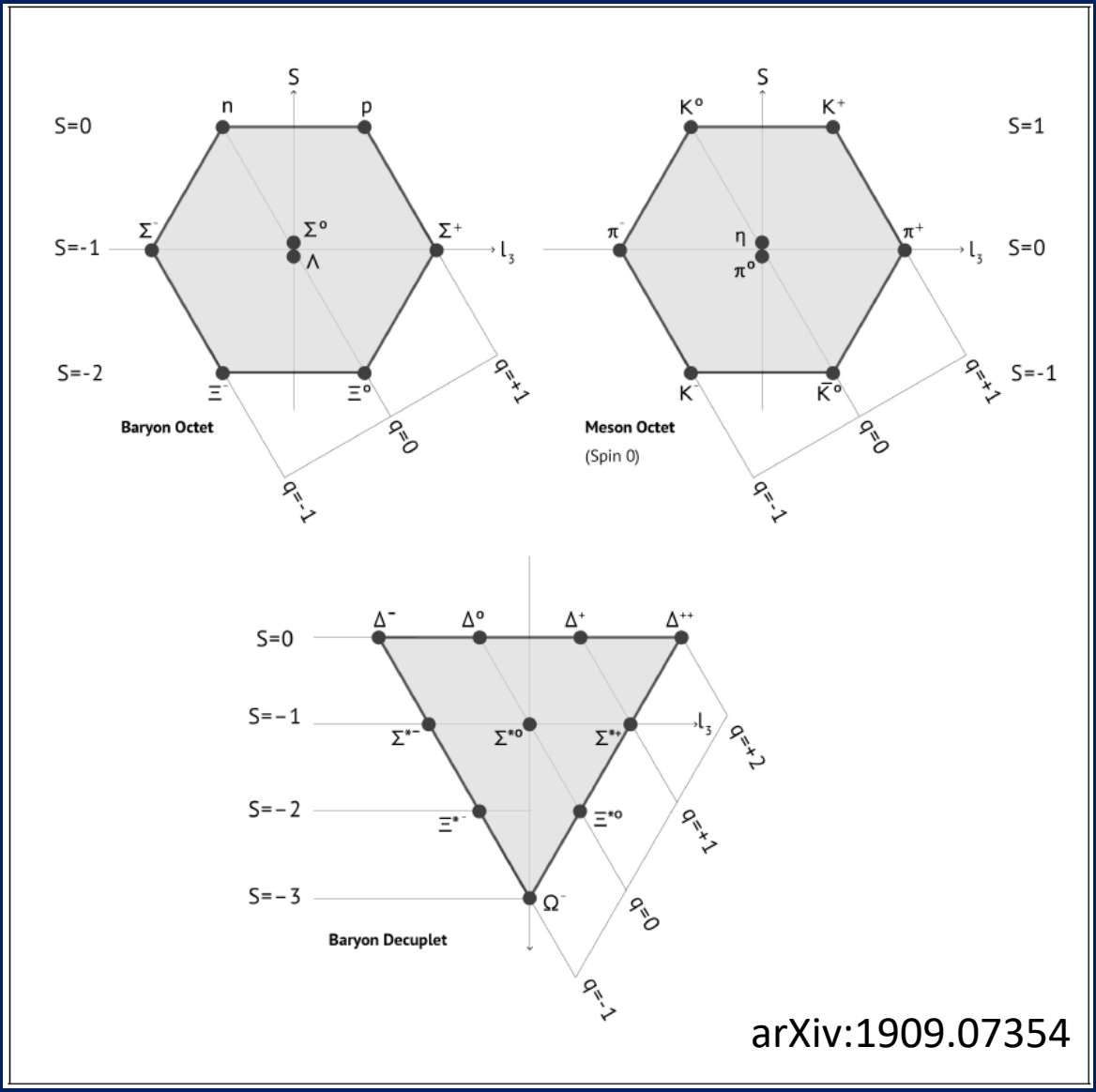
- Polarized heavy flavor baryons provide opportunities to measure their electric and magnetic dipole moments
- More experimental data needed, and on its way! Opportunities at the LHC and Belle II.

Extra



arXiv:1909.07354

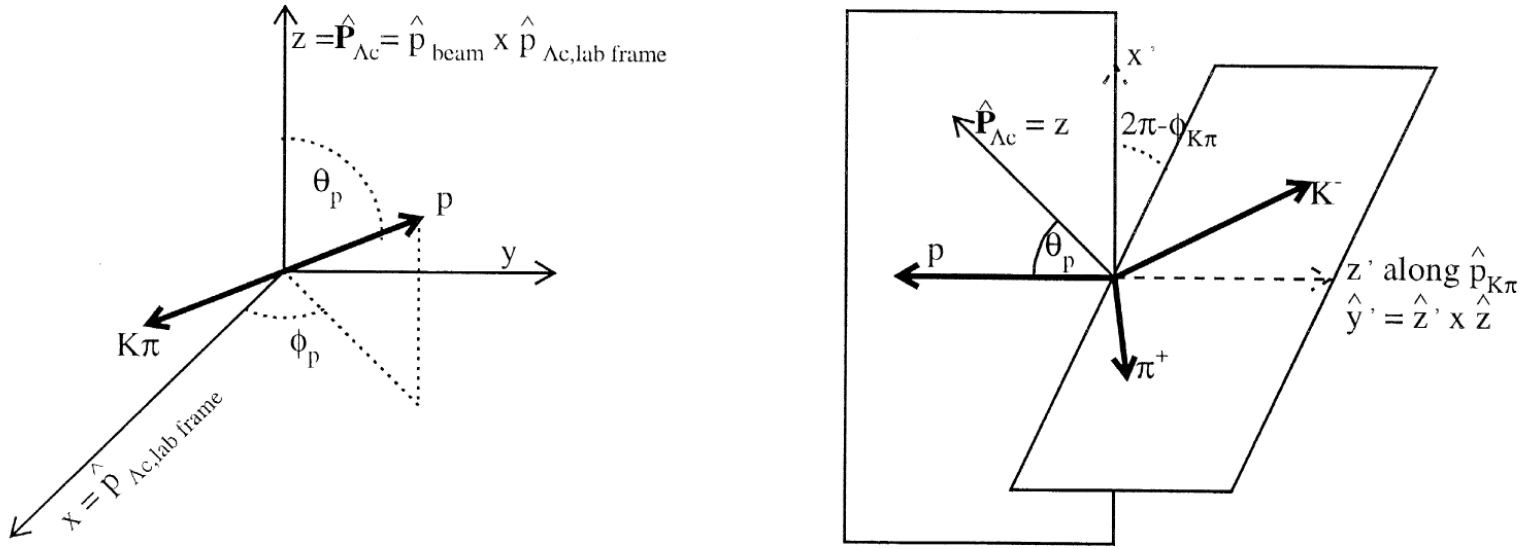


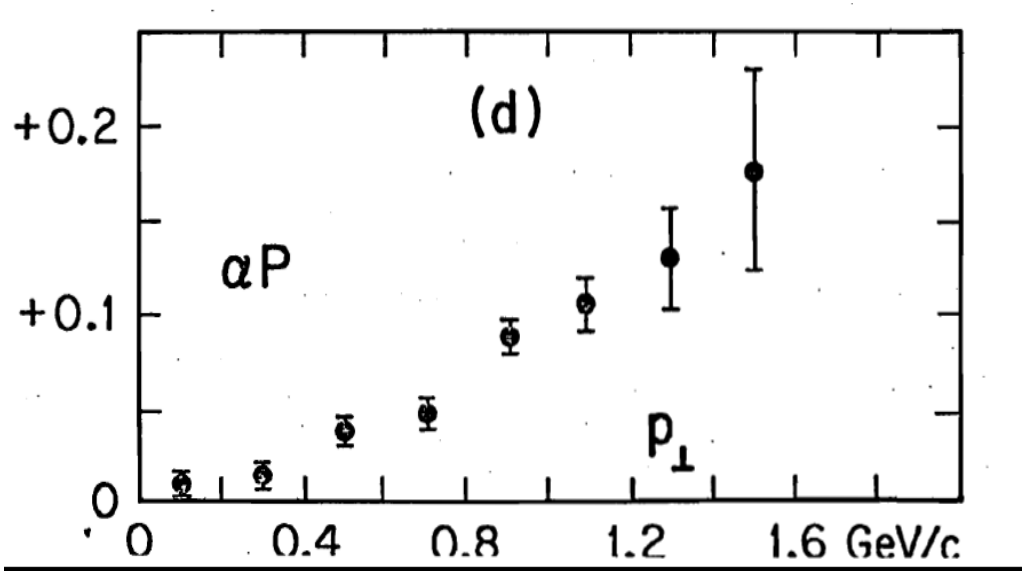
Fig. 1. Definition of angles using $\Lambda_c^+ \to p\overline{K}^{*0} \to pK^-\pi^+$ as an example. In both figures the Λ_c^+ is at rest. In the first figure, which defines (θ_p, ϕ_p), the x-axis is along the direction of motion of the Λ_c^+ in the lab frame and the z-axis is the polarization axis, normal to the plane of production. In the second figure we define $\phi_{K\pi}$ as the angle between the plane containing the $\overline{K}^{*0}$ decay products and the plane containing the proton and the x-axis.

Aitala et al. (E791), PLB471, 449 (2000)

Hyperon polarization from unpolarized collisions

Λ° Hyperon Polarization
in Inclusive Production
by 300 GeV Protons on
Beryllium

PRL36, 1113 (1976)



- 1976 lambda polarization discovery: p+Be, 300 GeV beam
- Polarization transverse to production plane up to ~20% for forward-angle lambda production
- Confirmed 1977 at CERN, p+Pt, 24 GeV beam (and by various proton-nucleus and proton-proton experiments afterwards . . .)