Possible CP symmetry tests in semileptonic hyperon decays

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CP violation in non-leptonic decays

[Andrzej's slides]

$$A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}}$$

- BESIII result: $A_\Lambda = -0.006 \pm 0.012 \pm 0.007$ [NaturePhys.15(2019)631]
- CKM: $-3 \cdot 10^{-5} \leq A_\Lambda \leq 4 \cdot 10^{-5}$ [PRD67(2003)056001]
  Extensions of SM: $A_{\Lambda \to p\pi^-} \sim (0.05 - 1.2) \cdot 10^{-4}$ [Chin.Phys.C42(2018)013101]

Experiment	N_{evt}	$\sigma(A_\Lambda)$	
BESIII (2018)	$4.2 \cdot 10^5$	$1.2 \cdot 10^{-2}$	$N_{J/\psi} = 1.31 \cdot 10^9$
Some estimations			
BESIII	$3 \cdot 10^6$	$5 \cdot 10^{-3}$	$N_{J/\psi} = 10^{10}$ $\mathcal{L} = 0.47 \cdot 10^{33}/\text{cm}^2/\text{s}$, ΔE=0.9 MeV
SuperTauCharm	$6 \cdot 10^8$	$3 \cdot 10^{-4}$	$N_{J/\psi} = 2 \cdot 10^{12}$ $\mathcal{L} = 10^{35}/\text{cm}^2/\text{s}$, ΔE=0.9 MeV
SuperTauCharm + reduced ΔE	$3 \cdot 10^9$	$1.4 \cdot 10^{-4}$	$N_{J/\psi} = 10^{13}$ $\mathcal{L} = 10^{35}/\text{cm}^2/\text{s}$, ΔE<0.9 MeV (?)

CP symmetry test A_Λ^{av}

$$A_\Lambda^{av} = \frac{g_{av}^{\Lambda}(0) + g_{av}^{\bar{\Lambda}}(0)}{g_{av}^{\Lambda}(0) - g_{av}^{\bar{\Lambda}}(0)}$$

- $g_{av}(0) = \frac{F_1^A(0)}{F_1^V(0)}$
  - Determination of $F_1^V(0)$ value by CVC hypothesis: $F_1^V(0) < 0$
  - No determination of $F_1^A(0)$ value by any general theoretical arguments
- Some assumptions:
  - $F_1^A(0) \lessgtr 0$ then $g_{av}(0) \gtrless 0$
  - ? Naïve assumption $g_{av}^{\Lambda} = -g_{av}^{\bar{\Lambda}}$
    $\Longrightarrow$ Need to be care with sign of g_{av}

Experiment	$\mathrm{N_{evt}}$	Result	Reference
E555 (Fermilab)	37286	$g_{av}(0) = 0.719 \pm 0.016 \pm 0.012$ constrain on $g_w(0) = 0.97$	[PRD41(1990)780]
SPS (CERN)	7111	$g_{av}(0) = 0.70 \pm 0.03$ measured $F_2^V(0) = 1.32 \pm 0.81$	[ZPC21(1983)1]
AGS (BNL)	10^4	$\lvert g_{av}(0)\rvert = 0.734 \pm 0.031$ used $g_w(0) = 0.97$	[PLB98(1981)123]

$g_{av}(0)$ and ϕ_{av} parameters

$$\langle B_f|\gamma_\mu(F_1^V(0) + F_1^A(0)\gamma_5) + \frac{F_2^V(0)}{M_1}\sigma_{\mu\nu}q^\nu|B_i\rangle,$$

$$g_{av}(0) = |g_{av}(0)|e^{i\phi_{av}} = \left|\frac{F_1^A(0)}{F_1^V(0)}\right| e^{i\phi_{av}}$$

- $\phi_{av} = (0 + n\pi)$ [PR106(1957)517]
  $\Longrightarrow$ If time-reversal invariance holds
- Experiments on leptonic baryon decays other than $n\beta$ decay assume $\phi_{av} = 0$ or $\pi \Longrightarrow$ measurement of magnitude and sign of g_{av}
- Experiments on $n \to pe^-\bar{\nu}_e$ are sensitive to measure ϕ_{av} more precisely

$$\phi_{av} = 180.017 \pm 0.026^\circ \qquad \text{[PDG2020]}$$

$\Longrightarrow$ consistent with time-reversal invariance, then $g_{av}(0) < 0$

CP symmetry test A_Λ^w

$$A_\Lambda^w = \frac{g_w^\Lambda(0) + g_w^{\bar{\Lambda}}(0)}{g_w^\Lambda(0) - g_w^{\bar{\Lambda}}(0)}$$

- $g_w(0) = \frac{F_2^V(0)}{F_1^V(0)}$
  - Assumption of $F_2^V(0)$ value from CVC hypothesis and SU(3) [PRL10(1963)531]

CP symmetry test A^w_Λ

$$A^w_\Lambda = \frac{g^\Lambda_w(0) + g^{\bar{\Lambda}}_w(0)}{g^\Lambda_w(0) - g^{\bar{\Lambda}}_w(0)}$$

- $g_w(0) = \frac{F^V_2(0)}{F^V_1(0)}$
  - Assumption of $F^V_2(0)$ value from CVC hypothesis and SU(3) [PRL10(1963)531]
- $(\Lambda \to p)$-transition: $g_w(0) = \frac{M_\Lambda}{M_p}\frac{\mu_p}{2}$
- Differences between particle and anti-particle [PDG2020]:

$$\frac{M_\Lambda - M_{\bar{\Lambda}}}{M_\Lambda} = (-0.1 \pm 1.1)\cdot 10^{-5}; \quad \frac{M_p - M_{\bar{p}}}{M_p} < 7\cdot 10^{-10}; \quad \frac{\mu_p + \mu_{\bar{p}}}{\mu_p} = (2 \pm 4)\cdot 10^{-9}$$

$$\frac{M_\Lambda}{M_p} = \frac{M_{\bar{\Lambda}}}{M_{\bar{p}}} \quad \Longrightarrow \quad A^w_\Lambda \approx \frac{\mu_p + \mu_{\bar{p}}}{\mu_p - \mu_{\bar{p}}}$$

- Sign of g_w is predicted by μ_p value

Experiment	$\mathrm{N_{evt}}$	Result	Reference
E555 (Fermilab)	37286	$g_w(0) = 0.15 \pm 0.30$ for $g_{av}(0) = 0.731 \pm 0.016$	[PRD41(1990)780]
SPS (CERN)	7111	$g_w(0) = 1.32 \pm 0.81$	[ZPC21(1983)1]
AGS (BNL)	10^4	used $g_w(0) = 0.97$	[PLB98(1981)123]

Corrections in the SLH helicity formalism

Decay chain: $\frac{1}{2} \to \frac{1}{2} + \{0, \pm 1\}$ (1)

- Relation between helicity amplitudes and decay parameters

$$\text{normalization}\ \ \frac{1}{4}(1-\cos\theta_l)^2|H_{\frac{1}{2}1}|^2 + \frac{1}{4}(1+\cos\theta_l)^2|H_{-\frac{1}{2}-1}|^2 + \frac{1}{2}\sin^2\theta_l(|H_{-\frac{1}{2}0}|^2 + |H_{\frac{1}{2}0}|^2) = 1,$$

$$\alpha_D^{sl} = \frac{1}{4}(1-\cos\theta_l)^2|H_{\frac{1}{2}1}|^2 - \frac{1}{4}(1+\cos\theta_l)^2|H_{-\frac{1}{2}-1}|^2 + \frac{1}{2}\sin^2\theta_l(|H_{-\frac{1}{2}0}|^2 - |H_{\frac{1}{2}0}|^2),$$

$$\beta_D^{sl} = \frac{1}{\sqrt{2}}\sin\theta_l\sin\chi((1+\cos\theta_l)\Im(H^*_{-\frac{1}{2}0}H_{-\frac{1}{2}-1}) + (1-\cos\theta_l)\Im(H^*_{\frac{1}{2}1}H_{\frac{1}{2}0})),$$

$$\gamma_D^{sl} = \frac{1}{\sqrt{2}}\sin\theta_l\cos\chi((1+\cos\theta_l)\Re(H^*_{-\frac{1}{2}0}H_{-\frac{1}{2}-1}) + (1-\cos\theta_l)\Re(H^*_{\frac{1}{2}1}H_{\frac{1}{2}0}))$$

$$\text{where}\ \beta_D^{sl} = \sqrt{1-(\alpha_D^{sl})^2}\sin\phi_D^{sl}\ \text{and}\ \gamma_D^{sl} = \sqrt{1-(\alpha_D^{sl})^2}\cos\phi_D^{sl}$$

- Corrected relation:

$$\text{normalization}\ \ \frac{1}{4}(1-\cos\theta_l)^2|H_{\frac{1}{2}1}|^2 + \frac{1}{4}(1+\cos\theta_l)^2|H_{-\frac{1}{2}-1}|^2 + \frac{1}{2}\sin^2\theta_l(|H_{-\frac{1}{2}0}|^2 + |H_{\frac{1}{2}0}|^2) = 1,$$

$$\alpha_D^{sl} = \frac{1}{4}(1-\cos\theta_l)^2|H_{\frac{1}{2}1}|^2 - \frac{1}{4}(1+\cos\theta_l)^2|H_{-\frac{1}{2}-1}|^2 + \frac{1}{2}\sin^2\theta_l(|H_{-\frac{1}{2}0}|^2 - |H_{\frac{1}{2}0}|^2),$$

$$\beta_D^{sl} = \frac{1}{\sqrt{2}}\sin\theta_l\cancel{\sin\chi}((1+\cos\theta_l)\Im(H^*_{-\frac{1}{2}0}H_{-\frac{1}{2}-1}) + (1-\cos\theta_l)\Im(H^*_{\frac{1}{2}1}H_{\frac{1}{2}0})),$$

$$\gamma_D^{sl} = \frac{1}{\sqrt{2}}\sin\theta_l\cancel{\cos\chi}((1+\cos\theta_l)\Re(H^*_{-\frac{1}{2}0}H_{-\frac{1}{2}-1}) + (1-\cos\theta_l)\Re(H^*_{\frac{1}{2}1}H_{\frac{1}{2}0}))$$

$$\text{where}\ \beta_D^{sl} = \sqrt{1-(\alpha_D^{sl})^2}\sin\phi_D^{sl}\ \text{and}\ \gamma_D^{sl} = \sqrt{1-(\alpha_D^{sl})^2}\cos\phi_D^{sl}$$

Decay chain: $\frac{1}{2} \to \frac{1}{2} + \{0, \pm 1\}$ (2)

- Non-zero elements of the decay matrix $b_{\mu\nu}$:

$$
\begin{aligned}
b_{00} &= 1, & b_{21} &= -\gamma_D^{sl} \cos\theta \sin\phi - \beta_D^{sl} \cos\phi, \\
b_{03} &= \alpha_D^{sl}, & b_{22} &= \beta_D^{sl} \cos\theta \sin\phi - \gamma_D^{sl} \cos\phi, \\
b_{10} &= \alpha_D^{sl} \cos\phi \sin\theta, & b_{23} &= \sin\theta \sin\phi, \\
b_{11} &= -\gamma_D^{sl} \cos\theta \cos\phi + \beta_D^{sl} \sin\phi, & b_{30} &= \alpha_D^{sl} \cos\theta, \\
b_{12} &= \beta_D^{sl} \cos\theta \cos\phi + \gamma_D^{sl} \sin\phi, & b_{31} &= \gamma_D^{sl} \sin\theta, \\
b_{13} &= \sin\theta \cos\phi, & b_{32} &= -\beta_D^{sl} \sin\theta, \\
b_{20} &= \alpha_D^{sl} \sin\theta \sin\phi, & b_{33} &= \cos\theta
\end{aligned}
$$

- Corrected elements:

$$
\begin{aligned}
b_{00} &= 1, & b_{21} &= -(\gamma_D^{sl} \cos\chi + \beta_D^{sl} \sin\chi) \cos\theta \sin\phi \\
b_{03} &= \alpha_D^{sl}, & &\quad - (\gamma_D^{sl} \sin\chi - \beta_D^{sl} \cos\chi) \cos\phi, \\
b_{10} &= \alpha_D^{sl} \cos\phi \sin\theta, & b_{22} &= (\gamma_D^{sl} \sin\chi - \beta_D^{sl} \cos\chi) \cos\theta \sin\phi \\
b_{11} &= -(\gamma_D^{sl} \cos\chi + \beta_D^{sl} \sin\chi) \cos\theta \cos\phi & &\quad - (\gamma_D^{sl} \cos\chi + \beta_D^{sl} \sin\chi) \cos\phi, \\
&\quad + (\gamma_D^{sl} \sin\chi - \beta_D^{sl} \cos\chi) \sin\phi, & b_{23} &= \sin\theta \sin\phi, \\
b_{12} &= (\gamma_D^{sl} \sin\chi - \beta_D^{sl} \cos\chi) \cos\theta \cos\phi & b_{30} &= \alpha_D^{sl} \cos\theta, \\
&\quad + (\gamma_D^{sl} \cos\chi + \beta_D^{sl} \sin\chi) \sin\phi, & b_{31} &= \quad (\gamma_D^{sl} \cos\chi + \beta_D^{sl} \sin\chi) \sin\theta, \\
b_{13} &= \sin\theta \cos\phi, & b_{32} &= -(\gamma_D^{sl} \sin\chi - \beta_D^{sl} \cos\chi) \sin\theta, \\
b_{20} &= \alpha_D^{sl} \sin\theta \sin\phi, & b_{33} &= \cos\theta
\end{aligned}
$$

- Main parameters: $\theta \equiv \theta_p$, $\phi \equiv \phi_p$, $\alpha_D^{sl} = \alpha_\Lambda^{sl}(\theta_l, \cancel{\chi}, q^2)$, $\phi_D^{sl} = \phi_D^{sl}(\theta_l, \cancel{\chi}, q^2)$
- Each element of $b_{\mu\nu}$ is multiplied by $q^2 p$ where $p = \sqrt{M_+(q^2) M_-(q^2)}/(2M_1)$

Intermediate step (1)

- $\alpha_\Lambda^{sl}(\theta_l, q^2, g_{av}^\Lambda, g_w^\Lambda) \Rightarrow \{\alpha, \alpha', \alpha'', \beta_{1,2}, \gamma_{1,2}\}(q^2)$: g_{av}^Λ, g_w^Λ
- Introduce the intermediate parameters:

$$\begin{aligned}
\text{normalization} \quad 1 &= |H_{\frac{1}{2}1}|^2 + |H_{-\frac{1}{2}-1}|^2 + 2(|H_{-\frac{1}{2}0}|^2 + |H_{\frac{1}{2}0}|^2), \\
\alpha &= |H_{\frac{1}{2}1}|^2 - |H_{-\frac{1}{2}-1}|^2 + 2(|H_{-\frac{1}{2}0}|^2 - |H_{\frac{1}{2}0}|^2), \\
\alpha' &= |H_{\frac{1}{2}1}|^2 + |H_{-\frac{1}{2}-1}|^2 - 2(|H_{-\frac{1}{2}0}|^2 + |H_{\frac{1}{2}0}|^2), \\
\alpha'' &= |H_{\frac{1}{2}1}|^2 - |H_{-\frac{1}{2}-1}|^2 - 2(|H_{-\frac{1}{2}0}|^2 - |H_{\frac{1}{2}0}|^2), \\
\beta_{1,2} &= 2(\Im(H^*_{-\frac{1}{2}0} H_{-\frac{1}{2}-1}) \pm \Im(H^*_{\frac{1}{2}1} H_{\frac{1}{2}0})), \\
\gamma_{1,2} &= 2(\Re(H^*_{-\frac{1}{2}0} H_{-\frac{1}{2}-1}) \pm \Re(H^*_{\frac{1}{2}1} H_{\frac{1}{2}0})),
\end{aligned}$$

where $\beta_{1,2} = \frac{1}{2}\sqrt{1 - \alpha^2 - (\alpha')^2 + (\alpha'')^2}\sin\phi_{1,2}$ and $\gamma_{1,2} = \frac{1}{2}\sqrt{1 - \alpha^2 - (\alpha')^2 + (\alpha'')^2}\cos\phi_{1,2}$

- $\alpha^2 + (\alpha')^2 - (\alpha'')^2 + 2(\gamma_1^2 + \gamma_2^2 + \beta_1^2 + \beta_2^2) = 1$
- Using the definition of helicity amplitudes the main parameters to describe semileptonic hyperon decays are:

  - $F_1^V(0)$, $F_2^V(0)$, $F_1^A(0)$

  or

  - $g_{av}^D(0) = \dfrac{F_1^A(0)}{F_1^V(0)}$, $\quad g_w^D(0) = \dfrac{F_2^V(0)}{F_1^V(0)}$

Intermediate step (2)

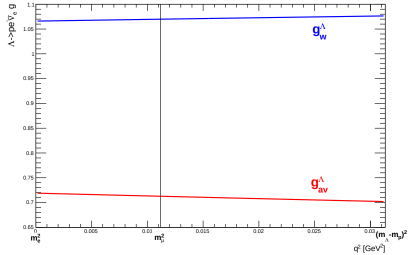
- Relations between intermediate and decay parameters:

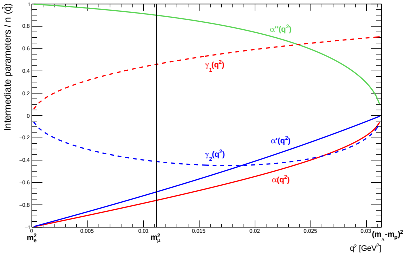
$$\alpha = 2\sqrt{(M_-M_+)^2 - 2q^2(M_1^2+M_2^2)+q^4}\left[g_{av}^D(q^2)(q^2 - M_-M_+) + 2g_{av}^D(q^2)g_w^D(q^2)q^2\frac{M_2}{M_1}\right]$$

$$\alpha' = (M_-^2 - q^2)(M_+^2 - q^2)\left[-(1+(g_{av}^D(q^2))^2) + (g_w^D(q^2))^2\frac{q^2}{M_1^2}\right]$$

$$\alpha'' = 2\sqrt{(M_-M_+)^2 - 2q^2(M_1^2+M_2^2)+q^4}\left[g_{av}^D(q^2)(q^2 + M_-M_+) + 2g_{av}^D(q^2)g_w^D(q^2)q^2\right]$$

where $M_- = M_1 - M_2$ and $M_+ = M_1 + M_2$





Intermediate step (3)

- Non-zero elements of the decay matrix $b_{\mu\nu}$:

$$
\begin{aligned}
&\boxed{b_{00} = 1,} && b_{21} = -A\cos\theta_p \sin\phi_p - B\cos\phi_p,\\
&b_{03} = \alpha_D^{sl}(\theta_l, q^2), && b_{22} = B\cos\theta_p \sin\phi_p - A\cos\phi_p,\\
&\boxed{b_{10} = \alpha_D^{sl}(\theta_l, q^2)\cos\phi_p \sin\theta_p,} && b_{23} = \sin\theta_p \sin\phi_p,\\
&b_{11} = -A\cos\theta_p \cos\phi_p + B\sin\phi_p, && \boxed{b_{30} = \alpha_D^{sl}(\theta_l, q^2)\cos\theta_p,}\\
&b_{12} = B\cos\theta_p \cos\phi_p + A\sin\phi_p, && b_{31} = A\sin\theta_p,\\
&b_{13} = \sin\theta_p \cos\phi_p, && b_{32} = -B\sin\theta_p,\\
&\boxed{b_{20} = \alpha_D^{sl}(\theta_l, q^2)\sin\theta_p \sin\phi_p,} && b_{33} = \cos\theta_p,
\end{aligned}
$$

where $A = \frac{1}{2\sqrt{2}}\sin\theta_l[\cos\chi(\gamma_1 + \cos\theta_l\gamma_2) + \sin\chi(\beta_1 + \cos\theta_l\beta_2)]$

and $B = \frac{1}{2\sqrt{2}}\sin\theta_l[\sin\chi(\gamma_1 + \cos\theta_l\gamma_2) - \cos\chi(\beta_1 + \cos\theta_l\beta_2)]$

- $\alpha_\Lambda^{sl}(\theta_l, q^2) = \alpha + \alpha''\cos^2\theta_l - (1+\alpha')\cos\theta_l$

Joint angular distribution

- Process $e^+e^- \to (\Lambda \to p e^- \bar{\nu}_e)(\bar{\Lambda} \to \bar{p}\pi^+)$

$$\mathrm{Tr}\rho_{pW\bar{p}} \propto \mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} b^{\Lambda}_{\mu 0} a^{\bar{\Lambda}}_{\bar{\nu}0}$$

  - $C_{\mu\bar{\nu}}(\theta_\Lambda;\alpha_\psi,\Delta\Phi)$
  - $b_{\mu 0}$ matrices for $1/2 \to 1/2 + \{0,\pm 1\}$ decays $\Leftrightarrow b^{\Lambda}_{\mu 0} \equiv b_{\mu 0}(\theta_p,\varphi_p,\theta_e,\chi,q^2;\boxed{g^{\Lambda}_{av},g^{\Lambda}_{w}})$
  - $a_{\bar{\nu}0}$ matrices for $1/2 \to 1/2+0$ decays $\Leftrightarrow a^{\bar{\Lambda}}_{\bar{\nu}0} \equiv a_{\bar{\nu}0}(\theta_{\bar{p}},\varphi_{\bar{p}};\boxed{\alpha_{\bar{\Lambda}}})$
    - $\boldsymbol{\xi} \equiv (\theta_\Lambda,\theta_p,\varphi_p,\theta_e,\chi,q^2,\theta_{\bar{p}},\varphi_{\bar{p}})$
    - $\boldsymbol{\omega} \equiv (\alpha_\psi,\Delta\Phi,\boxed{g^{\Lambda}_{av},g^{\Lambda}_{w}},\boxed{\alpha_{\bar{\Lambda}}})$

- Range of $q^2 \in (m_l^2,(M_1-M_2)^2)$ is specific for each decay

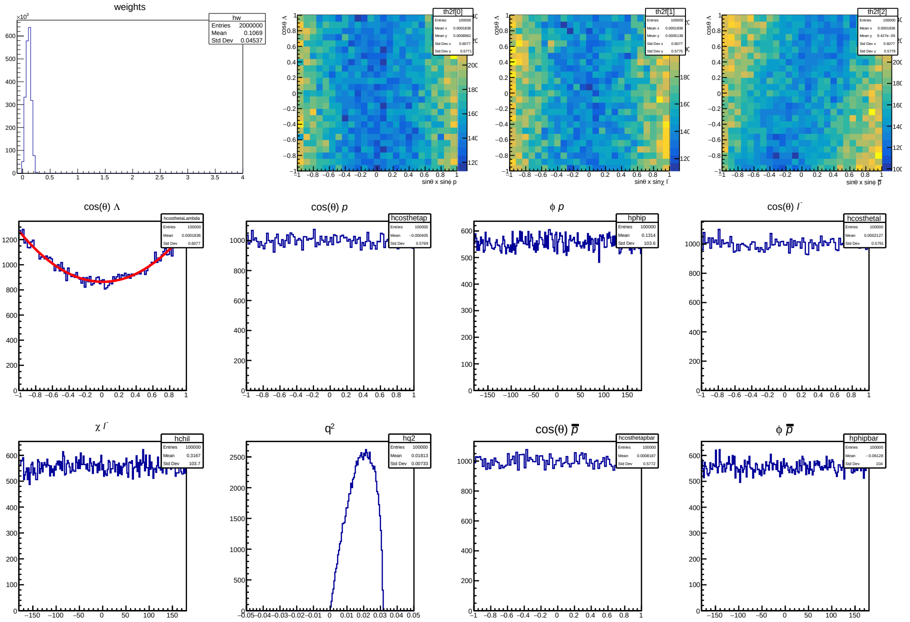
MC generator (step 1)

- Using **`YYbar_example`** package by Patrik, the presented process can be generated
  - MC samples: $N_{\mathrm{evt}}^{\mathrm{sig}}$=$10^5$ and $N_{\mathrm{evt}}^{\mathrm{phsp}}$=$10^6$
  - Generate $q^2 \in (m_e^2, (M_\Lambda - M_p)^2)$
  - Set of input values:

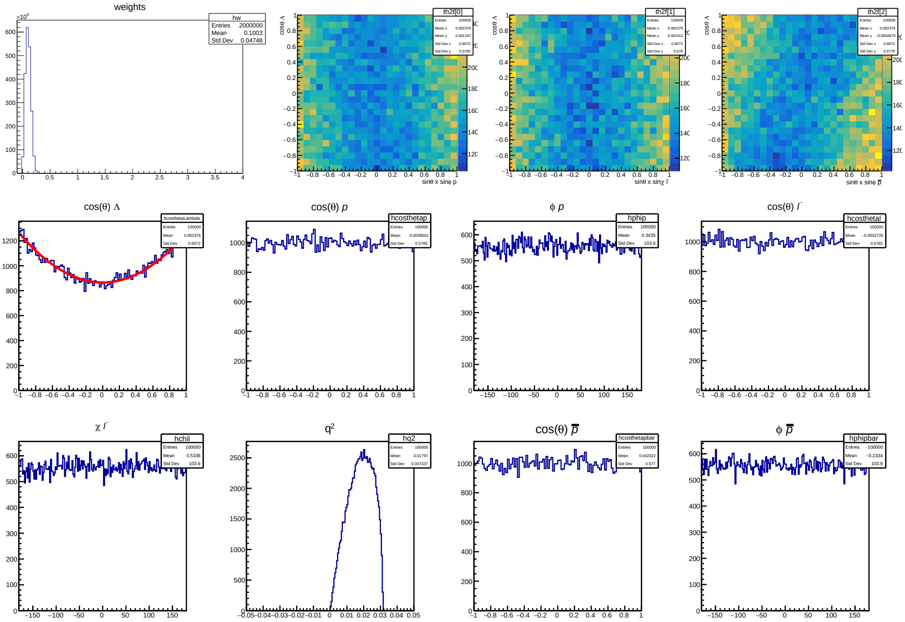
```
pp[0] =  0.461;      // alpha_J/psi (arxiv:1808.08917)
pp[1] =  0.74;       // Delta_Phi (arxiv:1808.08917, equal 42.4deg)
pp[2] =  0.719;       // gav Lambda->p e- nu_ebar
pp[3] =  1.066;       // gw Lambda->p e- nu_ebar
pp[4] = -0.758;       // alpha_D LambdaBar->pbar pi+ (arxiv:1808.08917)
```

- No negative weights are observed
- Maximal weight: ∼0.26 (old) and ∼0.34 (new)

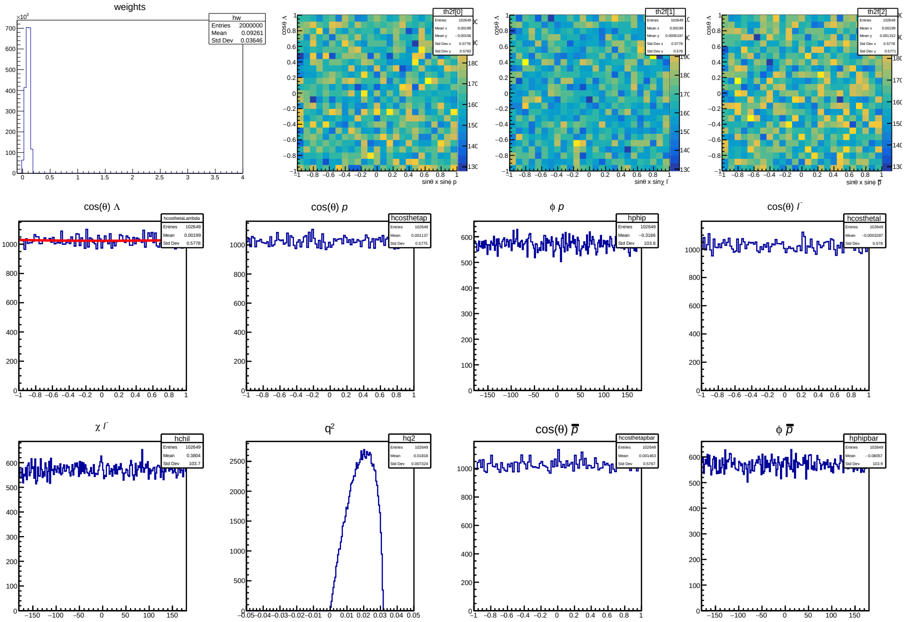
Random samples ($N_{sig} = 10^5$, old) (step 1)



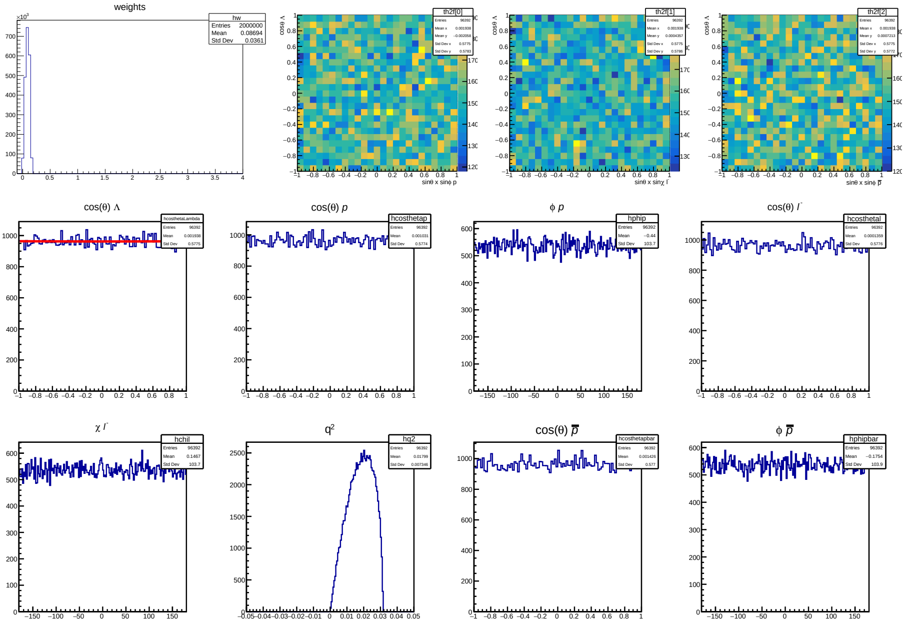
Random samples ($N_{sig} = 10^5$, new) (step 1)



Random samples ($N_{phsp} = 10^6$, old) (step 1)



Random samples ($N_{phsp} = 10^6$, new) (step 1)



Run through fit method (step 2)

- Set input values in the fit

```
void mainMLL(){

      // instantiating the values to be measured
      Double_t pp[4];
      for( int i = 0; i < 4; i++ ) pp[i]=0;

      // starting values for fit
      Double_t alpha_jpsi      = 0.461;     // alpha_J/Psi
      Double_t dphi_jpsi       = 0.74;       // relative phase, Dphi_J/Psi
      Double_t gav_lam_plnu    = 0.719;      // gav (Lam->p l nubar_l)
      Double_t gw_lam_plnu     = 1.066;      // gw (Lam->p l nubar_l)
      Double_t alpha_lam_pbarpip  = -0.758;    // alpha (Lambar->pbar pi+)

      alpha_jpsi         = gRandom->Rndm();
      dphi_jpsi          = gRandom->Rndm();
      gav_lam_plnu    = 0.719;
      gw_lam_plnu    = 1.066;
      alpha_lam_pbarpip = -0.758;

      ReadData();
      ReadMC();
```

- Output value of fit method

Parameter	$N_{sig}^{MC} = 10^5, N_{phsp}^{MC} = 10^6$	
	old*	new
α_Ψ	0.4550±0.0142	0.4605±0.0122
$\Delta\Phi$	1.4397±0.2372	0.7952±0.0315
g_{av}	0.8917±0.0727	0.7680±0.1061
g_w	-0.1524±0.9170	0.3106±1.0044
$\alpha_{\bar{\Lambda}}$	-0.4909±0.0244	-0.7374±0.0153

	new\old				
	α_Ψ	$\Delta\Phi$	g_{av}	g_w	$\alpha_{\bar{\Lambda}}$
α_Ψ	1	0.040	-0.033	-0.010	-0.212
$\Delta\Phi$	0.300	1	0.074	0.075	0.563
g_{av}	0.012	-0.013	1	0.381	0.182
g_w	0.022	-0.036	0.594	1	0.004
$\alpha_{\bar{\Lambda}}$	0.120	0.376	-0.261	-0.239	1

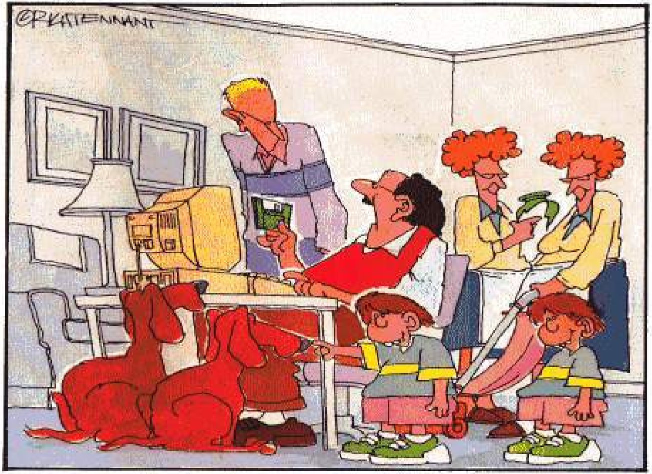
* Significant correlation between $\Delta\Phi$ and $\alpha_{\bar{\Lambda}}$ for "old" formalism

ToDo list and next steps

- Test formalism using
  1. Production of `mDIY` and `MC PhSp` for $e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$
     ∘ true and reco `mDIY` and `MC PhSp`
     ∘ allow to extract true and reco values of α_Λ and $\alpha_{\bar{\Lambda}}$ decay parameters
     ♠ MC samples are produced ⇒ verification is ongoing
  2. Modification of `mDIY` to include the semileptonic decay formalism
     ♠ Done for Λ and $\bar{\Lambda}$ decays
  3. Production of true and reco `mDIY` and `MC PhSp` for $\Lambda \to pe^-\bar{\nu}_e$
     ∘ extraction of the g_{av}^Λ and g_w^Λ decay parameters
     ♠ Production process is running
  4. If all steps work, consider more difficult scenario, mixed `MC` samples
  5. If previous step works, move to the real data

- Additional steps:
  - Estimate sensitivity to g_{av} and g_w decay parameters
  - Detailed study of possible *CP* tests

Backups



"I ALWAYS BACK UP EVERYTHING."

Semileptonic Λ decay

- Momenta and masses: $\Lambda(p_1, M_1) \to p(p_2, M_2) + e^-(p_e, m_e) + \bar{\nu}_e(p_{\bar{\nu}_e}, 0)$
- Standard set of invariant FF for weak current-induced baryonic $\frac{1}{2}^+ \to \frac{1}{2}^+$ transitions:

$$M_\mu = M_\mu^V + M_\mu^A = \langle p(p_2)|J_\mu^{V+A}|\Lambda(p_1)\rangle =$$

$$= \bar{u}(p_2)\left[\gamma_\mu\left(F_1^V(q^2) + F_1^A(q^2)\gamma_5\right) + \frac{i\sigma_{\mu\nu}q^\nu}{M_1}\left(F_2^V(q^2) + F_2^A(q^2)\gamma_5\right) + \frac{q_\mu}{M_1}\left(F_3^V(q^2) + F_3^A(q^2)\gamma_5\right)\right]u(p_1)$$

where $q_\mu = (p_1 - p_2)_\mu$

- For $\Lambda \to p e^- \bar{\nu}_e$ at $\mathcal{O}(\frac{m_e^2}{2q^2}) \to 0 \Rightarrow F_3^{V,A} \to 0$

- Helicity amplitude is $H_{\lambda_2\lambda_W} = (H^V_{\lambda_2\lambda_W} + H^A_{\lambda_2\lambda_W})$ with $(\lambda_2 = \pm\frac{1}{2};\ \lambda_W = 0, \pm 1)$:

vector

$$\begin{cases} H^V_{\frac{1}{2}1} = \sqrt{2M_-}\left(-F_1^V - \frac{M_1 + M_2}{M_1}F_2^V\right), \\ H^V_{\frac{1}{2}0} = \frac{\sqrt{M_-}}{\sqrt{q^2}}\left((M_1 + M_2)F_1^V + \frac{q^2}{M_1}F_2^V\right), \end{cases}$$

axial-vector

$$\begin{cases} H^A_{\frac{1}{2}1} = \sqrt{2M_+}\left(F_1^A - \frac{M_1 - M_2}{M_1}F_2^A\right), \\ H^A_{\frac{1}{2}0} = \frac{\sqrt{M_+}}{\sqrt{q^2}}\left(-(M_1 - M_2)F_1^A + \frac{q^2}{M_1}F_2^A\right). \end{cases}$$

where $M_\pm(q^2) = (M_1 \pm M_2)^2 - q^2;\ H^{V,A}_{-\lambda_2,-\lambda_W} = \pm H^{V,A}_{\lambda_2\lambda_W}$

Form factors

$$F_i^{V,A}(q^2) = F_i^{V,A}(0) \prod_{n=0}^{n_i} \frac{1}{1 - \frac{q^2}{m_{V,A}^2 + n\alpha'^{-1}}} \approx F_i^{V,A}(0) \left(1 + q^2 \sum_{n=0}^{n_i} \frac{1}{m_{V,A}^2 + n\alpha'^{-1}} \right) \equiv F_i^{V,A}(0) c_i^{V,A}(q^2)$$

	$F_i^{V,A}(0)(\Lambda \to p)$	$m_{V,A}$	α' [GeV^{-2}]	n_i
$F_1^V(q^2)$	$-\sqrt{\frac{3}{2}}$ [1]	$m_{K^*(892)^0}$ $(J^P = 1^-)$	0.9	$n_1 = 1$
$F_2^V(q^2)$	$\frac{M_\Lambda \mu_p}{2M_p} F_1^V(0)$ [2]			$n_2 = 2$
$F_3^V(q^2)$	0 [4]	-		$n_3 = 2$
$F_1^A(q^2)$	$0.719 F_1^V(0)$ [3]	$m_{K^*(1270)^0}$ $(J^P = 1^+)$		$n_1 = 1$
$F_2^A(q^2)$	0 [4]	$-$		$n_2 = 2$
$F_3^A(q^2)$	$\frac{M_\Lambda (M_\Lambda + M_p)}{(m_{K^-})^2} F_1^A(0)$ [4]	m_K $(J^P = 0^-)$		$n_3 = 2$

- [1] [PR135(1964)B1483], [PRL13(1964)264]
- [2] $\mu_p = 1.793$ [Lect.NotesPhys.222(1985)1], [Ann.Rev.Nucl.Part.Sci.53(2003)39], [JHEP0807(2008)132]
- [3] [PRD41(1990)780]
- [4] Vanish in the $SU(3)$ symmetry limit; Goldberger-Treiman relation [PR110(1958)1178], [PR111(1958)354]

Helicity amplitudes of the lepton pair $h^l_{\lambda_l \lambda_\nu}$

- Lepton and antineutrino spinors

$$\bar{u}_{l^-}(\mp\frac{1}{2}, p_{l^-}) = \sqrt{E_l + m_l}\left(\chi^\dagger_\mp, \frac{\pm|\vec{p}_{l^-}|}{E_l + m_l}\chi^\dagger_\mp\right),$$
$$v_{\bar{\nu}}(\frac{1}{2}) = \sqrt{E_\nu}\begin{pmatrix}\chi_+ \\ -\chi_+\end{pmatrix},$$

where $\chi_+ = \begin{pmatrix}1\\0\end{pmatrix}$ and $\chi_- = \begin{pmatrix}0\\1\end{pmatrix}$ are Pauli two-spinors

- SM form of the lepton current ($\lambda_W = \lambda_{l^-} - \lambda_{\bar{\nu}}$)

$$h^l_{\lambda_{l^-}=\mp 1/2, \lambda_{\bar{\nu}}=1/2} = \bar{u}_{l^-}(\mp\frac{1}{2})\gamma^\mu(1+\gamma_5)v_{\bar{\nu}}(\frac{1}{2})\begin{Bmatrix}\epsilon_\mu(-1)\\ \epsilon_\mu(0)\end{Bmatrix}$$

where $\epsilon^\mu(0) = (0;0,0,1)$ and $\epsilon^\mu(\mp 1) = (0;\mp 1, -i, 0)/\sqrt{2}$

- Moduli squared of the helicity amplitudes [EPJ C59 (2009) 27]

$$\text{nonflip}(\lambda_W = \mp 1) : |h^l_{\lambda_l=\mp\frac{1}{2}, \lambda_\nu=\pm\frac{1}{2}}|^2 = 8(q^2 - m_l^2),$$

$$\text{flip}(\lambda_W = 0) : |h^l_{\lambda_l=\pm\frac{1}{2}, \lambda_\nu=\pm\frac{1}{2}}|^2 = 8\frac{m_l^2}{2q^2}(q^2 - m_l^2)$$

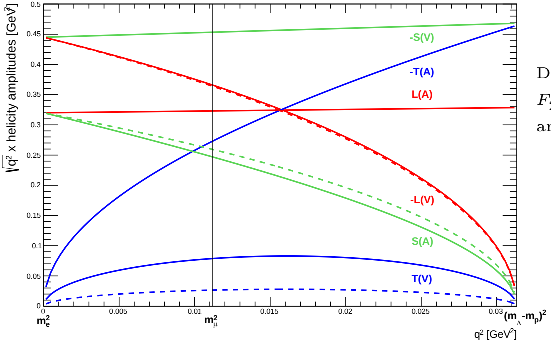
- Upper and lower signs refer to the configurations $(l^-, \bar{\nu}_l)$ $(\lambda_\nu = 1/2)$ and (l^+, ν_l) $(\lambda_\nu = -1/2)$, respectively
- In case of the e-mode only nonflip transition remains under assumption $\frac{m_e^2}{2q^2} \to 0$

Size estimations of helicity amplitudes

$T(V,A) := \sqrt{q^2} H^{V,A}_{\frac{1}{2}1}$

$L(V,A) := \sqrt{q^2} H^{V,A}_{\frac{1}{2}0}$

$S(V,A) := \sqrt{q^2} H^{V,A}_{\frac{1}{2}t}$



Dashed lines: $F_2^V(q^2)$ and $F_3^A(q^2)$ are switched off

- If $q^2 = m_e^2 \Rightarrow H^V_{\frac{1}{2}0}$ and $H^A_{\frac{1}{2}0}$ are dominated
- If $q^2 = (M_\Lambda - M_p)^2 \Rightarrow H^A_{\frac{1}{2}1} = -\sqrt{2} H^A_{\frac{1}{2}0}$ are dominated
- Using data of the E-555 experiment (Fermilab) [PRD41 (1990) 780]
  $\Rightarrow \frac{F_1^A(0)}{F_1^V(0)}(\Lambda \to p e^- \bar{\nu}_e) = 0.731 \pm 0.016$ and $\frac{F_2^V(0)}{F_1^V(0)}(\Lambda \to p e^- \bar{\nu}_e) = 0.15 \pm 0.30$
  $\Rightarrow \frac{F_1^A(0)}{F_1^V(0)}(\Lambda \to p e^- \bar{\nu}_e) = 0.719 \pm 0.016$ with constraint $\frac{F_2^V(0)}{F_1^V(0)}(\Lambda \to p e^- \bar{\nu}_e) \to 0.97$ (CVC)

Two boundary cases: $q^2_{\min}$ and $q^2_{\max}$

- $q^2_{\min} = m_e^2 \longrightarrow 0$:

$$
\begin{aligned}
b_{00} &= 1, \\
b_{03} &= -2 g_{av}^D(0) \sin^2\theta_l \equiv -2 F_1^V(0) F_1^A(0) \sin^2\theta_l, \\
b_{10} &= b_{03} \sin\theta_p \cos\phi_p, \\
b_{13} &= b_{00} \sin\theta_p \cos\phi_p, \\
b_{20} &= b_{03} \sin\theta_p \sin\phi_p, \\
b_{23} &= b_{00} \sin\theta_p \sin\phi_p, \\
b_{30} &= b_{03} \cos\theta_p, \\
b_{33} &= b_{00} \cos\theta_p.
\end{aligned}
$$

- $q^2_{\max} = (M_1 - M_2)^2$:

$$
\begin{aligned}
b_{00} &= (g_{av}^D(q^2))^2 \equiv (F_1^A(q^2))^2 \Longrightarrow 1 & b_{21} &= \sqrt{2}\sin\theta_l(-A\cos\theta_p\sin\phi_p - B\cos\phi_p), \\
b_{03} &= -b_{00}\cos\theta_l, & b_{22} &= \sqrt{2}\sin\theta_l(B\cos\theta_p\sin\phi_p - A\cos\phi_p), \\
b_{10} &= b_{03}\sin\theta_p\cos\phi_p, & b_{23} &= b_{00}\sin\theta_p\sin\phi_p, \\
b_{11} &= \sqrt{2}\sin\theta_l(-A\cos\theta_p\cos\phi_p + B\sin\phi_p), & b_{30} &= b_{03}\cos\theta_p, \\
b_{12} &= \sqrt{2}\sin\theta_l(B\cos\theta_p\cos\phi_p + A\sin\phi_p), & b_{31} &= \sqrt{2}A\sin\theta_l\sin\theta_p, \\
b_{13} &= b_{00}\sin\theta_p\cos\phi_p, & b_{32} &= -\sqrt{2}B\sin\theta_l\sin\theta_p, \\
b_{20} &= b_{03}\sin\theta_p\sin\phi_p, & b_{33} &= b_{00}\cos\theta_p,
\end{aligned}
$$

where $A = \frac{1}{2}b_{00}[\cos\chi(\cos\phi_1 + \cos\theta_l\cos\phi_2) + \sin\chi(\sin\phi_1 + \cos\theta_l\sin\phi_2)]$
and $B = \frac{1}{2}b_{00}[\sin\chi(\cos\phi_1 + \cos\theta_l\cos\phi_2) - \cos\chi(\sin\phi_1 + \cos\theta_l\sin\phi_2)]$