Hyperons: from structure and strong interactions to CP violation studies

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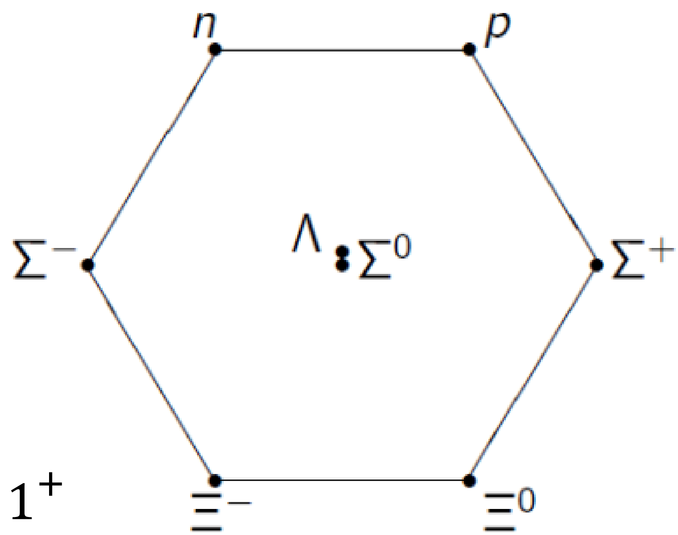
- Hyperon structure: transition form factors
- Non leptonic weak decays: baryon-meson interactions

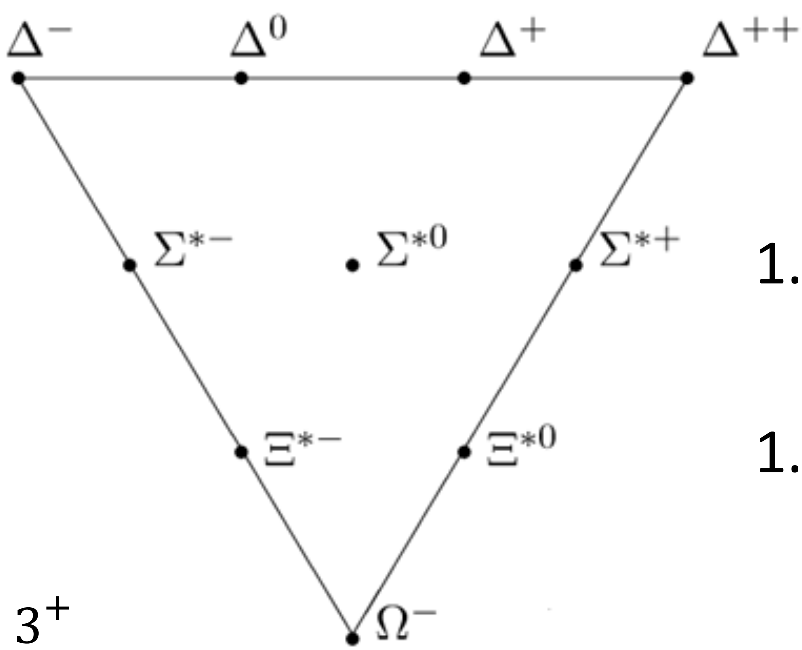
Light baryons



B

$J^P = \frac{1}{2}^+$

	Mass	$c\tau$	decay	
$\Lambda(uds)$	1.116	7.9	$p\pi^-$	64%
			$n\pi^0$	36%
$\Sigma^+(uus)$	1.189	2.4	$p\pi^0$	52%
			$n\pi^+$	48%
$\Sigma^-(dds)$	1.197	4.4	$n\pi^-$	100%
$\Xi^0(uss)$	1.315	8.7	$\Lambda\pi^0$	100%
$\Xi^-(dss)$	1.321	5.1	$\Lambda\pi^-$	100%
$\Omega^-(sss)$	1.672	2.5	ΛK^-	68%
			$\Xi^0\pi^-$	24%
			$\Xi^-\pi^0$	9%



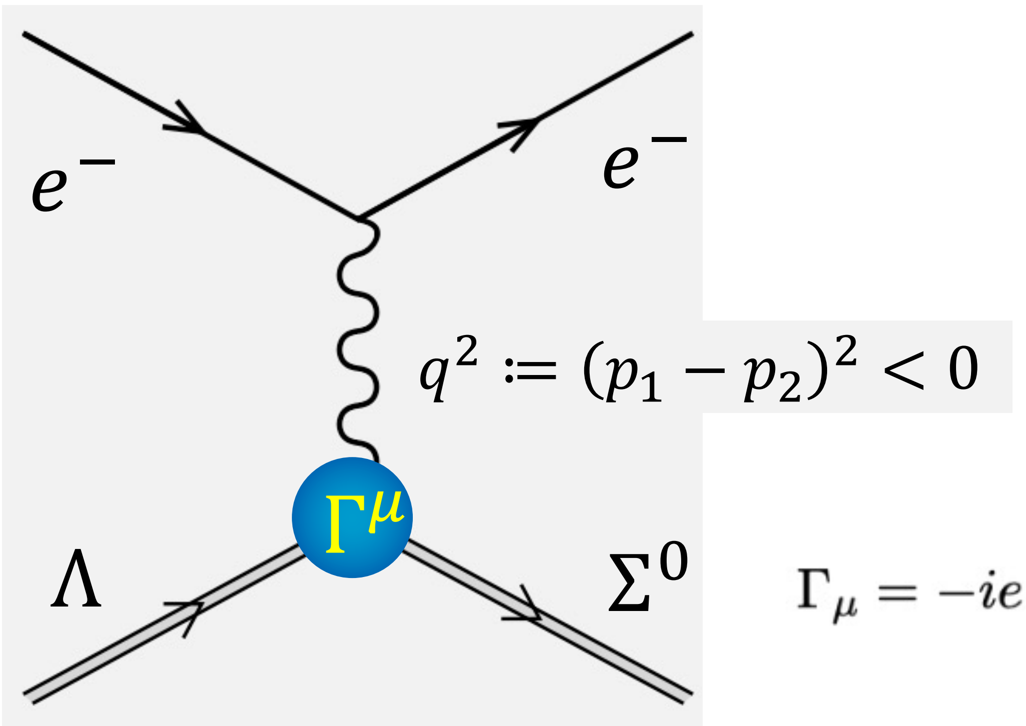
1.385 GeV

1.530 GeV

B'

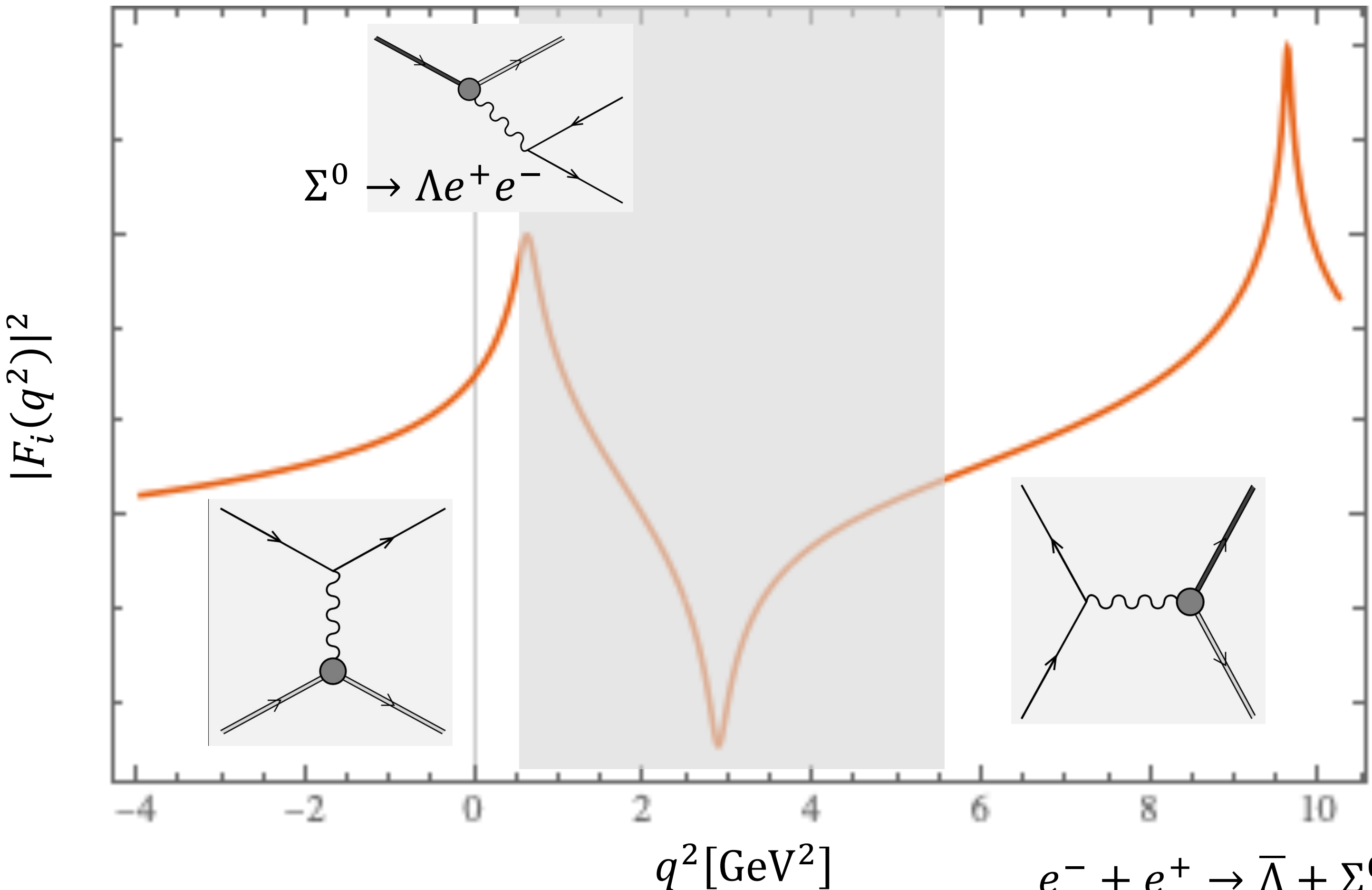
$J^P = \frac{3}{2}^+$

Transition Form Factors



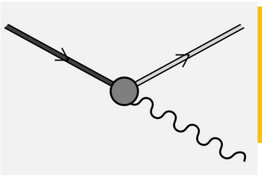
$$\Gamma_\mu = -ie\left[F_1(q^2)\,\gamma_\mu + F_2(q^2)\,\frac{i\sigma_{\mu\nu}q^\nu}{M_\Lambda + M_\Sigma}\right]$$

EM Transition Form Factors



$e^- + e^+ \to \overline{\Lambda} + \Sigma^0$

$e^- + \Lambda \to e^- + \Sigma^0$

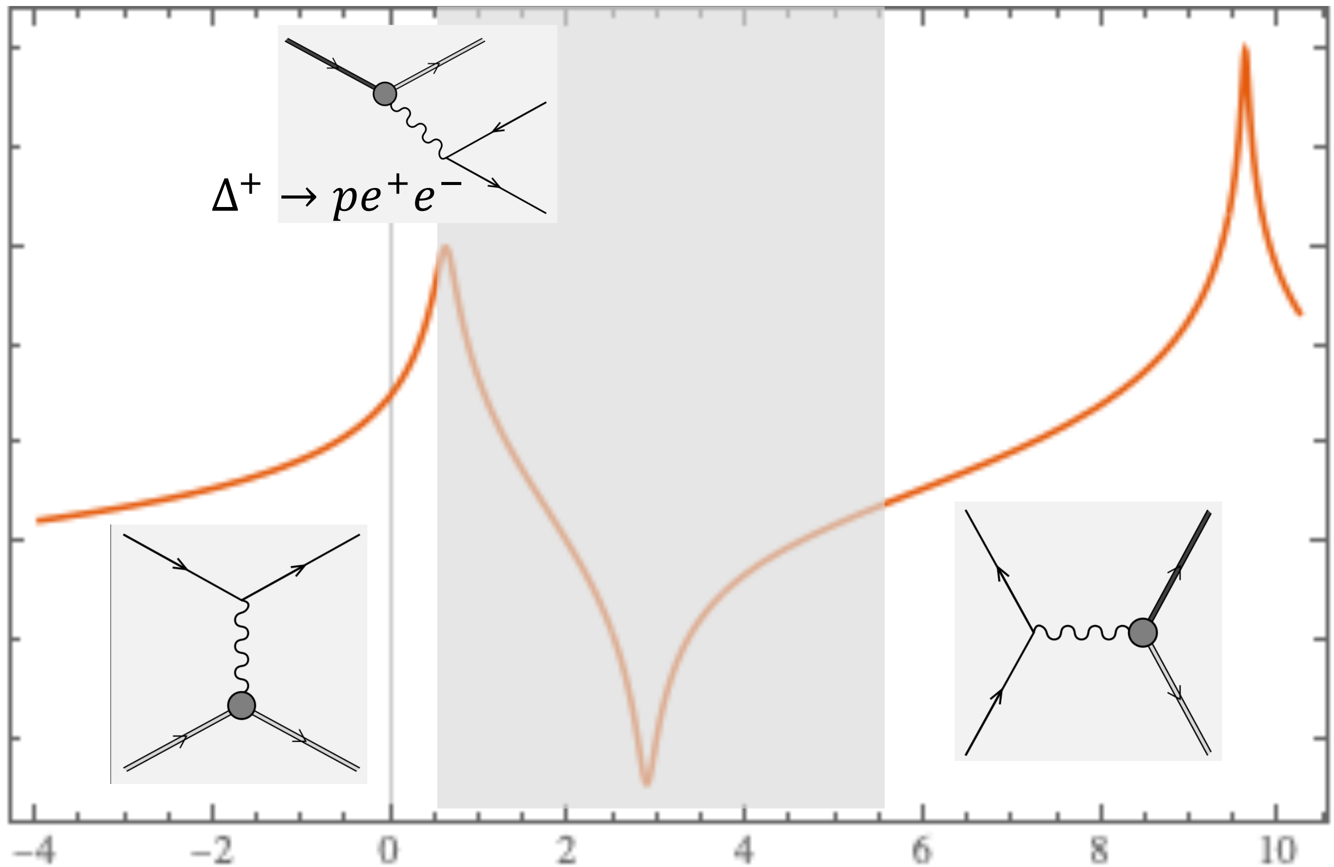


$\Sigma^0 \to \Lambda + \gamma$

$F_i(q^2)$ complex functions for $q^2 > 4m_\pi^2$
Observables: $|F_i(q^2)|^2$ and $\mathrm{Arg}\big(F_1(q^2)F_2^*(q^2)\big)$

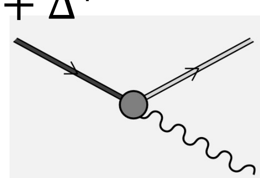
$$\langle r^2 \rangle = 6 \frac{\mathrm{d}\ln F_i(q^2)}{\mathrm{d}q^2}\Bigg|_{q^2=0}$$

EM Transition Form Factors



$e^- + p \to e^- + \Delta^+$

$e^- + e^+ \to \bar{p} + \Delta^+$



$\Delta^+ \to p + \gamma$

$B(\Delta^+ \to p e^+ e^-) = 4.2(7)\times 10^{-5}$ HADES

$$G_1 \left(q^\nu \gamma^\mu - \not{q}\, g^{\nu\mu}\right)\gamma_5 + G_2 \left(q^\nu p_2^\mu - (q\cdot p_2)\, g^{\nu\mu}\right)\gamma_5 + G_3 \left(q^\nu q^\mu - q^2\, g^{\nu\mu}\right)\gamma_5$$

Radiative Decays $B' \to B\gamma$

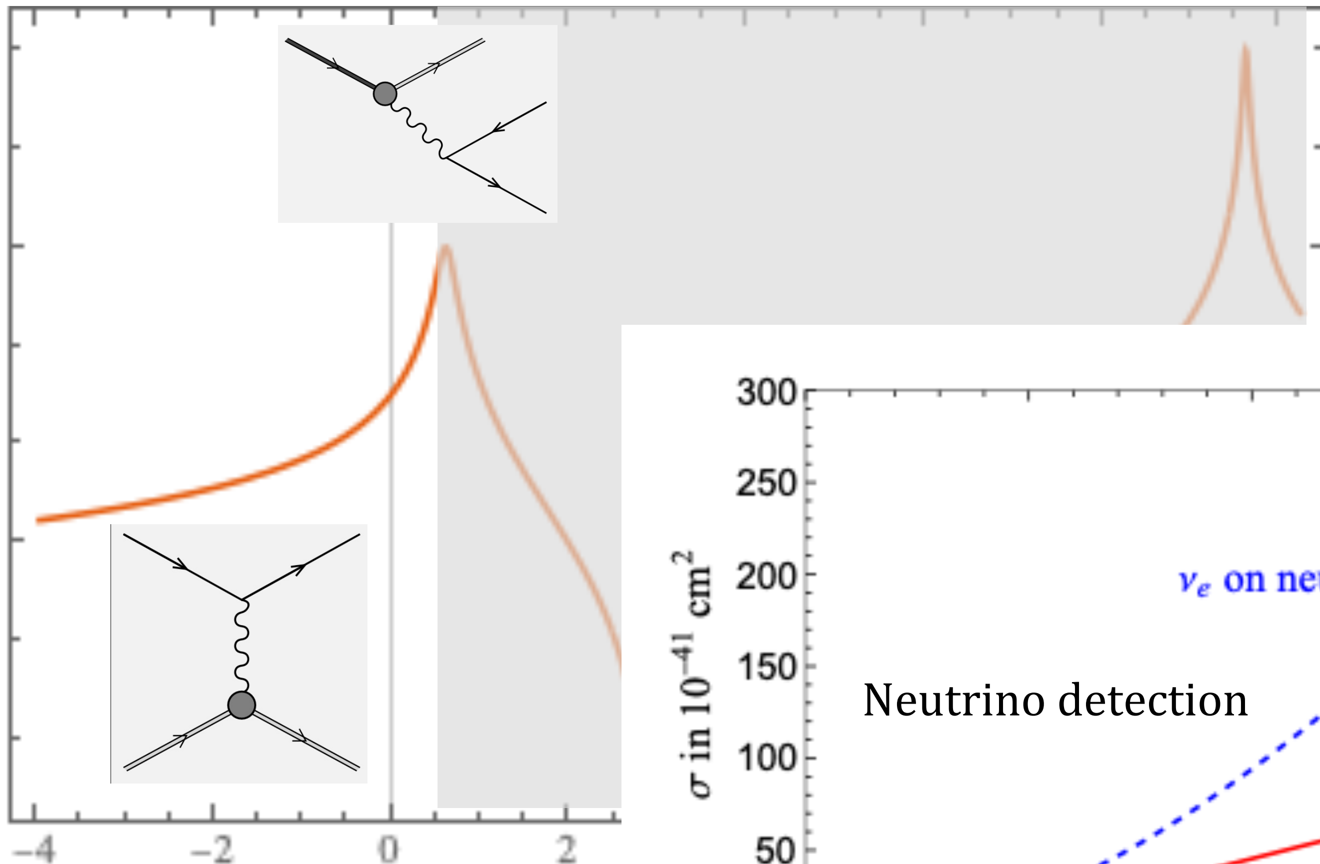
	BF
$\Sigma^{*0} \to \Lambda\gamma$	1.2×10^{-2}
$\Sigma^{*0} \to \Sigma^{+}\gamma$	7×10^{-3}
$\Sigma^{*+} \to \Sigma^{+}\gamma$	7×10^{-3}
$\Sigma^{*-} \to \Sigma^{-}\gamma$	$< 2 \times 10^{-4}$
$\Xi^{*} \to \Xi\gamma$	$< 4 \times 10^{-2}$

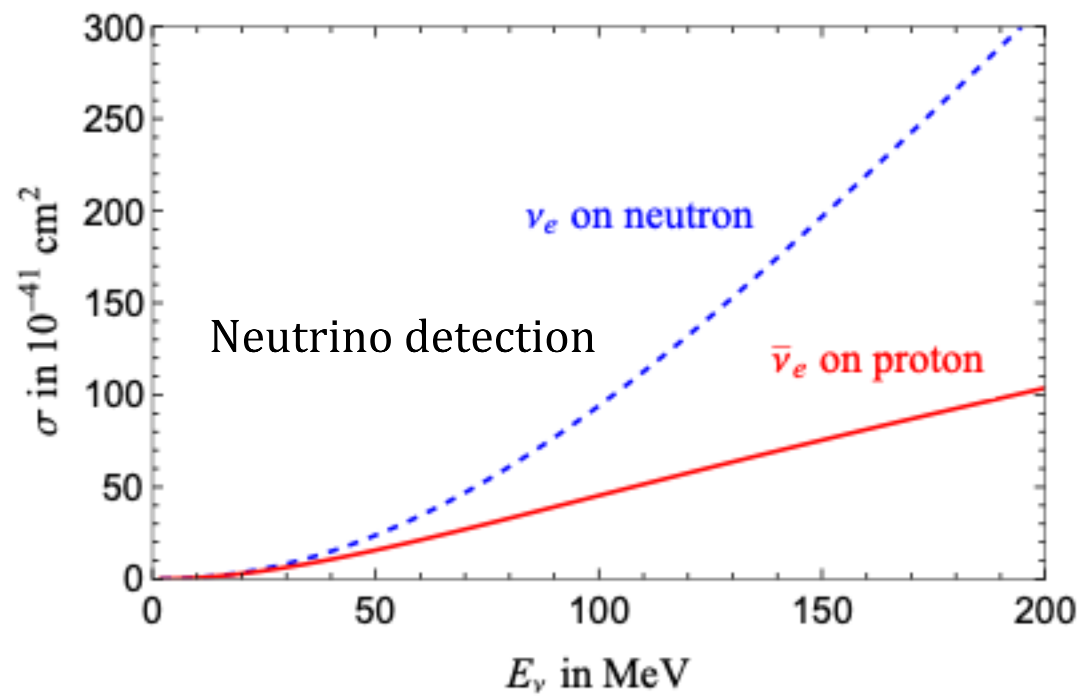
Radiative Decays $B' \to B\pi\gamma$

Decay	LEC dependence at NLO	BR at LO	BR at NLO
$\Xi^{*-} \to \Xi^- \pi^0 \gamma$	h_A, d_M, $b_{M,D}$, $b_{M,F}$	8.2×10^{-6}	8.6×10^{-6}
$\Xi^{*-} \to \Xi^0 \pi^- \gamma$	h_A, H_A, c_M, c_E, d_M, $b_{M,D}$	1.4×10^{-3}	1.4×10^{-3}
$\Xi^{*0} \to \Xi^- \pi^+ \gamma$	h_A, D, F, c_M, c_E, $b_{M,D}$, $b_{M,F}$	1.2×10^{-3}	1.2×10^{-3}
$\Xi^{*0} \to \Xi^0 \pi^0 \gamma$	h_A, H_A, D, F, c_M, $b_{M,D}$	0	1.9×10^{-6}
$\Sigma^{*+} \to \Sigma^+ \pi^0 \gamma$	h_A, H_A, D, c_M, d_M, $b_{M,D}$, $b_{M,F}$	8.9×10^{-7}	1.2×10^{-6}
$\Sigma^{*+} \to \Sigma^0 \pi^+ \gamma$	h_A, H_A, F, c_M, c_E, d_M, $b_{M,D}$	3.6×10^{-5}	3.7×10^{-5}
$\Sigma^{*-} \to \Sigma^- \pi^0 \gamma$	h_A, d_M, $b_{M,D}$, $b_{M,F}$	6.3×10^{-7}	6.6×10^{-7}
$\Sigma^{*-} \to \Sigma^0 \pi^- \gamma$	h_A, H_A, c_M, c_E, d_M, $b_{M,D}$	4.4×10^{-5}	4.5×10^{-5}
$\Sigma^{*0} \to \Sigma^+ \pi^- \gamma$	h_A, H_A, D, F, c_M, c_E, $b_{M,D}$, $b_{M,F}$	5.9×10^{-5}	5.9×10^{-5}
$\Sigma^{*0} \to \Sigma^- \pi^+ \gamma$	h_A, D, F, c_M, c_E, $b_{M,D}$, $b_{M,F}$	3.3×10^{-5}	3.4×10^{-5}
$\Sigma^{*0} \to \Sigma^0 \pi^0 \gamma$	h_A, D, c_M, $b_{M,D}$	0	2.6×10^{-8}
$\Sigma^{*0} \to \Lambda \pi^0 \gamma$	h_A, D, c_M, $b_{M,D}$	0	3.6×10^{-6}
$\Delta^{++} \to p \pi^+ \gamma$	h_A, H_A, c_M, c_E, d_M, $b_{M,D}$, $b_{M,F}$	1.7×10^{-3}	1.8×10^{-3}
$\Delta^+ \to p \pi^0 \gamma$	h_A, H_A, D, F, c_M, d_M, $b_{M,D}$, $b_{M,F}$	5.6×10^{-5}	7.2×10^{-5}
$\Delta^+ \to n \pi^+ \gamma$	h_A, H_A, D, F, c_M, c_E, d_M, $b_{M,D}$	7.5×10^{-4}	7.6×10^{-4}
$\Delta^0 \to p \pi^- \gamma$	h_A, H_A, D, F, c_M, d_M, $b_{M,D}$, $b_{M,F}$	1.0×10^{-3}	1.0×10^{-3}
$\Delta^0 \to n \pi^0 \gamma$	h_A, H_A, D, F, c_M, $b_{M,D}$	0	7.6×10^{-6}
$\Delta^- \to n \pi^- \gamma$	h_A, H_A, c_M, c_E, d_M, $b_{M,D}$	2.3×10^{-3}	2.3×10^{-3}

Homberg, Leupold Phys.Rev.D 100 (2019) 114001

Weak Transition Form Factors





$\bar{\nu}_e + p \rightarrow e^+ + n$

$n \rightarrow p + e^- + \bar{\nu}_e$

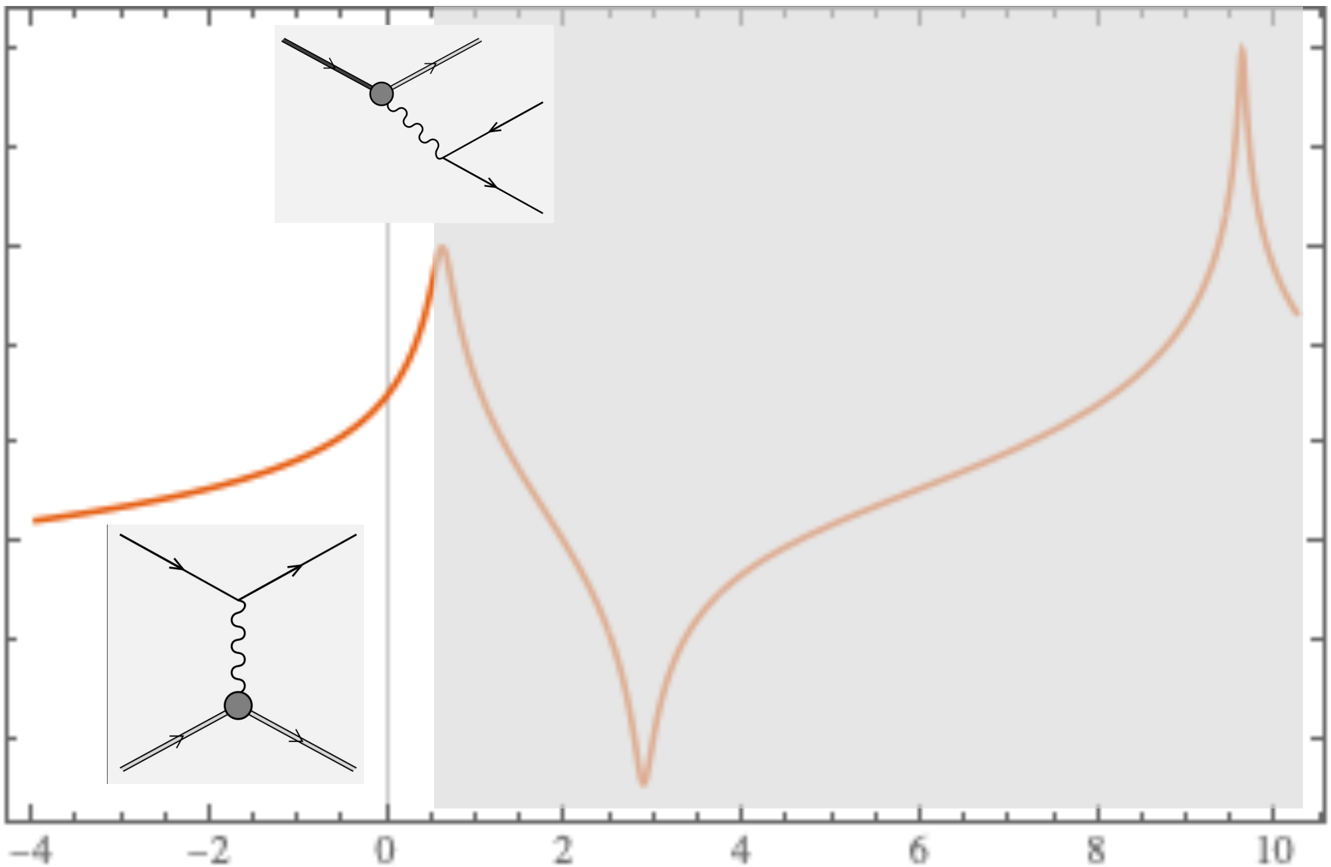
$\bar{\nu}_e + p \rightarrow e^+ + n$ $\quad$ $\nu_e + n \rightarrow e^- + p$

$\bar{\nu}_e + p \rightarrow e^+ + \Lambda$

$\Lambda \rightarrow p + e^- + \bar{\nu}_e$

$\boldsymbol{V_{us}}$

Weak Transition Form Factors



$\nu_e + p \rightarrow e^- + \Delta^{++}$

$\Delta^{++} \rightarrow p + e^+ + \nu_e \qquad (\Omega^- \rightarrow \Xi^0 + e^- + \bar{\nu}_e)$

Hyperon semi-leptonic decays

Process	ΔM [MeV]	ΔS	μ-mode	BF(e-mode) $\times 10^{-5}$
$\Sigma^+ \to \Lambda e^+ \nu_e$	74	0		2
$\Sigma^- \to \Lambda e^- \bar{\nu}_e$	82	0	–	6
$\Lambda \to p e^- \bar{\nu}_e$	177	1	yes	83
$\Sigma^- \to n e^- \bar{\nu}_e$	258	1	yes	107
$\Xi^- \to \Lambda e^- \bar{\nu}_e$	206	1	yes	56
$\Xi^- \to \Sigma^0 e^- \bar{\nu}_e$	129	1	yes	9
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$	126	1	yes	25
$\Xi^- \to \Xi^0 e^- \bar{\nu}_e$	7	0	–	–
$\Sigma^- \to \Sigma^0 e^- \bar{\nu}_e$	5	0	–	–
$\Xi^0 \to \Sigma^- e^+ \nu_e$	117	1	yes	–
$\Omega^- \to \Xi^0 e^- \bar{\nu}_e$	357	1	yes	560
$\Omega^- \to \Xi^{*0} e^- \bar{\nu}_e$	142	1	yes	–

	$\Gamma_{\Omega\to\Xi^*\ell\bar{\nu}_\ell}/\Gamma_{\Omega,\mathrm{tot}}$
$\ell = e,\ H_A = +2$	$4.7 \cdot 10^{-4}$
$\ell = e,\ H_A = 0$	$2.7 \cdot 10^{-4}$
$\ell = e,\ H_A = -2$	$4.7 \cdot 10^{-4}$
$\ell = \mu,\ H_A = +2$	$1.7 \cdot 10^{-5}$
$\ell = \mu,\ H_A = 0$	$9.9 \cdot 10^{-6}$
$\ell = \mu,\ H_A = -2$	$1.7 \cdot 10^{-5}$

Semileptonic Decays

for $1/2^+ \to 1/2^+$ transitions

$$\langle B_2 | J_\mu^V + J_\mu^A | B_1 \rangle =$$

$$J_\mu^V = \gamma_\mu f_1(q^2) - \frac{i\sigma_{\mu\nu} q^\nu}{M_1} f_2(q^2) + \frac{q_\mu}{M_1} f_3(q^2)$$

$$J_\mu^A = \left[\gamma_\mu g_1(q^2) - \frac{i\sigma_{\mu\nu} q^\nu}{M_1} g_2(q^2) + \frac{q_\mu}{M_1} g_3(q^2) \right] \gamma_5$$

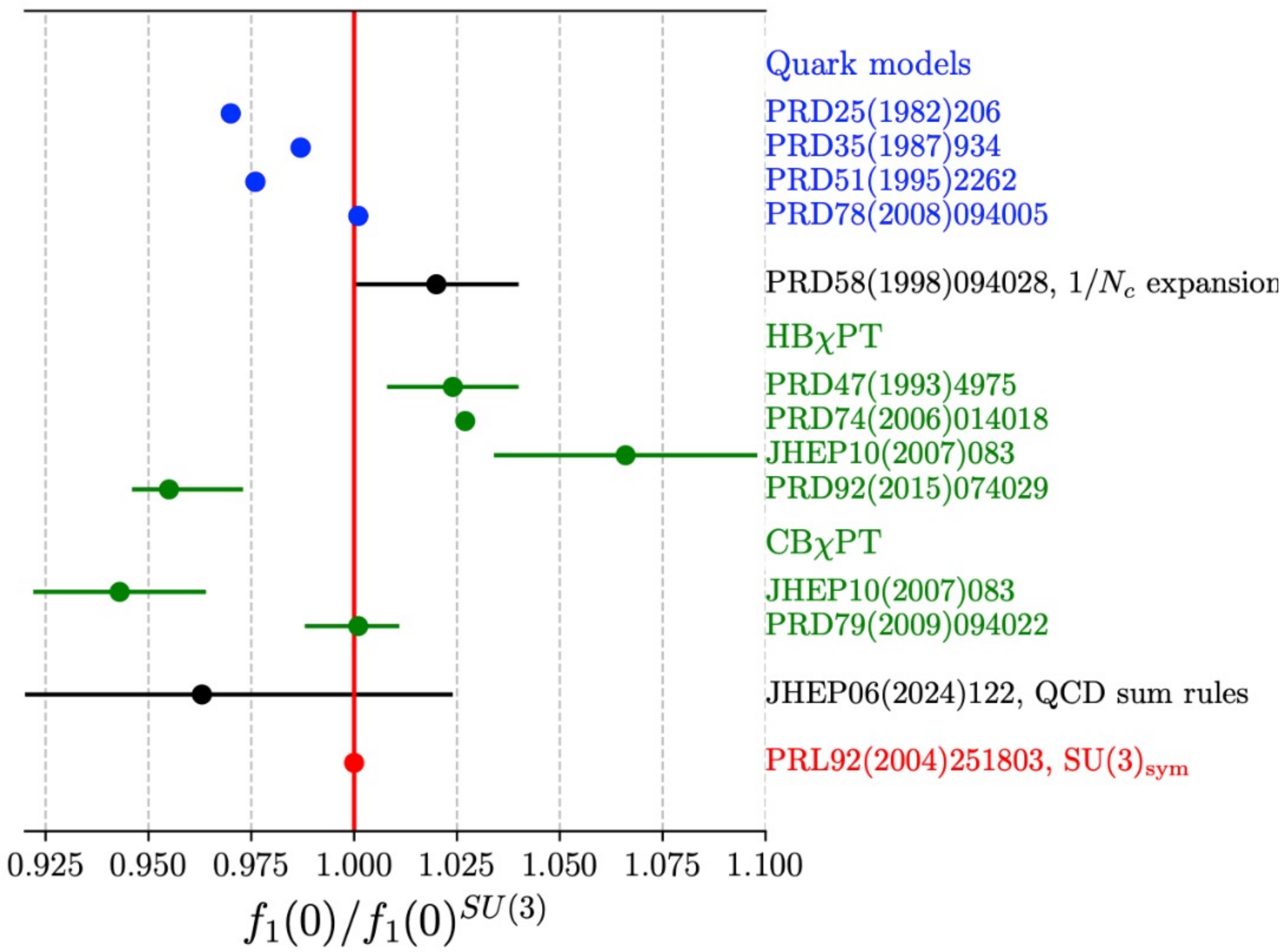
$$\langle B | J_\mu^{V,A} | B \rangle = \sum_{k=1}^{3} F_k^{V,A}(q^2) \bar{u} \left[\Gamma_\mu^{V,A} \right]_k v$$

$$\langle B | J_\mu^{V,A} | B' \rangle = \sum_{k=1}^{4} F_k^{V,A}(q^2) \bar{u} \left[\Gamma_{\beta\mu}^{V,A} \right]_k v^\beta$$

$$\langle B' | J_\mu^{V,A} | B' \rangle = \sum_{k=1}^{7} F_k^{V,A}(q^2) \bar{u}^\alpha \left[\Gamma_{\alpha\beta\mu}^{V,A} \right]_k v^\beta$$

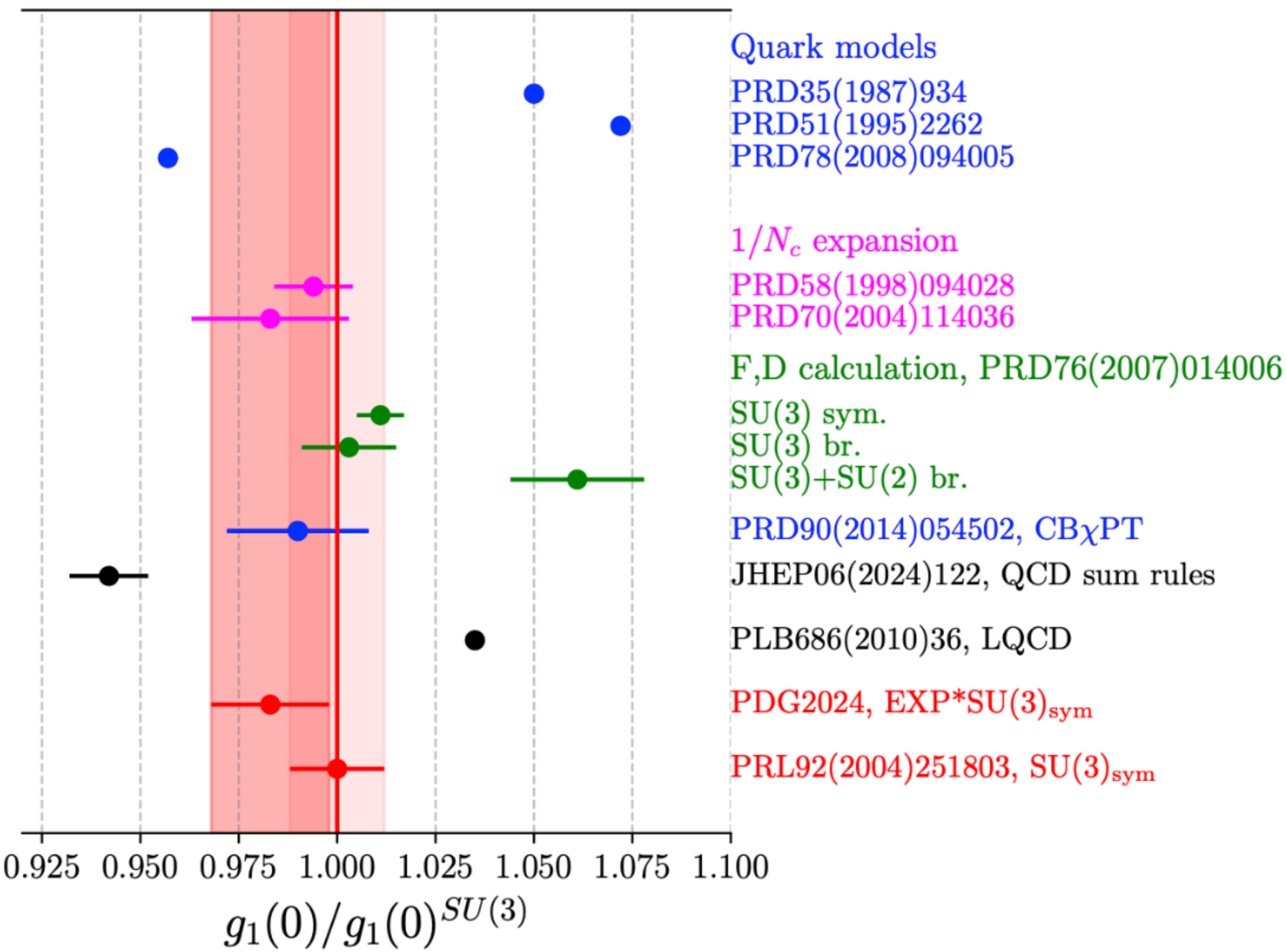
- *PRD* 106 (2022) 093001
- *PRD* 109 (2024) 034028

Predictions for $\Lambda \to p e^- \bar{\nu}_e$: $f_1(0)$



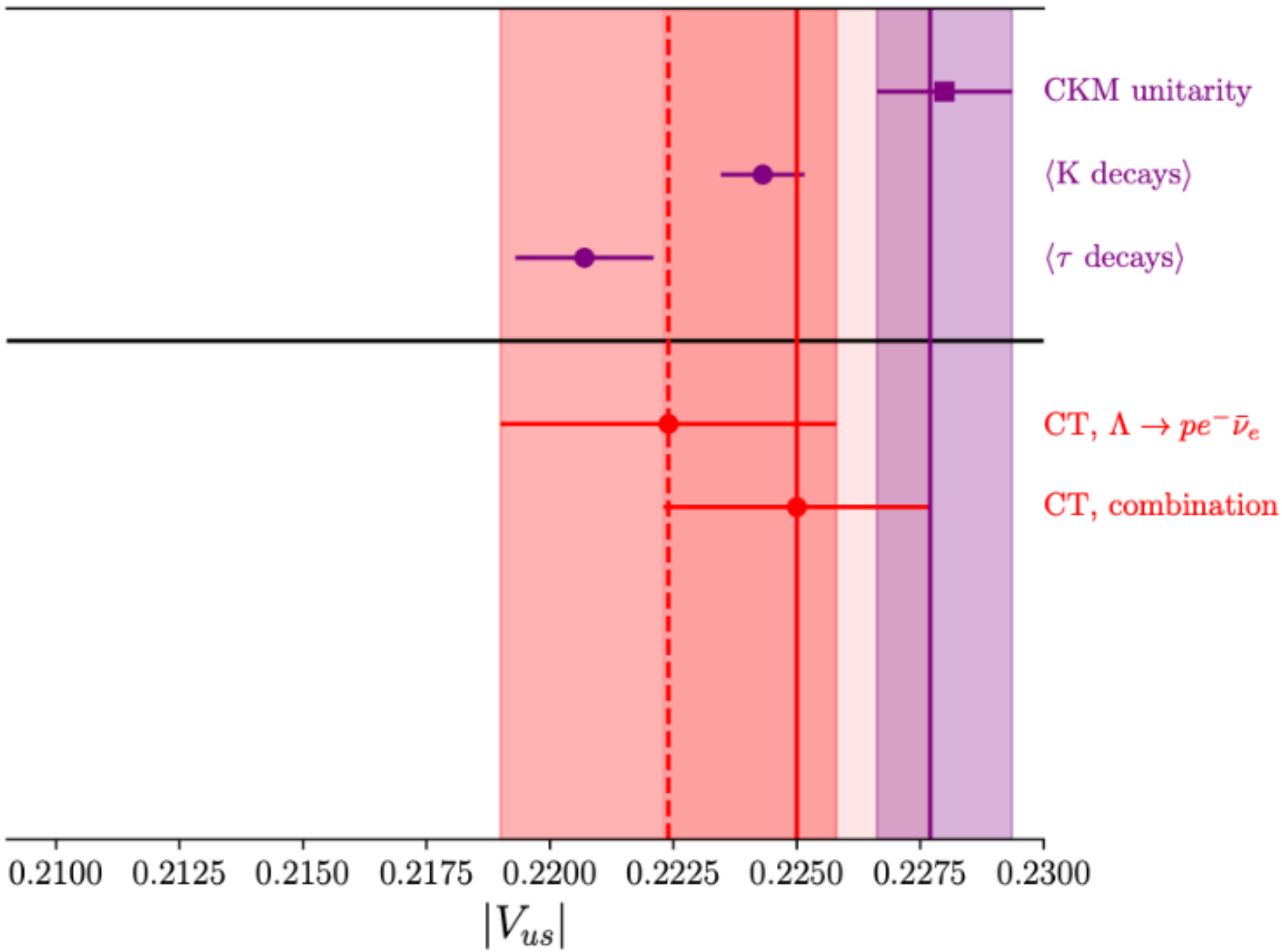
- SU(3) symmetry: $f_1(0) = -\sqrt{3/2}$

Predictions for $\Lambda \to p e^- \bar{\nu}_e$: $g_1(0)$



- SU(3) symmetry: $g_1(0) = -(D+3F)/\sqrt{6} = -0.730(12)$,
  D and F parameters are reduced matrix elements of Wigner-Eckart theorem for SU(2)
- Exper. result: $g_1(0)/f_1(0) = 0.718(15)$ [PDG2024]

Status of V_{us}



V_{us} Determination

$$\mathcal{B} = \frac{\tau_\Lambda}{\hbar} G_F^2 |V_{us}|^2 \frac{\beta^5 {M_\Lambda}^5}{60\pi^3} \left[(1 - \frac{3}{2}\beta)(f_1^2 + 3g_1^2) - 4\beta g_1 g_2 + \frac{2}{7}\beta^2 \mathcal{F}_2 + \mathcal{O}(\beta^3) \right]$$

where $\mathcal{F}_2 = 3f_1^2 + 3f_1 f_2 + 2{f_2}^2 + 6{g_1}^2 + 6g_2^2 + 21 g_1 g_2$

with $\beta = (M_\Lambda - M_p)/M_\Lambda \sim 0.159$ for $\Lambda \to p l^- \bar{\nu}_l$

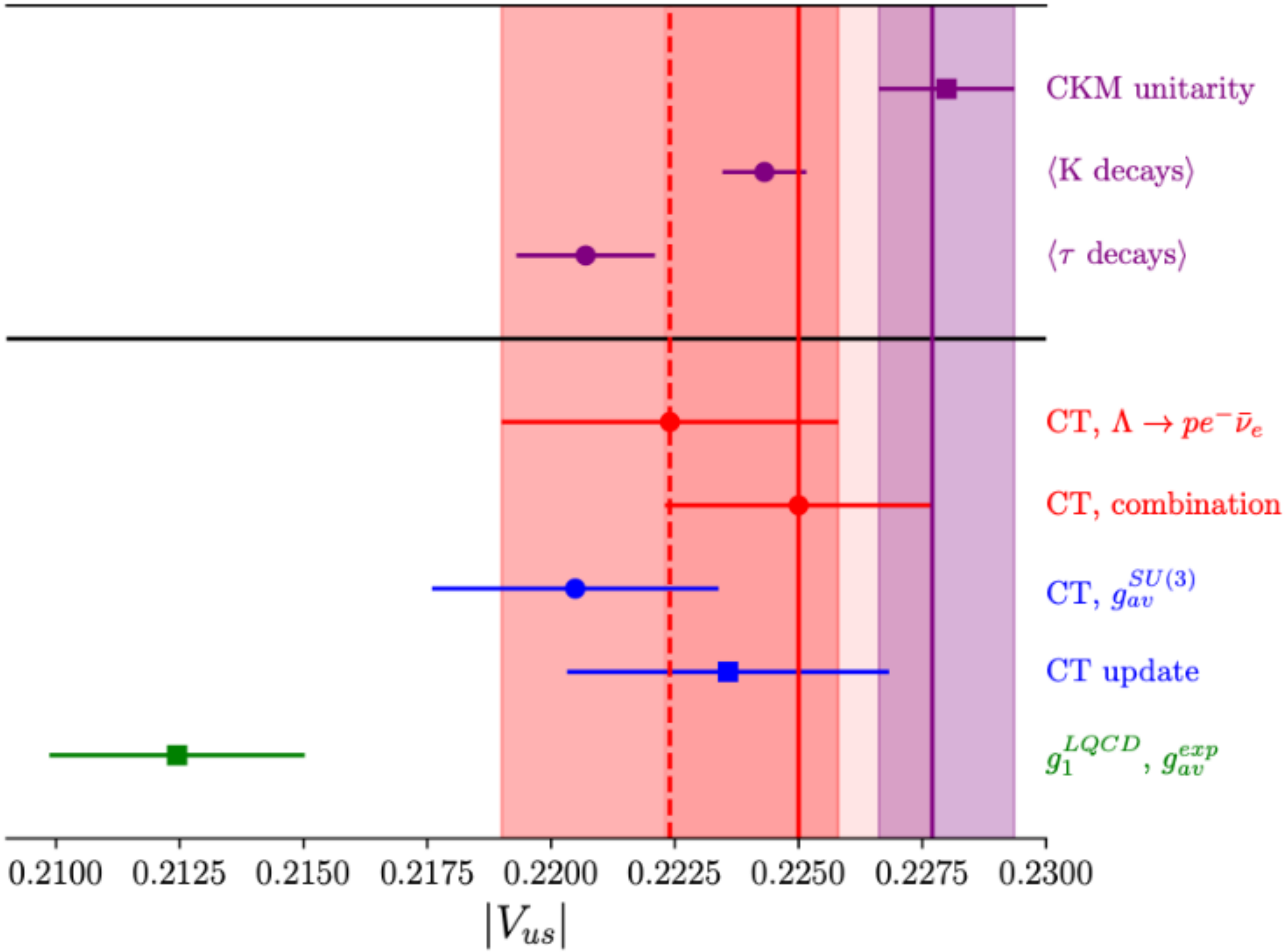
Two ways to extract V_{us}:

1. $$\frac{\mathcal{B}}{\tau_\Lambda} \simeq |V_{us}|^2 f_1^2 \left[(1 - \tfrac{3}{2}\beta)(1 + 3g_{av}^2) + \tfrac{2}{4}\beta^2 \frac{\mathcal{F}_2}{f_1^2} \right]$$

2. $$\frac{\mathcal{B}}{\tau_\Lambda} \simeq |V_{us}|^2 g_1^2 \left[(1 - \tfrac{3}{2}\beta)(\frac{1}{g_{av}^2} + 3) + \tfrac{2}{4}\beta^2 \frac{\mathcal{F}_2}{g_1^2} \right]$$

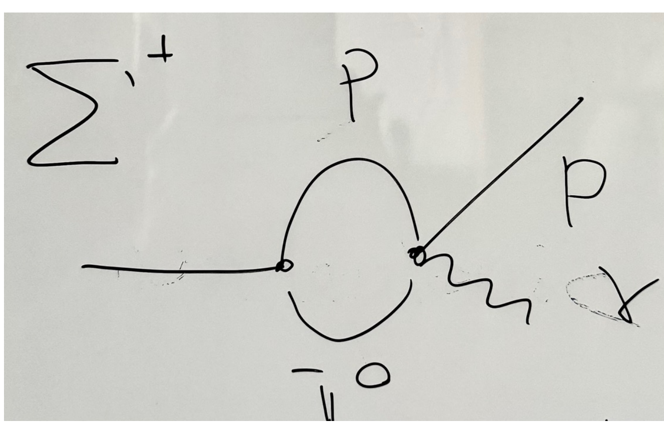
1. Experiment: $\{\mathcal{B},\ \tau_\Lambda,\ g_{av},\ M_{\Lambda,p}\}$ and Theory: $\{f_1 \text{ or } g_1\}$
2. Experiment: $\{\mathcal{B},\ \tau_\Lambda,\ M_{\Lambda,p}\}$ and Theory: $\{f_1,\ g_1 \to g_{av}\}$

Status of V_{us}



Weak radiative decays

	BF	
$\Xi^0 \to \Lambda\gamma$	1.2×10^{-3}	
$\Xi^0 \to \Lambda e^+ e^-$	7.6×10^{-6}	
$\Xi^0 \to \Sigma^0\gamma$	3×10^{-3}	
$\Xi^- \to \Sigma^-\gamma$	1.3×10^{-4}	
$\Sigma^+ \to p\gamma$	1.0×10^{-3}	
$\Sigma^+ \to p\mu^+\mu^-$	1.1×10^{-8}	LHCb, 2504.06096 [hep-ex]
$\Omega^- \to \Xi^-\gamma$	$< 5 \times 10^{-4}$	



$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.09 \pm 0.17) \times 10^{-8},$$

LQCD 2504.07727 [hep-lat]

Non leptonic decays

	Mass	$c\tau$	decay	
$\Lambda(uds)$	1.116	7.9	$p\pi^-$	64%
			$n\pi^0$	36%
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			$\Xi^0\pi^-$	24%
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Direct CP violation in K^0 decays

(I) $K^0 \to \pi^+\pi^-$ (II) $K^0 \to \pi^0\pi^0$

Two weak transitions needed
$|\Delta I| = \frac{1}{2}$ and $|\Delta I| = \frac{3}{2}$

$K^0 \to \pi^+\pi^-$ $\mathcal{A}_I = A_0 \exp(i\xi_0 + i\delta_0) + A_2 \exp(i\xi_2 + i\delta_2)$

$\bar{K}^0 \to \pi^+\pi^-$ $\bar{\mathcal{A}}_I = A_0 \exp(-i\xi_0 + i\delta_0) + A_2 \exp(-i\xi_2 + i\delta_2)$

$(\pi\pi)_{I=0,2}$

$$\text{Re}(\epsilon') := \frac{1}{2}\frac{|\mathcal{A}_I|^2 - |\bar{\mathcal{A}}_I|^2}{|\mathcal{A}_I|^2 + |\bar{\mathcal{A}}_I|^2} \approx (\xi_0 - \xi_2)\sin(\delta_0 - \delta_2)\frac{A_2}{A_0}$$

Exp. avg PDG

$\text{Re}(\epsilon'/\epsilon) = (16.6 \pm 2.3) \cdot 10^{-4}$

$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$

$$3.7(5)\times 10^{-6} \approx (\xi_0 - \xi_2)\sin 47.7^\circ \frac{1}{22}$$

$$(\xi_0 - \xi_2) \approx 10^{-4} \text{ rad}$$

ϵ' in SM and BSM

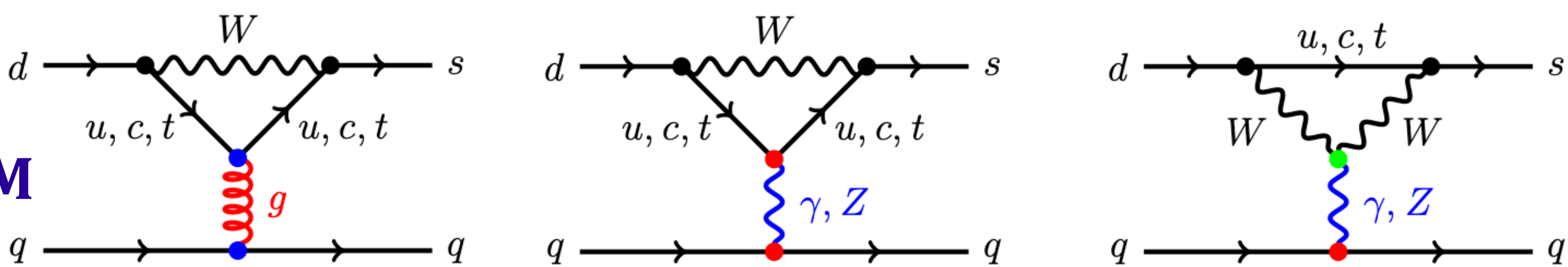
$\mathrm{Re}(\epsilon'/\epsilon) = (16.6 \pm 2.3) \cdot 10^{-4}$ Exp. avg PDG

$(21.7 \pm 8.2) \times 10^{-4}$ Lattice QCD — *PRD* 102 (2020) 054509

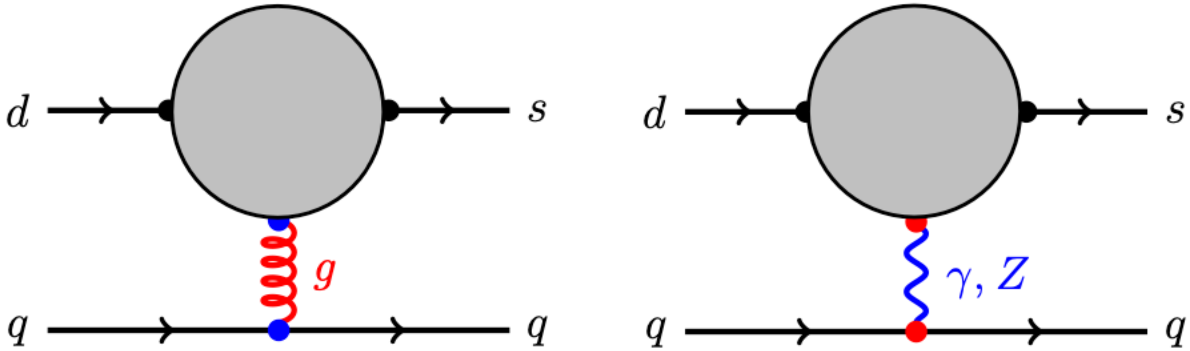
$(9.4 \pm 3.5) \times 10^{-4}$ NNLO QCD — *EPJC* 80 (2020)1

$(14 \pm 5) \times 10^{-4}$ EFT — *RPP* 81 (2018) 076201, *JHEP* 02 (2020) 032

SM



BSM



Hyperon decays

$\Lambda(dsu)$ $\qquad A(\Lambda \to p\pi^-)$

$\Xi^-(dss)$ $\qquad A(\Xi^- \to \Lambda\pi^-)$

$$\left.\begin{matrix} A(\Lambda \to p\pi^-) \\ A(\Xi^- \to \Lambda\pi^-) \end{matrix}\right\} = S\sigma_0 + P\,\boldsymbol{\sigma}\cdot\hat{\mathbf{n}}$$

Transitions:
- P (parity even) final state in p-wave
- S (parity odd) final state in s-wave

weak CP-odd phases

$$S = |S|\exp(i\xi_S)\exp(i\delta_S)$$
$$P = |P|\exp(i\xi_P)\exp(i\delta_P)$$

Strong phase: interaction of final particles

Measurable: Γ and two decay parameters:

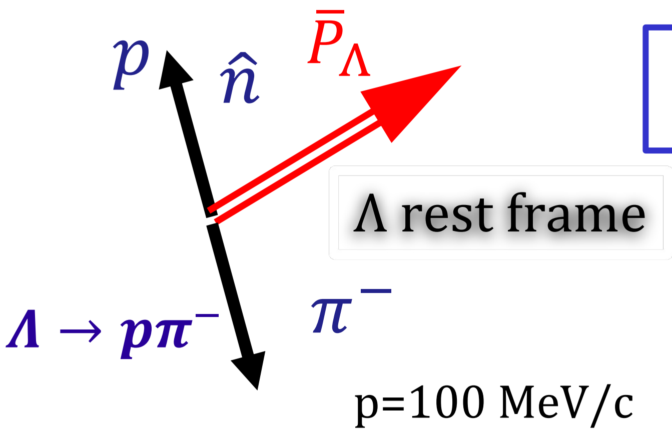
$$\alpha = \frac{2\ \mathrm{Re}(S^*P)}{|S|^2 + |P|^2}$$

$$\beta = \frac{2\mathrm{Im}(S^*P)}{|P|^2 + |S|^2}$$

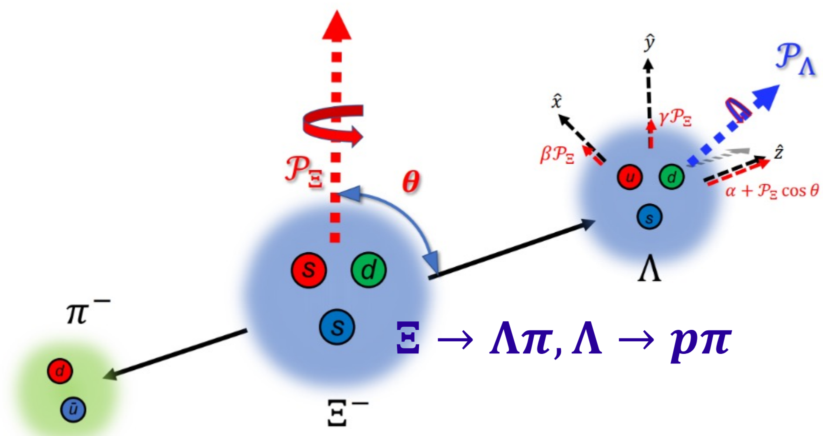
$$\beta = \sqrt{1-\alpha^2}\sin\phi$$
$$\gamma = \sqrt{1-\alpha^2}\cos\phi$$

Neglecting $|\Delta I| = \frac{3}{2}$ transitions

Hyperon decay parameters



$$\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \hat{n}\,\bar{P}_\Lambda)$$



α_Λ= 0.750(10)

α_Ξ=-0.392(8)

ϕ_Λ=-0.113(61)

ϕ_Ξ=-0.042(16)

$$\mathbf{P}_p = \frac{(\alpha + P_\Lambda \cos\theta)\,\hat{\mathbf{z}} + \beta P_\Lambda \hat{\mathbf{x}} + \gamma P_\Lambda \hat{\mathbf{y}}}{1 + \alpha P_\Lambda \cos\theta}$$

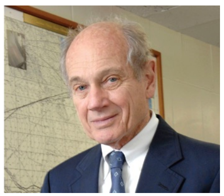
Accesible if daughter baryon polarization measured eg in decay sequence:
$\Xi \to \Lambda\pi, \Lambda \to p\pi$

$$\sigma_\mu^\Lambda \to \sum_{\mu'=0}^{3} a_{\mu,\mu'}^\Lambda \, \sigma_{\mu'}^p$$

$$\frac{\beta_-}{\alpha_-} = \frac{\beta_0}{\alpha_0} = \tan(\delta_2^P - \delta_2^S)$$

α, β, γ measurements for $\Lambda \to p\pi^-$

James Cronin
1931-2016



Oliver Overseth
1928-2008

PHYSICAL REVIEW VOLUME 129, NUMBER 4 15 FEBRUARY 1963

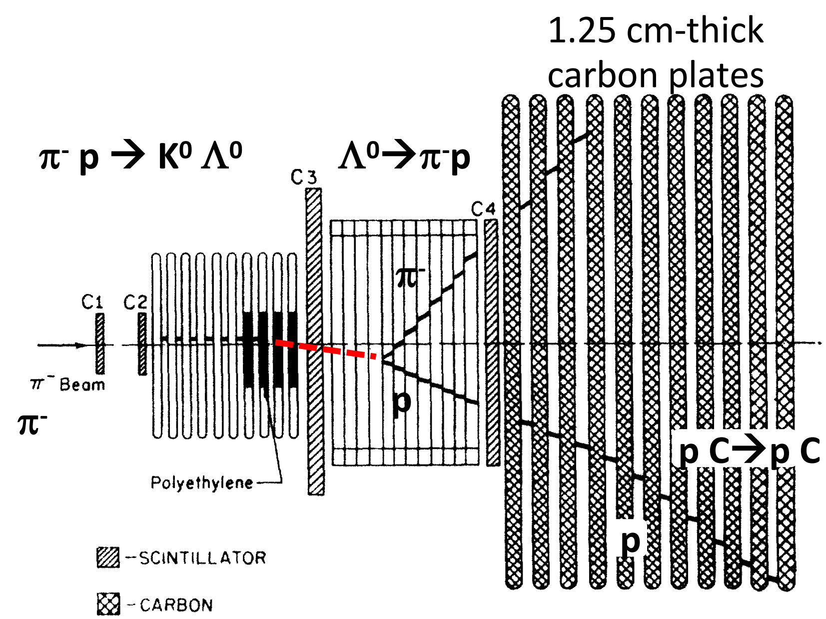
Measurement of the Decay Parameters of the Λ^0 Particle*

James W. Cronin and Oliver E. Overseth†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 26 September 1962)

The decay parameters of $\Lambda^0 \to \pi^- + p$ have been measured by observing the polarization of the decay protons by scattering in a carbon-plate spark chamber. The experimental procedure is discussed in some detail. A total of 1156 decays with useful proton scatters was obtained. The results are expressed in terms of polarization parameters, α, β, and γ given below:

$$\alpha = 2\,\mathrm{Re}\,sp^*/(|s|^2+|p|^2) = +0.62 \pm 0.07,$$
$$\beta = 2\,\mathrm{Im}\,sp^*/(|s|^2+|p|^2) = +0.18 \pm 0.24,$$
$$\gamma = |s|^2 - |p|^2/(|s|^2+|p|^2) = +0.78 \pm 0.06,$$

where s and p are the s- and p-wave decay amplitudes in an effective Hamiltonian $s + p\boldsymbol{\sigma}\cdot\mathbf{p}/|\mathbf{p}|$, where $\mathbf{p}$ is the momentum of the decay proton in the center-of-mass system of the Λ^0, and $\boldsymbol{\sigma}$ is the Pauli spin operator. The helicity of the decay proton is positive. The ratio $|p|/|s|$ is $0.36_{-0.06}^{+0.05}$ which supports the conclusion that the $K\Lambda N$ parity is odd. The result $\beta = 0.18 \pm 0.24$ is consistent with the value $\beta = 0.08$ expected on the basis of time-reversal invariance.



no H_2 target, no magnet;
use kinematics and proton's
range in carbon to infer E_p

$$P_p = \frac{(\alpha + P_\Lambda \cos\theta)\hat{z}' + \beta P_\Lambda \hat{x}' + \gamma P_\Lambda \hat{y}'}{1 + \alpha P_\Lambda \cos\theta}$$

$\alpha_\Lambda = 0.62(7)$

Slide from Steve Olsen

nature physics LETTERS
https://doi.org/10.1038/s41567-019-0494-8

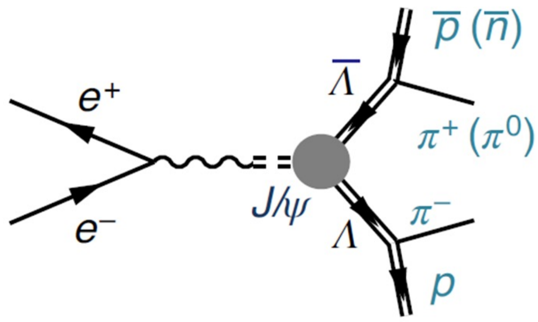
$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$$

Polarization and entanglement in baryon-antibaryon pair production in electron-positron annihilation

The BESIII Collaboration*

Nature Phys. 15 (2019) 631

Phys.Rev.Lett. 129 (2022) 131801

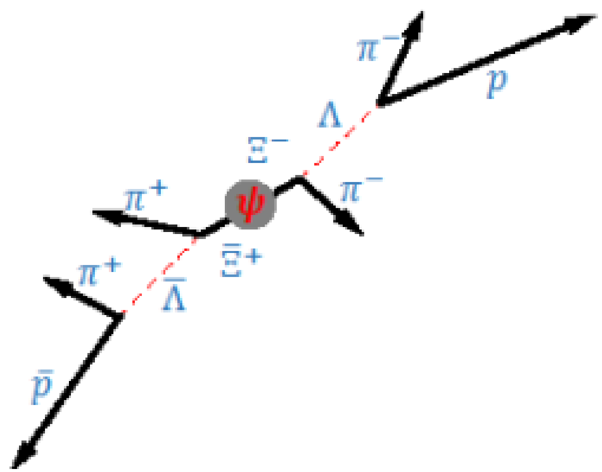


$$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$$

Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

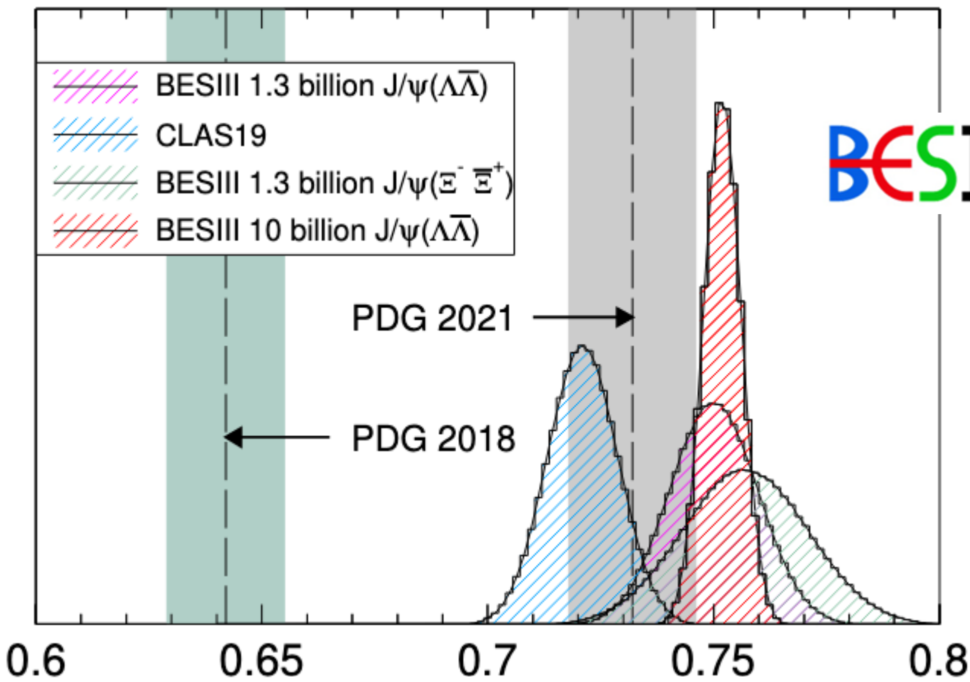
Nature **606**, 64–69 (2022)



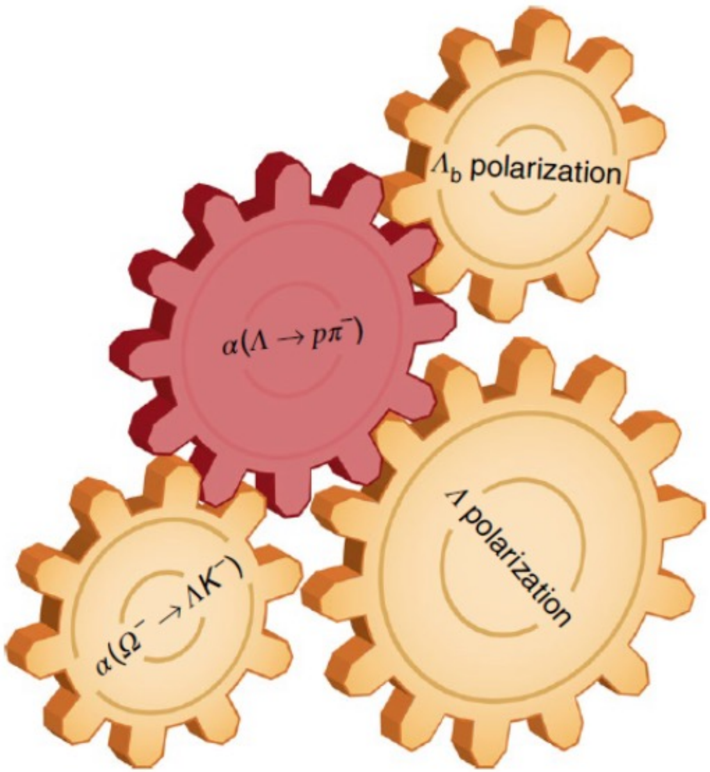
Methods:

Fäldt, AK PLB 772, 16
Perotti, Fäldt, AK, Leupold, Song PRD99,056008
Adlarson, AK PRD 100, 114005
Salone,Adlarson,Batozskaya, AK,Leupold,Tandean PRD 105, 116022
Batozskaya, AK, Salone,Wiechnik PRD 108, 016011

Decay parameters



$\alpha(\Lambda \to p\pi^-)$



news & views

PARTICLE PHYSICS

Anomalous asymmetry

A measurement based on quantum entanglement of the parameter describing the asymmetry of the Λ hyperon decay is inconsistent with the current world average. This shows that relying on previous measurements can be hazardous.

Ulrik Egede

CPV tests in hyperon decays

$\Xi^- \to \Lambda\pi^-$

$$S = |S| \exp(i\xi_S + i\delta_S)$$
$$P = |P| \exp(i\xi_P + i\delta_P)$$

$\bar{\Xi}^+ \to \bar{\Lambda}\pi^+$

$$\bar{S} = |S| \exp(-i\xi_S + i\delta_S)$$
$$\bar{P} = -|P| \exp(-i\xi_P + i\delta_P)$$

CP-odd phases

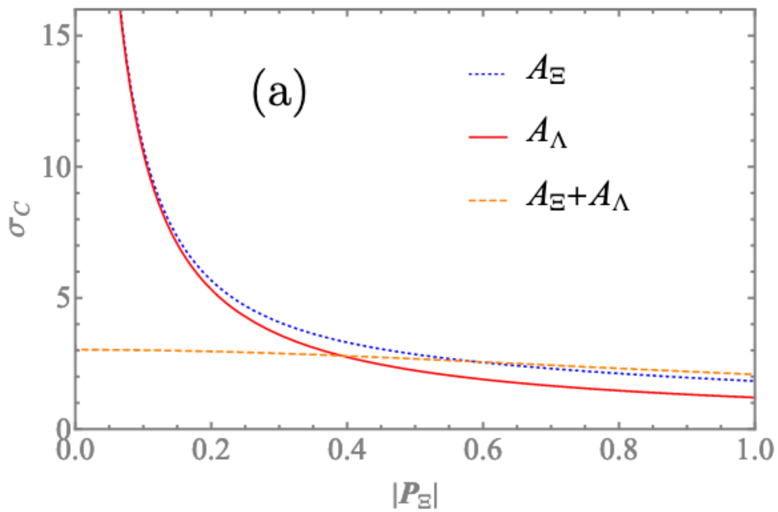
$$A_{CP} := \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \text{ and } B_{CP} := \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}} \qquad \Phi_{CP} = \frac{\phi + \bar{\phi}}{2}$$

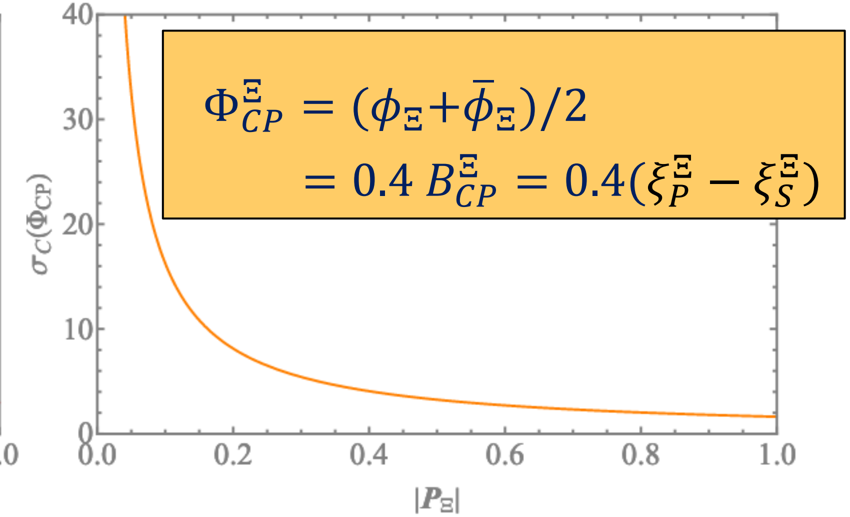
$$A_{\mathrm{CP}} = -\frac{\sqrt{1-\alpha^2}}{\alpha} \sin\phi \tan(\xi_P - \xi_S)$$
$$= -\tan(\delta_P - \delta_S) \tan(\xi_P - \xi_S)$$
$$B_{\mathrm{CP}} = \tan(\xi_P - \xi_S) \ ,$$
$$\Phi_{\mathrm{CP}} = \frac{\alpha}{\sqrt{1-\alpha^2}} \cos\phi \tan(\xi_P - \xi_S)$$

$|\Delta I| = \frac{1}{2}$ limit

HyperCP measurements

$\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$+c.c



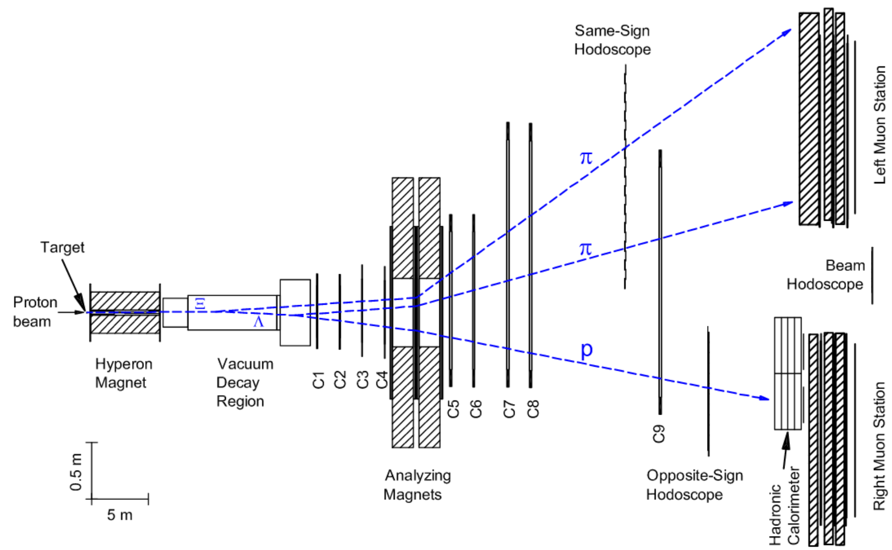


$$\Phi_{CP}^{\Xi} = (\phi_\Xi + \bar{\phi}_\Xi)/2$$
$$= 0.4\, B_{CP}^{\Xi} = 0.4(\xi_P^{\Xi} - \xi_S^{\Xi})$$

$$A_\Xi + A_\Lambda = (0.0 \pm 5.1 \pm 4.4)\times 10^{-4}$$

HyperCP PRL 93 (2004) 262001

1.2×10^8 Ξ^- **4.1×10^7** $\bar{\Xi}^+$

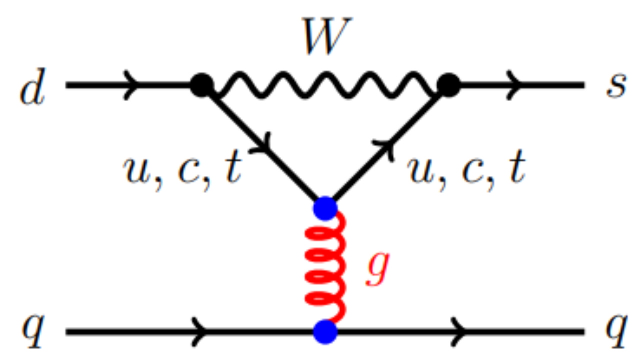


Ξ^- **Polarization (** 3.7%)

Hyperon CPV in SM and BSM

weak *P*-*S* phase difference

$$\xi_P - \xi_S$$



	$\xi_P - \xi_S$			C_B	C'_B
	$(\eta\lambda^5 A^2)$ SM ref *	$[10^{-4}$ rad] SM ref *	$[10^{-2}$ rad] Exp	BSM ref **	BSM ref **
$\Lambda \to p\pi^-$	0.2 ± 1.6	0.3 ± 2.2	4.7 ± 9.4	1.1 ± 2.2	0.4 ± 0.8
$\Xi^- \to \Lambda\pi^-$	-1.4 ± 1.2	-1.9 ± 1.6	1.2 ± 3.5	-0.5 ± 1.0	0.4 ± 0.7

$$(\xi_P - \xi_S)_{BSM} = \frac{C'_B}{B_G}\left(\frac{\epsilon'}{\epsilon}\right)_{BSM} + \frac{C_B}{\kappa}\epsilon_{BSM}$$

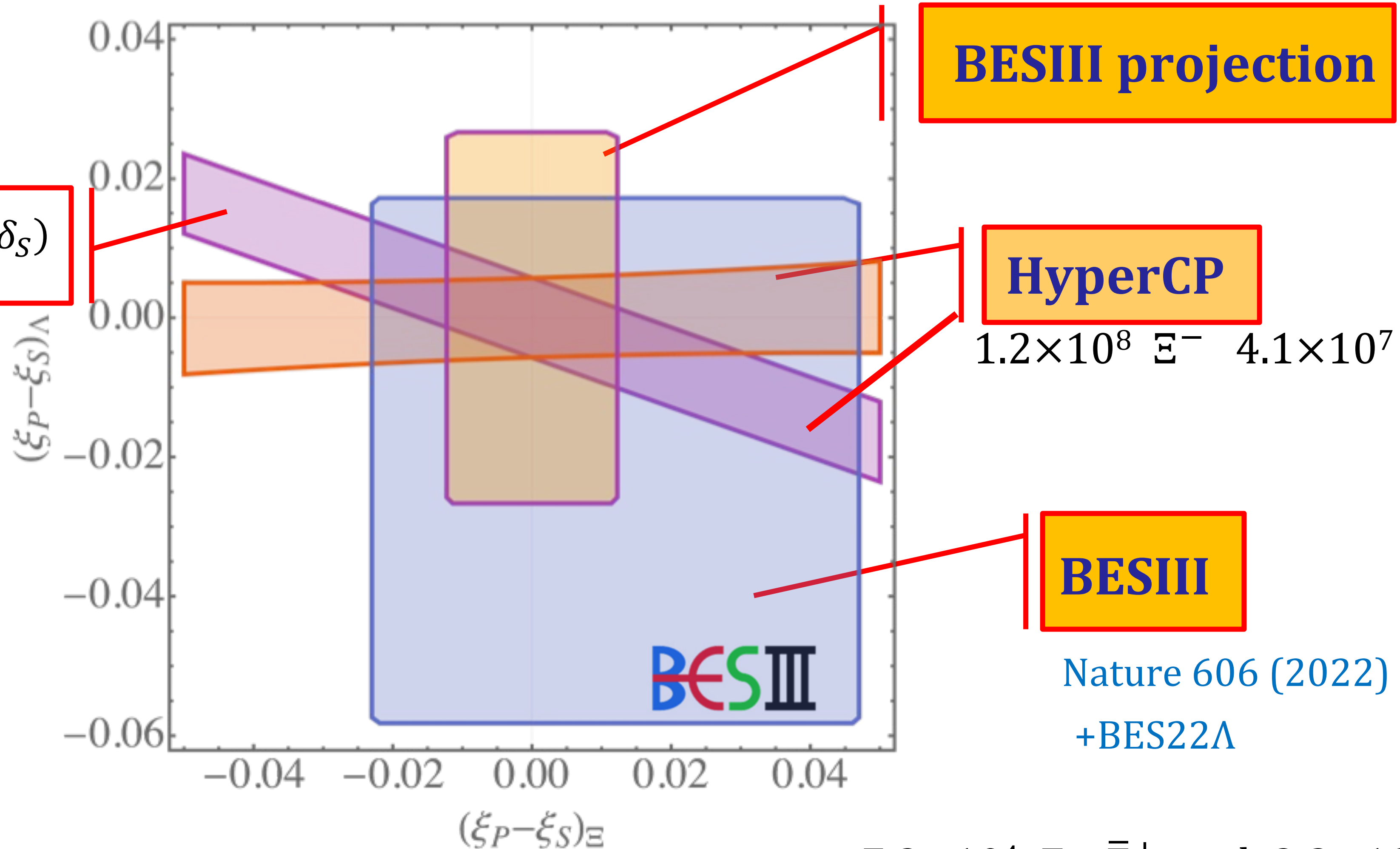
$$0.5 < B_G < 2 \text{ and } 0.2 < |\kappa| < 1$$

* Tandean, Valencia PRD67 (2003) 056001

** Tandean Phys.Rev.D 69 (2004) 076008

Kaon bounds for CPV in hyperon decays assuming chromomagnetic penguin

Hyperon weak phases



$1.2\times10^8\ \Xi^- \quad 4.1\times10^7\ \bar{\Xi}^+$

Nature 606 (2022) 64
+BES22Λ

$7.3\times10^4\ \Xi^-\ \bar{\Xi}^+$ and $3.2\times10^6\ \Lambda\bar{\Lambda}$

$$-3.8\times10^{-4} < (\xi_P - \xi_S)_\Xi^{SM} < -0.4\times10^{-4}$$

$$-2.4\times10^{-4} < (\xi_P - \xi_S)_\Lambda^{SM} < -2.0\times10^{-4}$$

HyperCP PRL 93 (2004) 262001

Baryon-meson interactions

CPV in hadronic baryon decays:

- (V-A) transition
- CPV phases derived from CKM or BSM
- Strong final state interactions

Hyperon decays:

$\Lambda, \Sigma \to N\pi$ (S=0 I=1/2, 3/2)

$\Xi \to \Lambda\pi$ (S=-1, I=1)

$\Omega \to \Lambda K^-, \Xi\pi$ (S=-2, I=1/2,3/2)

Charmed baryons:

$\Lambda_c, \Xi_c \to pK^-\pi^+$ (S=-1,I=0,1)

$N\pi$ scattering

$\sigma^+_{tot}, \sigma^-_{tot}$ the $\pi^\pm p$ total cross sections,

$\mathrm{Ref}^+, \mathrm{Ref}^-$: the real part of the elastic forward scattering amplitude,

$\sigma^+_{in}, \sigma^-_{in}$: $\pi^\pm p$ inelastic cross sections,

$\frac{d\sigma^+}{d\Omega}, \frac{d\sigma^-}{d\Omega}, \frac{d^{(0)}}{d\Omega}$: $\pi^\pm p$ and charge exchange elastic differential cross sections (unpolarized targets),

$\vec{P}^+, \vec{P}^-, \vec{P}^{(0)}$: polarization of the recoil proton in $\pi^\pm p$ elastic scattering and of the recoil neutron in charge exchange (unpolarized targets) and

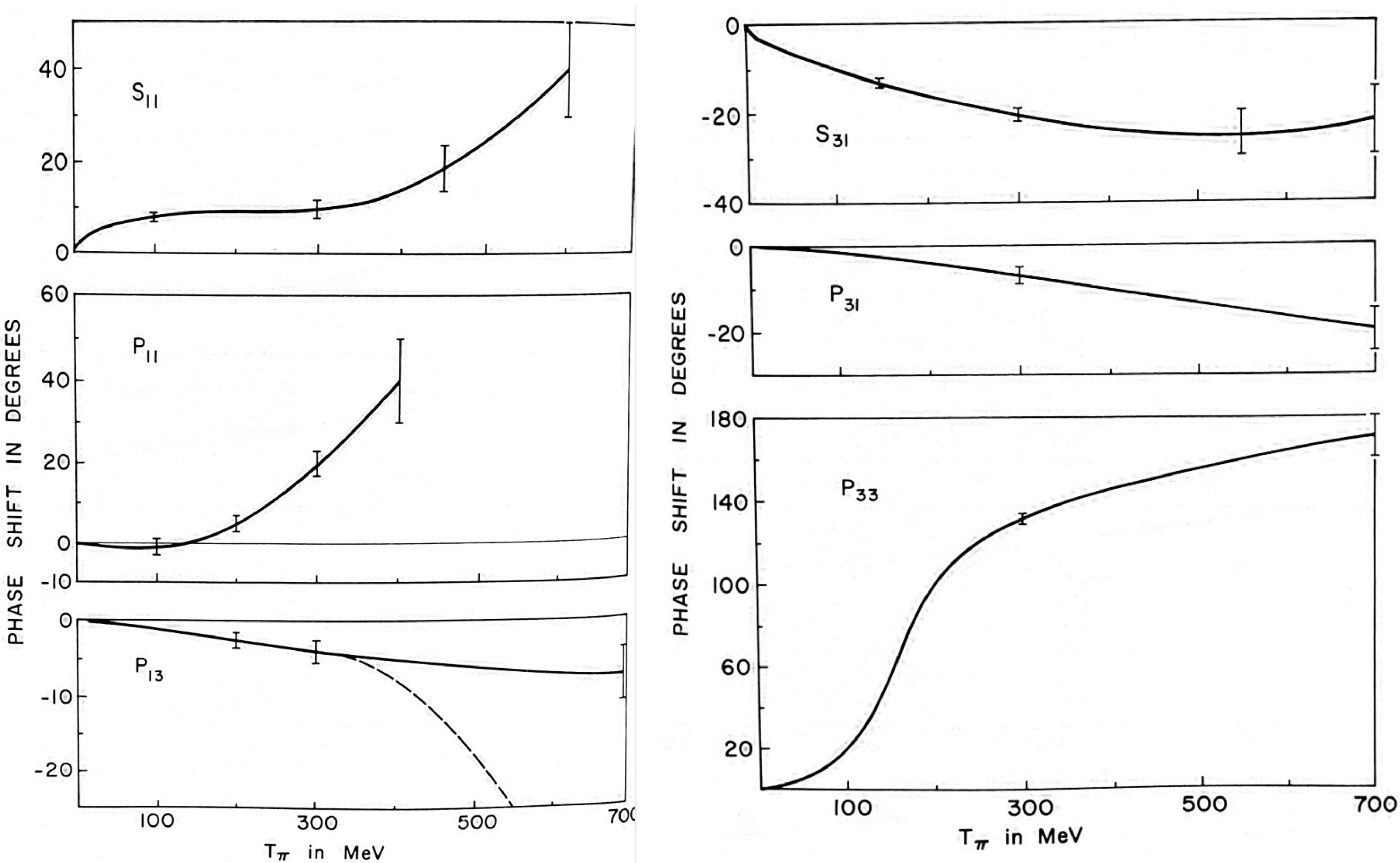
$A^+, A^-, A^{(0)}$: rotation parameters in $\pi^\pm p$ and charge
$R^+, R^-, R^{(0)}$: exchange scattering

Phase Shift analysis

TABLE III. Values of the N–π scattering phase shifts δ^L_{2I} relevant for Λ and Σ decays from [56].

	$\lvert\mathbf{q}\rvert$ [MeV/c]	δ^S_1 [°]	δ^S_3 [°]	δ^P_1 [°]	δ^P_3 [°]
$\Lambda \to N\pi$	103	6.52(9)	−4.60(7)	−0.79(8)	−0.75(4)
$\Sigma \to N\pi$	190	9.98(23)	−10.70(13)	−0.04(33)	−3.27(15)

Nπ scattering

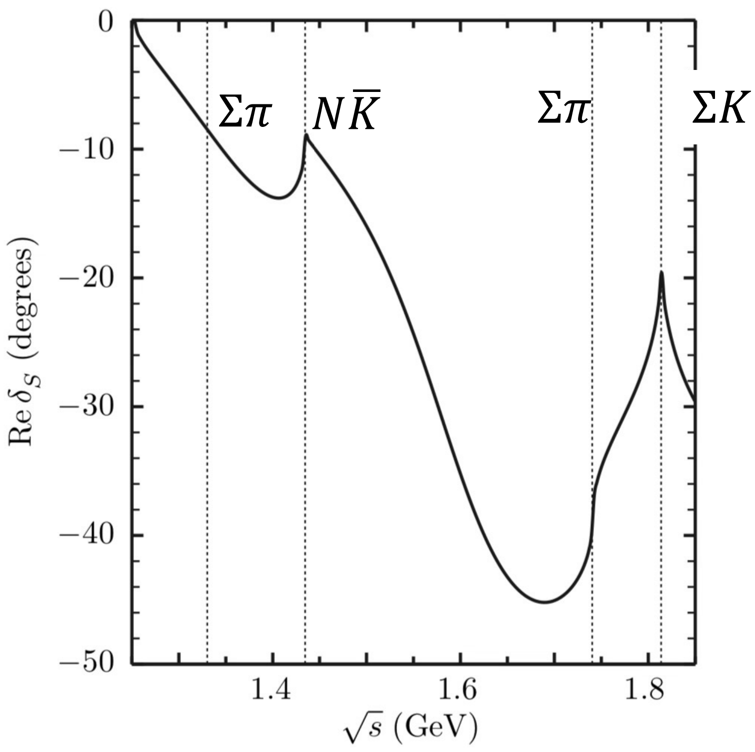


Determination from polarization rotation angle in $\Xi \to \Lambda\pi$

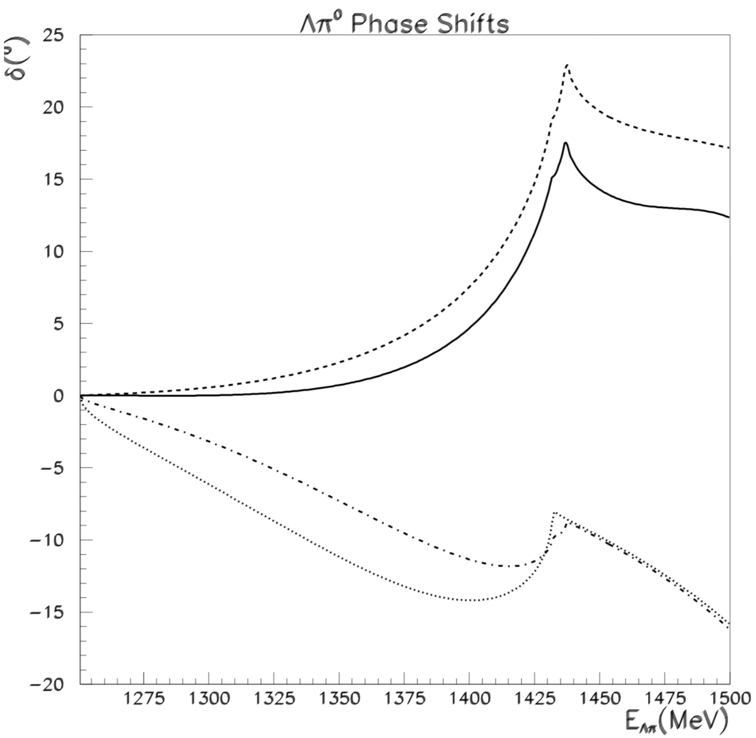
VALUE (°)	*EVTS*	*DOCUMENT ID*		*TECN*
$\mathbf{-1.2 \pm 1.0}$	**OUR AVERAGE** Error includes scale factor of 1.4. See the ideogram below.			
$0.63 \pm 1.09 \pm 0.52$	73k	[1] ABLIKIM	2022AD	BES3
$-2.39 \pm 0.64 \pm 0.64$	144M	[2] HUANG	2004	HYCP
$-1.61 \pm 2.66 \pm 0.37$	1.35M	[3] CHAKRAVORTY	2003	E756
5 ± 10	11k	ASTON	1985B	LASS
14.7 ± 16.0	21k	[4] BENSINGER	1985	MPS
11 ± 9	4303	BALTAY	1974	HBC
5 ± 16	2436	COOL	1974	OSPK
-14 ± 11	2781	DAUBER	1969	HBC
0 ± 12	1004	[5] BERGE	1966	HBC

$$\frac{\beta}{\alpha} = \frac{\sqrt{1-\alpha^2}}{\alpha}\sin\phi = \tan\left(\delta^{P}_{I=1} - \delta^{S}_{I=1}\right)$$

$\Lambda\pi$ scattering



Tandean, Thomas, Valencia PRD64(2001)014005

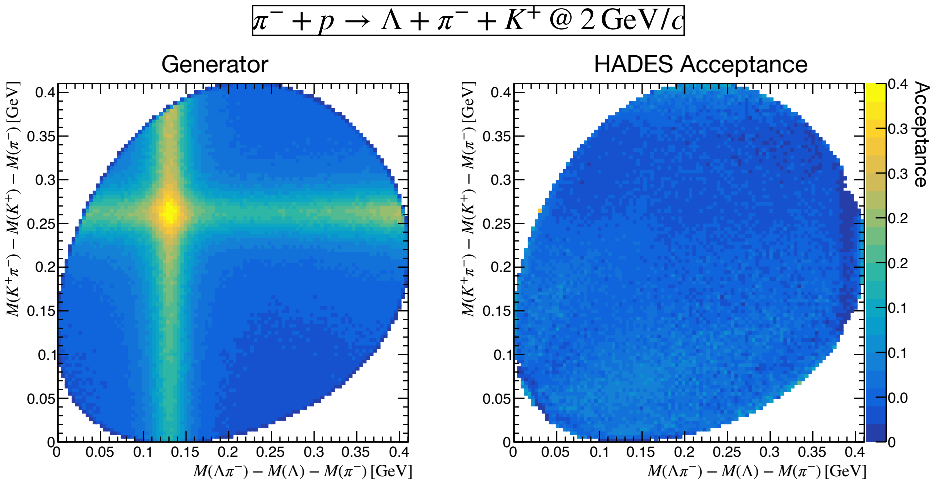


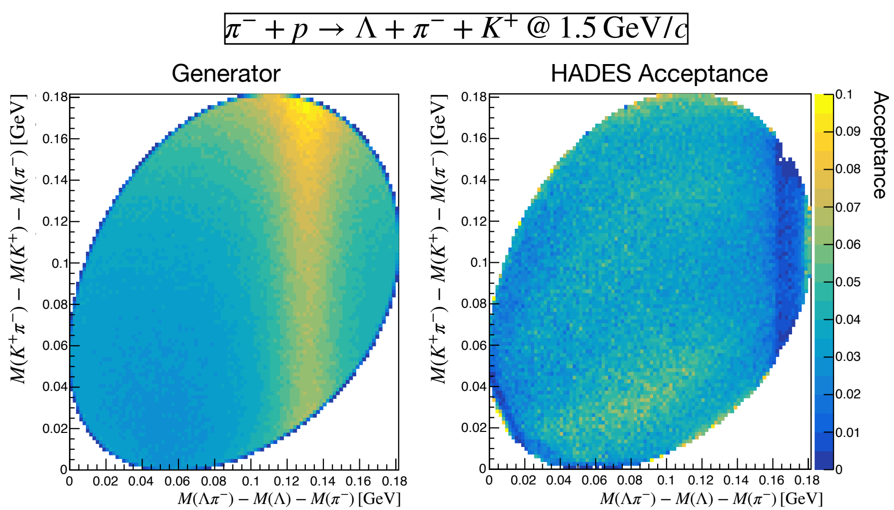
Meissner,Oller PRD64 (2001) 014006

$\pi^- p \to \Lambda\pi^- K^+$ at HADES

Proposed measurement at HADES

- $M(\Lambda\pi^-) = M_\Xi$ is covered
- Extraction of $\Lambda\pi^-$ s-wave phase shift using PWA/Omnes function?
- Synergy with BESIII and LHCb analyses?





Amplitude A:

$$A = \sum_\alpha A^\alpha_{\rm tr}(s) Q^{\rm in}_{\mu_1..\mu_j}(S, L, J) A_{2b}(i, S_2, L_2, J_2)$$
$$Q^{\rm fin}_{\mu_1..\mu_j}(i, S_2, L_2, J_2, S', L', J).$$

BW resonances:

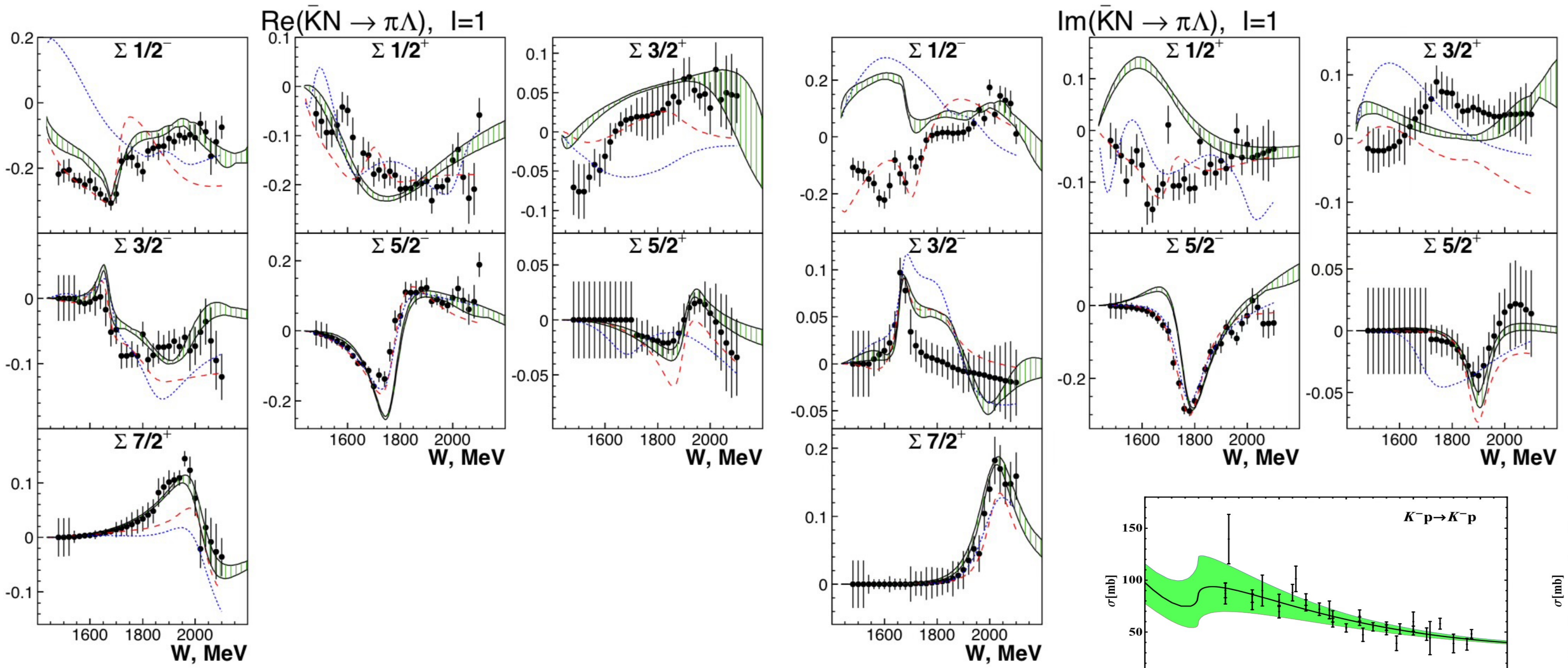
$$A^\beta_{2b} = \frac{1}{(M^2 - s - {\rm i}\Gamma M)}$$

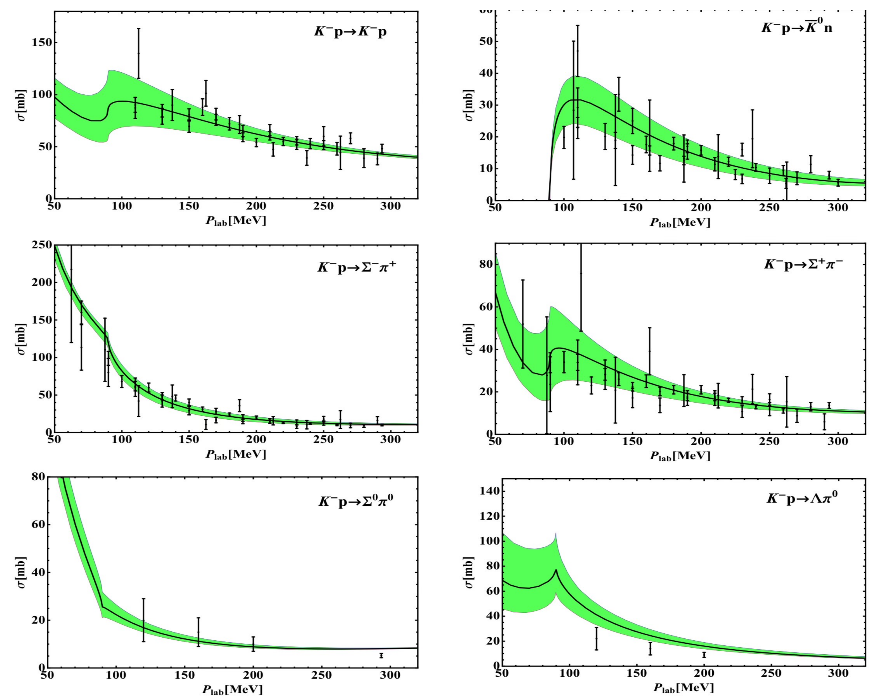
Scattering length a and range r:

$$A^\beta_{2b} = \frac{\sqrt{s_i}}{1 - \frac{1}{2} r^\beta q^2 a^\beta_{p\Lambda} + {\rm i} q a^\beta_{p\Lambda} q^{2L}/F(q, r^\beta, L)}$$

PLB 785 (2018) 574

pK^- scattering





https://www.sciencedirect.com/science/article/pii/S0370269319300413

$\Omega^- \to \Lambda K^-$

$$I = \frac{1}{2} : \Lambda K^- \leftrightarrow \Xi\pi$$

$$S = \begin{bmatrix} e^{2i\delta_{\Xi\pi}} & 2i\sqrt{\varepsilon}e^{i(\delta_{\Xi\pi}+\delta\Lambda K)} \\ 2i\sqrt{\varepsilon}e^{i(\delta_{\Xi\pi}+\delta\Lambda K)} & e^{2i\delta_{\Lambda K}} \end{bmatrix}$$

$$\eta = 1 - 2\varepsilon$$

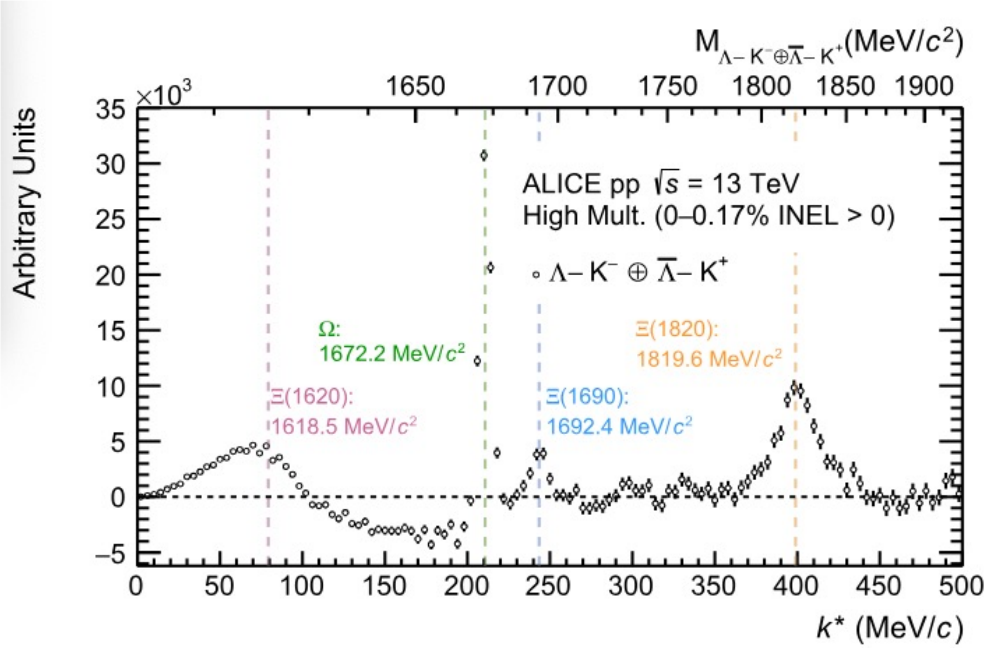
$$\frac{\beta}{\alpha} = \frac{\tan(\delta^D_{\Lambda K} - \delta^P_{\Lambda K}) + \Delta}{1 + \tan(\delta^D_{\Lambda K} - \delta^P_{\Lambda K})\Delta}$$

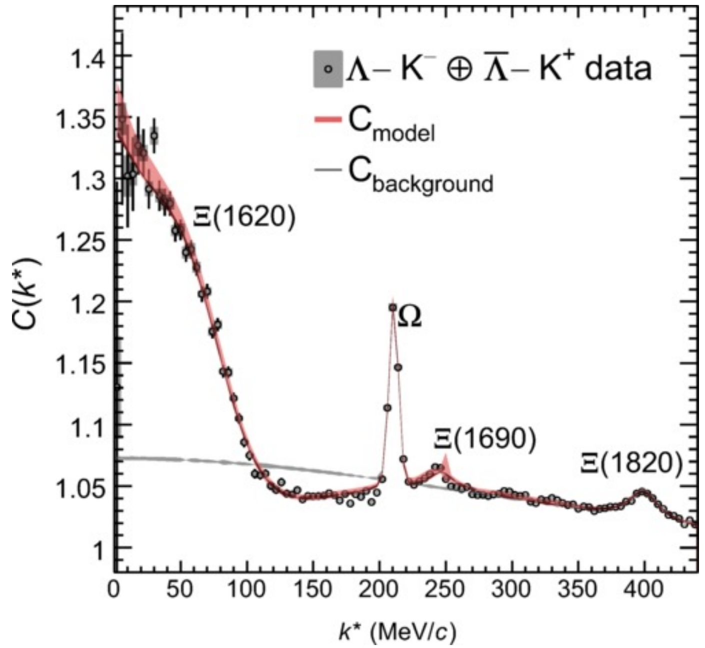
$$\Delta = \sqrt{\varepsilon_P}\frac{p_\Xi}{p_\Lambda} - \sqrt{\varepsilon_D}\frac{d_\Xi}{d_\Lambda}$$

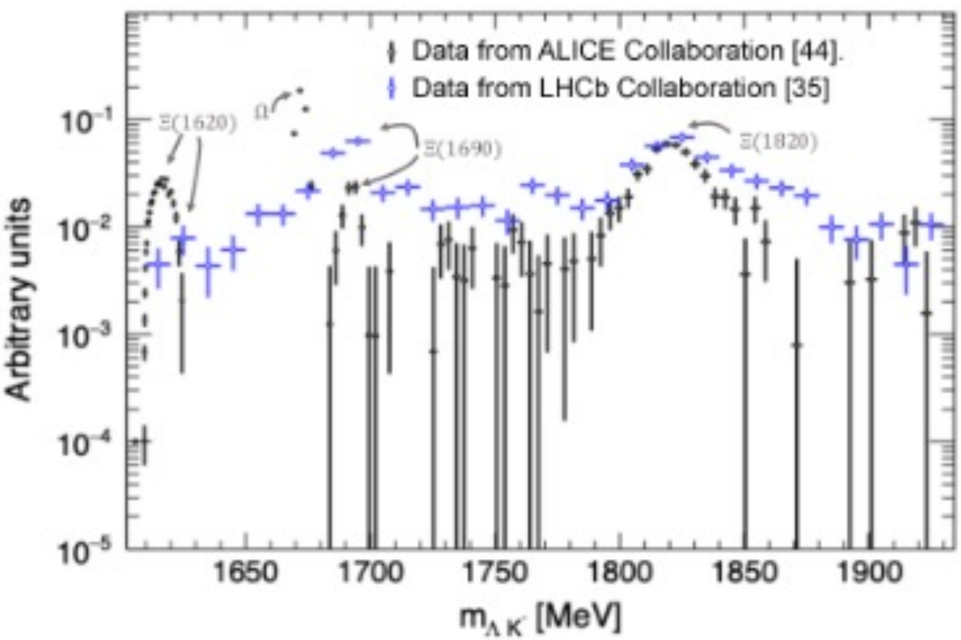
$$A_{CP} = -\tan(\delta^D_{\Lambda K} - \delta^P_{\Lambda K})\sin(\xi^D_\Lambda - \xi^P_\Lambda) + \Delta'$$
$$B_{CP} = -\sin(\xi^D_\Lambda - \xi^P_\Lambda) + \tan(\delta^D_{\Lambda K} - \delta^P_{\Lambda K})\Delta'$$

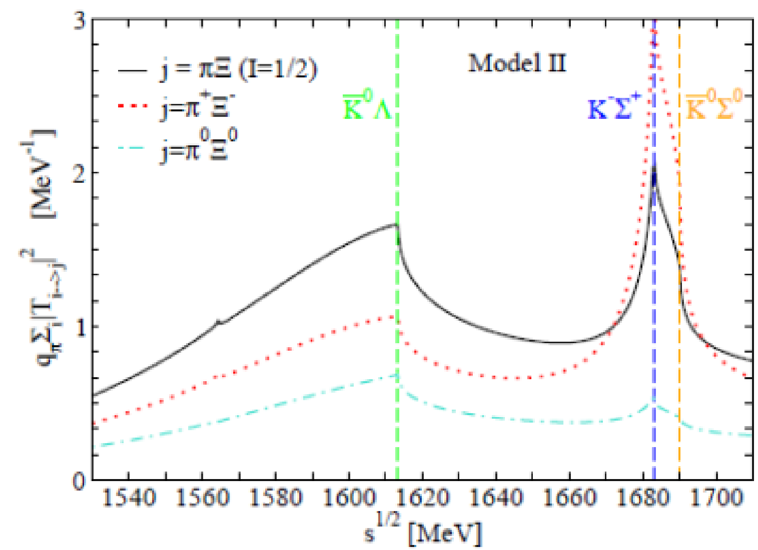
$$\Delta' = \sqrt{\epsilon_P}\frac{p_\Xi}{p_\Lambda}\sin(\xi^D_\Lambda - \xi^P_\Xi) + \sqrt{\epsilon_D}\frac{d_\Xi}{d_\Lambda}\sin(\xi^D_\Xi - \xi^P_\Lambda)$$

ΛK^- scattering









PRD 110 (2024) L011505

Summary

Opportunities for FAIR experiments:

- Complementary measurements to LHCb: exclusive measurements, electrons
- Synergy with LQCD - form factors: transitions to ground state vs excited states
- CPV in baryon hadronic decays require PWA methods beyond BW isobar model and understanding of baryon-meson interactions
- Proton polarimetry?   arXiv:2501.02439 [hep-ph]