Hyperon structure

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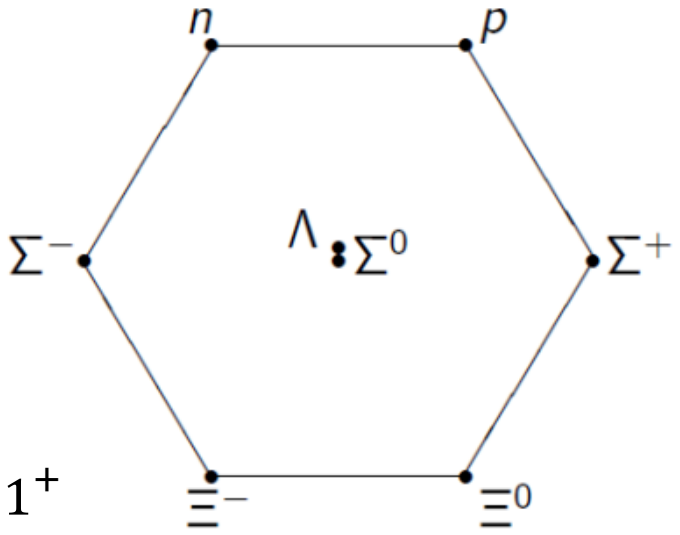
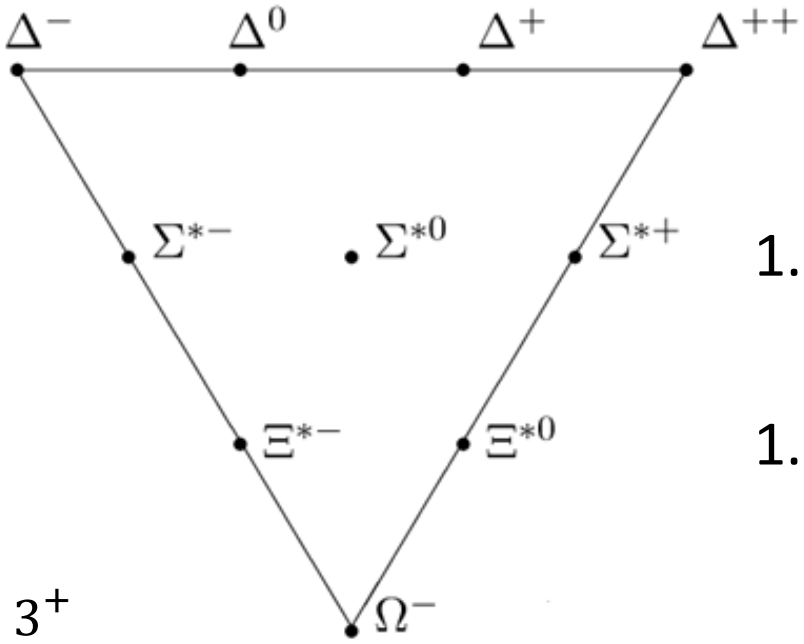
Hyperon structure: transition form factors

Light baryons



B

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



B'

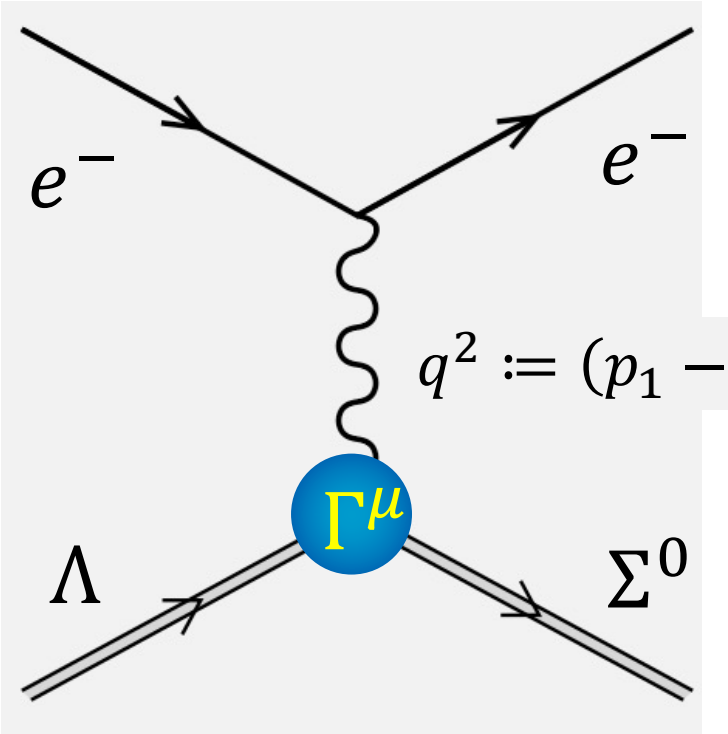
$J^P = \frac{3^+}{2}$

	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

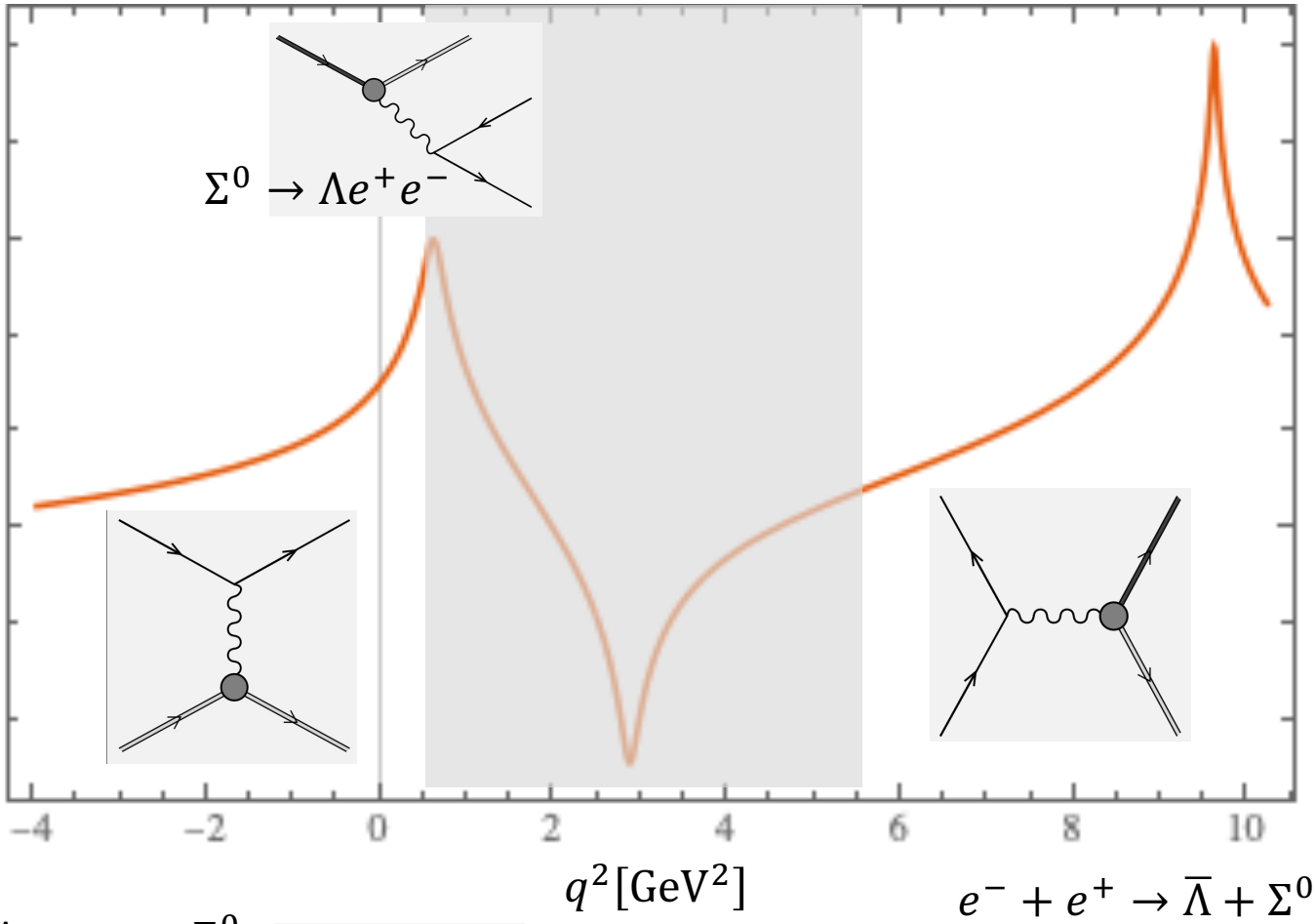
1.530 GeV

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



BESIII

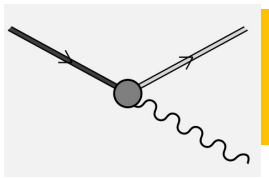
Nature Commun. 15 (2024) 8812

$\left|\frac{G_E}{G_M}\right| = 0.86(3)$

$\mathrm{Arg}\frac{G_E}{G_M} = 1.01(9)$ rad

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

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



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

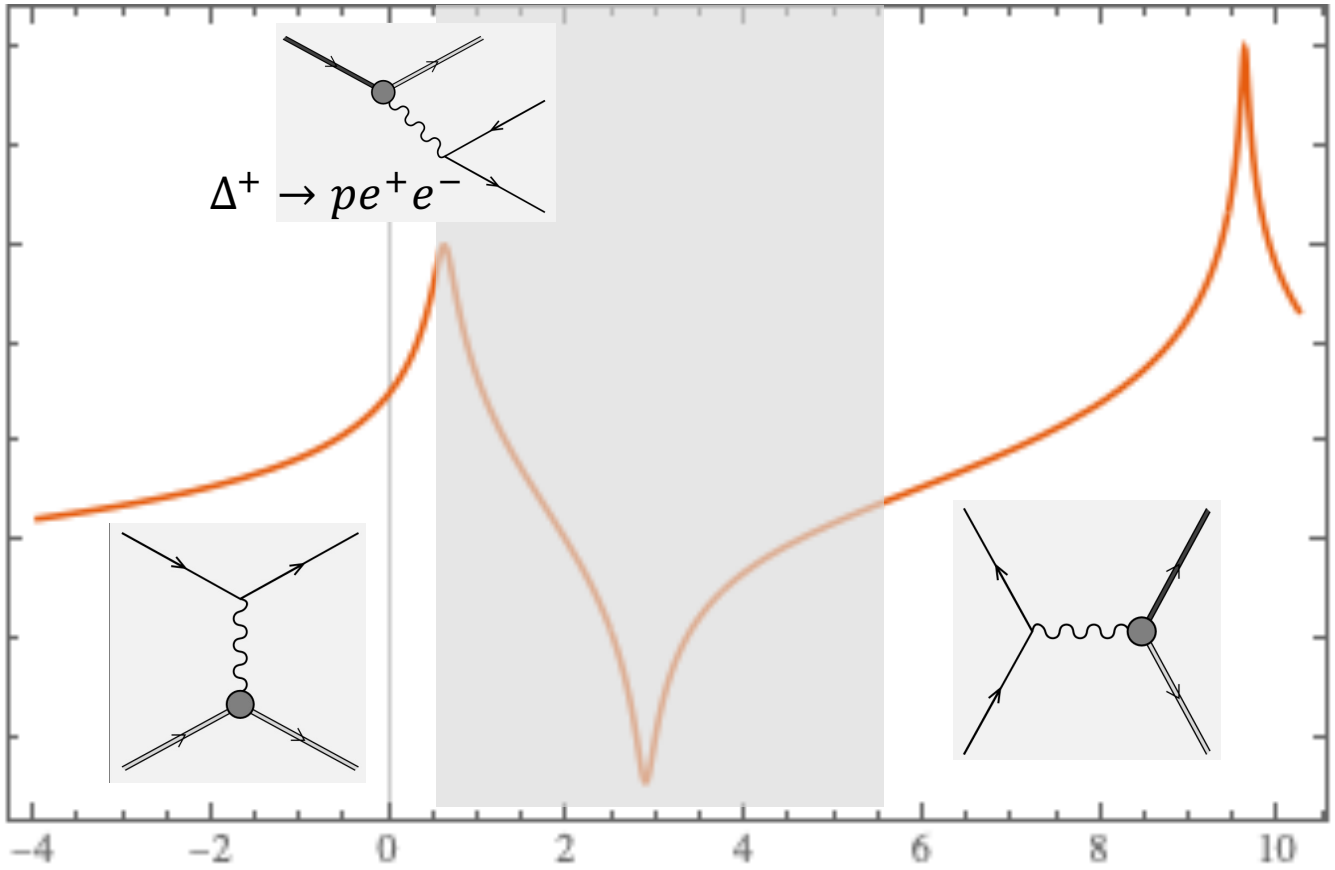
$F_i(q^2)$ complex functions for $q^2 > 4m_\pi^2$

Observables: $|F_i(q^2)|^2$ and $\mathrm{Arg}\left(F_1(q^2)F_2^*(q^2)\right)$

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

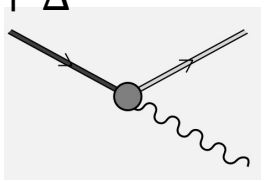
$$F_i(q^2) \approx F_i(0)\left[1 + \frac{1}{6} r_i^2 \, q^2\right]$$

EM Transition Form Factors



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

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



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

$B(\Delta^+ \to pe^+e^-) = 4.2(7)\times10^{-5}$ 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 $B' \to B\gamma$

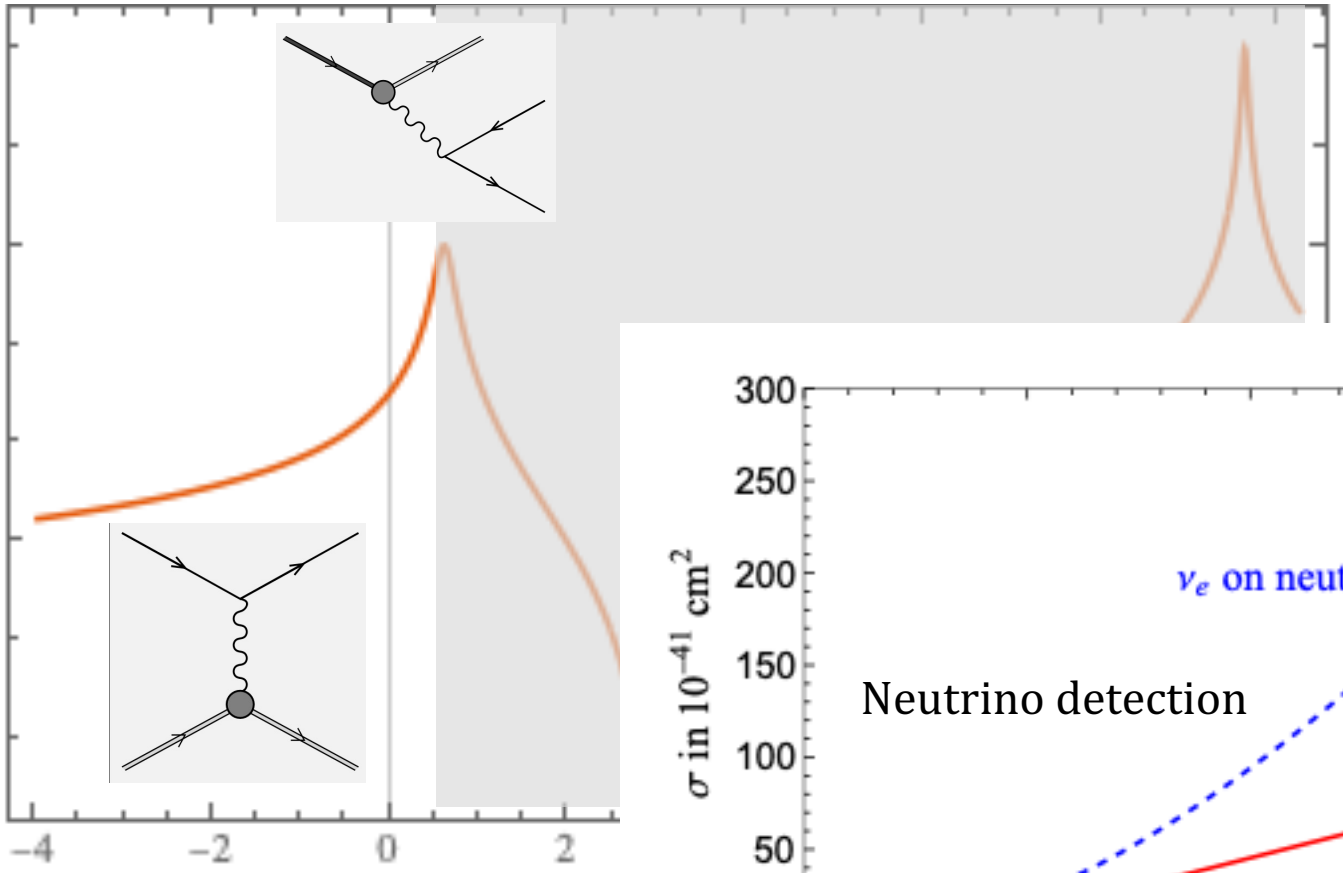
	BF
$\Sigma^{*0} \to \Lambda\gamma$	1.2×10^{-2}
$\Sigma^{*0} \to \Sigma^{+}\gamma$	7×10^{-3}
$\Sigma^{*+} \to \Sigma^{+}\gamma$	7×10^{-3}
$\Sigma^{*-} \to \Sigma^{-}\gamma$	$< 2 \times 10^{-4}$
$\Xi^{*} \to \Xi\gamma$	$< 4 \times 10^{-2}$

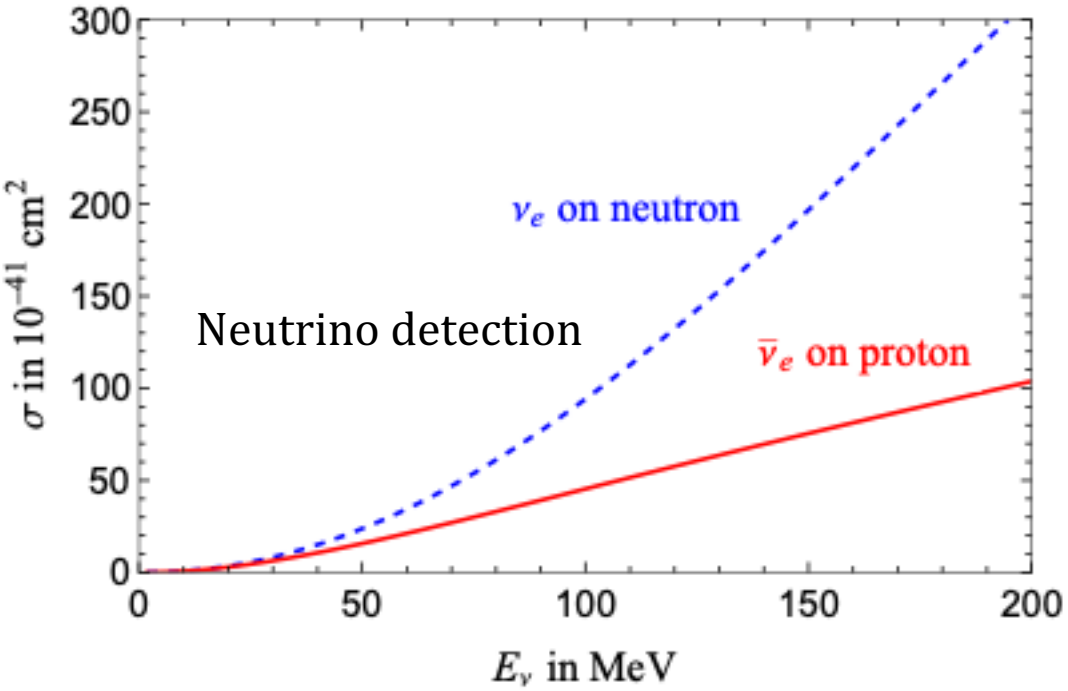
Radiative Decays $B' \to B\pi\gamma$

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





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

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

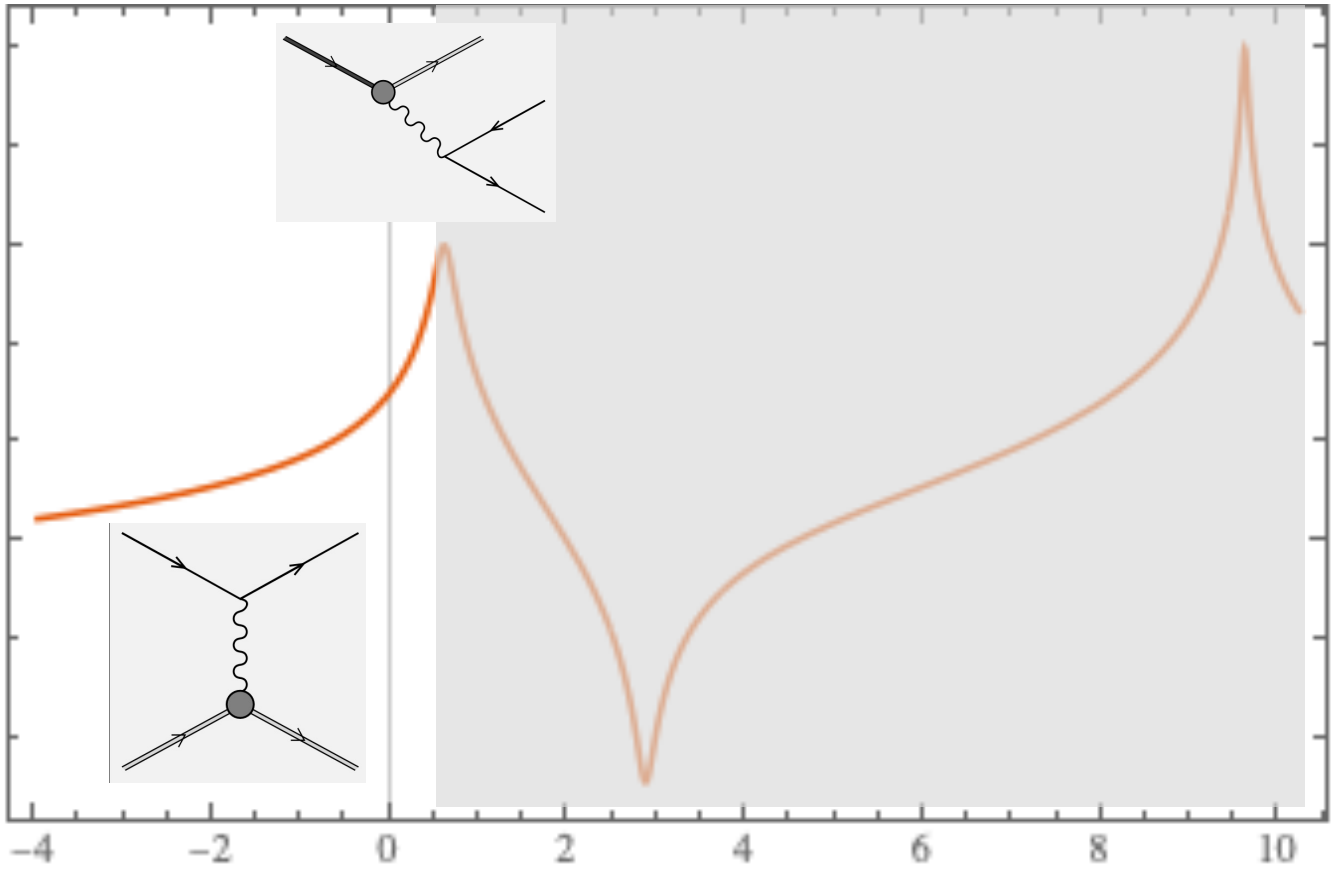
$\bar{\nu}_e + p \rightarrow e^+ + \Lambda$

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

V_{us}

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

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) $\times 10^{-5}$
1	$\Sigma^+ \to \Lambda e^+ \nu_e$	74	0	–	2
2	$\Sigma^- \to \Lambda e^- \bar{\nu}_e$	82	0	–	6
3	$\Lambda \to p e^- \bar{\nu}_e$	177	1	yes	83
	$\Sigma^- \to n e^- \bar{\nu}_e$	258	1	yes	107
4	$\Xi^- \to \Lambda e^- \bar{\nu}_e$	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	–	–

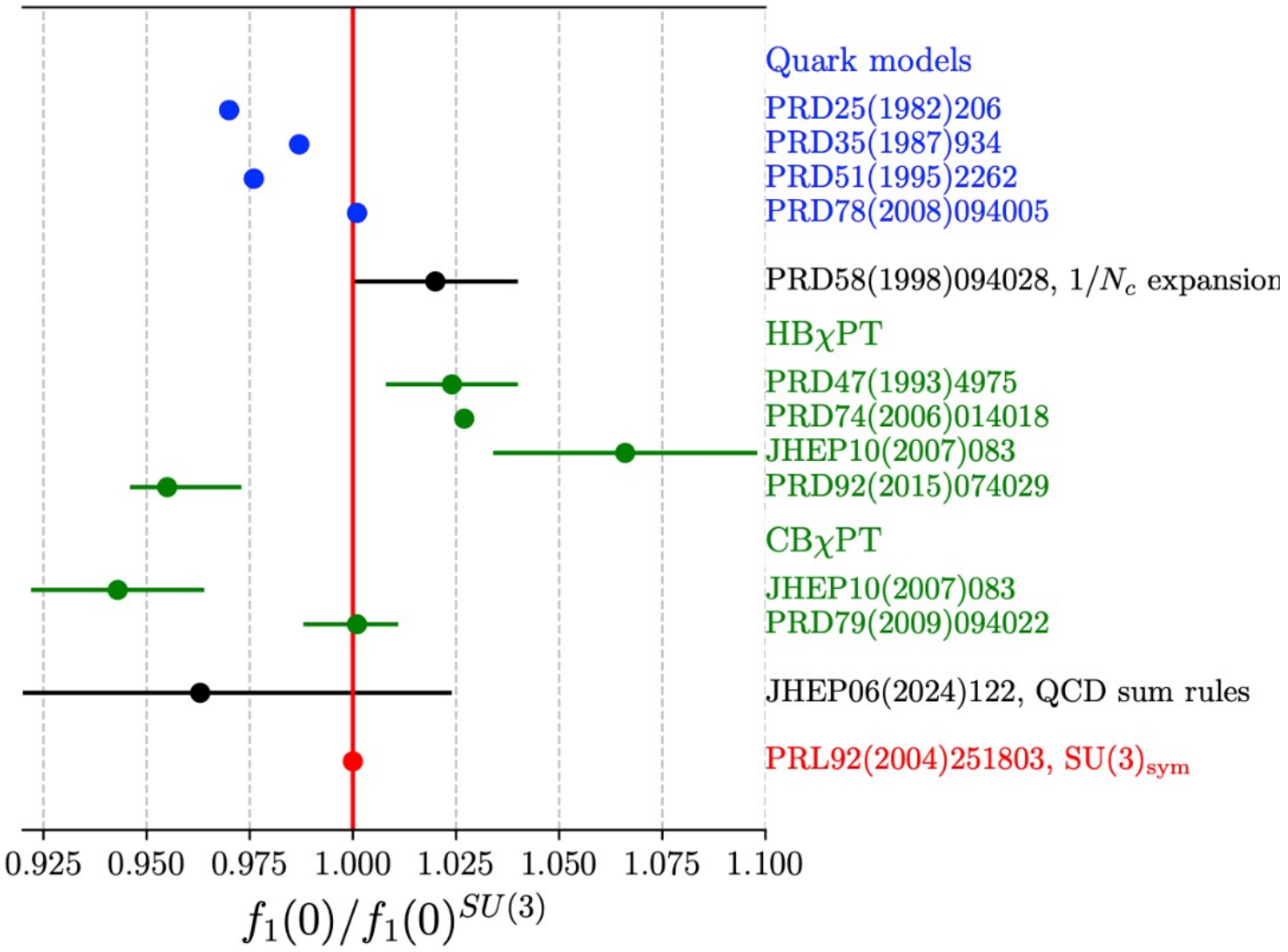
for $1/2^+ \to 1/2^+$ transitions

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

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

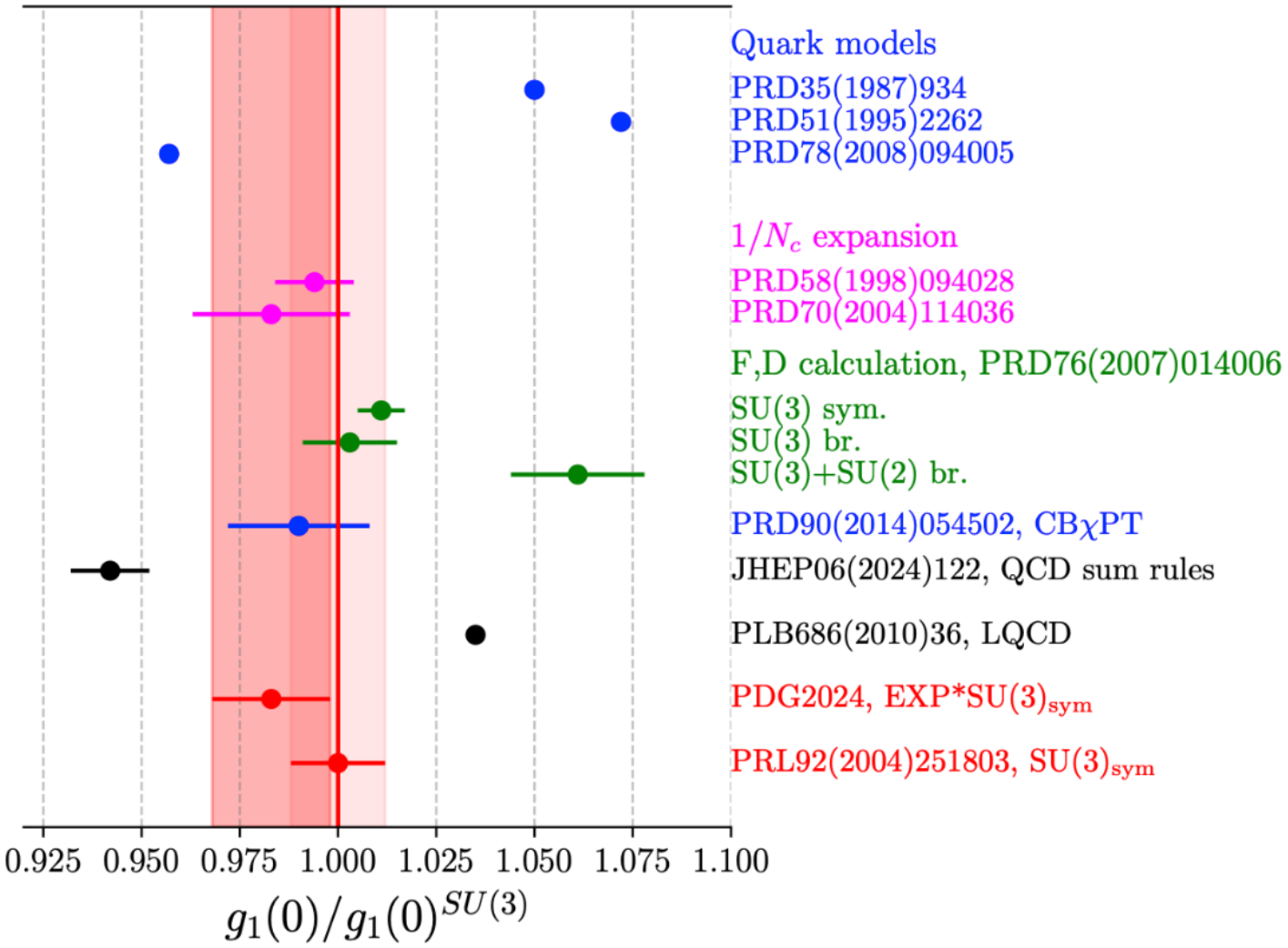
$$J_\mu^A = \left[\gamma_\mu g_1(q^2) - \frac{i\sigma_{\mu\nu} q^\nu}{M_1} g_2(q^2) + \frac{q_\mu}{M_1} g_3(q^2) \right] \gamma_5$$

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

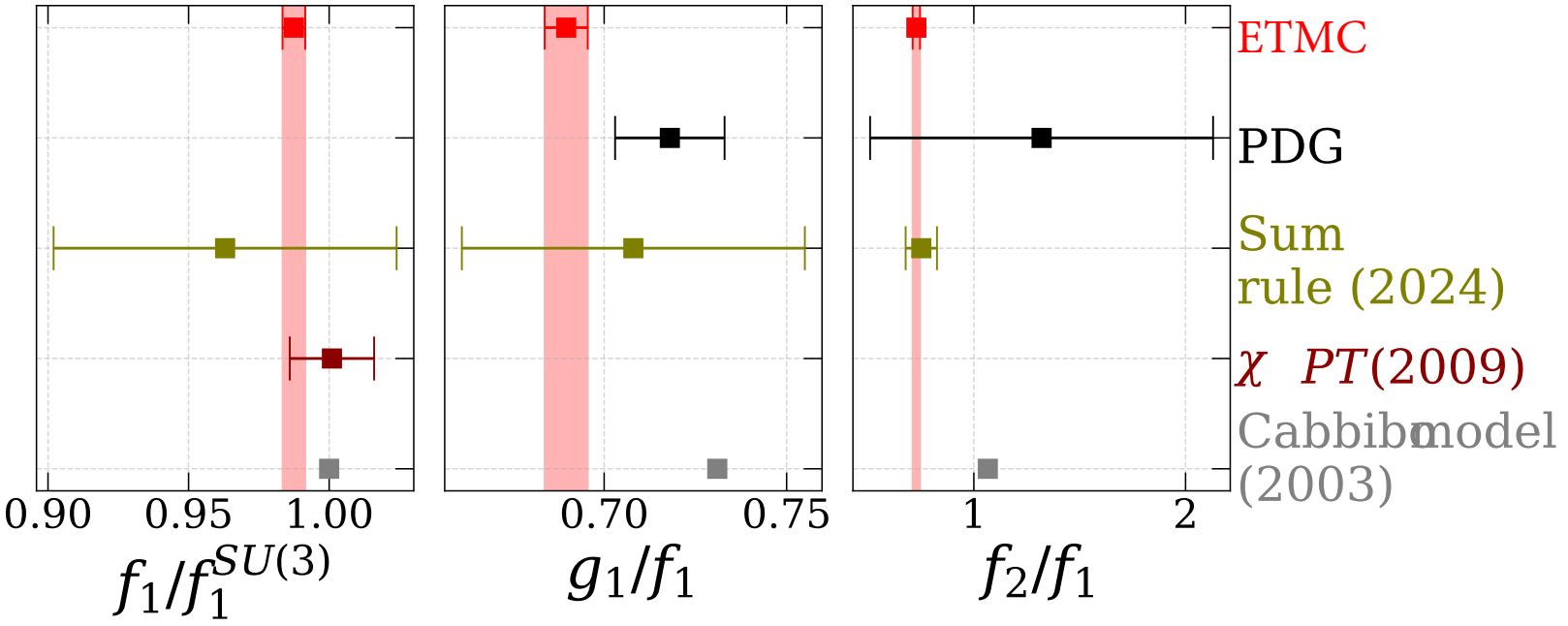


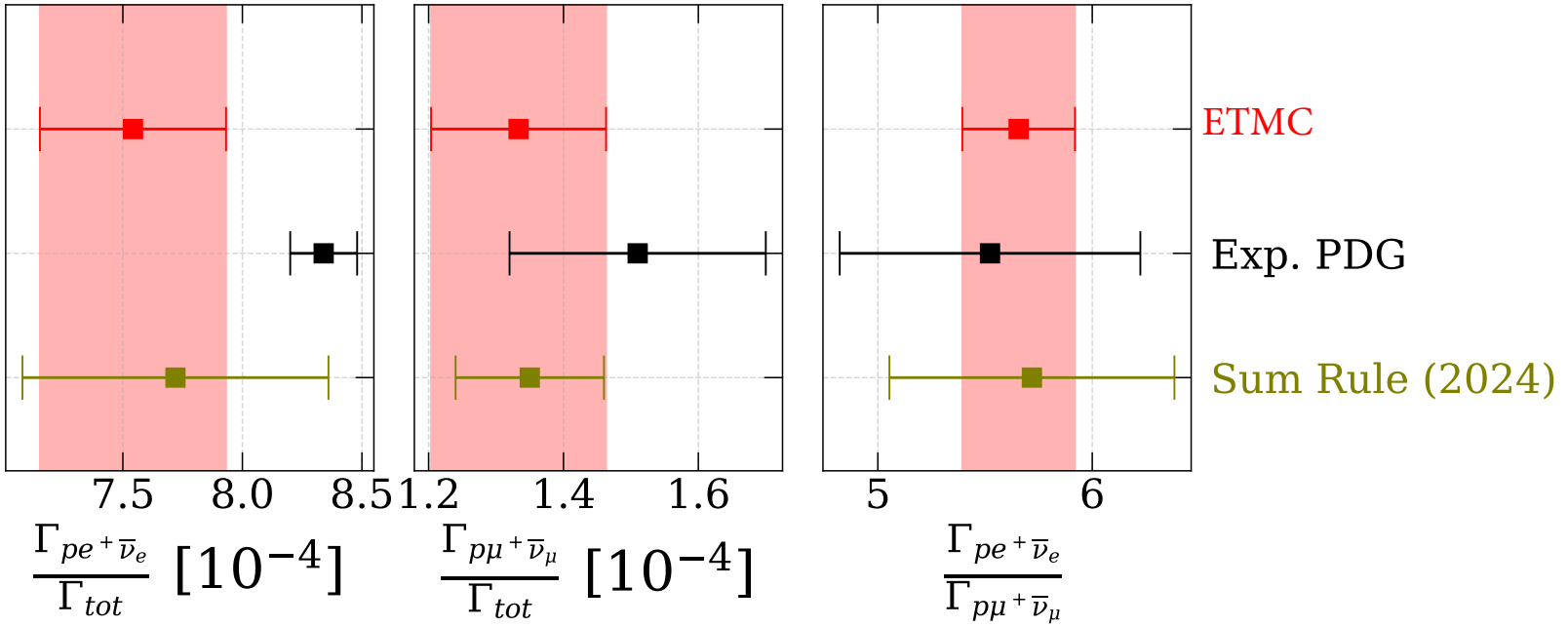
- SU(3) symmetry: $f_1(0) = -\sqrt{3/2}$

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]





ETMC C.Alexandrou, S.Bacchio et al. (2025)

Determination of V_{us}

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

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

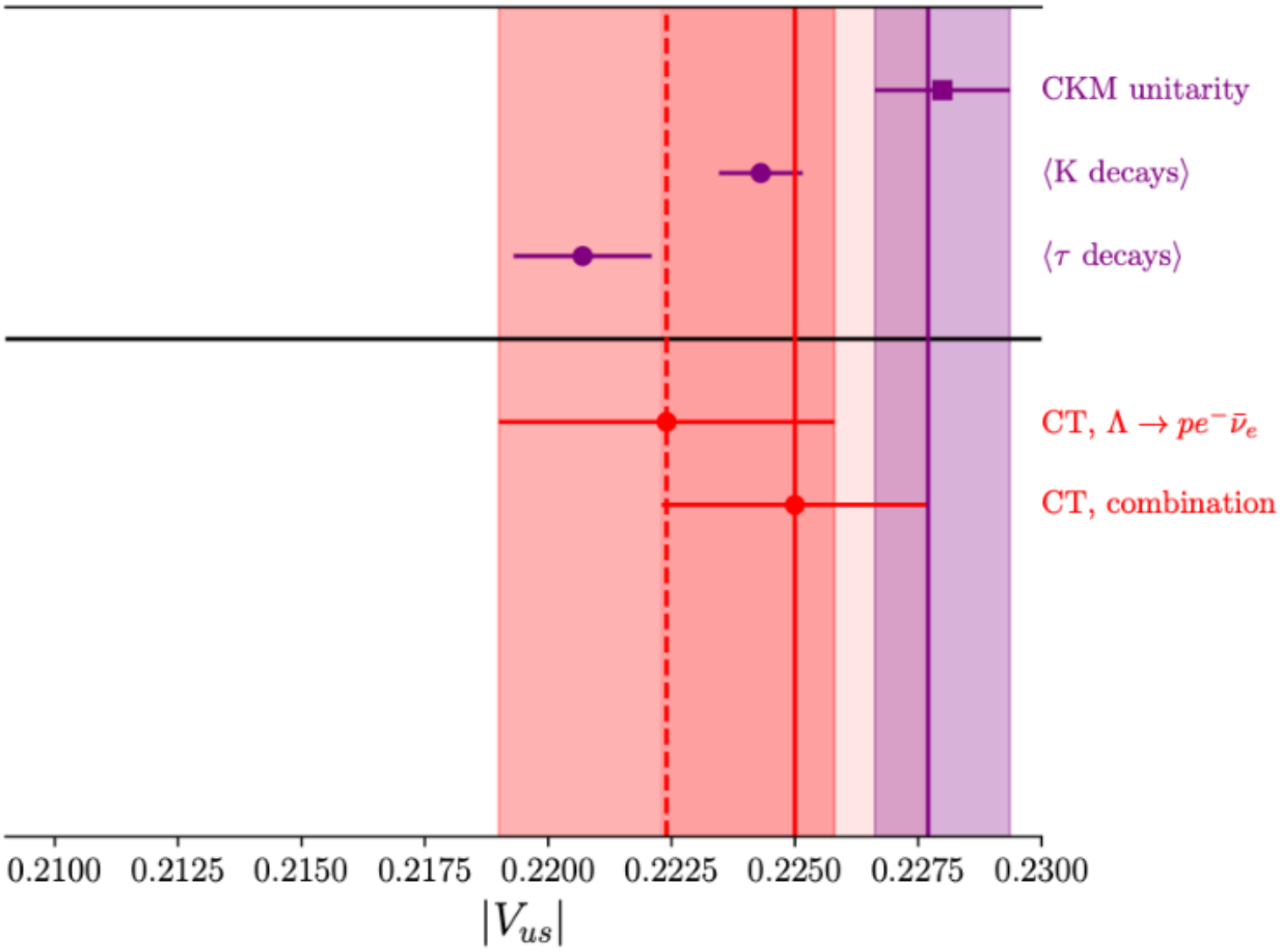
with $\beta = (M_\Lambda - M_p)/M_\Lambda \sim 0.159$ for $\Lambda \to p l^- \bar{\nu}_l$

Two ways to extract V_{us}:

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

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

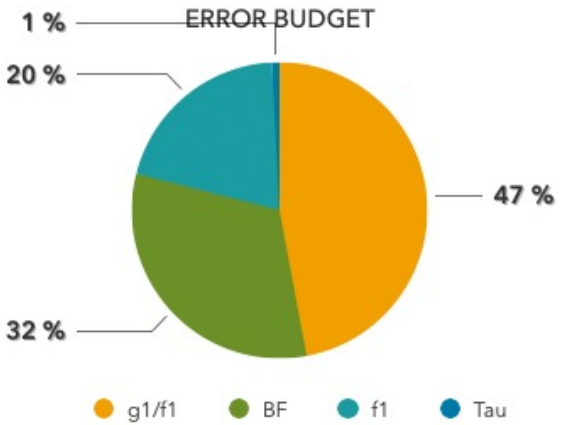
Status of V_{us}

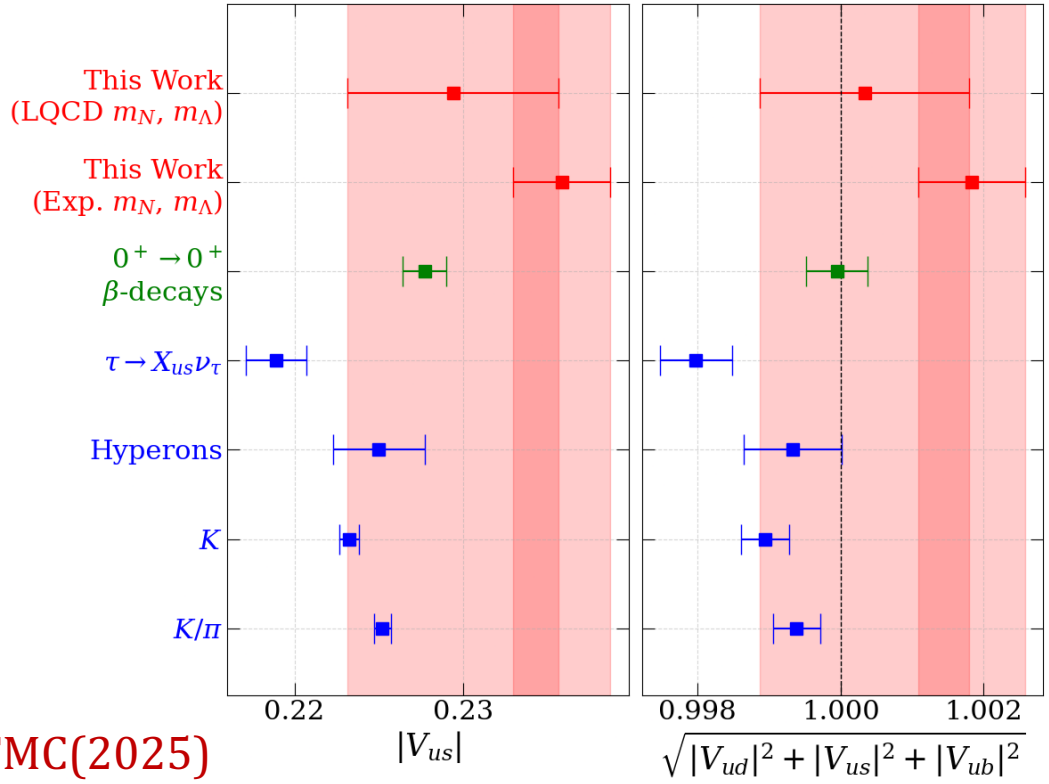


Status of V_{us}

f_1	f_2	f_3
1.2028(64)	0.878(20)	1.662(25)
$\langle r^2_{F_1} \rangle$	$\langle r^2_{F_2} \rangle$	$\langle r^2_{F_3} \rangle$
4.99(39)	14.3(16)	11.22(38)
g_1	g_2	g_3
0.8329(70)	-0.062(29)	-5.26(14)
$\langle r^2_{G_1} \rangle$	$\langle r^2_{G_2} \rangle$	$\langle r^2_{G_3} \rangle$
5.17(62)	7(43)	22.2(15)

Cabibbo





LQCD ETMC(2025)

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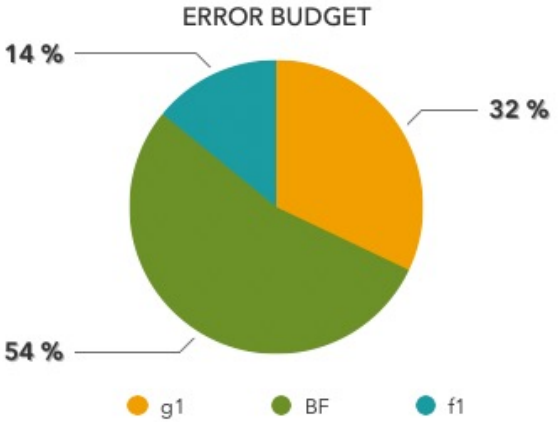

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	$\Sigma^- \to \Sigma^0 e^- \bar{\nu}_e$	5	0	–	–
5	$\Sigma^- \to p \pi^- e^- \bar{\nu}_e$	120	1	yes	–
6	$\Xi^0 \to \Lambda \pi^+ e^- \bar{\nu}_e$	64	1	–	–
	$\Omega^- \to \Xi^0 e^- \bar{\nu}_e$	357	1	yes	560
7	$\Omega^- \to \Xi^{*0} e^- \bar{\nu}_e$	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

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

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

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

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

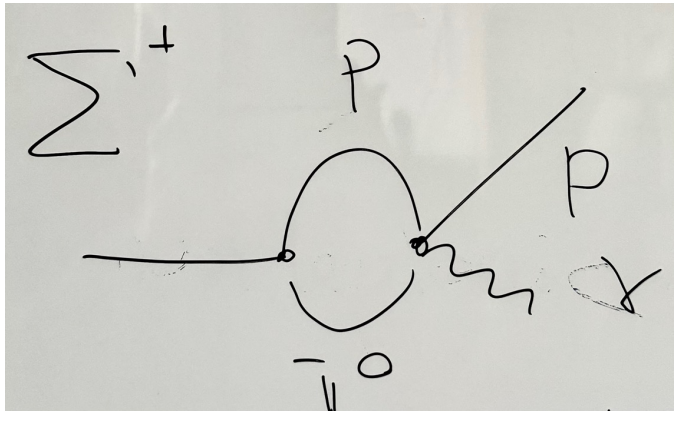
$$\langle B|J_\mu^{V,A}|\,B'\rangle = \sum_{k=1}^{4} F_k^{V,A}(q^2)\bar{u}\,\left[\Gamma_{\beta\mu}^{V,A}\right]_k\,v^\beta$$

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

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

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]

Summary

Soon results on $\Lambda \to p l \bar{\nu}_l$: BESIII, LHCb and LQCD ETMC

Opportunities for FAIR (CBM):

- Complementary to LHCb: exclusive measurements, electrons
- Synergy with LQCD - form factors: transitions to ground state vs excited states
- Precision physics V_{us}