Photo- and electroproduction of $\Lambda(1405)$ via $\gamma\, p \to K^+ \pi^+ \Sigma^-$

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Contents based on **S.i.N., Phys. Rev. D 96, 076021 (2017)**

Λ(1405)

The lowest Λ-hyperon s-wave resonance: J^P = 1/2^-

Its internal structure has been a long-standing puzzle

Generic SU(6) quark model: uds

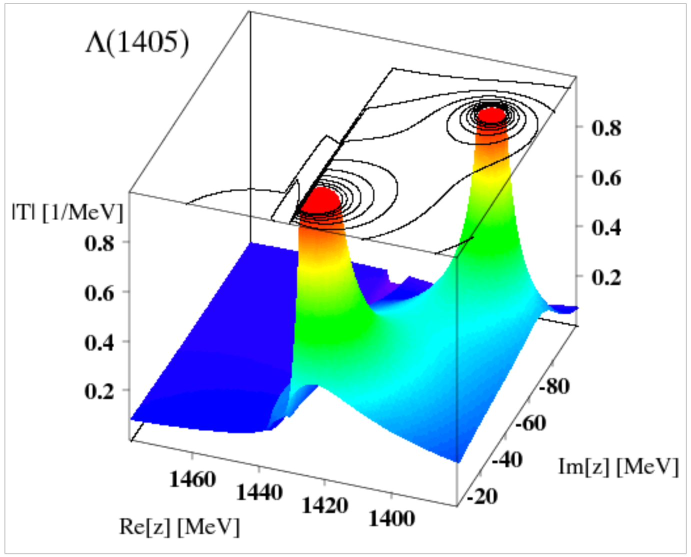
Chiral unitary model (ChUM): Meson-Baryon molecular state

Exotic hadron approach: A pentaquark: udsq$\underline{q}$

We employ ChUM scenario here!!
Higher pole Λ_H and lower pole Λ_L
$\Lambda_H + \Lambda_L \sim \Lambda(1405)$

Supports from recent lattice QCD

J. M. M. Hall et al.,, Phys. Rev. Lett. 114, no. 13, 132002

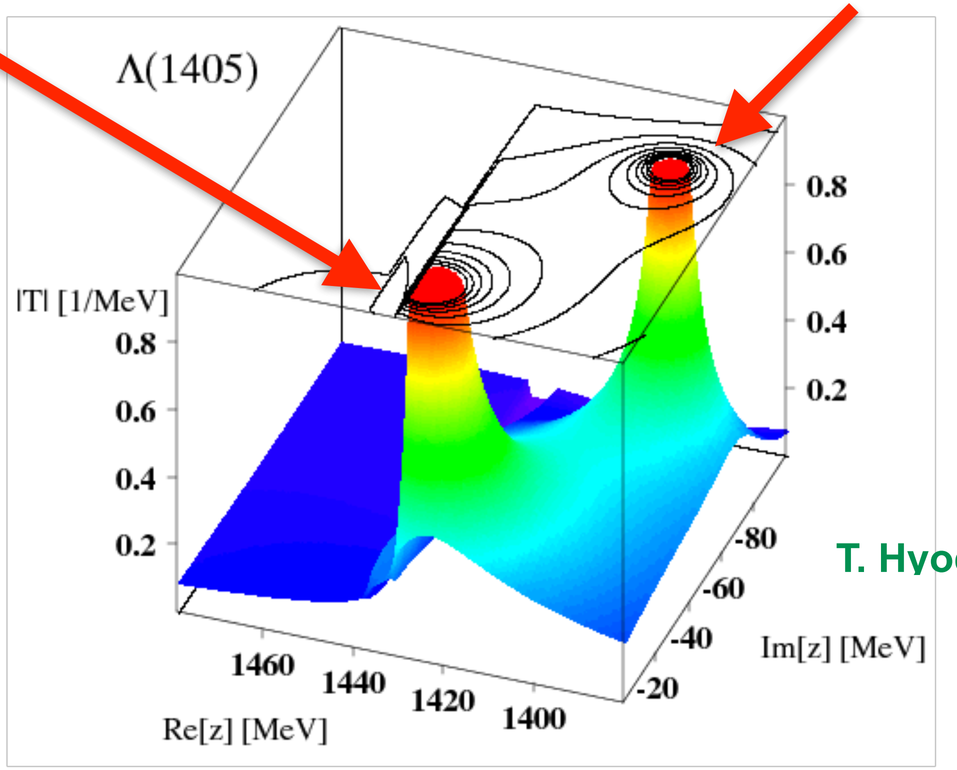


T. Hyodo, Doctoral thesis

Λ(1405)

In ChUM, Λ(1405) is generated dynamically in S = -1 meson-baryon scattering channel as a sum of higher and lower poles:

Λ_H ~ (1430 - 14*i*) MeV: **Λ_L ~ (1398 - 74*i*) MeV**

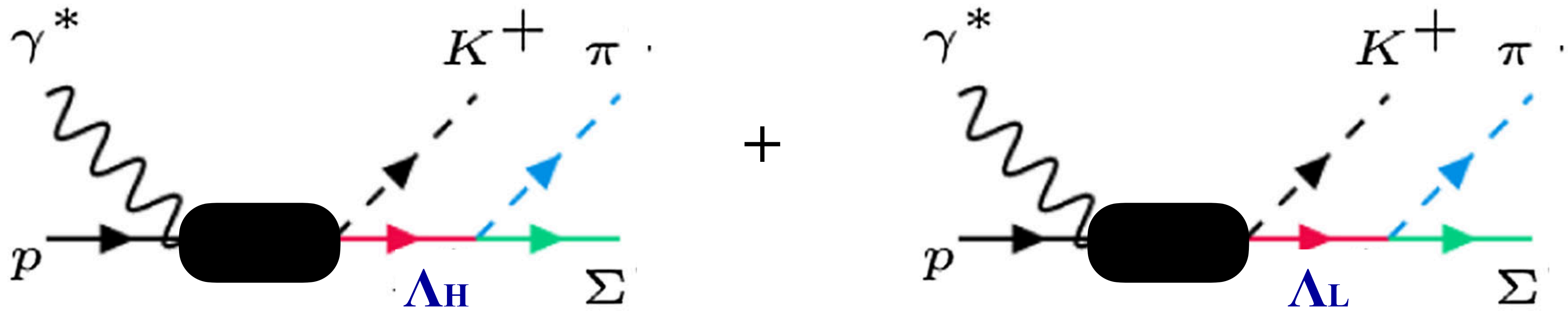


T. Hyodo, Doctoral thesis

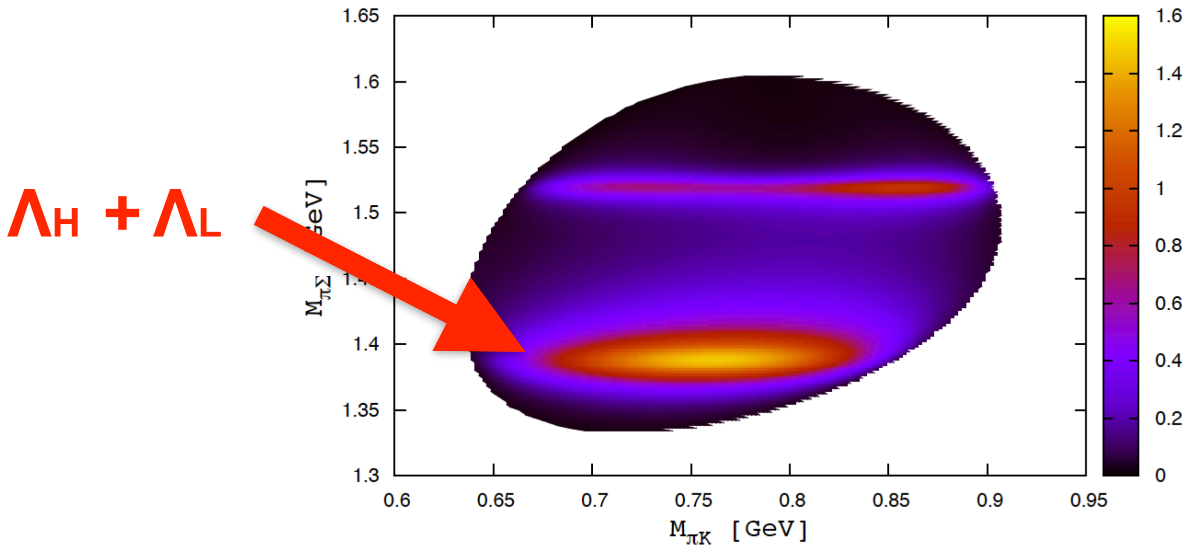
T.Hyodo and D.Jido, Prog.Part. Nucl.Phys.67, 55 (2012)

Λ(1405)

Λ(1405) production through Λ_H and Λ_L in Dalitz process $\gamma\, p \rightarrow K^+ \pi\, \Sigma$

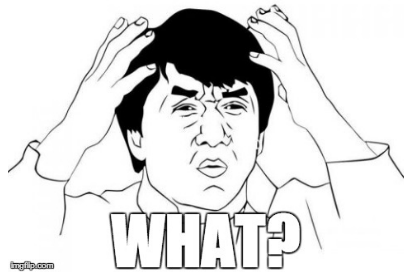


Interference between Λ_H and Λ_L, resulting in invariant-mass shape

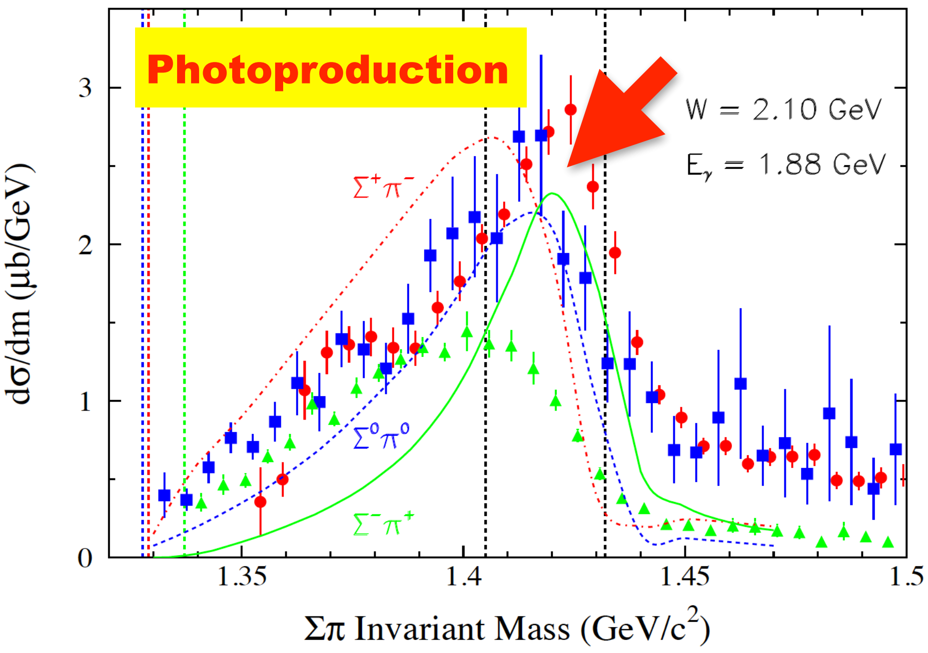


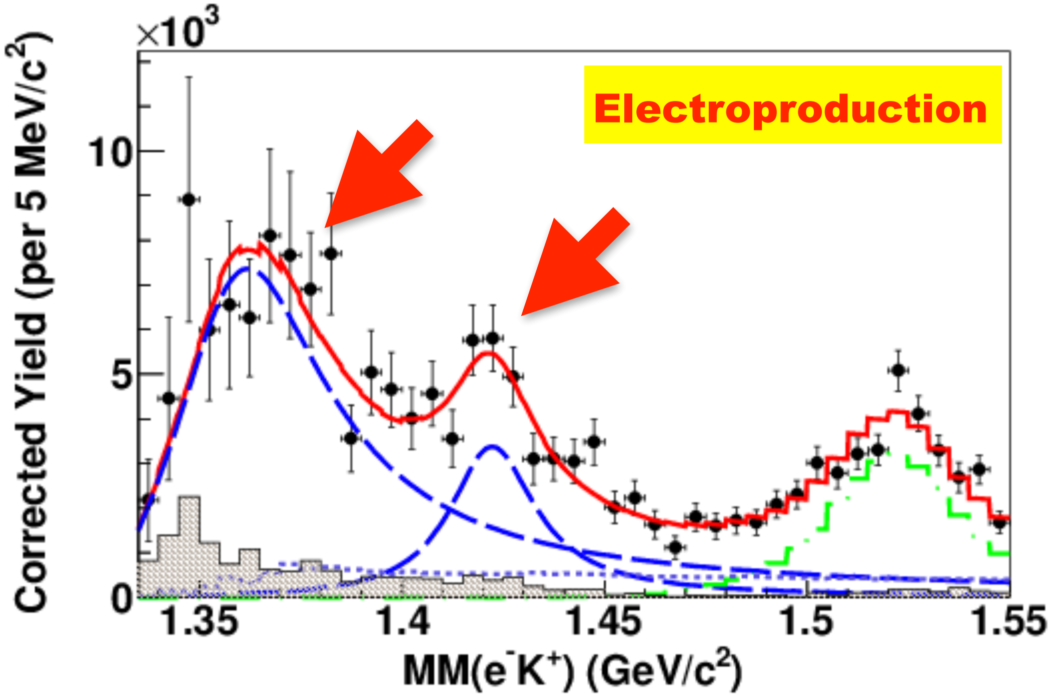
Photoproduction at E_{cm} = 2.1 GeV

Motivation



Obvious difference between Λ(1405) invariant masses from photo- and electro-production in experiments: **Why??**





K. Moriya et al. [CLAS], PRC87, no. 3, 035206 (2013)

H. Y. Lu et al. [CLAS], PRC88, 045202 (2013)

Single peak vs. Double peak

Possible explanations (real vs. virtual photon)

Virtual photon has scalar component→ Increasing t-ch contribution?

In terms of strong interaction,
No differences for two poles
(even more, numerically small...)

Virtual photon probes Λ(1405) EM form factor → New EM excitation?

Hadron EM form factors play the roles
then, nontrivial interference occurs?

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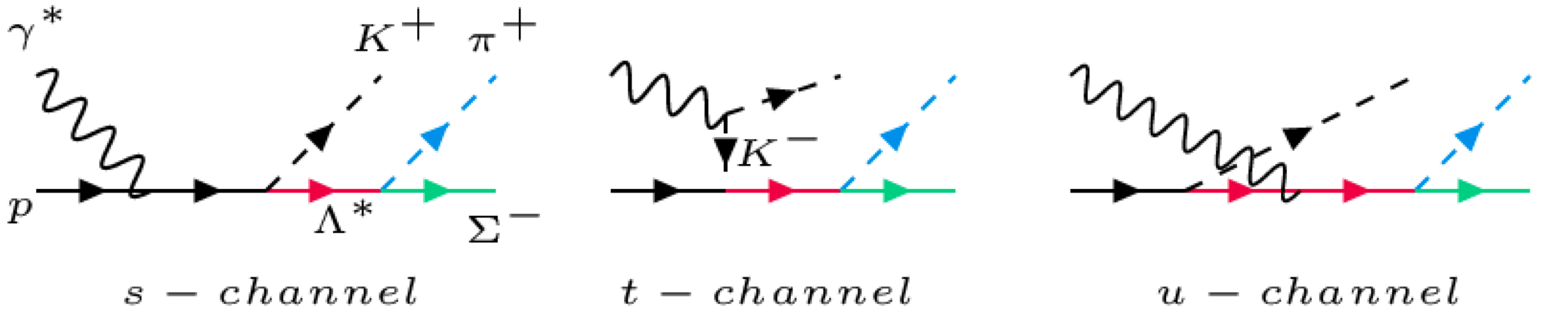
then, nontrivial interference occurs?

We will take this scenario!!!

Theoretical framework

Effective Lagrangian approach in Born approximation at tree level



+ Small far-off-shell contributions

Relevant strong couplings from ChUM

B	Mass	Width	g_{KNB}	$g_{\pi\Sigma B}$	κ_B
p	938.272 MeV	~ 0 MeV	$-$	$-$	2.79
L	1368 MeV	100 MeV	$1.2 + 1.7i$	$-2.5 - 1.5i$	0.30
H	1423 MeV	50 MeV	$-2.5 + 0.94i$	$0.42 - 1.4i$	0.41

T. Sekihara, T. Hyodo and D. Jido, PL669, 133 (2008).

Theoretical framework

Scattering amplitudes conserving WT identity for arb. Q² values

$$i\mathcal{M}_{\rm total} = \sum_{\Lambda^*=H,L}\sum_{x} i\mathcal{M}_x^{\Lambda^*},\quad i\mathcal{M}_x^{\Lambda^*} = ieg_{KN\Lambda^*}g_{\pi\Sigma\Lambda^*}\frac{\bar{u}(k_5)[\not{q}_{4+5}+M_{\Lambda^*}^2]\Gamma_x^{\Lambda^*}u(k_2)}{M_{\pi^+\Sigma^-}^2 - M_{\Lambda^*}^2 - i\Gamma_{\Lambda^*}M_{\Lambda^*}},$$

$$\Gamma_s^{\Lambda^*} = \frac{\not{k}_1+\not{k}_2+M_N}{s-M_N^2}\left[\not{\epsilon}+(F_1^p-1)\left[\not{\epsilon}+\frac{(\epsilon\cdot k_1)\not{k}_1}{Q^2+\delta}\right]-\frac{\kappa_p F_2^p}{2M_N}(\not{\epsilon}\not{k}_1-\epsilon\cdot k_1)\right]F_c,$$

$$\Gamma_t^{\Lambda^*} = \frac{1}{t-M_K^2}\left[\epsilon\cdot(2k_3-k_1)+(F_K-1)\left[\epsilon\cdot(2k_3-k_1)+\frac{(\epsilon\cdot k_1)[k_1\cdot(2k_3-k_1)]}{Q^2+\delta}\right]\right]F_c,$$

$$\Gamma_u^{\Lambda^*} = F_u\left[F_1^{\Lambda^*}\left[\not{\epsilon}+\frac{(\epsilon\cdot k_1)\not{k}_1}{Q^2+\delta}\right]-\frac{\kappa_{\Lambda^*}F_2^{\Lambda^*}}{2M_N}(\not{\epsilon}\not{k}_1-\epsilon\cdot k_1)\right]\frac{\not{k}_2-\not{k}_3+M_{\Lambda^*}}{u-M_{\Lambda^*}^2},$$

Strong form factors satisfying WT identity as well

$$i\mathcal{M}_{\rm total}^{\rm dressed} = (i\mathcal{M}_{Es}+i\mathcal{M}_{Et}+i\mathcal{M}_{Eu})F_c + i\mathcal{M}_{Ms}F_s + i\mathcal{M}_{Mt}F_t + i\mathcal{M}_{Mu}F_u.$$

$$F_c = 1-(1-F_s)(1-F_t).$$

S.i.N. et al., JKPS59, 2676 (2011).

Theoretical framework

Photon polarization in cm frame

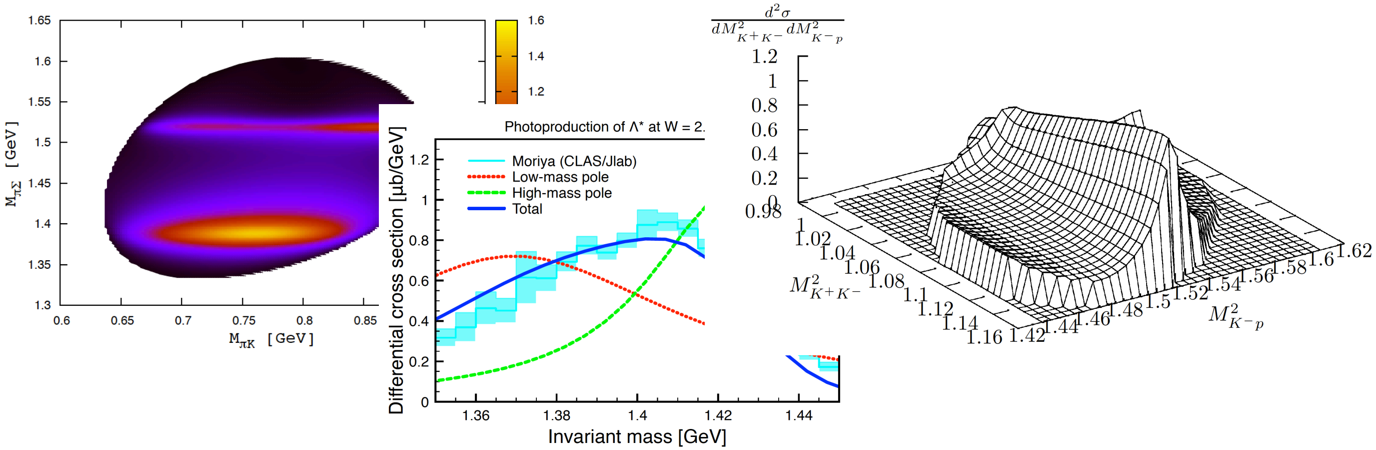
$$\varepsilon_x = \left(0, \sqrt{1+\varepsilon}, 0, 0\right), \quad \varepsilon_y = \left(0, 0, \sqrt{1-\varepsilon}, 0\right), \quad \varepsilon_z = \frac{\sqrt{2\varepsilon}}{\sqrt{|Q^2|}}\left(k, 0, 0, E_1\right).$$

Transverse-polarization parameter ε = (0.3~0.7) at CLAS, so that

we choose it ε = 0.5

We compute double differential cross section W=2.4 GeV

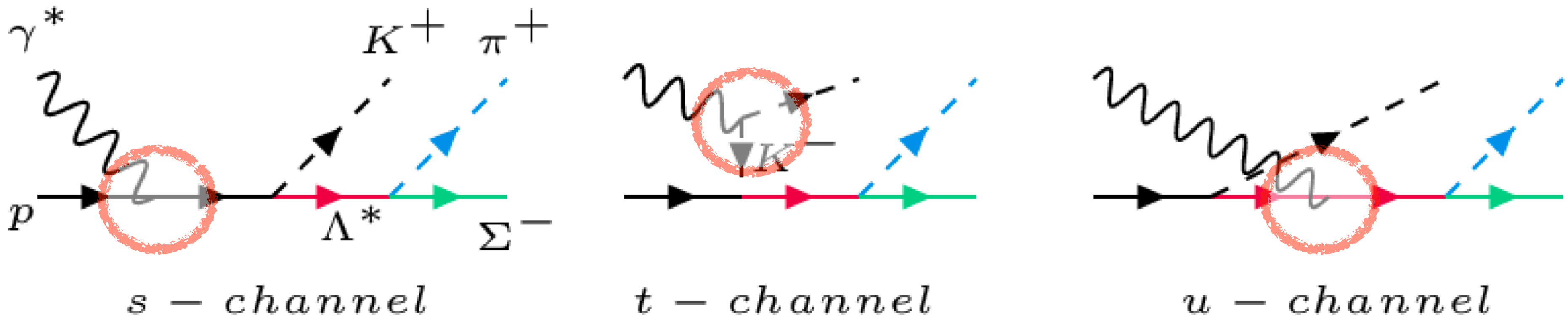
$$\frac{d^2\sigma_{\gamma^{(*)}p\to K^+\pi^+\Sigma^-}}{dM_{K^+\pi^+}dM_{\pi^+\Sigma^-}} = \frac{1}{4|\vec{k}_{\gamma^{(*)}}|\,|E_{\gamma^{(*)}}-E_N|}\frac{1}{128\pi^4 s}\int M_{K^+\pi^+}M_{\pi^+\Sigma^-}\,d\cos\theta_{K^+}\,d\phi_{\Sigma^-}\,\frac{1}{2n}\sum\left|\mathcal{M}_{\gamma^{(*)}p\to K^+\pi^+\Sigma^-}\right|^2$$



Theoretical framework

Hadron EM form factors for electroproduction

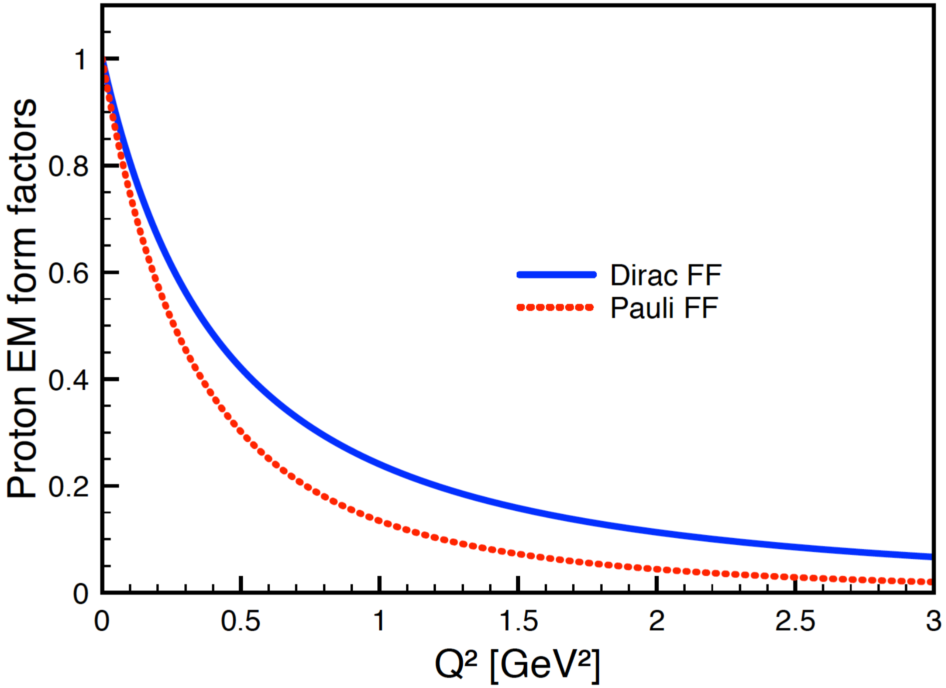
Where hadron EM form factors appear?

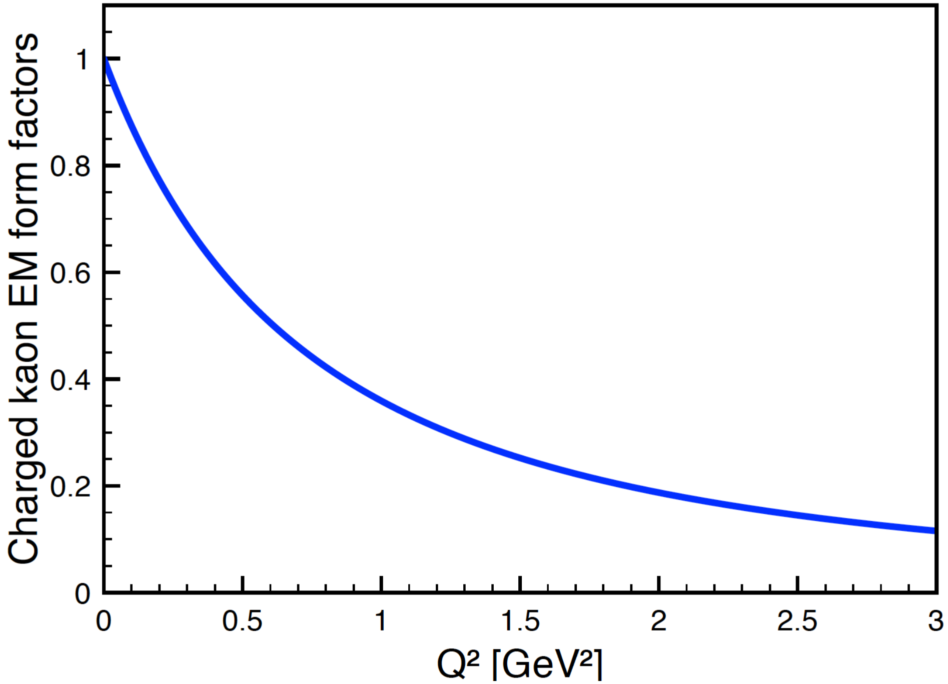


Proton, Kaon, and Λ(1405), three EM form factors necessary

Theoretical framework

EM form factors (FF) for proton and kaon: Well known





$$G_E^p(Q^2) \simeq G_D(Q^2), \quad G_M^p(Q^2) \simeq \mu_p G_D(Q^2), \quad G_D(Q^2) = \left[\frac{1}{1 + Q^2 \langle r^2 \rangle_E^p / 12}\right]^2,$$

J. J. Kelly, Phys. Rev. C 70, 068202 (2004).

$$F_K(Q^2) = \frac{1}{[1 + Q^2/(0.845\,\mathrm{GeV})^2 + Q^4/(1.270\,\mathrm{GeV})^4]},$$

W. Jaus, Phys. Rev. D 44, 2851 (1991).

Theoretical framework

EMFF for Λ(1405): **Less known so far. So How to model it?**

How can we construct Λ(1405) EMFF???

1) It's neutral so possibly similar structure to neutron EMFF

2) EM charge rms radii relates to EMFF

cf) Galster parameterization

$$G_E^n(Q^2) \simeq -\frac{a\mu_n \tau}{1+b\tau} G_D(Q^2)$$

$$\langle r^2 \rangle_E^{H,L} = -6 \frac{dG_E^{H,L}(Q^2)}{dQ^2}\Big|_{Q^2=0}, \quad \langle r^2 \rangle_M^{H,L} = -\frac{6}{\mu_{H,L}} \frac{dG_M^{H,L}(Q^2)}{dQ^2}\Big|_{Q^2=0},$$

$$G_E^{H,L}(Q^2) = -\frac{\langle r^2 \rangle_E^{H,L}}{6} Q^2 F_K(Q^2) \left[\frac{1}{1+Q^2 \langle r^2 \rangle_M^{H,L}/12} \right]^2, \quad G_M^{H,L}(Q^2) \approx \mu_{H,L} \left[\frac{1}{1+Q^2 \langle r^2 \rangle_M^{H,L}/12} \right]^2$$

M.M.Kaskulov, P.Grabmayr, EPJA 19, 157 (2004).

2) EM information of Λ(1405) from ChUM: EM charge rms radii

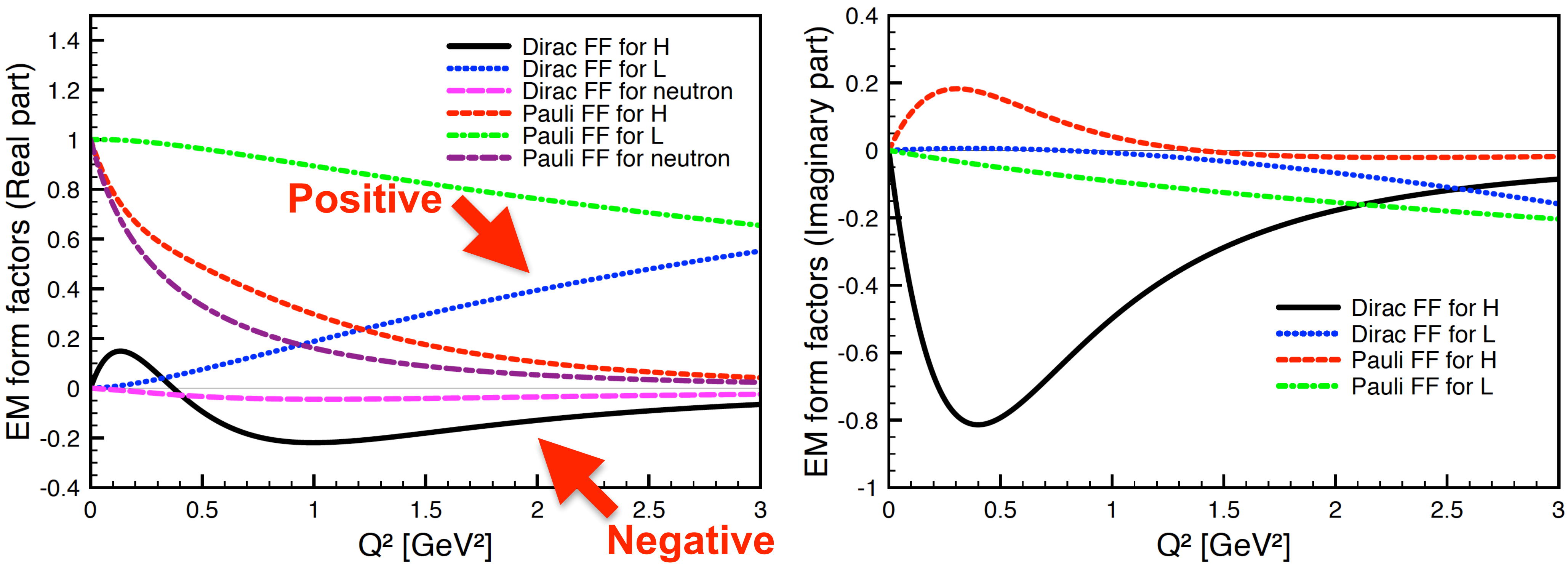
Neutron EMFF + Charge rms radii from ChUM ≈ Λ(1405) EMFF

Theoretical framework

EMFF for Λ(1405): **Less known so far. So How to model it?**

T. Sekihara, T. Hyodo and D. Jido, Phys. Lett. B 669, 133 (2008).

$\langle r^2\rangle_E^H$	$\langle r^2\rangle_M^H$	$\langle r^2\rangle_E^L$	$\langle r^2\rangle_M^L$	$\langle r^2\rangle_E^n$
$-3.365 + 7.783i$	$6.859 - 10.455i$	$0.462 - 0.051i$	$-0.334 + 0.539i$	-2.877 ± 0.077

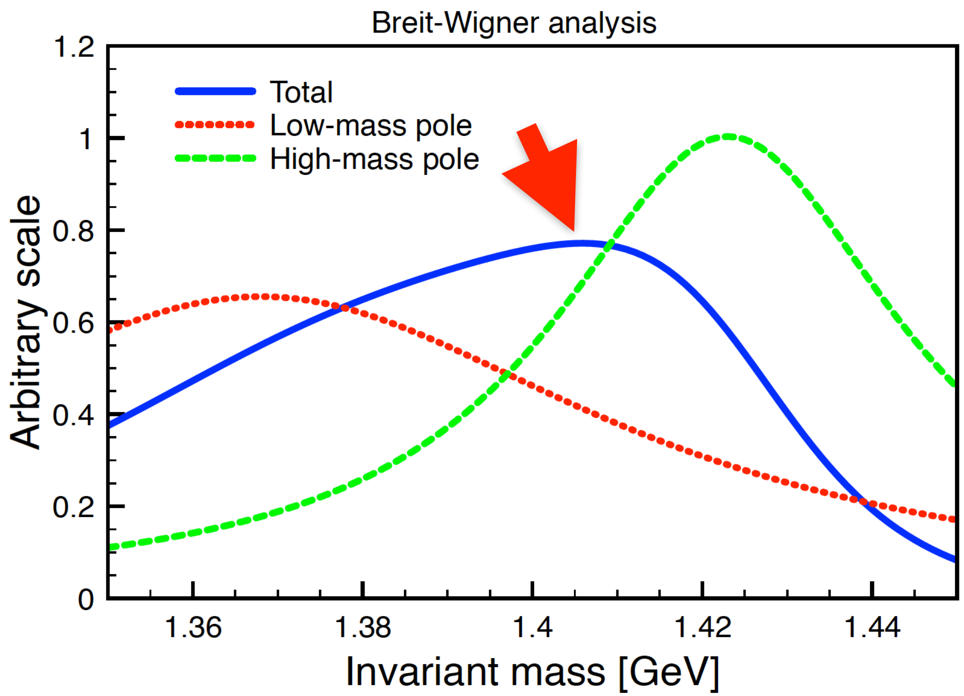


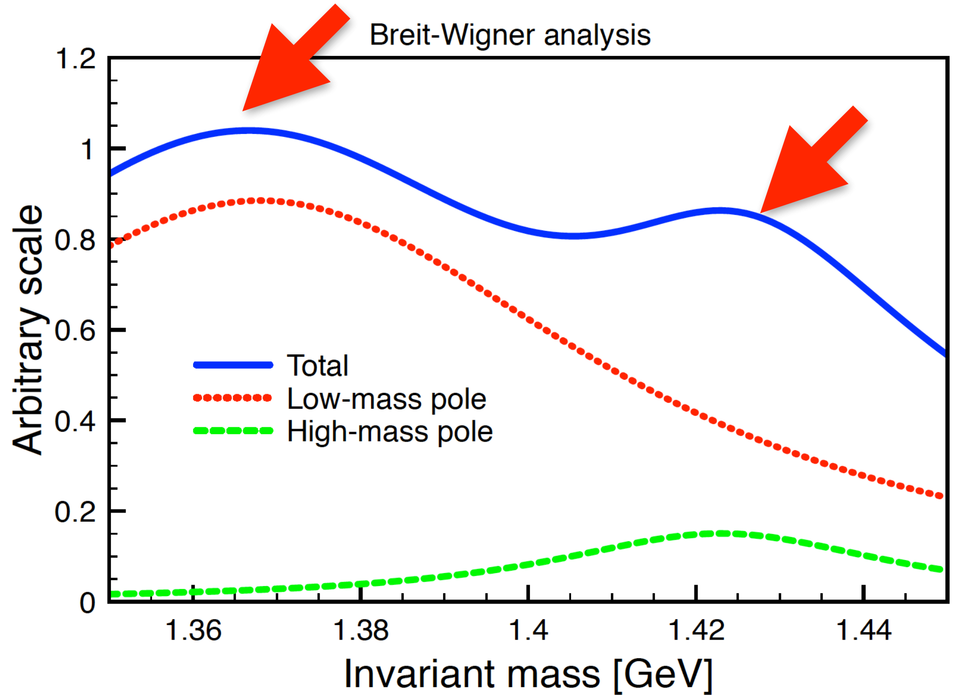
Theoretical framework

Invariant mass plots with Breit-Wigner type distributions (test)

$$i\mathcal{M}_H = \frac{g_{KNH}\, g_{\pi\Sigma H} A_H}{M^2_{\pi^+\Sigma^-} - M_H^2 - i\Gamma_H M_H}, \quad i\mathcal{M}_L = \frac{g_{KNL}\, g_{\pi\Sigma L} A_L}{M^2_{\pi^+\Sigma^-} - M_L^2 - i\Gamma_L M_L}.$$

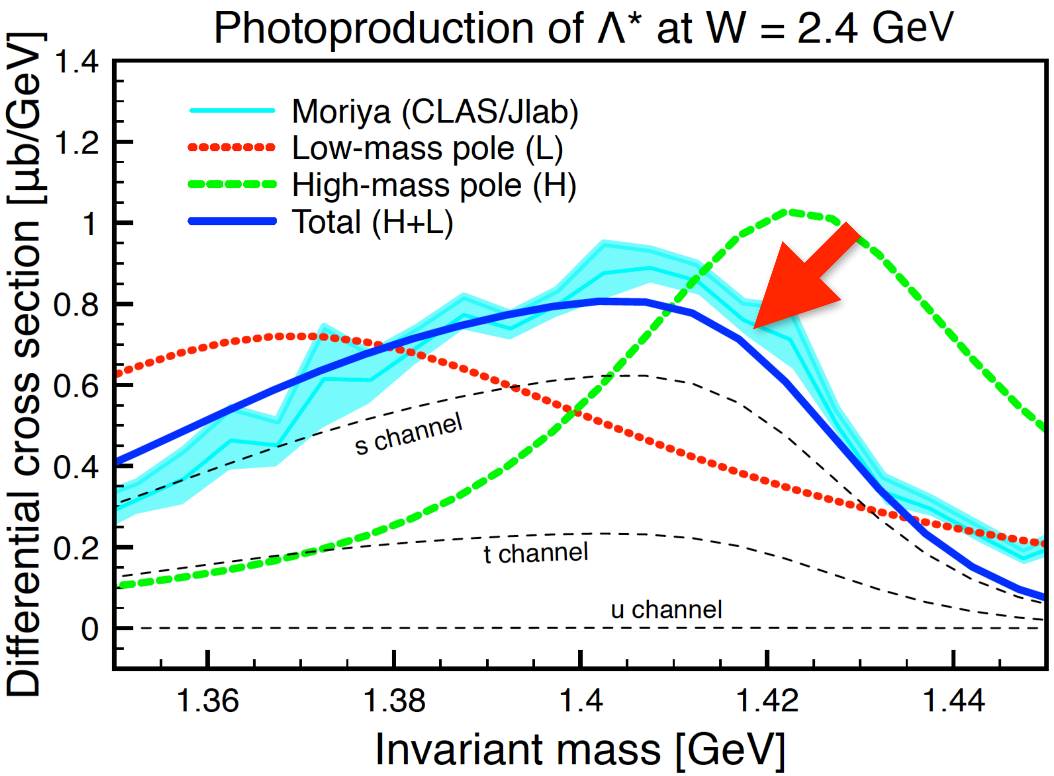
$$g_{KNL}\, g_{\pi\Sigma L}\, F_1^L = \underline{0.660} - 0.549i, \quad g_{KNH}\, g_{\pi\Sigma H}\, F_1^H = \underline{-0.583} - 2.363i.$$

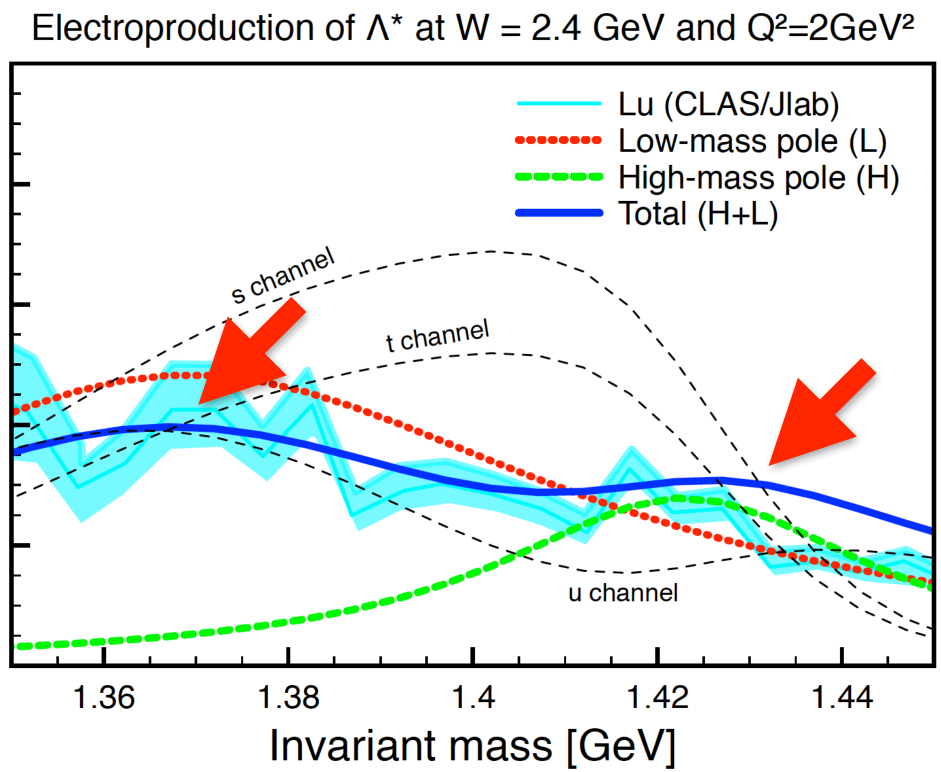




Theoretical framework

Invariant mass plots: Full calculations



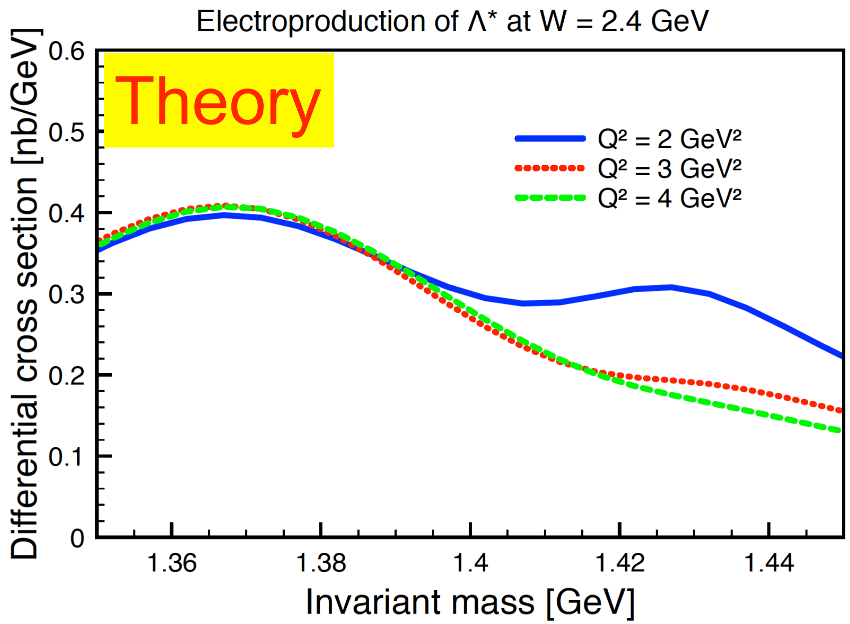


Destructive interference for photoproduction ⇒ Single pole

vs.

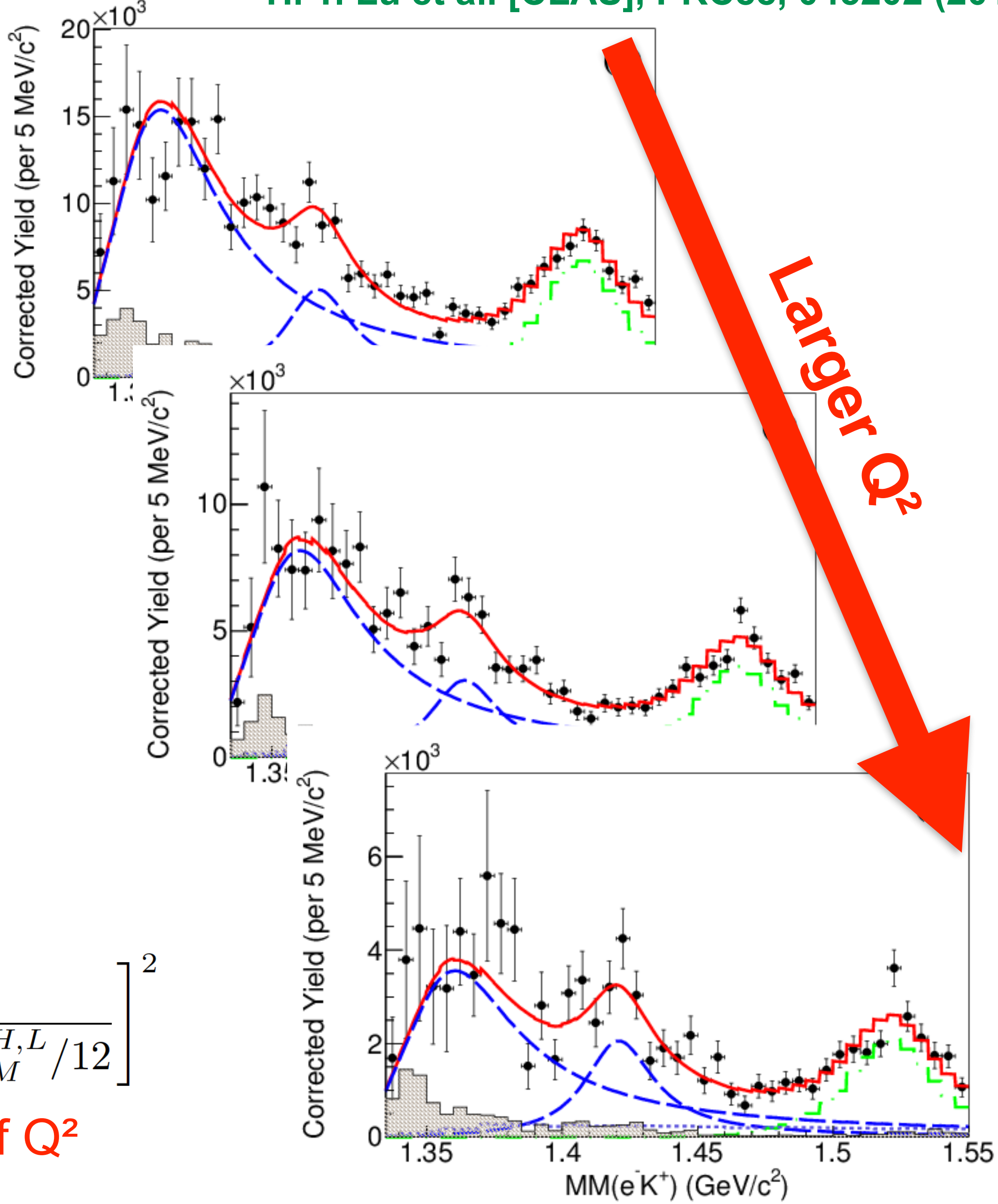
Constructive interference for electroproduction ⇒ Double pole

Caveat



Experiment

H. Y. Lu et al. [CLAS], PRC88, 045202 (2013)



Q²-dependence necessary for Λ(1405) EMFF

$$G_E^{H,L}(Q^2) = -\frac{\langle r^2\rangle_E^{H,L}}{6} Q^2 F_K(Q^2)\left[\frac{1}{1+Q^2\langle r^2\rangle_M^{H,L}/12}\right]^2$$

× additional function of Q²

Suggests for confirming Λ(1405) structure

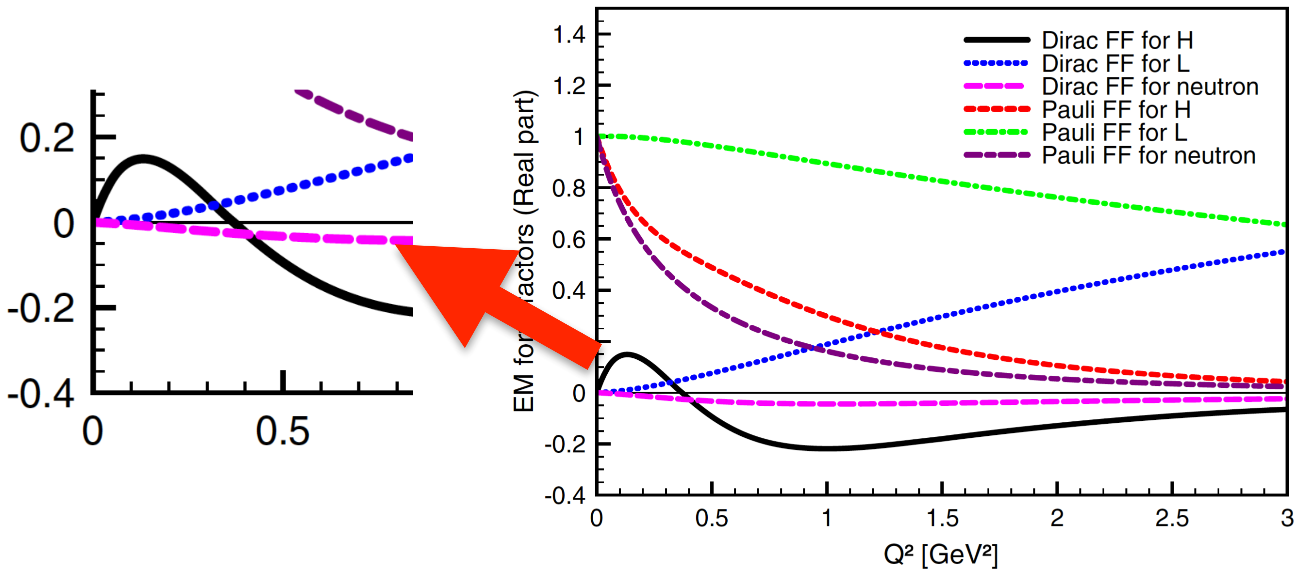
Possible suggests for experiment and lattice QCD

1. Measurements for Λ(1405) Dirac EMFF (How?)

2. Invariant mass of Λ(1405) at small Q^2 region in backward scattering

What can we expect?

Transition from
single (destructive)
to
double (constructive)
peak



Summary and perspective

- The difference between photo- and electro-production of Λ(1405) explained successfully
- Λ(1405) Dirac EMFF (neutron EMFF + ChUM charge rms radii) plays a important tole
- Constructive (Destructive) interference for electro- and photo-one
- Experimental and theoretical Λ(1405) EMFF studies will reveal its internal structure: Lattice QCD would help?
- Two-pole scenario of ChUM becomes more plausible: Molecular state of $\underline{K}N$ and πΣ
- EMFF and small Q^2 region search: Answers for Λ(1405) structure?

Thank you for your attention!!!

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Cheomseongdae, astronomical observatory built 1400 years ago in Korea