Study of $\eta' N$ interaction from η/η' production data and in-medium η' properties

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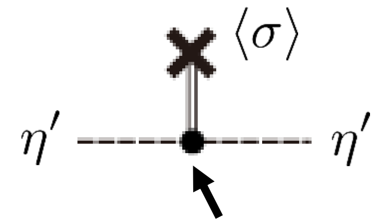
Introduction



Anomaly-induced coupling

- Origin of the η' mass

  ←U$_A$(1) anomaly and **chiral symmetry breaking** (3flavor)

  Witten(1979),'t Hooft(1986),… Pisarski-Wilzek(1984), Kunihiro-Hatsuda(1988), Cohen (1996), Lee-Hatsuda (1996),…

⬇ ← Chiral restoration in nuclear medium
(reduction of order parameter of chiral symmetry breaking)

In-medium η' as a probe of chiral symmetry in nuclear medium

- η' mass in finite density
  Costa-Ruivo-Kalinovsky(2003), Kwon-Lee-Morita-Wolf(2012), Fejos-Hosaka(2017)…
- η'-nucleus system
  Tsushima(2000),Nagahiro-Hirenzaki(2005),Nagahiro-Takizawa-Hirenzaki (2006),Jido-Nagahiro-Hirenzaki (2012), Tanaka *et al*. (2016),Metag-Naova-Paryev (2017),…

η'-nucleon interaction = basic information

Borasoy (2000), Bass-Thomas (2006), Oset-Ramos (2011), S.S.-Jido(2013),

Moskal(2000), Czerwinski *et al.*(2014),…

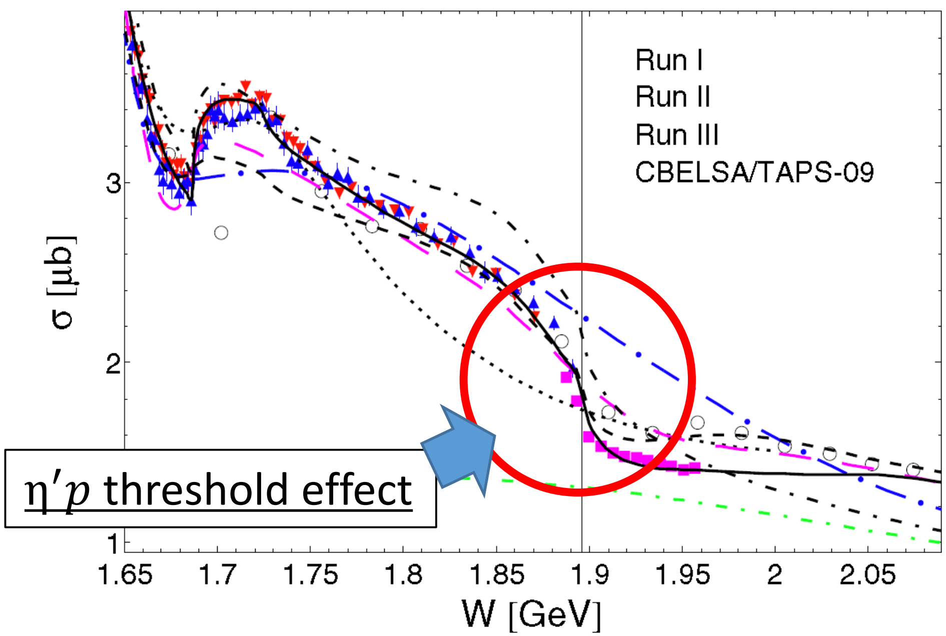
s-wave η'p scattering length from pp→ppη'

$$\begin{cases} \mathrm{Re}\,(a_{\eta' p}) = 0.00 \pm 0.43_{\mathrm{stat}}\ \mathrm{fm} \\ \mathrm{Im}\,(a_{\eta' p}) = 0.37^{+0.02_{\mathrm{stat}}+0.38_{\mathrm{syst}}}_{-0.11_{\mathrm{stat}}-0.05_{\mathrm{syst}}}\ \mathrm{fm} \end{cases}$$

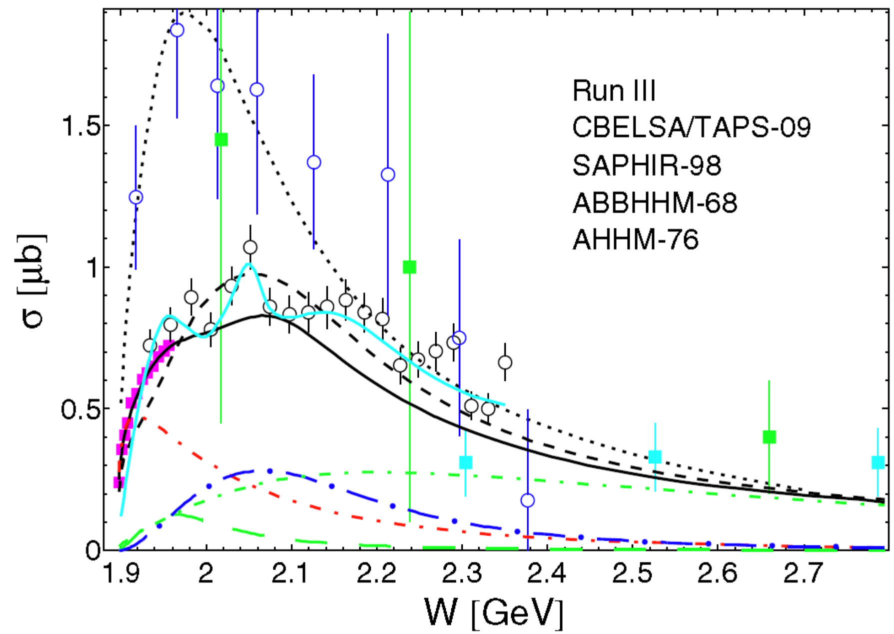
➔ Study of η'-few nucleon system:
Sekihara-Fujioka-Ishikawa(2018) for η'd

Recent data on η/η′ photoproduction

$\gamma p \to \eta p$



$\gamma p \to \eta' p$

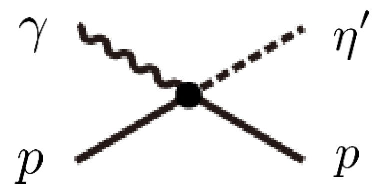


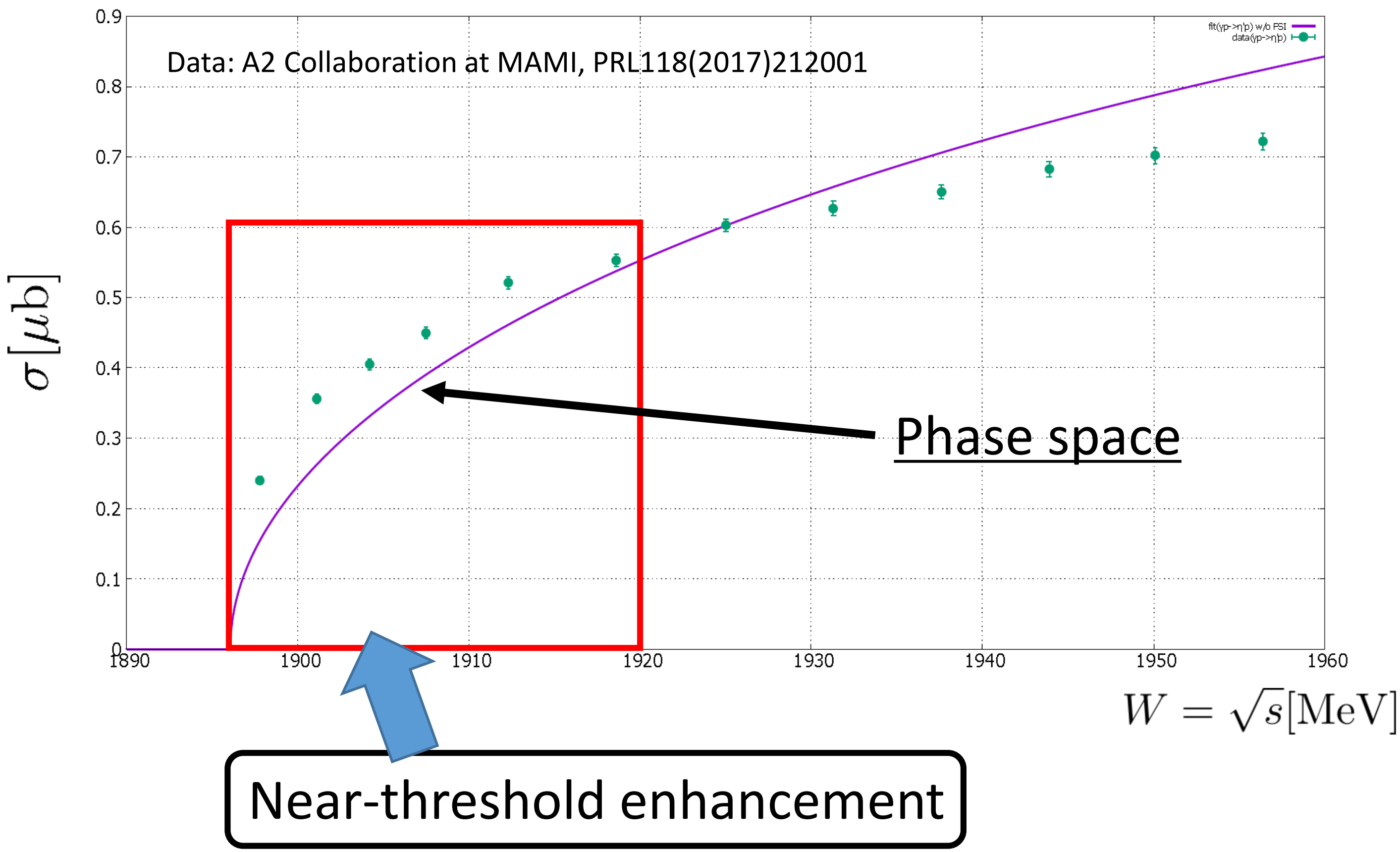
A2 Collaboration at MAMI, PRL118(2017)212001

- η′ photoproduction from proton

-- **Comparison with phase space**

$$T_{\gamma p,\eta' p} = v_{\gamma p,\eta' p}$$





■ N(1895) contribution:
PRL118(2017)212001[A2 Collaboration], PLB785(2018)626[Anisovich et al.]

$N(1895)\ 1/2^-$ from latest PDG [PRD98,030001(2018)]

N(1895) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1890 to 1930 (≈ 1910) OUR ESTIMATE				
1895 ± 15	ANISOVICH	17A	DPWA	Multichannel
1906 ± 17	[1] ANISOVICH	17A	L+P	$\gamma p, \pi^- p \to K \Lambda$
$1917 \pm 19 \pm 1$	[2] SVARC	14	L+P	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1907 ± 10	ANISOVICH	17C	DPWA	Multichannel
1907 ± 10	SOKHOYAN	15A	DPWA	Multichannel
1900 ± 15	ANISOVICH	12A	DPWA	Multichannel
1858	SHRESTHA	12A	DPWA	Multichannel
1797 ± 26	BATINIC	10	DPWA	$\pi N \to N\pi, N\eta$
1795	VRANA	00	DPWA	Multichannel
2150 ± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

[1] Statistical error only.
[2] Fit to the amplitudes of HOEHLER 79.

−2×IMAGINARY PART

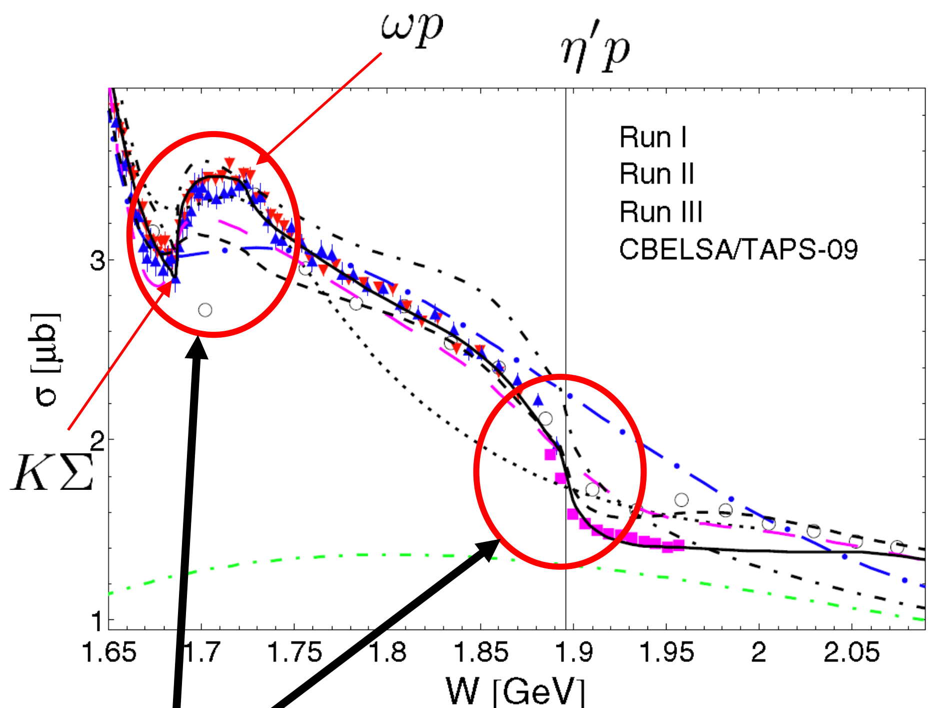
VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 to 140 (≈ 110) OUR ESTIMATE				
132 ± 30	ANISOVICH	17A	DPWA	Multichannel
100 ± 10	[1] ANISOVICH	17A	L+P	$\gamma p, \pi^- p \to K \Lambda$
$101 \pm 36 \pm 1$	[1,2] SVARC	14	L+P	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
100^{+40}_{-10}	ANISOVICH	17C	DPWA	Multichannel
100^{+40}_{-15}	SOKHOYAN	15A	DPWA	Multichannel
90^{+30}_{-15}	ANISOVICH	12A	DPWA	Multichannel
479	SHRESTHA	12A	DPWA	Multichannel
420 ± 45	BATINIC	10	DPWA	$\pi N \to N\pi, N\eta$
220	VRANA	00	DPWA	Multichannel
350 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

[1] Statistical error only.
[2] Fit to the amplitudes of HOEHLER 79.

Broad resonance @$\eta' p$ threshold(=1896MeV)

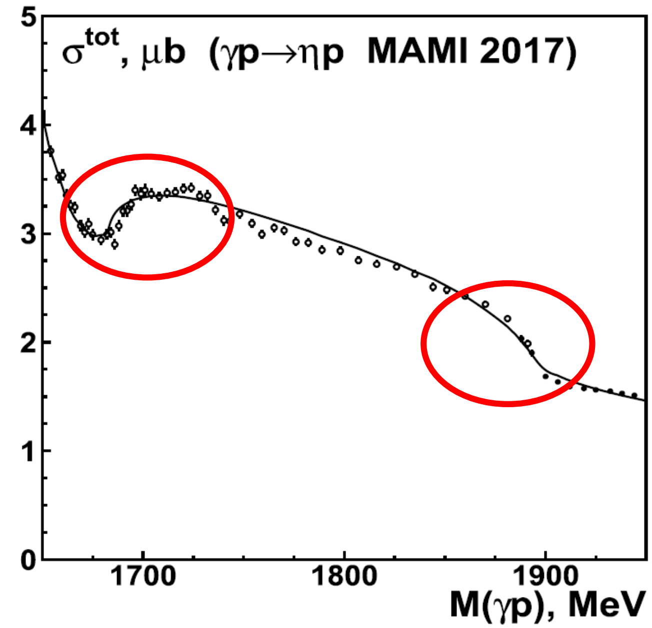
- πN→πN: PRC89(2014)045205[Svarc *et al.*]
- γp→K*Λ: PLB771(2017)142[CLAS Collab.]
- γp and πp→KΛ: EPJA53(2017)242[Anisovivh *et al.*]
- Multichannel: PRL119(2017)062004[Anisovich *et al.*]

- η photoproduction from proton

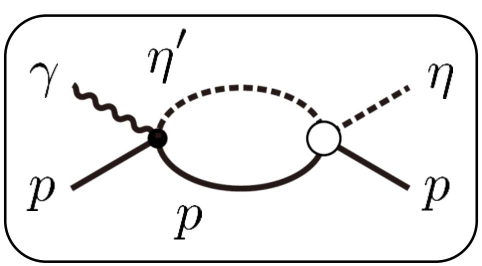


MAID analysis: A2MAMI, PRL118(2017)212001

Threshold effect



Partial-wave analysis: Anisovich *et al*, arxiv:1803.06814



-- Threshold effect: Flatte parametrization or K-matrix approach

Partial-wave analysis ➔ s-wave $\eta' p$ scattering length

Anisovich *et al.*, arxiv:1803.06814

$$|a_{\eta' p}| = (0.403 \pm 0.020 \pm 0.0600)\ \text{fm} \quad \delta_{N\pi} = (87 \pm 2)^\circ \quad \delta_{N\eta'} = (1.5 \pm 0.5)^\circ$$

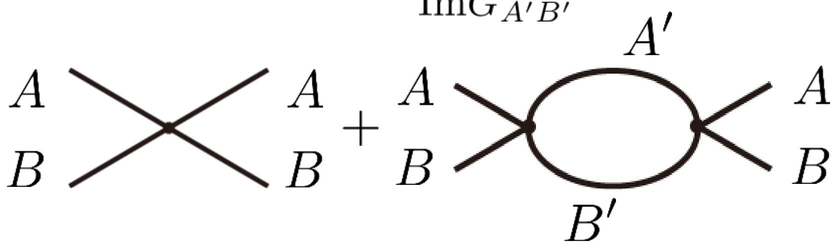
Threshold cusp

- A simple t matrix with channel coupling:

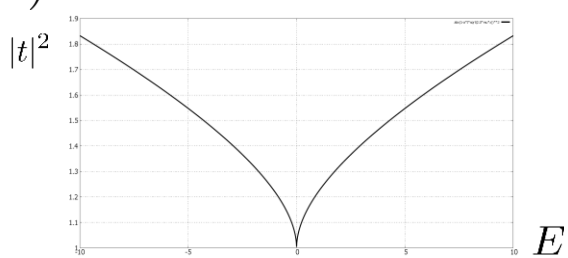
$$t_{AB,AB} = t \sim 1 + C(-ip_{A'B'}) \begin{cases} p_{A'B'} = \sqrt{2\mu E} \text{ (above threshold; } E > 0) \\ p_{A'B'} = i\sqrt{2\mu |E|} \equiv i\kappa \text{ (below threshold; } E < 0) \end{cases}$$

$\mathrm{Im}G_{A'B'}$

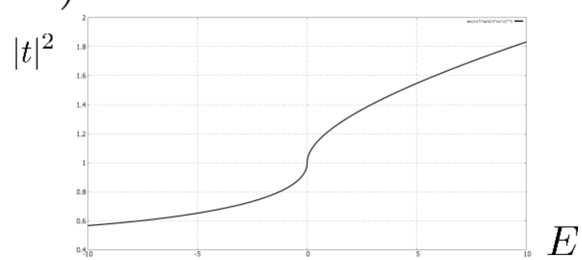
(κ: real and positive)



$a.)\ C = 0.1e^{i\pi/4}$

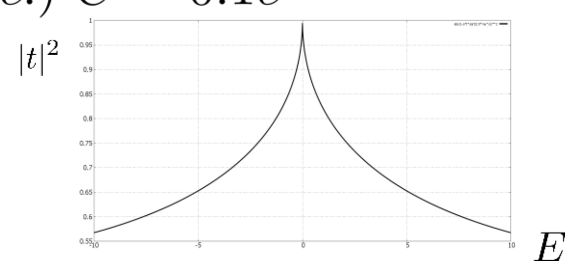


$b.)\ C = 0.1e^{i3\pi/4}$

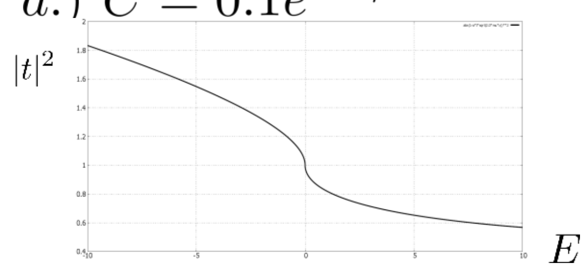


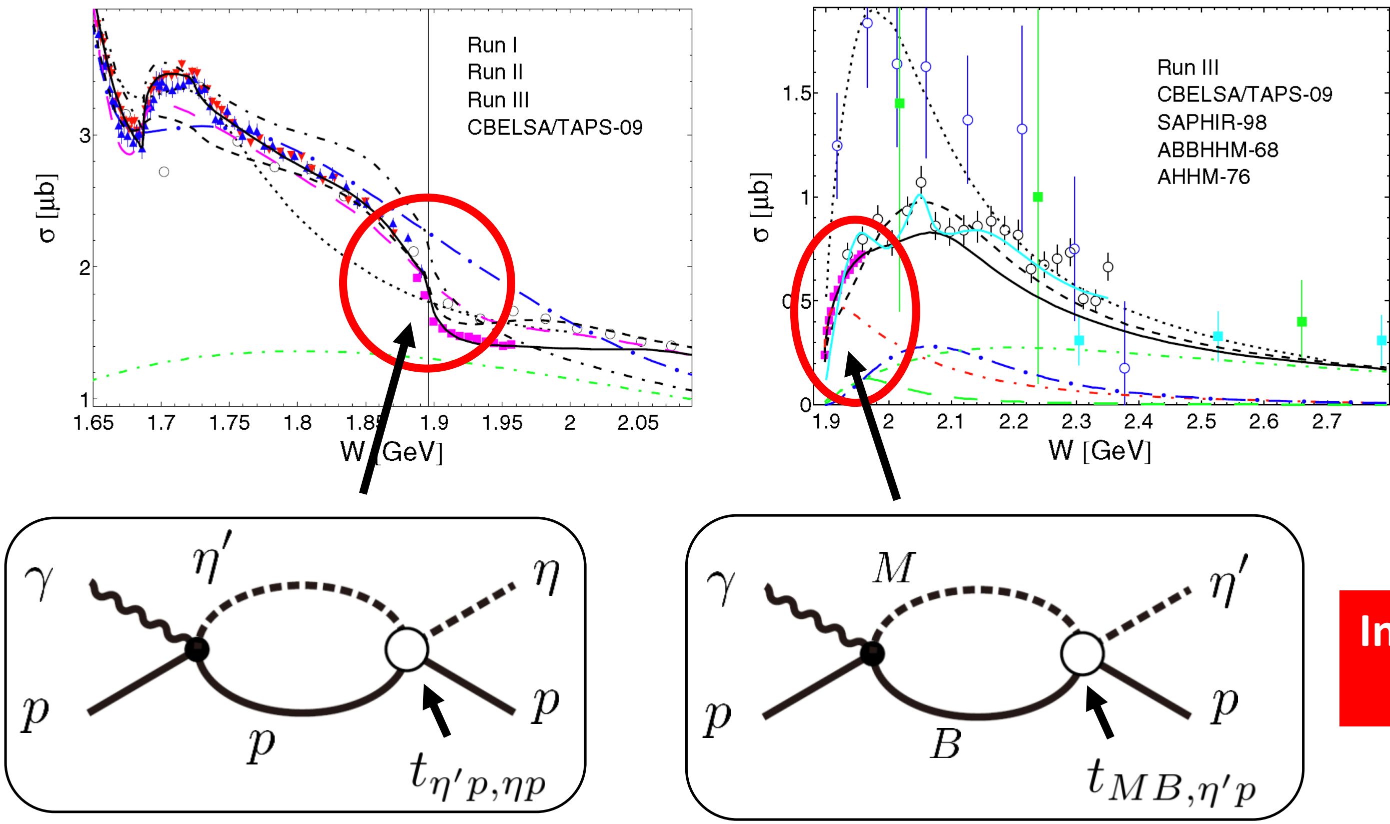
$(\mu = 0.5)$

$c.)\ C = 0.1e^{i5\pi/4}$



$d.)\ C = 0.1e^{i7\pi/4}$





Information on $\eta' p$ amplitude

(MB can be $\eta' p$, ηp, πp, $K\Lambda$, $K\Sigma$, ωp,...)

Extraction of the $\eta' p$ amplitude from η/η'-photoproduction data

➡

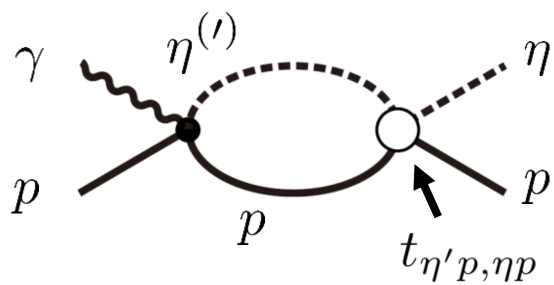
- ☐ $\eta' p$ scattering length
- ☐ η'-optical potential

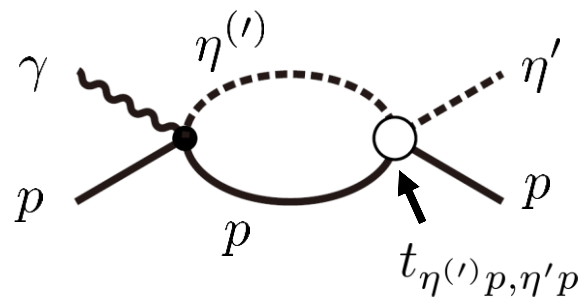
-- Focus on $\eta' p$-threshold behavior

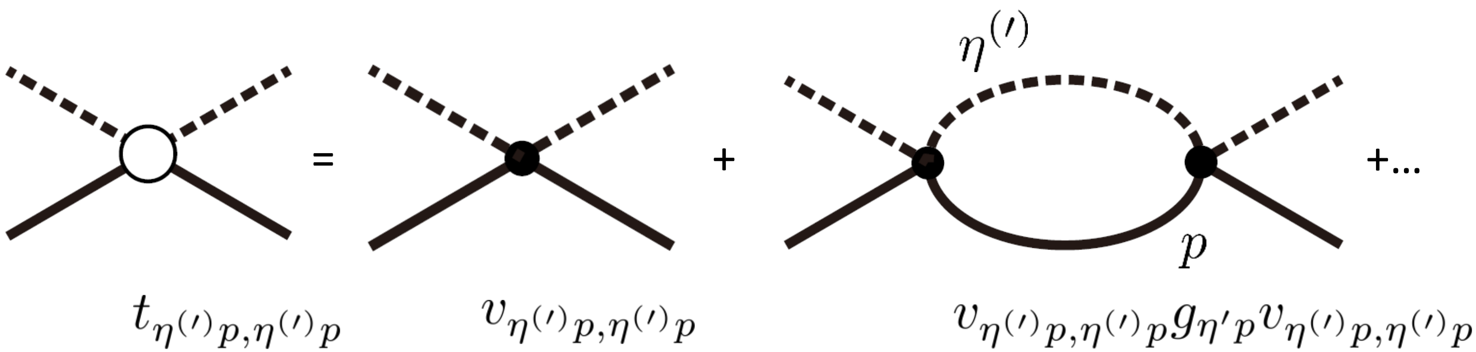
➔ Focus on the $\eta' p$-threshold region (~100MeV around $\eta' p$ threshold)

Setup

○ Final-State Interaction







$$
\begin{aligned}
t &= v + vgt = v + vgv + vgvgv + \ldots \\
&= (1 - vg)^{-1} v
\end{aligned}
$$

~1.7GeV

-- $v \in \mathcal{C}$ for channel coupling effect (πp, $K\Lambda$, $K\Sigma$, ωp)

※ Resonance is not assumed in $\eta^{(\prime)}p$ amplitude

$$T_{\gamma p,\eta p} = v_{\gamma p,\eta p}\left(1 + g_{\eta p} t_{\eta p,\eta p}\right) + v_{\gamma p,\eta' p} g_{\eta' p} t_{\eta' p,\eta p}$$

$$T_{\gamma p,\eta' p} = v_{\gamma p,\eta p} g_{\eta p} t_{\eta p,\eta' p} + v_{\gamma p,\eta' p}\left(1 + g_{\eta' p} t_{\eta' p,\eta' p}\right)$$

-- $v_{\gamma p,\eta^{(\prime)} p}$: polynomial of s

$$v_{\gamma p,\eta' p} = \sum_{n=0}^{n_{\max}} v^{(n)}_{\gamma p,\eta' p} s^n, \; v_{\gamma p,\eta p} = e^{i\theta}\left(\sum_{n=0}^{n_{\max}} v^{(n)}_{\gamma p,\eta p} s^n\right)$$

with $v^{(n)}_{\gamma p,\eta^{(\prime)} p} \in \mathcal{R}$

-- $t = (1 - vg)^{-1} v$ for ηp and η′p

--- $v_{ij} = \mathrm{Re}[v_{ij}] + i\,\mathrm{Im}[v_{ij}]$ to take account of other channels

(πp, $K\Lambda$, $K\Sigma$, ωp,…)

$$\sigma_{\gamma p\to\eta p} = \frac{(2m_p)^2}{16\pi s}\frac{|\vec{p}_\eta|}{|\vec{p}_\gamma|}\left(|T_{\gamma p,\eta p}|^2 + |T^{\mathrm{higer}}_{\gamma p,\eta p}|^2\right)$$

$$\sigma_{\gamma p\to\eta' p} = \frac{(2m_p)^2}{16\pi s}\frac{|\vec{p}_{\eta'}|}{|\vec{p}_\gamma|}|T_{\gamma p,\eta' p}|^2$$

⇨ Fit η/η′-photoproduction data

in $W \in [m_p + m_{\eta'} - \Delta, m_p + m_{\eta'} + \Delta]$ (Δ<70MeV)

Fit parameter -- Interaction kernel of $\eta^{(\prime)}p$

-- $\eta^{(\prime)}p$ production amplitude from photon

Constraint on scattering amplitude

○ Optical theorem

$$\mathrm{Im} f(E) = \frac{k}{4\pi}\sigma_{\rm tot} > 0 \quad \left(f(W) = -\frac{m_p}{4\pi W}t(W)\right)$$

$V_{ij} \in \mathcal{C}$ ➡ $\mathrm{Im} f(E) < 0$ can happen

Restriction

$$F'(W) = F(W) + \mathcal{N}\theta(-\mathrm{Im} f_{\eta p,\eta p}(W)) + \mathcal{N}\theta(-\mathrm{Im} f_{\eta' p,\eta' p}(W))$$

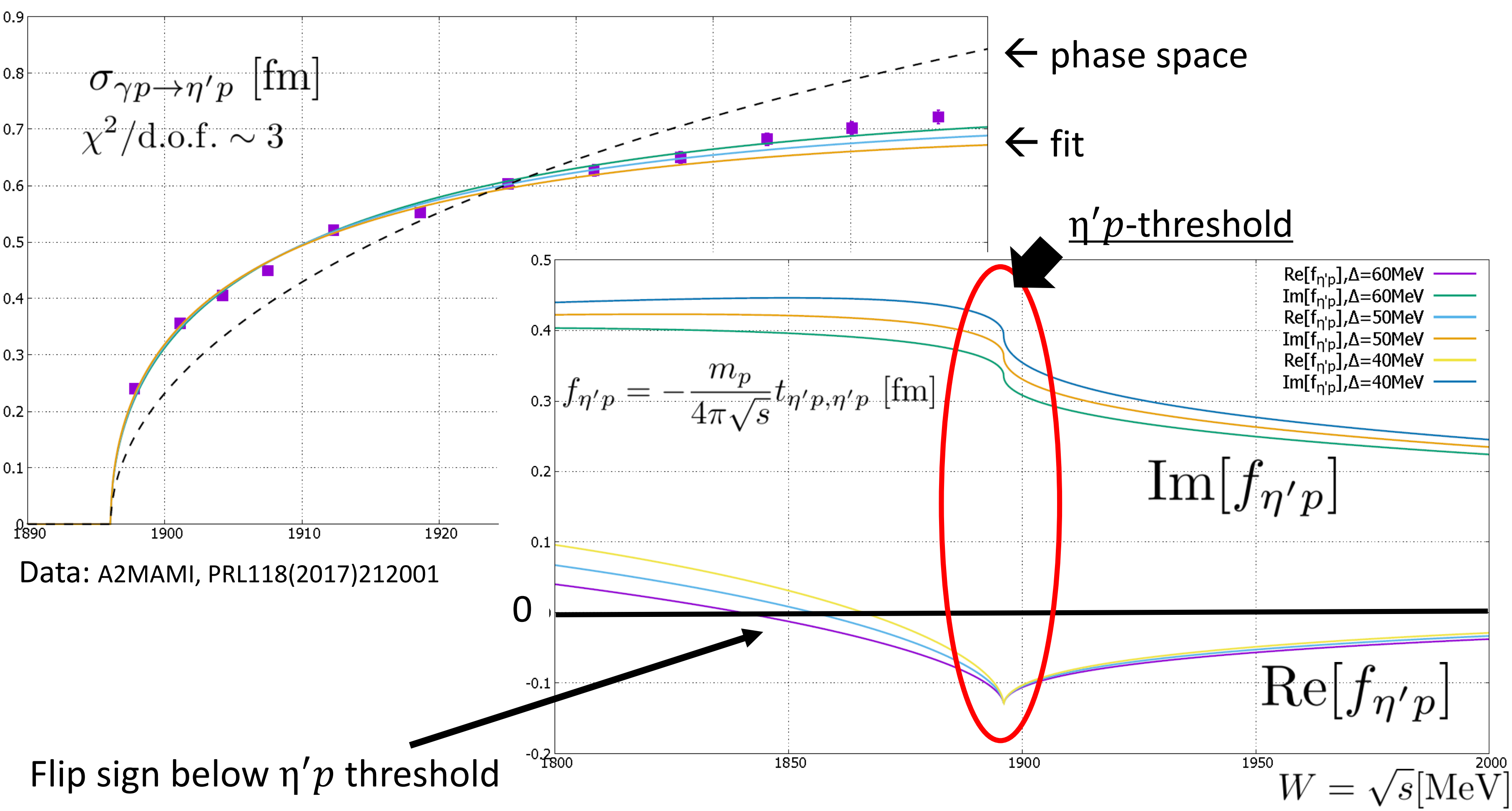
$$F(W) = \sigma_{\gamma p,\eta^{(\prime)} p}(W)$$

$\mathcal{N}$: a large number

A simple test: fit $\gamma p \to \eta' p$ data with $\eta' p$ FSI

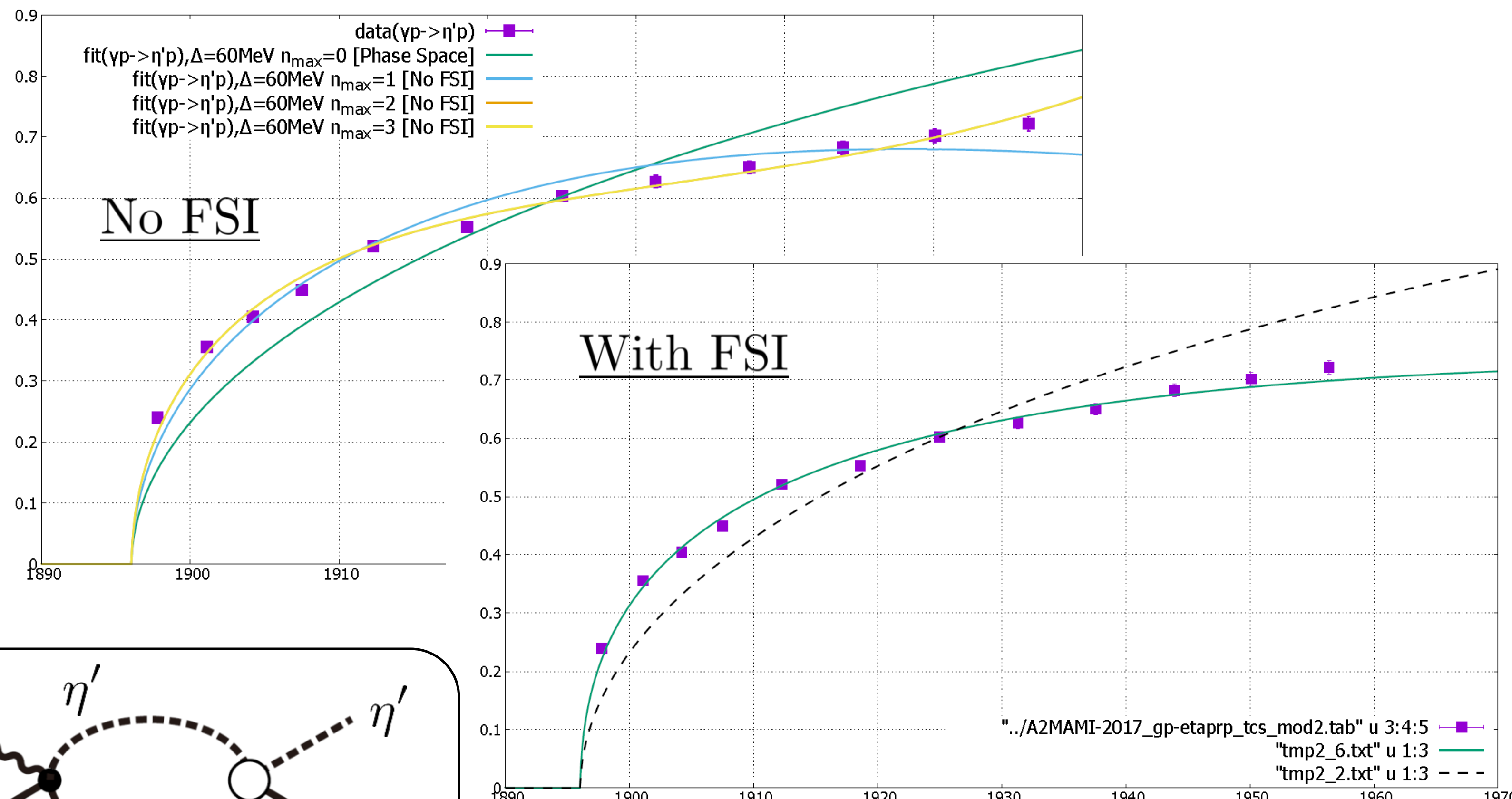
$$T_{\gamma p,\eta' p} = v_{\gamma p,\eta' p}\left(1 + g_{\eta' p} t_{\eta' p,\eta' p}\right)$$

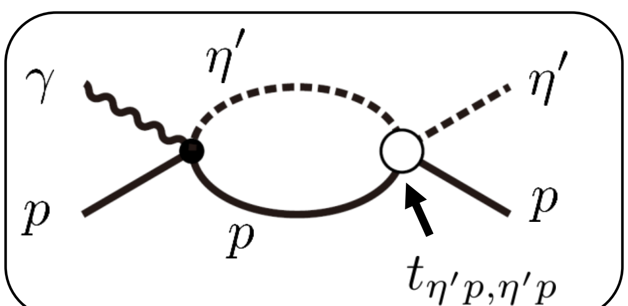
$$\begin{aligned} t_{\eta' p,\eta' p} &= v_{\eta' p,\eta' p} + v_{\eta' p,\eta' p} g_{\eta' p} t_{\eta' p,\eta' p} \\ &= (1 - v_{\eta' p,\eta' p} g_{\eta' p})^{-1} v_{\eta' p,\eta' p} \quad \text{with } v_{\eta' p,\eta' p} \in \mathcal{C} \end{aligned}$$



A simple test: fit $\gamma p \to \eta' p$ data with $\eta' p$ FSI

$$T_{\gamma p,\eta' p} = v_{\gamma p,\eta' p} \text{ with } v_{\gamma p,\eta' p} = \sum_{n=0}^{n_{\max}} v^{(n)}_{\gamma p,\eta' p} s^n$$



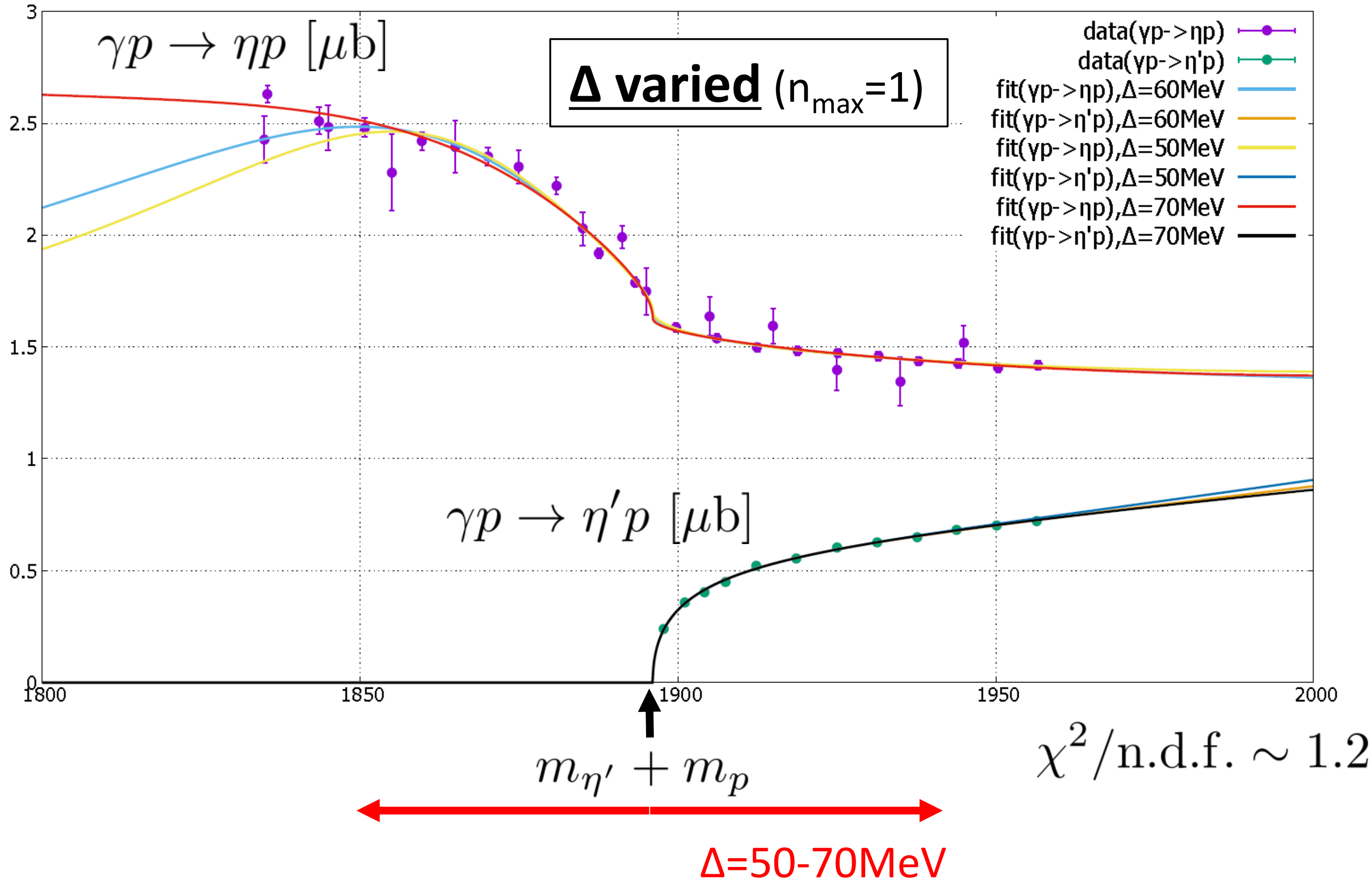


$MB = \eta' p$ would be responsible for the enhancement

Results of $\gamma p \to \eta^{(\prime)} p$ fitting

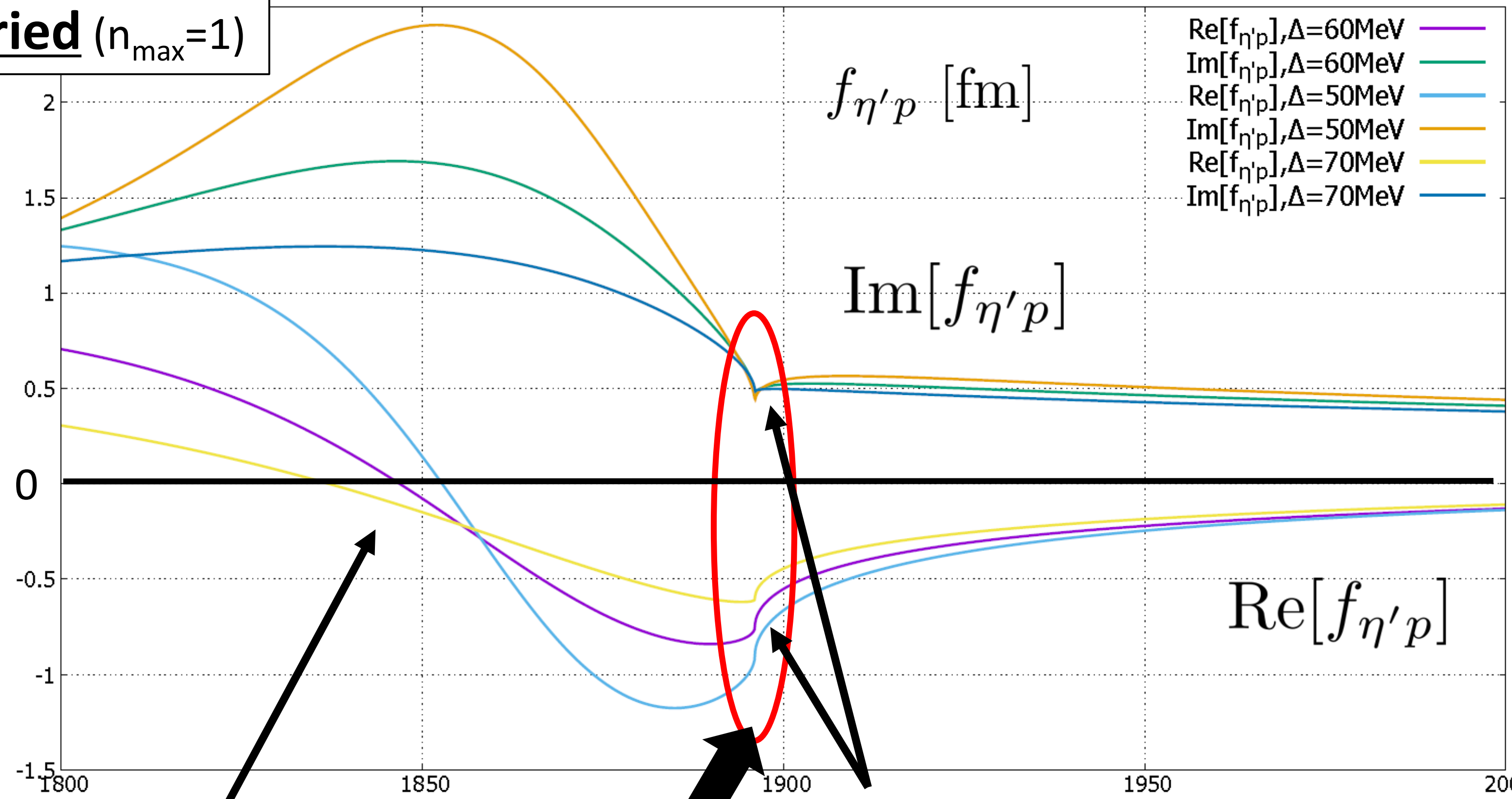
$\gamma p \to \eta p$ data: A2MAMI, PRL118(2017)212001 and CLAS, PRC80(2009)045213
$\gamma p \to \eta' p$ data: A2MAMI, PRL118(2017)212001

Fit



η′p scattering amplitude $f_{\eta' p}$

Δ varied (n_{max}=1)



η′p-threshold

$a_{\eta' p} = -0.75 + i0.46$ fm (Δ=60MeV)

Flip sign below η′p threshold

-- pole~(1877-63i)MeV(Δ=60MeV)

○ Too far away from real axis…

※Error of parameters: ~10%

pp → *pp*η′ [Czerwinski *et al.*, PRL113, 062004(2014)]

$\mathrm{Re}\,(a_{\eta' p}) = 0.00 \pm 0.43_{\mathrm{stat}}$ fm

$\mathrm{Im}\,(a_{\eta' p}) = 0.37^{+0.02_{\mathrm{stat}}+0.38_{\mathrm{syst}}}_{-0.11_{\mathrm{stat}}-0.05_{\mathrm{syst}}}$ fm

Anisovich *et al.*, arxiv:1803.06814

$|a_{\eta' p}| = (0.403 \pm 0.020 \pm 0.0600)$ fm $\quad \delta_{N\pi} = (87 \pm 2)^\circ$, $\delta_{N\eta'} = (1.5 \pm 0.5)^\circ$

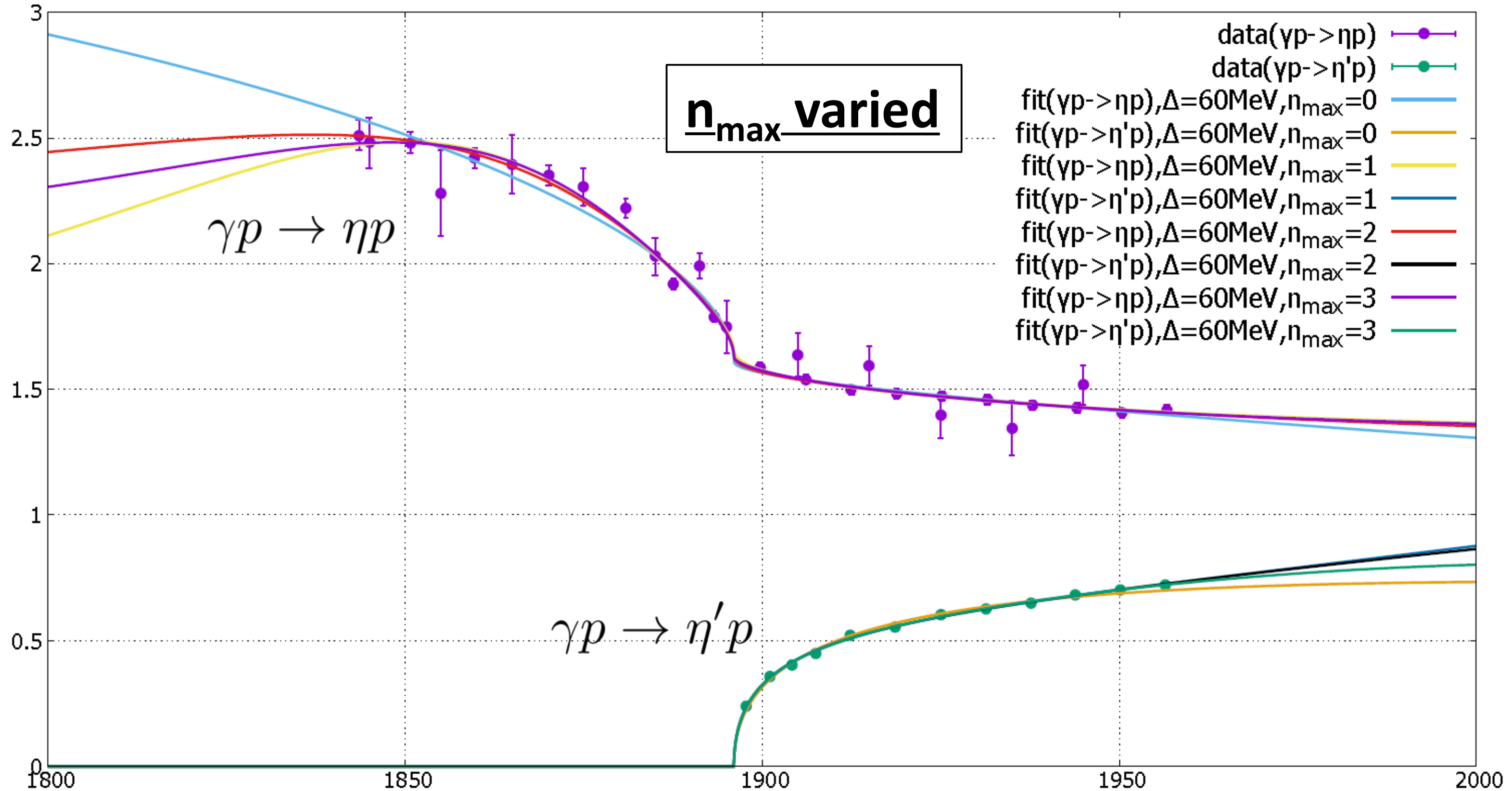
$$a_{\eta p, \eta' p} \equiv -m_p t_{\eta p, \eta' p}/[4\pi\sqrt{s}]|_{\sqrt{s}=\eta' p \text{ th.}} = (-0.13 - i0.22) \text{ fm}$$

Results of $\gamma p \to \eta^{(\prime)} p$ fitting

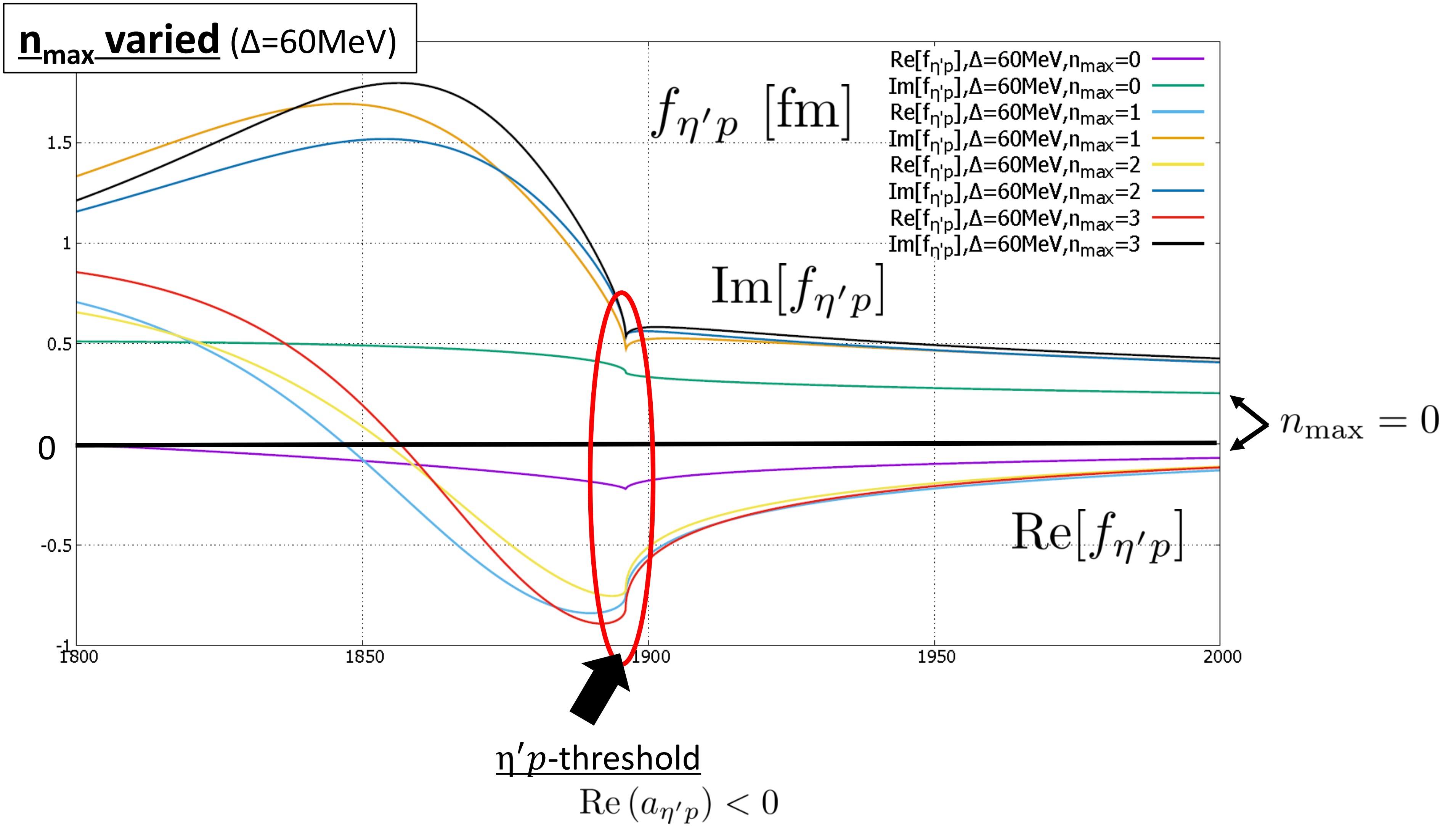
-- $v_{\gamma p,\eta^{(\prime)}p}$: polynomial of s

$$v_{\gamma p,\eta' p} = \sum_{n=0}^{n_{\max}} v_{\gamma p,\eta' p}^{(n)} s^n, \quad v_{\gamma p,\eta p} = e^{i\theta}\left(\sum_{n=0}^{n_{\max}} v_{\gamma p,\eta p}^{(n)} s^n\right)$$

Fit (Δ=60MeV fixed)

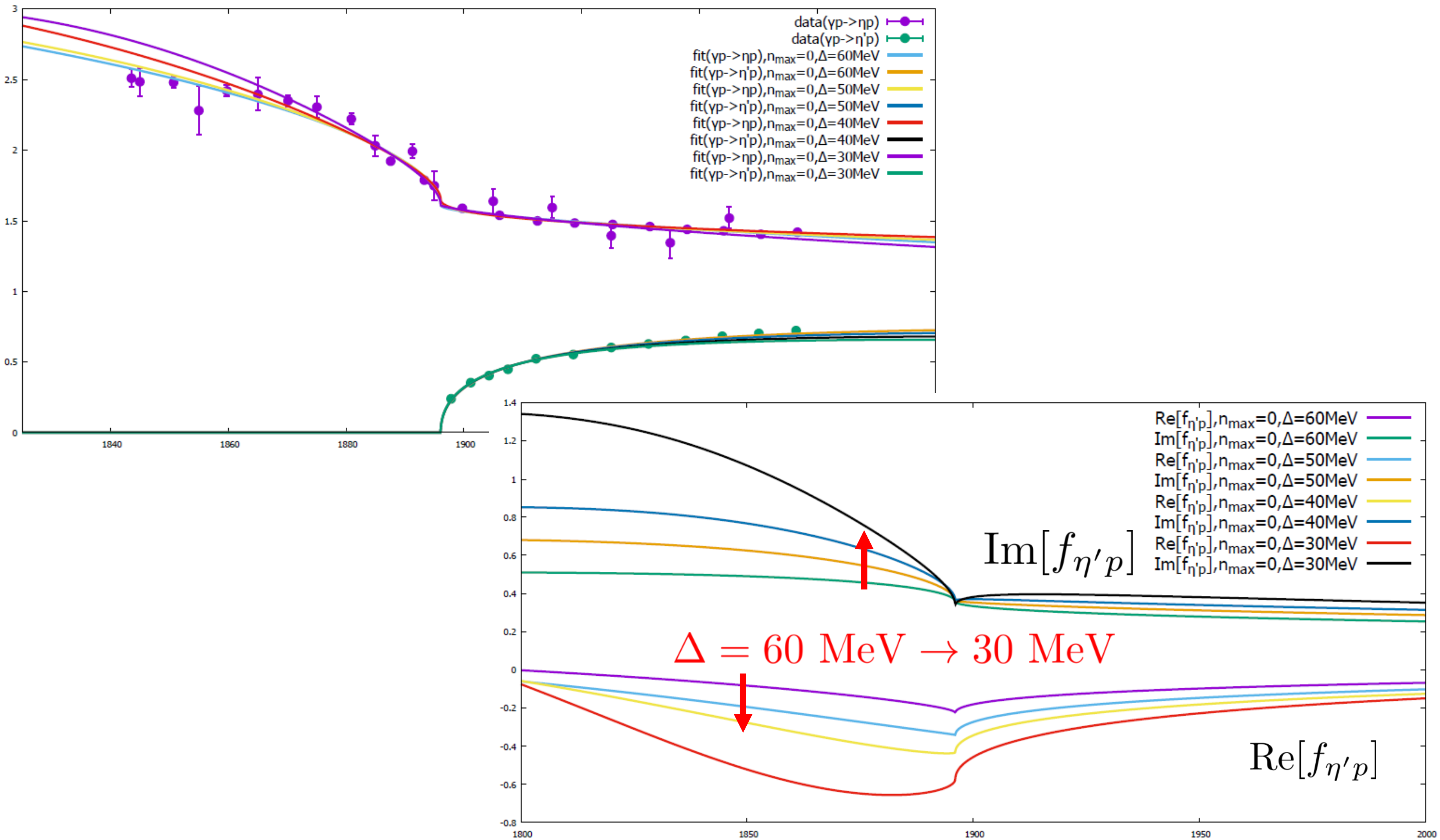


$\eta' p$ scattering amplitude



$n_{\mathrm{max}} = 0$

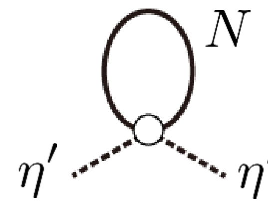
Δ varied



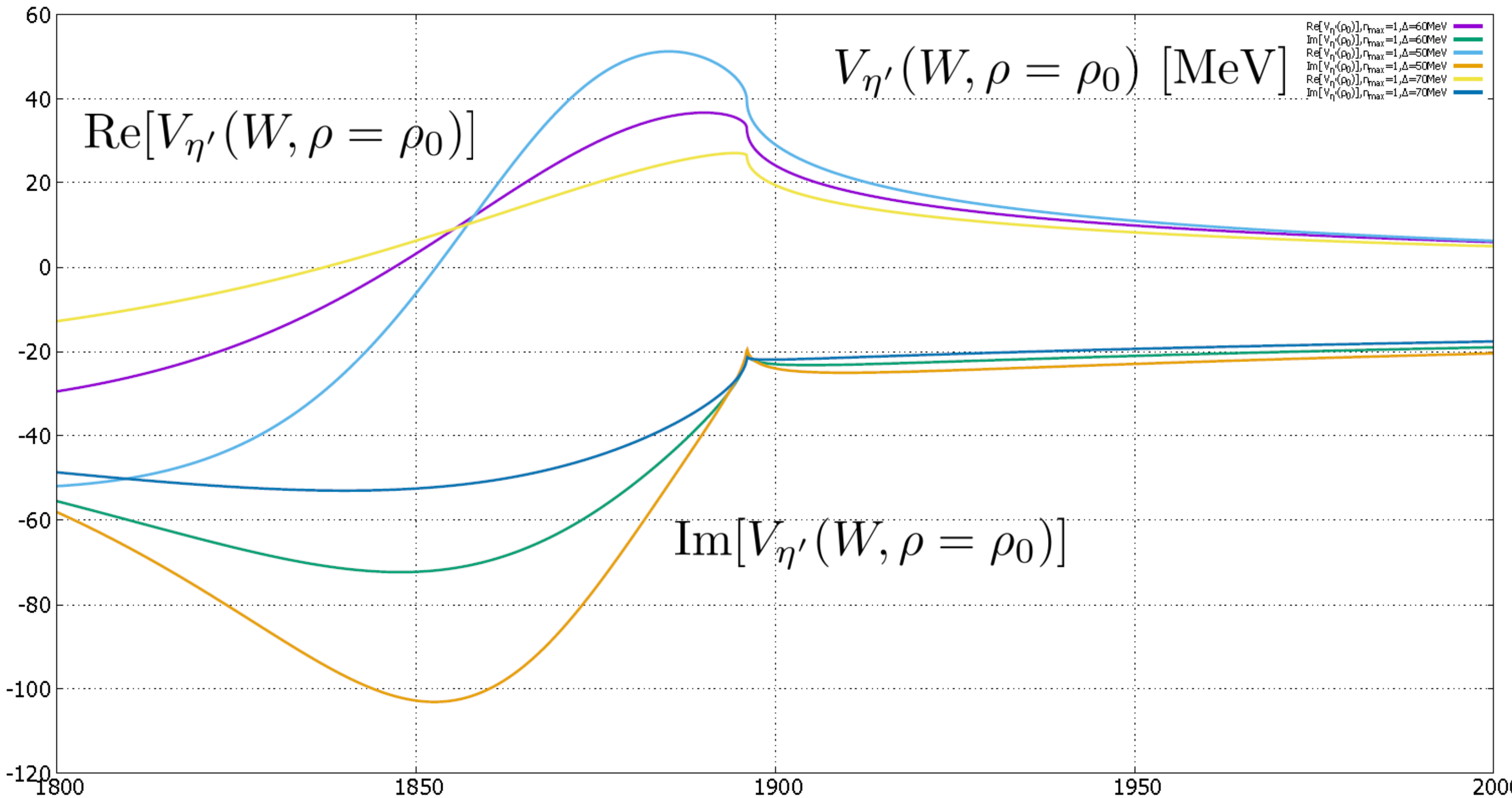
$a_{\eta' p} = -0.57 + i0.34\ \mathrm{fm}$ (Δ=30MeV)

η'-optical potential @$\rho = \rho_0$

$$V_{\eta'}(W,\rho) = \frac{1}{2m_{\eta'}} t_{\eta' p}(W)\rho$$

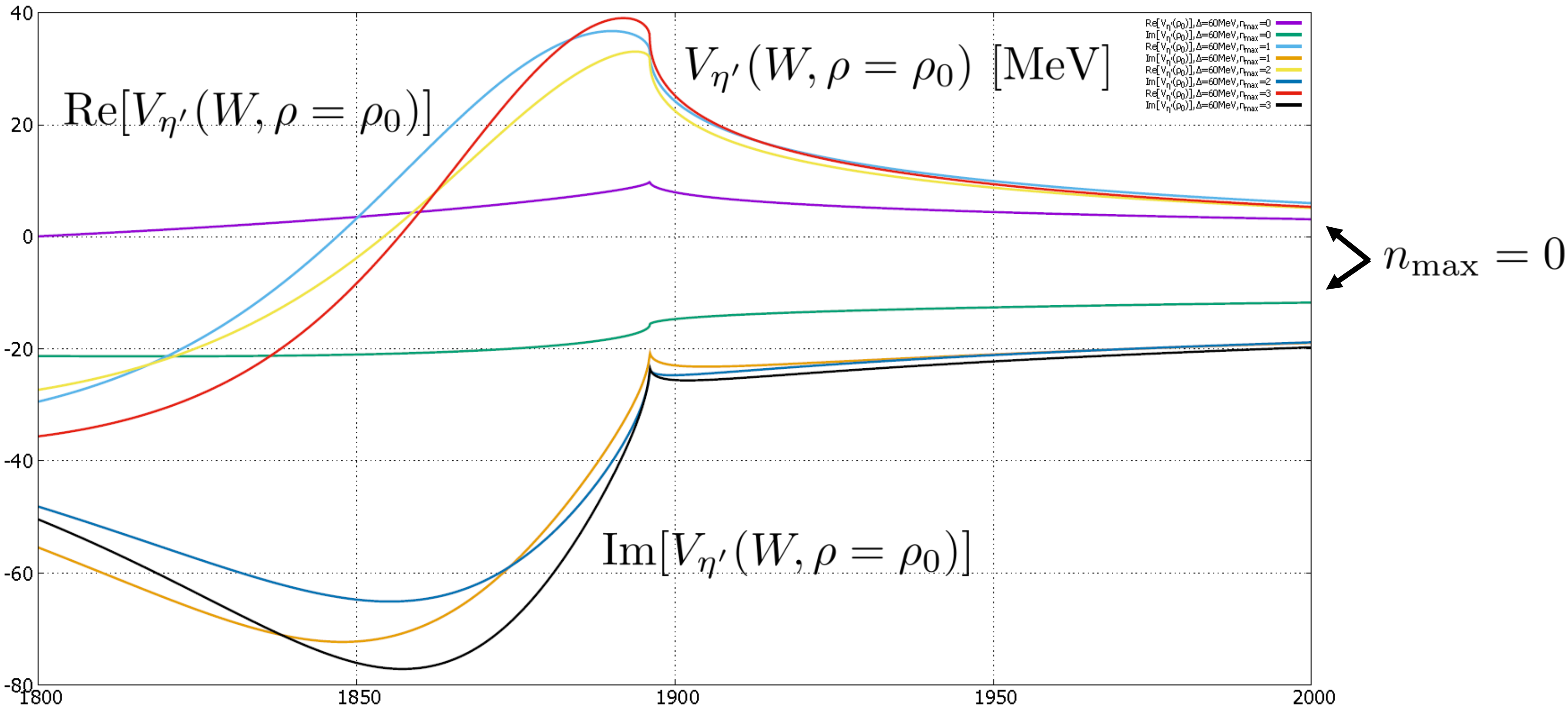


<u>Δ varied</u> (n_{max}=1)

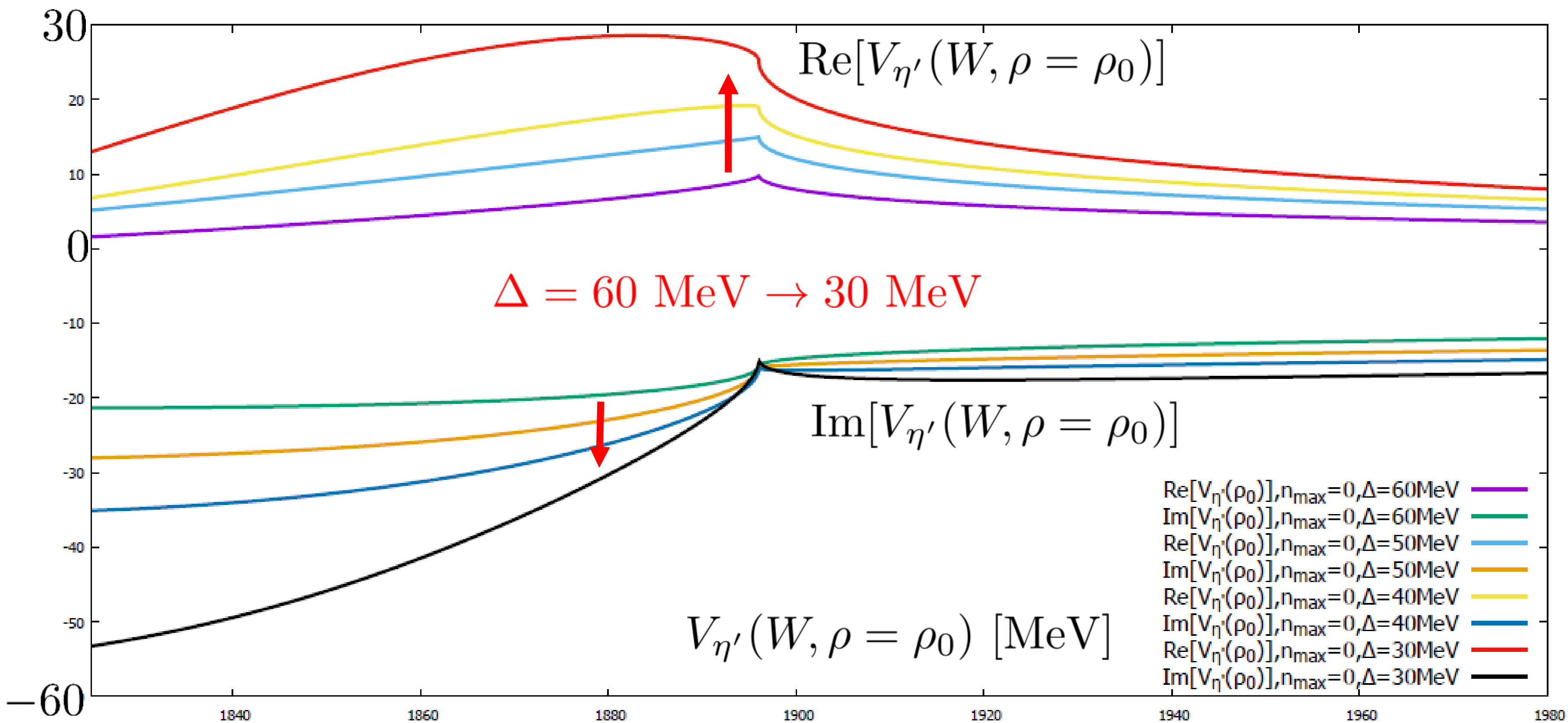


η′-optical potential @ρ = ρ_0

n_{max} varied (Δ=60MeV)



$n_{max} = 0$ **Δ varied**



Summary

- Analysis of η/η' photoproduction data with $\eta^{(\prime)}p$ Final-State Interaction
  - Threshold effect
    - Near-threshold enhancement in $\gamma p \to \eta' p$
    - Cusp of $\gamma p \to \eta p$ cross section @$\eta' p$ thr.

  Reproduced by $\eta^{(\prime)}p$ FSI well

  - For s-wave $\eta' p$ scattering length,

$$\mathrm{Re}\,(a_{\eta' p}) \sim -(0.6-0.9)\ \mathrm{fm}(<0), \mathrm{Im}\,(a_{\eta' p}) \sim (0.3-0.5)\ \mathrm{fm}$$

  +some uncertainties…

  - Contribution from broad resonance @1880MeV? ~N(1895)?

    -- Similar result to other analyses

    -- Too far away from real axis: large uncertainties…
- η'-optical potential from $\eta' p$ amplitude with $t\rho$ approximation
  - Magnitude: O(10) MeV @$\rho=\rho_0$ (typical hadronic scale)
  - Characteristic energy dependence near $\eta' p$ threshold