Role of triangle singularity in $\gamma p \rightarrow \pi^0 \eta p$ reaction

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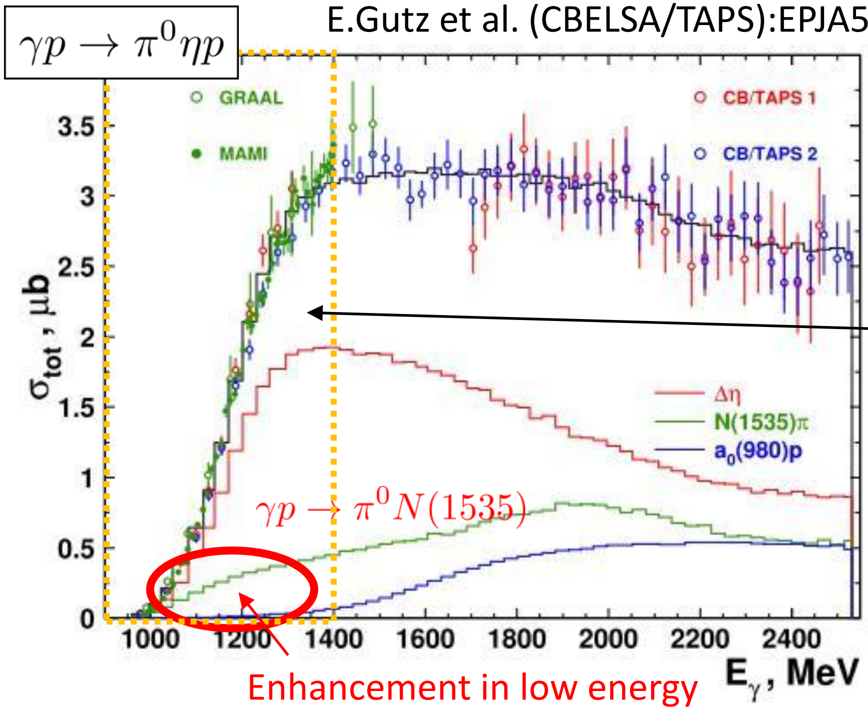
Phys. Rev. C96(2017)025201

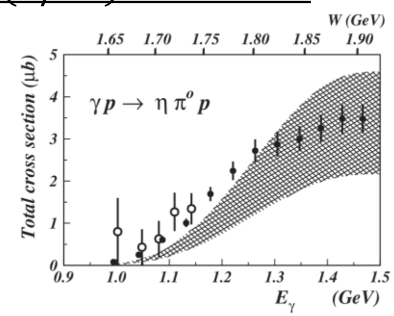
Eur. Phys. J. C(2019)79:69

Near threshold $\pi^0\eta$ photoproduction

E.Gutz et al. (CBELSA/TAPS):EPJA50,74(2014)



$\Delta(1700)(3/2^-)$ dominance



Ajaka et al., PRL100, 052003(2008)

(Data: LNS@Tohoku Univ.)

- From $\Delta(1700)(3/2^-)$

  → $\pi^0 N(1535)$ production ≠ S wave

  - $N(1535)$: **Strong coupling to ηN channel**

    [RPP: Br(Nπ)=32-52% and Br(Nη)=30-55%]

  = One peculiar feature of $N(1535)$

  → Unconventional (penta-quark etc.) state?

  See, e.g., Kaiser-Siegel-Weise:PLB362(1995)23

- One possible description of $N(1535)$

-- πN-ηN-$\boldsymbol{K\Lambda}$-$\boldsymbol{K\Sigma}$ coupled-channel dynamics

$[q\bar{s}][sqq]$

Kaiser-Siegel-Weise: PLB362(1995)23,…

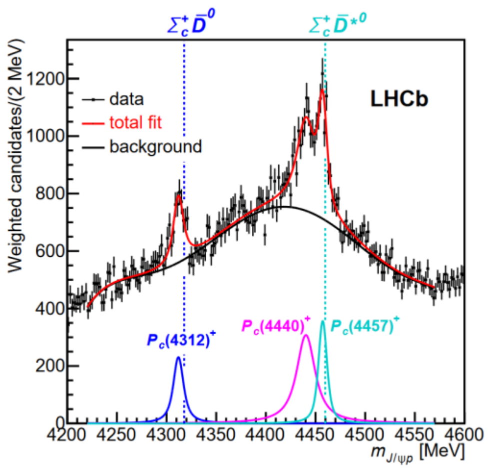
Extension to charm sector ($s\bar{s} \to c\bar{c}$)

-- Dynamically generated $\bar{D}^{(*)}\Sigma_c$ state?

J.J. Wu et al., PRL105, 232001(2010),…

$P_c(4312, 4440, 4457)$

$[\Lambda_b \to K^- J/\psi p]$



PRL122(2019)222001(LHCb)

- $\bar{D}^{(*)}\Sigma_c^*$ siblings? (HQSS)

  M.Z. Liu et al., PRL122, 232001(2019),…

- Signal in $\eta_c N$ channel

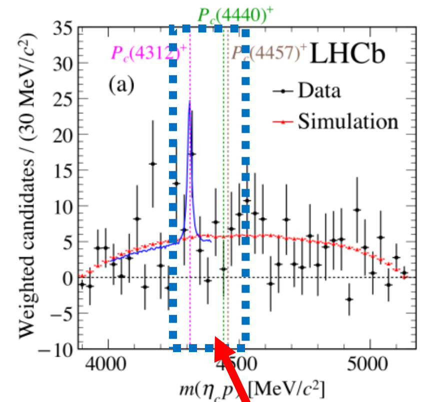
  J.J. Wu et al. PRC84,015202(2011)
  M.B. Voloshin,PRD100, 034020 (2019)
  S.S. et al., PRD100, 074007(2019)…

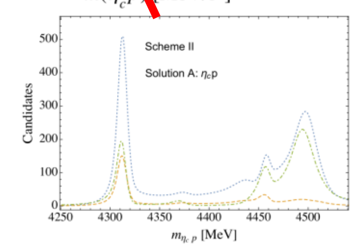
- Signal in other reactions?

  GlueX, PRL123, 072001(2019),…

[Further studies should be done…]

LHCb, PRD102,112012(2020)



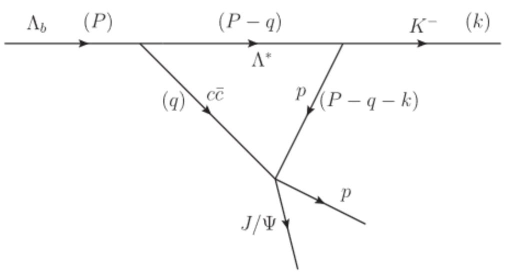


M.L. Du et al., PRL122, 232001(2019)

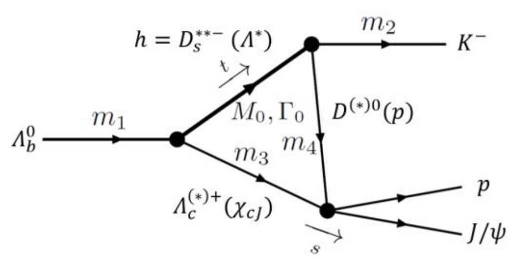
Better understanding of baryons in light (strange) sector

⇔ Hints for/from heavy sector

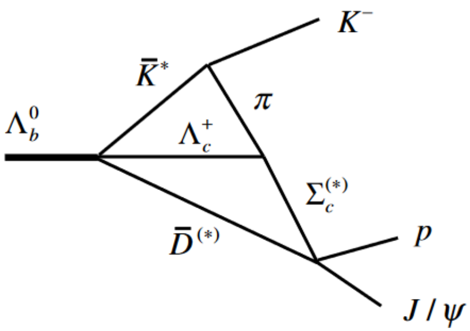
Relevant role of triangle loop?



Guo et al., PRD92, 071502(R) (2015)
Bayar et al., PRD94, 074039(2016)
Guo et al., EPJA (2016)52:318



LHCb PRL122(2019)222001



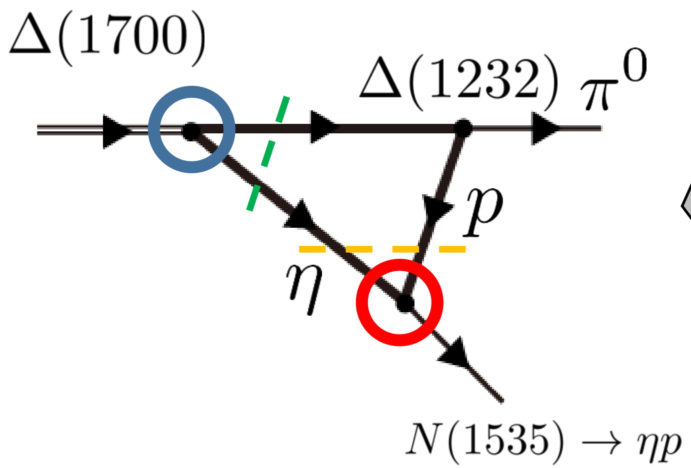
S.X. Nakamura, PRD103 (2021) L111503

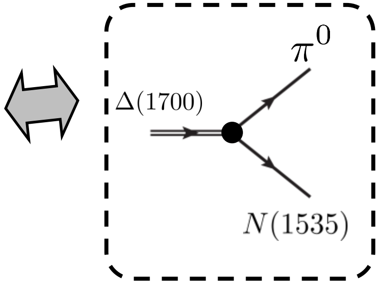
[Further studies should be done…]

Potential importance in some reactions

[Nontrivial structure without resonance]

Triangle diagram for $N(1535)$ production in $\Delta^* \to \pi^0 \eta p$

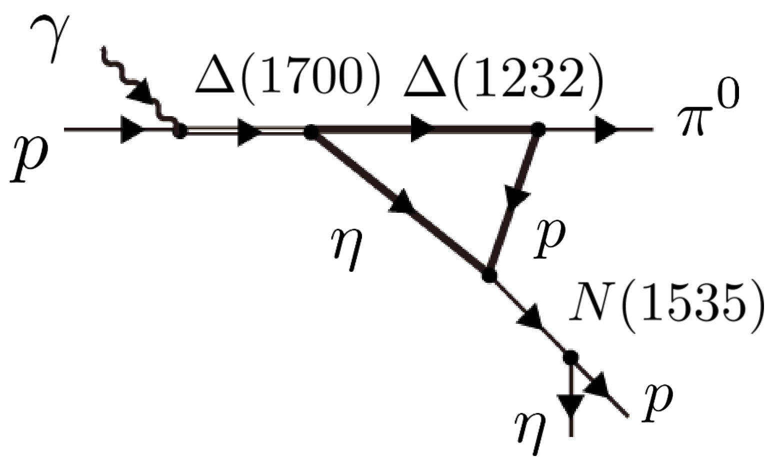




- Closeness of resonance mass and threshold
  -- Nearby $\eta\Delta(1232)$ and ηN threshold (kinematical)
- Strong coupling of $\Delta(1700)/N(1535)$ to $\eta\Delta/\eta N$ (dynamical)

<u>Triangle-loop contribution can be important</u>
<u>in $\pi^0\eta$ production</u>

Triangle singularity (TS) in $\gamma p \to \pi^0 \eta p$



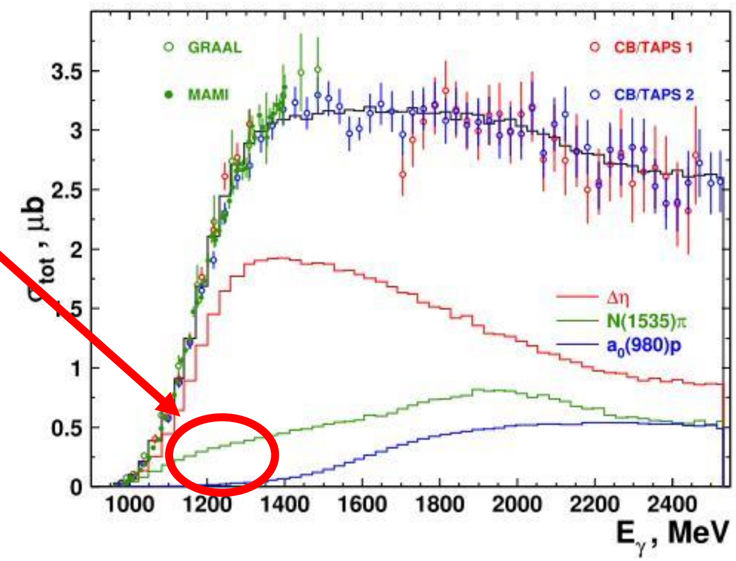
Singularity $\sim E_\gamma = 1220$ MeV

$[M_{\rm inv}(\pi^0 N(1535))$=1780MeV]

[See formula in Bayar et al., PRD94, 074039(2016)]

Smeared by the internal particle width

➔ Finite peak

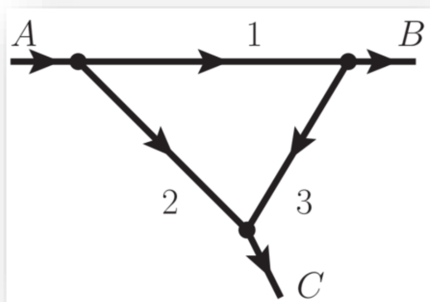


<u>Manifestation of unconventional nature of $N(1535)$</u>

(Strong coupling to ηN channel)

Triangle singularity

L.D. Landau, Nucl.Phys.13,181(1959)



Divergence of loop amplitude

← some conditions are satisfied

Coleman-Norton discussion

Nuovo Cim. 38, 438(1965)

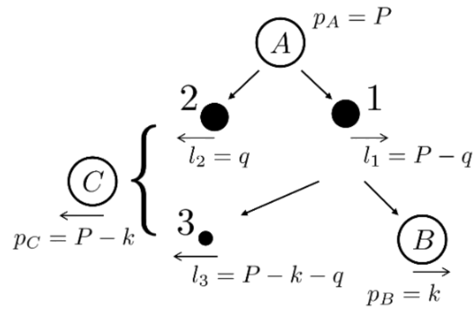
Triangle singularity

⇕

Classical process

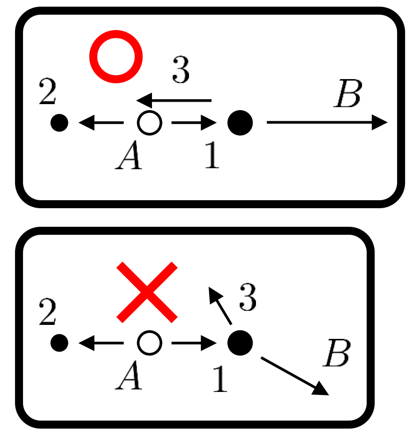
- All internal particles are onshell
- Energy-mom. conservation of all vertices

[See also Bayar et al., PRD94, 074039(2016)]

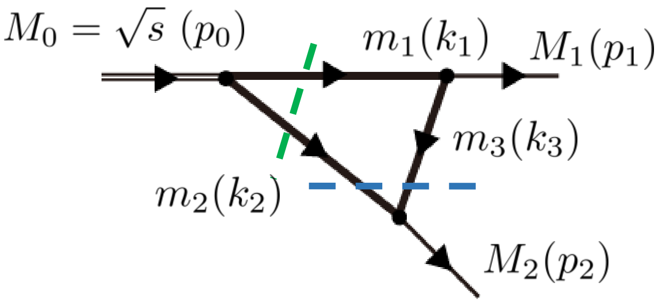


$\vec{p}_2 \parallel \vec{p}_3$: $2 + 3$ form C

+particle 3: sufficiently fast



Triangle singularity with **cutting formula**



Pick up onshell contribution
of intermediate particles

$$i/(p^2 - m^2 + i\epsilon) \to (2\pi)\delta^+(p^2 - m^2)$$

Cutkosky, J.Math.Phys.1,429(1960)

$$\mathrm{disc}_{12}(t_T) = \frac{-i}{16\pi|\vec{p}|\sqrt{s}} \log\frac{\tilde{A}+1+i\epsilon}{\tilde{A}-1+i\epsilon}$$

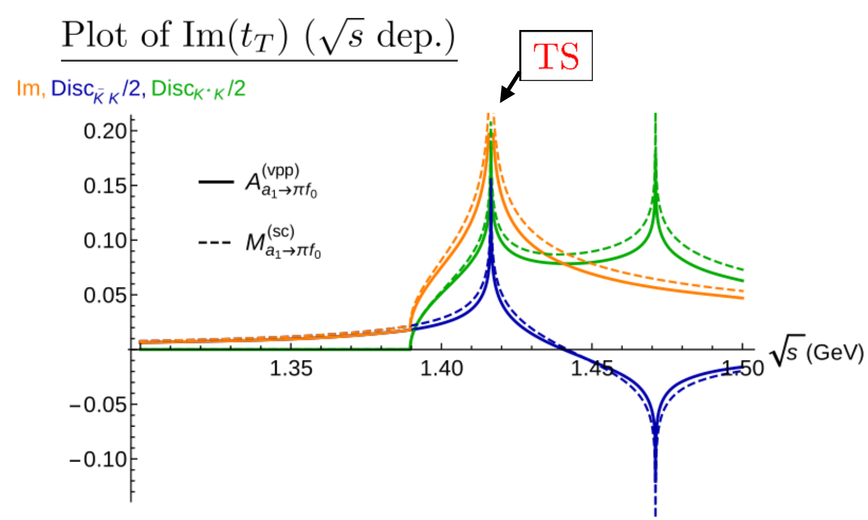
$$\mathrm{disc}_{23}(t_T) = \frac{-i}{16\pi|\vec{p}\,'|M_2} \log\frac{\tilde{C}+1-i\epsilon}{\tilde{C}-1-i\epsilon}$$

$$\mathrm{Im}(t_T) = \frac{1}{2i}\left[\mathrm{disc}_{12}(t_T) + \mathrm{disc}_{23}(t_T)\right]$$

$$\begin{cases} \tilde{A} = \dfrac{1}{2|\vec{k}_1||\vec{p}_1|}(m_3^2 - m_1^2 - M_1^2 + 2E_1^p E_1^k) \\ \tilde{C} = \dfrac{1}{2|\vec{k}'_1||\vec{p}'_2|}(m_1^2 - s - m_2^2 + 2E_0^{p'} E_2^{k'}) \end{cases}$$

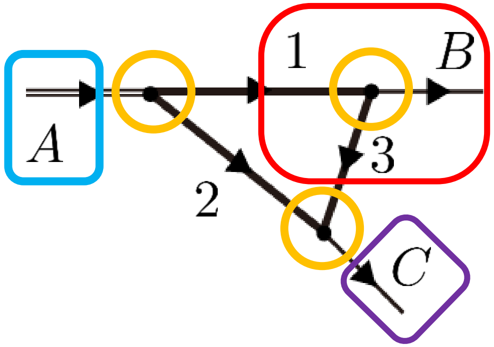
Logarithmic divergence at $\tilde{A}, \tilde{C} = \pm 1$

Smeared into finite peak (particle width)



Mikhasenko-Ketzer-Sarantsev, PRD91,094015(2015)

Singularity of triangle graph



- Onshell condition of internal particles
- One angular condition ~ 2+3→C (collinear process)

Position of TS: determined by particle mass and energy (purely kinematical effect)

- Width of particles
  - -- Possible 1→3B decay ~ Inevitable particle-1 width: Divergence → finite peak
- Vertex structure
  - -- Energy, momentum dependence
- Production process of initial state (A: intermediate resonance) ← $\Delta(1700)$ in this work
- Subsequent decay of particle C or rescattering
  - -- Coupling to resonance,… ← $N(1535)$ in this work
- Order of magnitude
  - -- Triangle graph: particle width + 1-loop process

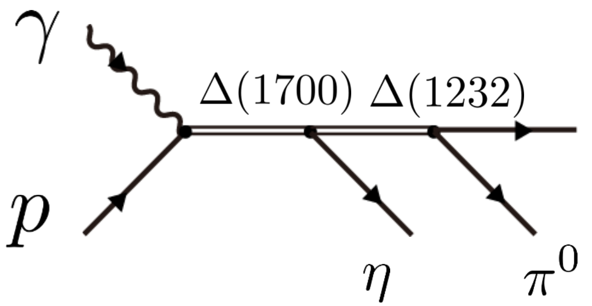
Necessity of phenomenological study on TS

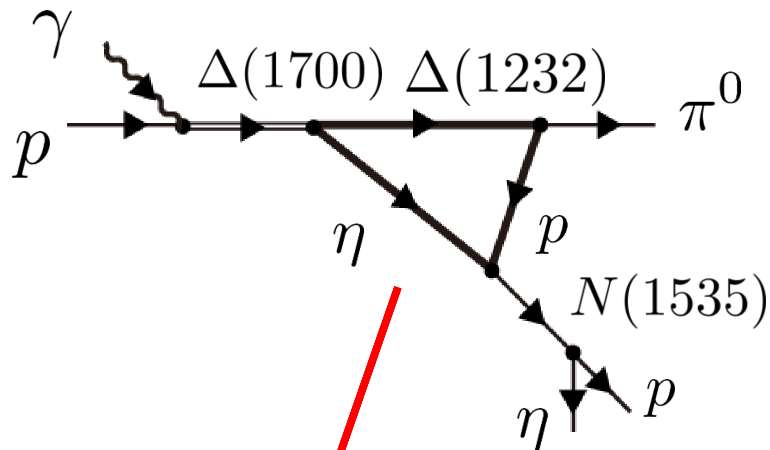
(even though TS position is fixed by mass and energy)

Purpose of this work

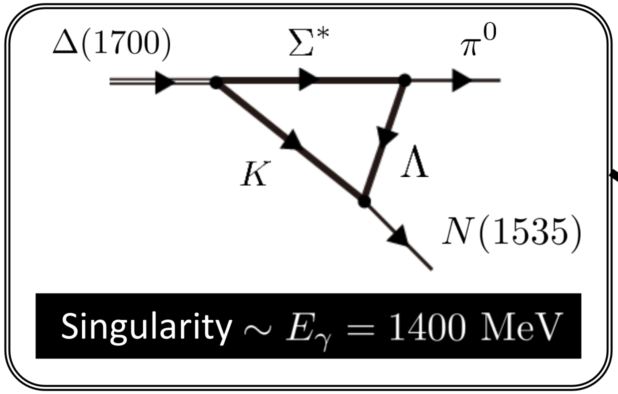
Investigate the role of the triangle-loop contribution in low-energy $\gamma p \to \pi^0 \eta p$ process with $N(1535)$

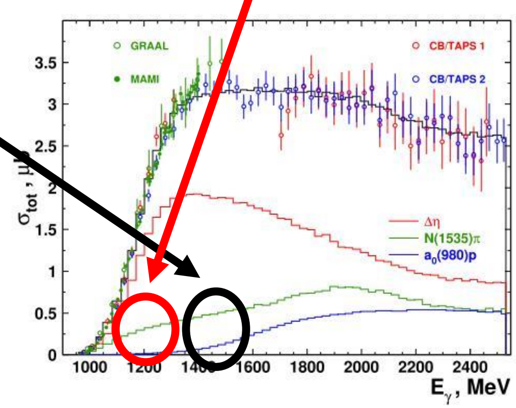
V.R. Debastiani et al., Phys. Rev. C96(2017)025201



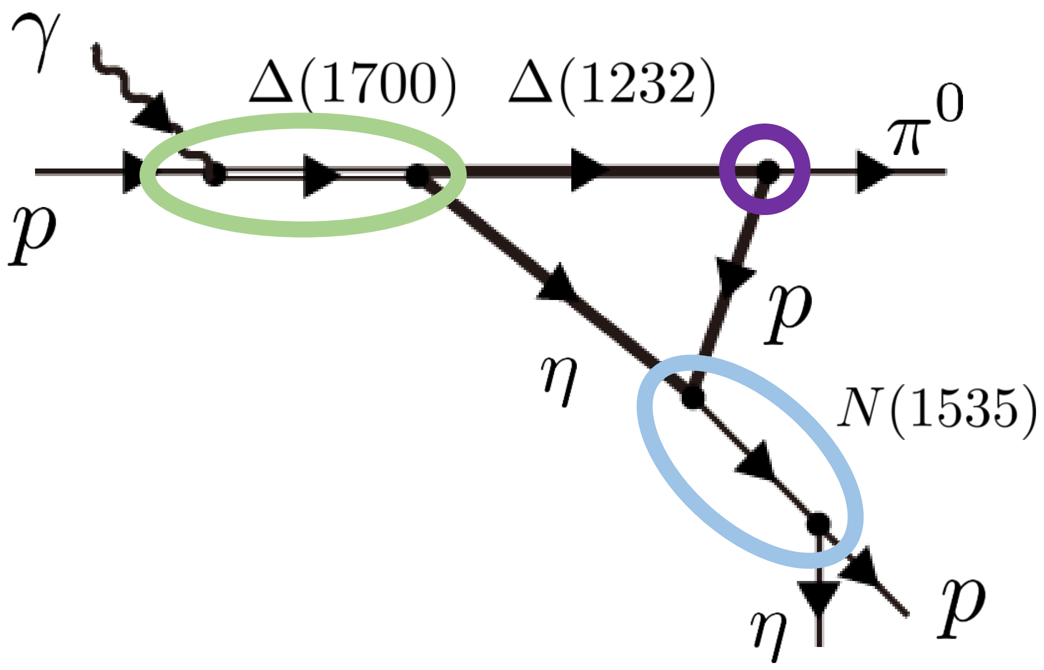


Singularity $\sim E_\gamma = 1220$ MeV

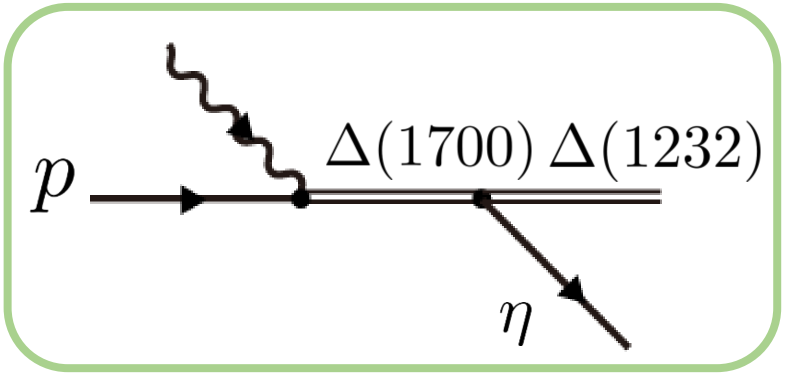




Evaluation of triangle loop amplitude



- Δ(1700) part



-- γp - Δ(1700) and $\eta\Delta$-Δ(1700) processes: S wave

※ $J^P(\Delta(1700)) = 3/2^-$

$$\begin{cases} -it_{\Delta^*,\gamma p} = -ig_{\Delta^*,\gamma p}\vec{S}\cdot\vec{\epsilon} \\ -it_{\Delta^*,\eta\Delta} = -ig_{\Delta^*,\eta\Delta} \end{cases}$$

$$t_{\Delta^*} = \frac{g_{\Delta^*,\gamma p}\, g_{\Delta^*,\eta\Delta}\vec{S}\cdot\vec{\epsilon}}{\sqrt{s} - M_{\Delta^*} + i\Gamma_{\Delta^*}/2}$$

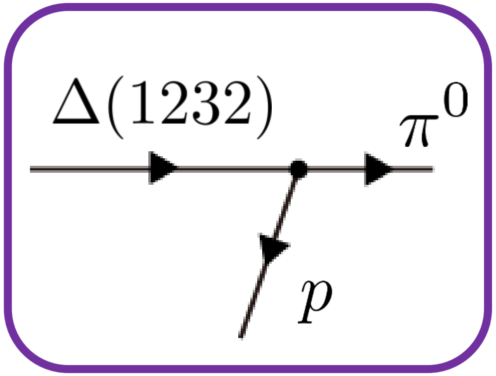
○ $M_{\Delta^*}, \Gamma_{\Delta^*}, g_{\Delta^*,\gamma p}$ from PDG data:
M_{Δ^*}=1640-1690 MeV, Γ_{Δ^*}=200-300 MeV,
$\mathrm{Br}(\Delta^* \to \gamma N)$=0.22-0.60%

○ $g_{\Delta^*,\eta\Delta}$ from output of theoretical calculation

[Sarkar et al. NPA750,294(2006)]

Δ(1700): $\eta\Delta$-$K\Sigma^*$-$\pi\Delta$ coupled channel dynamics

- $\Delta(1232)\pi N$ vertex



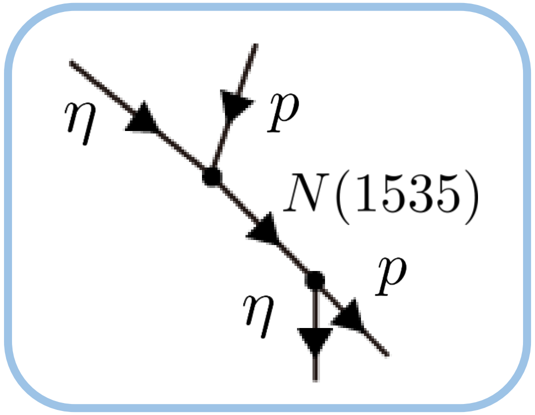
$$-it_{\Delta,\pi^0 p} = \sqrt{\frac{2}{3}}\frac{f_{\Delta\pi N}}{m_\pi}\vec{S}\cdot\vec{p}_{\pi^0}$$

Spin transition operator from 3/2 to 1/2

From observed width of $\Delta(1232)\sim 120$ MeV

Clebsch-Gordon coefficient for $\Delta^+ \rightarrow \pi^0 p$

- $N(1535)$ part

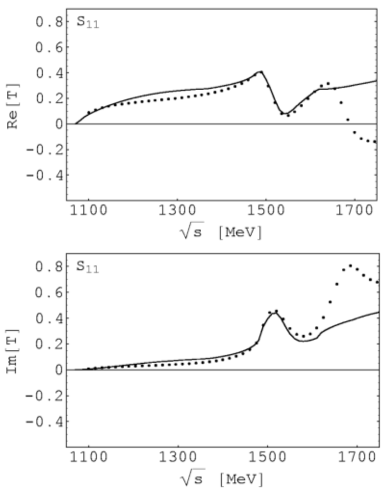


-- Breit-Wigner amplitude

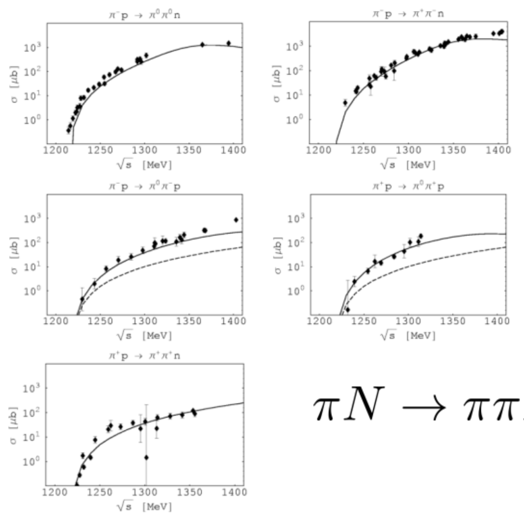
$$t_{N^*} = \frac{g^2_{N^*,\eta p}}{M_{\rm inv}(\eta p) - M_{N^*} + i\Gamma_{N^*}/2}$$

○ $M_{N^*}, \Gamma_{N^*}, g_{N^*,\eta p}$ from theory: Inoue et al., PRC65,035204(2002)

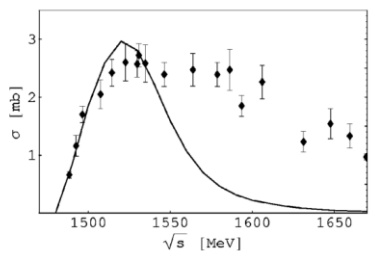
-- chiral Lagrangian + unitarity with scattering equation
-- πN-$\pi\pi N$-ηN-$K\Lambda$-$K\Sigma$ coupled-channel system



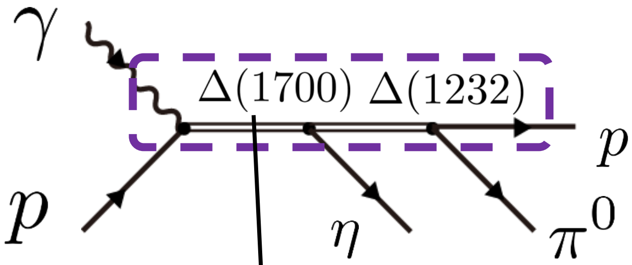
S_{11} amplutde

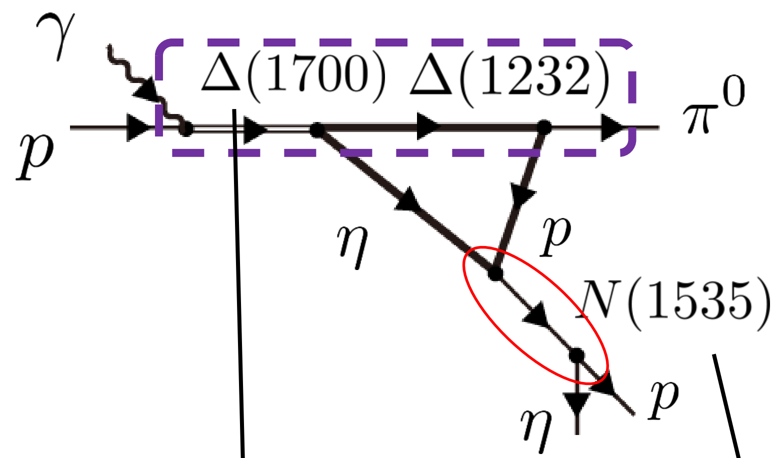


$\pi N \to \pi\pi N$



$\pi N \to \eta N$





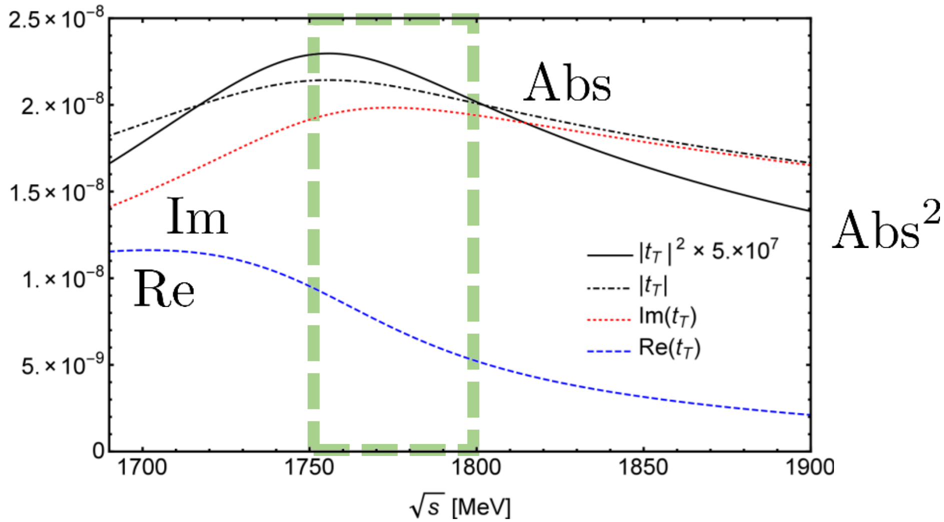
$$-it^{\text{tree}}_{\gamma p\to\pi^0\eta p} = \frac{t_{\Delta^*}\sqrt{\frac{2}{3}}\frac{f_{\Delta\pi N}}{m_\pi}}{M_{\pi^0 p} - M_\Delta + i\Gamma_\Delta/2}\,\vec{S}\cdot\vec{k}\,\vec{S}^\dagger\cdot\vec{\epsilon}$$

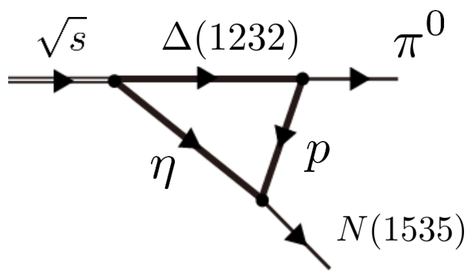
$$-it^{\text{loop}}_{\gamma p\to\pi^0\eta p} = t_{\Delta^*}\sqrt{\frac{2}{3}}\frac{f_{\Delta\pi N}}{m_\pi}\,\vec{S}\cdot\vec{k}\,\vec{S}^\dagger\cdot\vec{\epsilon}\,t_T\,t_{\eta p,\eta p}$$

Triangle-loop amplitude

✓ Plot of t_T

V.R. Debastiani et al., Phys. Rev. C96(2017)025201





$$(\Delta \text{ width effect} : E_\Delta \to E_\Delta - i\Gamma_\Delta/2)$$

t_T amplitude around $\sqrt{s}$=1780 MeV is dominated by its **imaginary part**

(E_γ~1200 MeV)

TS appears

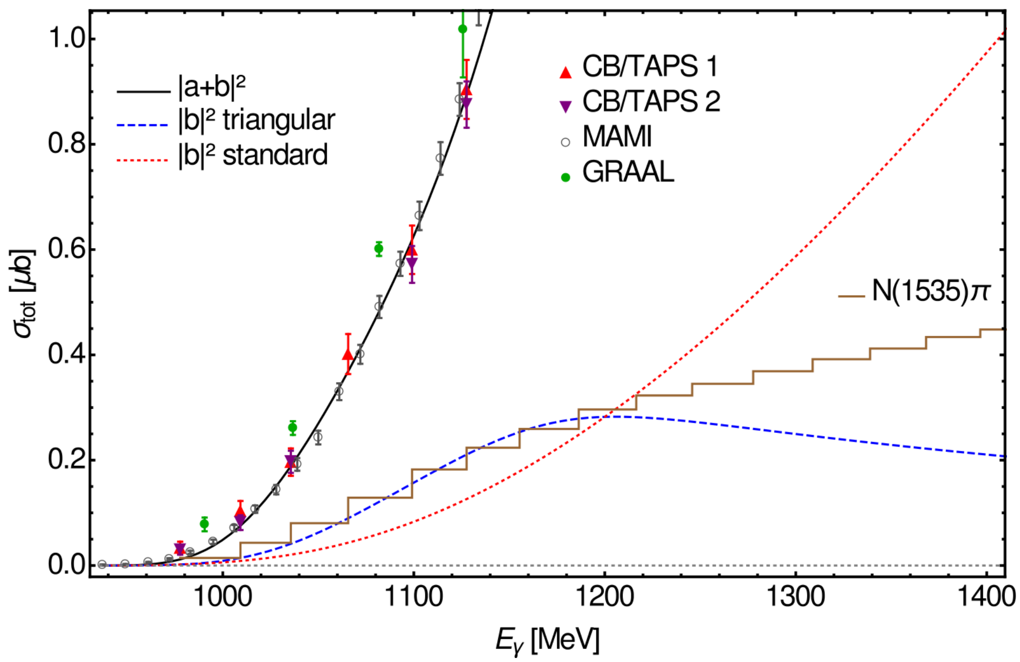
➡ Peak @E_γ = 1.2 GeV ~ remnant of TS

Results

Result [$N(1535)$ production]

Total (tree+loop): fit with Δ^* parameters $(M_{\Delta^*}, \Gamma_{\Delta^*}, g_{\Delta^*,\gamma p})$

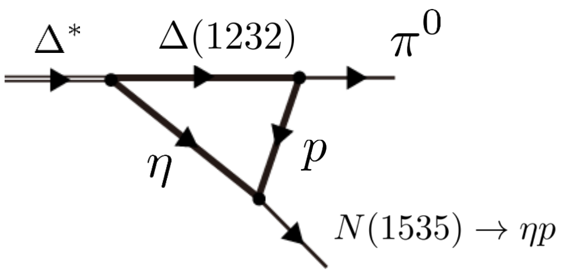
V.R. Debastiani et al., Phys. Rev. C96(2017)025201



p-wave $\propto k^2$

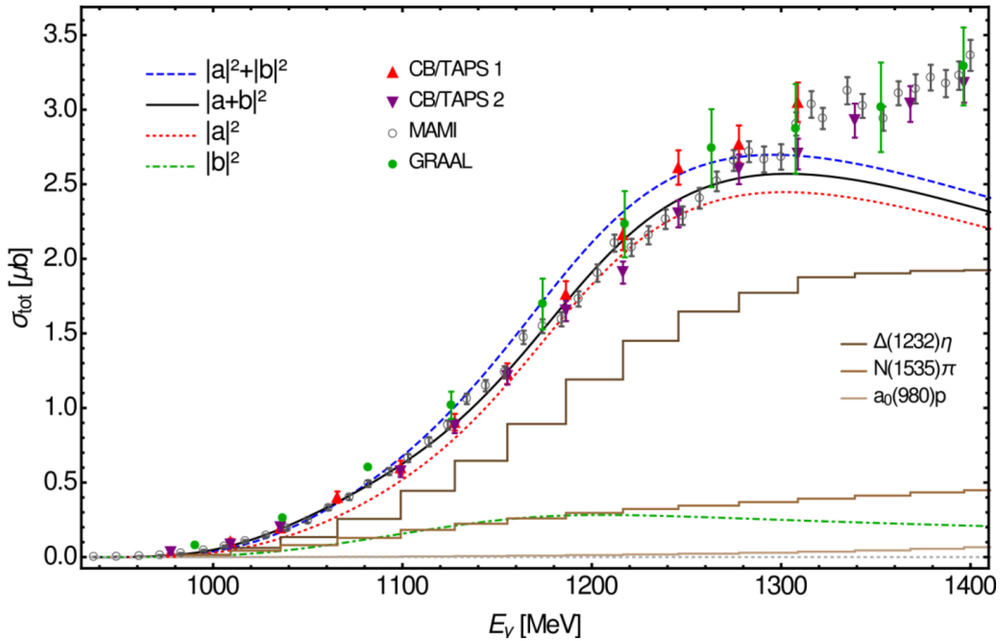
$N(1535)\pi^0$ (PWA)

From $t^{\text{loop}}_{\gamma p \to \pi^0 \eta p}$



Result

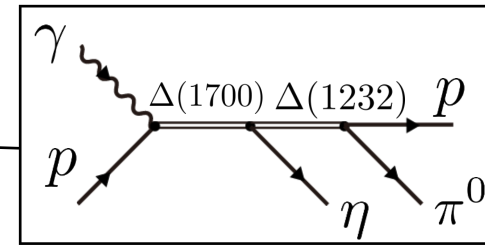
V.R. Debastiani et al., Phys. Rev. C96(2017)025201



Total (tree+loop)

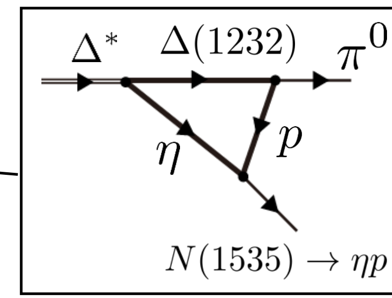
$t^{\mathrm{tree}}_{\gamma p\to\pi^0\eta p}$

$\Delta(1232)\eta$ (PWA)

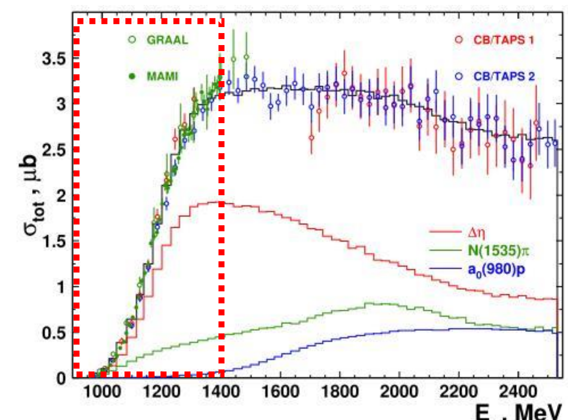


$N(1535)\pi^0$ (PWA)

$t^{\mathrm{loop}}_{\gamma p\to\pi^0\eta p}$



- Difference in tree-Δη contribution

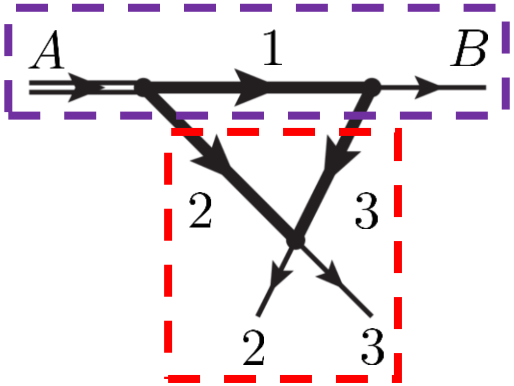


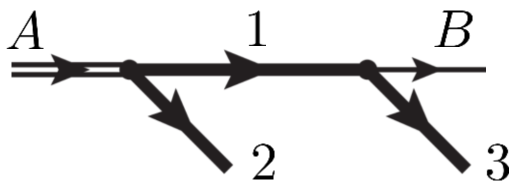
E.Gutz et al. (CBELSA/TAPS):EPJA50,74(2014)

Remarks on **Schmid theorem**

Schmid:Phys.Rev.154,1363(1967), Anisovich-Anisovich:PLB345,321(1995), Szczepaniak:PLB757,61(2016), Debastiani et al.:EPJC79:69(2019)

- Schmid theorem





~onshell process @TS

$$t_T + t_{\rm tree} \sim S t_{\rm tree} \quad [S = e^{2i\delta} : 23 \to 23 \; S \text{ matrix element}]$$

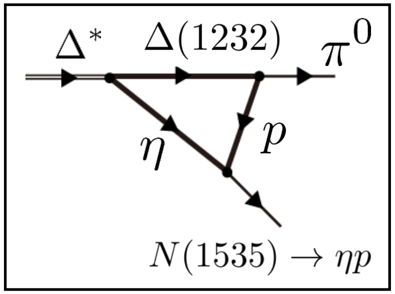
$S = 1 - iT$

t_T: phase modification

[Inelasticity$\to$ $S \sim \eta e^{2i\delta}$]

$$t_T \sim t_{\rm tree} t_{23,23}$$

Keep singular terms @TS



Summary

- Triangle diagram in $\gamma p \to \pi^0 N(1535) \to \pi^0 \eta p$ process

  -- Large contribution to low-energy $\pi^0 N(1535)$ production

  --- **Large $\Delta(1700)\eta\Delta$ and $N(1535)\eta p$ couplings**

  -- Different energy dependence from the direct production from Δ^*

  -- Strongly tied to the nature of $N(1535)$

  --- **ηp component of $N(1535)$: essential**

  -- Difference from PWA

  --- **Tied to onshell nature of TS**?

Thank you for your attention