Detecting pure triangle singularity effect through $\psi(2S) \to \bar{p}p\eta$ process

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arXiV: 2011.14590

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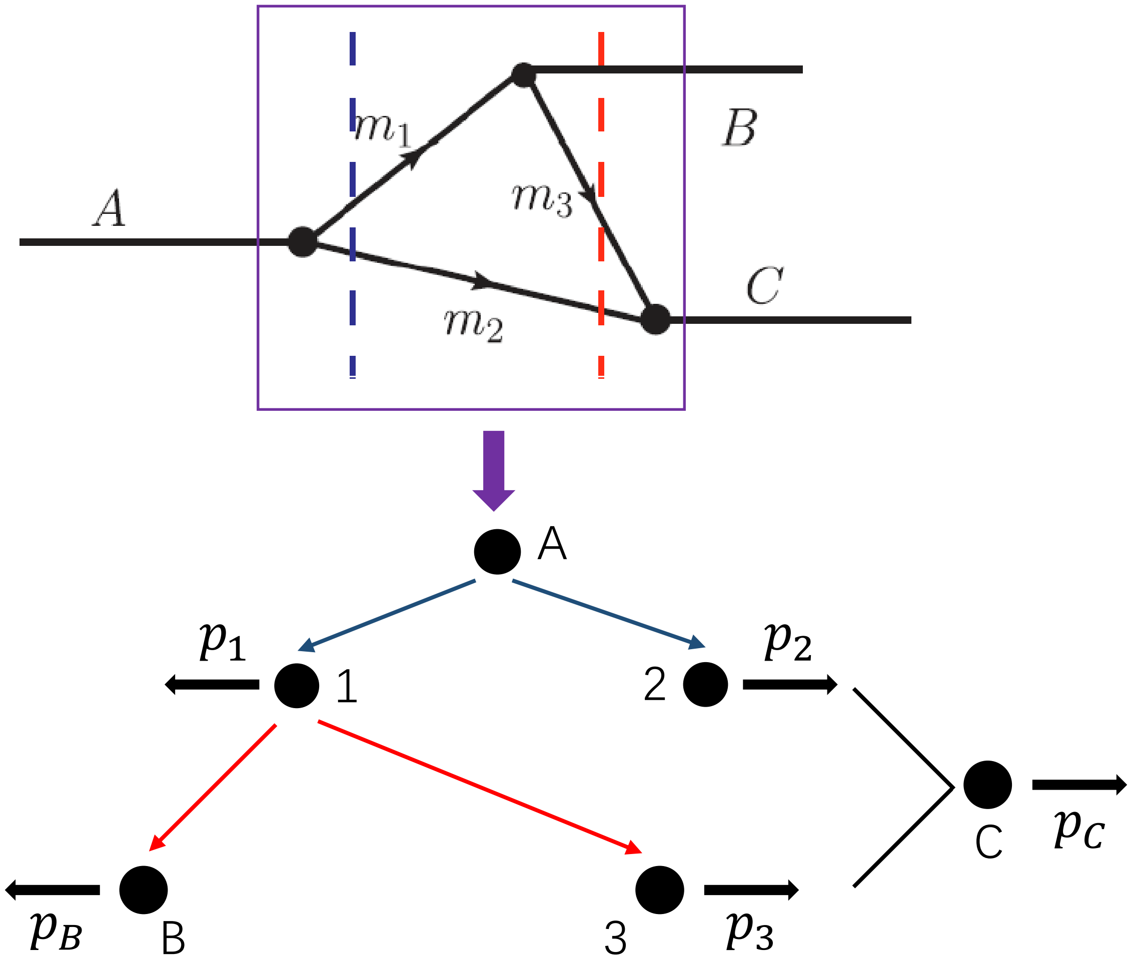
Outline

- Motivation
- Results
- Summary

Motivation

Triangle Singularity (TS): L. D. Landau, Nucl. Phys. 13, 181-192 (1959) ⇒ Concept.



How the TS happens :

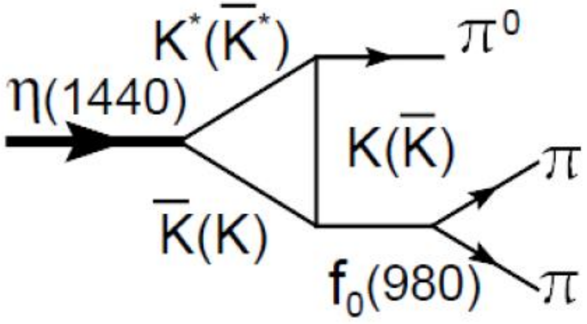
(1). Particle 1, 2 and 3 are all real particles,

(2). $\vec{p}_2$ and $\vec{p}_3$ have same direction,

(3). Particle 3 can catch up particle 2 ⇒ $v_3 > v_2$.

Purely kinematical effect, model independent !

Motivation



BESIII, 2012: Isospin breaking process $\eta(1405) \to \pi^0 f_0(980)$.

Nature of $a_1(1420)$: Triangle singularity caused by $K^* \bar{K} K$ loop.

Still not confirmed experimentally !

Interpretation of exotic states via triangle singularity:

$Z_c(3900)/Z_c(4025)$: $D_1 \bar{D} D^* / D_1 \bar{D}^* D^*$

$\mathrm{P}_c(4450)$: $\Lambda^* \chi_{c1} p$

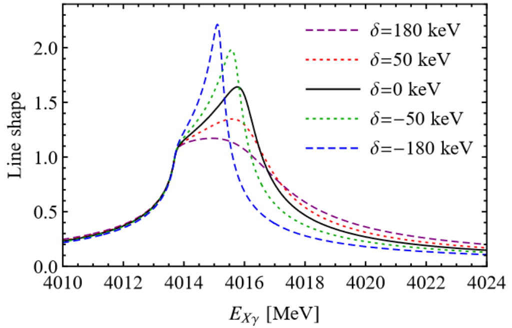
$X_{0/1}(2900)$: $\chi_{c1} \mathrm{K}^{*+} \mathrm{D}^{*-} / \mathrm{D}_{sJ}^{+} \bar{\mathrm{D}}_1^0 \mathrm{K}^0$

....

Meaning:

1. **Understand triangle singularity itself.**
2. **Confirm hadron loop mechanism.**
3. **Help studying properties of hadrons.**

↳ X(3872): F.-K. Guo, PRL 122,202002 (2019).



➡ Lots of theoretical works.

A recent review:
F. K. Guo, et. al., Prog. Part. Nucl. Phys. 112, 103757 (2020)

Motivation

1. Threshold

Example:

$Z_c(3900) - \bar{D}D^*$ threshold ~ 25 MeV
P_c~$4.45\ GeV - \chi_{c1}p$ threshold ~ O(10) MeV

X.-H. Liu, M. Oka and Q. Zhao, Phys. Lett. B753, 297 (2016):

If a threshold enhancement falls into the TS kinematic region, distinguishing it from TS will be complicated.

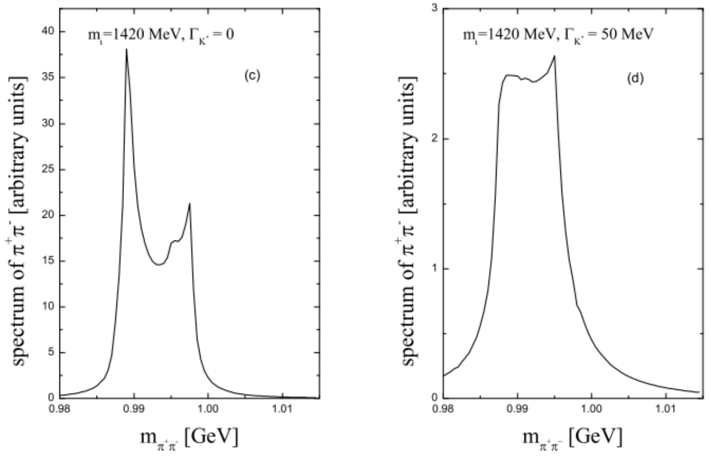
2. Width of internal particles

Example:

$\eta(1405) \rightarrow \pi^0 f_0(980) \rightarrow 3\pi$

N. N. Achasov, et.al., Phys. Rev. D92, 036003 (2015):

Changing width of K^* ⇒



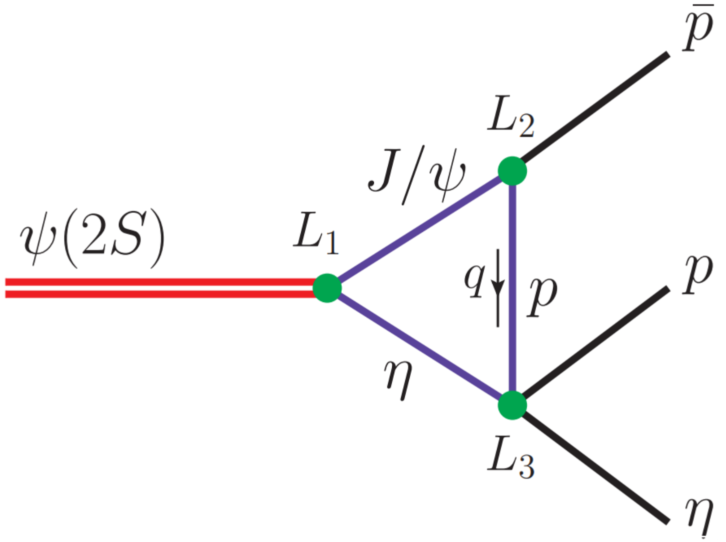
3. Information of interaction vertex

Example:

$P_c(4450)$: $\Lambda_b \rightarrow J/\psi pK$ via $\chi_{c1}p\Lambda^*$ loop.

No experimental data to constraint the $\Lambda_b \chi_{c1} \Lambda^*$ vertex ⇒ **Line shape only.**

Motivation



m_{TS} @ $m_{p\eta}$: 1.56387 GeV

1. **Far away from the threshold of the relative channel.**

   Position of TS is 80 MeV away from $p\eta$ threshold.
   TS and threshold can be separated clearly.

2. **Narrow widths of all internal particles.**

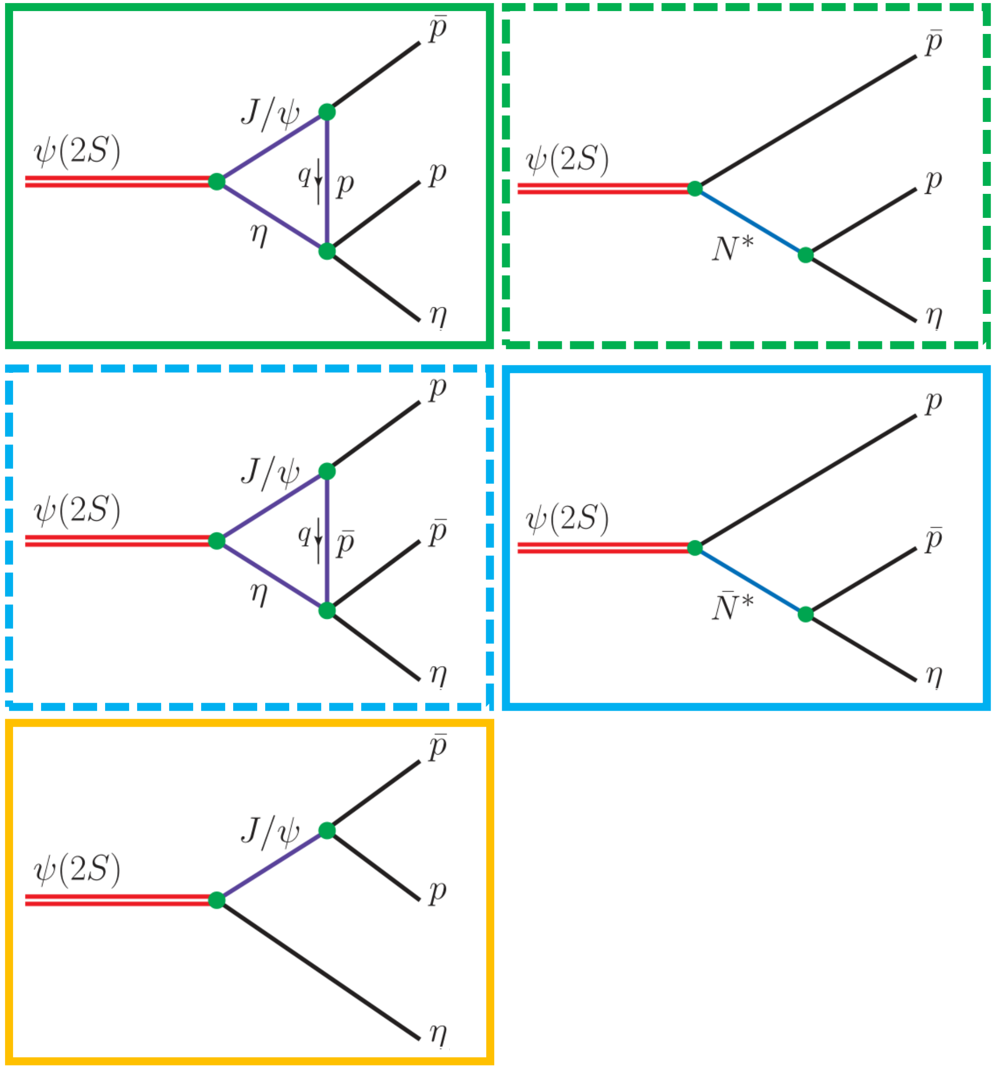
   Peak caused by triangle singularity must be very sharp.
   Distinguishing it from N^* states is very easy.

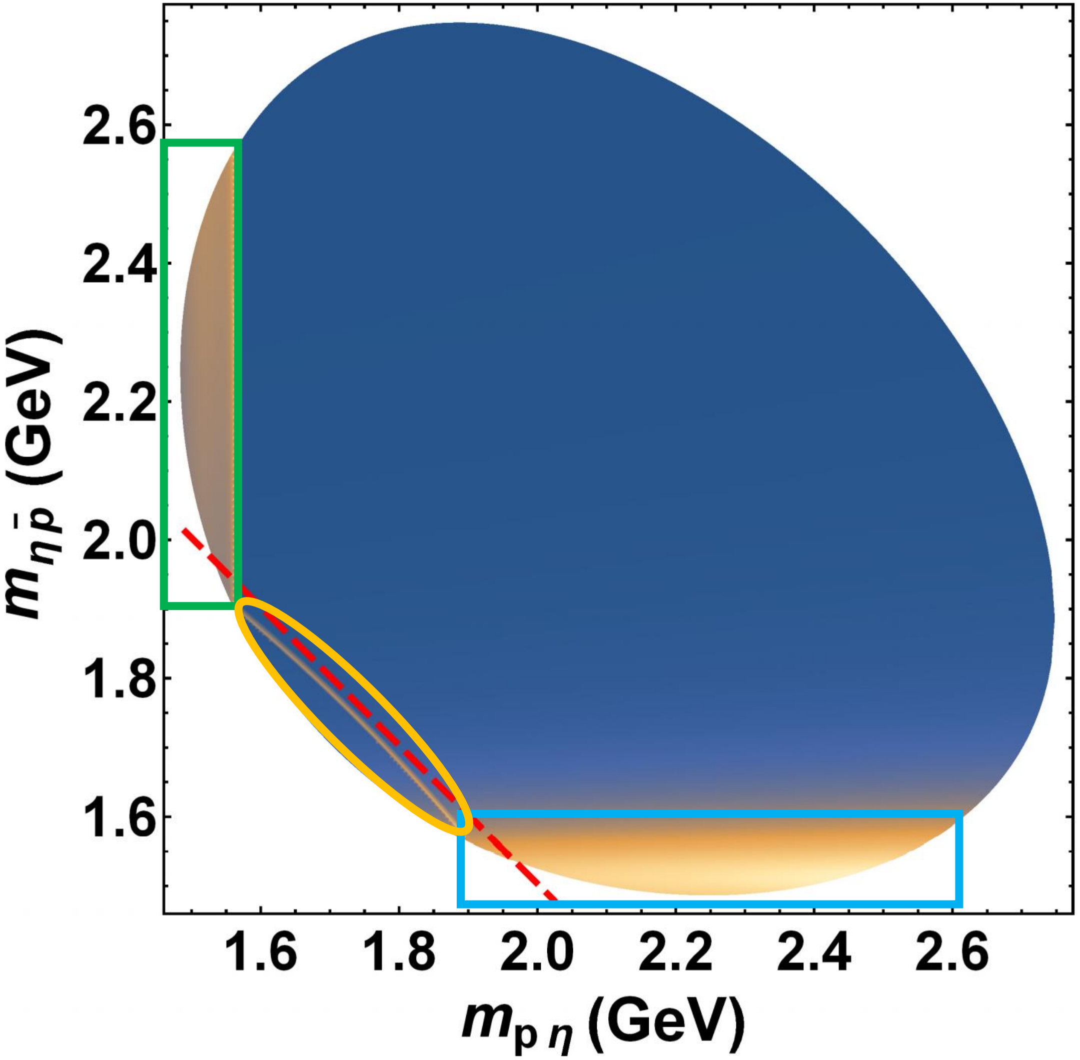
3. **The well known three vertices in the triangle loop.**

   All three vertices can be constrained by experimental data.
   Strength of TS can be predicted precisely.

TS in $\psi(2S) \to p\bar{p}\eta$ process

Main decay mechanism:





TS in $\psi(2S) \to p\bar{p}\eta$ process

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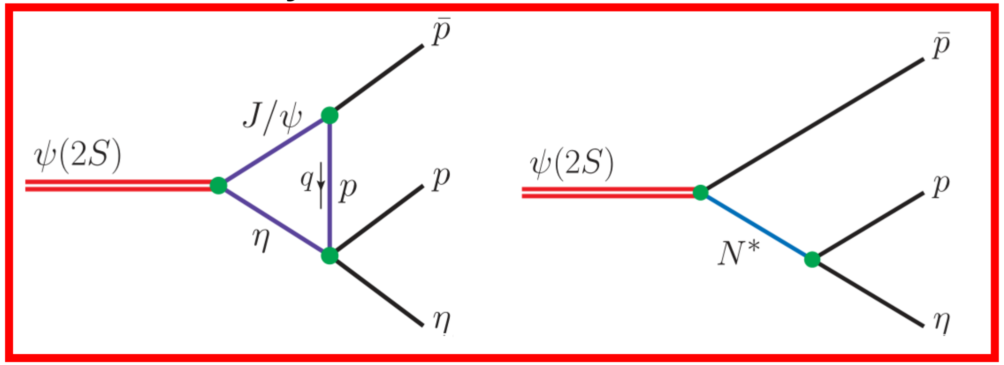
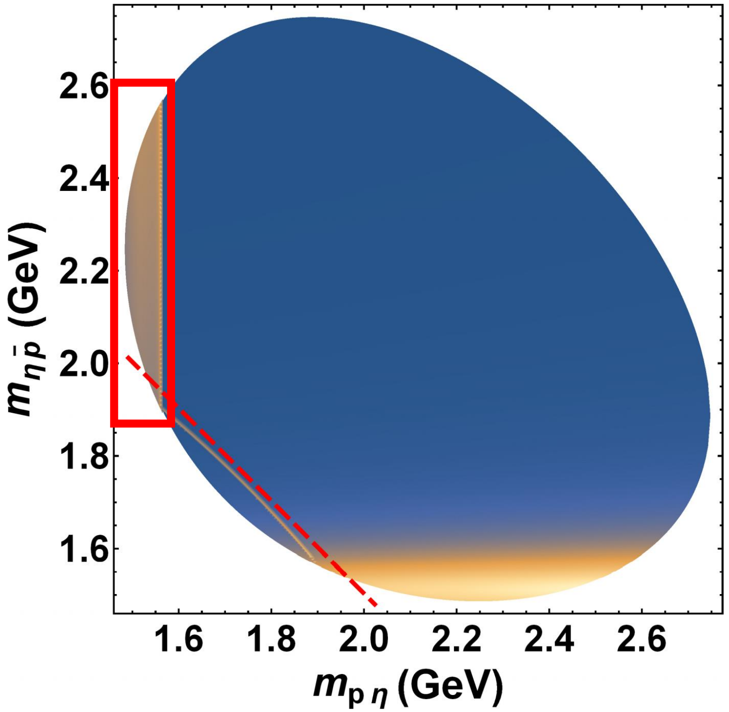
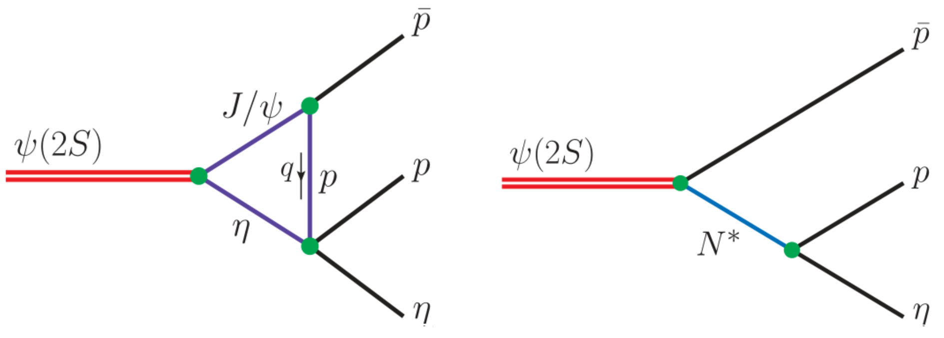




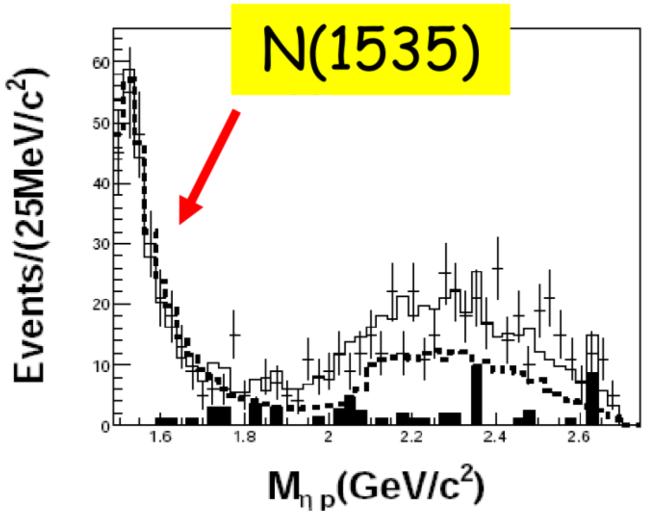
TS in $\psi(2S) \to p\bar{p}\eta$ process

Main decay mechanism:



Tree diagram: Dominant!

BESIII: PRD 88, 032010(2013)



$\Longrightarrow N^* = N(1535)$.

Loop diagram:

$p\eta \to p\eta$ vertex: s-channel contribution: $p\eta \to N^* \to p\eta$

N^* near m_{TS}: $N(1440), N(1520), N(1535), N(1650)$.

Considerable $B(N^* \to p\eta)$: $N(1535), N(1650)$.

$\Longrightarrow N^* = N(1535), N(1650)$.

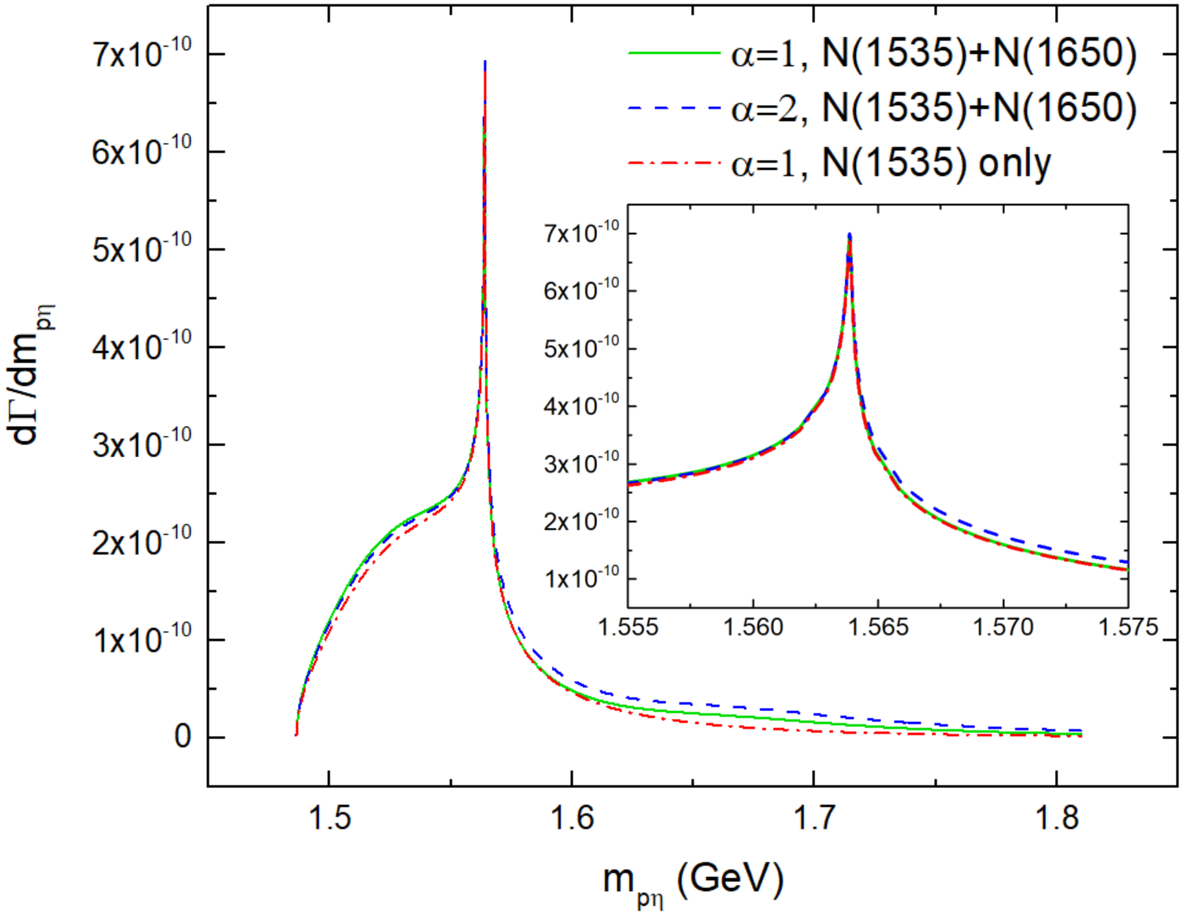
$\mathcal{F}(q, m, \Lambda) = \frac{\Lambda^4}{(q^2-m^2)^2+\Lambda^4}$, $\Lambda = m + \alpha\,\Lambda_{QCD}$.

Purpose:

To check if the narrow peak caused by the triangle loop diagram is visible after mixing it with the tree diagram.

TS in $\psi(2S) \to p\bar{p}\eta$ process

Loop diagram only



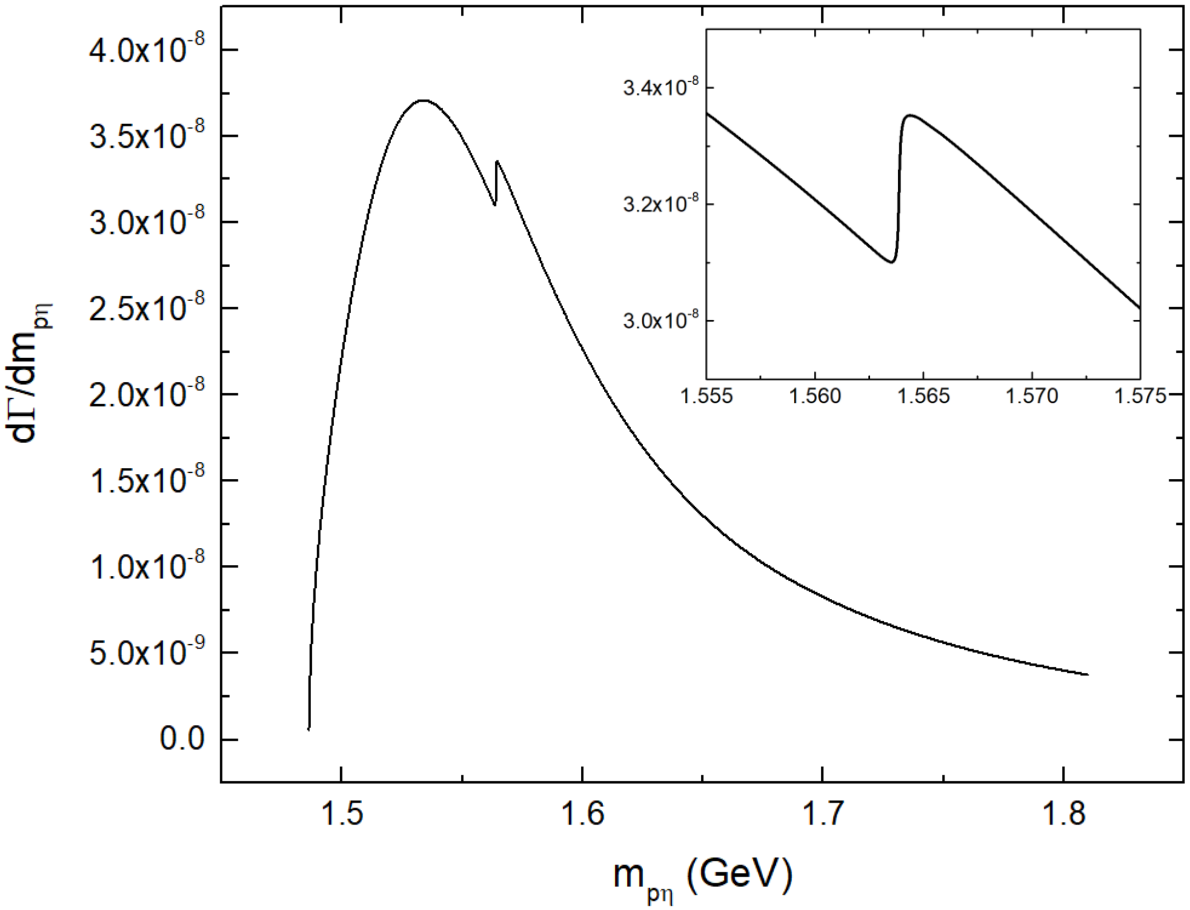
1. The peak caused by the triangle singularity is very sharp, its width is only about 1 MeV.
2. The contribution of N(1650) is negligible.
3. The peak at the triangle singularity is little dependent on the α that appears in the expression of form factor.

Stable!

TS in $\psi(2S) \to p\bar{p}\eta$ process

Interference between tree and loop diagrams

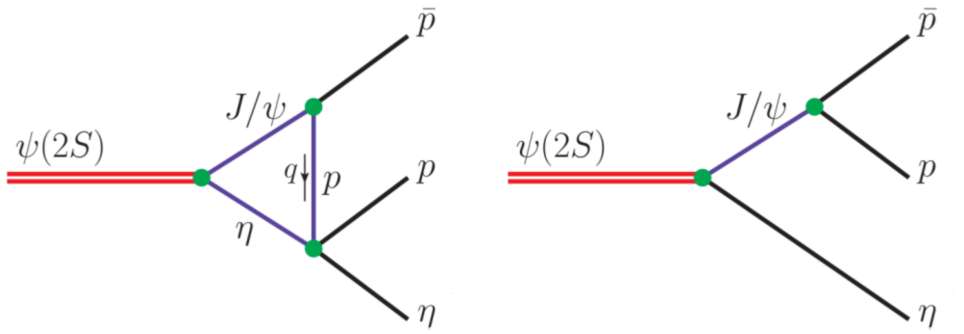
Loop diagram: $\alpha = 1, N(1535) + N(1650)$.



1. There exists a visible enhancement at the right shoulder of N(1535).
2. The width of the peak caused by the triangle singularity is enlarged to 5 MeV.
3. The enhancement of the peak comparing to the tree diagram is about 10%.

TS in $\psi(2S) \to p\bar{p}\eta$ process

Effect of the tree diagram $\psi(2S) \to \eta(J/\psi \to p\bar{p})$



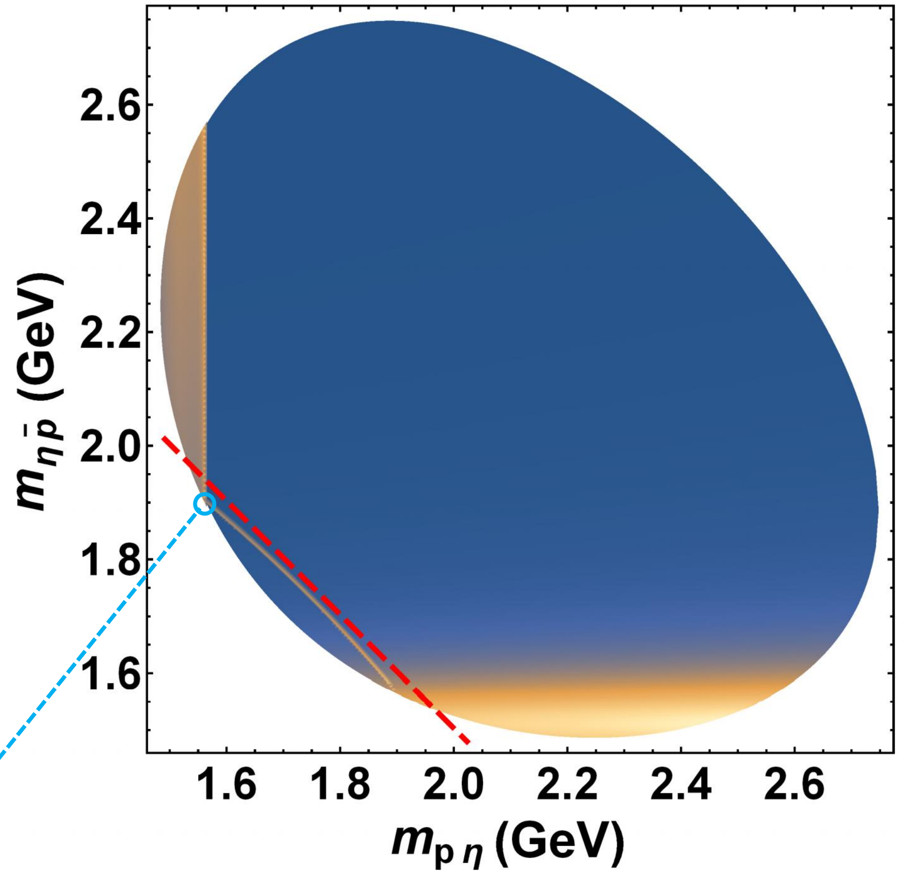
Schmid theorem: $\left|t_{J/\psi}^{Tree} + t_{elastic}^{Loop}\right|^2 = \left|t_{J/\psi}^{Tree} e^{i\delta}\right|^2 = \left|t_{J/\psi}^{Tree}\right|^2$.

Schmid theorem can't be applied directly here:

1. $p\eta \to p\eta$ is not purely elastic process, $p\pi$ channel must couples with it, which is effectively included in the imaginary part of N^* propagator.

2. $\psi(2S) \to \bar{p}(N^* \to p\eta)$ will modify the amplitude to $\left|t_{J/\psi}^{Tree} + t^{Loop} + t_{N^*}^{Tree}\right|^2$, where $t^{Loop} \neq t_{elastic}^{Loop}$.

3. Contribution of $\psi(2S) \to \eta(J/\psi \to p\bar{p})$ can be removed by applying a cut $m_{p\bar{p}} < m_{J/\psi}$.



Red dashed line:

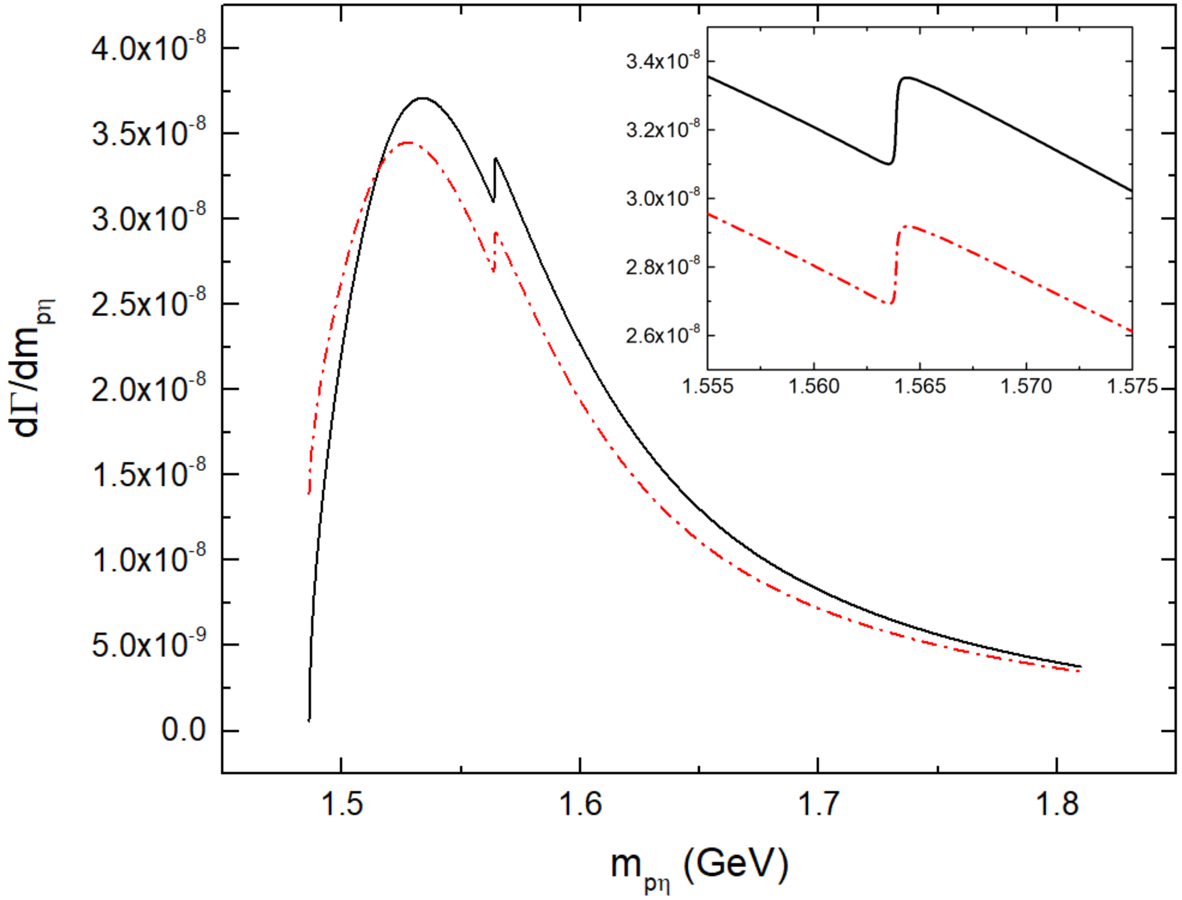
BESIII: PRD 88, 032010,

$m_{p\bar{p}} < 3.067$ GeV.

TS in $\psi(2S) \to p\bar{p}\eta$ process

Interference between tree and loop diagrams

Loop diagram: $\alpha = 1, N(1535) + N(1650)$.



Black solid: No $\psi(2S) \to \eta(J/\psi \to p\bar{p})$, no cut.

Red dashed: $\psi(2S) \to \eta(J/\psi \to p\bar{p})$, $m_{p\bar{p}} < 3.067$ GeV.

1. The contribution of $\psi(2S) \to \eta(J/\psi \to p\bar{p})$ can be neglected after applying the $m_{p\bar{p}}$ cut, thus there will be no effect of Schmid theorem.

2. The line changes little, our previous conclusions on the triangle singularity that appears in the $m_{p\eta}$ of $\psi(2S) \to p\bar{p}\eta$ process are still valid.

TS in $\psi(2S) \to p\bar{p}\eta$ process

Discussion with experimentalists:

1. **High statistics**: 4 billion $\psi(2S) \Rightarrow$ about 120 events.

2. **High resolution**: The resolution of the detector should be less than 2-3 MeV (BESIII: ~4.3 MeV).

An unavoidable weakness:

Phase angle between tree and loop diagrams:

In our calculation, the phase angle is set to 0.

←

Only assumption but as a weak point with no solution:

Enhancement might be invisible at some specific values.

We still hope the future experiments such as STCF could do precise analysis on this process.

Improvement: Selection of internal particles

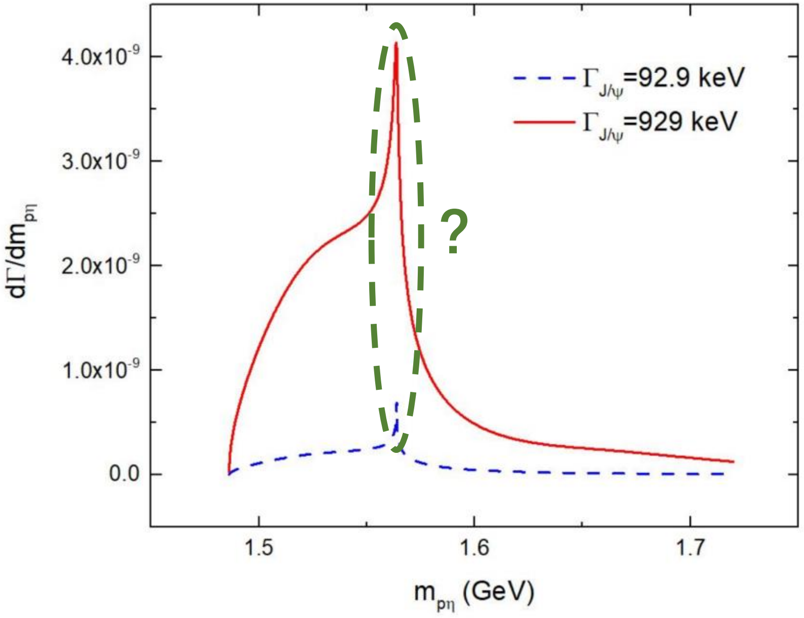
A lesson: Widths of internal particles should not be too narrow !

Or:

1. Peak of TS is too sharp to be detected by experiment. ➡ Requirement of the resolution is too high.

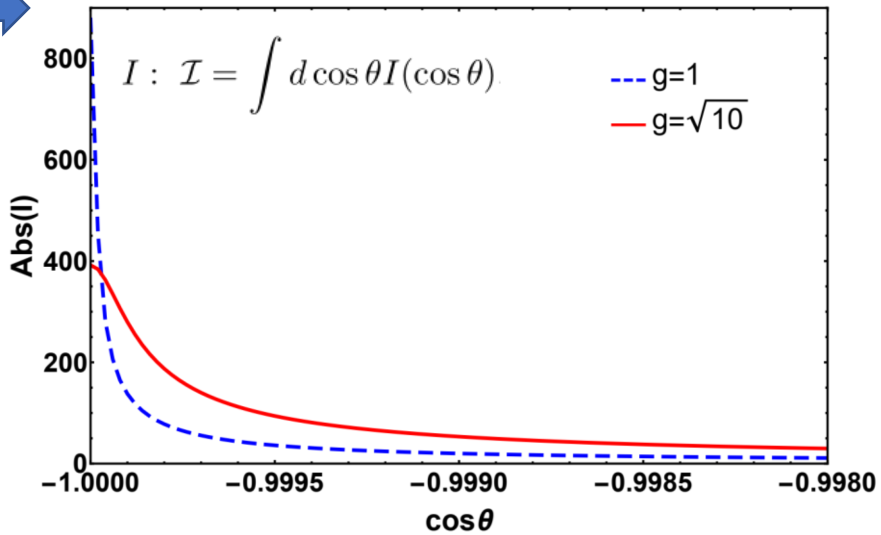
2. The intensity of the peak is weakened.

Fix $B(J/\psi \to p\bar{p})$, change width of J/ψ.



$@m_{TS}$ ➡

$$\mathcal{I} \equiv g\int \frac{d^4q}{(2\pi)^4}\frac{\mathcal{F}(p_3+p_4-q,m_\eta,\Lambda_\eta)}{(p_3+p_4-q)^2-m_\eta^2+im_\eta\Gamma_\eta} \times \frac{\mathcal{F}(p_2+q,m_{J/\psi},\Lambda_{J/\psi})}{(p_2+q)^2-m_{J/\psi}^2+im_{J/\psi}\Gamma_{J/\psi}} \times \frac{\mathcal{F}(q,m_p,\Lambda_p)}{q^2-m_p^2+im_p\Gamma_p},$$



Blue/Red:

$\cos\theta$=-1: $p_{J/\psi}^2 - m_{J/\psi}^2 = 0$

difference of $g/\Gamma_{J/\psi} \sim \sqrt{10}$

$\cos\theta$>-1: $p_{J/\psi}^2 - m_{J/\psi}^2 \neq 0$

difference of g $\sim 1/\sqrt{10}$

$\mathcal{I}$:

Blue: 0.360

Red: 0.514

Balance:

Strength,

Width,

Significance.

Our next step.

Summary

- We predict a detectable pure TS effect in $\psi(2S) \to p\bar{p}\eta$ process.
- A precise calculation on the strength of this TS is done.
- A visible enhancement shows up on the $m_{p\eta}$ invariant mass spectrum.
- We suggest experiments do a precise analysis on $\psi(2S) \to \bar{p}p\eta$ process.

Thank you ~