Establishing the missing $\Sigma^*(\frac{1}{2}^-)$ states by probing the triangle singularity effect in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

HuangQi

NNU

Based on arXiV: 2405.11127 [hep-ph]

Together with Z. X. Ma, J. J. Wu, R. G. Ping, J. He, and H. X. Huang

2024-07-09, Lanzhou

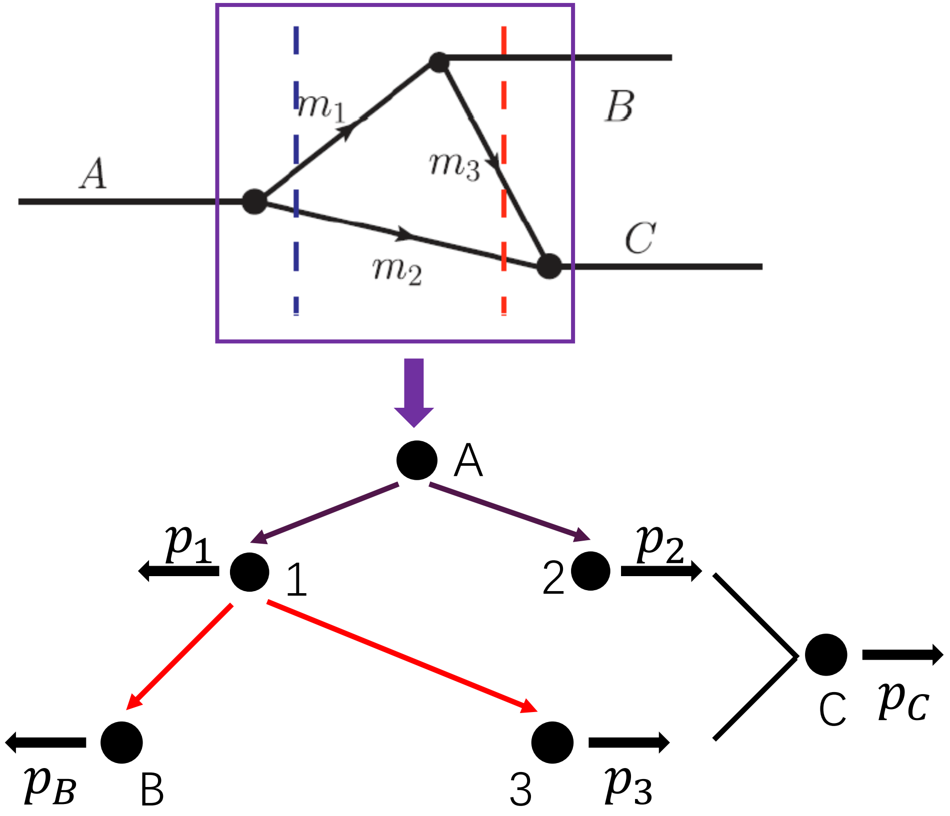
Outline

- Motivation
- Results
- Summary

Motivation

Abundant data, better analysis method ⇒ Precise measurements, BESIII, **STCF**...

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



How the TS happens (Coleman-Norton theorem) :

(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.

Still not confirmed experimentally.

Motivation

1. Threshold

Example:

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

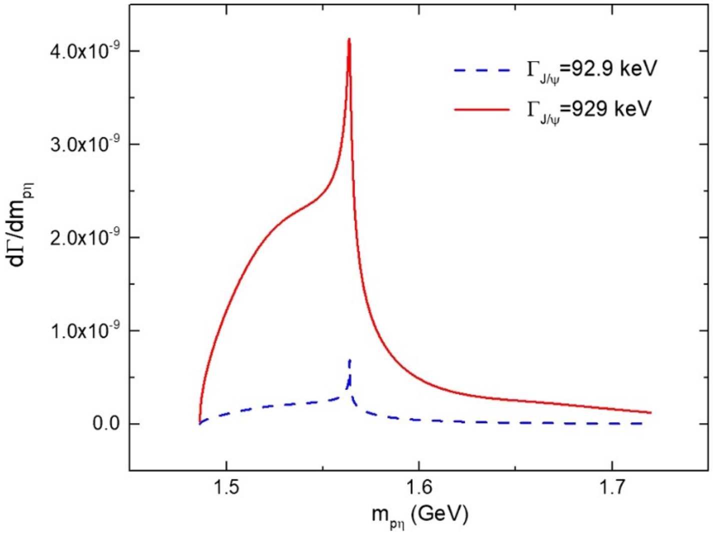
Example:

$\psi(3686) \to p\bar{p}\eta$ via $J/\psi\eta p$ loop

Phys. Rev. D103, 016014 (2021):

Changing width of J/ψ (toy) ⇨

Mixing with resonance ?



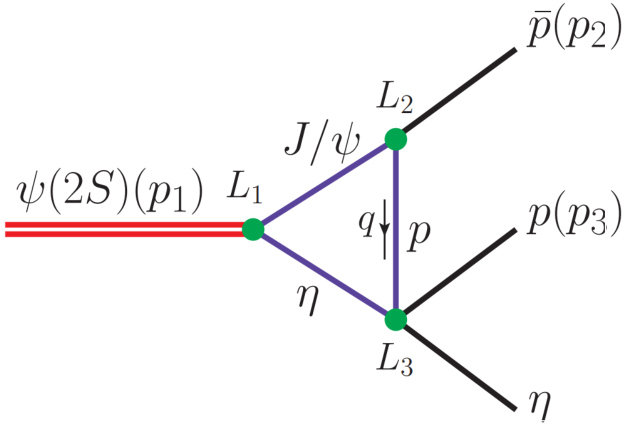
3. Information of interaction vertex

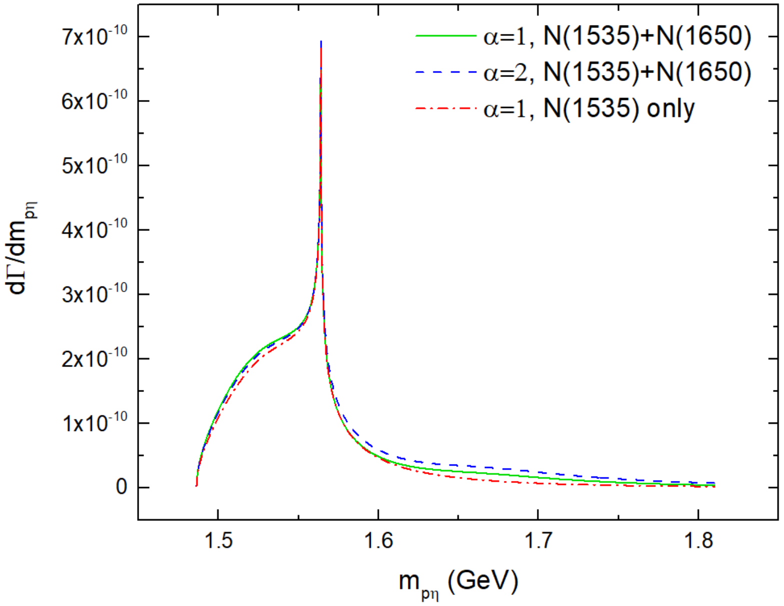
Example:

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

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

Motivation

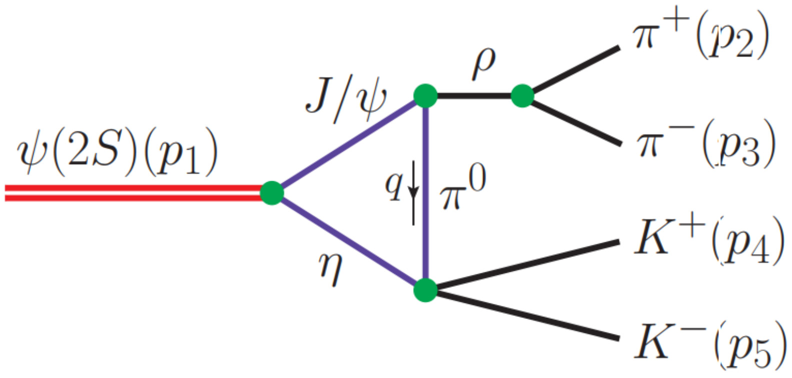


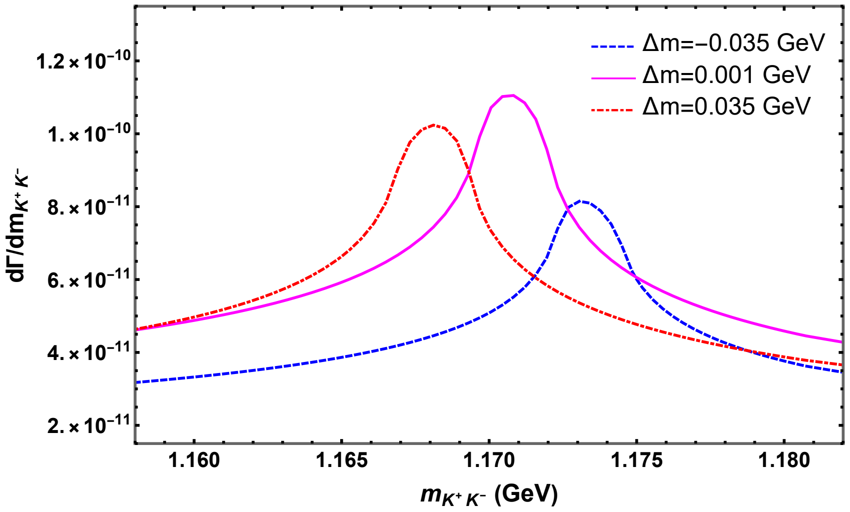


1. 80 MeV from $p\eta$
2. Narrow inner width
3. Known vertices
4. Small width

PRD, 103, 016014

m_{TS} @ $m_{p\eta}$: 1.564 GeV





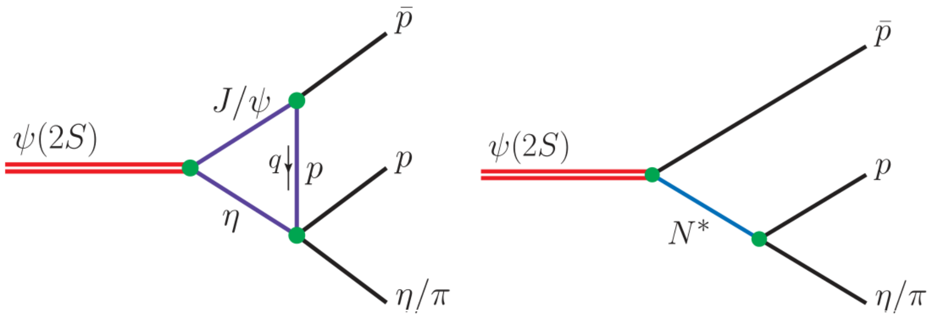
1. Moving effect
2. Larger width
3. Distribution of ρ

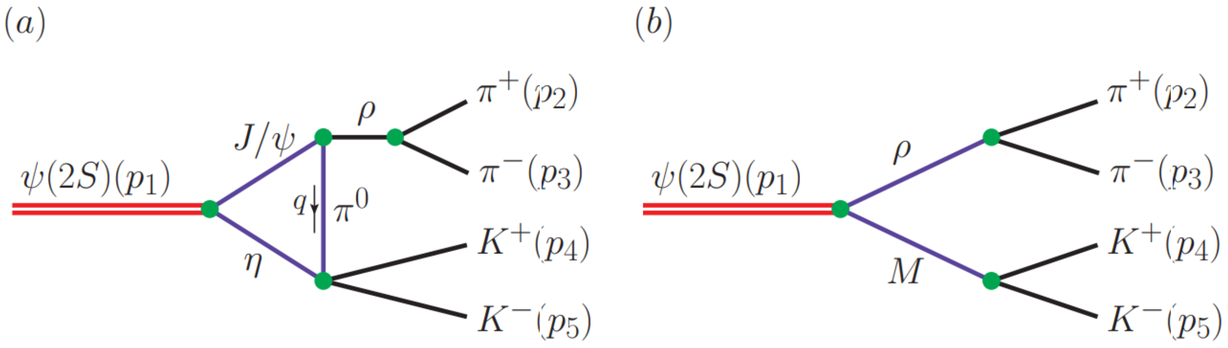
PRD, 104, 116003

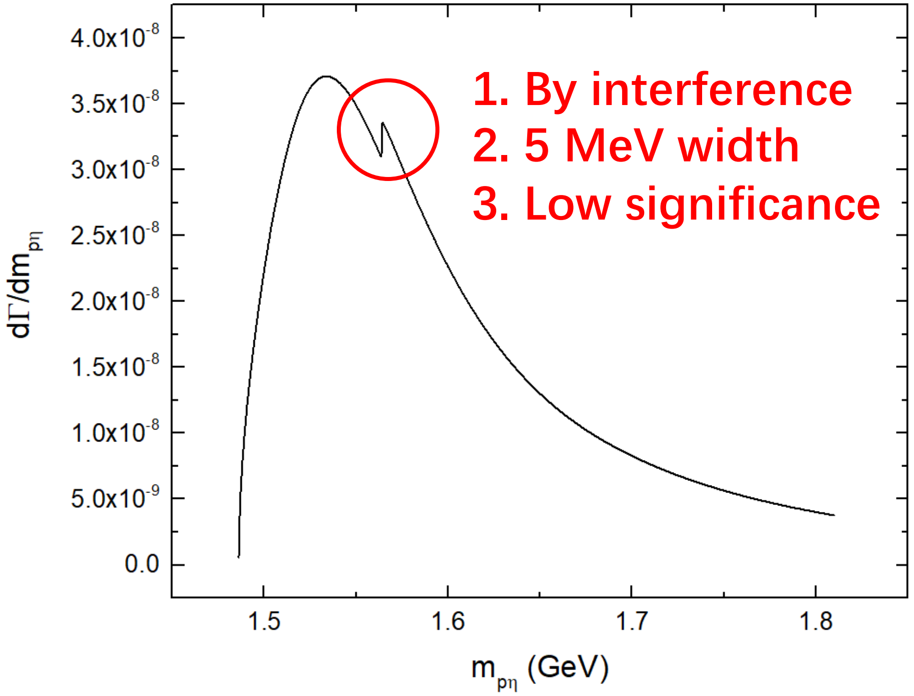
m_{TS} @ $m_{K\bar{K}}$: $\in$ [1.16,1.18] GeV

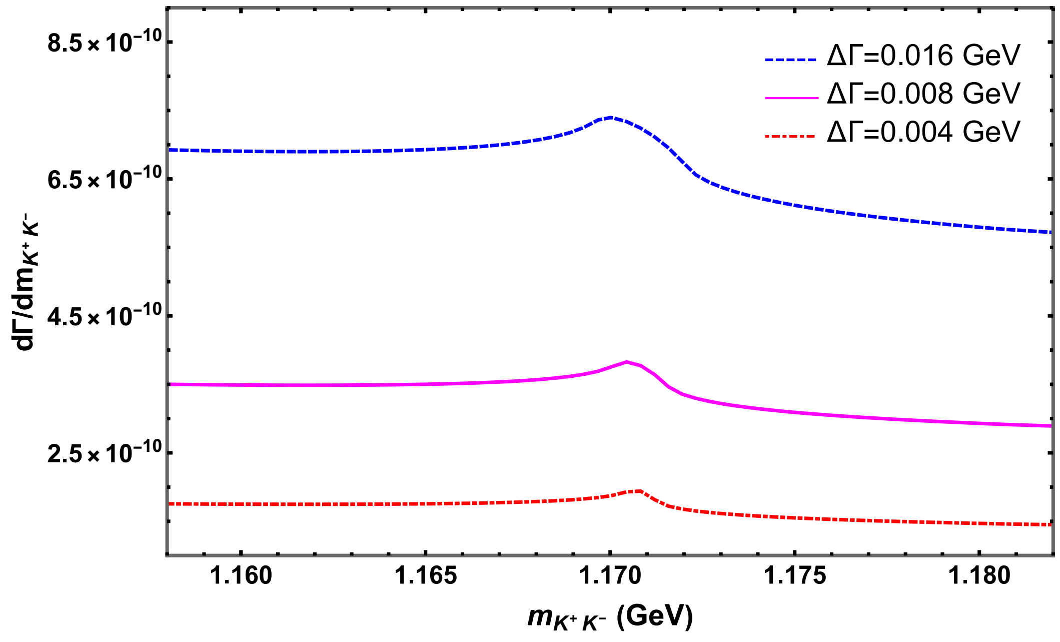
Motivation

Weakness: Background ⇒ phase angle, incomplete estimation





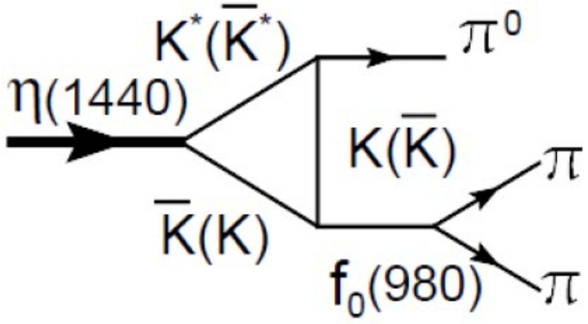


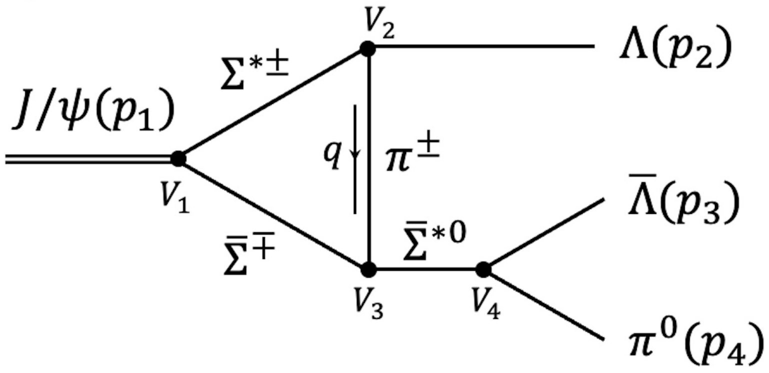


Motivation

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

J. J. Wu, et. al, PRL, 108, 081803



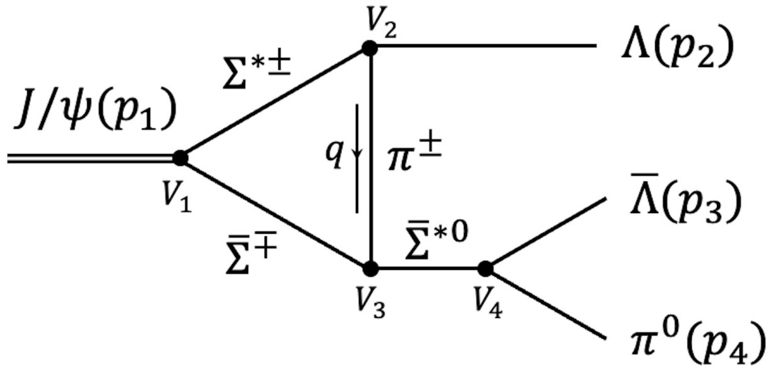


1. **Triangle singularity and isospin breaking happen simultaneously**
   (1). Different masses for $\Sigma^{(*)}$ with different charges ⇒ loop diagrams will not cancel to each other.
   (2). Triangle singularities with different positions happen ⇒ cause a distribution in $\Lambda\pi$ spectrum after cancellation.

2. **Suppression of the background due to isospin breaking**
   $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process is suppressed under tree level.
   ⇒ (1). Interference is unnecessary, phase angle problem solved
   (2). More significant triangle singularity effect.

3. **Large amount of J/ψ events in BESIII and future STCF**
   more than 10^9 J/ψ already, 100 times larger luminosity of STCF
   ⇒ High statistics, good platform to perform precise measurements on the J/ψ physics.

TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process



V_3: $\Sigma^0\Sigma^{*0}\pi^0, \langle 1,0;1,0|1,0\rangle = 0$
⇒ no neutral loop contribution

Small intermediate width, have TS
⇒ $\Sigma^{*\pm}$ in V_1:

1. $\Sigma(1670)$: $\frac{3}{2}^-$, ≈ 55 MeV, ****
2. $\Sigma(1620)$: $\frac{1}{2}^-$, ≈ 70 MeV, *

1. TS position:

$\Sigma(1670)^+\bar{\Sigma}^-\pi^+$: 1.409 GeV
$\Sigma(1670)^-\bar{\Sigma}^+\pi^-$: 1.401 GeV

$\Sigma(1620)^+\bar{\Sigma}^-\pi^+$: 1.403 GeV
$\Sigma(1620)^-\bar{\Sigma}^+\pi^-$: 1.395 GeV

⇒ To enhance TS, need $\Sigma^{*0}\sim 1.4$ GeV
⇒ $\Sigma(1385)$: $\frac{3}{2}^+$, ****

2. Low momentum process:
⇒ Amplitude of V_3 and V_4: $\sim k^l$
⇒ Ideal: interaction with l asap, $\Sigma\left(\frac{1}{2}^-\right)\sim 1.4$ GeV
⇒ Significant effect

TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

Surprise: From Prof. En Wang, 2024.04, ChengDu

Low-lying baryons with $J^P=1/2^-$

$1/2^-$ baryon nonet with strangeness

Zou, EPJA 35 (2008) 325

- Mass pattern : quenched or unquenched ?

  uds (L=1) $1/2^-$ ~ $\Lambda^*(1670)$ ~ $[us][ds]\bar{s}$

  uud (L=1) $1/2^-$ ~ $N^*(1535)$ ~ $[ud][us]\bar{s}$

  uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ $[ud][su]\bar{u}$

  uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\bar{d}$

  Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206

- Strange decays of $N^*(1535)$ and $\Lambda^*(1670)$:

  $N^*(1535)$ large couplings $g_{N^*N\eta}$, $g_{N^*K\Lambda}$, $g_{N^*N\eta'}$, $g_{N^*N\phi}$

  $\Lambda^*(1670)$ large coupling $g_{\Lambda^*\Lambda\eta}$

邹冰松老师报告

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022)

$\Sigma(1620)$ $1/2^-$ $I(J^P) = 1(\frac{1}{2}^-)$ Status: $*$

OMITTED FROM SUMMARY TABLE

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 updat

$\Sigma(1480)$ Bumps $I(J^P) = 1(?^?)$ Status: $*$

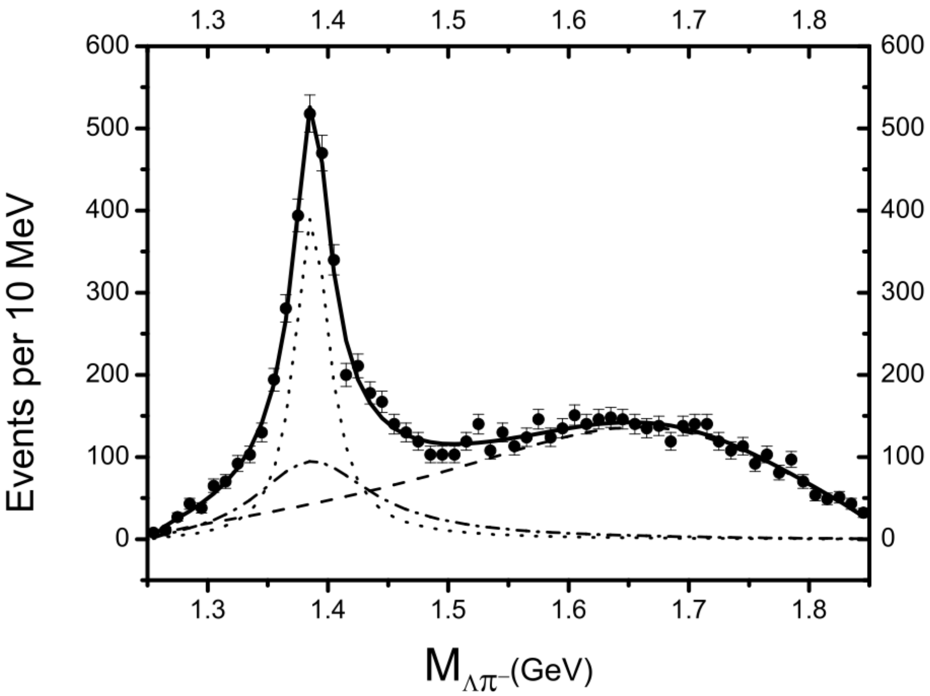
OMITTED FROM SUMMARY TABLE

These are peaks seen in $\Lambda\pi$ and $\Sigma\pi$ spectra in the reaction $\pi^+ p \to (Y\pi)K^+$ at 1.7 GeV/c. Also, the Y polarization oscillates in the same region.

TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

Previous: J. J. Wu, et.al., PRD 80, 017503

$K^- p \to \Lambda\pi^+\pi^-$

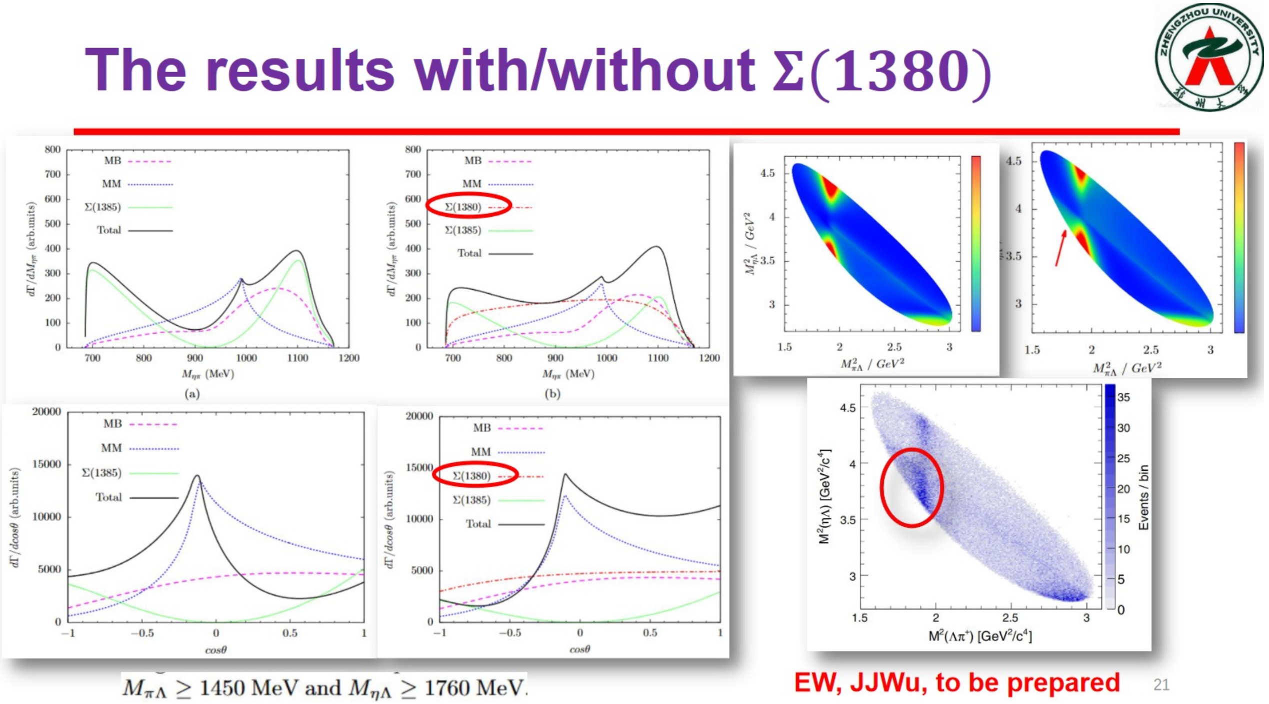


$\Sigma(1381)$: $M = 1381.3\ \mathrm{GeV}, \Gamma = 118.6\ \mathrm{GeV}$

$\Rightarrow \chi^2/d.o.f: 10.1/9 \to 3.2/9$

Recent: E. Wang, et.al., arXiV: 2405.09226

$\Lambda_c^+ \to \eta\pi^+\Lambda$: **From Prof. En Wang, ChengDu**



A lot of other works

Review: E. Wang, et.al., arXiV: 2406.07839

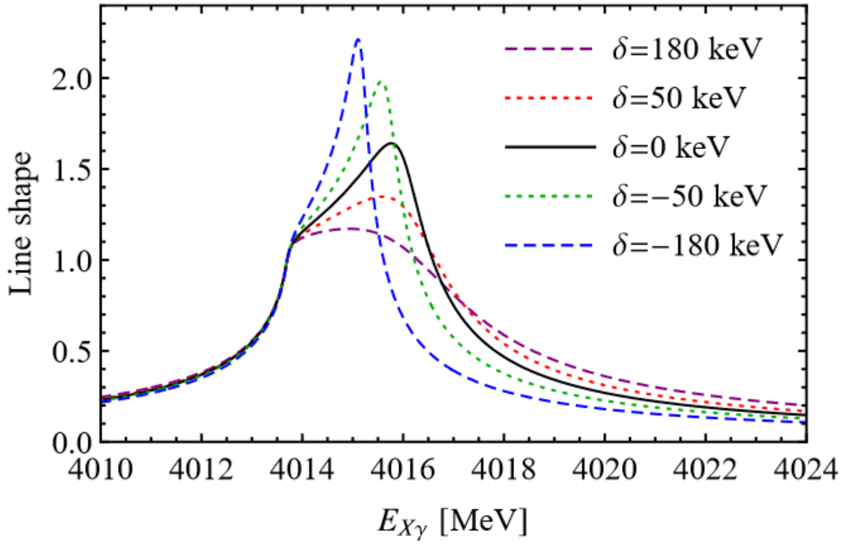
TS in $J/\psi \rightarrow \Lambda\bar{\Lambda}\pi^0$ process

$$\left.\begin{array}{c} S-\text{wave interaction is needed} \\ \Sigma^*\left(\frac{1}{2}^-\right) \text{ around 1.4 GeV is needed} \\ \Sigma(1381) \text{ has been predicted} \\ \Sigma(1620) \text{ is still on one star status} \end{array}\right\} \Rightarrow \text{New extra motivation: use TS to establish } \Sigma^*\left(\frac{1}{2}^-\right) \text{ states}$$

Meaning:

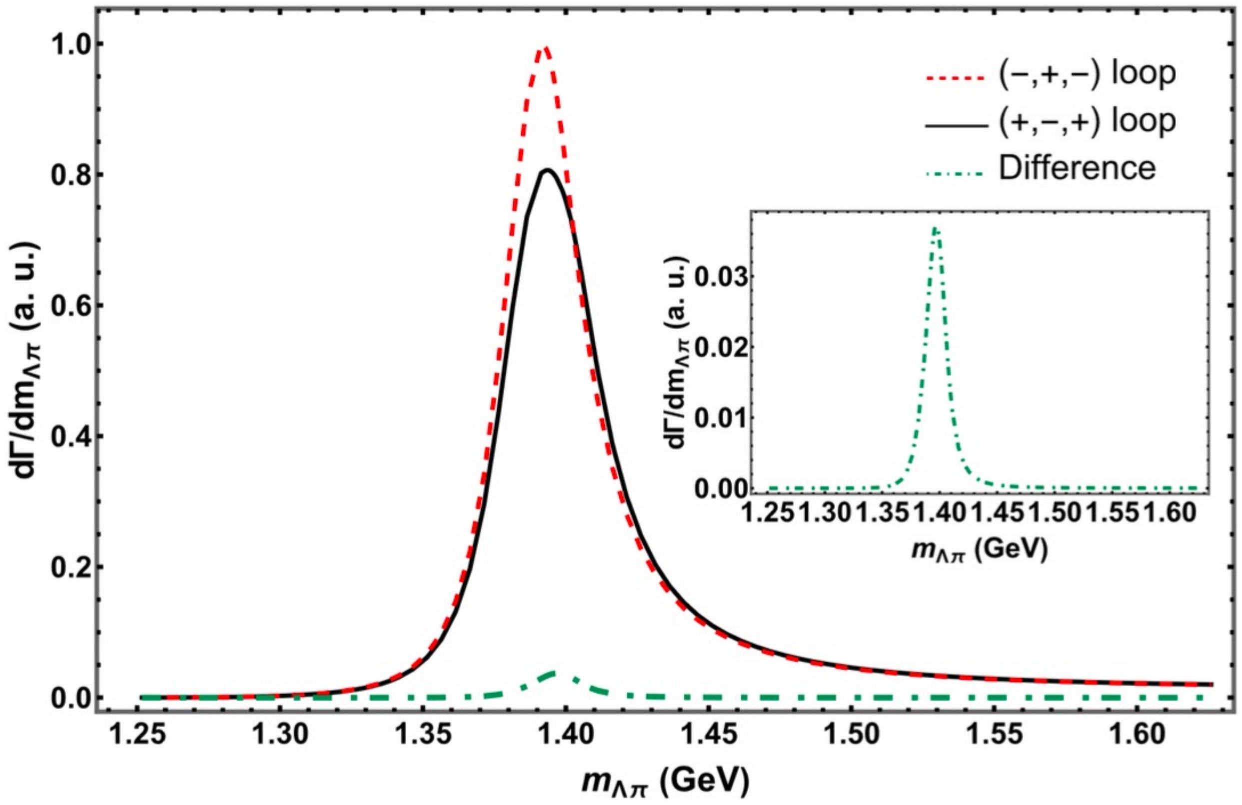
1. **Understand triangle singularity itself.**
2. **Confirm hadron loop mechanism.**
3. **Help studying properties of hadrons.**

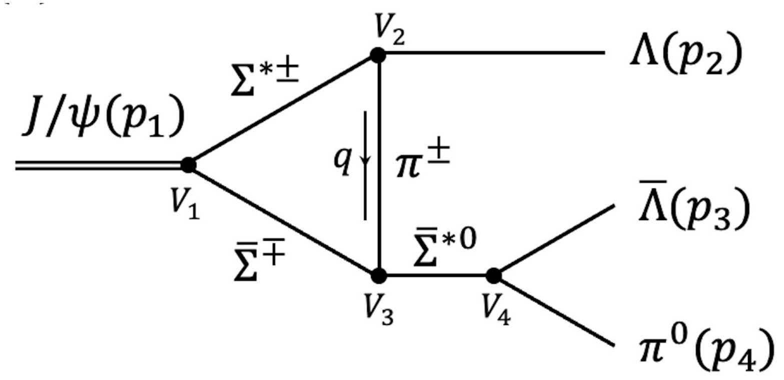
X(3872): F. K. Guo, PRL 122,202002 (2019).



TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

Loop diagram contribution





$\Sigma(1670)^{\pm}\bar{\Sigma}^{\mp}\pi^{\pm}$ loop with $\bar{\Sigma}^{*0} = \Sigma(1381)$

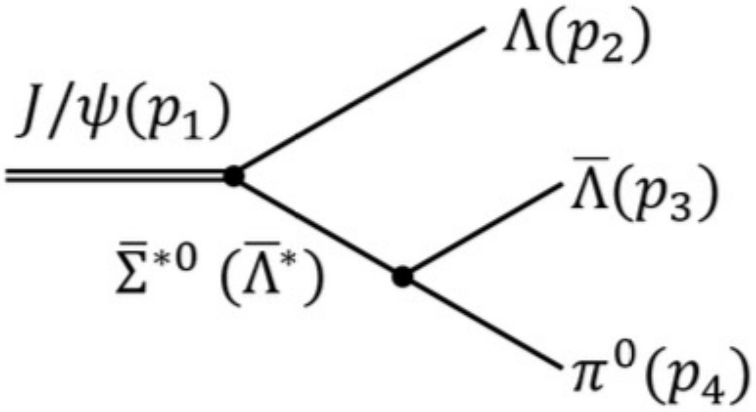
1. Contributions of different charge configurations are different
2. **A resonance-like structure around 1.4 GeV with 20 MeV width appears**

TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

Resonance-like structure around 1.4 GeV 😱

This world contains not only strong interactions

$\Rightarrow$ Background $\Rightarrow$ Need a comparison between TS and background



$\bar{\Sigma}^{*0}$: first vertex is isospin breaking
$\bar{\Lambda}^*$: second vertex is isospin breaking

Generally:
Strong : Electromagnetic : Weak $\sim 1 : 10^{-2} : 10^{-7}$
$\Rightarrow$ Electromagnetical interaction is preferred

PDG:
$Br(J/\psi \to \Sigma(1385)\bar{\Sigma}) = (3.1 \pm 0.5)\times 10^{-4}$
$Br(J/\psi \to \Sigma(1385)\bar{\Lambda}) < 4.1\times 10^{-6}$

TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

Σ^{*0} in the diagram can also be $\Sigma(1385)$
$\Sigma^{*\pm}$ in the diagram can also be $\Sigma(1620)$
$\Rightarrow$ All the combinations are studied

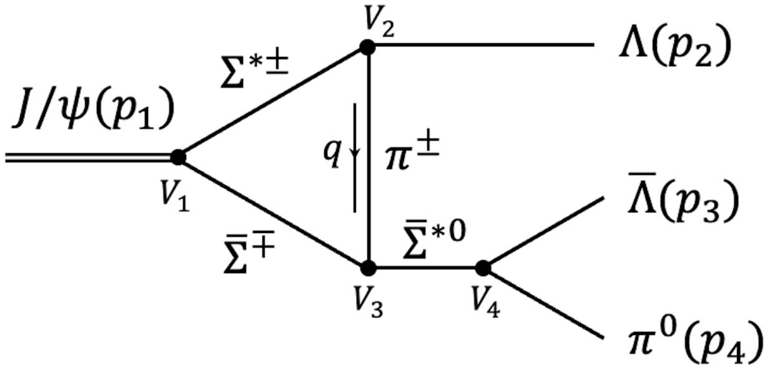


TABLE I: The coupling constants extracted from RPP [57].

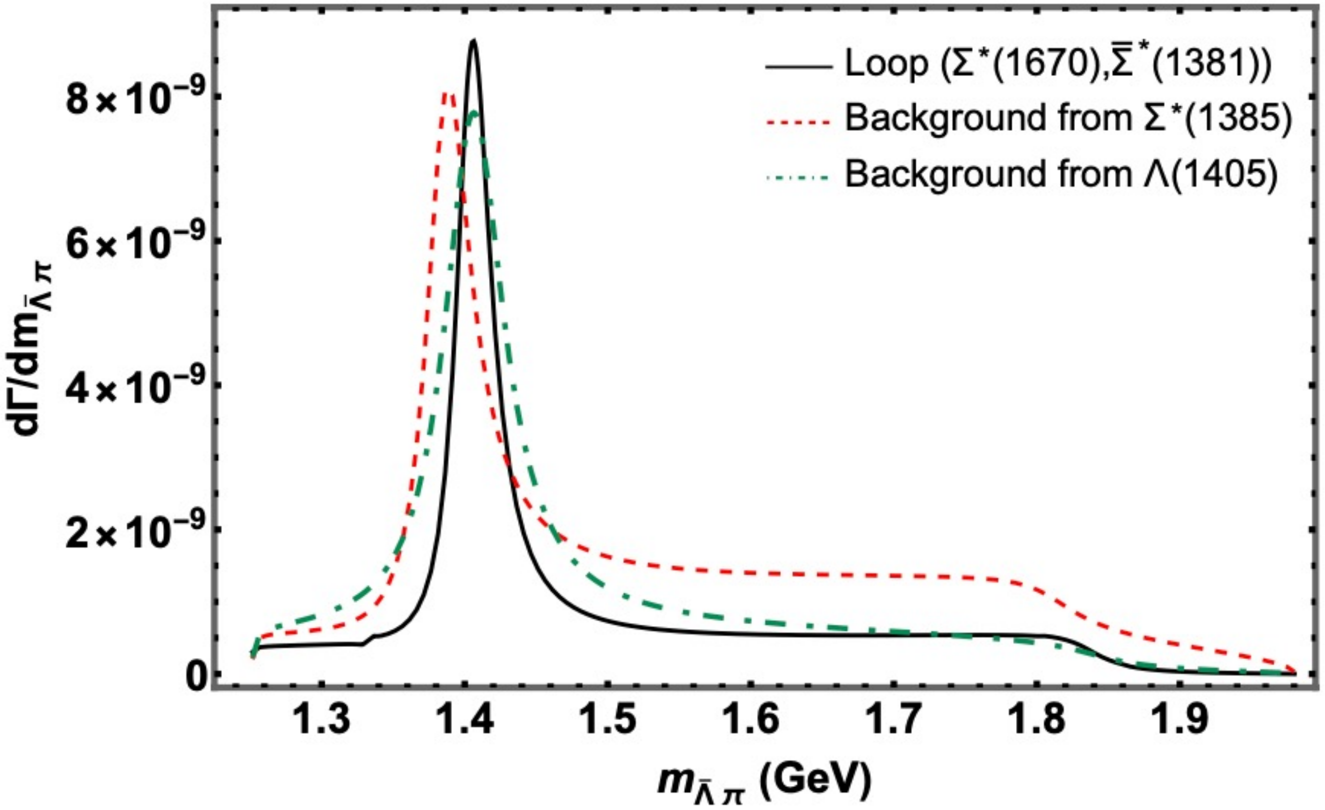
Couplings	Branching Ratio	Value
$g_{J/\psi\Sigma(1385)\Sigma}$	$(3.1 \pm 0.5) \times 10^{-4}$	$(2.7 \pm 0.2) \times 10^{-4}$ GeV^{-1}
$g_{J/\psi\Sigma(1385)\Lambda}$	$< 4.1 \times 10^{-6}$	$< 3.101 \times 10^{-5}$ GeV^{-1}
$g_{\Sigma(1385)\Lambda\pi}$	$(87.0 \pm 1.5)\%$	9.034 ± 0.081 GeV^{-1}
$g_{\Sigma(1385)\Sigma\pi}$	$(11.7 \pm 1.5)\%$	6.830 ± 0.432 GeV^{-1}
$g_{\Sigma(1620)\Lambda\pi}$	$(9.0 \pm 3.0)\%$	0.273 ± 0.045
$g_{\Sigma(1620)\Sigma\pi}$	$(17 \pm 5)\%$	0.392 ± 0.052
$g_{\Sigma(1670)\Lambda\pi}$	$(10 \pm 5)\%$	3.713 ± 0.765 GeV^{-2}
$g_{\Sigma(1670)\Sigma\pi}$	$(45 \pm 15)\%$	10.299 ± 1.600 GeV^{-2}
$g_{\Lambda(1405)\Sigma\pi}$	$\sim 100\%$	~ 1.569
$g_{J/\psi\Lambda(1405)\Lambda}$	$(8.3 \pm 0.7) \times 10^{-4}$	$(1.335 \pm 0.021) \times 10^{-3}$

TABLE II: The estimated coupling constants calculated by the estimated branching ratios.

Coupling constant	Branching Ratio	Value
$g_{\Lambda(1405)\Lambda\pi}$	$\sim 1\%$	~ 0.131
$g_{J/\psi\Sigma(1670)\Sigma}$	$\sim 6.2 \times 10^{-5}$	$\sim 7.129 \times 10^{-3}$
$g_{J/\psi\Sigma(1620)\Sigma}$	$\sim 6.2 \times 10^{-5}$	$\sim 1.475 \times 10^{-3}$
$g_{\Sigma(1381)\Lambda\pi}$	$\sim 85\%$	~ 2.585
$g_{\Sigma(1381)\Sigma\pi}$	$\sim 15\%$	~ 0.815

TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

$\Sigma(1670)\bar{\Sigma}\pi$ loop with $\Sigma(1381)$



1. TS contribution is just located at $\Lambda(1405)$
2. TS and $\Sigma(1385)$ may be well separated
3. Branching ratios:

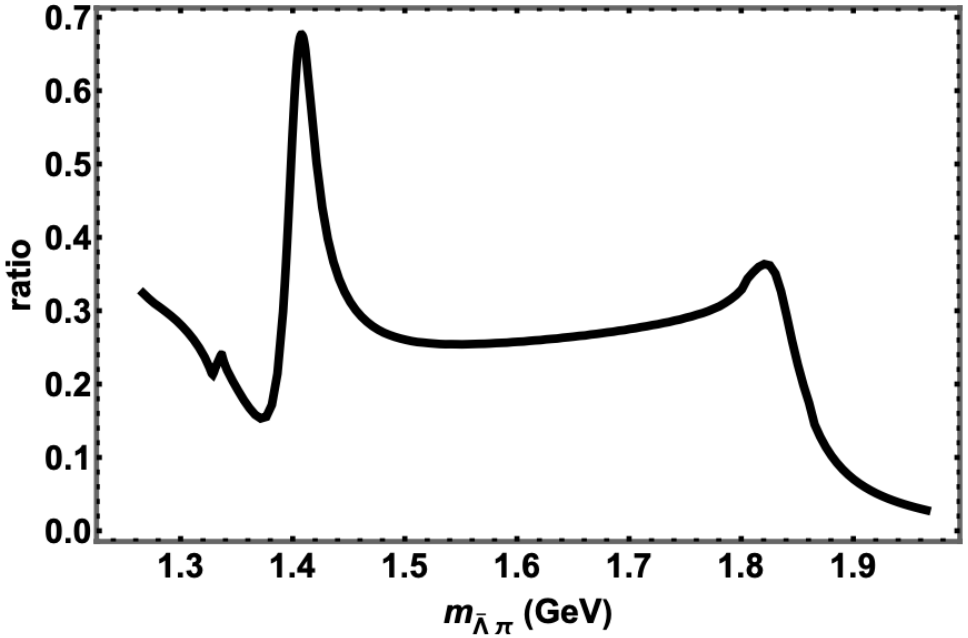
$$\begin{cases} \Sigma(1381): 1.18\times10^{-5} \\ \Lambda(1405): 9.27\times10^{-6} \\ \text{TS}: 6.76\times10^{-6} \end{cases}$$ ⇐ Narrow, still smallest

Distinguish: Spin observables,
K. Wang, et.al, PRD, 106, 094032
Our next step

TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

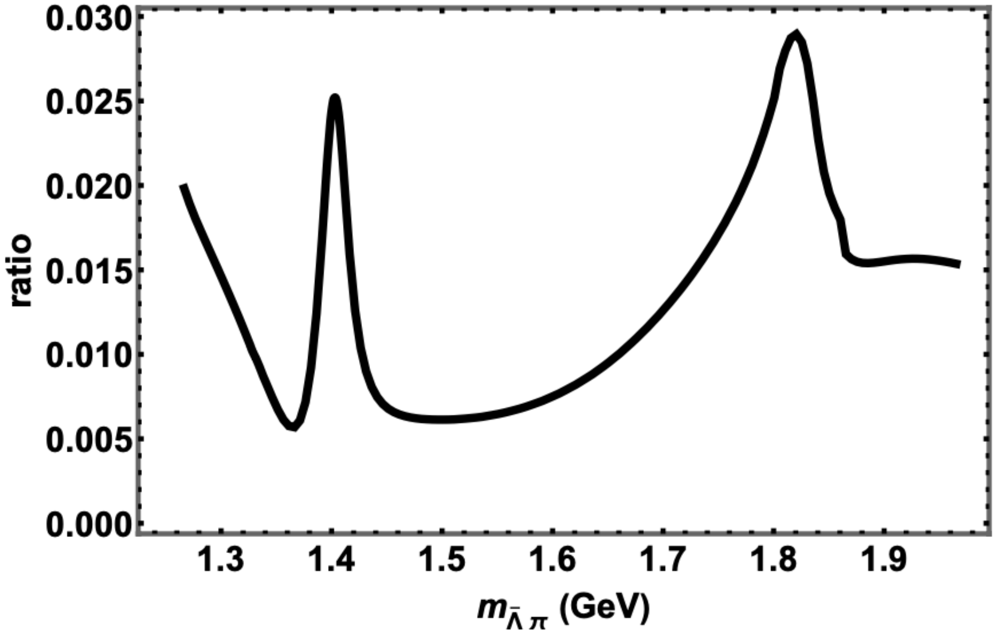
Other combinations: $ratio(m_{\Lambda\pi}) \equiv \dfrac{(d\Gamma/dm_{\Lambda\pi})_{TS}}{(d\Gamma/dm_{\Lambda\pi})_{background}}$, **no phase angle**

$\Sigma(1670)\bar{\Sigma}\pi$ loop with $\Sigma(1381)$



$V_1, V_2, V_3, V_4 = P, D, S, S$

$\Sigma(1670)\bar{\Sigma}\pi$ loop with $\Sigma(1385)$

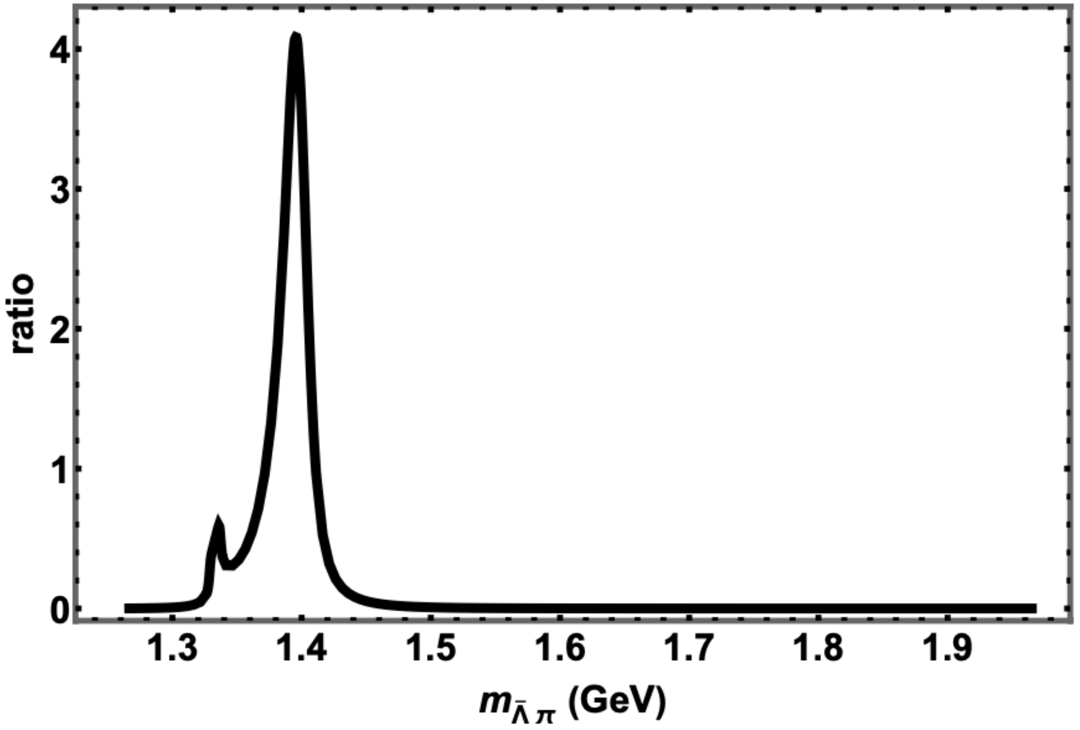


$V_1, V_2, V_3, V_4 = P, D, P, P$

TS will be suppressed by higher partial wave

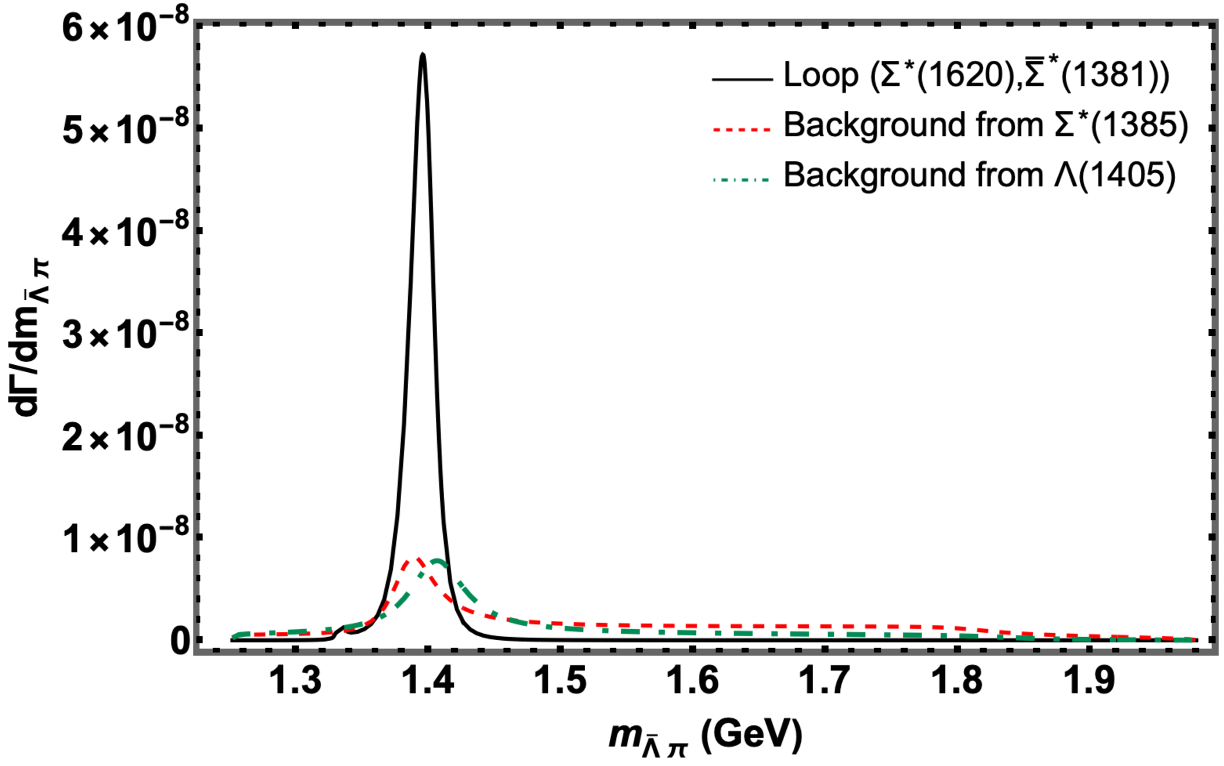
TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

$\Sigma(1620)\bar{\Sigma}\pi$ loop with $\Sigma(1381)$



$V_1, V_2, V_3, V_4 = P, S, S, S$

TS contribution is dominant



Maybe all the existences of TS, $\Sigma(1381)$, and $\Sigma(1620)$ can be ensured.

TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

Example: STCF, from Prof. H. P. Peng

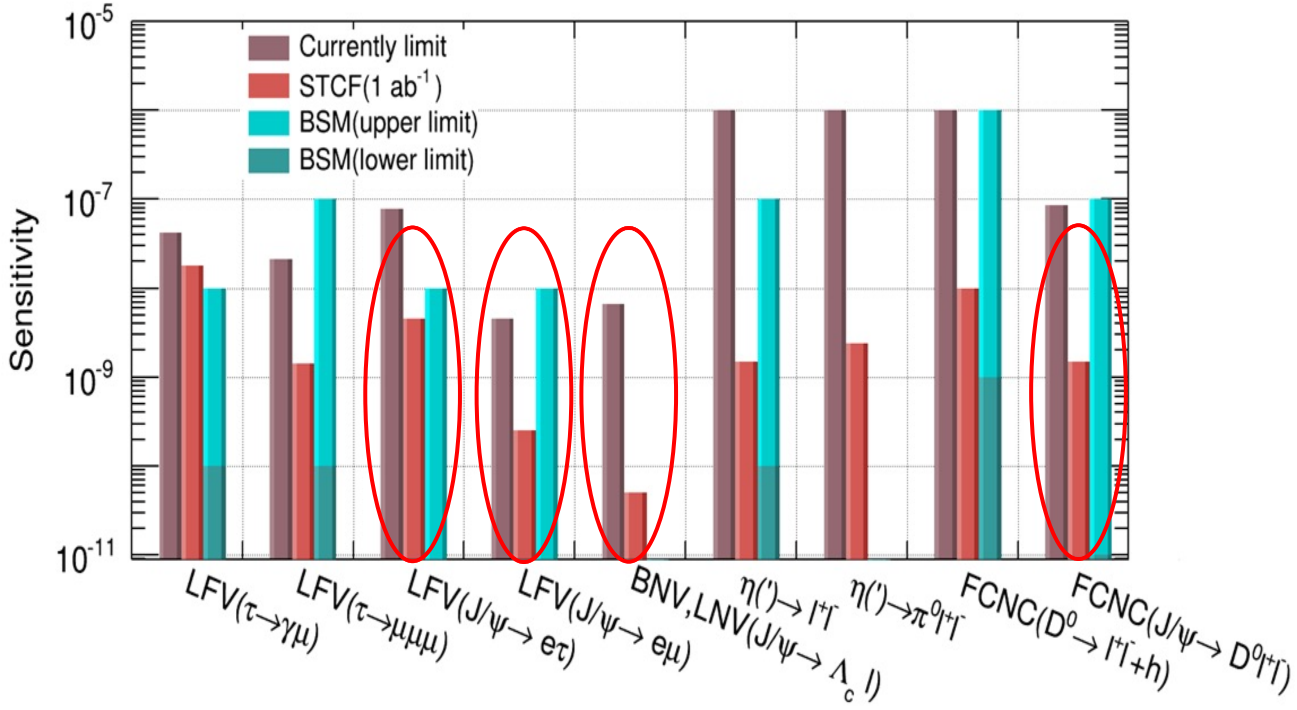
High Statistical Data : > 1 ab^{-1}/year

CME (GeV)	Lumi (ab^{-1})	samples	σ(nb)	No. of Events	remark
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	
		$\tau^+\tau^-$	2.5	2.5×10^{9}	
		$\ldots^+\tau^-$		2.0×10^{9}	
3.770	1		3.6	3.6×10^{9}	
			2.8	2.8×10^{9}	
				7.9×10^{8}	Single Tag
		$D^+\bar{D}^-$		5.5×10^{8}	Single Tag
		$\tau^+\tau^-$	2.9	2.9×10^{9}	
4.009		$D^{*0}\bar{D}^0 + c.c$	4.0	1.4×10^{9}	$CP_{D^0\bar{D}^0} = +$
		$D^{*0}\bar{D}^0 + c.c$	4.0	2.6×10^{9}	$CP_{D^0\bar{D}^0} = -$
			0.20	2.0×10^{8}	
			3.5	3.5×10^{9}	
4.180	1	…c.	0.90	9.0×10^{8}	
		$D_s \ldots D_s$ +c.c.		1.3×10^{8}	Single Tag
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^{7}	
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^{7}	
			3.5	3.5×10^{9}	
4.420		…$\pi^+\pi^-$	0.040	4.0×10^{7}	
			3.5	3.5×10^{9}	
4.630	1	…$\pi^+\pi^-$	0.033	3.3×10^{7}	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^{8}	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^{7}	Single Tag
		$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0-7.0	3	300 points scan with 10 MeV step, 1 fb^{-1}/point			
> 5	2-7	several ab^{-1} high energy data, details dependent on scan results			

J/ψ 10^{12}

D pair 10^9

$\tau^+\tau^-$ 10^9

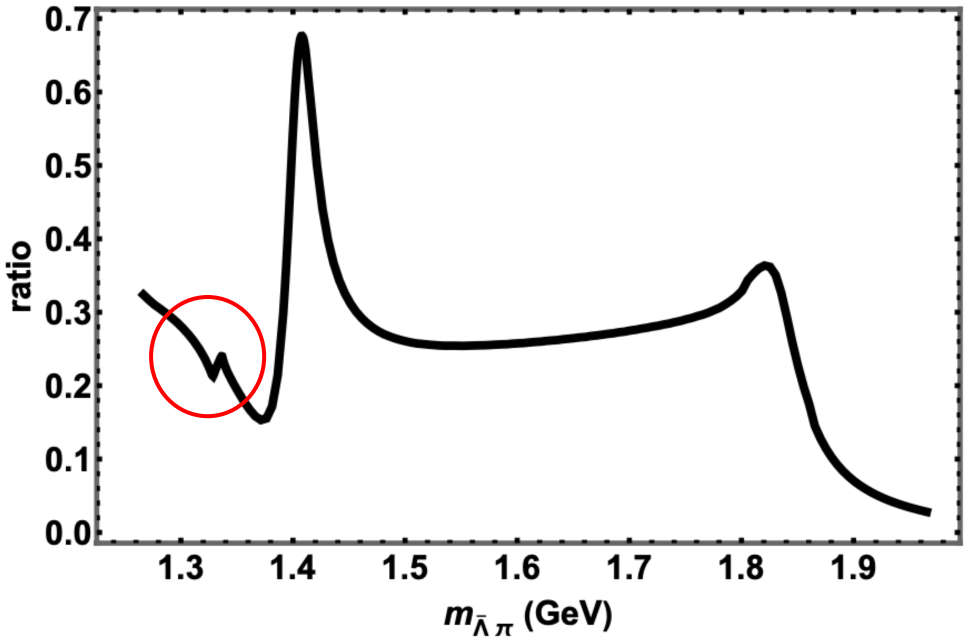


Maybe the sensitivity of J/ψ physics is $\sim10^{-8}$? 🤔

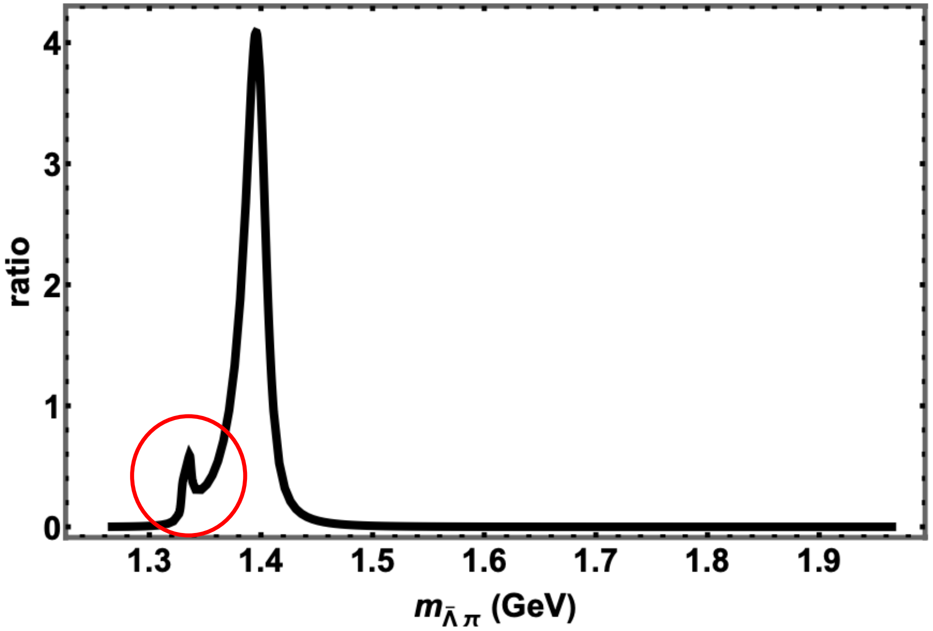
TS in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process

$10^{12} J/\psi, 10^{-8}$ sensitivity ?

$\Sigma(1670)\bar{\Sigma}\pi$ loop with $\Sigma(1381)$



$\Sigma(1620)\bar{\Sigma}\pi$ loop with $\Sigma(1381)$



Detection:

1. Polarization
2. CUSP ? 🤔

$$\text{Events: } \begin{cases} \Sigma(1670)\bar{\Sigma}\pi \text{ loop with } \Sigma(1381), \text{Br(TS/CUSP)}: 3.783\times10^{-6}/1.009\times10^{-7} \\ \Sigma(1620)\bar{\Sigma}\pi \text{ loop with } \Sigma(1381), \text{Br(TS/CUSP)}: 2.978\times10^{-6}/4.025\times10^{-9} \Rightarrow > 10^5/4000 \text{ events?} \\ \Sigma(1670)\bar{\Sigma}\pi \text{ loop with } \Sigma(1385), \text{Br(TS/CUSP)}: 1.345\times10^{-7}/1.855\times10^{-7} \end{cases}$$

Summary

- We predict a detectable pure TS effect in $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ process.
- Background and phase angle problem are solved here
- Our TS may be a probe used to search $\Sigma(1381)$ and $\Sigma(1620)$
- Further spin observables analysis will be done due to $\Lambda(1405)$
- A precise analysis on $J/\psi \to \Lambda\bar{\Lambda}\pi^0$ is suggested, especially in future STCF

Thank you ~