The Curious Case of the $a_1(1420)$

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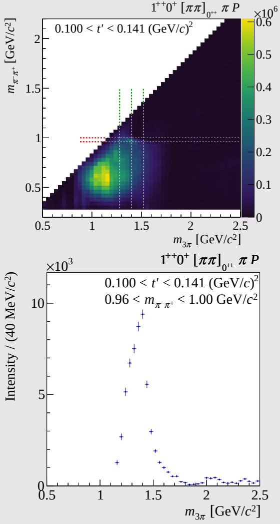
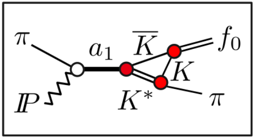


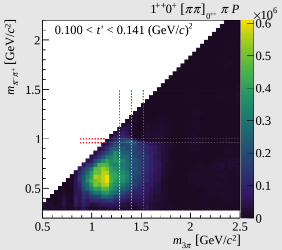
[COMPASS, 2017]

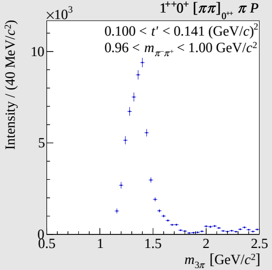
- Enhancement around 1.4 GeV in the $f_0(980)\pi$ final state corresponding to a_1 quantum numbers [COMPASS, 2015].
- Triangle singularity: $K^*(892)$, $\bar{K}$ rescattering through a K exchange [Mikhasenko et al., 2015].



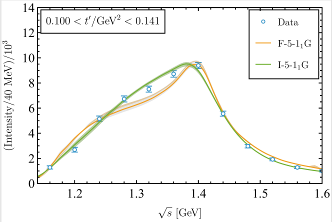
[COMPASS, 2021]

- Produces a logarithmic branch point that resembles a resonance [Review by Guo et al., 2020].



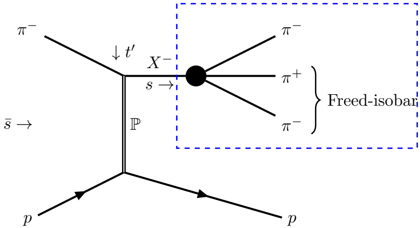


[COMPASS, 2017]

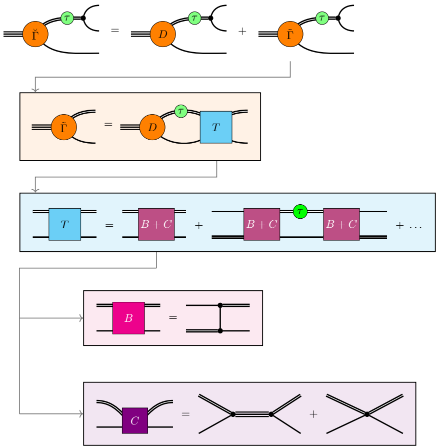


The Infinite Volume Unitarity Framework

- A fully unitary method to study three-body processes [Mai et al., 2017]. See also talks by Maxim Mai and Michael Döring from yesterday.
- Previous applications: the $a_1(1260)$ pole position and lineshape [Sadasivan et al., 2021, 2022].
- Application to the $a_1(1420)$:



- Mesonic system but the framework is universal. Future applications to nucleonic systems, e.g., the Roper resonance and $N\pi\pi$, see also Jinzi Wu's talk from yesterday.



The Main Ingredients:

- $\check{\Gamma}$: Total amplitude for a $1 \to 3$ process—connected and disconnected amplitudes.
- D: Dissociation vertex.
- $\tilde{\Gamma}$: The connected part of the amplitude.
- T: The Lippmann-Schwinger-like equation.
- B: The long-range interaction constrained by unitarity.
- C: The short-range interaction—contact term and poles.
- τ: The two-body component constrained by unitarity.

The Main Ingredients:

- *B*-term:

Isospin factor

Vertices:

$(p-q)^\mu \, \epsilon_\mu(\boldsymbol{p}+\boldsymbol{q},\lambda)$, for $\ell=1$ isobars,

1, for $\ell=0$ isobars.

$$B_{ji}(s,p',p) = \frac{(\boldsymbol{I}_F)_{ji}\, v_j^*(p, P_3-p-p')v_i(p', P_3-p-p')}{2E_{p'+p}(\sqrt{s}-E_p-E_{p'}-E_{p'+p})+i\epsilon}$$

$E_{p'+p}$: exchange spectator energy

$E_p, E_{p'}$: incoming/outgoing spectator energy

$\sqrt{s}$: total three-body invariant mass

The Main Ingredients:

- C-term:

fit parameters

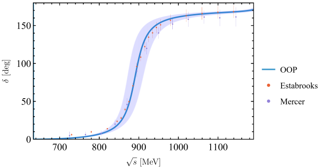
$$\mathring{D}_L(p;\lambda_{BW}) = \begin{cases} 1, & L=0, \\ \frac{p}{\sqrt{\lambda_{BW}^2 p^2+1}}, & L=1, \\ \frac{p^2}{\sqrt{\lambda_{BW}^4 p^4+3\lambda_{BW}^2 p^2+9}}, & L=2 \end{cases}$$

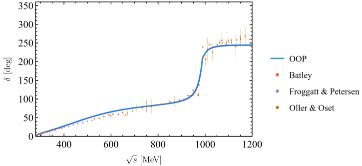
$$\boxed{C_{ji}(p',p) = \left(\frac{g_j g_i}{s-m^2}\right) \mathring{D}_{L_j}(p';\lambda_{BW}) \mathring{D}_{L_i}(p;\lambda_{BW}) \times H(p';\lambda_H) H(p;\lambda_H)}$$

$$H(p;\lambda_H) = \frac{\lambda_H^4}{p^4+\lambda_H^4}$$

The Main Ingredients:

- τ-term:
  - Matched to $2 \to 2$ scattering amplitudes.
  - Unitarised ChPT/(modified) Inverse Amplitude Method [Oller, Oset & Peláez, 1998], e.g., $I = 1/2$, $J = 1$ and $I = 0$, $J = 0$ channels.





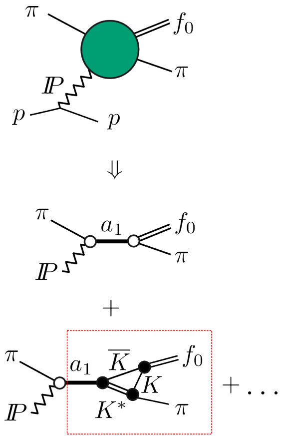
- D-term:

$$D_i(p) = \left(d_i + d \frac{g_i}{s - m^2} \right) \mathring{D}_{L_i}(p; \lambda_{BW}) H(p; \lambda_H)$$

Channel space:

- The following channels are included in this work:

Channel	Content
Channel 1	$(\rho\pi)_S$
Channel 2	$(\rho\pi)_D$
Channel 3	$(K^*(892)\bar{K})_S$
Channel 4	$(K^*(892)\bar{K})_D$
Channel 5	$((\pi\pi)_{(0,0)}\pi)_P$
Channel 6	$((K\bar{K})_{(0,0)}\pi)_P$
Channel 7	$((\pi\pi)_{(2,0)}\pi)_P$
Channel 8	$(K_0^*(700)K)_P$
Channel 9	$((K\pi)_{(\frac{3}{2},0)}K)_P$



[COMPASS, 2021]

The Recipe:

- Construct the coupled channel system.
- Solve the Lippmann-Schwinger-like equation.
- Construct the full amplitude.
- Fit to data.

The Lippmann-Schwinger-like equation:

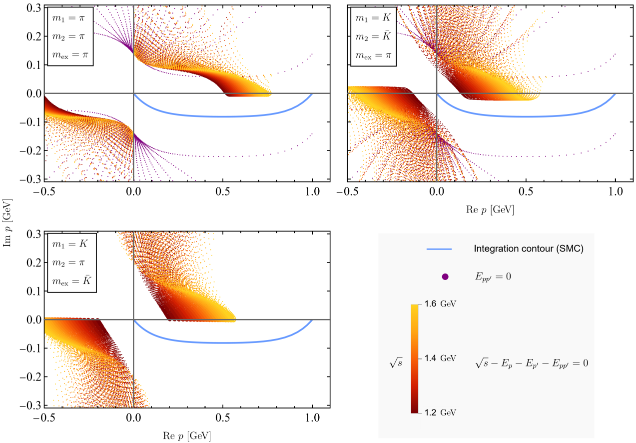
$$
\begin{aligned}
T_{ji}(s, \boldsymbol{p}', \boldsymbol{p}) = {} & B_{ji}(s, \boldsymbol{p}', \boldsymbol{p}) + C_{ji}(s, \boldsymbol{p}', \boldsymbol{p}) \\
& + \int \frac{\mathrm{d}^3 l}{(2\pi)^3\, 2E_{l,k}} \left(B_{jk}(s, \boldsymbol{p}', \boldsymbol{l}) + C_{jk}(s, \boldsymbol{p}', \boldsymbol{l})\right) \tau_{kk'}(\sigma_{l,k})\, T_{k'i}(s, \boldsymbol{l}, \boldsymbol{p})
\end{aligned}
$$

⤳ It can be solved by discretisation and using the resolvent formalism.

$$
T = (1 - (B + C)\tilde{\tau})^{-1}(B + C)
$$

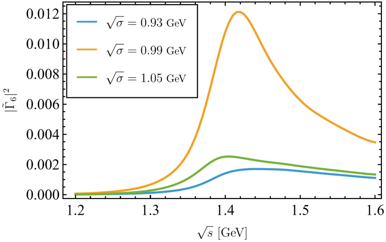
⤳ The resolvent is often singular!

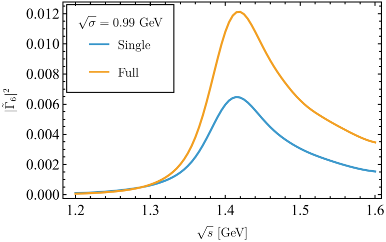
- Solve by contour deformation—spectator momenta promoted to complex.
- Use continued fractions to construct the analytic continuation.



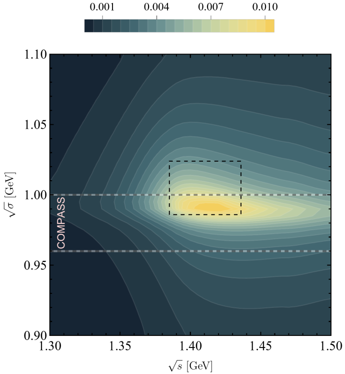
The Triangle Singularity

- Channels 3–6 are enough to reproduce the triangle singularity.
- Sensitive to the mass of the $K^*(892)$.
- Sensitive to the outgoing 2π invariant mass.
- Final state interactions have sizeable contribution.

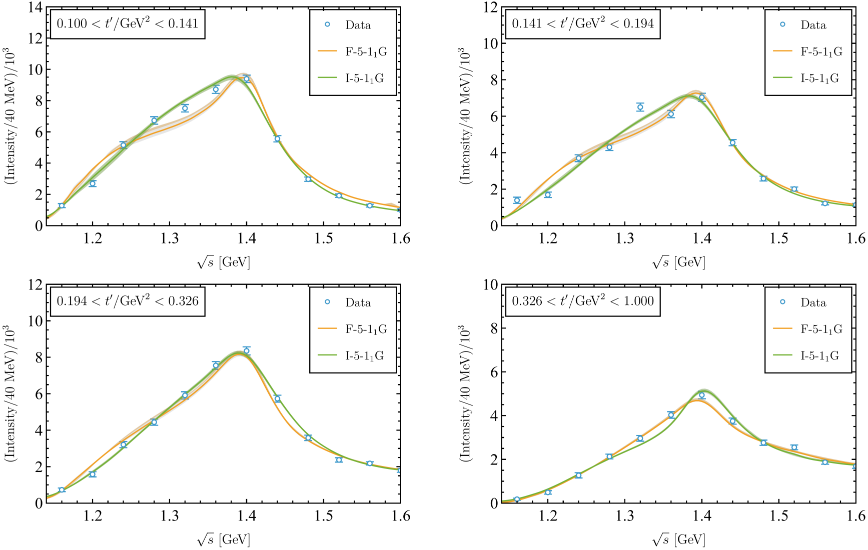




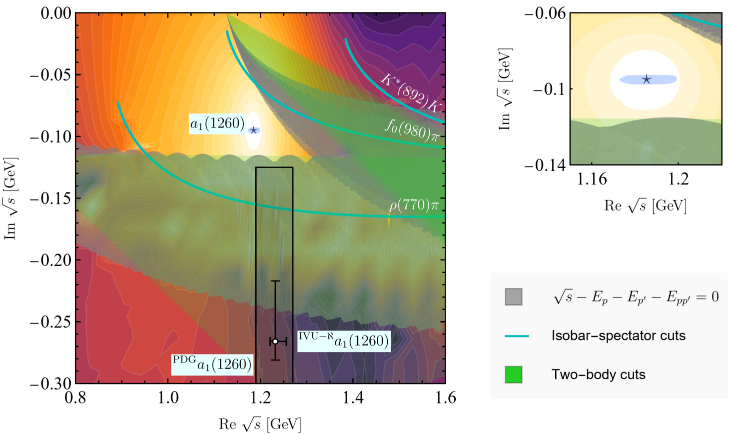
- The triangle singularity region is very restricted.



The fits


0.100 < t′/GeV² < 0.141
0.141 < t′/GeV² < 0.194
0.194 < t′/GeV² < 0.326
0.326 < t′/GeV² < 1.000
Data
F-5-1₁G
I-5-1₁G
(Intensity/40 MeV)/10³
√s [GeV]

The $a_1(1260)$?


0.00
−0.05
−0.10
−0.15
−0.20
−0.25
−0.30
0.8
1.0
1.2
1.4
1.6
Re $\sqrt{s}$ [GeV]
Im $\sqrt{s}$ [GeV]
$a_1(1260)$
$K^*(892)K$
$f_0(980)\pi$
$\rho(770)\pi$
${}^{\mathrm{IVU-}\aleph}a_1(1260)$
${}^{\mathrm{PDG}}a_1(1260)$
−0.06
−0.1
−0.14
1.16
1.2
Re $\sqrt{s}$ [GeV]
Im $\sqrt{s}$ [GeV]
$\sqrt{s} - E_p - E_{p'} - E_{pp'} = 0$
Isobar–spectator cuts
Two–body cuts

Summary

- The $a_1(1420)$ has been studied within the IVU framework.
  - $\rightsquigarrow$ Unitarity and chiral symmetry.
  - $\rightsquigarrow$ Final state interactions taken into account.
- Within the IVU, triangle singularity sufficiently explains the COMPASS data; a genuine resonance pole is not necessary.
- The additional pole fit to the data is more compatible with the $a_1(1260)$.
- IVU is a fully unitary three-body framework—future applications to nucleonic systems (?)

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Thanks for listening!