

Recent results on light-meson exotics from the COMPASS experiment

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on behalf of the COMPASS Collaboration

Excellence Cluster ORIGINS, Munich, Germany
Joint Physics Analysis Center

July 27th, 2021



Variety of the hadronic states

QCD at low-energy regime:

- color interaction confined
- effective d.o.f. - **constituent** quarks (gluons?)

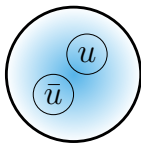
Variety of the hadronic states

QCD at low-energy regime:

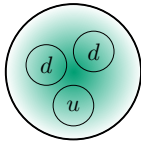
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Ordinary matter:

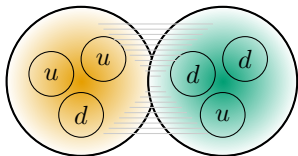
QUARKS	mass →	~2.3 MeV/c ²	~1.275 GeV/c ²	~173.07 GeV/c ²
	charge →	2/3	2/3	2/3
	spin →	1/2	1/2	1/2
		u	c	t
		up	charm	top
	mass →	~4.8 MeV/c ²	~95 MeV/c ²	~4.18 GeV/c ²
	charge →	-1/3	-1/3	-1/3
	spin →	1/2	1/2	1/2
		d	s	b
		down	strange	bottom



meson



baryon



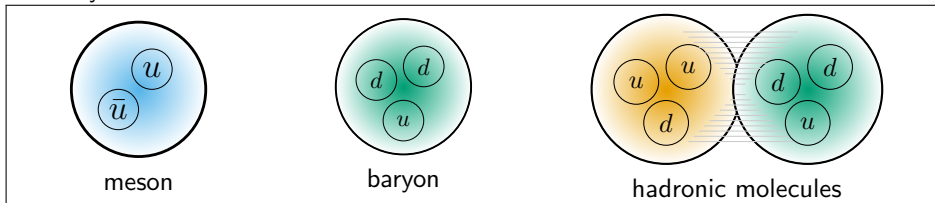
hadronic molecules

Variety of the hadronic states

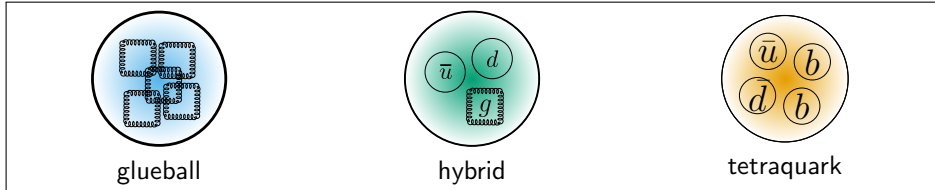
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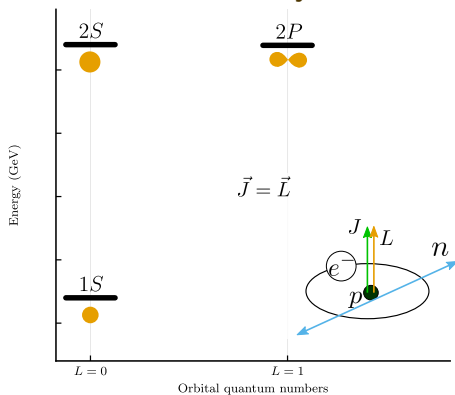
Exotic matter:



	mass \rightarrow ≈ 2.3 MeV/c ²	≈ 1.275 GeV/c ²	≈ 173.07 GeV/c ²
charge \rightarrow	$2/3$	$2/3$	$2/3$
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	u up	c charm	t top
QUARKS	≈ 4.8 MeV/c ²	≈ 95 MeV/c ²	≈ 4.18 GeV/c ²
	$-1/3$	$-1/3$	$-1/3$
	$1/2$	$1/2$	$1/2$
	d down	s strange	b bottom

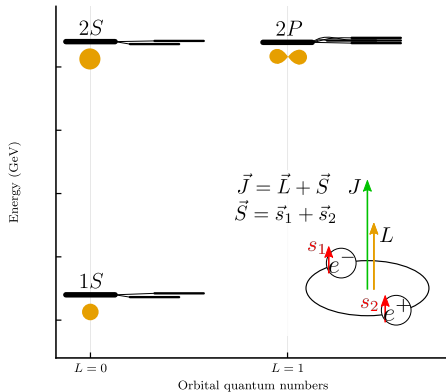
Excitation spectrum of a bound system

QED



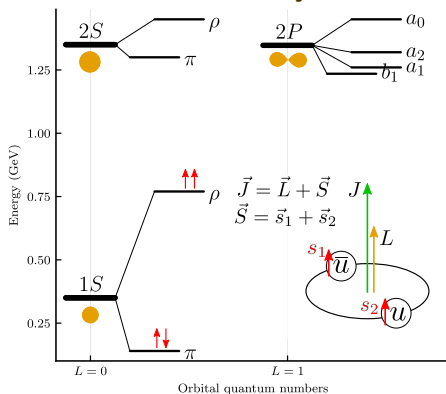
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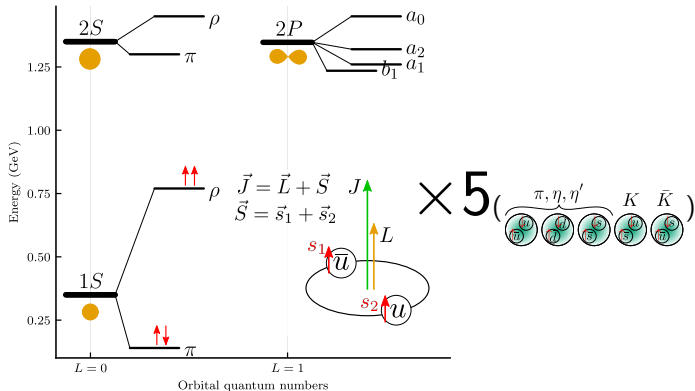
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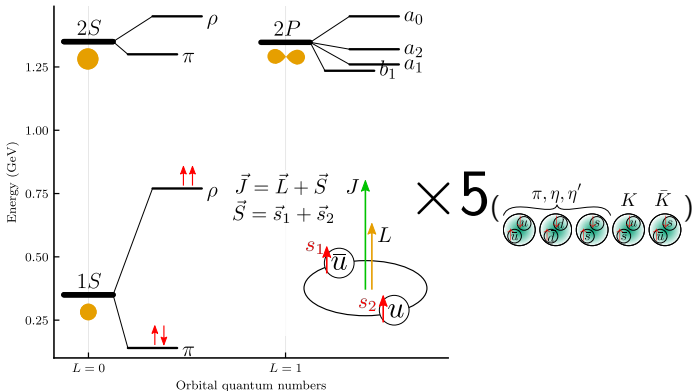
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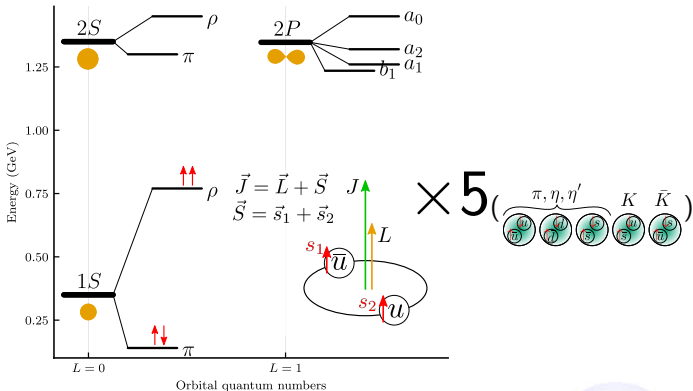
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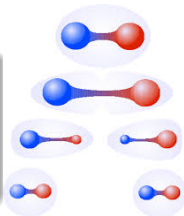
- QED: hyperfine splitting
- QCD: is far not hyperfine

Excitation spectrum of a bound system

QCD



- QED: hyperfine splitting
- QCD: is far not hyperfine
- Example of spin-flip transition:
 $\rho(\uparrow\uparrow) \rightarrow \pi(\uparrow\downarrow)$ transition is a “QCD-cell division”



The plan of the talk

1 Introduction

- Meson spectrum
- Mass, width, pole position
- Experimental setup

2 Hybrid candidate $\pi_1(1600)$

- $\pi_1(1600) \rightarrow \eta^{(\prime)}\pi$
- $\pi_1(1600) \rightarrow 3\pi$

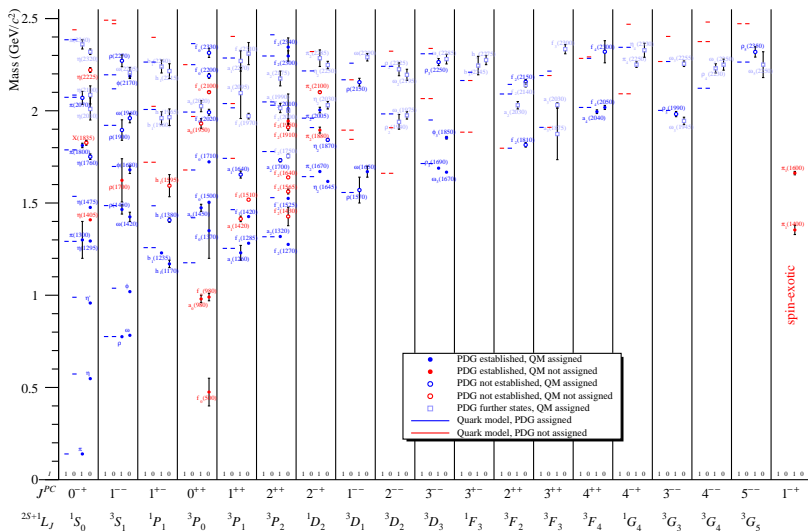
3 Tetraquark candidate $a_1(1420)$

- Observation and interpretations
- Triangle Singularity in three-body decays, interference

4 Summary

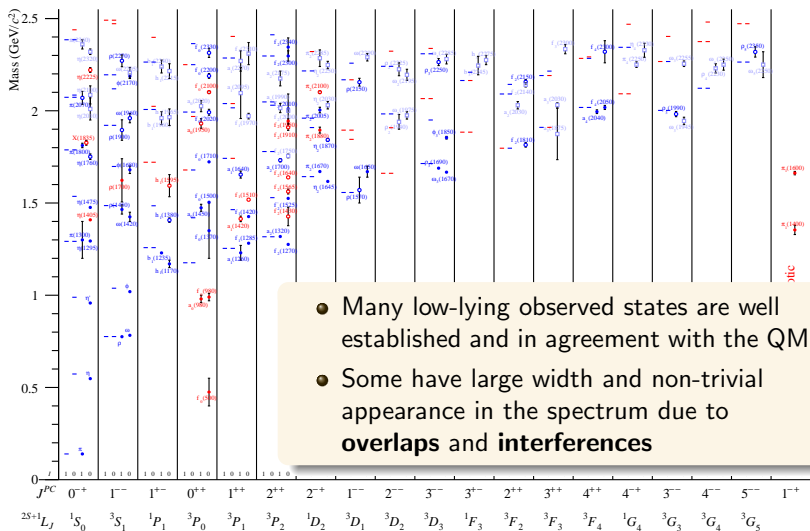
Experimental situation on (non-strange) Light mesons

[B. Ketzner, B. Grube, D. Rvabchikov, PPNP, arXiv:1909.06366]

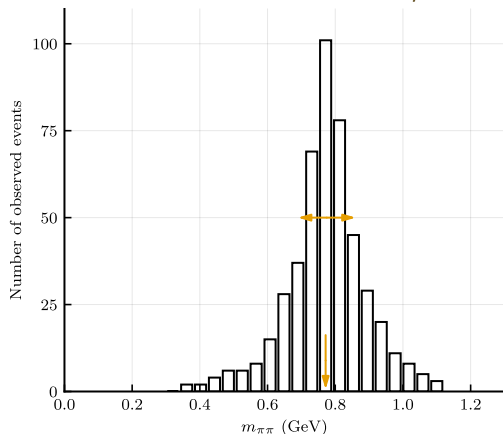


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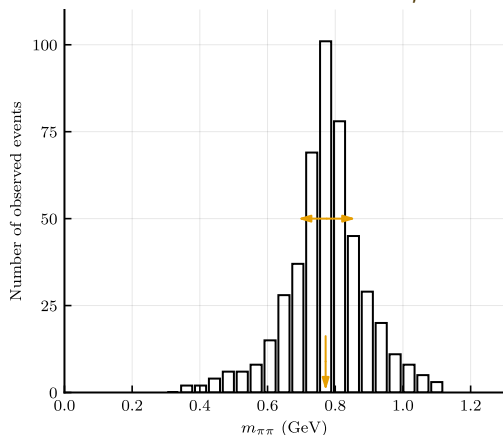
Invariant-mass distribution, resonances



Hadronic state is a particle

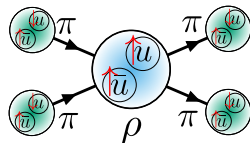
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Invariant-mass distribution, resonances



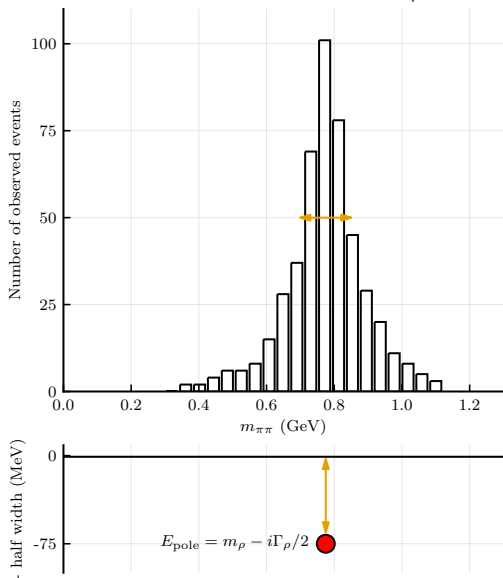
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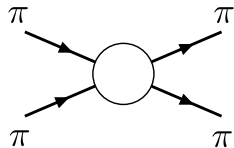
- Hadronic states are **resonances** of the hadronic system
- Read m , Γ from spectrum

Invariant-mass distribution, resonances



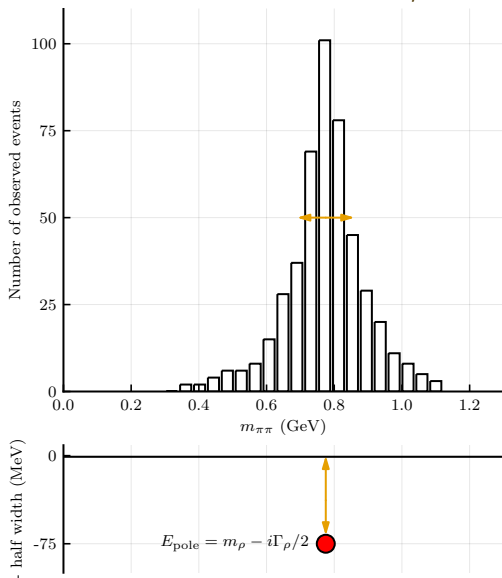
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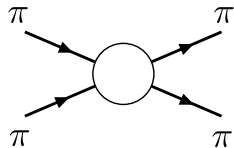
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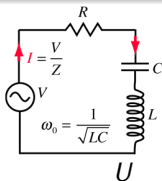


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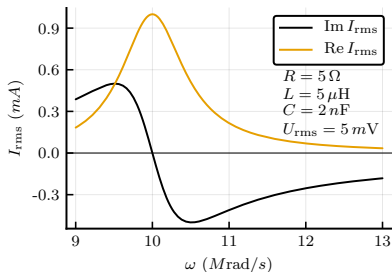
- resonances are **poles** of scattering amplitude.

Resonances are poles of the amplitude

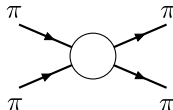
Electric circuit



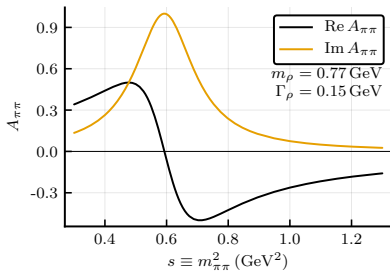
$$I_{\text{rms}} = \frac{U}{R + iL\omega - \frac{i}{C\omega}}$$



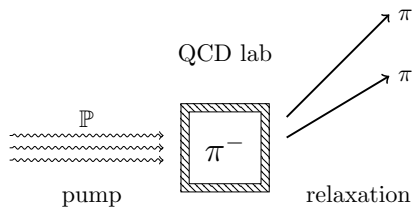
Scattering



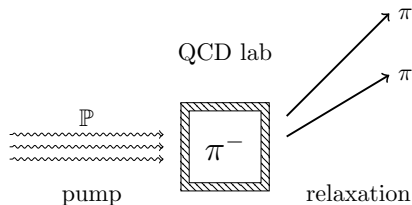
$$A_{\pi\pi} = \frac{m\Gamma}{m^2 - s - im\Gamma}$$



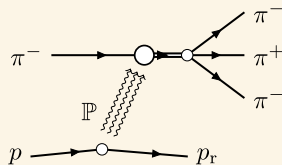
Laboratory to study hadronic excitations



Laboratory to study hadronic excitations

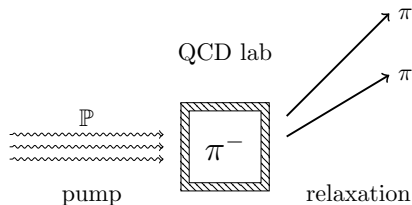


Diffractive reaction

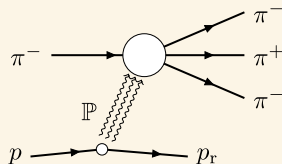


- Pion beam scattered off the proton target
- High energy guarantees t -channel process.
- The target provide the gluonic field
- 3π production has the largest cross section (inelastic)

Laboratory to study hadronic excitations



Diffractive reaction



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[Image: Maximilien Brice/CERN]



SUISSE
FRANCE

CMS

LHCb

ATLAS

CERN Meyrin

CERN Preessin

SPS - 7 km

ALICE

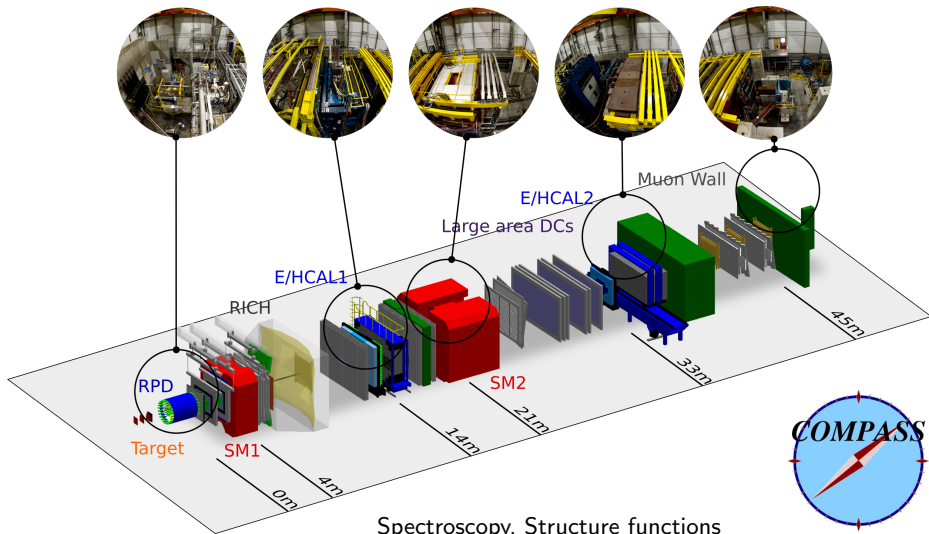
LHC - 27 km

[Image: Maximilien Brice/CERN]



COMPASS Experiment

[NIM A779 (2015) 69-115]



Spectroscopy, Structure functions
 π/μ beam, 10^7 particles per 10s spill



Note on the history of $\pi_1(1600)$



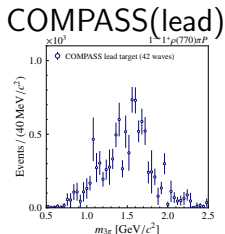
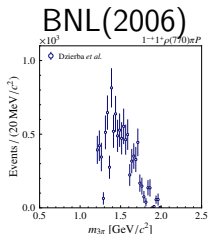
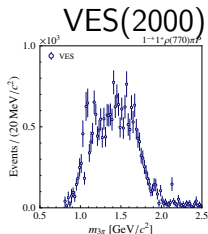
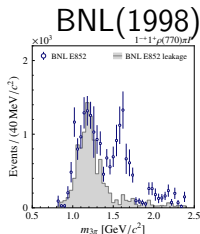
a resonance with non- $q\bar{q}$ quantum numbers, $J^{PC} = 1^{-+}$.

Two states in PDG: $\pi_1(1400)$ and $\pi_1(1600)$

- $\pi_1(1400) \rightarrow \eta\pi$
- $\pi_1(1600) \rightarrow \eta'\pi$ and $\rightarrow \rho\pi$ *P*-wave

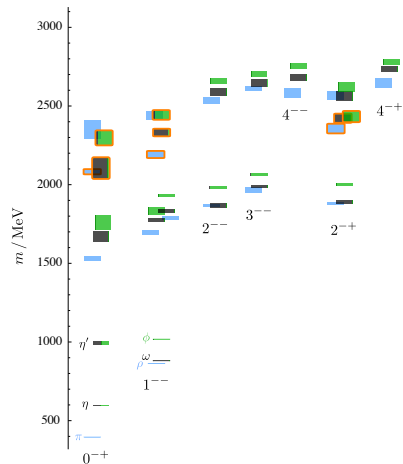
Contradictions on $\pi_1(1600) \rightarrow \rho\pi$ *P*-wave (PWA)

- Four analyses in the past arrive to different conclusions on **existence** and parameters of $\pi_1(1600)$

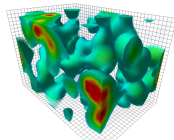
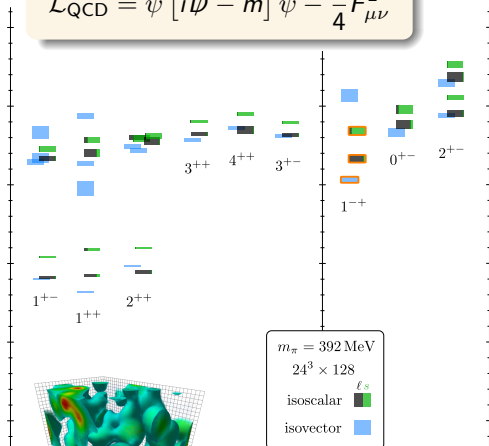


Light-meson excitations from Lattice QCD

[Dudek et al., PRD 88, 094505 (2013)]



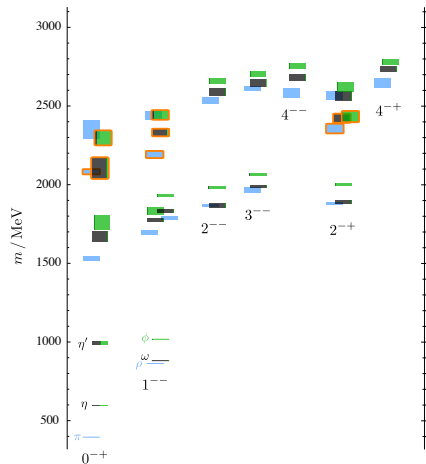
$$\mathcal{L}_{\text{QCD}} = \bar{\psi} [i\mathcal{D} - m] \psi - \frac{1}{4} F_{\mu\nu}^2$$



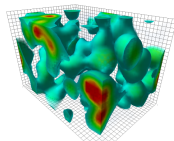
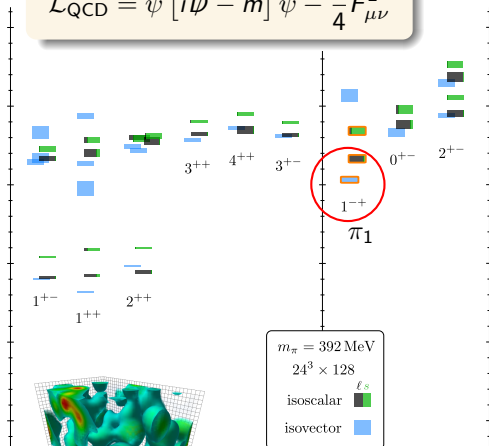
mass of pion is 391 MeV

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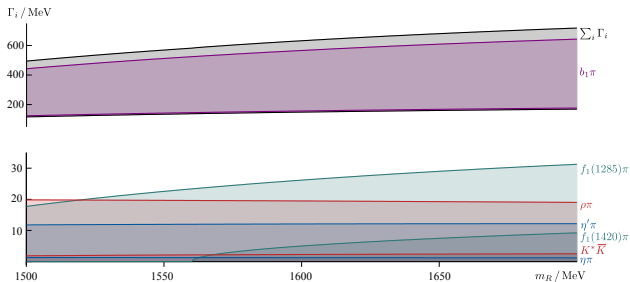


$m_\pi = 392 \text{ MeV}$
 $24^3 \times 128$
 ℓ_s
 isoscalar ■
 isovector ■

mass of pion is 391 MeV

Exotic mesons in two-body scattering on lattice

[A.Woss et al., PRD 103, 054502 (2021)]

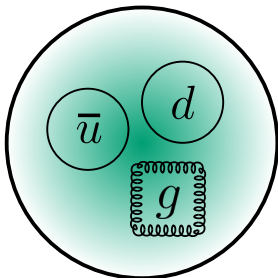


Setup:

- $SU(3) : m_u = m_d = m_s$
- $m_\pi \approx 700 \text{ MeV}$
- 8 coupled two-body channels
- Wide range of operators

- Strong coupling to $b_1\pi$
- Much smaller to $\rho\pi, f_1\pi, \eta^{(\prime)}\pi$
- Extrapolation width agrees with experimental analysis

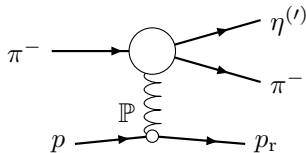
$\pi_1(1600)$ hybrid candidate



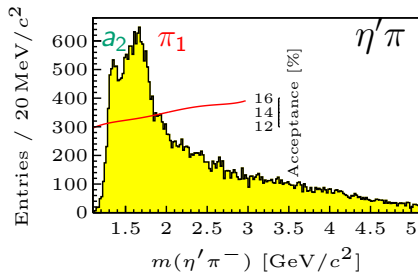
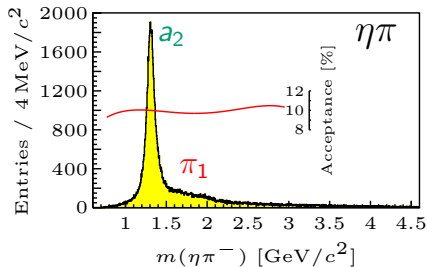
as a resonance in $\eta^{(\prime)}\pi$ system

$\eta\pi$ vs $\eta'\pi$ at COMPASS

[COMPASS, PLB 740 (2015) 303]



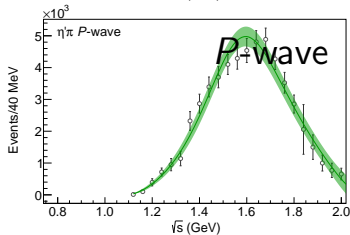
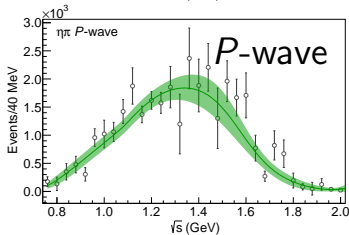
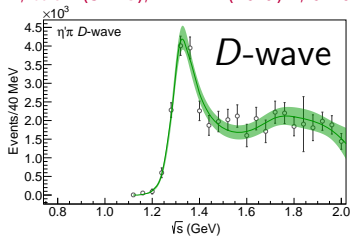
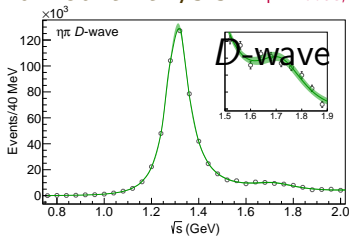
- Exclusive reactions are selected
- $\eta \rightarrow \gamma\gamma$, $\eta' \rightarrow \pi^+\pi^-\eta$



Angular analysis attributes the intensity to different $J^{PC} = 1^{-+}, 2^{++}, \dots$

Combined analysis

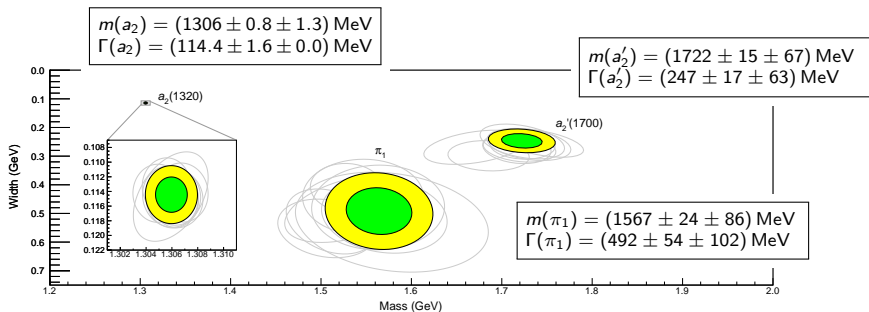
[A.Rodas, A.Pilloni, MM, et al. (JPAC), PRL122 (2019) 4, 042002]



- Unitary analytic model:
2 poles for D -wave, and a single pole in P -wave
- Consistent description of the data in $\eta\pi$ and $\eta'\pi$!

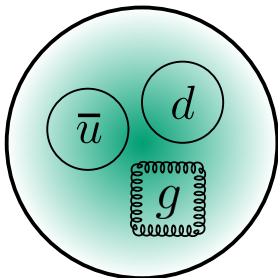
Results: pole positions

[JPAC, PRL122 (2019) 4, 042002]



- A dominant systematic uncertainties is related to the model.
- More data, inclusion of $\rho\pi$, $f_1\pi$, and $b_1\pi$ will help to reduce the uncertainty

$\pi_1(1600)$ hybrid candidate



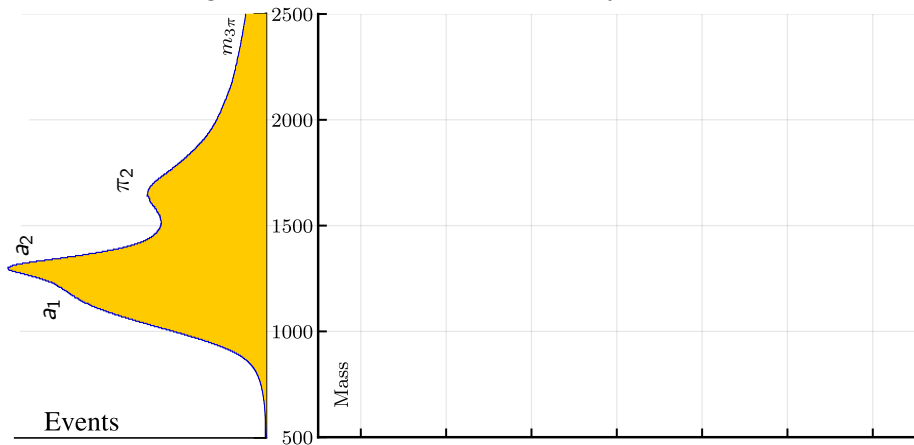
as a resonance in 3π system

Understanding of the 3π spectrum

[COMPASS, PRD95 (2017) 032004]

The results of the main big fit

— 14 interfering waves \times 11 t' -slices simultaneously.

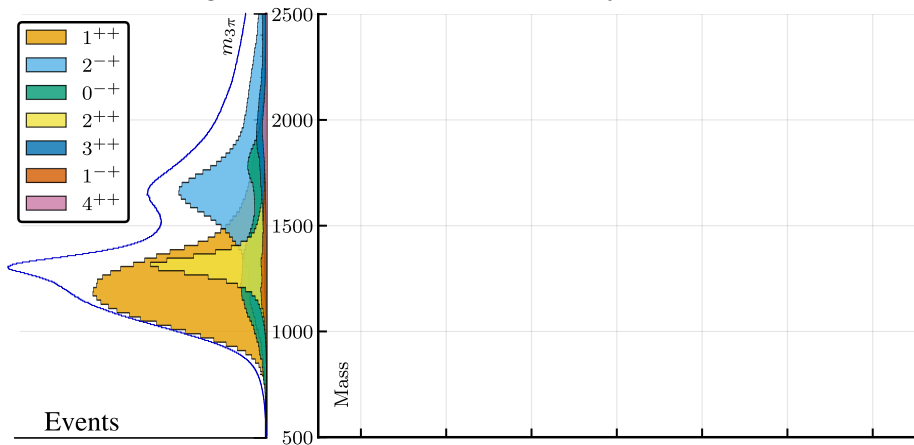


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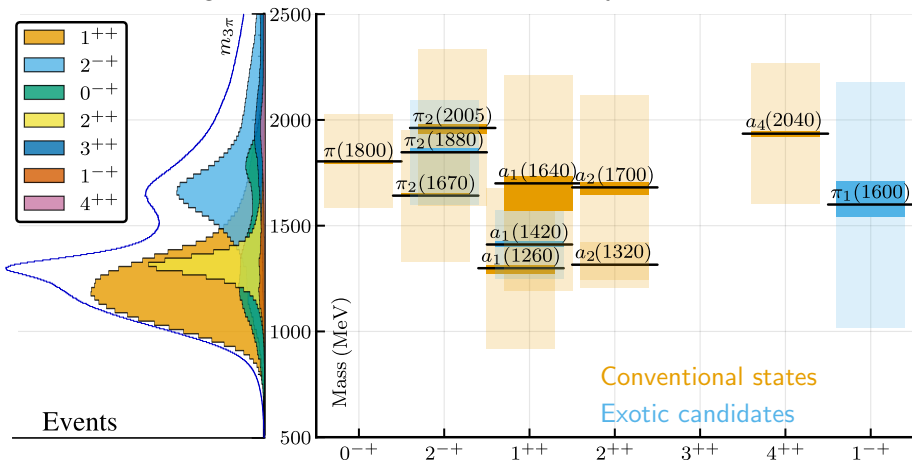


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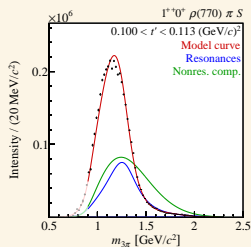


- 11 resonances are established including a new $a_1(1420)$

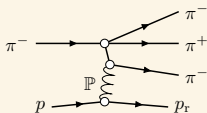
Resonance model fit

The main mass-dependent fit

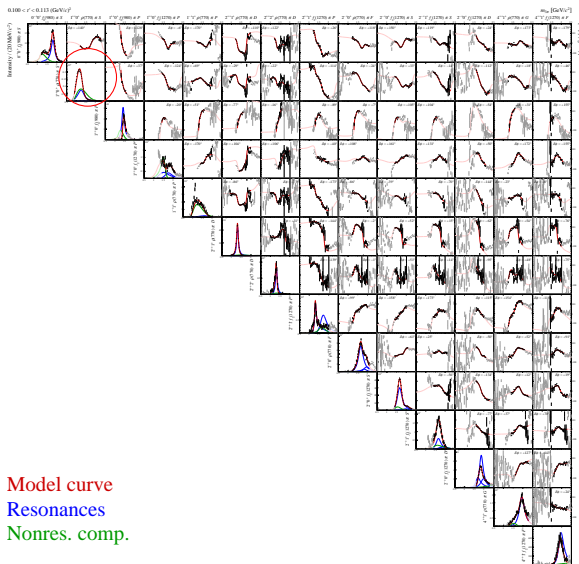
Axial vector 1^{++}



- Non-resonant coherent background



[COMPASS, PRD98 (2018) 092003]



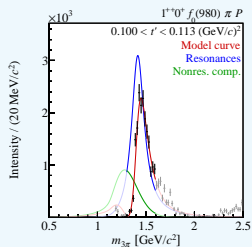
Model curve
 Resonances
 Nonres. comp.

Resonance model fit

The main mass-dependent fit

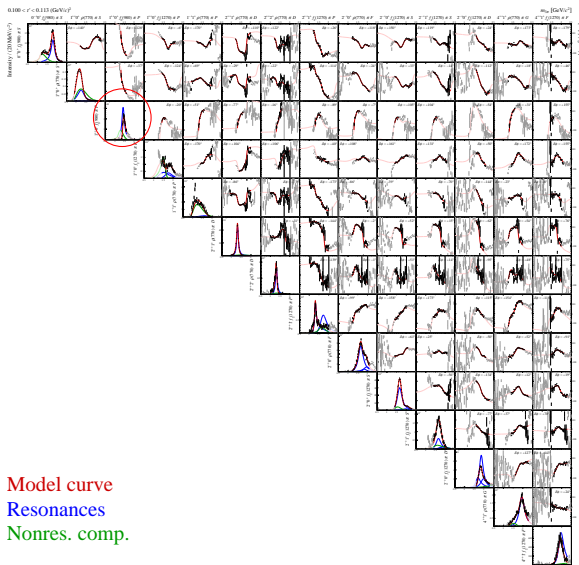
Axial “?”

1^{++}



● Exotic candidate!

[COMPASS, PRD98 (2018) 092003]

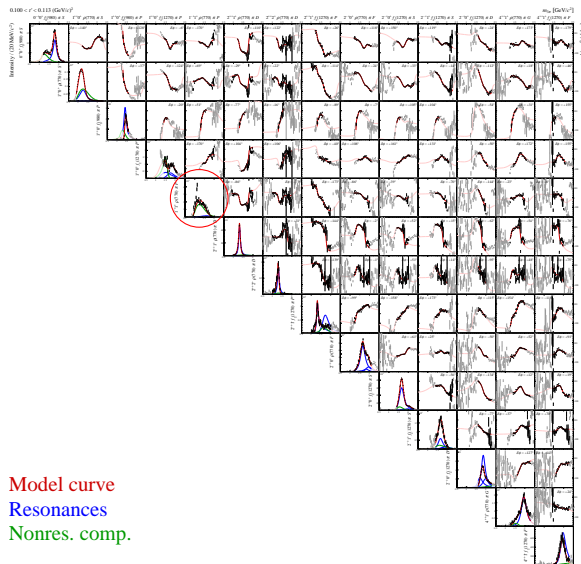
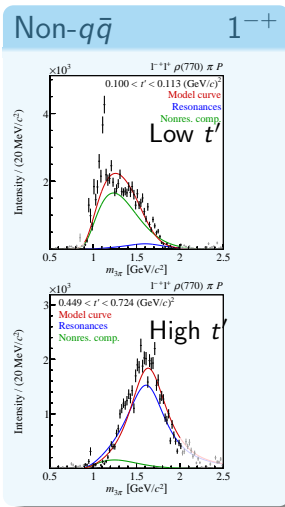


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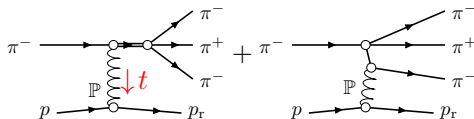
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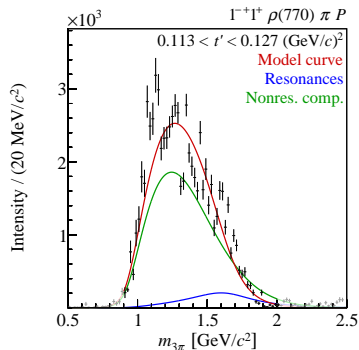


Parameters of the $\pi_1(1600)$ in 3π

[COMPASS, PRD98 (2018) 092003]

 $\rho\pi$ P-wave from the 14-waves fit.

- Background changes with virtuality of \mathbb{P} (t')
- The resonance mass and width are constrained to be the same for all t'

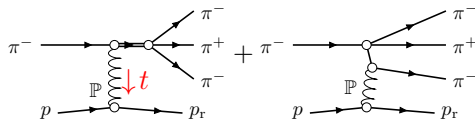


$$m(\pi_1) = 1550_{-60}^{+110} \text{ (syst.) MeV}, \quad \Gamma(\pi_1) = 580_{-230}^{+100} \text{ (syst.) MeV}$$

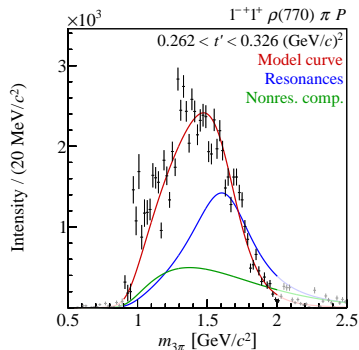
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Parameters of the $\pi_1(1600)$ in 3π

[COMPASS, PRD98 (2018) 092003]

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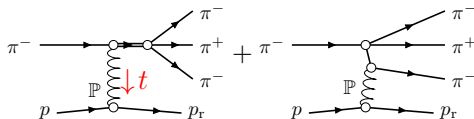


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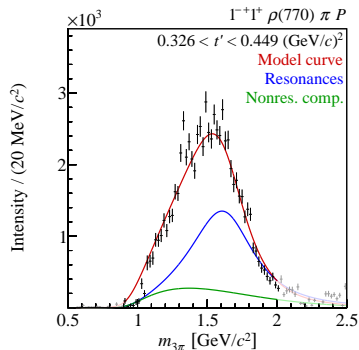
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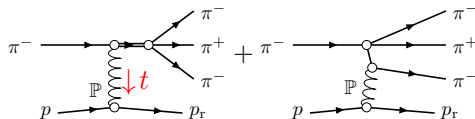


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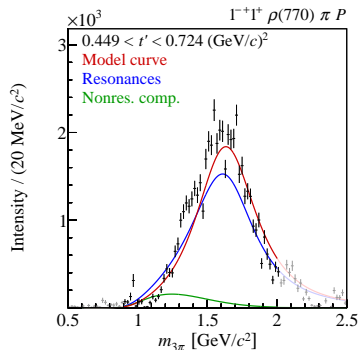
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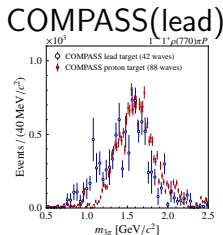
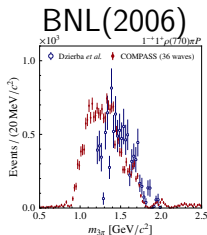
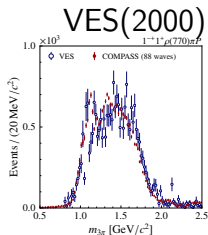
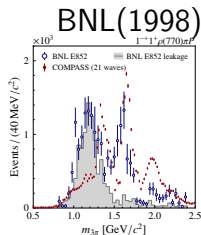


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Wave set and consistency with previous results

Two reasons of troubles with $\rho\pi$ P -wave [COMPASS, to appear on arxiv]

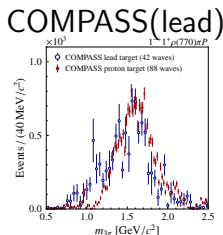
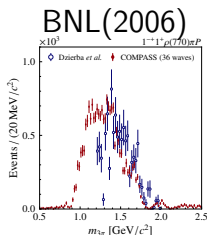
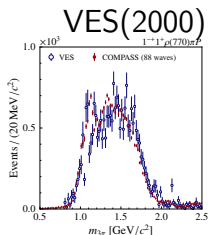
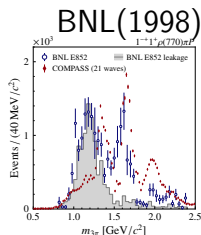


Two effects:

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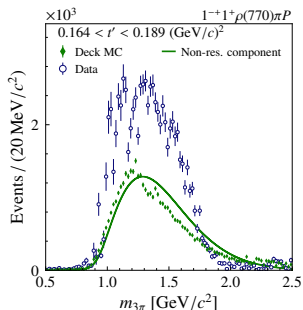
Two reasons of troubles with $\rho\pi$ P -wave [COMPASS, to appear on arxiv]



Two effects:

- Wave set: leakage to $\rho\pi$ P -wave
- Non-resonant background depends on t' (Deck [PRL 13 (1964) 169-173])

$$= t_{\pi p} \frac{e^{-bt_1}}{m_{\pi}^2 - t_1} t_{\pi\pi}$$



Wrap up on $\pi_1(1600)$

- Analysis of $\eta^{(\prime)}\pi$:

- ▶ [COMPASS, PLB 740 (2015) 303]
- ▶ [JPAC/COMPASS, PLB 779, 464-472]
- ▶ [JPAC, PRL122 (2019) 4, 042002]

establish $\pi_1(1400)/\pi_1(1600)$ is the same resonance with

$$\eta^{(\prime)}\pi : \quad m_{\text{pole}}(\pi_1) = 1567 \pm 24 \pm 86 \text{ MeV} \quad \Gamma_{\text{pole}}(\pi_1) = 492 \pm 54 \pm 102 \text{ MeV}$$

- Analysis of 3π :

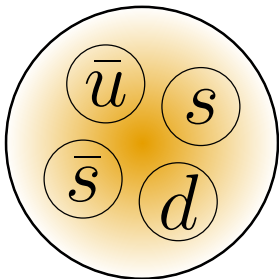
- ▶ [COMPASS, PRD95 (2017) 032004]
- ▶ [COMPASS, PRD98 (2018) 092003]
- ▶ [COMPASS, to appear on arxiv]

solved the long-standing puzzle on inconsistency of past analyses

$$3\pi : \quad m_{\text{pole}}(\pi_1) = 1630_{-60}^{+110}(\text{syst}) \text{ MeV} \quad \Gamma_{\text{pole}}(\pi_1) = 570_{-230}^{+100}(\text{syst}) \text{ MeV}$$

$\Rightarrow \pi_1(1600)$ is lightest meson with exotic quantum numbers $J^{PC} = 1^{-+}$

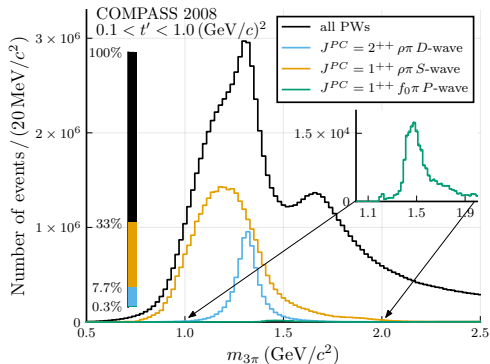
$a_1(1420)$ tetraquark candidate



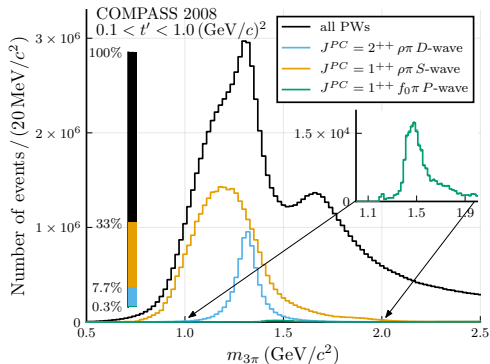
as a resonance in the 3π system

Observation of the $a_1(1420)$

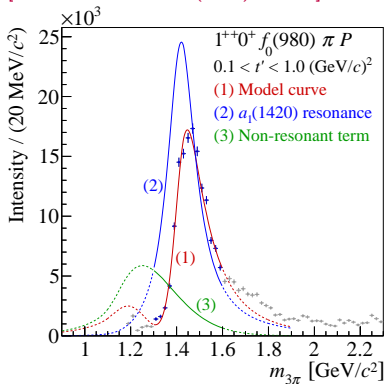
[COMPASS, PRL 115 (2015) 082001]



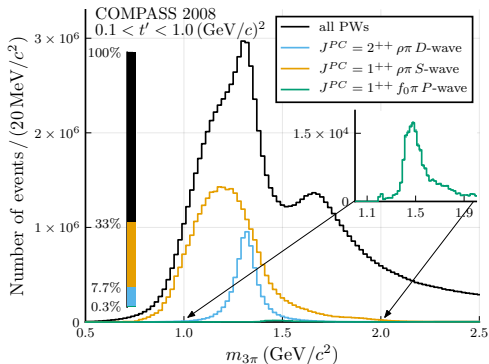
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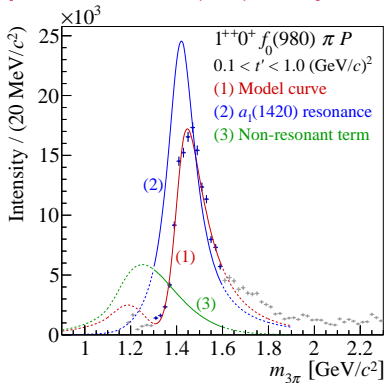
[COMPASS, PRL 115 (2015) 082001]



Observation of the $a_1(1420)$



[COMPASS, PRL 115 (2015) 082001]



New particle may be made of four quarks



Not something ordinary

- Too close to the ground state $a_1(1260)$
- Its width is narrower than the ground state
- Close to threshold $K^* \bar{K}$, i.e. $(d\bar{s}) + (\bar{u}s)$, $E_{\text{th}} = 1.39 \text{ GeV}$.

$a_1(1420)$ interpretations

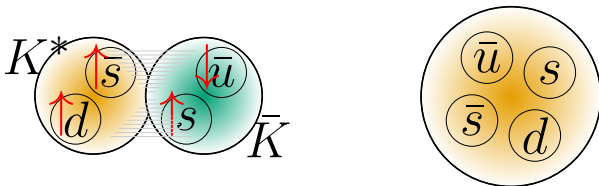
Possible scenaria

- **Pole** in the amplitude – Genuine resonance
- Singularity of the **non-pole** type

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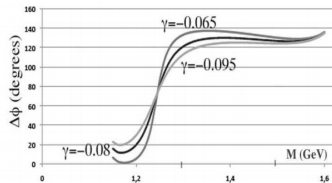
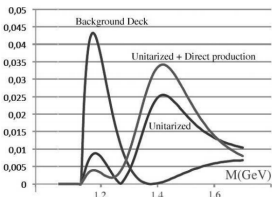
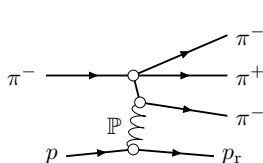
- **Pole** in the amplitude – Genuine resonance
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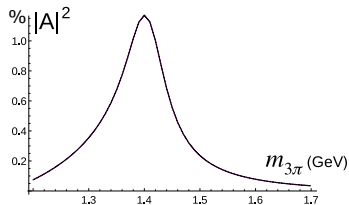
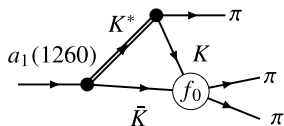


[J.-L. Basdevant, Ed. Berger, PRL114 (2015) no.19, 192001]

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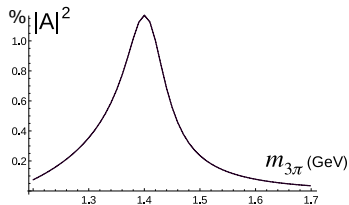
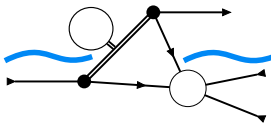


[MM, A. Sarantsev, B. Ketzer, PRD 91, 094015 (2015)],
confirmed by [Aceti et al, PRD 94, 096015 (2016)]

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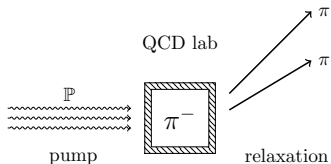
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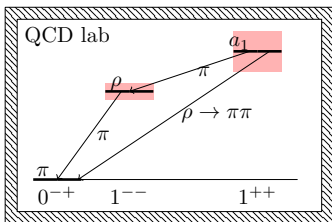
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Decay chains, subchannel resonances

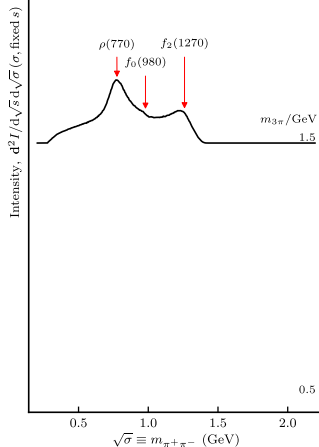


- The relaxation via an intermediate meson
 - Direct emission of ρ -meson
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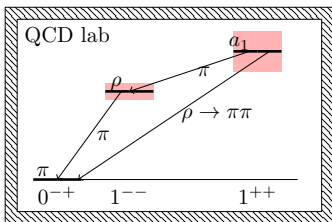
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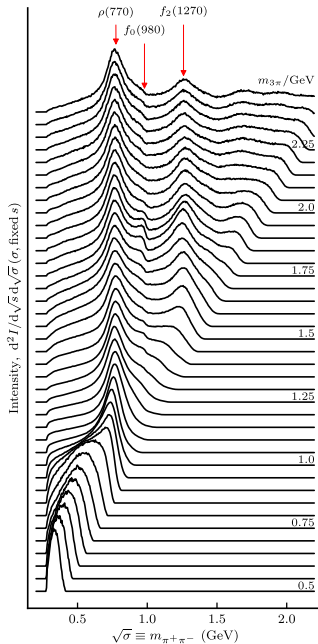
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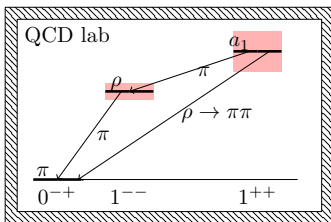
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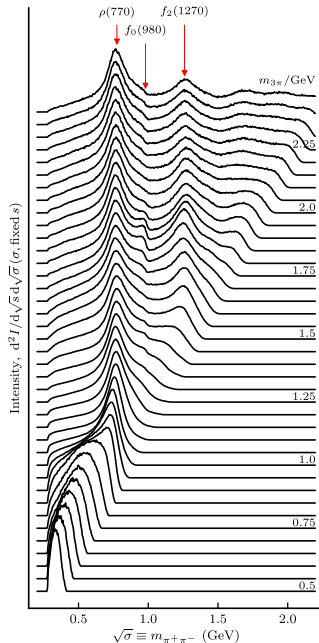
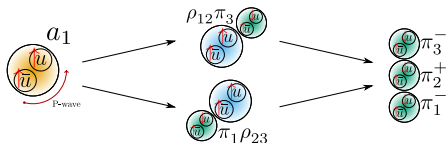
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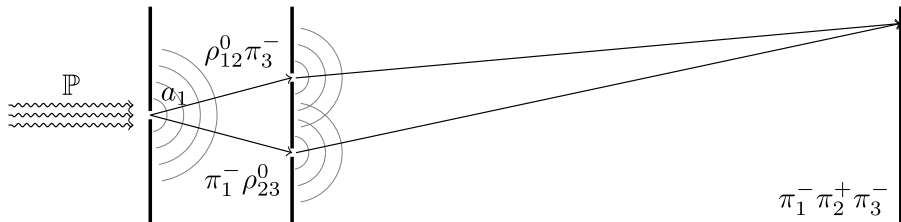
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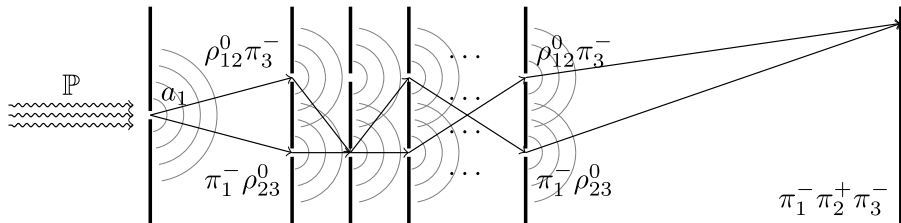


Hadronic double-slit experiment



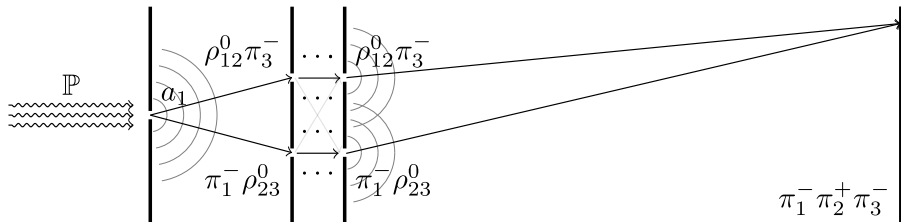
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- Intermediate states are entangled

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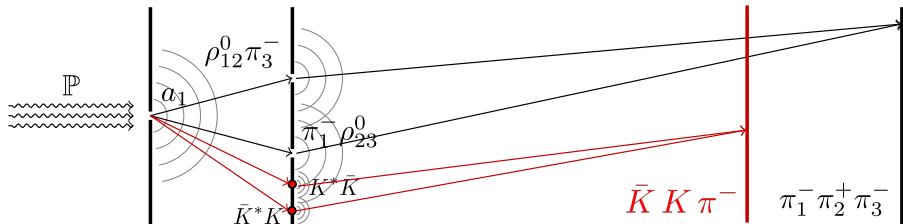
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 - Cross-channel effect scales with the resonance width

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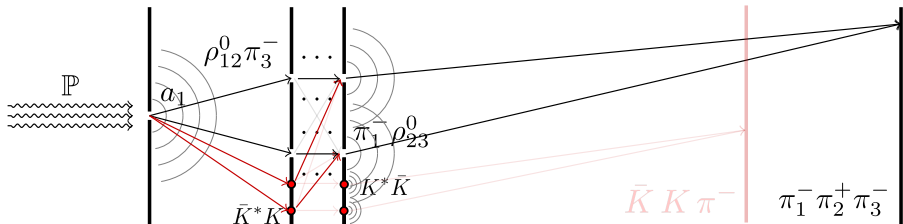
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Coupled channels (schematically)



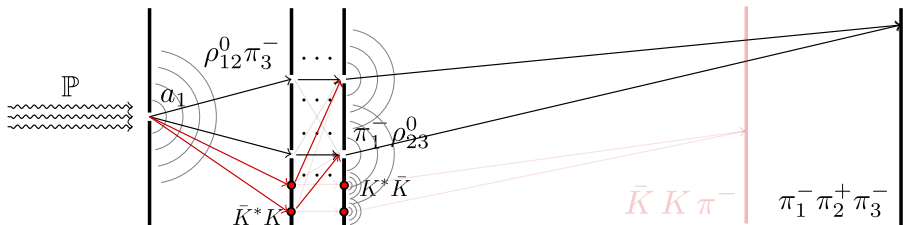
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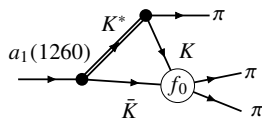
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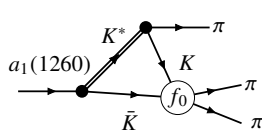
- Tiny fraction of the $a_1 \rightarrow K \bar{K} \pi$ probability gets into $\pi \pi \pi$,
- However, only above $K^* \bar{K}$ threshold!

The key effect - the triangle rescattering graph

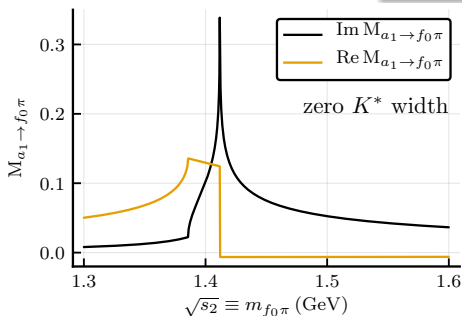


- f_0 is a resonance in $(K\bar{K})$ and also in $(\pi\pi)$ system.
- Ordinary a_1 decays to $K\bar{K}\pi$ via $K^*\bar{K}$
- $K\bar{K}$ form f_0 that decays to $\pi\pi$

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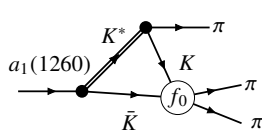


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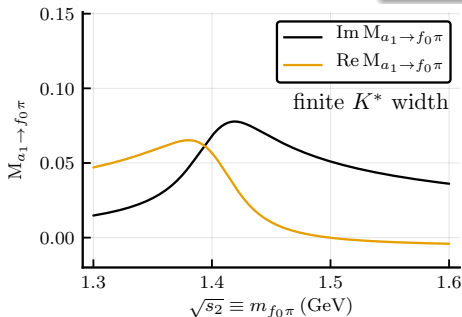


- has a logarithmic singularity (divergence at a single point)
- $A \sim \log(s_0 - m_{3\pi}^2)$ with s_0 determined by masses of involved particles.

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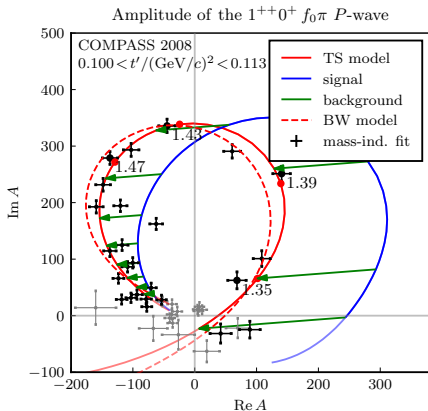
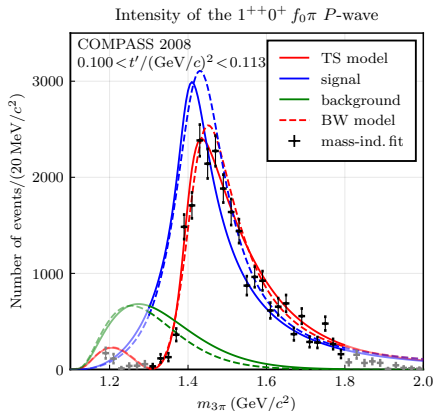
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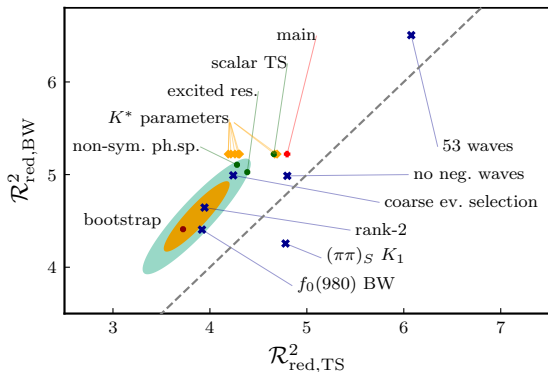
Fit with the rescattering model [COMPASS, PRL(2021)]

Fit perfectly describes the intensity and the phase motion



- No shape parameters for the signal component (TS)
- Background with constant phase is needed to shift the amplitude
- TS model shows a comparable quality to the resonance model (BW-model)

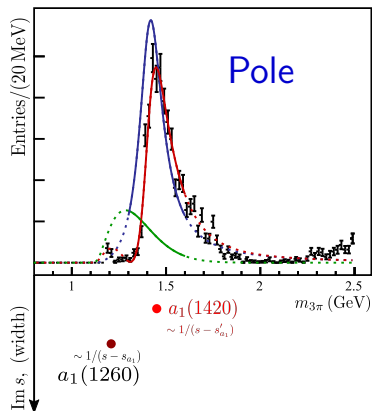
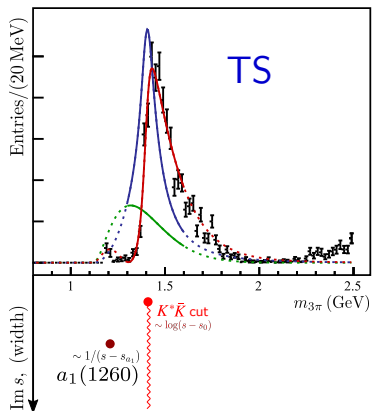
Systematic studies



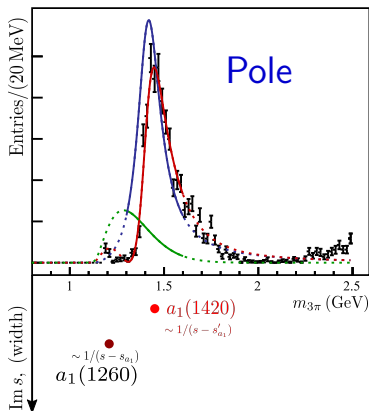
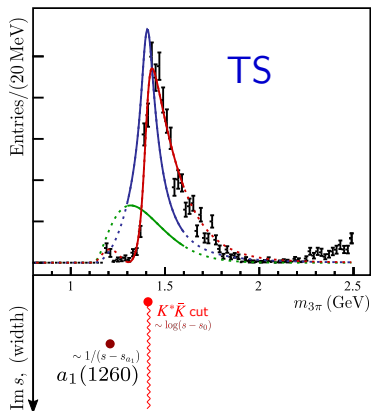
TS model systematically yields a similar $\mathcal{R}_{\text{red}}^2$ as the BW model.

- Neglecting interference of the conjugated decay chains,
- Neglecting the spins of the particles involved,
- Including the excitations $a_1(1640)$ and $a_2(1700)$
- Varying mass and width of the K^* resonance

Emerging interpretation [COMPASS, PRL (2021)]



Emerging interpretation [COMPASS, PRL (2021)]



- $a_1(1420)$ signal can be described with $a_1(1260)$ as source for the **rescattering** via the triangle diagram \Rightarrow the first clear observation of the TS
- An additional pole is not needed, although, not excluded

Summary on $a_1(1420)$

- Peak and phase motion are not unique sign of a resonance!
- $a_1(1420)$ signal can be described with ordinary a_1 as source for the rescattering via the triangle diagram
- Old theoretical concept, but clearly observed for the first time!
- Intensity of signal $\sim 1\%$, in agreement with experiment

Signal in $f_0\pi$ P -wave \Rightarrow established Triangle Singularity,
no need for the tetraquark

Conclusions and outlook

- Hadron **spectroscopy** is a unique tool for understanding the QCD, the theory of matter formation
- **Diffraction** reaction is a clean setup for measurements of the excitation spectrum
- **COMPASS** leads the effort of large combined light-quark meson studies
- Many new surprises with new data (GlueX, BESIII, AMBER(?))
- Lattice QCD already provides quantities accessible at COMPASS, we should catch up
- Strengthen the TH+EXP collaboration

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Outlook for hadron spectroscopy at COMPASS

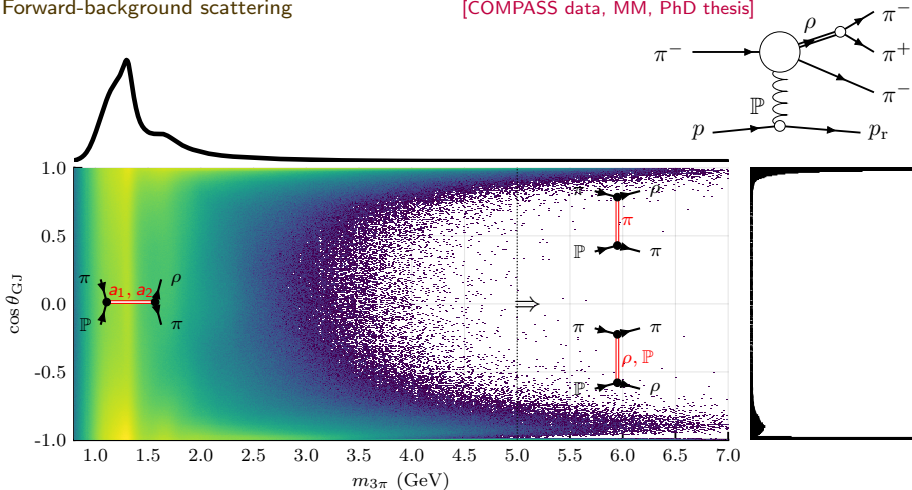
- $\pi_1(1600) \rightarrow b_1\pi$ and $\pi_1(1600) \rightarrow f_1\pi$ are under study in COMPASS
- Kaon diffraction reaction $K^- p \rightarrow K^- \pi^+ \pi^- p$ is under study
The first results are coming soon
- Extensive kaon spectroscopy program with AMBER at CERN is proposed

Thank you for the attention

Interfering background

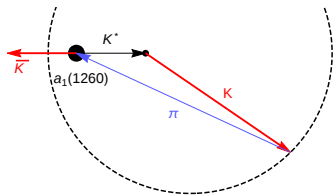
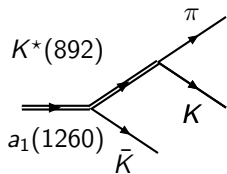
Forward-background scattering

[COMPASS data, MM, PhD thesis]

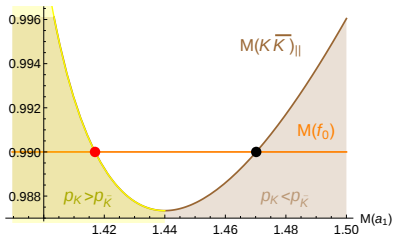


The high-energy exchange processes penetrate to the low energy and make resonance characterization difficult

Classical picture of near-mass-shell rescattering



Imagine cascade reaction $a_1(1260) \rightarrow K^*(892)\bar{K}$, then $K^* \rightarrow K\pi$, and calculate invariant mass of K and \bar{K} for the case when K is parallel to \bar{K} .



Partial form of Landau conditions

[[Nucl. Phys. **13**, 181 (1959)]]:

- All particles in loop are on mass shell.
- The alignment of moments $\vec{p}_K \uparrow \vec{p}_{\bar{K}}$.
- K is faster than \bar{K} .