

Introduction to the amplitude analysis: studying hadrons as resonances in scattering

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CERN, Switzerland

14.08.2020



short bio



Mikhail
Mikhasenko

Curriculum Vitae

Links to the pages of the collaborations:

- LHCb
- COMPASS
- JPAC

Thanks to my colleagues who are connected today and will help with the workshop

Education

- 2014–2019 **PhD (Physics)**, Helmholtz Institute for Radiation and Nuclear Physics (University of Bonn), Germany.
Thesis: "Three-pion dynamics at COMPASS: resonances, rescattering and non-resonant processes".
Honor: summa cum laude
- 2011–2013 **Master of Science (Physics)**, Moscow Institute for Physics and Technology (State University), Russia.
Thesis: "Partial Wave Analysis of the $\pi^-\pi^0$ system"
- 2007–2011 **Bachelor of Science (Physics)**, Moscow Institute of Physics and Technology (State University), Russia.
Thesis: "Geant4 simulation of the Active Target Detector for VES experiment"

Employment

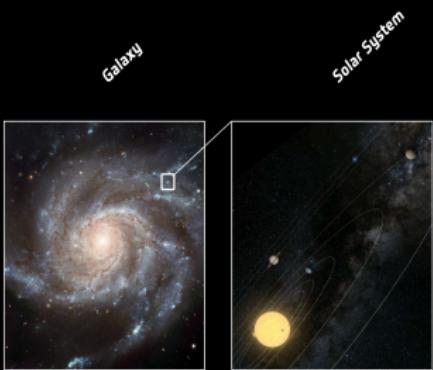
- 2019–Present **Research Fellow**, CERN, Switzerland.
- 2019–Present **Member of Particle Data Group (Meson Team)**, CERN, Switzerland.
- 2015–Present **Member of Joint Physics Analysis Center**, Indiana University & Thomas Jefferson National Accelerator Facility, USA.
- 2014–2019 **Researcher (PhD program)**, Helmholtz Institute for Radiation and Nuclear Physics, University of Bonn, Germany.
- 2013–2014 **Research associate**, Institute for High Energy Physics, Protvino, Russia.
- 2011–2013 **Technician**, Institute for High Energy Physics, Protvino, Russia.

[ESA "Planck history of Universe" (modified)]

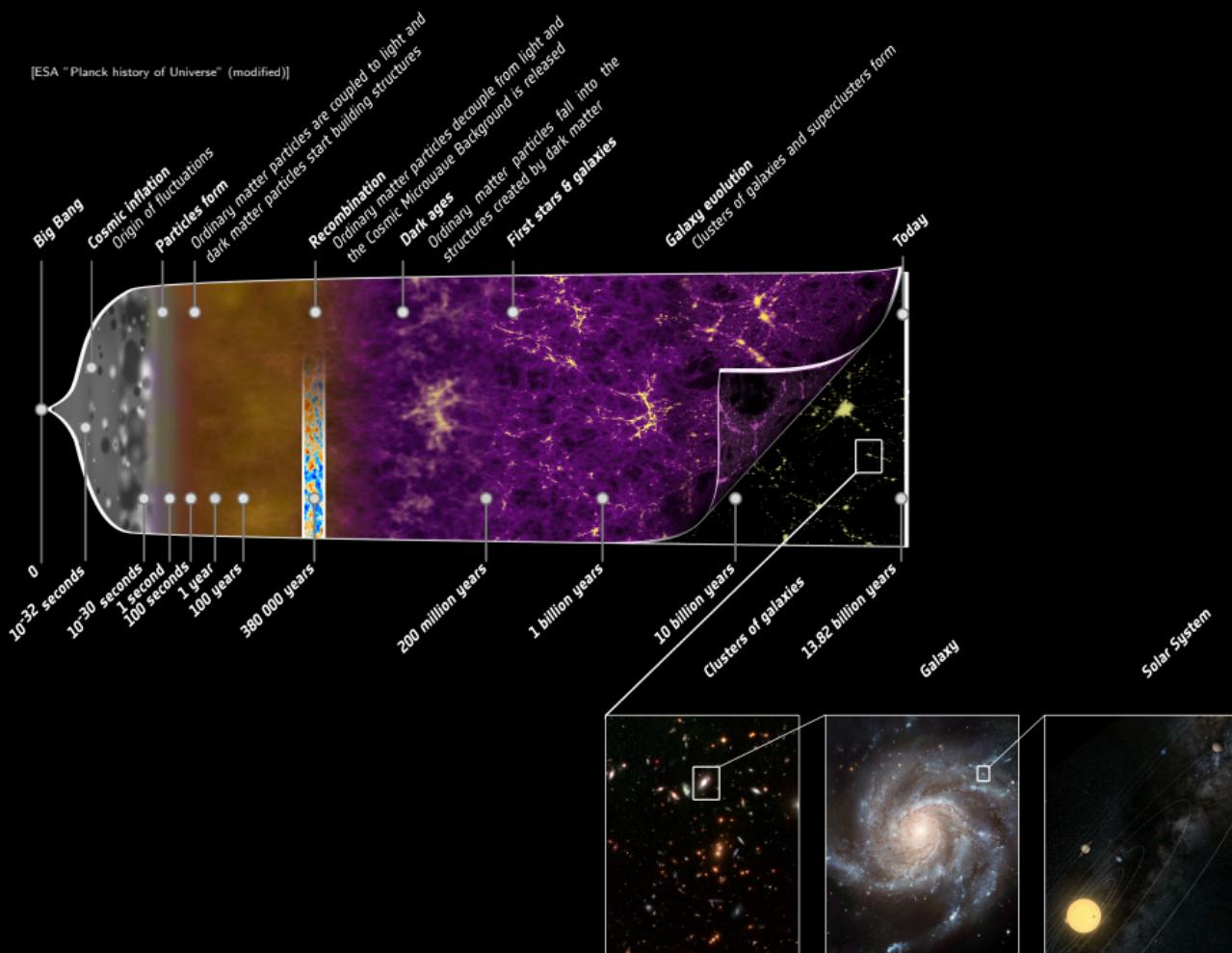
Solar System



[ESA "Planck history of Universe" (modified)]



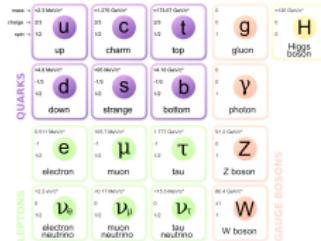




Variety of the hadronic states

Low-energy regime:

Effective d.o.f. - constituent quarks (gluons?)

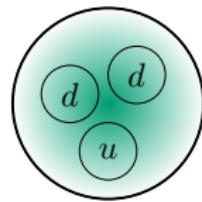


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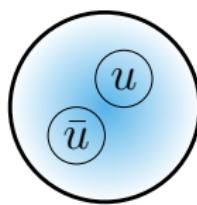
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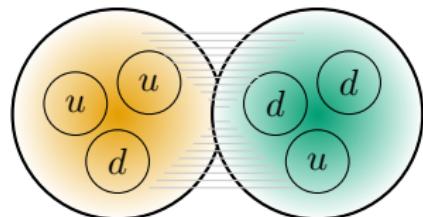
Ordinary matter:



baryon



meson



hadronic molecules

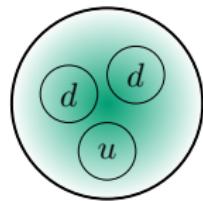
Mass [GeV]		Charge		Spin		Color		Name	
4.13 MeV	0	2/3	-1/3	0	1/2	1	1	u	up
4.13 MeV	0	2/3	-1/3	0	1/2	1	1	c	charm
4.13 MeV	0	2/3	-1/3	0	1/2	1	1	t	top
4.13 MeV	0	2/3	-1/3	0	1/2	1	1	g	gluon
44.4 MeV	-1/3	0	0	0	1/2	0	0	H	Higgs boson
144 MeV	-1/3	0	0	0	1/2	0	0	γ	photon
444 MeV	-1/3	0	0	0	1/2	0	0	Z	Z boson
877 MeV	-1/3	0	0	0	1/2	0	0	W	W boson
Mass [GeV]		Charge		Spin		Color		Name	
0.01 MeV	1	1/2	-1/2	0	1/2	1	1	e	electron
0.01 MeV	1	1/2	-1/2	0	1/2	1	1	μ	muon
0.01 MeV	1	1/2	-1/2	0	1/2	1	1	τ	tau
0.01 MeV	1	1/2	-1/2	0	1/2	1	1	ν_e	electron neutrino
0.01 MeV	1	1/2	-1/2	0	1/2	1	1	ν_μ	muon neutrino
0.01 MeV	1	1/2	-1/2	0	1/2	1	1	ν_τ	tau neutrino
Mass [GeV]		Charge		Spin		Color		Name	
0.01 GeV	0	0	0	0	1/2	0	0	ρ	rho
0.01 GeV	0	0	0	0	1/2	0	0	ω	omega
0.01 GeV	0	0	0	0	1/2	0	0	ϕ	phi
0.01 GeV	0	0	0	0	1/2	0	0	χ_1^0	chi 1
0.01 GeV	0	0	0	0	1/2	0	0	χ_2^0	chi 2
0.01 GeV	0	0	0	0	1/2	0	0	χ_3^0	chi 3
0.01 GeV	0	0	0	0	1/2	0	0	χ_4^0	chi 4

Variety of the hadronic states

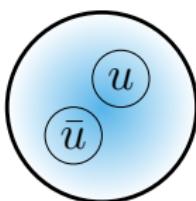
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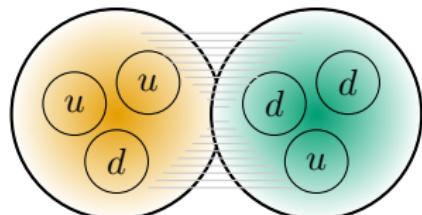
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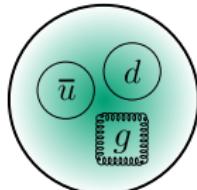


hadronic molecules

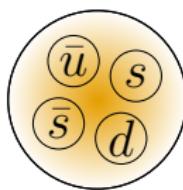
Exotic matter:



glueball



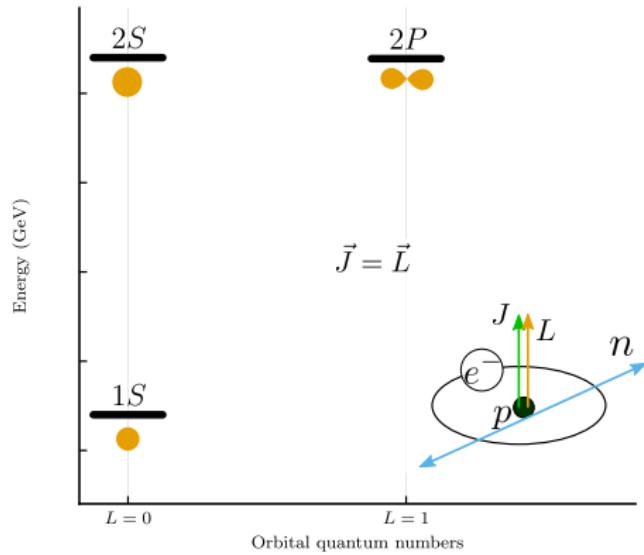
hybrid



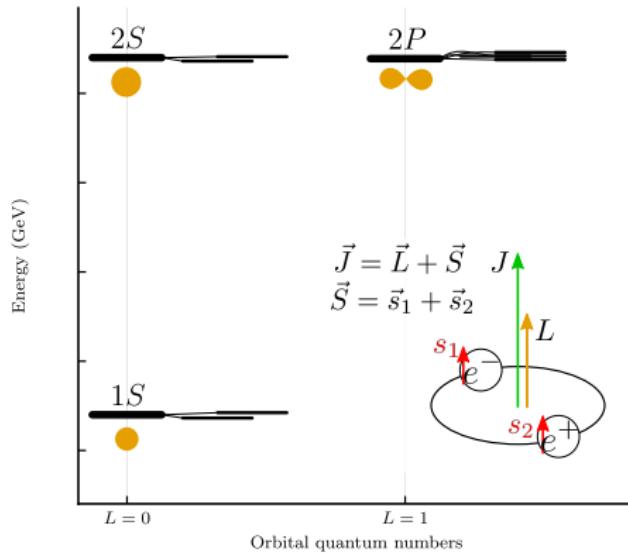
tetraquark

Mass	40.2 MeV/c ²	14.4 MeV/c ²	14.2 MeV/c ²	14.5 MeV/c ²				
charge	0	-1/3	-1/3	-1/3	-1/3	-1/3	-1/3	-1/3
spin - par	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
u	up	c	t	s	b	e	\mu	\tau
d	down	charm	top	strange	bottom	electron	muon	tau
\bar{u}	down	charmed	top	strange	bottomed	electron neutrino	muon neutrino	tau neutrino
\bar{d}	up	up	down	down	down	\nu_e	\nu_\mu	\nu_\tau
\gamma								Z boson
g								W boson
H								Higgs boson

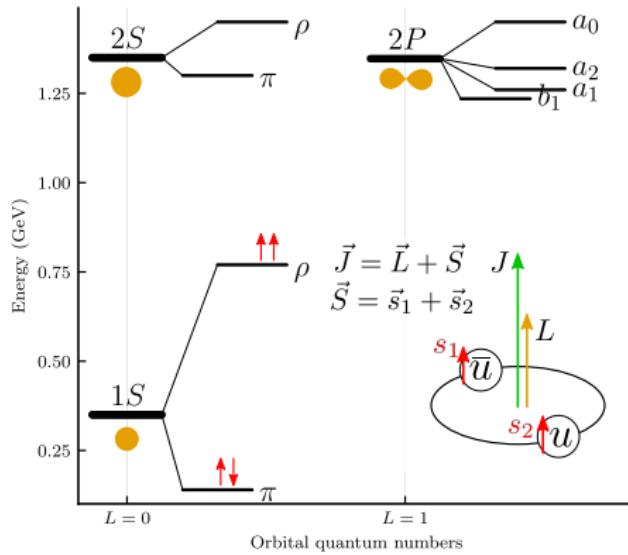
Excitation spectrum of a bound system



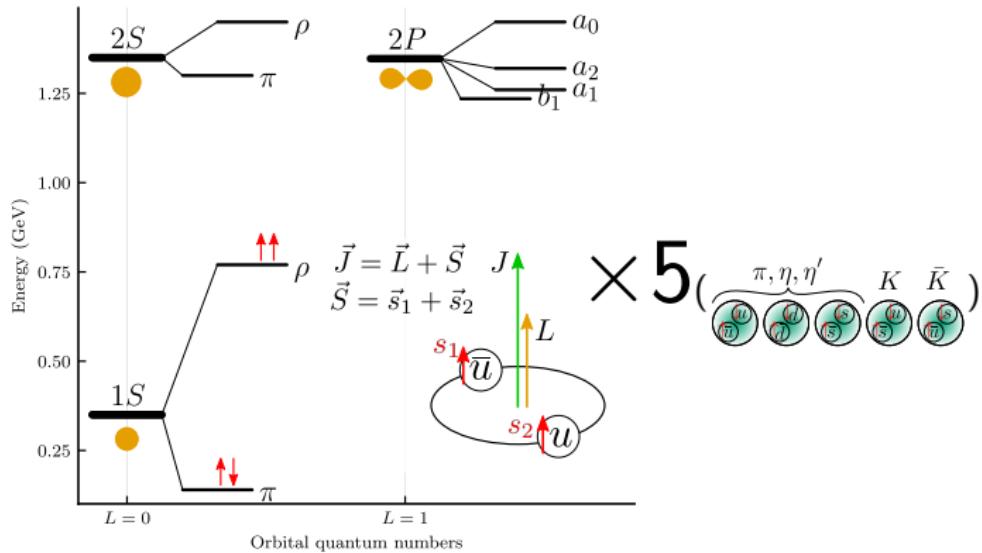
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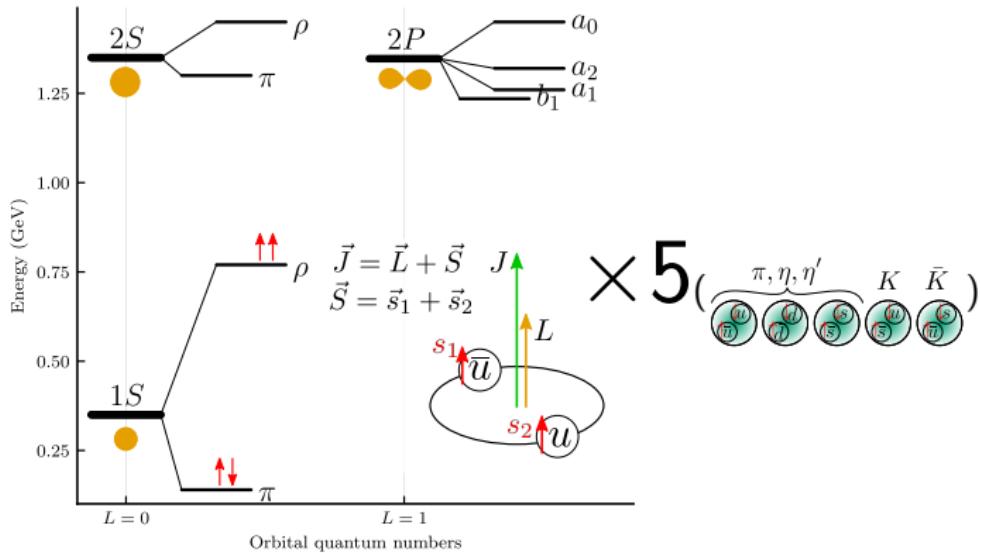
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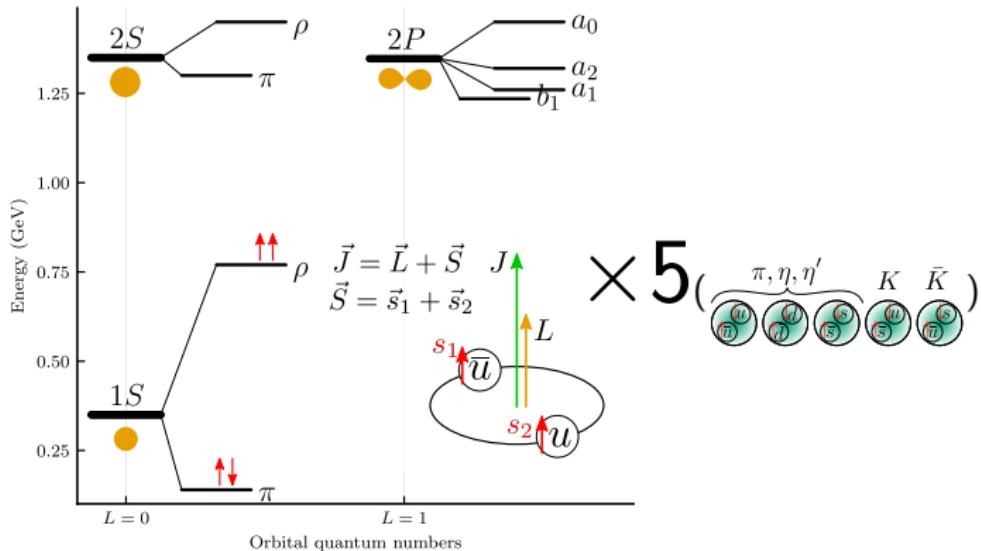
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Example: “Spin-flip” transition of the $1S$ state

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

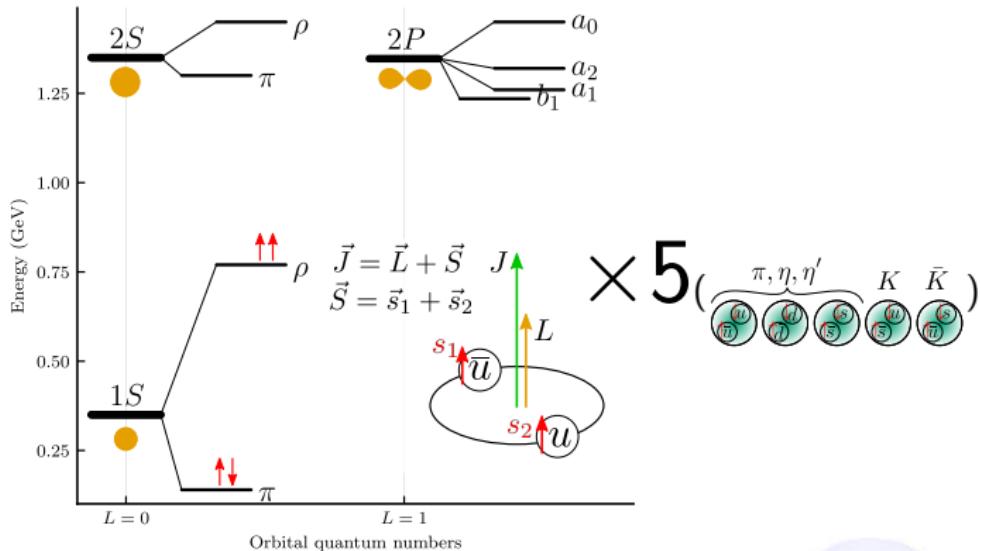
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Example: “Spin-flip” transition of the $1S$ state

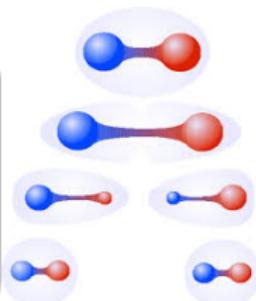
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- $\rho(\uparrow\uparrow) \rightarrow \pi(\uparrow\downarrow)$ transition

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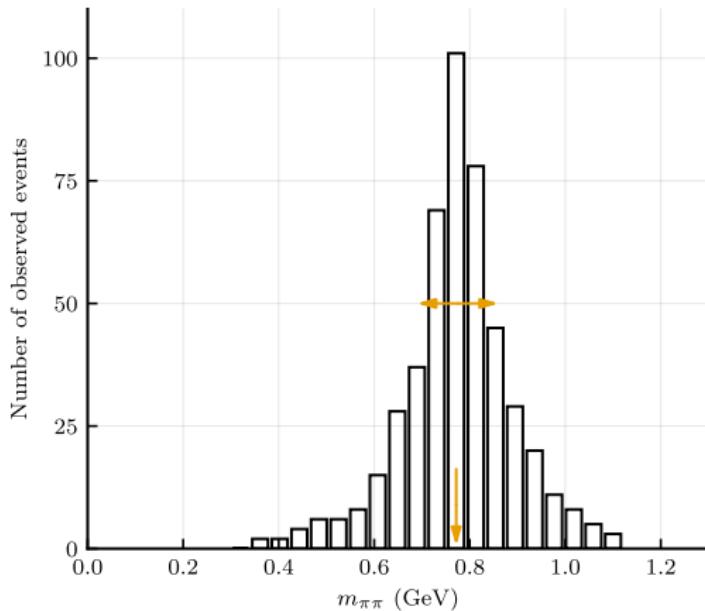


Example: “Spin-flip” transition of the 1S state

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



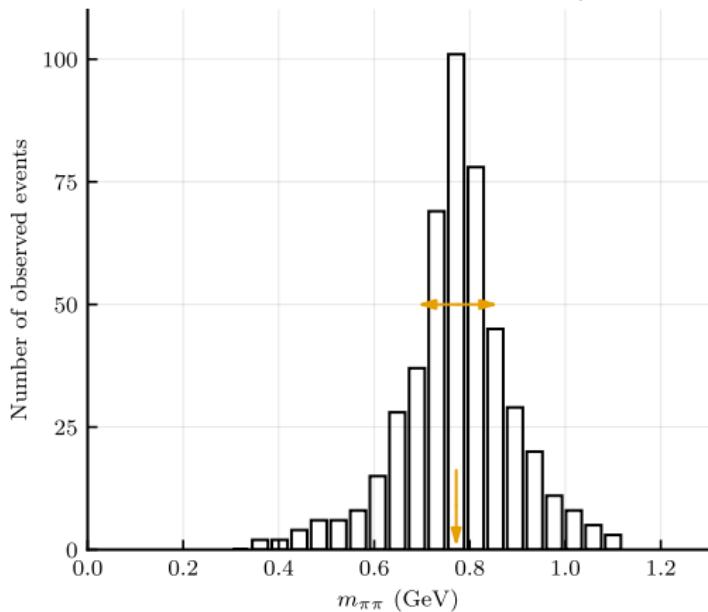
Invariant-mass distribution, resonances



Hadronic state is a particle

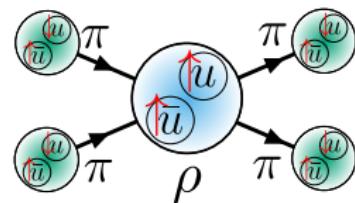
- charact. by **mass** (energy) and **width** (lifetime)

Invariant-mass distribution, resonances



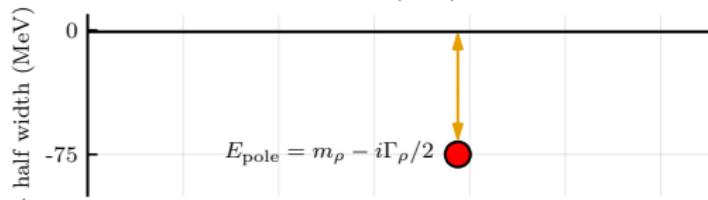
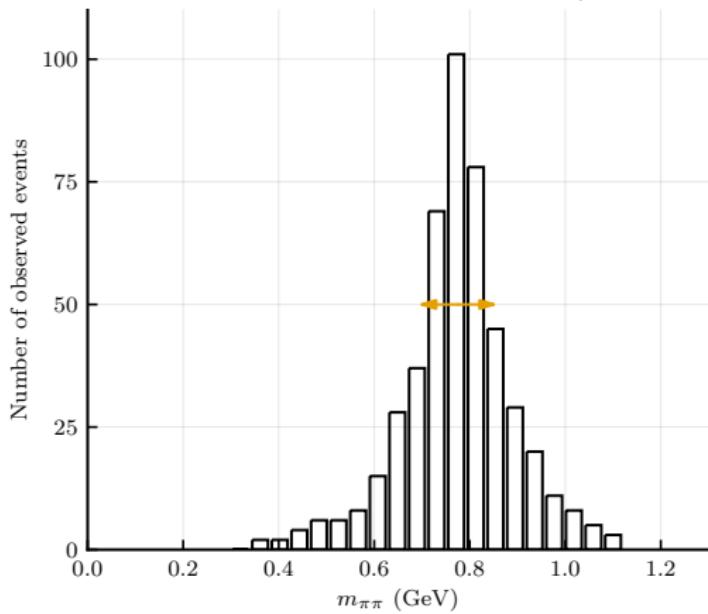
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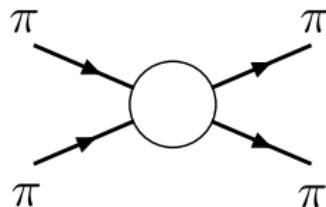
- Hadronic states are **resonances** of the hadronic system
- Read m , Γ from spectrum

Invariant-mass distribution, resonances



Hadronic state is a particle

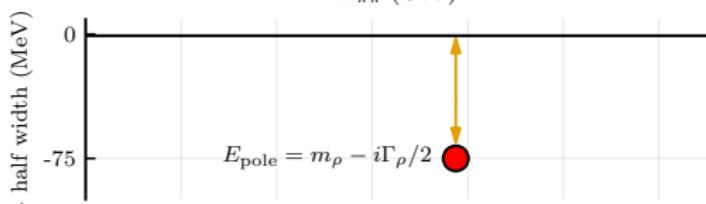
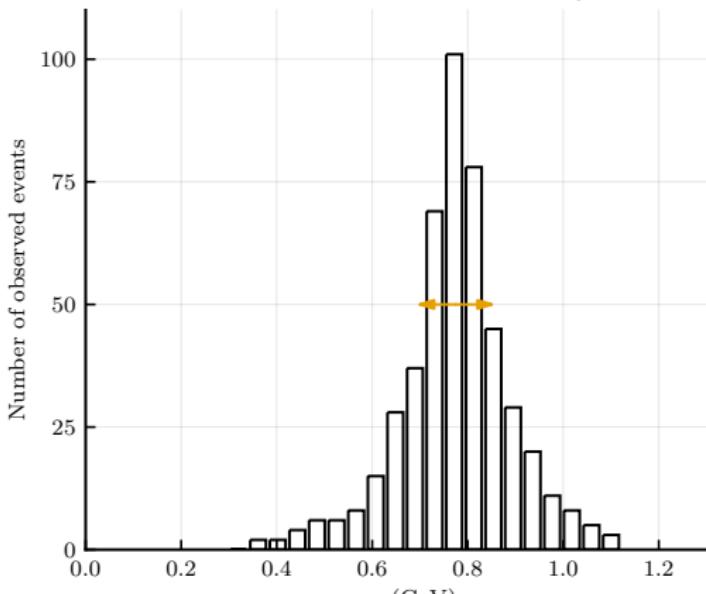
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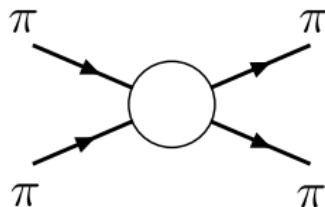
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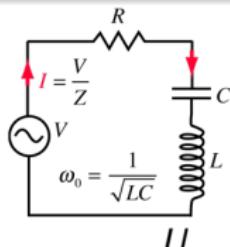
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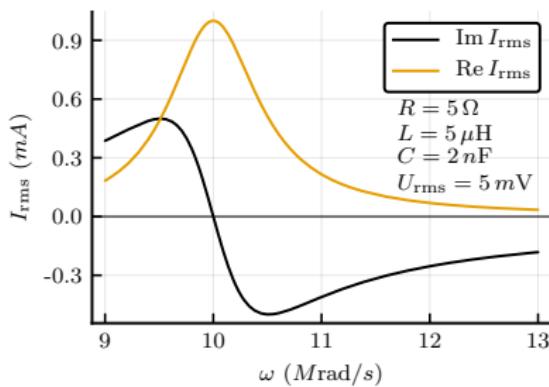
- resonances are **poles** of scattering amplitude.

Resonances are poles of the amplitude

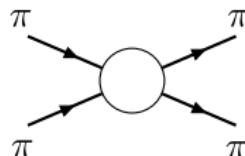
Electric circuit



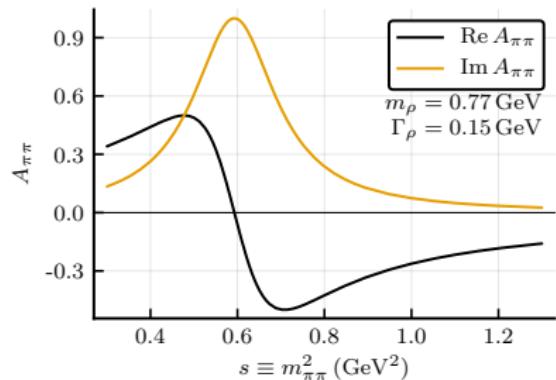
$$I_{\text{rms}} = \frac{U}{R + iL\omega - \frac{i}{C\omega}}$$



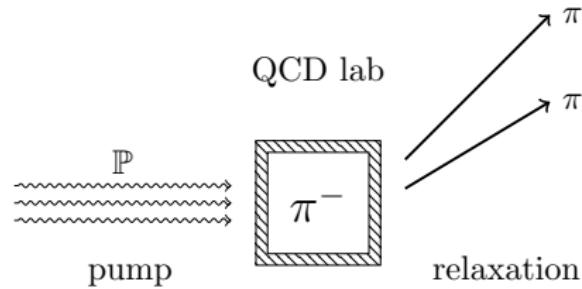
Scattering



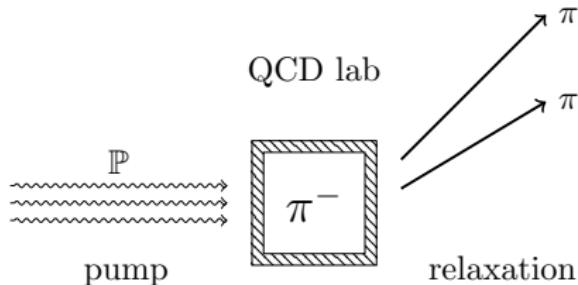
$$A_{\pi\pi} = \frac{m\Gamma}{m^2 - s - im\Gamma}$$



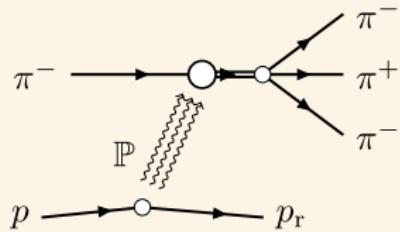
Another way to study hadronic excitations



Another way to study hadronic excitations

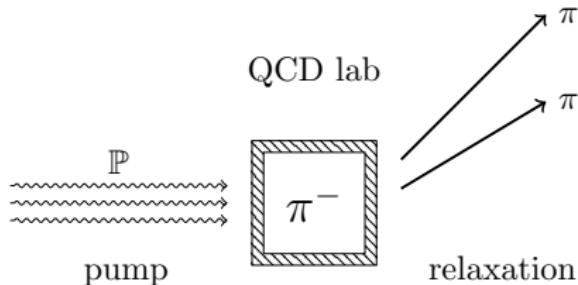


Diffractive reaction

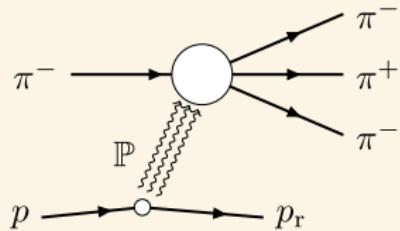


- pion beam scattered off the proton target
- high energy guarantees t -channel process.
- the target provide the gluonic field
- 3π production has the largest cross section (inelastic)

Another way to study hadronic excitations

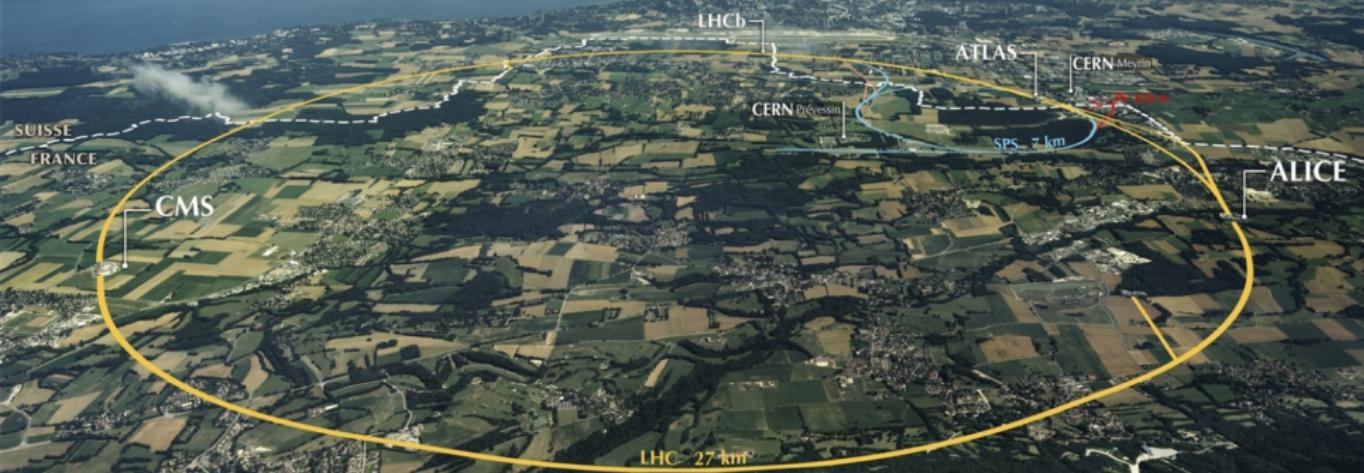


Diffractive reaction



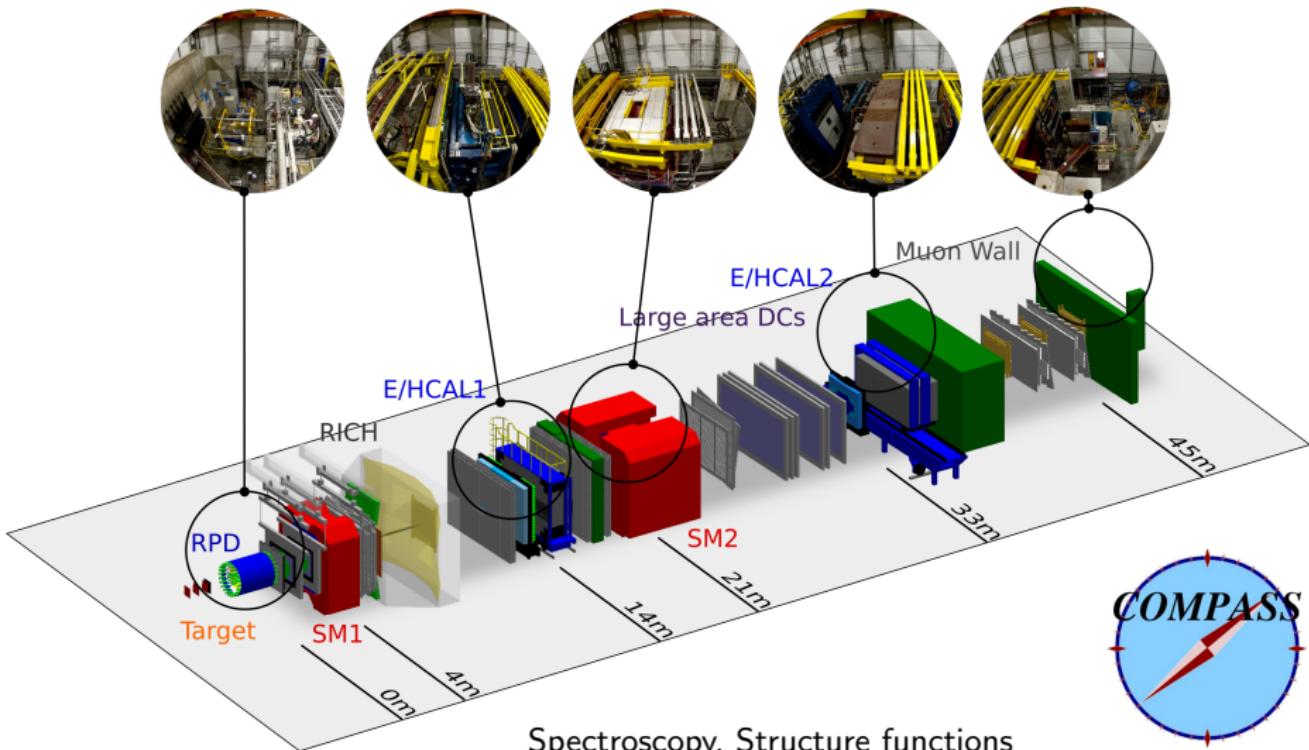
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[Image: Maximilien Brice/CERN]





COMPASS Experiment



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

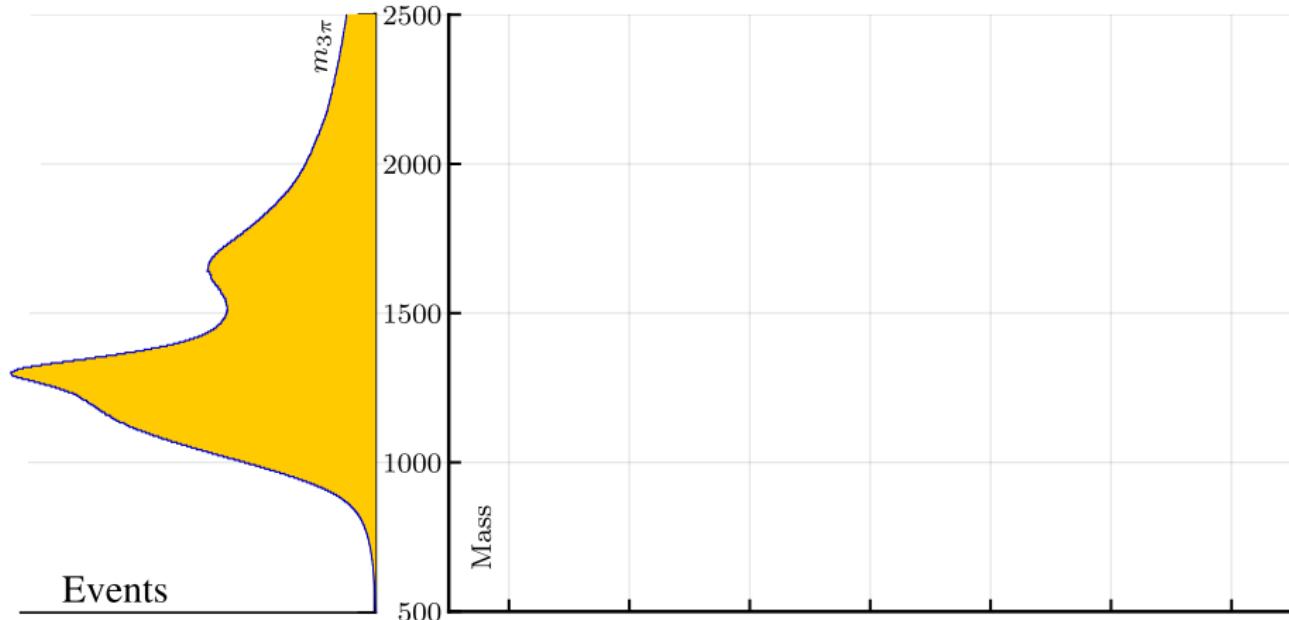


Understanding of the 3π spectrum

[(COMPASS) PRD95 (2017) 032004]

The results of the main big fit

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

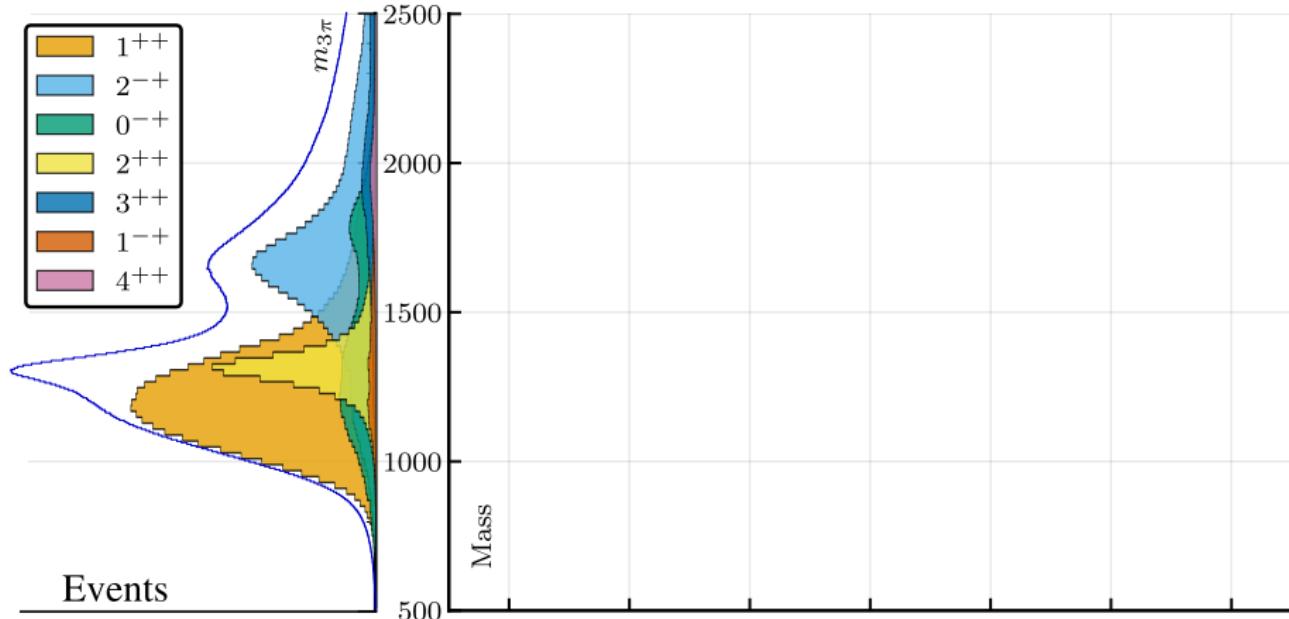


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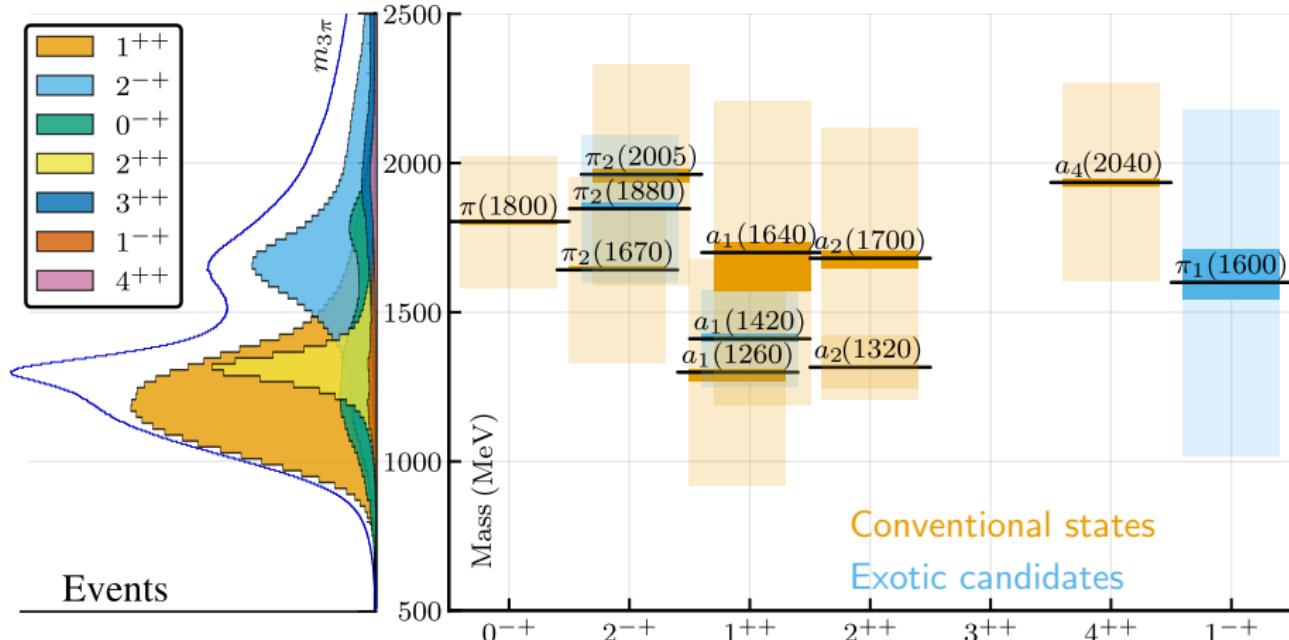


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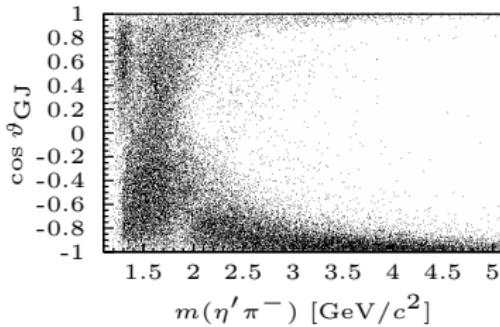
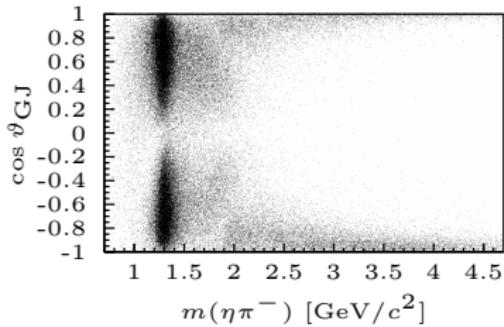
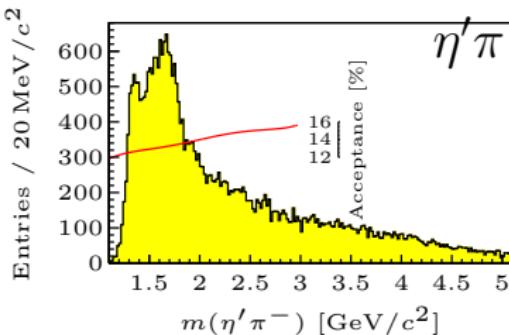
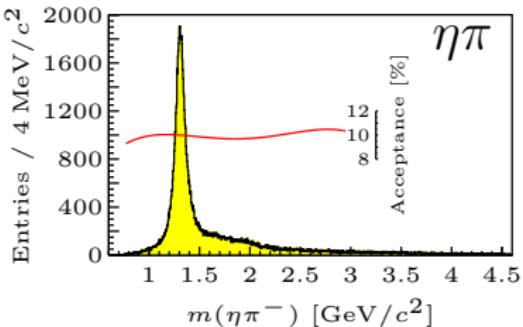
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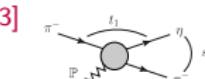
- 11 resonances are established including potentially exotic contributions

$\eta^{(\prime)}$ π analyses

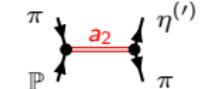
$\eta\pi$ vs $\eta'\pi$ at COMPASS



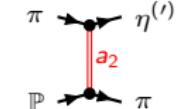
$\eta^{(\prime)}(0^-)\pi(0^-)$, $J^{PC} = L^{P+}$ \Rightarrow $\cos \theta_{\text{GJ}}$ asymmetry \Rightarrow exotic waves!



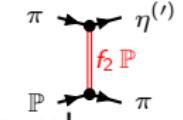
Resonance production



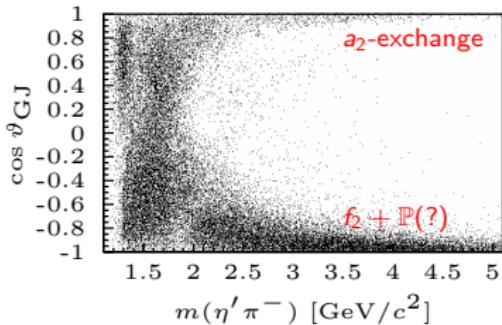
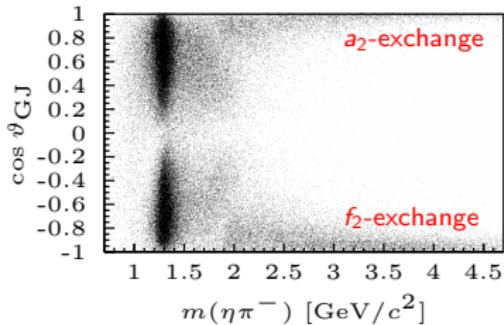
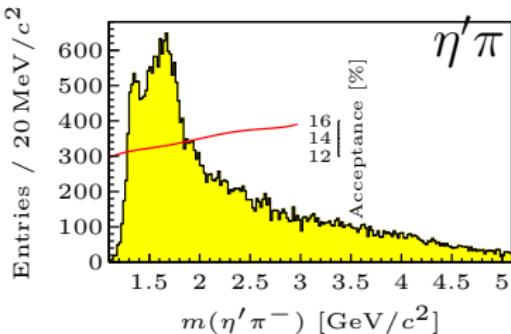
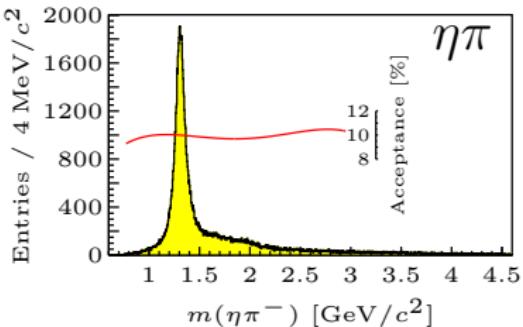
η -forward production



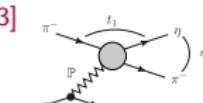
π -forward production



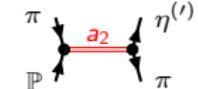
$\eta\pi$ vs $\eta'\pi$ at COMPASS



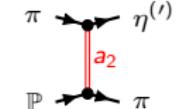
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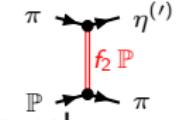
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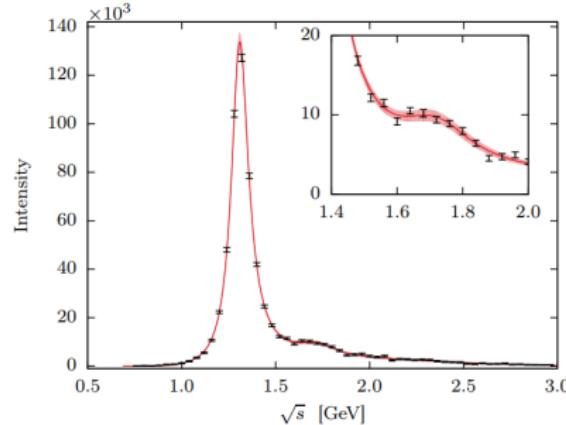
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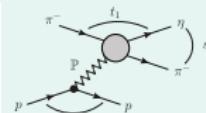
Tensor mesons ($J^{PC} = 2^{++}$)

Advanced $\eta\pi$ analysis

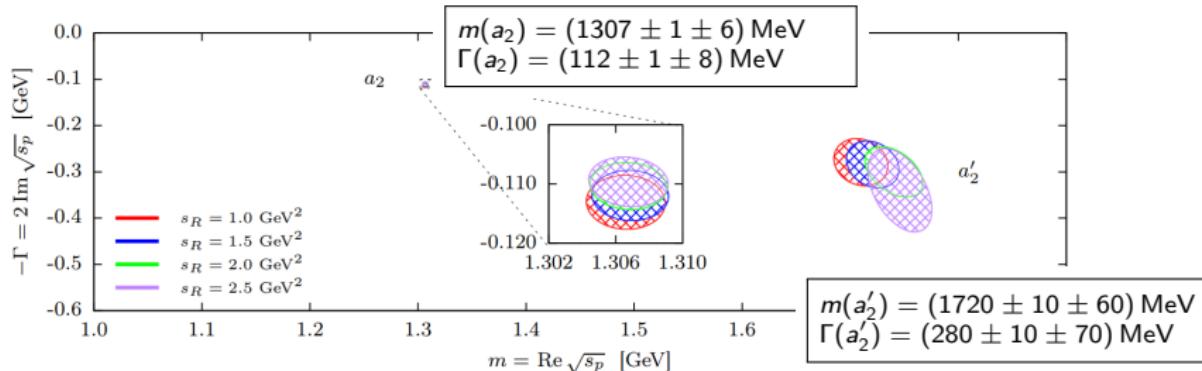
[A.Jackura, MM,A.Pilloni,et al. (JPAC-COMPASS), PLB779, 464-472]



Single channel: $\eta\pi D$ -wave



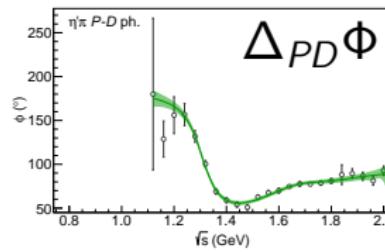
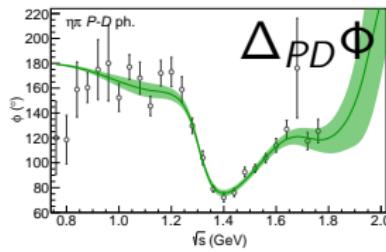
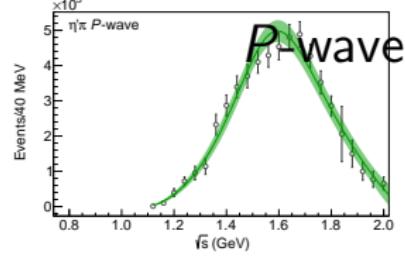
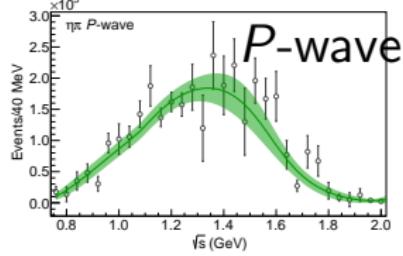
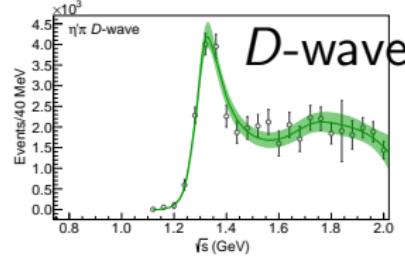
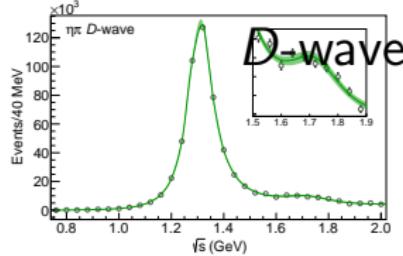
- Elastic unitarity
- Two CDD-poles



Multiple-channel analysis

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

$\chi^2/\text{ndf} = 162/122$, the band - 2σ bootstrap error



D-wave difference

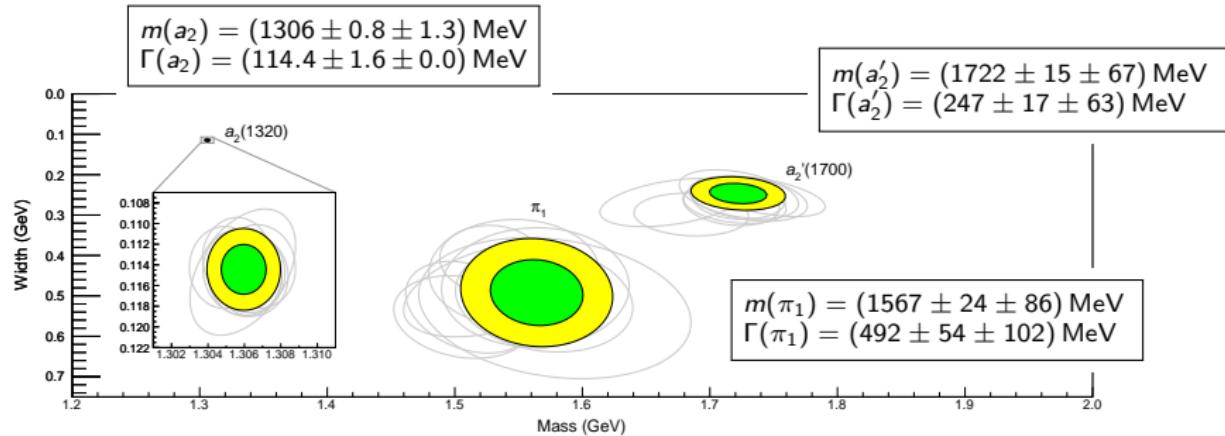
- Kinematics
 $(m_{\eta'} > m_\eta)$
- ⇒ Same amplitude.

P-wave difference

- production mechanism
- + kinematics.

Results: pole positions

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



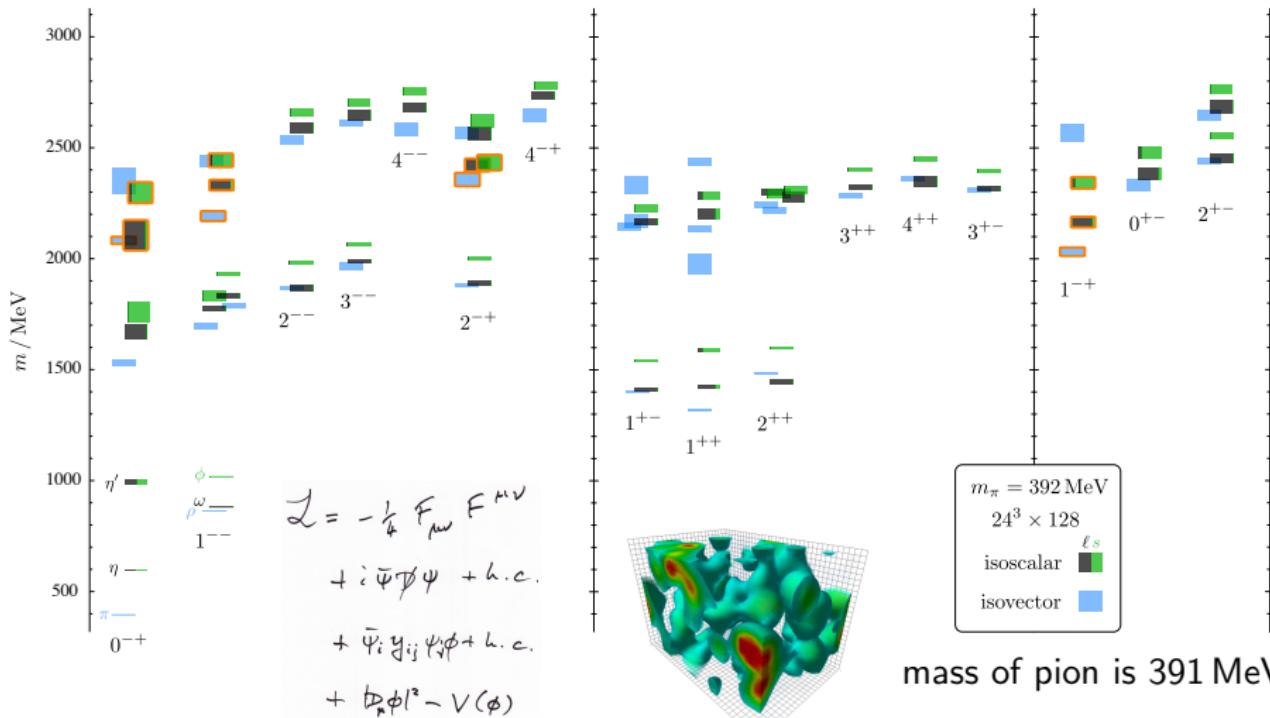
- Change parametrization of the denominator $\rho N_{ki}^J(s') = \delta_{ki} \frac{(p_{\eta^{(\prime)}\pi}\sqrt{s}/2)^{2J+1}}{(s'+s_L)^{2J+1+\alpha}}$,
 - ▶ $s_R = 1 \text{ GeV} \rightarrow 0.8, 1.8 \text{ GeV}$.
 - ▶ $\alpha = 2 \rightarrow 1 \text{ GeV}$.
 - ▶ Different function, $\rho N_{ki}^J(s') = \delta_{ki} Q_J(z_{s'}) s'^{-\alpha} \lambda^{-1/2}(s', m_{\eta^{(\prime)}}^2, m_\pi^2)$
- Change of parameters in the numerator $n(s)$
 - ▶ Effective transferred momentum $t_{\text{eff}} = -0.1 \text{ GeV}^2 \rightarrow -0.5 \text{ GeV}^2$.
 - ▶ Order of the polynomial 3rd-order \rightarrow 4th-order.

On the lattice QCD

Hadronic excitations

Results of lattice QCD

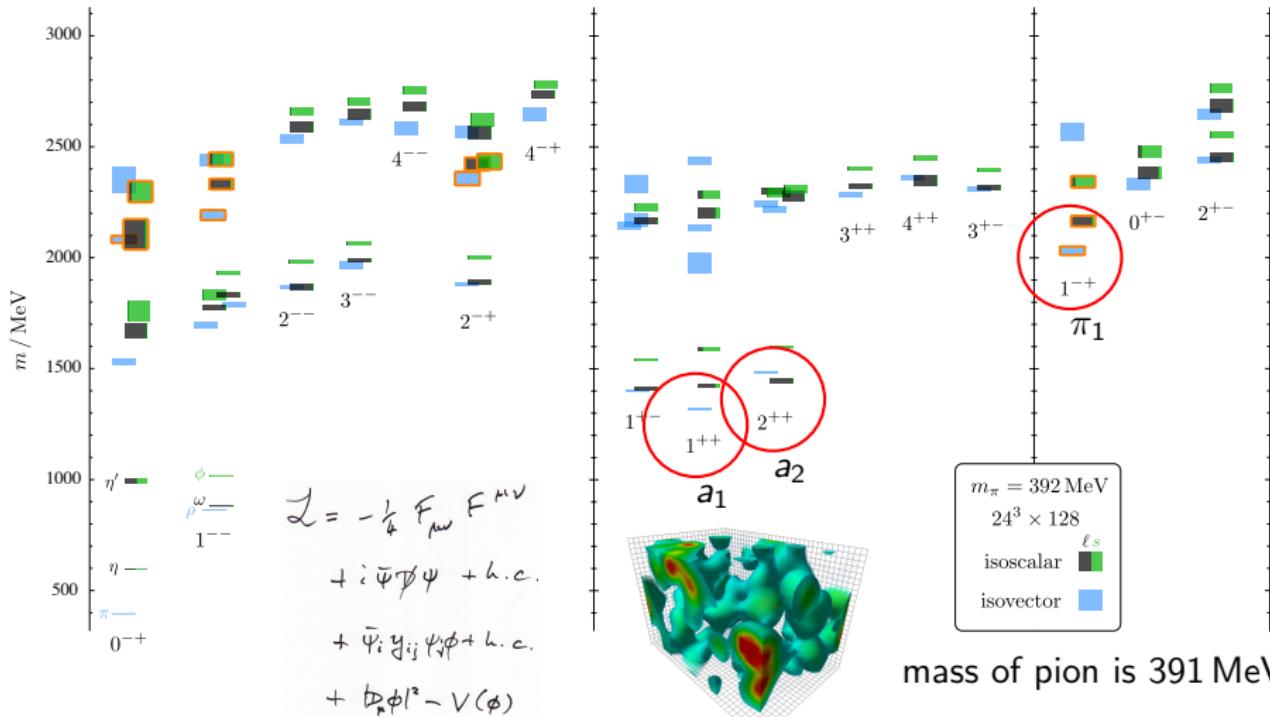
[Dudek et al., PRD 88, 094505 (2013)]



Hadronic excitations

Results of lattice QCD

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



Part 1: light mesons

Live coding #1

3. Find the pole position of a_2

White board

$\eta\pi$ system

Live coding #2

1. PWA: get angular variables
2. PWA fit: extended log Likelihood

Part 2: Three body physics

White board

Introduction to the three body decays

Live coding #3:

4. Three-body kinematics
5. Three-body dynamics

White board

Helicity formalism

Live coding #4:

6. The pentaquark decay