Accessing and Understanding QCD spectrum: Introduction and goals of the workshop

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INT, March 20th, 2023

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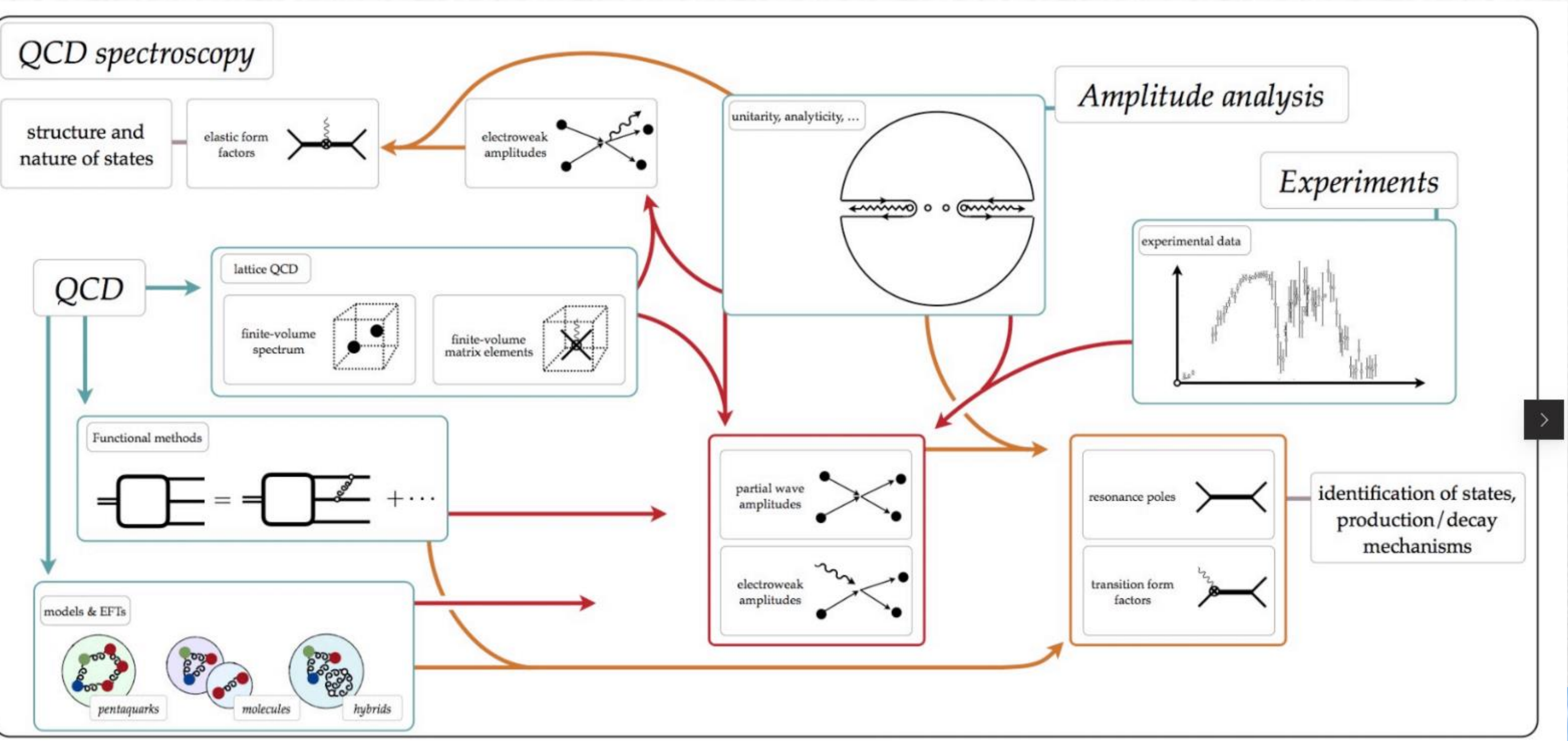
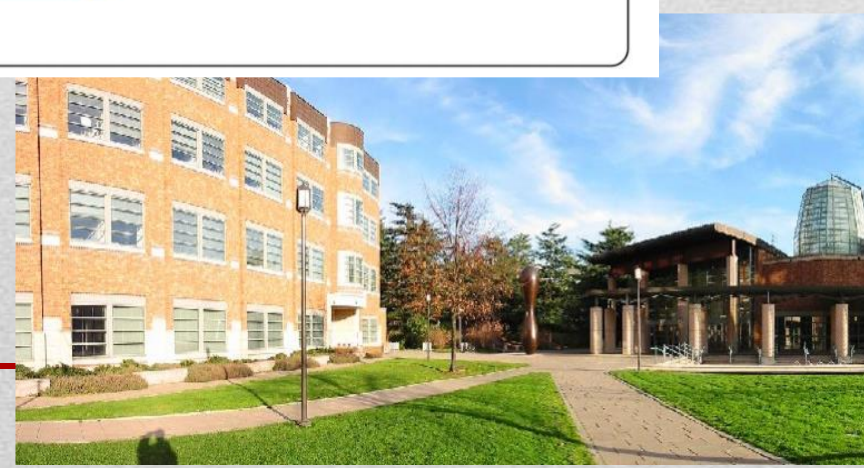
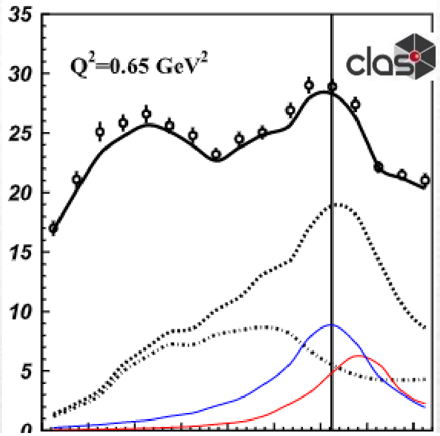
Workshop in ~~2020~~ 2023 (finally!)

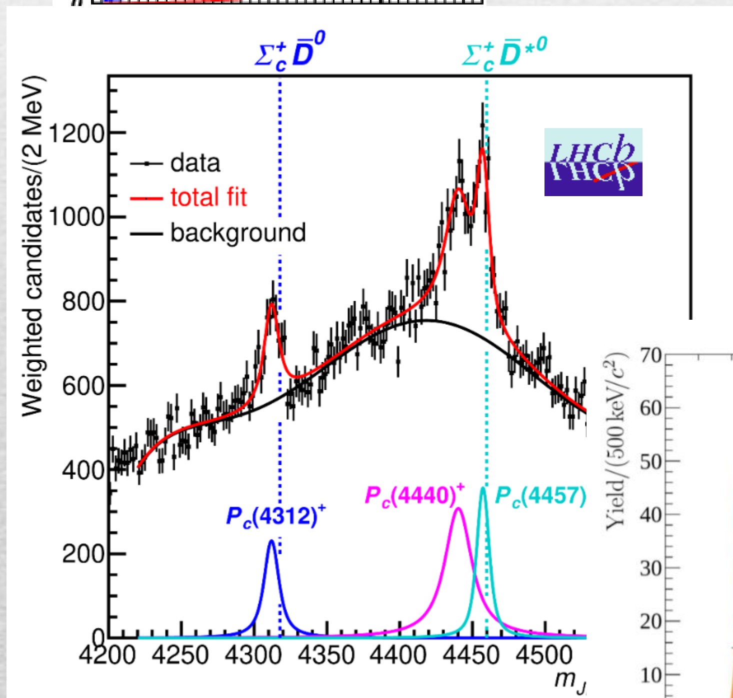


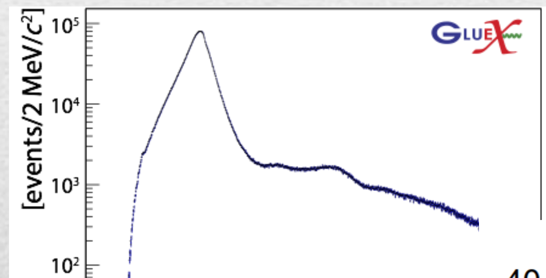


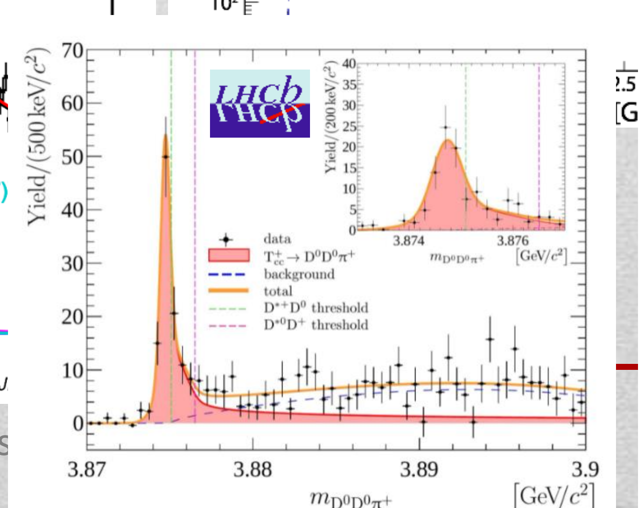
The richness of hadron spectrum

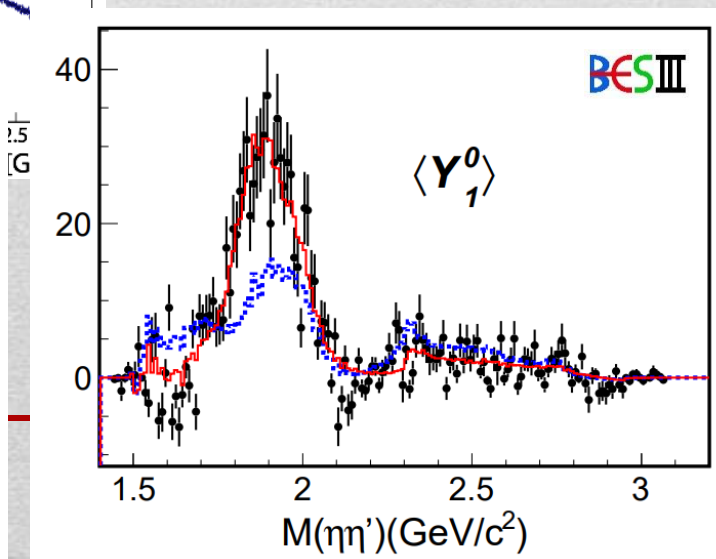


- The structures populating hadron reactions are extremely rich
- Ultimate goal is to understand them in term of QCD degrees of freedom
- To do so, the spectrum of resonances must be correctly reconstructed









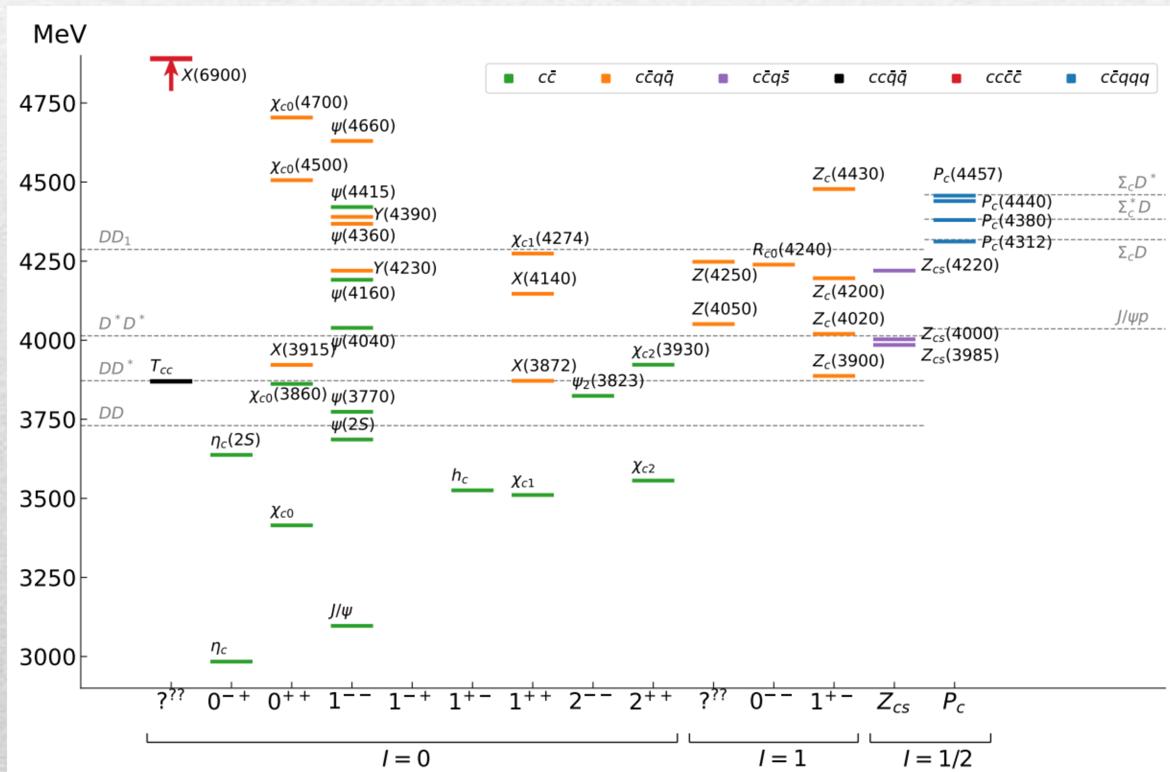
Exotics

The quark model is still the simplest tool to organize the spectrum

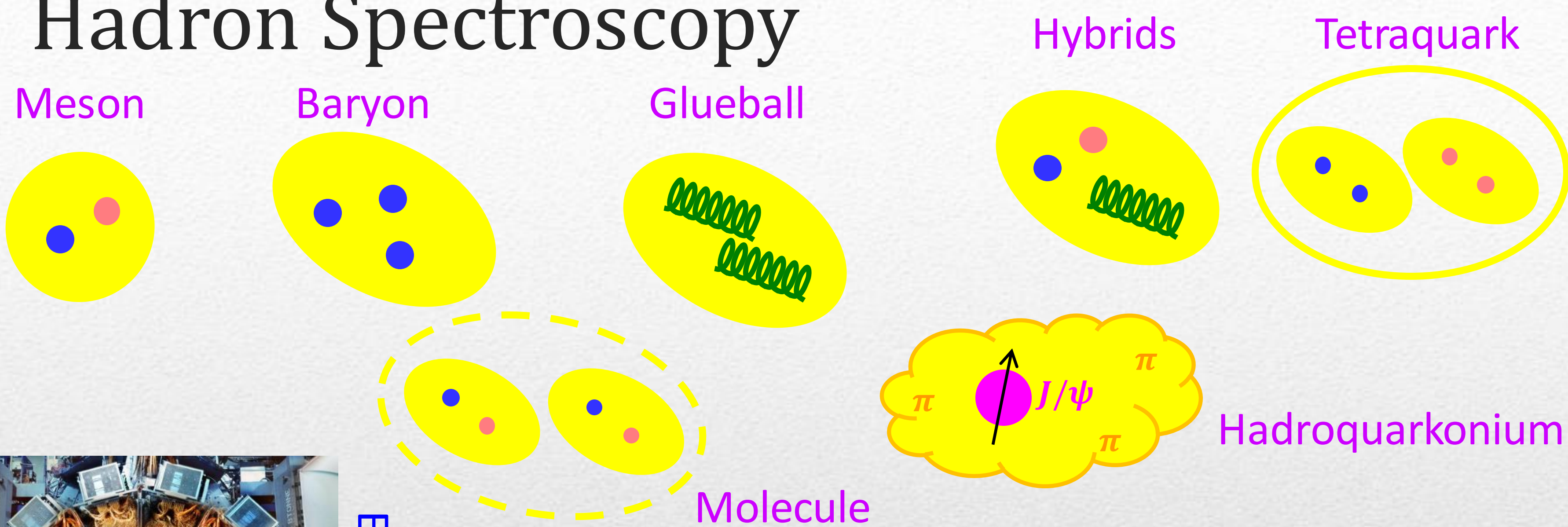
JPAC, PPNP 127 (2022), 103981

«Exotic hadrons» are Beyond the Standard (quark) Model

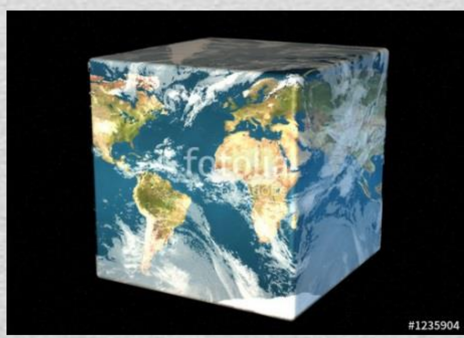
Organizing them teaches us some more about quark-gluon interactions



Hadron Spectroscopy



Experiment



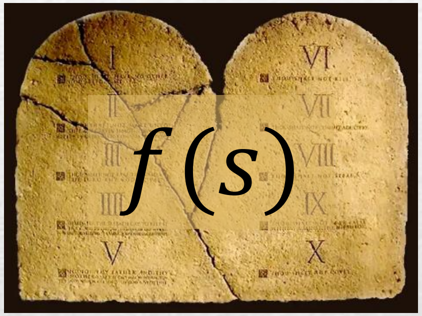
Lattice QCD

Data → Amplitude analysis → QCD

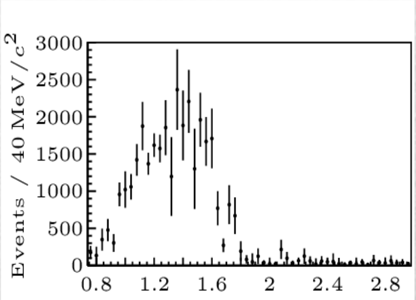
Interpretations on the spectrum leads to understanding fundamental laws of nature

Top-down approach

1) You are given a model/theory



2) You calculate the amplitude



3) You compare with data.
   Or you don't.

Predictive power ✓
Physical interpretation ✓
(within the model! ✘)
Biased by the input ✘

Options on the market

Quark-level calculations:

- Quark models, pNRQCD, Functional methods, Coulomb gauge, Holography, large-N QCD, Sum Rules…
- Spectrum generally calculated as bound states of some potential
- Decay rates as «overlap integrals» between two static configurations

Comprehensive picture ✓ Little scattering dynamics ✘

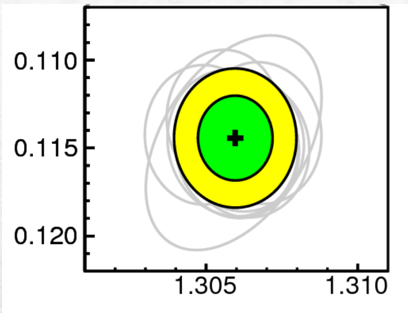
Hadron level calculations:

- Microscopic models inspired to EFT + Unitarization
- Compact states vs. molecules, triangles...
- States as poles of scattering amplitudes
- Couplings as residues at the poles

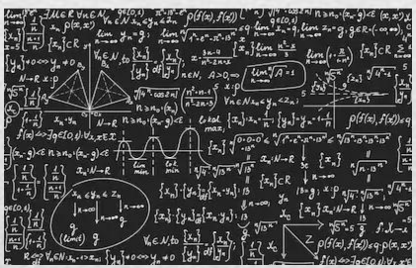
Scattering dynamics ✓ More case-by-case ✓✘

Bottom-up approach

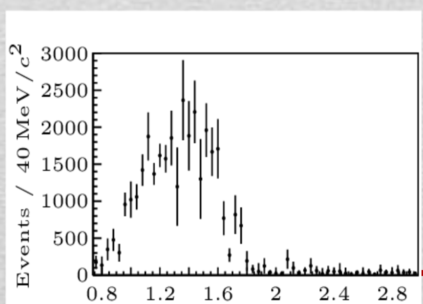
Less predictive power ✘
Some physical interpretation ✘
Minimally biased ✓



3) You extract physics

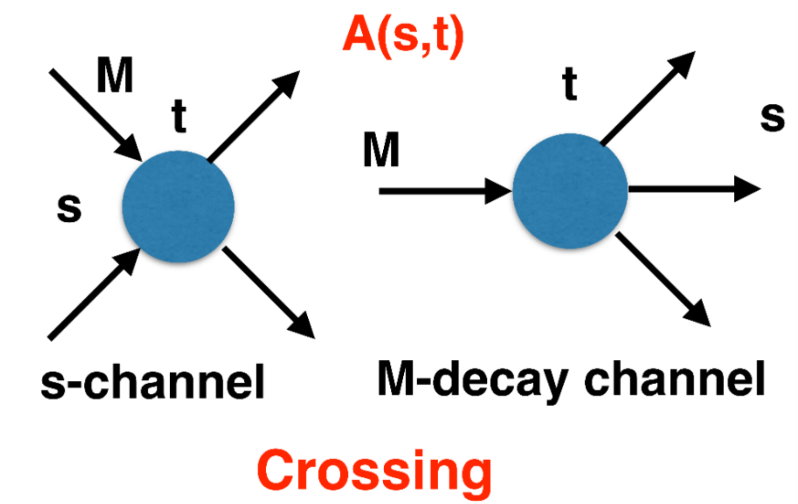


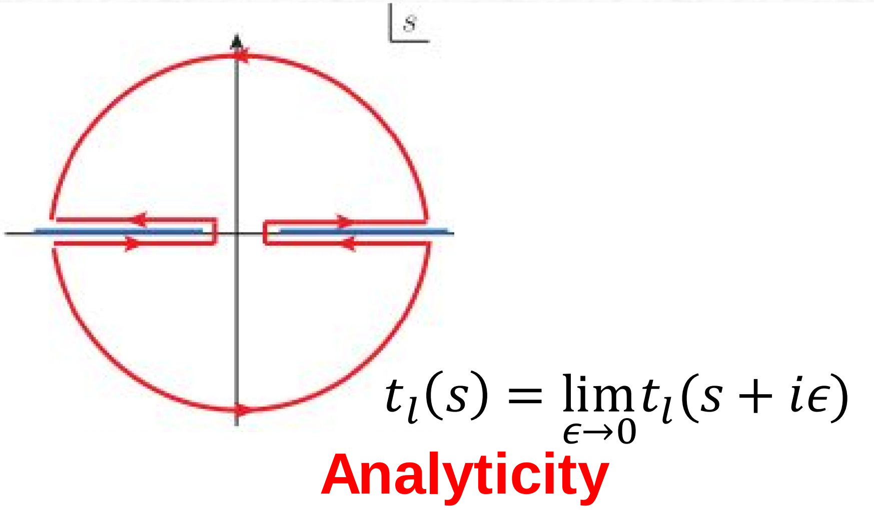
2) You choose a set of generic amplitudes

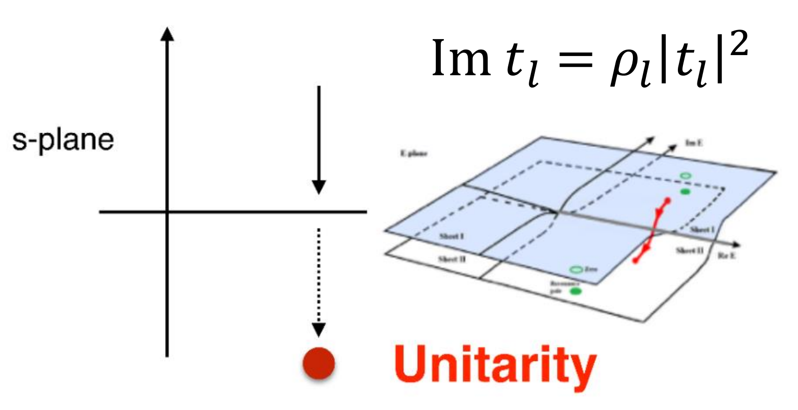


1) You start with data

S-Matrix principles







+ Lorentz, discrete & global symmetries

These are constraints the amplitudes have to satisfy, but do not fix the dynamics

They can be imposed increasing amount of rigor, to extract physics information from data

They can be imposed strictly to browse the «theory space» and assess where QCD sits among them

The questions we want to address

When cardinales reunite in conclave, they first agree on the characteristics that the new pope should have

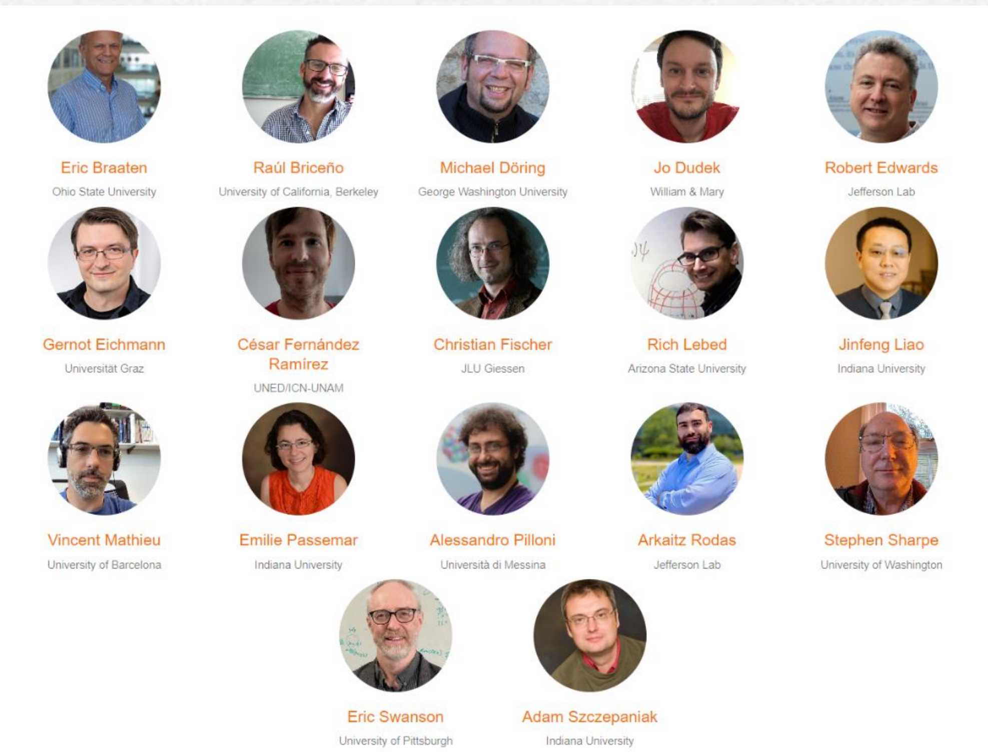
Then doors are shut and fights start

The questions we want to address

- What «understanding» mean?
  What would be the acceptable end of the hadron quest?
- Once we have the determined the spectrum and interactions of hybrids/XYZ/glueballs etc., what do we really want to learn?
- What level of complementarity can we expect between Lattice QCD and experimental data in the next decade?
- Is the present model of collaboration between theory and experiment efficient?
- Could AI technology provide groundbreakingly different tools?

Examples of collaborative efforts

ExoHad
Exotic Hadrons Topical Collaboration

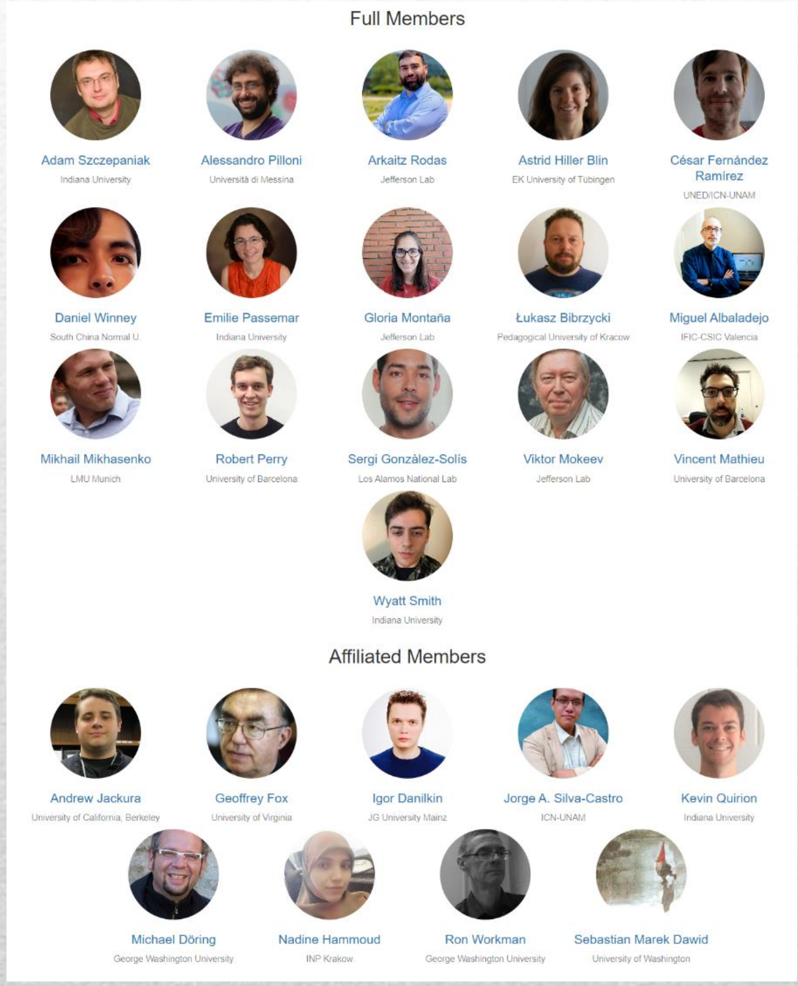


Funded in 2023 by DoE as a Topical Collaboration in Nuclear Physics

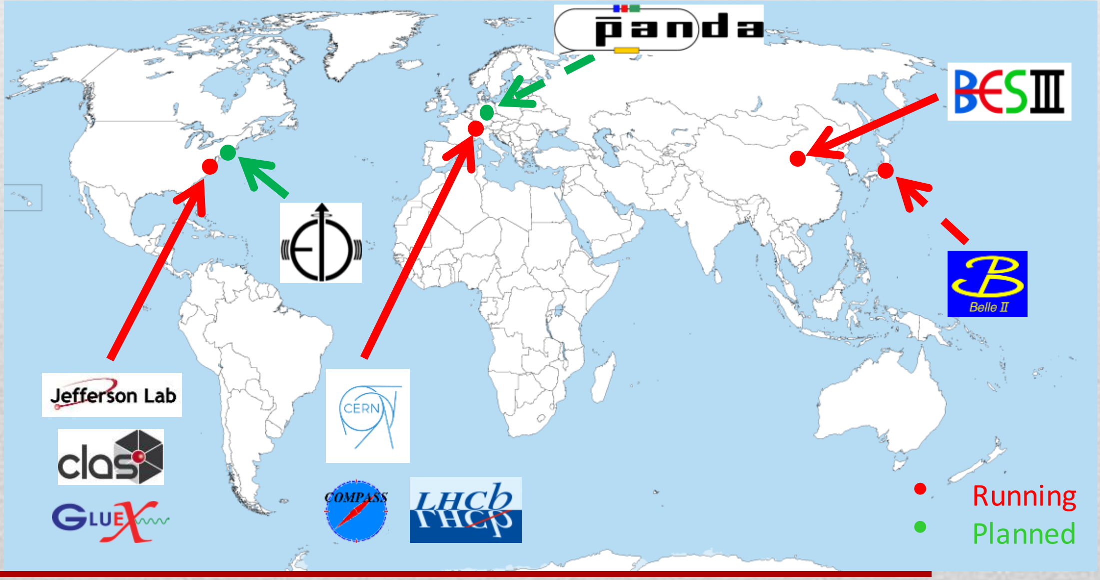
Aims at exploring all aspects of exotics (= hybrids at GlueX)

1. from predictions within lattice QCD
2. through reliable extraction of their existence and properties from experimental data,
3. to descriptions of their structure within phenomenological models.

Examples of collaborative efforts



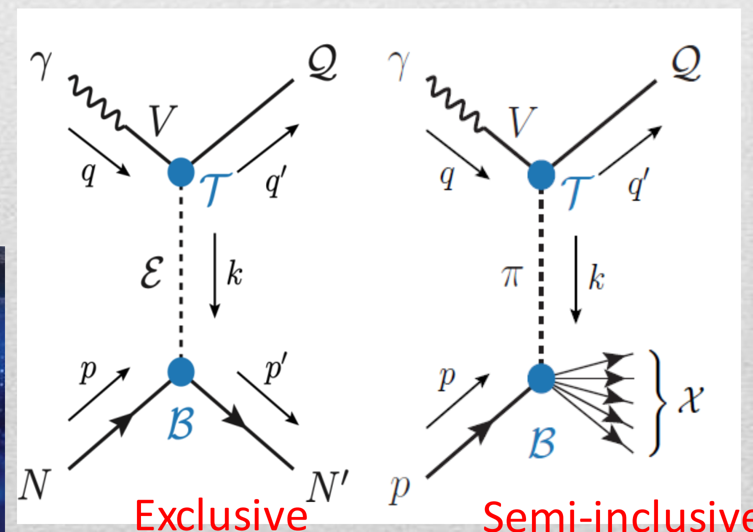
Funded in 2013 as theory support originally for JLab exps, but grew up much larger
Creates bridges between theorists and experimentalists



Shaping future experiments

Spectroscopy is one of the main physics cases to push for new facilities,
e.g. the energy upgrade at JLab

The community must act coherently to show that such facilities are much needed ($$$!)

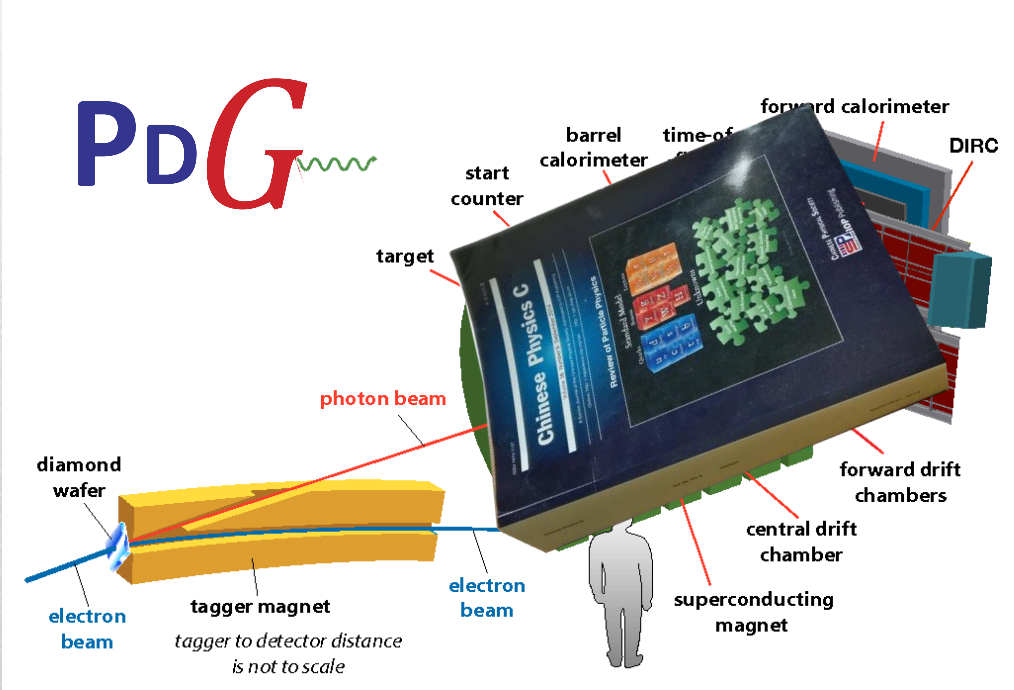


	Monday 03/20	Tuesday 03/21	Wednesday 03/22	Thursday 03/23	Friday 03/24
09:00	Pilloni - Introduction	Glazier - EIC	Free Morning	Shepherd - Light @GlueX	Prelovsek - Tcc in LQCD
09:30	Athenodorou - Glueballs in LQCD	Dobbs - Charmonia @GlueX			Fischer - 4q with DSE
10:00	Markus - Glueballs in DSE	Tripolt - Pole searches		Wunderlich - Bayesian truncation of partial waves	Mohler - Λ(1405) in LQCD
10:30	Coffee			Coffee	
11:00	Smith - Coulomb gauge in LQCD	Guerrieri - Bootstrapping QCD		Dawid - Analytic continuation of 3-body amplitudes	Rusetski - 3-body in Finite Volume
11:30	Segovia - Constituent Quark Model			Islam - Analytic continuation of 3-body amplitudes	Ortega-Gama - Inserting currents in Finite Volume
12:00	Swanson - Constituent gluons	Danilkin - Dispersive $\gamma\gamma \to DD$		Döring - 3-body in LQCD with FVU	Pefkou - 3-body amplitudes with bound states
12:30		Diversity lunch - Sharpe		Outreach lunch - Briceño	
13:00					
13:30					
14:00	Bruschini - Potentials	Pelaez - Dispersive $f_0(1370)$	Nicholson - NN in LQCD	Mai - 3-body in LQCD with FVU	Mikhasenko - Scattering parameters for Tcc
14:30	Lebed - Diquarks vs. molecules	Ruiz de Elvira - Dispersive isospin breaking	Hanlon - NN in LQCD	Shuryak - Light Front	Discussion: Oustanding problems, Eichmann
15:00	Mohapatra - Heavy Hybrids	Rodas - σ in LQCD	Romero-Lopez - maximal isospin 3-meson in LQCD	Brodsky - Light Front	
15:30	Coffee				
16:00	Ikeno - Molecules	Hanhart - Molecules	Walker-Loud - πN in LQCD	Dudek - Radiative decay of K* in LQCD	Sharpe - 3-body with spin
16:30	Discussion: Models, Swanson	Discussion: Analysis, Szczepaniak	Discussion: Lattice, Jackura	Discussion: Experiments, Austregesilo	
17:00					
17:30					

BACKUP

How theorists think of experiments

All the information about hadrons is collected by the Particle Data Group



What theorists see...

What experimentalists present...

Changing beam and target, you can change the font

$a_1(1260)$ [i] $\quad I^G(J^{PC}) = 1^-(1^{++})$

Mass $m = 1230 \pm 40$ MeV [j]
Full width $\Gamma = 250$ to 600 MeV

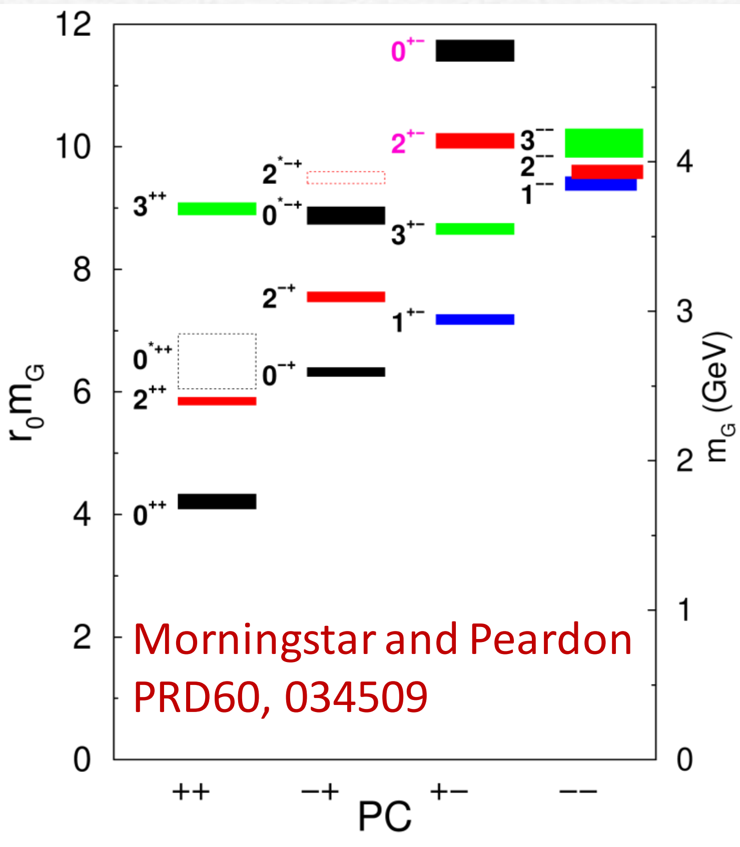
a_1(1260) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
3π	seen	577
$(\rho\pi)_{S-\text{wave}}, \ \rho \to \pi\pi$	seen	353
$(\rho\pi)_{D-\text{wave}}, \ \rho \to \pi\pi$	seen	353
$(\rho(1450)\pi)_{S-\text{wave}}, \ \rho \to \pi\pi$	seen	†
$(\rho(1450)\pi)_{D-\text{wave}}, \ \rho \to \pi\pi$	seen	†
$f_0(500)\pi, \ f_0 \to \pi\pi$	seen	–
$f_0(980)\pi, \ f_0 \to \pi\pi$	not seen	179
$f_0(1370)\pi, \ f_0 \to \pi\pi$	seen	†
$f_2(1270)\pi, \ f_2 \to \pi\pi$	seen	†
$\pi^+\pi^-\pi^0$	seen	576
$\pi^0\pi^0\pi^0$	not seen	577
$KK\pi$	seen	250
$K^*(892)K$	seen	†
$\pi\gamma$	seen	608

The scalar glueball

Glueballs

The clearest sign of confinement in pure Yang-Mills

The worst state to search in real life



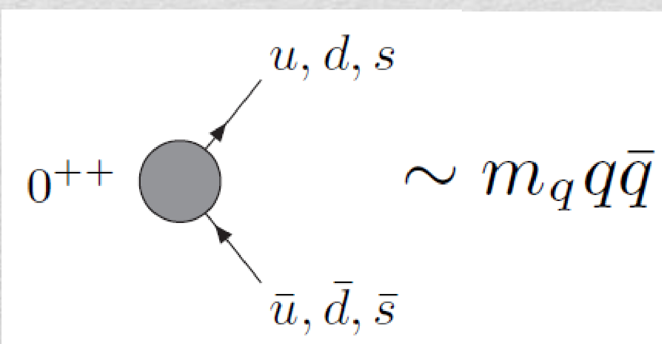
J^{PC}	Mass MeV			
	Unquenched	Quenched		
	This work	M&P	Ky	Meyer
0^{-+}		2590(40)(130)	2560(35)(120)	2250(60)(100)
2^{-+}	3460(320)	3100(30)(150)	3040(40)(150)	2780(50)(130)
0^{-+}	4490(590)	3640(60)(180)		3370(150)(150)
2^{-+}				3480(140)(160)
5^{-+}				3942(160)(180)
0^{--} (exotic)	5166(1000)			
1^{--}		3850(50)(190)	3830(40)(190)	3240(330)(150)
2^{--}	4590(740)	3930(40)(190)	4010(45)(200)	3660(130)(170)
2^{--}				3.740(200)(170)
3^{--}		4130(90)(200)	4200(45)(200)	4330(260)(200)
1^{+-}	3270(340)	2940(30)(140)	2980(30)(140)	2670(65)(120)
3^{+-}	3850(350)	3550(40)(170)	3600(40)(170)	3270(90)(150)
3^{+-}				3630(140)(160)
2^{+-} (exotic)		4140(50)(200)	4230(50)(200)	
0^{+-} (exotic)	5450(830)	4740(70)(230)	4780(60)(230)	
5^{+-}				4110(170)(190)
0^{++}	1795(60)	1730(50)(80)	1710(50)(80)	1475(30)(65)
2^{++}	2620(50)	2400(25)(120)	2390(30)(120)	2150(30)(100)
0^{++}	3760(240)	2670(180)(130)		2755(30)(120)
3^{++}		3690(40)(180)	3670(50)(180)	3385(90)(150)
0^{++}				3370(100)(150)
0^{++}				3990(210)(180)
2^{++}				2880(100)(130)
4^{++}				3640(90)(160)
6^{++}				4360(260)(200)

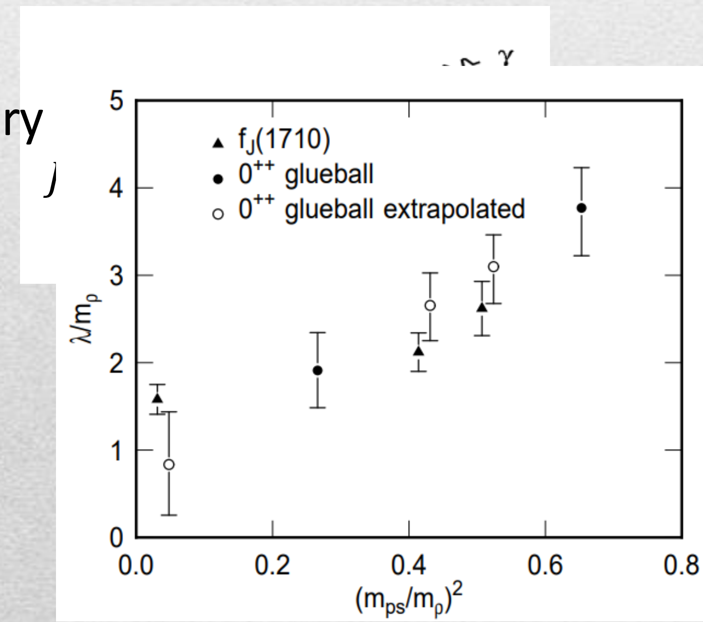
Gregory *et al.*
JHEP1210, 170

How to identify a glueball

You don’t. Since it mixes with light isoscalars, there is no model-independent way of saying which state is (mostly) the glueball. Only suggestions:

- There is one too many wrt QM. Indeed, $f_0(1370), f_0(1500), f_0(1710)$
- A glueball couples to photons only throughout mixing, so radiative widths should be small
- Their production is enhanced in gluon-rich processes, as J/ψ radiative decays
- It couples equally to mesons of all flavors (?)
  However, an argument based on chiral symmetry claims the coupling proportional to quark mass

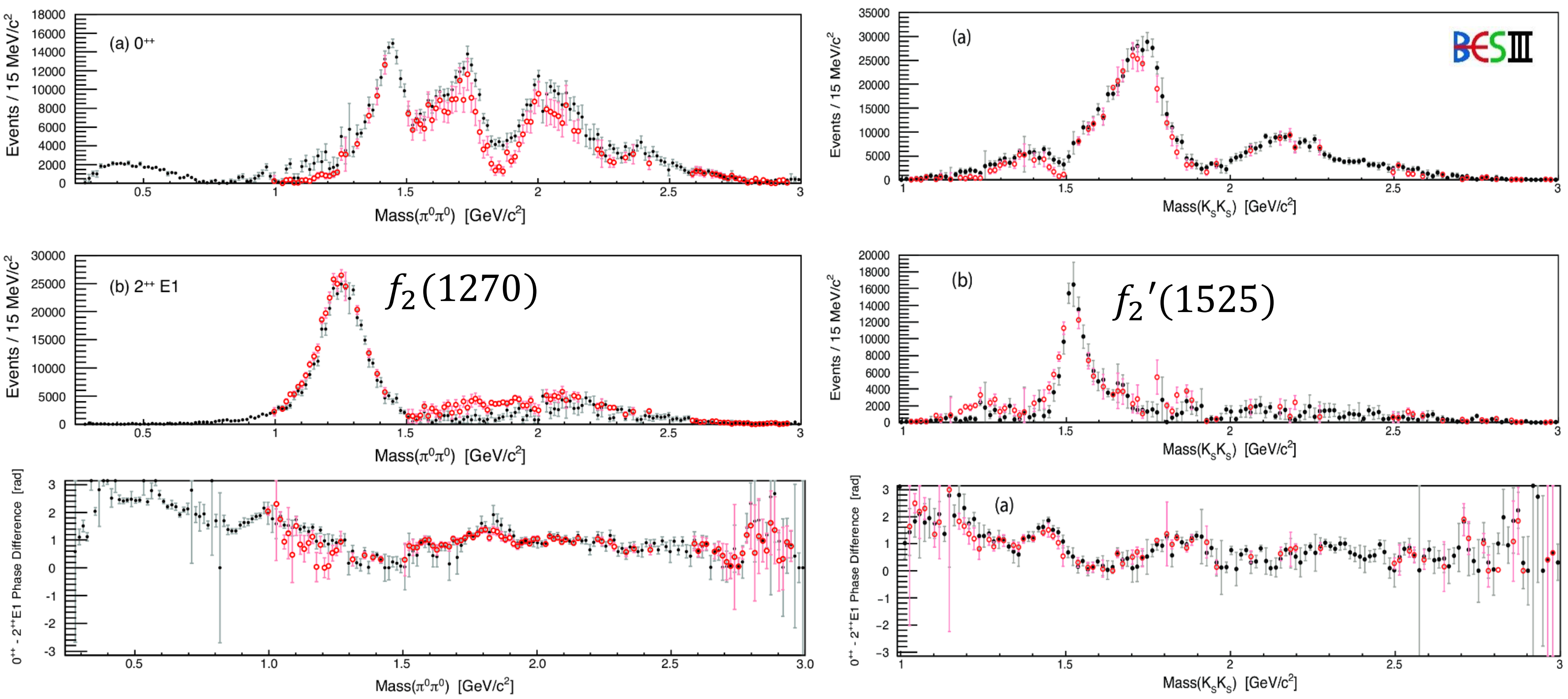




$J/\psi \to \gamma\, \pi^0\pi^0$ and $\to \gamma\, K_S^0 K_S^0$

We consider the S and D wave by BESIII to use the information about their relative phase.

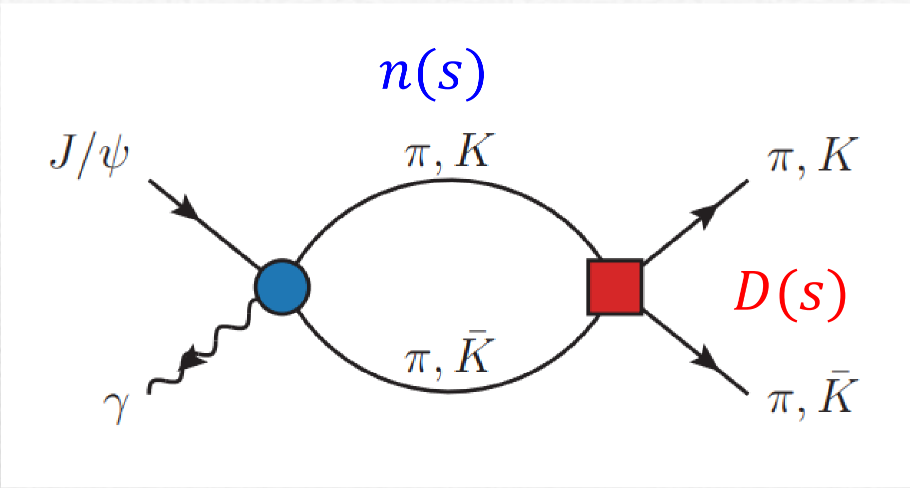
The D-wave is populated by two almost elastic resonances: the $f_2(1270)$ and $f_2'(1525)$



Amplitudes for $J/\psi \to \gamma\, PP$

We build the partial wave amplitudes according to the N/D method

$$a(s) = \frac{n(s)}{D(s)}$$



The $n(s)$ → background physics, process-dependent, smooth

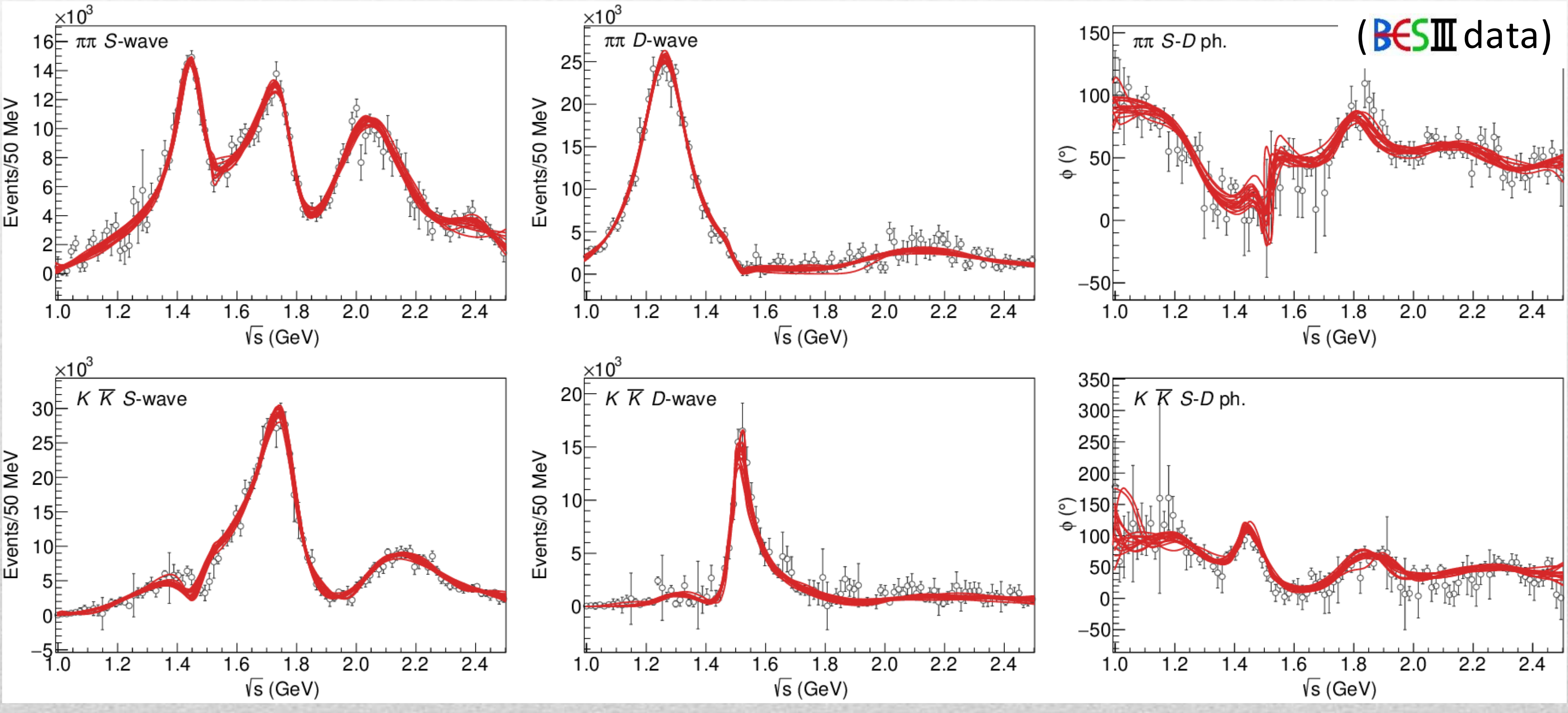
The $D(s)$ contains all the Final State interactions constrained by unitarity → universal

$J/\psi \to \gamma\, \pi^0\pi^0$ and $\to \gamma\, K_S^0 K_S^0$

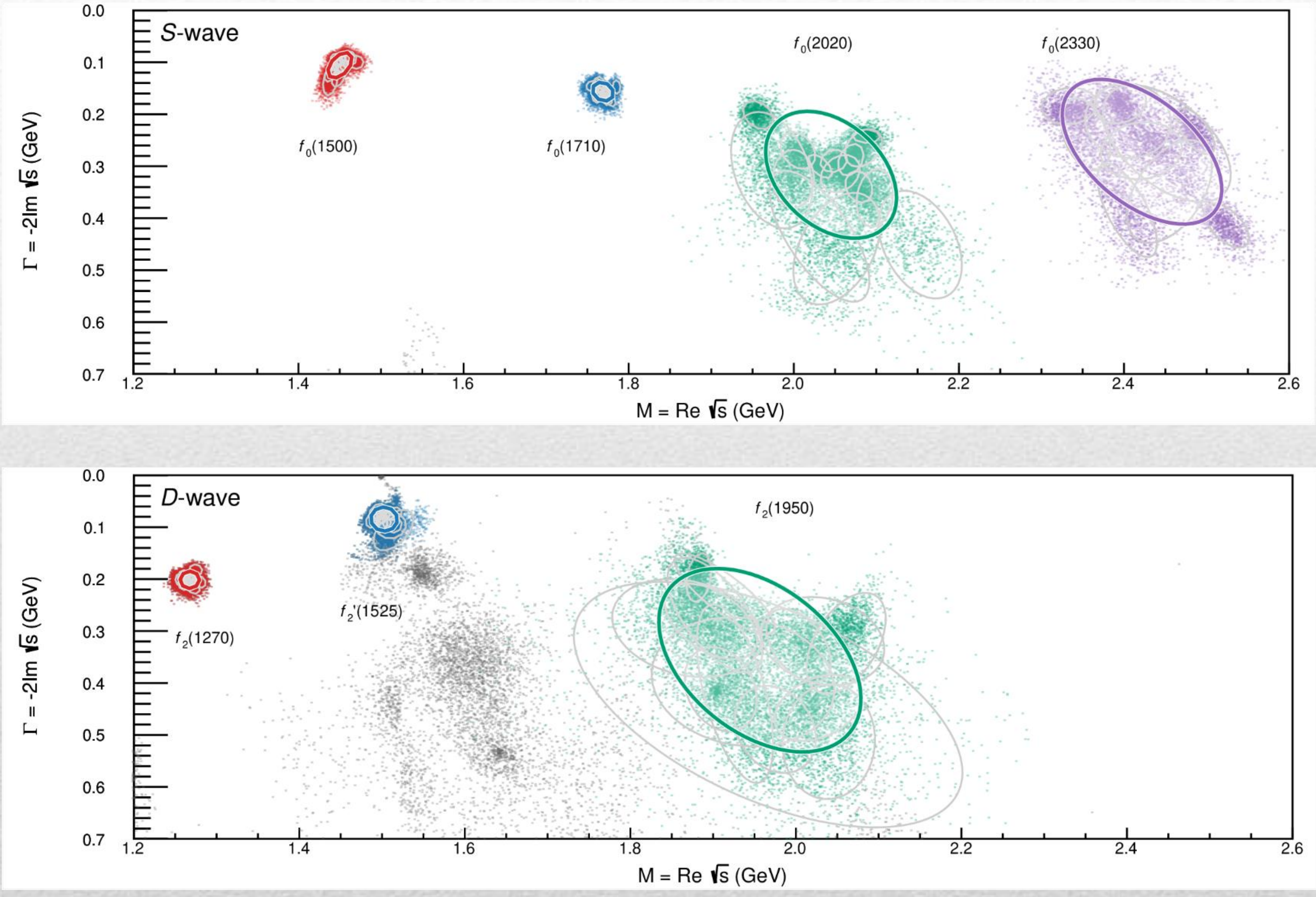
Fit is decent, but it's struggling in getting the f_2' right

The quality and description improve when the third channel is added

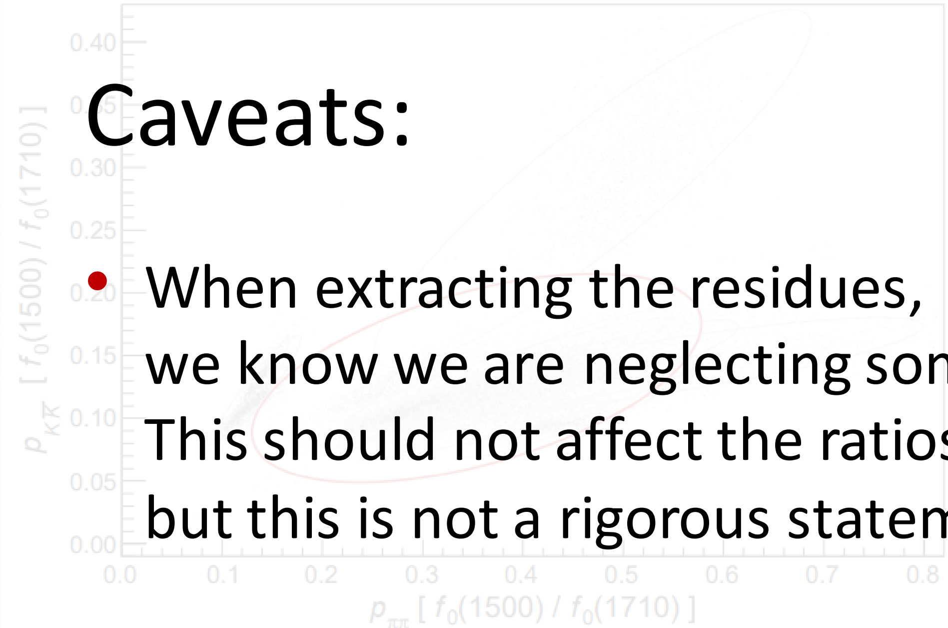
Being quasi-elastic, it's too constrained



Pole extraction



Looking at the residues



Despite the large systematics, the $f_0(1710)$ couples to kaons more than the $f_0(1500)$

Also, the $f_0(1710)$ couples to the initial gluon-rich state more than the $f_0(1500)$

Both these fact suggest a sizeable glueball component for the $f_0(1710)$

Caveats:

- When extracting the residues,
  we know we are neglecting some of the relevant channels.
  This should not affect the ratios seriously,
  but this is not a rigorous statement
- There is a contribution to the residues from the left-hand cut of the scattering process. To do that, a more realistic model for $N(s')$ is required.
  Again, this should not affect the ratios seriously

Conclusions

Bottom-up approaches are important!

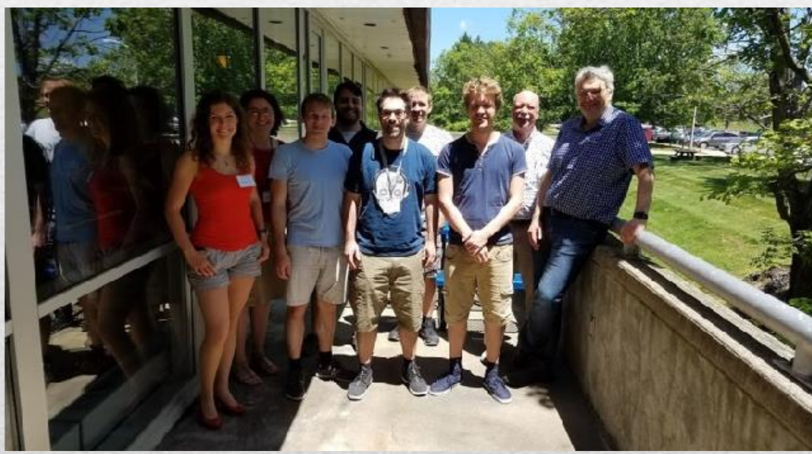
- They allow us to get the most out of high statistics data!
- The study of analytic stuctrures offer insights ino the nature of resonances
- Dispersive methods can improve the rigour and robustness in the extraction of the spectrum

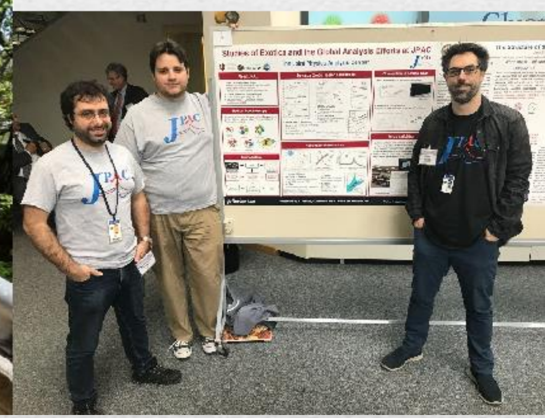
Thank you!

Joint Physics Analysis Center

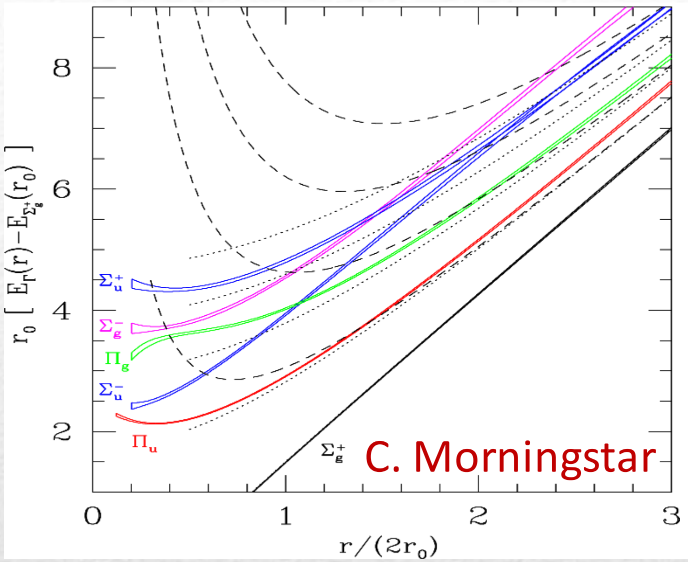
- Joint effort between theorists and experimentalists in support of experimental data from JLab12 and other accelerator laboratories
- Cooperation between JPAC and experiments: co-authoring papers

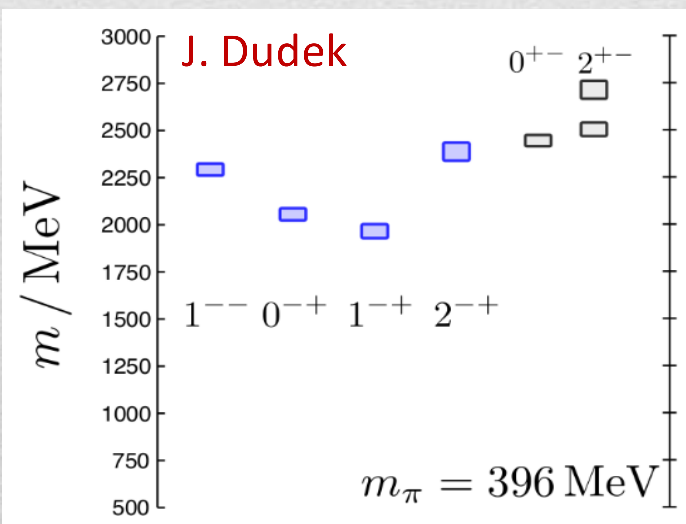
https://www.jpac-physics.org





Learning about confinement





If quarks were infinitely heavy, gluonic field is confined in a string

What is a constituent gluon?

- vibration of the string?
  → degenerate $J^{PC} = (0, \mathbf{1}, 2)^{-+}, (\mathbf{0}, 1, \mathbf{2})^{+-}$
- excitation of a quasiparticle!
  → degenerate $J^{PC} = (0, \mathbf{1}, 2)^{-+}, 1^{--}$
- excitation of a quasiparticle?

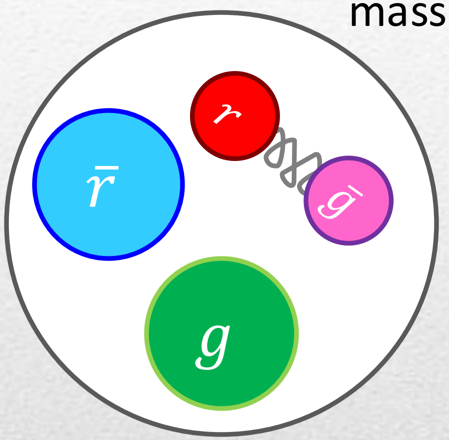
says Lattice QCD...

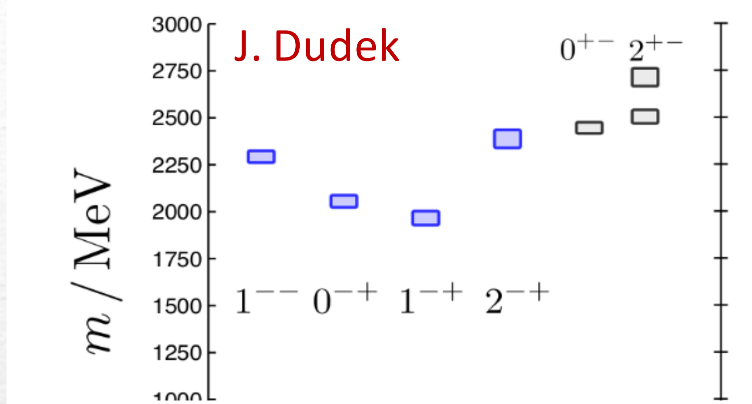
→ degenerate $J^{PC} = (0, \mathbf{1}, 2)^{-+}, 1^{--}$

What about real data?

Hybrid hunting

Excited gluon,
$J^{PC} = 1^{+-}$
mass ~ 1.0–1.5 GeV

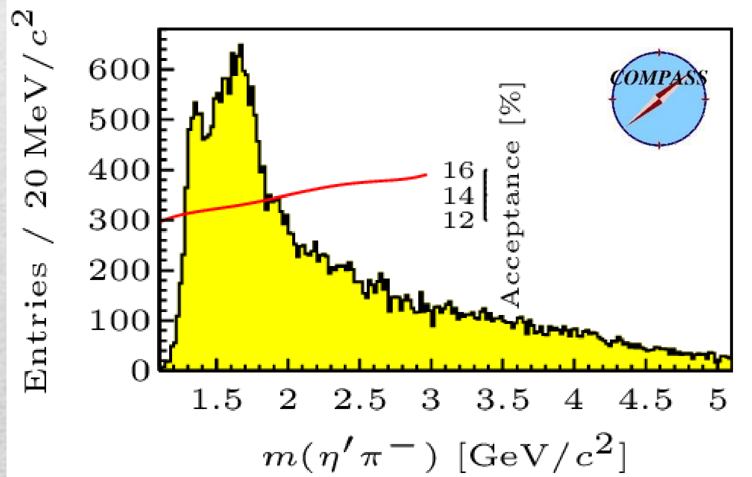




excitation of a quasiparticle?
→ degenerate $J^{PC} = (0, \mathbf{1}, 2)^{-+}, 1^{--}$

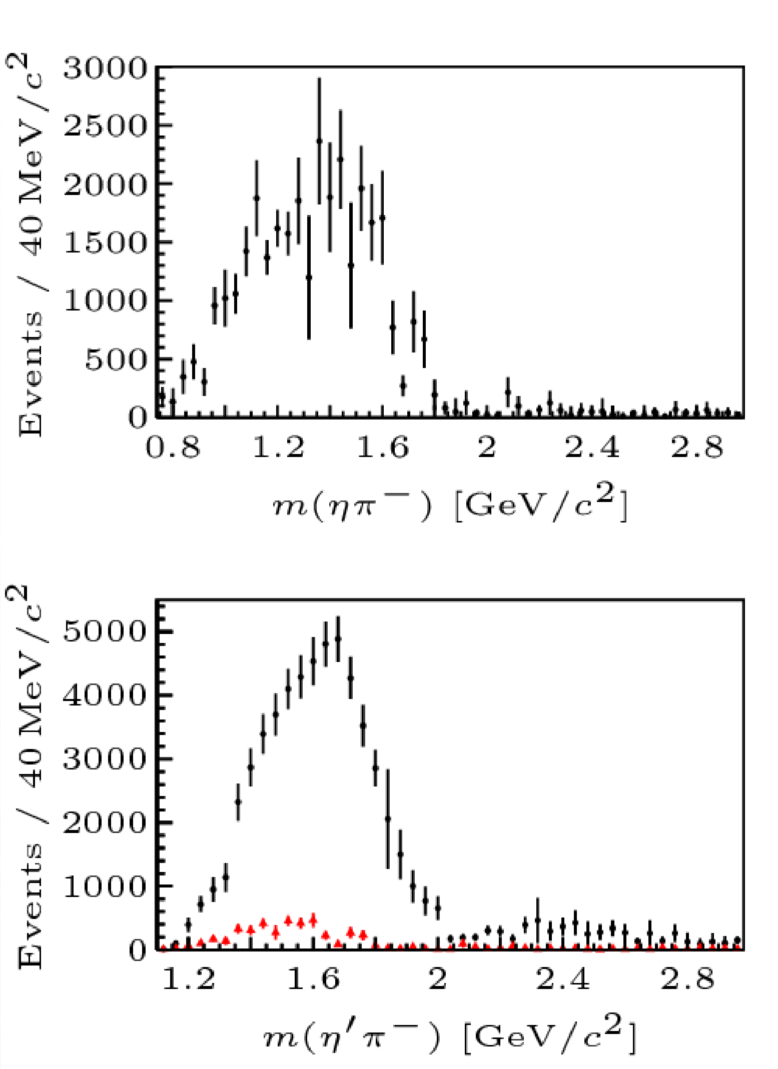
Look for a π_1 state with $\boldsymbol{J^{PC} = 1^{-+}}$

decaying into $\begin{cases} \eta\,\pi \text{ and } \eta'\pi \\ \rho\,\pi \to 3\pi \\ b_1\pi \to 5\pi \end{cases}$



Small signal in data

Two hybrid states???



$\pi_1(1400)$ $I^G(J^{PC}) = 1^-(1^{-+})$

See also the mini-review under non-$q\bar{q}$ candidates in PDG 2006 , Journal of Physics G33 1 (2006).

$\pi_1(1400)$ MASS	1354 ± 25 MeV (S = 1.8)
$\pi_1(1400)$ WIDTH	330 ± 35 MeV

Decay Modes

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level
Γ_1	$\eta\pi^0$	seen	
Γ_2	$\eta\pi^-$	seen	
Γ_3	$\eta'\pi$		

Neither lattice nor models predict two 1^{-+} states in this region!

$\pi_1(1600)$ $I^G(J^{PC}) = 1^-(1^{-+})$

$\pi_1(1600)$ MASS	1662^{+8}_{-9} MeV
$\pi_1(1600)$ WIDTH	241 ± 40 MeV (S = 1.4)

Decay Modes

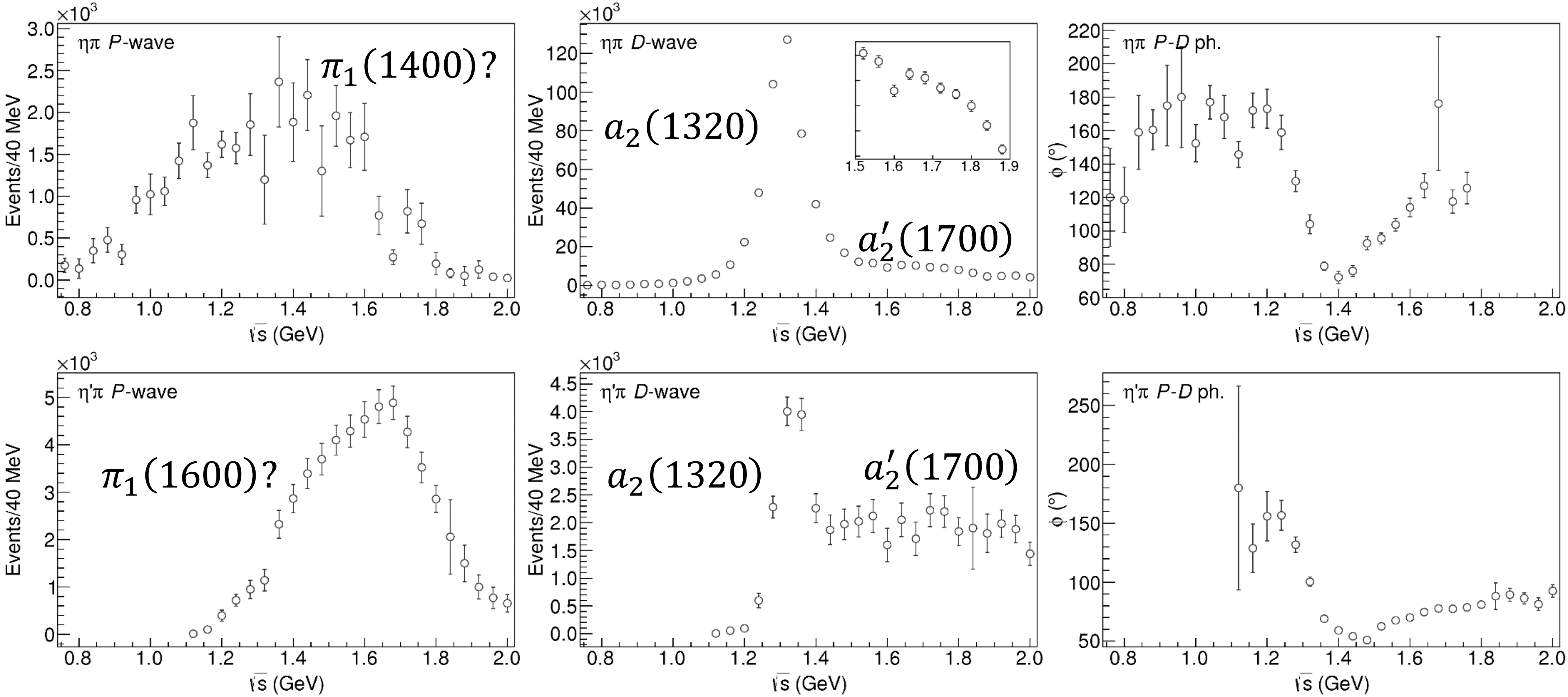
A hybrid meson ($\mathbf{8}$) cannot decay into $\eta\pi$ in the SU(3) limit

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level
Γ_1	$\pi\pi\pi$	seen	
Γ_2	$\rho^0\pi^-$	seen	
Γ_3	$f_2(1270)\pi^-$	not seen	
Γ_4	[illegible]	[illegible]	
Γ_5	$\eta'(958)\pi^-$	seen	
Γ_6	$f_1(1285)\pi$	seen	

Tetraquark ($\mathbf{10} \oplus \overline{\mathbf{10}}$)? Requires doubly charged

Data in $\eta^{(\prime)}\pi$

(data)



$J^{PC} = 1^{-+}$ $\quad$ $J^{PC} = 2^{++}$

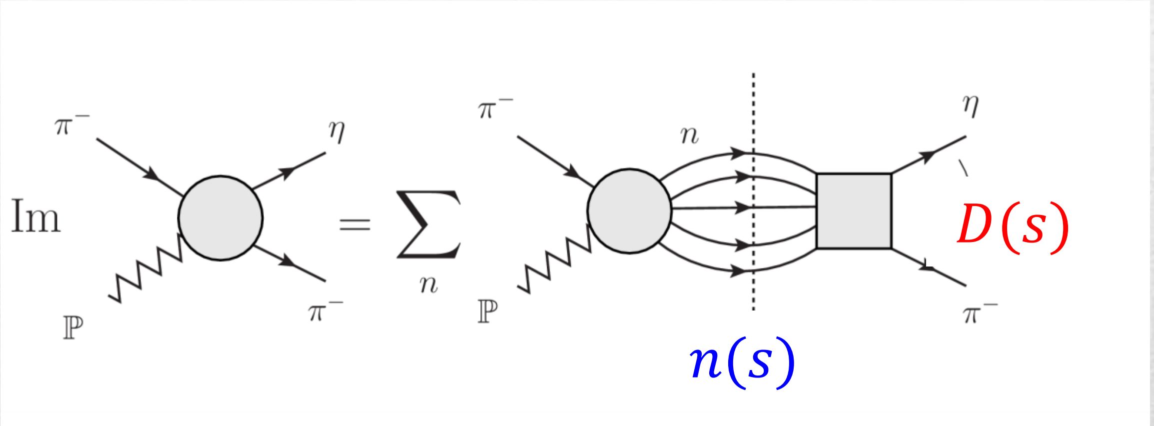
Amplitudes for $\eta^{(\prime)}\pi$

We build the partial wave amplitudes according to the N/D method

Jackura, Mikhasenko, AP *et al.* (JPAC & COMPASS), PLB

Rodas, AP *et al.* (JPAC), PRL

$$a(s) = \frac{n(s)}{D(s)}$$



The $n(s)$ → background physics, process-dependent, smooth

The $D(s)$ contains all the Final State Interactions constrained by unitarity → universal

Coupled channel: the model

A. Rodas, AP *et al.* (JPAC) PRL122, 042002

Two channels, $i,k=\eta\pi,\eta'\pi$

Two waves, $J=P,D$

37 fit parameters

$$D_{ki}^J(s)=\left[K^J(s)^{-1}\right]_{ki}-\frac{s}{\pi}\int_{s_k}^{\infty}ds'\frac{\rho N_{ki}^J(s')}{s'(s'-s-i\epsilon)}$$

$$K_{ki}^J(s)=\sum_R\frac{g_k^{(R)}g_i^{(R)}}{m_R^2-s}+c_{ki}^J+d_{ki}^J\,s$$

1 K-matrix pole for the P-wave
2 K-matrix poles for the D-wave

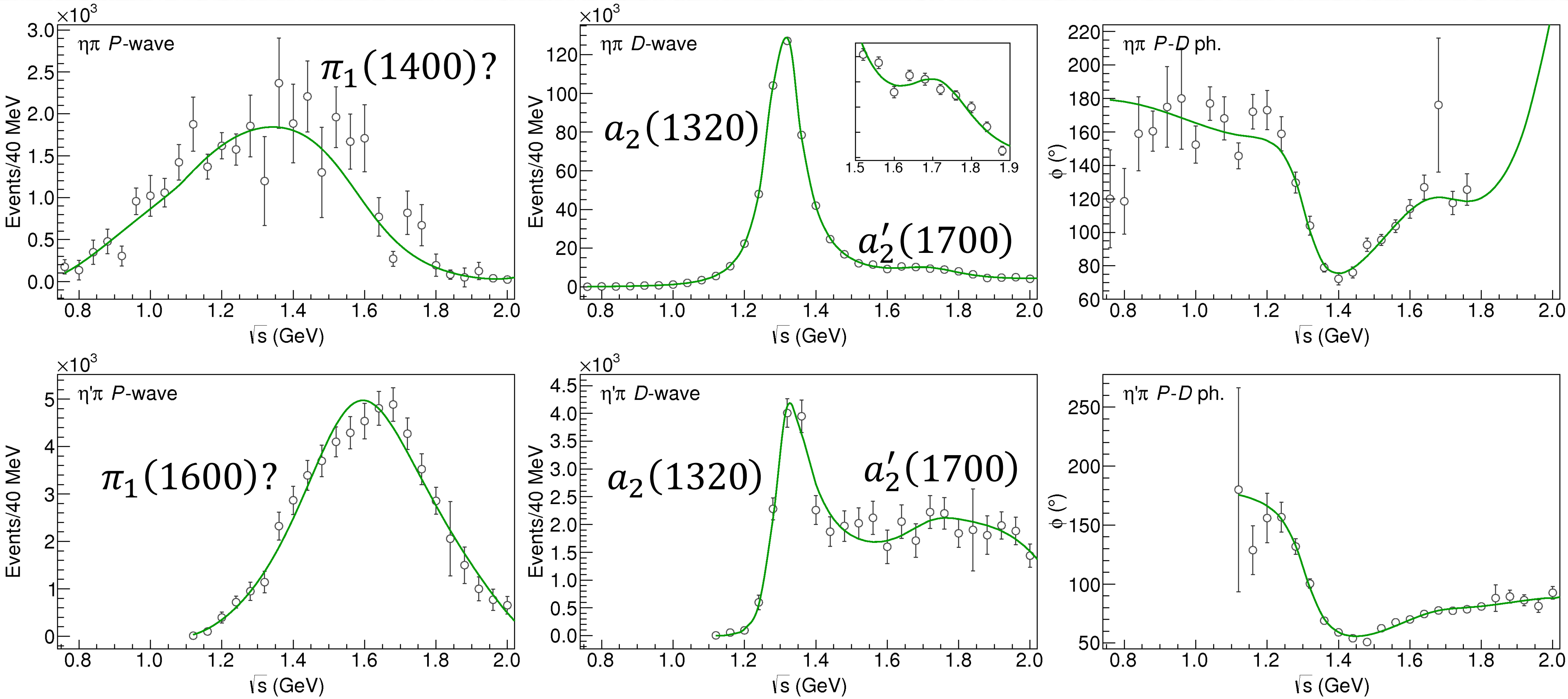
$$\rho N_{ki}^J(s')=\delta_{ki}\frac{\lambda^{J+1/2}\left(s',m_{\eta^{(\prime)}}^2,m_\pi^2\right)}{(s'+s_R)^{2J+1+\alpha}}$$

$$n_k^J(s)=\sum_{n=0}^{3}a_n^{J,k}\,T_n\!\left(\frac{s}{s+s_0}\right)$$

Left-hand scale (Blatt-Weisskopf radius) $s_R=s_0=1\text{ GeV}^2$
$\alpha=2$, 3rd order polynomial for $n_k^J(s)$

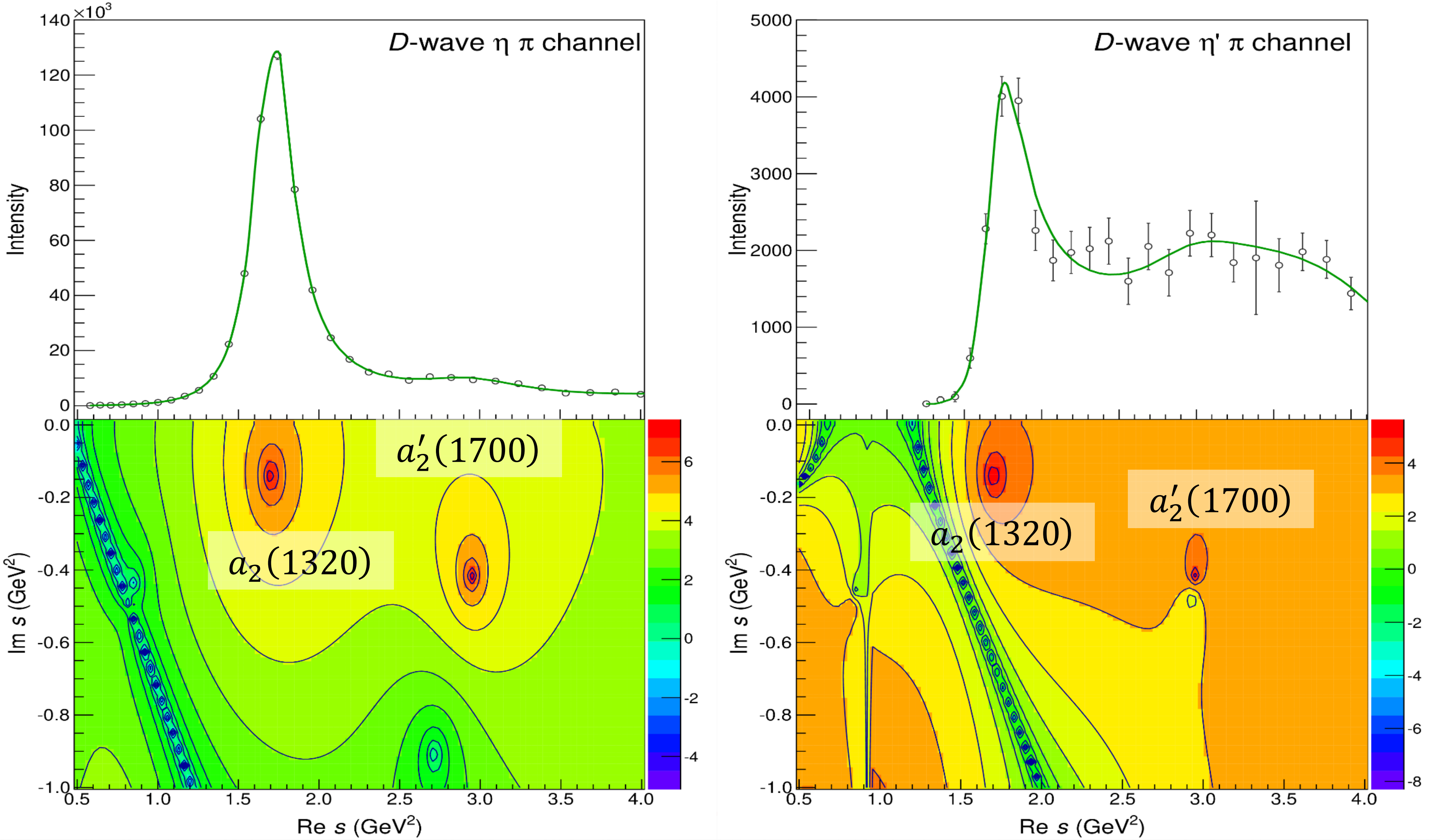
Fit to $\eta^{(\prime)}\pi$

(data)

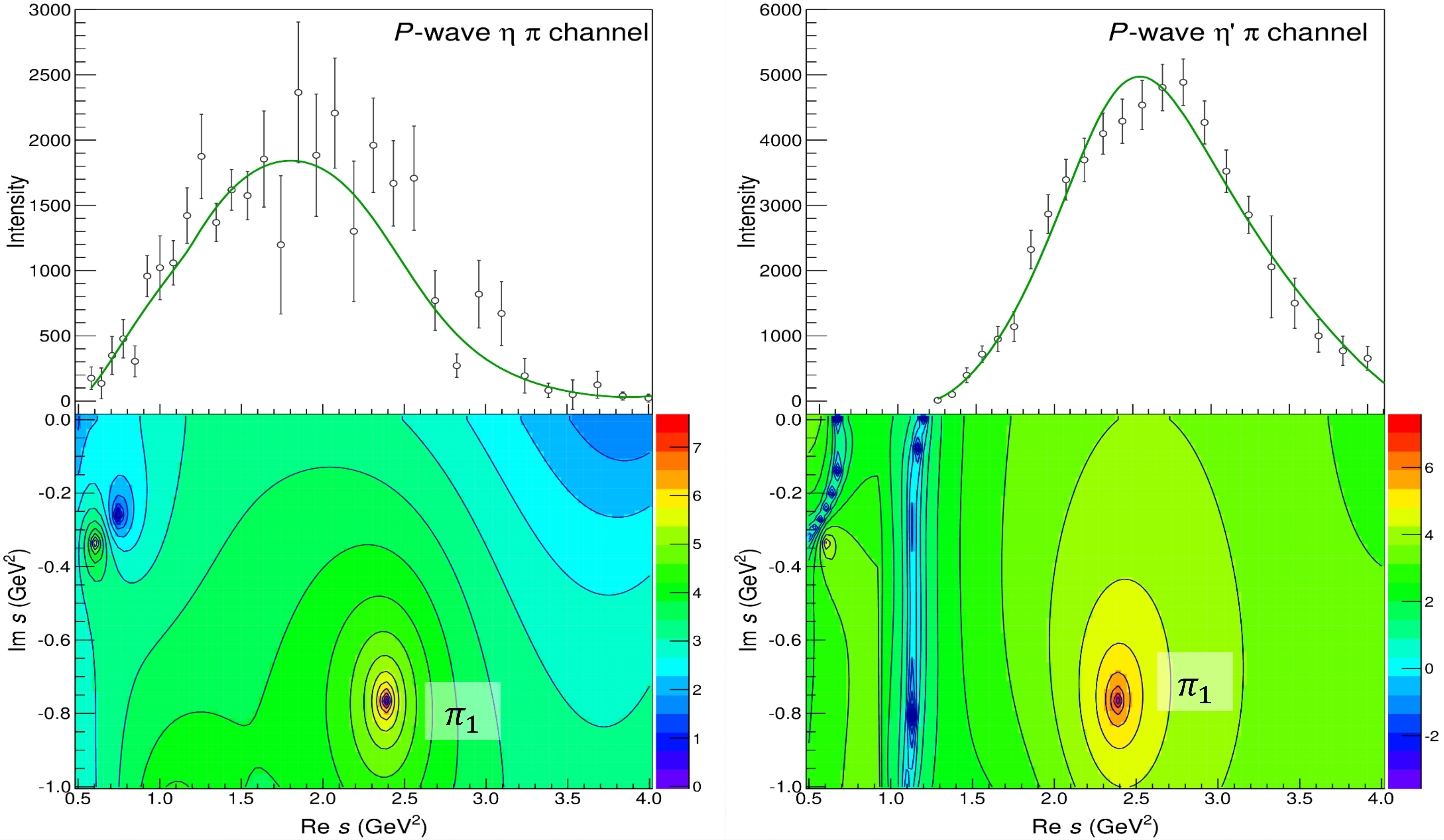


$J^{PC} = 1^{-+}$ $\quad$ $J^{PC} = 2^{++}$

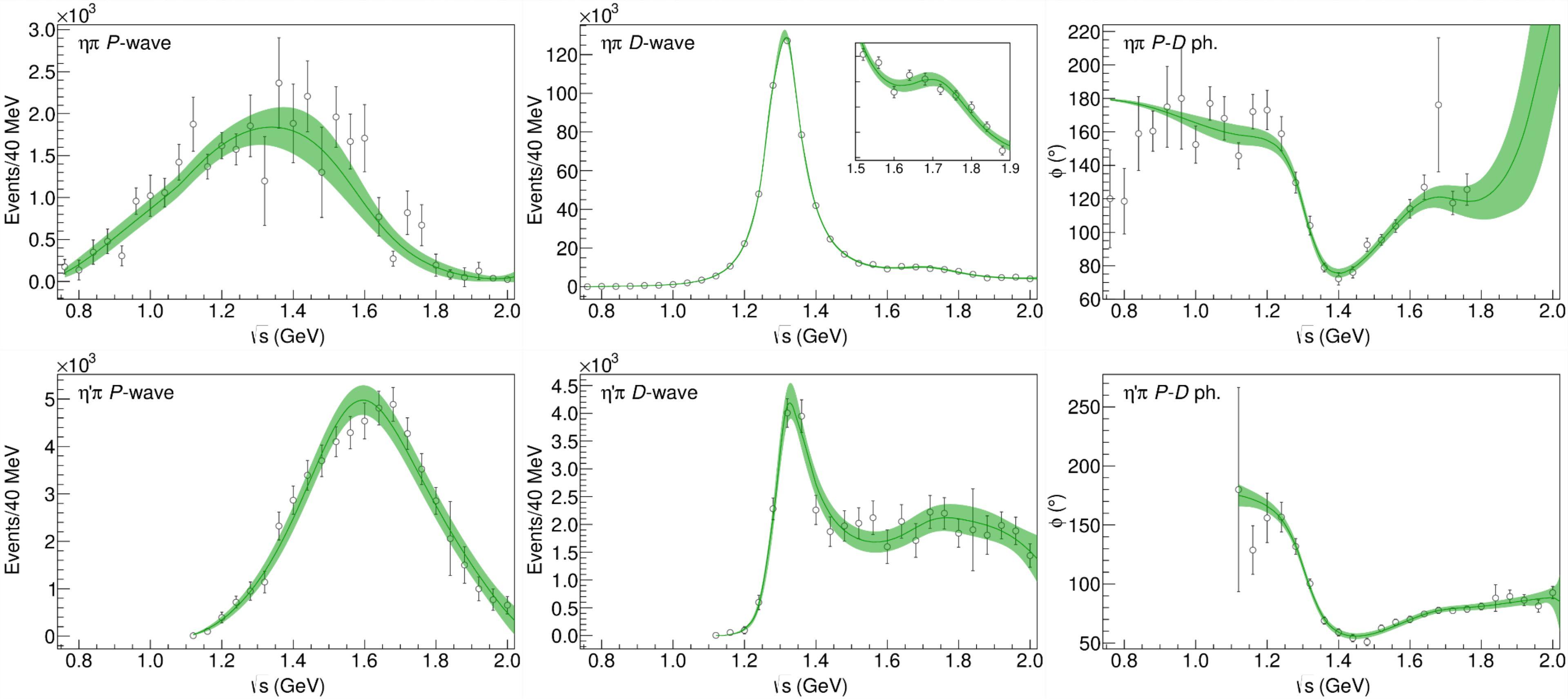
Pole hunting



Pole hunting



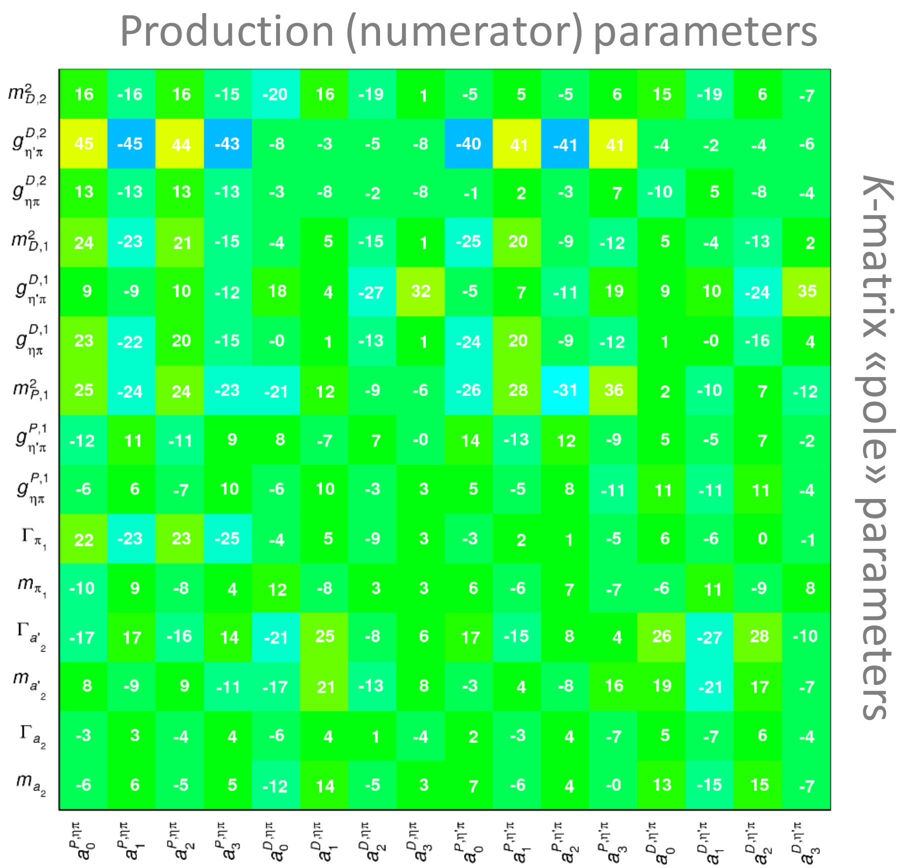
Statistical Bootstrap

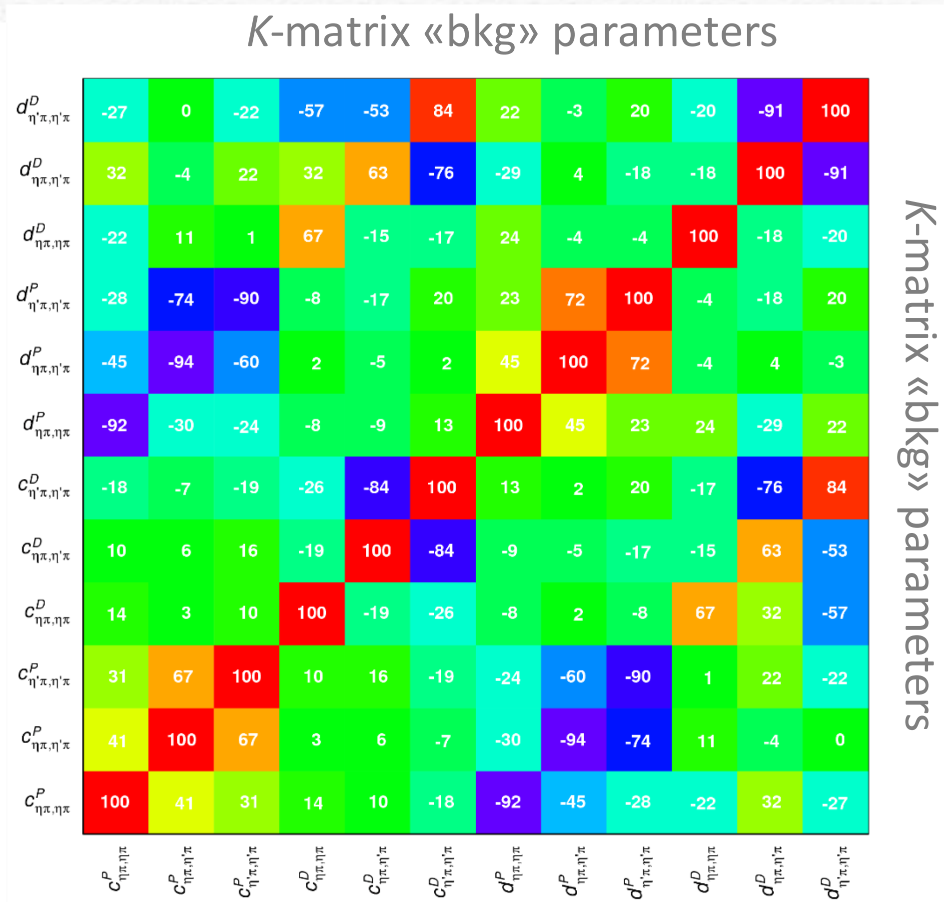


Correlations

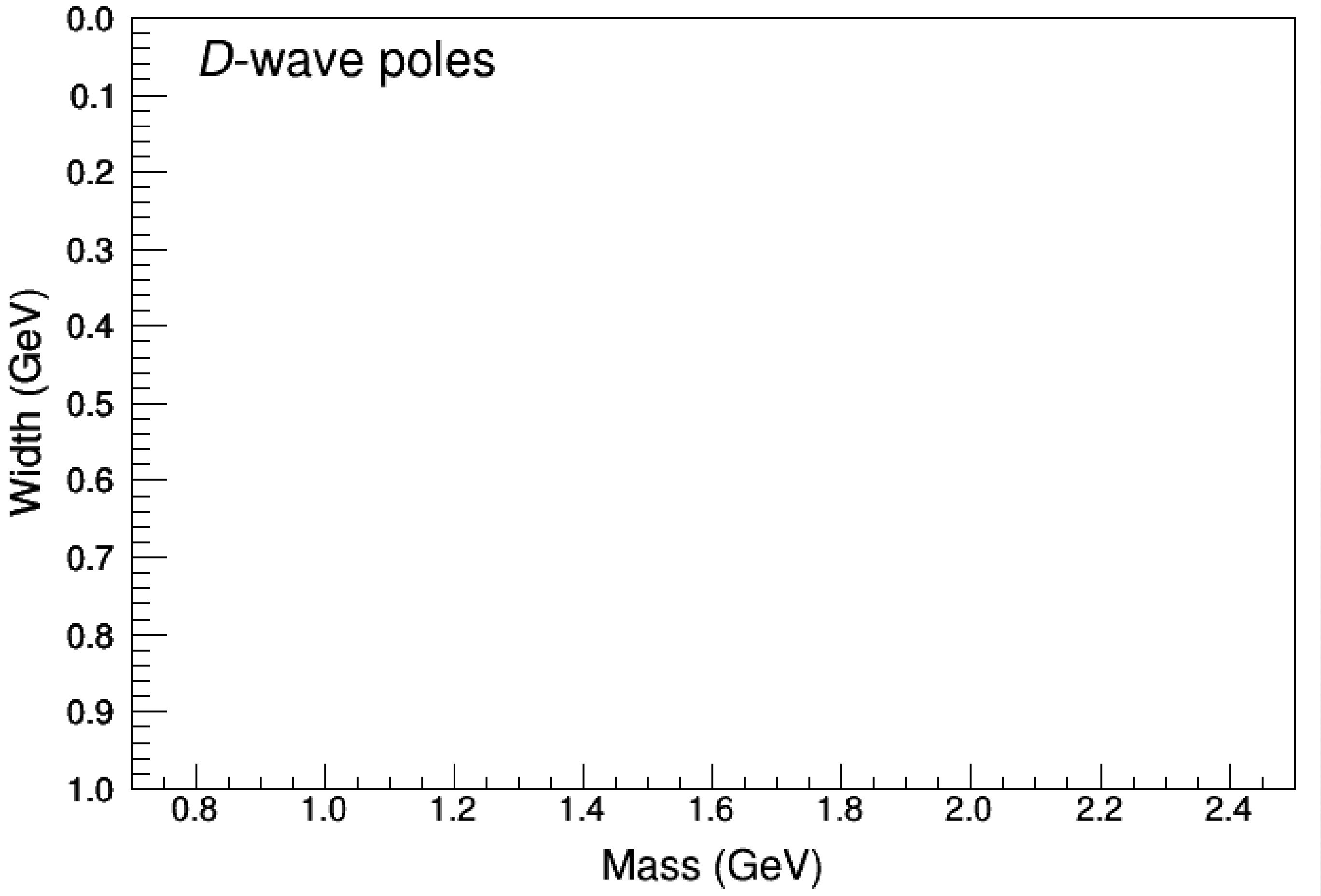
Denominator parameters uncorrelated with the numerator ones ✓

Denominator parameters uncorrelated between *P*- and *D*-wave ✓



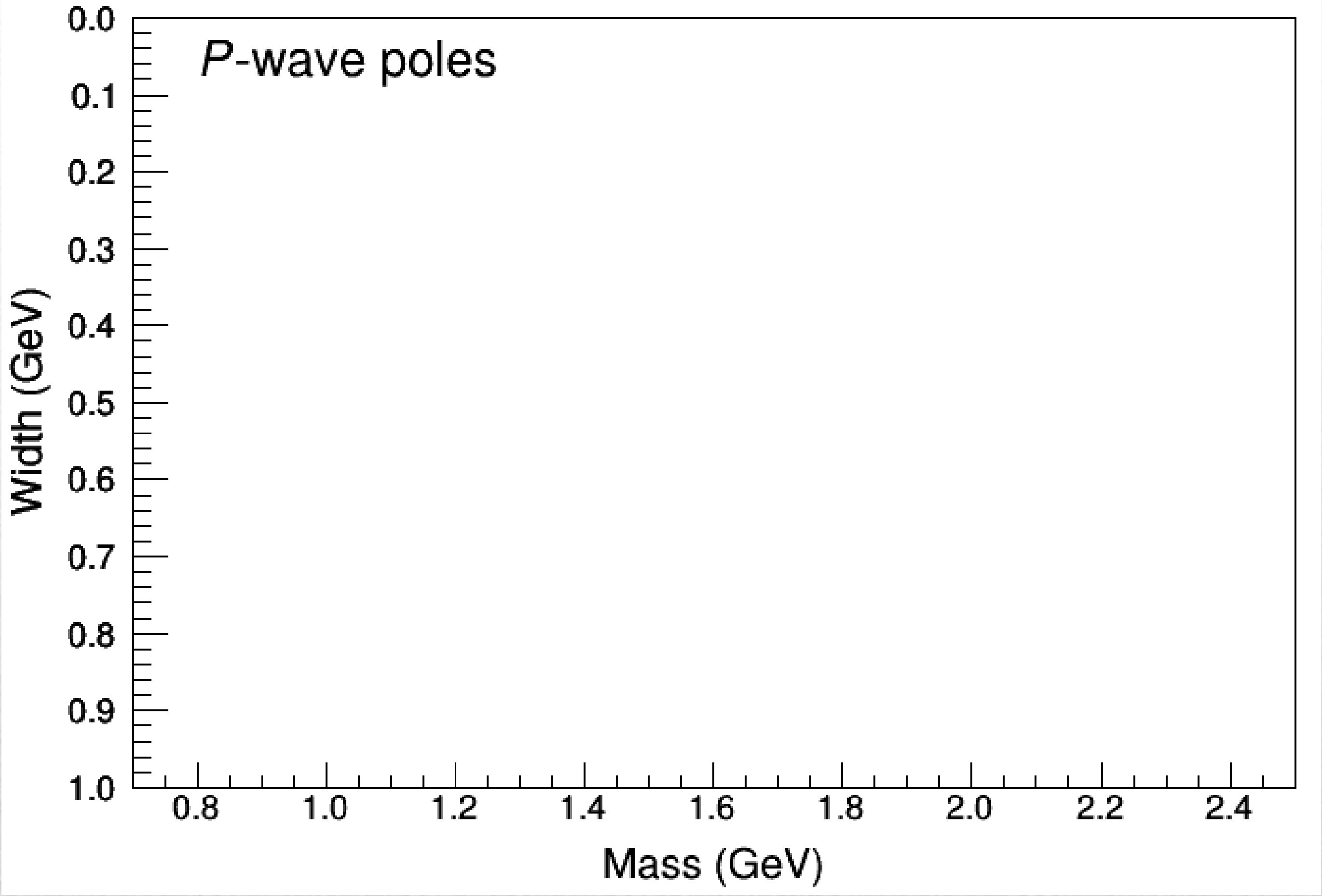


Statistical Bootstrap



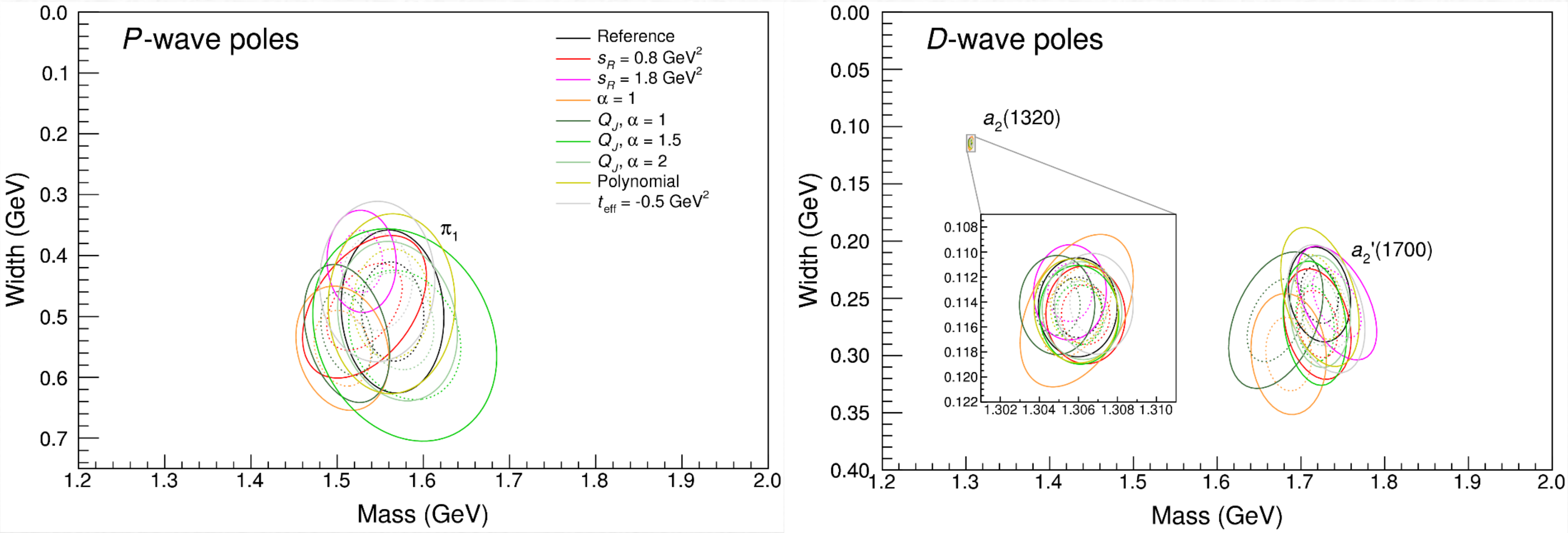
For each fit, we search poles: two clusters in *D*-wave: $a_2(1320)$ and $a_2'(1700)$

Statistical Bootstrap



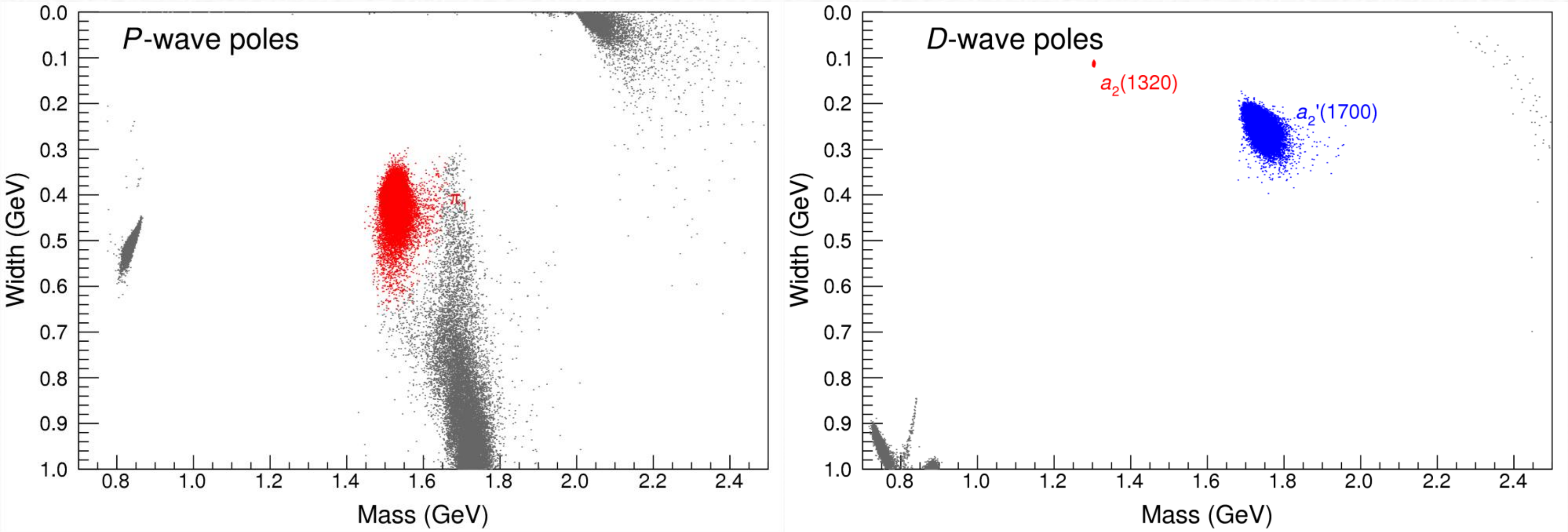
Only one stable cluster in P-wave: a single π_1

Systematic studies



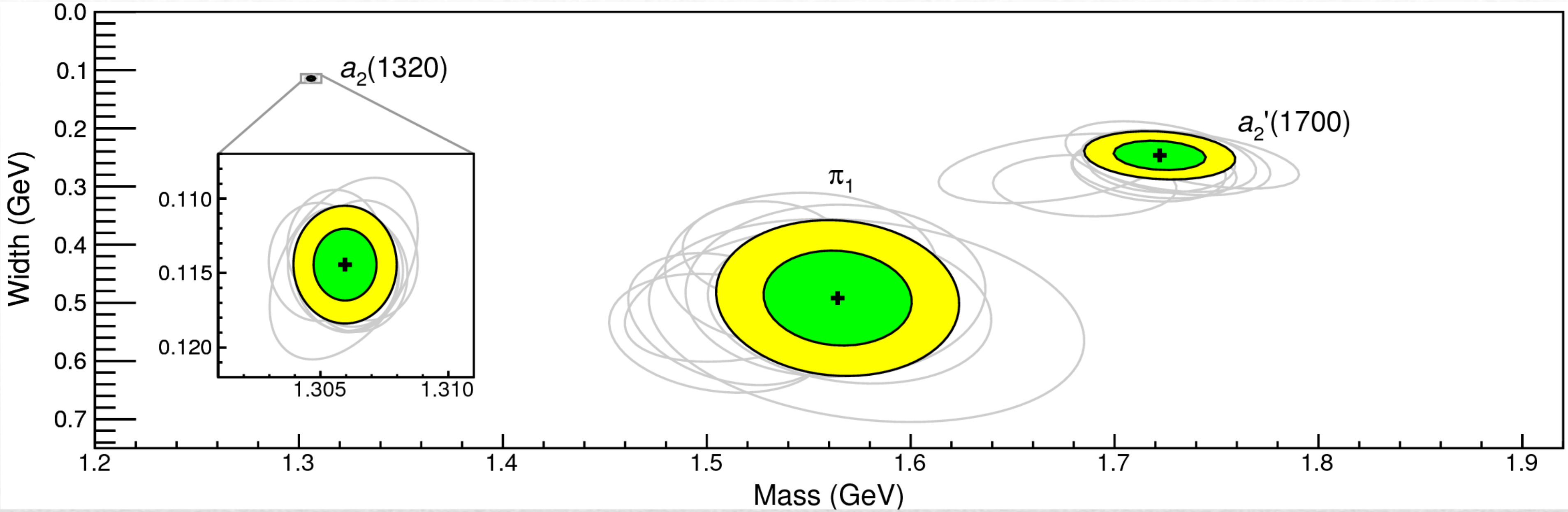
For each class, the maximum deviation of mass and width is taken as a systematic error
Deviation smaller than the statistical error are neglected
Systematic of different classes are summed in quadrature

Bootstrap for $s_R = 1.8\ \text{GeV}^2$



Our skepticism about a second pole in the relevant region is confirmed:
It is unstable and not trustable

Final results



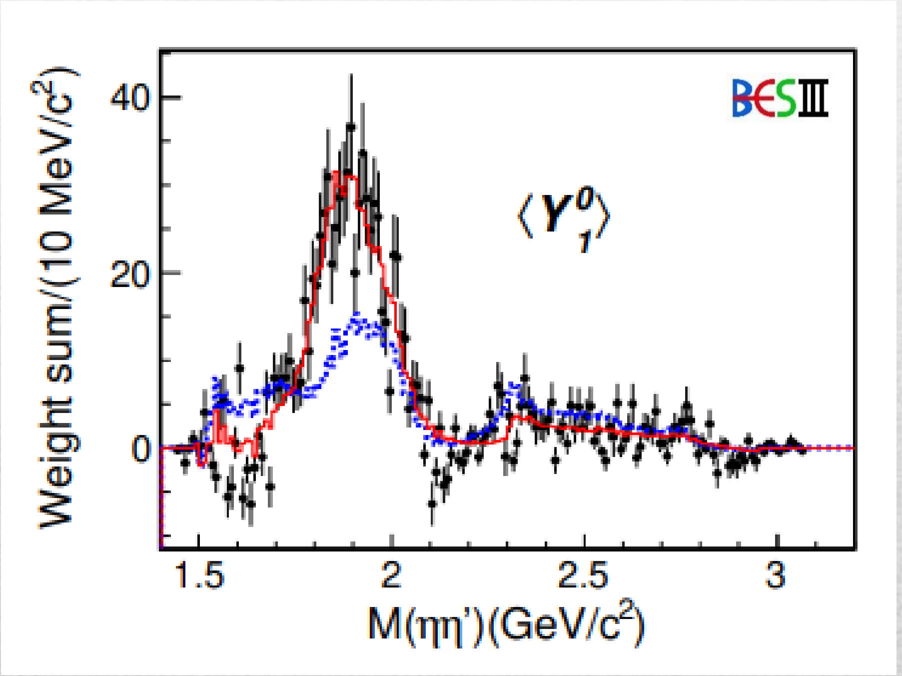
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

Agreement with Lattice is restored

That's the most rigorous extraction of an exotic meson available so far!

An isoscalar η_1?

There is a recent claim by BESIII in $J/\psi \to \gamma\, \eta\, \eta'$ of resonant activity in P-wave

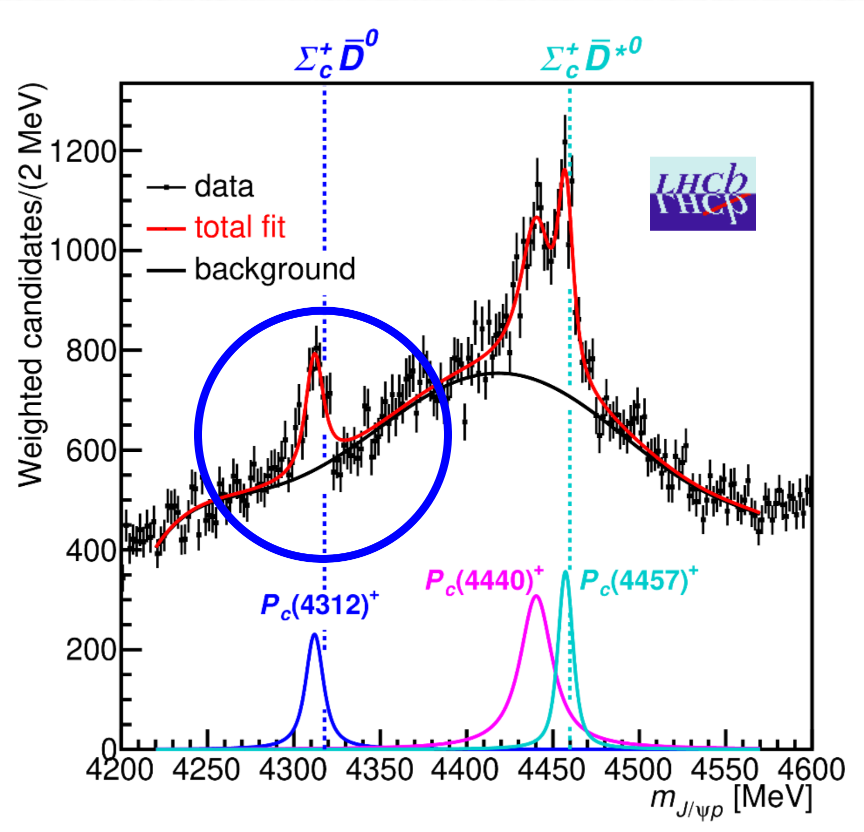


Not enough information
to perform a similar analysis but…
stay tuned!

BW parameters:

$$M = 1855 \pm 9^{+6}_{-1}\ \mathrm{MeV},$$
$$\Gamma = 188 \pm 18^{+3}_{-8}\ \mathrm{MeV}$$

New pentaquarks discovered



The lowest $P_c(4312)$ appears as an isolated peak at the $\Sigma_c^+ \bar{D}^0$ threshold

A detailed study of the lineshape provides insight on its nature

Bottom-up:
DON'T YOU DARE describing everything!!!
Focus on the peak region

Minimal(istic) model for $P_c(4312)$

(LHCb data)

Fernandez-Ramirez, AP *et al.* (JPAC), PRL 123, 092001

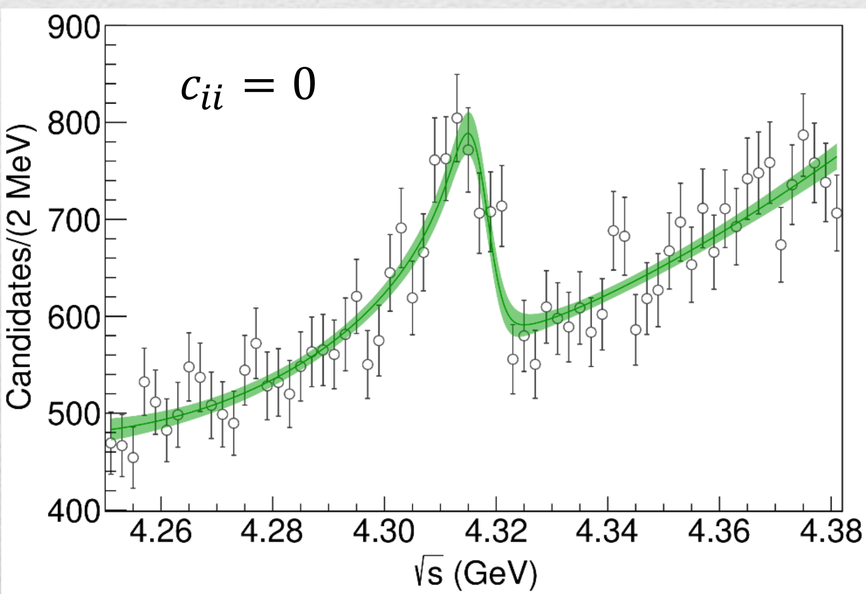
$$\frac{dN}{d\sqrt{s}} = \rho(s)\left[|F(s)|^2 + b_0 + b_1 s\right]$$

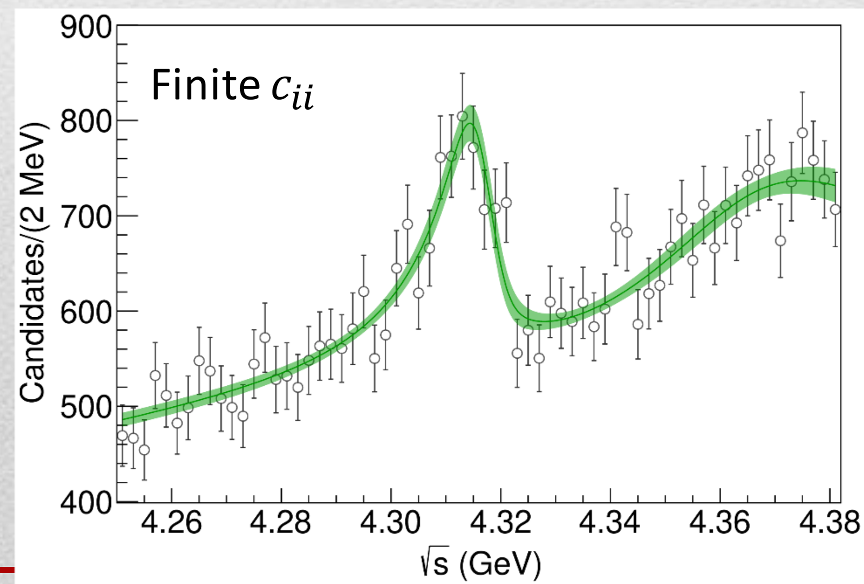
Effective range expansion

$$F(s) = (N_1 + N_2 s)\, T_{11}(s)$$

$$T(s) = \begin{pmatrix} m_{11} - c_{11}s - i\rho_1(s) & m_{12} \\ m_{12} & m_{22} - c_{22}s - i\rho_2(s) \end{pmatrix}^{-1}$$

We can set $c_{ii} = 0$ to reduce to the scattering length approximation





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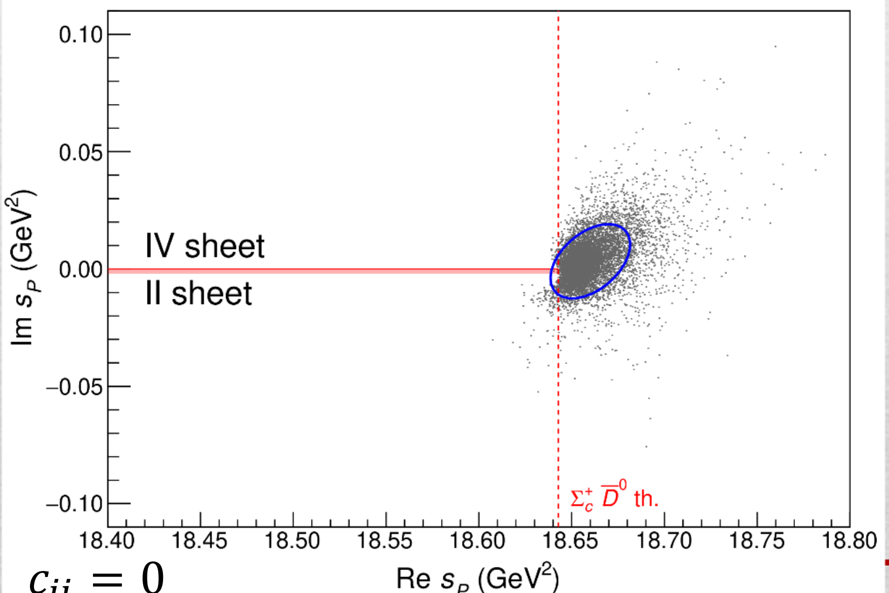
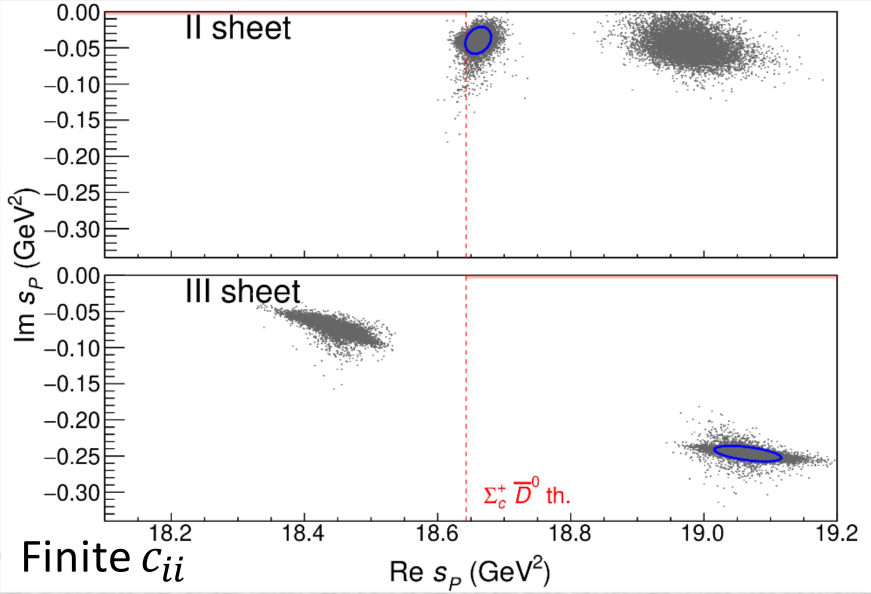


$c_{ii} = 0$



Finite c_{ii}

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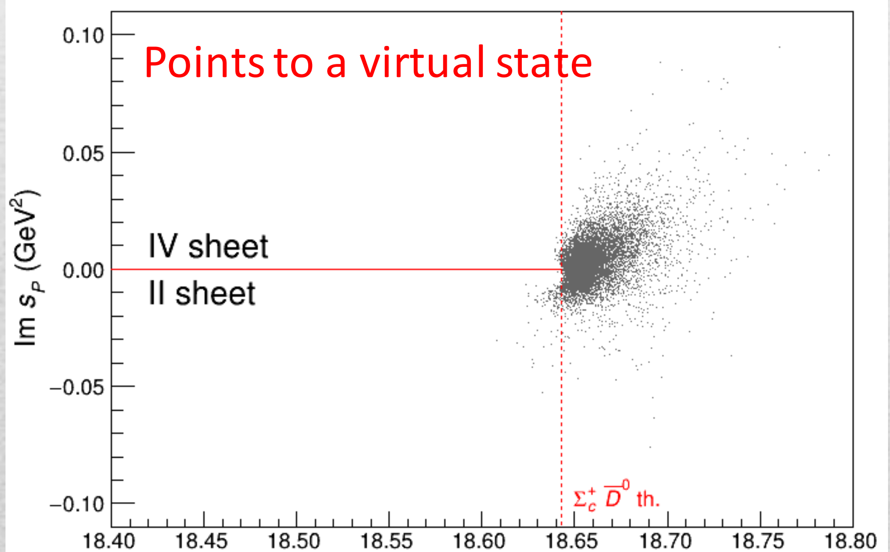

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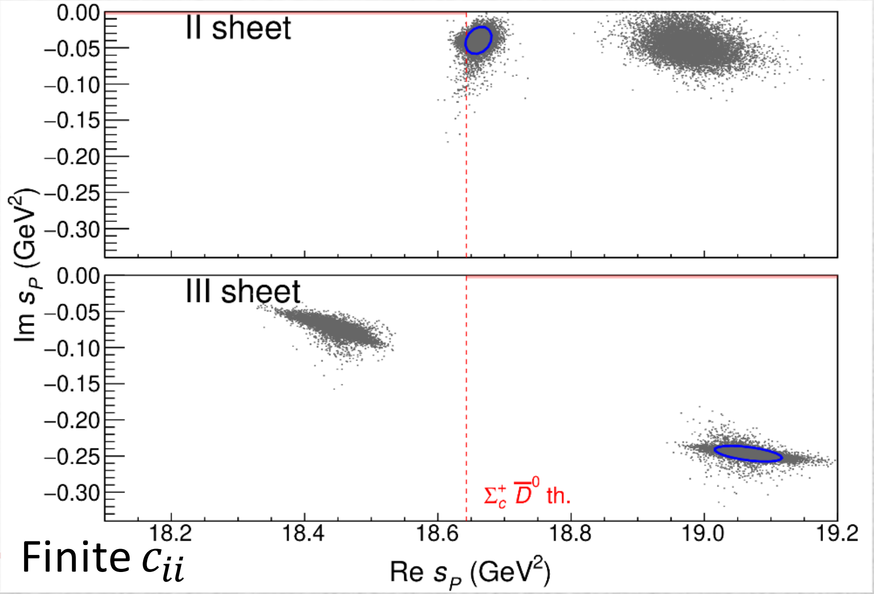

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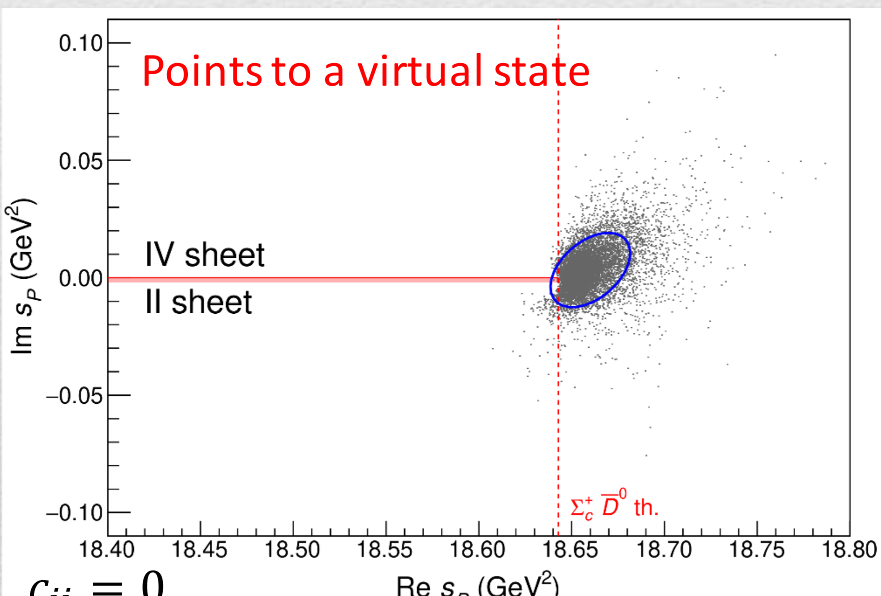

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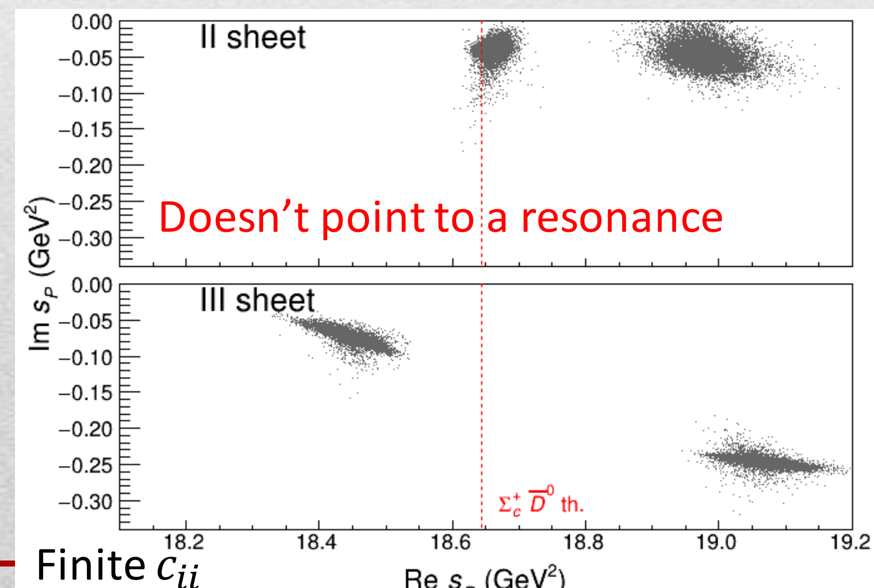

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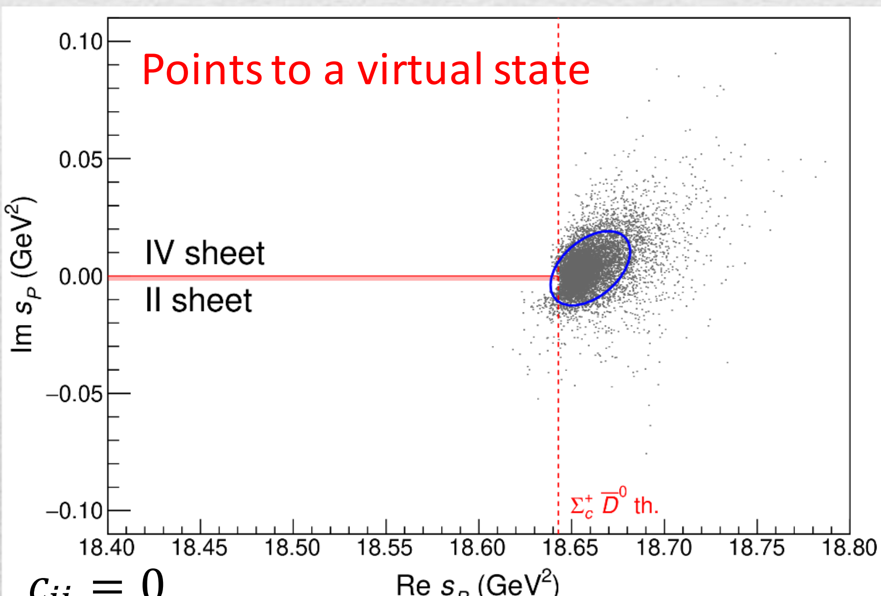

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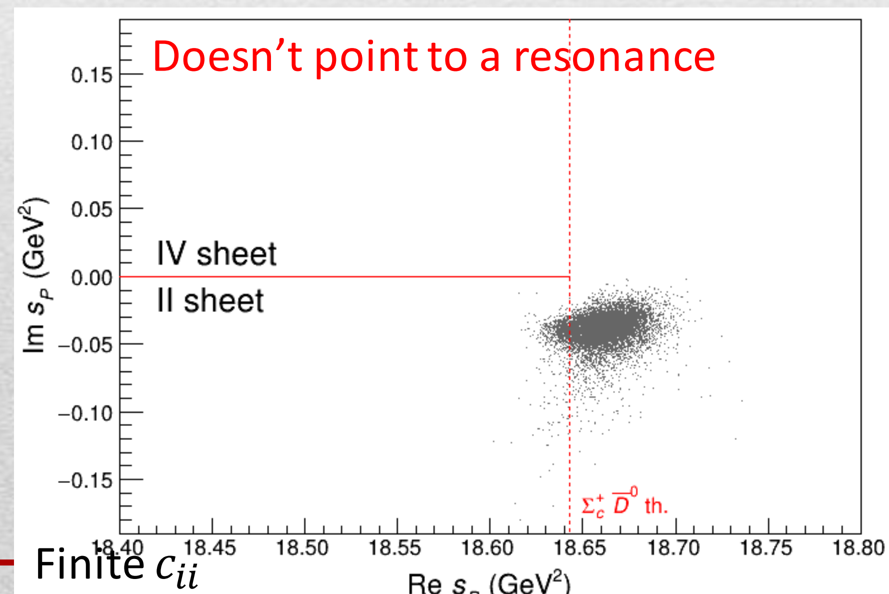
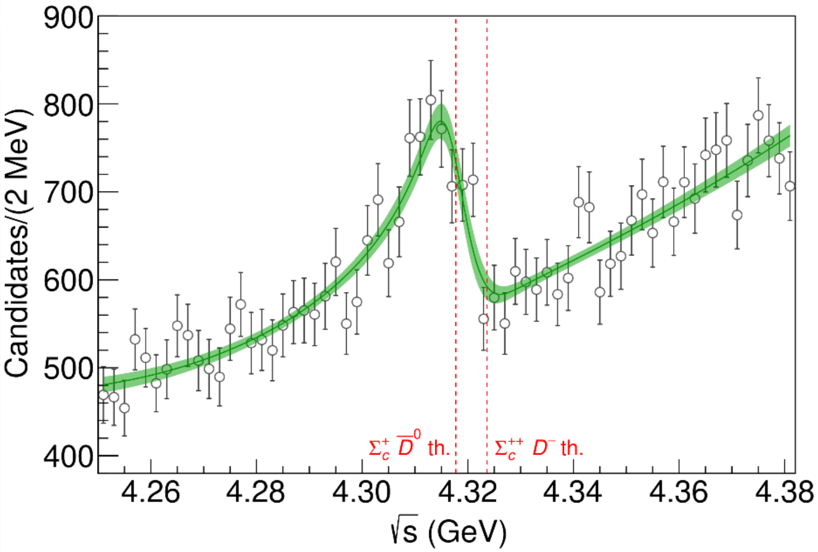


Finite c_{ii}

3 channels



$$T(s) = \begin{pmatrix} m_{11} - c_{11}s - i\sqrt{s - s_1} & m_{12} & \lambda\, m_{12} \\ m_{12} & m_{22} - c_{22}s - i\sqrt{s - s_2} & \lambda\, m_{23} \\ \lambda\, m_{12} & \lambda\, m_{23} & 1 + \lambda\left(-1 + m_{22} - c_{22}s - i\sqrt{s - s_3}\right) \end{pmatrix}^{-1},$$