Non-ordinary hadron analyses at ExoHad

JLUO 2023

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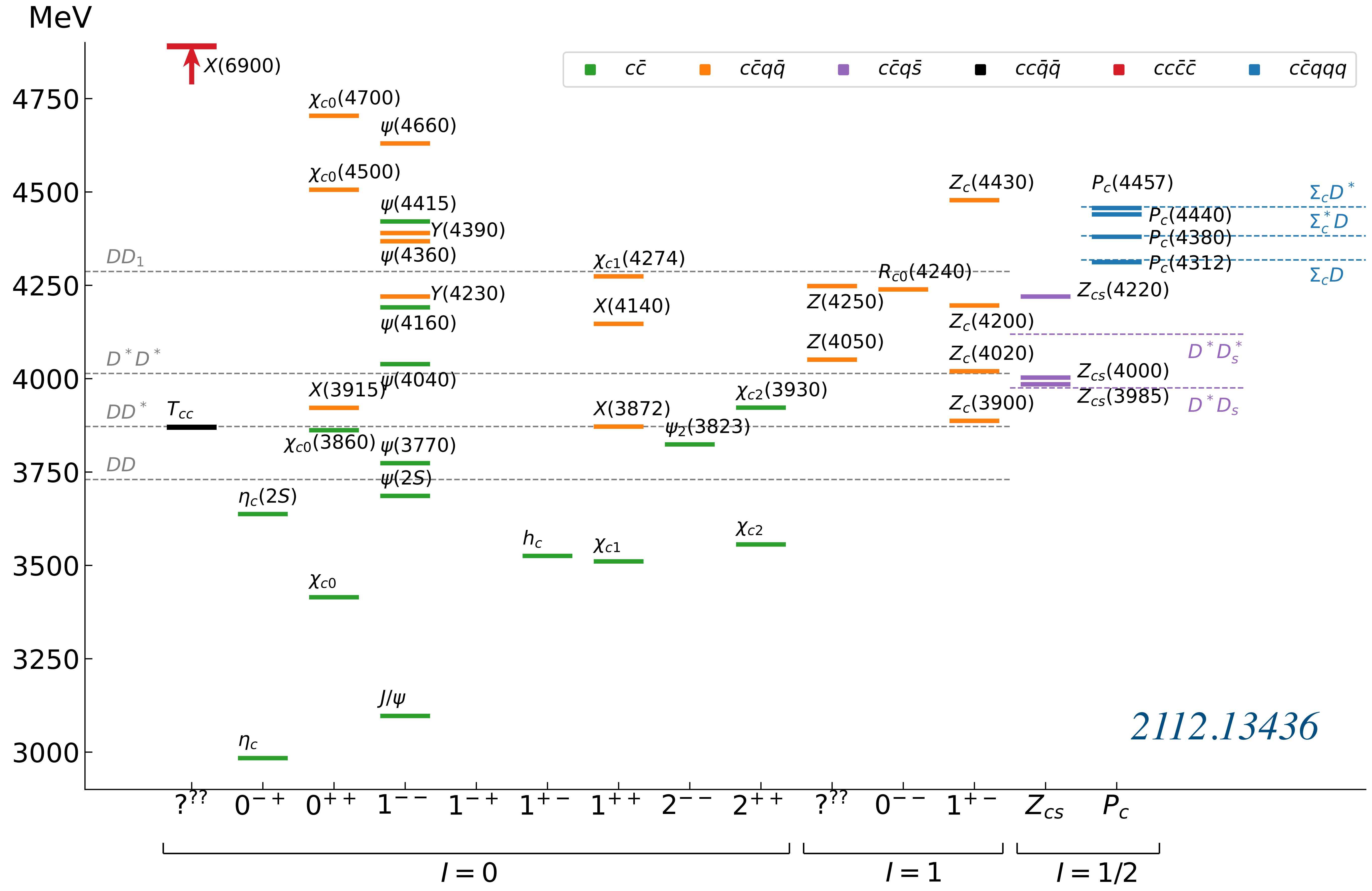
Jefferson Lab
Thomas Jefferson National Accelerator Facility

ExoHad
Exotic Hadrons Topical Collaboration

Example: Exotics in $c\bar{c}$

A plethora of unexpected resonances

- ✓ **Not $q\bar{q}$**
- **Different production mechanisms**
- **No single theoretical interpretation**
- **Most unconfirmed**



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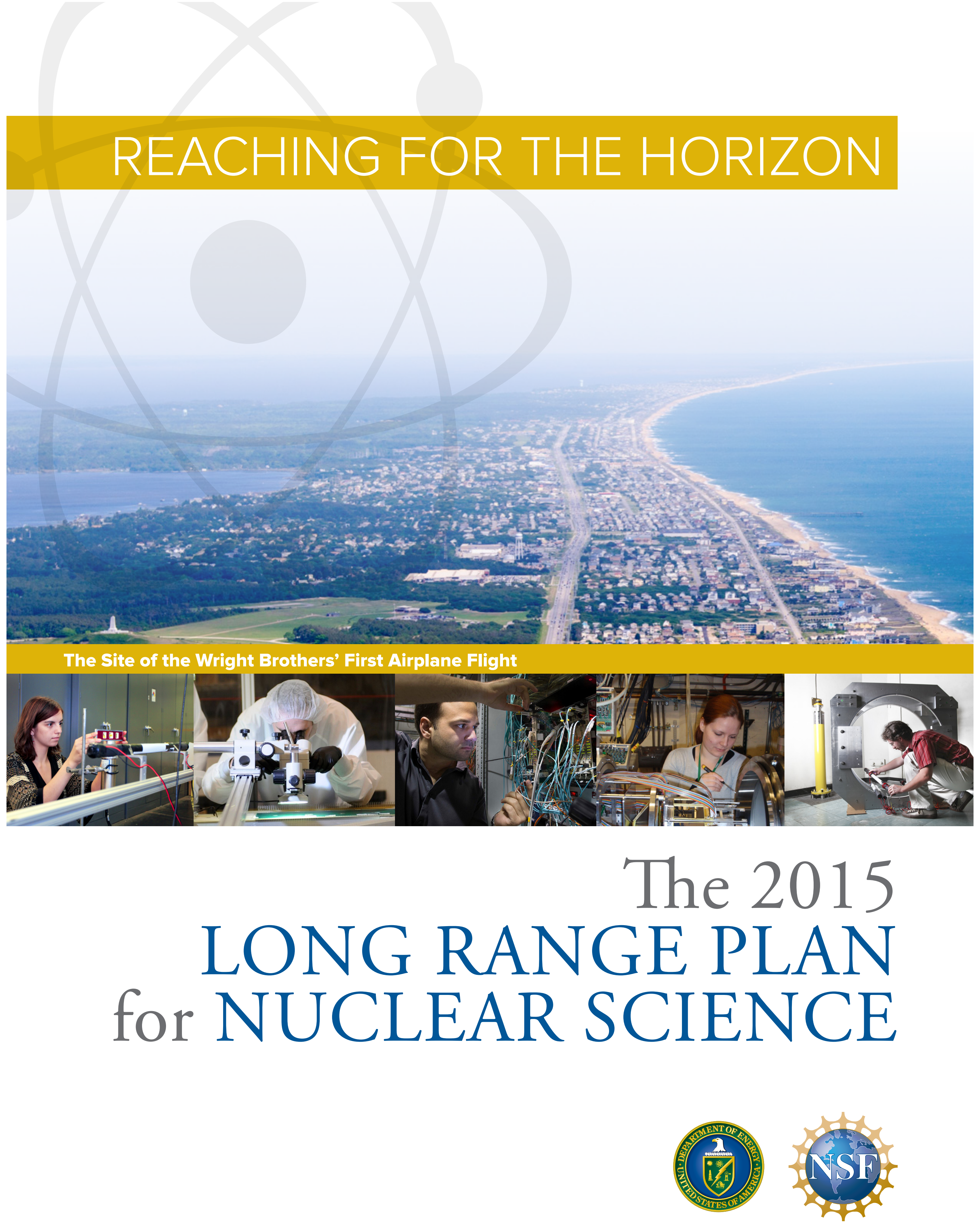

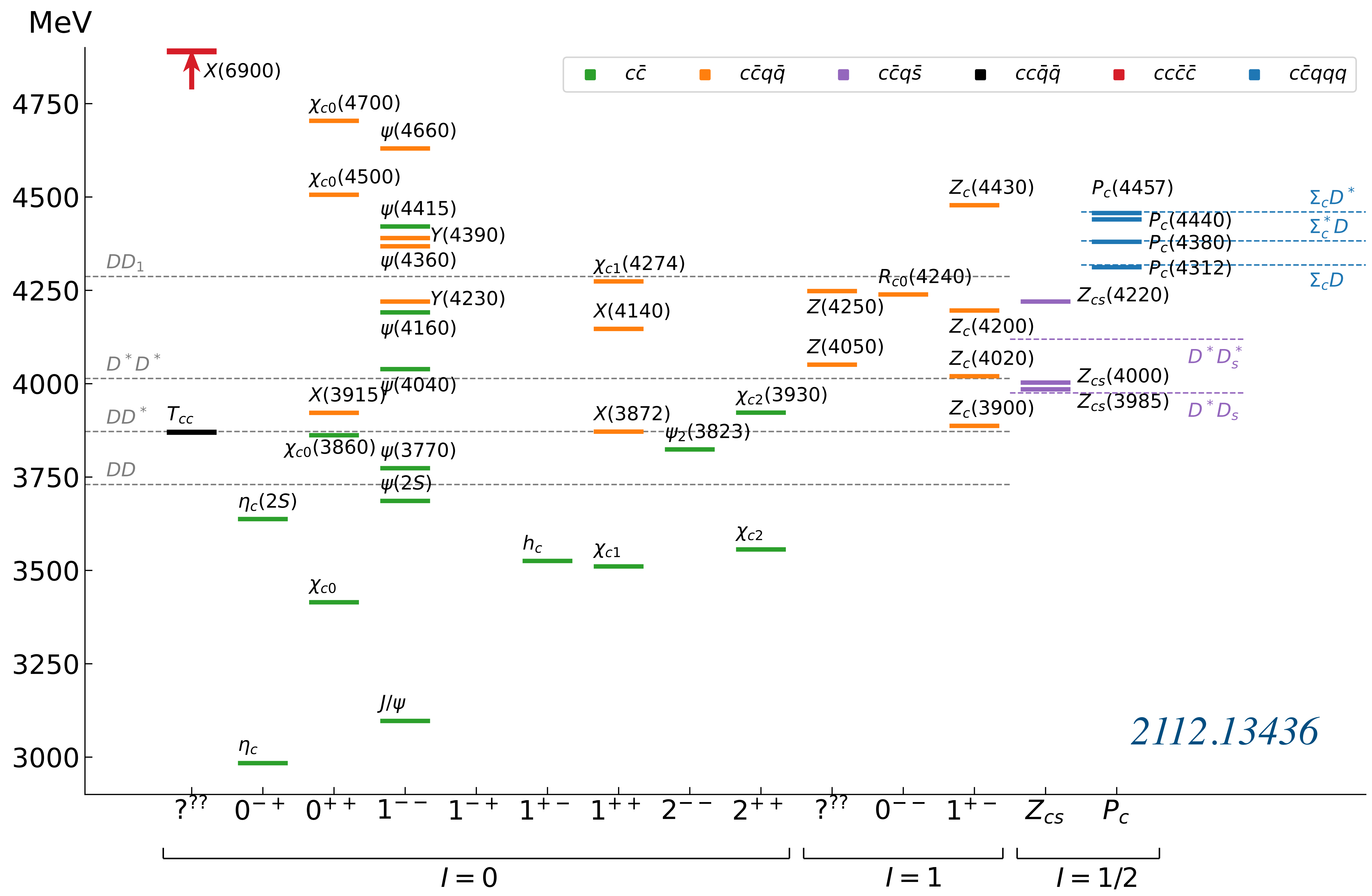

"... hadron spectroscopy illuminates the QCD interaction that binds quarks."

Coordinated Theoretical Approach for Exotic Hadron Spectroscopy

Aims at exploring aspects of exotics

- **Relevant predictions**
- **Confirm existence**
- **Guide/support experiments**
- **Study nature**


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Jo Dudek
William & Mary


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University of Washington


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University of Pittsburgh


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Indiana University

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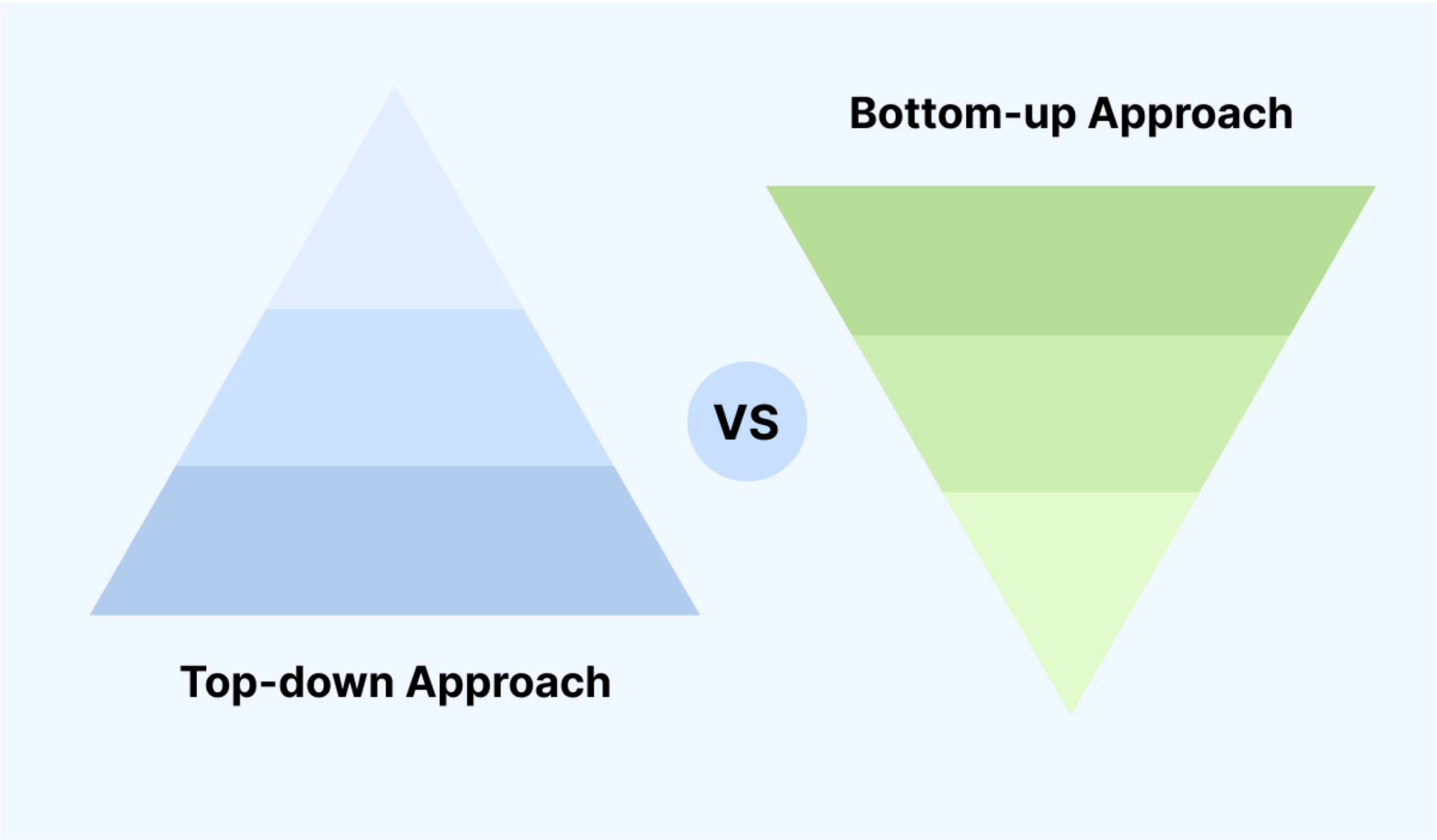


Observables

Functional methods

Amplitude analyses

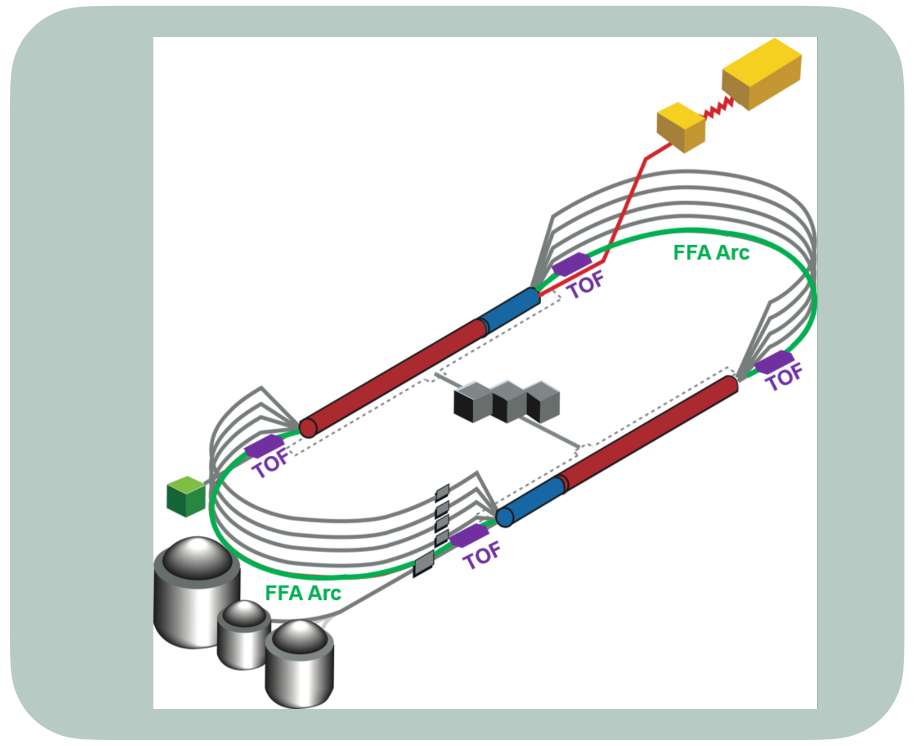
S-matrix

Models

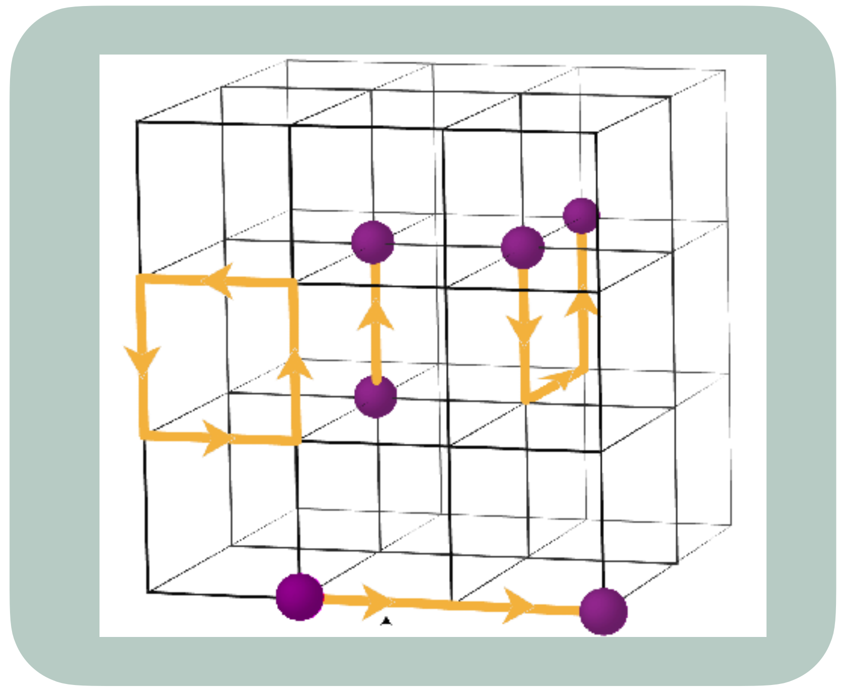
HQET

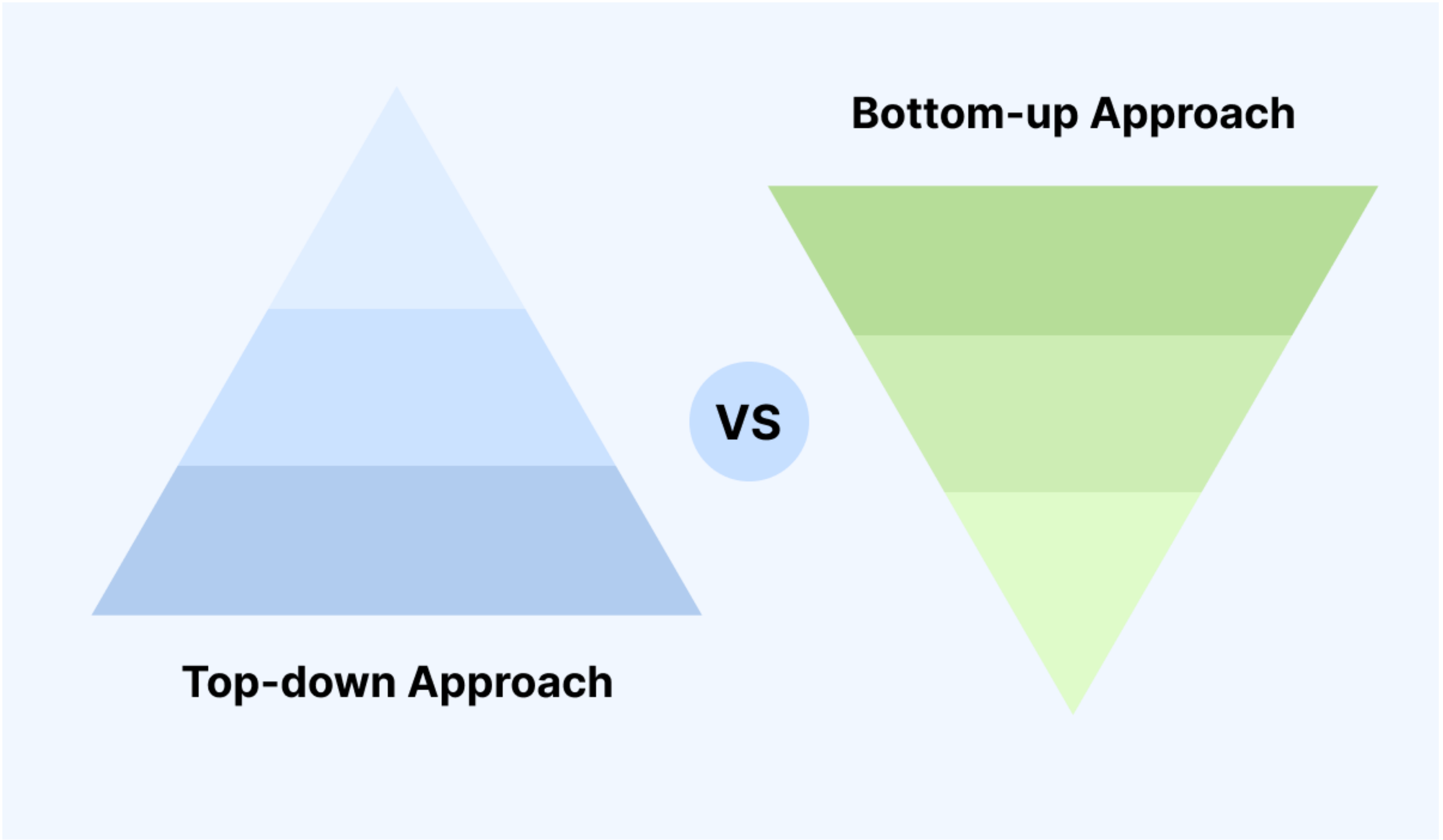
ChPT

NREFT



Events





Observables ← Functional methods

Relevant predictions

Amplitude analyses

S-matrix

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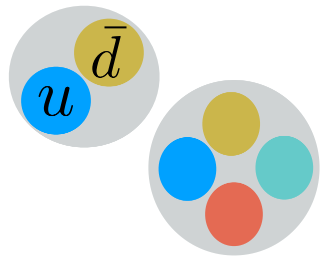

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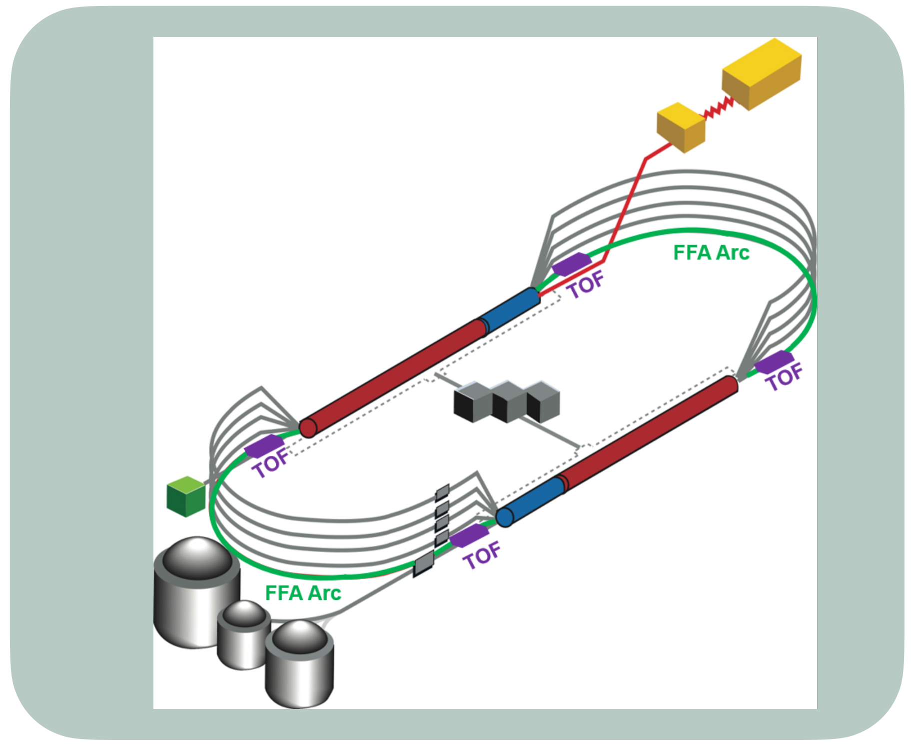
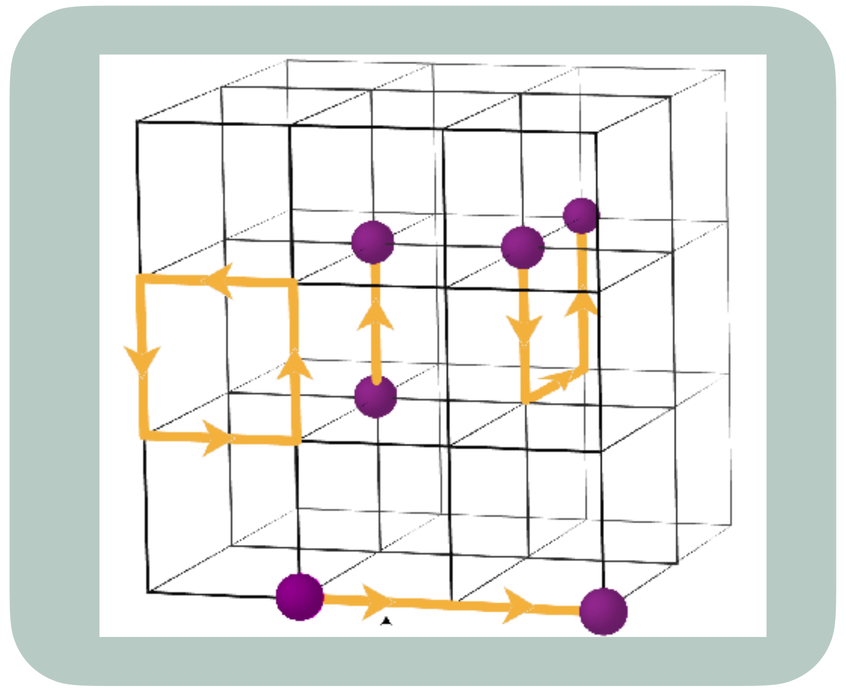
Guide/support experiments

Study nature



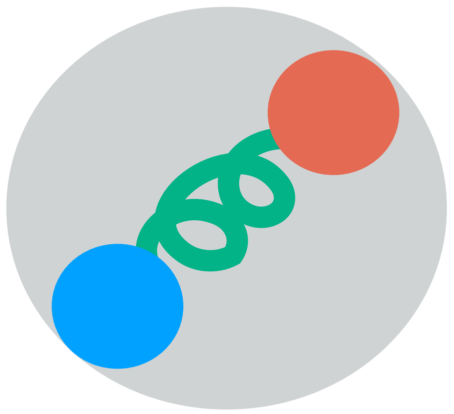
Events



Confirm existence

Example: the π_1

Hybrid mesons ($q\bar{q}g$) were predicted long ago



It is expected that these hadrons can offer us valuable information about the interactions between gluons and quarks

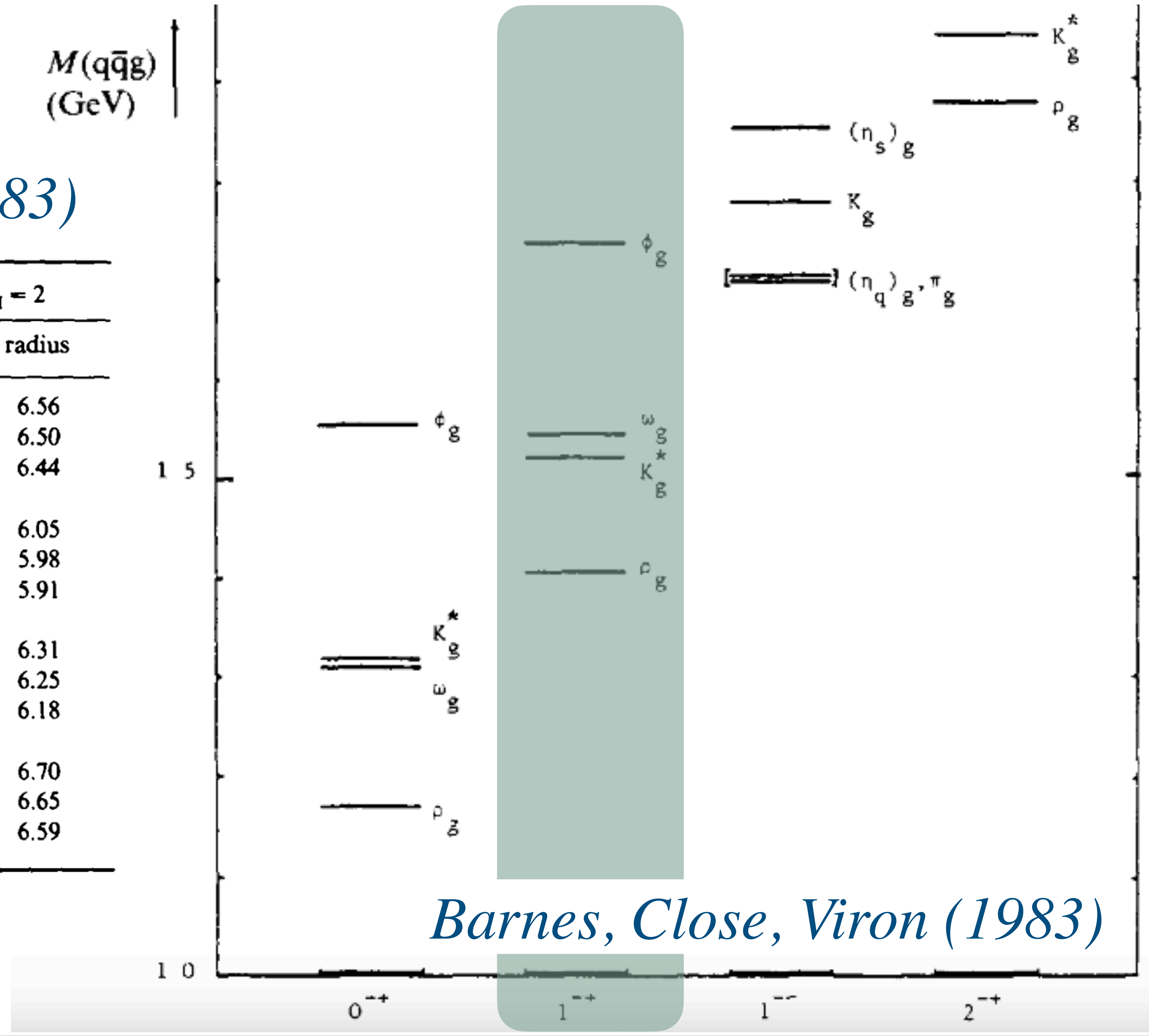
Different pictures (constituent gluons, flux-tube, bag models) predict a $J^{PC} = 1^{-+}$ state between 1.5-2 GeV

Isgur, Paton (1985)

Flavor	J^{PC} or J^{P}	Mass (GeV) for $f=1$	$\frac{dm}{df}$ (GeV)	Δm [a] (GeV)	m [b] (GeV)
$I=1$	$2^{\pm\mp},1^{\pm\mp},0^{\pm\mp},1^{\pm\pm}$	1.67	0.08	0.19	~ 1.9
$I=\frac{1}{2}$	$2^{\pm},1^{\pm},0^{\pm},1^{\pm}$	1.80	0.10	0.17	~ 2.0
$I=0$ $\left[\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right]$	$2^{\pm\mp},1^{\pm\mp},0^{\pm\mp},1^{\pm\pm}$	1.67	0.08	0.19	~ 1.9
$I=0$ $(s\bar{s})$	$2^{\pm\mp},1^{\pm\mp},0^{\pm\mp},1^{\pm\pm}$	1.91	0.12	0.14	~ 2.1
$c\bar{c}$	$2^{\pm\mp},1^{\pm\mp},0^{\pm\mp},1^{\pm\pm}$	4.19	0.18	0.06	~ 4.3
$b\bar{b}$	$2^{\pm\mp},1^{\pm\mp},0^{\pm\mp},1^{\pm\pm}$	10.79	0.28	0.02	~ 10.8

Chanowitz, Sharpe (1983)

J^{PC}	Type	$C_{TE}/C_{TM}=\frac{1}{2}$ mass	$C_{TE}/C_{TM}=\frac{1}{2}$ radius	$C_{TE}/C_{TM}=1$ mass	$C_{TE}/C_{TM}=1$ radius	$C_{TE}/C_{TM}=2$ mass	$C_{TE}/C_{TM}=2$ radius
1^{--}	ρ/ω	1.64	6.10	1.83	6.35	2.02	6.56
	K*	1.80	6.03	1.99	6.29	2.18	6.50
	ϕ	1.96	5.95	2.16	6.22	2.35	6.44
0^{-+}	ρ/ω	1.20	5.50	1.41	5.81	1.61	6.05
	K*	1.41	5.42	1.62	5.74	1.82	5.98
	ϕ	1.61	5.34	1.82	5.67	2.03	5.91
1^{-+}	ρ/ω	1.41	5.80	1.61	6.05	1.80	6.31
	K*	1.59	5.73	1.80	5.98	1.99	6.25
	ϕ	1.78	5.66	1.99	5.90	2.18	6.18
2^{-+}	ρ/ω	1.79	6.30	1.97	6.51	2.15	6.70
	K*	1.94	6.24	2.13	6.45	2.31	6.65
	ϕ	2.09	6.17	2.28	6.39	2.47	6.59

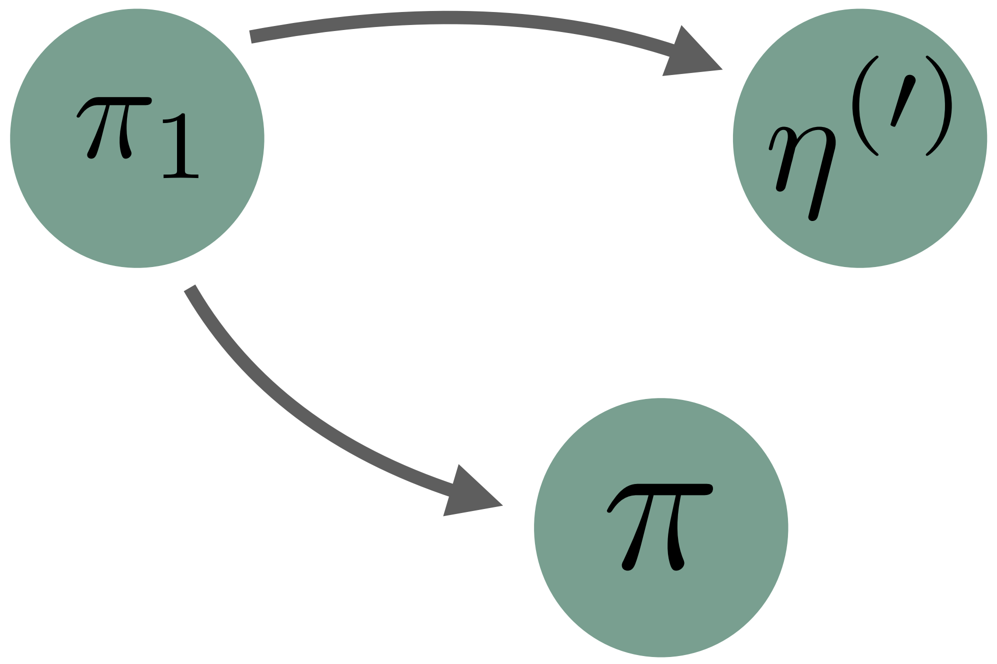


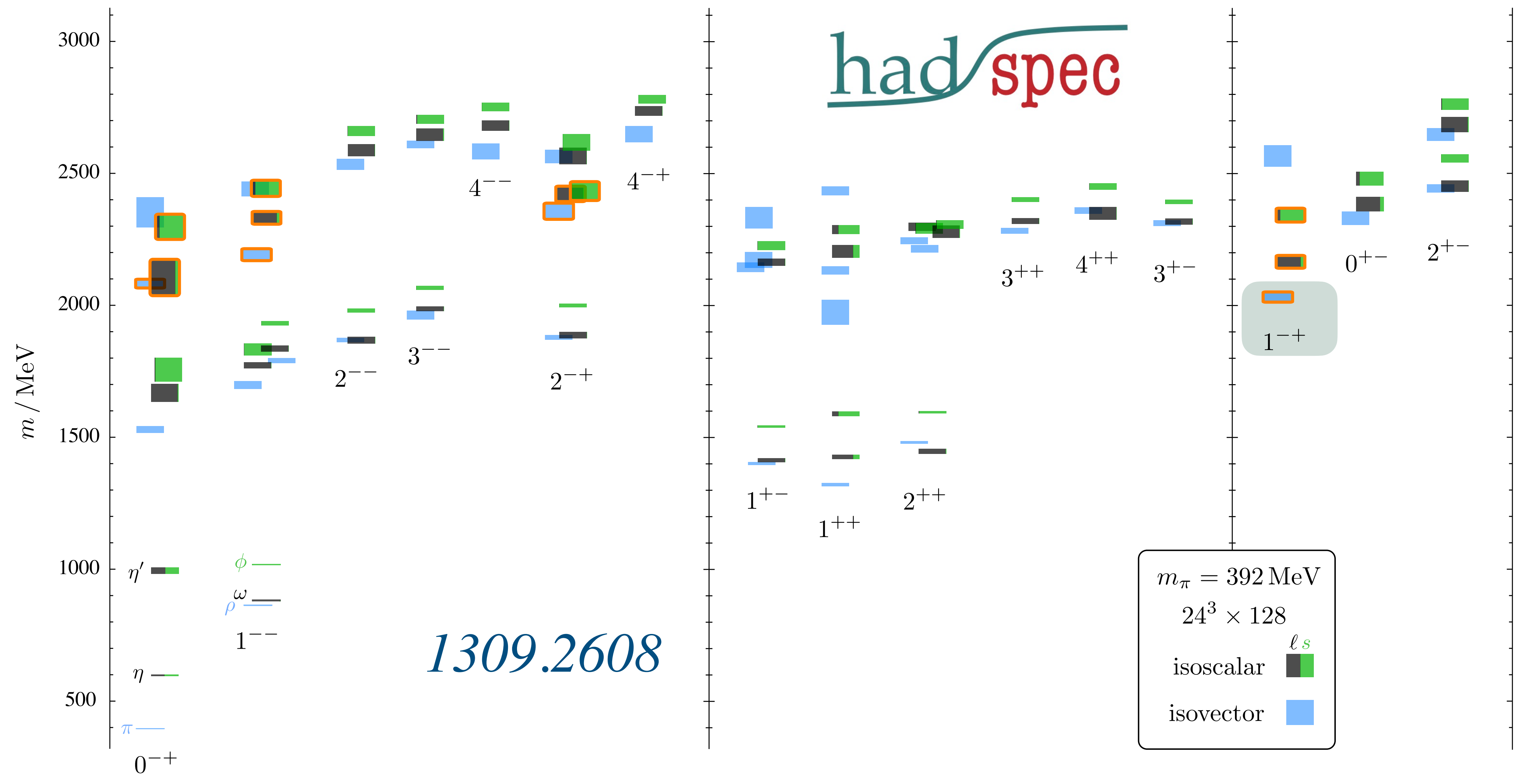
Barnes, Close, Viron (1983)

π_1 predictions

Lattice QCD "models" predict a lightest $J^{PC}=1^{-+}$, isolated hybrid

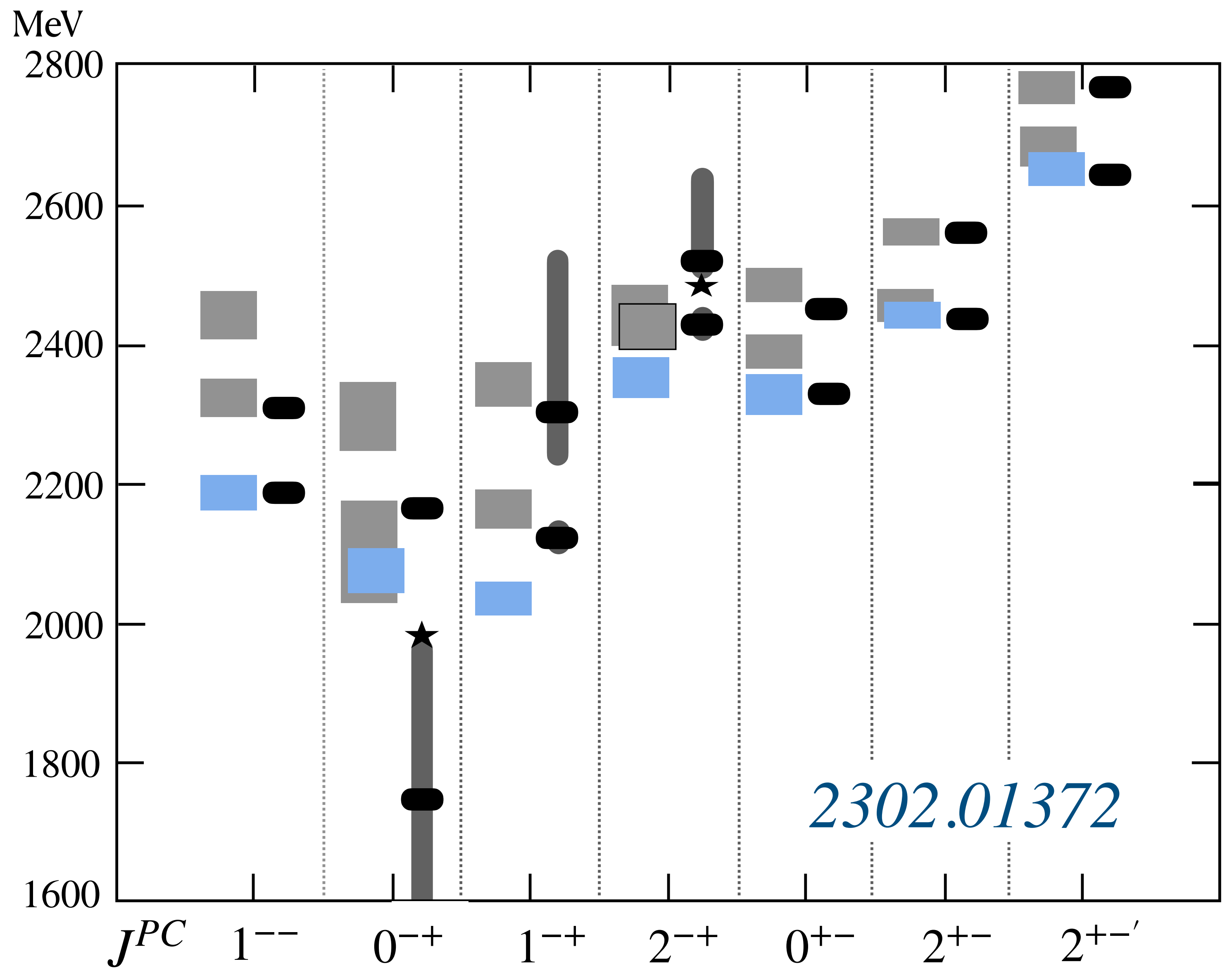
$$J^{PC}(\pi_1) = \boxed{1^{-+}}$$



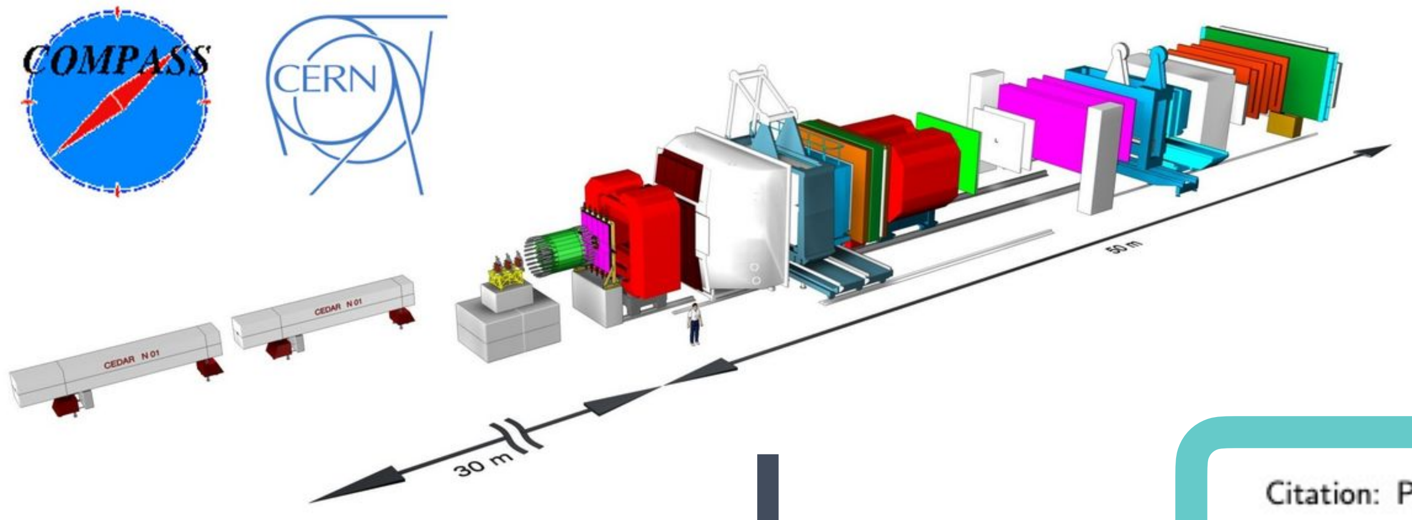


It can decay to two pseudo-scalar mesons (easiest decay product type)

Recent predictions (constituent gluons) agree with LQCD and previous model expectations

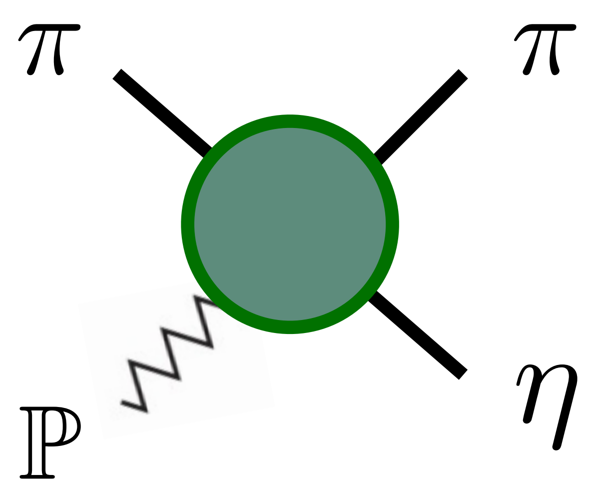


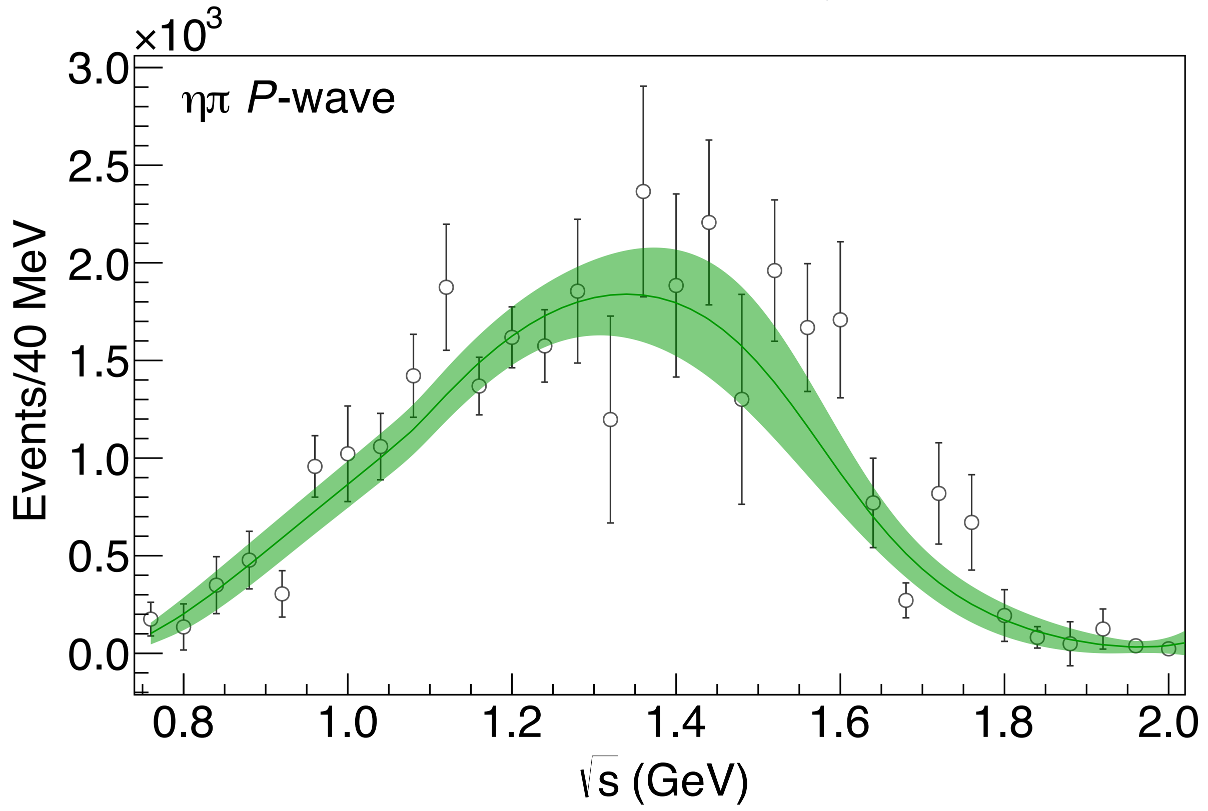
π_1 confirmation



<u>**Experiment does not agree with theory**</u>

Different final states produce different hybrids





Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

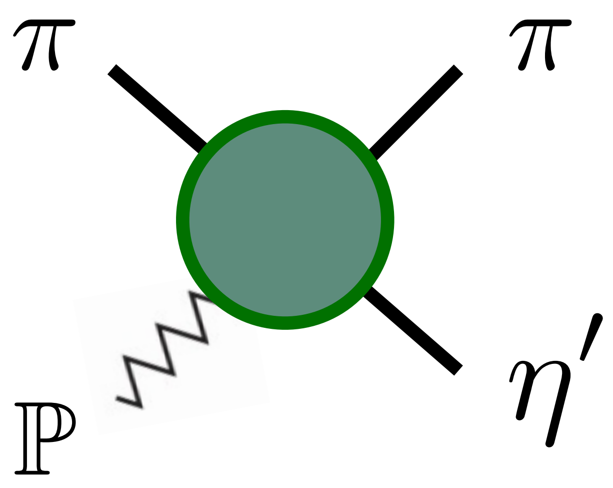
$\pi_1(1400)$ $I^G(J^{PC}) = 1^-(1^{-+})$

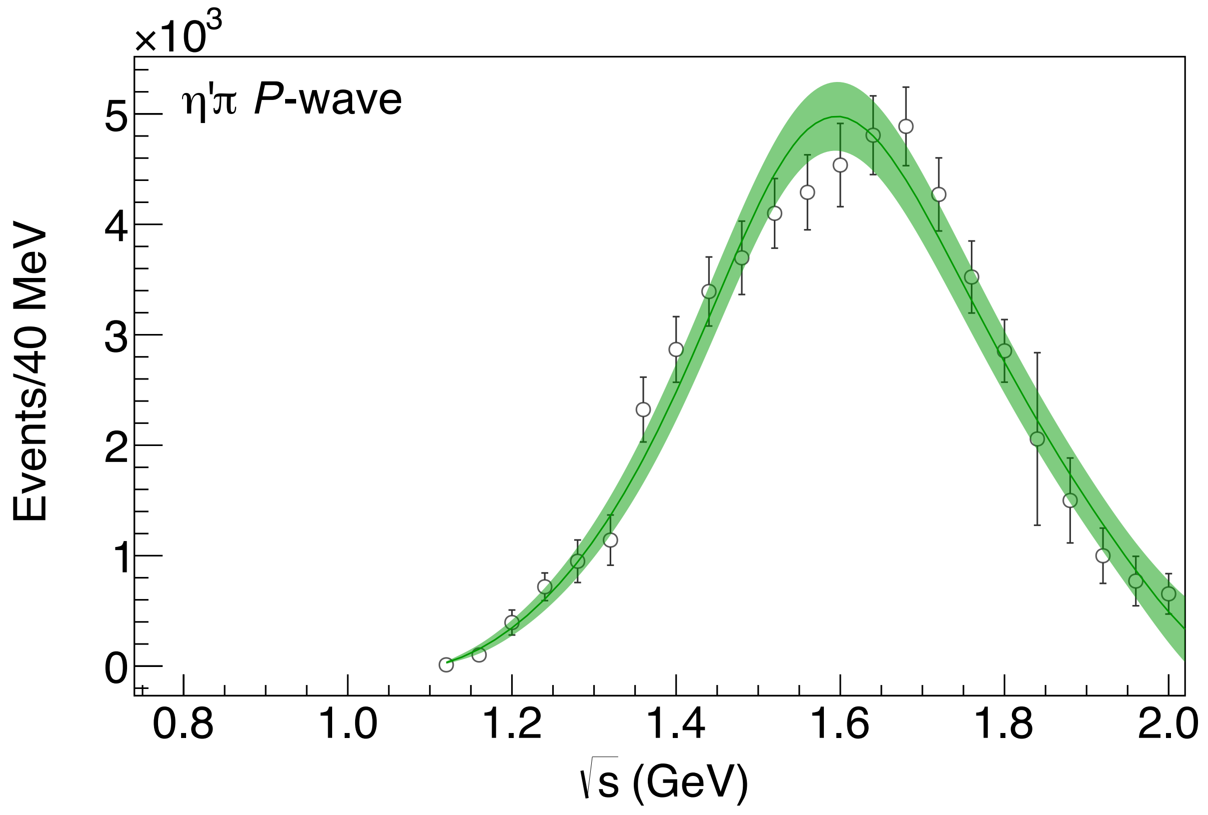
See the review on "Non-$q\bar{q}$ Mesons" and a note in PDG 06, Journal of Physics **G33** 1 (2006).

$\pi_1(1400)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1354 ±25	**OUR AVERAGE**	Error includes scale factor of 1.8. See the ideogram below.			

These simplistic analyses did not include both channels at once





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

See the review on "Non-$q\bar{q}$ Mesons" and a note in PDG 06, Journal of Physics **G33** 1 (2006).

$\pi_1(1600)$ T-Matrix Pole $\sqrt{s}$

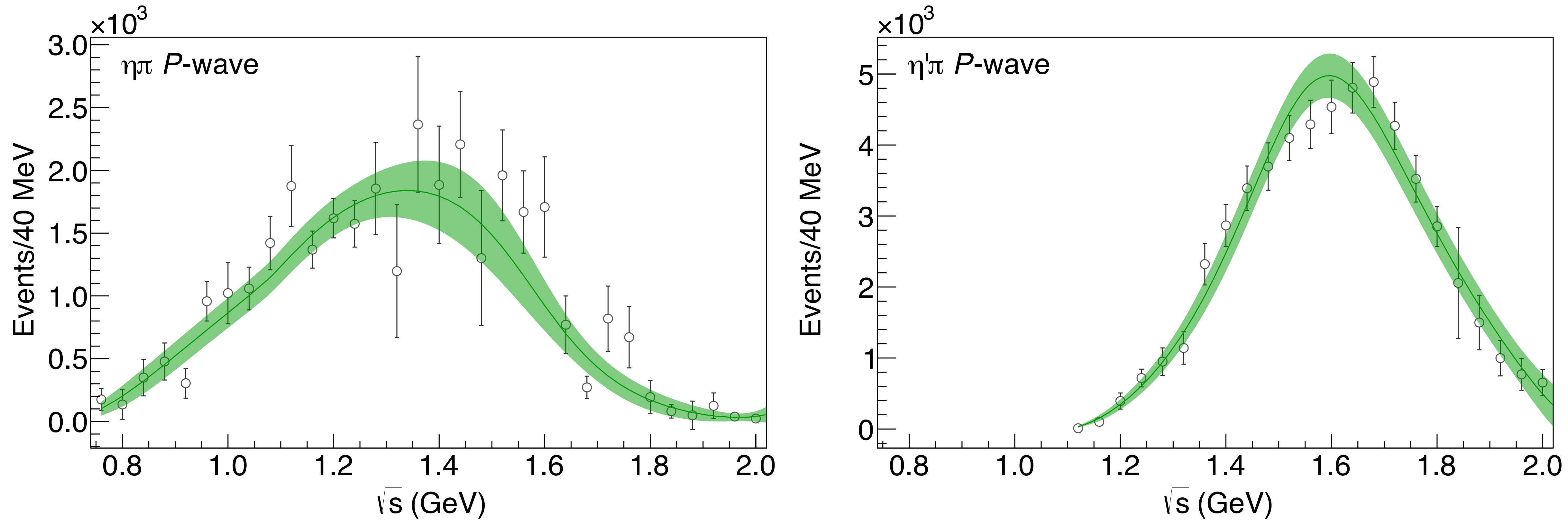
VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
$(1564 \pm 24 \pm 86) - i\,(246 \pm 27 \pm 51)$	[1] RODAS	19	JPAC	191 $\pi^- p \to \eta^{(\prime)} \pi^- p$

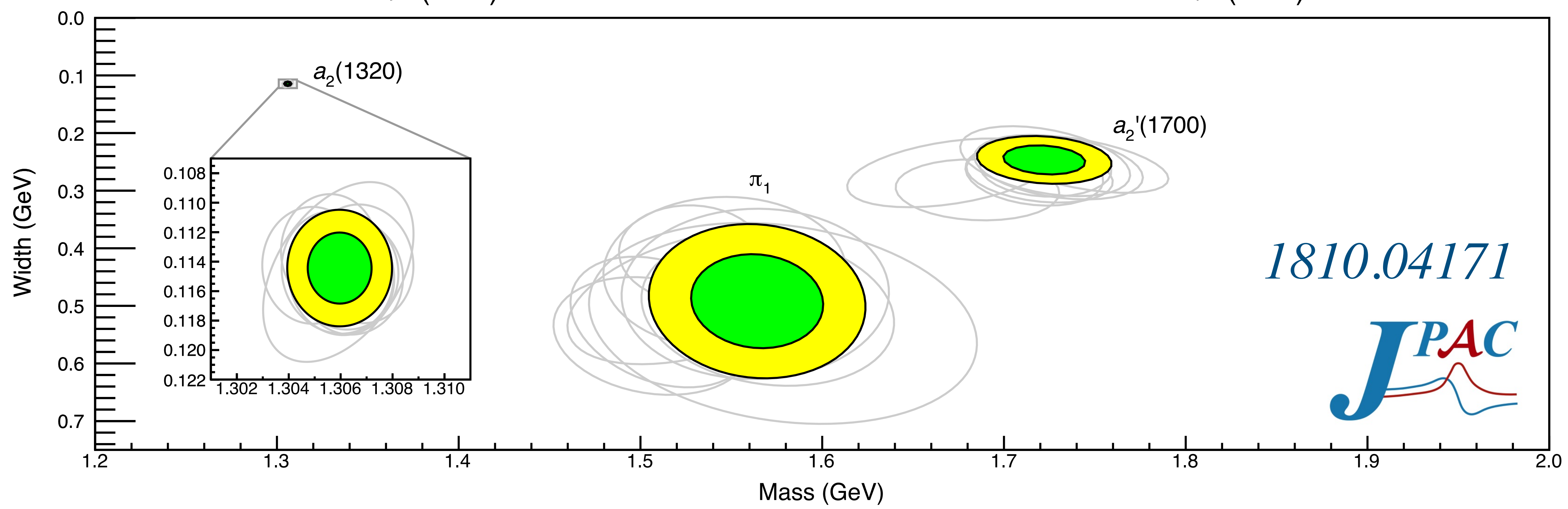
[1] The coupled-channel analysis of both the $\eta\pi$ and $\eta'\pi$ systems using ADOLPH 15 data.

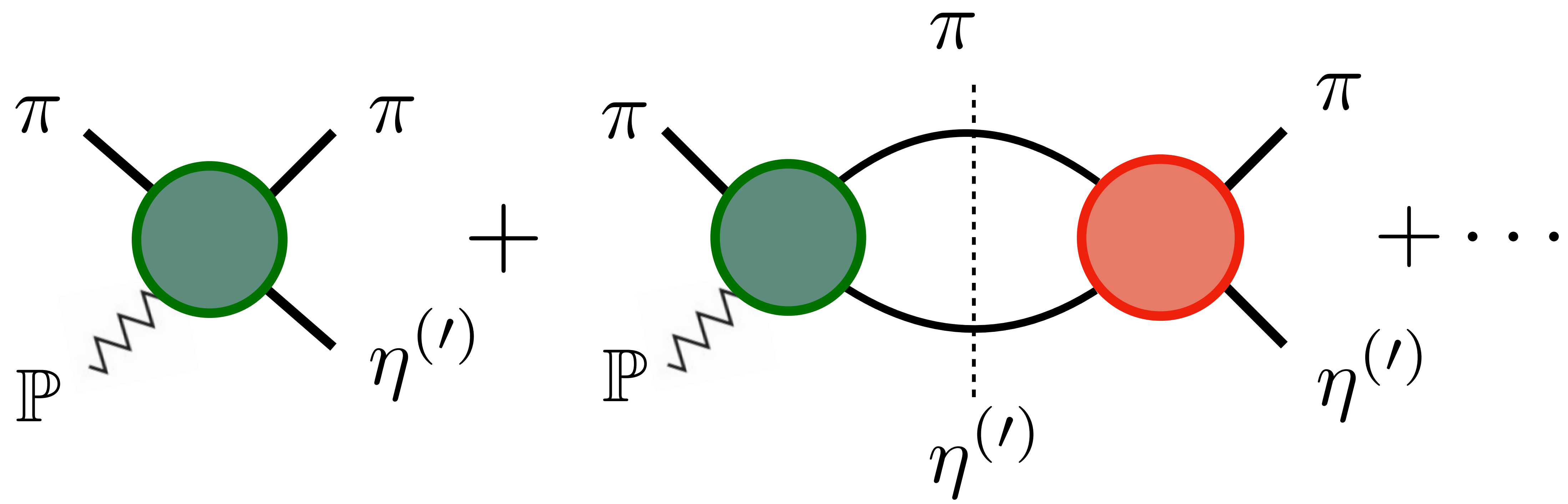
$\pi_1(1600)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1661^{+15}_{-11}	**OUR AVERAGE**	Error includes scale factor of 1.2.		

Only one hybrid is actually required to describe this scenario







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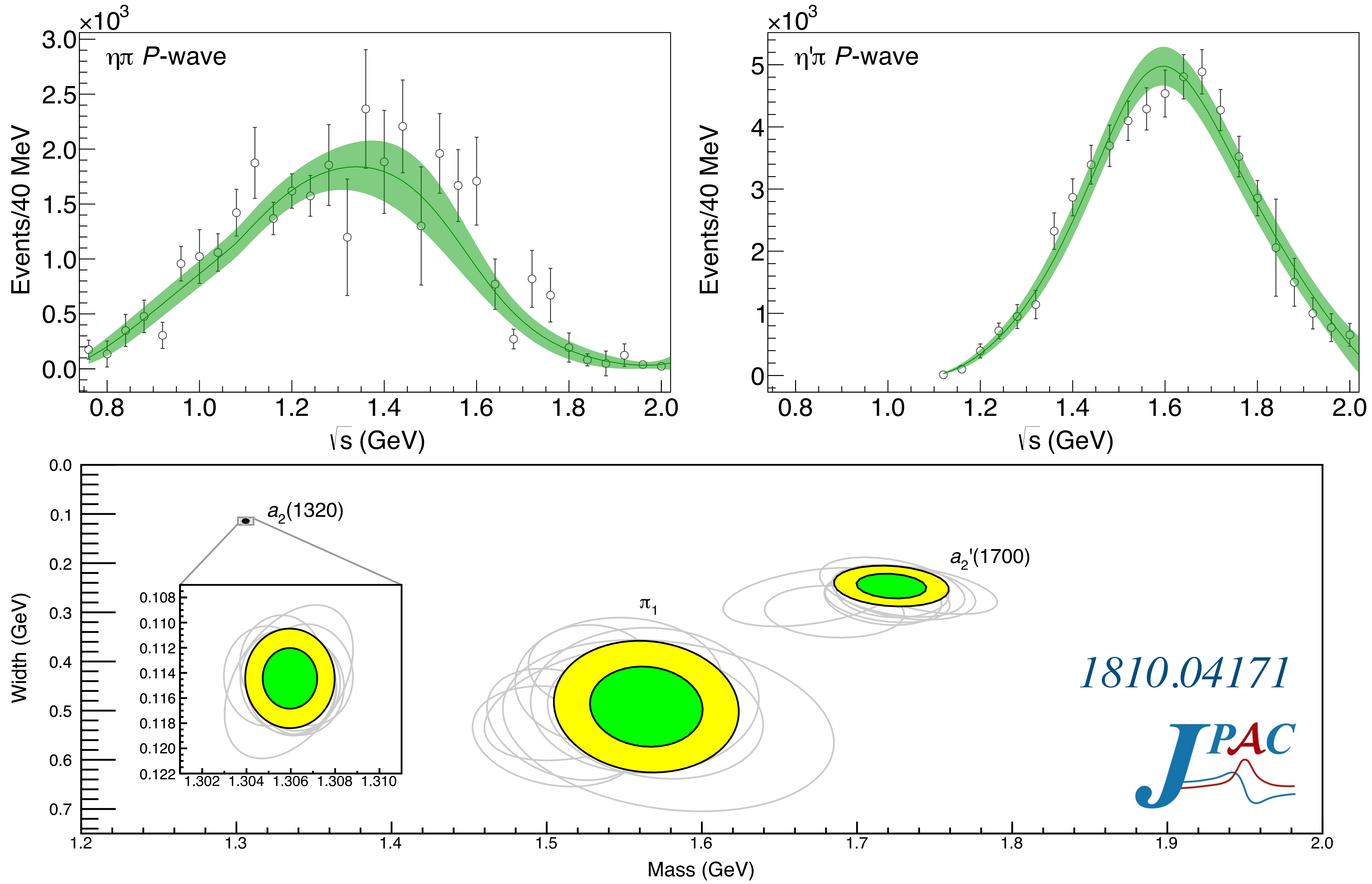

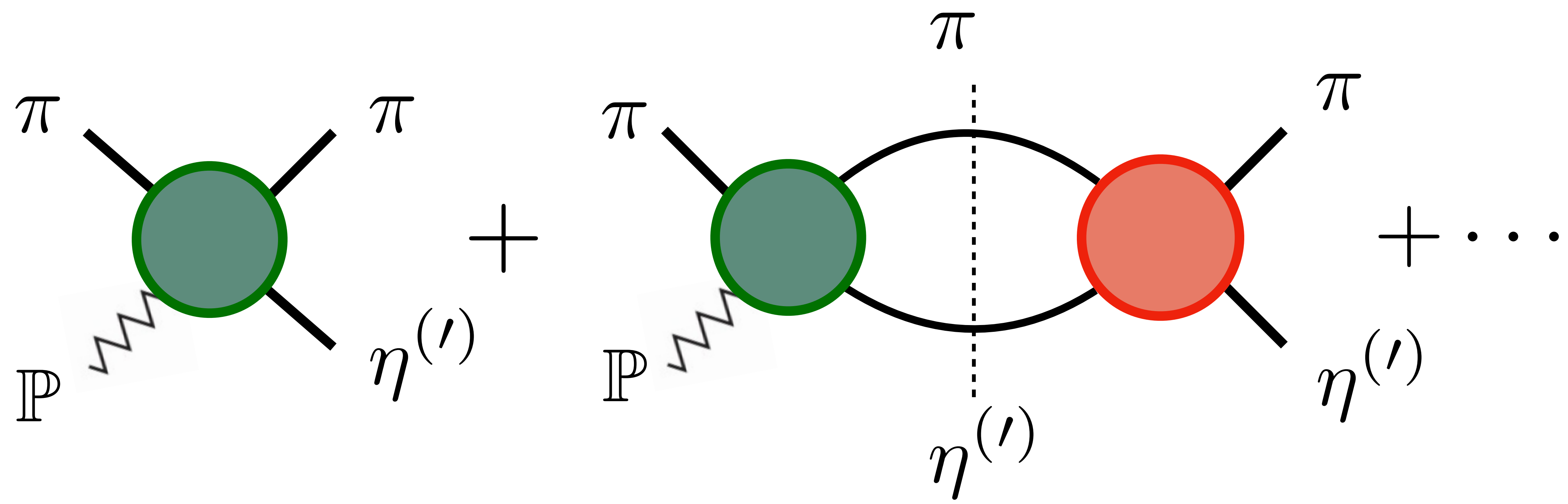

Exp. + pheno. confirmed

Investigation of the lightest hybrid meson candidate with a coupled-channel analysis of $\bar{p}p$-, $\pi^- p$- and $\pi\pi$-Data

B. Kopf (Ruhr U., Bochum), M. Albrecht (Ruhr U., Bochum), H. Koch (Ruhr U., Bochum), M. Küßner (Ruhr U., Bochum (main)), J. Pychy (Ruhr U., Bochum) et al. (Aug 26, 2020)

Published in: *Eur.Phys.J.C* 81 (2021) 12, 1056 • e-Print: 2008.11566 [hep-ph]

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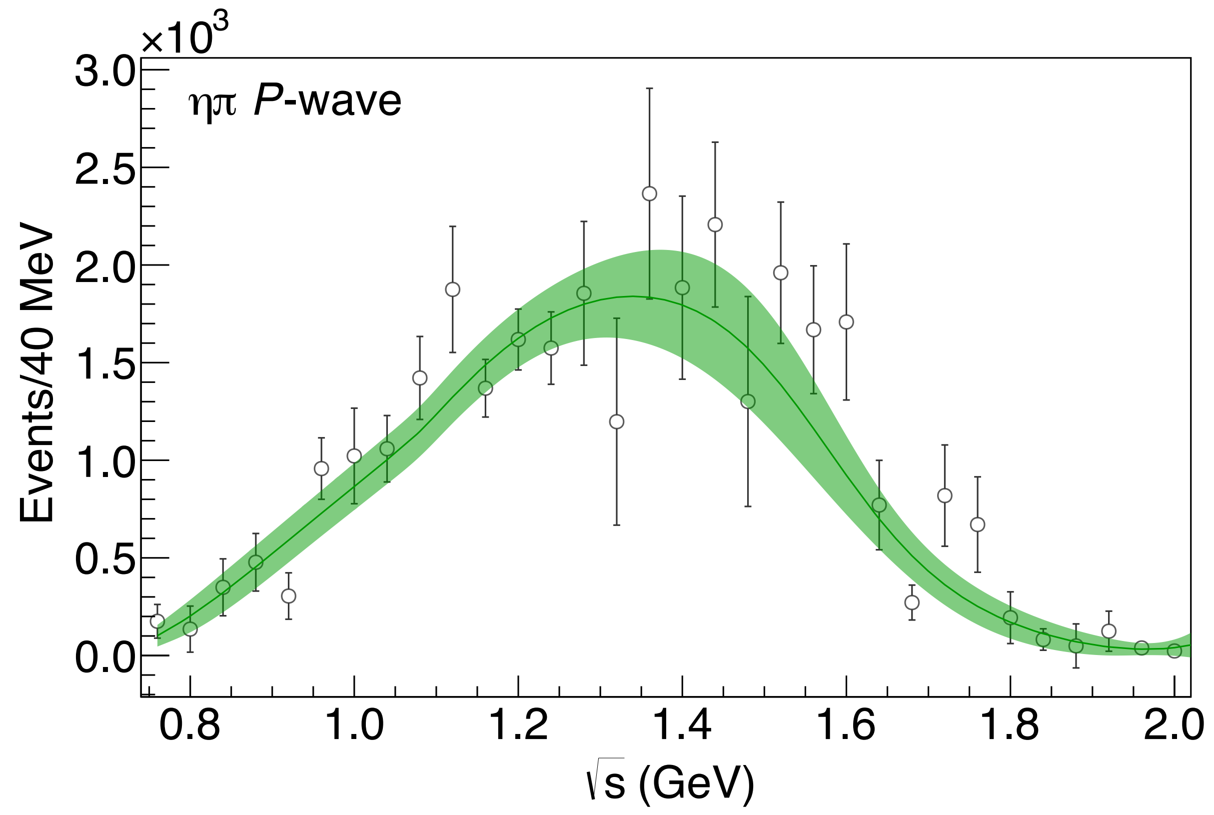

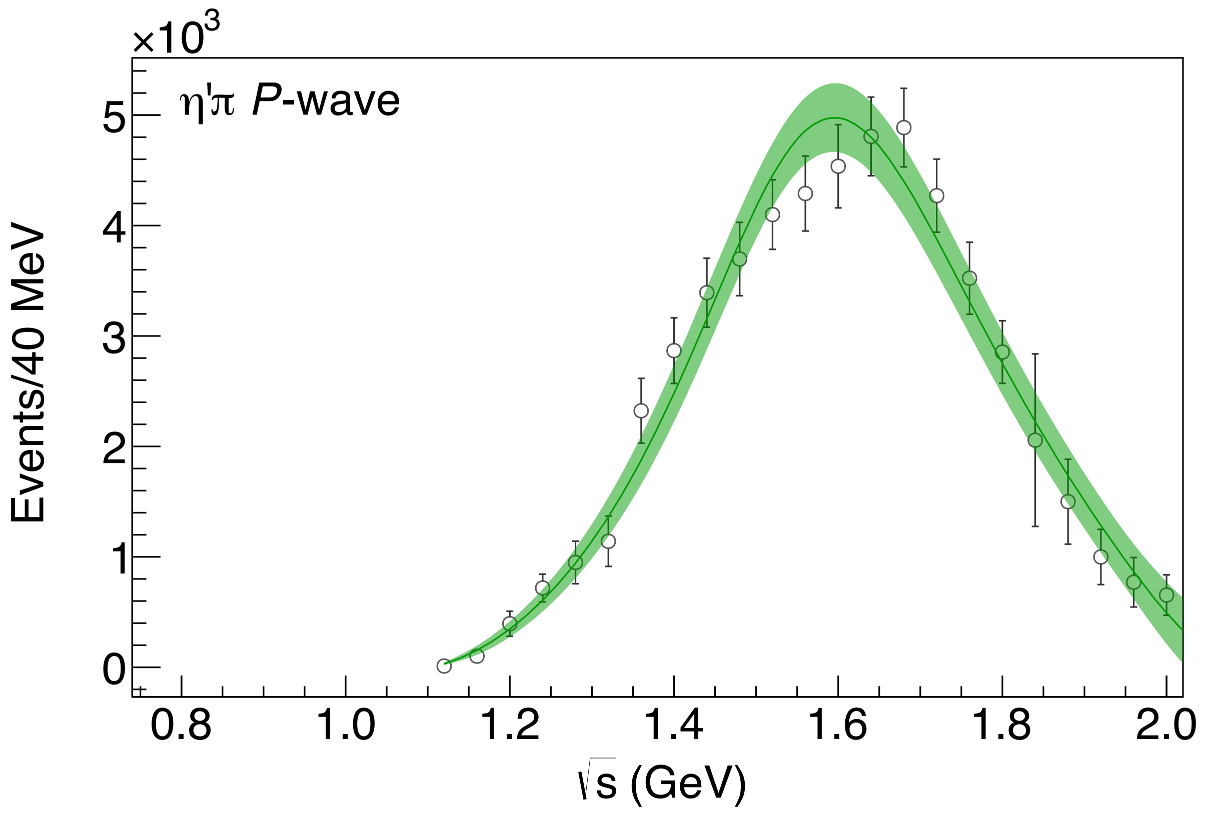

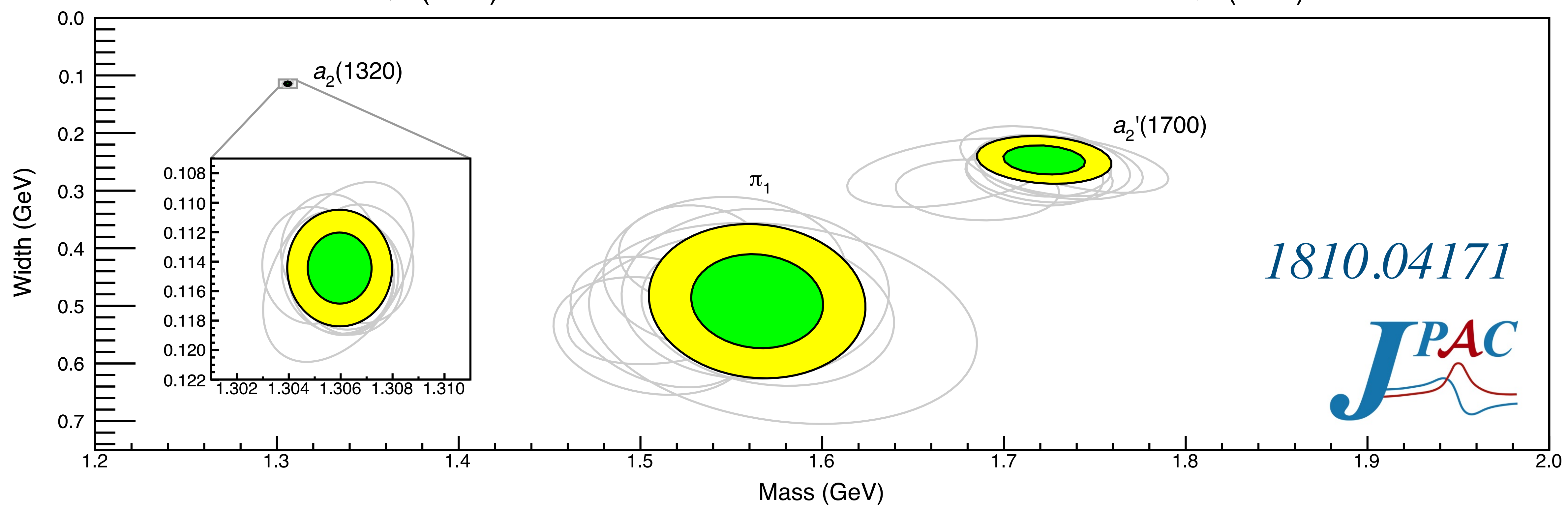

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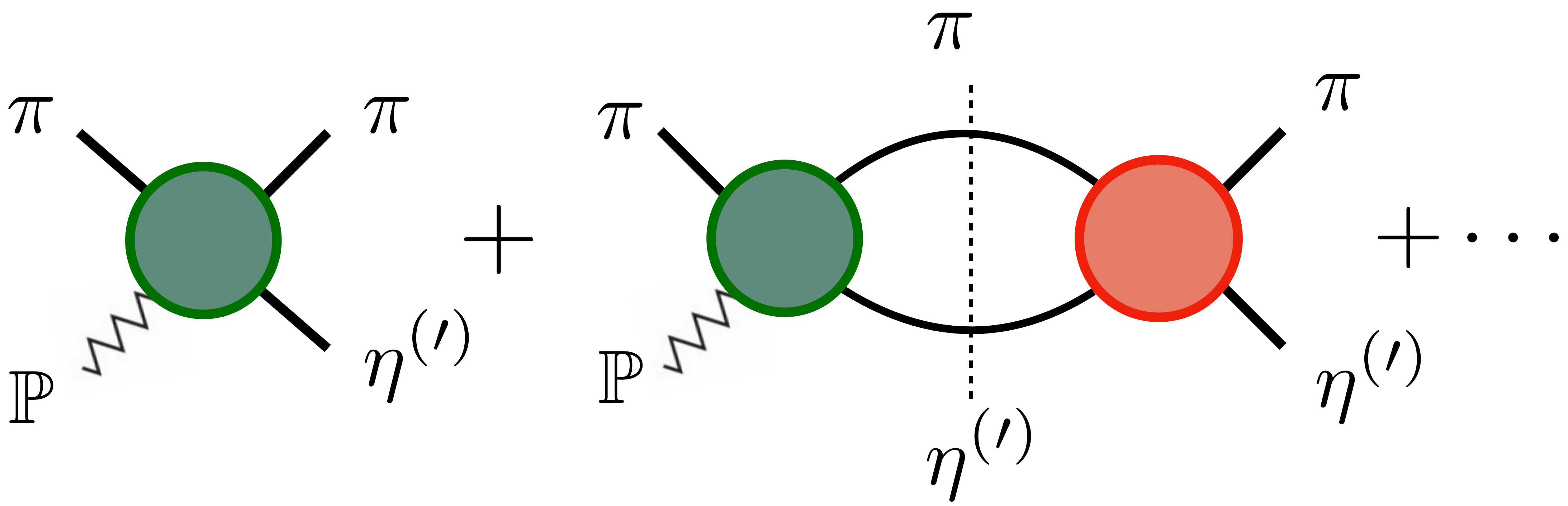
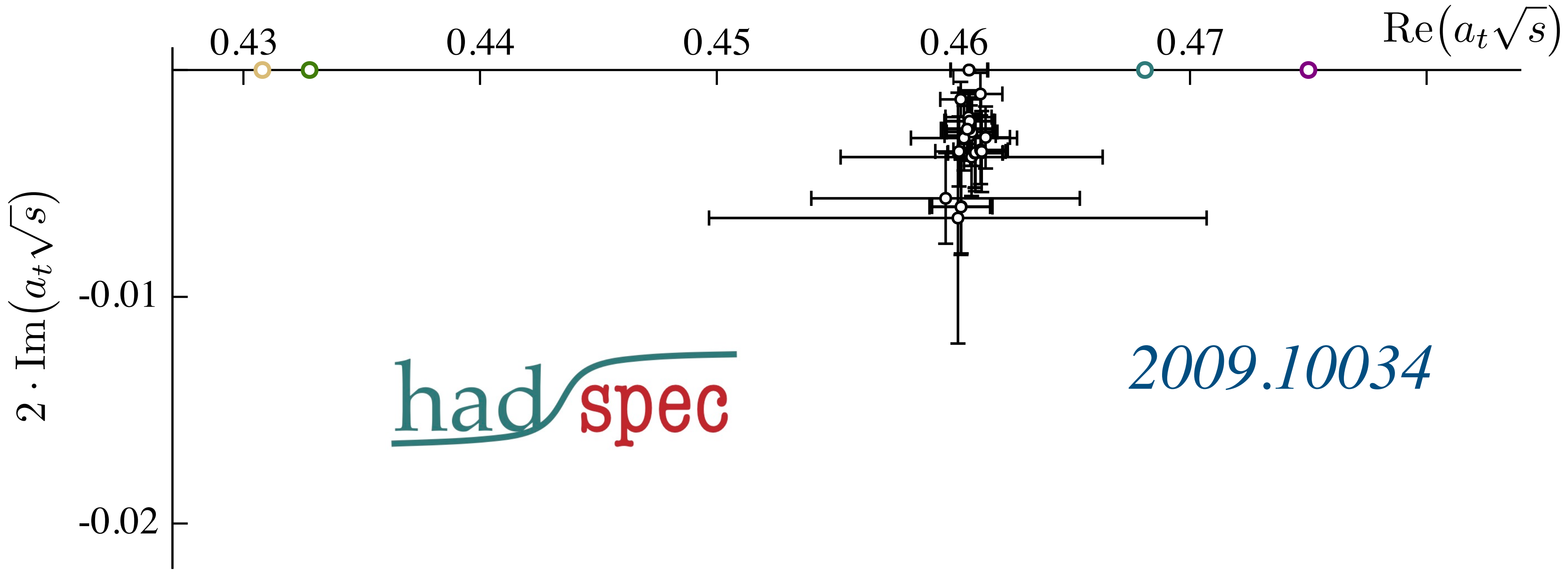
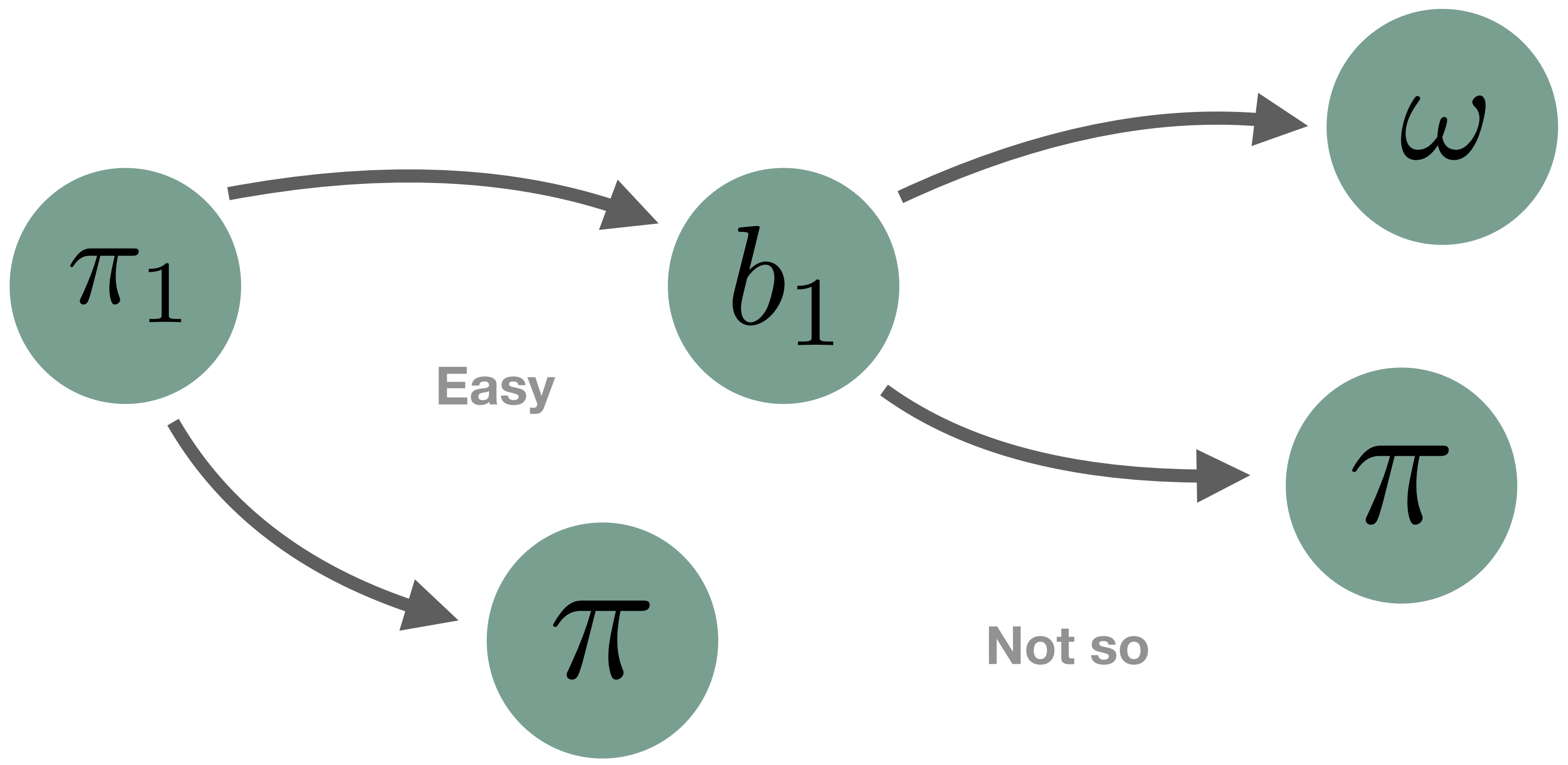


Confirm existence

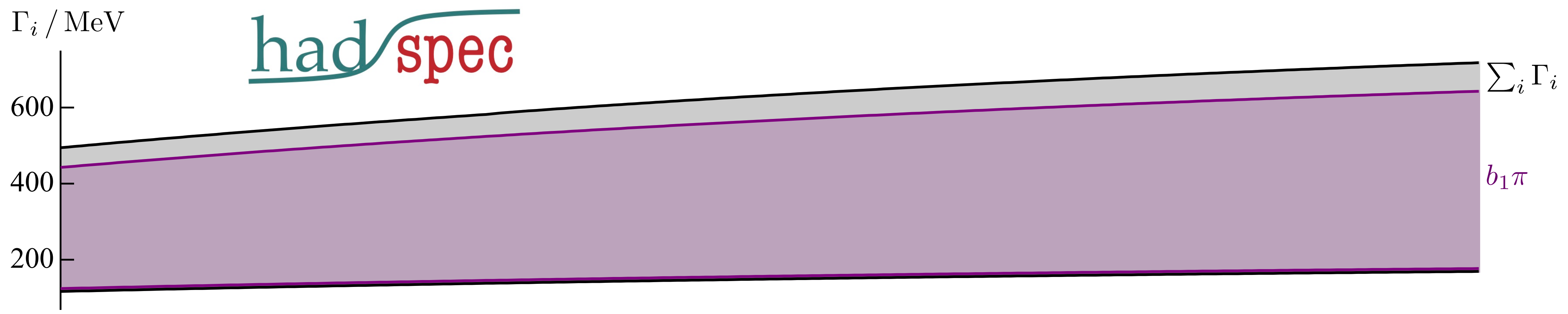
Lattice QCD confirmed



Experiment guidance

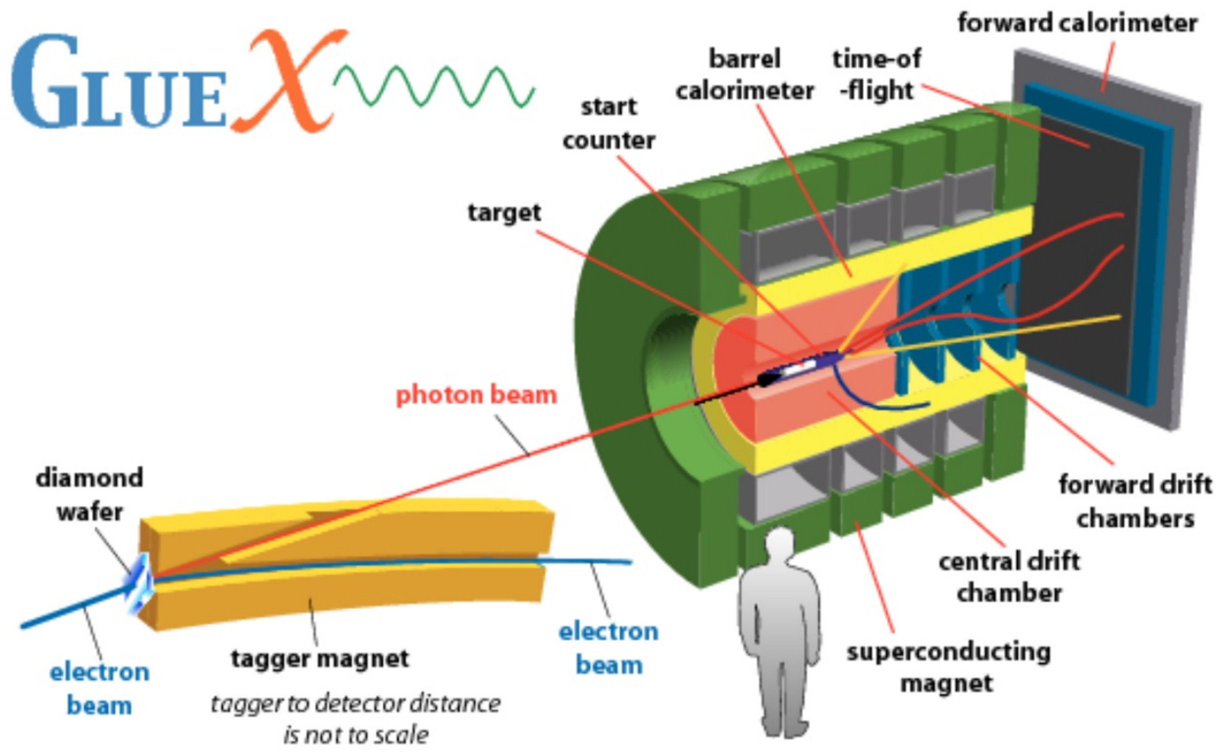


Lattice QCD predicted that the previous channels used to extract this state play a suppressed role



$$\Gamma(R) \sim \Gamma(R \to b_1\pi)$$

This state couples mostly to $b_1\pi$ out of 8 possible decay modes



Searches are "simplified", however, the main decay mode is now a "3-body" (5-body actually) decay

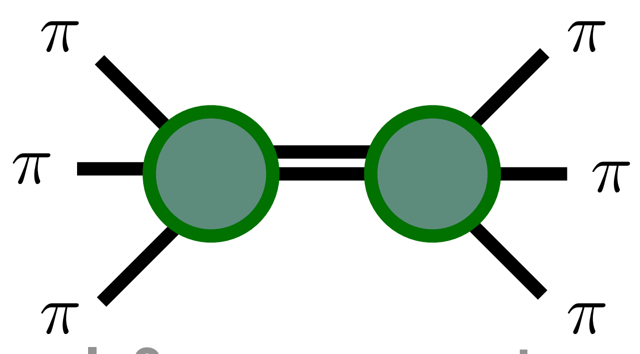
Experiment/LQCD support

We know how to describe 2-body decays, but the 3-body formalism is under development

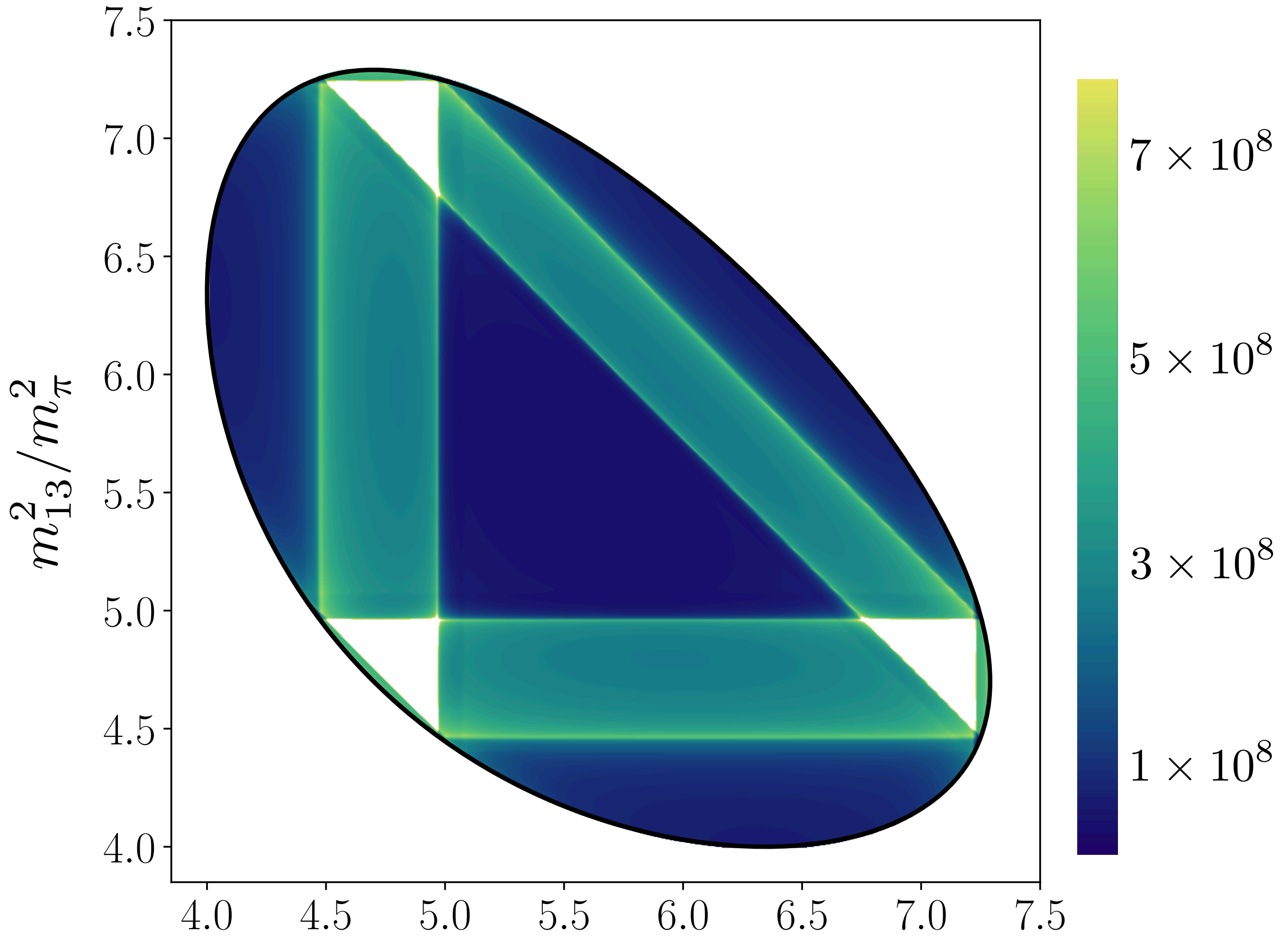
$$\rho(s) \rightarrow \int d\sigma_1 \int d\sigma_3 \, F(s,\sigma_1,\sigma_3)$$

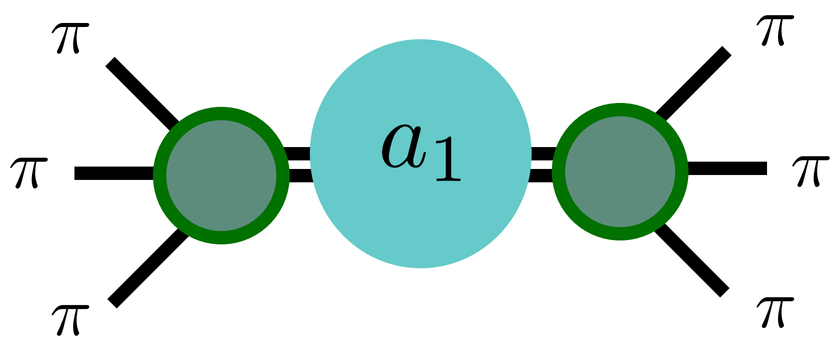
$2 \rightarrow 2$ amplitudes inside

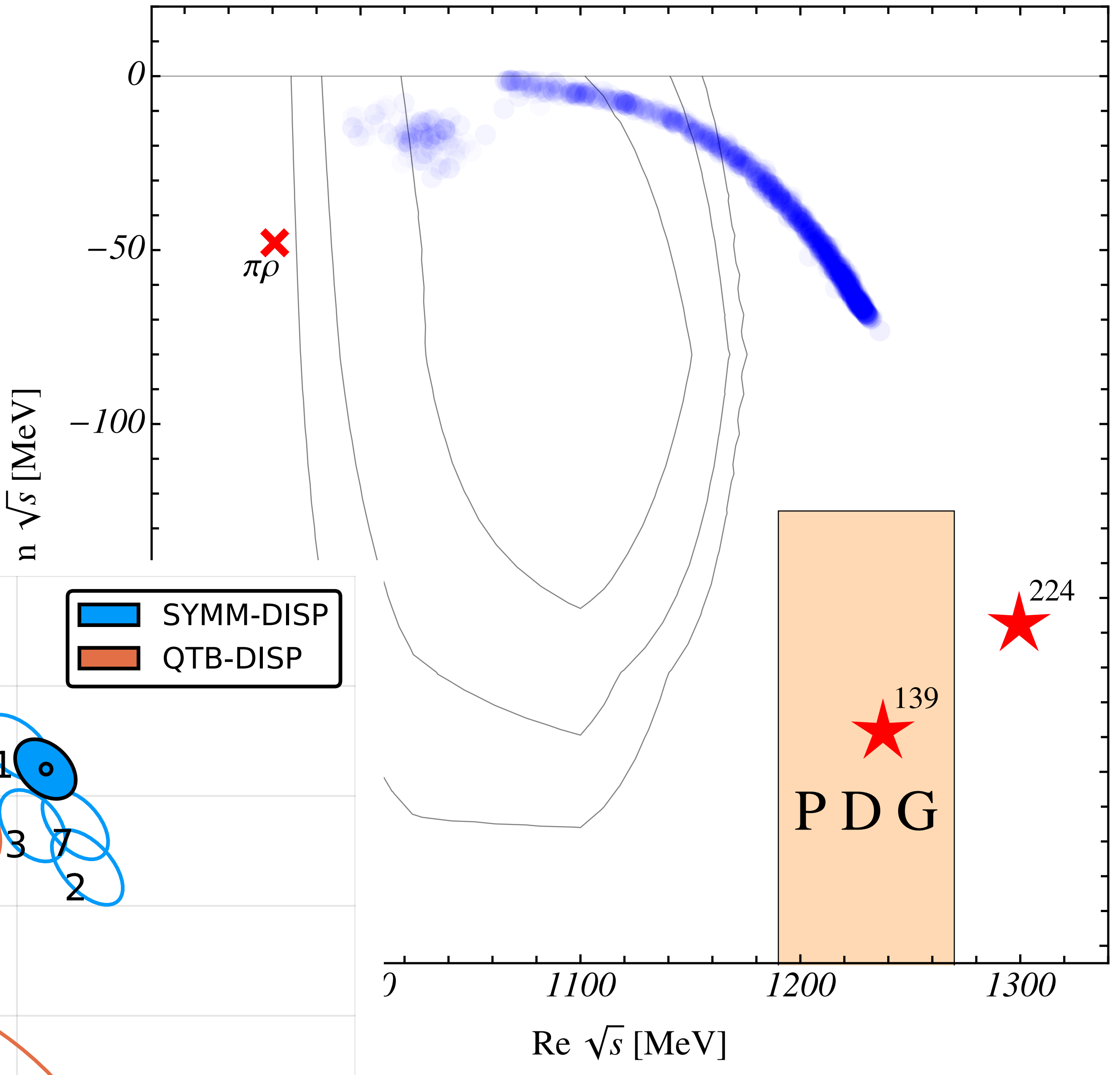
Much more cumbersome

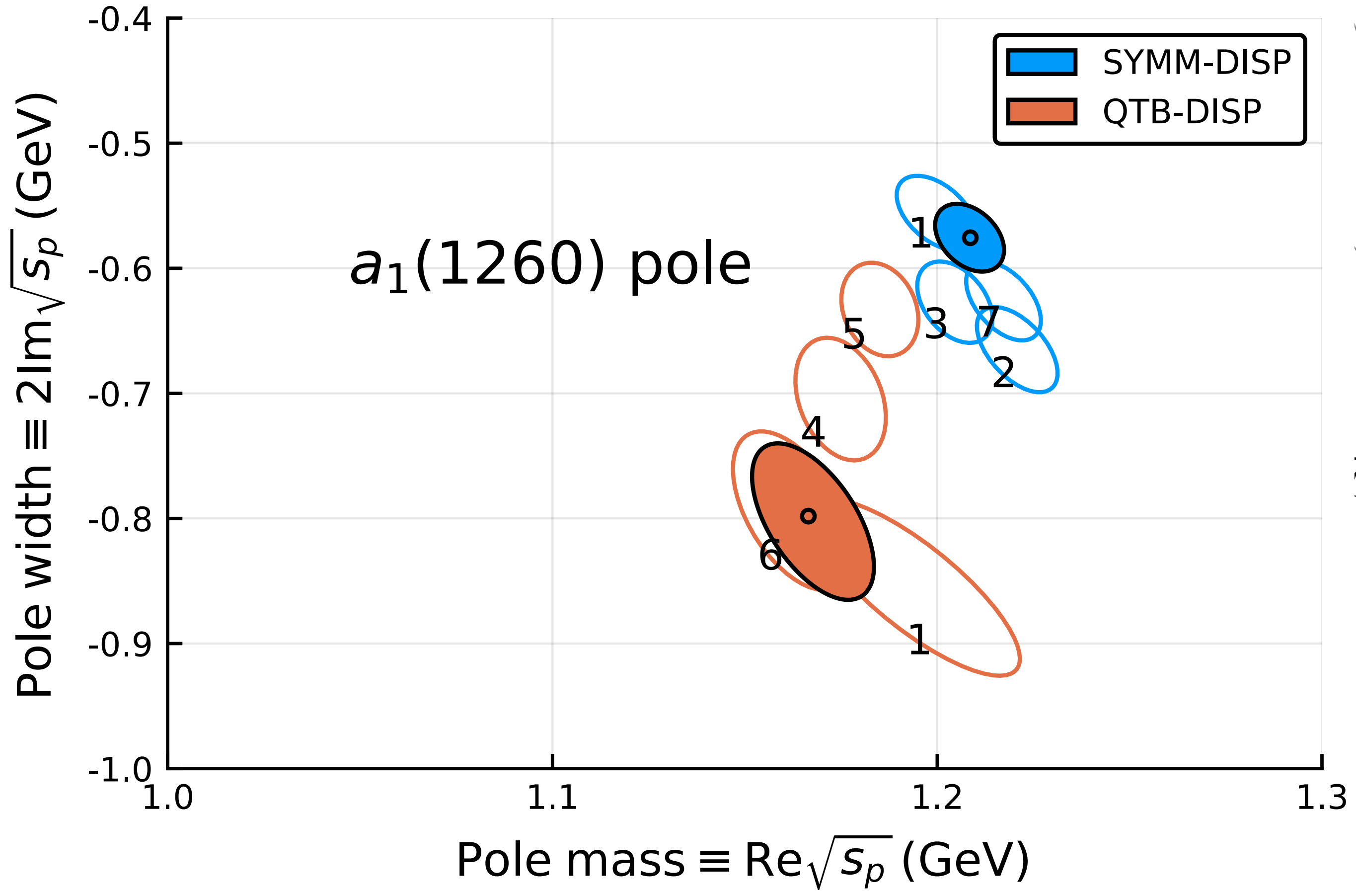


I=3, non-resonant









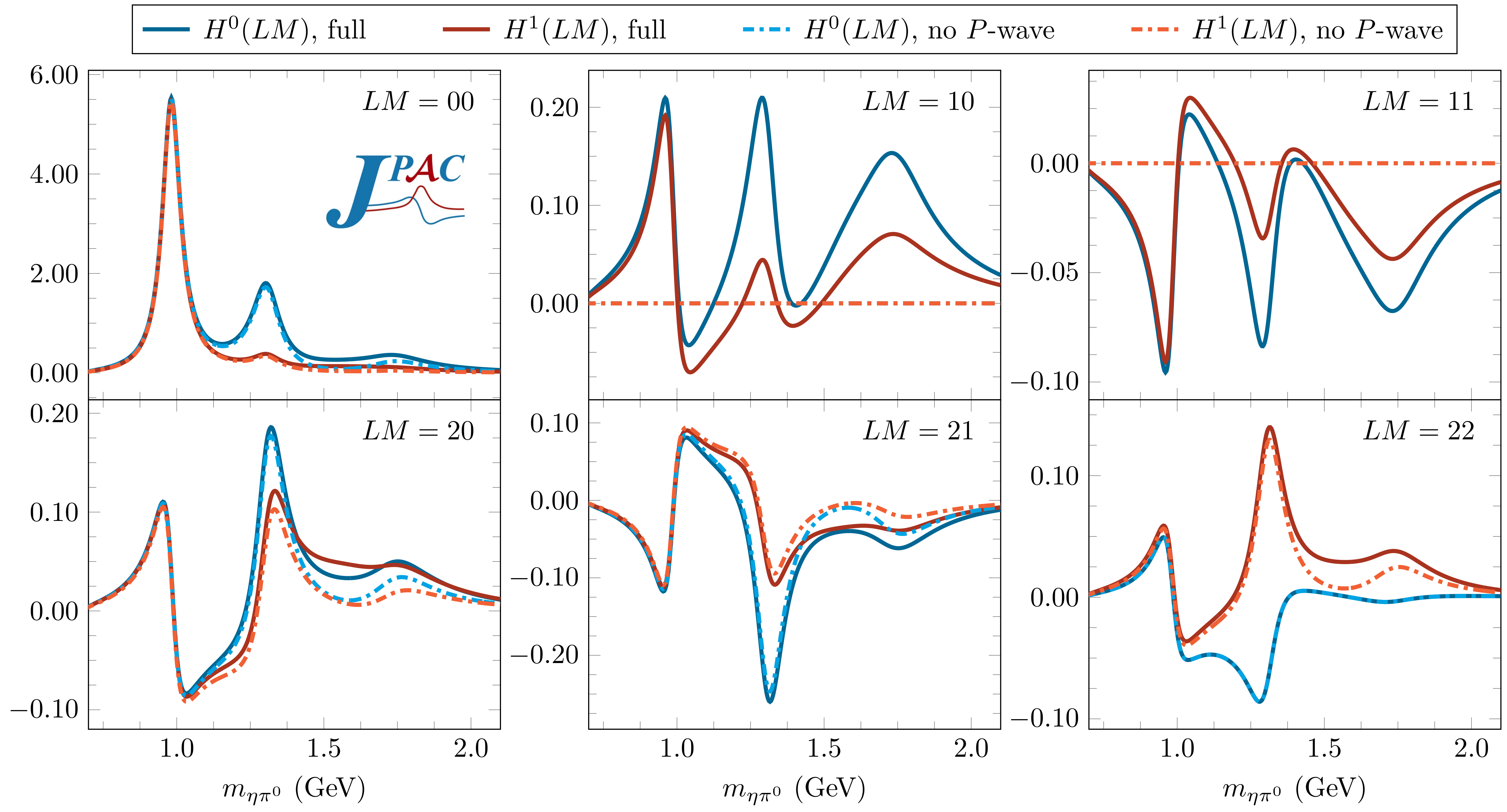
Some recent developments and applications by members of the ExoHad collaboration

2303.10219 *2212.09951* *2009.04931* *1810.00016*

2101.10246 *2107.03973* *1905.12007* *1809.10523*

+ many others

Experiment support

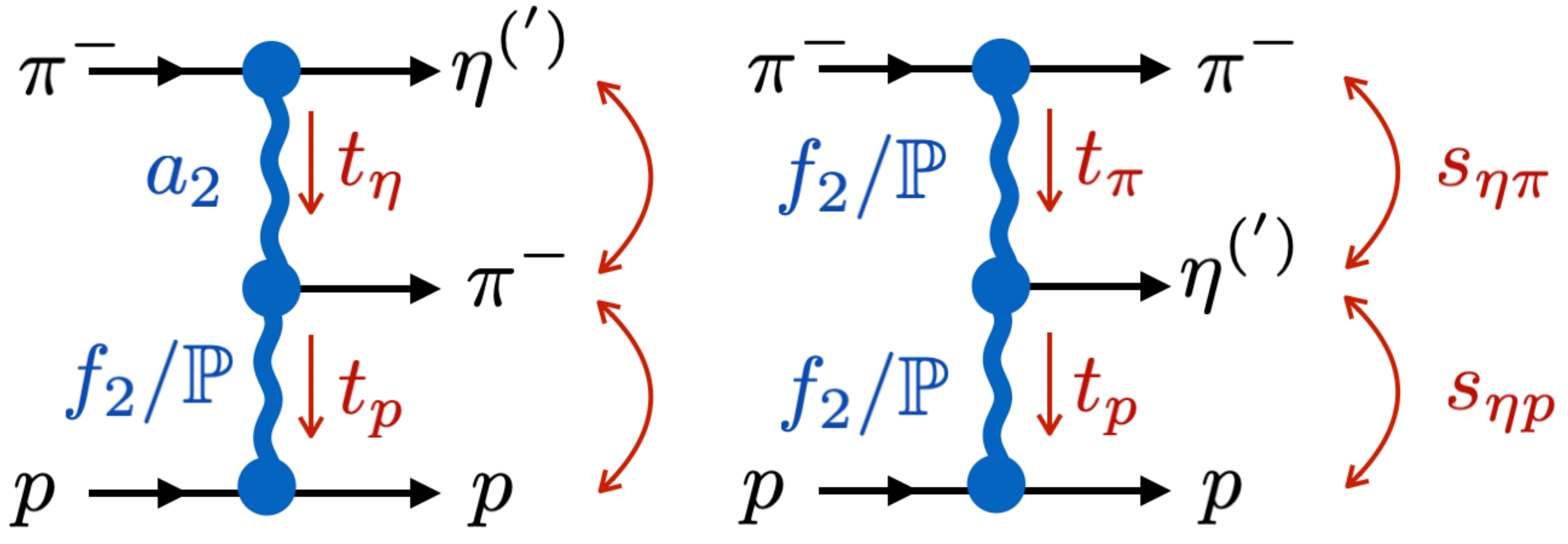


Relevant 2-body decays→ which observables are most sensitive to an exotic π_1 ??

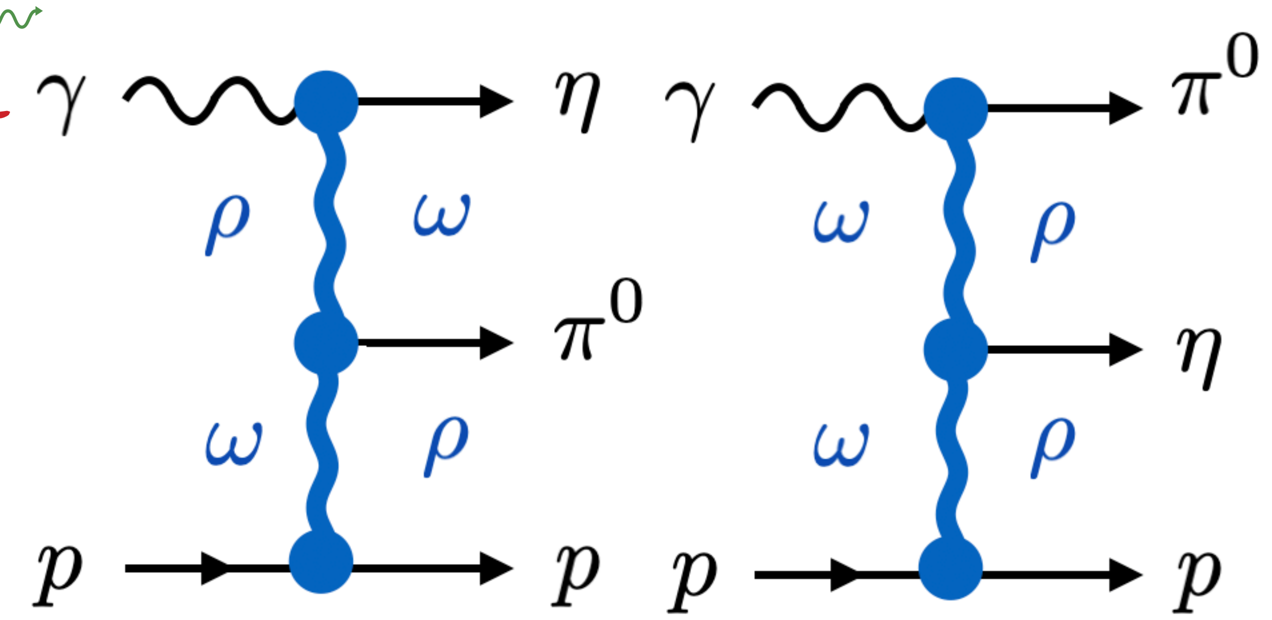
1906.04841

Relevant 2-body decays at GlueX contain important backgrounds → theoretical description

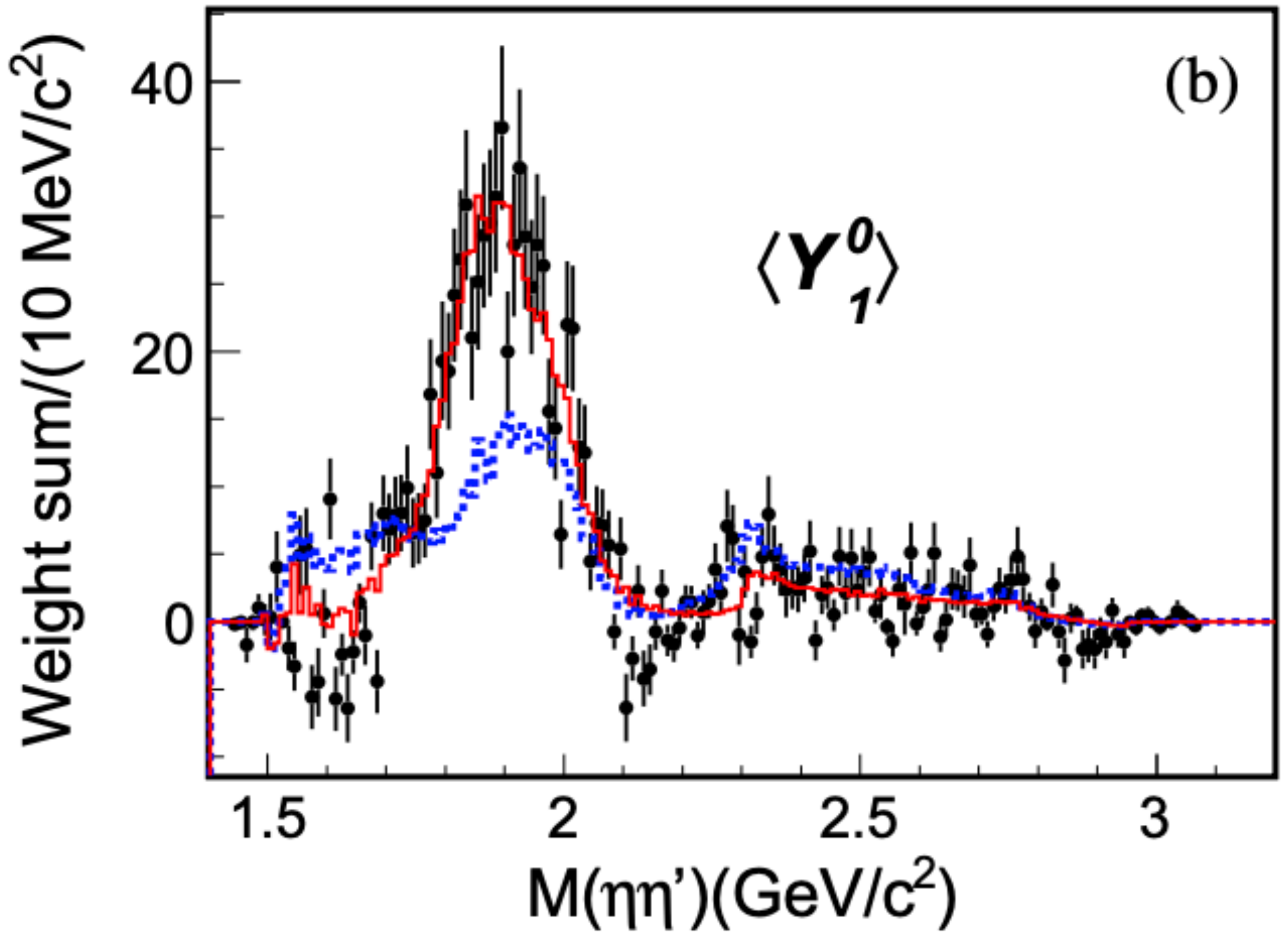
2104.10646



Ongoing

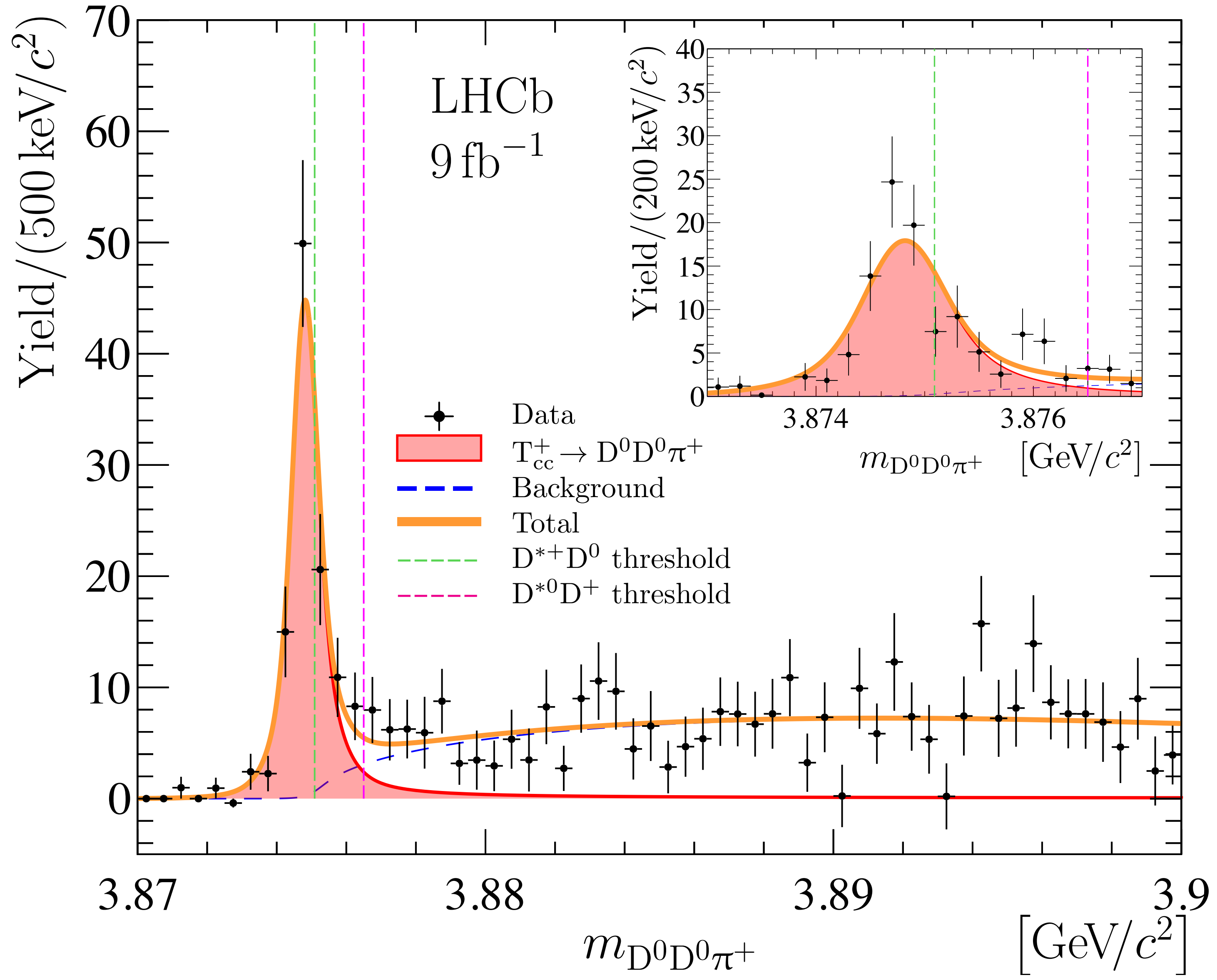


Other exotics



π_1 **partner (**η_1**) found recently by BESIII.**

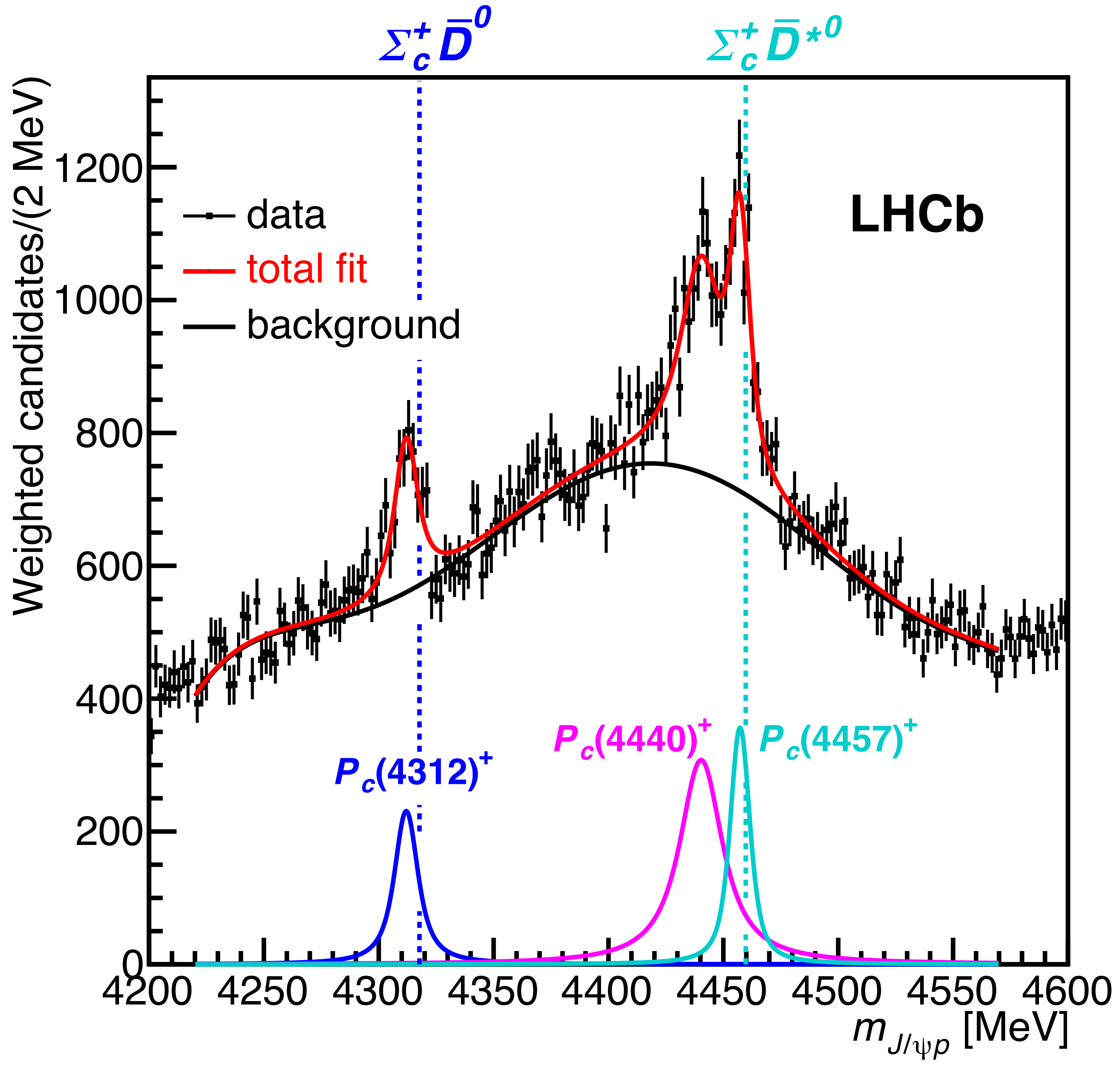
Now we are missing a state!!



T_{cc}^{+} **seen by LHCb → 3-body effects**

2203.04622

2110.02944



Pentaquark searches at LHCb, GlueX

2110.13742

1904.10021

Other exotics

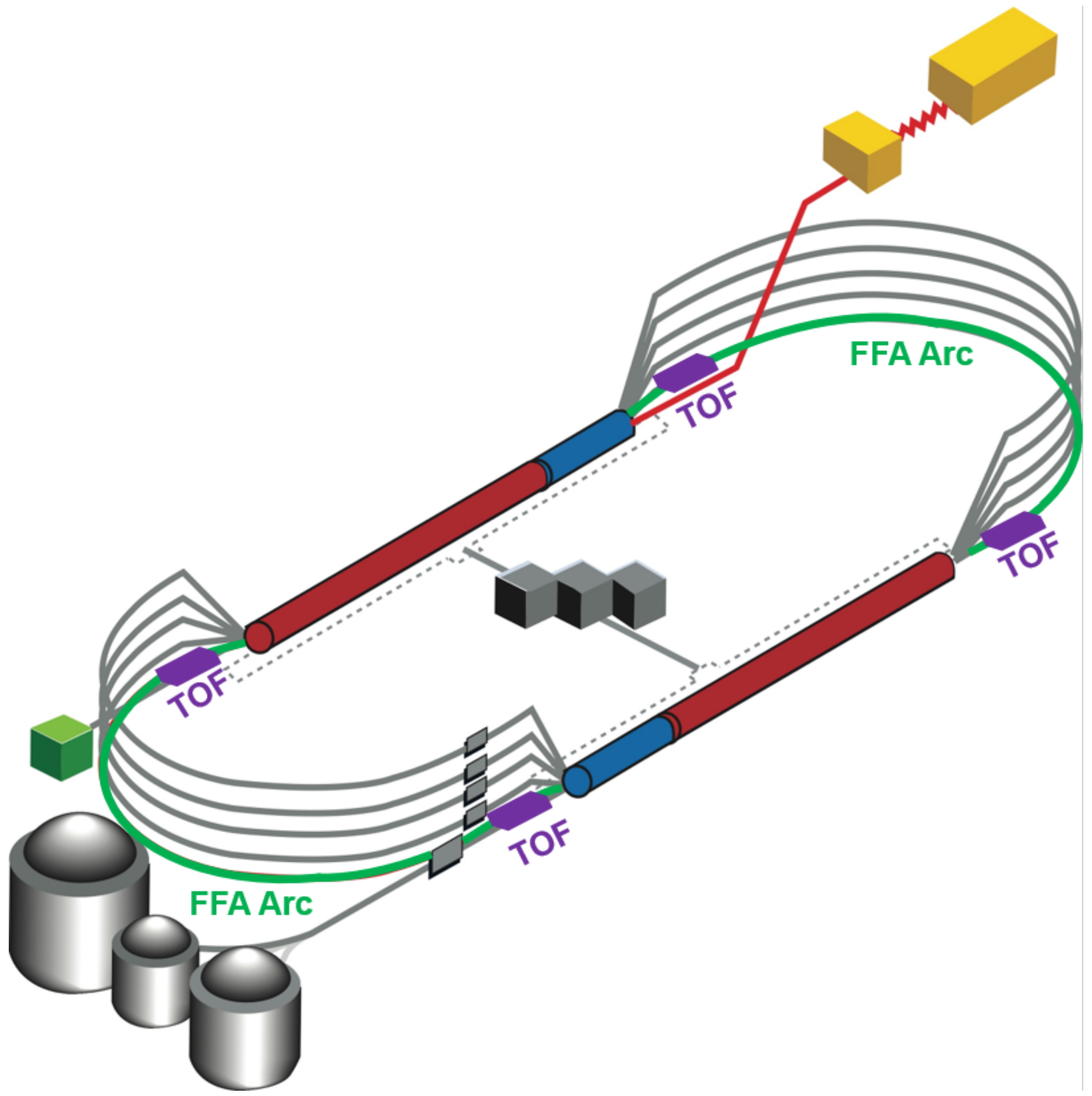
XYZ spectroscopy thanks to a possible JLab upgrade

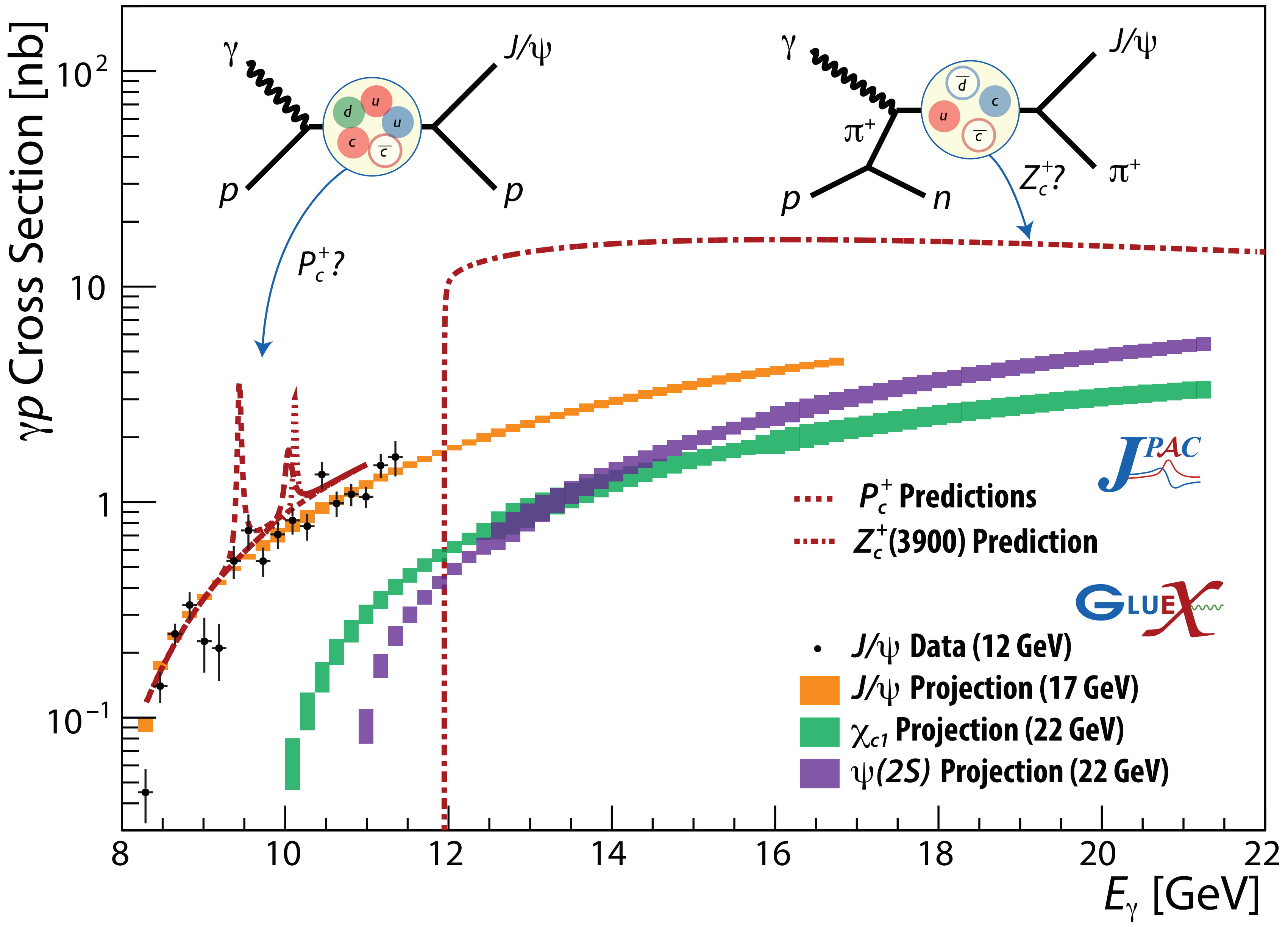
Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

A. Accardi (Hampton U.), P. Achenbach (Jefferson Lab), D. Adhikari (Virginia Tech.), A. Afanasev (George Washington U.), C.S. Akondi (Florida State U.) Show All(435)

Jun 13, 2023

e-Print: 2306.09360 [nucl-ex]
Report number: JLAB-THY-23-3848





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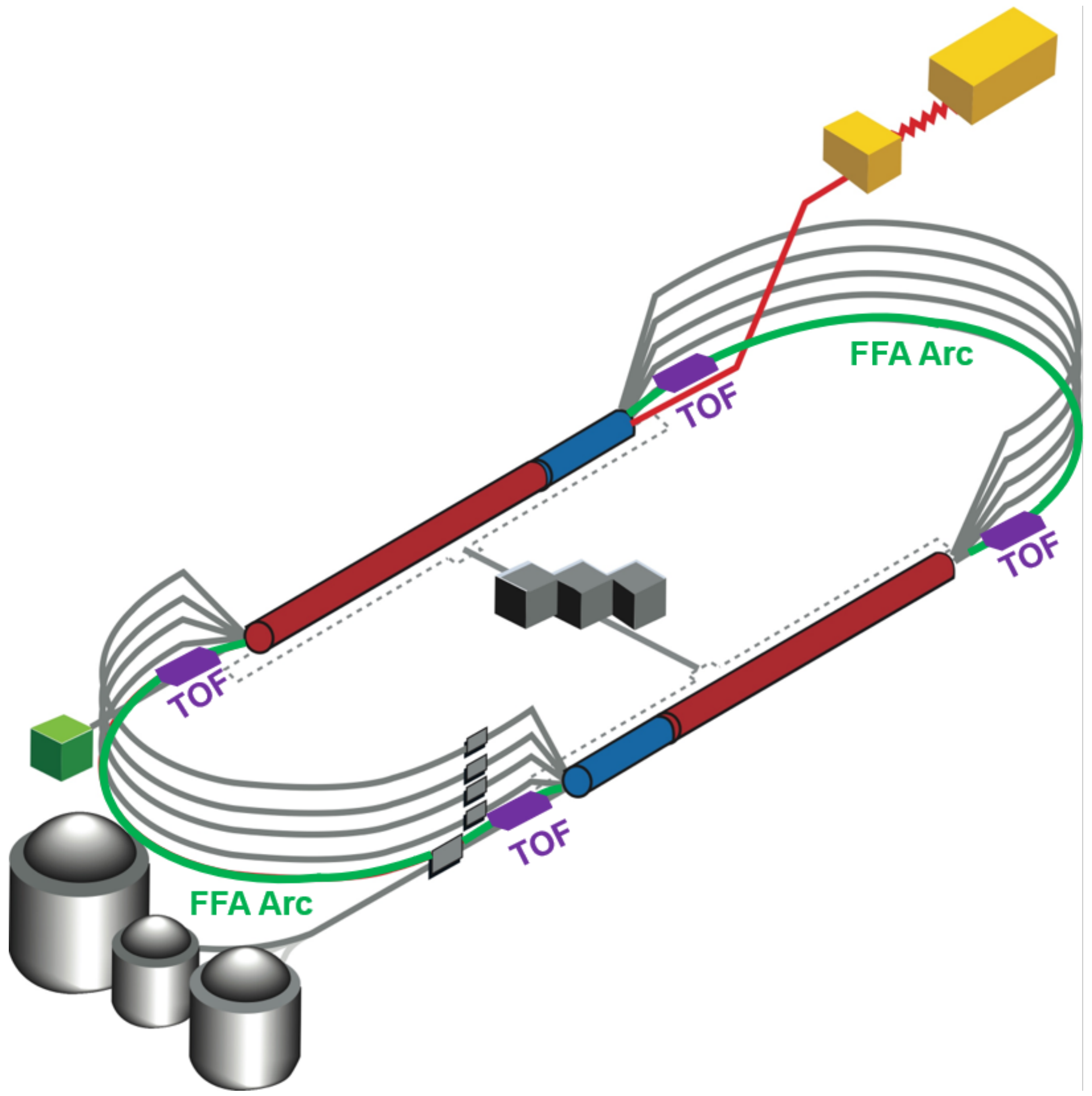
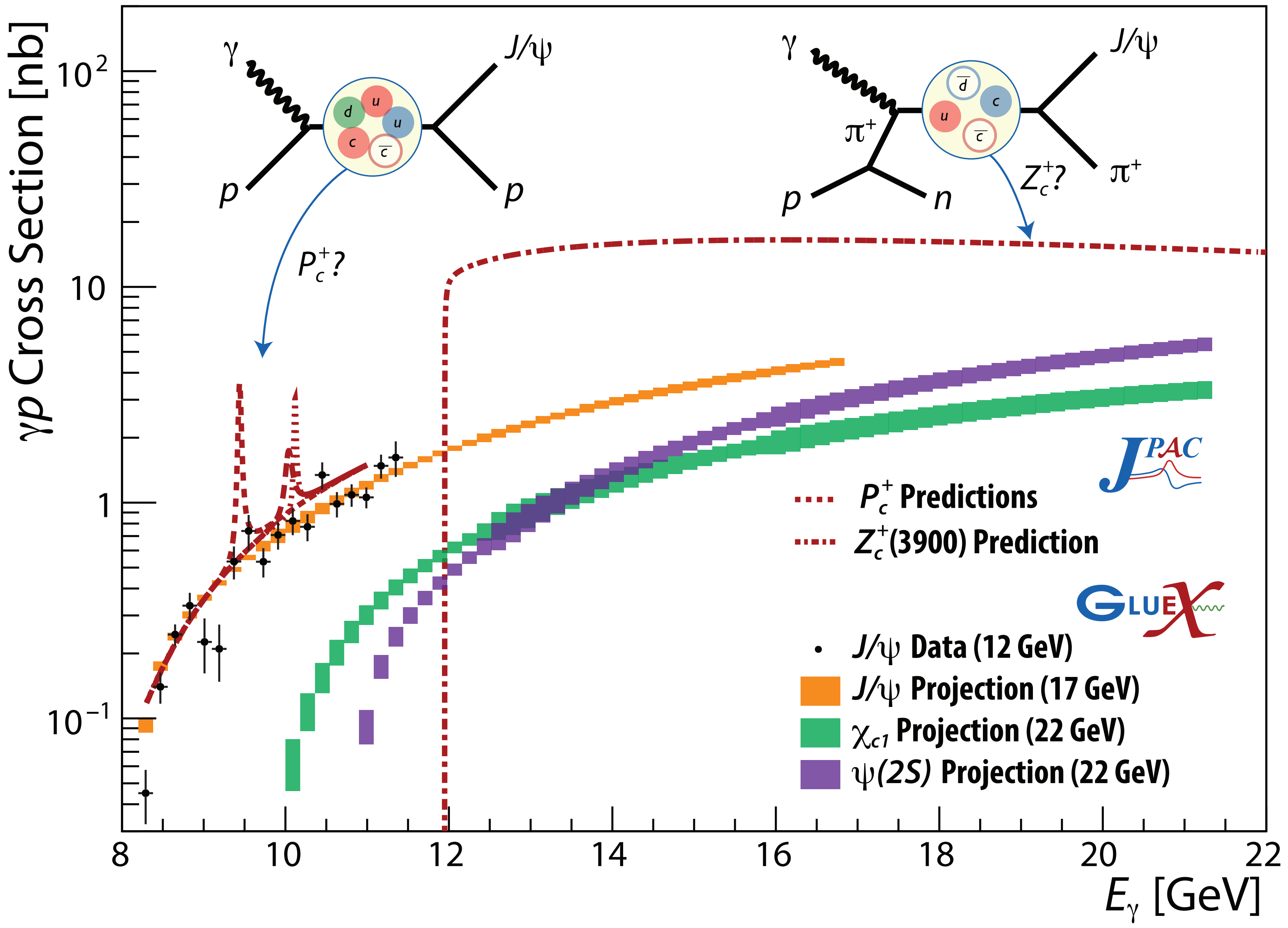
Report number: JLAB-THY-23-3848

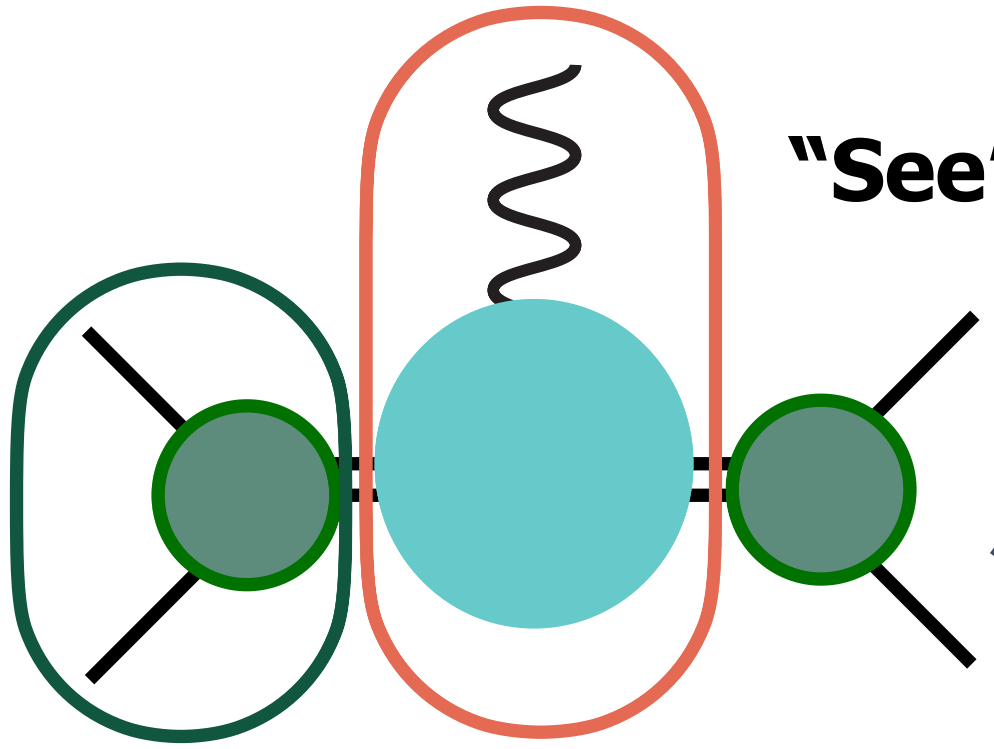
- EFTs for XYZ
- LQCD for XYZ
- ML/AI for exotics
- Dispersive analyses for exotics





Nature/compositeness (LQCD)

Complementary to experiment



"See" the resonance

1509.08507

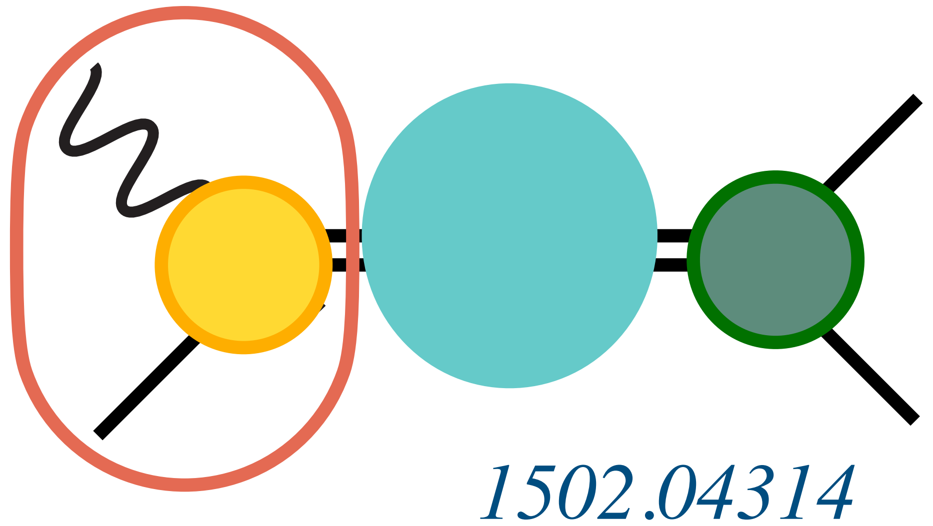
Produce the resonance

Couplings

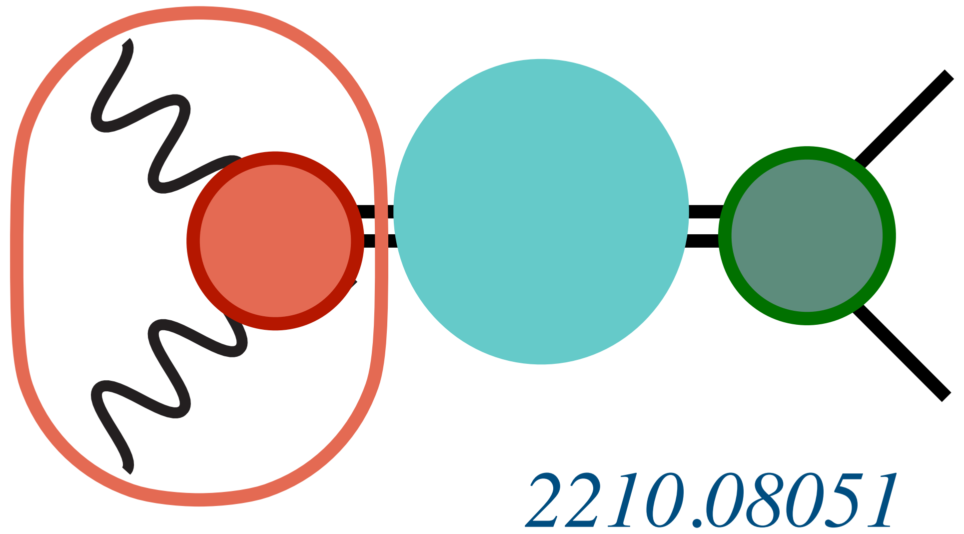
Form factors

Radii

New observables allow us to access fundamental properties of resonances



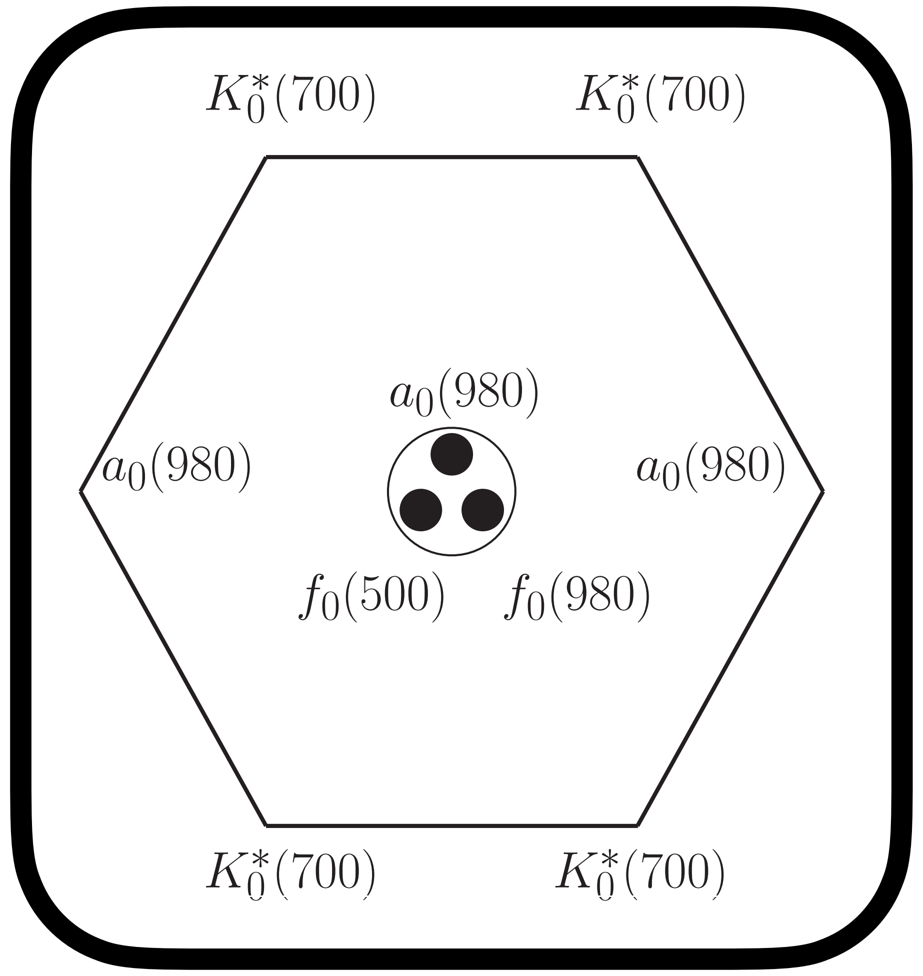
1502.04314

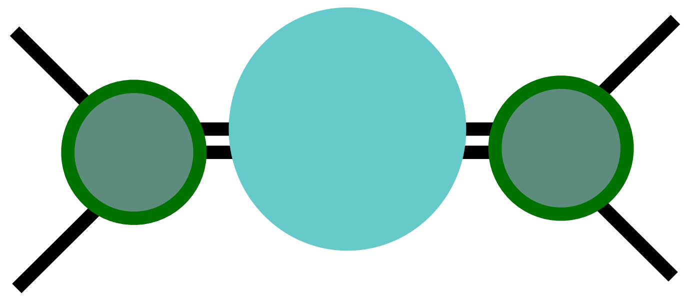


2210.08051

Different production processes → study unknown vertexes

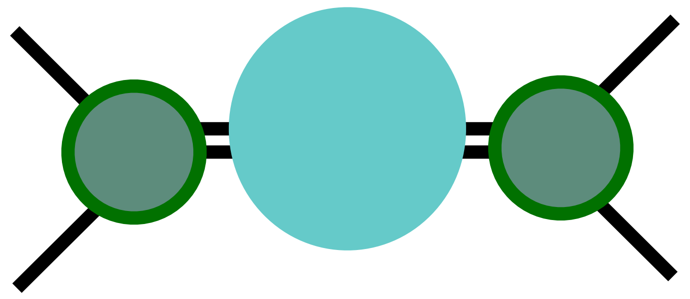
For example, do scalars couple to glueballs?





It all starts from the beginning → determining the resonance fundamental parameters from scattering

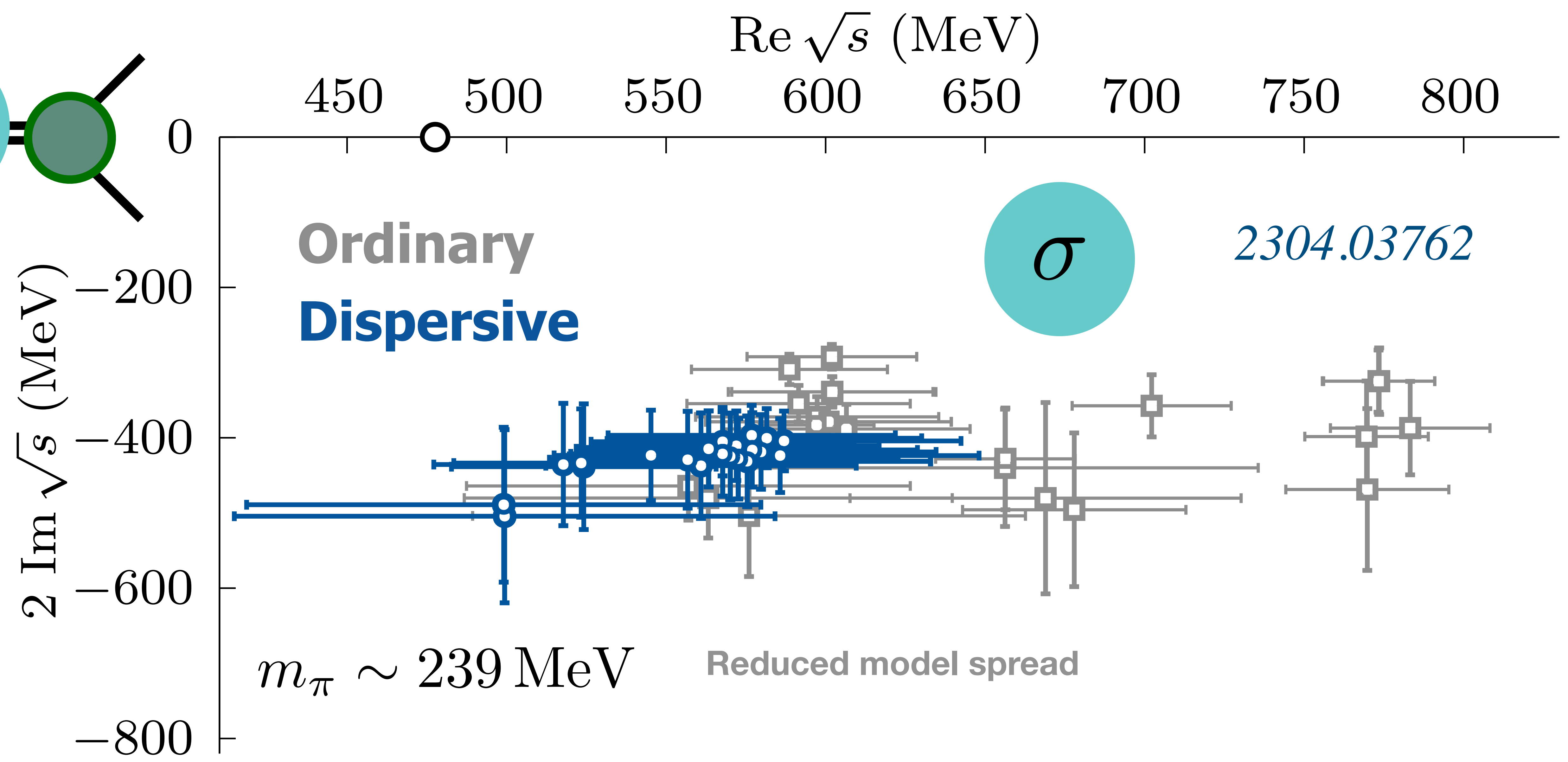
Nature/compositeness



Ordinary amplitude analyses are not suited for broad resonances, like the σ → LQCD+dispersive analyses

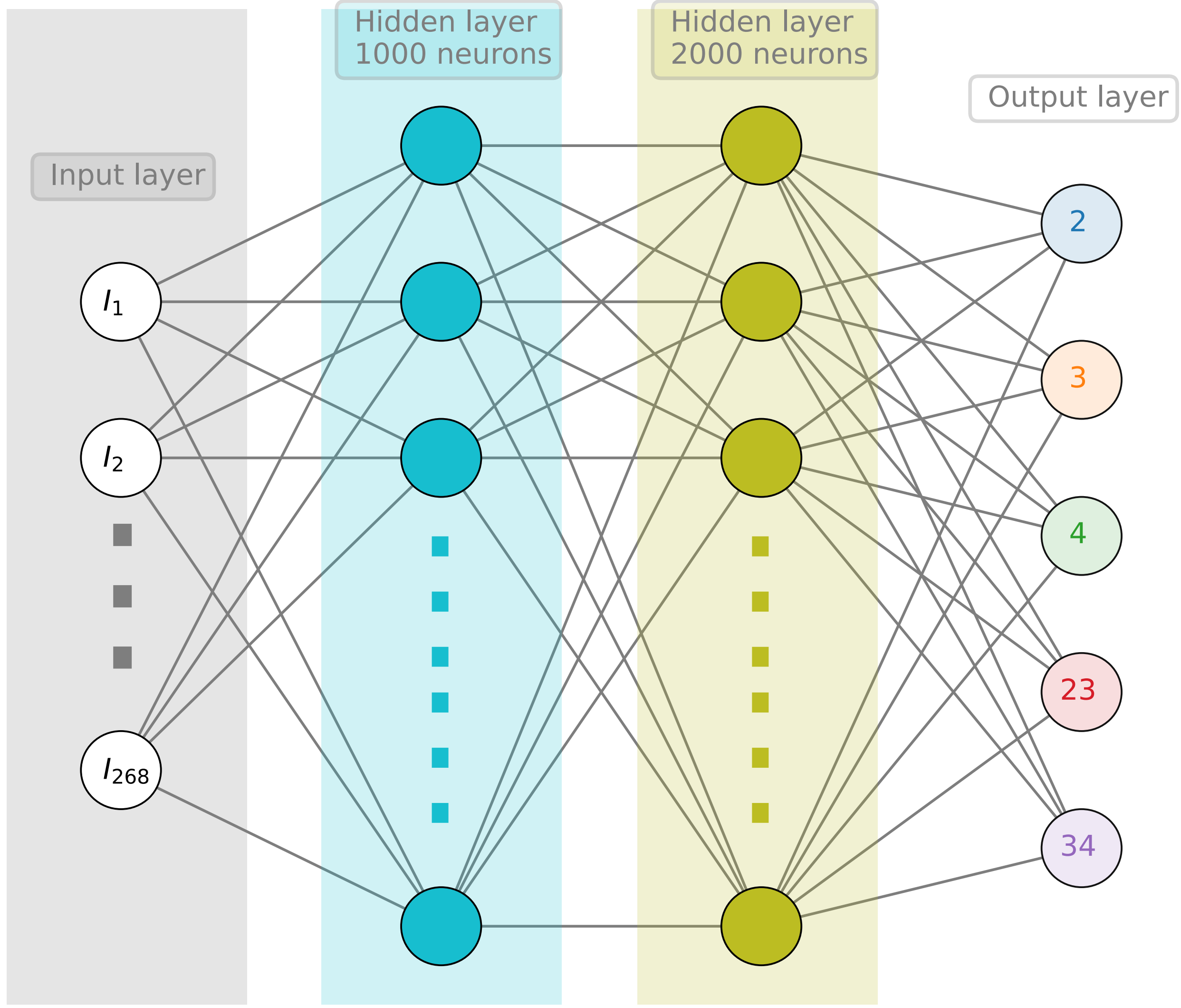
$$t^I_\ell(s) \rightarrow \tilde{t}^I_\ell(s) = \tau^I_\ell(s) + \int_{4m_\pi^2}^{\infty} ds' K^{II'}_{\ell\ell'}(s',s)\,\mathrm{Im}\, t^{I'}_{\ell'}(s')$$

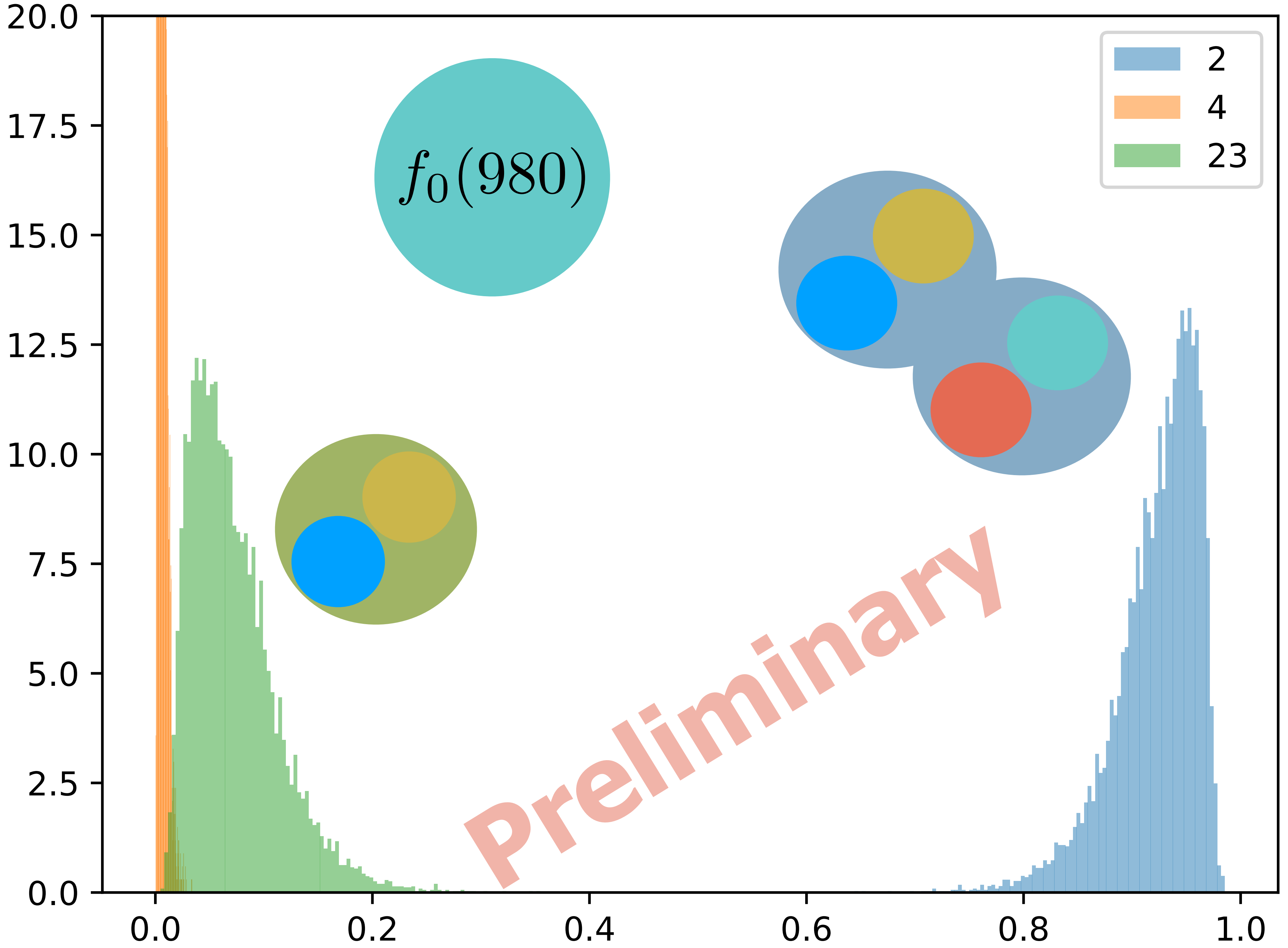
Much more cumbersome



Others, like $f_0(980)$, appear "locally"

ML/AI+Experiment analyses can help us discern between compact or molecular objects

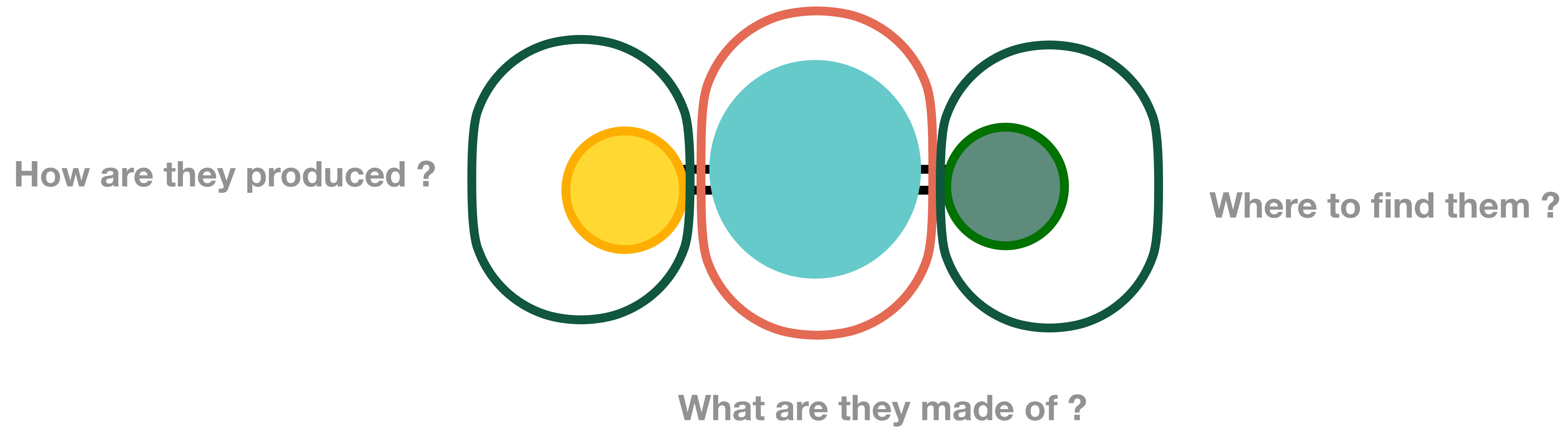




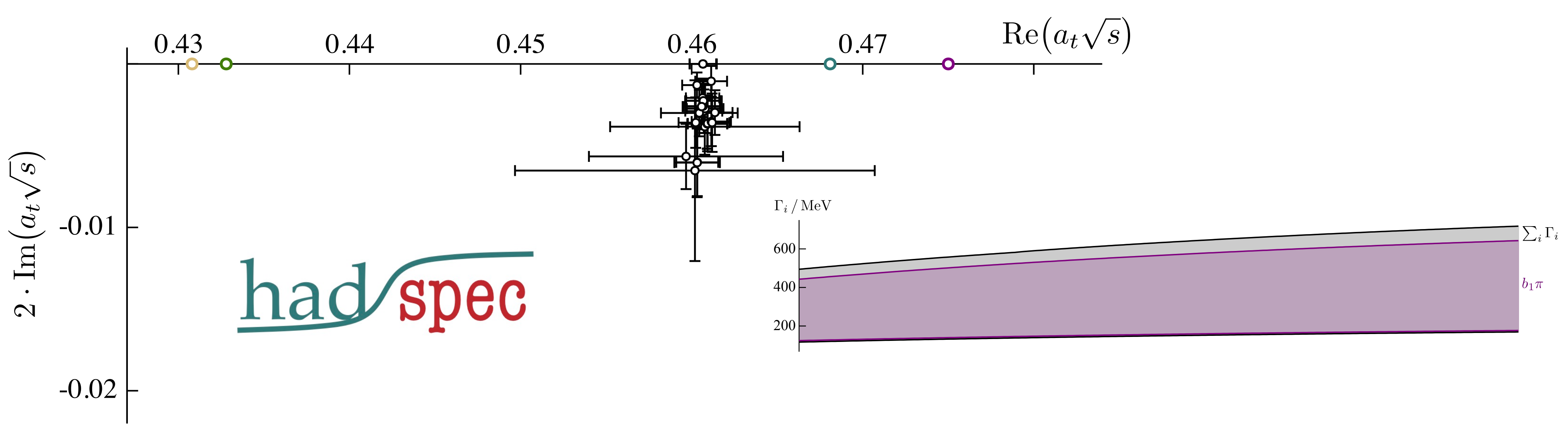
Summary and outlook

EXOHAD
Exotic Hadrons Topical Collaboration

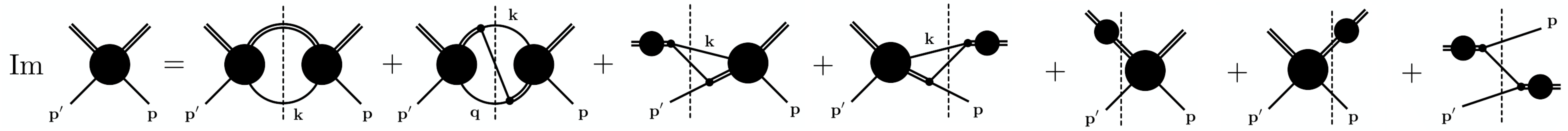
A coordinated theoretical effort is necessary to access all possible information on exotics



LQCD, DSE, EFTs, and models offer confirmation, predictions, and guidance to experiments



Our pheno+reaction theory expertise is devoted to support JLab experiments



Thank you!!