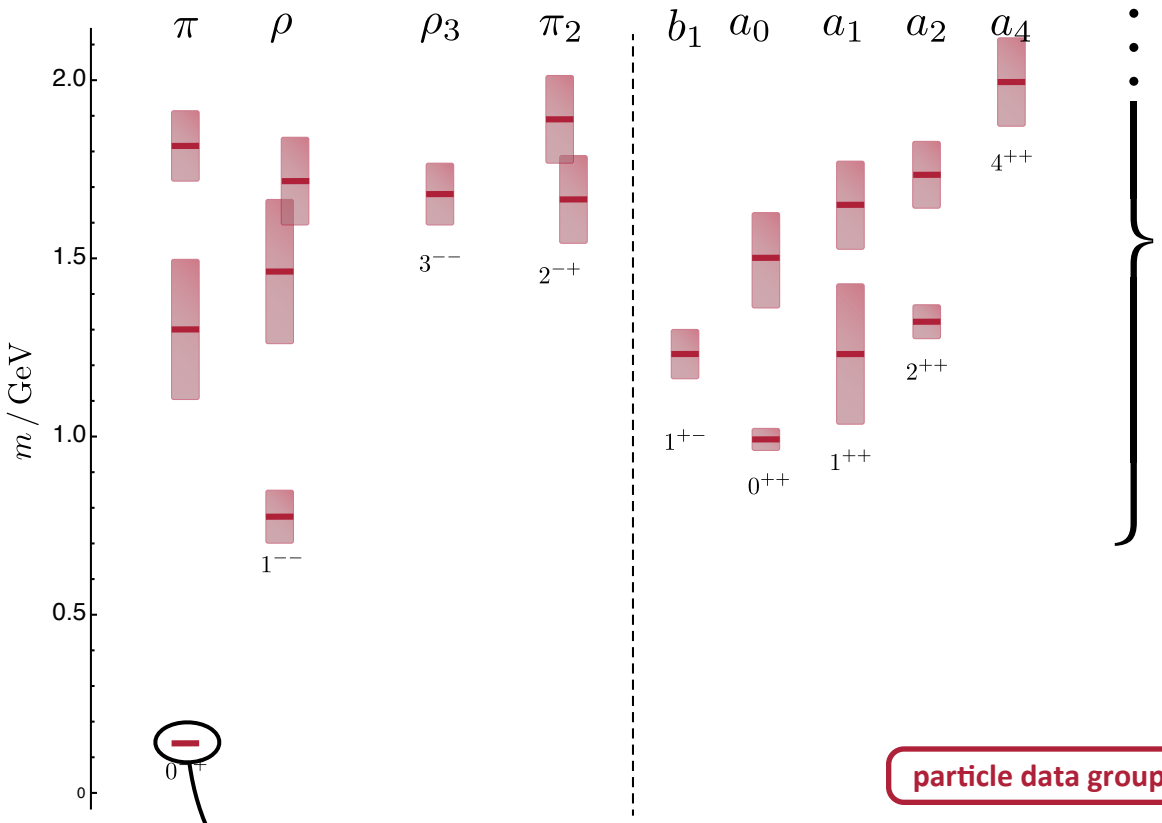
Advances in Meson Spectroscopy

Jozef Dudek

Jefferson Lab Theory Center
& Old Dominion University

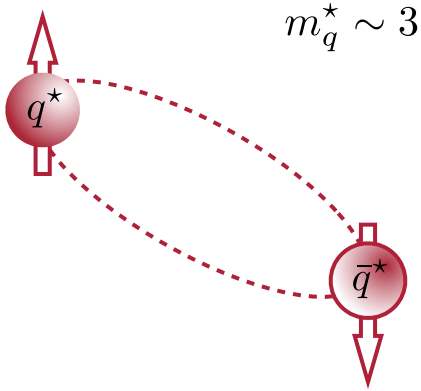
the experimental meson spectrum

isospin = 1



broadly compatible with
spatial excitations
of **constituent quark-antiquark** pair

$m_q^\star \sim 350\,\mathrm{MeV}$



$$q^\star \bar{q}^\star ({}^{2S+1}L_J) \implies J^{PC}$$

excluding

$0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$

particle data group

pion as pseudo-Goldstone boson of
dynamical chiral symmetry breaking

$m_q \sim \mathcal{O}(1)\,\mathrm{MeV}$

quantum chromodynamics

$$\mathcal{L}_{\text{QCD}} = \sum_{q=uds} \bar{\psi}_q \left(i\gamma^\mu \partial_\mu - m_q\right) \psi_q + g\, \bar{\psi}_q \gamma^\mu t^a \psi_q\, A^a_\mu - \frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a$$

relativistic quarks . . . strongly coupled to the gluonic field . . . which is massless and strongly coupled to itself

strongly coupled QCD

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color confinement

strongly coupled QCD

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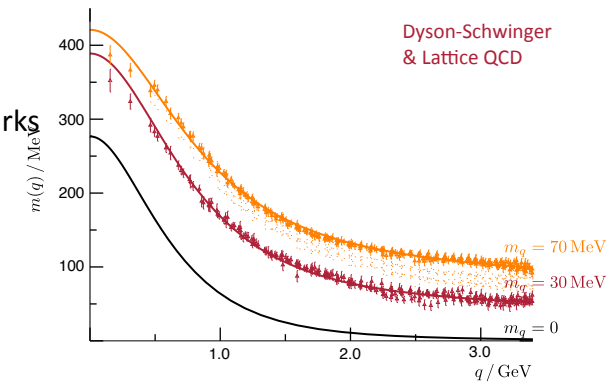
strongly coupled QCD

→ color confinement

→ dynamical chiral symmetry breaking
- light pion
- ‘constituent’ quarks



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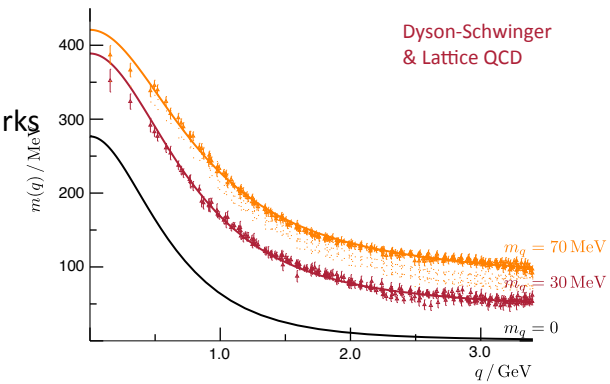
strongly coupled QCD

- color confinement
- dynamical chiral symmetry breaking
  - light pion
  - 'constituent' quarks
- ⋮
- **gluonic field excitations ?**



what role do gluonic excitations play in the spectrum of hadrons ?

gluonic excitations in QCD - hybrid mesons

quark-antiquark pair coupled to a **gluonic excitation**

gluonic excitation can contribute to J^{PC} quantum numbers ⇒ **'exotic' J^{PC}**

$$0^{--},\ 0^{+-},\ 1^{-+},\ 2^{+-}$$

experimental signature

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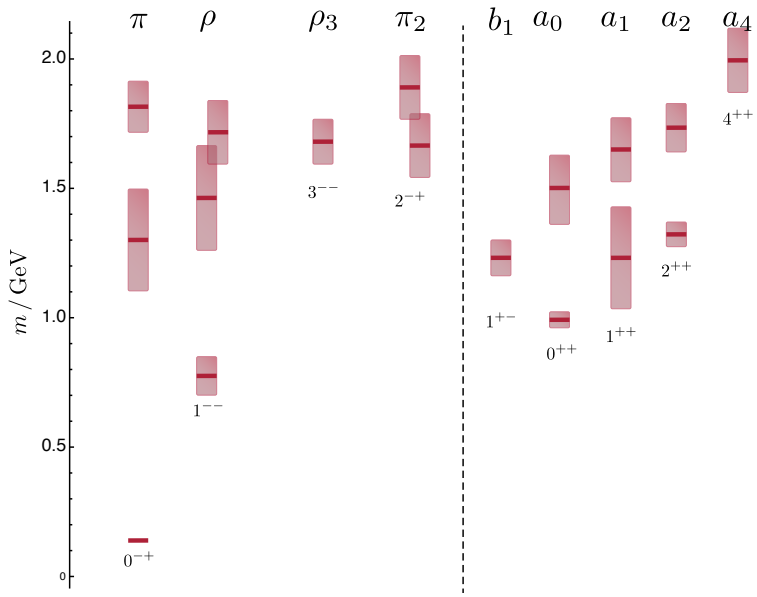

- too heavy ?
- using unfavored production methods ?
- looking in unfavored decay channels ?

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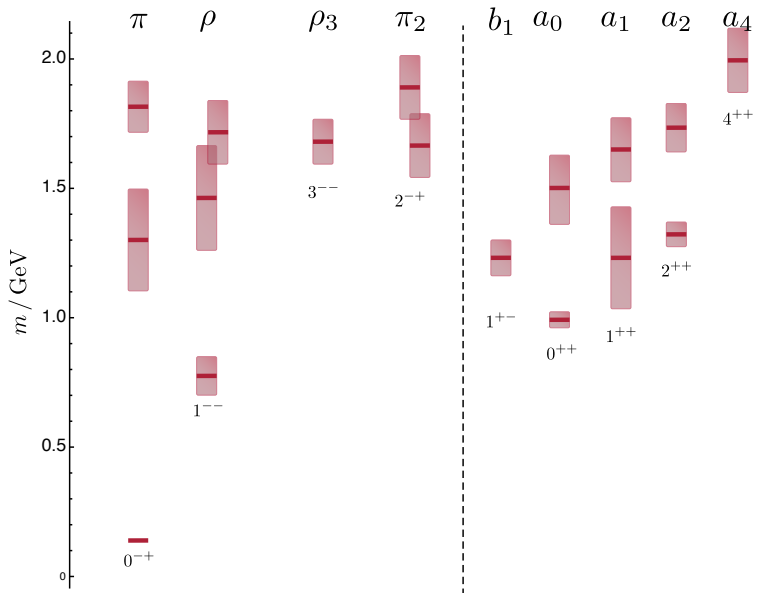

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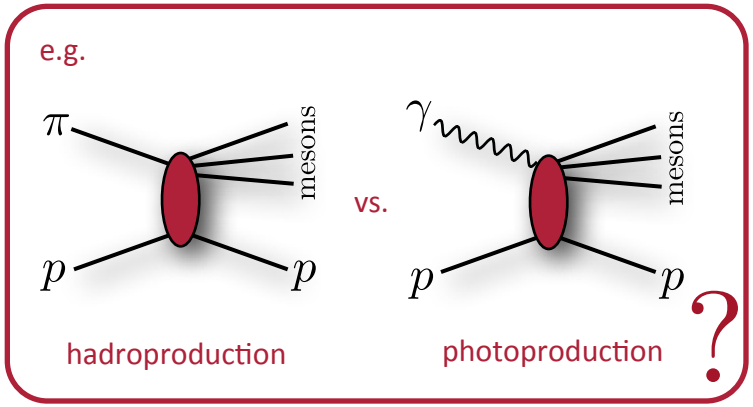

⇒ photon beam

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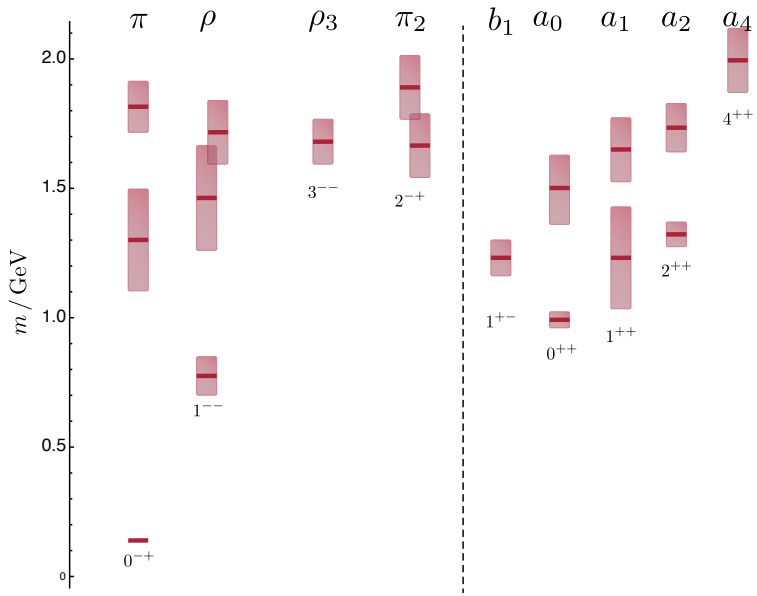

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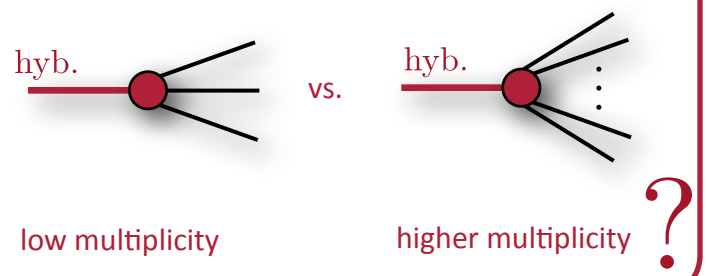
e.g.



⇒ look in a range of final states

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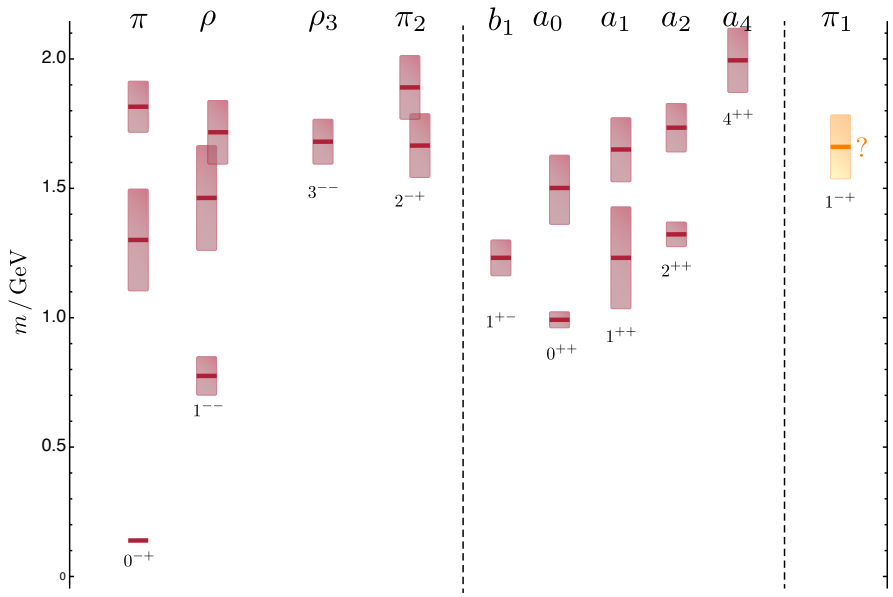


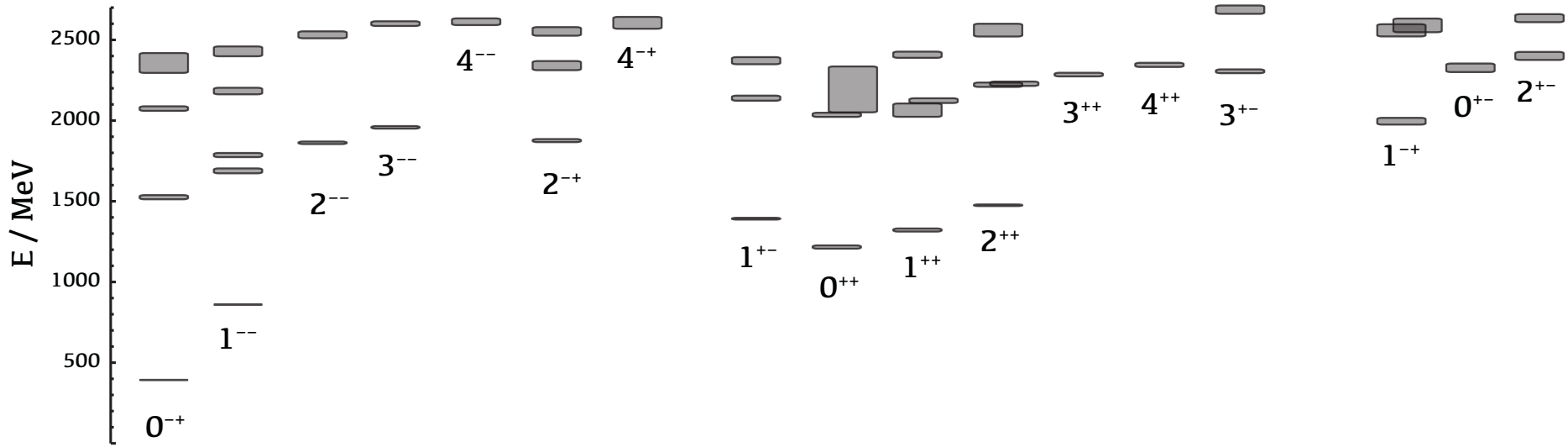
actually a controversial candidate exotic state

... more to say about this later

meson spectroscopy in lattice QCD

a calculation of the excited meson spectrum (at $m_\pi \sim 400$ MeV)

hadron spectrum collaboration '11



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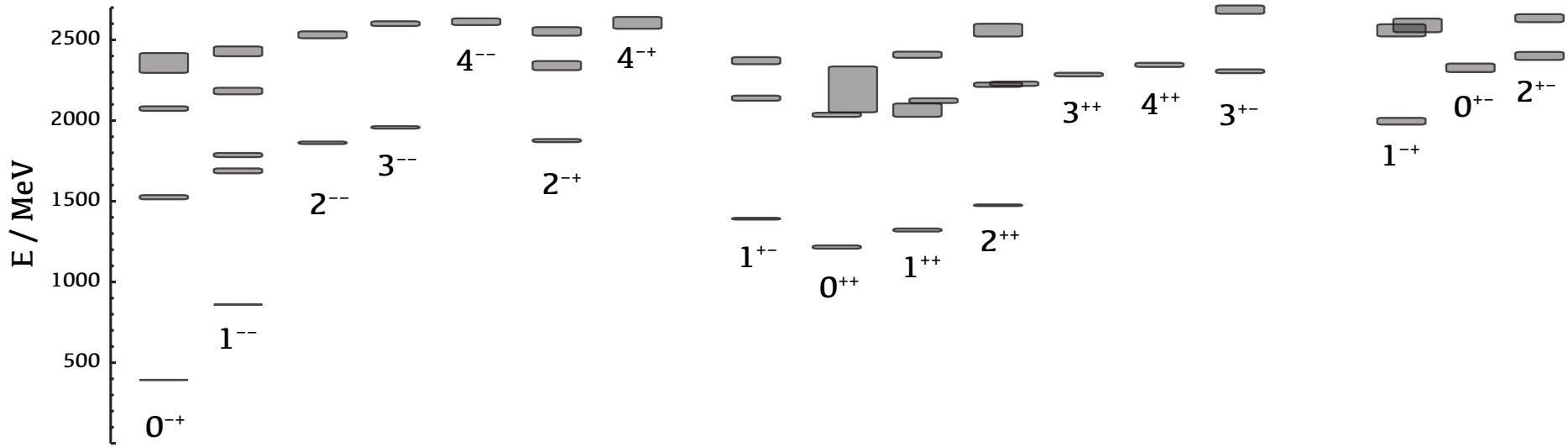
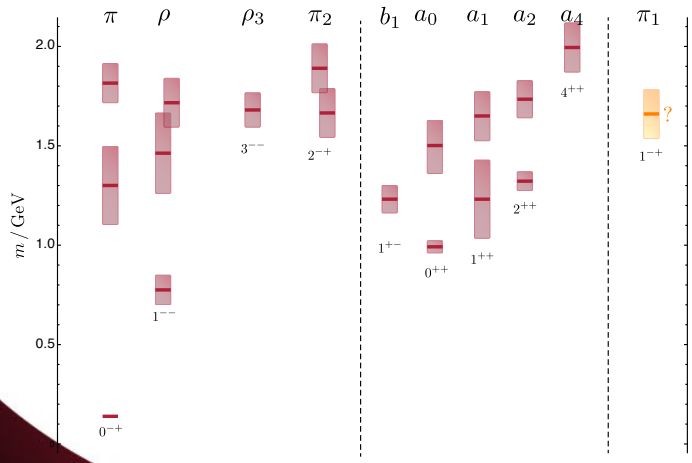


reflects many of the experimental systematics



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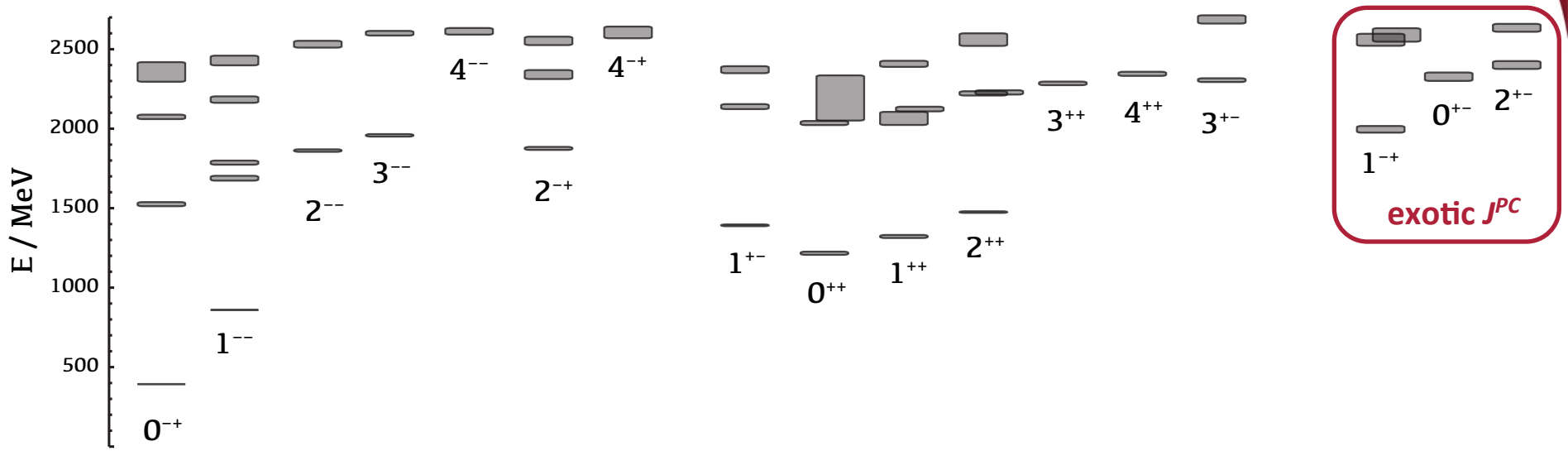

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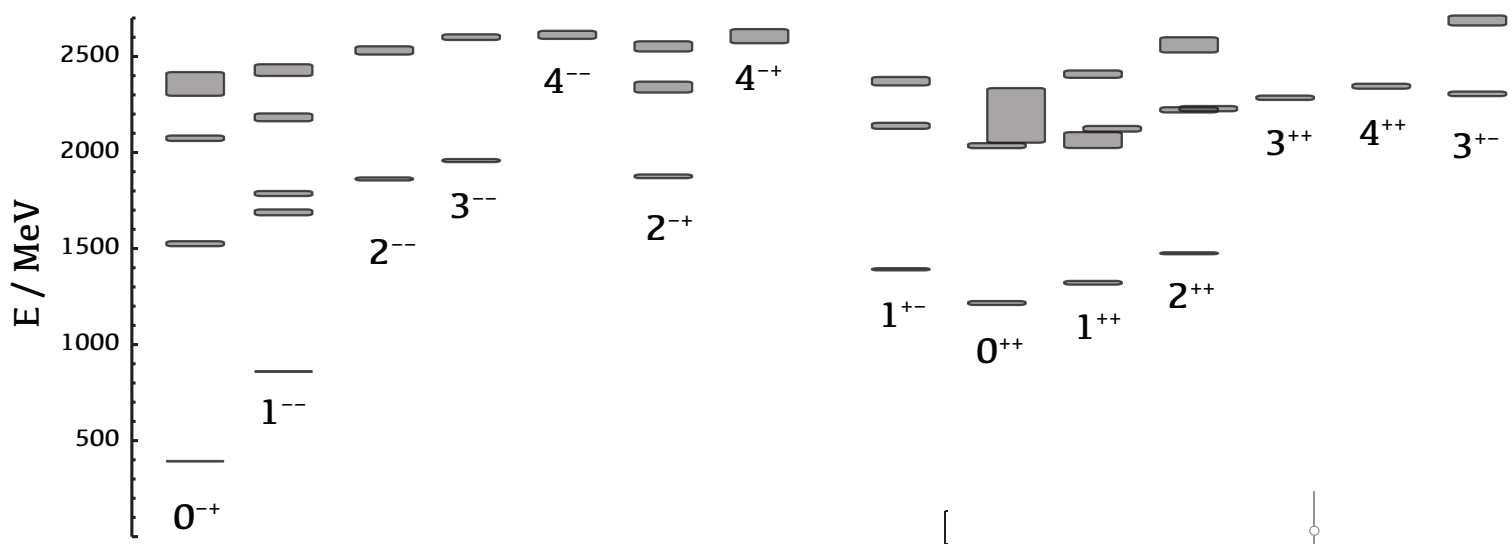

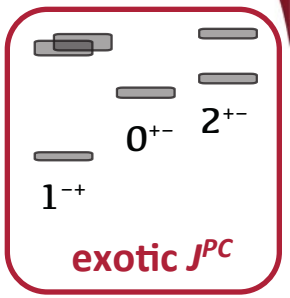

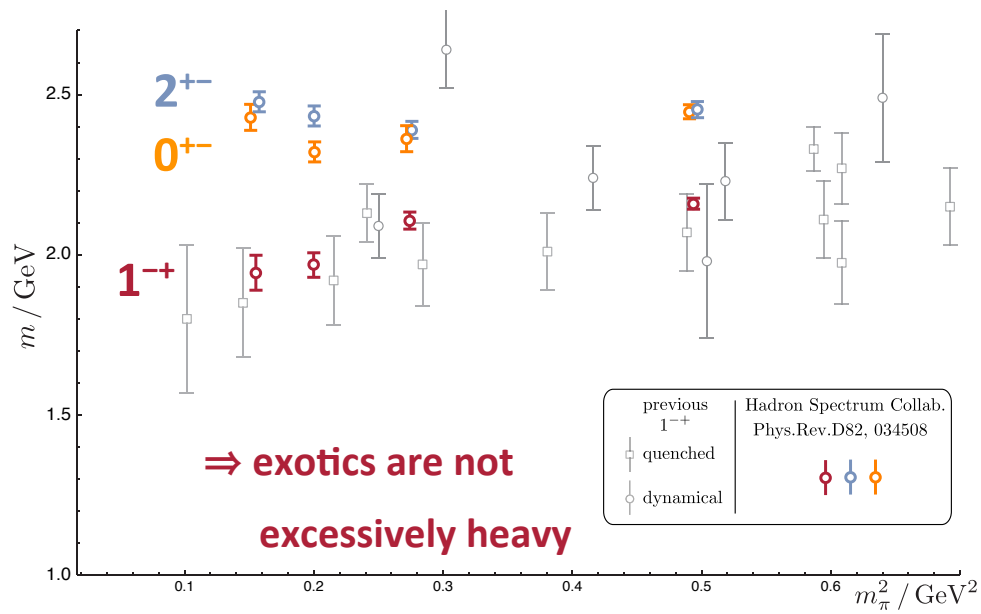

⇒ exotics are not excessively heavy

meson spectroscopy in lattice QCD

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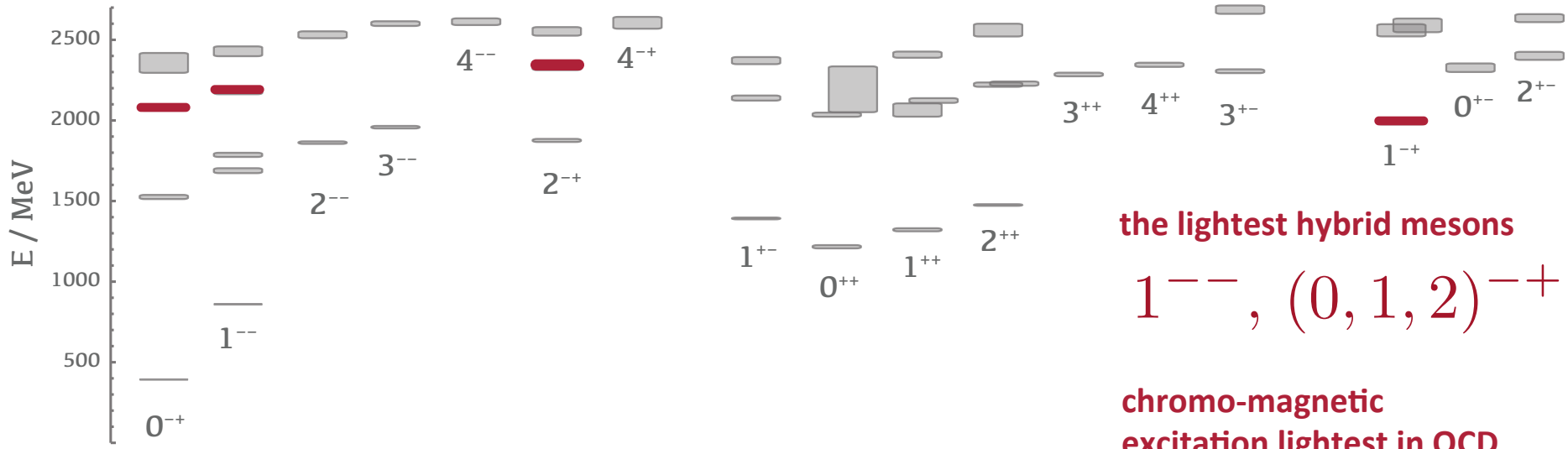


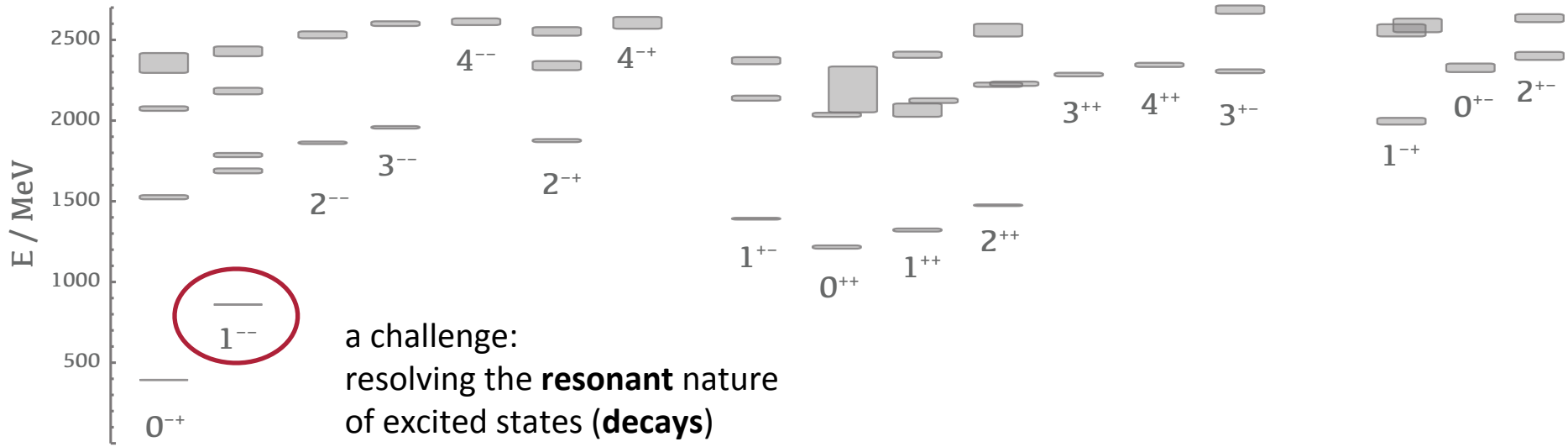
the lightest hybrid mesons

$$1^{--},\ (0,1,2)^{-+}$$

chromo-magnetic excitation lightest in QCD

meson spectroscopy in lattice QCD

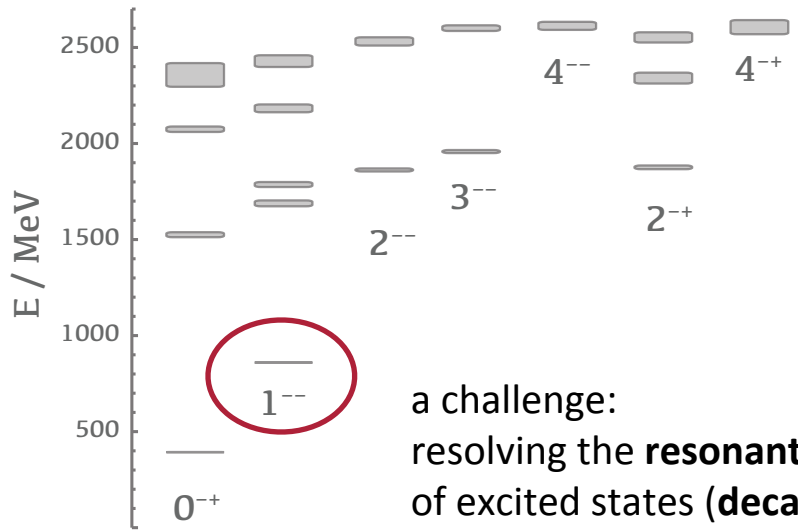
hadron spectrum collaboration '11



a challenge:
resolving the **resonant** nature
of excited states (**decays**)

$$\pi\pi \rightarrow \rho \rightarrow \pi\pi$$

meson spectroscopy in lattice QCD



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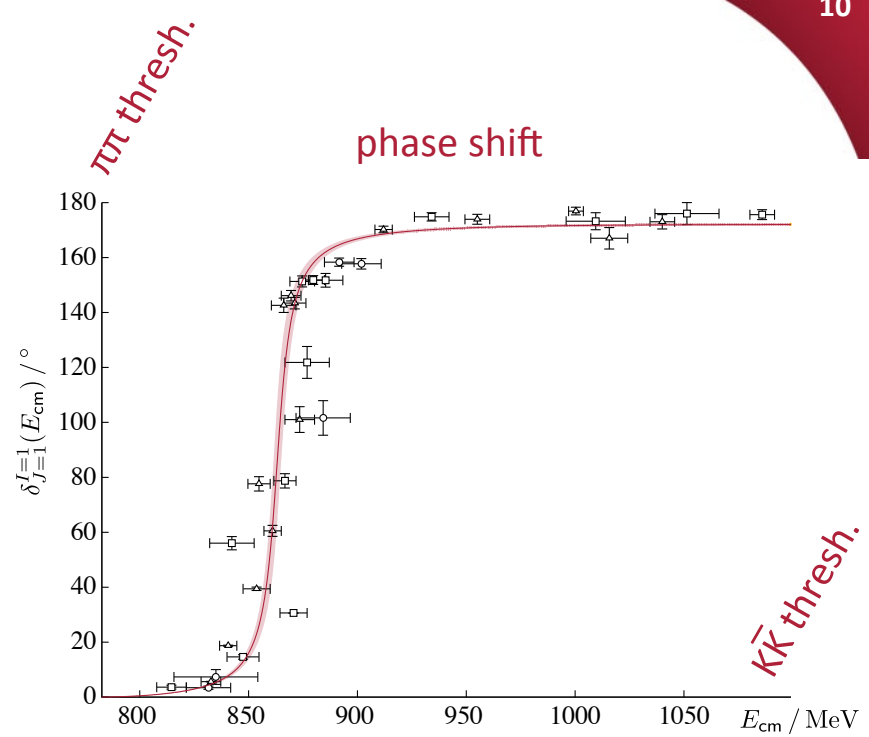
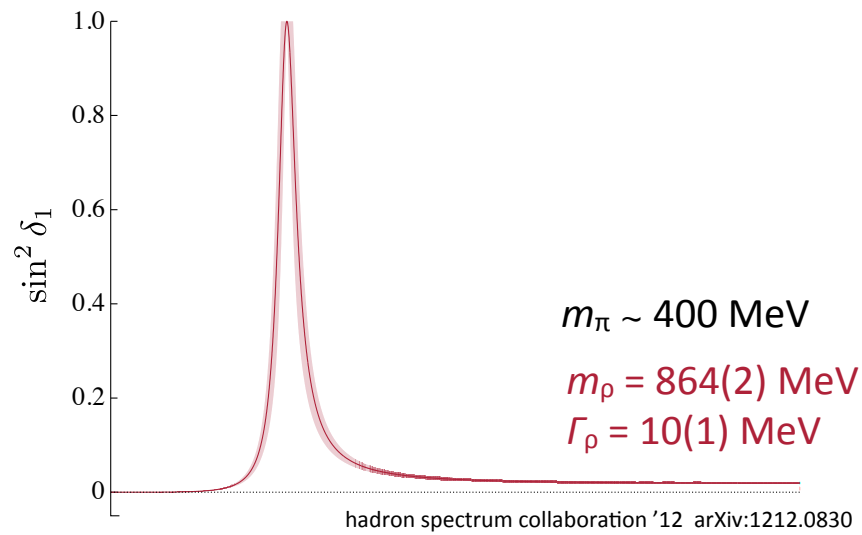
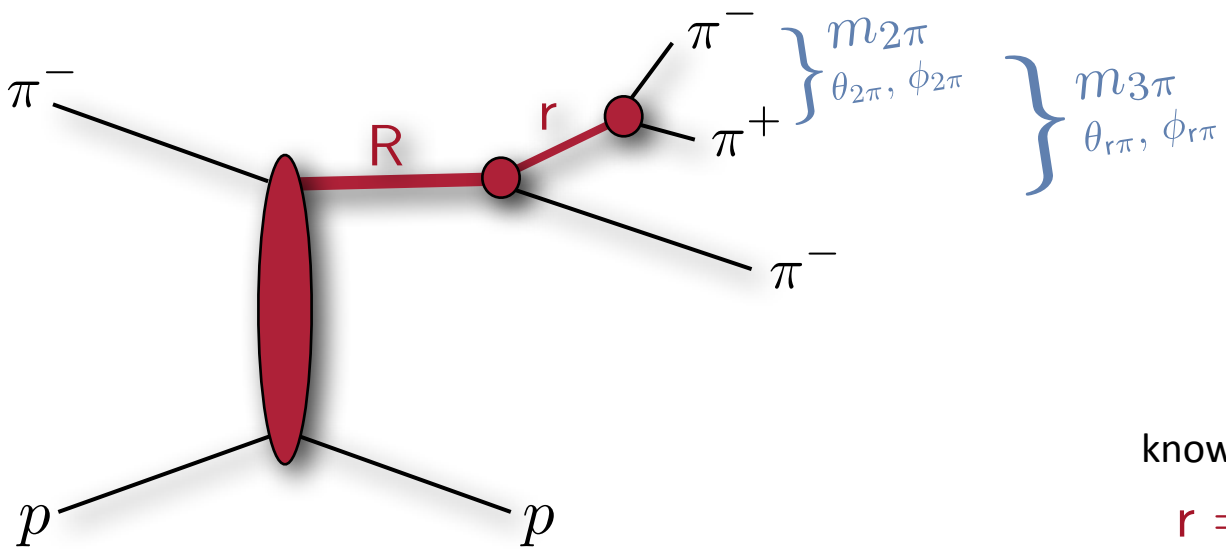




hadron spectrum collaboration '12 arXiv:1212.0830

amplitude analysis or "PWA"

e.g. three-pion resonances



known two-pion 'isobars',

$$\mathrm{r} = \sigma,\ \rho,\ f_2 \ldots$$

$$A_J(m_{3\pi})\ Y_J(\theta_{r\pi}, \phi_{r\pi})\ \cdot\ P_r(m_{2\pi})\, Y_{j_r}(\theta_{2\pi}, \phi_{2\pi})$$

unknown amplitudes

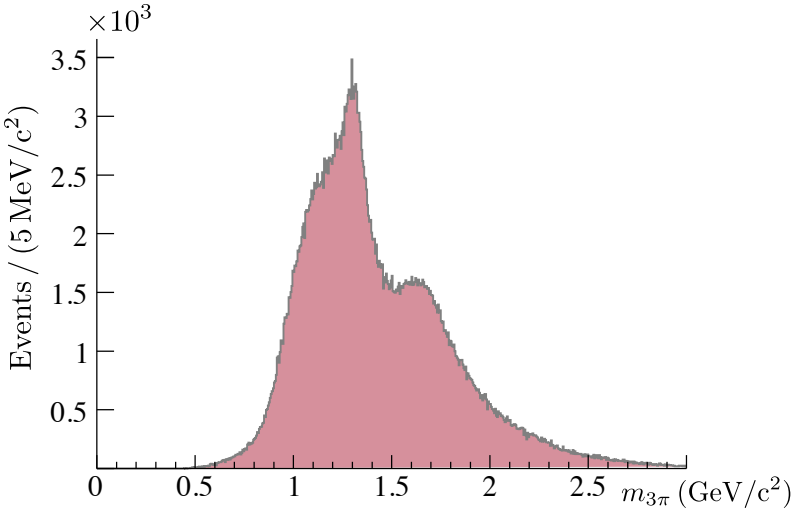
'fixed' basis functions

look for resonant behavior
(in amplitude and phase)

multi-dimensional fitting
to (potentially) 10s of millions of events

COMPASS $\pi^- Pb \rightarrow \pi^-\pi^-\pi^+ Pb$

Phys.Rev.Lett. 104 (2010) 241803



40 MeV bins

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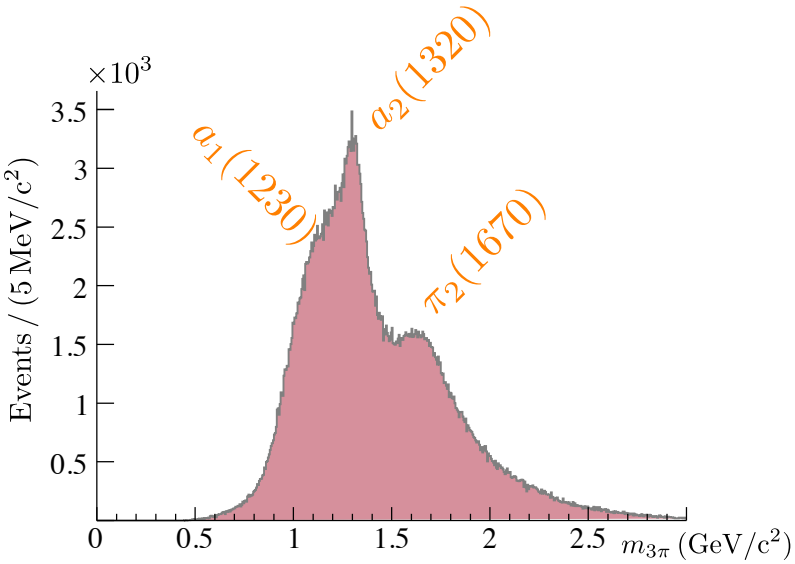

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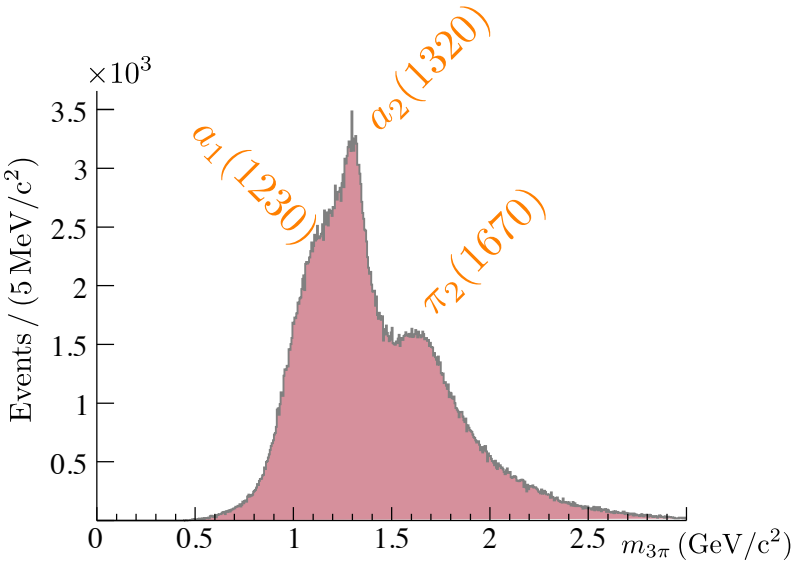

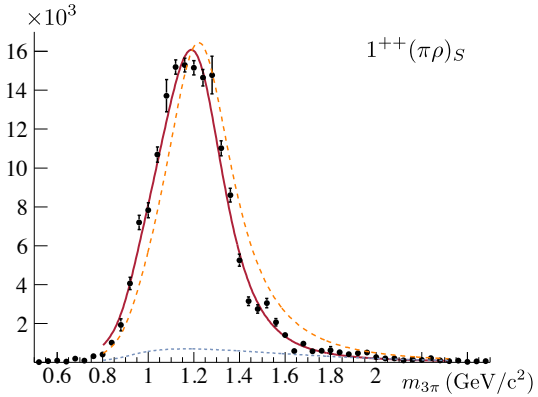

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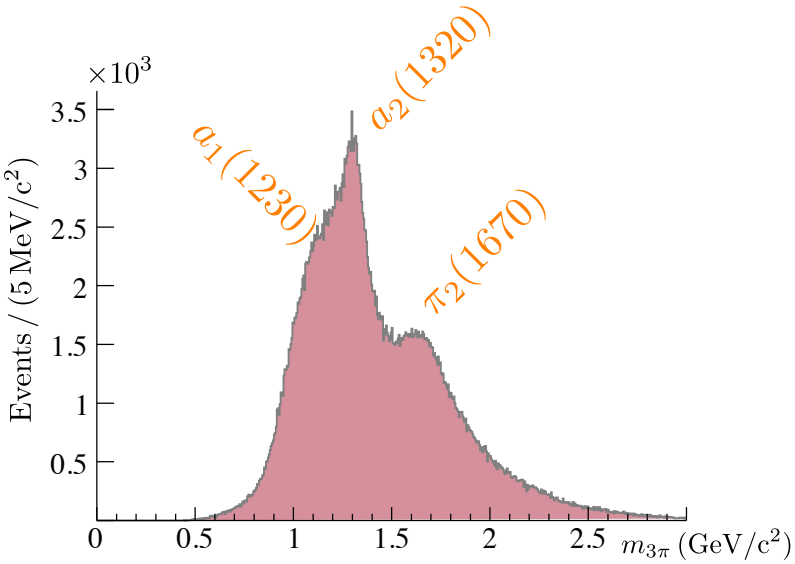

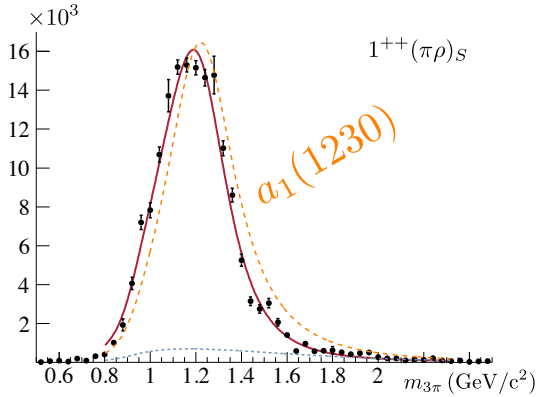

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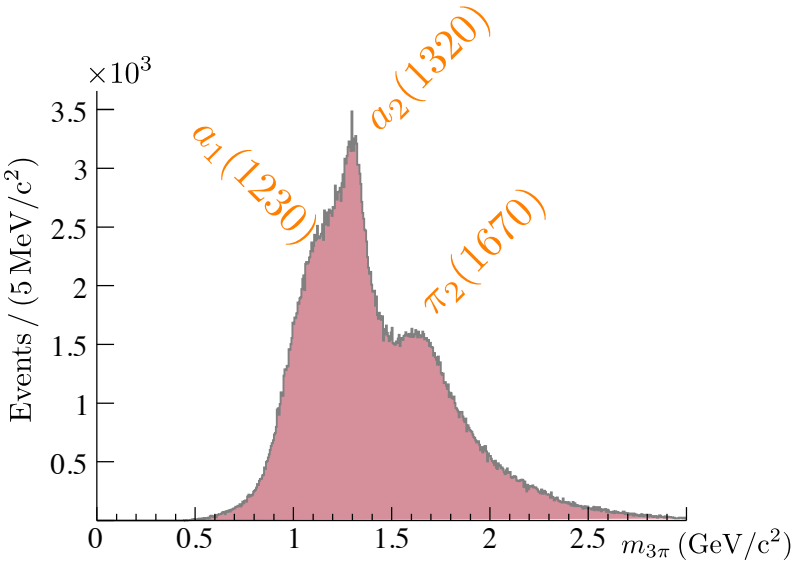

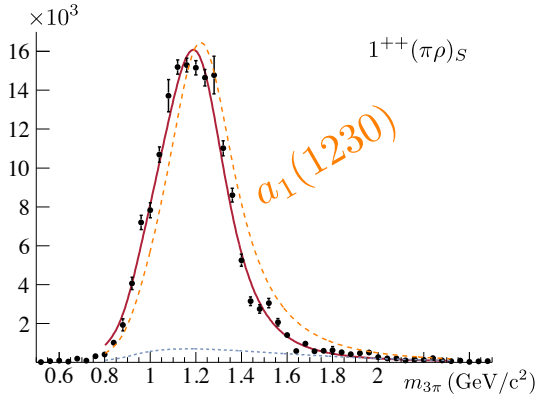

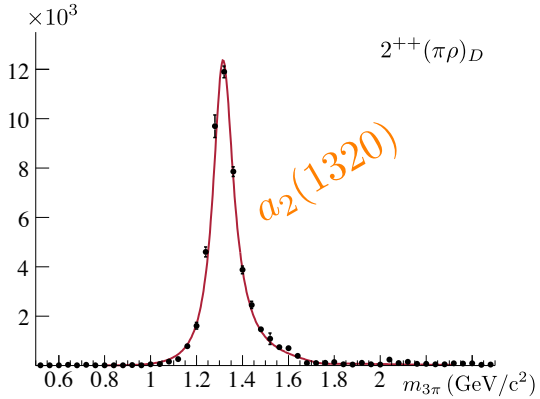

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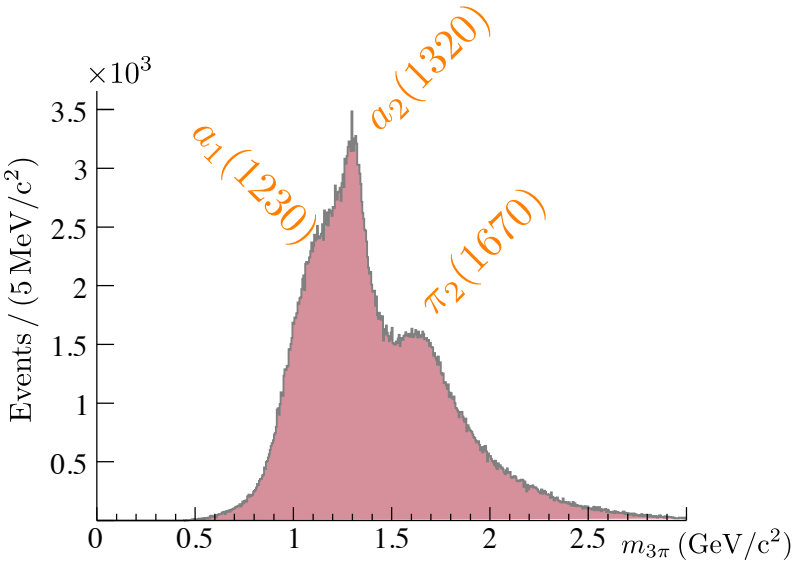

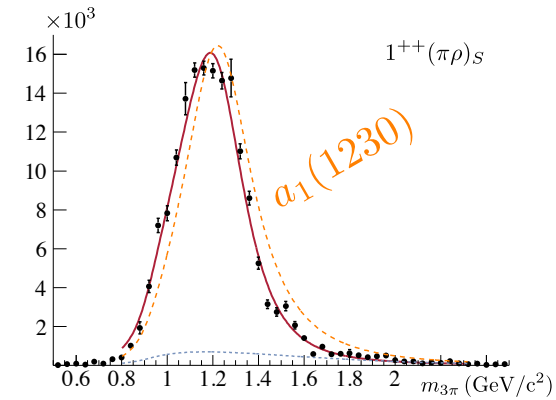

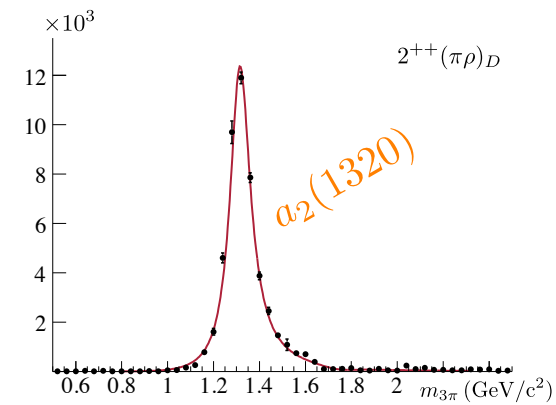

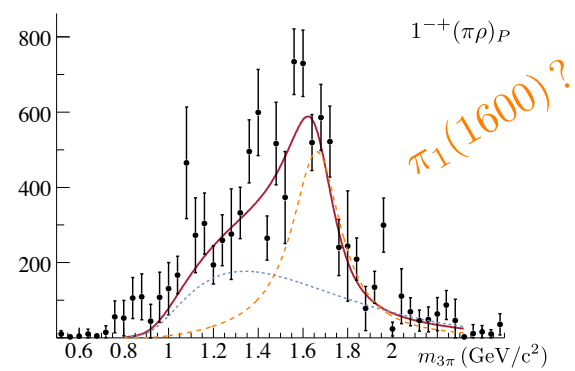

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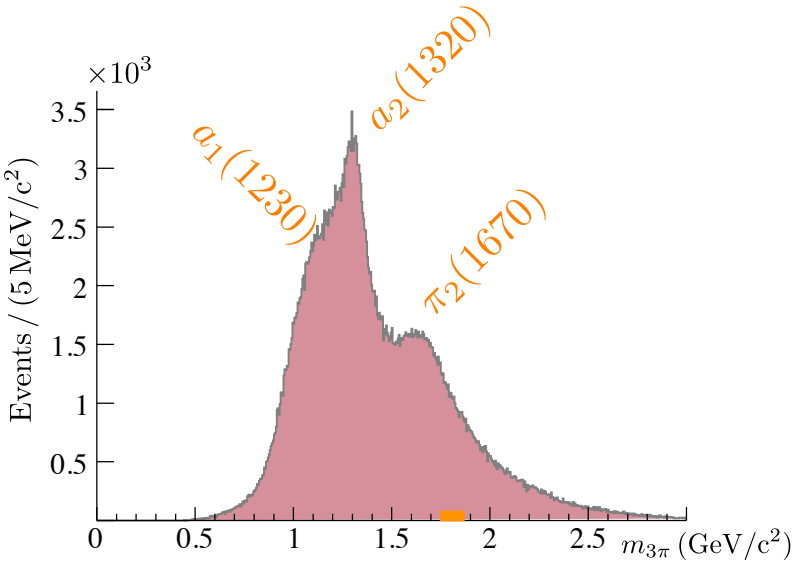
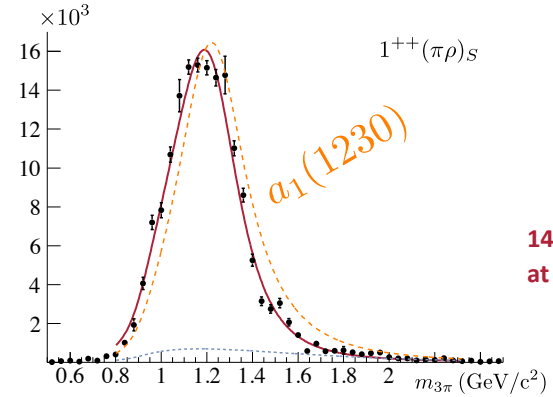
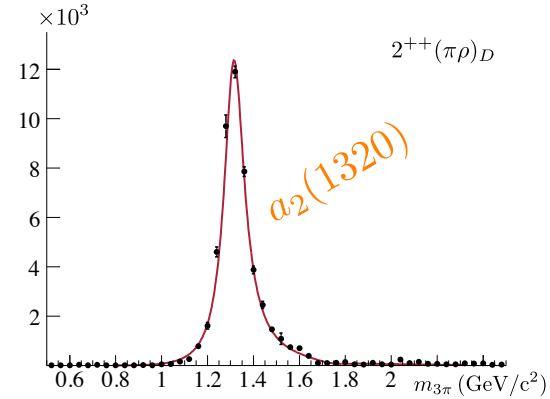
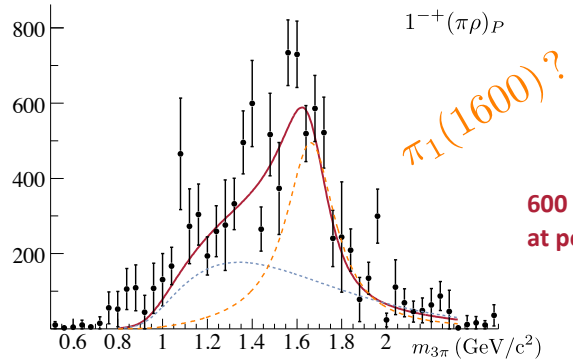




14,000 events at peak





600 events at peak

$\mathcal{O}(1\%)$

40 MeV bins

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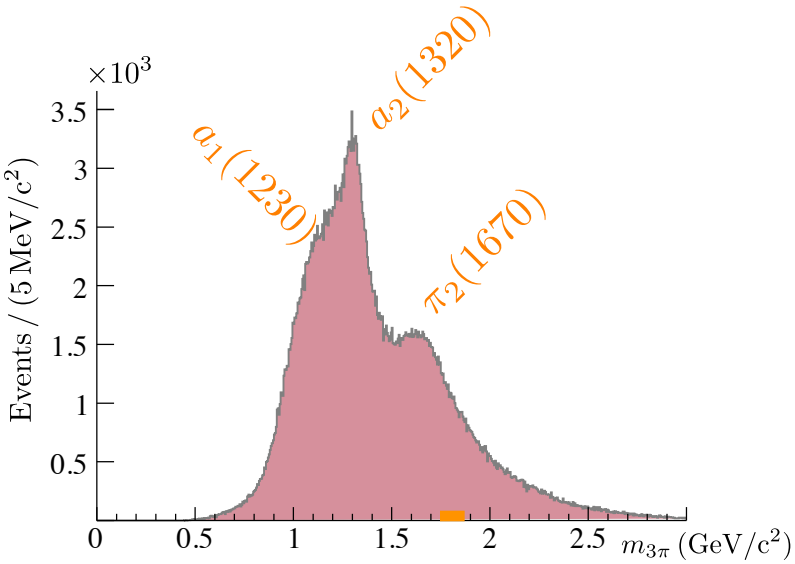

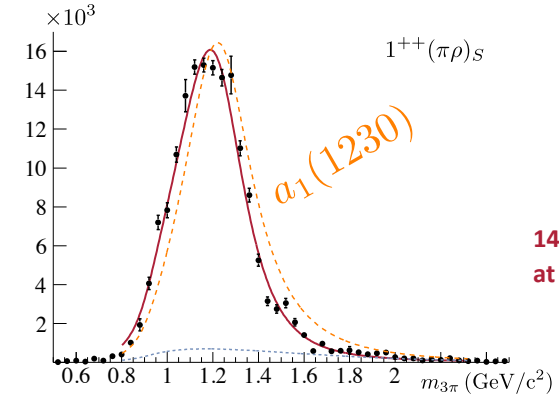

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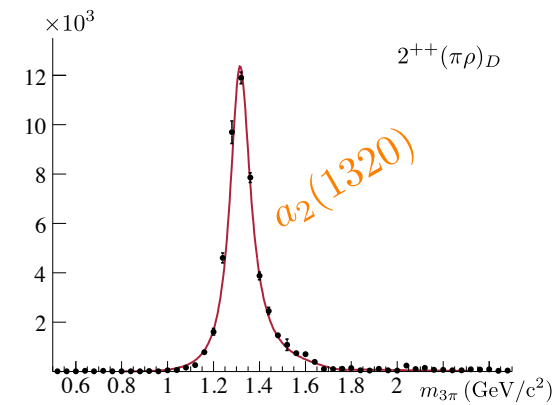
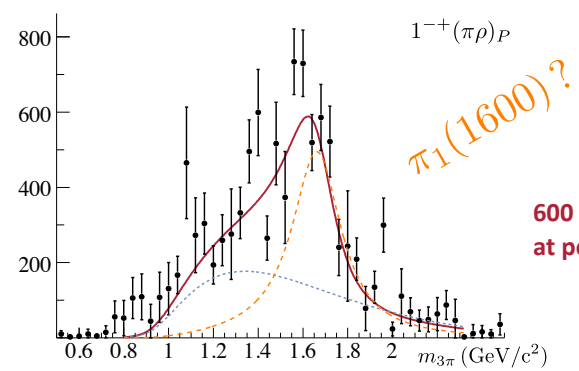


needle in a haystack

- need a good model of haystacks — improved amplitude analysis

- or a bigger needle ! — more favorable production method



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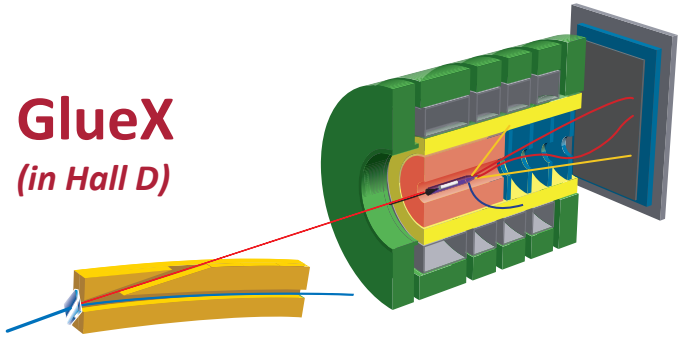
$\mathcal{O}(1\%)$

40 MeV bins

JLab 12GeV - complimentary meson production programs

GlueX
(in Hall D)

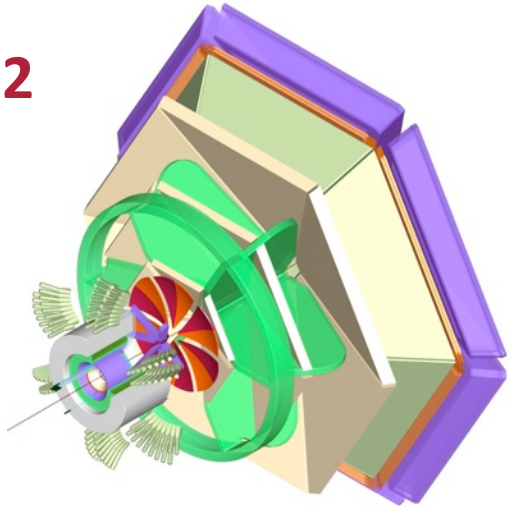


real 9 GeV photon beam (~10^8 γ/s) *high statistics*

high degree of linear polarisation *aids PWA*

hermetic detector *high/flat acceptance*
high multiplicity final states

CLAS12
(in Hall B)



quasi-real photoproduction
(electroproduction at tiny Q^2) *high statistics*
[forward tagged electrons]

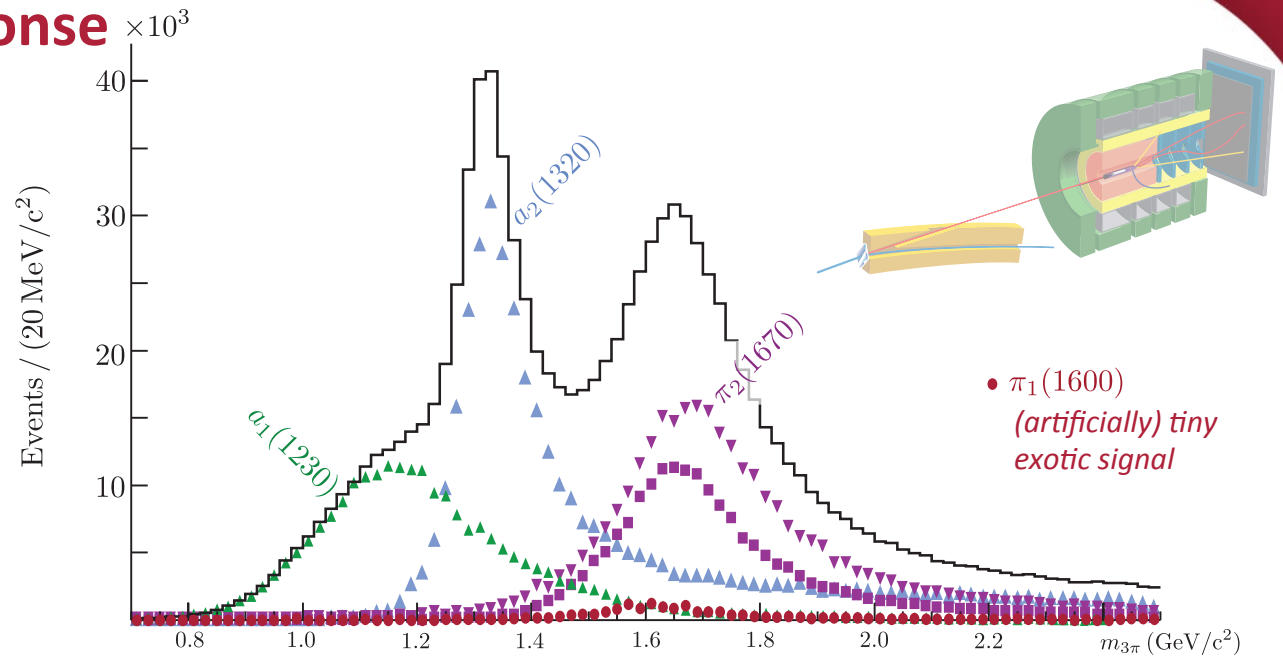
high degree of linear polarisation

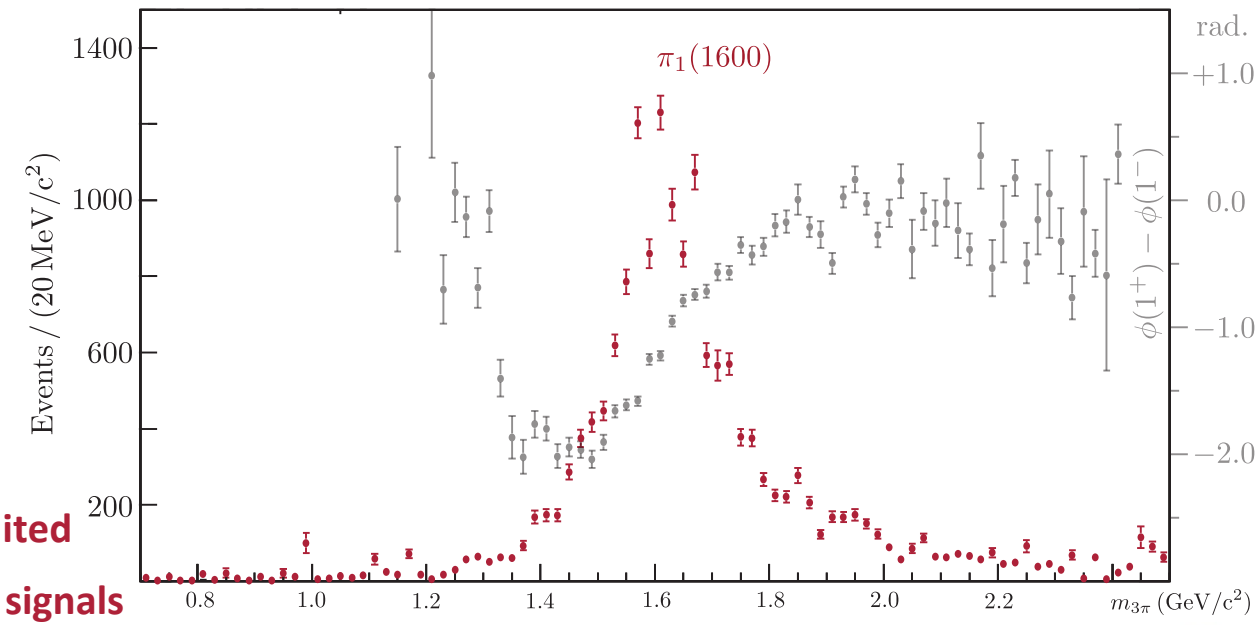
near hermetic detector *low multiplicity final states*
including kaons

new world database of meson photoproduction events
with systematic cross-check between two detectors

GlueX detector response

$$\gamma\, p \rightarrow \pi^+\pi^+\pi^- n$$

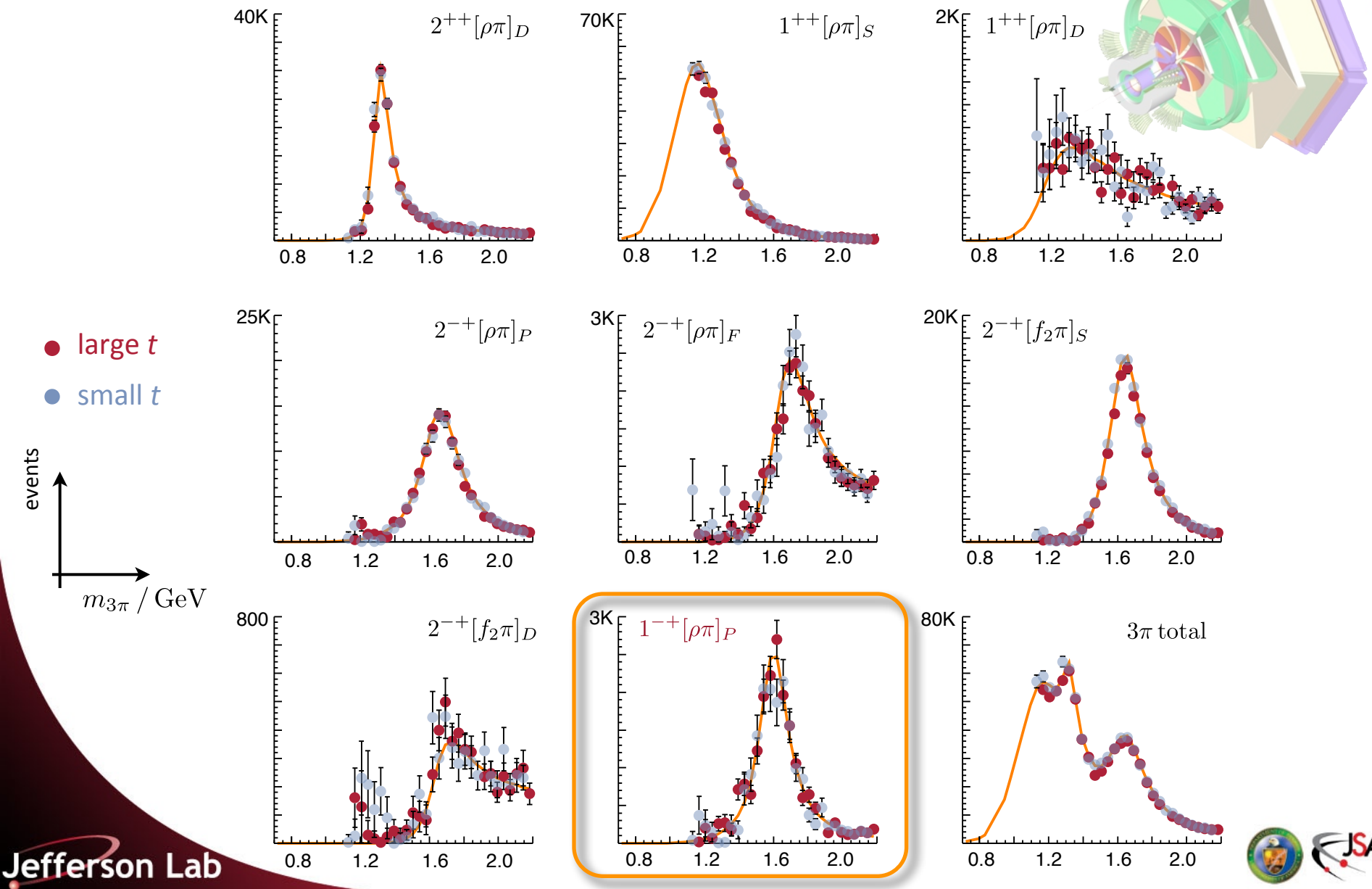




⇒ detector well suited to extracting small signals

CLAS12 detector response

$$\gamma\, p \rightarrow \pi^+\pi^+\pi^- n$$



summary

Post 12 GeV have a major new experimental tools in **GlueX** & **CLAS12** through meson (quasi) photoproduction
- complimentary measurements

➤ **a new production method, can only happen at 12 GeV JLab**

Recent technical progress in PWA computing + unprecedented statistics
→ requires theoretical improvements to PWA formalism (**Physics Analysis Center**)

➤ **controlled formalism to make any observation robust**

Experimental improvements coupled to significant progress in QCD theory
- **lattice QCD** now computing excited state spectra
- couplings of excited meson states to photons coming soon (demonstrated in charmonium)
- first computations of excited hadrons as **resonances** with **decay widths** underway

➤ **reliable QCD results for hadron spectroscopy**

➤ **convergence of theory & experiment into the 12 GeV era**