Update for JPAC

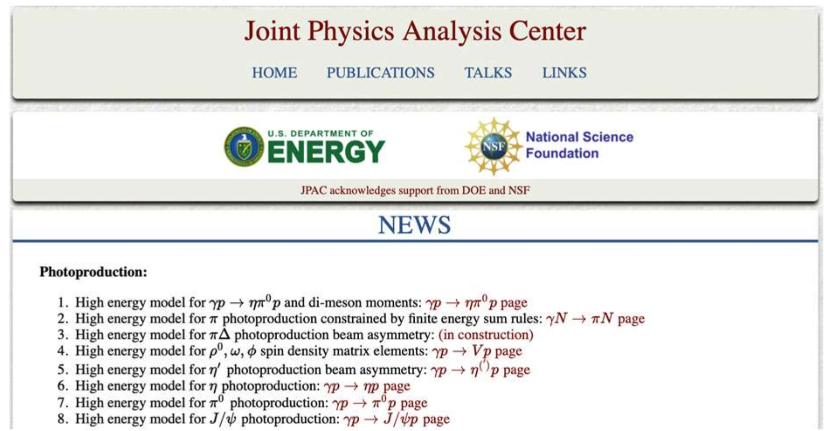
Adam Szczepaniak
Indiana University/Jefferson Lab

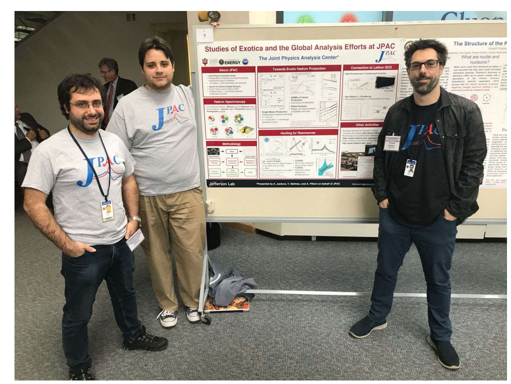
César Fernández-Ramírez
UNED/ICN-UNAM

With slides from Adam Szczepaniak and Alessandro Pilloni

Activities JPAC

- Over 120 Research Articles (since 2013)
- Over 200 Invited Talks and Seminars
- Workshops and Conferences Summer Schools (2015,2017), INT Program (2020) Our own series "Future Directions and Hadron Spectroscopy Analysis" (JLab, Mexico, Beijing), Graduate course on reaction theory (2019,2020)
- Scattering course (2021, 2022)
- Affiliated membership in CLAS, GlueX, BESIII, COMPASS, LHCb
- Recent PhD's: D.Winney (2021), N.Sherrill (2021), A.Jackura (2019), A.Rodas (2019), M.Mikhasenko (2019), J.Nys (2018), A.Hiller-Blin (2018).
- Review: 2112.13436





Joint Physics Analysis Center Full Members


Misha


Cesar


Daniel


Viktor


Sergi


Alessandro


Lukasz


Astrid


Vincent


Adam


Miguel


Akaitz

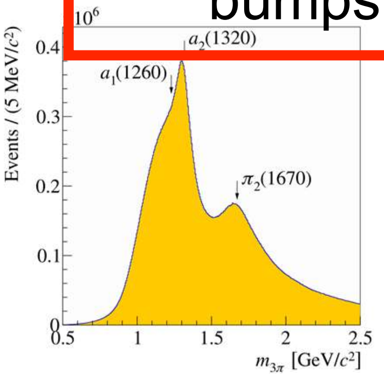

Robert


Jorge

JPAC

Identifying resonances

Experimental or lattice signatures (real axis data: cross section bumps and dips, energy levels)

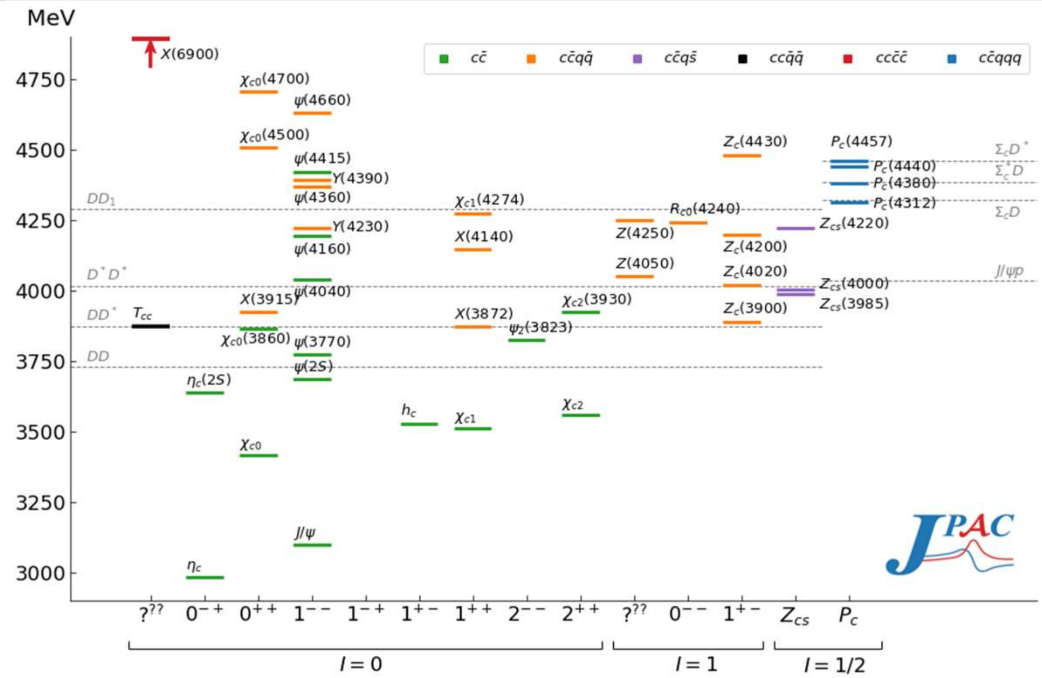


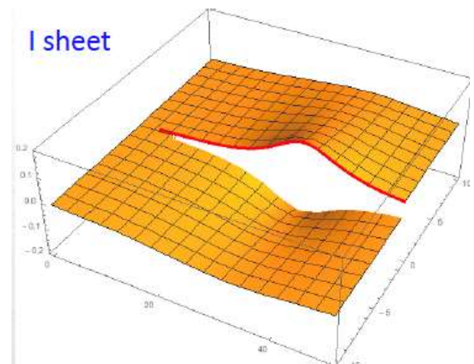
Reaction amplitudes

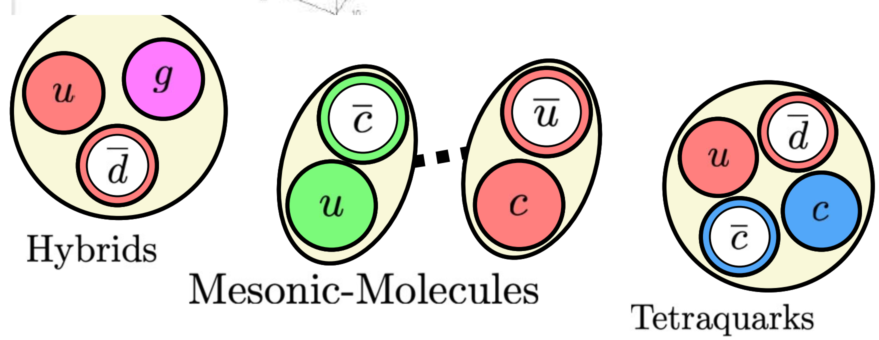
Theoretical signatures (complex plane singularities: poles, cusps)

Microscopic Models

What is the interpretation (constituent quarks, molecules,…)?





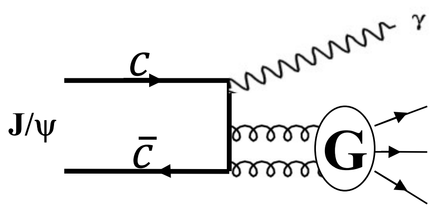


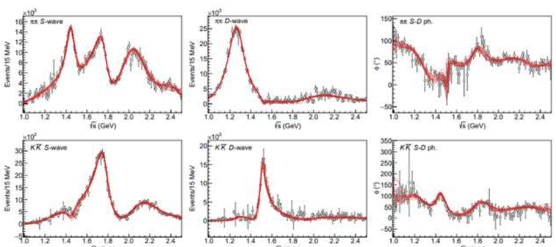
Joint Physics Analysis Center

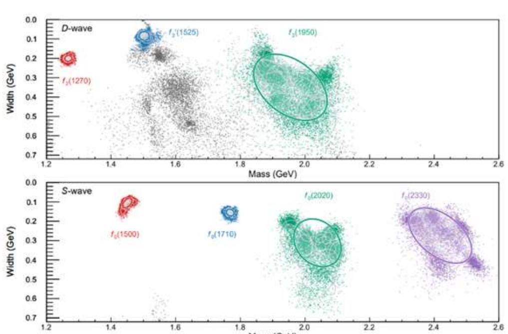
- Scalars in J/Ψ radiative decay

Rodas et al, EPJC 82 (2022) 1

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







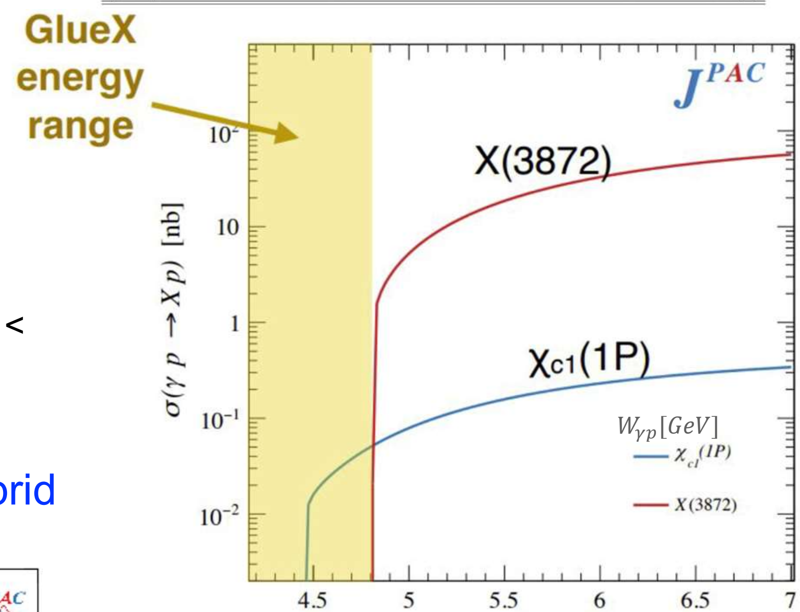
- DNN: see my talk past Thursday

- XYZ studies at EIC/Jlab++ and GlueX-like setup

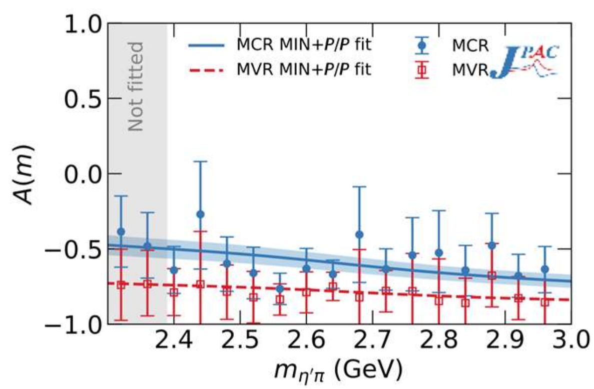
- Yields in direct production at (future) JLab++ comparable to BESIII, Belle, LHCb. The later involve more complicated final states.
- Variable photon energy is important, it probes different production mechanisms : Y production at higher energies W>10 GeV, XZPc , at lower W < 10 GeV

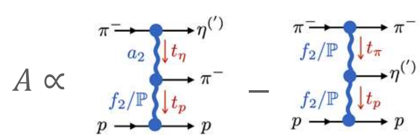
Albaladejo, et al. PRD 102 (2020) 114010

	$W_{\gamma p}$ (GeV)	σ (nb)	$\mathcal{B}(\mathcal{Q} \to \ell^+\ell^- n\pi)$ ($\times 10^{-3}$)	Counts	Comparison
$X(3872)$	6	33.1	5.3	877	$\sim$ 90 [56]
$Z_c(3900)^+$		15.9	12.5	994	$\sim$ 1300 [15]
$Z_b(10610)^+$	15	2.8	2.6	36	$\sim$ 750 [57]
$Z_b'(10650)^+$		0.66	2.1	7	$\sim$ 200 [57]



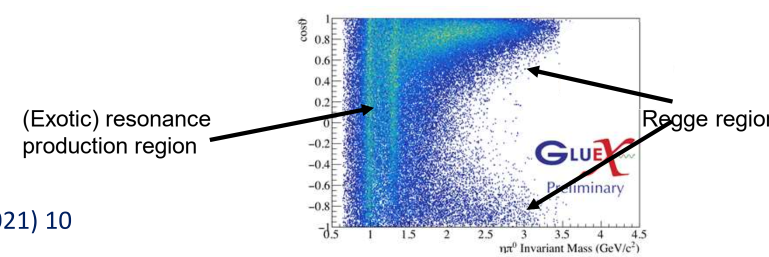
- Search for the exotic hybrid





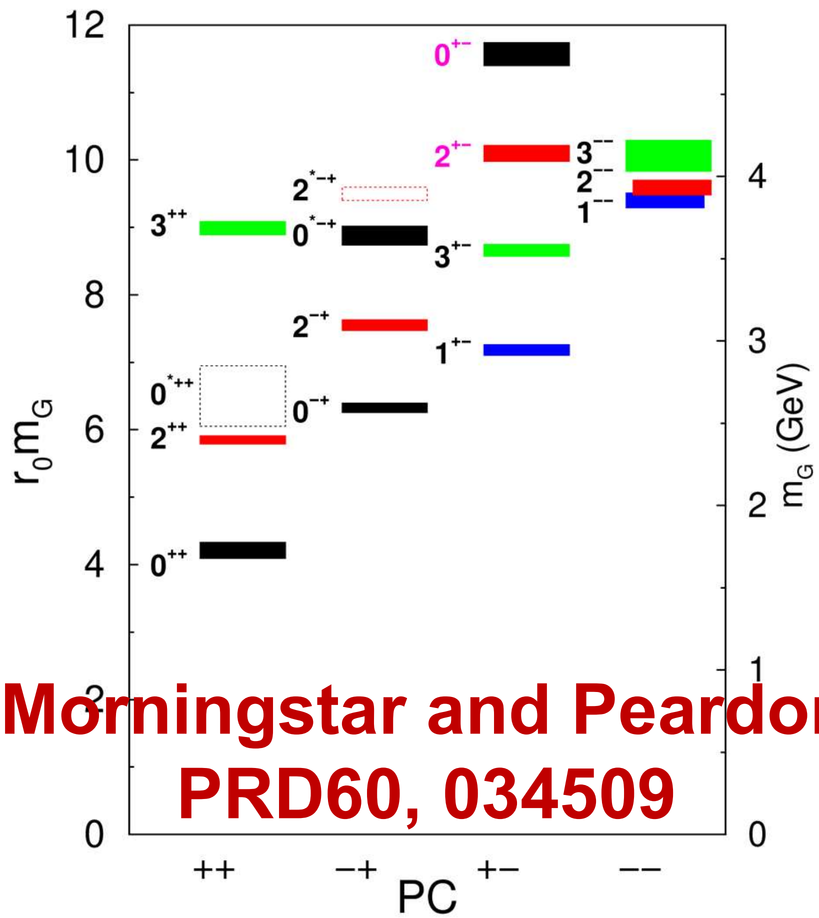
Bibrzycki et al, EPJC 81 (2021) 10

- Angular asymmetry in $\eta^{(\prime)}\pi$ production at COMPASS explained with Regge theory.
- This will constraint extraction of exotic meson (P-wave) from GlueX data



Light scalars and the Glueballs

The clearest sign of confinement in pure Yang-Mills
The worst state to search in real life

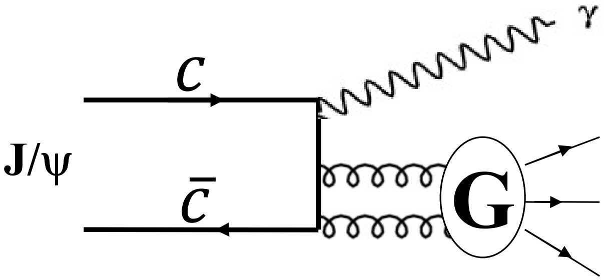


Morningstar and Peardon PRD60, 034509

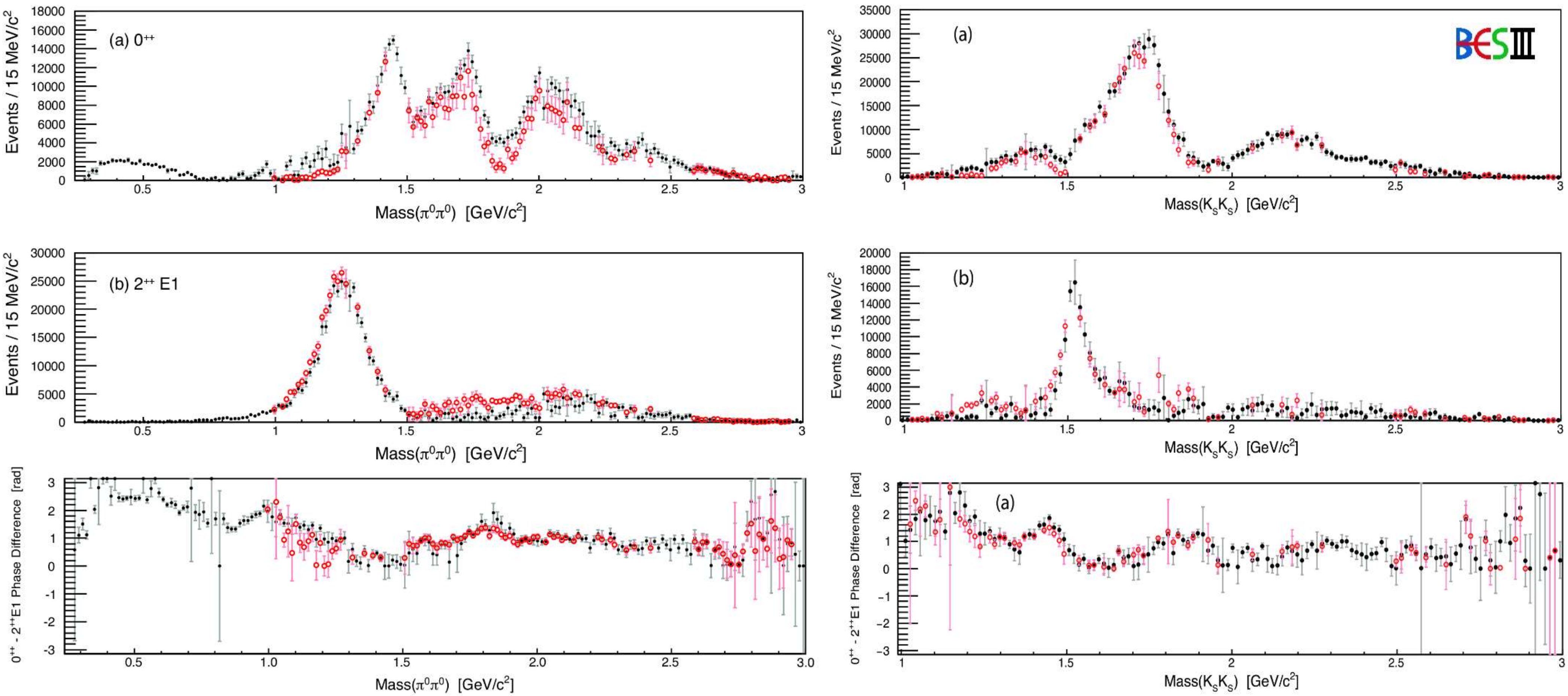
J^{PC}	Mass MeV			
	Unquenched	Quenched		
	This work	M&P	Ky	Meyer
0^{-+}		2590(40)(130)	2560(35)(120)	2250(60)(100)
2^{-+}	3460(320)	3100(30)(150)	3040(40)(150)	2780(50)(130)
0^{-+}	4490(590)	3640(60)(180)		3370(150)(150)
2^{-+}				3480(140)(160)
5^{-+}				3942(160)(180)
0^{--} (exotic)	5166(1000)			
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

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



This is a gluon-rich process, expected to be one of the golden channels for the search of the scalar glueball



Same model as before

Two/three channels, $i, k = \pi\pi, KK, (\rho\rho)$ **Two waves,** $J = S, D$

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

$$K^J_{ki}(s) = \sum_R \frac{g_k^{(R)} g_i^{(R)}}{m_R^2 - s} + c^J_{ki} + d^J_{ki}\, s$$

3 *K*-matrix pole for the S-wave
3 *K*-matrix poles for the D-wave

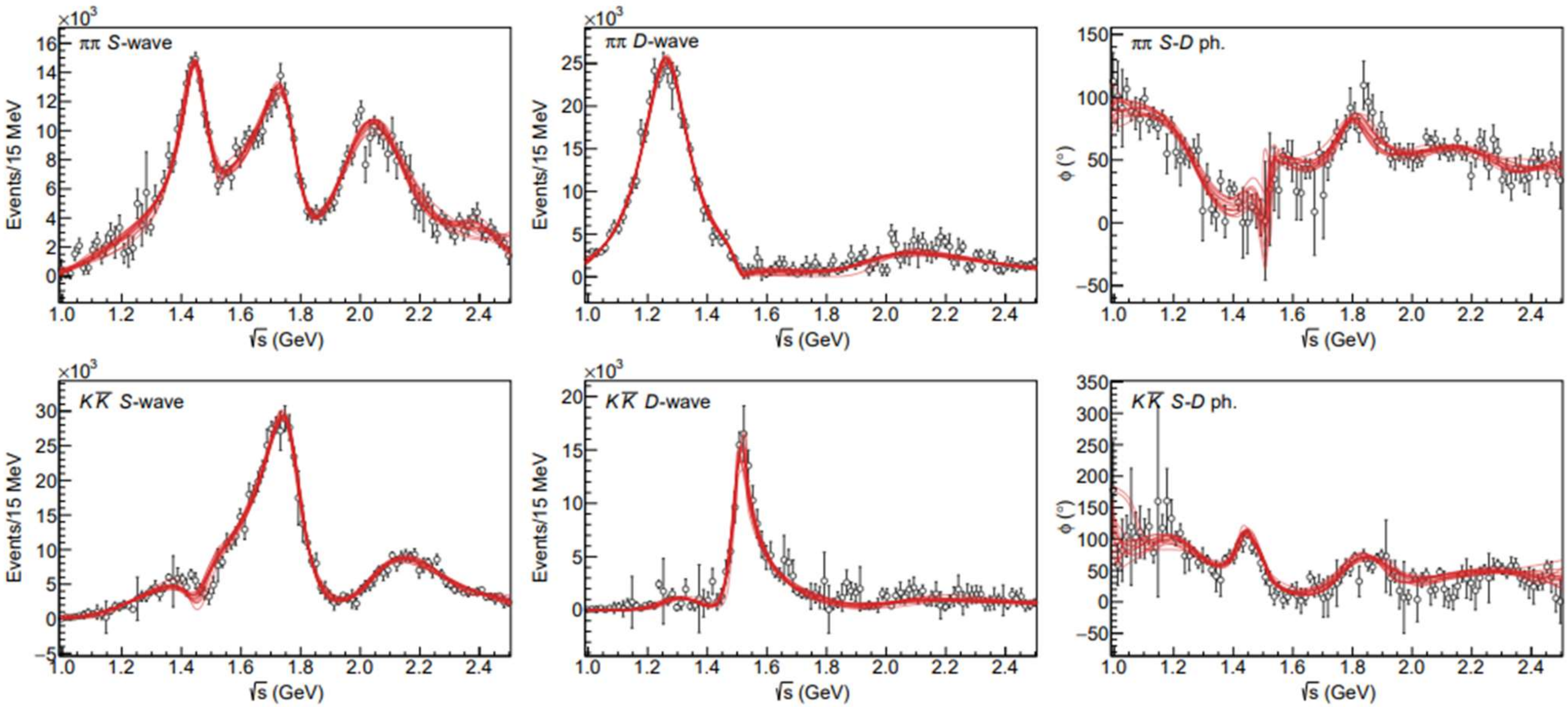
$$\rho N^J_{ki}(s') = \delta_{ki} \frac{\lambda^{J+1/2}\left(s', m^2_{\eta^{(\prime)}}, m^2_\pi\right)}{(s'+s_R)^{2J+1+\alpha}}$$

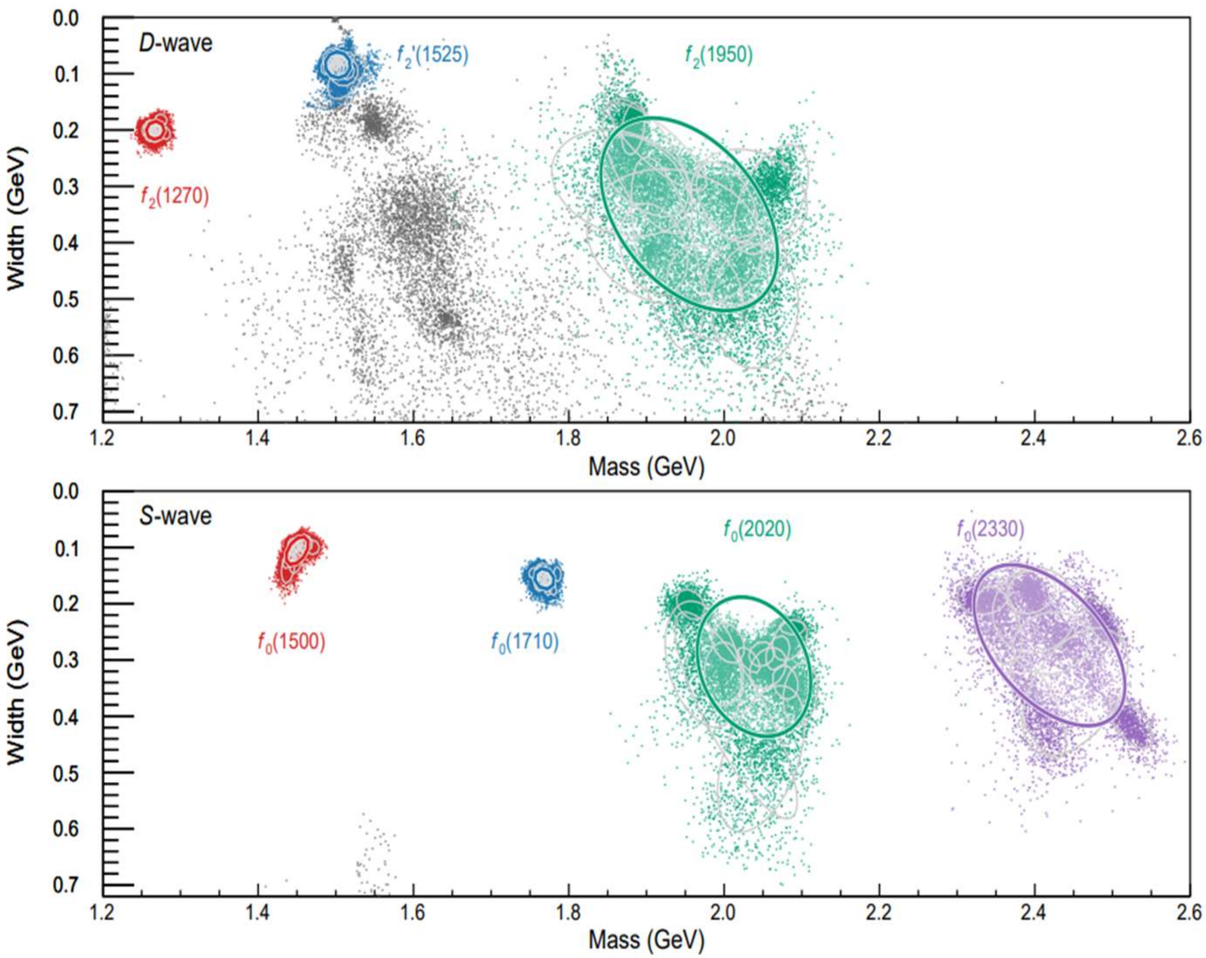
$$n^J_k(s) = \sum_{n=0}^{3} a_n^{J,k}\, T_n\left(\frac{s}{s+s_0}\right)$$

Lead by Arkaitz & Alessandro

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

Rodas et al, EPJC 82 (2022) 1





Poles:

- **Large systematic uncertainty for the heavier poles**
- **Study of residues ongoing**
- **Interpretation as glueballs? See Alexey's talk today**

Spectroscopy at EIC & Jlab++

Target: high saturated gluon content

Beam/probe: high resolution photons, point-like quark-antiquary production

- Clean mode for production of heavy quarks is, especially bottomonia, possibly with enchanted production of hybrids
- Excellent kinematic separation, incoherent charge exchange, production of tetraquarks and baryon exotics, pentaquarks
- Wide kinematic coverage, from diffraction to DIS gives access to a wide range of production mechanisms

Lead by Miguel, Astrid, Vincent, Daniel & Alessandro

X(3872)

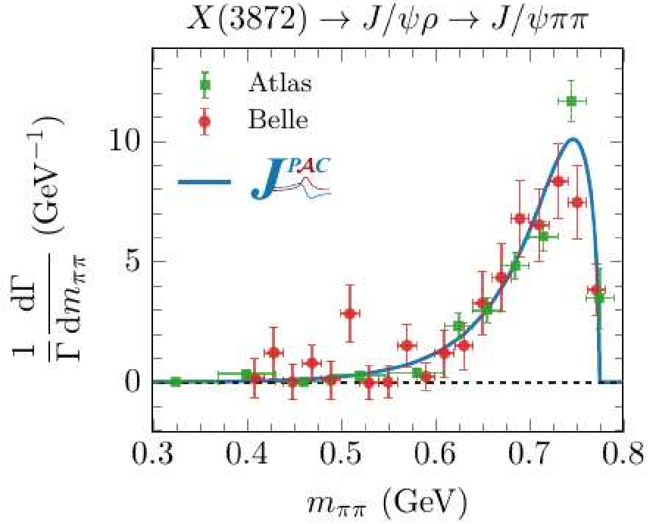
For production/detection, its main decay channels are $J/\psi\rho$ and $J/\psi\omega$ with Br=4.1% and 4.4%, respectively.

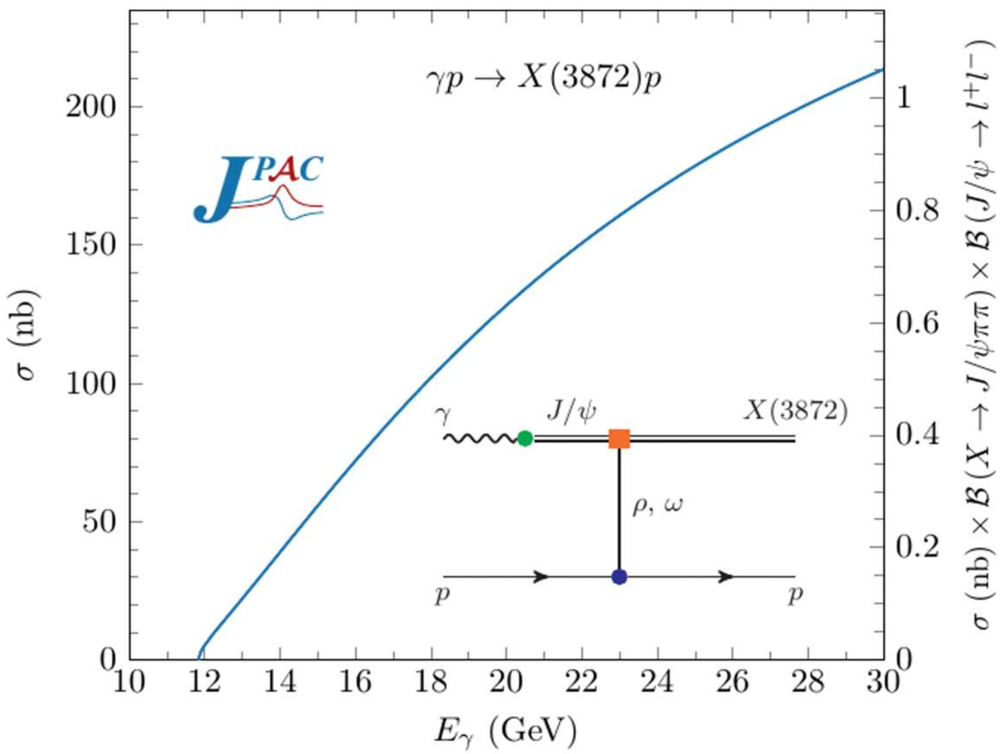
The couplings $J/\psi\rho$ and $J/\psi\omega$ are determined from the branching ratios and assuming a width 1.2 MeV.

The other parts of the amplitude, $\gamma \to J/\psi$ given by VMD, and VNN (bottom vertex) also well known. [1]

[1] Phys. Rev. D 96, 093008 (2017)

The $X \to J/\psi\rho$, $\rho \to \pi\pi$ distribution also agrees with data.



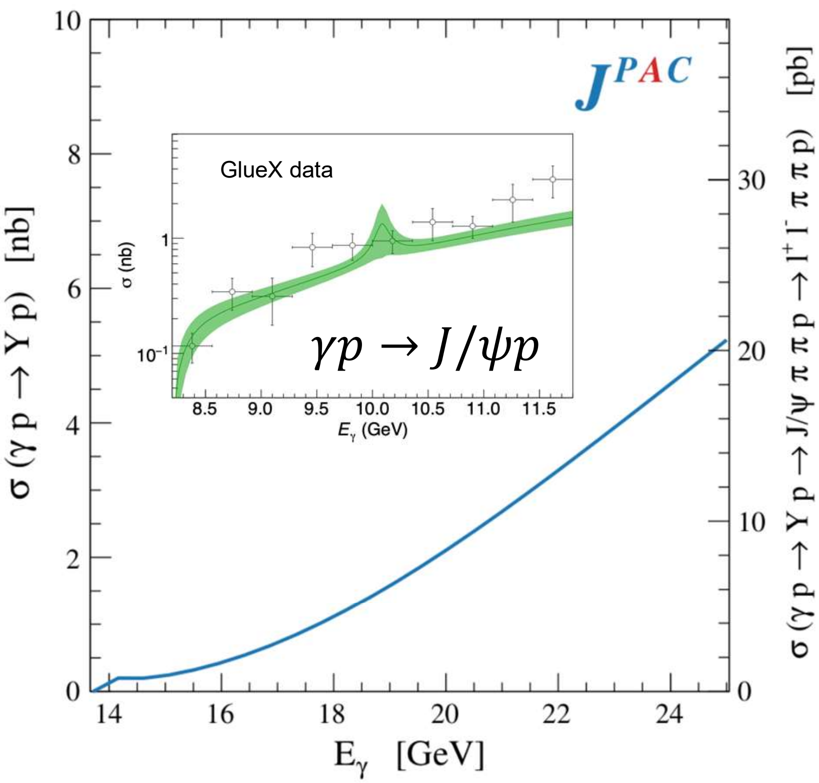


$\mathcal{L} \sim 500pb^{-1}/yr$ (at $E_\gamma = 20GeV$) with 1% eff.

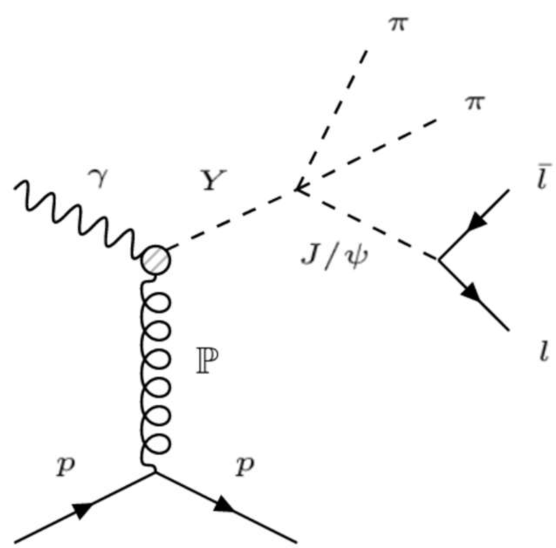
Number of events ~3000 events/yr

BESIII efficiency ~50% due to enhanced acceptance of the symmetric detector — thus our efficiency estimate of 1% is probably conservative

Y(4260)



J/ψ photoproduction near threshold by Pomeron exchange studied by JPAC in [1, 2]



Same bottom ($g_{\mathbb{P}pp}$) coupling. Top couplings ($g_{\mathbb{P}\gamma\psi}/g_{\mathbb{P}\gamma Y}$) related by [3] (omitting phase space factors):

$$\frac{g_{\mathbb{P}\gamma Y}}{g_{\mathbb{P}\gamma\psi}} = \frac{g_{Y\to\gamma gg}}{g_{\psi\to\gamma gg}} = \sqrt{4\pi\alpha}\,\frac{f_\psi}{m_\psi}\sqrt{\frac{\Gamma_Y}{\Gamma_{\psi(1S)}}\,\frac{\mathcal{B}(Y\to\psi(1S)\pi\pi)\,\mathcal{B}(\psi(2S)\to\psi gg)}{\mathcal{B}(\psi(1S)\to\gamma gg)\,\mathcal{B}(\psi(2S)\to\psi\pi\pi)}}$$

$$\frac{g_{\mathbb{P}\gamma Y}}{g_{\mathbb{P}\gamma\psi}} \sim 1.5$$

[1] Phys. Rev. D 94, 034002 (2016)
[2] Phys. Rev. D 100, 034019 (2019)
[3] Phys. Rev. Lett. 45, 688 (1980)

~50 events/yr

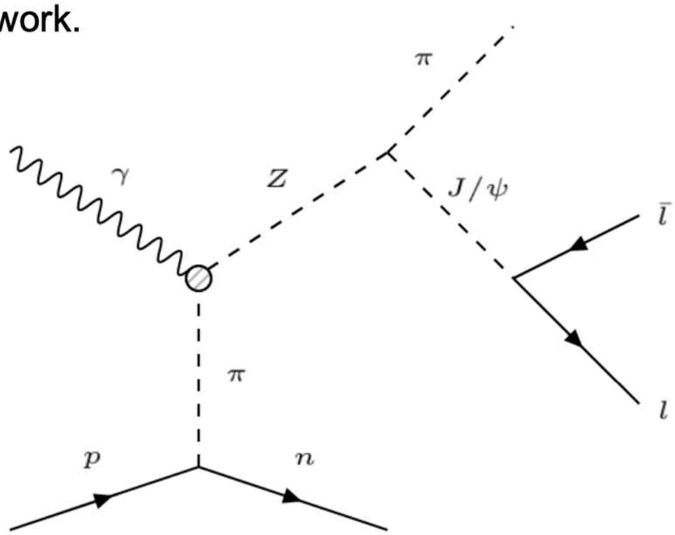
The reason why J/ψ photo production is larger is due to the small $Y \to J/\psi\pi\pi$ branching ratio of 3%

Y production increases with energy : AMBER/EIC

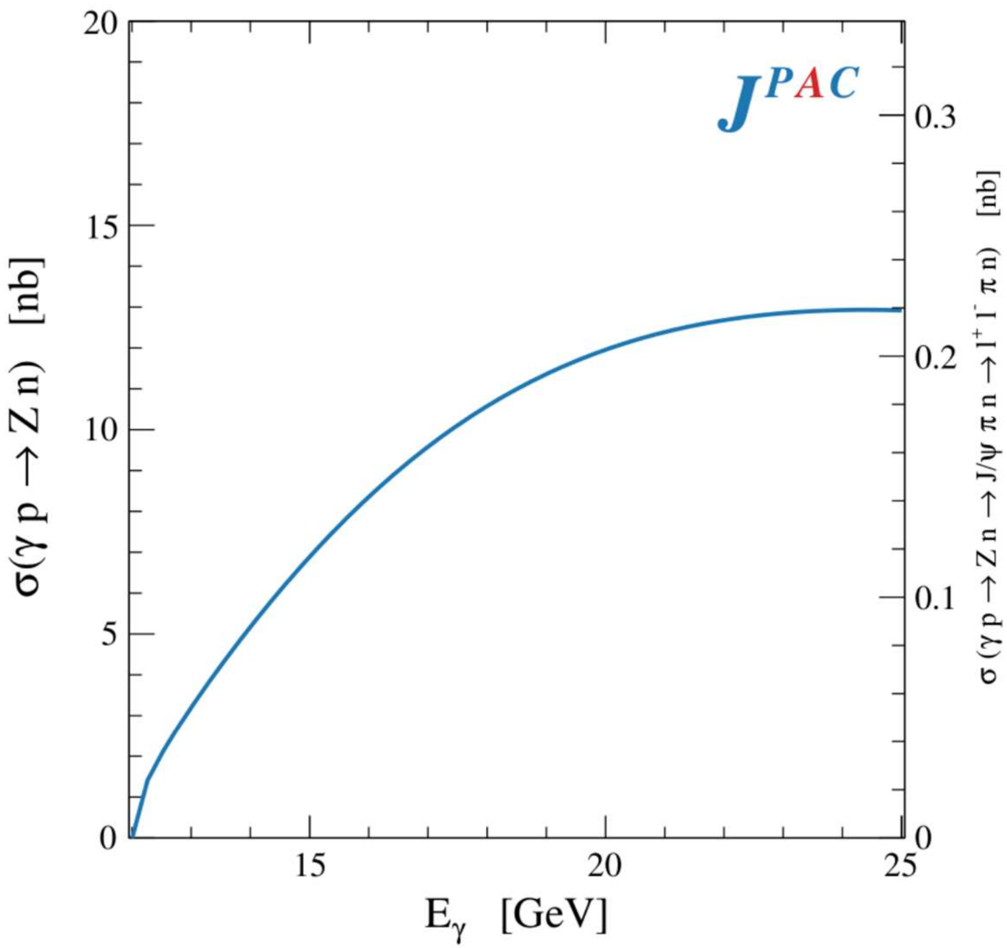
Z(3900)

Photoproduction by charged pion exchange considered in [1] but decay widths were largely unknown.

BESIII determination [2] of $\Gamma(Z \to D\bar{D}^*)/\Gamma(Z \to J/\psi\pi)$ allows more accurate estimation of the coupling within VMD framework.



[1] Phys. Rev. D 88, 114009 (2013)
[2] Phys. Rev. Lett. 112, 022001 (2014)



~1000 events/yr

Branching ratio $Z \to J/\psi\pi$ is larger than that of $Y \to J/\psi\pi\pi$

Summary

TABLE VIII. Estimates of yields for one year of data taking under the conditions described in the text. The branching ratios $\mathcal{B}(\mathcal{Q} \to \ell^+\ell^- n\pi)$ are given by $\sum_V \mathcal{B}(\mathcal{Q} \to V n\pi) \times \mathcal{B}(V \to \ell^+\ell^-)$. Comparison with existing datasets are also given. The efficiency is assumed to be 1%. Higher efficiencies are certainly possible, e.g., 50% for the $Z_c(3900)^+$ at BESIII. The results for the $X(6900)$ must be rescaled by the yet unknown $\mathcal{B}[X(6900) \to \psi\psi]$.

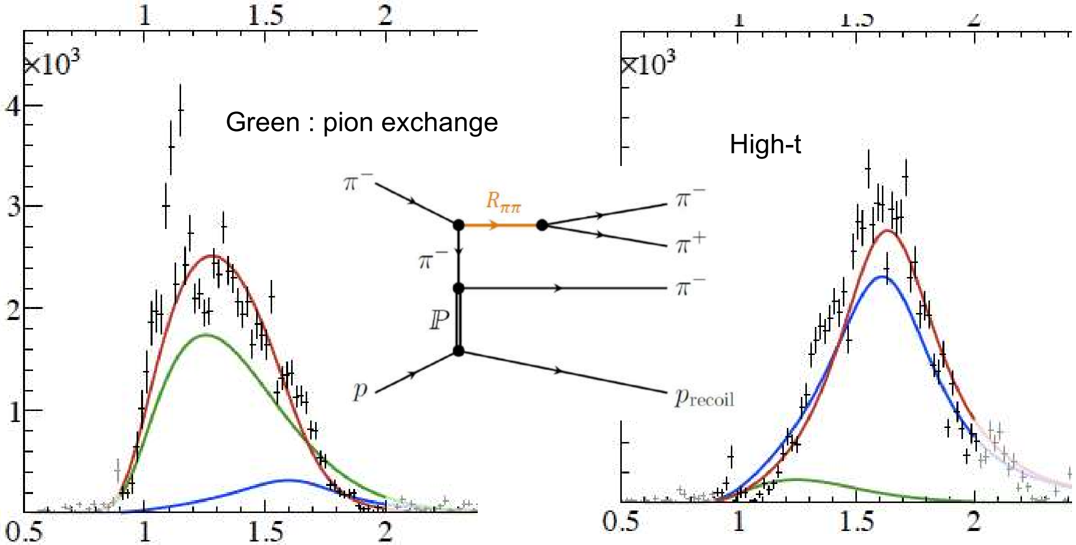
	$W_{\gamma p}$ (GeV)	σ (nb)	$\mathcal{B}(\mathcal{Q} \to \ell^+\ell^- n\pi)$ ($\times 10^{-3}$)	Counts	Comparison
$X(3872)$	6	33.1	5.3	877	~90 [60]
$Z_c(3900)^+$		15.9	12.5	994	~1300 [15]
$Z_b(10610)^+$	15	2.8	2.6	36	~750 [61]
$Z_b'(10650)^+$		0.66	2.1	7	~200 [61]
			$\mathcal{B}(J/\psi \to \ell^+\ell^-)^2$ ($\times 10^{-3}$)		
$X(6900)$	12	1.9	14	133	~800 [33]

Plenty of signatures: hybrids

- Exotic $J^{PC}=1^{-+}$ (hybrid) mesons expected (VES, GAMS, E852, COMPASS, and theory)
- In low-t pion diffraction (COMPASS) exotic wave production compatible with one pion exchange (but not at high-t)
- In photoproduction (GlueX,CLAS12) exotic mesons produced via pion exchange

Low-t

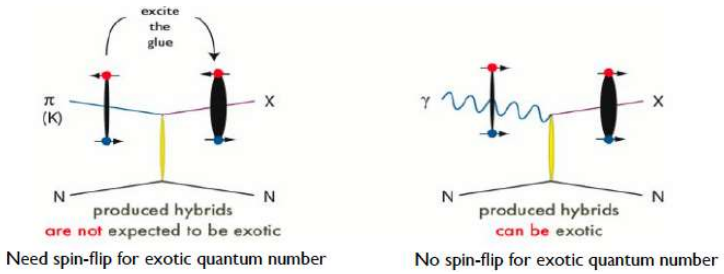
Red : Exotic resonance

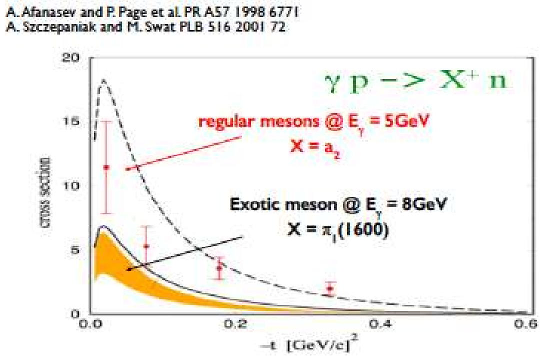


COMPASS (2018)

$\pi^- p \to \eta^{(')} \pi^- p$

[B.Grube, proc. HADRON2019]

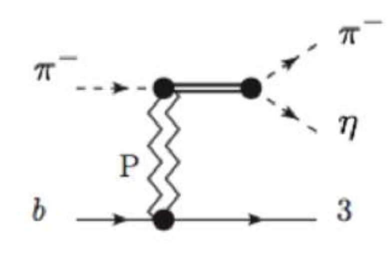




See Bernhard’s talk today

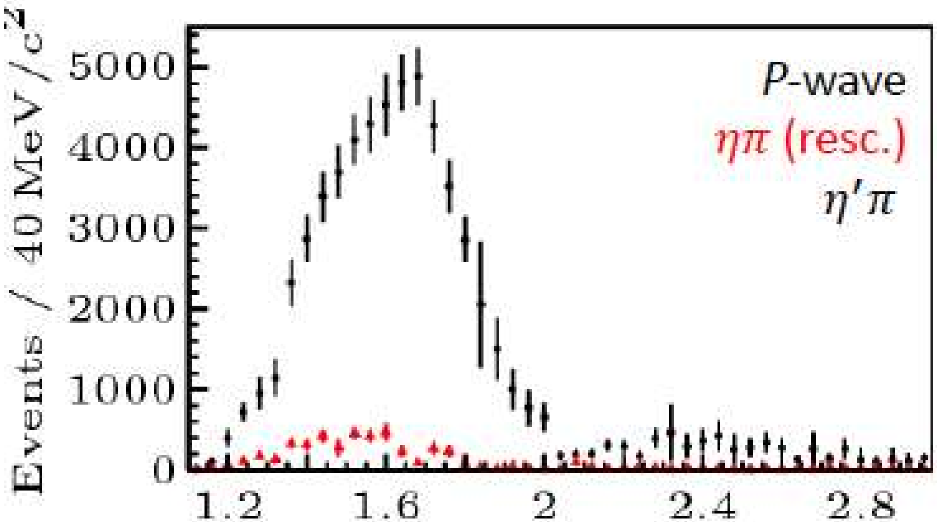
M.Swat, AS Phys.Lett.B 516 (2001)

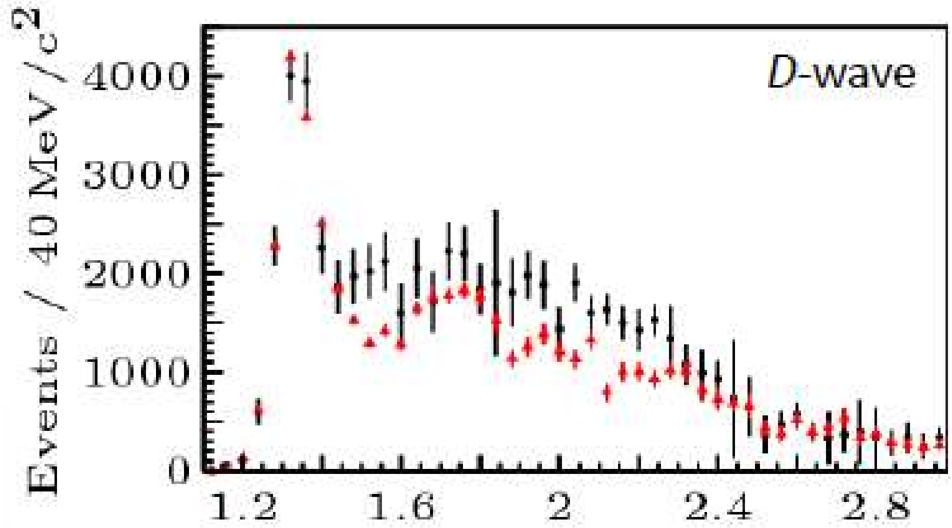
adding P wave and η’π channel

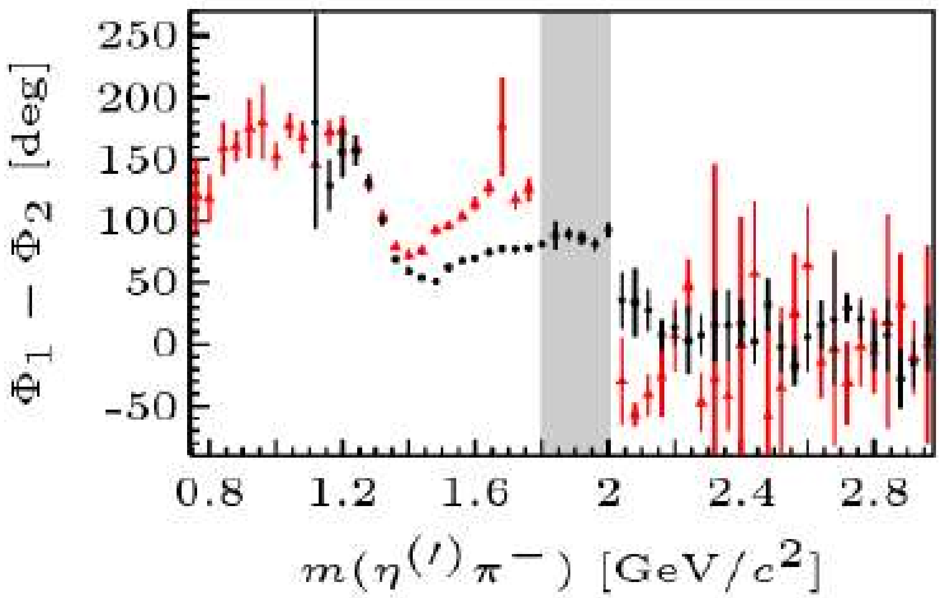


Data

COMPASS, PLB740, 303-311







A sharp drop appears at 2 GeV in *P*-wave intensity and phase

No convincing physical motivation for it

It affects the position of the $a_2'(1700)$

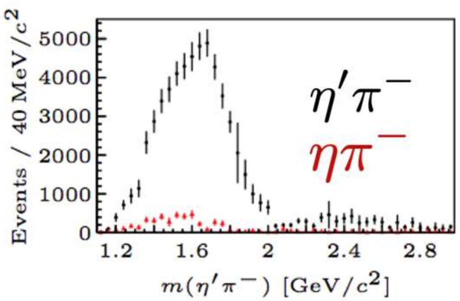
We decided to fit up to 2 GeV only

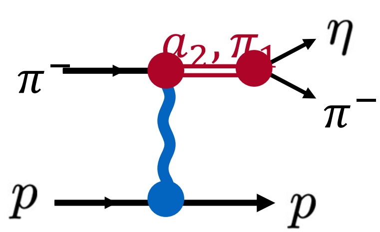
Single vs Double Regge exchange

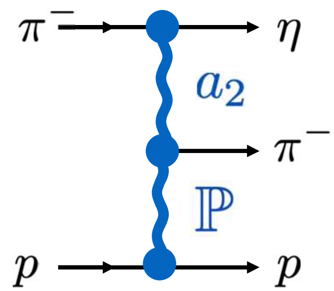
If a2 and f2 exchanges were equal and no Pomeron

NO ASYMMETRY and NO π_1

Responsible for asymmetry
In eta-Prime - pion?

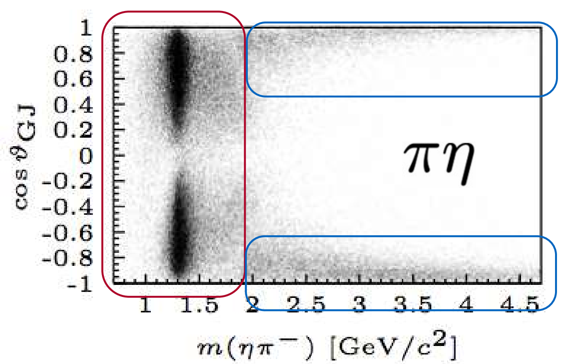


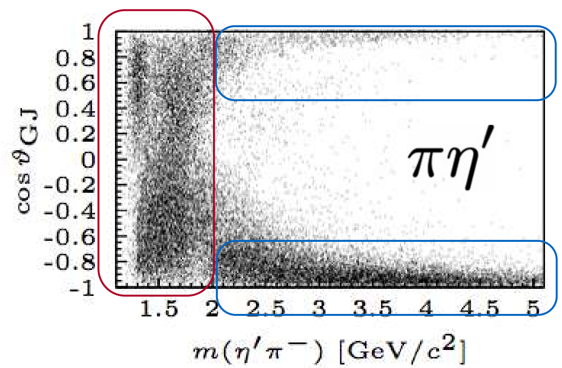




$\cos\theta_{GF} \sim 1 \rightarrow \eta$ forward

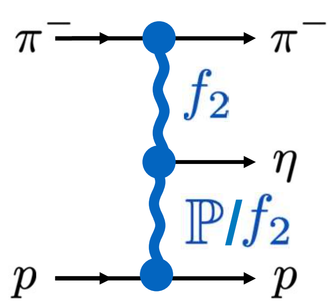
$\cos\theta_{GF} \sim -1 \rightarrow \eta$ backward

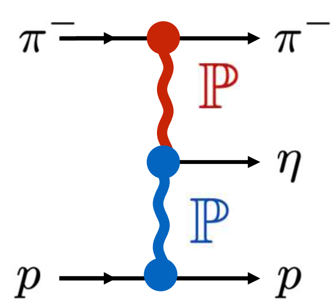




Exotic meson = P wave

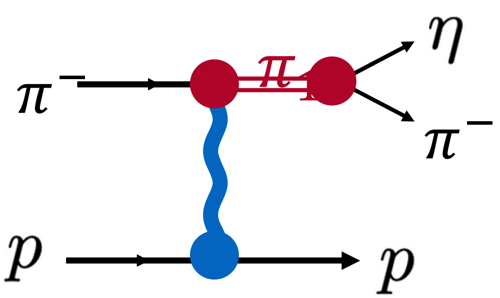
Existence of forward-backward asymmetry is related to existence of the exotic wave

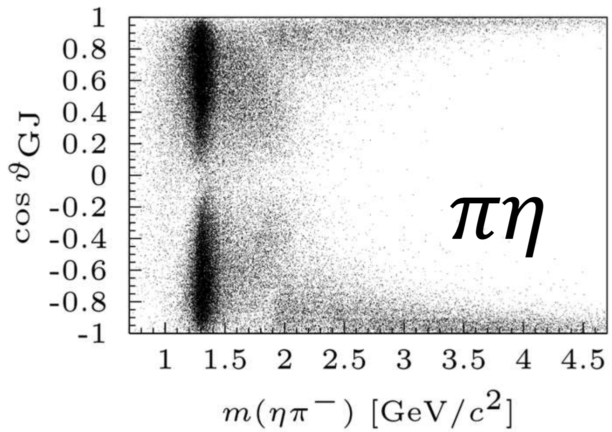


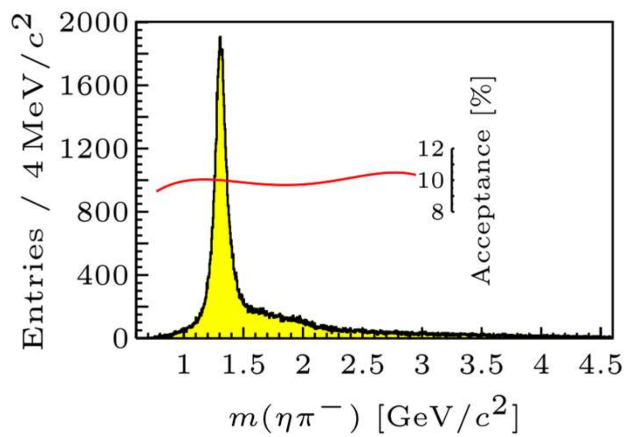


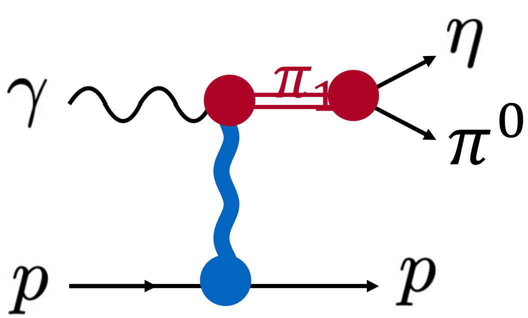
COMPASS vs GlueX

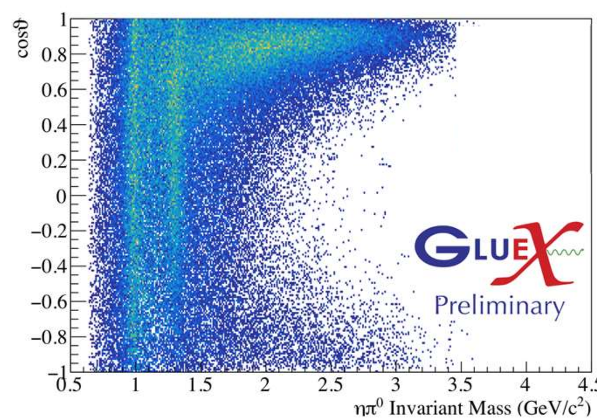
[C.Adolph, et all COMPASS, Phys.Lett.B 740 (2015) 303]

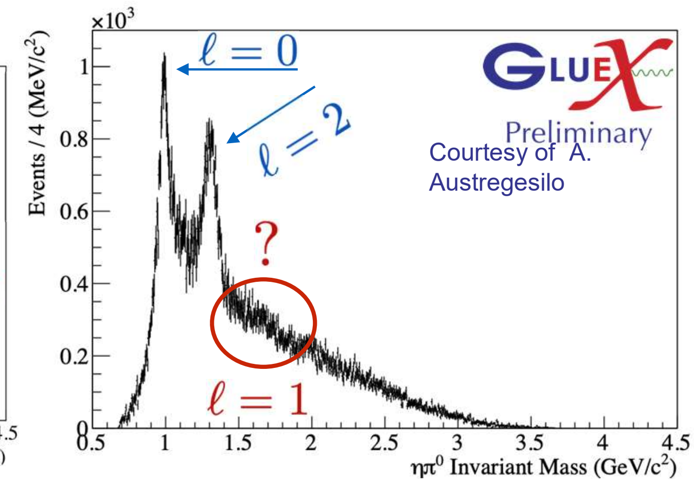












- Also charge exchange

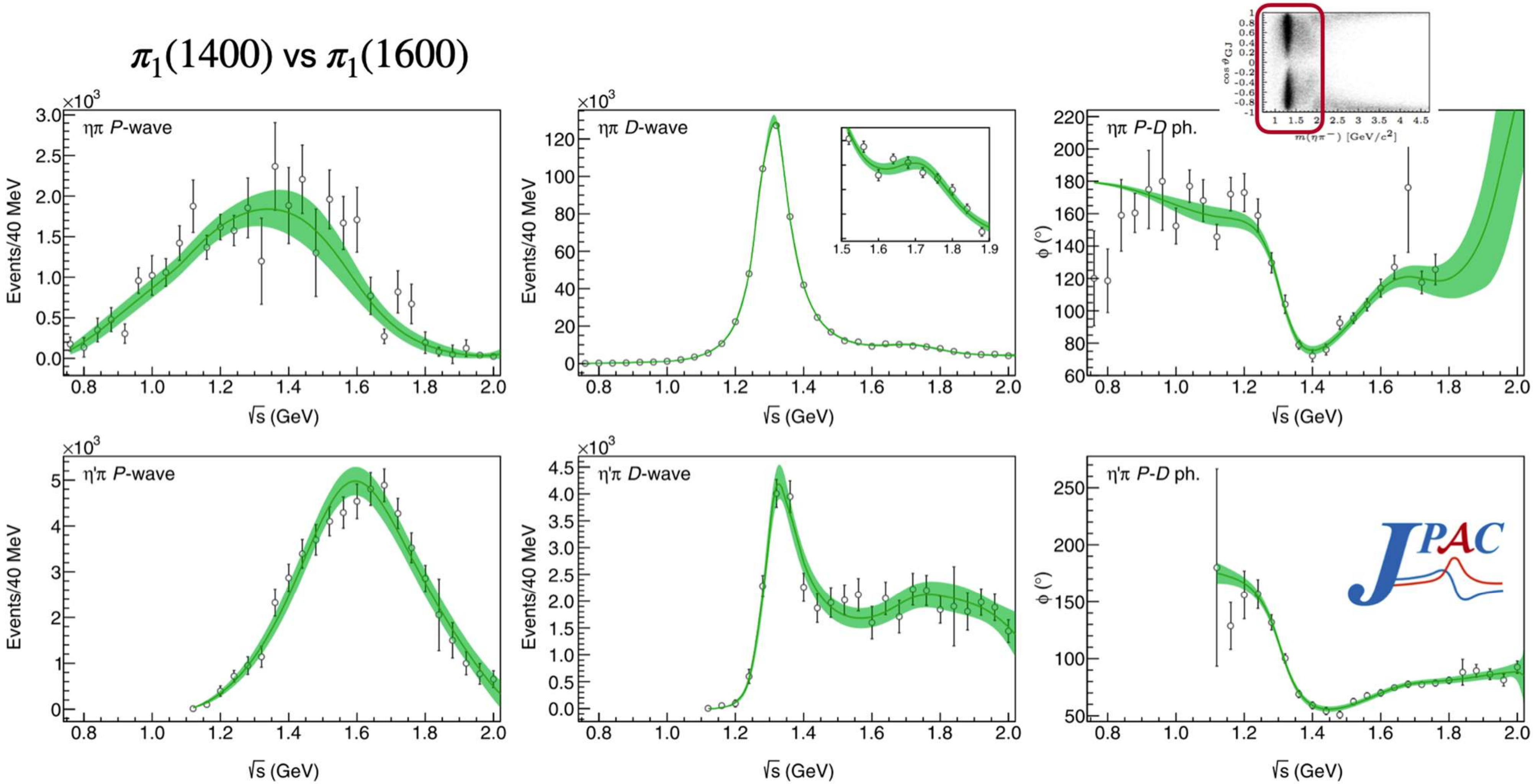
See Sean’s talk today

- Thanks to V. Mathieu from APS 2021

Low energy fit (L=1,2)

Rodas et al (JPAC) PRL 122 (2019) 042002

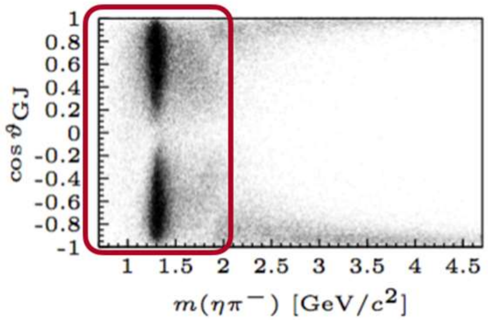
$\pi_1(1400)$ vs $\pi_1(1600)$

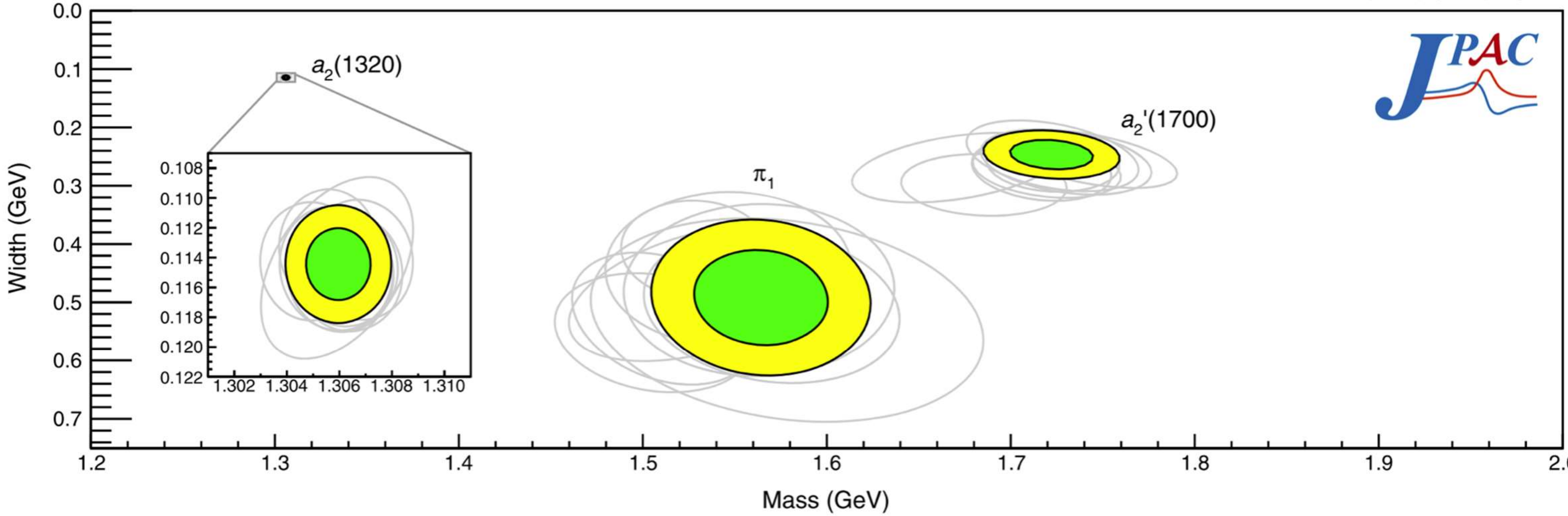


Lead by Arkaitz & Alessandro

Pole postions

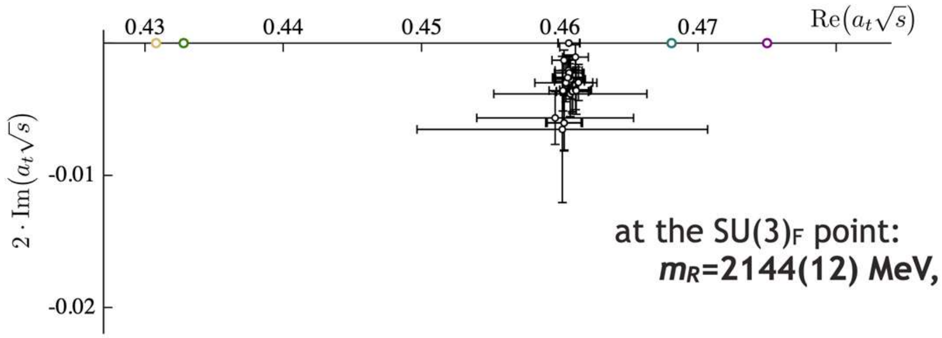
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$





1^{-+} from lattice

octet 1^{-+} resonance pole & couplings



at the $SU(3)_F$ point:
m_R=2144(12) MeV, Γ_R=21(21) MeV

generates for a π_1 at 1564 MeV:

Γ_{TOT} ~ 140-600 MeV

$\Gamma(\pi\eta) \lesssim$ 1 MeV
$\Gamma(\pi\eta') \lesssim$ 20 MeV
$\Gamma(\pi\rho) \lesssim$ 12 MeV
$\Gamma(\pi b_1)$ ~ 140-530 MeV

JPAC/COMPASS
$M{\sim}1560,\ \Gamma{\sim}490$ MeV

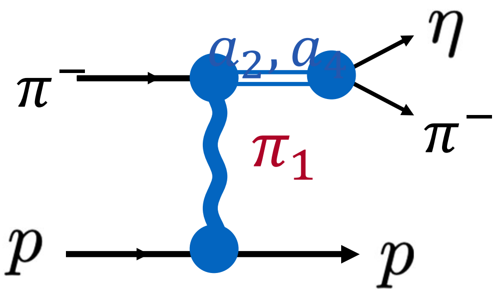
Kopf et al.
$M{\sim}1620, \Gamma{\sim}455$ MeV

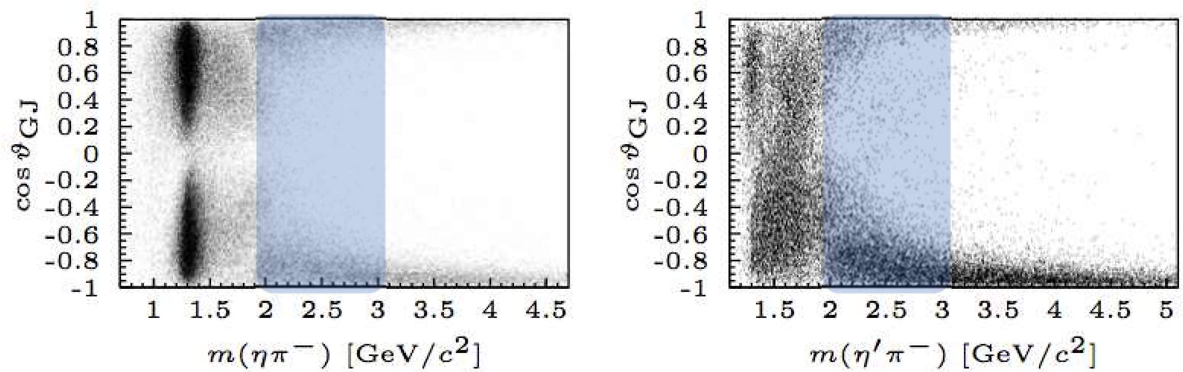
See Dudek's talk

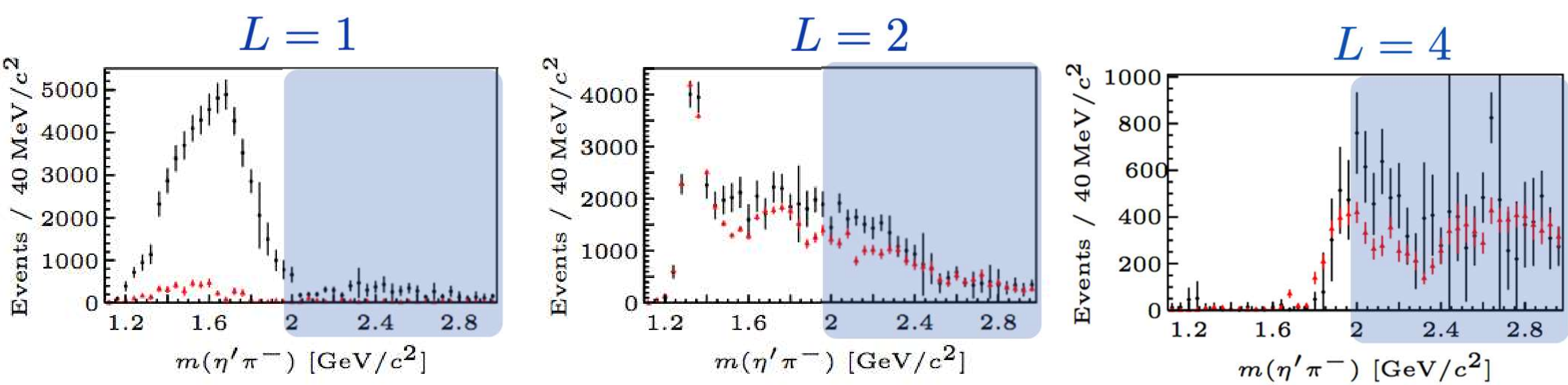
See Kopf's talk

Partial wave expansion

[C.Adolph, et all COMPASS, Phys.Lett.B 740 (2015) 303]





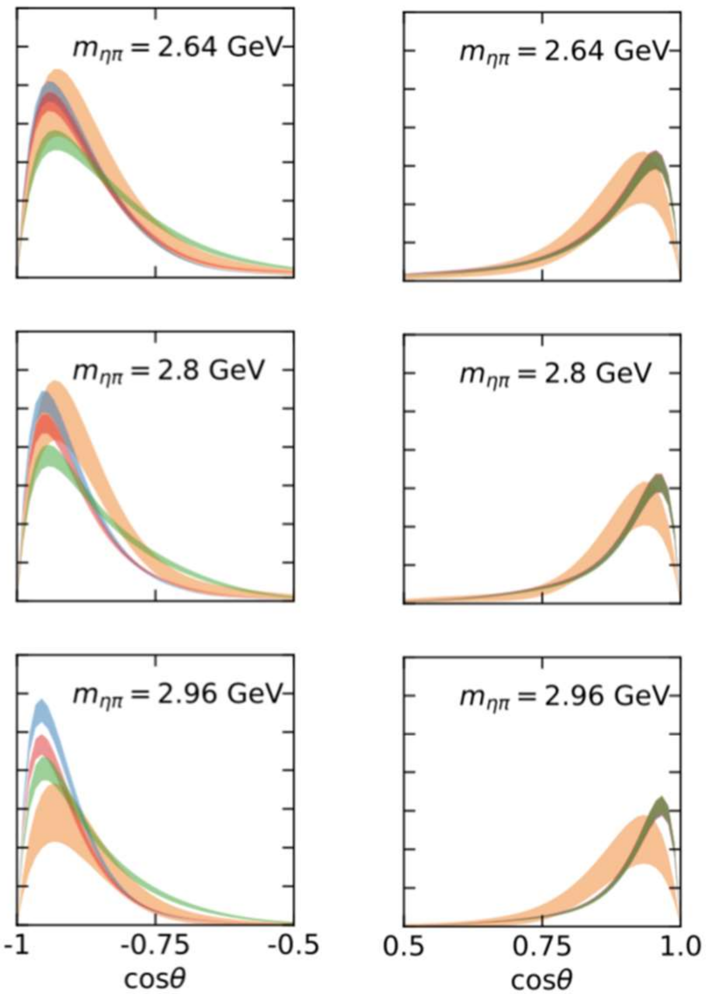


black: $\pi\eta'$ red: $\pi\eta$ (scaled)

Lead by Lukasz, Misha, Vincent & CFR

Fit results : $\eta\pi$

Bibrzycki et al. EPJC 81 (2021) 647



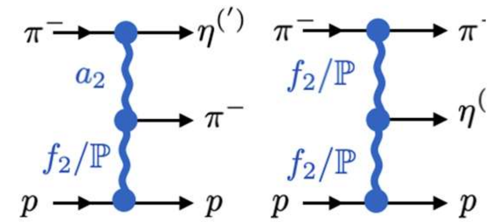
$(a_2,f_2+\mathbb{P})+(f_2,f_2)$

$(a_2,f_2+\mathbb{P})+(f_2,f_2+\mathbb{P})$

$(a_2,f_2+\mathbb{P})+(f_2,f_2)+(\mathbb{P},\mathbb{P})$

Data (reconstructed)

6 diagrams total



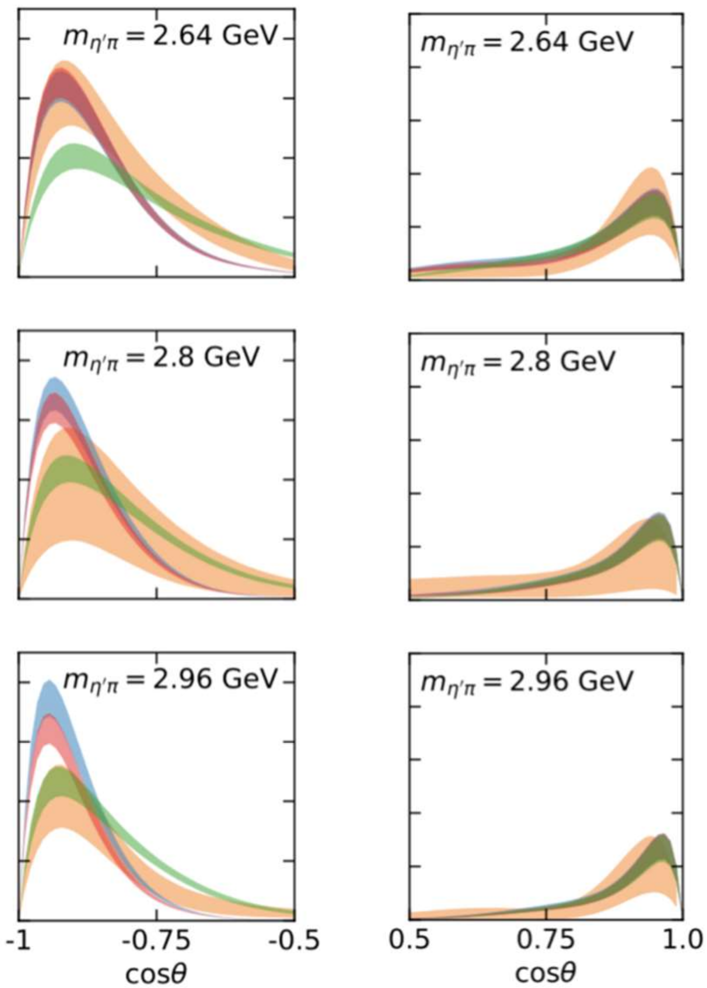
Forward intensity requires both (a_2,f_2) and $(a_2,\mathbb{P})$

Backward intensity requires (f_2,f_2) and either $(f_2,\mathbb{P})$ or $(\mathbb{P},\mathbb{P})$

$(a_2,\mathbb{P})$	0.40 ± 0.04
(a_2,f_2)	3.4 ± 0.4
$(f_2,\mathbb{P})$	$\cdot 0.30 \pm 0.05$
(f_2,f_2)	$\cdot 6.6 \pm 0.7$

Asymmetry from difference between (a_2,f_2) and (f_2,f_2)

Fit results : $\eta'\pi$



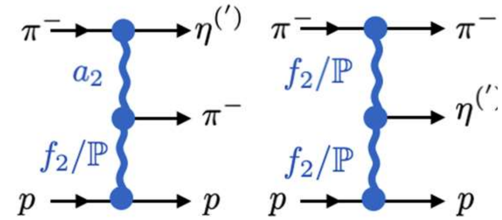
$(a_2, f_2 + \mathbb{P}) + (f_2, f_2)$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2 + \mathbb{P})$

$(a_2, f_2 + \mathbb{P}) + (f_2, f_2) + (\mathbb{P}, \mathbb{P})$

Data (reconstructed)

6 diagrams total



Forward intensity requires both (a_2, f_2) and $(a_2, \mathbb{P})$

Backward intensity requires (f_2, f_2) and $(\mathbb{P}, \mathbb{P})$

$(a_2, \mathbb{P})$	0.35 ± 0.05
(a_2, f_2)	0.6 ± 0.5
(f_2, f_2)	7.1 ± 0.6
$(\mathbb{P}, \mathbb{P})$	0.018 ± 0.002

Asymmetry coming from difference between

(a_2, f_2) and (f_2, f_2)

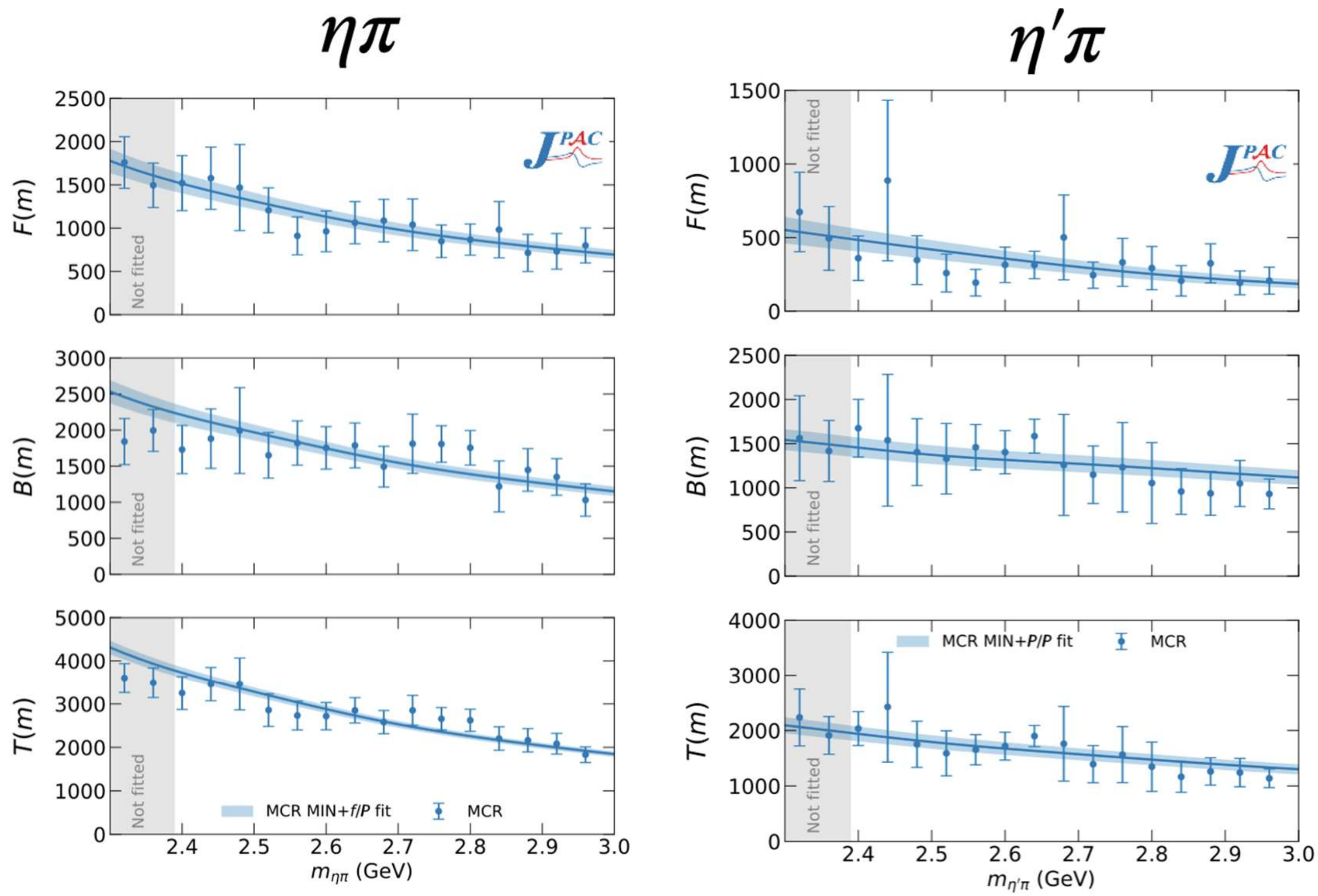
+ contribution from $(\mathbb{P}, \mathbb{P})$

Forward-backward intensities

Forward intensity

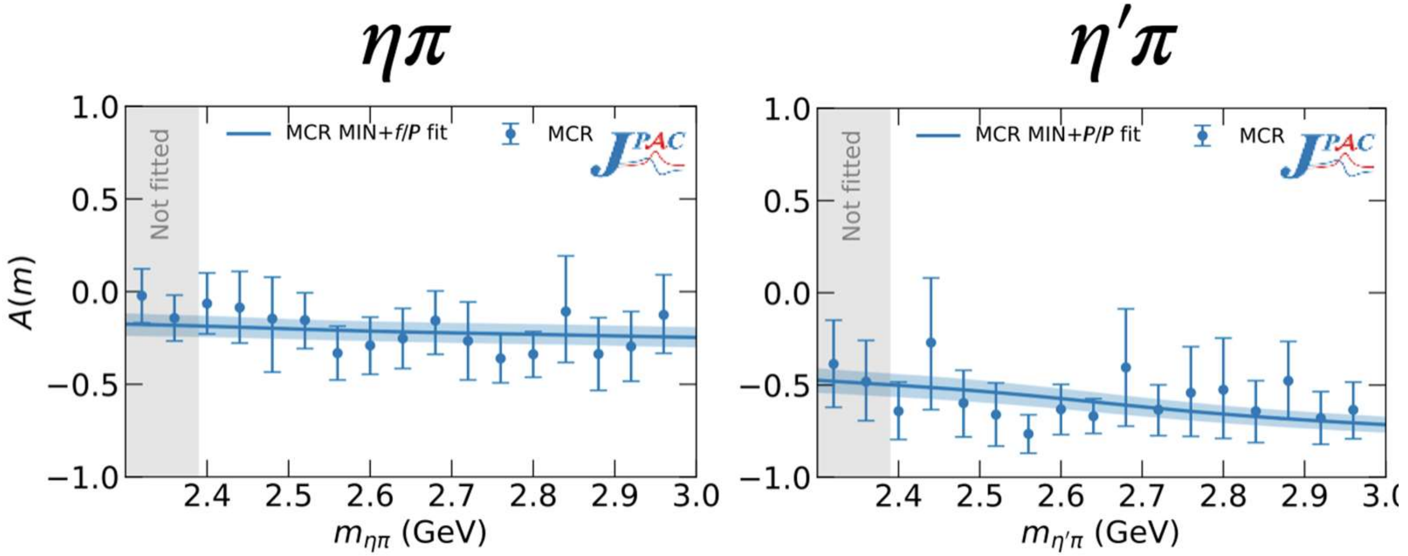
Backward intensity

Total intensity

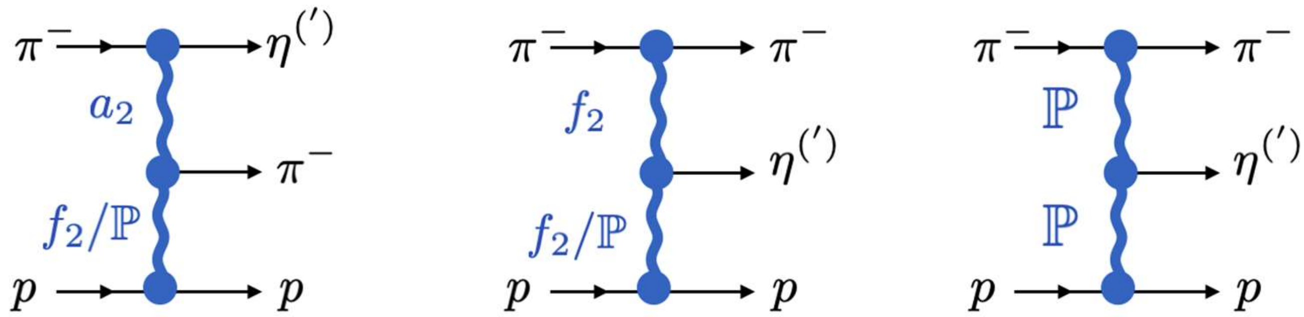


Forward-backward asymmetry

$$A = \frac{\text{Forward} - \text{Backward}}{\text{Forward} + \text{Backward}}$$

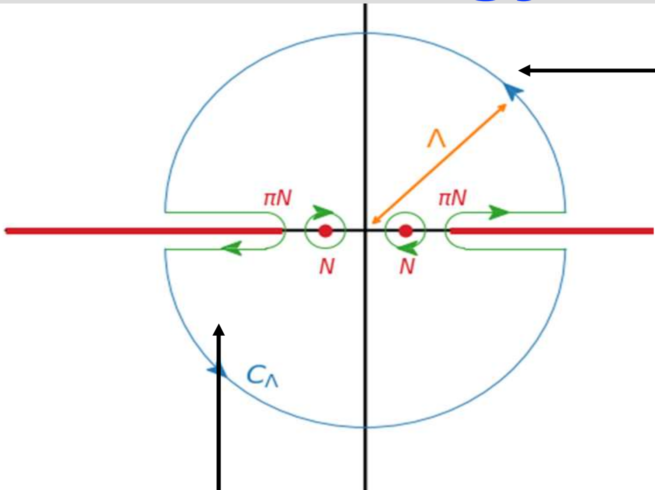


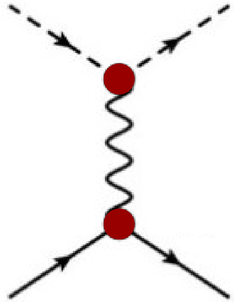
Asymmetry originating mainly from $(a_2, f_2/\mathbb{P}) \neq (f_2, f_2/\mathbb{P})$ and from $(\mathbb{P}, \mathbb{P})$ in $\eta'\pi$

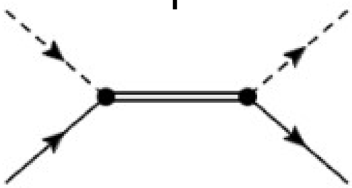


Finite Energy Sum Rules

[V. Mathieu, J.Nys. *et al.* (JPAC) 1708.07779 (2017)]



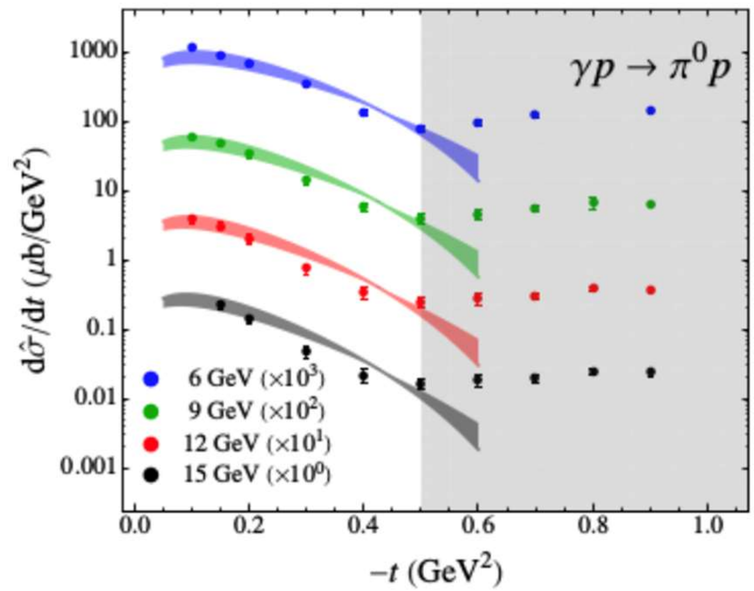


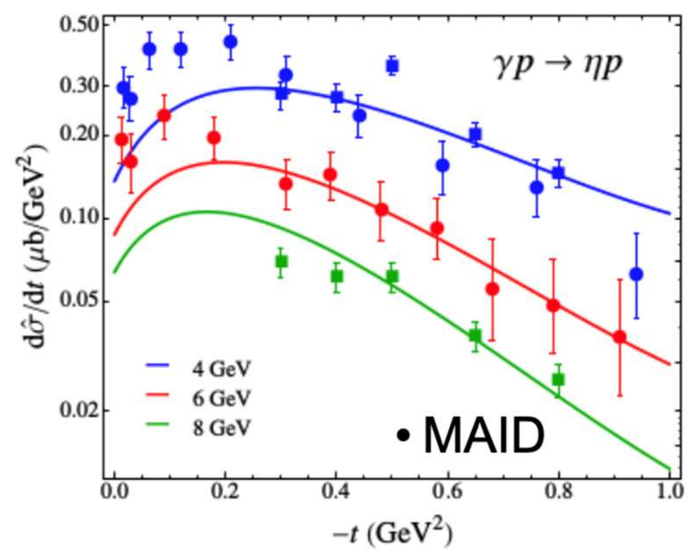


- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

$$A_{\lambda';\lambda\lambda_\gamma}(s,t) = \overline{u}_{\lambda'}(p')\left(\sum_{k=1}^{4} A_k(s,t)M_k\right)u_\lambda(p)$$

$$\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu = \beta_i(t)\frac{\Lambda^{\alpha(t)+k}}{\alpha(t)+k}$$





Summary

- Existence of exotic hadrons (hybrids in particular) are a consequence of gluon dynamics.
- Forward-backward asymmetry in eta-pi and eta'-pi is evidence of exotics
- Regge physics needed to extract exotic multiplet
- FESR constraints

- The XYZ phenomena are yet to be understood. There may be molecules or compact tera-, penta- quark states
- Their photo- and electro-production can provide insight (EIC & Jlab++)

- Poles for scalars and tensor states from radiative J/Ψ decay determined
- Nature?