Light and Heavy Hybrids

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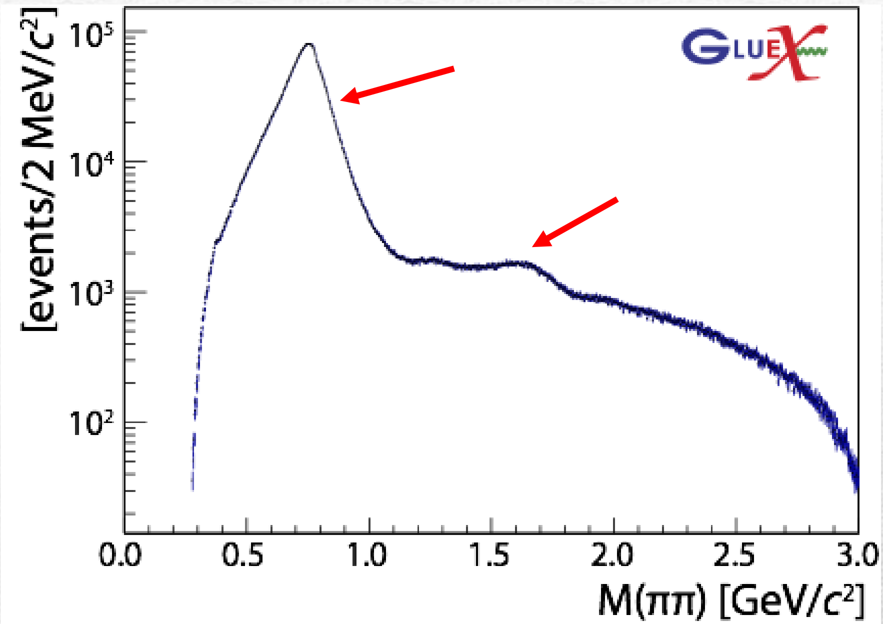
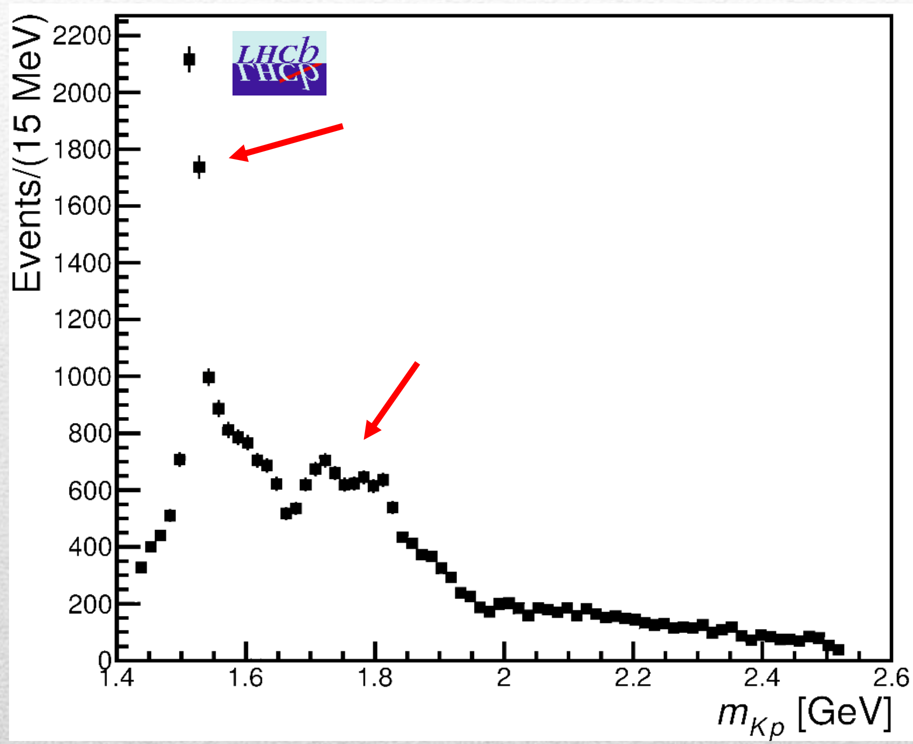
Spectroscopy at EIC, December 19th, 2018

ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

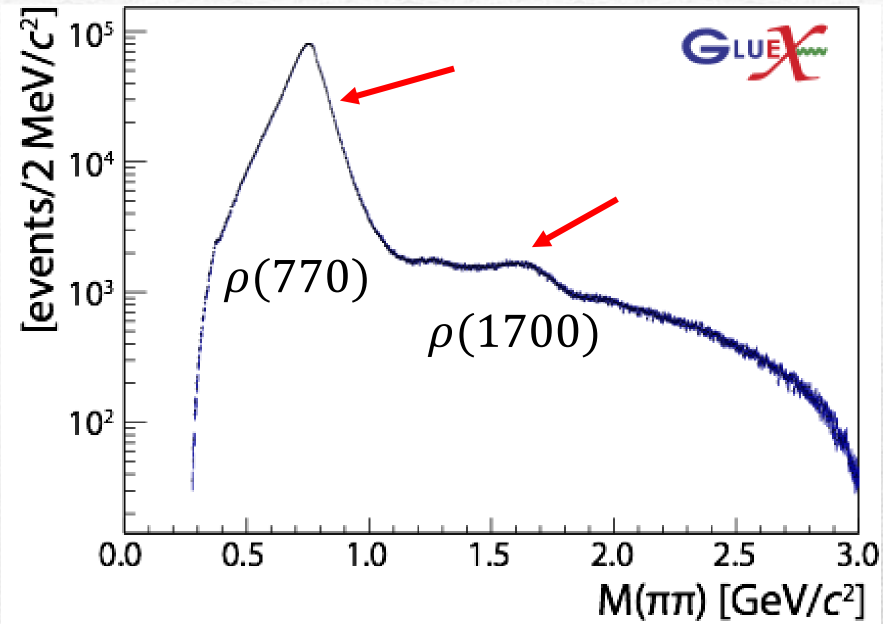
From data to the spectrum

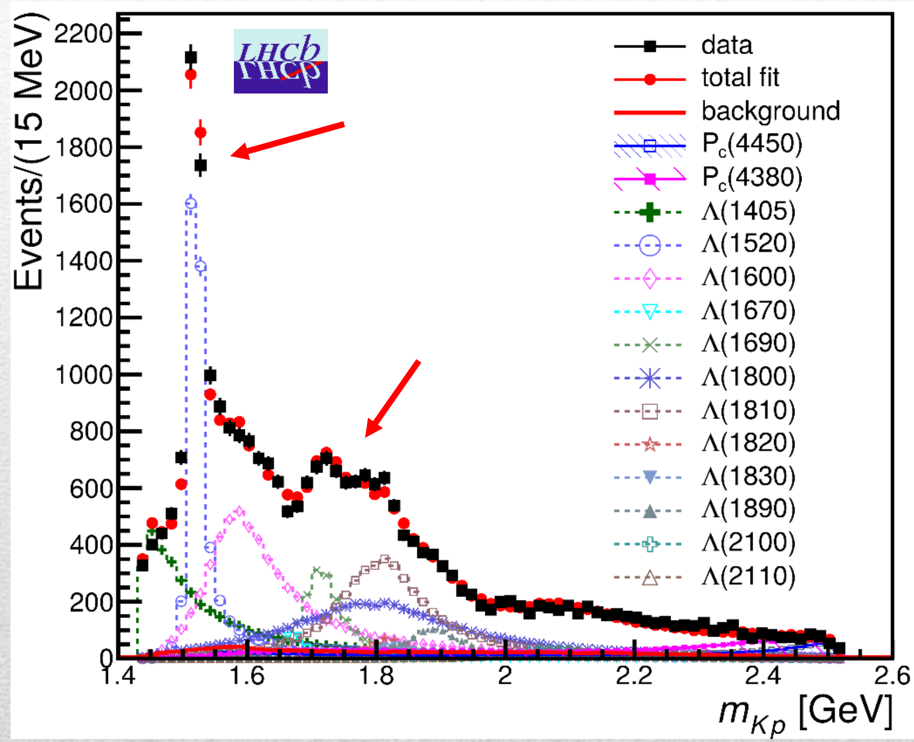




The connection between data and resonances is not straightforward
Using unconstrained functions, one risks to get random results

From data to the spectrum





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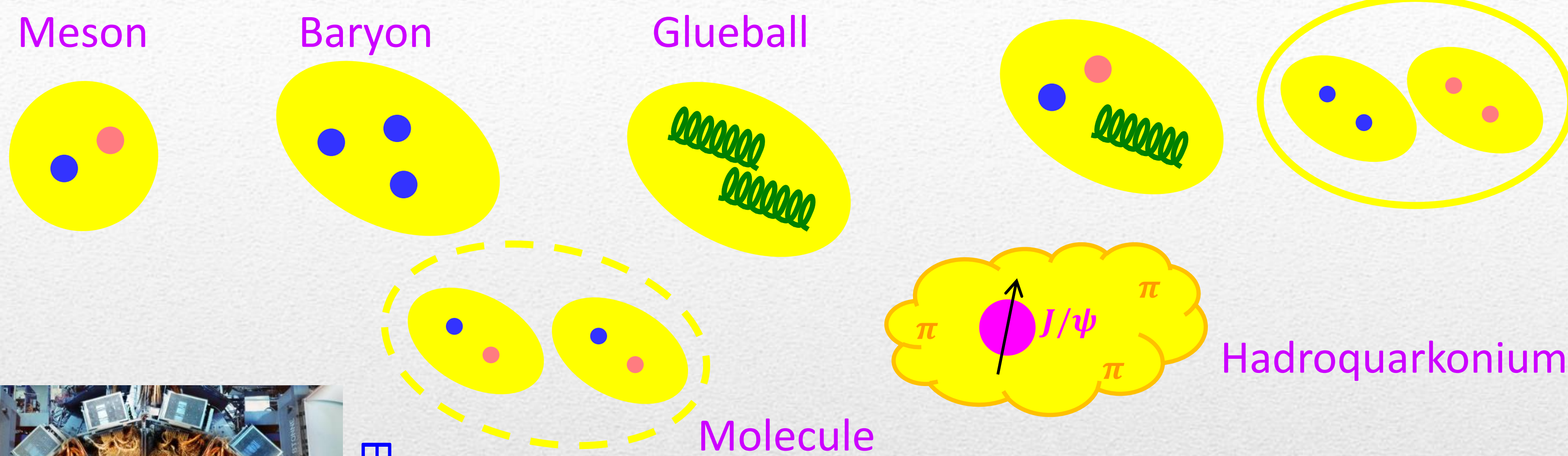
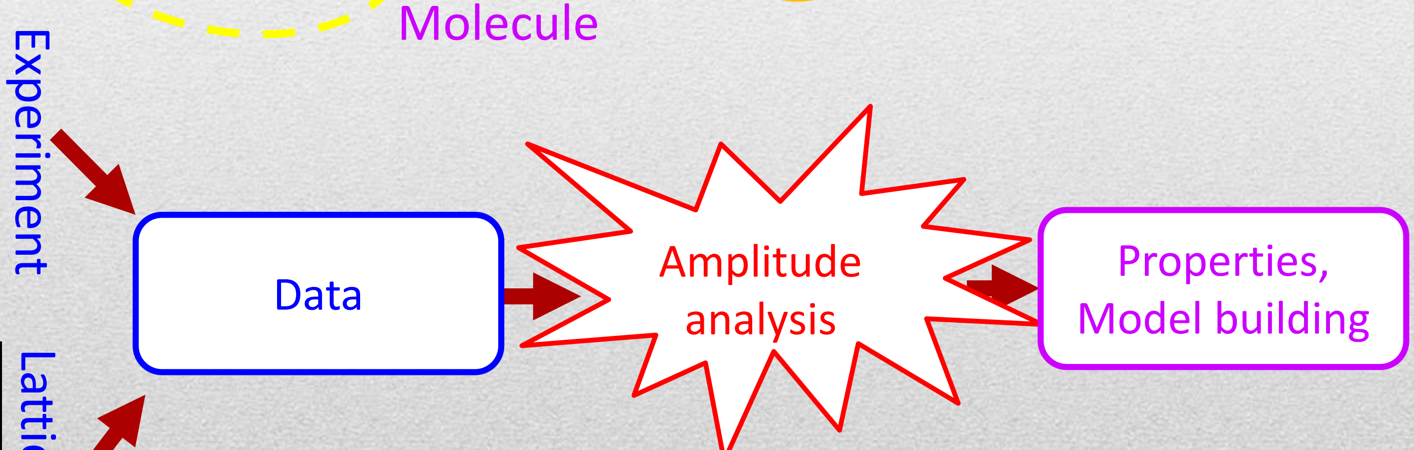
Using unconstrained functions, one risks to get random results

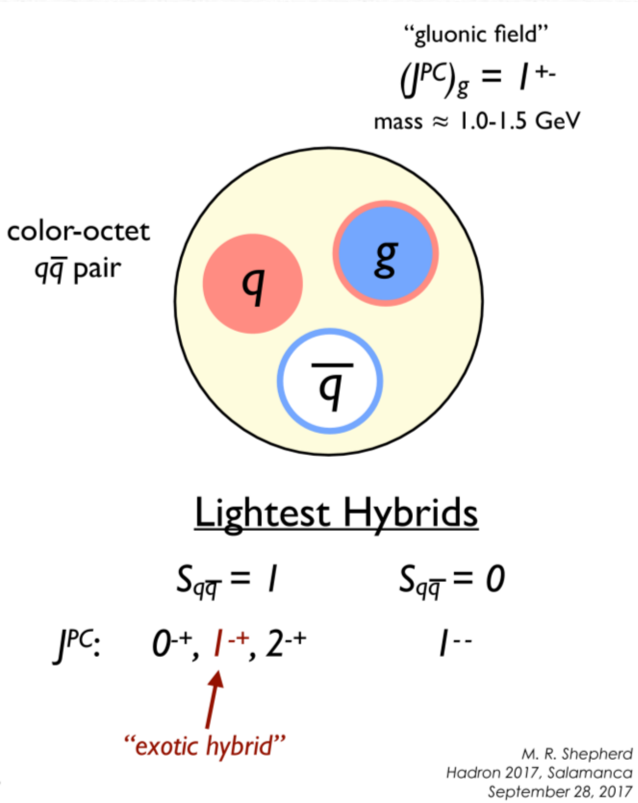
Hadron Spectroscopy



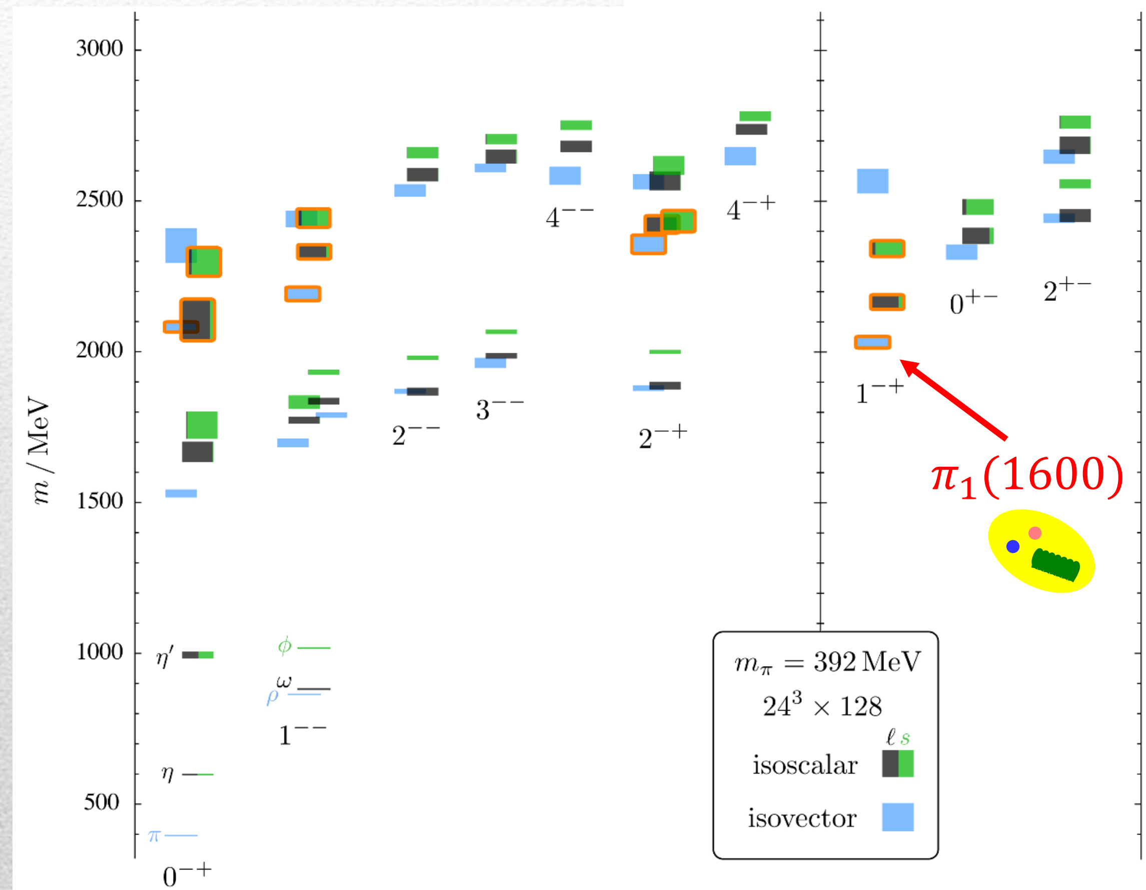


Interpretations on the spectrum leads to understanding fundamental laws of nature

Hybrids hunting



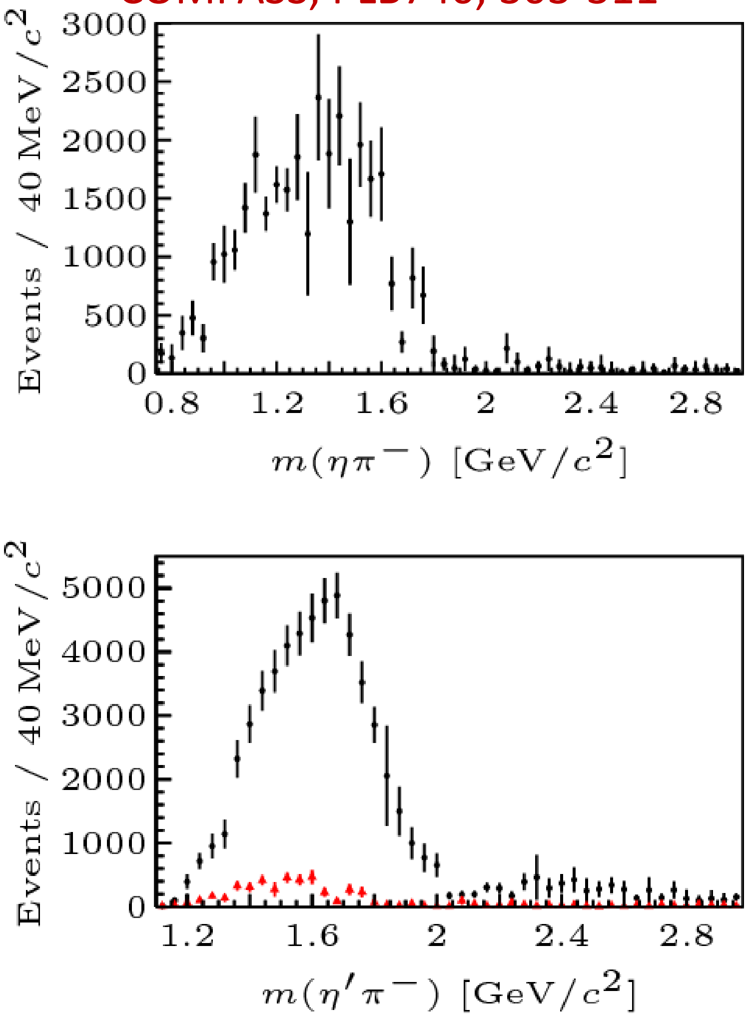
HadSpec PRD88, 094505



Supermultiplet expected
in Bag models and Coulomb gauge
constituent models

Two light 1^{-+} hybrid states?

COMPASS, PLB740, 303-311



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

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

Decay Modes

Mode		Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^0$	seen
Γ_2	$\eta\pi^-$	seen
Γ_3	$\eta'\pi$	

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

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

Decay Modes

Mode		Fraction (Γ_i/Γ)
Γ_1	$\pi\pi\pi$	seen
Γ_2	$\rho^0\pi^-$	seen
Γ_3	$f_2(1270)\pi^-$	not seen
Γ_4	$b_1(1235)\pi$	seen
Γ_5	$\eta'(958)\pi^-$	seen
Γ_6	$f_1(1285)\pi$	seen

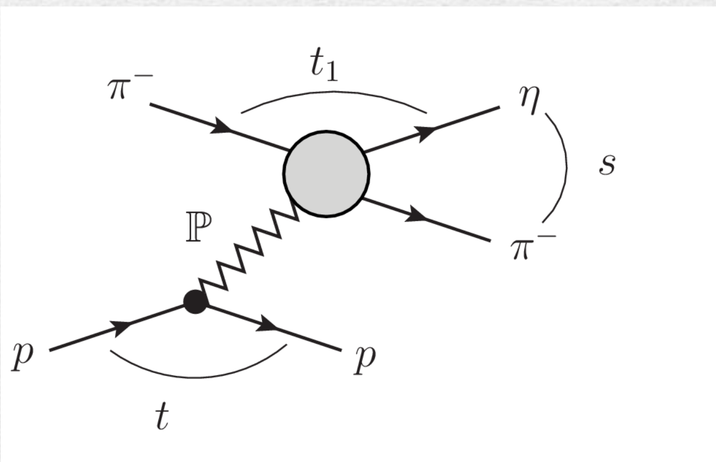
Amplitudes for $\eta^{(\prime)}\pi$

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

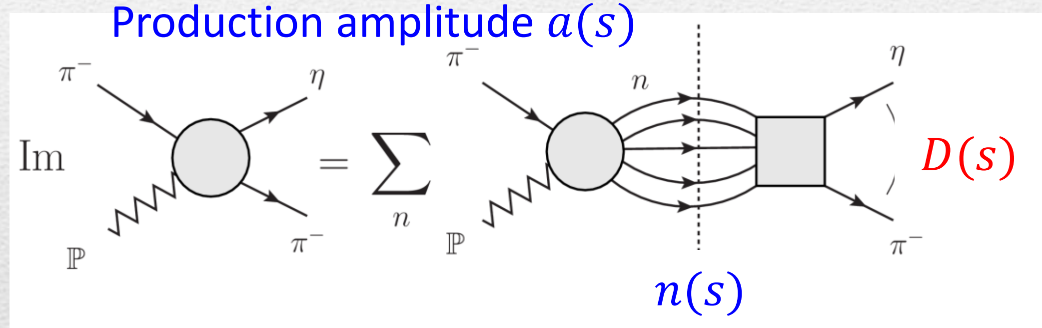
A. Jackura, M. Mikhasenko, AP *et al.* (JPAC & COMPASS), PLB779, 464-472

A. Rodas, AP *et al.* (JPAC), 1810.04171

At COMPASS kinematics,
Pomeron is the dominant exchange



Production amplitude $a(s)$



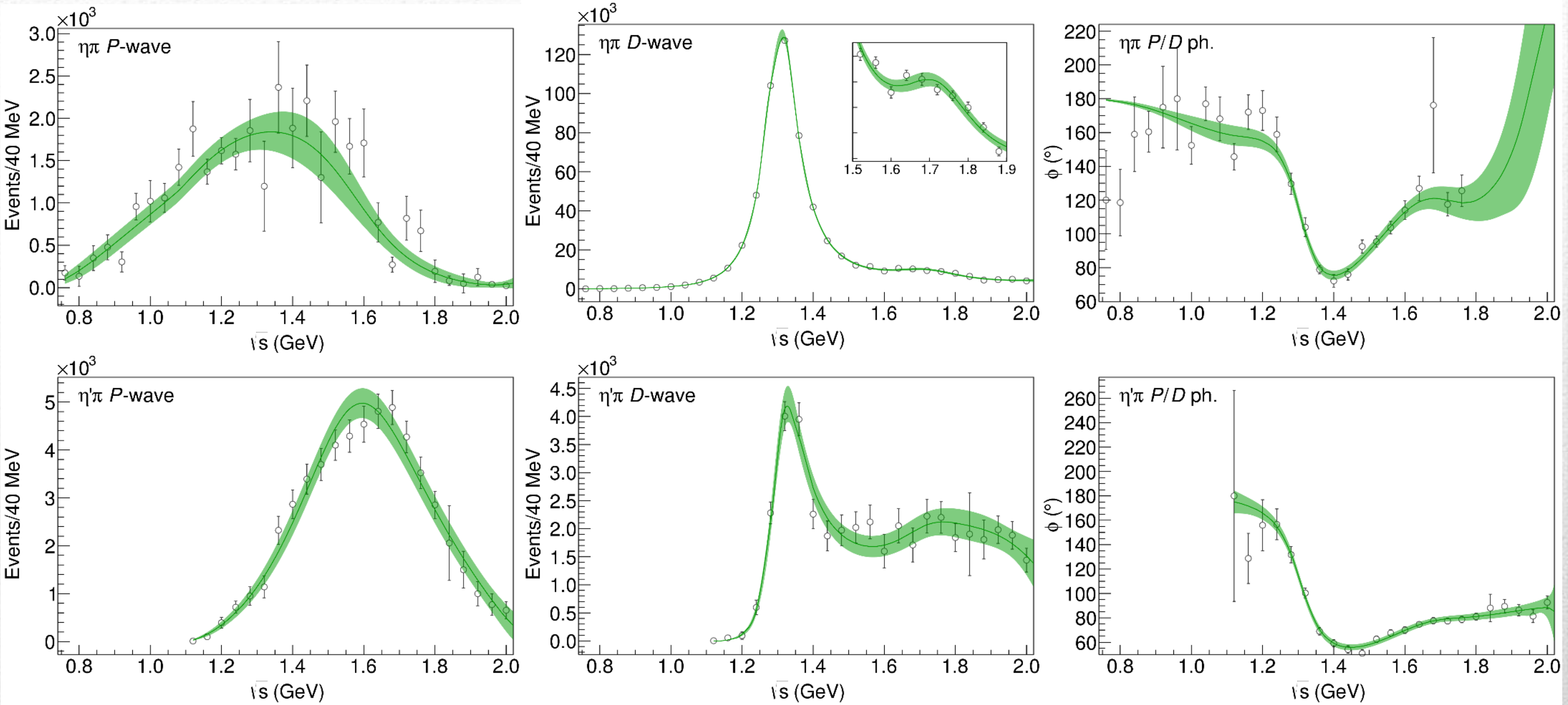
$$a(s) = \frac{n(s)}{D(s)}$$

The $D(s)$ has only right hand cuts;
it contains all the Final State Interactions
constrained by unitarity → universal

The $n(s), N(s)$ have left hand cuts only,
they depend on the exchanges →
process-dependent, smooth

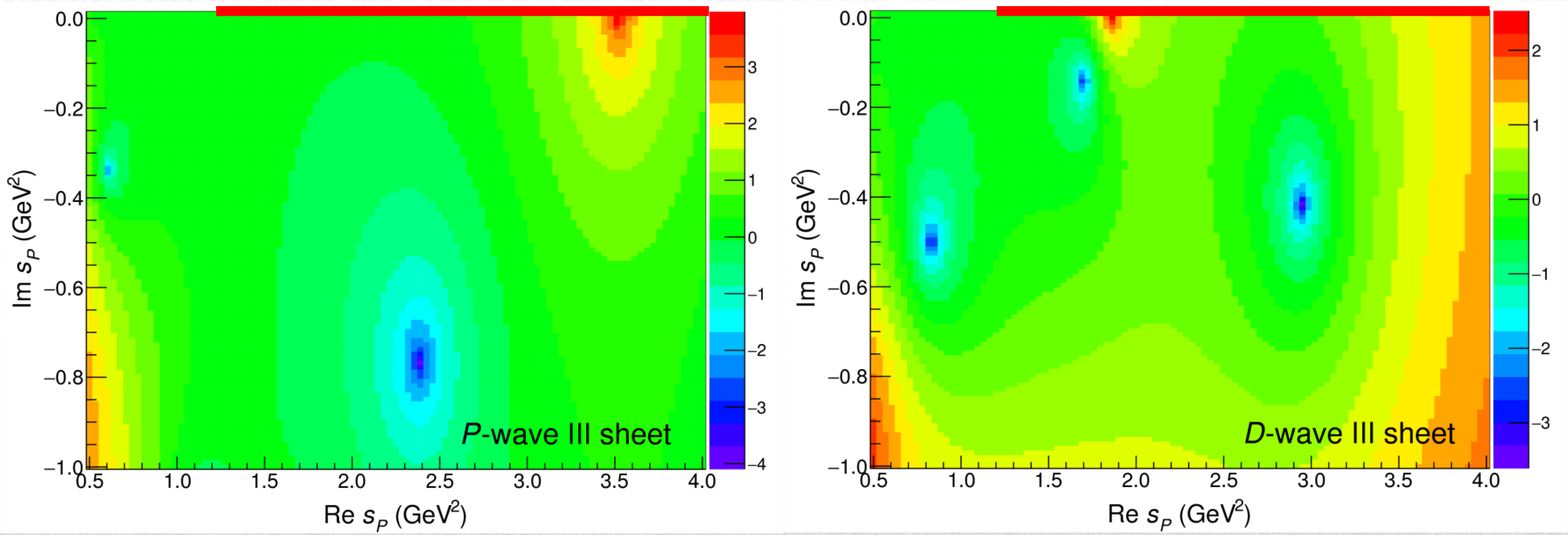
Fit to P- and D-wave

A. Rodas, AP *et al.* (JPAC), 1810.04171



$\chi^2/\mathrm{dof} \sim 1.3$, statistical error estimated via 50k bootstraps

Complex plane

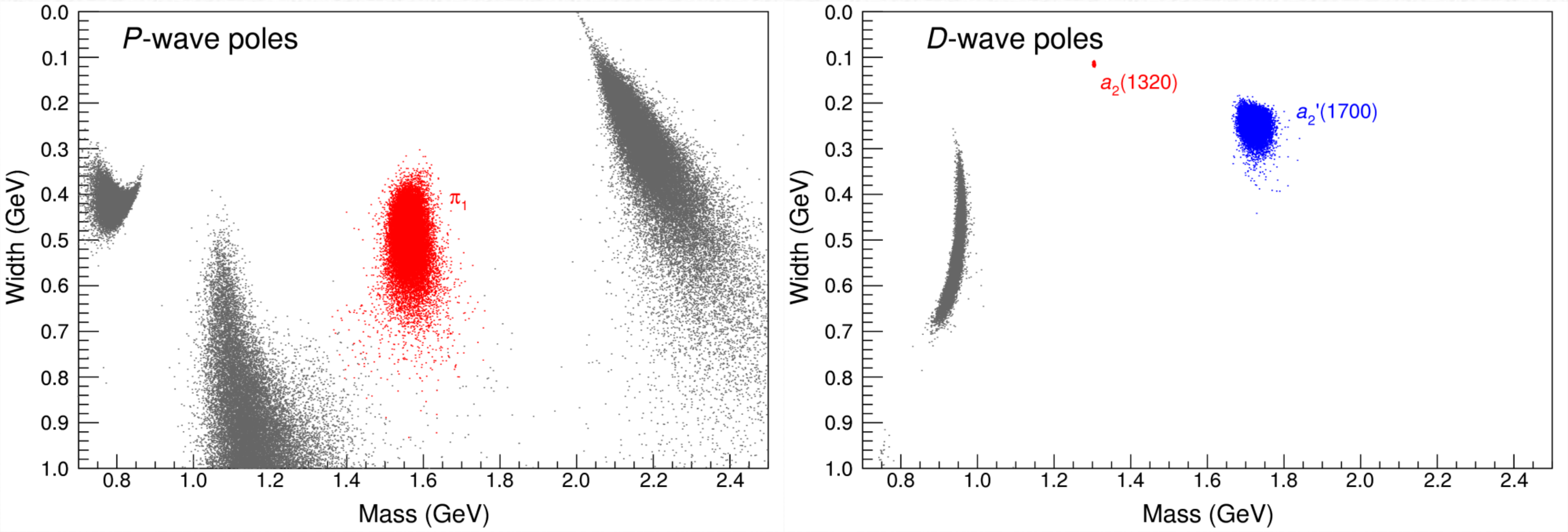


For the best fit solution, we look at the closest Riemann sheet in the complex plane
We see a limited amount of poles in the relevant region

We also see some close-to-threshold poles, which are artifacts of the model for $N(s)$

How to distinguish the two?

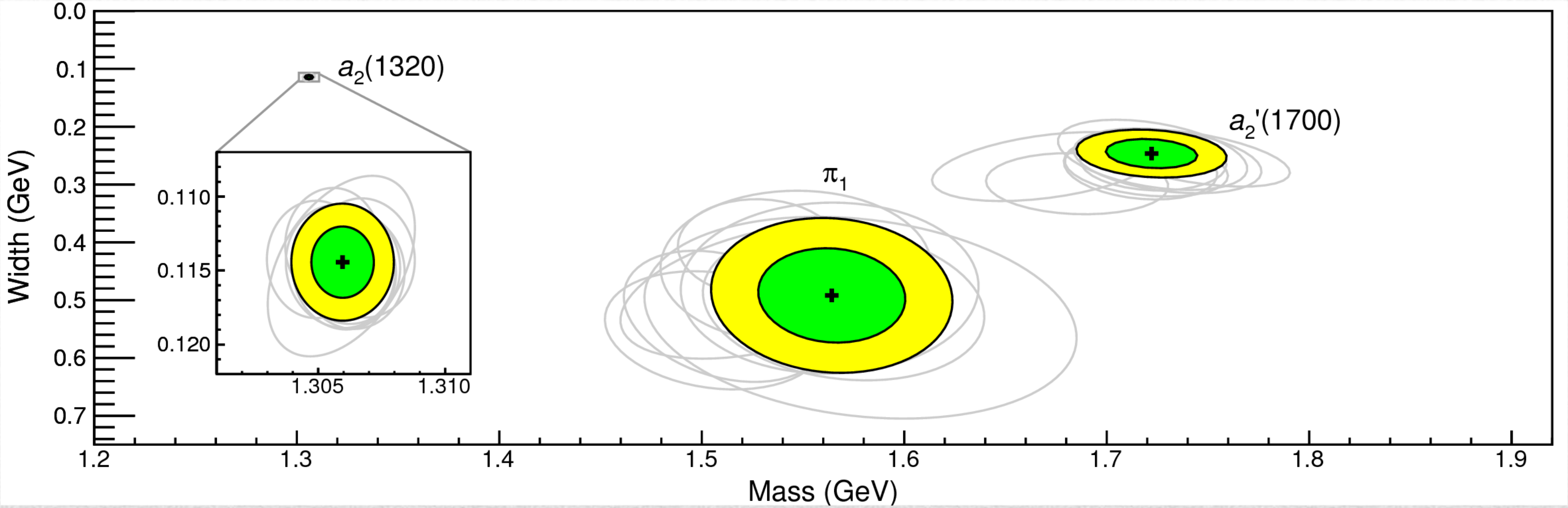
Bootstrap



We can identify the poles in the region $m \in [1.2, 2]$ GeV, $\Gamma \in [0, 1]$ GeV

Two stable isolated poles are indentifiable in the *D*-wave
Only one is stable in the *P*-wave

Final results

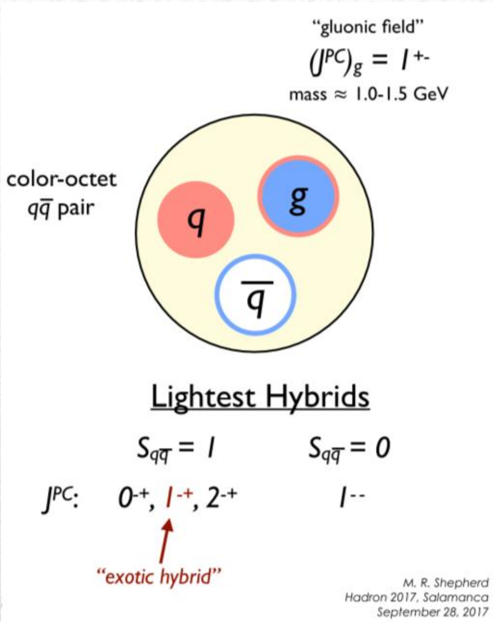


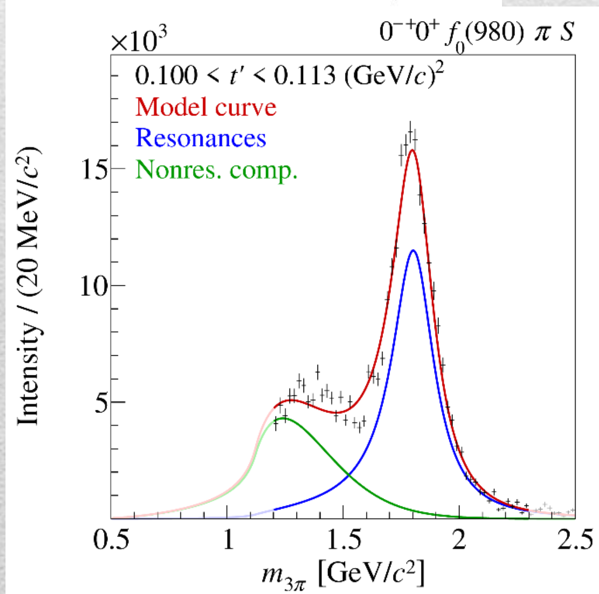
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

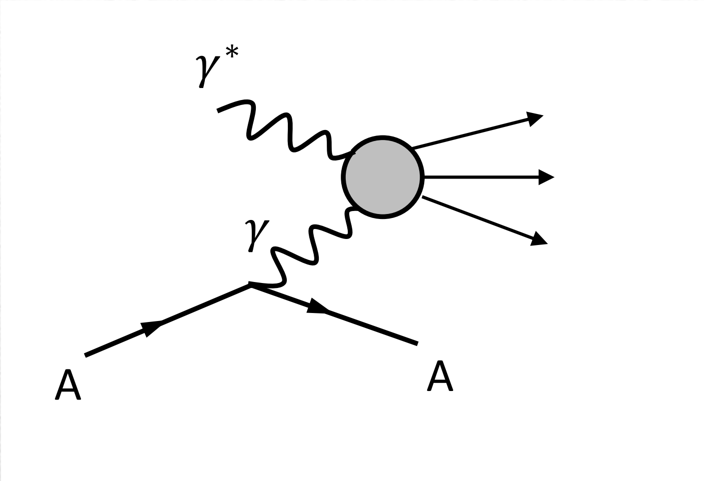
We reconciled the theory expectations with the experimental data

This is the most robust extraction of exotic resonance to date

Search for 0^{-+} and 2^{-+}





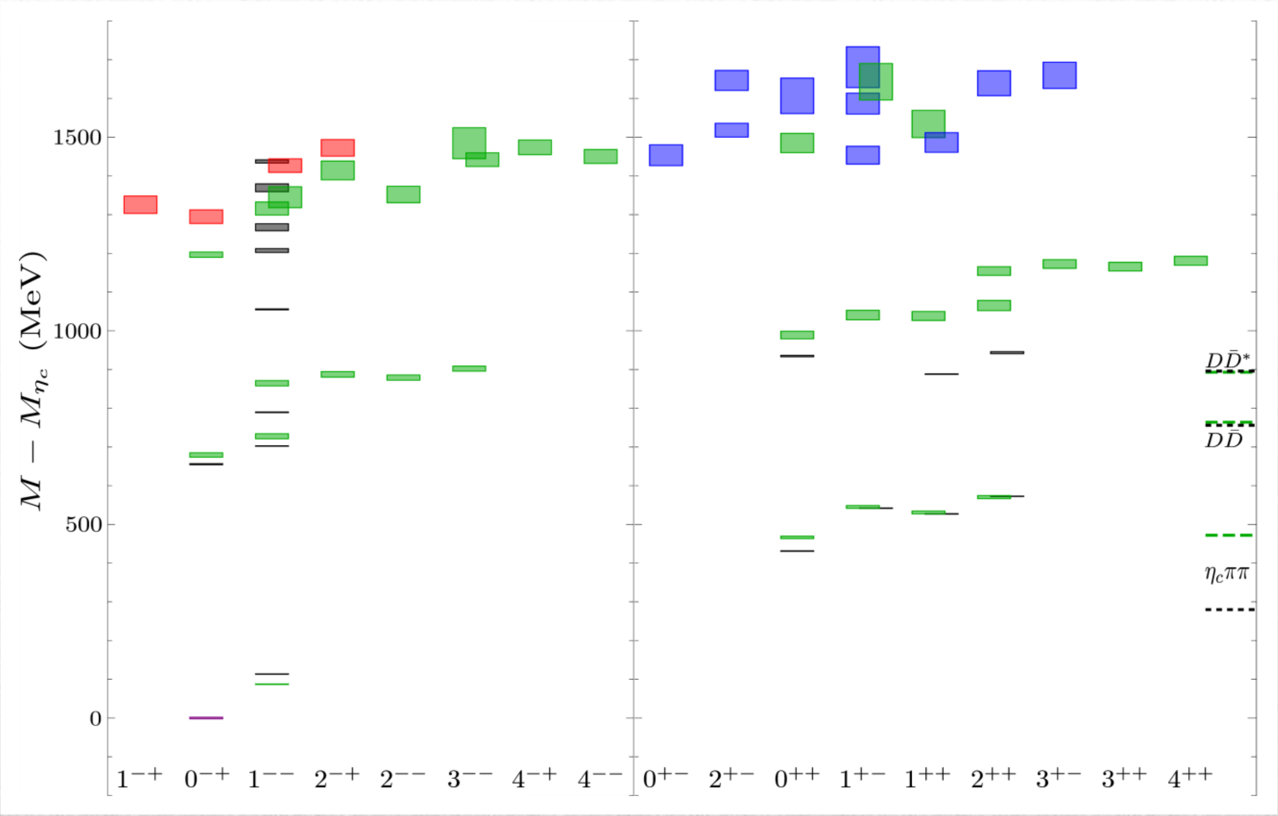


For example, photon collision available at EIC, $C = +$ states available

Complementary to pion + Pomeron at COMPASS

Access to Q^2 dependence, hints on the nature

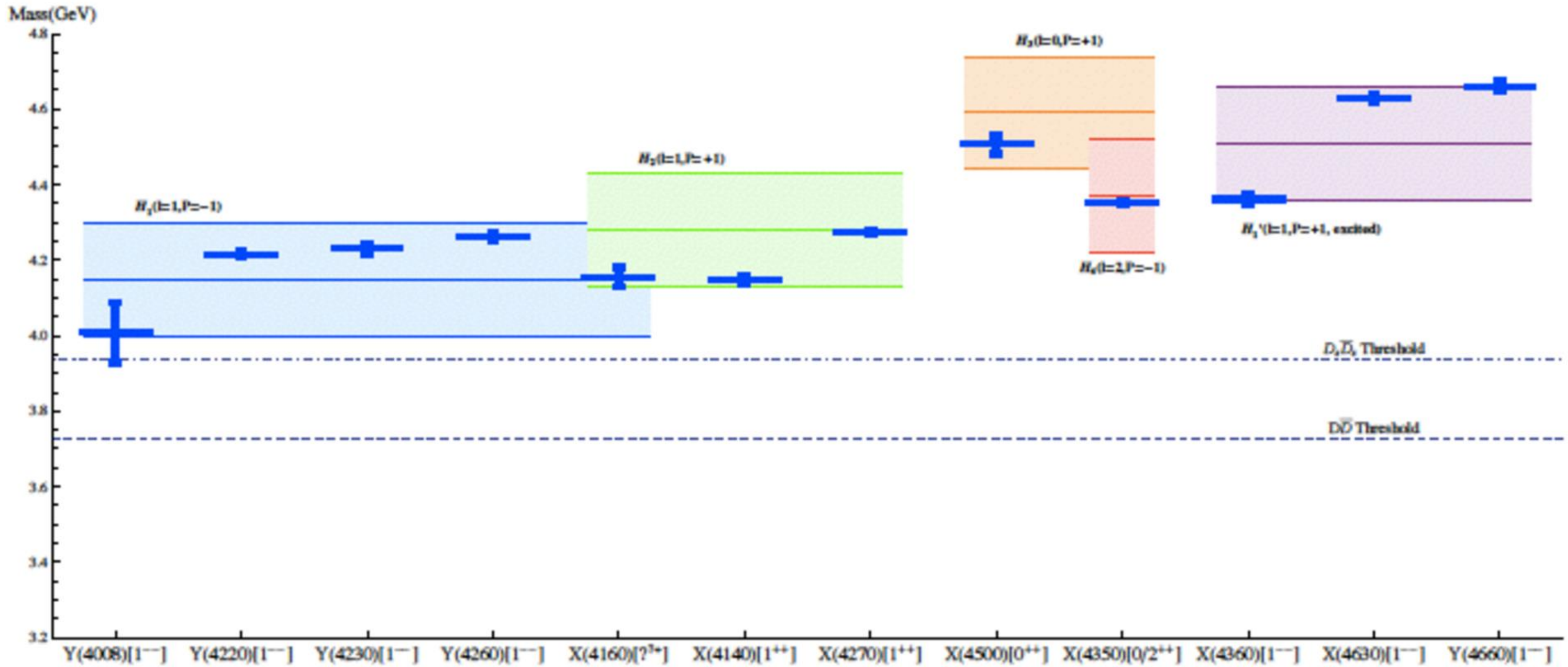
Heavy hybrids



HadSpec, JHEP 1612 (2016), 089
P. Guo *et al.*, PRD78 (2008), 056003
M. Berwein *et al.*, PRD92 (2015), 114019

Charmonium Hybrid spectrum for $\kappa = 1^{+-}$

M. Berwein, N. Brambilla, JTC, A. Vairo. Phys.Rev.D92 (2015)

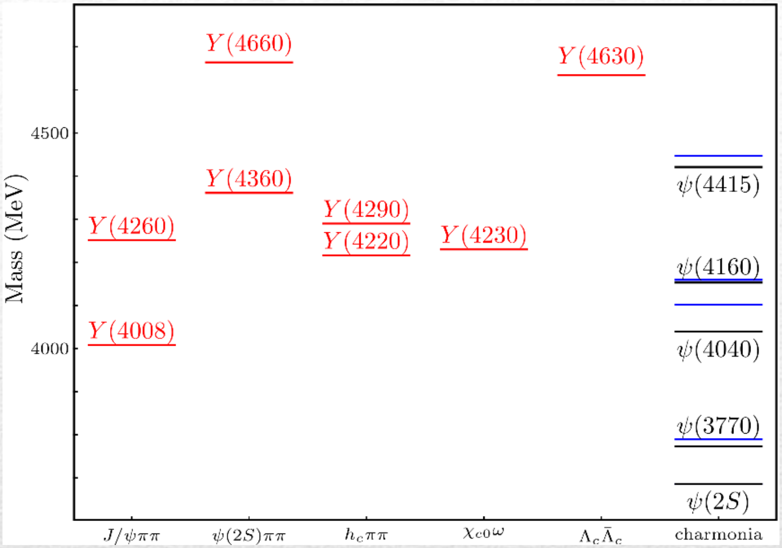


1. Solid blue bars: Neutral exotic charmonium states (Belle, CDF, BESIII, Babar, LHCb).
2. Bands: Predicted masses for hybrid spin-symmetry multiplets $\pm$ uncertainty of $\Lambda_{1^{+-}}$.

- Spin-symmetry multiplets

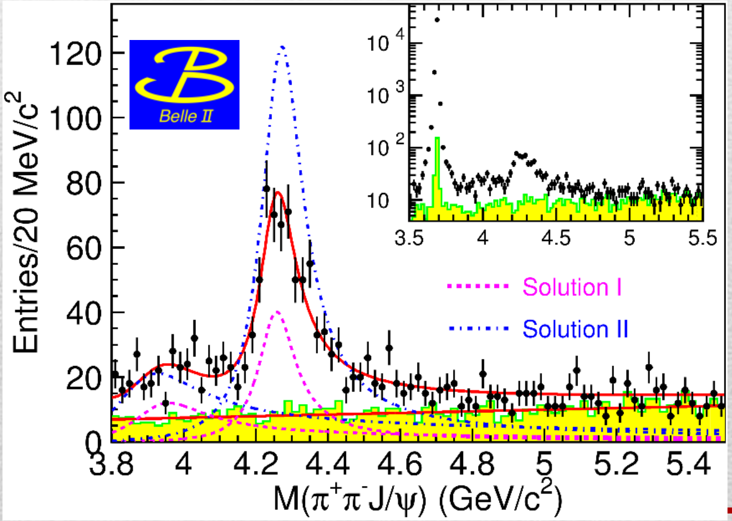
	l	J^{PC}	
H_1	1	$\{1^{--}, (0,1,2)^{-+}\}$	Σ_u^-, Π_u
H_2	1	$\{1^{++}, (0,1,2)^{+-}\}$	Π_u
H_3	0	$\{0^{++}, 1^{+-}\}$	Σ_u^-
H_4	2	$\{2^{++}, (1,2,3)^{+-}\}$	Σ_u^-, Π_u

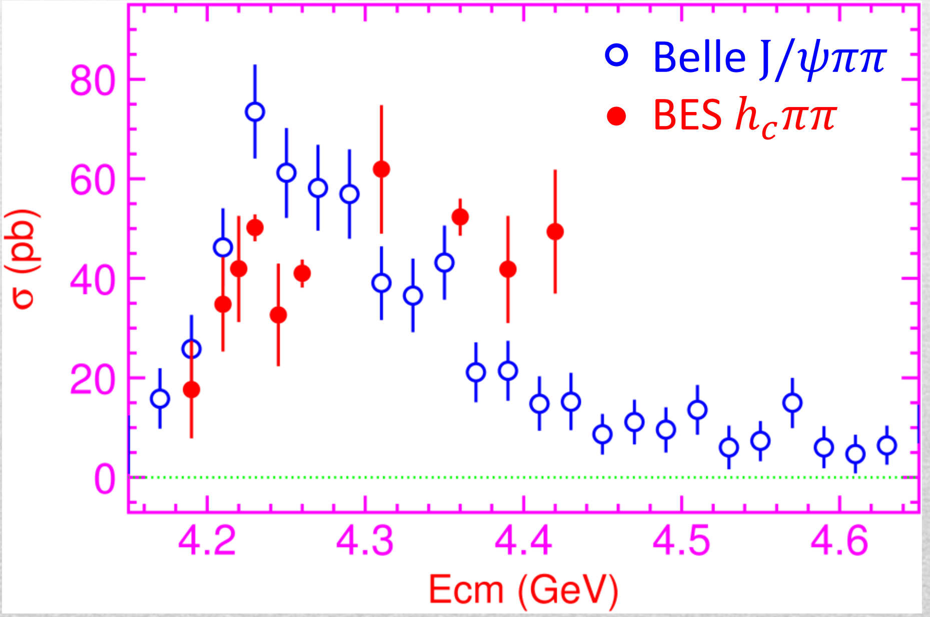
Vector Y states



Lots of unexpected $J^{PC} = 1^{--}$ states
found in ISR/direct production (and nowhere else!)
Seen in few final states,
mostly $J/\psi\ \pi\pi$ and $\psi(2S)\ \pi\pi$

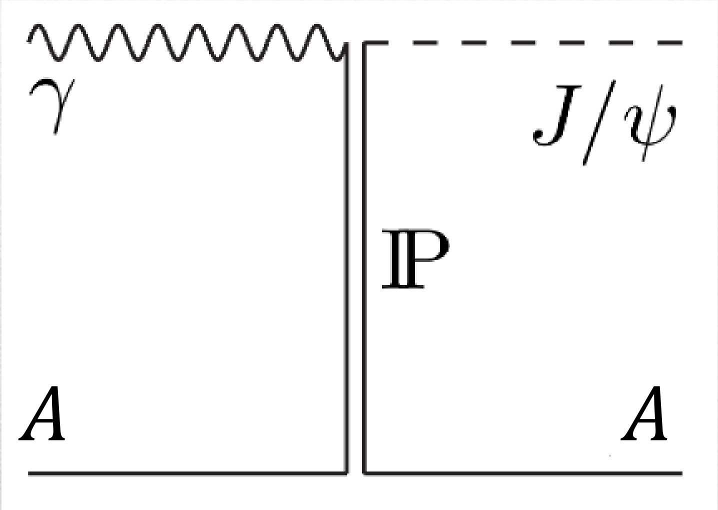
Not seen decaying into open charm pairs (...?)
Large HQSS violation

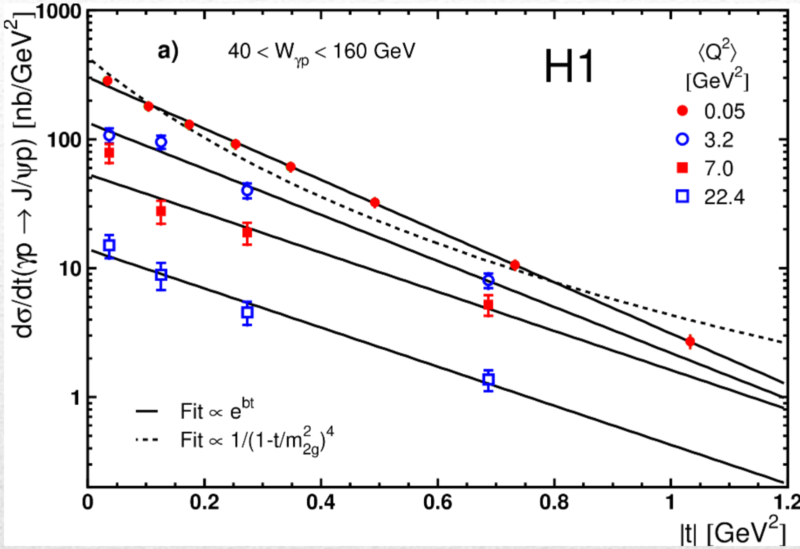




Search for vectors

Vector meson photoproduction is well known, e.g. at HERA
Same mechanism to be applied for Υ states too





Hybrid production cross section can be estimated using NRQCD + some modeling:
- G. Chiladze *et al.*, PRD58 (1998), 034013 for *B* decays
- No calculation available yet for prompt production

BACKUP

Hadron Spectroscopy

$\rho(770)$ $I^G(J^{PC}) = 1^+(1^{--})$

Review: The $\rho(770)$

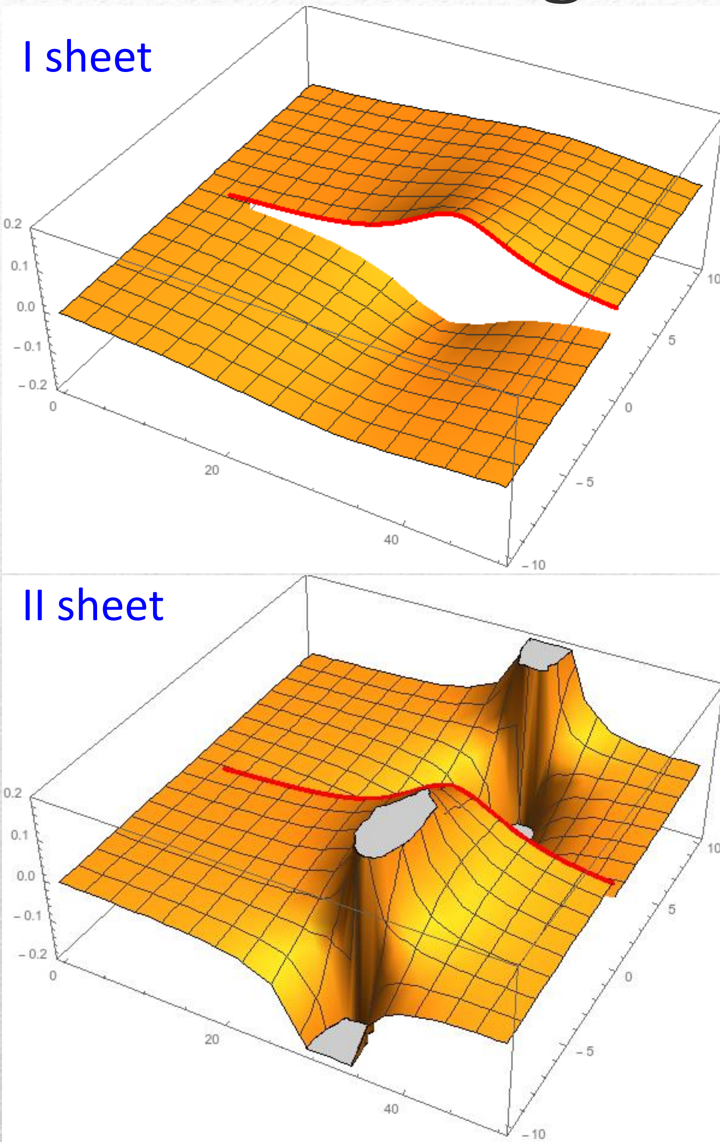
$\rho(770)$ MASS

NEUTRAL ONLY, e^+e^-	775.26 ± 0.25 MeV
CHARGED ONLY, τ DECAYS and e^+e^-	775.11 ± 0.34 MeV
MIXED CHARGES, OTHER REACTIONS	763.0 ± 1.2 MeV
Mass m	
CHARGED ONLY, HADROPRODUCED	766.5 ± 1.1 MeV
NEUTRAL ONLY, PHOTOPRODUCED	769.0 ± 1.0 MeV
NEUTRAL ONLY, OTHER REACTIONS	769.0 ± 0.9 MeV (S = 1.4)
$m_{\rho(770)^0} - m_{\rho(770)^\pm}$	-0.7 ± 0.8 MeV (S = 1.5)
$m_{\rho(770)^+} - m_{\rho(770)^-}$	
$\rho(770)$ RANGE PARAMETER	$5.3^{+0.9}_{-0.7}$ GeV^{-1}

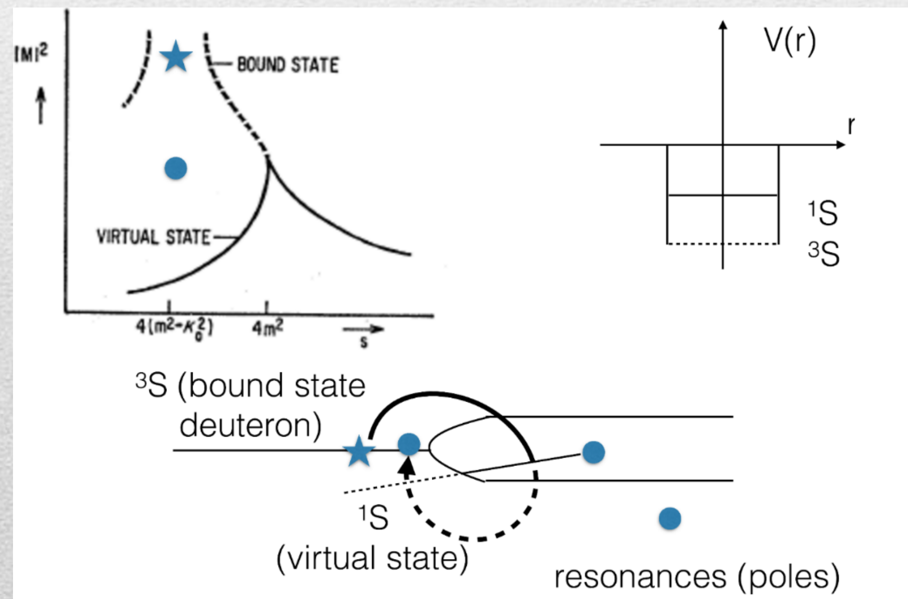
$\rho(770)$ WIDTH

NEUTRAL ONLY, e^+e^-	147.8 ± 0.9 MeV (S = 2.0)
CHARGED ONLY, τ DECAYS and e^+e^-	149.1 ± 0.8 MeV
MIXED CHARGES, OTHER REACTIONS	149.5 ± 1.3 MeV
CHARGED ONLY, HADROPRODUCED	150.2 ± 2.4 MeV
NEUTRAL ONLY, PHOTOPRODUCED	151.7 ± 2.6 MeV
NEUTRAL ONLY, OTHER REACTIONS	150.9 ± 1.7 MeV (S = 1.1)
$\Gamma_{\rho(770)^0} - \Gamma_{\rho(770)^\pm}$	0.3 ± 1.3 (S = 1.4)
$\Gamma_{\rho(770)^+} - \Gamma_{\rho(770)^-}$	1.8 ± 2.1

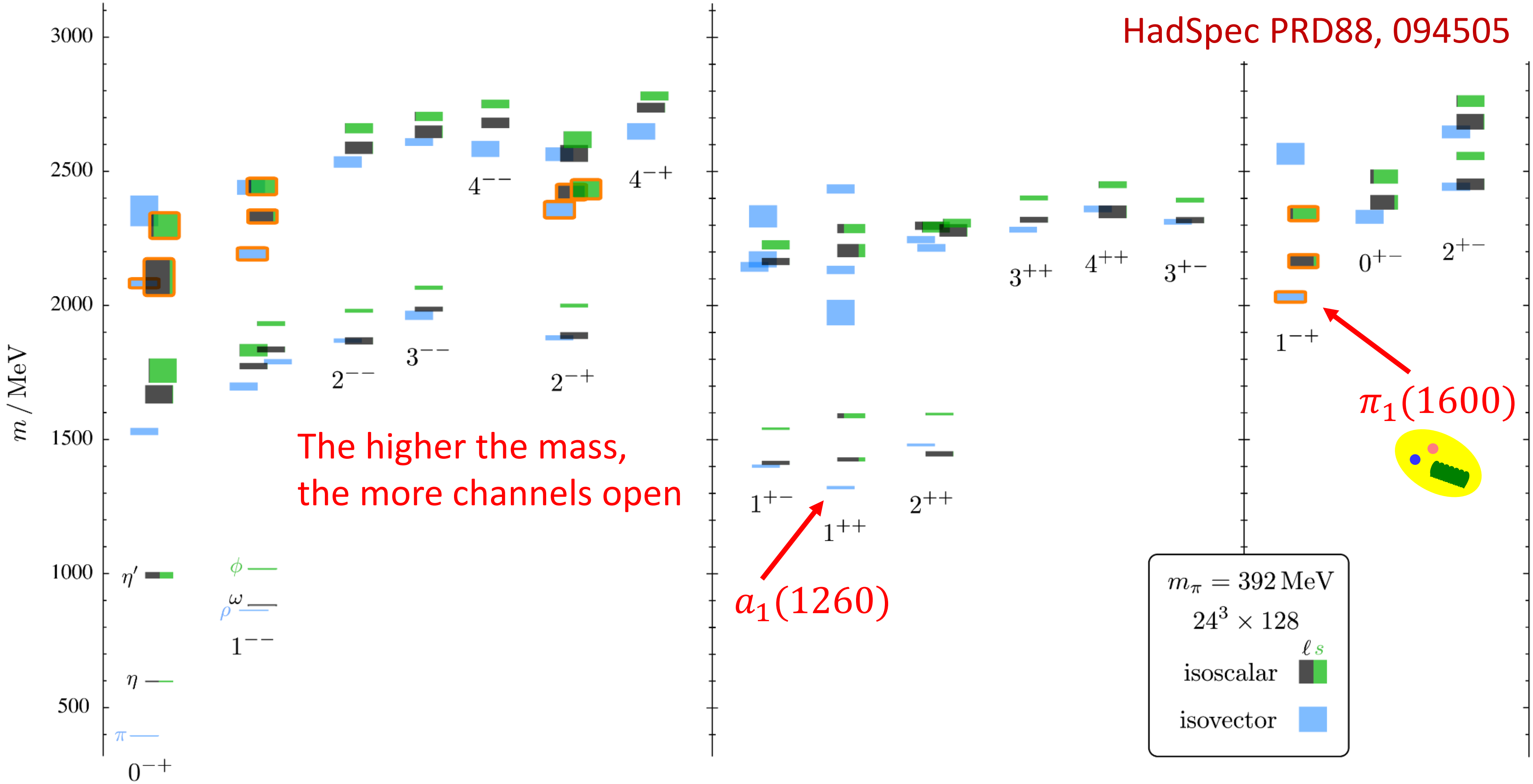
Pole hunting



Bound states on the real axis 1st sheet
Not-so-bound (virtual) states on the real axis 2nd sheet

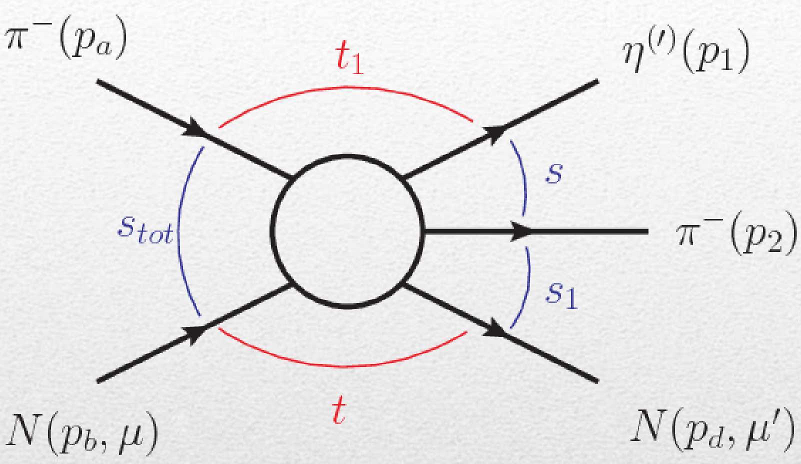


Light spectrum (1-particle correlators)



Formalism

- Process is at fixed s_{tot}, and integrated t. Interested in resonances in s
- Recoil proton kinematically decouples from final state $\eta\pi$



- Expand amplitude into partial waves

$$A_{\mu'\mu}(s_{tot}, s, t, s_1, t_1) = \sum_{LM\epsilon} a^{\epsilon}_{LM,\mu'\mu}(s_{tot}, t, s) Y^{\epsilon}_{LM}(\theta, \phi)$$

Formalism

- The differential cross section is

$$\frac{d\sigma}{ds} = \frac{1}{2(4\pi)^4\sqrt{s}}\left(\frac{\hbar c}{m_N P_{lab}}\right)^2 \frac{1}{2}\sum_{LM\epsilon}\int_{t_-}^{t_+} dt\,|\mathbf{p}|\sum_{\mu\mu'}|a^{\epsilon}_{LM,\mu'\mu}(s_{tot},t,s)|^2$$

$$\equiv \frac{\mathcal{N}}{\sqrt{s}}\sum_{LM\epsilon}\mathcal{I}^{\epsilon}_{LM}(s_{tot},s)$$

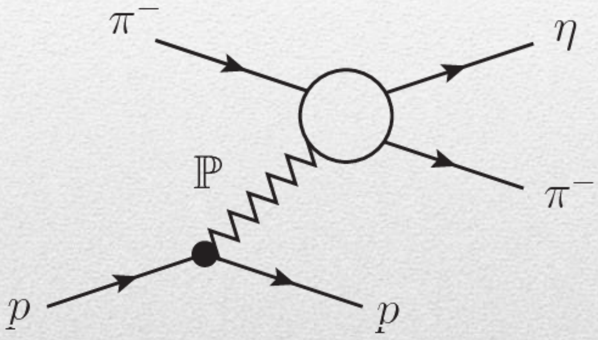
where the intensity distribution is defined

$$\mathcal{I}^{\epsilon}_{LM}(s_{tot},s) = \int_{t_-}^{t_+} dt\,|\mathbf{p}|\sum_{\mu\mu'}|a^{\epsilon}_{LM,\mu'\mu}(s_{tot},t,s)|^2$$

- Model will be compared to intensity distributions given by COMPASS

Formalism

- $\pi p \to \eta\pi p$ is high-energy peripheral process $\Longrightarrow$ pomeron dominated exchange
- Factorize pomeron-nuclear vertex
- Pomeron has effective mass $\sqrt{-t}$



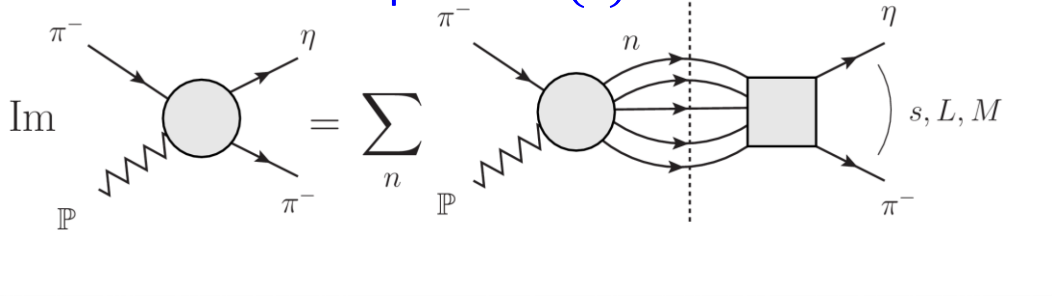
- Denote $p = |\mathbf{p}|$ the momentum of the $\eta\pi$ system, and $q = |\mathbf{q}|$ the momentum of the $\pi\mathbb{P}$ system

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

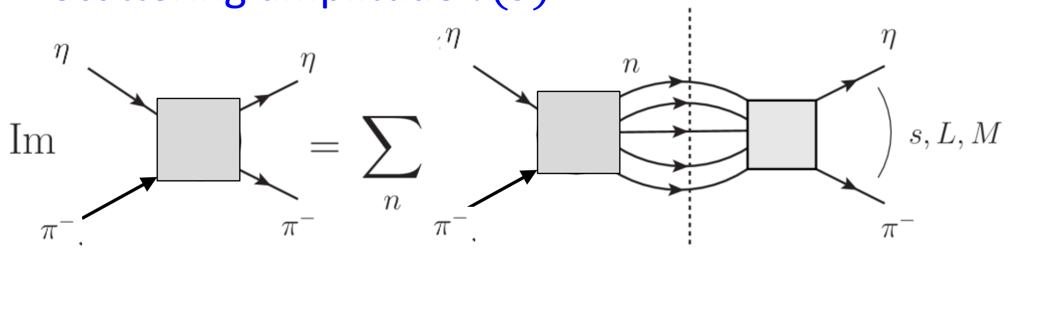
We build the partial wave amplitudes according to the N/D method

$a(s)$ is an effective $2 \to 2$ process, where the Pomeron is treated as a vector quasi-particle with virtuality $t_{\text{eff}} = -0.1\ \text{GeV}^2$

Production amplitude $a(s)$



Scattering amplitude $t(s)$



Recap: single channel $\eta\pi$

The denominator $D(s)$ contains all the FSI constrained by unitarity → universal

$$D(s) = (K^{-1})(s) - \frac{s}{\pi}\int_{s_i}^{\infty} \frac{\rho(s')N(s')}{s'\left(s'-s\right)} ds'$$

$$K(s) = \sum_R \frac{g_R^2}{M_R^2 - s}$$

OR

$$K^{-1}(s) = c_0 - c_1 s + \sum_i \frac{c_i}{M_i^2 - s}$$

$$\rho(s)N(s) = g\frac{\lambda^{(2l+1)/2}\left(s, m_\pi^2, m_\eta^2\right)}{\left(s+s_R\right)^7}$$

$$n(s) = \sum_n a_n T_n\left(\frac{s}{s+s_0}\right)$$

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$$K(s) = \sum_R \frac{g_R^2}{M_R^2 - s}$$

K-matrix
more QFT motivated
poles on the 1st sheet unlikely

OR

$$K^{-1}(s) = c_0 - c_1 s + \sum_i \frac{c_i}{M_i^2 - s}$$

CDD parameterization
more *S*-matrix motivated
poles on the 1st sheet impossible

Recap: single channel $\eta\pi$

The denominator $D(s)$ contains all the FSI constrained by unitarity → universal

$$D(s) = (K^{-1})(s) - \frac{s}{\pi}\int_{s_i}^{\infty} \frac{\rho(s')N(s')}{s'(s'-s)} ds'$$

Numerator functions
know about crossed channel dynamics
unconstrained, we use a smooth model

$$\rho(s)N(s) = g\frac{\lambda^{(2l+1)/2}\left(s, m_\pi^2, m_\eta^2\right)}{(s+s_R)^7} \qquad n(s) = \sum_n a_n T_n\left(\frac{s}{s+s_0}\right)$$

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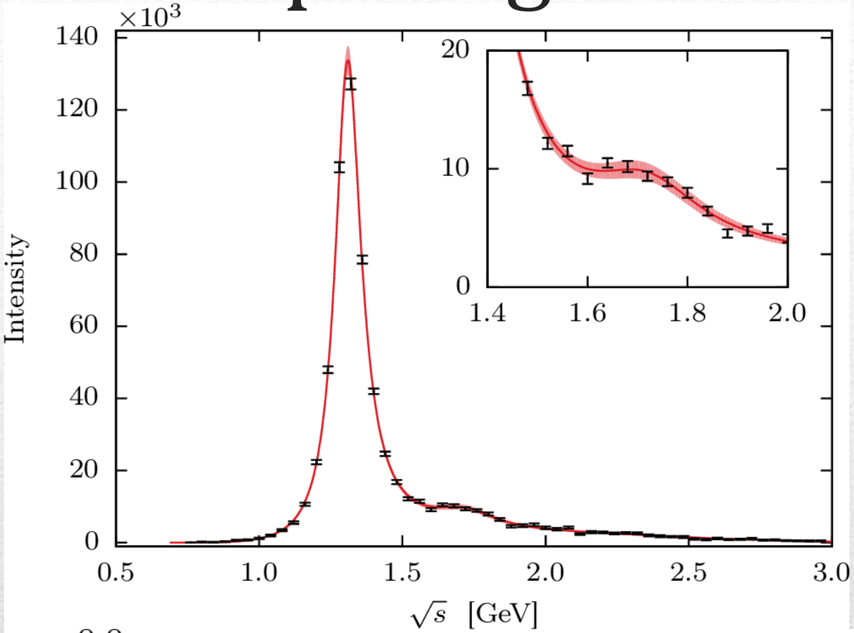
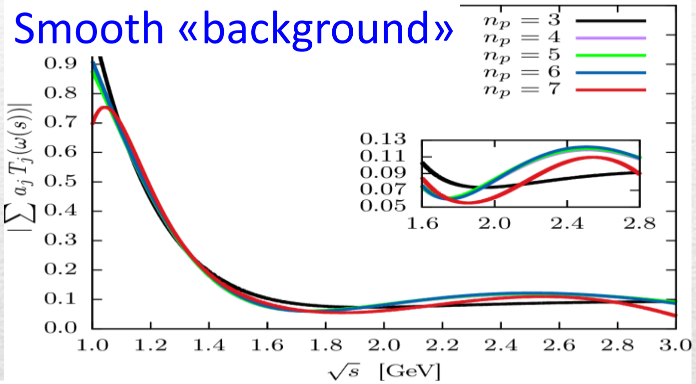
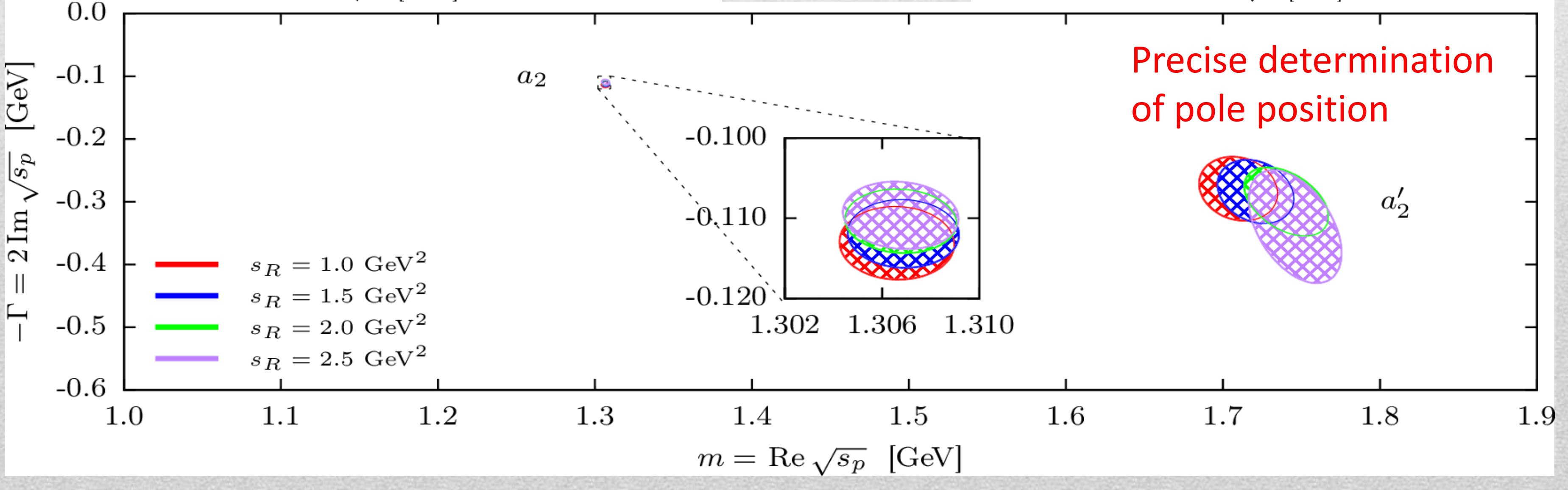


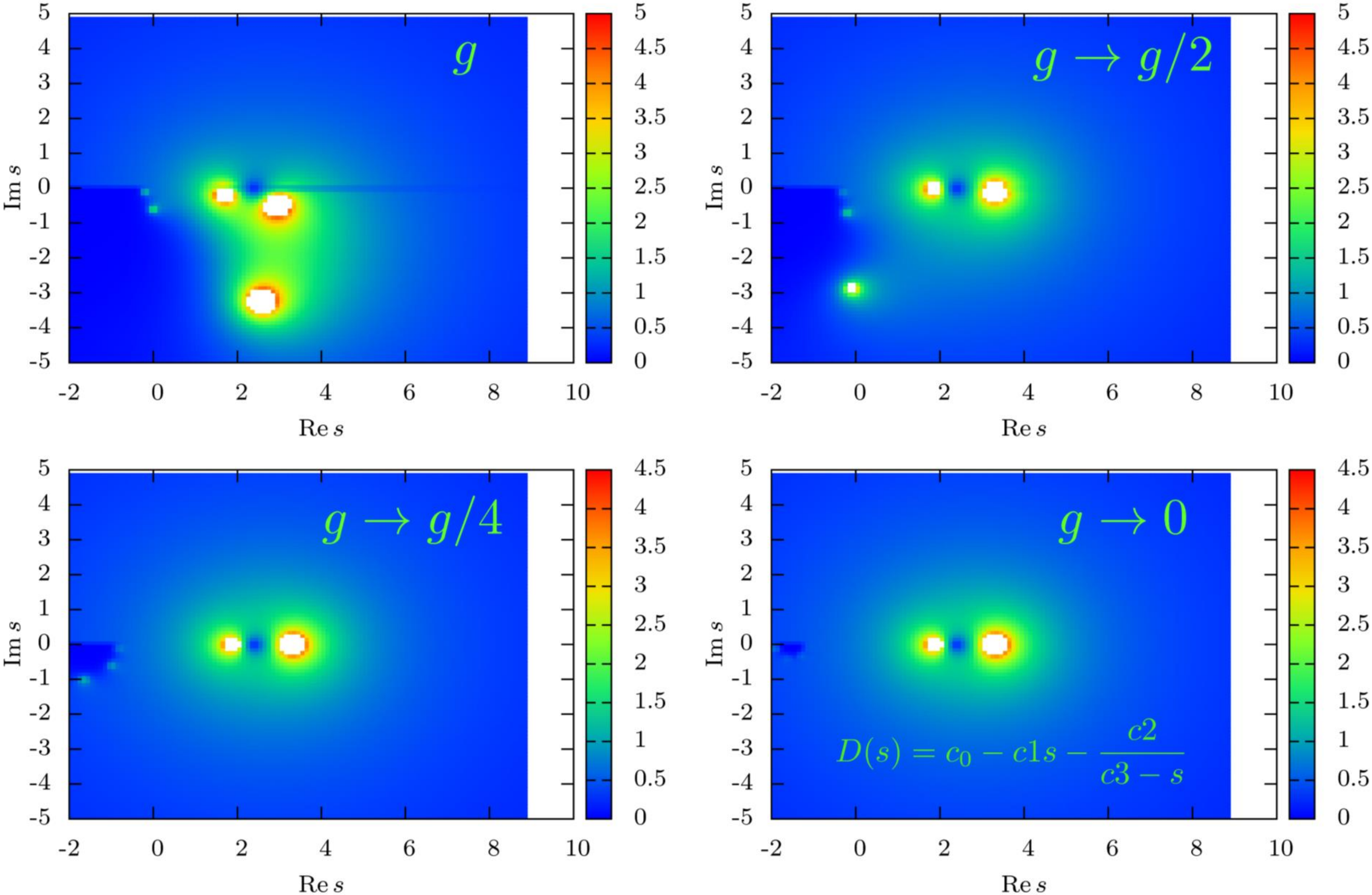
Test against the D-wave $\eta\pi$ data, where the a_2 and the a_2' show up

Smooth «background»





Precise determination of pole position



g
$g \to g/2$
$g \to g/4$
$g \to 0$
$D(s) = c_0 - c1s - \frac{c2}{c3 - s}$
Im s
Re s

Coupled channel: the model

A. Rodas, AP *et al.* 1810.04171

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

Two waves, $J = P, D$

37 fit parameters

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

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

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

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

Coupled channel: the model

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

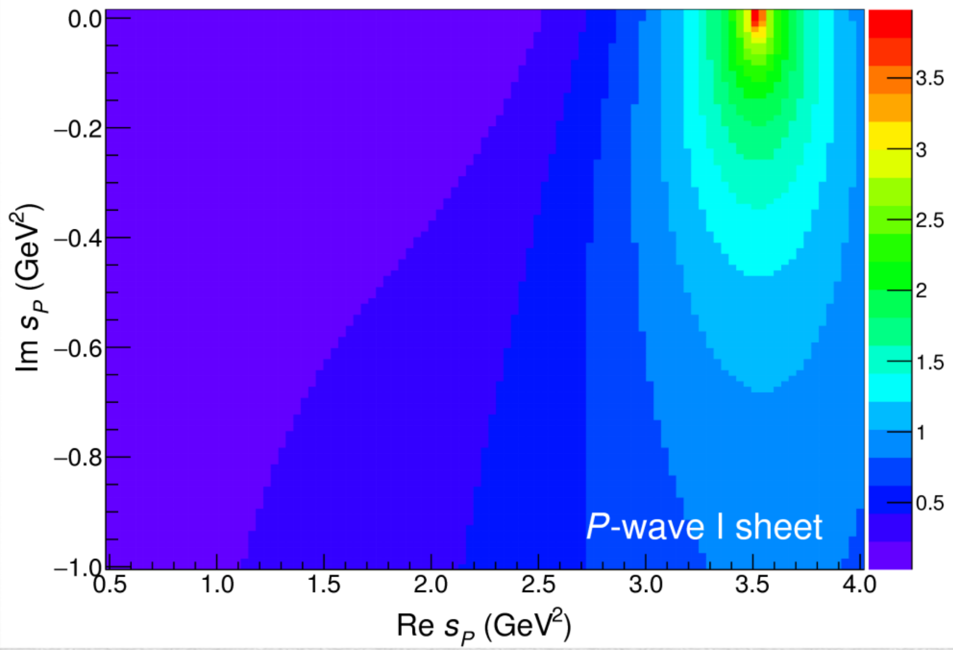
1 K-matrix pole for the P-wave
2 K-matrix poles for the D-wave

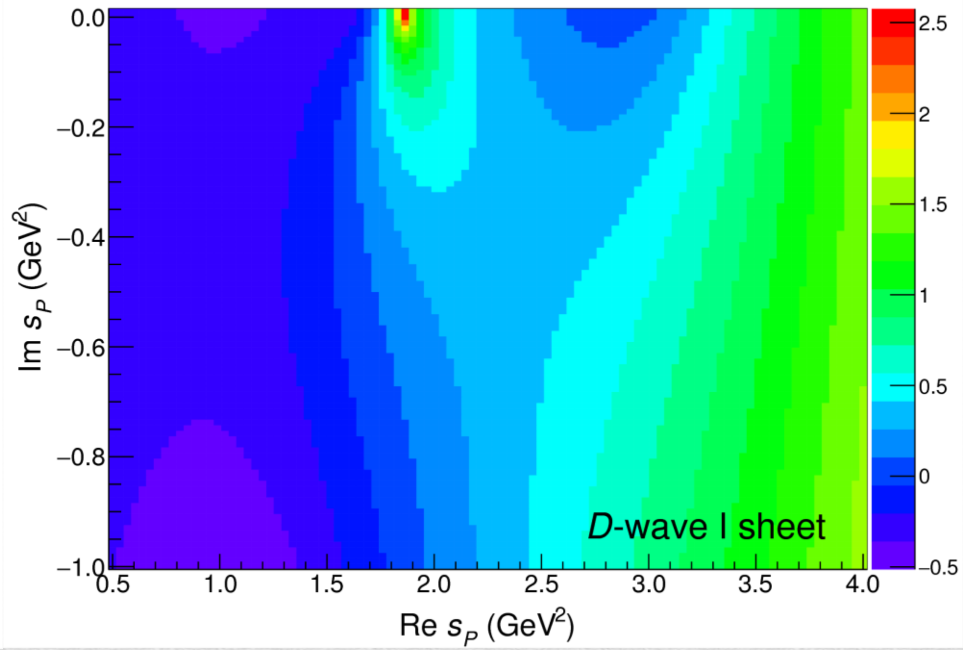
$$\rho N^J_{ki}(s') = \delta_{ki} \frac{\lambda^{J+1/2}\left(s', m^2_{\eta^{(\prime)}}, m^2_\pi\right)}{(s'+s_R)^{2J+1+\alpha}}$$

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

Left-hand scale (Blatt-Weisskopf radius) $s_R = s_0 = 1\ \mathrm{GeV}^2$
$\alpha = 2$ as in the single channel, 3rd order polynomial for $n^J_k(s)$

Complex plane





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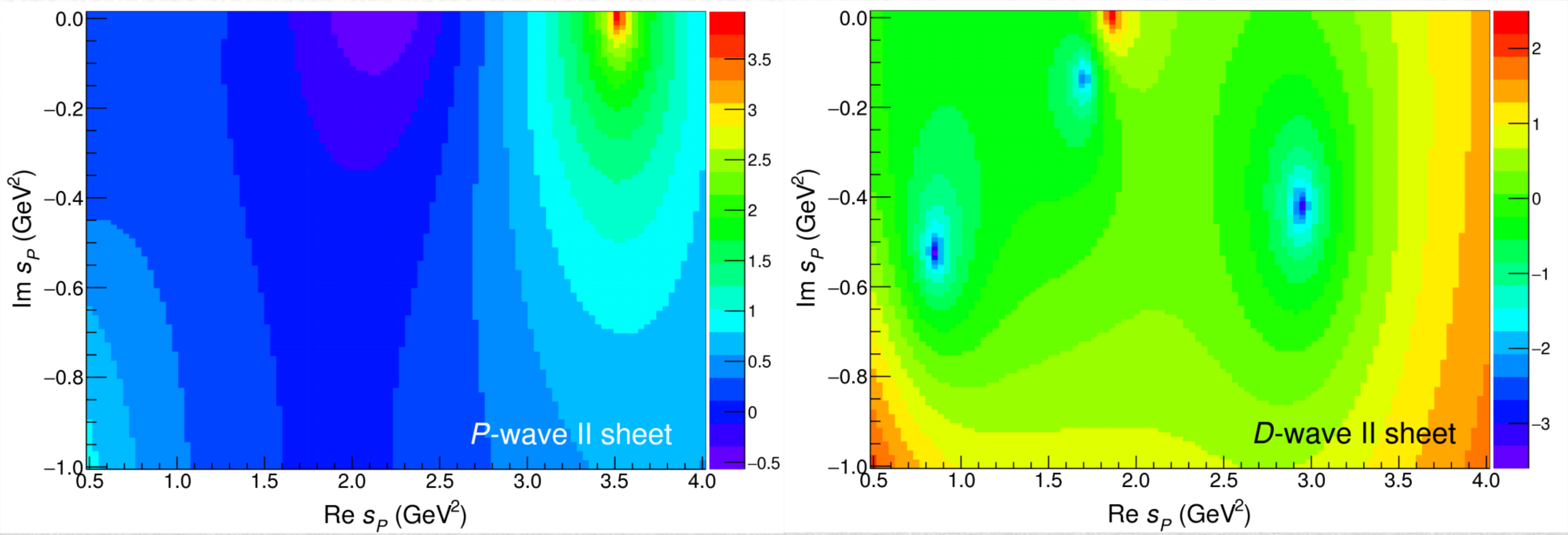
We also see some close-to-threshold poles, which are artifacts of the model for $N(s)$

How to distinguish the two?

Complex plane

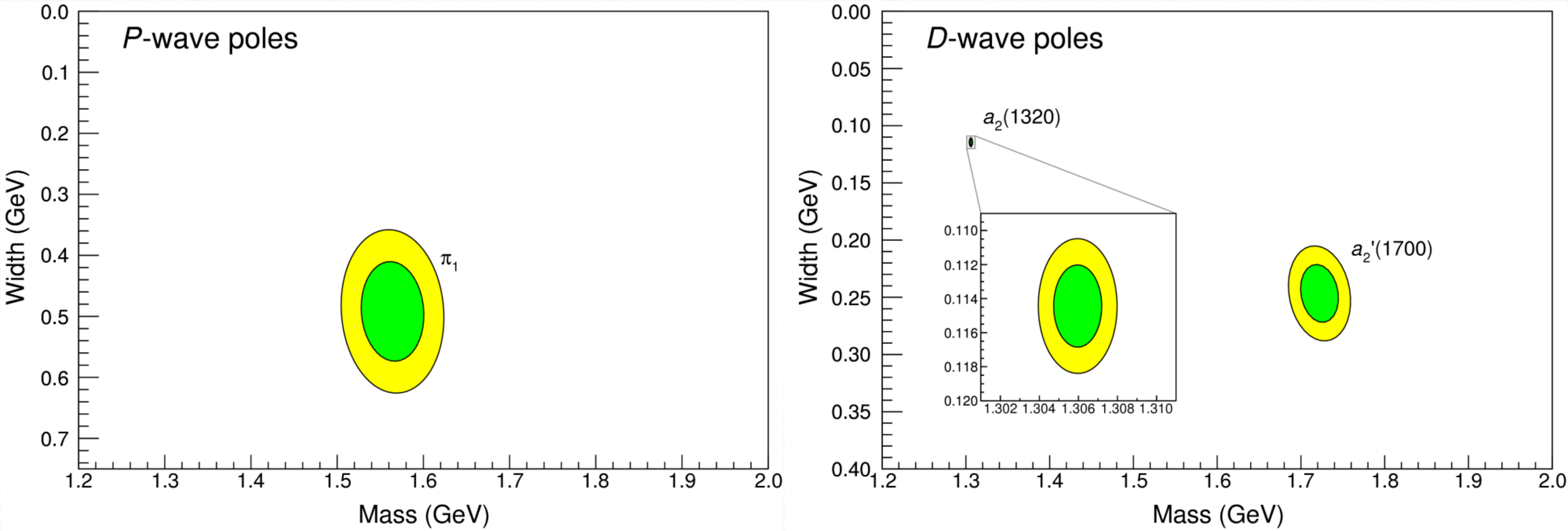


For the best fit solution, we look at the closest Riemann sheet in the complex plane
We see a limited amount of poles in the relevant region

We also see some close-to-threshold poles, which are artifacts of the model for $N(s)$

How to distinguish the two?

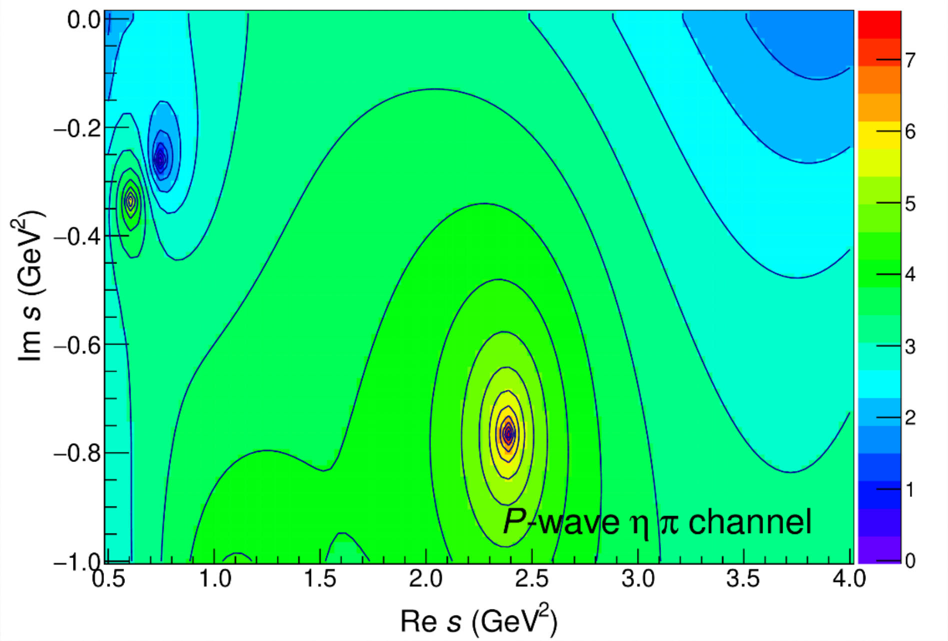
Result (stat. error only)

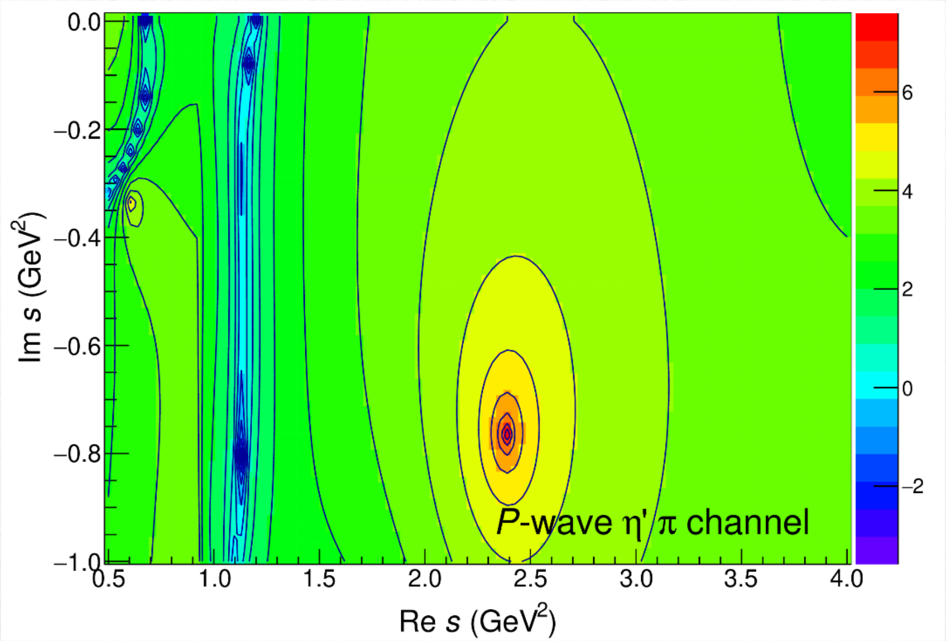


The variance of the bootstrapped poles gives the statistical error

Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	1306.0 ± 0.8	114.4 ± 1.6
$a_2'(1700)$	1722 ± 15	247 ± 17
π_1	1564 ± 24	492 ± 54

Again into the complex plane

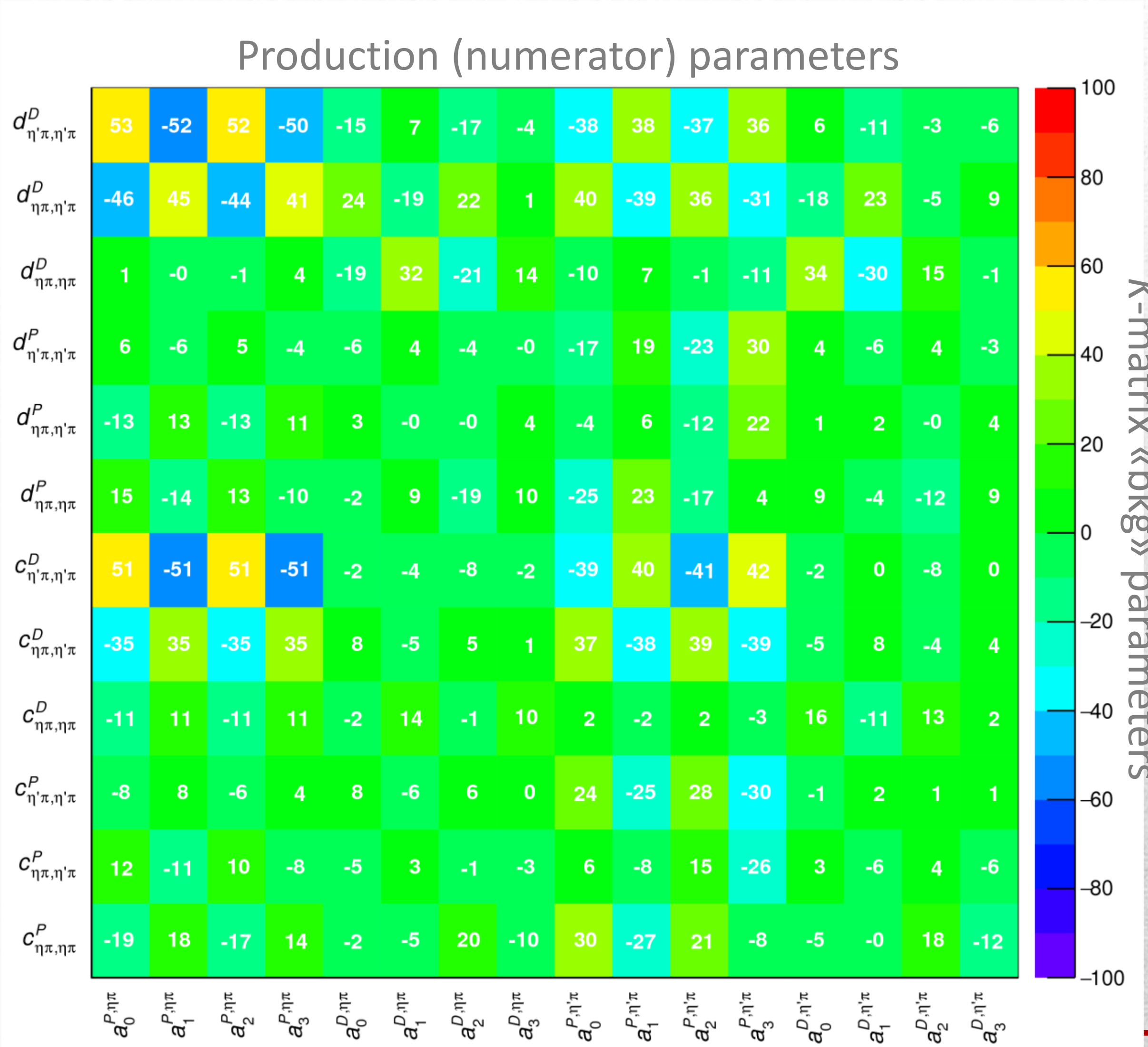




The strength of the pole propagates differently in the two channels

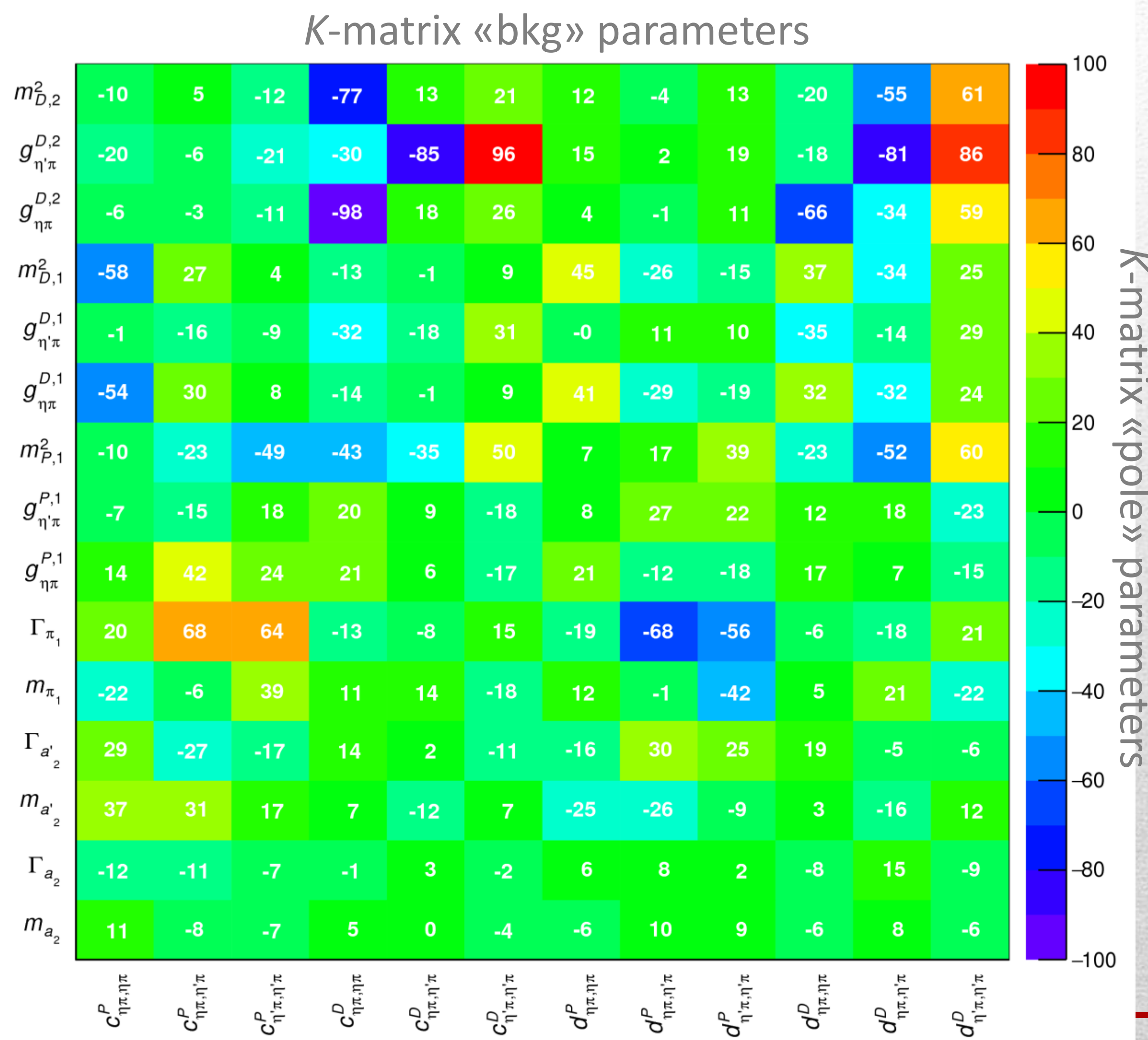
In $\eta\pi$ the strength move to lighter values

Correlations



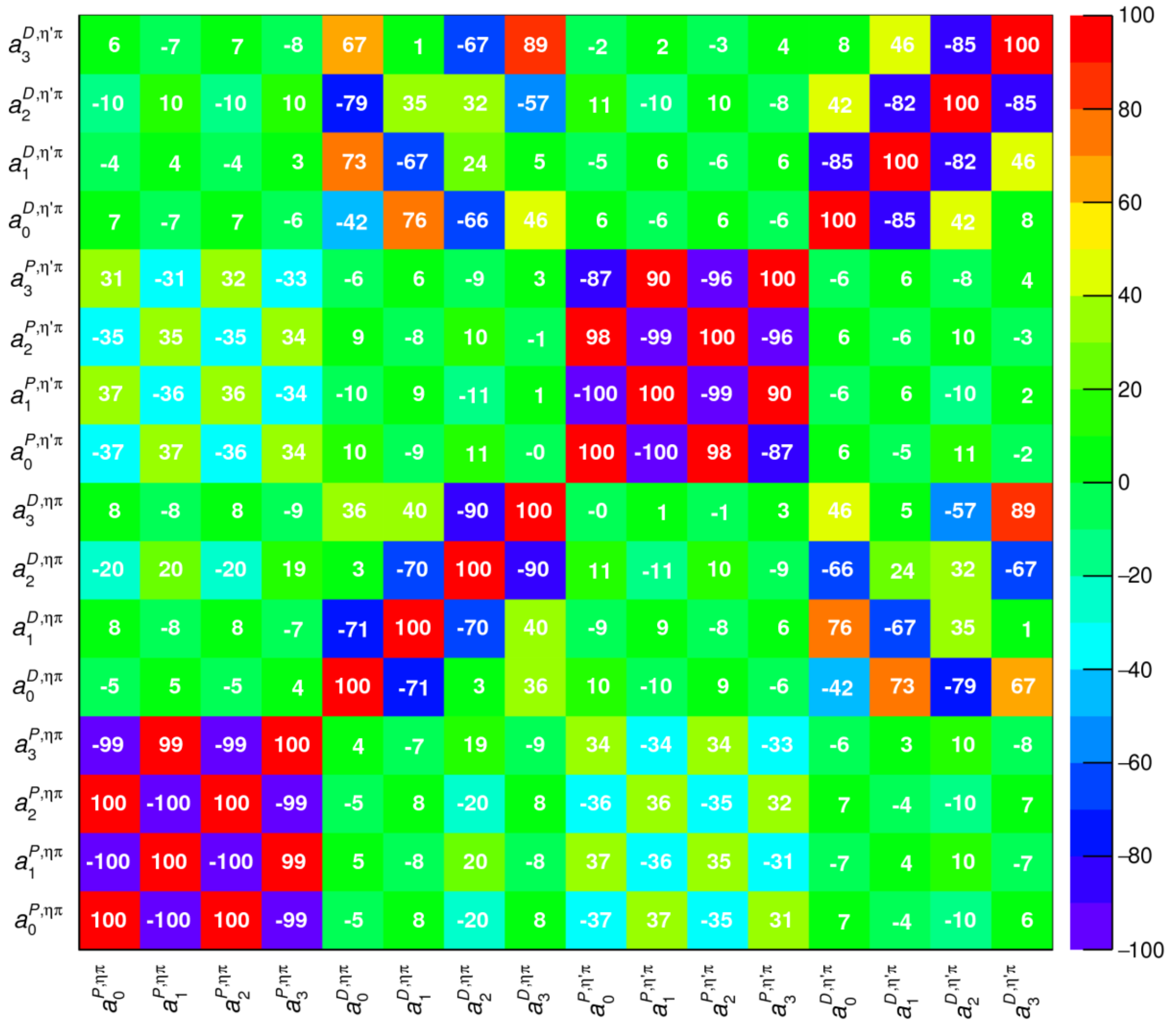
Denominator parameters not very correlated with the numerator ones ✓

Correlations



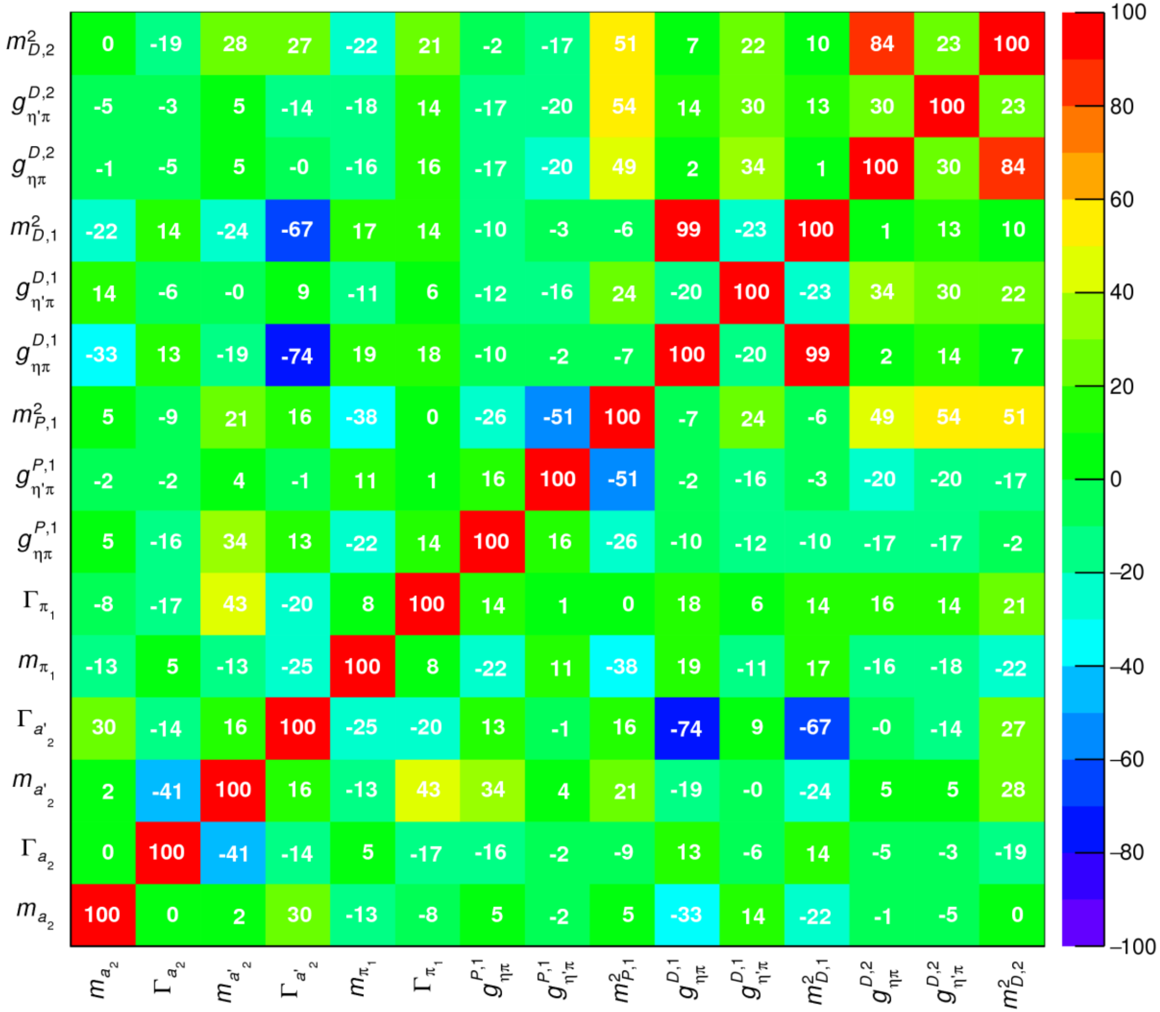
Denominator parameters uncorrelated between *P*- and *D*-wave ✓

Correlations



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

Correlations



Systematic studies

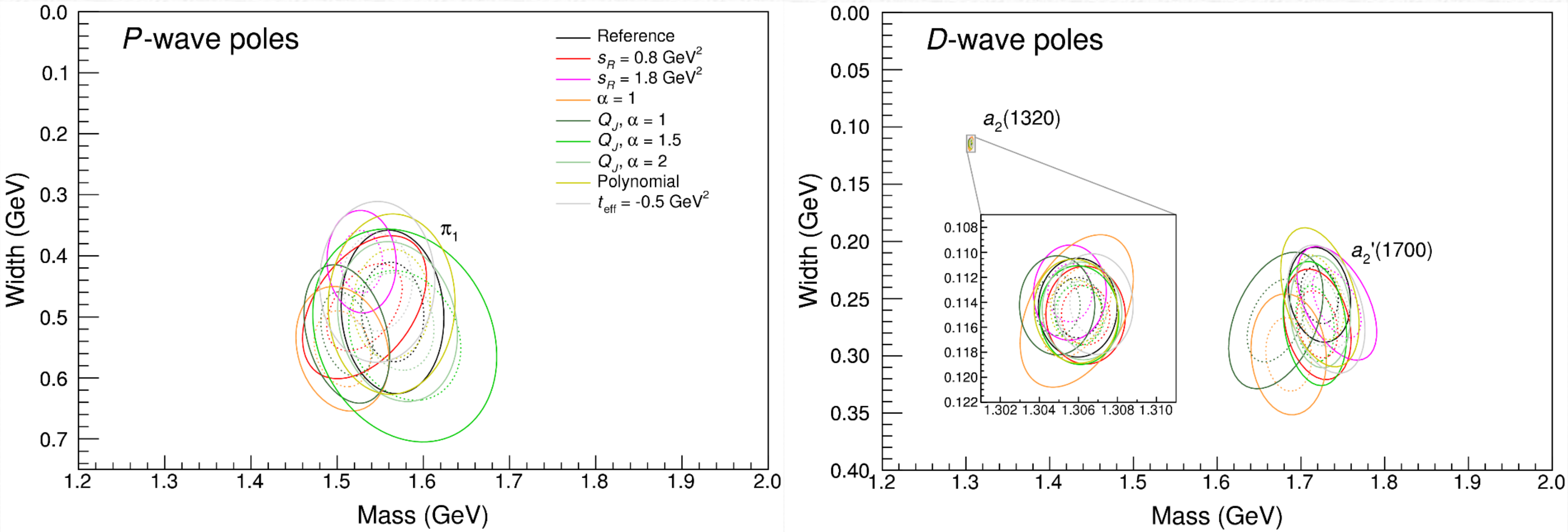
- Change of functional form and parameters in the denominator

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

  - Default: $s_R = 1\ \text{GeV}^2$. We try $s_R = 0.8, 1.8\ \text{GeV}^2$
  - Default: $\alpha = 2$. We try $\alpha = 1$
  - We also try a different function: $\rho N_{ki}^J(s') = g\,\delta_{ki}\,\frac{Q_J(z_{s'})}{s'^\alpha \lambda^{1/2}(s', m_{\eta^{(\prime)}}, m_\pi)}$ with $\alpha = 2, 1.5, 1$

- Change of parameters in the numerator
  - Default: $t_{\text{eff}} = -0.1\ \text{GeV}^2$. We try$t_{\text{eff}} = -0.5\ \text{GeV}^2$
  - Default: 3rd order polynomial. We try 4th

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

Systematic studies

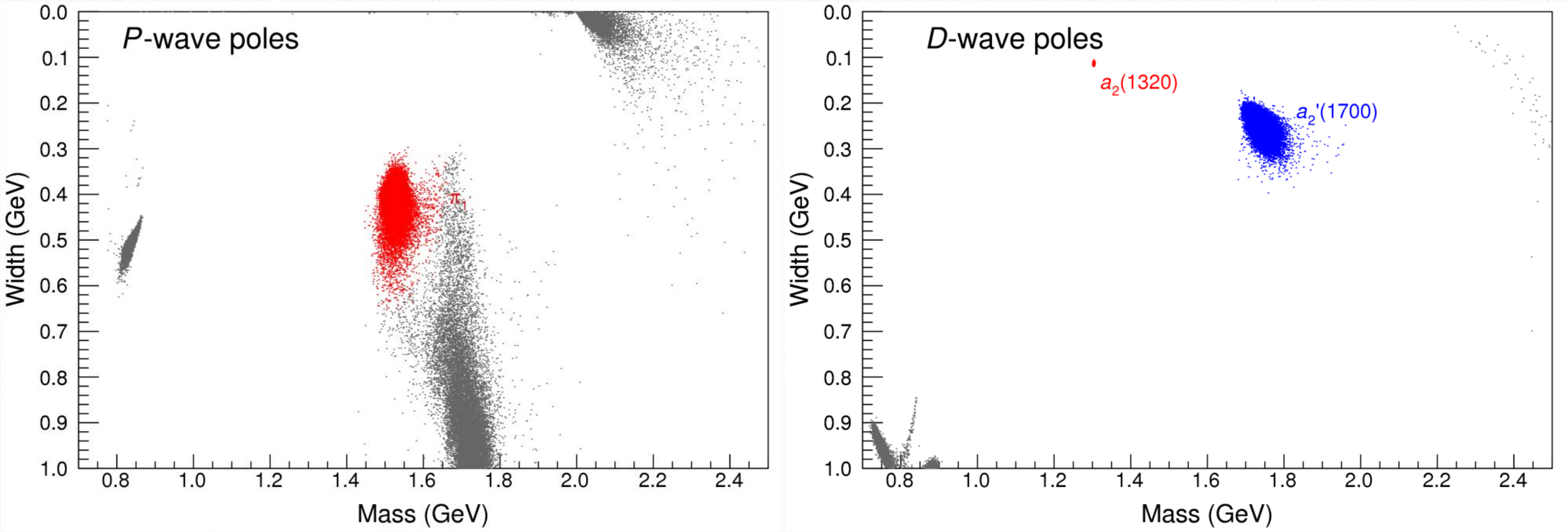
Systematic	Poles	Mass (MeV)	Deviation (MeV)	Width (MeV)	Deviation (MeV)
Variation of the function $\rho N(s')$					
$s_R = 0.8\,\mathrm{GeV}^2$	$a_2(1320)$	1306.4	0.4	115.0	0.6
	$a_2'(1700)$	1720	-3	272	26
	π_1	1532	-33	484	-8
$s_R = 1.8\,\mathrm{GeV}^2$	$a_2(1320)$	1305.6	-0.4	113.2	-1.2
	$a_2'(1700)$	1743	21	254	7
	π_1	1528	-36	410	-82
Systematic assigned	$a_2(1320)$		0.0		0.0
	$a_2'(1700)$		21		26
	π_1		36		82
$\alpha = 1$	$a_2(1320)$	1305.9	-0.1	114.7	0.3
	$a_2'(1700)$	1685	-37	299	52
	π_1	1506	-58	552	60
Systematic assigned	$a_2(1320)$		0.0		0.0
	$a_2'(1700)$		37		52
	π_1		58		60
$Q_J, \alpha = 1$	$a_2(1320)$	1304.9	-1.1	114.2	-0.2
	$a_2'(1700)$	1670	-52	269	22
	π_1	1511	-53	528	36
$Q_J, \alpha = 1.5$	$a_2(1320)$	1306.0	0.1	115.0	0.6
	$a_2'(1700)$	1717	-5	272	25
	π_1	1578	14	530	39
$Q_J, \alpha = 2$	$a_2(1320)$	1306.2	0.2	114.7	0.3
	$a_2'(1700)$	1723	1	261	15
	π_1	1570	6	508	16
Systematic assigned	$a_2(1320)$		1.1		0.0
	$a_2'(1700)$		52		25
	π_1		53		0

Systematic studies

Variation of the numerator function $n(s)$

Polynomial expansion	$a_2(1320)$	1305.9	-0.1	114.7	0.3
	$a_2'(1700)$	1723	1	249	2
	π_1	1563	-1	479	-13
Systematic assigned	$a_2(1320)$		0.0		0.0
	$a_2'(1700)$		0		0
	π_1		0		0
$t_{\text{eff}} = -0.5\,\text{GeV}^2$	$a_2(1320)$	1306.8	0.8	114.1	-0.3
	$a_2'(1700)$	1730	8	259	13
	π_1	1546	-18	443	-49
Systematic assigned	$a_2(1320)$		0.8		0.0
	$a_2'(1700)$		0		0
	π_1		0		0

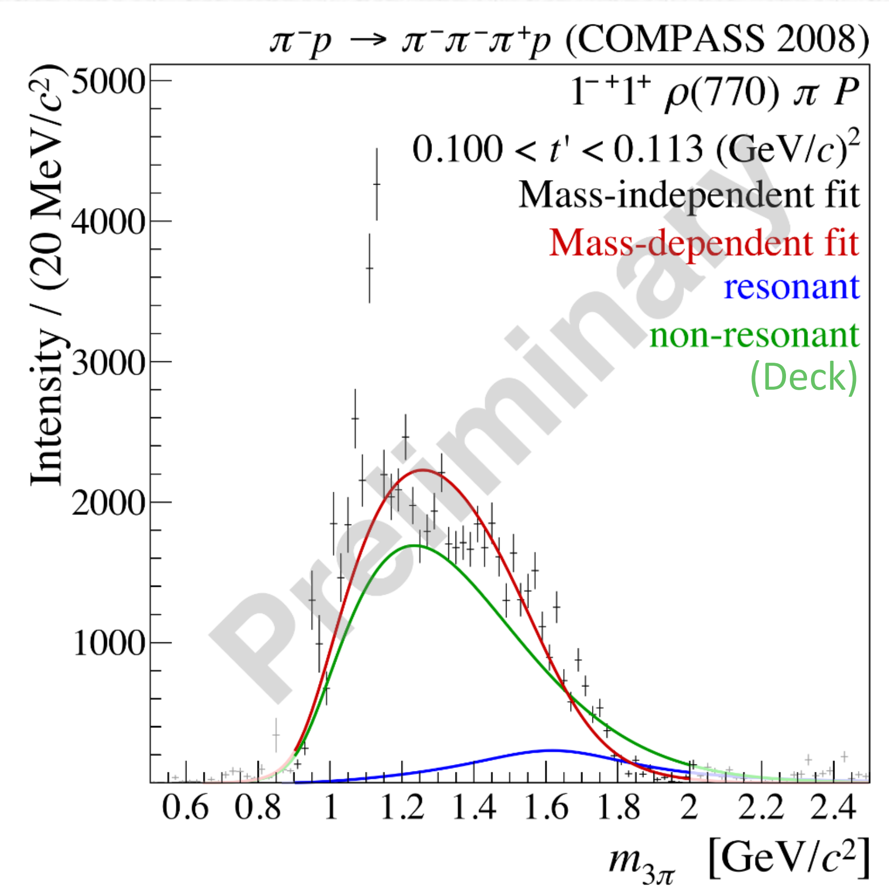
Bootstrap for $s_R = 1.8\ \mathrm{GeV}^2$

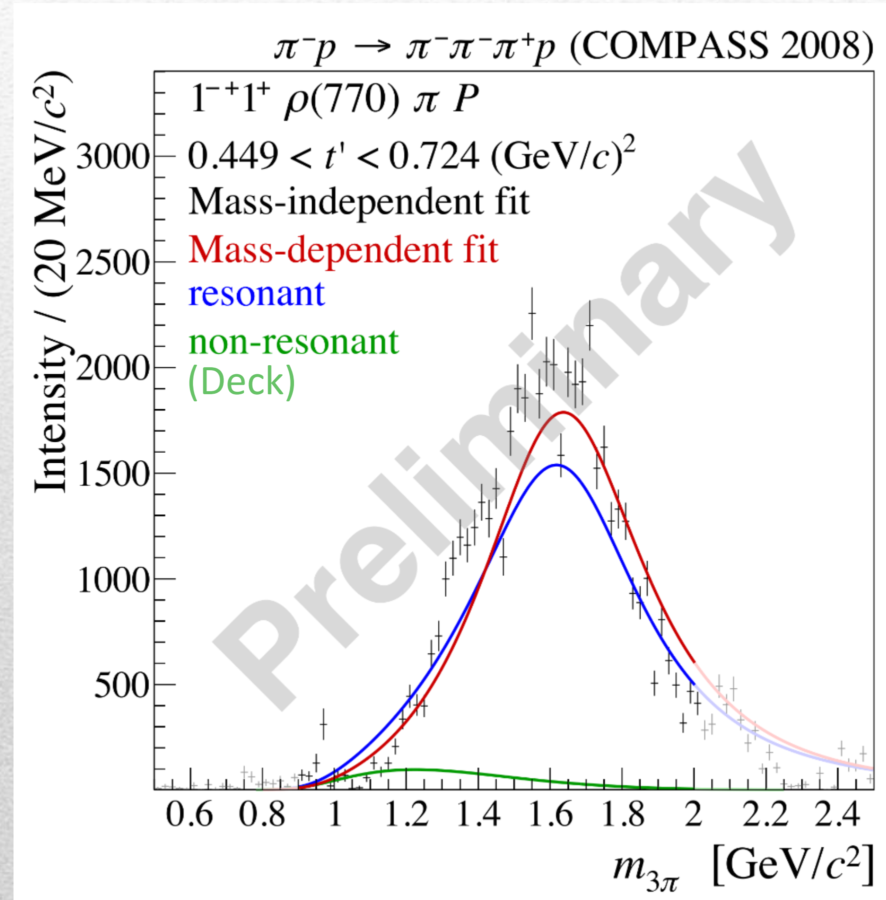


Our skepticism about a second pole in the relevant region is confirmed:
It is unstable and not trustable

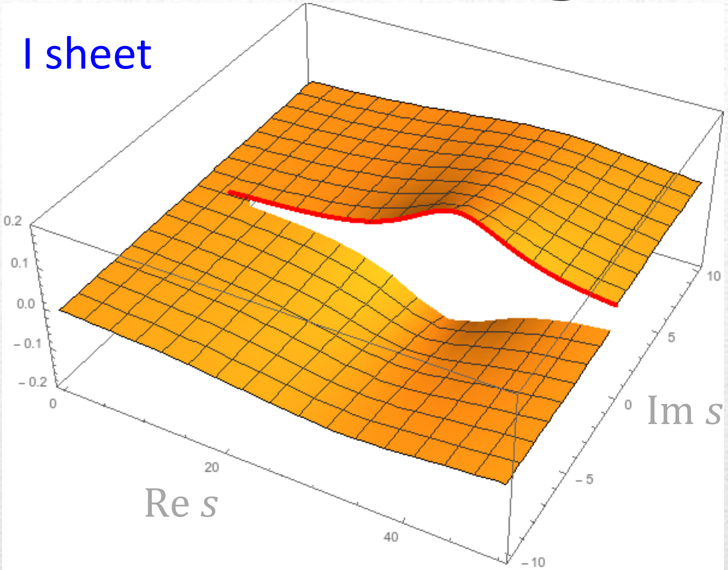
$\pi_1(1600) \to \rho\pi \to \pi\pi\pi$

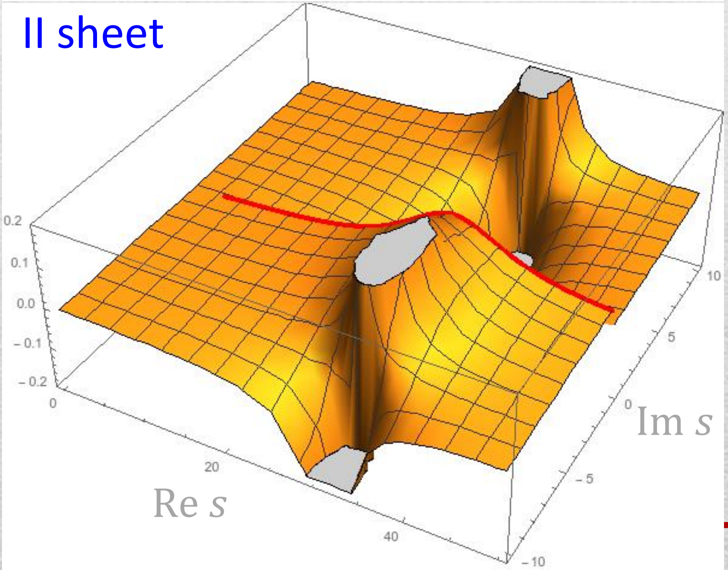
The strength of the Deck effect depends on the momentum transferred t, but the precise estimates rely on the model for the Deck amplitude





Pole hunting

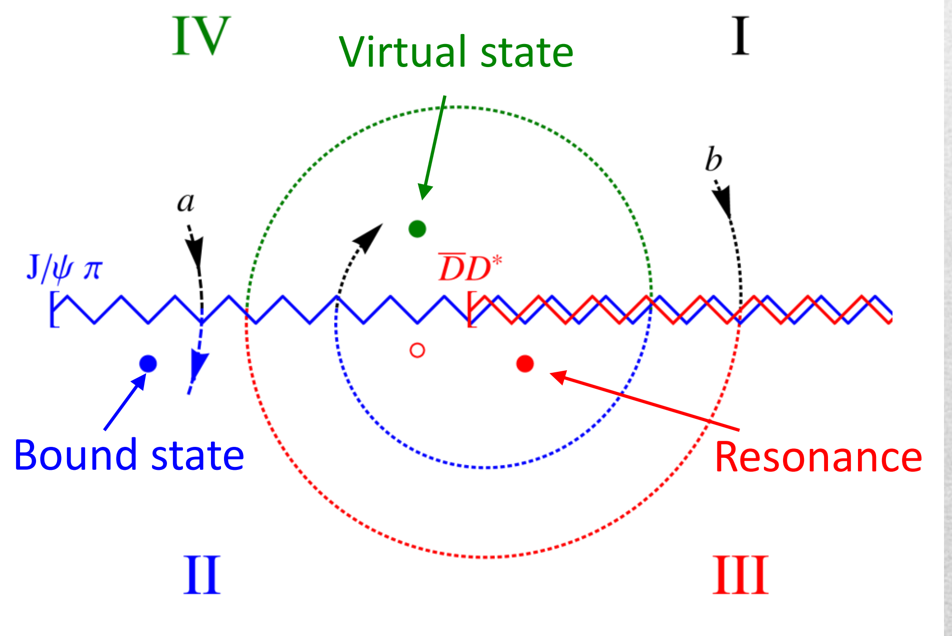




More complicated structure when more thresholds arise: two sheets for each new threshold

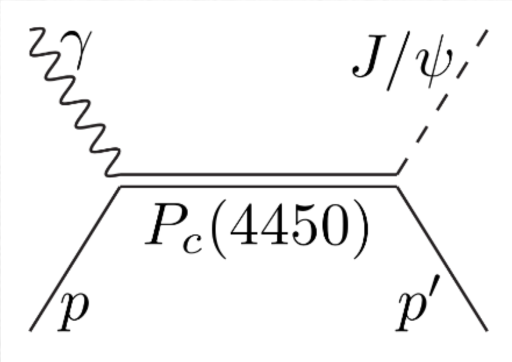
III sheet: usual resonances

IV sheet: cusps (virtual states)



P_c photoproduction

To exclude any rescattering mechanism, we propose to search the $P_c(4450)$ state in photoproduction.



Hadronic vertex EM vertex

$$\langle \lambda_\psi \lambda_{p'} | T_r | \lambda_\gamma \lambda_p \rangle = \frac{\boxed{\langle \lambda_\psi \lambda_{p'} | T_{\text{dec}} | \lambda_R \rangle} \boxed{\langle \lambda_R | T^\dagger_{\text{em}} | \lambda_\gamma \lambda_p \rangle}}{M_r^2 - W^2 - i\Gamma_r M_r}$$

Hadronic part

- 3 independent helicity couplings,
  → approx. equal, $g_{\lambda_\psi, \lambda_{p'}} \sim g$
- g extracted from total width and (unknown) branching ratio

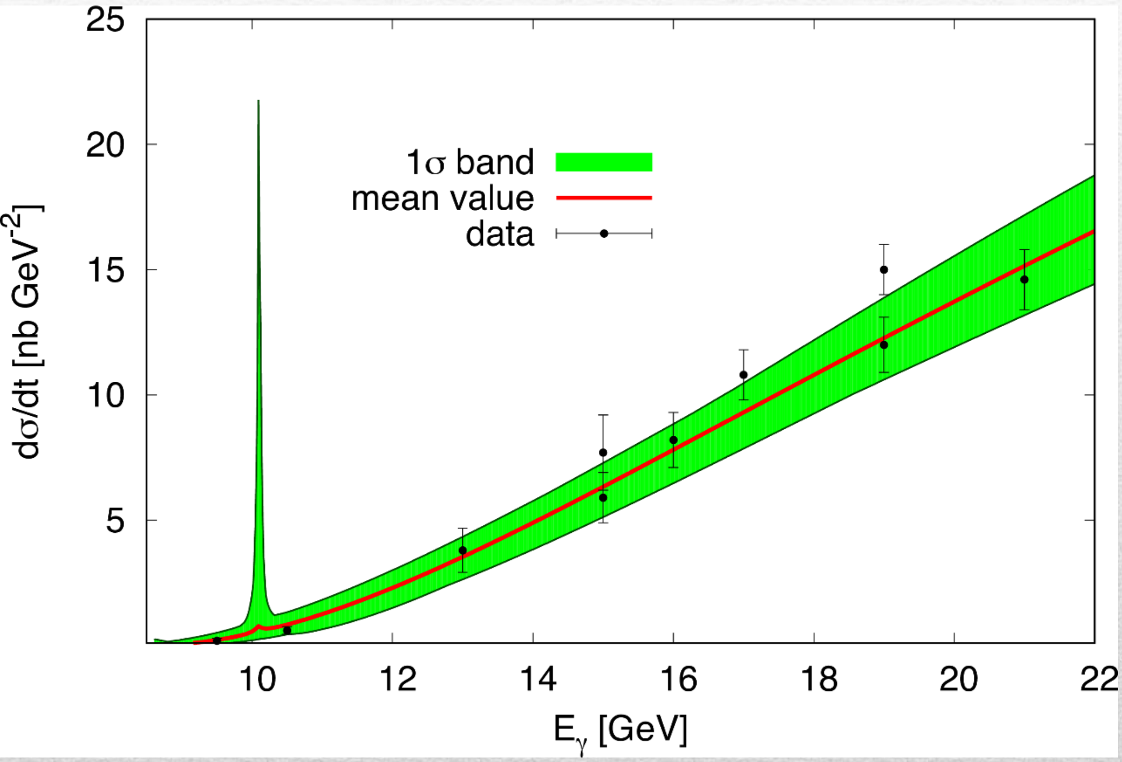
Vector meson dominance relates the radiative width to the hadronic width

$$\Gamma_\gamma = 4\pi\alpha\, \Gamma_{\psi p} \left(\frac{f_\psi}{M_\psi} \right)^2 \left(\frac{\bar{p}_i}{\bar{p}_f} \right)^{2\ell+1} \times \frac{4}{6}$$

Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

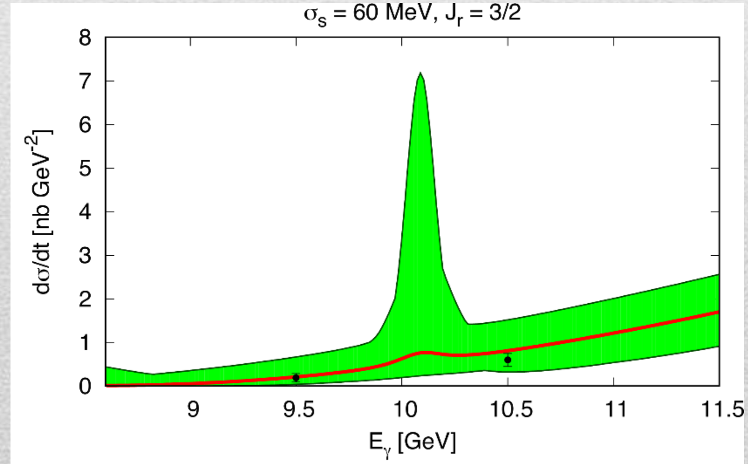
Pentaquark photoproduction

$J^P = (3/2)^-$



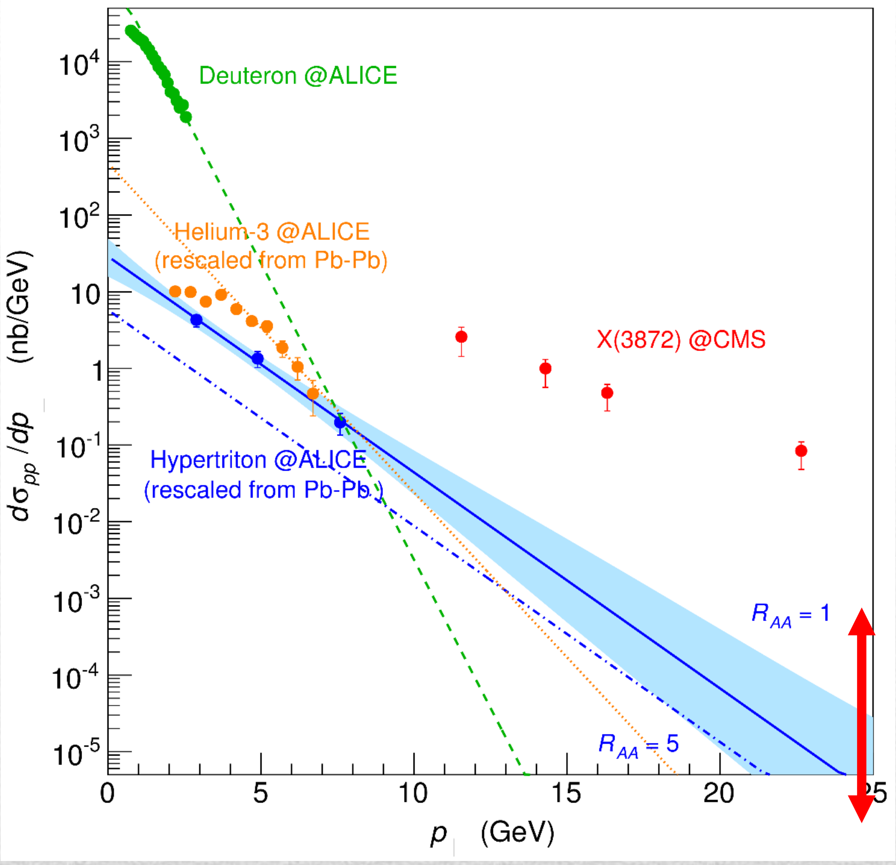
σ_s (MeV)	0	60
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$
b_0 (GeV^{-2})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$
$\mathcal{B}_{\psi p}$ (95% CL)	≤ 29 %	≤ 30 %

With smearing

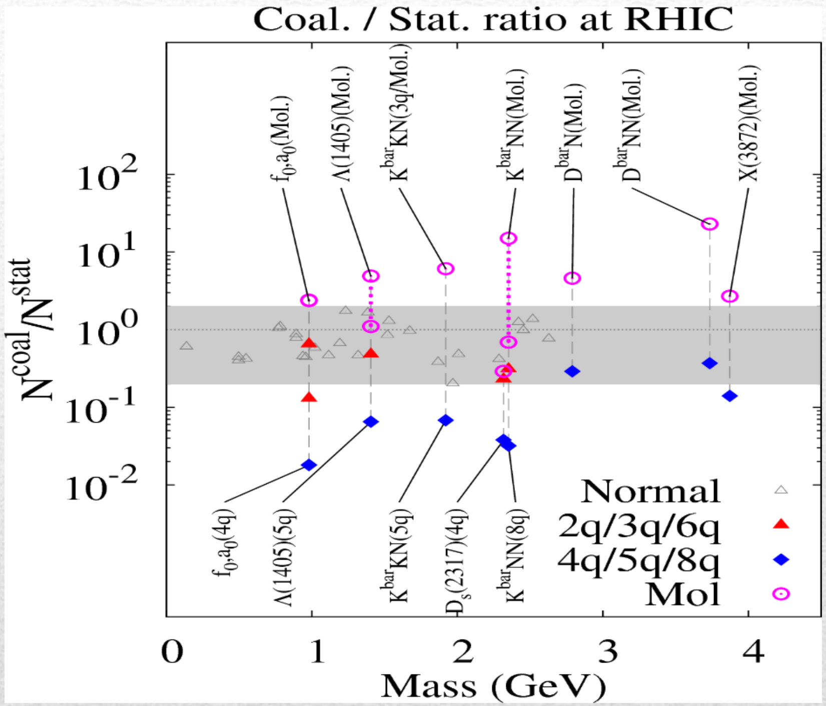


Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Interaction with nuclear media



Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028



ExHIC, PRL106, 212001

The interaction of (exotic) resonances with nuclear media is of primary interest to identify their nature

Also study the lineshape dependence