Progress in hadron spectroscopy analysis

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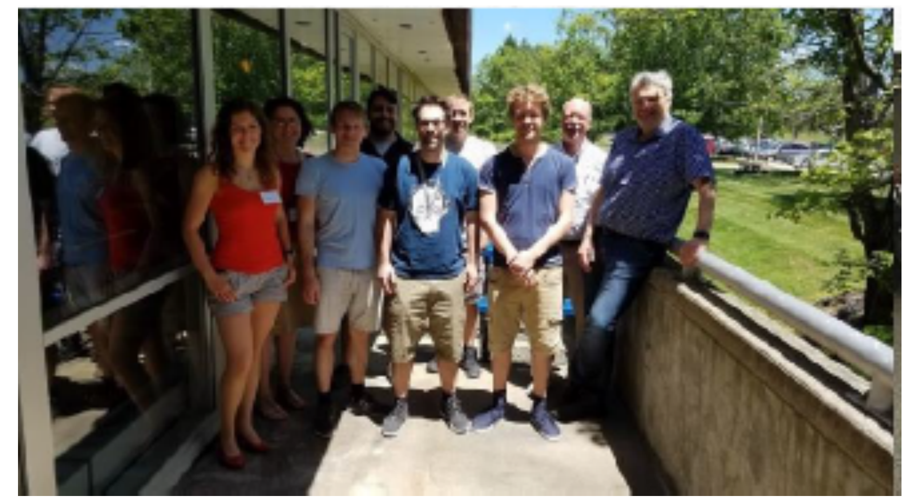
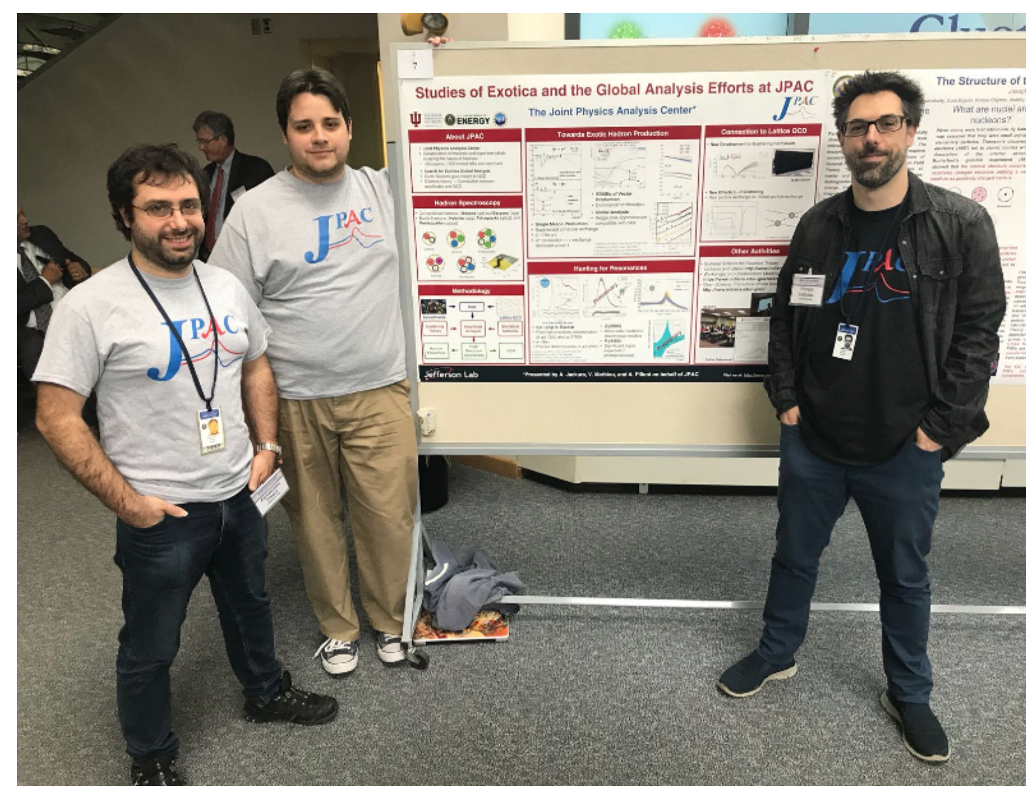
INDIANA UNIVERSITY

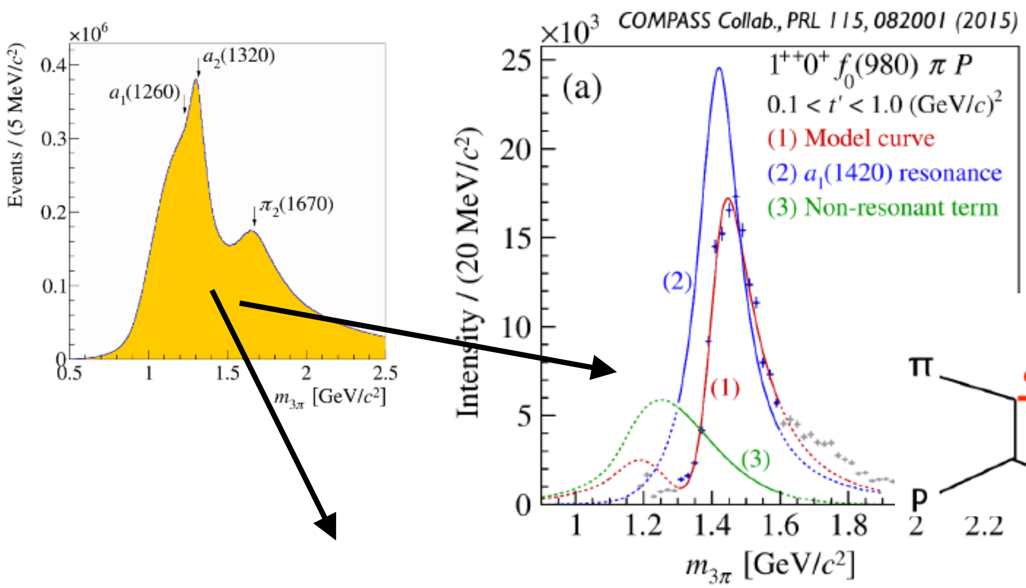
Joint Physics Analysis Center

- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other accelerator laboratories.
- Contribute to education of new generation of practitioners in physics of strong interactions.
- In this talk : JPAC's role in spectroscopy analysis, new results on di-pion resonance fits to CLAS data, the $J^{PC}=1^{-+}$ exotic, on connecting with lattice and some "exotic" physics

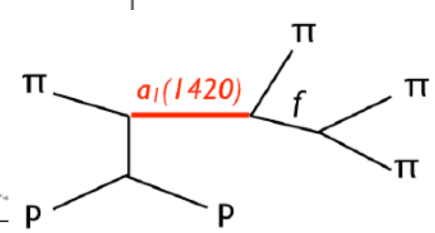




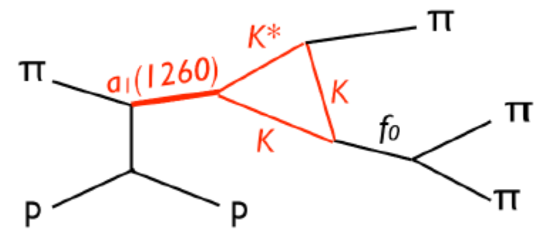
Signatures of new, unusual light resonances



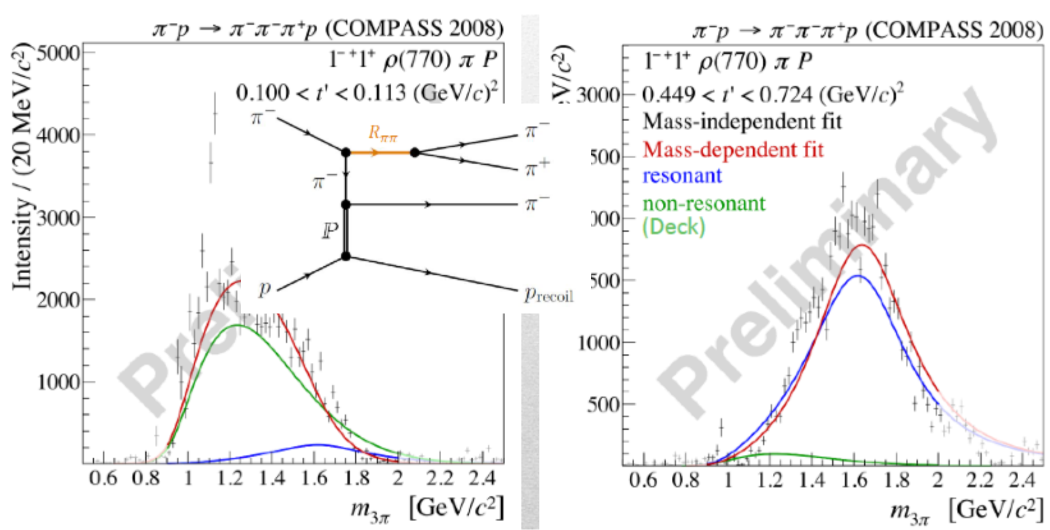
- High precision PWA of 3pi diffractive association yields a new $a_1(1420)$ incompatible with the quark model/Regge expectations.



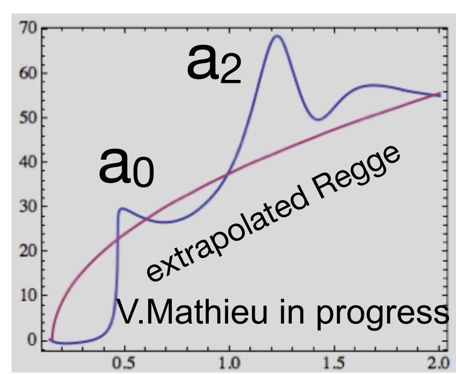
Or ?

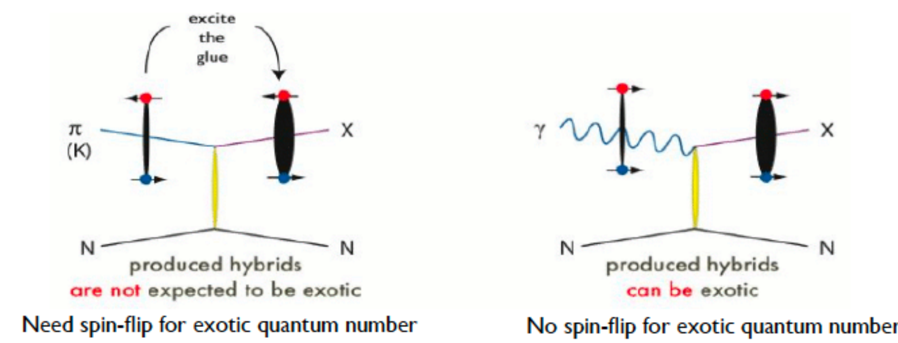


- At low-t exotic wave production compatible with one pion exchange

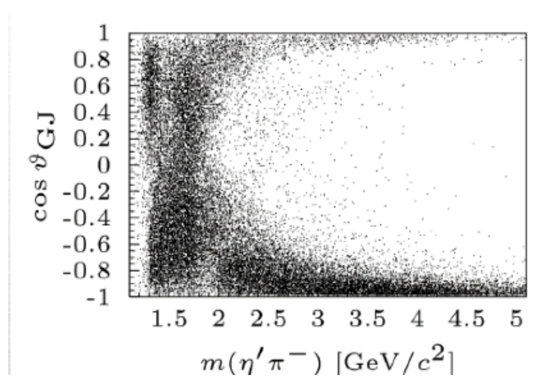


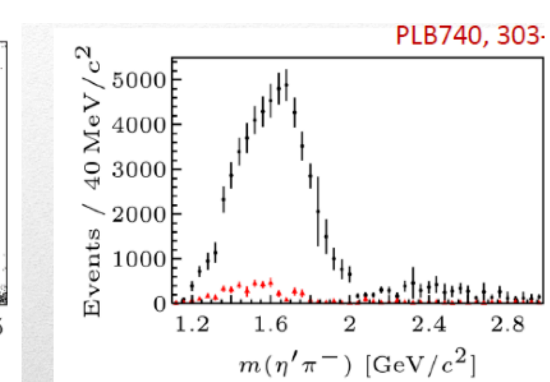
- In photoproduction exotic mesons be produced via pion exchange

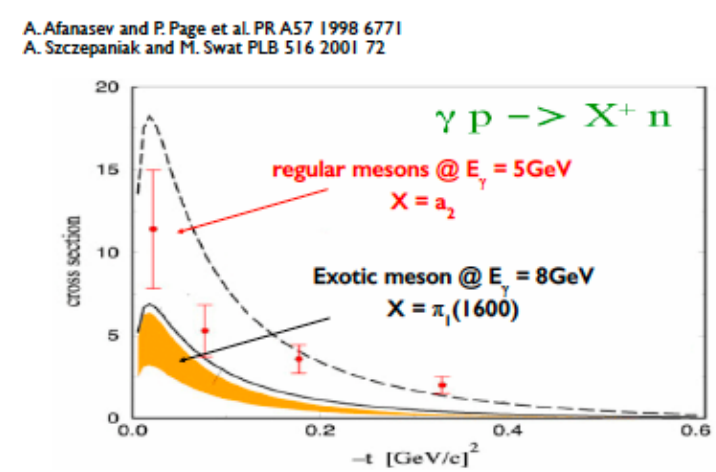




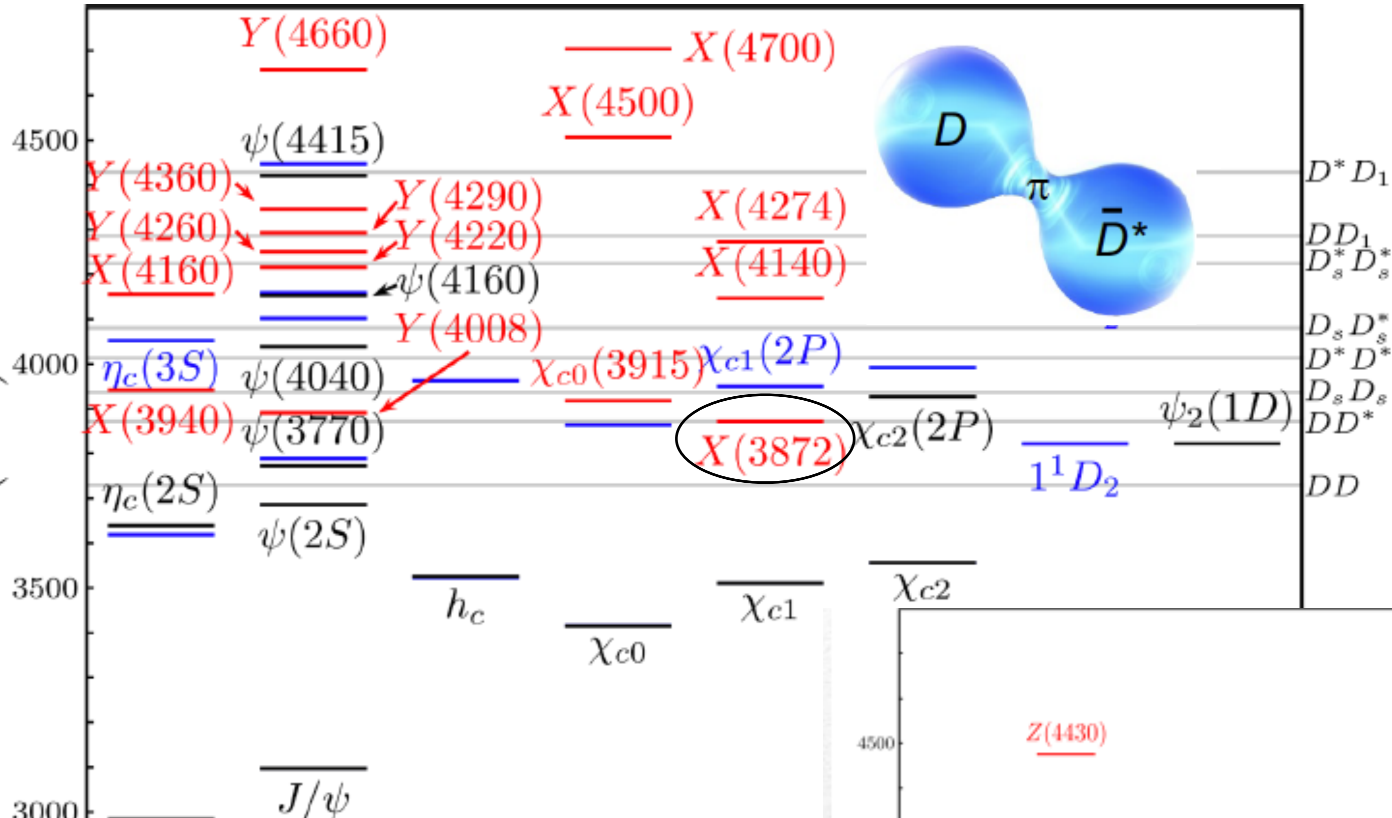
- Large exotic wave seen in η(') π production : FESR's to constrain P-wave



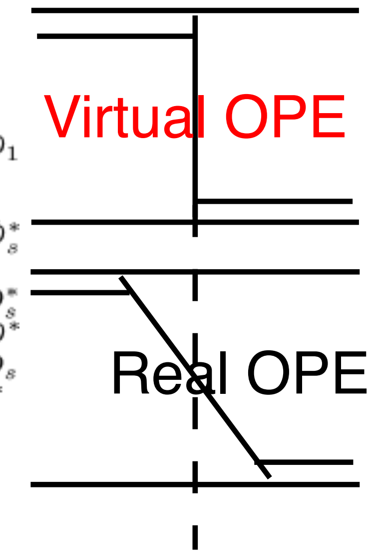




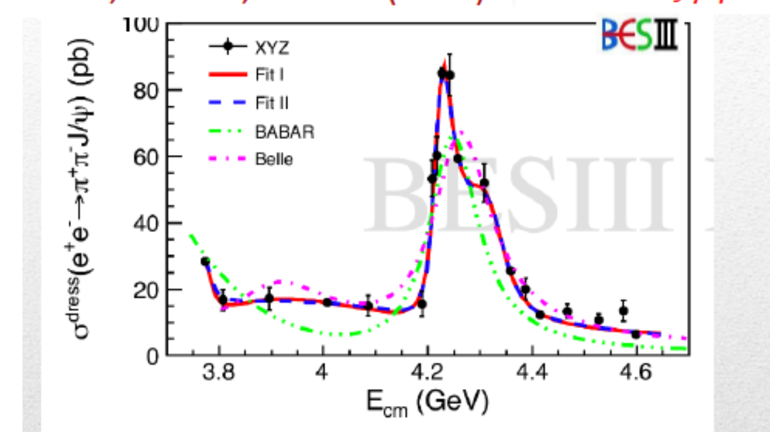
Signatures of unusual heavy quark resonances

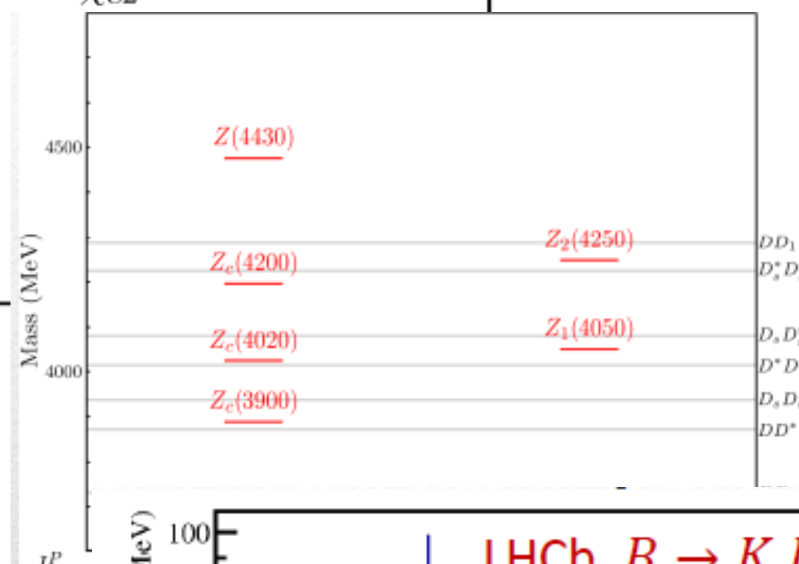


Esposito, Pilloni, Polosa, Phys. Rep.



BESIII, PRL118, 092001 (2017) $e^+e^- \to J/\psi\,\pi\pi$

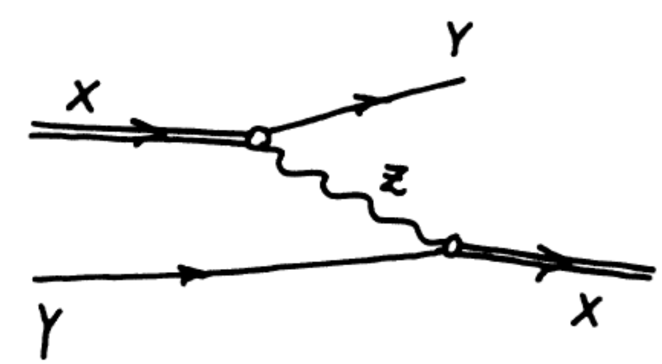




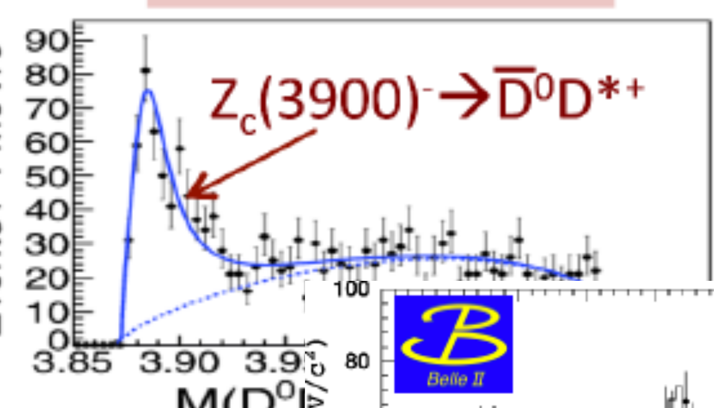
EMARK ON ENERGY PEAKS IN MESON SYSTEMS

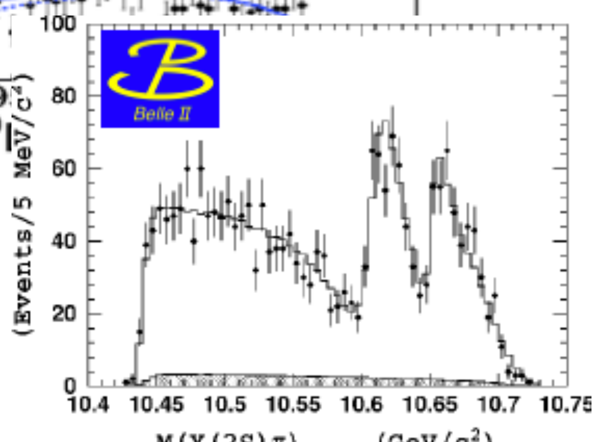
M. Nauenberg A. Pais

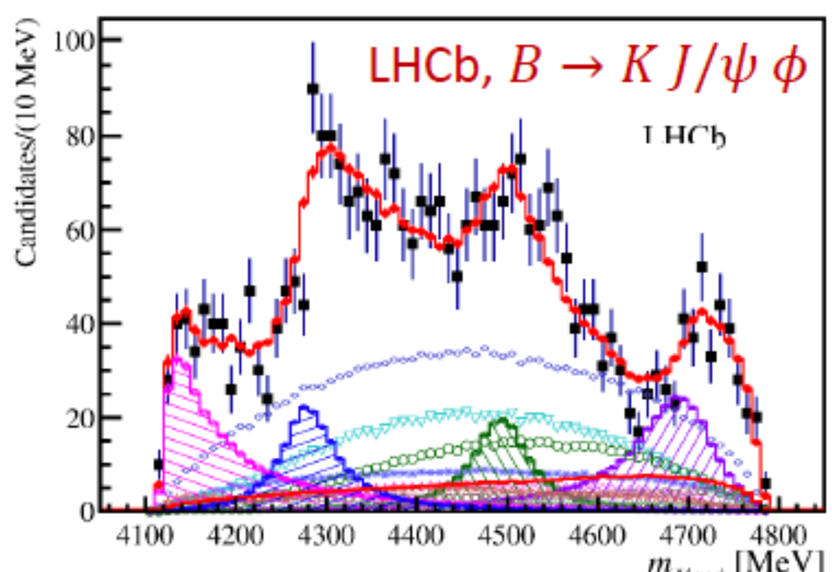
If the width of particle X is not very large we will stay close to the physical region. This almost singular behavior of $A(s)$ for certain physical s causes the peaking effect to which we refer as an (X, Y, Z) peak.



BESIII PRL 112, 022001







Identifying resonances

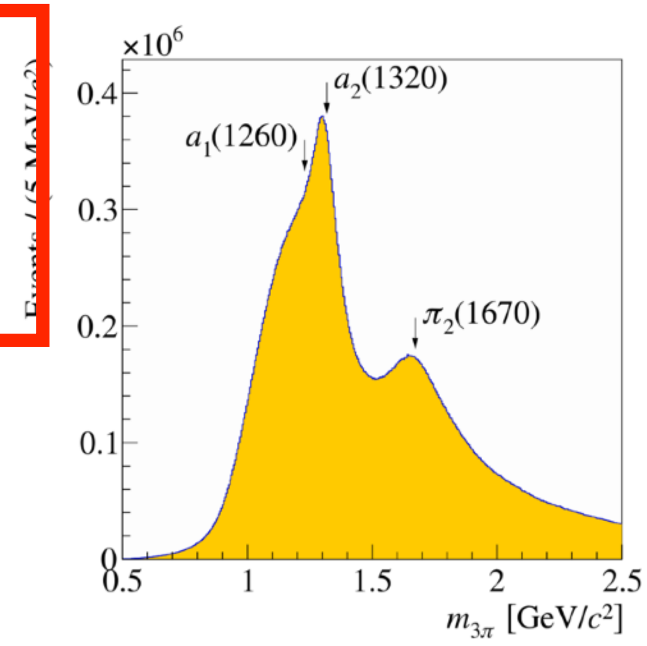
Experimental or lattice signatures (real axis data: cross section bumps and dips, energy levels)

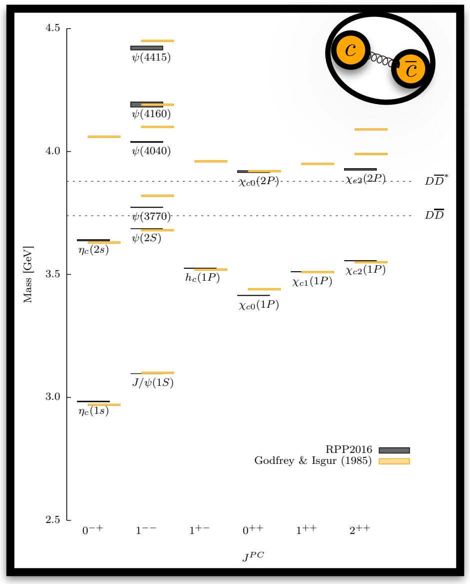
Reaction amplitudes

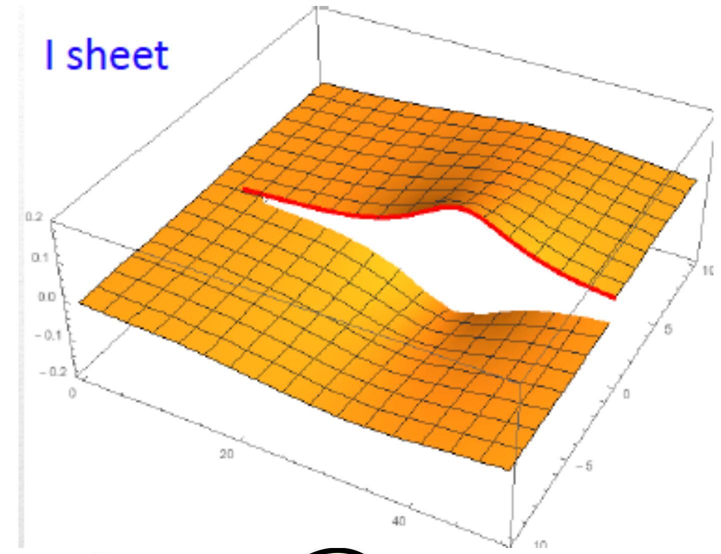
Theoretical signatures (complex plane singularities: poles, cusps)

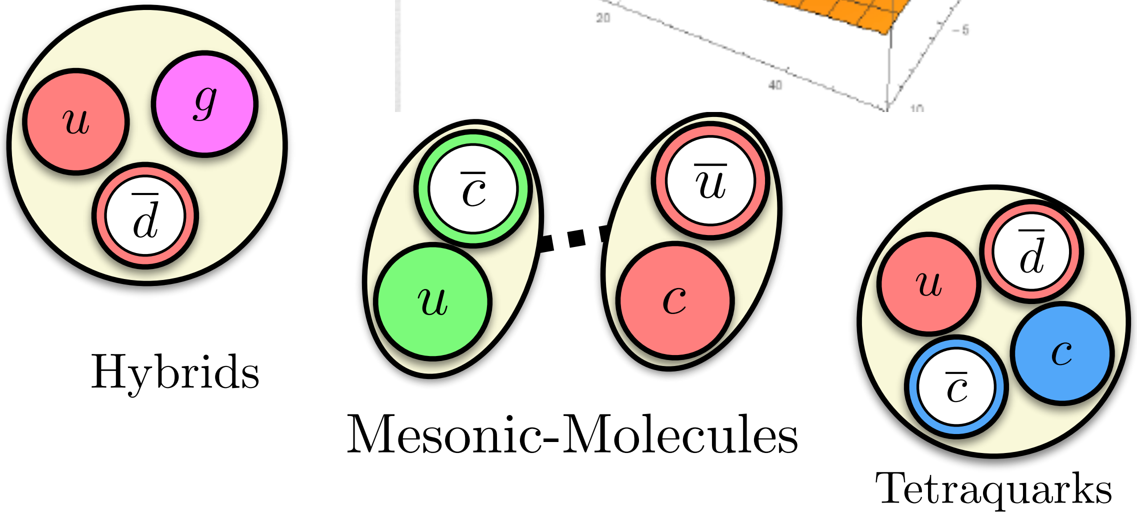
Microscopic Models

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

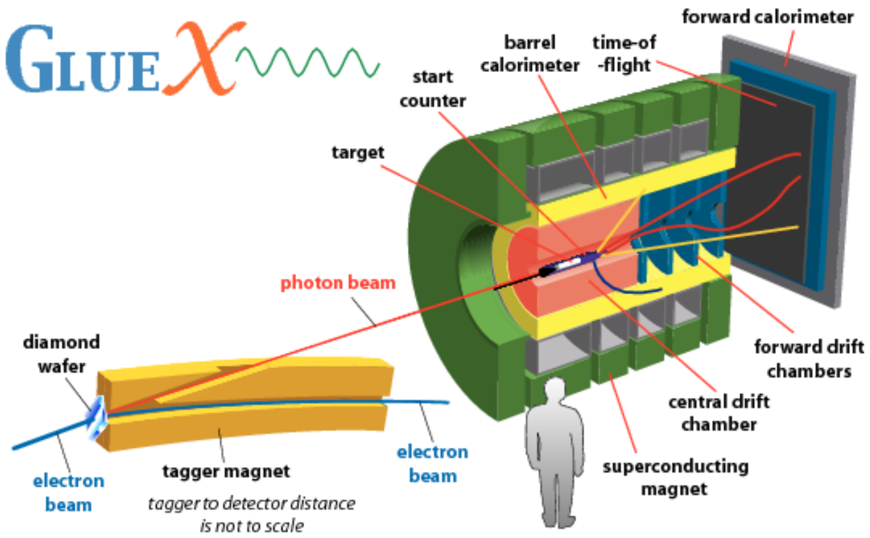


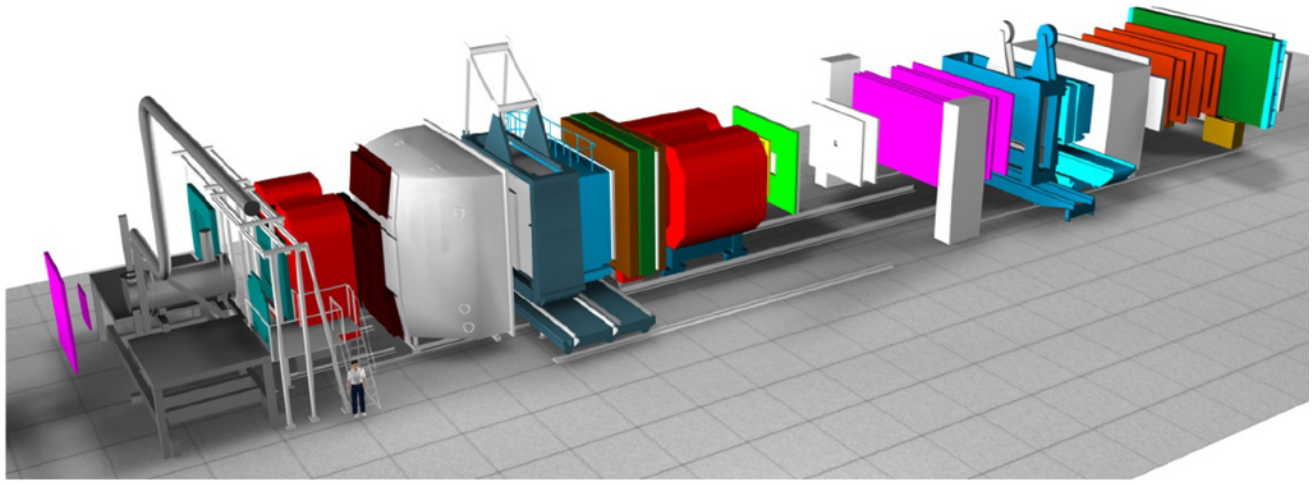


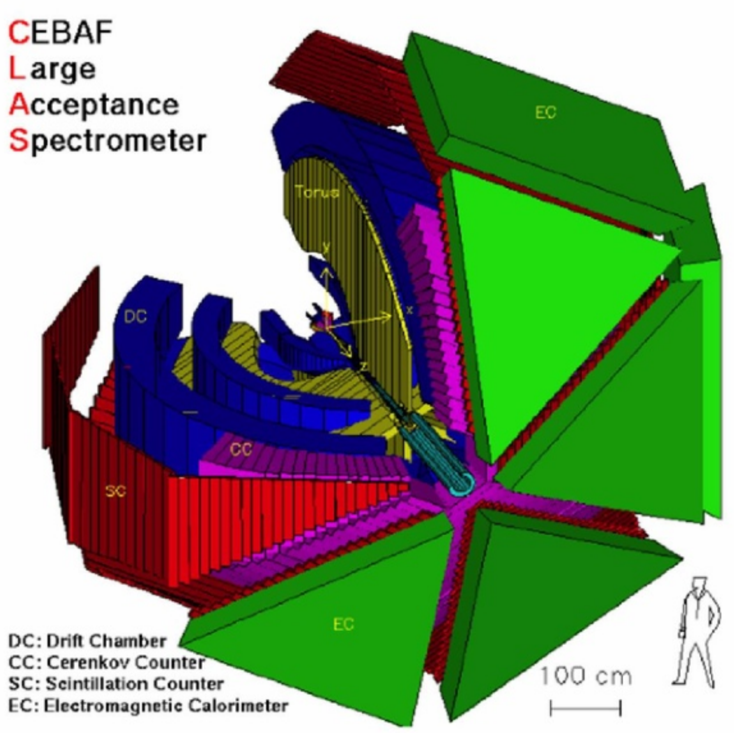




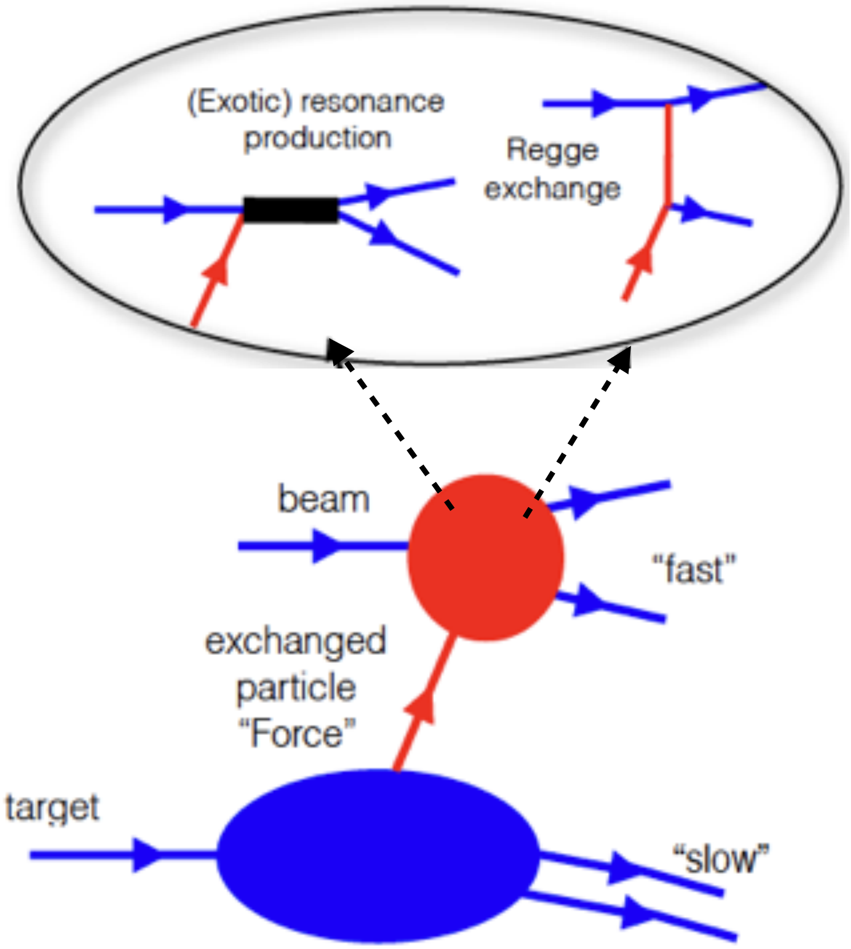
Spectroscopy from peripheral production





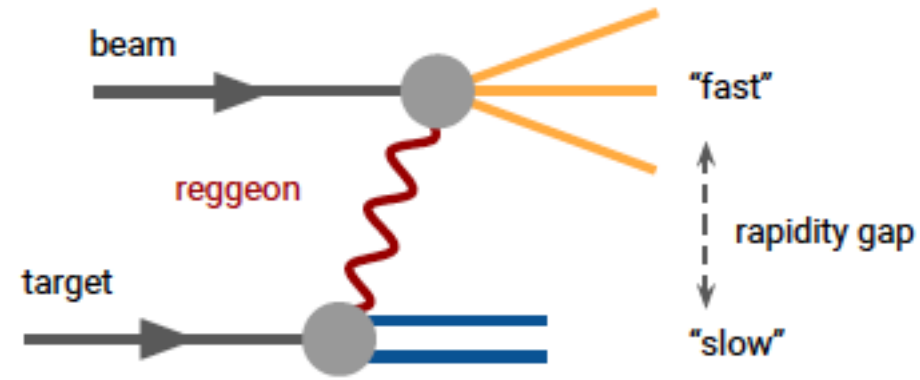


- Need to establish factorization between beam and target fragmentation (Regge factorization)
- Single Regge pole exchange dominate over cut other singularities (cuts, daughters)



Global Regge analysis

- Test Regge pole hypothesis and estimate corrections (daughters, cuts)



- Factorizable Regge pole exchange

$$\mathcal{R}(s,t) \equiv \left(\frac{1-z_s}{2}\frac{\nu}{-t}\right)^{\frac{1}{2}|\mu-\mu'|}\left(\frac{1+z_s}{2}\right)^{\frac{1}{2}|\mu+\mu'|}$$

$$A_{\mu_4\mu_3\mu_2\mu_1} = \mathcal{R}(s,t)\sqrt{-t}^{|\mu_1-\mu_3|}\sqrt{-t}^{|\mu_2-\mu_4|}\,\hat{\beta}^{e13}_{\mu_1\mu_3}(t)\hat{\beta}^{e24}_{\mu_2\mu_4}(t)\mathcal{F}_e(s,t)$$

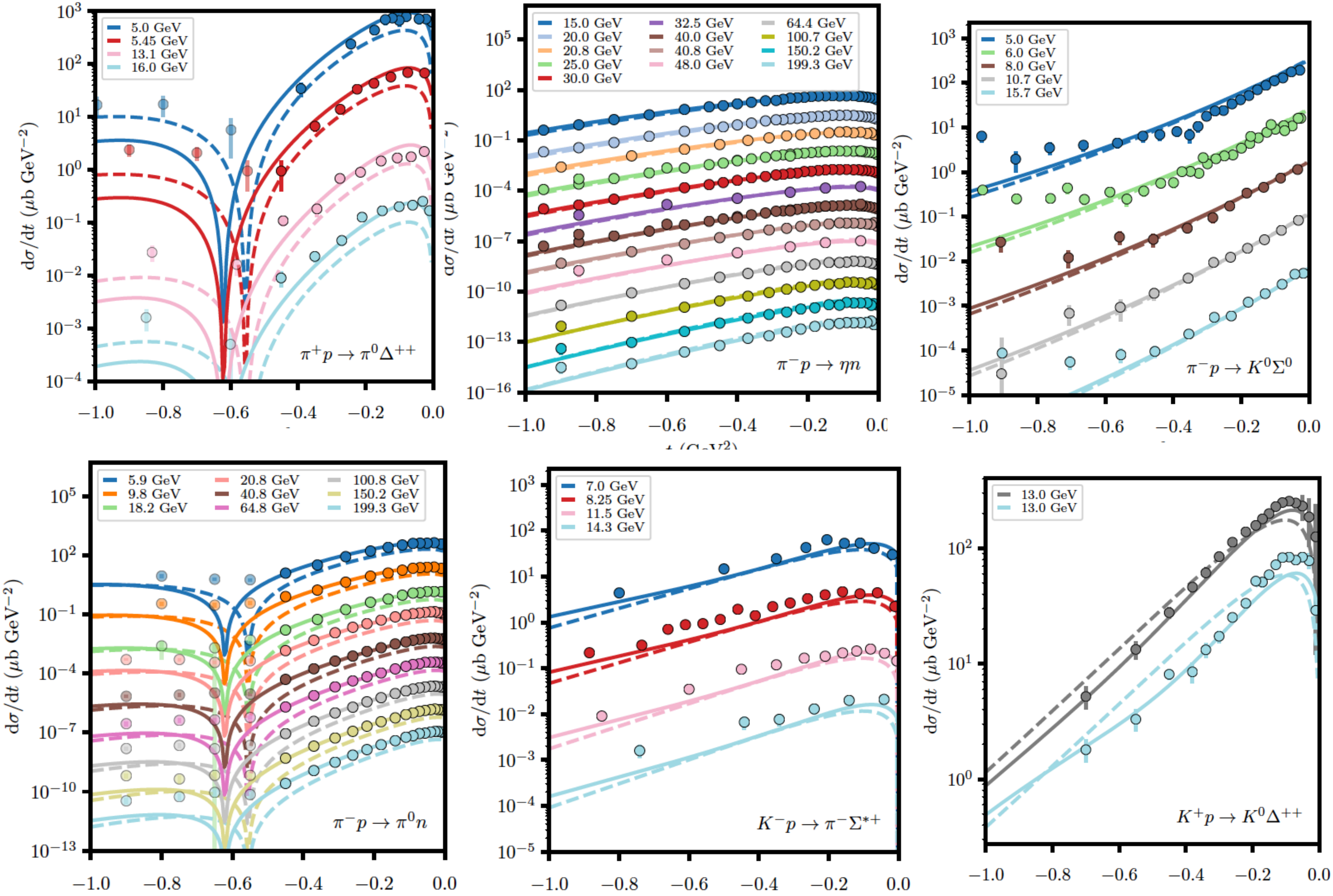
$$\mathcal{F}_e(s,t) = -\frac{\zeta_e \pi \alpha_e^1}{\Gamma(\alpha_e(t)-l_e+1)}\frac{1+\zeta_e e^{-i\pi\alpha_e(t)}}{2\sin\pi\alpha_e(t)}\left(\frac{s}{s_0}\right)^{\alpha_e(t)}$$

- $N_{Data}=1271$, $N_{par}=9$

$$\mathcal{F}_e(s,t) \underset{t\to m_e^2}{\longrightarrow} \frac{(s/s_0)^{J_e}}{m_e^2-t}.$$

(6 SU(3) couplings, 1 mixing angle, 2 exp. slopes)

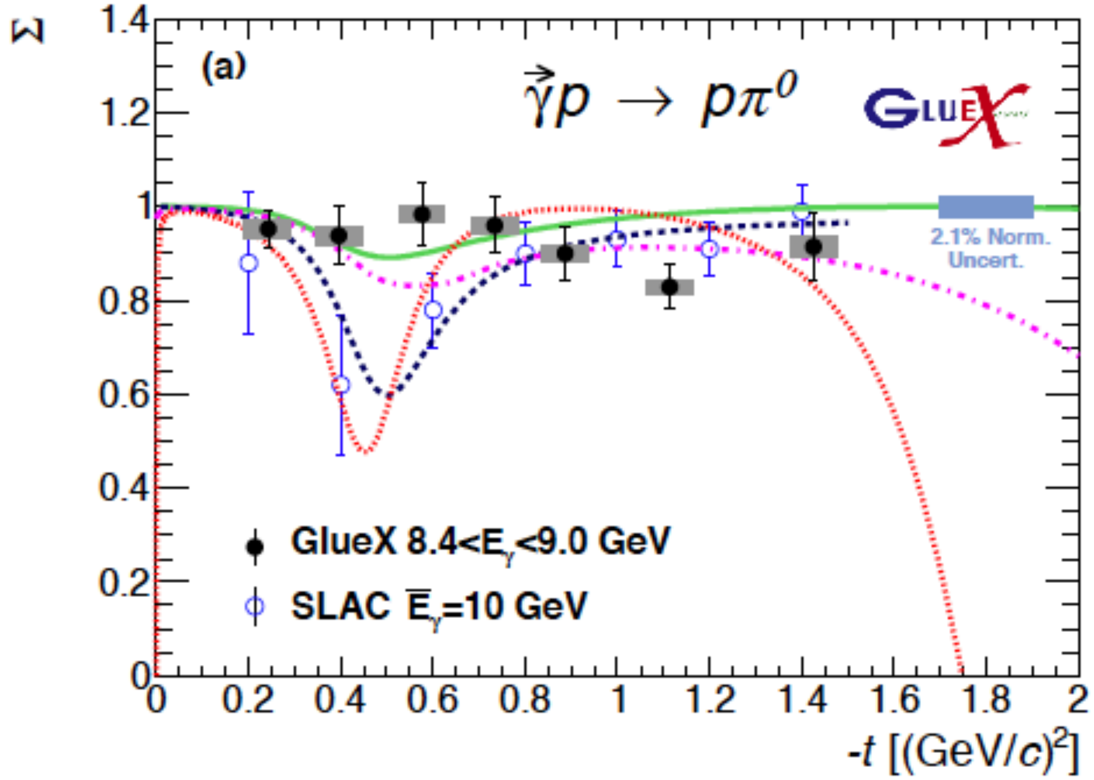
Global Regge pole analysis

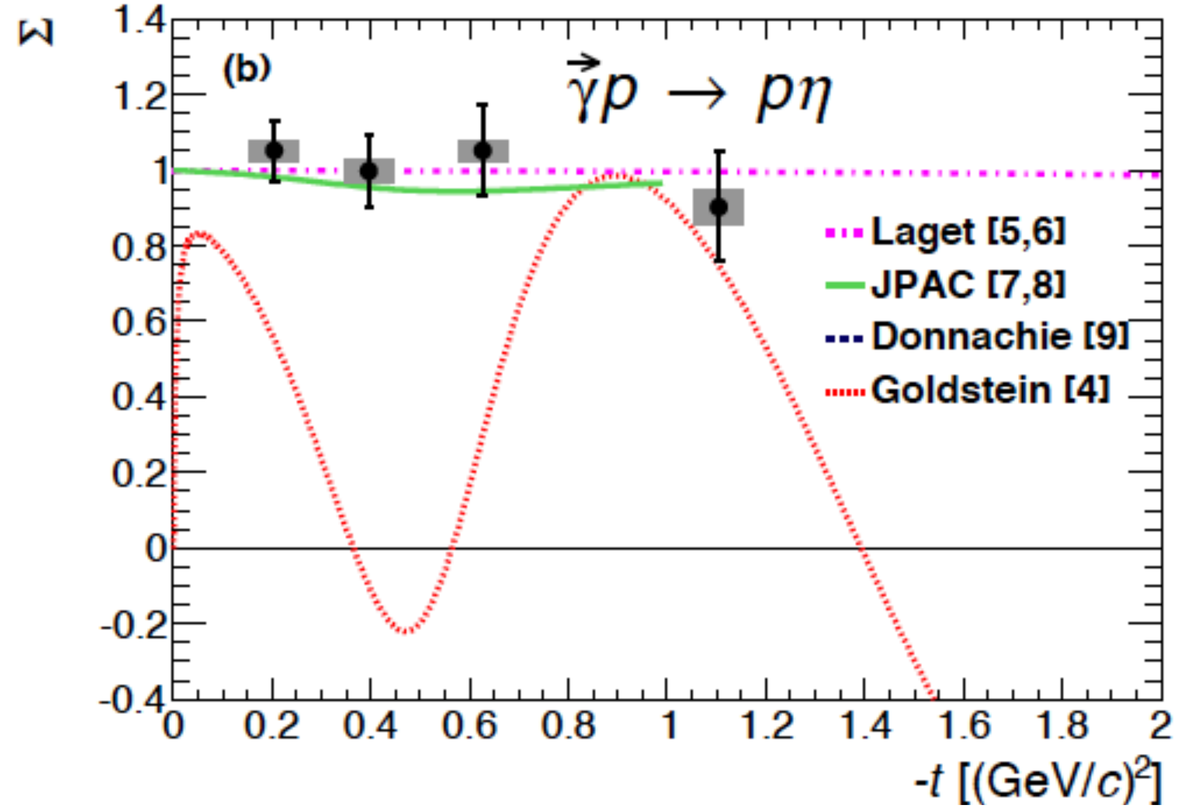


Beam asymmetry: measurement of the exchange process

$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

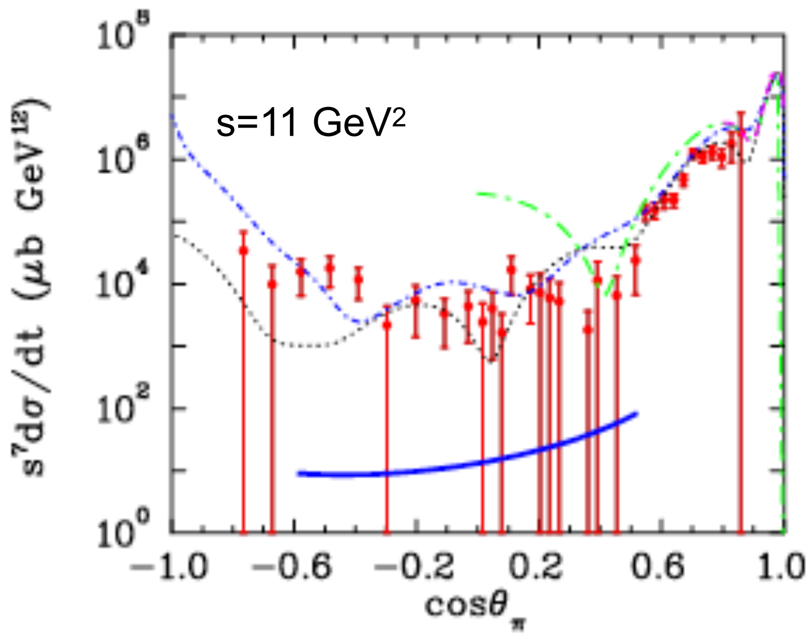
H. Al Ghoul et al. [GlueX]
Phys. Rev. C95 (2017) no.4, 042201
+V. Mathieu, J. Nys [JPAC]



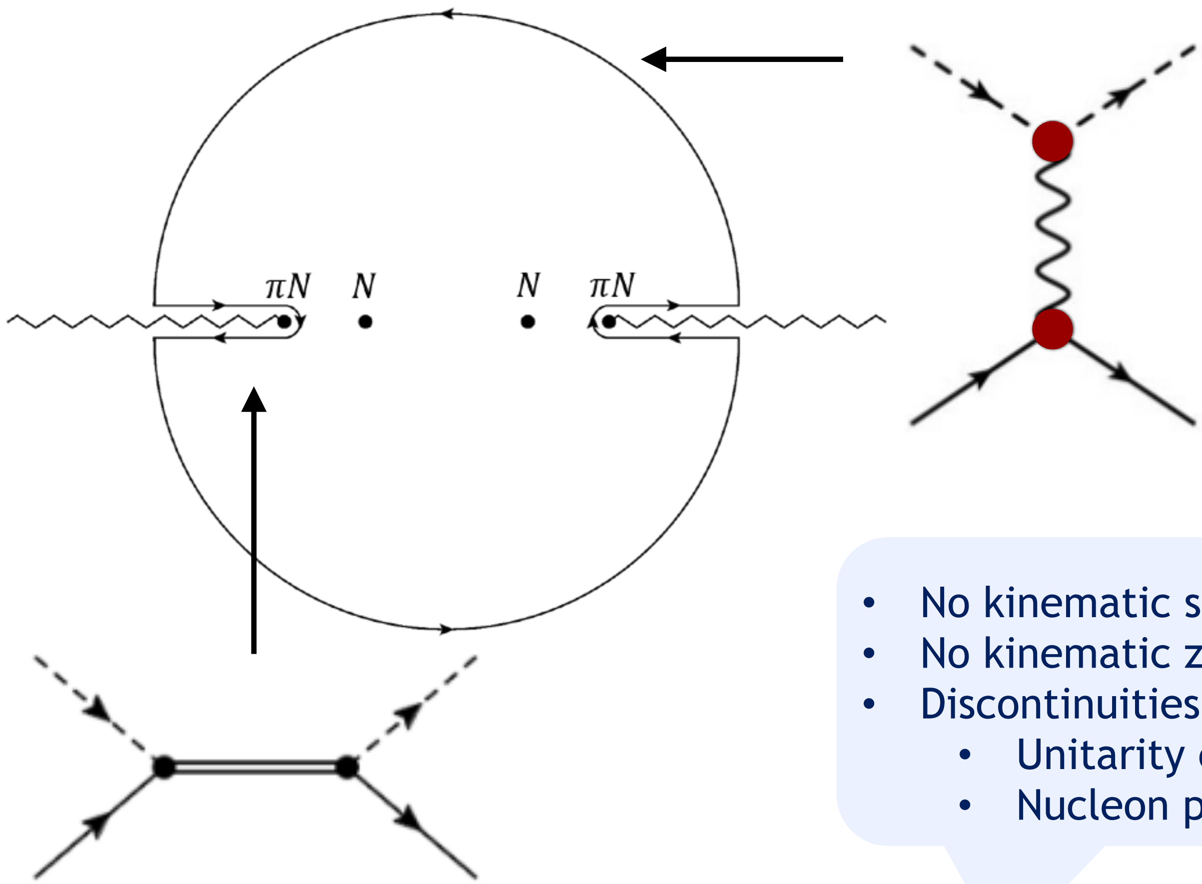


- Possible tension between GlueX and SLAC data ?

  - Regge theory agrees with CLAS data (what's going on with QCD-based models —— ?)



Finite Energy Sum Rules

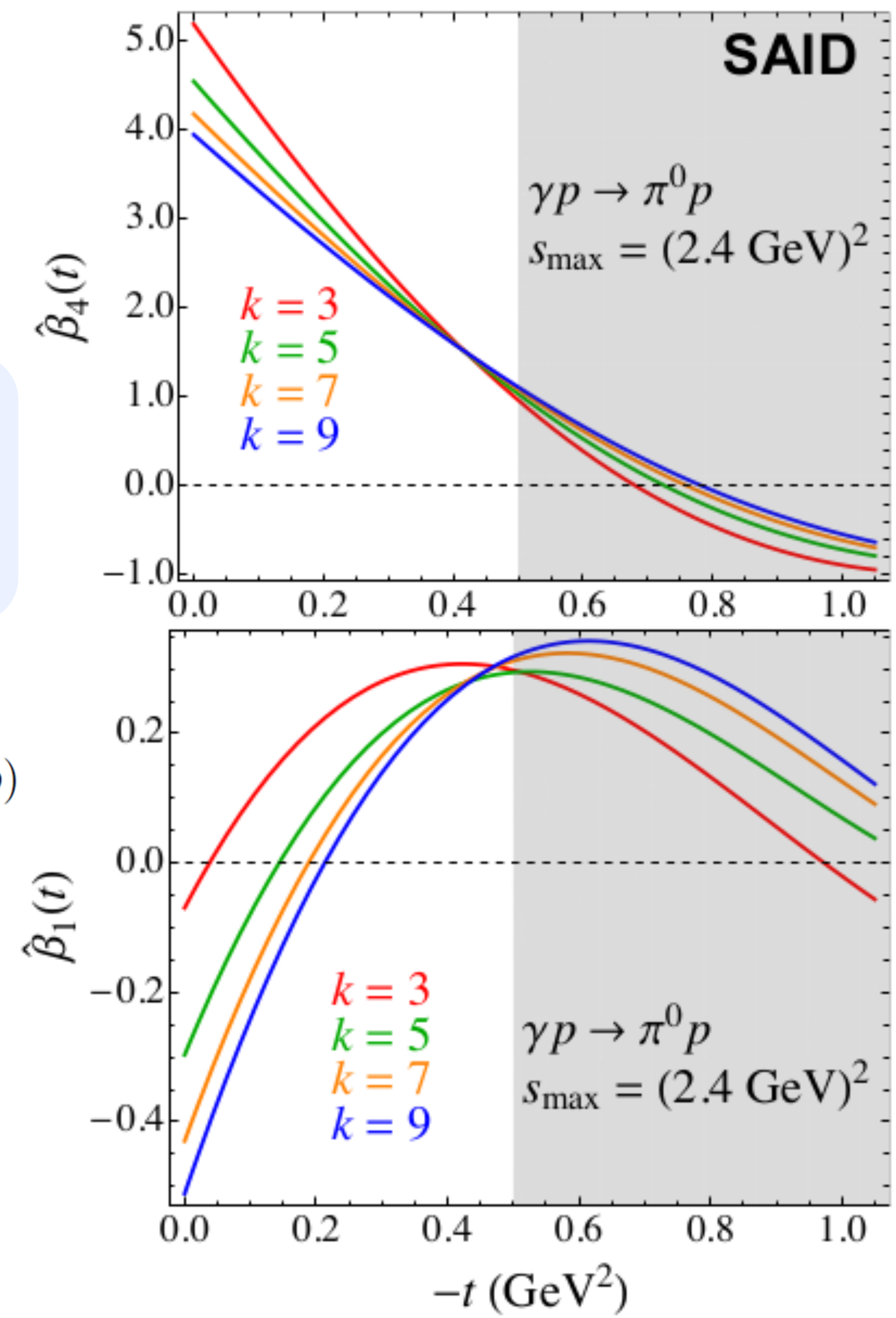


- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

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

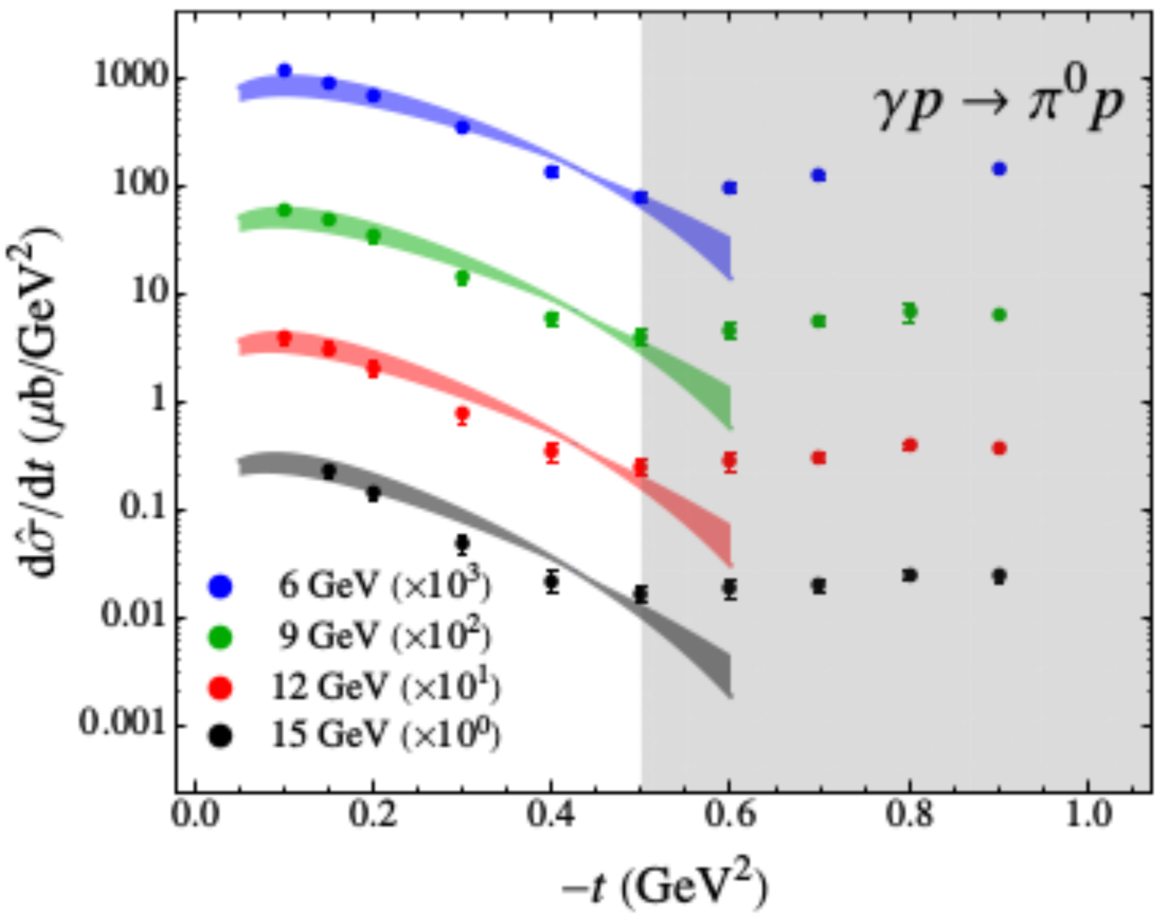
$$\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu = \beta_i(t)\frac{\Lambda^{\alpha(t)+k}}{\alpha(t)+k}$$

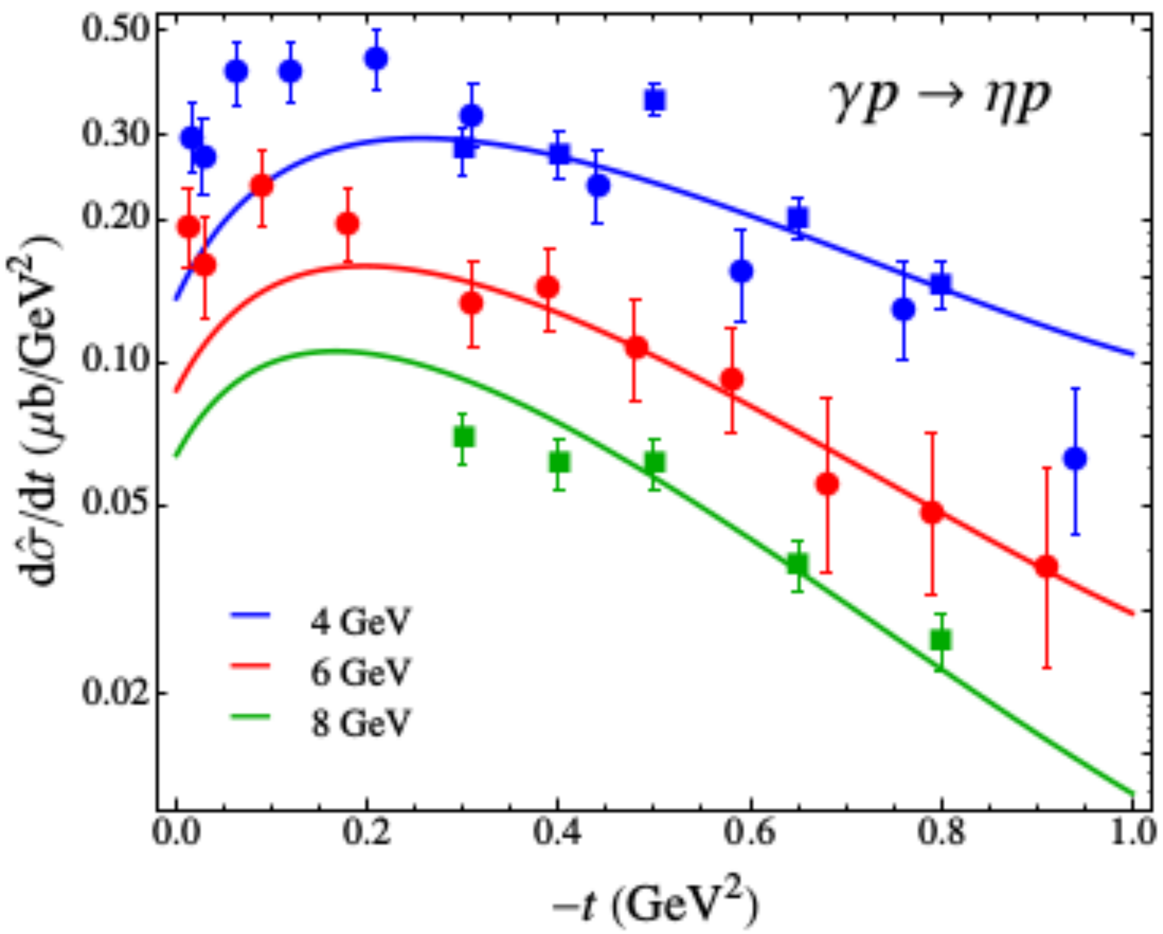
$$\beta_i(t) = \frac{\alpha(t)+k}{\Lambda^{\alpha(t)+k}}\int_0^\Lambda \mathrm{Im}\ A_i(\nu,t)\nu^k d\nu$$



Finite Energy Sum Rules

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





Combine energy regimes

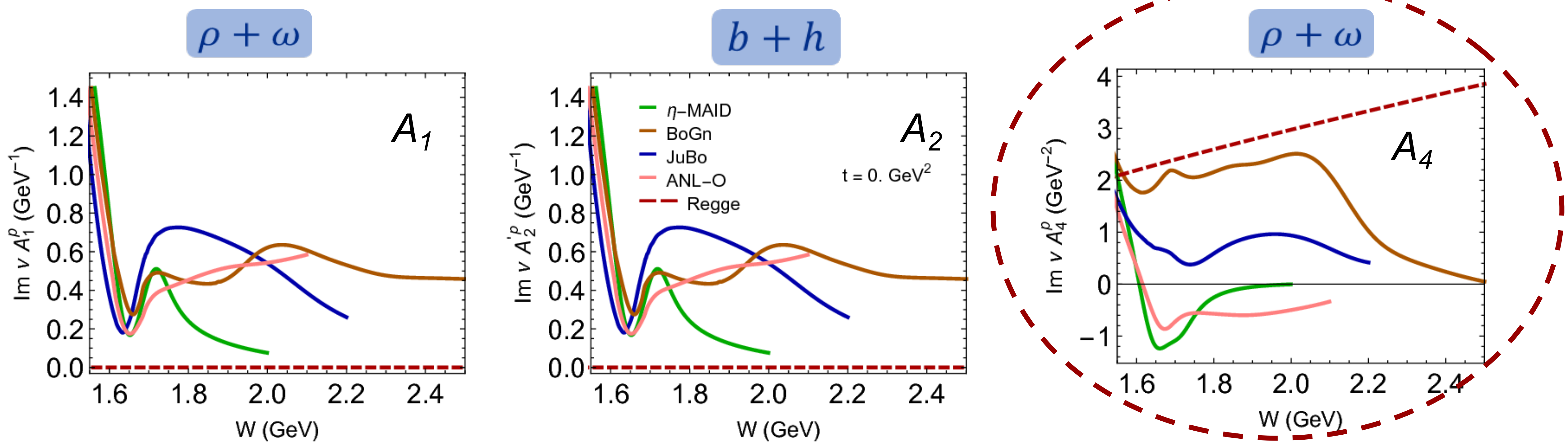
- Low-energy model ((SAID, MAID, Bonn-Gatchina, Julich-Bonn,…)
- Predict high-energy observables

Two applications

- Understand high-energy dynamics
- Constraining low-energy models

Constraining the resonance spectrum

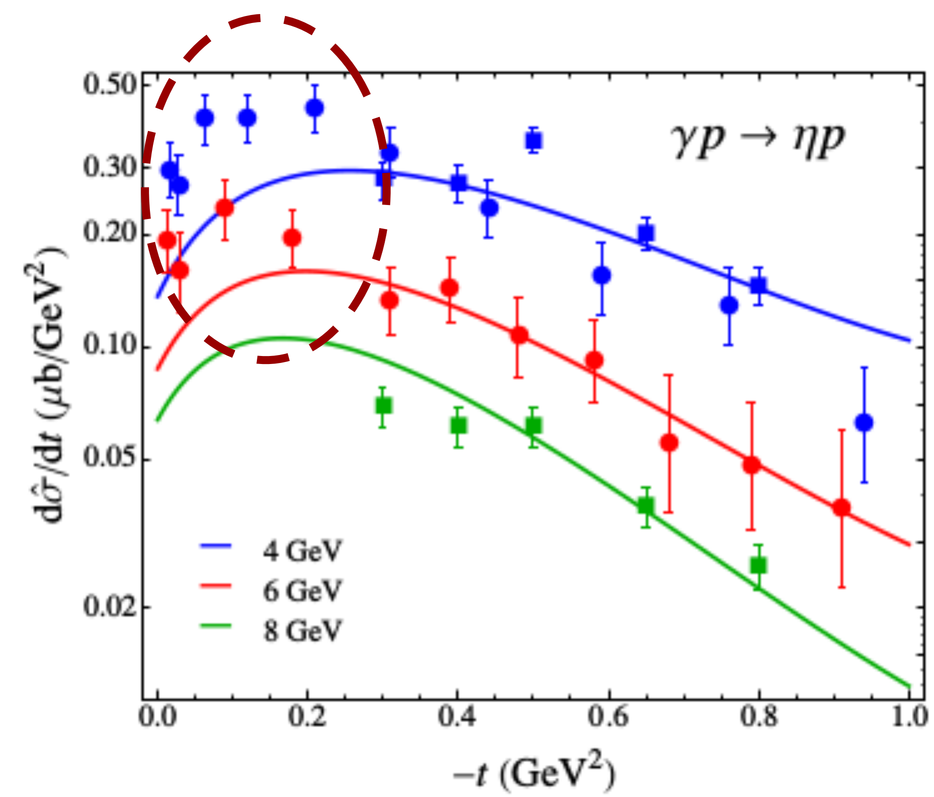
[J.Nys *et al.*, PRD95 (2017) 034014]



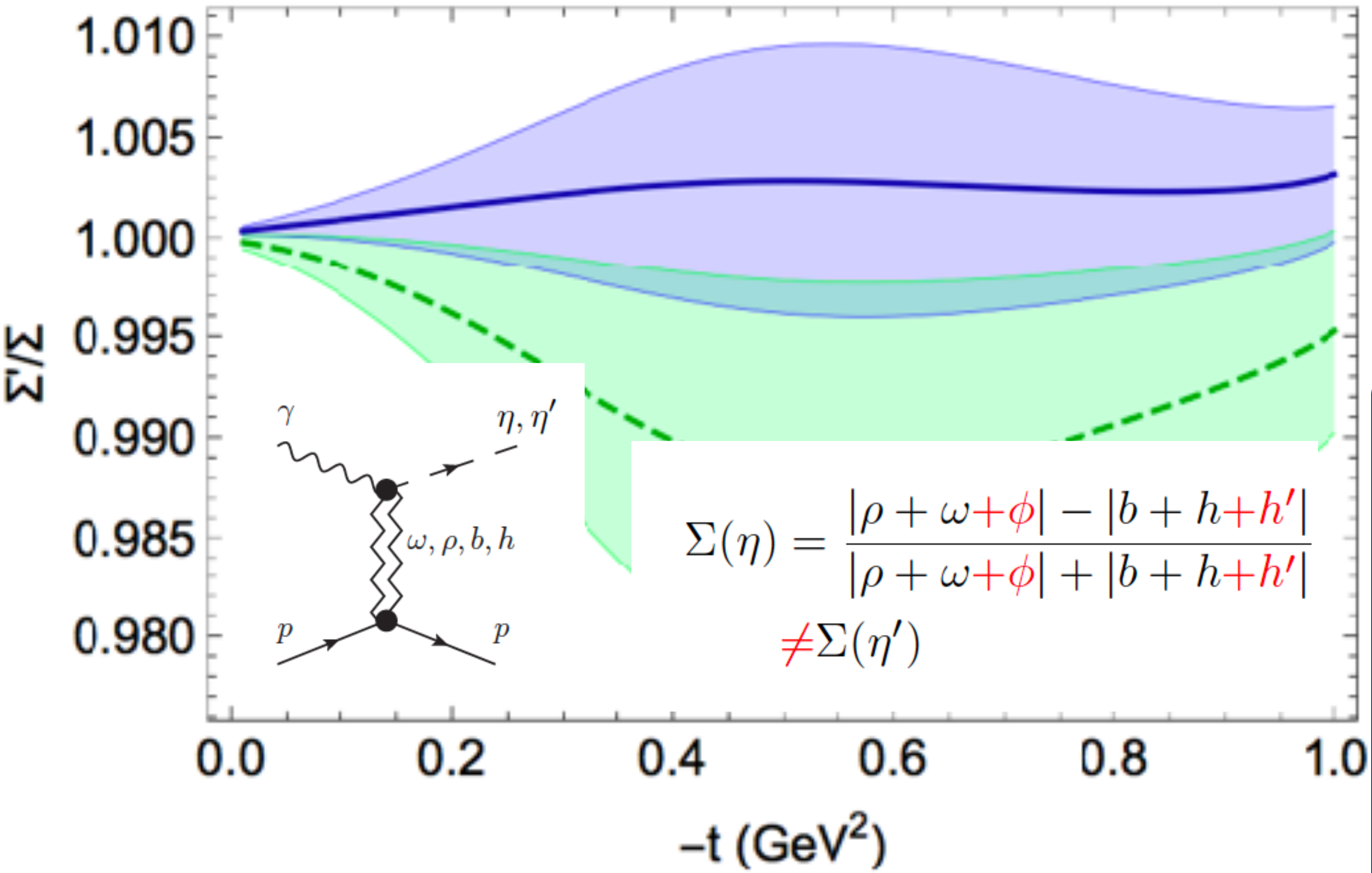
Ambiguities in the low-energy model (η-MAID)
→ Mismatch with high-energy data

Possibilities

- Low-energy model inconsistent
- Cut-off not high enough
    - High mass resonances!



η/η' asymmetry probes coupling to strangeness



$$\Sigma(\eta) = \frac{|\rho + \omega + \phi| - |b + h + h'|}{|\rho + \omega + \phi| + |b + h + h'|} \neq \Sigma(\eta')$$

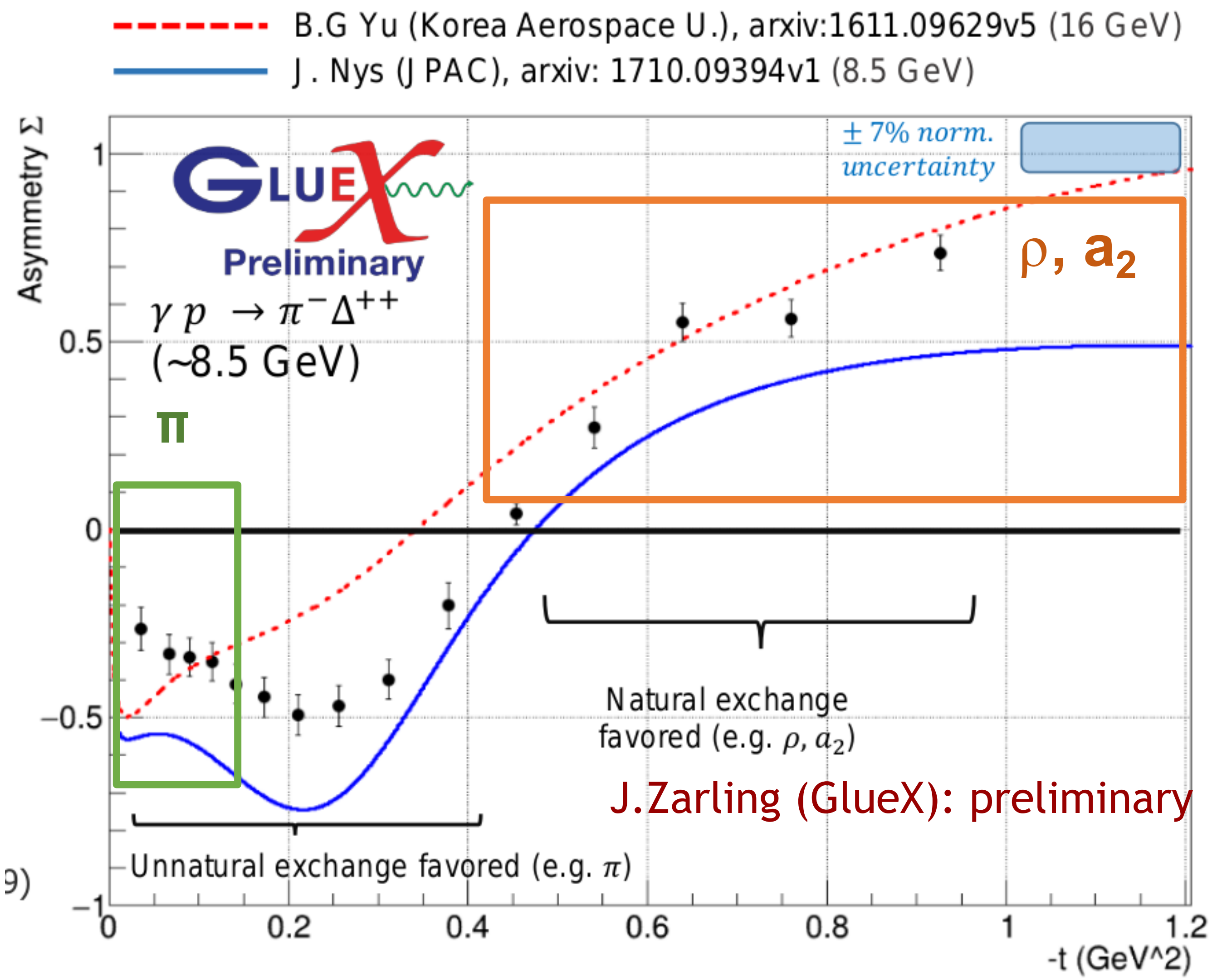
Based on the FESR for η:
predict beam asymmetry for η'

- Same exchanges
- Natural exchanges (ρ,ω) dominant
  - Couplings from radiative decays
  - Mixing angle cancels in ratio
- Unknown behavior of
  - ϕ exchange
  - unnatural exchanges (b,h)

Prediction: ≈ same beam asymmetry

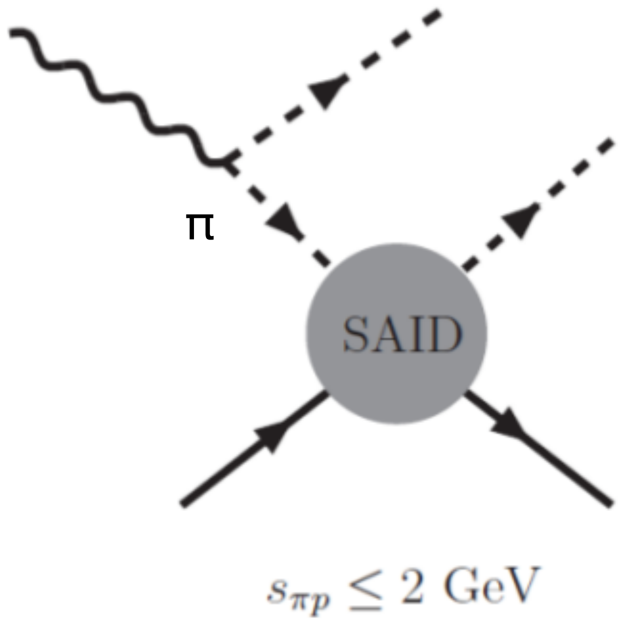
V.Mathieu et al. (JPAC) Phys. Lett. B774, 362 (2017)

πΔ photoproduction



- Stringent test of one-pion-exchange production
- Possible to make parameter-free predictions

J.Nys et al. (JPAC) Phys.Lett. B779, 77 (2018)

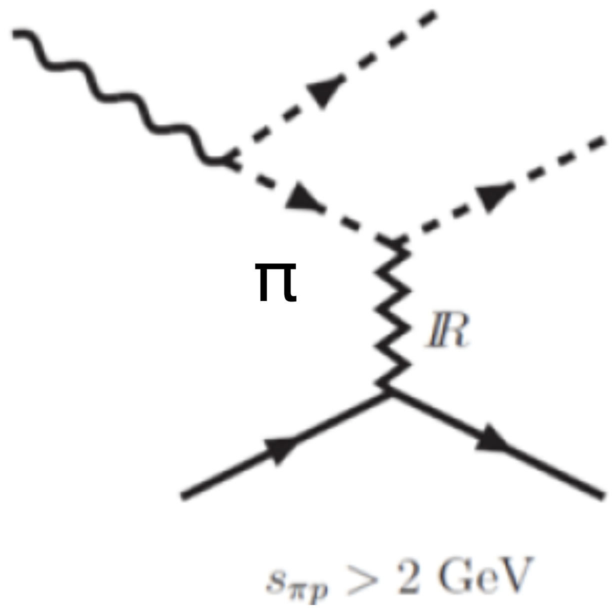


Łukasz Bibrzycki et al. (Cracow,JPAC)

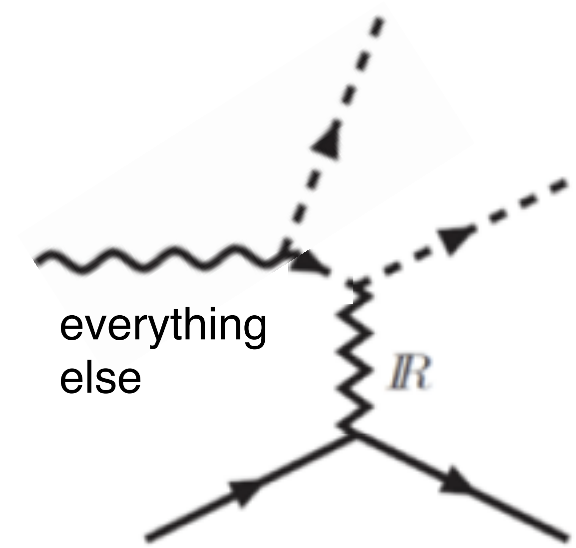
Comparison to GlueX data

- Confirmation of interference pattern
- High -t: natural, low -t: unnatural
- Mismatch: oddly behaved π exchange
  - Ongoing analysis
  - Experimental or theoretical?

OPE vs other exchanges

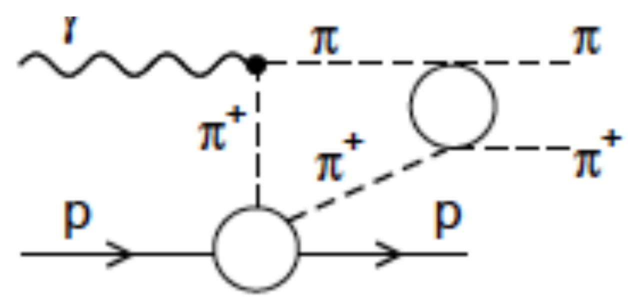


- Long range exchange

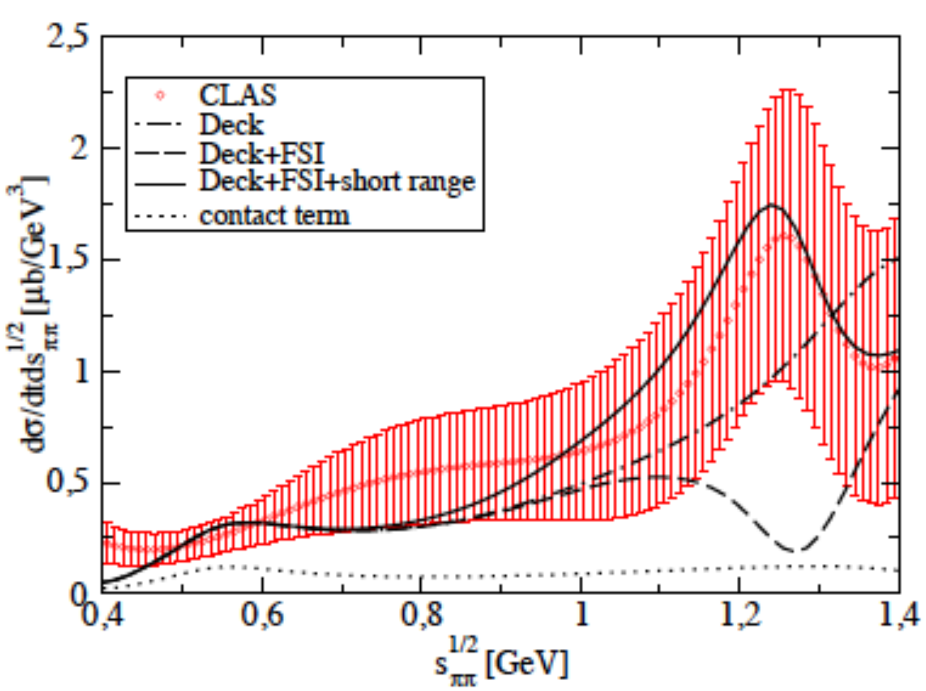


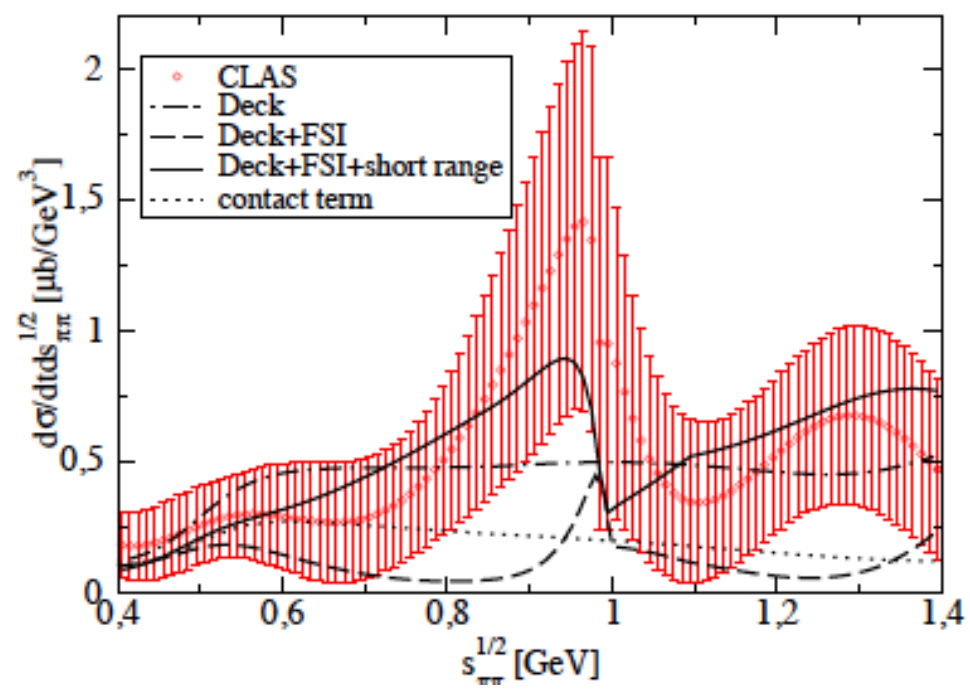
- Short range exchange

- When Final State Interactions are taken into account one produces a dip the other a pick at a resonance mass



Bibrzycki,Bydzovsky,Kaminski,AS (2018)



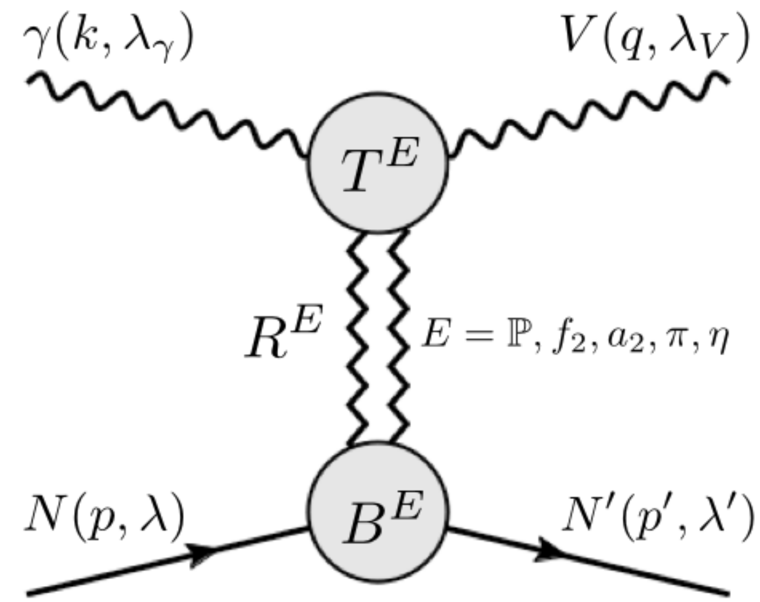


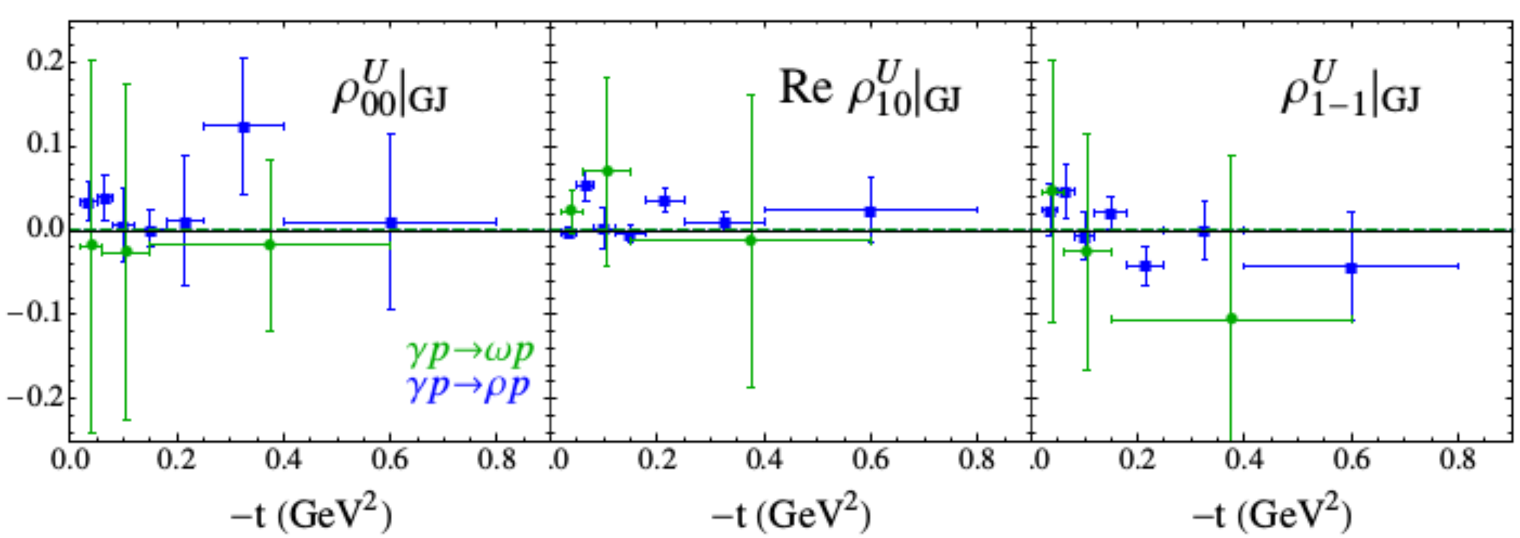
Vector meson production

- Pomeron dominates at high energies
- Isoscalar exchanges dominantly helicity non-flip (λ=λ’)
- Unnatural exchanges: only helicity flip (|λ-λ’|=1)

$$\mathcal{M}_{\substack{\lambda_V,\lambda_\gamma \\ \lambda',\lambda}}(s,t) = \sum_{E=\pi,\eta,\mathbb{P},f_2,a_2} \mathcal{M}^{E}_{\substack{\lambda_V,\lambda_\gamma \\ \lambda',\lambda}}(s,t)$$

$$\mathcal{M}^{\substack{N\\U}}_{\substack{-\lambda_\gamma,-\lambda_V \\ \lambda,\lambda'}} = \pm(-1)^{\lambda_\gamma-\lambda_V}\mathcal{M}^{\substack{N\\U}}_{\substack{\lambda_\gamma,\lambda_V \\ \lambda,\lambda'}}$$





$$\rho^{\substack{N\\U}}_{00} = \frac{1}{2}\left(\rho^0_{00} \mp \rho^1_{00}\right),$$

$$\mathrm{Re}\,\rho^{\substack{N\\U}}_{10} = \frac{1}{2}\left(\mathrm{Re}\,\rho^0_{10} \mp \mathrm{Re}\,\rho^1_{10}\right),$$

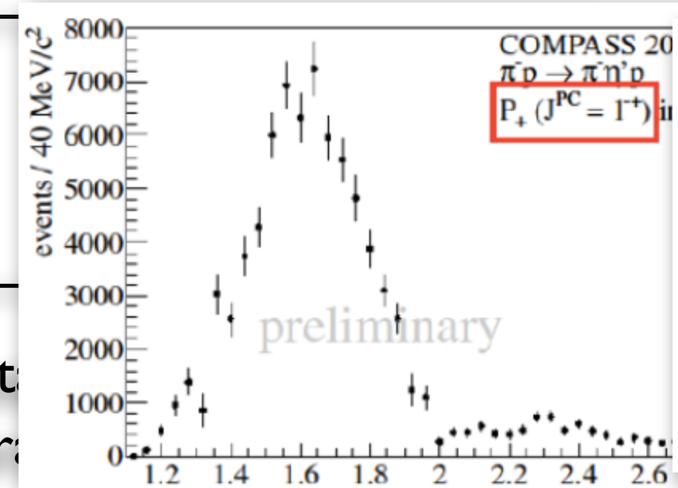
$$\rho^{\substack{N\\U}}_{1-1} = \frac{1}{2}\left(\rho^1_{1-1} \pm \rho^1_{11}\right).$$

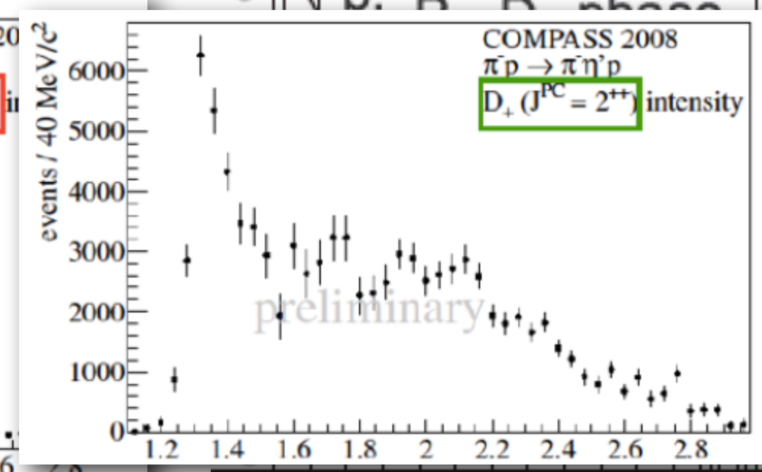
V.Mathieu, et al. (JPAC) Phys.Rev. D97, 094003 (2018)

$\pi^- p \to \eta \pi^- p$

$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

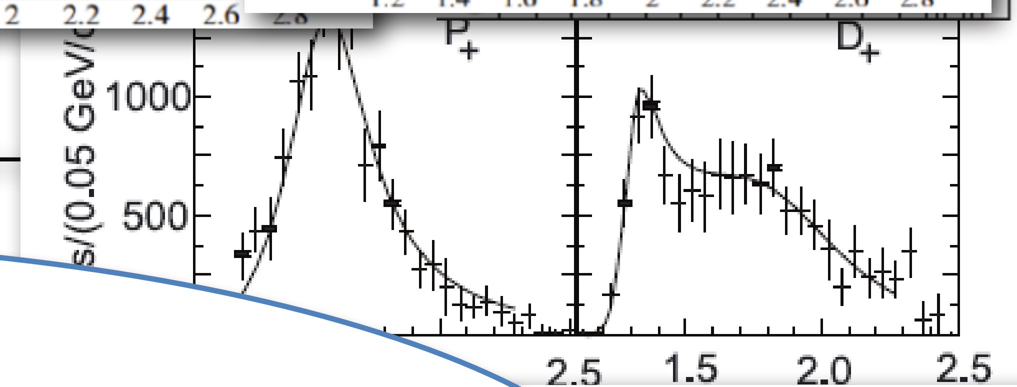
$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2





$\pi^- p \to \eta \pi^0 n$

No consistent B-W interpret
possible but a weak ηπ inter
exists and can reproduce the exotic wave



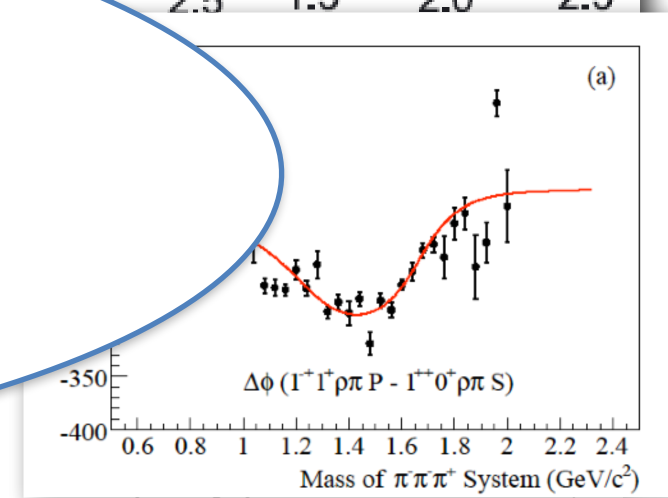
$\pi^- p \to \eta' \pi^- p$

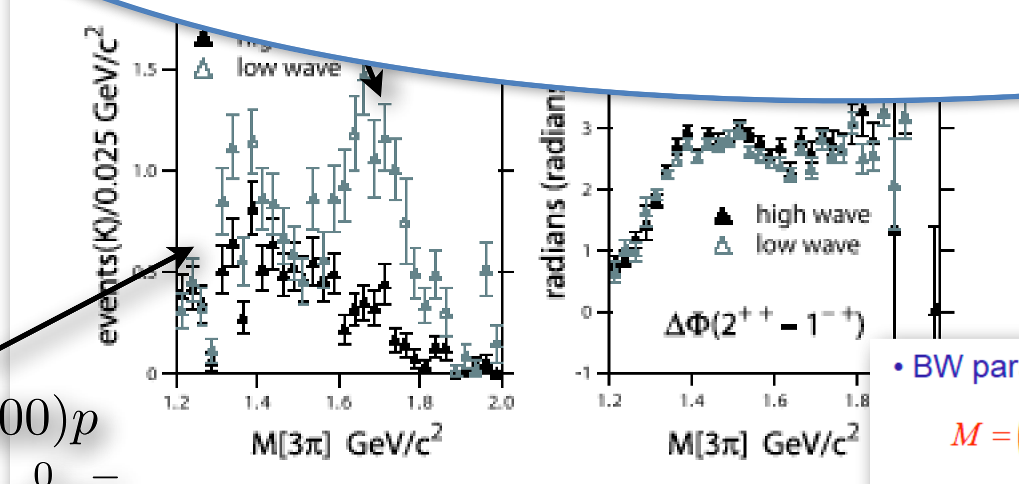
$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

$\Gamma = 34$

$\pi^- p \to \rho^0$

Need to be confirmed



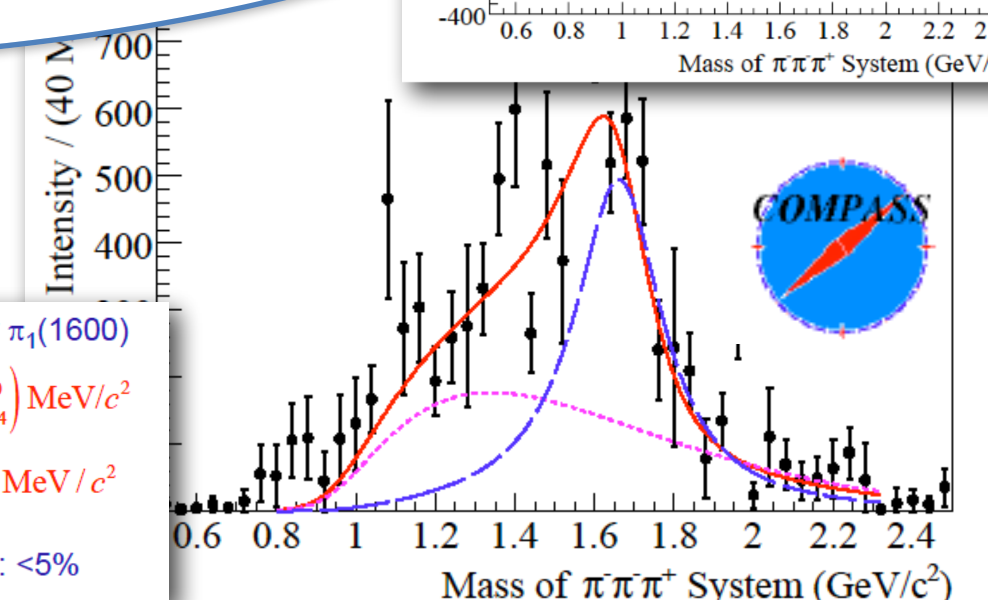


$\pi^- p \to \pi_2^-(1600) p$

$\pi_2^- \to \rho^0 \pi^-$

$\rho^0 \to \pi^+ \pi^-$

FIG. 25: (a) The $1^{-+}1^+$ P-wave $\rho\pi$ partial wave charged mode ($\pi^-\pi^-\pi^+$) for the high-wave set PWA a low-wave set PWA and (b) the phase difference $\Delta\Phi$ b the 2^{++} and 1^{-+} for the two wave sets.

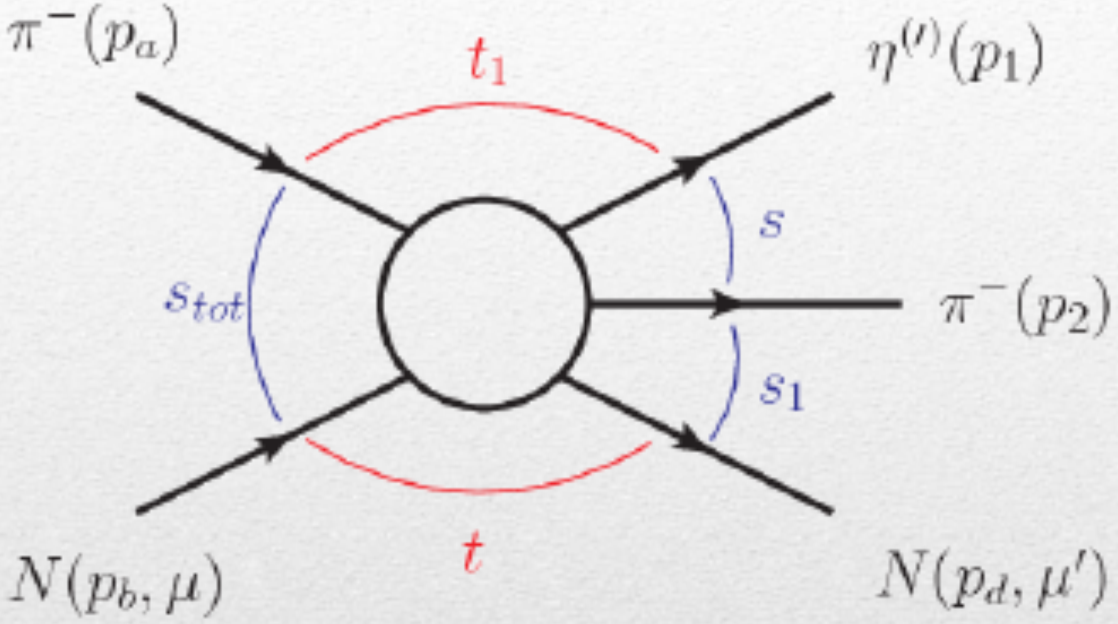


- BW parameters for $\pi_1(1600)$
  - $M = \left(1660 \pm 10^{+0}_{-64}\right)$ MeV/c^2
  - $\Gamma = \left(269 \pm 21^{+42}_{-64}\right)$ MeV / c^2
- Leakage negligible: <5%

2-meson peripheral production : ηπ

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

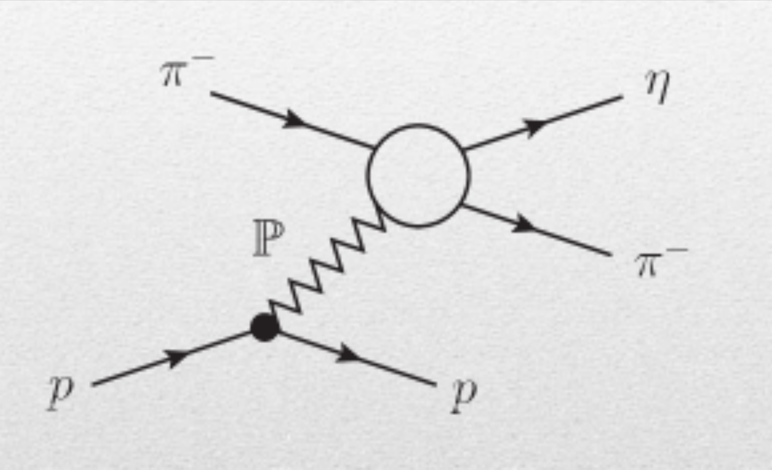
- Process is at fixed s_{tot}, and integrated t. Interested in resonances in s
- Recoil proton kinematically decouples from final state $\eta\pi$



- Expand amplitude into partial waves

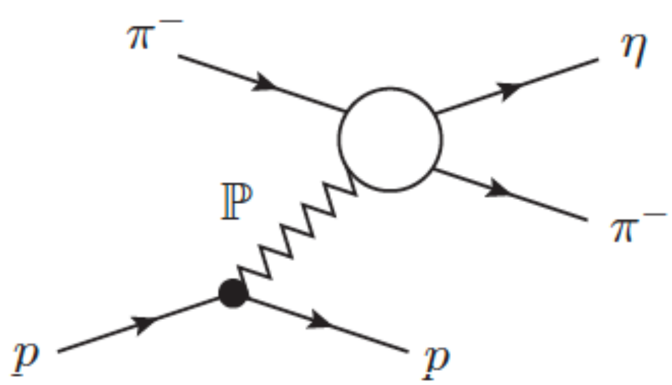
$$A_{\mu'\mu}(s_{tot}, s, t, s_1, t_1) = \sum_{LM\epsilon} a^{\epsilon}_{LM,\mu'\mu}(s_{tot}, t, s) Y^{\epsilon}_{LM}(\theta, \phi)$$

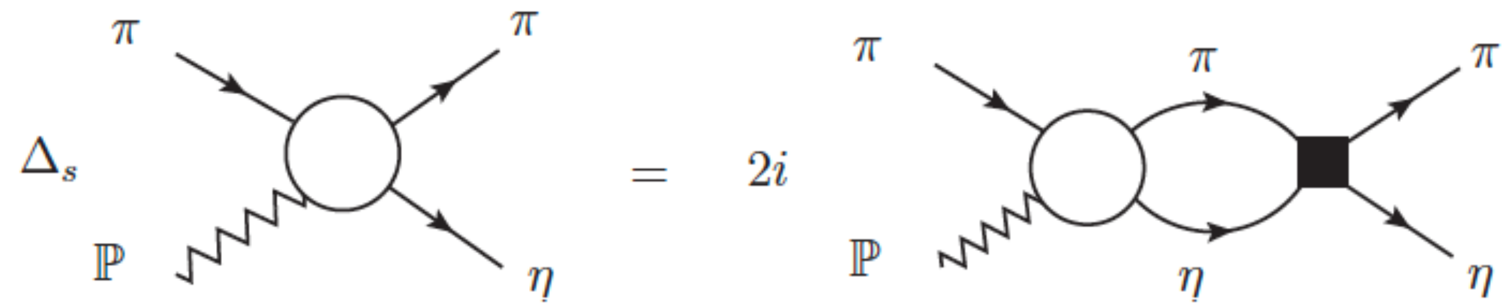
$$a^{\epsilon}_{LM,\mu'\mu}(s_{tot}, t, s) \to a^{1}_{L,M=\pm 1}(s_{tot}, t, s)$$



A.Jackura et al. (JPAC/COMPASS) Phys.Lett. B779, 464 (2018)

$$\Delta_s\, a_{\ell m_\ell}(s) = 2i\,\rho_\ell(s) t^*_\ell(s) a_{\ell m_\ell}(s)$$





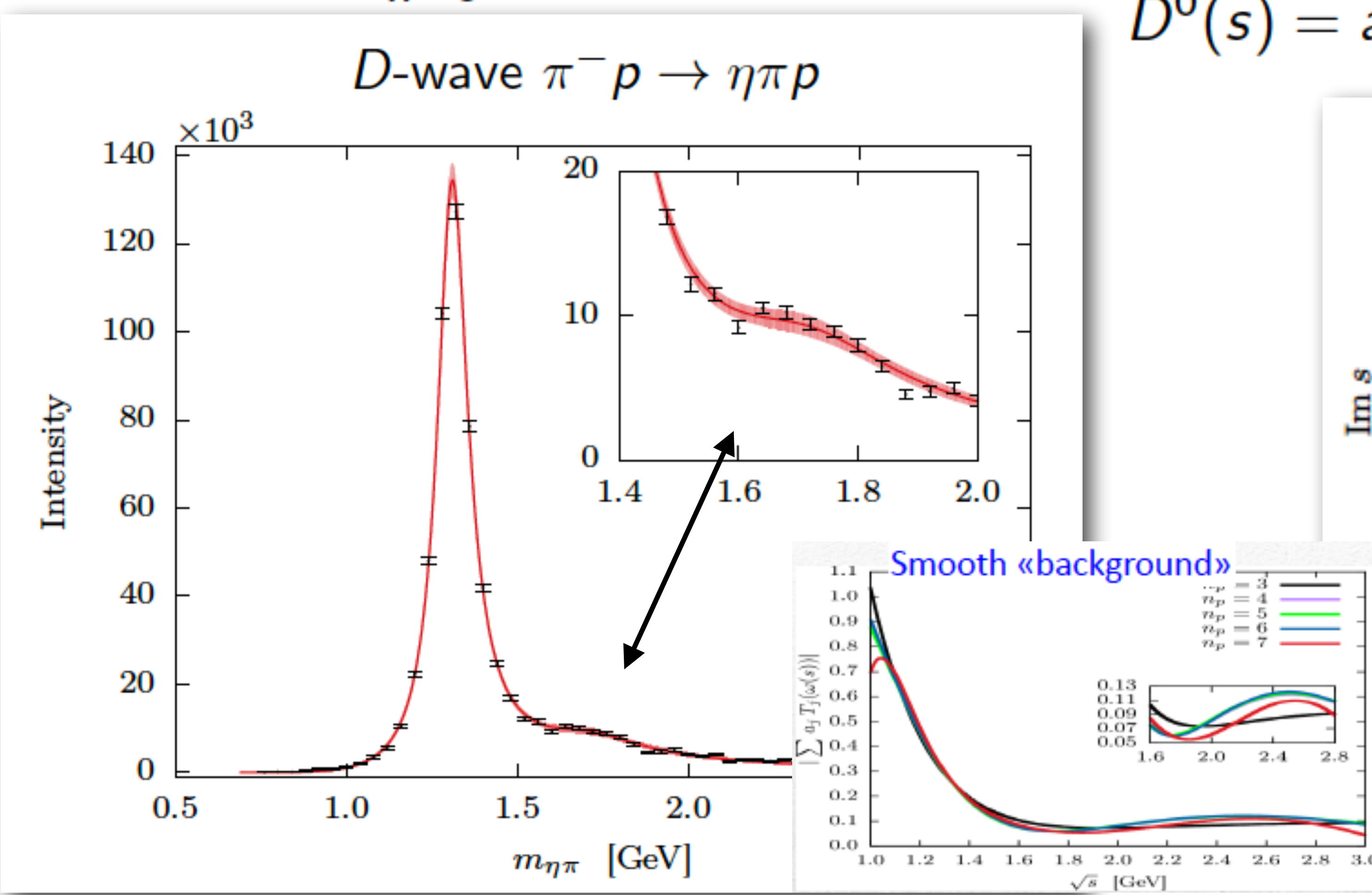
Production($s_{\eta\pi}$) x Interactions in ηπ ($s_{\eta\pi}$)

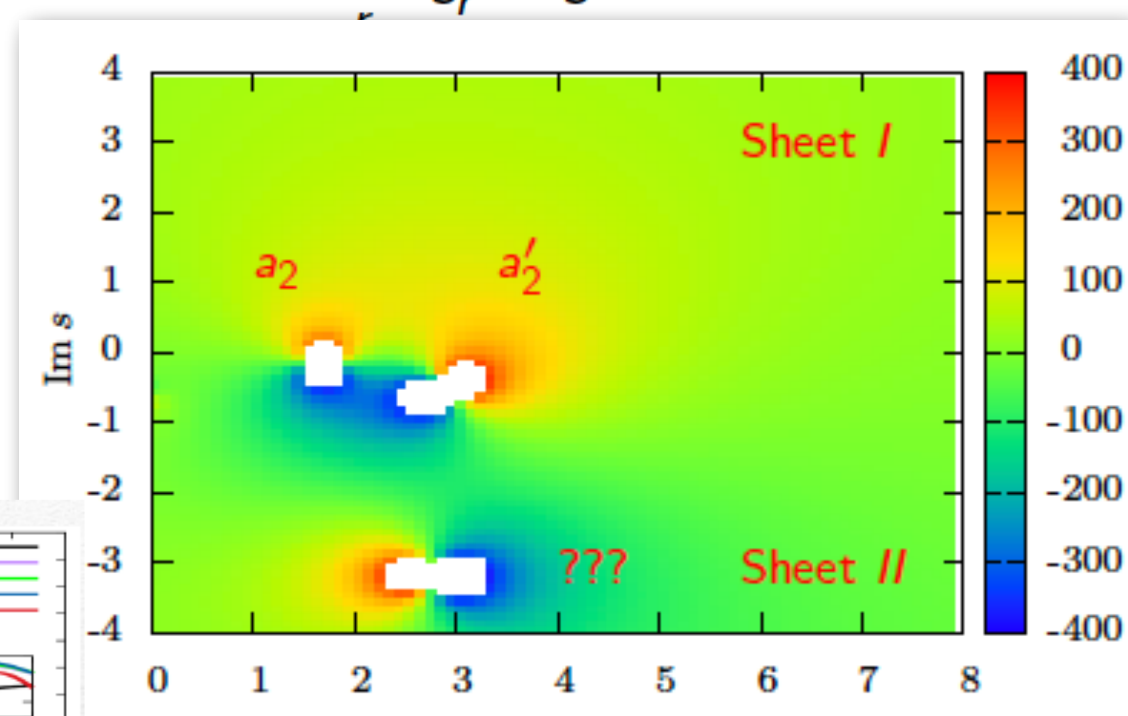
Constrained by unitary

$$a_{\ell m_\ell} = f_{\ell m_\ell}(s) t_\ell(s)$$

$$f_{\ell m_\ell}(s) = \sum_{n=0} \alpha_n T_n(\omega(s)) \quad t_\ell(s) = N(s)/D(s) \quad D(s) = D^0(s) - \frac{s}{\pi}\int_{s_{th}}^{\infty} ds' \frac{\rho(s')N(s')}{s'(s'-s)}$$

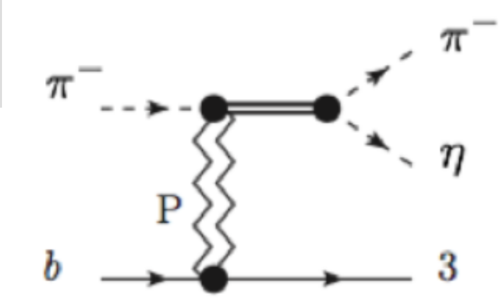
$$D^0(s) = a - bs - \sum_r \frac{c_r}{s_r - s}$$





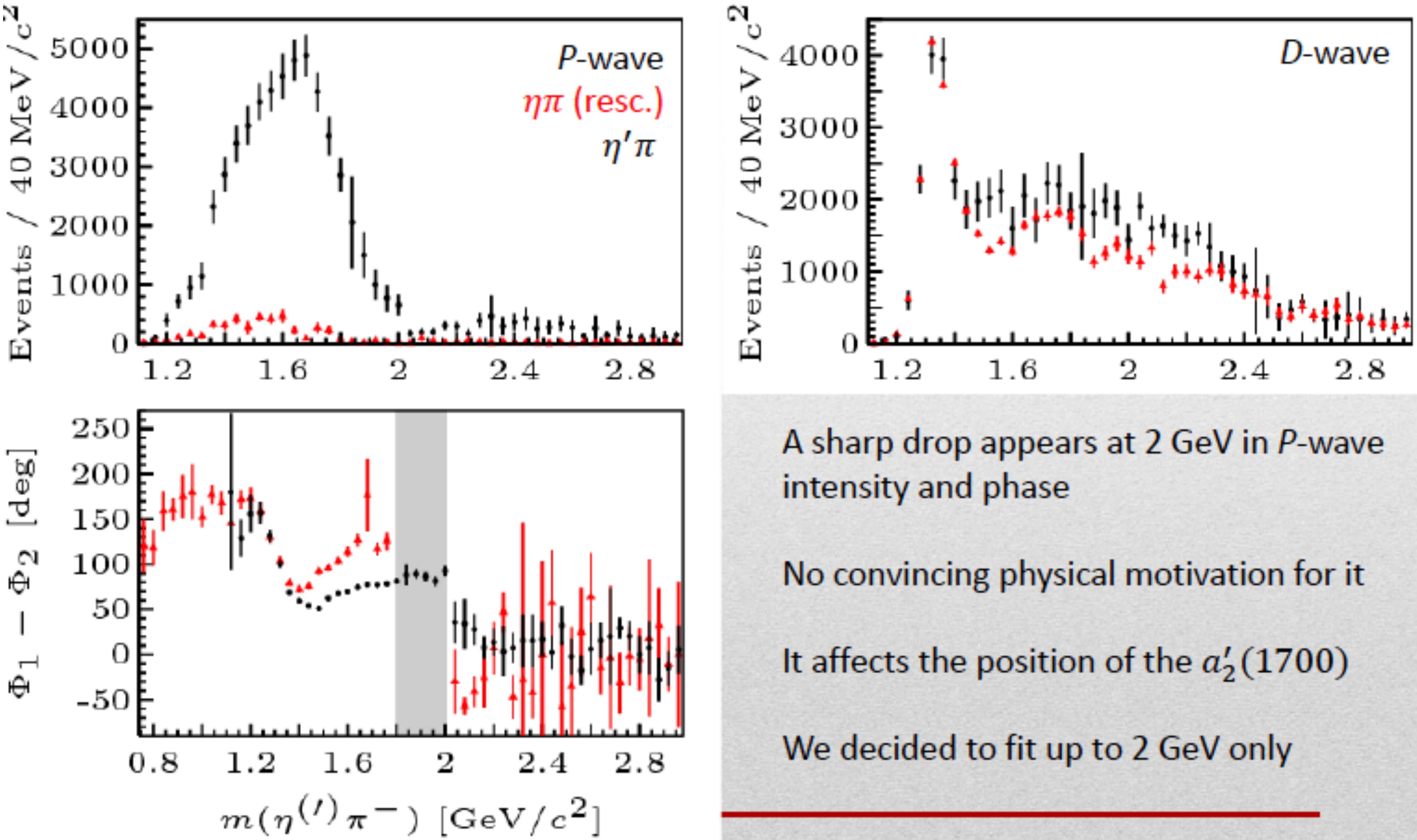
$M(1320) = 1.308(2)$ GeV, $\Gamma(1320) = 0.113(1)$ GeV
$M(1700) = 1.71(6)$ GeV, $\Gamma(1700) = 0.30(6)$ GeV

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

Coupled channel: the model

A. Rodas, AP *et al.* (JPAC), to appear

Two channels, $i,k=\eta\pi,\eta'\pi$ Two waves, $J=P,D$ 37 fit parameters

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

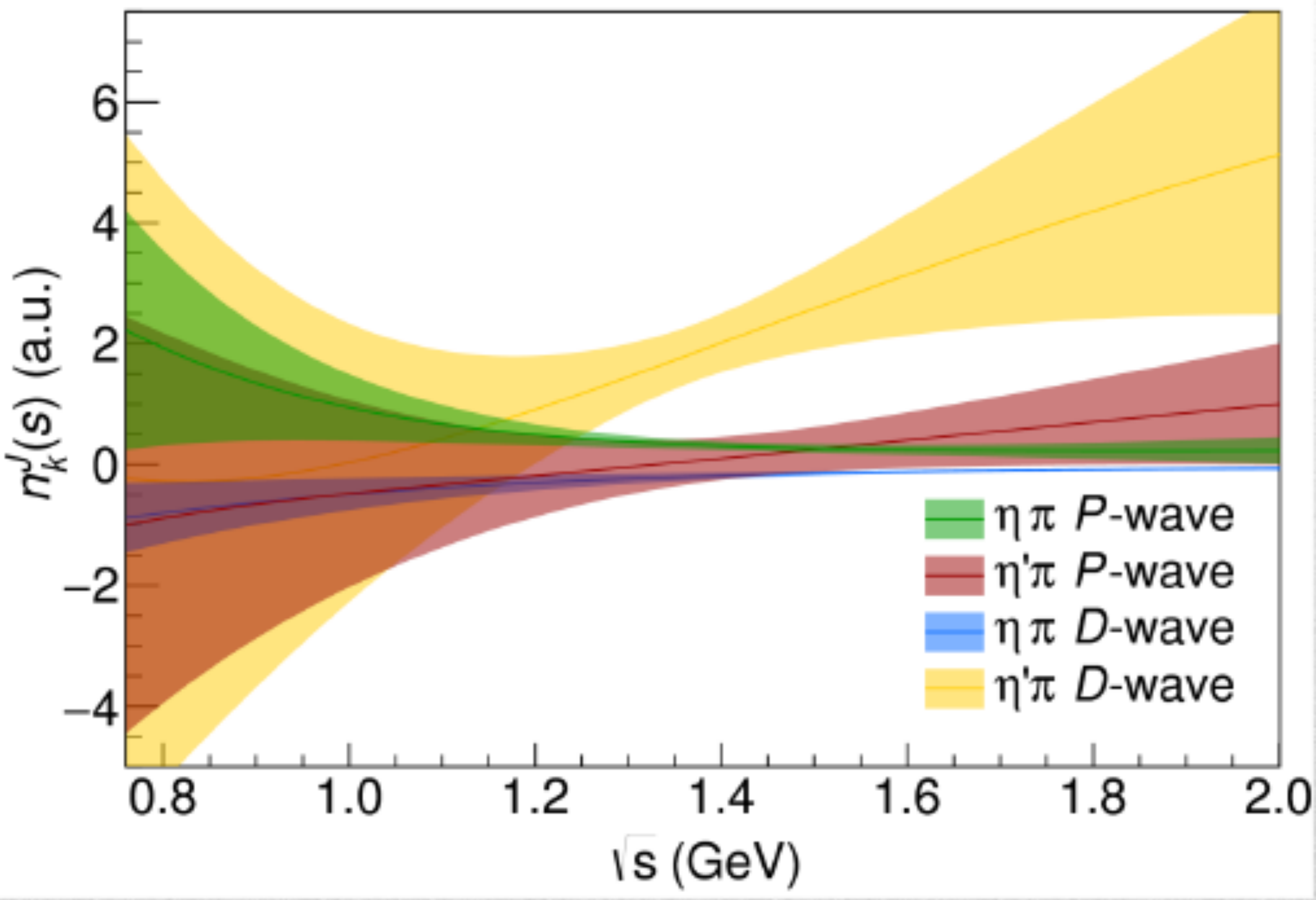
$$K^J_{ki}(s)=\sum_R\frac{g_k^{(R)}\,g_i^{(R)}}{m_R^2-s}+c^J_{ki}+d^J_{ki}\,s$$

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

$$\rho N^J_{ki}(s')=g\,\delta_{ki}\frac{\lambda^{J+1/2}\left(s',m^2_{\eta^{(\prime)}},m^2_\pi\right)}{(s'+s_R)^{2J+1+\alpha}}\qquad n^J_k(s)=\sum_{n=0}^{3}a^{J,k}_n\,T_n\left(\frac{s}{s+s_0}\right)$$

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

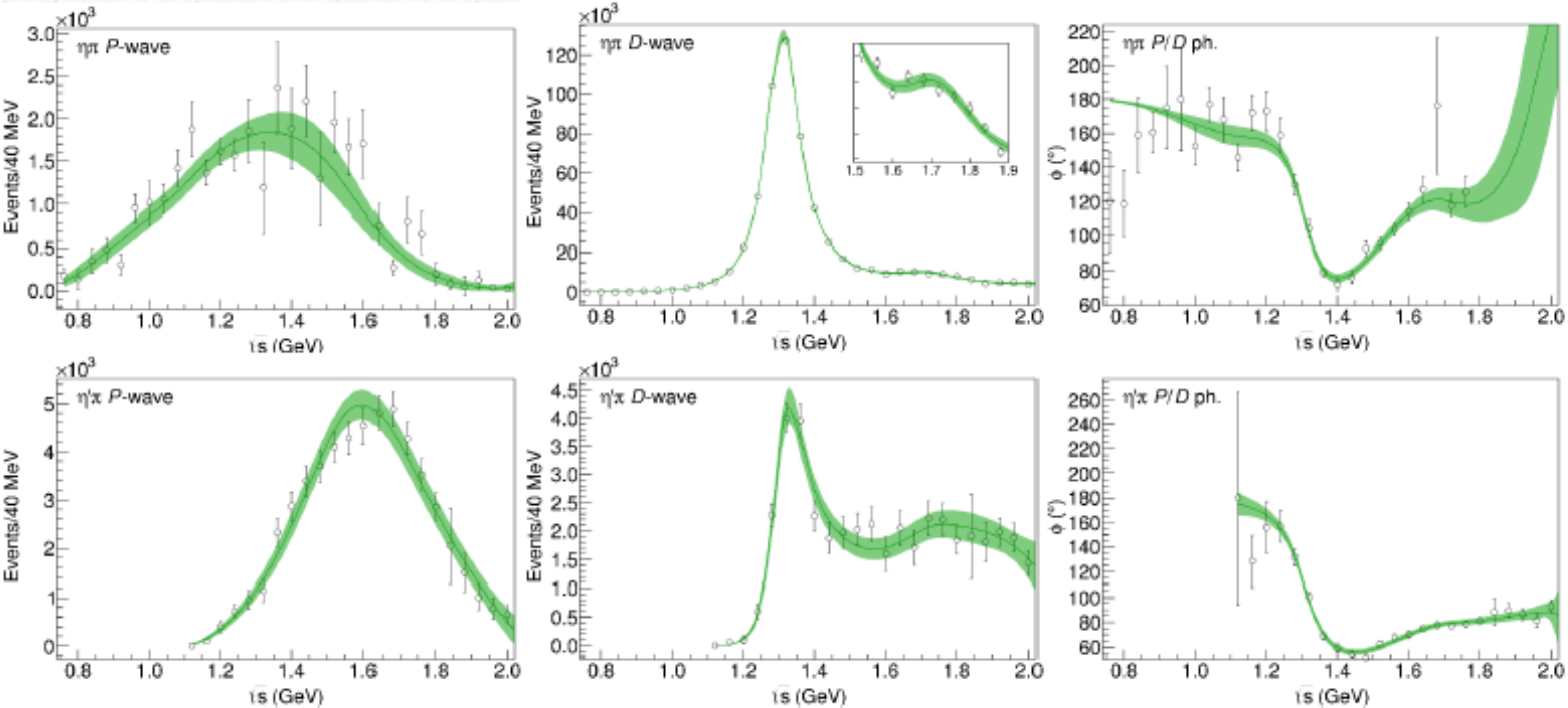
Polynomial in the numerator



The numerator should be smooth and have variation milder that the typical resonance width

This happens indeed

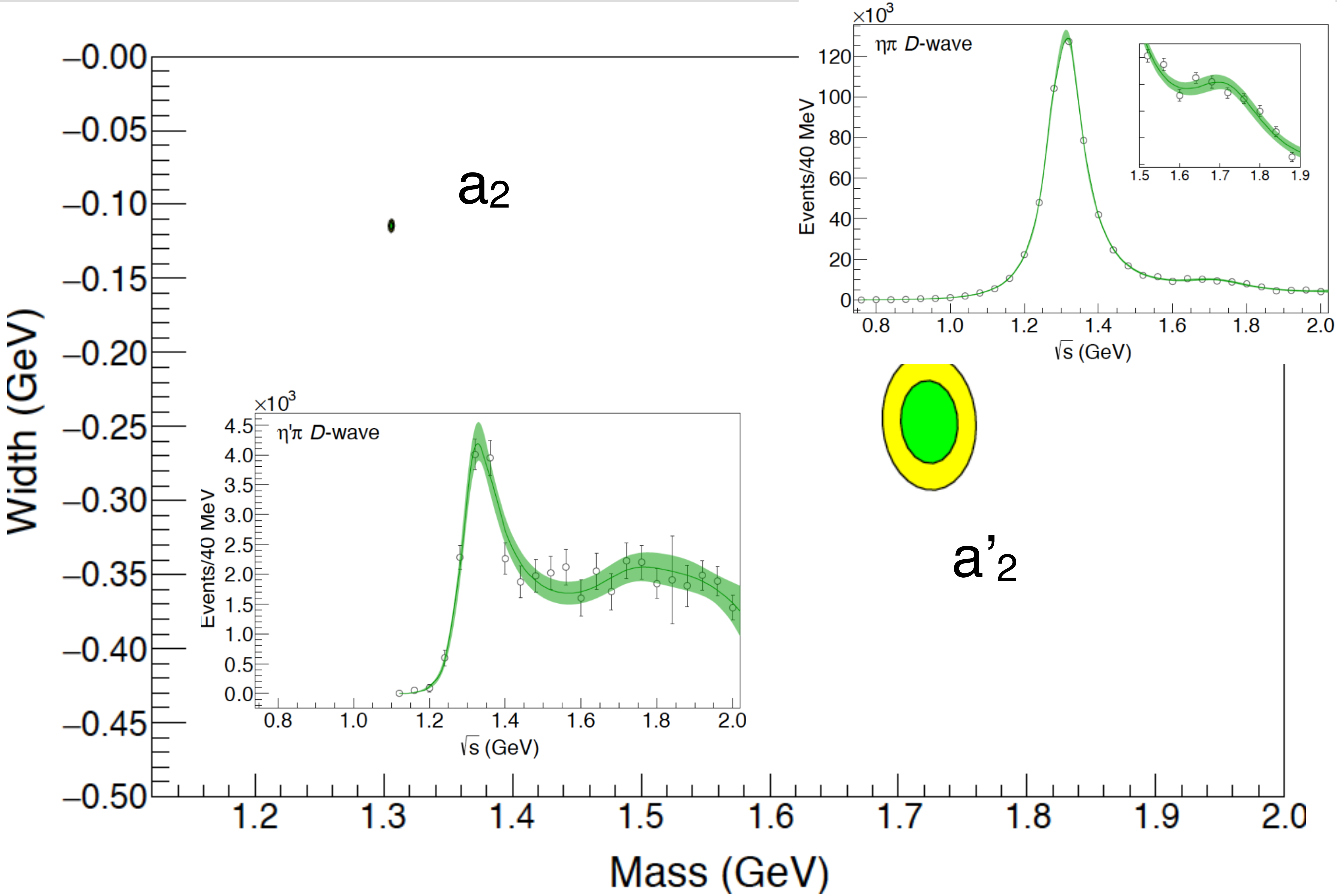
Fit



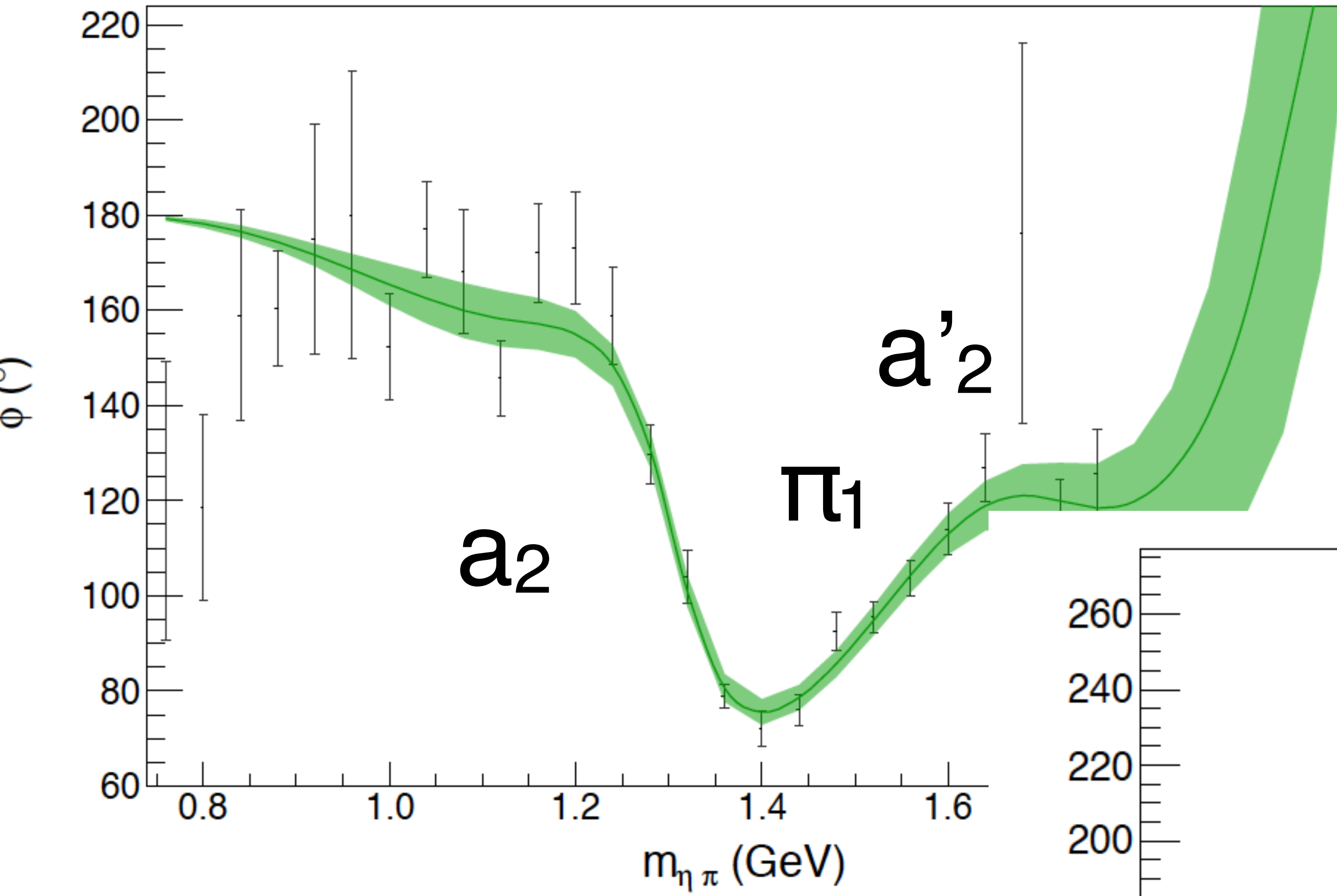
$\chi^2/\text{dof} = 162/122 \sim 1.3$, statistical error estimated via 50k bootstraps

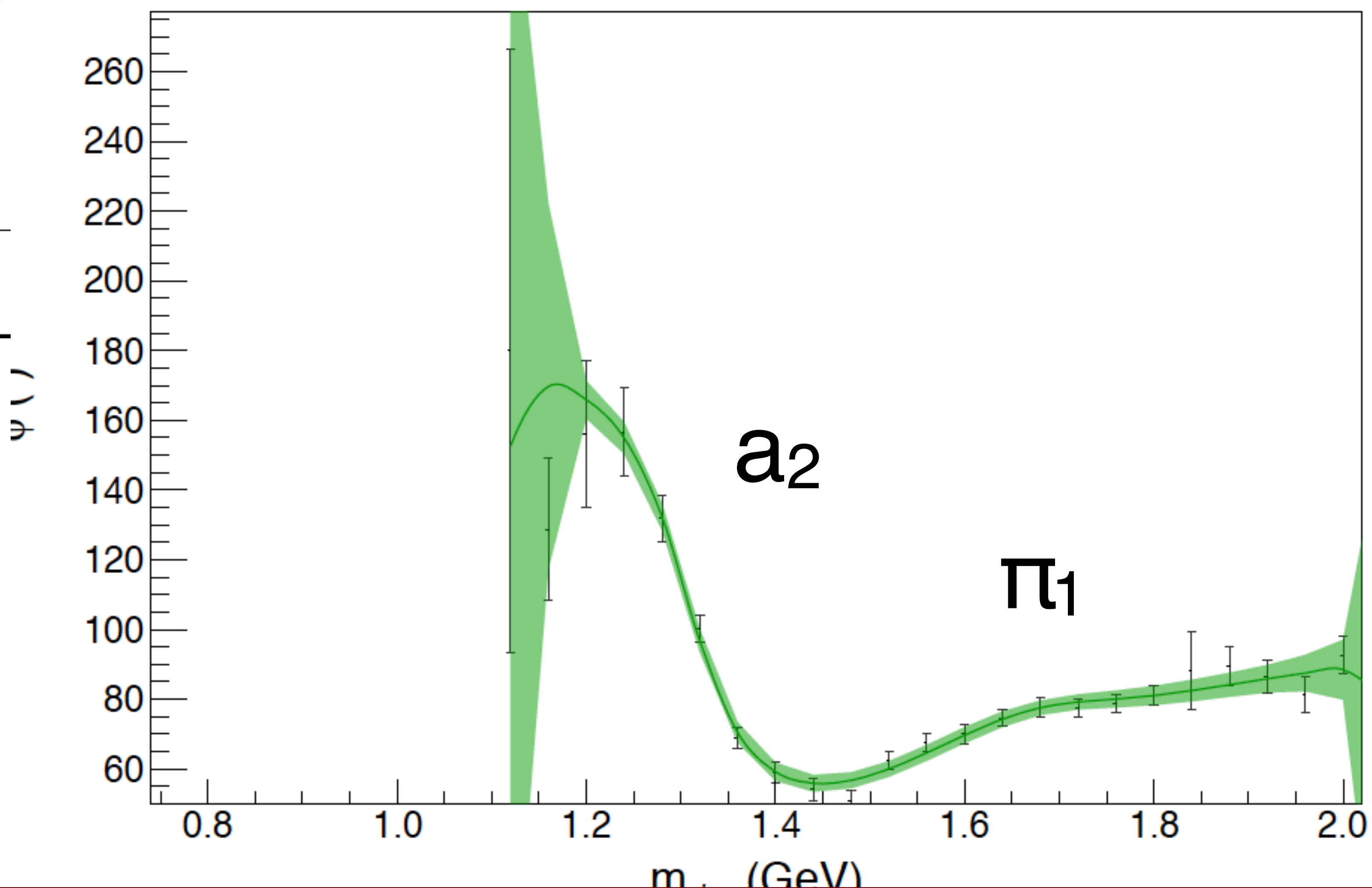
Bands show the 2σ error

Fits to COMPASS : D-wave

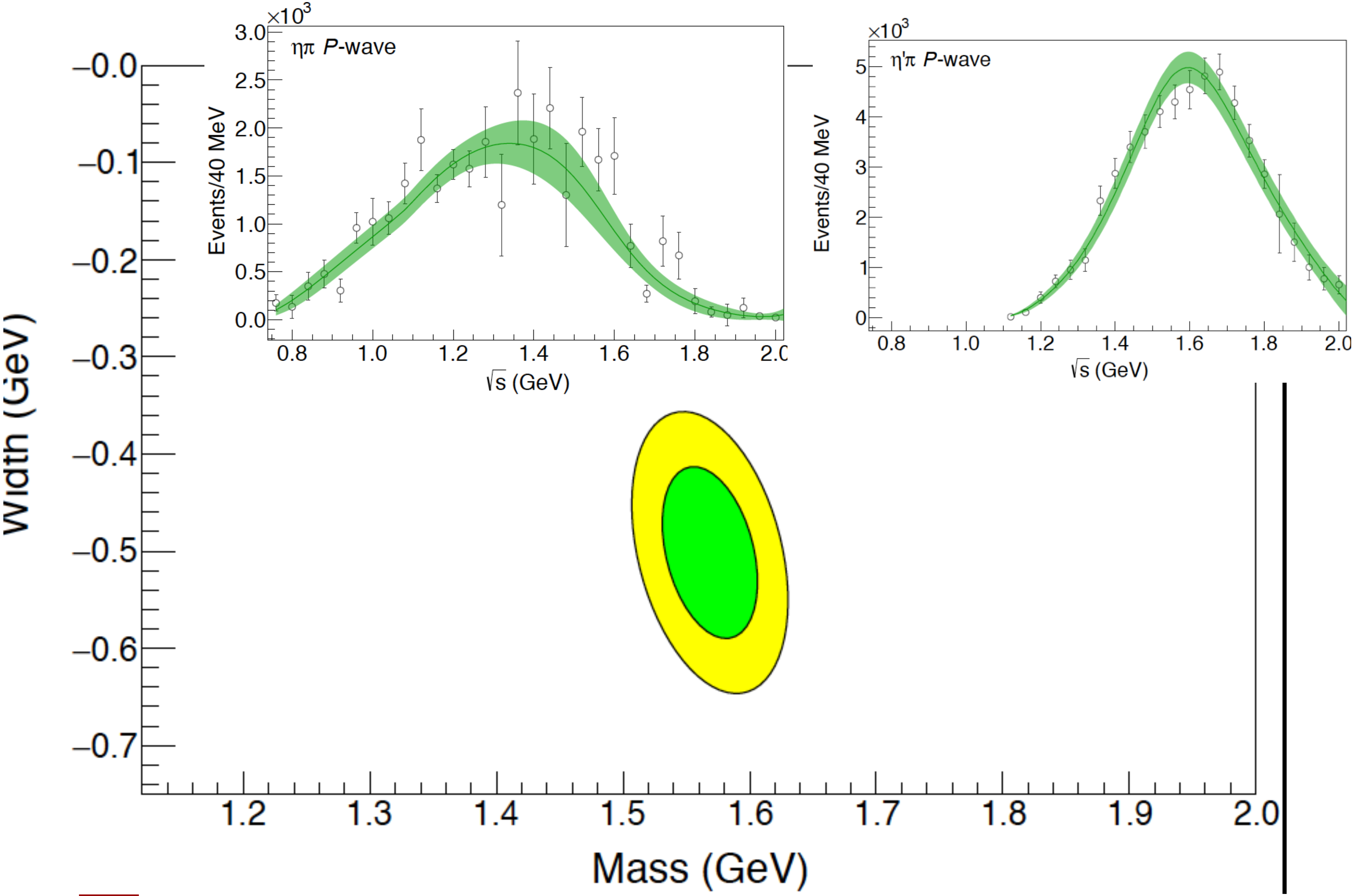


P-D interference

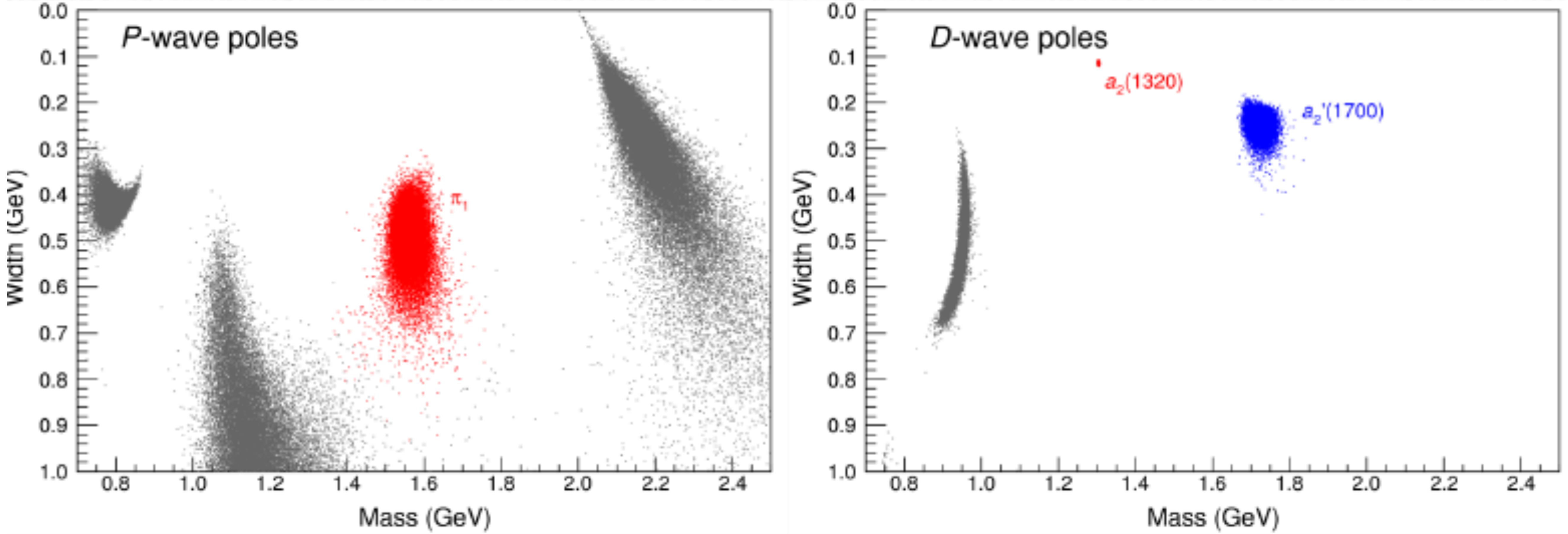




P-wave


ηπ P-wave
η'π P-wave
×10^3
Events/40 MeV
√s (GeV)
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
1
2
3
4
5
Width (GeV)
−0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
Mass (GeV)
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0

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