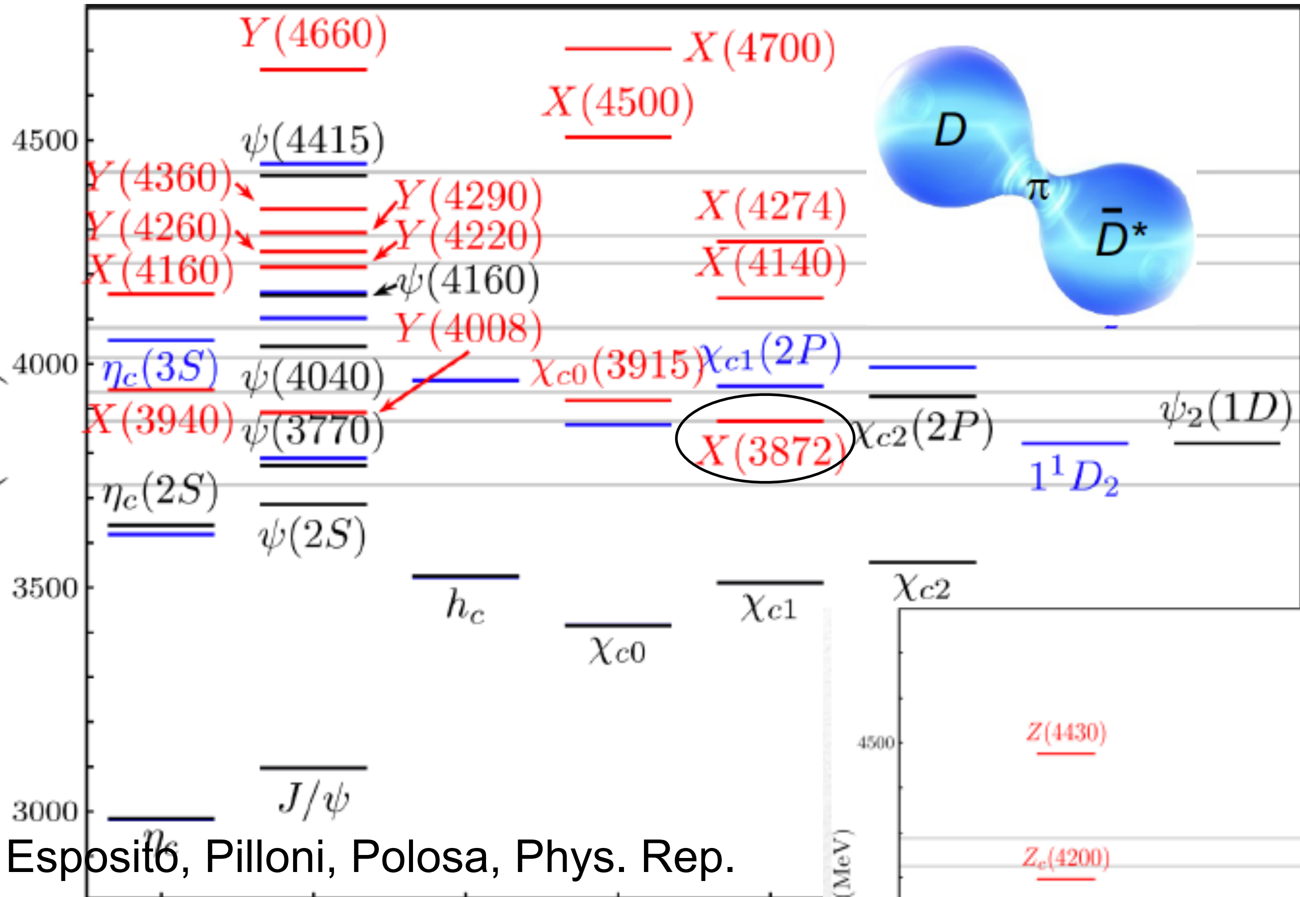
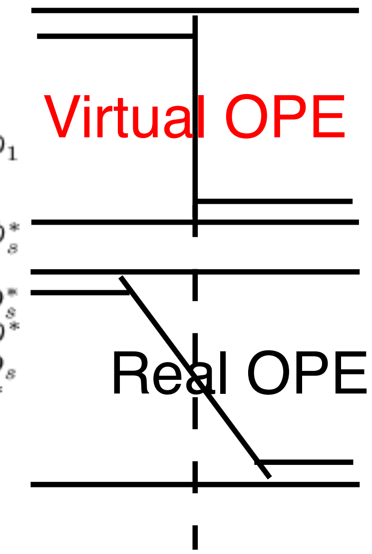
How to reconstruct resonances (and determine where they come from)

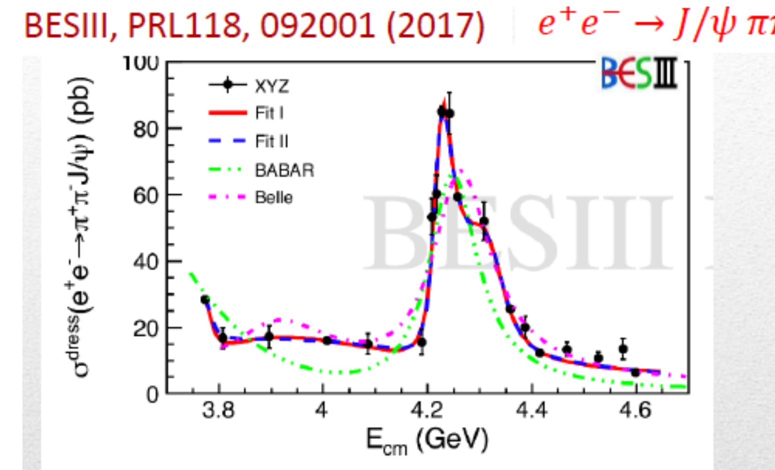
Adam Szczepaniak, Indiana University/Jefferson Lab

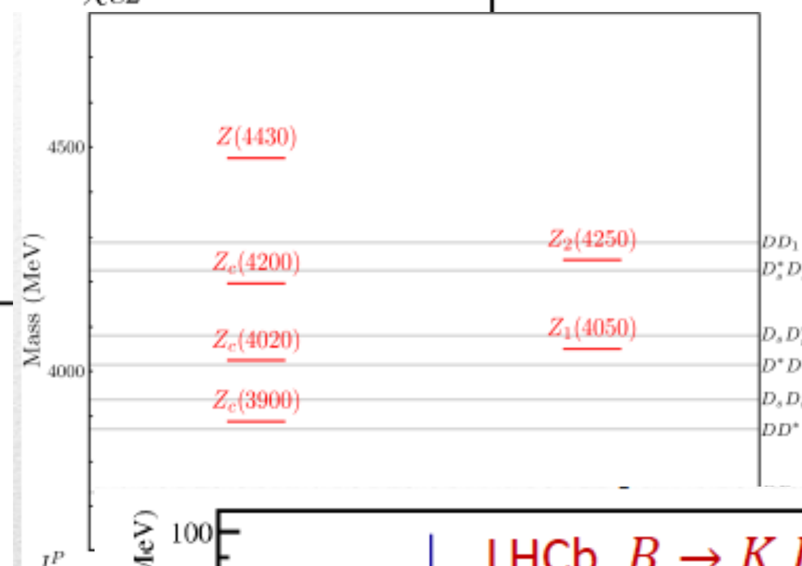
Join Physics Analysis Center

Signatures of unusual heavy quark resonances





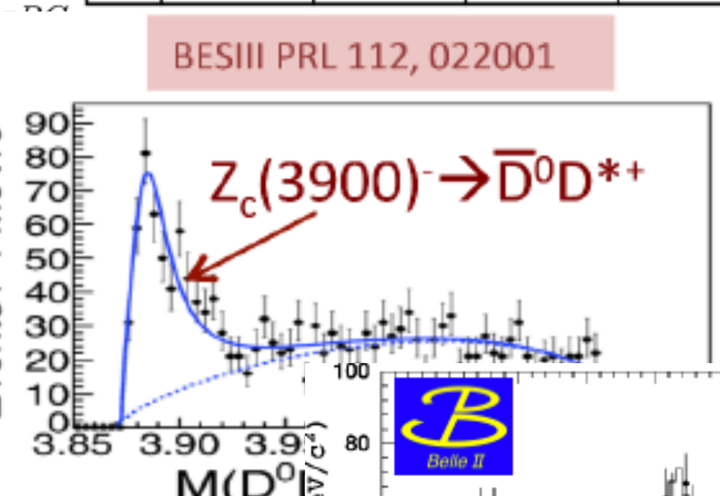


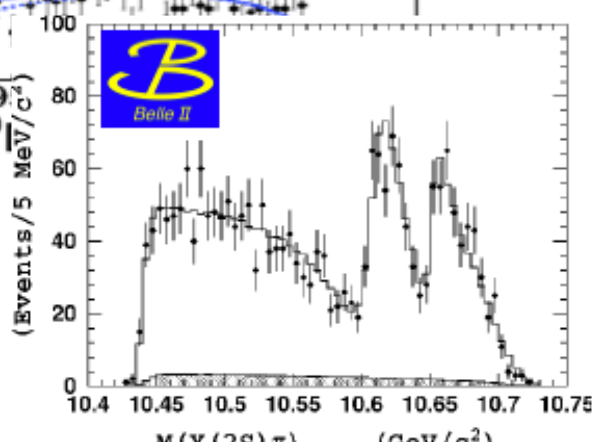


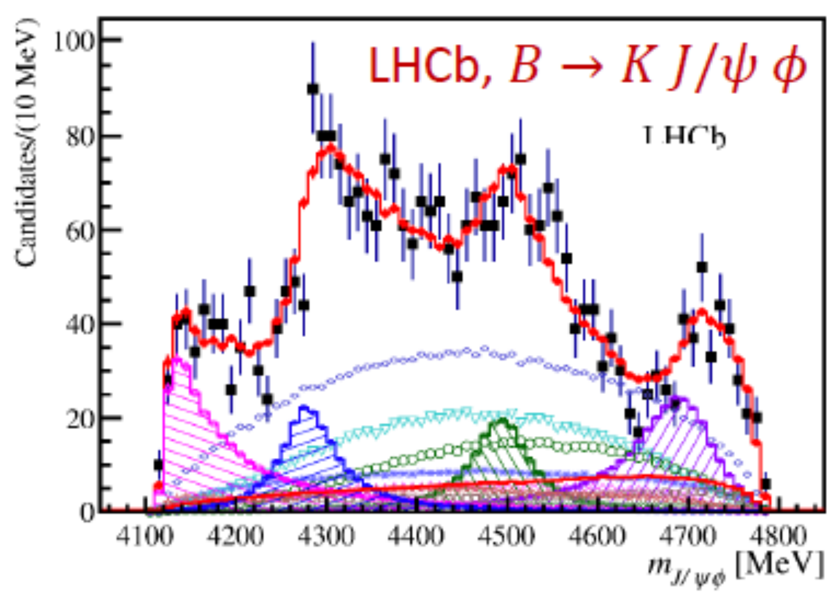
EMARK ON ENERGY PEAKS IN MESON SYSTEMS

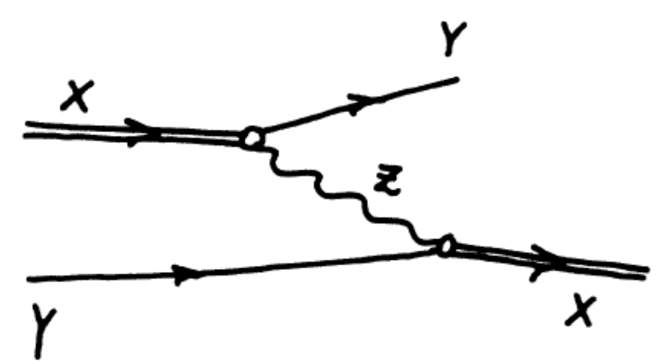
M. Nauenberg A. Pais

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.





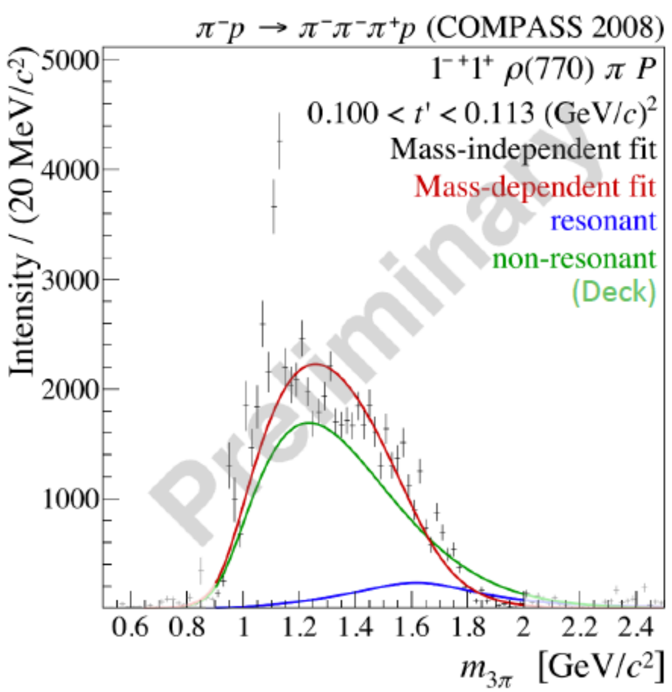


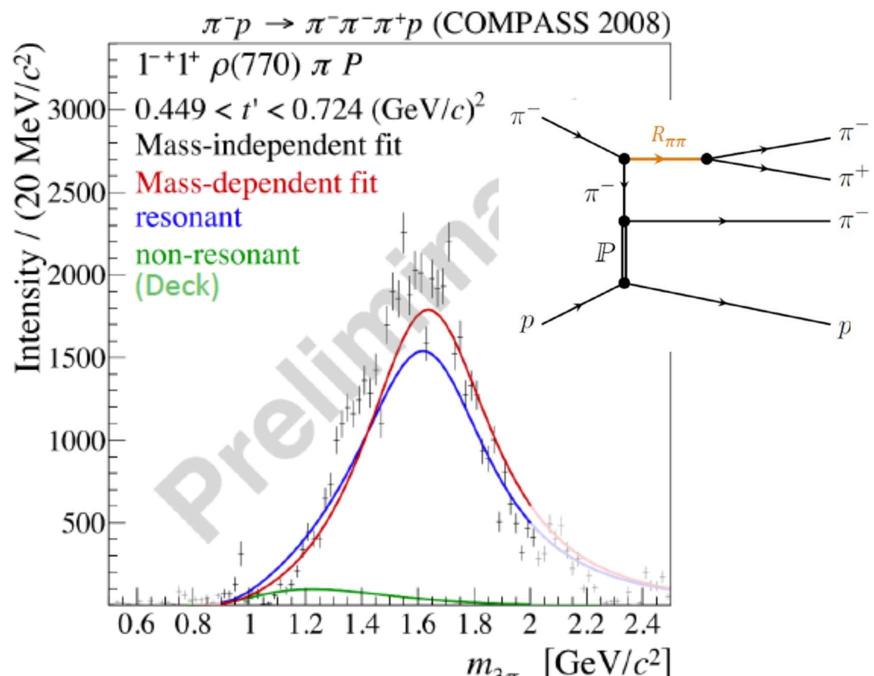


Signatures of new, unusual light resonances

- Exotic $J^{PC}=1^{-+}$ (hybrid) mesons expected (VES, GAMS,E852, COMPASS, and theory)

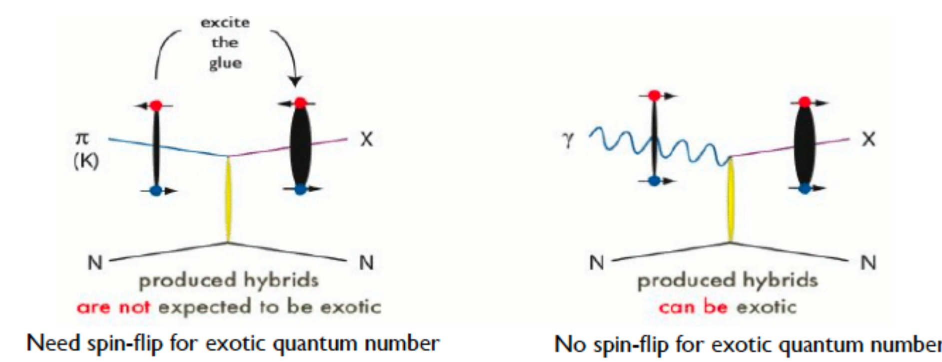
- In low-t pion diffraction (COMPASS) exotic wave production compatible with one pion exchange (but not at high-t)





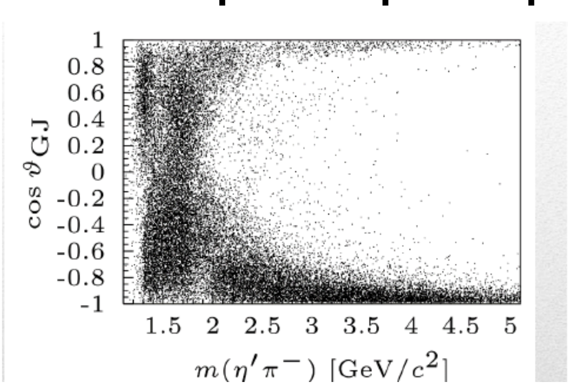
V.Mathieu in progress

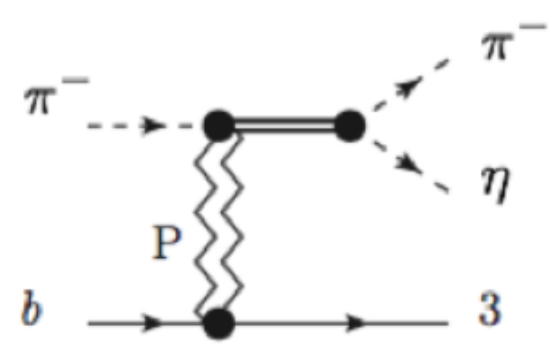
- In photoproduction (GlueX) exotic mesons produced via pion exchange (both good and bad)

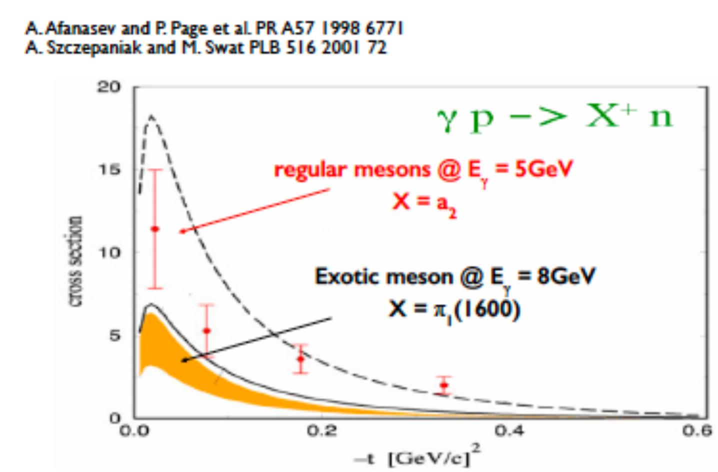


- Large exotic wave seen in $\eta^{(')}\pi$ production : Golden Channel

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







Amplitude analysis : connecting data to QCD

Bottom → Up

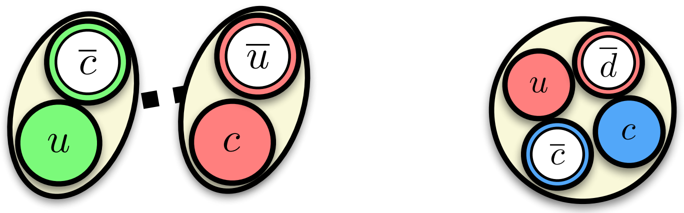
Amplitudes

↑

Rules (bubbles, regularization, renormalization, etc.)

Data

Microscopic model



Mesonic-Molecules Tetraquarks

Top → Bottom

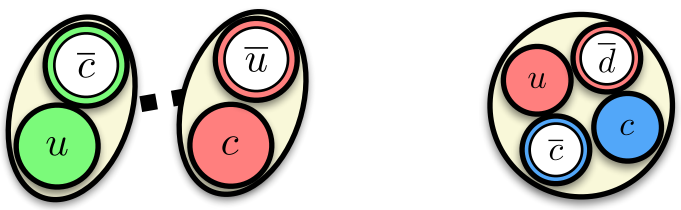
Amplitudes

↓

Data

Physical interpretation of poles, cuts,

Microscopic model



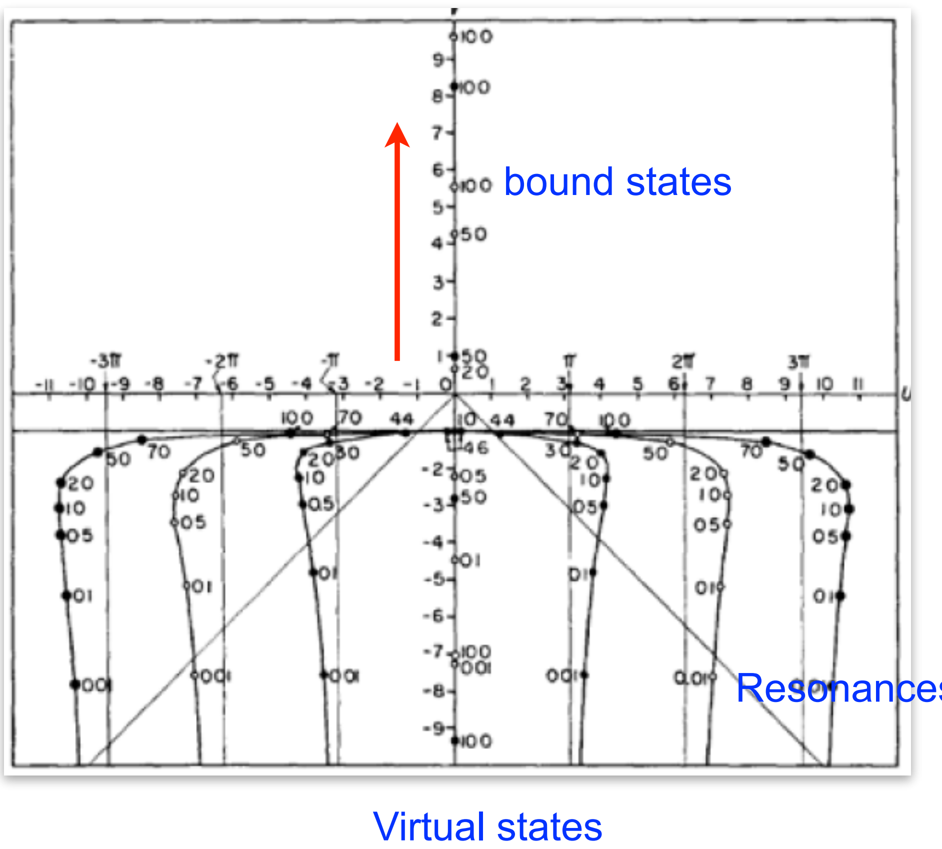
Mesonic-Molecules Tetraquarks

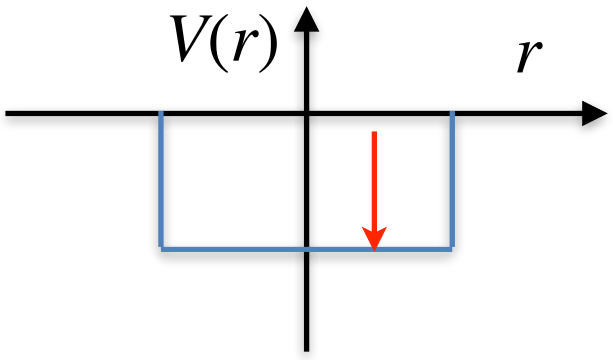
In practice

- Reconstruct amplitudes from its singularities (poles, cuts) Recall that each singularity has its own physical interpretation

- Use data to determine best hypothesis

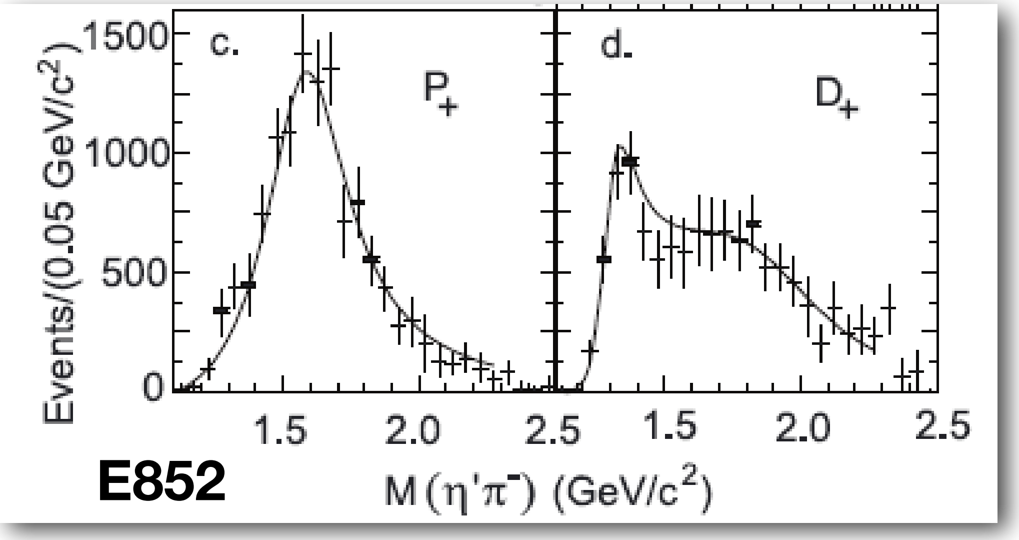
- Test how singularities depend on parameters (channel couplings, thresholds, etc.) to infer their microscopic origins.



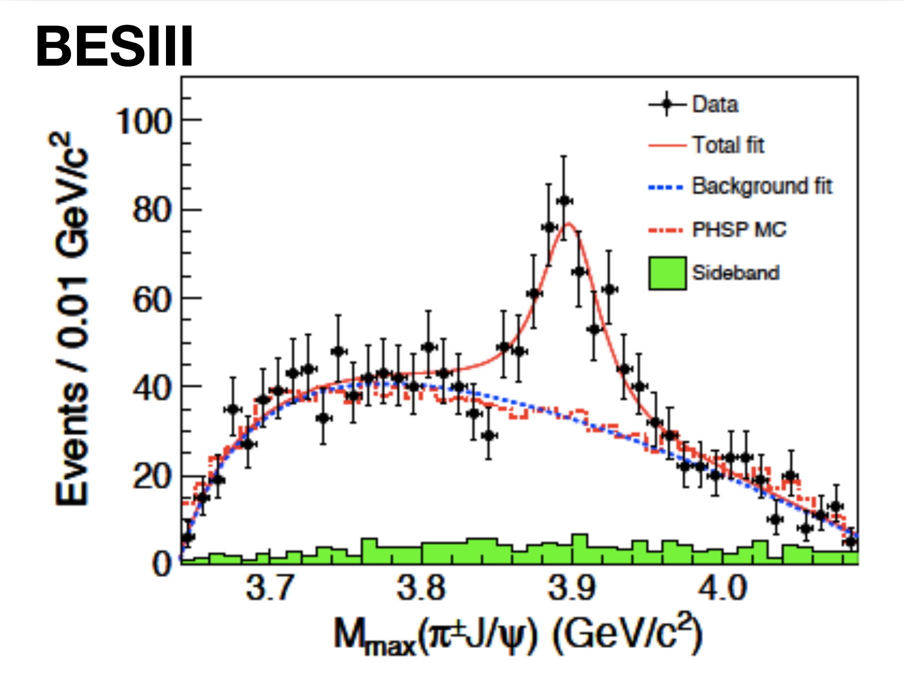


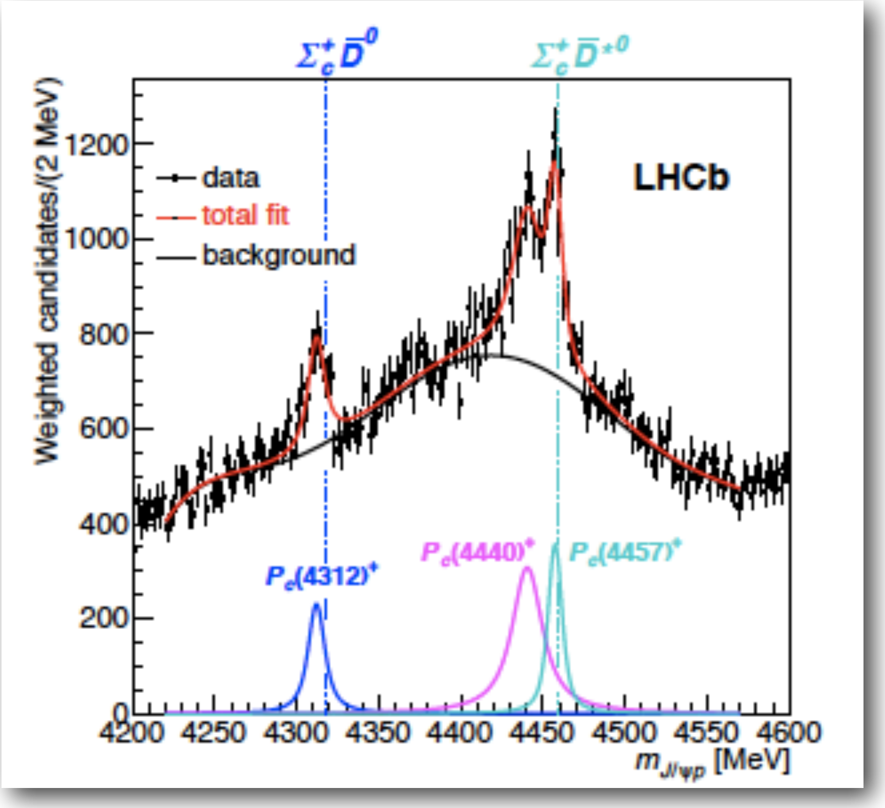
In this talk

- $J^{PC}=1^{-+}$ I=1, light exotic hybrid ?



- $Z_c(3900)$ in J/ψ π π, $\bar{D}D^*$?



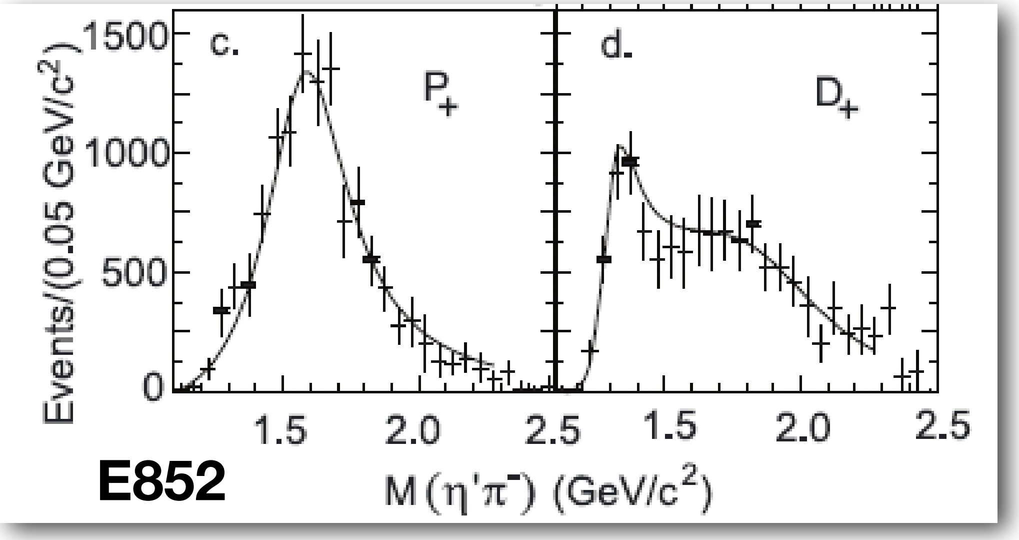


- $P_c(4312)$ in $\Lambda_b \rightarrow$ J/ψ p K

In this talk

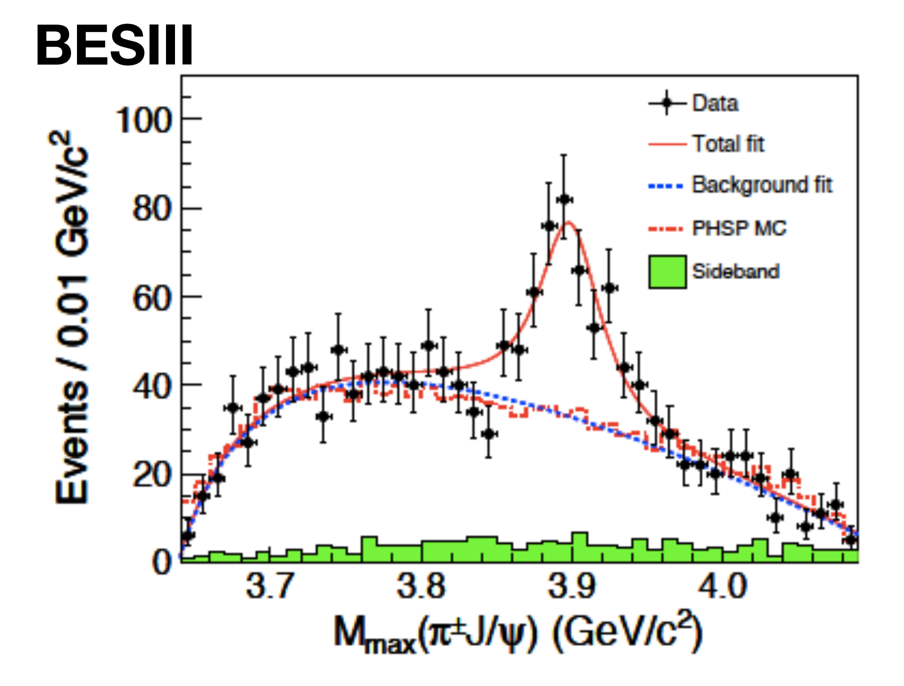
- $J^{PC}=1^{-+}$ I=1, light exotic hybrid ?

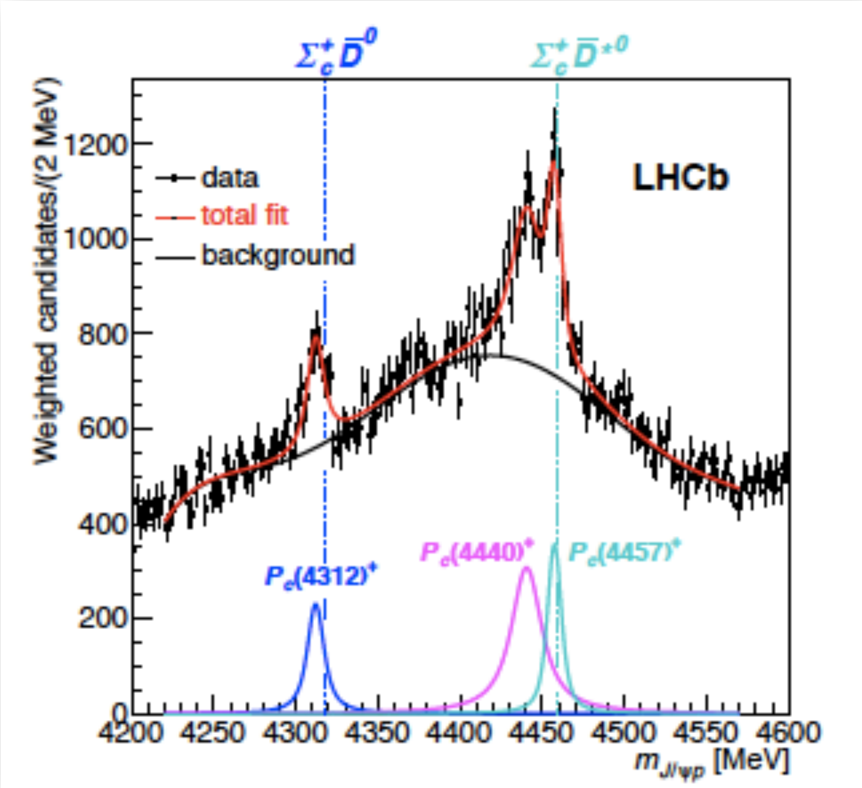
  Yes : “Normal resonance”



- $Z_c(3900)$ in J/ψ π π, $\bar{D}D^*$?

  Inconclusive

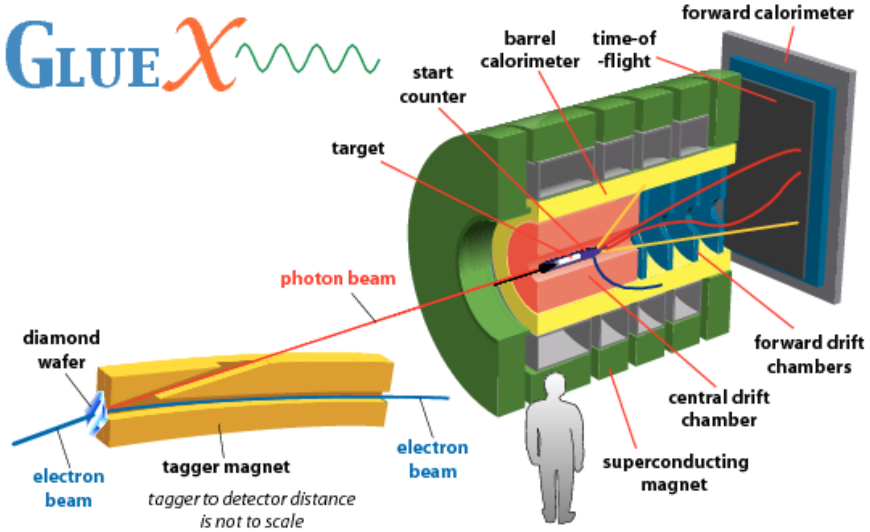


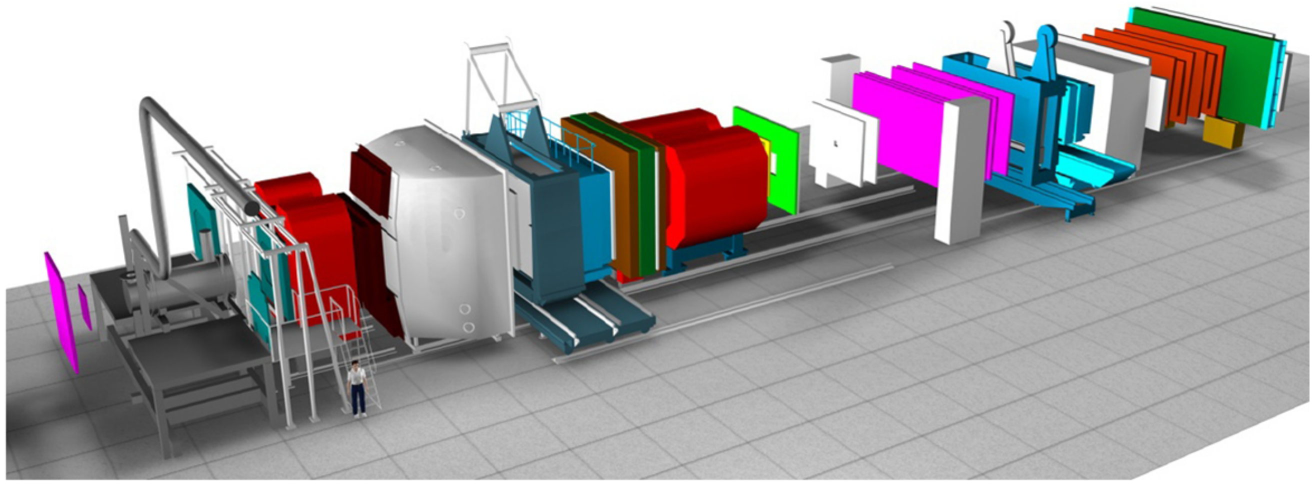


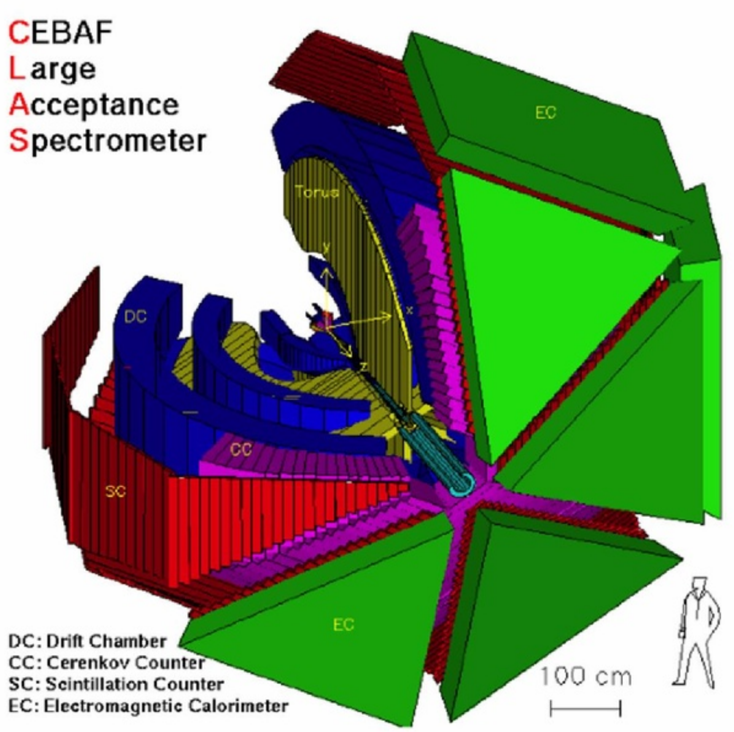
- $P_c(4312)$ in $\Lambda_b \rightarrow$ J/ψ p K

  No : Unbound

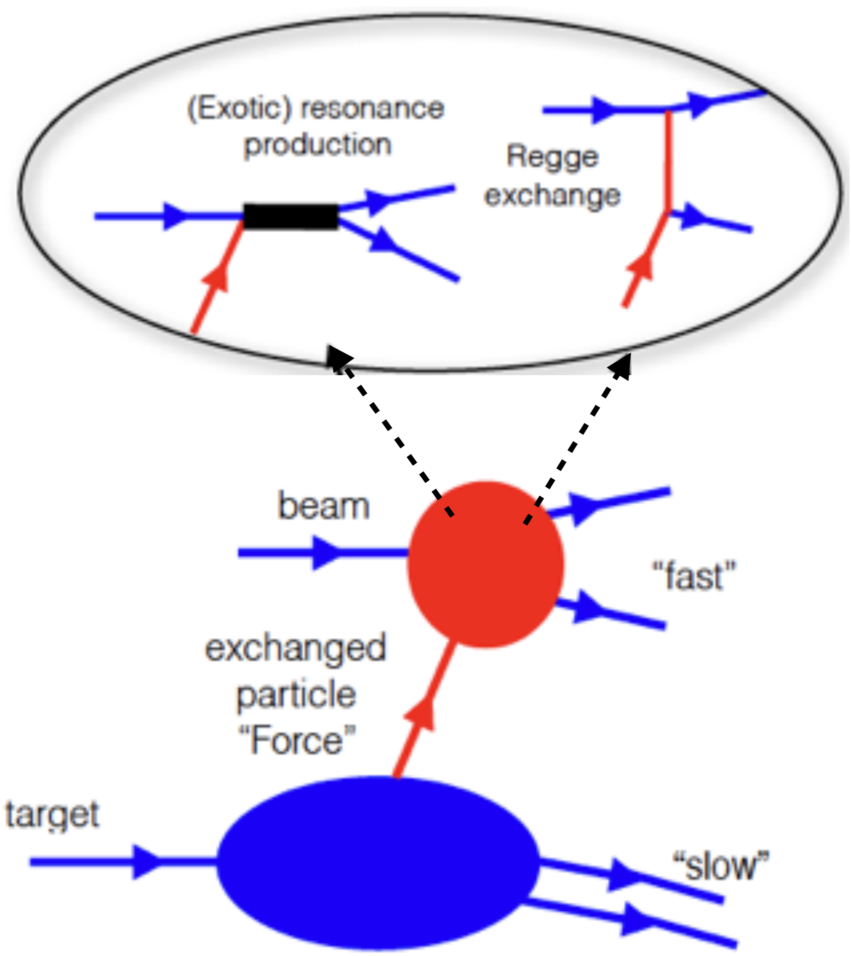
Spectroscopy from peripheral production



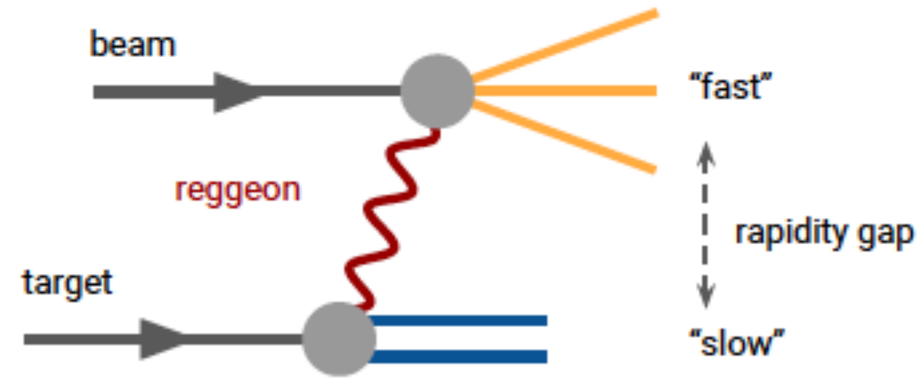




- Need to establish factorization between beam and target fragmentation (Regge factorization)
- Single Regge pole exchange dominate over cut other singularities (cuts, daughters)



Global Regge analysis



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

- Factorizable Regge pole exchange

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

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

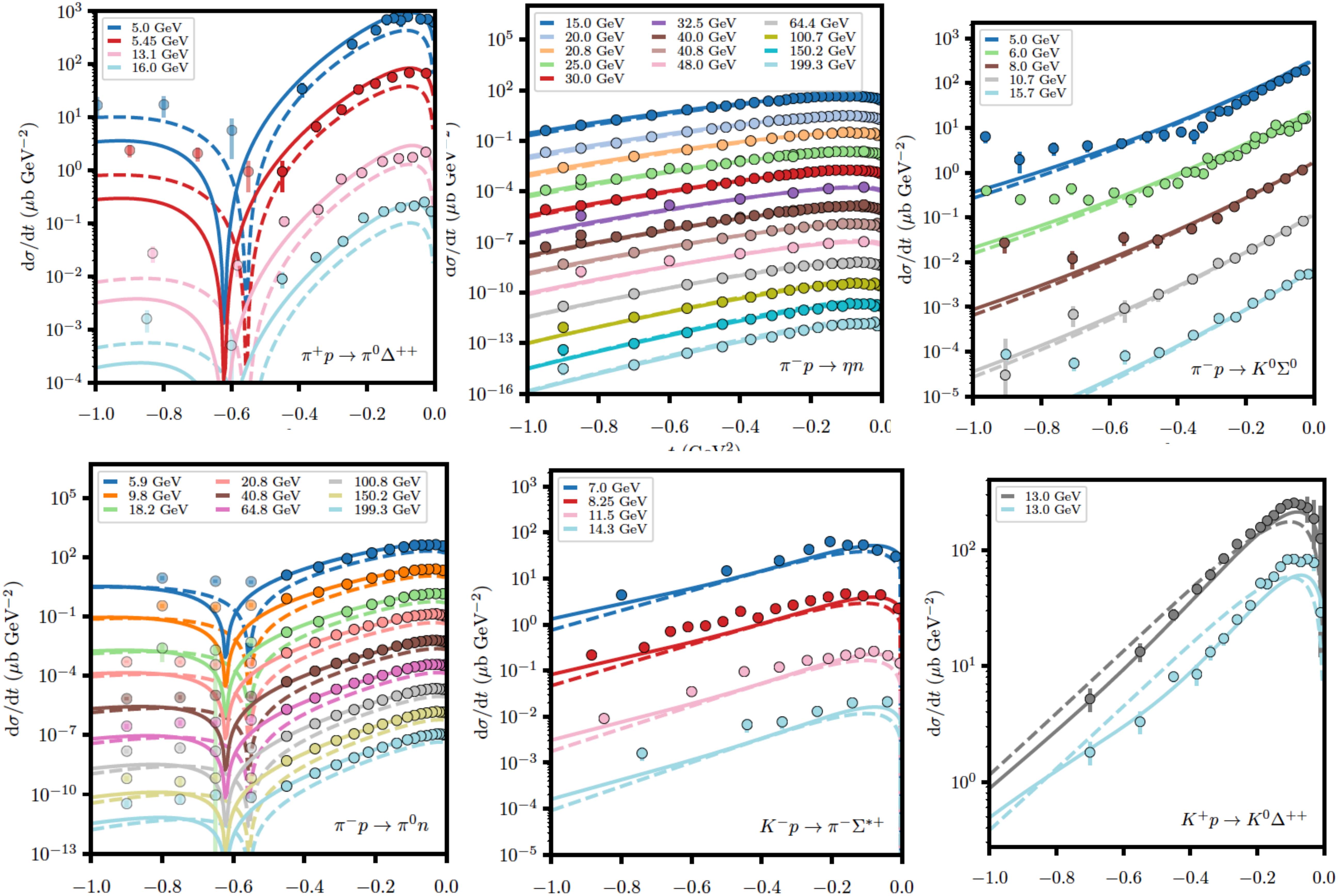
$$\mathcal{F}_e(s,t) = -\frac{\zeta_e \pi \alpha_e^1}{\Gamma(\alpha_e(t)-l_e+1)}\frac{1+\zeta_e e^{-i\pi\alpha_e(t)}}{2\sin\pi\alpha_e(t)}\left(\frac{s}{s_0}\right)^{\alpha_e(t)}$$

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

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

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

Global Regge pole analysis



The π_1 (exotic) meson candidate

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

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

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

π_1 (1400) E852, also GAMS, VES, Crystal Barrel

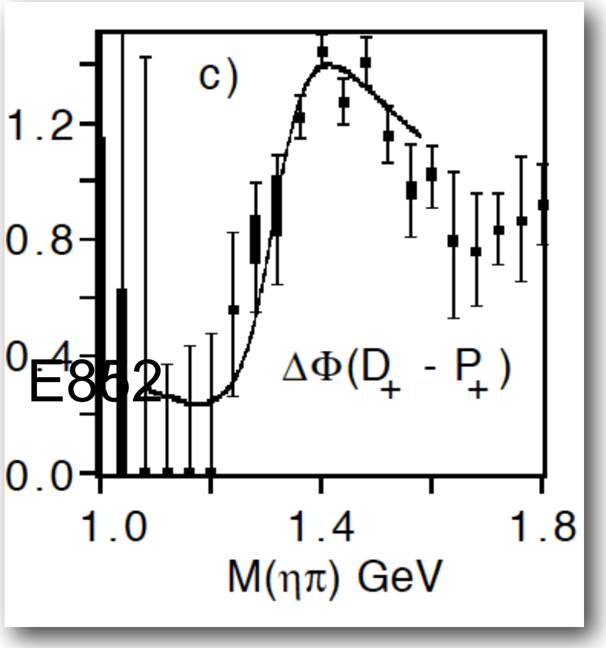
$\pi^- p \to \eta' \pi^- p$

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

$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2

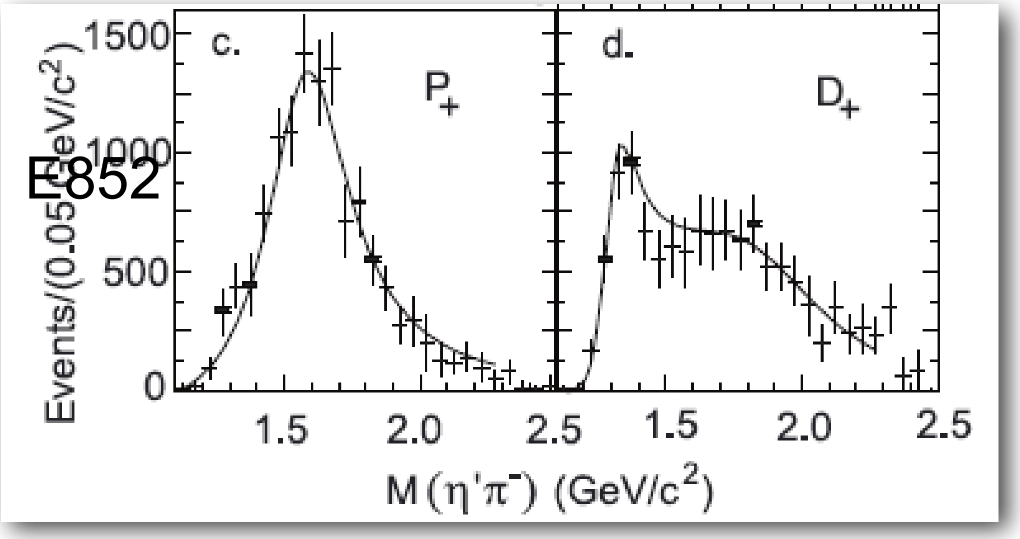
π_1 (1600)

E852, also COMPASS,CLEO

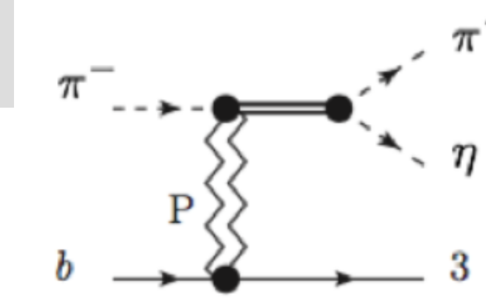


Is it 1400 or 1600 ?

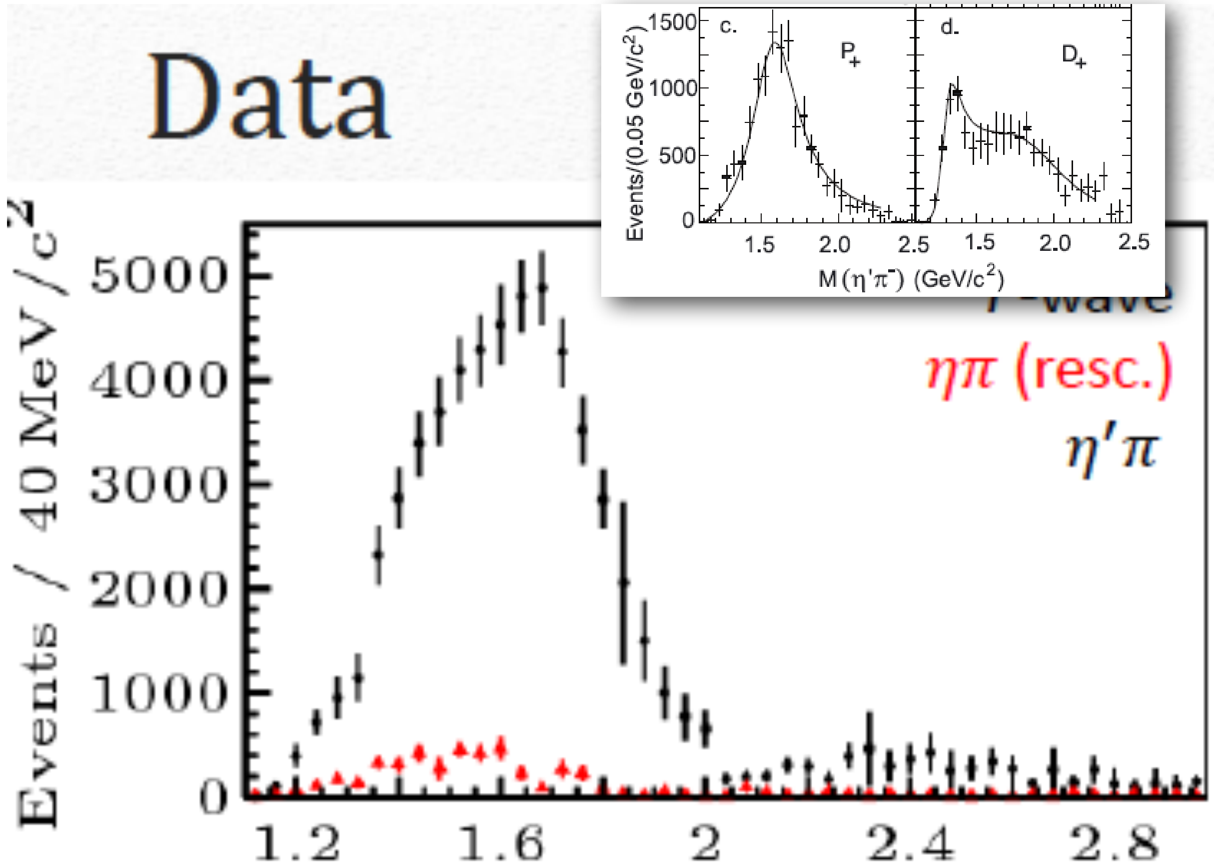
COMPASS consistent with both

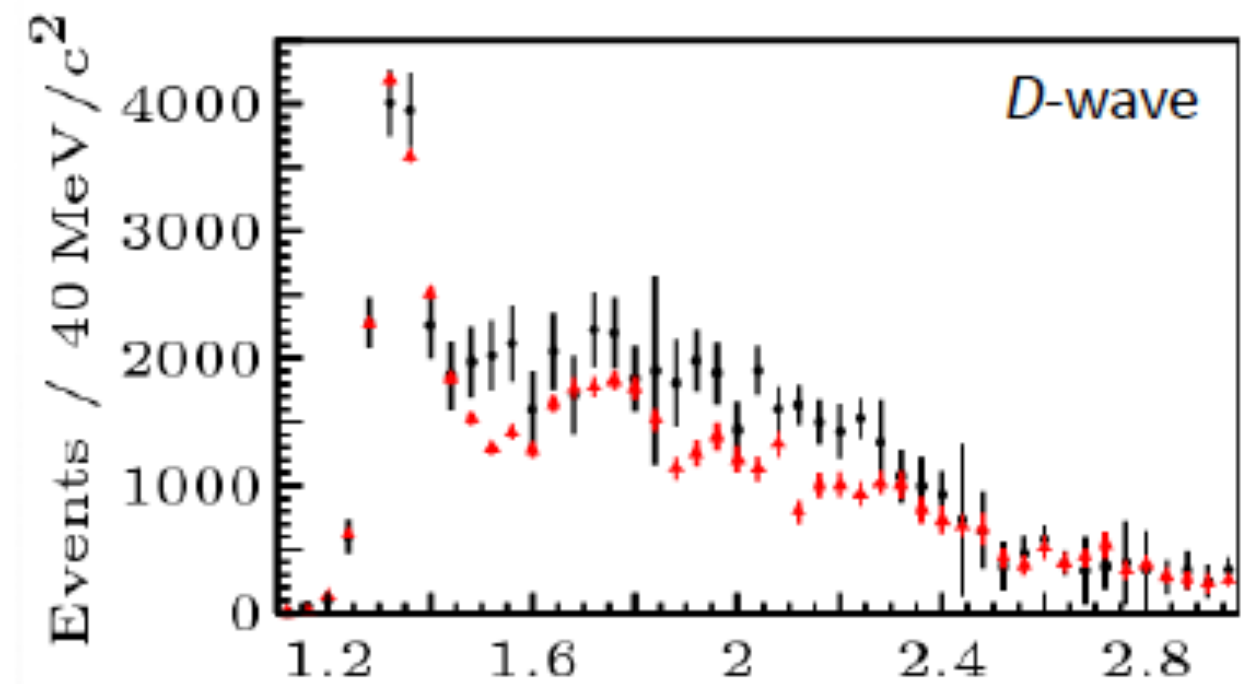


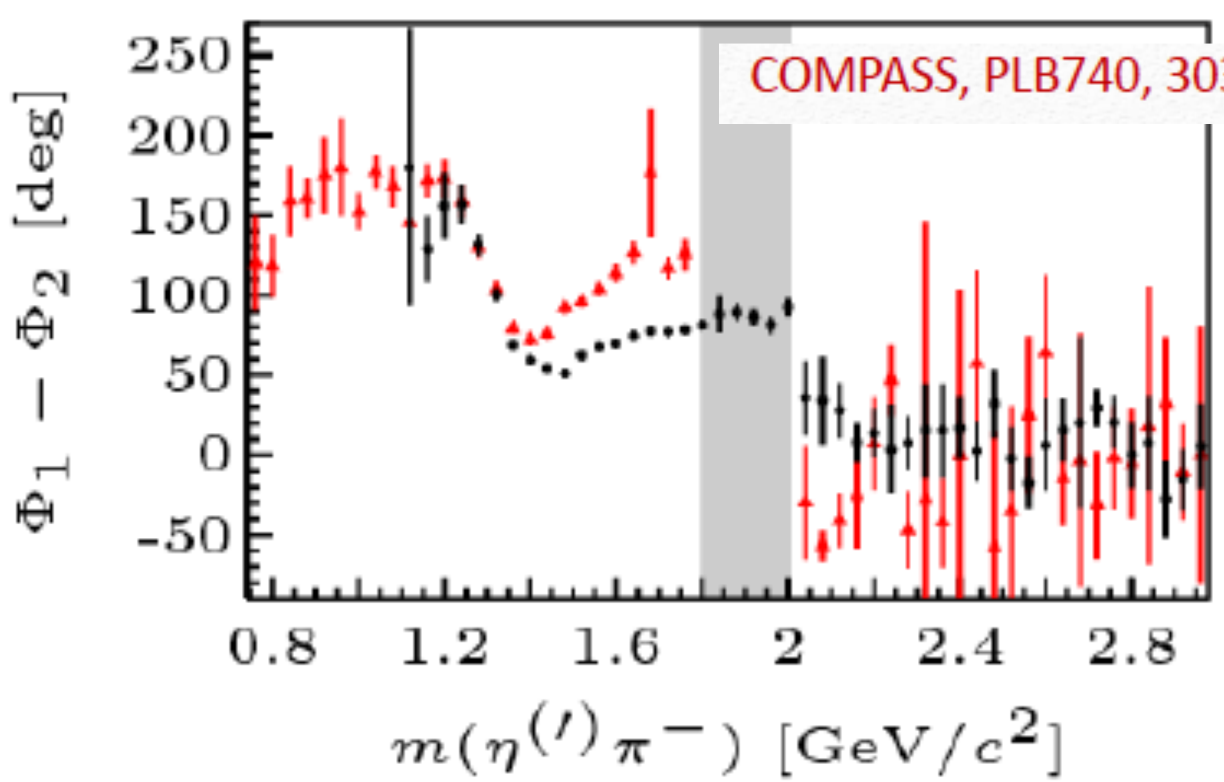
COMAPSS data



Data







COMPASS, PLB740, 303-311

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

No convincing physical motivation for it

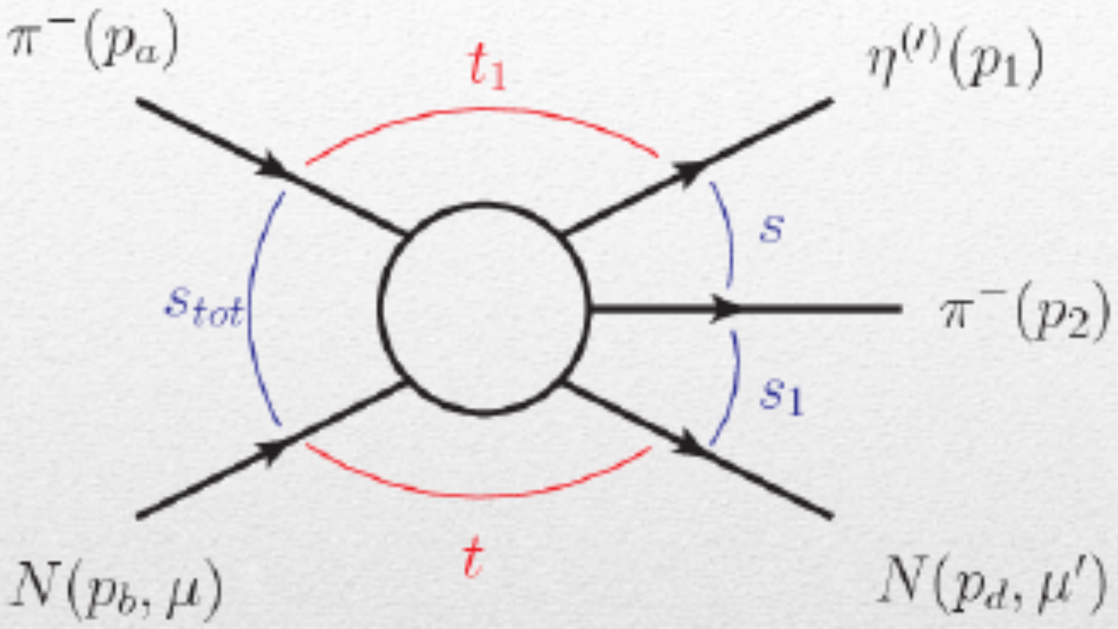
It affects the position of the $a_2'(1700)$

We decided to fit up to 2 GeV only

2-meson peripheral production : ηπ

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

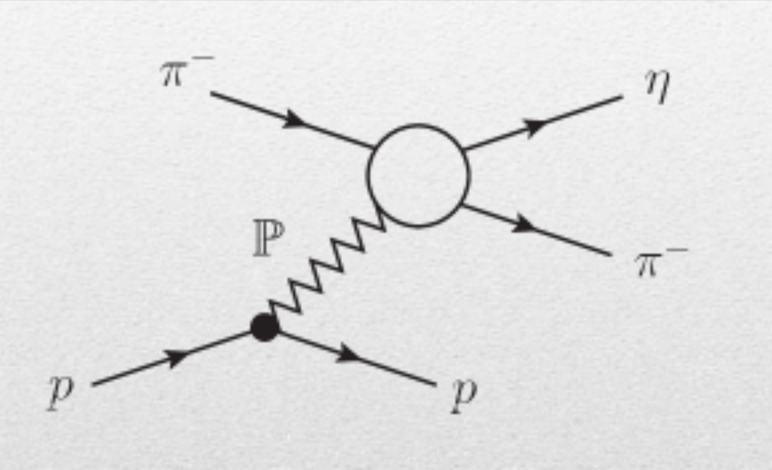
- Process is at fixed s_{tot}, and integrated t. Interested in resonances in s
- Recoil proton kinematically decouples from final state $\eta\pi$



- Expand amplitude into partial waves

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

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



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

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

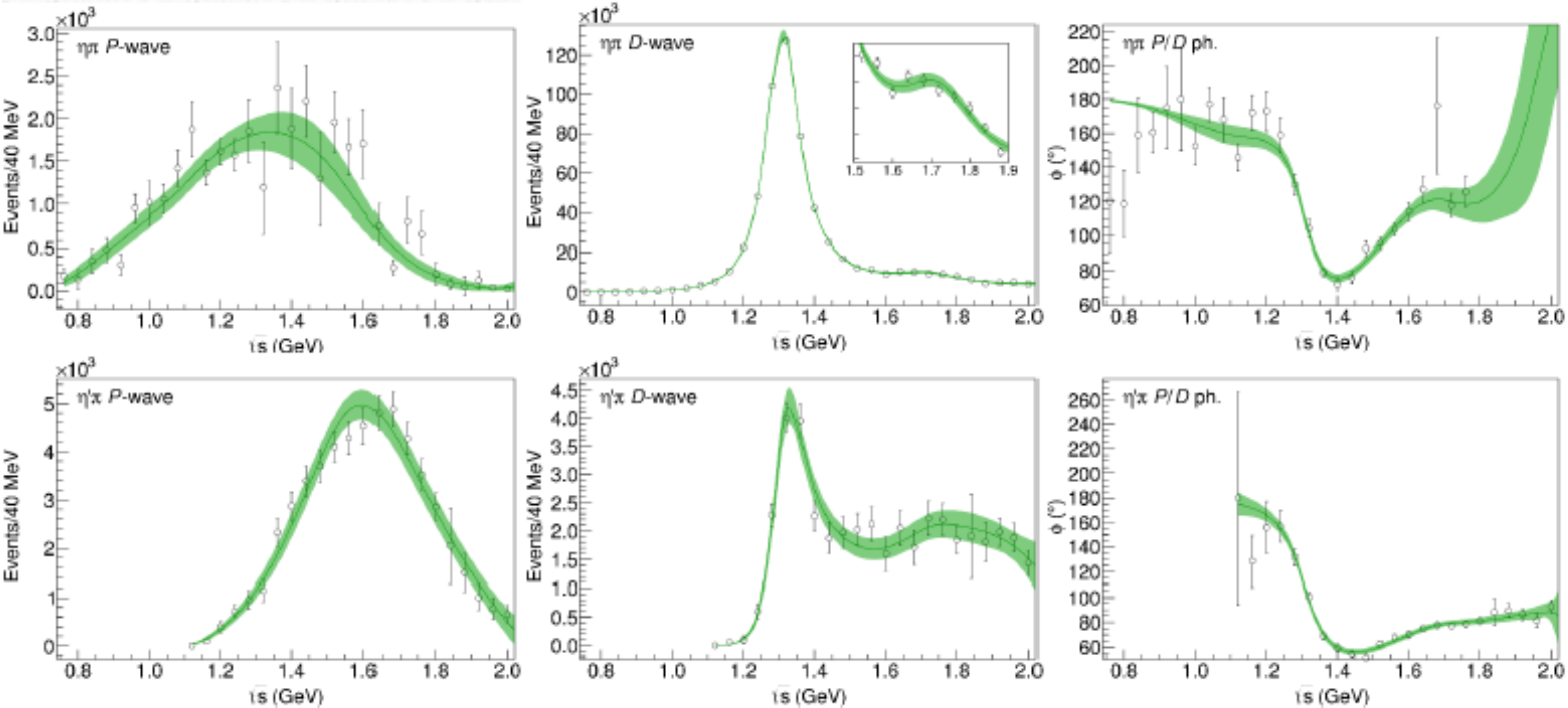
$$K^J_{ki}(s) = \sum_R \frac{g_k^{(R)} g_i^{(R)}}{m_R^2 - s} + c^J_{ki} + d^J_{ki}\, s$$

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

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

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 $n^J_k(s)$

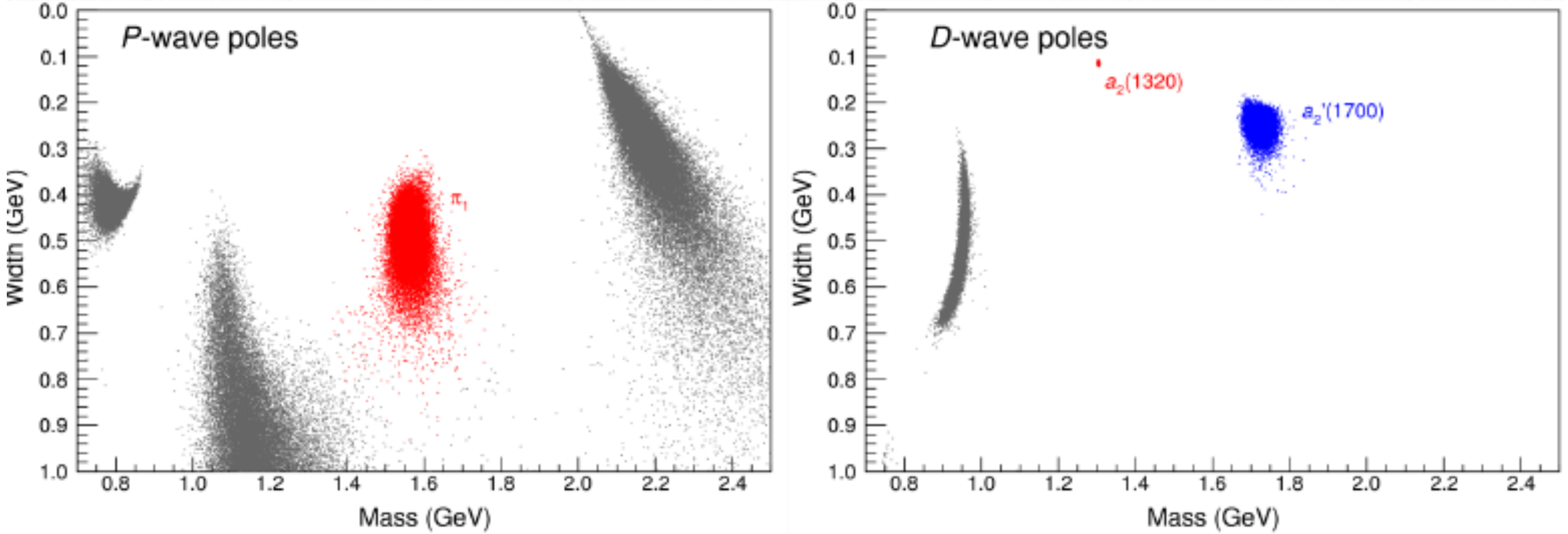
Fit



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

Bands show the 2σ error

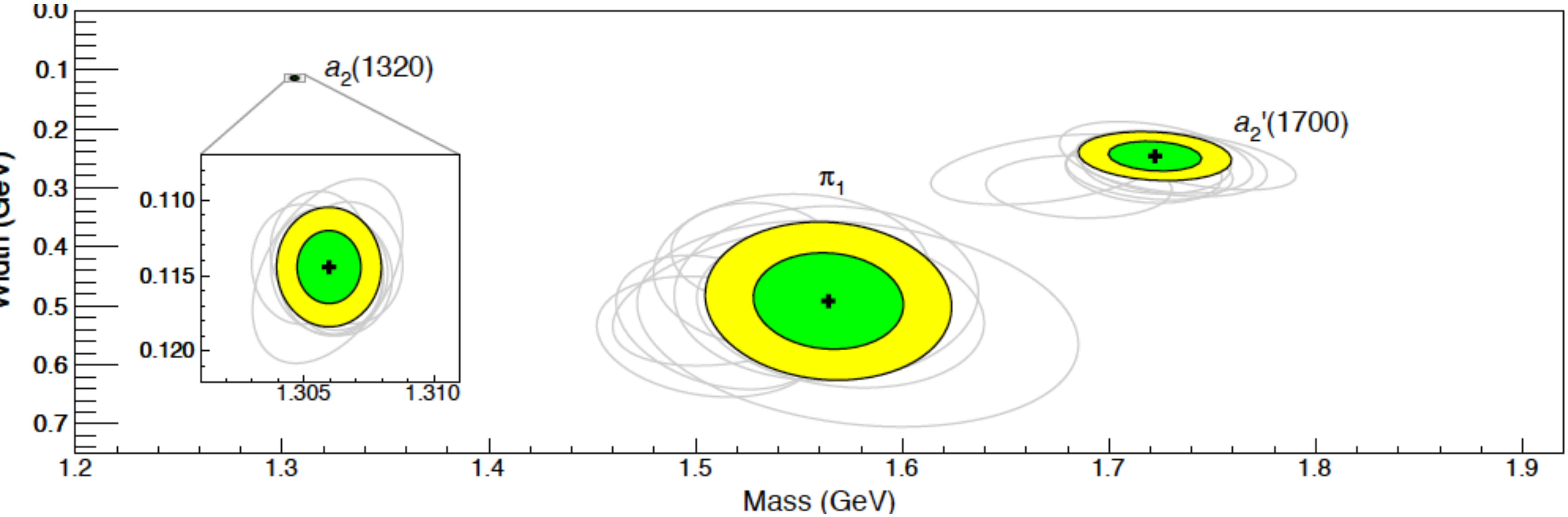
Bootstrap



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

Bootstrap + model variations



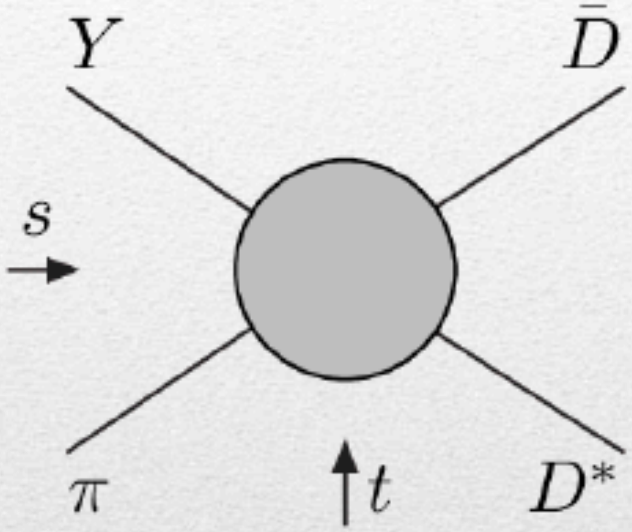
The variance of the bootstrapped poles gives the statistical error

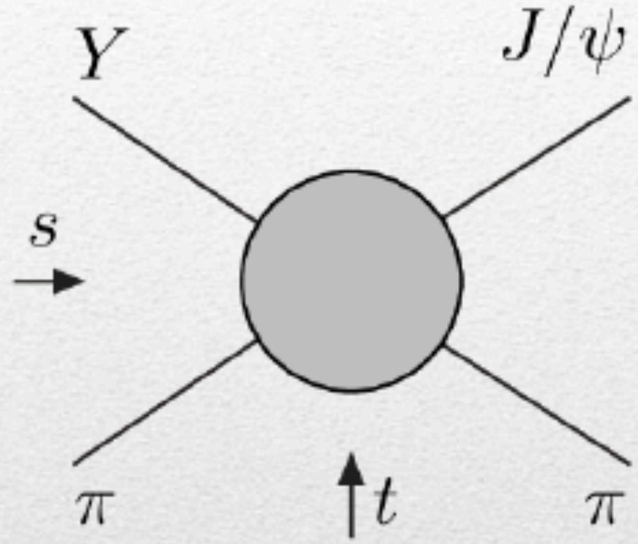
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	1306.0 ± 0.8	114.4 ± 1.6
$a_2'(1700)$	1722 ± 15	247 ± 17
π_1	1564 ± 24	492 ± 54

Amplitude analysis for $Z_c(3900)$

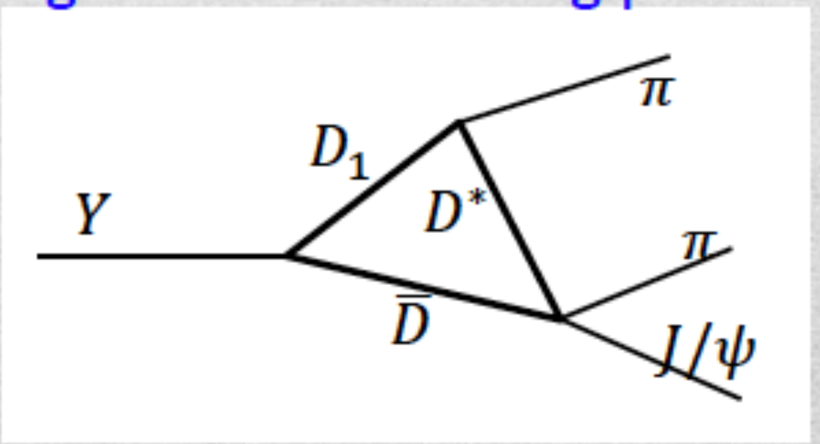
One can test different parametrizations of the amplitude, which correspond to
different singularities → different natures

AP *et al.* (JPAC), arXiv:1612.06490





Triangle rescattering,
logarithmic branching point

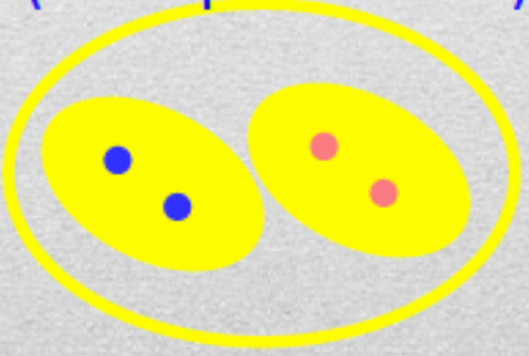


Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo *et al.* PRD92, 071502

(anti)bound state,
II/IV sheet pole
(«molecule»)

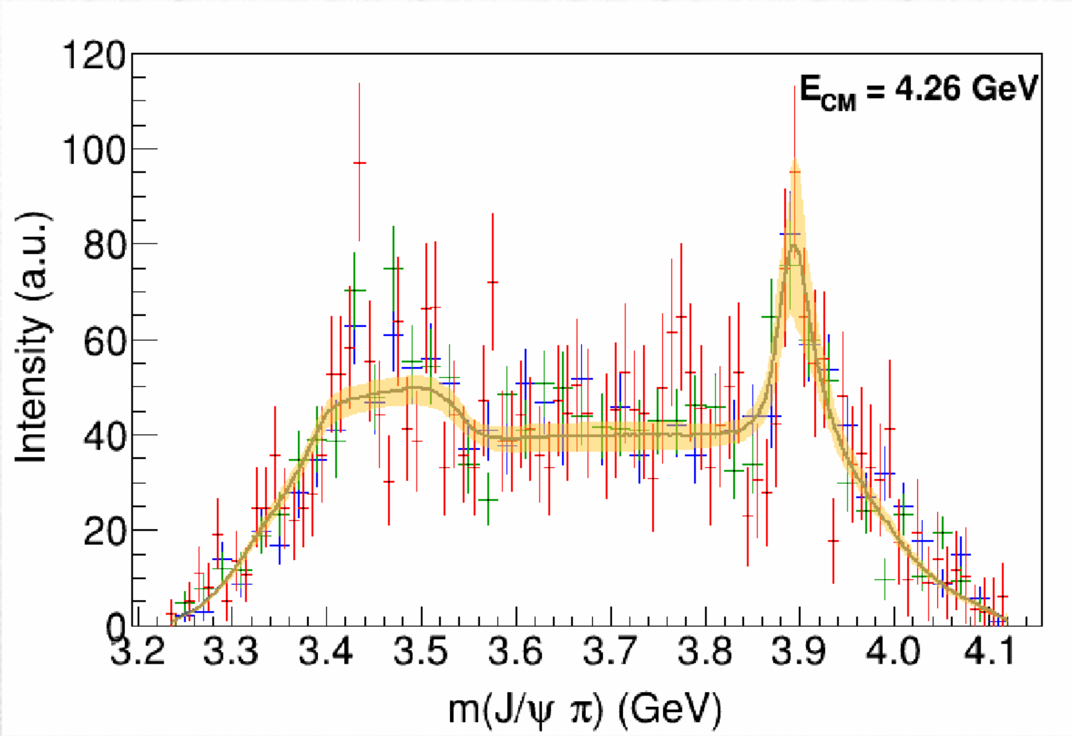
Tornqvist, Z.Phys. C61, 525
Swanson, Phys.Rept. 429
Hanhart *et al.* PRL111, 132003

Resonance,
III sheet pole
(«compact state»)

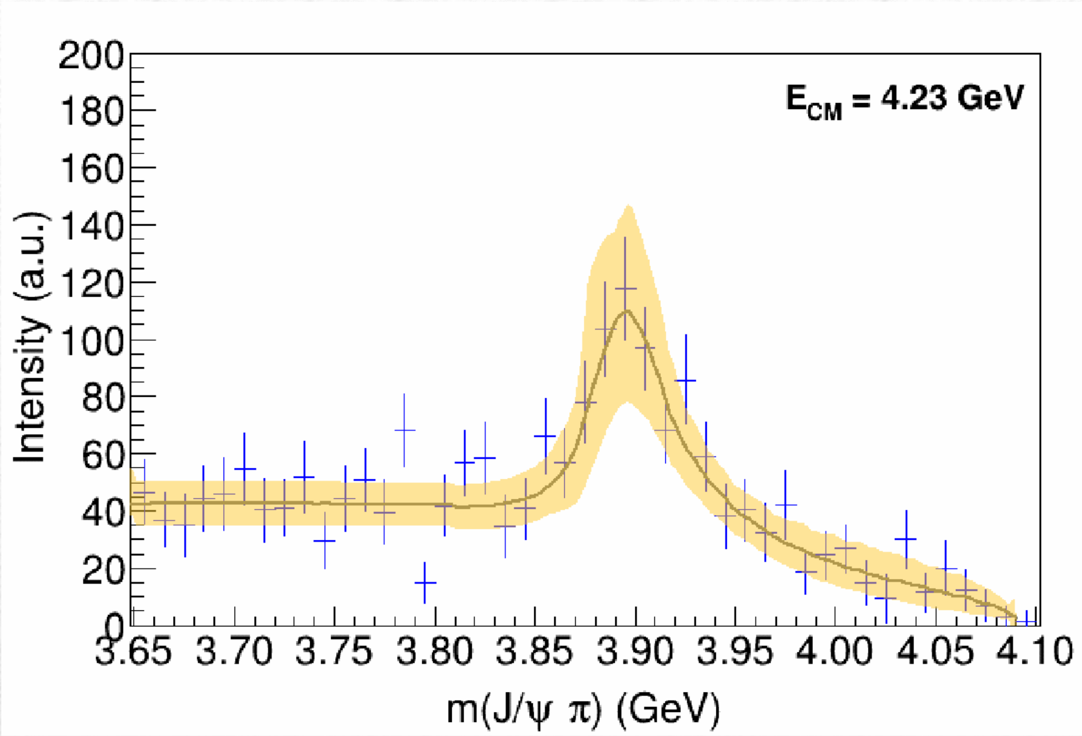


Maiani *et al.*, PRD71, 014028
Faccini *et al.*, PRD87, 111102
Esposito *et al.*, Phys.Rept. 668

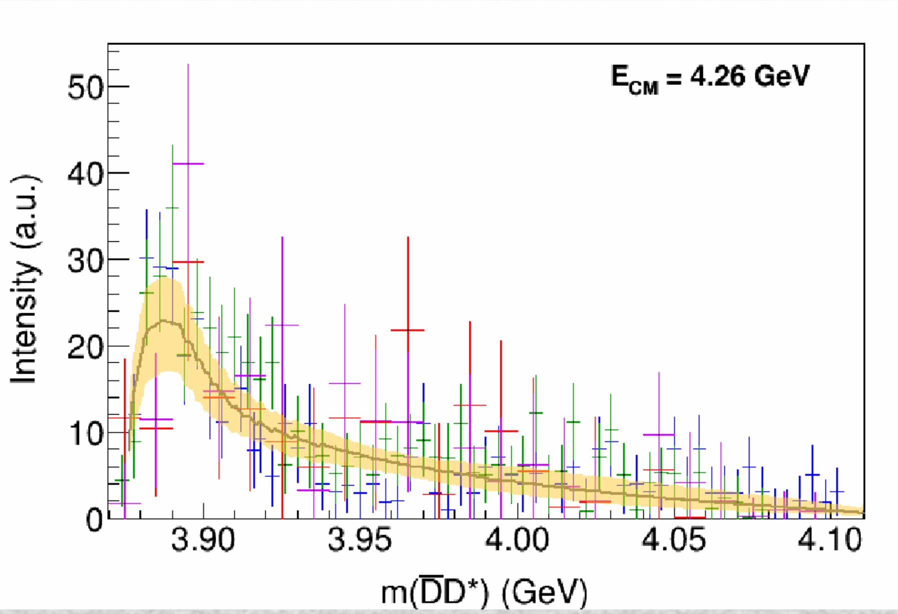
Fit: III



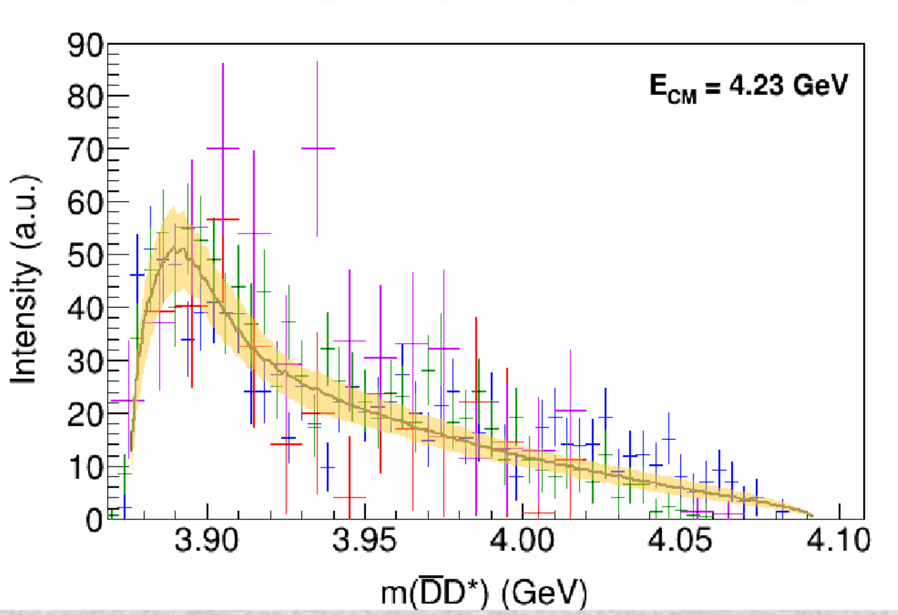
E_CM = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)



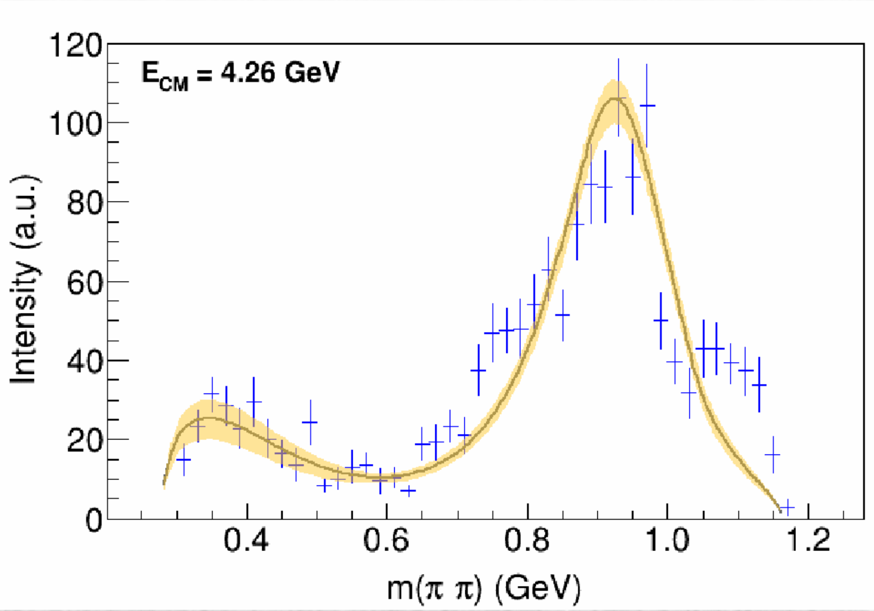
E_CM = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)



E_CM = 4.26 GeV
Intensity (a.u.)
m(D̄D*) (GeV)

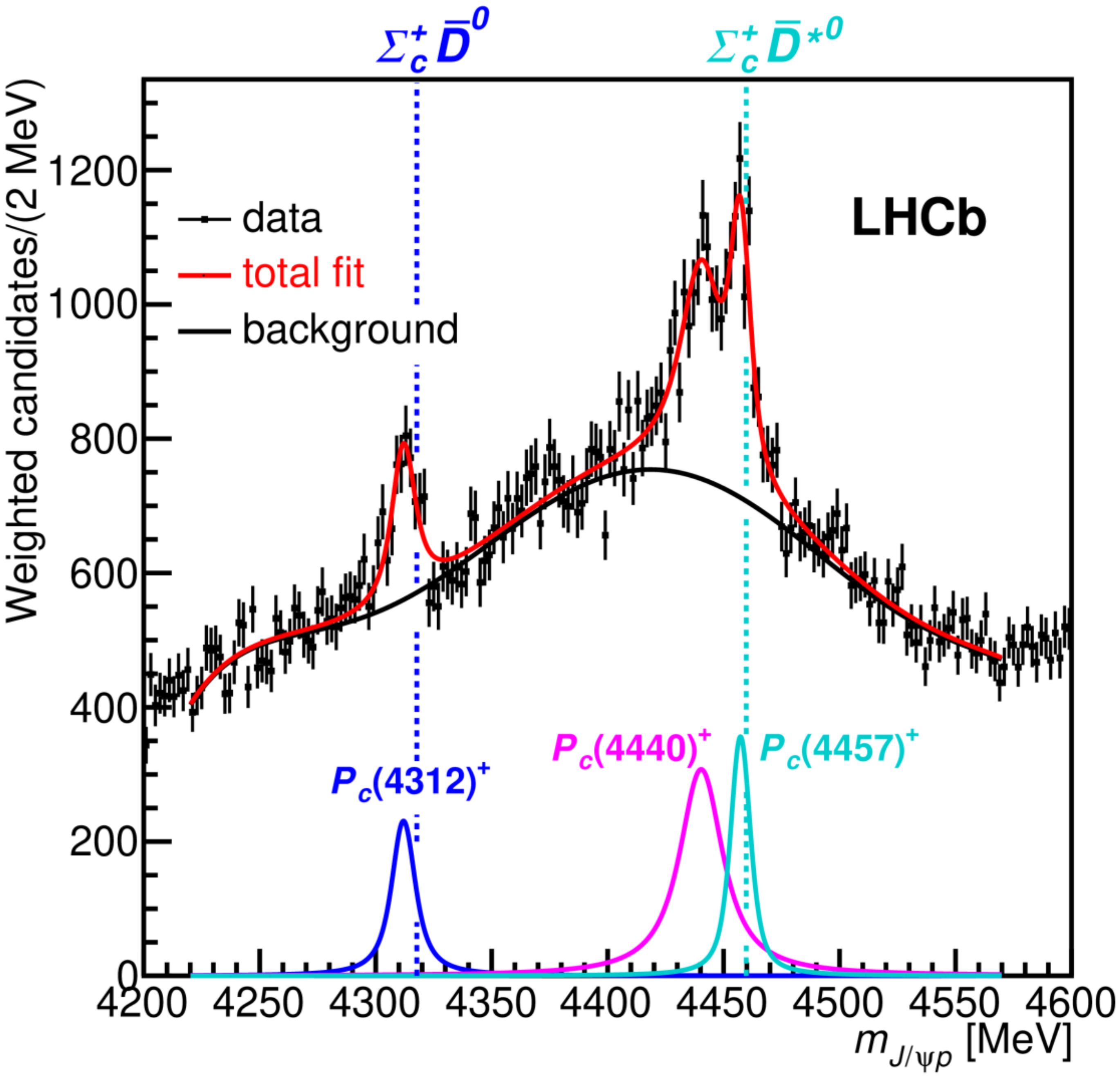


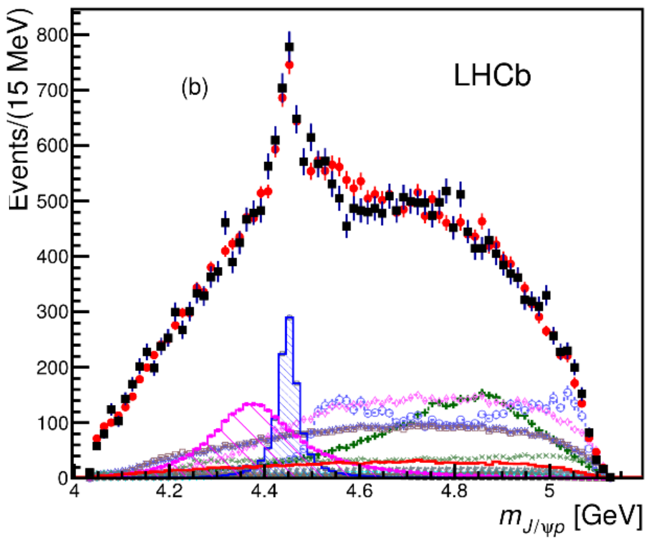
E_CM = 4.23 GeV
Intensity (a.u.)
m(D̄D*) (GeV)



E_CM = 4.26 GeV
Intensity (a.u.)
m(π π) (GeV)

New pentaquarks ?





The lowest $Pc(4312)$ appears as an isolated peak at the $\Sigma_c^+ D^0$ threshold

A detailed study of the line-shape can provide insight on its nature.

Is the resolution good enough to distinguish between, molecules, unbound virtual states, or compact pentaquarks?

New pentaquarks ?

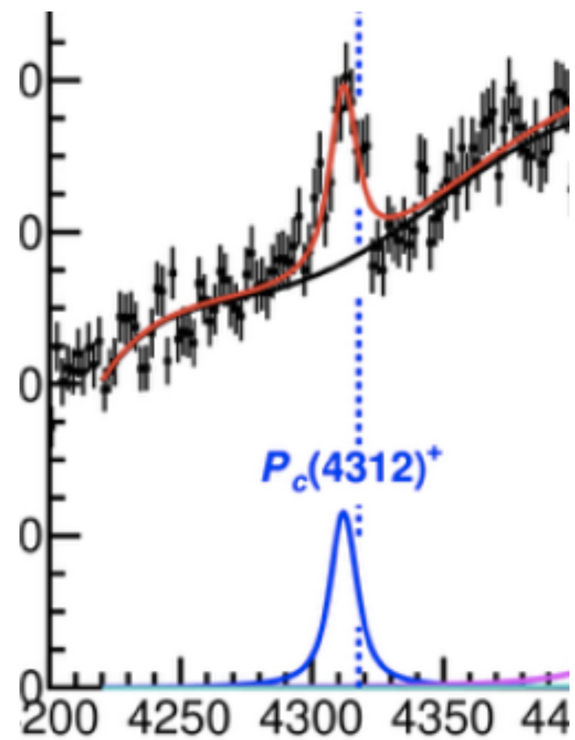
B(s) = higher p.w's

$$\frac{dN}{d\sqrt{s}} = \rho(s)[|A(s)|^2 + B(s)]$$

A(s) = assumed in a single p.w

$$A(s) = P(s)T(s)$$

$$T^{-1}(s) = M(s) - ik(s)$$



Case A

$$M(s) = M$$

virtual or bound states
(sheet IV or II but no sheet III)

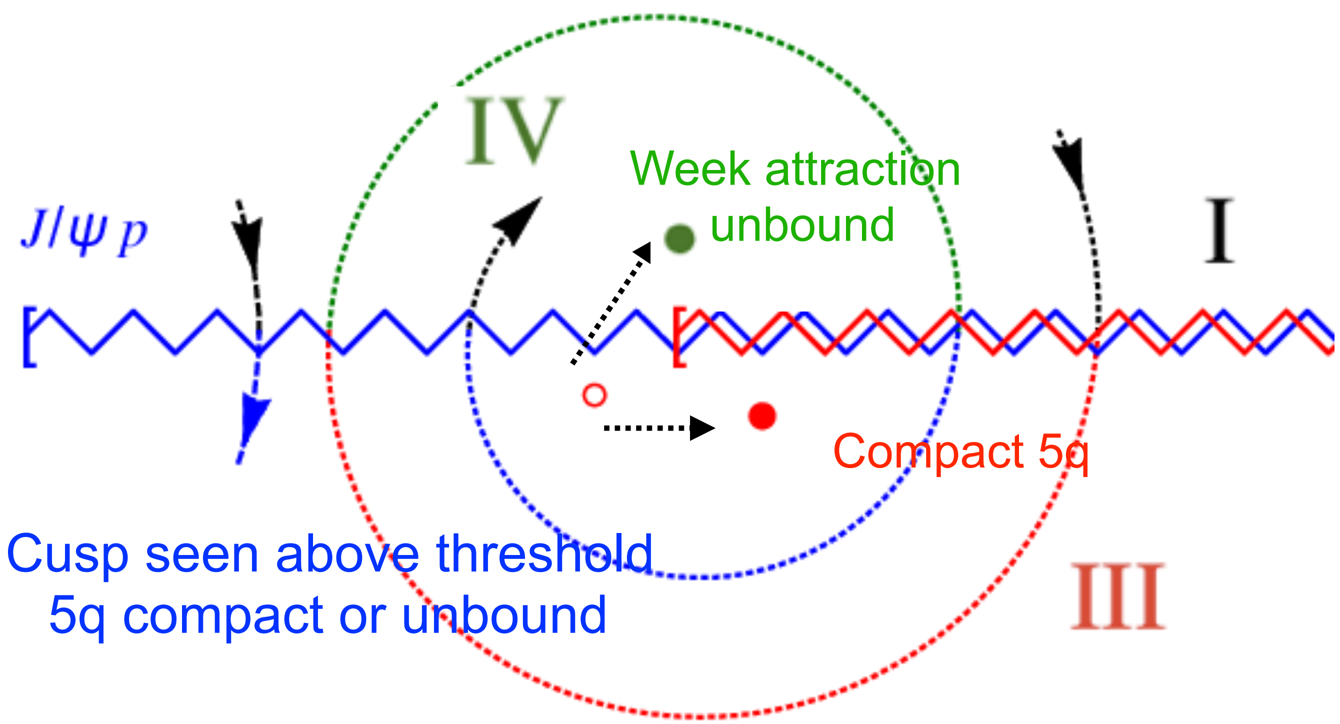
M (s) = 2 x 2 scattering lengt matrix

Case B

additional compact
states (sheet III)

$$M(s) = M + Cs$$

M = 2 x 2 scattering length
+ effective range



New pentaquarks ?

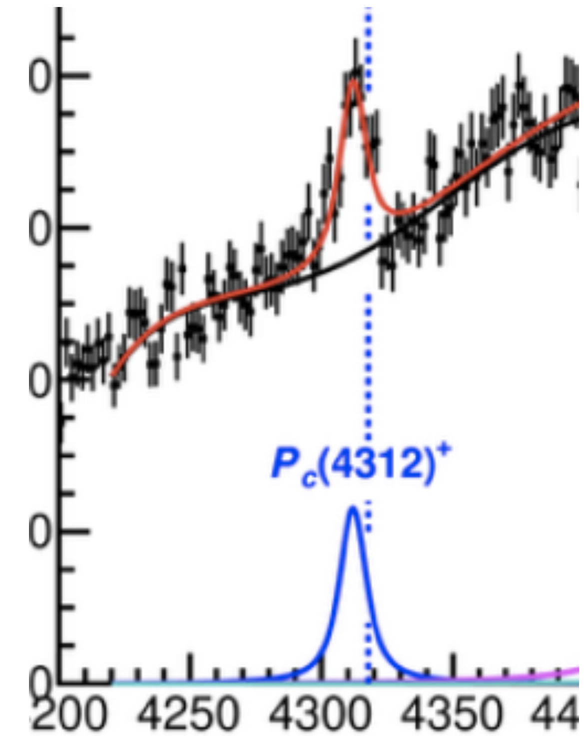
B(s) = higher p.w's

$$\frac{dN}{d\sqrt{s}} = \rho(s)[A(s)|^2 + B(s)]$$

A(s) = assumed in a single p.w

$$A(s) = P(s)T(s)$$

$$T^{-1}(s) = M(s) - ik(s)$$



Case A

$$M(s) = M$$

virtual or bound states (sheet IV or II)

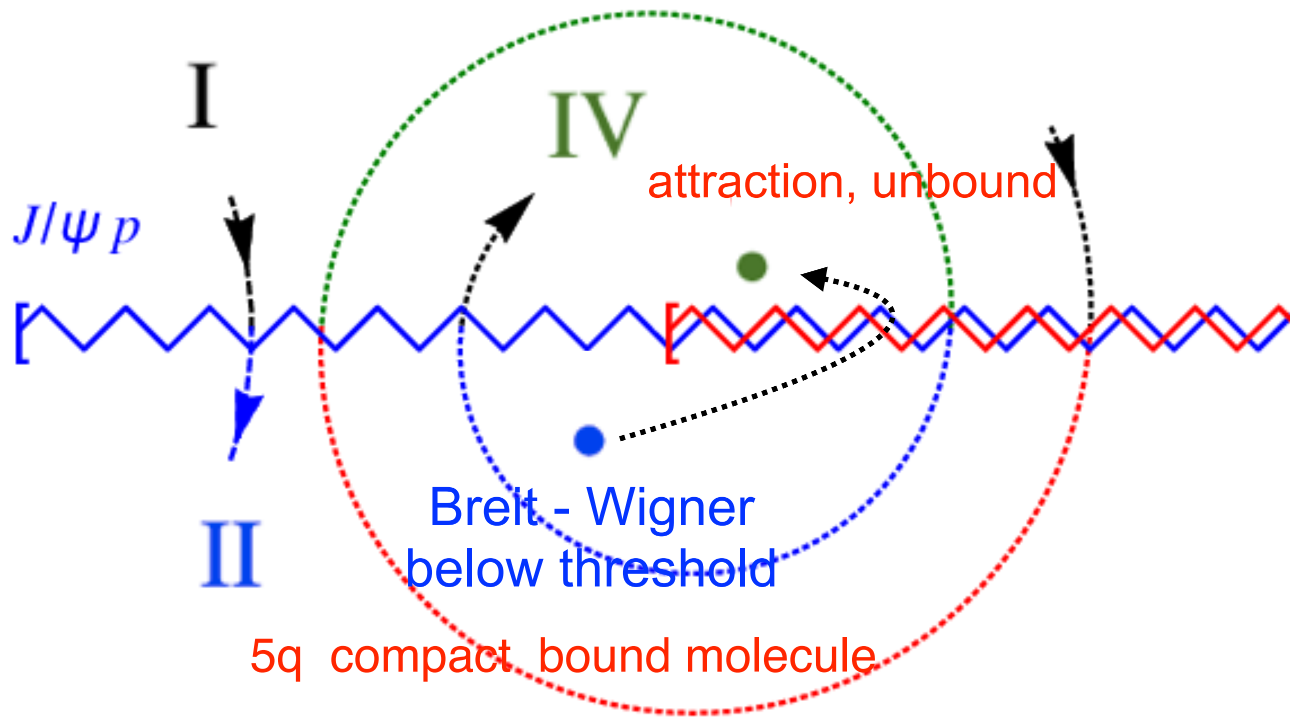
M (s) = 2 x 2 scattering lengt matrix

Case B

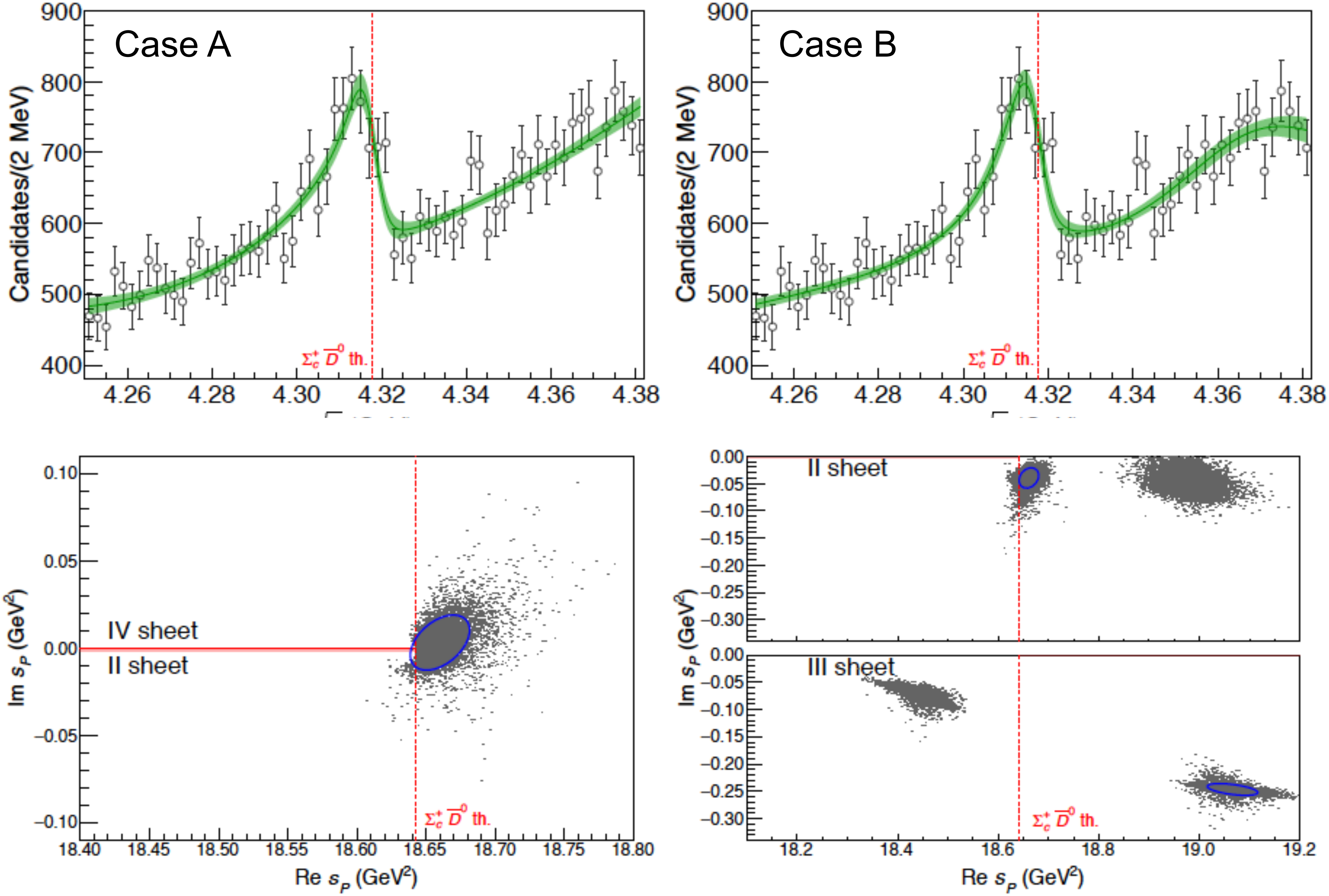
$$M(s) = M + Cs$$

additional compact states (sheet III)

M = 2 x 2 scattering length
+ effective range

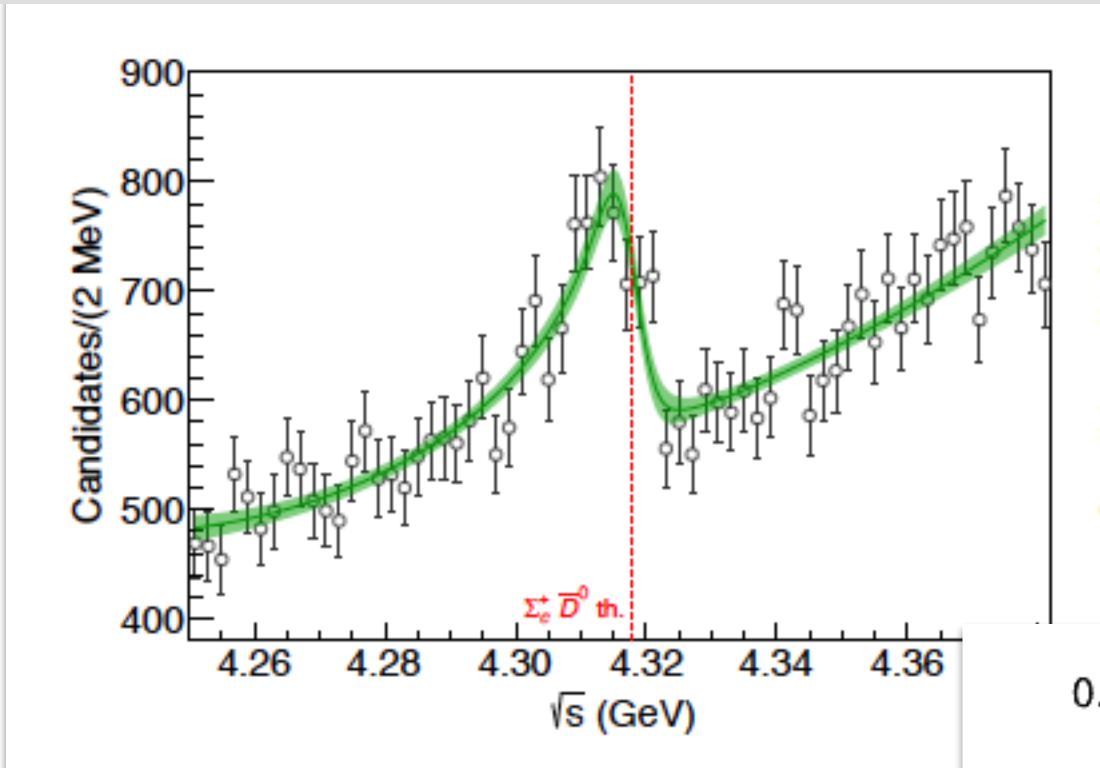


New pentaquarks ?



New pentaquarks ?

Case A



$$T^{-1} = M - i\rho(s)$$

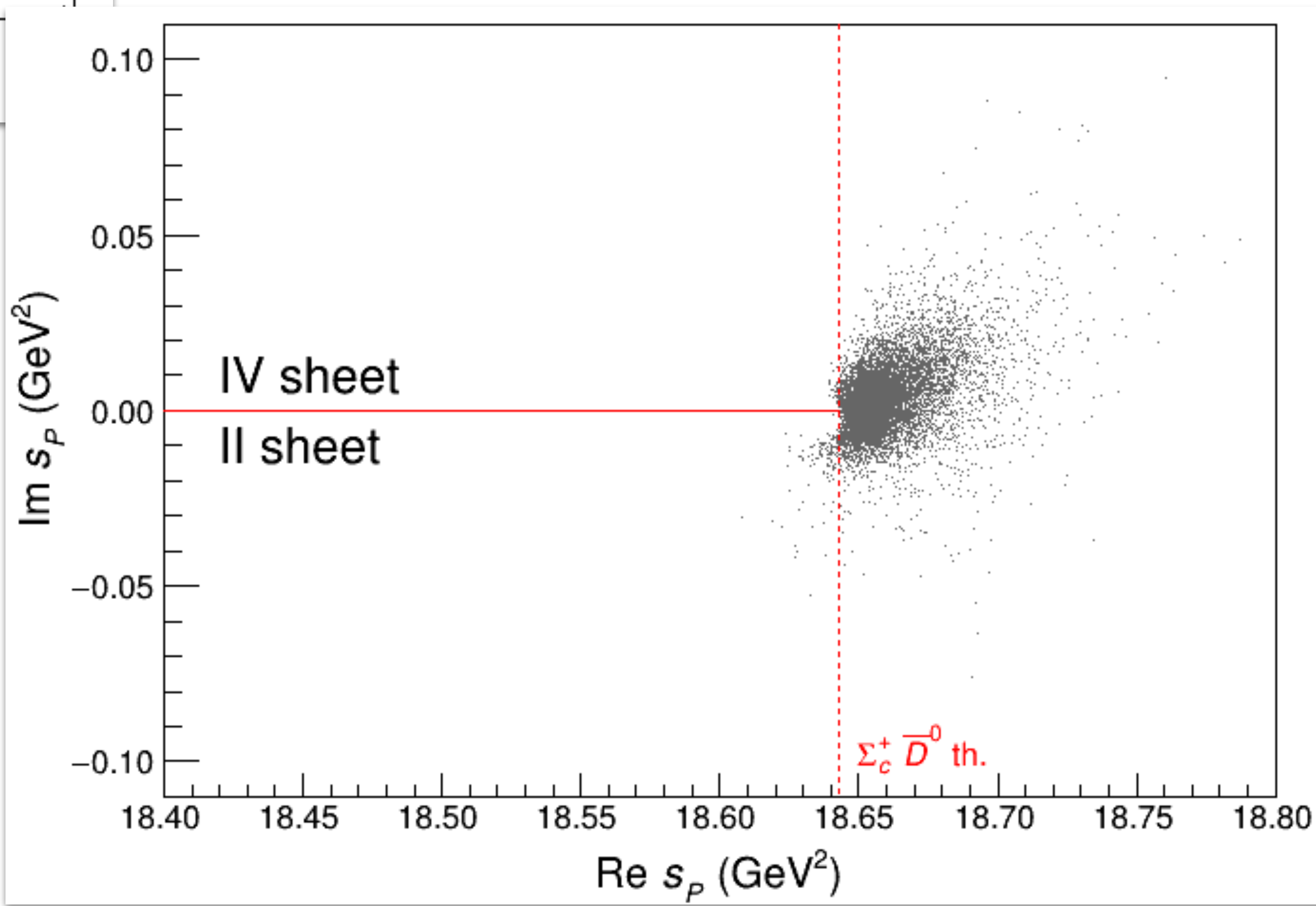
M = 2 x 2 scattering lengt

Decrease coupling between J/ψ p and $\Sigma^+\overline{D}$ channels

IV sheet pole moves onto real axis (virtual state)

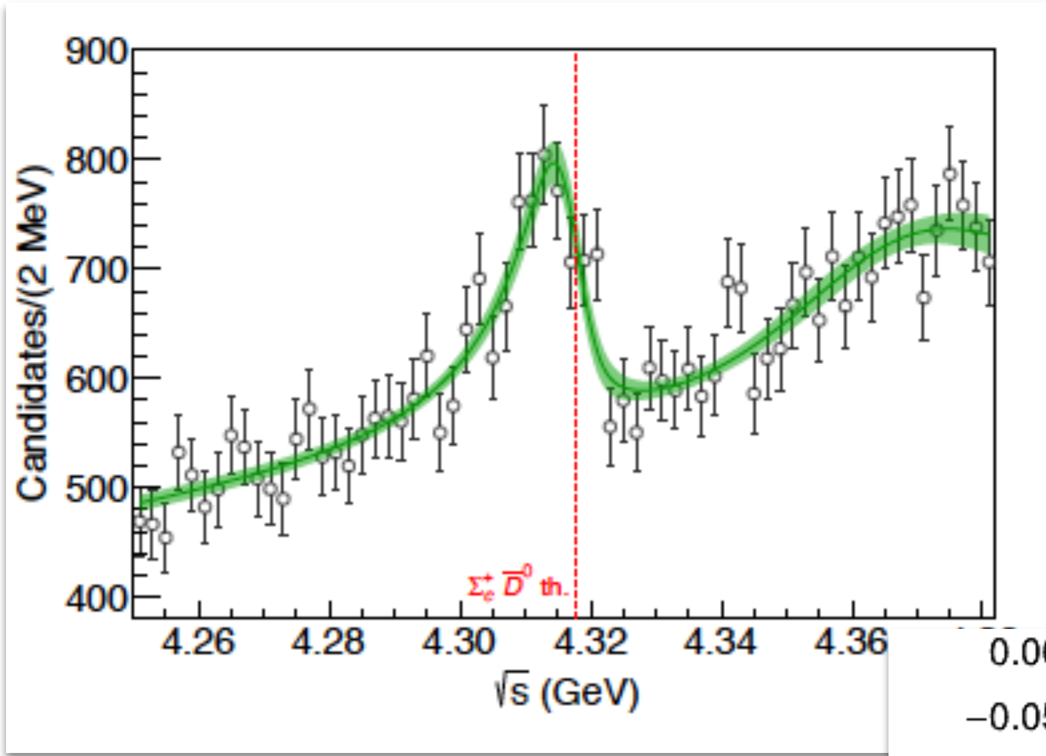
II sheet pole moves onto real axis (bound state)

Virtual state in (>90%)



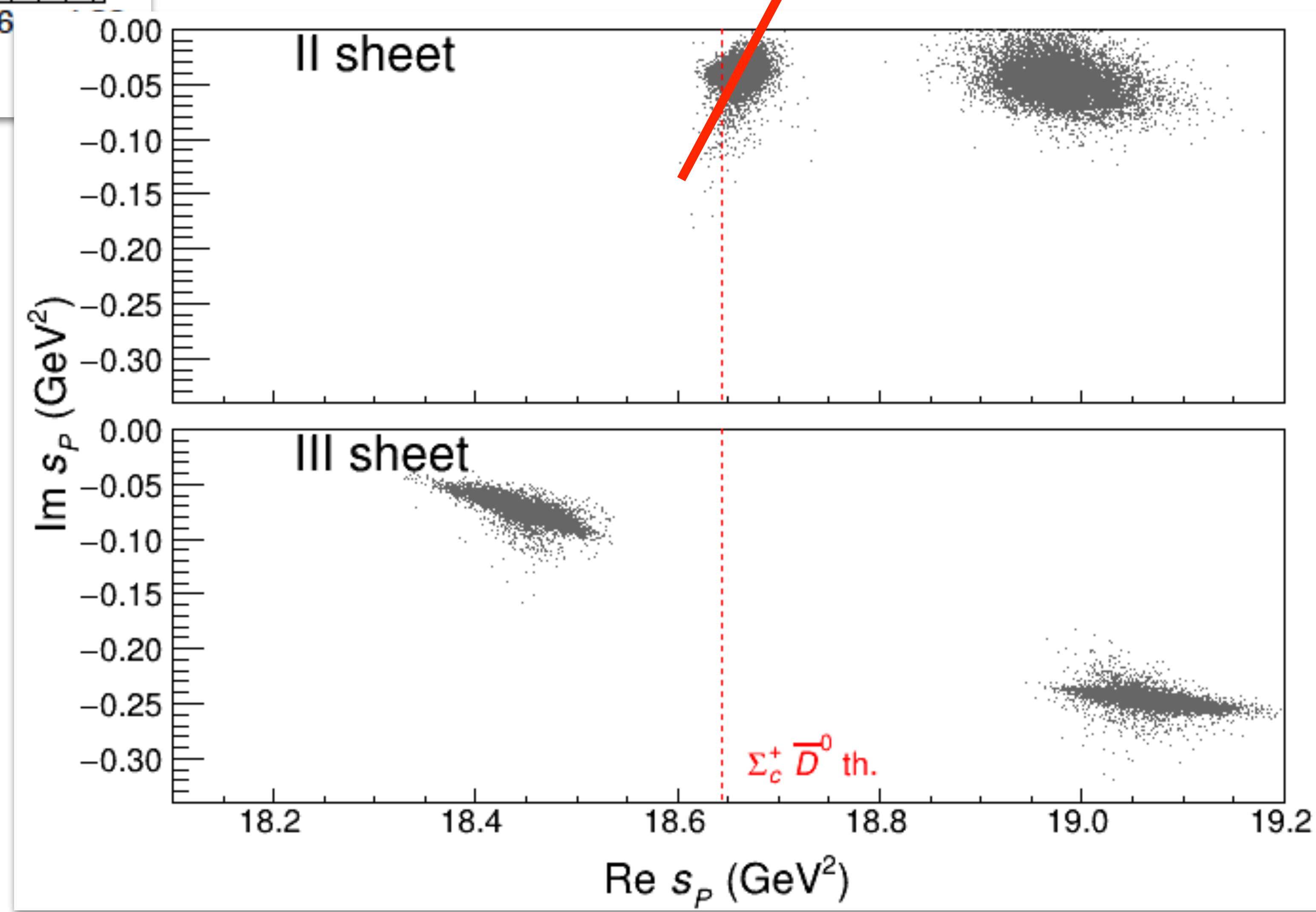
New pentaquarks ?

Case B



$$T^{-1} = M - i\rho(s)$$

M = 2 x 2 scattering length + effective range matrix



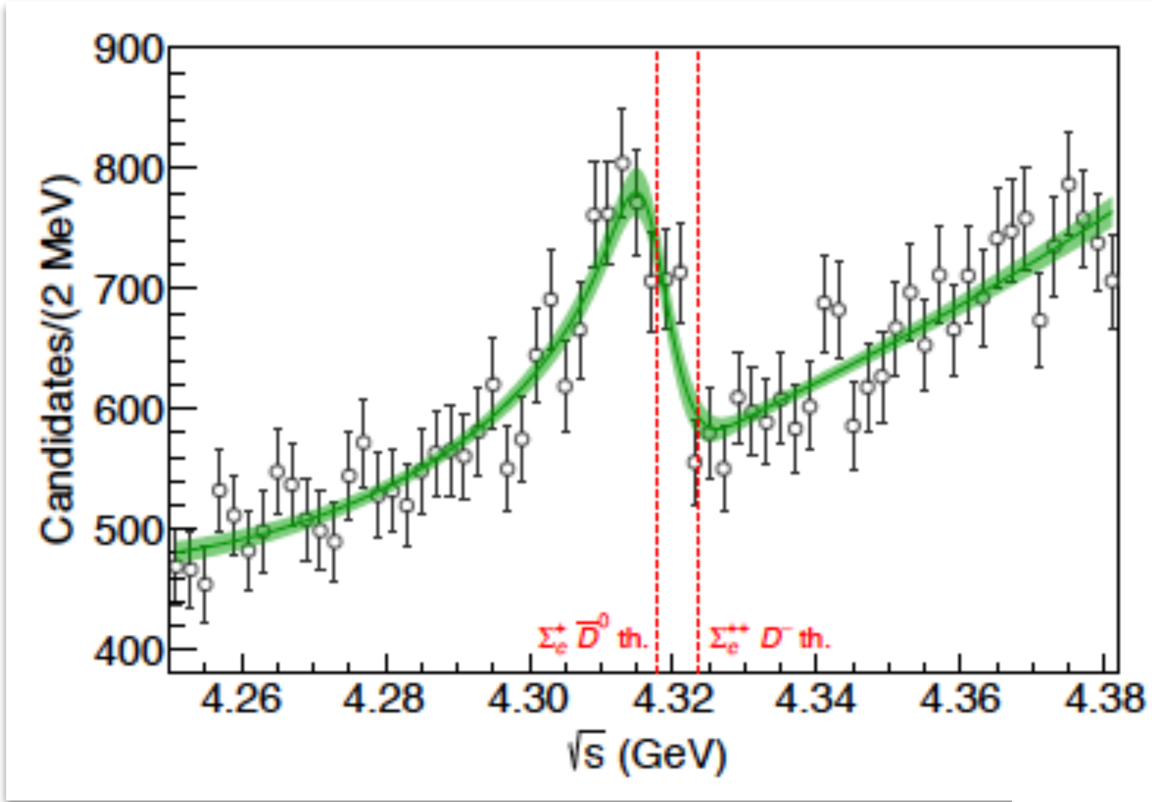
Decrease coupling between J/ψ p and $\Sigma^+\overline{D}$ channel

Remove imaginary parts

Peak generated by the II sheet pole which is “eaten” by a zero on IV sheet. Same with the lower III she pole

New pentaquarks ?

3 channel fit



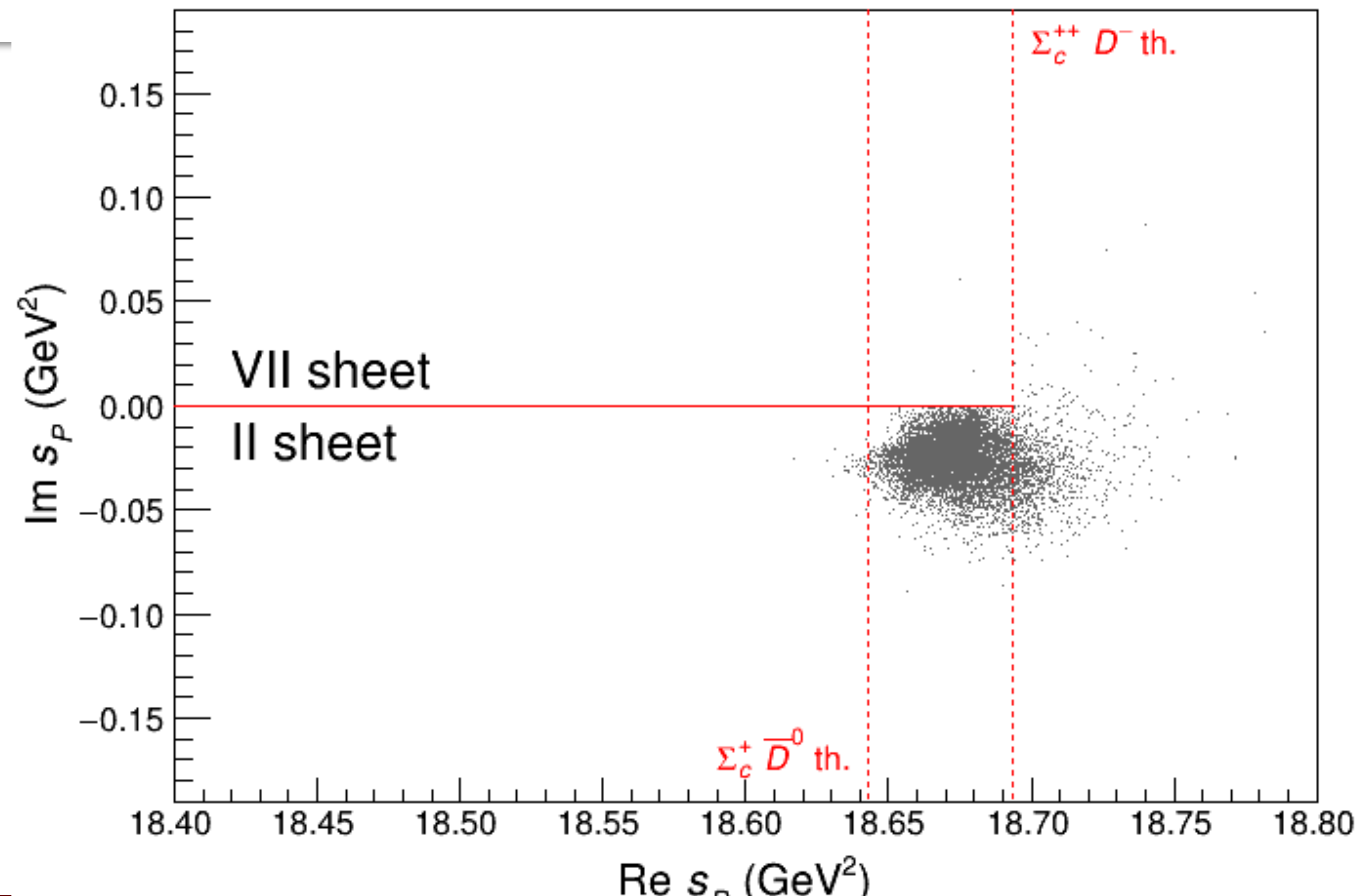
$$T^{-1} = M - i\rho(s)$$

M = 3 x 3 scattering lengt matrix

Decrease coupling between J/ψ p and $\Sigma^+\overline{D}$ channels

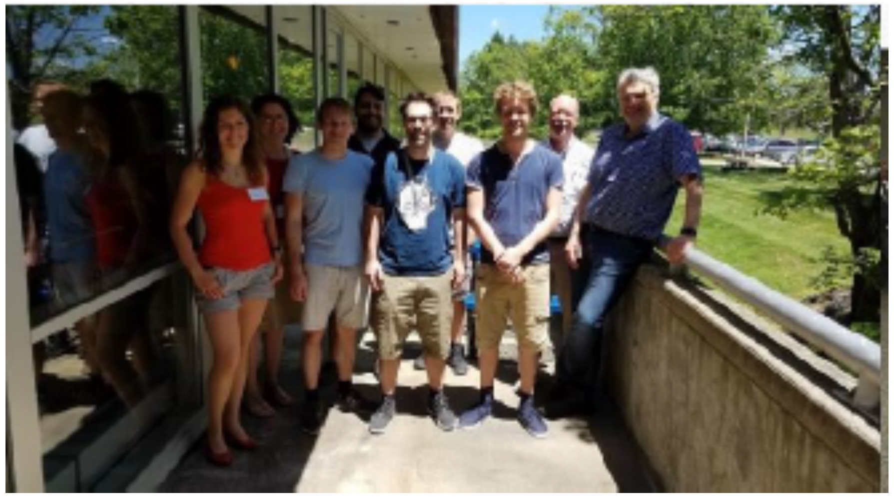
Remove imaginary parts

Consistent with unbound state



Joint Physics Analysis Center

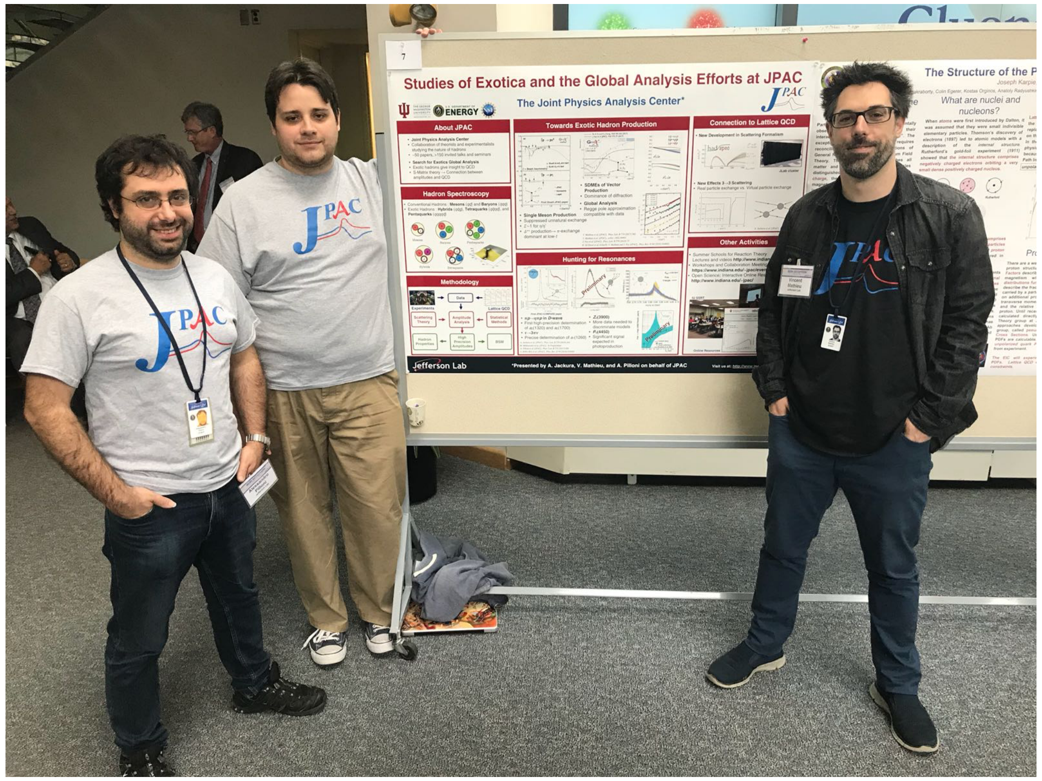
- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other accelerator laboratories.



- Contribute to education of new generation of practitioners in physics of strong interactions.

https://jpac.jlab.org

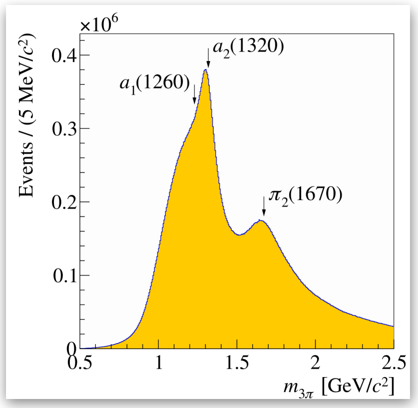
http://www.indiana.edu/~jpac/

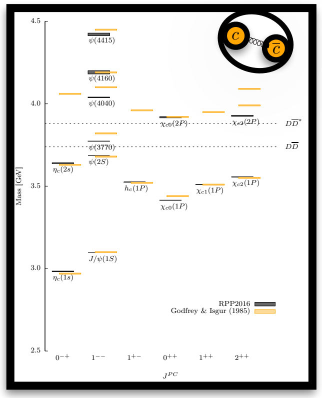


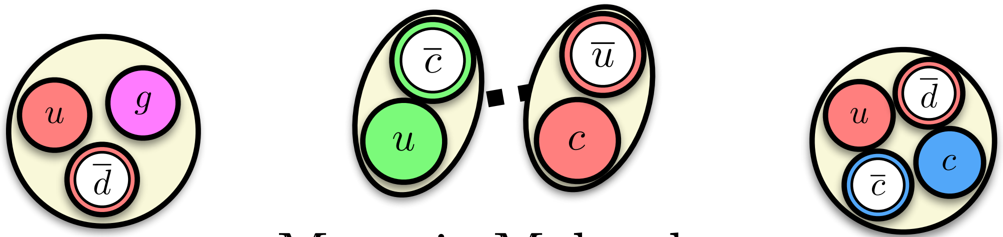
Spares

Amplitude analysis : connecting data to QCD

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







Hybrids

Mesonic-Molecules

Tetraquarks

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

$$d\sigma \propto |T(s,t,\cdots)|^2$$

Luscher quantization condition

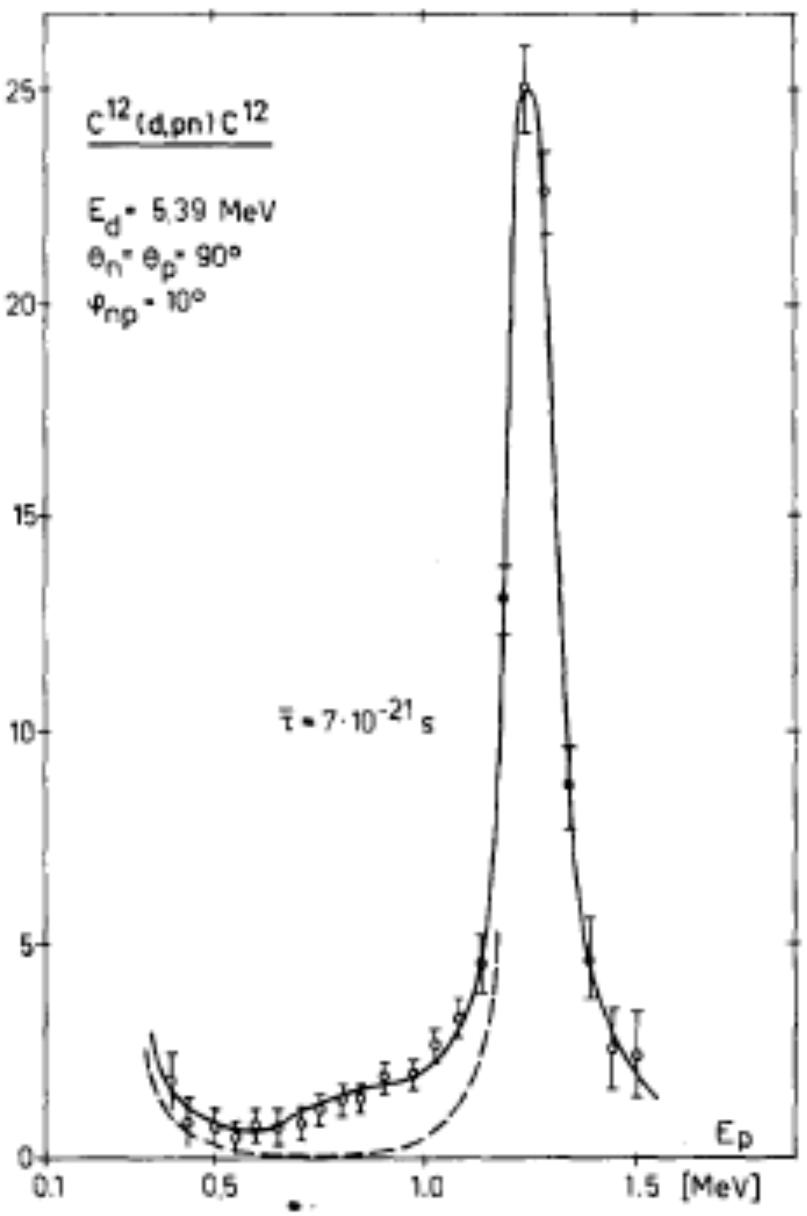
Amplitude analysis

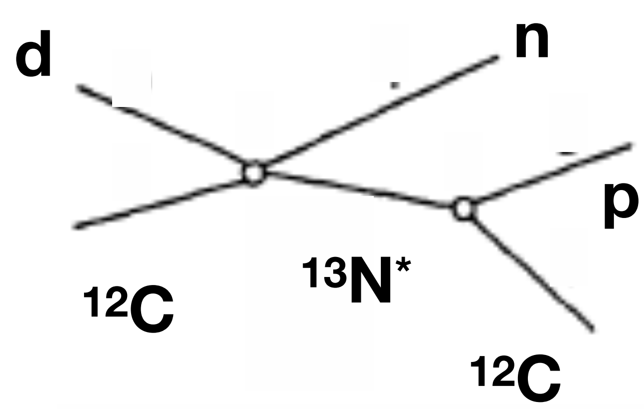
Triangle singularities

DIRECT DETERMINATION OF A SHORT NUCLEAR LIFETIME ($\approx 10^{-20}$ s) BY THE PROXIMITY SCATTERING METHOD

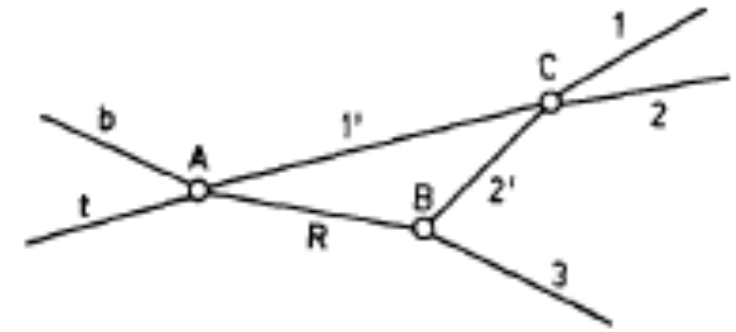
J. LANG, R. MÜLLER, W. WÖLFLI, R. BÖSCH and P. MARMIER
Laboratorium für Kernphysik, Eidg. Techn. Hochschule, Zürich †

Received 4 February 1966

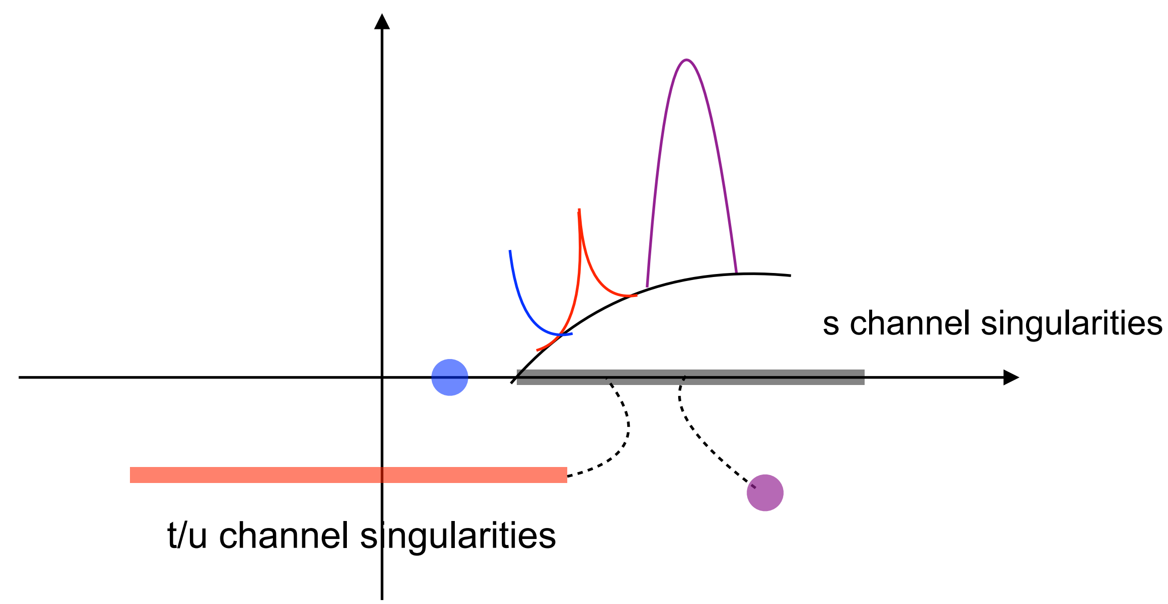




$[d + {}^{12}C \rightarrow n + p + {}^{12}C]$,

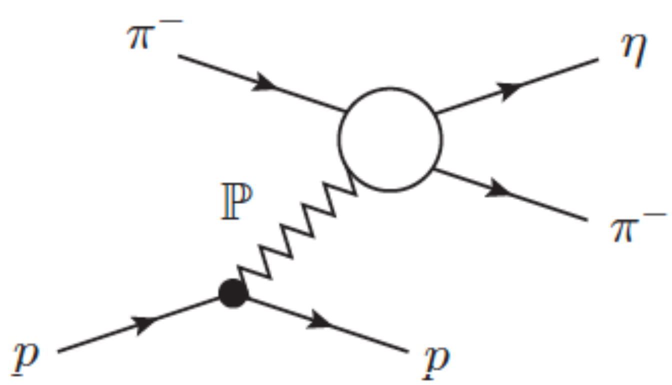


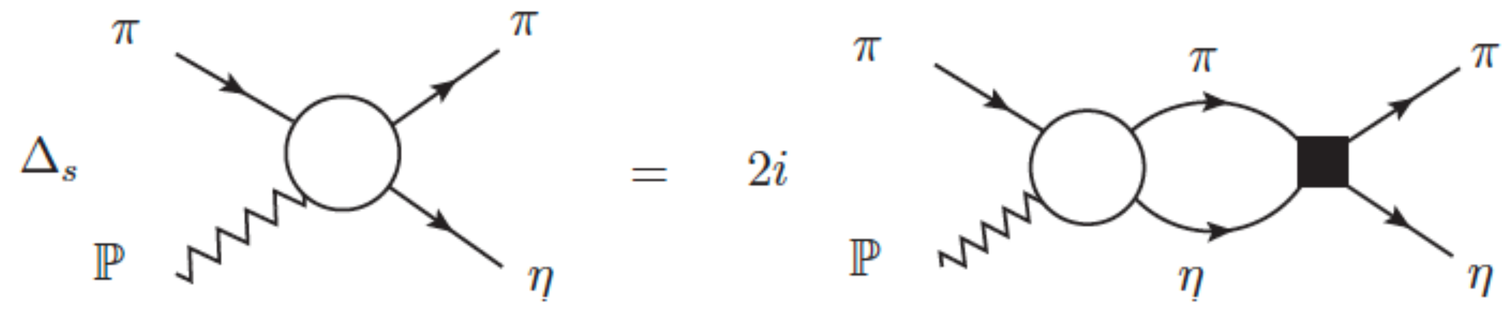
$[{}^{13}N^* \rightarrow p + {}^{12}C$,



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

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





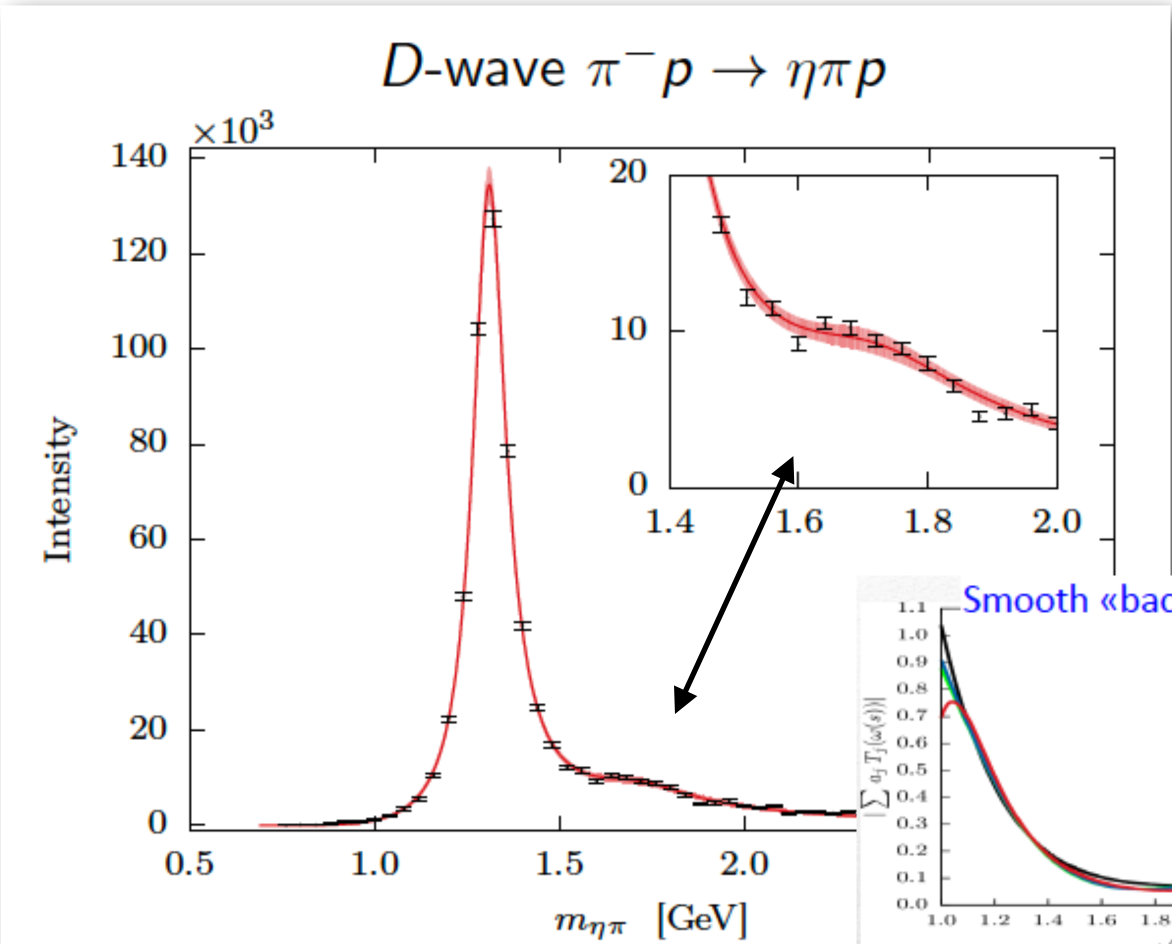
Production($s_{\pi\pi}$) x Interactions in ηπ ($s_{\pi\pi}$)

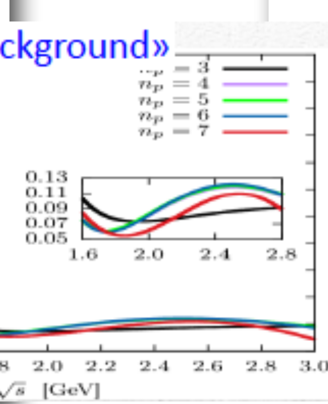
Constrained by unitary

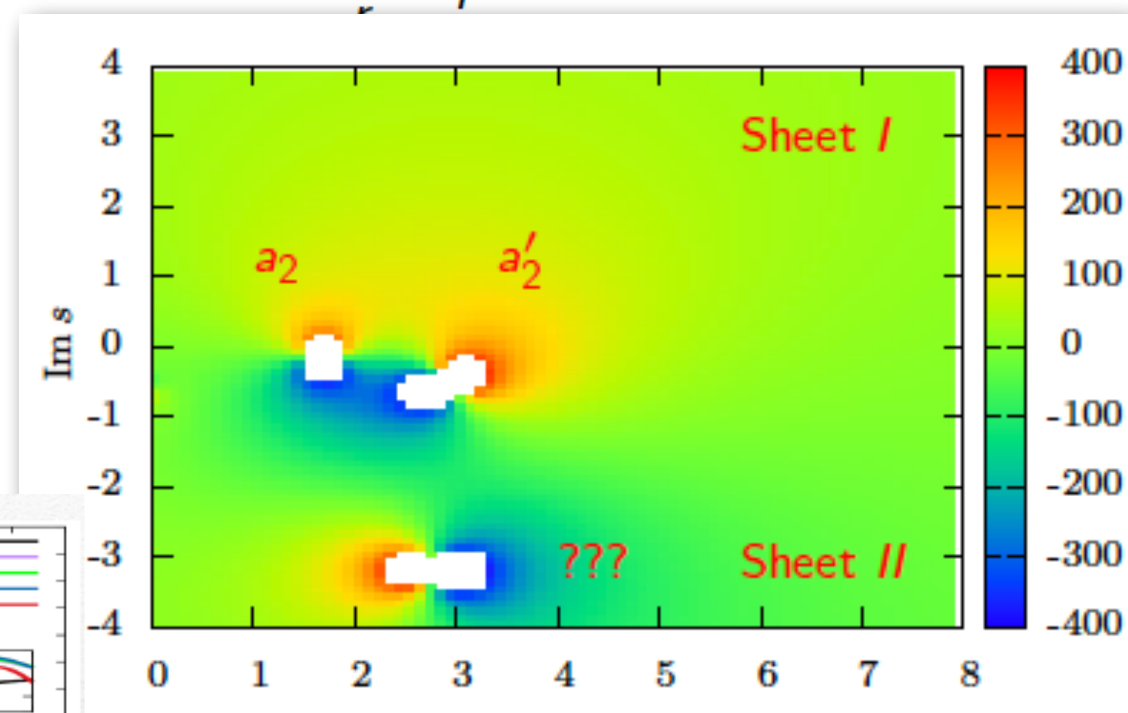
$$a_{\ell m_\ell} = f_{\ell m_\ell}(s) t_\ell(s)$$

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

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







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

Flate Formula

1 Channel

$$f^{-1}(s) = K^{-1}(s) - i\rho(s)$$

Phase space for deal
~ break up momentum

Analytic near threshold

$$K = \frac{g^2}{m^2 - s} \longrightarrow f(s) = \frac{g^2}{m^2 - s - i\rho(s)}$$

Breit-Wigner

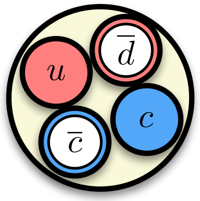
2 Channels

$$f_{11} = \frac{g_1^2}{m^2 - s - ig_1^2\rho_1(s) - ig_2^2\rho_2(s)}$$

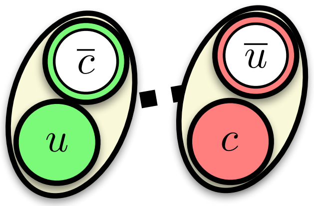
$$\mathbf{f}^{-1} = \mathbf{K}^{-1} - i\rho(s)$$

$$\mathbf{K} = \frac{1}{m^2 - s}\begin{pmatrix} g_1^2 & g_1 g_2 \\ g_1 g_2 & g_2^2 \end{pmatrix}$$

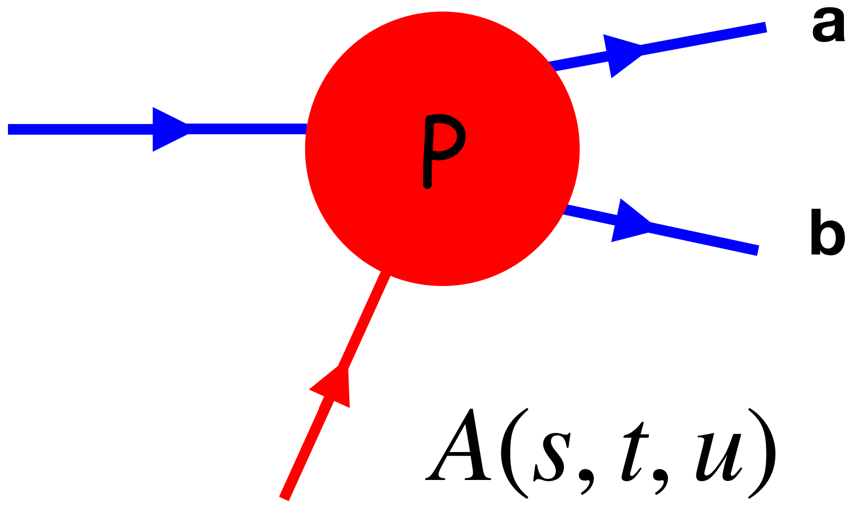
K-matrix pole produces a pole on the complex plane. But its existence is independent from that of decay channels



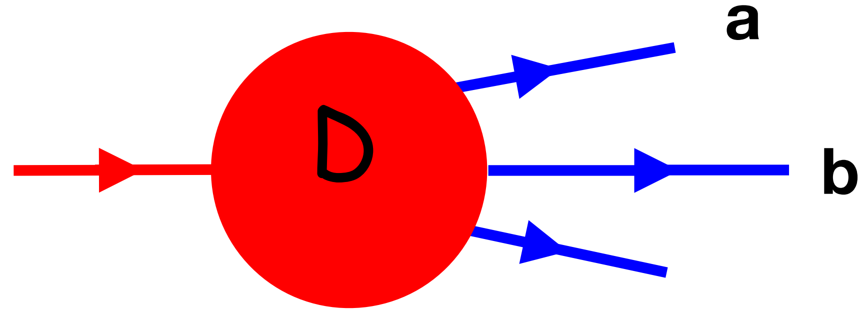
If $m^2, g_i >> 1$, it becomes an effective range approximation $\rightarrow$ threshold (bound state of virtual state) poles



Amplitude analysis: observables as reflection of singularities



$A(s, t, u)$



$A(m_{12}^2, m_{23}^2, m_{13}^2)$

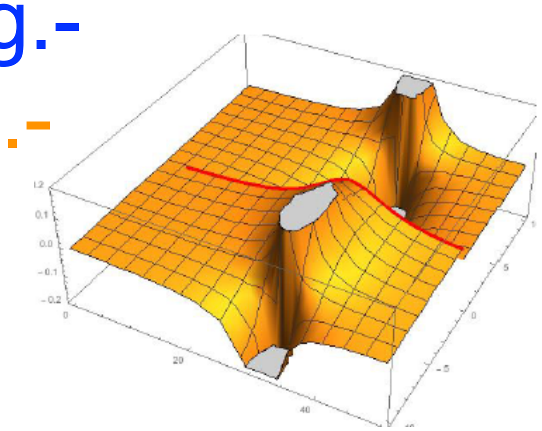
What constrains resonance in e.g. ab?

- A is analytical with unitarity branch points

$$A_l(s) = \int dz P_l(z) A(s, t(z,s), u(z,s))$$

- Partial waves are constrained by unitarity; it exposes singularities hidden under cuts: poles (resonance), log.-branch points ("forces" e.g. triangle singularities), sqrt.-branch points (multi-particle production), etc.

  → all singularities have physical origin !



Systematic Studies

- Change of functional form and parameters in the denominator

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

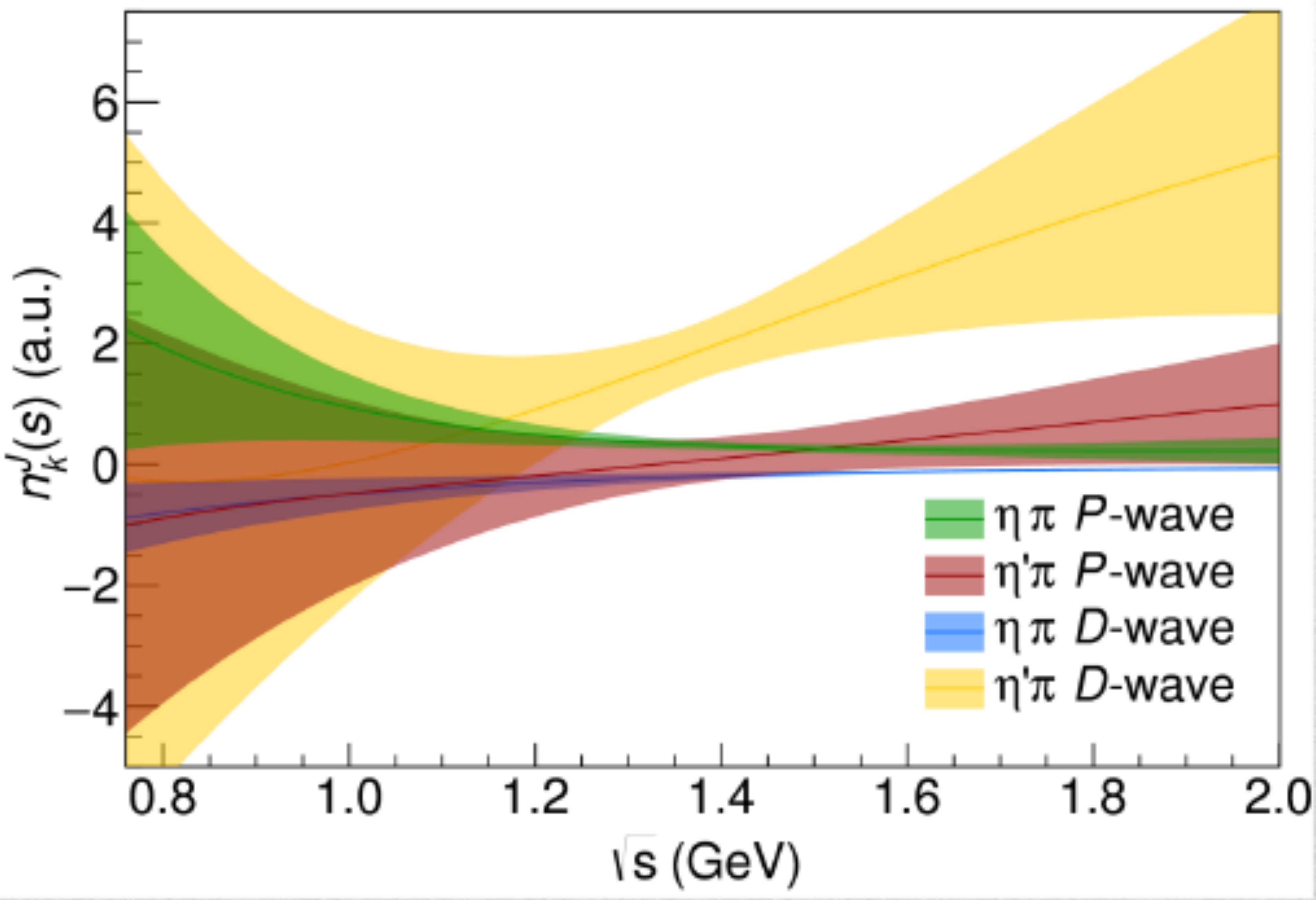
  - Default: $s_R = 1\ \mathrm{GeV}^2$. We try $s_R = 0.8, 1.8\ \mathrm{GeV}^2$
  - Default: $\alpha = 2$. We try $\alpha = 1$
  - We also try a different function: $\rho N_{ki}^{J}(s') = g\,\delta_{ki}\,\frac{Q_J(z_{s'})}{s'^{\alpha}\lambda^{1/2}(s', m_{\eta^{(\prime)}}, m_\pi)}$ with $\alpha = 2, 1.5,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

- Change of parameters in the numerator

  - Default: $t_{\mathrm{eff}} = -0.1\ \mathrm{GeV}^2$. We try $t_{\mathrm{eff}} = -0.5\ \mathrm{GeV}^2$
  - Default: 3rd order polynomial. We try 4th

Separating "exchange forces" from "resonances"

Polynomial in the numerator



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

This happens indeed