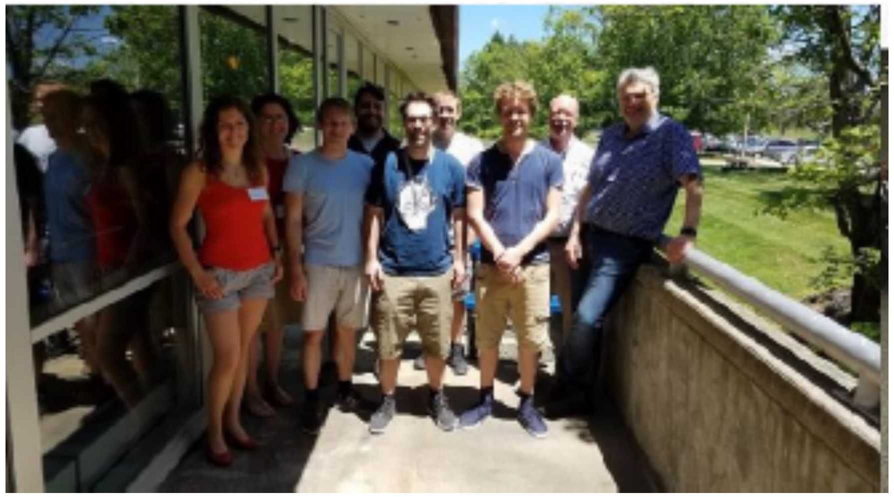
How to reconstruct resonances (and determine where they come from) JPAC update

Adam Szczepaniak, Indiana University/Jefferson Lab

Join Physics Analysis Center

Joint Physics Analysis Center

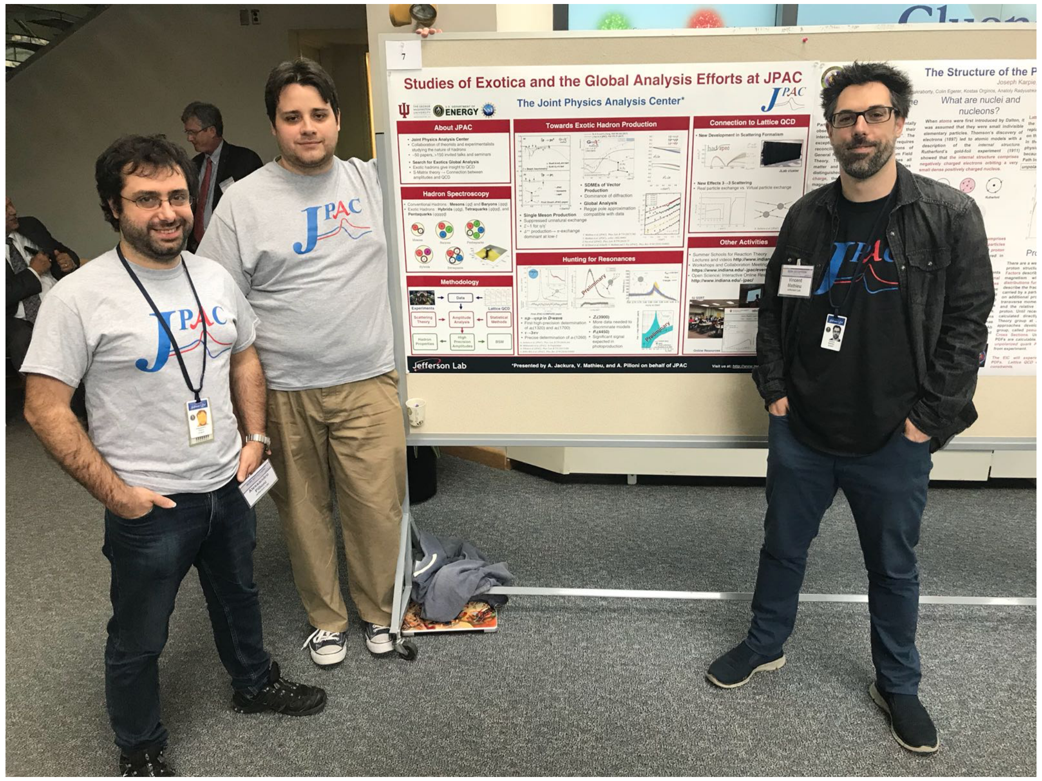
- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other accelerator laboratories: one meeting/week + working groups



- Contribute to education of new generation of practitioners in physics of strong interactions : NEW: Graduate course on reaction theory

https://jpac.jlab.org

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



Full members

Students

- Andrew Jackura (PhD2019 IU -> OUD) 2019 IU Outstanding Graduate Student Award
- Nathan Sherrill (4th year, IU) 2019 Indiana Space Grant Consortium graduate fellowship
- Daniel Winney (3th year, IU) (Currently attending HUGS)
- Sebastian David (2nd year, IU)
- Jorge Silva-Castro (1st year, UNAM)
- Misha Mikhasenko (PhD 2019 Bonn -> CERN)
- Jannes Nys (PhD 2018 U.Ghent -> Startup

Postdocs

- Alessandro Pilloni (JLab -> ECT*)
- Vincent Mathieu (JLab -> U. Computense)
- Miguel Albaladejo (JLab)
- Astrid Hiller-Blin (Mainz -> JLab)
- Lukasz Bibrzycki (Krakow -> JLab)
- A.Rodas (U.Computense -> Jlab)

+ several affiliated members

Good use of JPAC to leverage !

Recent activities

- ~30 papers in 2018-2019 (PRL,PLB,PRD,PRC,EPJ)

  Includes 3 collaborative papers with CLAS, contributed to 2 GlueX papers 1 with LHCb

- O(50) invited talks

  Every major conference has JPAC update (delivered by junior members !)

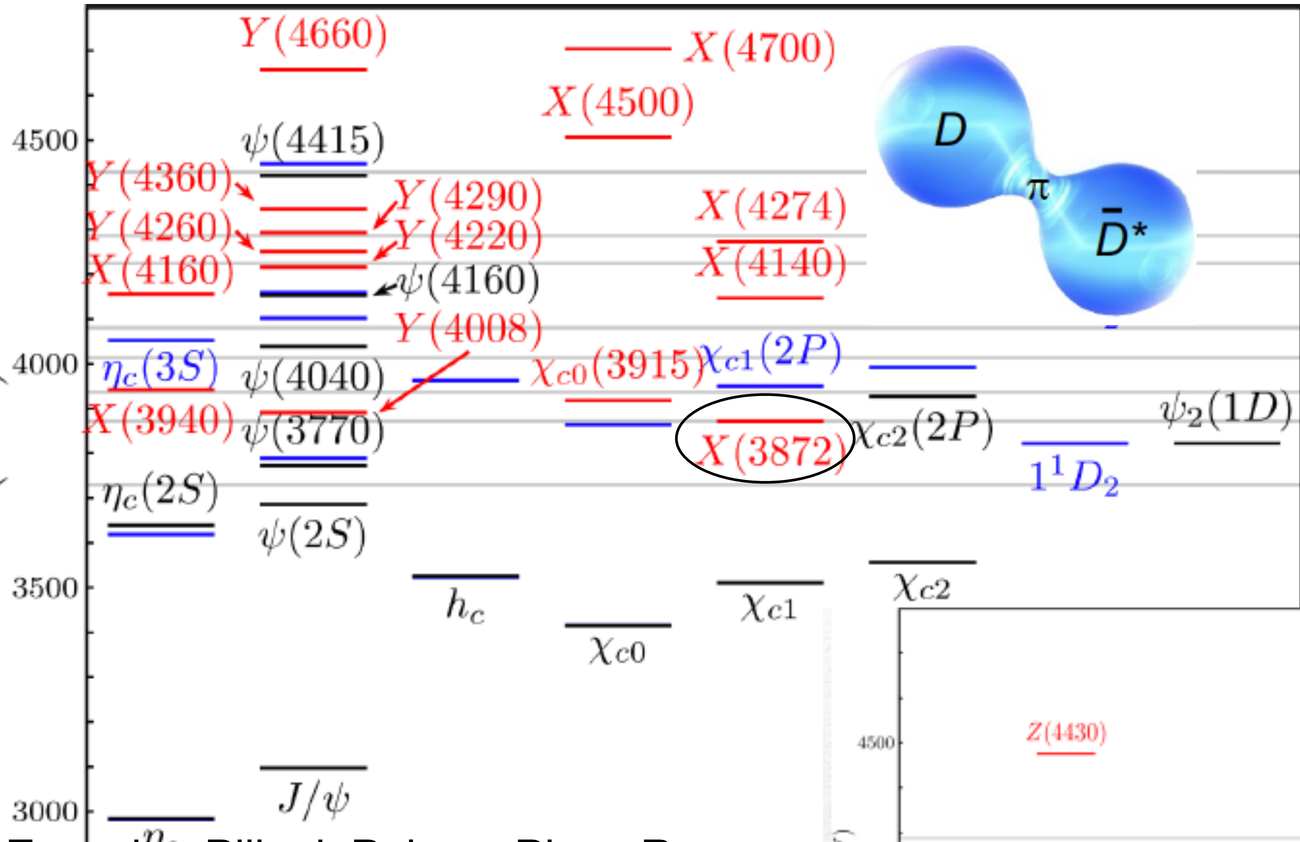
- Affiliated with CLAS,BESIII,COMPASS,LHCb

  - Organization :

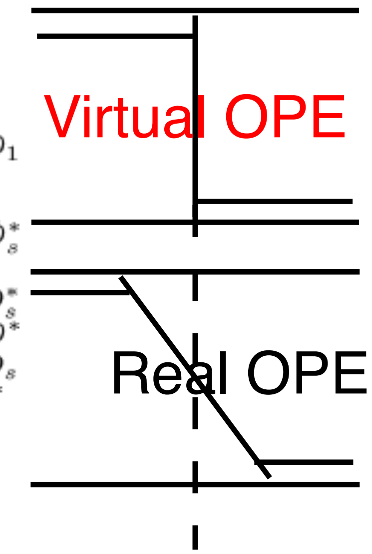
    - Spectroscopy at EIC (ECT*, 2018)
    - FDHS3, BESIII-JPAC Collaboration, Beijing (2019)
    - ATHOS/PWA (Rio de Janeiro (2019)
    - JPAC session at GHP (2019)
    - HADRON 2019 (Guilin, 2019)

  - Planed
    - HADRON NNPS (UNAM + IU, 2020)
    - INT Spectroscopy (2020)

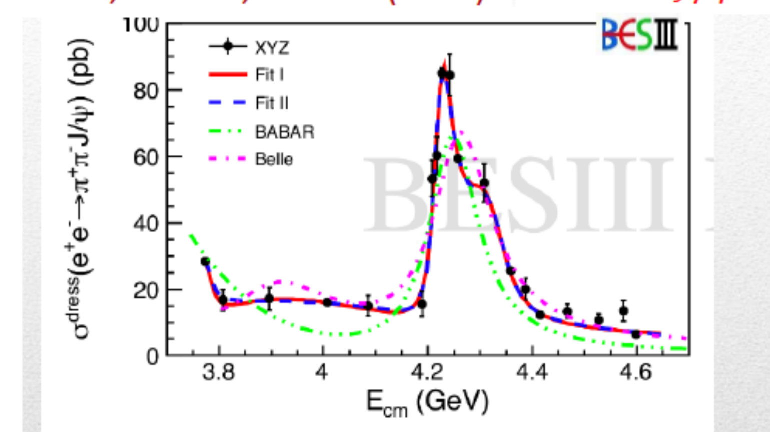
Signatures of unusual heavy quark resonances

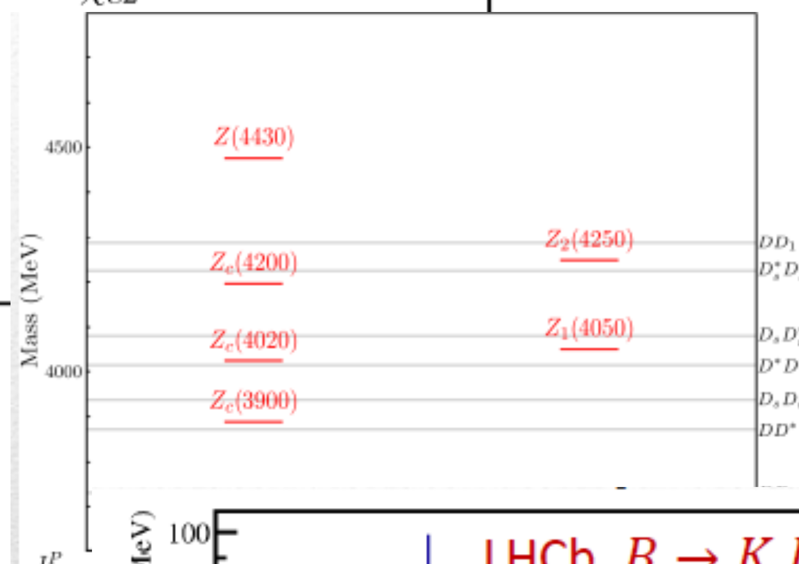


Esposito, Pilloni, Polosa, Phys. Rep.



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



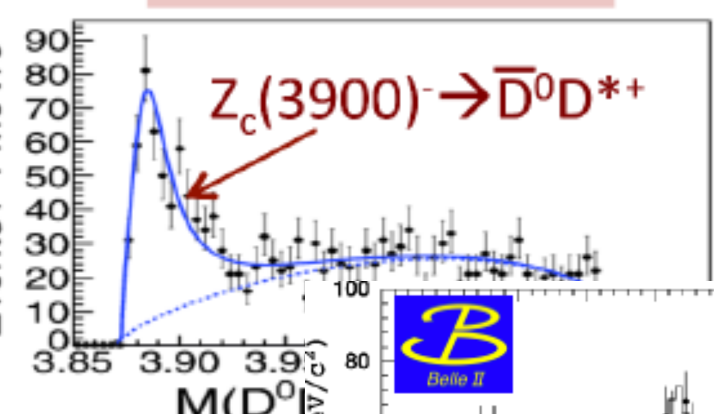


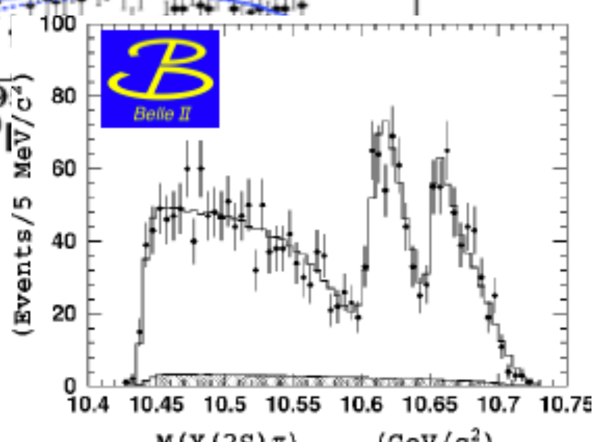
EMARK ON ENERGY PEAKS IN MESON SYSTEMS

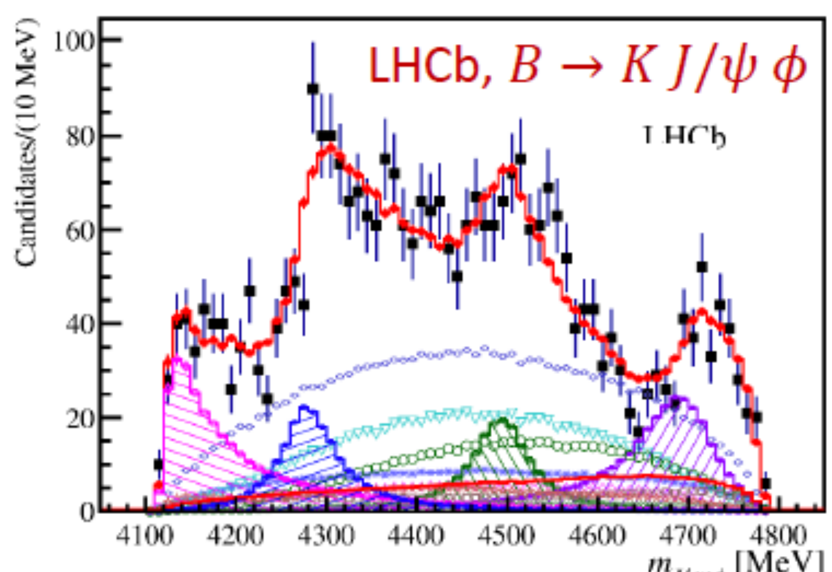
M. Nauenberg A. Pais

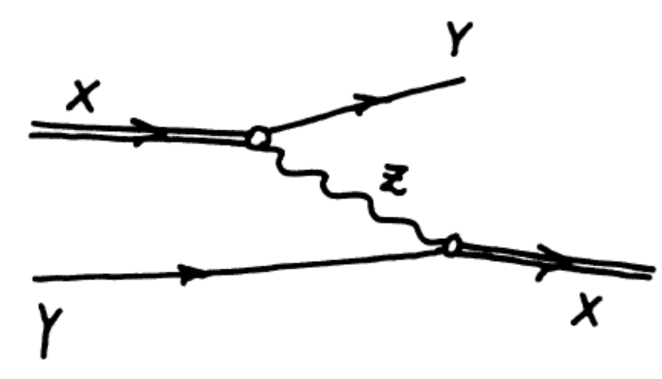
If the width of particle X is not very large we will stay close to the physical region. This almost singular behavior of $A(s)$ for certain physical s causes the peaking effect to which we refer as an (X, Y, Z) peak.

BESIII PRL 112, 022001



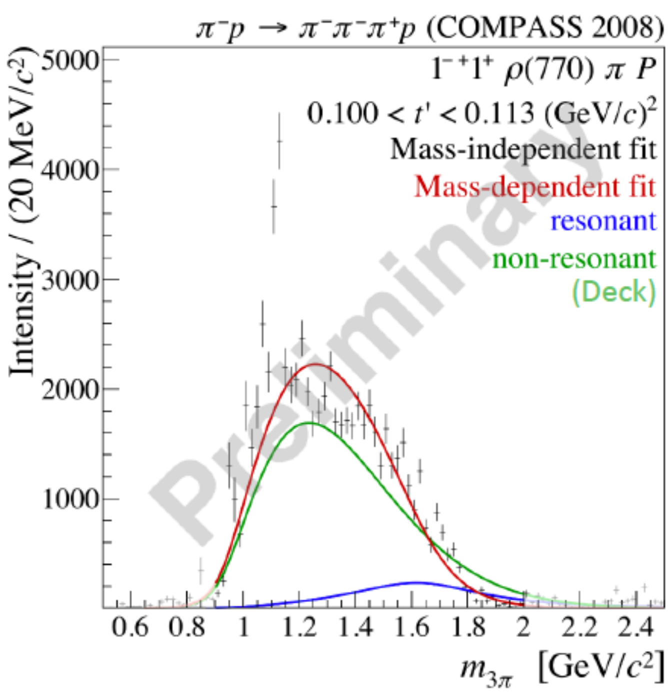


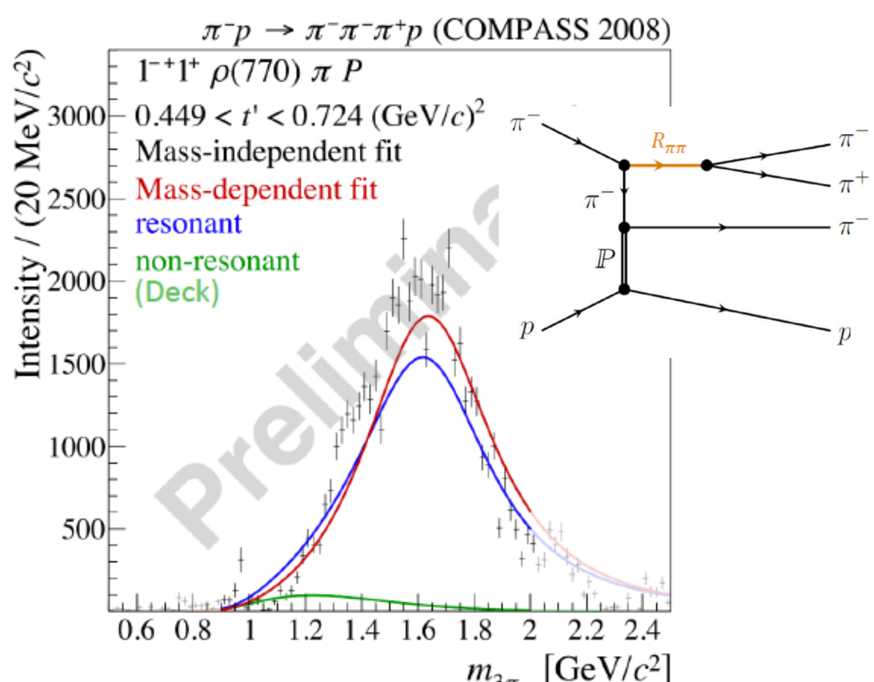




Signatures of new, unusual light resonances

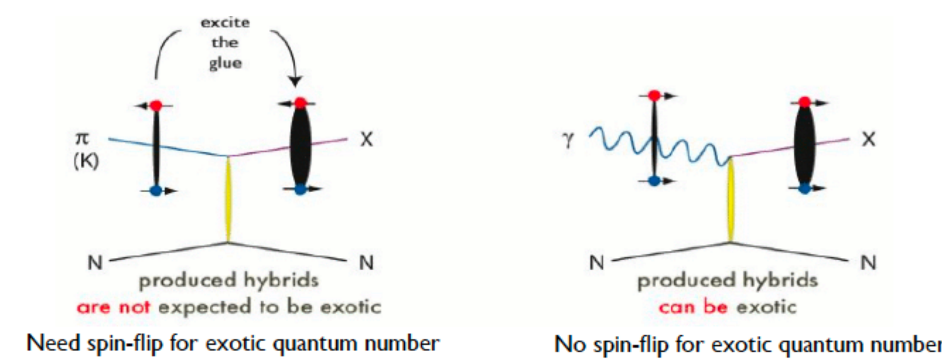
- Exotic $J^{PC}=1^{-+}$ (hybrid) mesons expected (VES, GAMS,E852, COMPASS, and theory)
- In low-t pion diffraction (COMPASS) exotic wave production compatible with one pion exchange (but not at high-t)





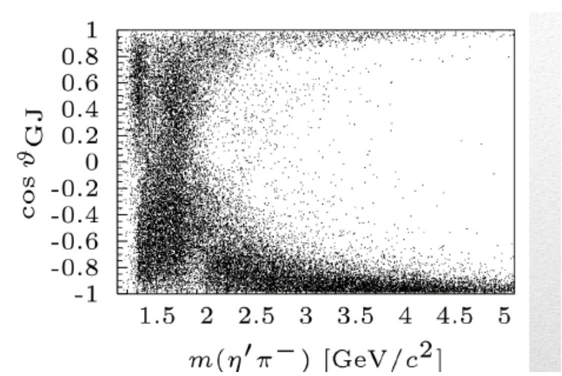
V.Mathieu in progress

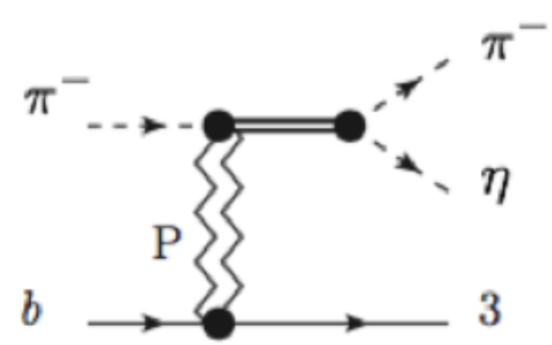
- In photoproduction (GlueX) exotic mesons produced via pion exchange (both good and bad)



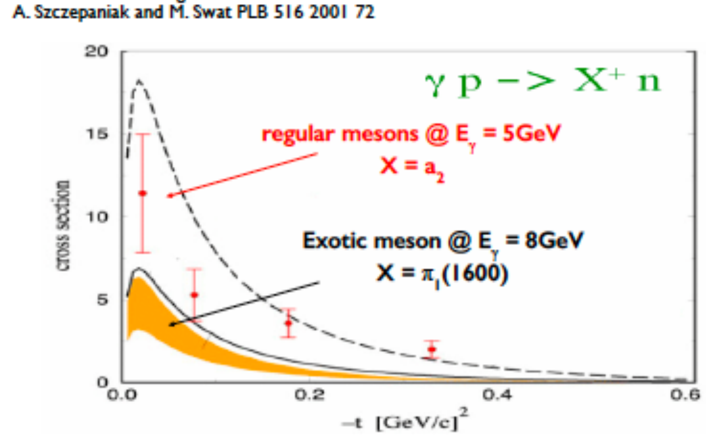
- Large exotic wave seen in $\eta^{(')}\pi$ production : Golden Channel

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





A. Afanasev and P. Page et al. PR A57 1998 6771
A. Szczepaniak and M. Swat PLB 516 2001 72



Amplitude analysis : connecting data to QCD

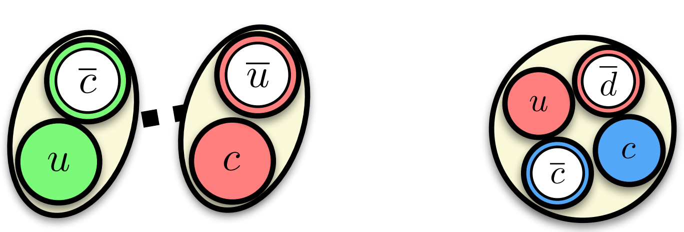
Bottom → Up

Amplitudes

↑ Data

Rules (bubbles, regularization, renormalization, etc.)

Microscopic model



Mesonic-Molecules   Tetraquarks

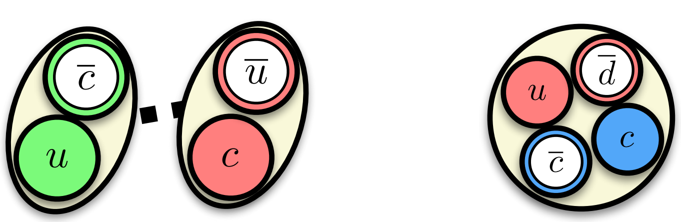
Top → Bottom

Amplitudes

Data ↓

Physical interpretation of poles, cuts,

Microscopic model



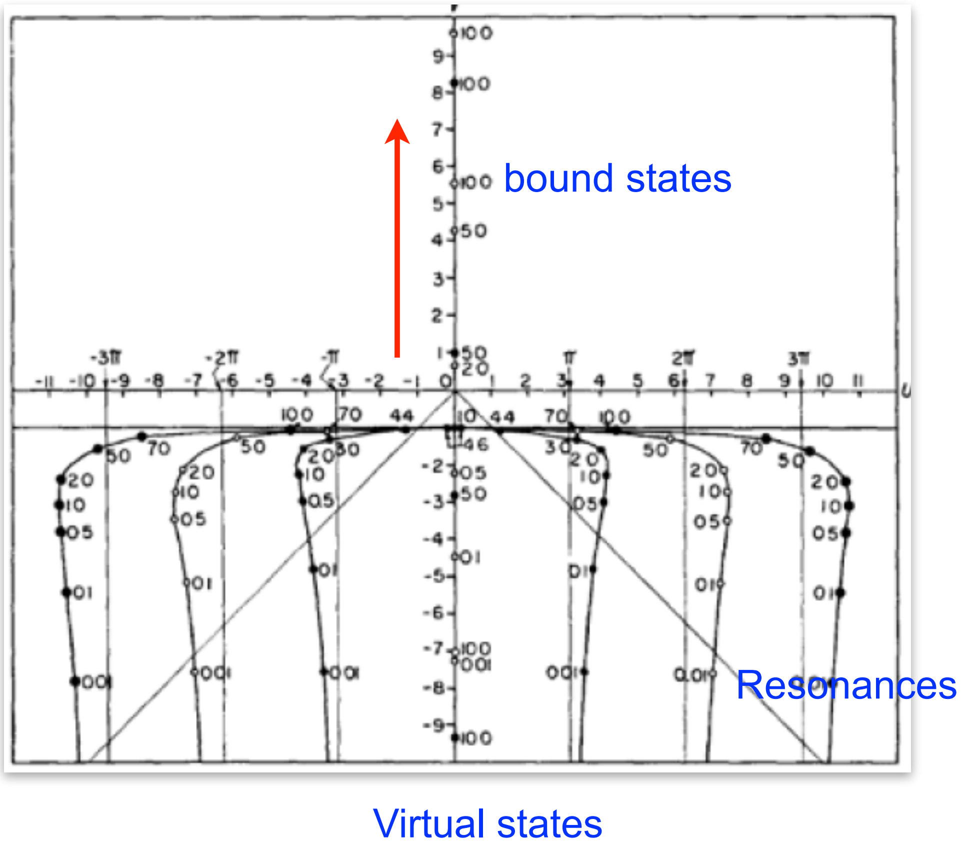
Mesonic-Molecules   Tetraquarks

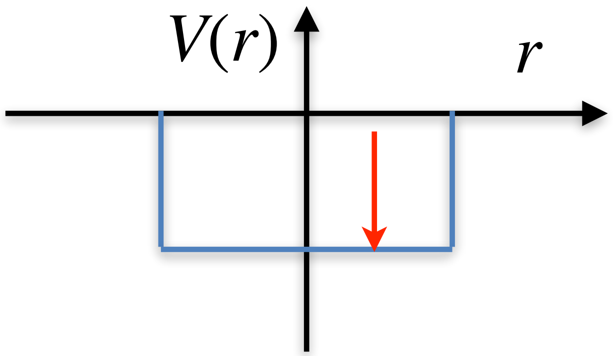
In practice

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

- Use data to determine best hypothesis

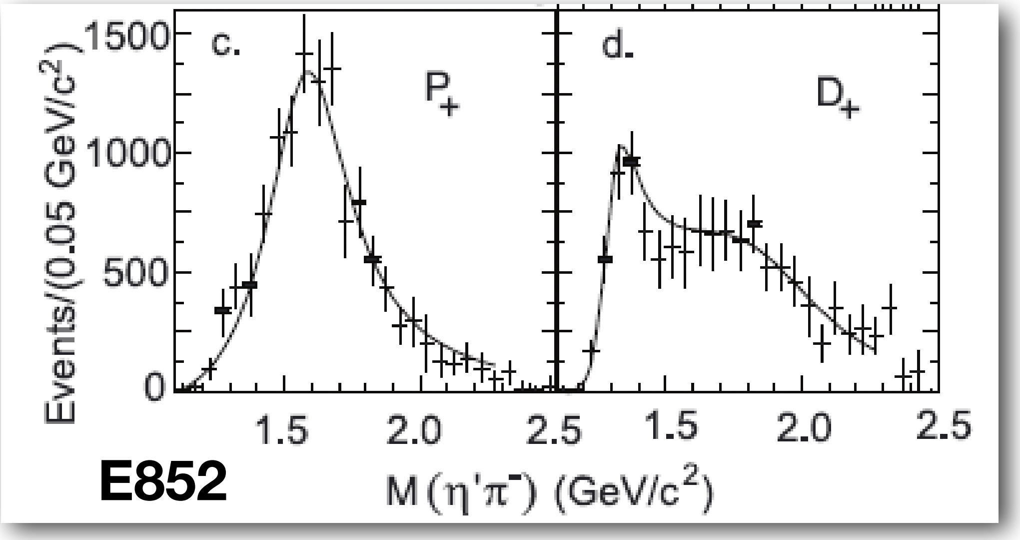
- Test how singularities depend on parameters (channel couplings, thresholds, etc.) to infer their microscopic origins.



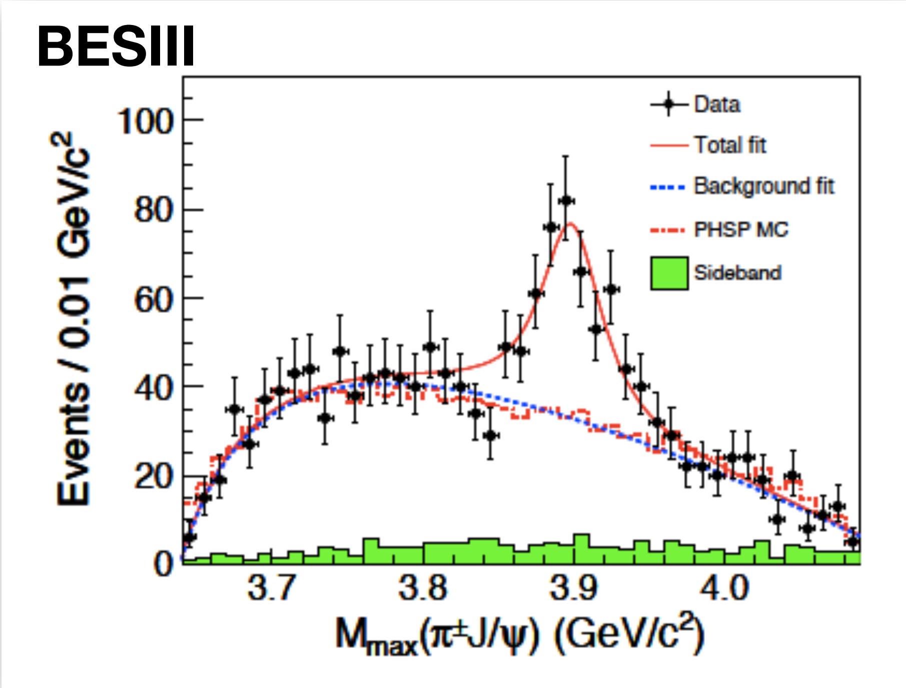


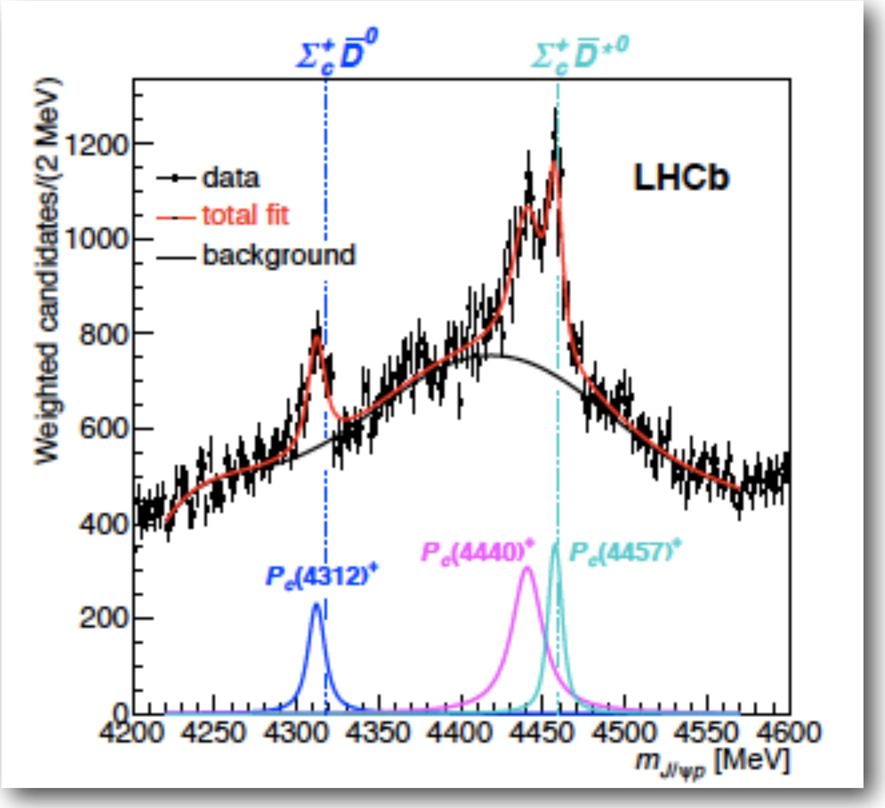
In this talk

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



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



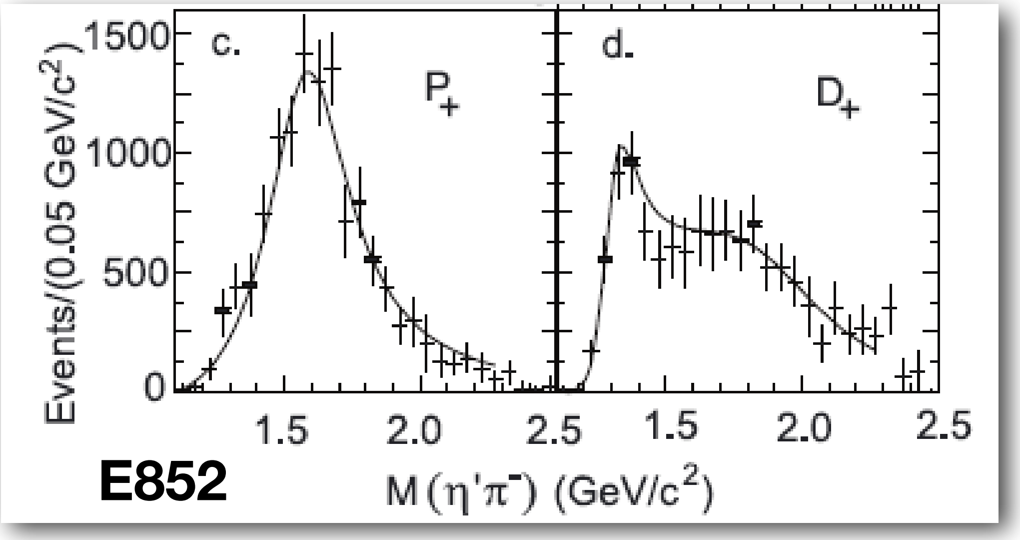


- $P_c(4312)$ in $\Lambda_b \rightarrow J/\psi\ p\ K$

In this talk

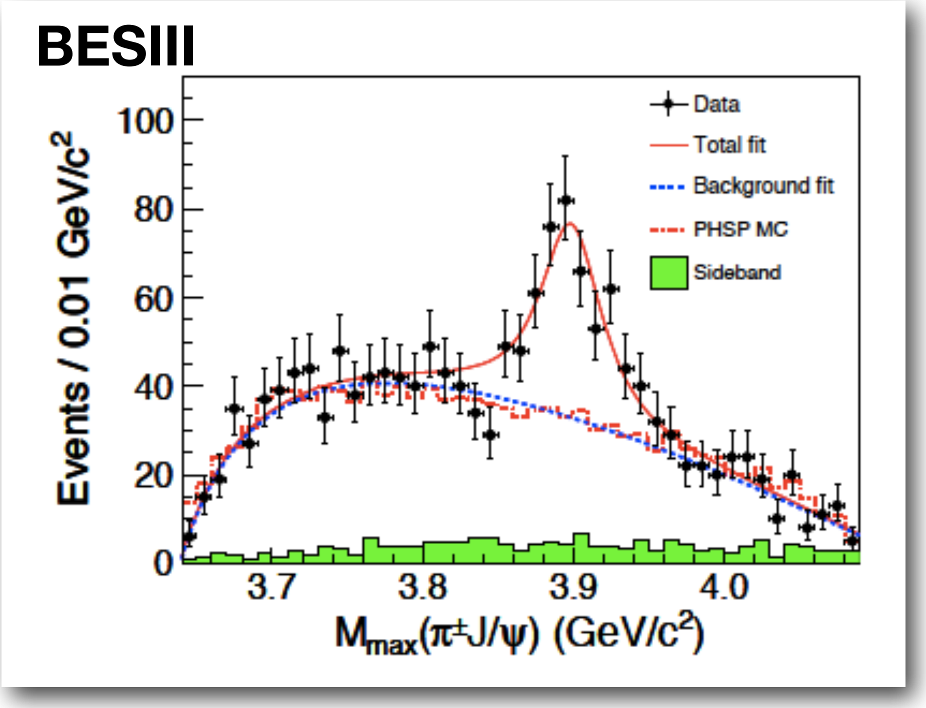
- $J^{PC}=1^{-+}$ I=1, light exotic hybrid ?

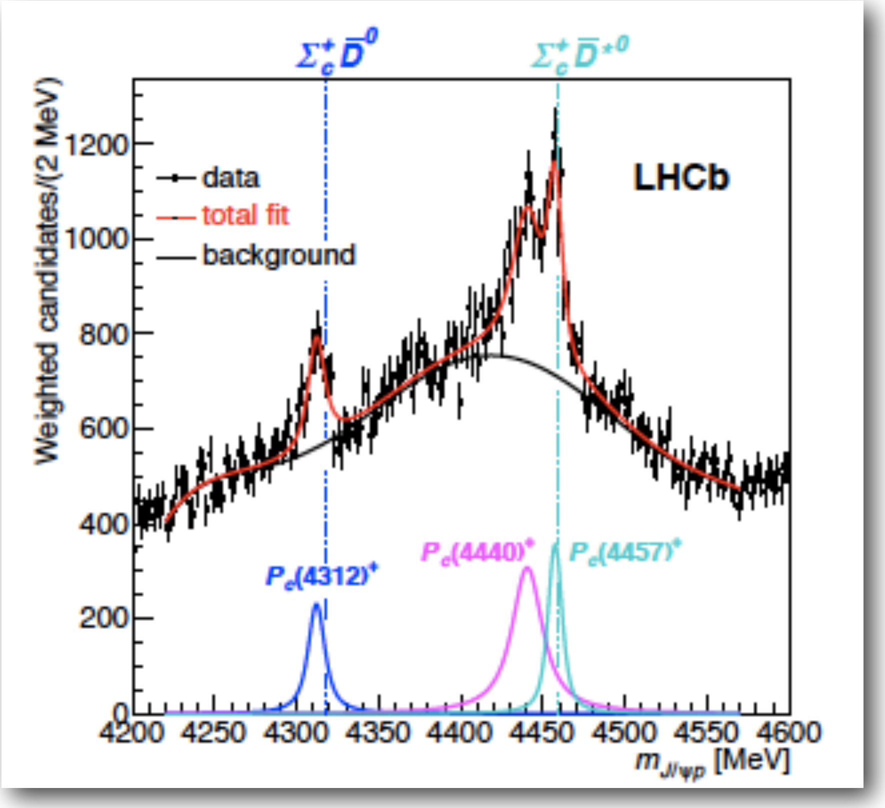
  Yes : "Normal resonance"



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

  Inconclusive

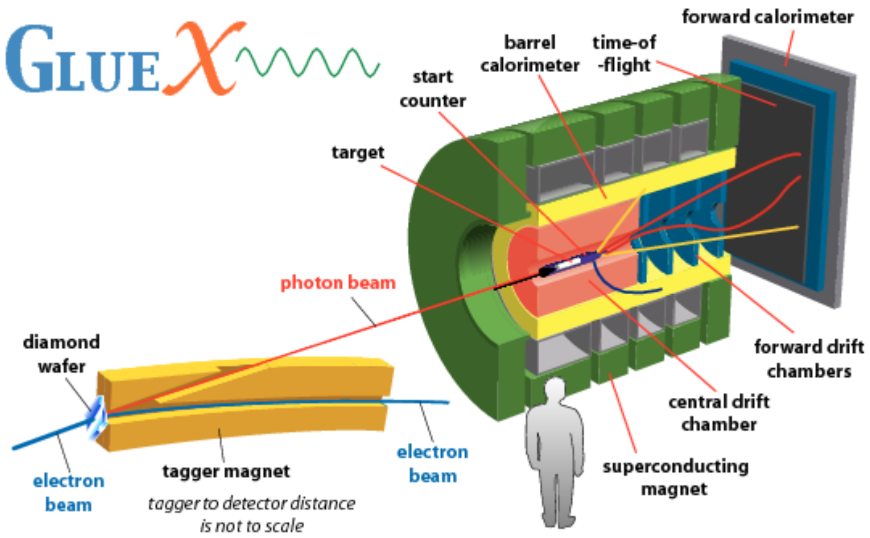


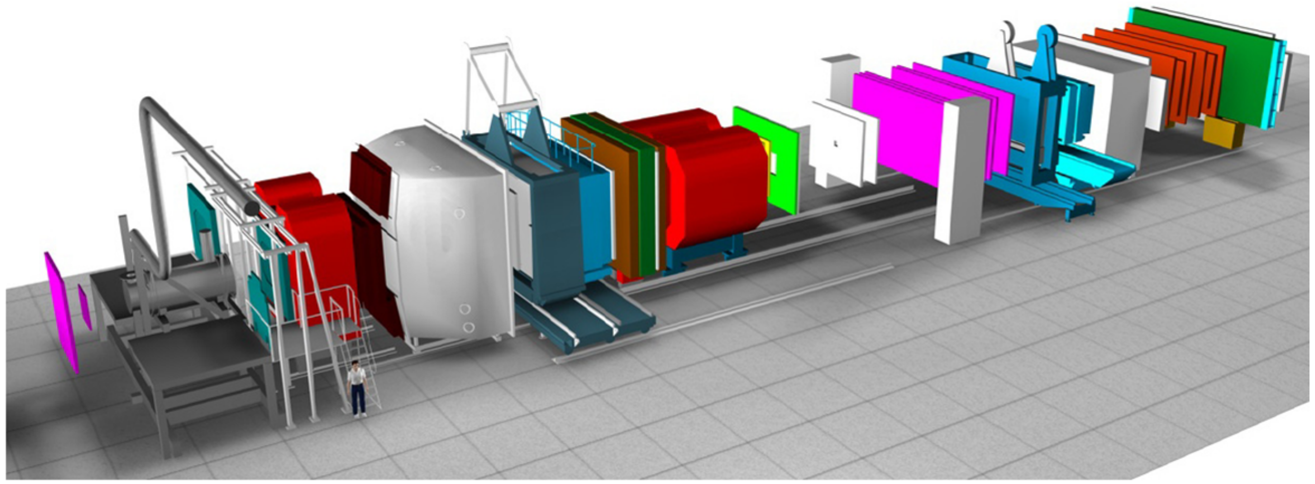


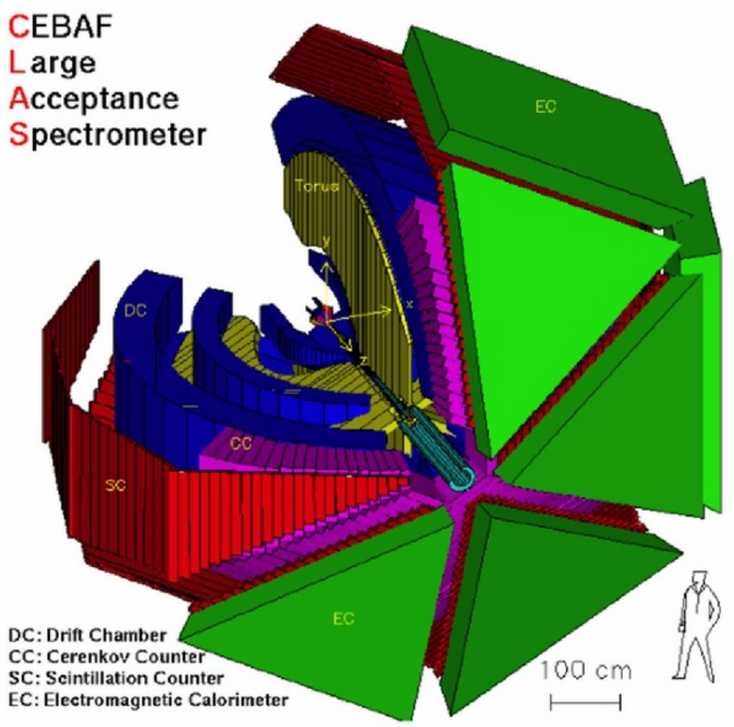
- $P_c(4312)$ in $\Lambda_b \rightarrow J/\psi\, p\, K$

  No : Unbound

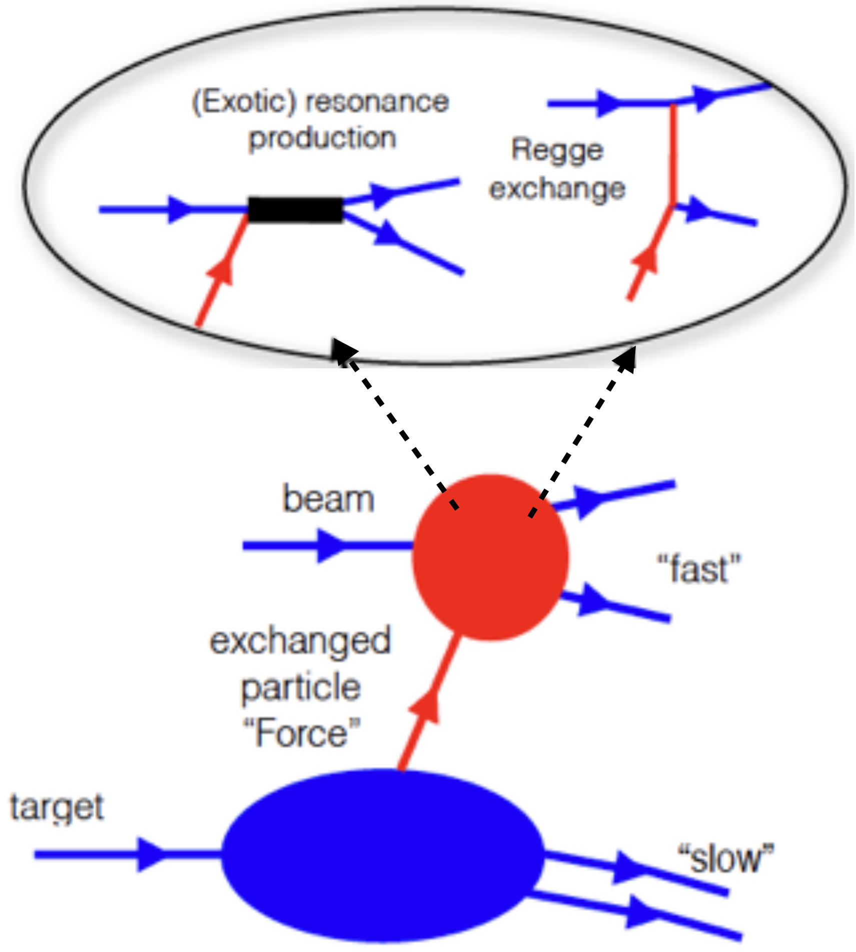
Spectroscopy from peripheral production





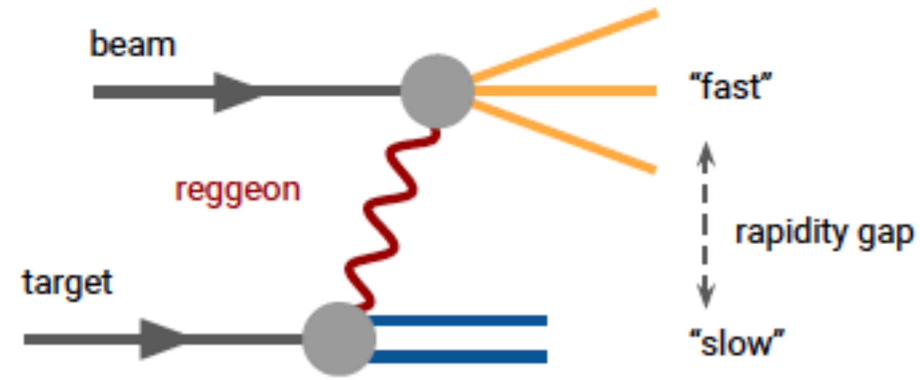


- Need to establish factorization between beam and target fragmentation (Regge factorization)
- Single Regge pole exchange dominate over cut other singularities (cuts, daughters)



Global Regge analysis

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



- Factorizable Regge pole exchange

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

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

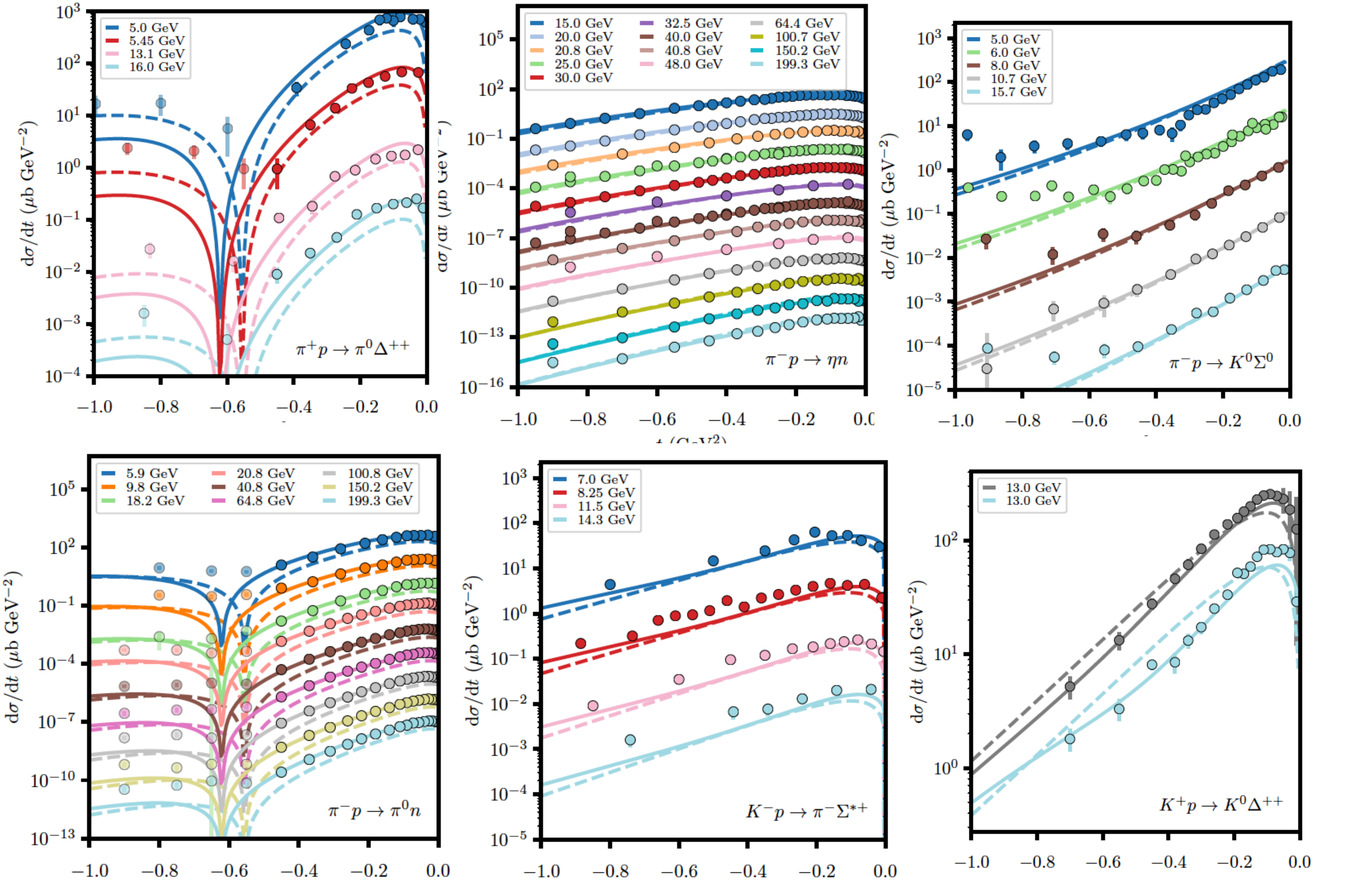
$$\mathcal{F}_e(s,t) = -\frac{\zeta_e \pi \alpha_e^1}{\Gamma(\alpha_e(t)-l_e+1)}\frac{1+\zeta_e e^{-i\pi\alpha_e(t)}}{2\sin\pi\alpha_e(t)}\left(\frac{s}{s_0}\right)^{\alpha_e(t)}$$

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

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

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

Global Regge pole analysis



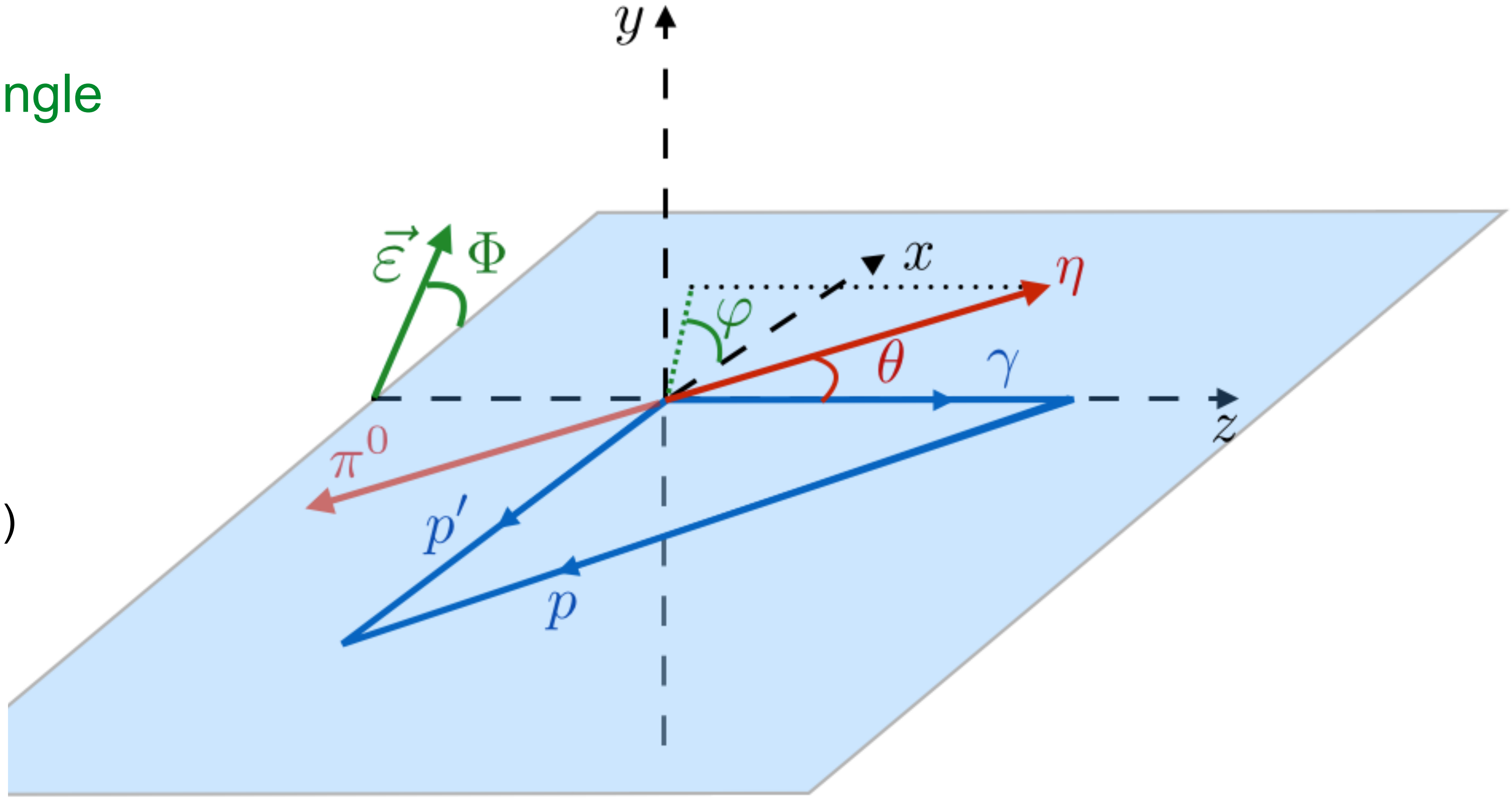
Moment analysis

$$I(\Omega, \Phi) = I^0(\Omega) - P_\gamma I^1(\Omega)\cos 2\Phi - P_\gamma I^2(\Omega)\sin 2\Phi$$

polarization angle

η decay angles

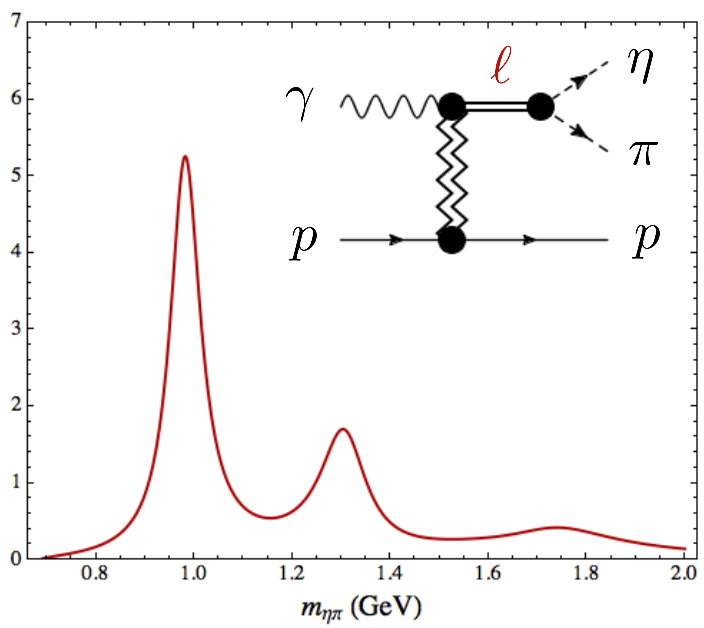
$\Omega = (\theta, \phi)$



Beam energy (fixed)

momentum transfer (integrated)

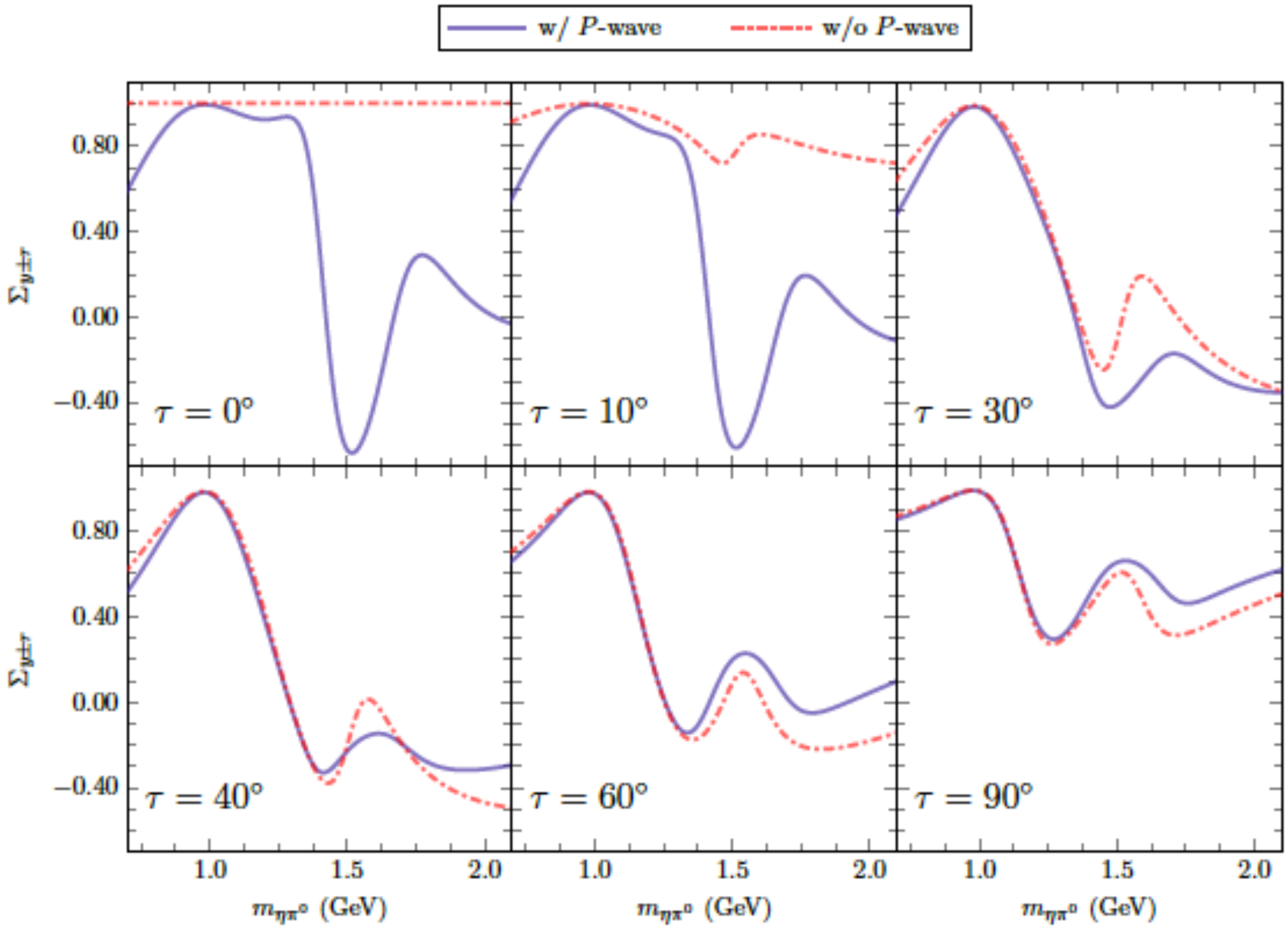
$\eta\pi$ invariant mass (binned)

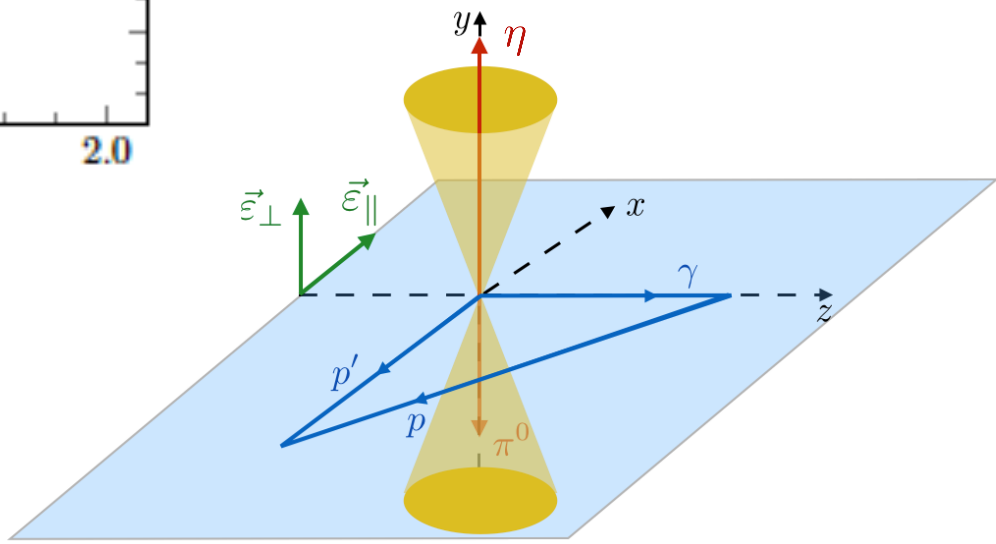


$$R = \{\underbrace{a_0(980)}_{S_0^{(+)}}, \underbrace{\pi_1(1600)}_{P_{0,1}^{(+)}}, \underbrace{a_2(1320), a_2(1700)}_{D_{0,1,2}^{(+)}}\}$$

V.Mathieu et al (JPAC), arXiv:1906.04841

Beam asymmetry





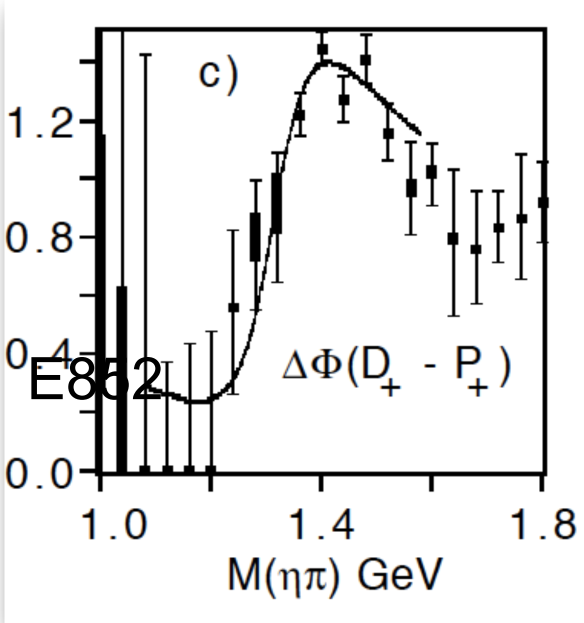
The π_1 (exotic) meson candidate

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

$M = 1370 \pm 16^{+50}_{-30}$ 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

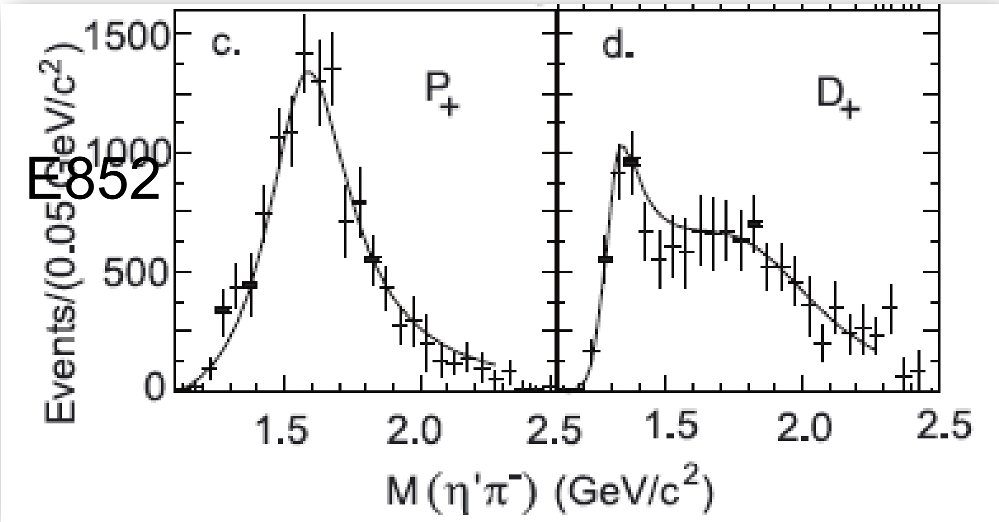
$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2

π_1 (1600)

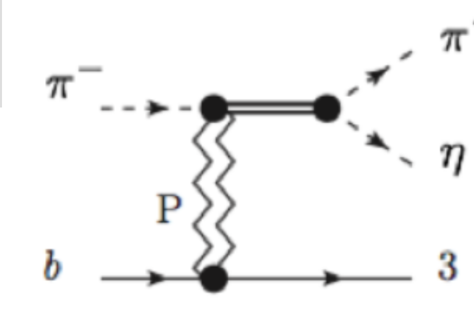
E852, also COMPASS,CLEO

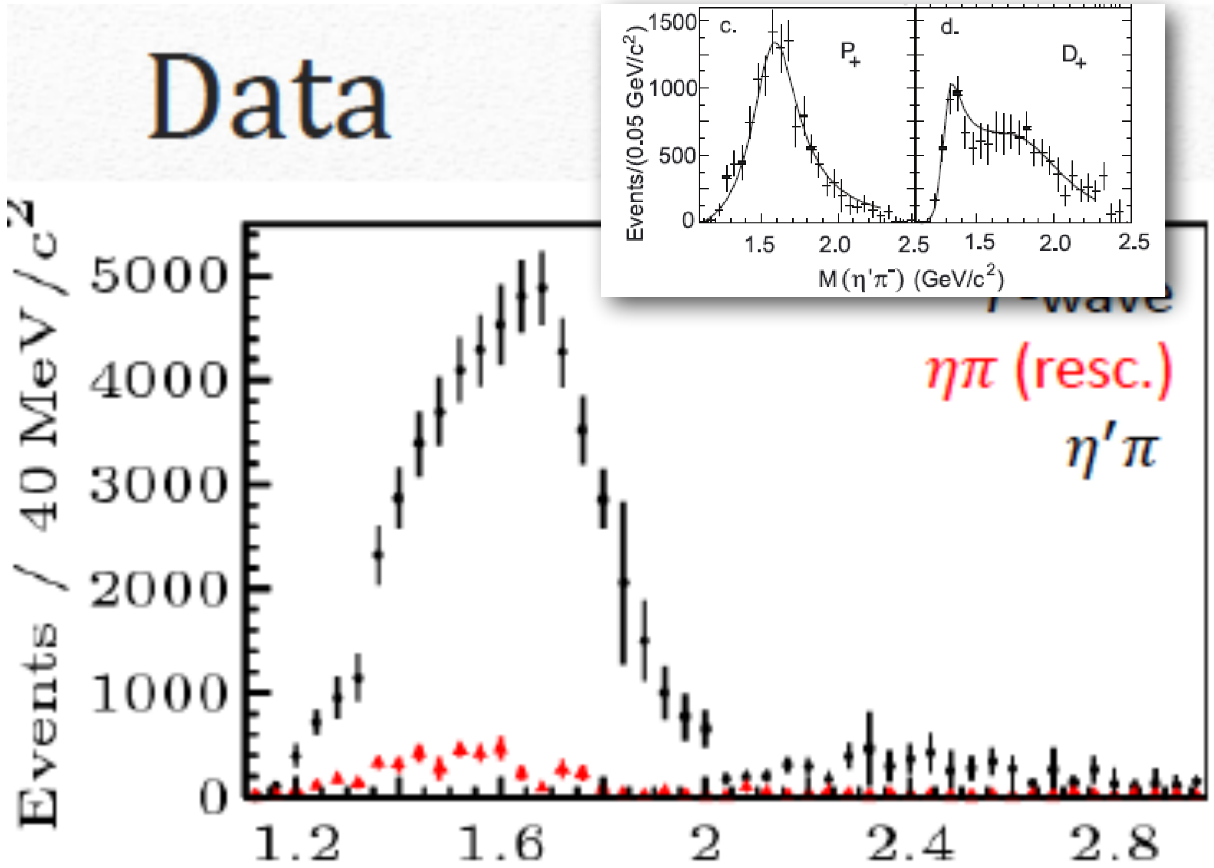
Is it 1400 or 1600 ?

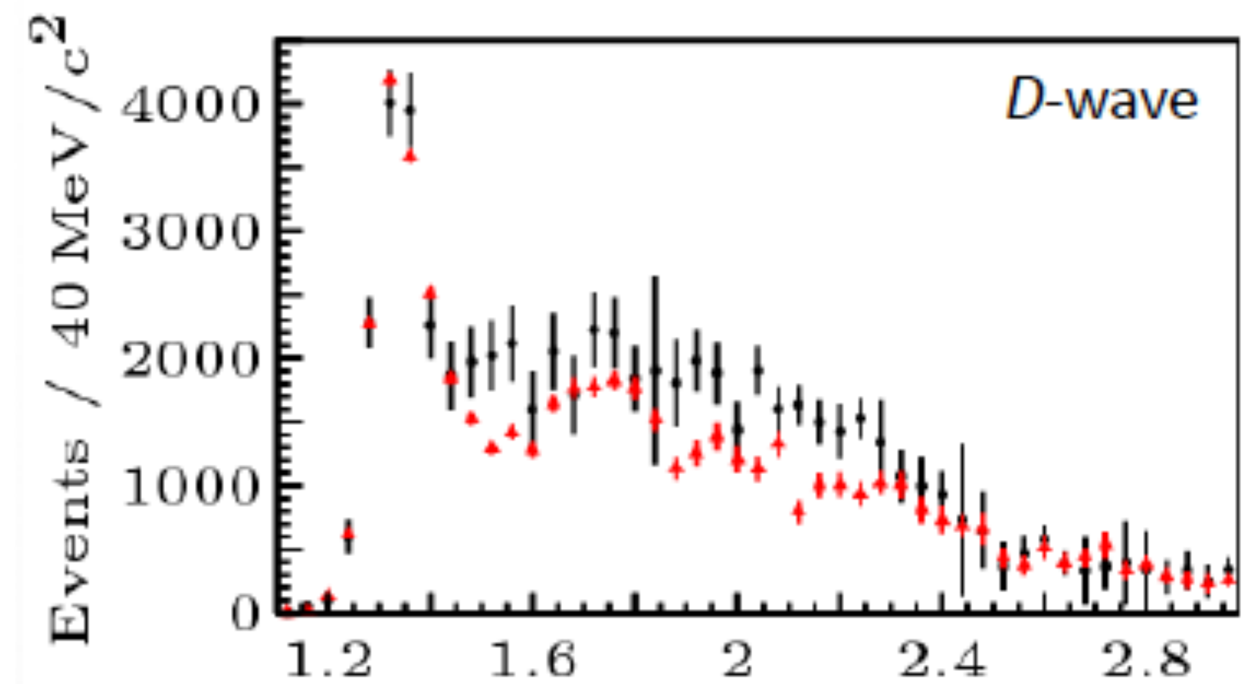
COMPASS consistent with both

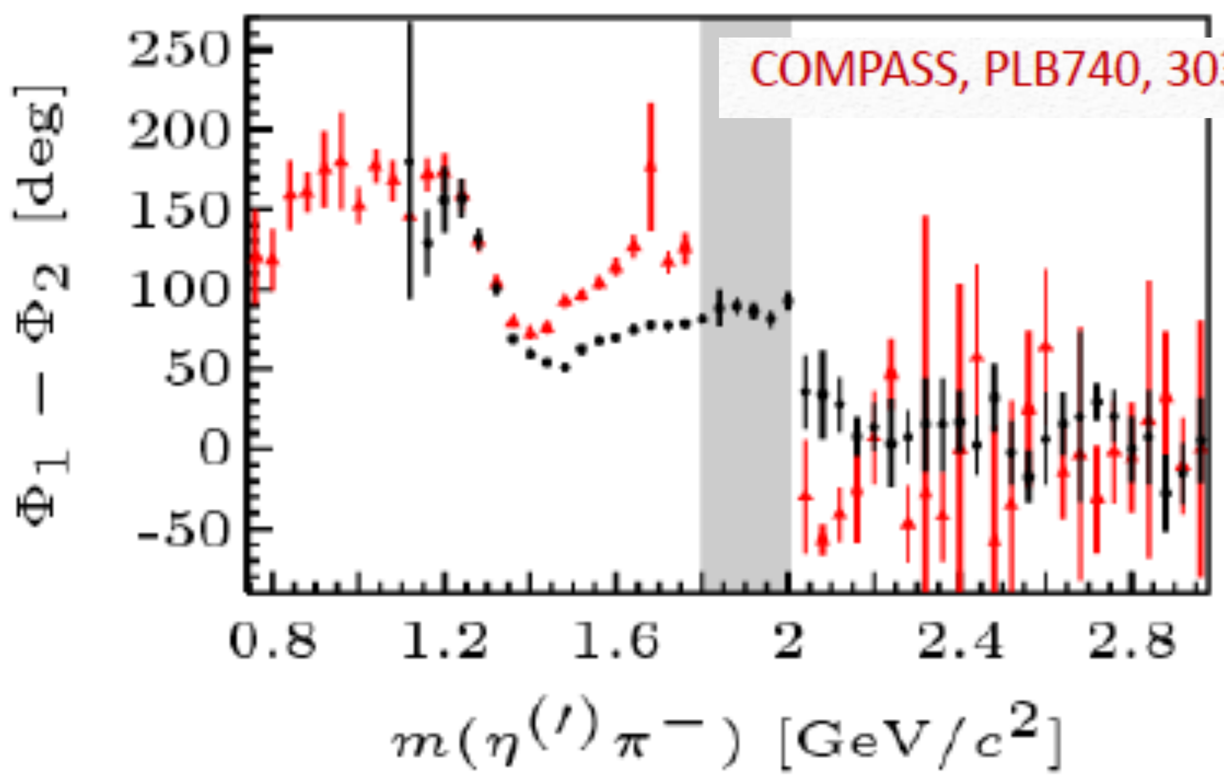


COMAPSS data









COMPASS, PLB740, 303-311

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

No convincing physical motivation for it

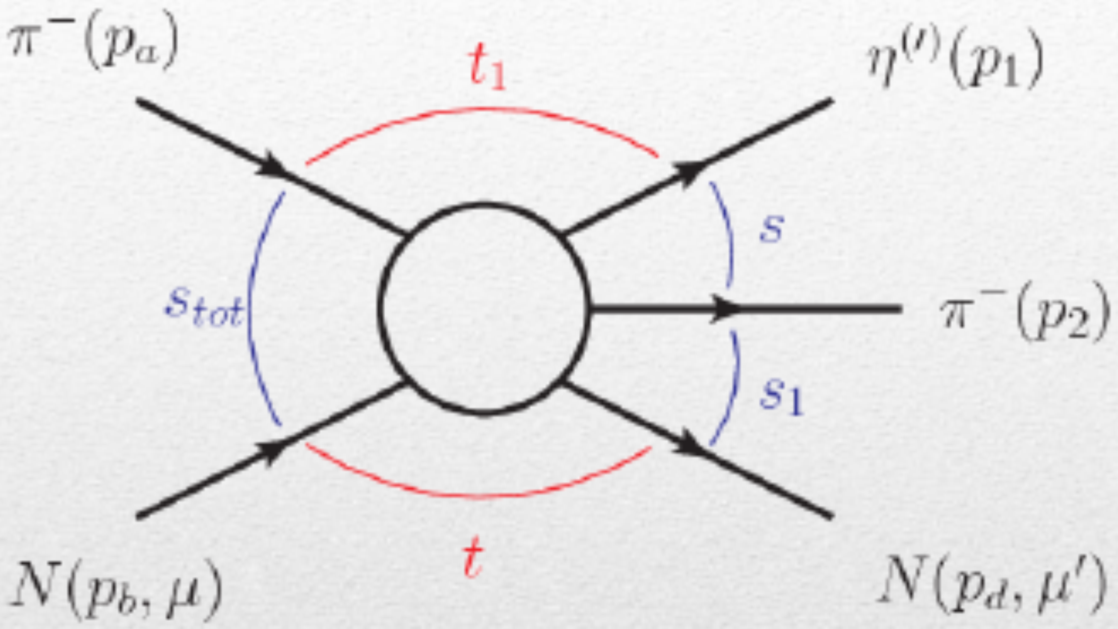
It affects the position of the $a_2'(1700)$

We decided to fit up to 2 GeV only

2-meson peripheral production : ηπ

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

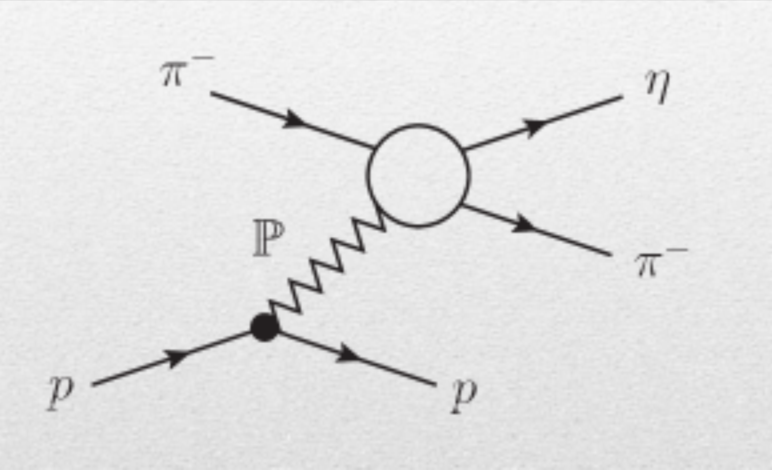
- Process is at fixed s_{tot}, and integrated t. Interested in resonances in s
- Recoil proton kinematically decouples from final state $\eta\pi$



- 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

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

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

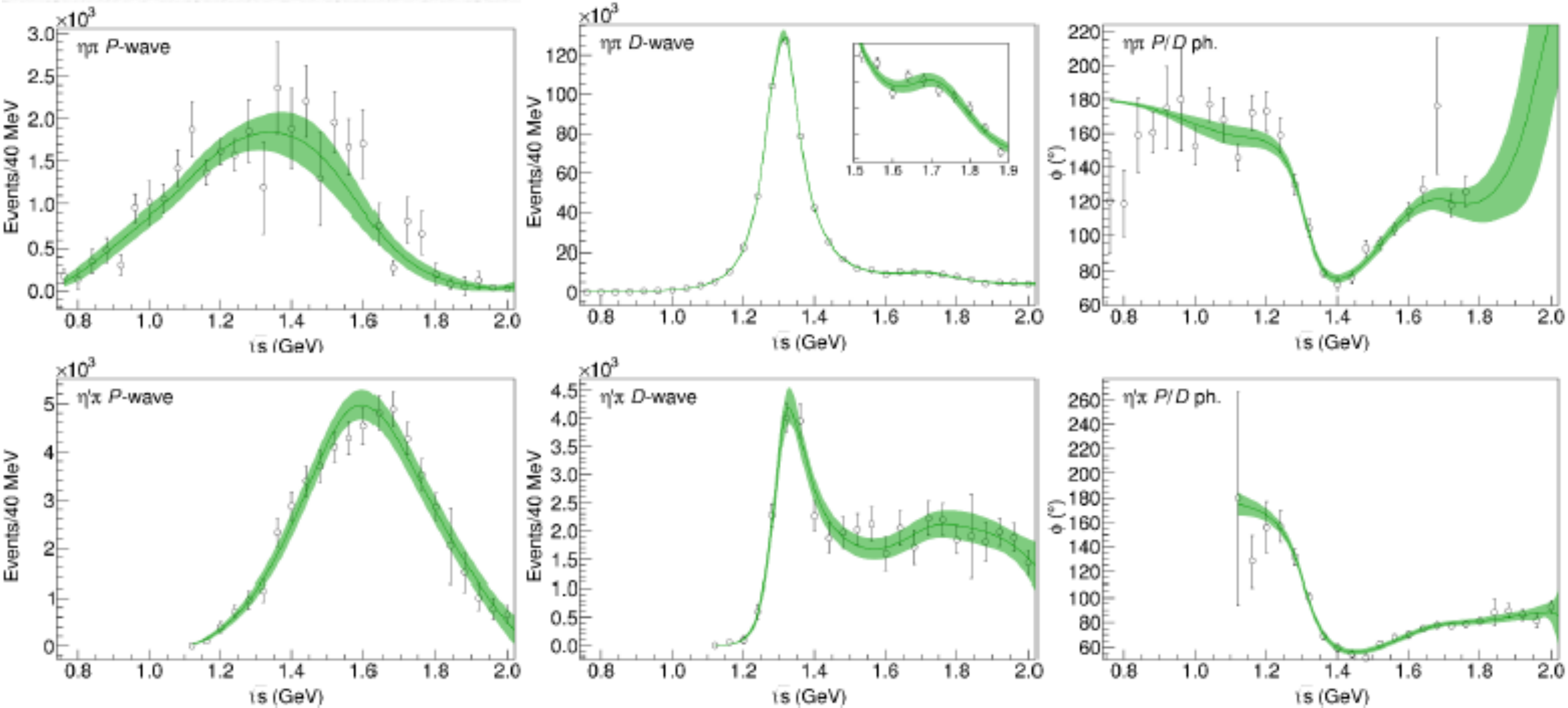
1 K-matrix pole for the P-wave
2 K-matrix poles for the D-wave

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

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

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 $n^J_k(s)$

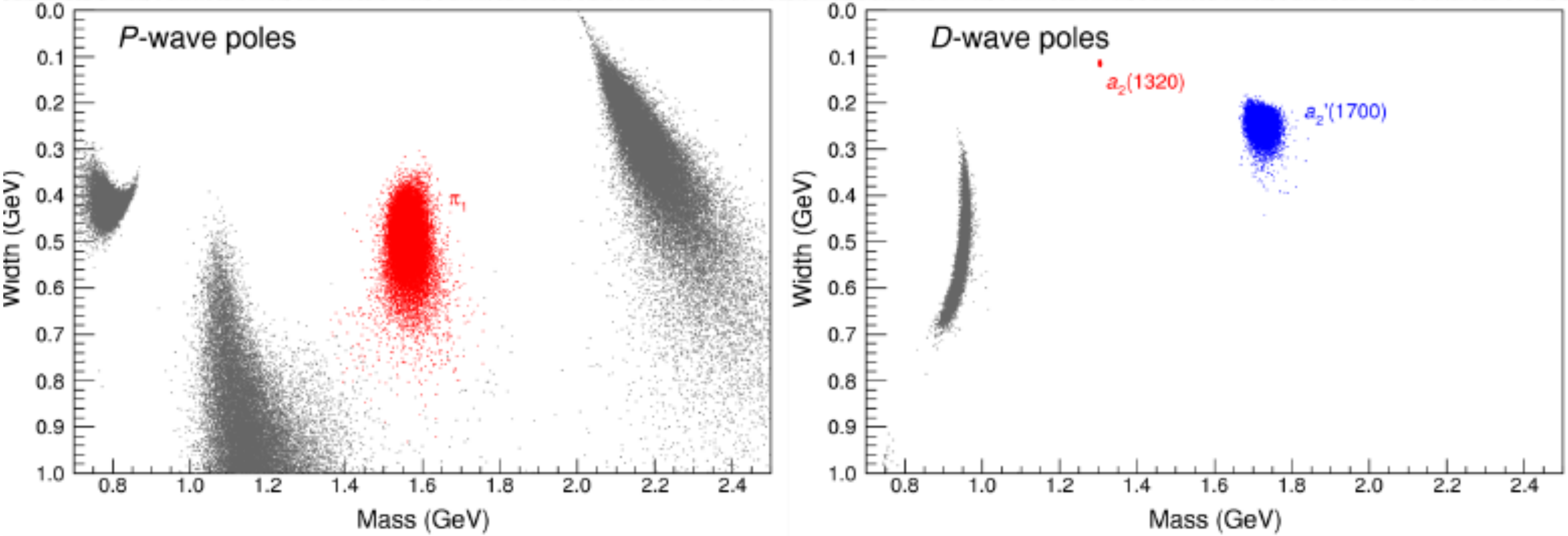
Fit



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

Bands show the 2σ error

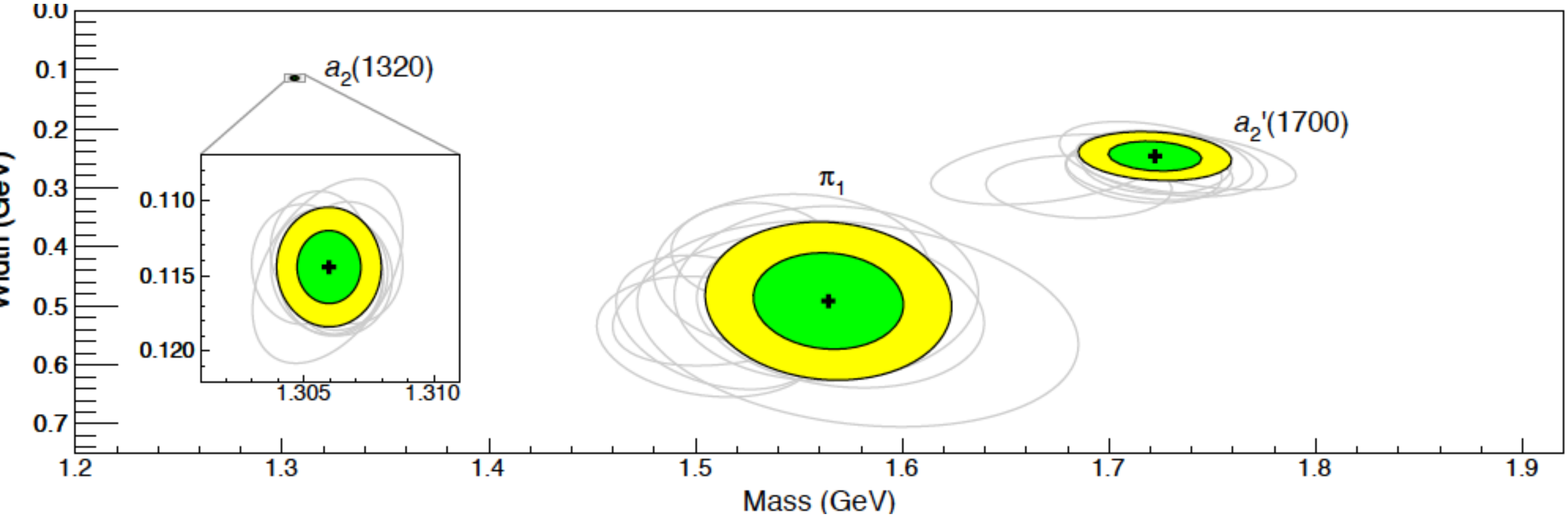
Bootstrap



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



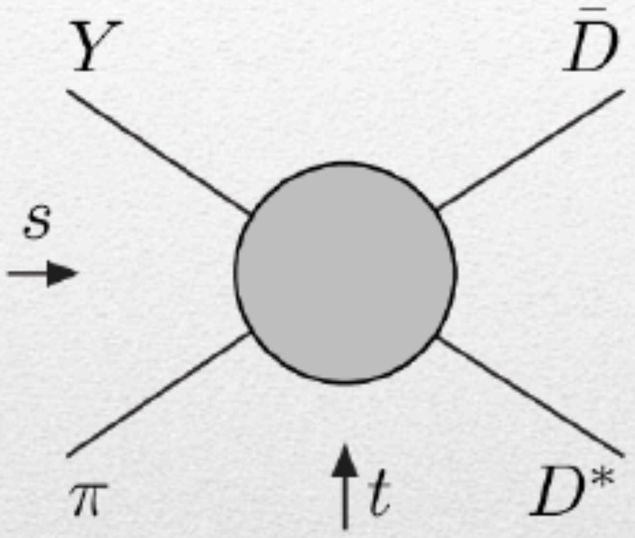
The variance of the bootstrapped poles gives the statistical error

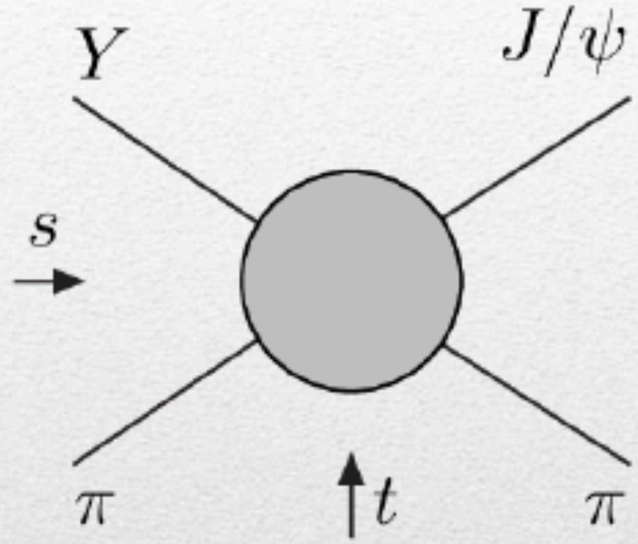
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	1306.0 ± 0.8	114.4 ± 1.6
$a_2'(1700)$	1722 ± 15	247 ± 17
π_1	1564 ± 24	492 ± 54

Amplitude analysis for $Z_c(3900)$

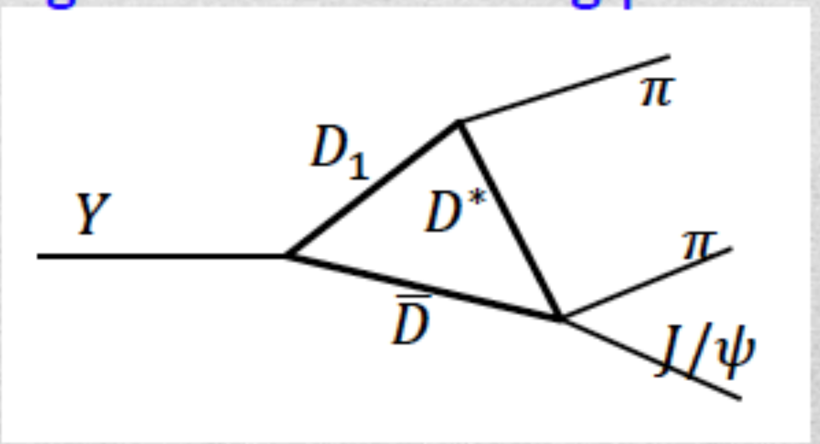
One can test different parametrizations of the amplitude, which correspond to
different singularities → different natures

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





Triangle rescattering,
logarithmic branching point

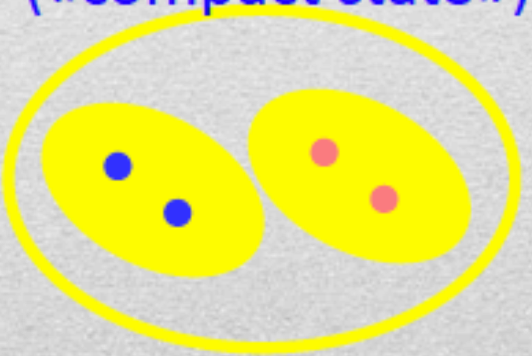


Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo *et al.* PRD92, 071502

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

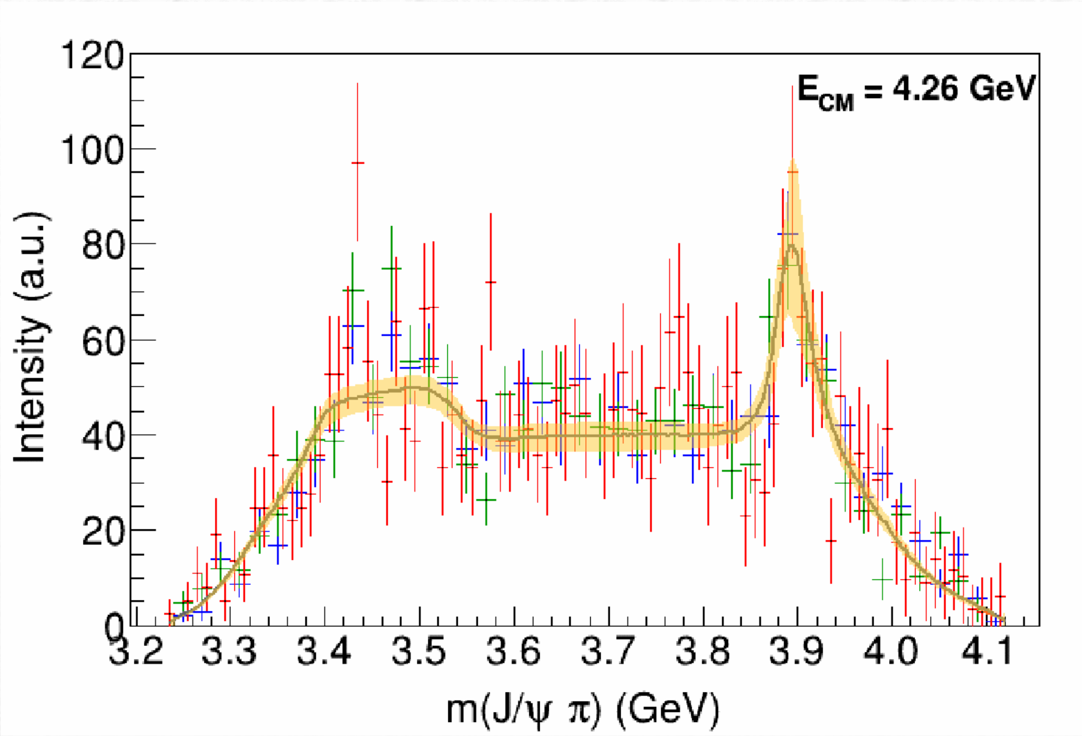
Tornqvist, Z.Phys. C61, 525
Swanson, Phys.Rept. 429
Hanhart *et al.* PRL111, 132003

Resonance,
III sheet pole
(«compact state»)

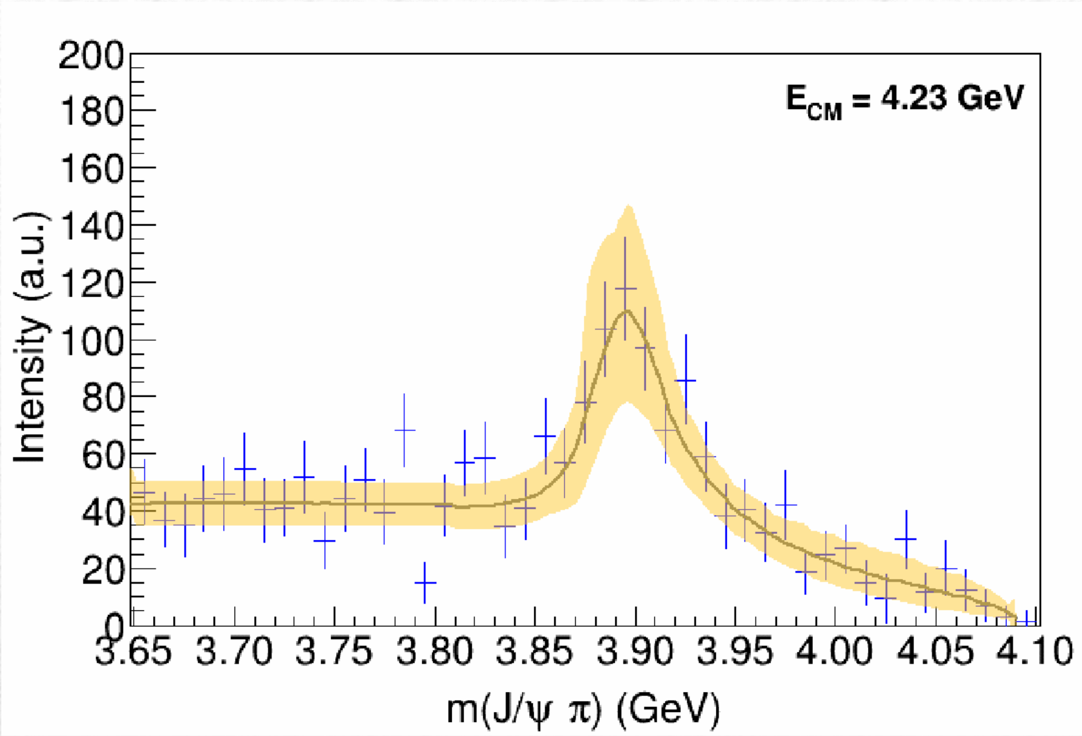


Maiani *et al.*, PRD71, 014028
Faccini *et al.*, PRD87, 111102
Esposito *et al.*, Phys.Rept. 668

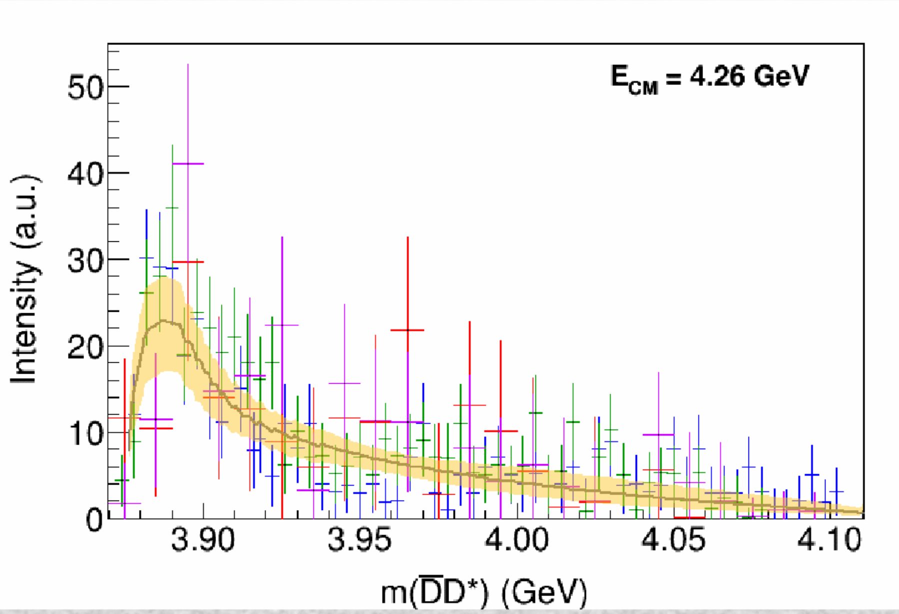
Fit: III



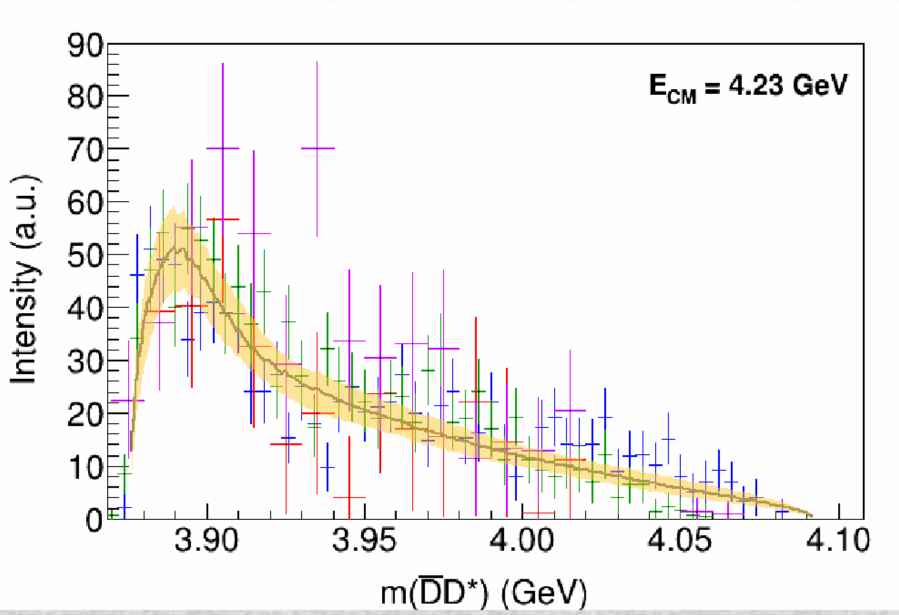
E_{CM} = 4.26 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)



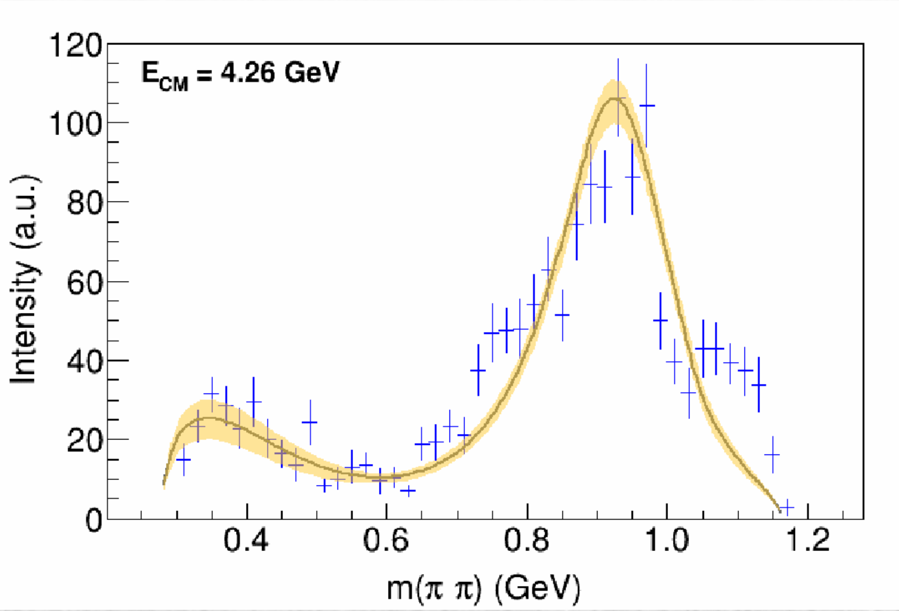
E_{CM} = 4.23 GeV
Intensity (a.u.)
m(J/ψ π) (GeV)



E_{CM} = 4.26 GeV
Intensity (a.u.)
m($\bar{D}D^*$) (GeV)

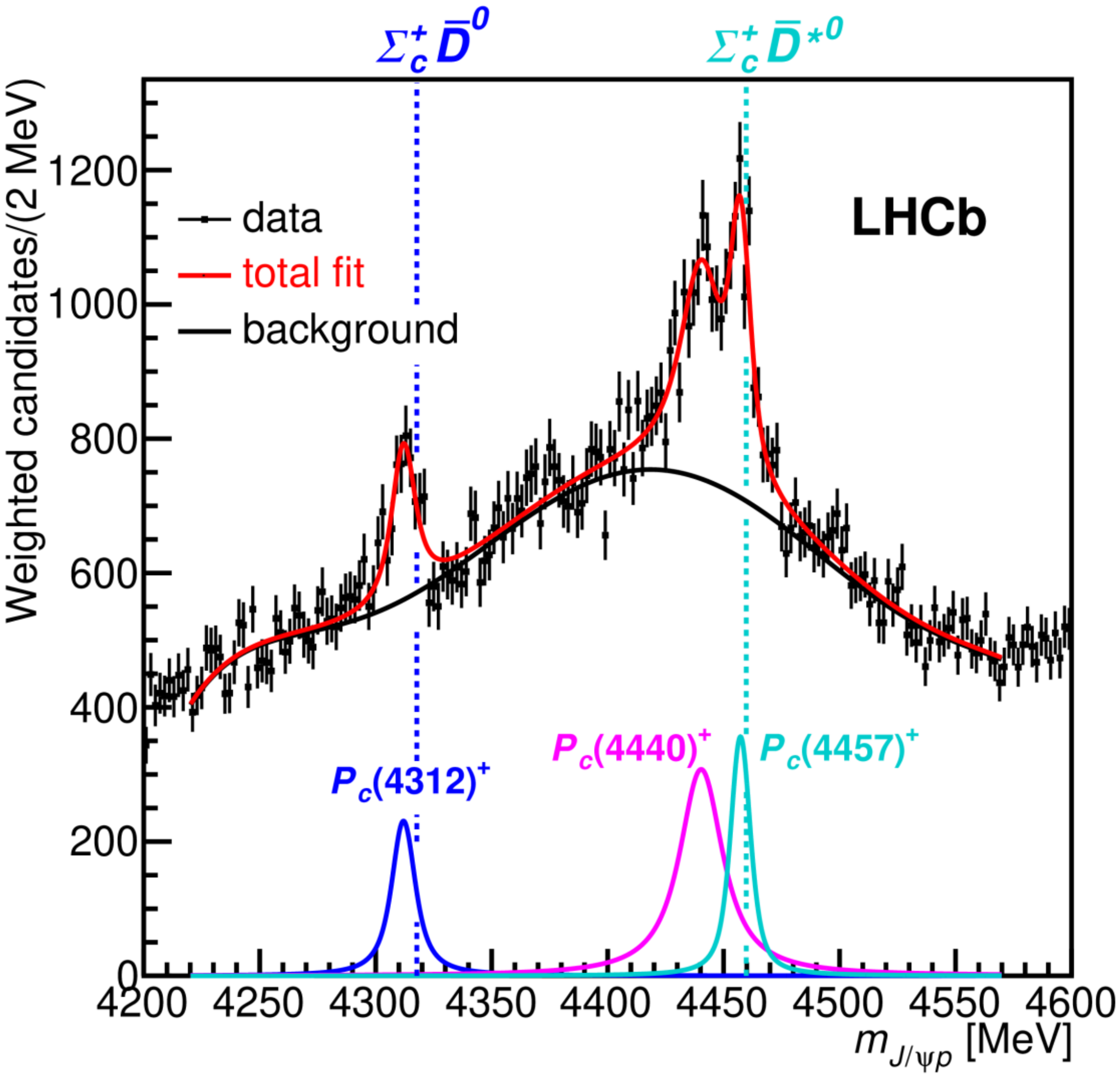


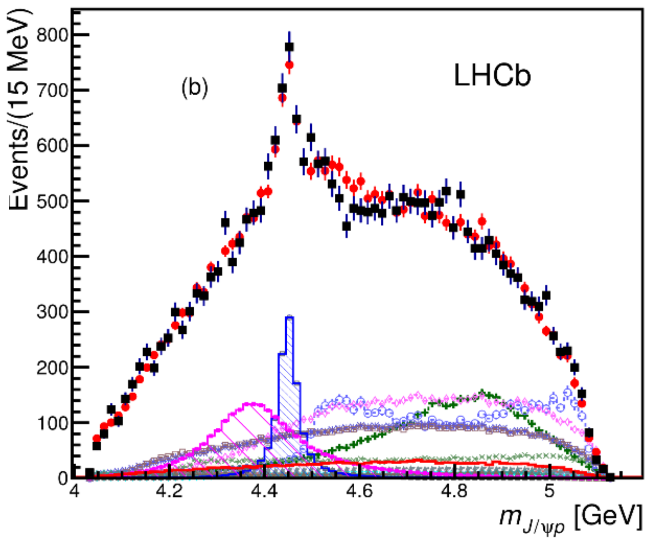
E_{CM} = 4.23 GeV
Intensity (a.u.)
m($\bar{D}D^*$) (GeV)



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 ?

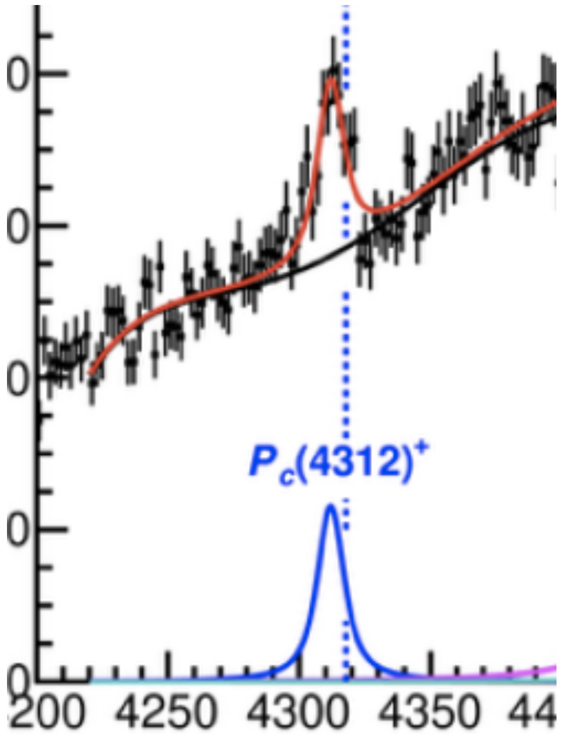
B(s) = higher p.w's

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

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)

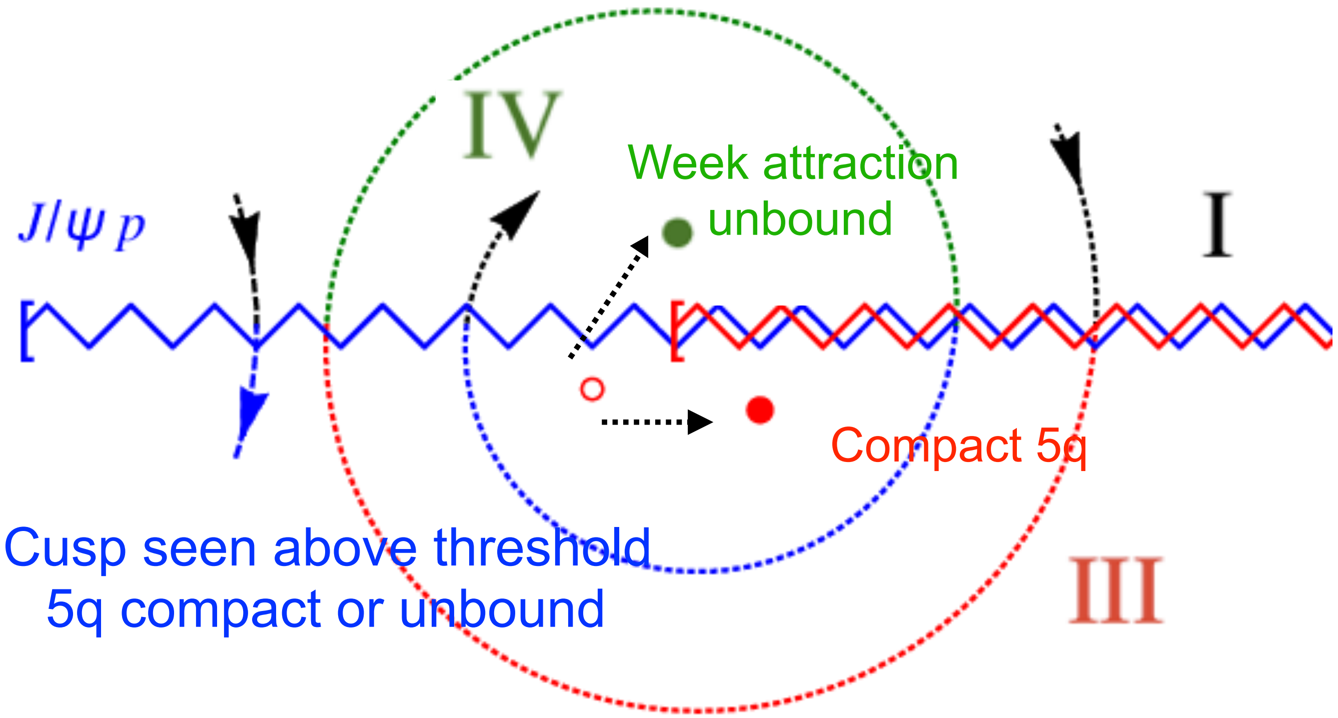
M (s) = 2 x 2 scattering lengt matrix

Case B

additional compact states (sheet III)

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

M = 2 x 2 scattering length
+ effective range



New pentaquarks ?

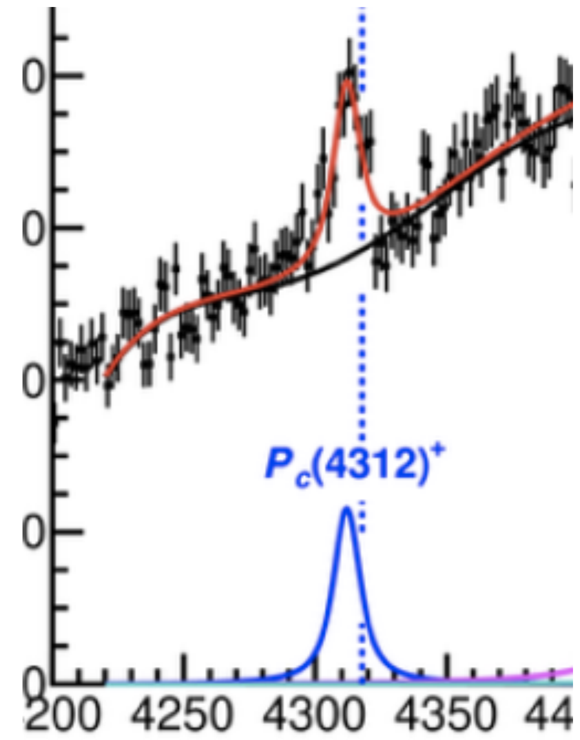
B(s) = higher p.w's

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

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)

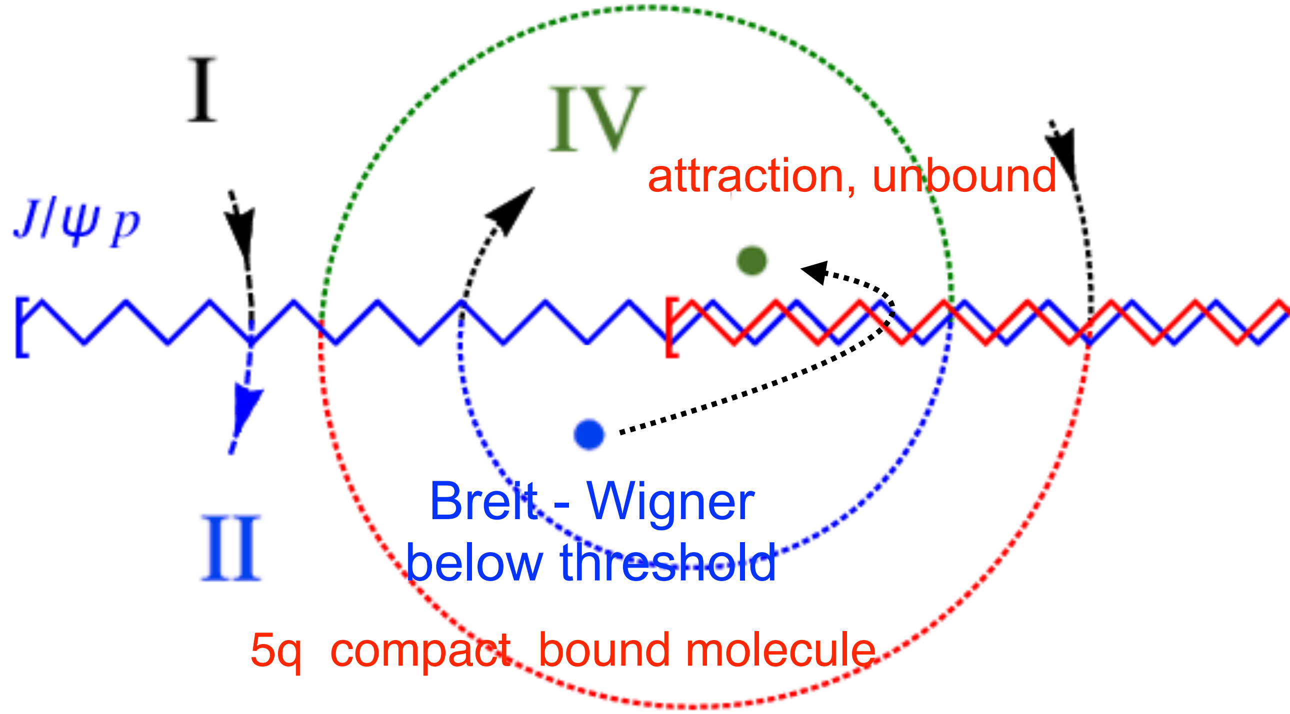
M (s) = 2 x 2 scattering lengt matrix

Case B

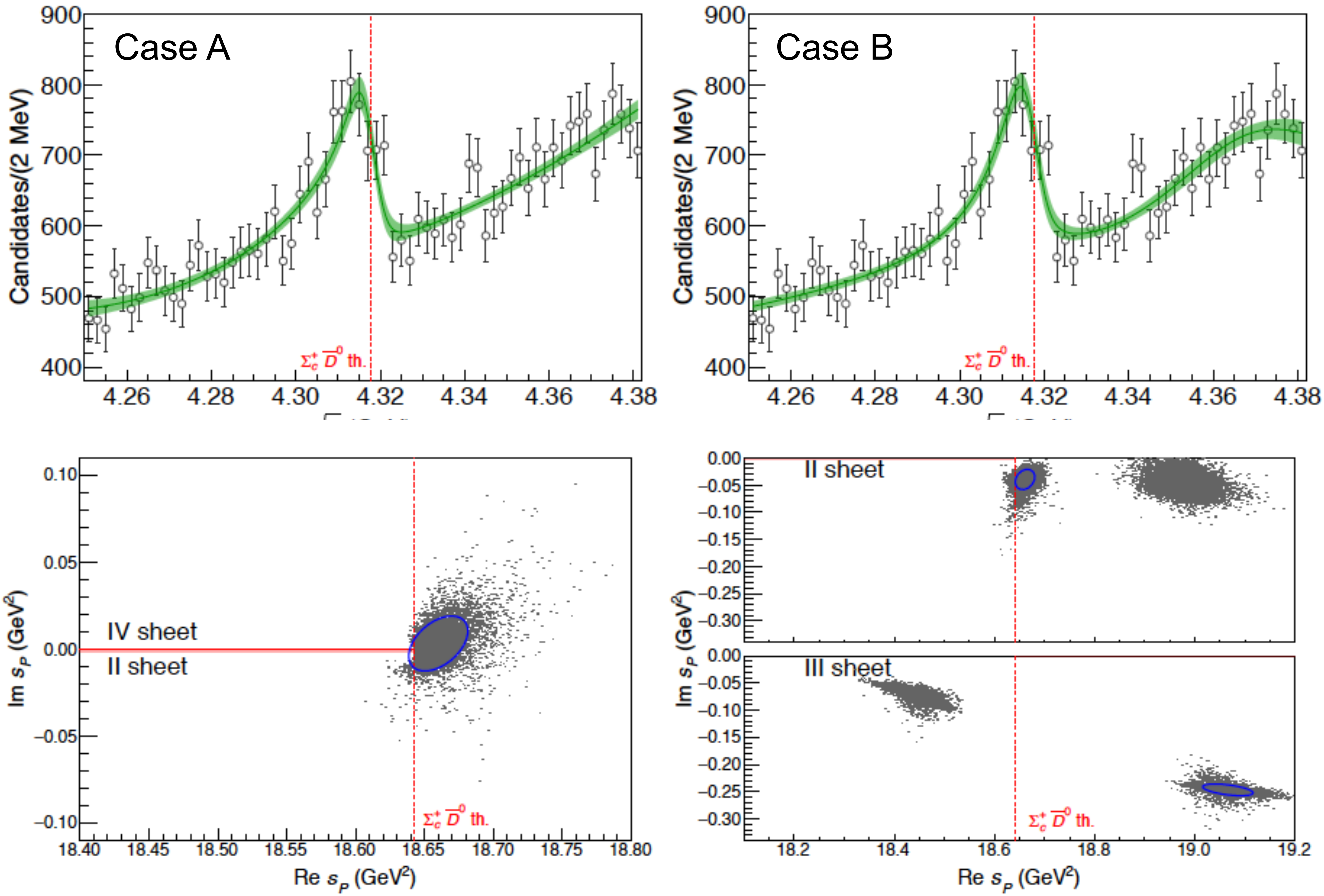
$$M(s) = M + Cs$$

additional compact states (sheet III)

M = 2 x 2 scattering length + effective range

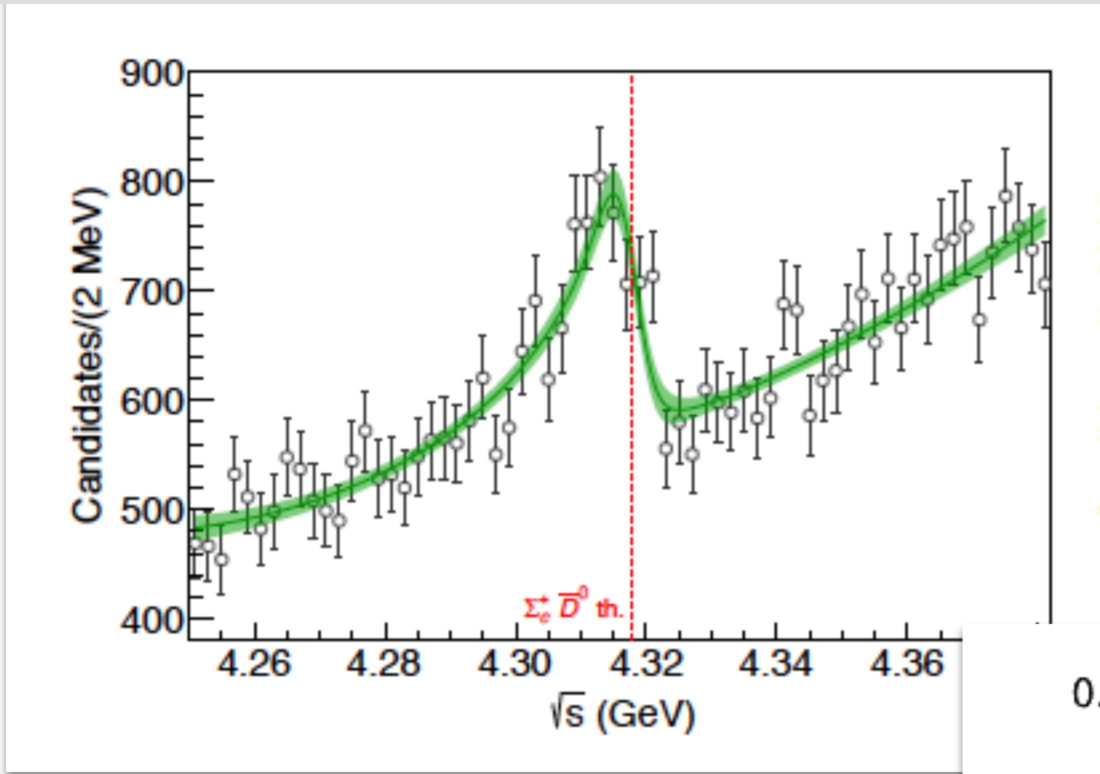


New pentaquarks ?



New pentaquarks ?

Case A



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

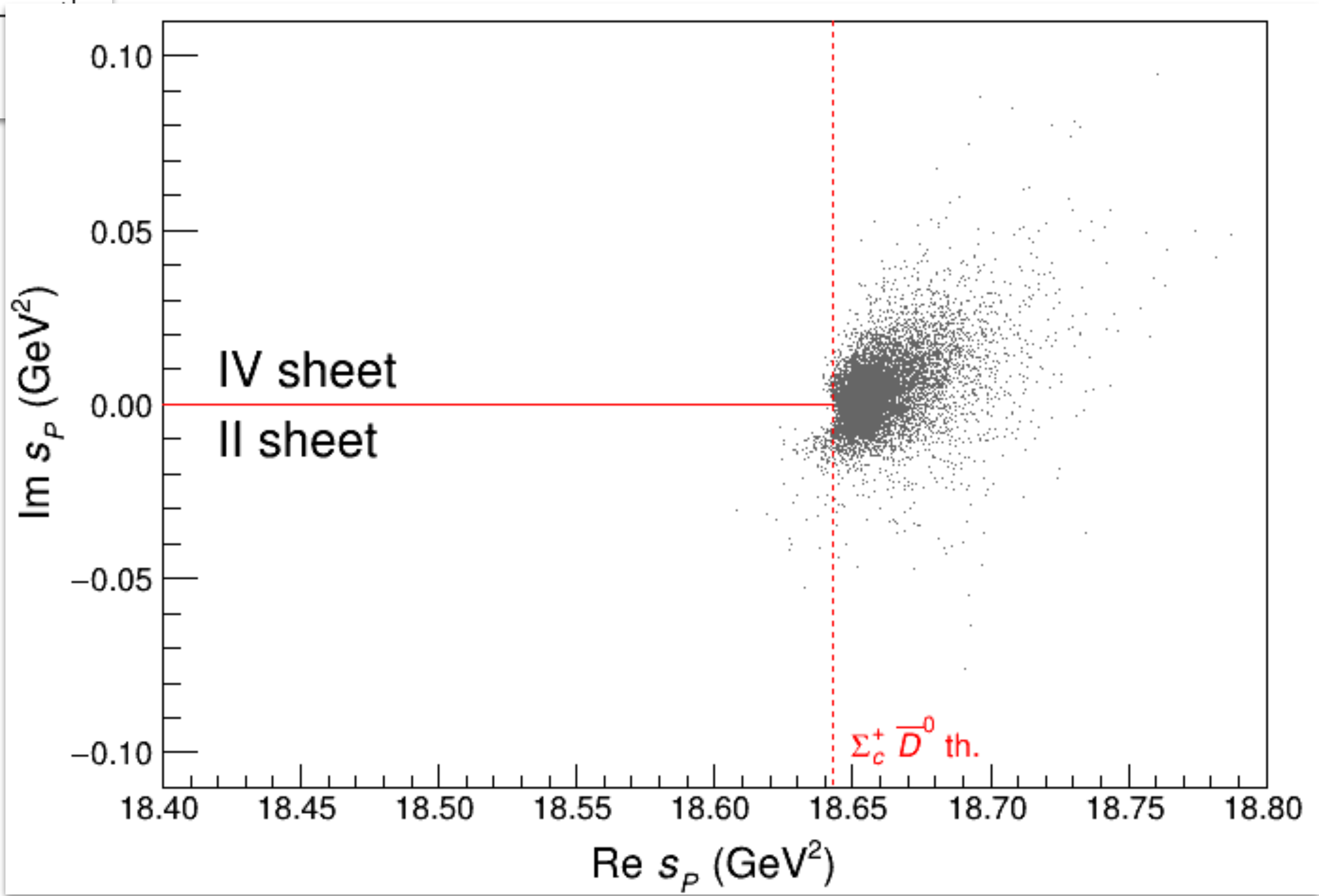
M = 2 x 2 scattering lengt

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

IV sheet pole moves onto real axis (virtual state)

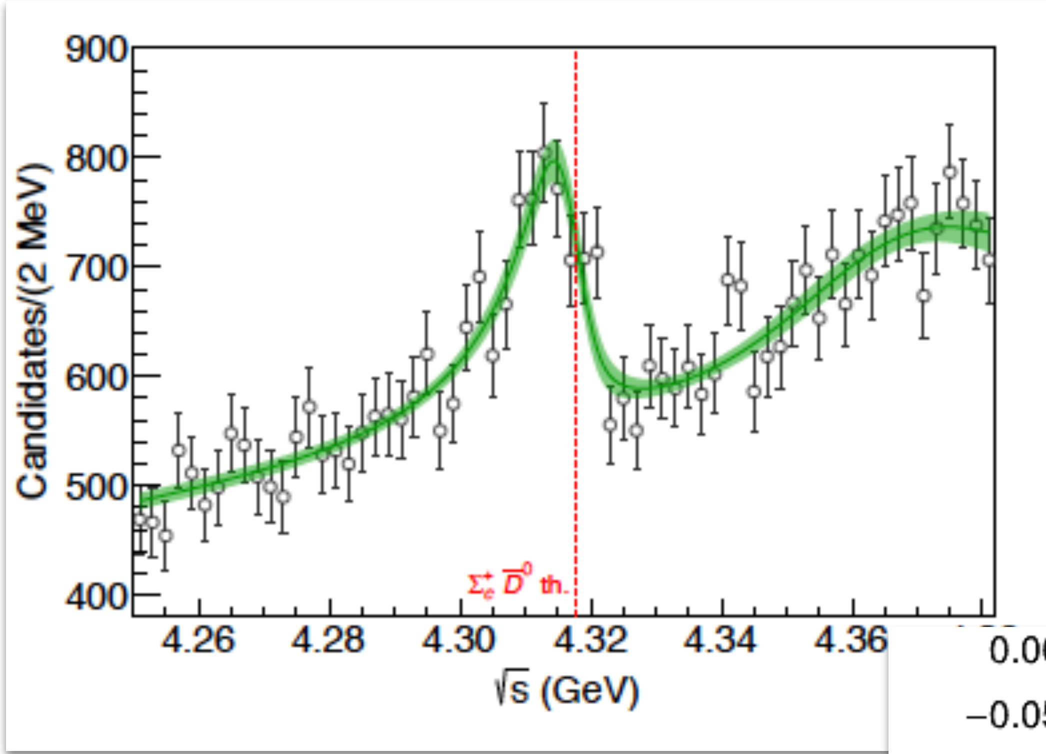
II sheet pole moves onto real axis (bound state)

Virtual state in (>90%)



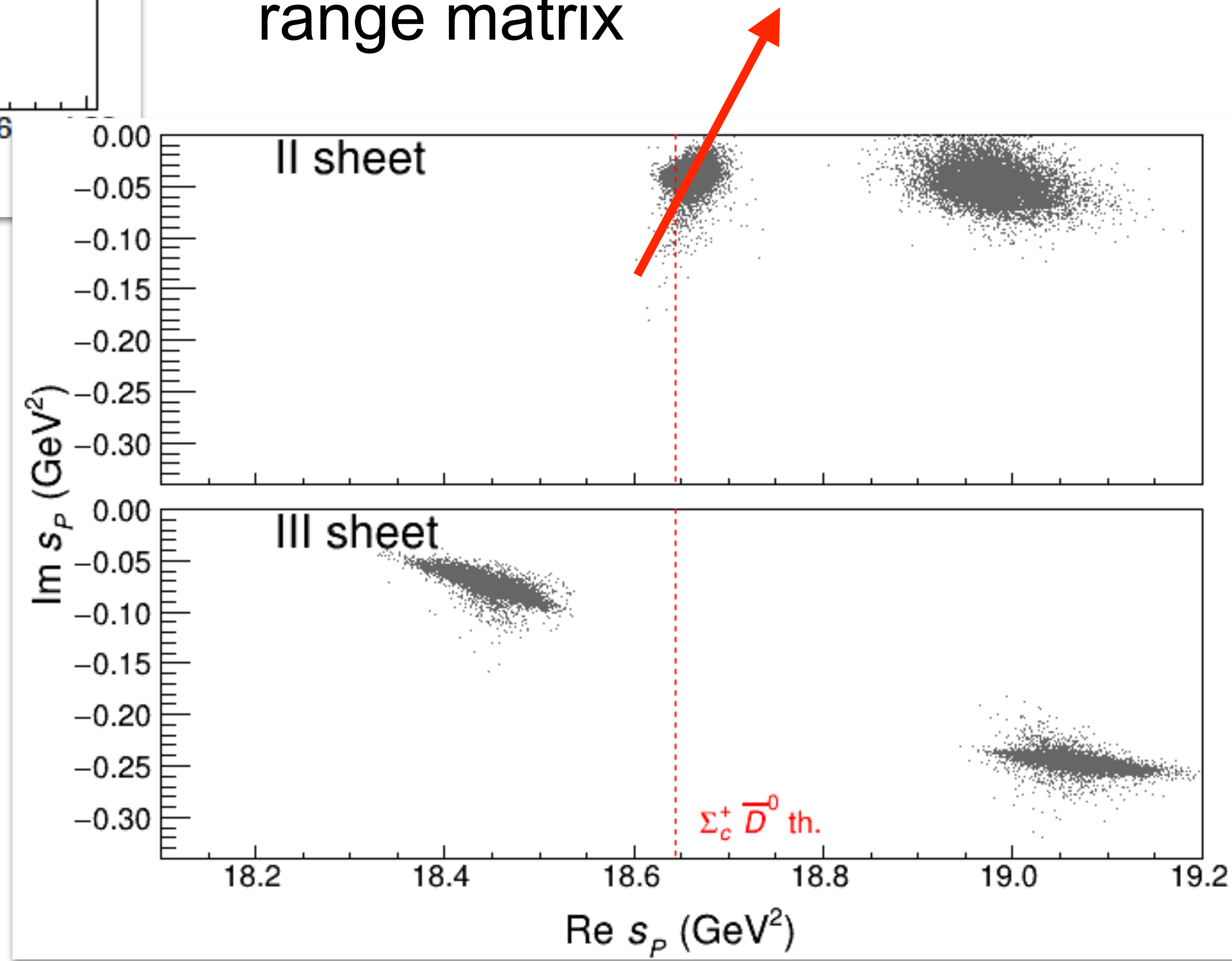
New pentaquarks ?

Case B



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

M = 2 x 2 scattering length + effective range matrix



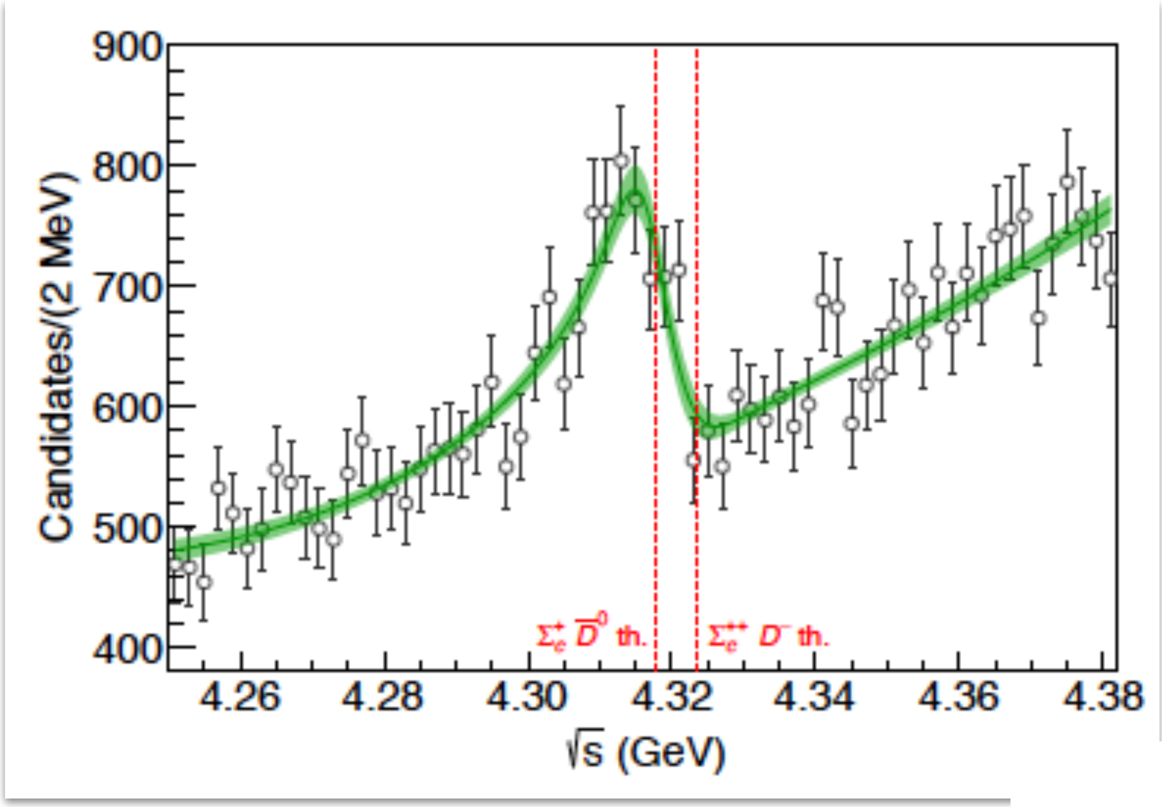
Decrease coupling between J/ψ p and $\Sigma^+\overline{D}$ channel

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



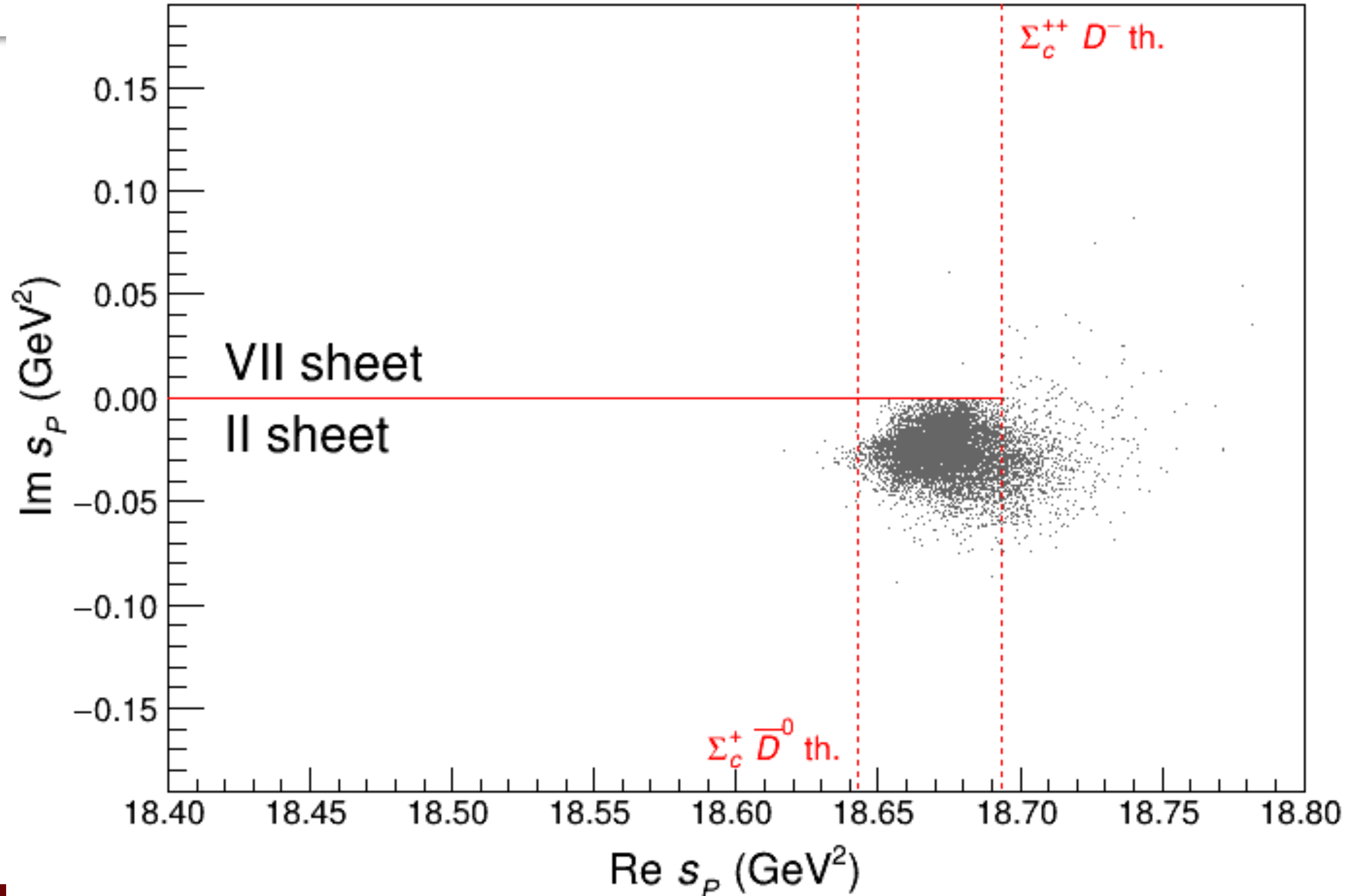
$$T^{-1} = M - i\rho(s)$$

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



Near future

- Strengthen collaborations CLAS12, GlueX and beyond
  EIC, BESIII, LHCb, Belle (?)

- Strengthen overlap with lattice
  3 resent papers on amplitude analysis of 3-to-3 reactions,
  Andrew Jackura, Arkaitz Rodas @ Jlab, Sebastian David @ IU

- Grow the “user base”

  Bridge faculty position

  NNPS Summer school, HUGS: spectroscopy lectures (!) IU graduate course people from JLab community enrolling (?)

  Participate in the IUCSS (Center fro Space Time Symmetries)