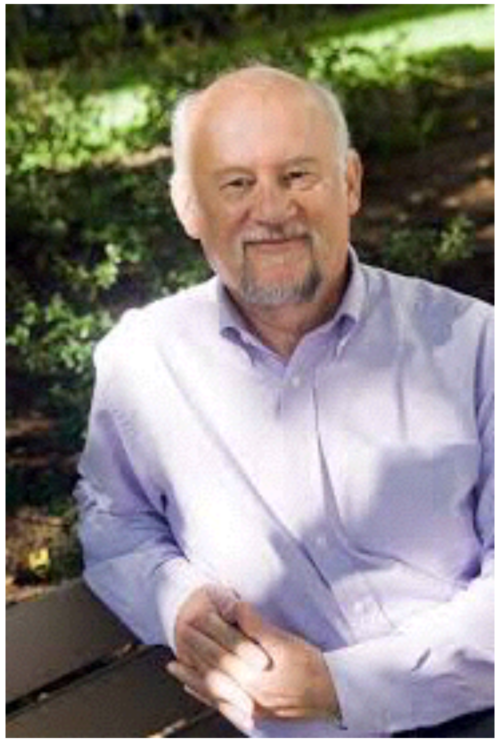
Hadron reactions and spectroscopy studies at the Joint Physics Analysis Center

In honor of Mike Pennington



To be or not to be,… to do partial wave expansion or not ?

JPAC Mission

- JPAC was funded to support the extraction of physics results from analysis of experimental data from JLab12 and other accelerator laboratories.

- This is achieved through work on theoretical, phenomenological and data analysis tools.

- JPAC aims to facilitate close collaboration between theorists, phenomenologists, and experimentalists worldwide.

- It is engaged in education of further generation of hadron physics practitioners

JPAC People

- Postdocs:
  - (past) L.Dai (Bonn), I.Danilkin (Mainz), P.Guo (Cal. State U.), C.Fernandez-Ramires (UNAM), D.Schott (Med. Coll. of Wis.)
  - (current) V.Mathieu (IU), I.Lorentz (IU), A.Pilloni, (JLab) V.Pauk (JLab), D.Ronchen (Bonn U.)
- Students:
  - (past) M.Shi (Pekin U.)
  - (current) E.Alexeev (IU), A.Blin (Valencia), B. Hu (GWU), A.Jackura (IU), M.Mikhasenko (Bonn), J.Nis (U. Gent)

- Faculty: M.Doering (GWU), G.Fox (IU), J.T.Londergan (IU),I.Mokeev (JLab), M.Pennington (JLab), E.Passemar (IU), A.Szczepaniak (IU/JLab), R.Workman (GWU)

Products

- > 40 Research Papers (Phys. Rev., Phys. Lett, Eur. J. of Phys.)
- ~120 Invited Talks and Seminars
- Several Reaction/Reference Web Pages (include summer school + database)
- ~O(10) Ongoing Analyses
- 1 Summer School on Reaction Theory (IU,2015), 1 Workshop (Future Directions in Hadron Spectroscopy, (JLab, 2014)
- JPAC Review May-3-4, 2014

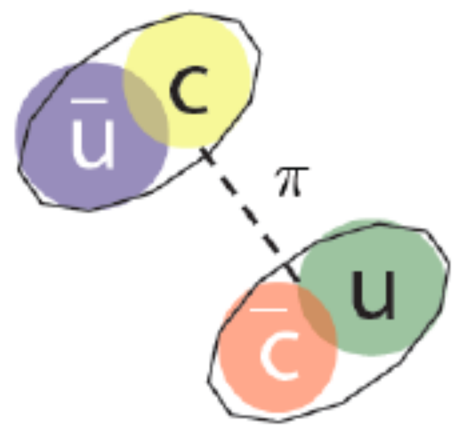
There may be hadrons that look like …

dibaryon

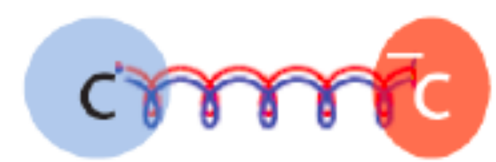
pentaquark

glueball

diquark + di-antiquark



dimeson molecule

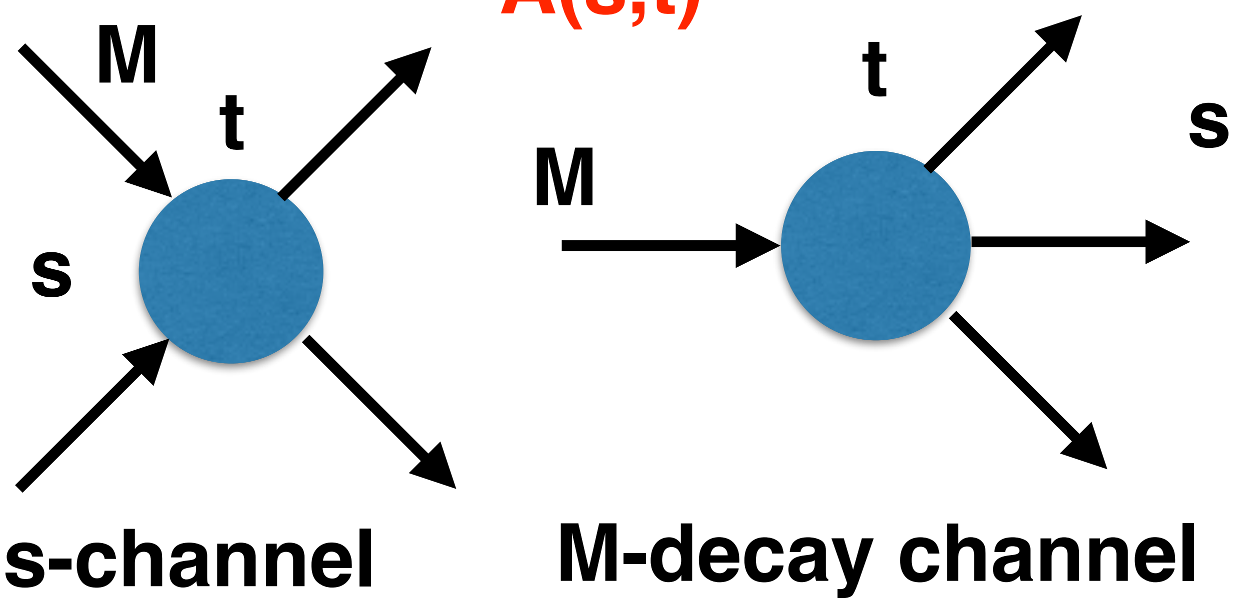


$q\,\bar{q}\,g$ hybrid

…before we know these exist it is necessary to identify resonances

S-matrix principles: Crossing, Analyticity, Unitarity

A(s,t)



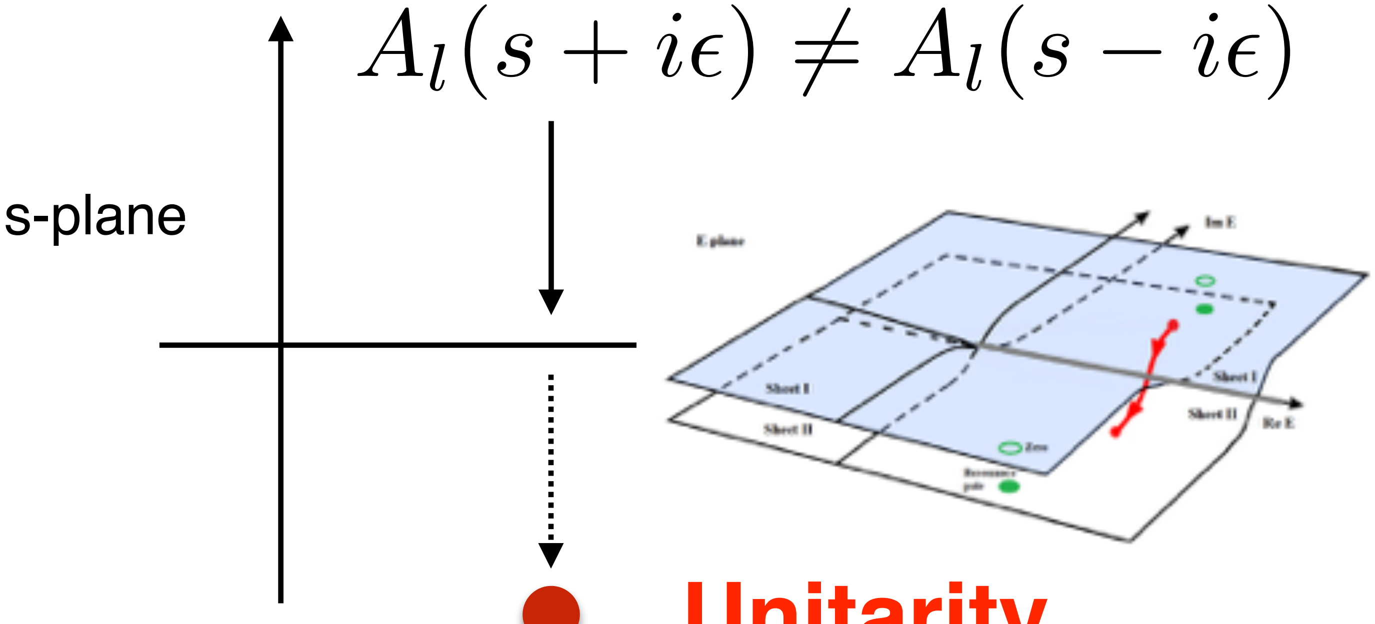
Crossing

$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

Analyticity

$$A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)$$

$$A_l(s + i\epsilon) \neq A_l(s - i\epsilon)$$

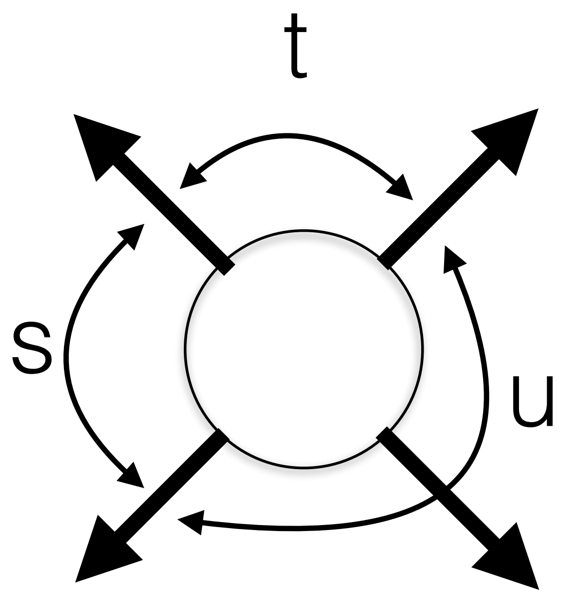


Unitarity

Resonances : bumps/ peaks on the real axis (experiment) come from singularities in unphysical sheets

These singularities come from QCD

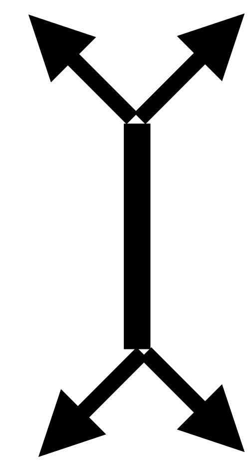
To do partial wave expansion or not ?



A(s,t) has singularities in s, t and u

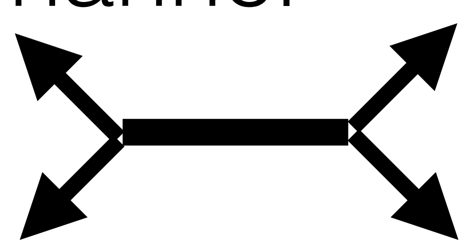
but partial wave expansions selects a specific channel, e.g. the t-channel:

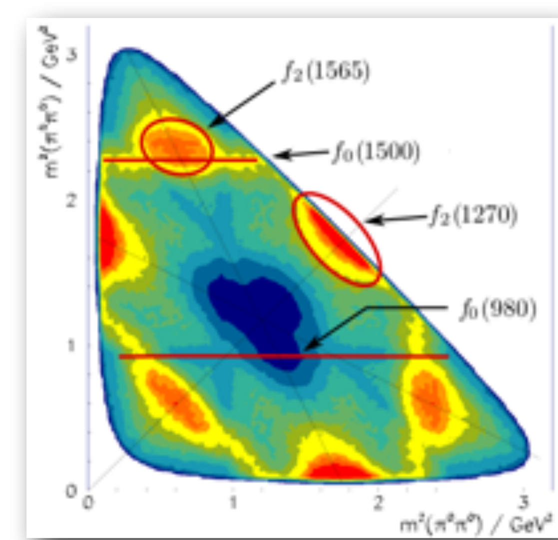
$$A(s,t) = \sum_{l}^{L_{max}} (2l+1) a_l(t) P_l(z_t) \qquad z_t = \frac{s-u}{t-4\mu^2}$$



$a_l(t)$

valid (convergent) in the t-channel physical region





$L_{max}=\infty$ is needed to reproduce s and u channel singularities (e.g. resonance)

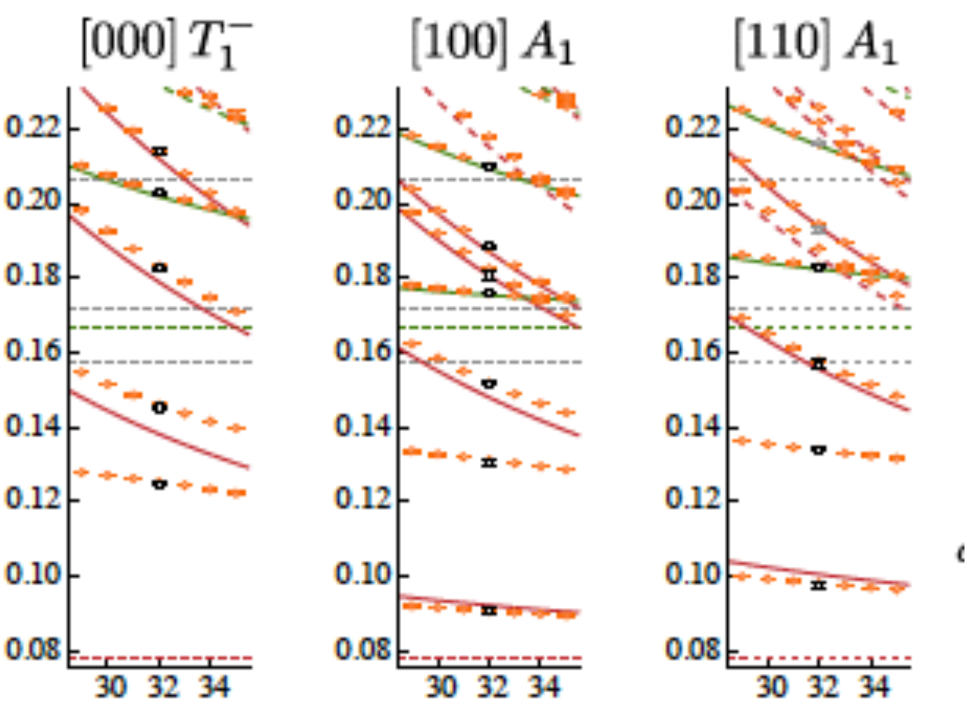
QCD on the Lattice : simulated scattering experiment

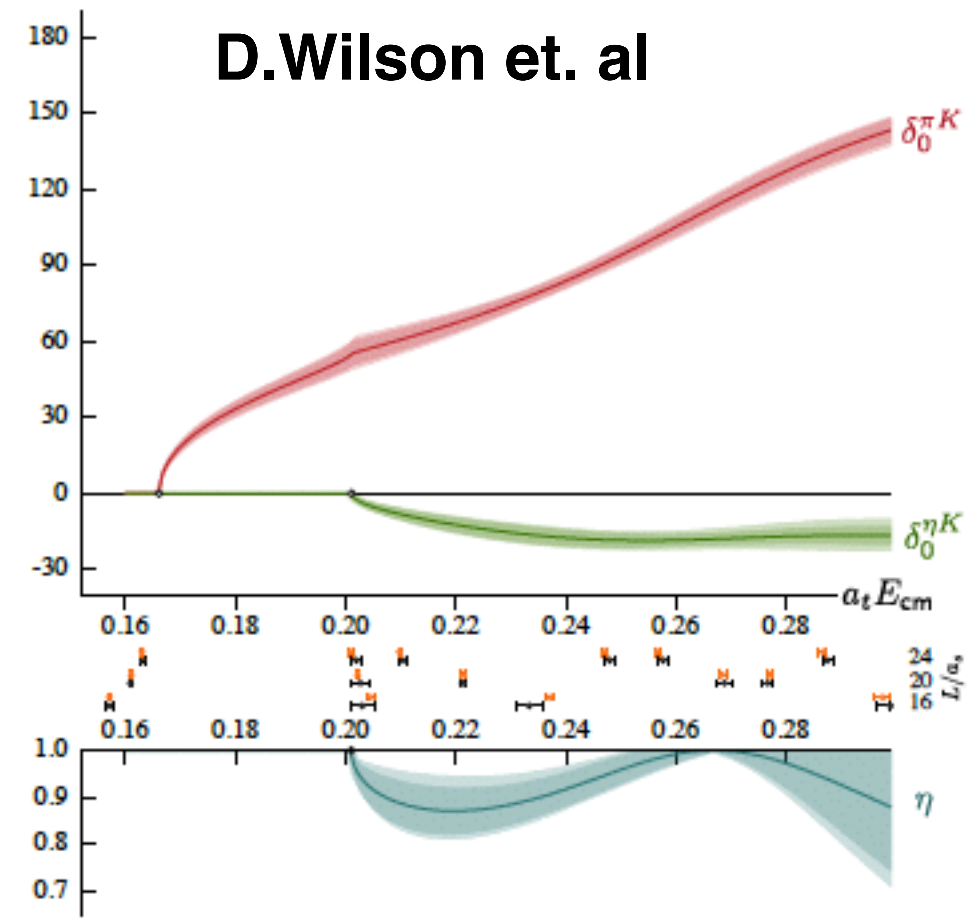
(known kinematical function)

$$Z(E_i(L),L) = T(E_i)$$

(infinite volume amplitude)

E_i = discrete energy spectrum of states in the lattice

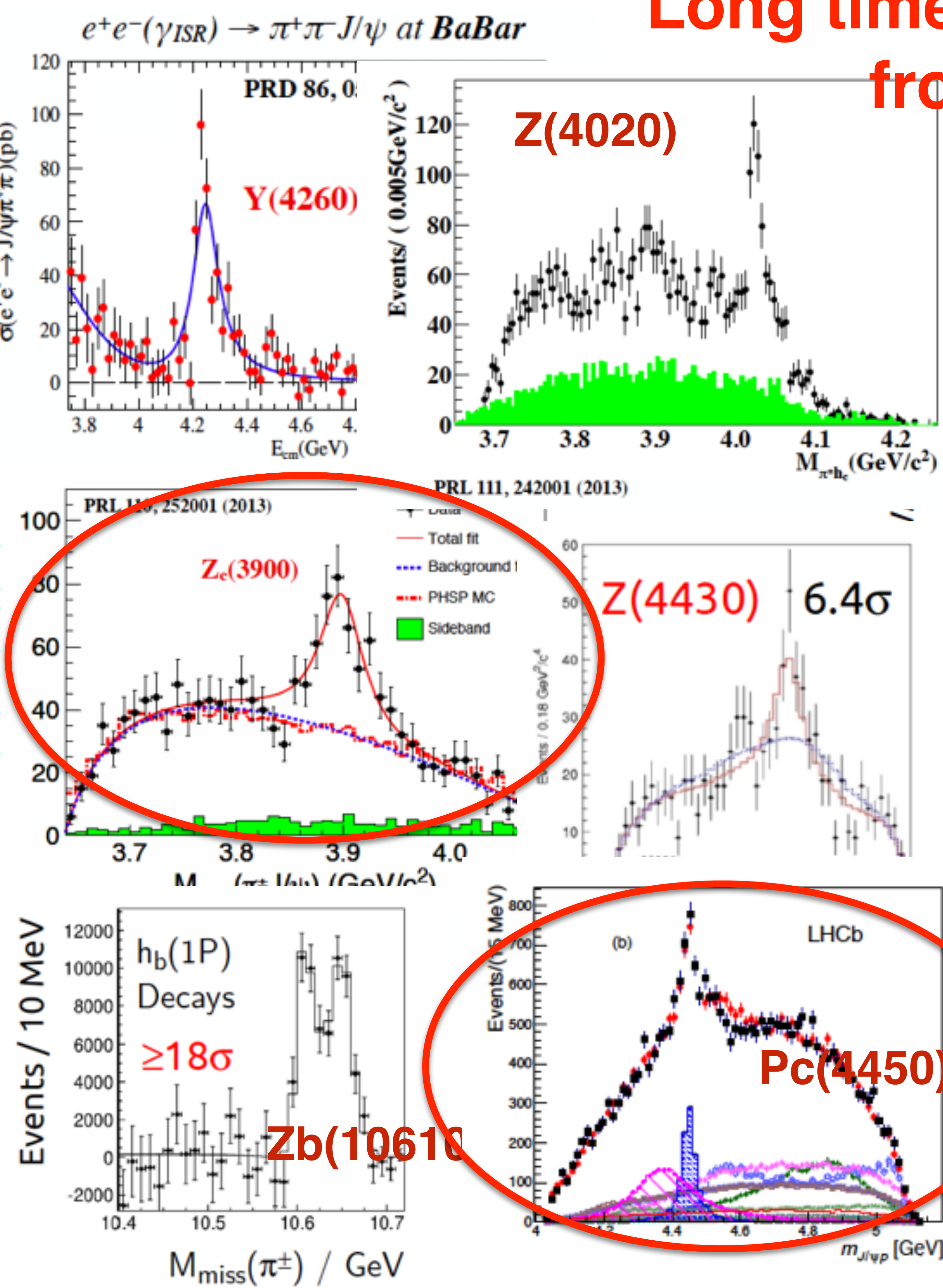


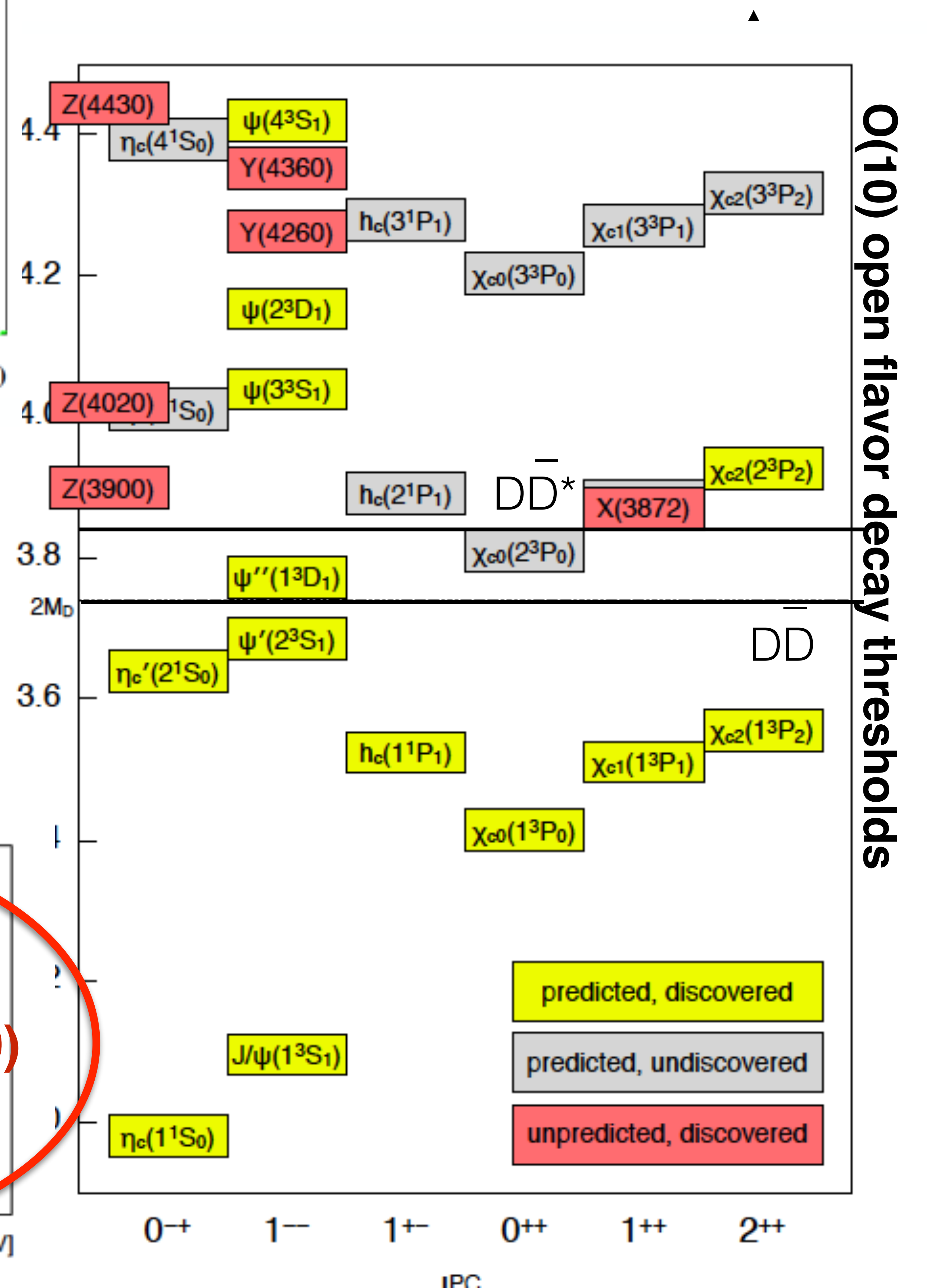


in general “solution” of the Luscher condition requires an analytical model for T

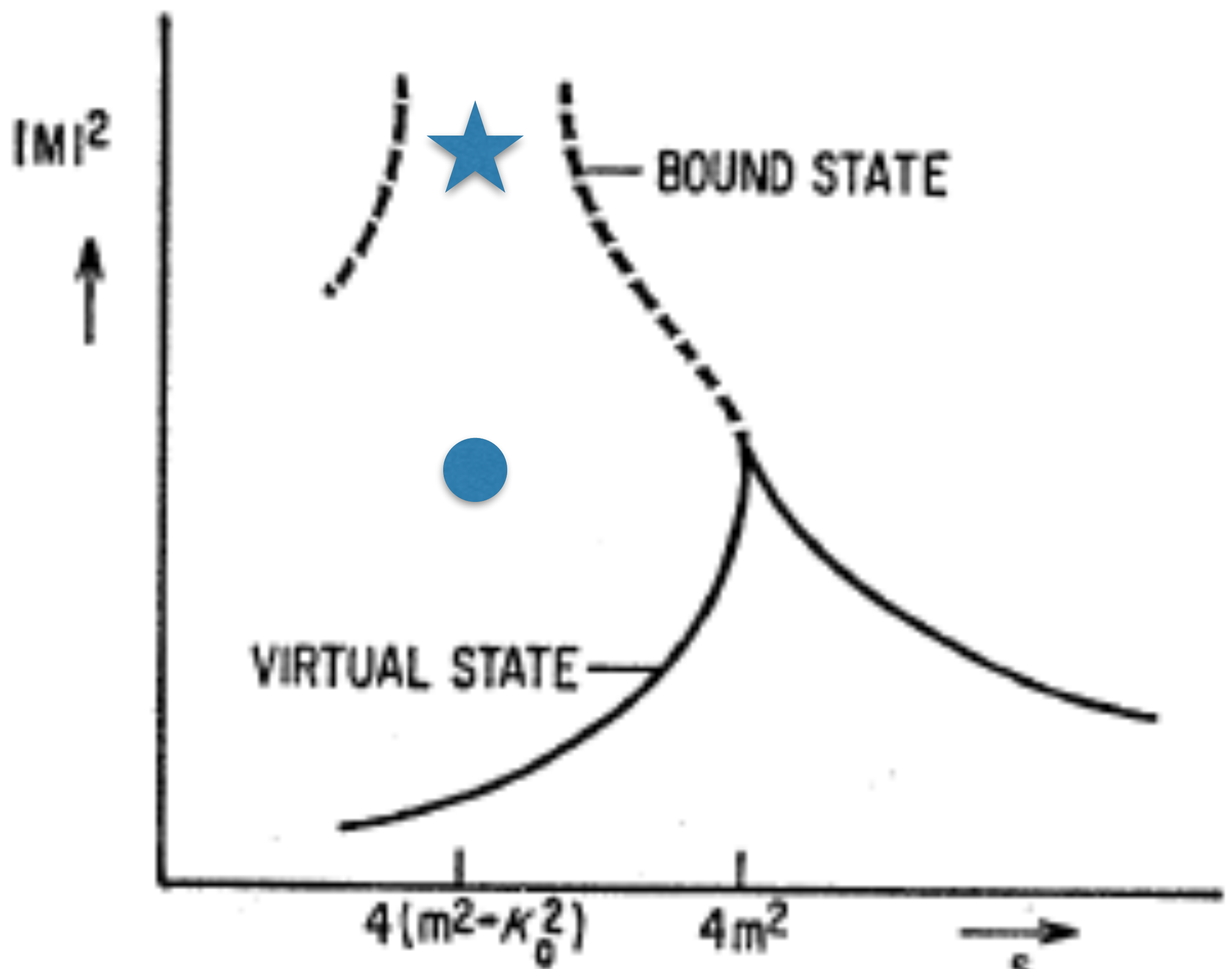
XYZ
“dynamics”

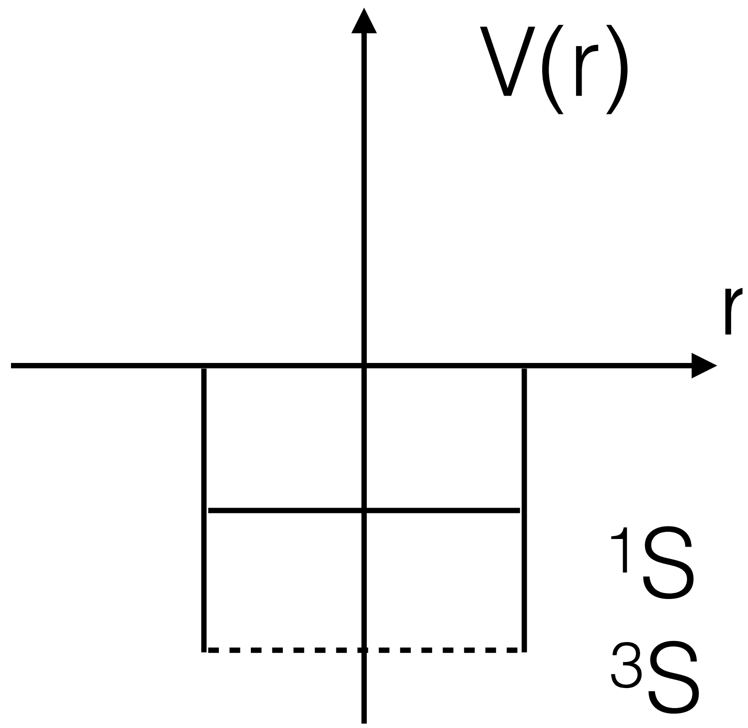
Long time ago hadrons were made from valence quarks

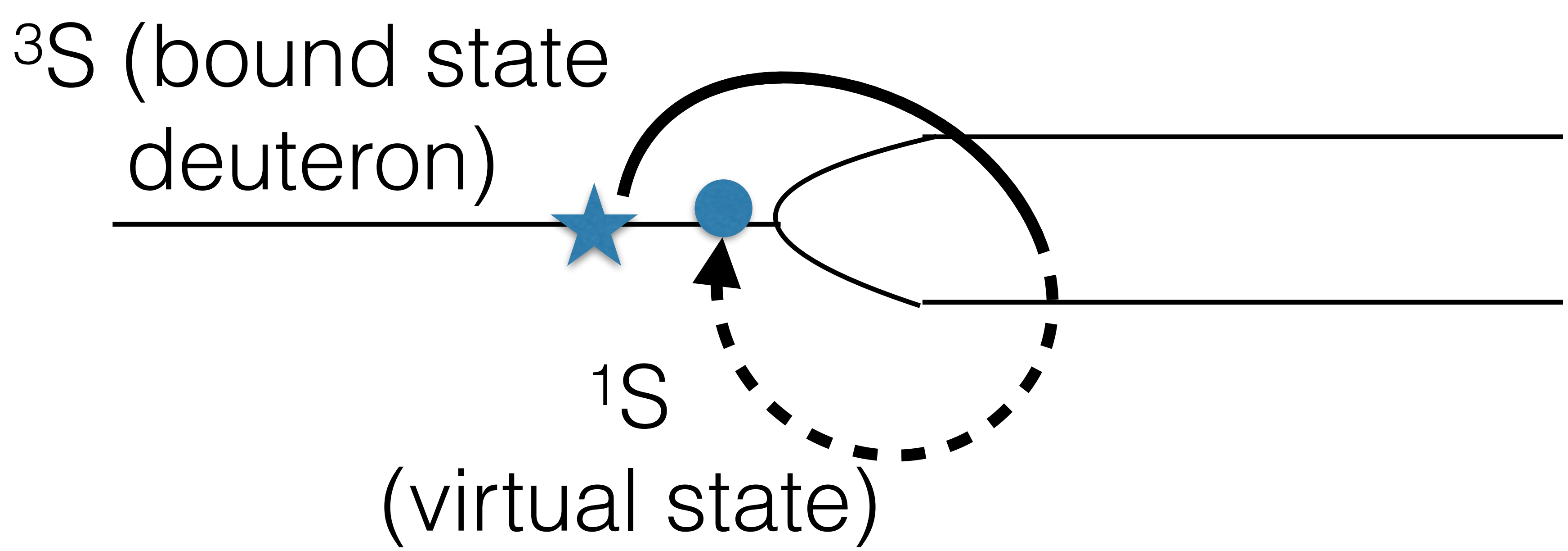




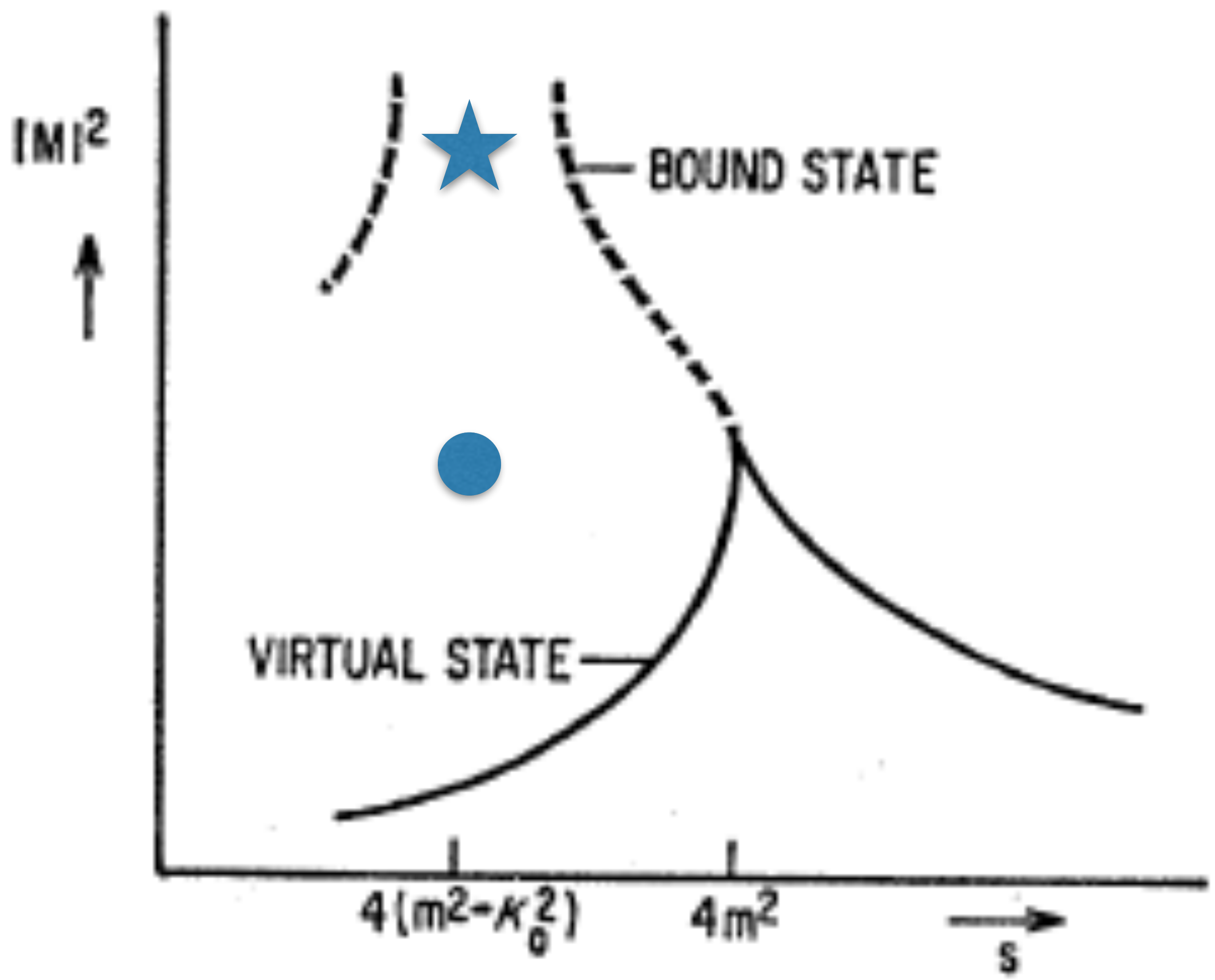
Singularities, is all that matters: cusps, poles and more cusps

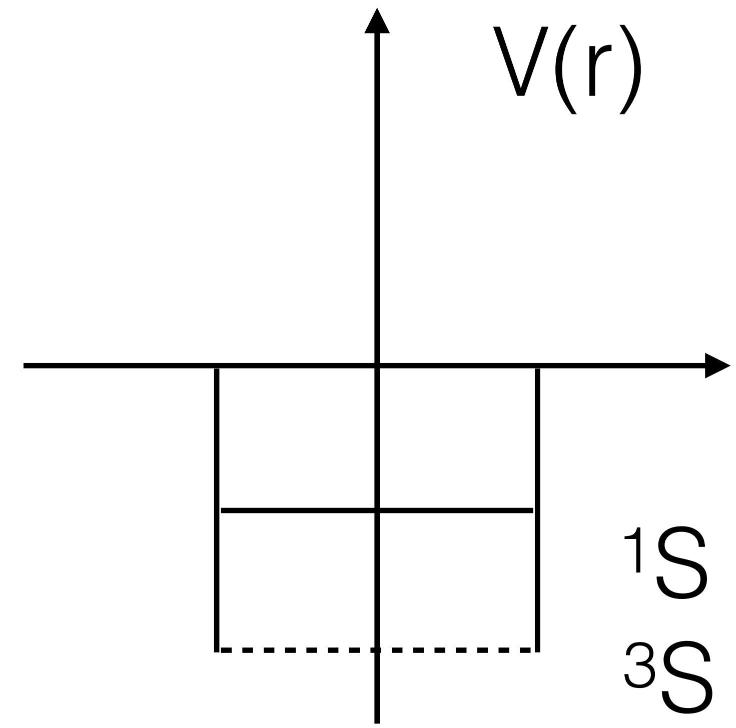


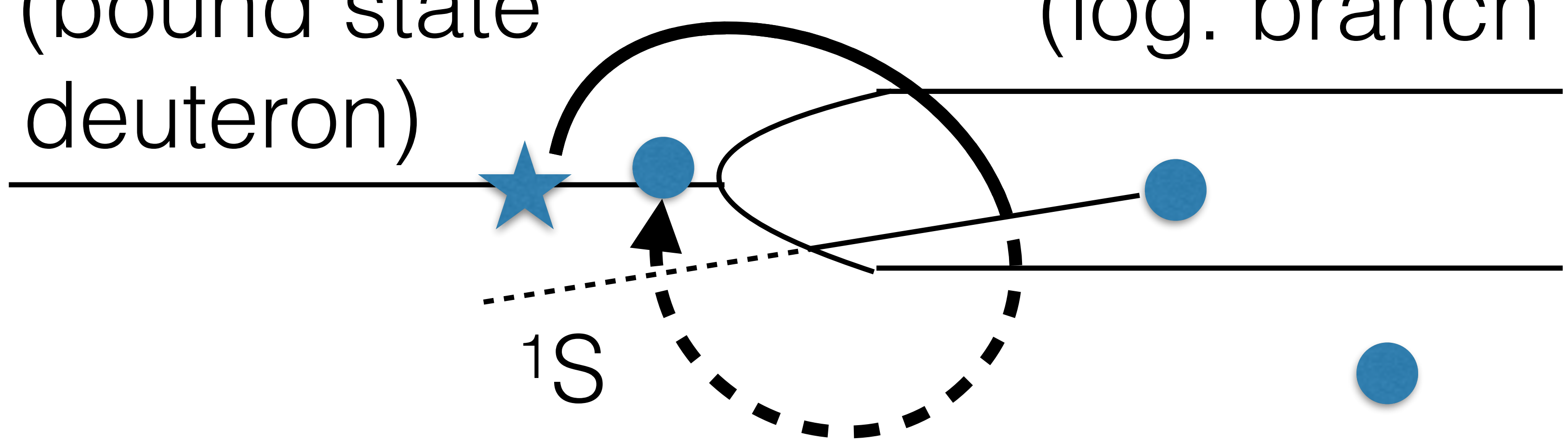




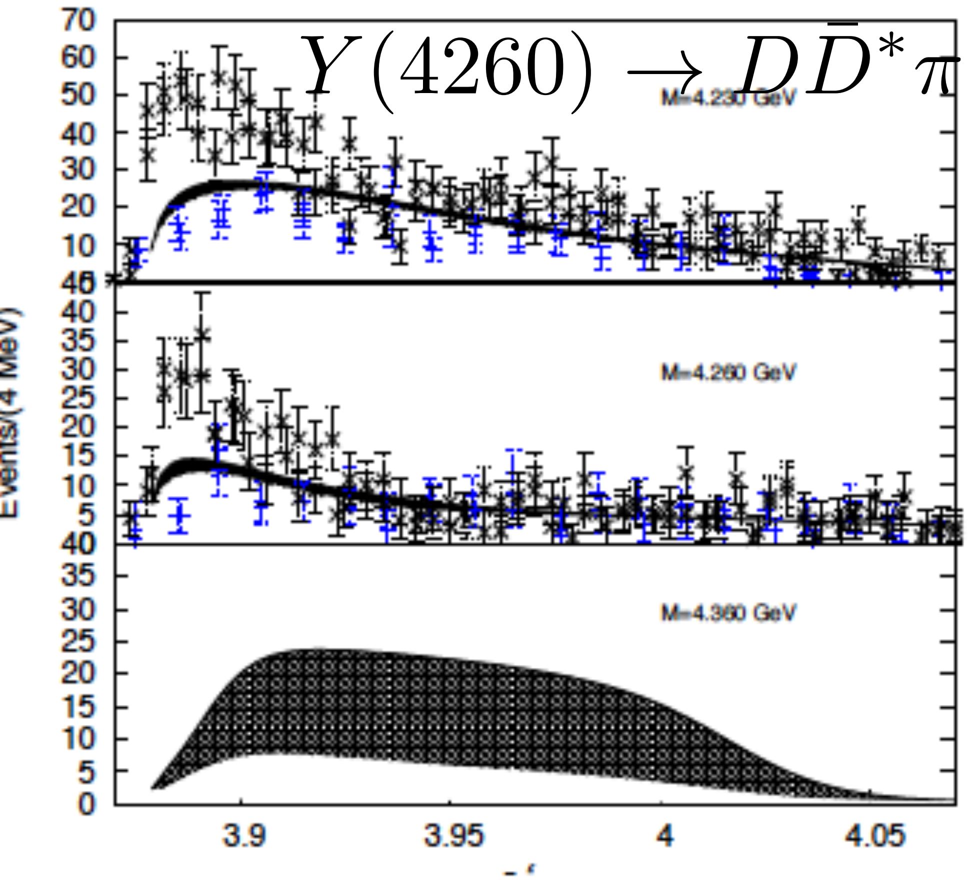
Singularities, is all that matters: cusps, poles and more cusps

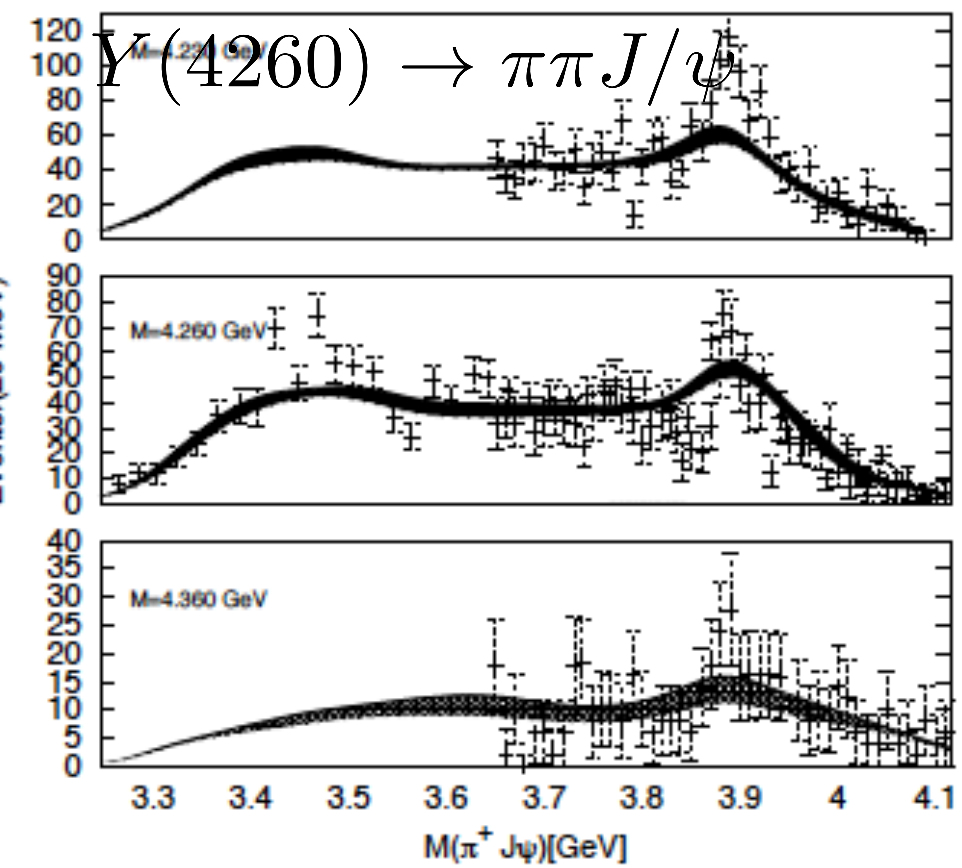




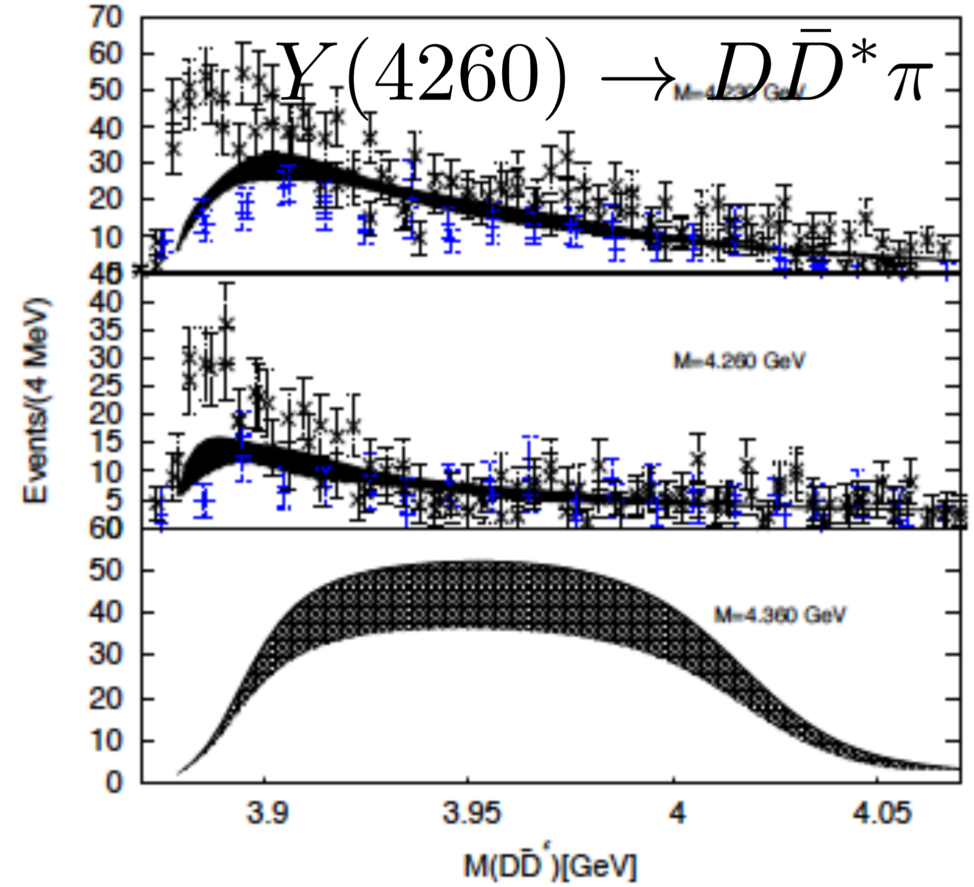


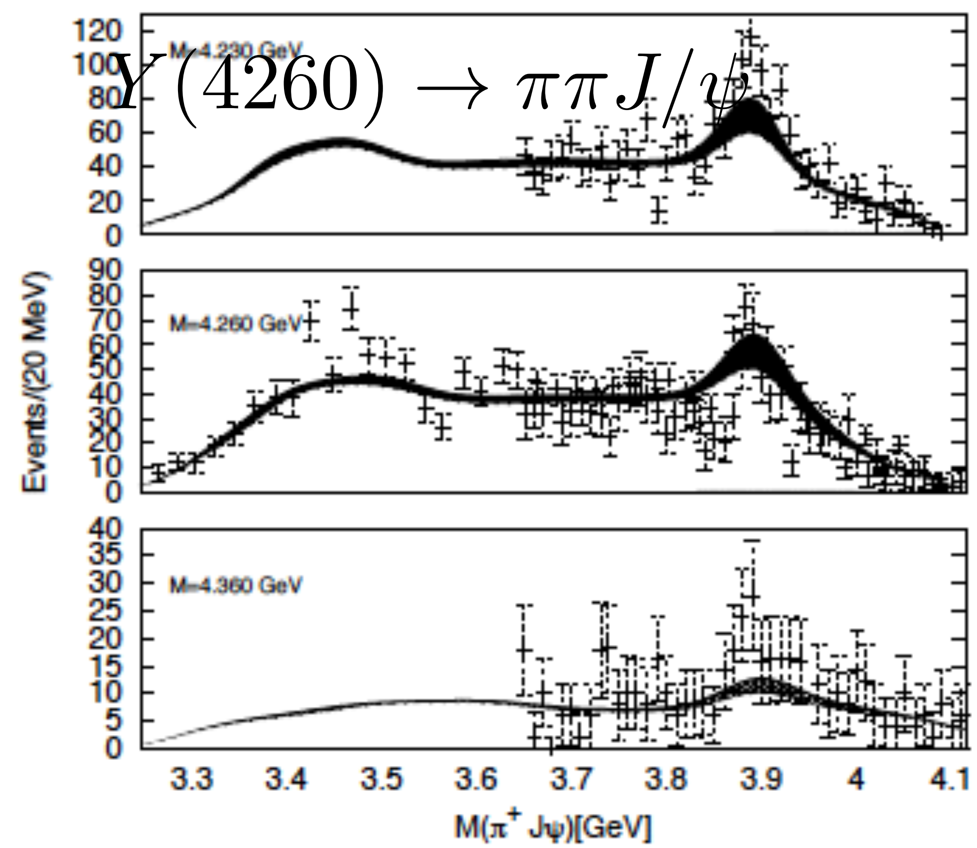
Model I





Model II





Amplitude analysis has to be applied at the event-by-event basis

Fitting projection may not be enough to discriminate between amplitude models/ dyamics

2.4 $\omega/\phi \to 3\pi$

Danilkin et al., JPAC'15

- Simple system: restricted to odd partial waves
  ⇨ P wave interactions only (neglecting F- and higher)

- Amplitude:
$$\mathcal{A}_\lambda(s,t,u) = \varepsilon_{\mu\nu\alpha\beta}\epsilon^\mu_\lambda p^\nu_{\pi^+} p^\alpha_{\pi^-} p^\beta_{\pi^0}\mathcal{F}(s,t,u)$$
$$\mathcal{F}(s,t,u) = \mathcal{F}(s)+\mathcal{F}(t)+\mathcal{F}(u)$$

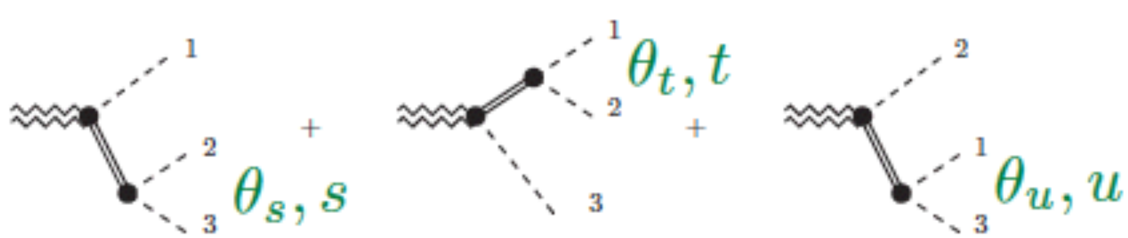
- F(s) function of one variable with only a right-hand cut

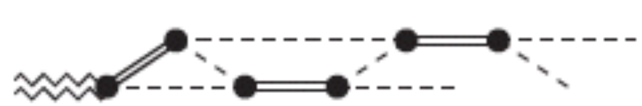
- Unitarity relation:
$$\mathrm{Disc}\,F(s) = \rho(s)\,\overbrace{t^*(s)}^{\pi\pi\to\pi\pi}\left(F(s)+\hat{F}(s)\right)$$

- Relation of dispersion to reconstruct the amplitude everywhere:

$$F(s) = \Omega(s)\left(\int_{4M_\pi^2}^{s_i}\frac{ds'}{\pi}\frac{\mathrm{Disc}\,F(s)}{\Omega^*(s')\left(s'-s-i\varepsilon\right)} + \sum_{i=0}^{N} a_i\omega^i(s)\right)$$

$$\omega(s) = \frac{\sqrt{s_i}-\sqrt{s_i-s}}{\sqrt{s_i}+\sqrt{s_i-s}}$$

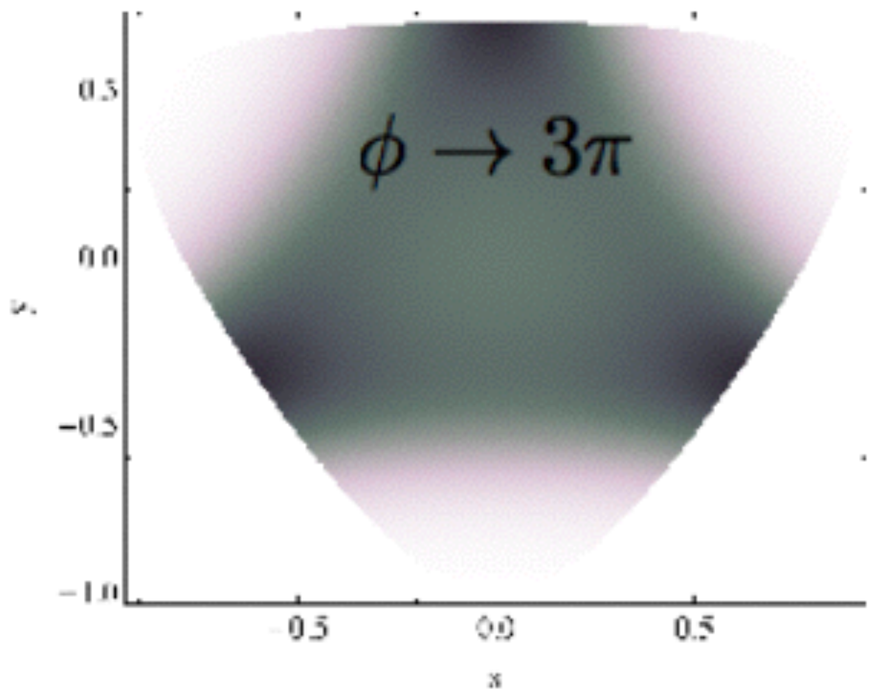


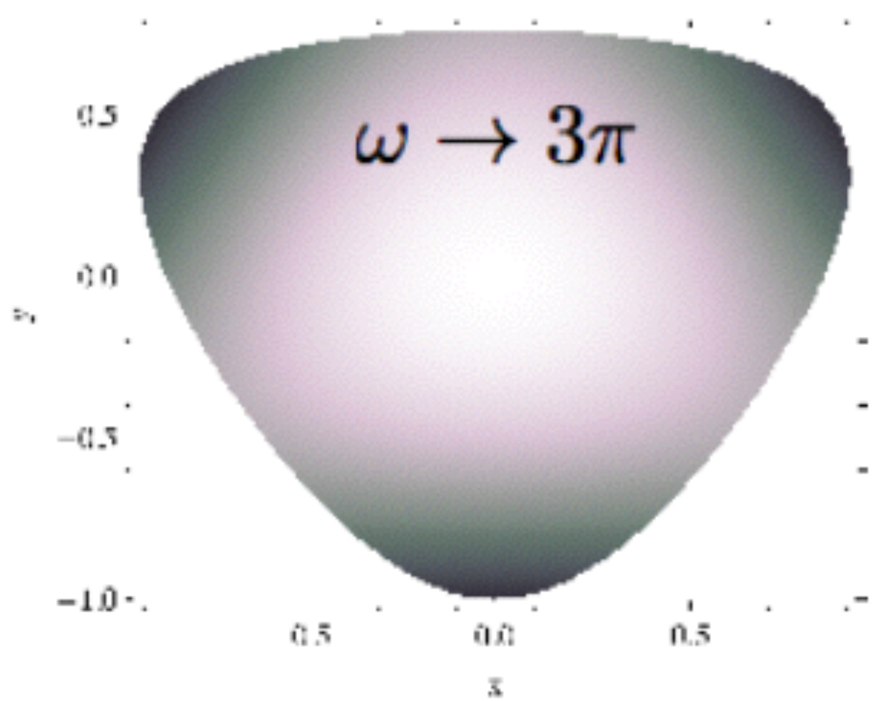


2.4 ω/φ → 3π

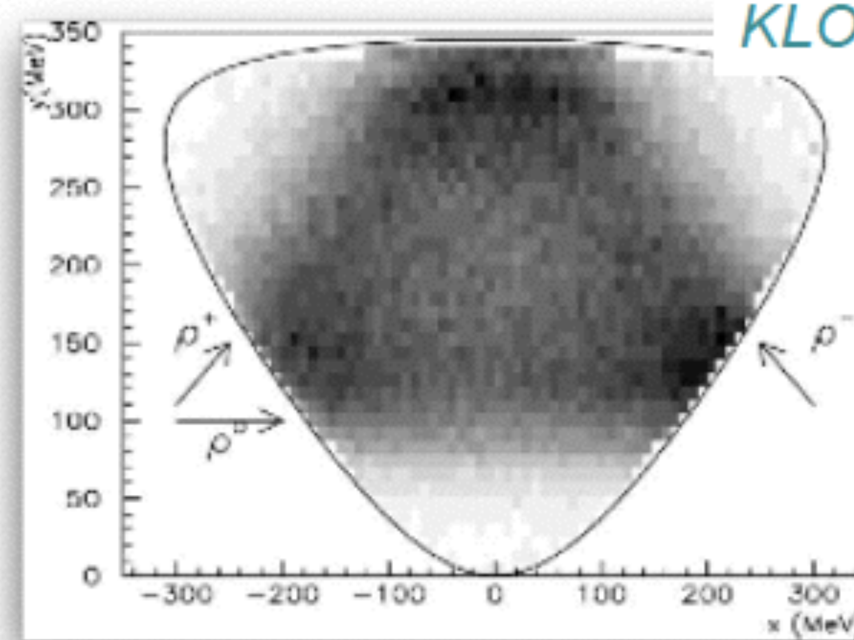
- Dalitz plots:

Danilkin et al., JPAC'15



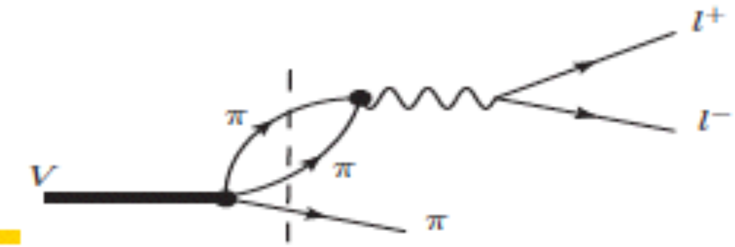


KLOE'03



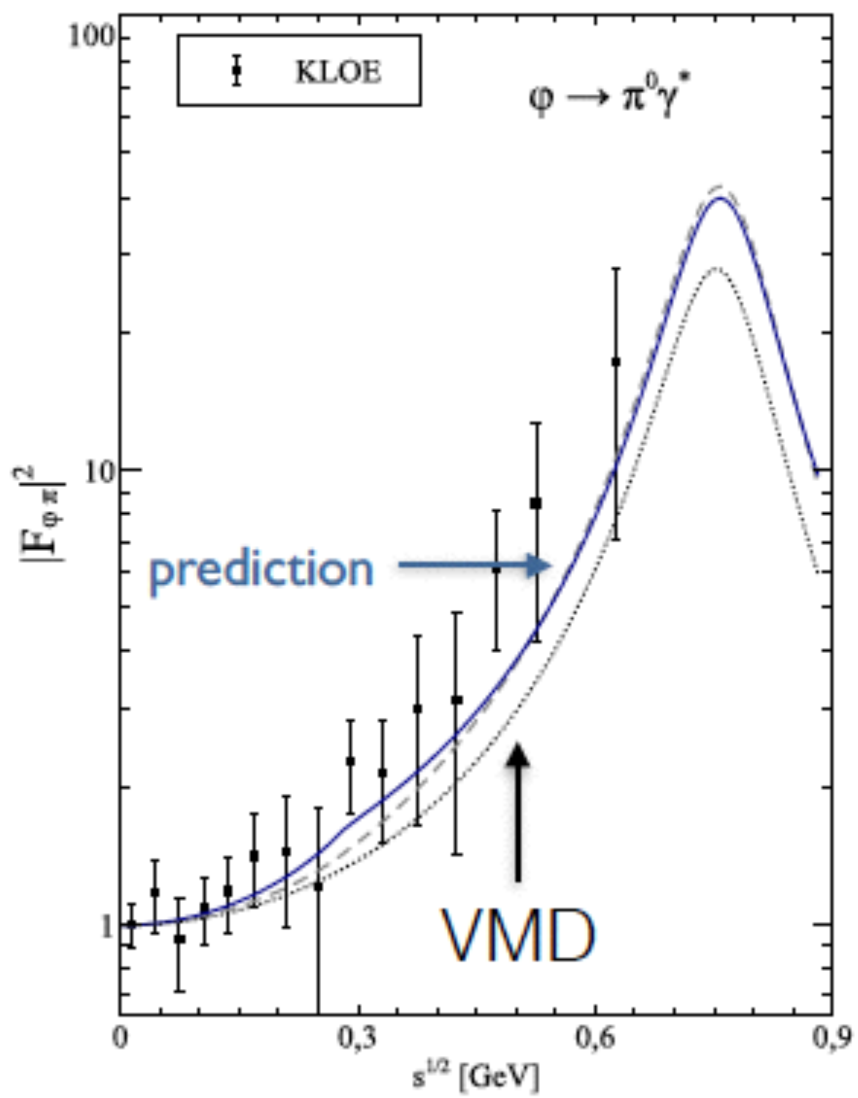
- Only one parameter (overall normalization)
  ➡ fixed from Γ_{exp} (ω/φ→3π)
- ω→3π: distribution is relatively flat.
  Upcoming high-statistic data from *CLAS, WASA, KLOE2*
- Fit event by event by event *g12 CLAS data* in progress:
  C. Salgado, V. Crede, C Zeoli

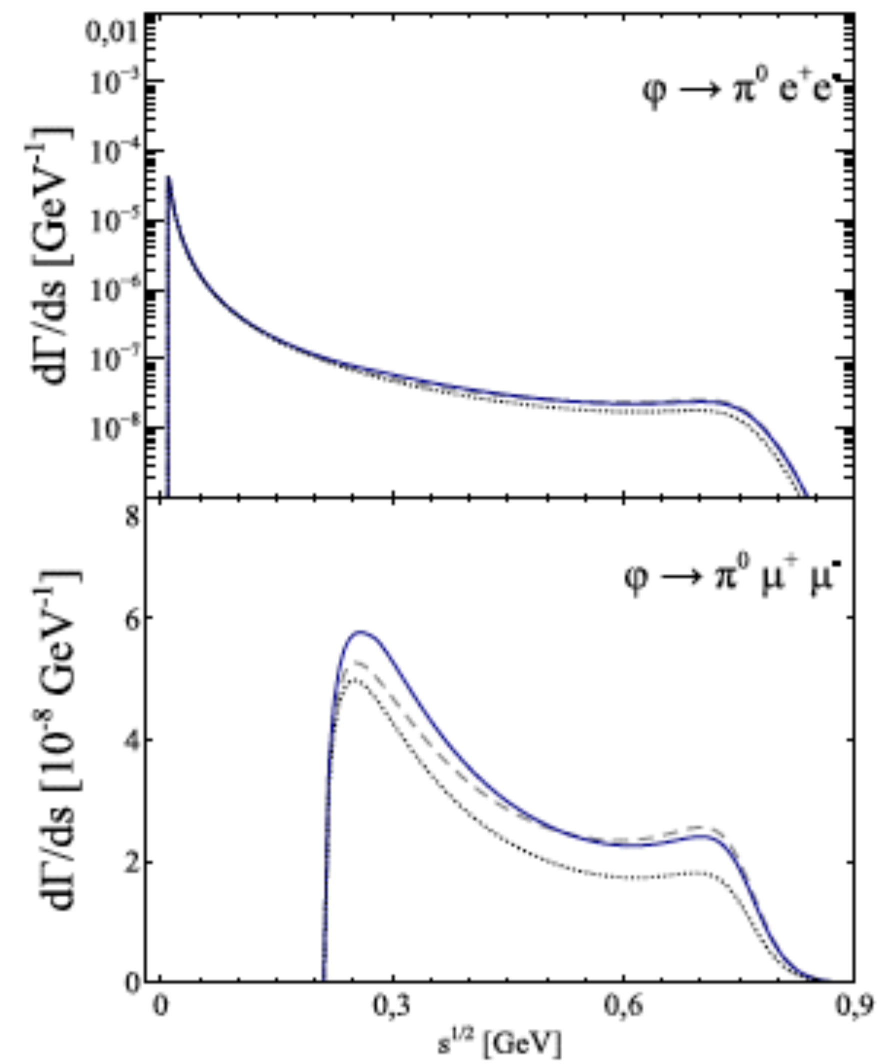
2.5 Application: $\phi \to \pi^0 \gamma^*$



Danilkin et al., JPAC

- Form factor: $f_{V\pi}(s) = \int_{s_\pi}^{s_i} \frac{ds'}{\pi} \frac{\text{Disc}\, f_{V\pi}(s')}{s'-s} + \sum_{i=0}^{N} C_i\, \omega(s)^i$

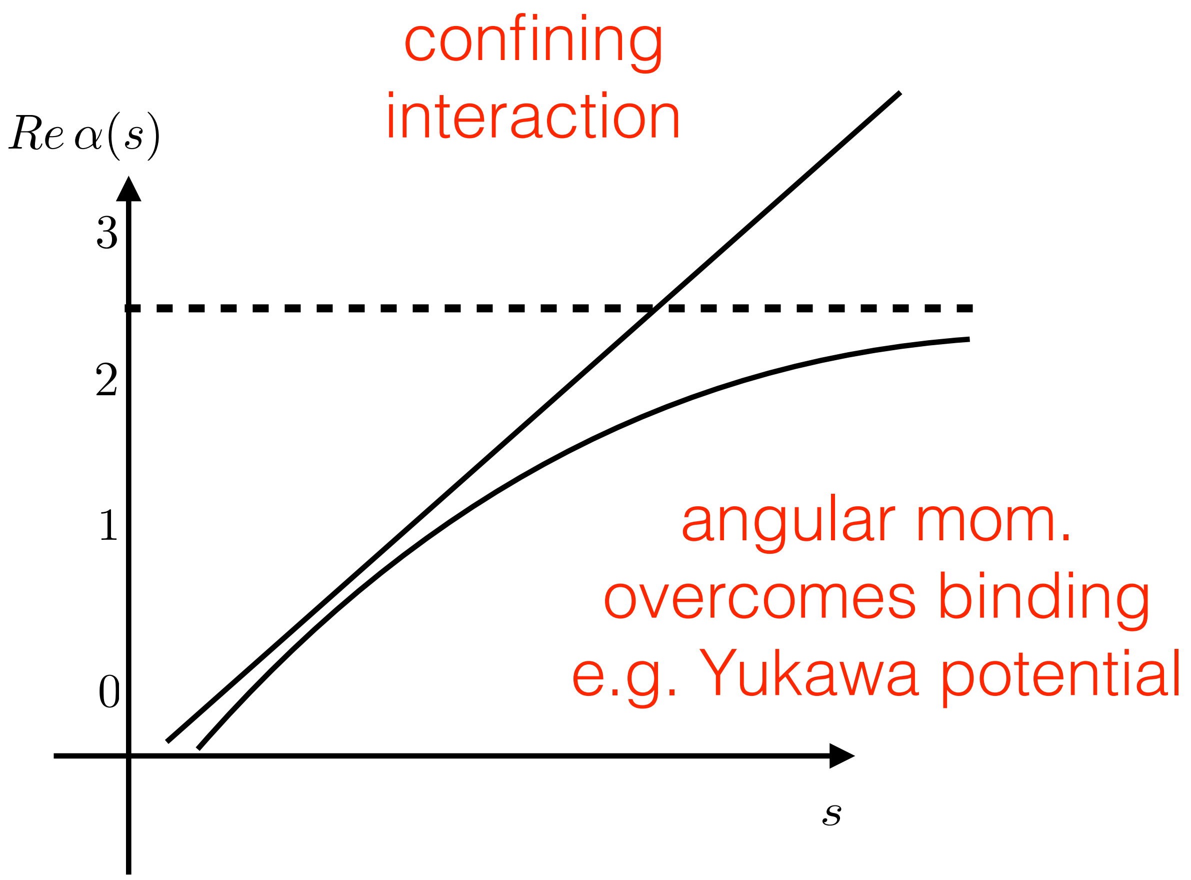




- C_0 fixed from Γ_{exp} ($\varphi \to \pi\gamma$). Grey: no 3 body effects
- Prediction consistent with new *KLOE* data'16
- Possible future data from *VEPP-2000*

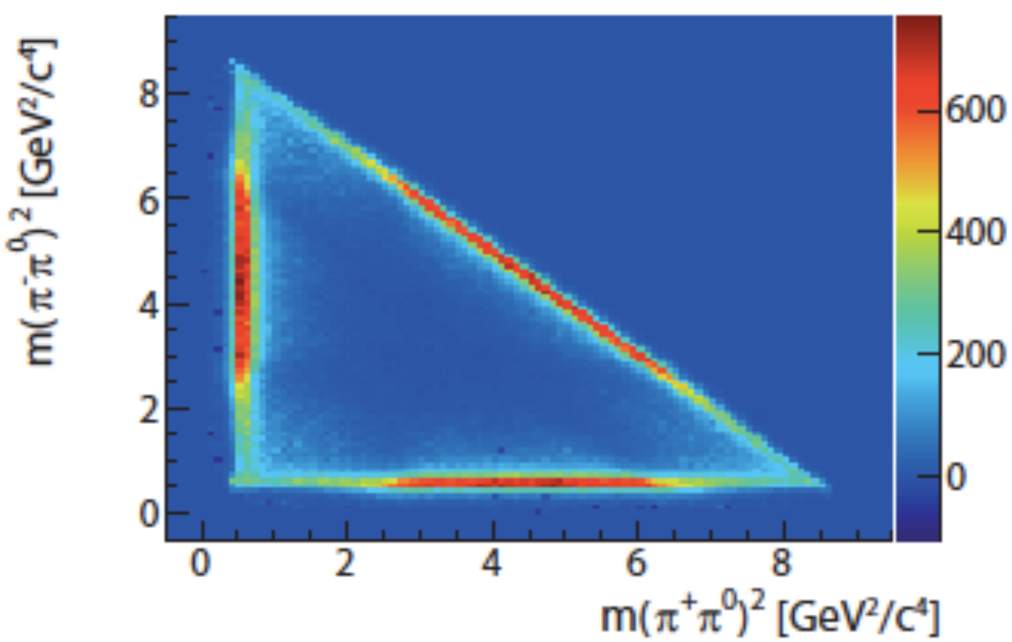
Reggeons vs Resonances

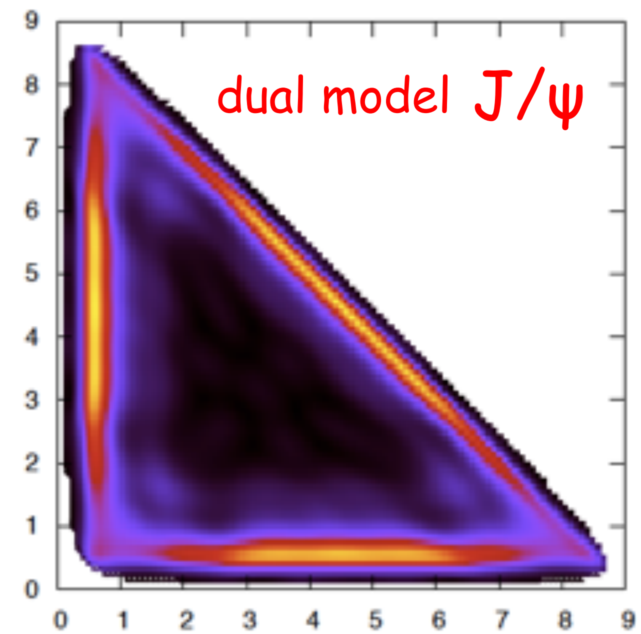
- Resonances are not constrained by S-matrix principles -> need priori knowledge
- Resonates are poles in s at fixed L; Reggeons are poles in L at fixed s

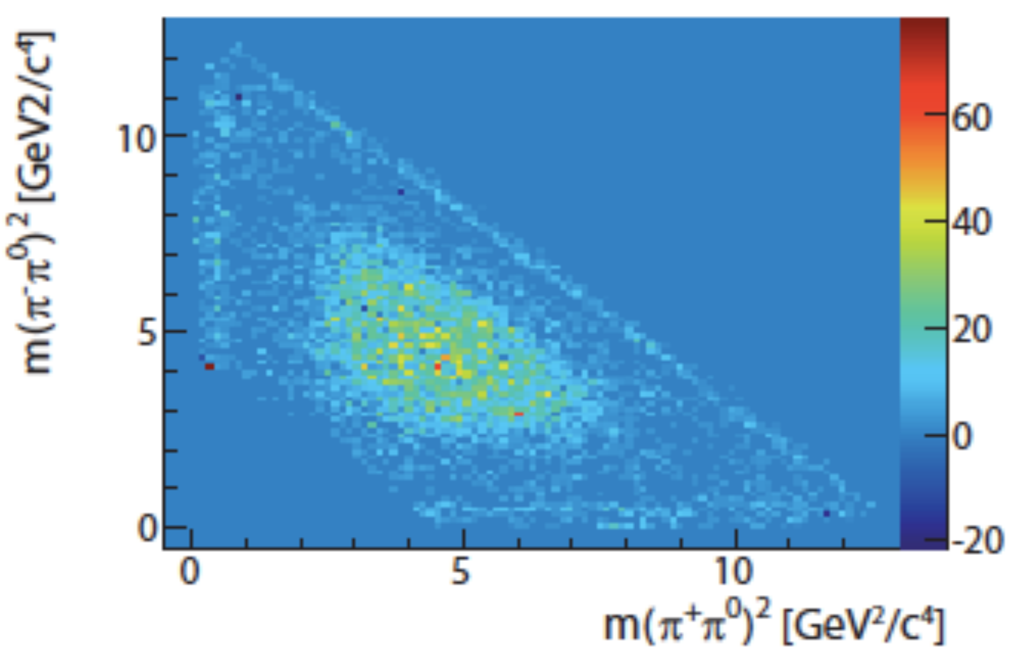


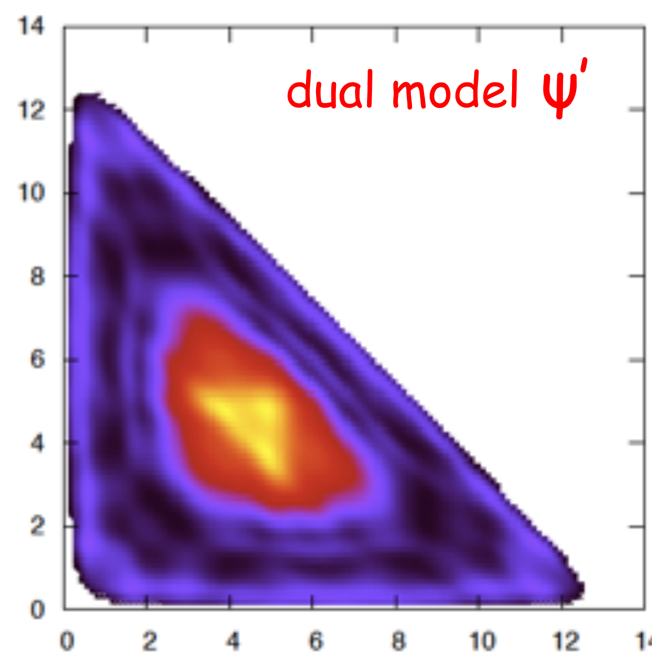
Revival of “old” ideas e.g. dual models

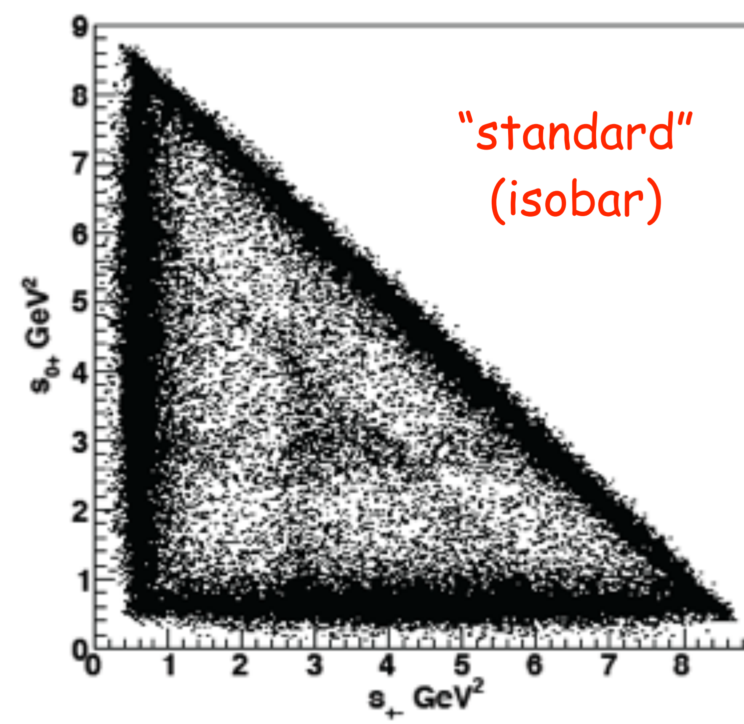
$$A(s,t) = \frac{\Gamma(-J(s))\Gamma(-J(t))}{\Gamma(-J(s)-J(t))}$$







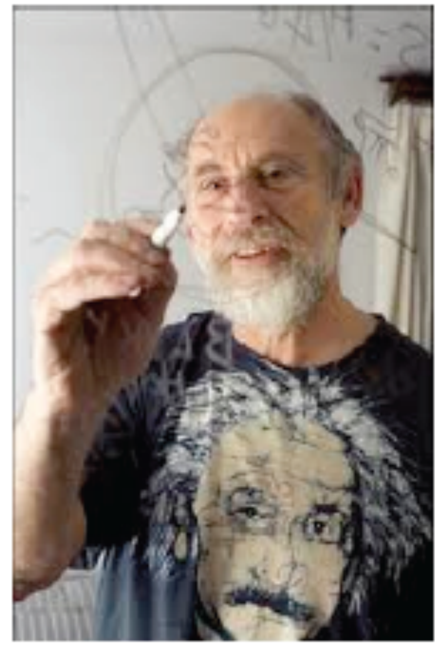




BESIII, Phys.Lett. B710 (2012) 594-599

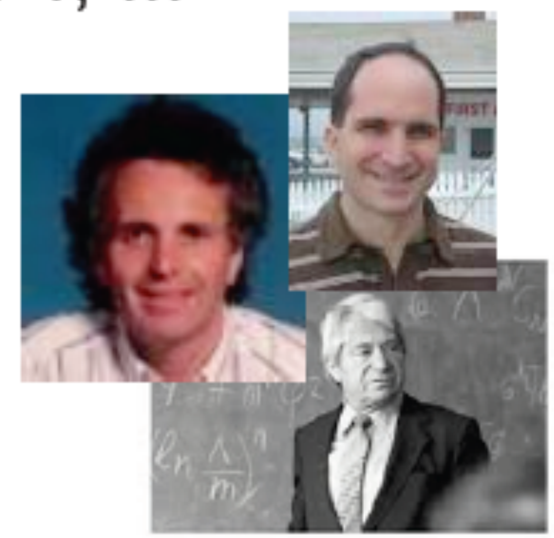
Based on M.R. Pennington, A.S Phys.Lett. B737 (2014) 283

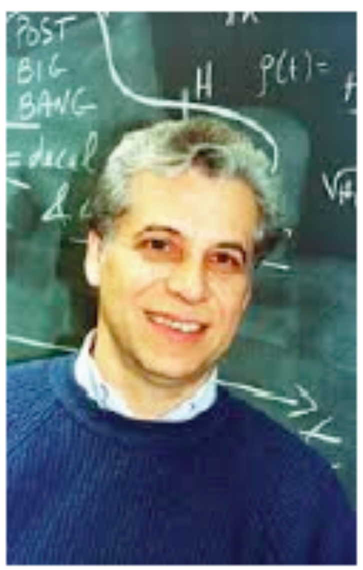
relativistic h.o.



string of relativistic oscillators

QCD, loop representation, large-N_c, AdS/CFT, ...





$\omega \to 3\pi$

$$A(s,t) = \frac{\Gamma(-J(s))\Gamma(-J(t))}{\Gamma(-J(s)-J(t))}$$

string revolution

Dynamical assumptions

• Duality: resonances in direct channel dual to reggeons in cross channels and backgrounds are dual to the pomeron

• All resonances are “connected”: resonances belong to Regge trajectories (reggeons)

• Asymptotics: determined by Regge poles

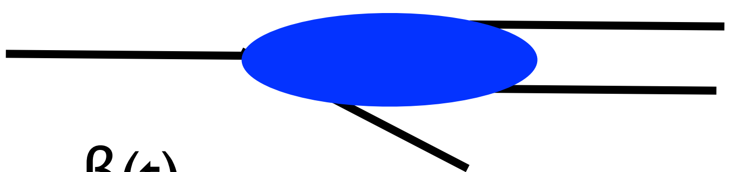
• Unitarity: imaginary parts determined by decay thresholds

Veneziano amplitude satisfies all of the above except unitarity.

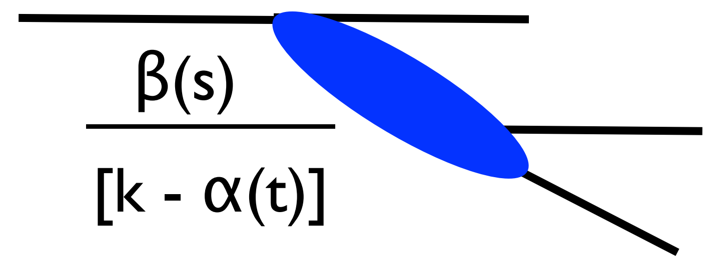
Veneziano amplitude: "compact" expression for the full amplitude

$$A(s,t) = \frac{\Gamma(-\alpha(s))\Gamma(-\alpha(t))}{\Gamma(-\alpha(s)-\alpha(t))} \qquad \alpha(s) = a + bs$$

resonance/reggeon in $s=m_{12}^2$



$\frac{\beta(t)}{[k - \alpha(s)]}$ ~ B.W. propagator



$\frac{\beta(s)}{[k - \alpha(t)]}$

resonance/reggeon in $t=m_{23}^2$

A(s,t) can be written as sum over resonances in ether channel.

$$A(s,t) = \sum_k \frac{\beta_k(t)}{k-\alpha(s)} = \sum_k \frac{\beta_k(s)}{k-\alpha(t)}$$

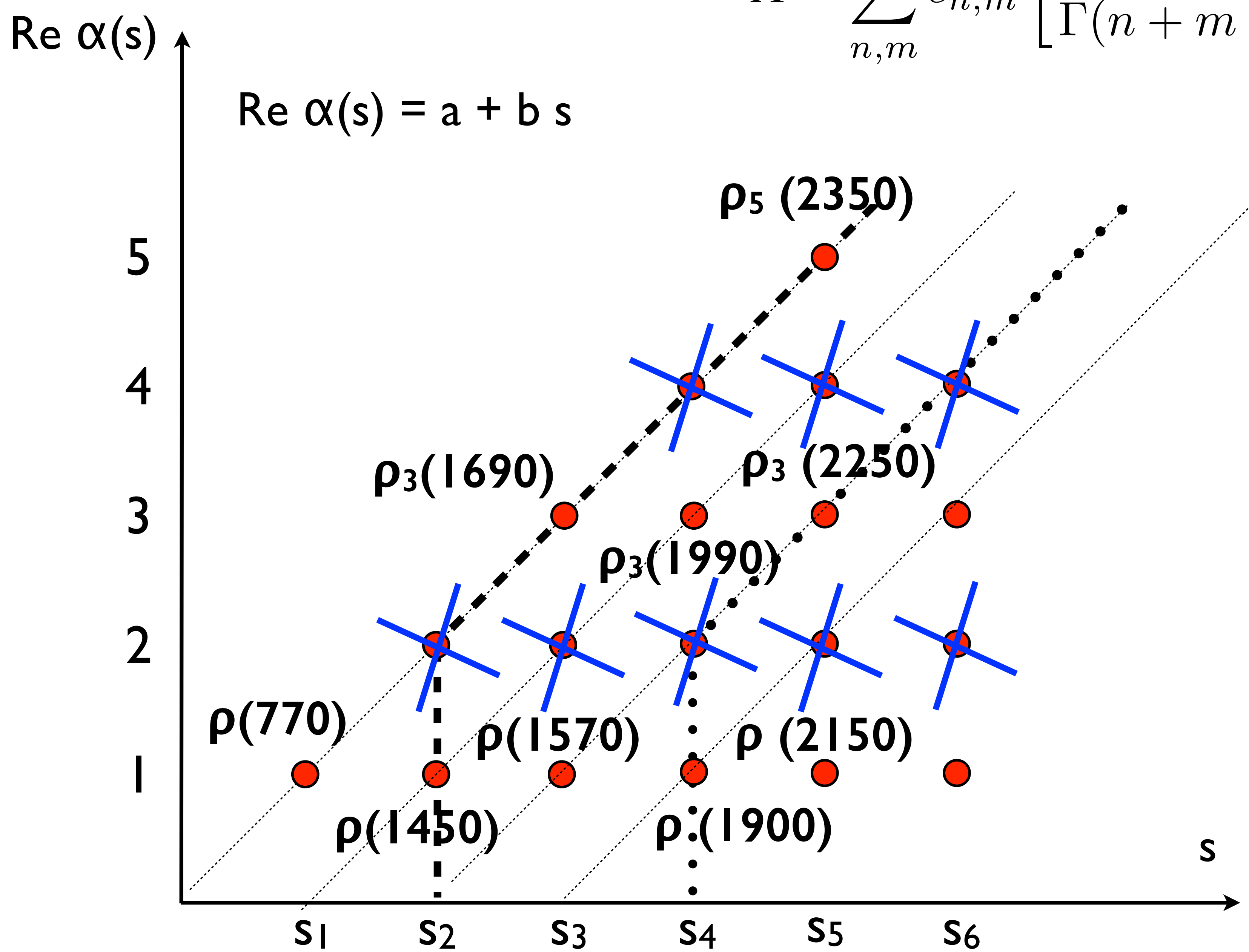
Note: in V-model resonance couplings, β, are fixed!

$$\beta_k(t) \propto (1+\alpha(t))(2+\alpha(t))\cdots(k+\alpha(t))$$

Resonances couplings, β, should depend on final state particles: a linear superposition of Veneziano amplitudes can be used to suppress or enhance individual resonances or trajectories

$$M = \epsilon_{\mu\nu\alpha\beta} p_1^\mu p_2^\nu p_3^\alpha \epsilon^\beta A(s,t,u)$$

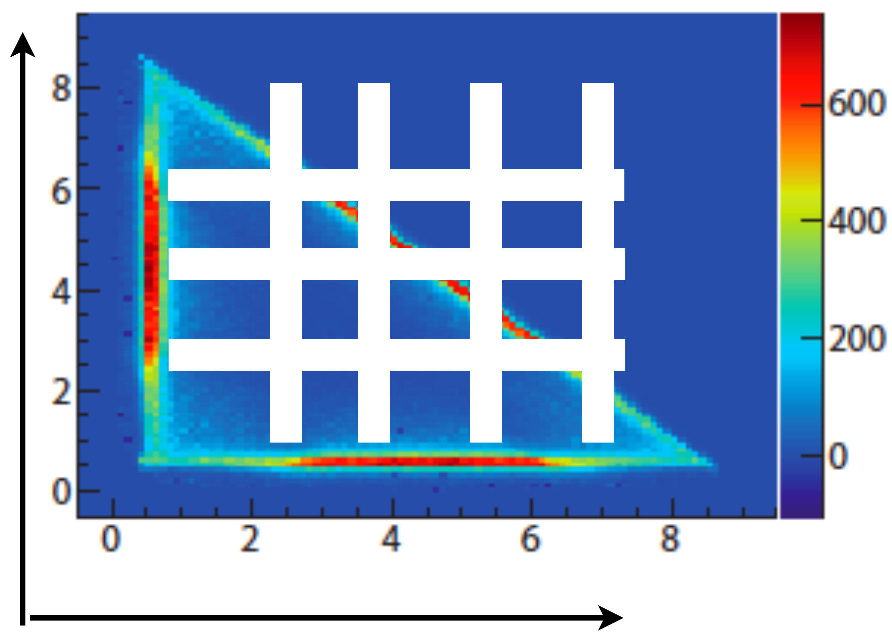
$$A = \sum_{n,m} c_{n,m} \left[\frac{\Gamma(n-\alpha(s))\Gamma(n-\alpha(t))}{\Gamma(n+m-\alpha(s)-\alpha(t))} + (s,u) + (t,u) \right]$$



- even-spin ρ's do not couple to π π and should decouple in J/ψ→3 π
- coupling of odd-spin ρ's depend of can depend vary depending on trajectory

$$A_{n,m}(s,t) \equiv \frac{\Gamma(n-\alpha_s)\Gamma(n-\alpha_t)}{\Gamma(n+m-\alpha_s-\alpha_t)}.$$

how to remove (infinite) number of poles?



$n \geq m \geq 1$

$$A_{1,1} = \frac{\Gamma(1-\alpha_s)\Gamma(1-\alpha_t)}{\Gamma(2-\alpha_s-\alpha_t)}$$

has poles at α_s=1,2,3,...

$$A_{2,1} = \frac{\Gamma(2-\alpha_s)\Gamma(2-\alpha_t)}{\Gamma(3-\alpha_s-\alpha_t)}$$

$$A_{2,2} = \frac{\Gamma(2-\alpha_s)\Gamma(2-\alpha_t)}{\Gamma(4-\alpha_s-\alpha_t)}$$

have poles at α_s=2,3,4,...

Use a linear combination of $A_{2,1}$ and $A_{2,2}$ to remove pole at α_s =2

$$A_{3,1}, A_{3,2}, A_{3,3}$$

have poles at α_s=3,4,5,...

Use a linear combination of $A_{3,1}$, $A_{3,2}$,$A_{3,3}$, to remove pole at α_s =3,

$$A_{4,1}, A_{4,2}, A_{4,3}, A_{4,4}$$

have poles at α_s=4,5,6,...

etc.

$$A_{n,m}(s,t) \to \mathcal{A}(s,t) = \sum_{n\geq 1, n\leq m\leq 1} c_{n,m} A_{n,m}(s,t)$$

remove all poles but the one at α=1

$$c_{n,1} = \frac{c_{1,1}}{\Gamma(n)},\ c_{n,2} = -\frac{c_{1,1}}{\Gamma(n-1)},\ c_{n,m} = 0 \text{ for } m > 2,$$

$$\mathcal{A}_1(s,t) = c_{1,1} \frac{2-\alpha_s-\alpha_t}{(1-\alpha_s)(1-\alpha_t)}.$$

... but the Regge limit is now lost !

remove all poles between N ≥ α ≥ 2

$$\begin{aligned} \mathcal{A}_1(s,t;N) &= c_{1,1} \frac{2-\alpha_s-\alpha_t}{(1-\alpha_s)(1-\alpha_t)} \\ &\times \frac{\Gamma(N+1-\alpha_s)\Gamma(N+1-\alpha_t)}{\Gamma(N)\Gamma(N+2-\alpha_s-\alpha_t)} \end{aligned}$$

has Regge limit is for s > N

In the past this was done by choosing an arbitrary set of n,m and fitting c(n,m) to the data (e.g. Lovelace, Phys. Lett. B28, 265 (1968),Altarelli, Rubinstein, Phys. Rev. 183, 1469 (1969))

We do in a systematic way. In addition it allows for imaginary non-linear (and complex) trajectories without introducing "ancestors"

$$\mathcal{A}_n(s,t;N) = \frac{2n-\alpha_s-\alpha_t}{(n-\alpha_s)(n-\alpha_t)} \sum_{i=1}^{n} a_{n,i}(-\alpha_s-\alpha_t)^{i-1} \times \frac{\Gamma(N+1-\alpha_s)\Gamma(N+1-\alpha_t)}{\Gamma(N+1-n)\Gamma(N+n+1-\alpha_s-\alpha_t)}.$$

n: number of Regge trajectories

$a_{n,i}$: determine resonance couplings

N: determines the onset of Regge behavior

$\alpha(s), \alpha(t) = \mathrm{Re}\,\alpha + i\,\mathrm{Im}\,\alpha$: with Im α related to resonance widths

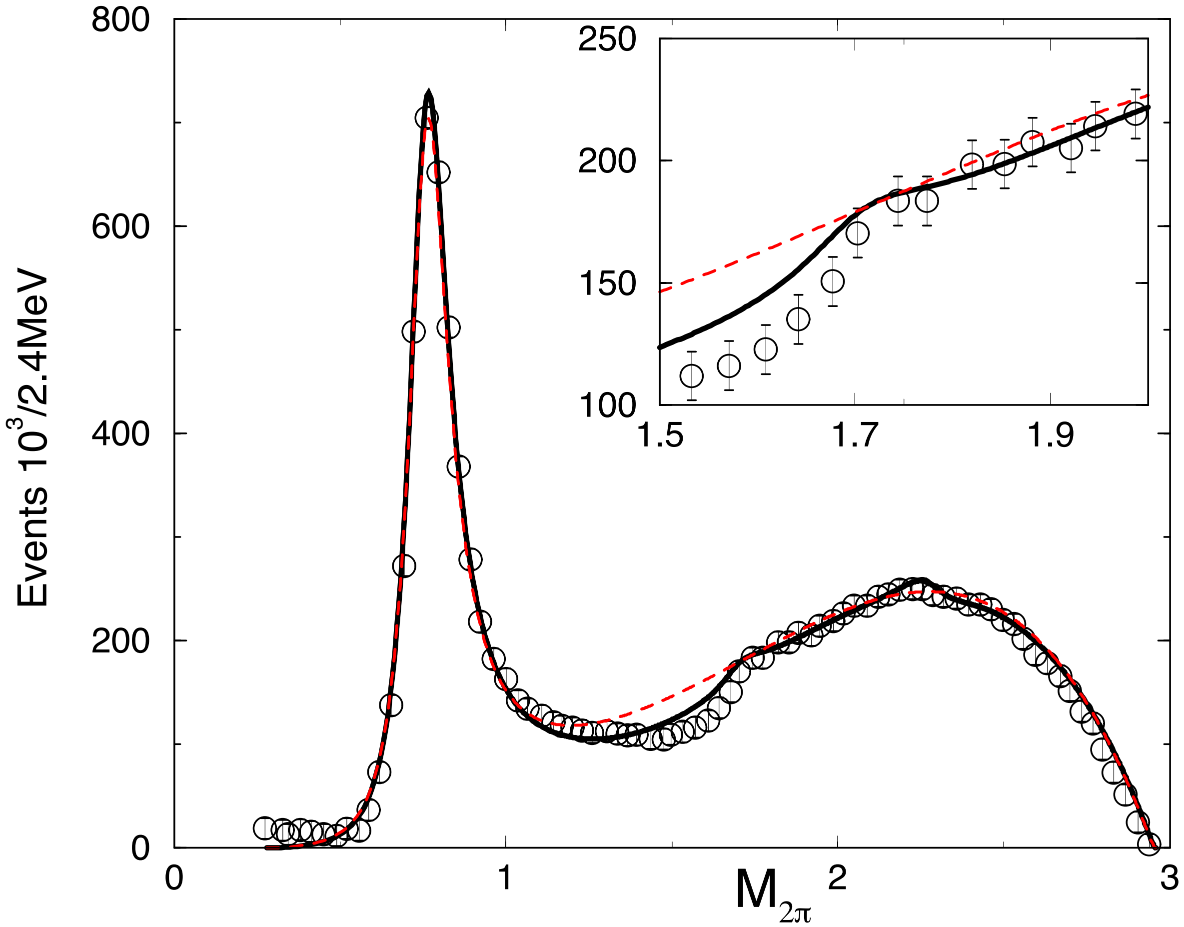


FIG. 2: Dalitz plot projection of the di-pion mass distribution from J/ψ decay. The solid is the result of the fit with three amplitudes and the dashed line with the amplitude $\mathcal{A}_1$ alone. The insert shows the mass region of the ρ_3 and its contribution from the fit with the full set of amplitudes (solid line) as compared. Absence of the structure at 1.7GeV from the fit with the $\mathcal{A}_1$ amplitude is indicated by the dashed line.

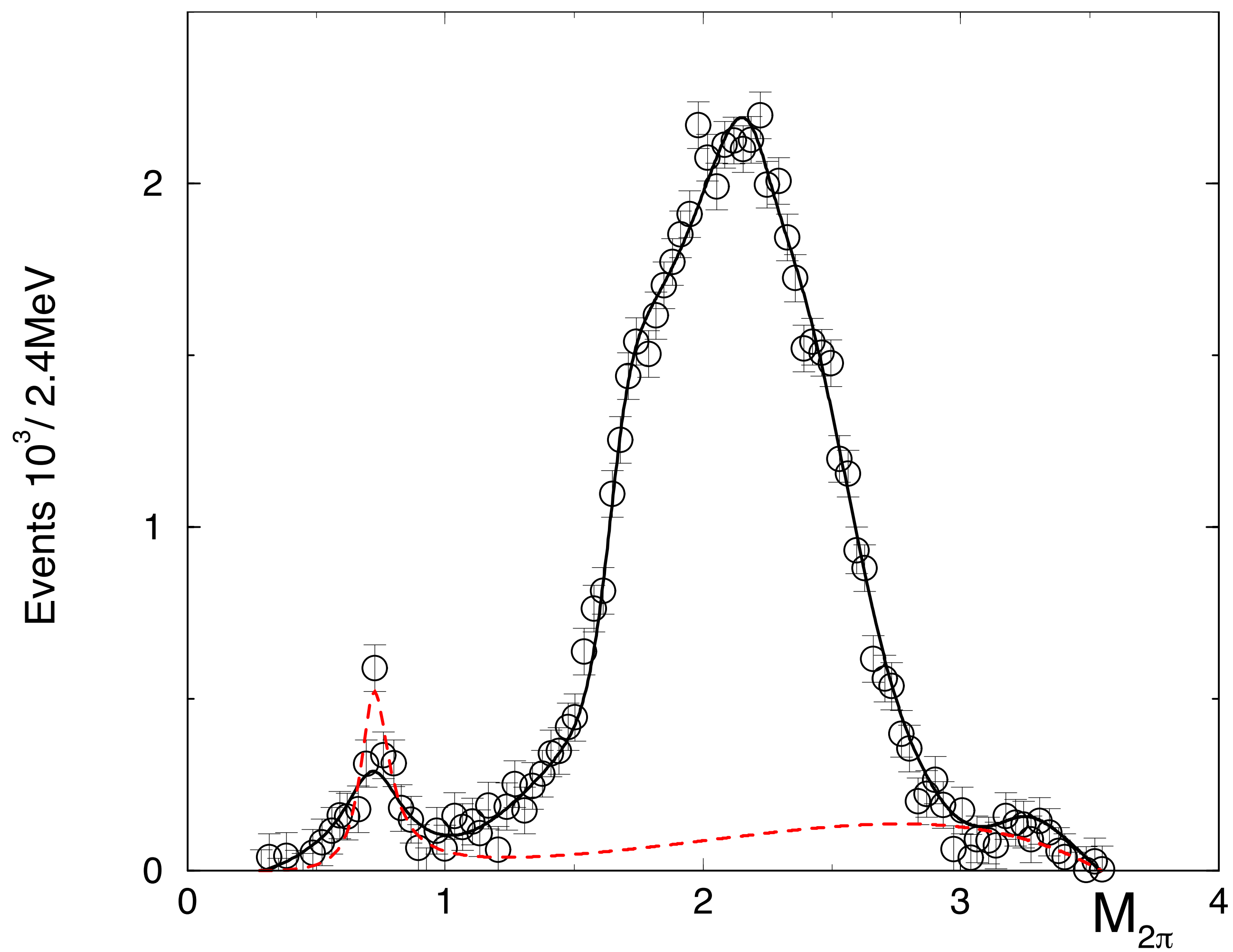


FIG. 3: Dalitz plot projection of the di-pion mass distribution from ψ' decay. The solid is the result of the fit with three amplitudes and the dashed line is the fit with $\mathcal{A}_1$ alone.

Ongoing analyses

$J/\psi \rightarrow 3\pi$ from BaBar (A.Palano) and BESIII (S.Fergan)

$\omega \rightarrow 3\pi$ from CLAS (g11, A.Celentano, g8, C.Zeoli)

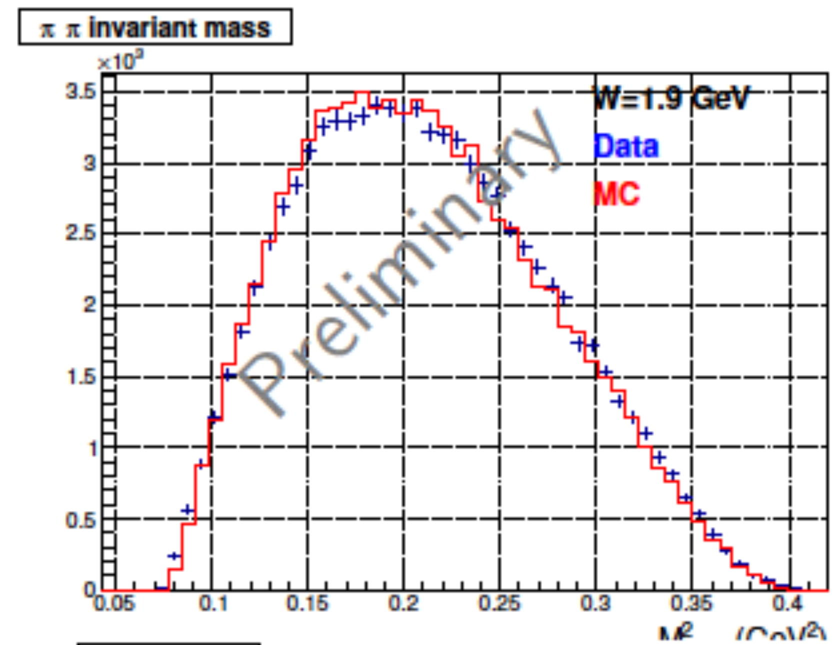
$\phi \rightarrow 3\pi$ from CLAS (GlueX, C.Salgado)

$f_1 \rightarrow 3\pi$ from CLAS (g11, A.Rizo)

First fit: $A = A_1$ only (ρ pole), using the "nominal" $\pi\,\pi$ Regge trajectory parametrization:

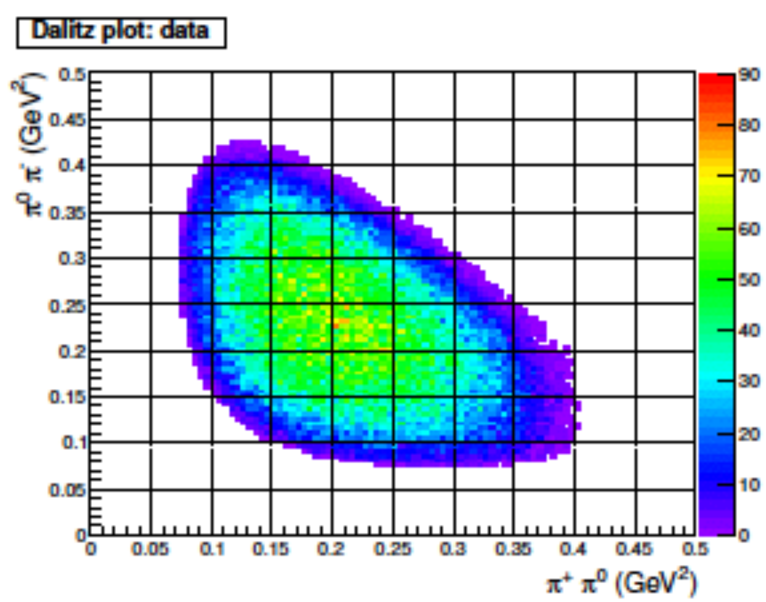
$$\alpha_s = 0.47 + 0.9s + 0.12\,i\,\sqrt{s - 4m_\pi^2} \;\;\rightarrow\;\; s_\rho = 0.58 - 0.095\,i\,(M = 0.76 \text{ GeV},\, \Gamma = 0.124 \text{ GeV})$$

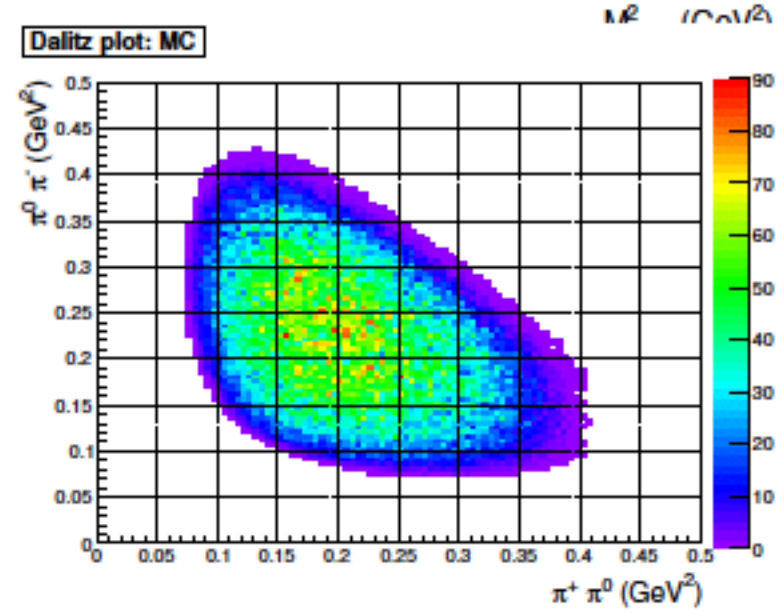
Fit parameters: a_1 (overall normalization)



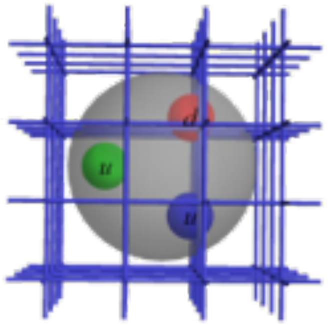
Results

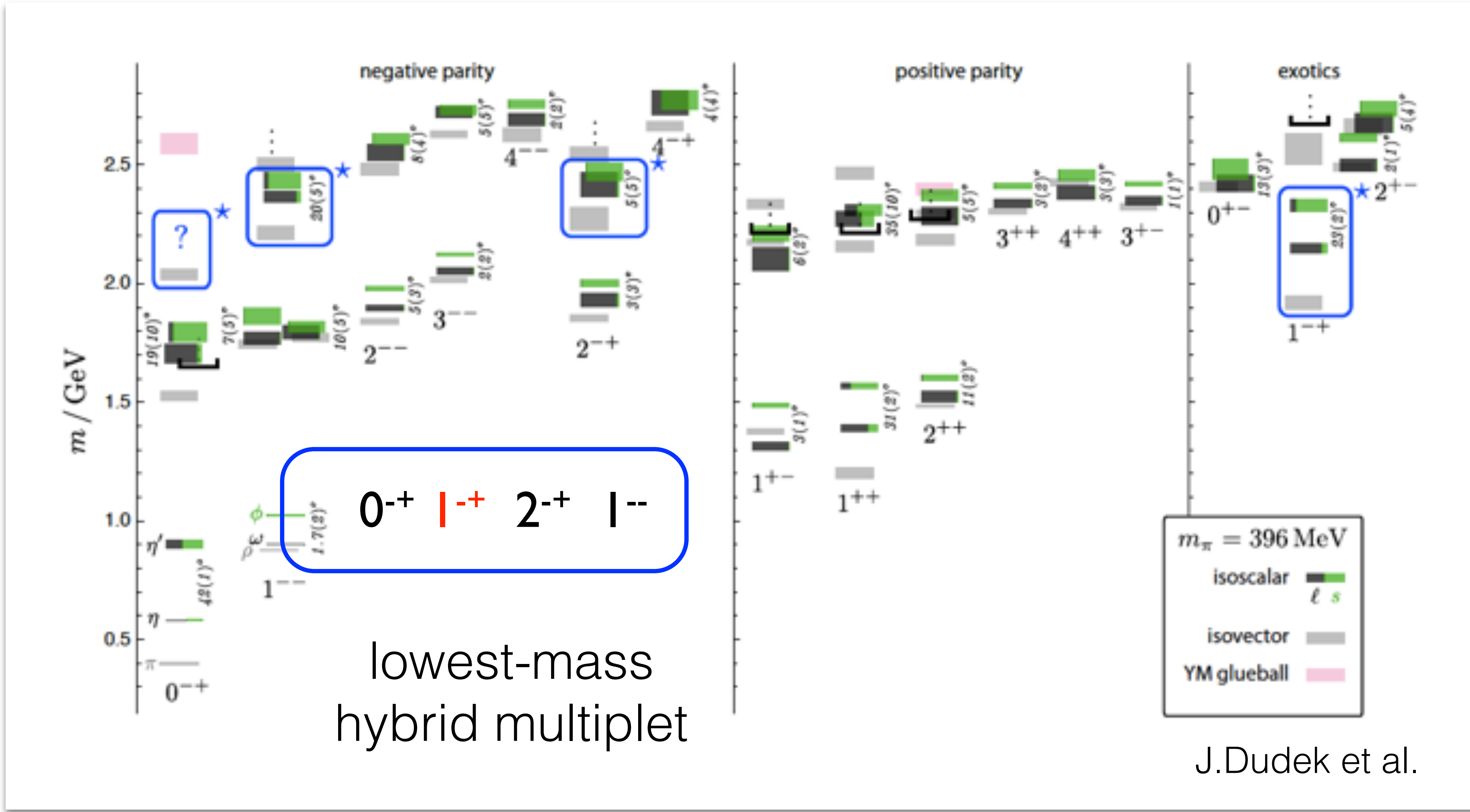
- Very good agreement data-weighted MC for production variables
- Veneziano model describes well the $\omega \rightarrow 3\pi$ decay
- Fit results are stable as a function of $\sqrt{s}$

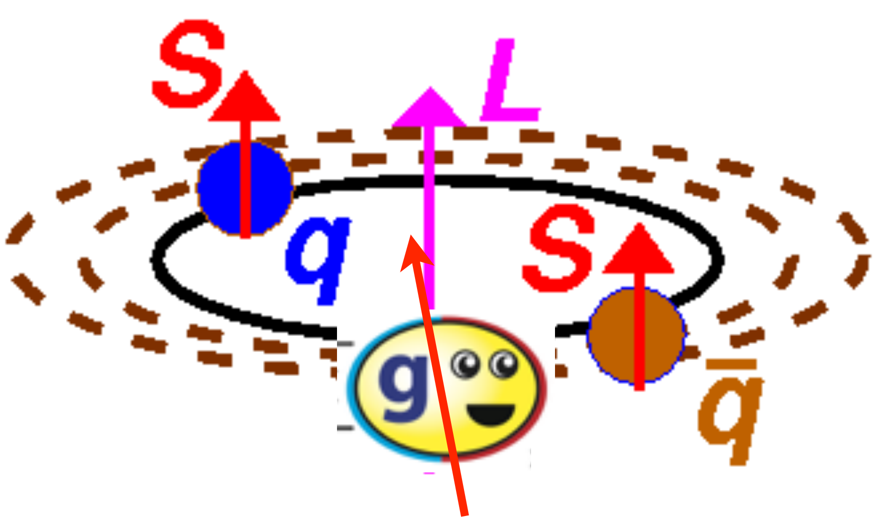




Hybrids







behave

J^{PC} glue

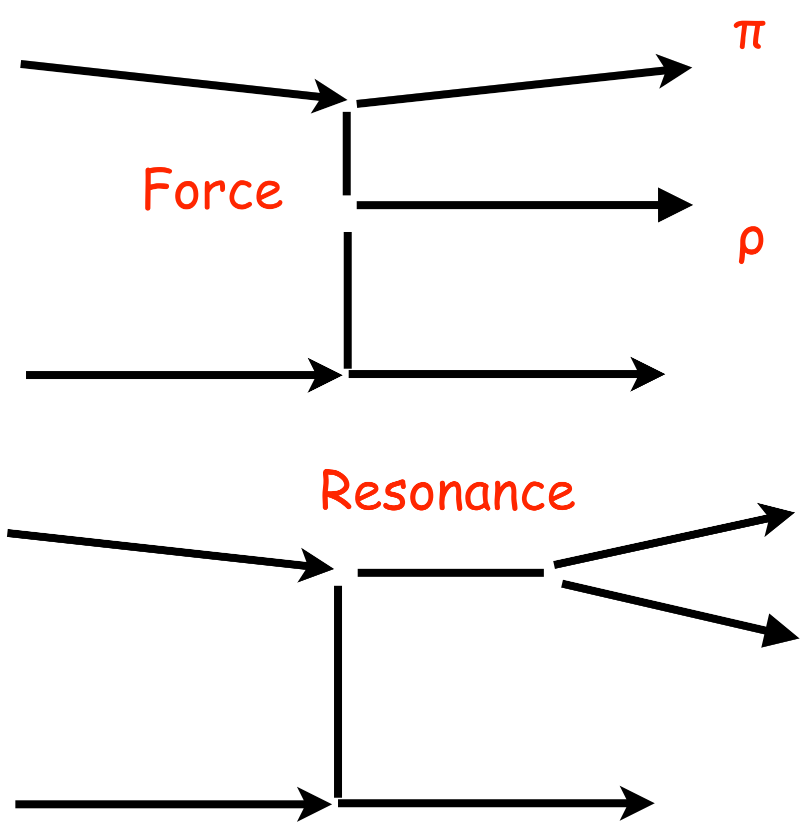
J^{PC} $Q\bar{Q}$

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

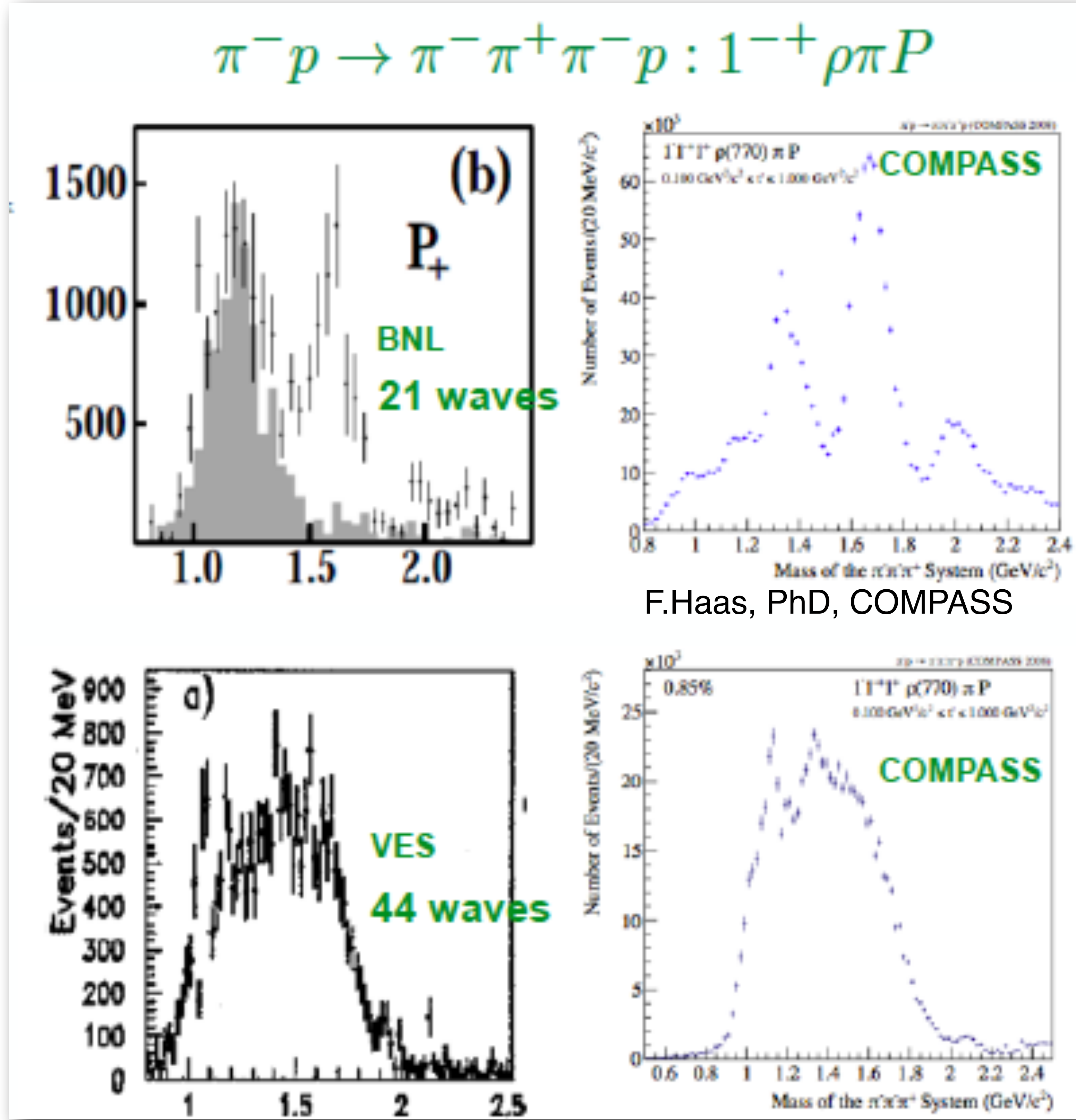
$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} = \boxed{0^{-+}, 1^{-+}, 2^{-+}}$$

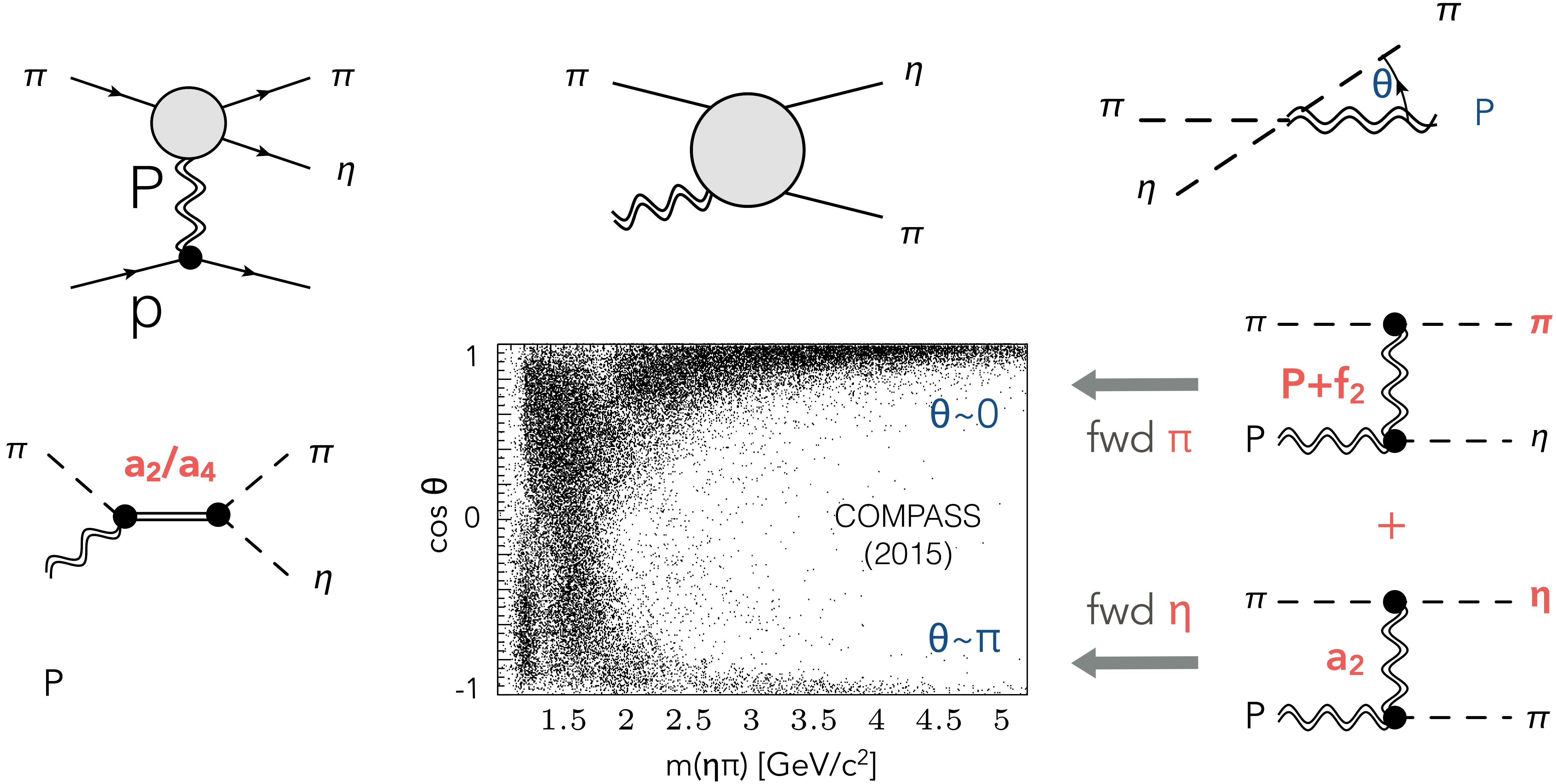
Gluons behave as 1^{+-} quasi-particle

Prediction of (Coulomb gauge) QCD



interpretation ambiguous without implementing force-resonance duality >> Finite Energy Sum Rules





Even Waves

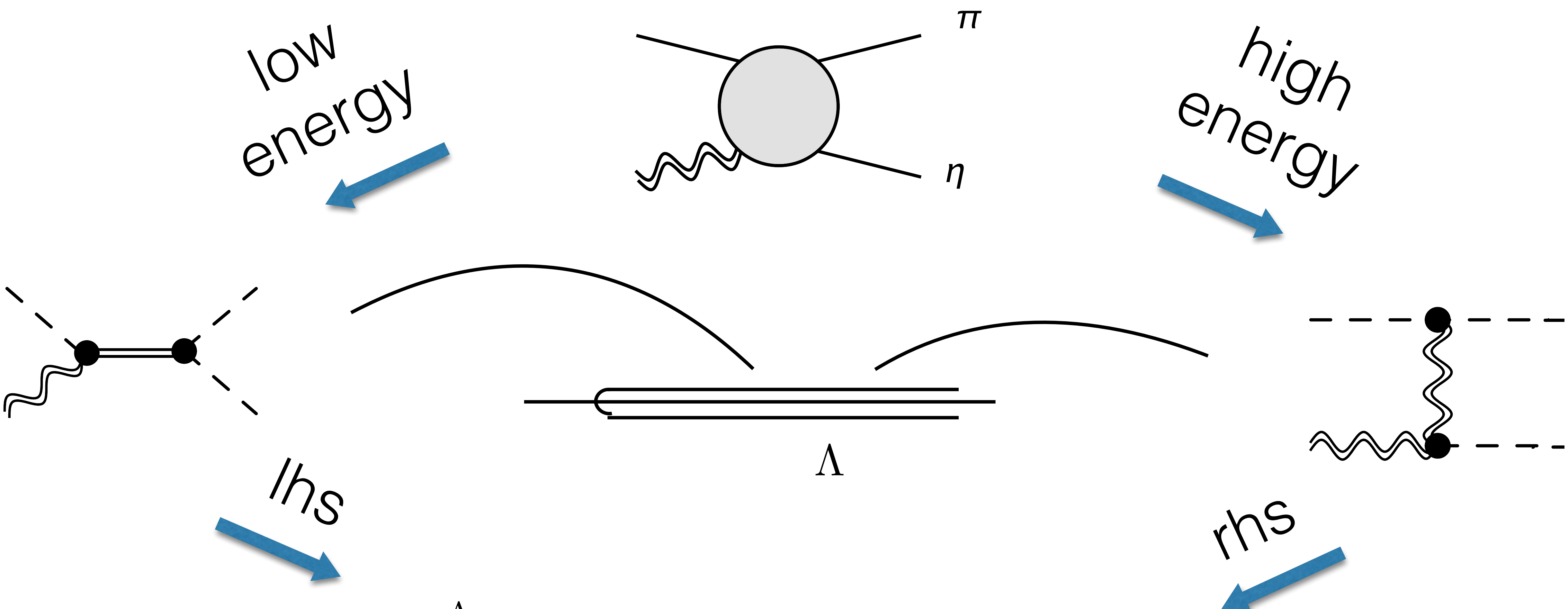
Odd (Exotic) Waves

Asymmetry due P-exchange

Vlad Pauk, JPAC

Finite energy sum rules

$$A(s_1, t_1, t_2, s_2/s) = \sum_i A_i(s_1, t_1, t_2) \left(\frac{s_2}{s}\right)^2$$



at fixed $t_{1,}t_2$ $$\int^{\Lambda} ImA_i(s_1, t_1, t_2) = \int_{\Lambda} ImA_i(s_1, t_1, t_2)$$

first time (ever) to be applied in analysis of 2-to-3 reactions!

Summary

- Precision in amplitude analysis is a key to a successful hadron spectroscopy program.
- This requires close collaboration between theory, phenomenology and experiment practitioners.
- Thanks to Mike's vision the foundations for such an effort are now in place through JPAC.