Hadron Reaction and Spectroscopy Studies at JPAC

Adam Szczepaniak
Indiana University
Jefferson Lab

Evidence of new hadrons

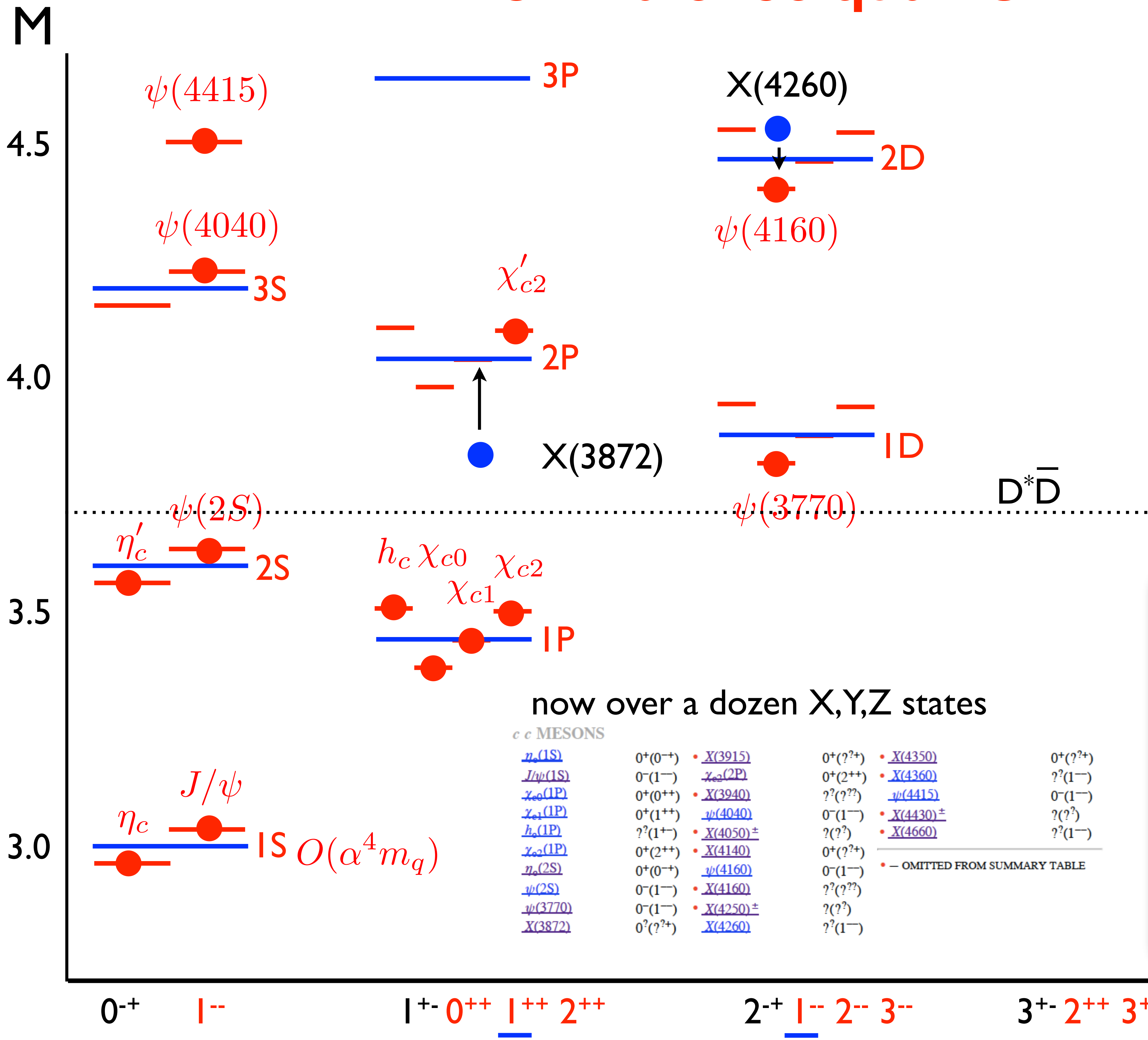
Role of reaction theory

The XYZ's and exotics

Joint Physics Analysis Center

supported by US DOE, US NSF

Long time ago hadrons were made from valence quarks

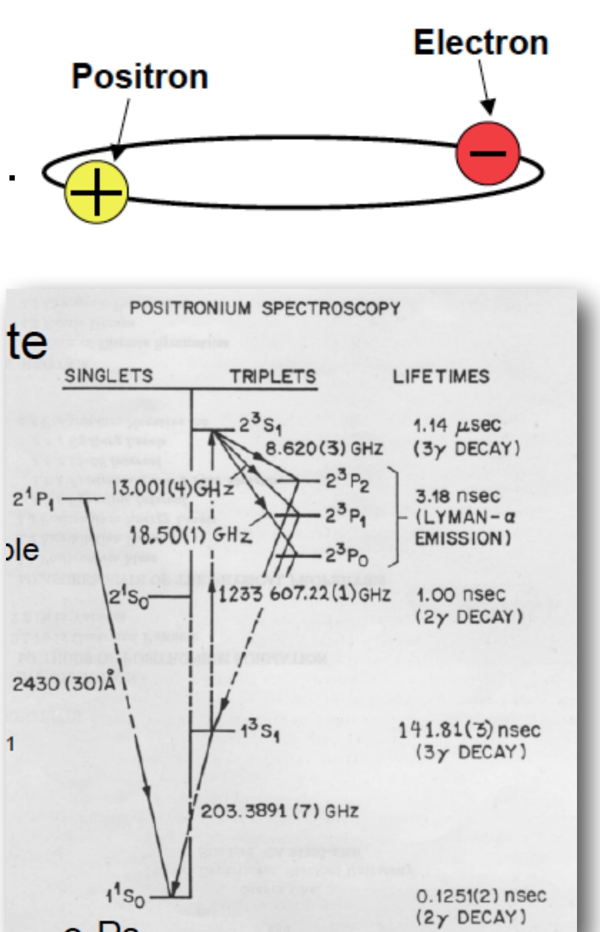


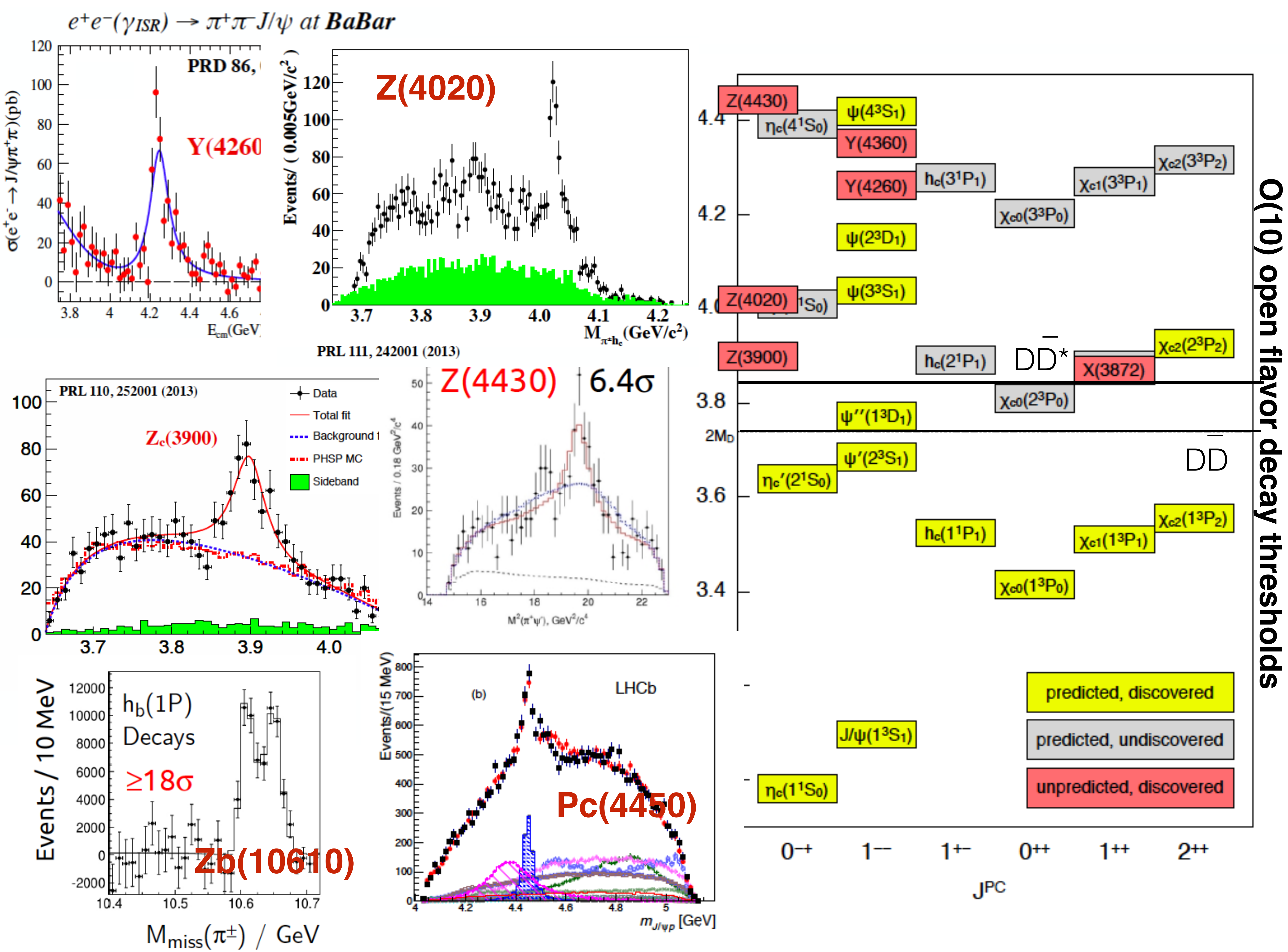
now over a dozen X,Y,Z states

c c MESONS

$\eta_c(1S)$	$0^+(0^{-+})$	• $X(3915)$	$0^+(?^{?+})$	• $X(4350)$	$0^+(?^{?+})$
$J/\psi(1S)$	$0^-(1^{--})$	$\chi_{c2}(2P)$	$0^+(2^{++})$	• $X(4360)$	$?^?(1^{--})$
$\chi_{c0}(1P)$	$0^+(0^{++})$	• $X(3940)$	$?^?(?^{??})$	$\psi(4415)$	$0^-(1^{--})$
$\chi_{c1}(1P)$	$0^+(1^{++})$	$\psi(4040)$	$0^-(1^{--})$	• $X(4430)^\pm$	$?(?^?)$
$h_c(1P)$	$?^?(1^{+-})$	• $X(4050)^\pm$	$?(?^?)$	• $X(4660)$	$?^?(1^{--})$
$\chi_{c2}(1P)$	$0^+(2^{++})$	• $X(4140)$	$0^+(?^{?+})$		
$\eta_c(2S)$	$0^+(0^{-+})$	$\psi(4160)$	$0^-(1^{--})$		
$\psi(2S)$	$0^-(1^{--})$	• $X(4160)$	$?^?(?^{??})$		
$\psi(3770)$	$0^-(1^{--})$	• $X(4250)^\pm$	$?(?^?)$		
$X(3872)$	$0^?(?^{?+})$	$X(4260)$	$?^?(1^{--})$		

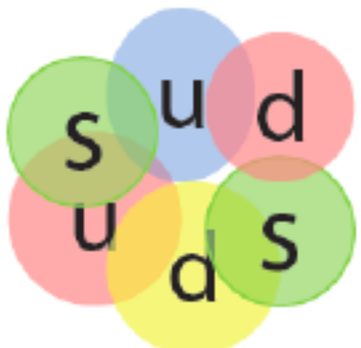
• — OMITTED FROM SUMMARY TABLE





e+e−(γISR) → π+π−J/ψ at BaBar
PRD 86,
Y(4260
σ(e+e− → J/ψπ+π−)(pb)
Ecm(GeV
Z(4020)
Events/ (0.005GeV/c2)
Mπ±hc(GeV/c2)
PRL 111, 242001 (2013)
PRL 110, 252001 (2013)
Zc(3900)
Data
Total fit
Background f
PHSP MC
Sideband
Z(4430)
6.4σ
Events / 0.18 GeV2/c4
M2(π+ψ′), GeV2/c4
hb(1P)
Decays
≥18σ
Zb(10610)
Events / 10 MeV
Mmiss(π±) / GeV
(b)
LHCb
Pc(4450)
Events/(15 MeV)
mJ/ψp [GeV]
Z(4430)
ηc(41S0)
ψ(43S1)
Y(4360)
Y(4260)
hc(31P1)
χc0(33P0)
χc1(33P1)
χc2(33P2)
ψ(23D1)
Z(4020)
ψ(33S1)
Z(3900)
hc(21P1)
DD̄*
X(3872)
χc2(23P2)
χc0(23P0)
ψ′′(13D1)
2MD
DD̄
ψ′(23S1)
ηc′(21S0)
hc(11P1)
χc1(13P1)
χc2(13P2)
χc0(13P0)
J/ψ(13S1)
ηc(11S0)
predicted, discovered
predicted, undiscovered
unpredicted, discovered
0−+
1−−
1+−
0++
1++
2++
JPC
O(10) open flavor decay thresholds

before we can address the following question…

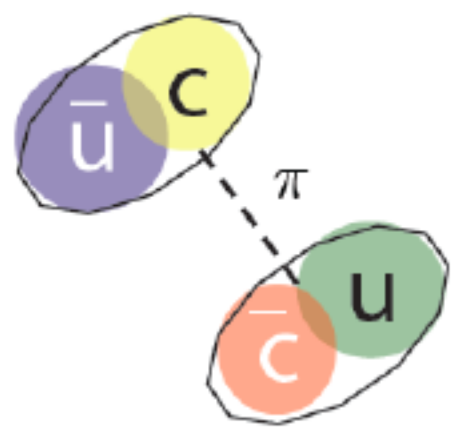


dibaryon

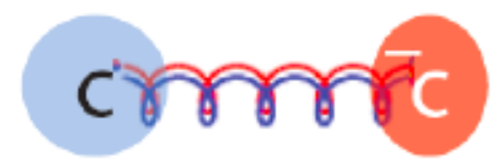
pentaquark

glueball

diquark + di-antiquark

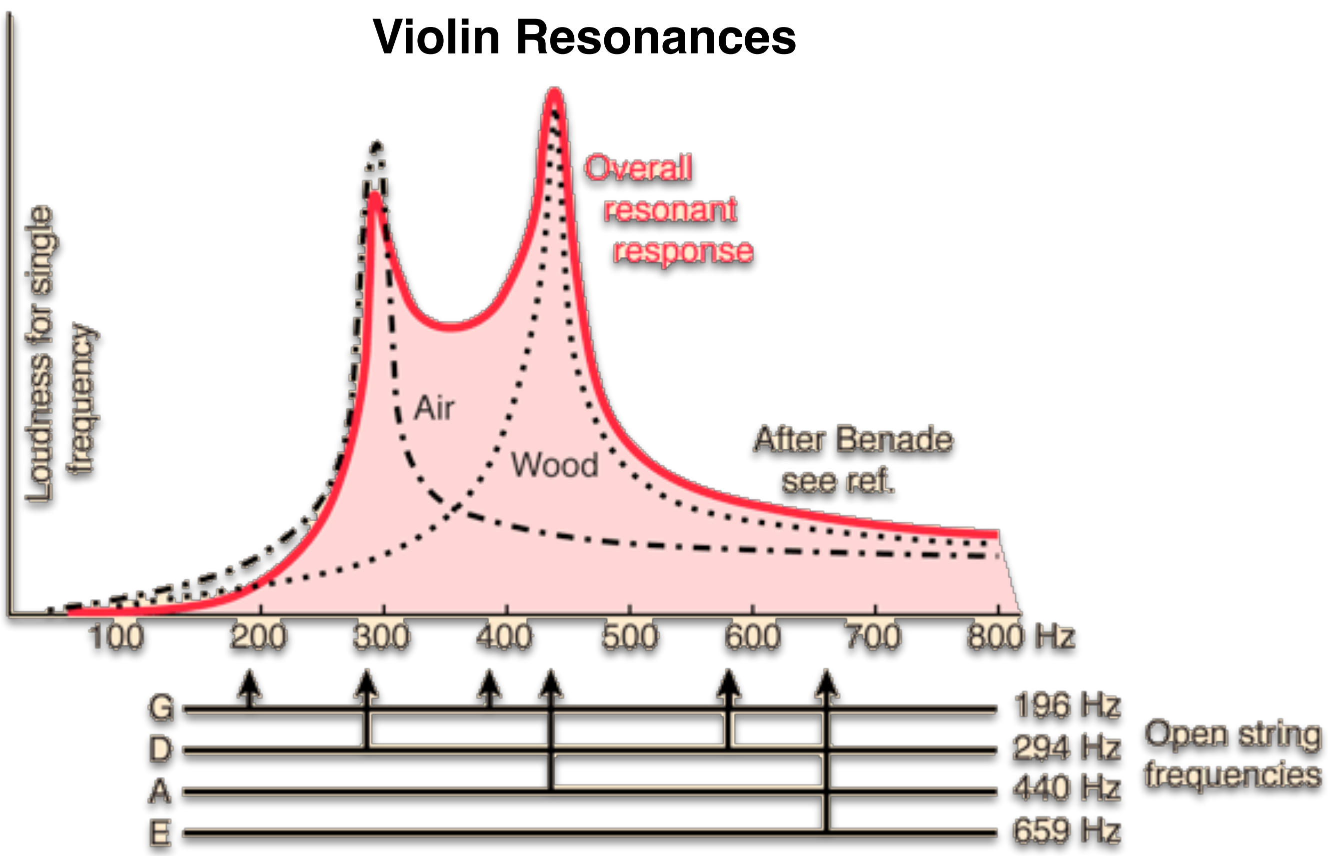


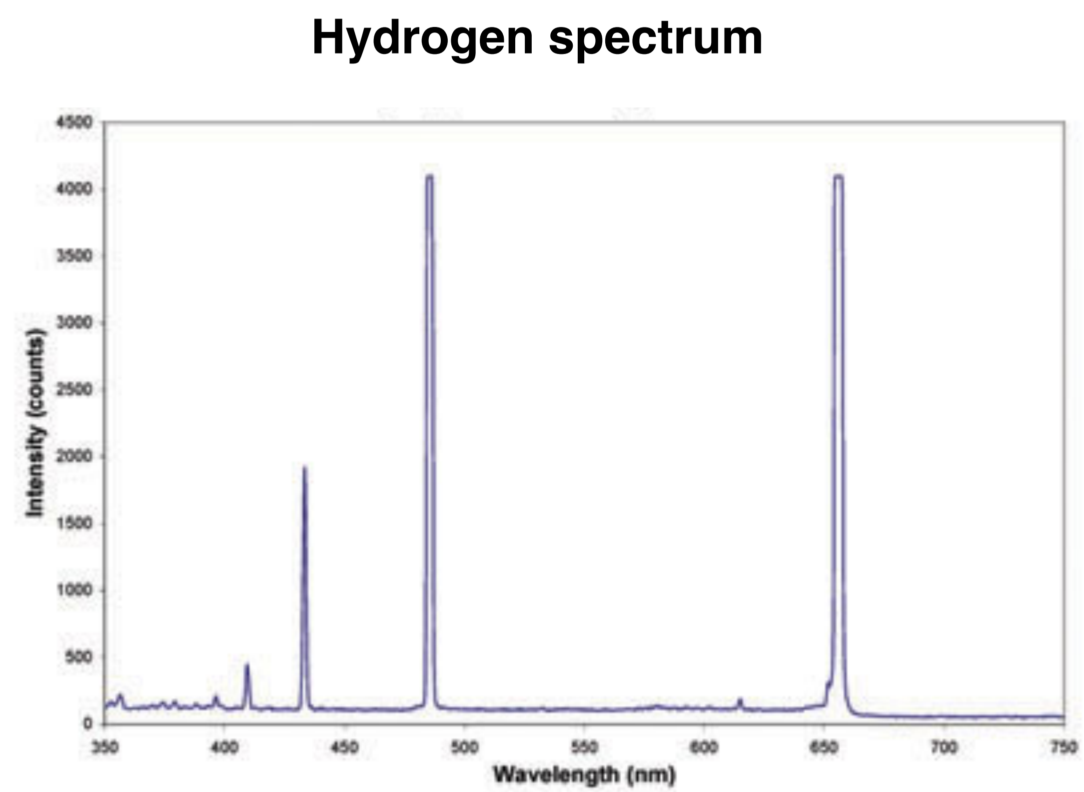
dimeson molecule

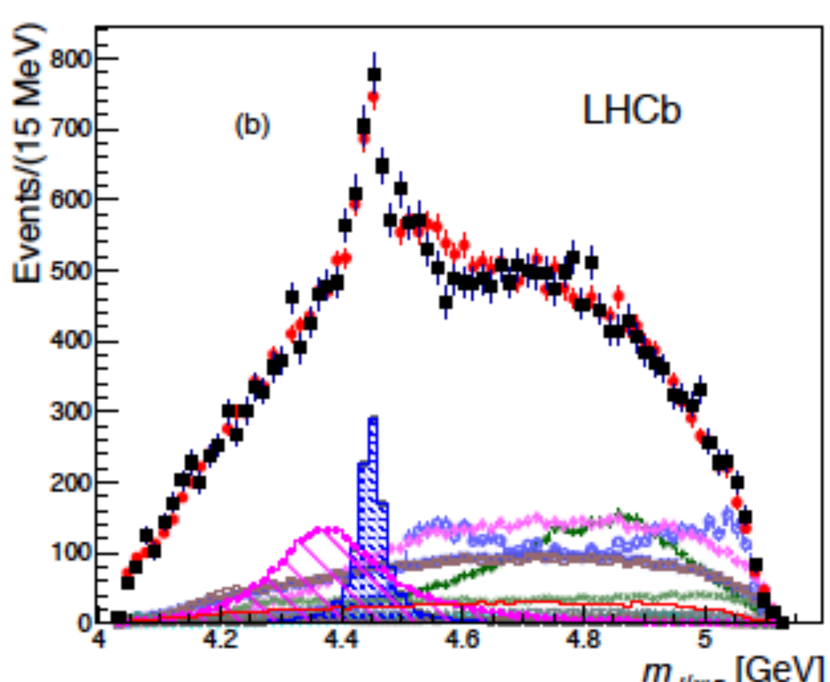


$q\,\bar{q}\,g$ hybrid

…we need to know how to interpret "peaks"

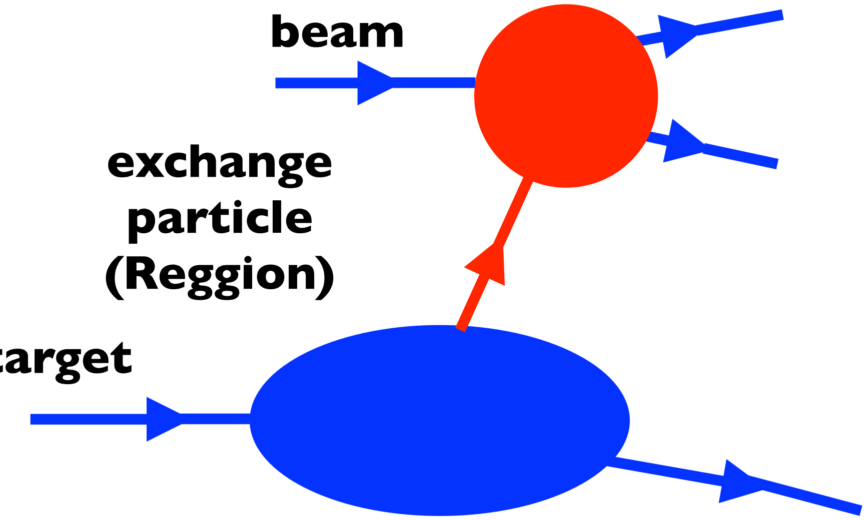




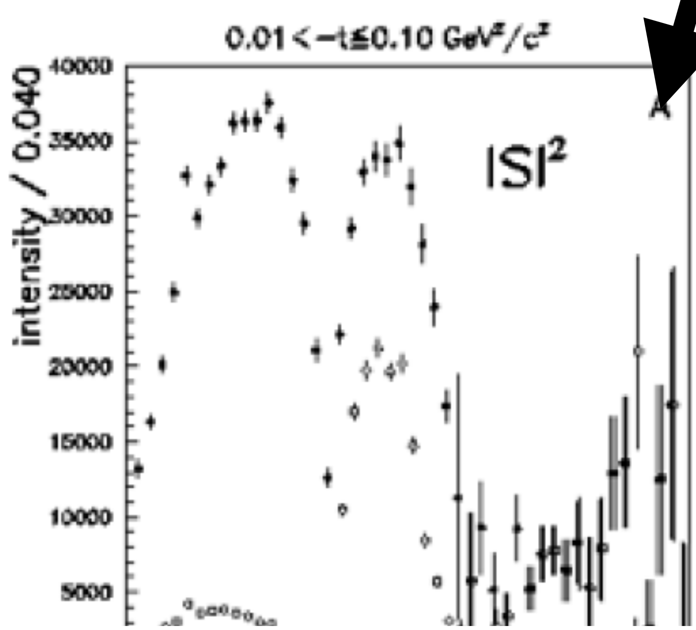


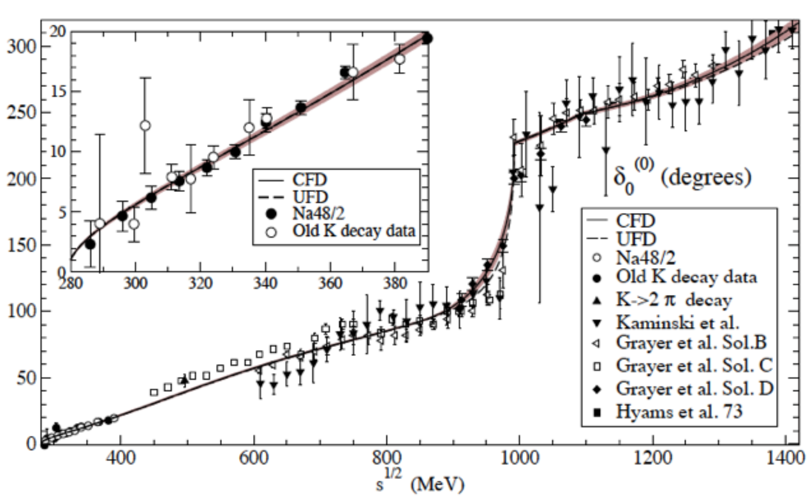
… but state of the art analyst is based on analogy with a "very simple world"

the sigma meson story

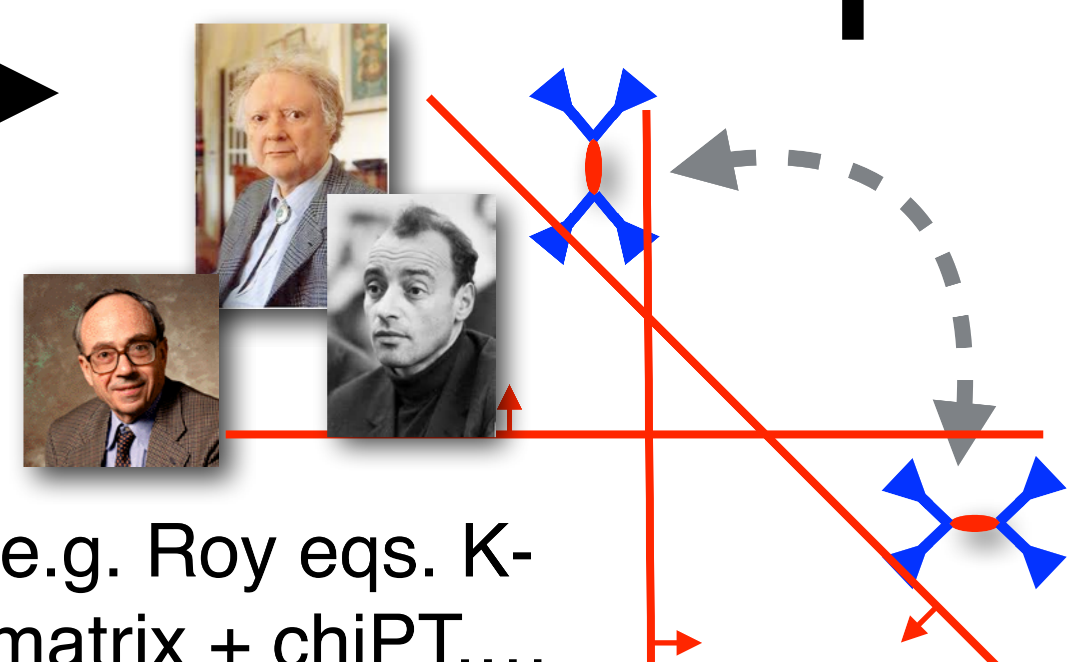


partial wave extraction





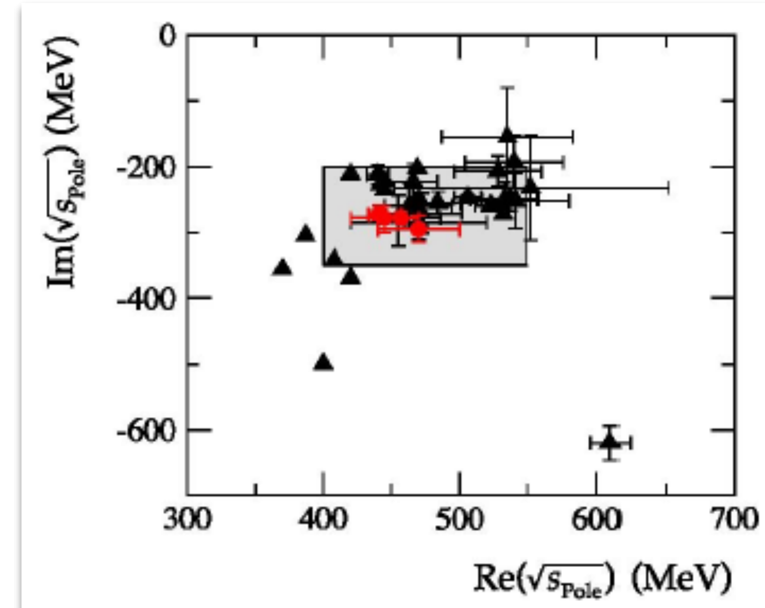
amplitude model



e.g. Roy eqs. K-matrix + chiPT,…

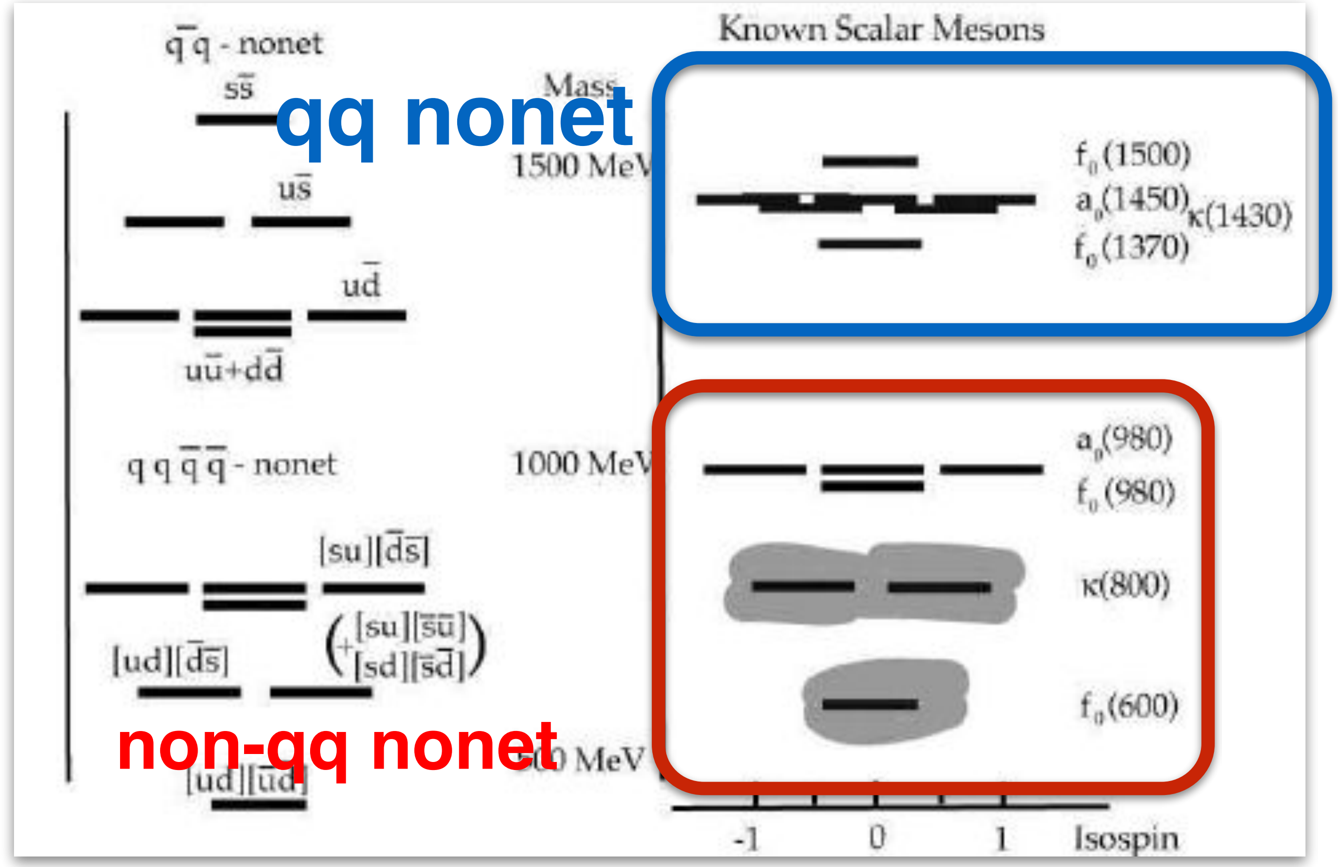
analytical continuation

$$\sqrt{s^{\sigma}_{\rm Pole}} = (446 \pm 6) - i(276 \pm 5)\ \text{MeV}\ .$$



Exploring the σ pole

Possible evidence for non-qq nature of light scalars



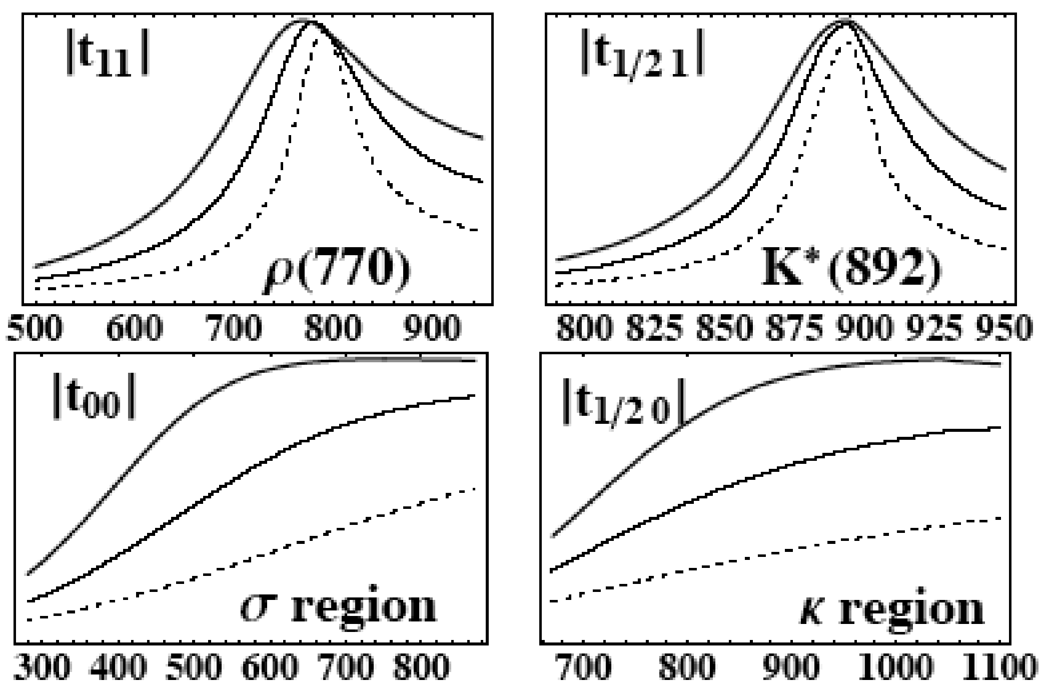
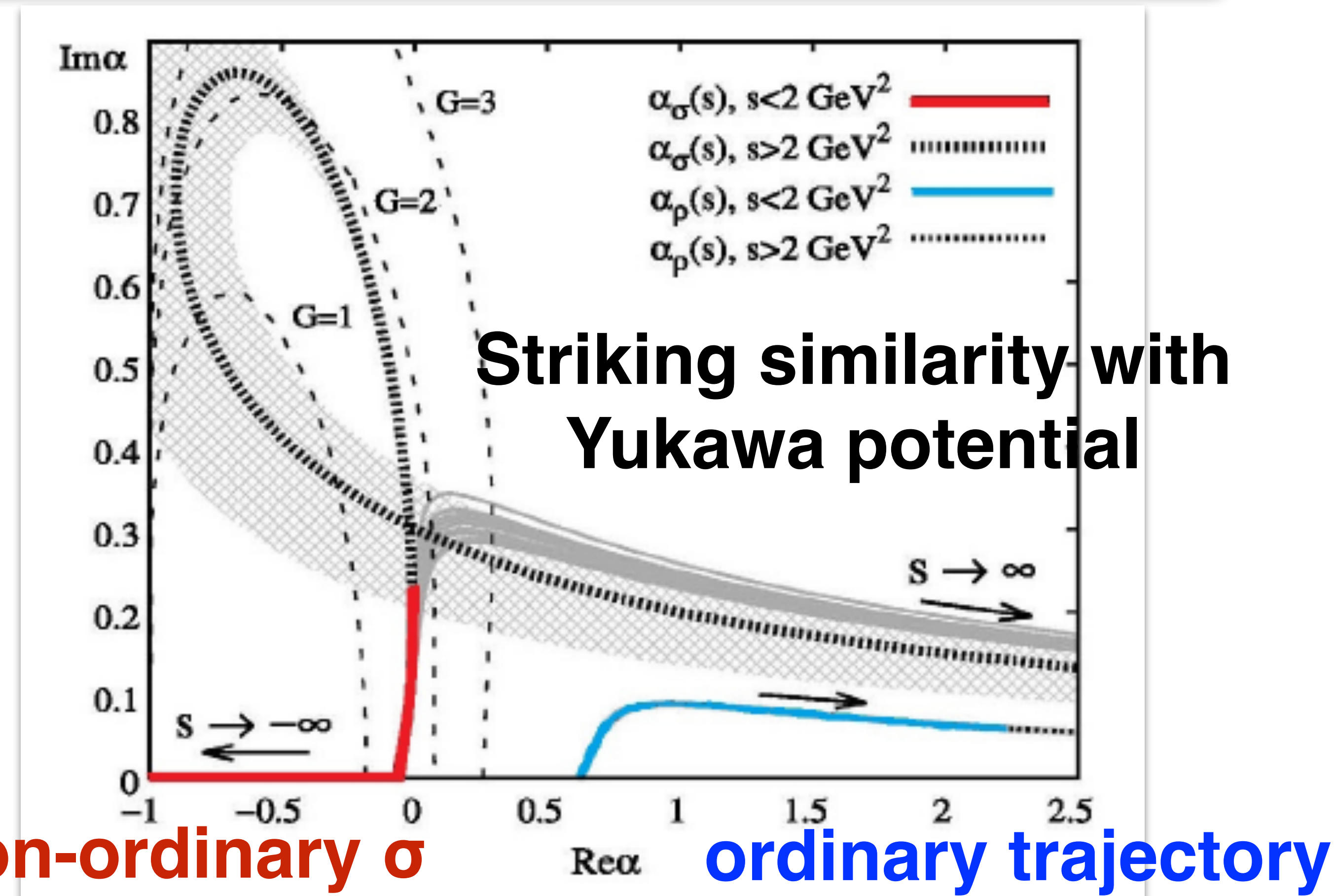


FIG. 1: Modulus of amplitudes in different meson-meson channels for $N_c = 3$ (thick line) $N_c = 5$ (thin continuous line) and $N_c = 10$ (thin dotted line), scaled at $\mu = 770$ MeV.

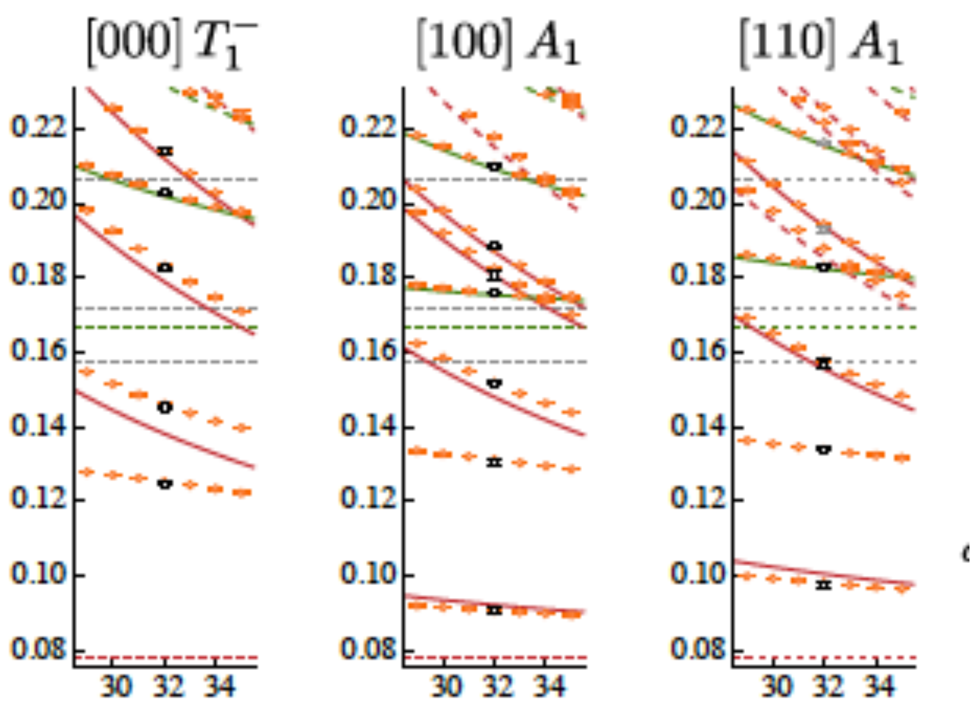
Pelaez

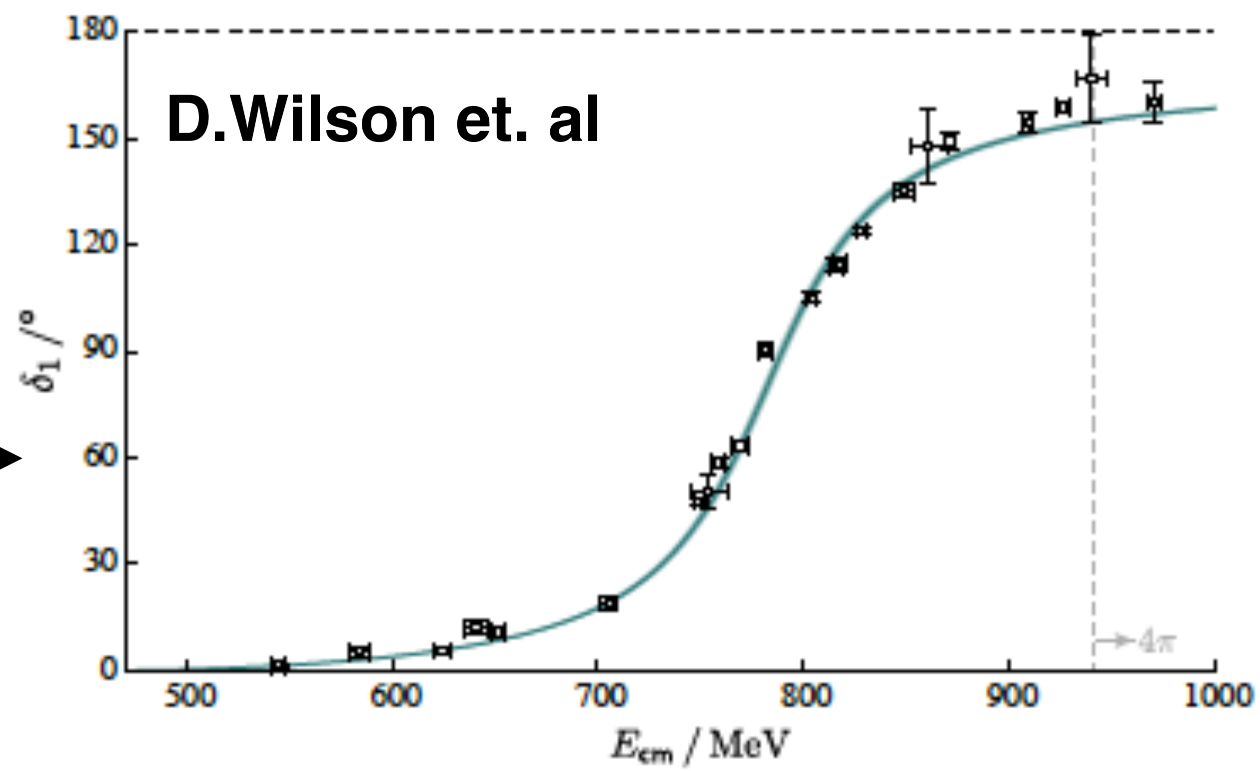


QCD on the Lattice : simulated scattering experiment

(known kinematical function) $Z(E_i) = T(E_i)$ (infinite volume amplitude)

E_i = discrete energy spectrum of states in the lattice

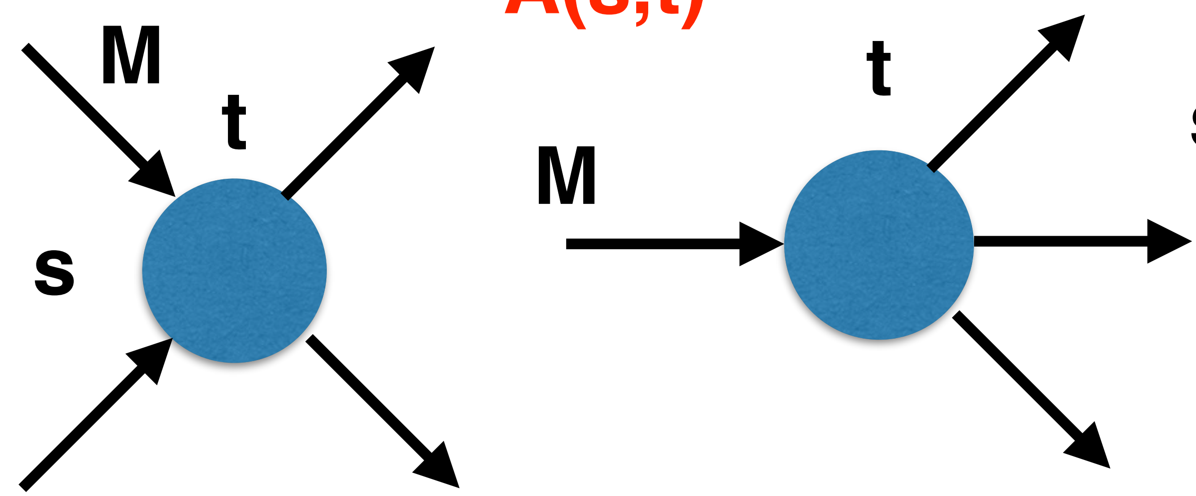




in general "solution" of the Lusher condition requires an analytical model for T

S-matrix principles: Crossing, Analyticity, Unitarity

A(s,t)



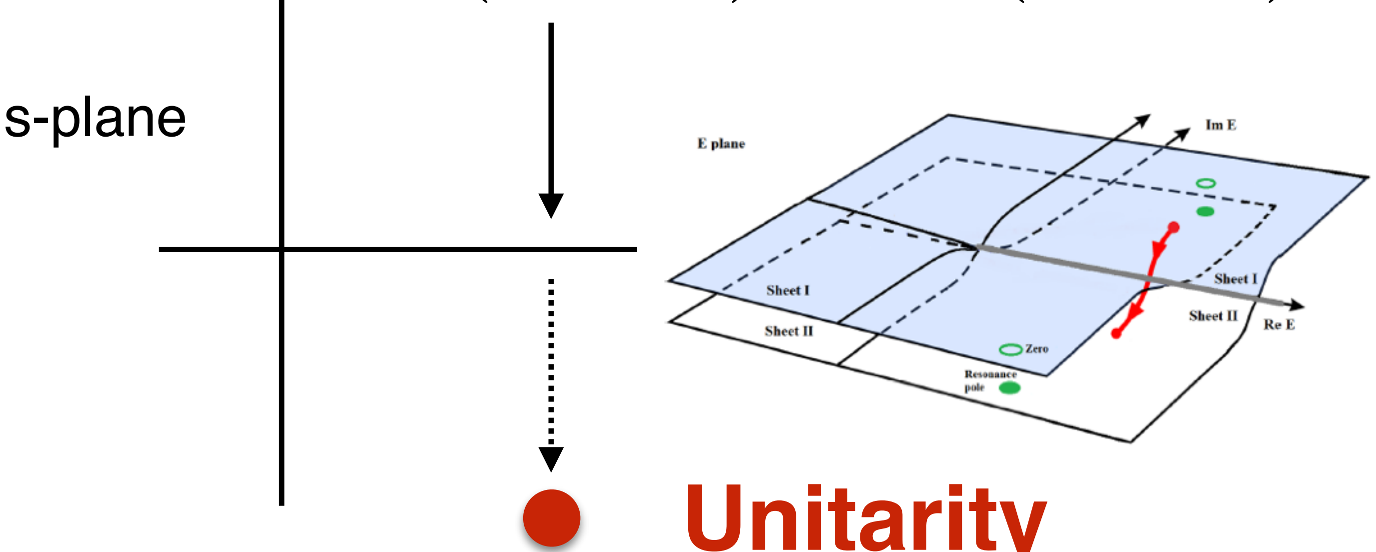
Crossing

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

Analyticity

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

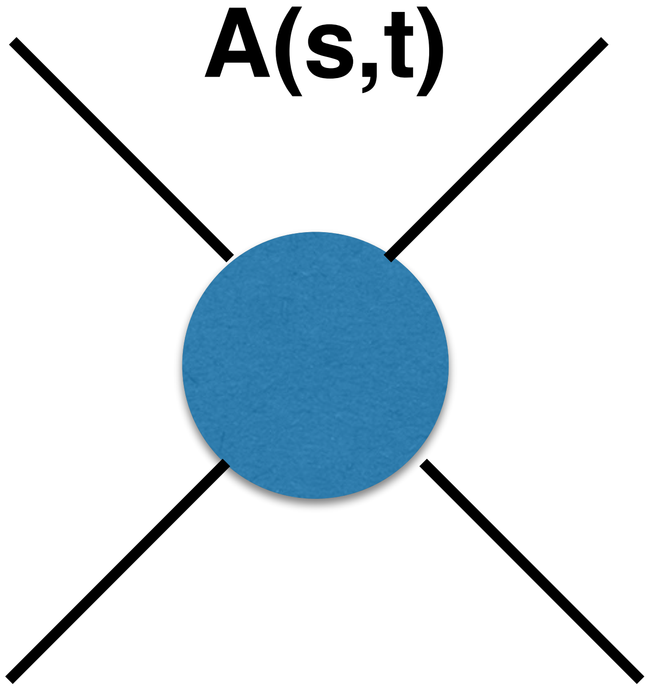
$$A_l(s + i\epsilon) \neq A_l(s - i\epsilon)$$



Unitarity

bumps/peaks on the real axis (experiment) come from singularities in the complex domain.

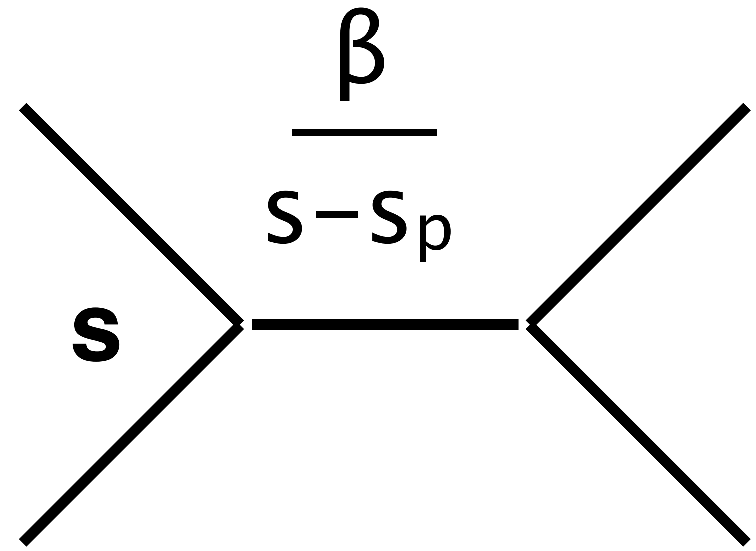
Origin of singularities (exchanges constrained by unitarity)

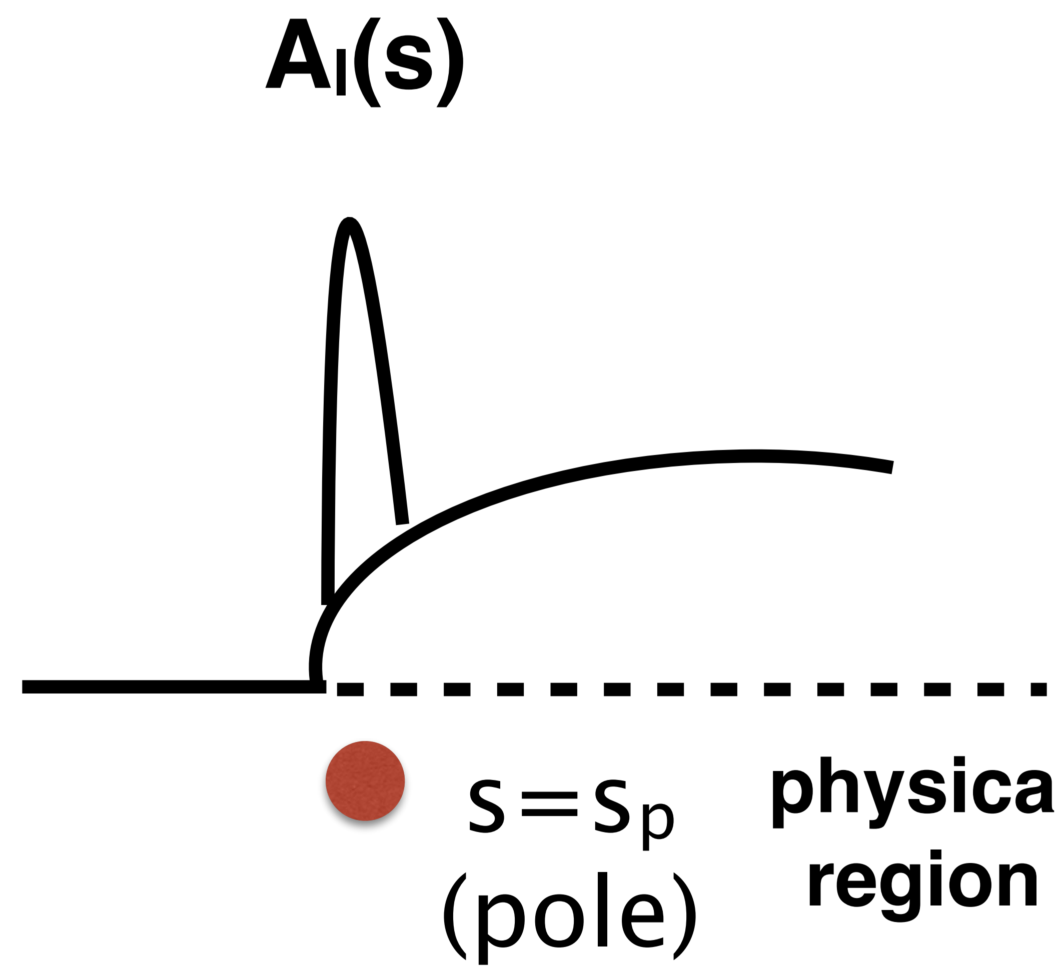


t

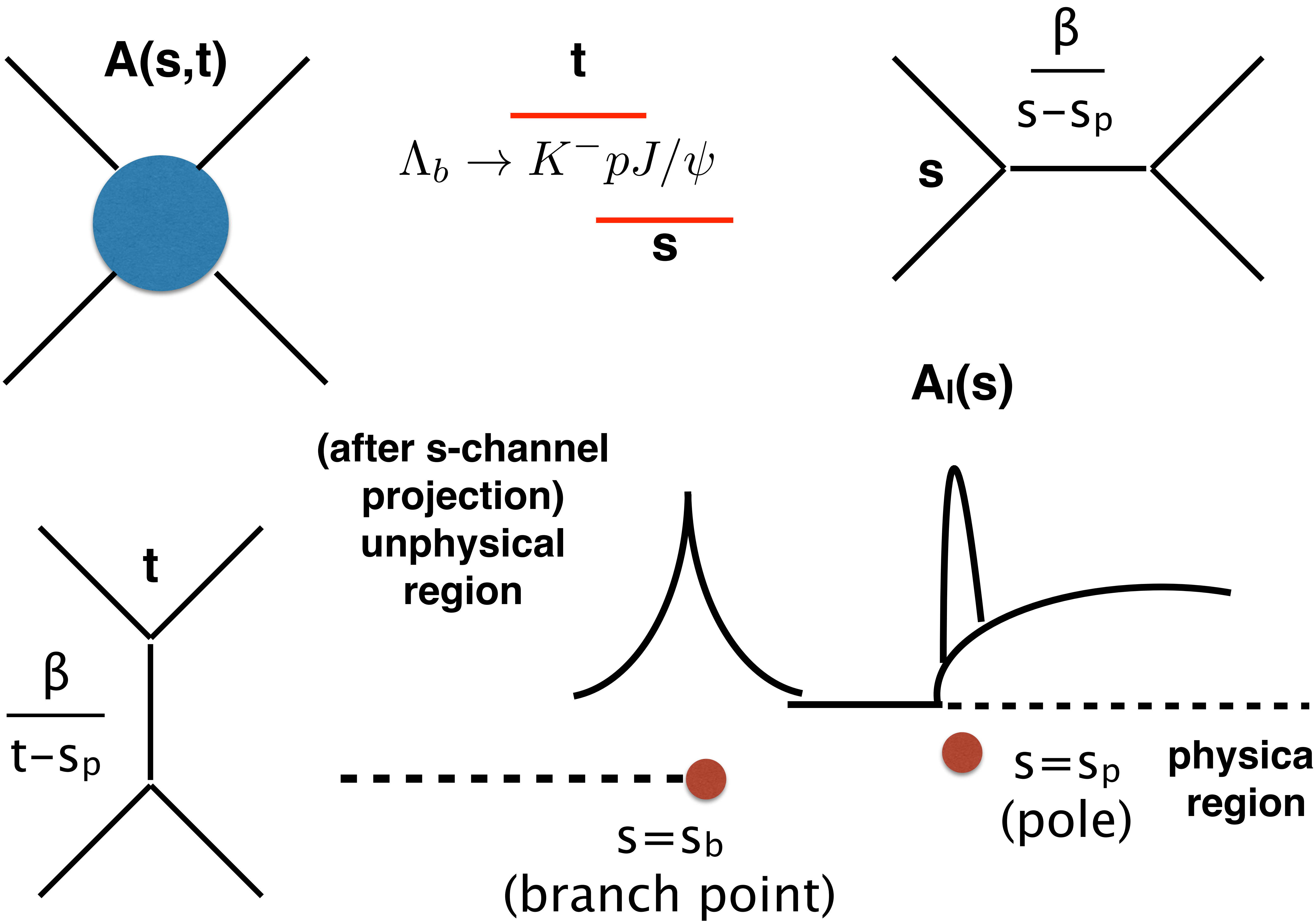
$$\Lambda_b \to K^- p J/\psi$$

s

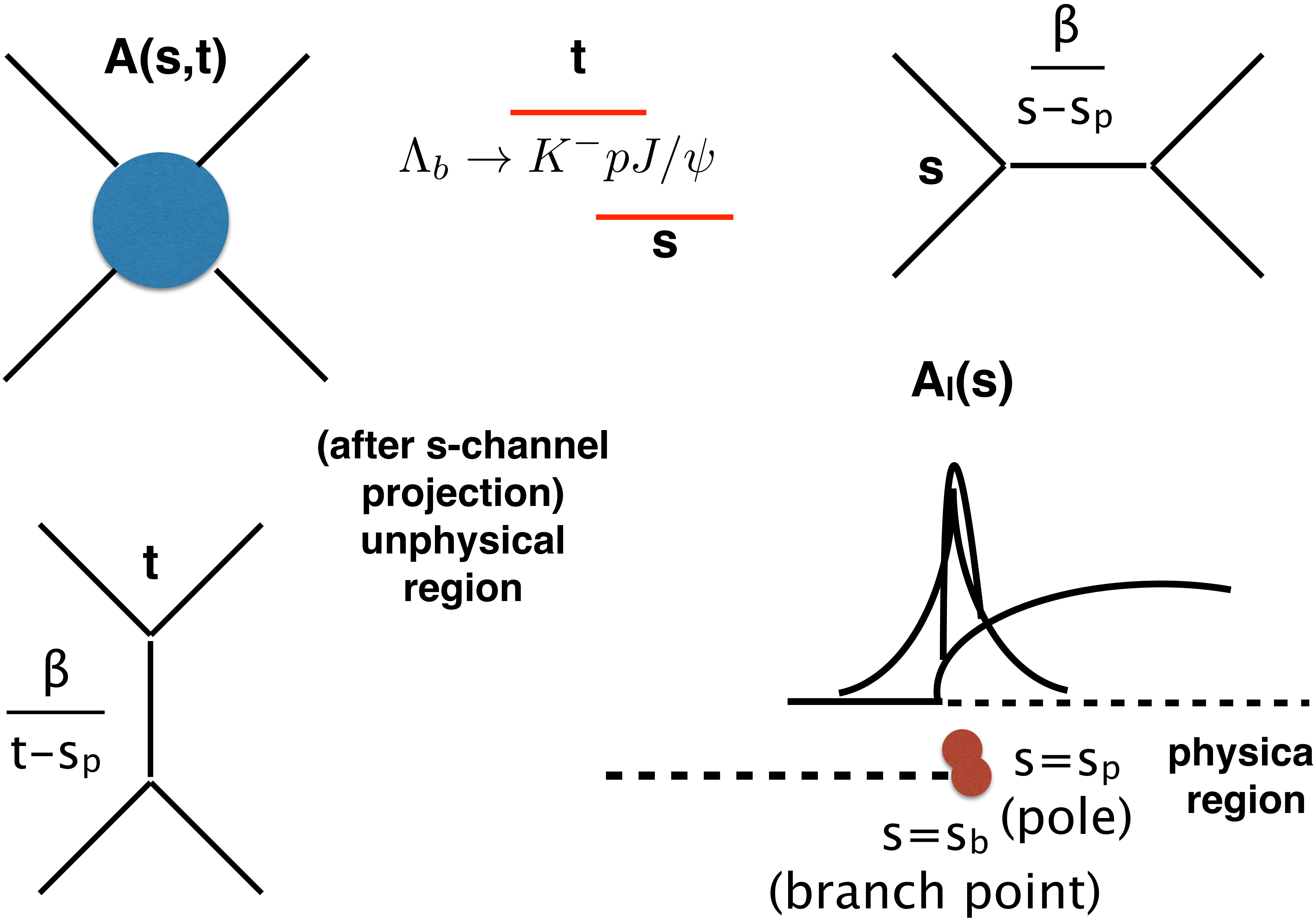




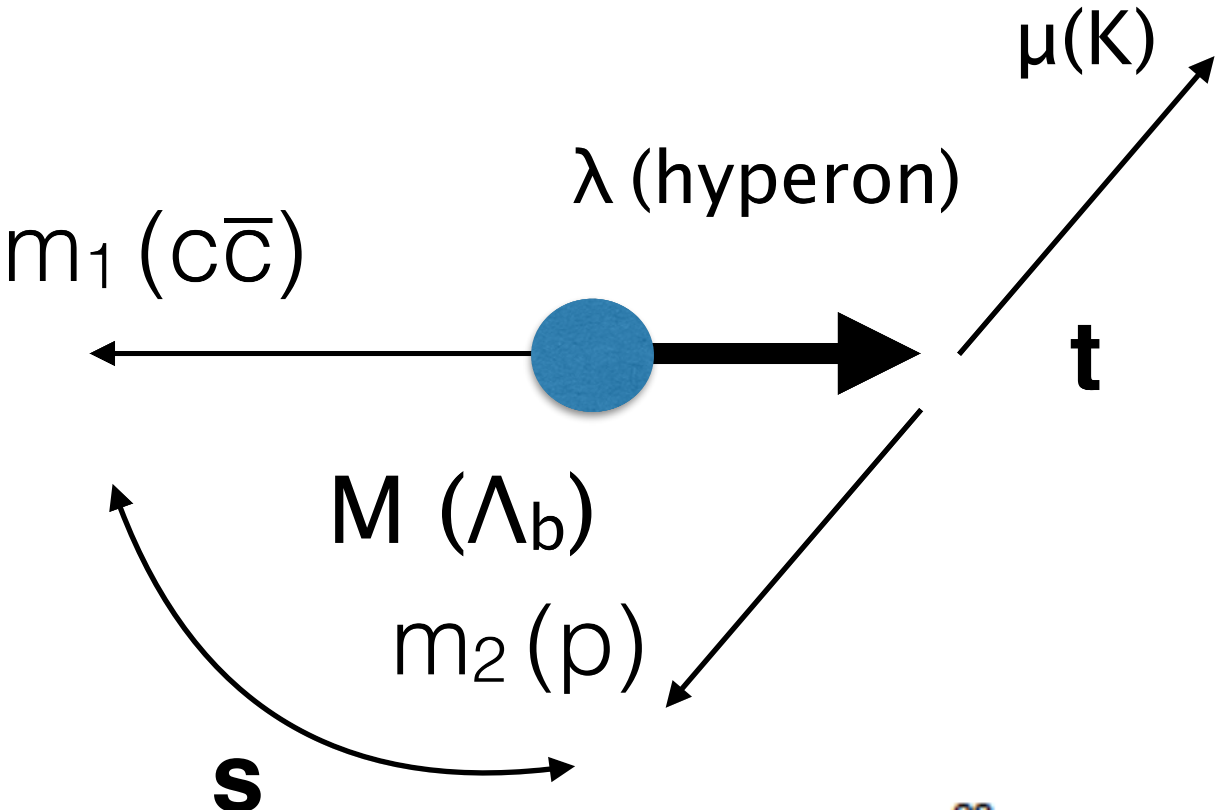
Origin of singularities (exchanges constrained by unitarity)



Origin of singularities (exchanges constrained by unitarity)



Coleman-Norton theorem



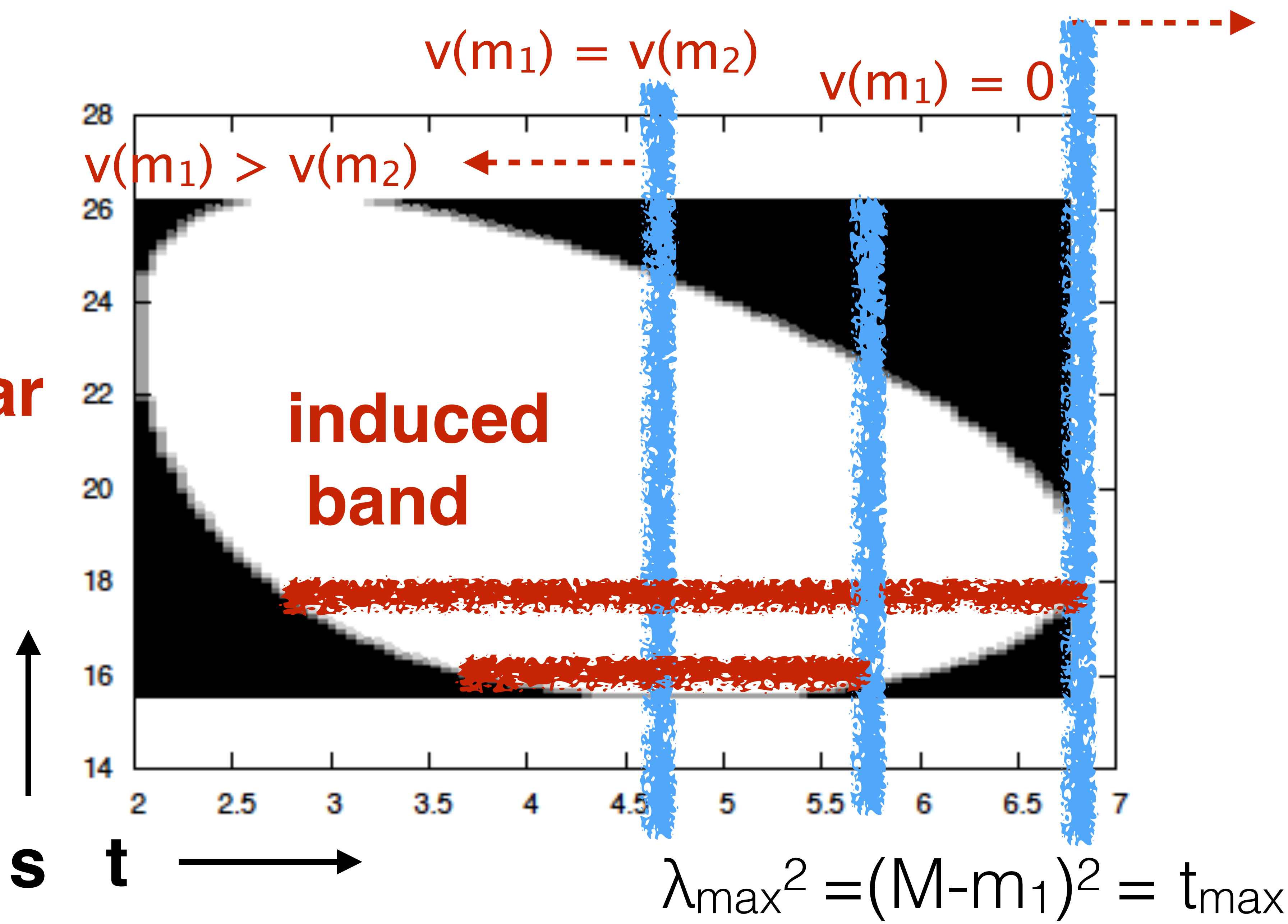
t-channel resonance can produce s-channel "band" if:

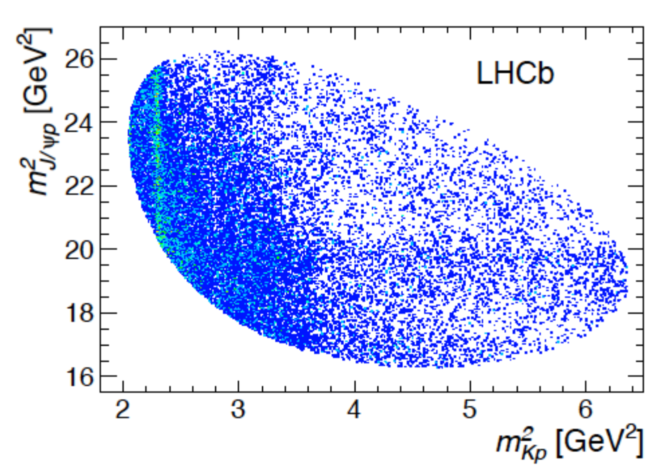
$\lambda_{min}^2 = t$ @ $s_{treshold}$
and u_{max}

all particles on-shell

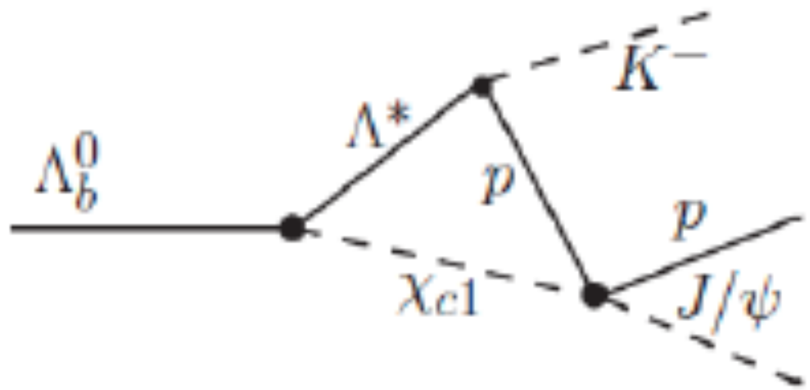
m_2 and m_1 collinear

$v(m_2) > v(m_1)$





The key to the YZ phenomena are the many nearby channels



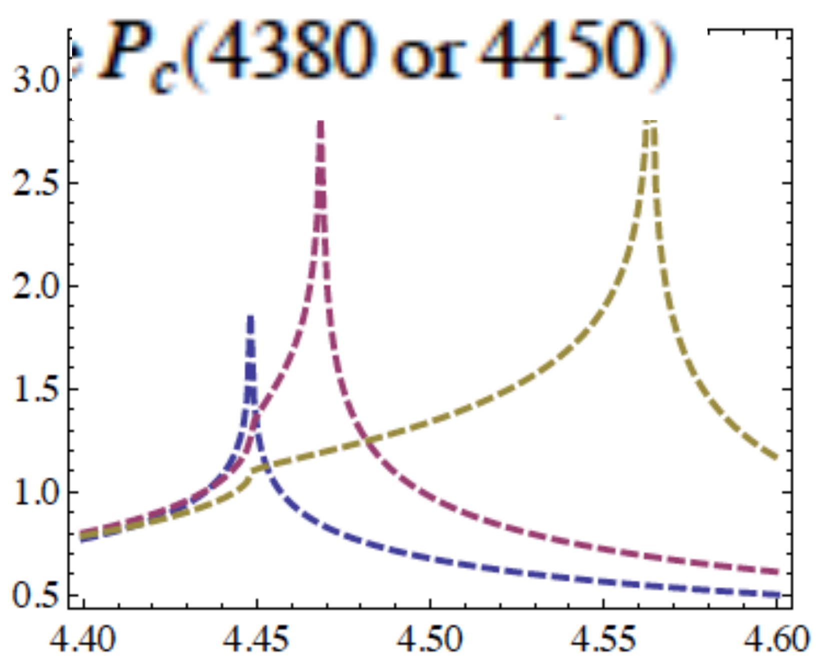
$$M_{\Lambda_b^0} = 5.6195,\ \mu_{K^-} = 0.4937,\ m_1 = m_{\chi_{c1}} = 3.510,\ m_2 = m_p = 0.93827$$

$$\lambda = m_{\Lambda^*} = 1.89 \text{ (they take)}$$

Coleman-Norton requires

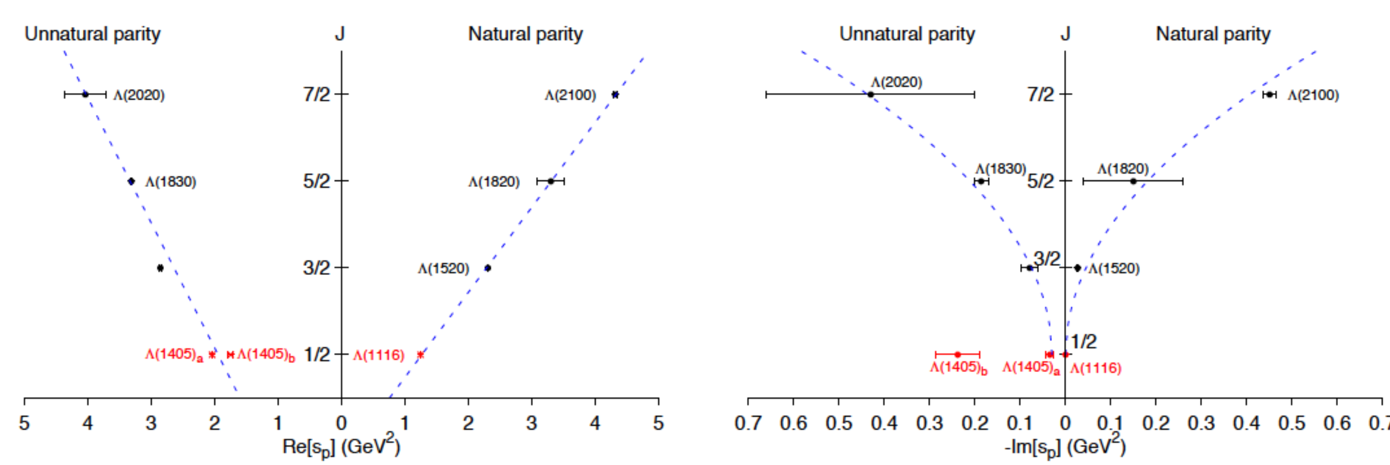
$$1.89 < \lambda < 2.11 \text{ GeV}$$

$$4.45 < \sqrt{s_{\text{peak}}} < 4.65 \text{ GeV}$$

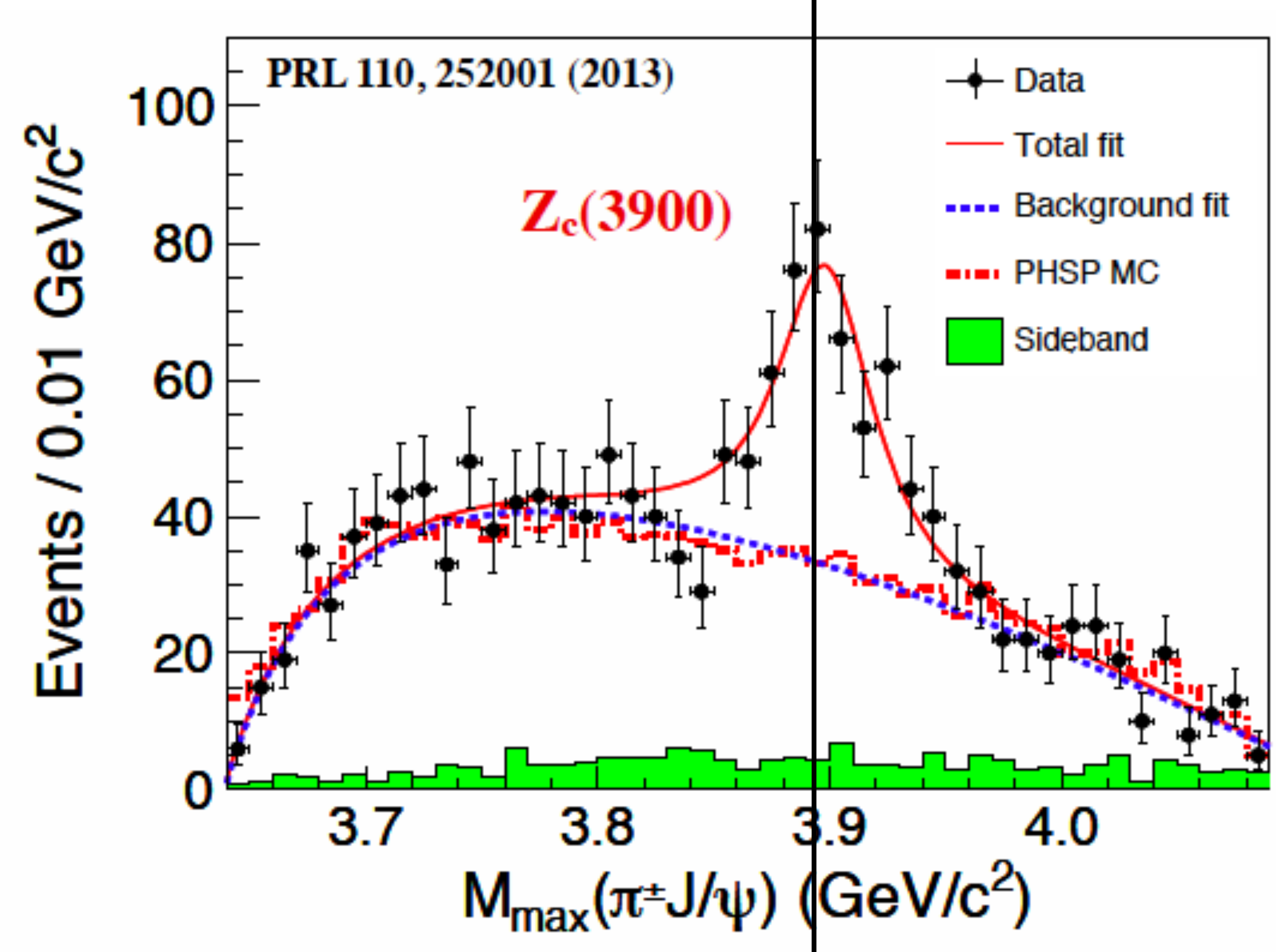


Axes : Abs[$T(s)$], $\sqrt{s}$

Lines : blue (λ = 1.89 GeV), red (λ = 1.99 GeV), yellow (λ = 2.09



$Z_c(3900)$ Charged charmonium ?



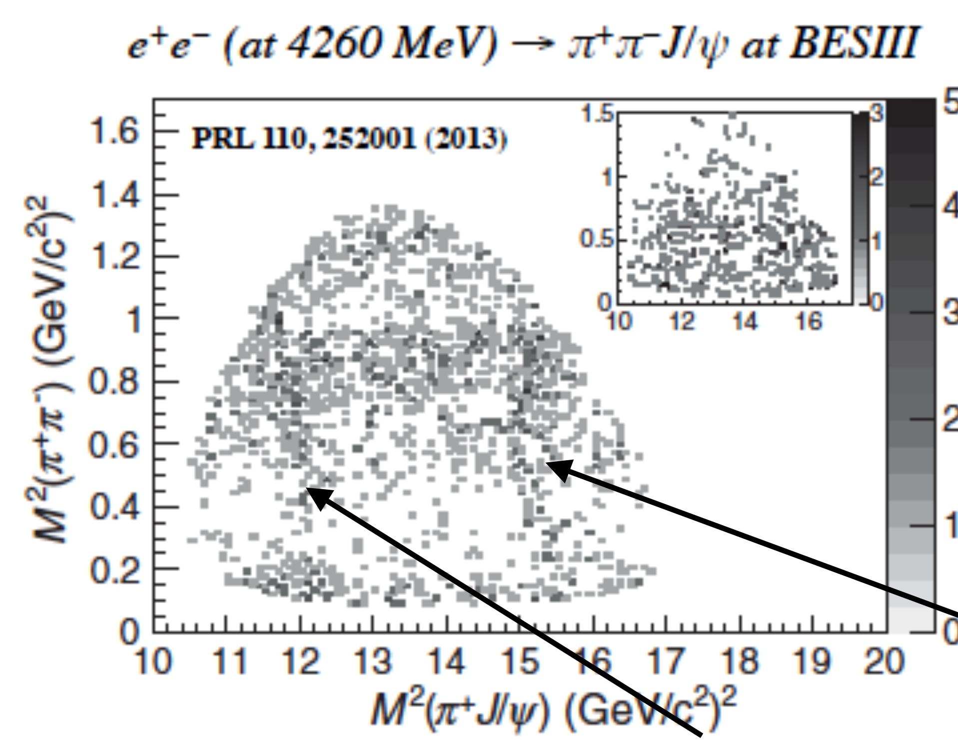
M = 3899.0 ± 3.6 ± 4.9 MeV

Γ = 46 ± 10 ± 20 MeV

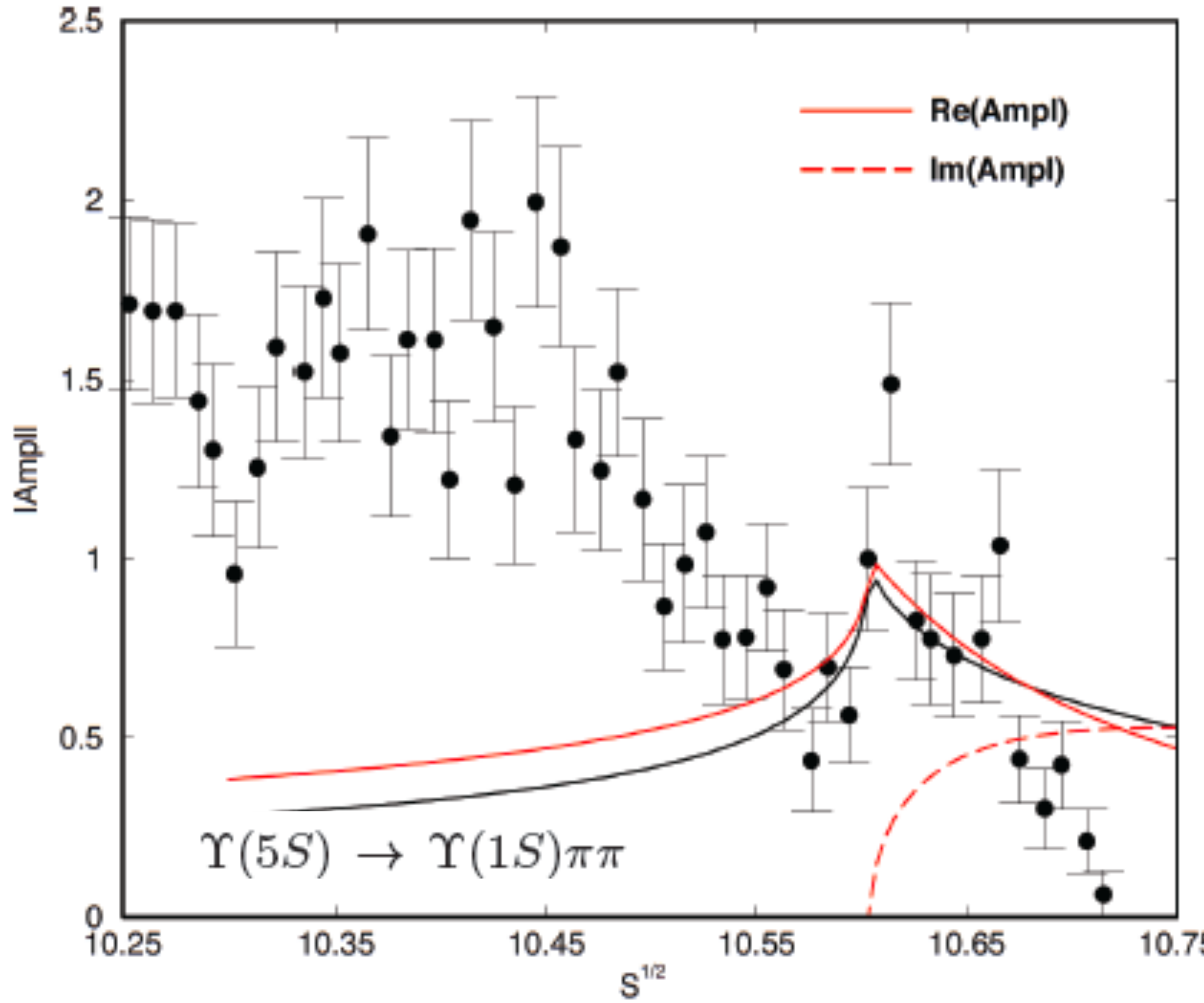
Breit-Wigner model fit

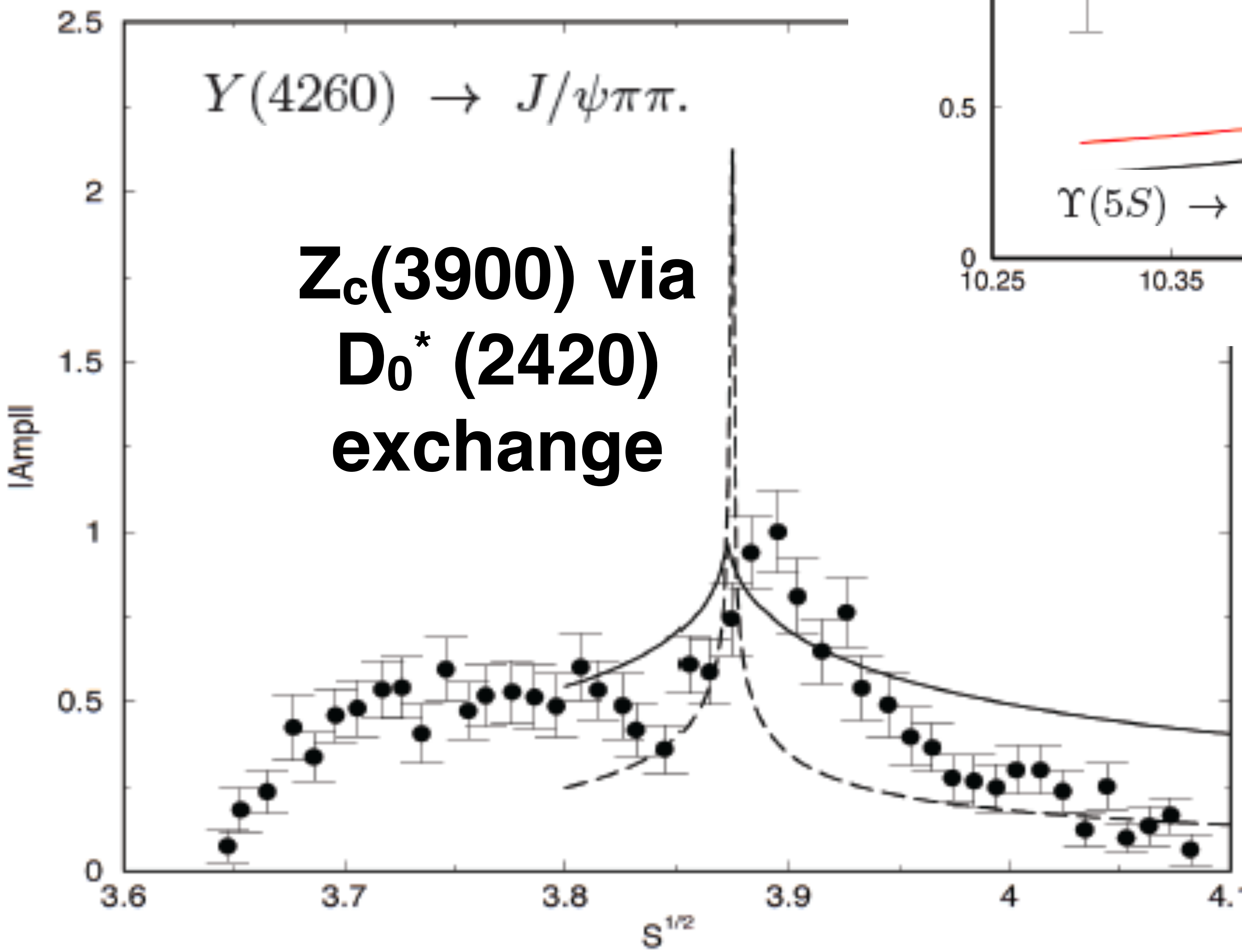
close to D*D threshold

$$e^+e^- \to Y(4260)$$
$$\to \pi^+ Z_c^-(3900)$$
$$\to \pi^+\pi^- J/\psi$$



coupling to DD*

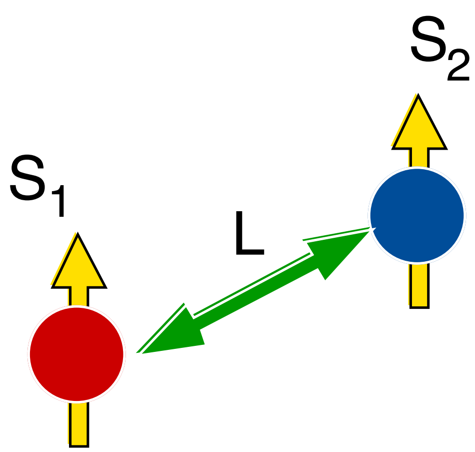




Z_c(3900) via D_0^* (2420) exchange

Z_b(10610) via B_J^{**}(5698) exchange

Gluon excitations

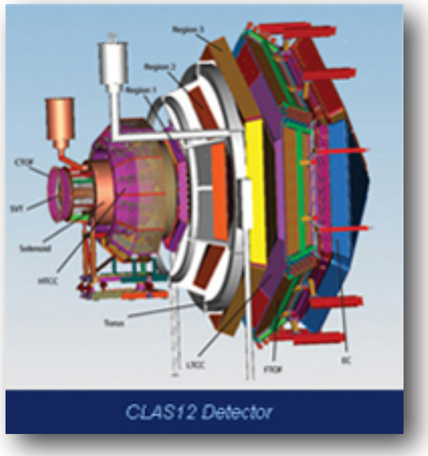


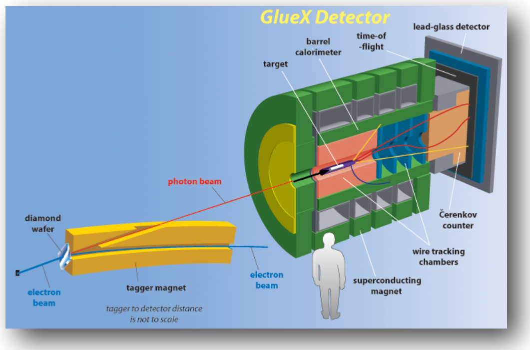
$S = S_1 + S_2$

$J = L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

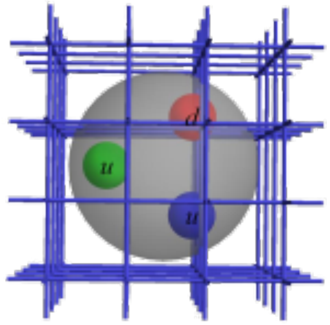




Mesons with $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$: Exotic Quantum Numbers

π_1

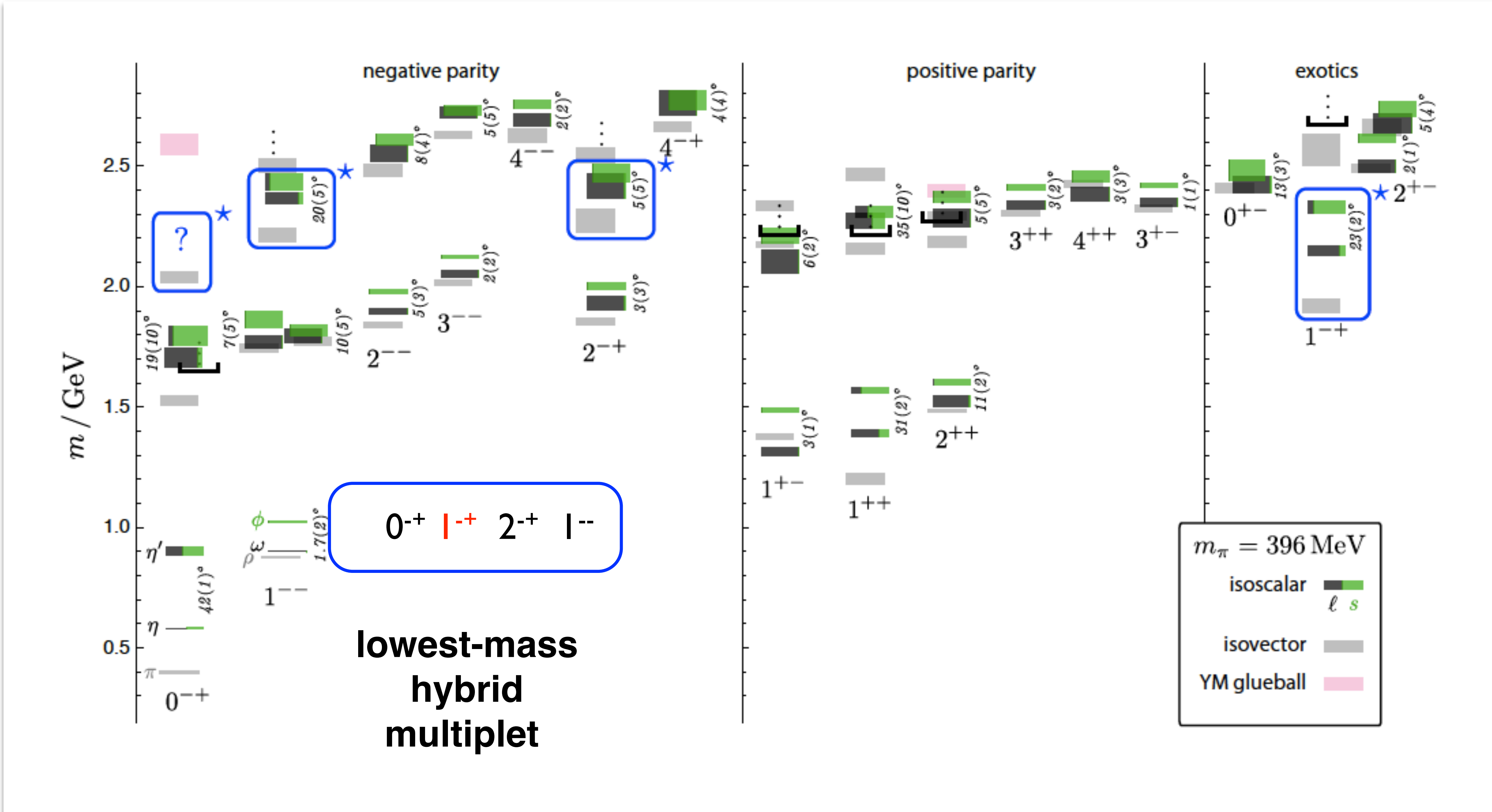
Expected to have very similar properties to ordinary $Q\bar{Q}$ mesons

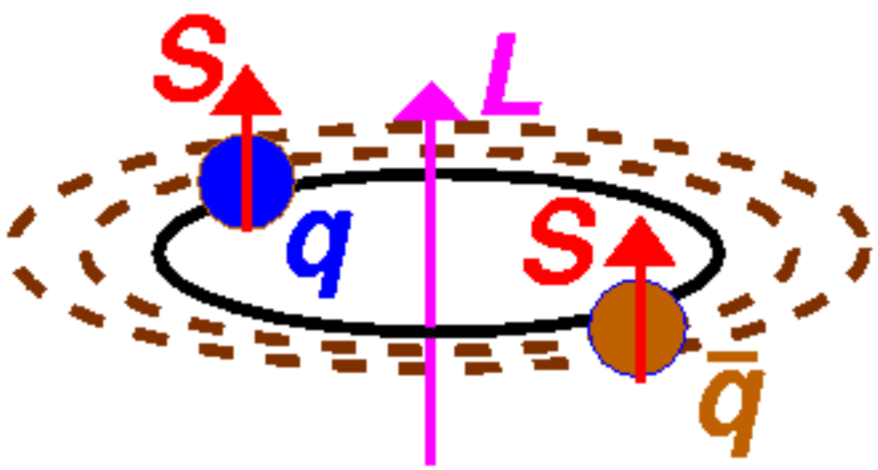


J. Dudek et al.

same pattern in $s\bar{s}$, $c\bar{c}$

hybrid interpretation of the **Y(4260)**

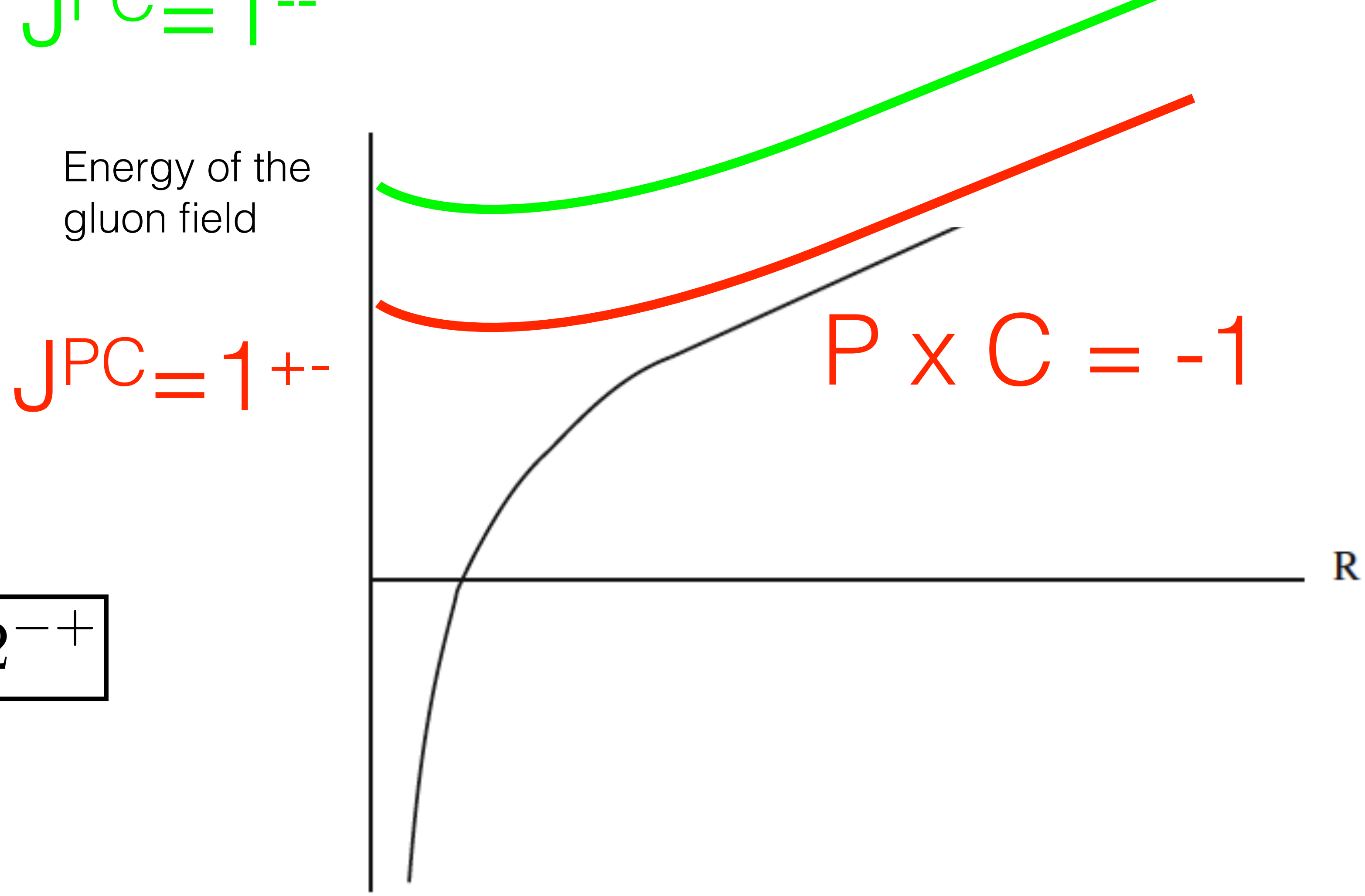




$$P_{q\bar{q}} = (-1)^{L+1}$$

$$C_{q\bar{q}} = (-1)^{L+S}$$

$$J_g^{PC} = 1^{+-}$$



J^{PC} glue

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

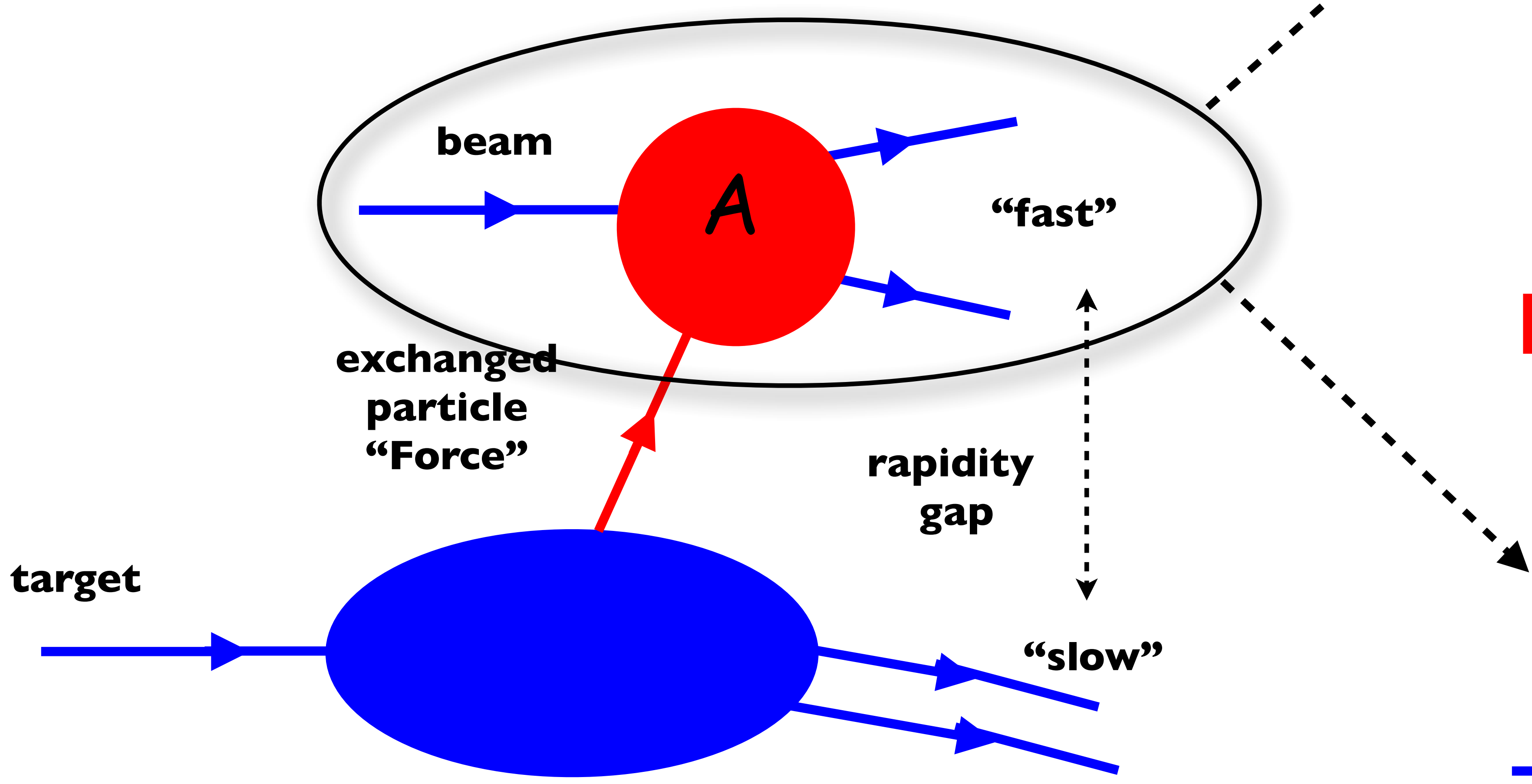
$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

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

Prediction of Coulomb gauge QCD

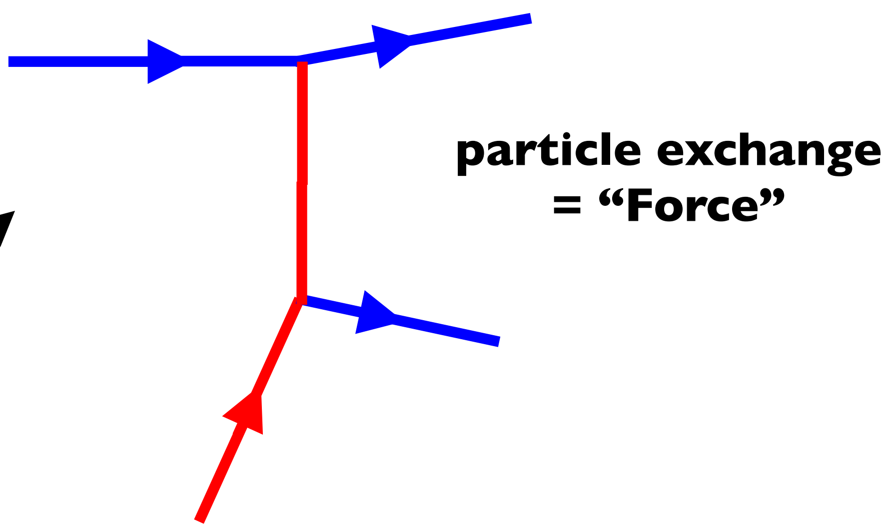
Hunting for Resonances in fixed target experiments

COMPASS, JLAB 12 GeV

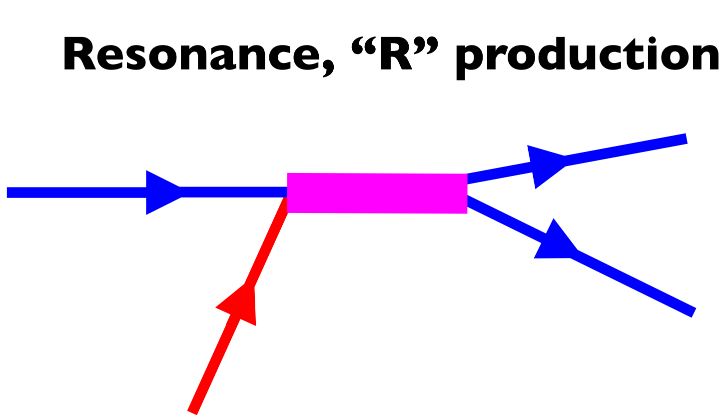


target = photon (JLab)
pion (COMPAS)

diffractive-dissociation



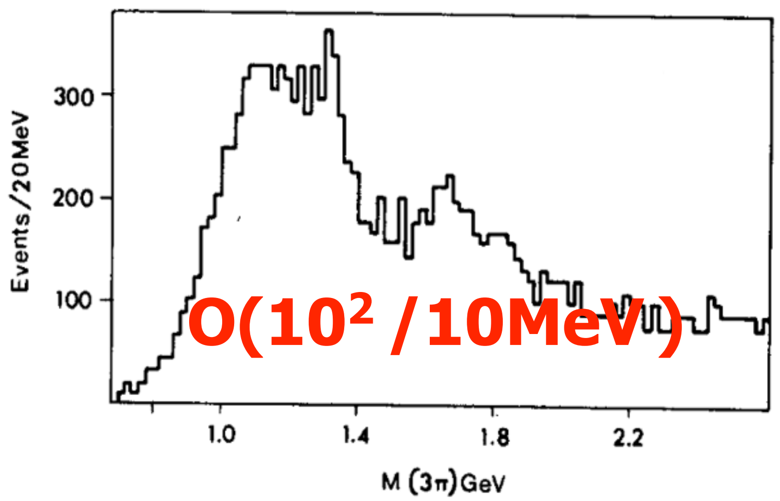
Particle ↔ Force duality

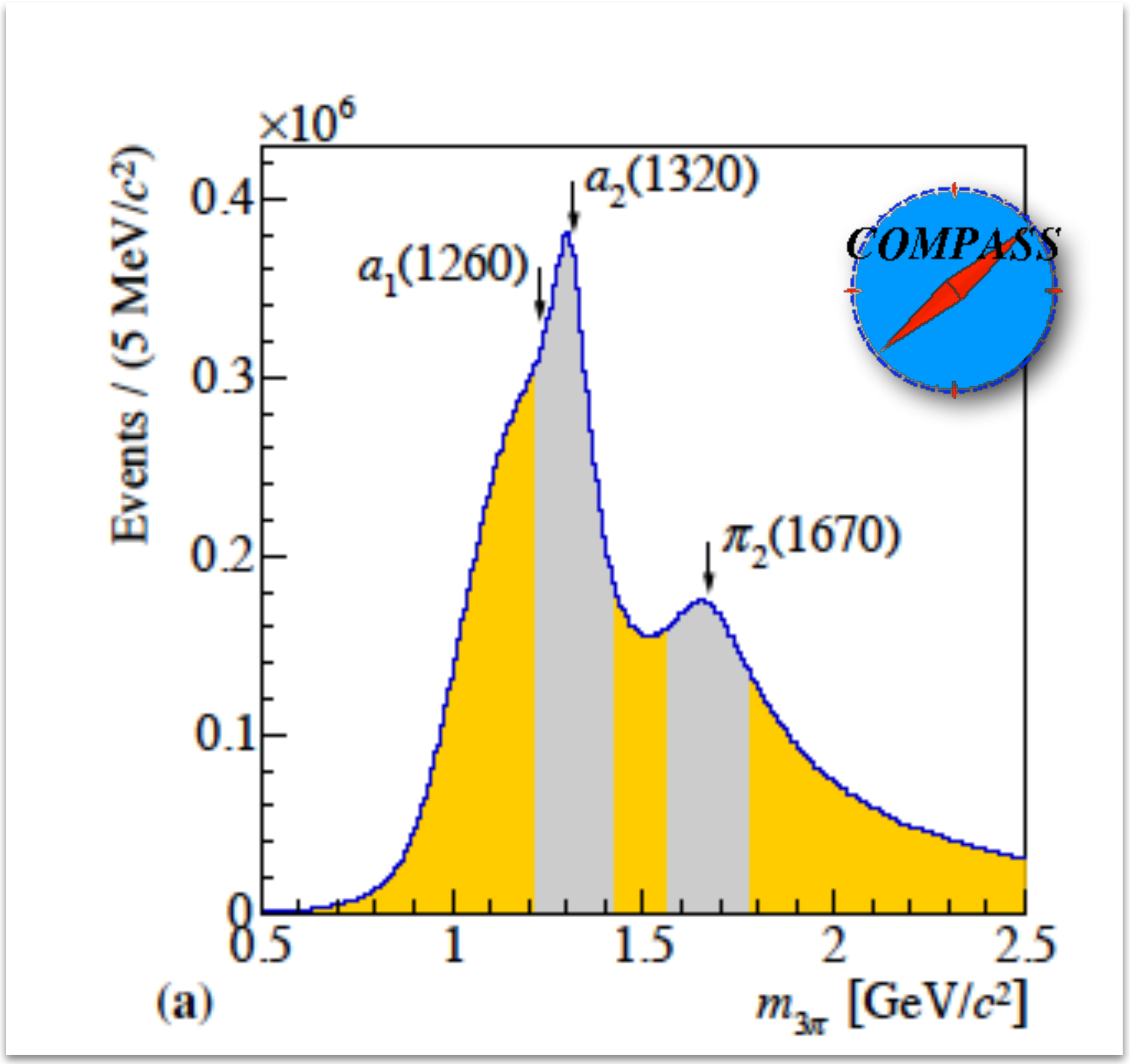


Evolution in statistics

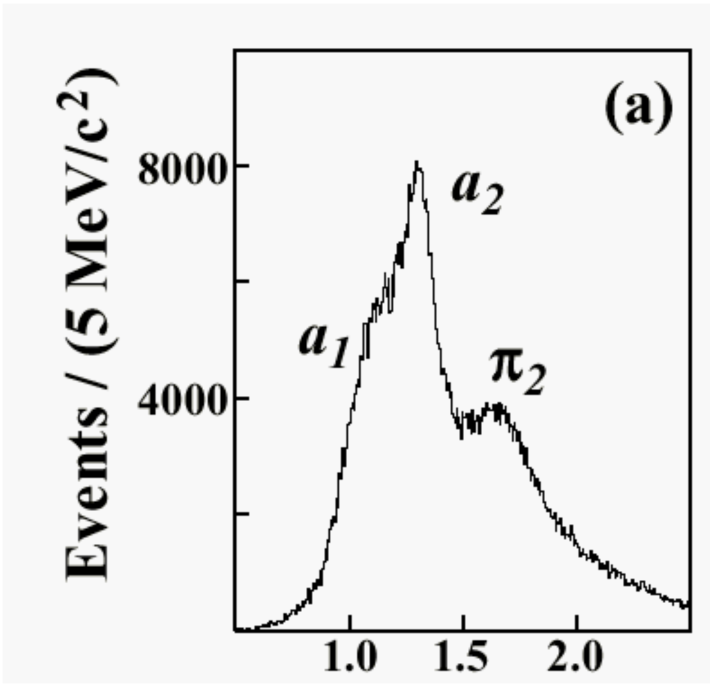
$\pi^- p \rightarrow \pi^-\pi^+\pi^- p$

CERN ca. 1970





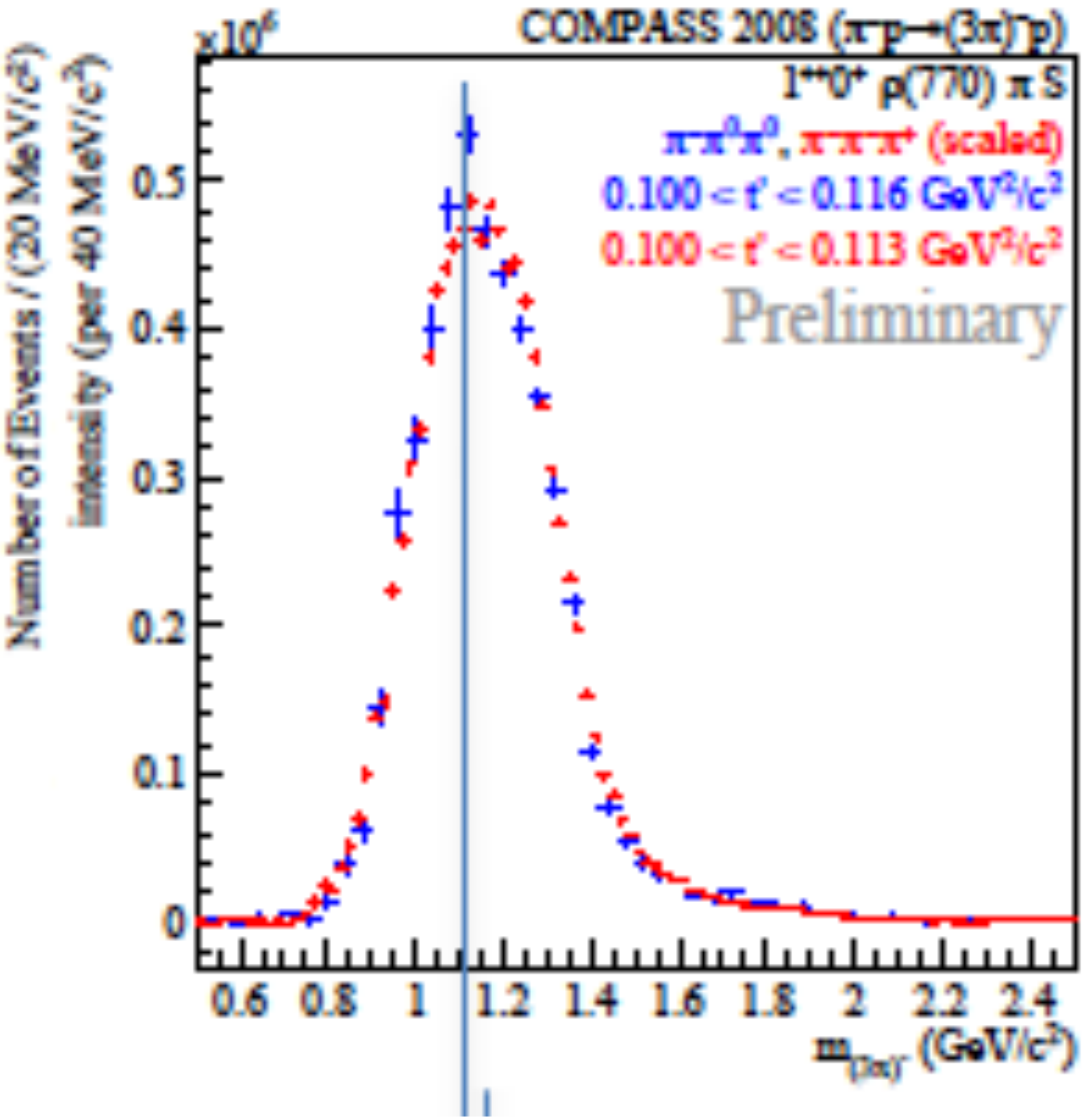
BNL (E852) ca 1995



E852 (Full sample) ~ 10^5/10MeV

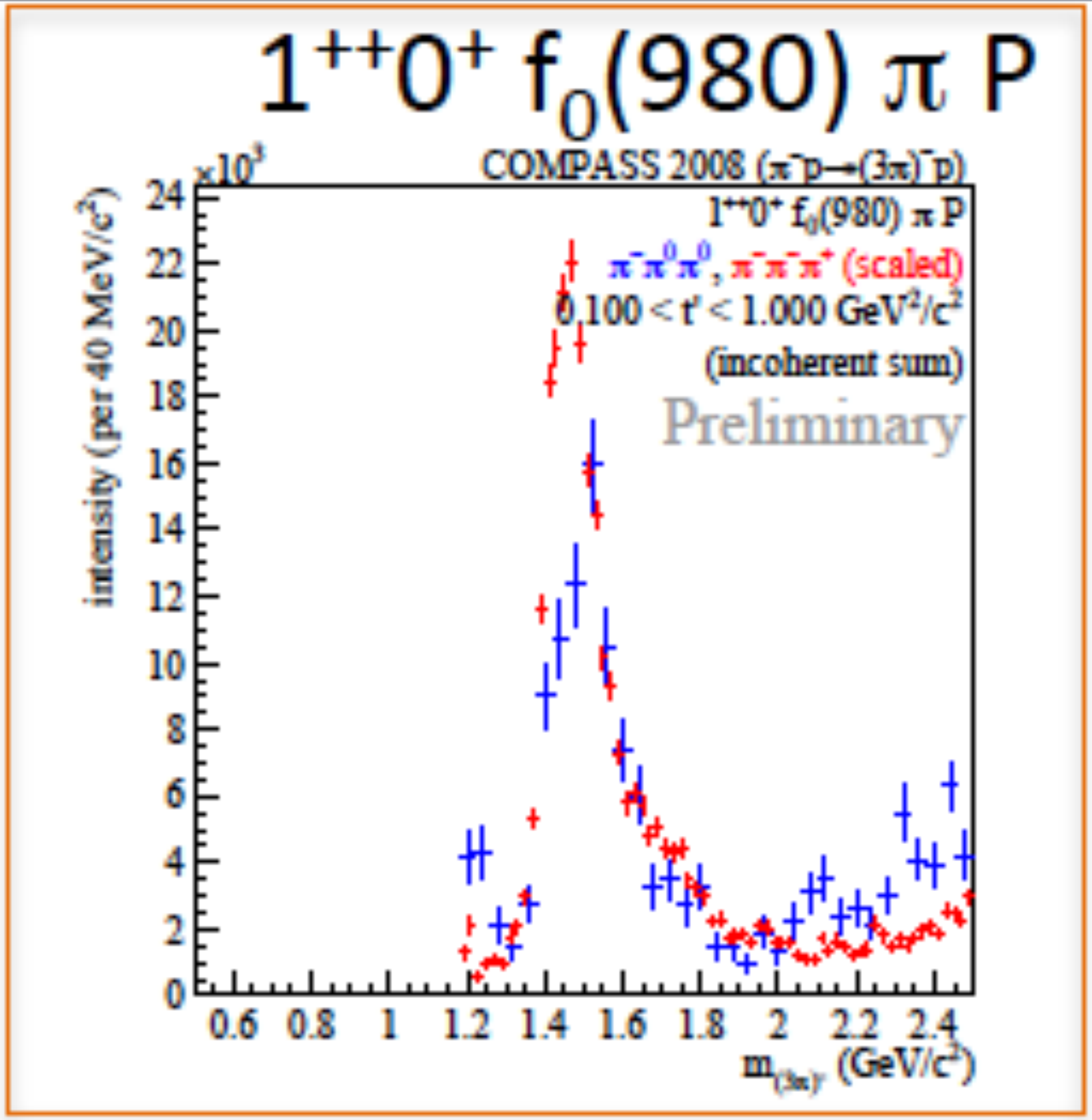
O(10^6 / 10MeV)

COMPASS's a_1 meson(s) $J^{PC} = 1^{++}$ (L=1,S=1)



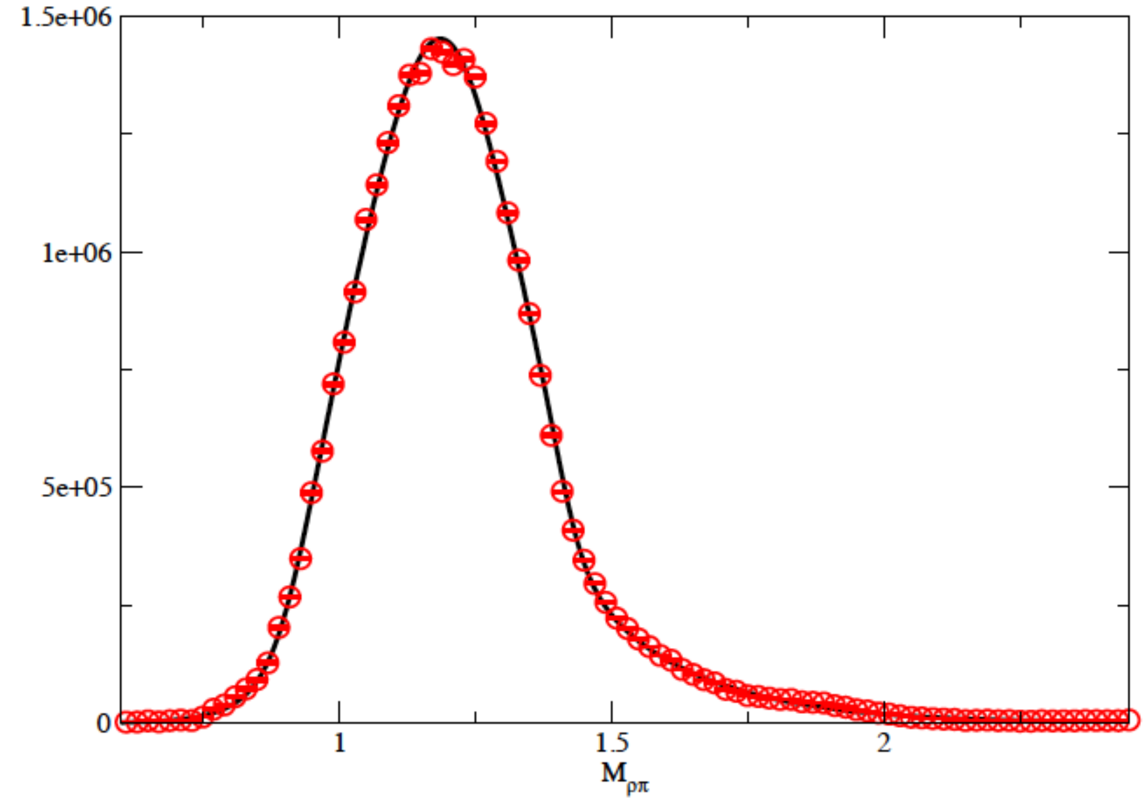
"Old" a1 in ρπ S-wave

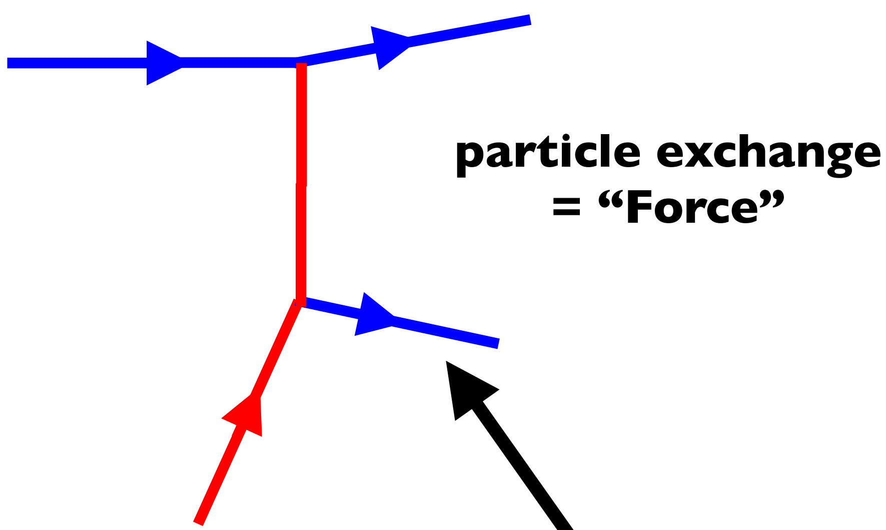
New a1 in f0 π P-wave



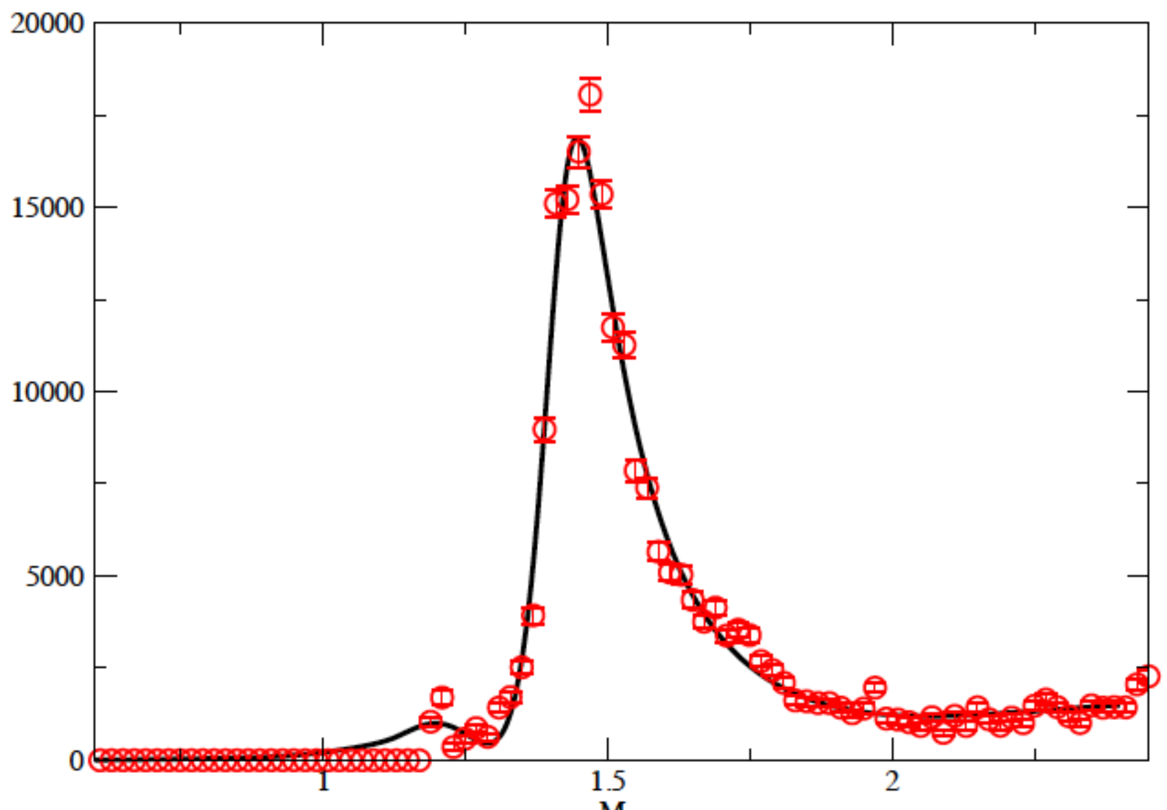
Two Breit-Wigner resonances (COMPASS)

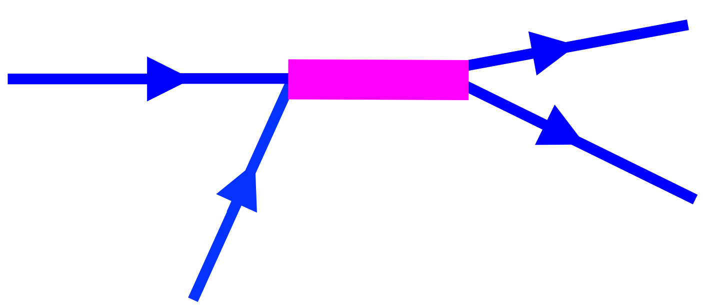
$$\Delta A_i(s) = \sum_{j=f_0\pi,\rho\pi} T^*_{ij}(s)\rho_j(s)A_j(s)$$





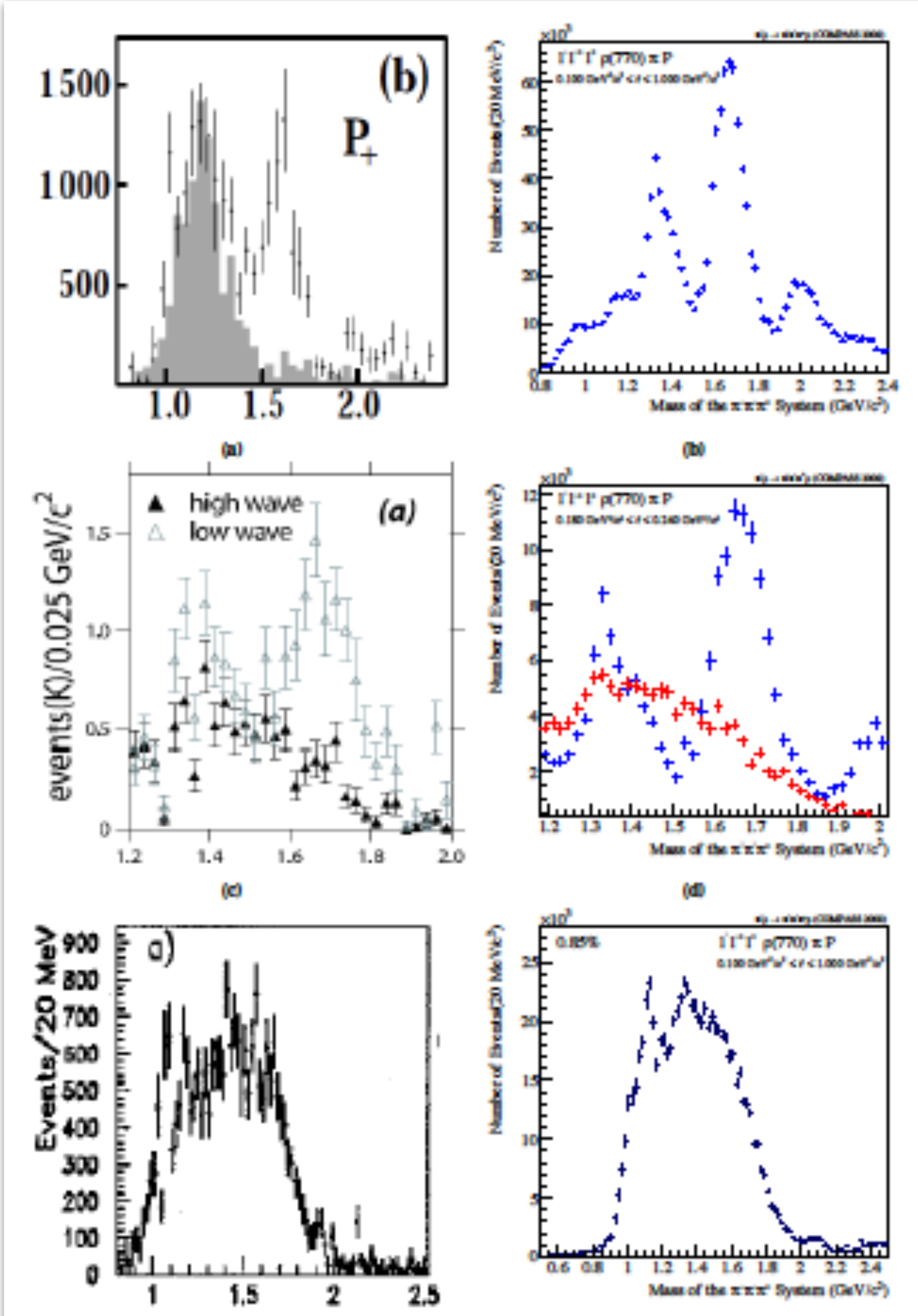
$$A_i(s) = \sum_{j=f_0\pi,\rho\pi} T_{ij}(s)P_j(s)$$

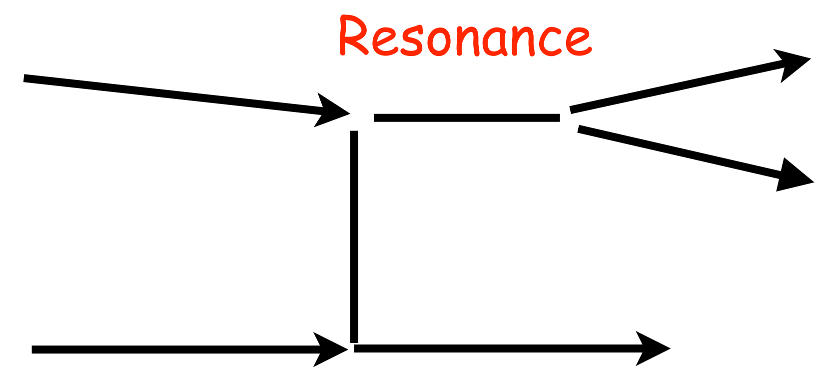


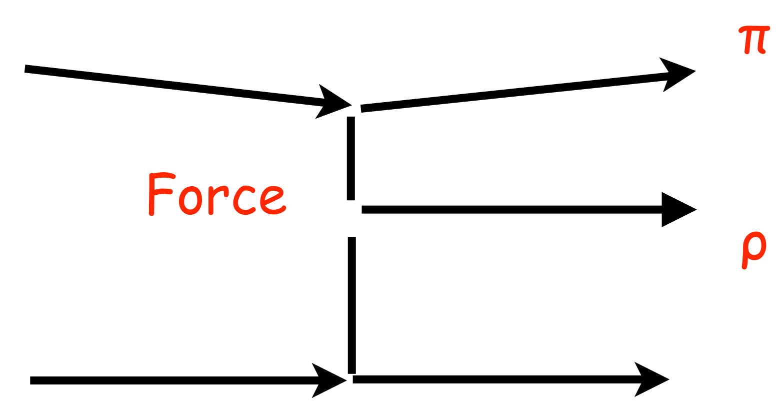


One resonance underlies both peaks

3pion spectrum in diffractive dissociation on hydrogen COMPASS vs E852/BNL and VES

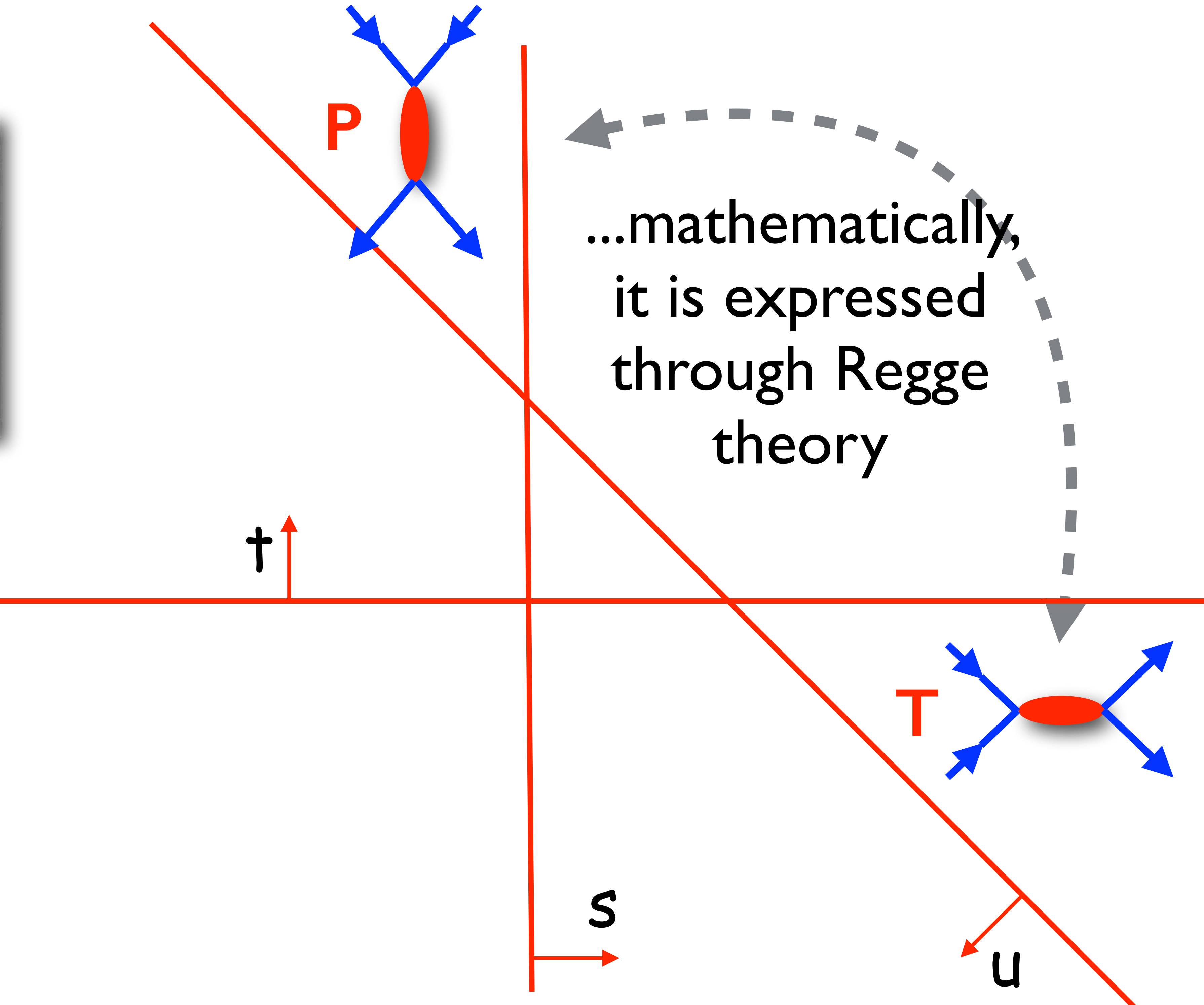






Forces (P) and Resonances (T) are not independent

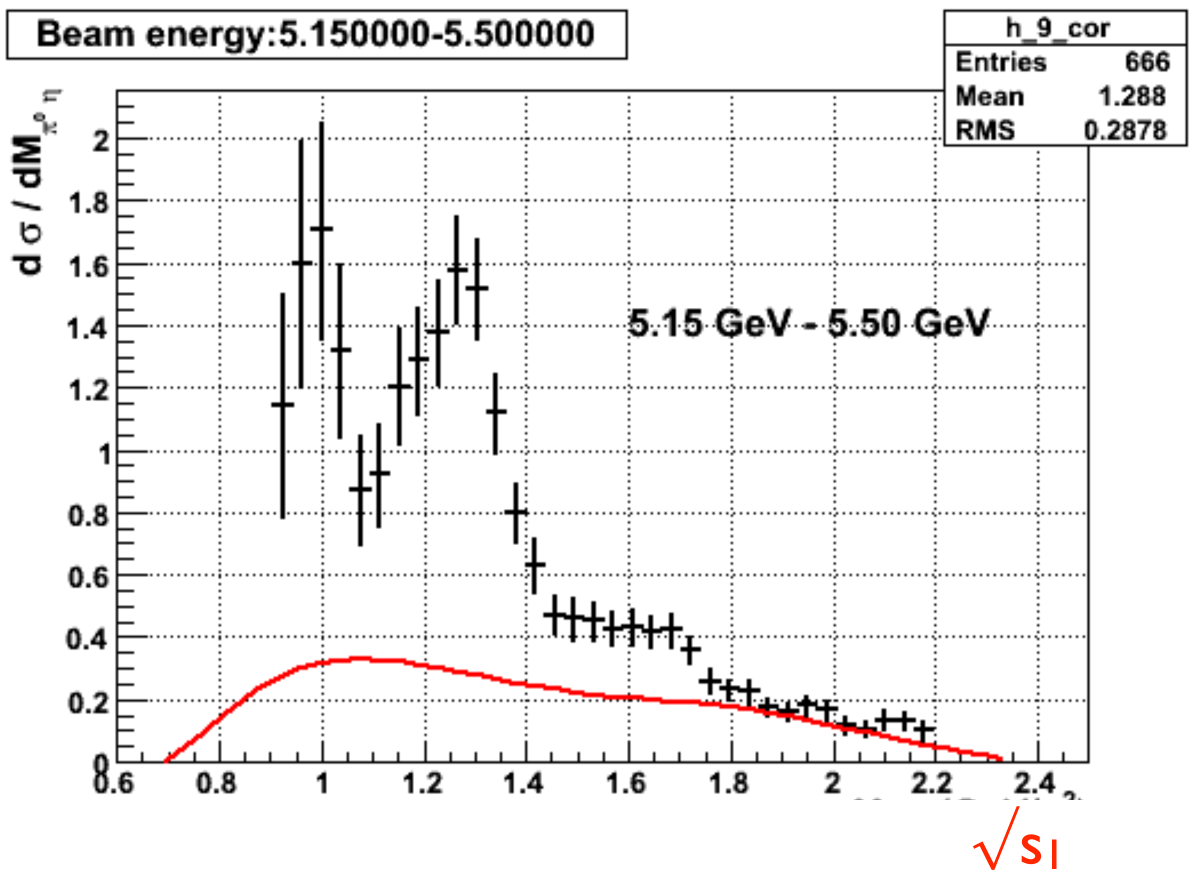


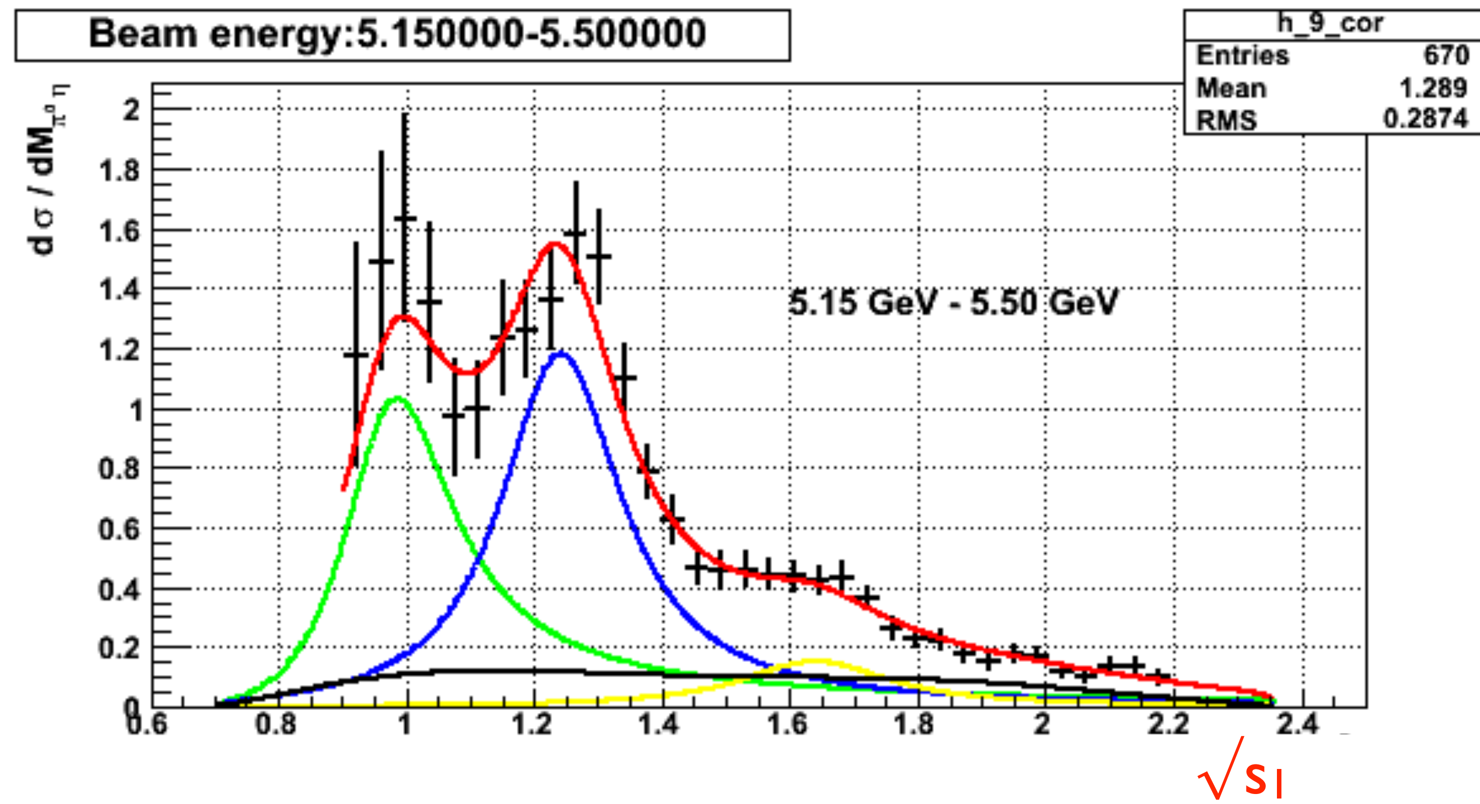



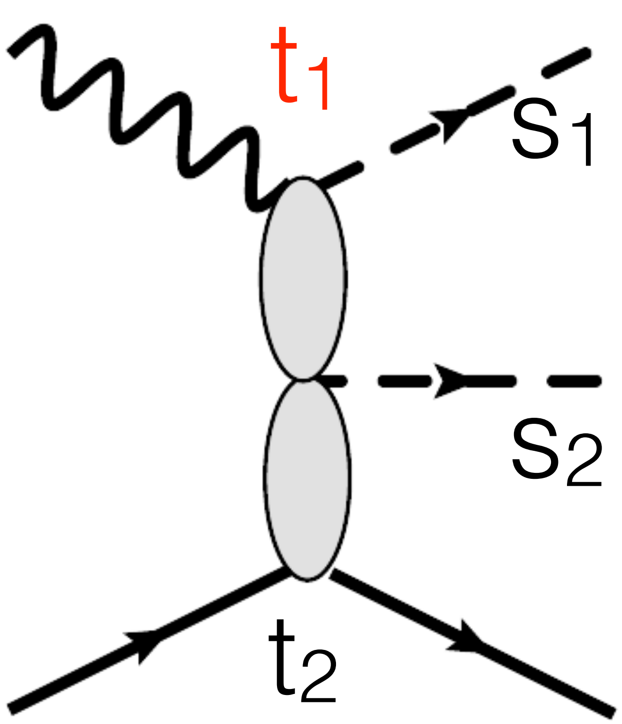
Unitarity enforces Force-Resonance duality = Regge theory

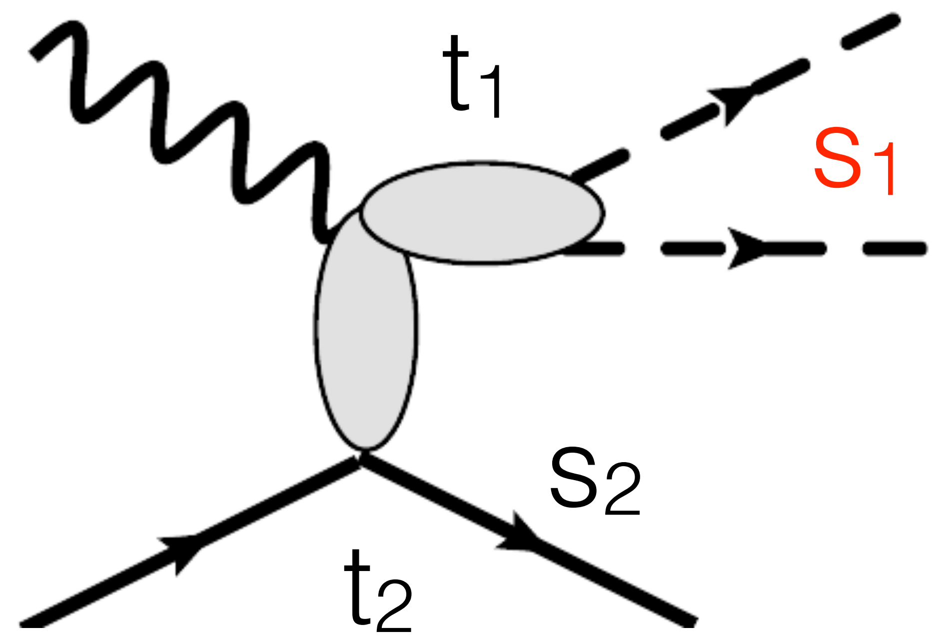
$\gamma p \rightarrow \eta \pi^0 p$ (g12)

A.Celentano, PhD, HASPEC/JPAC

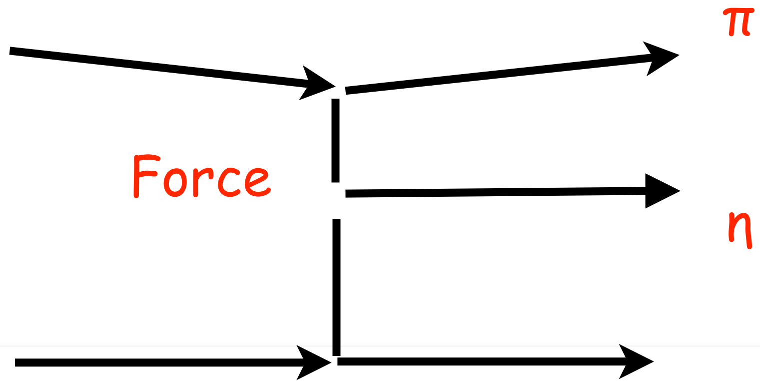


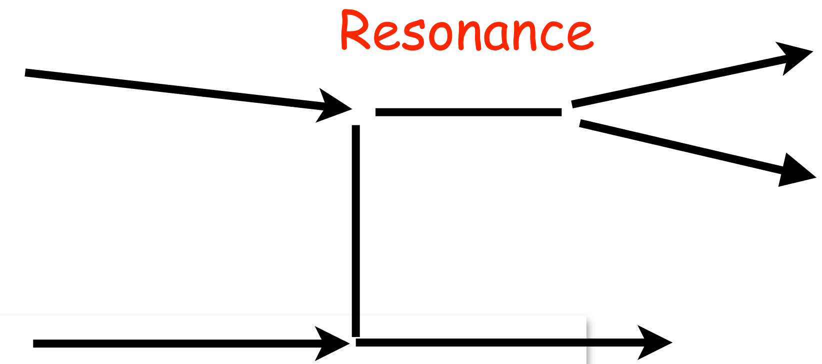


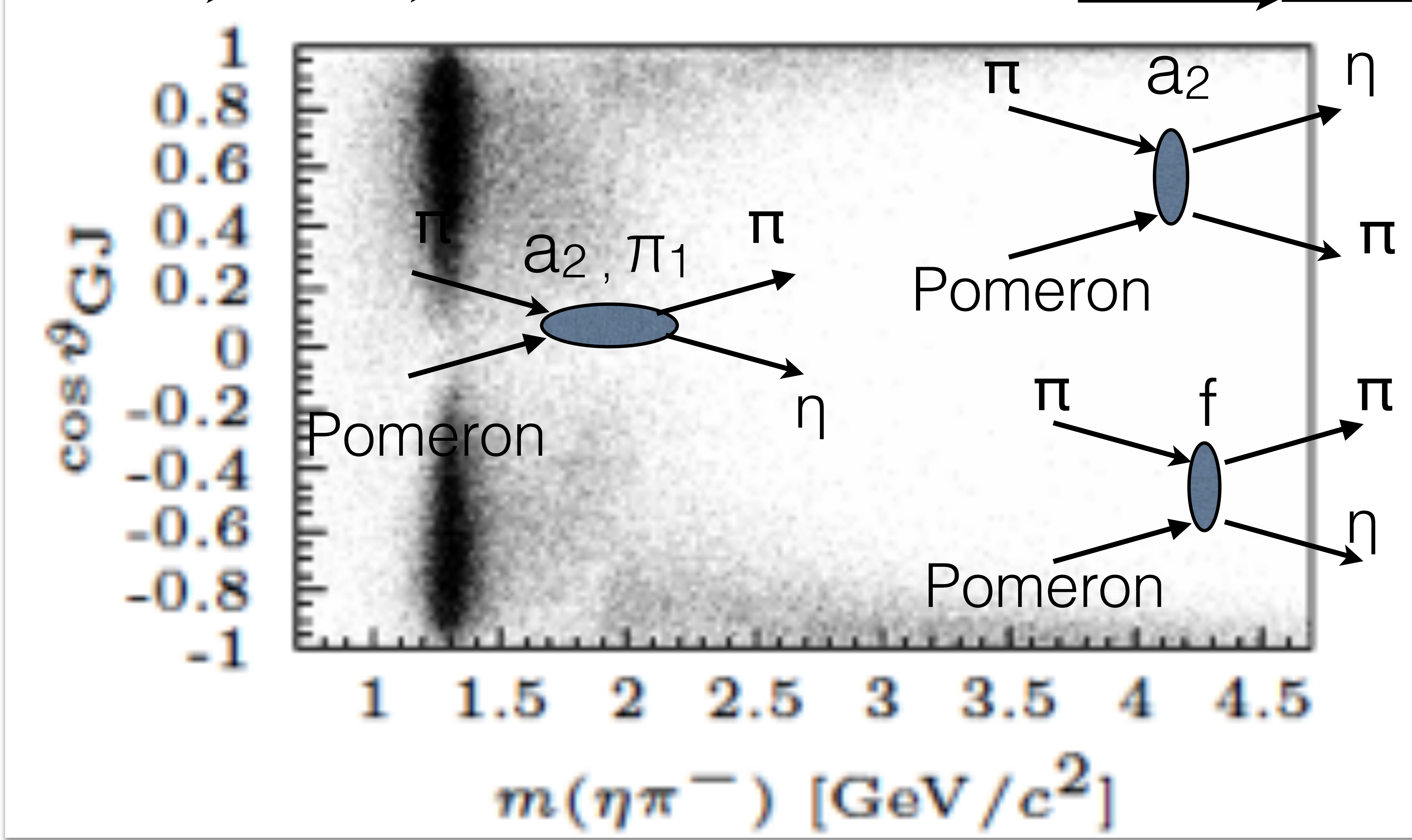




1-+ Exotic
COMPASS







duality —> the production channel is dominated by spin-even partial waves. What is the exotic (P-wave) dual to ?

JPAC: helping to repair the gap

Develop theoretical,phenomenological/ computational tools for hadron experiments

Experiment-theory collaboration

GLOBAL EFFORT

Create a vibrant community

JPAC : Specific Analyses

Light meson decays and light quark resonance

- $\omega/\phi \to 3\pi$, $\pi\gamma$ (Khuri-Treiman)
- $\omega \to 3\pi$ (Veneziano, B4)
- $\eta \to 3\pi$, $\eta \to \eta'\pi\pi$ (Khuri-Treiman)
- $J/\Psi \to \gamma\pi 0\pi 0$

Photoproduction: (production models, FESR and duality)

- $\gamma p \to \pi 0 p$
- $\gamma p \to pK{+}K{-}$

Launched in the Fall of 2014
~20 papers published

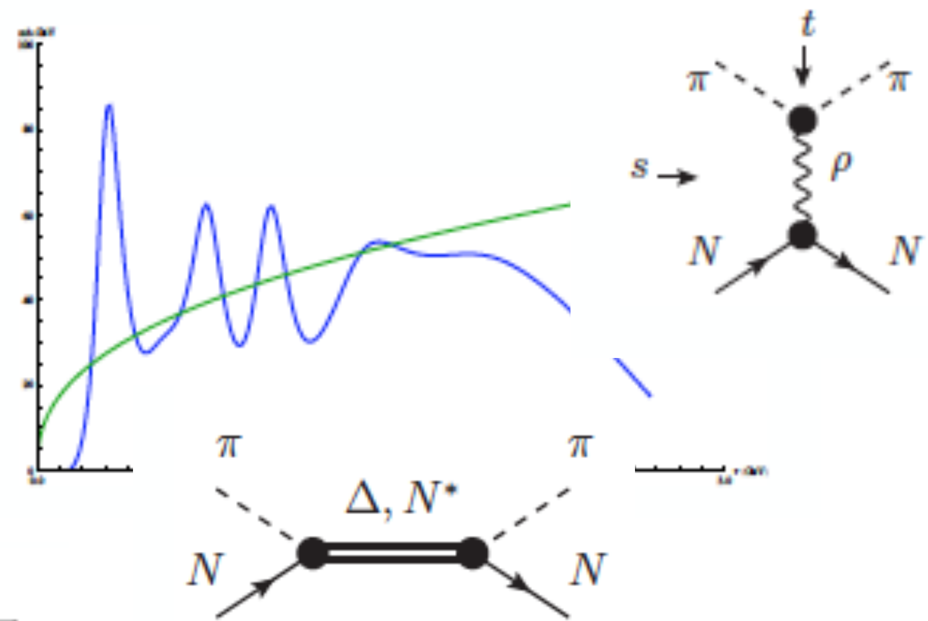
Exotica and XYZ's:

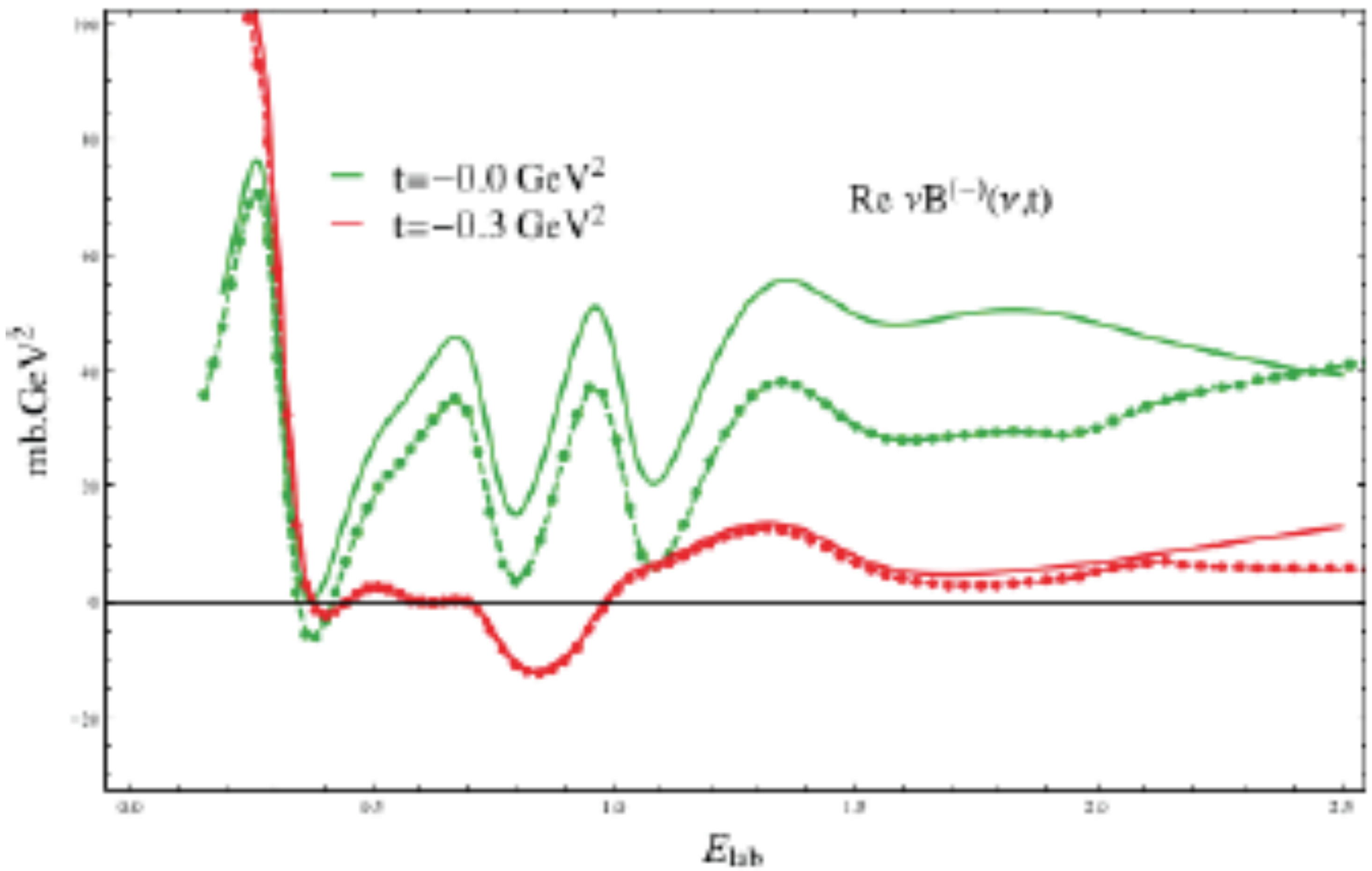
- $\pi{-}p \to \pi{-}\eta p$ & $\pi{-}p \to \pi{-}\eta' p$ (FESR)
- $B0 \to \Psi'\ \pi{-}\ K{+}\ u$, $\Psi(4260) \to J/\Psi\ \pi{+}\pi{-}$
- $J/\Psi \to 3\pi$ (Veneziano, B4)

Resonance-Regge physics in meson-baryon scattering

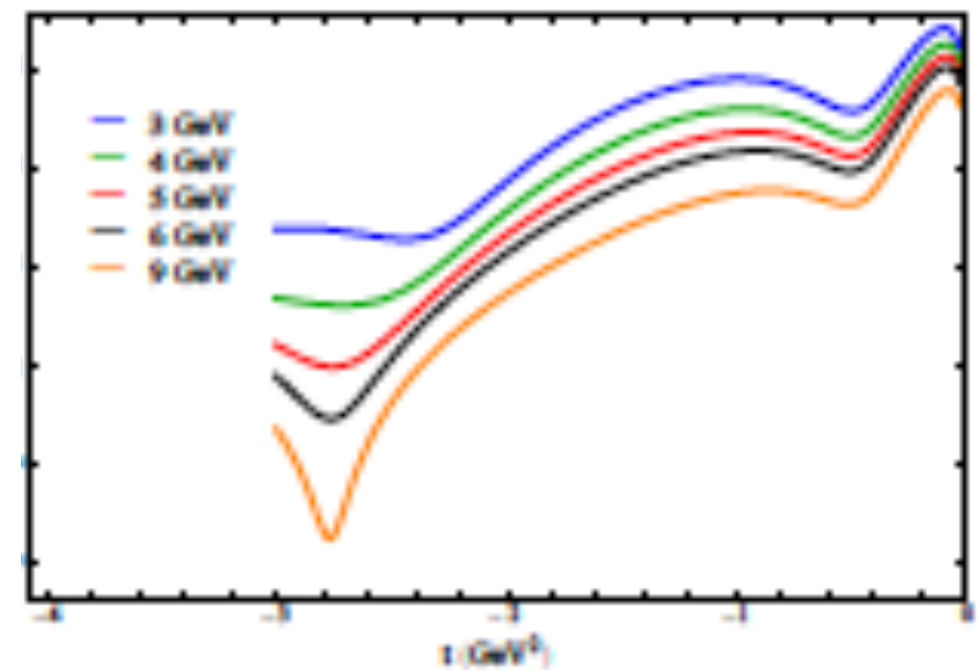
$$\int_{\nu_0}^{\Lambda} \text{Im } A^{(-)}(\nu', t)\nu'^{2k} d\nu' = \beta(t)\frac{\Lambda^{\alpha_\rho(t)+2k+1}}{\alpha_\rho(t)+2k+1}$$

Resonance Regge





$\pi N \to \pi N$



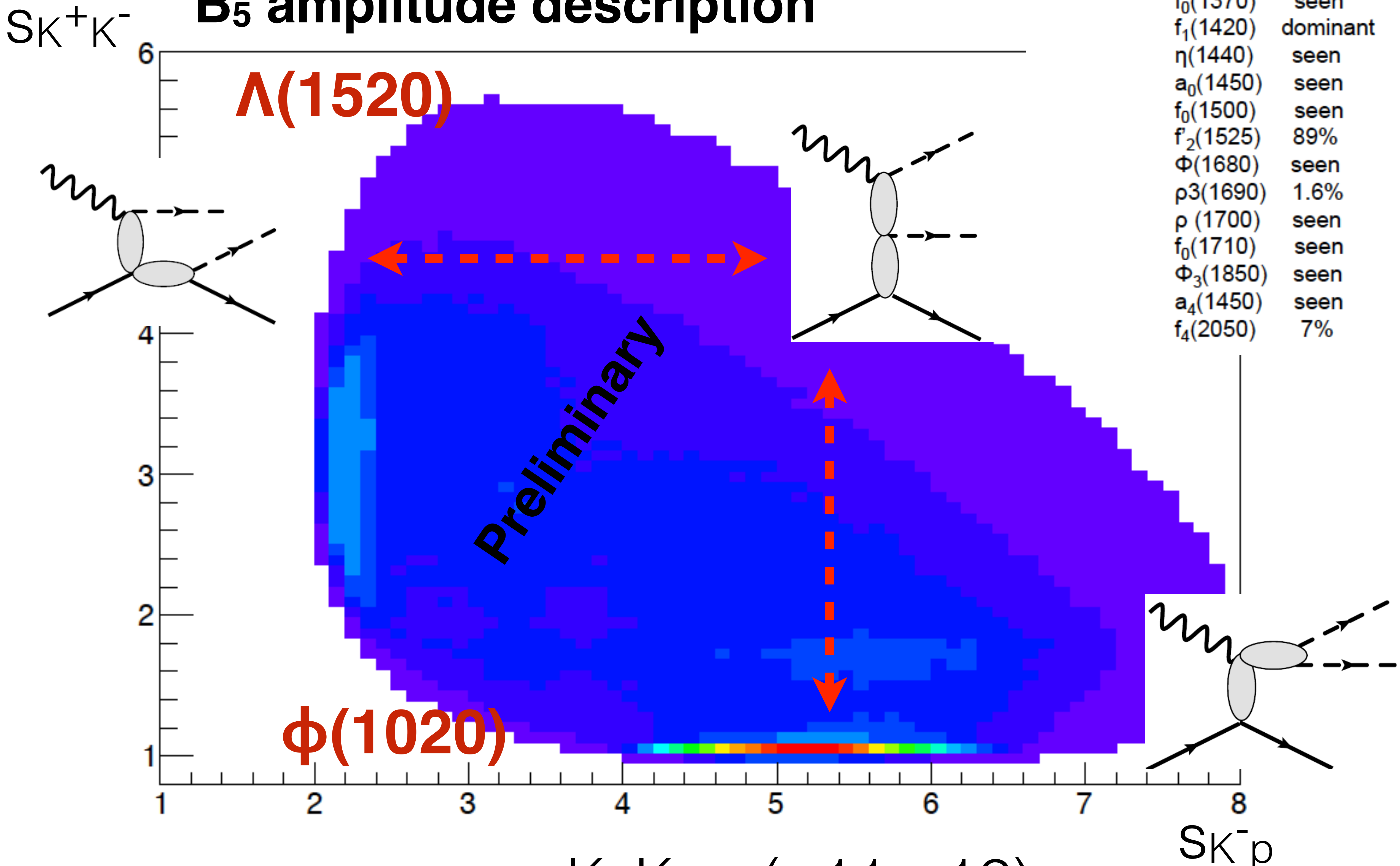
section at CLAS and GlueX energies.

$\gamma p \to \pi^0 p$

V.Mathieu, JPAC

Duality @ JLab

B_5 amplitude description

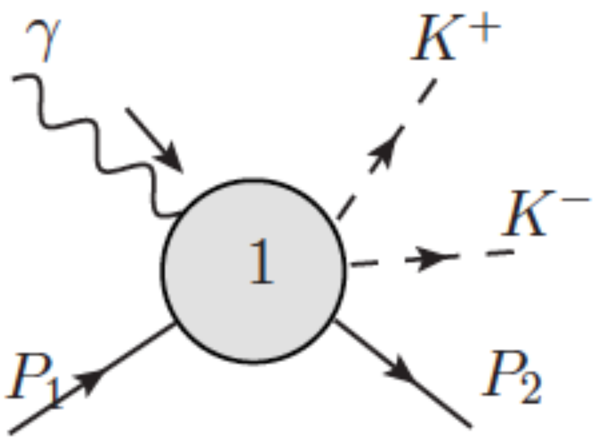


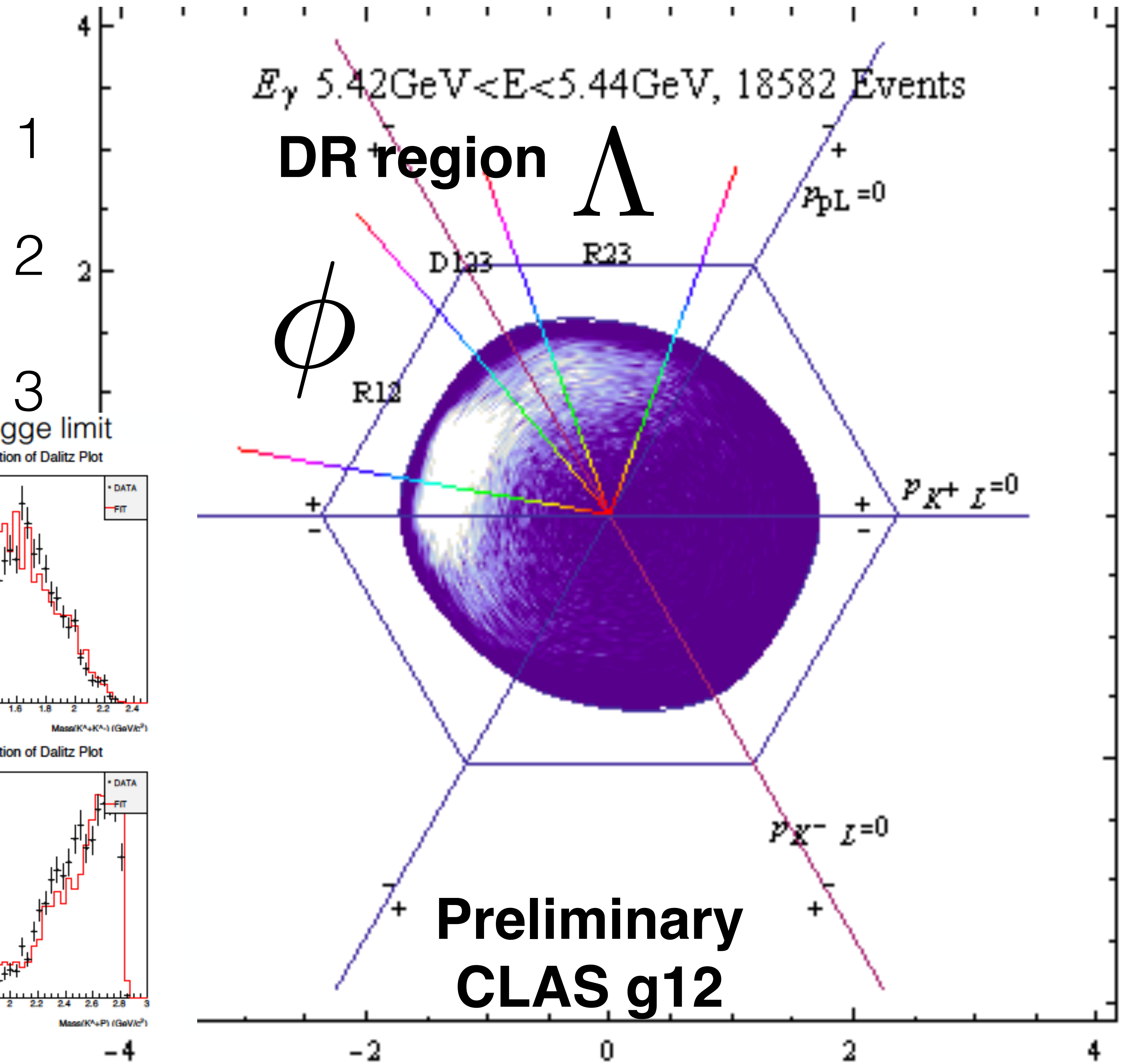
Φ(1020)	49%
f_2(1270)	46%
f_1(1285)	9%
a_2(1320)	49%
f_0(1370)	seen
f_1(1420)	dominant
η(1440)	seen
a_0(1450)	seen
f_0(1500)	seen
f'_2(1525)	89%
Φ(1680)	seen
ρ3(1690)	1.6%
ρ (1700)	seen
f_0(1710)	seen
$Φ_3$(1850)	seen
a_4(1450)	seen
f_4(2050)	7%

$\gamma p \to K^+K^-p$ (g11,g12)

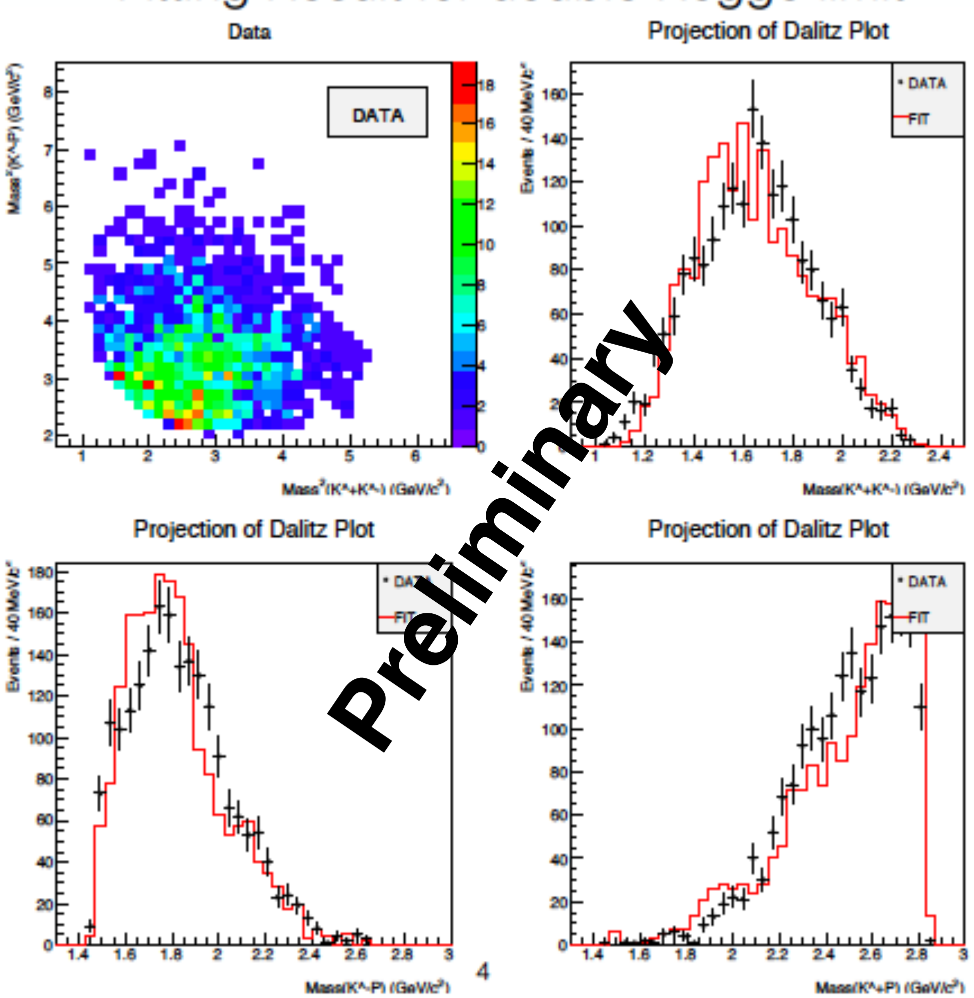
D.Schott, JPAC/GWU
M. Shi JPAC/Pekin U.

van Hove longitudinal plot



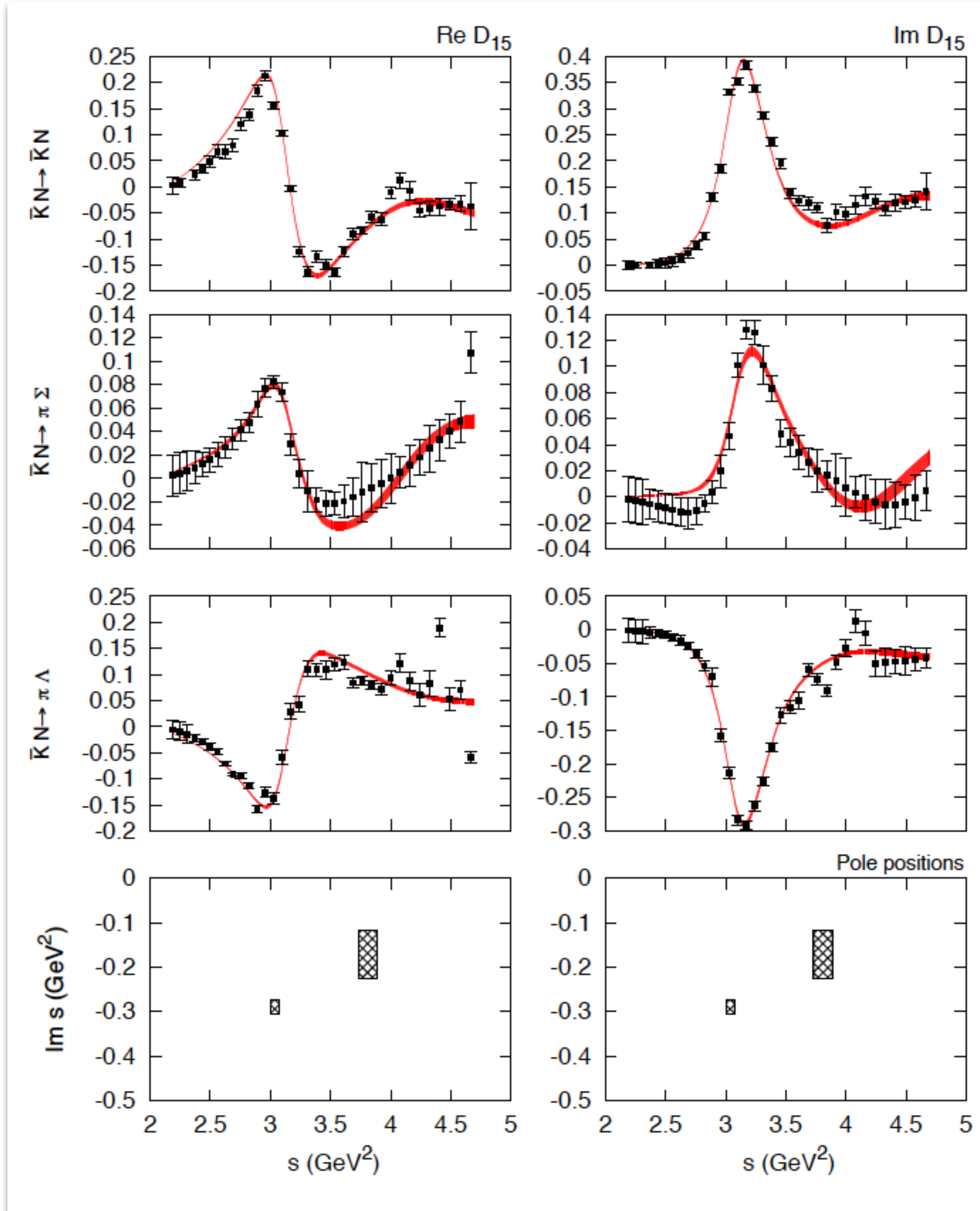


Fitting Result for double Regge limit



$$(\bar{K}N), (\pi\Sigma), (\pi\Lambda) \rightarrow (\bar{K}N), (\pi\Sigma), (\pi\Lambda)$$

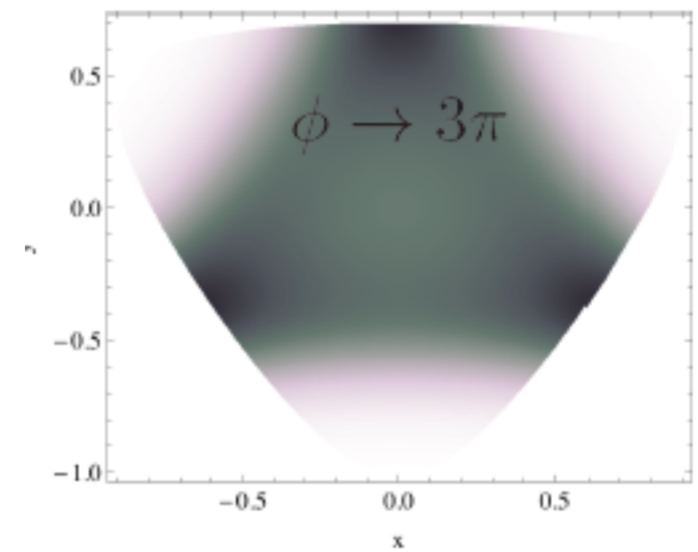
Hyperon production
what is Lambda(1405)?

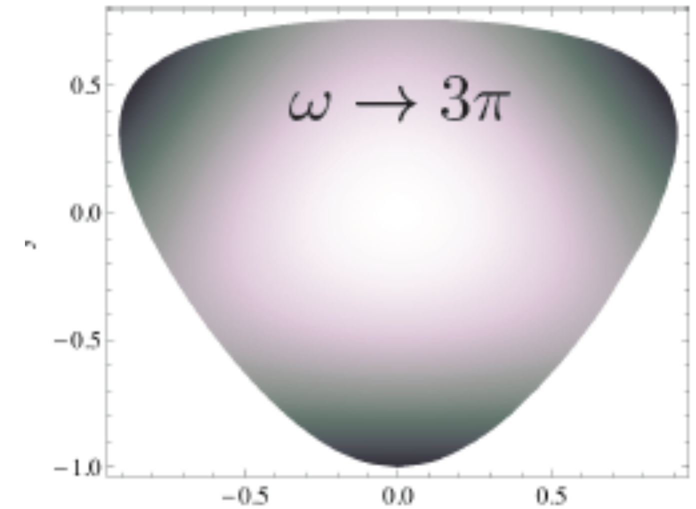


C.Fernandez Ramirez, JPAC

Light meson decays

$\eta \to 3\pi \quad \omega \to 3\pi \quad \phi \to 3\pi$





- **Constrained phase space,**
- **Effective (chiral) dynamics,**
- **Small number of partial waves,**
- **Amendable to dispersive methods**

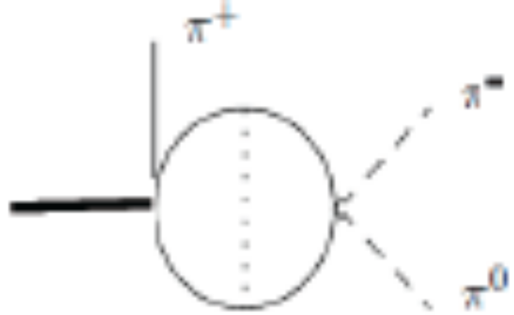
$\eta \to 3\pi$

$$A(s,t,u) = -\frac{1}{Q^2}\frac{M_K^2}{M_\pi^2}\frac{M_K^2 - M_\pi^2}{3\sqrt{3}F_\pi^2} M(s,t,u) \qquad \left(Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \right)$$

$\eta \to 3\pi$

Ex: $\eta \to 3\pi$ $\quad \Gamma_{\eta \to 3\pi} = 66\text{ eV} + 94\text{ eV} + \ldots = 296\text{ eV}$

LO NLO Experiment



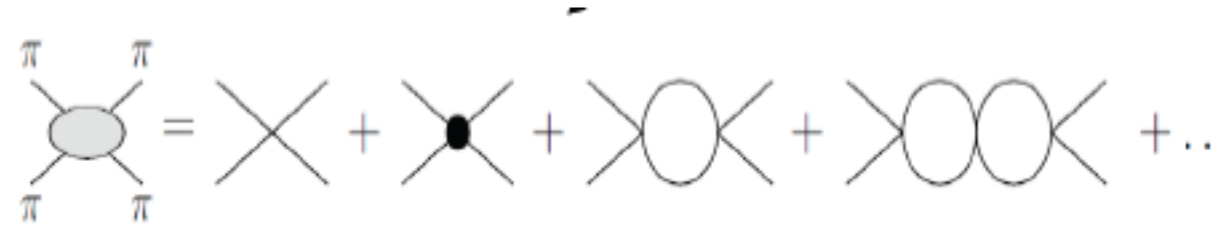


TABLE III: Dalitz plot parameters for $\eta \to 3\pi^0$. Set 1 and Set 2 correspond to $(I,L) = (0,0), (1,1)$ and $(I,L) = (0,0), (2,0), (1,1)$ cases respectively (see Table I).

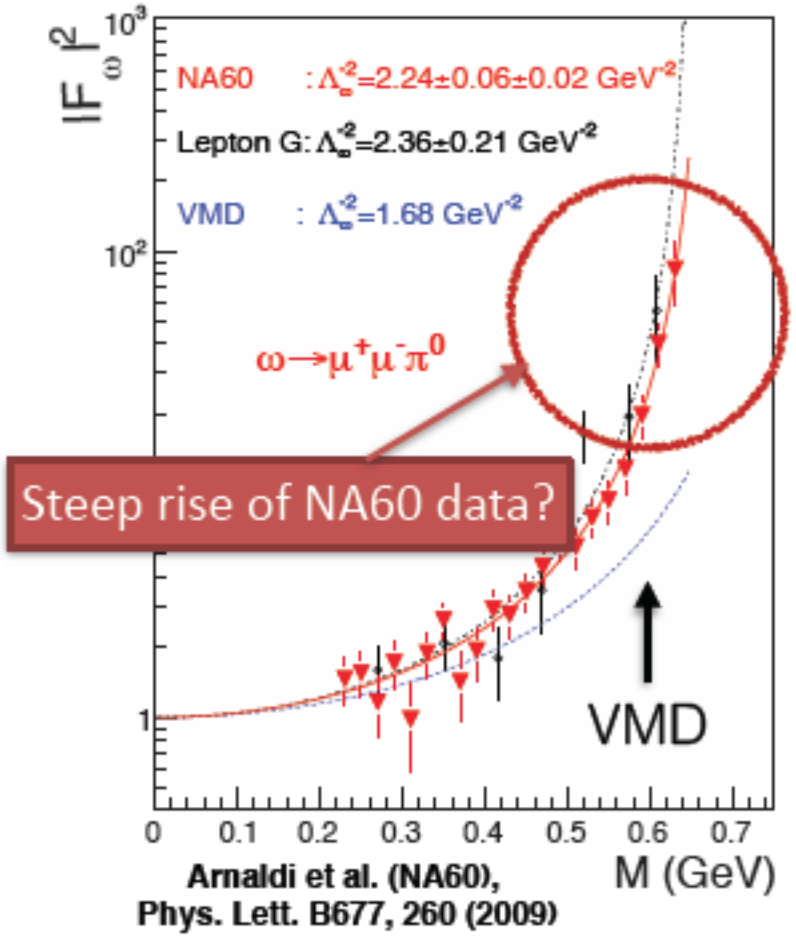
	α	β
GAMS-2000 [49]	-0.022 ± 0.023	–
Crystal Barrel, LEAR [50]	-0.052 ± 0.020	–
Crystal Ball, BNL [14]	-0.031 ± 0.004	–
SND [51]	-0.010 ± 0.023	–
CELSIUS-WASA [12]	-0.026 ± 0.014	–
WASA-at-COSY [52]	-0.027 ± 0.009	–
MAMI-B [53]	-0.032 ± 0.004	–
MAMI-C [46]	-0.032 ± 0.003	–
KLOE [16]	-0.0301 ± 0.0050	–
PDG average [1]	-0.0317 ± 0.0016	–
Theory		
Set 1	-0.023 ± 0.004	-0.000 ± 0.002
Set 2	-0.020 ± 0.004	-0.001 ± 0.003
NLO [21]	$+0.013$	–
NNLO [22]	$+0.013 \pm 0.032$	–
Kambor *et al.* [23]	$-0.007 \ldots -0.014$	–
NREFT [28]	-0.025 ± 0.005	-0.004 ± 0.001
Kampf *et al.* [29]	-0.044 ± 0.004	–

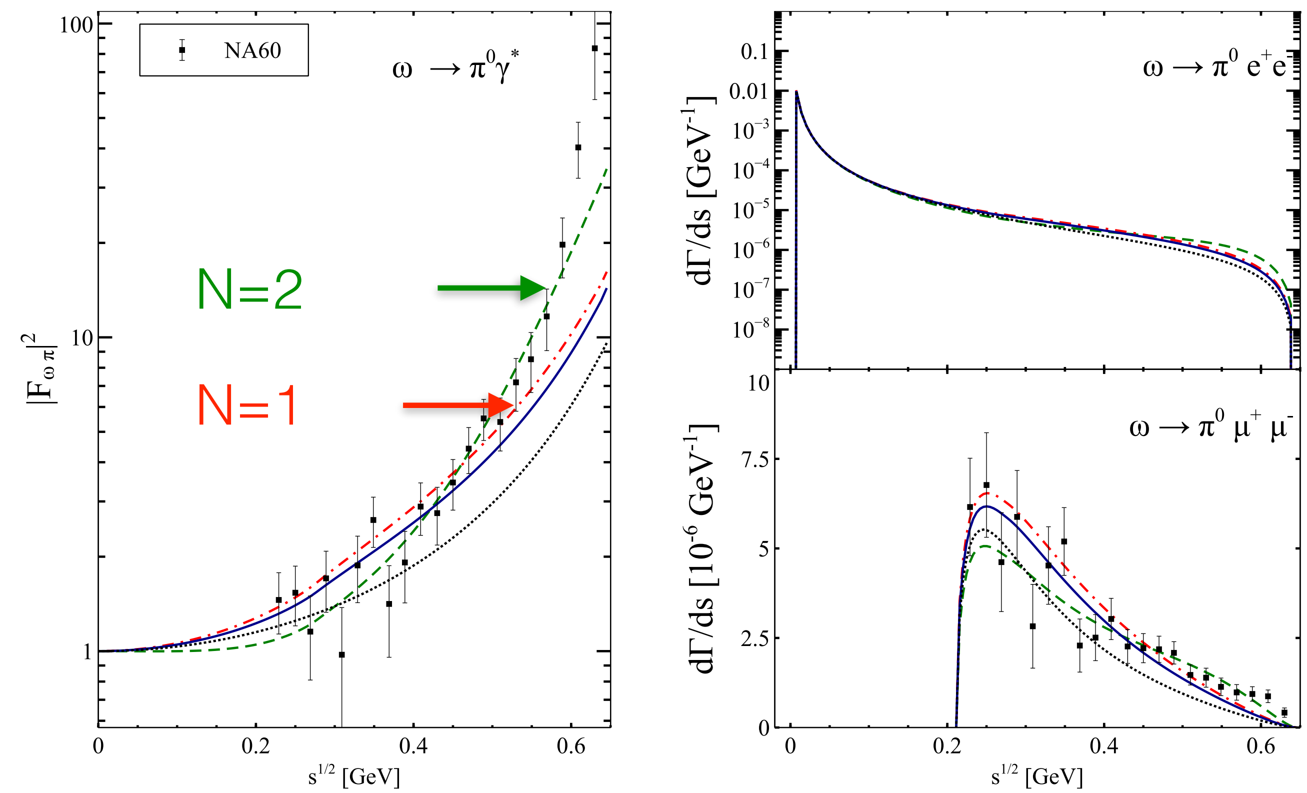
TABLE II: Dalitz plot parameters for $\eta \to \pi^+\pi^-\pi^0$. Set 1 and Set 2 correspond to $(I,L) = (0,0), (1,1)$ and $(I,L) = (0,0), (2,0), (1,1)$ cases respectively (see Table I).

	a	b	d	f
WASA-at-COSY [11]	-1.144 ± 0.018	$0.219 \pm 0.019 \pm 0.037$	$0.086 \pm 0.018 \pm 0.018$	0.115 ± 0.037
KLOE [15]	$-1.090 \pm 0.005^{+0.008}_{-0.019}$	$0.124 \pm 0.006 \pm 0.010$	$0.057 \pm 0.006^{+0.007}_{-0.016}$	$0.14 \pm 0.01 \pm 0.02$
CBarrel [13]	-1.22 ± 0.07	0.22 ± 0.11	0.06 ± 0.04 (fixed)	–
Layter *et al.* [47]	-1.080 ± 0.014	0.03 ± 0.03	0.05 ± 0.03	–
Gormley *et al.* [48]	-1.17 ± 0.02	0.21 ± 0.03	0.06 ± 0.04	–
Theory				
Set 1	-1.116 ± 0.030	0.188 ± 0.010	0.047 ± 0.005	0.093 ± 0.004
Set 2	-1.117 ± 0.035	0.188 ± 0.014	0.079 ± 0.003	0.090 ± 0.003
NLO [21]	-1.371	0.452	0.053	0.027
NNLO [22]	-1.271 ± 0.075	0.394 ± 0.102	0.055 ± 0.057	0.025 ± 0.160
Kambor *et al.* [23]	-1.16	$0.24 \ldots 0.26$	$0.09 \ldots 0.10$	–
NREFT [28]	-1.213 ± 0.014	0.308 ± 0.023	0.050 ± 0.003	0.083 ± 0.019

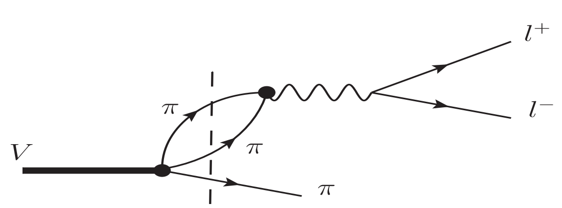
P.Guo, I.Danilkin, HASPEC/JPAC

$\omega \to \pi^0 \gamma^*$

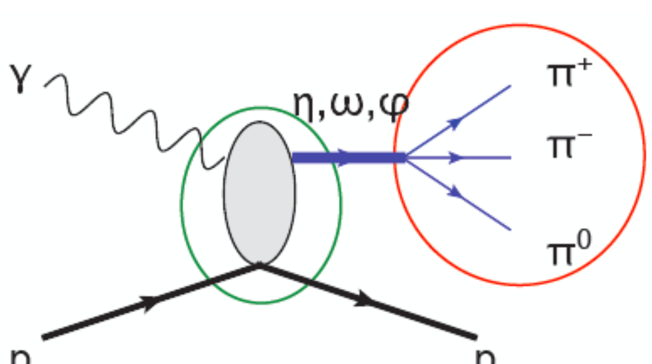




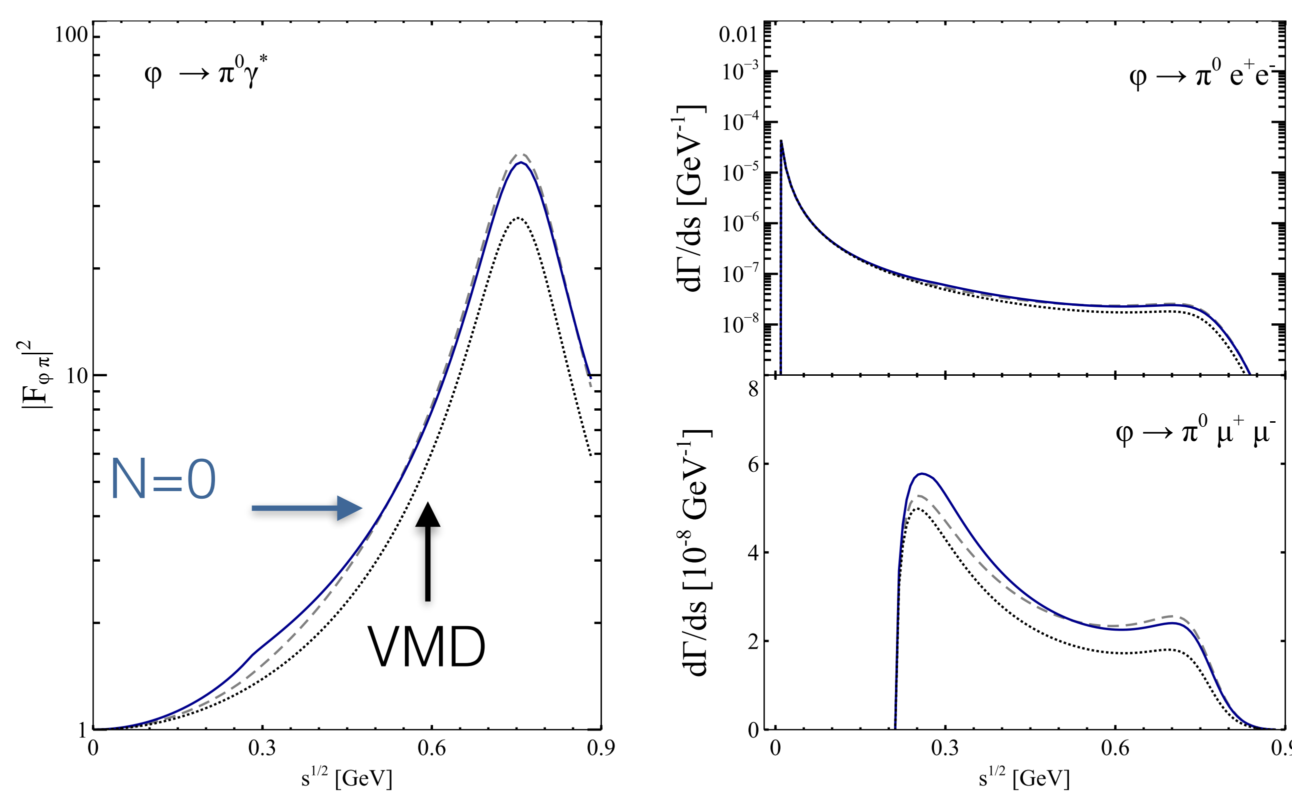
I.Danilkin, JPAC



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



upcoming
CLAS g12



JPAC memebrs

Igor Danilkin
Viktor Mokeev
Peng Guo
Michael Pennington
Cesar Ramirez
Meng Shi
Lingun Dai
Geoffrey Fox

Andrew Jackura
Vincent Mathieu
Emilie Passemar
Michael Doering
Ron Workman
Diane Schott
Adam S.

Astrid Blin (Valencia)
Ina Lorenz (Bonn)
Alessandro Piloni (Rome)
Vlad Pauk (Mainz)
Misha Mikhasenko (Bonn)

https://wiki.jlab.org/jpac/

- $\gamma p \to \pi^0 p$
  - Formalism
  - Model
  - Resources
  - Run

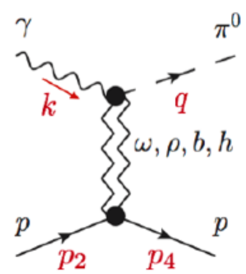
Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

INDIANA UNIVERSITY BLOOMINGTON — Jefferson Lab, Thomas Jefferson National Accelerator Facility — THE GEORGE WASHINGTON UNIVERSITY, WASHINGTON, DC

$\gamma p \to \pi^0 p$

We present the model published in [Mat15a] .
The differential cross section for $\gamma p \to \pi^0 p$ is computed with Regge amplitudes in the domain $E_\gamma \geq 4\,\text{GeV}$ and $0.01 \leq |t| \leq 3$ (in GeV^2).
The formulas can be extrapolated outside these intervals.
We use the CGLN invariant amplitudes A_i defined in [Chew57a].
See the section Formalism for the definition of the variables.
The fitting procedure is detailed in [Mat15a] . We report here only the main feature of the model.



Formalism

The differential cross section is a function of 2 variables. The first is the beam energy in the laboratory frame E_γ (in GeV) or the total energy squared s (in GeV^2). The second is the cosine of the scattering angle in the rest frame $\cos\theta$ or the momentum transfered squared t (in GeV^2).
The momenta of the particles are k (photon), q (pion), p_2 (target) and p_4 (recoil). The pion mass is μ and the proton mass is M.
The Mandelstam variables, $s = (k + p_2)^2, t = (k - q)^2, u = (k - p_4)^2$ are related through $s + t + u = 2M^2 + \mu^2$.

The differential cross section is expressed in term of the parity conserving helicity invariant amplitudes in the t −channel F_i

$$\frac{d\sigma}{dt} = \frac{389.4}{64\pi}\frac{k_t^2}{4M^2E_\gamma^2}\left[2\sin^2\theta_t\left(t|F_1|^2 + 4p_t^2|F_2|^2\right) + (1-\cos\theta_t)^2|F_3 + 2\sqrt{t}p_tF_4|^2 + (1+\cos\theta_t)^2|F_3 - 2\sqrt{t}p_tF_4|^2\right]$$

The differential cross section is expressed in μb/GeV^2. We used $(\hbar c)^2 = 0.3894\,\text{mb.GeV}^2$.
The t −channel is the rest frame of the process $\gamma\pi^0 \to p\bar{p}$.
In the t −channel, the momenta of the nucleon p_t and the pion k_t and the cosine of the scattering angle are

$$k_t = \frac{1}{2}\sqrt{t - 4M^2}, \qquad q_t = \frac{t-\mu^2}{2\sqrt{t}}, \qquad \cos\theta_t = \frac{s-u}{4p_tk_t}. \tag{A.1}$$

The invariant amplitudes F_i are related through the CGLN A_i amplitudes [Chew57a] by

$$F_1 = -A_1 + 2MA_4, \quad \eta = +, \quad CP = + \tag{A.2}$$
$$F_2 = A_1 + tA_2, \quad \eta = -, \quad CP = - \tag{A.3}$$
$$F_3 = 2MA_1 - tA_4, \quad \eta = +, \quad CP = + \tag{A.4}$$
$$F_4 = A_3 \quad \eta = -, \quad CP = + \tag{A.5}$$

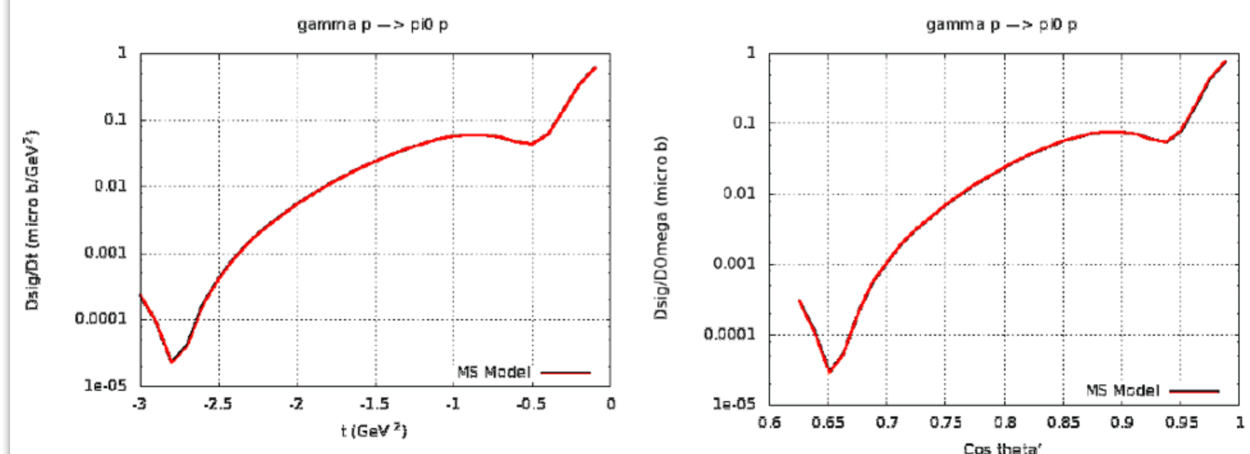
The F_i amplitudes have good quantum numbers of the t −channel, the naturality $\eta = P(-1)^J$ and the product CP.

Run the code

Choose the beam energy in the lab frame E_γ, the other variable (t or $\cos\theta$) and its minimal, maximal, and increment values.
If you choose t (cos) only the min, max and step values of t ($\cos\theta$) are read.

E_γ in GeV	9		
⊙ t ○ cos			
t in GeV^2 (min max step)	-3	-0.1	0.1
$\cos\theta$ (min max step)	0.5	0.95	0.01

Download the output file, the plot with Ox=t , the plot with Ox=cos .
In the file, the columns are: t (GeV^2), cos, Dsig/Dt (micro barn/GeV^2), Dsig/DOmega (micro barn)



special thanks to Vincent Mathieu

http://cgl.soic.indiana.edu/jpac

supported by NSF "Physics at the Information Frontier: Extensible Computational Services for Discovery of New Particles"