Hadron Spectroscopy: challenges and opportunities

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Evidence of new hadrons

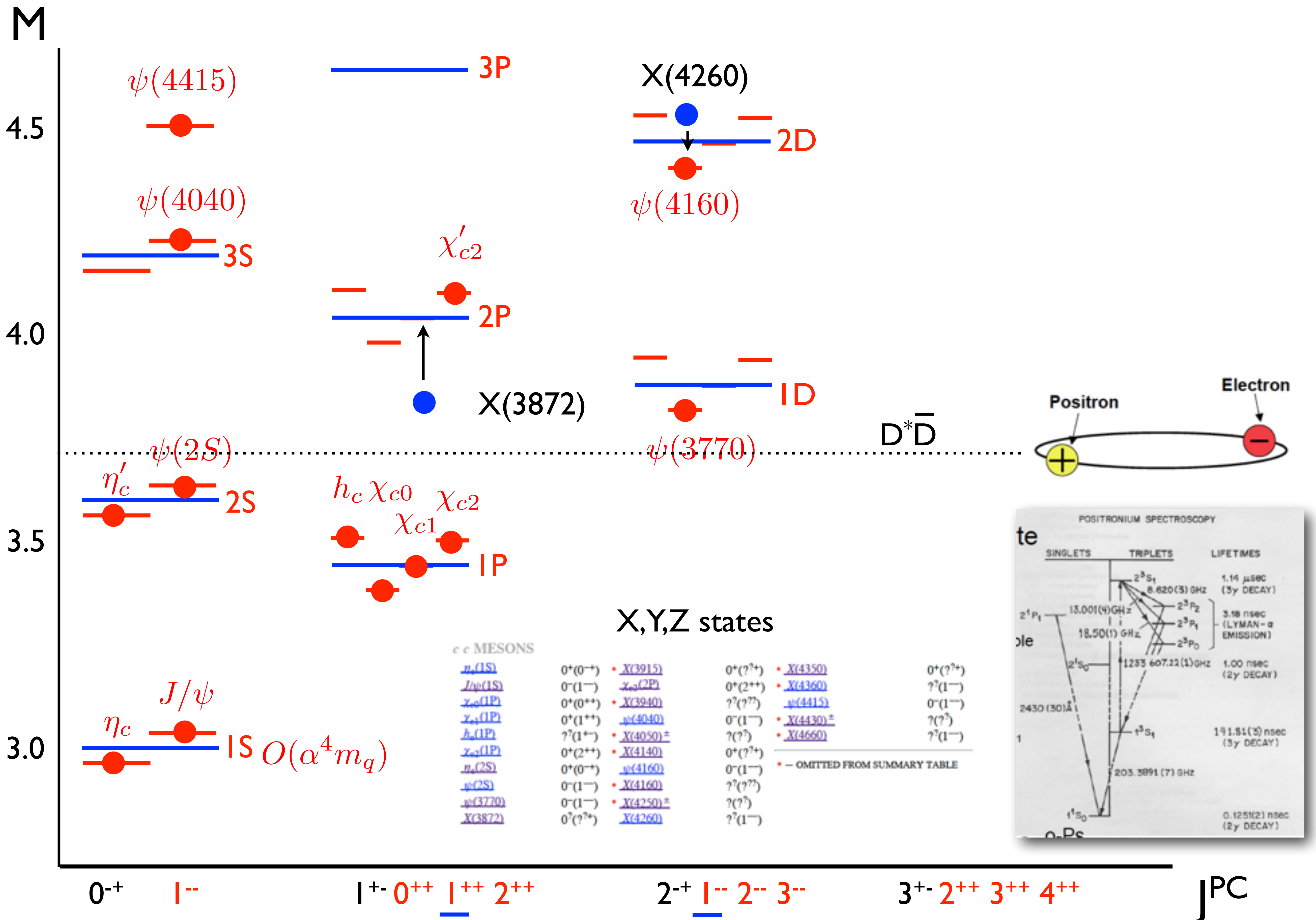
Role of reaction theory

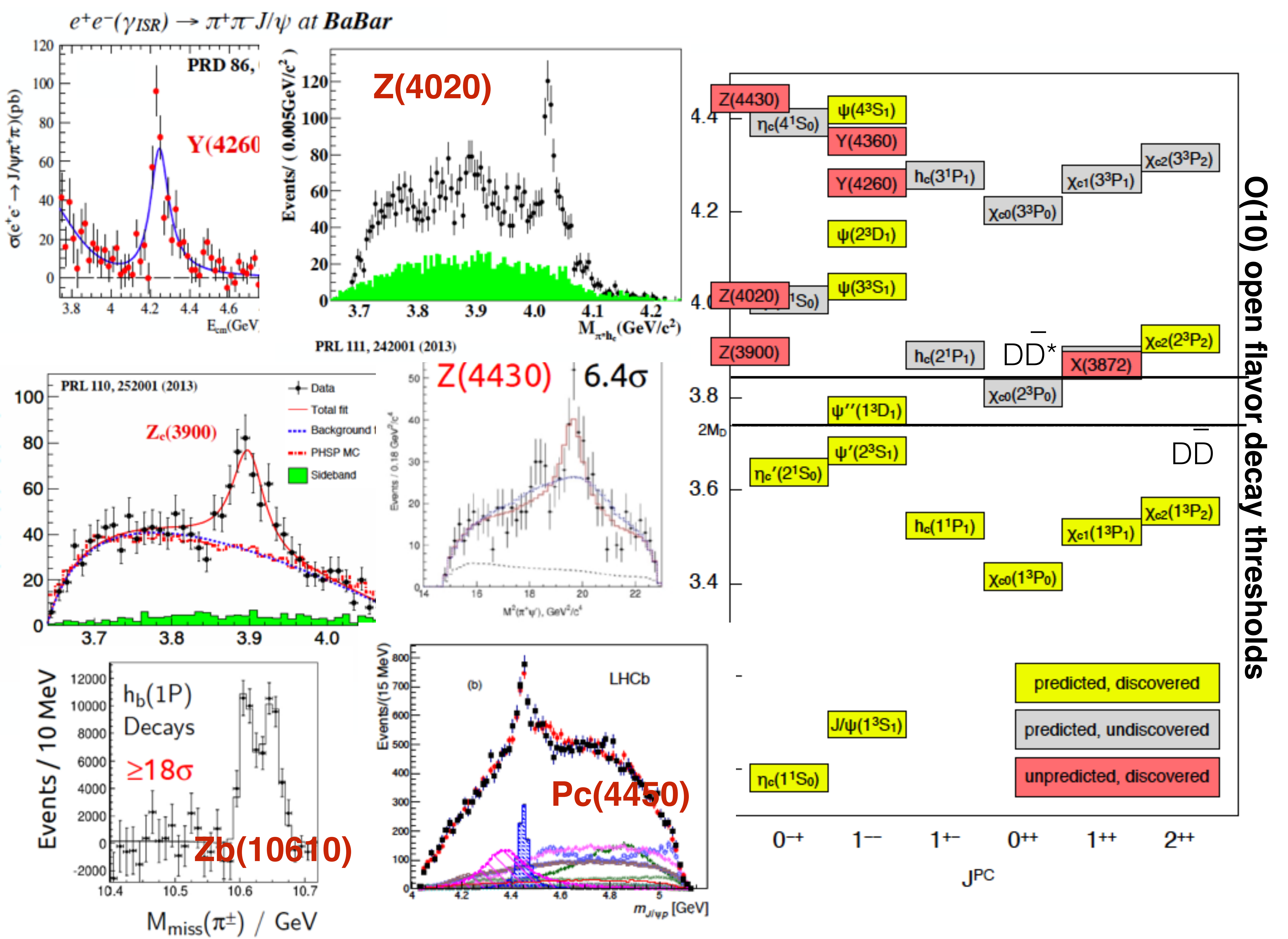
The XYZ's and exotics

JPAC

supported by US DOE,
US NSF

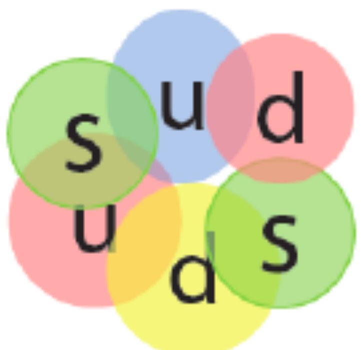
Long time ago hadrons were made from valence quarks





$e^+e^-(\gamma_{ISR}) \to \pi^+\pi^- J/\psi$ at BaBar
PRD 86,
Y(4260
$\sigma(e^+e^- \to J/\psi\pi^+\pi^-)$(pb)
E_{cm}(GeV)
Z(4020)
Events/ (0.005GeV/c^2)
$M_{\pi^+ h_c}$(GeV/c^2)
PRL 111, 242001 (2013)
PRL 110, 252001 (2013)
Data
Total fit
Background
PHSP MC
Sideband
$Z_c(3900)$
Z(4430)
6.4σ
$M^2(\pi^+\psi')$, GeV^2/c^4
$h_b(1P)$
Decays
≥18σ
Zb(10610)
Events / 10 MeV
$M_{miss}(\pi^\pm)$ / GeV
(b)
LHCb
Pc(4450)
Events/(15 MeV)
$m_{J/\psi p}$ [GeV]
Z(4430)
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
Y(4360)
Y(4260)
$h_c(3^1P_1)$
$\chi_{c0}(3^3P_0)$
$\chi_{c1}(3^3P_1)$
$\chi_{c2}(3^3P_2)$
$\psi(2^3D_1)$
Z(4020)
$\psi(3^3S_1)$
Z(3900)
$h_c(2^1P_1)$
$D\bar{D}^*$
X(3872)
$\chi_{c2}(2^3P_2)$
$\chi_{c0}(2^3P_0)$
$\psi''(1^3D_1)$
$2M_D$
$D\bar{D}$
$\psi'(2^3S_1)$
$\eta_c'(2^1S_0)$
$h_c(1^1P_1)$
$\chi_{c1}(1^3P_1)$
$\chi_{c2}(1^3P_2)$
$\chi_{c0}(1^3P_0)$
$J/\psi(1^3S_1)$
$\eta_c(1^1S_0)$
predicted, discovered
predicted, undiscovered
unpredicted, discovered
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
J^{PC}
O(10) open flavor decay thresholds

before we can address this question…

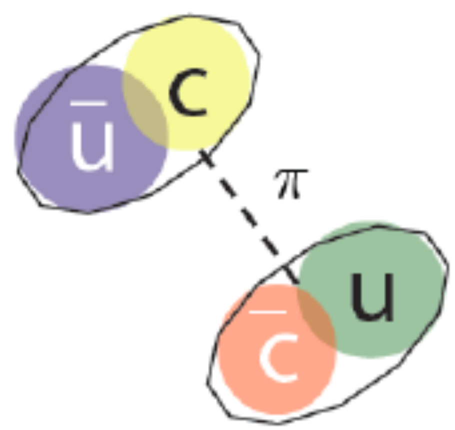


dibaryon

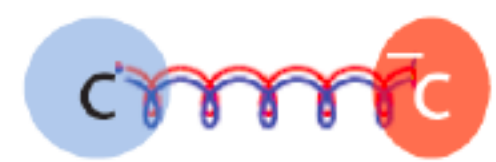
pentaquark

glueball

diquark + di-antiquark

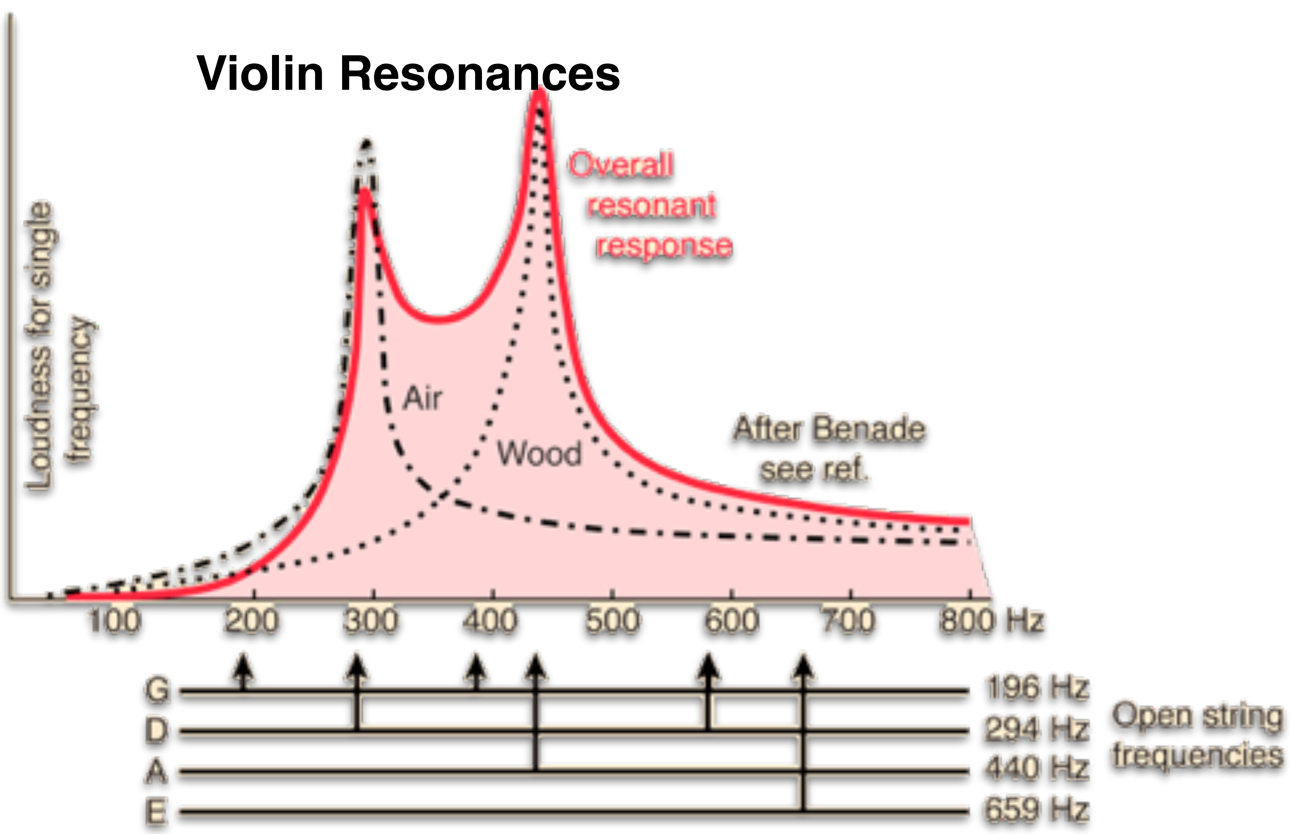


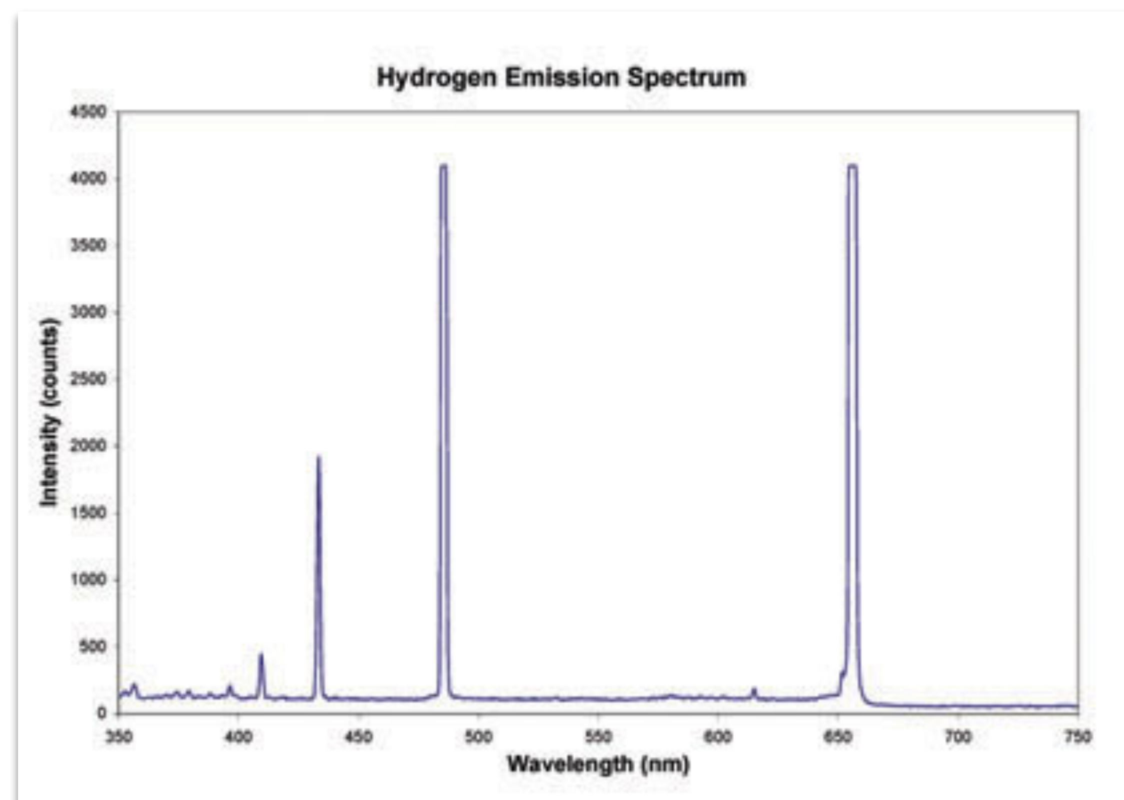
dimeson molecule



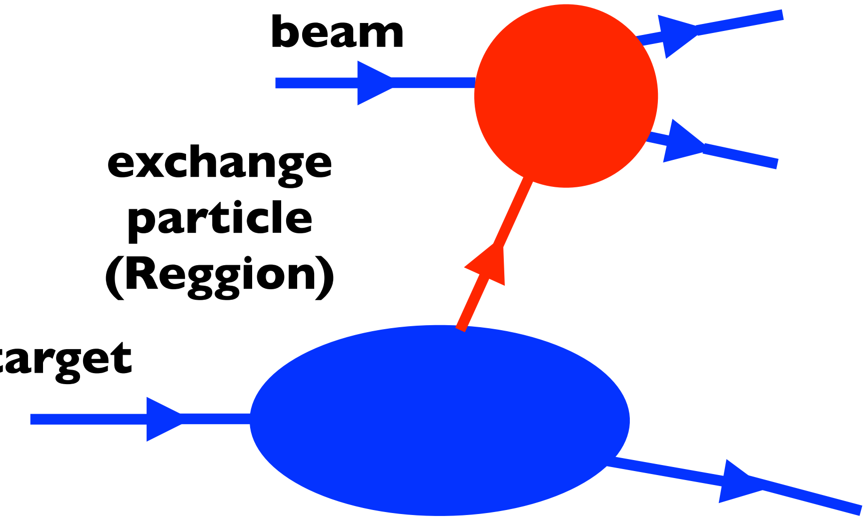
$q\,\bar{q}\,g$ hybrid

…we need to know how to interpret “peaks”

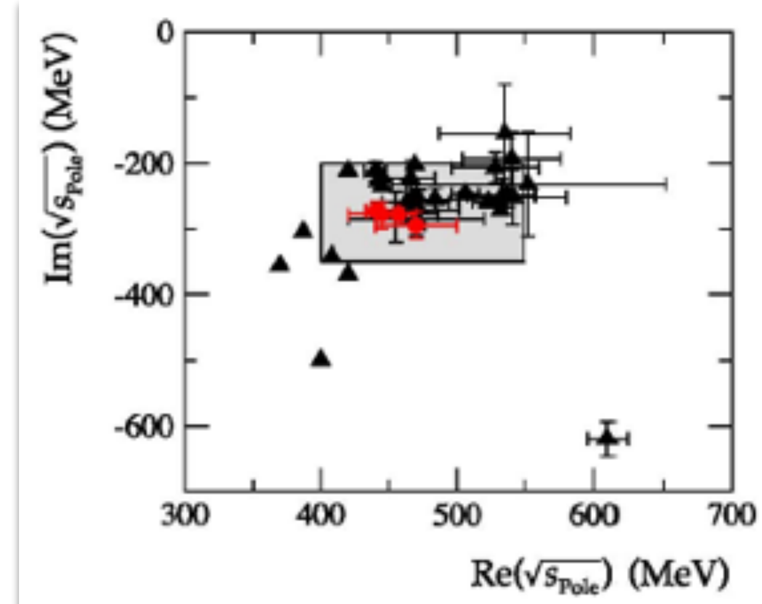




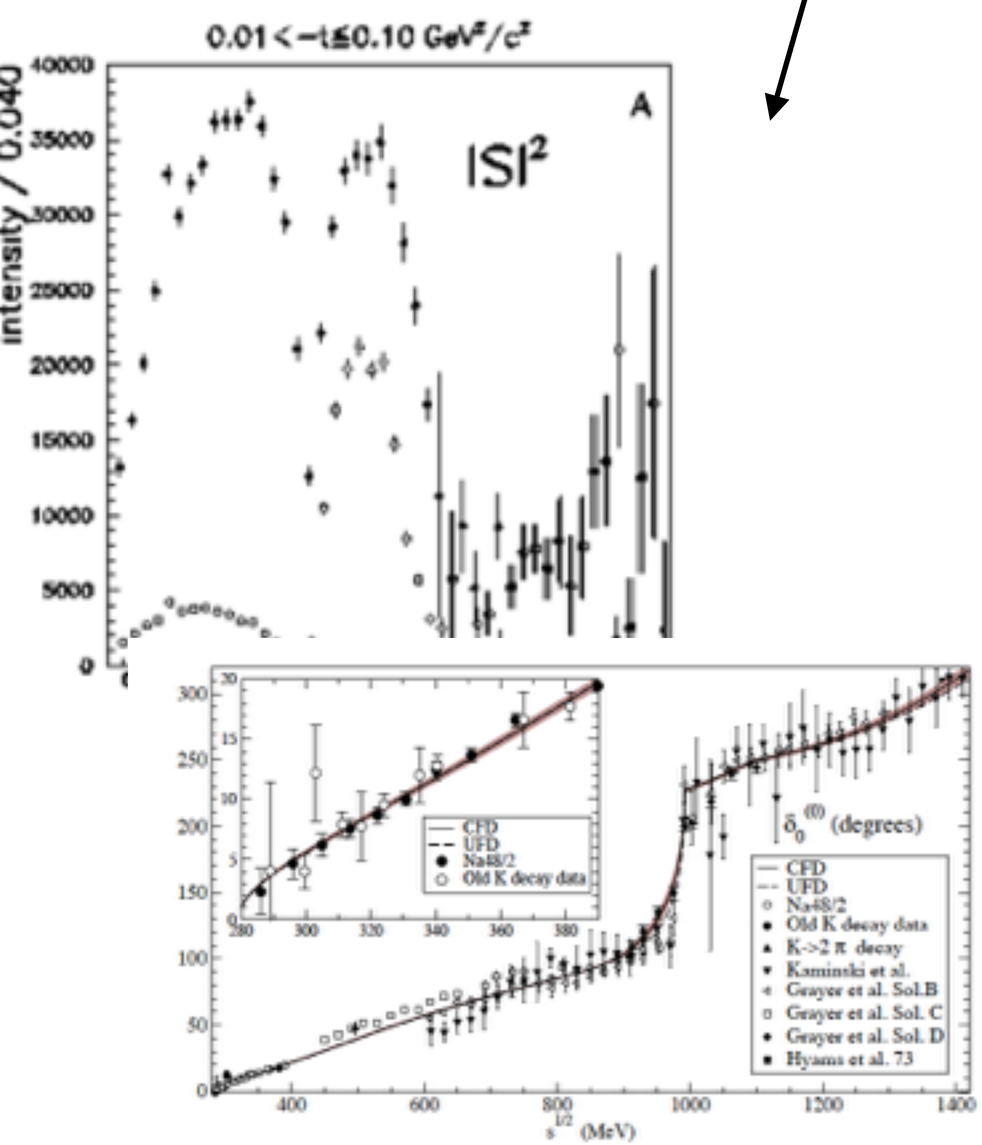
… but state of the art analyst is based on analogy with



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



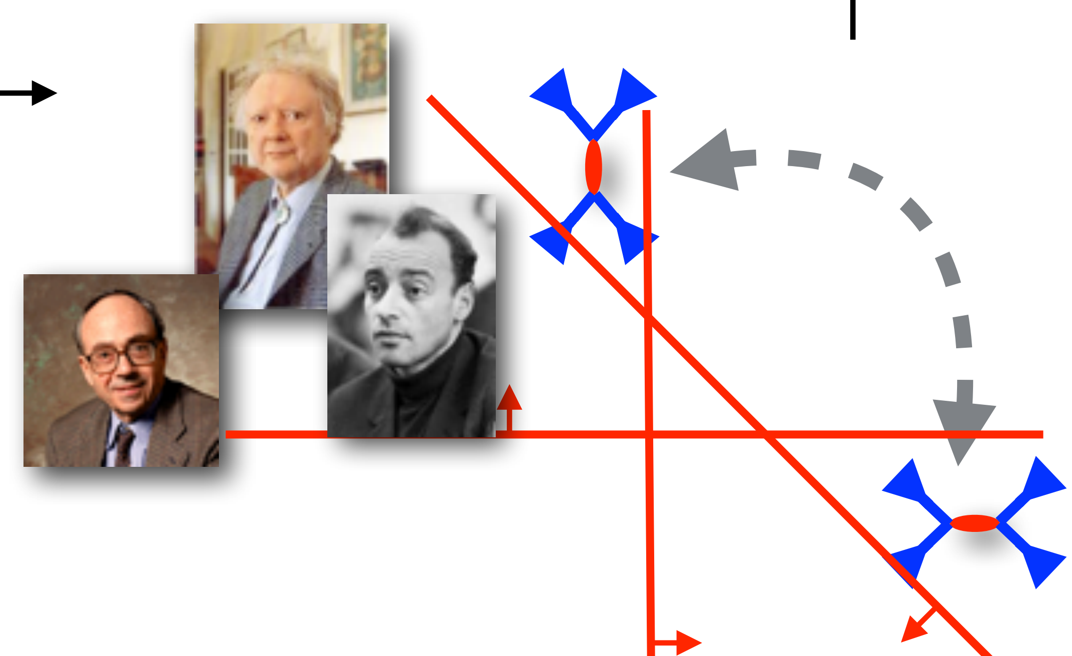
partial wave
extraction



the sigma
meson story

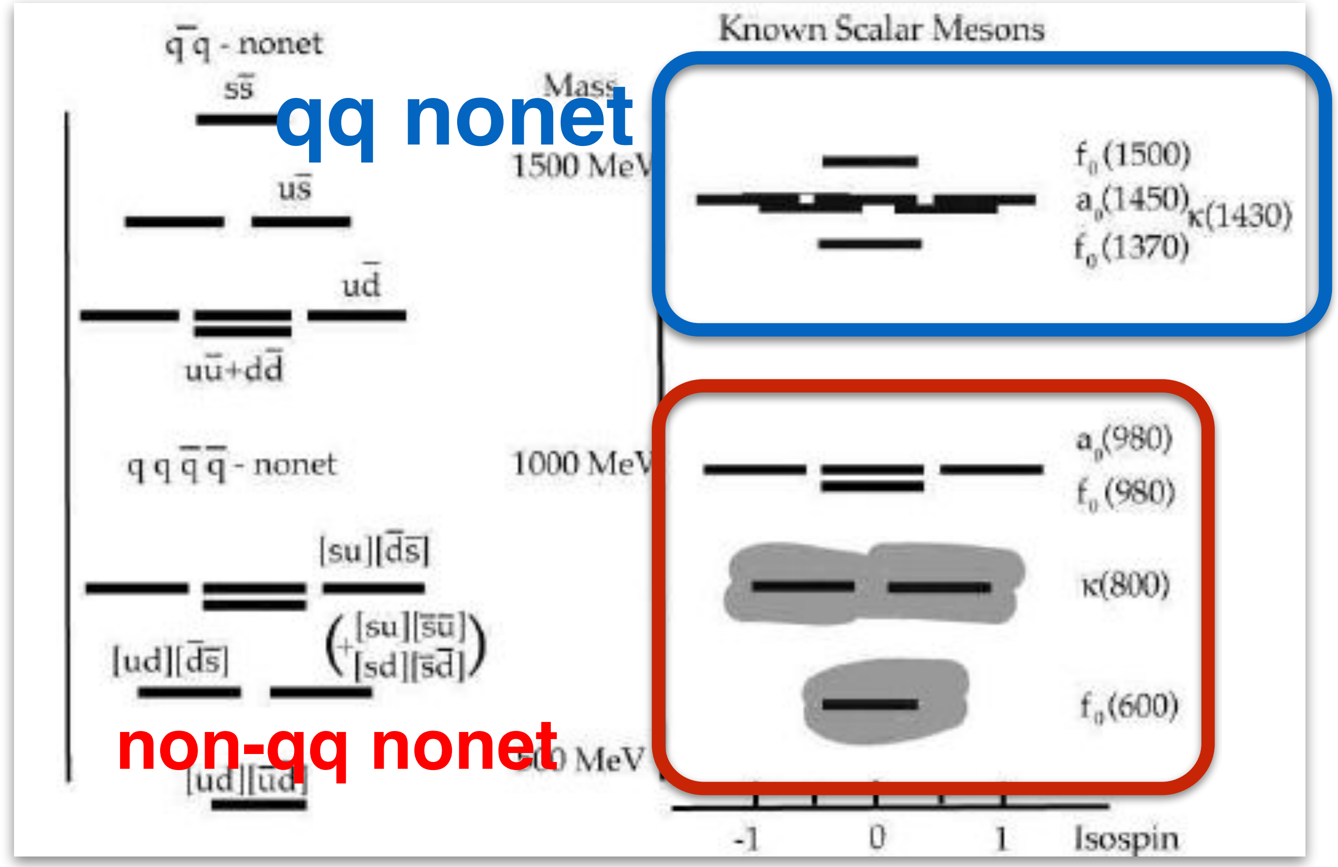
analytical
continuation

amplitude
model



Example of known non-ordinary: σ

Possible evidence for non-qq nature of light scalars



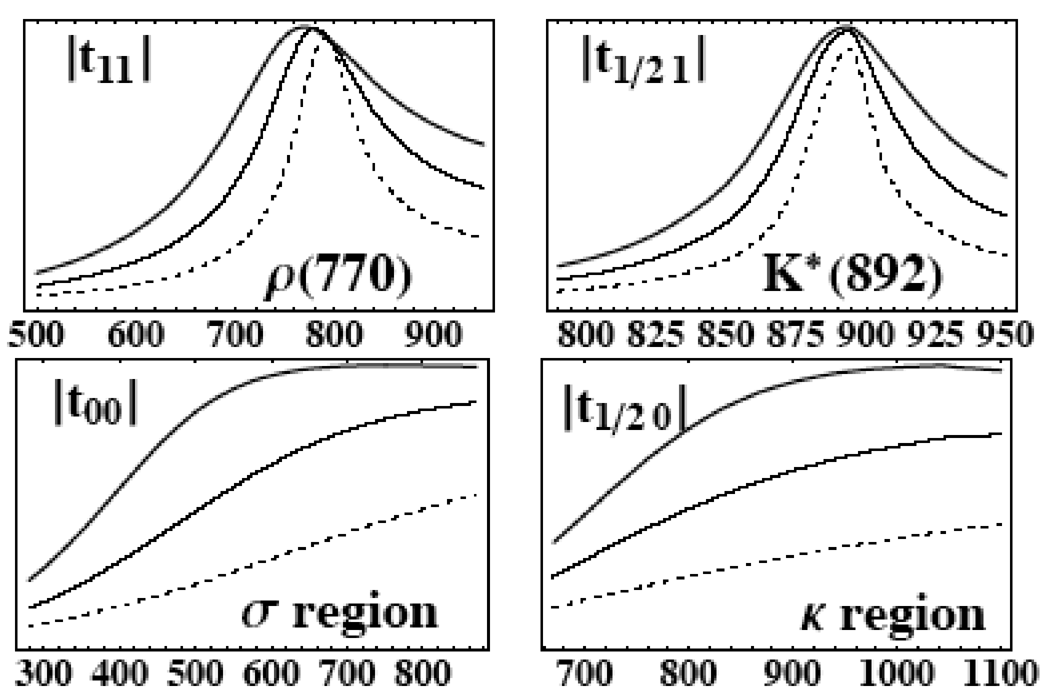
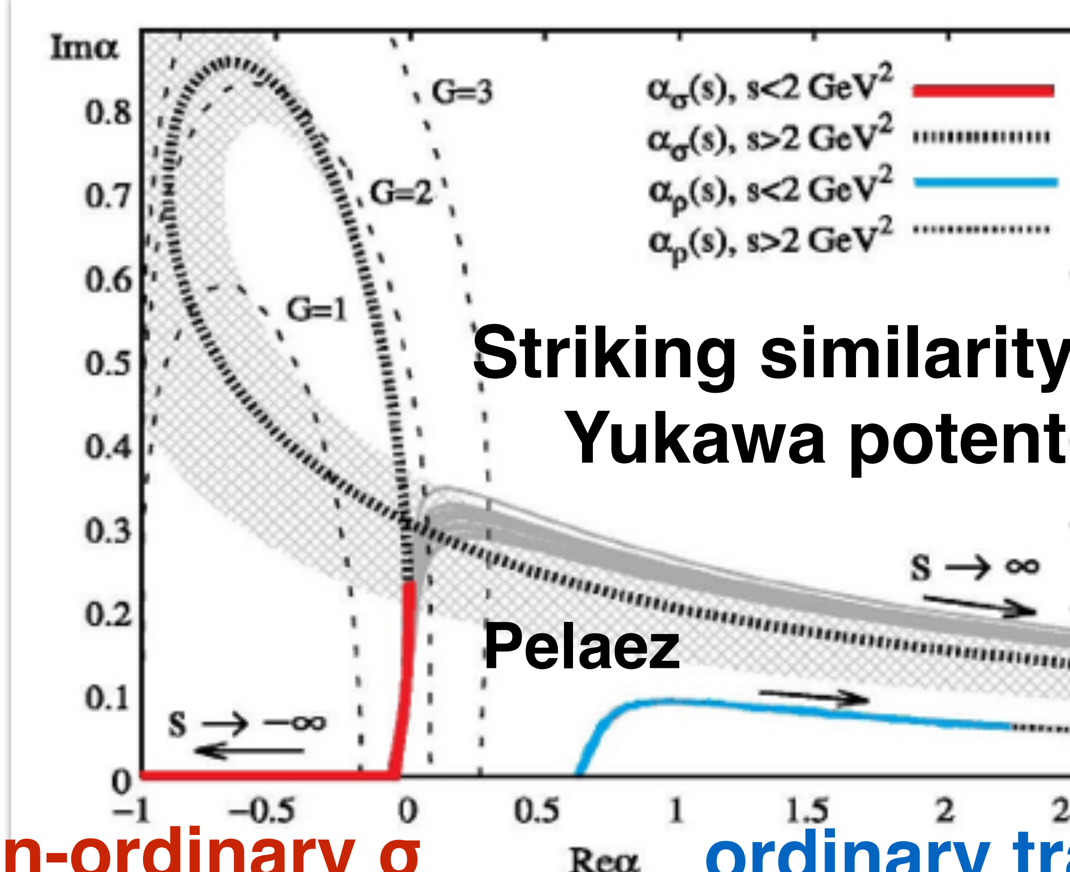


FIG. 1: Modulus of amplitudes in different meson-meson channels for $N_c = 3$ (thick line) $N_c = 5$ (thin continuous line) and $N_c = 10$ (thin dotted line), scaled at $\mu = 770$ MeV.

Pelaez

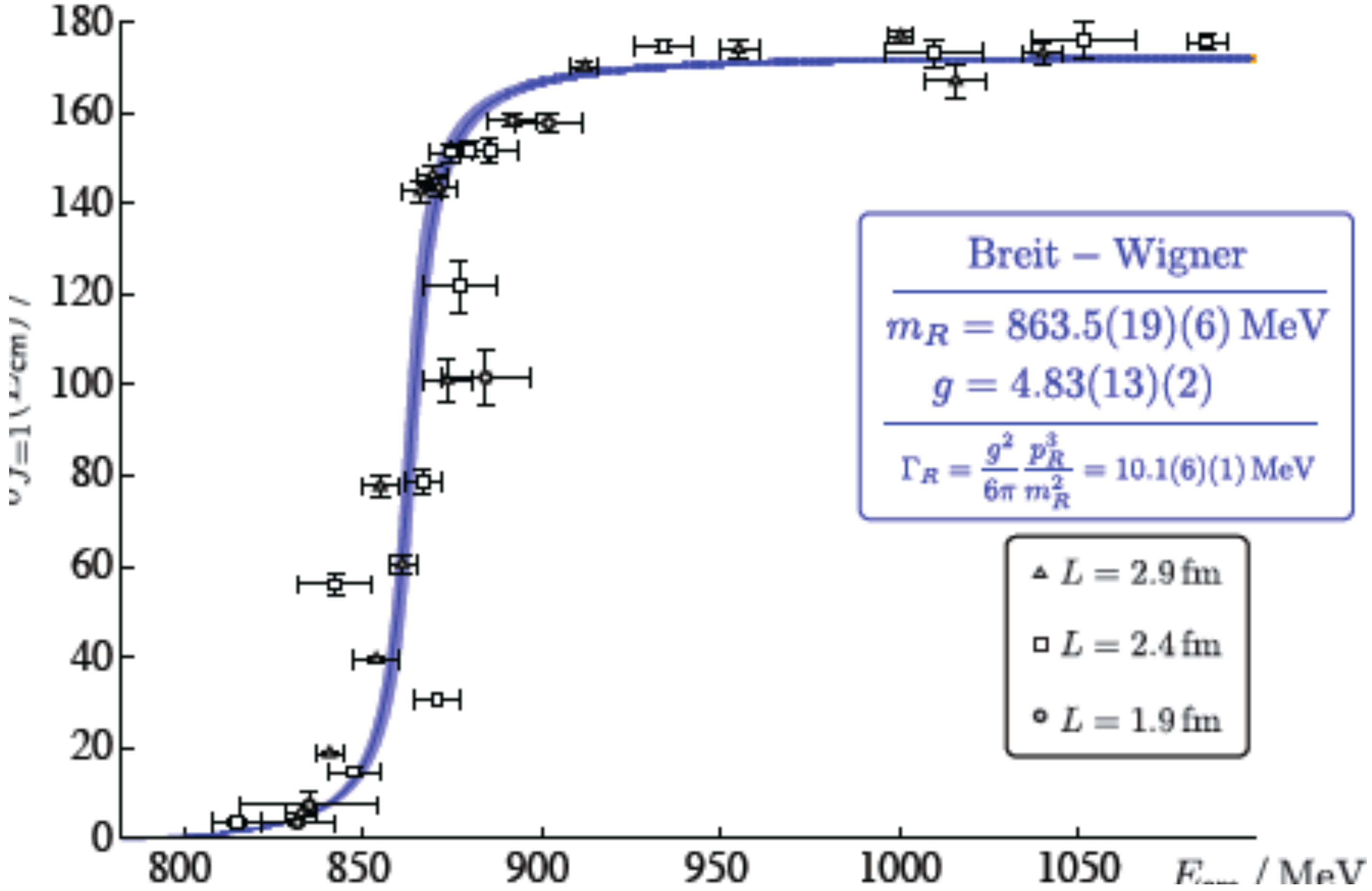


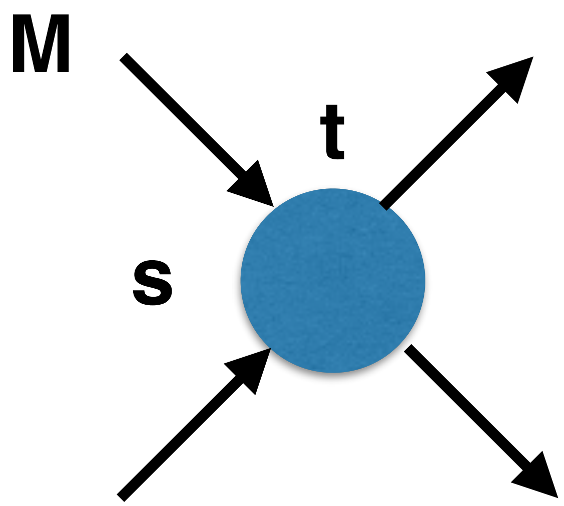
non-ordinary σ ordinary trajectory

lattice : simulated scattering experiment

Lusher condition :

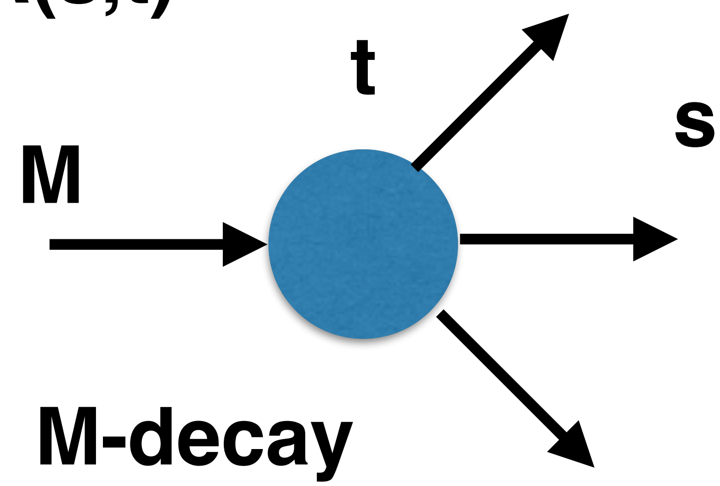
(lattice) $Z(E_i) = T(E_i)$ (infinite volume)





s-channel

A(s,t)

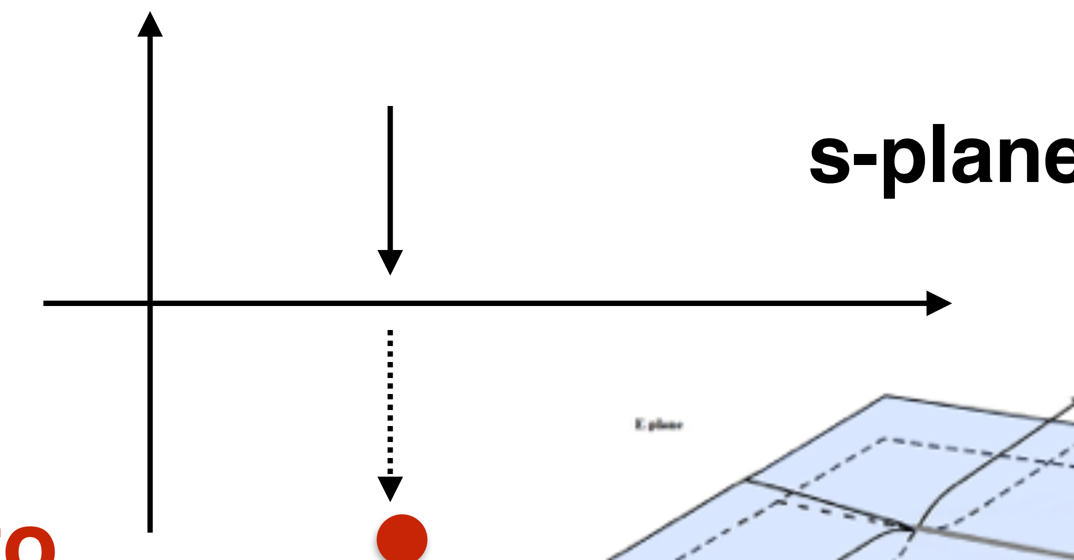


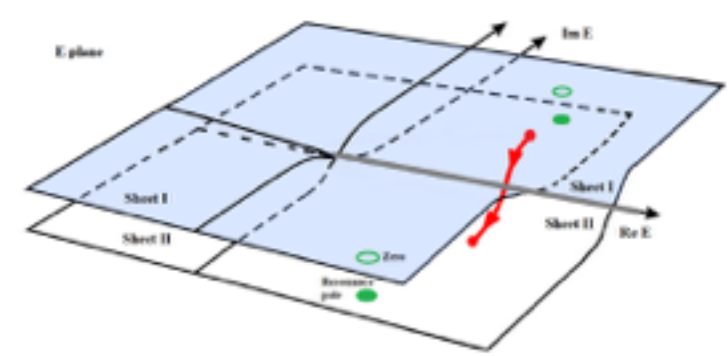
M-decay channel

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

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

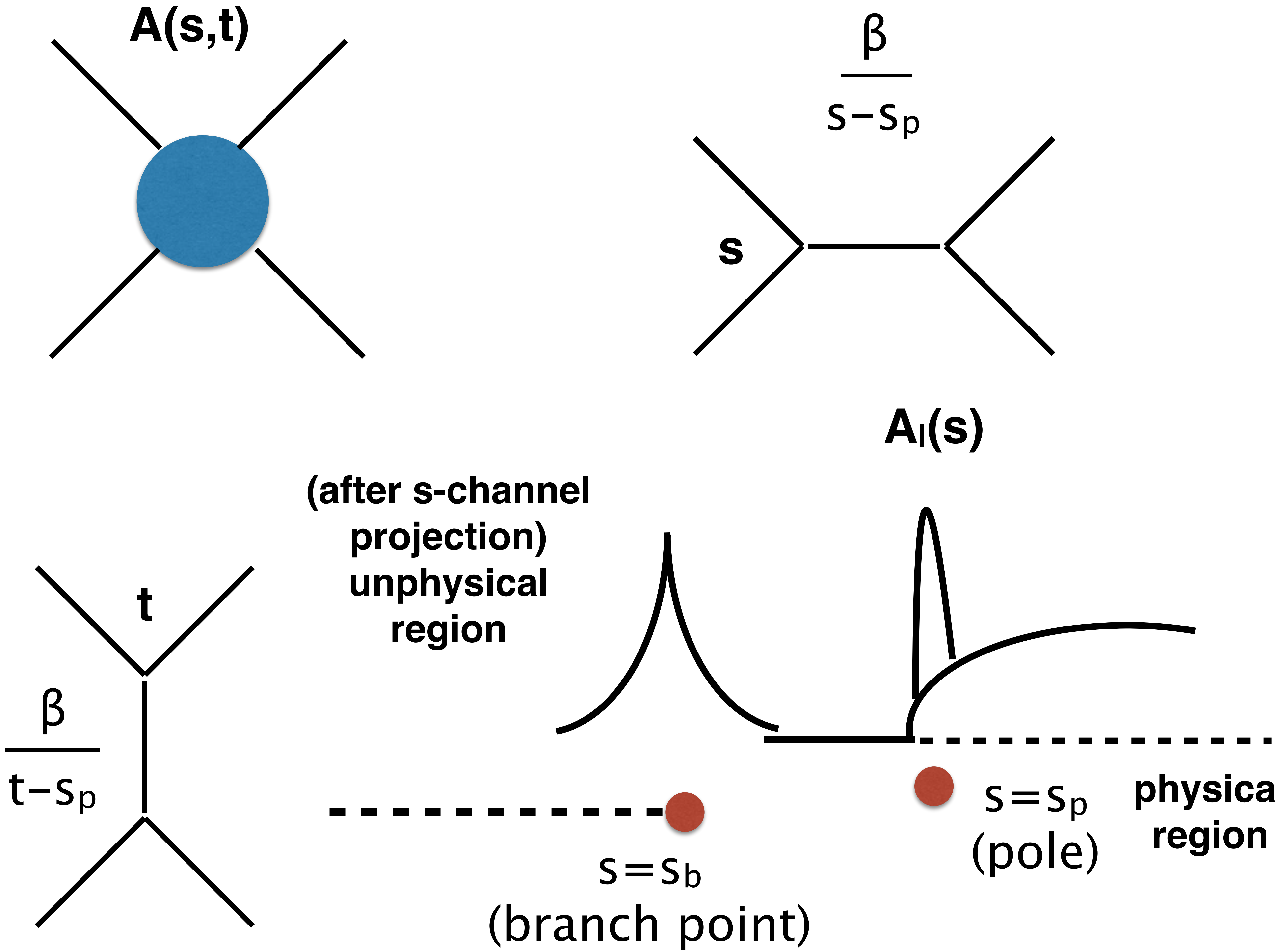
$$A_l(s + i\epsilon) \neq A_l(s - i\epsilon)$$



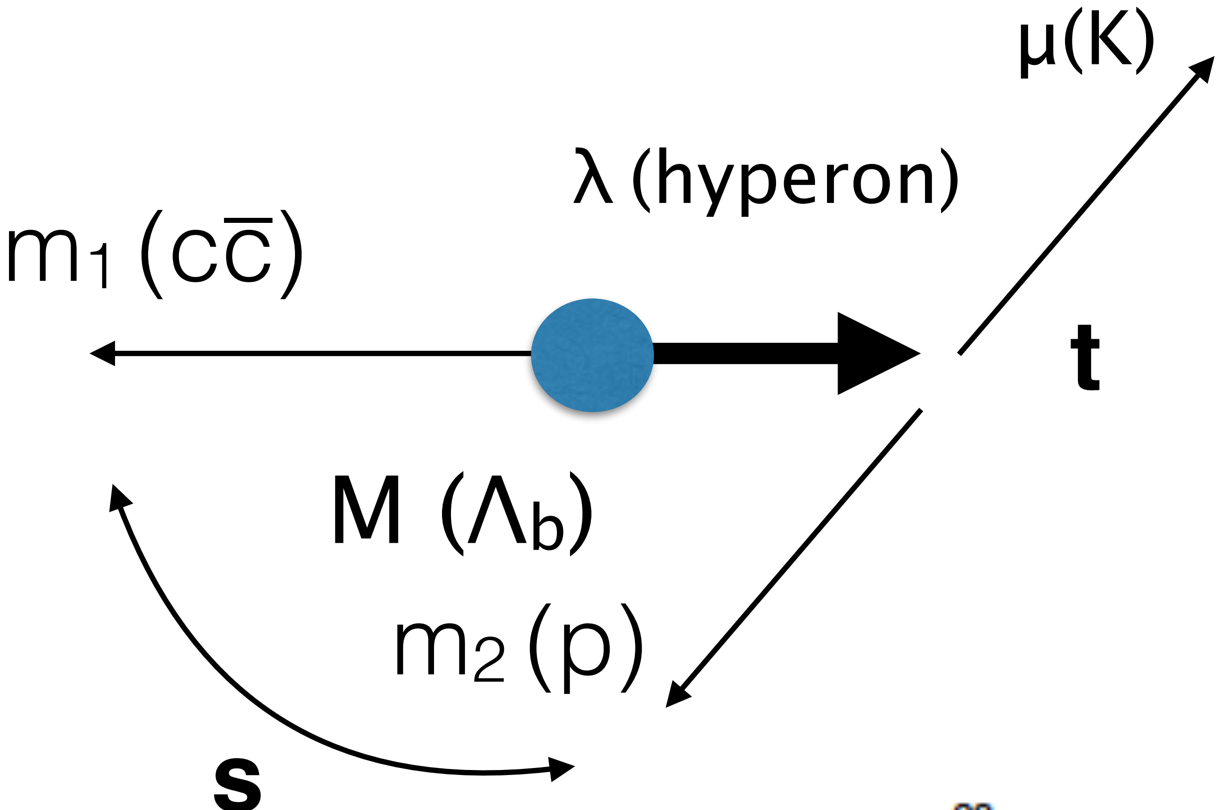


Bumps/peaks on the real axis (experiment) come from singularities of in the complex domain. Complexity of A_l due to open channels, in t,s,u (unitarity)

Unitarity forces cuts : the name of the game is analyticity (different from microscopic models)


A(s,t)
β
s−sp
s
Al(s)
(after s-channel
projection)
unphysical
region
t
β
t−sp
s=sp
(pole)
physical
region
s=sb
(branch point)

Coleman-Norton theorem



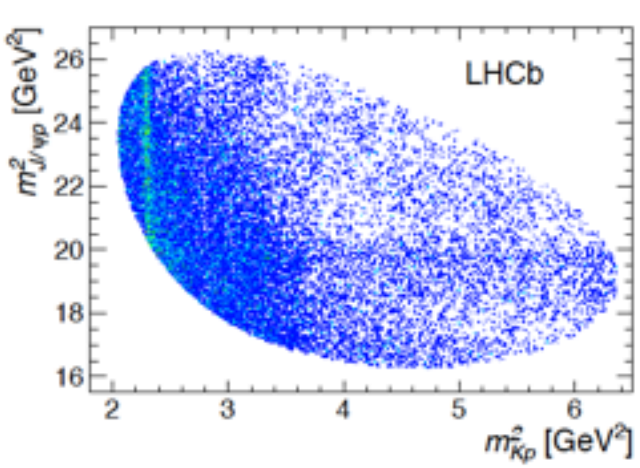
t-channel resonance can produce s-channel "band" if:

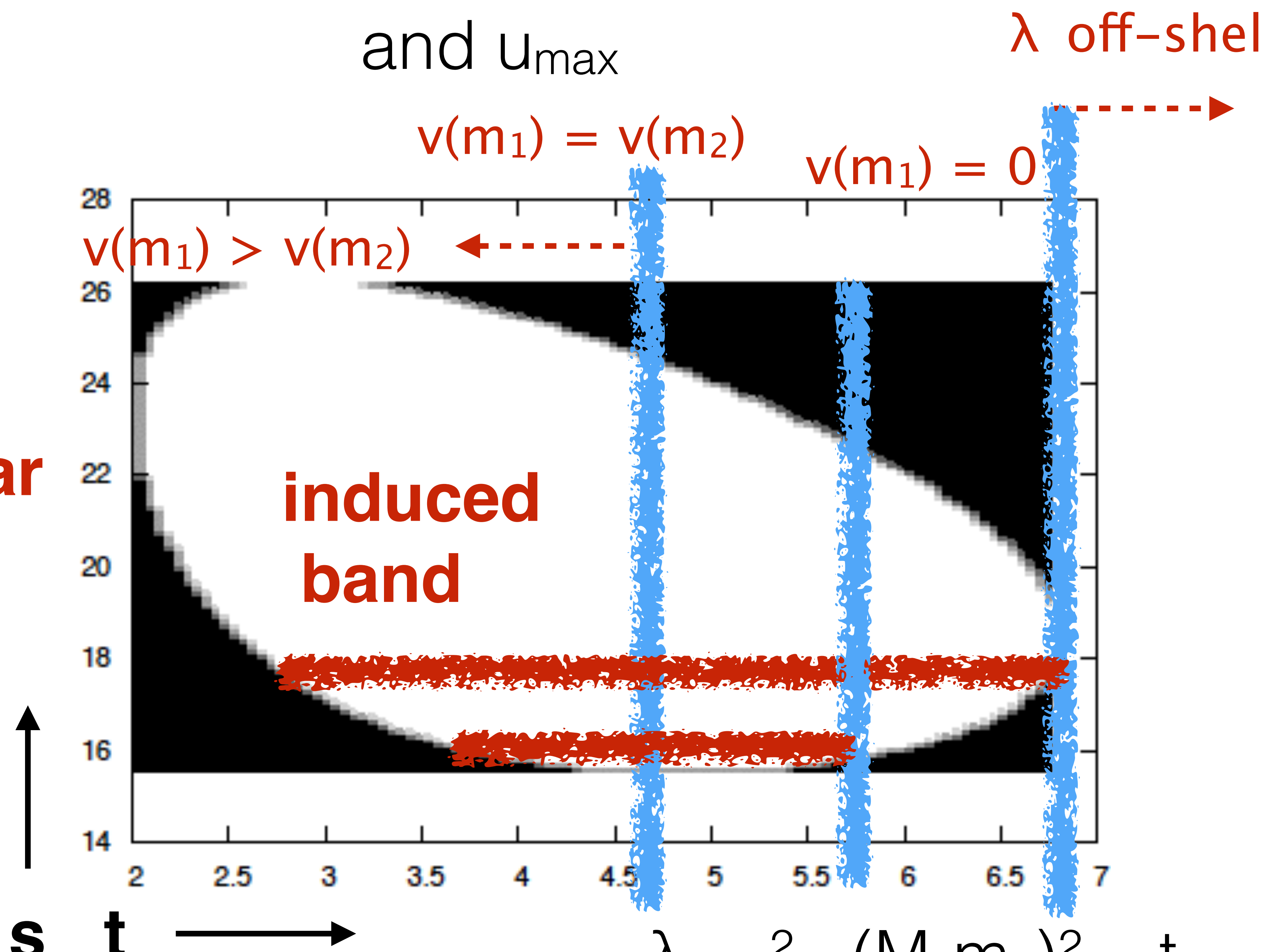
$\lambda_{min}^2 = t$ @ $s_{treshold}$
and u_{max}

all particles on-shell

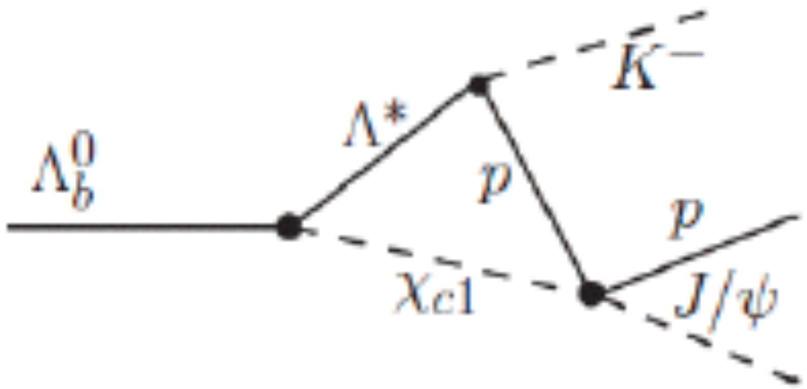
m_2 and m_1 collinear

$v(m_2) > v(m_1)$





$\lambda_{max}^2 = (M-m_1)^2 = t_{max}$



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

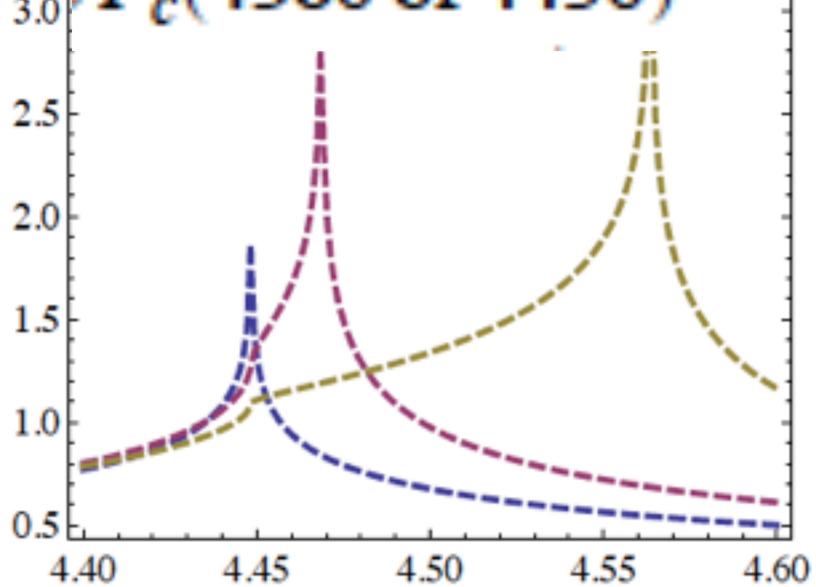
$\lambda = m_{\Lambda^*} = 1.89$ (they take)

Coleman-Norton requires

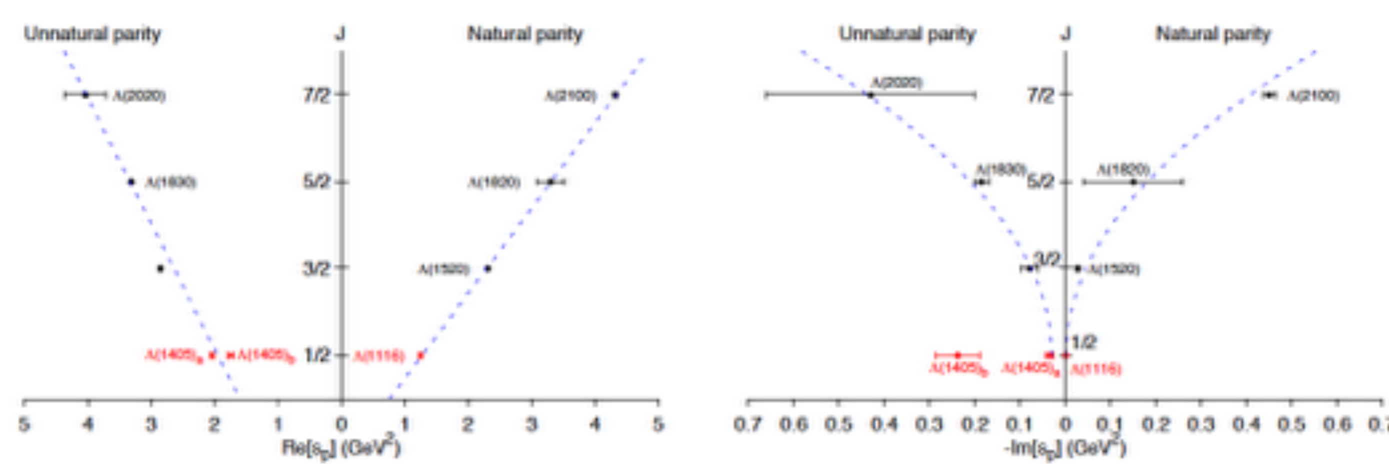
$$1.89 < \lambda < 2.11\ \text{GeV}$$

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

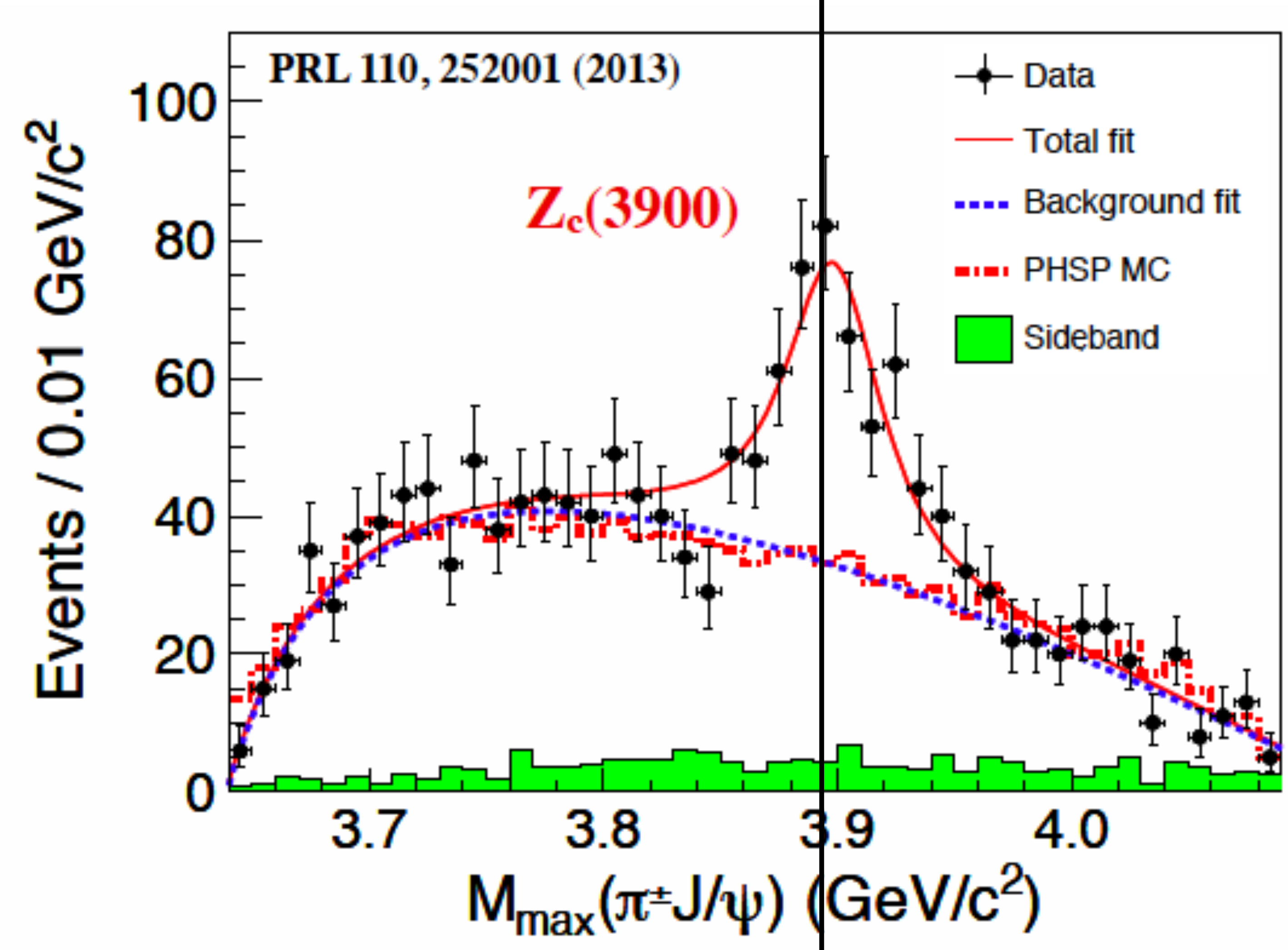
$P_c(4380 \text{ or } 4450)$



Axes : Abs$[T(s)]$, $\sqrt{s}$
Lines : blue ($\lambda = 1.89$ GeV), red ($\lambda = 1.99$ GeV), yellow ($\lambda = 2.0$



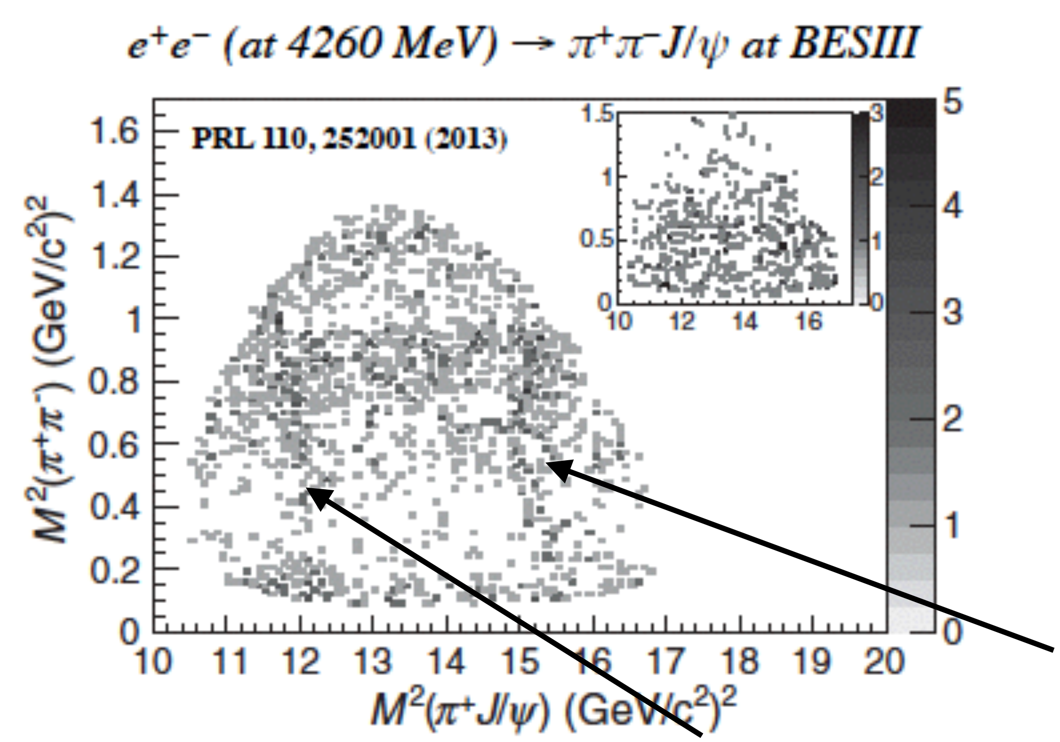
$Z_c(3900)$ Charged charmonium ?



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

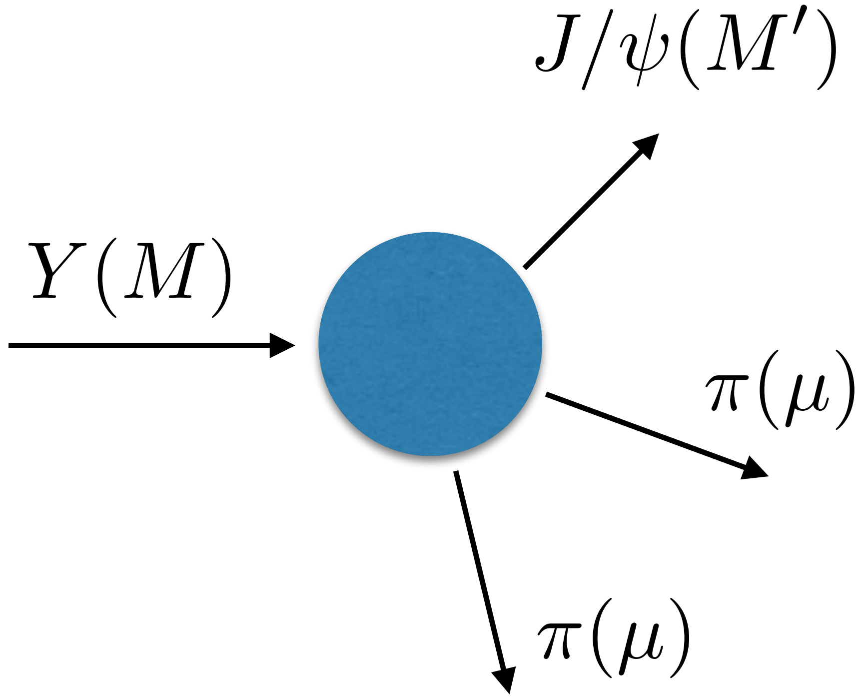
M = 3899.0 ± 3.6 ± 4.9 MeV
Γ = 46 ± 10 ± 20 MeV

Breit-Wigner model fit

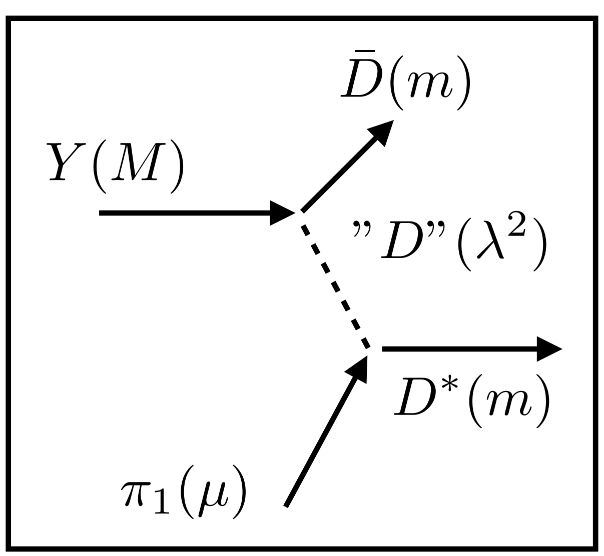


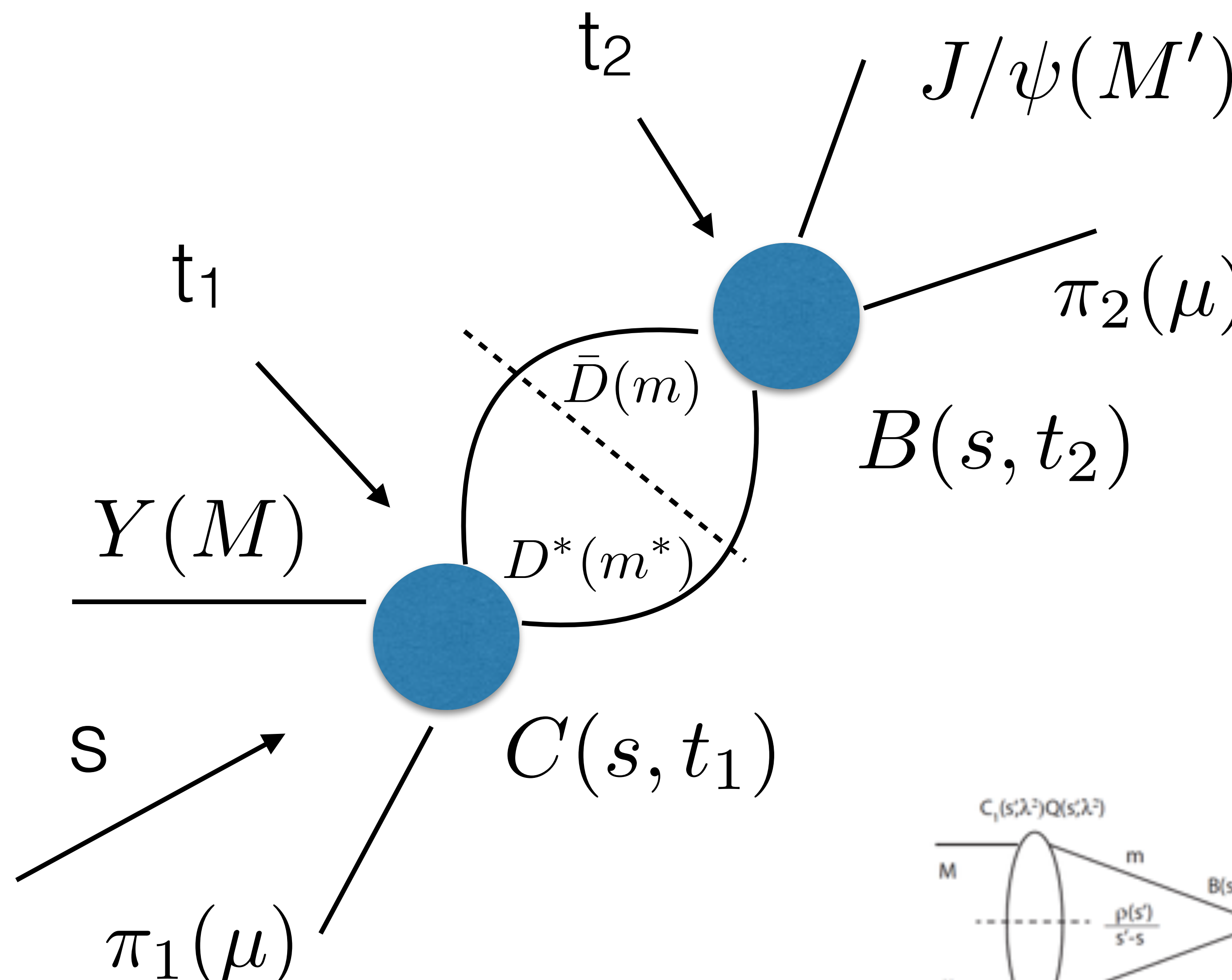
close to D*D threshold

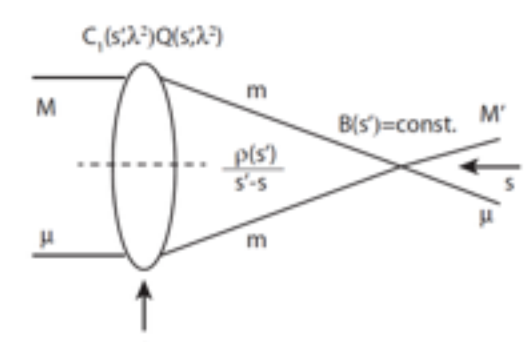
coupling to DD*

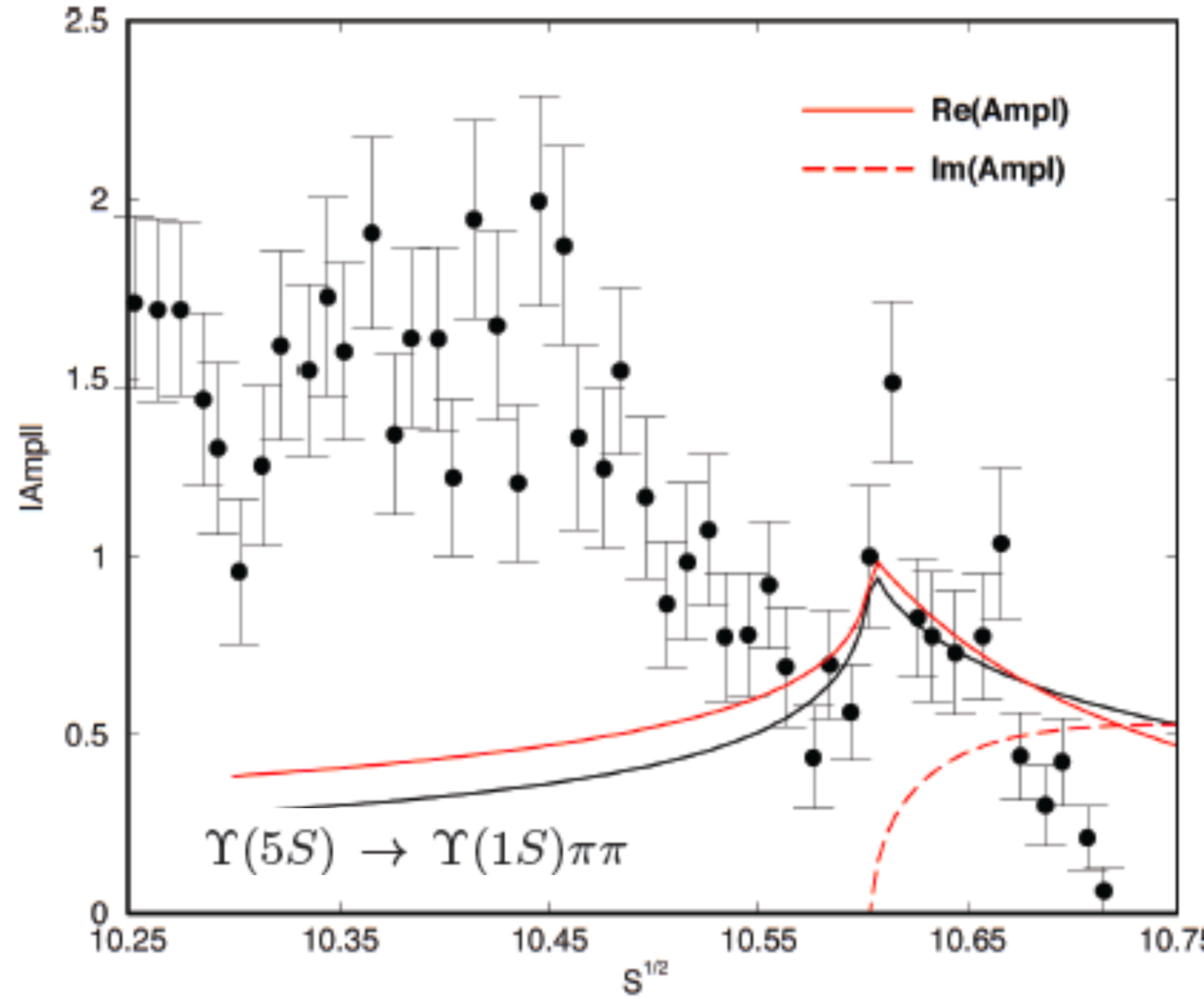


Often enhances by a nearby direct channel, e.g. DD*

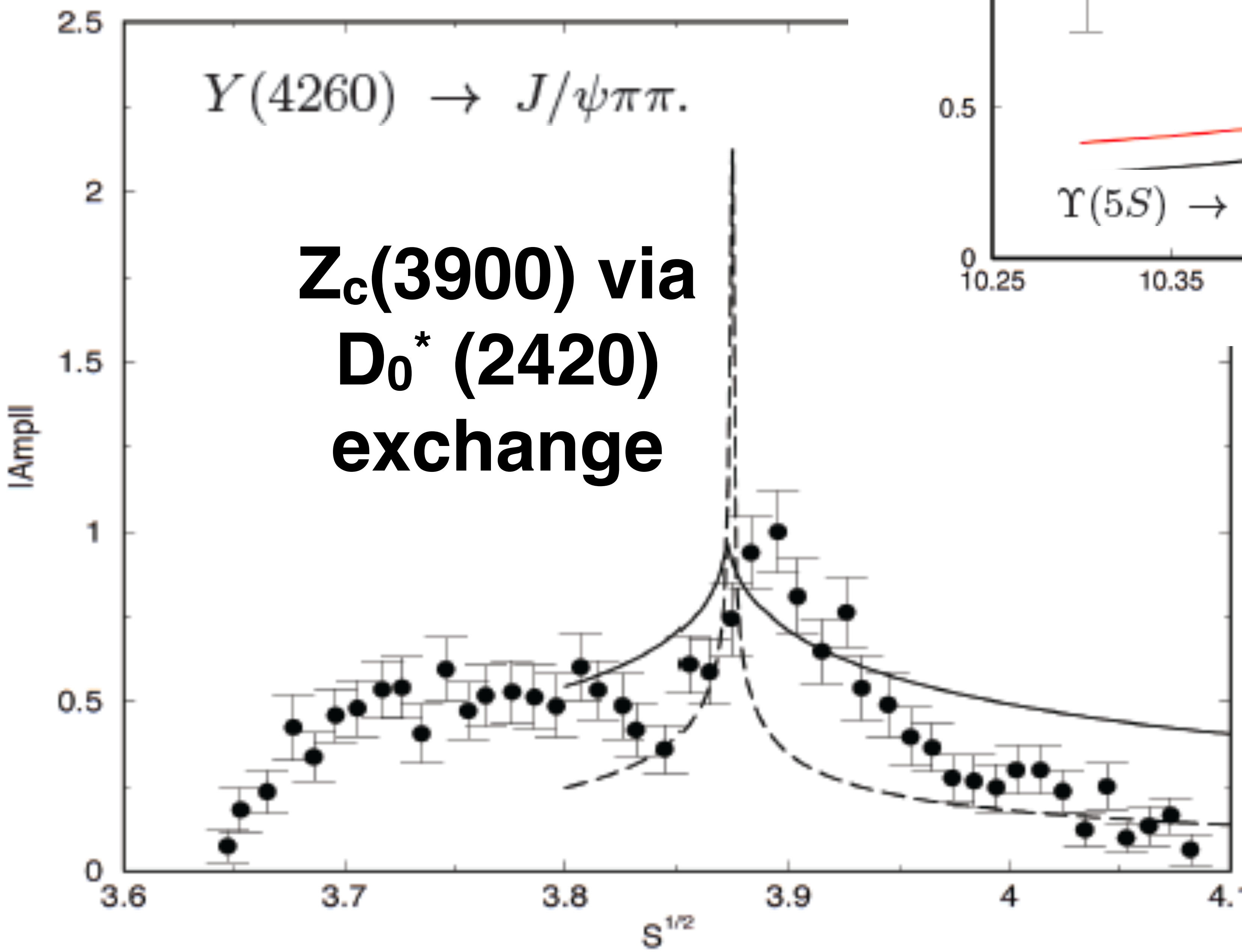






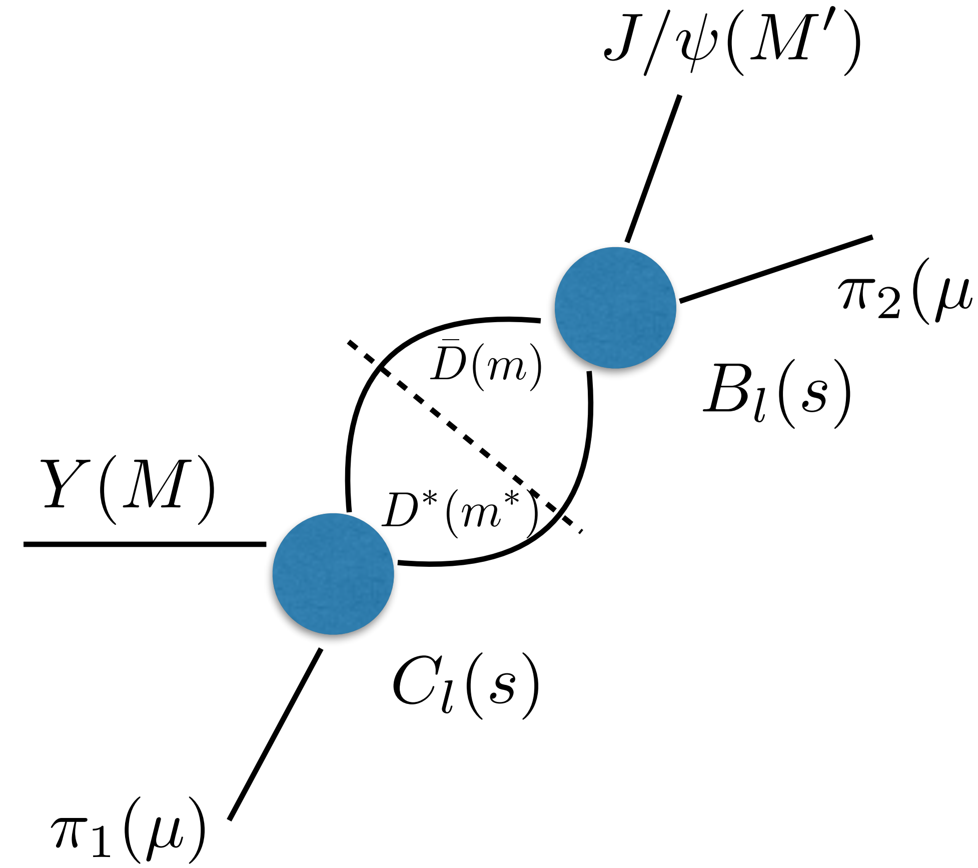


$Z_b(10610)$ via $B_J^{**}(5698)$ exchange



Analyticity is a powerful constraint !

$$C_l(s), B_l(s) \sim \exp(-s/1\ \mathrm{GeV}^2)$$

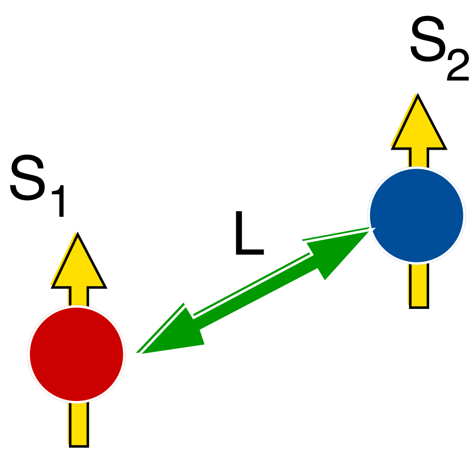


(e.g. Bugg,Swanson)

Violates causality

Artifact of a model (quark model wave function overlap)

Gluon excitations

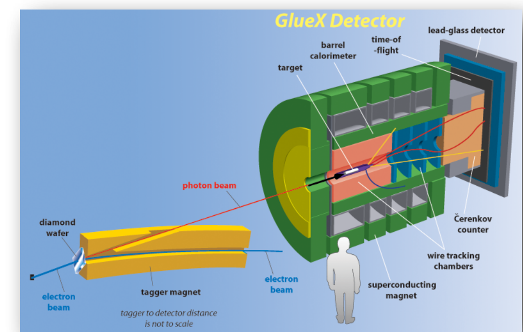


$S = S_1 + S_2$

$J = L + S$

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

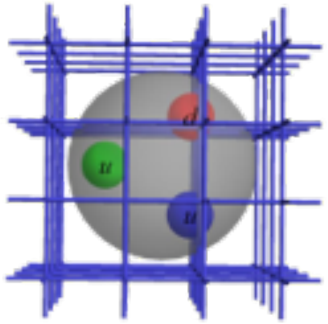
$C = (-1)^{L+S}$



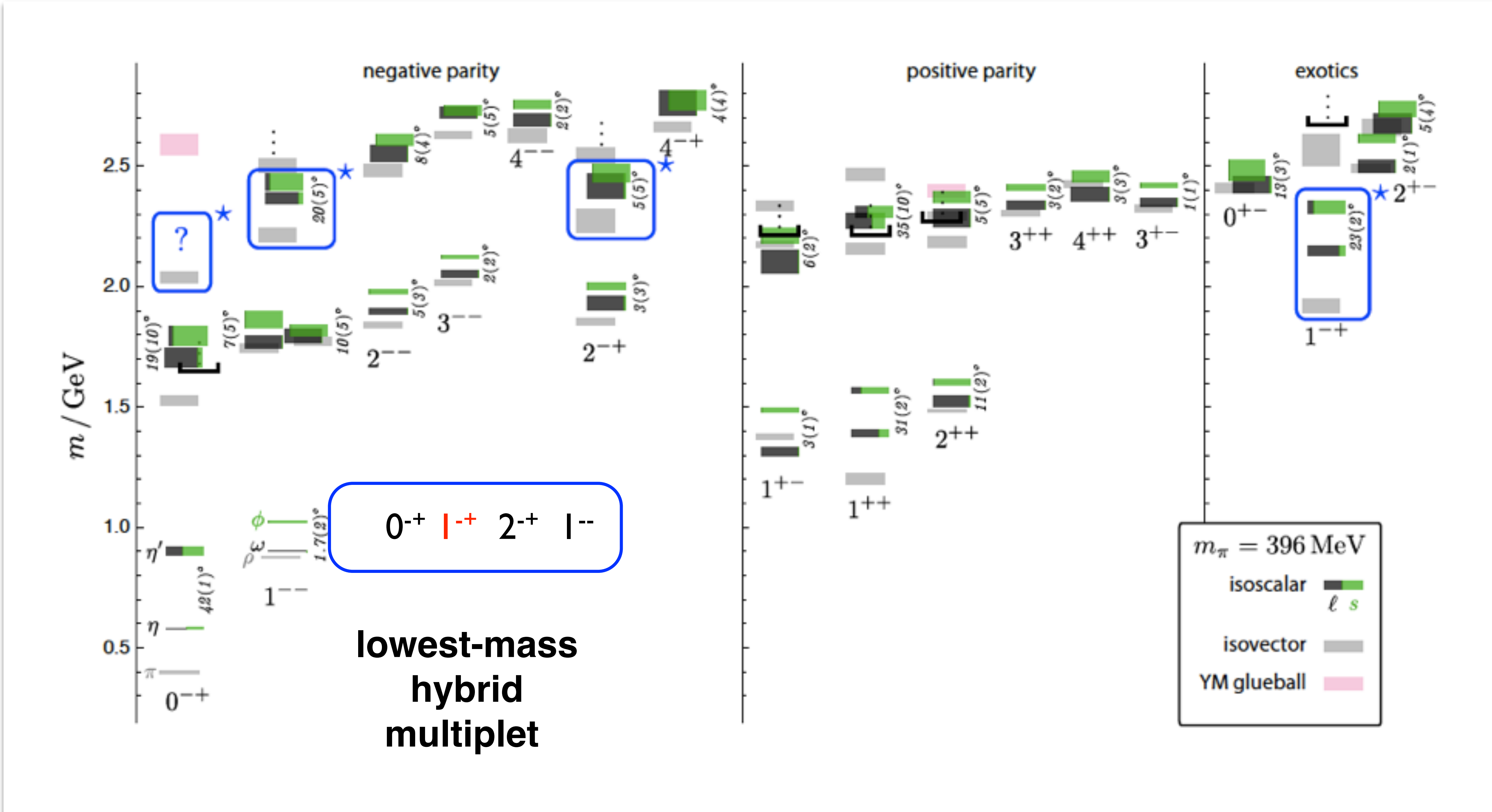
Mesons with $J^{PC} = 0^{--}, 0^{+-}, \underline{1^{-+}}, 2^{+-}$: Exotic Quantum Numbers

π_1

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



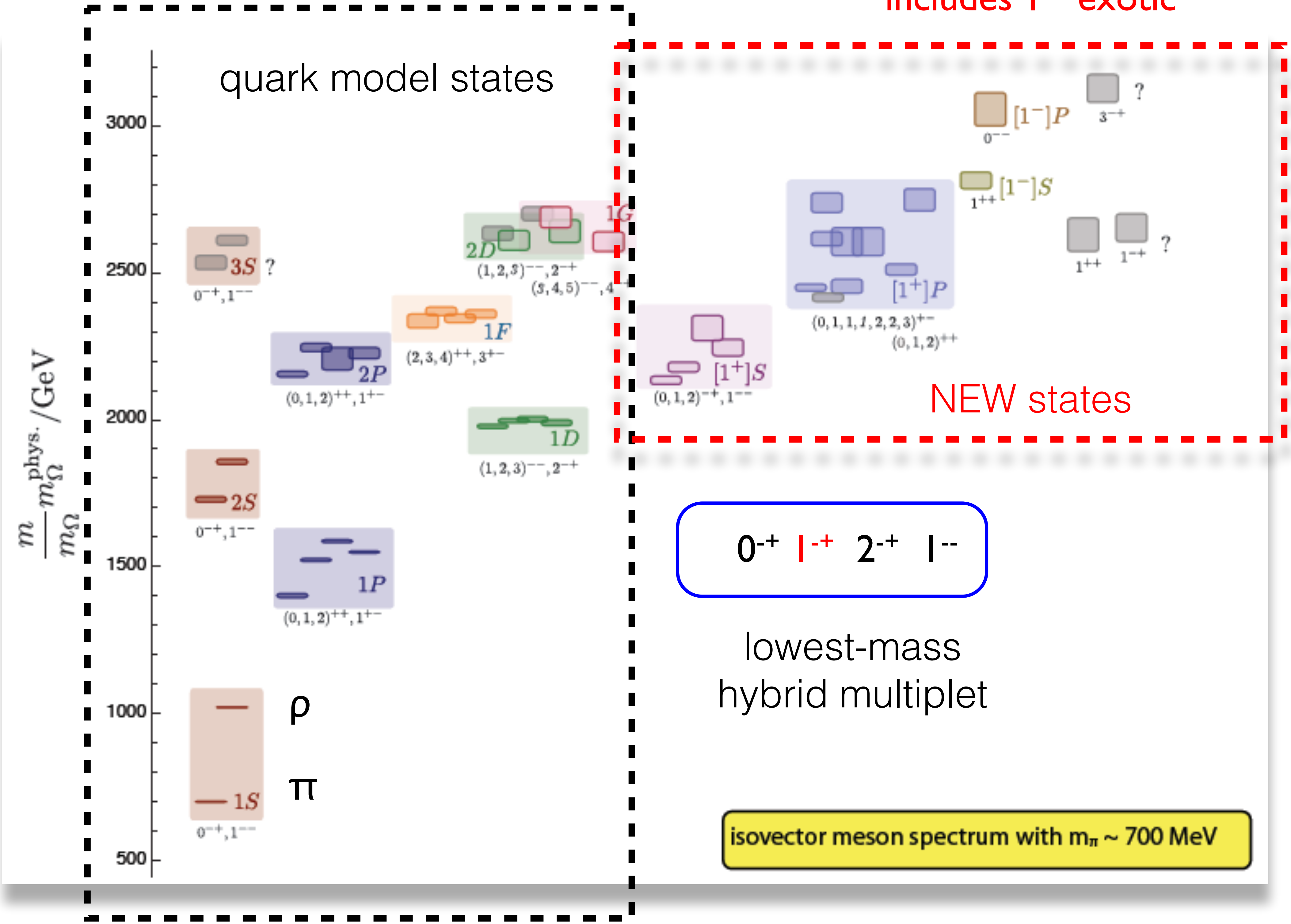
J. Dudek et al.



negative parity
positive parity
exotics
m / GeV
2.5
2.0
1.5
1.0
0.5
0⁻⁺
1⁻⁻
2⁻⁻
3⁻⁻
2⁻⁺
4⁻⁻
4⁻⁺
1⁺⁻
1⁺⁺
2⁺⁺
3⁺⁺
4⁺⁺
3⁺⁻
0⁺⁻
2⁺⁻
1⁻⁺
?
η′
η
π
φ
ω
ρ
0-+ 1-+ 2-+ 1--
lowest-mass hybrid multiplet
$m_\pi = 396$ MeV
isoscalar
ℓ s
isovector
YM glueball

new multiplets from lattice

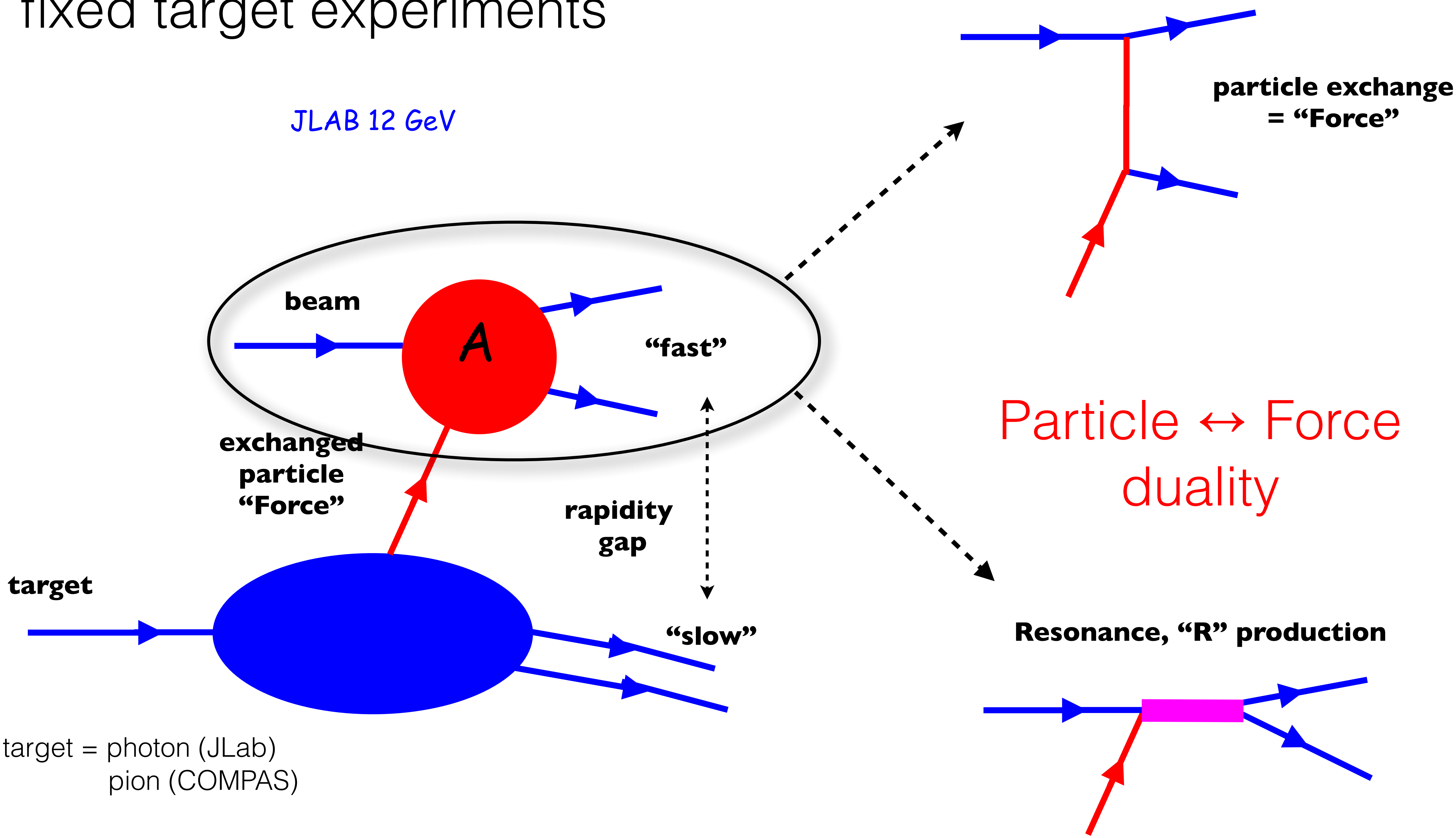
large overlap with
gluonic operators
includes 1^{-+} exotic



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

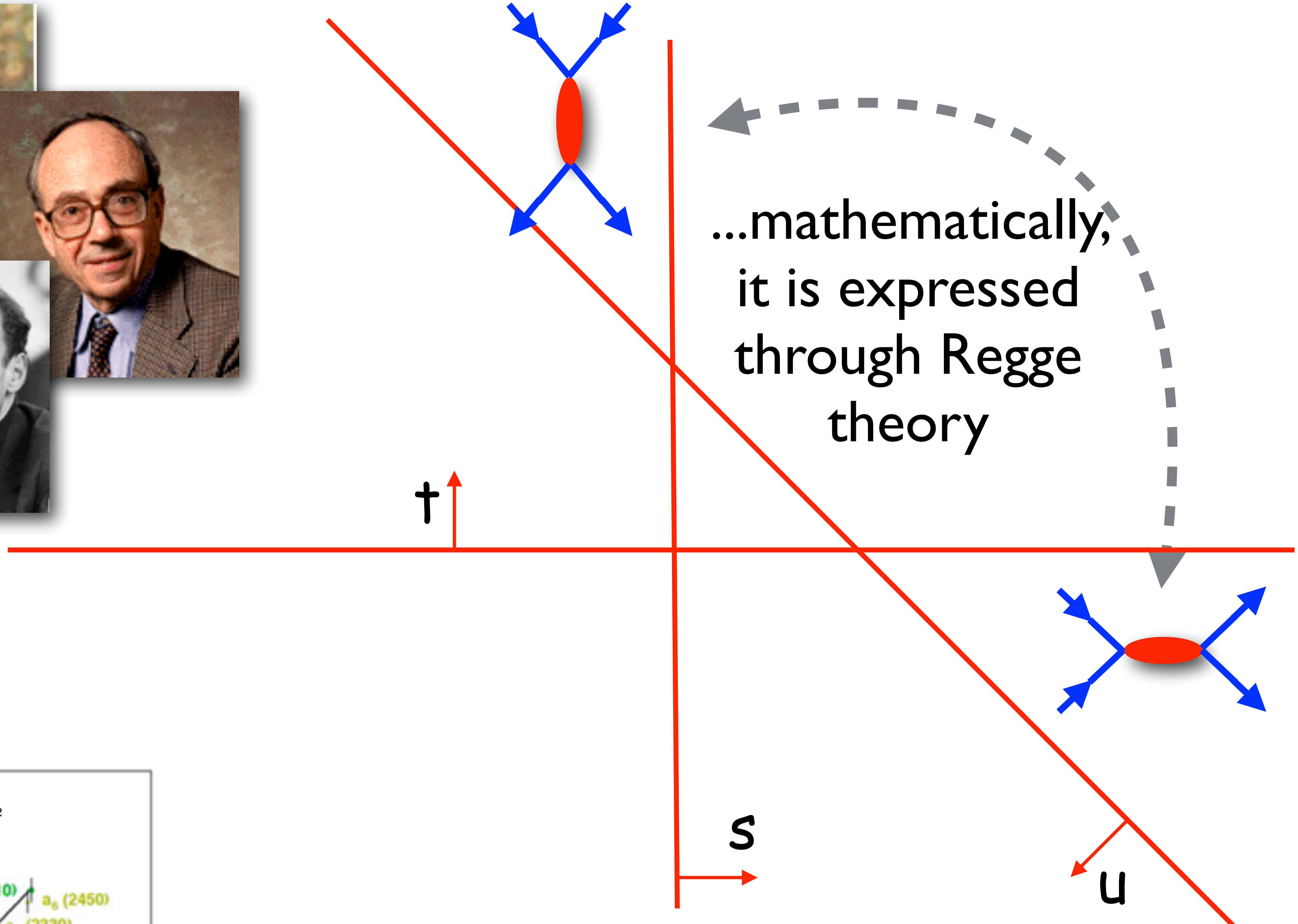
hybrid interpretation of the **Y(4260)**

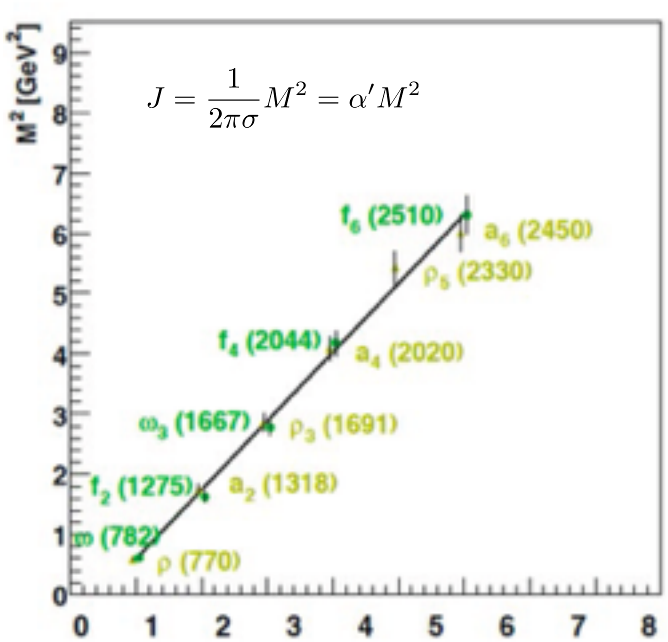
Hunting for Resonances in fixed target experiments



target = photon (JLab)
pion (COMPAS)

diffractive-dissociation



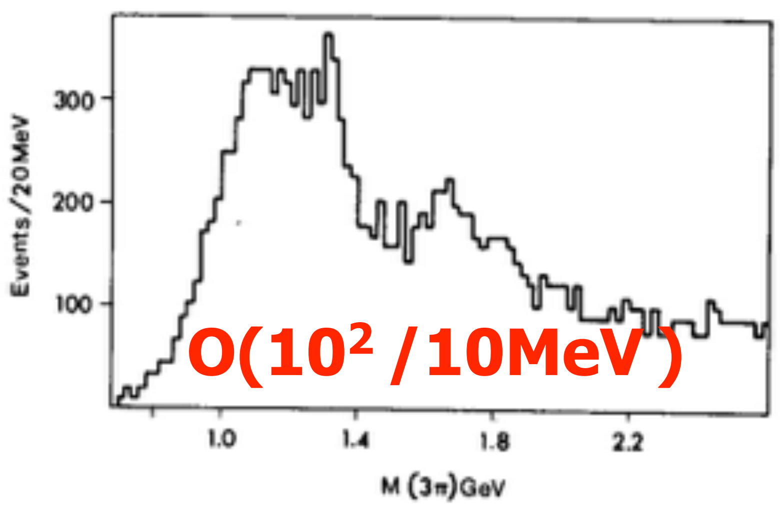


Force-Resonance duality =
Regge theory

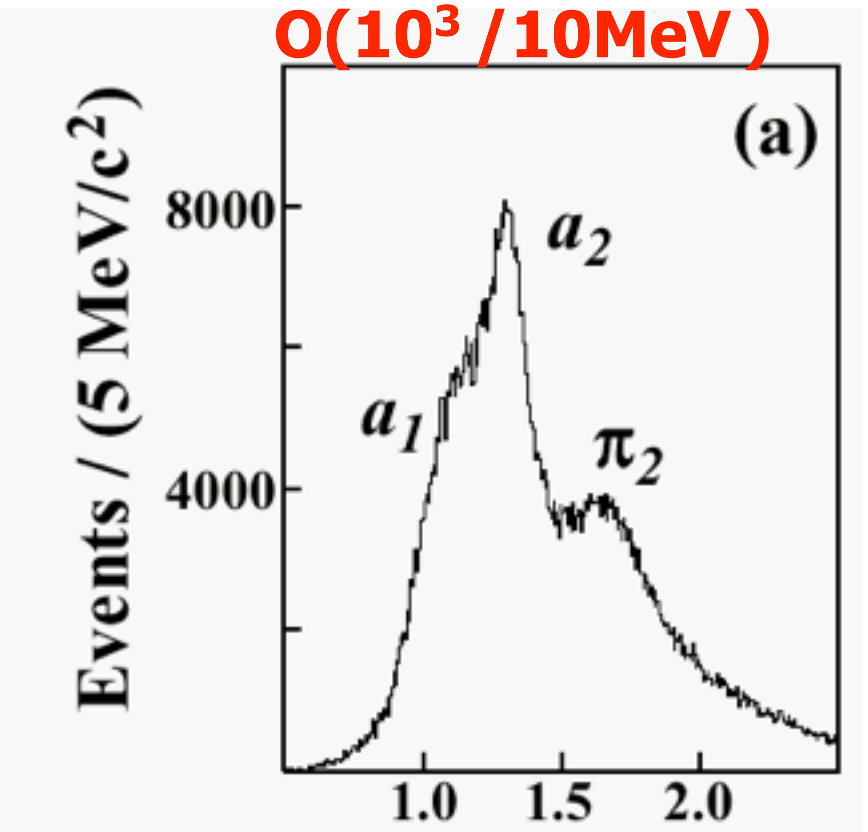
evolution in statistics

$\pi^- p \to \pi^-\pi^+\pi^- p$

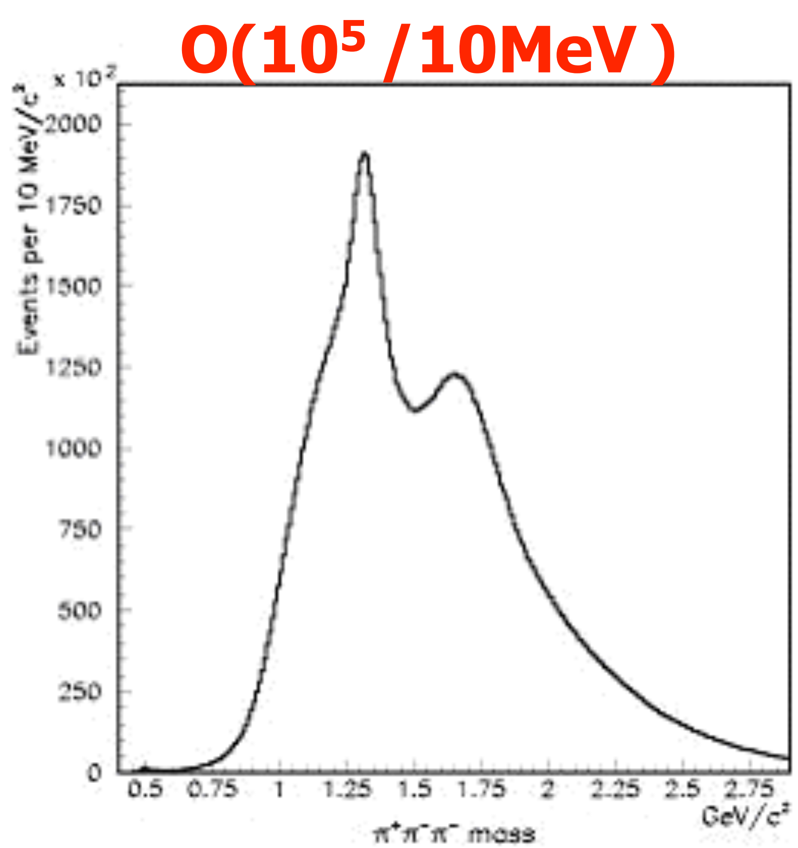
CERN ca. 1970



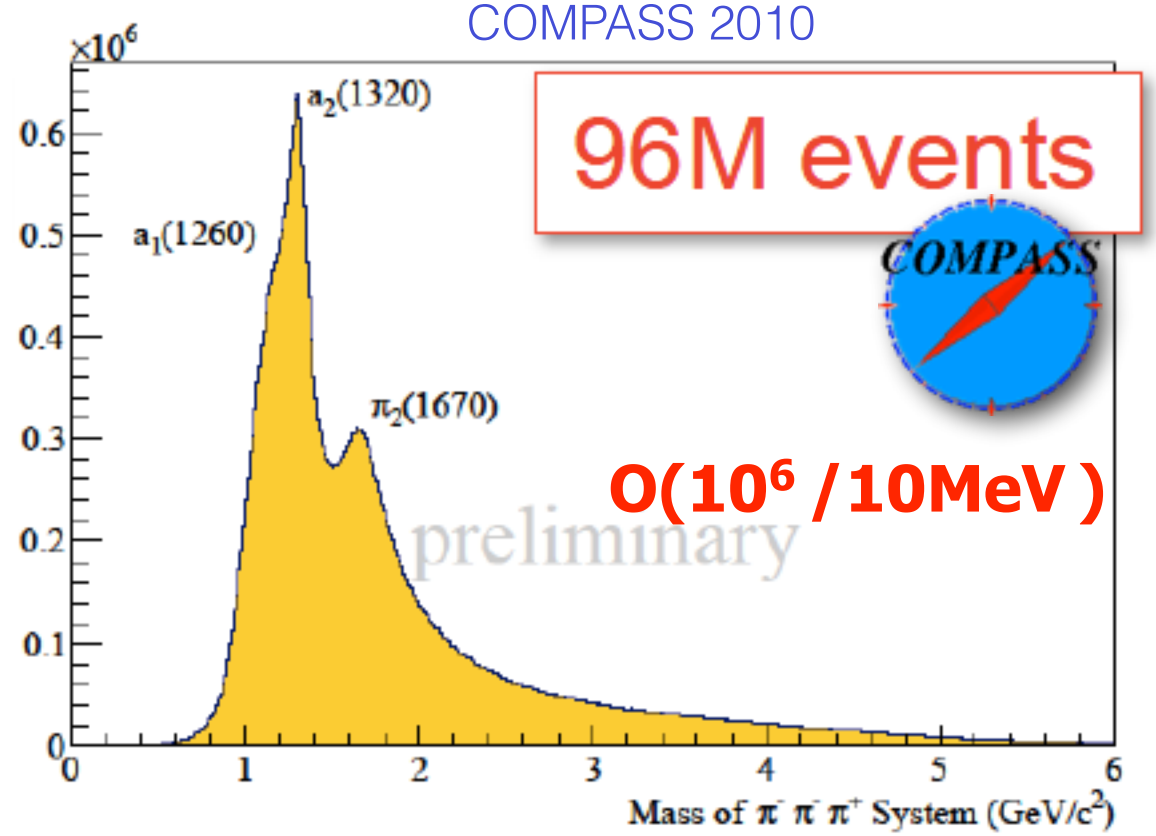
BNL (E852) ca 1995

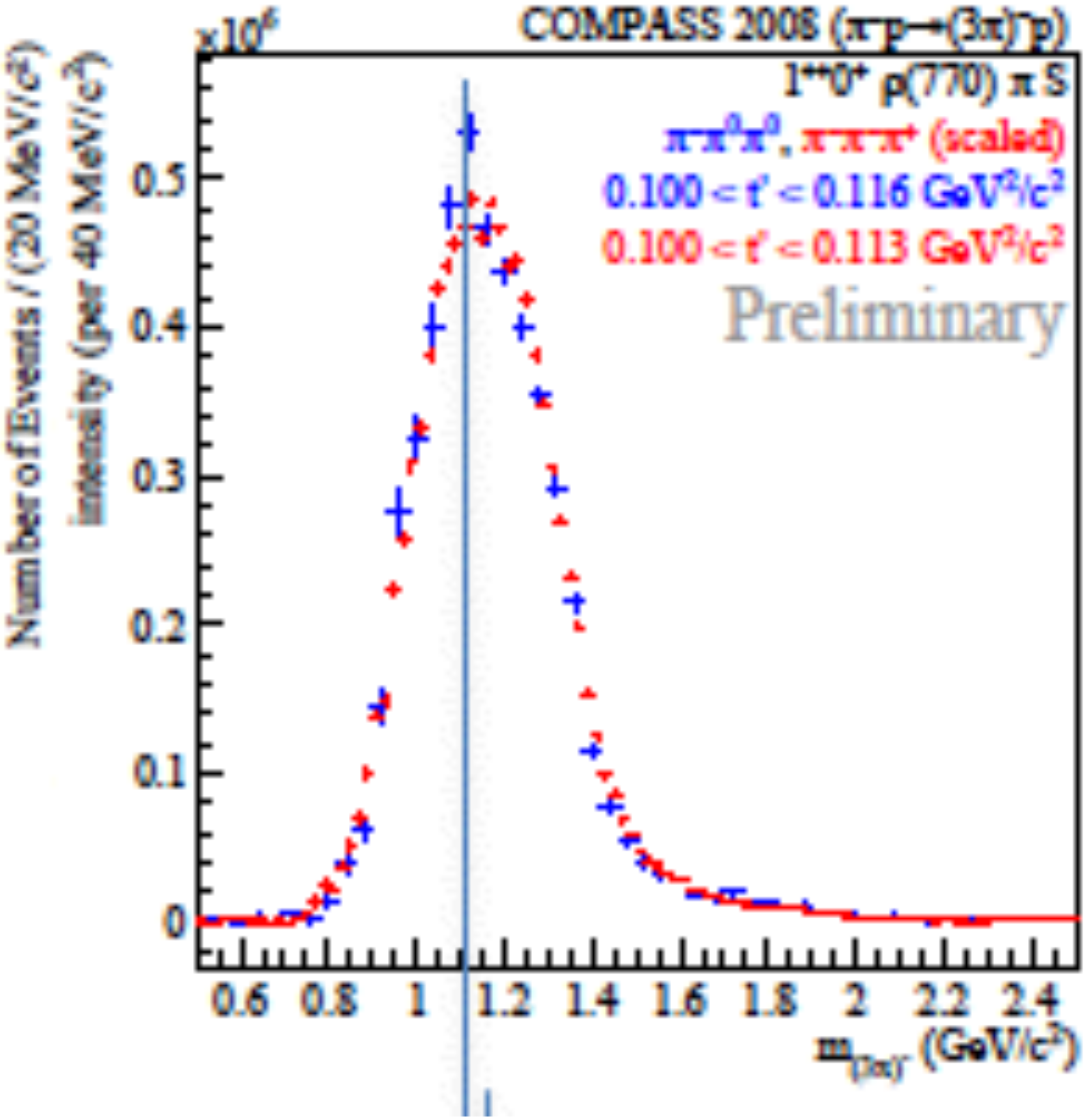


E852 (Full sample)

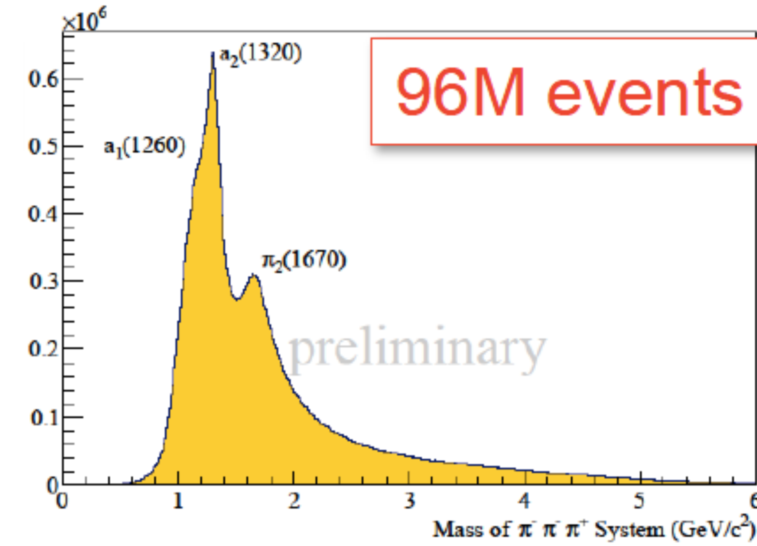


COMPASS 2010



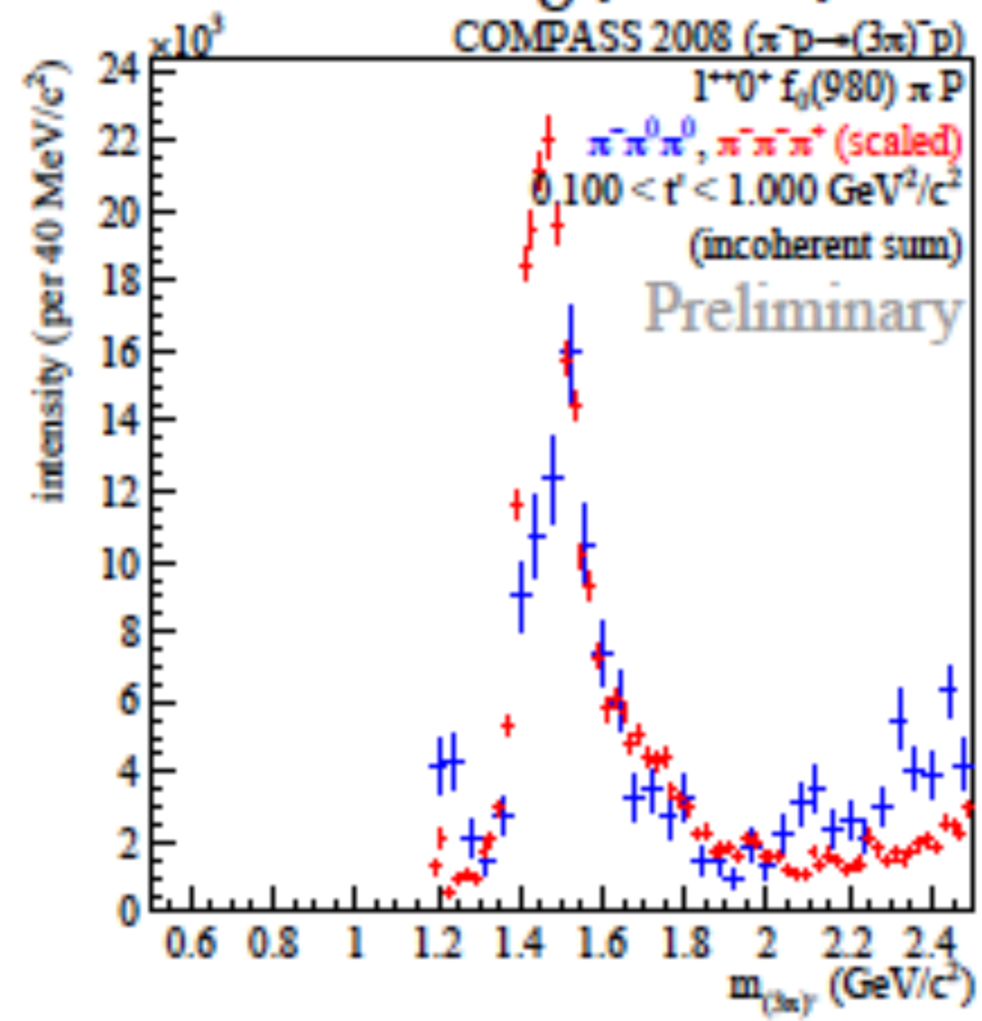


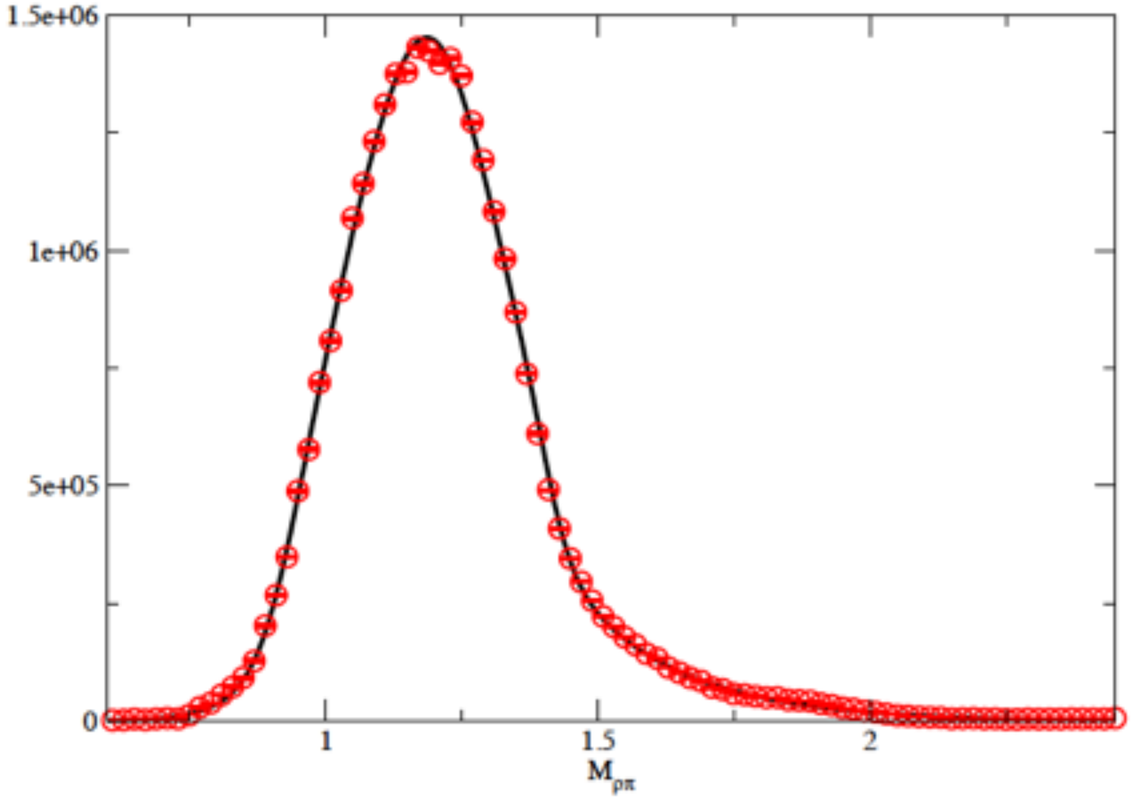
“Old” a1 in ρπ S-wave

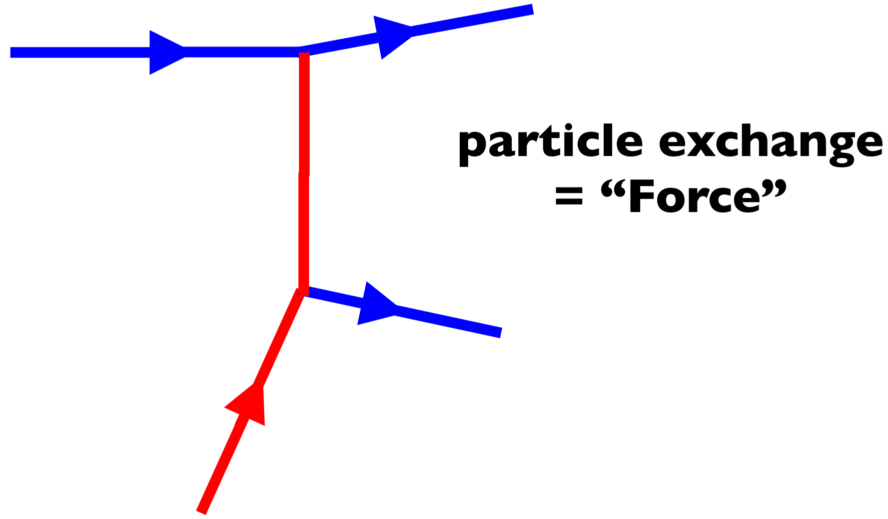


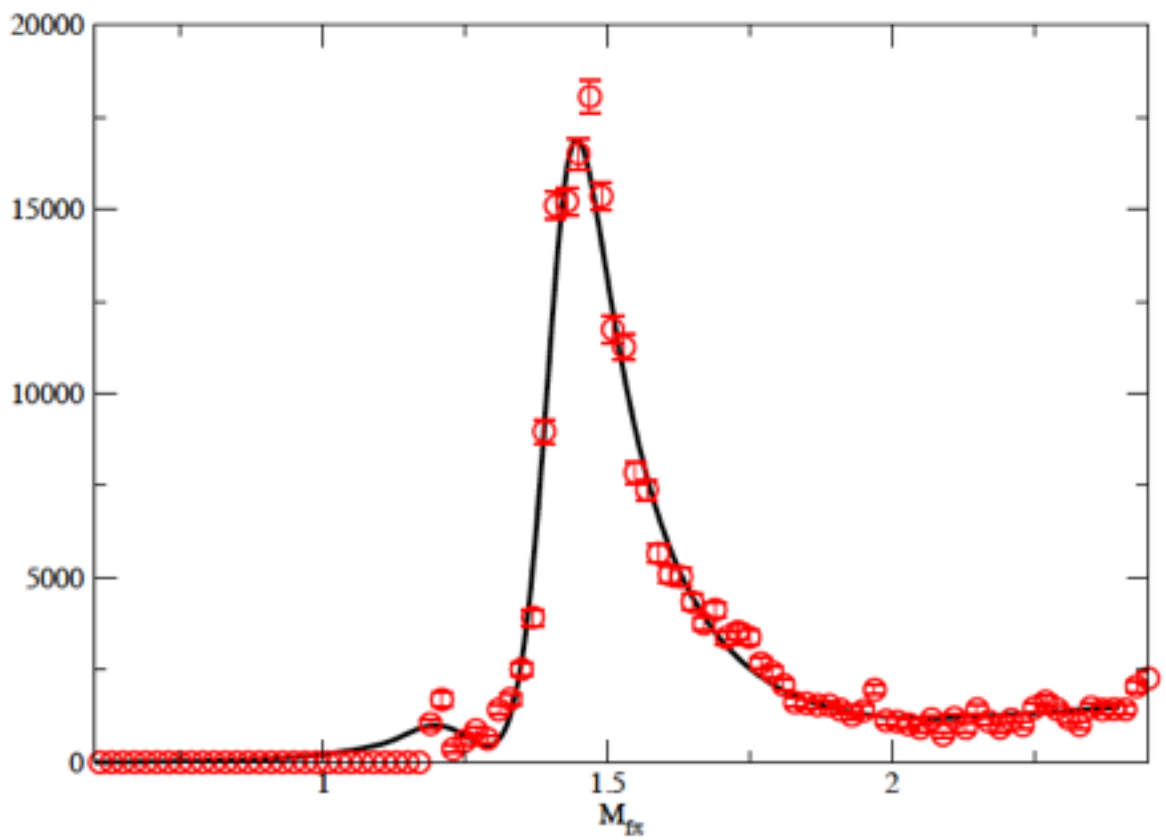
New a1 in f0 π P-wave

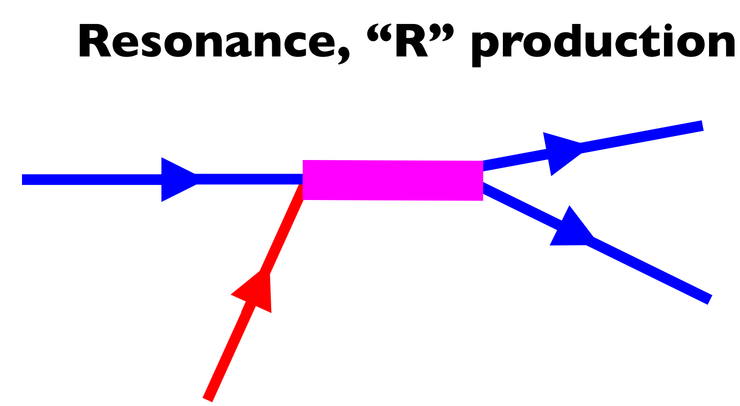
$1^{++}0^+$ $f_0(980)$ π P



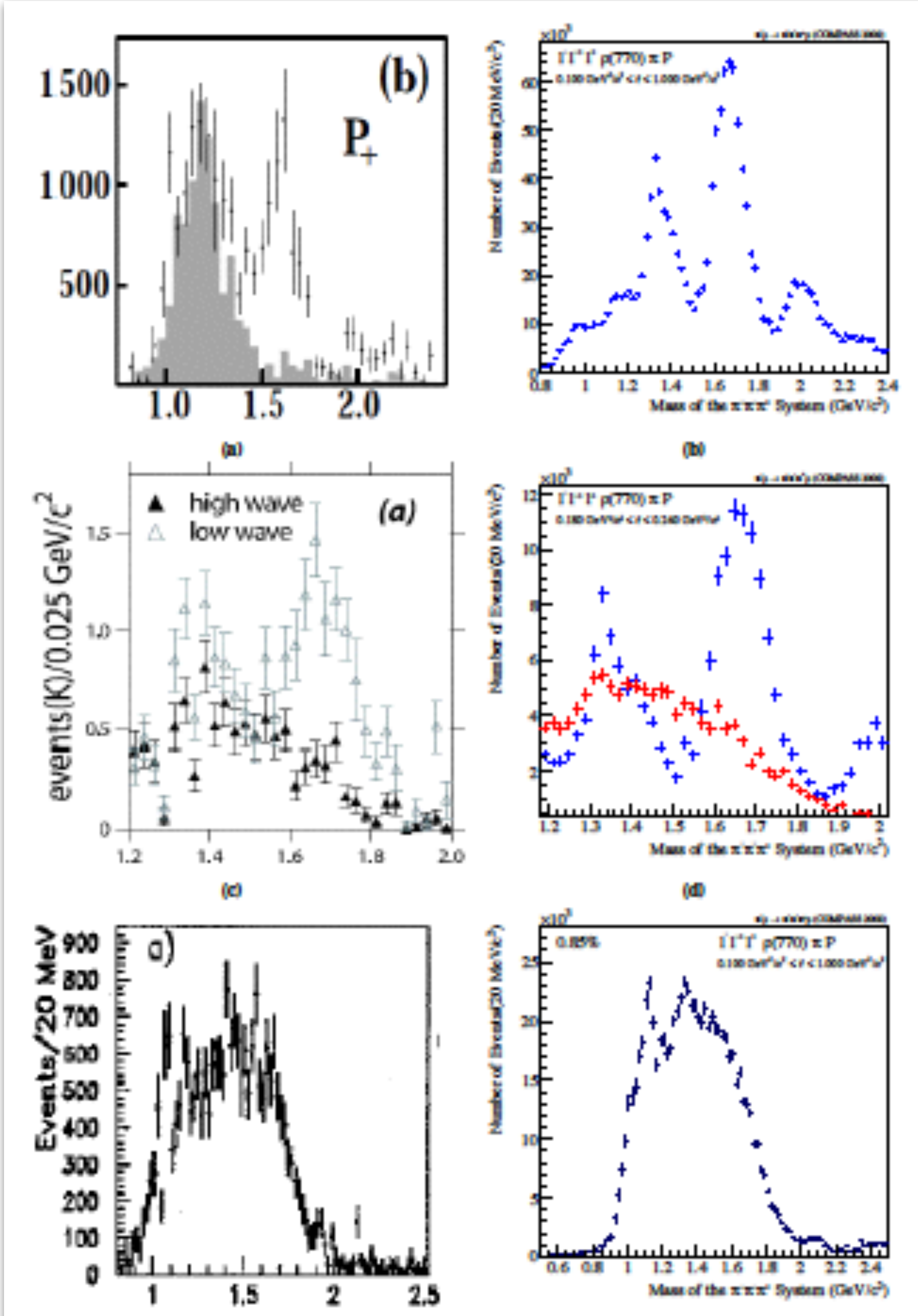

1.5e+06
1e+06
5e+05
0
1
1.5
2
$M_{\rho\pi}$

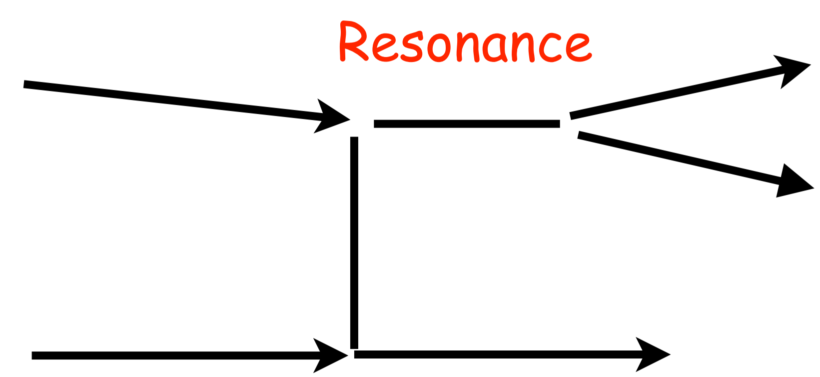

particle exchange
= “Force”

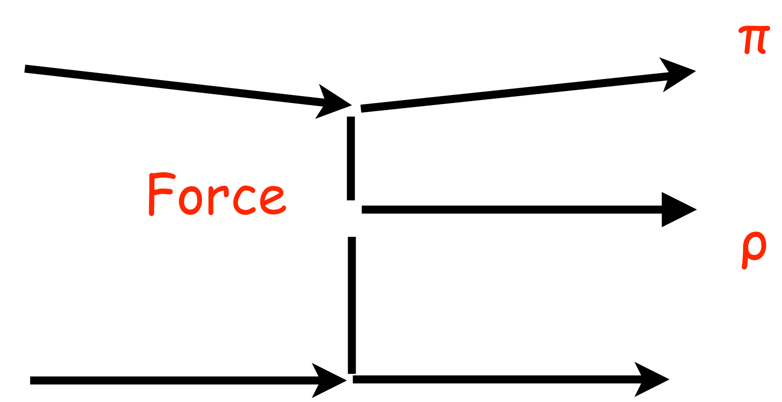

20000
15000
10000
5000
0
1
1.5
2
$M_{f\pi}$

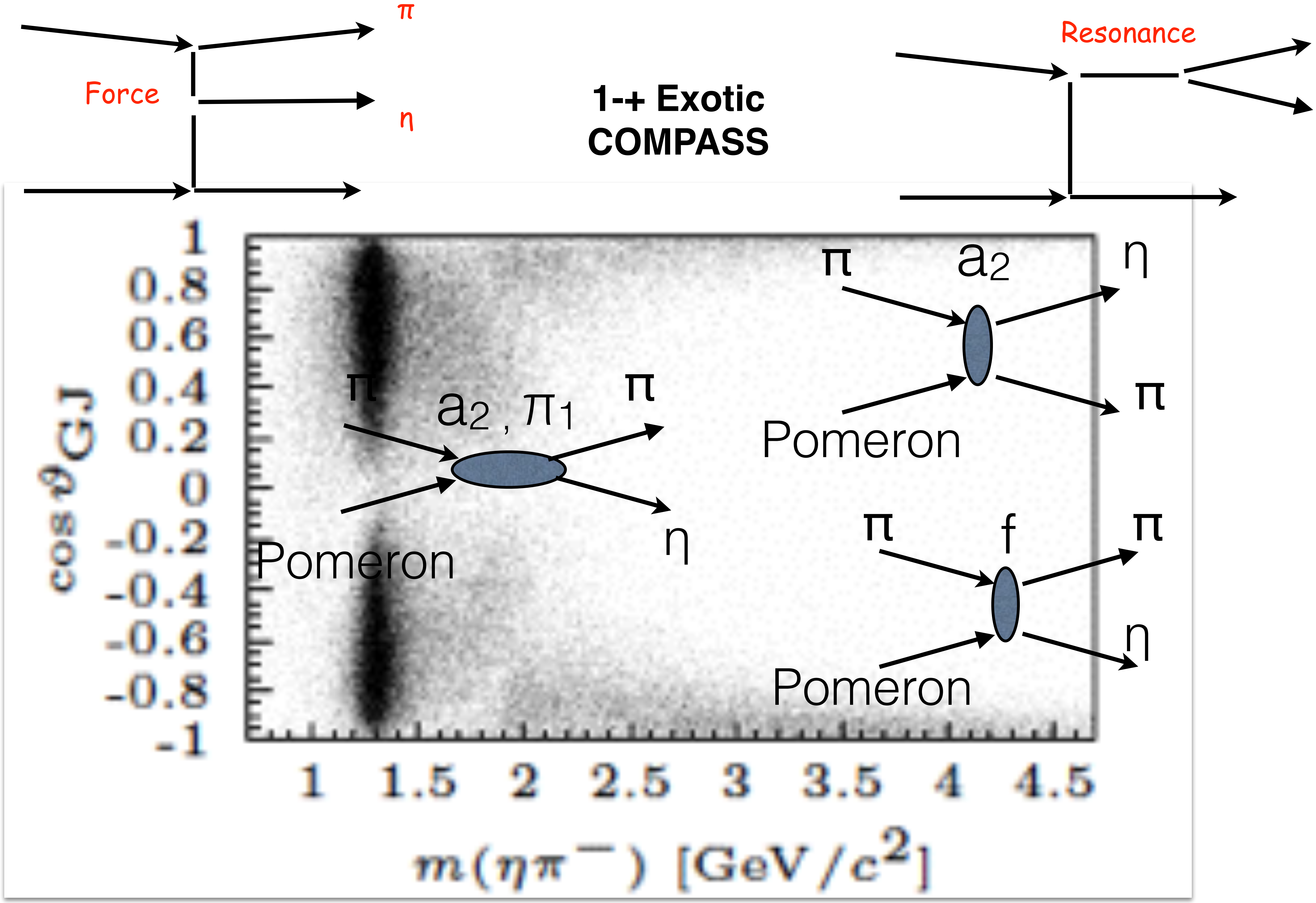

Resonance, “R” production

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





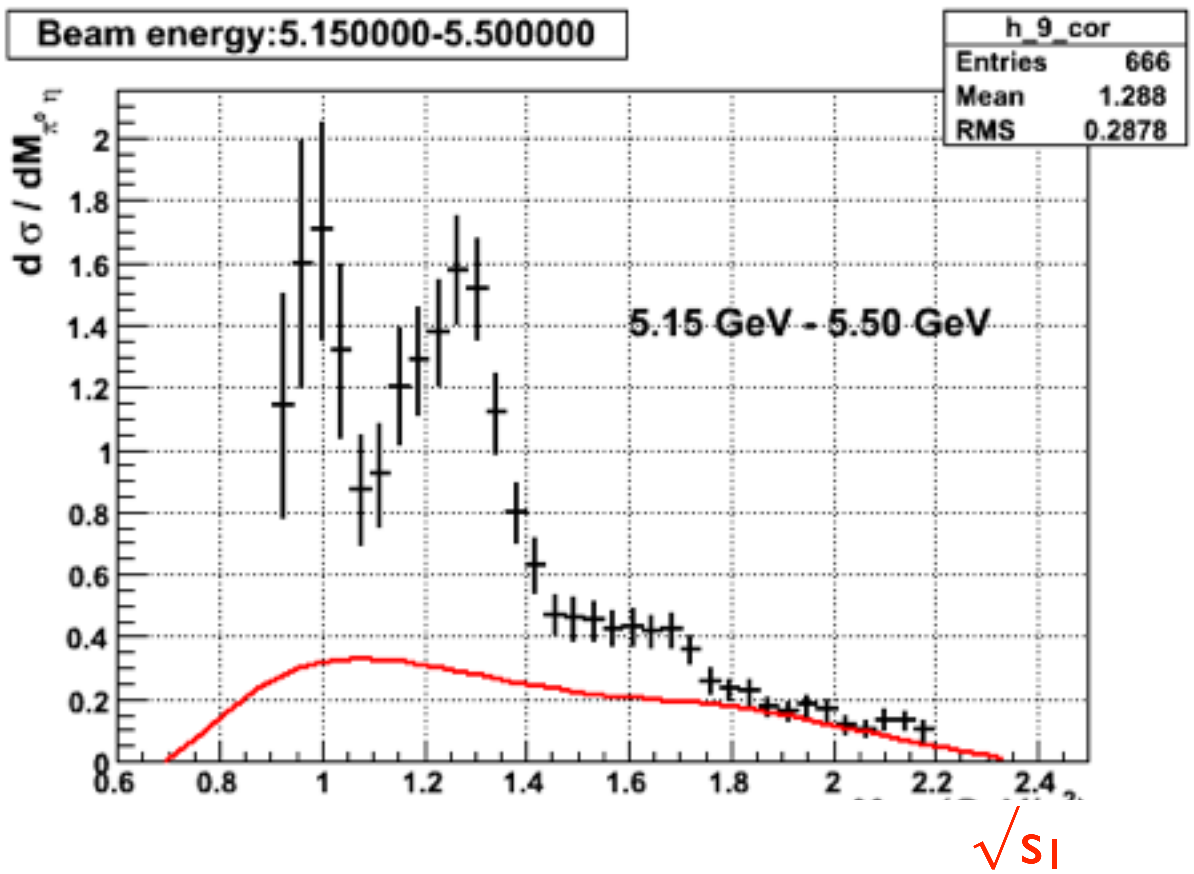


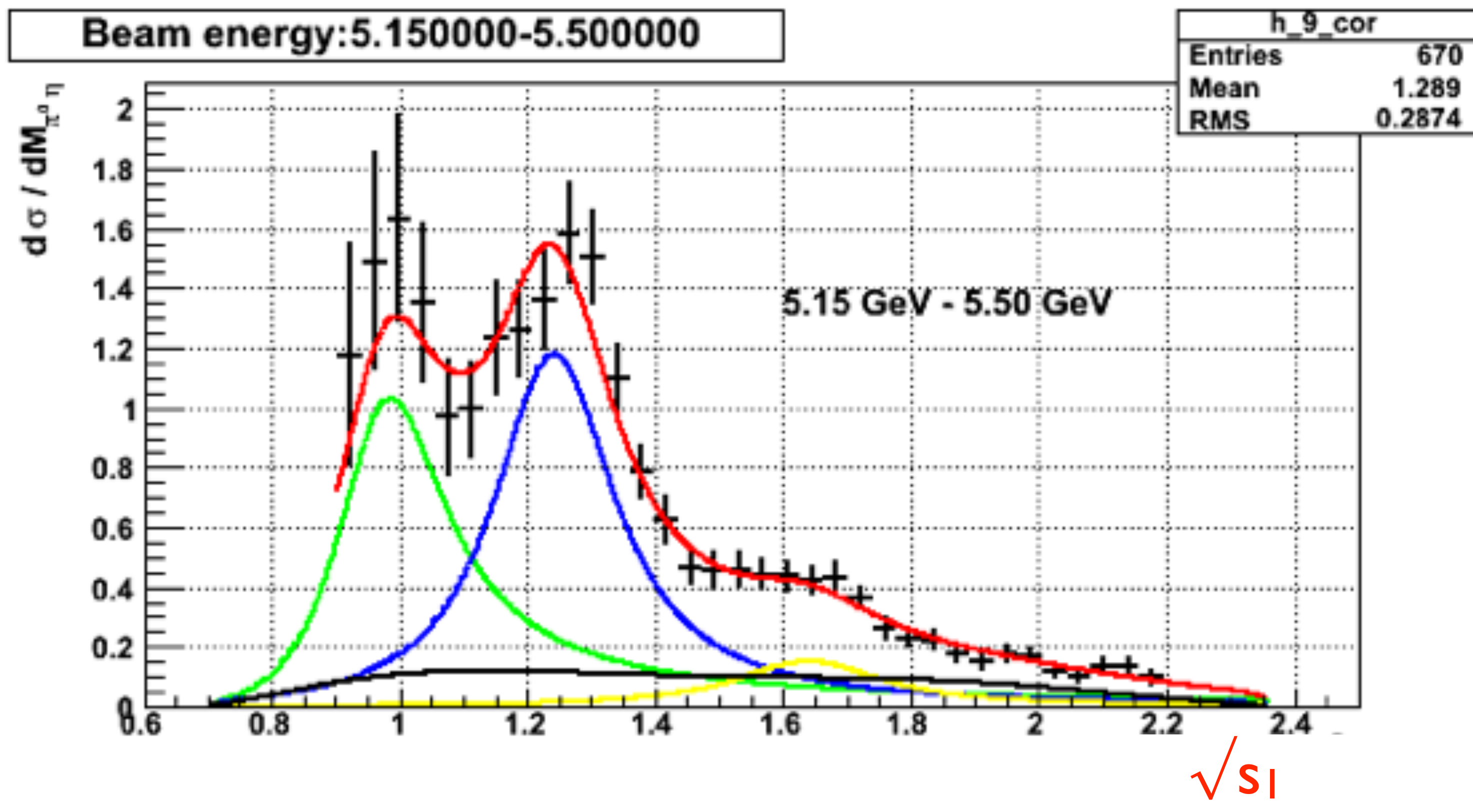


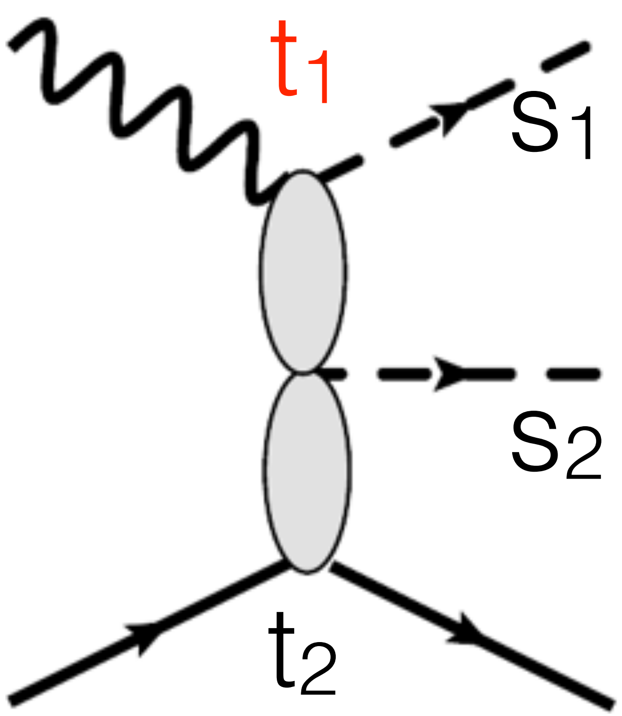
duality —> the production channel is dominated by spin-even partial waves. What is the exotic (P-wave) dual to ?

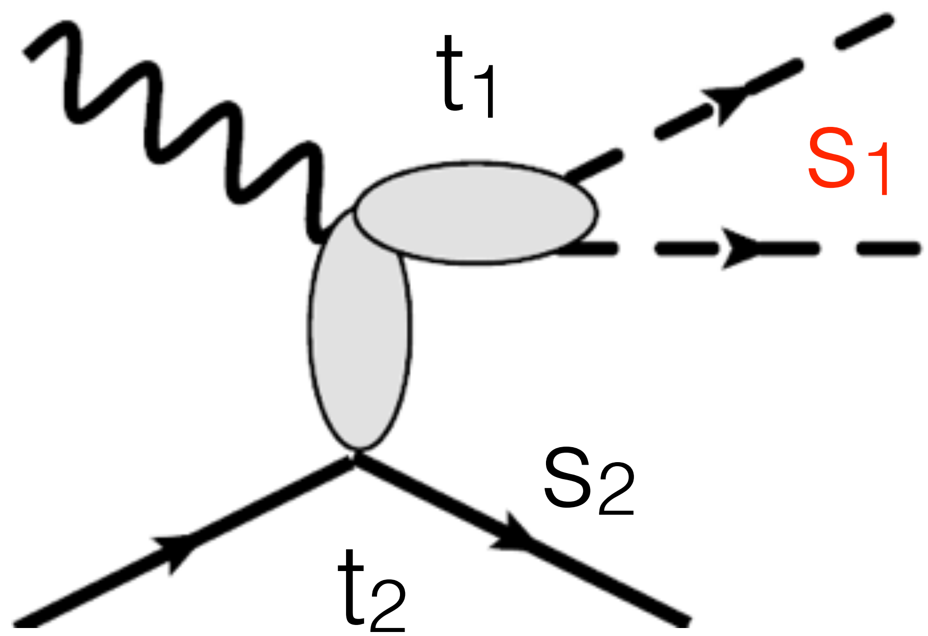
Yp→ηπ⁰p (g12)

A.Celentano, PhD, HASPEC/JPAC









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)

$J/\Psi \to \gamma\pi0\pi0$

Photoproduction: (production models, FESR and duality)

$\gamma p \to \pi 0 p$

$\gamma p \to pK+K-$

Exotica and XYZ's:

$\pi\text{-}p \to \pi\text{-}\eta p$ & $\pi\text{-}p \to \pi\text{-}\eta' p$ (FESR)

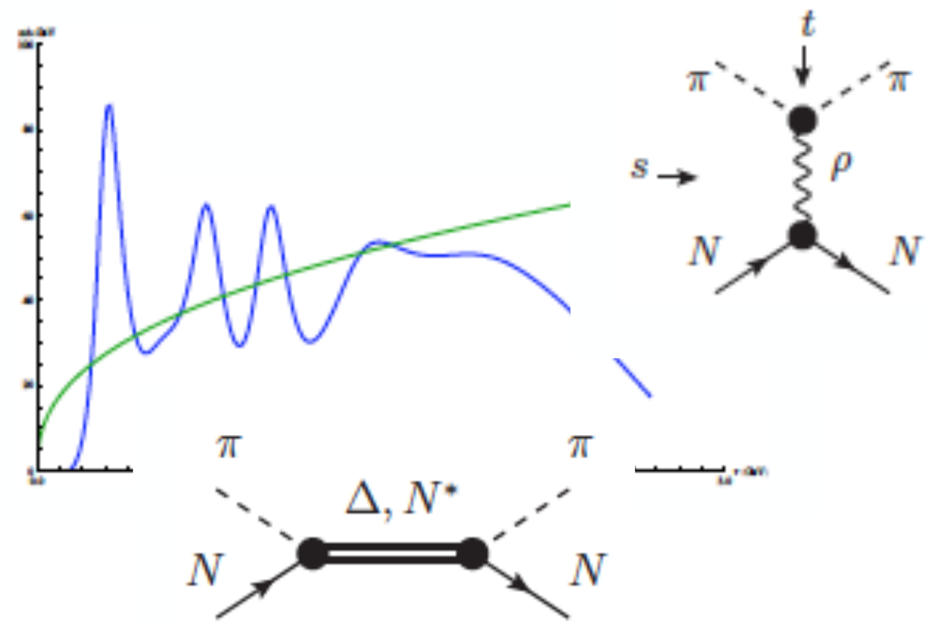
$B0 \to \Psi' \pi\text{-} K+ u$, $\Psi(4260) \to J/\Psi\ \pi+\pi\text{-}$

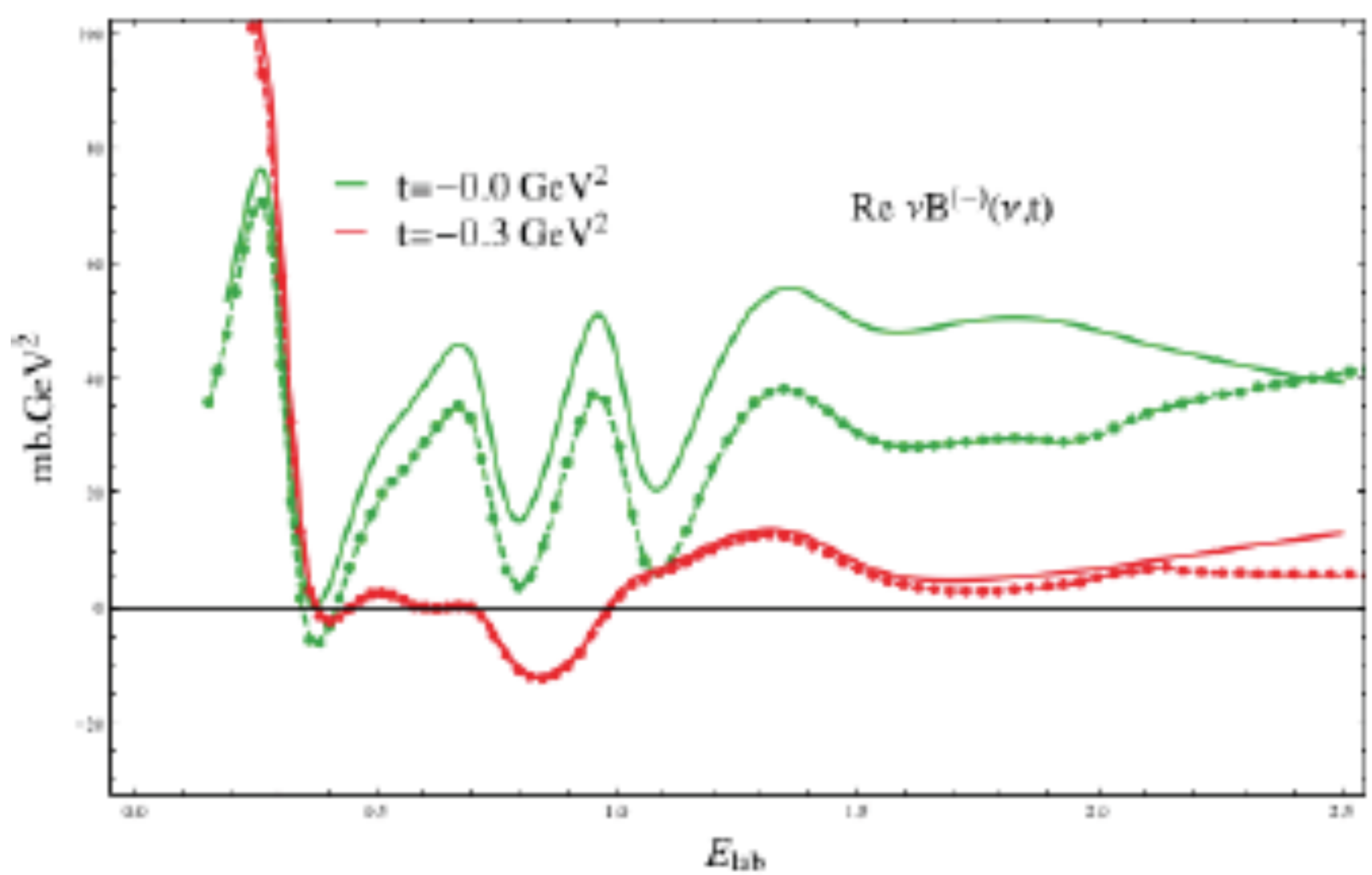
$J/\Psi \to 3\pi$ (Veneziano, B4)

Resonance-Regge physics in meson-baryon scattering

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

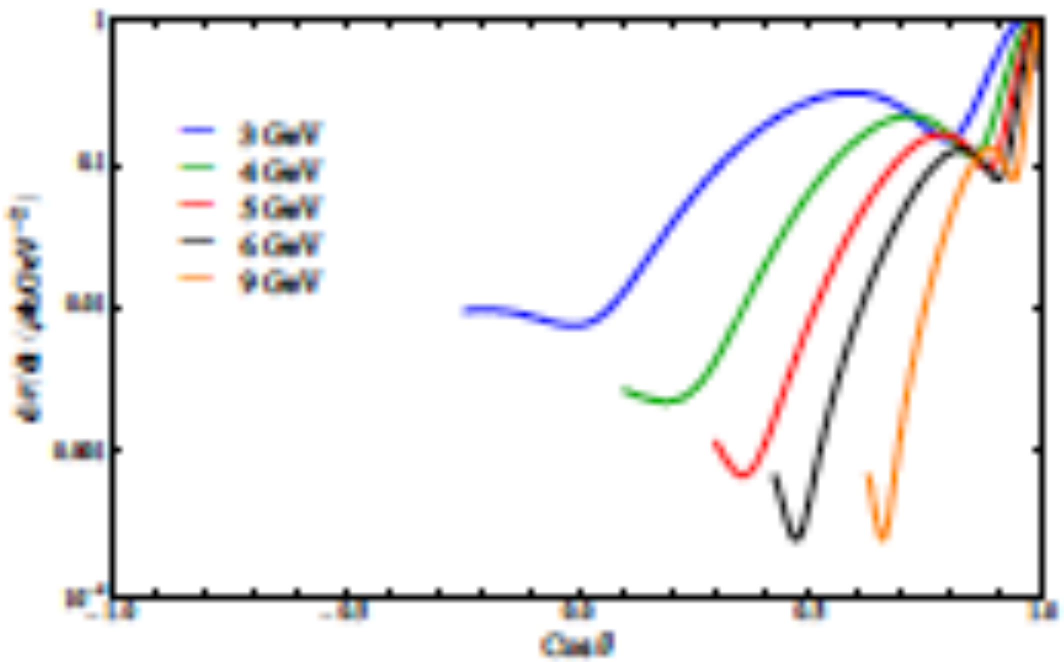
Resonance Regge





V.Mathieu, JPAC

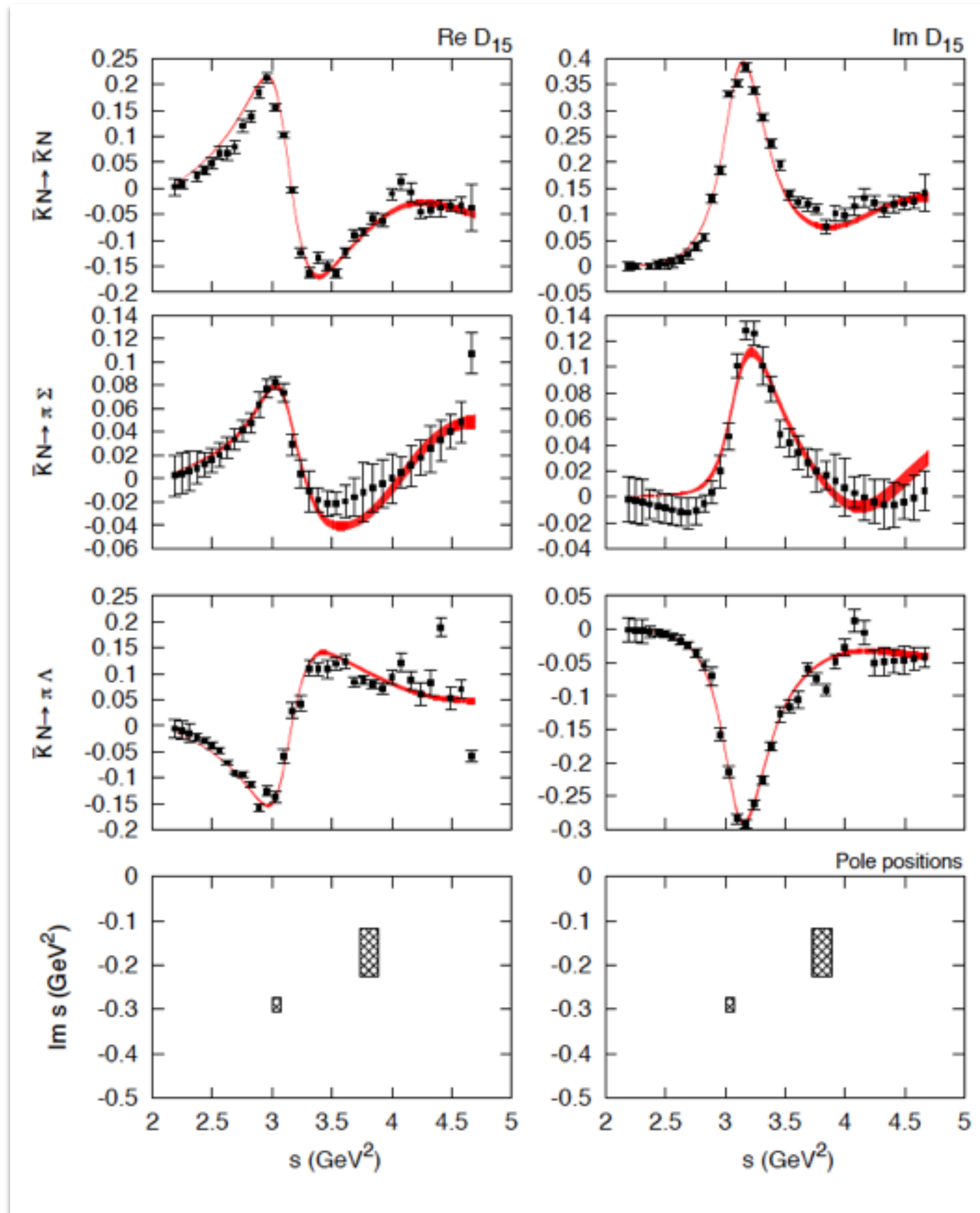
Neutral pion photo-production



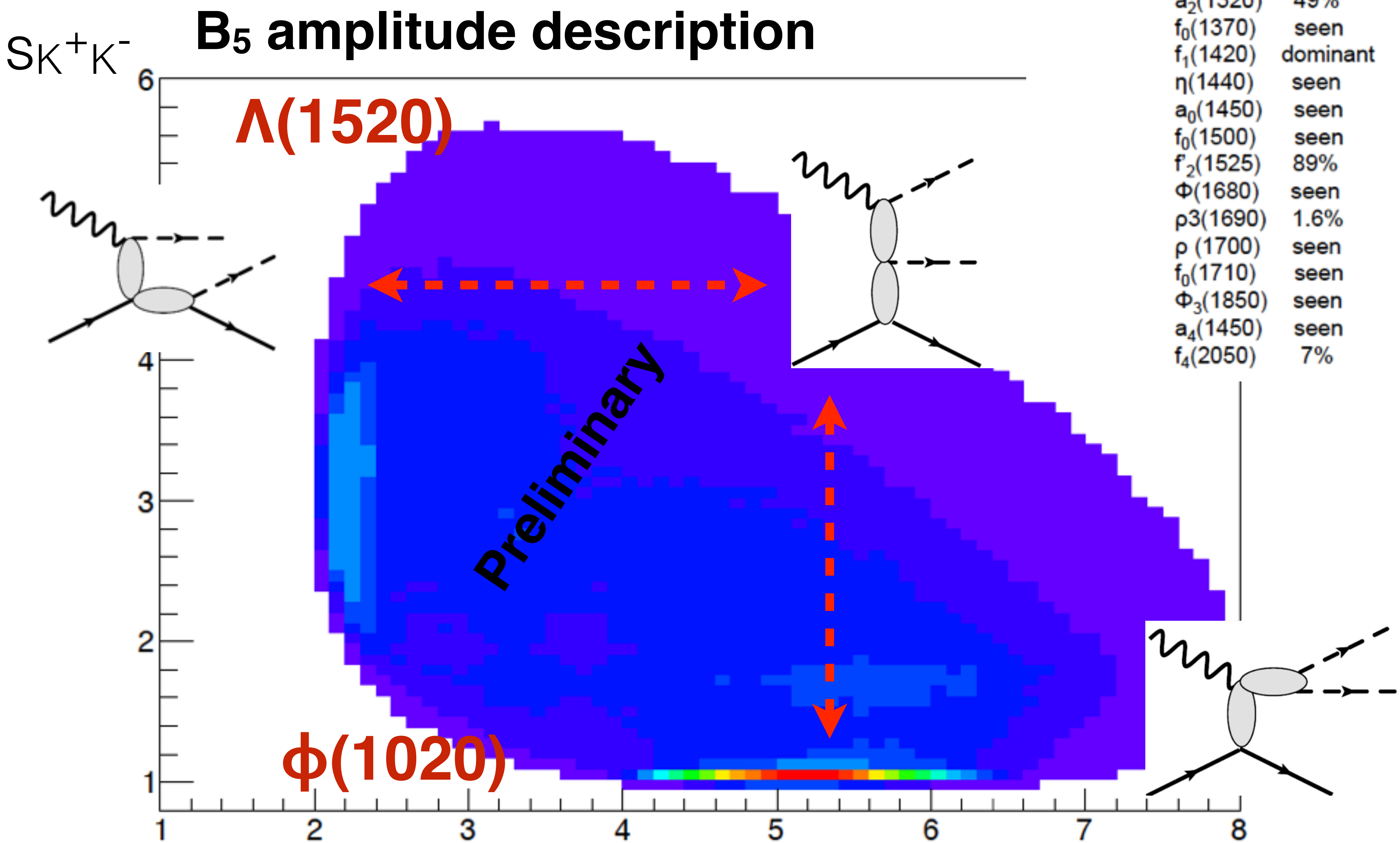
V.Mathieu, JPAC

Hyperon production
what is Lambda(1405)?

C.Fernandez Ramirez, JPAC



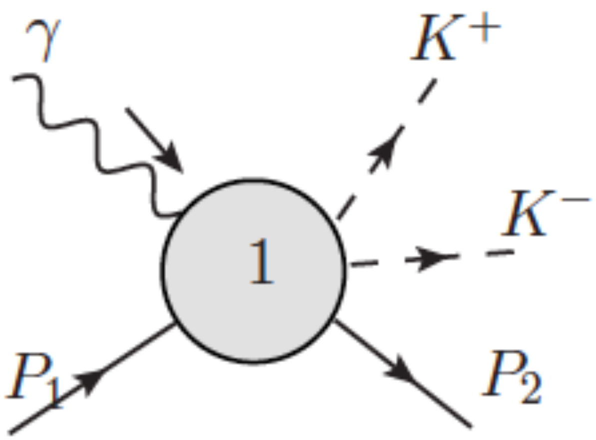
Duality @ JLab

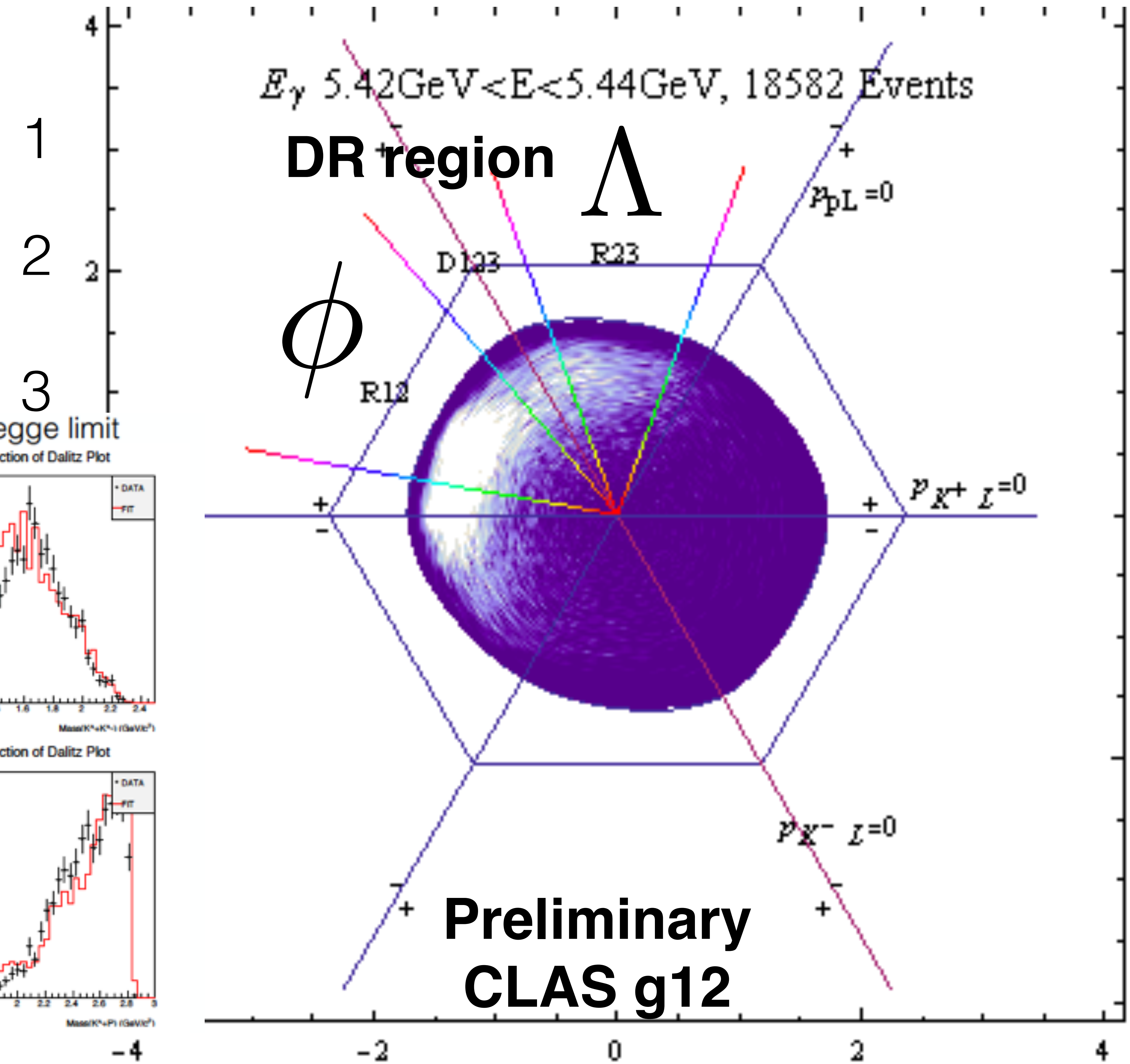


$\gamma p \rightarrow K^+K^-p$ (g11,g12)

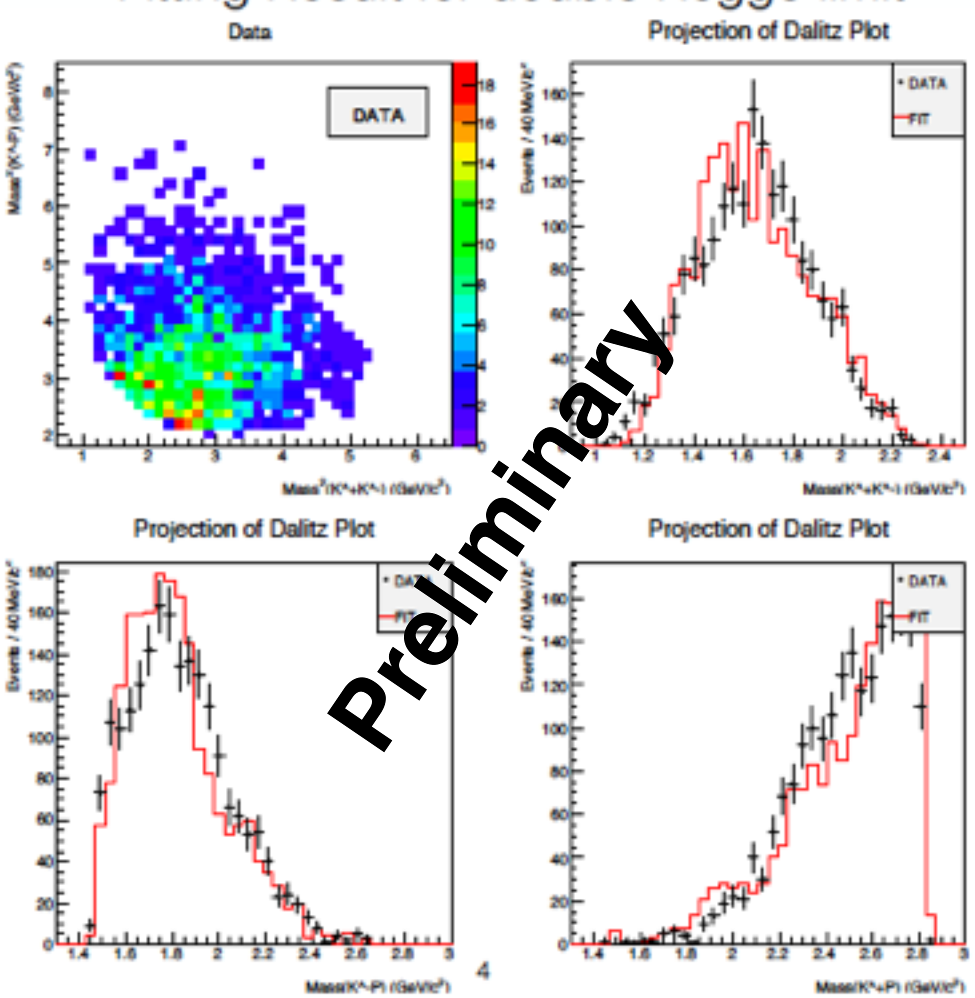
D.Schott, JPAC/GWU
M. Shi JPAC/Pekin U.

van Hove longitudinal plot



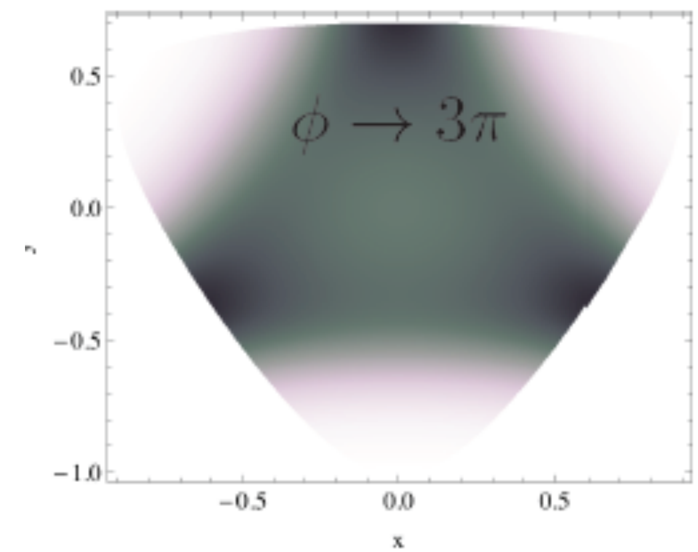


Fitting Result for double Regge limit

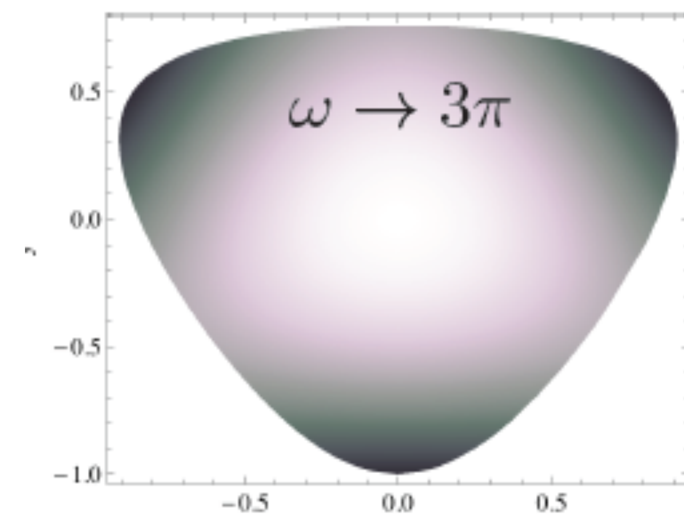


- **Light meson decays**

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



Constrained phase space: effective (chiral) dynamics, low partial waves, amendable to dispersive methods

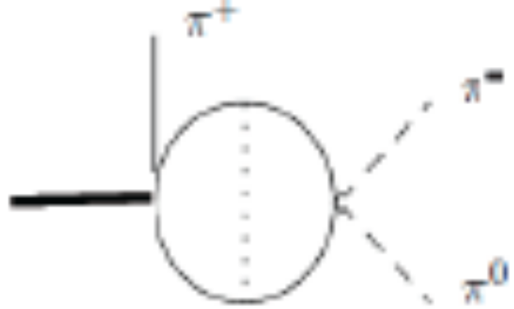


$\eta \to 3\pi$ $$\boxed{A(s,t,u) = -\frac{1}{Q^2}\frac{M_K^2}{M_\pi^2}\frac{M_K^2 - M_\pi^2}{3\sqrt{3}F_\pi^2}M(s,t,u)} \quad \left(Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}\right)$$

$\eta \to 3\pi$

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

LO NLO Experiment



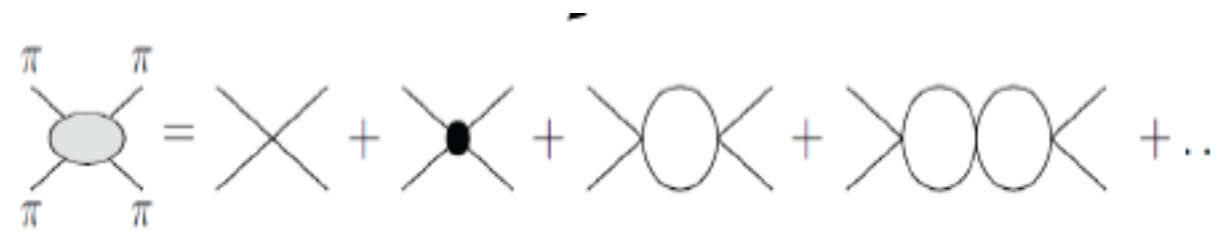


TABLE III: Dalitz plot parameters for $\eta \to 3\pi^0$. Set 1 and Set 2 correspond to $(I, L) = (0, 0), (1, 1)$ and $(I, L) = (0, 0), (2, 0), (1, 1)$ cases respectively (see Table I).

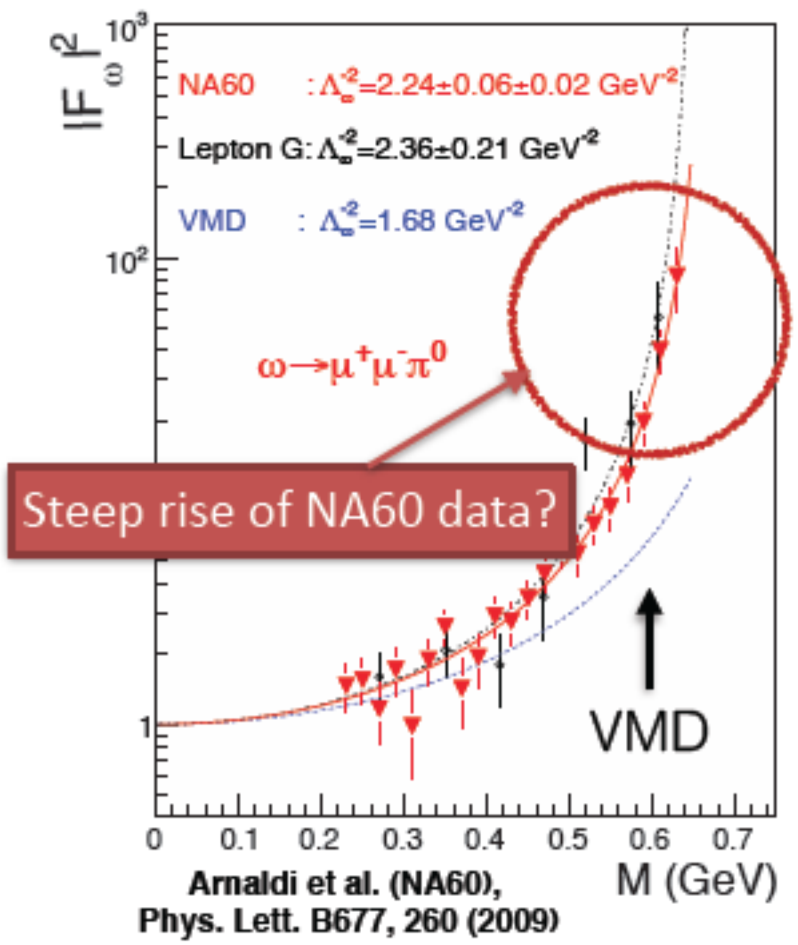
	α	β
GAMS-2000 [49]	-0.022 ± 0.023	–
Crystal Barrel, LEAR [50]	-0.052 ± 0.020	–
Crystal Ball, BNL [14]	-0.031 ± 0.004	–
SND [51]	-0.010 ± 0.023	–
CELSIUS-WASA [12]	-0.026 ± 0.014	–
WASA-at-COSY [52]	-0.027 ± 0.009	–
MAMI-B [53]	-0.032 ± 0.004	–
MAMI-C [46]	-0.032 ± 0.003	–
KLOE [16]	-0.0301 ± 0.0050	–
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	–

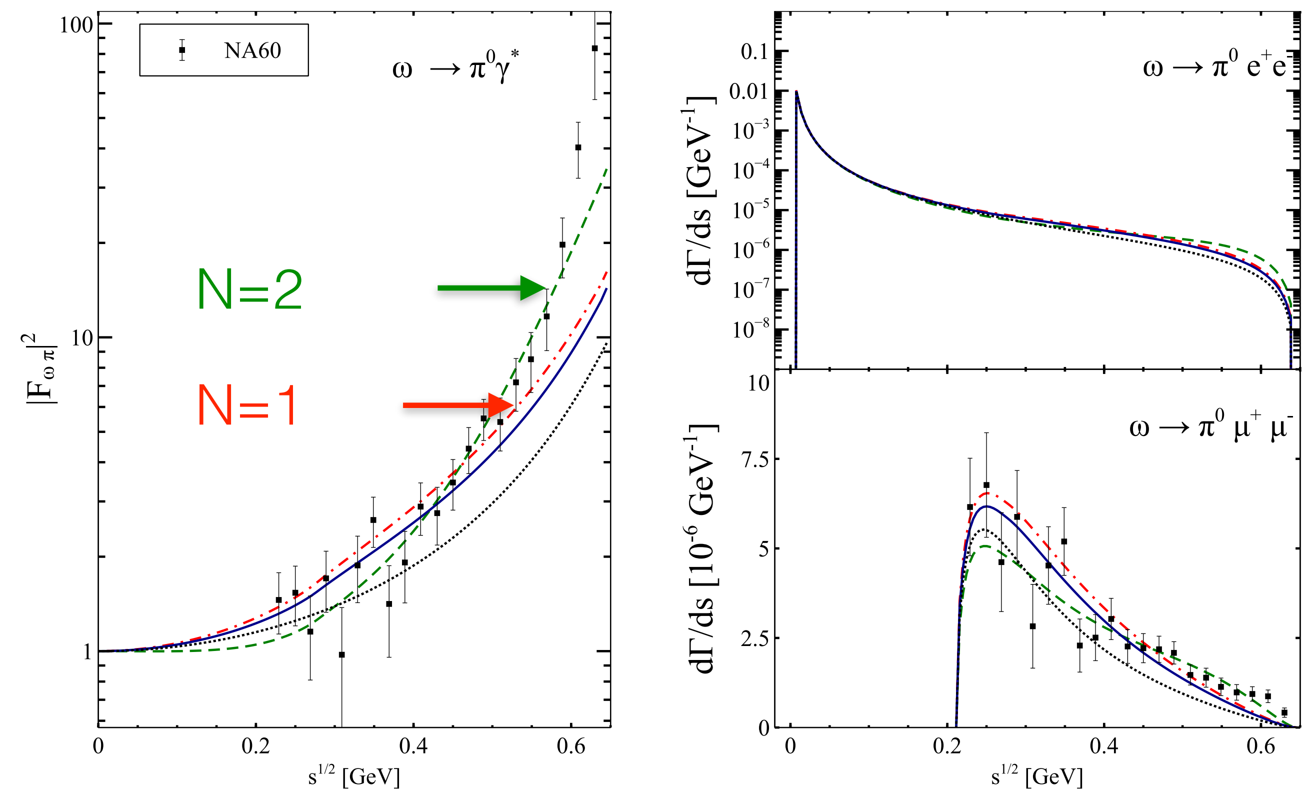
TABLE II: Dalitz plot parameters for $\eta \to \pi^+\pi^-\pi^0$. Set 1 and Set 2 correspond to $(I, L) = (0, 0), (1, 1)$ and $(I, L) = (0, 0), (2, 0), (1, 1)$ cases respectively (see Table I).

	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

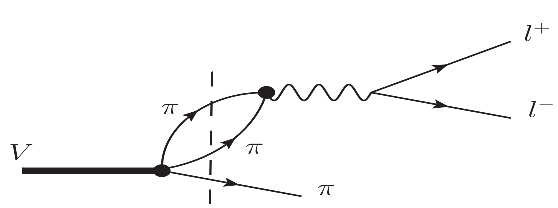
P.Guo, I.Danilkin, HASPEC/JPAC

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

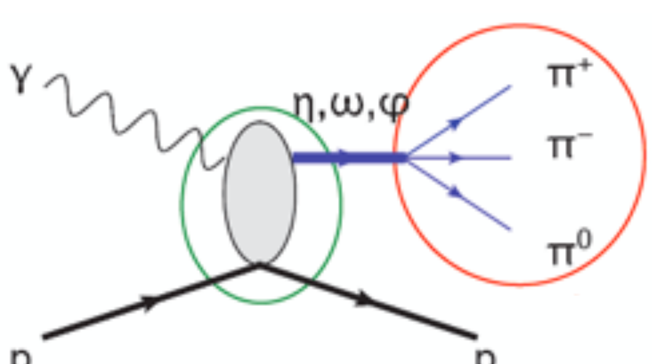




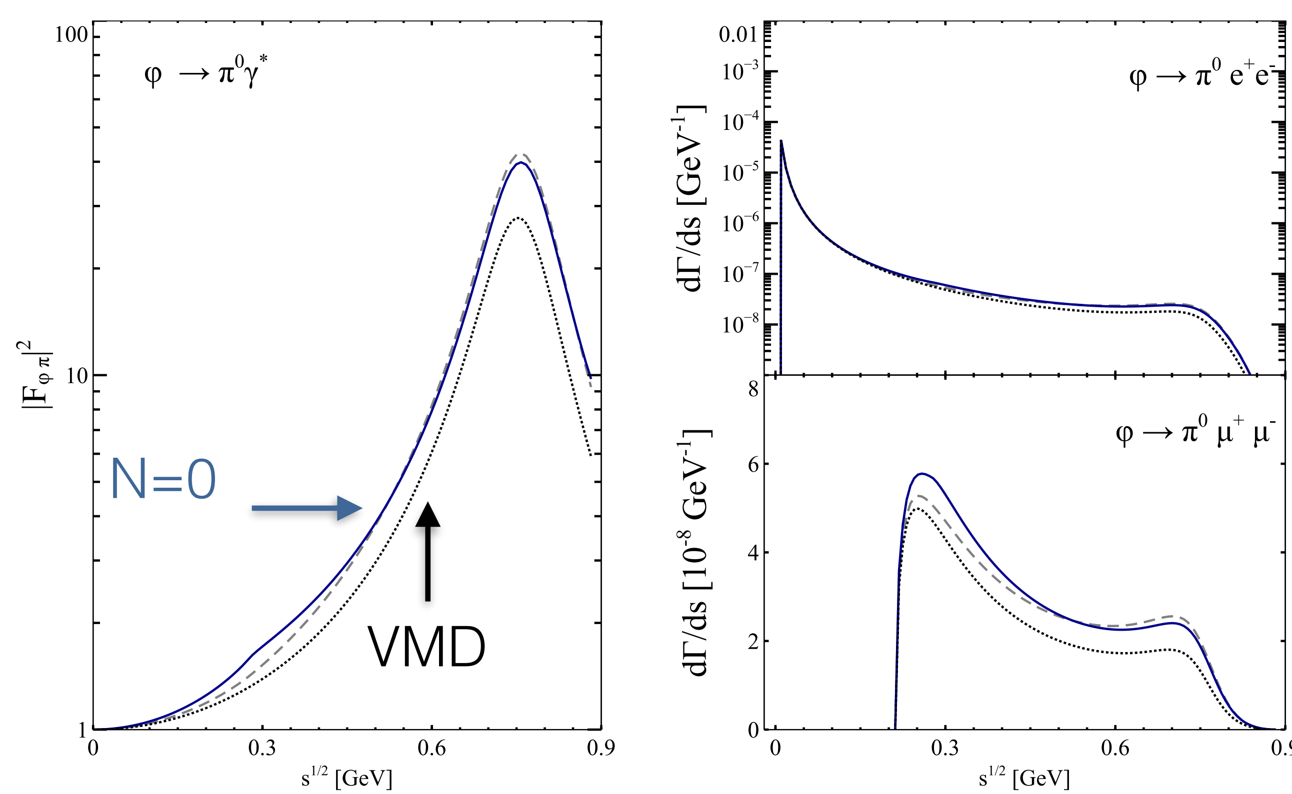
I.Danilkin, JPAC



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



upcoming CLAS g12



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

- Formalism
- Model
- Resources
- Run

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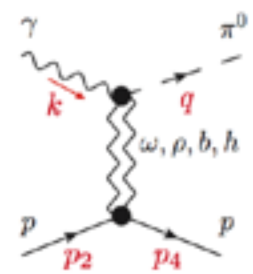
$\gamma p \to \pi^0 p$

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 $E_\gamma \geq 4\,\mathrm{GeV}$ 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

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

The differential cross section is expressed in μb/GeV^2. We used $(\hbar c)^2 = 0.3894\,\mathrm{mb.GeV}^2$.
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

$$\begin{aligned}
F_1 &= -A_1 + 2MA_4, & \eta &= +, & CP &= + && \text{(A.2)}\\
F_2 &= A_1 + tA_2, & \eta &= -, & CP &= - && \text{(A.3)}\\
F_3 &= 2MA_1 - tA_4, & \eta &= +, & CP &= + && \text{(A.4)}\\
F_4 &= A_3 & \eta &= -, & CP &= + && \text{(A.5)}
\end{aligned}$$

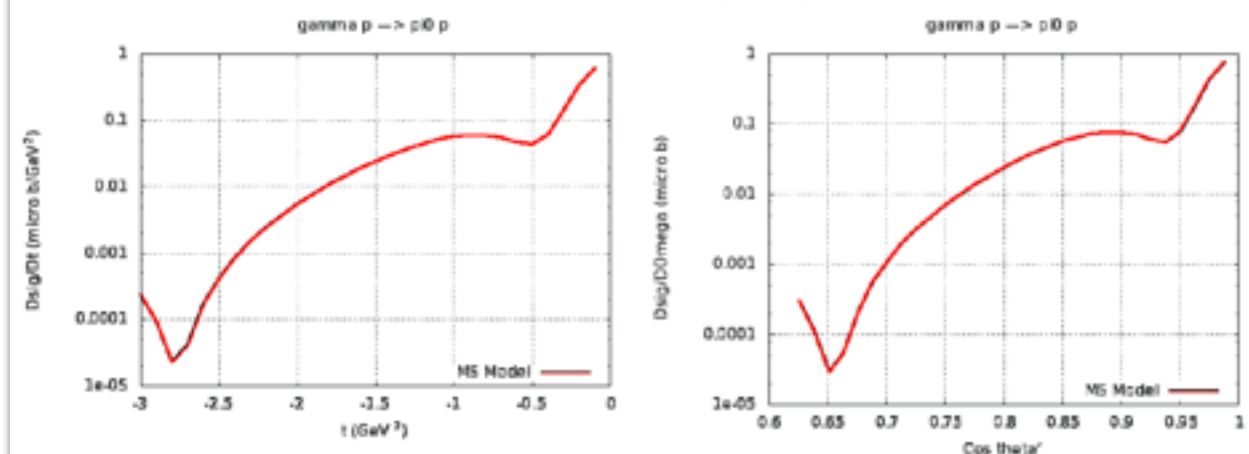
The F_i amplitudes have good quantum numbers of the t −channel, the naturality $\eta = P(-1)^J$ and the product CP.

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"