Hyperon Studies at JPAC

Who we are
and what we do

General approach:
Role of reaction theory

Hyperon Studies

Adam Szczepaniak
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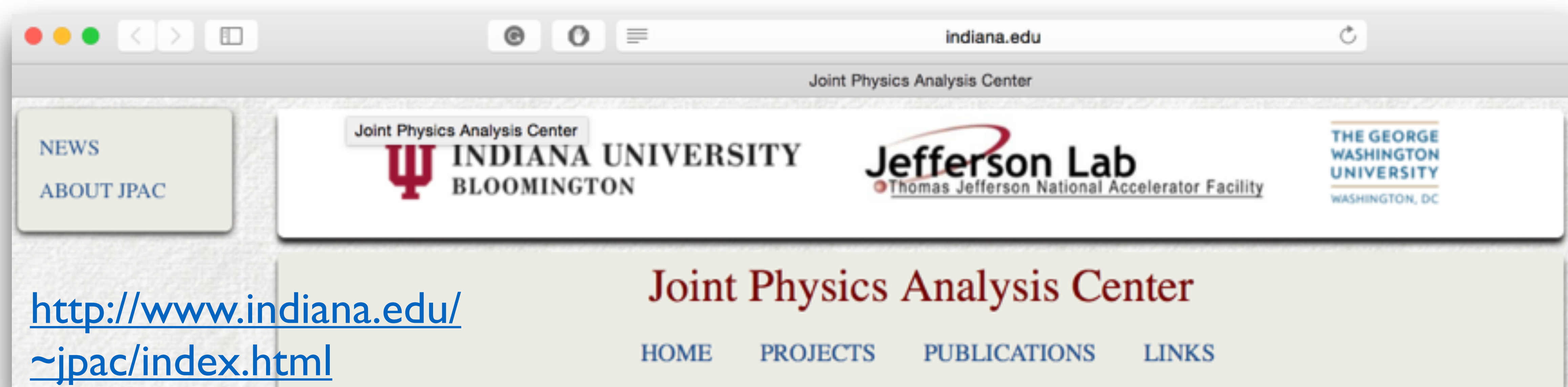
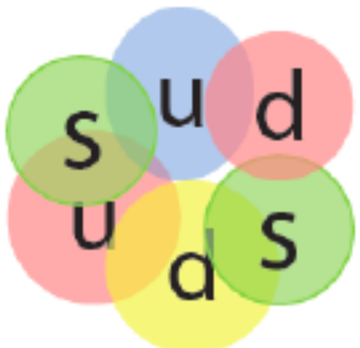
Jefferson Lab



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

There may be hadrons that look like …

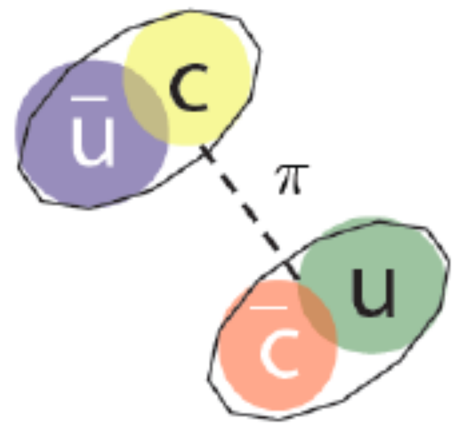


dibaryon

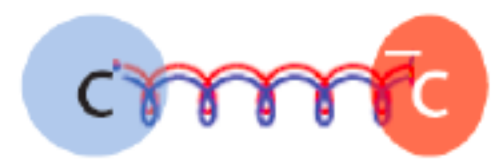
pentaquark

glueball

diquark + di-antiquark



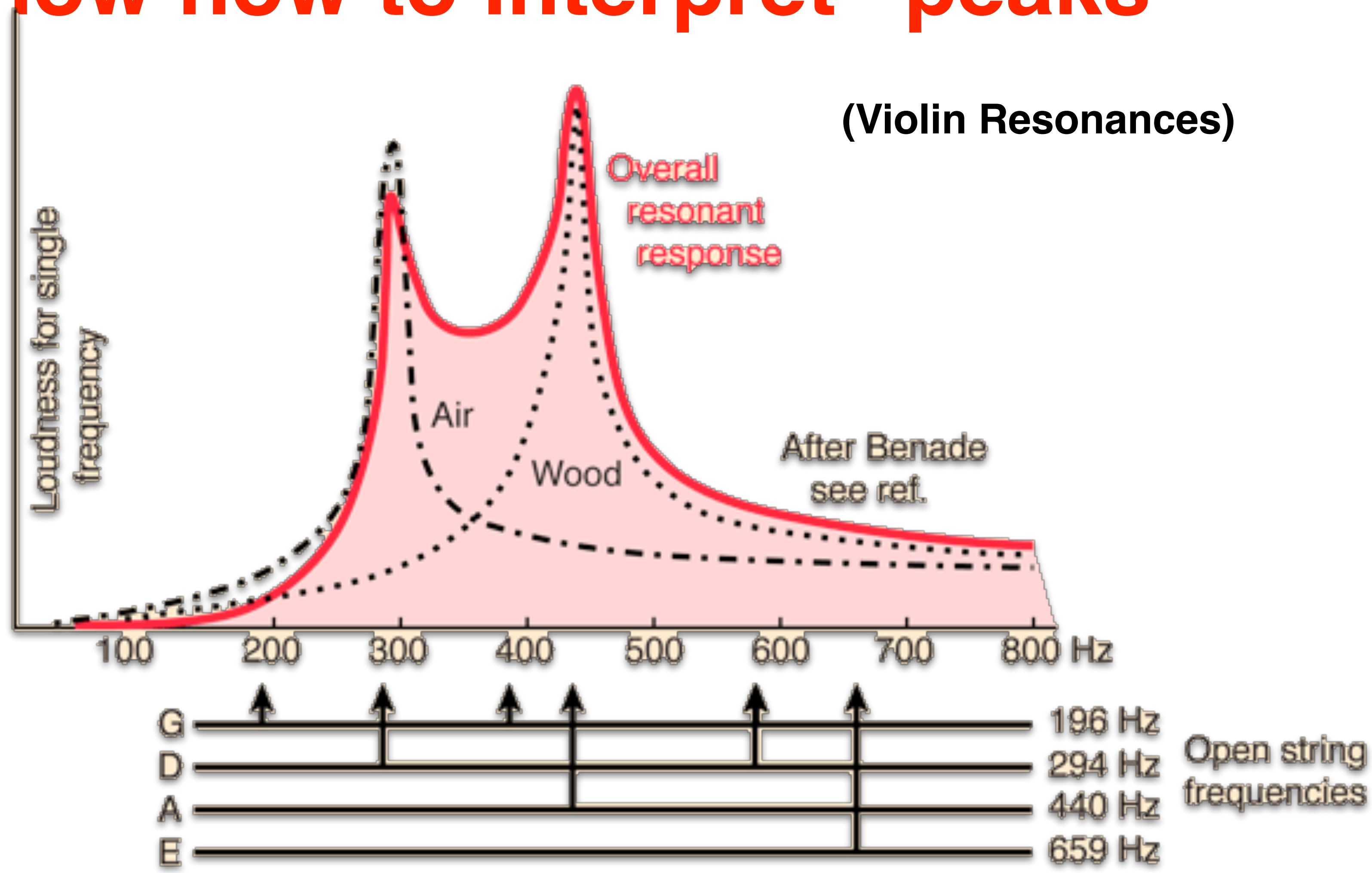
dimeson molecule



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

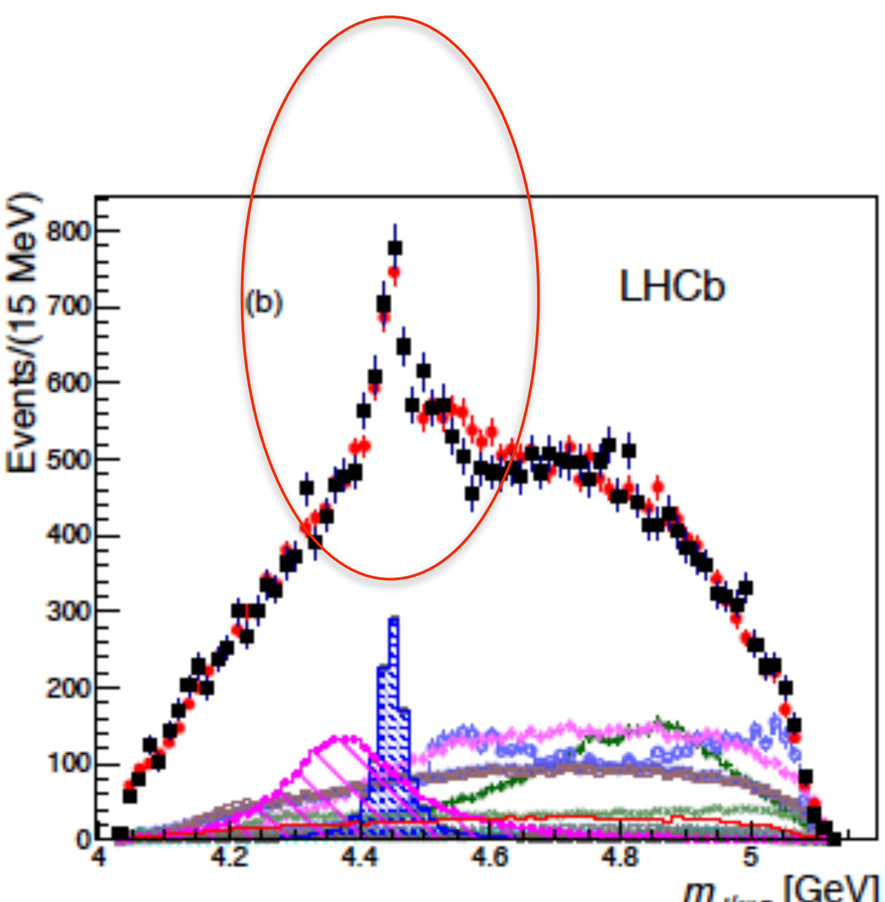
…but before we know this it is necessary to identify resonances

…we need to know how to interpret "peaks"



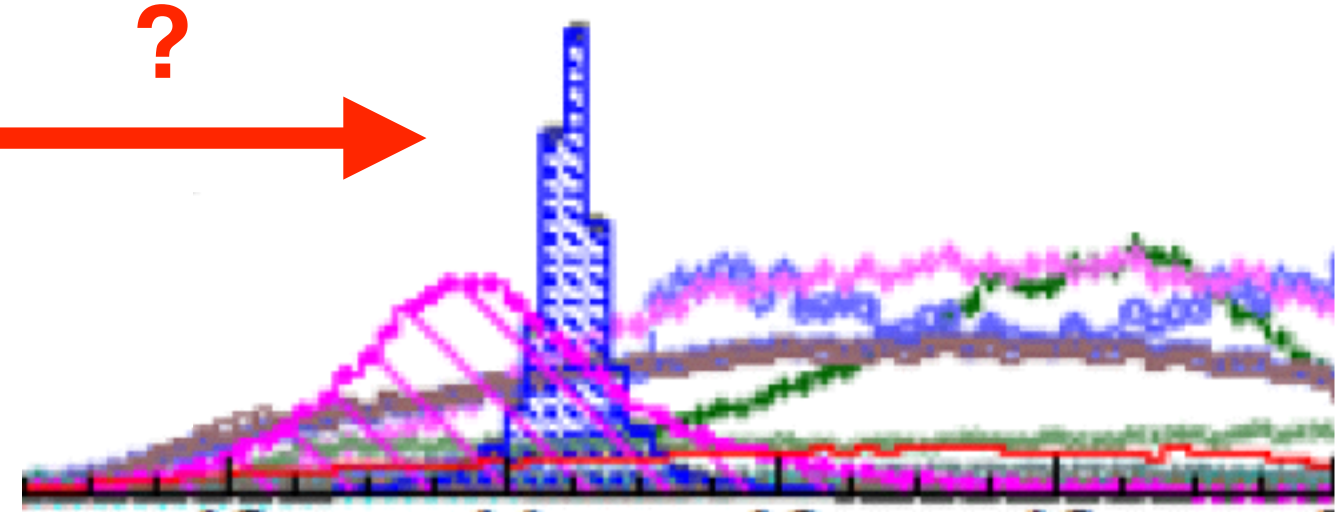
$\Lambda_b \to K^- p J/\psi$

a resonance in pJ/ψ ?



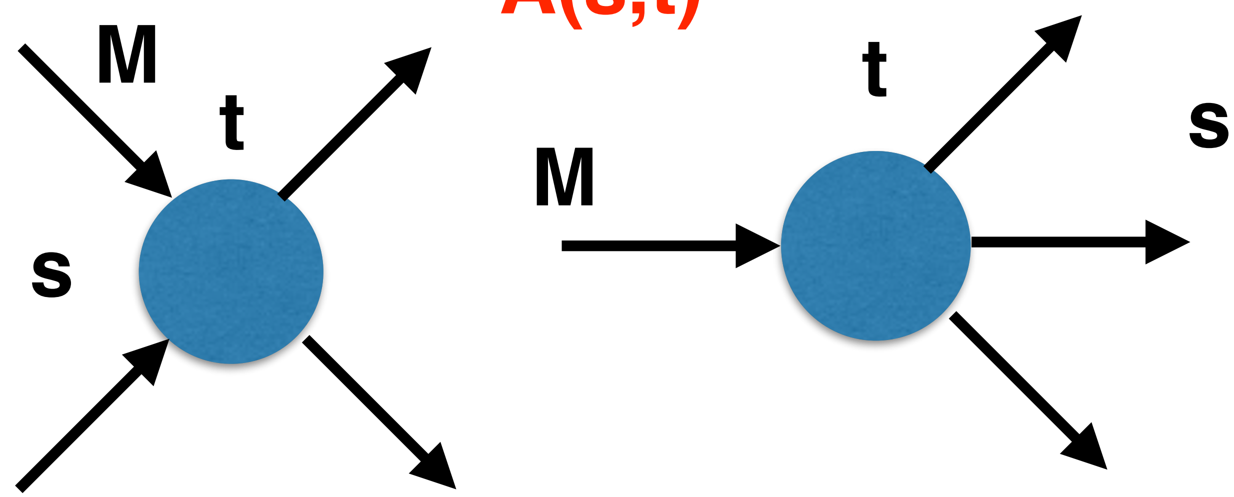
?

... or a $\overline{K}\,p$ reflection ?



S-matrix principles: Crossing, Analyticity, Unitarity

A(s,t)



s-channel M-decay channel

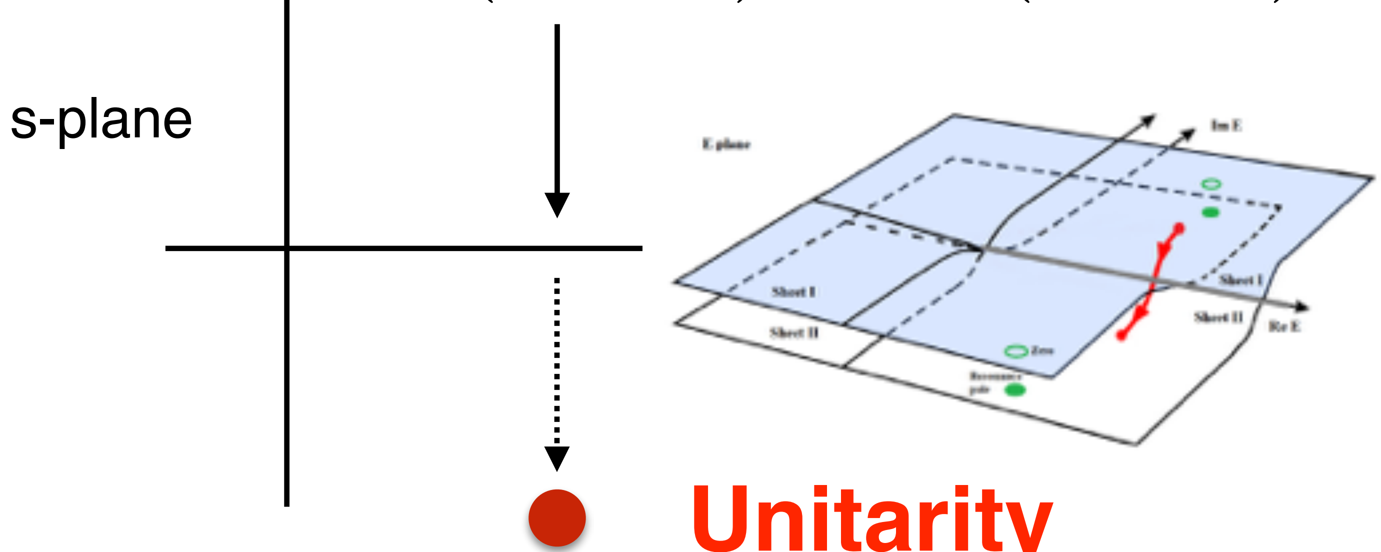
Crossing

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

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

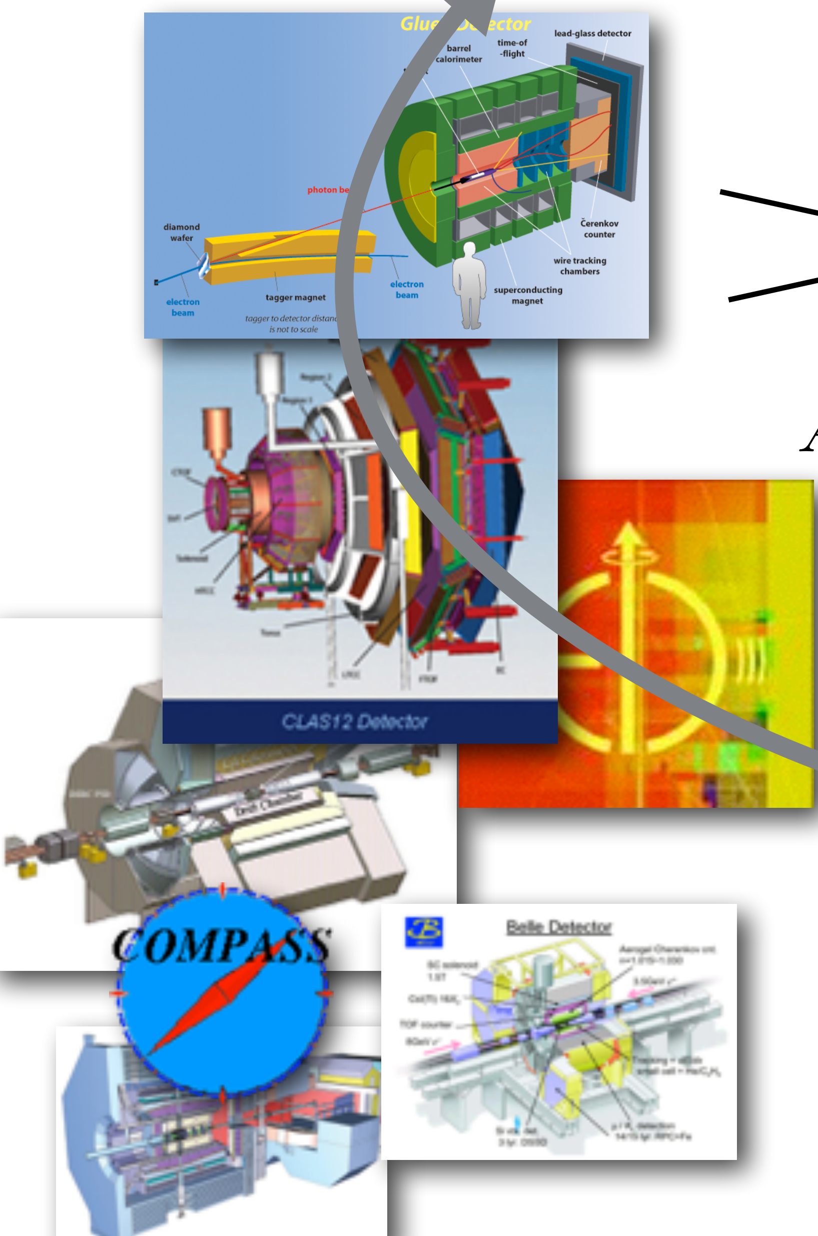
bumps/peaks on the real axis (experiment) come from singularities in unphysical sheets

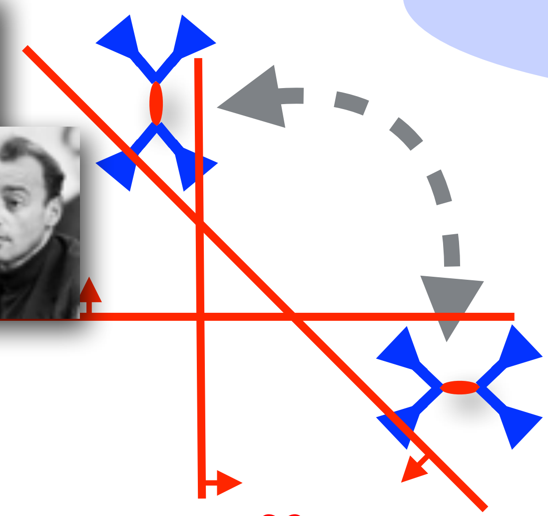
These singularities come from QCD

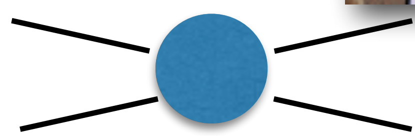
Amplitude Analysis @ JPAC

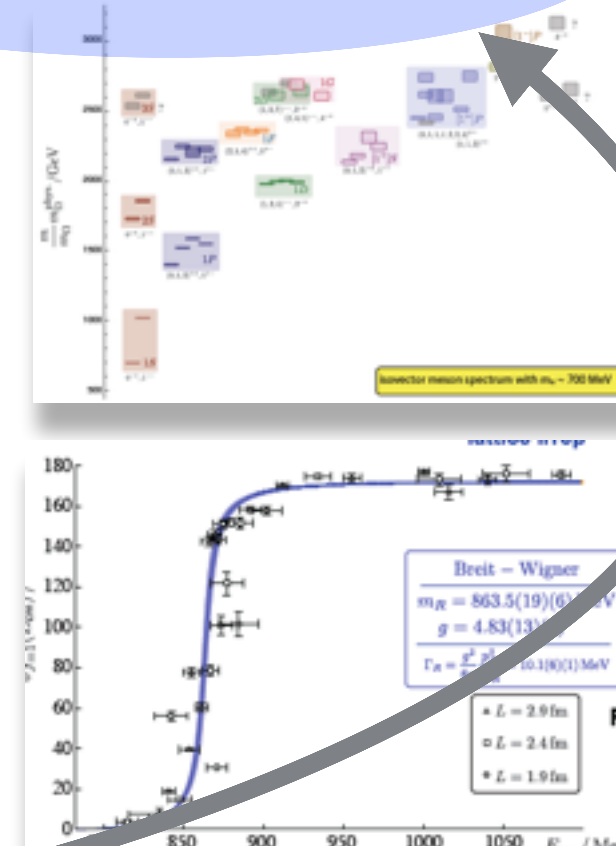
Events, X-sections,MC

QCD Predictions









$$A(s,t) = \sum_{l=0}^{\infty} f_l(s) P_l(z_s) = \sum_{l=0}^{\infty} g_l(t) P_l(z_t)$$

Amplitude analysis:
based on S-matrix principles:

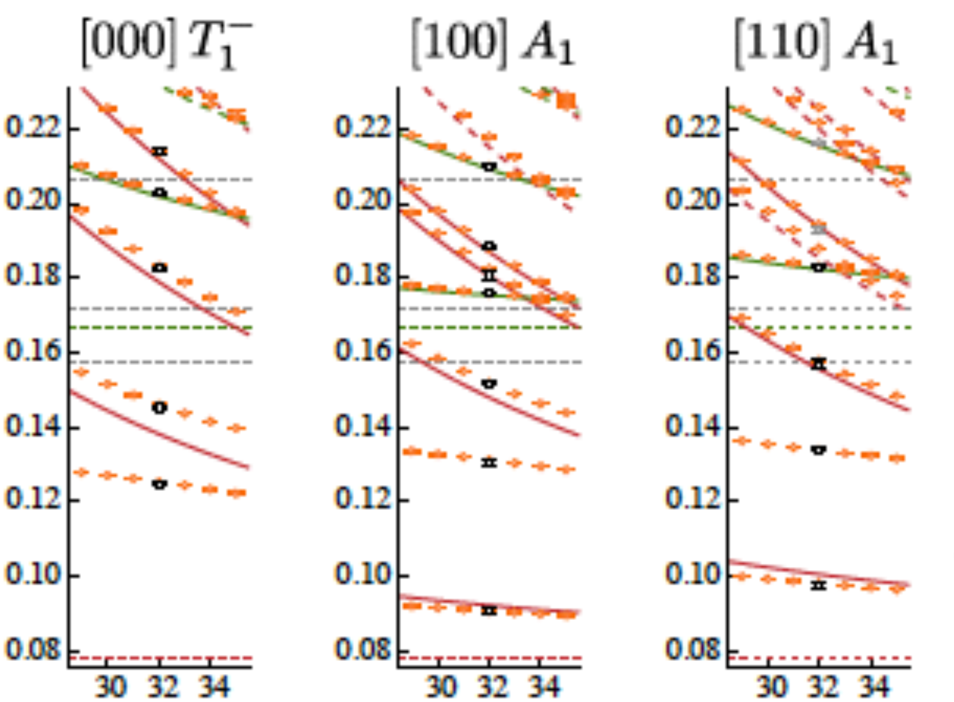
- **analyticity**
- **unitarity**
- **crossing**

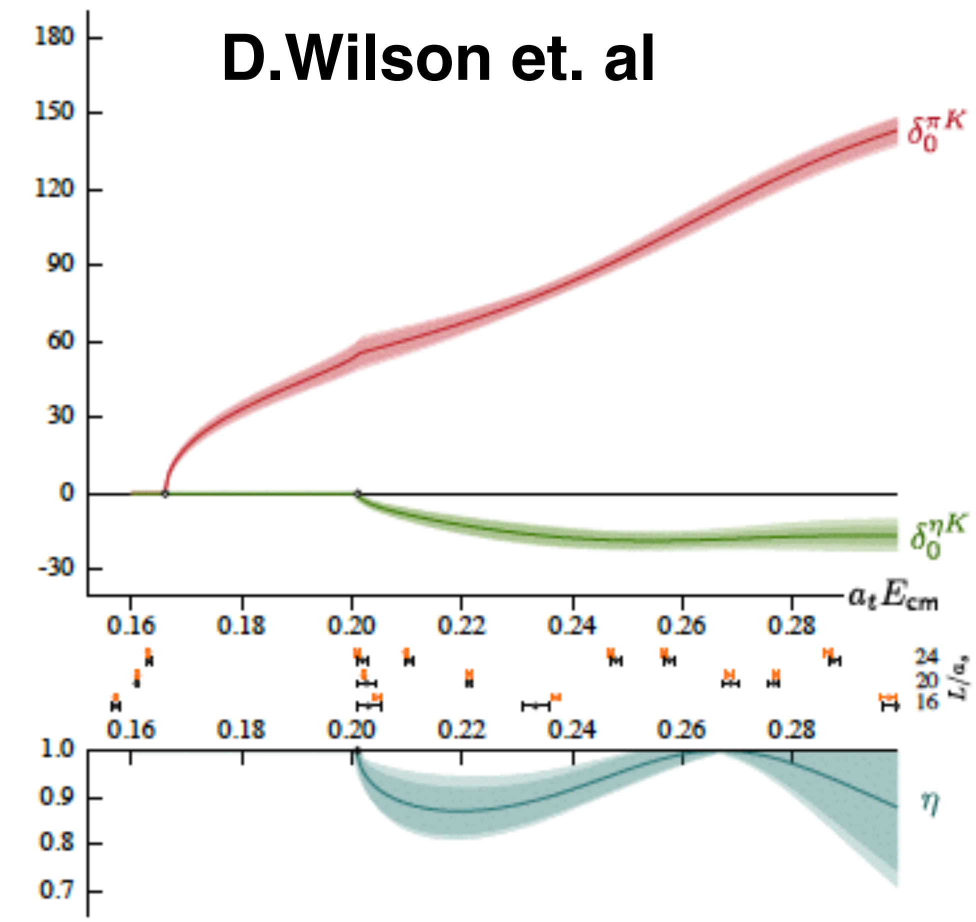
Global effort
JLab/IU/GWU Physics Analysis Center

QCD on the Lattice : simulated scattering experiment

(known kinematical function) **$Z(E_i$=“data”$) = T(E_i)$** (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

JPAC : Example of Analysis Projects

Light meson decays and light quark resonance

- **$\omega/\phi \to 3\pi$, $\pi\gamma$ (dispersive)**
- $\omega \to 3\pi$ (Veneziano, B4)
- $\eta \to 3\pi$, $\eta'/f1 \to \eta\pi\pi$, (Khuri-Treiman, B4)
- $J/\Psi \to \gamma\pi0\pi0$

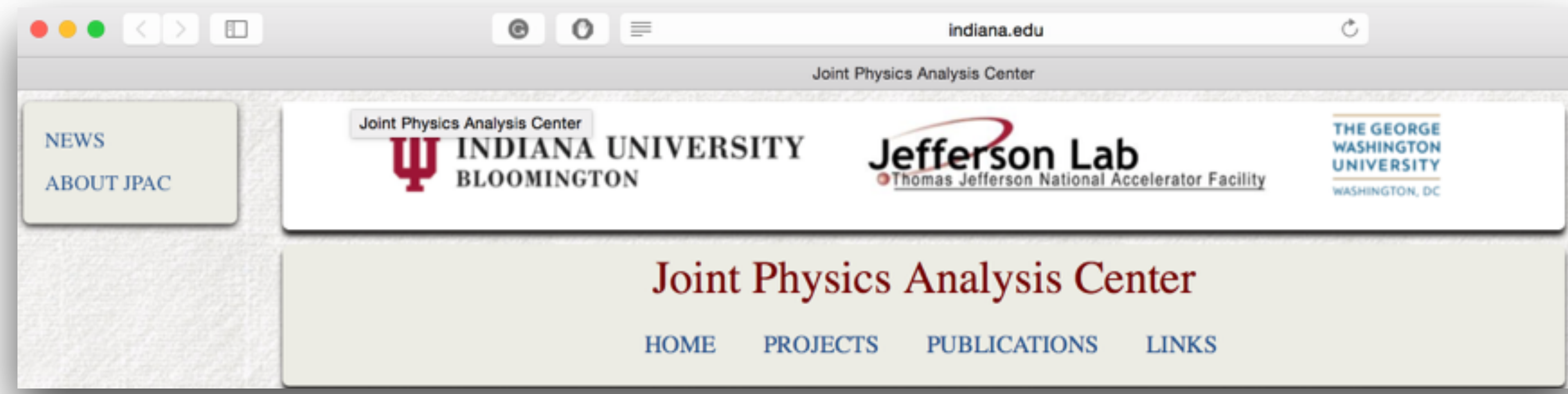
Photo-production: (production models, FESR and duality)

- $\gamma p \to \pi0p$
- $\gamma p \to pK+K-$ (and Kp)
- $\gamma p \to \pi+\pi-p$, $\pi0\eta p$, ωp

Launched in the Fall of 2013
>20 analysis/papers published

Exotica and XYZ's:

- **$\pi-p \to \pi-\eta p$ & $\pi-p \to \pi-\eta' p$ (FESR)**
- **$B^0 \to \Psi' \pi- K^+ u$, $\Psi(4260) \to J/\Psi \pi+\pi-$, $\Lambda_b \to K- pJ/\Psi$**
- $J/\Psi \to 3\pi$, $KK\pi$ (Veneziano, B4)



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GlueX collaboration
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CLAS collaboration
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HASPECT
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Raffaella De Vita (Genoa)
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BESIII collaboration
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LHCb collaboration
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J.Rademacker, (Bristol)
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COMPASS collaboration
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Fabian Krinner (TUM)
Boris Grube (TUM)
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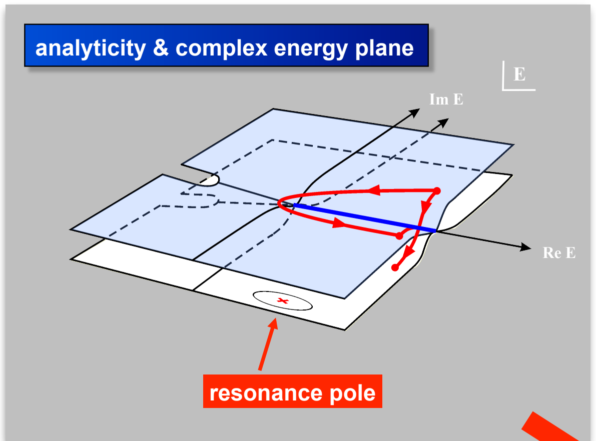
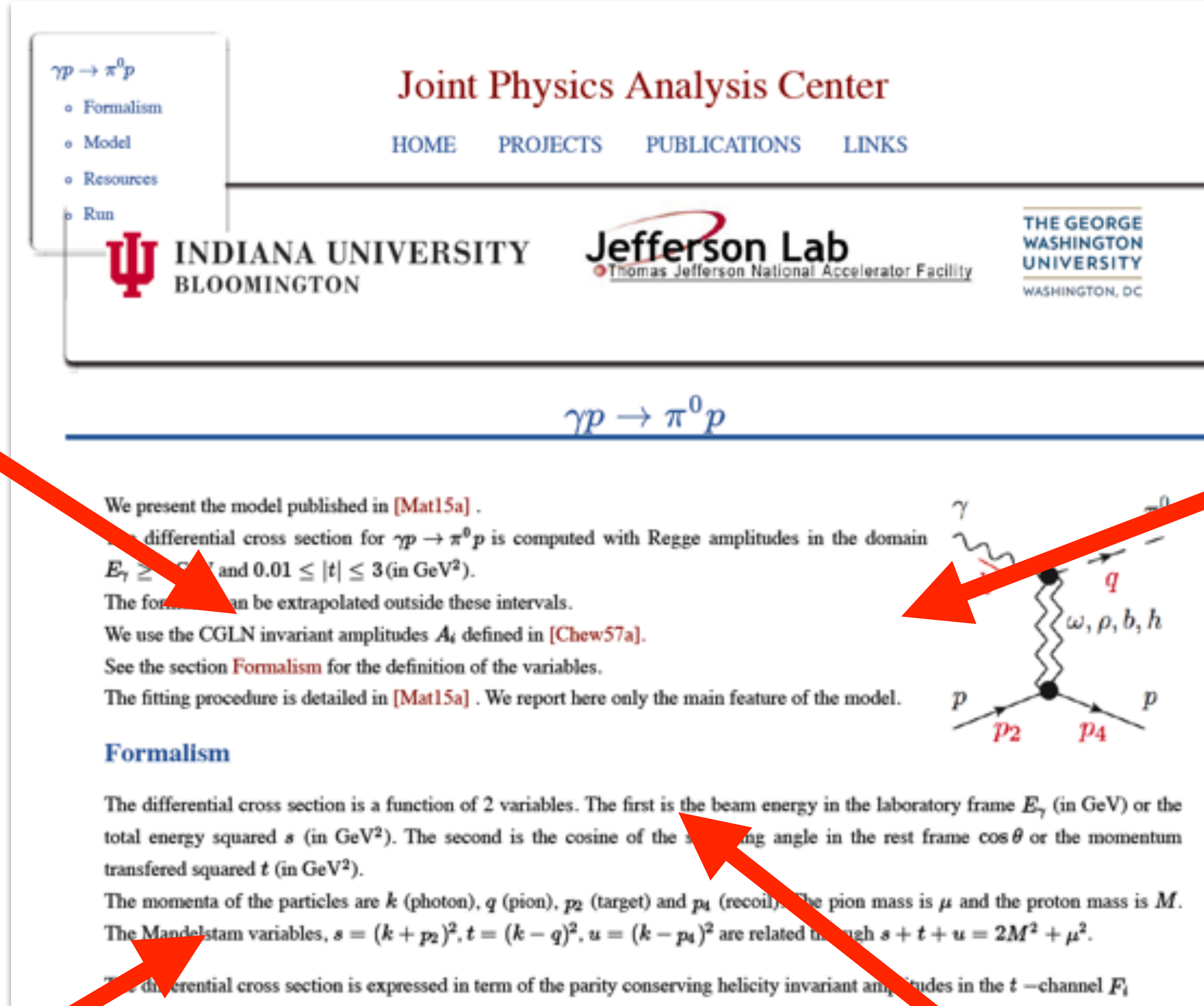
BaBar collaboration
Antimo Palano (Bari)
…



special thanks to
Vincent Mathieu

```
double complex function A(gamma,target,recoil,pip,pim,
                         ,lambda_g,lambda_t,lambda_r,
                          params)
implicit double precision (a-h,o-z)
dimension gamma(4)
dimension target(4)
dimension recoil(4)
dimension pip(4),pim(4)
dimension params(100)

 double complex Ampl

s = (gamma(4)+target(4))**2 - (gamma(1)+target(1))**2
$   - (gamma(2)+target(2))**2 - (gamma(3)+target(3))**2

s1 = (pip(4)+pim(4))**2 - (pip(1)+pim(1))**2
$    - (pip(2)+pim(2))**2 - (pip(3)+pim(3))**2

s2 = (pip(4)+recoil(4))**2 - (pip(1)+recoil(1))**2
$    - (pip(2)+recoil(2))**2 - (pip(3)+recoil(3))**2

t1 = (gamma(4)-pim(4))**2 - (gamma(1)-pim(1))**2
$    - (gamma(2)-pim(2))**2 - (gamma(3)-pim(3))**2

t1 = (target(4)-recoil(4))**2 - (target(1)-recoil(1))**2
$    - (target(2)-recoil(2))**2 - (target(3)-recoil(3))**2

call Ath(s,s1,s2,t1,t2,lambda_g,lambda_t,lambda_r,params,Ampl)

A = Ampl

return
end
```



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

Joint Physics Analysis Center

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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 $E_\gamma \geq$ ... GeV and $0.01 \leq |t| \leq 3$ (in GeV²).

The for... 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 GeV²). The second is the cosine of the s...ing angle in the rest frame $\cos\theta$ or the momentum transfered squared t (in GeV²).

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

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

The differential cross section is expressed in μb/GeV². We used $(\hbar c)^2$ ...

The t −channel is the rest frame of the process $\gamma\pi^0 \to p\bar{p}$.

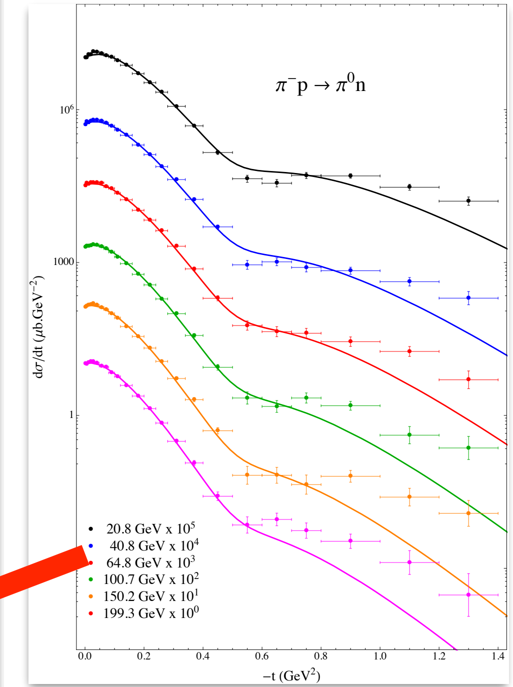
In the t −channel, the momenta of the nucleon p_t and the pion k_t and ...

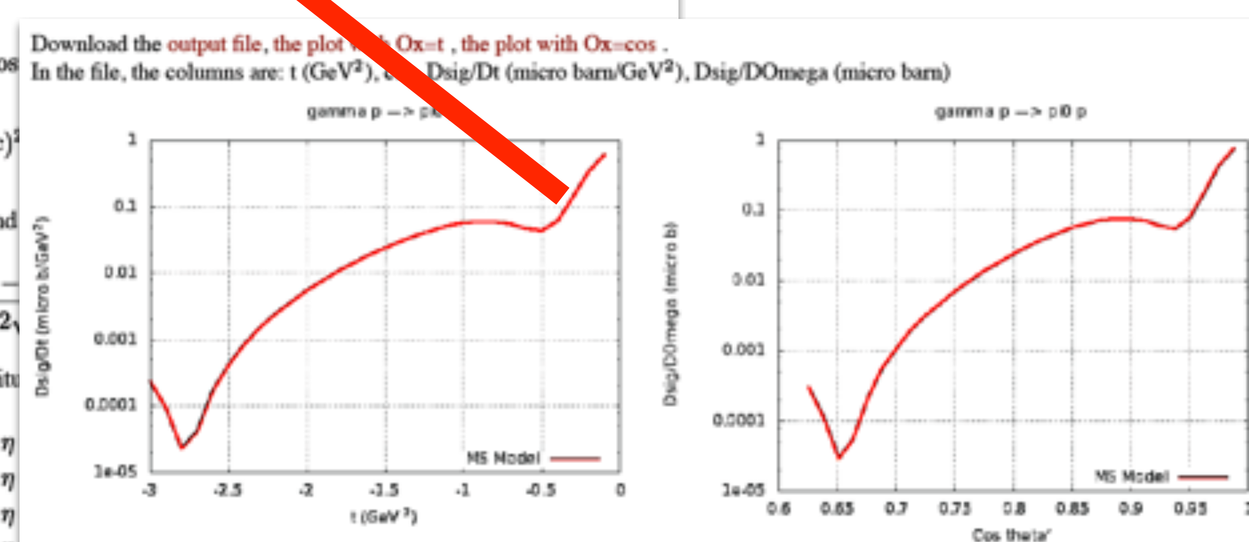
$$k_t = \frac{1}{2}\sqrt{t-4M^2}, \qquad q_t = \frac{t-\ldots}{2\ldots}$$

The invariant amplitudes F_i are related through the CGLN A_i amplitu...

$$F_1 = -A_1 + 2MA_4, \quad \eta \ldots$$
$$F_2 = A_1 + tA_2, \quad \eta \ldots$$
$$F_3 = 2MA_1 - tA_4, \quad \eta \ldots$$
$$F_4 = A_3 \quad \eta \ldots$$

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





Hyperon Physics

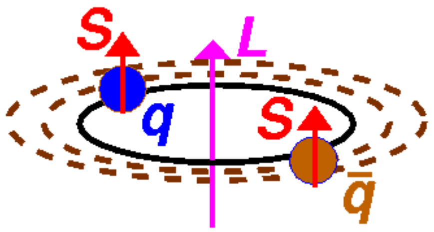
Bridge between light (u,d) and heavy (c,b) quark baryons

Test Quark Model vs QCD (lattice)

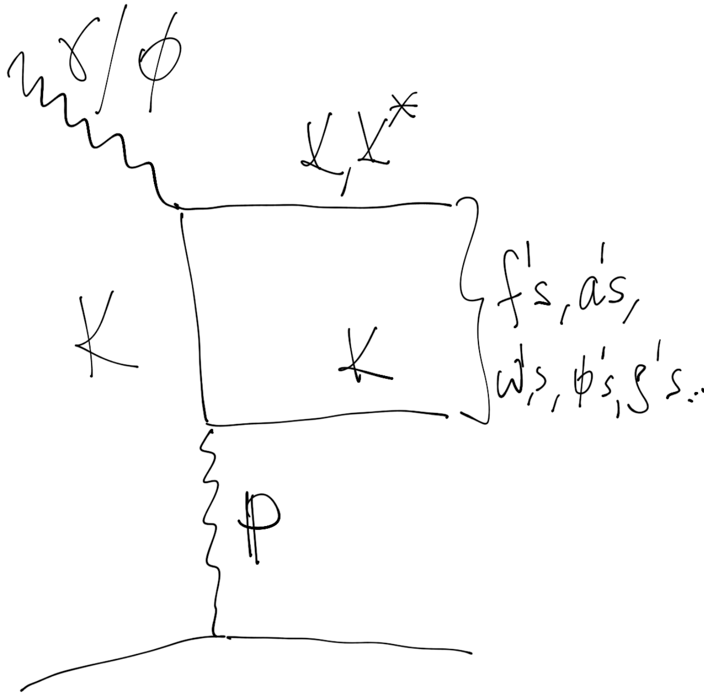
Photon couples to quarks is, glueballs , hybrids or use in associated production of K*'s and Hyperons

Hyperon spectrum less understood e.g Λ(1405) only recently pole positions have started to be reported by the PDG

Some quark model states have not been seen yet



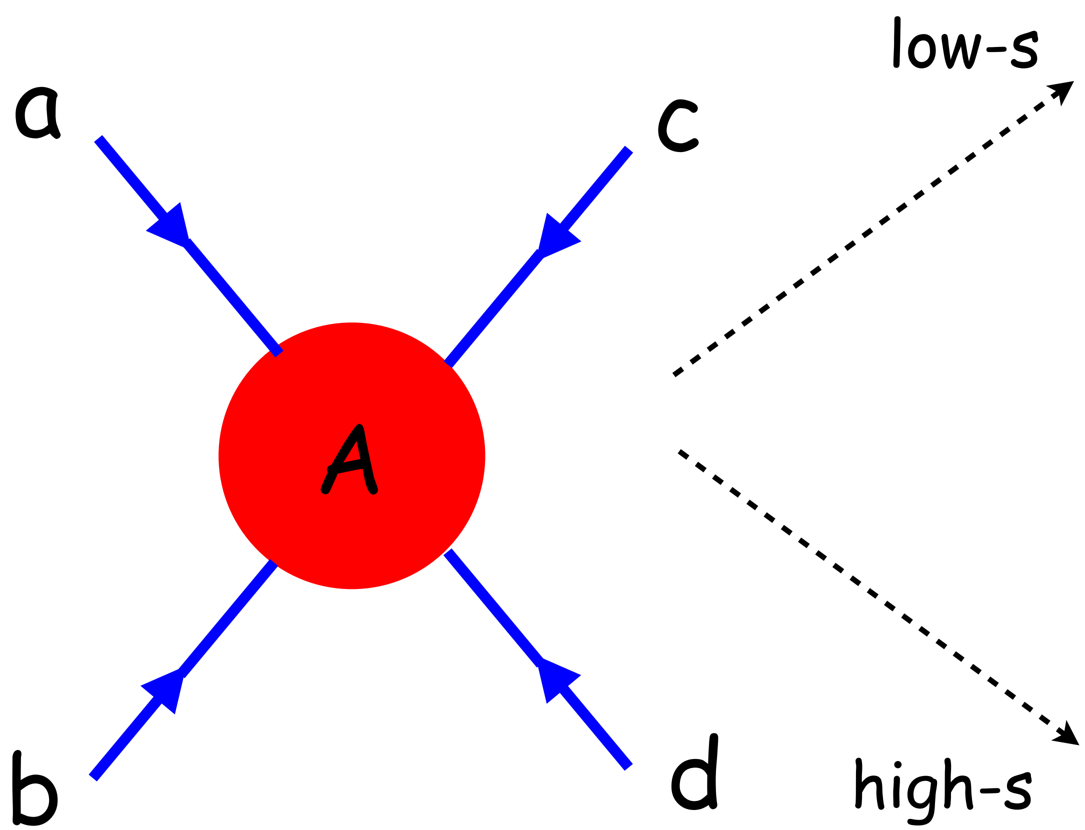
2^{--} (L=2,S=1)

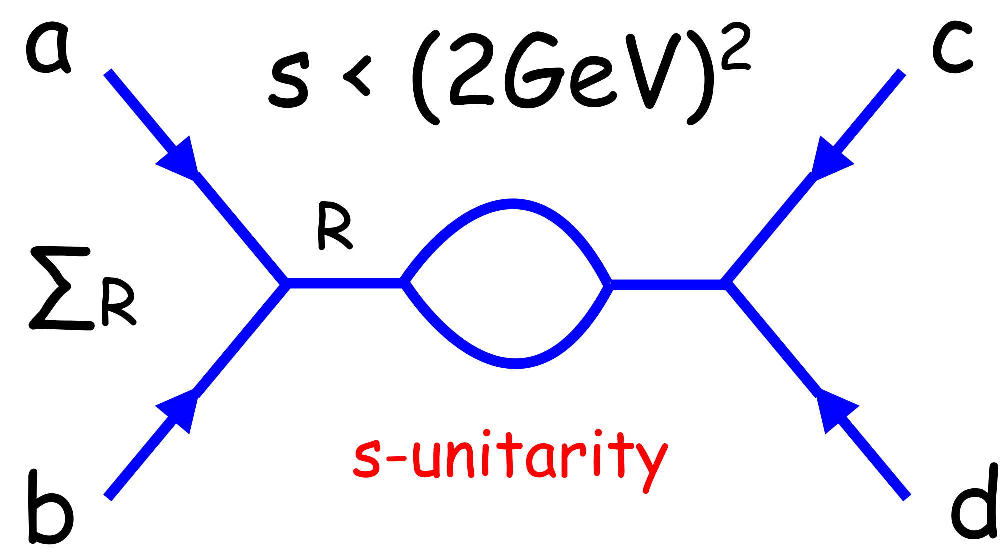


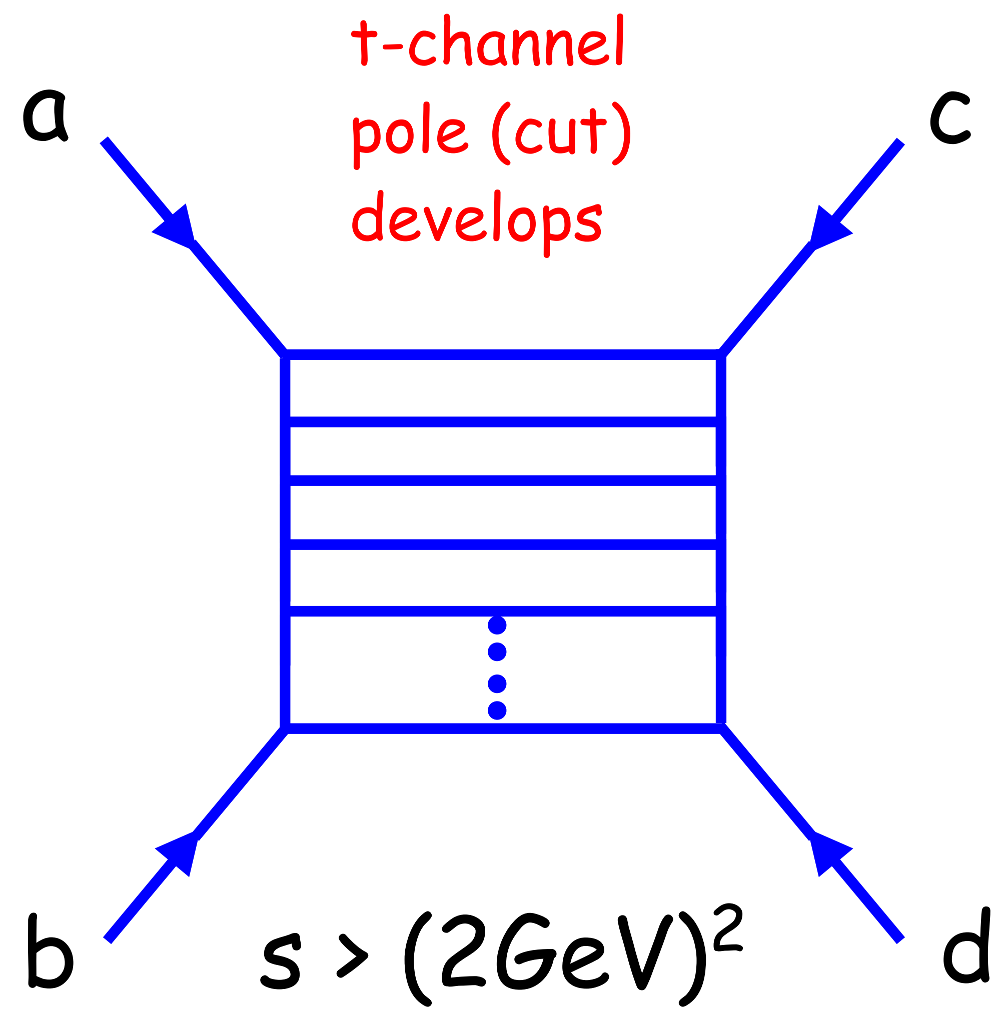
I^G	naturality $=P(-1)^J$	twist =+1 if J=0,2,.. =-1 if J=1,3...	name
0^+	+1	+1	f_0, f_2,...
0^+	+1	-1	$\eta/\eta'_1, \eta/\eta'_3$,... ($1^{-+}, 3^{-+}$,..)
0^+	-1	+1	$\eta/\eta'_0, \eta/\eta'_2$,...
0^+	-1	-1	f_1, f_3,...
0^-	+1	+1	h_0, h_2,.. ($0^{+-}, 2^{+-}$,..)
0^-	+1	-1	$\omega/\phi_1, \omega/\phi_3$,..
0^-	-1	+1	$\omega/\phi_0, \omega/\phi_2$,...($0^{--}, 2^{--}$,.. :not seen)
0^-	-1	-1	h_1, h_3,...
1^+	+1	+1	b_0, b_2,.. ($0^{+-}, 2^{+-}$,..)
1^+	+1	-1	ρ_1, ρ_3,..
1^+	-1	+1	ρ_0, ρ_2,... ($0^{--}, 2^{--}$,.. :not seen)
1^+	-1	-1	b_1, b_3,..
1^-	+1	+1	a_0, a_2,...
1^-	+1	-1	π_1, π_3,... ($1^{-+}, 3^{-+}$,..)
1^-	-1	+1	π, π_2,...
1^-	-1	-1	a_1, a_3,...

Analyticity is a powerful constraint

cf. Bonn/Gatchina, EBAC, Julich, Giessen,GWU, Mainz, Zagreb,)

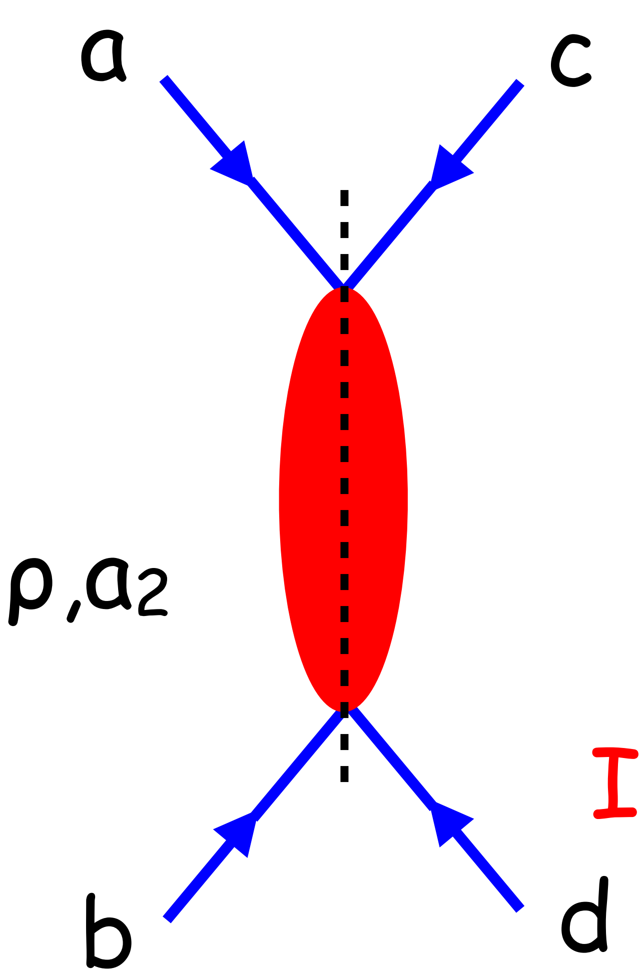






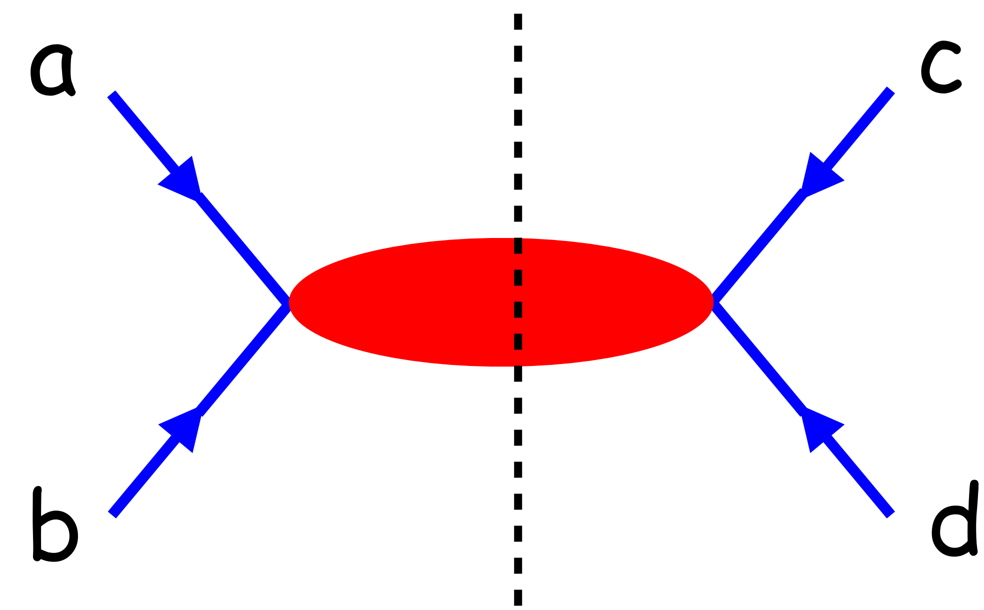
cf. Regge phenomenology

Im $A_{Regge}(N,t)$

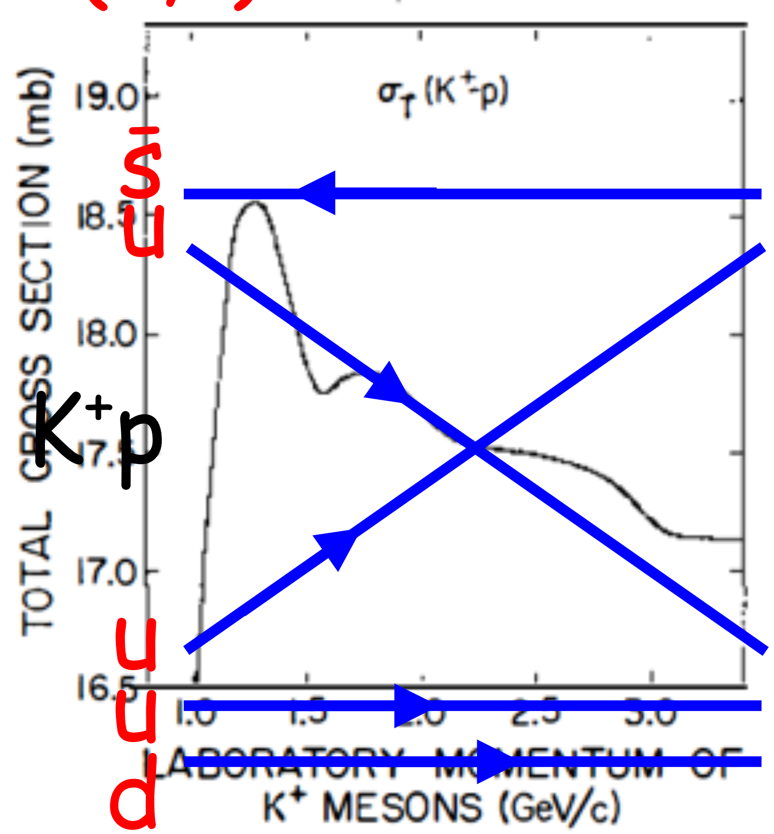


Can use cross-channel reggeons to study direct channel resonances

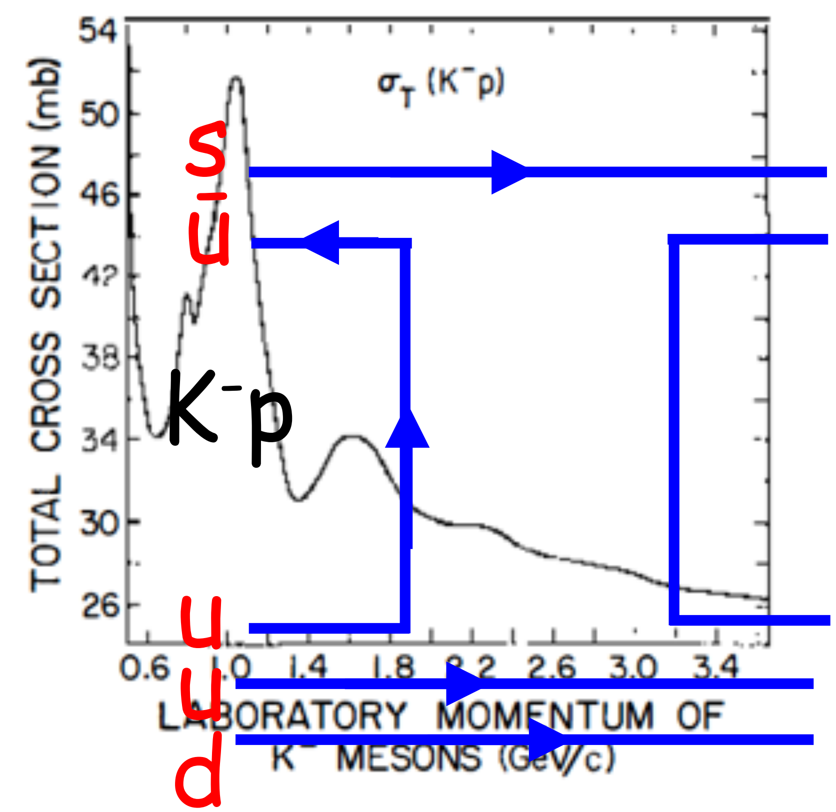
$\int^{N} ds$ Im $A(s,t)$



Im $A(s,t) = 0$



Im $A(s,t) \neq 0$



PWA for $\bar{K}N$

Model the amplitude

Fit to data

Analytically continue to complex values of energy to search for poles

Partial-wave analysis (Lmax= 5), Coupled channels, Unitarity

Analyticity: Right threshold behavior (angular momentum barrier), Resonances and backgrounds are incorporated “by-hand” through K matrices

In the range 2.19<s<4.70 GeV2 (8000 data points, 7500 data points, 5000 data points) We fit the KSU analysis single-energy partial waves [Zhang et al., PRC 88, 035204 (2015)]
Caveat: we lose correlations among partial waves

Cesar Fernandez Ramirez et al., arXiv:1510.07065 [hep-ph]

$$S_\ell = I + 2i\left[C_\ell(s)\right]^{1/2} T_\ell(s)\left[C_\ell(s)\right]^{1/2}$$

$$T_\ell(s) = \left[K^{-1}(s) - i\rho_\ell(s)\right]^{-1}$$

$$\left[i\rho_\ell(s)\right]_{kk} = \frac{s - s_k}{\pi}\int_{s_k}^{\infty}\frac{\left[C_\ell(s)\right]_{kk}}{s' - s}\frac{ds'}{s' - s_k}$$

$k = \pi\Sigma, \bar{K}N, \pi\Lambda, \pi\Sigma(1385), \pi\Lambda(1520), \eta\Sigma, \eta\Lambda, \bar{K}^*N, \pi\Delta(1232), \pi\pi\Sigma, \pi\pi\Lambda$

Resonance

$$\left[K_a(s)\right]_{kj} = x_k^a\,\frac{M_a}{M_a^2 - s}\,x_j^a$$

Generates pole in the
2nd Riemann sheet

Background

$$\left[K_b(s)\right]_{kj} = x_k^b\,\frac{M_b}{M_b^2 + s}\,x_j^b$$

Generates pole in the real
axis for s<0 in the1st Riemann sheet

Phase Space/Analicticity

$$[C_\ell(s)]_{kk} = \frac{q_k(s)}{q_0}\left[\frac{q_k^2(s)r^2}{1+q_k^2(s)r^2}\right]^\ell$$

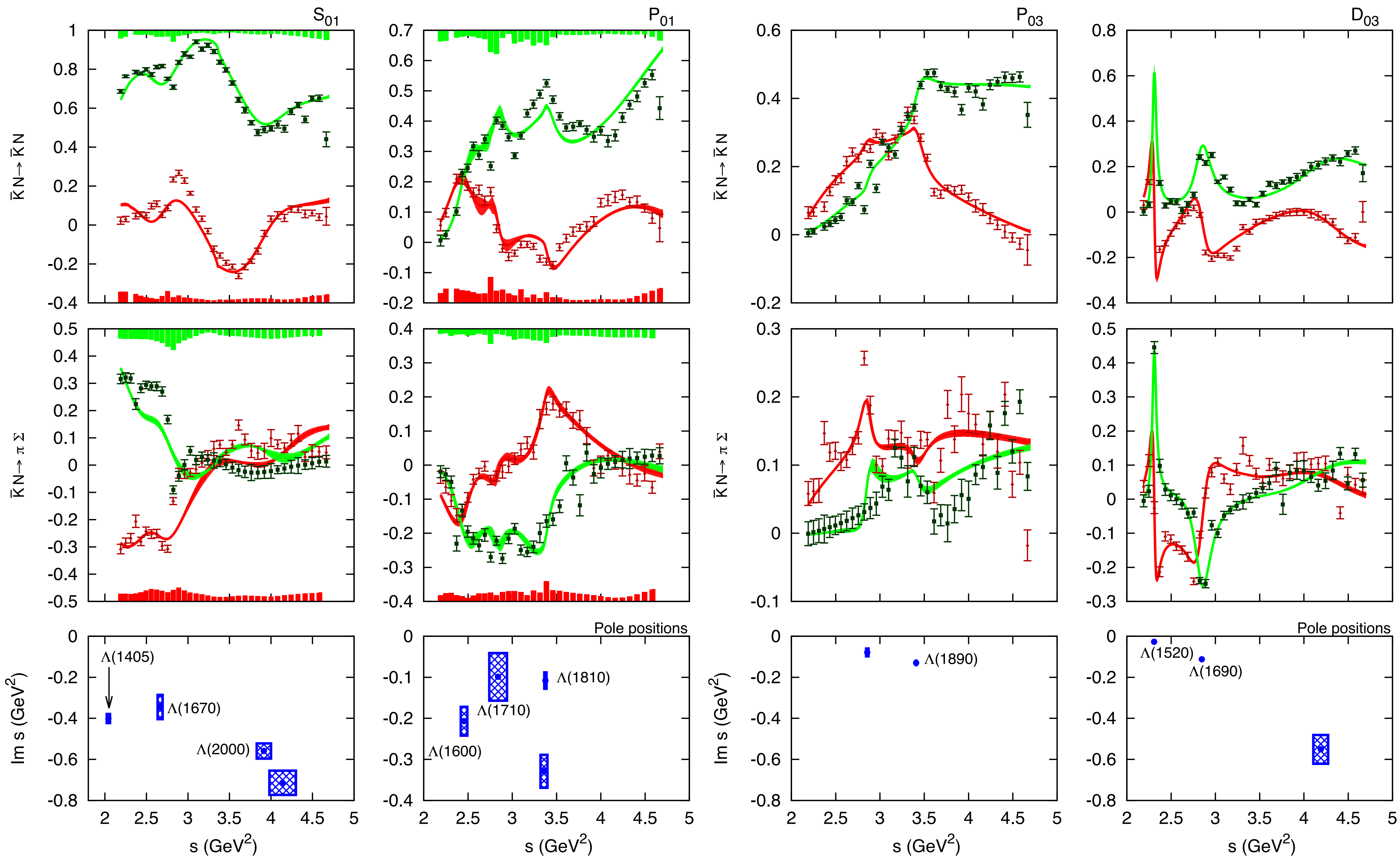
- Right threshold behavior
  - Angular momentum barrier
- Right high-energy behavior
- r =1 fm (interaction radius)

$$[q_k(s)]^2 = \frac{m_1 m_2}{s_k}\left[s - s_k\right]$$

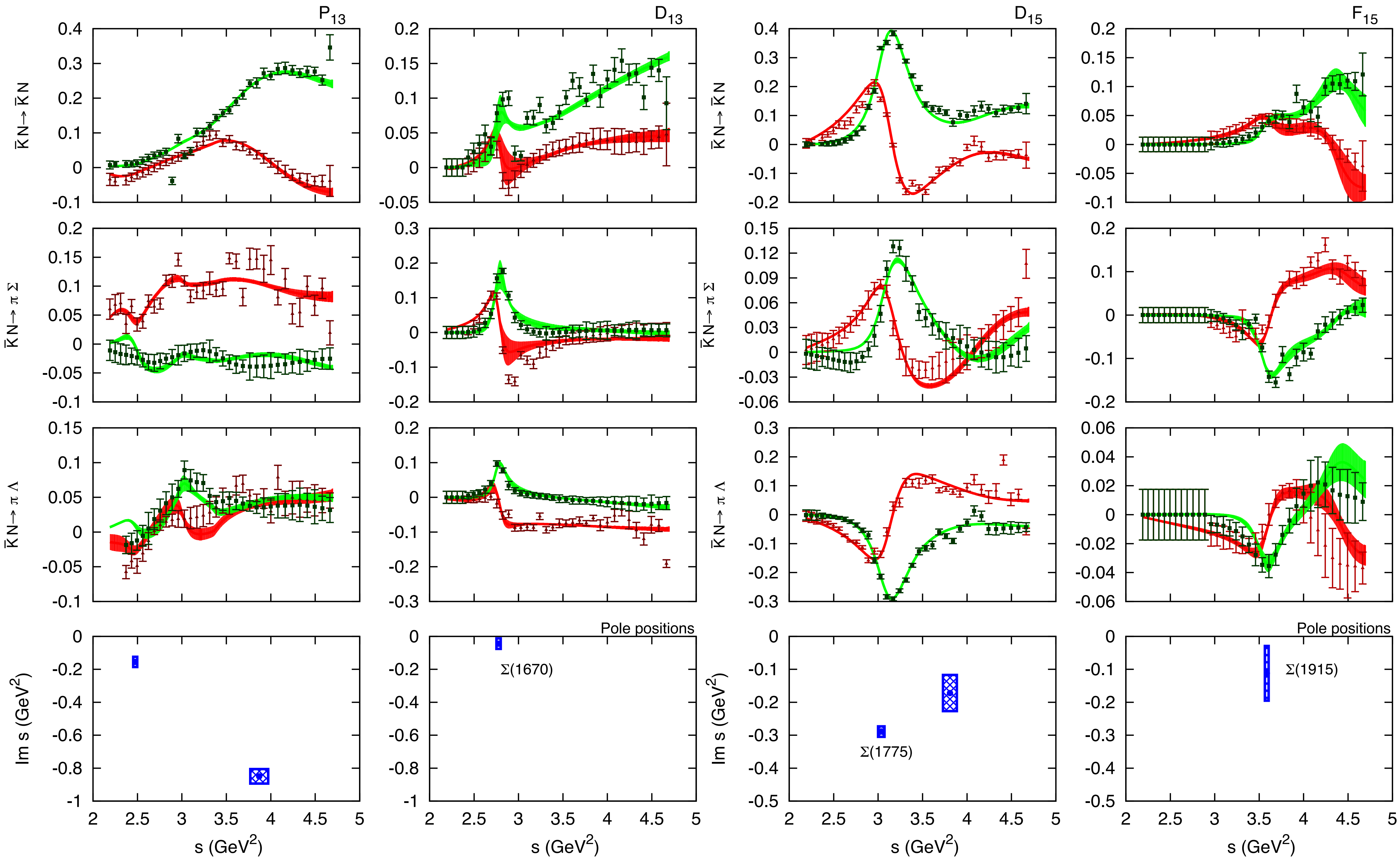
$$[i\rho_\ell(s)]_{kk} = \frac{s-s_k}{\pi}\int_{s_k}^{\infty}\frac{[C_\ell(s')]_{kk}}{s'-s}\frac{ds'}{s'-s_k} = -a_0\frac{a^\ell}{\pi\Gamma(\ell)}\left[\frac{\pi\Gamma(\ell)(s-s_k)\sqrt{s_k-s}}{1+a\,(s-s_k)}\right.$$
$$-\frac{\sqrt{\pi}\Gamma(\ell+\frac{1}{2})}{\ell\;a^{\ell+1/2}}\left([1+a(s-s_k)]\,{}_2F_1\left[1,\ell+1/2,-1/2,1/a(s_k-s)\right]\right.$$
$$\left.\left.-\left[3+2\ell+a(s-s_k)\right]{}_2F_1\left[1,\ell+1/2,1/2,1/a(s_k-s)\right]\right)\right]$$

Valid for l real and bigger than -1/2

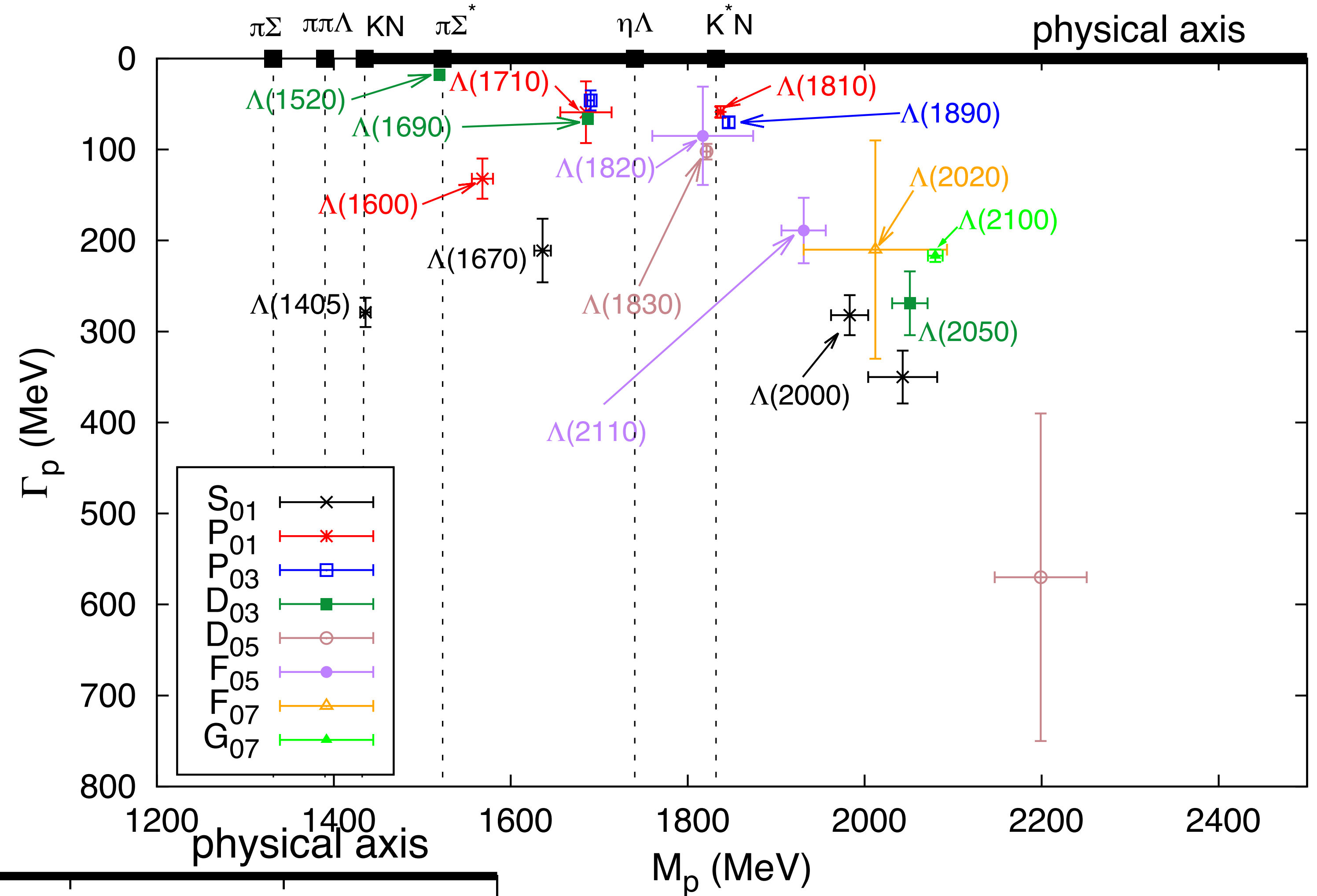
Partial Waves

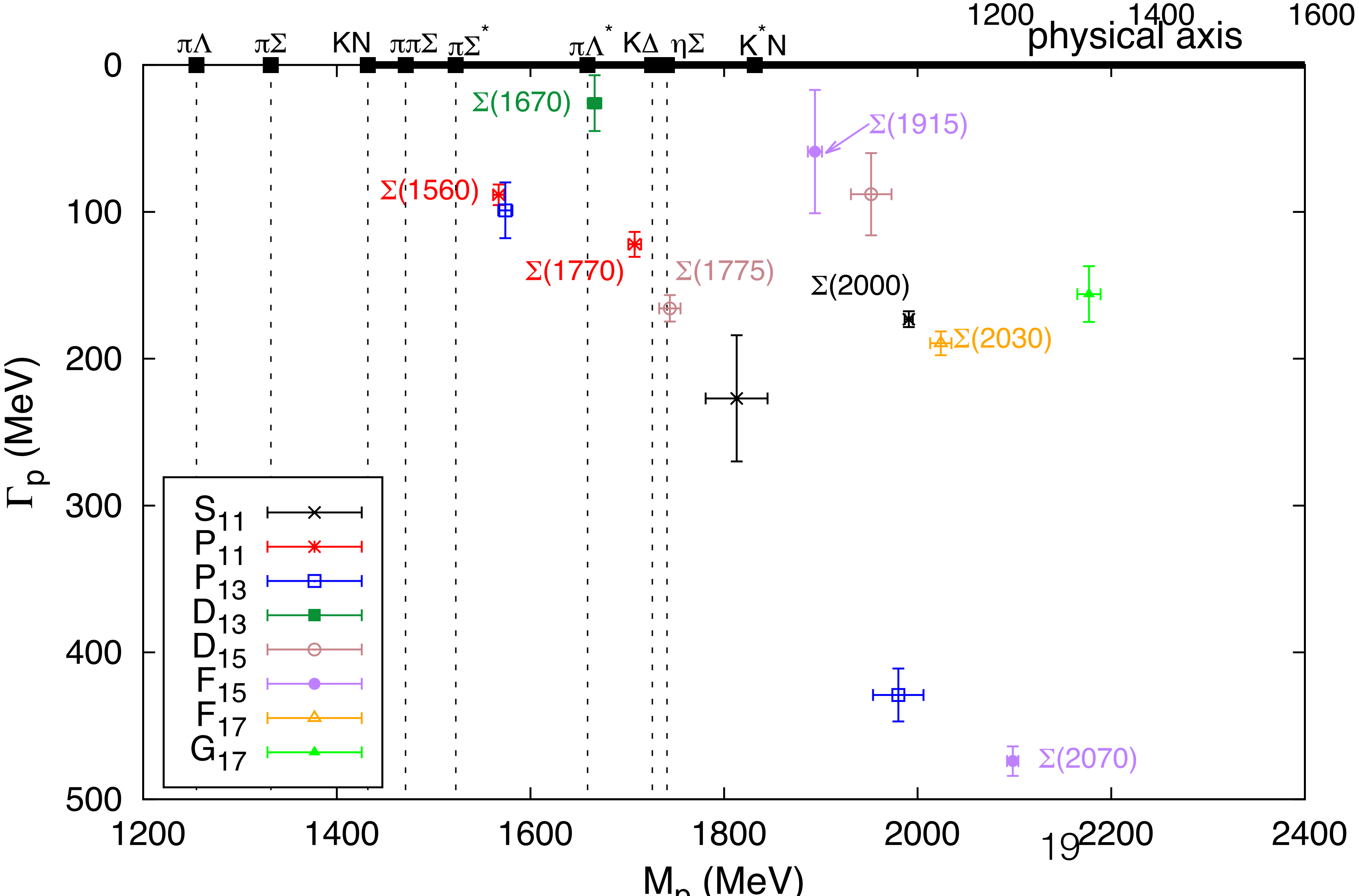


Partial Waves



Pole Positions





Resonances as Regge Poles

near the resonance pole

$$\alpha' \sim 1 \text{ GeV}^{-2}$$

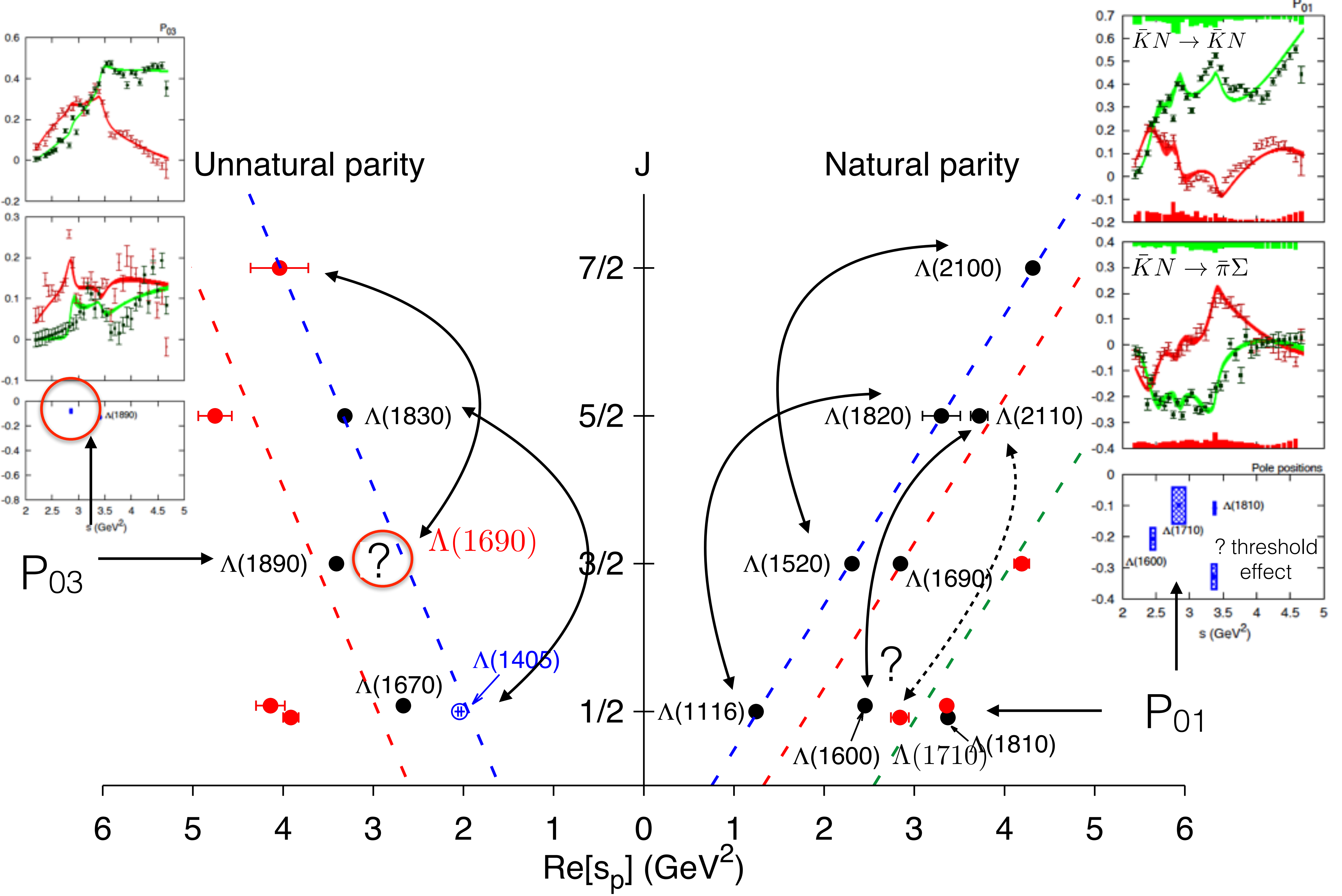
$$T_l \sim \frac{1}{\alpha'(m_l^2 - s)} = \frac{1}{l - (l - \alpha' m_l^2 + \alpha' s)}$$

if $l = \alpha_0 + \alpha' m_l^2$ **than** $T_l \sim \frac{1}{l - \alpha(s)}$ **with**

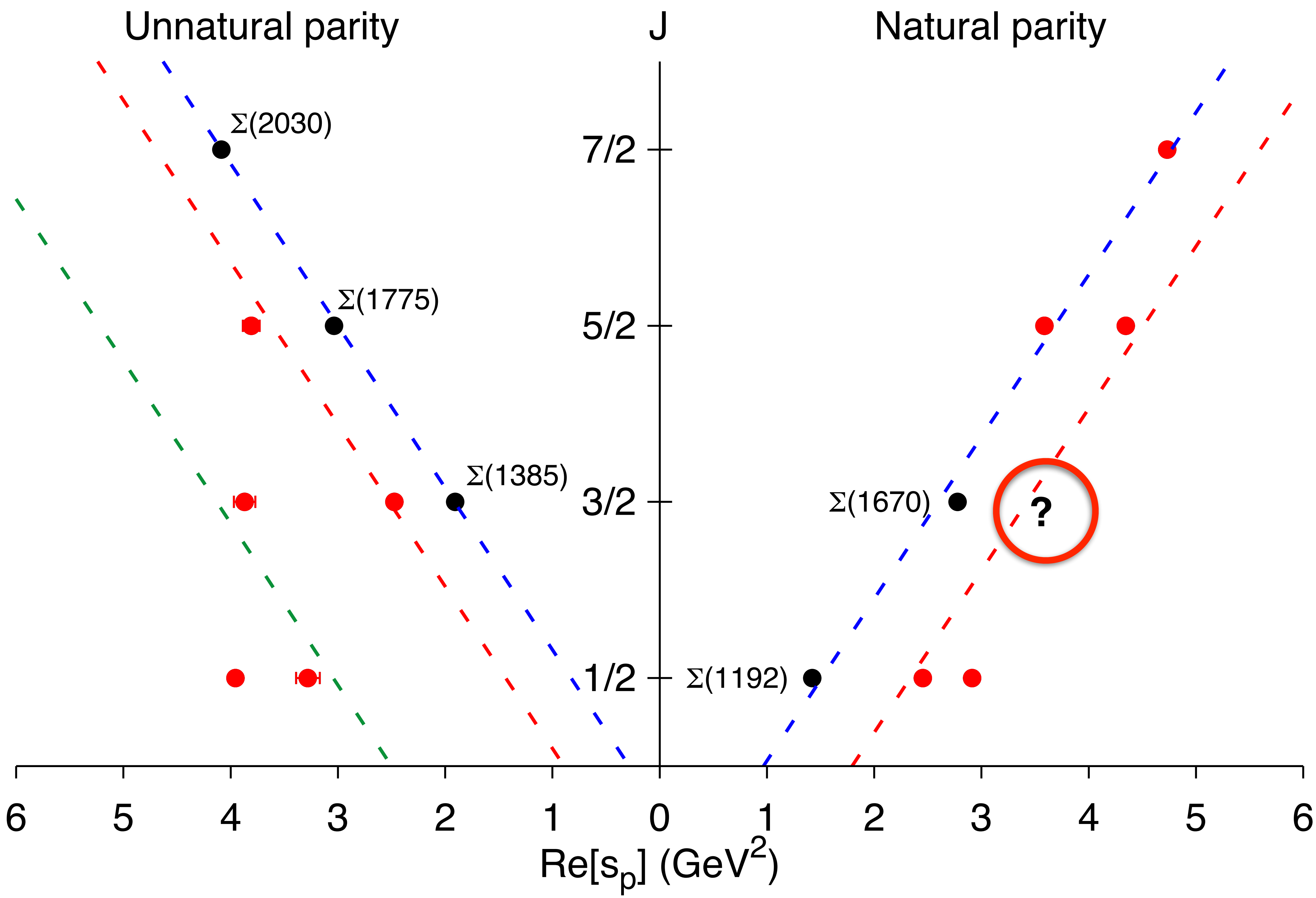
$$\alpha(s) = \alpha_0 + \alpha' s$$

In general $T = T(l, s)$ **and a pole corresponds to a trajectory in the l,s space**

A pole in s at a fixed integer l is connected to another pole at a different integer l



Unnatural parity
J
Natural parity
7/2
5/2
3/2
1/2
Λ(1830)
Λ(1890)
Λ(1690)
Λ(1670)
Λ(1405)
Λ(2100)
Λ(1820)
Λ(2110)
Λ(1520)
Λ(1690)
Λ(1116)
Λ(1600)
Λ(1710)
Λ(1810)
?
P03
P01
Re[sp] (GeV²)
P03
s (GeV²)
P01
$\bar{K}N \to \bar{K}N$
$\bar{K}N \to \bar{\pi}\Sigma$
Pole positions
? threshold effect

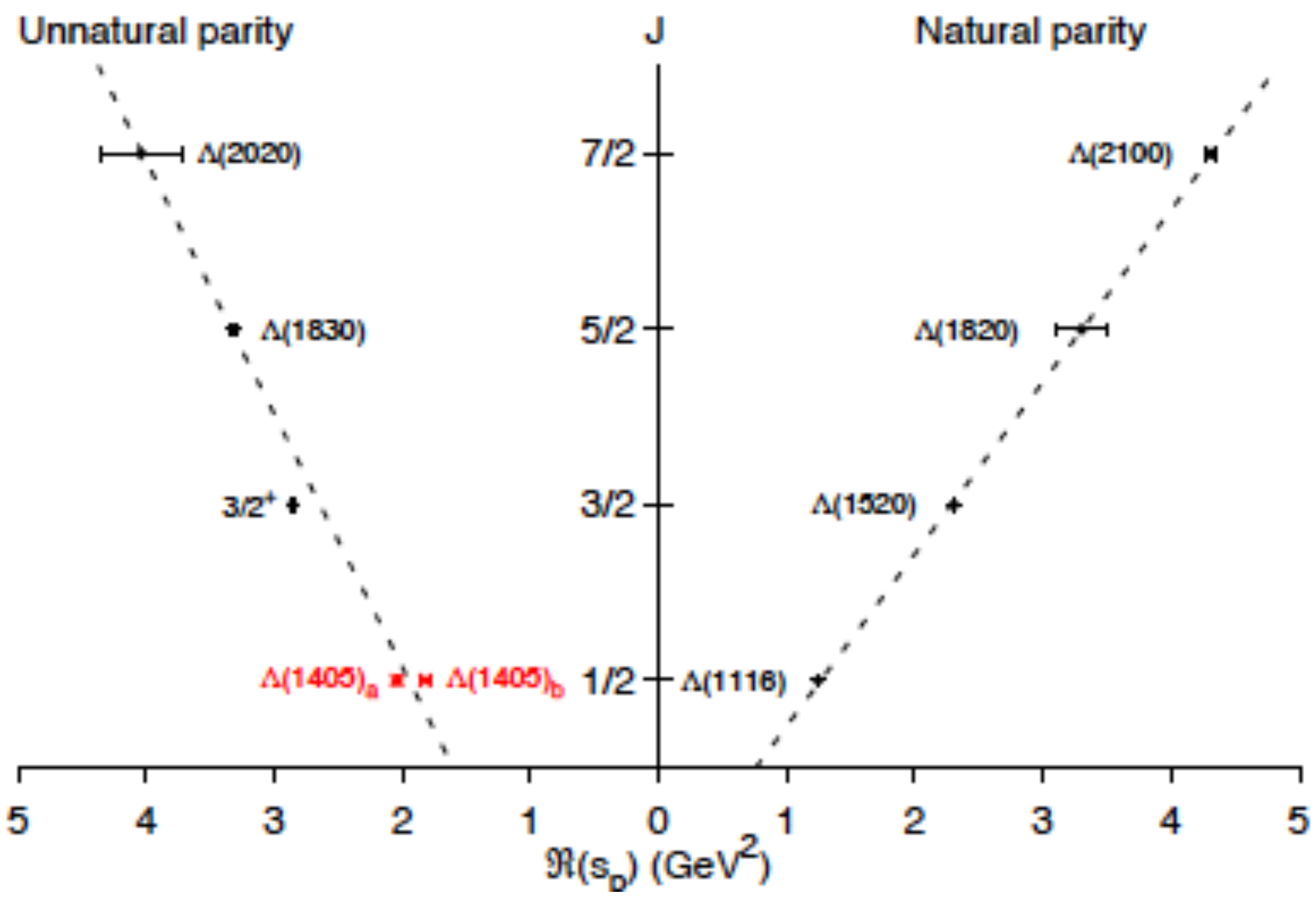


(3 *) Σ(1940) nobody gets it, but there is a gap in Ragge trajectory

On the nature of Λ(1405)

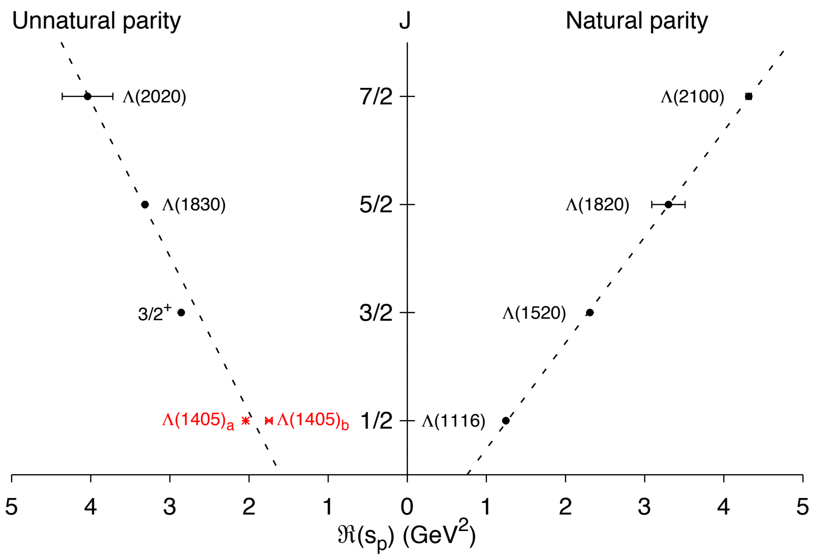
- Puzzle since the 60’s
- Quantum numbers those of a uds state
- Constituent quark models fail to reproduce the mass
  - 1550 MeV [Capstick, Isgur, PRD 34, 2809 (1986)]
  - 1524 MeV [Löring, Metsch, Petry, EPJA 10, 447 (2001)]
- Amplitude analysis of KN scattering and $\pi\Sigma K^+$ data finds two poles [Mai, Meiβner, EPJA 51, 30 (2015)]
  - 1429-12i MeV
  - 1325-90i MeV
- Lattice says: KN molecule [Hall et al., PRL 114, 132002 (2015)]
- Lattice says: three-quark state [Engel et al., PRD 87, 034502 (2013); PRD 87, 074504 (2013)]
- Regge phenomenology [Fernandez-Ramirez et al., arXiv:1512.03136 (2015)]
- Quark-diquark models obtain one Λ(1405) with the right energy
  - 1430 MeV [Santopinto, Ferretti, PRC 92, 025202 (2015)]
  - 1406 MeV [Faustov, Galkin, PRD 92, 054005 (2015)]

Λ(1405)

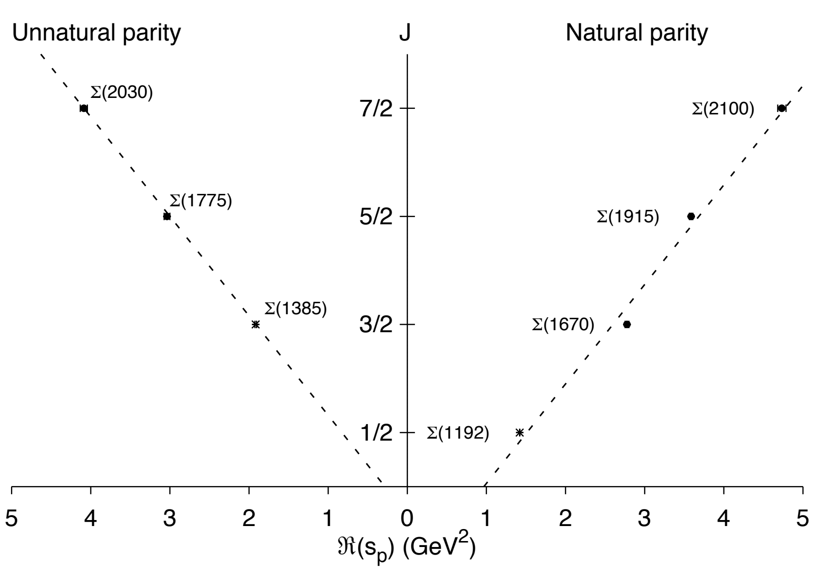


Unnatural parity
J
Natural parity
7/2
5/2
3/2
1/2
Λ(2020)
Λ(1830)
3/2+
Λ(1405)a
Λ(1405)b
Λ(2100)
Λ(1820)
Λ(1520)
Λ(1116)
5 4 3 2 1 0 1 2 3 4 5
ℜ(sD) (GeV2)

Re



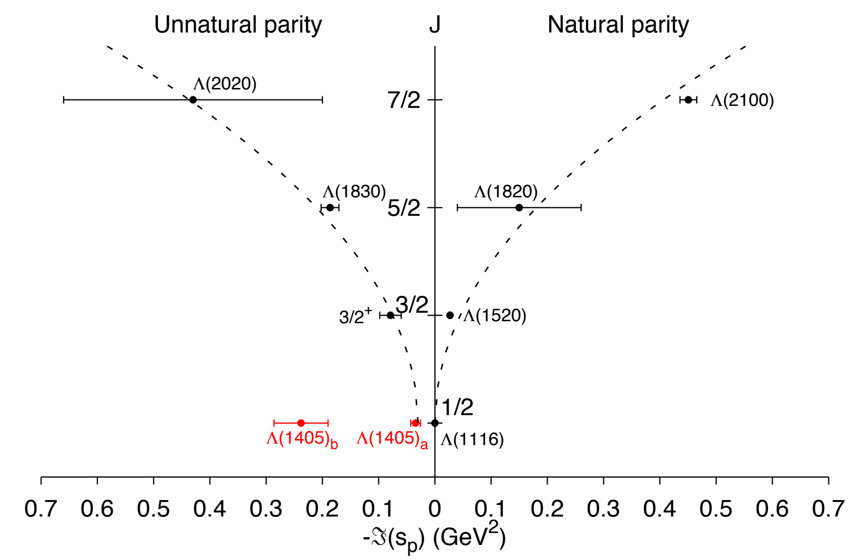
(a) Λ resonances.



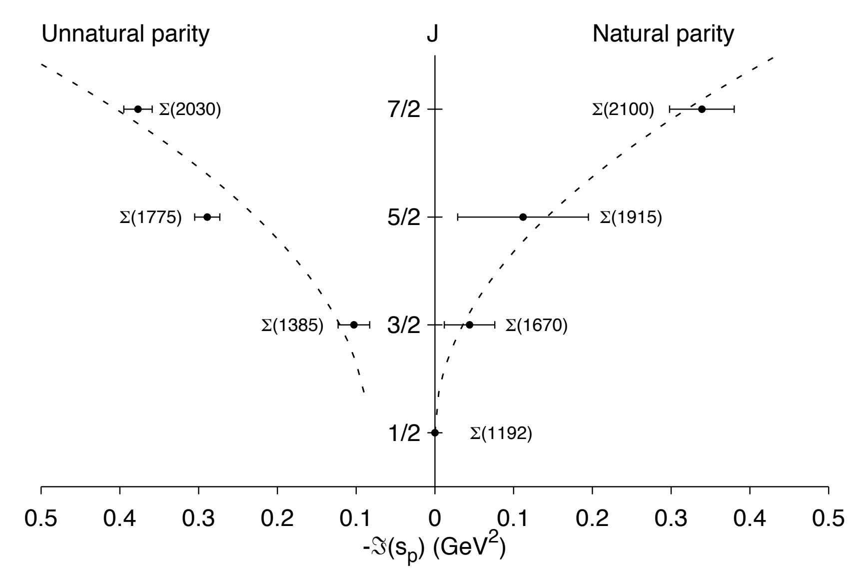
(b) Σ resonances.

FIG. 1. (color online). Chew–Frautschi plot for the the leading Λ and Σ Regge trajectories. Dashed lines are displayed to guide the eye.

Im



(a) Λ resonances.



(b) Σ resonances.

FIG. 2. (color online). Projections of the leading Λ and Σ Regge trajectories onto the $(-\Im(s_p), J)$ plane. Dashed lines are displayed to guide the eye.

$$\alpha(s) = \alpha_0 + \alpha' s + i\,\gamma\,\rho(s, s_t)$$

Compare fits 0^-_a, 0^-_b, 0^-_c

$$i\,\rho_A(s, s_t) = i\,\sqrt{s - s_t}\,,$$

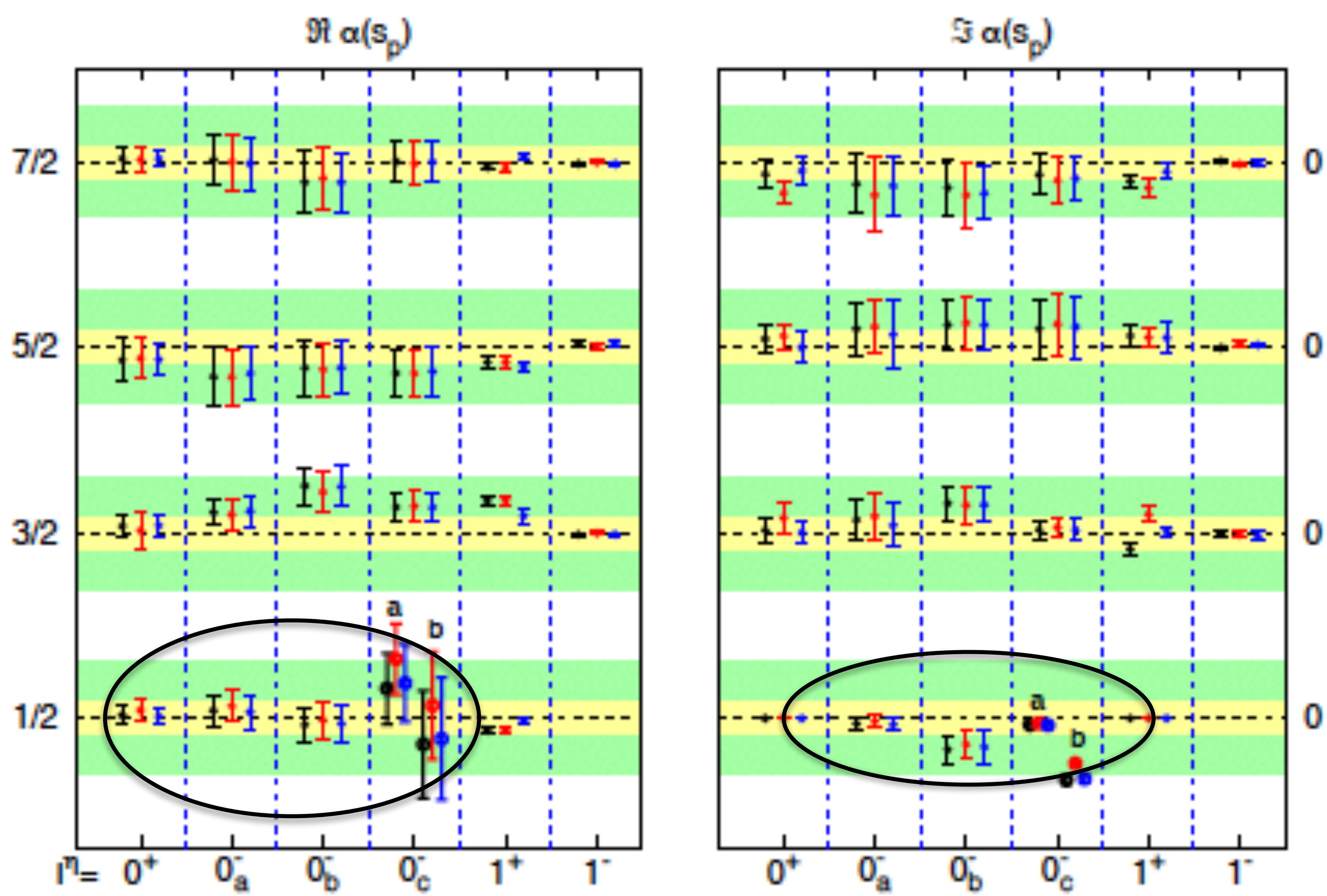
$$i\,\rho_B(s, s_t) = i\,\sqrt{1 - s_t/s}\,,$$

$$i\,\rho_C(s, s_t) = \frac{s - s_t}{\pi} \int_{s_t}^{\infty} \frac{\sqrt{1 - s_t/s'}}{s' - s_t} \frac{ds'}{s' - s}$$

$$= \frac{2}{\pi} \frac{s - s_t}{\sqrt{s(s_t - s)}} \arctan \sqrt{\frac{s}{s_t - s}}$$

$$\Lambda_a(1405) = 1429 - 12i \text{ MeV}$$

$$\Lambda_b(1405) = 1352 - 90i \text{ MeV}$$



$\Lambda_a(1405)$ is closer to the "normal" trajectory

Summary

- New, analytical model for hyperon spectrum
- Need to incorporate Regge constraints
  - in direct channel as a constraint on, eg, K-matrix matrix poles
  - in cross channels, as constrained on p.w. extraction,
- Λ(1405): One more piece to the puzzle (more confusion?)

TABLE II. Summary of Λ^* pole masses ($M_p = \mathrm{Re}\,\sqrt{s_p}$) and widths ($\Gamma_p = -2\,\mathrm{Im}\,\sqrt{s_p}$) in MeV. Our poles are depicted in Fig. 5 unless they have a very large imaginary part. In [2] the $\Lambda(1520)$ pole was obtained at ($M_p = 1518.8$, $\Gamma_p = 17.2$). Ref. [5] implements two models labeled as KA and KB (see text). I stands for isospin, η for naturality, J for total angular momentum, P for parity, and ℓ for orbital angular momentum. For baryons, $\eta = +$, natural parity, if $P = (-1)^{J-1/2}$ and $\eta = -$, unnatural parity, if $P = -(-1)^{J-1/2}$ where P stands for parity. Resonances marked with † are unreliable themselves due to systematics and lack of good-quality χ^2/dof. Resonances marked with ‡ are most likely artifacts of the fits.

	This work		KSU from [3]		KA from [5]		KB from [5]		PDG [1]	
$I^\eta\ J^P\ \ell$	M_p	Γ_p	M_p	Γ_p	M_p	Γ_p	M_p	Γ_p	Name	Status
$0^-\ \frac{1}{2}^-\ S$	$1435.8 \pm 5.9^\dagger$	279 ± 16	1402	49	—	—	—	—	$\Lambda(1405)$	****
	$1573^\ddagger$	300	—	—	—	—	1512	370	—	—
	$1636.0 \pm 9.4^\dagger$	211 ± 35	1667	26	1669	18	1667	24	$\Lambda(1670)$	****
	—	—	1729	198	—	—	—	—	$\Lambda(1800)$	***
	$1983 \pm 21^\dagger$	282 ± 22	1984	233	—	—	—	—	$\Lambda(2000)$	*
	$2043 \pm 39^\dagger$	350 ± 29	—	—	—	—	—	—	—	—
$0^+\ \frac{1}{2}^+\ P$	1568 ± 12	132 ± 22	1572	138	1544	112	1548	164	$\Lambda(1600)$	***
	$1685 \pm 29^\dagger$	59 ± 34	1688	166	—	—	—	—	$\Lambda(1710)$	*
	$1835 \pm 10^\ddagger$	180 ± 22	—	—	—	—	—	—	—	
	$1837.2 \pm 3.4^\dagger$	58.7 ± 6.5	1780	64	—	—	1841	62	$\Lambda(1810)$	
	—	—	2135	296	2097	166	—	—	—	
$0^-\ \frac{3}{2}^+\ P$	1690.3 ± 3.8	46.4 ± 11.0	—	—	—	—	1671	10	—	
	1846.36 ± 0.81	70.0 ± 6.0	1876	145	1859	112	—	—	$\Lambda(1890)$	*
	—	—	2001	994	—	—	—	—	—	
$0^+\ \frac{3}{2}^-\ D$	1519.33 ± 0.34	17.8 ± 1.1	1518	16	1517	16	1517	16	$\Lambda(1520)$	*
	1687.40 ± 0.79	66.2 ± 2.3	1689	53	1697	66	1697	74	$\Lambda(1690)$	*
	2051 ± 20	269 ± 35	1985	447	—	—	—	—	$\Lambda(2050)$	
	$2133 \pm 120^\ddagger$	1110 ± 280	—	—	—	—	—	—	$\Lambda(2325)$	
$0^-\ \frac{5}{2}^-\ D$	1821.4 ± 4.3	102.3 ± 8.6	1809	109	1766	212	—	—	$\Lambda(1830)$	*
	—	—	1970	350	1899	80	1924	90	—	
	2199 ± 52	570 ± 180	—	—	—	—	—	—	—	
$0^+\ \frac{5}{2}^+\ F$	1817 ± 57	85 ± 54	1814	85	1824	78	1821	64	$\Lambda(1820)$	*
	1931 ± 25	189 ± 36	1970	350	—	—	—	—	$\Lambda(2110)$	
$0^-\ \frac{7}{2}^+\ F$	—	—	—	—	1757	146	—	—	—	
	2012 ± 81	210 ± 120	1999	146	—	—	2041	238	$\Lambda(2020)$	
$0^+\ \frac{7}{2}^-\ G$	2079.9 ± 8.3	216.7 ± 6.8	2023	239	—	—	—	—	$\Lambda(2100)$	*

TABLE III. Summary of Σ^* pole masses ($M_p = \mathrm{Re}\sqrt{s_p}$) and widths ($\Gamma_p = -2\,\mathrm{Im}\sqrt{s_p}$) in MeV. Our poles are depicted in Fig. 5 unless they have a very large imaginary part. Notation is the same as in Table II. Resonances marked with † are unreliable themselves due to systematics and lack of good-quality χ^2/dof.

Σ*

	This work		KSU from [3]		KA from [5]		KB from [5]		PDG [1]	
$I^\eta\ J^P\ \ell$	M_p	Γ_p	M_p	Γ_p	M_p	Γ_p	M_p	Γ_p	Name	Status
$1^-\ \frac{1}{2}^-\ S$	—	—	1501	171	—	—	1551	376	Σ(1620)	*
	—	—	1708	158	1704	86	—	—	Σ(1750)	***
	$1813 \pm 32^\dagger$	227 ± 43	—	—	—	—	—	—	—	—
	—	—	1887	187	—	—	—	—	Σ(1900)	*
	$1990.8 \pm 4.3^\dagger$	173.1 ± 5.4	—	—	—	—	1940	172	Σ(2000)	*
	—	—	2040	295	—	—	—	—	—	—
$1^+\ \frac{1}{2}^+\ P$	1567.3 ± 5.7	88.4 ± 7.0	—	—	1547	184	1457	78	Σ(1560)	**
	—	—	—	—	—	—	—	—	Σ(1660)	***
	1707.7 ± 6.6	122.1 ± 8.5	1693	163	1706	102	—	—	Σ(1770)	*
	—	—	1776	270	—	—	—	—	Σ(1880)	**
	—	—	—	—	—	—	2014	140	—	—
$1^-\ \frac{3}{2}^+\ P$	1574.1 ± 7.2	99 ± 19	—	—	—	—	—	—	—	—
	—	—	1683	243	—	—	—	—	—	—
	—	—	1874	349	—	—	—	—	—	—
	1980 ± 26	429 ± 18	—	—	—	—	—	—	—	—
$1^+\ \frac{3}{2}^-\ D$	—	—	—	—	1607	252	1492	138	Σ(1580)	*
	1666.3 ± 7.0	26 ± 19	1674	54	1669	64	1672	66	Σ(1670)	****
	—	—	—	—	—	—	—	—	Σ(1940)	***
$1^-\ \frac{5}{2}^-\ D$	1744 ± 11	165.7 ± 9.0	1759	118	1767	128	1765	128	Σ(1775)	****
	1952 ± 21	88 ± 28	2183	296	—	—	—	—	—	—
$1^+\ \frac{5}{2}^+\ F$	—	—	—	—	—	—	1695	194	—	—
	1893.9 ± 7.2	59 ± 42	1897	133	1890	99	—	—	Σ(1915)	****
	2098.2 ± 5.8	474 ± 10	2084	319	—	—	—	—	Σ(2070)	*
$1^-\ \frac{7}{2}^+\ F$	2024 ± 11	189.5 ± 8.1	1993	176	2025	130	2014	206	Σ(2030)	****
$1^+\ \frac{7}{2}^-\ G$	2177 ± 12	156 ± 19	2252	290	—	—	—	—	Σ(2100)	*