3-body structure of exotics hadrons

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Introduction

- Until recently, meson-meson and meson-baryon structure of meson and baryon resonances has been explored extensively using chiral dynamics, e.g. :

$$\underbrace{\sigma(600), f_0(980), a_0(980), \kappa}_{\text{MM}}, \underbrace{\Lambda(1405), \Lambda(1520)}_{\text{MB}}, etc.$$ [1, 2, 3, 4,5]

- Some states in the meson & baryon spectrum, however, could very well possess a more complicated molecular structure

M + MM

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[1] J. A. Oller, E. Oset, Nucl. Phys. A 620 (1997) 438.
[2] J. A. Oller, Ulf-G. Meissner, Phys. Lett. B 500 (2001) 263-272.
[3] J. A. Oller, E. Oset, J. R. Peláez, Phys. Rev. D 59 074001 (199).
[4] D. Jido, J. A. Oller, E. Oset, A. Ramos, U. G. Meissner, Nucl. Phys. A 725 (2003) 181-200.
[5] L. Roca, Sourav Sarkar, V.K. Magas, E. Oset Phys. Rev. C73, 045208 (2006).

- Indeed, there are evidences for significant branching ratios to three-hadrons for some resonances, e.g.,

$N(1710)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	(6.2±1.0) %
Γ_3	$N\omega$	(13.0±2.0) %
Γ_4	ΛK	5–25 %
Γ_5	ΣK	
Γ_6	$N\pi\pi$	40–90 %
Γ_7	$\Delta\pi$	15–40 %
Γ_8	$\Delta(1232)\pi$, P-wave	
Γ_9	$N\rho$	5–25 %
Γ_{10}	$N\rho$, $S=1/2$, P-wave	
Γ_{11}	$N\rho$, $S=3/2$, P-wave	
Γ_{12}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–40 %
Γ_{13}	$p\gamma$	0.002–0.05%
Γ_{14}	$p\gamma$, helicity=1/2	0.002–0.05%
Γ_{15}	$n\gamma$	0.0–0.02%
Γ_{16}	$n\gamma$, helicity=1/2	0.0–0.02%

$\Sigma(1620)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma(1385)\pi$
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The model

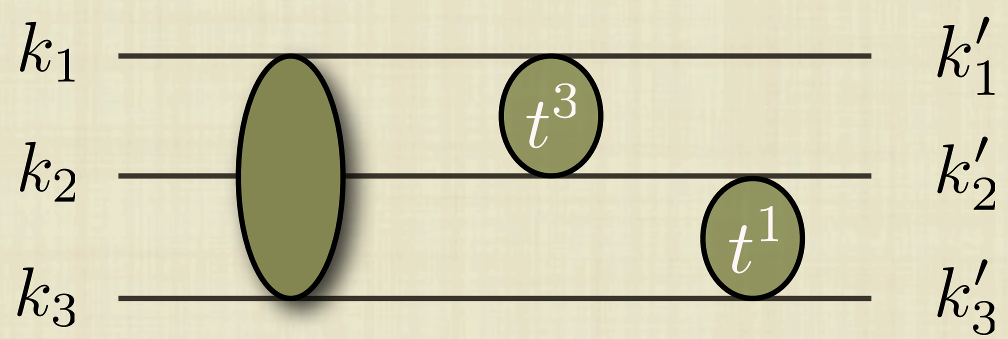
- We solve the Faddeev equations

$$T = T^1 + T^2 + T^3$$

$$T^i = t^i \delta^3(\vec{k}_i' - \vec{k}_i) + T_R^{ij} + T_R^{ik}$$

- The T_R^{ij} matrices contain all the possible diagrams where the last two successive interactions are t^i and t^j

$$T_R^{13} =$$

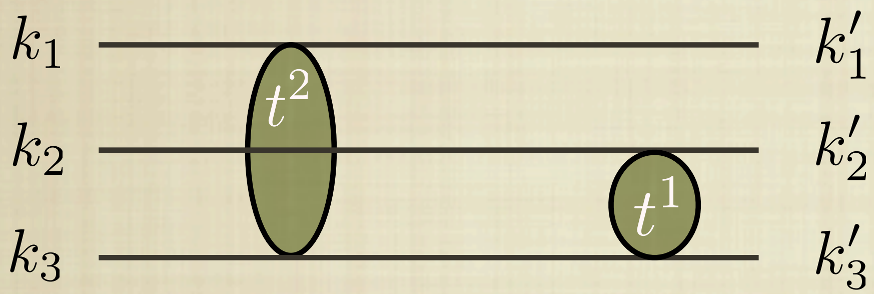


- And they satisfy the equations:

$$\begin{aligned}
T_R^{12} &= t^1 g^{12} t^2 + t^1 \left[G^{121}\, T_R^{21} + G^{123}\, T_R^{23}\right] \\
T_R^{13} &= t^1 g^{13} t^3 + t^1 \left[G^{131}\, T_R^{31} + G^{132}\, T_R^{32}\right] \\
T_R^{21} &= t^2 g^{21} t^1 + t^2 \left[G^{212}\, T_R^{12} + G^{213}\, T_R^{13}\right] \\
T_R^{23} &= t^2 g^{23} t^3 + t^2 \left[G^{231}\, T_R^{31} + G^{232}\, T_R^{32}\right] \\
T_R^{31} &= t^3 g^{31} t^1 + t^3 \left[G^{312}\, T_R^{12} + G^{313}\, T_R^{13}\right] \\
T_R^{32} &= t^3 g^{32} t^2 + t^3 \left[G^{321}\, T_R^{21} + G^{323}\, T_R^{23}\right]
\end{aligned}$$

- t^{I} is the two body t-matrix $\quad t = V + V\tilde{g}t$

- g^{IJ} is the three-body green function.



$$g^{ij}(\vec{k_i}', \vec{k_j}) = \left(\prod_{r=1}^{D} \frac{N_r}{2E_r} \right) \frac{1}{\sqrt{s} - E_i(\vec{k_i}') - E_l(\vec{k_i}' + \vec{k_j}) - E_j(\vec{k_j})}$$

$$N_r = \begin{cases} 1 & \text{meson-meson interaction} \\ 2M_r & \text{meson-baryon interaction} \end{cases}$$

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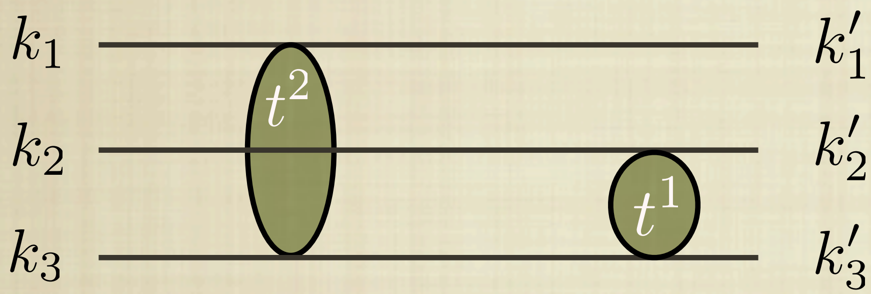

Chiral amplitudes

On-shell part

Off-shell part

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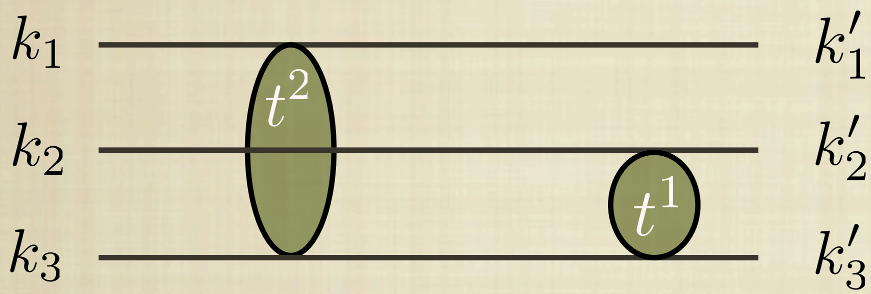
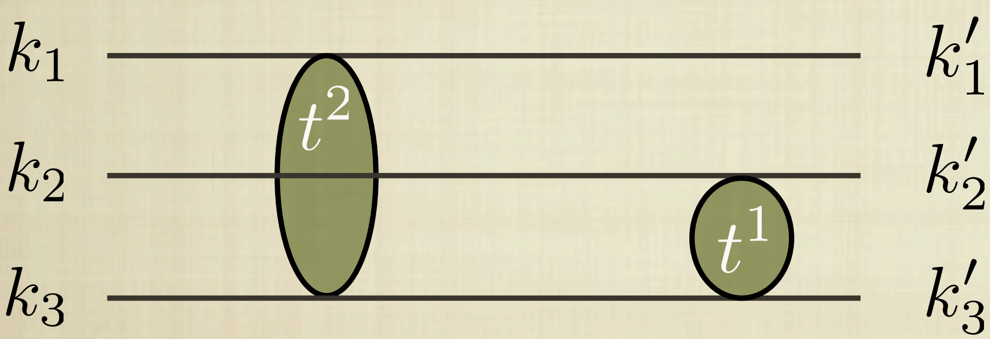


Chiral amplitudes → On-shell part

Chiral amplitudes → Off-shell part



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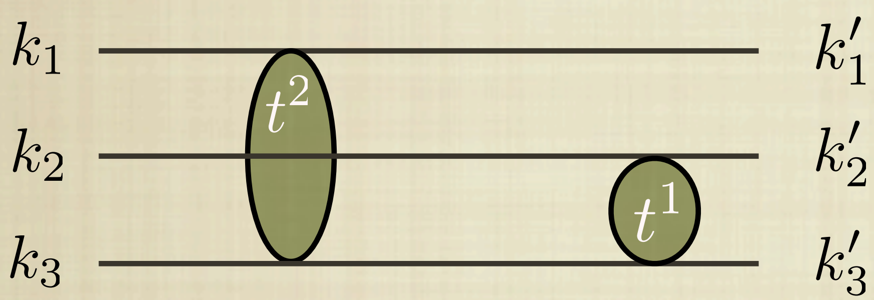

Chiral amplitudes

On-shell part

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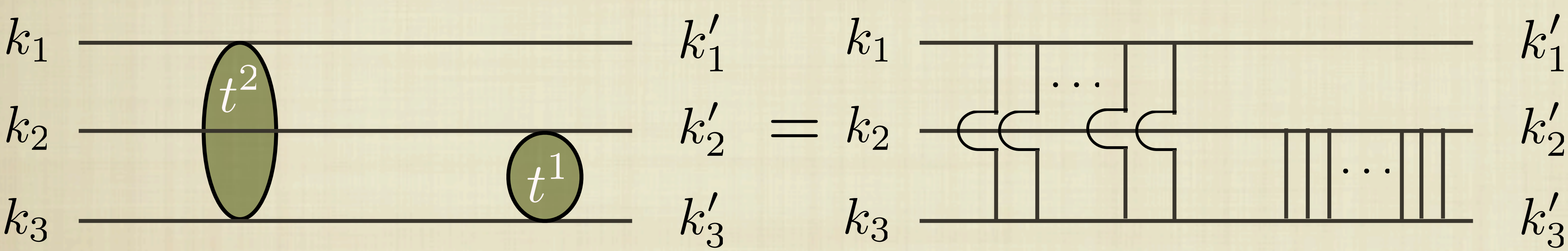

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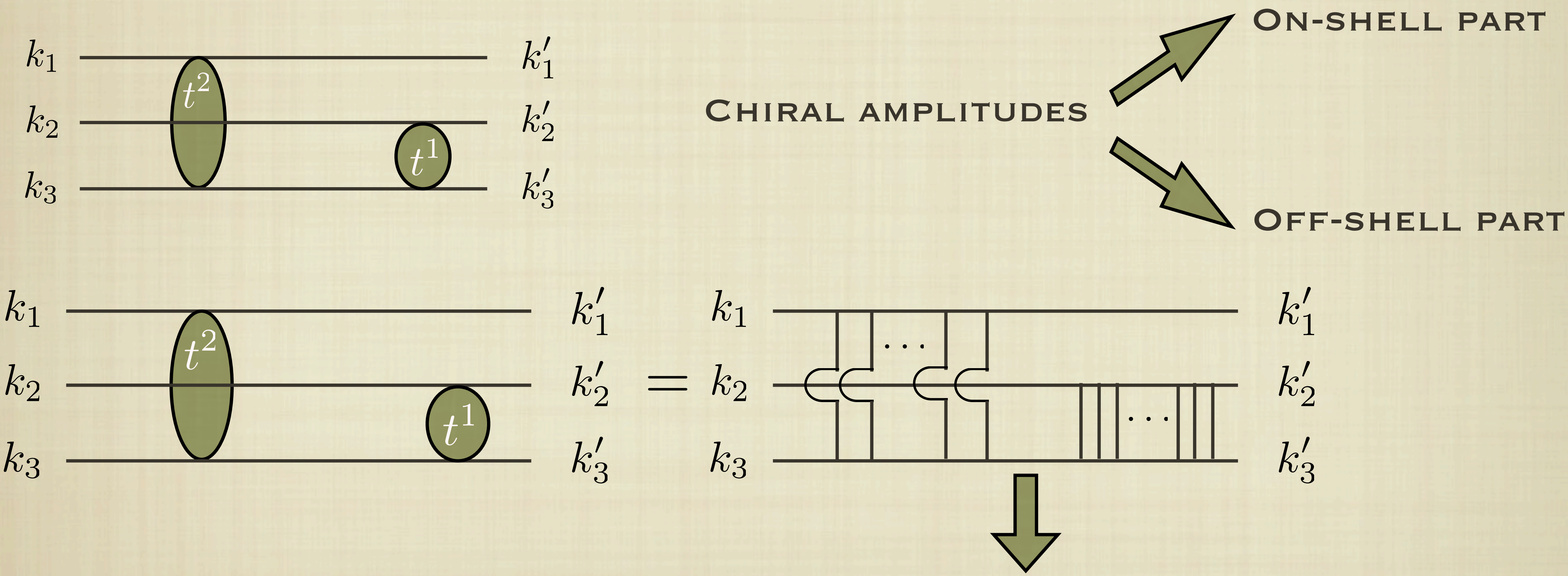

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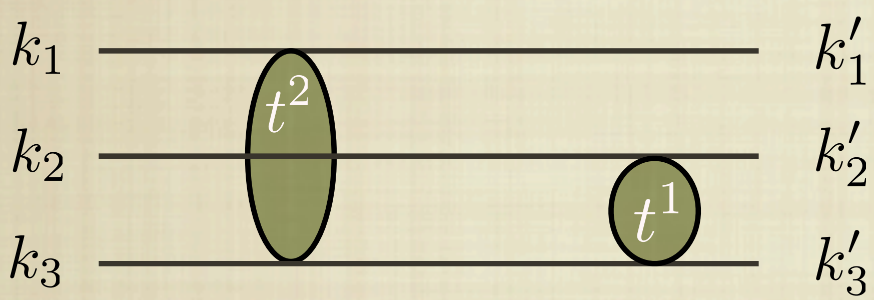
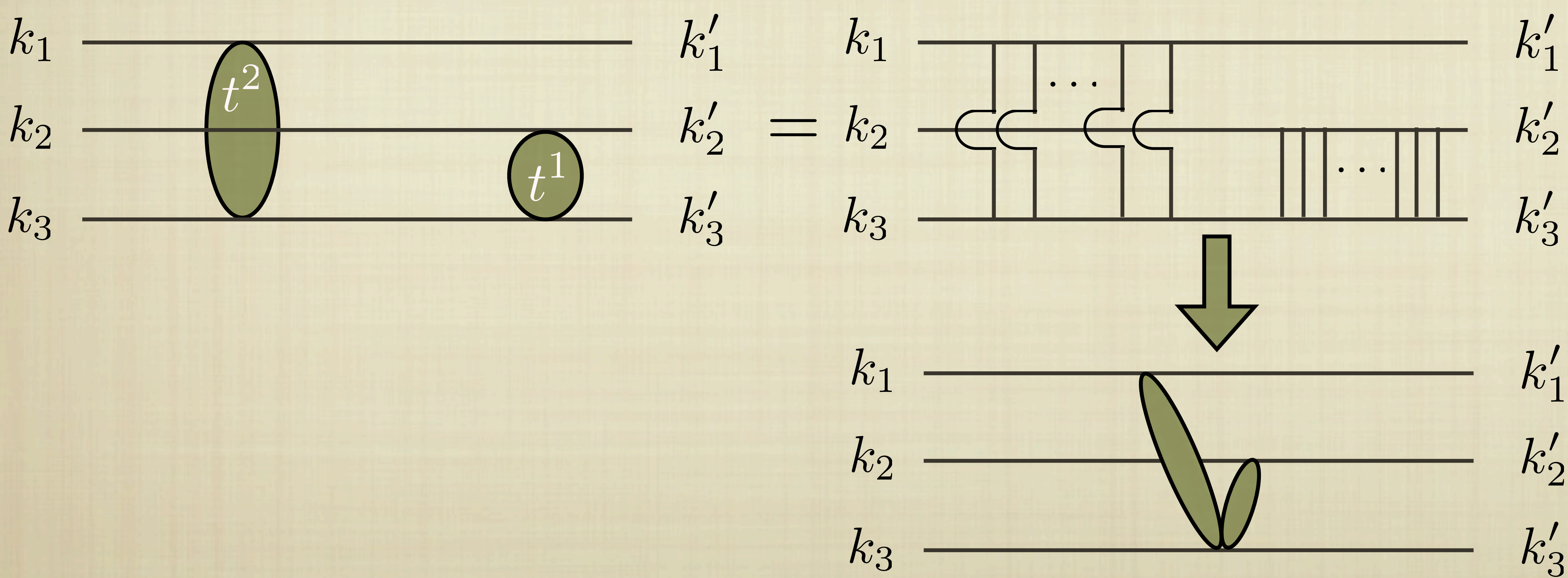


CHIRAL AMPLITUDES → ON-SHELL PART

CHIRAL AMPLITUDES → OFF-SHELL PART



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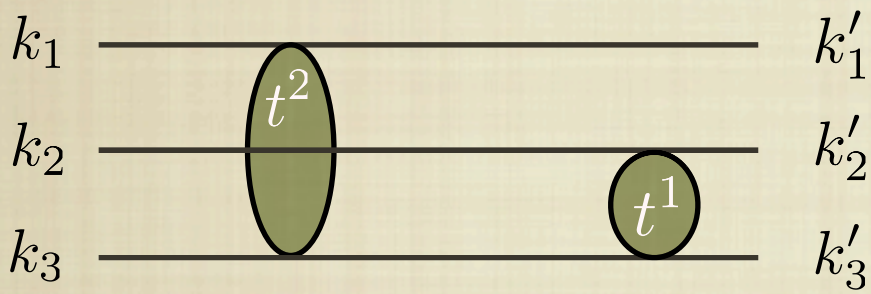
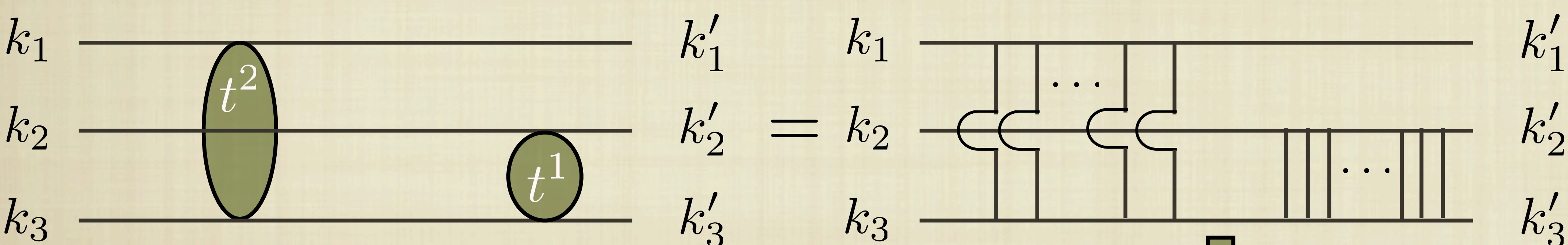
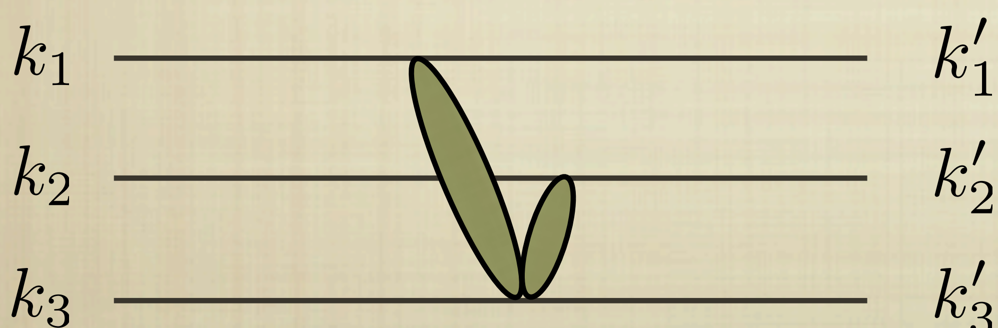


Chiral amplitudes → On-shell part; Off-shell part





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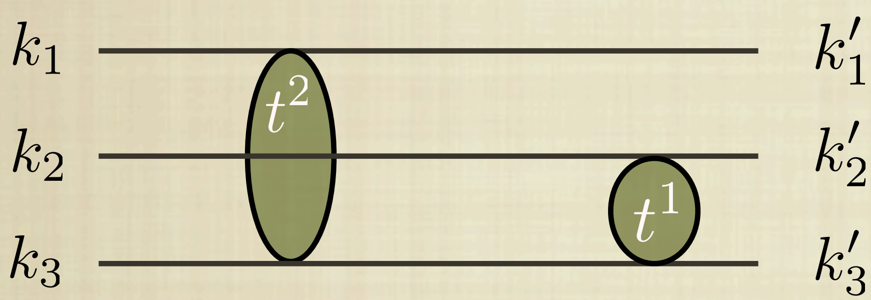

Chiral amplitudes

On-shell part

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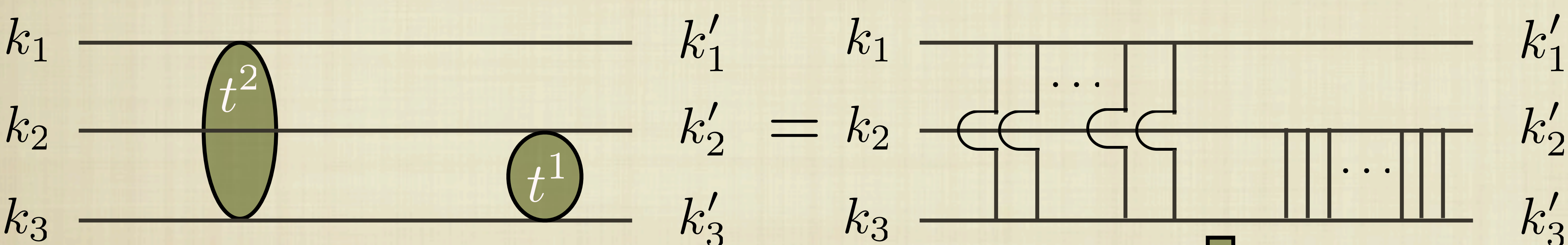

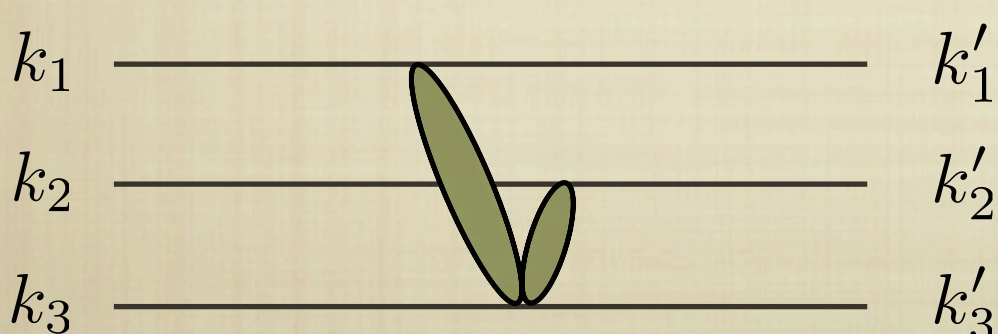

[14] F J. Llanes-Estrada, E. Oset and V. Mateu, Phys. Rev. C 69, 055203 (2004).

- t^I IS THE TWO BODY t-MATRIX $\Longrightarrow$ $t = V + V\tilde{g}t$

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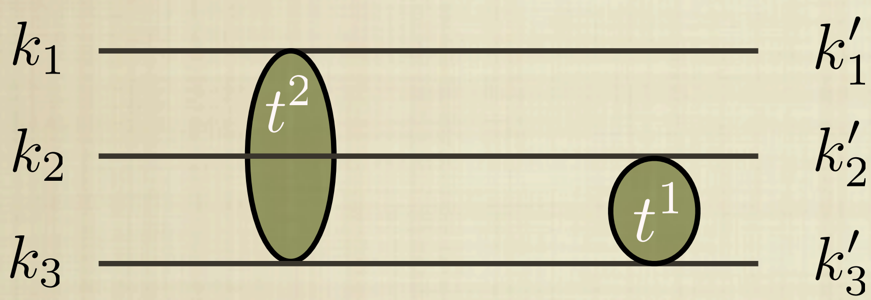
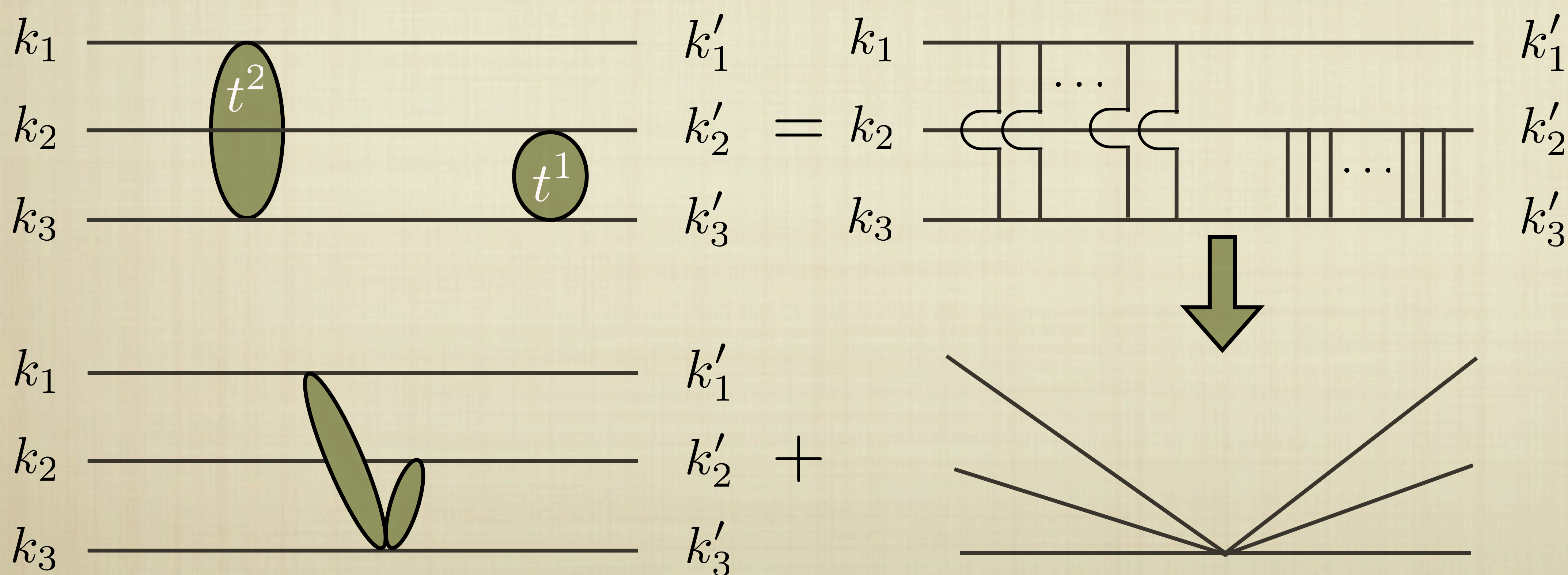


CHIRAL AMPLITUDES → ON-SHELL PART

CHIRAL AMPLITUDES → OFF-SHELL PART



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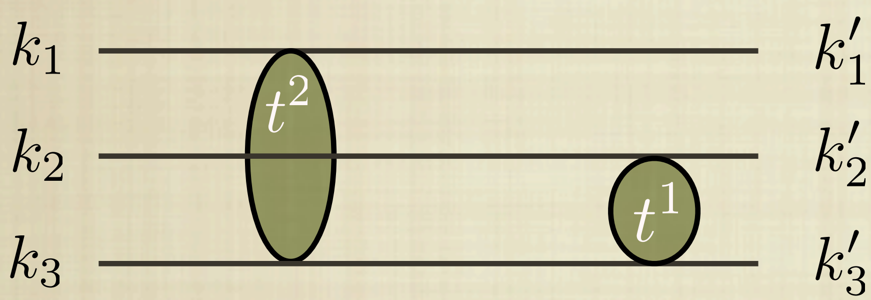
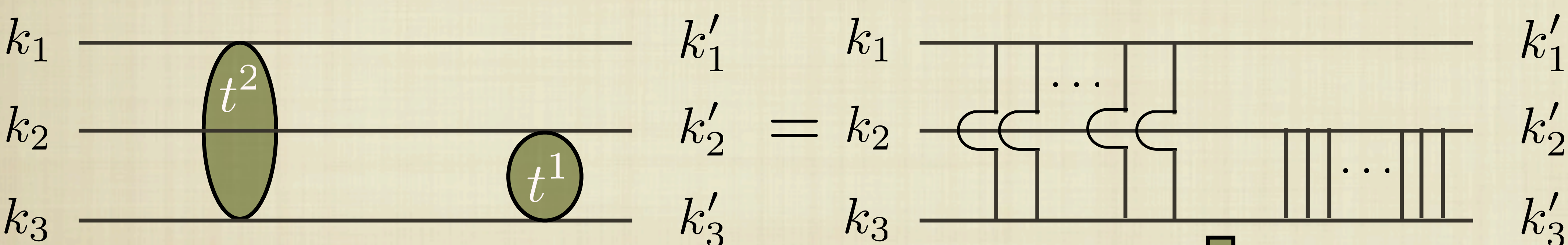
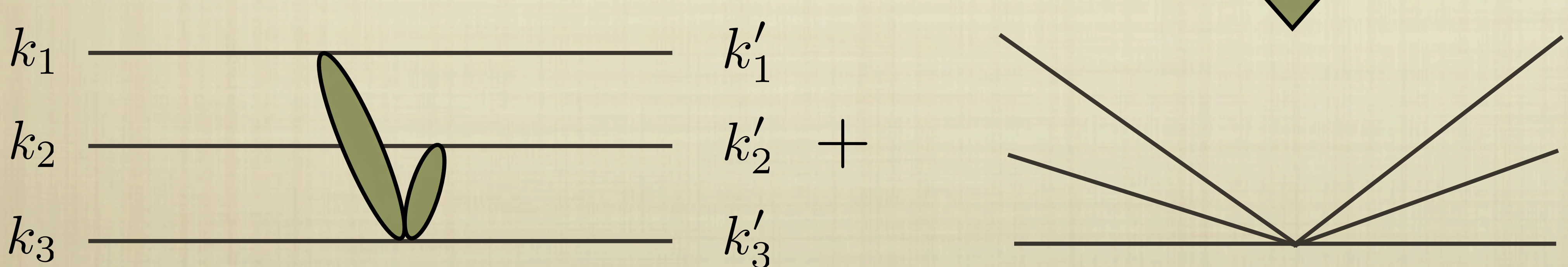


CHIRAL AMPLITUDES → ON-SHELL PART; → OFF-SHELL PART





→ CANCELLATION IN THE SU(3) LIMIT

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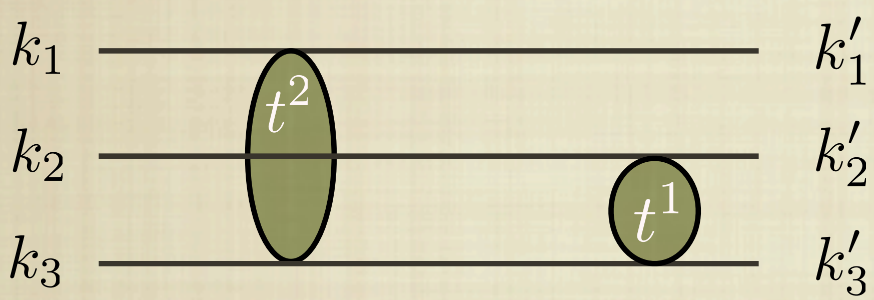

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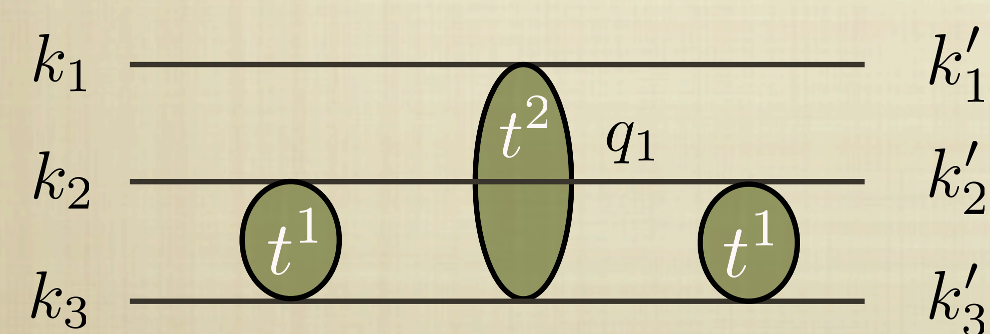
- G^{IJK} IS THE LOOP FUNCTION FOR DIAGRAMS INVOLVING THREE t MATRICES.



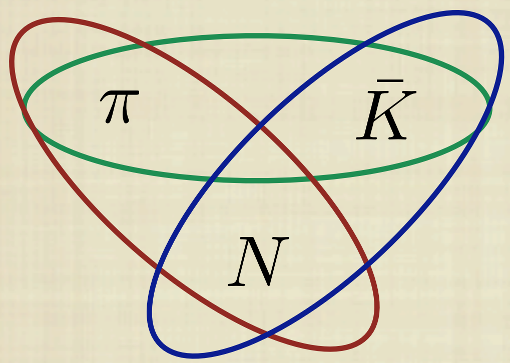
$$\int \frac{d^3 q_1}{(2\pi)^3} t^1(\sqrt{s_{23}}) g^{12} t^2(q_1^2) g^{21} t^1(\sqrt{s_{23}})$$

$$G^{121} = \int \frac{d^3 q_1}{(2\pi)^3} g^{12} t^2(q_1^2) g^{21} [g^{21}(\vec{k}_2', \vec{k}_1)]^{-1} [t^2(\sqrt{s_{23}})]^{-1}$$

$$t^1(\sqrt{s_{23}}) G^{121} t^2(\sqrt{s_{13}}) g^{21}(\vec{k}_2', \vec{k}_1) t^1(\sqrt{s_{23}})$$

THE $\pi\bar{K}N$ SYSTEM

- WE STARTED STUDYING THE $\pi\bar{K}N$ SYSTEM:



$$\Lambda(1405) \Rightarrow \bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Sigma, \eta\Lambda, K\Xi \text{ [7]}$$

$$N^*(1535) \Rightarrow \pi N, K\Sigma, K\Lambda, \eta N \text{ [8]}$$

$$\kappa(700) \Rightarrow \pi\bar{K}, \eta\bar{K} \text{ [9]}$$

- ALL THE INTERACTIONS ARE IN S-WAVE $\Rightarrow J^\pi = 1/2^+$.

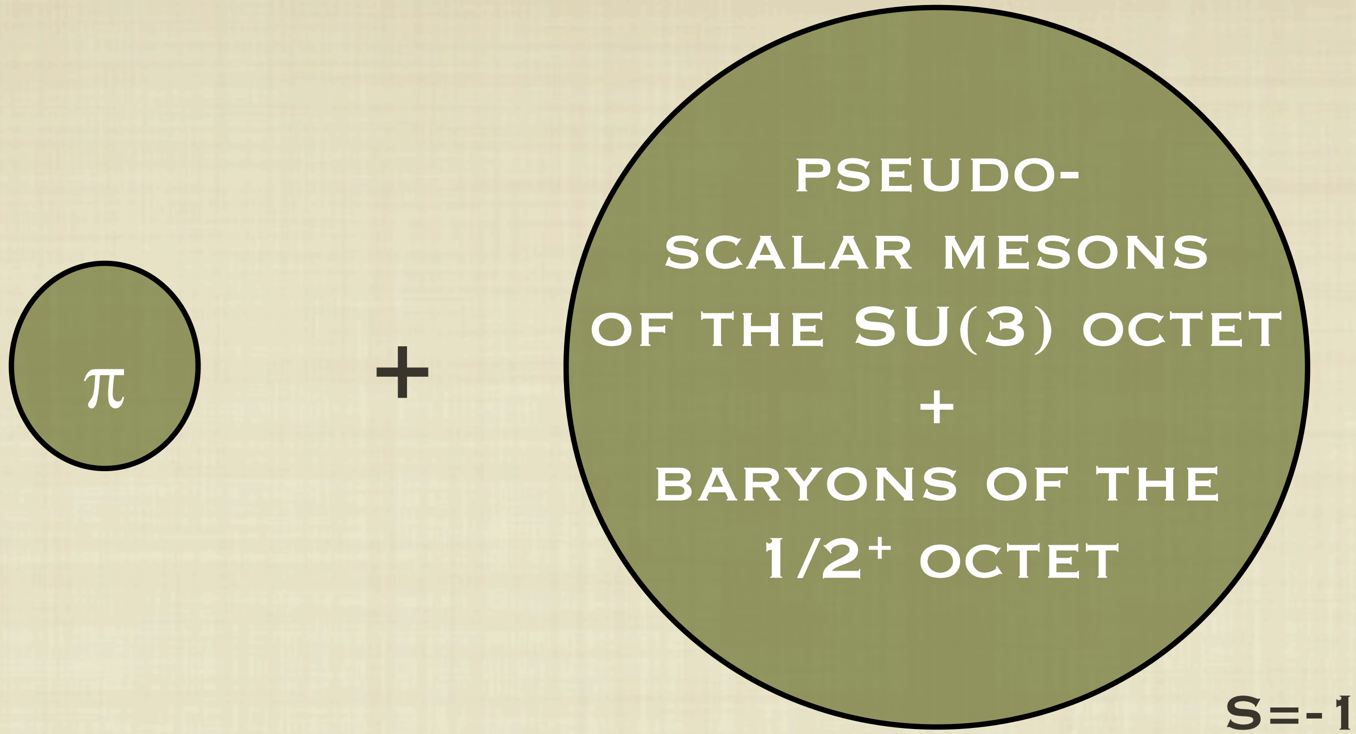
- THERE ARE SOME S=-1, $1/2^+$ BARYONIC STATES IN THE ENERGY REGION 1500-1800 MEV WHOSE PROPERTIES, AS SPIN-PARITY, ARE NOT WELL UNDERSTOOD.

- SIGNATURES OF Σ(1660), Λ(1600) HAVE BEEN FOUND IN SOME RECENT EXPERIMENTS, E.G.,

$$K^-p \to \pi\pi\Sigma \text{ [10]} \qquad K^-p \to \pi\pi\Lambda \text{ [11]}$$

[7] D. JIDO, J. A. OLLER, E. OSET, A. RAMOS, U. G. MEISSNER, NUCL. PHYS. A 725 (2003) 181-200.
[8] T. INOUE, E. OSET, M. J. VICENTE VACAS, PHYS. REV. C 65 035204 .
[9] J. A. OLLER, E. OSET, J. R. PELÁEZ, PHYS. REV. D 59 074001 (199).
[10] S. PRAKHOV ET AL. PHYS. REV. C 69, 042202 (2004).
[11] S. PRAKHOV ET AL. PHYS. REV. C 70, 034605 (2004).

- How many coupled channels do we have?



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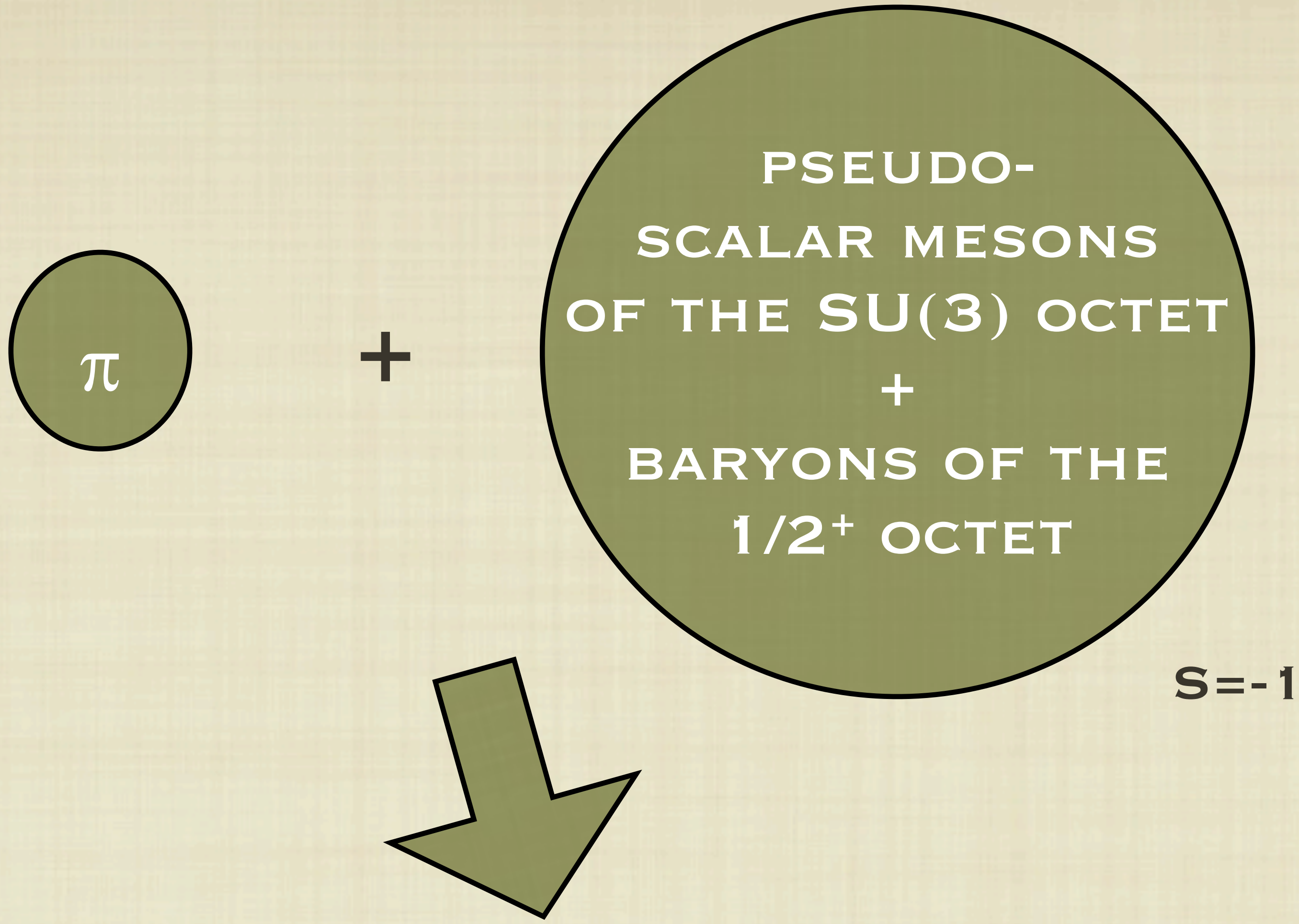

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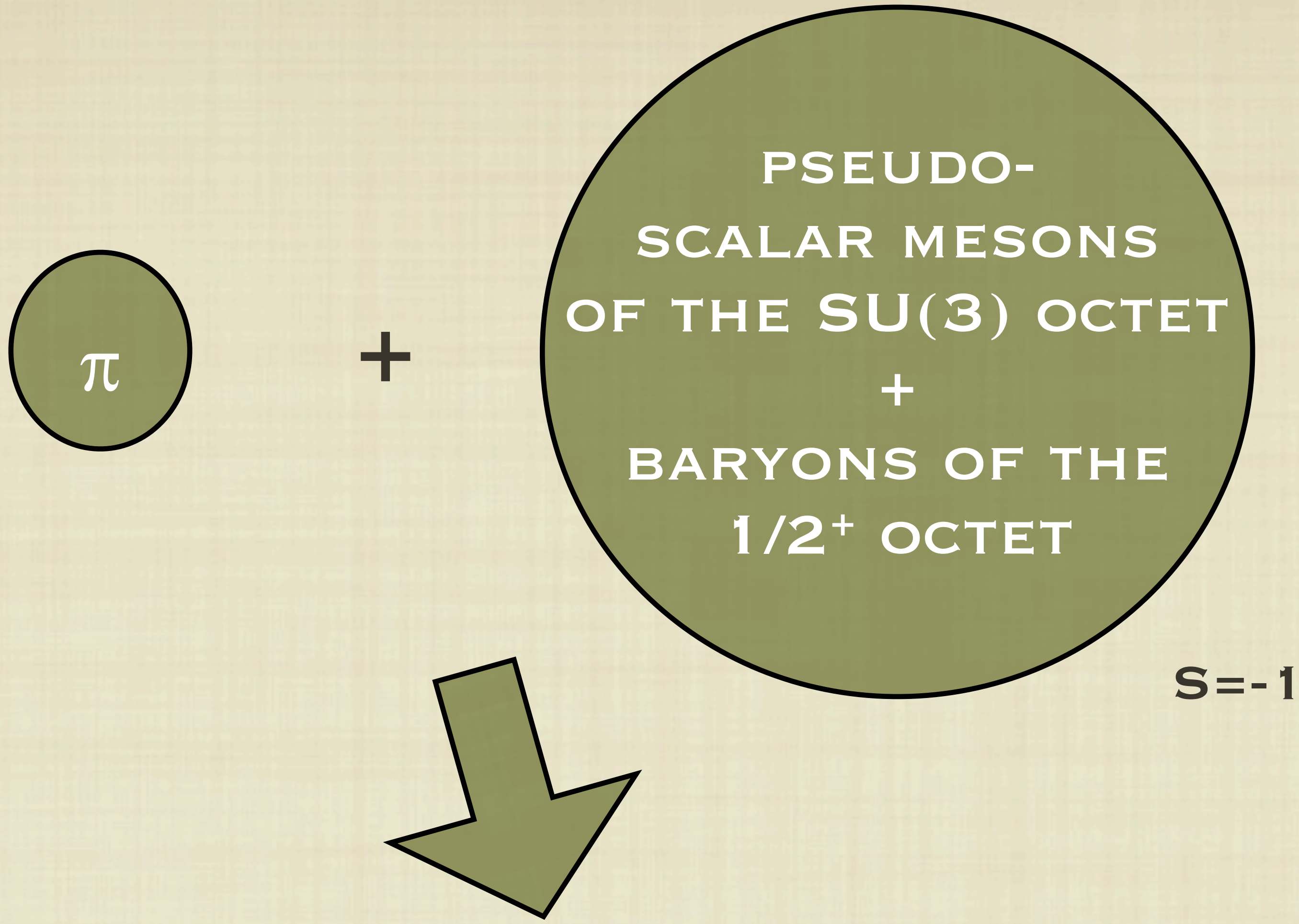
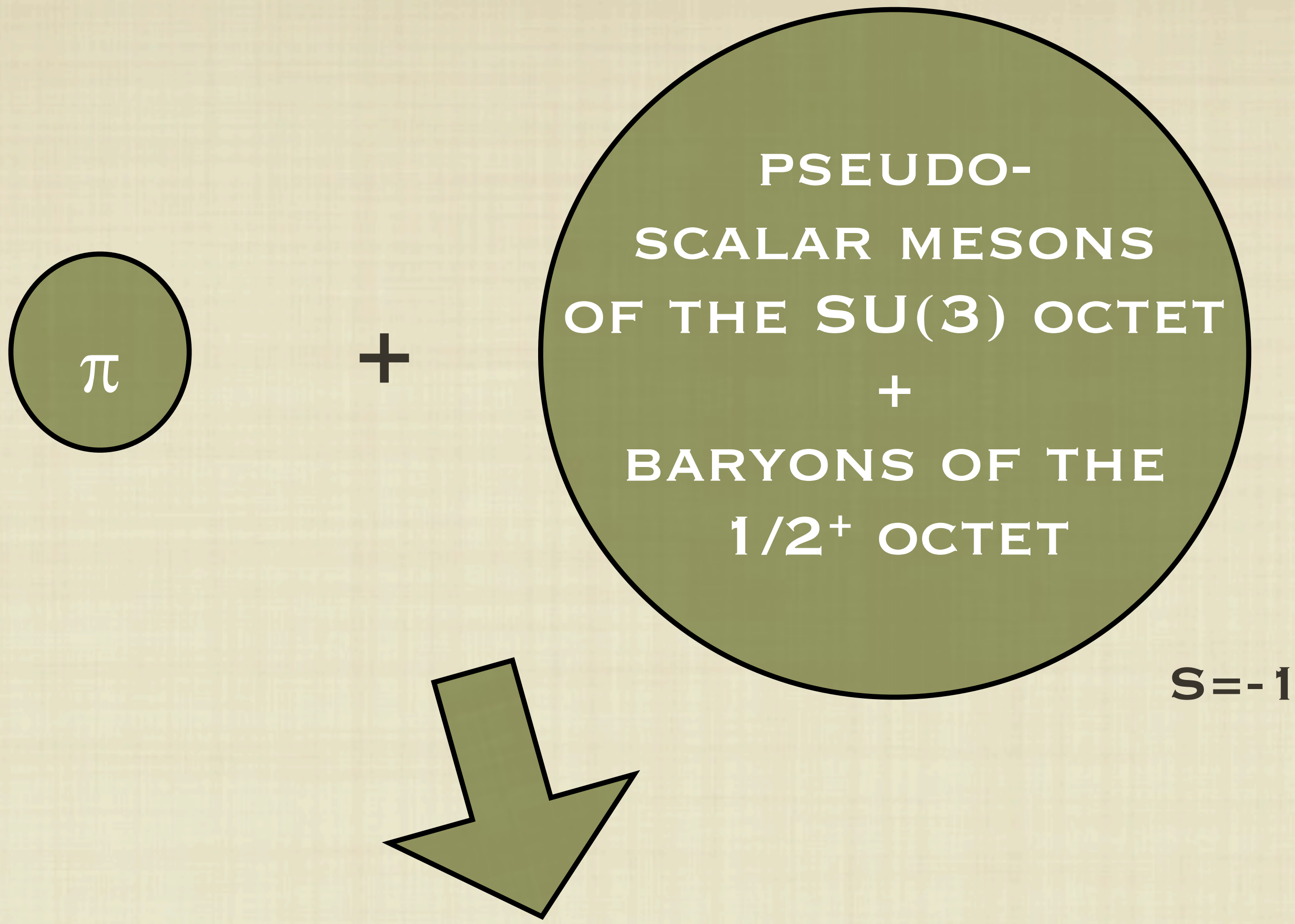


$\pi^0 \eta \Lambda, \pi^0 K^+ \Xi^-, \pi^0 K^0 \Xi^0,$

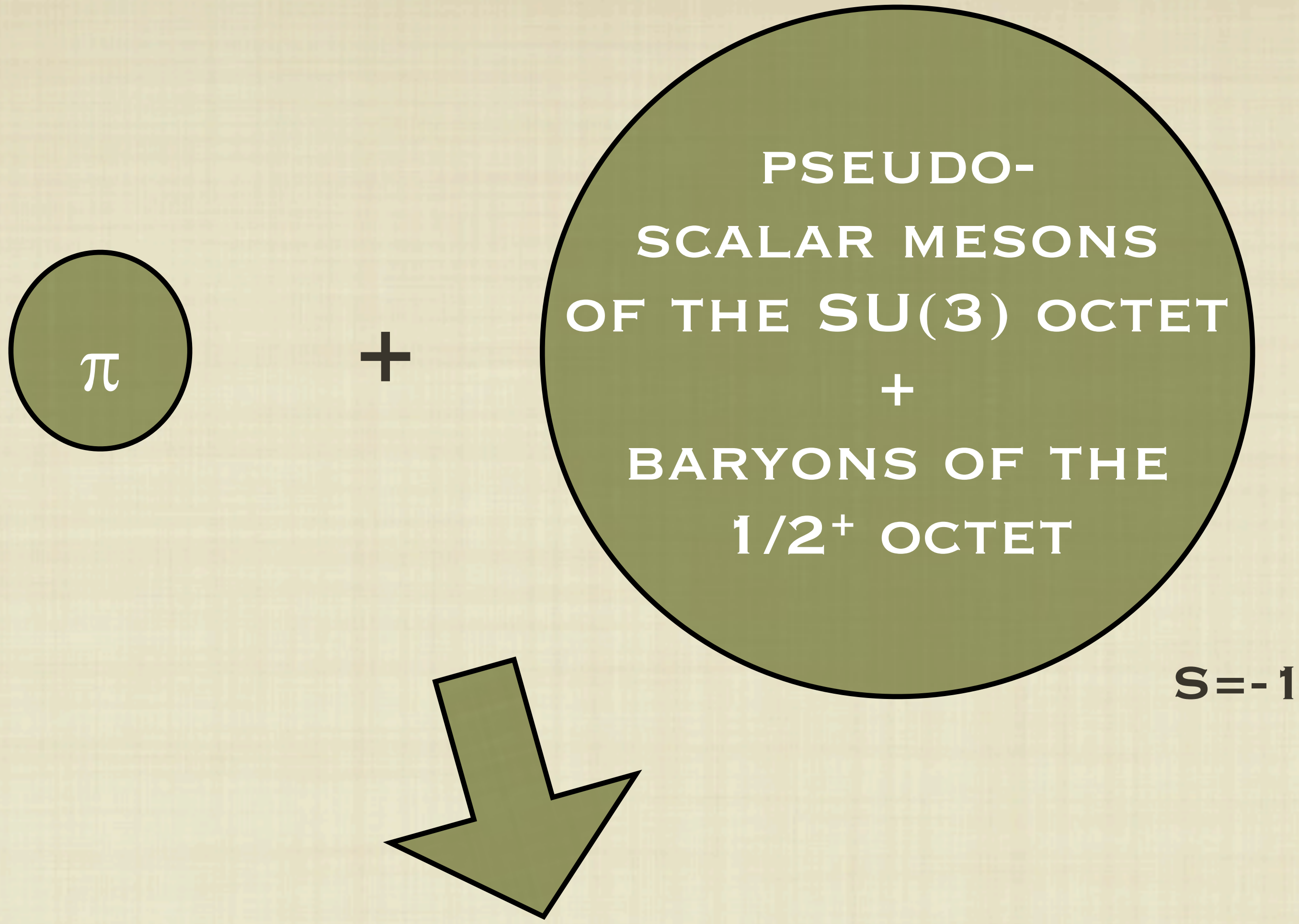
- HOW MANY COUPLED CHANNELS DO WE HAVE?



$$\pi^0\eta\Lambda, \pi^0 K^+\Xi^-, \pi^0 K^0\Xi^0,$$

$$\pi^-\pi^0\Sigma^+, \pi^-\pi^+\Sigma^0, \pi^-\pi^+\Lambda,$$

How many coupled channels do we have?



$$\pi^0\eta\Lambda, \pi^0K^+\Xi^-, \pi^0K^0\Xi^0,$$

$$\pi^-\pi^0\Sigma^+, \pi^-\pi^+\Sigma^0, \pi^-\pi^+\Lambda,$$

$$\pi^-\eta\Sigma^+, \pi^-K^+\Xi^0$$

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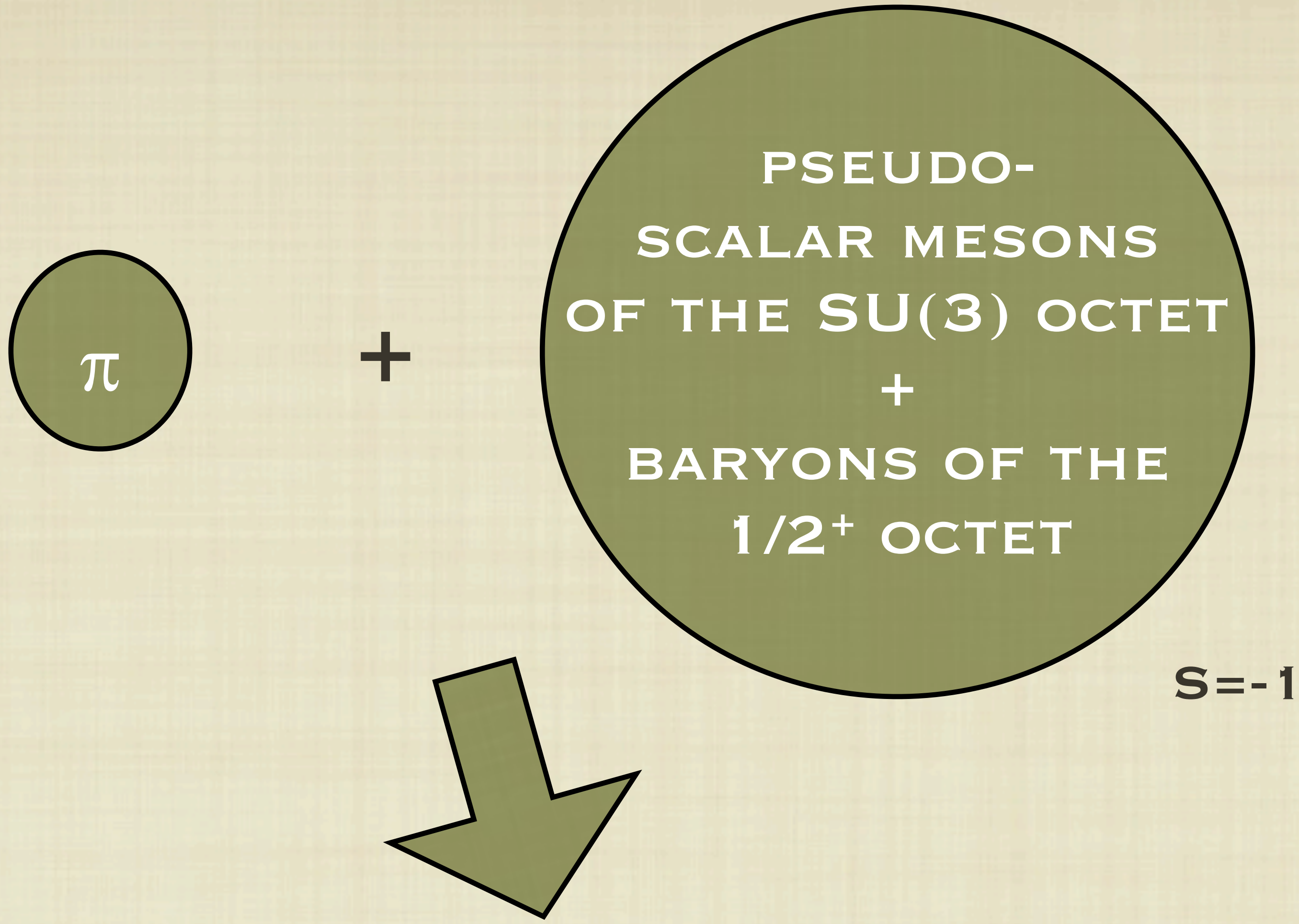
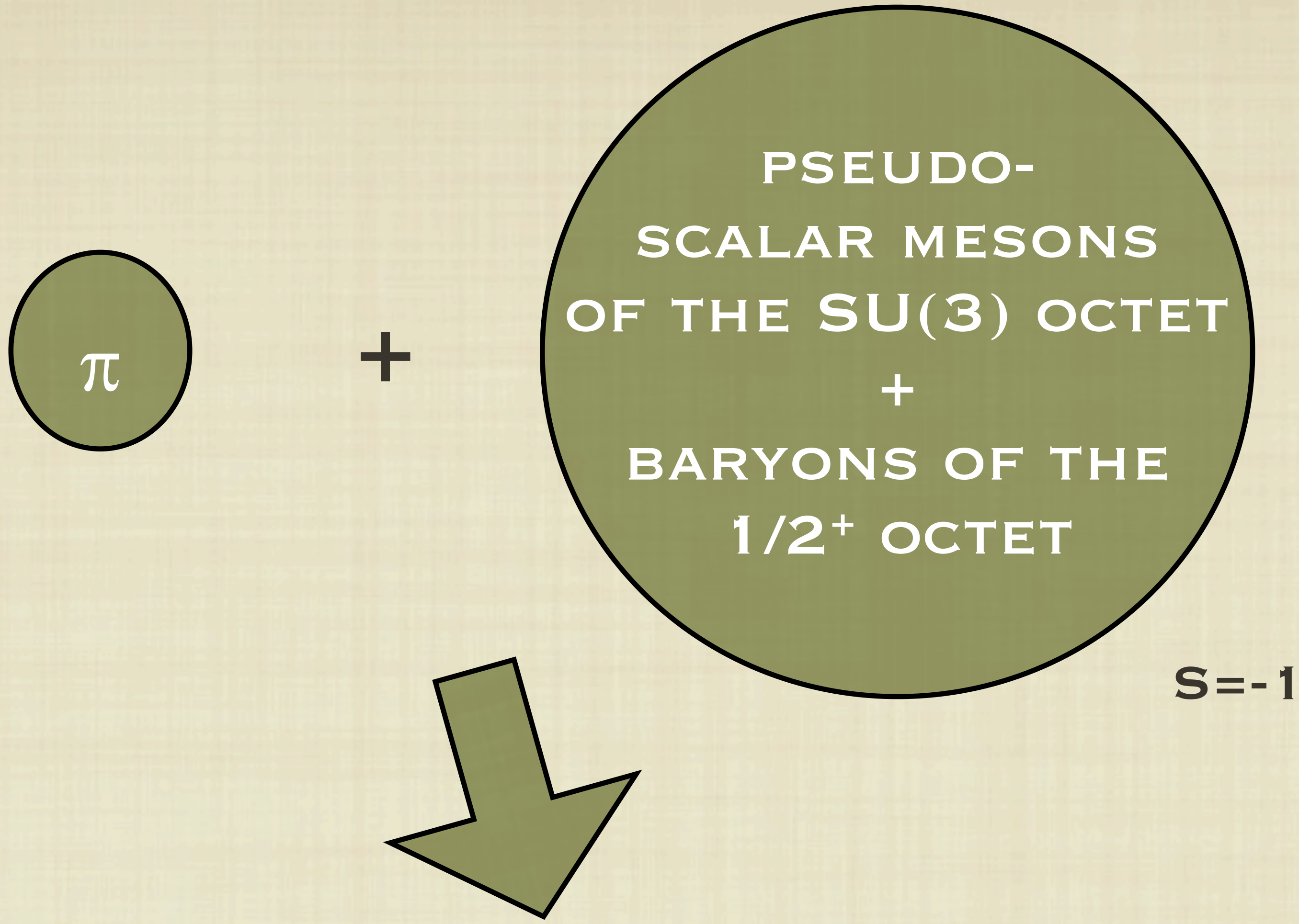


$$\pi^0\eta\Lambda, \pi^0K^+\Xi^-, \pi^0K^0\Xi^0,$$

$$\pi^+\pi^-\Sigma^0, \pi^+\pi^-\Lambda, \pi^+\eta\Sigma^-, \ \pi^-\pi^0\Sigma^+, \pi^-\pi^+\Sigma^0, \pi^-\pi^+\Lambda,$$

$$\pi^-\eta\Sigma^+, \pi^-K^+\Xi^0$$

How many coupled channels do we have?

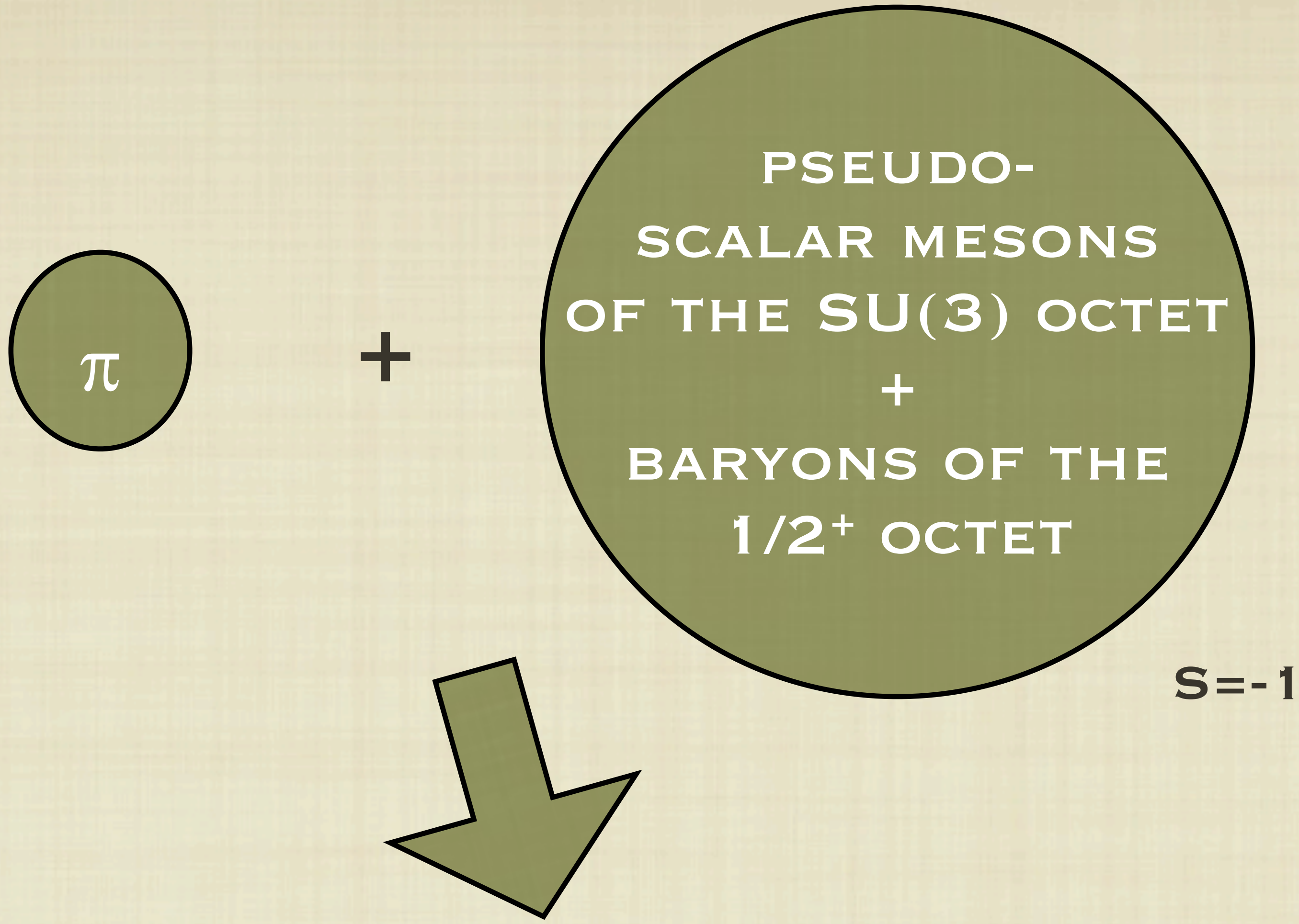


$$\pi^0\eta\Lambda, \pi^0 K^+\Xi^-, \pi^0 K^0\Xi^0,$$

$$\pi^+\pi^-\Sigma^0, \pi^+\pi^-\Lambda, \pi^+\eta\Sigma^-, \; \pi^-\pi^0\Sigma^+, \pi^-\pi^+\Sigma^0, \pi^-\pi^+\Lambda,$$

$$\pi^0 K^- p, \pi^0\bar{K}^0 n, \pi^0\pi^0\Sigma^0, \pi^0\pi^+\Sigma^-, \qquad \pi^-\eta\Sigma^+, \pi^- K^+\Xi^0$$

- How many coupled channels do we have?

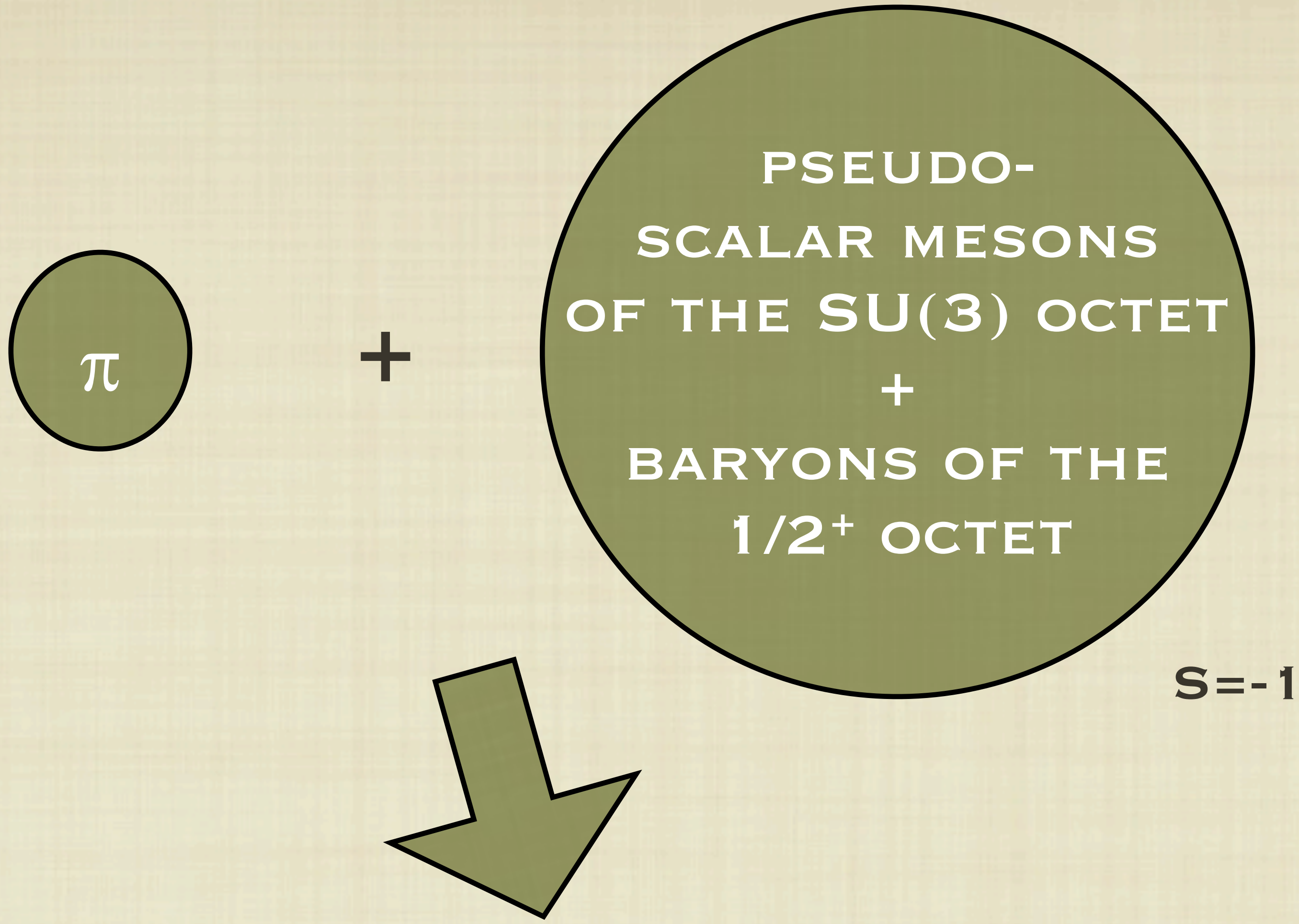


$$\pi^0\eta\Lambda, \pi^0 K^+\Xi^-, \pi^0 K^0\Xi^0, \; \pi^+ K^- n, \pi^+\pi^0\Sigma^-,$$

$$\pi^+\pi^-\Sigma^0, \pi^+\pi^-\Lambda, \pi^+\eta\Sigma^-, \; \pi^-\pi^0\Sigma^+, \pi^-\pi^+\Sigma^0, \pi^-\pi^+\Lambda,$$

$$\pi^0 K^- p, \pi^0\bar{K}^0 n, \pi^0\pi^0\Sigma^0, \pi^0\pi^+\Sigma^-, \qquad \pi^-\eta\Sigma^+, \pi^- K^+\Xi^0$$

How many coupled channels do we have?



$\pi^0\eta\Lambda, \pi^0K^+\Xi^-, \pi^0K^0\Xi^0, \ \pi^+K^-n, \pi^+\pi^0\Sigma^-, \ \pi^+K^0\Xi^-, \pi^-\bar{K}^0p,$

$\pi^+\pi^-\Sigma^0, \pi^+\pi^-\Lambda, \pi^+\eta\Sigma^-, \ \pi^-\pi^0\Sigma^+, \pi^-\pi^+\Sigma^0, \pi^-\pi^+\Lambda,$

$\pi^0K^-p, \pi^0\bar{K}^0n, \pi^0\pi^0\Sigma^0, \pi^0\pi^+\Sigma^-, \qquad \pi^-\eta\Sigma^+, \pi^-K^+\Xi^0$

How many coupled channels do we have?

π + pseudo-scalar mesons of the SU(3) octet + baryons of the 1/2⁺ octet

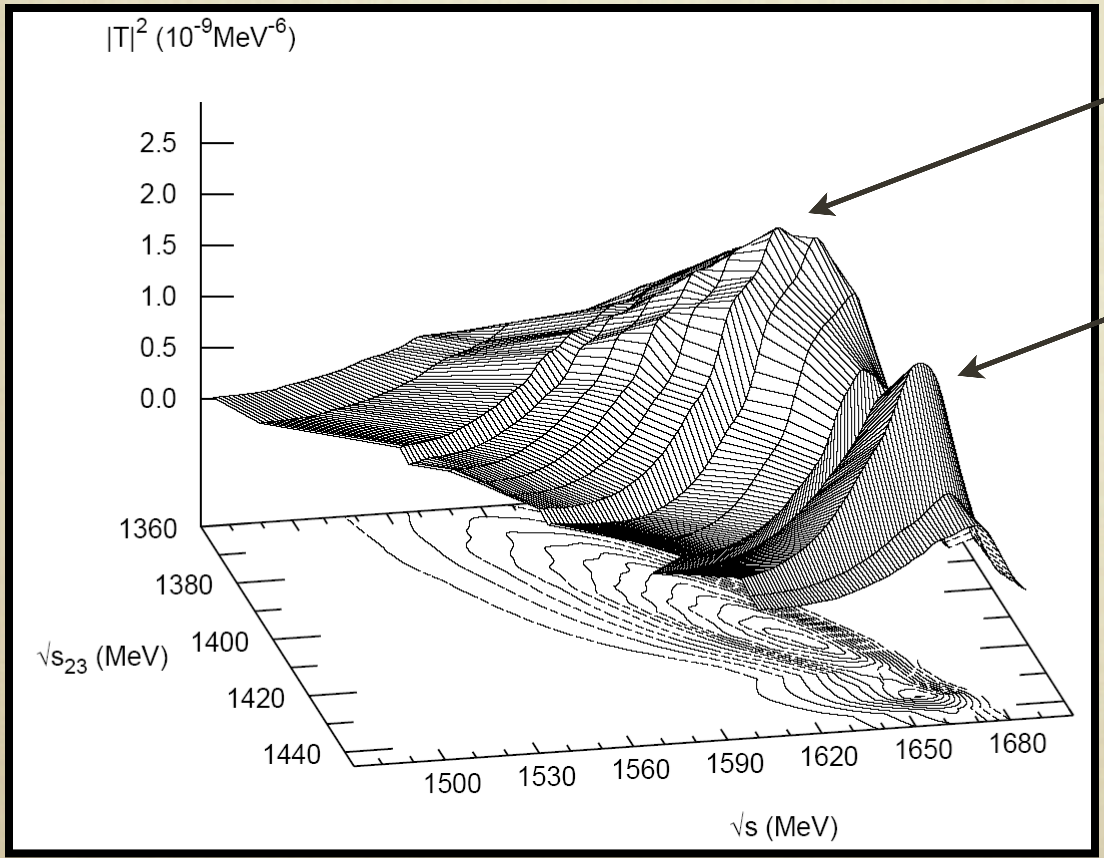
S=-1

$$\pi^0\eta\Lambda, \pi^0K^+\Xi^-, \pi^0K^0\Xi^0, \pi^+K^-n, \pi^+\pi^0\Sigma^-, \pi^+K^0\Xi^-, \pi^-\bar{K}^0p,$$
$$\pi^+\pi^-\Sigma^0, \pi^+\pi^-\Lambda, \pi^+\eta\Sigma^-, \pi^-\pi^0\Sigma^+, \pi^-\pi^+\Sigma^0, \pi^-\pi^+\Lambda,$$
$$\pi^0K^-p, \pi^0\bar{K}^0n, \pi^0\pi^0\Sigma^0, \pi^0\pi^+\Sigma^-, \pi^0\pi^-\Sigma^+, \pi^0\pi^0\Lambda, \pi^0\eta\Sigma^0, \pi^-\eta\Sigma^+, \pi^-K^+\Xi^0$$

Results $\pi \bar{K} N$ sytem

$\Sigma(1620)$ S_{11} [$I(J^P)=1(1/2^-)$] **

$\Sigma(1660)$ P_{11} [$I(J^P)=1(1/2^+)$] ***



$1630 - i39/2\ MeV$

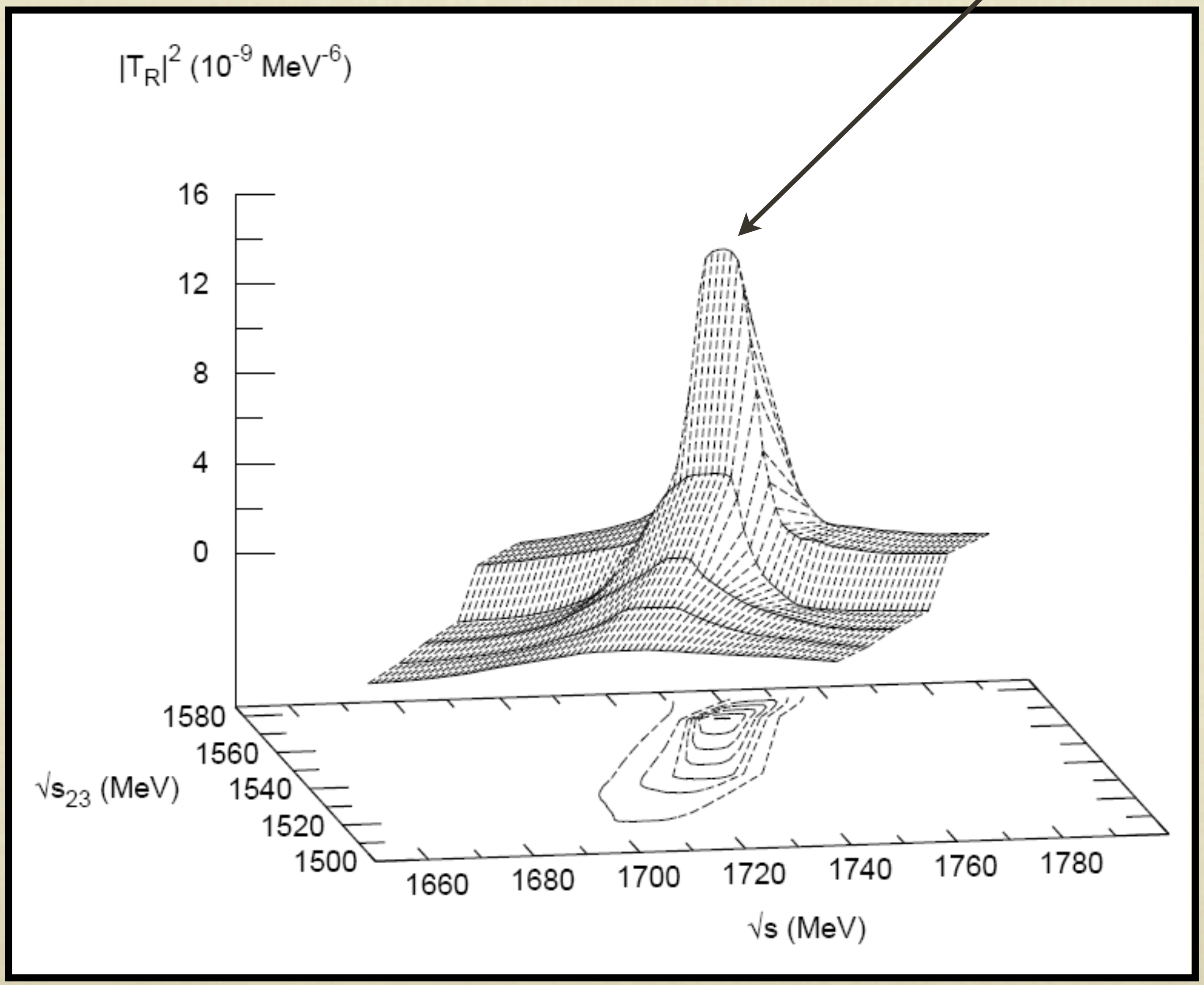
$1656 - i30/2\ MeV$

R. Armenteros et al. Nucl. Phys. B 8, 183 (1968).
B. R. Martin et al, Nucl. Phys. B 127, 349 (1977).

Results $\pi \bar{K} N$ sytem

Λ(1810) P_{01} [$I(J^P)=0(1/2^+)$] ***
1750 to 1850 (~ 1810) OUR ESTIMATE

$1740 - i24/2 \; MeV$



Results $\pi \bar{K} N$ sytem

	Γ (PDG) (MeV)	Peak position (this work) (MeV)	Γ (this work) (MeV)
Isospin = 1			
Σ(1560)	10-100	1590	70
Σ(1620)	10-100	1630	39
Σ(1660)	40-200	1656	30
Σ(1770)	60-100	1790	24
Isospin = 0			
Λ(1600)	50-250	1568,1700	60, 136
Λ(1810)	50-250	1740	20

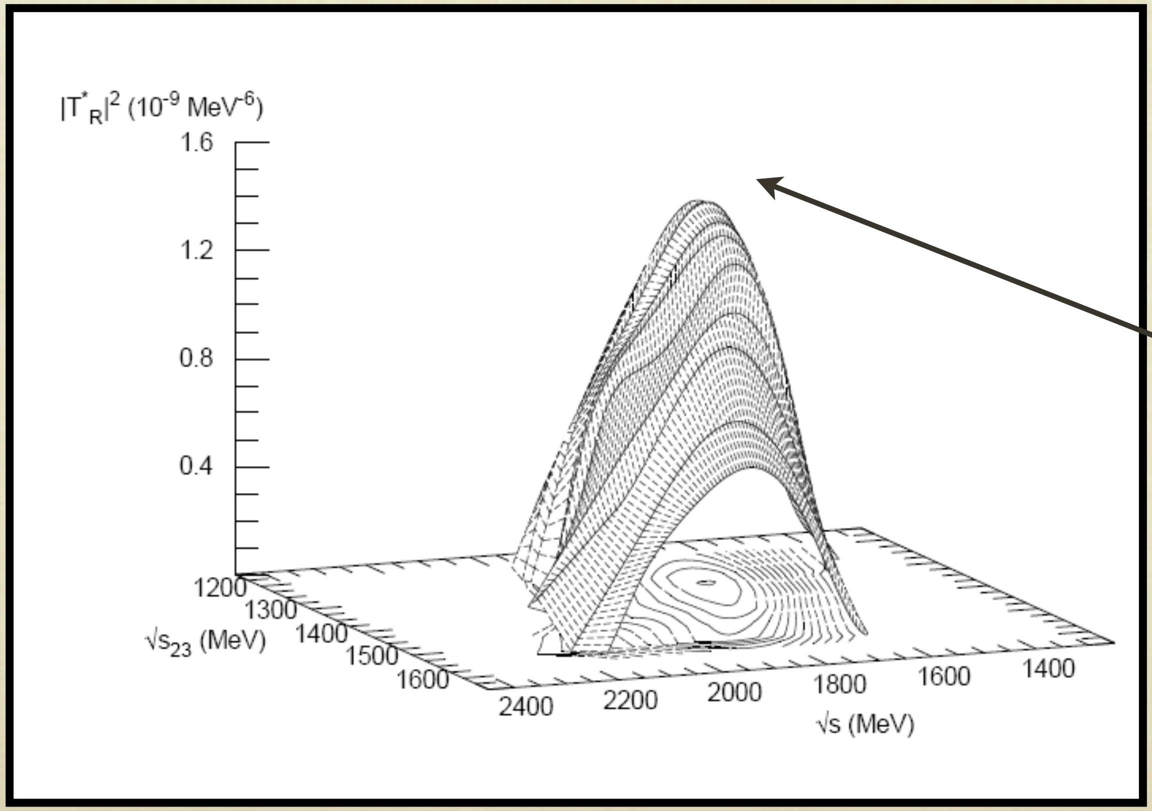
[12] A. Martínez Torres, K. P. Khemchandani, E. Oset , Phys. Rev. C77,042203,2008; Eur. Phys. J. A35: 295-297,2008

THE ππN SYSTEM

- WE CONSIDER THE CHANNELS $\pi^0\pi^0 n, \pi^+\pi^- n, \pi^-\pi^+ n, \pi^0\pi^- p, \pi^-\pi^0 p$.

- NEGLIGIBLE EFFECT OF THE πKΣ, πKΛ, AND $\pi\,\eta\,\mathrm{N}$ CHANNELS IN THE ENERGY REGION EXPLORED.

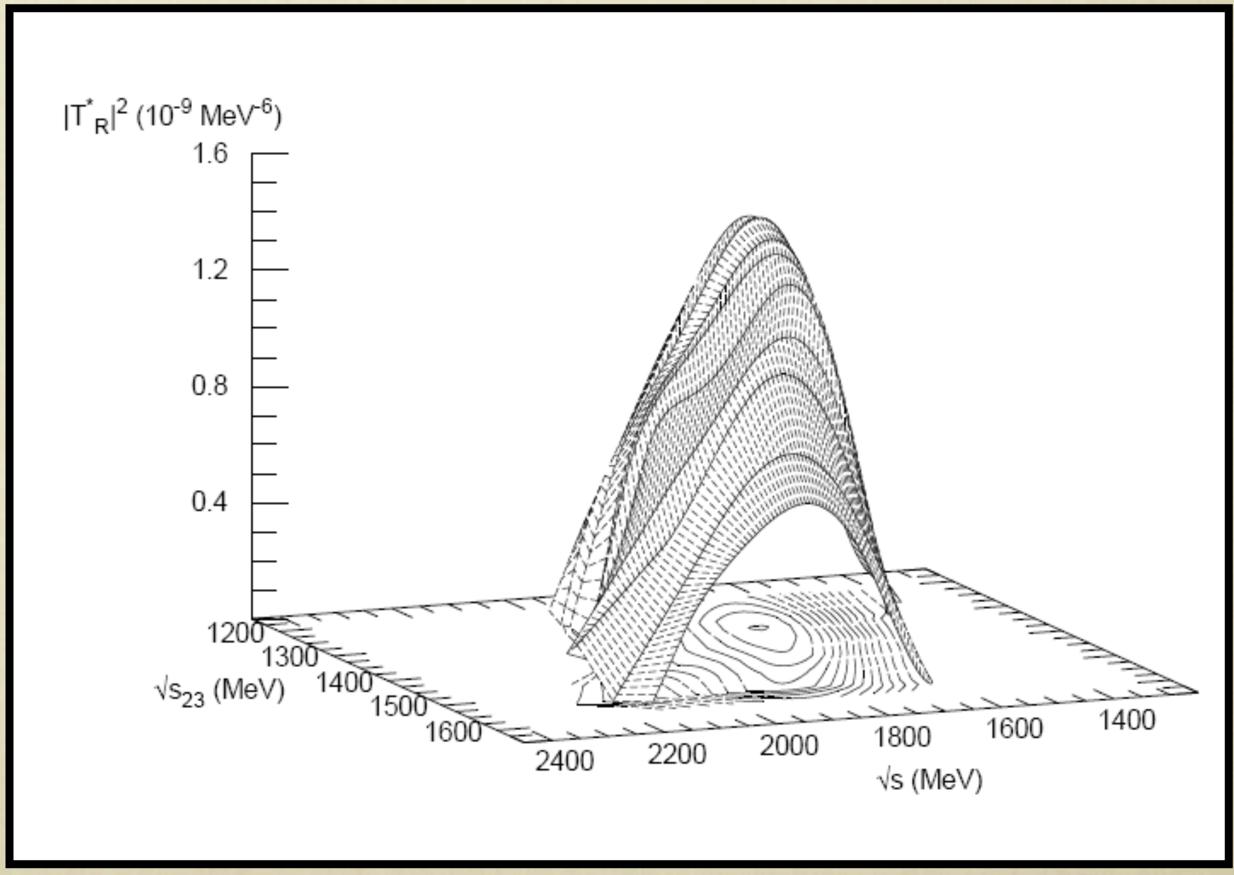
N*(1710) P_{11} [I(J^P)=1/2(1/2$^+$)] ***



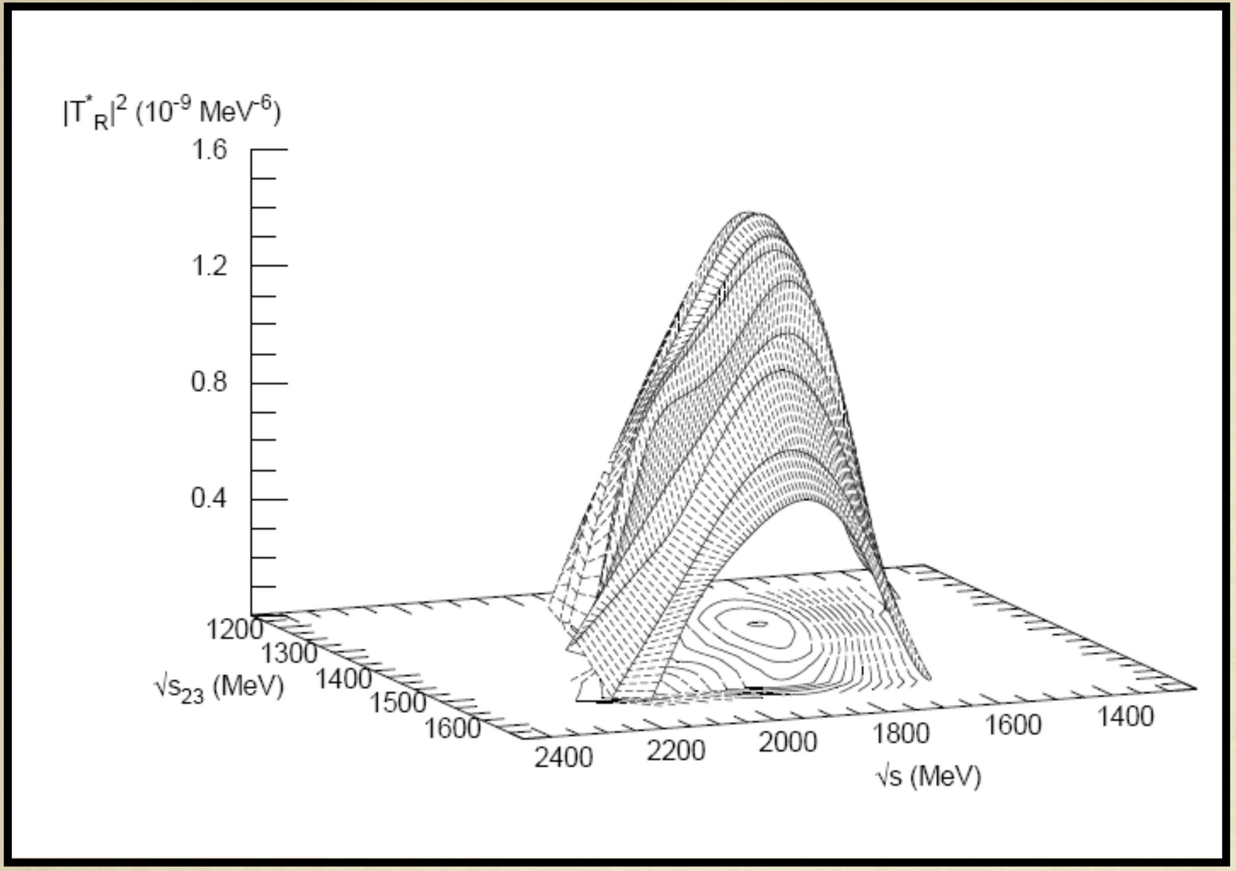
$1704 - i375/2MeV$

[13] K. P. KHEMCHANDANI, A. MARTÍNEZ TORRES, E. OSET , EUR. PHYS. J. A35:295-297,2008.

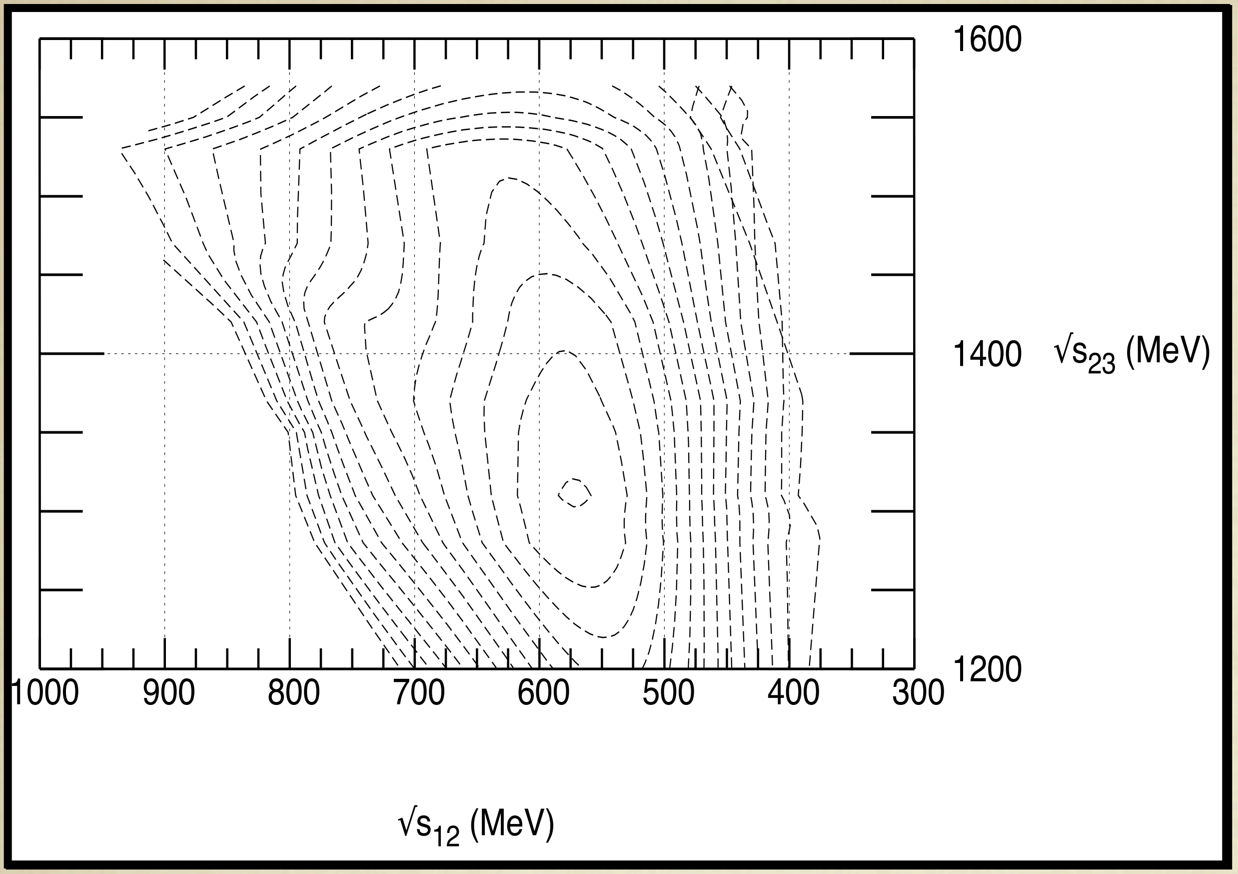
N*(1710) P_{11} [$I(J^P)=1/2(1/2^+)$] ***



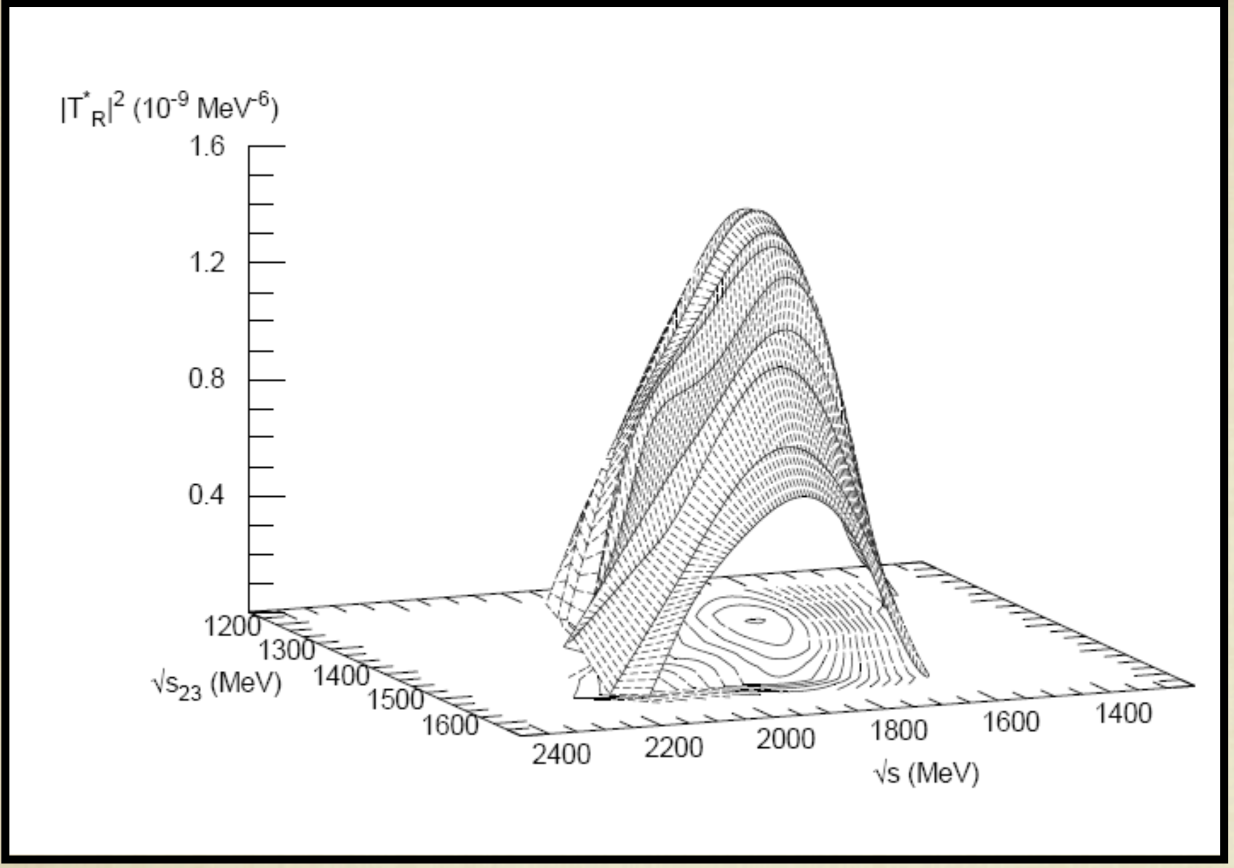
N*(1710) P_{11} [$I(J^P)=1/2(1/2^+)$] ***

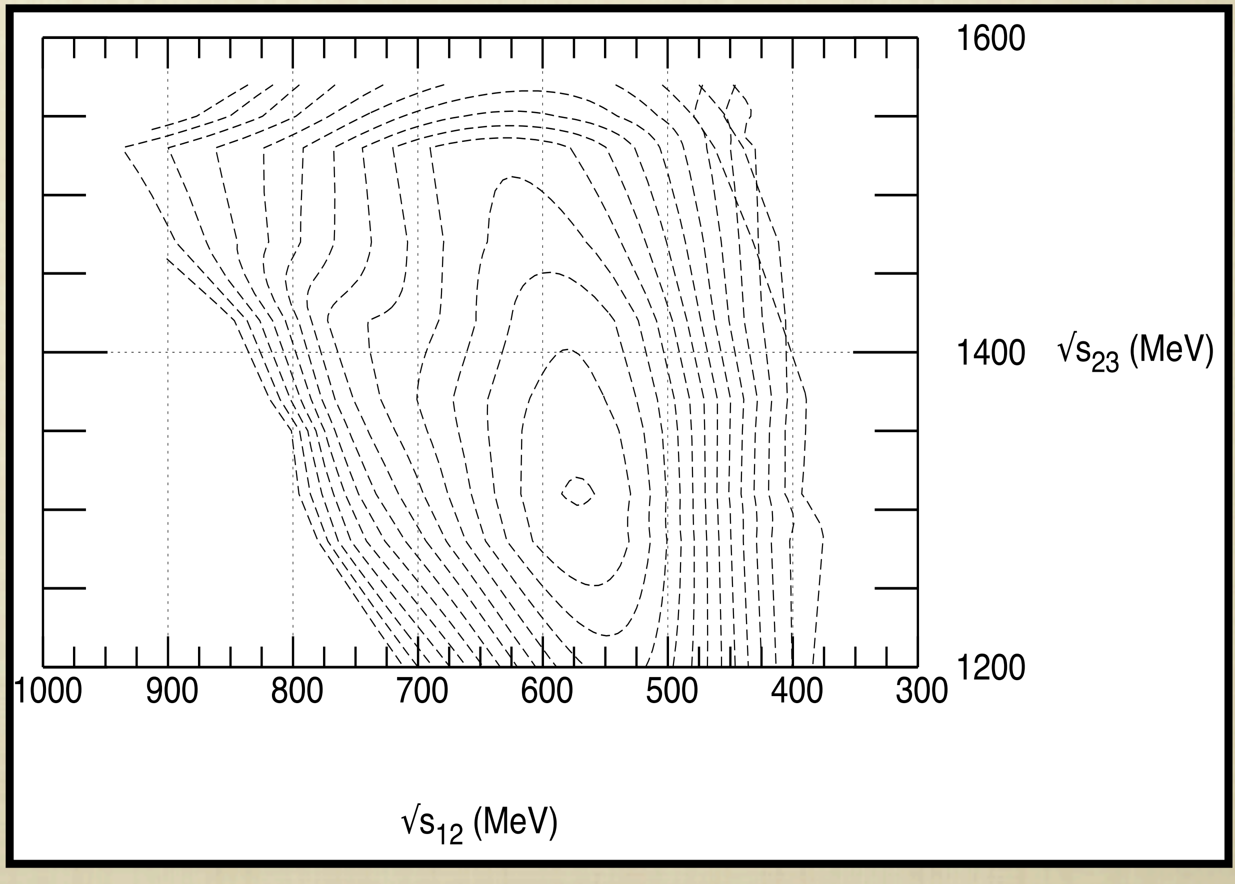


N*(1710) P_{11} [$I(J^P)=1/2(1/2^+)$] ***

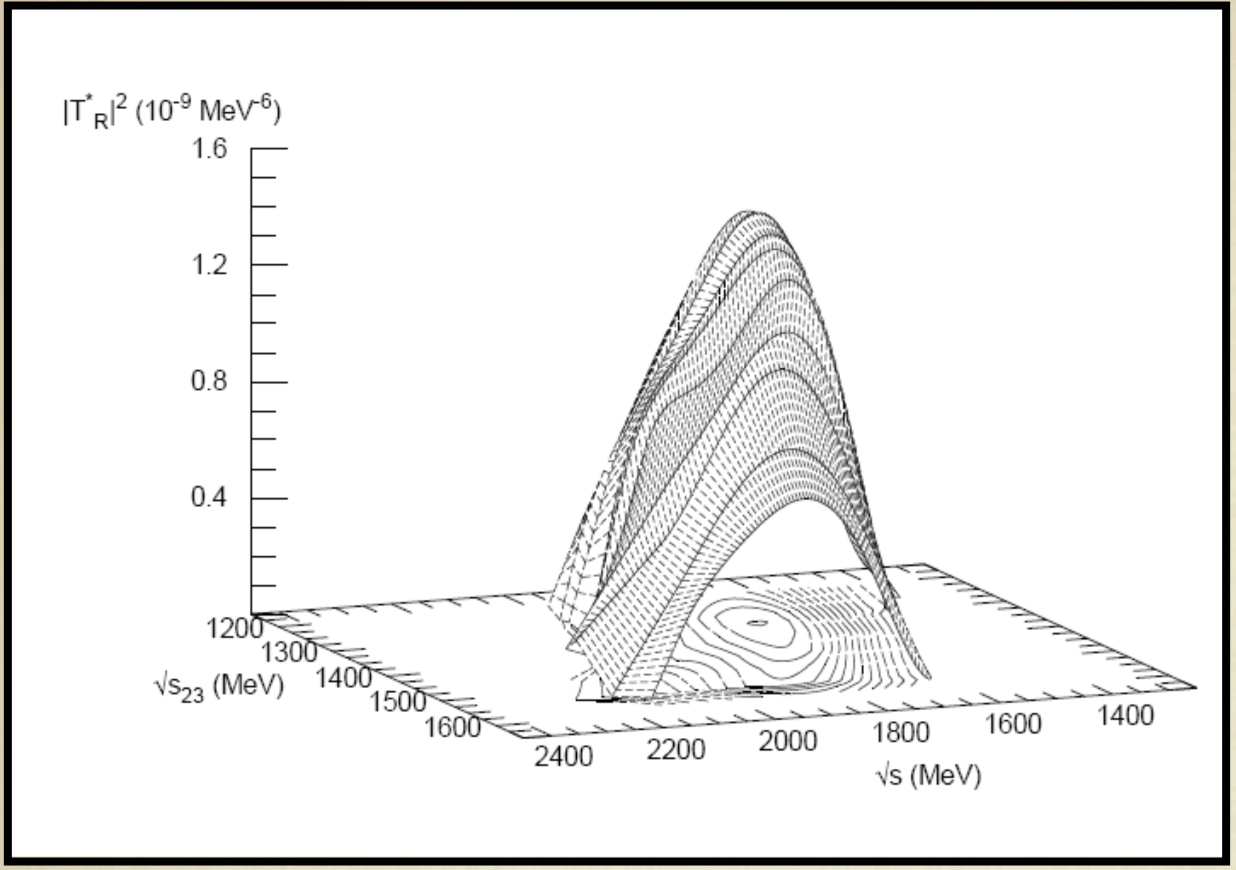


N*(1710) P_{11} [$I(J^P)=1/2(1/2^+)$] ***

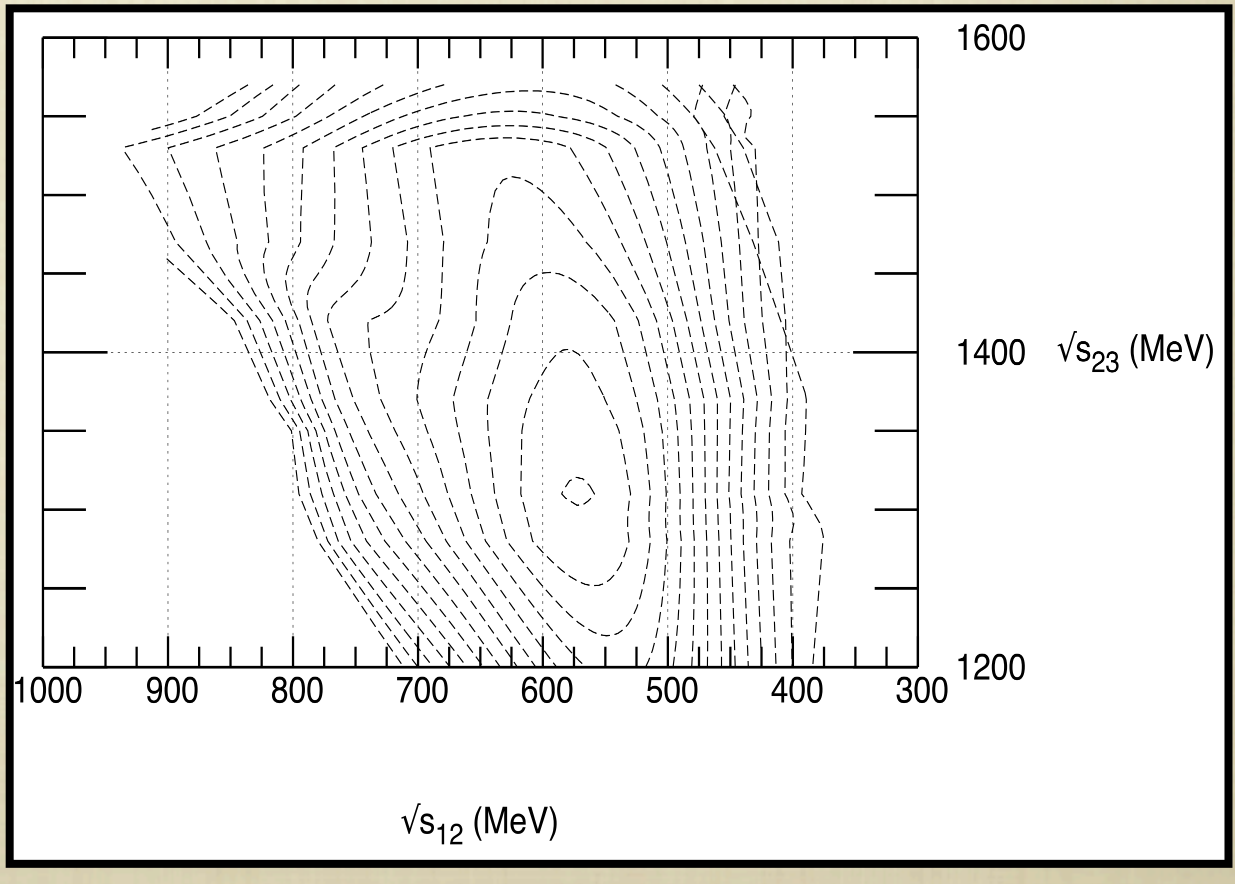




$N^*(1710)$ P_{11} [$I(J^P)=1/2(1/2^+)$] ***

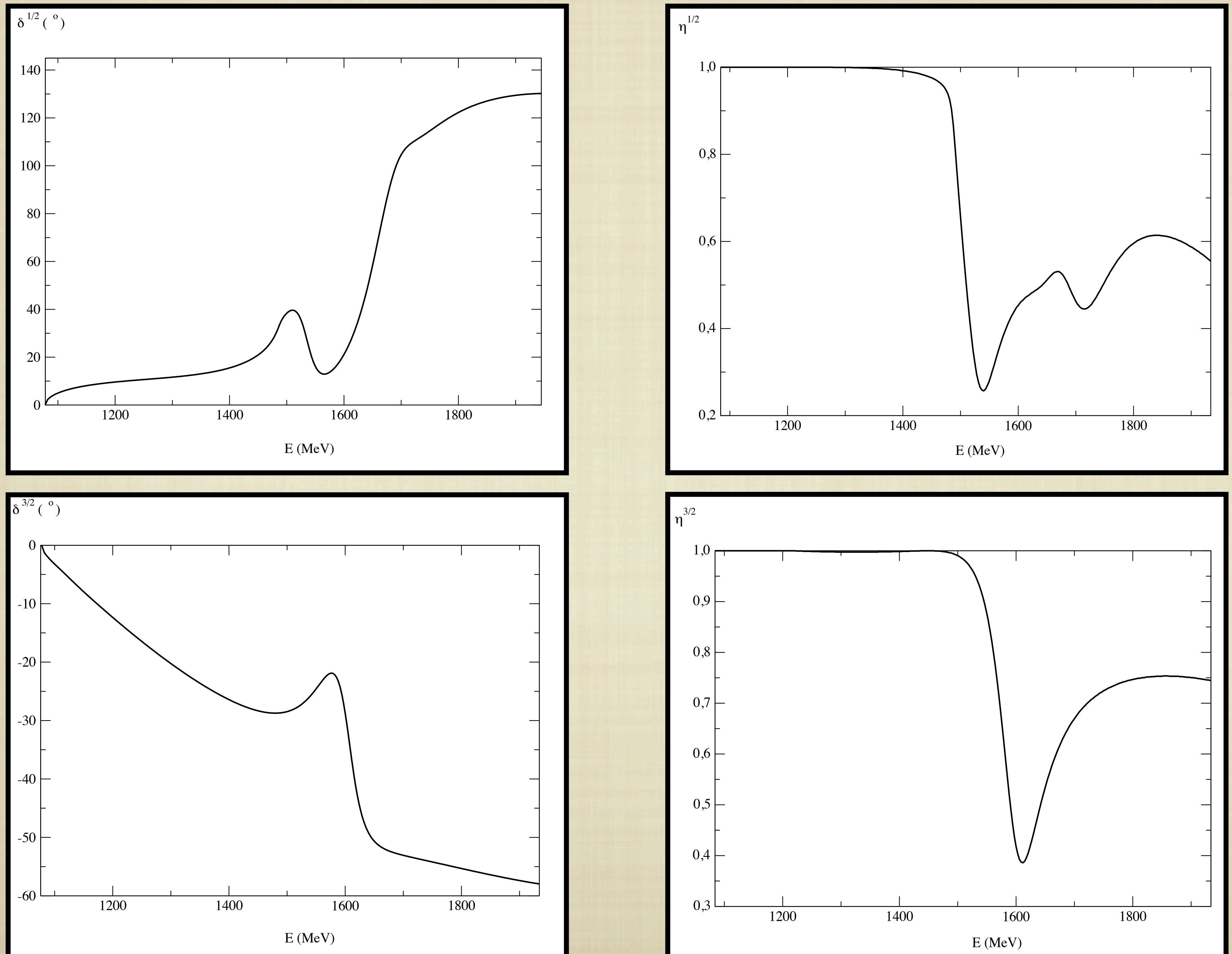


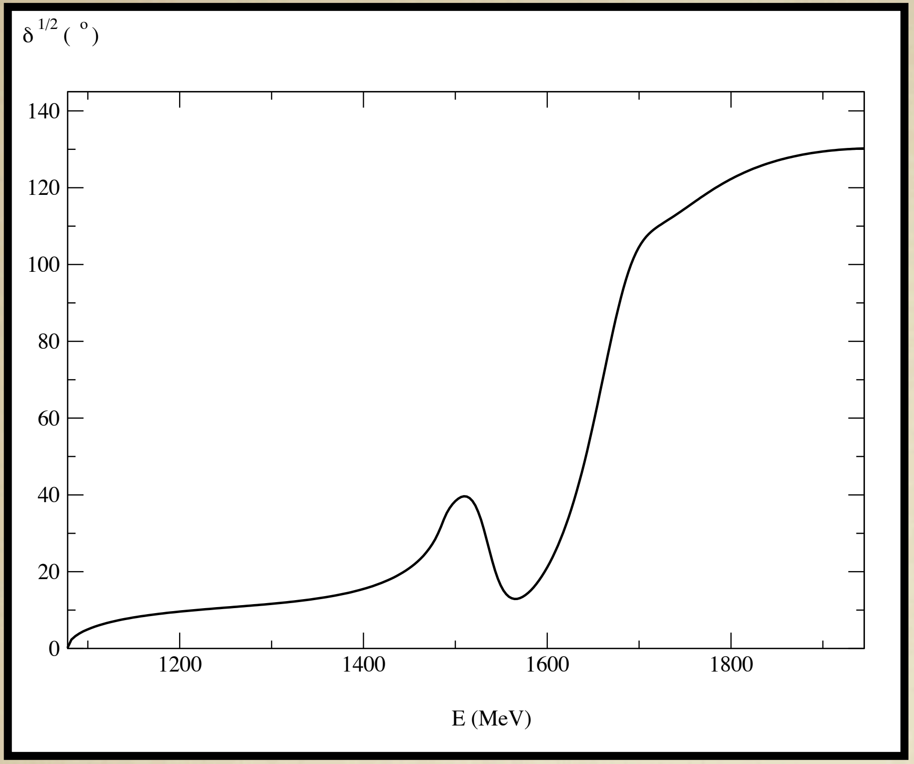
$\sigma(600)N$

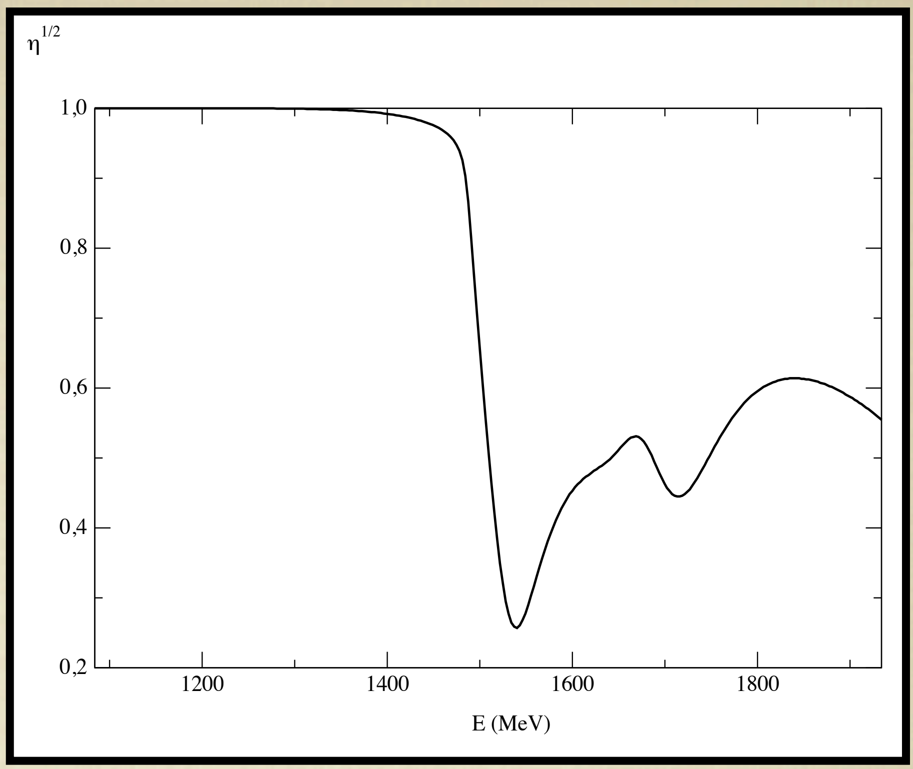


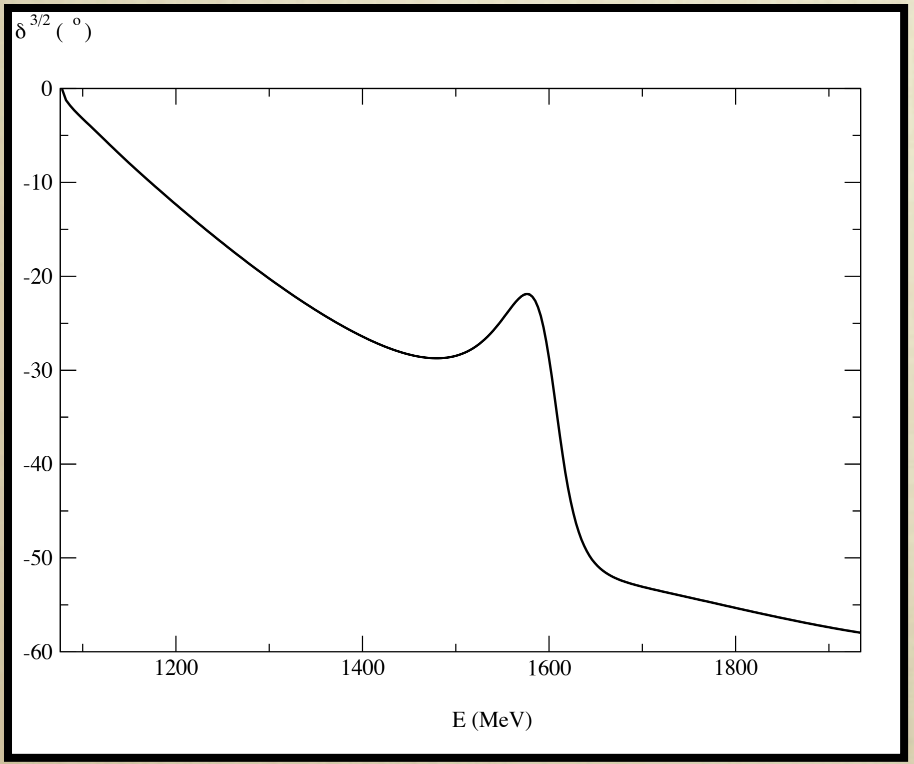
- **There are other 1/2$^+$ states: N*(2100), $\Delta(1750)$, $\Delta(1910)$.**

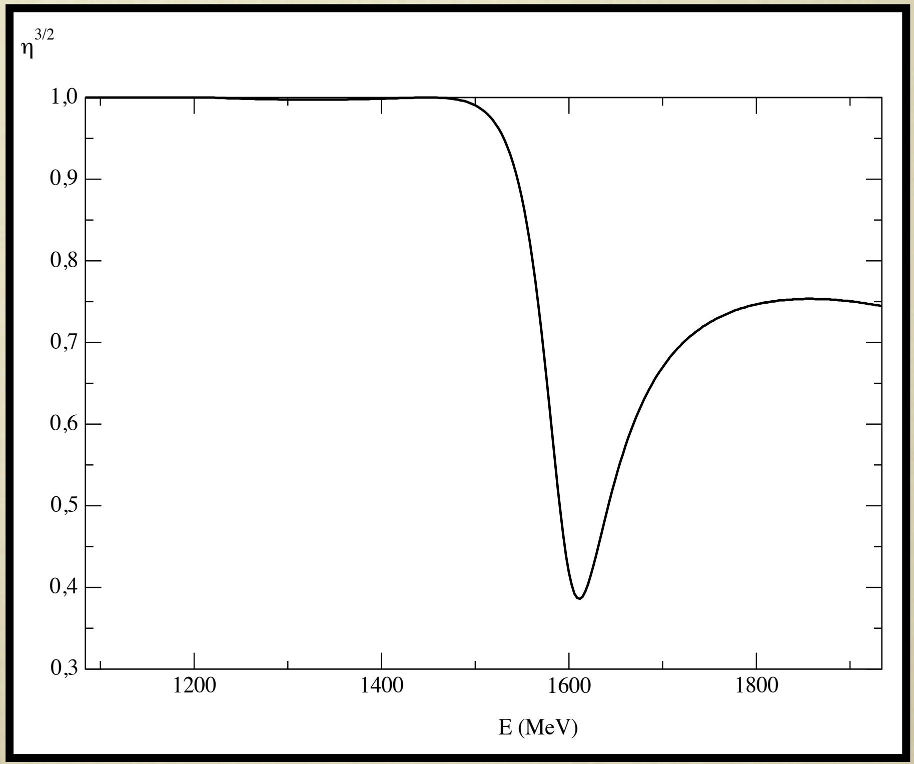
- **The πN t-matrix used generates the N*(1535), but no the N*(1650).**

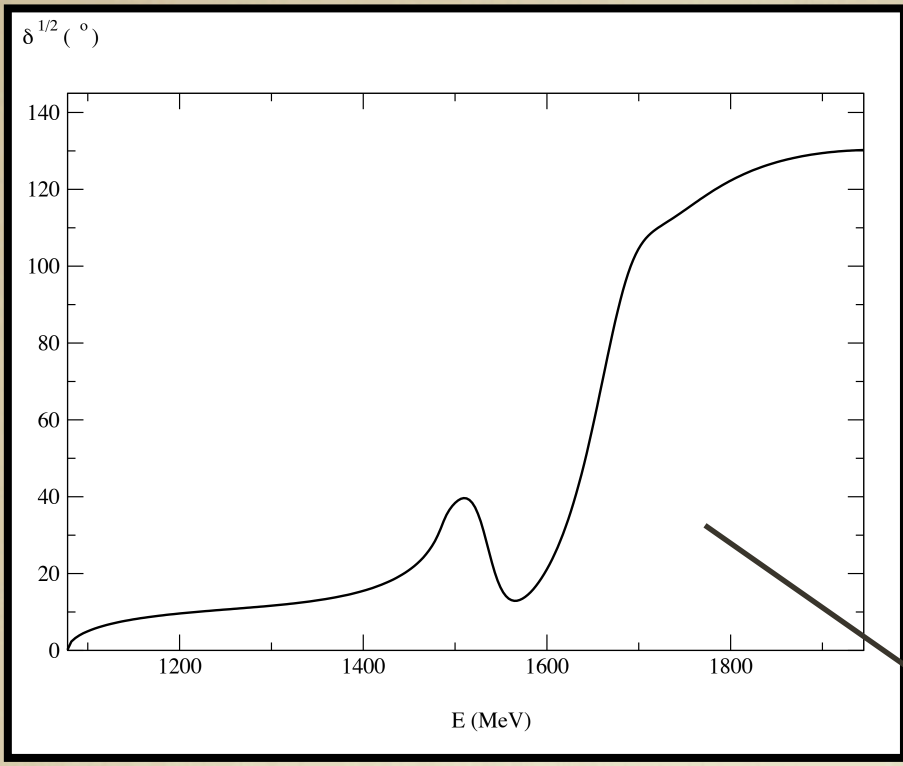


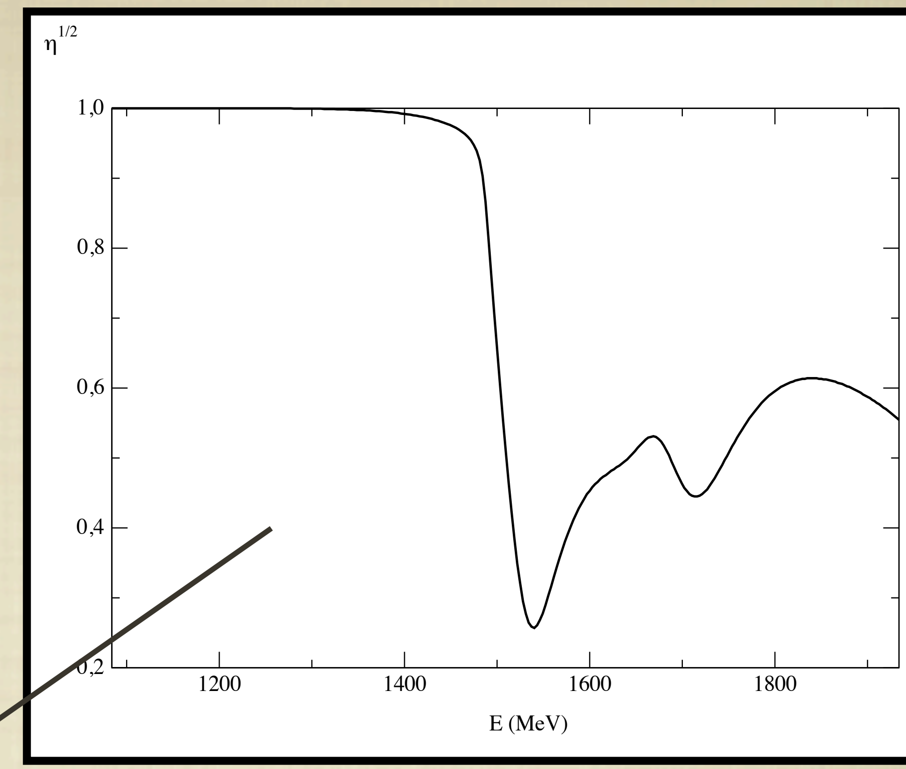

δ 1/2 (º)
0
20
40
60
80
100
120
140
1200
1400
1600
1800
E (MeV)


η 1/2
0,2
0,4
0,6
0,8
1,0
1200
1400
1600
1800
E (MeV)


δ 3/2 (º)
0
-10
-20
-30
-40
-50
-60
1200
1400
1600
1800
E (MeV)

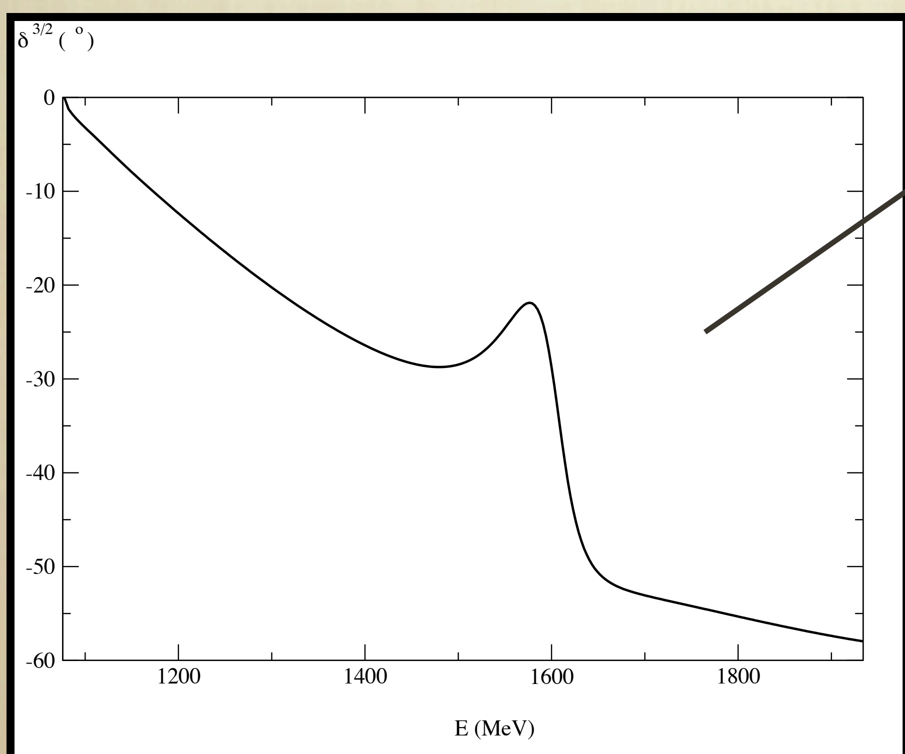

η 3/2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1200
1400
1600
1800
E (MeV)

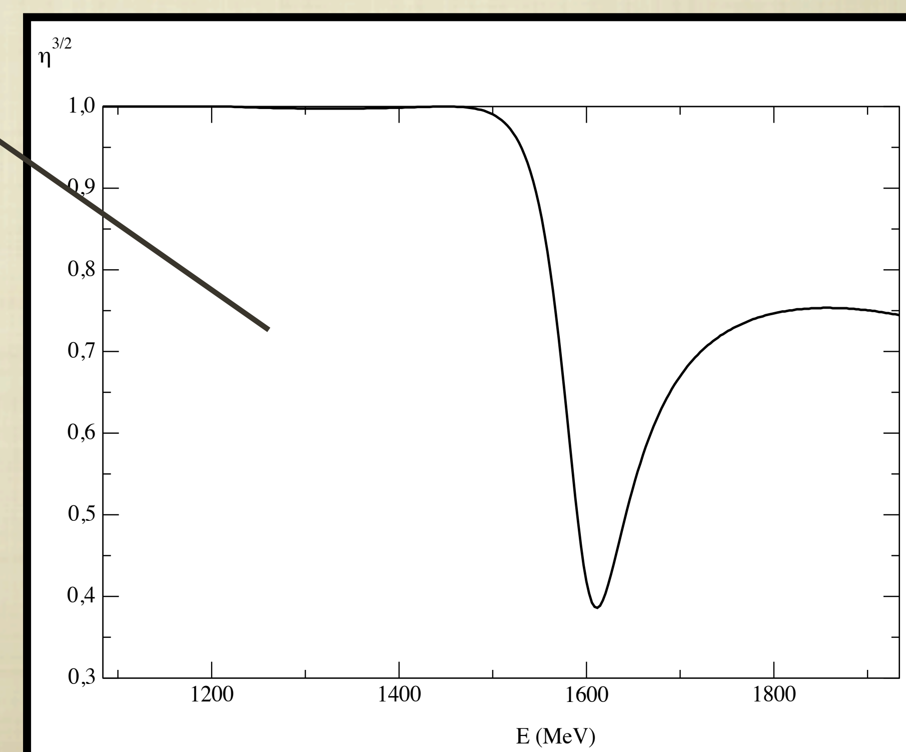




$$f^I = \frac{\eta^I e^{2i\delta^I} - 1}{2iq}$$

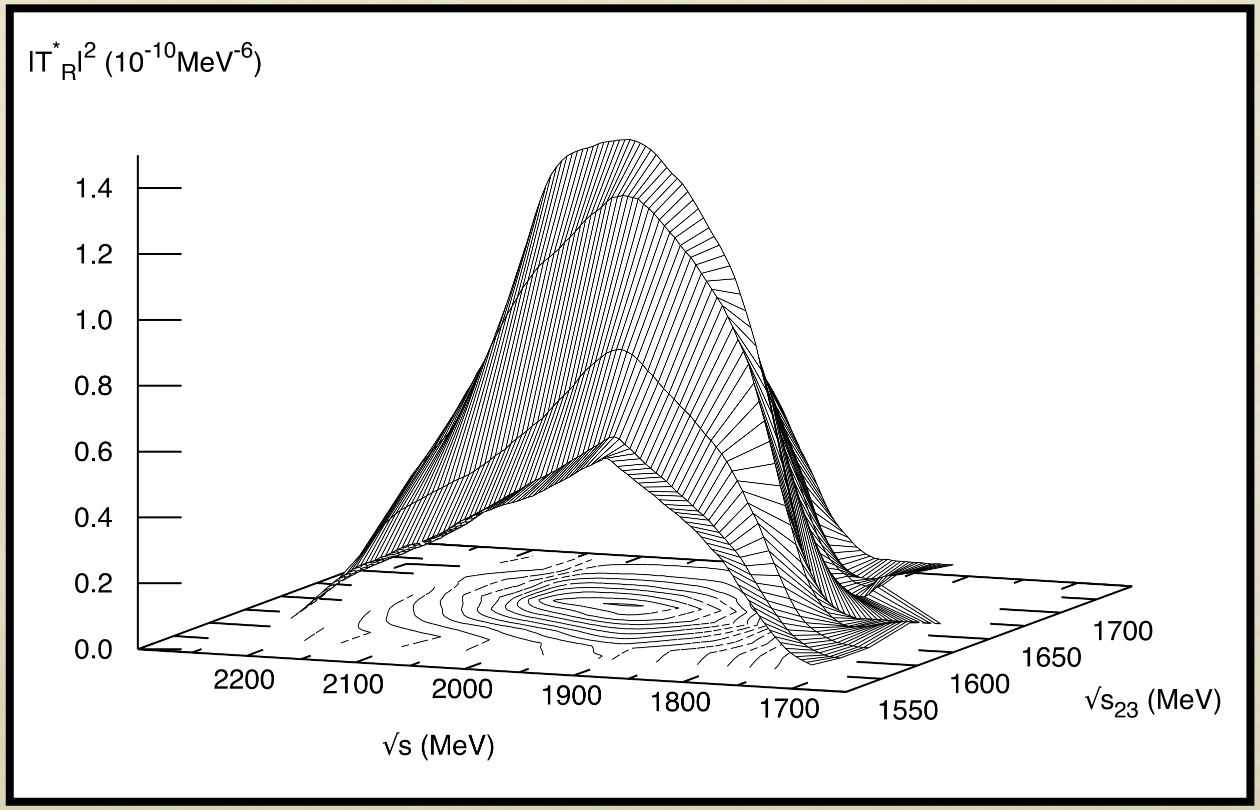
$$t^I = -\frac{4\pi E}{M} f^I, \quad \text{I}=1/2, 3/2$$





- π N INTERACTION
  - → MODEL FOR THE N*(1535) BELOW THRESHOLD.
  - → EXPERIMENTAL RESULTS ABOVE THRESHOLD.
- π π INTERACTION CALCULATED WITH THE MODEL OF NUCL. PHYS. A 620, 438-456, 1997.
- CONSIDERING ONLY THE $\pi\pi$N CHANNELS $\pi^0\pi^0 n, \pi^+\pi^- n, \pi^-\pi^+ n, \pi^0\pi^- p, \pi^-\pi^0 p$

N*(2100) P_{11} [I(J^P)=1/2(1/2$^+$)] *

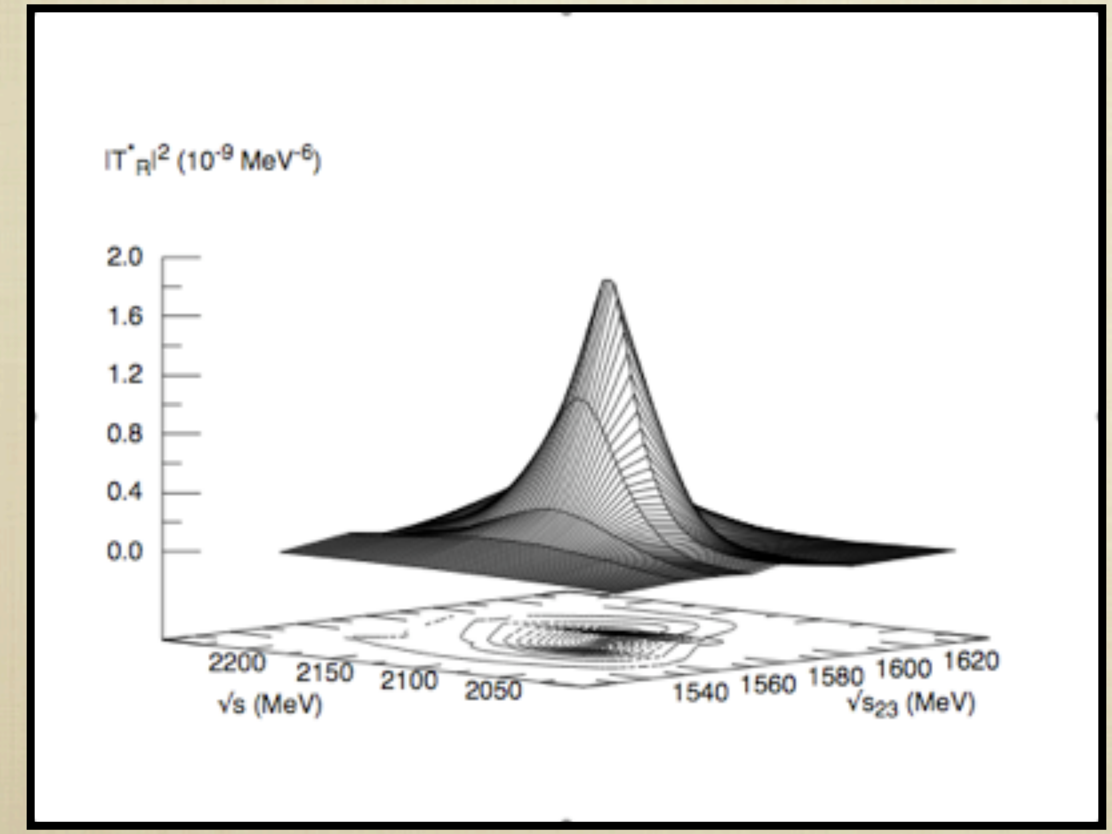


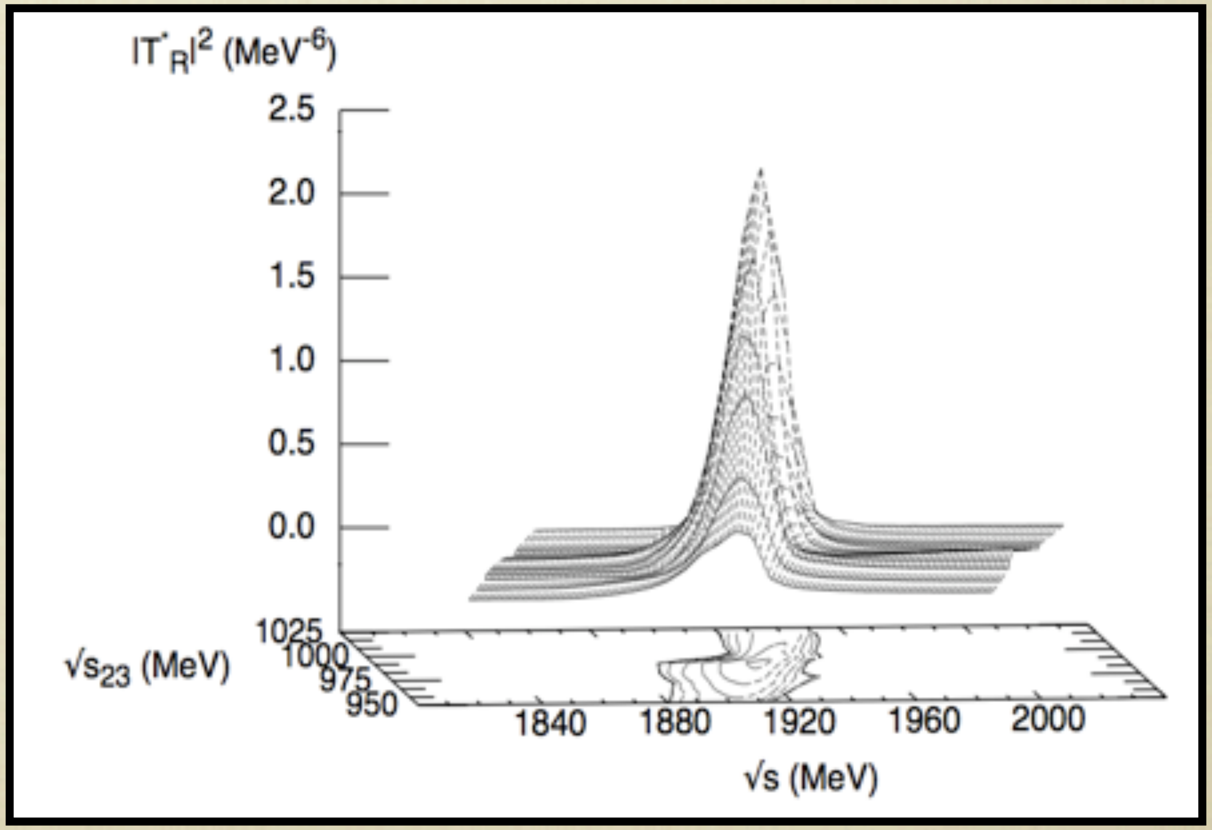
- WE ADD THE $\pi K\Sigma$, $\pi K\Lambda$ AND $\pi\eta N$ CHANNELS $\longrightarrow$ $\Delta(1910)$.

- WE DON'T SEE ANY SIGNAL FOR $\Delta(1750)$.

- WE HAVE STUDY THE $a_0(980)N$, $f_0(980)N$ SYSTEMS BY INCLUDING THE COUPLED CHANNEL $K\bar{K}N$ (D. JIDO AND Y.KANADA-EN'YO, PHYS.REV. C78,035203 (2008)).

$\Delta(1910)$ P_{31} [$I(J^P)=3/2(1/2^+)$] ****





[14] A. MARTÍNEZ TORRES, K. P. KHEMCHANDANI, E. OSET , PHYS.REV.D78, 074031,2008.

Why study the NπK system?

- A peak in the K^+n invariant mass in the $\gamma\, n \rightarrow K^+K^-n$ reaction at the Spring8/Osaka pentaquark

- Chiral Lagrangians: K^+N interaction is repulsive.

$$\downarrow$$

$$\pi K N$$

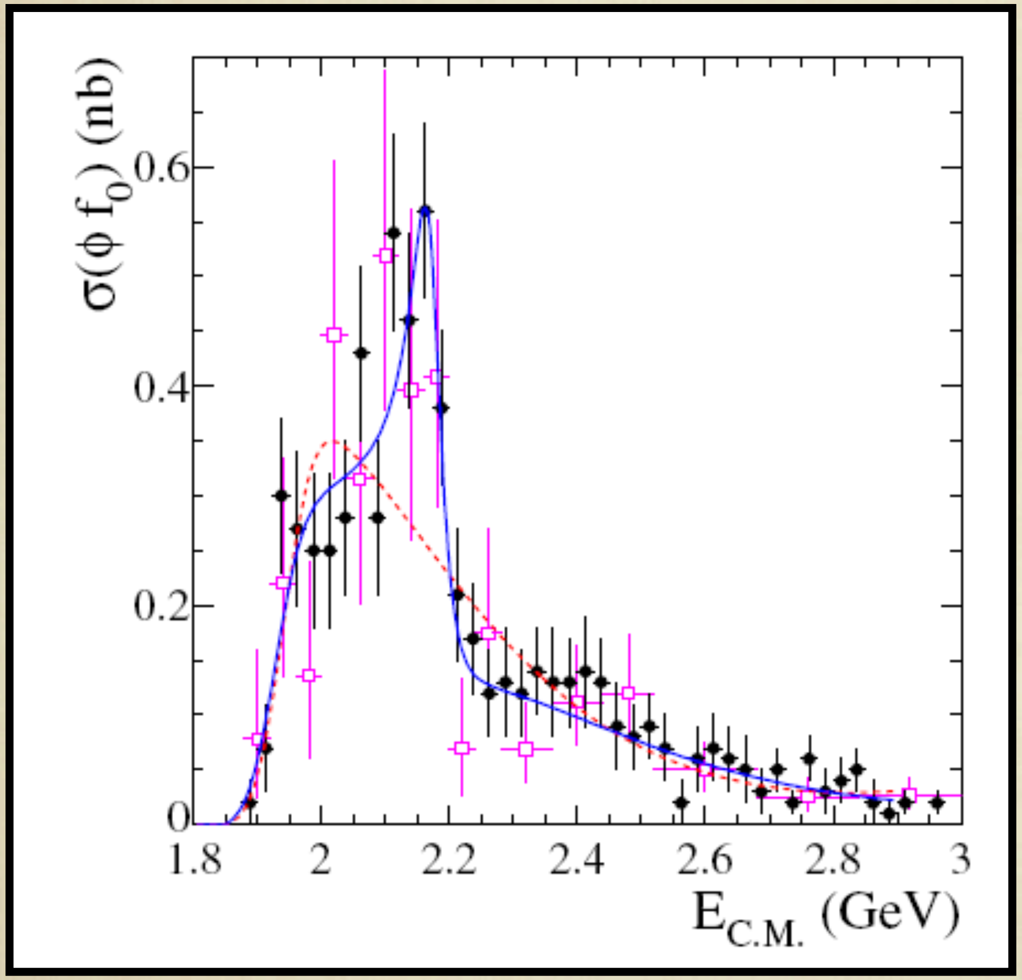
- Some investigations have already been done and the results do not look promising[15,16]

[15] P. Bicudo, G. M. M. Marques, Phys. REV. D 69 011503 (2004).
[16] Felipe J. Llanes-Estrada, E. Oset, V. Mateu, Phys. Rev. C 69 055203 (2004).

Three-meson systems

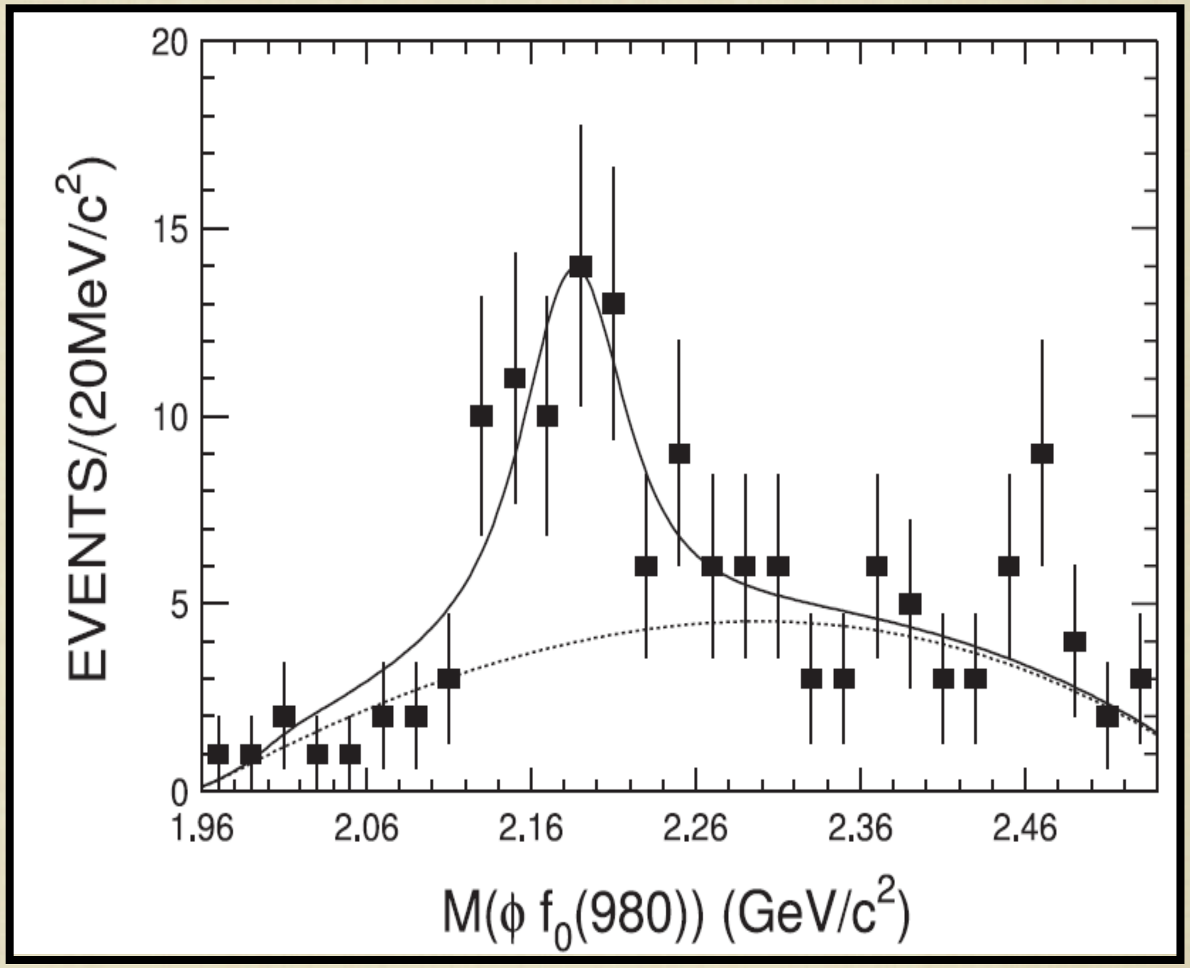
BaBar

$e^+e^- \to \phi f_0(980)$



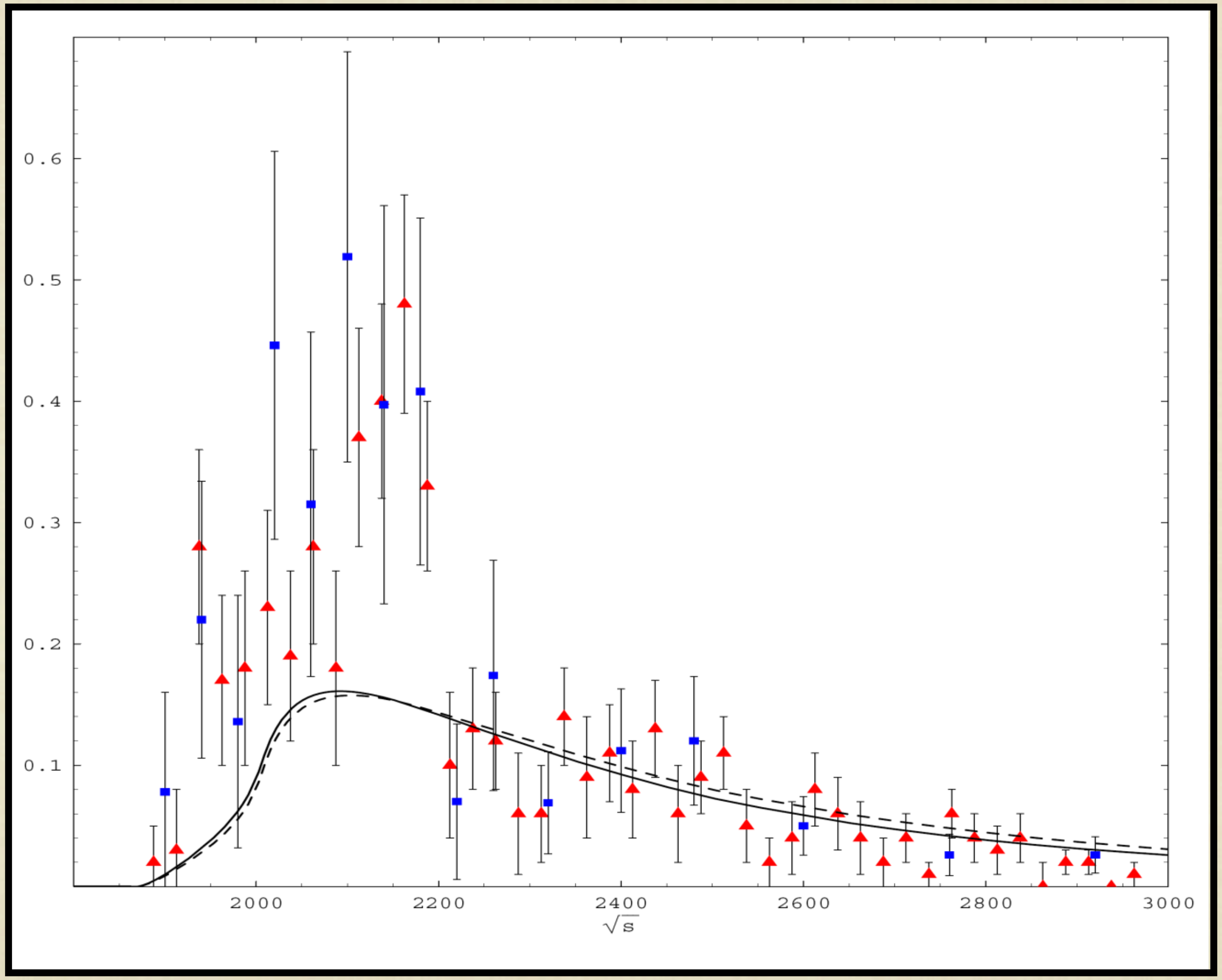
BES

$J/\Psi \to \eta\phi f_0(980)$



$X(2175)$

Theoretical Investigations*



*see a review on different studies (for example) : "New hadron states", Shi-Lin Zhu , Int.J.Mod.Phys.E17:283-322,2008; e-Print: hep-ph/0703225

- We have studied the system $\phi K\bar{K}$, $\phi\pi\pi$.
- We get a peak around 2150 MeV with a width of 27 MeV.

[15] A. Martínez Torres, K. P. Khemchandani, E. Oset , Phys. Rev. D78: 074031,2008

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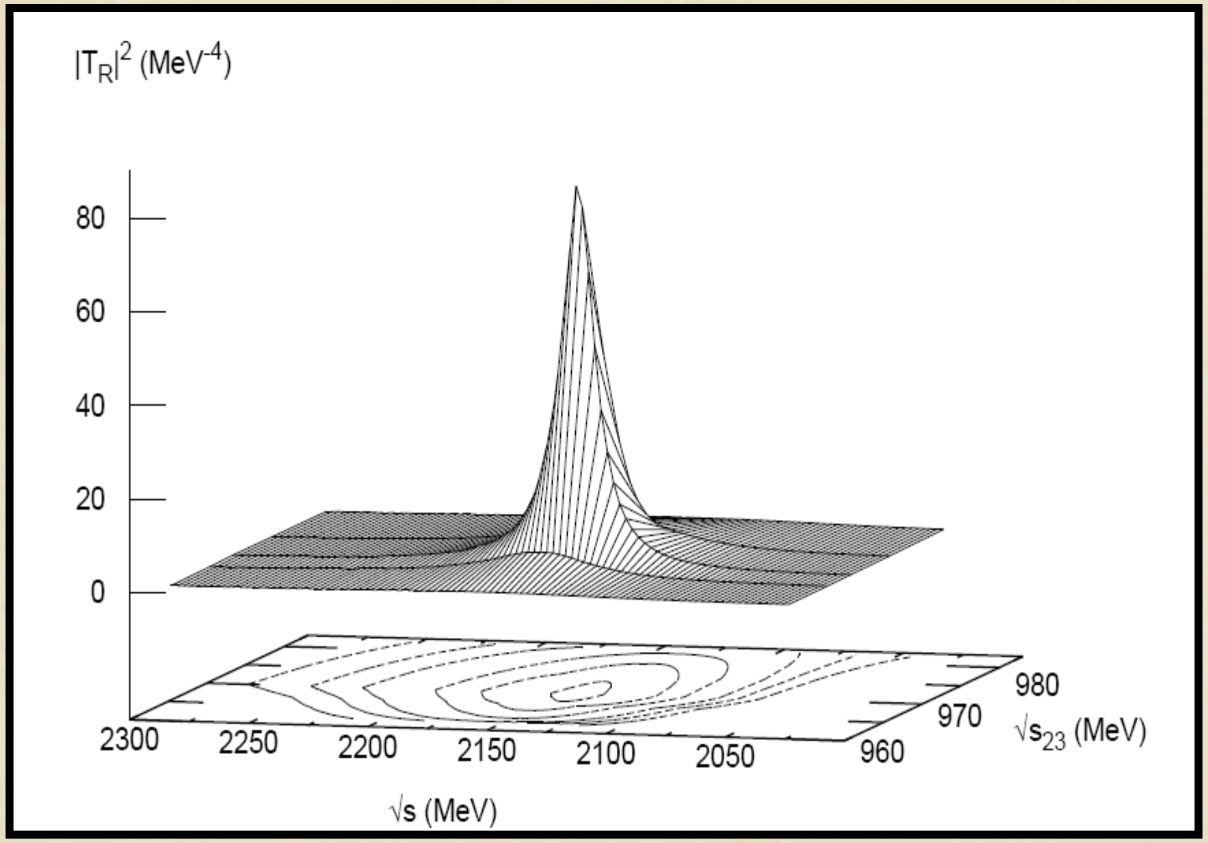

[15] A. Martínez Torres, K. P. Khemchandani, E. Oset , Phys. Rev. D78: 074031,2008

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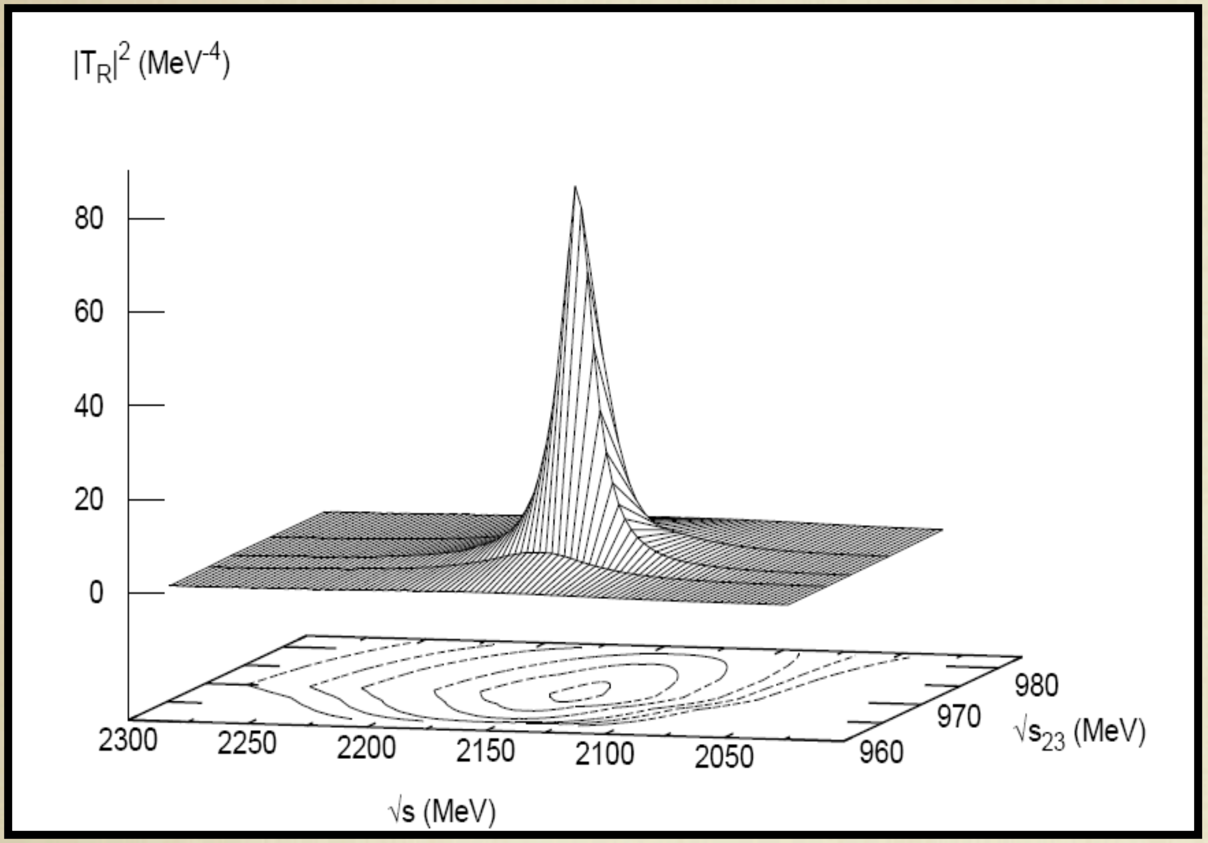

[15] A. Martínez Torres, K. P. Khemchandani, E. Oset , Phys. Rev. D78: 074031,2008

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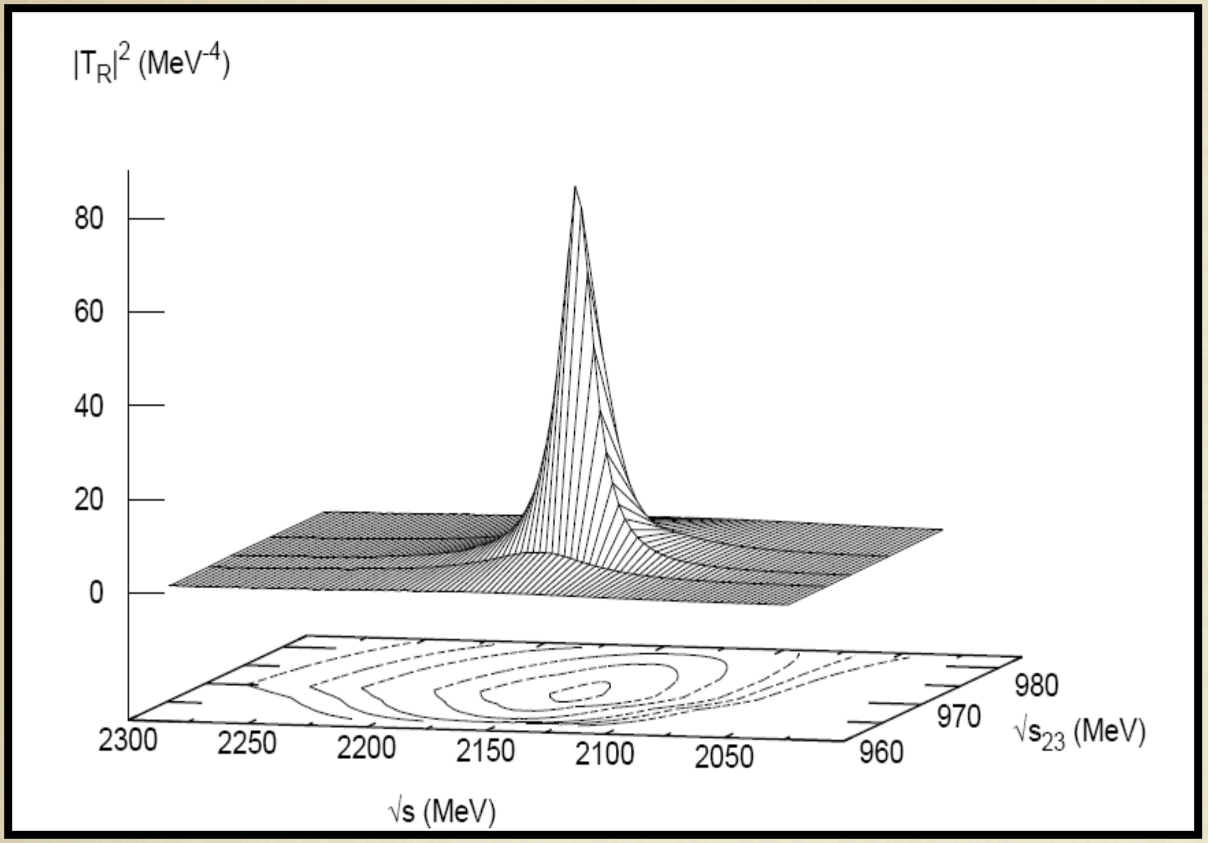

$$T_{pw}^{\phi f_0}[1 + G_{\phi f_0} T_{\phi f_0}]$$

[15] A. Martínez Torres, K. P. Khemchandani, E. Oset , Phys. Rev. D78: 074031,2008

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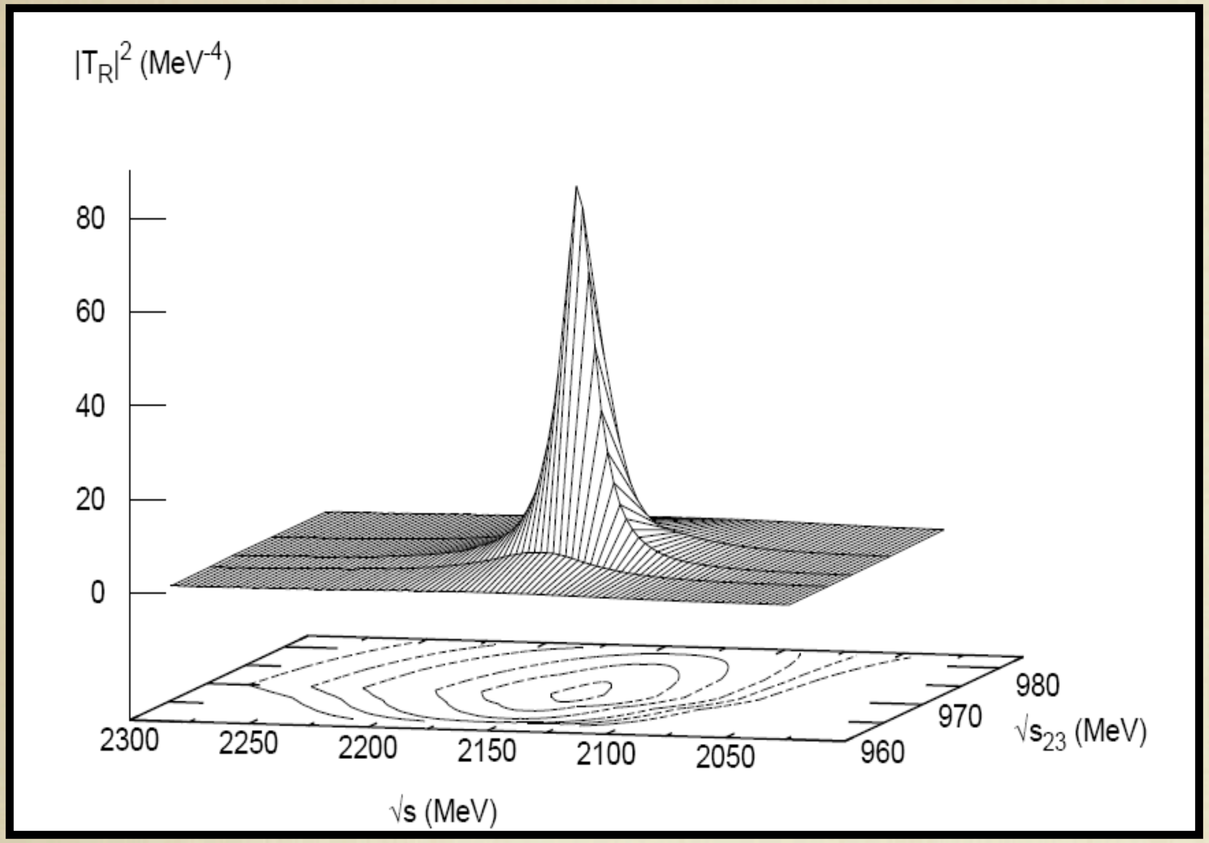
- WE GET A PEAK AROUND 2150 MEV WITH A WIDTH OF 27 MEV.

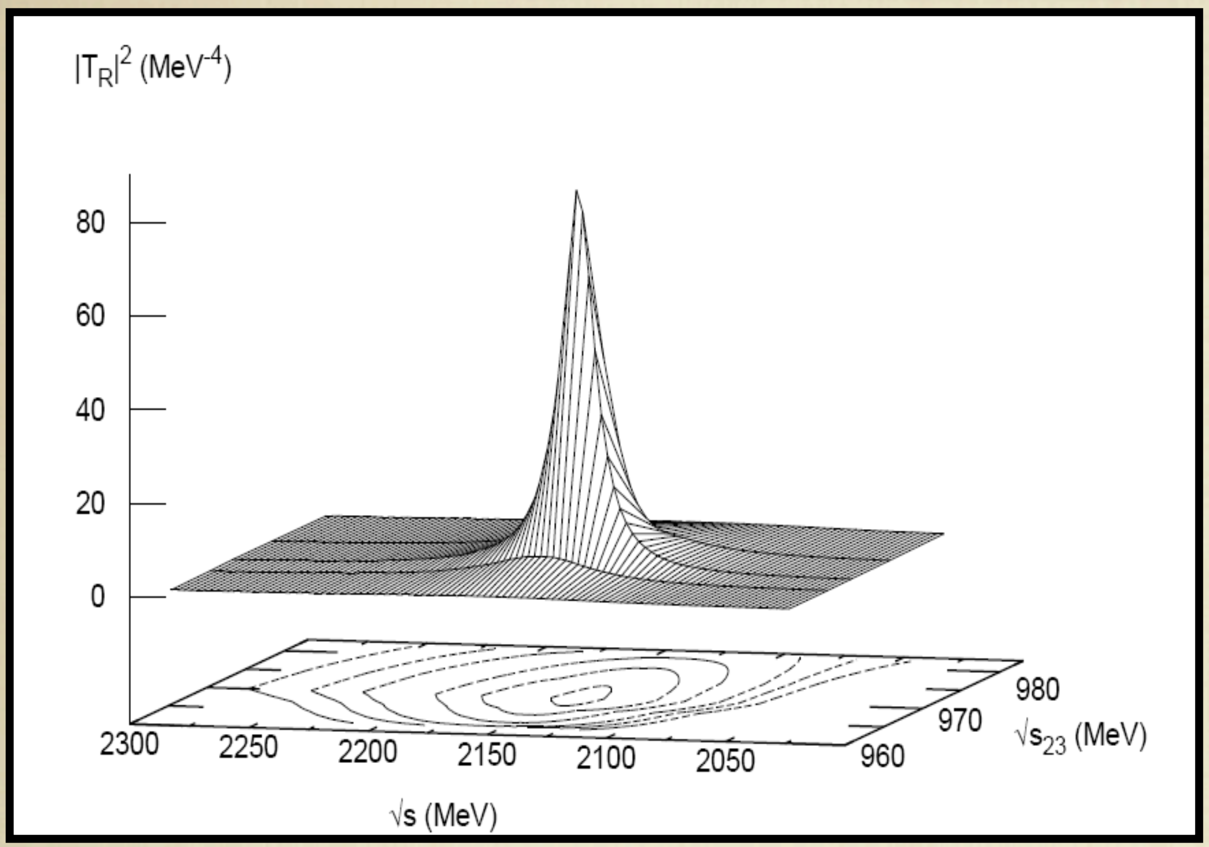


$$T_{pw}^{\phi f_0}[1 + G_{\phi f_0} T_{\phi f_0}]$$

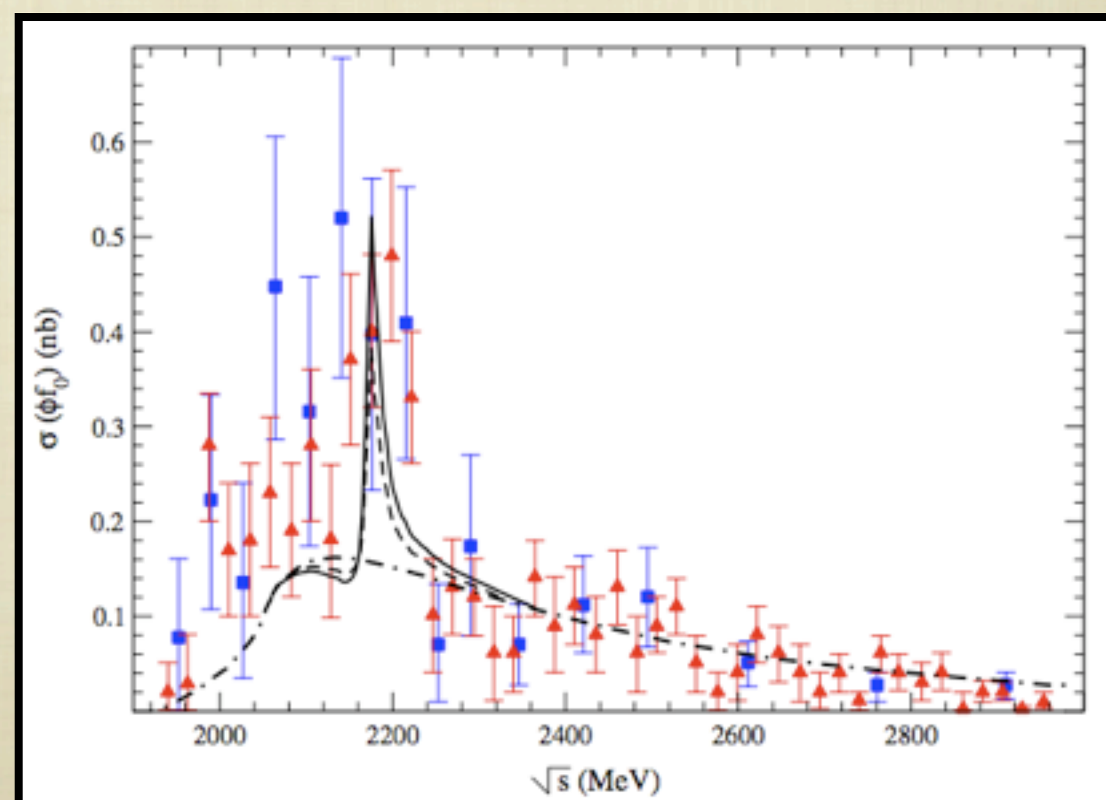
[15] A. MARTÍNEZ TORRES, K. P. KHEMCHANDANI, E. OSET , PHYS. REV. D78: 074031,2008

- **We have studied the system $\phi K\bar{K}$, $\phi\pi\pi$.**

- **We get a peak around 2150 MeV with a width of 27 MeV.**



$$T_{pw}^{\phi f_0}[1 + G_{\phi f_0} T_{\phi f_0}]$$

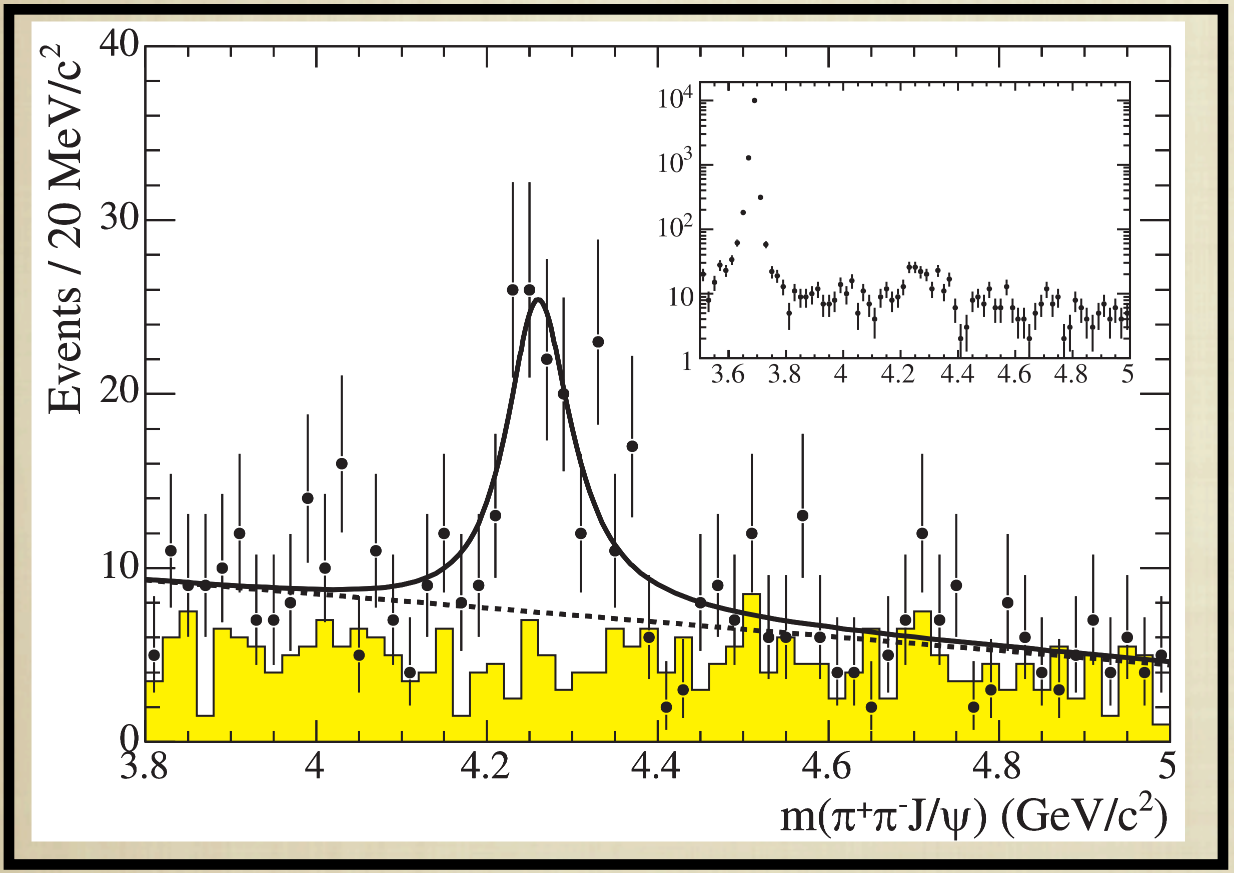


[15] A. Martínez Torres, K. P. Khemchandani, E. Oset , Phys. Rev. D78: 074031,2008

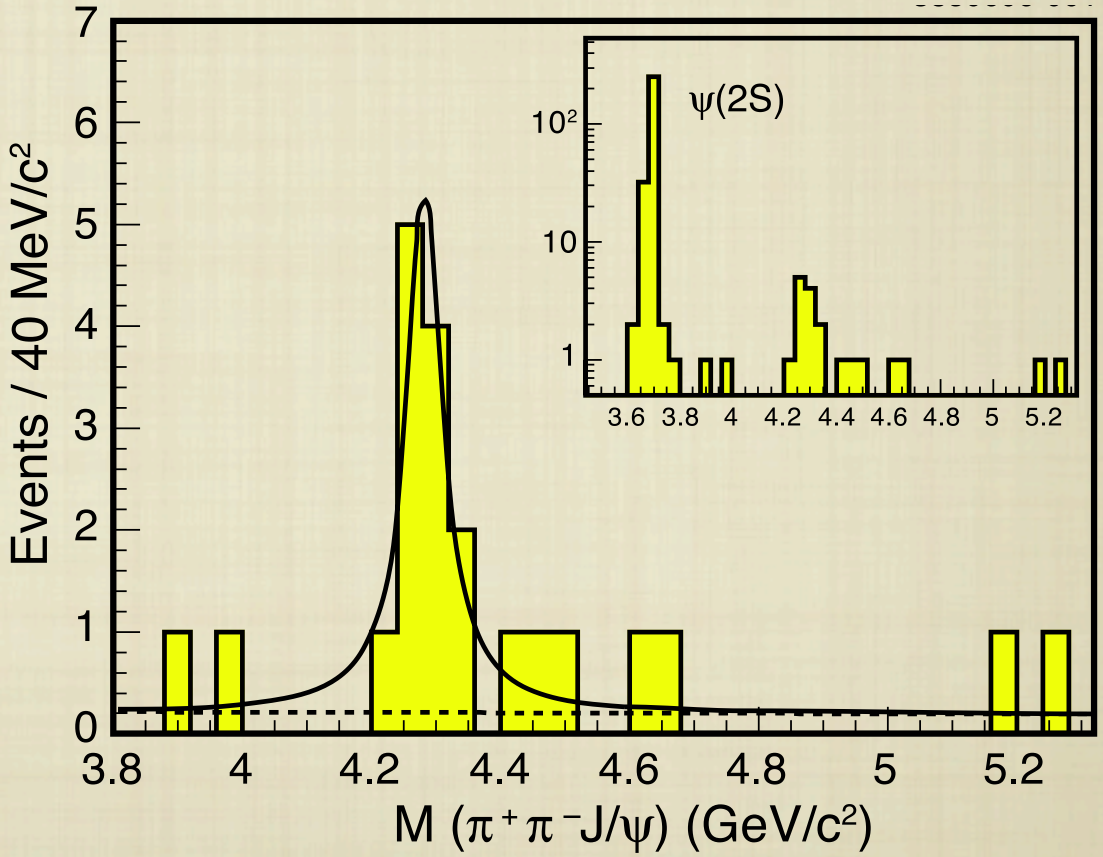
The Y(4260) resonance

- Observed in the reaction $e^+e^- \to \pi^+\pi^- J/\psi$.

BaBar

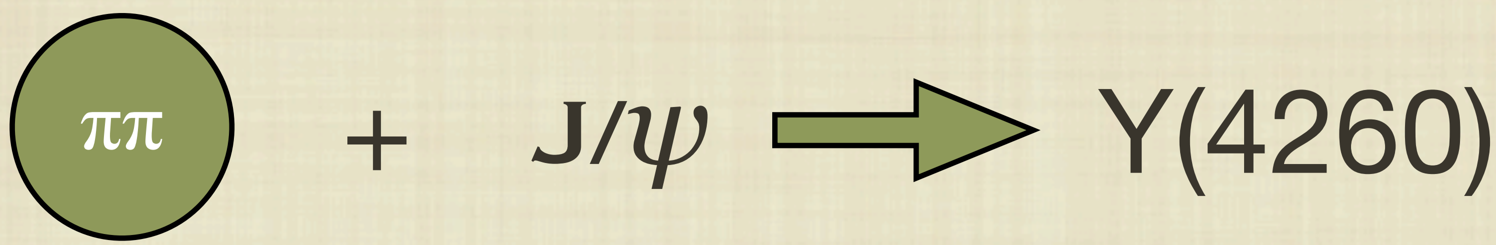


CLEO



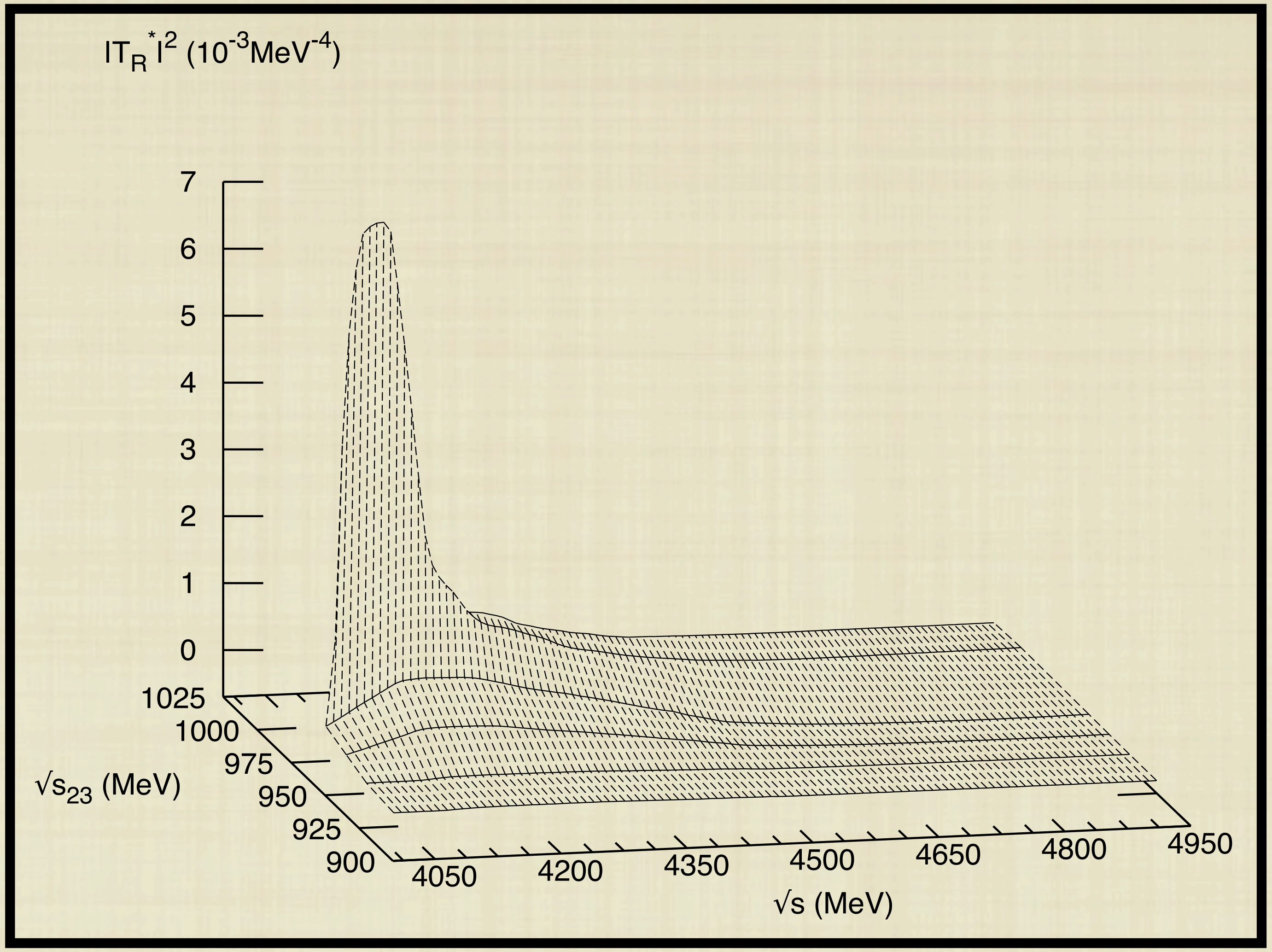
- Enhancement near 1 GeV in the ππ invariant mass.

- Analogy with X(2175) :



f_0(980)

- We consider $J/\psi\pi\pi, J/\psi K\bar{K}$ as coupled channels.



|T_R*|^2 (10^-3 MeV^-4)
7
6
5
4
3
2
1
0
1025
1000
975
950
925
900
√s23 (MeV)
4050
4200
4350
4500
4650
4800
4950
√s (MeV)

Summary and Future plans

- We have obtained four Σ's and two Λ's resonances in the $\pi\bar{K}N$, which correspond to all the $1/2^+$ Σ and Λ states in the energy region 1500-1870.
- We observed the N*(1710), N*(2100), Δ(1910) in the $\pi\pi$N system and coupled channels and a possible N*(1910) with $J^P=1/2^+$ in the $K\bar{K}N$ system .
- We have studied the three-meson systems, $\phi K\bar{K}$, $\phi\pi\pi$, where we got the resonance X(2175) .
- A broad bump is obtained in the study of the πKN system around 1700 MeV.
- In the $J/\psi K\bar{K}$, $J/\psi\pi\pi$ systems we obtain the Y(4260).
- Study of the systems $\omega\pi\pi, \rho\pi\pi, K^*\pi K, etc.$, to get the low-lying vector resonances as w(1420), w(1650),etc.

And many more!!