Sequential single pion production explaining the ”dibaryon d*(2380)” peak

E. Oset, N. Ikeno, R. Molina IFIC, U. Valencia- CSIC

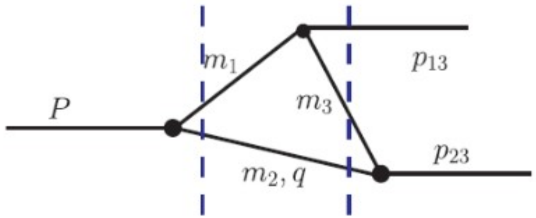
Triangle singularities

TS in the pp → π^+ d reaction

A new interpretation of the “d*(2380) dibaryon” peak

Triangle singularities: Introduced by Landau

L. D. Landau, Nucl. Phys. **13**, 181 (1959).



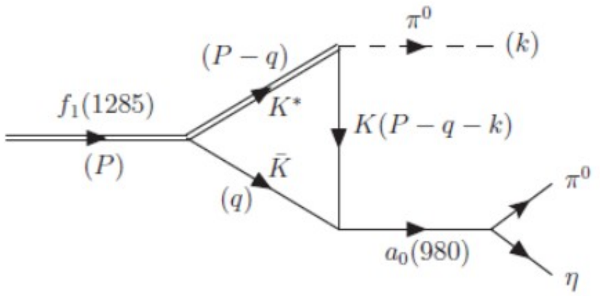
Some reaction mechanism involve a Feynman diagram with a loop of three particles. Sometimes this mechanism develops a singularity (becomes infinity) .

No experimental confirmation was found at that time

Nowadays we find many experimental cases

The search goes on….

THE $\pi a_0(980)$ DECAY MODE OF THE $f_1(1285)$



$$t_T = i \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \vec{\epsilon}_{f_1} \cdot \vec{\epsilon}_{K^*}\, \vec{\epsilon}_{K^*} \cdot (2\vec{k} + \vec{q}) \frac{1}{q^2 - m_K^2 + i\epsilon} \frac{1}{(P-q)^2 - m_{K^*}^2 + i m_{K^*}\Gamma_{K^*}} \frac{1}{(P-q-k)^2 - m_K^2 + i\epsilon}$$

$$\widetilde{t}_T = \int \frac{\mathrm{d}^3 q}{(2\pi)^3} \left(2 + \frac{\vec{k}\cdot\vec{q}}{\vec{k}^2}\right) \frac{1}{8\,\omega(q)\omega'(q)\omega^*(q)} \frac{1}{k^0 - \omega'(q) - \omega^*(q) + i\epsilon} \frac{1}{P^0 - \omega^*(q) - \omega(q) + i\epsilon}$$
$$\times \frac{2P^0\omega(q) + 2k^0\omega'(q) - 2(\omega(q)+\omega'(q))(\omega(q)+\omega'(q)+\omega^*(q))}{(P^0 - \omega(q) - \omega'(q) - k^0 + i\epsilon)(P^0 + \omega(q) + \omega'(q) - k^0 - i\epsilon)},$$

$$\omega(q) = \sqrt{\vec{q}^{\,2} + m_K^2},\ \omega'(q) = \sqrt{(\vec{q}+\vec{k})^2 + m_K^2},\ \omega^*(q) = \sqrt{\vec{q}^{\,2} + m_{K^*}^2}$$

Poles in the integration

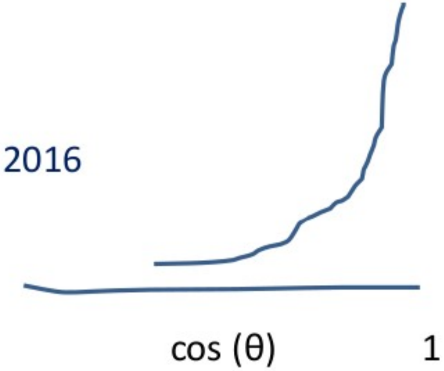
$$P^0 - \omega^*(q) - \omega(q) + i\epsilon = 0, \qquad q_{\text{on}+} = q_{\text{on}} + i\,\epsilon \quad \text{with} \quad q_{\text{on}} = \frac{1}{2M}\sqrt{\lambda(M^2, m_1^2, m_2^2)}$$

$$P^0 - \omega(q) - \omega'(q) - k^0 + i\epsilon = 0$$

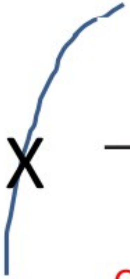
$$P^0 - \omega(q) - \omega'(q) - k^0 + i\epsilon \quad = \quad 0 \qquad \omega'(q) \; = \; \sqrt{(\vec{q}+\vec{k})^2 + m_K^2}$$

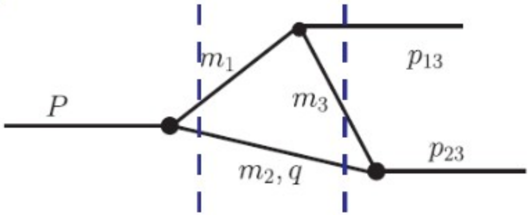
If we fix cos (θ)= ± 1 and we make this expression zero, then in the integral of cos(θ) one cannot cancel the divergence with the principal value, and the divergence remains. Θ is the angle between $\vec{k}$ and $\vec{q}$.

Bayar, Aceti, Guo, E. O, PRD 2016



For cos(θ)=-1





Calculate solution when p_{23} is at rest (p_2*) and make a boost

$$q_{a+} = \gamma\,(v\,E_2^* + p_2^*) + i\,\epsilon\,, \qquad q_{a-} = \gamma\,(v\,E_2^* - p_2^*) - i\,\epsilon$$

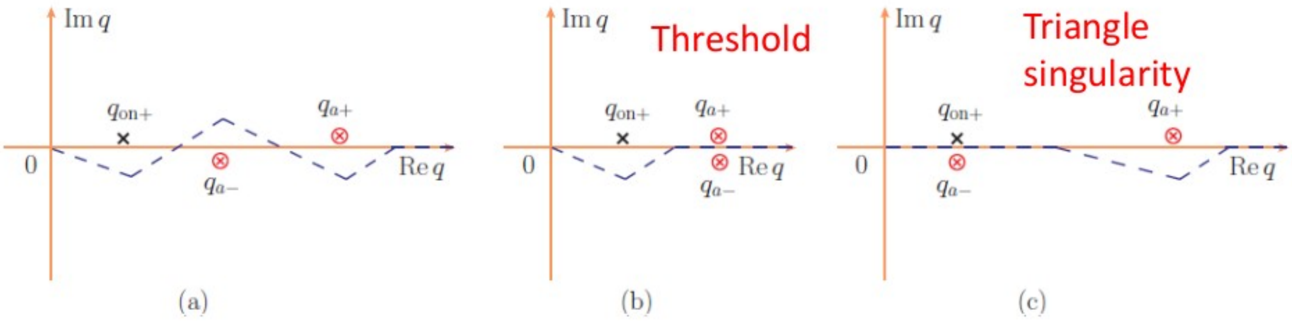
$$v = \frac{k}{E_{23}}, \qquad \gamma = \frac{1}{\sqrt{1-v^2}} = \frac{E_{23}}{m_{23}},$$

$$E_2^* = \frac{1}{2m_{23}}\left(m_{23}^2 + m_2^2 - m_3^2\right), \qquad p_2^* = \frac{1}{2m_{23}}\sqrt{\lambda(m_{23}^2, m_2^2, m_3^2)}$$

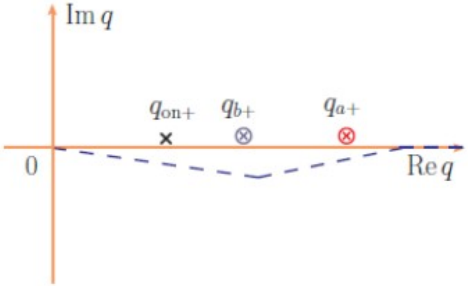
For cos(θ)=1

$$q_{b+} = \gamma\,(-v\,E_2^* + p_2^*) + i\,\epsilon\,, \qquad q_{b-} = -\gamma\,(v\,E_2^* + p_2^*) - i\,\epsilon$$

For cos(θ)=-1



For cos(θ)=1



Triangle singularity

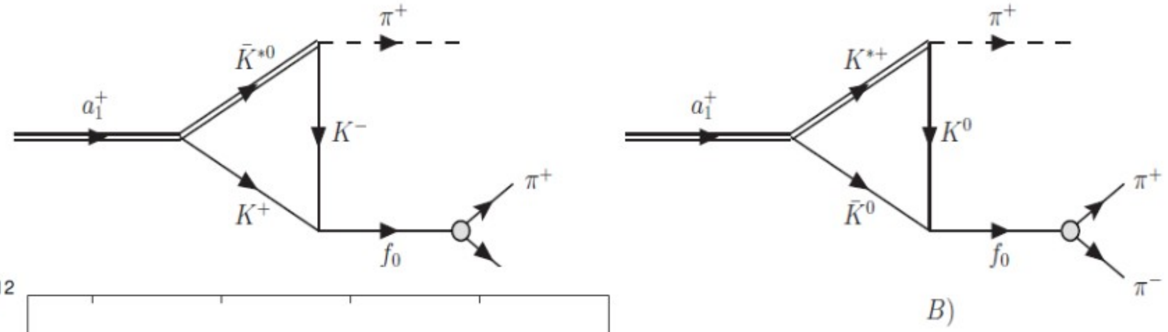
$$\lim_{\epsilon \to 0} (q_{on+} - q_{a-}) = 0$$

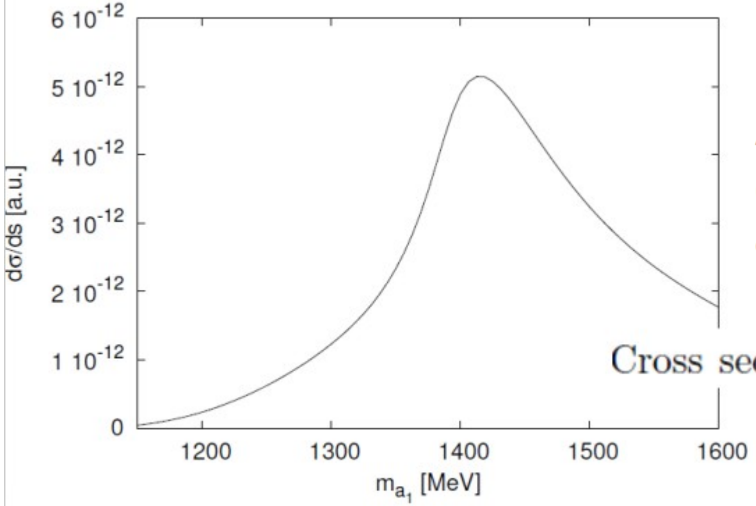
Very simple expression to see where the TS appears , and to explain the Coleman-Norton theorem, Nuovo Cim. 1965, (TS appears when the decays in the loop can occur at the classical level).

These results are a replica of what was found for the "a_1(1420)"

In M. Mikhasenko, B. Ketzer, A. Sarantsev, PRD 2015
F. Aceti, L.R. Dai, E. O., PRD 2016
suggested in X.H. Liu, M. Oka, Q. Zhao, PLB 2016

The "a1(1420)" peak is a manifestation of the decay of the a_1(1260) into π f_0(980)





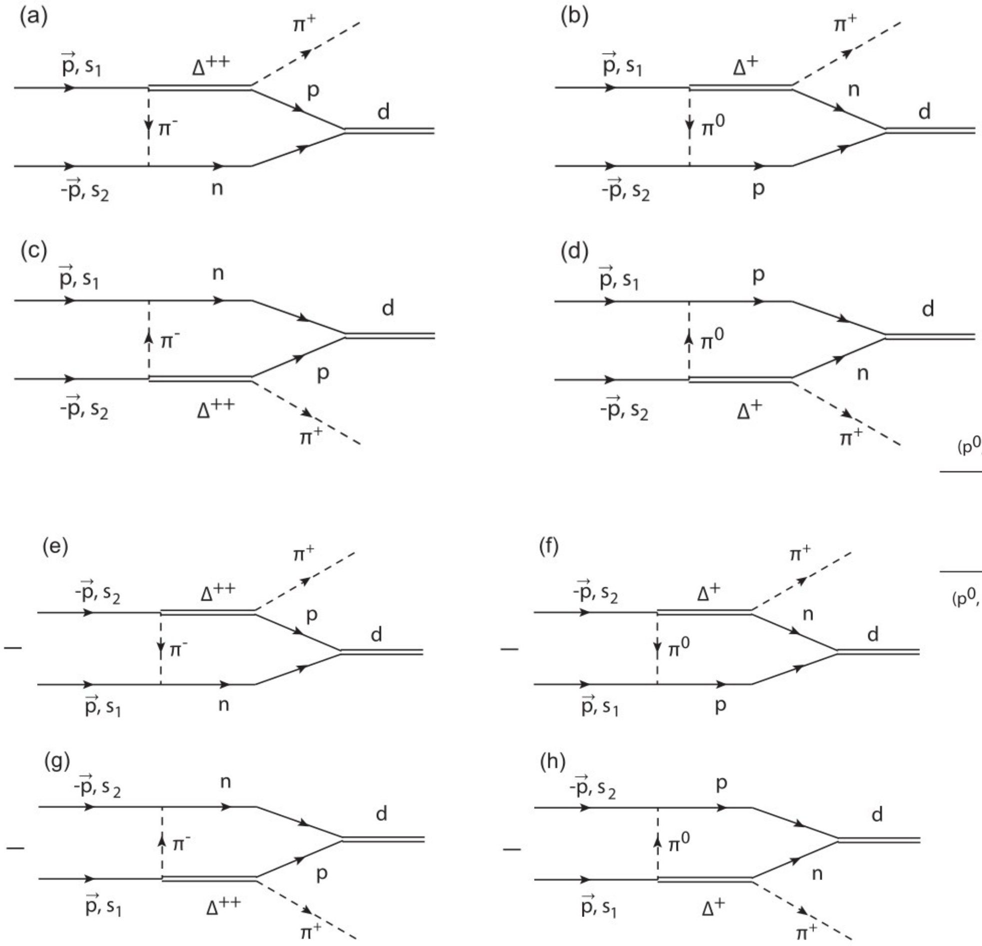
Cross section for the decay $a_1^+(1260) \to \pi^+ f_0(980)$

A Triangle Singularity as the Origin of the $a_1(1420)$

COMPASS Collaboration • M.G. Alexeev (Turin U. and INFN, Turin) et al. (Jun 9, 2020)

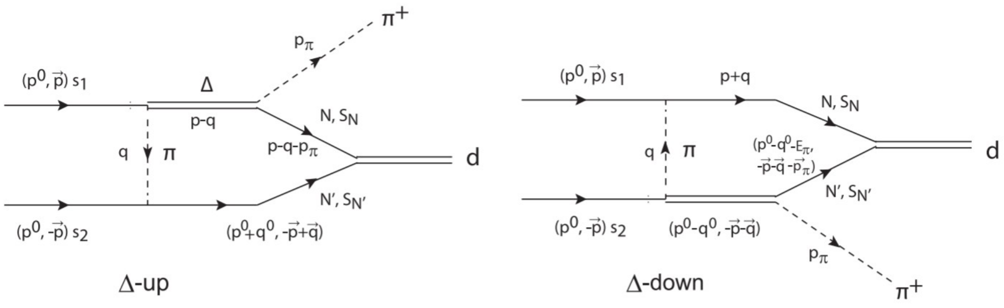
e-Print: 2006.05342 [hep-ph]

The pp → π⁺ d reaction   N. Ikeno, R. Molina, E. Oset, arXiv 2103.01712



$$-i\delta H_{\pi NN} = \frac{f}{m_\pi}\vec{\sigma}\cdot\vec{q}\;\tau^{\lambda}; \qquad f = 1.00,$$

$$-i\delta H_{\pi N\Delta} = \frac{f^*}{m_\pi}\vec{S}^{\dagger}\cdot\vec{q}\;T^{\dagger\lambda}; \qquad f^* = 2.13,$$



The triangle singularity condition is found at √s=2179 MeV

The time reversed reaction was much studied in the past, using a Quantum Mechanics formalism, not Field Theory, and the triangle singularity was not identified.

It explains why the cross section is much bigger than expected for fusion reactions.

Pionic Disintegration of the Deuteron

D.O. Riska (Michigan State U.), M. Brack (SUNY, Stony Brook), W. Weise (SUNY, Stony Brook) (1976)

Published in: *Phys.Lett.B* 61 (1976) 41-44

P Wave Meson Production in p p --> d pi+

Anthony M. Green (Helsinki U.), J.A. Niskanen (Helsinki U.) (1976)

Published in: *Nucl.Phys.A* 271 (1976) 503-524

Pionic Disintegration of the Deuteron

M. Brack (SUNY, Stony Brook), D.O. Riska (Michigan State U.), W. Weise (Regensburg U.) (1977)

Published in: *Nucl.Phys.A* 287 (1977) 425-450

A covariant theory of the pionic disintegration of the deuteron

D. Schiff, J. Tran Thanh Van (1968)

Published in: *Nucl.Phys.B* 5 (1968) 529-559

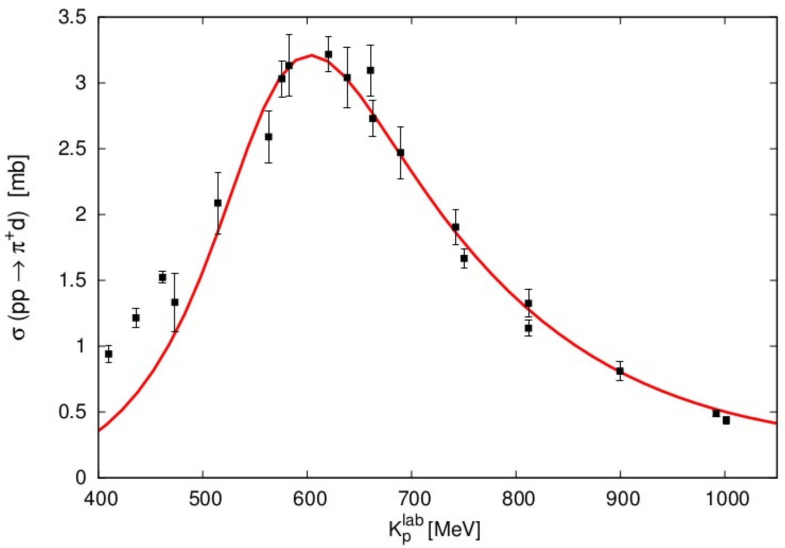
$$
\begin{aligned}
-it^{\pi} &= -g_d \frac{4\sqrt{2}}{3}\left(\frac{f^*}{m_\pi}\right)^2 \left(\frac{f}{m_\pi}\right) \int \frac{d^3q}{(2\pi)^3}\left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + \vec{q}^{\,2}}\right)^2 \\
&\cdot \left\{ \vec{S}_1 \cdot \vec{p}_\pi \; \vec{S}_1 \cdot \vec{q} \; \vec{\sigma}_2 \cdot \vec{q} \; F(\vec{p}, \vec{q}, \vec{p}_\pi) \; - \vec{\sigma}_1 \cdot \vec{q} \; \vec{S}_2 \cdot \vec{p}_\pi \; \vec{S}_2^\dagger \cdot \vec{q} \; F(-\vec{p}, \vec{q}, \vec{p}_\pi) \right\}
\end{aligned}
$$

$$
\begin{aligned}
F(\vec{p}, \vec{q}, \vec{p}_\pi) &= \frac{M_N}{E_N(-\vec{p}+\vec{q})} \frac{M_N}{E_N(\vec{p}-\vec{q}-\vec{p}_\pi)} \frac{M_\Delta}{E_\Delta(\vec{p}-\vec{q})} \frac{1}{2\omega(q)} \frac{1}{2p^0 - E_\pi - E_N(-\vec{p}+\vec{q}) - E_N(\vec{p}-\vec{q}-\vec{p}_\pi) + i\epsilon} \\
&\cdot \left\{ \frac{1}{p^0 - \omega(q) - E_\Delta(\vec{p}-\vec{q}) + i\frac{\Gamma_\Delta}{2}} \frac{1}{p^0 - \omega(q) - p_\pi^0 - E_N(\vec{p}-\vec{q}-\vec{p}_\pi) + i\epsilon} \right. \\
&+ \frac{1}{p^0 - \omega(q) - E_\Delta(\vec{p}-\vec{q}) + i\frac{\Gamma_\Delta}{2}} \frac{1}{2p^0 - E_\Delta(\vec{p}-\vec{q}) - E_N(-\vec{p}+\vec{q}) + i\frac{\Gamma_\Delta}{2}} \\
&\left. + \frac{1}{p^0 - \omega(q) - E_N(-\vec{p}+\vec{q}) + i\epsilon} \frac{1}{2p^0 - E_\Delta(\vec{p}-\vec{q}) - E_N(-\vec{p}+\vec{q}) + i\frac{\Gamma_\Delta}{2}} \right\} \cdot \theta(q_{\max} - |\vec{p} - \vec{q} - \frac{\vec{p}_\pi}{2}|).
\end{aligned}
$$

g_d is the coupling of NN to the deuteron together with the θ(.) function.

q_{max} is chosen such as to reproduce the np triplet scattering length.

ρ exchange is also taken into account and reduces the π exchange contribution.



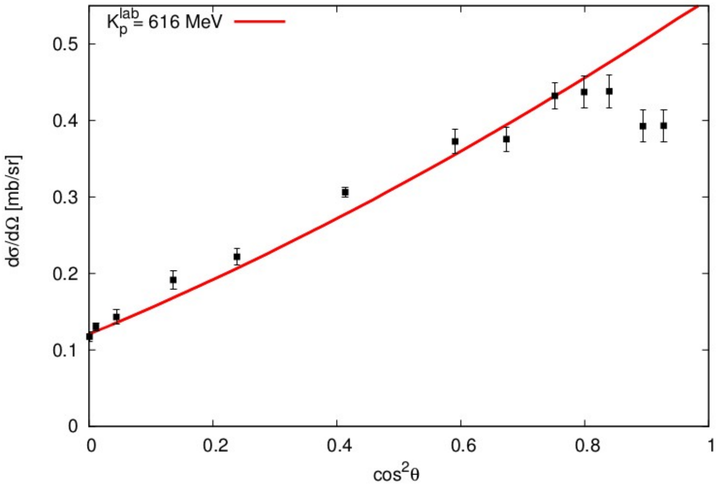
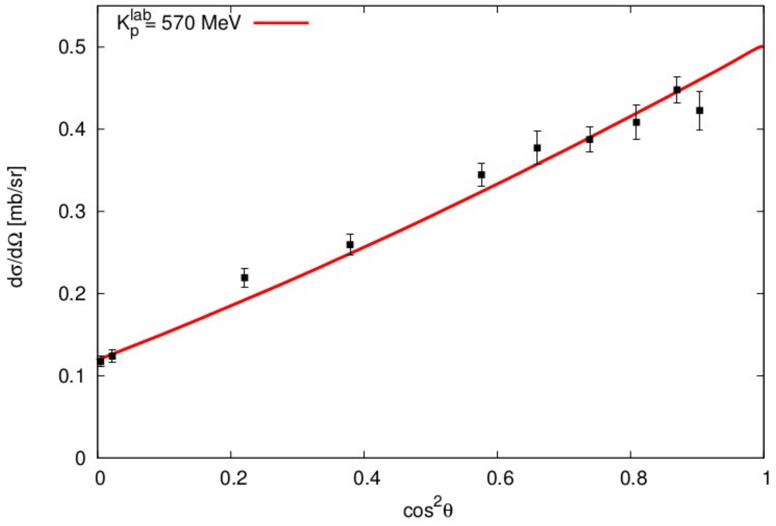
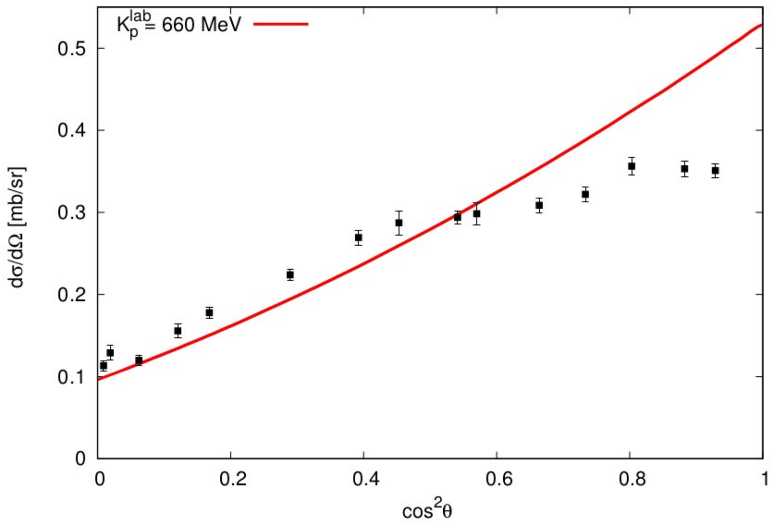
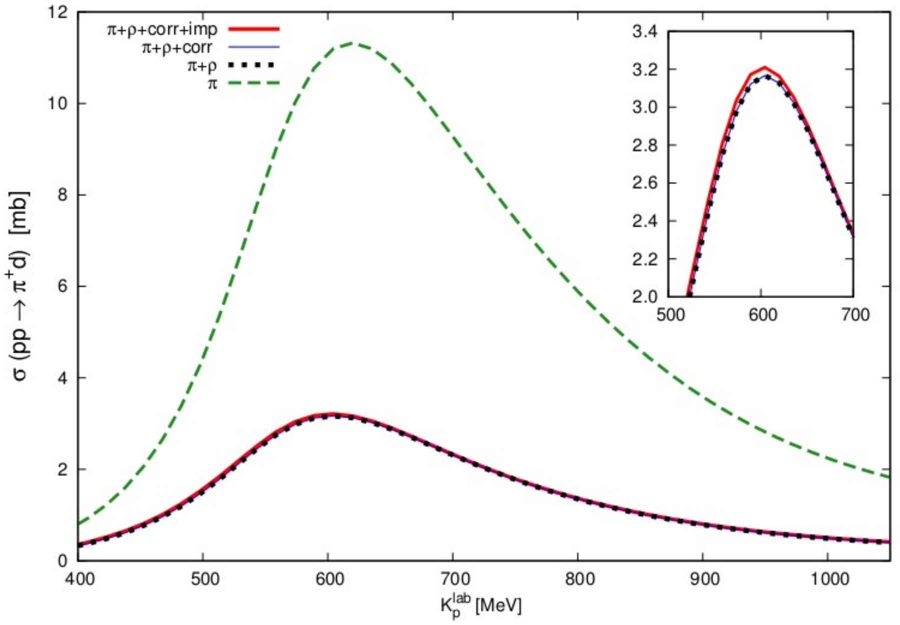


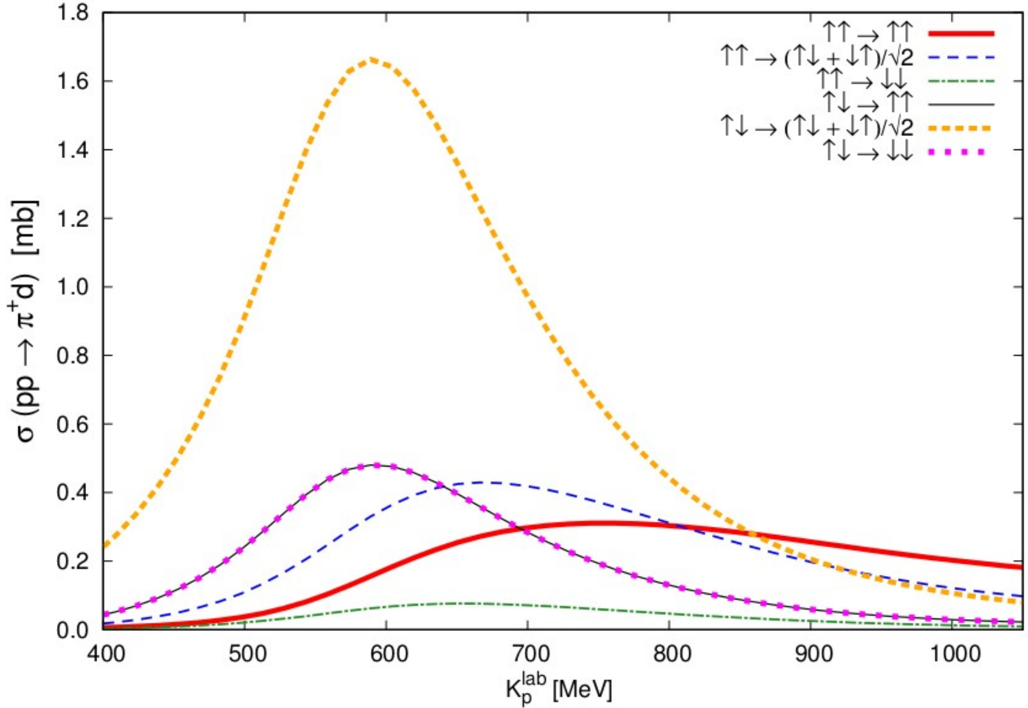
FIG. 6: $d\sigma/d\Omega = \frac{1}{2\pi}\frac{d\sigma}{d\cos\theta_\pi}$ as a function of $\cos^2\theta_\pi$ for $K_p^{\rm lab} = 616$ MeV.

Data from Richard-Serre et al. , NP B 20, 413 (1970)









Note the dominance of $\uparrow\downarrow \rightarrow \frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow)$

But we see that the initial state is

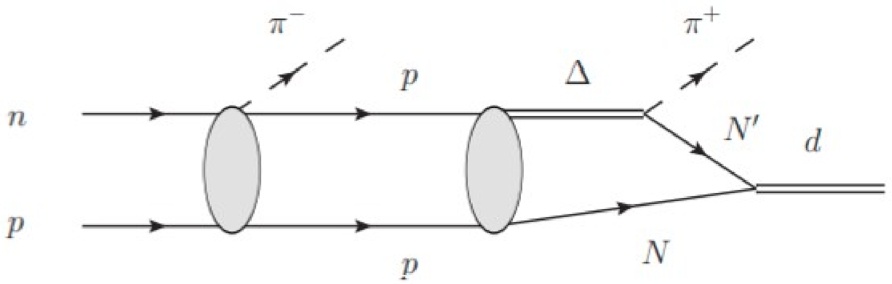
$\frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$ S=0 for pp

And also find L=2 dominance in pp, in agreement with experiment Albrow et al. PLB 34 (1971) 337

Sequential single pion production explaining the dibaryon "$d^*(2380)$" peak

R. Molina,[1,*] Natsumi Ikeno,[1,2,†] and Eulogio Oset[1,‡]

Arxiv 2102.05575



Plus π^+ π^- with n n intermediate states

Idea taken from

Analysis of the reaction n p ---> d pi+ pi- below 3.5 gev/c

#11

I. Bar-Nir (Heidelberg U.), E. Burkhardt (Heidelberg U.), H. Filthuth (Heidelberg U.), H. Oberlack (Heidelberg U.), A. Putzer (Heidelberg U.) et al. (1973)

Published in: *Nucl.Phys.B* 54 (1973) 17-28

An on shell approximation was done, suggesting that this should be improved in the future. We prove that it is quite good, but go beyond.

With some good approximations we find:

$$\sigma_{np\to\pi^+\pi^-p} = \frac{M_{\rm inv}(p_1p_1')}{6\pi}\,\frac{\sigma^I_{np\to NN\pi}\,\sigma_{pp\to\pi^+d}}{M_{\rm inv}(\pi\pi)}\,\frac{\tilde{p}_1^2}{p_\pi p_\pi'}\,p_d\tilde{p}_\pi$$

The $\pi^+ \pi^-$ move mainly with small M_{inv} because they behave as identical particles in I=0 and Bose statistics favors this situation.

$$\frac{d\sigma_{np\to\pi^+\pi^-d}}{dM_{\text{inv}(\pi^+\pi^-)}} = \sigma_{np\to\pi^+\pi^-d}\,\delta(M_{\text{inv}}(\pi^+\pi^-) - \bar{M}_{\pi\pi})$$

$$E_{2\pi} = \frac{s + M^2_{\text{inv}}(\pi\pi) - M_d^2}{2\sqrt{s}}$$

$$\delta\bar{M}_{\pi\pi},\ \bar{M}_{\pi\pi} = 2m_\pi + \delta\bar{M}_{\pi\pi}$$

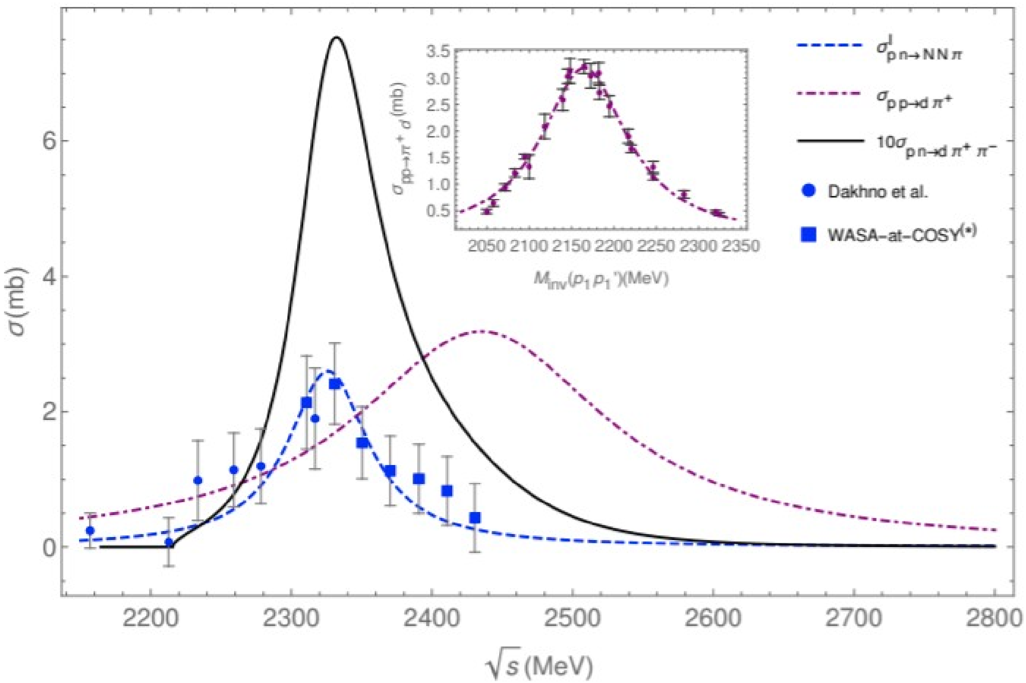
$$M^2_{\text{inv}}(p_1 p'_1) = (P(np) - p_{\pi^-})^2 = s + m_\pi^2 - 2\sqrt{s}E_\pi$$

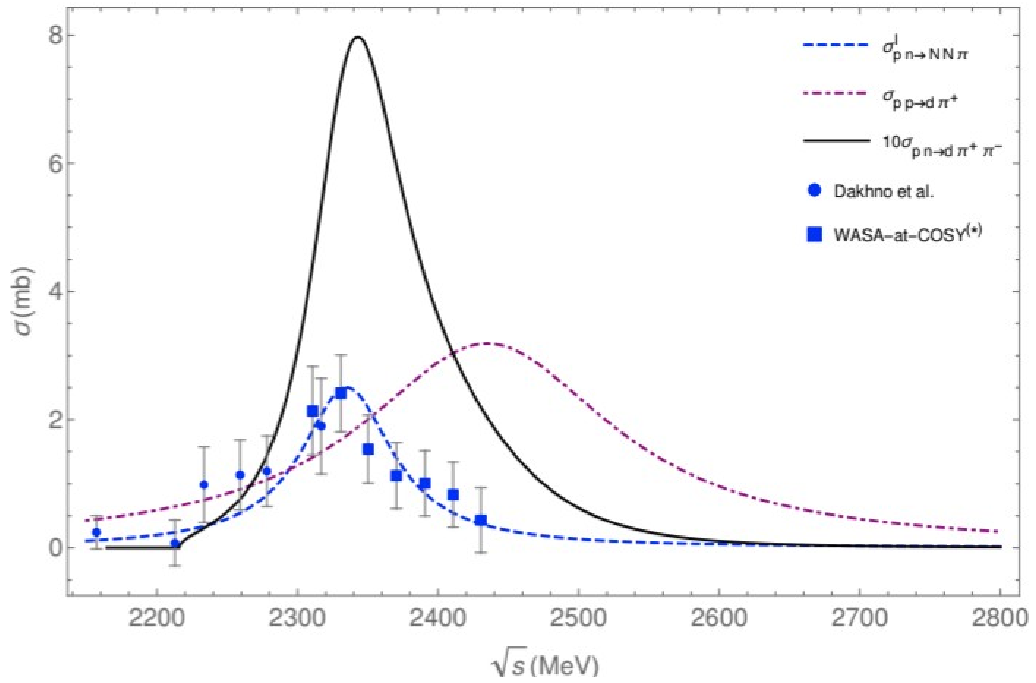
This relates √s and $M_{inv}(p_1\ p'_1)$

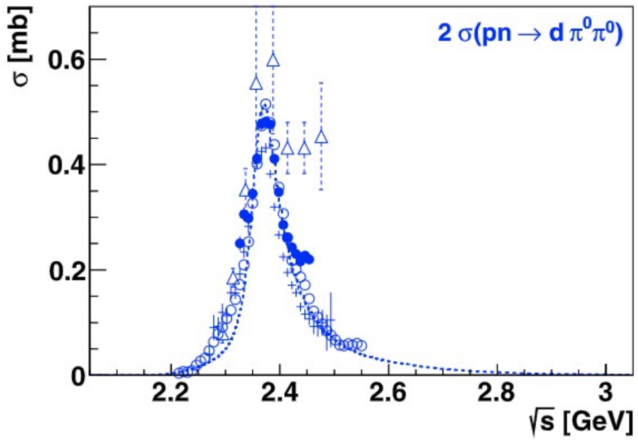
	$\delta\bar{M}_{\pi\pi}$ (MeV)			$p_{1,\max}^{\text{o.s.}}$ (MeV)	
Set I	40	60	80	700	800
strength (mb)	0.72	0.76	0.75	0.82	0.95
position (MeV)	2332	2332	2332	2332	2332
width (MeV)	76	76	81	75	75
Set II					
strength (mb)	0.75	0.80	0.80	0.85	0.96
position (MeV)	2342	2345	2345	2343	2342
width (MeV)	86	87	88	87	84

P. Adlarson et al. (WASA-at-COSY), Phys. Lett. B **774**, 599 (2017), [Erratum: Phys.Lett.B 806, 135555 (2020)],

They have uncertainty of 20 MeV in √s and bins of 50 MeV when determining $\sigma_{np(\text{I}=0)\to pp\pi^-}$

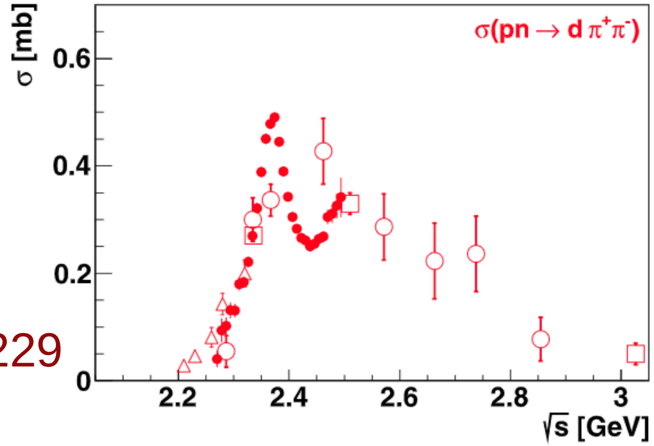


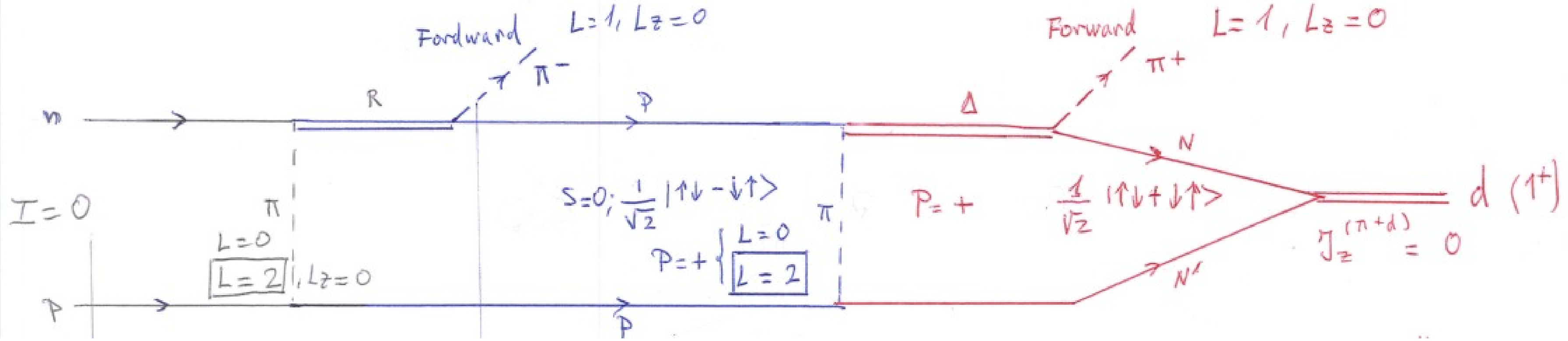




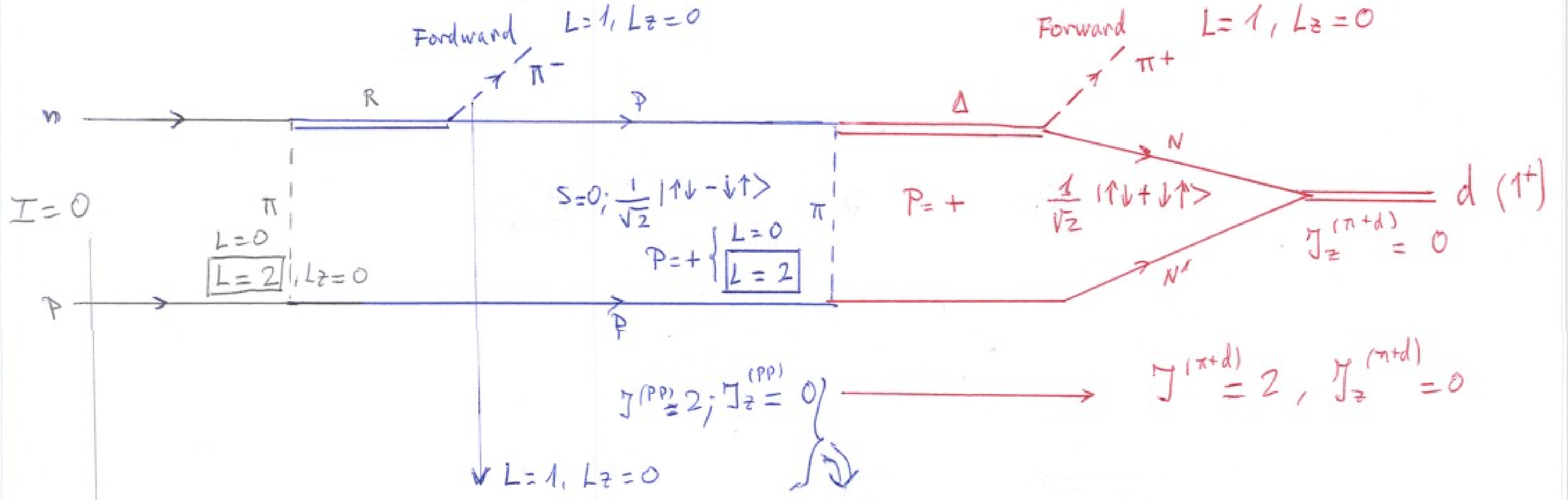
WASA at COSY

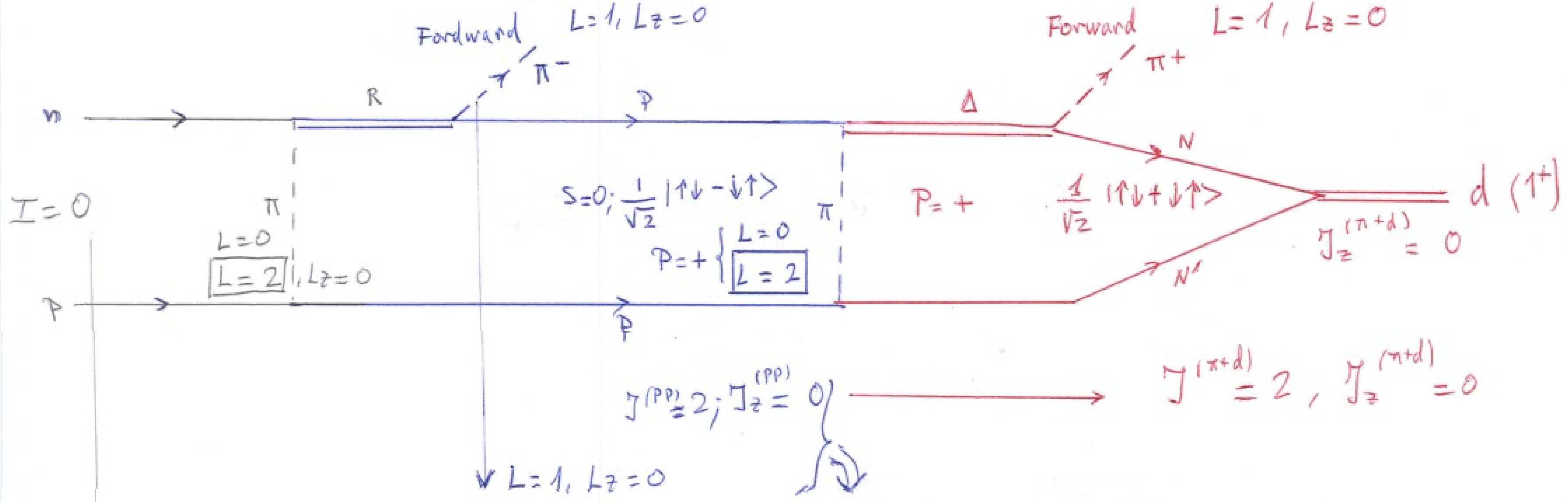
PLB 721 (2013) 229





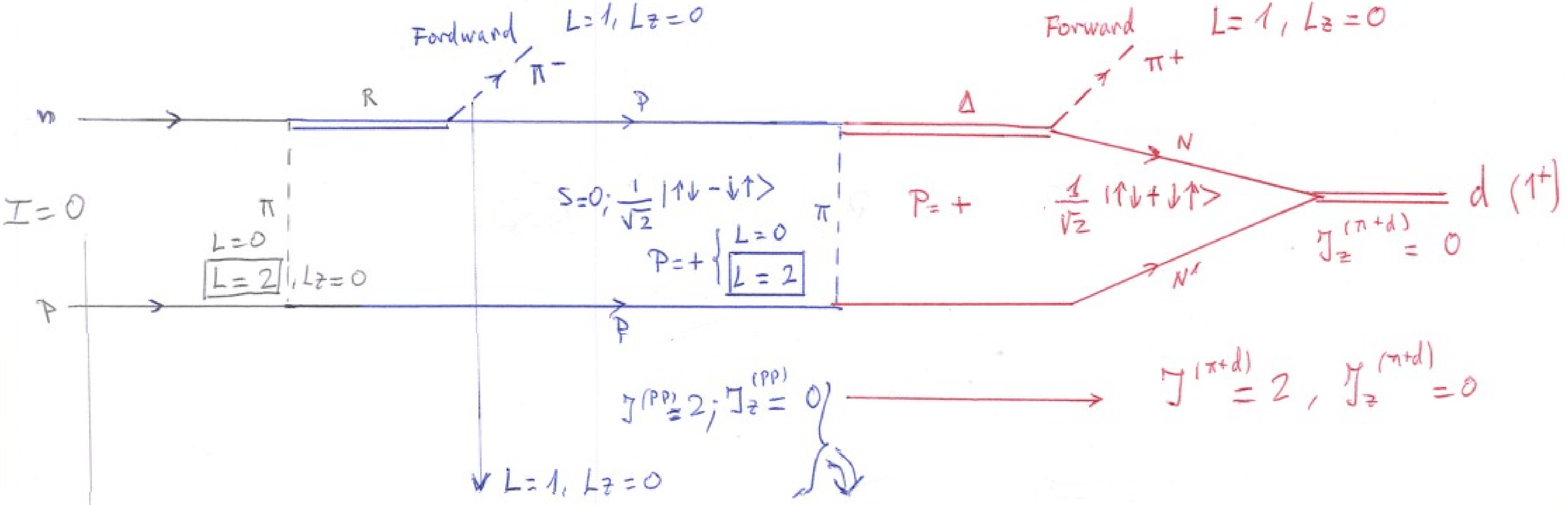
Fordward
L=1, Lz=0
π⁻
R
p
Δ
Forward
L= 1, Lz = 0
π+
n
N
I=0
π
L=0
L=2 , Lz=0
S=0; 1/√2 |↑↓ - ↓↑>
π
P=+ L=0 L=2
P=+
1/√2 |↑↓+↓↑>
d (1+)
Jz (π+d) = 0
N'
p
p


Fordward
L=1, Lz=0
π-
R
n
p
Forward
L=1, Lz=0
π+
Δ
N
I=0
π
L=0
L=2, Lz=0
S=0; 1/√2 |↑↓ - ↓↑>
P=+ L=0 L=2
π
P=+
1/√2 |↑↓+↓↑>
d (1+)
N'
p
J(PP)=2; Jz(PP)=0
J(π+d)=2, Jz(π+d)=0
L=1, Lz=0



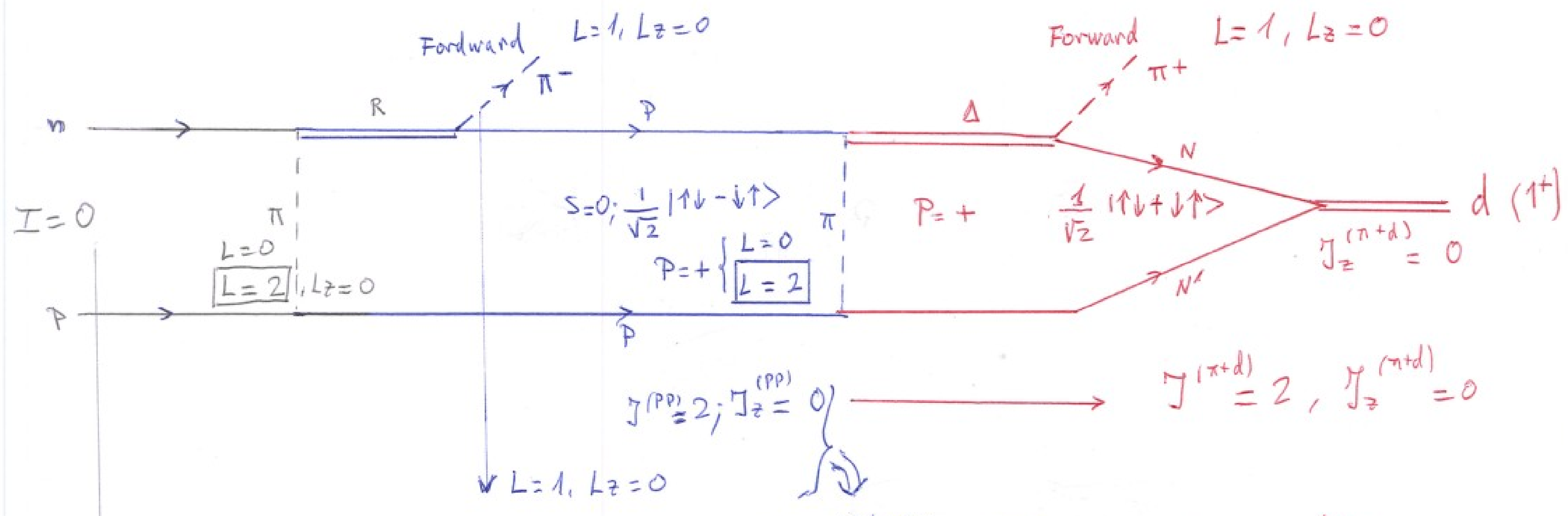
$$np^{(I=0)} \equiv |2,0\rangle\,|1,0\rangle = \sqrt{\frac{3}{5}}\,|3,0\rangle - \sqrt{\frac{2}{5}}\,|1,0\rangle \equiv |\pi^-\pi^+ d\rangle$$

($J^{tot}\ M^{tot}$)



$$np^{(I=0)} \equiv |2,0\rangle\,|1,0\rangle = \sqrt{\frac{3}{5}}\,\overset{j^{tot}\,\mu^{tot}}{|3,0\rangle} - \sqrt{\frac{2}{5}}\,|1,0\rangle \equiv |\pi^-\pi^+ d\rangle$$

$$I=0\,,\ L=2 \Rightarrow S=1\ ;\quad \overset{L}{|2,0\rangle}\,\overset{S}{|1,0\rangle} = \sqrt{\frac{3}{5}}\,|3,0\rangle - \sqrt{\frac{2}{5}}\,|1,0\rangle$$



$$np^{(I=0)} \equiv |2,0\rangle\,|1,0\rangle = \sqrt{\tfrac{3}{5}}\,\overset{J^{tot}\,M^{tot}}{|3,0\rangle} - \sqrt{\tfrac{2}{5}}\,|1,0\rangle \equiv |\pi^-\pi^+ d\rangle$$

$$I=0,\ L=2 \Rightarrow S=1\ ;\quad \overset{L}{|2,0\rangle}\,\overset{S}{|1,0\rangle} = \sqrt{\tfrac{3}{5}}\,|3,0\rangle - \sqrt{\tfrac{2}{5}}\,|1,0\rangle$$

$^{2S+1}L_J$:	$^3D_3$	$^1D_2$	$^3P_2$	$J^{tot,P} = 3^+$
	np	pp	$\pi^+ d$	preferred

Conclusions

Triangle singularities are catching up the attention of the community, explaining some features formely associated to resonances.

The $a_1(1420)$ case is one of them

We showed that the $pp \rightarrow \pi^+ d$ reaction offers a clear case, not identified before as a TS

The sequential one pion production in $np(I=0) \rightarrow \pi^- pp$ followed by $pp \rightarrow \pi^+ d$ offers a natural explanation of the peak so far associated to the dibaryon d*(2380).

The mechanism naturally gives rise to the dominant quantum numbers observed in the experiments