“Exotic” hadron-hadron S-wave Interaction

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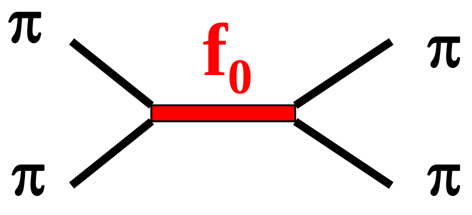
1. "Exotic" ππ S-wave Interaction

Why interested ?

1) a fundamental strong interaction process and a necessary input for many reactions involving multi-pions

2) I=0 ππ S-wave has the same quantum number of f_0 resonances which include :

σ/f_0(500) (σ-model, σ–exchange for NN interaction) and the lightest glueball candidate f_0(1500)/f_0(1710)



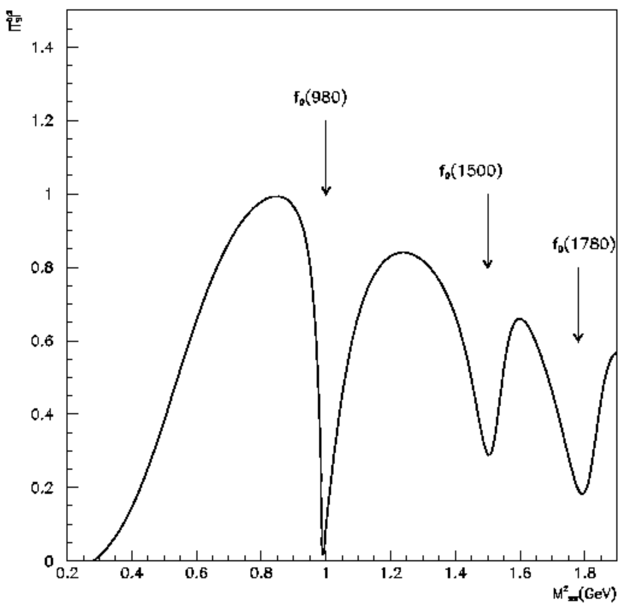
Time dependent well established f_0 resonances

PDG1992

f_0(980)
Γ=46 MeV

f_0(1300)
BR(ππ)>90%

f_0(1590)



PDG1996

f_0(980)
Γ= 46-400 MeV

f_0(1370)
BR(ππ) very small

f_0(1500)

f_0(400-1200)

References:

B.S.Zou, D.V.Bugg, Phys. Rev. D48, R3948 (1993)
"Is $f_0(975)$ a narrow resonance?"

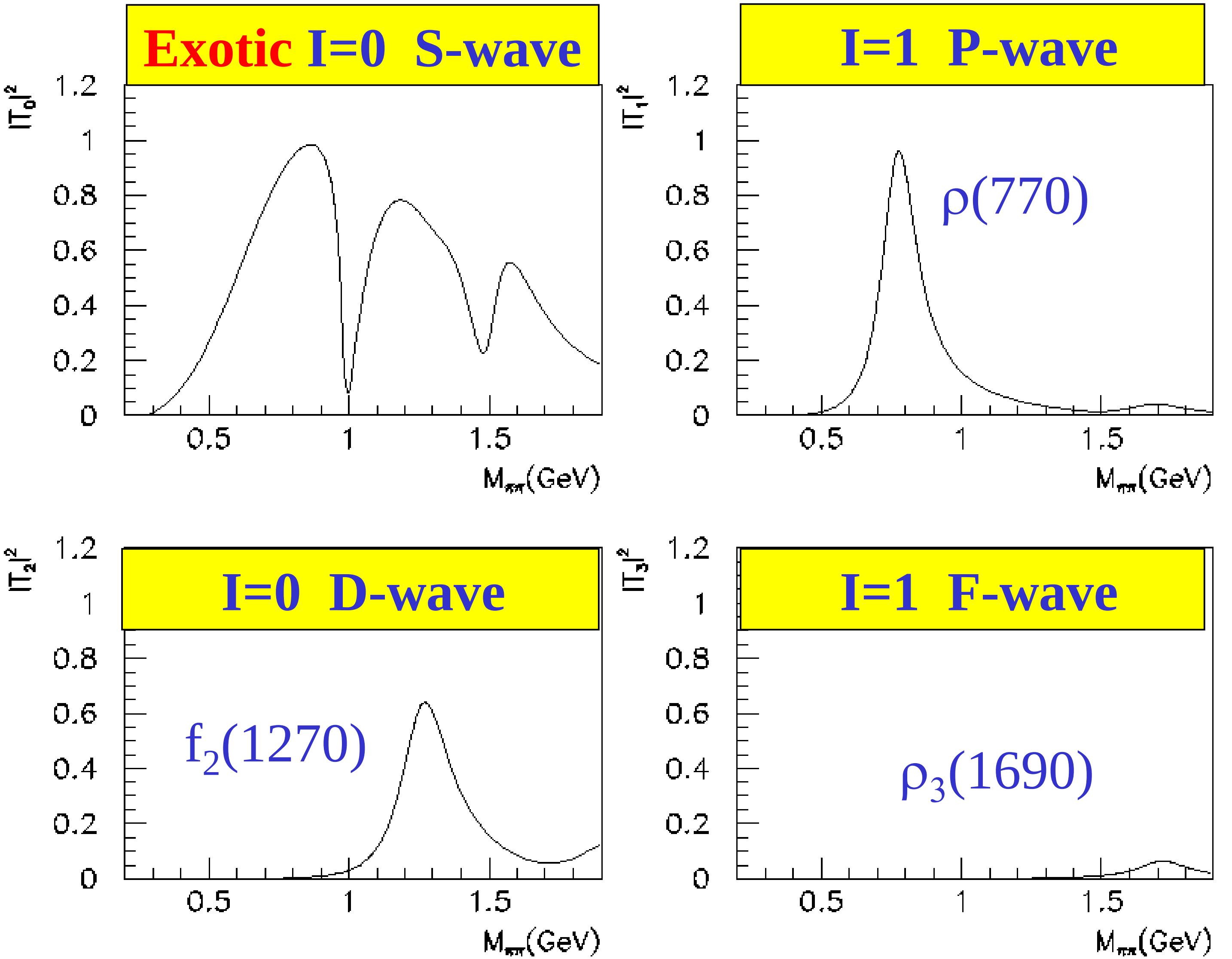
B.S.Zou, D.V.Bugg, Phys. Rev. D50, 591 (1994)
"Remarks on I=0 JPC=0++ States:σ/ε and $f_0(975)$"

Cbar Coll., B.S.Zou, Phys. Lett. B323, 233 (1994)
"Observation of two $J^{PC}=0^{++}$ resonances at 1365 and 1520 MeV"

D.V.Bugg,I.Scott, B.S.Zou et al, Phys. Lett. B353, 378 (1995)
"Further amplitude analysis of $J/\psi \rightarrow \gamma(\pi\pi\pi\pi)$"

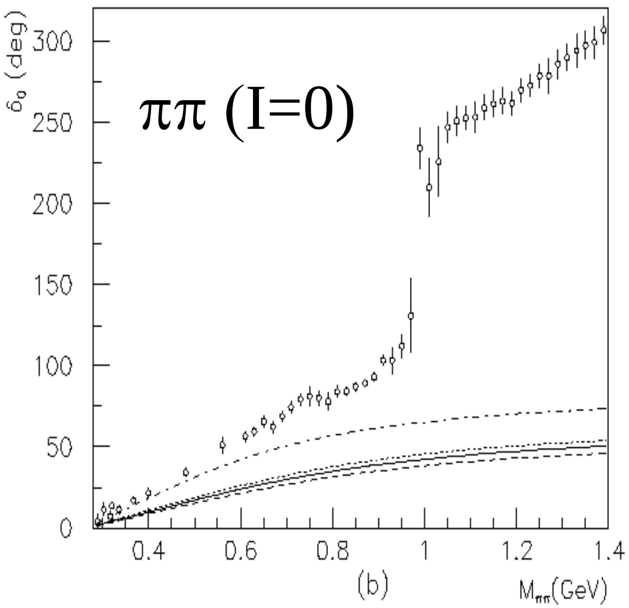
D.V.Bugg, A.Sarantsev, B.S.Zou, Nucl. Phys. B471, 59 (1996)
"New results on ππ phase shifts between 600 and 1900 MeV"

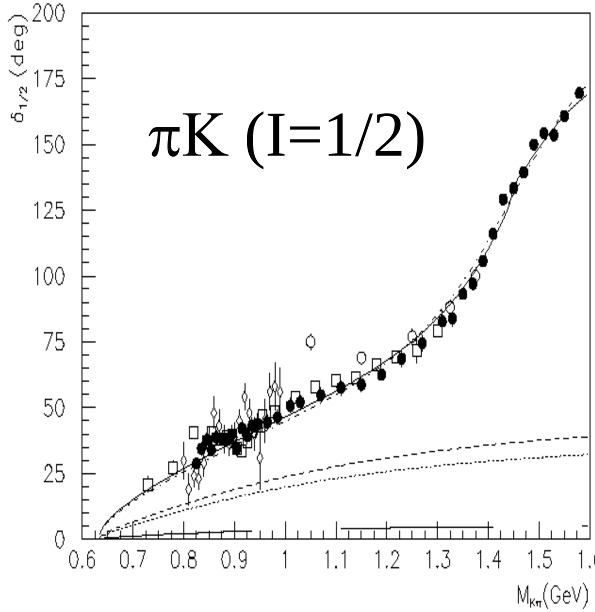
"Exotic" ππ S-wave interaction : broad σ–background with narrow resonances as dips instead of peaks

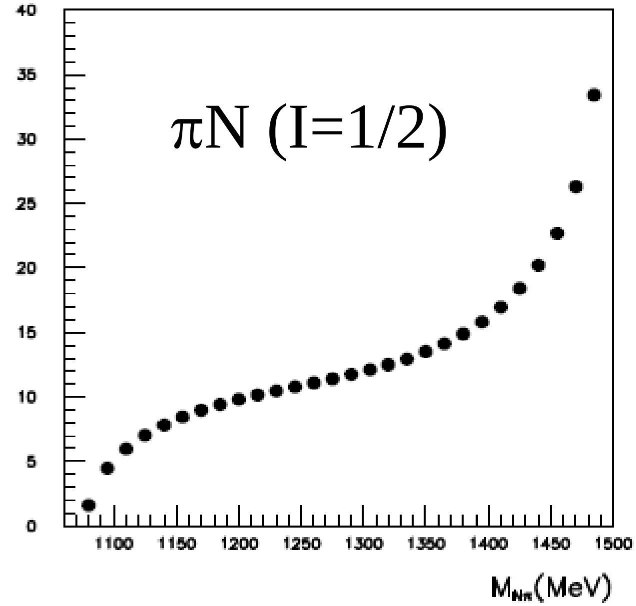


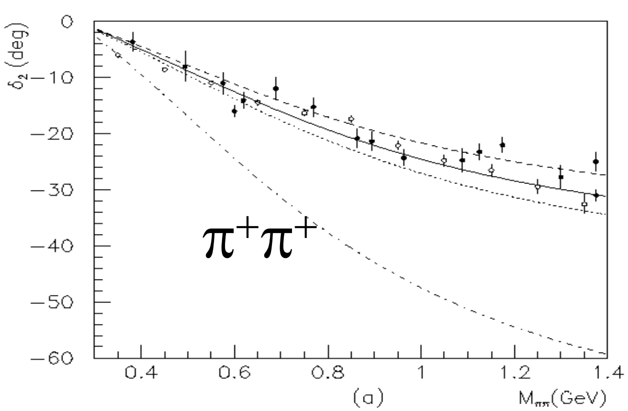
D.V.Bugg, A.Sarantsev,B.S.Zou, Nucl. Phys. B471 (1996) 59

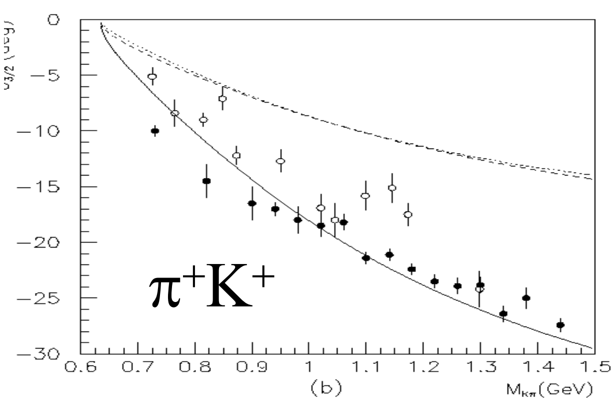
Similarity for ππ, πK and πN s-wave scattering

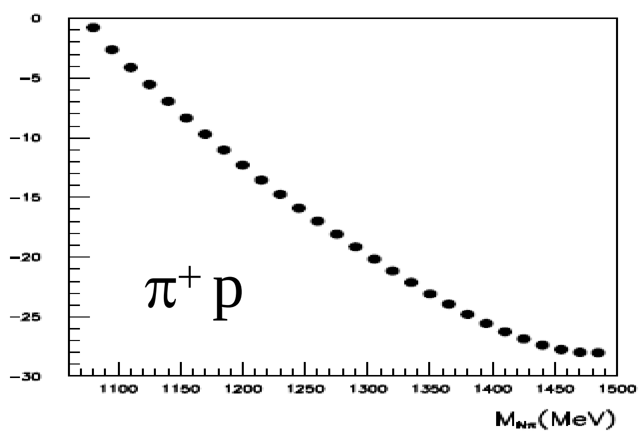






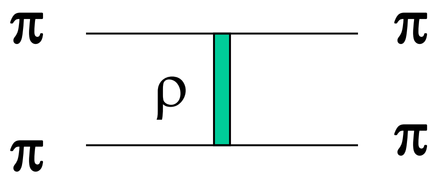






What's the nature of the broad σ ?

Important role by t-channel ρ exchange for all these processes



ππ **πK & πN**

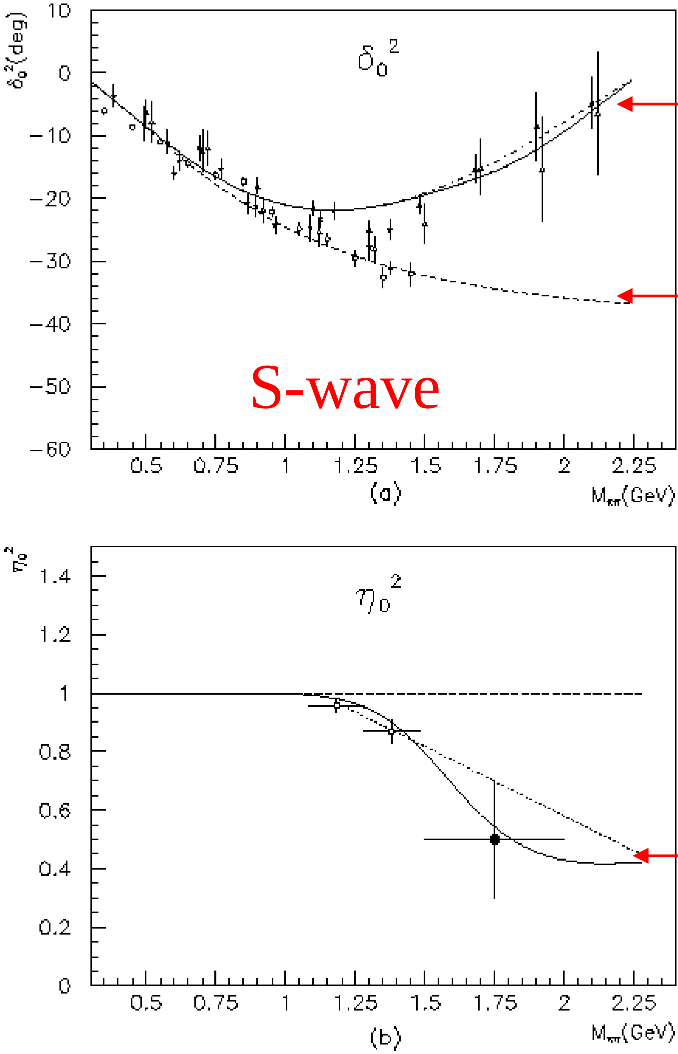
$$K_\rho^{I=0} = -2\, K_\rho^{I=2}, \qquad K_\rho^{I=1/2} = -2\, K_\rho^{I=3/2}$$

D. Lohse, J.W. Durso, K. Holinde, J. Speth, Nucl.Phys.A516, 513 (1990)
B.S.Zou, D.V.Bugg, Phys. Rev. D50, 591 (1994)

An interesting paper by T.Hyodo, D.Jido, A.Hosaka, PRL 97 (2006) 192002
"Exotic hadrons in s-wave chiral dynamics"

Basic features of I=2 $\pi\pi$ Interaction

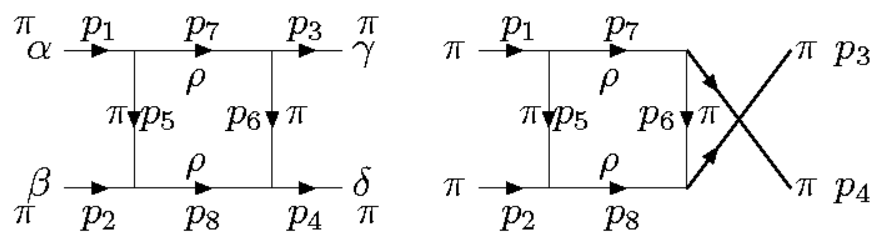
F.Q.Wu, B.S.Zou et al., Nucl. Phys.A735 (2004) 111



S-wave

attractive force by t-channel f_2

repulsive force by t-channel ρ



Inelasticity by $\pi\pi \leftrightarrow \rho\rho$

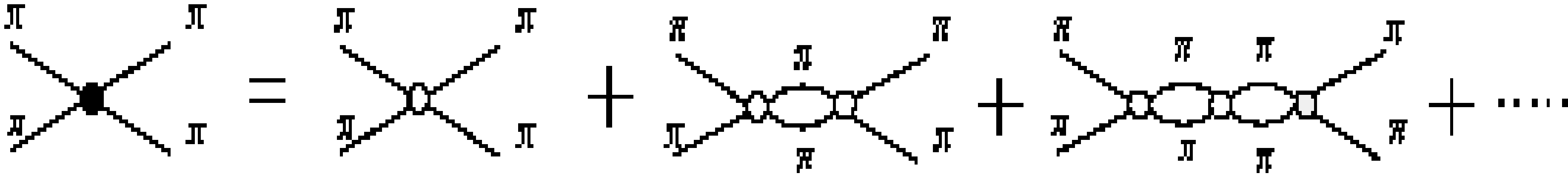
An important cause for hadron-hadron S-wave interactions appearing “exotic” is

t-channel meson-exchange amplitude has a comparable strength as s-channel resonance contribution for S-waves.

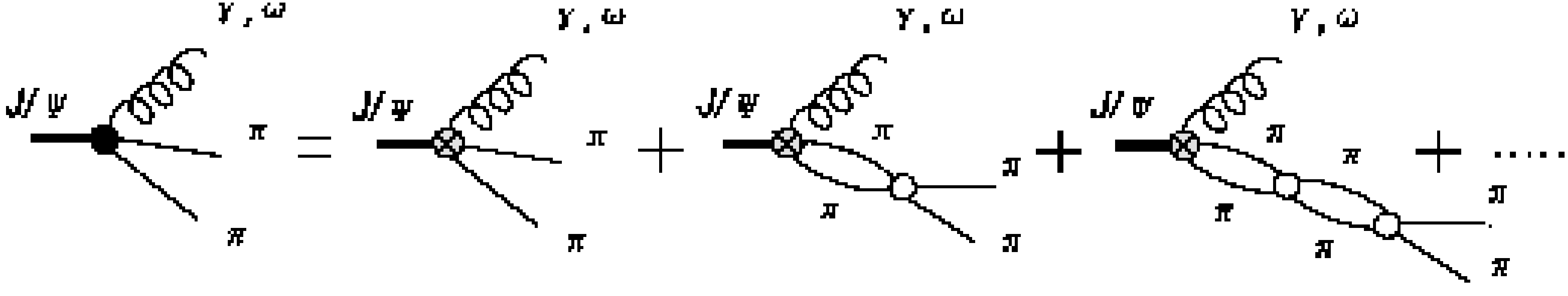
For higher partial waves, s-channel resonance contribution dominates.

Why broad σ appears narrower in production processes than in ππ elastic scattering?

$$T_{el} = K/(1 - i\rho K) = K + K i \rho K + K i \rho K i \rho K + \ldots$$



$$T_{prod} = P/(1 - i\rho K) = P + P i \rho K + P i \rho K i \rho K + \ldots$$

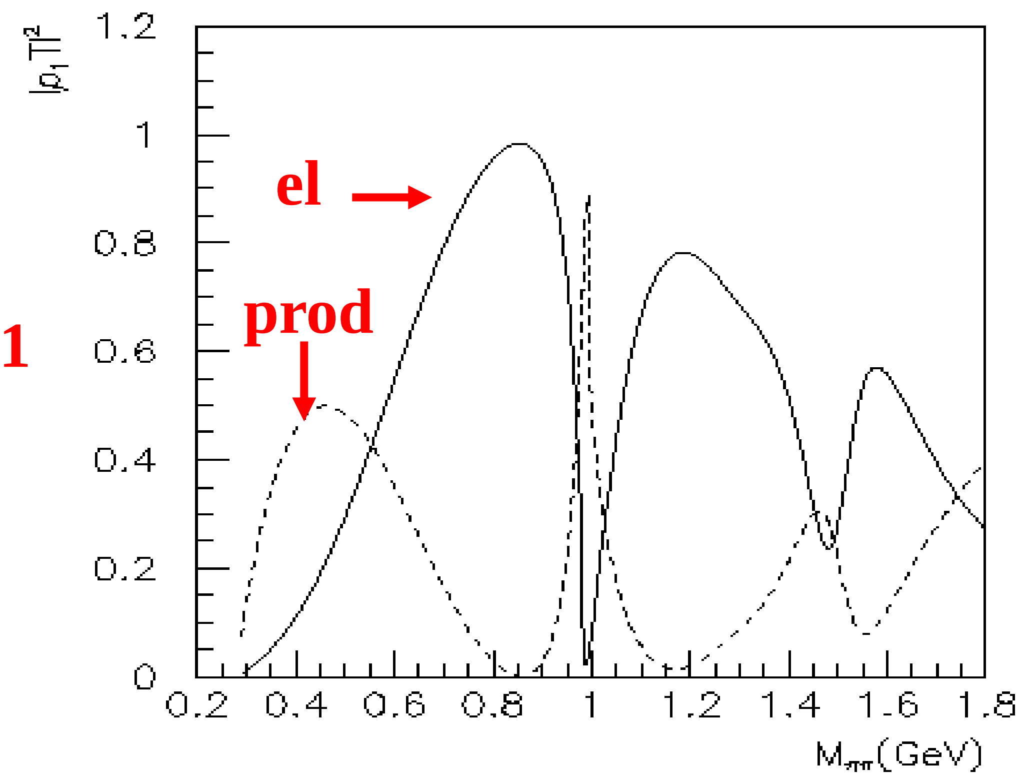


T_{el} from Bugg,Sarantsev,Zou Nucl. Phys. B471 (1996) 59

with σ pole at (0.571 – i 0.420) GeV

$$T_{prod} = T_{el} * P / K , \quad K = \tan\delta / \rho$$

assuming P=1



How about production vertex P ?

$$\mathbf{P(V' \rightarrow V\pi^+\pi^-)} = -\frac{4}{F_0^2} \left[\frac{g}{2}(m_{\pi\pi}^2 - 2M_\pi^2) + g_1 E_{\pi^+} E_{\pi^-} \right] \epsilon_{\Psi}^* \cdot \epsilon_{\Psi'}$$

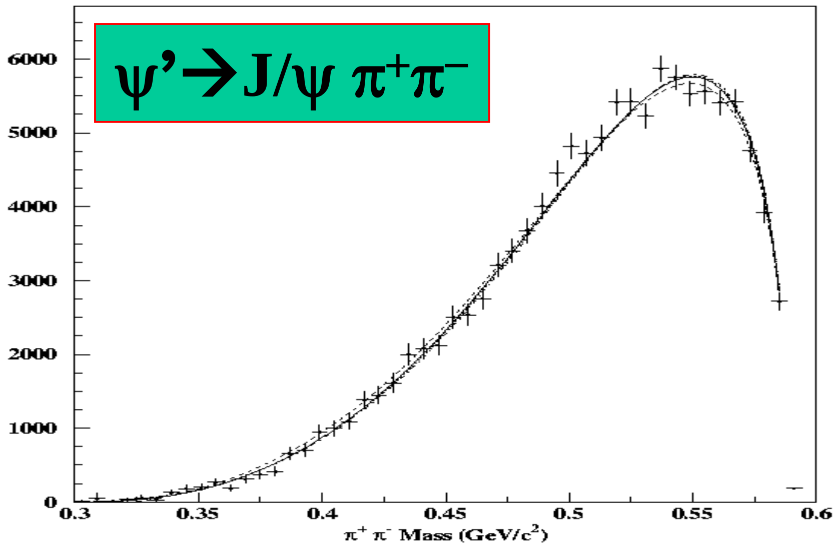
T. Mannel, R. Urech, Z. Phys.C73, 541 (1997);
Ulf-G. Meißner, J.Oller, Nucl.Phys. A679 (2001) 671;
M.Ishida et al., Phys. Lett. B518 (2001) 47;
L. Roca, J. Palomar, E. Oset, H.C.Chiang, Nucl. Phys. A744 (2004) 127
F.K.Guo,P.N.Shen, H.C.Chiang, R.G.Ping, Nucl.Phys.A761 (2005) 269

For $\psi' \rightarrow J/\psi\ \pi^+\pi^-$, E_π small, 1st term dominates
$\rightarrow$ higher σ peak

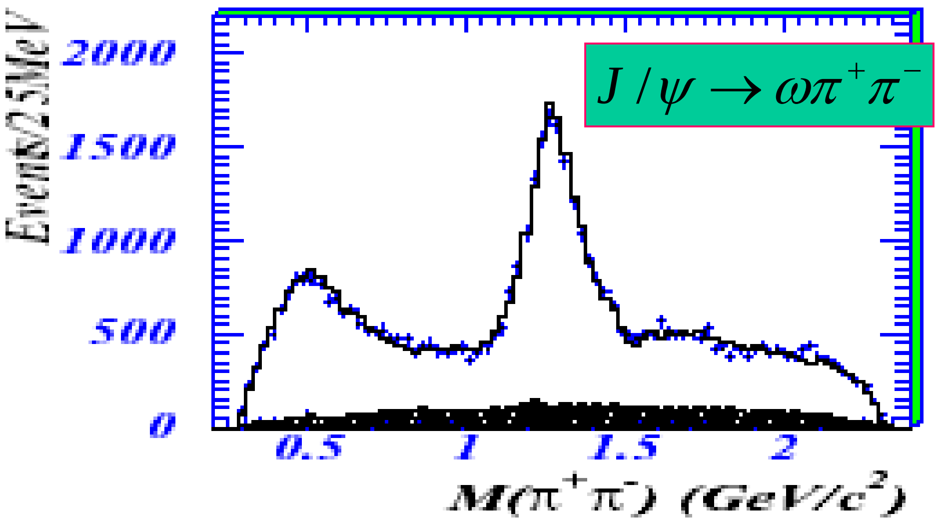
For $\psi \rightarrow\ \omega\ \pi^+\pi^-$, E_π large, 2nd term dominates
$\rightarrow$ lower σ peak

σ peak position is process dependent !

$$\mathbf{P \sim c_1 + c_2\, s}$$



BES, Phys.Rev. D62 (2000) 032002



BES, Phys.Lett. B598 (2004) 149

Why $f_0(980)$'s peak width is so narrow ?

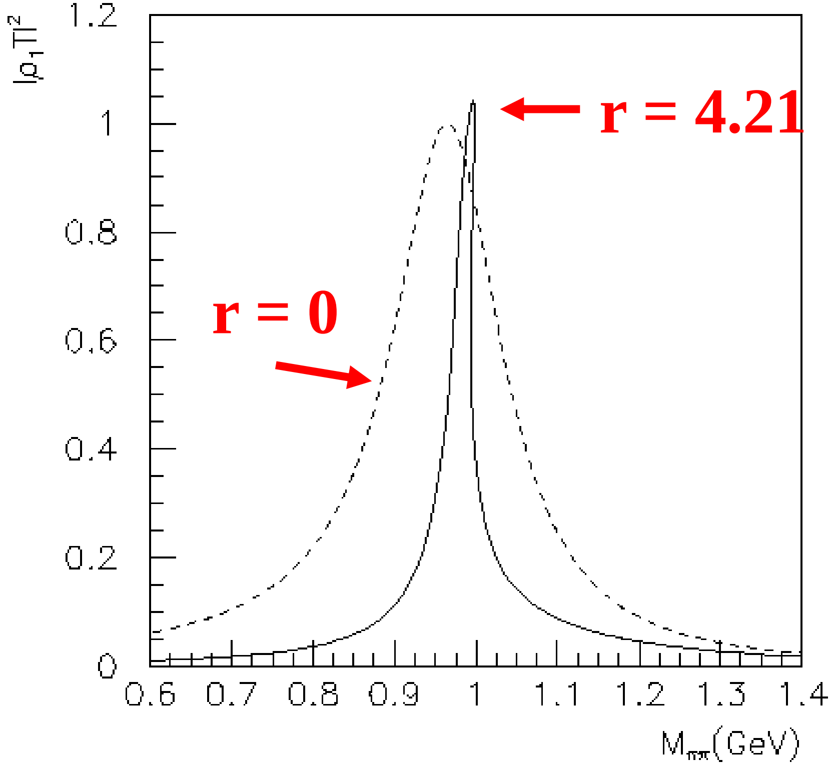
BES, PLB 607 (2005) 243

$$f = \frac{1}{M^2 - s - i(g_1\rho_{\pi\pi} + g_2\rho_{K\bar{K}})}$$

M = 965 MeV

g_1 = 165 MeV^2

$r = g_2/g_1 = 4.21$



$$\rho_{K\bar{K}} = (1 - 4m_K^2/s)^{1/2}$$

Strong coupling to $\bar{K}K$ strongly reduce the peak width of $f_0(980)$

Unitarity and K-matrix approach

Relations among S-matrix, T-matrix, K-matrix

$$S = I + 2i\rho T, \qquad T = \frac{K}{1 - i\rho K}$$

Unitarity relation: $S^{+}S = I \rightarrow \mathrm{Im}T = T^{+}\rho T, \quad \mathrm{Im}\frac{1}{T} = -\rho$

$$\rightarrow \frac{1}{T} = \frac{1}{K} - i\rho \;, \quad K \sim \text{real}$$

For a single channel BW resonance:

$$S = \frac{M_R^2 - s + ig^2\rho(s)}{M_R^2 - s - ig^2\rho(s)}, \quad T = \frac{g^2}{M_R^2 - s - ig^2\rho(s)}, \quad K = \frac{g^2}{M_R^2 - s}$$

How to add two resonances for a single channel 2-body scattering ?

1) $$T = \frac{g_1^2}{M_1^2 - s - ig_1^2\rho(s)} + \frac{g_2^2}{M_2^2 - s - ig_2^2\rho(s)}$$ **violates unitarity**

2) $$K = \frac{g_1^2}{M_1^2 - s} + \frac{g_2^2}{M_2^2 - s} \rightarrow T = \frac{g_1^2(M_2^2 - s) + g_2^2(M_1^2 - s)}{(M_1^2 - s)(M_2^2 - s) - i\rho(s)[g_1^2(M_2^2 - s) + g_2^2(M_1^2 - s)]}$$

3) $$S = \frac{M_1^2 - s + ig_1^2\rho(s)}{M_1^2 - s - ig_1^2\rho(s)} \times \frac{M_2^2 - s + ig_2^2\rho(s)}{M_2^2 - s - ig_2^2\rho(s)}$$

$$\rightarrow \quad T = \frac{g_1^2(M_2^2 - s) + g_2^2(M_1^2 - s)}{[M_1^2 - s - ig_1^2\rho(s)][M_2^2 - s - ig_2^2\rho(s)]}$$

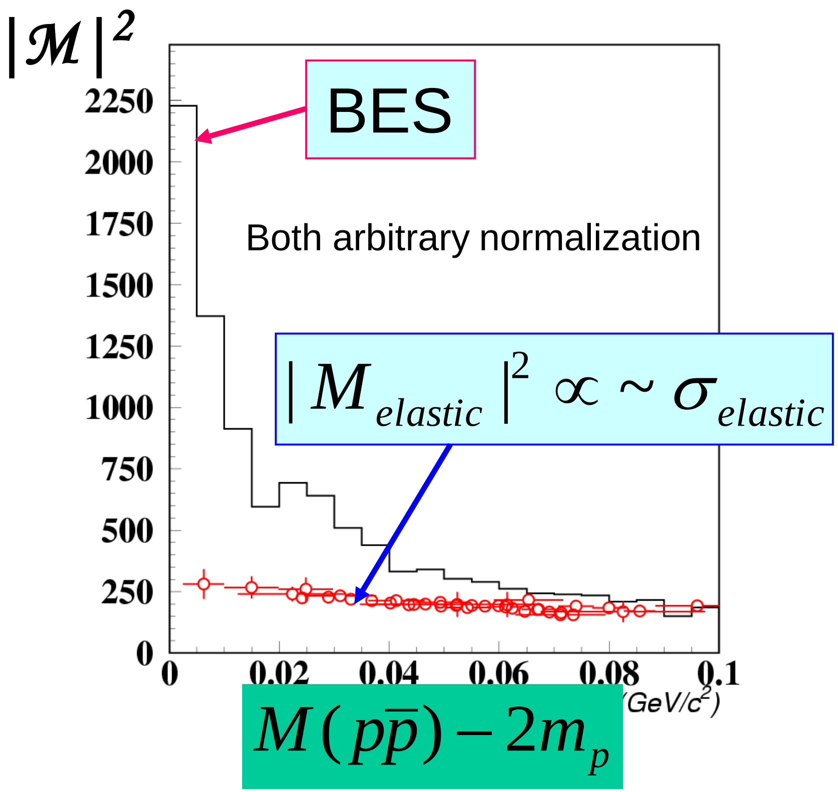
For a multi-hadron production final state

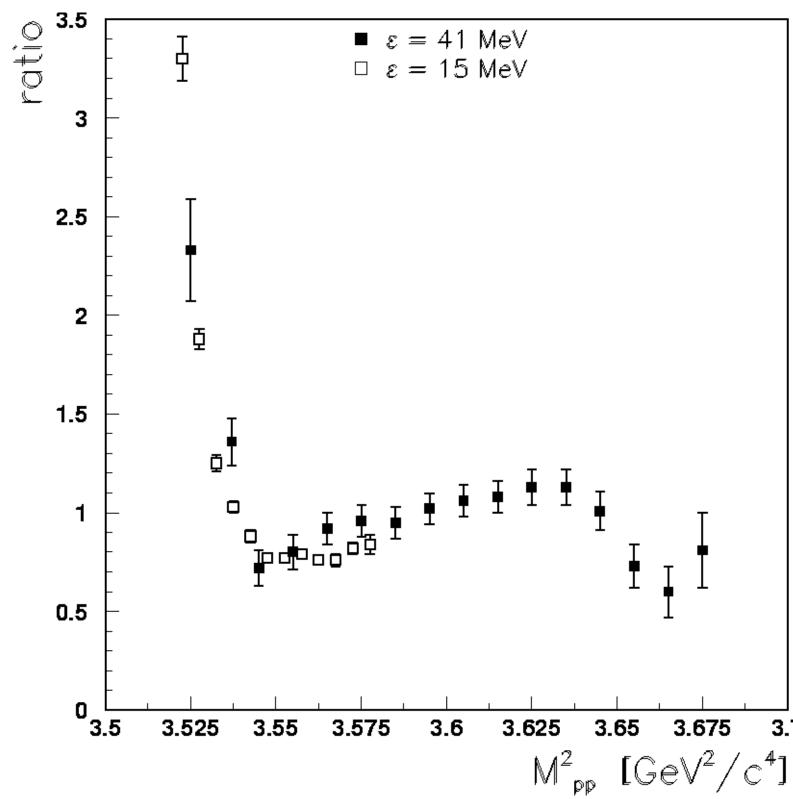
$$T_p = \frac{C_1(s)}{M_1^2 - s - ig_1^2\rho(s)} + \frac{C_2(s)}{M_2^2 - s - ig_2^2\rho(s)}$$ **not violating unitarity**

2. I=0 $^1S_0$ $\bar{p}p$ & I=1 $^1S_0$ pp near threshold enhancement

$J/\psi \rightarrow \gamma\ p\bar{p}$

$p\,p \rightarrow p\,p\,\eta$





BES, Phys. Rev. Lett. 91, 022001 (2003)

COSY-TOF, Eur.Phys.J.A16, 127 (2003)

What should be the largest decay mode of I=0 $^1S_0$ $\bar{p}p$ state ?

I=0 $^1S_0$ $\bar{p}p$ atom : $\pi^0\pi^0\eta$ / $\pi^0\pi^0\eta' \sim 2$

C.Amsler et al., B.S.Zou, Nucl. Phys. A720 (2003) 357

$J/\psi \to \gamma\, \eta\, \pi^+\pi^-$: **BES, Phys. Lett. B446 (1999) 356**

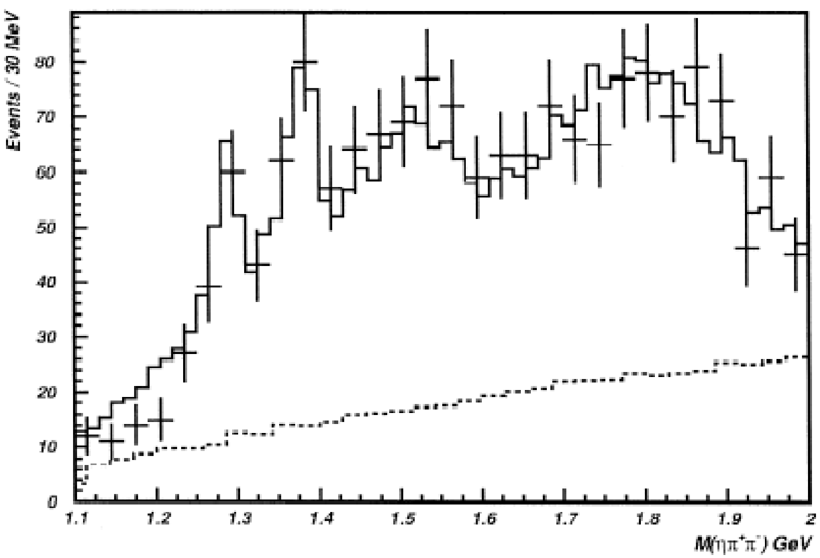
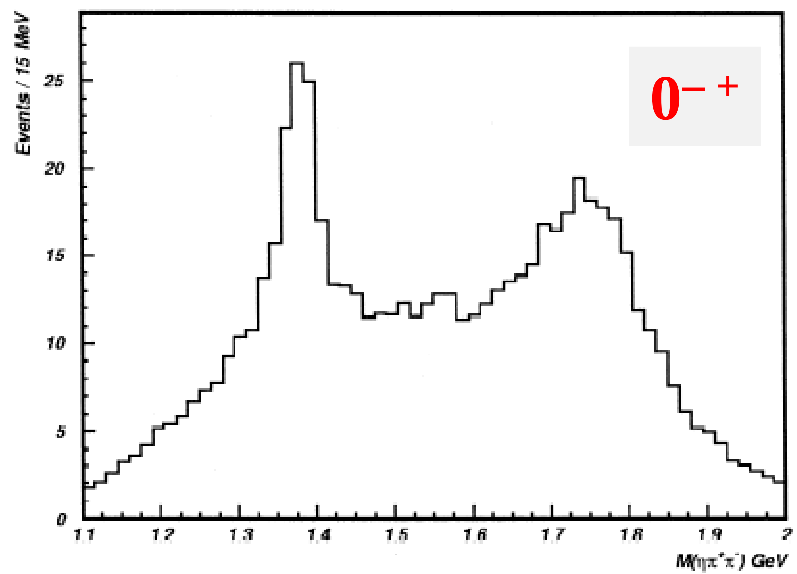


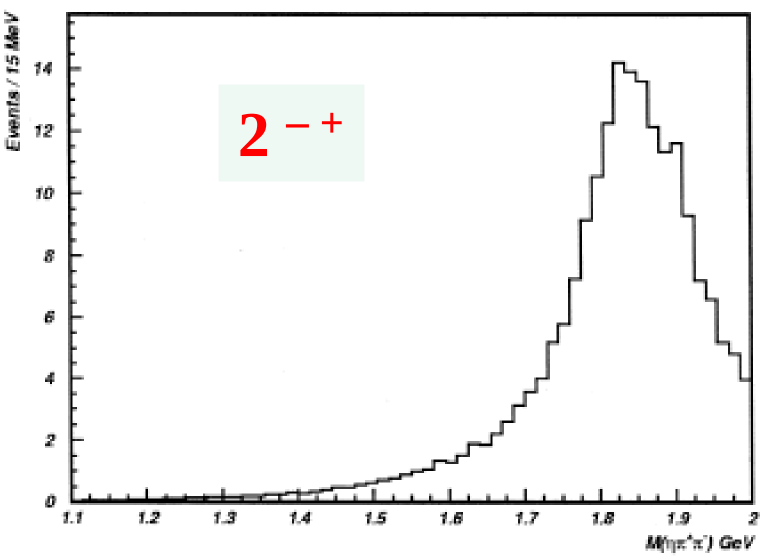
Fig. 2. The $\eta\pi^+\pi^-$ mass spectrum.



$\bar{p}p$ near threshold enhancement
= some broad sub-threshold 0^{-+} resonance(s) + FSI

Zou B.S., Chiang H.C., Phys.Rev.D69 (2004) 034004
A.Sibirtsev et al., Phys.Rev. D71 (2005) 054010

$J/\psi \rightarrow \gamma\, \eta\, \pi^+\pi^-$: BES, Phys. Lett. B446 (1999) 356



$M = 1840 \pm 15$ MeV

$\Gamma = 170 \pm 40$ MeV

What's its relation with X(1835) observed in $J/\psi \rightarrow \gamma\, \eta'\, \pi^+\pi^-$

One-Pion-Exchange and BES $p\bar{p}$ ($^1S_0$) near threshold enhancement

Zou B.S., Chiang H.C. Phys.Rev.D69 (2004) 034004

NN interaction : $V_\pi^{NN}(t) = \frac{f_\pi^2}{m_\pi^2 - t}\,\frac{1}{3}\,\vec{\sigma}_1\cdot\vec{\sigma}_2\vec{\tau}_1\cdot\vec{\tau}_2$

$$\vec{\sigma}_1\cdot\vec{\sigma}_2\vec{\tau}_1\cdot\vec{\tau}_2 = \begin{cases} 9 & (S, I) = (0,0) \\ 1 & (S, I) = (1,1) \\ -3 & (S, I) = (1,0) \text{ or } (0,1) \end{cases}$$

deuteron

$\bar{N}N$ interaction : $V_\pi^{N\bar{N}}(t) = -V_\pi^{NN}(t)$

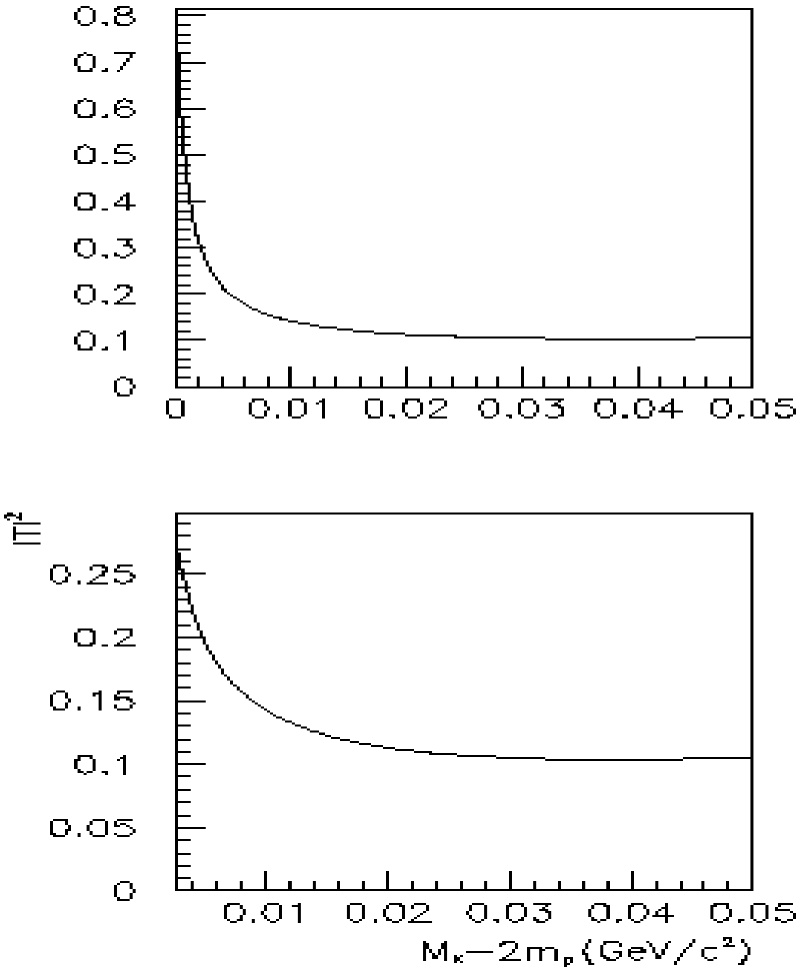
I=0, $\bar{p}p$ ($^1S_0$) gets the biggest attractive force !

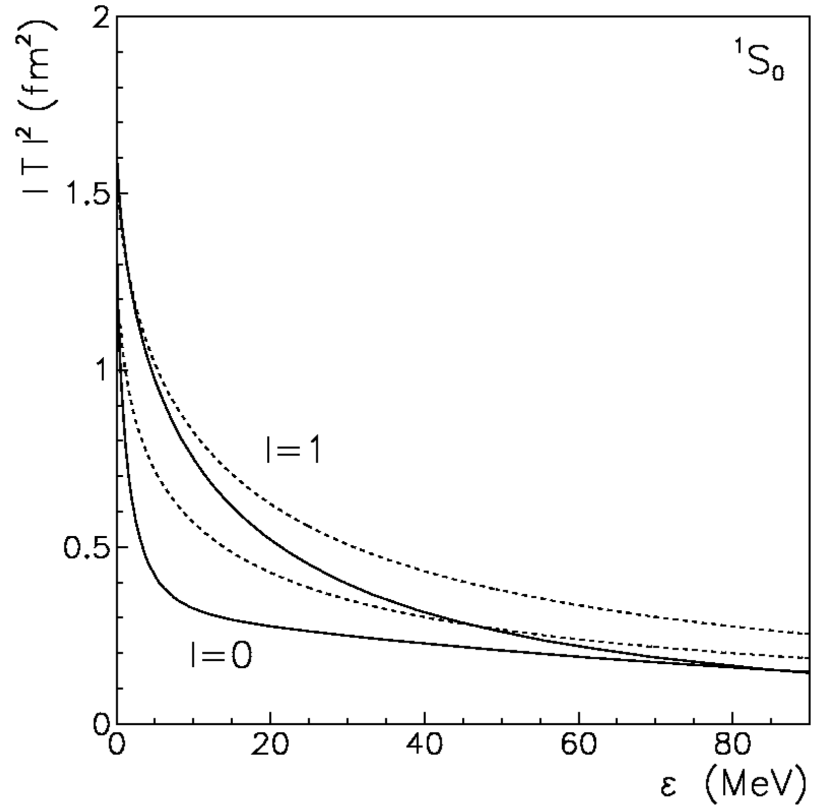
$$K_s = \frac{1}{4k^2}\int_{-4k^2}^{0} dt V_{p\bar{p}}^{\pi}(t) = -\frac{3f_\pi^2}{4k^2} ln(1+\frac{4k^2}{m_\pi^2})$$

$$T_{J/\psi\to\gamma p\bar{p}} = \frac{T_{J/\psi\to\gamma p\bar{p}}^{(0)}}{1 - i\rho_{p\bar{p}}K_s} = \frac{CK_\gamma}{1 + i\frac{3M_p^2}{k\sqrt{s}}\frac{f_\pi^2}{4\pi} ln(1+\frac{4k^2}{m_\pi^2})}$$

π+σ+ρ+ω exchange FSI & full FSI by A.Sibirtsev et al.

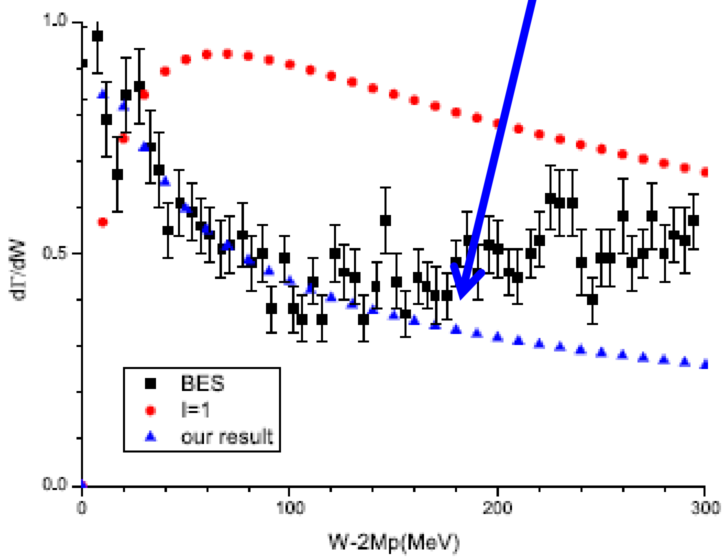
Phys.Rev. D71 (2005) 054010





G.Y. Chen, H.R. Dong, J.P. Ma, **Phys.Rev.D78:054022,2008**

One-pion-exchange including zero-range repulsive force



In summary, $\bar{p}p$ near threshold enhancement is very likely due to some broad sub-threshold 0^{-+} resonance(s) plus FSI.

3. KΛ s-wave near threshold enhancement

complimentary BES and COSY experiments

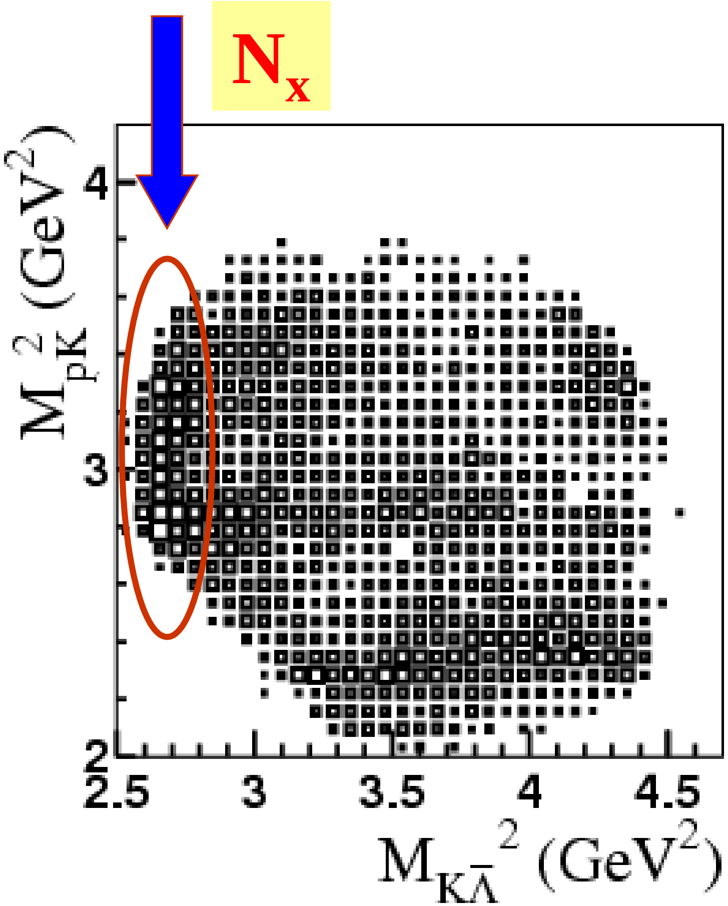
$J/\psi \rightarrow P K^- \bar{\Lambda}$ vs $P P \rightarrow P K^+ \Lambda$

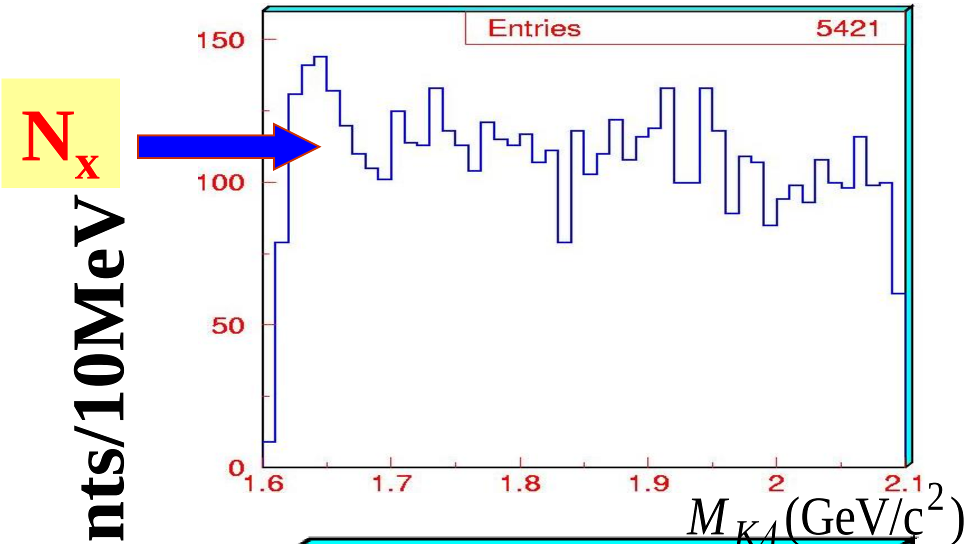
$P \bar{\Lambda}$ & $P \Lambda$ the same t-channel interaction

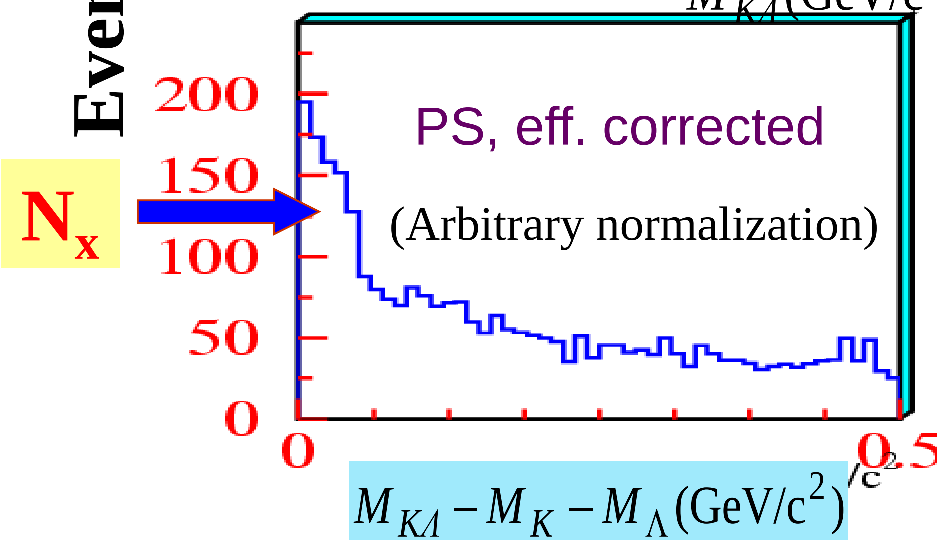
$K^- \bar{\Lambda}$ & $K^+ \Lambda$ the same interaction

$P K^-$ for Λ^* $P K^+$ for pentaquarks

Near-threshold enhancement in $M_{K\Lambda}$

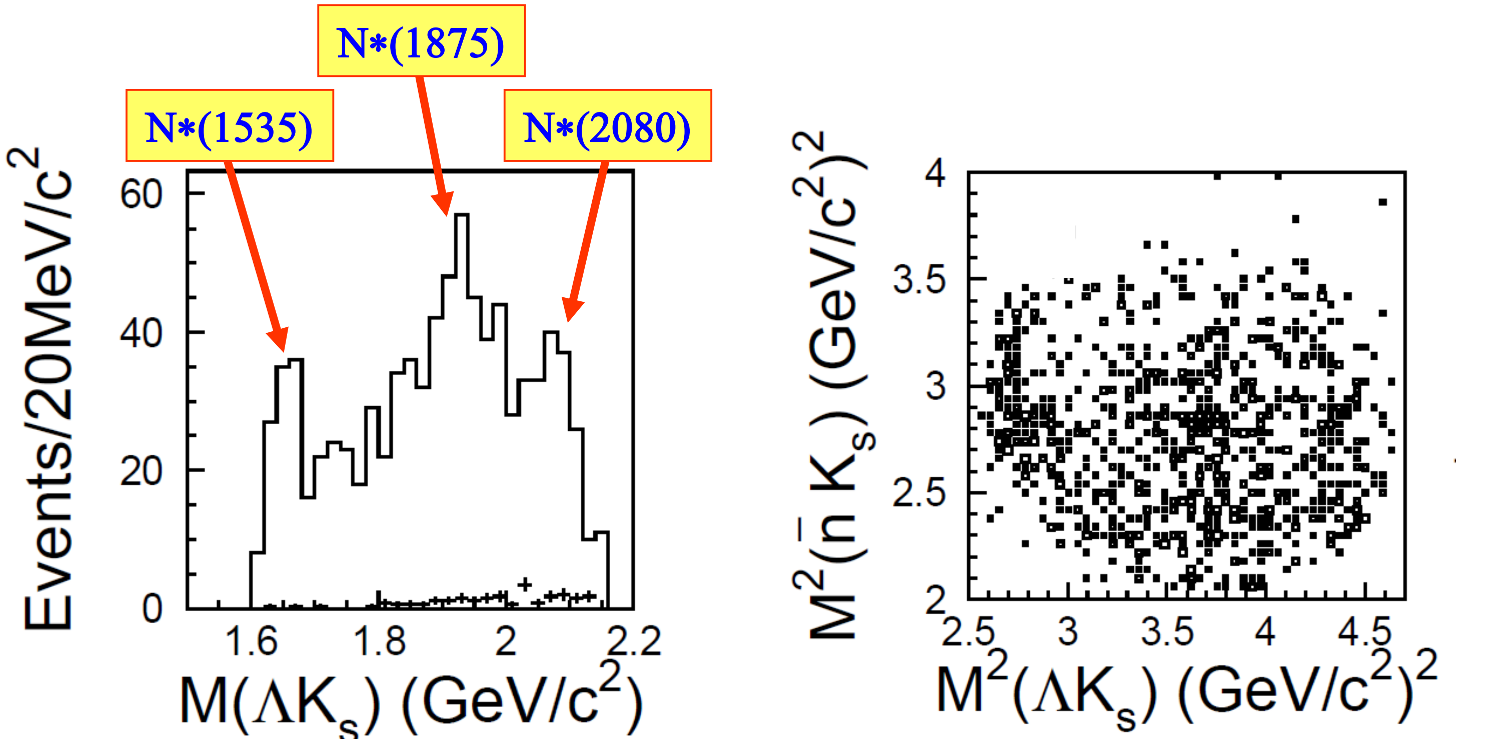






$$J/\psi \rightarrow nK_S^0\overline{\Lambda}$$

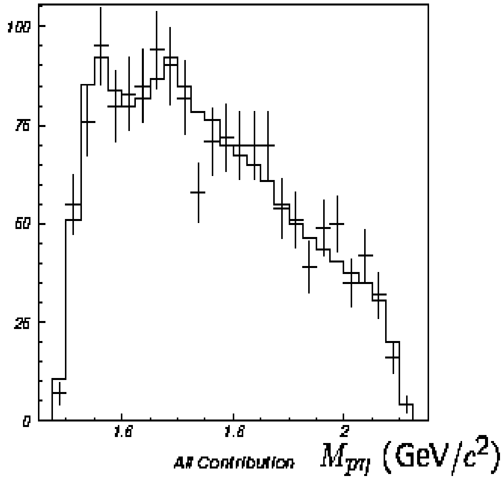
BESII, Phys. Lett. B659 (2008) 789

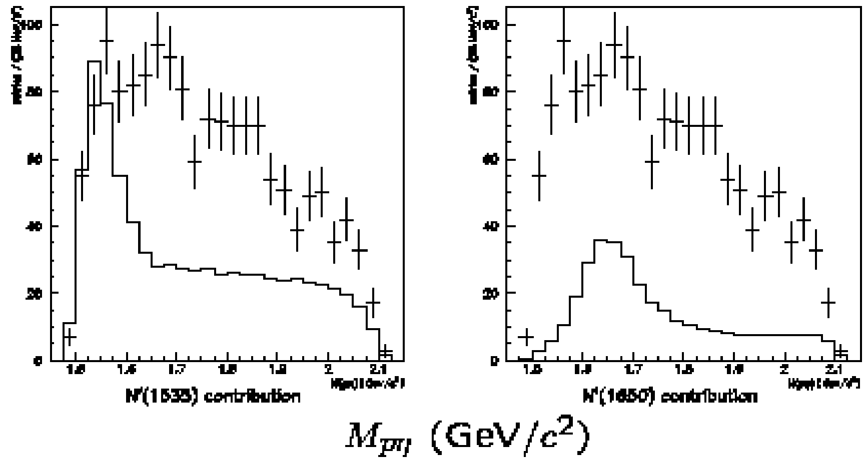


- *An enhancement near ΛK_S threshold is evident*
- *2 other peaks just below thresholds of $K\Sigma^*$ & $K^*\Sigma$*

$K\Sigma^*$ ~1880 MeV **$K^*\Sigma$ ~ 2086 MeV**

PWA Results from $J/\psi \to p\bar{p}\eta$ (BESI 7.8M)





$N^*(1535)$ parameters	BES	PDG2000
Mass (MeV) Γ (MeV)	1530 ± 10 95 ± 25	$1520 - 1555$ $100 - 250$
$N^*(1650)$ parameters	BES	PDG2000
Mass (MeV) Γ (MeV)	1647 ± 20 145^{+80}_{-45}	$1640 - 1680$ $145 - 190$

BES Collaboration, Phys. Lett. B510 (2001) 75

B.C.Liu and B.S.Zou, Phys. Rev. Lett. 96 (2006) 042002

From relative branching ratios of
$J/\psi \rightarrow p \bar{N}^* \rightarrow p (K^- \bar{\Lambda}) / p (\bar{p}\eta)$

↓

$g_{N^*K\Lambda} / g_{N^*p\eta} / g_{N^*p\pi} \sim 1.3 : 1 : 0.6$

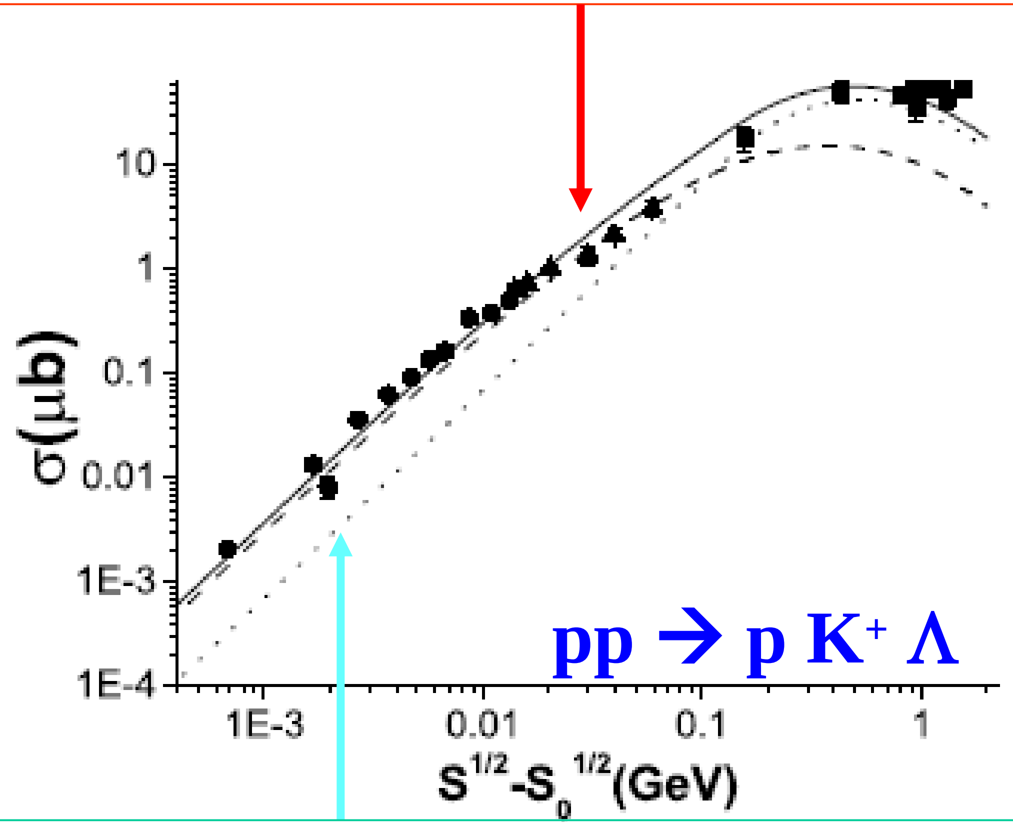
↓

Smaller N*(1535) BW mass

previous results 0 ~ 2.6 from πN and γN data

Evidence for large $g_{N^*K\Lambda}$ from $pp \rightarrow p K^+ \Lambda$

Total cross section and theoretical results with N*(1535), N*(1650), N*(1710), N*(1720)
B.C.Liu, B.S.Zou, Phys. Rev. Lett. 96 (2006) 042002



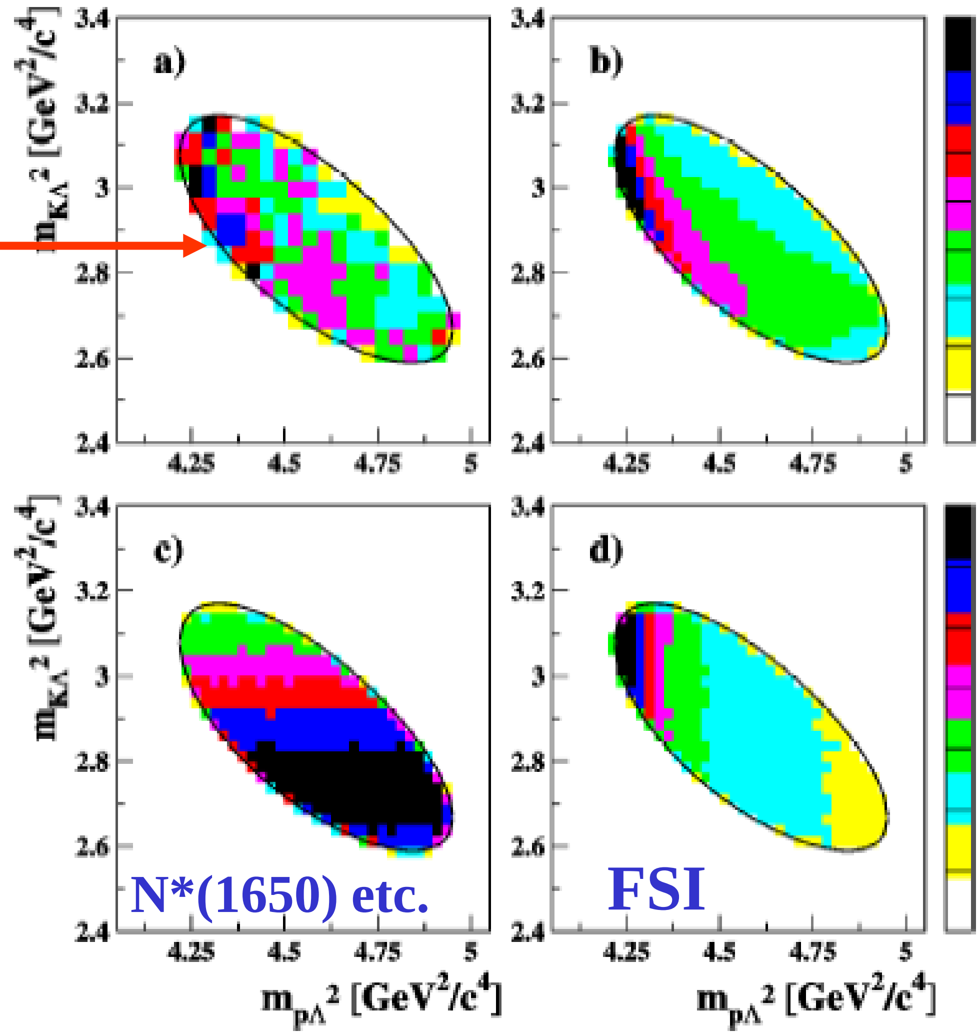
Tsushima,Sibirtsev,Thomas, PRC59 (1999) 369, without including N*(1535)

FSI vs N*(1535) contribution in pp → p K^+ Λ

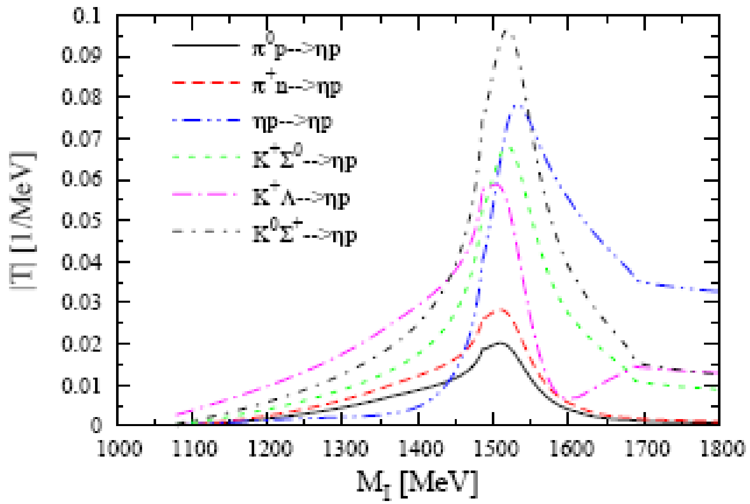
B.C.Liu & B.S.Zou, Phys. Rev. Lett. 98 (2007) 039102 (reply)
A.Sibirtsev et al., Phys. Rev. Lett. 98 (2007) 039101 (comment)

COSY-TOF data
S. Abdel-Samad *et al.*,
Phys.Lett.B632:27(2006)

Both FSI & N*(1535) are needed !



Interference between N*(1535) and non-resonant FSI



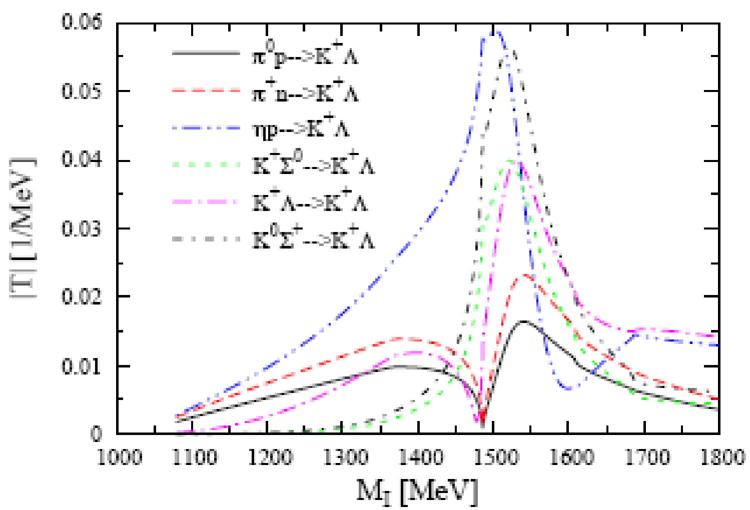


FIG. 1: The moduli of the transition amplitudes in different channels leading to the ηp and $K^+\Lambda$ final states.

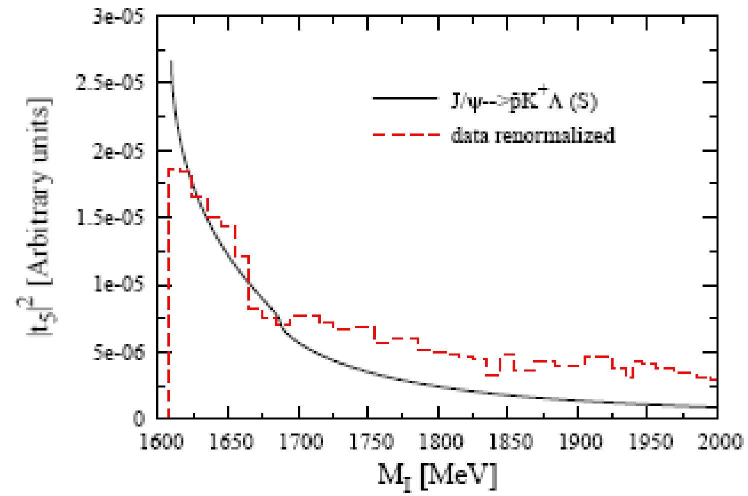


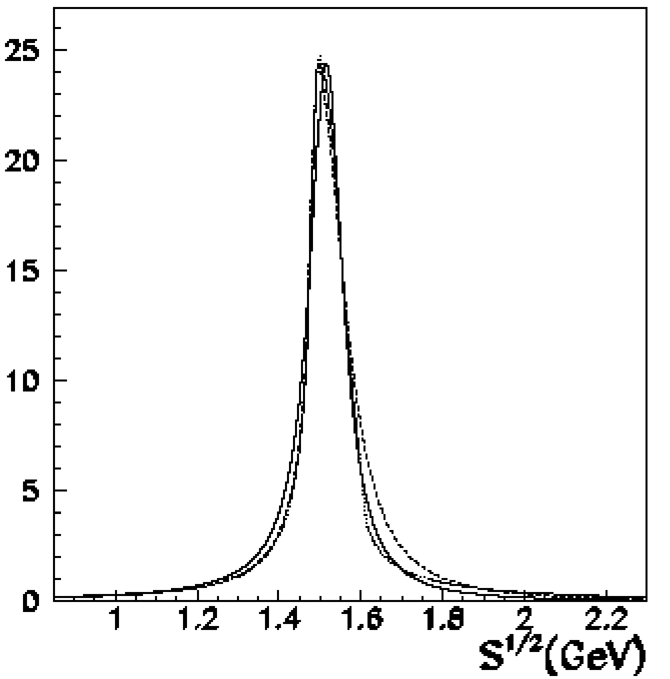
FIG. 4: Modulus squared of the amplitude of $J/\psi \to \bar{p}K^+\Lambda$ in comparison with the equivalent quantity obtained experimentally (integrated cross section weighted by phase space) [17].

$$R = \frac{|g_{N^*(1535)K\Lambda}|}{|g_{N^*(1535)\eta N}|} = 0.5 \sim 0.7.$$

L.S.Geng, E.Oset, B.S.Zou, M.Döring, Phys.Rev.C79:025203,2009

Mass of N*(1535)

$$BW(p_{N^*}) = \frac{1}{M_{N^*}^2 - s - iM_{N^*}\Gamma_{N^*}(s)}$$



(1)

$$\Gamma_{N^*}(s) = 98 MeV$$

$$M_{N^*} = 1515 MeV$$

(2) $$\Gamma_{N^*}(s) = \Gamma_{N^*}^0 \left(0.5\frac{\rho_{\pi N}(s)}{\rho_{\pi N}(M_{N^*}^2)} + 0.5\frac{\rho_{\eta N}(s)}{\rho_{\eta N}(M_{N^*}^2)}\right) = \Gamma_{N^*}^0 \left[0.8\rho_{\pi N}(s) + 2.1\rho_{\eta N}(s)\right]$$

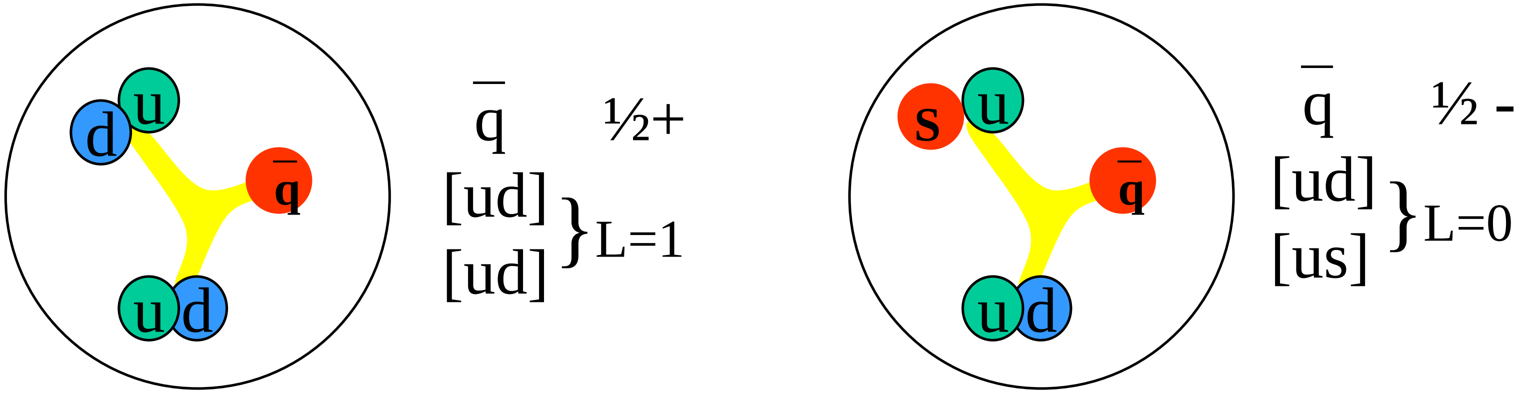
$$M_{N^*} = 1535 MeV \text{ and } \Gamma_{N^*}^0 = 150 MeV$$

(3) $$\Gamma_{N^*}(s) = \Gamma_{N^*}^0 \left[0.8\rho_{\pi N}(s) + 2.1\rho_{\eta N}(s) + 3.5\rho_{\Lambda K}(s)\right]$$

$$M_{N^*} \approx 1400 MeV$$

$$\Gamma_{N^*}^0 = 270 MeV$$

Nature of N*(1535) and its 1/2⁻ octet partner



Zhang et al, hep-ph/0403210

N*(1535) ~ uud (L=1) + ε [ud][us] $\bar{s}$ + …

N*(1440) ~ uud (n=1) + ξ [ud][ud] $\bar{d}$ + …

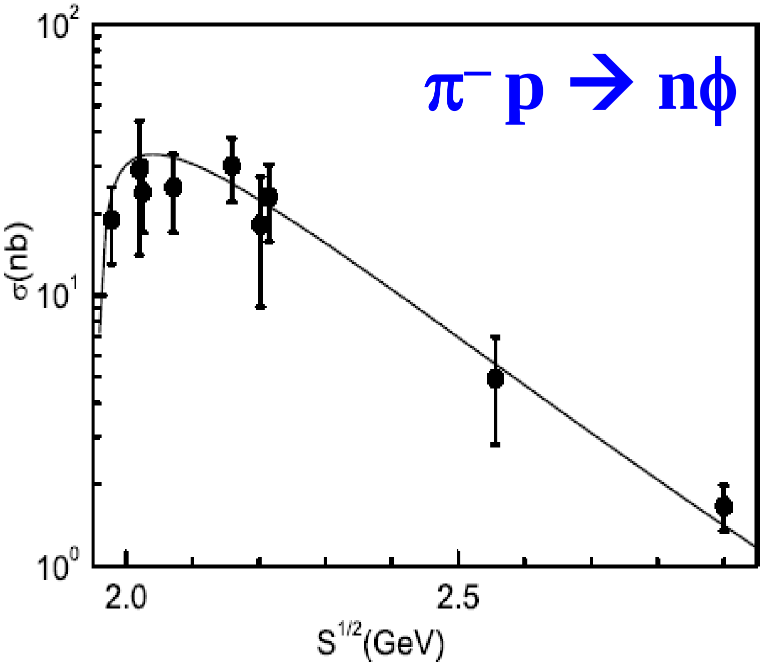
Λ*(1405) ~ uds (L=1) + ε [ud][su] $\bar{u}$ + …

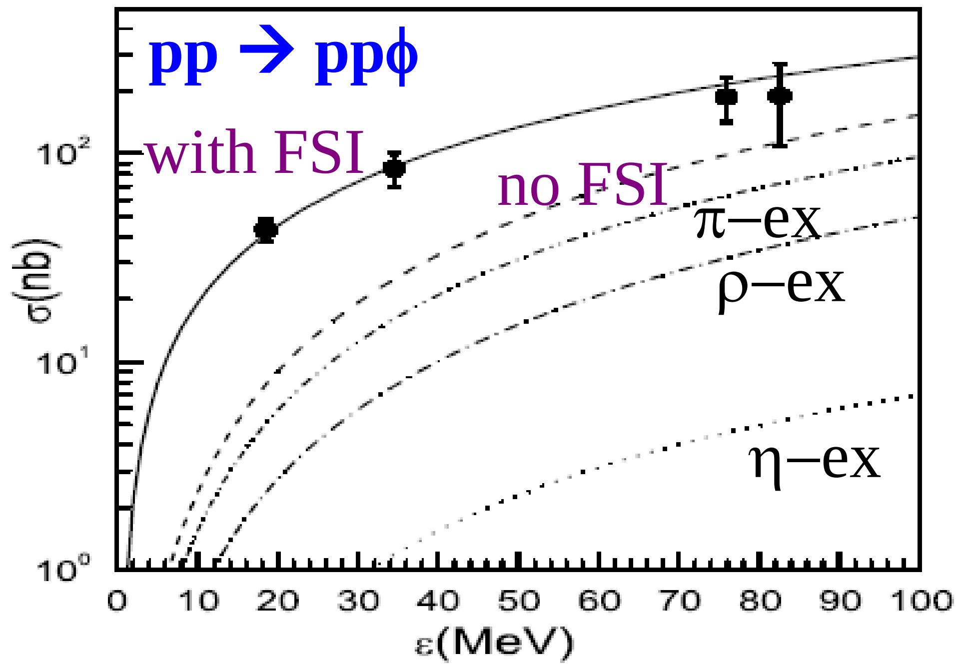
N*(1535): [ud][us] $\bar{s}$ → larger coupling to Nη, Nη', Nϕ & KΛ, weaker to Nπ & KΣ, and heavier !

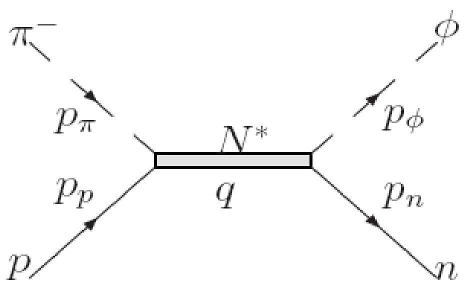
B.C.Liu, B.S.Zou, PRL 96(2006)042002

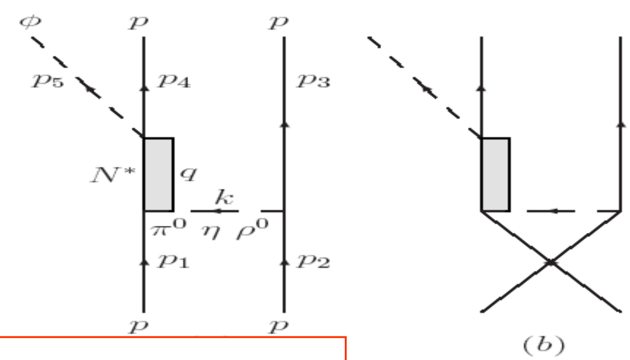
Evidence for large $g_{N^*N\phi}$ from $\pi^- p \to n\phi$ & $pp \to pp\phi$

Xie, Zou & Chiang, PRC77(2008)015206









Evasion of OZI rule by N*(1535) !

Sub-threshold $\Delta^{++*}(1620)$ in $pp \rightarrow nK^+\Sigma^+$

J.J.Xie, B.S.Zou, PLB649 (2007) 405

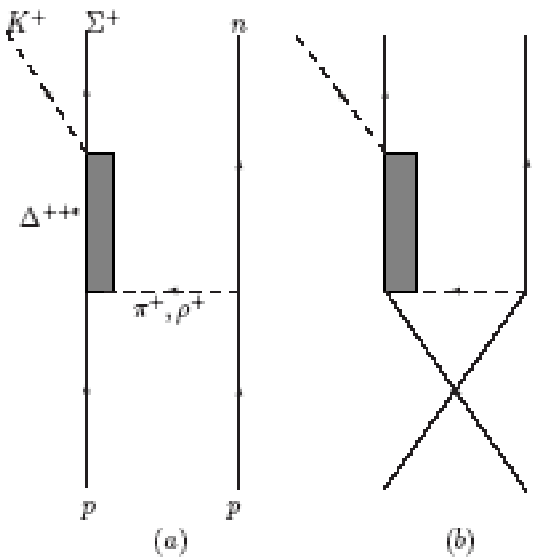
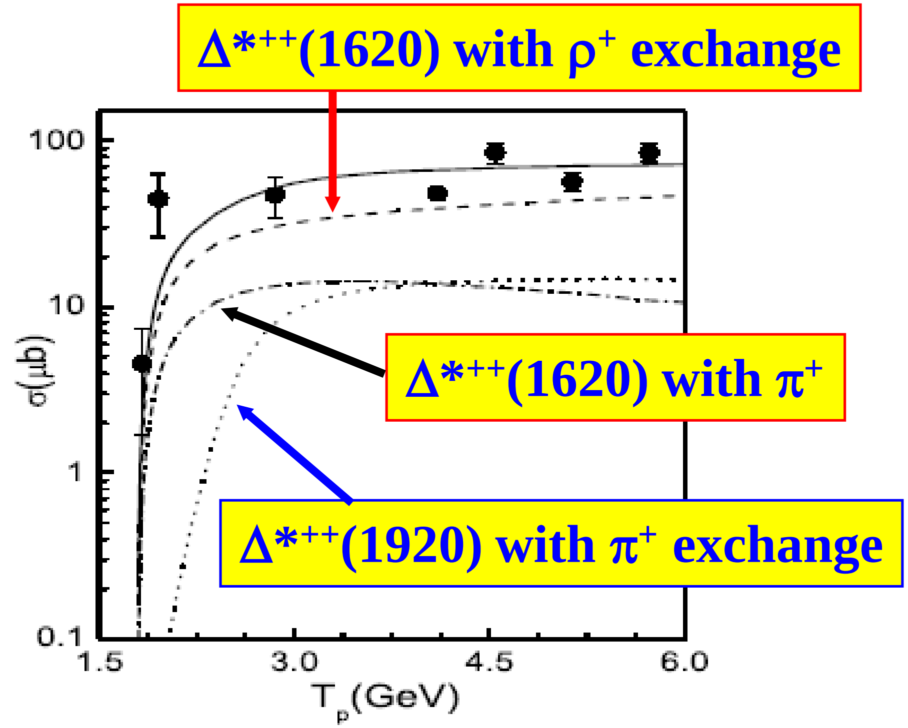


Figure 1: Feynman diagrams for $pp \rightarrow nK^+\Sigma^+$ reaction.



t-channel ρ-exchange plays important role !

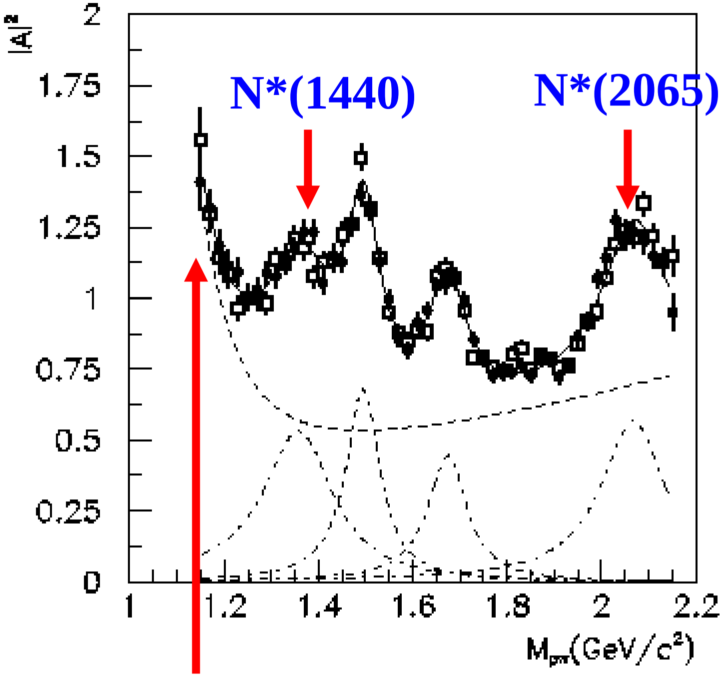
Summary for our study on $J/\psi \rightarrow P K^- \bar{\Lambda}$ and $P P \rightarrow P K^+ \Lambda$

1) **$K\Lambda$ near-threshold enhancement due to sub-threshold N*(1535) with large $g_{N^*K\Lambda}$**

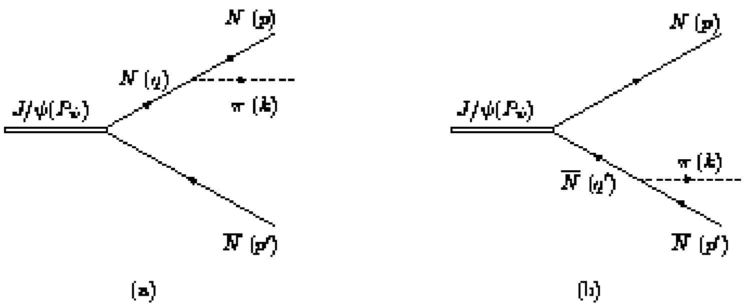
2) **Larger [ud][us] $\bar{s}$ component in N*(1535) makes it coupling stronger to strangeness and heavier !**

Observation of Two New N^* Peaks in $J/\psi \to p\pi^-\bar{n}$ and $\bar{p}\pi^+n$ Decays

BES Collaboration



The first experiment "see" N*(1440) and a "missing" N*(2065) peak



Nucleon-pole diagrams for $J/\psi \to \pi N \bar{N}$ decay.

Off-shell nucleon contribution

If fitting it with a simple BW formula, its mass and width are not compatible with any PDG known particle; and it has an "un-usual large BR" to πN !

But it is NOT a new resonance !

Comment on BR of sub-threshold resonances

$a_0(980)$ has large BR to $\bar{K}K$

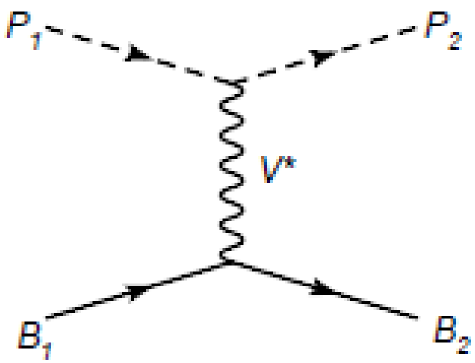
X(1859) has large BR to $\bar{p}p$?

Nucleon has large BR to πN

One should either change "large" to "zero"
or change "BR" to "coupling"

4. From $K\Sigma$, Kp → $\bar{D}\Sigma_c$, $\bar{D}_s\Lambda_c$ → $B\Sigma_b$, $B_s\Lambda_b$ bound states

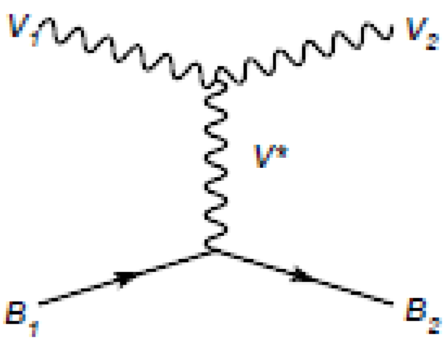
J.J.Wu, R.Molina, E.Oset, B.S.Zou, PRL 105 (2010) 232001



$$\mathcal{L}_{VVV} = ig\langle V^\mu[V^\nu, \partial_\mu V_\nu]\rangle$$
$$\mathcal{L}_{PPV} = -ig\langle V^\mu[P, \partial_\mu P]\rangle$$
$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)$$

$$V_{ab(P_1B_1\to P_2B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1}+E_{P_2}),$$

$$V_{ab(V_1B_1\to V_2B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1}+E_{V_2})\vec{\epsilon}_1\cdot\vec{\epsilon}_2,$$



$$T = [1 - VG]^{-1}V$$

$$T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

$\bar{D}\Sigma_c$ with different approaches:

J.J.Wu, R.Molina, E.Oset, B.S.Zou, PRL 105 (2010) 232001 -- **Valencia**

J.J.Wu, T.S.H.Lee, B.S.Zou, PRC85(2012)044002 -- **EBAC**

C.W.Shen, D.Ronchen, U.Meissner, B.S.Zou, CPC42(2018)023106 --**JuBonn**

$\bar{D}\Sigma_c$ Valencia 4269MeV

EBAC ~ 4309MeV

$$T = V + VG^{Valencia}T$$

$$G^{Valencia} = \int \frac{dp^4}{(2\pi)^4} \frac{2m_B}{(p^2 - m_B^2)((P-p)^2 - m_M^2)}$$

$$G_V^{\mu\nu} = \frac{p_V^\mu p_V^\nu / m_V^2 - g^{\mu\nu}}{p_V^2 - m_V^2} \sim \frac{p_V^\mu p_V^\nu / m_V^2 - g^{\mu\nu}}{-m_V^2} \sim \frac{-g^{\mu\nu}}{-m_V^2}$$

$$V_{ab(P_1B_1 \to P_2B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_1})$$

$$V_{ab(V_1B_1 \to V_2B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1} + E_{V_2})\vec{\varepsilon}_1 \cdot \vec{\varepsilon}_2$$

$$T_{ab} = \lim_{\sqrt{s} \to z_R} \frac{g_a g_b}{\sqrt{s} - z_R}$$

$$T(q_1, q_2) = V + \int q_3^2 dq_3 \, V(q_1, q_3) G(q_3) T(q_3, q_2)$$

$$G(q_3) = \frac{1}{\sqrt{S} - E_M - E_B},$$

$$VF^{I,V}_{P_1B_1 -> P_2B_2} = C^{I,V}_{P_1B_1 -> P_2B_2} \frac{M_V^2}{4f^2} G_V^{\mu\nu} \bar{u}_{B_2} \gamma_\mu (p_{P_1} + p_{P_2})_\nu u_{B_1}$$

$$VF^{I,V}_{V_1B_1 -> V_2B_2} = C^{I,V}_{V_1B_1 -> V_2B_2} \frac{M_V^2}{4f^2} G_V^{\mu\nu} \bar{u}_{B_2} \gamma_\mu (p_{V_1} + p_{V_2})_\nu u_{B_1} (-\varepsilon_{V_1} \cdot \varepsilon_{V_2})$$

JuBonn ~ 4295MeV

Hidden charm N* by other approaches

$\bar{D}\Sigma_c$ + $\bar{D}^*\Sigma_c$ coupled channel state ~ 4.26 GeV

C.W.Xiao, J.Nieves, E.Oset, PRD 88 (2013) 056012

$\bar{D}\Sigma_c$ state in a chiral quark model ~ 4.3 GeV

W.L.Wang, F.Huang, Z.Y.Zhang, B.S.Zou, PRC84(2011)015203

$\bar{D}\Sigma_c$ state in EBAC-DCC model ~ 4.3 GeV

J.J.Wu, T.S.H.Lee, B.S.Zou, PRC85(2012)044002

$\bar{D}\Sigma_c$ state in Schoedinger Equation method ~ 4.3 GeV

Z.C.Yang, Z.F. Sun, J. He, X.Liu, S.L.Zhu, CPC36(2012)6

$\bar{c}cqqq$ with 3 kinds of qq hyperfine interaction ~ 4.1 GeV

S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, EPJA48(2012)61

$\bar{D}\Sigma_c - \eta_c N - \eta' N$ coupled channel state ~ 3.5 GeV

J. Hofmann, M.F.M. Lutz, Nucl. Phys. A 763 (2005) 90

$\bar{c}c$-N bound states in topological soliton model ~ 3.9 GeV

C. Gobbi, D.O. Riska, N.N. Scoccola, Phys. Lett. B 296 (1992) 166

J.J.Wu, R.Molina, E.Oset, B.S.Zou, PRL 105 (2010) 232001

	(I,S)	z_R (MeV)		g_a		J^P
N*	$(1/2,0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$		$1/2^-$
		4269	2.85	0		
Λ*	$(0,-1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$	
		4213	1.37	3.25	0	
		4403	0	0	2.64	

TABLE III: Pole positions z_R and coupling constants g_a for the states from $PB \to PB$.

	(I,S)	z_R (MeV)		g_a		
N*	$(1/2,0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$		$1/2^-$, $3/2^-$
		4418	2.75	0		
Λ*	$(0,-1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$	
		4370	1.23	3.14	0	
		4550	0	0	2.53	

TABLE IV: Pole position and coupling constants for the bound states from $VB \to VB$.

J.J.Wu, R.Molina, E.Oset, B.S.Zou, PRL 105 (2010) 232001

	(I,S)	M	Γ	Γ_i						J^P
N*	$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$	
		4261	56.9	3.8	8.1	3.9	17.0		23.4	$1/2^-$
	$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$	
Λ*		4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8	
		4394	43.3	0	10.6	7.1	3.3	5.8	16.3	

TABLE V: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $PB \to PB$, with units in MeV.

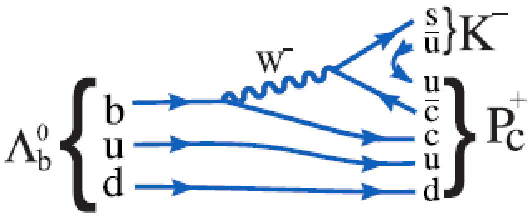
	(I,S)	M	Γ	Γ_i						
N*	$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$	
		4412	47.3	3.2	10.4	13.7			19.2	$1/2^-$, $3/2^-$
	$(0,-1)$			$\bar{K}^* N$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$	
Λ*		4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4	
		4544	36.6	0	8.8	9.1	0	5.0	13.8	

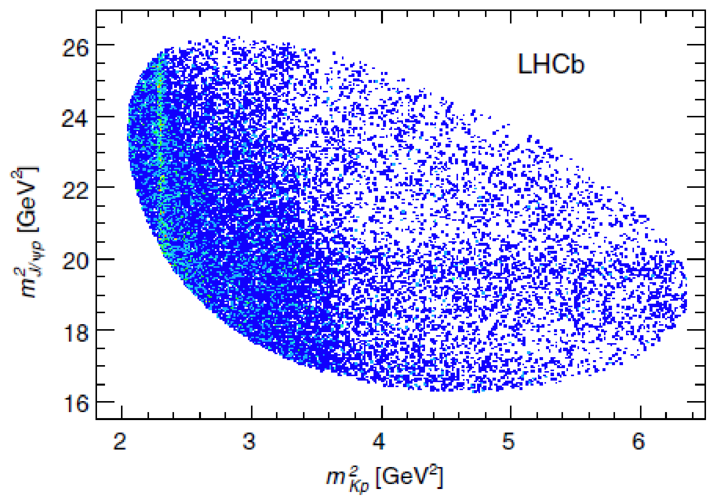
TABLE VI: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $VB \to VB$ with units in MeV.

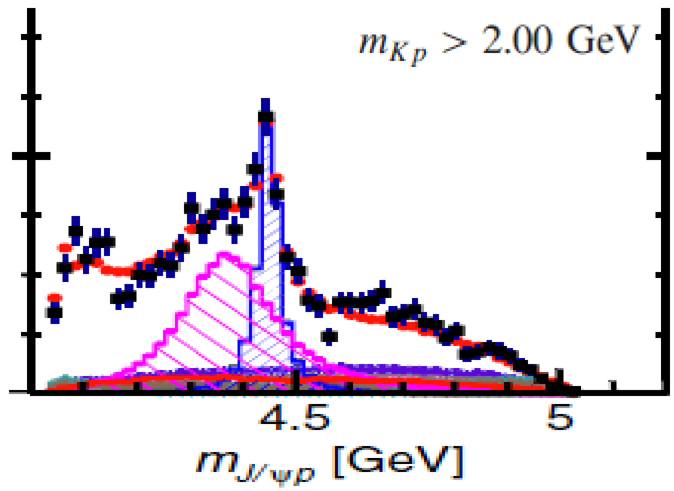
LHCb observation of 2 pentaquarks

LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$







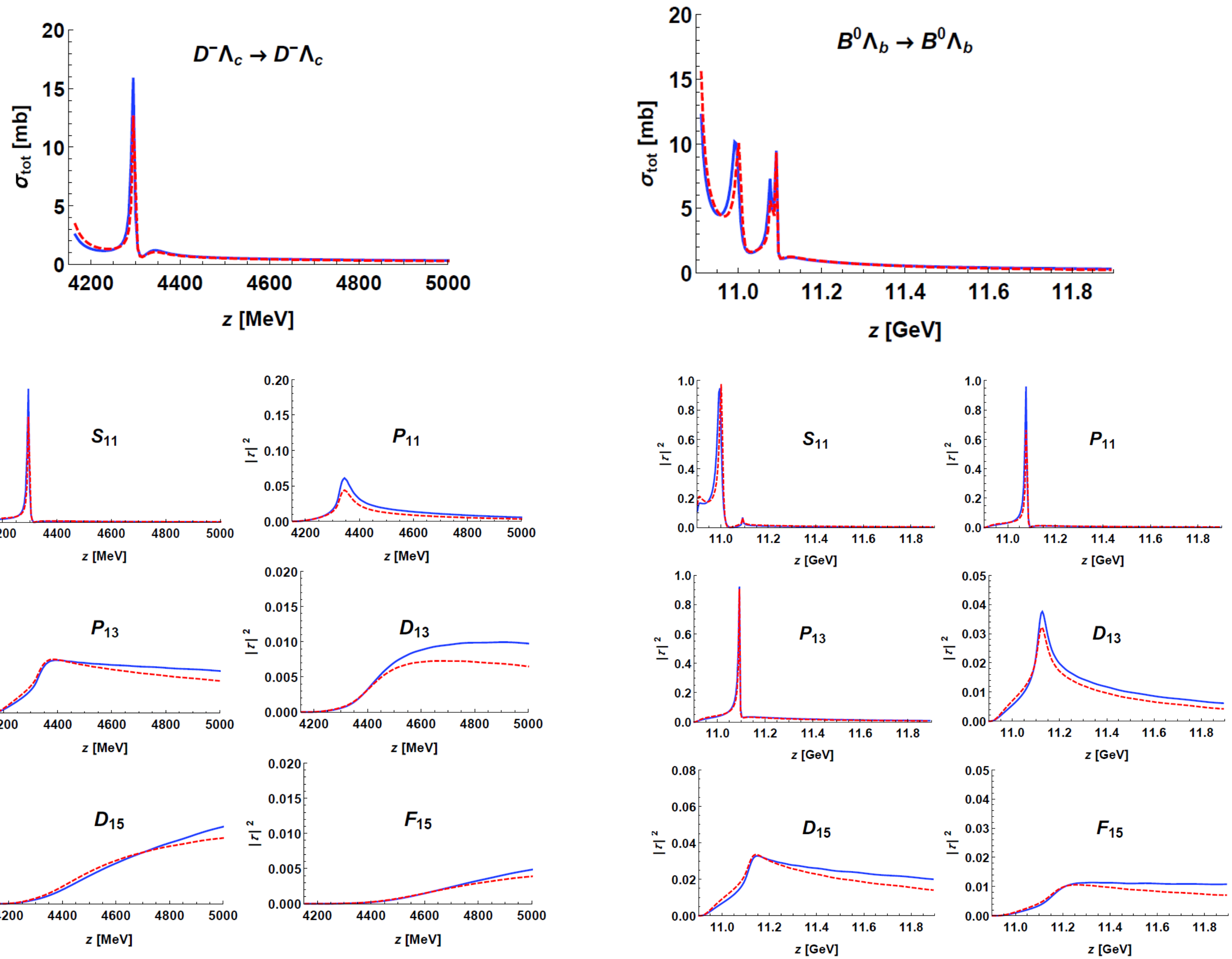
1) 4380±8±29 MeV , 205±18±86 MeV, $P_c^+(4380)$

2) 4450±2±3 MeV , 39±5±19 MeV, $P_c^+(4450)$

The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

$\bar{D}\Lambda_c - \bar{D}\Sigma_c$ and $B\Lambda_b - B\Sigma_b$ dynamical coupled channel study

C.W.Shen, Roechen, Meissner, Zou, CPC42(2018) 023106



More pentaquarks with hidden beauty than with hidden charm

Conclusion

Similar to deuteron, there are many hadronic molecules

Most newly observed exotic states fit into this picture

F.K.Guo, C.Hanhart, U.Meissner,Q.Wang,Q.Zhao,B.Zou,
“Hadonic molecules”, **Rev.Mod.Phys.90 (2018)015004**