

# Construction and decay of hadrons in the heavy quark sector

E. Oset, W.H. Liang, J.J. Xie, M. Bayar, R. Pavao, J. Nieves, V. Debastiani, Z.S Xie, L. Roca, S. Sakai

Chiral Lagrangians and the local hidden gauge approach

Pseudoscalar meson-baryon and vector-baryon interaction

Extension to the heavy quark sector. The BD interaction and bound states

Generation of the  $\Lambda_c(2595)$  ( $1/2^-$ ) and  $\Lambda_c(2625)$  ( $3/2^-$ ) states

Weak decays of Hadrons:  $B^0 \rightarrow J/\psi \pi^+ \pi^-$ ;  $B^0 s \rightarrow J/\psi \pi^+ \pi^-$

$\chi_{c1} \rightarrow \eta \pi \pi$  and  $f_0(500)$ ,  $f_0(980)$ ,  $a_0(980)$  production

The  $\Lambda_b \rightarrow \pi^- \Lambda_c(2595)$ ,  $\Lambda_b \rightarrow \pi^- \Lambda_c(2595)$  reactions

The semileptonic  $\Lambda_b \rightarrow \bar{v} \Lambda_c(2595)$ ,  $\bar{v} \Lambda_c(2595)$  reactions

Extension to  $\Xi_b$  decays into the  $\Xi_c$  ( $1/2^-$ ) and  $\Xi_c$  ( $3/2^-$ ) resonances

## Hidden gauge formalism for vector mesons, pseudoscalars and photons

Bando et al. PRL, 112 (85); Phys. Rep. 164, 217 (88); U.G. Meissner Phys Rep 1988

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}_{III} \quad (1)$$

with

$$\mathcal{L}^{(2)} = \frac{1}{4} f^2 \langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + \chi^\dagger U \rangle \quad (2)$$

$$\mathcal{L}_{III} = -\frac{1}{4} \langle V_{\mu\nu} V^{\mu\nu} \rangle + \frac{1}{2} M_V^2 \langle [V_\mu - \frac{i}{g} \Gamma_\mu]^2 \rangle, \quad (3)$$

where  $\langle \dots \rangle$  represents a trace over  $SU(3)$  matrices. The covariant derivative is defined by

$$D_\mu U = \partial_\mu U - ieQ A_\mu U + ieU Q A_\mu, \quad (4)$$

with  $Q = \text{diag}(2, -1, -1)/3$ ,  $e = -|e|$  the electron charge, and  $A_\mu$  the photon field. The chiral matrix  $U$  is given by

$$U = e^{i\sqrt{2}\phi/f} \quad (5)$$

$$\phi \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}, \quad V_\mu \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu \quad (6)$$

In  $\mathcal{L}_{III}$ ,  $V_{\mu\nu}$  is defined as

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu] \quad (9)$$

and

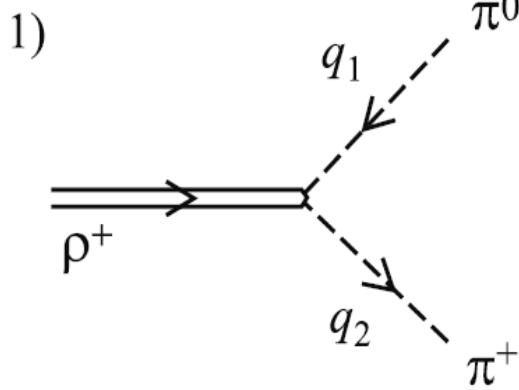
$$\Gamma_\mu = \frac{1}{2}[u^\dagger(\partial_\mu - ieQA_\mu)u + u(\partial_\mu - ieQA_\mu)u^\dagger] \quad (10)$$

with  $u^2 = U$ . The hidden gauge coupling constant  $g$  is related to  $f$  and the vector meson mass ( $M_V$ ) through

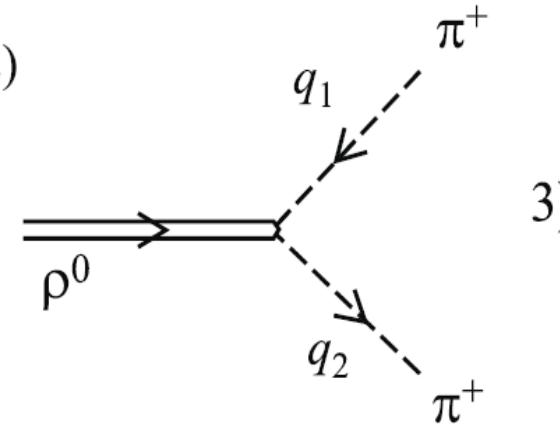
$$g = \frac{M_V}{2f}, \quad (11)$$

$$\begin{aligned} \mathcal{L}_{V\gamma} &= -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q \rangle \\ \mathcal{L}_{V\gamma PP} &= e \frac{M_V^2}{4gf^2} A_\mu \langle V^\mu (Q\phi^2 + \phi^2 Q - 2\phi Q\phi) \rangle \\ \mathcal{L}_{VPP} &= -i \frac{M_V^2}{4gf^2} \langle V^\mu [\phi, \partial_\mu \phi] \rangle \end{aligned}$$

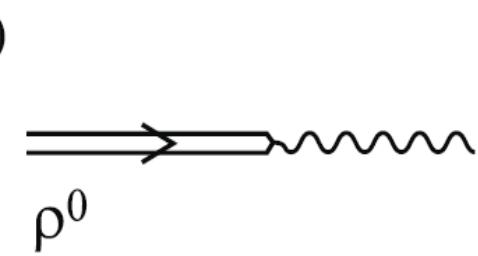
$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2} \langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu \rangle , \quad \mathcal{L}_{III}^{(3V)} = ig \langle (\partial_\mu V_\nu - \partial_\nu V_\mu) V^\mu V^\nu \rangle ,$$



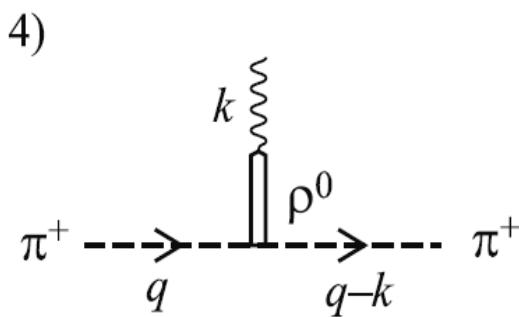
(a)



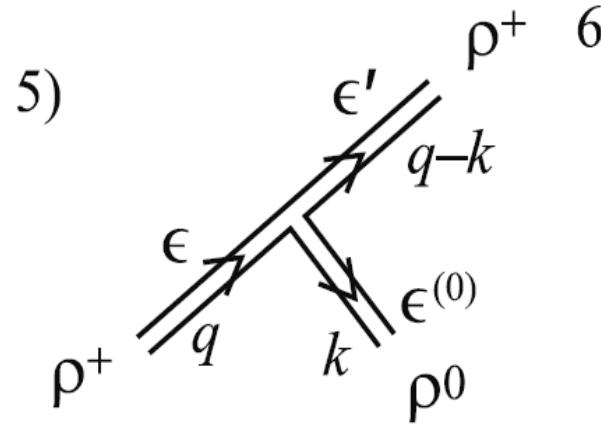
3)



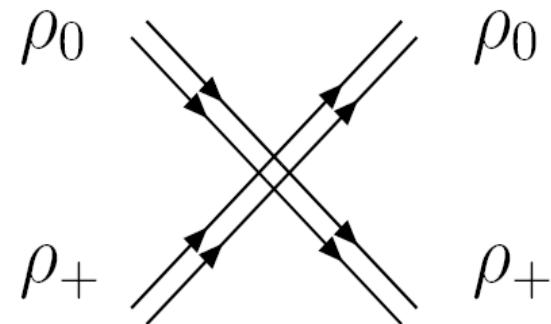
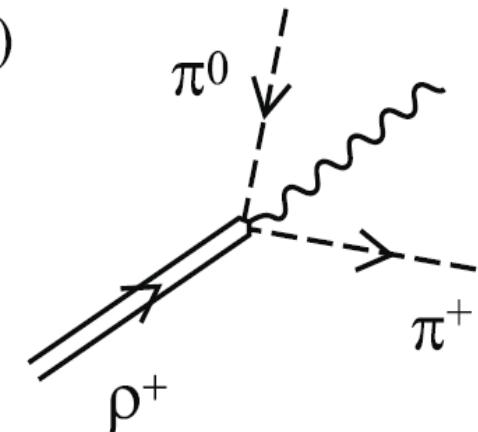
(c)



5)



6)



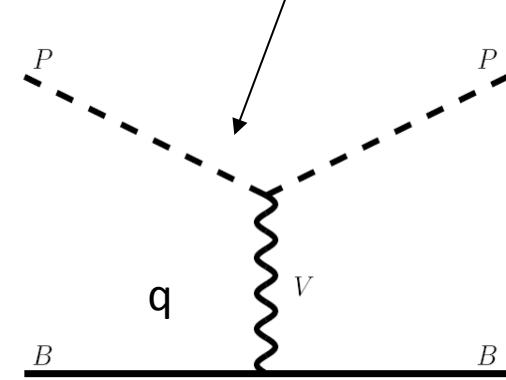
# Extension to the baryon sector

$$\mathcal{L}_{BBV} = -\frac{g}{2\sqrt{2}} (tr(\bar{B}\gamma_\mu[V^\mu, B]) + tr(\bar{B}\gamma_\mu B)tr(V^\mu))$$

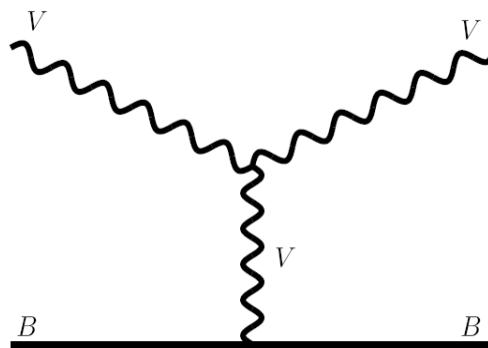
Vector propagator  $1/(q^2 - M_V^2)$

In the approximation  $q^2/M_V^2 = 0$  one recovers the chiral Lagrangians Weinberg-Tomozawa term. For consistency, for vectors we take  $\vec{q}/M_V = 0$

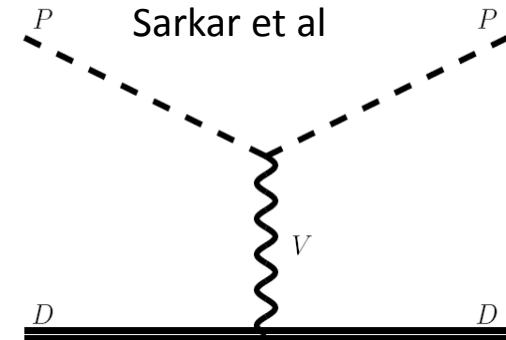
> 200 works



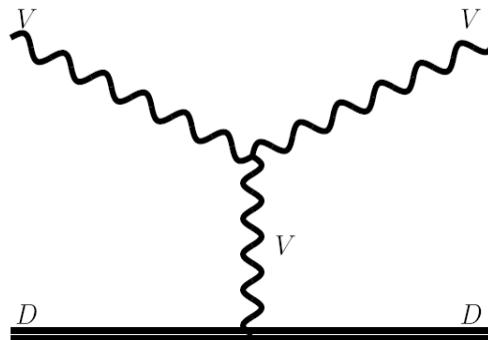
A. Ramos, E. O.



Kolomeitsev et al  
Sarkar et al



J. Vijande, P. Gonzalez. E.O  
PRC, 2009  
Sarkar, Vicente Vacas, B.X.Sun, E.O



# Vector octet – baryon octet interaction

$$\begin{aligned}\mathcal{L}_{III}^{(3V)} &= ig \langle V^\nu \partial_\mu V_\nu V^\mu - \partial_\nu V_\mu V^\mu V^\nu \rangle \\ &= ig \langle V^\mu \partial_\nu V_\mu V^\nu - \partial_\nu V_\mu V^\mu V^\nu \rangle \\ &= ig \langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu) V^\nu \rangle ,\end{aligned}$$

$$\mathcal{L}_{VPP} = -ig \operatorname{tr} ([P, \partial_\mu P] V^\mu) \quad \downarrow \quad B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

$V^\nu$  cannot correspond to an external vector.

Indeed, external vectors have only spatial components in the approximation of neglecting three momenta,  $\varepsilon^0 = k/M$  for longitudinal vectors,  $\varepsilon^0 = 0$  for transverse vectors. Then  $\partial_\nu$  becomes three momentum which is neglected.  $\rightarrow$

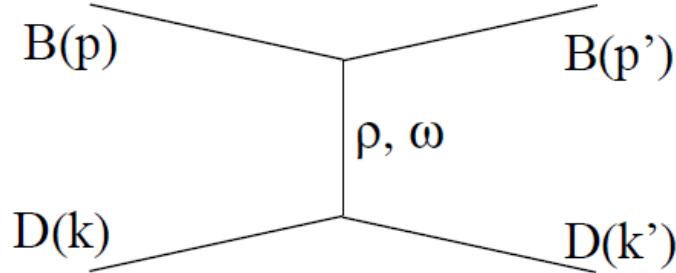
$V^\nu$  corresponds to the exchanged vector.  $\rightarrow$  complete analogy to VPP

Extra  $\varepsilon_\mu \varepsilon^\mu = -\varepsilon_i \varepsilon_i$  but the interaction is formally identical to the case of PB  $\rightarrow$  PB

In the same approximation only  $\gamma^0$  is kept for the baryons  $\rightarrow$  the spin dependence is only  $\varepsilon_i \varepsilon_i$  and the states are degenerate in spin 1/2 and 3/2

$$V_{ij} = -C_{ij} \frac{1}{4f^2} (k^0 + k'^0) \vec{\epsilon} \vec{\epsilon}' \quad K^0 \text{ energy of vector mesons}$$

# Extrapolation to the heavy quark sector. The BD interaction



S. Sakai, L. Roca , E.O,  
Arxiv 1704. 02196

In SU(3)

$$\mathcal{L}_{VPP} = -ig \langle V^\mu [P, \partial_\mu P] \rangle$$

Extrapolation to SU(4):

$$P = \begin{pmatrix} 0 & 0 & B^+ & \bar{D}^0 \\ 0 & 0 & B^0 & D^- \\ B^- & \bar{B}^0 & 0 & B_c^- \\ D^0 & D^+ & B_c^+ & 0 \end{pmatrix} \quad V = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & B^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & B^{*0} & D^{*-} \\ B^{*-} & \bar{B}^{*0} & 0 & B_c^{*-} \\ D^{*0} & D^{*+} & B_c^{*+} & 0 \end{pmatrix}$$

How good is it? → exact if the heavy quark is a spectator

$$B^0 B^0 \rho^0, \quad D^+ D^+ \rho^0 \quad B^0 = \bar{b}d, D^+ = c\bar{d}$$

$$g \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d}) , \quad \text{for } \rho^0 \text{ exchange,}$$

$$g \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) , \quad \text{for } \omega \text{ exchange,}$$

**ρ vector coupling to quarks**       $-g \frac{1}{\sqrt{2}} ((u\partial_\mu \bar{u} - \partial_\mu u \bar{u}) - (d\partial_\mu \bar{d} - \partial_\mu d \bar{d}))$

**ω vector coupling**      ..... +

for  $B^0 B^0 \rho^0$        $-\langle \bar{b}d | g \frac{1}{\sqrt{2}} ((u\partial_\mu \bar{u} - \partial_\mu u \bar{u}) - (d\partial_\mu \bar{d} - \partial_\mu d \bar{d})) | \bar{b}d \rangle$   
 $= -g \frac{1}{\sqrt{2}} (-ip_\mu - ip'_\mu)$

for  $D^+ D^+ \rho^0$        $-\langle c\bar{d} | g \frac{1}{\sqrt{2}} ((u\partial_\mu \bar{u} - \partial_\mu u \bar{u}) - (d\partial_\mu \bar{d} - \partial_\mu d \bar{d})) | c\bar{d} \rangle$   
 $= -g \frac{1}{\sqrt{2}} (ip_\mu + ip'_\mu)$

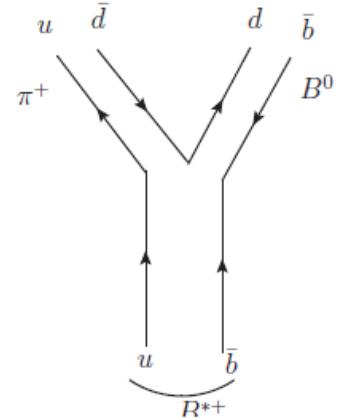
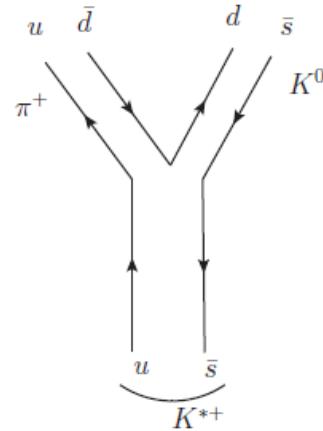
**At threshold**       $p_\mu + p'_\mu \rightarrow 2m_q \delta_{\mu 0}$

$K^0 \bar{K}^0 \rho^0$       is like       $B^0 B^0 \rho^0$ ,      ( $K^0 = s\bar{d}$ ) , hence same results at quark level

For  $\omega$  exchange we get opposite signs, and so on : SU(2) symmetry

## At the hadron macroscopic level

$$S^{mic} = 1 - it \sqrt{\frac{2m_L}{2E_L}} \sqrt{\frac{2m'_L}{2E'_L}} \sqrt{\frac{1}{2\omega_\pi}} \frac{1}{\mathcal{V}^{3/2}} (2\pi)^4 \delta(P_{in} - P_{out}),$$



$$S_{K^*}^{mac} = 1 - it_{K^*} \frac{1}{\sqrt{2\omega_{K^*}}} \frac{1}{\sqrt{2\omega_K}} \frac{1}{\sqrt{2\omega_\pi}} \frac{1}{\mathcal{V}^{3/2}} (2\pi)^4 \delta(P_{in} - P_{out}),$$

$$S_{B^*}^{mac} = 1 - it_{B^*} \frac{1}{\sqrt{2\omega_{B^*}}} \frac{1}{\sqrt{2\omega_B}} \frac{1}{\sqrt{2\omega_\pi}} \frac{1}{\mathcal{V}^{3/2}} (2\pi)^4 \delta(P_{in} - P_{out}).$$

W.H. Liang, C. W. Xiao, E. O  
PRD 2014

At threshold  $\rightarrow$

$$\frac{t_{B^0 B^0 \rho^0}}{t_{K^0 K^0 \rho^0}} = \frac{M_B}{M_K}$$

Spectator results:

$$\text{SU(3)} \quad -it_{K^0 K^0 \rho^0, \mu} = -g \frac{1}{\sqrt{2}} (-iM_K - iM_K) \delta_{\mu 0}, \rightarrow -it_{B^0 B^0 \rho^0, \mu} = -g \frac{1}{\sqrt{2}} (-iM_B - iM_B) \delta_{\mu 0}$$

in covariant form  $\rightarrow$

$$-it_{B^0 B^0 \rho^0, \mu} = -g \frac{1}{\sqrt{2}} (-ip_\mu - ip'_\mu)$$

which is the result with the SU(4) formalism. NOTE: SINCE b, c QUARKS ARE SPECTATORS, observables are then independent of the heavy quarks. Within this picture we obtain good agreement with the  $D^* \rightarrow D \pi$  decay, and lattice results for the  $B^* B \pi$  coupling.

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

$$G = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_B^2 + i\epsilon} \frac{1}{(q - P)^2 - m_D^2 + i\epsilon}$$

$$G = \int_0^{q_{\max}} \frac{d^3 q}{(2\pi)^3} \frac{\omega_D + \omega_B}{2\omega_D \omega_B} \frac{1}{(P^0)^2 - (\omega_D + \omega_B)^2 + i\epsilon}$$

J. X. Lu, Y. Zhou, H. X. Chen, J. J. Xie and L. S. Geng  
Phys. Rev. D **92** (2015) no.1, 014036.

$$q_{\max} \in [400, 600] \text{ MeV}$$

	$I(J^P)$	$\sqrt{s_p}$	$B$	$g$	$a$ [fm]
$BD$	$0(0^+)$	7133 7111	15 38	33484  49867	-1.78 -1.45
$B^*D$	$0(1^+)$	7179 7156	15 38	33742  50243	-1.78 -1.45
$BD^*$	$0(1^+)$	7270 7247	16 39	35171  52262	-1.75 -1.45
$B^*D^*$	$0(0^+, 1^+, 2^+)$	7316 7293	16 39	35438  52652	-1.75 -1.45
$B\bar{D}$	$0(0^+)$	7146 7140	1.7 8.4	13225  23296	-3.77 -1.93
$B^*\bar{D}$	$0(1^+)$	7192 7186	1.7 8.4	13357  23494	-3.74 -1.93
$B\bar{D}^*$	$0(1^+)$	7284 7277	2.1 9.5	14539  24915	-3.32 -1.83
$B^*\bar{D}^*$	$0(0^+, 1^+, 2^+)$	7330 7322	2.1 9.5	14678  25123	-3.31 -1.83
$B\bar{D}$	$1(0^+)$	—	—	—	-0.53 -0.46
$B^*\bar{D}$	$1(1^+)$	—	—	—	-0.53 -0.46
$B\bar{D}^*$	$1(1^+)$	—	—	—	-0.55 -0.46
$B^*\bar{D}^*$	$1(0^+, 1^+, 2^+)$	—	—	—	-0.55 -0.47

They show that in the unitary coupled channels, heavy quark invariance requires the use of the same cutoff independent of flavor.

→ Similar to DK that generates the  $D_{s0}(2317)$

# Generation of the $\Lambda_c(2595)$ ( $1/2^-$ ) and $\Lambda_c(2625)$ ( $3/2^-$ )

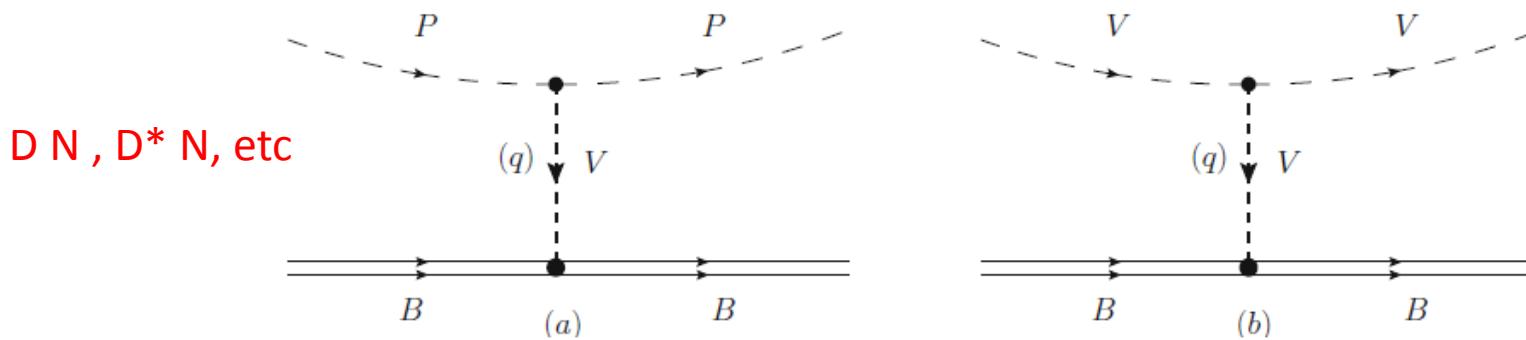
Early work: Hofmann, Lutz, NPA 2005; Mizutani, Ramos PRC 2006,

Only pseudoscalar-baryon states in coupled channels

Romanets, Tolos, Garcia-Recio, Nieves, Salcedo, Timmermans, SU(8) mixing PB and VB  
PRD 2012

We use the local Hidden Gauge Approach (Bando et al.) :

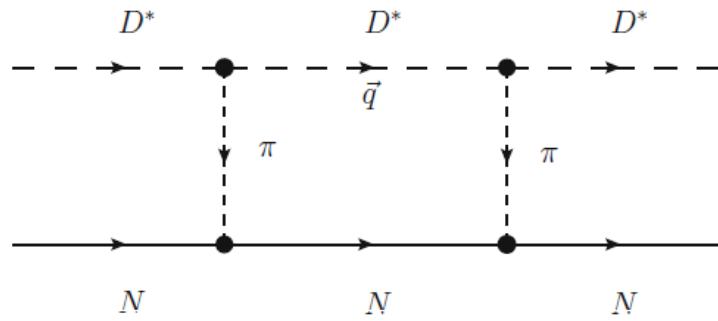
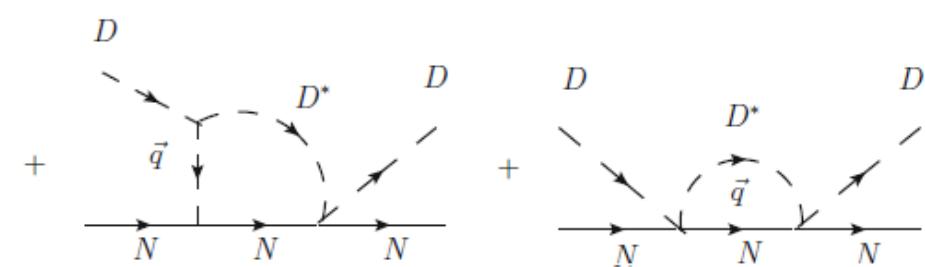
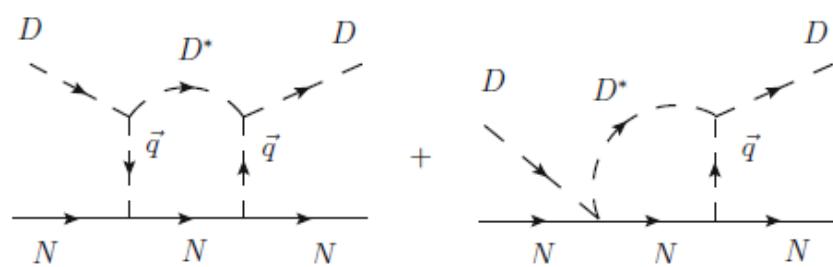
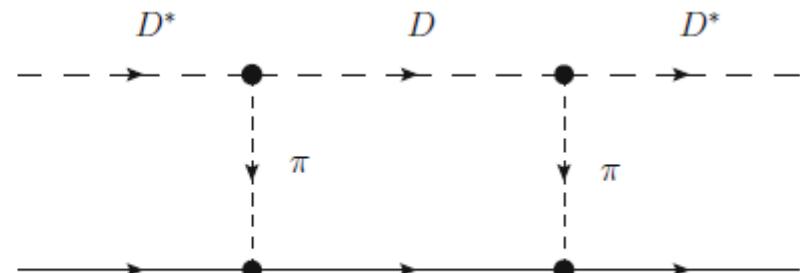
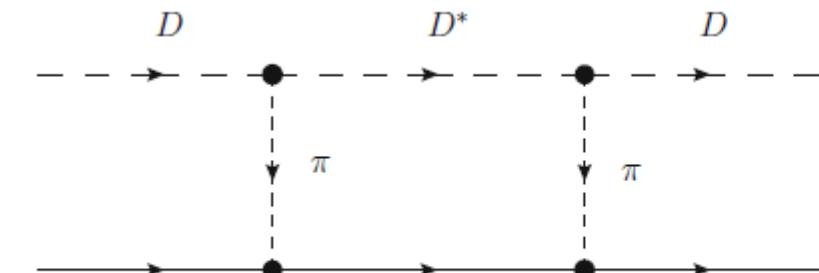
Chiral Lagrangians come from exchange of vector mesons, the theory extends the Chiral Lagrangians incorporating the interaction of vector mesons



$$V_{ij} = -C_{ij} \frac{1}{4f^2} (2\sqrt{s} - M_{B_i} - M_{B_j}) \sqrt{\frac{M_{B_i} + E_i}{2M_{B_i}}} \sqrt{\frac{M_{B_j} + E_j}{2M_{B_j}}}, \quad (1)$$

When heavy quarks are involved one can see that the exchange of light vectors respects Heavy Quark Spin Symmetry because the heavy quarks act as spectators in this exchange

# Mixture of PB and VB states



$$\mathcal{L}_{VPP} = -ig \langle [P, \partial_\mu P] V^\mu \rangle$$

$$\mathcal{L}_{VVP} = \frac{G'}{\sqrt{2}} \epsilon^{\mu\nu\alpha\beta} \langle \partial_\mu V_\nu \partial_\alpha V_\beta P \rangle$$

$$g = m_V/2f_\pi \text{ with } m_V \approx 780 \text{ MeV}, f_\pi = 93 \text{ MeV}$$

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix},$$

$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu.$$

# Baryon states with open charm in the extended local hidden gauge approach

W.H. Liang (Guangxi Normal U.), T. Uchino, C.W. Xiao, E. Oset (Valencia U. & Valencia U., IFIC). Feb 21, 2014. 23 pp.

Published in **Eur.Phys.J. A51 (2015) no.2, 16**

A unitary scheme in coupled channels is used

$$T = (1 - VG)^{-1} V$$

**Table 4.** The coupling constants to various channels for the poles in the  $I = 0, J^P = 1/2^-$  sector, with the anomalous term and taking  $q_{\max}^{B,V,P} = 800, 737, 500$  MeV. In bold face we highlight the main components.

$2592.26 + i0.56$	$DN$	$\pi\Sigma_c$	$\eta\Lambda_c$	
$g_i$	<b><math>-8.18 + i0.61</math></b>	<b><math>0.54 + i0.00</math></b>	$-0.40 - i0.03$	
$g_i G_i^{II}$	<b><math>13.88 - i1.06</math></b>	<b><math>-10.30 - i0.69</math></b>	$1.76 - i0.14$	
	$D^* N$	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
$g_i$	<b><math>9.81 + i0.77</math></b>	$-0.45 - i0.04$	$0.42 + i0.03$	$-0.59 - i0.05$
$g_i G_i^{II}$	<b><math>-26.51 - i2.10</math></b>	$2.07 + i0.17$	$-2.31 - i0.19$	$2.10 + i0.17$

**Table 2.** The coupling constants to various channels for the poles in the  $I = 0, J^P = 3/2^-$  sector of  $D^* N$  and coupled channels, with the anomalous term and taking  $q_{\max}^{B,V} = 800, 737$  MeV. In bold face we highlight the main components.

$2628.35$	$D^* N$	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
$g_i$	<b><math>10.11</math></b>	$-0.55$	$0.49$	$-0.68$
$g_i G_i^{II}$	<b><math>-29.10</math></b>	$2.60$	$-2.78$	$2.50$

# Weak decays of hadrons: ab initio calculations from QCD or using quark models suffer from large uncertainties : usually two orders of magnitude!!

J. Sun, N. Wang, Q. Chang and Y. Yang, Adv. High Energy Phys. 2015, 104378 (2015) [arXiv:1504.01286 [hep-ph]].

In most cases there are added uncertainties because of lack of knowledge on final state interaction of hadrons or the nature of hadronic states formed in the final state.

Final state interaction considered in

Dedonder, Kaminski, Lesniak, Loiseau,  $D^0 \rightarrow K_S^0 \pi^+ \pi^-$  decays, PRD 2104  
A different approach has been developed by looking explicitly into the final state interaction of hadrons and calculating ratios of rates to eliminate the microscopical process of the weak interaction and earlier formation of hadronic components.

## Weak decays of heavy hadrons into dynamically generated resonances

Int.J.Mod.Phys. E25 (2016) 1630001

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Lisheng Geng Natsumi Ikeno Pedro Fernández-Soler Zhi Feng Sun

# Meson interaction

J.A. Oller and E. O. NPA 1998

N.Kaiser, F.K. Guo, W.H. Liang

L.R Dai...

Pseudoscalar-pseudoscalar interaction: channels

- 1)  $\pi^+ \pi^-$
- 2)  $\pi^0 \pi^0$
- 3)  $K^+ K^-$
- 4)  $K^0 \bar{K}^0$
- 5)  $\eta \eta$

We use the chiral unitary approach: Bethe Salpeter equations  
in coupled channels

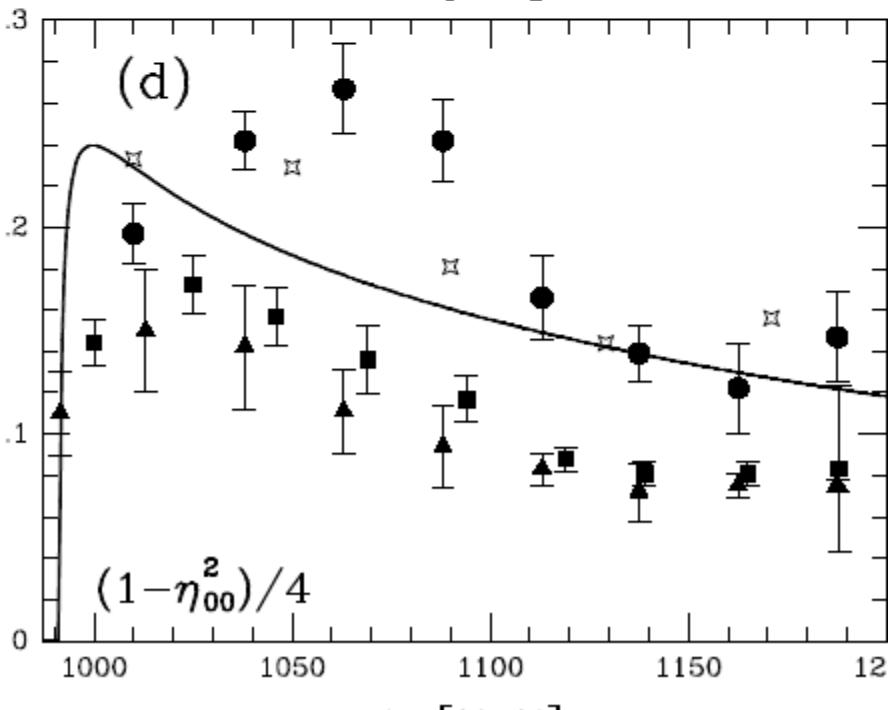
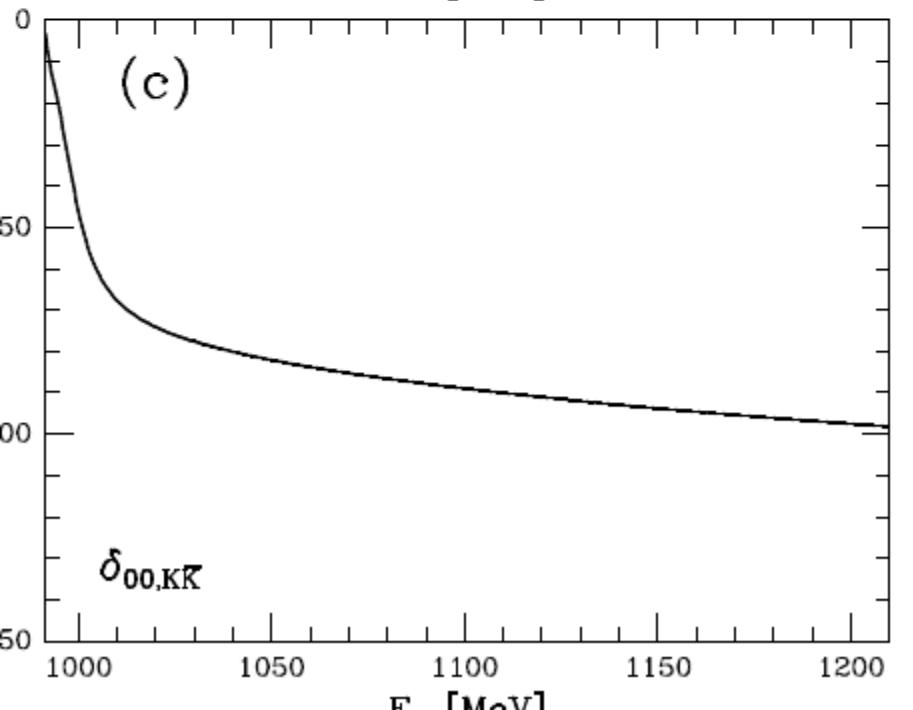
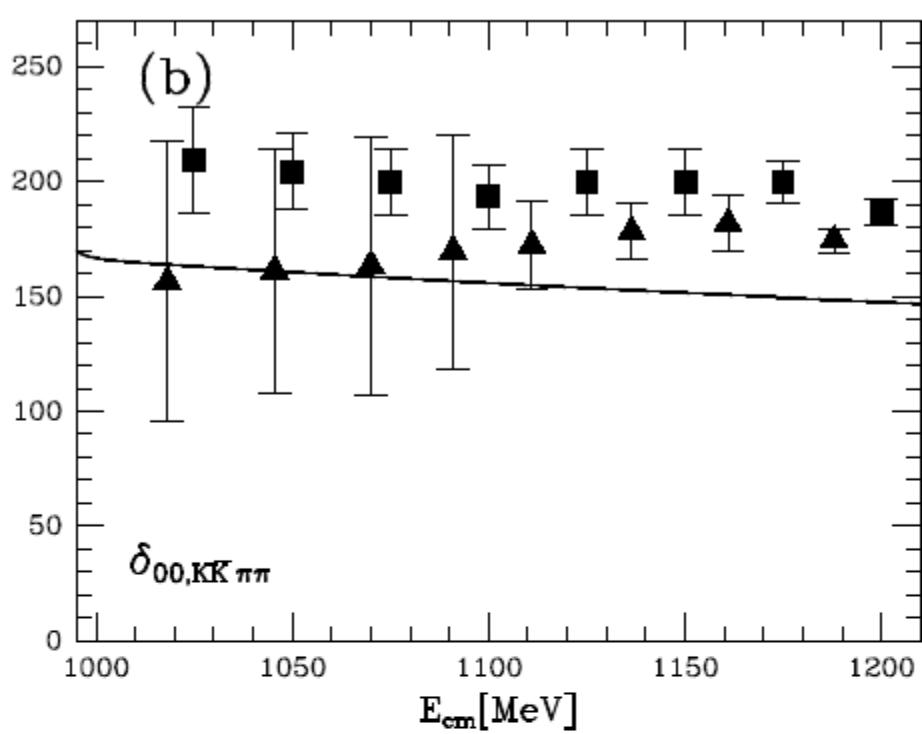
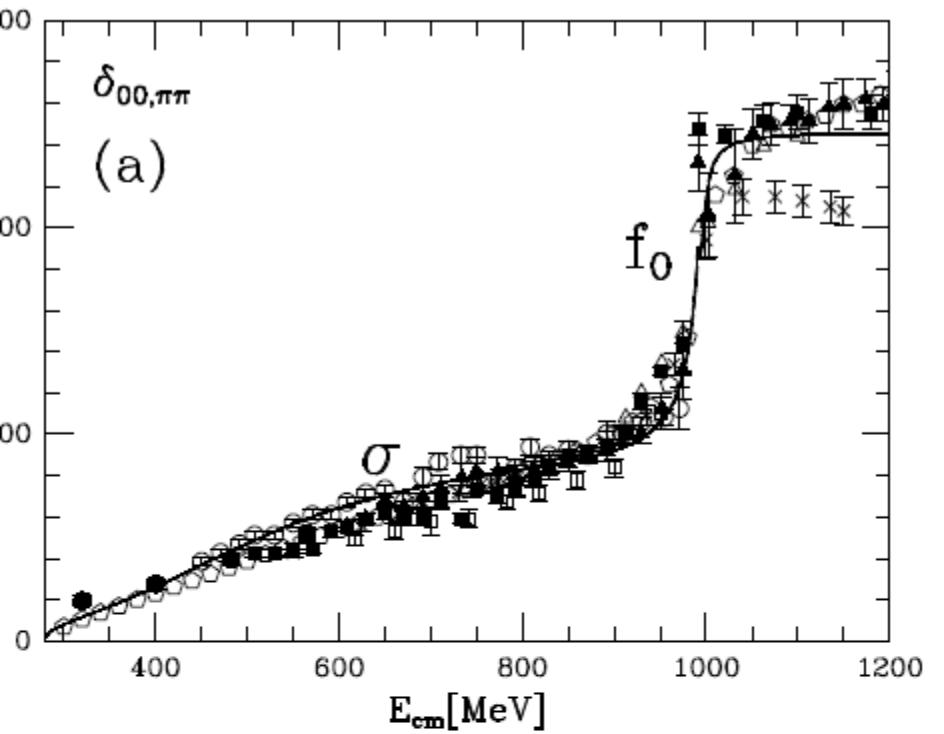
$$T = (1 - V G)^{-1} V$$

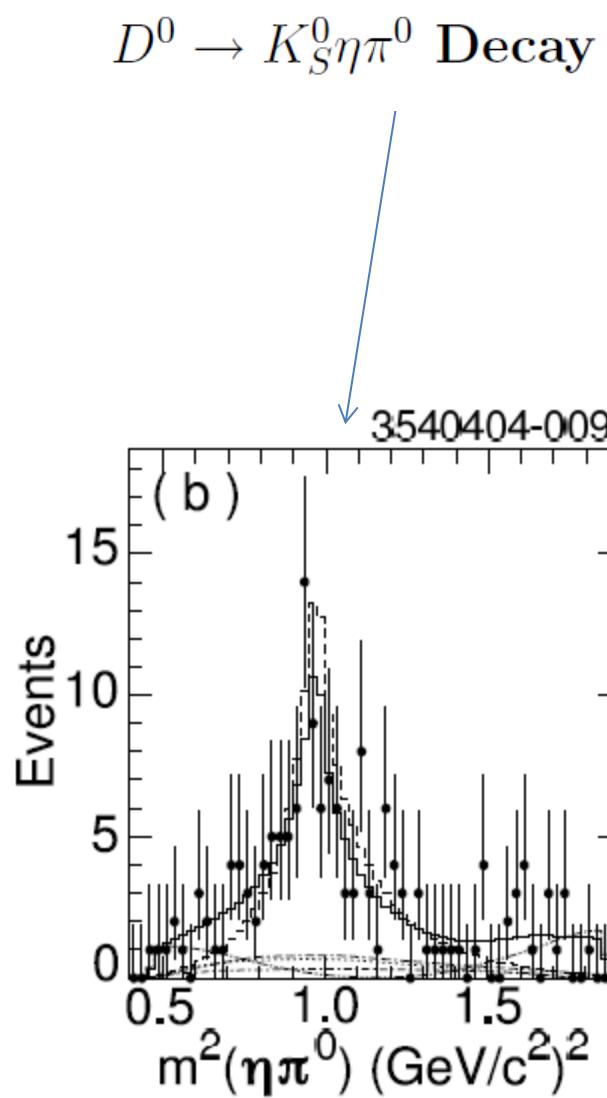
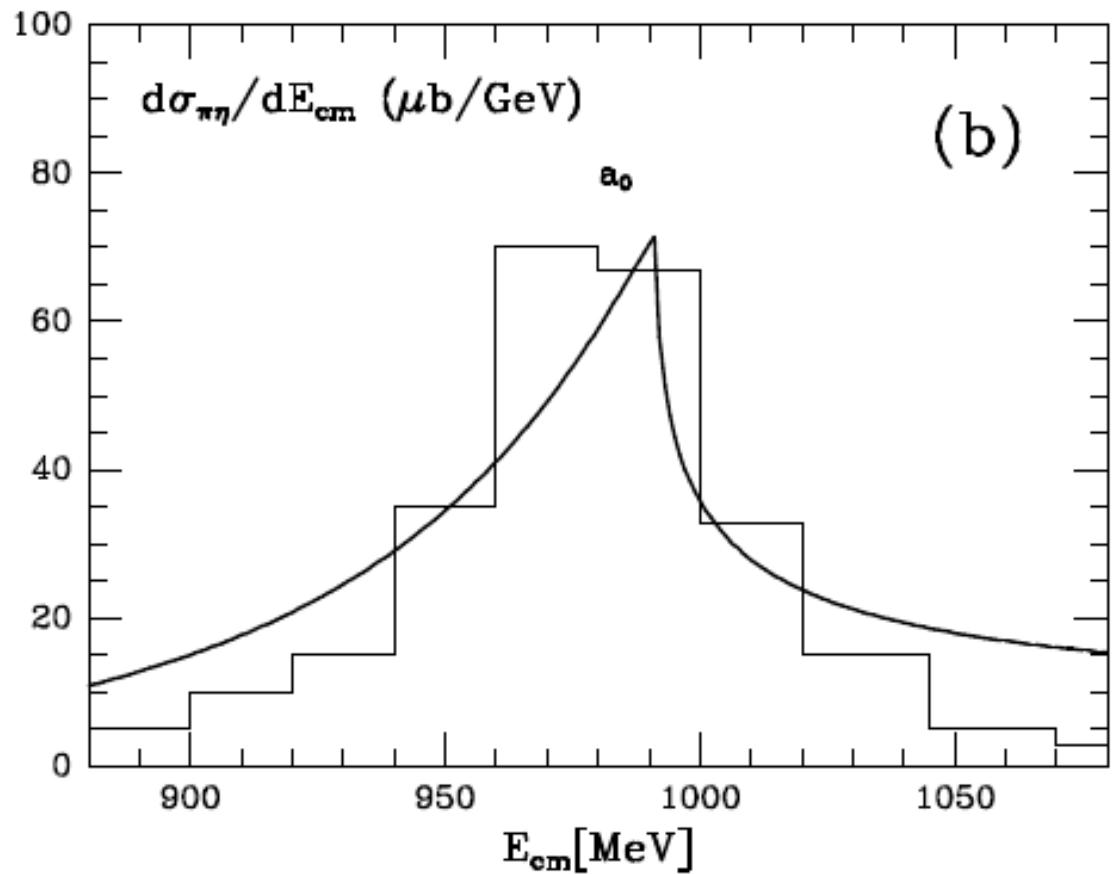
With  $V$  obtained from the chiral Lagrangians and  $G$  the loop function  
of two meson propagators .

$$G_{jj}(s) = \int_0^{q_{max}} \frac{q^2 dq}{(2\pi)^2} \frac{\omega_1 + \omega_2}{\omega_1 \omega_2 [P^{02} - (\omega_1 + \omega_2)^2 + i\epsilon]}$$

$V_{11} = -\frac{1}{2f^2}s,$	$V_{12} = -\frac{1}{\sqrt{2}f^2}(s - m_\pi^2),$	$V_{13} = -\frac{1}{4f^2}s,$
$V_{14} = -\frac{1}{4f^2}s,$	$V_{15} = -\frac{1}{3\sqrt{2}f^2}m_\pi^2,$	$V_{22} = -\frac{1}{2f^2}m_\pi^2,$
$V_{23} = -\frac{1}{4\sqrt{2}f^2}s,$	$V_{24} = -\frac{1}{4\sqrt{2}f^2}s,$	$V_{25} = -\frac{1}{6f^2}m_\pi^2,$
$V_{33} = -\frac{1}{2f^2}s,$	$V_{34} = -\frac{1}{4f^2}s,$	$V_{35} = -\frac{1}{12\sqrt{2}f^2}(9s - 6m_\eta^2 - 2m_\pi^2),$
$V_{44} = -\frac{1}{2f^2}s,$	$V_{45} = -\frac{1}{12\sqrt{2}f^2}(9s - 6m_\eta^2 - 2m_\pi^2),$	$V_{55} = -\frac{1}{18f^2}(16m_K^2 - 7m_\pi^2),$

(8)





$B^0$  and  $B_s^0$  decays into  $J/\psi$   $f_0(980)$  and  $J/\psi$   $f_0(500)$  and the nature of the scalar resonances

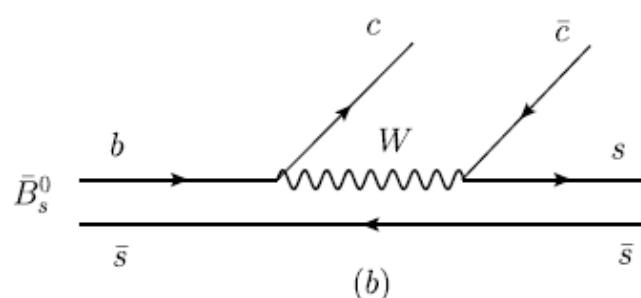
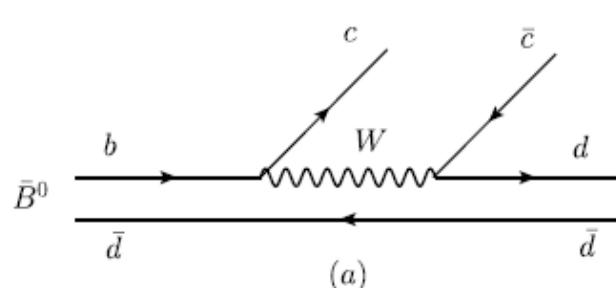
Much debate on recent LHCb experiments  
(see S. Stone, L. Zhang, PRL 2013)

In  $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ , a big peak is seen for  $f_0(980)$ ,  
and no signal for  $f_0(500)$ . LHCb PLB 2011, PRD 2012  
Corroborated by Belle, CDF, D0 collaborations.

Conversely, in  $B^0 \rightarrow J/\psi \pi^+ \pi^-$  the  $f_0(500)$  is seen and only a tiny  
signal for the  $f_0(980)$  is observed , LHCb PRD 2013.

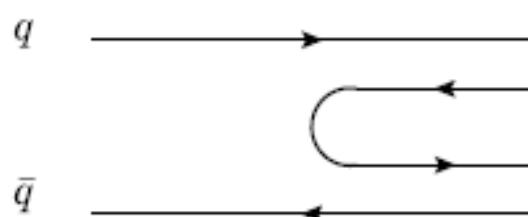
# $B^0$ and $B_s^0$ decays into $J/\psi f_0(980)$ and $J/\psi f_0(500)$ and the nature of the scalar resonances

W.H. Liang, EO



Cabibbo suppressed

u    c    t  
d    s    b



$$q\bar{q}(u\bar{u} + d\bar{d} + s\bar{s})$$

$$M = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix}$$

$$M \cdot M = M \times (u\bar{u} + d\bar{d} + s\bar{s})$$

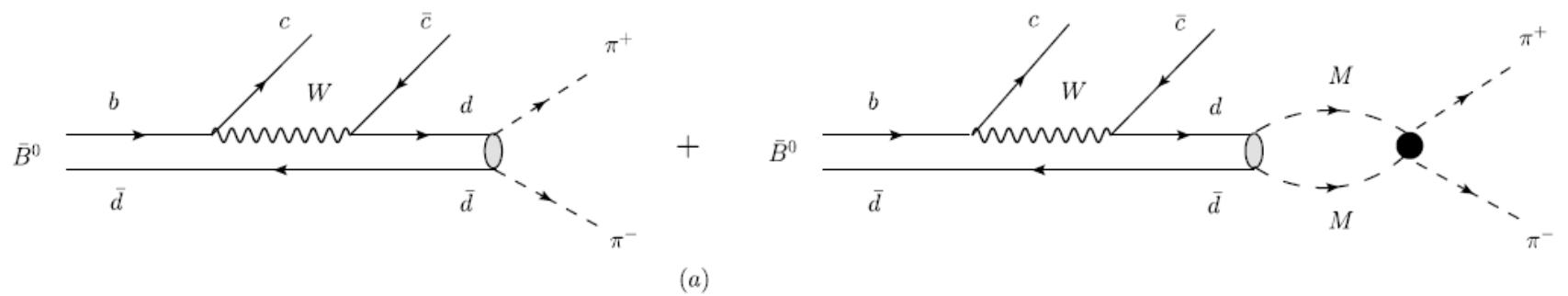
Cabibbo allowed

$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix} M \cdot M = \begin{bmatrix} u \\ d \\ s \end{bmatrix} (\text{bar } u, \text{ bar } d, \text{ bar } c) \begin{bmatrix} u \\ d \\ s \end{bmatrix} (\text{bar } u, \text{ bar } d, \text{ bar } c)$$

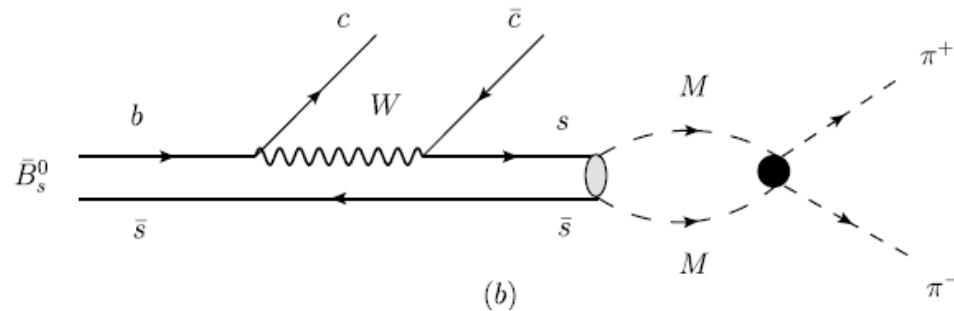
$$d\bar{d}(u\bar{u} + d\bar{d} + s\bar{s}) \equiv (\phi \cdot \phi)_{22}$$

$$= \pi^- \pi^+ + \frac{1}{2} \pi^0 \pi^0 - \frac{1}{\sqrt{3}} \pi^0 \eta + K^0 \bar{K}^0 + \frac{1}{6} \eta \eta,$$

$$s\bar{s}(u\bar{u} + d\bar{d} + s\bar{s}) \equiv (\phi \cdot \phi)_{33} = K^- K^+ + K^0 \bar{K}^0 + \frac{4}{6} \eta \eta. \quad (4)$$



(a)



(b)

$$t(\bar{B}^0 \rightarrow J/\psi \pi^+ \pi^-)$$

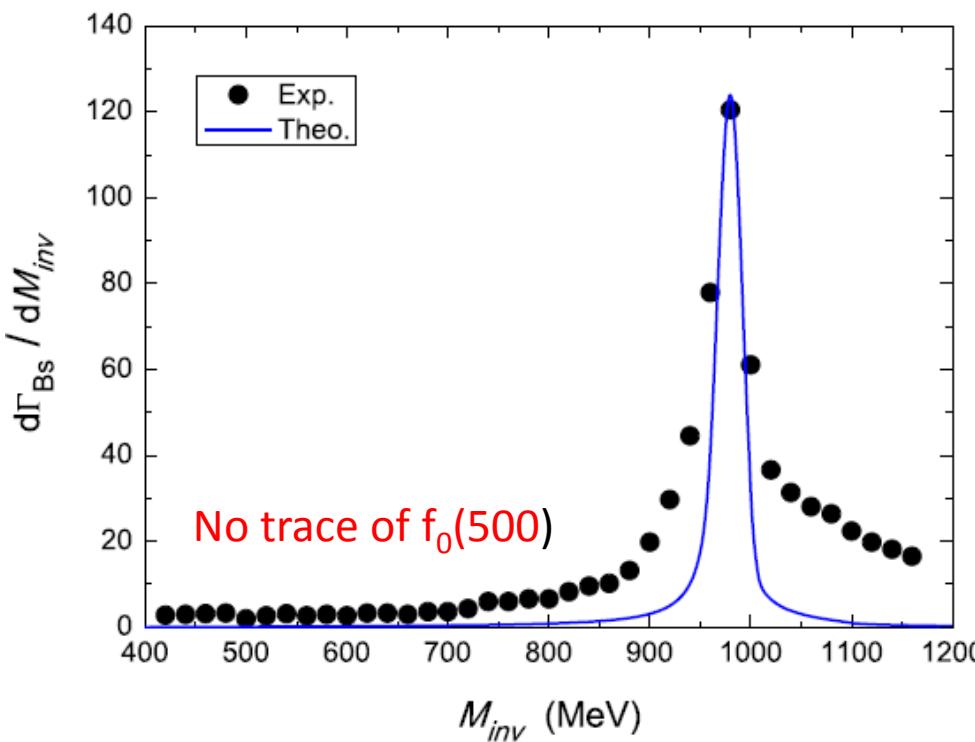
$$= V_P V_{cd} \left( 1 + G_{\pi^+ \pi^-} t_{\pi^+ \pi^- \rightarrow \pi^+ \pi^-} + \frac{1}{2} \frac{1}{2} G_{\pi^0 \pi^0} t_{\pi^0 \pi^0 \rightarrow \pi^+ \pi^-} + G_{K^0 \bar{K}^0} t_{K^0 \bar{K}^0 \rightarrow \pi^+ \pi^-} + \frac{1}{6} \frac{1}{2} G_{\eta \eta} t_{\eta \eta \rightarrow \pi^+ \pi^-} \right),$$

$$t(\bar{B}_s^0 \rightarrow J/\psi \pi^+ \pi^-)$$

$$= V_P V_{cs} \left( G_{K^+ K^-} t_{K^+ K^- \rightarrow \pi^+ \pi^-} + G_{K^0 \bar{K}^0} t_{K^0 \bar{K}^0 \rightarrow \pi^+ \pi^-} + \frac{4}{6} \frac{1}{2} G_{\eta \eta} t_{\eta \eta \rightarrow \pi^+ \pi^-} \right), \quad (5)$$

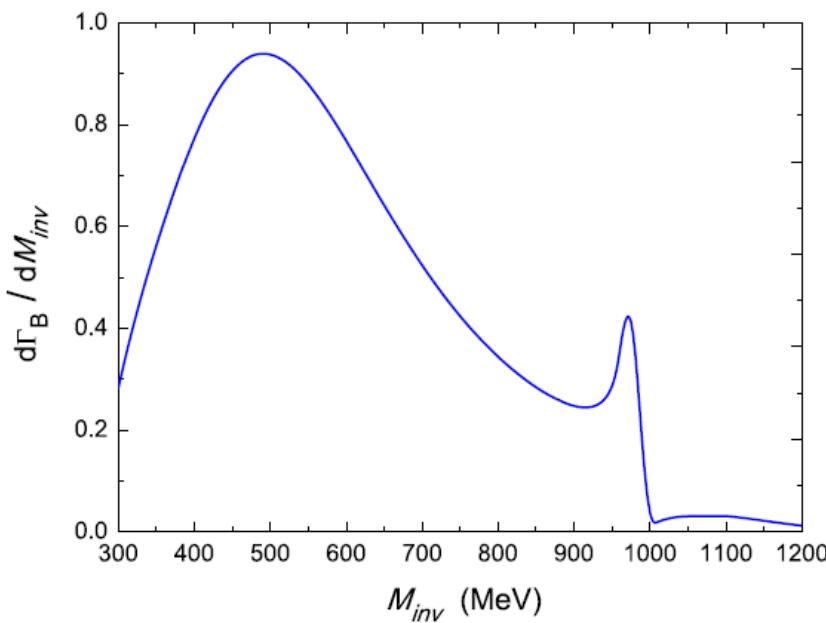
$$V_{cd} = -\sin \theta_c = -0.22534$$

$$V_{cs} = \cos \theta_c = 0.97427.$$



$\bar{B}_s^0 \rightarrow J/\psi \pi^+ \pi^-$  decay,

One normalization is arbitrary but  
the two decays share the same  
normalization



$\bar{B}^0 \rightarrow J/\psi \pi^+ \pi^-$  decay

$$\frac{\mathcal{B}[\bar{B}^0 \rightarrow J/\psi f_0(980), f_0(980) \rightarrow \pi^+ \pi^-]}{\mathcal{B}[\bar{B}^0 \rightarrow J/\psi f_0(500), f_0(500) \rightarrow \pi^+ \pi^-]} = 0.033 \pm 0.007$$

Our result

Exp:  $(0.6^{+0.7+3.3}_{-0.4-2.6}) \times 10^{-2}$  0–0.046

$$\frac{\Gamma(B^0 \rightarrow J/\psi f_0(500))}{\Gamma(B_s^0 \rightarrow J/\psi f_0(980))} \simeq (4.5 \pm 1.0) \times 10^{-2}.$$

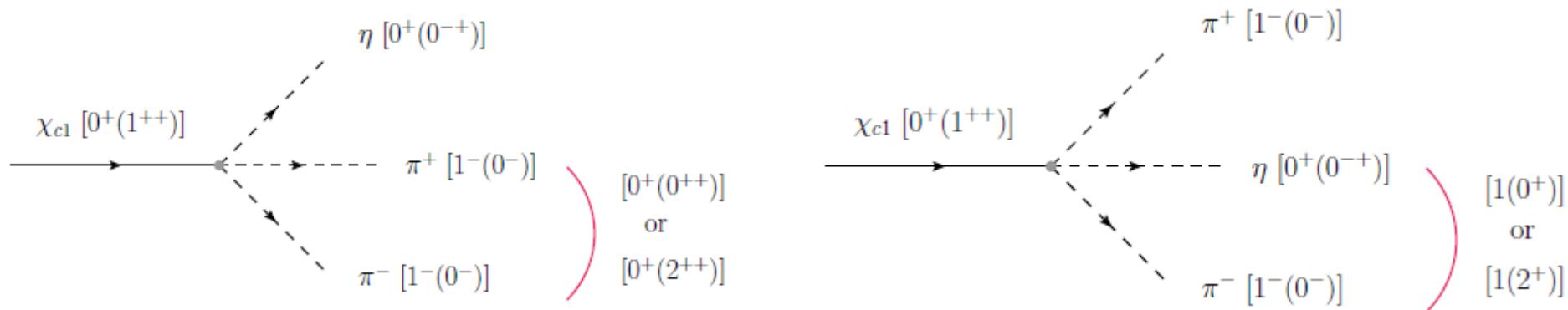
Our result

Exp:  $(2.08\text{--}4.13) \times 10^{-2}$

Note: all the ratios and the mass distributions are obtained with no free parameters, the only one has been fitted to scattering data.

# $f_0(500)$ , $f_0(980)$ , and $a_0(980)$ production in the $\chi_{c1} \rightarrow \eta\pi^+\pi^-$ reaction

W.H. Liang, J.J. Xie and E. O, EPJ C, 2016



$$M \rightarrow \phi$$

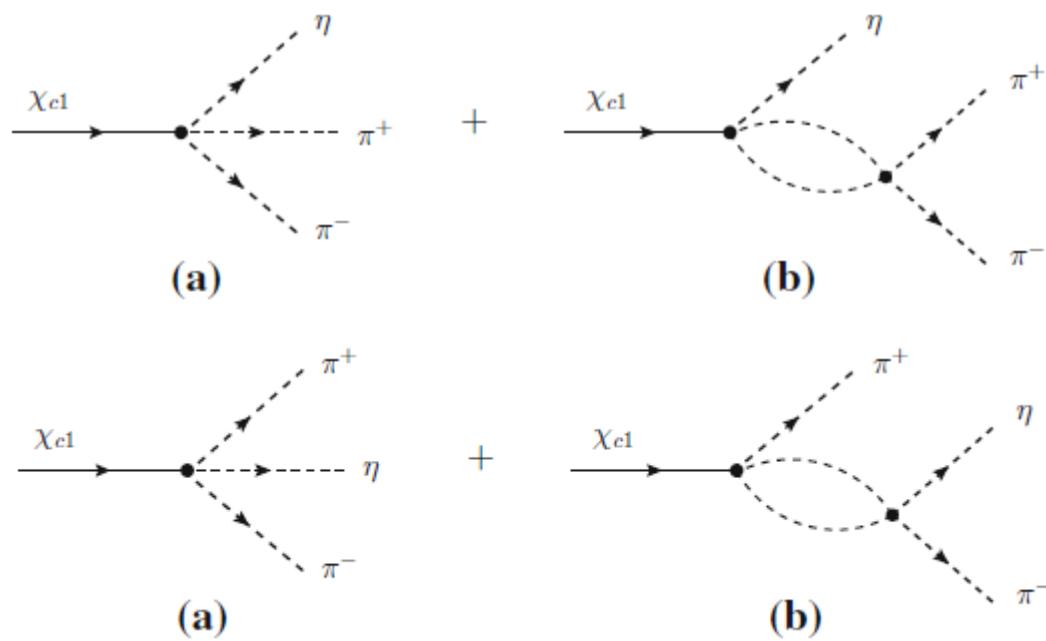
$$\equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' \end{pmatrix}.$$

$$\text{SU}(3)[\text{scalar}] \equiv \text{Trace}(\phi\phi\phi)$$

$$C_1 : \eta \left( \frac{6}{\sqrt{3}} \pi^+ \pi^- + \frac{3}{\sqrt{3}} \pi^0 \pi^0 + \frac{1}{3\sqrt{3}} \eta \eta \right)$$

$$C_2 : \pi^+ \left( \frac{6}{\sqrt{3}} \pi^- \eta + 3 K^0 \bar{K}^0 \right)$$

$$C_3 : \pi^- \left( \frac{6}{\sqrt{3}} \pi^+ \eta + 3 K^+ \bar{K}^0 \right)$$

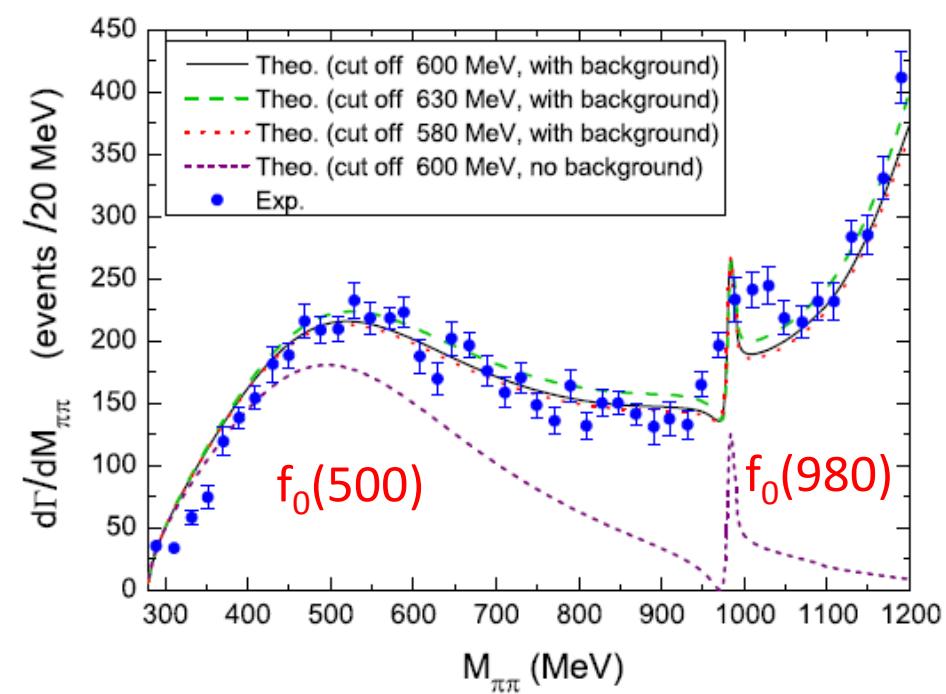
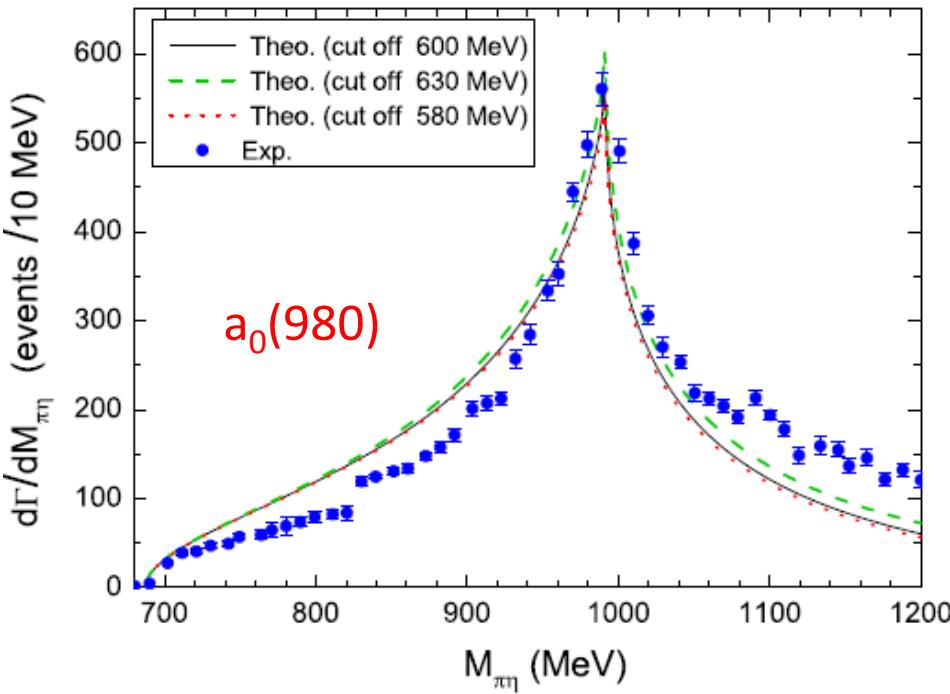


$$\tilde{t}_\eta = V_P \left( h_{\pi^+\pi^-} + \sum_i h_i S_i G_i(M_{\text{inv}}) t_{i,\pi^+\pi^-} \right)$$

$$h_{\pi^+\pi^-} = \frac{6}{\sqrt{3}}, \quad h_{\pi^0\pi^0} = \frac{3}{\sqrt{3}}, \quad h_{\eta\eta} = \frac{1}{3\sqrt{3}}$$

$$S_{\pi^0\pi^0} = 2 \times \frac{1}{2} \text{ (for two } \pi^0\text{)}; \quad S_{\eta\eta} = 3! \frac{1}{2} \text{ (for three } \eta\text{)}$$

## Data from BESIII, PRD 2017

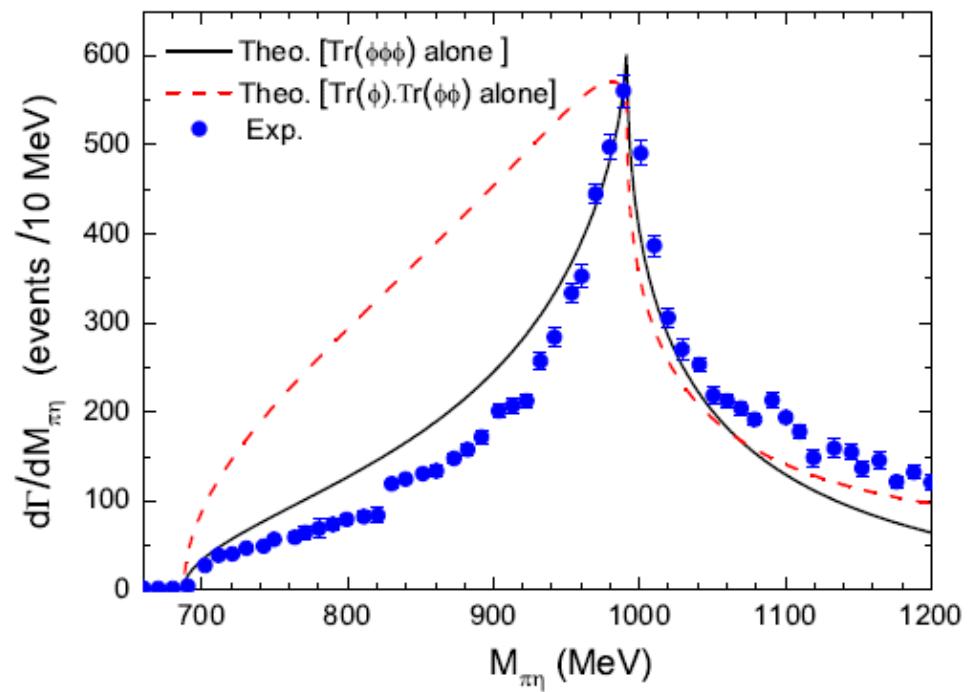
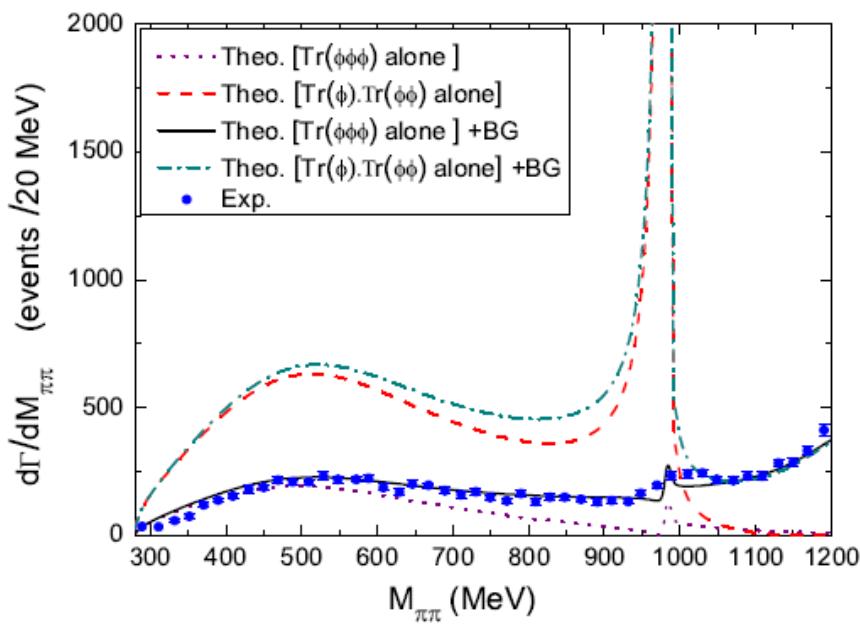


$$\begin{aligned} \text{Trace}(\phi\phi\phi) &= 2\sqrt{3}\eta\pi^+\pi^- + \sqrt{3}\eta\pi^0\pi^0 + \frac{\sqrt{3}}{9}\eta\eta\eta \\ &\quad + 3\pi^+K^0K^- + 3\pi^-K^+\bar{K}^0, \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Trace}(\phi)\text{Trace}(\phi\phi) &= \frac{\sqrt{3}}{3}\eta(2\pi^+\pi^- + \pi^0\pi^0 + 2K^+K^- \\ &\quad + 2K^0\bar{K}^0 + \eta\eta), \end{aligned} \quad (4)$$

$$[\text{Trace}(\phi)]^3 = \frac{\sqrt{3}}{9}\eta\eta\eta. \quad (5)$$

The last two forms are clearly rejected by the data.



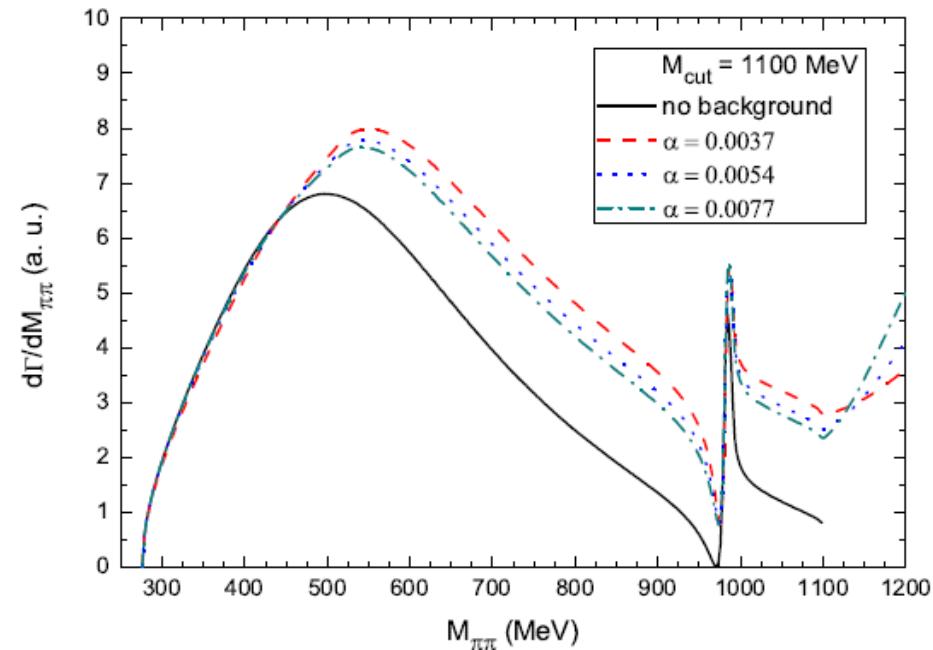
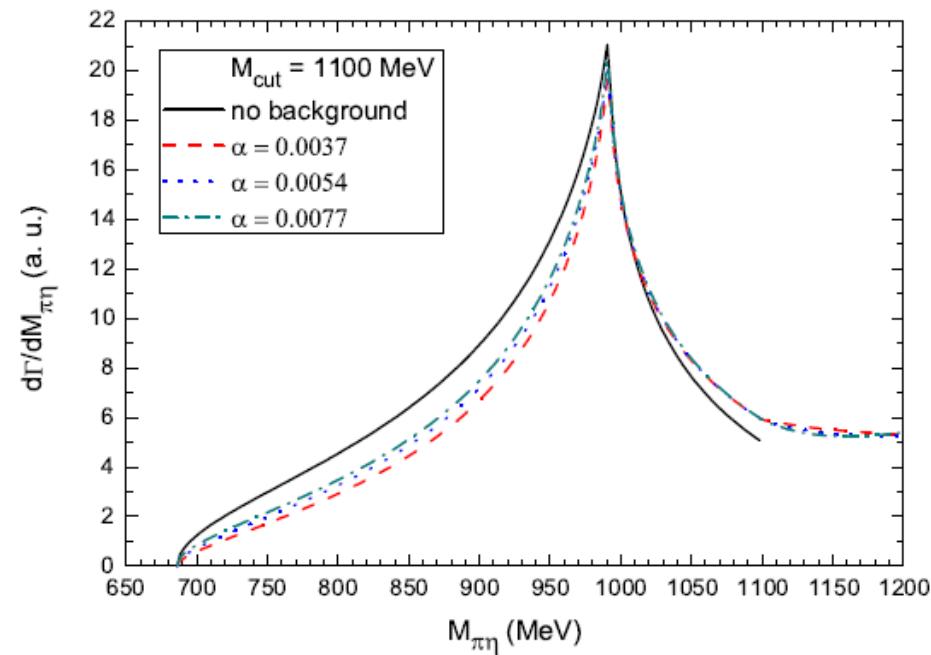
# Predictions for $\eta_c \rightarrow \eta\pi^+\pi^-$ producing $f_0(500)$ , $f_0(980)$ and $a_0(980)$

Debastiani, Liang, Xie, E. O. PLB 2017

$$\text{SU}(3)[\text{scalar}] \equiv \text{Trace}(\phi\phi\phi)$$

Same flavor combinations as in  $\chi_{c1}$  decay, but the vertex now is s-wave

The background is estimated extrapolating the  $\pi\eta$  mass distribution beyond the  $a_0(980)$  peak

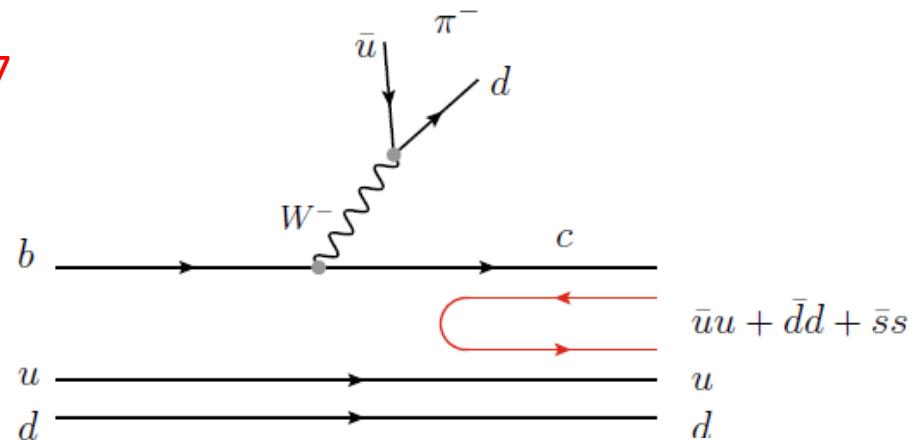


# $\Lambda_b \rightarrow \pi^-(D_s^-)\Lambda_c(2595), \pi^-(D_s^-)\Lambda_c(2625)$ decays and $DN, D^*N$ molecular components

W. H. Liang, M. Bayar, E. Oset, EPJC 2017

$$\left[ \begin{array}{c} u \\ d \end{array} \right] \left[ \begin{array}{c} c \\ s \end{array} \right] \left[ \begin{array}{c} t \\ b \end{array} \right]$$

$$\Lambda_b \quad S=0, I=0$$



$$|\Lambda_b\rangle = \frac{1}{\sqrt{2}}|b(u\bar{d} - \bar{u}d)\rangle \quad |H\rangle = \frac{1}{\sqrt{2}}|c(u\bar{d} - \bar{u}d)\rangle$$

The hadronization converts this state into  $|H'\rangle$

$$|H'\rangle = \frac{1}{\sqrt{2}}|c(\bar{u}u + \bar{d}d + \bar{s}s)(u\bar{d} - \bar{u}d)\rangle$$

Arguments used in the study of the  $\Lambda_b \rightarrow J/\Psi K^- p$  reaction prior to the LHCb experiment findings the pentaquarks, in Roca, Mai, E. O., Meissner EPJC 2015

$$|H'\rangle = \frac{1}{\sqrt{2}} \sum_{i=1}^3 |P_{4i} q_i (u\bar{d} - \bar{u}d)\rangle$$

$$P \rightarrow \phi \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}$$

$$P \equiv (q\bar{q}) = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} & u\bar{c} \\ d\bar{u} & d\bar{d} & d\bar{s} & d\bar{c} \\ s\bar{u} & s\bar{d} & s\bar{s} & s\bar{c} \\ c\bar{u} & c\bar{d} & c\bar{s} & c\bar{c} \end{pmatrix}$$

$$|H'\rangle = \frac{1}{\sqrt{2}} [D^0 u(ud - du) + D^+ d(ud - du) + D_s^+ s(ud - du)].$$

$$|p\rangle = \frac{1}{\sqrt{2}} |u(ud - du)\rangle,$$

F. E. Close convention

$$|n\rangle = \frac{1}{\sqrt{2}} |d(ud - du)\rangle,$$

$$|\Lambda\rangle = \frac{1}{\sqrt{12}} |(usd - dsu) + (dus - uds) + 2(sud - sdu)\rangle$$

$$\begin{aligned} |H'\rangle &= \left| D^0 p + D^+ n + \sqrt{\frac{2}{3}} D_s^+ \Lambda \right\rangle \\ &\simeq \sqrt{2} |DN, I=0\rangle, \end{aligned}$$

One should change the sign to the  $\Lambda$  for consistency with chiral Lagrangians

Same decomposition for  $D^* N$  from flavor considerations

c quark       $|JM\rangle = \sum_m \mathcal{C}\left(1\frac{1}{2}J; m, M-m\right) Y_{1m} \left|\frac{1}{2}, M-m\right\rangle$       c quark in L=1, such that c u d has negative parity

q qbar from hadronization       $|00\rangle = \sum_{M_3, S_3} \mathcal{C}(110; M_3, S_3, 0) Y_{1M_3} |1 S_3\rangle$        ${}^3P_0$  configuration

$$|JM\rangle |00\rangle = \frac{1}{4\pi} \sum_j (-1)^{j-J+1/2} \sqrt{2j+1} W\left(1\frac{1}{2}Jj; \frac{1}{2}\frac{1}{2}\right)$$

j is the spin of the meson, 0 for P, 1 for V

$$\times |JM, \text{meson-baryon}\rangle \equiv \sum_j \mathcal{C}(j, J) |JM, \text{meson-baryon}\rangle$$

From Miyahara, Hyodo, Oka , Nieves, E. O , PRC 2017

Baryon	3q representation
$p$	$\frac{1}{\sqrt{2}} u(u d - d u)$
$n$	$\frac{1}{\sqrt{2}} d(u d - d u)$
$\Sigma^+$	$\frac{1}{\sqrt{2}} u(s u - u s)$
$\Sigma^0$	$\frac{1}{2} [u(d s - s d) - d(s u - u s)]$
$\Sigma^-$	$\frac{1}{\sqrt{2}} d(d s - s d)$
$\Xi^0$	$\frac{1}{\sqrt{2}} s(s u - u s)$
$\Xi^-$	$\frac{1}{\sqrt{2}} s(d s - s d)$
$\Lambda$	$\frac{1}{2\sqrt{3}} [u(d s - s d) + d(s u - u s) - 2s(u d - d u)]$

**Table 1**  $\mathcal{C}(j, J)$  coefficients in Eq. (24)

$\mathcal{C}(j, J)$	$J = 1/2$	$J = 3/2$
(pseudoscalar) $j = 0$	$\frac{1}{4\pi} \frac{1}{2}$	0
(vector) $j = 1$	$\frac{1}{4\pi} \frac{1}{2\sqrt{3}}$	$-\frac{1}{4\pi} \frac{1}{\sqrt{3}}$

$$\mathcal{L}_{W,\pi} \sim W^\mu \partial_\mu \phi, \quad \mathcal{L}_{\bar{q}Wq} = \bar{q}_{\text{fin}} W_\mu \gamma^\mu (1 - \gamma_5) q_{\text{in}}$$

$$V_P \sim q^0 + \vec{\sigma} \cdot \vec{q}$$

$$J=1/2 : q^0 \Big|_{\text{quark level}} \rightarrow i \frac{w_\pi}{q} \text{ME}(q) \vec{\sigma} \cdot \vec{q} \Big|_{\text{macroscopical level}}$$

Matrix element between  
 $\Lambda_b$  and  $\Lambda_c^*$

$$J=3/2 : q^0 \Big|_{\text{quark level}} \rightarrow -i \frac{w_\pi}{q} \text{ME}(q) \sqrt{3} \vec{S}^+ \cdot \vec{q} \Big|_{\text{macroscopical level}}$$

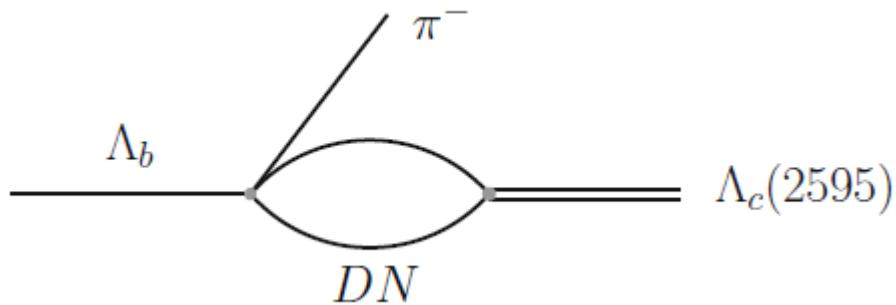
$$\left\langle JM' \right| \vec{\sigma} \cdot \vec{q} \left| \frac{1}{2} M \right\rangle \rightarrow iq \delta_{J,\frac{1}{2}} \text{ME}(q) \quad \text{macroscopical level}$$

$$\text{ME}(q) \equiv \int r^2 dr j_1(qr) \varphi_{\text{in}}(r) \varphi_{\text{fin}}^*(r) \quad \text{Difficult and uncertain to evaluate, but it cancels in ratios.}$$

Final operator

$$\left( iq + i \frac{w_\pi}{q} \vec{\sigma} \cdot \vec{q} \right) \delta_{J,\frac{1}{2}} + \left( -i \frac{w_\pi}{q} \sqrt{3} \vec{S}^+ \cdot \vec{q} \right) \delta_{J,\frac{3}{2}}$$

Up to the unknown factor ME and global factors



$$t_R = V_P \; \sqrt{2} \; G_{DN} \cdot g_{R,DN}$$

$$\begin{aligned} t_R = & \left( iq + i \frac{w_\pi}{q} \vec{\sigma} \cdot \vec{q} \right) \left( \frac{1}{2} G_{DN} \; g_{R,DN} + \frac{1}{2\sqrt{3}} G_{D^*N} \; g_{R,D^*N} \right) \delta_{J,\frac{1}{2}} \\ & - \left( +i \frac{w_\pi}{q} \sqrt{3} \vec{S}^+ \cdot \vec{q} \right) \frac{1}{\sqrt{3}} G_{D^*N} \; g_{R,D^*N} \; \delta_{J,\frac{3}{2}} \end{aligned}$$

$$\Gamma_R=\frac{1}{2\pi}\frac{M_{\Lambda_c^*}}{M_{\Lambda_b}}\overline{\sum}\sum |t_R|^2\; p_{\pi^-}$$

Prediction

$$\frac{\Gamma[\Lambda_b \rightarrow \pi^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \rightarrow \pi^- \Lambda_c(2625)]} = 0.76$$

Experiment

$$\left. \frac{\Gamma[\Lambda_b \rightarrow \pi^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \rightarrow \pi^- \Lambda_c(2625)]} \right|_{\text{Exp.}} = 1.03 \pm 0.60$$

Prediction

$$\frac{\Gamma[\Lambda_b \rightarrow D_s^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \rightarrow D_s^- \Lambda_c(2625)]} = 0.54$$

Prediction

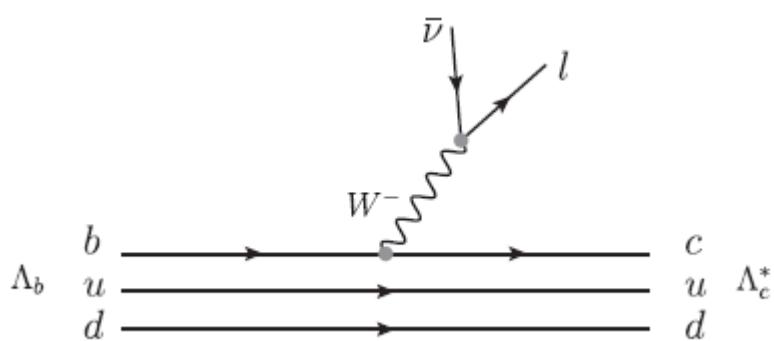
$$\begin{aligned} \text{BR}[\Lambda_b \rightarrow D_s^- \Lambda_c(2595)] &\sim (2.22 \pm 0.97) \times 10^{-4} \\ \text{BR}[\Lambda_b \rightarrow D_s^- \Lambda_c(2625)] &\sim (3.03 \pm 1.70) \times 10^{-4} \end{aligned}$$

If the  $D^*N$  coupling had opposite sign there is a near cancellation and sheer disagreement with experiment.

Relativistic corrections are about 30% for individual rates, but about 1% en the ratios.  
Uncertainties from neglecting the  $\Lambda D_s$  channel about 20%.

# Semileptonic $\Lambda_b \rightarrow \bar{\nu}_l l \Lambda_c(2595)$ and $\Lambda_b \rightarrow \bar{\nu}_l l \Lambda_c(2625)$ decays in the molecular picture of $\Lambda_c(2595)$ and $\Lambda_c(2625)$

W. H. Liang, E. Oset and Z.S. Xie, PRD 2017



$$T = -iG_F \frac{V_{bc}}{\sqrt{2}} L^\alpha Q_\alpha V_{\text{had}}$$

$$L^\alpha \equiv \bar{u}_l \gamma^\alpha (1 - \gamma_5) v_\nu, \quad Q_\alpha \equiv \bar{u}_c \gamma_\alpha (1 - \gamma_5) u_b$$

$$\begin{aligned} \sum_{\text{pol}} L^\alpha L^{\dagger\beta} &= \text{tr} \left[ \gamma^\alpha (1 - \gamma_5) \frac{p/\nu - m_\nu}{2m_\nu} (1 + \gamma_5) \gamma^\beta \frac{p/l + m_l}{2m_l} \right] \\ &= 2 \frac{p_\nu^\alpha p_l^\beta + p_l^\alpha p_\nu^\beta - p_\nu \cdot p_l g^{\alpha\beta} - i\epsilon^{\rho\alpha\sigma\beta} p_{\nu\rho} p_{l\sigma}}{m_\nu m_l}. \end{aligned}$$

$$Q_\alpha \rightarrow V_P \sim q^0 + \vec{\sigma} \cdot \vec{q}$$

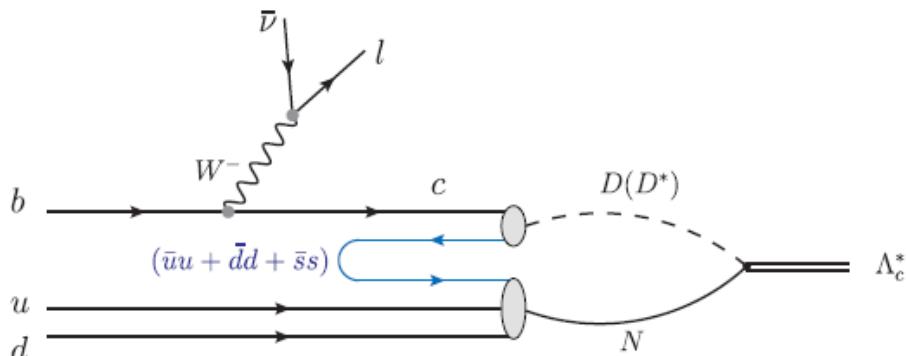
$$\begin{aligned} \sum_{\text{lepton pol}} L^\alpha L^{\dagger\beta} Q_\alpha Q_\beta^\dagger &= \frac{2}{m_\nu m_l} [2p_\nu^0 p_l^0 - p_\nu \cdot p_l + 4p_\nu^0 \vec{p}_l \cdot \vec{\sigma} \\ &\quad + (\vec{p}_\nu \cdot \vec{\sigma})(\vec{p}_l \cdot \vec{\sigma}) + (\vec{p}_l \cdot \vec{\sigma})(\vec{p}_\nu \cdot \vec{\sigma}) + (p_\nu \cdot p_l)(\vec{\sigma} \cdot \vec{\sigma})] \end{aligned}$$

$$\sum_{\text{lepton pol}} L^\alpha L^{\dagger\beta} Q_\alpha Q_\beta^\dagger = \frac{2}{m_\nu m_l} [2p_\nu^0 p_l^0 - p_\nu \cdot p_l + 2\vec{p}_\nu \cdot \vec{p}_l + 3p_\nu \cdot p_l] = \frac{8}{m_\nu m_l} p_\nu^0 p_l^0$$

$$\overline{\sum} \sum L^\alpha L^{\dagger\beta} Q_\alpha Q_\beta^\dagger \equiv \frac{8}{m_\nu m_l} p_\nu^0 p_l^0 \frac{1}{2\vec{q}^2} \sum_{M,M'} \begin{cases} \langle \frac{1}{2}M | \vec{\sigma} \cdot \vec{q} | \frac{1}{2}M' \rangle \langle \frac{1}{2}M' | \vec{\sigma} \cdot \vec{q} | \frac{1}{2}M \rangle, & \text{for } J = 1/2 \\ 3 \langle \frac{1}{2}M | \vec{S} \cdot \vec{q} | \frac{3}{2}M' \rangle \langle \frac{3}{2}M' | \vec{S}^+ \cdot \vec{q} | \frac{1}{2}M \rangle, & \text{for } J = 3/2 \end{cases}$$

$$\overline{\sum} \sum L^\alpha L^{\dagger\beta} Q_\alpha Q_\beta^\dagger \equiv A_J \frac{8}{m_\nu m_l} p_\nu^0 p_l^0$$

with  $A_{1/2} = 1$  and  $A_{3/2} = 2$ .



$$\overline{\sum} \sum |T|^2 = C \frac{8}{m_\nu m_l} p_\nu^0 p_l^0 A_J V_{\text{had}}(J)$$

$$A_J V_{\text{had}}(J)$$

$$\equiv \begin{cases} |\frac{1}{2}G_{DN} \cdot g_{R,DN} + \frac{1}{2\sqrt{3}}G_{D^*N} \cdot g_{R,D^*N}|^2, & \text{for } J = 1/2 \\ 2|\frac{1}{\sqrt{3}}G_{D^*N} \cdot g_{R,D^*N}|^2, & \text{for } J = 3/2 \end{cases}$$

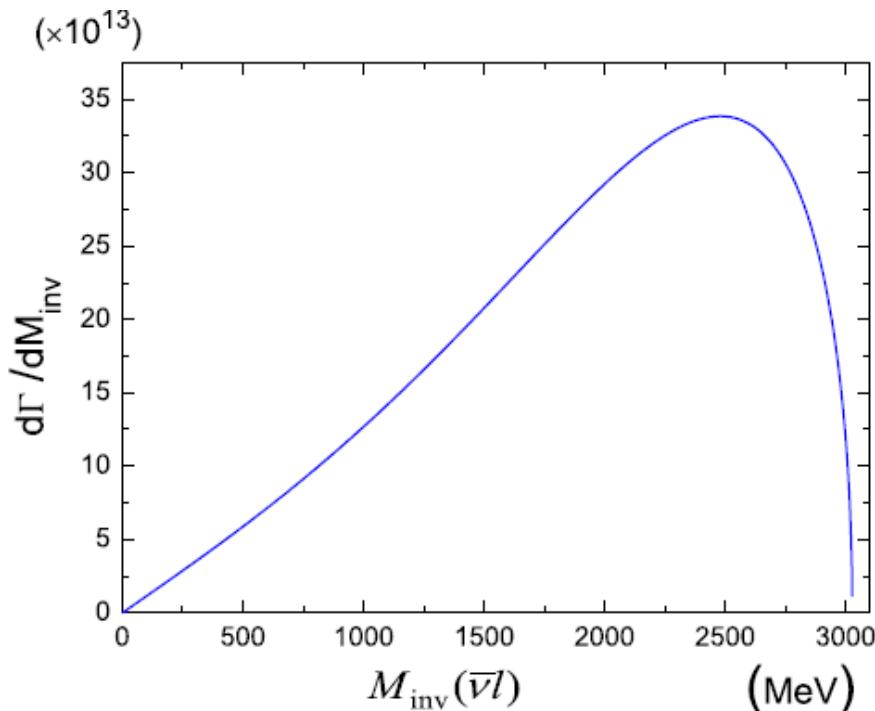
$$\frac{d\Gamma}{dM_{\text{inv}}} = 2M_{\Lambda_b} 2M_{\Lambda_c^*} 2m_\nu 2m_l \frac{1}{4M_{\Lambda_b}^2} \frac{1}{(2\pi)^3} p_{\Lambda_c^*} \tilde{p}_l \sum \sum |T|^2$$

Prediction

$$\frac{\Gamma[\Lambda_b \rightarrow \bar{\nu}_l l \Lambda_c(2595)]}{\Gamma[\Lambda_b \rightarrow \bar{\nu}_l l \Lambda_c(2625)]} = 0.391$$

Experiment

$$\left. \frac{\Gamma[\Lambda_b \rightarrow \bar{\nu}_l l \Lambda_c(2595)]}{\Gamma[\Lambda_b \rightarrow \bar{\nu}_l l \Lambda_c(2625)]} \right|_{\text{Exp.}} = 0.6^{+0.4}_{-0.3}$$

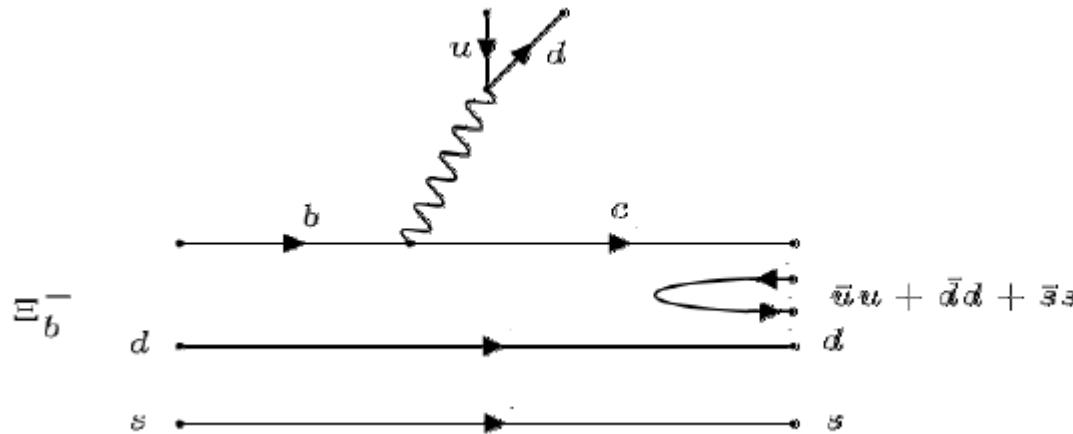


Relativistic corrections  
of the order of 30 %,  
but of 1% in the ratios.

FIG. 3.  $\frac{d\Gamma}{dM_{\text{inv}}}$  for the  $(\bar{\nu}l)$  pair as a function of  $M_{\text{inv}}(\bar{\nu}l)$  in the  $\Lambda_b \rightarrow \bar{\nu}_l l \Lambda_c(2595)$  decay.

Predictions for  $\Xi_b^- \rightarrow \pi^- (D_s^-)$   $\Xi_c^0(2790) (\Xi_c^0(2815))$   
 and  $\Xi_b^- \rightarrow \bar{\nu}_l l$   $\Xi_c^0(2790) (\Xi_c^0(2815))$

R. P. Pavao, W. H. Liang, J. Nieves and E. O, EPJC 2017.



$$|\Xi_b^- \rangle \equiv \frac{1}{\sqrt{2}} |b(ds - sd)\rangle$$

$$|H\rangle = \frac{1}{\sqrt{2}} |c(ds - sd)\rangle$$

$$|H'\rangle = \frac{1}{\sqrt{2}} \sum_{i=1}^3 |P_{4i} q_i (ds - sd)\rangle$$

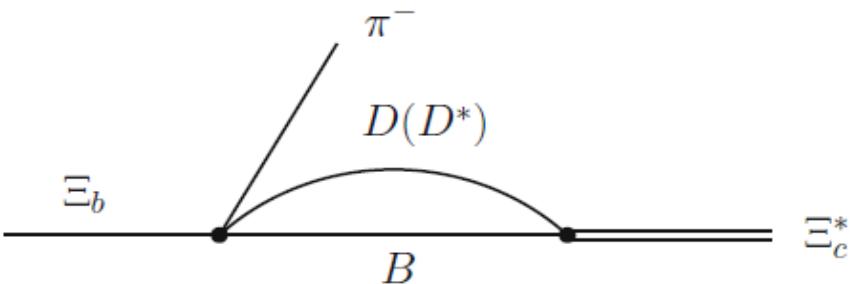
$$\phi \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}$$

$$|H'\rangle = \frac{1}{\sqrt{2}} [ |D^0 u(ds - sd)\rangle + |D^+ d(ds - sd)\rangle + |D_s^+ s(ds - sd)\rangle ]$$

From Miyahara, Hyodo, Oka , Nieves, E. O , PRC 2017

Baryon	3q representation
$p$	$\frac{1}{\sqrt{2}} u(u\bar{d} - d\bar{u})$
$n$	$\frac{1}{\sqrt{2}} d(u\bar{d} - d\bar{u})$
$\Sigma^+$	$\frac{1}{\sqrt{2}} u(s\bar{u} - u\bar{s})$
$\Sigma^0$	$\frac{1}{2} [u(ds - sd) - d(su - us)]$
$\Sigma^-$	$\frac{1}{\sqrt{2}} d(ds - sd)$
$\Xi^0$	$\frac{1}{\sqrt{2}} s(s\bar{u} - u\bar{s})$
$\Xi^-$	$\frac{1}{\sqrt{2}} s(ds - sd)$
$\Lambda$	$\frac{1}{2\sqrt{3}} [u(ds - sd) + d(su - us) - 2s(u\bar{d} - d\bar{u})]$

$$|H'\rangle = \frac{1}{\sqrt{2}} |D^0 \Sigma^0\rangle + |D^+ \Sigma^-\rangle - \frac{1}{\sqrt{6}} |D^0 \Lambda\rangle \quad |H'\rangle = -\sqrt{\frac{3}{2}} \left| \Sigma D(J = \frac{1}{2}) \right\rangle + \frac{1}{\sqrt{6}} \left| \Lambda D(J = \frac{1}{2}) \right\rangle$$



$$\Gamma_{\Xi_b \rightarrow \pi^- \Xi_c^*} = \frac{1}{2\pi} \frac{M_{\Xi_c^*}}{M_{\Xi_b}} q \overline{\sum} \sum |t|^2$$

$$J = \frac{1}{2} : \overline{\sum} \sum |t|^2 = C^2 \left( q^2 + \omega_\pi^2 \right)$$

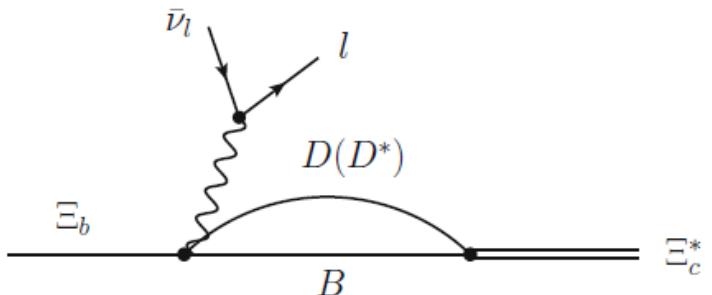
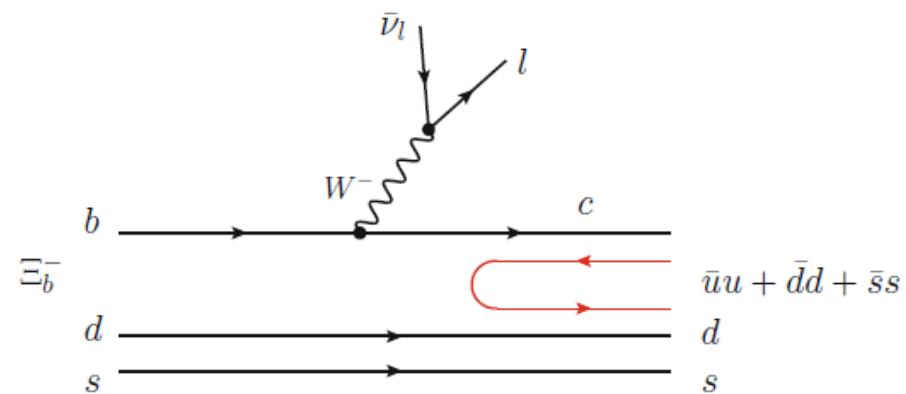
$$\times \left| \frac{1}{2} \left( -\sqrt{\frac{3}{2}} \right) g_{R,\Sigma D} G_{\Sigma D} + \frac{1}{2} \frac{1}{\sqrt{6}} g_{R,\Lambda D} G_{\Lambda D} \right.$$

$$\left. + \frac{1}{2\sqrt{3}} \left( -\sqrt{\frac{3}{2}} \right) g_{R,\Sigma D^*} G_{\Sigma D^*} + \frac{1}{2\sqrt{3}} \frac{1}{\sqrt{6}} g_{R,\Lambda D^*} G_{\Lambda D^*} \right|^2$$

$$J = \frac{3}{2} : \overline{\sum} \sum |t|^2 = C^2 2\omega_\pi^2$$

$$\times \left| \frac{1}{\sqrt{3}} \left( -\sqrt{\frac{3}{2}} \right) g_{R,\Sigma D^*} G_{\Sigma D^*} + \frac{1}{\sqrt{3}} \frac{1}{\sqrt{6}} g_{R,\Lambda D^*} G_{\Lambda D^*} \right|^2$$

## Semileptonic

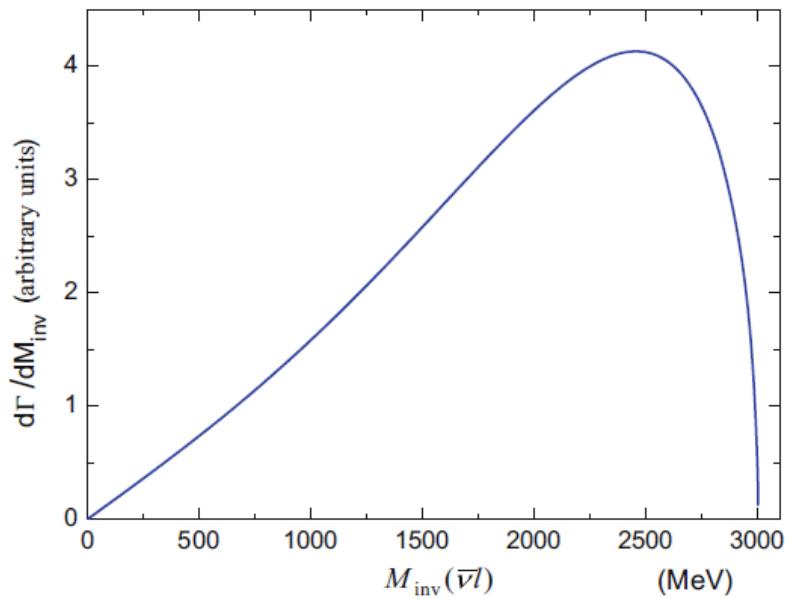


$$\frac{d\Gamma}{dM_{\text{inv}}(\bar{\nu}_l l)} = \frac{M_{\Xi_c^*}}{M_{\Xi_b}} 2m_\nu 2m_l \frac{1}{(2\pi)^3} p_{\Xi_c^*} \tilde{p}_l \overline{\sum} \sum |t'|^2$$

$$\begin{aligned} \overline{\sum} \sum |t'|^2 &= C'^2 \frac{8}{m_\nu m_l} \frac{1}{M_{\Xi_b}^2} \left( \frac{M_{\text{inv}}}{2} \right)^2 \\ &\times \left[ \tilde{E}_{\Xi_b}^2 - \frac{1}{3} \tilde{\vec{p}}_{\Xi_b}^2 \right] A_J V_{\text{had}}(J) \end{aligned}$$

$$\begin{aligned} J = \frac{1}{2}: \quad &A_J V_{\text{had}}(J) \\ = &\left| \frac{1}{2} \left( -\sqrt{\frac{3}{2}} \right) g_{R,\Sigma D} G_{\Sigma D} + \frac{1}{2} \frac{1}{\sqrt{6}} g_{R,\Lambda D} G_{\Lambda D} \right. \\ &\left. + \frac{1}{2\sqrt{3}} \left( -\sqrt{\frac{3}{2}} \right) g_{R,\Sigma D^*} G_{\Sigma D^*} + \frac{1}{2\sqrt{3}} \frac{1}{\sqrt{6}} g_{R,\Lambda D^*} G_{\Lambda D^*} \right|^2 \end{aligned}$$

$$\begin{aligned} J = \frac{3}{2}: \quad &A_J V_{\text{had}}(J) \\ = &2 \left| \frac{1}{\sqrt{3}} \left( -\sqrt{\frac{3}{2}} \right) g_{R,\Sigma D^*} G_{\Sigma D^*} + \frac{1}{\sqrt{3}} \frac{1}{\sqrt{6}} g_{R,\Lambda D^*} G_{\Lambda D^*} \right|^2 \end{aligned}$$



	$\Sigma D$	$\Sigma D^*$	$\Lambda D$	$\Lambda D^*$
$g$	$-1.178 - i0.101$	$0.777 + i0.285$	$-1.396 + i0.892$	$0.569 - i0.601$
$gG$	$6.544 + i0.239$	$-3.372 - i1.067$	$8.277 - i5.921$	$-2.45 + i2.844$

Values taken from Romanets , Tolos, Garcia-Recio, Nieves, Salcedo, Timmermans PRD 2012 reevaluated to get relative phases.

**Table 2** Values of  $g$  and  $gG$  for the different channels for the resonance  $\Xi_c^0(2790)(\frac{1}{2}^-)$

	$\Lambda D^*$	$\Sigma D^*$
$g$	$2.346 - i0.599$	$0.791 + i0.49$
$gG$	$-12.297 + i4.213$	$-4.148 - i2.15$

**Table 3** Values of  $g$  and  $gG$  for the different channels for the resonance  $\Xi_c^0(2815)(\frac{3}{2}^-)$

## Predictions

$$R_1 = \frac{\Gamma_{\Xi_b \rightarrow \pi^- \Xi_c^0(2790)}}{\Gamma_{\Xi_b \rightarrow \pi^- \Xi_c^0(2815)}} = 0.384, \quad R_2 = \frac{\Gamma_{\Xi_b \rightarrow D_s^- \Xi_c^0(2790)}}{\Gamma_{\Xi_b \rightarrow D_s^- \Xi_c^0(2815)}} = 0.273, \quad R_3 = \frac{\Gamma_{\Xi_b \rightarrow D_s^- \Xi_c^0(2790)}}{\Gamma_{\Xi_b \rightarrow \pi^- \Xi_c^0(2790)}} = 0.686.$$

$$R = \frac{\Gamma_{\Xi_b \rightarrow \bar{\nu}_l l \Xi_c(2790)}}{\Gamma_{\Xi_b \rightarrow \bar{\nu}_l l \Xi_c(2815)}} = 0.191.$$

## Predictions of absolute rates:

$$\frac{BR(\Xi_b \rightarrow \pi^- \Xi_c^*)}{BR(\Lambda_b \rightarrow \pi^- \Lambda_c^*)} = \frac{M_{\Xi_c^*}}{M_{\Xi_b}} \frac{M_{\Lambda_b}}{M_{\Lambda_c^*}} \frac{q \overline{\sum} \sum |t|^2 \Big|_{\Xi_b}}{q \overline{\sum} \sum |t|^2 \Big|_{\Lambda_b}} \cdot \frac{\Gamma_{\Lambda_b}}{\Gamma_{\Xi_b}}$$

$$\frac{\Gamma_{\Lambda_b}}{\Gamma_{\Xi_b}} = \frac{\tau_{\Xi_b}}{\tau_{\Lambda_b}} = 1.08 \pm 0.19$$

$$BR[\Lambda_b \rightarrow \pi^- \Lambda_c(2595)] = \frac{(3.4 \pm 1.5) \times 10^{-4}}{BR[\Lambda_c(2595) \rightarrow \Lambda_c \pi^+ \pi^-]},$$

$$BR[\Lambda_b \rightarrow \pi^- \Lambda_c(2625)] = \frac{(3.3 \pm 1.3) \times 10^{-4}}{BR[\Lambda_c(2625) \rightarrow \Lambda_c \pi^+ \pi^-]},$$

$$BR[\Xi_b \rightarrow \pi^- \Xi_c(2790)] = (7 \pm 4) \times 10^{-6},$$

$$BR[\Xi_b \rightarrow \pi^- \Xi_c(2815)] = (13 \pm 7) \times 10^{-6},$$

$$BR[\Xi_b \rightarrow \bar{\nu}_l l \Xi_c(2790)] = \left(1.0^{+0.6}_{-0.5}\right) \times 10^{-4}$$

$$BR[\Xi_b \rightarrow \bar{\nu}_l l \Xi_c(2815)] = \left(3.3^{+1.8}_{-1.6}\right) \times 10^{-4}$$

## Conclusions:

Chiral dynamics and its extension with the local hidden gauge has allowed to deal with the interaction of hadrons in a very efficient way. In many cases one obtains a strong interaction that can lead to poles in the scattering amplitudes -> bound states or resonances dynamically generated.

In weak and strong decays, one can factorize the amplitude in the first step and then study the final state interaction. Present experiments of resonance production are offering very good information on such interaction, supporting the theoretical pictures that we are using, and providing evidence about the nature of some of these states as dynamically generated states.

One experiment only provides support, but 20 experiments explained with the same picture drastically reduce the probability that this is not the right picture.