Hadron substructure
from
QCD spectral sum rules

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INTRODUCTION

- Light scalar mesons : the QCD Higgs : long standing problem
  - Confirmation of the $\sigma/f_0(600)$ Bern group, Yndurain-Madrid group
  - BUT Proliferation of the number of f_0 mesons: $f_0(0.6),\ f_0(0.98),\ f_0(1.36),\ f_0(1.5),\ f_0(1.7)\ ,...?$
  - Less known values of their hadronic and $\gamma\gamma$ couplings.
  - Speculations on their nature : $\bar{q}q\ ,\ 4q$ or gluonia/glueball states or their mixings ?

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- Heavy hadrons : new experimental observations
  - Mass splittings of Charm and Beauty baryons : $\Omega_b(bss),\ldots$
  - Nature of Exotic mesons: $X(3872)$, $Y_c(4660)$ and $Y_b(10890)$,...

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  - Nature of Exotic mesons: $X(3872)$, $Y_c(4660)$ and $Y_b(10890)$,...
- The aim of this talk
  - Uses of QCD Spectral Sum Rules (QSSR) $\oplus$ Low Energy Theorem (LET) $\oplus$ data ($\pi\pi$, $\gamma\gamma$ scatterings, e^+e^-,...) for understanding the hadron substructure.

QSSR

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  - Duality between What one can calculate in QCD with What one can measure
- QCD two-point function
  - $\Pi(q^2) \equiv \int e^{iqx} \langle 0|\mathcal{T} J_\Gamma(x) J_\Gamma^\dagger(0)|0\rangle$: $J_\Gamma(x) \equiv \bar\psi\Gamma\psi$ ψ : quark fields
  - $\Pi(Q^2 \equiv -q^2 \geq \Lambda^2) = \sum_{0,1,\dots} C_{2n} \langle O_{2n}\rangle / Q^{2n}$: *OPE*
  - C_{2n} calculable in pQCD
  - $\langle O_2 \rangle$: m_q^2 quark masses, λ^2tachyonic gluon mass [parametrization of UV renormalons *(not in the usual OPE)*] Zakharov 90, Chetyrkin-SN-Z 99, SN-Z 2010
  - Condensates $\langle O_{2n\geq 4}\rangle$: $m\langle\bar\psi\psi\rangle, \dots$quark ; $\langle \alpha_s G^a_{\mu\nu} G_a^{\mu\nu}\rangle, \dots$gluons
  - Understanding the OPE from AdS/QCD SN-Z $\oplus$ Ratsimbarison $\oplus$ Jugeau (in progress)

DIFFERENT FORMS OF QSSR

- Exponential Sum Rules (LSR) SVZ 79
  - $\Pi(Q^2 \equiv -q^2) = \int_{t_<}^{\infty} \frac{dt}{t+Q^2+i\varepsilon} \frac{1}{\pi} \mathrm{Im}\Pi(t) + \ldots \Longrightarrow \mathcal{L}[\Pi](\tau) = \int_{t_<}^{\infty} dt\, e^{-t\tau} \frac{1}{\pi} \mathrm{Im}\Pi(t)$
  - $\mathrm{Im}\Pi(t)$: measurable experimentally *exp* enhances the ground state contribution
  - Ratio: $\mathcal{R}_1 \equiv -\frac{d}{d\tau} \log \mathcal{L}_1(\tau) \simeq M_{R_1}^2$: *"one resonance"* $+\Theta(t-t_c) \times$ *QCD continuum.*
  - Double Ratio: $r_{12} \equiv \frac{\mathcal{R}_2}{\mathcal{R}_1} \simeq \frac{M_{R_2}^2}{M_{R_1}^2}$: Mass-splittings SN 88.
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- Optimal Results
  - Stability criteria : versus the sum rule variable τ and QCD continuum threshold t_c

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- $O_{\bar{u}q} = (m_u + m_q)\bar{u}q \quad : \quad q \equiv d, s$

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Needs 2 resonances for consistency of the substracted and unsbtracted sum rules

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Strong coupling evaluation of the gluon propagator Frasca 08

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- No conclusive structure from mass predictions !

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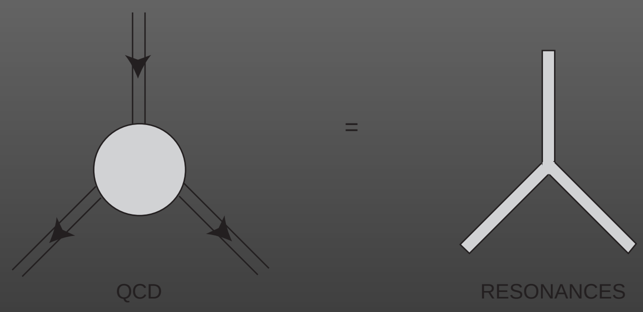
- From 3-point quark correlation functions

Approach tested from $\rho \to \pi^+\pi^-,\ \omega\rho\pi$ (SN - Paver 84) and $\pi^0 \to \gamma\gamma$ decay (SN 86)



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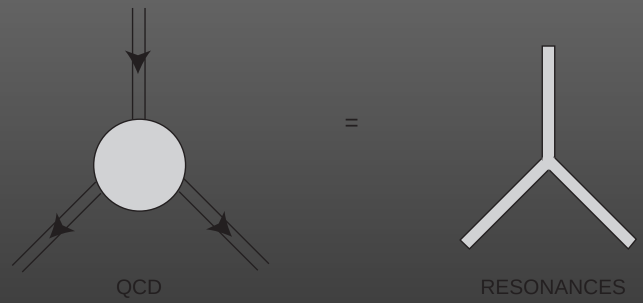

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- $\Gamma_{a_0(\bar{u}u-\bar{d}d)\to\pi^0\eta} \approx 84$ MeV : $g_{a_0\eta\pi} = \sqrt{\frac{2}{3}} g_{a_0K^+K^-}$ (SN 86, 06)

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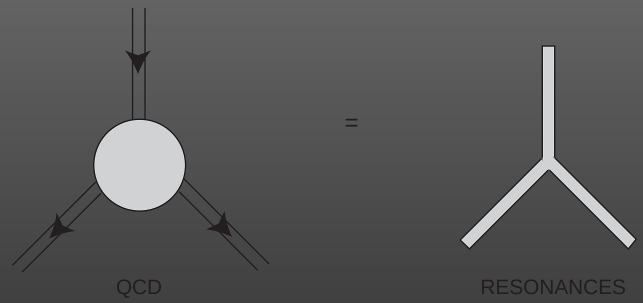

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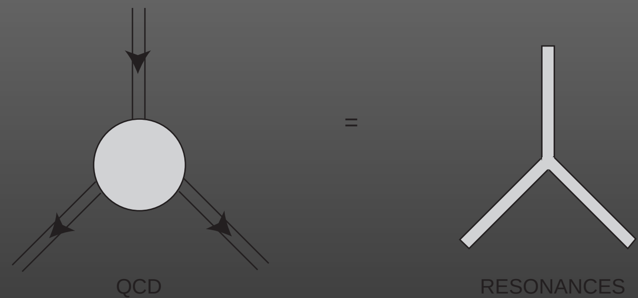

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- $\frac{\Gamma_{S_{4q}\to\gamma\gamma}}{\Gamma_{S_2\to\gamma\gamma}} \simeq (1 \sim 2) \times 10^{-3} \approx \left(\frac{\alpha_s}{\pi}\right)^2 \Longrightarrow \Gamma_{S_{4q}\to\gamma\gamma} \leq 12\ \mathrm{eV}$ (SN 86)

Widths of bare Gluonia from LET$\oplus$QSSR

Widths of bare Gluonia from LET⊕QSSR

- From 3-point hadron vertices (SN-Veneziano 89)

$$V[q^2 \equiv (q_1 - q_2)^2] \equiv \langle \pi_1 | \theta^\mu_\mu | \pi_2 \rangle = V(0) + q^2 \int_{4m_\pi^2}^\infty \frac{dt}{t} \frac{1}{t - q^2 - i\epsilon} \frac{1}{\pi} \mathrm{Im} V(t)$$

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- Euler – Heisenberg Effective Lagrangian : $gg \longrightarrow \gamma\gamma$ (NSVZ 80)

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- $\Gamma_{\sigma_B \to \gamma\gamma} \simeq (0.2 \sim 0.6)$ keV $\sim M_{\sigma_B}^3$ (SN-Veneziano 89, SN 98)

Fit of $\pi\pi \to \pi\pi$, $\bar{K}K$ and Ke_4 data

Mennessier-SN-Ochs 09, Kaminski-Mennessier-SN 10, X-G.Wang-Mennessier-SN 10

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- Model parameters fixed from $\pi\pi$ data
- Results for the σ
  - $M_\sigma \simeq 452(13) - i\ 259(16)$ MeV ; $|g_{\sigma\pi^+\pi^-}| \simeq 2.64(10)$ GeV, OK with Bern & Yndurain et al

    BUT $|g_{\sigma K^+K^-}|/|g_{\sigma\pi^+\pi^-}| = 0.37(6)$ large ! : does not favour 4q & $\pi\pi$ molecule:

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- Results for the $f_0(980)$
  - $M_{f_0} \simeq 981(34) - \mathrm{i}\ 18(11)$ MeV ; $|g_{f_0\pi^+\pi^-}| \simeq 1.12(31)$ GeV, $|g_{f_0K^+K^-}|/|g_{f_0\pi^+\pi^-}| = 2.59(1.34)$: does not favour pure $\bar{u}u + \bar{d}d$ BUT 4q or gluonium + $\bar{q}q$?

Fit of $\gamma\gamma$ scattering

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- Separation of the direct $\sigma\gamma\gamma$ coupling with $\pi\pi$ rescattering terms
  - NOT possible with dispersion relation BUT with K-Matrix models :

$$T_\gamma^{(0)} = \sqrt{\frac{2}{3}}\alpha\left(f_0^B + G\,\frac{\tilde{f}_0^B}{\mathcal{D}}\right) + \alpha\frac{\mathcal{P}}{\mathcal{D}} \quad : \mathrm{Born} + \mathrm{Rescattering} + \mathrm{Direct\ coupling}$$

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$$\Gamma^{\mathrm{dir}}_{\sigma\to\gamma\gamma} \simeq (0.16 \pm 0.04)\ ,\ \Gamma^{\mathrm{resc}}_{\sigma\to\gamma\gamma} \simeq (1.9 \pm 0.8) \implies \Gamma^{\mathrm{tot}}_{\sigma\to\gamma\gamma} \simeq (3.1 \pm 0.8)$$

$$\Gamma^{\mathrm{dir}}_{f_0\to\gamma\gamma} \simeq (0.28 \pm 0.01)\ ,\ \Gamma^{\mathrm{resc}}_{f_0\to\gamma\gamma} \simeq (0.85 \pm 0.05) \implies \Gamma^{\mathrm{tot}}_{f_0\to\gamma\gamma} \simeq (0.16 \pm 0.01)$$

  - Total: OK with dispersion relations approaches

QSSR and the $\sigma / f_0(600)$

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- What σ mass to be used ? (Minkowski)-Mennessier-SN-Ochs 07,08
  - QSSR mass obtained in the real axis !
  - USE the on-shell or Breit-Wigner mass (amplitude purely imaginary at the phase 90^0) Kniehl-Sirlin 08 BUT NOT the mass in the Complex plane : often (mis)used in the literature !
  - $M_\sigma|_{pole} \simeq$ 452(12)-i 260(15) MeV $\Longrightarrow$ $M_\sigma|_{on\ shell} \simeq M_\sigma|_{BW} \simeq$ 1 GeV

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- On-shell $\sigma\pi\pi$ and direct $\sigma\gamma\gamma$ couplings
  - Can be compared with QSSR-LET predictions :

$$\Gamma_{\sigma|_{on\ shell}\to\pi^+\pi^-} \simeq 1.0\ \text{GeV}, \qquad \Gamma_{\sigma|_{on\ shell}\to\gamma\gamma}|_{direct} \simeq (1.0\pm0.4)\ \text{keV.}$$

QSSR and the $\sigma/f_0(600)$

- What σ mass to be used ? (Minkowski)-Mennessier-SN-Ochs 07,08
  - QSSR mass obtained in the real axis !
  - USE the on-shell or Breit-Wigner mass (amplitude purely imaginary at the phase 90^0) Kniehl-Sirlin 08 BUT NOT the mass in the Complex plane : often (mis)used in the literature !
  - $M_\sigma|_{pole} \simeq$ 452(12)-i 260(15) MeV $\Longrightarrow$ $M_\sigma|_{on\ shell} \simeq M_\sigma|_{BW} \simeq$ 1 GeV
- On-shell $\sigma\pi\pi$ and direct $\sigma\gamma\gamma$ couplings
  - Can be compared with QSSR-LET predictions :

    $\Gamma_{\sigma|_{on\ shell}\to\pi^+\pi^-} \simeq 1.0\ \mathrm{GeV}, \qquad \Gamma_{\sigma|_{on\ shell}\to\gamma\gamma}|_{direct} \simeq (1.0 \pm 0.4)$ keV.
- What internal structure of the σ from QSSR is favoured by the data?
  - NOT pure $\bar{q}q$: too large $\gamma\gamma$ (5 keV) AND too small $\pi\pi$ [(120-180) MeV] widths !
  - NOT pure $4q$: too small $\gamma\gamma$ width (few 10 eV)
  - MOST PROBABLY a large Gluonium component: $\gamma\gamma$ and $\pi\pi$ widths OK !

QSSR and the $f_0(980)$

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- Direct $\gamma\gamma$ width = 0.27 keV :
  - Does not favour a 4q scenario : too small width !
  - Does not favour a $\bar{u}u+\bar{d}d$ scheme: : too large width !
  - A $\bar{s}s$ scenario looks OK : 0.4 keV BUT $|g_{f_0K^+K^-}|/|g_{f_0\pi^+\pi^-}| = 2.59(1.34)$ allows a coupling to $\pi\pi$!
  - σ and $f_0(980)$: maximally mixed gg and $\bar{q}q$? Bramon-SN 89, SN 98

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- States above 1 GeV ?
  - More Involved : Mixings - Spectroscopic Chemistry !
    SN 98, Amsler-Close 99, Close-Zhao 05,...
  - $\exists\ \sigma'_B$ as a radial excitation $\equiv f_0(1300)$?
  - G(1.5-1.6) as "true OZI glueball" ! : couples weakly to $\pi\pi,\ \bar{K}K$ BUT strongly to $\eta'\eta',\ \eta'\eta$: U(1) anomaly-like decays : GAMS

SU(3) Heavy Baryon Mass-spillings :

Spin 1/2

♠ *General choice of lowest dimension currents*

$$\eta_{\Xi_Q} = \epsilon_{abc}\left[(q_a^T C\gamma_5 s_b) + b(q_a^T C s_b)\gamma_5\right] Q_c \ ,$$

$$\eta_{\Lambda_Q} = \eta_{\Xi_Q} \quad (s \to q) \ ,$$

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Spin 3/2

♣ Interpolating currents

$$\eta^{\mu}_{\Xi^*_Q} = \sqrt{\frac{2}{3}}\left[(q^T C\gamma_\mu Q)s + (s^T C\gamma_\mu Q)q + (q^T C\gamma_\mu s)Q\right]$$

Study the 2-point-correlators

$$S(q) = i\int d^4x\, e^{iqx}\, \langle 0|\mathcal{T}\,\overline{\eta}_Q(x)\eta_Q(0)|0\rangle \equiv \hat{q}F_1 + F_2\ ,$$

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♣ *QCD: SVZ-OPE in terms of quark & gluon condensates*

♢ *EXP: One resonance + QCD continuum*

QCD input

QCD input

Parameters	Values	Ref.
Λ	(353 ± 15) MeV	[SNTau]
$\hat{m}_d$	(6.1 ± 0.5) MeV	
$\hat{m}_s$	(114.5 ± 20.8) MeV	[SNB, PDG]
$\hat{\mu}_d$	(263 ± 7) MeV	[SNB]
$\kappa \equiv \langle \bar{s}s \rangle / \langle \bar{d}d \rangle$	(0.7 ± 0.1)	[SNB, DOSCH]
M_0^2	(0.8 ± 0.1) GeV^2	[DOSCH, SN]
$\langle \alpha_s G^2 \rangle$	$(6.8 \pm 1.3) \times 10^{-2}$ GeV^4	[SNB, LNT, YND, BB]
$\rho \alpha_s \langle \bar{d}d \rangle^2$	$(4.5 \pm 0.3) \times 10^{-4}$ GeV^6	[SNTAU, LNT]
m_c	$(1.18 \sim 1.47)$ GeV	[SNB, PDG]
m_b	$(4.18 \sim 4.72)$ GeV	[SNB, PDG]

Baryons $J^P = \frac{1}{2}^+$

Baryons	I	$r^{sd}_{B^*_Q}$	Mass	Data
$\Xi_c(cqs)$	$\frac{1}{2}$		input	2467.9 ± 0.4 [PDG]
$\Omega_c(css)$	0		input	2697.5 ± 2.6 [PDG]
$\Xi_b(bqs)$	$\frac{1}{2}$		input	5792.4 ± 3.0 [PDG]
$\Xi'_c(cqs)$	$\frac{1}{2}$	1.043(10)	2559(25)	2575.7 ± 3.1 [PDG]
$\Xi'_b(bqs)$	$\frac{1}{2}$	1.014(7)	5893(42)	–
$\Omega_b(bss)$	0	1.0455(64)	6076(37)	6071.0 ± 40 [PDG]

$Baryons\ J^P = \frac{3}{2}^+$

Baryons	I	$r^{sd}_{B^*_Q}$	Mass	Data
$J^P = \frac{3}{2}^+$				
$\Xi^*_c(cqs)$	$\frac{1}{2}$	1.049(8)	2641(21)	2646.1 ± 1.3 [PDG]
$\Omega^*_c(css)$	0	1.109(17)	2792(38)	2768.3 ± 3.0 [PDG]
$\Xi^*_b(bqs)$	$\frac{1}{2}$	1.024(8)	5961(21)	–
$\Omega^*_b(bss)$	0	1.040(9)	6066(49)	–

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Mass of the $X(3872) \to J/\psi\, \pi\pi, \gamma$

♠ *Lowest dimension interpolating* 1^{++} *currents*

- $\bar{3} - 3$ *diquark – antidiquark* : $\sim i\epsilon_{abc}\epsilon_{dec}[(q_a^T C\gamma_5 c_b)(\bar{q}_d \gamma^\mu C \bar{c}_e^T) + \ldots]$
- $\bar{6} - 6$ *diquark – antidiquark* : $(q_a^T C\gamma_5 \lambda_{ab}^S c_b)(\bar{q}_d \gamma^\mu C \lambda_{de}^S \bar{c}_e^T)$
- $D^* - D$ *molecule* : $\sim (\bar{q}\gamma_5 c)(\bar{c}\gamma^\mu q) - (\bar{q}\gamma^\mu c)(\bar{c}\gamma_5 q)$
- $\lambda - J/\psi -$ *like molecule* : $\sim (\bar{c}\lambda^a \gamma^\mu c)(\bar{q}\lambda_a \gamma_5 q)$

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♣ $M_3^c \simeq 3925(127)$ MeV $M_3^b \simeq 10144(106)$ MeV

$\frac{M_s^b}{M^b} = (0.988 \pm 0.018)$ Matheus, SN, Nielsen, Richard 2007

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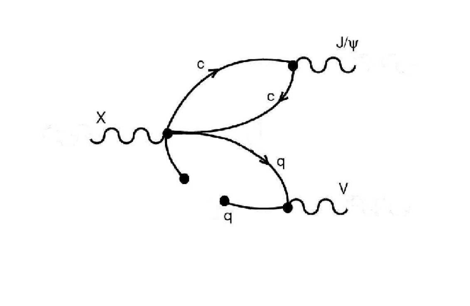
♢ $\frac{M_6}{M_3} \simeq \frac{M_{mol}}{M_3} \simeq 1.00 \pm 0.00..$ $\quad \frac{M_\lambda}{M_3} \simeq 0.96 \pm 0.03$

SN, Nielsen, Navarra 2010

$X \to J/\psi\pi\pi, \gamma$ *from vertex sum rules*

- *Diquark-antidiquark,* $D^* - D$ *molecule*



Fall-apart decay

$$\Gamma^{3,mol}_{X\to J/\psi+n\pi} \approx 50 \text{ MeV} \quad (\text{data}: \Gamma_{X\to\ all} \leq 2.3 \text{ MeV})$$

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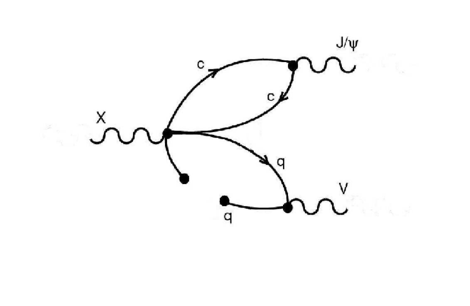

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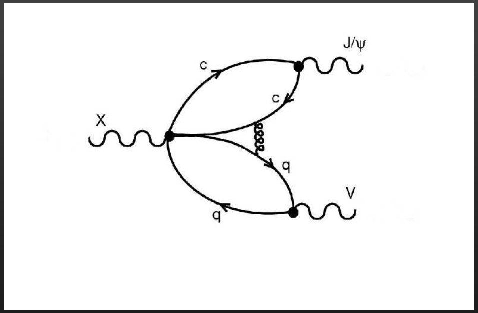

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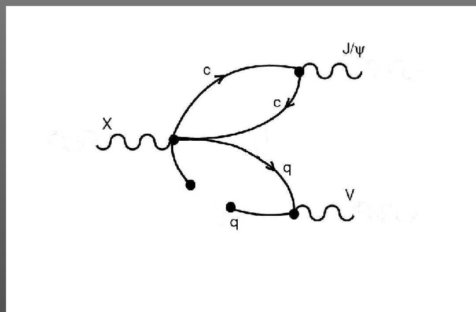

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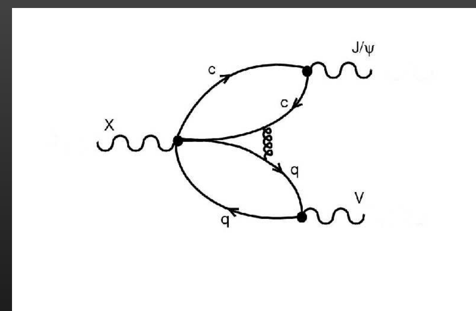

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♢ X a $\lambda - J/\psi$ molecule ? SN, Nielsen, Navarra 2010

$Y_c(4660) \to J/\psi\pi\pi$, $Y_b(10890) \to \Upsilon\pi\pi$

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♢ Check of reliability and extension to Y_b :

- Stability criteria
- Double ratio of sum rules: 4q/molecule, $SU(3)$ breakings
- Study of the Decays using vertex sum rules

Albuquerque, Navarra, Nielsen, Simonetti (Sao Paulo)
Rabemananjara, Fanomezana (Madagascar)
Mennessier, SN, Richard (France)
Q. Zhao, Z. Guo,... (Beijing)
Kaminski (Poland)

Conclusions : the FCPPL program

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Thanks for your attention !

Thanks to the organizers !

Thanks to the French-IN2P3 !

Thanks to the Chinese sponsors !