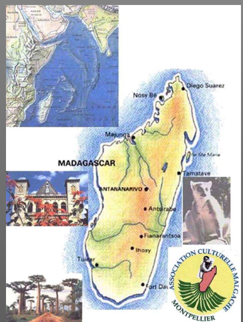

PUZZLES IN HADRON SPECTROSCOPY

Stephan Narison

CNRS / IN2P3 - LPTA (Montpellier)

1. *Light Hadron Spectroscopy*

- Light Quarks:

  u,d,s : $m_q \leq \Lambda_{QCD} \approx$ 350 MeV;

  $Q_u = 2/3; Q_d = Q_s = -1/3$

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♡ Light Ordinary Mesons

$\pi^- \equiv \bar{u}d : J^{PC} = 0^{-+}$; $\rho^- \equiv \bar{u}d : J^{PC} = 1^{--}$;

$A_1 \equiv \bar{u}d : J^{PC} = 1^{++}$

Well understood in QCD : associated resp. to the pseudoscalar, vector and axial-vector currents.

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  - $K_0^*(700-900)$ ...?
  - Confirmation of the $\sigma/f_0(600)$ Bern group, 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 the hadronic and $\gamma\gamma$ couplings: Recent analysis of $\gamma\gamma\to\pi\pi$ and $\pi\pi\to\pi\pi, K\bar{K}$ (Kaminski+Minkowski+Mennessier+ S.N+Ochs) leads to :
    $\Gamma(\sigma\to\gamma\gamma)|_{direct}\simeq(0.13\pm0.05)$ KeV , $\Gamma(\sigma\to\gamma\gamma)|_{rescat}\simeq(2.7\pm0.4)$ KeV

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- Aims in this talk
  - QCD Spectral Sum Rules (QSSR) $\oplus$ Low Energy Theorem (LET) analysis (without any prejudices) of Unmixed States

QSSR

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- SVZ Sum Rules M.A. Shifman - A.I. Vainshtein - V.I. Zakharov 79
  - 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
  - $\Pi(Q^2 \equiv -q^2 \geq \Lambda^2) = \sum_{0,1,\ldots} C_{2n} \langle O_{2n}\rangle / Q^{2n}$: *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, Chetyrkin-SN-Zakharov 99
  - Condensates $\langle O_{2n\geq 4}\rangle$: $m\langle\bar{\psi}\psi\rangle$, ...quark $\langle \alpha_s G^a_{\mu\nu} G_a^{\mu\nu}\rangle$, ...gluons

    Note: The coeff. of G^2 is not generated by the quark propagator put in external fields !

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
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- Finite Energy & τ-like Sum Rules (FESR)
  Bramon-Etim-Greco 72, Shankar 77, Chetyrkin-Krasnikov-Tavkhelidze 78, Floratos-SN-de Rafael 79, Bertlmann-Launer-de Rafael 85, Braaten-SN-Pich 92
  - $\mathcal{M}_n \equiv \int_{t_<}^{Q^2} dt\ \rho(t) t^n \mathrm{Im}\Pi(t)$ $\rho(t) \equiv \left(1 - \frac{t}{Q^2}\right)^2$ for τ-decay...

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- Optimal Results
  - Stability in the change of the sum rules variables and QCD continuum threshold

    ($\simeq$ variational calculation)

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

$M_{\bar{u}d} \simeq$ 1 GeV , $\quad M_{\bar{u}s} \simeq M_{\bar{u}d}$

Different positions of the optimization scales cancel SU(3) breaking effects SN 06

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- $O_{4q} = (\bar{u}\Gamma u)(\bar{s}\Gamma s) + \ldots , \quad O_{6d} = (uu)(\overline{ss})$

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

$M_{\sigma_B} \simeq$ 1 GeV, $\quad M_G \simeq$ (1.5 - 1.6) GeV SN-Veneziano 89

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- No conclusive structure from spectra predictions !

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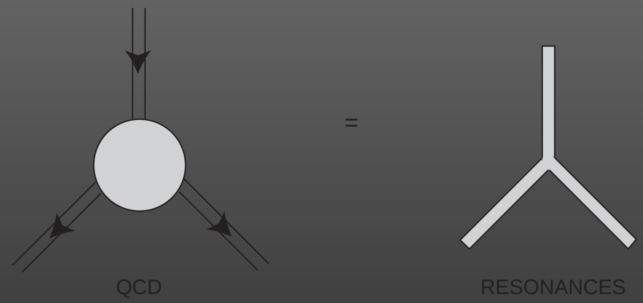
- From 3-point quark correlation functions

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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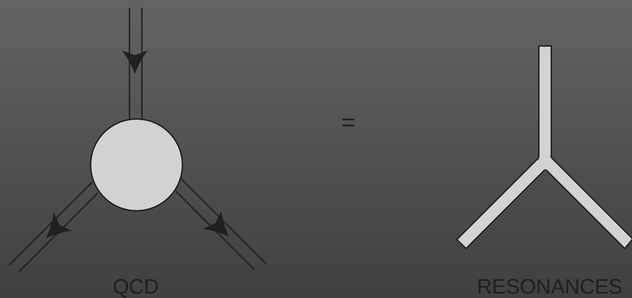

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- $\Gamma_{a_0(\bar{u}u-\bar{d}d)\to\pi^0\eta} \approx 84$ MeV : $g_{a_0\eta\pi} = \sqrt{\frac{2}{3}} g_{a_0K^+K^-}$ (SN 86, 06)

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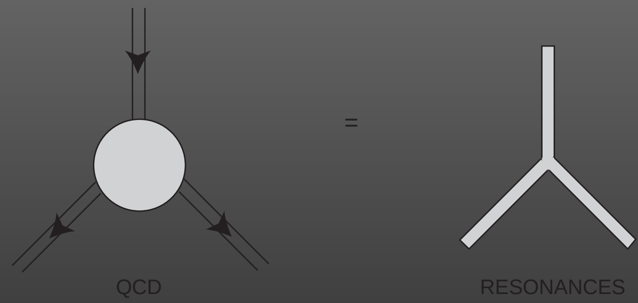

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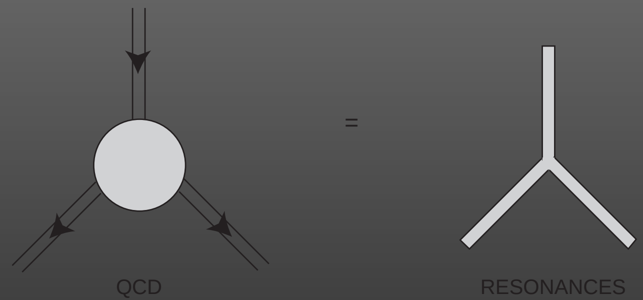

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- $\frac{\Gamma_{S_{4q}\to\gamma\gamma}}{\Gamma_{S_2\to\gamma\gamma}} \simeq (1 \sim 2) \times 10^{-3} \approx \left(\frac{\alpha_s}{\pi}\right)^2 \Longrightarrow \Gamma_{S_{4q}\to\gamma\gamma} \leq 12$ eV (SN 86)

Widths of bare Gluonia from LET$\oplus$QSSR

Widths of bare Gluonia from LET⊕QSSR

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

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

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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)

Comparison with the data

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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 !
    - $M_\sigma|_{pole} \simeq$ 422-i 290 GeV $\Longrightarrow$ $M_\sigma|_{on\ shell} \simeq M_\sigma|_{BW} \simeq$ 1 GeV

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- On-shell σππ and direct σγγ couplings
  - Comparable with previous QSSR⊕LET predictions :

    $\Gamma_{\sigma|_{on\ shell}\to\pi^+\pi^-} \simeq 1.0\ \text{GeV}, \qquad \Gamma_{\sigma|_{on\ shell}\to\gamma\gamma}|_{direct} \simeq (1.0 \pm 0.4)$ keV.

Comparison with the data

- 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 !
  - $M_\sigma|_{pole} \simeq$ 422-i 290 GeV $\Longrightarrow$ $M_\sigma|_{on\ shell} \simeq M_\sigma|_{BW} \simeq$ 1 GeV
- On-shell $\sigma\pi\pi$ and direct $\sigma\gamma\gamma$ couplings
  - Comparable with previous QSSR$\oplus$LET predictions :

    $\Gamma_{\sigma|_{on\ shell}\to\pi^+\pi^-} \simeq 1.0\ \mathrm{GeV}, \quad \Gamma_{\sigma|_{on\ shell}\to\gamma\gamma}|_{direct} \simeq (1.0 \pm 0.4)$ 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) and $g_{\sigma\bar{K}K} \ll g_{\sigma\pi\pi}$
  - MOST PROBABLY a large Gluonium component: $\gamma\gamma$, $\pi\pi$ and $\bar{K}K$ couplings OK !

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  - $B_{\phi\to\sigma_B\gamma} \approx 12 \times 10^{-5}$ SN-V 89, SN 98, 06 : KLOE $B_{\phi\to\pi^0\pi^0\gamma} = (10.9 \pm 0.06) \times 10^{-5}$
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  - Needs a precise determination of the hadronic couplings and their ratio.
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- Present interpretations seem to be premature !

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- Analogous problems for clarifying the nature of the other scalars !
- Further efforts from theory and experiments are still needed :
  - Poor $\gamma\gamma \to \pi\pi$ data below 700 MeV
  - Separation of the direct $\gamma\gamma$ coupling and rescattering contributions
  - Data from $J/\psi \to \gamma\sigma,\ \pi^+\pi^-,\ K^+K^-, \ldots$
  - ...

3. 1^{-+} *LIGHT EXOTICS*

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  - $M_H = 2.2$ GeV (Lattice with 2 fermions)
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- Nature of the $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$
  - $\pi_1(1400)$, $\pi_1(1600)$ can result from 4q $\oplus$ molecule mixing : $\theta_{mix} = 11.7 \pm 2.2^0$
  - $\pi_1(2015)$ more hybrid component.

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- QSSR analysis
  - X(3872) as a 4-quark state (Matheus-Nielsen-SN-Richard 07)
  - Y(4260) as a 1^{--} $\bar{D}^* D_0$ molecule (Albuquerque-Nielsen 08)

5. *OPEN CHARM & BOTTOM STATES*

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- $D_{sJ}(2317)$ & $D^*_{sJ}(2457)$ candidates
  - Decay into $D_s\pi,\ D_s\gamma$ and $D_s\pi\gamma$ (Belle-Babar)
- QSSR predictions for $\bar{Q}q$
  - $0^- - 0^+$ splittings controlled by the quark condensate $\langle\bar{q}q\rangle$ (SN 09)
  - $M_{D_s(0^+)} = 2297(113)$ MeV $M_{D_s(0^+)} - M_{D_{(0^+)}} \simeq 25$ MeV
  - $M_{D^*_s(1^{++})} \simeq 2440(113)$ MeV ($\approx$ flavour & spin symmetries for the splittings)
  - $M_{B(0^+)} - M_{B(0^-)} \simeq 422(196)$ MeV $\approx M_{D(0^+)} - M_{D(0^-)}$

6. *CHARM & BOTTOM BARYONS*

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Table 2: QSSR predictions of the strange heavy baryon masses in units of MeV from the double ratio (DR) of sum rules. The data for the Ω_b come respectively from the D0 and the CDF collaborations (Albuquerque-Nielsen-S.N. 09)

Baryons	$r^{sd}_{B^*_Q}$	Mass	Data
Octet (spin 1/2)			
$\Xi_c(csq)$	1.075(21)	2458(50)	2467.9 ± 0.4
$\Omega_c(css)$	1.141(39)	2800(96)	2697.5 ± 2.6
$\Xi_b(bsq)$	1.048(15)	5888(81)	5792.4 ± 3.0
$\Omega_b(bss)$	1.051(12)	6108(71)	6165.0 ± 13
			6054.4 ± 6.9
Decuplet (spin 3/2)			
Ξ^*_c	1.065(21)	2682(53)	2646.1 ± 1.3
Ω^*_c	1.135(37)	2858(92)	2768.3 ± 3.0
Ξ^*_b	1.024(8)	5973(44)	–
Ω^*_b	1.051(17)	6130(99)	–

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- New data for heavy mesons are available and will come soon
- Related theoretical progresses are expected.