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Darmstadt - October 05, 2011

Exotic States

in QCD Sum Rules

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SCIENCES ET TECHNIQUES

FAPESP

Hadronic Physics

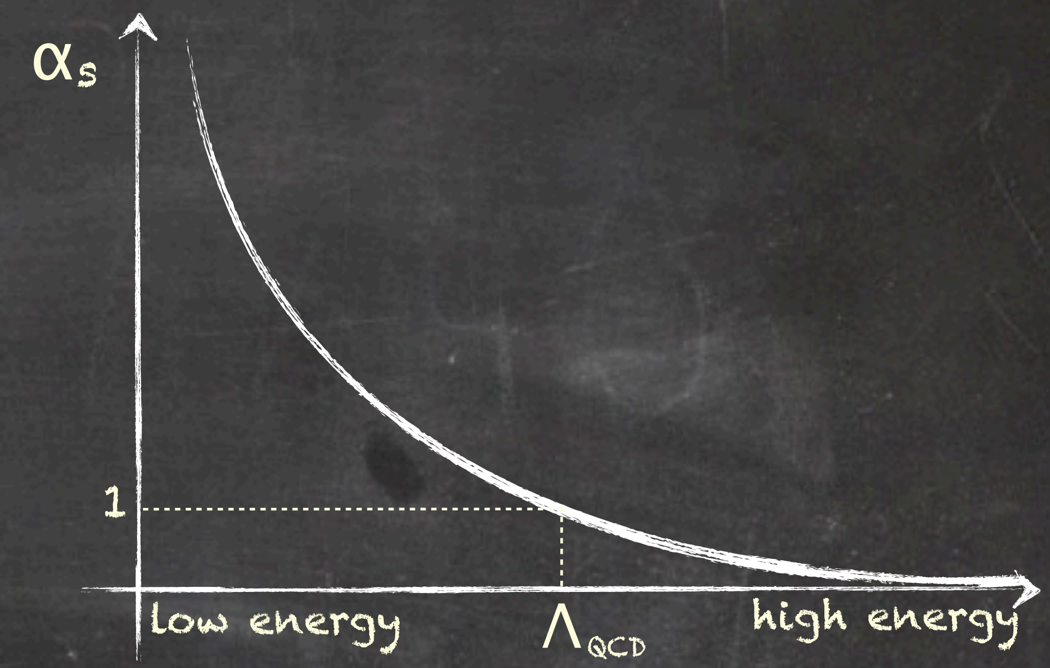
QCD

Quarks are always CONFINED within hadrons.

At high energies, quarks behave like free particles since the coupling α_s is quite small (Asymptotic Freedom).

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f)\, \ln(Q^2/\Lambda^2)}$$

At low energies, Perturbation Theory for QCD is no longer valid ($\alpha_s \gg 1$) and VEV becomes highly nontrivial giving rise to the Condensates.



Hadrons are made of quarks and gluons held together by the strong interactions.

non-pertubative theoretical
model to study hadrons

QCD SUM RULES

M.A. Shifman, A.I. Vainshtein, V.I. Zakharov
Nucl. Phys. B147 (1979) 385

"QCD as a Theory of Hadrons - from partons to confinement"
S. Narison (2004) - Cambridge Press

QCD Sum Rules

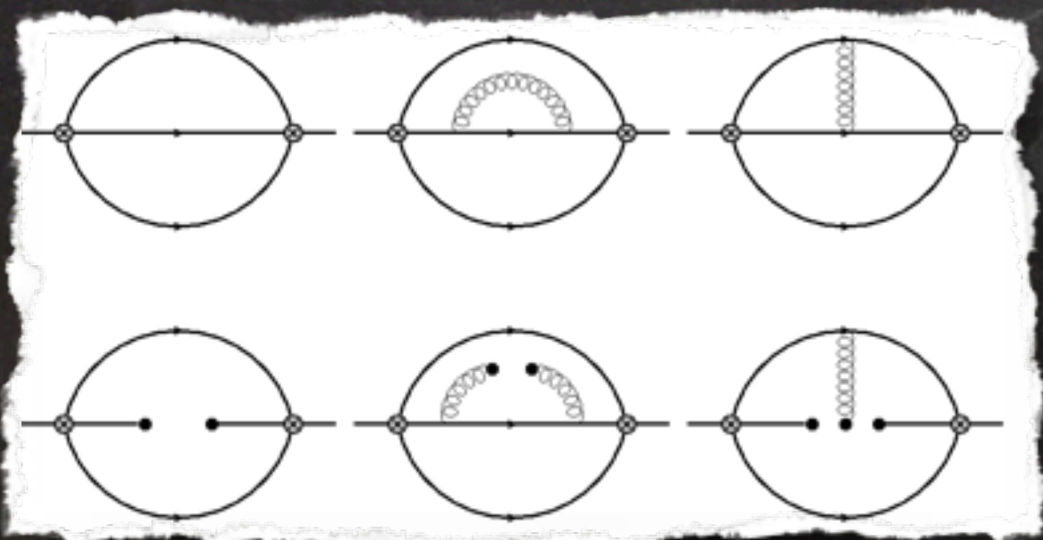
$$\Pi^{\mu\nu}_{(q)} = i \int d^4x\, e^{iqx} \langle 0 | T[J^{\mu}_{(x)} \bar{J}^{\nu}_{(0)}] | 0 \rangle = g^{\mu\nu} (\hat{q} F_1 + F_2)$$

Principle of Duality says that we can describe a hadron at both quark and hadronic level.

$$\Pi^{QCD}_{(q)} = \Pi^{Phen}_{(q)}$$

Quarks and gluons
Wilson OPE
$\langle \bar{q}q \rangle$ and $\langle G^2 \rangle$ Condensates
Dispersion Relation

Mesons and Baryons
Hadronic parameters
Phenomenology
Dispersion Relation

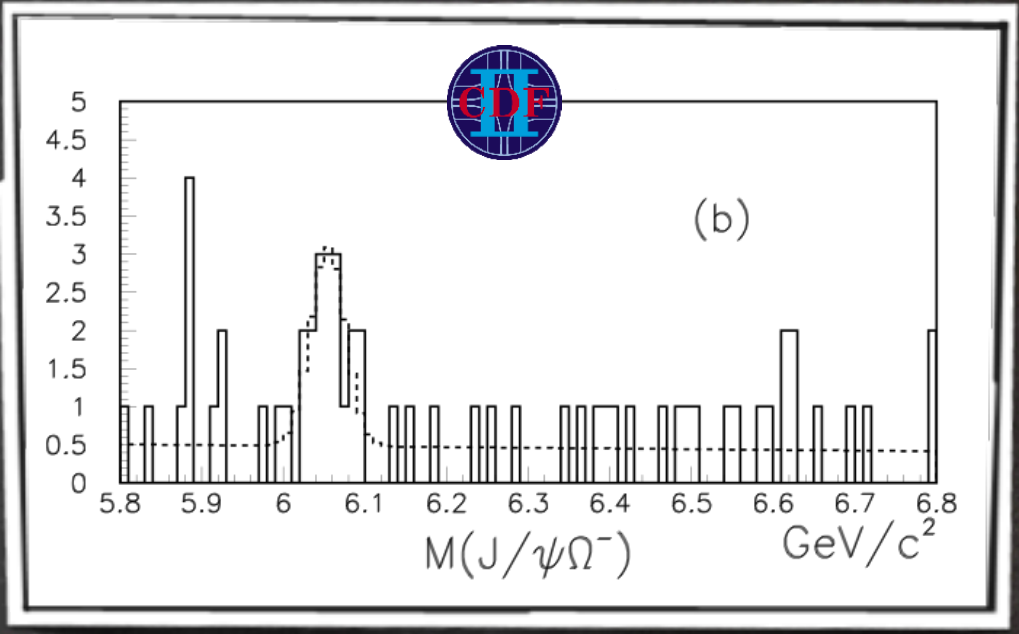


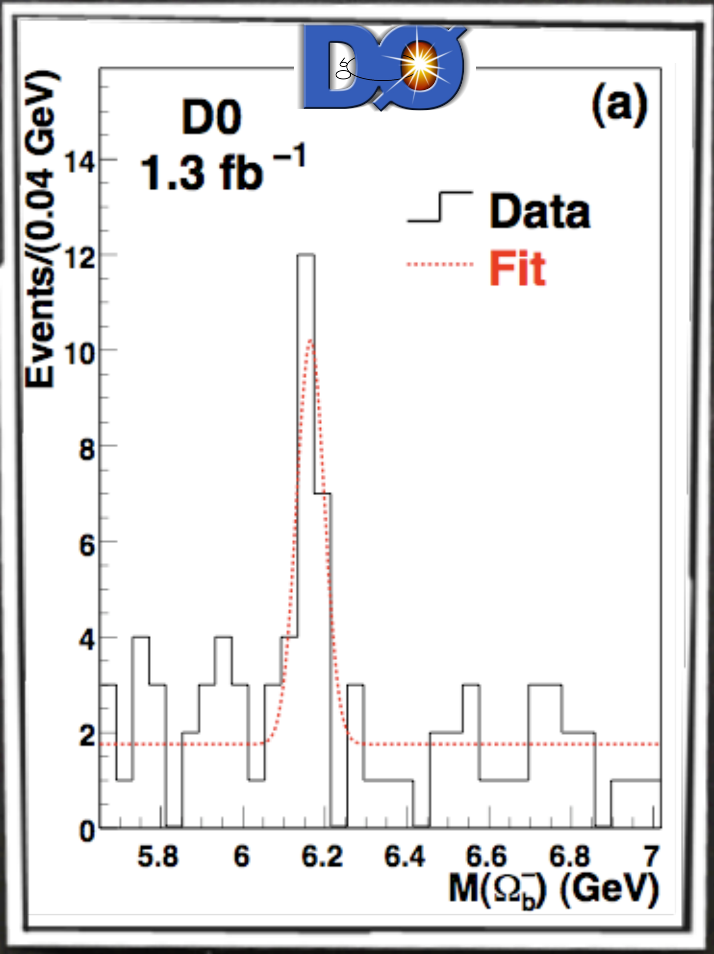
Masses

Heavy Baryons

Ω_b Baryon

	m_{Ω_b} (MeV)	
CDF	6054.4 ± 6.8	PRD 80 (2009) 72003
DØ	6165 ± 10	PRL 101 (2008) 232002
QCDSR	6076 ± 37	Albuquerque, Narison, Nielsen PLB 684 (2010) 236
Lattice	6006 ± 10	R. Lewis et al. PRD 79 (2009) 014502
PM	6052.1 ± 5.6	Karliner et al. NPB 187 (2009) 21
1/Nc	6039.1 ± 8.3	E. Jenkins PRD 77 (2008) 034012





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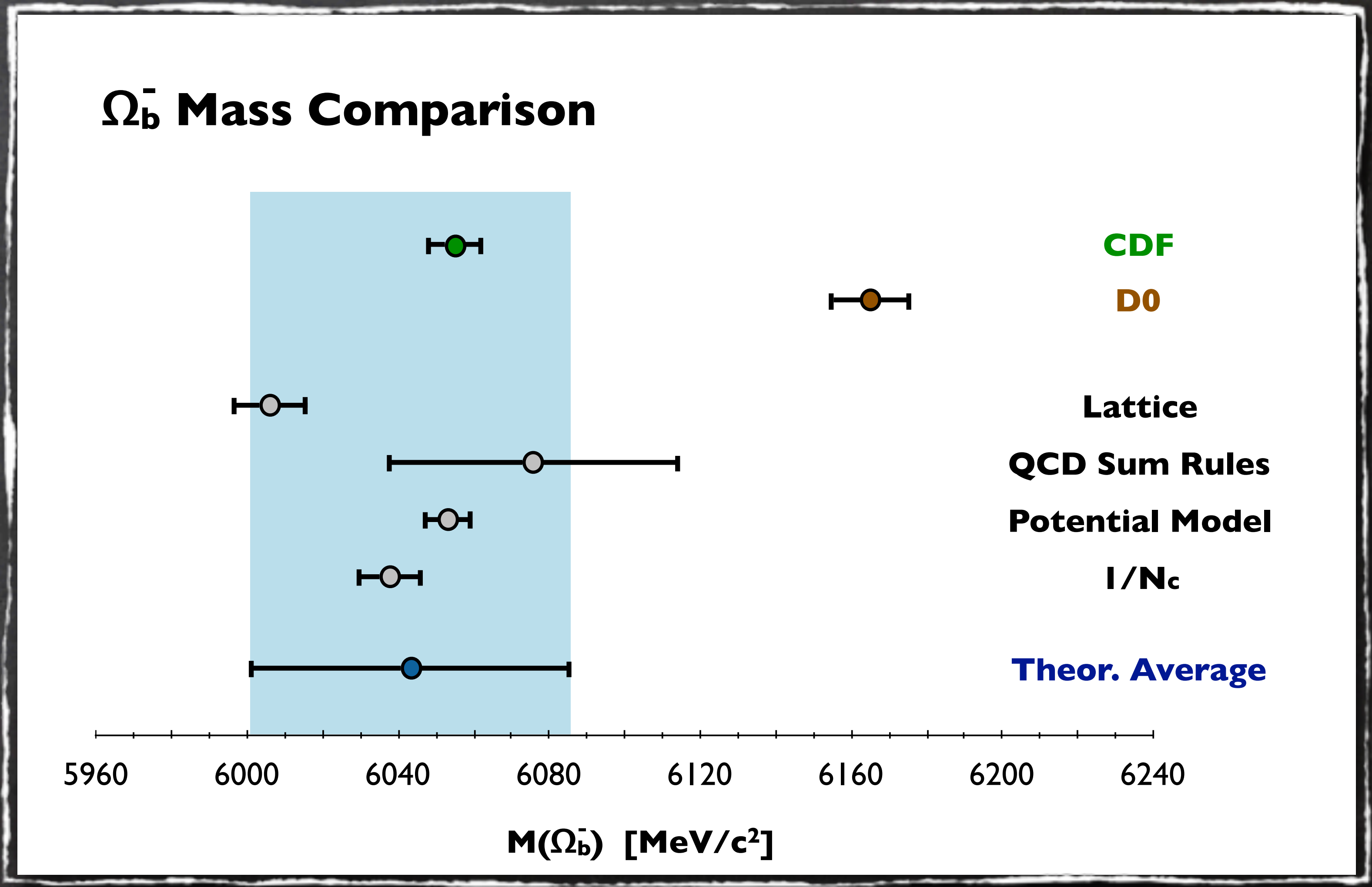


Theoretical predictions are in a much better agreement with CDF!!

And here we can see the importance of theoretical models to support one or another experimental observation.

Heavy Baryons

* why not study (QQQ) Tryply HB ?
* predictions for (QQs) Doubly HB
* expectative for more experimental results...
* good tests for QCDSR !

in progress

Ω^*_{ccb} Ω^*_{bbc}
Ω_{ccb} Ω_{bbc}
Ω_{ccc} Ω_{bbb}

Albuquerque, Narison
PLB 694 (2010)

Ω_{bc}
Ω^*_{cc} Ω^*_{bb}
Ω_{cc} Ω_{bb}
Λ_{bc}
Ξ^*_{cc} Ξ^*_{bb}
Ξ_{cc} Ξ_{bb}

Good concise review: "Baryon Spectroscopy"
E. Klempt, J-M. Richard, Rev.Mod.Phys. 82 (2010) 1095

Years	76	80	83	91	95	99	06	07	08	??
	Λ_c	Σ_c	Ξ_c, Ω_c	Λ_b	Σ^*_c	Ξ^*_c, Ξ'_c	Ω^*_c	Σ^*_b, Σ_b, Ξ_b	Ω_b	Ξ'_b, Ξ^*_b, Ω^*_b

Albuquerque, Narison, Nielsen
PLB 684 (2010)

Exotic States

REVIEWS:

1) S. Godfrey, S.L. Olsen. arXiv:0801.3867
Ann. Rev. Nucl. Part. Science, Vol. 58: 51-73 (2008).

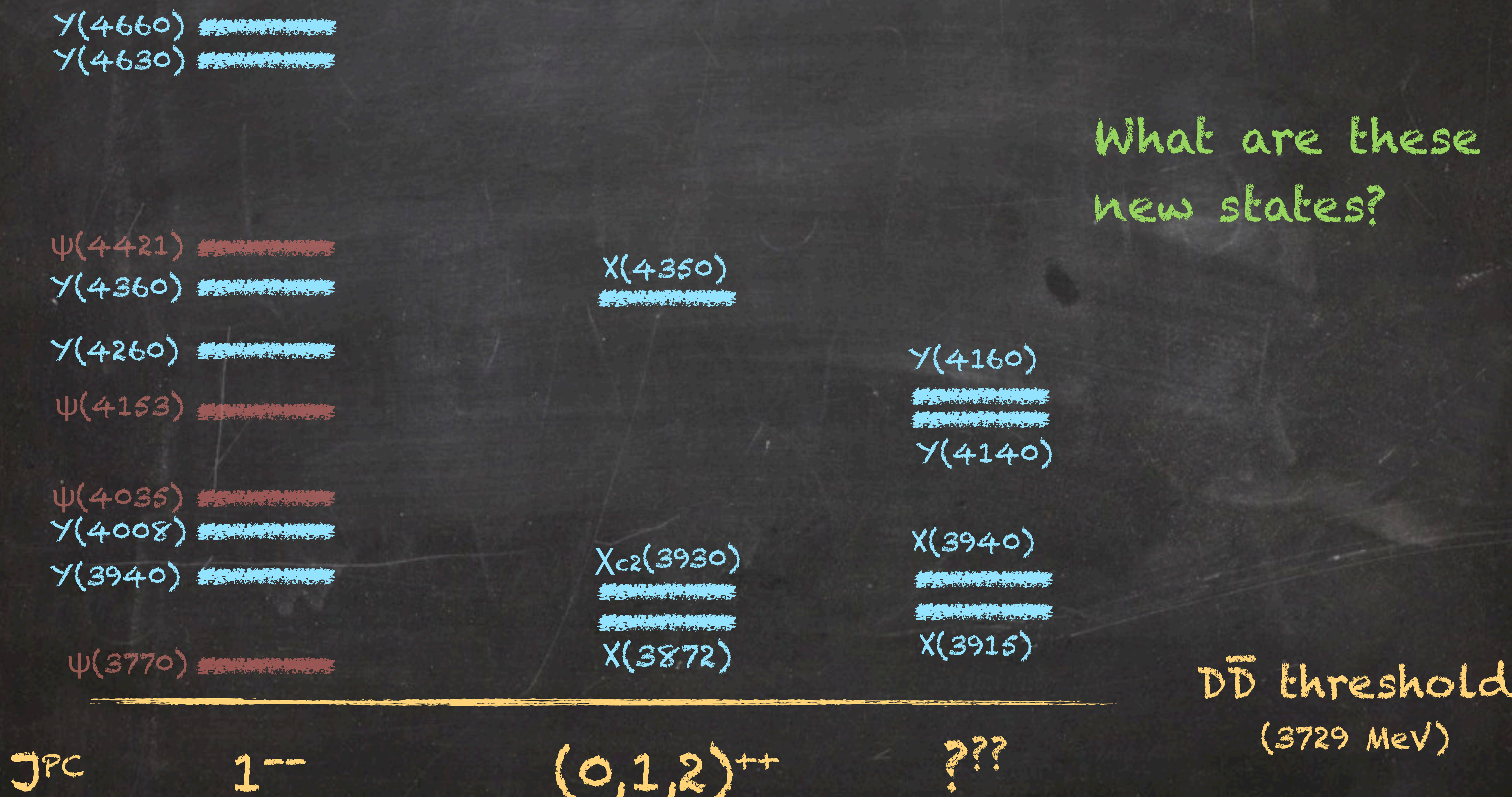
2) N. Brambilla et al. arXiv: 1010.5827
Eur. Phys. Journal C71: 1534 (2011).

Exotic States

charmonium spectroscopy **before** the B-factories

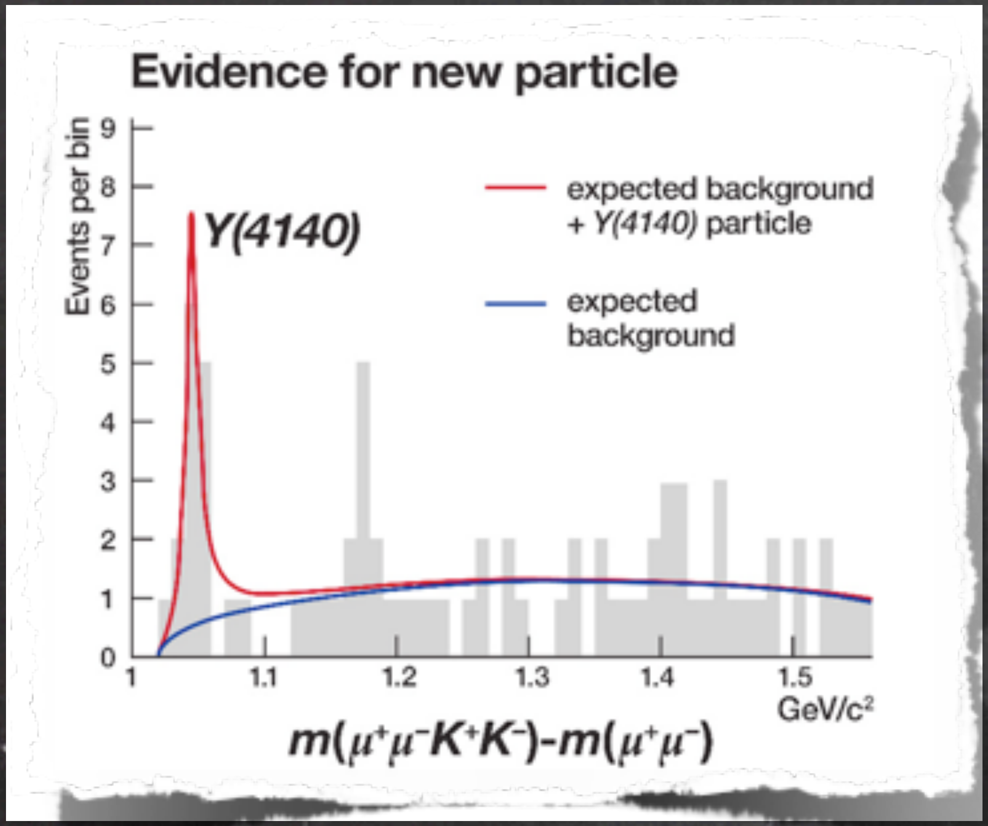
Exotic States

charmonium spectroscopy after the B-factories



Exotic States

What are these new states?



CDF

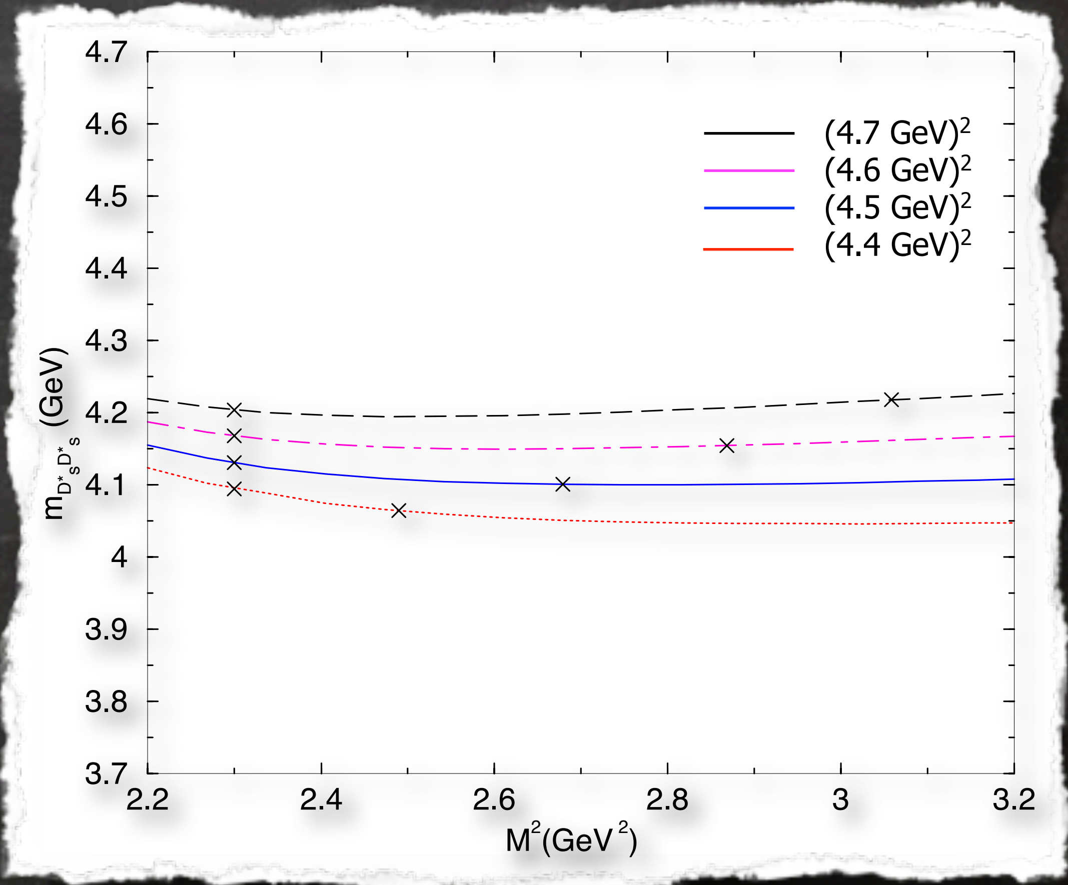
$$Y(4140) \longrightarrow J/\psi\ \phi$$

$$M_{exp} = (4143 \pm 2.9 \pm 1.2)\ \text{MeV}$$

$Y(4140)$ as $D_s^* \bar{D}_s^*$ molecular state, with $J^{PC} = 0^{++}$.

$$J = (\bar{s}_a \gamma^\mu c_a)(\bar{c}_b \gamma_\mu s_b)$$

$$M = 4.14 \pm 0.09\ \text{GeV}$$



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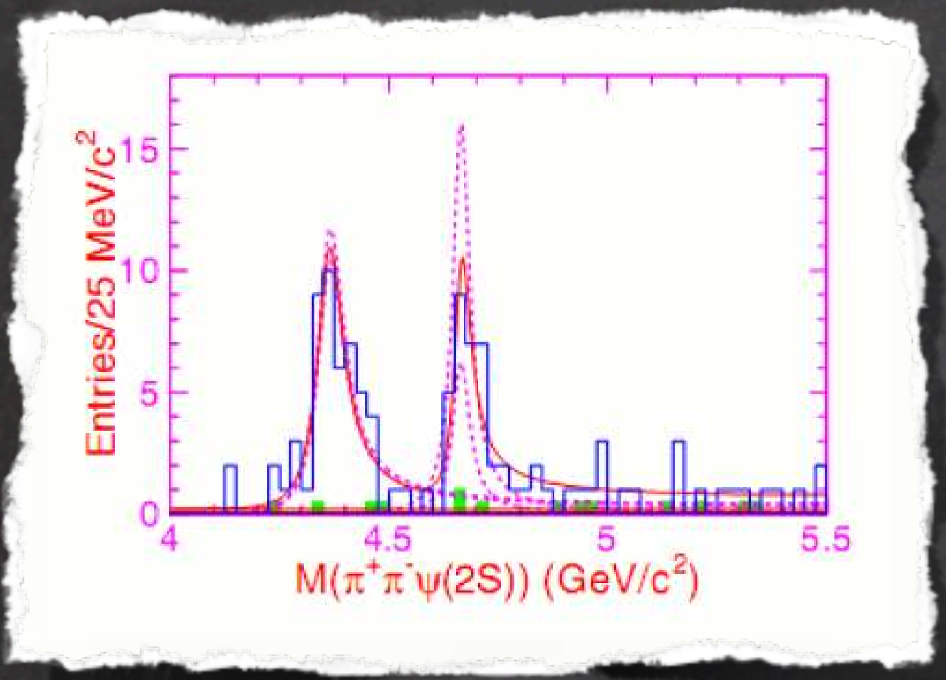


BaBar and Belle:

$$Y(4660) \longrightarrow \psi(2S)\,\pi^+\pi^-$$

$$M_{exp} = (4664 \pm 11 \pm 5)\ \mathrm{MeV}$$

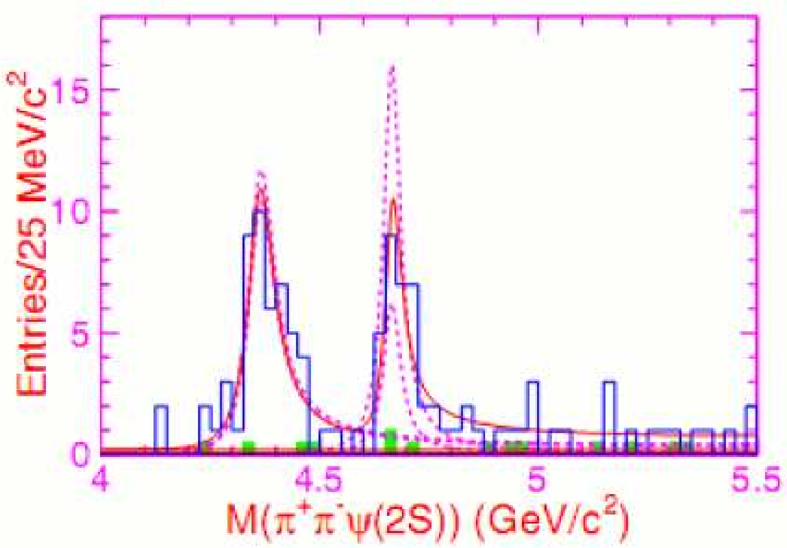
$Y(4660)$ as $[cs]_{s=0}[\bar{c}\bar{s}]_{s=1}$ tetraquark state, with $J^{PC} = 1^{--}$

$$J_\mu = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\left[(s_a^T C\gamma_5 c_b)(\bar{s}_d \gamma_\mu \gamma_5 \bar{c}_e^T) + (s_a^T C\gamma_5\gamma_\mu c_b)(\bar{s}_d \gamma_5 C\, \bar{c}_e^T) \right]$$

$$M = 4.65 \pm 0.10\ \mathrm{GeV}$$

Exotic States

What are these new states?



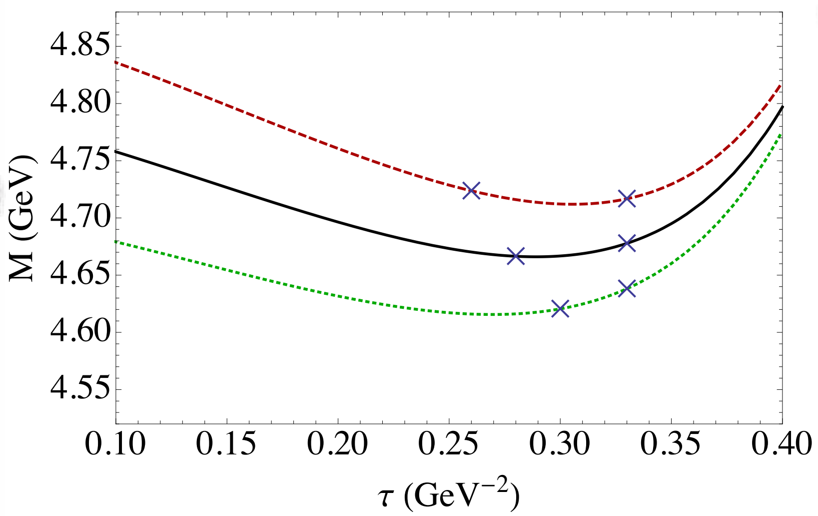
BaBar and Belle:

$$Y(4660) \longrightarrow \psi(2S)\,\pi^+\pi^-$$

$$M_{exp} = (4664 \pm 11 \pm 5)\ \text{MeV}$$

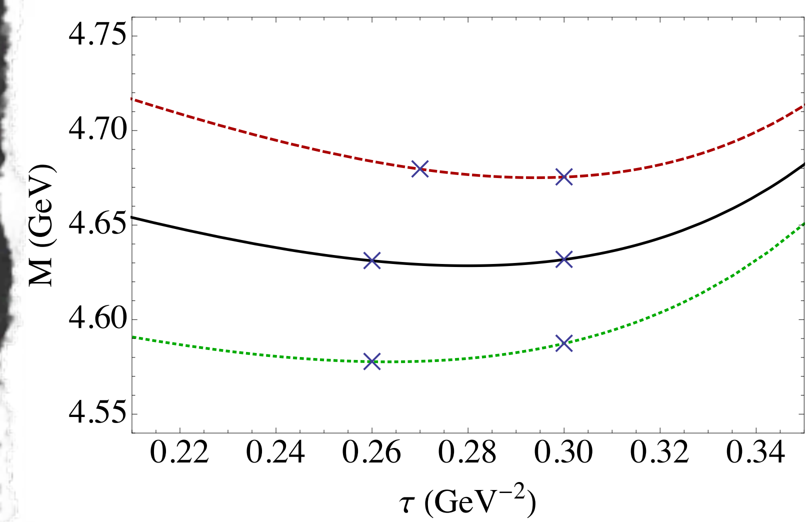
Another possibility are the molecular states:

$J/\psi - f_0(980)$



$M = 4.67 \pm 0.09$ GeV

$J/\psi - \sigma(600)$



$M = 4.63 \pm 0.10$ GeV

Exotic States

Besides, there is evidence for new $c\bar{c}$ states with eletric charge!!

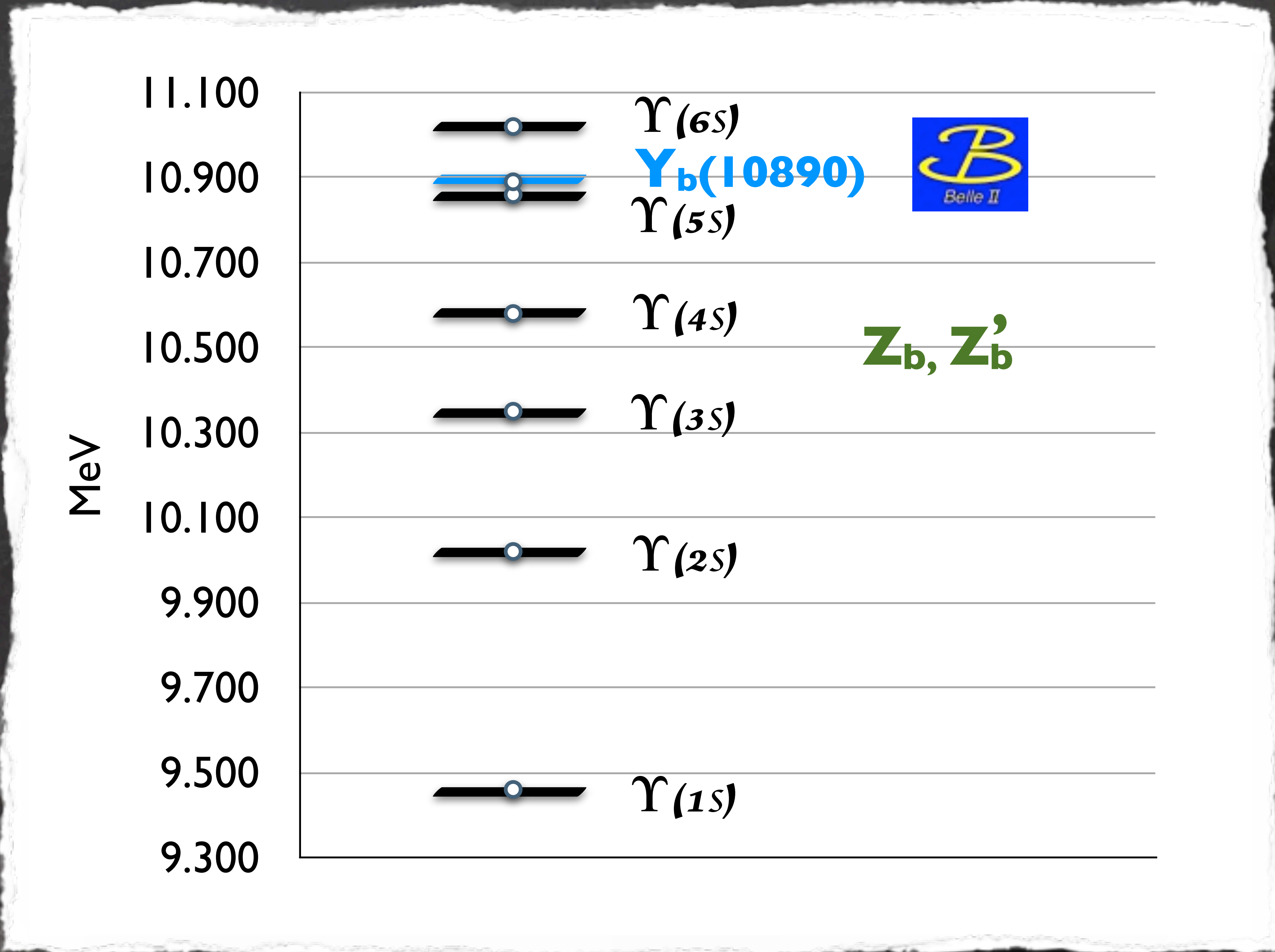
$$Z(4430)^+ \longrightarrow \psi(2S)\ \pi^+$$

$$Z_1(4050)^+ \longrightarrow \chi_c'\ \pi^+$$

$$Z_2(4250)^+ \longrightarrow \chi_c'\ \pi^+$$

- must have quark exotic constituents $[c\ \bar{c}\ u\ \bar{d}]$
- first decay channel can be observed at LHC.

b-Sector

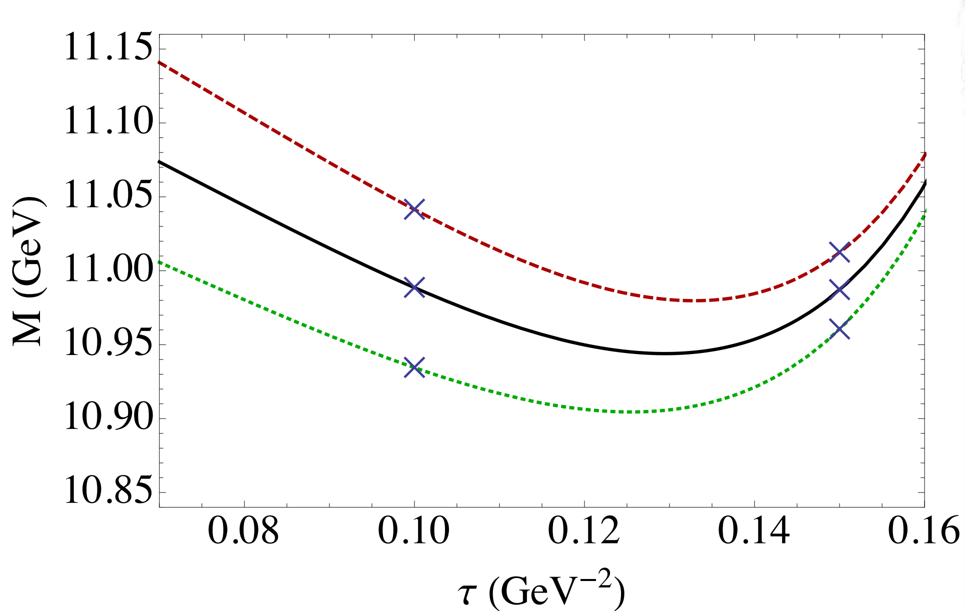


Beginning of new exotic states in $b\bar{b}$ spectroscopy?

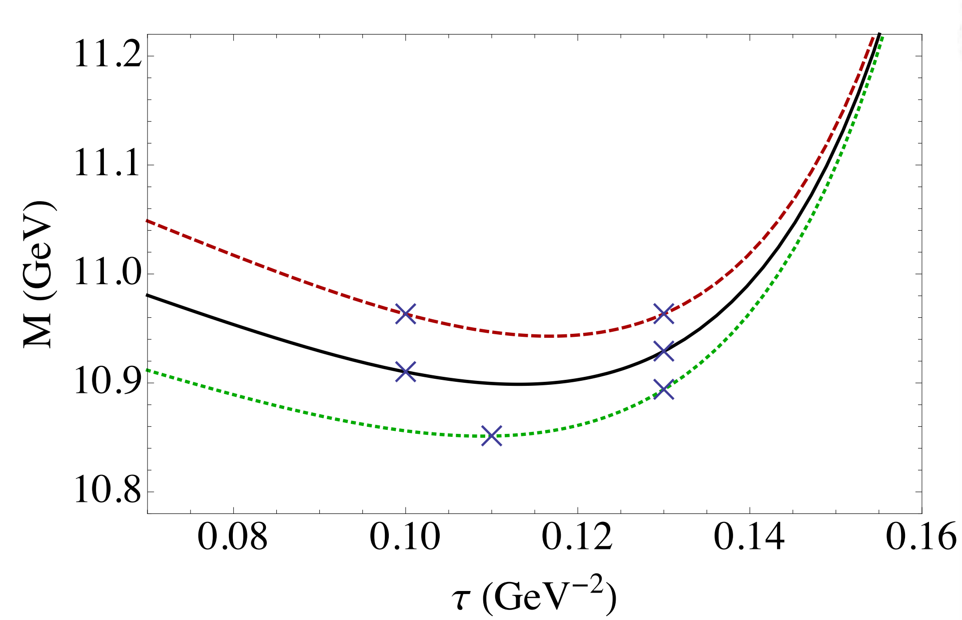
b-Sector

$Y_b(10890) \longrightarrow \Upsilon(nS)\,\pi^+\pi^-$ $\quad M_{exp} = (10888.4 \pm 2.7 \pm 1.2)$ MeV

Tetraquarks, in a P-wave scalar-diquark scalar-antidiquark configuration, could explain this new state?



$M = 10.97 \pm 0.10$ GeV



$M = 10.91 \pm 0.07$ GeV

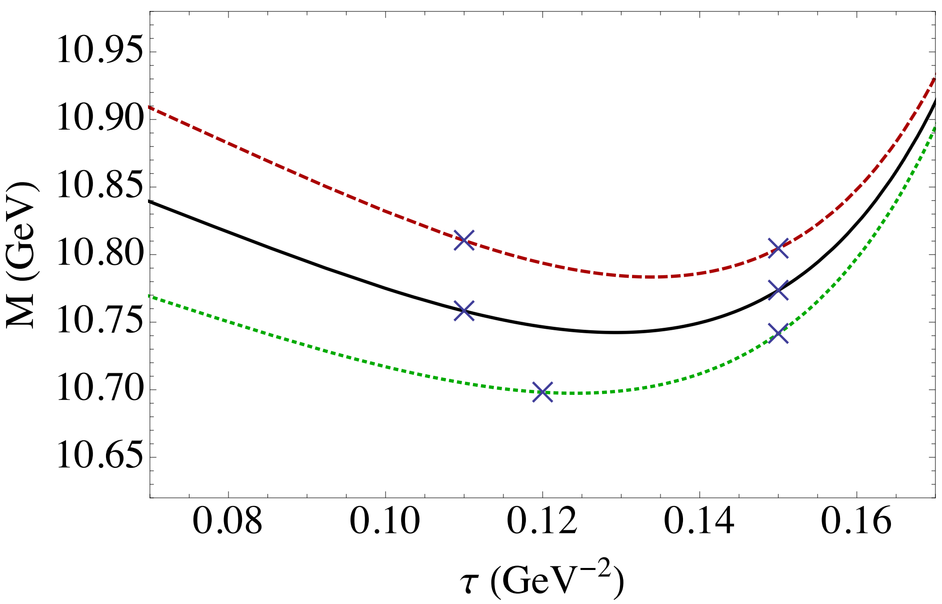
b-Sector

Belle II

$Y_b(10890) \longrightarrow \Upsilon(nS)\,\pi^+\pi^-$ $\quad M_{exp} = (10888.4 \pm 2.7 \pm 1.2)$ MeV

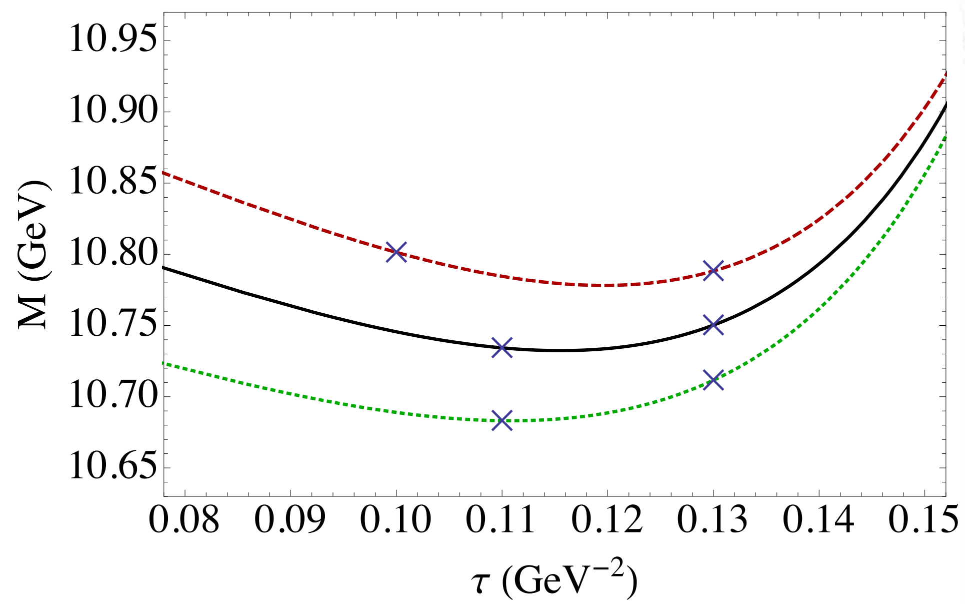
Molecular States

$\Upsilon - f_0(980)$



$M = 10.75 \pm 0.12$ GeV

$\Upsilon - \sigma(600)$



$M = 10.74 \pm 0.09$ GeV

Summary

- a lot of particles to be seen.

- understand which structure: hybrids, molecules, tetraquarks, hadro-charmonium, something else... fits better the hadronic spectroscopy.

- All these states could belong to the same puzzle inside the theory of hadrons? Some unknown mechanism?

- good test for the model to predict hadronic masses.

More Experimental Data

THANKS !!!

Currents

- reproduce the hadrons quantum numbers
- have the correct content of the quark fields
- we work with the lowest dimension, which means: without derivative terms.

TRIPLY HB $J^{\mu}_{\Omega^*_{QQQ}} = \epsilon_{abc}\,(Q_a^T C\gamma^{\mu} Q_b) Q_c$

Y(4140) $J = (\bar{s}_a \gamma^{\mu} c_a)\,(\bar{c}_b \gamma_{\mu} s_b)$

Y(4660) $J_{\mu} = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}} \left[(s_a^T C\gamma_5 c_b)(\bar{s}_d \gamma_{\mu}\gamma_5 \bar{c}_e^T) + (s_a^T C\gamma_5\gamma_{\mu} c_b)(\bar{s}_d \gamma_5 C \bar{c}_e^T) \right]$

QCD Sum Rules

$$\Pi^{\mu\nu}_{(q)} = i \int d^4x \, e^{iqx} \langle 0 | T[J^{\mu}_{(x)} \bar{J}^{\nu}_{(0)}] | 0 \rangle = g^{\mu\nu} (\hat{q} F_1 + F_2)$$

SVZ Sum Rules:

$$m_h \simeq \frac{\int_{t_q}^{t_c} ds \, e^{-s\tau} \, \mathrm{Im}\, F_2(s)}{\int_{t_q}^{t_c} ds \, e^{-s\tau} \, \mathrm{Im}\, F_1(s)} \equiv \mathcal{R}^q_{21}$$

$$m_h^2 \simeq \frac{\int_{t_q}^{t_c} ds \, s \, e^{-s\tau} \, \mathrm{Im}\, F_i(s)}{\int_{t_q}^{t_c} ds \, e^{-s\tau} \, \mathrm{Im}\, F_i(s)} \equiv \mathcal{R}^q_i$$

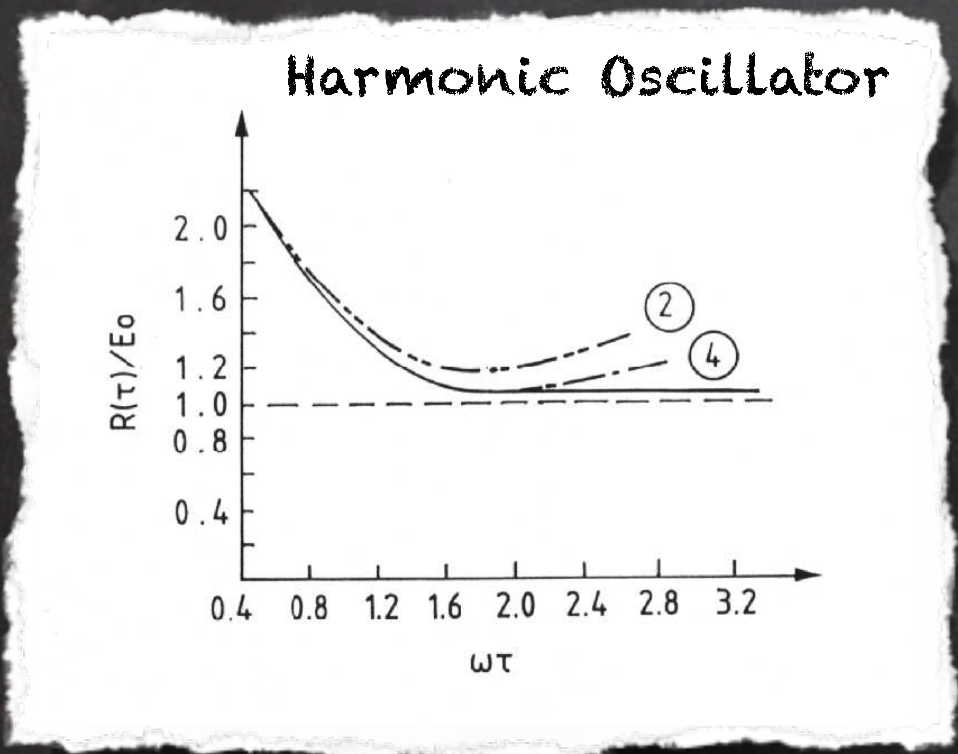
where $i = 1,2$

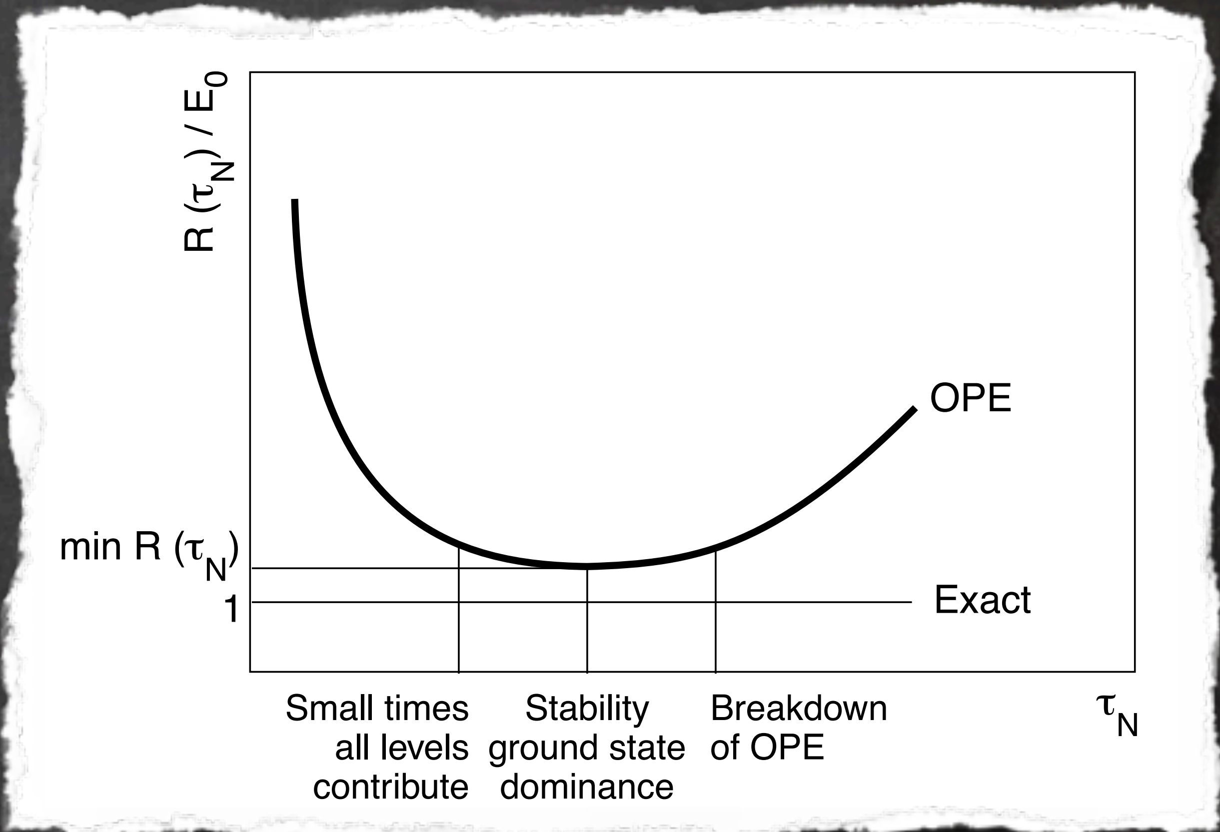
$t_q = 4m_Q^2$
t_c = continuum threshold
τ = Sum rule parameter

- These quantities have been used for getting the hadron masses and lead to a typical uncertainty of 10% - 15%

QCD Sum Rules

- Optimization criteria from Quantum Mechanics
  S. Narison, NPB Proc. Suppl. 207-208, 315 (2010).





- Then, we expect that SR must have τ-stability under Ground State Dominance (GSD).
- In GSD, we also expect t_c-stability.