1+ XTZ States Within Sum Rules

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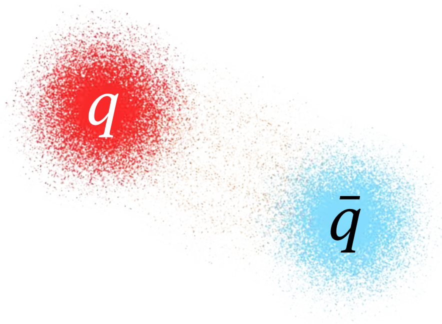
A VERY BRIEF SUMMARY ON EXOTIC HADRONS

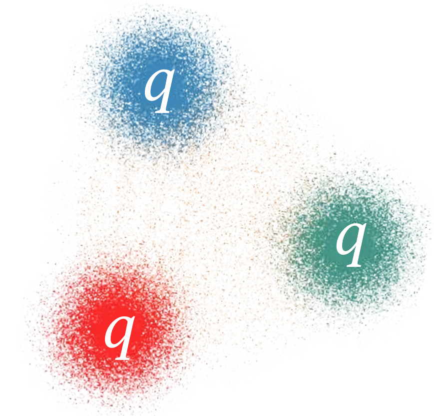
A very brief summary on Exotic Hadrons



Hadrons successfully explained by Quark Model

Gell-Mann & Zweig in 1964

PHYS. LETT. 8 (1964) *CERN-TH-201 & 412 (1964)*



First experimental evidence of a tetraquark state, the *S(1930)*

announced in 1974 by Brookhaven National Laboratory

A.S. CARROLL ET AL. (BNL COLLAB.), PHYS. REV. LETT. 32 (1974)

Within the string model, the tetraquark state could explain the S(1930) bump

Rossi & Veneziano in 1977 *NUCL. PHYS. B 123 (1977)*

The existence of a pentaquark state has been conjectured

Montanet, Rossi & Veneziano in 1980 *PHYS. REPT. 63 (1980)*

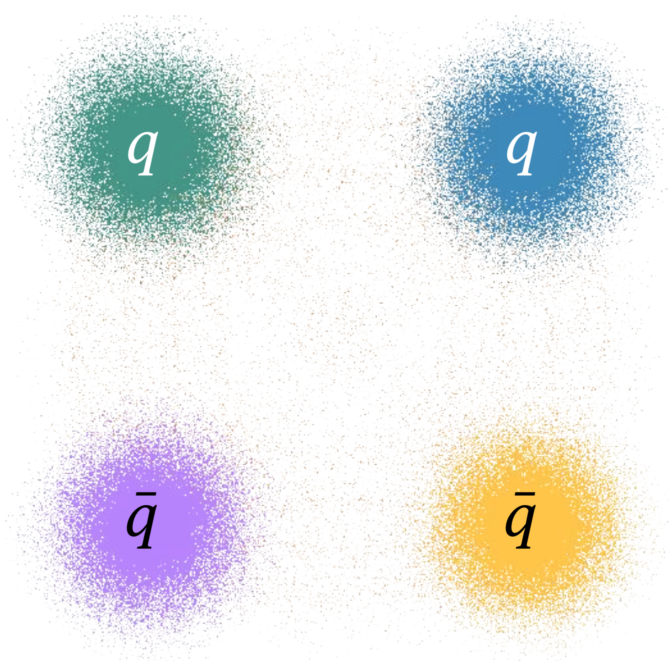
A very brief summary on Exotic Hadrons

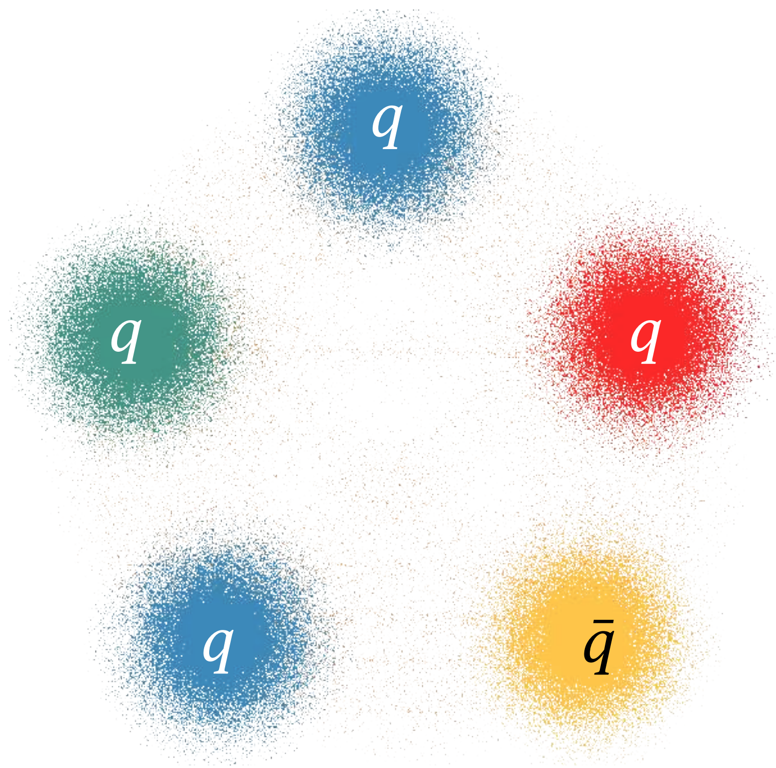
After almost 30 years…

New experimental data are announced on the existence of a tetraquark state *$X_{(3872)}$* and a pentaquark state $\Theta_{(1540)}$

both announced in 2003 by Belle Collaboration

S.K. Choi et al. [Belle Collab.], Phys. Rev. Lett. 91 (2003) 262001
T. Nakano et al. [Belle Collab.], Phys. Rev. Lett. 91 (2003) 261601

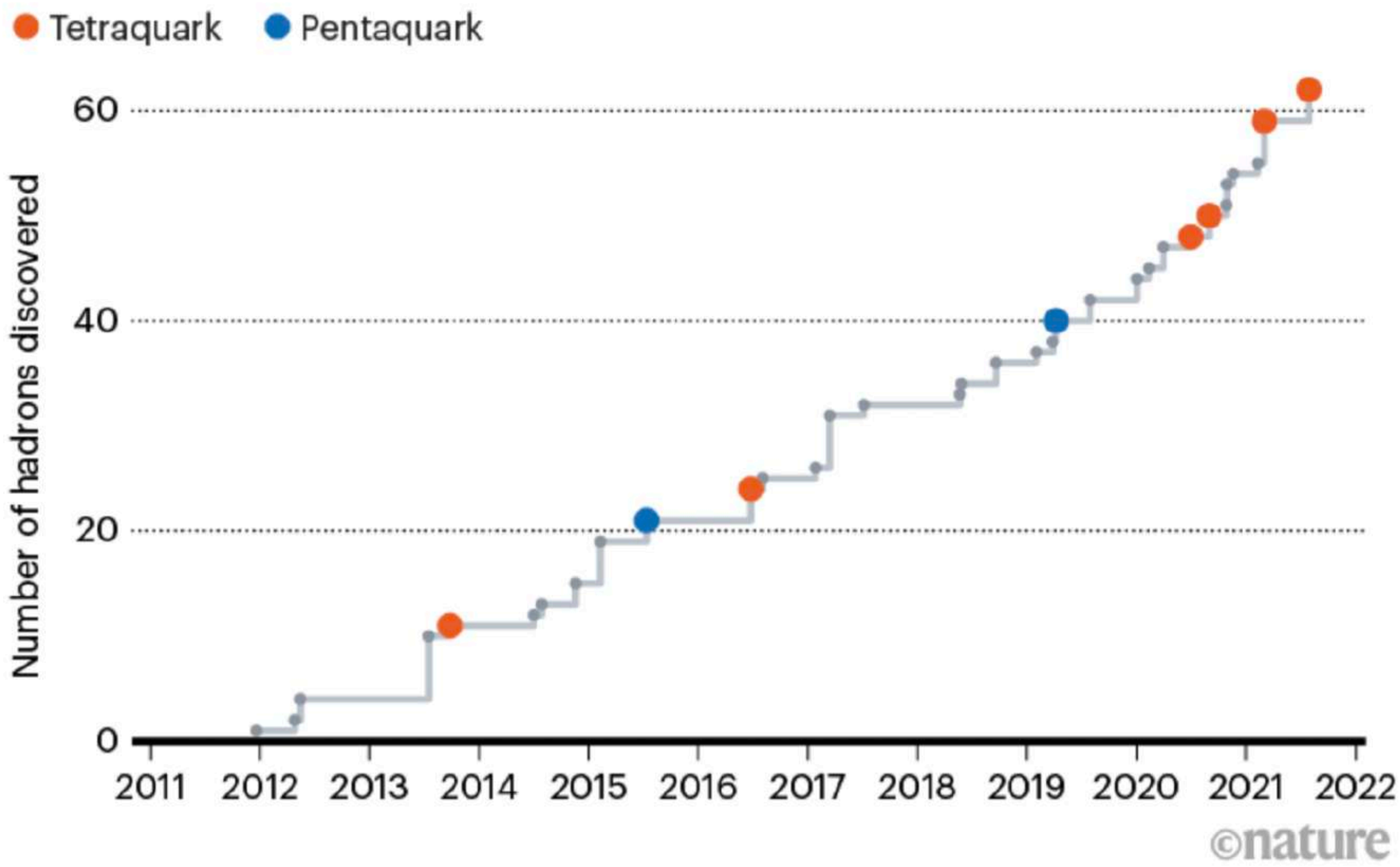


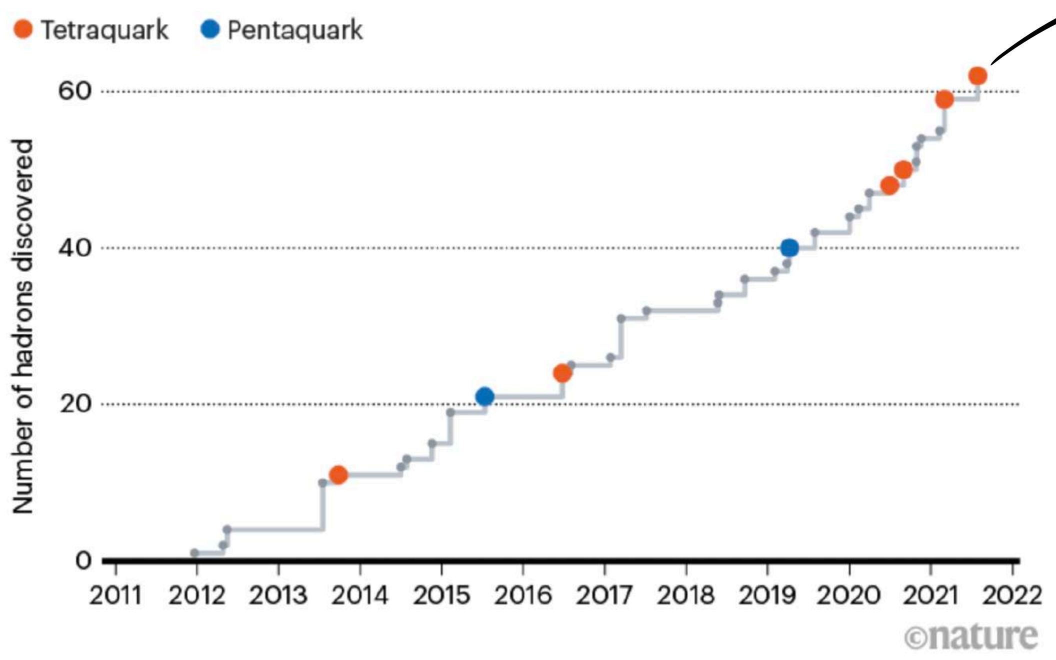


announced

Since 2013, LHCb collaboration announced the observation of several candidates for exotic hadrons

LHCb Collab., Nature Communications 13 (2022) 3351






nature COMMUNICATIONS

LHCb

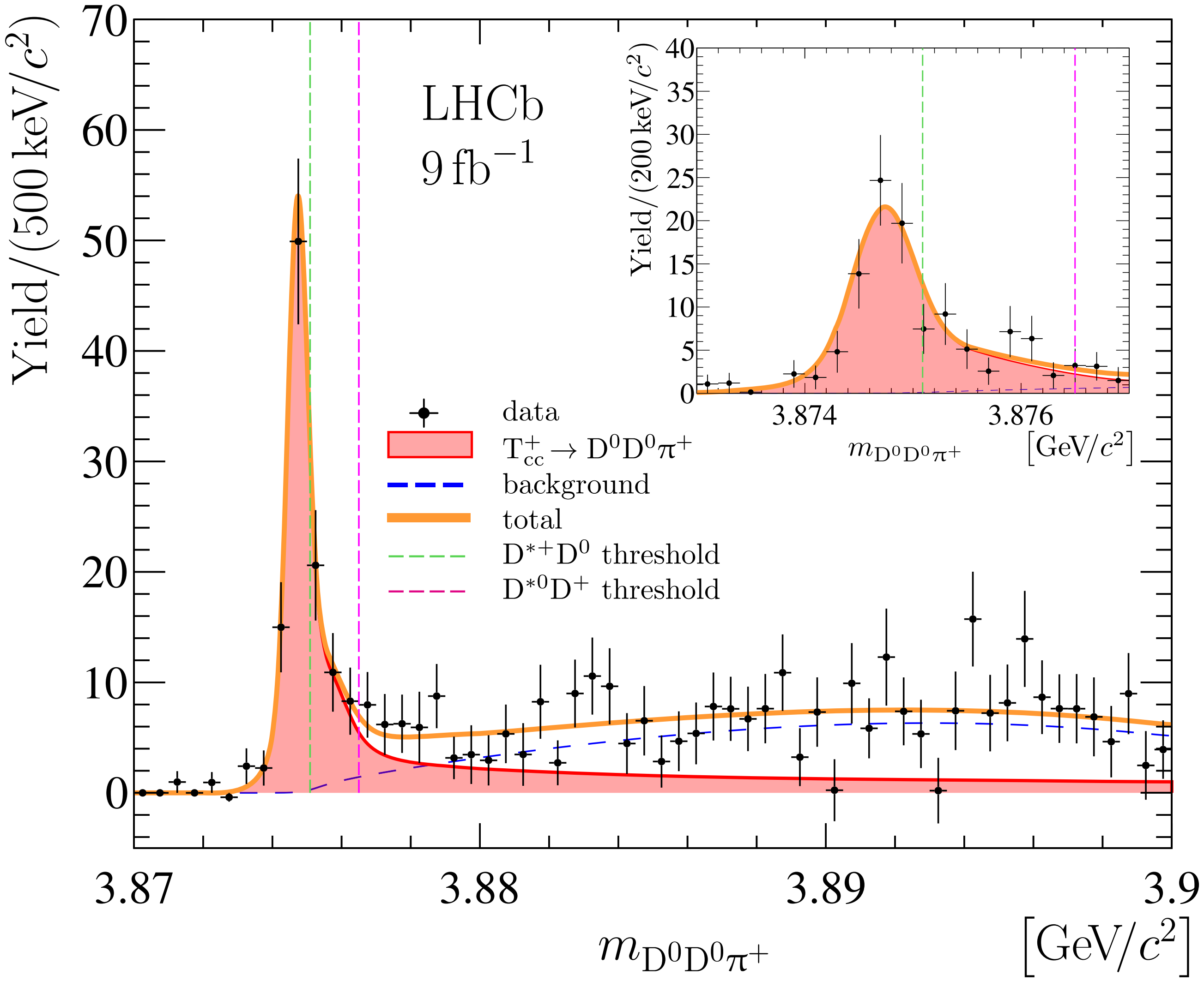
NATURE COMMUNICATIONS 13 (2022) 3351

ARTICLE

https://doi.org/10.1038/s41467-022-30206-w OPEN

Study of the doubly charmed tetraquark T_{cc}^{+}

LHCb Collaboration*



- LHCb Collab. announces the presence of a *1⁺* state in the $D^0D^0\pi^+$ *decays*.
- Absence of a signal in the D^0D^+ and $D^+D^0\pi^+$ mass distributions.
- Strong argument for interpreting such a state as the **isoscalar *T_{cc}* tetraquark, with *$J^P = 1^+$***.
- Mass around ***3875 MeV***.

THE METHOD IN QCD

QCD SUM RULES

M.A. Shifman, A.I. Vainshtein, V.I. Zhakarov

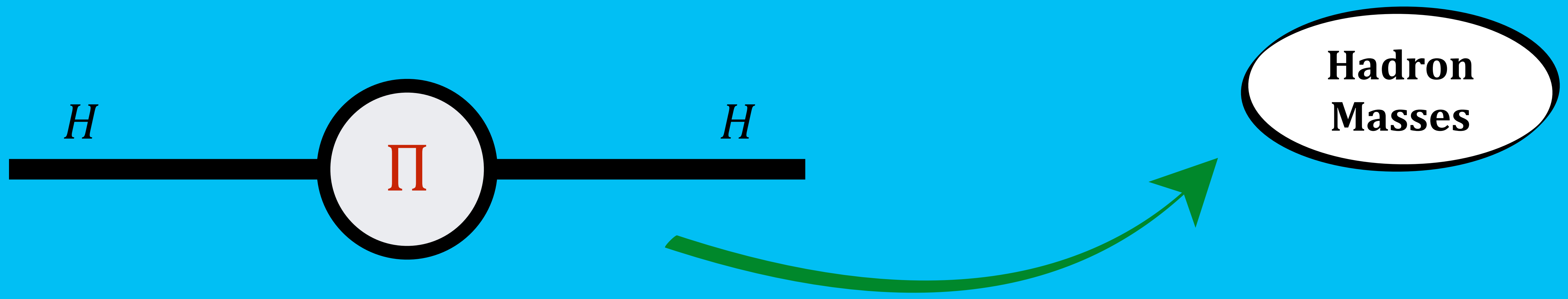
NUCL. PHYS. B 147 (1979)

Excellent reviews on the method can be found on…

- **P. Pascual and R. Tarrach, "***QCD: renormalization for practitioner*", Springer (1984)
- **L. J. Reinders, H. Rubinstein and S. Yazaki,** "*Hadron Properties from QCD Sum Rules*", Phys. Rept. 127 (1985)
- **S. Narison**, "*QCD Spectral Sum Rules*", World Sci. Lect. Notes Phys. 26 (1989)
- **S. Narison,** *"QCD as a Theory of Hadrons"*, Cambridge Monogr. Part. Phys. Nucl. Phys. Cosmol. 17 (2004)
- **B.L. Ioffe,** "QCD at Low Energies", Prog. Part. Nucl. Phys. 56 (2006)
- **H.G. Dosch, "***Nonperturbative methods in quantum chromodynamics", Prog. Part. Nucl. Phys. 33 (1994)*
- **E. de Rafael,** "*An Introduction to Sum Rules in QCD*", hep-ph/9802448 (1998)
- **F.J Yndurain, "**The Theory of Quark and Gluon Interactions", 3rd edition, Springer (1999)

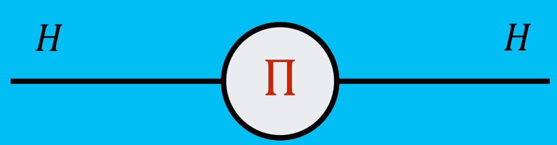
The QCD inverse Laplace sum rules (LSR) approach

2-point Correlator Function



The QCD inverse Laplace sum rules (LSR) approach

We shall be concerned with the two-point correlator:



$$\Pi^{\mu\nu}_{\mathcal{H}}(q^2) = i\int d^4x\ e^{iqx}\,\langle 0|\mathcal{T}\,\mathcal{O}^{\mu}_{\mathcal{H}}(x)\left(\mathcal{O}^{\nu}_{\mathcal{H}}(0)\right)^{\dagger}|0\rangle$$

- The local hadronic operators introduce the characteristics of the hadron H.
- It obeys Finite Energy Inverse Laplace Transform Sum Rule (LSR) and their ratios:

$$\mathcal{L}^c_n|_{\mathcal{H}}(\tau,\mu) = \int_{(2M_c+m_q+m_{q'})^2}^{t_c} dt\ t^n\ e^{-t\tau}\,\frac{1}{\pi}\mathrm{Im}\,\Pi^{(1,0)}_{\mathcal{H}}(t,\mu)$$

$$\mathcal{R}^c_{\mathcal{H}}(\tau) = \frac{\mathcal{L}^c_1|_{\mathcal{H}}}{\mathcal{L}^c_0|_{\mathcal{H}}}$$

- At the **optimization point**, we deduce the ground state mass of the hadron

$$\mathcal{R}^c_{\mathcal{H}}(\tau_0) = M^2_{\mathcal{H}}$$

The precision technique: Double Ratio of Sum Rule (DRSR)

S. NARISON, PHYS. LETT. B 210 (1988)

$$r_{\mathcal{H}'/\mathcal{H}}(\tau_0) \equiv \sqrt{\frac{\mathcal{R}^c_{\mathcal{H}'}}{\mathcal{R}^c_{\mathcal{H}}}} = \frac{M_{\mathcal{H}'}}{M_{\mathcal{H}}}$$

- In general, free from systematics errors.
- Provided that $\mathcal{R}^c_{\mathcal{H}}$ and $\mathcal{R}^c_{\mathcal{H}'}$ must **optimize** at the same values of τ and t_c.

OPTIMIZATION

The stability criteria for extracting the optimal results

- ***τ* - stability:** *region around of a minimum or inflexion points corresponding to a complete dominance of the lowest ground-state contribution.*

- ***t_c* - stability:** *we take the values until it to be around the mass of the first excitation state.*

- ***μ* - stability:** *used to fix in a rigorous optimal way, the arbitrary subtraction constant appearing in the perturbative calculation and in the QCD input renormalized parameters.*

Physical observables should not depend on these parameters.

NLO PT corrections

NLO PT corrections justify the use of **running heavy quark mass**.

QCD PARAMETERS

Parameters	Values	Sources	Refs.
$\alpha_s(M_Z)$	0.1181(16)(3)	$M_{\chi_{0c,b}}-M_{\eta_{c,b}}$	NARISON
$\overline{m}_c(m_c)$ [MeV]	1266(6)	$D,\, B_c \oplus J/\psi,\, \chi_{c1},\, \eta_c$	NARISON
$\overline{m}_b(m_b)$ [MeV]	4196(8)	$B_c \oplus \Upsilon$	NARISON
$\hat{\mu}_q$ [MeV]	253(6)	Light	NARISON
$\hat{m}_s$ [MeV]	114(6)	Light	NARISON
$\kappa \equiv \langle\bar{s}s\rangle/\langle\bar{d}d\rangle$	0.74(6)	Light-Heavy	ALBUQUERQUE, NARISON, NIELSEN
M_0^2 [GeV^2]	0.8(2)	Light-Heavy	NARISON, DOSCH, IOFFE, PIVOVAROV
$\langle\alpha_s G^2\rangle$ [GeV^4]	$6.35(35)10^{-2}$	Light-Heavy	NARISON
$\langle g^3 G^3\rangle/\langle\alpha_s G^2\rangle$	8.2(1.0) [GeV^2]	J/ψ	NARISON
$\rho\alpha_s\langle\bar{q}q\rangle^2$ [GeV^6]	$5.8(9)10^{-4}$	Light, τ-decay	NARISON, DOSCH, TARRACH

The full list of references can be found in

Nucl. Phys. A 1023 (2022)

RESULTS

THE T_{cc} STATE

PHYS. LETT. B 649 (2007)

Since, the pioneering work of **Navarra, Nielsen and Lee**, the mass and coupling of T_{cc} and its beauty analogue have been extracted from LSR by different groups.

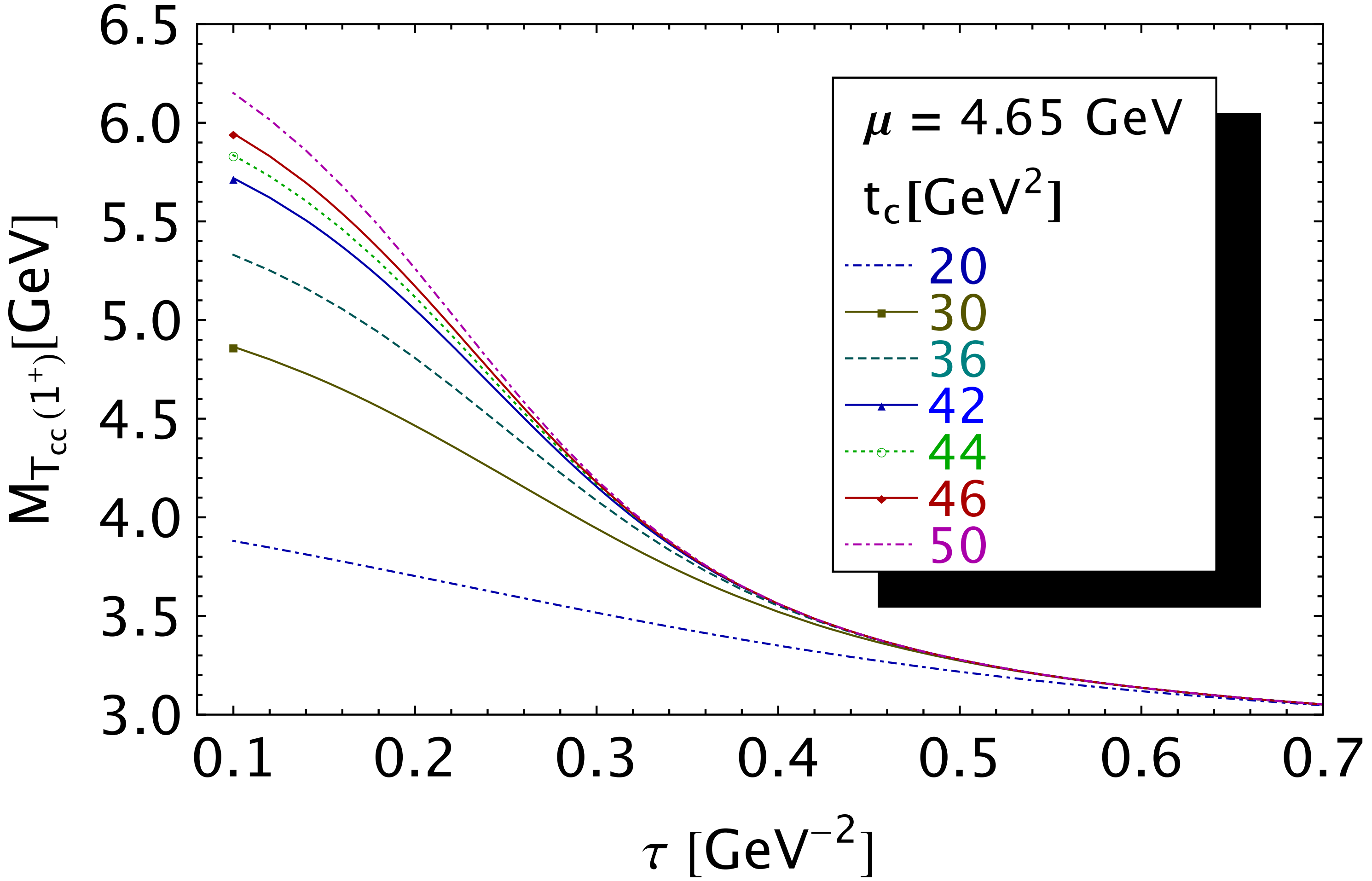
1. *Z.-G. WANG*
2. *AGAEV, AZIZI, H. SUNDU*
3. *TANG, WAN, MALTMAN, QIAO*
4. *DU, CHEN, ZHU*

We improve and extend the analysis using **LSR** and **DRSR** by including the factorized NLO PT contributions and controlling the different sources of the errors.

Tetraquark:

$$\mathcal{O}_T^{1^+} = \frac{1}{\sqrt{2}}\epsilon_{ijk}\,\epsilon_{mnk}\left(c_i^T\,C\gamma^\mu\,c_j\right)\left[\left(\bar{u}_m\,\gamma_5 C\,\bar{d}_n^T\right) - \left(\bar{d}_m\,\gamma_5 C\,\bar{u}_n^T\right)\right]$$

THE T_{cc} STATE



LSR Analysis

stability region for the set

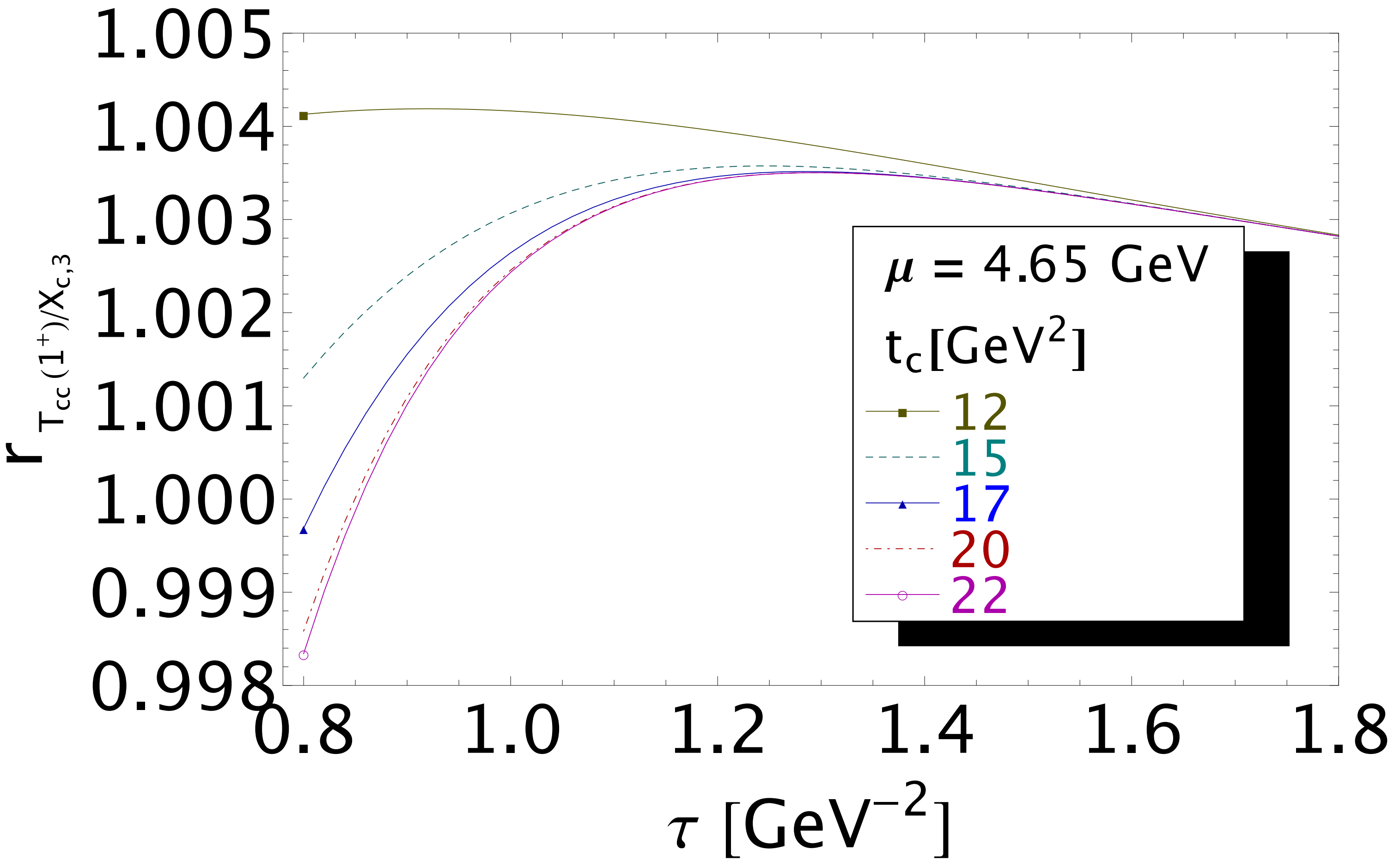
τ = 0.31 – 0.34 GeV^{-2}

t_c = 30 – 46 GeV^2

From which we deduce:

$$M_{T_{cc}}(1^+) = 3885(123)\ \text{MeV}$$

This mass can be compared with the experimental value ***3875 MeV***.



DRSR Analysis

Ratio between T_{cc} and X_{3872}

stability region for the set

τ = 1.24 – 1.30 GeV^{-2}

t_c = 15 – 20 GeV^2

From which we deduce:

$$r_{T_{cc}^{1^+}/X_c} = 1.0035(10)$$

Taking the experimental mass of ***X_{3872}*: *3871.65 ± 0.06 MeV***

$$M_{T_{cc}}(1^+) = 3886(4)\ \mathrm{MeV}$$

THE T_{cc} STATE

$$M_{T_{cc}}(1^+) = 3885(123)\ \text{MeV}$$

LSR Analysis

$$M_{T_{cc}}(1^+) = 3886(4)\ \text{MeV}$$

DRSR Analysis

- Both results are in agreement, but we obtain a very accurate one with DRSR
- This value is comparable with the recent LHCb data: $T_{cc}(1^+) = 3875\ \text{MeV}$
- *(9 ± 4) MeV* **above** the D*D threshold of *3877 MeV.*

THE T_{ccsu} STATE

Tetraquark: $$\mathcal{O}_{T^{1^+}_{us}} = \epsilon_{ijk}\,\epsilon_{mnk}\left(c_i\, C\gamma^\mu c_j^T\right)\left(\bar{u}_m\,\gamma_5 C\bar{s}_n^T\right)$$

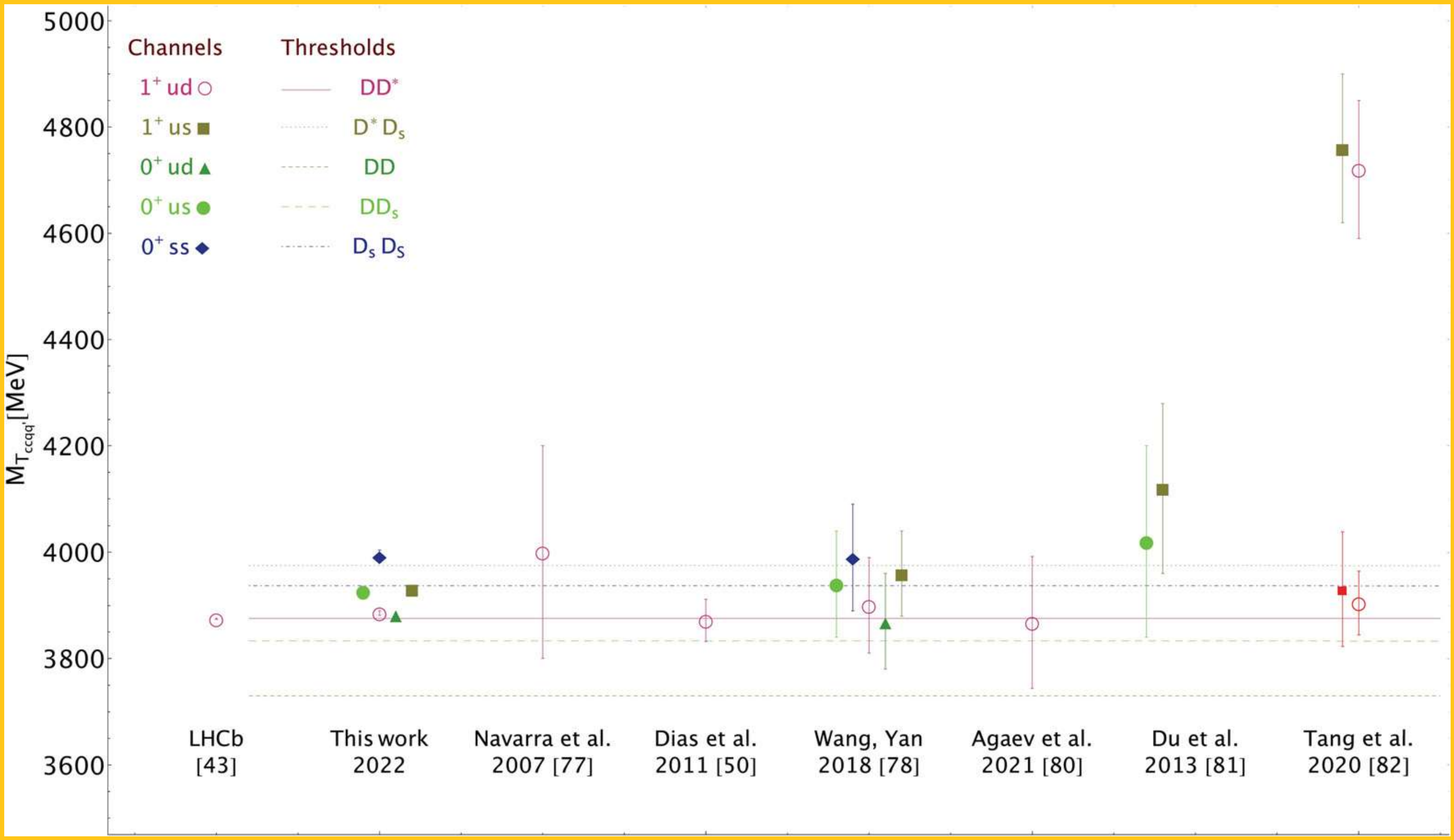
We can perform the SU(3) mass ratios between the $\boldsymbol{T_{ccsu}}$ and $\boldsymbol{T_{cc}}$

$$r_{T_{cc\bar{s}\bar{u}}/T_{cc}(1^+)} = 1.0115(13) \quad \Longrightarrow \quad M_{T_{cc\bar{s}\bar{u}}}(1^+) = 3931(7)\ \mathrm{MeV}$$

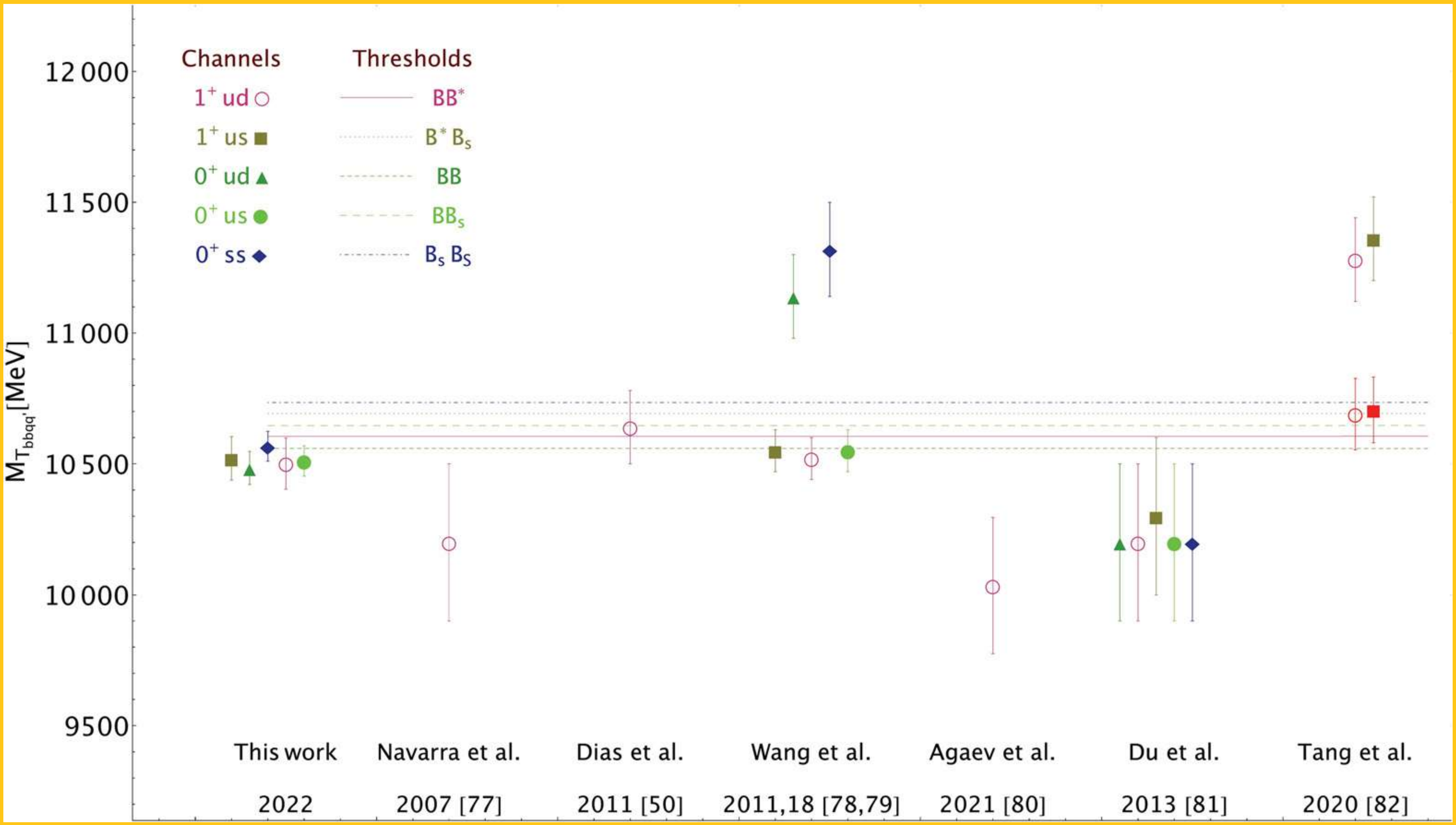
DRSR Analysis

- This value is a prediction for the SU(3) breaking mass symmetry.
- We notice that the mass value is **below** the $D^*\,D_s$ threshold of *3975 MeV.*
- *Then we do not expect strong decay channels for this state.*
- LHCb Collaboration could provide some new results on the *$D^*\,D_s$* decay channel in a future publications.

QCD SUM RULES RESULTS FOR T_{cc}



QCD SUM RULES RESULTS FOR T_{bb}



Confronting DRSR results with Lattice and Quark Models

CONCLUSIONS

CONCLUSIONS

- We do an extensive analysis on axialvector (1^+) T_{QQ}-like state.
- We confront our results with the ones from different approaches.
- The T_{cc} state is expected to be around the physical threshold.
- While the T_{bb} state is below the threshold.
- We do predictions for SU(3) breakings states and we hope LHCb could test them in a near future publications.
- In general, our results for the masses of different states are grouped around the physical thresholds.
- For more details, please check it out...

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THANK YOU FOR YOUR ATTENTION!

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