Observation of a family of all-charm tetraquarks

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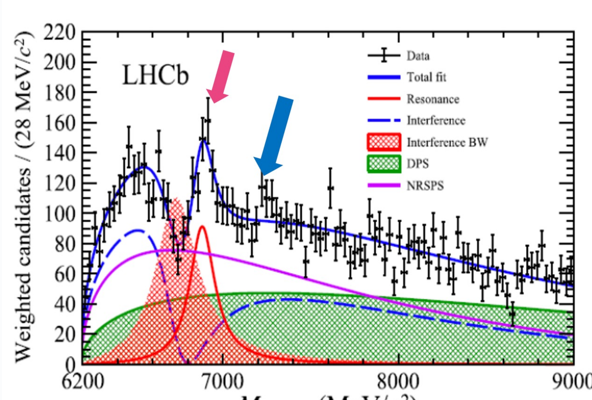
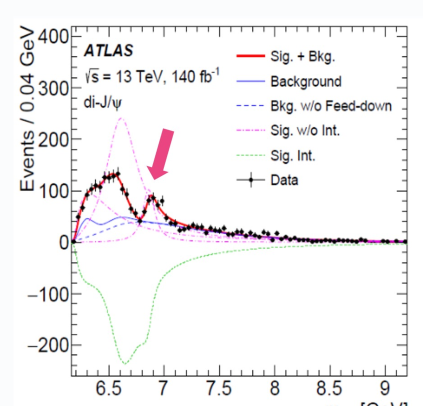
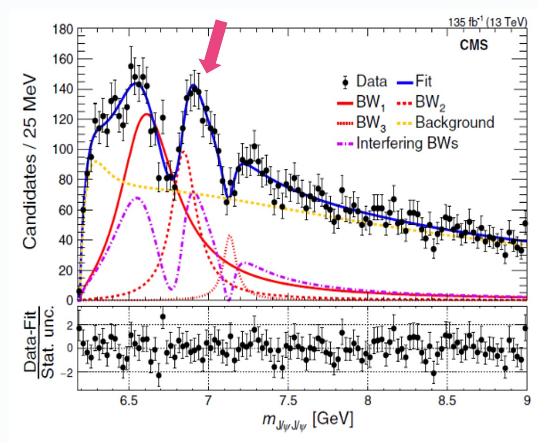
Introduction



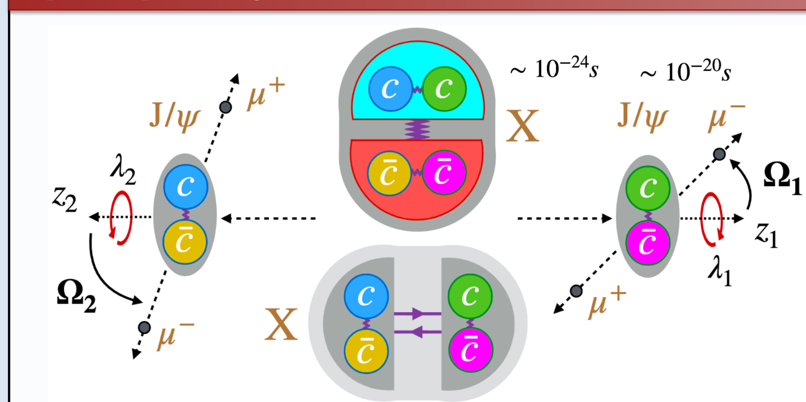




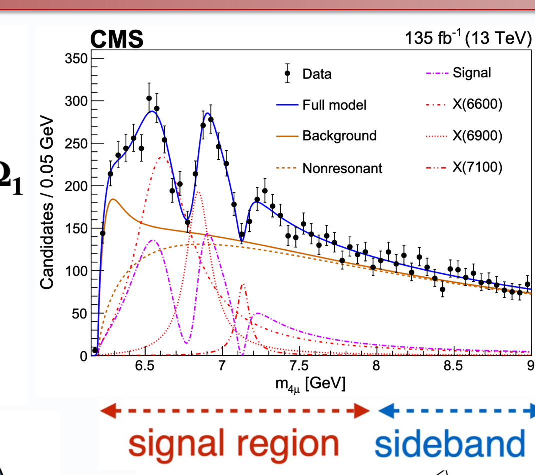
- **Three LHC experiments observe X(6900) + additional structure [1-3]**
  - Only CMS claimed X(6600) & X(7100)
  - Different modeling of "hump" below X(6900) (also called $T_{cc\bar{c}\bar{c}}(6900)^0$)
  - 7.2 GeV: LHCb hint but not considered; ATLAS 3σ (local) hint in $J/\psi\psi(2S)$
- **All experiments use interference, but in different ways**
  - LHCb added extra BW to interfere with SPS background: their X(6900) is NOT interfering!
- **All exp see a threshold excess, NOT explained! Classified as background**

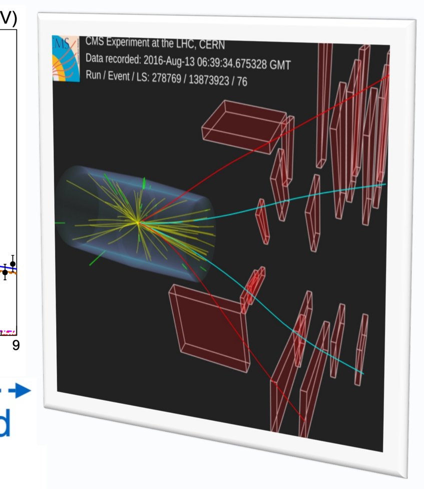
$$J^{PC} = ?$$

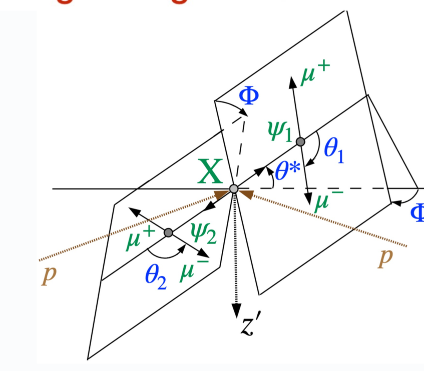
Spin-parity measurement with CMS Run 2 data



λ_1	decay helicity amplitudes	λ_2	
	A_{++}, A_{--}, A_{00}		$J_X = 0$
	A_{+0}, A_{0+}, A_{-0}, A_{0-}		$J_X = 1$
	A_{+-}, A_{-+}		$J_X \geq 2$







$\mathscr{P}(\Phi, \theta_1, \theta_2; m_{4\mu})$

Lorentz-invariant amplitudes for different spin-parity configurations

- Symmetries:
  - angular momentum: $|\lambda_1 - \lambda_2| \leq J$
  - identical J/ψ bosons $A_{\lambda_1\lambda_2} = (-1)^J A_{\lambda_2\lambda_1}$
  - P & C conserved in QCD: X with definite J^{PC}; $C = +1$; $A_{\lambda_1\lambda_2} = P(-1)^J A_{-\lambda_1-\lambda_2}$

Test 8+ J_X^P models:

0^{-+}	0^-	$A_{++} = -A_{--}$	
0^{++}	0_m^+ and 0_h^+	$A_{++} = A_{--}$ and A_{00}	← note 2 d.o.f.
1^{-+}	1^-	$A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$	
1^{++}	1^+	$A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$	
2^{-+}	2_m^- and 2_h^-	$A_{++} = -A_{--}$ and $A_{+0} = A_{0+} = -A_{-0} = -A_{0-}$	← note 2 d.o.f.
2^{++}	2_m^+	$A_{++} = A_{--}$, A_{00}, $A_{+0} = A_{0+} = A_{-0} = A_{0-}$, and $A_{+-} = A_{-+}$	

note 4 d.o.f. for 2^{++}, test one model

- Expect three X resonances to have the same tensor structure:

$$A(X_{J=0} \to V_1V_2) = \left(a_1(q^2)m_V^2\epsilon_1^*\epsilon_2^* + a_2(q^2)f_{\mu\nu}^{*(1)}f^{*(2),\mu\nu} + a_3(q^2)f_{\mu\nu}^{*(1)}\tilde{f}^{*(2),\mu\nu}\right)$$

0_m^+: $A_{00} = A_{++} = A_{--}$ at $2m_{J/\psi}$ threshold; A_{00} at large m_X, $A_{++} = A_{--}$

0_h^+

0^-: $A_{++} = -A_{--}$

empirical form factors $(m_{4\mu}^2)$

$$A(X_{J=1} \to V_1V_2) = \left(b_1(q^2)\left[(\epsilon_1^*q)(\epsilon_2^*\epsilon_X) + (\epsilon_2^*q)(\epsilon_1^*\epsilon_X)\right] + b_2(q^2)\epsilon_{\alpha\mu\beta\nu}\epsilon_X^{\alpha}\epsilon_1^{*,\mu}\epsilon_2^{*,\nu}\tilde{q}^{\beta}\right)$$

1^-: $A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$

1^+: $A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$

more for spin-2

$$A(X_{J=2} \to V_1V_2) = 2c_1(q^2)t_{\mu\nu}f^{*1,\mu\alpha}f^{*2,\nu\alpha} + 2c_2(q^2)t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2}f^{*1,\mu\alpha}f^{*2,\nu\beta} + c_3(q^2)\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2}t_{\beta\nu}(f^{*1,\mu\nu}f_{\mu\alpha}^{*2} + f^{*2,\mu\nu}f_{\mu\alpha}^{*1}) + c_4(q^2)\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2}t_{\mu\nu}f_{\alpha\beta}^{*1}f^{*(2),\alpha\beta} + m_V^2\left(2c_5(q^2)t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2c_6(q^2)\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}t_{\mu\nu}(\epsilon_1^{*\nu}\epsilon_2^{*\alpha} - \epsilon_1^{*\alpha}\epsilon_2^{*\nu}) + c_7(q^2)\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right) + c_8(q^2)\frac{\tilde{q}_\mu\tilde{q}_\nu}{\Lambda^2}t_{\mu\nu}f_{\alpha\beta}^{*1}\tilde{f}^{*(2),\alpha\beta} + c_9(q^2)\frac{t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho}q^\sigma + c_{10}(q^2)\frac{t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^4}\epsilon_{\mu\nu\rho\sigma}q^\rho\tilde{q}^\sigma(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*))$$

2_m^-: $(A_{++} = -A_{--})$

2_h^-: $(A_{+0} = A_{0+} = -A_{-0} = -A_{0-})$

2_m^+ — minimal representative model including all amplitudes:

4 d.o.f.: A_{00}, $A_{++} = A_{--}$, $A_{+0} = A_{0+} = A_{-0} = A_{0-}$, $A_{+-} = A_{-+}$ — unique for 2^{++} (or $J \geq 2$)

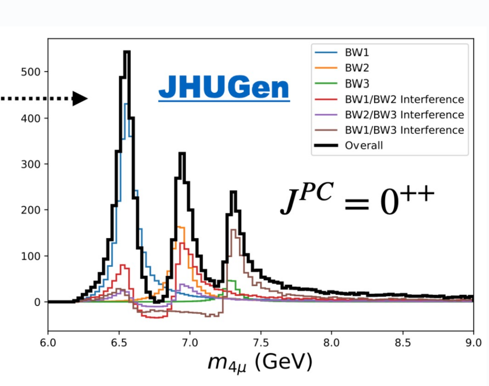
basis of 2^{++} could be equivalent to 2_m^+, 0_m^+, 0_h^+, 1^+

if data consistent with 2_m^+ ⇒ unambiguously 2^{++} (or $J \geq 2$)

Spin-parity analysis

- Full model possible, but very complex

$\mathscr{P}(\Phi, \theta_1, \theta_2; m_{4\mu})$



(1) Same properties of 3 resonances:

$$\mathscr{P}(m_{4\mu}, \vec{\Omega}) = \mathscr{P}(m_{4\mu}) \cdot T(\vec{\Omega}\,|\,m_{4\mu})$$

empirical — angular

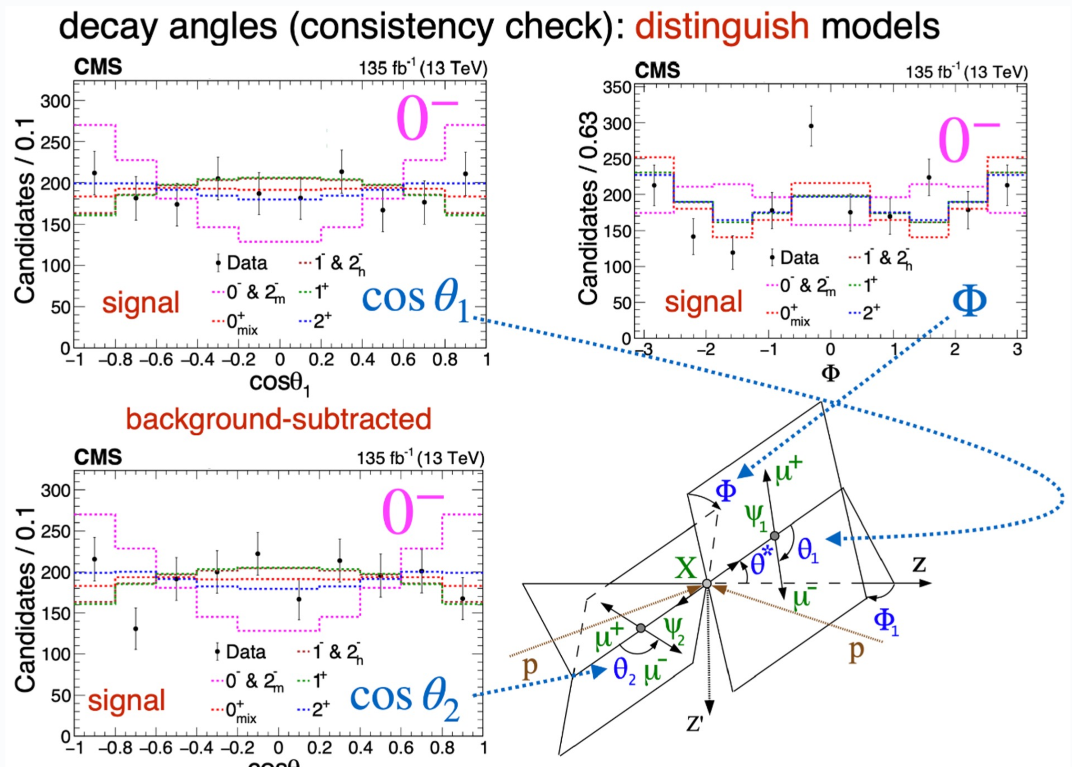
(2) Pairwise tests of J_X^P hypotheses i and j: arXiv:1208.4018

$$\text{MELA} \quad \mathscr{D}_{ij}(\vec{\Omega}\,|\,m_{4\mu}) = \frac{\mathscr{P}_i(\vec{\Omega}\,|\,m_{4\mu})}{\mathscr{P}_i(\vec{\Omega}\,|\,m_{4\mu}) + \mathscr{P}_j(\vec{\Omega}\,|\,m_{4\mu})}$$

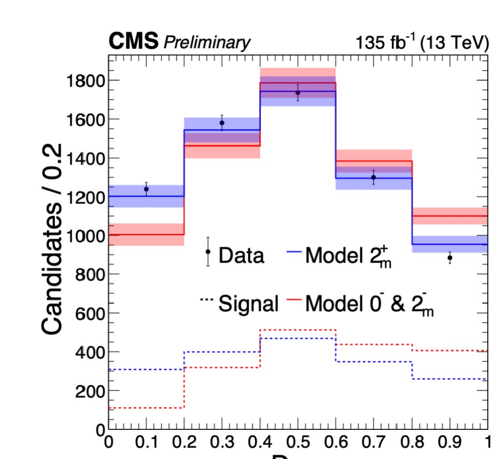
1 optimal observable ⇐ Higgs boson discovery and spin-parity

- Final 2D model: $\mathscr{P}_{ijk}(m_{4\mu}, \mathscr{D}_{ij}) = \mathscr{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathscr{D}_{ij}\,|\,m_{4\mu})$

decay angles (consistency check): distinguish models



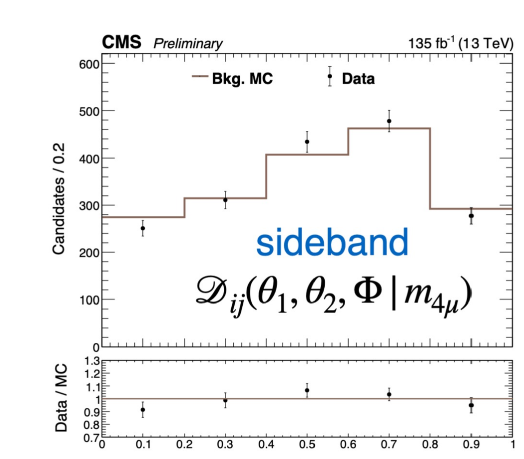
- 1D projection of data, optimal for $j = 0^-(2_m^-)$ vs $i = 2_m^+$



optimal observable

$$\text{MELA} \quad \mathscr{D}_{ij}(\vec{\Omega}\,|\,m_{4\mu}) = \frac{\mathscr{P}_i(\vec{\Omega}\,|\,m_{4\mu})}{\mathscr{P}_i(\vec{\Omega}\,|\,m_{4\mu}) + \mathscr{P}_j(\vec{\Omega}\,|\,m_{4\mu})}$$

1D projections from 2D ⇒ limited information

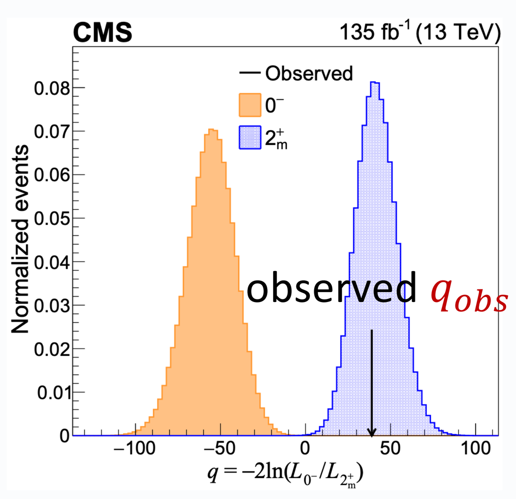


background model from MC
control in sidebands
systematic variations

Hypothesis tests and results

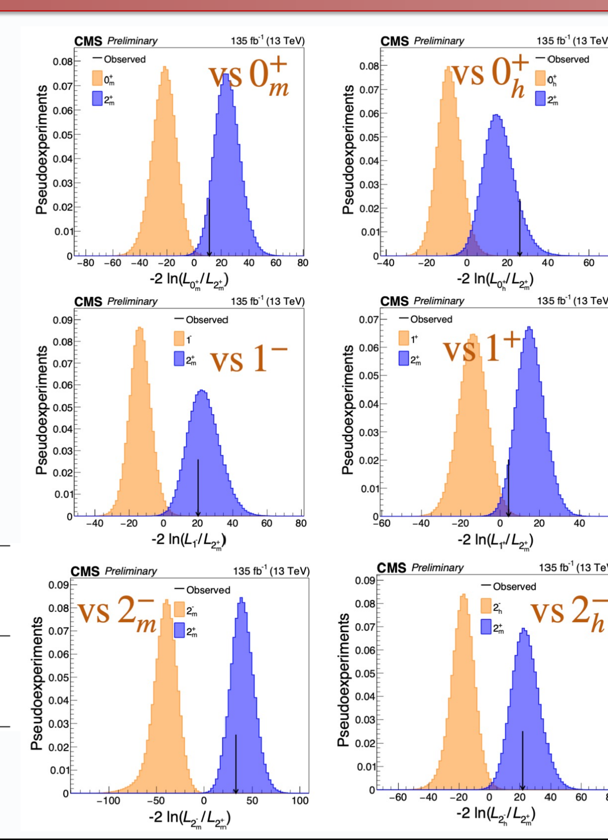
- Hypothesis test with toy MC for $J_1^P = 2_m^+$ vs $J_2^P = 0^-$
- Test statistic $q = -2\ln(\mathcal{L}_{J_2^P}/\mathcal{L}_{J_1^P})$
- Consistency of data with J_1^P/J_2^P using p-value:
  $p = P(q \leq q_{obs}|J_1^P + bkg)$
  $p = P(q \geq q_{obs}|J_2^P + bkg)$
- Significance: Converted from p-value via Gaussian one-sided tail integral
- Confidence level

$$CL_s = \frac{P(q \geq q_{obs}|J_2^P + bkg)}{P(q \geq q_{obs}|J_1^P + bkg)}$$



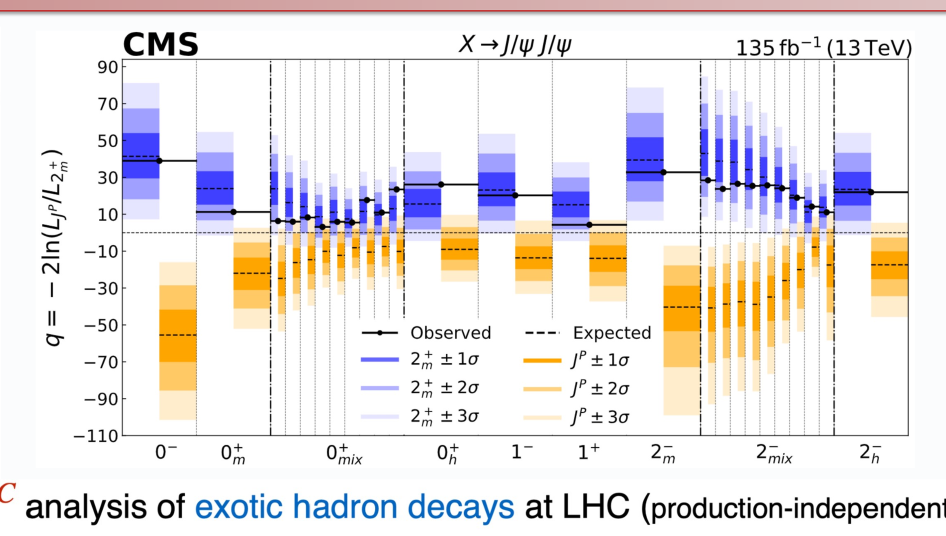
		Observed p-value	Observed Z-score	Expected p-value	Expected Z-score
0^- vs 2_m^+	0^-	2.7×10^{-13}	7.2	6.5×10^{-14}	7.4
	2_m^+	4.2×10^{-1}	0.2	0.50	0.0

[4]



- Combine 2D fit: $\mathscr{P}_{ijk}(m_{4\mu}, \mathscr{D}_{ij})$
  - $J^P = 2_m^+$ model survives

J_X^P	p-value	Z-score reject J_X^P	
0^-	2.7×10^{-13}	7.2	
0_m^+	4.3×10^{-5}	3.9	
0_{mix}^+	1.4×10^{-2}	2.2	mix
0_h^+	3.1×10^{-9}	5.8	
1^-	8.0×10^{-8}	5.2	
1^+	4.7×10^{-3}	2.6	
2_m^-	4.1×10^{-12}	6.8	
2_{mix}^-	6.5×10^{-4}	3.2	mix
2_h^-	2.2×10^{-8}	5.5	



J^{PC} analysis of exotic hadron decays at LHC (production-independent)

- consistent picture: set of 3 exotic teraquark resonances with the same J^{PC} $n = (1,)2,3,4$
- $PC = ++$ very certain
- $J \neq 1$ at $> 99\%$ CL
- $J \neq 0$ at $> 95\%$ CL
- $J > 2$ possible, but highly unlikely, require $L \geq 2$
- $J = 2$ consistent, rare in nature, naively expected $J = 0$

Bibliography

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